DARK MATTER SEARCHES WITH COSMIC RAYS

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NewDark

Searches for dark matter

1922

First attempt at a theory of the arrangement and motion of the sidereal system. APJ, 55.302

Jacobus Kapteyn

Consequently $m_1+m_2=1.60$, which agrees with Table IV if we suppose that the combined mass of the two components and not that of a single component is comparable with the mass of a single star, and especially if we further consider that there are theoretical grounds for expecting that the average mass will decrease for increasing distance.[1]

Remark. Dark matter. It is important to note that what has here been determined is the total mass within a definite volume, divided by the number of luminous stars. I will call this mass the average effective mass of the stars. It has been possible to include the luminous stars completely owing to the assumption that at present we know the luminosity-curve over so large a part of its course that further extrapolation seems allowable.

Now suppose that in a volume of space containing l luminous stars there be dark matter with an aggregate mass equal to Kl average luminous stars; then, evidently the effective mass equals $(l+K)\times$average mass of a luminous star.

We therefore have the means of estimating the mass of dark matter in the universe. As matters stand at present it appears at once that this mass cannot be excessive. If it were otherwise, the average mass as derived from binary stars would have been very much lower than what has been found for the effective mass.

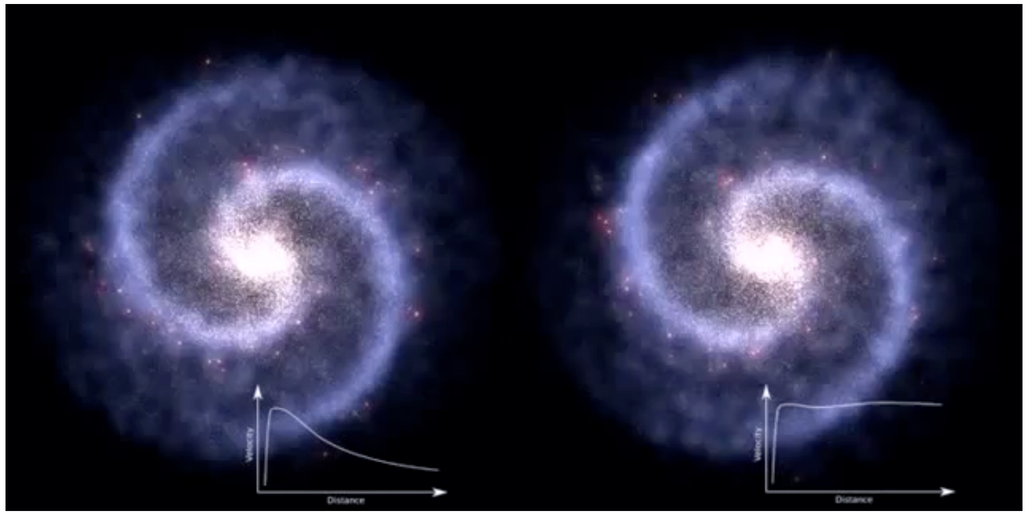
7. *Angular velocities* (ω) *in the plane of the galaxy.*—Ignoring for an instant the fact that the stars in the Milky Way cannot be systematically at rest and treating the stars near this plane in the same way as those near the axis, I am led by a formula analogous to (17) to values of η which are not quite half those given in Table IV. I suppose that the difference must be wholly due to the centrifugal force induced by the rotational motions. In fact, I assume that the average mass is the same throughout the whole system, at least for points on the same equidensity surface.

If, therefore, ρ and ρ' represent the distances from the center, of two points on the same equidensity surface, the first in the direction of the Pole, the second in the Milky Way, for which points

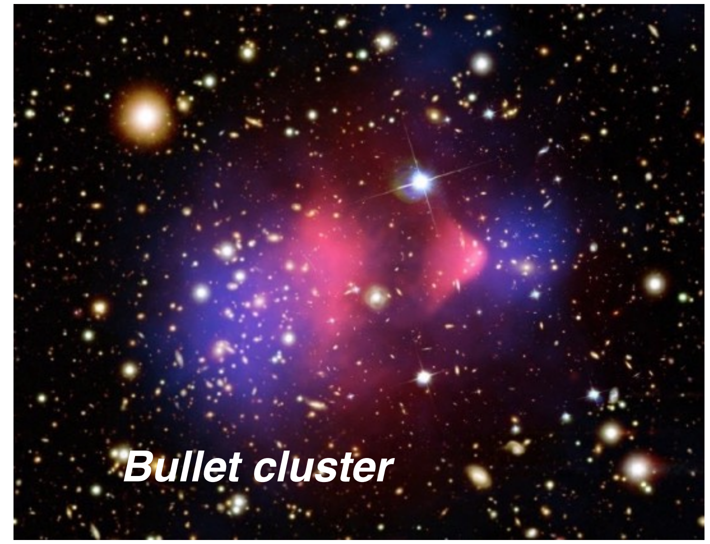
[1] Jeans, *Problems of Cosmogony and Stellar Dynamics* (1919), p. 239.

Evidences for dark matter

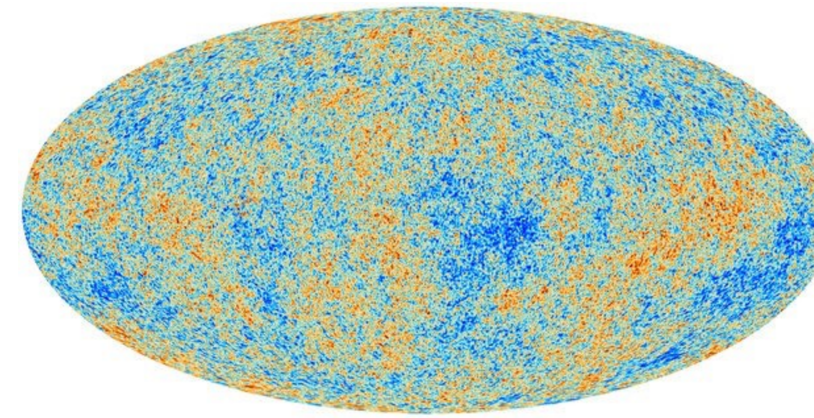
Spiral galaxies



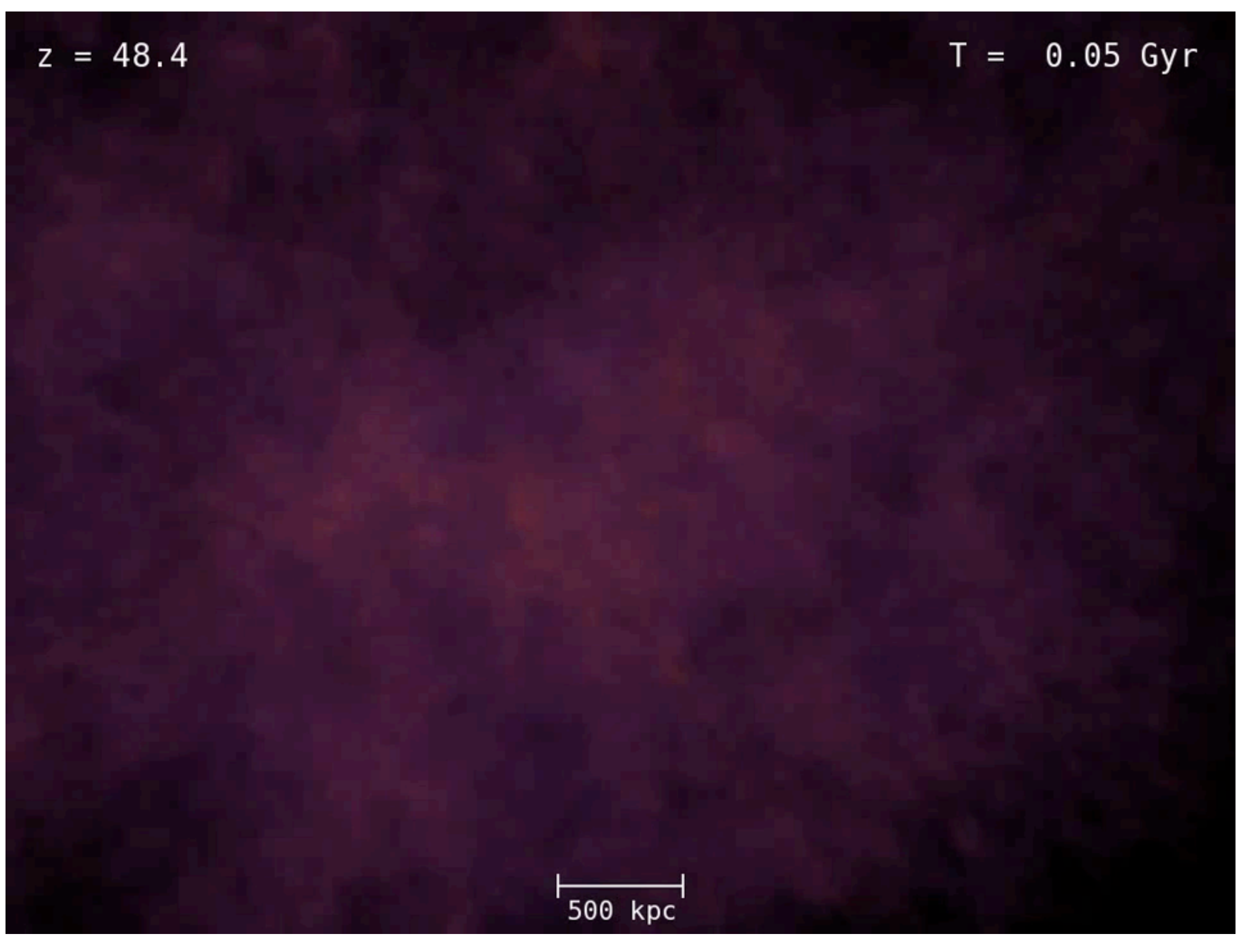
Galaxy clusters



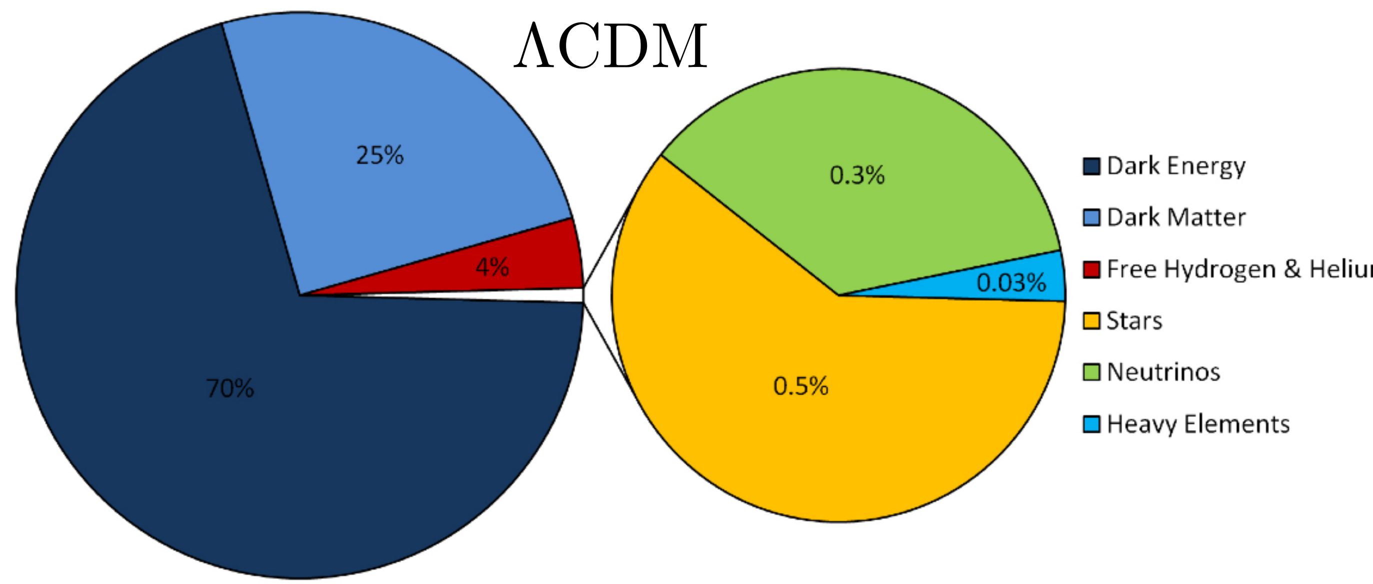
Cosmology

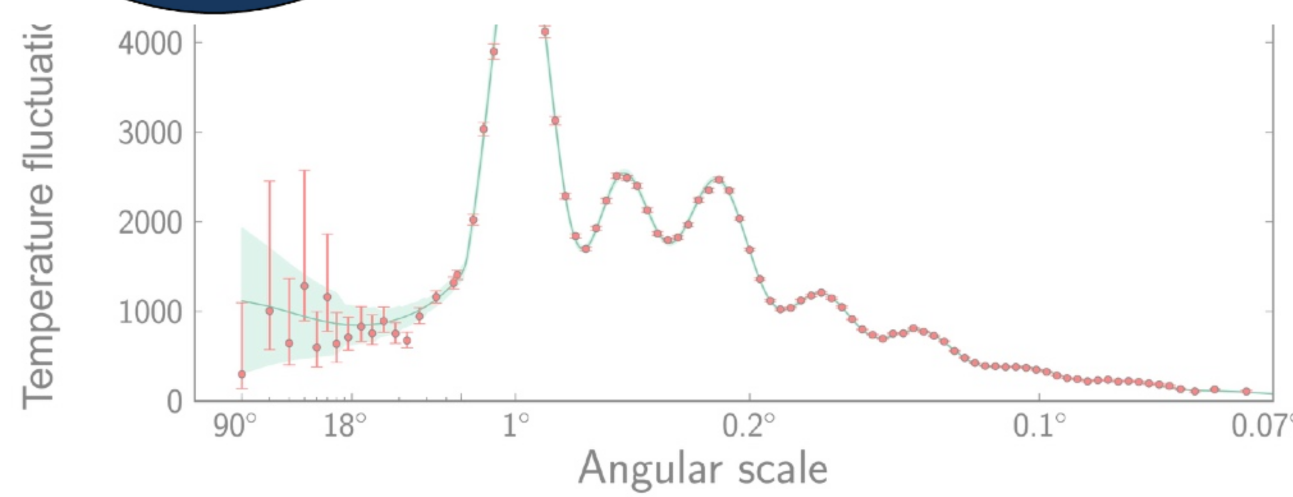


Planck - 2013



Cosmological simulations (Millenium)





Dark matter candidates

- Massive compact halo objects (MACHO): brown dwarfs, black holes…
  - ✗ Strong constraints from observations (microlensing …)
    But wait and see…

M. Milgrom

- Modified newtonian gravity (MOND)
  - ✗ Does not explain observations of galaxy clusters.
  - ✗ Does not explain CMB power spectrum.

- New particles beyond the Standard Model of particles

  Sterile neutrinos

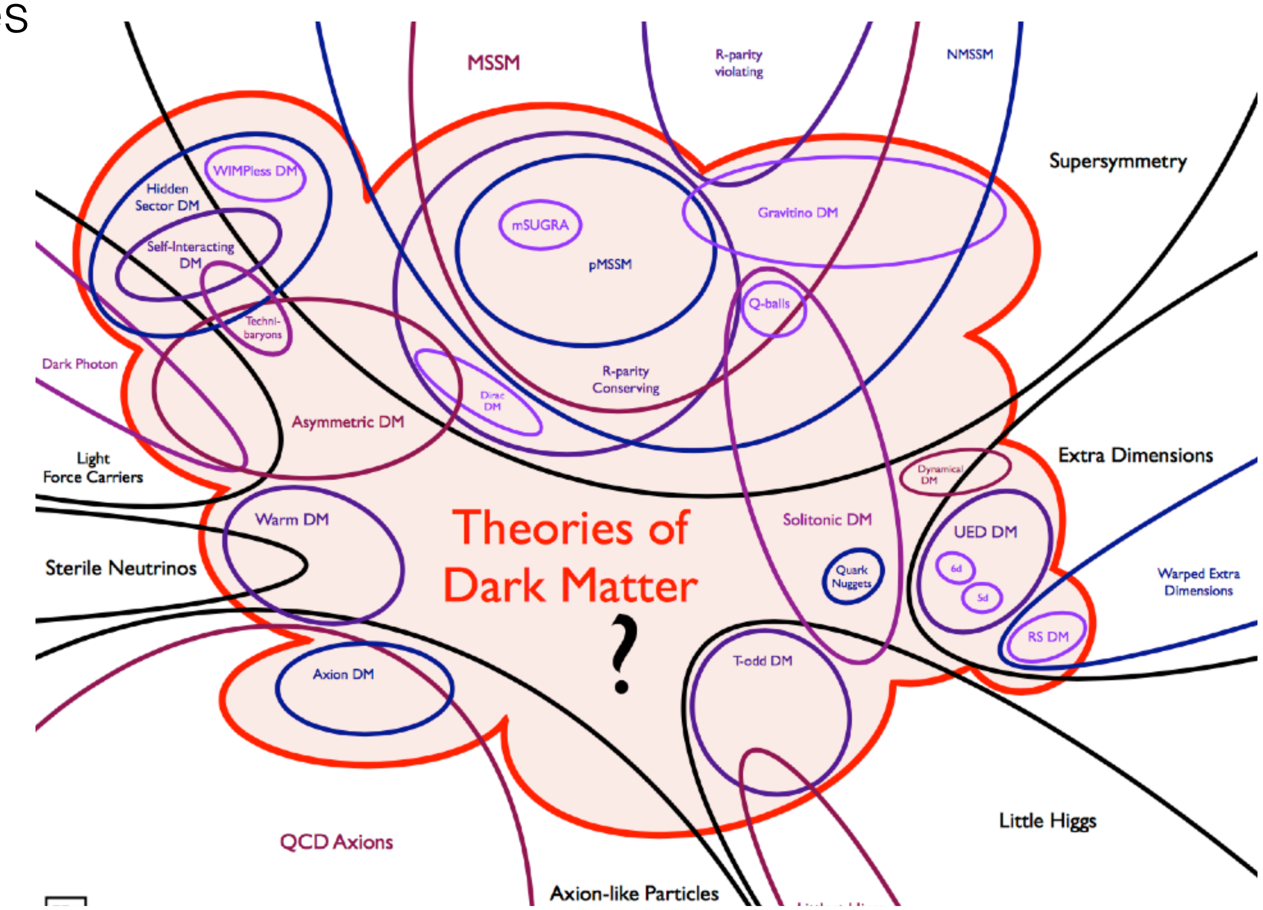
  Axions

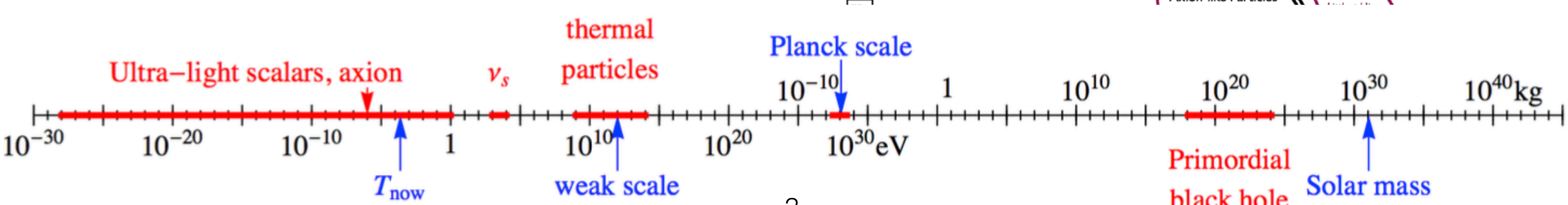
  Supersymetric particles (SUSY)

  Extra dimensions particles (UED)

  Grand unified theory (GUT)

  etc…





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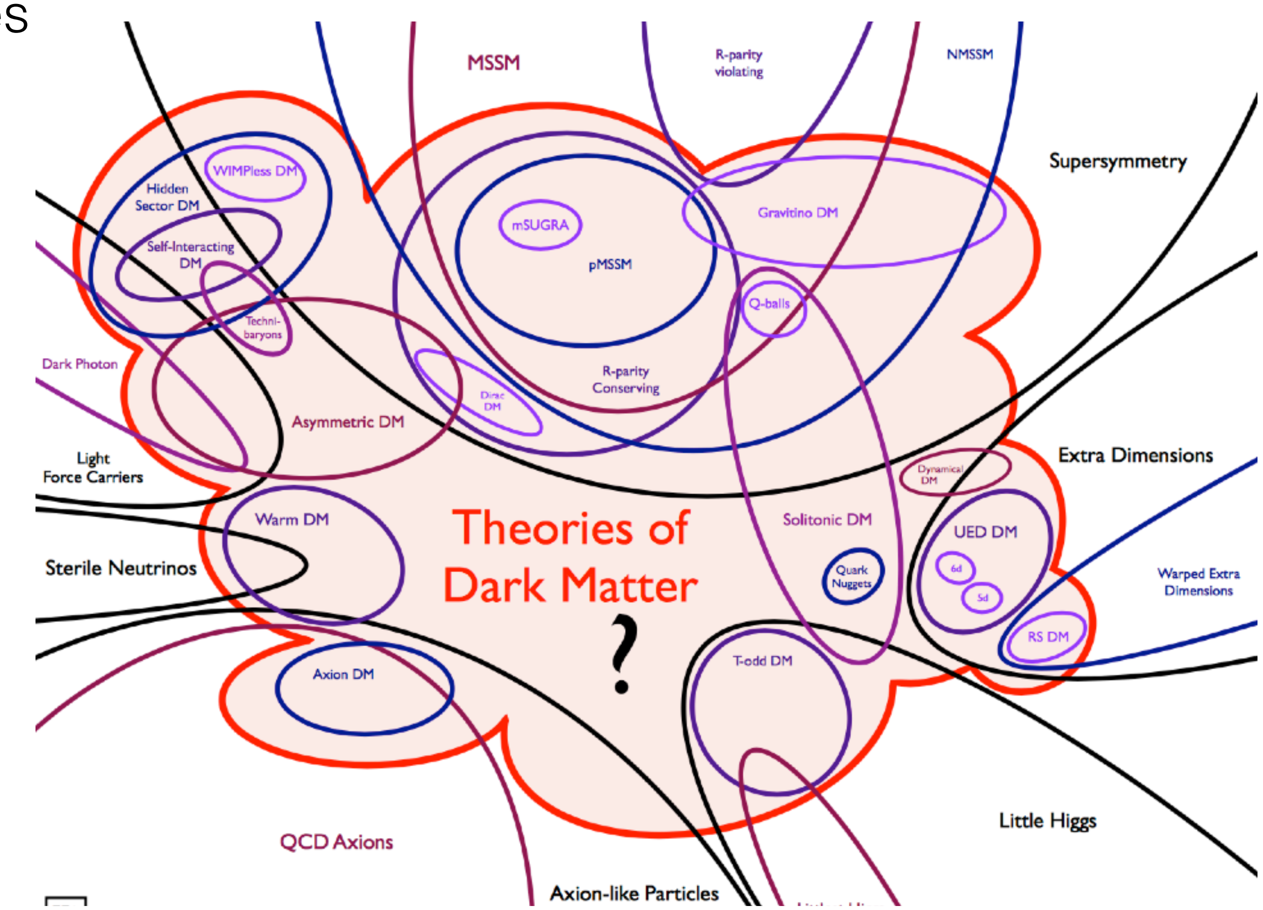
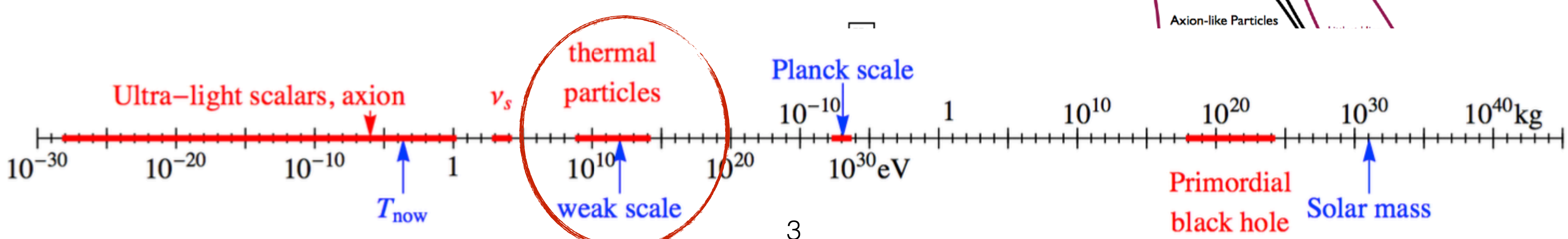


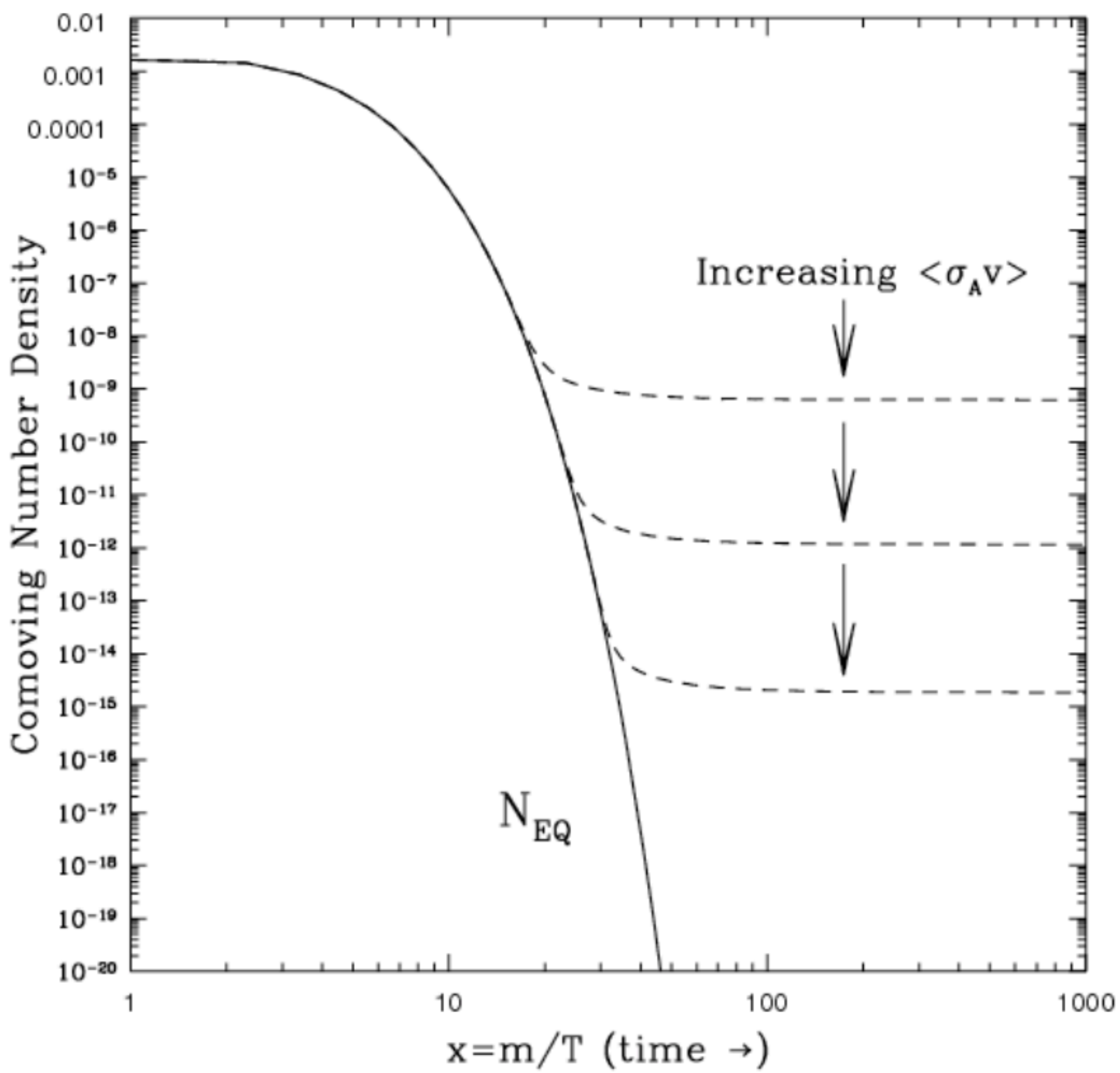


The WIMP paradigm (**W**eakly **I**nteractive **M**assive **P**articles)

Assuming DM particles are thermally produced in the early Universe:

Dark matter particles should be:

- ✓ Neutral
- ✓ Very long lived
- ✓ Cold ⇔ massive (≳ keV)
- ✓ Feebly interactive

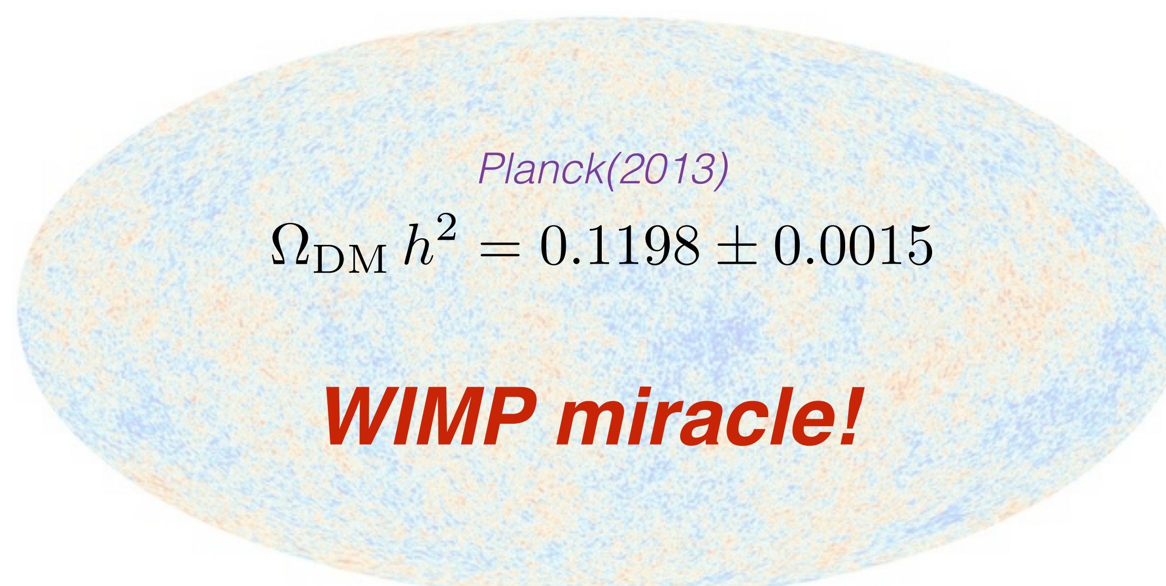


relic density

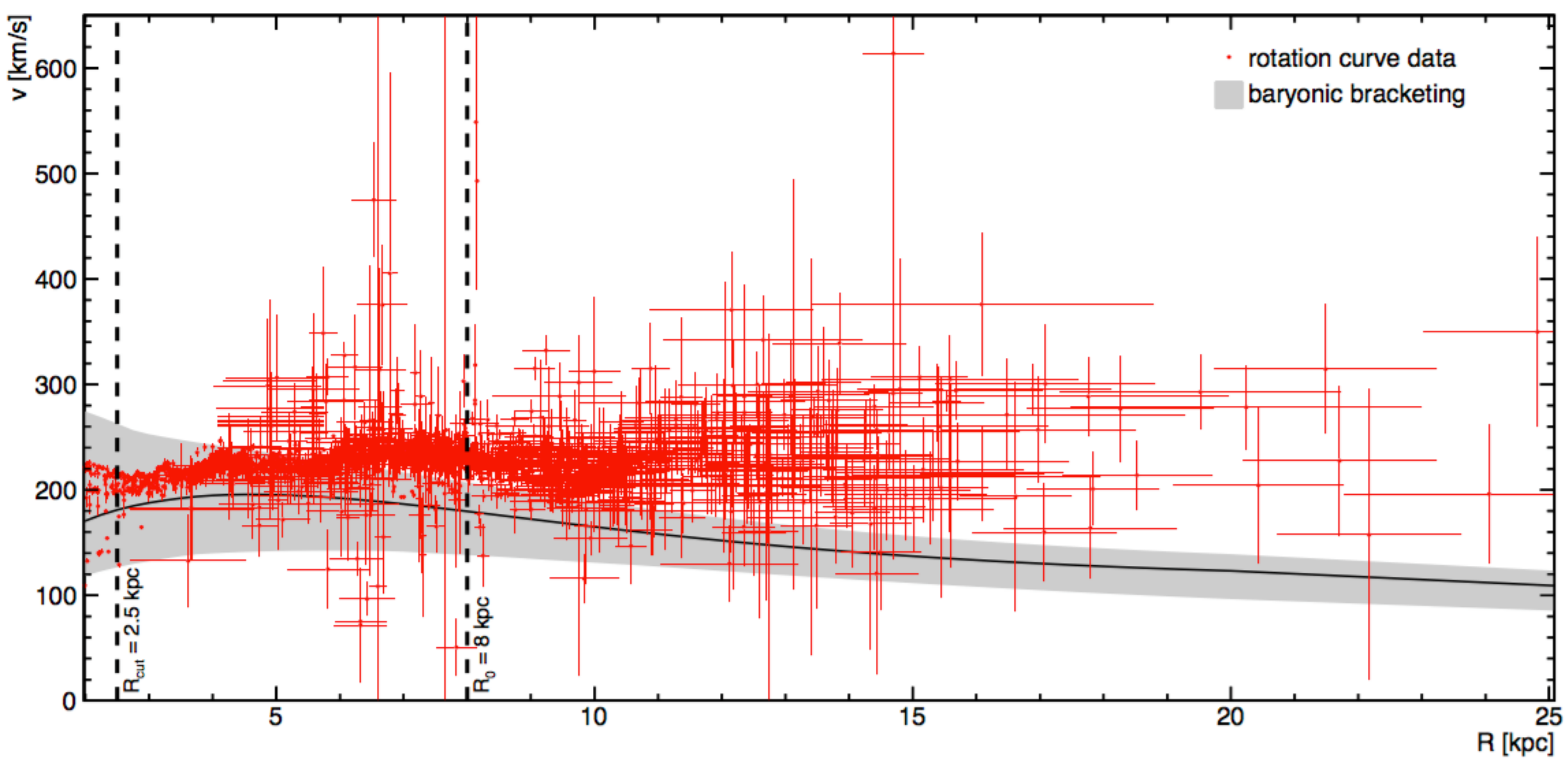
$$\Omega_{\rm DM}\, h^2 \simeq \frac{3\times 10^{-27}\ {\rm cm^3\, s^{-1}}}{\langle \sigma v \rangle}$$

annihilating cross section

- ***weak***-scale mass (10 GeV - 1 TeV)
- ***weak***-scale interaction $\langle \sigma v \rangle \simeq 3\times 10^{-26}\ {\rm cm^3\, s^{-1}}$



Dark matter in the Milky Way



Pato et al. 2015

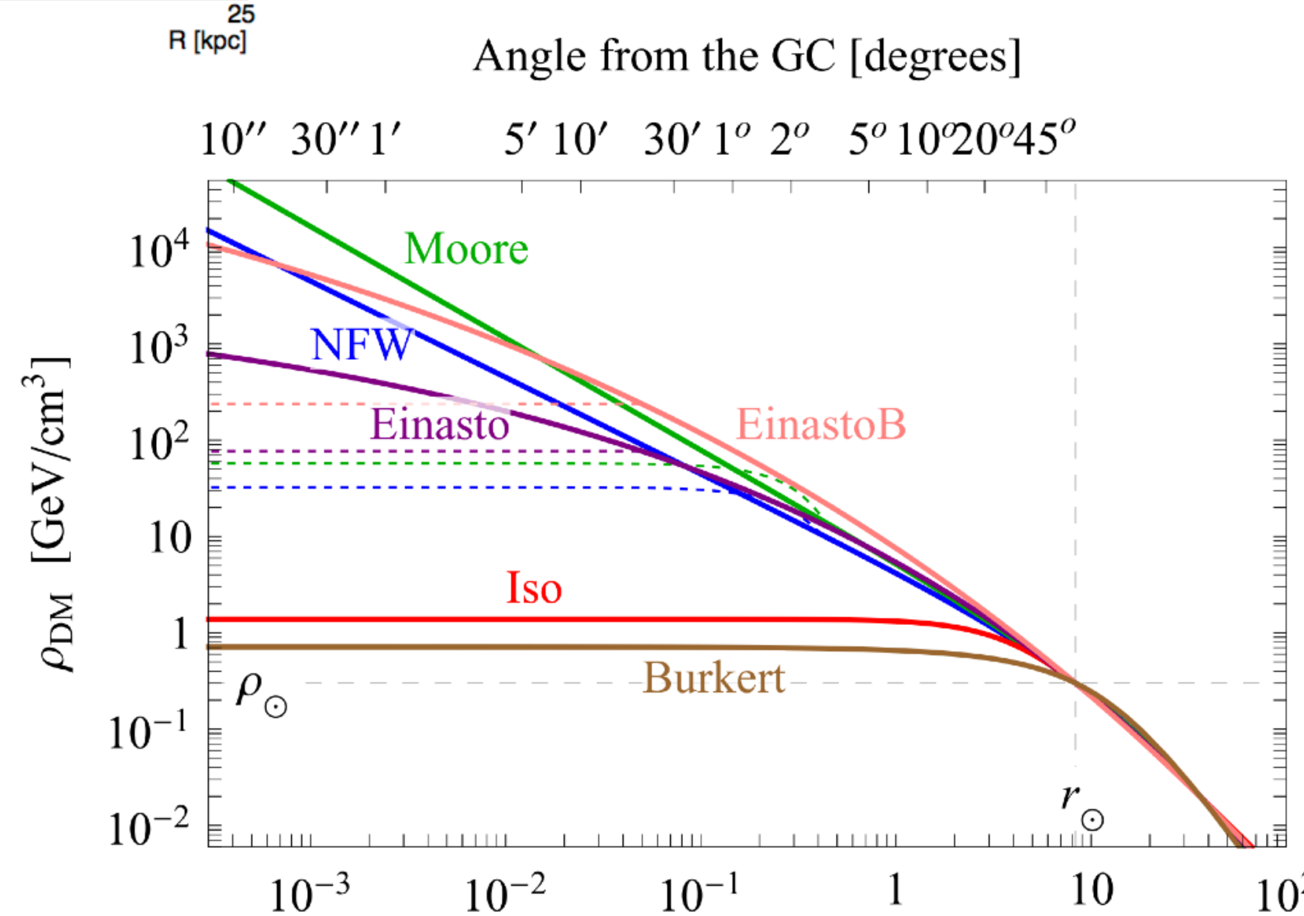
$$R_0 = 8\ \text{kpc}, \quad v_0 = 230\ \text{km}\,\text{s}^{-1}$$

$$\rho_0 \simeq 0.420\ \text{GeV}\,\text{cm}^{-3}$$

The dark matter mass distribution in the Milky Way is not well known, especially close to the Galactic center.

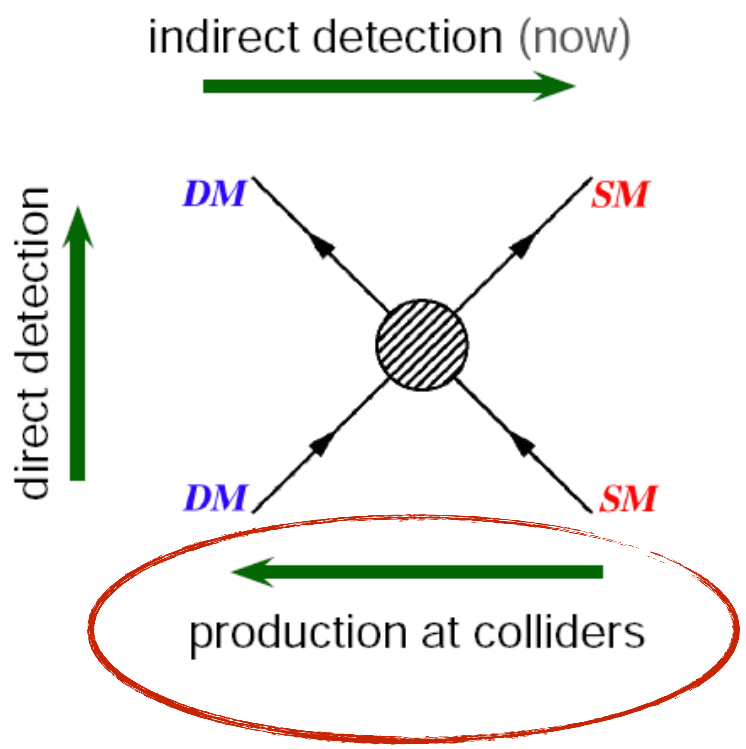
Core profiles
Isothermal, Burkert (rotation curve)

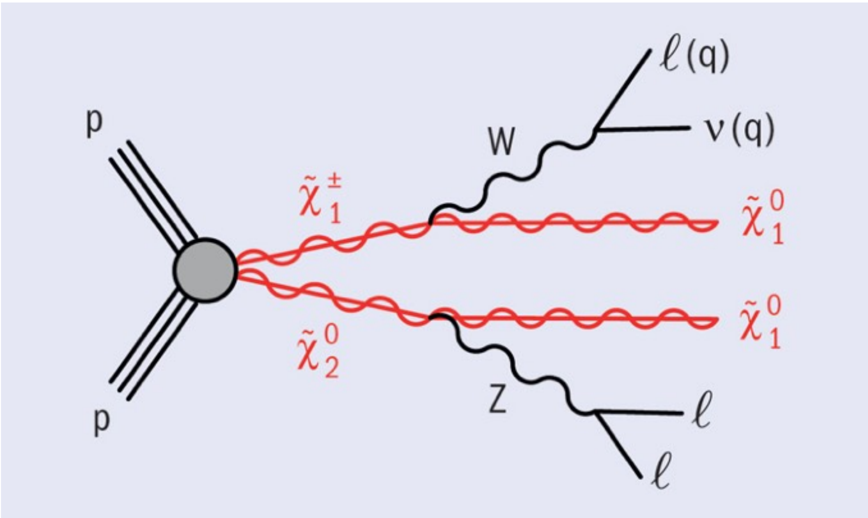
Cusp profiles
Moore, Navarro Frenk and White, Einasto (N-body simulations)

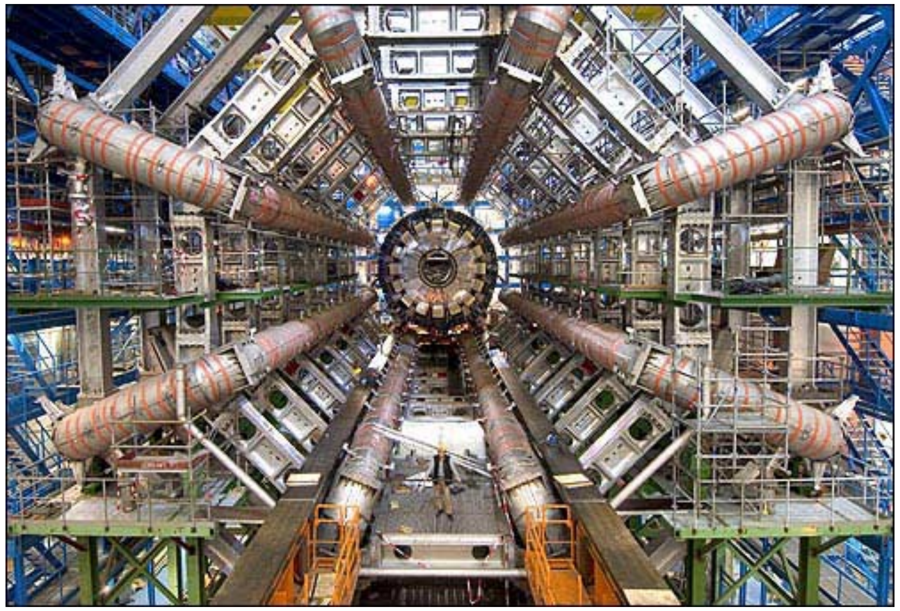


Dark matter production in colliders

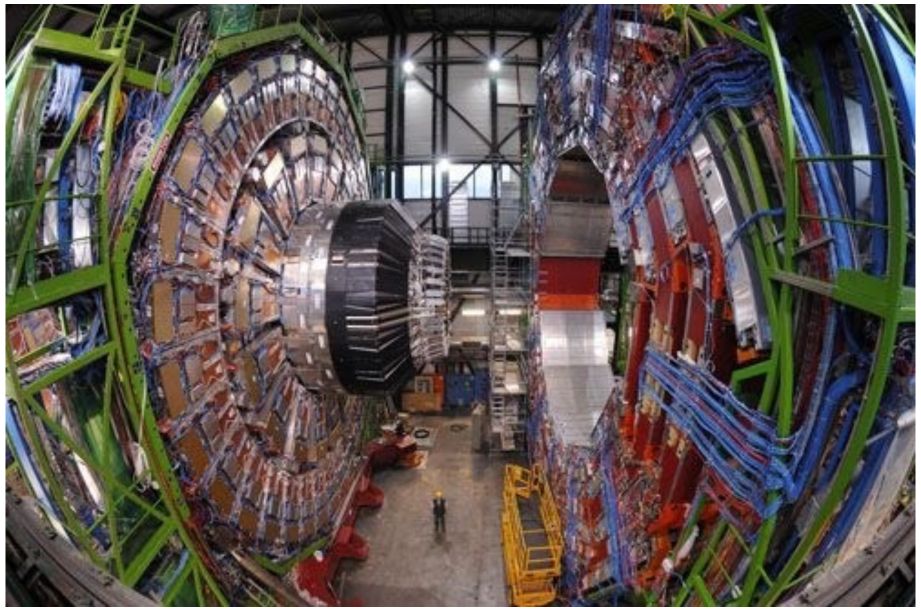
Production of dark matter particles in proton-proton interactions at the large hadron collider (LHC).







Atlas experiment at the LHC



CMS experiment at the LHC

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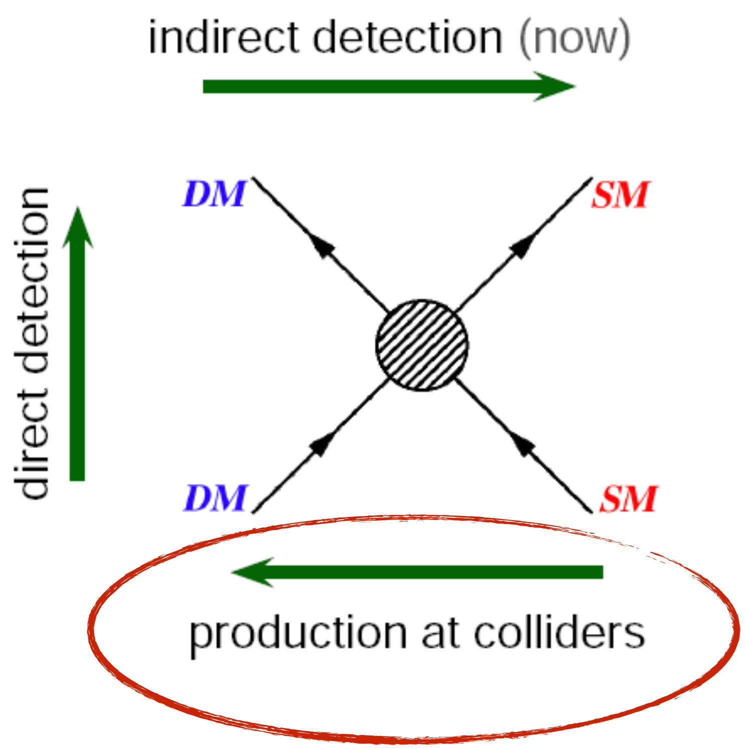
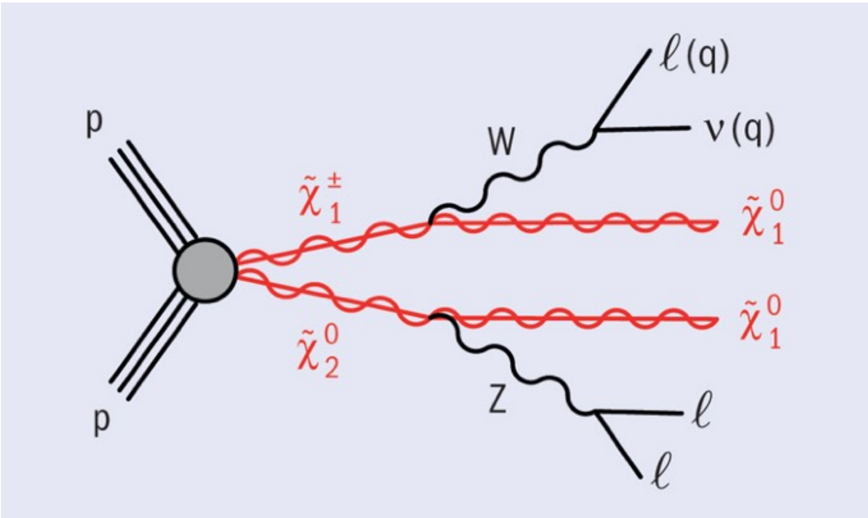
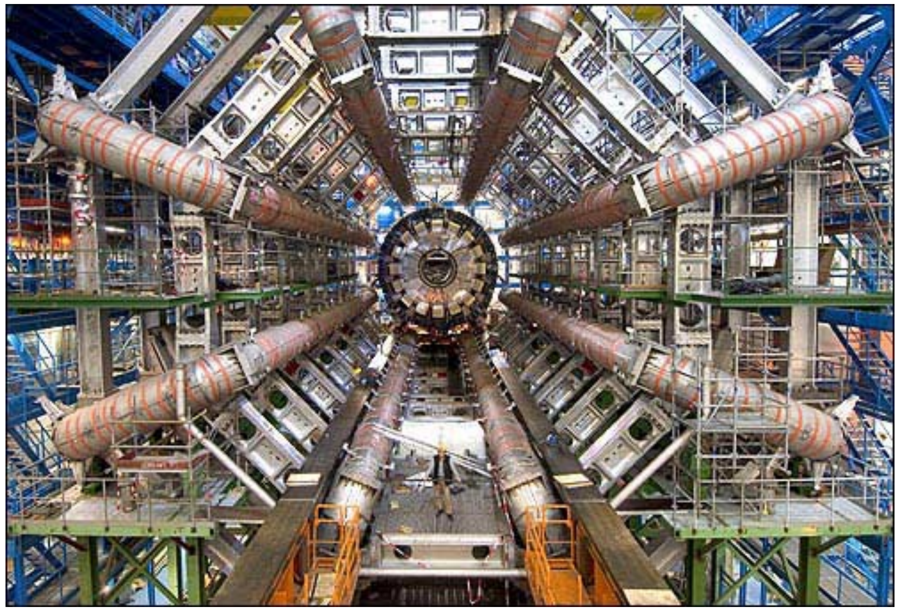
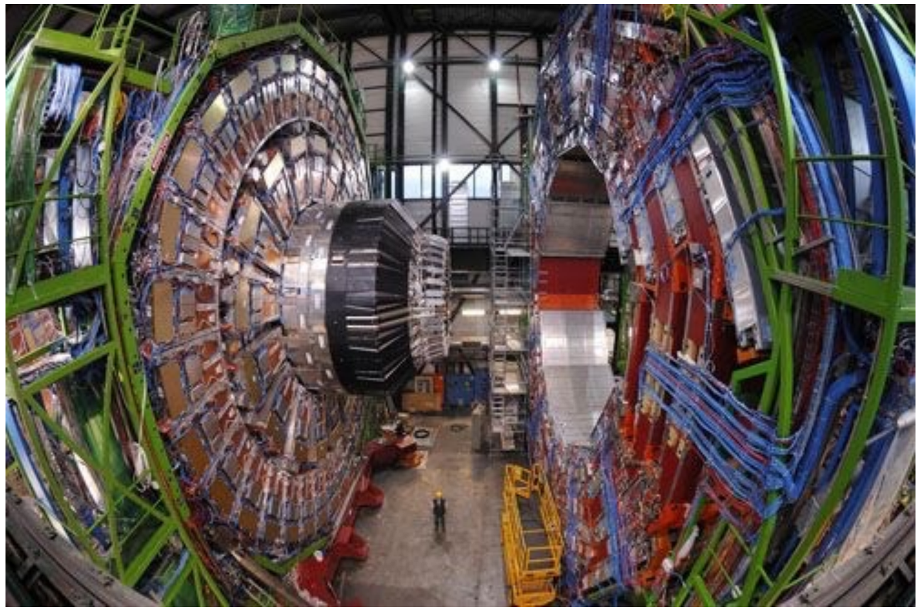




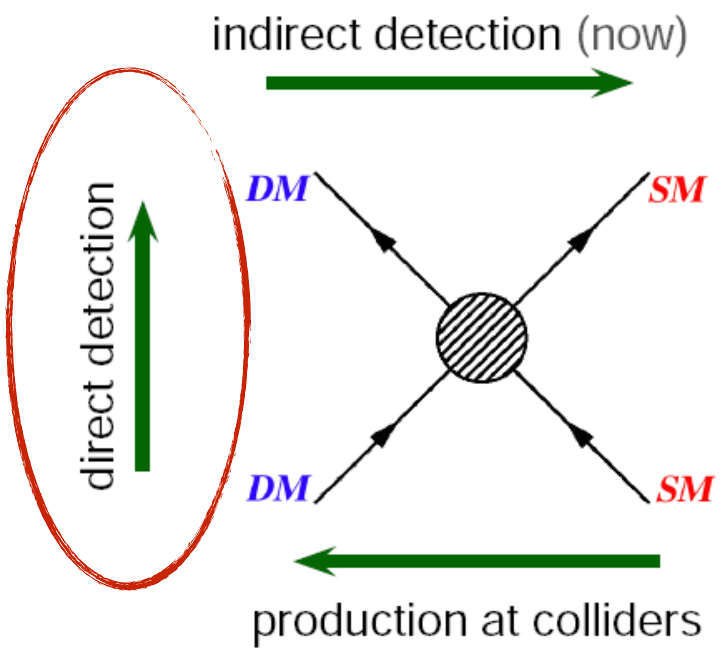

Atlas experiment at the LHC

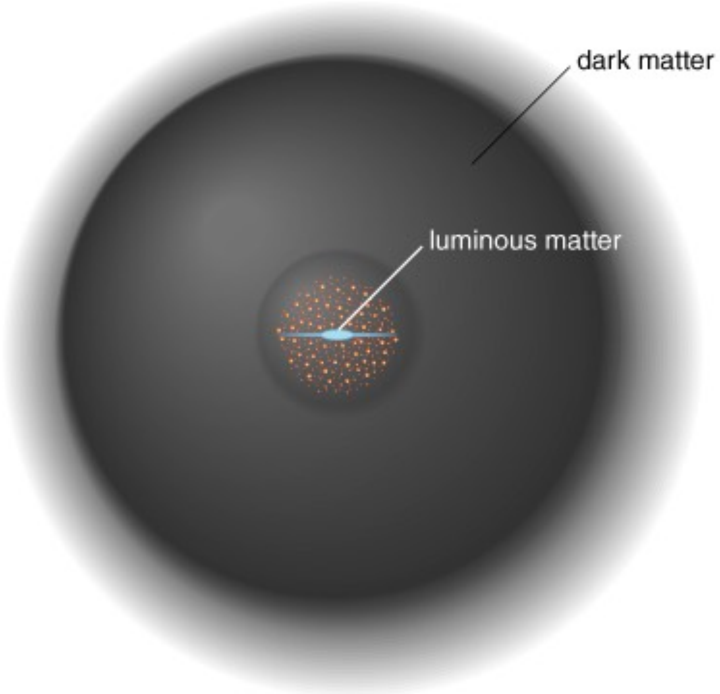

CMS experiment at the LHC

No hints for new physics so far.

Dark matter direct detection

Detection of interactions between dark matter particles and nuclei in a detector.





EDELWEISS experiment

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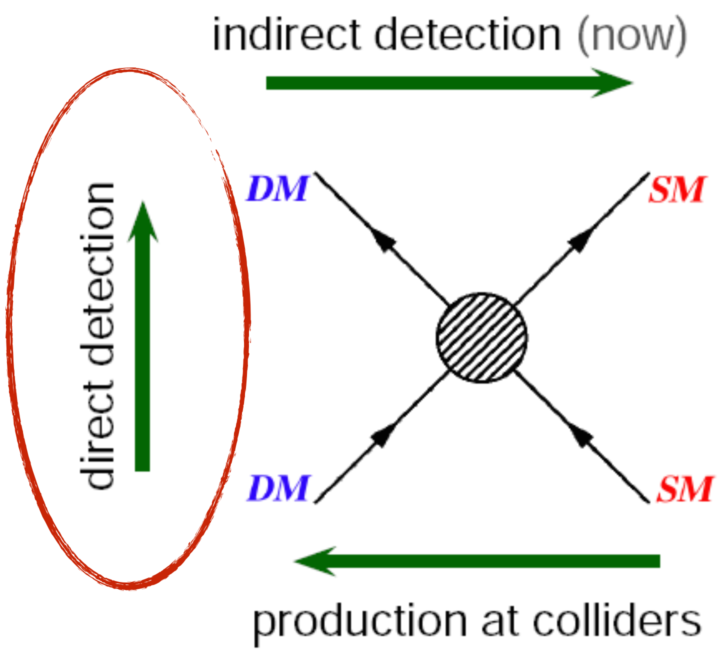
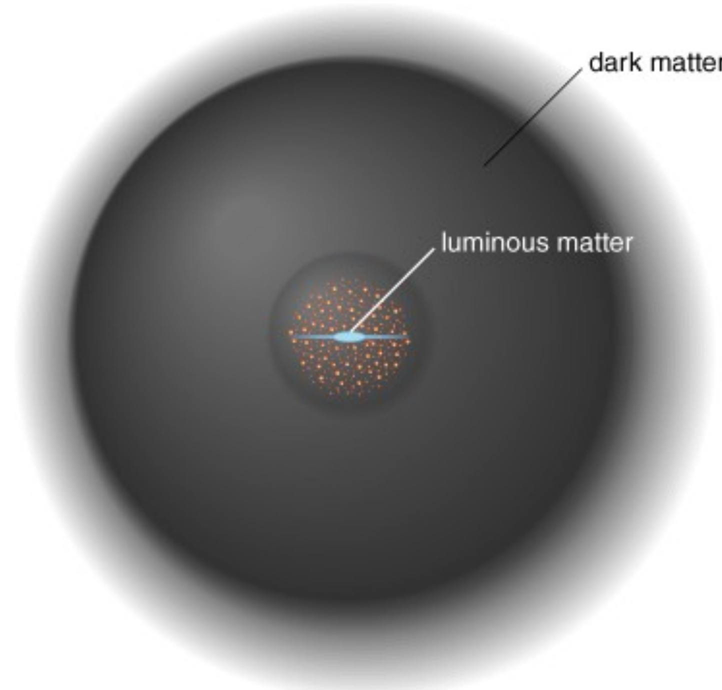
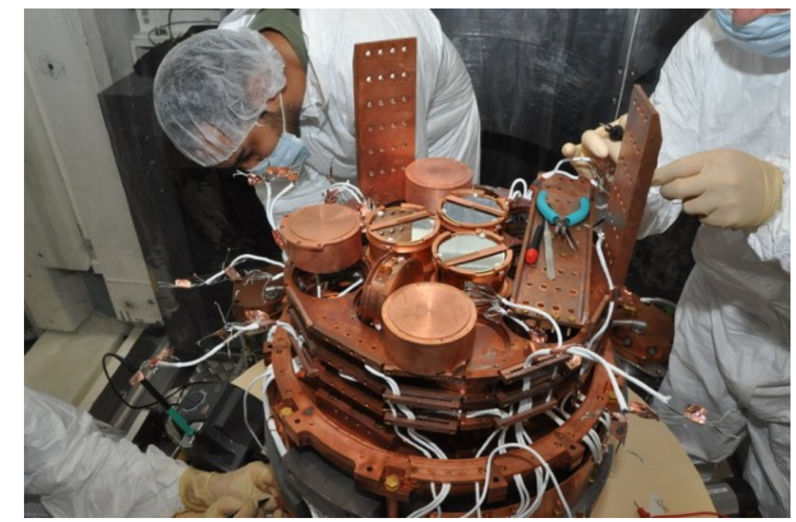
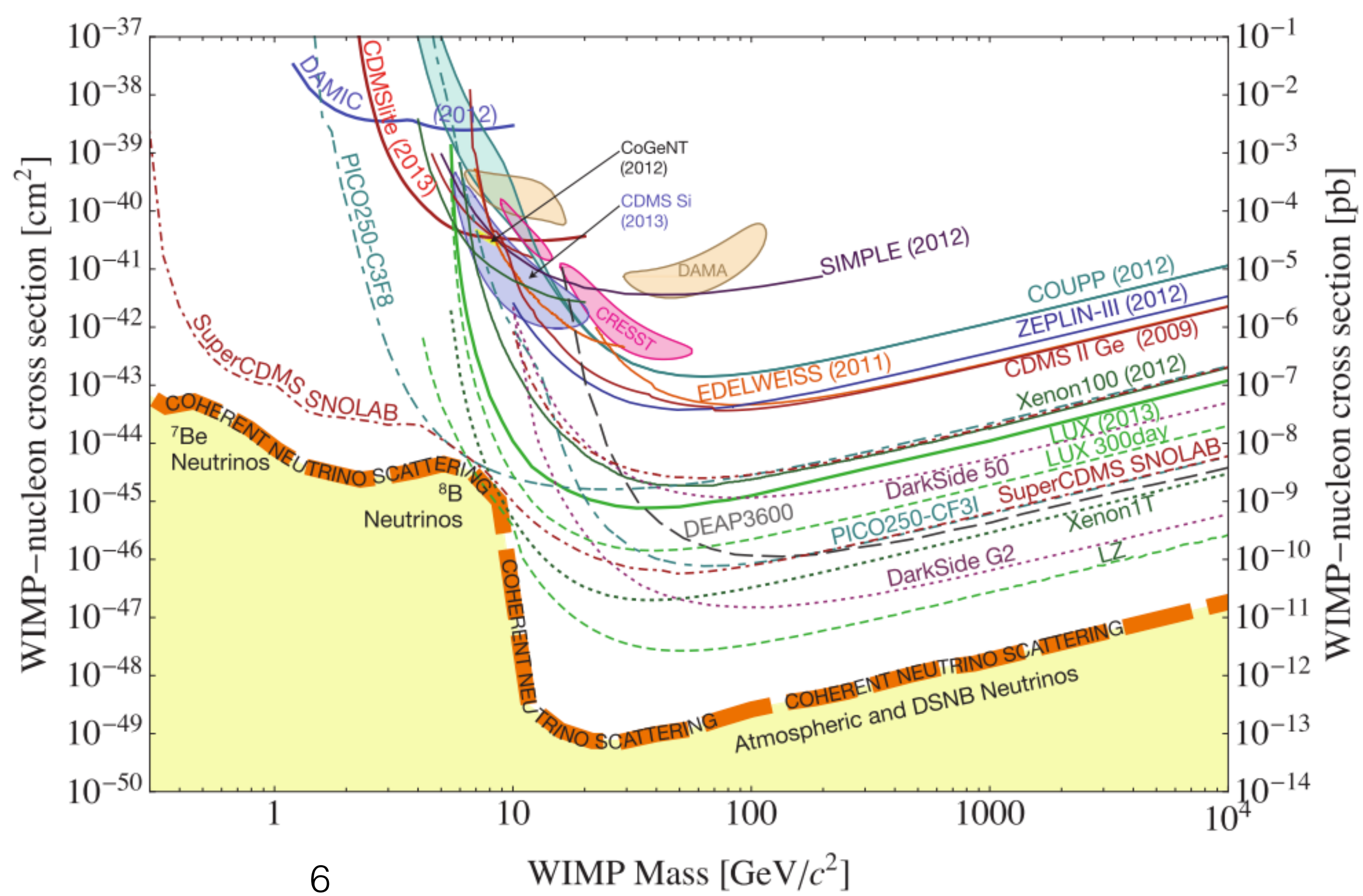






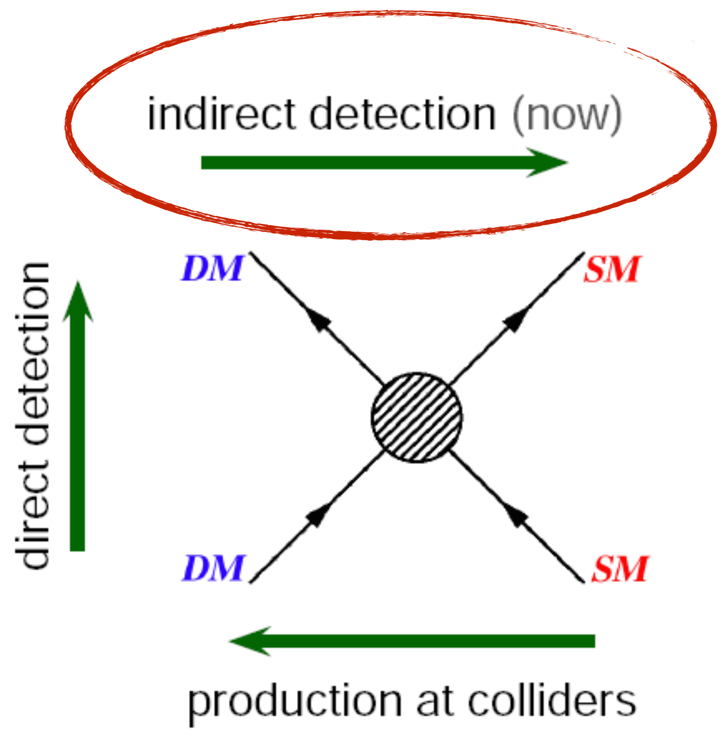
EDELWEISS experiment

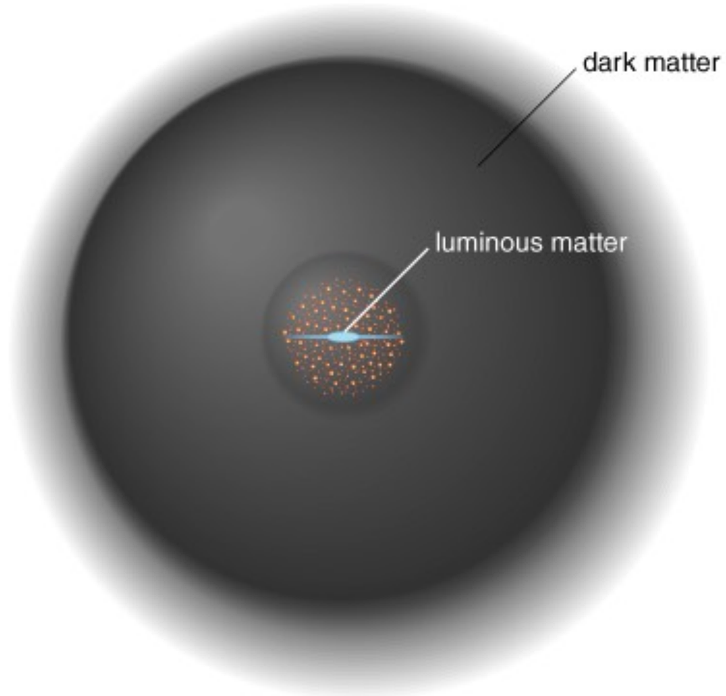
Spin independant cross section

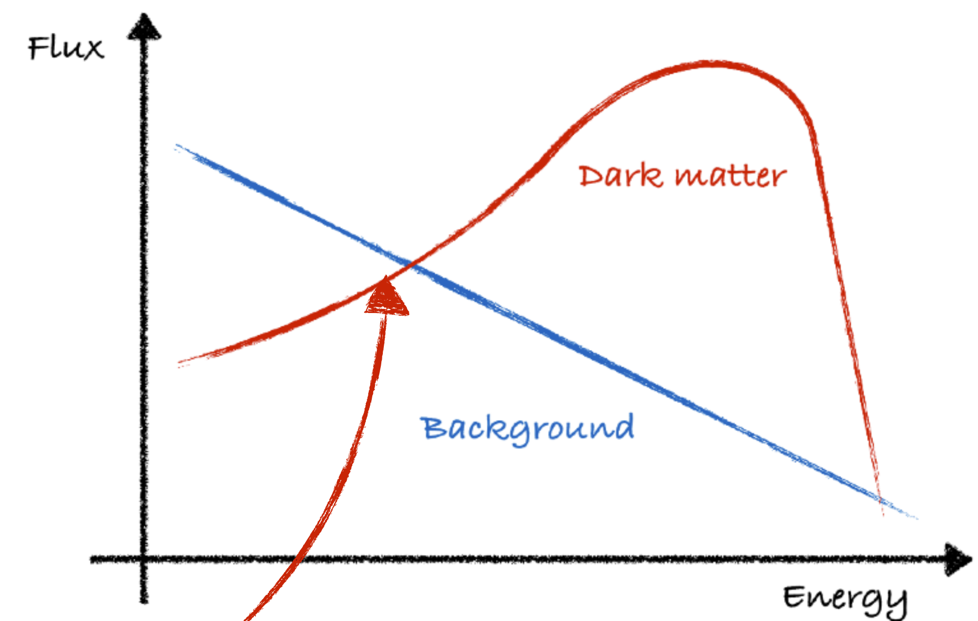


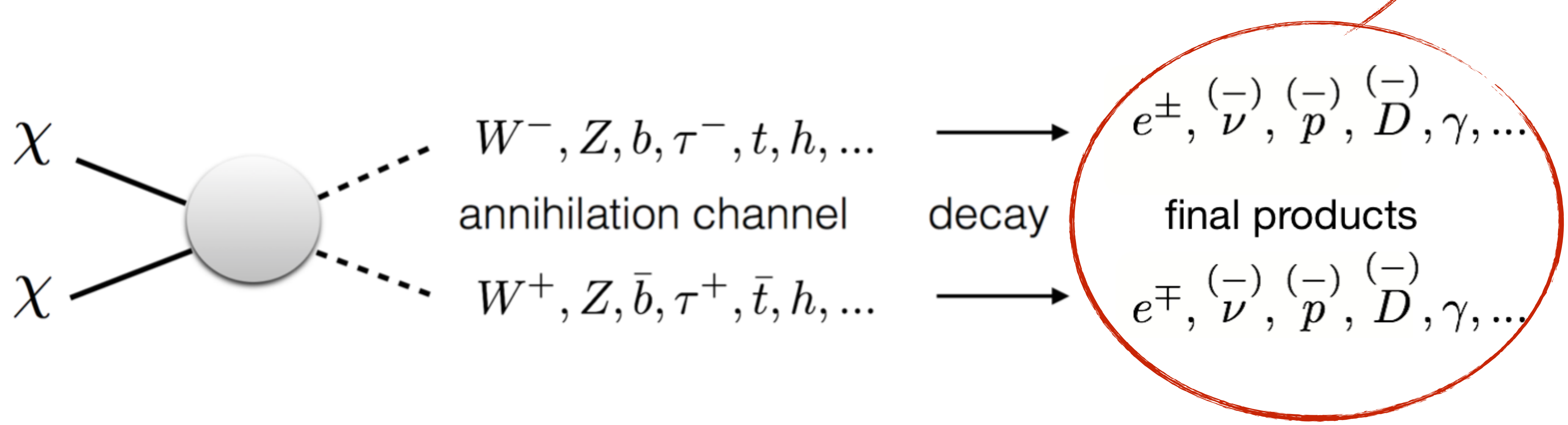
Dark matter indirect detection

Measure an excess of cosmic rays with respect to the astrophysical background.









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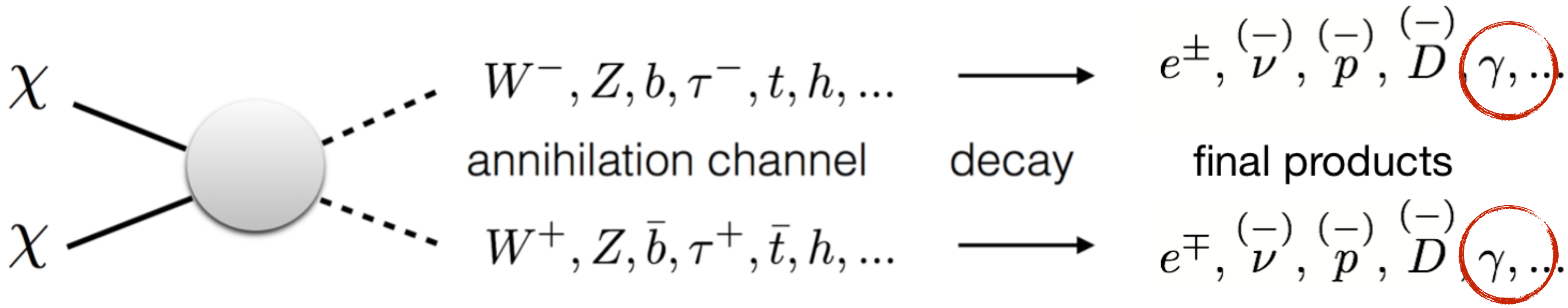
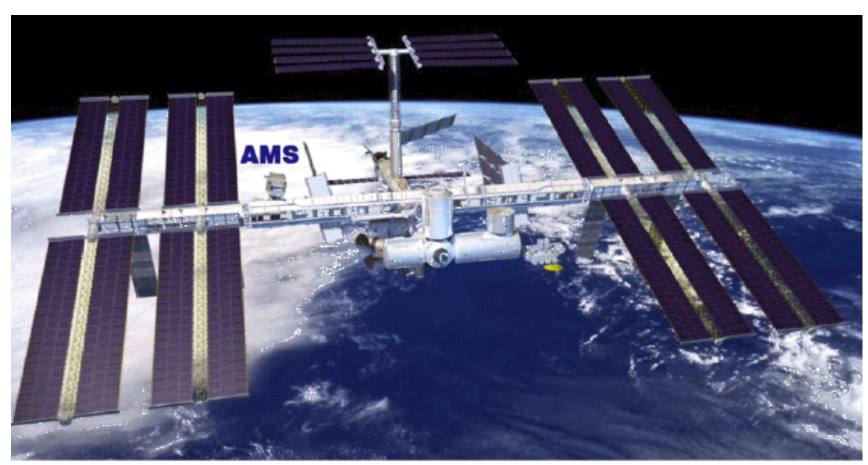


- Gamma rays

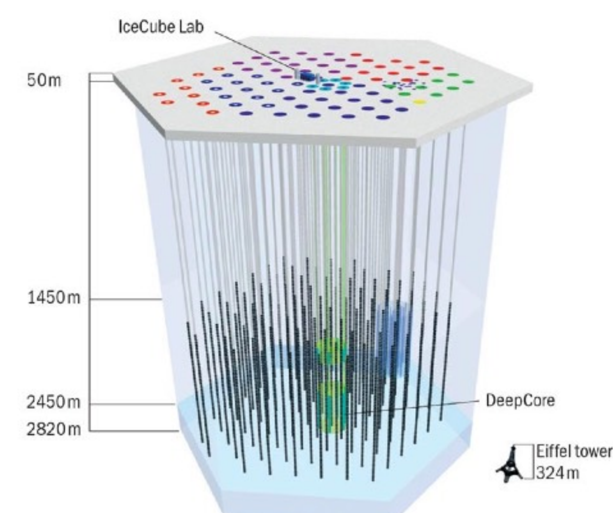
HESS experiment

- Charged cosmic rays



AMS-02 experiment

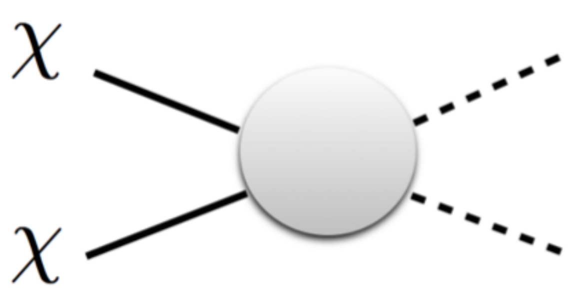
- Neutrinos



IceCube experiment

Dark matter indirect detection

Measure an excess of cosmic rays with respect to the astrophysical background.



χ χ → $W^-, Z, b, \tau^-, t, h, \ldots$ → $e^\pm, \overset{(-)}{\nu}, \overset{(-)}{p}, \overset{(-)}{D}, \gamma, \ldots$

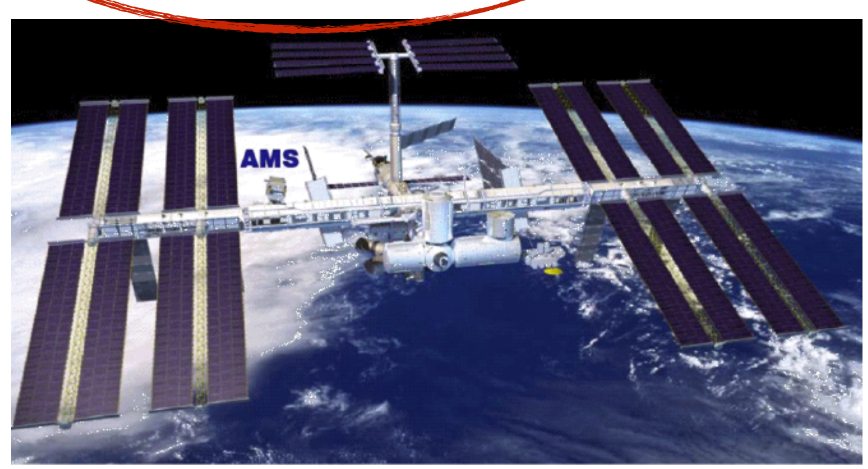
$W^+, Z, \bar{b}, \tau^+, \bar{t}, h, \ldots$ → $e^\mp, \overset{(-)}{\nu}, \overset{(-)}{p}, \overset{(-)}{D}, \gamma, \ldots$

annihilation channel — decay — final products

- Gamma rays

HESS experiment

- Charged cosmic rays



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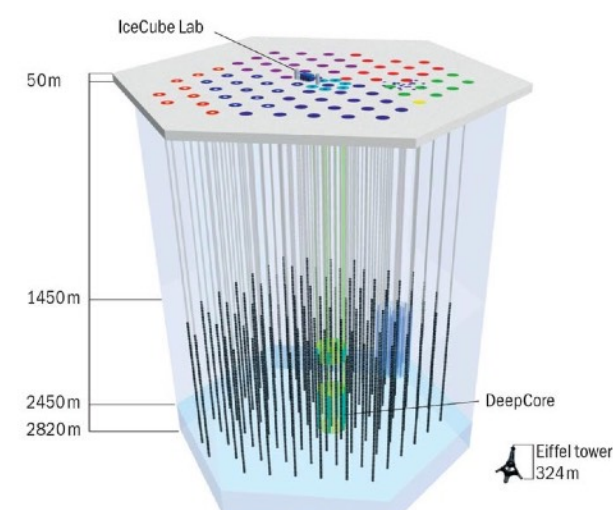

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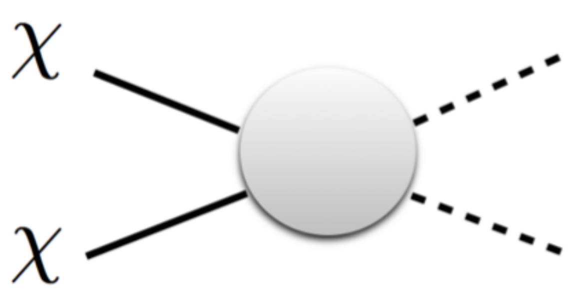

$W^-, Z, b, \tau^-, t, h, ...$ $\longrightarrow$ $e^\pm, \overset{(-)}{\nu}, \overset{(-)}{p}, \overset{(-)}{D}, \gamma, ...$

annihilation channel — decay — final products

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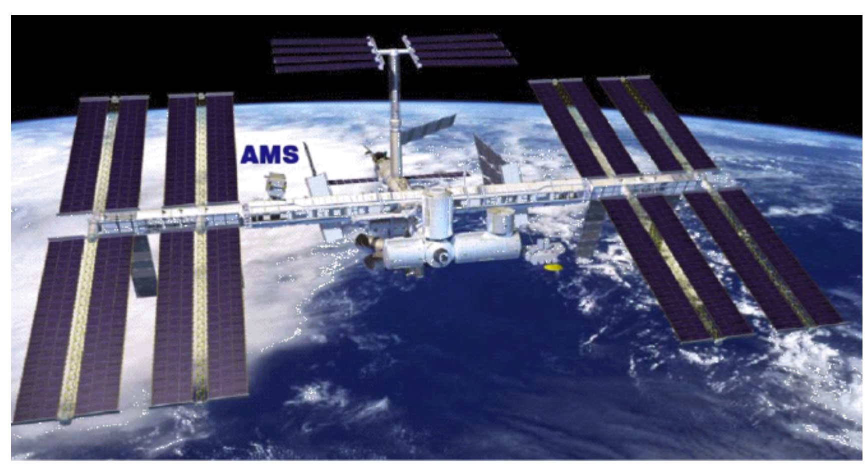

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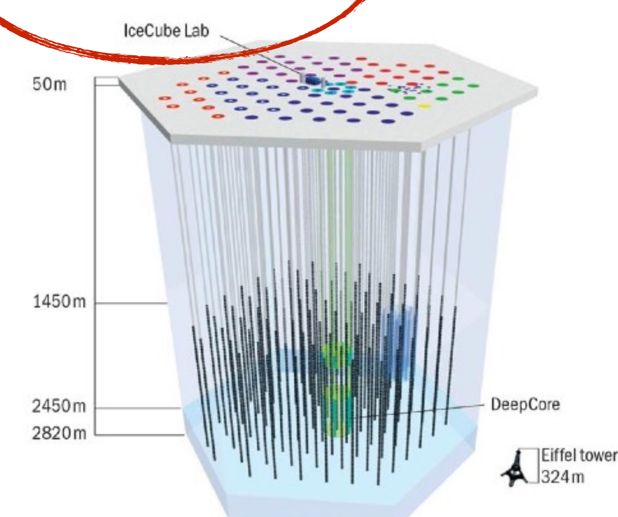

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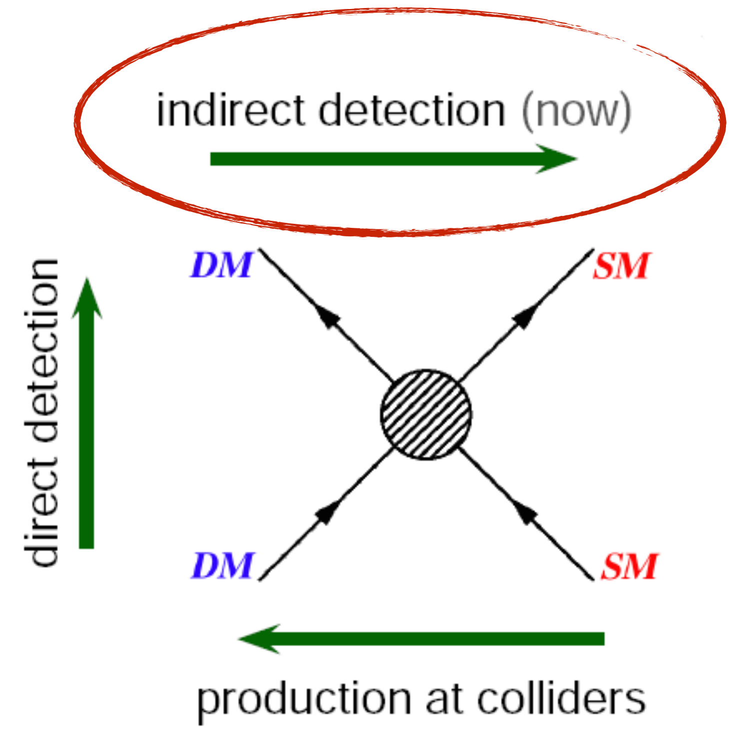

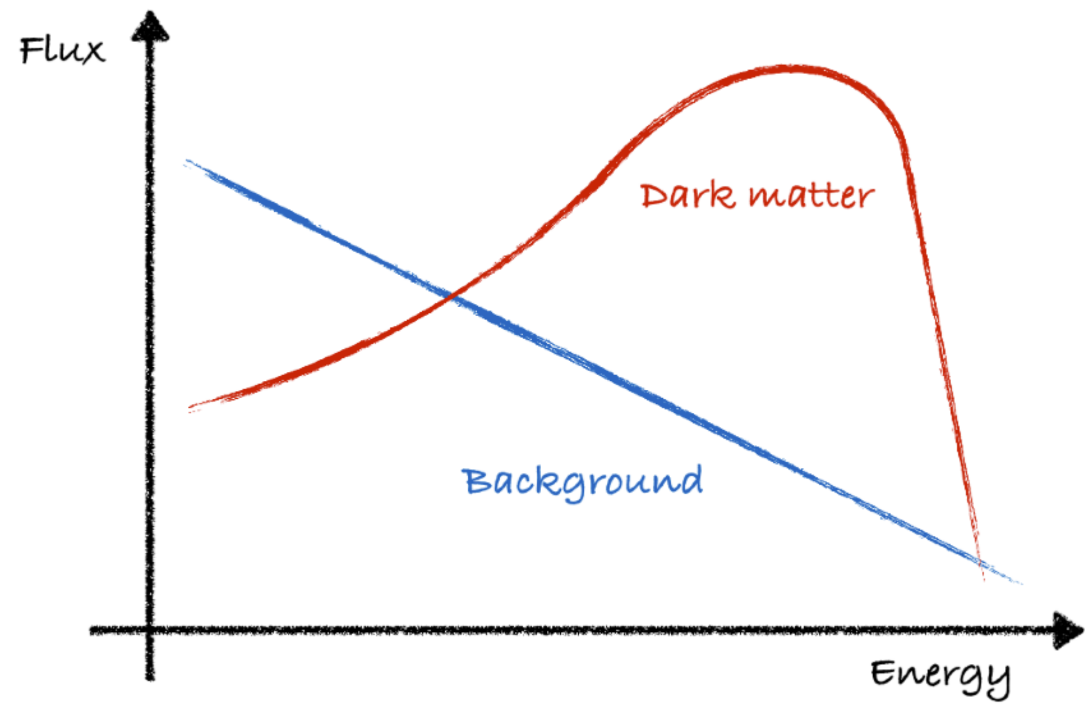

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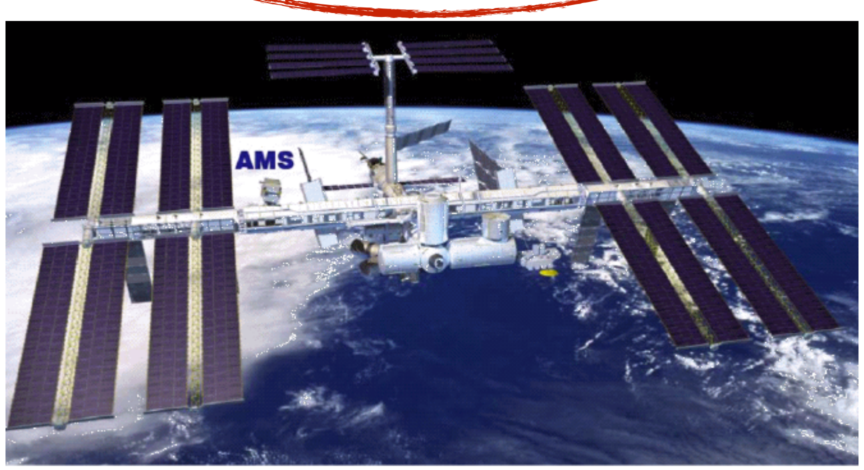


AMS-02 experiment

Antimatter cosmic rays

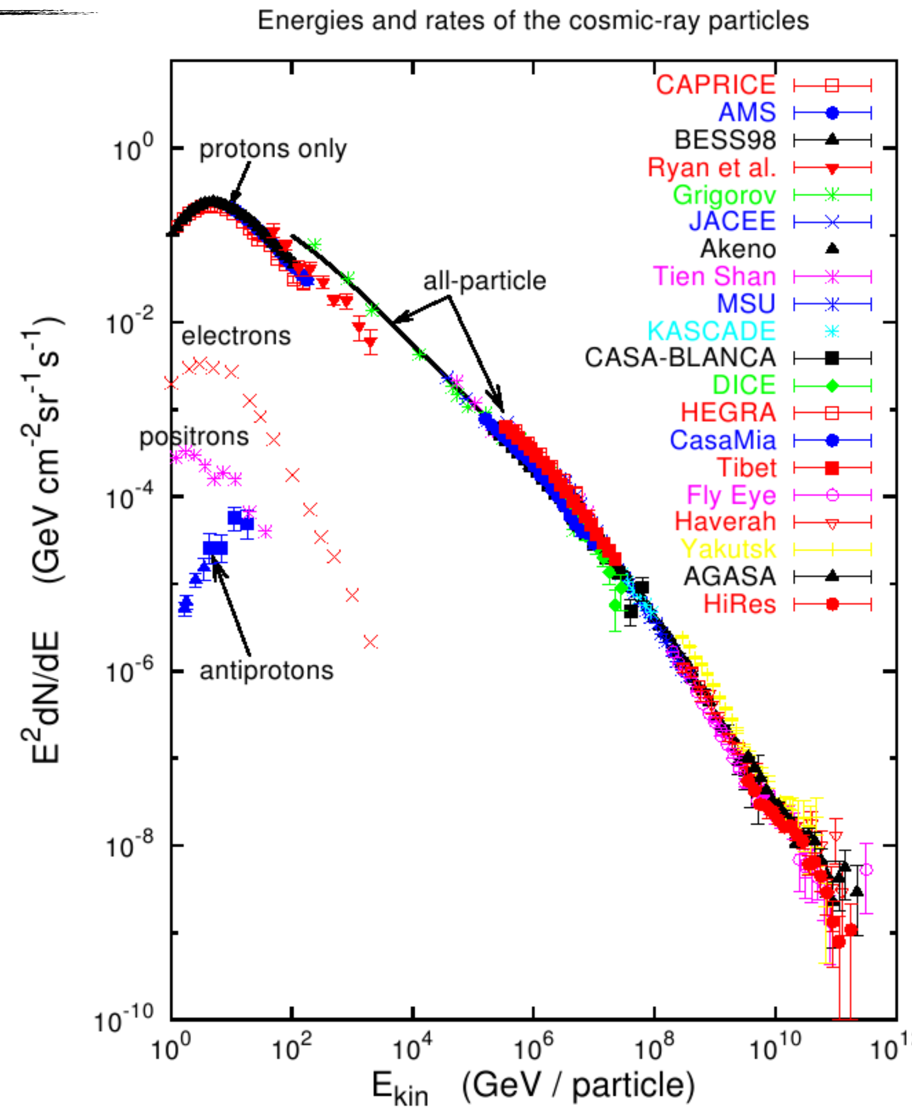
Antimatter is rare in the Galaxy, the astrophysical background is ***weak*** and ***easier*** to assess.

- Positrons e^+
- Antiprotons $\bar{p}$
- Antideutrons $\bar{D}$
- …

Propagation of cosmic rays: the diffusion model

Victor Hess - 1912

- ~200 particules m^{-2} s^{-1}
- ~99% of nuclei
  - ~89% of protons
  - ~10% of helium
  - ~1% of other nuclei
- ~1% of electrons
  - ~90% of electrons
  - ~10% of positrons



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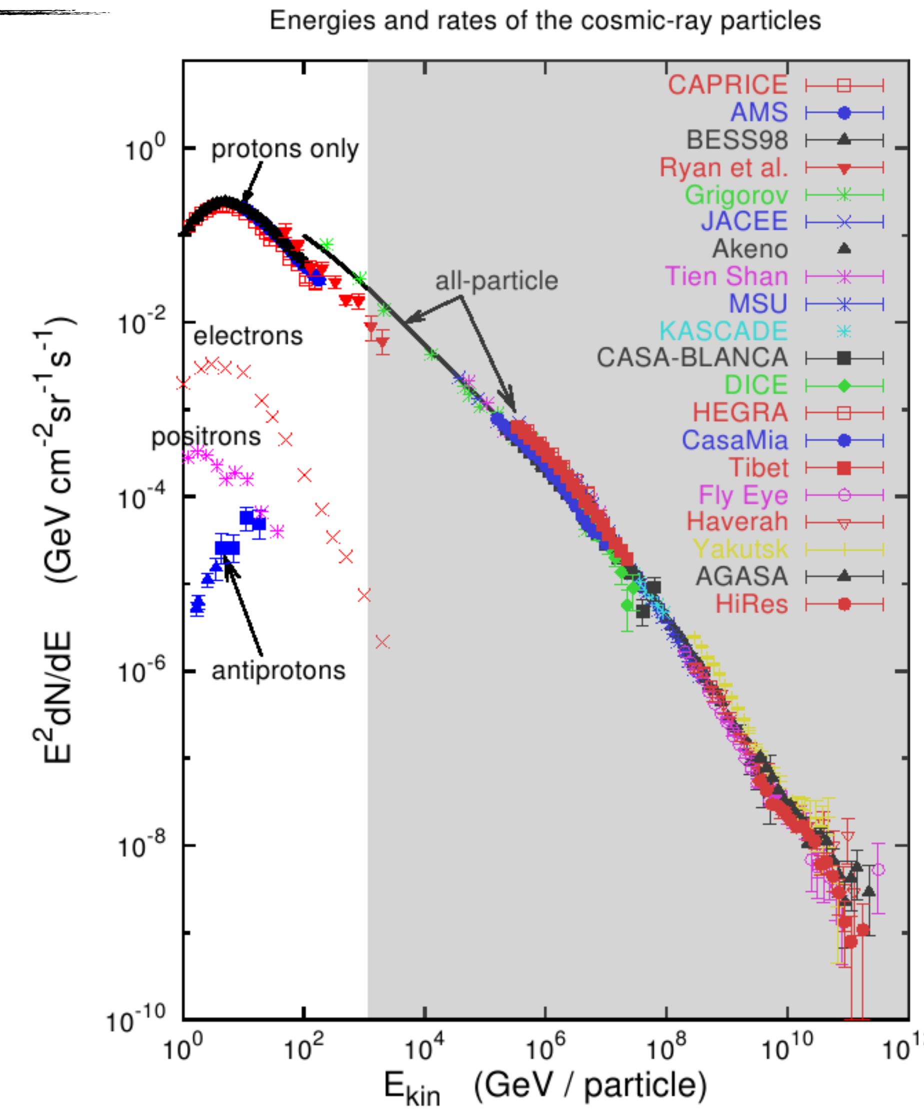

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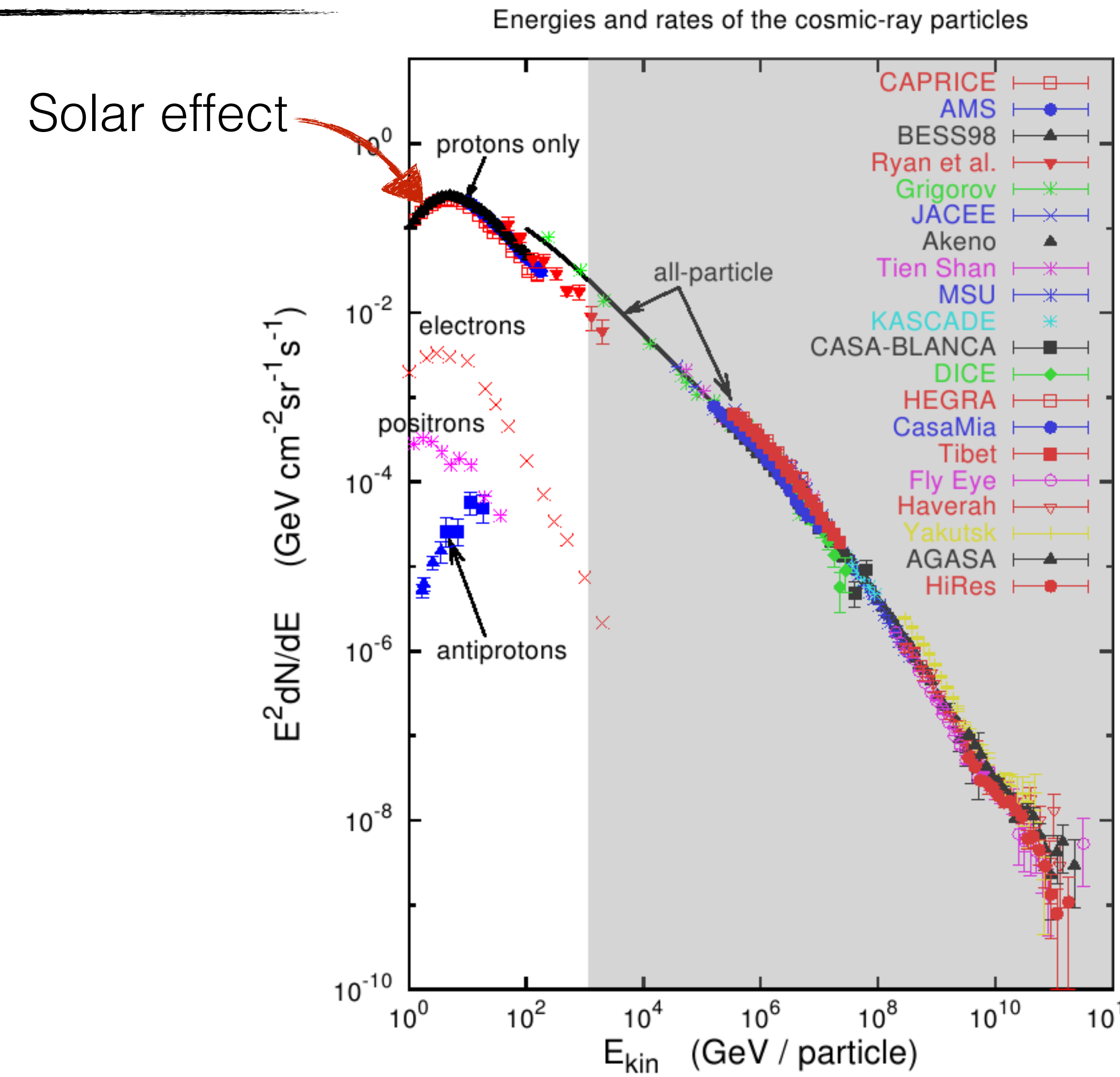

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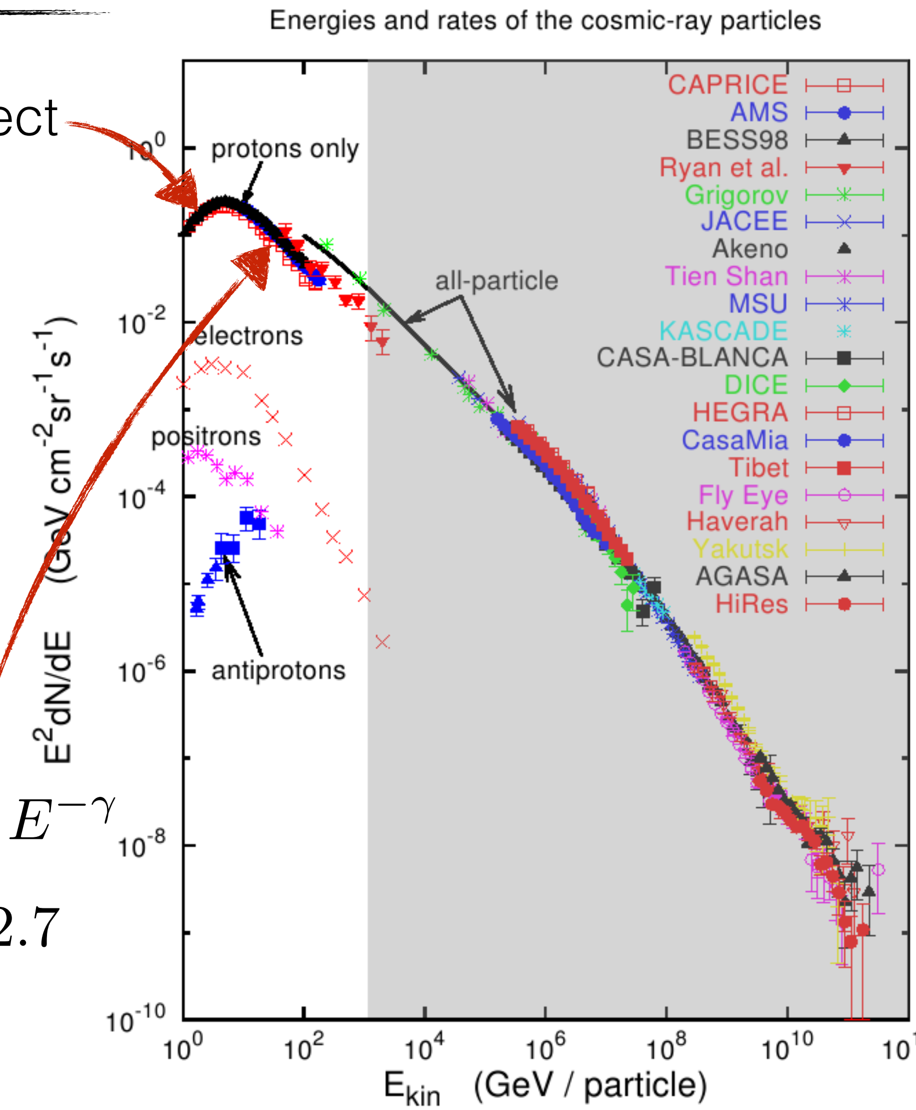
Solar effect

$$\Phi_\odot(E) \propto E^{-\gamma}$$

$$\gamma \simeq 2.7$$



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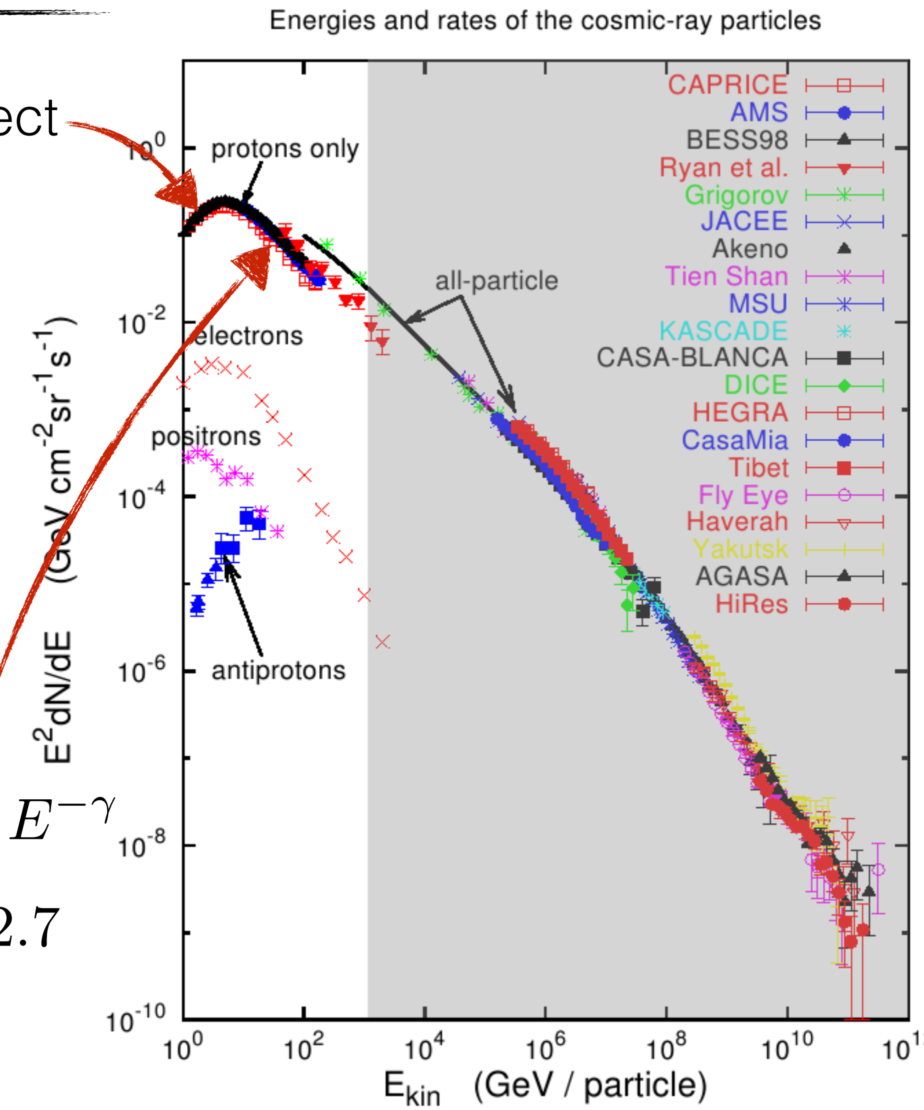
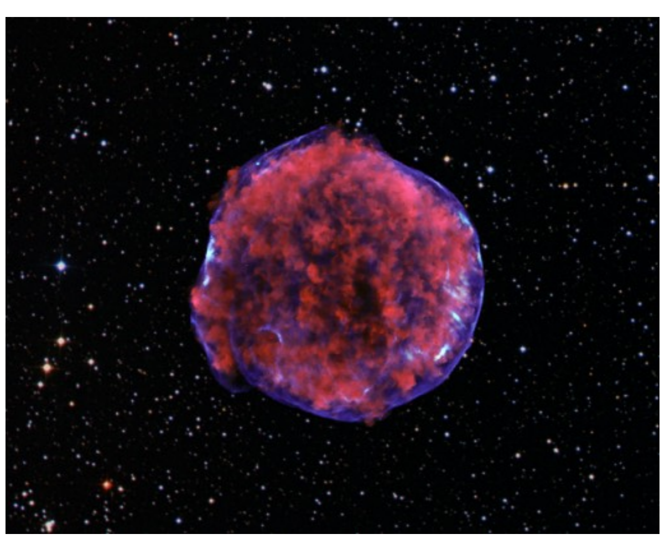


Supernovae remnants (SNR) as accelerators of cosmic rays (CR)



Tycho SNR - Chandra

$$\Phi_{\rm SNR}(E) \propto E^{-\alpha}, \quad \alpha \simeq 2$$

Diffusive Shock Acceleration

Victor Hess - 1912

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Solar effect

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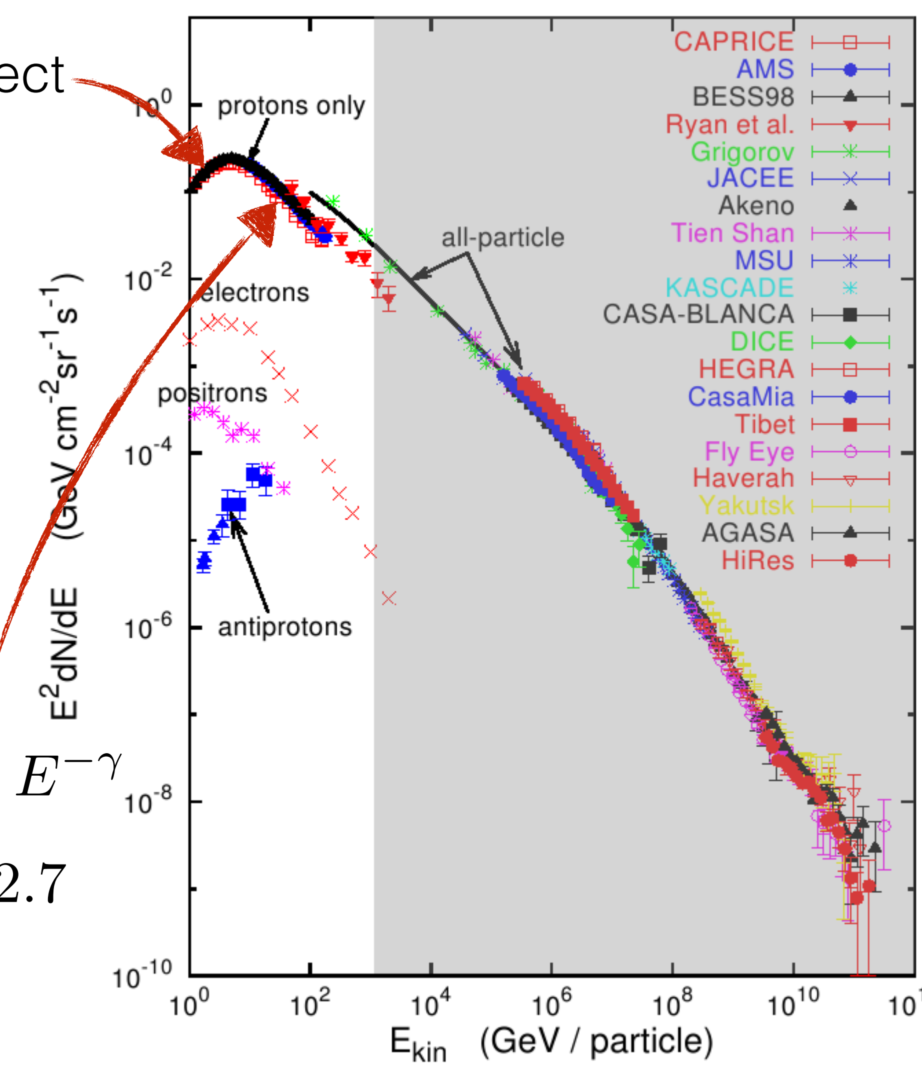
Energies and rates of the cosmic-ray particles



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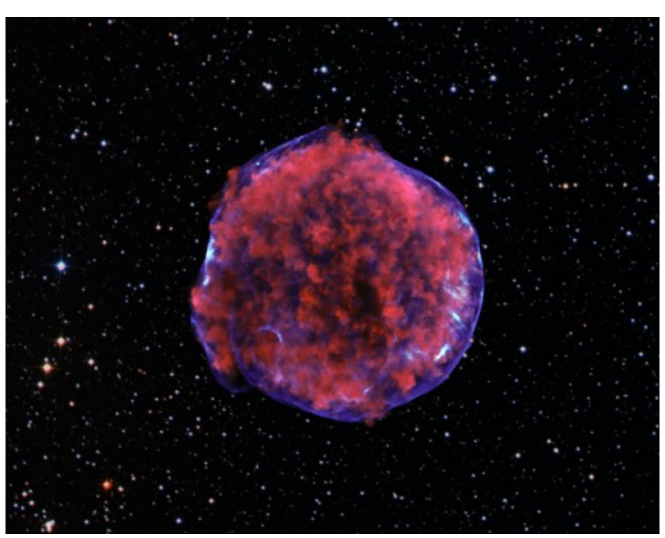

Tycho SNR - Chandra

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$$\Phi_{\mathrm{SNR}}(E) \propto E^{-\alpha}, \quad \alpha \simeq 2$$

$$\Phi_{\odot}(E) \propto E^{-\gamma}, \quad \gamma \simeq 2.7$$

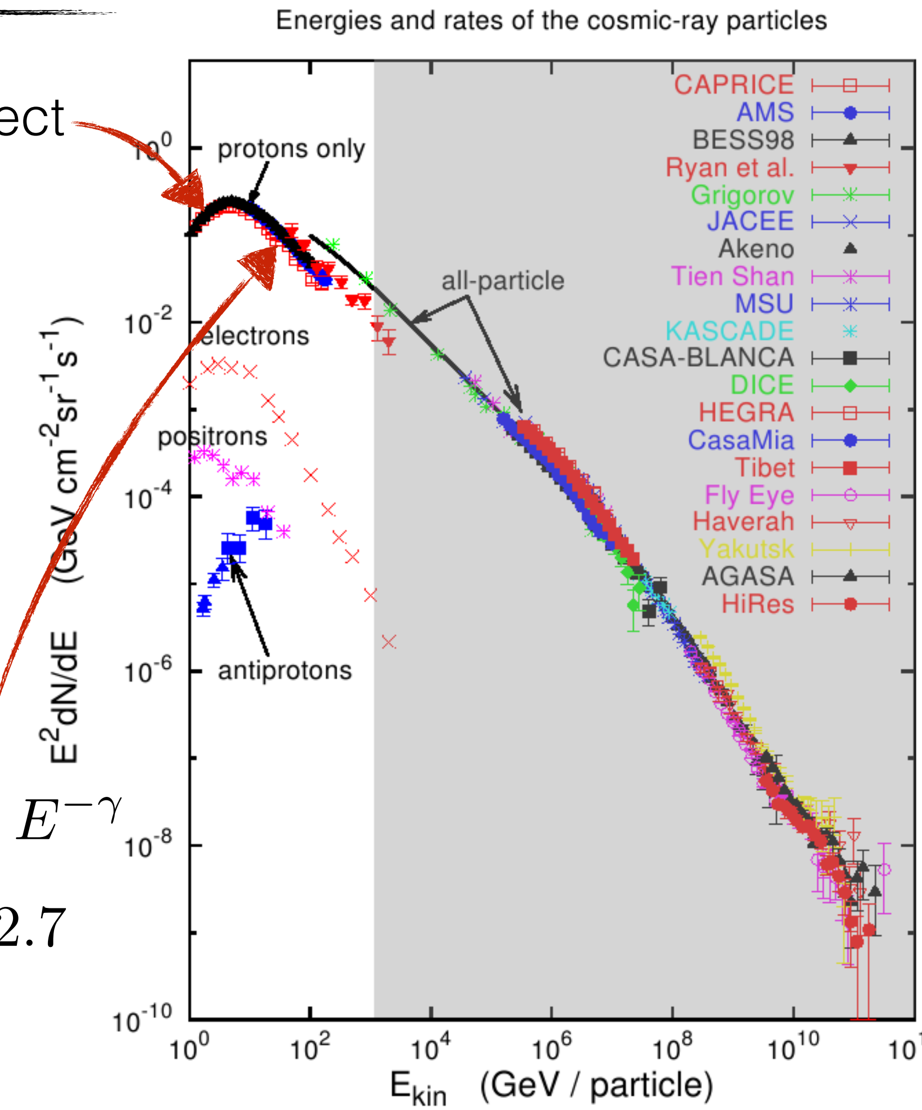
Victor Hess - 1912

- ~200 particules m^{-2} s^{-1}
- ~99% of nuclei
  - ~89% of protons
  - ~10% of helium
  - ~1% of other nuclei
- ~1% of electrons
  - ~90% of electrons
  - ~10% of positrons

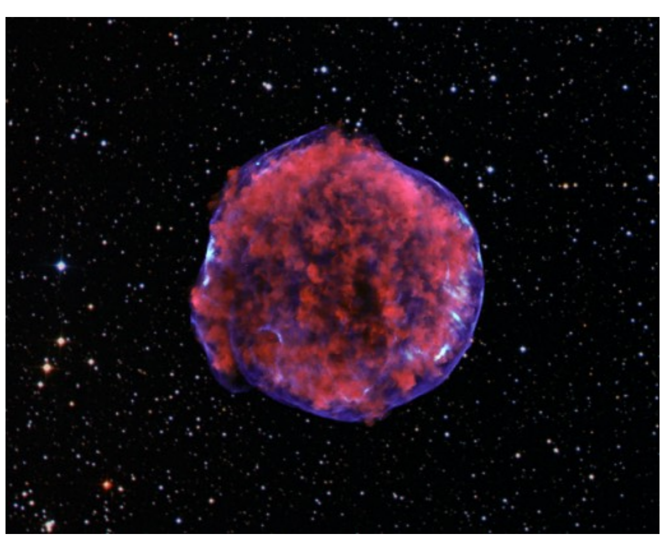
Solar effect

$$\Phi_{\odot}(E) \propto E^{-\gamma}$$

$$\gamma \simeq 2.7$$



Supernovae remnants (SNR) as accelerators of cosmic rays (CR)



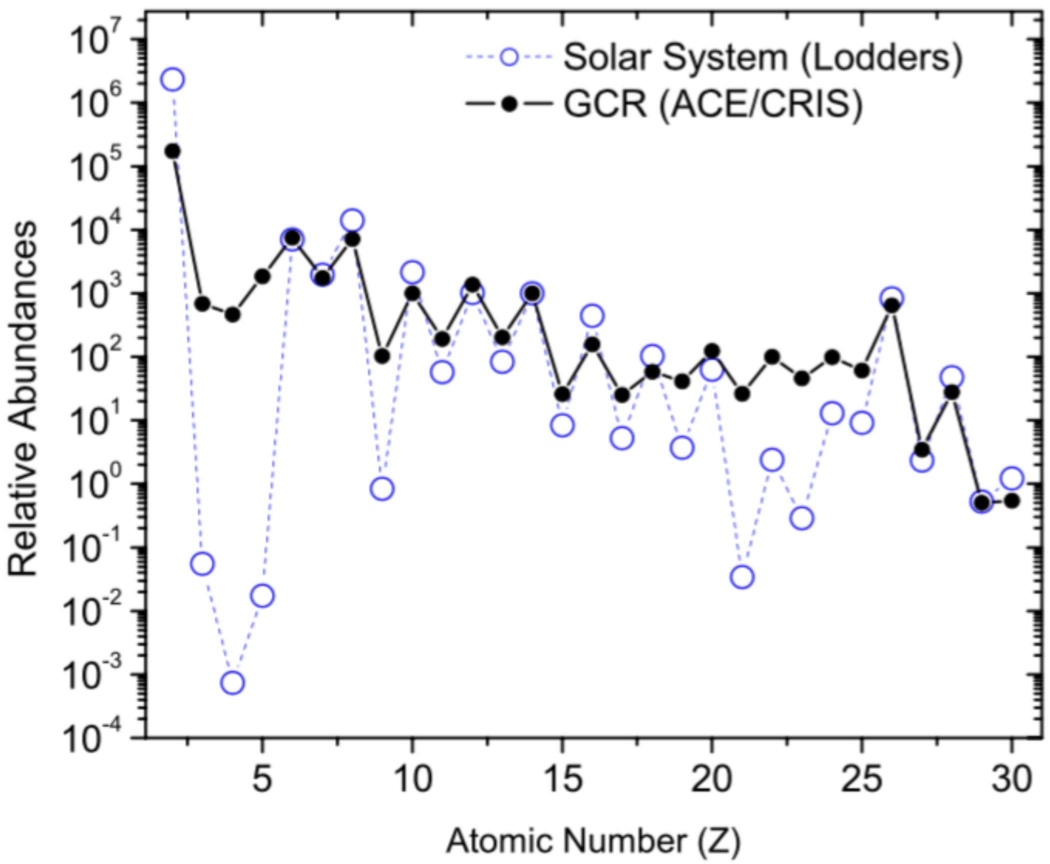
Tycho SNR - Chandra

Diffusive Shock Acceleration

$$\Phi_{\mathrm{SNR}}(E) \propto E^{-\alpha}, \quad \alpha \simeq 2$$

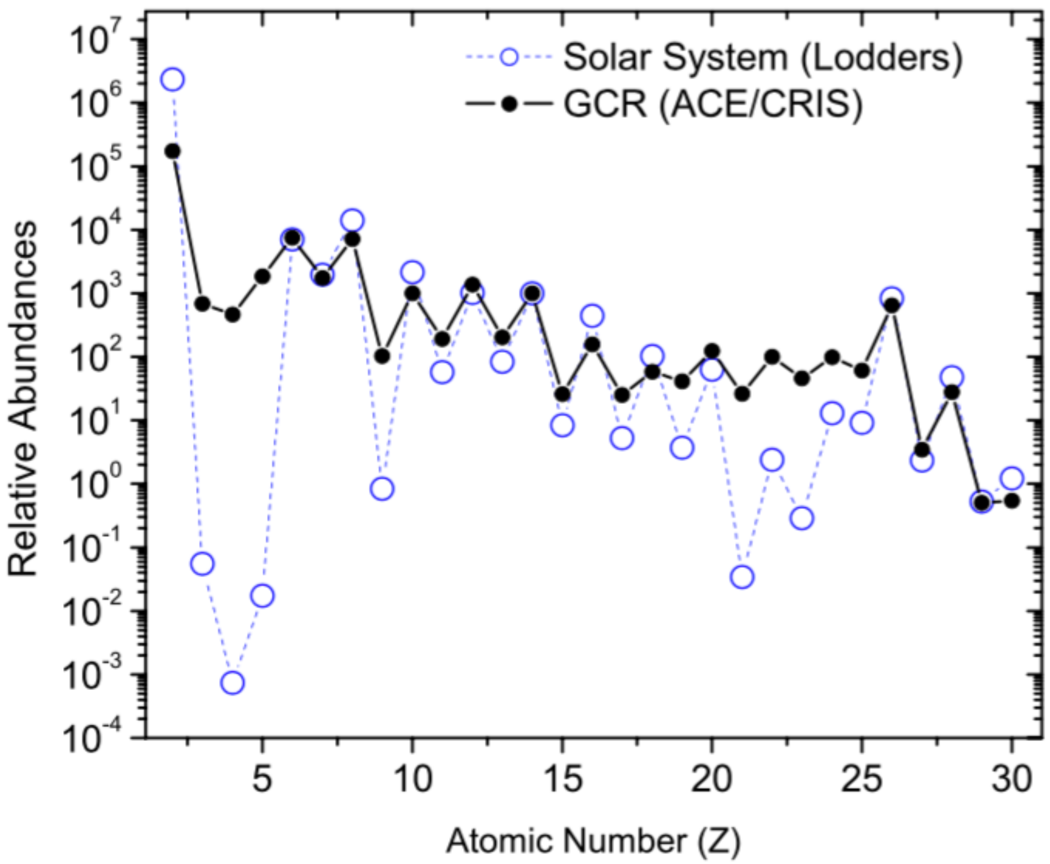
Propagation in the Galaxy

$$\Phi_{\odot}(E) \propto E^{-\gamma}, \quad \gamma \simeq 2.7$$



Li-Be-B (3-5) and Sc-Ti-V-Cr-Mn (21-25) are secondary CRs.

$$\mathrm{C\,(CR)} \;+\; \mathrm{H\,(ISM)} \;\longrightarrow\; \mathrm{B} \;+\; X$$



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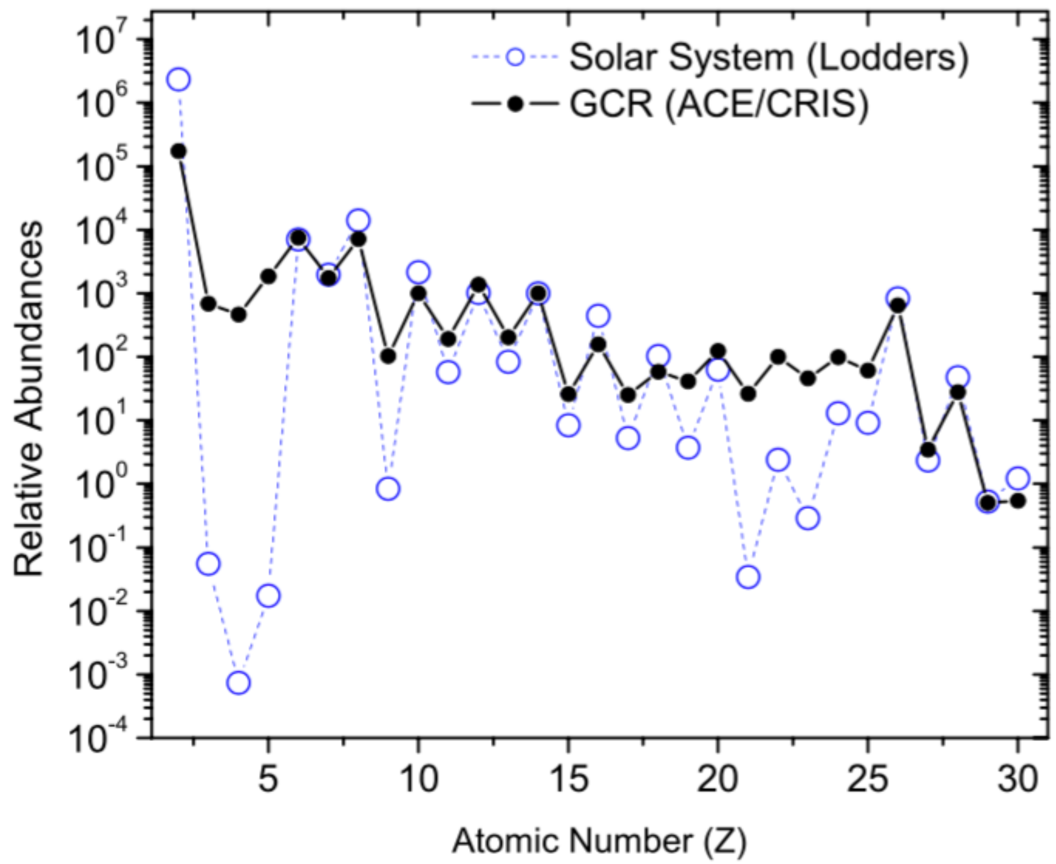
Leaky box model

$$\frac{\Phi_{\mathrm{B}}}{\Phi_{\mathrm{C}}}(\lambda) \simeq \frac{\sigma_{\mathrm{C}\to\mathrm{B}}\;\lambda}{1+\frac{\sigma_{\mathrm{B}}\;\lambda}{m_{\mathrm{H}}}}, \qquad \lambda \equiv \rho_{\mathrm{H}}\, v\, \tau^{esc}$$ *(grammage)*



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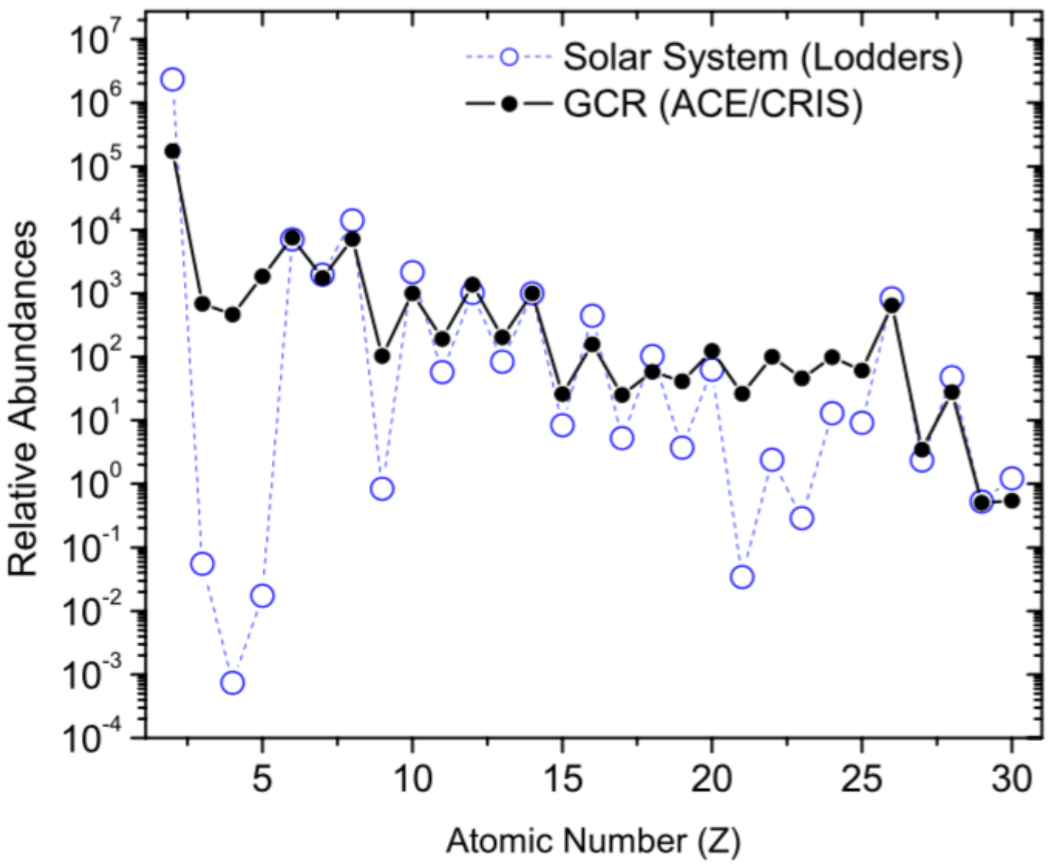
$$\lambda(100\ \mathrm{GeV}) \sim 10\ \mathrm{g\,cm^{-2}}, \quad \tau^{esc} \sim 10\ \mathrm{Myrs} \;\neq \tau = \frac{h}{c} \sim 600\ \mathrm{yrs}$$

Cosmic rays do not propagate straight ahead.



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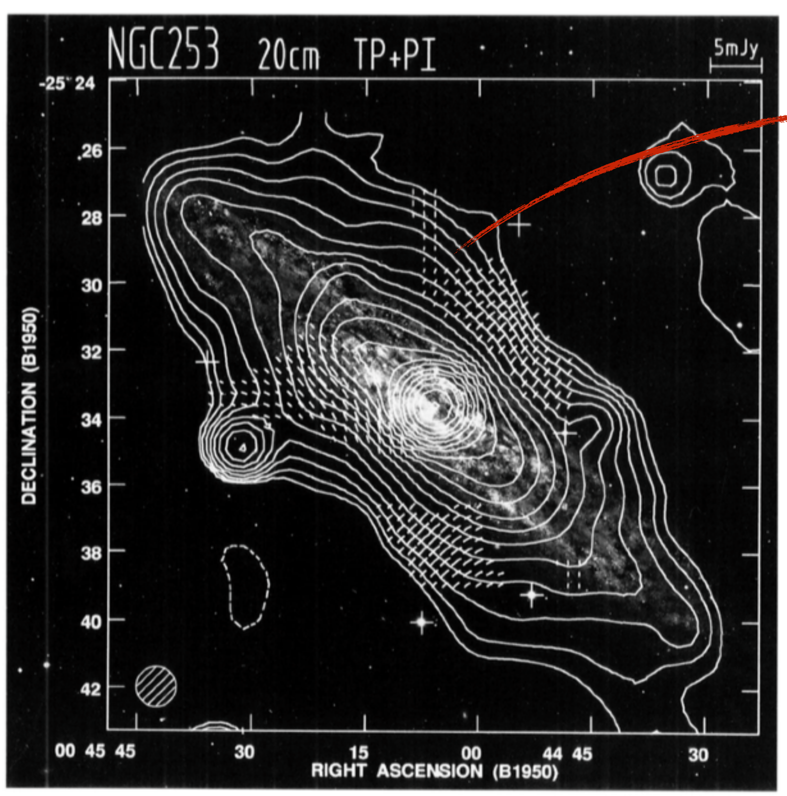


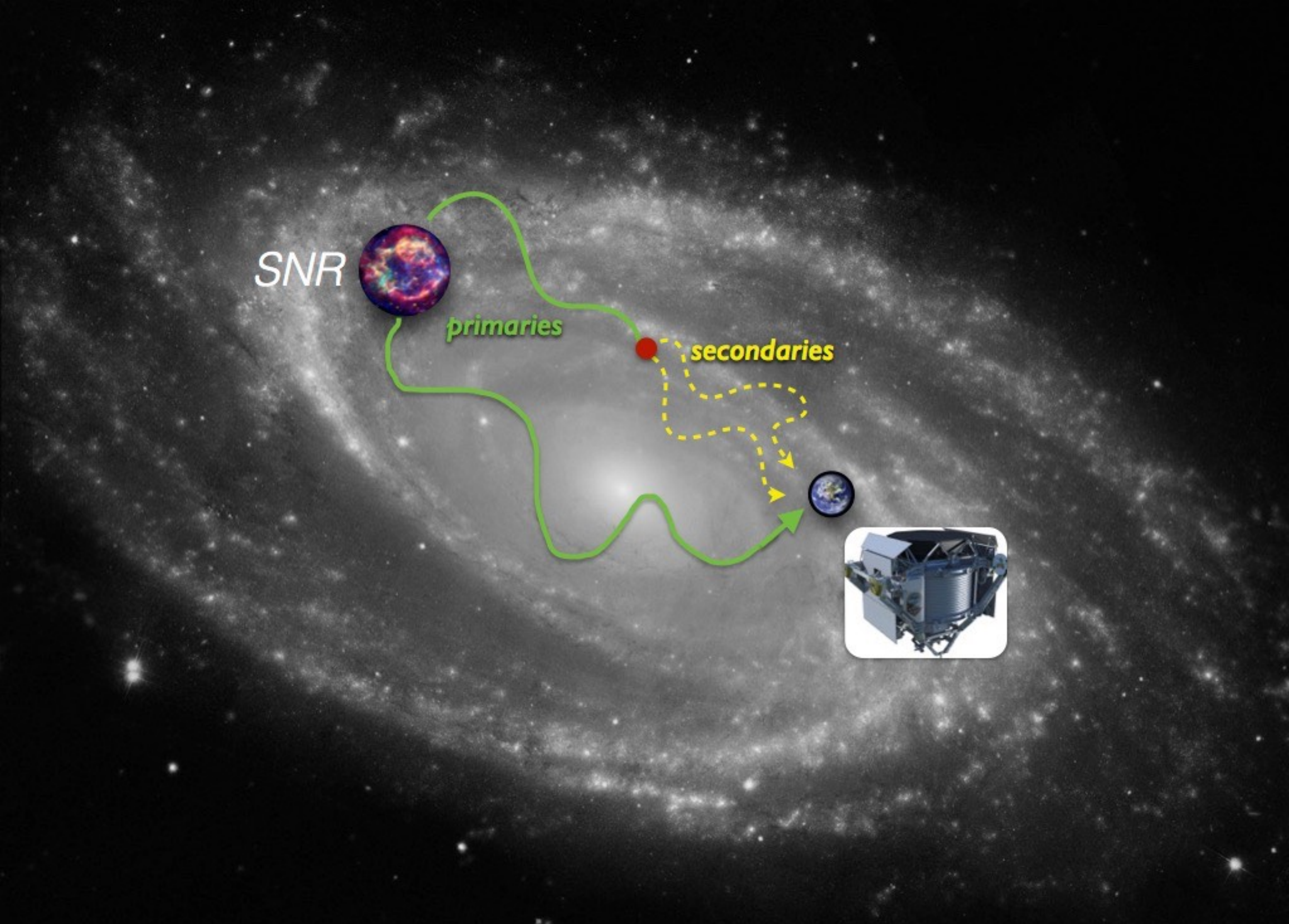
Galaxy NGC-253

Synchrotron radio emission.

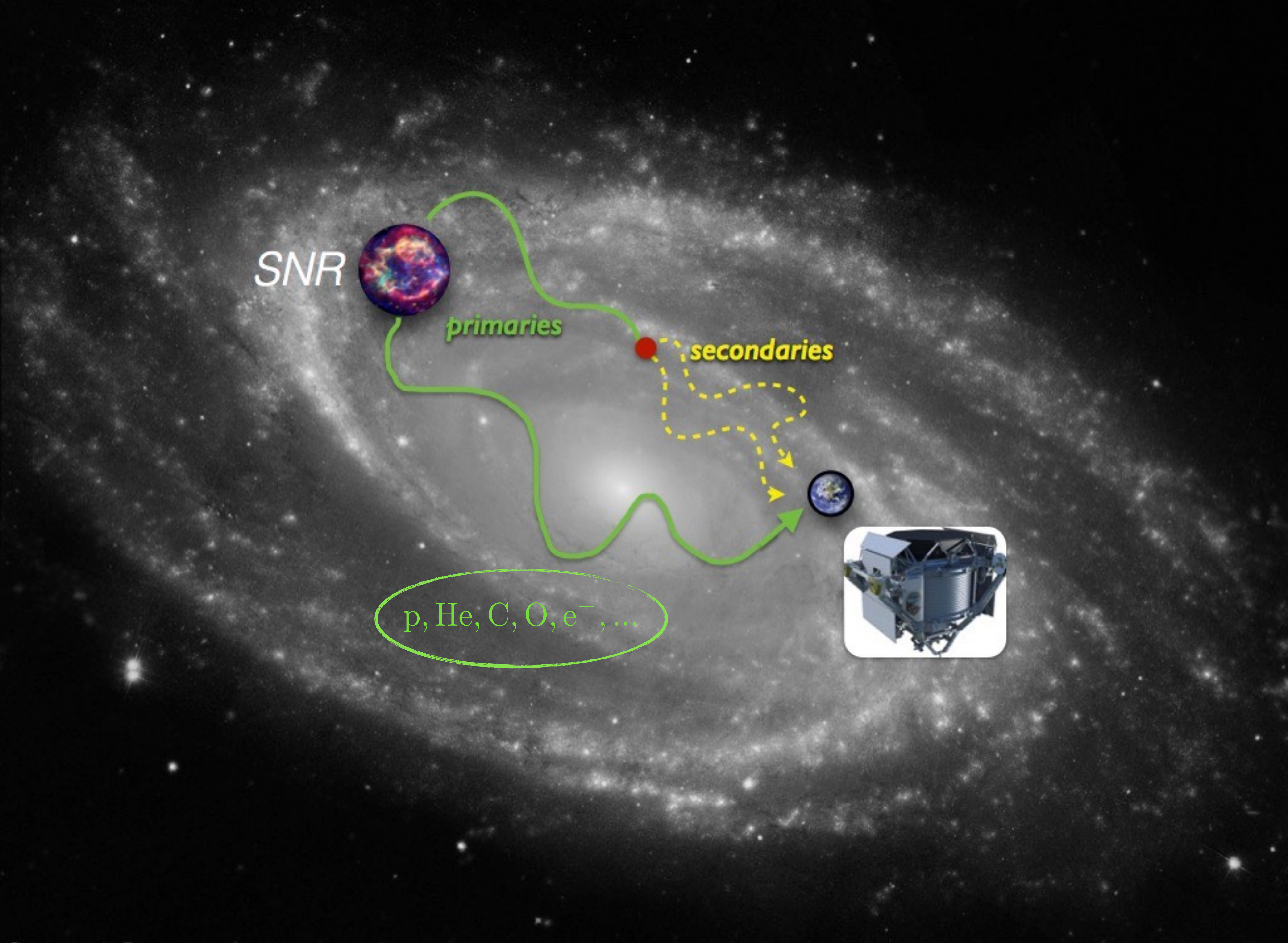
Cosmic ray electrons propagate in a spread out region around of the galactic disc.

The galactic disc is embedded in a magnetic halo with the height *L* ~ kpc.

The magnetic field explains why CRs are confined in the magnetic halo during Myrs.



Courtesy A. Putze



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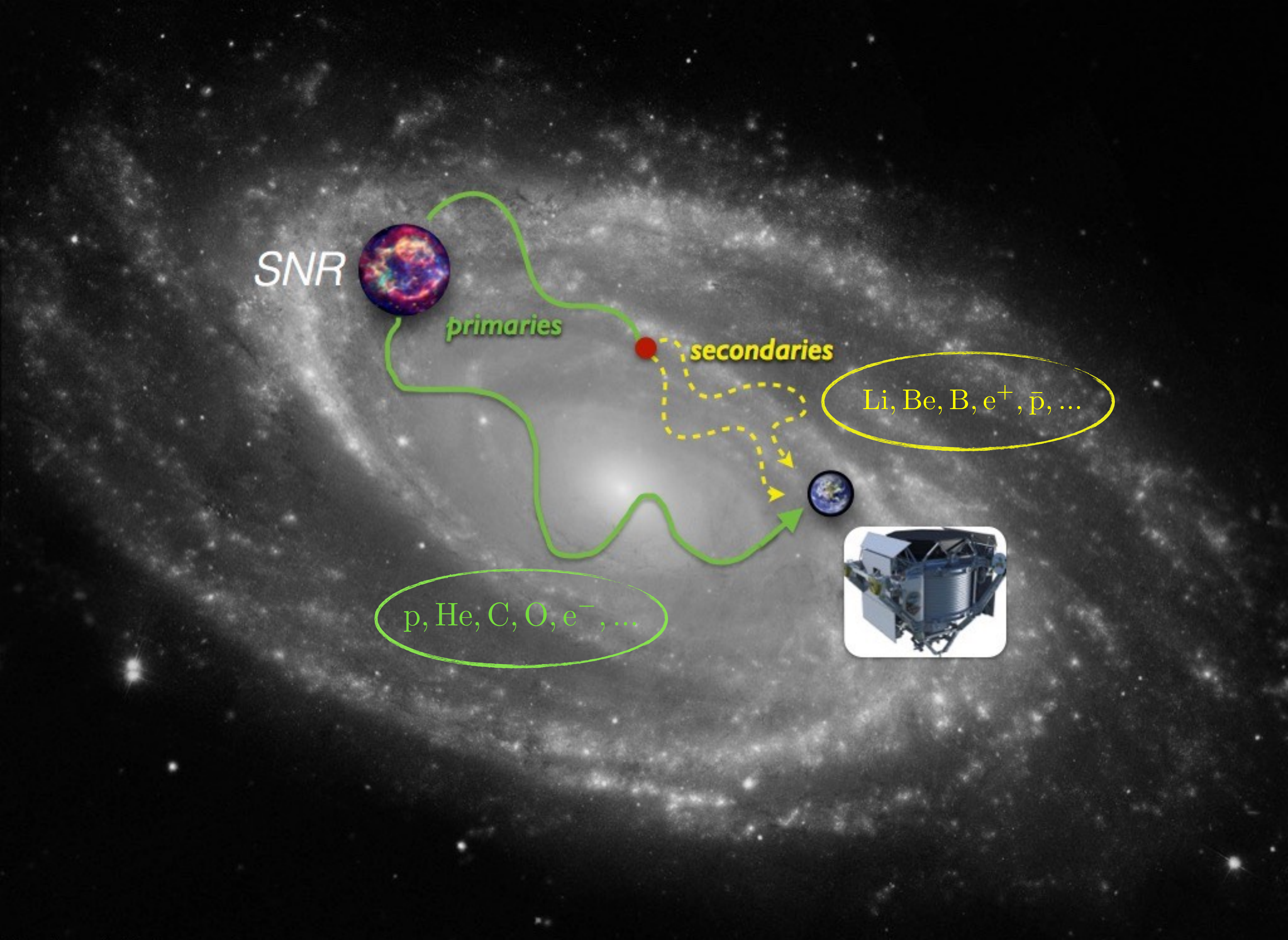

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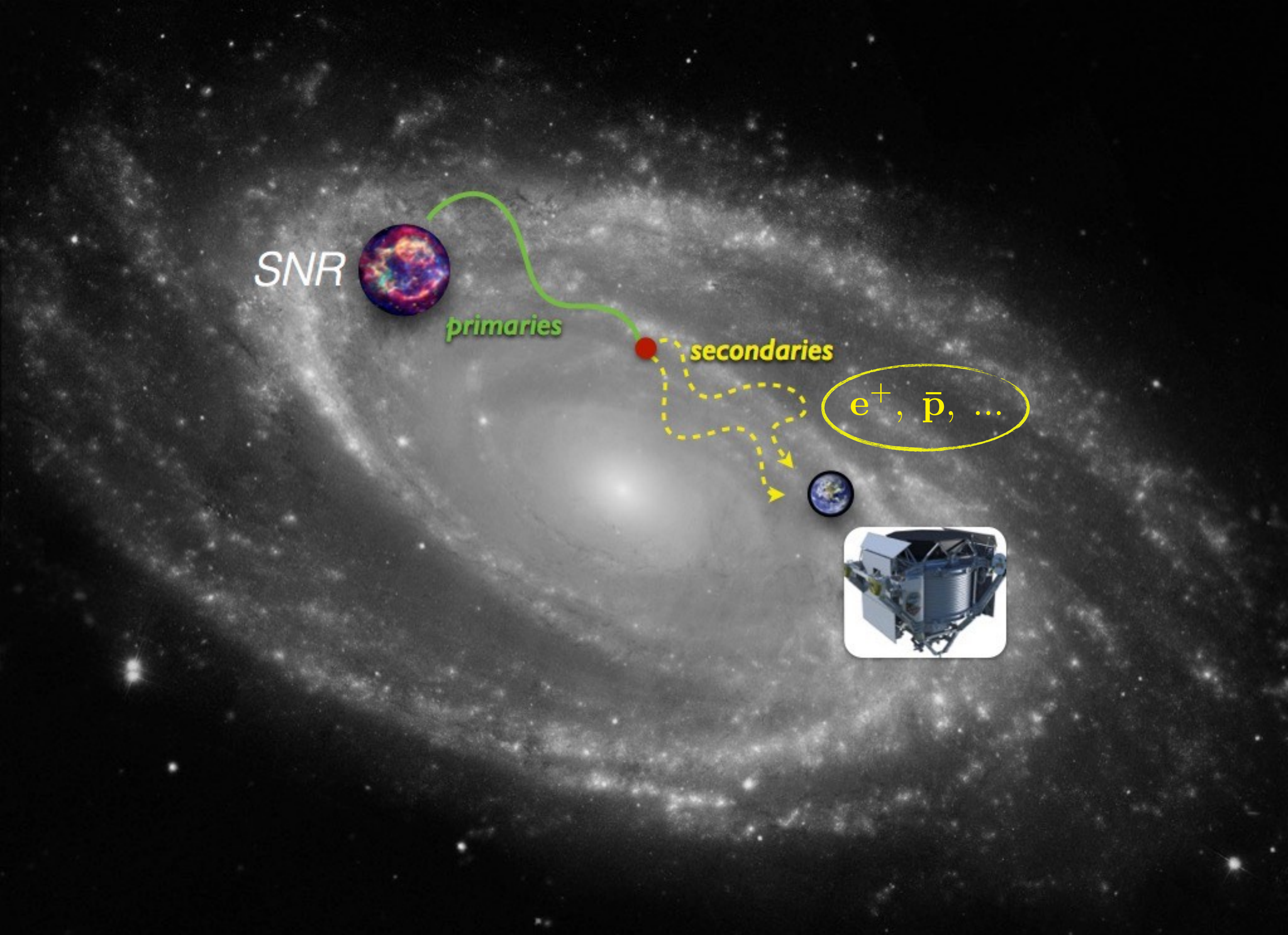

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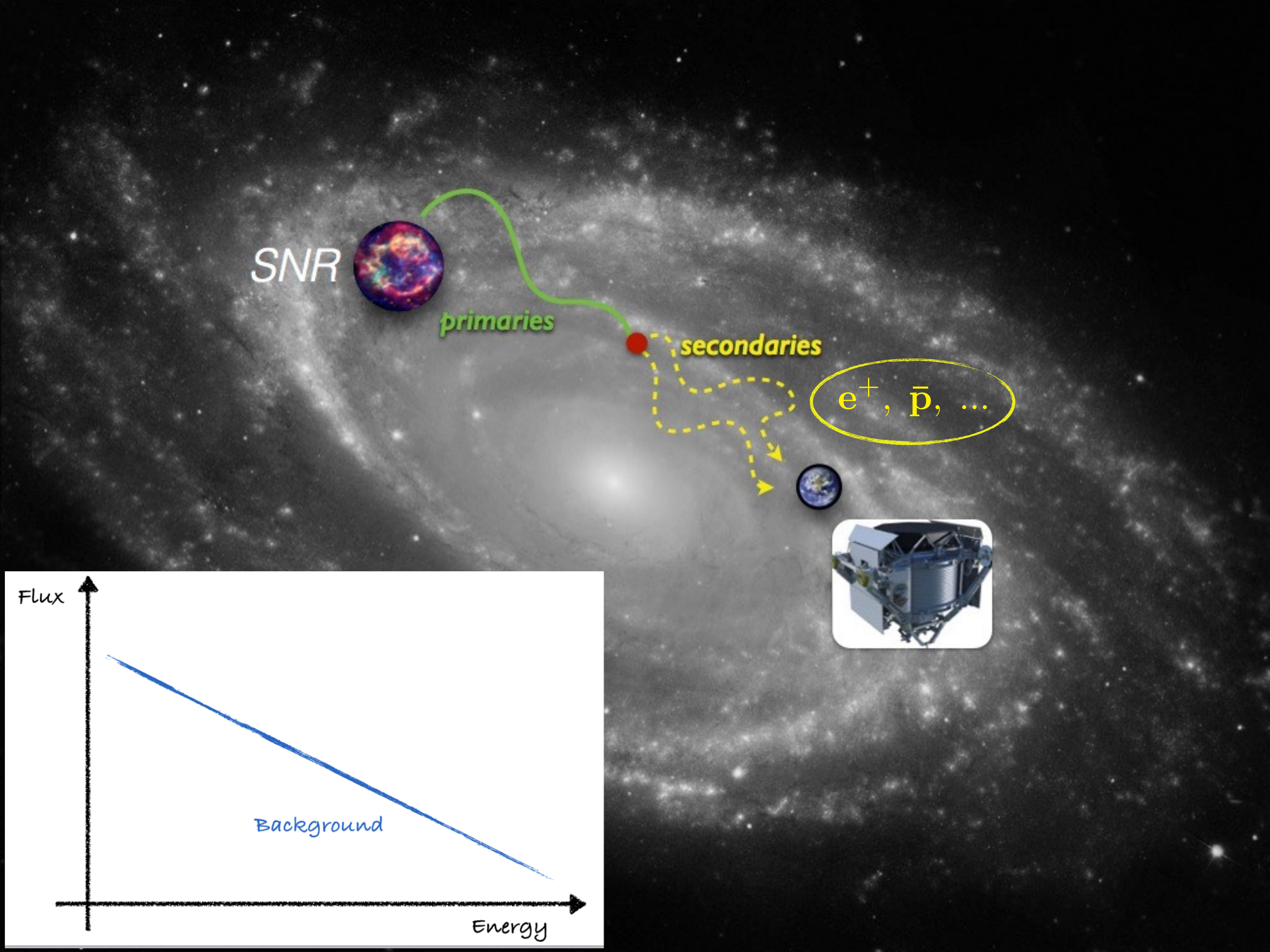
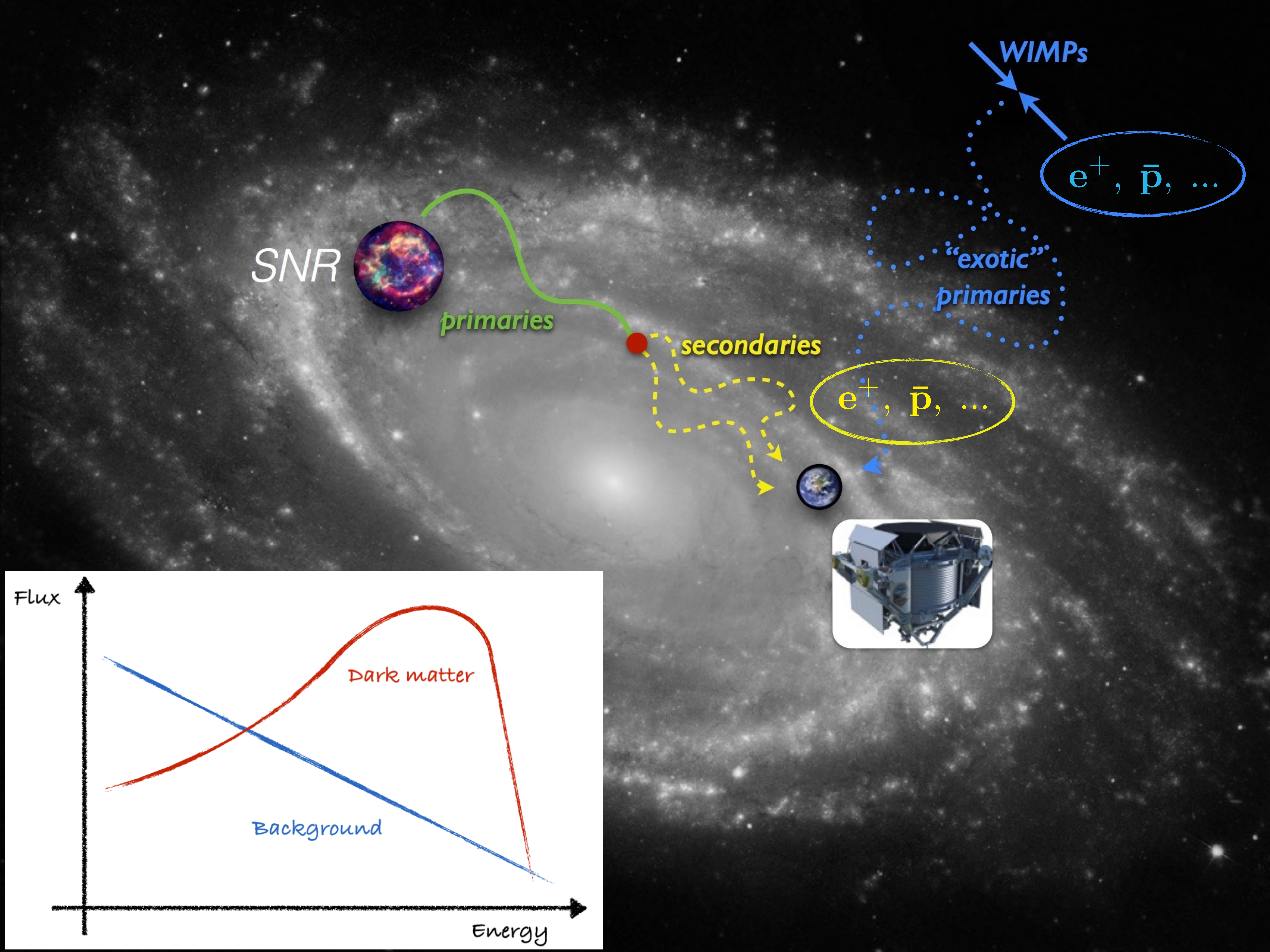
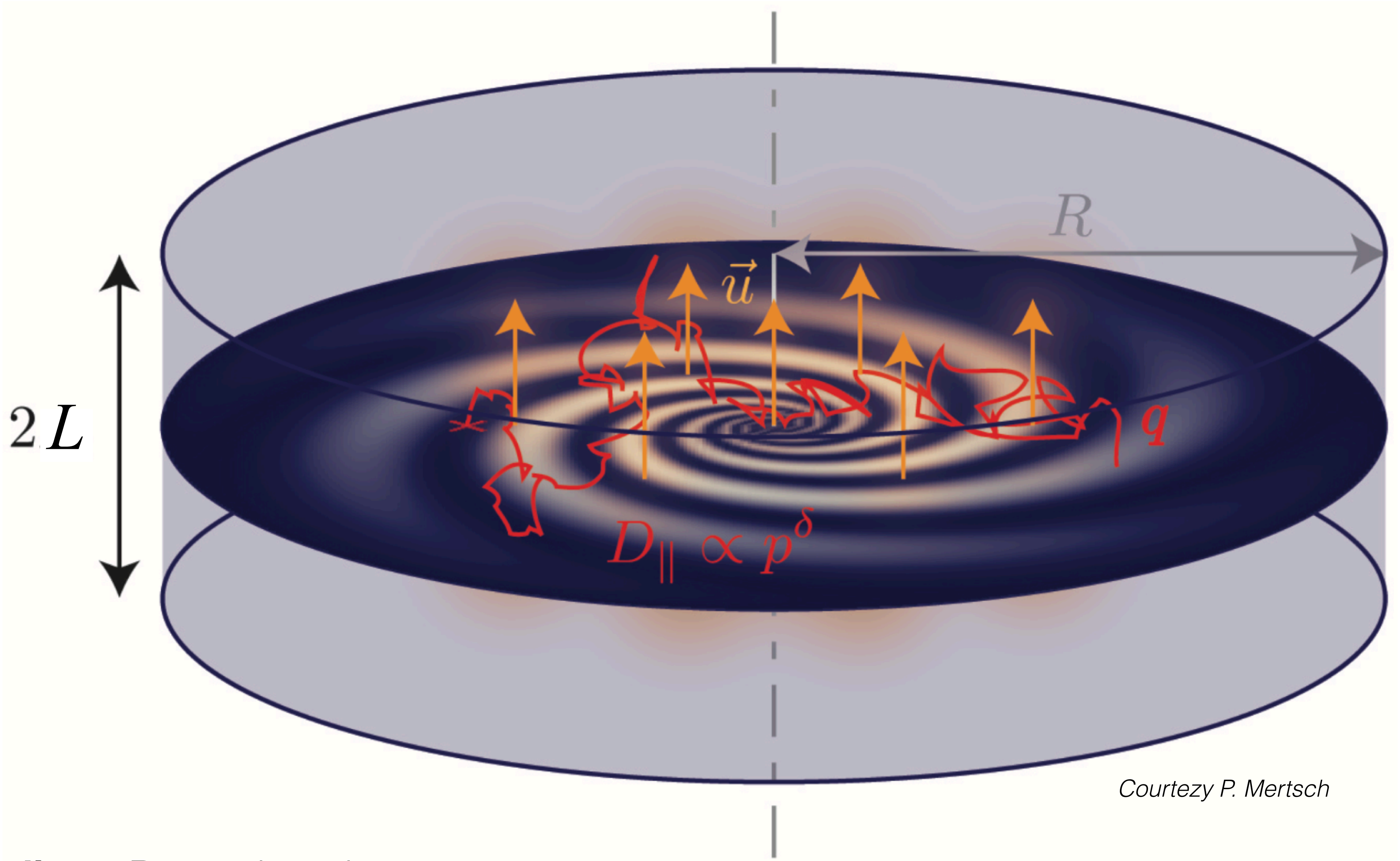


SNR
primaries
secondaries
$e^+, \bar{p}, ...$
Flux
Background
Energy


WIMPs
$e^+, \bar{p}, \ldots$
SNR
primaries
"exotic" primaries
secondaries
$e^+, \bar{p}, \ldots$
Flux
Dark matter
Background
Energy

The two-zone diffusion model



The galactic disc - *R ~ 20 kpc, h ~ 100 pc*

Contains the gaz, the stars and the dust of the Galaxy. Distributed in the spiral arms.
Cosmic rays are accelerated in the galactic disc.

The magnetic halo - *R ~ 20 kpc, 1 ≲ L ≲ 20 kpc*

The diffusion zone of the model. Cosmic rays that escape the magnetic halo cannot go back.

Interaction of cosmic rays

- **Space diffusion**

  Diffusion on the turbulent component of the magnetic field. $K(E, \vec{x})$

- **Convection**

  Galactic wind due to supernovae explosions in the galactic disc. $\vec{V}_C(\vec{x})$

- **Destruction** $Q^{sink}(E, \vec{x})$
  - Interaction with the interstellar medium (ISM)
  - Decay

- **Energy losses**
  - Interaction with the ISM (Coulomb, ionisation, bremsstrahlung, adiabatic expansion) $b(E, \vec{x})$
  - Synchrotron emission, inverse Compton scattering (electrons)

- **Diffusive reacceleration**

  Second order Fermi mechanism. Diffusion in momentum space.
  Depends on the velocity of the Alfven waves V_A.

$$D(E, \vec{x}) = \frac{2}{9} V_A^2 \frac{E^2 \beta^4}{K(E, \vec{x})}$$

The transport equation

$$\psi(E,t,\vec{x}) = \frac{\mathrm{d}^4 N}{\mathrm{d}^3 x\, \mathrm{d}E}$$

$$\partial_t \psi - K(E,\vec{x})\,\Delta\psi + \vec{\nabla}\cdot[\vec{V}_C(\vec{x})\,\psi] + \partial_E\,[b(E,\vec{x})\,\psi - D(E,\vec{x})\,\partial_E\psi] = Q(E,t,\vec{x})$$

$$Q(E,t,\vec{x}) = Q^{source}(E,t,\vec{x}) - Q^{sink}(E,\vec{x})$$

Production

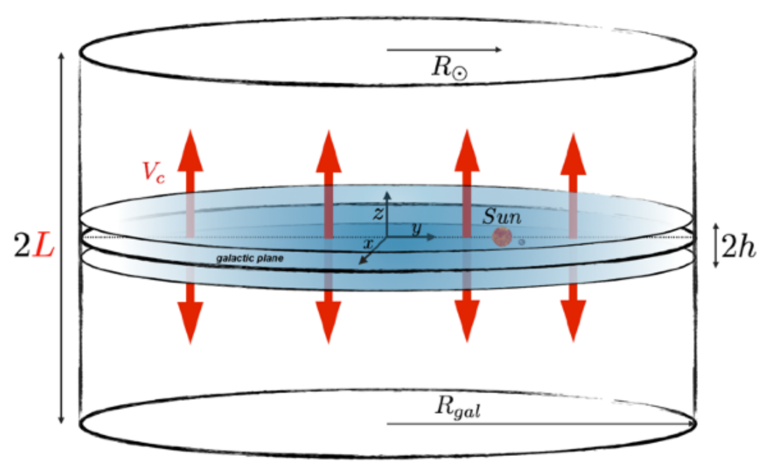
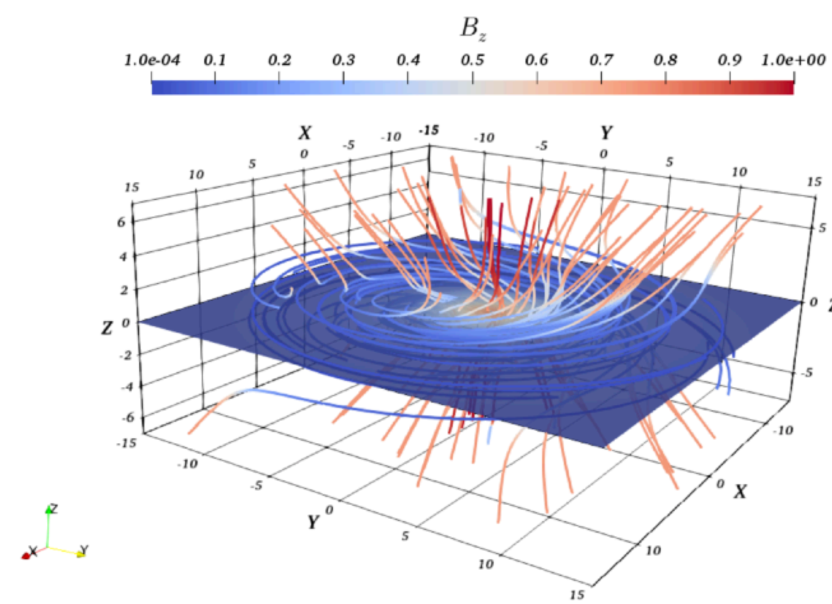
- Acceleration in supernova remnants (SNRs)
- Pulsar wind nebulae (PWNe)
- Spallation of primary CRs
- Decay of primary CRs
- *Dark matter?*

Destruction

- Spallation
- Decay
- Annihilation

Solving the transport equation

$$\partial_t \psi - K(E,\vec{x})\Delta\psi + \vec{\nabla}\cdot\left[\vec{V}_C(\vec{x})\psi\right] + \partial_E\left[b(E,\vec{x})\psi - D(E,\vec{x})\partial_E\psi\right] = Q^{source}(E,t,\vec{x}) - Q^{sink}(E,\vec{x})$$

	Semi-analytical	*Numerical*
Approach	*Simplify the geometry* *Green functions, Bessel and Fourier expansion* 	*Discretise the equation* *Numerical solvers* 
Pros	*Useful to understand the physics* *Fast-running time (extensive scans)*	*Structure of the Galaxy* *Any new input easily included*
Cons	*Only solve approximate model*	*Slow-running time*
Codes	*USINE, PPPC4DMID, **my code**, etc.*	*GALPROP, DRAGON, PICARD, etc.*

The propagation parameters

The diffusion model depends on **5** parameters.

$$1 < L < 15 \text{ kpc}$$

$$\vec{V}_C = V_C \, \text{sign}(z) \, \vec{e}_z$$

$$K(E) = K_0 \, \beta \left(\frac{R}{1\,\text{GV}} \right)^{\delta}$$

$$D(E) = \frac{2}{9} \, {V_A}^2 \, \frac{E^2 \beta^4}{K(E)}$$

These parameters can be constrained using the ratio between secondary to primaries species (B/C, etc.)

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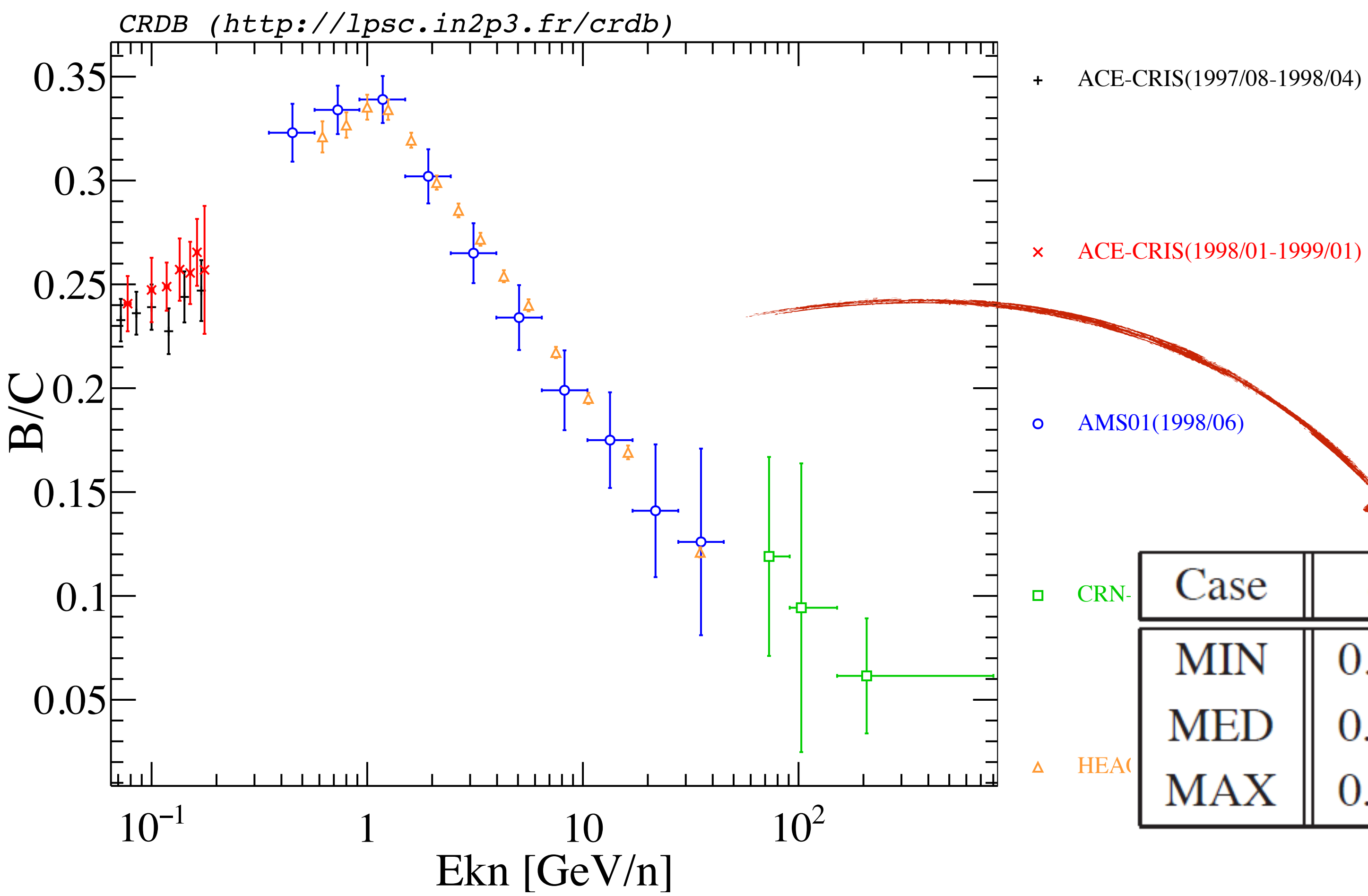
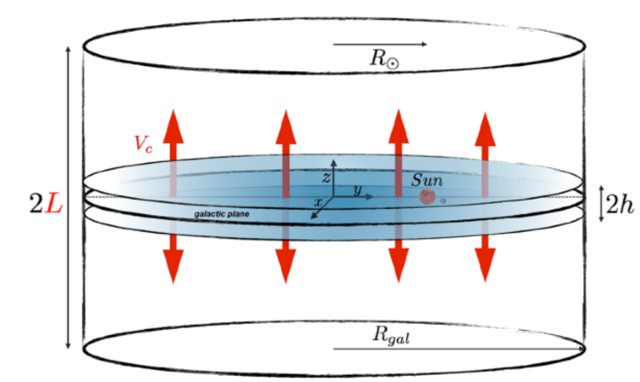


Semi-analytical

Maurin et al. (2001)
&
Donato et al. (2003)



Case	δ	K_0 [kpc^2/Myr]	L [kpc]	V_C [km/s]	V_a [km/s]
MIN	0.85	0.0016	1	13.5	22.4
MED	0.70	0.0112	4	12	52.9
MAX	0.46	0.0765	15	5	117.6

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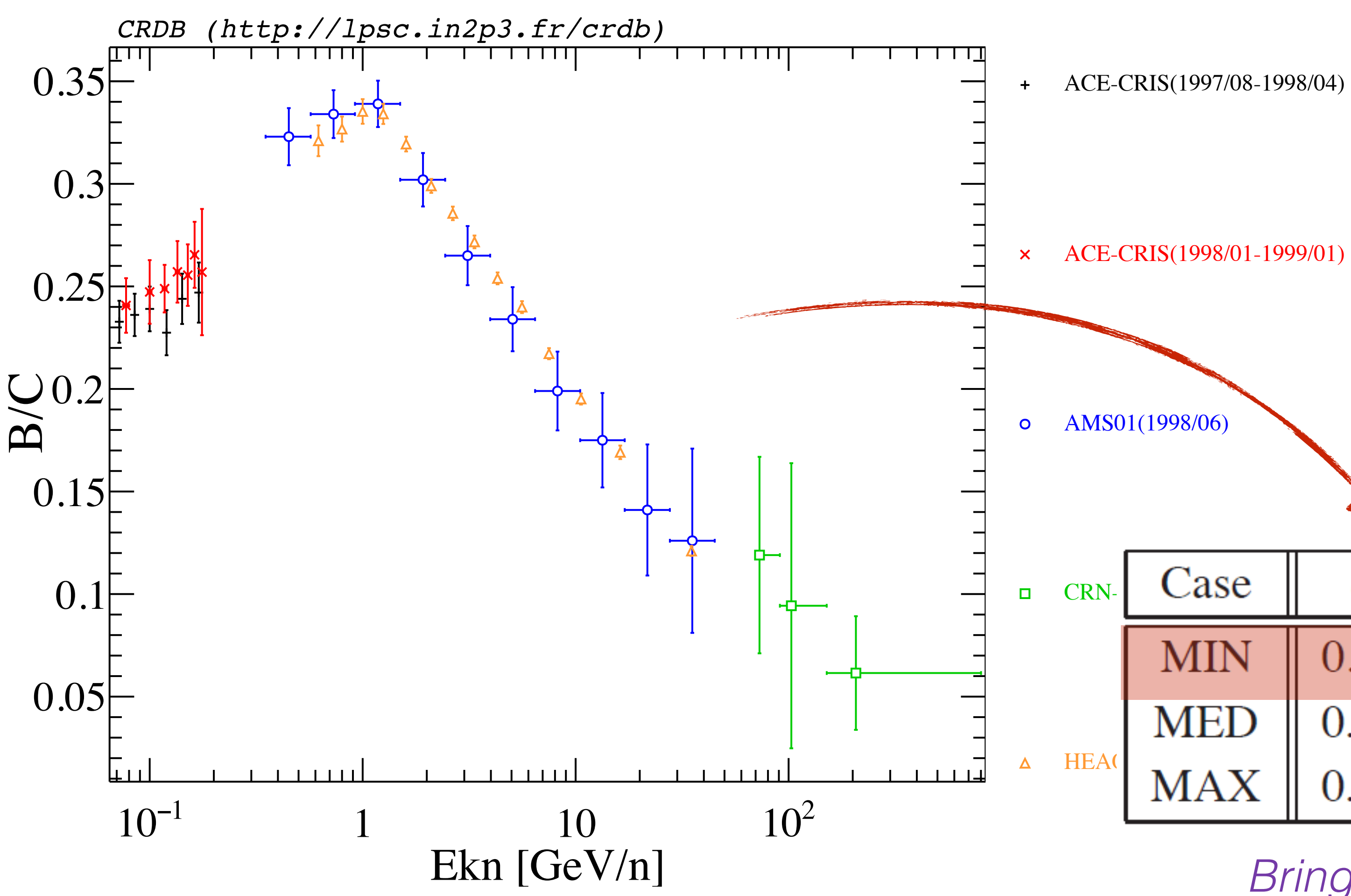
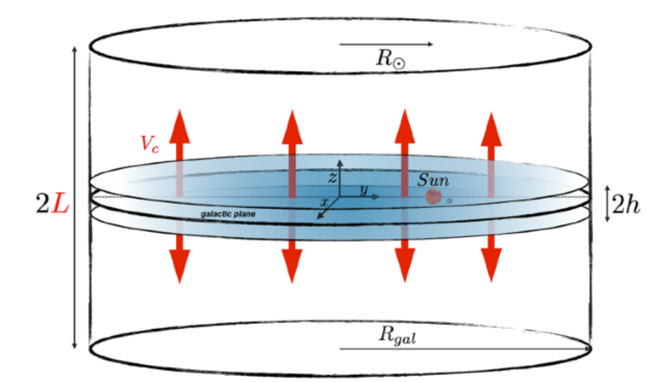


Semi-analytical



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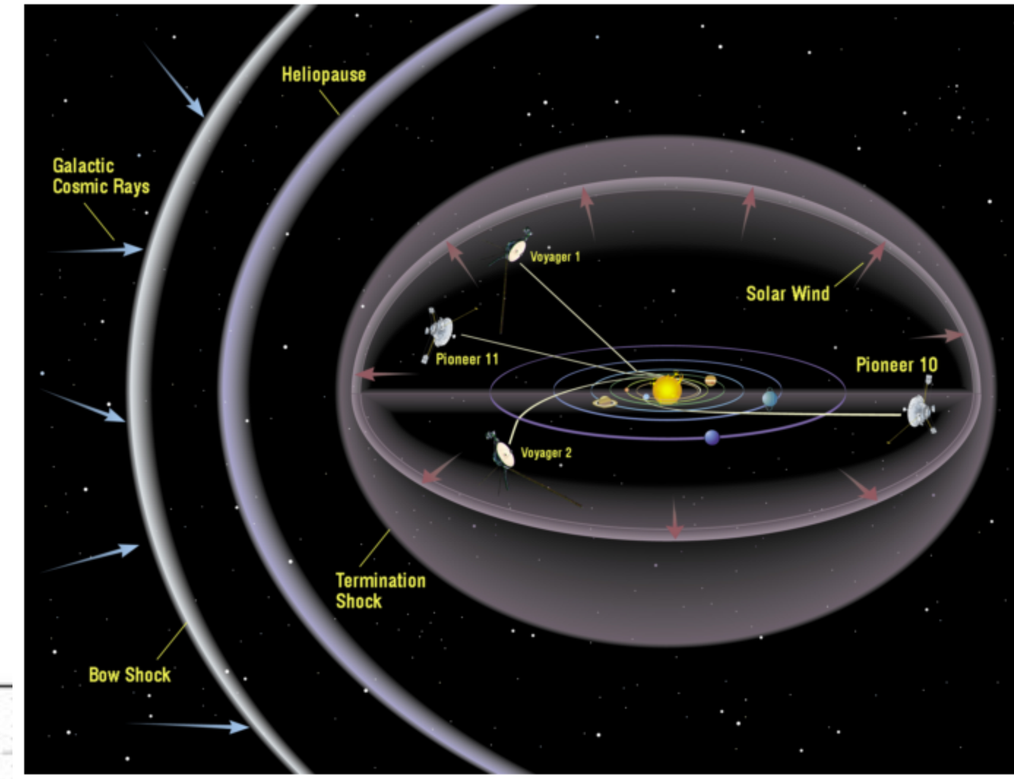
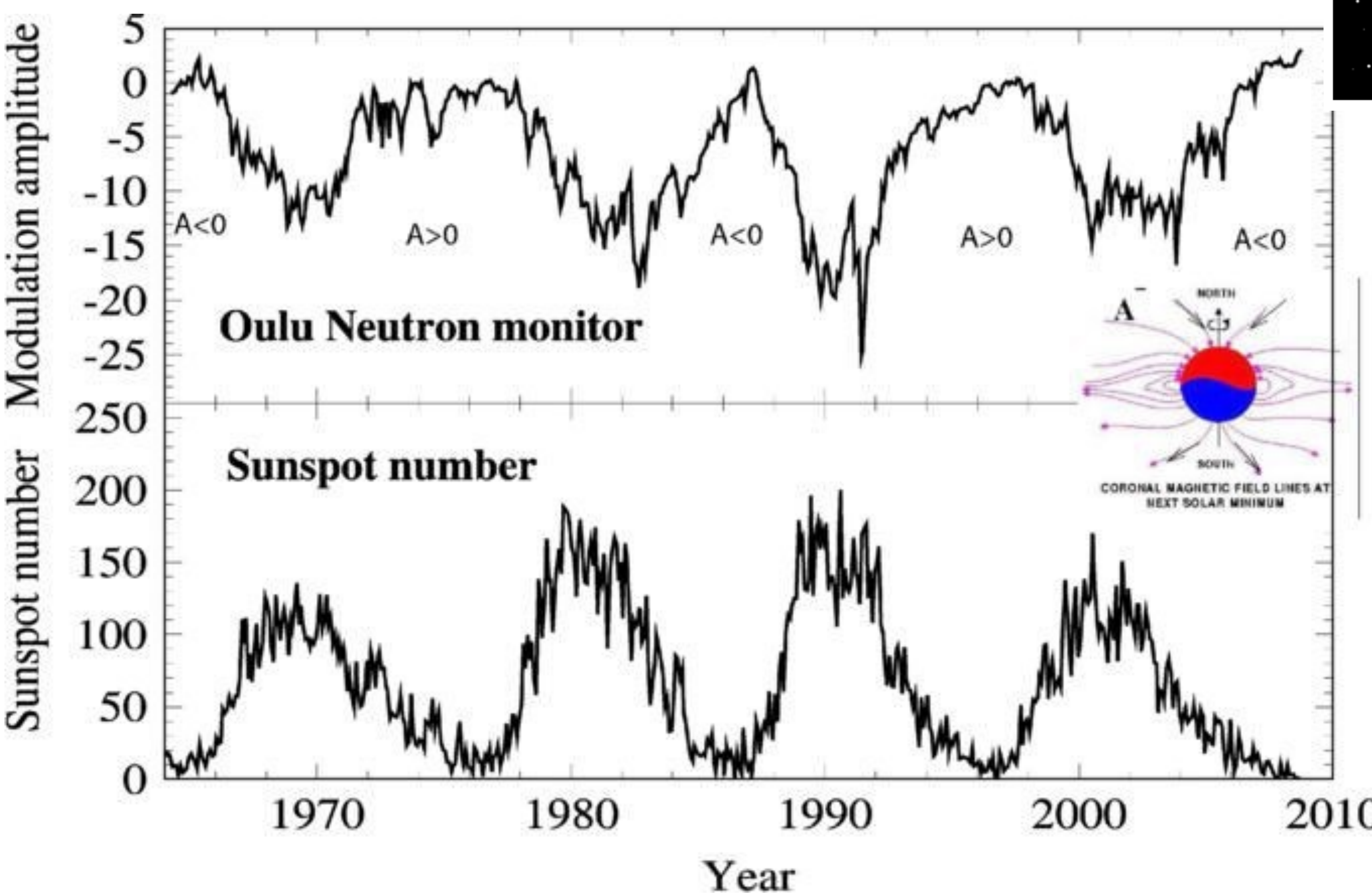
Bringmann+(2012), Ackerman+(2012), Lavalle+(2014)

Solar modulation



Cosmic rays lose energy when they interact with the solar wind.

The intensity of the solar effect on cosmic rays is correlated with the sun activity (22 years periodic). Solar modulation.

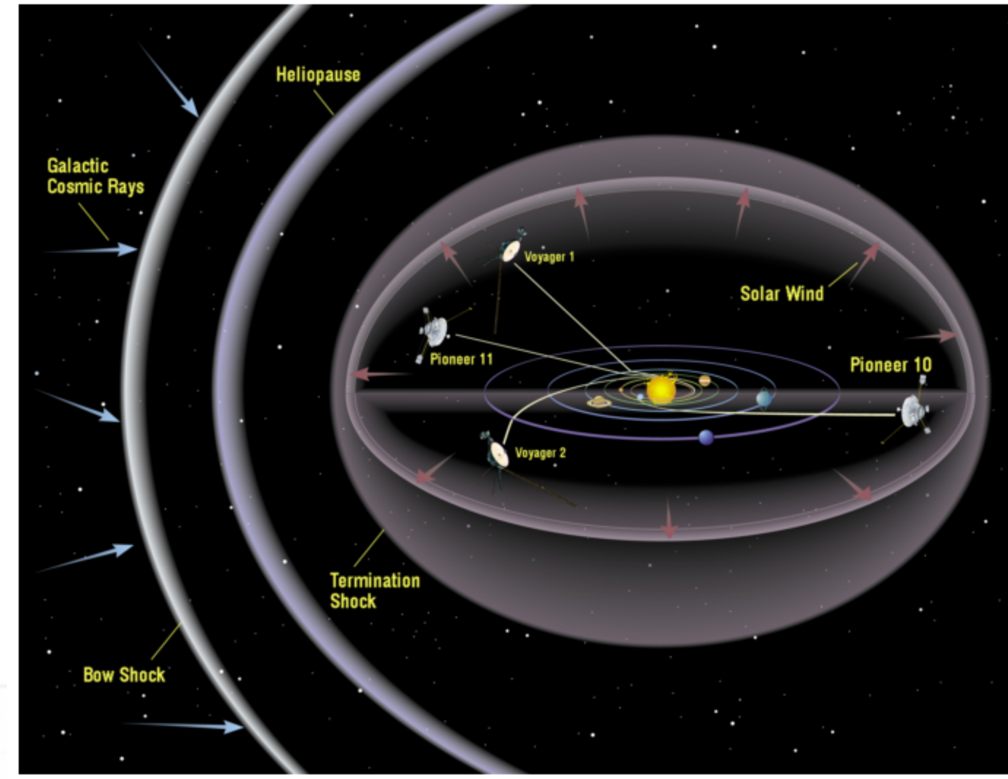


Solar modulation

Cosmic rays lose energy when they interact with the solar wind.

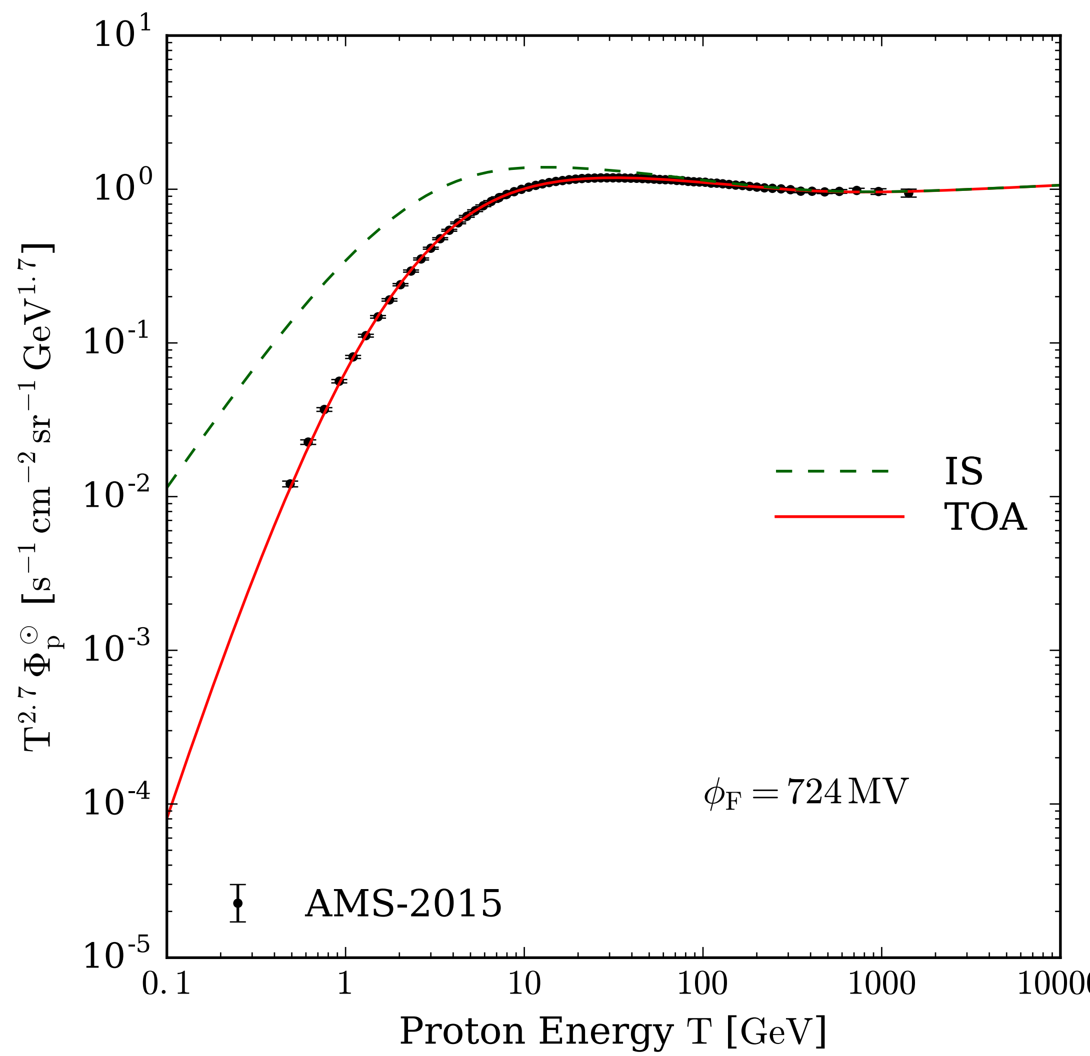
The intensity of the solar effect on cosmic rays is correlated with the sun activity (22 years periodic). Solar modulation.

This effect can be described using the force-field approximation that depends only on one parameter: the Fisk potential ϕ_F.



The forced-field approximation

$$\Phi^{\mathrm{TOA}}(T) = \Phi^{\mathrm{IS}}\left(T + Z\,e\,\phi_F/A\right)\frac{T(T+2m)}{(T+m+Z\,e\,\phi_F/A)^2 - m^2}$$



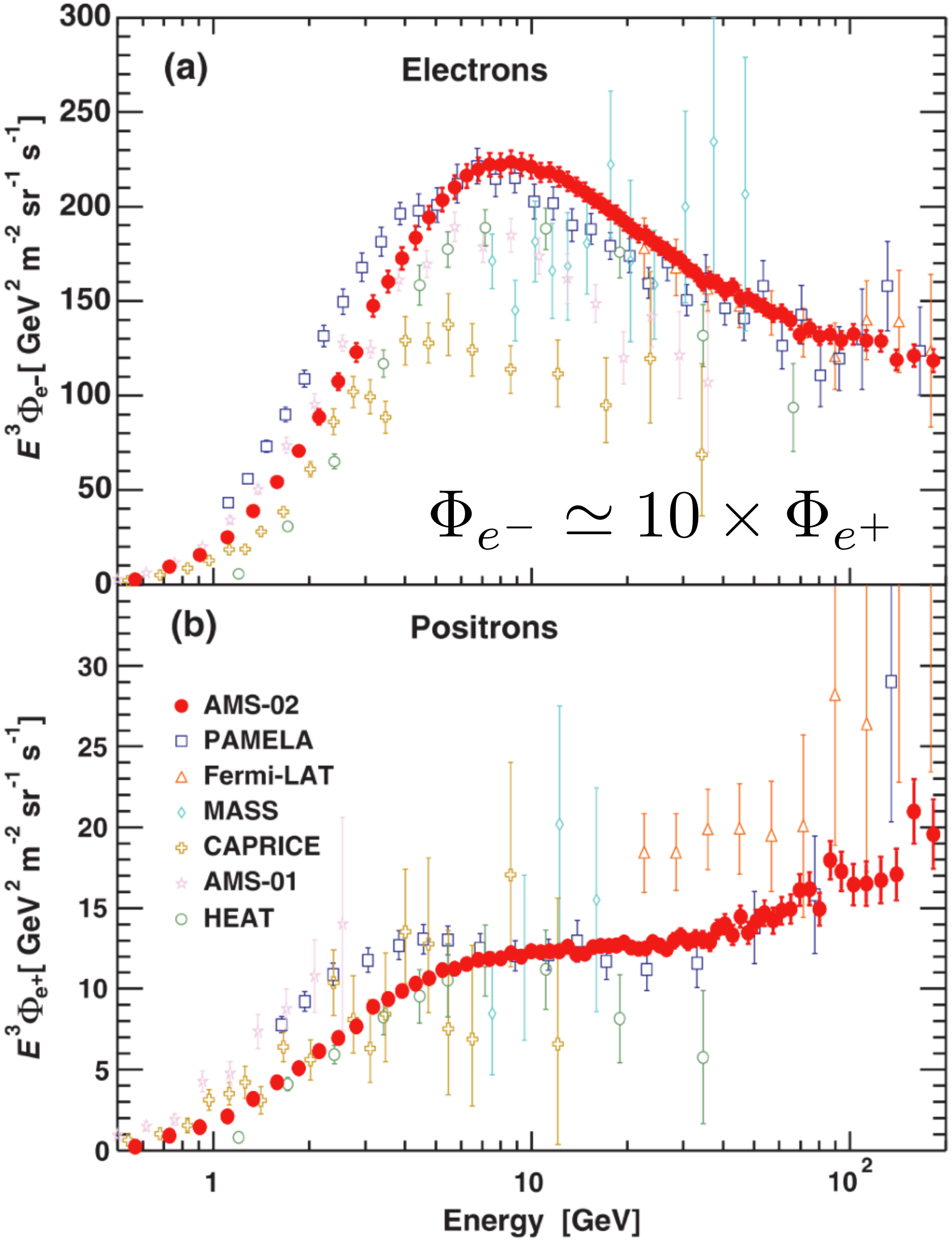
The positrons story

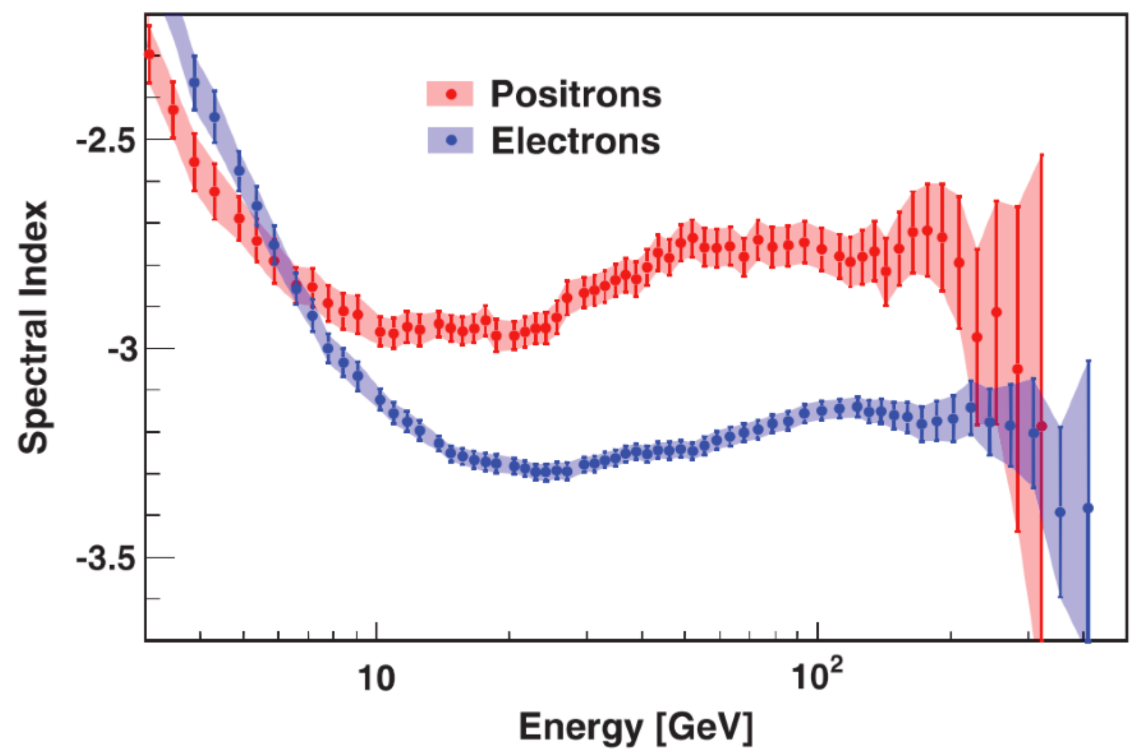
Positrons flux and positron fraction

AMS-02 collaboration published the fluxes of electrons, positrons and the positron fraction from ~ 0.5 GeV up to ~ 500 GeV with an unprecedented high accuracy.

$$\mathrm{PF} = \frac{\Phi_{e^+}}{\Phi_{e^- + e^+}}$$

PRL113,121102 (2014), PRL113,121101 (2014)

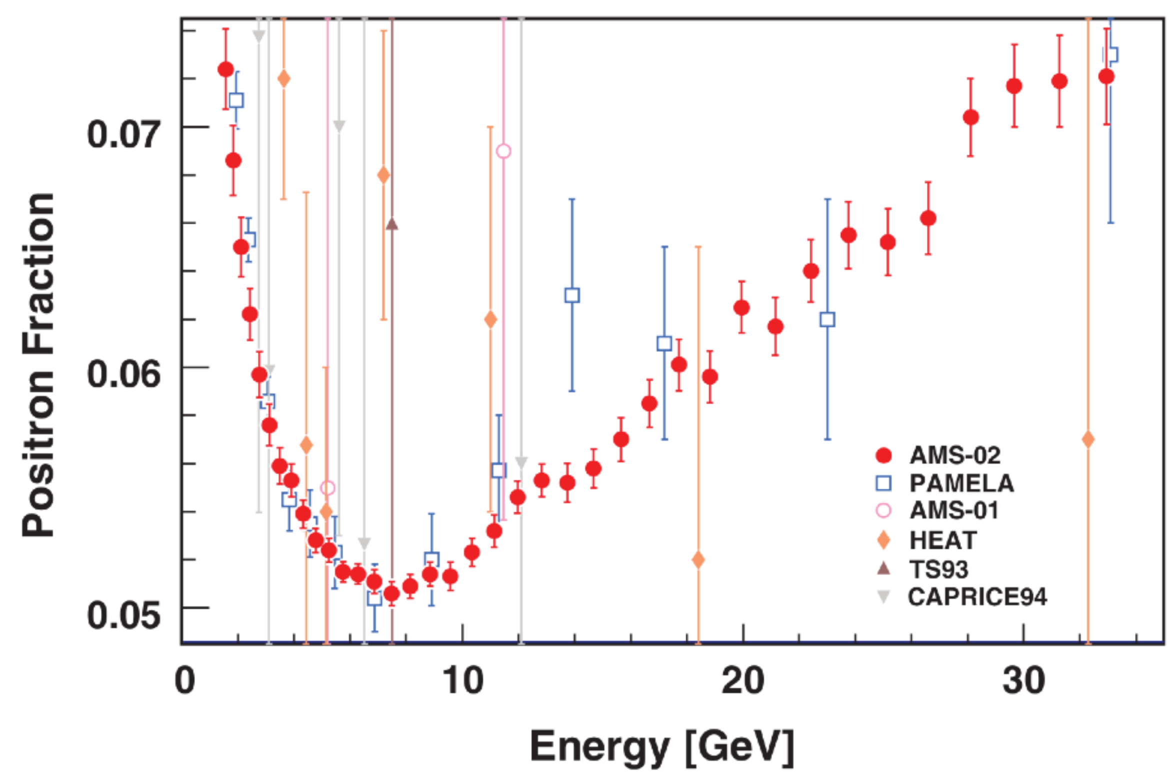




E ~ 100 GeV

$\gamma_{e^+} \simeq 2.75$

$\gamma_{e^-} \simeq 3.15$



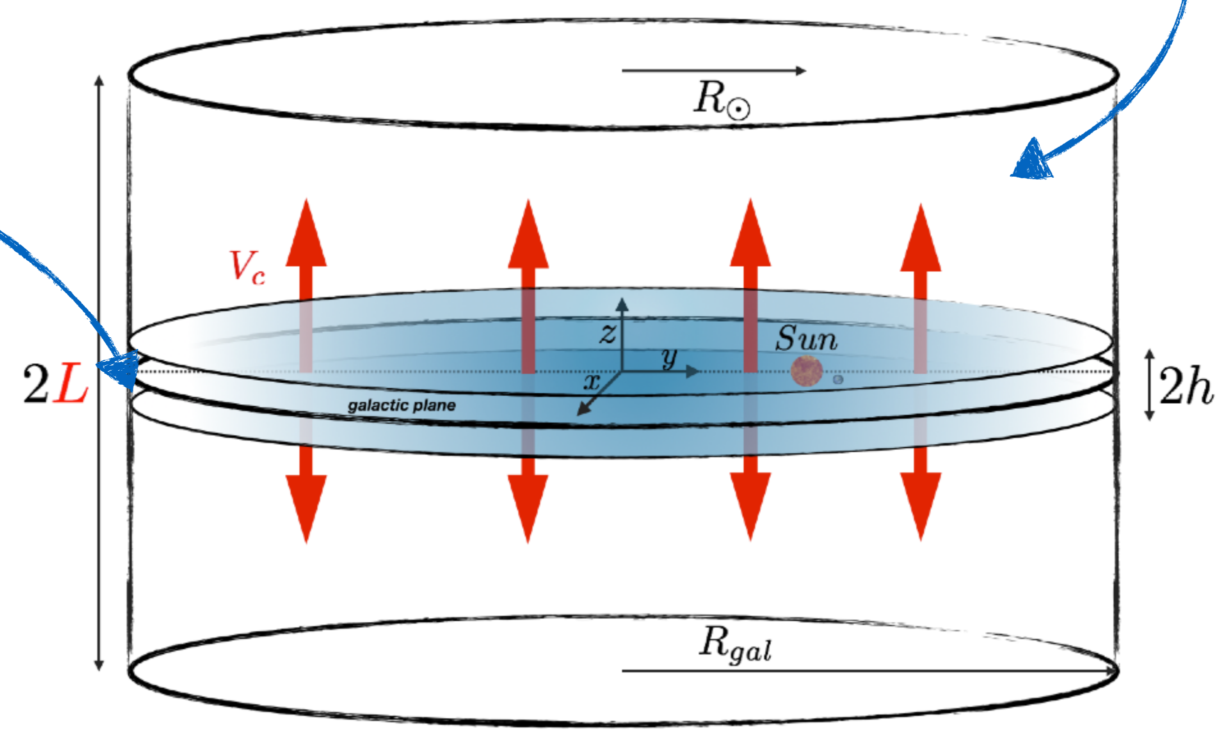
Electrons and positrons: the high-energy approximation

Cosmic rays transport equation (steady state)

$$\partial_z \left[V_C \, \mathrm{sign}(z)\, \psi\right] - K(E)\,\Delta\,\psi + 2h\,\delta(z)\,\partial_E\left[b_{\mathrm{disc}}(E)\,\psi - D(E)\,\partial_E\,\psi\right] + \partial_E\left[b_{\mathrm{halo}}(E)\,\psi\right] = Q(E,\vec{x})$$

$$b_{\mathrm{disc}} = b_{\mathrm{adia}} + b_{\mathrm{ioni}} + b_{\mathrm{brem}} + b_{\mathrm{coul}}$$

$$b_{\mathrm{halo}} = b_{\mathrm{IC}} + b_{\mathrm{sync}}$$



We cannot solve analytically the transport equation when energy losses processes take place in different places in the Galaxy.

We need a **numerical** algorithm to solve the transport equation (GALPROP, DRAGON, PICARD, etc.)

Electrons and positrons: the high-energy approximation

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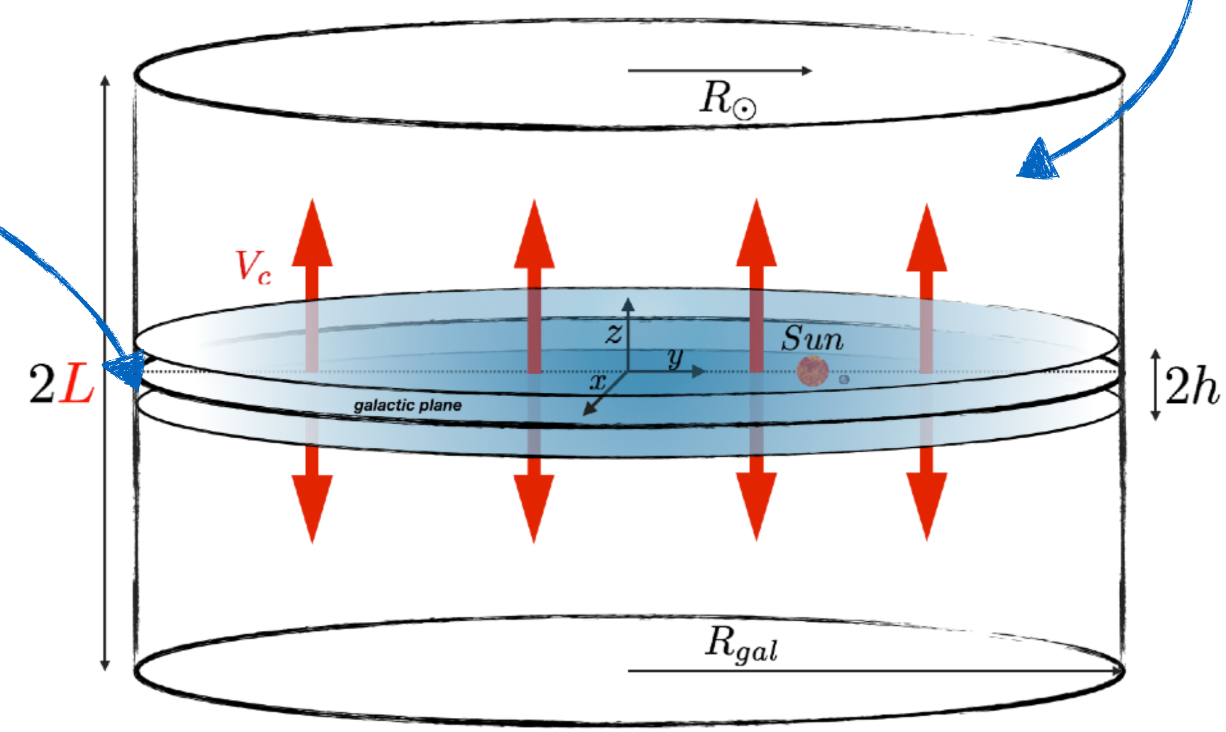
$$\partial_z \left[V_C \,\mathrm{sign}(z)\, \psi\right] - K(E)\, \Delta\, \psi + 2h\, \delta(z)\, \partial_E \left[b_{\rm disc}(E)\, \psi - D(E)\, \partial_E\, \psi\right] + \partial_E \left[b_{\rm halo}(E)\, \psi\right] = Q(E, \vec{x})$$

$$b_{\rm disc} = b_{\rm adia} + b_{\rm ioni} + b_{\rm brem} + b_{\rm coul}$$

$$b_{\rm halo} = b_{\rm IC} + b_{\rm sync}$$



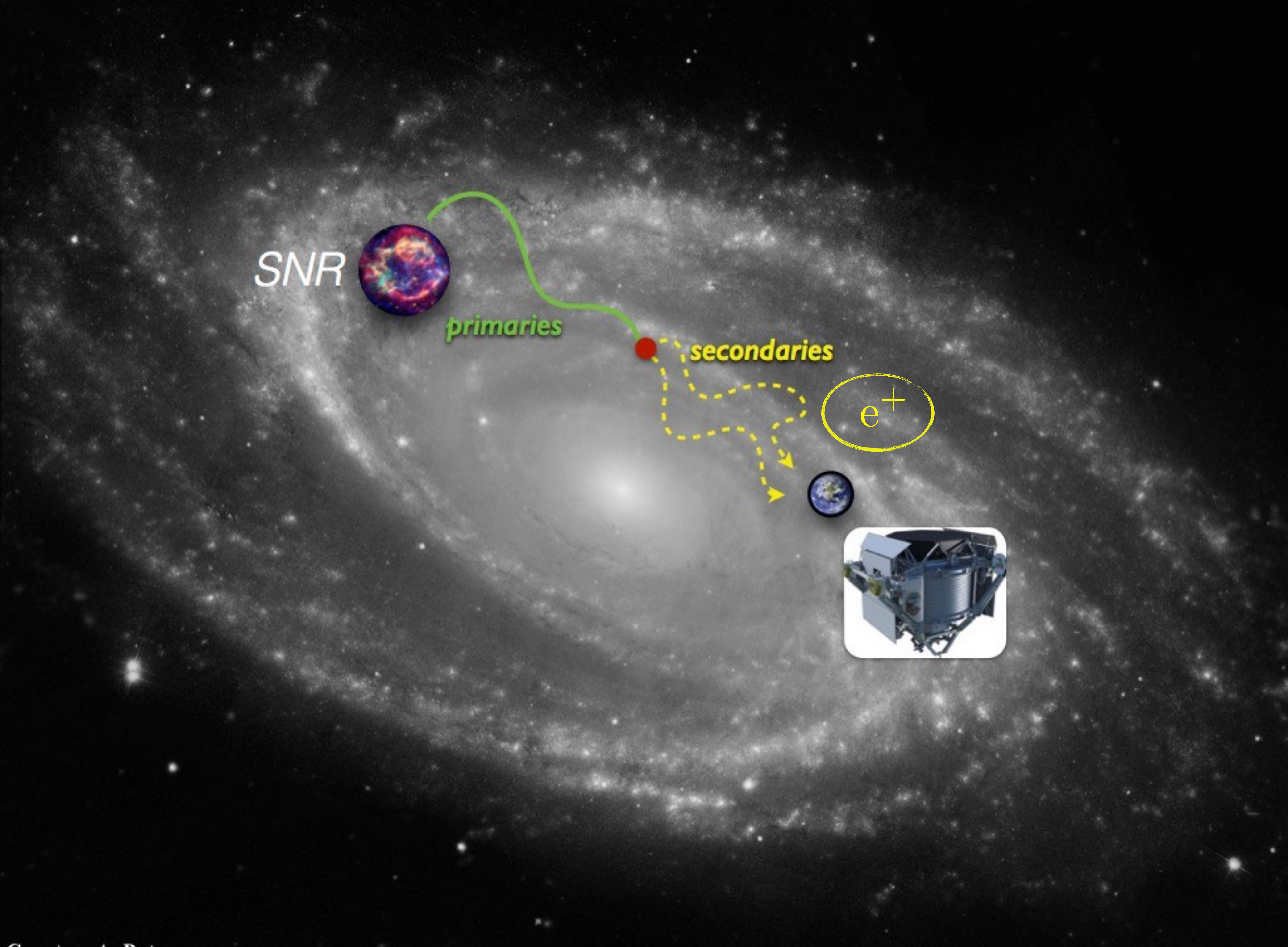
$E > 10$ GeV

High energy approximation

$$-K(E) + \partial_E \left[b_{\rm halo}(E)\psi\right] = Q(E, \vec{x})$$

Baltz & Edsjö (1998)
Delahaye+(2008)
MB+(2014)
etc.

Is E = 10 GeV a correct threshold to get rid of low energy effects?
(Especially with the high accuracy of the AMS-02 data at E ~ 10 GeV)

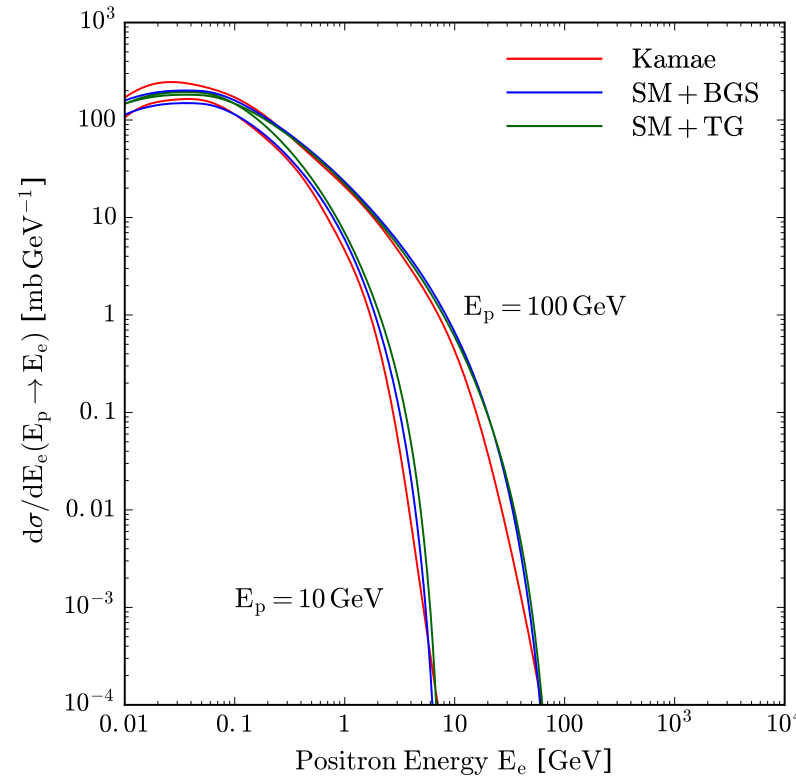


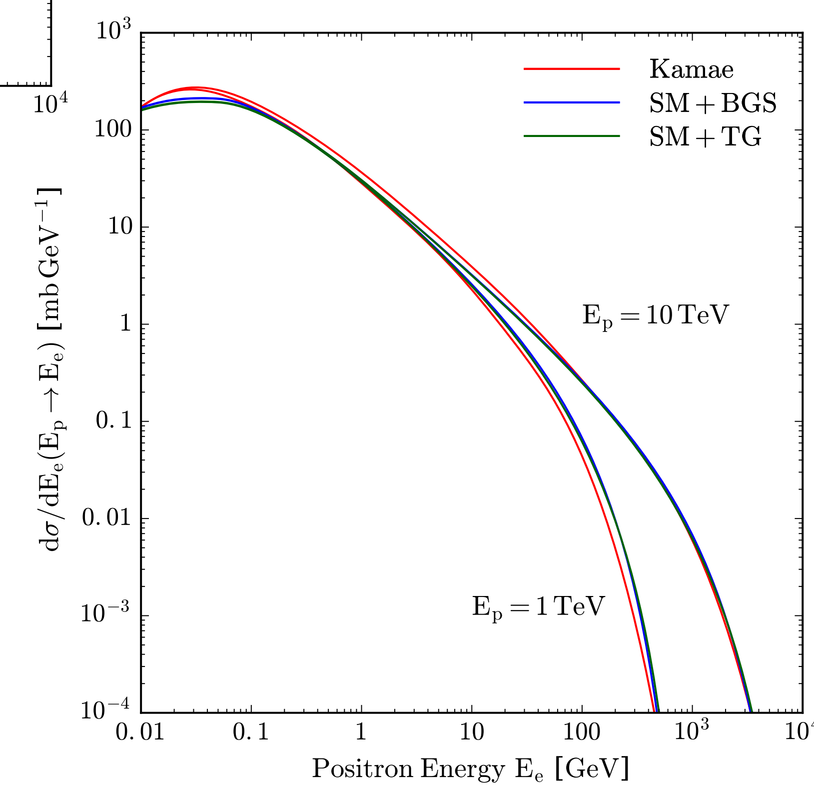
Courtesy A. Putze

Astrophysical background of secondary positrons

$$Q^{\mathrm{II}}(E,\vec{x}) = 4\pi \sum_{i=p,\alpha} \sum_{j=H,He} n_j \int_{E_0}^{+\infty} dE_i \, \phi_i(E_i,\vec{x}) \, \frac{d\sigma}{dE_i}(E_j \to E) \qquad \begin{cases} i = projectile \\ j = target \end{cases}$$

$$p + p \longrightarrow \begin{cases} p + \Delta^+ \\ \quad \Delta^+ \longrightarrow n + \pi^+ \\ \qquad \pi^+ \longrightarrow \nu_\mu + \mu^+ \\ \qquad\quad \mu^+ \longrightarrow \bar{\nu}_\mu + \nu_e + e^+ \\ X + \pi^+ \\ \quad \pi^+ \longrightarrow \nu_\mu + \mu^+ \\ \qquad \mu^+ \longrightarrow \bar{\nu}_\mu + \nu_e + e^+ \\ X + K^+ \\ \quad K^+ \longrightarrow \begin{cases} \nu_\mu + \mu^+ \\ \quad \mu^+ \longrightarrow \bar{\nu}_\mu + \nu_e + e^+ \\ \pi^0 + \pi^+ \\ \quad \pi^+ \longrightarrow \nu_\mu + \mu^+ \\ \qquad \mu^+ \longrightarrow \bar{\nu}_\mu + \nu_e + e^+ \end{cases} \end{cases}$$





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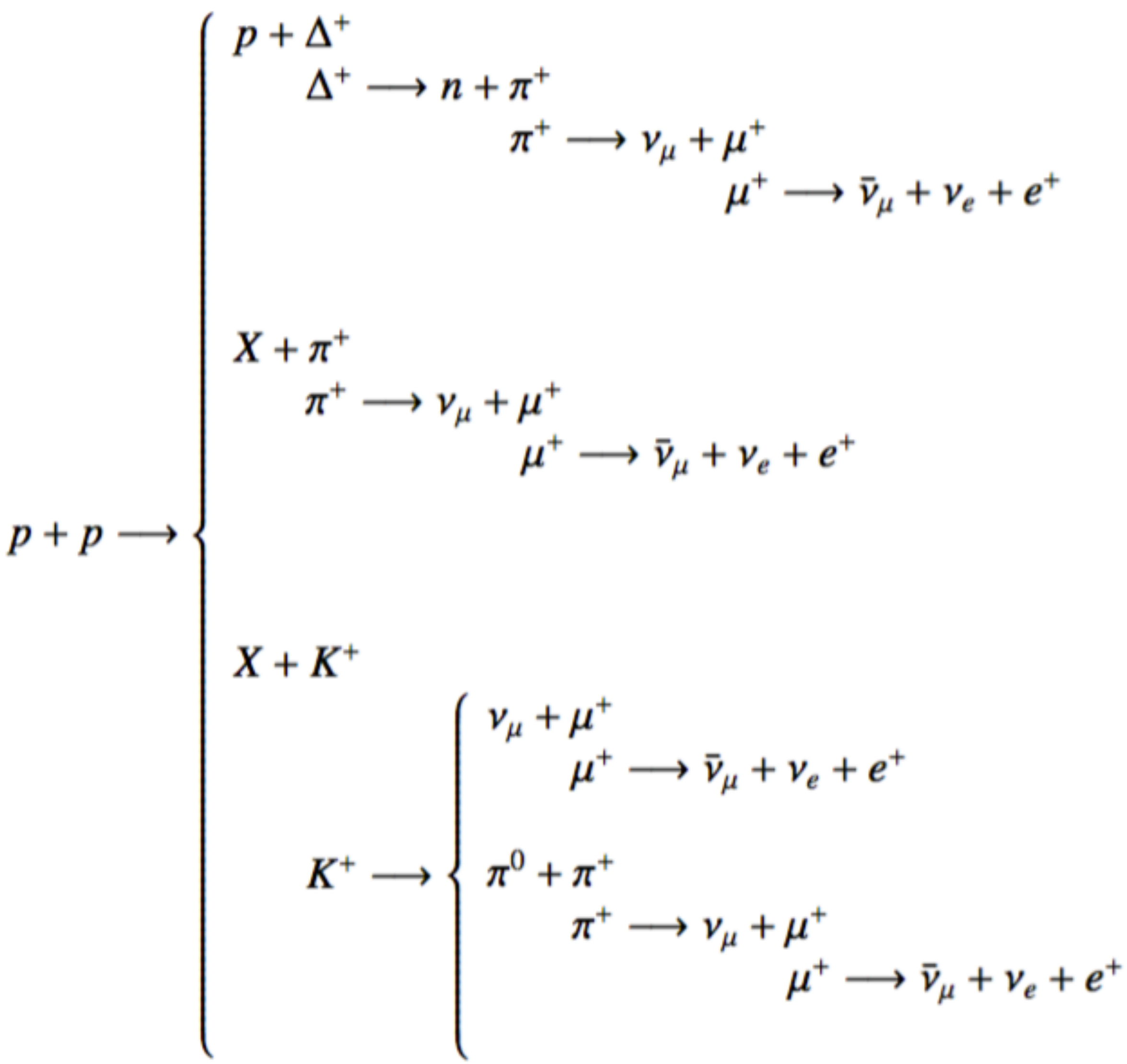
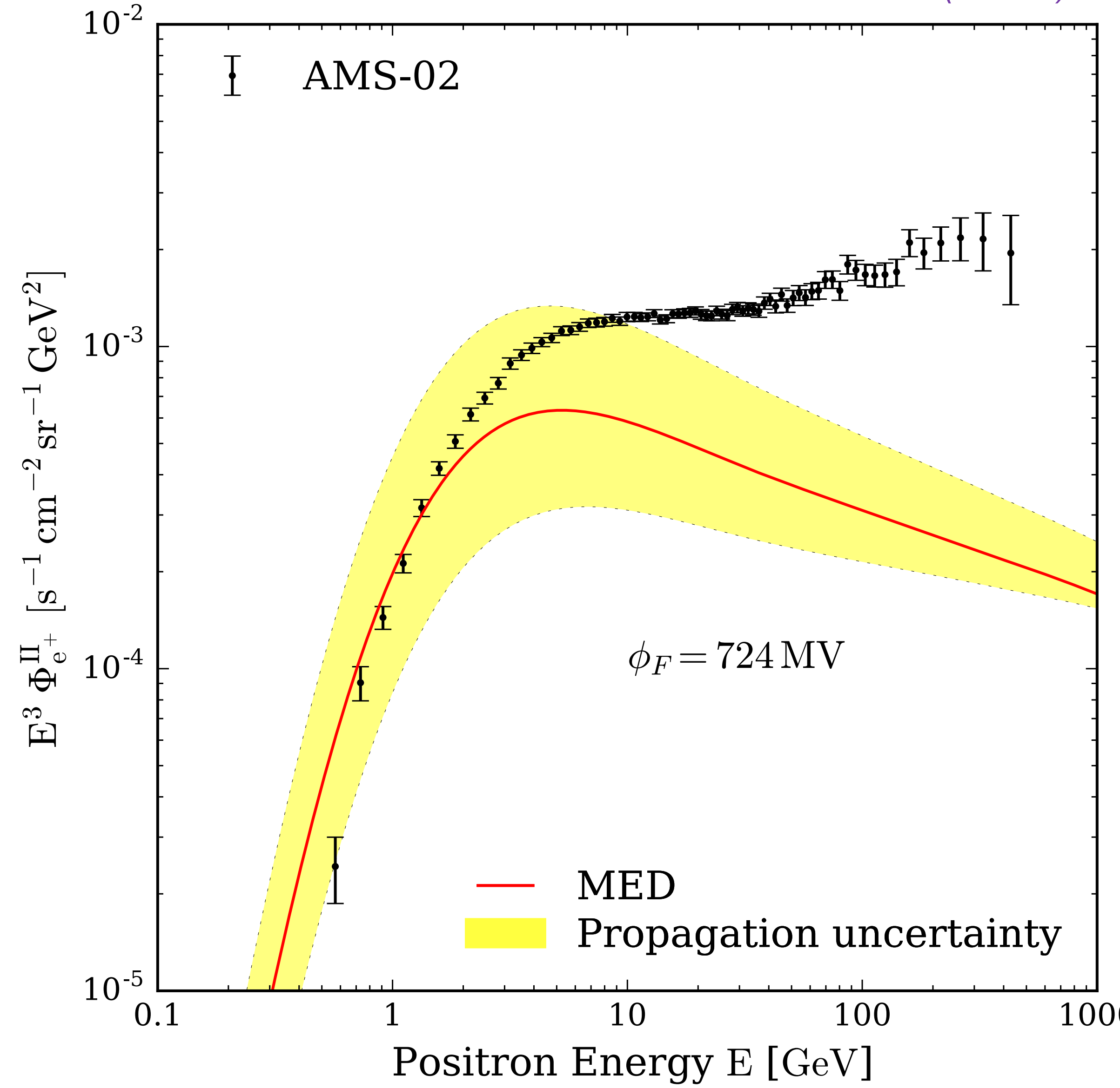


MB+(2014)



Positron excess above ~ 10 GeV!

Astrophysical background of secondary positrons

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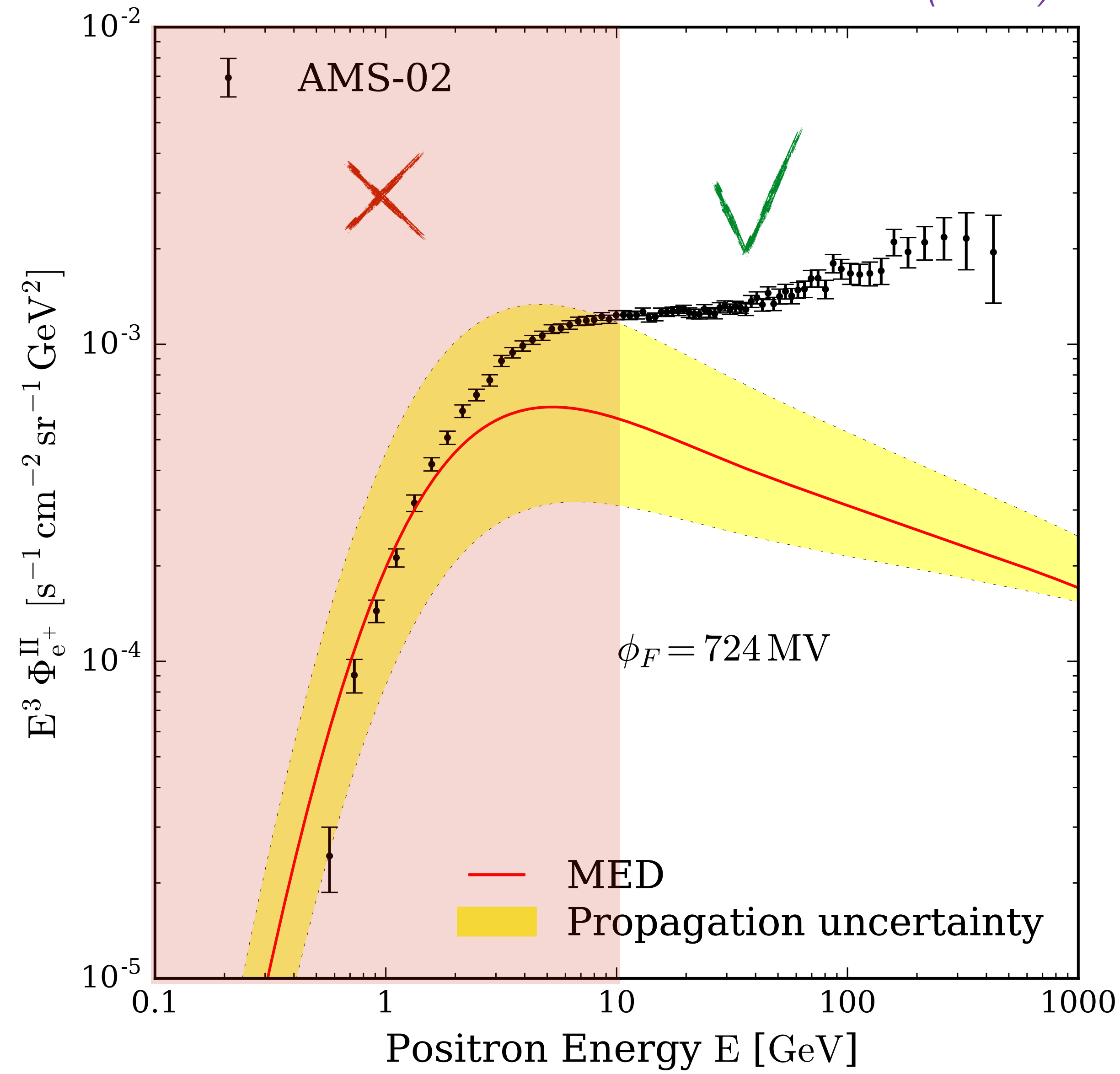
$p + p \longrightarrow$

- $p + \Delta^+$
  - $\Delta^+ \longrightarrow n + \pi^+$
    - $\pi^+ \longrightarrow \nu_\mu + \mu^+$
      - $\mu^+ \longrightarrow \bar{\nu}_\mu + \nu_e + e^+$
- $X + \pi^+$
  - $\pi^+ \longrightarrow \nu_\mu + \mu^+$
    - $\mu^+ \longrightarrow \bar{\nu}_\mu + \nu_e + e^+$
- $X + K^+$
  - $K^+ \longrightarrow$
    - $\nu_\mu + \mu^+$
      - $\mu^+ \longrightarrow \bar{\nu}_\mu + \nu_e + e^+$
    - $\pi^0 + \pi^+$
      - $\pi^+ \longrightarrow \nu_\mu + \mu^+$
        - $\mu^+ \longrightarrow \bar{\nu}_\mu + \nu_e + e^+$

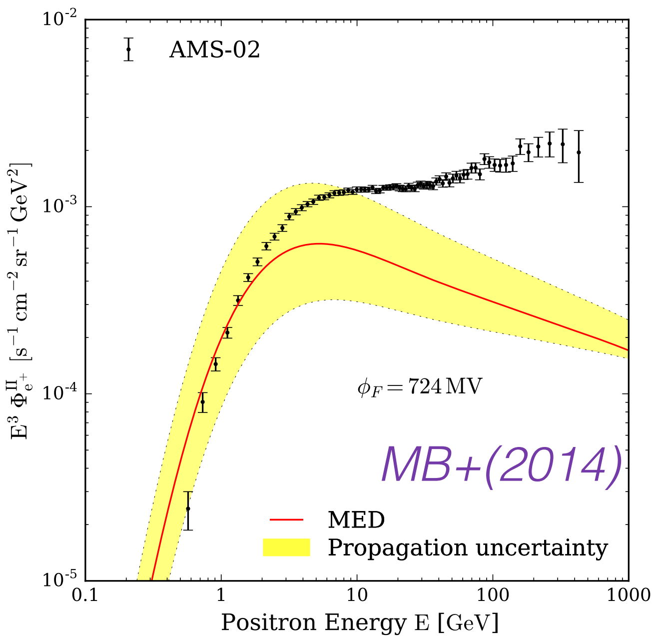
MB+(2014)



Positron excess above ~ 10 GeV!

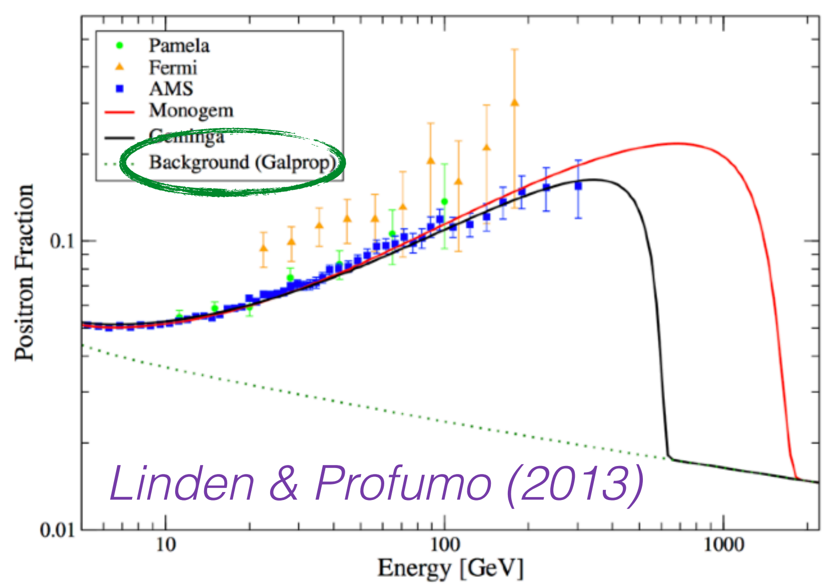
The positron excess

Semi-analytical

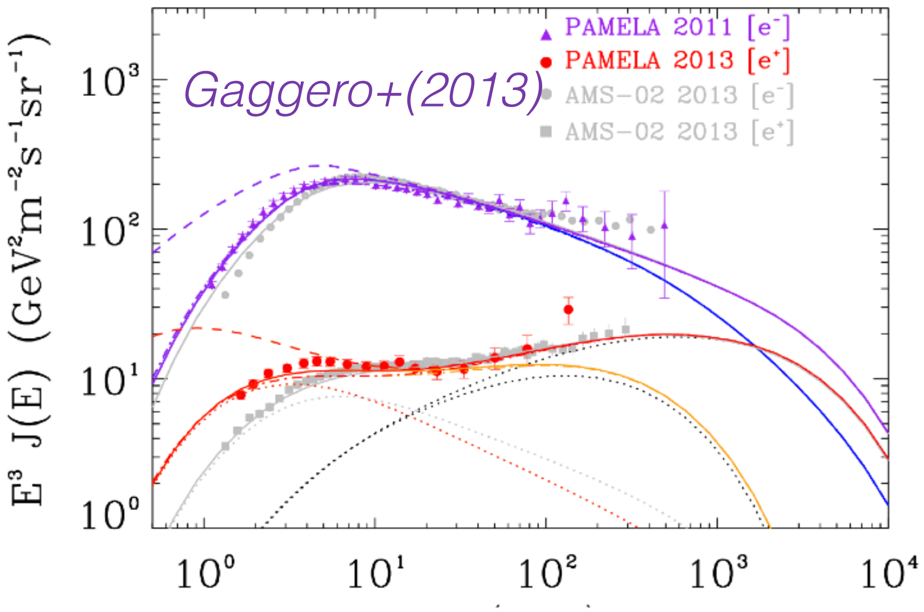


Numerical

(GALPROP)



(DRAGON)



The positron excess

Numerical

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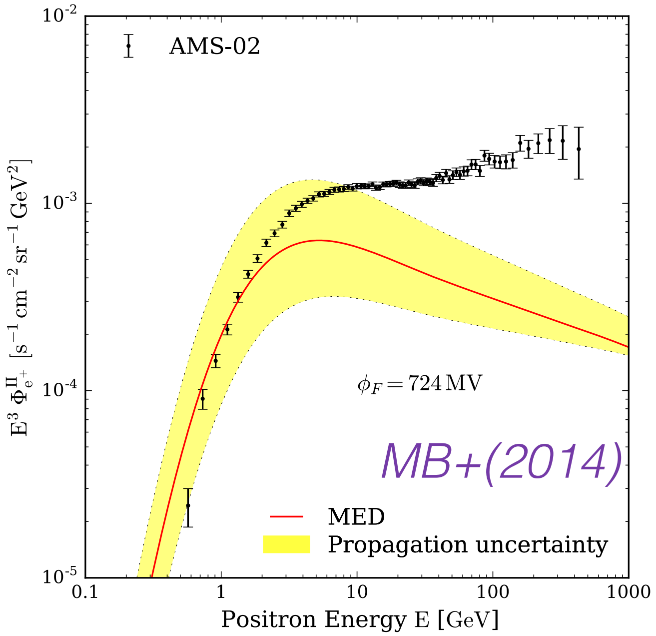
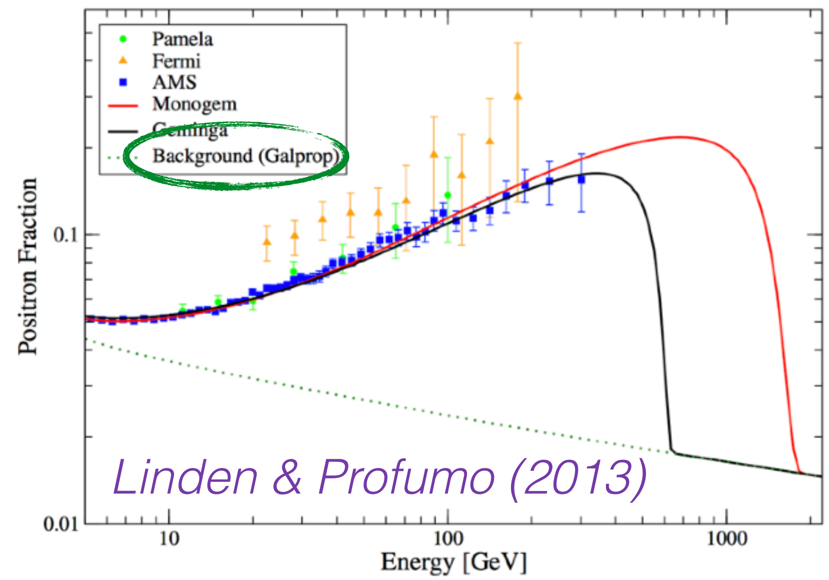
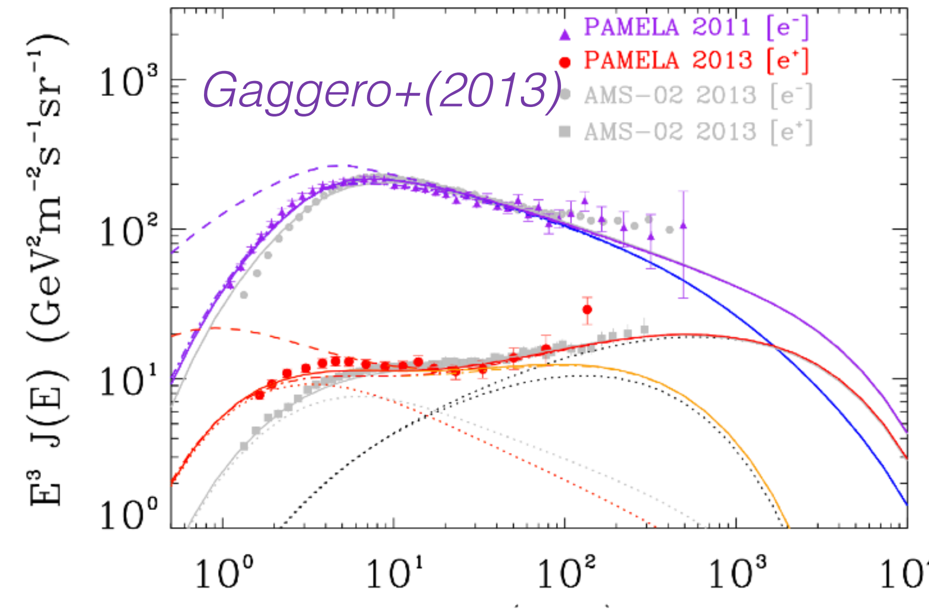


(GALPROP)



(DRAGON)



- Primary e⁺ from dark matter

  e.g: *Silk and Srednicki (1984), Baltz & Edsjö (1998), Cirelli & Strumia (2008), MB+(2014)*

The DM scenario confronts AMS-02 data

$$Q_{\mathrm{e}^+}^{\mathrm{DM}}(E,\vec{x}) = \underbrace{\left(\frac{\rho(\vec{x})}{m_\chi}\right)^2}_{astrophysics} \times \underbrace{\frac{1}{2}\sum_i \langle\sigma v\rangle\, B_i \frac{dN_i(E)}{dE}}_{particle\ physics}$$

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(NFW, Einasto, Burkert, etc.)

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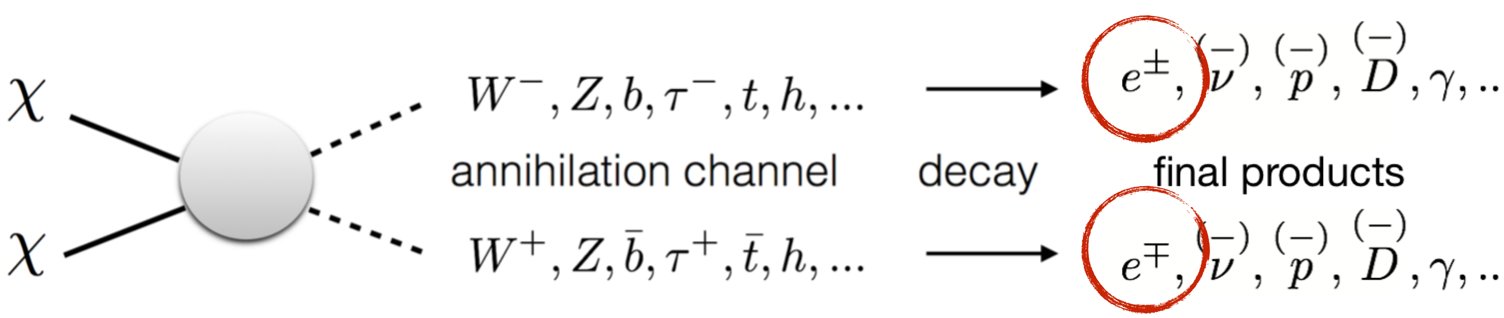
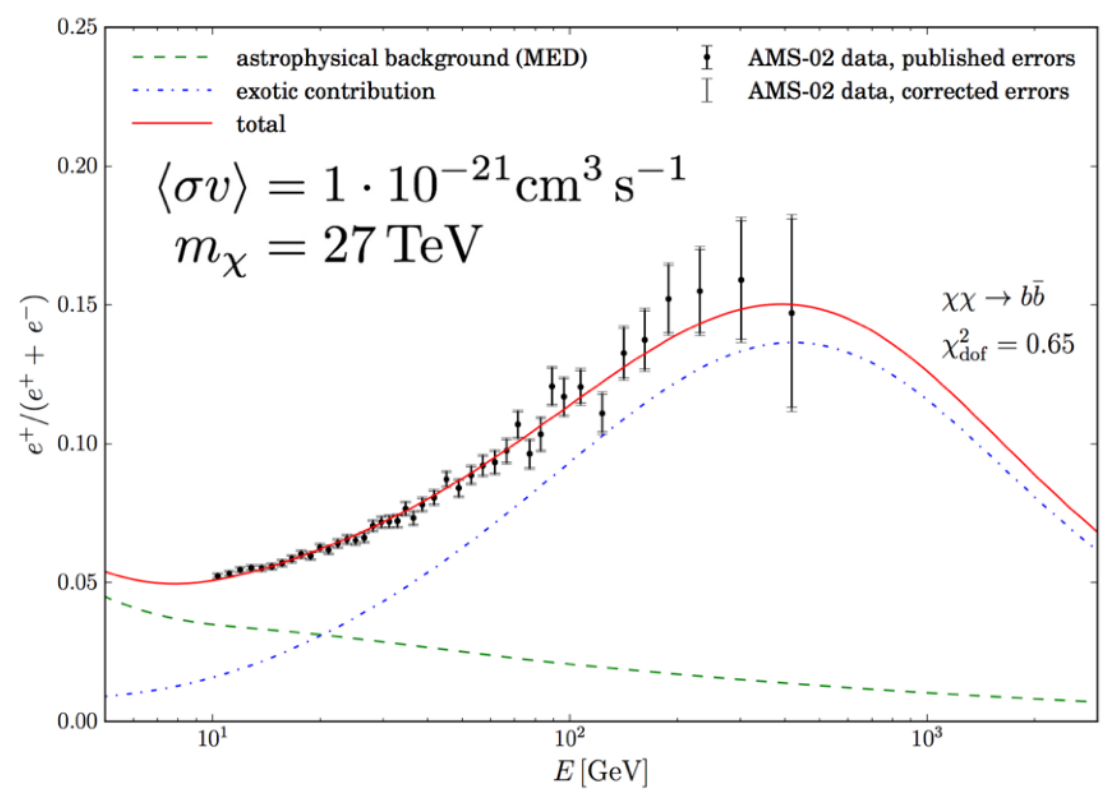


Channel	m_χ [TeV]	$\langle\sigma v\rangle$ [cm^3 s^{-1}]	χ^2	χ^2_{dof}	p
e	0.350 ± 0.004	$(2.31 \pm 0.02) \cdot 10^{-24}$	1489	37.2	0
μ	0.350 ± 0.003	$(3.40 \pm 0.03) \cdot 10^{-24}$	346	8.44	0
τ	0.894 ± 0.040	$(2.25 \pm 0.15) \cdot 10^{-23}$	93.0	2.27	$4.2 \cdot 10^{-6}$
u	31.5 ± 2.9	$(1.43 \pm 0.20) \cdot 10^{-21}$	25.2	0.61	0.97
b	27.0 ± 2.2	$(1.00 \pm 0.12) \cdot 10^{-21}$	26.5	0.65	0.95
t	42.5 ± 3.3	$(1.81 \pm 0.21) \cdot 10^{-21}$	29.4	0.72	0.89
Z	14.2 ± 0.9	$(6.02 \pm 0.58) \cdot 10^{-22}$	43.8	1.07	0.31
W	12.2 ± 0.08	$(5.10 \pm 0.48) \cdot 10^{-22}$	41.1	1.00	0.42
H	23.2 ± 1.5	$(8.17 \pm 0.77) \cdot 10^{-22}$	39.1	0.95	0.51
$\phi \to e$	0.350 ± 0.0008	$(1.56 \pm 0.01) \cdot 10^{-24}$	534	13.0	0
$\phi \to \mu$	0.590 ± 0.022	$(5.87 \pm 0.36) \cdot 10^{-24}$	175	4.27	0
$\phi \to \tau$	1.76 ± 0.08	$(4.51 \pm 0.32) \cdot 10^{-23}$	83.5	2.04	$7.7 \cdot 10^{-5}$



✓ quarks, gauge bosons, Higgs

✗ leptons, light scalar mediator

MB+(2014)

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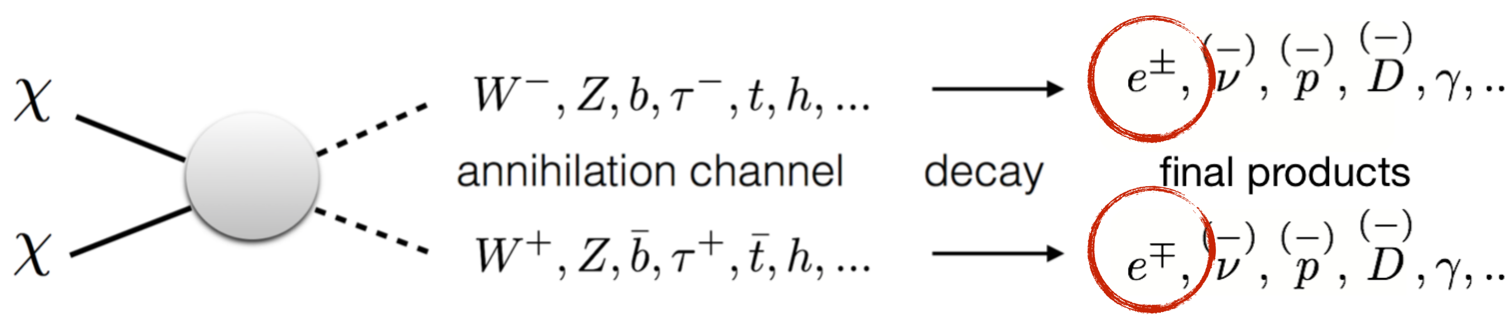

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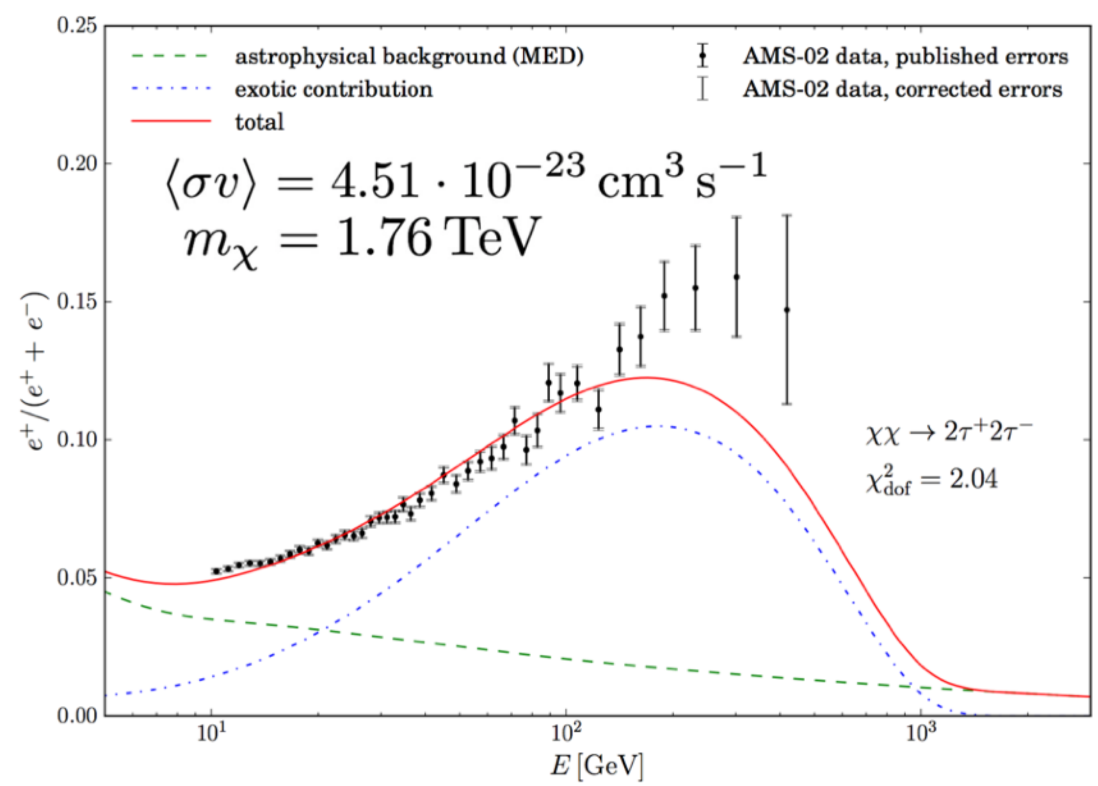

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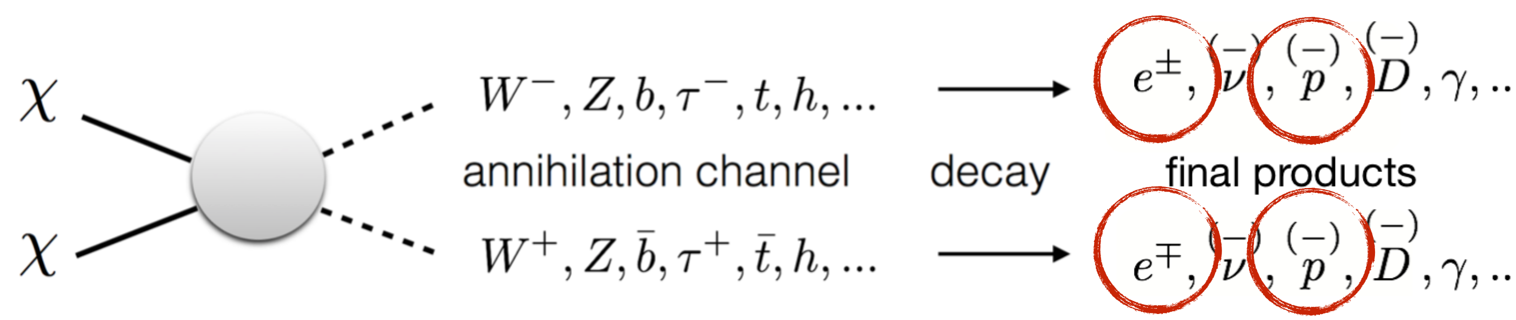
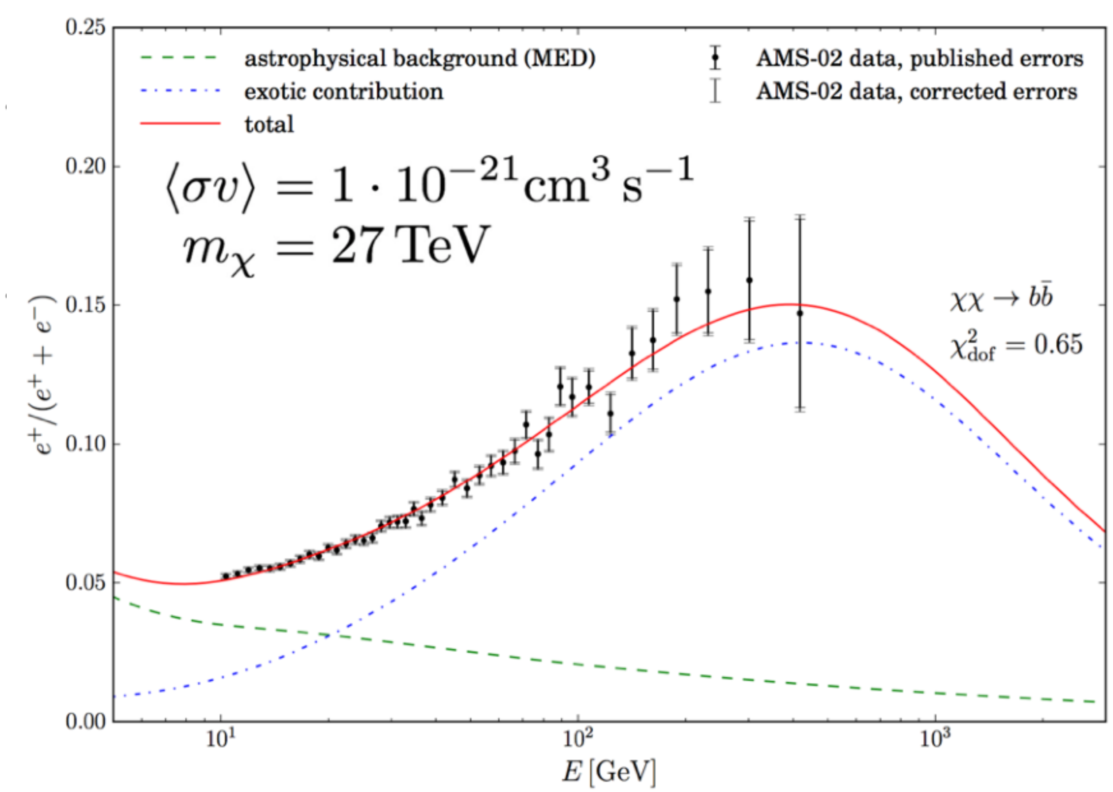
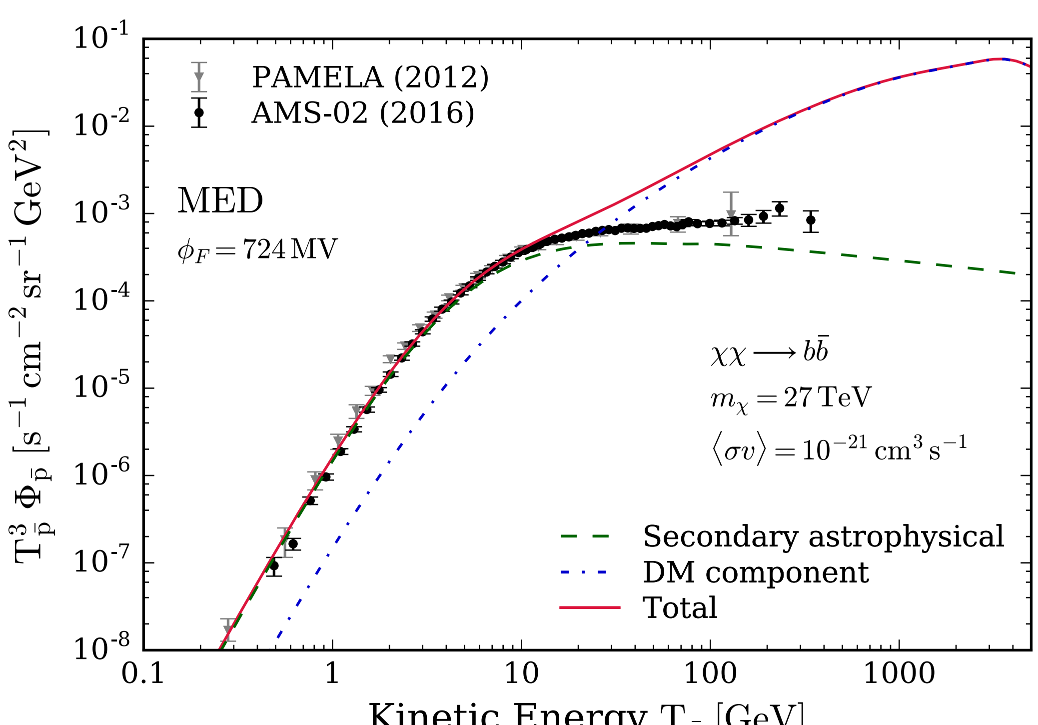




In tension with antiprotons data...



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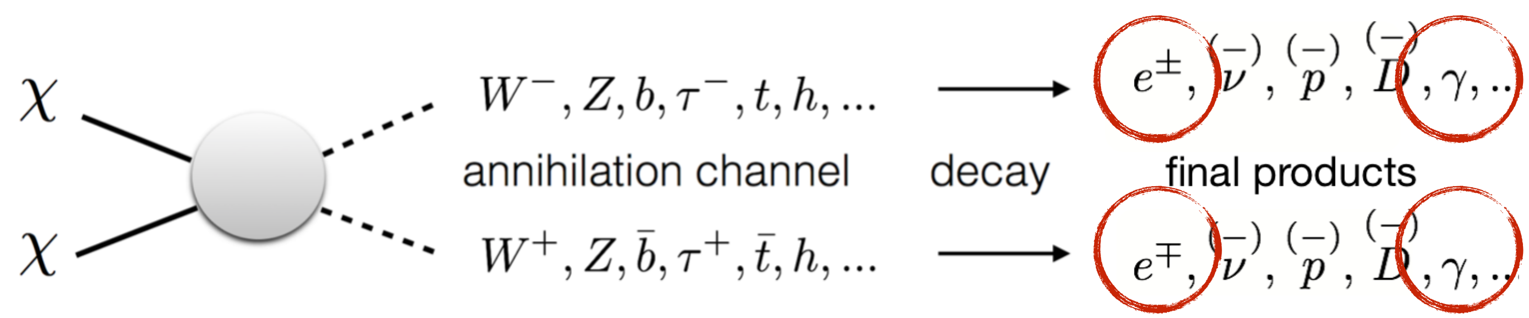

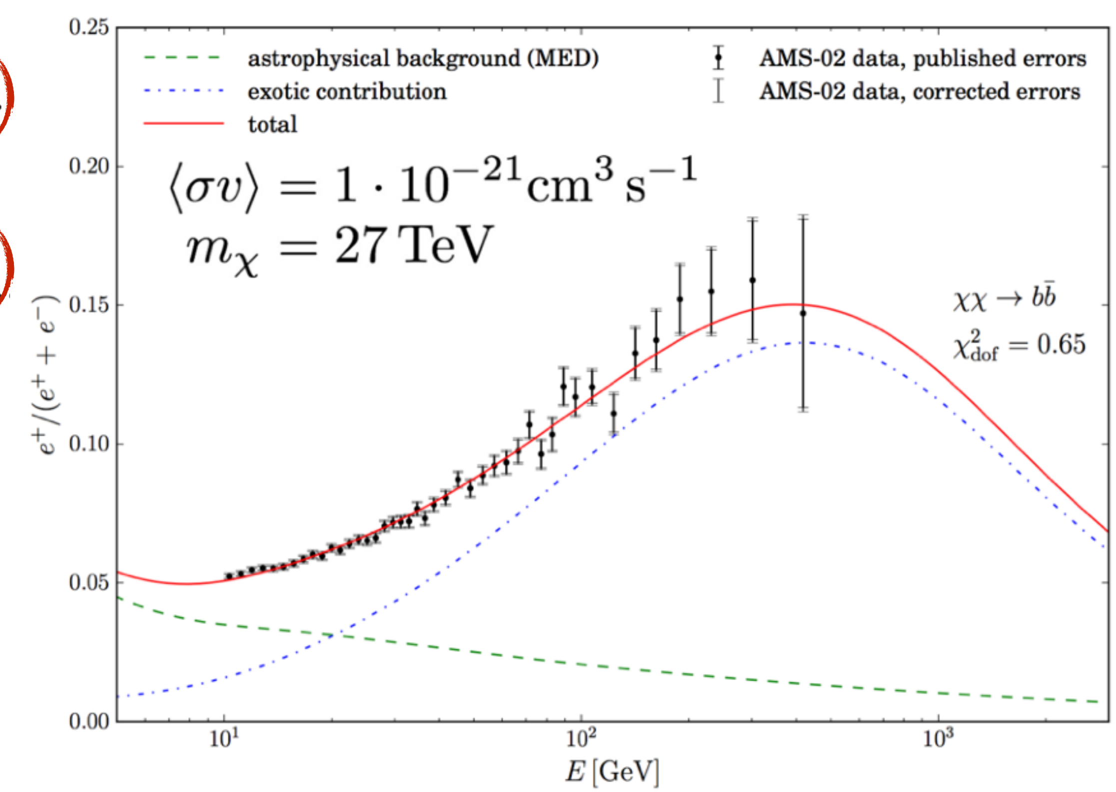

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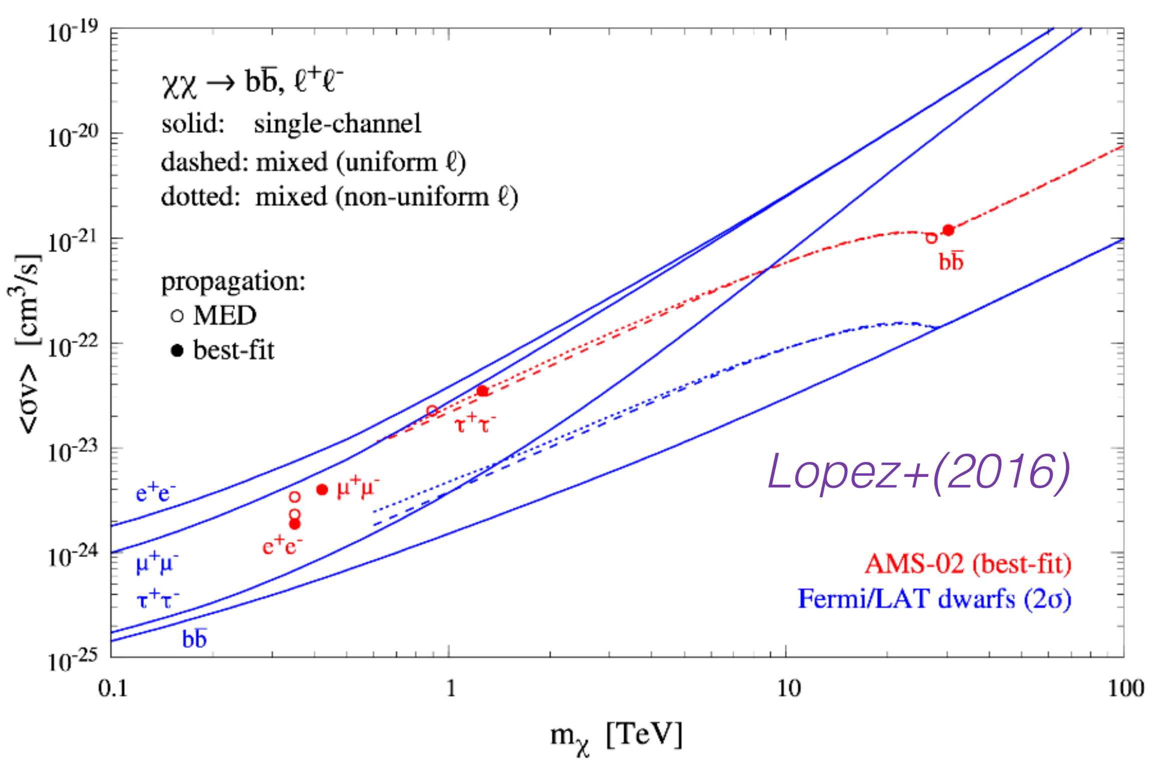
MB+(2014)

…and in tension with gamma rays data.

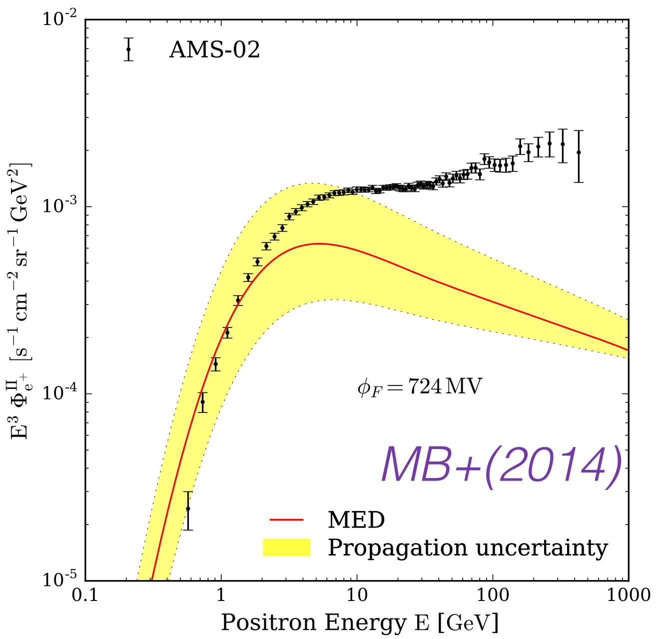


Lopez+(2016)

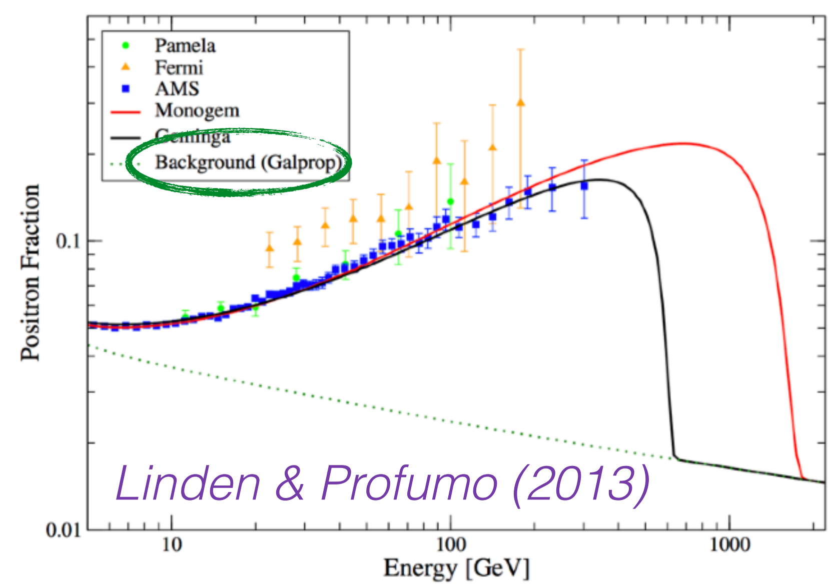
The positron excess

Numerical

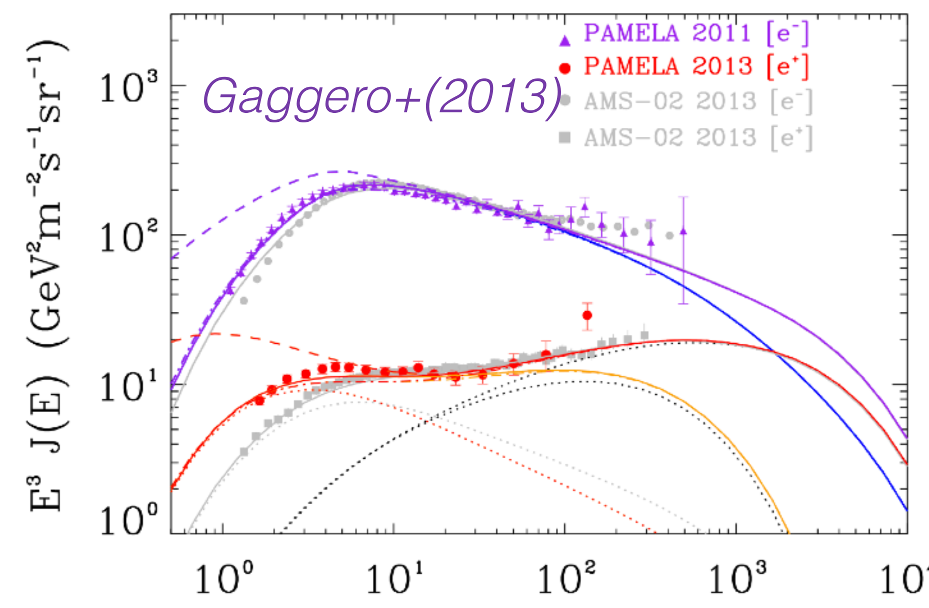
Semi-analytical



(GALPROP)



(DRAGON)



- Primary e$^+$ from dark matter

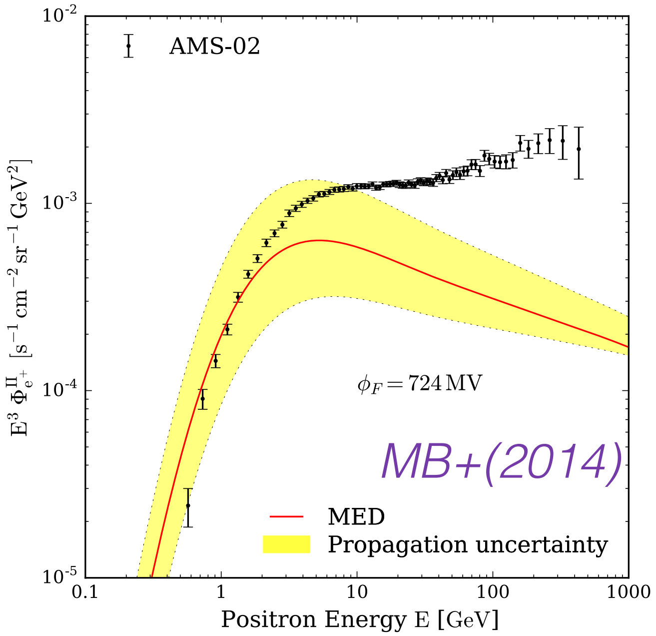
  e.g: *Silk and Srednicki (1984), Baltz & Edsjö (1998), Cirelli & Strumia (2008), MB+(2014)*

Serious tensions with antiprotons and gamma rays

The positron excess

Numerical

Semi-analytical



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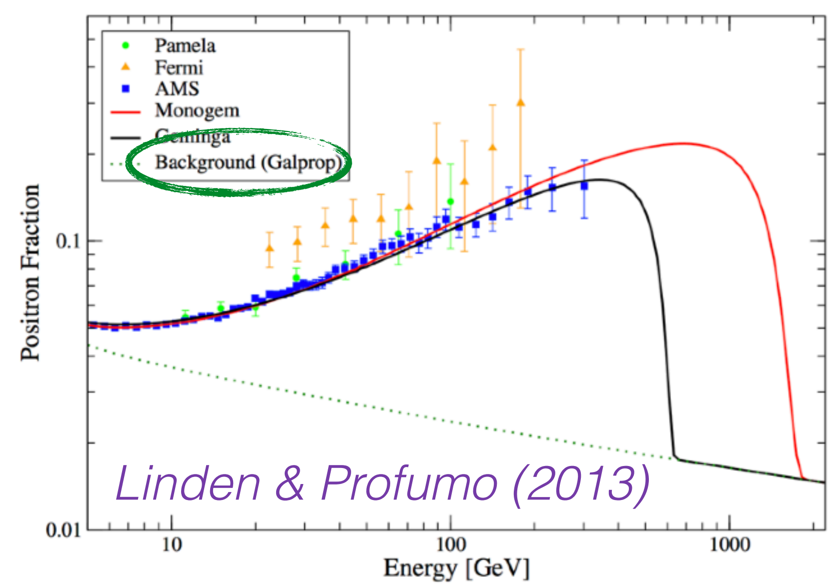

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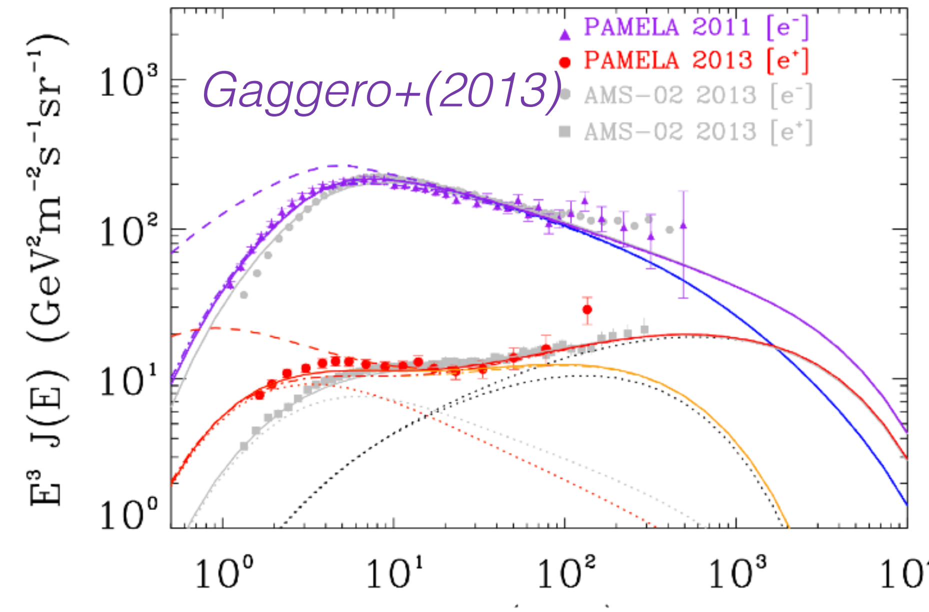

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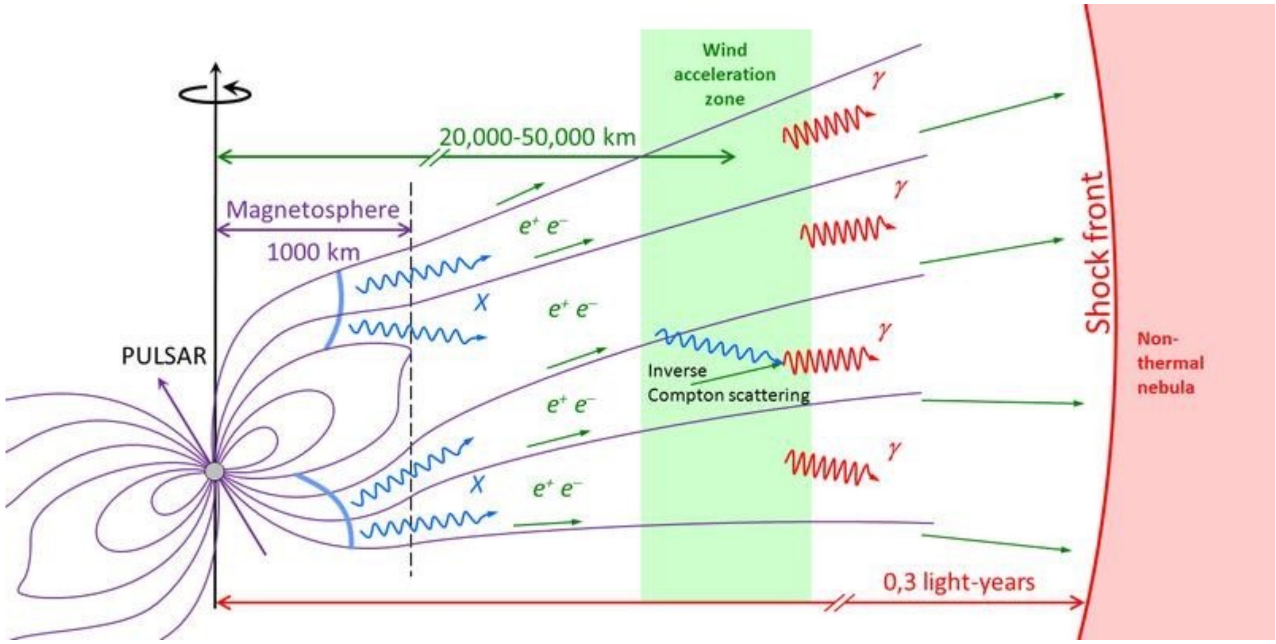
Serious tensions with antiprotons and gamma rays

- Nearby and young PWNe

  e.g: *Hooper, Blasi & Serpico (2009), Linden & Profumo (2013), Delahaye+(2010), Gaggero+(2013), Di Mauro+(2014), MB+(2014)*

PWNe confront AMS-02 data



- *Activity time (CRs acceleration)*
- *Propagation time in the Galaxy*

$$t_a \sim 1 - 10 \text{ kyr} \qquad << \qquad t_d = \left(\frac{d}{1 \text{ kpc}}\right)^2 \left(\frac{K_0}{10^{-2} \text{ kpc}^2 \text{ Myr}^{-1}}\right)^{-1} \left(\frac{E}{1 \text{ GeV}}\right)^{-\delta} \text{Myr.}$$

PWNe are modelled by a ***point source*** in time and space.

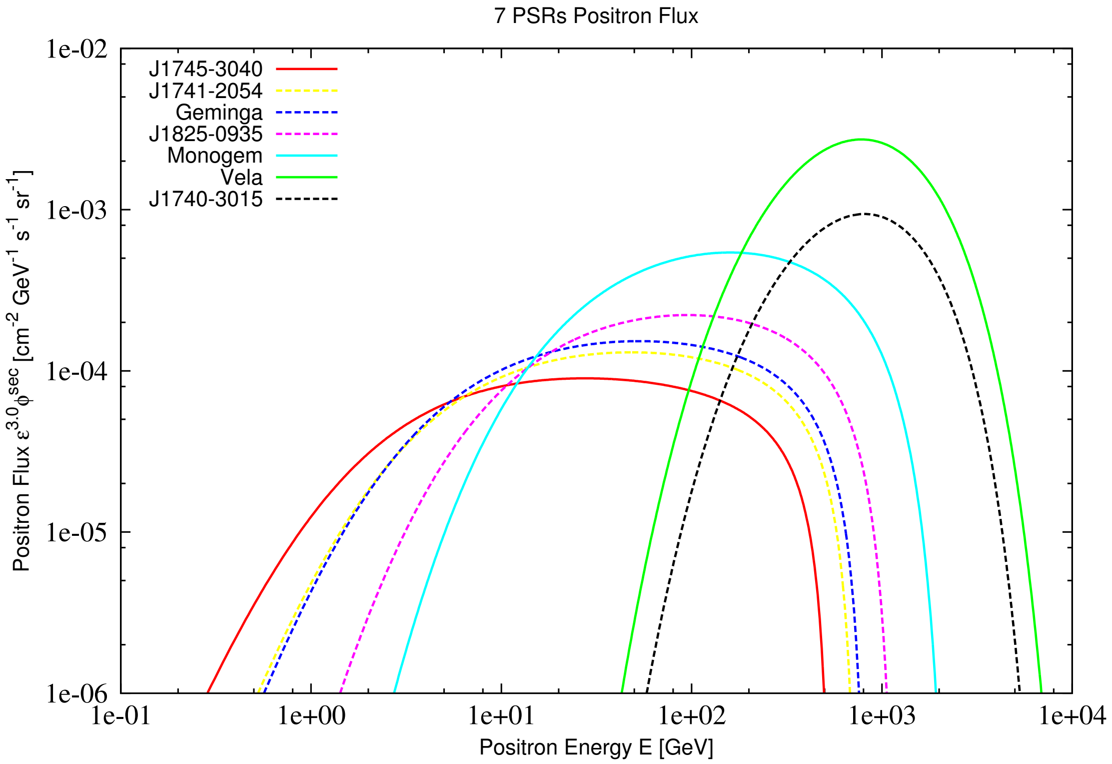
$$Q^{PSR}(E,t,\vec{x}) = \delta(t - t_*)\delta(\vec{x} - \vec{x}_*)Q_0 \left(\frac{E}{E_0}\right)^{-\gamma} \exp\left(-\frac{E}{E_C}\right)$$

age — position

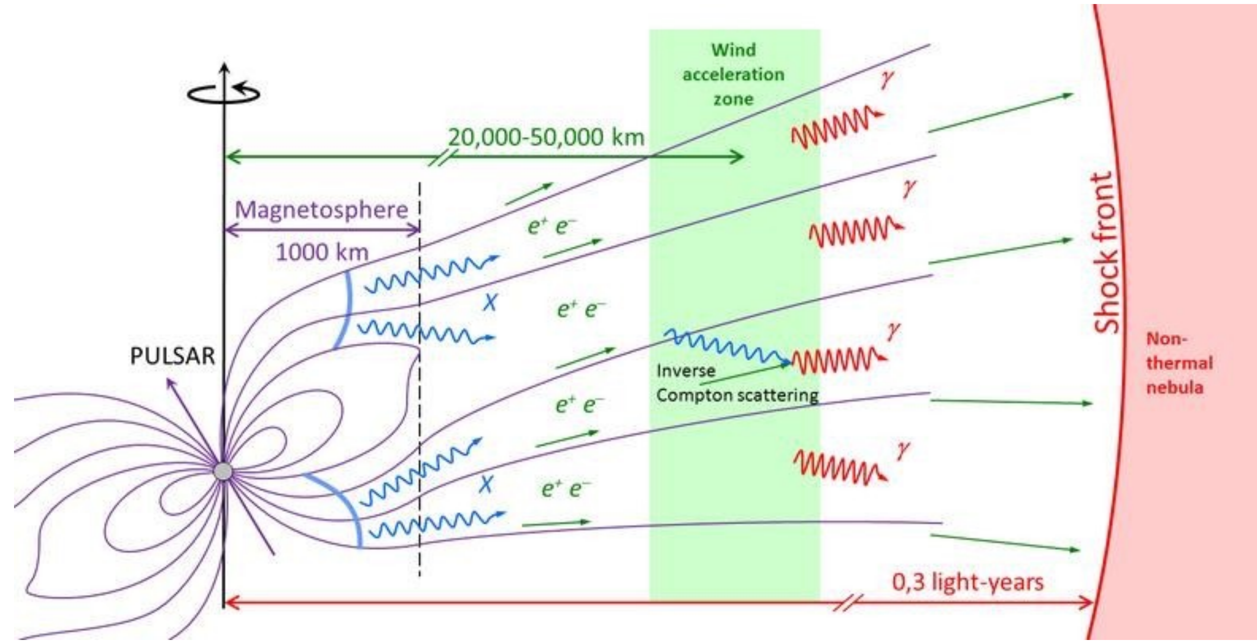
The positron flux is restricted between E_{min} and E_{max} where:

$$E_{max} = \frac{E_C}{1 + \frac{E_C}{1 \text{ GeV}} \frac{t_\star}{\tau_l}} \qquad E_{min} = \left(\frac{d^2}{4K_0 t_\star}\right)^{1/\delta}$$

(Thomson regime)



PWNe confront AMS-02 data



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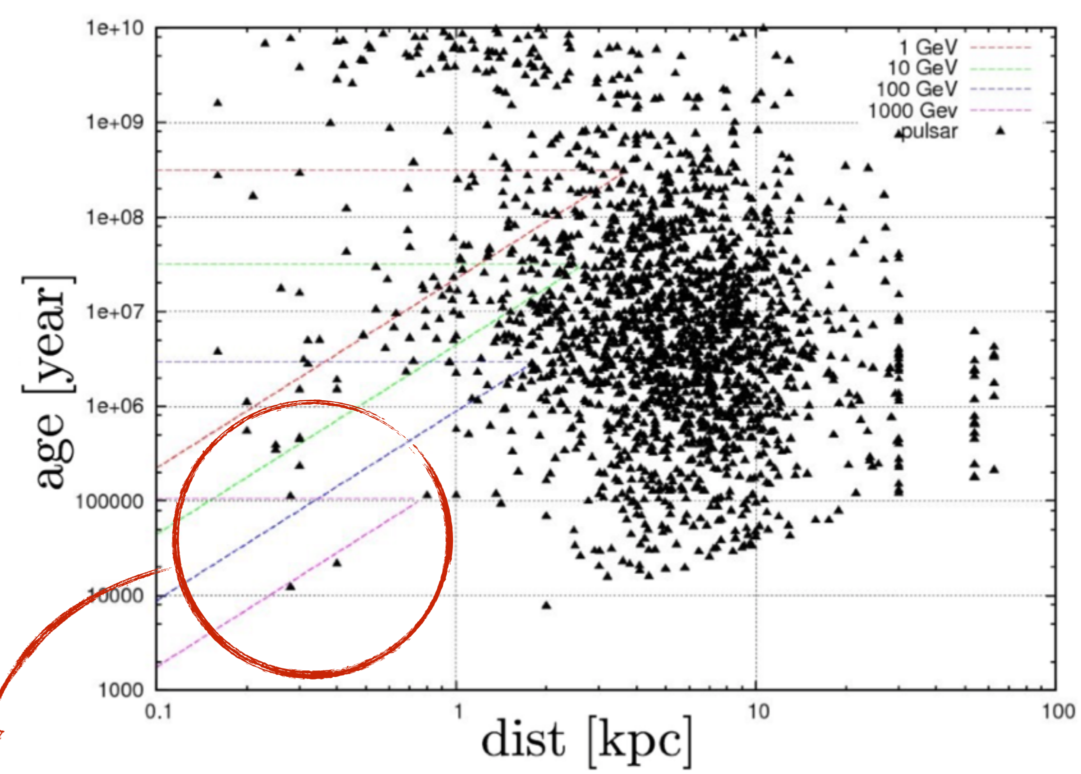


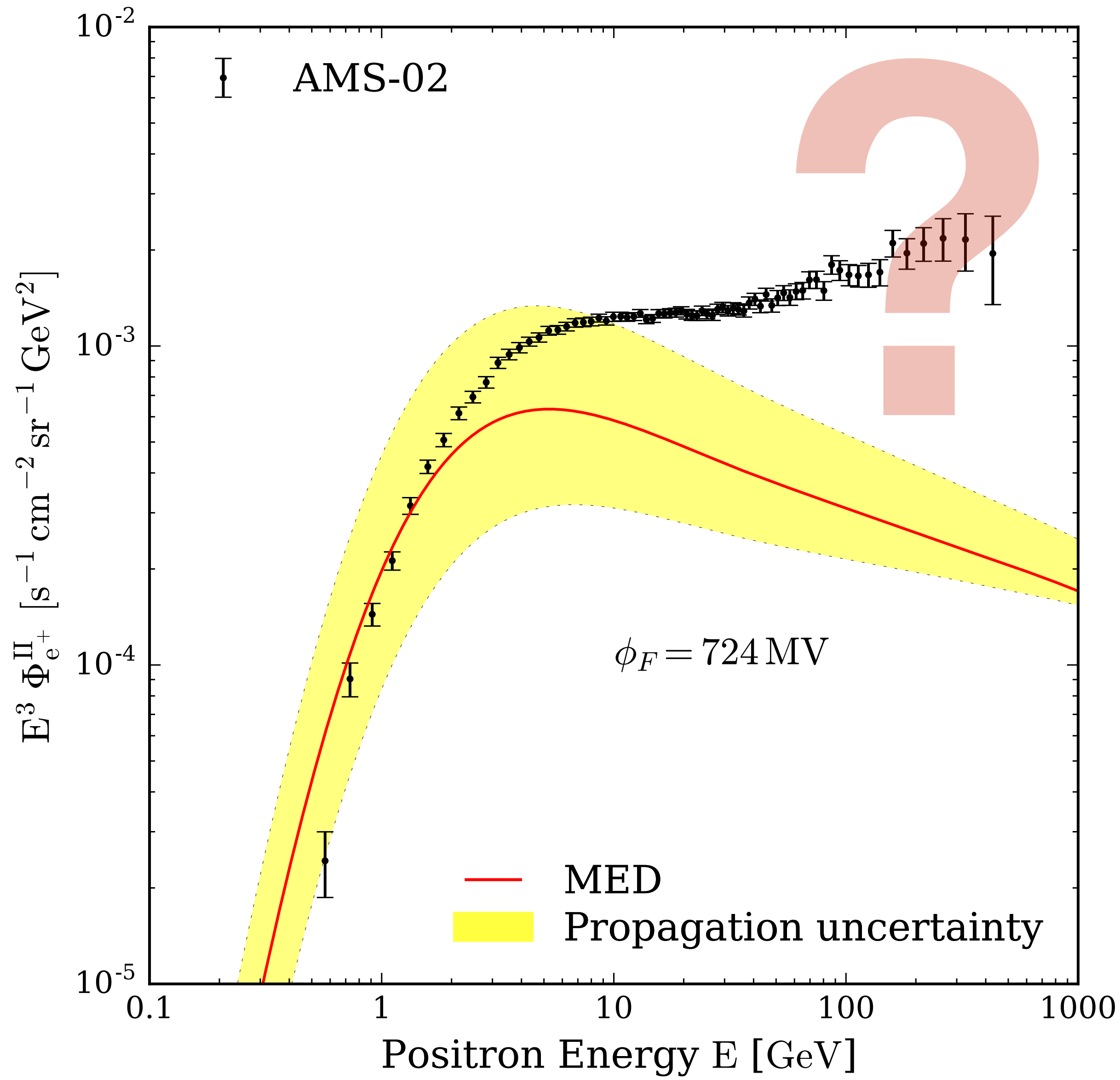
Only few young and nearby PSRs contribute to the positron flux for $E \gtrsim 10$ GeV.

The single pulsar scenario

- There is only an ***upper limit*** on the energy released by the PWN energy through e^+ (depends on *$P(t_0)$*).
- *$P(t_0)$* is expected to be different for each PSR .

⇒ if ***one single pulsar*** can explain the AMS-02 data, ***a collection of pulsars*** can do the job even better.

Is it possible to explain the AMS-02 e^+ data with ***only one single*** pulsar?



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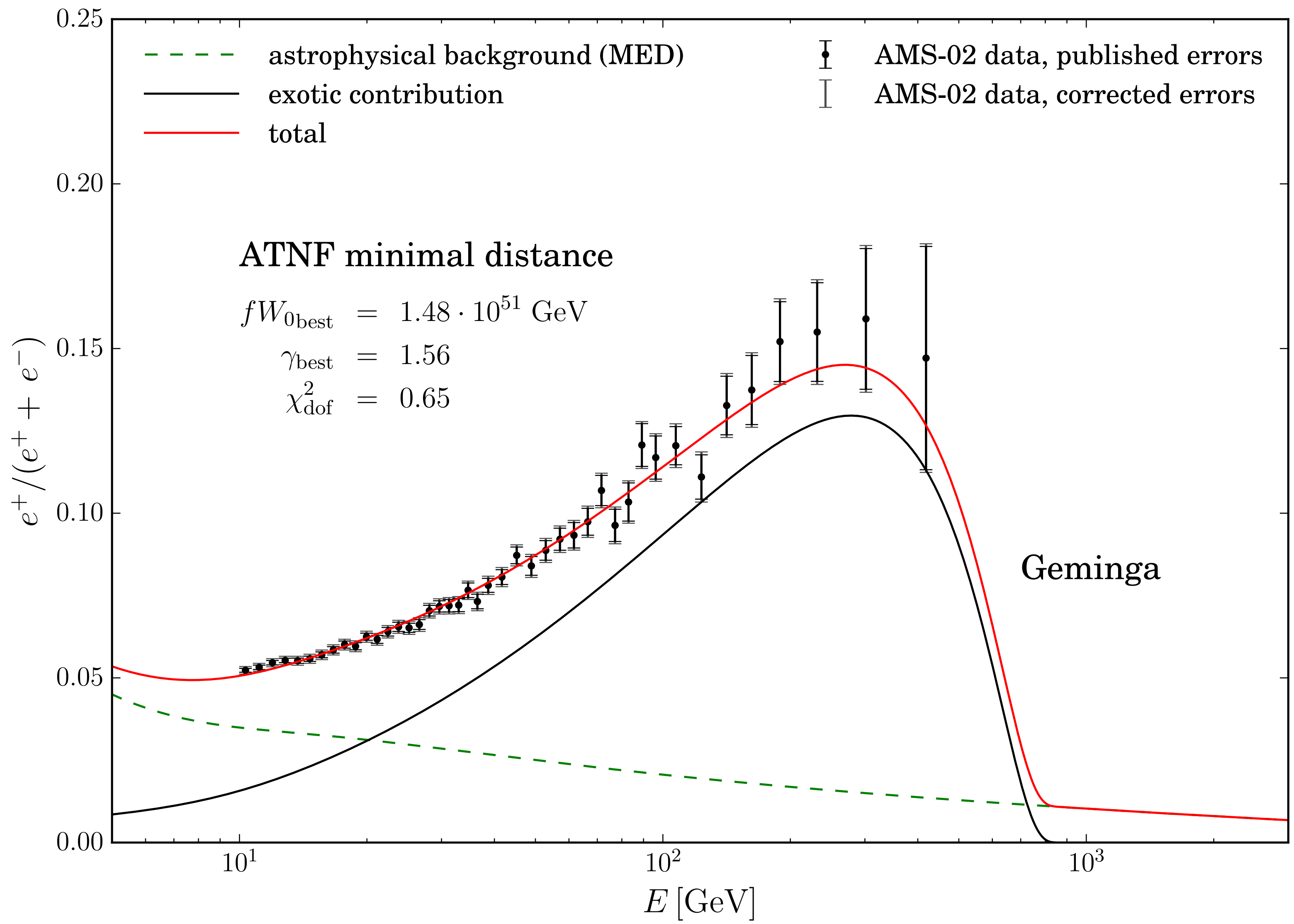

MB+(2014)

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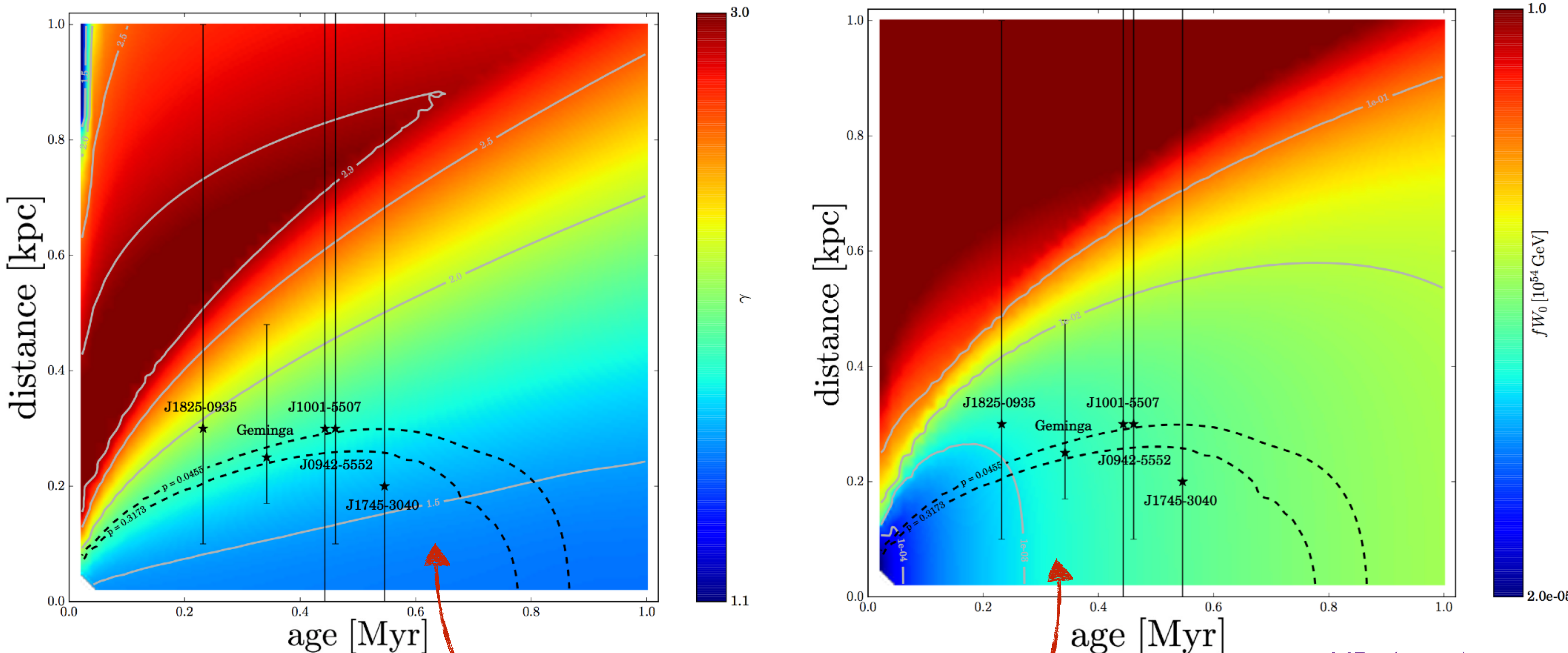
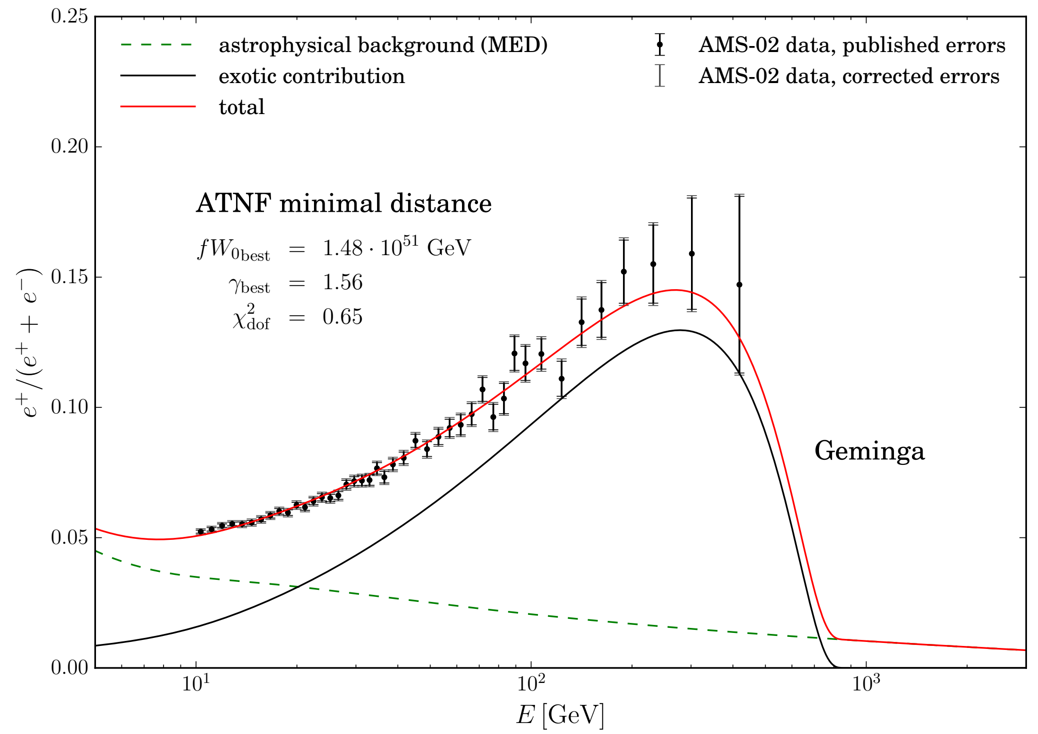


MB+(2014)

region of good fit to the AMS-02 data (p > 30%)

The single pulsar scenario (Geminga)

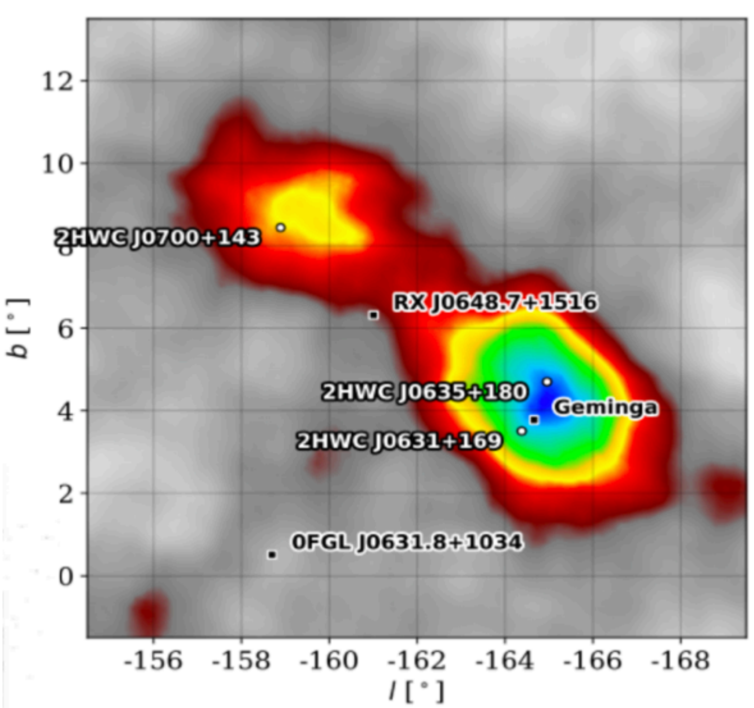
Name	Age [kyr]	Distance [kpc]	fW_0 [10^{54} GeV]	γ	χ^2	$\chi^2_{\rm dof}$	p
		0	$(2.95 \pm 0.07) \cdot 10^{-3}$	1.45 ± 0.02	23.4	0.57	0.99
J1745−3040	546	**0.20**	$\mathbf{(3.03 \pm 0.06) \cdot 10^{-3}}$	$\mathbf{1.54 \pm 0.02}$	**33.6**	**0.82**	**0.79**
		1.3	1	2.54	9902	241	0
		0.17	$(1.48 \pm 0.03) \cdot 10^{-3}$	1.56 ± 0.02	26.8	0.65	0.96
J0633+1746	342	**0.25**	$\mathbf{(1.63 \pm 0.02) \cdot 10^{-3}}$	$\mathbf{1.68 \pm 0.02}$	**49.6**	**1.21**	**0.17**
Geminga		0.48	$(1.01 \pm 0.06) \cdot 10^{-2}$	2.29 ± 0.02	332	8.10	0
		0.10	$(2.28 \pm 0.05) \cdot 10^{-3}$	1.48 ± 0.02	21.7	0.53	0.99
J0942−5552	461	**0.30**	$\mathbf{(2.61 \pm 0.04) \cdot 10^{-3}}$	$\mathbf{1.69 \pm 0.02}$	**61.0**	**1.49**	**0.02**
		1.1	1	2.65	7747	189	0
		0	$(2.13 \pm 0.05) \cdot 10^{-3}$	1.46 ± 0.02	19.8	0.48	0.99
J1001−5507	443	**0.30**	$\mathbf{(2.49 \pm 0.03) \cdot 10^{-3}}$	$\mathbf{1.70 \pm 0.02}$	**62.4**	**1.52**	**0.02**
		1.4	1	2.46	13202	322	0
		0.1	$(0.80 \pm 0.02) \cdot 10^{-3}$	1.52 ± 0.02	21.0	0.51	0.99
J1825−0935	232	**0.30**	$\mathbf{(1.45 \pm 0.03) \cdot 10^{-3}}$	$\mathbf{1.94 \pm 0.02}$	**126**	**3.07**	**0**
		1.0	1	2.64	12776	312	0



'HAWC Observations Strongly Favor Pulsar Interpretations of the Cosmic-Ray Positron Excess'

D. Hooper, I. Cholis, T. Linden and K. Fang (2017)

- use HAWC gamma data to constraint Geminga e^+ spectrum (spectral index)
- continuous injection of e^+ (dynamical model)



$$\gamma \simeq 1.5 - 1.9$$

$$f \simeq 7.2 - 29\%$$

(fraction of the total energy released through e^+)

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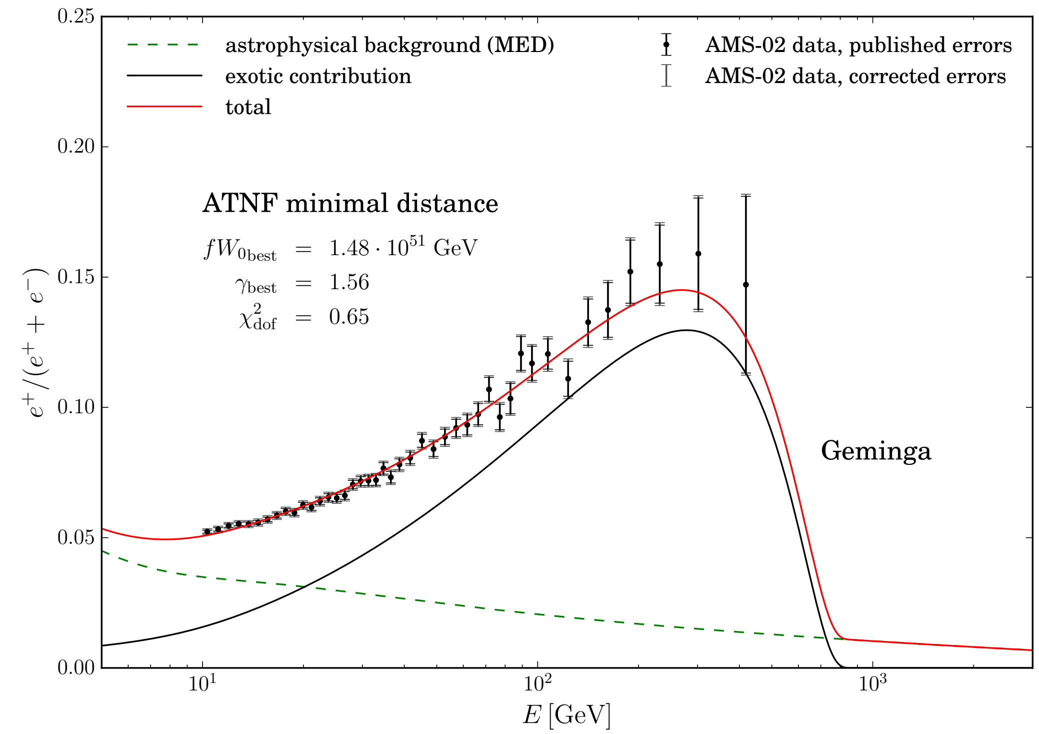
Name	Age [kyr]	Distance [kpc]	fW_0 [10^{54} GeV]	γ	χ^2	χ^2_{dof}	p
J1745−3040	546	0 **0.20** 1.3	$(2.95 \pm 0.07) \cdot 10^{-3}$ $\mathbf{(3.03 \pm 0.06) \cdot 10^{-3}}$ 1	1.45 ± 0.02 $\mathbf{1.54 \pm 0.02}$ 2.54	23.4 **33.6** 9902	0.57 **0.82** 241	0.99 **0.79** 0
J0633+1746 *Geminga*	342	0.17 **0.25** 0.48	$(1.48 \pm 0.03) \cdot 10^{-3}$ $\mathbf{(1.63 \pm 0.02) \cdot 10^{-3}}$ $(1.01 \pm 0.06) \cdot 10^{-2}$	1.56 ± 0.02 $\mathbf{1.68 \pm 0.02}$ 2.29 ± 0.02	26.8 **49.6** 332	0.65 **1.21** 8.10	0.96 **0.17** 0
J0942−5552	461	0.10 **0.30** 1.1	$(2.28 \pm 0.05) \cdot 10^{-3}$ $\mathbf{(2.61 \pm 0.04) \cdot 10^{-3}}$ 1	1.48 ± 0.02 $\mathbf{1.69 \pm 0.02}$ 2.65	21.7 **61.0** 7747	0.53 **1.49** 189	0.99 **0.02** 0
J1001−5507	443	0 **0.30** 1.4	$(2.13 \pm 0.05) \cdot 10^{-3}$ $\mathbf{(2.49 \pm 0.03) \cdot 10^{-3}}$ 1	1.46 ± 0.02 $\mathbf{1.70 \pm 0.02}$ 2.46	19.8 **62.4** 13202	0.48 **1.52** 322	0.99 **0.02** 0
J1825−0935	232	0.1 **0.30** 1.0	$(0.80 \pm 0.02) \cdot 10^{-3}$ $\mathbf{(1.45 \pm 0.03) \cdot 10^{-3}}$ 1	1.52 ± 0.02 $\mathbf{1.94 \pm 0.02}$ 2.64	21.0 **126** 12776	0.51 **3.07** 312	0.99 **0** 0



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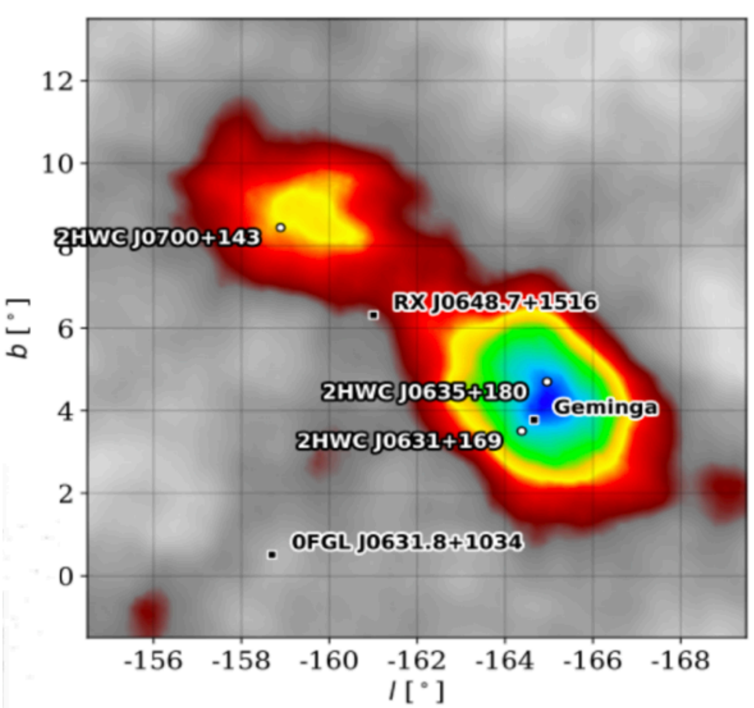


$$\gamma \simeq 1.5 - 1.9$$

$$f \simeq 7.2 - 29\%$$

(fraction of the total energy released through e+)

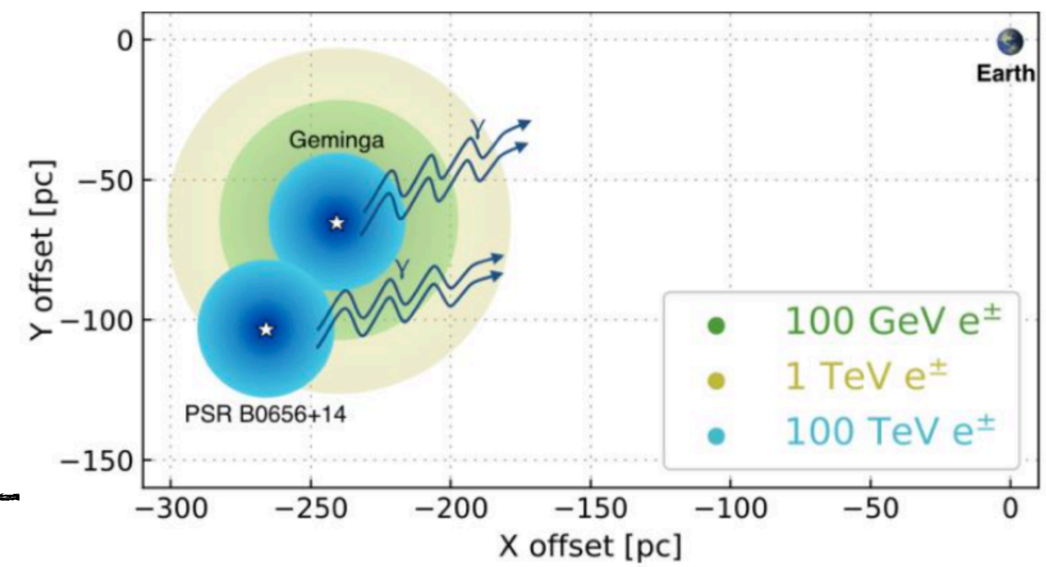
'Extended gamma-ray sources around pulsars constrain the origin of the positron flux at Earth'

HAWC collaboration (2017)

$$\gamma \xrightarrow{\text{IC}} e^+/e^- \xrightarrow{\text{propagation model}} K(E) \xrightarrow{\text{extrapolation at low E}} e^+/e^-$$

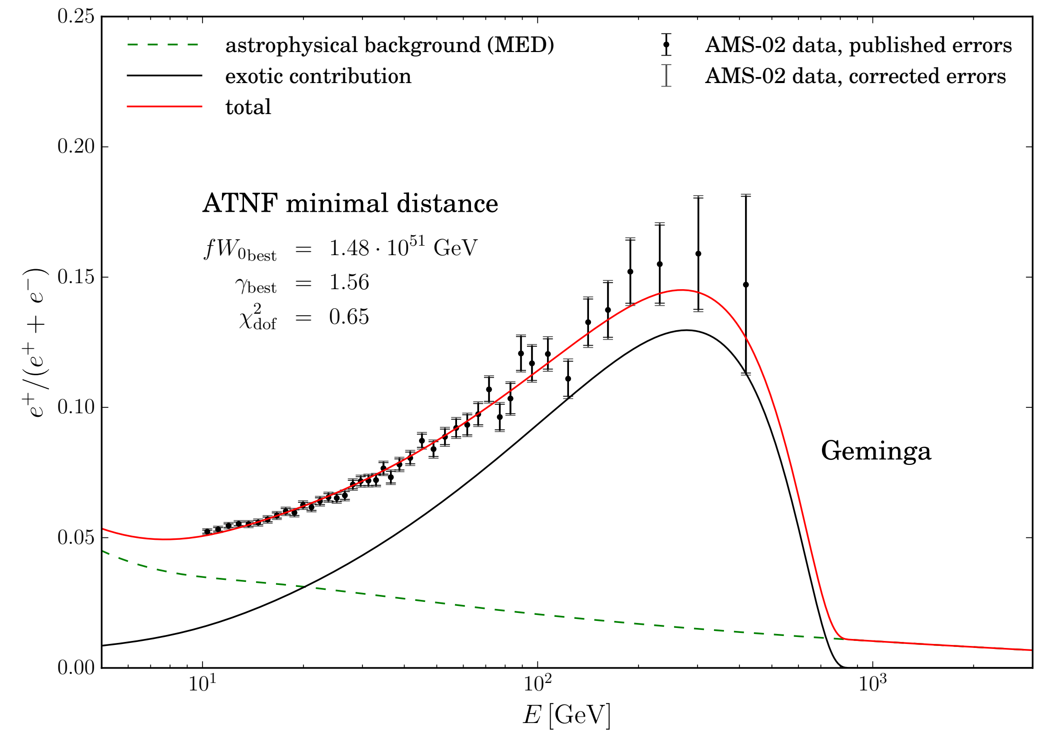
γ	e^+/e^-	$K(E)$	e^+/e^-
$\mathcal{O}(20)$ TeV	$\mathcal{O}(100)$ TeV	$\mathcal{O}(100)$ TeV	$\mathcal{O}(100)$ GeV
Geminga	**Geminga**	**Geminga**	**Earth**

$\Rightarrow K(E)$ ***too small*** to allow e+ to reach the Earth



The single pulsar scenario (Geminga)

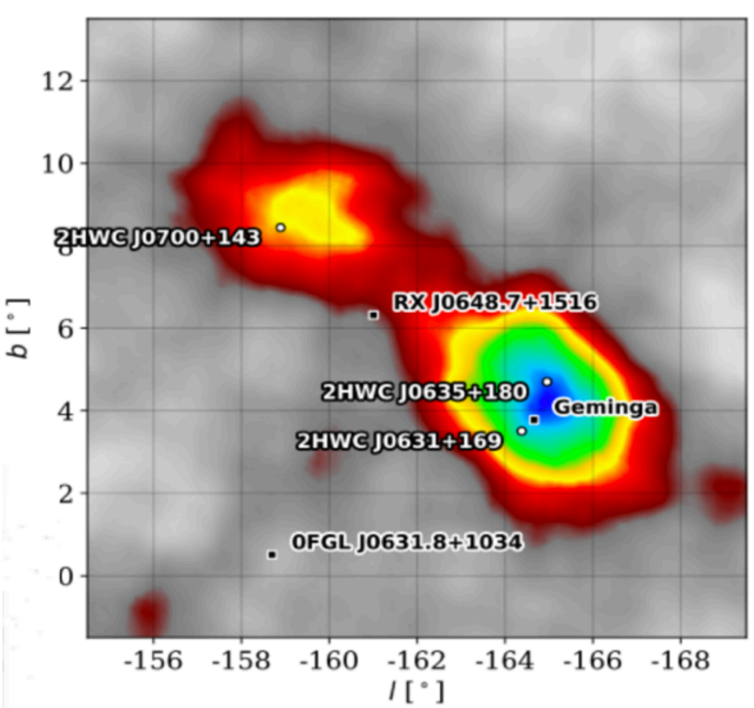
Name	Age [kyr]	Distance [kpc]	fW_0 [10^{54} GeV]	γ	χ^2	χ^2_{dof}	p
J1745−3040	546	0	$(2.95 \pm 0.07) \cdot 10^{-3}$	1.45 ± 0.02	23.4	0.57	0.99
		0.20	$\mathbf{(3.03 \pm 0.06) \cdot 10^{-3}}$	$\mathbf{1.54 \pm 0.02}$	**33.6**	**0.82**	**0.79**
		1.3	1	2.54	9902	241	0
J0633+1746 *Geminga*	342	0.17	$(1.48 \pm 0.03) \cdot 10^{-3}$	1.56 ± 0.02	26.8	0.65	0.96
		0.25	$\mathbf{(1.63 \pm 0.02) \cdot 10^{-3}}$	$\mathbf{1.68 \pm 0.02}$	**49.6**	**1.21**	**0.17**
		0.48	$(1.01 \pm 0.06) \cdot 10^{-2}$	2.29 ± 0.02	332	8.10	0
J0942−5552	461	0.10	$(2.28 \pm 0.05) \cdot 10^{-3}$	1.48 ± 0.02	21.7	0.53	0.99
		0.30	$\mathbf{(2.61 \pm 0.04) \cdot 10^{-3}}$	$\mathbf{1.69 \pm 0.02}$	**61.0**	**1.49**	**0.02**
		1.1	1	2.65	7747	189	0
J1001−5507	443	0	$(2.13 \pm 0.05) \cdot 10^{-3}$	1.46 ± 0.02	19.8	0.48	0.99
		0.30	$\mathbf{(2.49 \pm 0.03) \cdot 10^{-3}}$	$\mathbf{1.70 \pm 0.02}$	**62.4**	**1.52**	**0.02**
		1.4	1	2.46	13202	322	0
J1825−0935	232	0.1	$(0.80 \pm 0.02) \cdot 10^{-3}$	1.52 ± 0.02	21.0	0.51	0.99
		0.30	$\mathbf{(1.45 \pm 0.03) \cdot 10^{-3}}$	$\mathbf{1.94 \pm 0.02}$	**126**	**3.07**	**0**
		1.0	1	2.64	12776	312	0



'HAWC Observations Strongly Favor Pulsar Interpretations of the Cosmic-Ray Positron Excess'

D. Hooper, I. Cholis, T. Linden and K. Fang (2017)

- use HAWC gamma data to constraint Geminga e+ spectrum (spectral index)
- continuous injection of e+ (dynamical model)



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γ	e^+/e^-	$K(E)$	e^+/e^-
$\mathcal{O}(20)$ TeV	$\mathcal{O}(100)$ TeV	$\mathcal{O}(100)$ TeV	$\mathcal{O}(100)$ GeV
Geminga	**Geminga**	**Geminga**	**Earth**

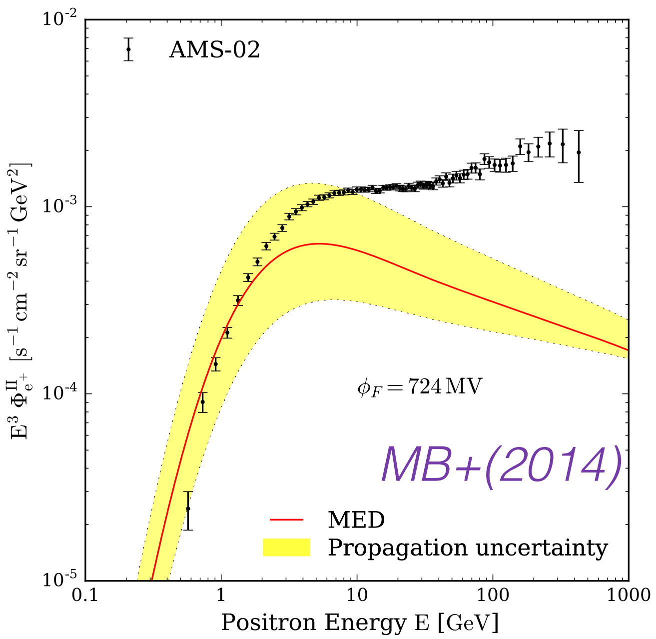
My concerns:

- extrapolation at low E
- local (Geminga) diffusion coefficient
- spectrum and diffusion coefficient today

$$t_\gamma = \frac{d}{c} \simeq 800 \text{ yr} \qquad t_{e^+} = \frac{100 \text{ GeV}}{b(E)} \simeq 100 \text{ kyr}$$

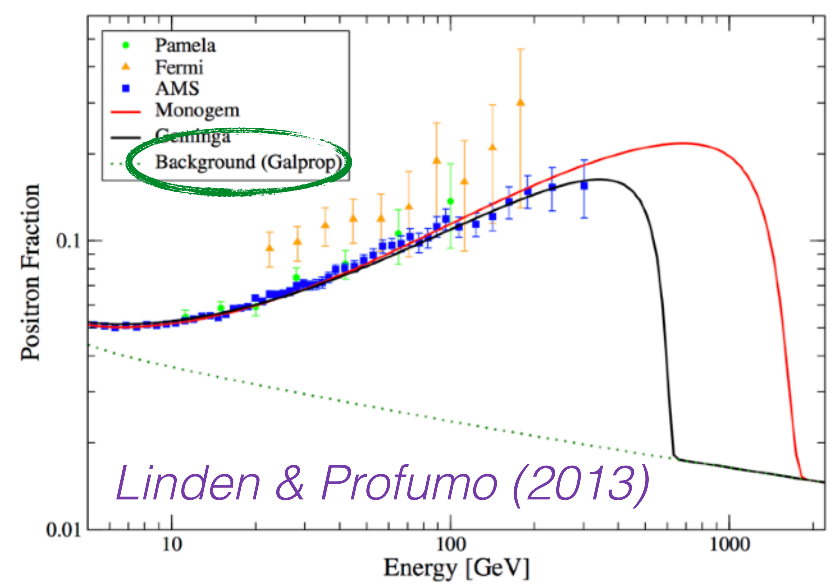
The positron excess

Semi-analytical

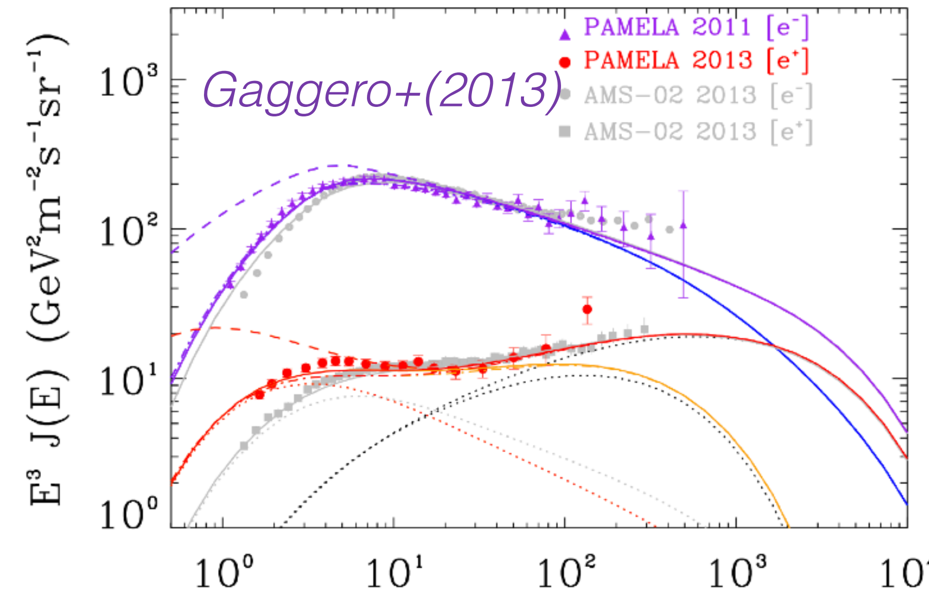


Numerical

(GALPROP)



(DRAGON)



- Primary e^+ from dark matter

  e.g: *Silk and Srednicki (1984), Baltz & Edsjö (1998), Cirelli & Strumia (2008), MB+(2014)*

Serious tensions with antiprotons and gamma rays

- Primary e^+ produced inside SNRs

  Blasi & Serpico (2009)
  Mertsch & Sarkar (2014)

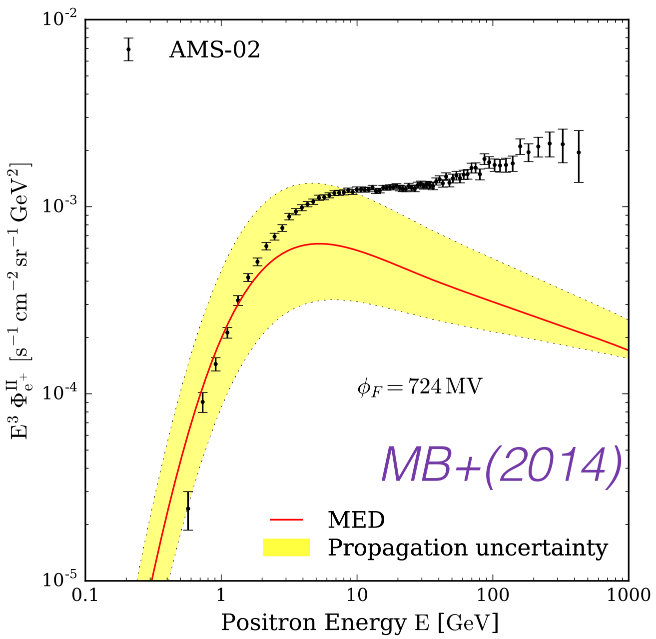
Serious tension with CR nuclei

- Nearby and young PWNe

  e.g: *Hooper, Blasi & Serpico (2009), Linden & Profumo (2013), Delahaye+(2010), Gaggero+(2013), Di Mauro+(2014), MB+(2014)*

The positron excess

Semi-analytical



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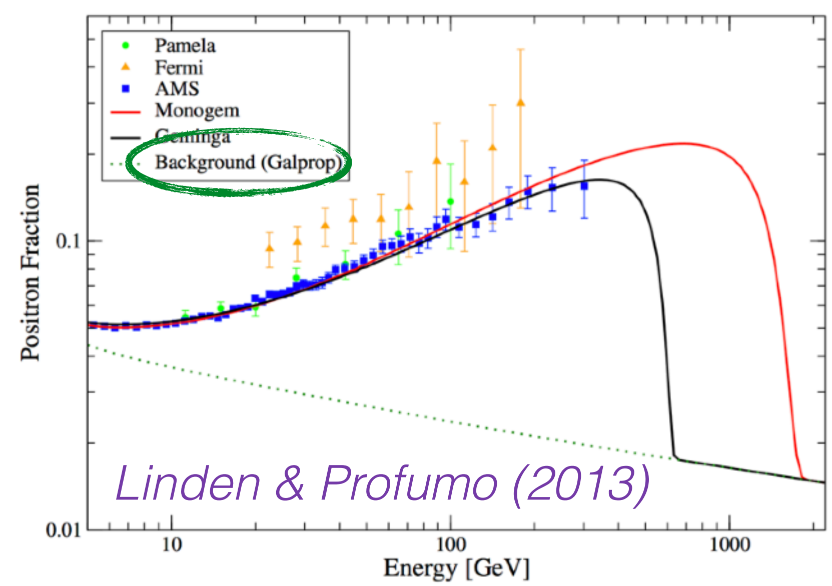
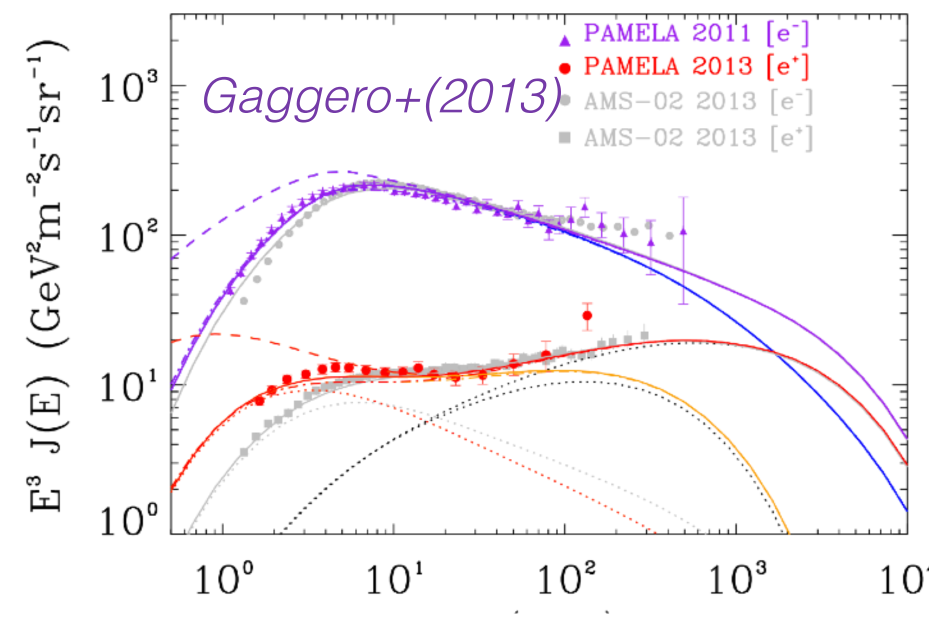


(DRAGON)



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- Nearby and ~2-3 Myr old SNR

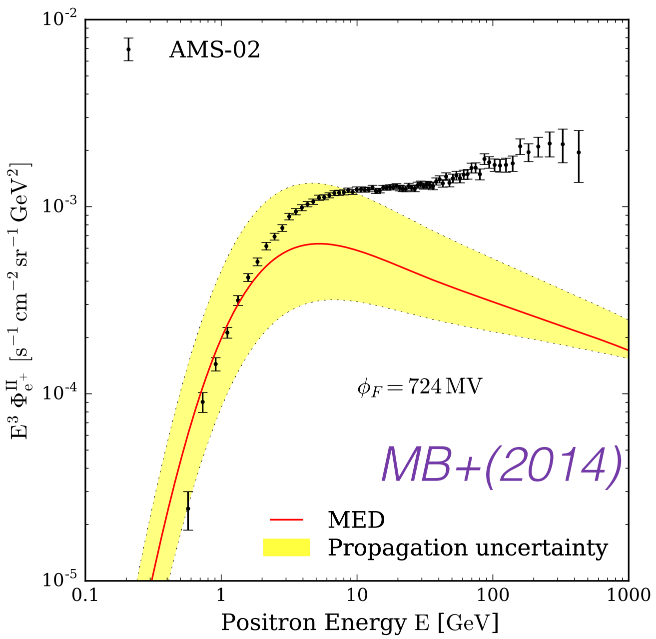
  e.g: *Kachelriess, Neronov & Semikoz (2017)*

Unlikely scenario ($p < 0.1\%$) for isotropic diffusion

Genolini, Salati, Serpico & Taillet (2016)

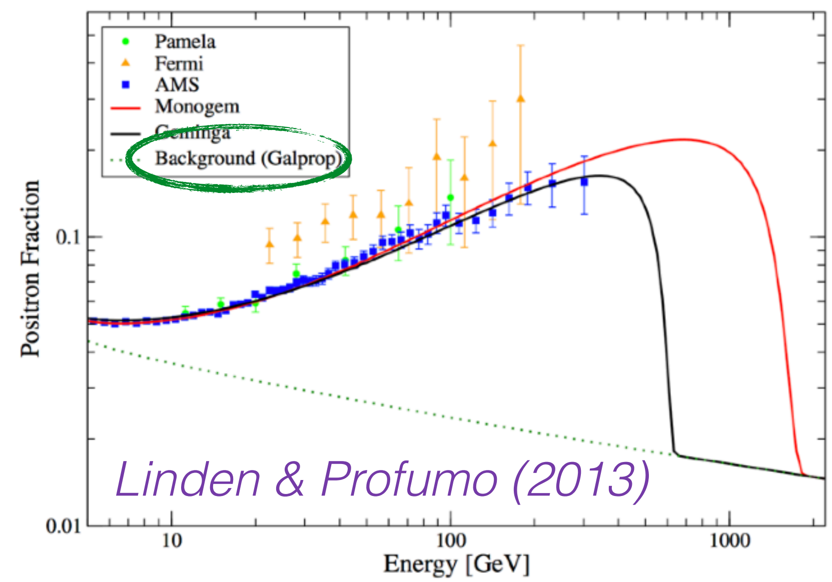
The positron excess

Semi-analytical

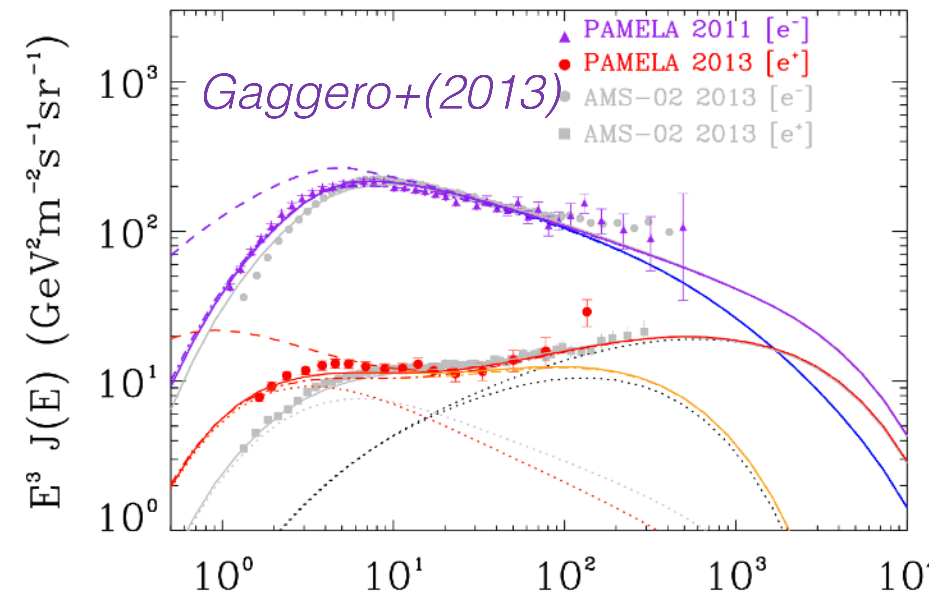


Numerical

(GALPROP)



(DRAGON)



- Primary e⁺ from dark matter

  e.g: *Silk and Srednicki (1984), Baltz & Edsjö (1998), Cirelli & Strumia (2008), MB+(2014)*

Serious tensions with antiprotons and gamma rays

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  Blasi & Serpico (2009)
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  e.g: *Hooper, Blasi & Serpico (2009), Linden & Profumo (2013), Delahaye+(2010), Gaggero+(2013), Di Mauro+(2014), MB+(2014)*

- Nearby and ~2-3 Myr old SNR

  e.g: *Kachelriess, Neronov & Semikoz (2017)*

Unlikely scenario ($p < 0.1\%$) for isotropic diffusion

Genolini, Salati, Serpico & Taillet (2016)

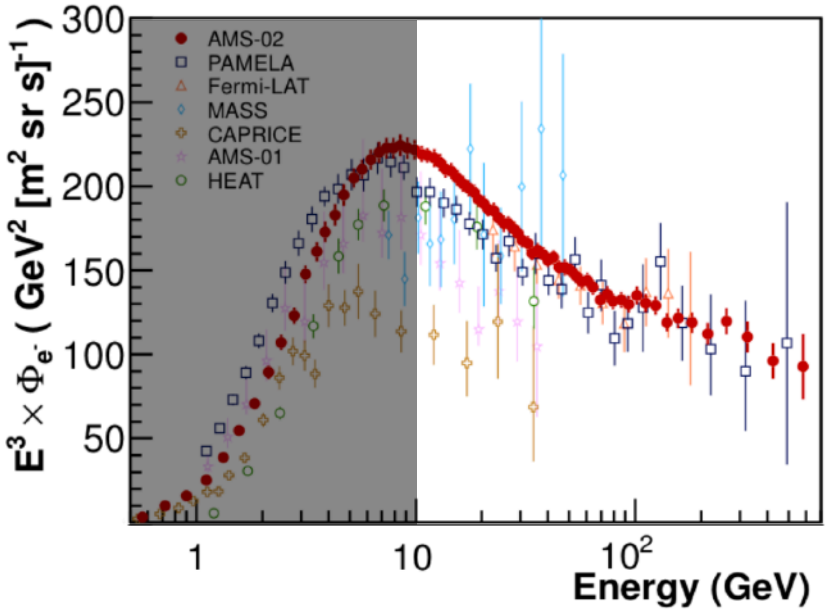
- Different propagation model

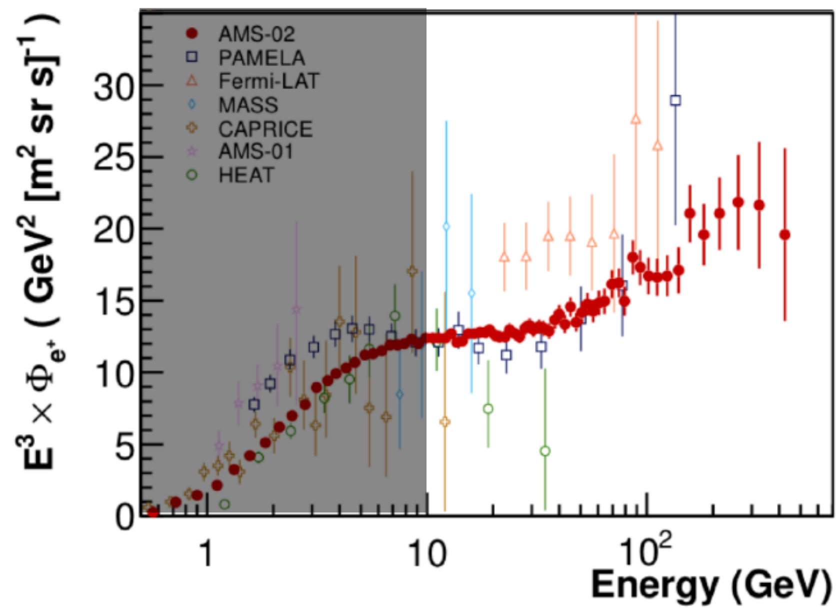
  e.g: *Lipari (2017), Blum, Sato & Waxman (2017)*

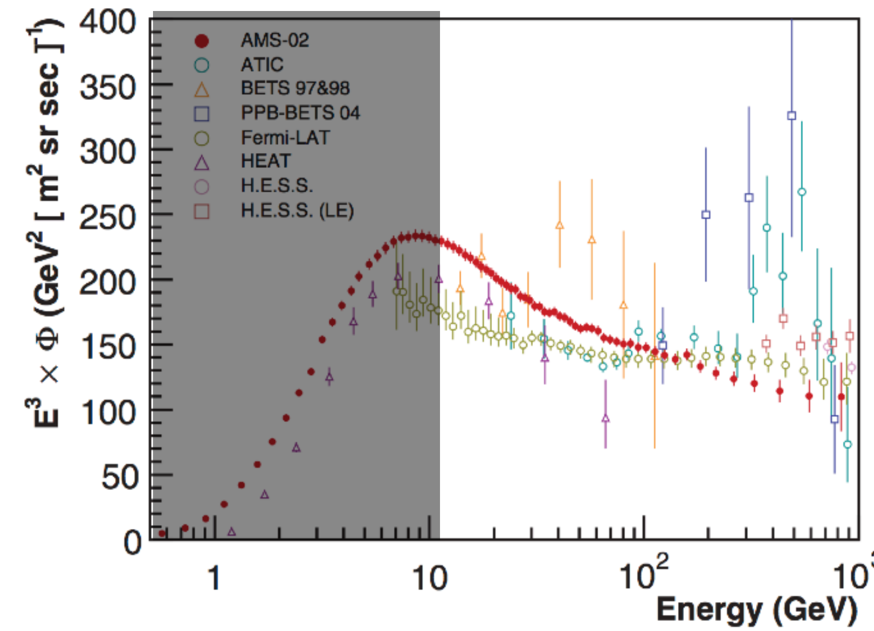
Inconsistent with energy losses, CR nuclei

Pinching method

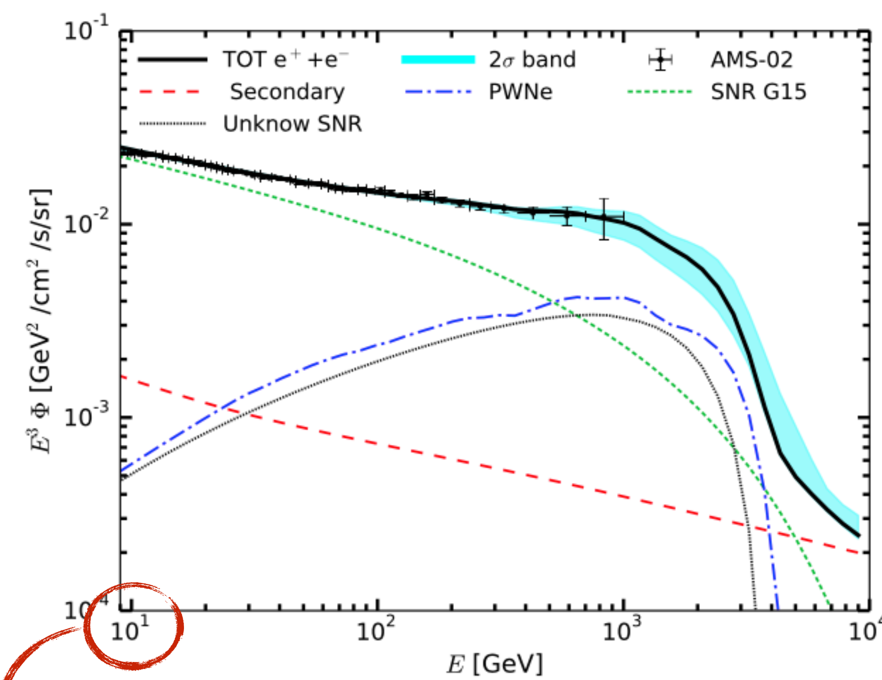
Interpretation of AMS-02 e+/e- data

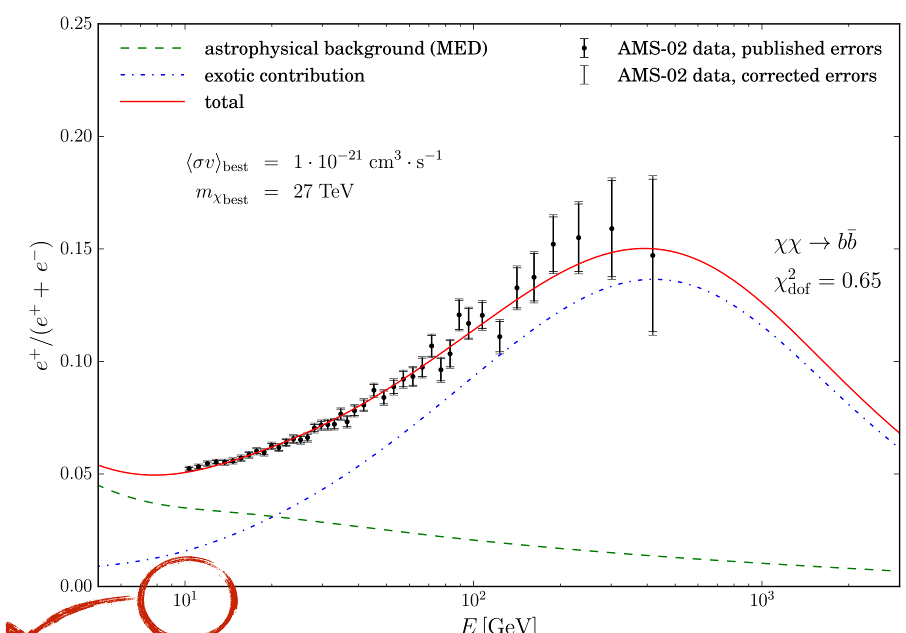






Semi-analytic method analysis e.g.:





Di Mauro+(2016)

10 GeV

MB+(2014)

10 GeV

Why the low energy data points (< 10 GeV) are not used?

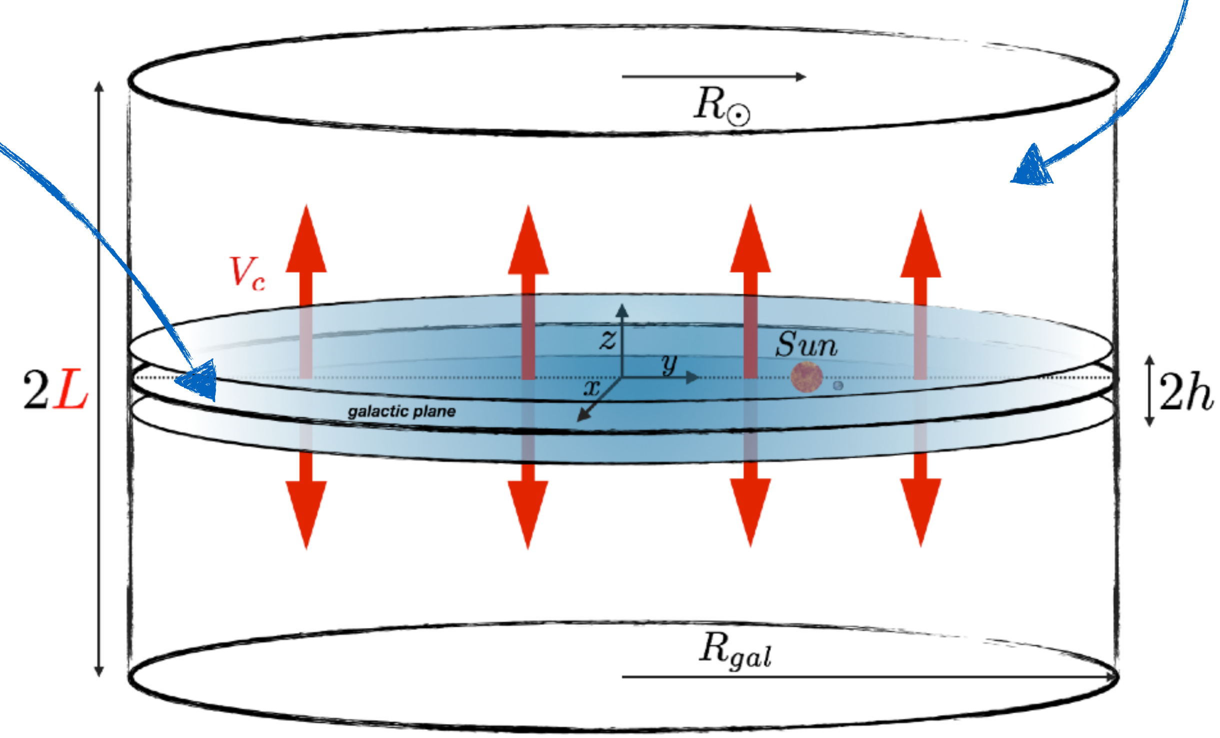
The pinching method

Cosmic rays transport equation (steady state)

$$\partial_z \left[V_C \, \mathrm{sign}(z) \, \psi\right] - K(E) \, \Delta \, \psi + 2h \, \delta(z) \, \partial_E \left[b_{\mathrm{disc}}(E) \, \psi - D(E) \, \partial_E \, \psi\right] + \partial_E \left[b_{\mathrm{halo}}(E) \, \psi\right] = Q(E, \vec{x})$$

$$b_{\mathrm{disc}} = b_{\mathrm{adia}} + b_{\mathrm{ioni}} + b_{\mathrm{brem}} + b_{\mathrm{coul}}$$

$$b_{\mathrm{halo}} = b_{\mathrm{IC}} + b_{\mathrm{sync}}$$



We cannot solve analytically the transport equation when cosmic rays lose energy in the hole magnetic halo!

We need a **numerical** algorithm to solve the transport equation (GALPROP, DRAGON, PICARD, etc.)

The pinching method

Cosmic rays transport equation (steady state)

$$\partial_z \left[V_C \, \mathrm{sign}(z)\, \psi\right] - K(E)\, \Delta \psi + 2h\, \delta(z)\, \partial_E \left[b_{\mathrm{disc}}(E)\, \psi - D(E)\, \partial_E \psi\right] + \partial_E \left[b_{\mathrm{halo}}(E)\, \psi\right] = Q(E, \vec{x})$$

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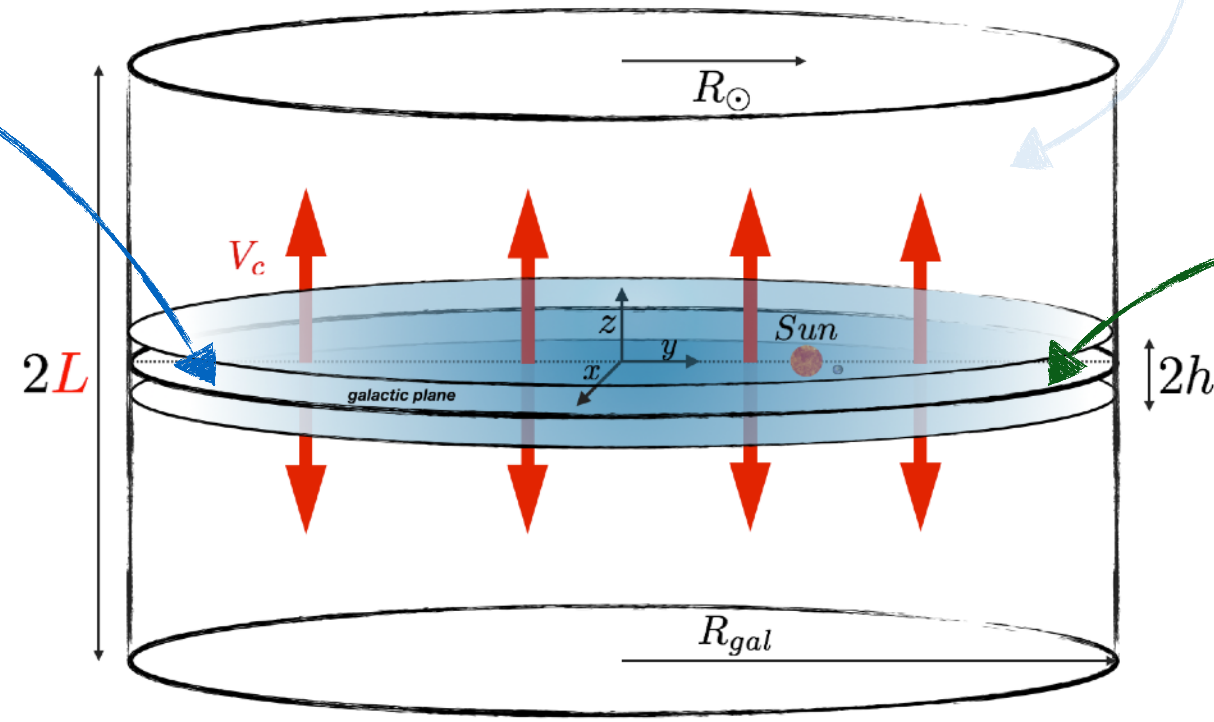
$$b^{eff}_{\mathrm{halo}}$$



The pinching method

MB+(2016)

The pinching method

Cosmic rays transport equation (steady state)

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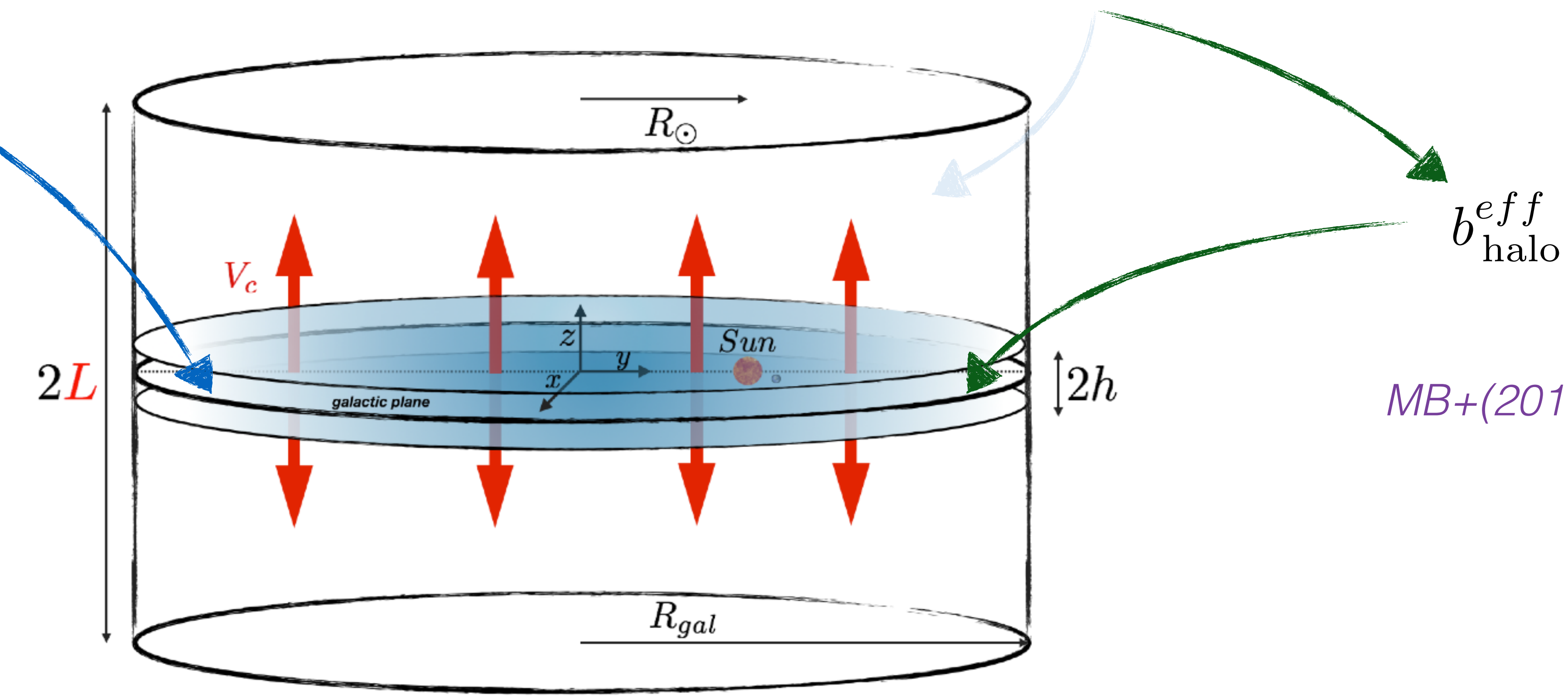

MB+(2016)

The pinching method

$$\partial_z [V_C \, \text{sign(z)}\, \psi] - K(E)\, \Delta\, \psi + 2h\, \delta(z)\, \partial_E \left\{ \left[b_{\text{disc}}(E) + b^{eff}_{\text{halo}}(E) \right] \psi - D(E)\, \partial_E\, \psi \right\} = Q(E, \vec{x})$$

The pinching method

MB+(2016)

$$\partial_z[V_C\,\mathrm{sign(z)}\,\psi] - K(E)\,\Delta\,\psi + 2h\,\delta(z)\,\partial_E\left\{\left[b_{\mathrm{disc}}(E) + b^{eff}_{\mathrm{halo}}(E)\right]\,\psi - D(E)\,\partial_E\,\psi\right\} = Q(E,\vec{x})$$

$$b_{\,\mathrm{halo}} = b_{\,\mathrm{IC}} + b_{\mathrm{sync}} \longrightarrow b^{eff}_{\mathrm{halo}}(E,r) = \bar{\xi}(E,r)\,b_{\,\mathrm{halo}}(E)$$

pinching factor

$$\bar{\xi}(E,r) = \frac{1}{\psi(E,r,0)}\sum_{i=1}^{+\infty} J_0(\alpha_i\frac{r}{R})\,\bar{\xi}_i(E)\,P_i(E,0)$$

$$\bar{\xi}_i(E) = \frac{\int\limits_E^{+\infty} dE_S\left[J_i(E_S) + 4k_i^2\int\limits_E^{E_S} dE'\,\frac{K(E')}{b(E')}\,B_i(E',E_S)\right]}{\int\limits_E^{+\infty} dE_S\,B_i(E,E_S)}$$

$$J_i(E_S) = \frac{1}{h}\int_0^L dz_S\;\mathcal{F}_i(z_S)\,Q_i(E_S,z_S) \qquad Q_i(E,z) = \frac{2}{R^2J_1^2(\alpha_i)}\int_0^R dr\,r\,J_0(\xi_i)\;Q(E,r,z)$$

$$B_i(E,E_S) = \sum_{n=2m+1}^{+\infty} Q_{i,n}(E_S)\exp\left[-C_{i,n}\lambda_D^2\right] \qquad C_{i,n} = \frac{1}{4}\left[\left(\frac{\alpha_i}{R}\right)^2 + (nk_0)^2\right]$$

$$Q_{i,n}(E) = \frac{1}{L}\int_{-L}^{L} dz\;\varphi_n(z)\;\frac{2}{R^2J_1^2(\alpha_i)}\int_0^R dr\,r\,J_0\left(\alpha_i\frac{r}{R}\right)\;Q(E,r,z)$$

The pinching method

Cosmic rays transport equation (steady state)

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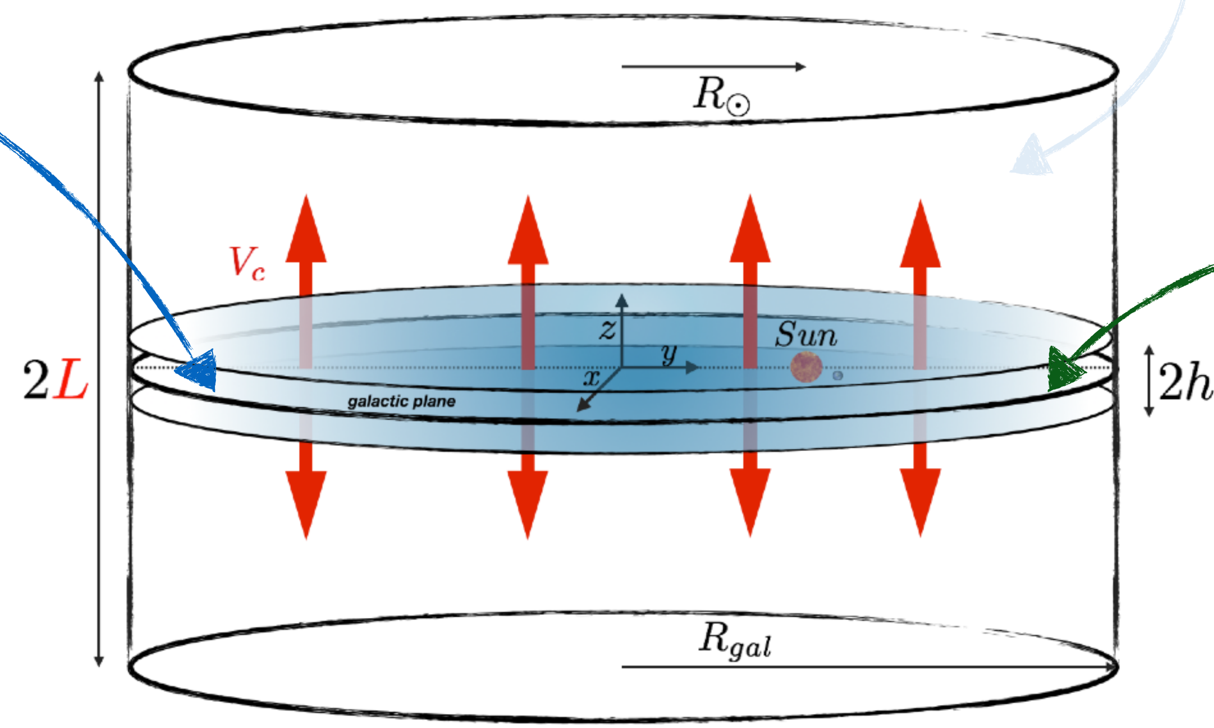


MB+(2016)

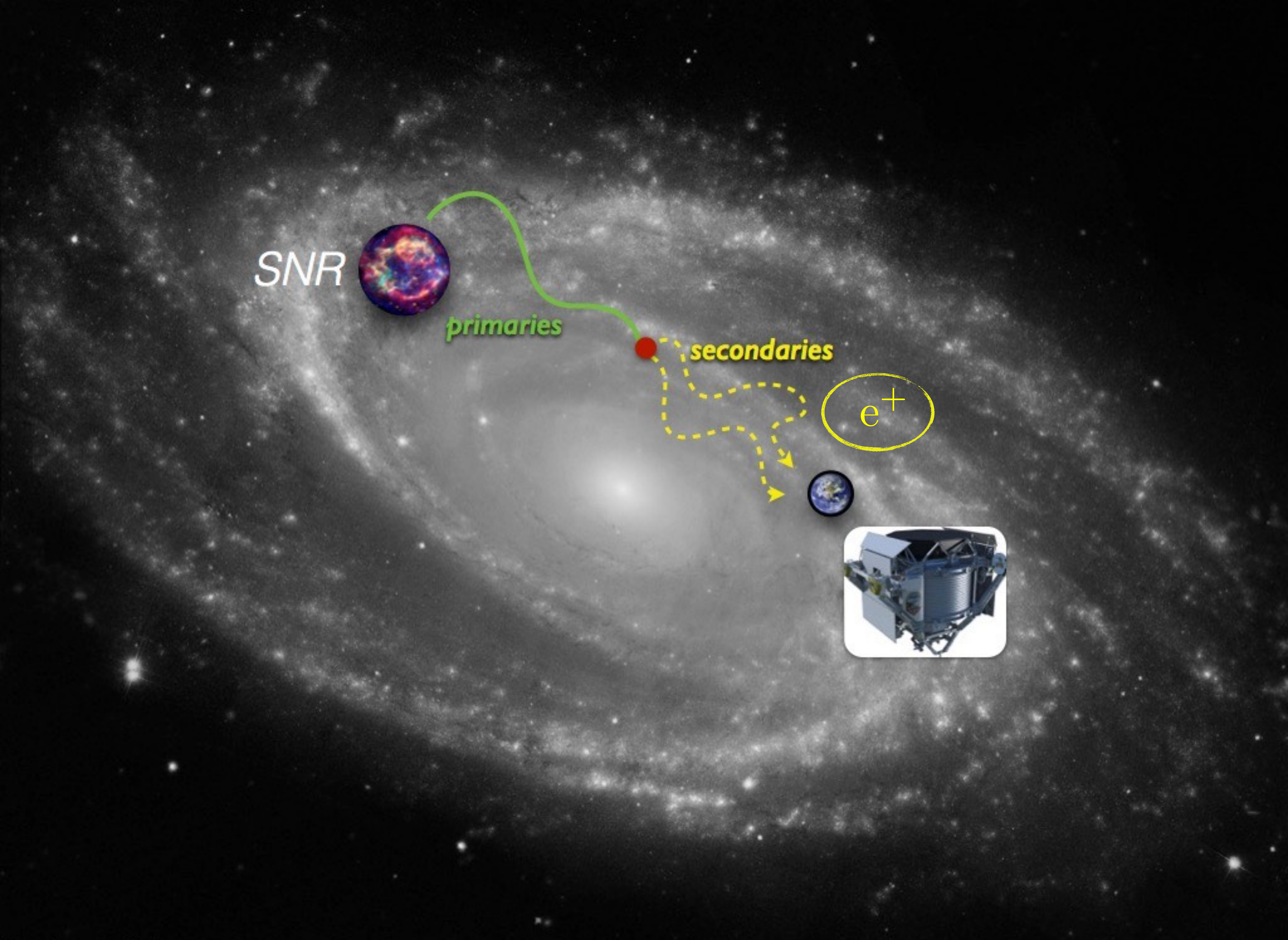
The pinching method

$$\partial_z[V_C\,\mathrm{sign(z)}\,\psi] - K(E)\,\Delta\,\psi + 2h\,\delta(z)\,\partial_E\left\{\left[b_{\mathrm{disc}}(E) + b^{eff}_{\mathrm{halo}}(E)\right]\,\psi - D(E)\,\partial_E\,\psi\right\} = Q(E,\vec{x})$$

From now we are able to compute the positron flux **analytically**, **including all propagation effects**!

Pinching method

I. The positron excess revisited



Courtesy A. Putze

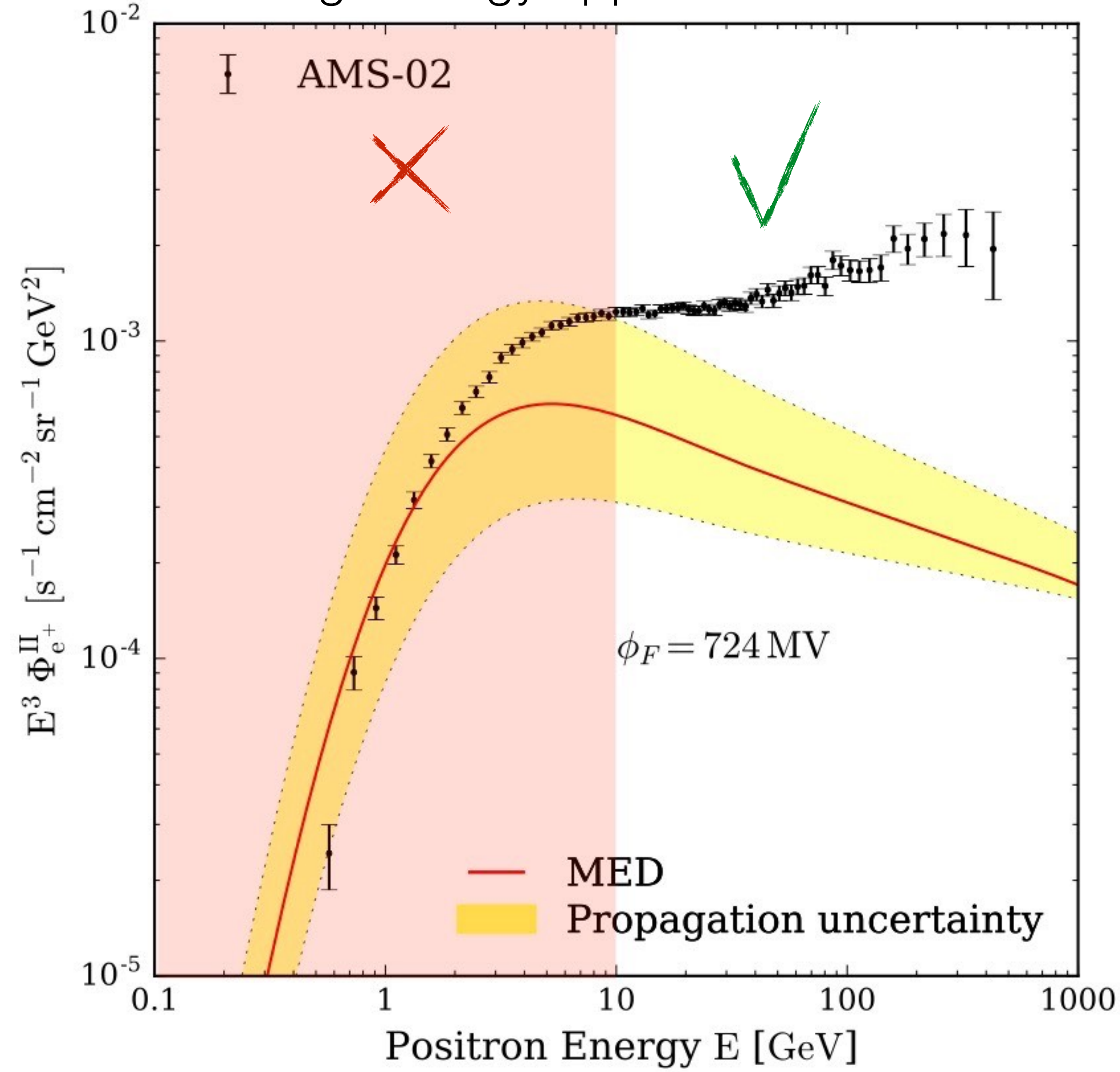
Astrophysical secondary positrons

$$Q^{\mathrm{II}}(E,\vec{x}) = 4\pi \sum_{i=p,\alpha} \sum_{j=H,He} n_j \int_{E_0}^{+\infty} dE_i \, \phi_i(E_i,\vec{x}) \, \frac{d\sigma}{dE_i}(E_j \to E) \qquad \begin{cases} i = projectile \\ j = target \end{cases}$$

$p + p \longrightarrow$

- $p + \Delta^+$
  - $\Delta^+ \longrightarrow n + \pi^+$
  - $\pi^+ \longrightarrow \nu_\mu + \mu^+$
  - $\mu^+ \longrightarrow \bar{\nu}_\mu + \nu_e + e^+$
- $X + \pi^+$
  - $\pi^+ \longrightarrow \nu_\mu + \mu^+$
  - $\mu^+ \longrightarrow \bar{\nu}_\mu + \nu_e + e^+$
- $X + K^+$
  - $K^+ \longrightarrow$
    - $\nu_\mu + \mu^+$
      - $\mu^+ \longrightarrow \bar{\nu}_\mu + \nu_e + e^+$
    - $\pi^0 + \pi^+$
      - $\pi^+ \longrightarrow \nu_\mu + \mu^+$
      - $\mu^+ \longrightarrow \bar{\nu}_\mu + \nu_e + e^+$

High energy approximation



Astrophysical secondary positrons

$$Q^{\mathrm{II}}(E,\vec{x}) = 4\pi \sum_{i=p,\alpha} \sum_{j=H,He} n_j \int_{E_0}^{+\infty} dE_i\, \phi_i(E_i,\vec{x})\, \frac{d\sigma}{dE_i}(E_j \to E) \qquad \begin{cases} i = projectile \\ j = target \end{cases}$$

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  - $K^+ \longrightarrow$
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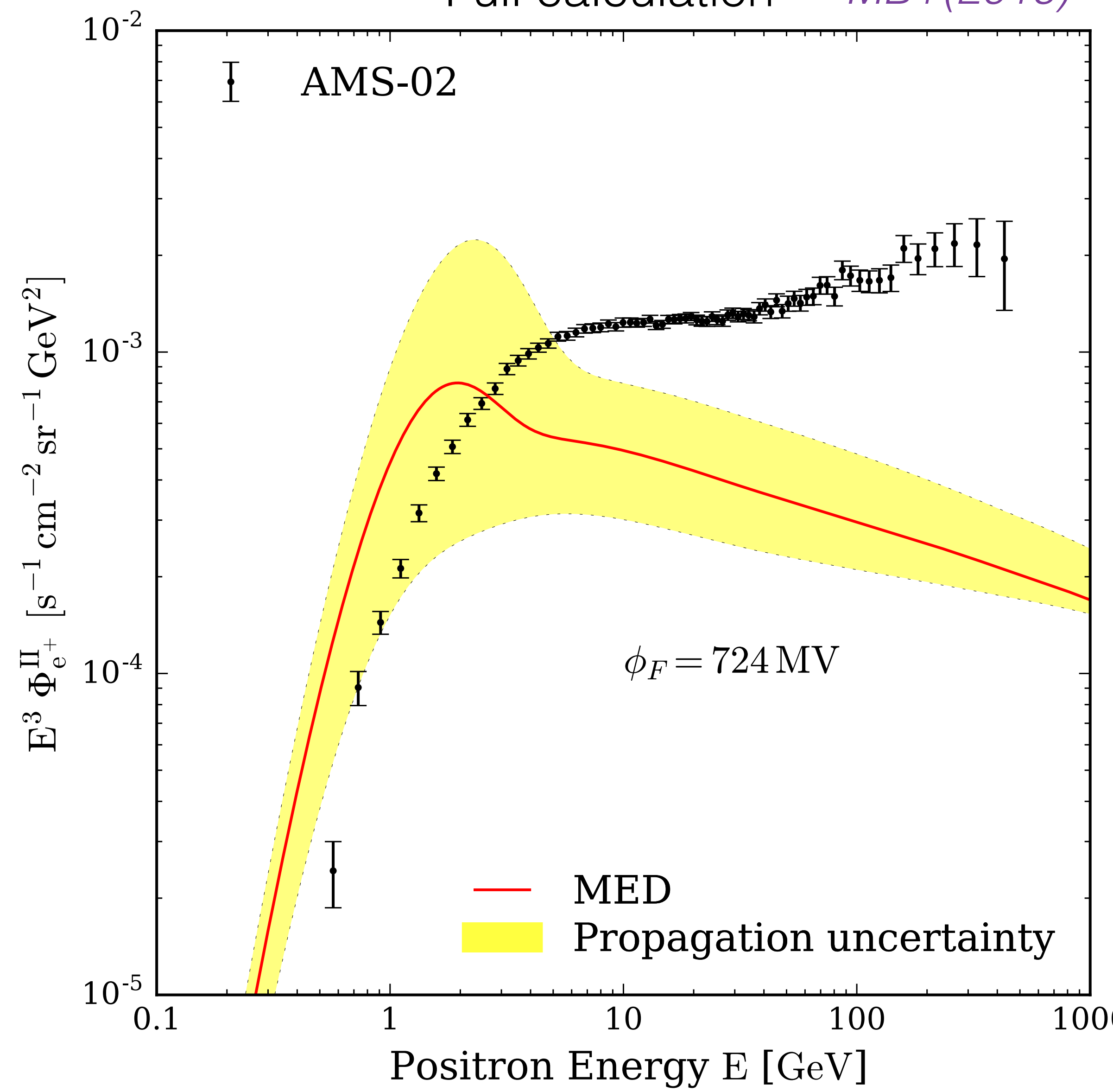
      - $\mu^+ \longrightarrow \bar{\nu}_\mu + \nu_e + e^+$
    - $\pi^0 + \pi^+$
      - $\pi^+ \longrightarrow \nu_\mu + \mu^+$
      - $\mu^+ \longrightarrow \bar{\nu}_\mu + \nu_e + e^+$

Full calculation *MB+(2016)*



The HE approximation ⇒ error up to 50% at 10 GeV!

Astrophysical secondary positrons

$$Q^{\rm II}(E,\vec{x}) = 4\pi \sum_{i=p,\alpha} \sum_{j=H,He} n_j \int_{E_0}^{+\infty} dE_i\, \phi_i(E_i,\vec{x})\, \frac{d\sigma}{dE_i}(E_j \to E) \qquad \begin{cases} i = projectile \\ j = target \end{cases}$$

$p + p \longrightarrow$

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      - $\mu^+ \longrightarrow \bar{\nu}_\mu + \nu_e + e^+$

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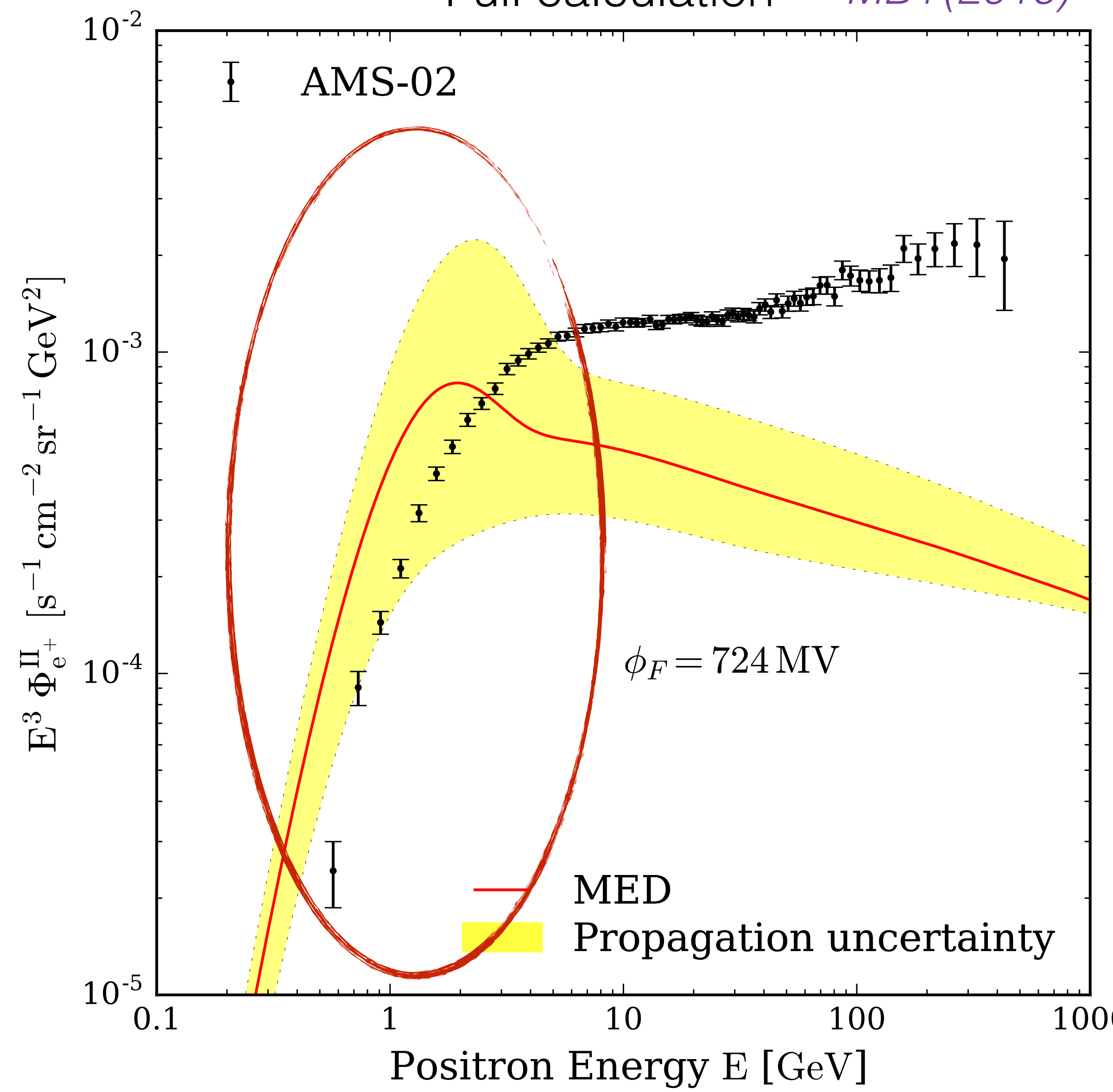

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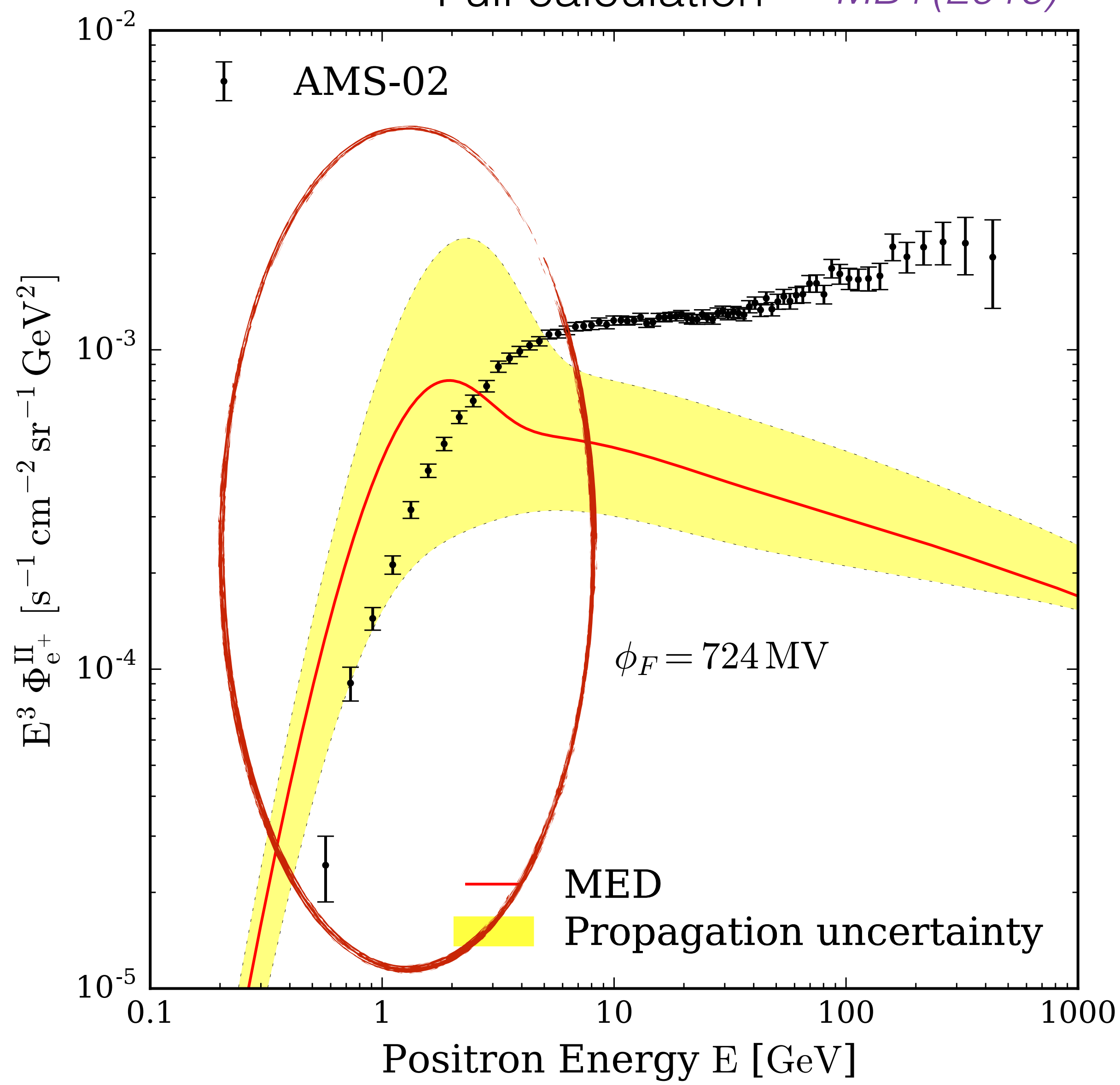
$$Q^{\mathrm{II}}(E,\vec{x}) = 4\pi \sum_{i=p,\alpha} \sum_{j=H,He} n_j \int_{E_0}^{+\infty} dE_i \, \phi_i(E_i,\vec{x}) \, \frac{d\sigma}{dE_i}(E_j \to E) \qquad \begin{cases} i = projectile \\ j = target \end{cases}$$

Positrons can be used as an independent probe for the propagation parameters.

The degeneracy between K_0 and L can be lifted!

Lavalle+(2014)

Full calculation *MB+(2016)*



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Positrons can be used as an independent probe for the propagation parameters.

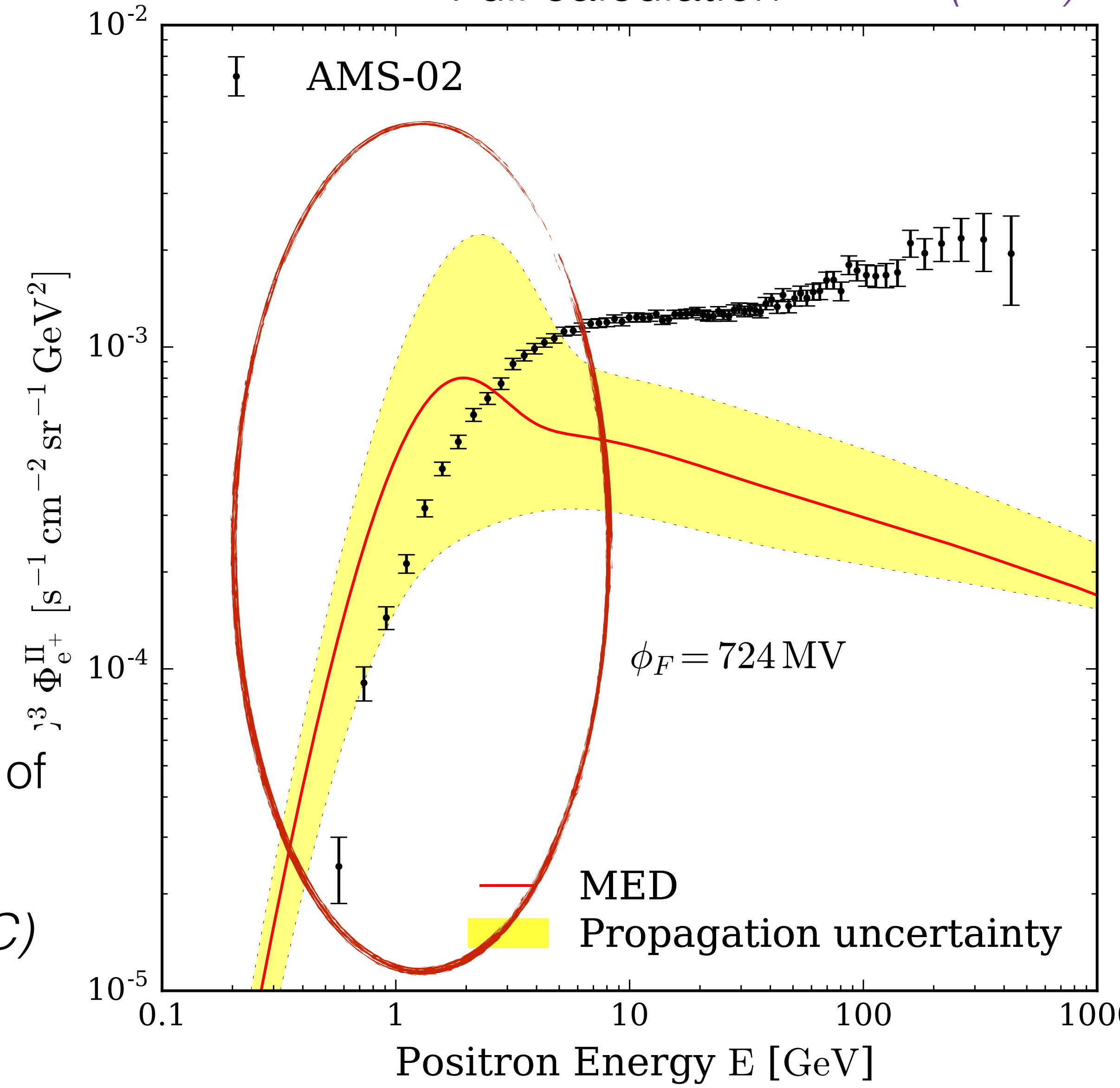
The degeneracy between K_0 and L can be lifted!

Lavalle+(2014)

Case	δ	K_0 [kpc^2/Myr]	L [kpc]	V_C [km/s]	V_a [km/s]
MIN	0.85	0.0016	1	13.5	22.4
MED	0.70	0.0112	4	12	52.9
MAX	0.46	0.0765	15	5	117.6

Ruled out!

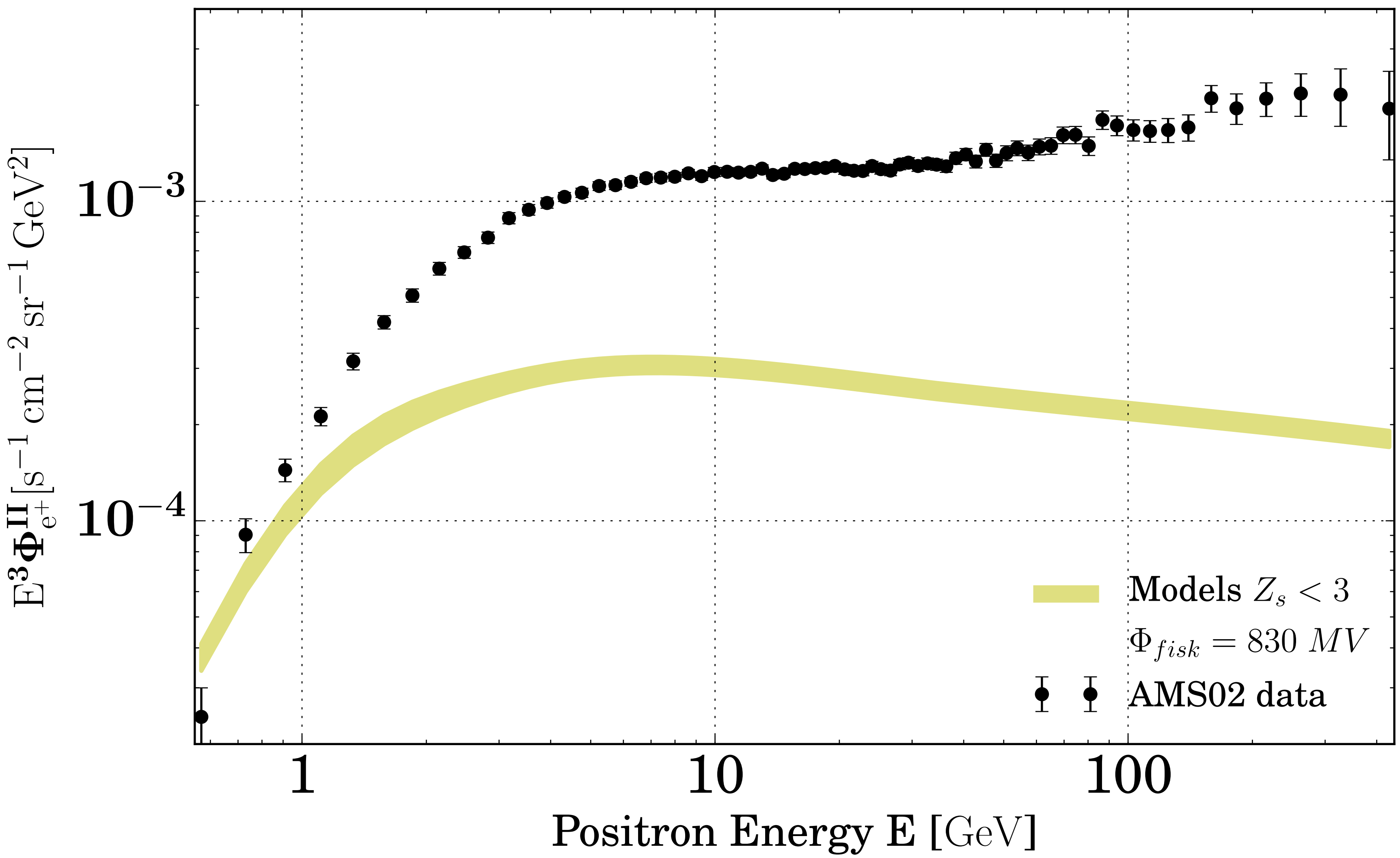
Full calculation *MB+(2016)*



The AMS-02 positrons data favour the **MAX-type** sets of propagation parameters.

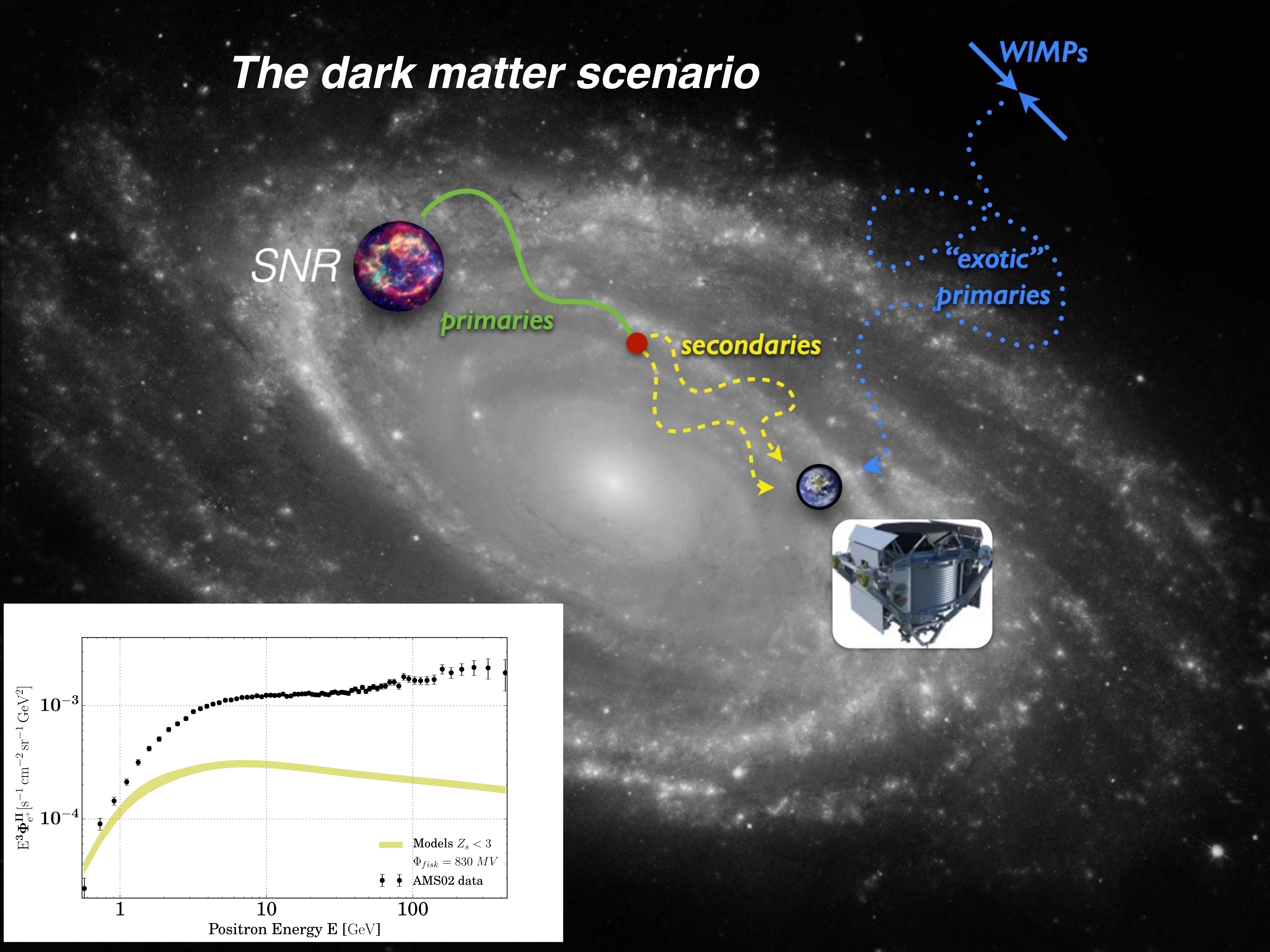
(result confirmed by AMS-02 antiprotons and recent B/C)

Astrophysical secondary positrons



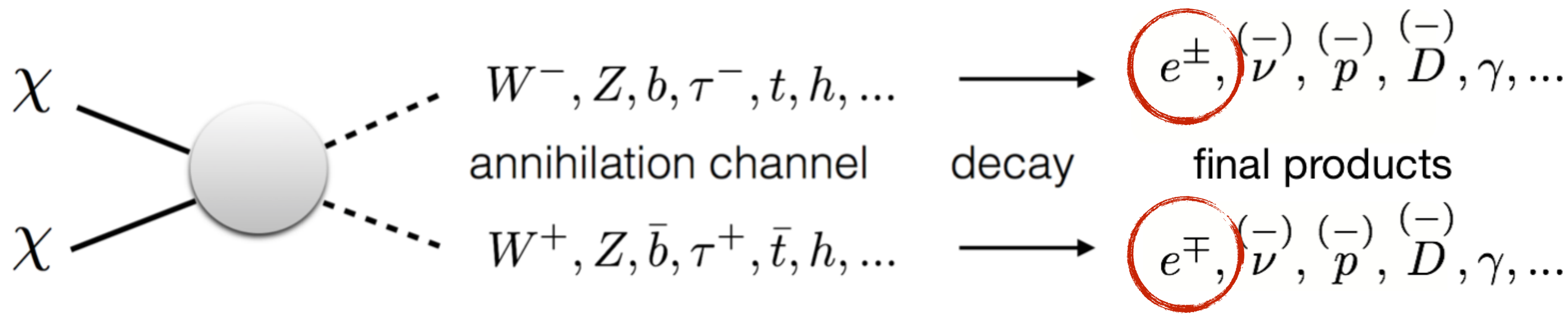
MB+(2016a)

- The uncertainty band for the e+ is now very narrow.
- The positron excess appears now from ~1 GeV.
- Where do come from the remaining positrons?
- We need another component(s) to explain the positron data **from ~1 GeV to ~500 GeV**.



The dark matter scenario
WIMPs
SNR
primaries
secondaries
"exotic" primaries
10^{-3}
10^{-4}
$E^3\Phi^{II}_{e^+}[s^{-1}\,cm^{-2}\,sr^{-1}\,GeV^2]$
1
10
100
Positron Energy E [GeV]
Models $Z_s < 3$
$\Phi_{fisk} = 830\ MV$
AMS02 data

The dark matter scenario



A very generic class of models

$$\chi\chi \longrightarrow B_b\, \bar{b}b + B_W\, W^+W^- + B_\tau\, \tau^+\tau^- + B_\mu\, \mu^+\mu^- + B_e\, e^+e^-$$

Free parameters

- Propagation parameters (consistent with secondaries)

  K_0, δ, L, V_C, V_A

- Solar modulation (Phisk potential)

  $\phi_F \in [647, 830]\,\mathrm{MV}$ (3 σ CL) *Ghelfi+(2015)*

- Dark matter parameters

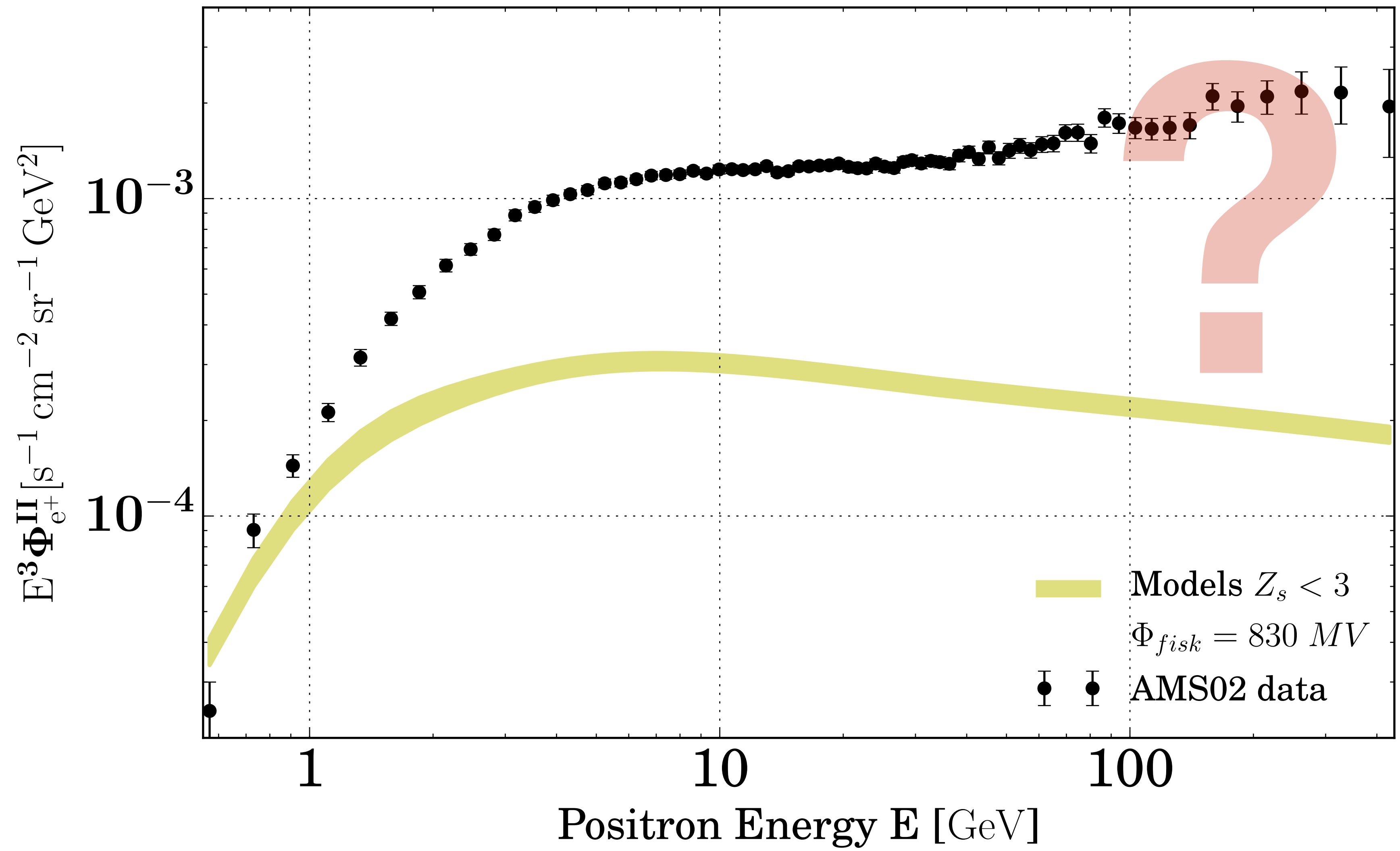
  The mass m_χ

  The annihilating cross section $\langle\sigma v\rangle$

  The branching ratios $B_b, B_W, B_\tau, B_\mu, B_e$

The Dark Matter scenario

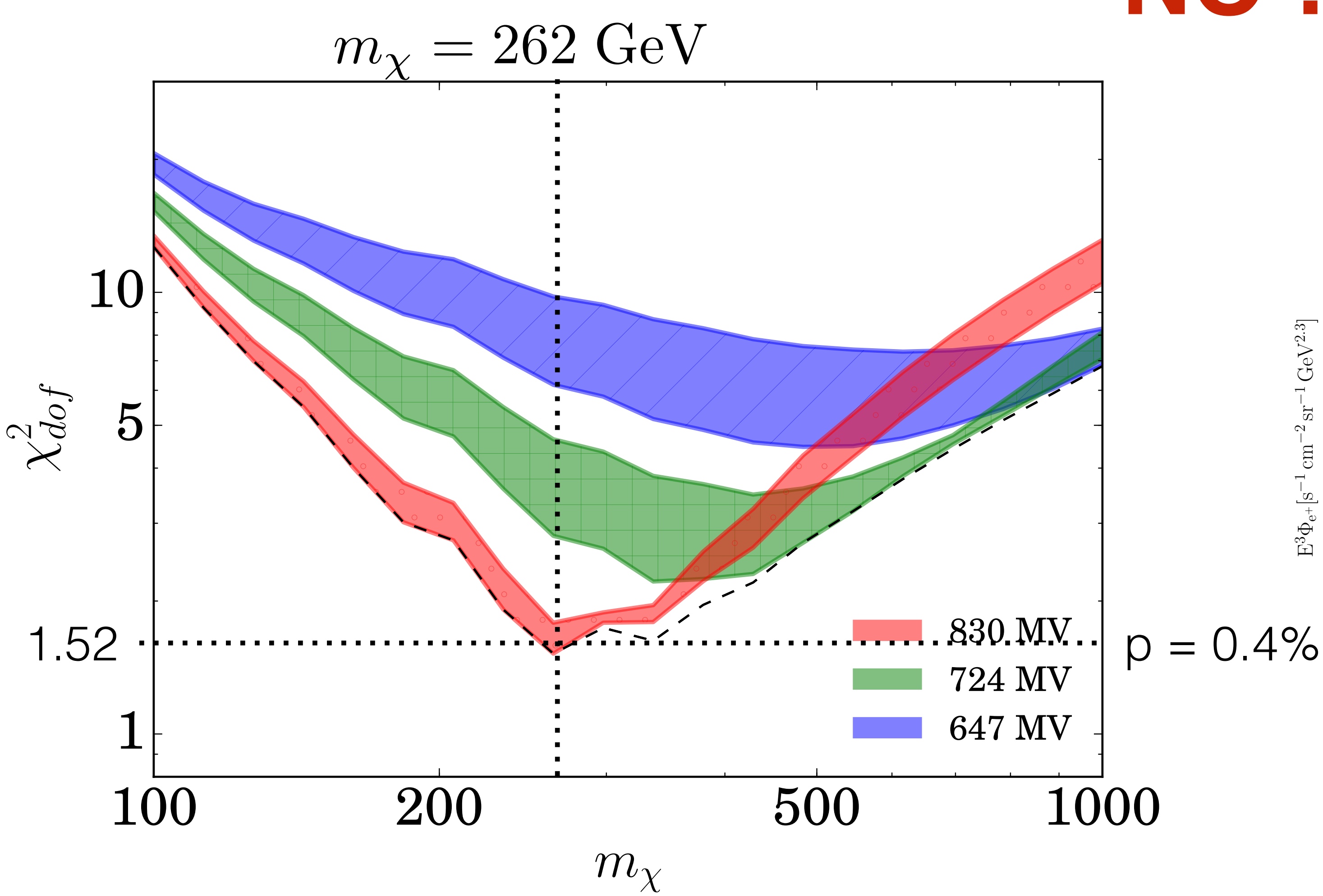
Is it possible to obtain a satisfactory fit to the AMS-02 data?



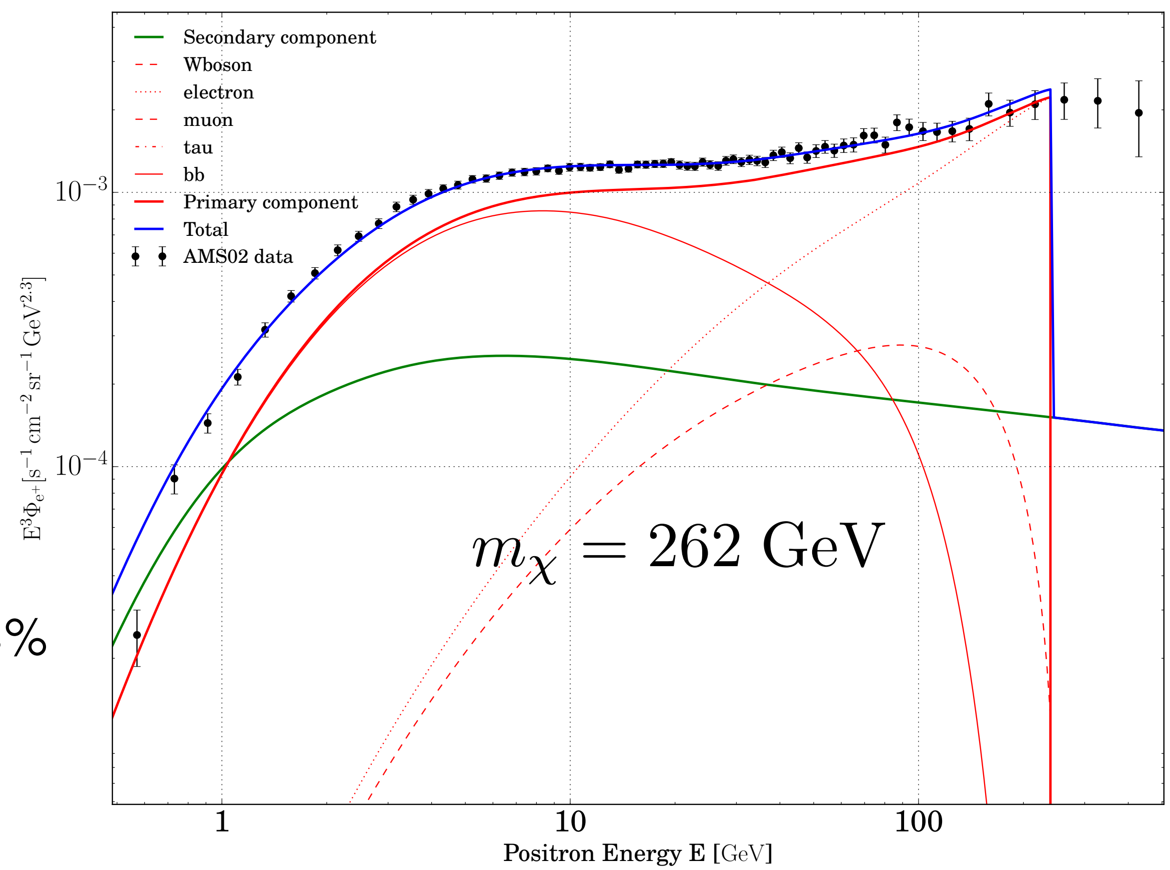
The Dark Matter scenario

Is it possible to obtain a satisfactory fit to the AMS-02 data?

NO !



MB+(2016)



The spectrum of e+ from DM annihilations **cannot** account for the **shape** of the spectrum measured by AMS-02.

The positron flux produced by DM is restricted « around » the DM mass.

The poor quality of the fit disfavours a pure DM explanation for the positron excess!

The Dark Matter scenario

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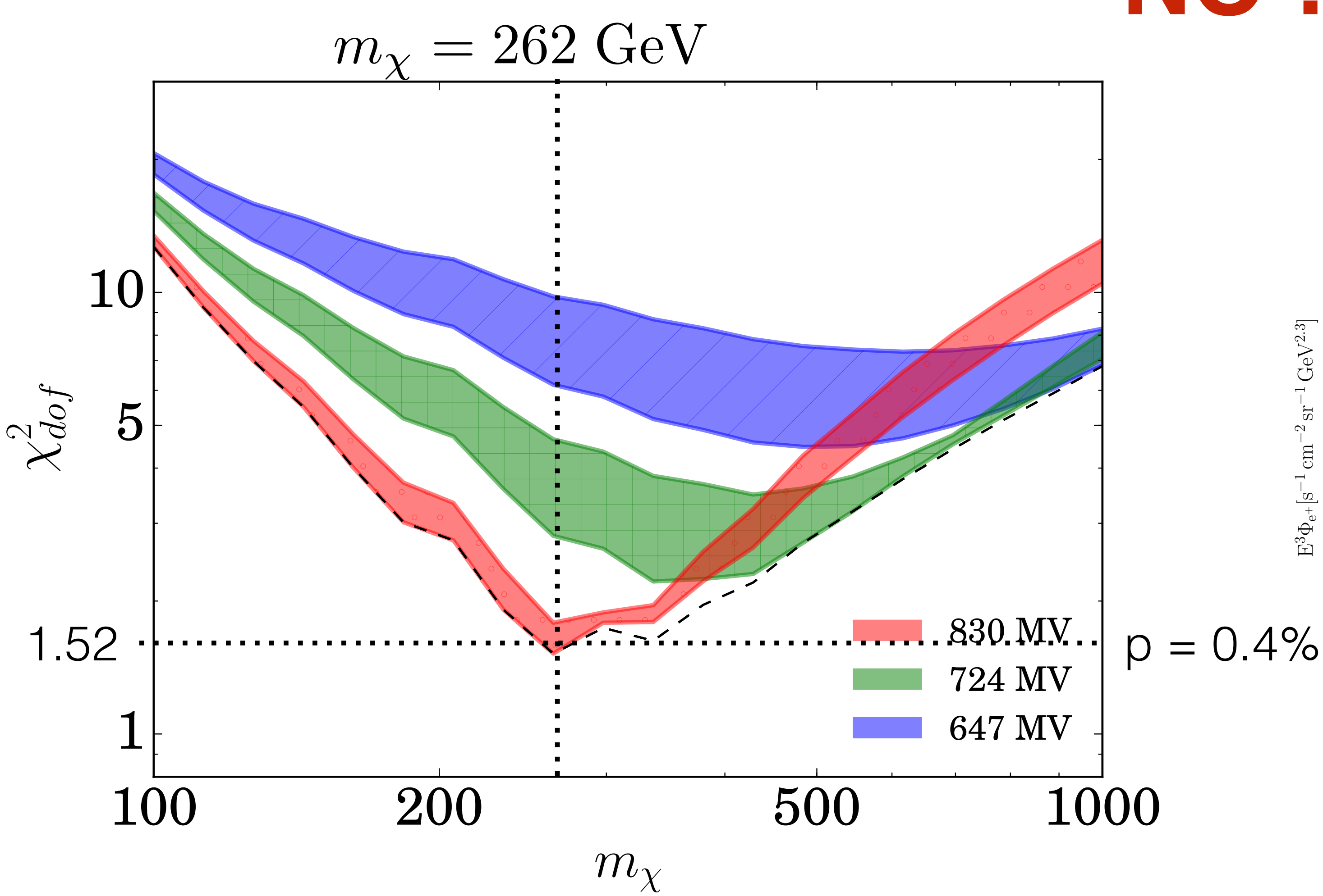
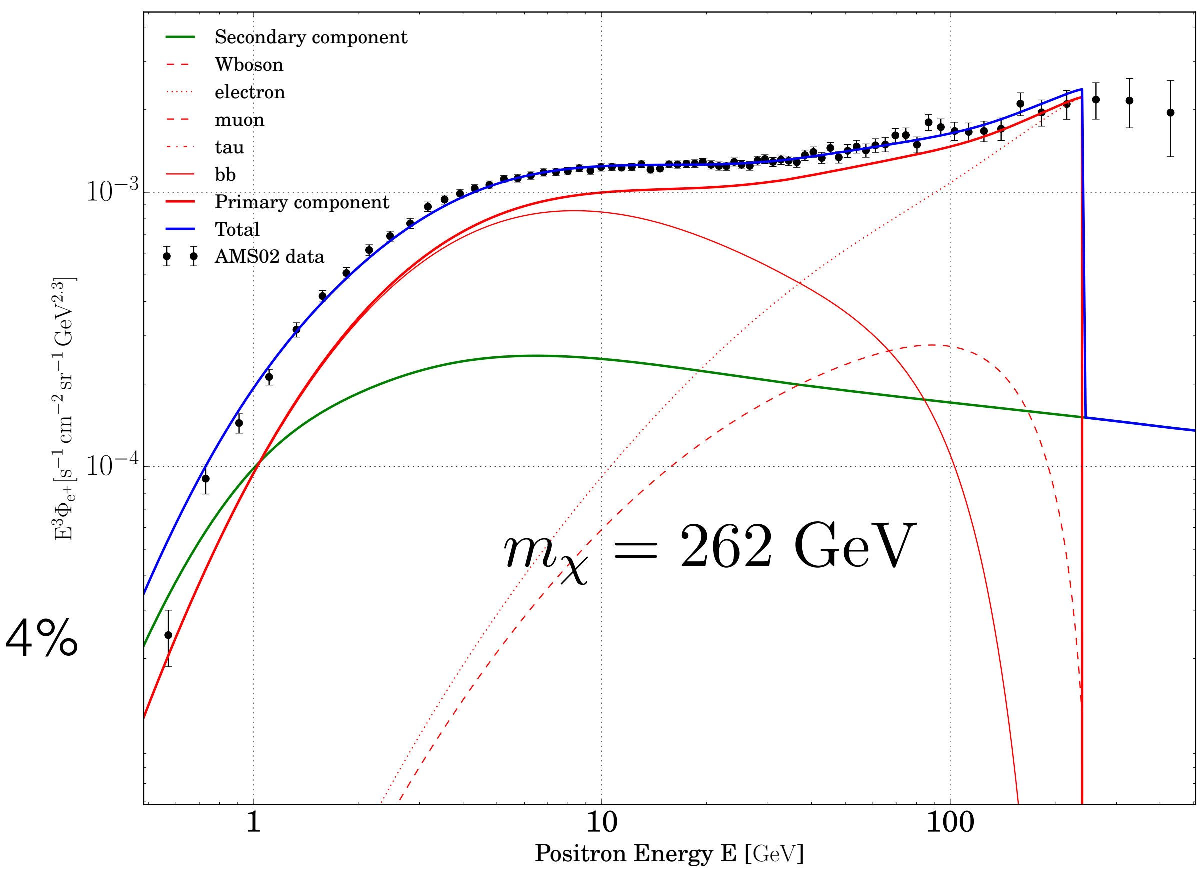
MB+(2016)





The spectrum of e+ from DM annihilations **cannot** account for the **shape** of the spectrum measured by AMS-02.

The positron flux produced by DM is restricted « around » the DM mass.

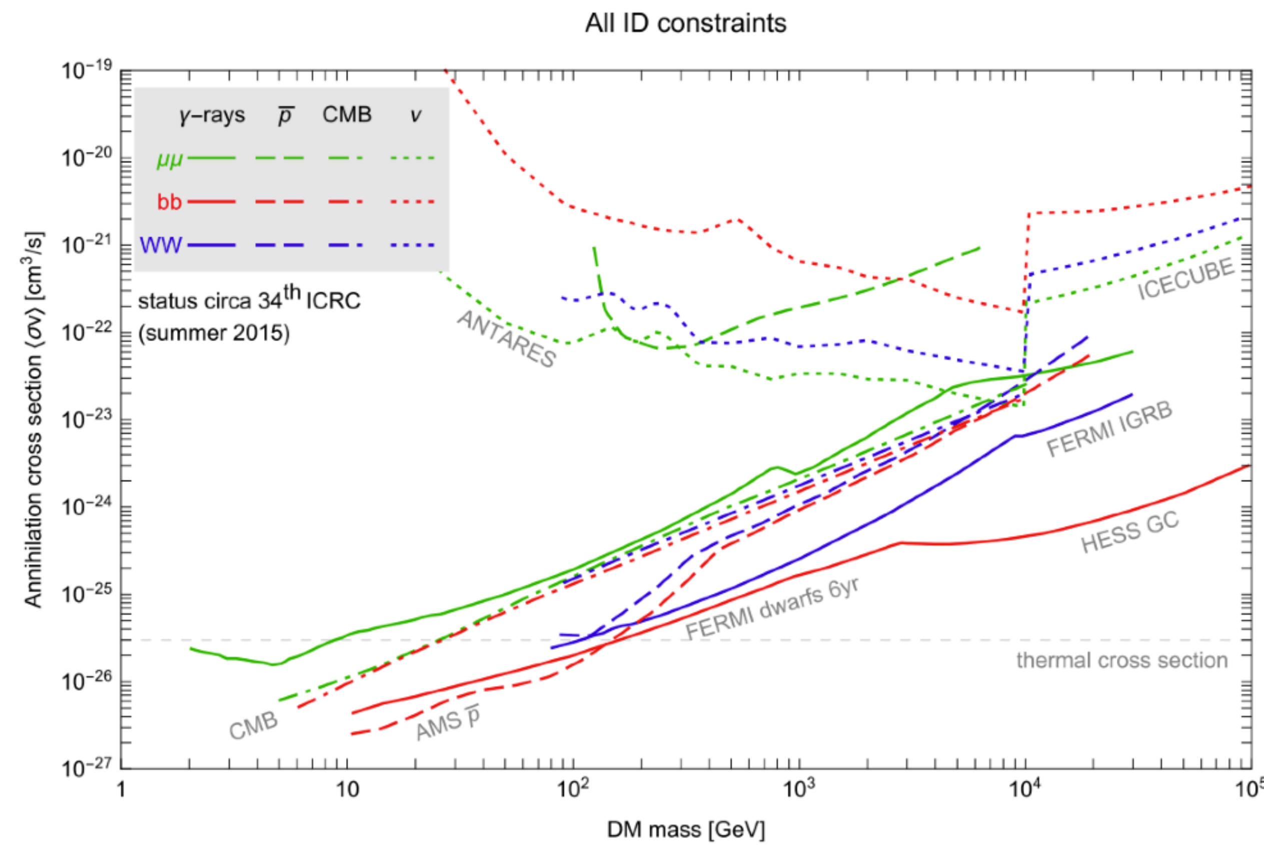
The poor quality of the fit disfavours a pure DM explanation for the positron excess!

This conclusion is based only on the positron data and does not require constraints from other channels (gamma rays, antiprotons, CMB, etc.)

Pinching method

II. Novel constraints on MeV dark matter

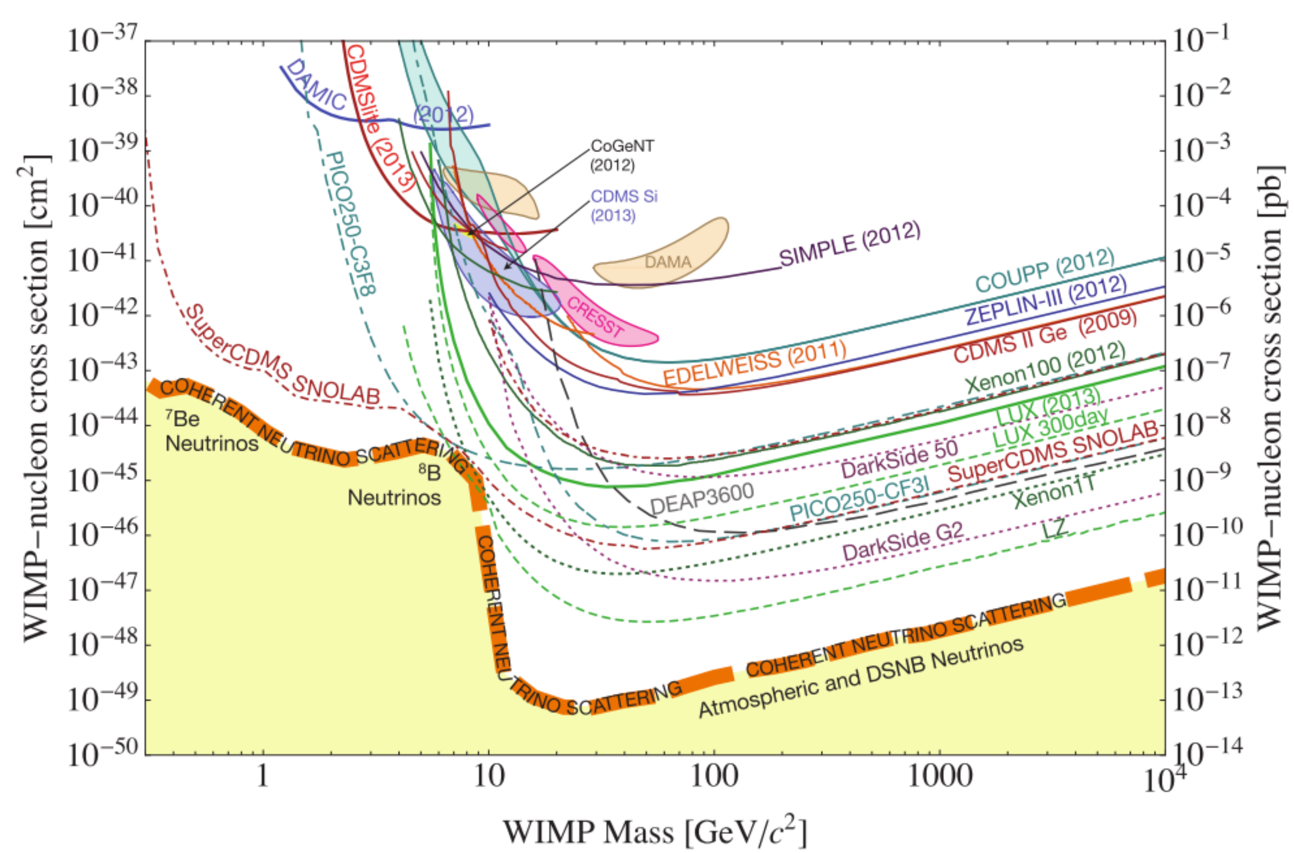
Why MeV dark matter?



GeV-TeV dark matter

Motivated by SUSY theories.

- Gamma rays: No (clear) signal in the Galactic center. No signal in dSphs galaxies.
- Antiprotons: No (clear) signal.
- Direct detection: No (clear) signal.



MeV dark matter

- Not many channels kinematically available:
  - Pions (> 140 MeV)
  - Muons (> 105 MeV)
  - Electrons
  - Neutrinos
  - Photons
- Difficult to detect in direct detection experiments.

Why there is no constraints on MeV dark matter from CR e^- and e^+?

- So far, we needed numerical codes to solve the transport equation in the sub-GeV energy range to predict the interstellar (IS) flux of e^- and e^+. Important CPU time to derive bounds on the DM particle annihilation cross-section.

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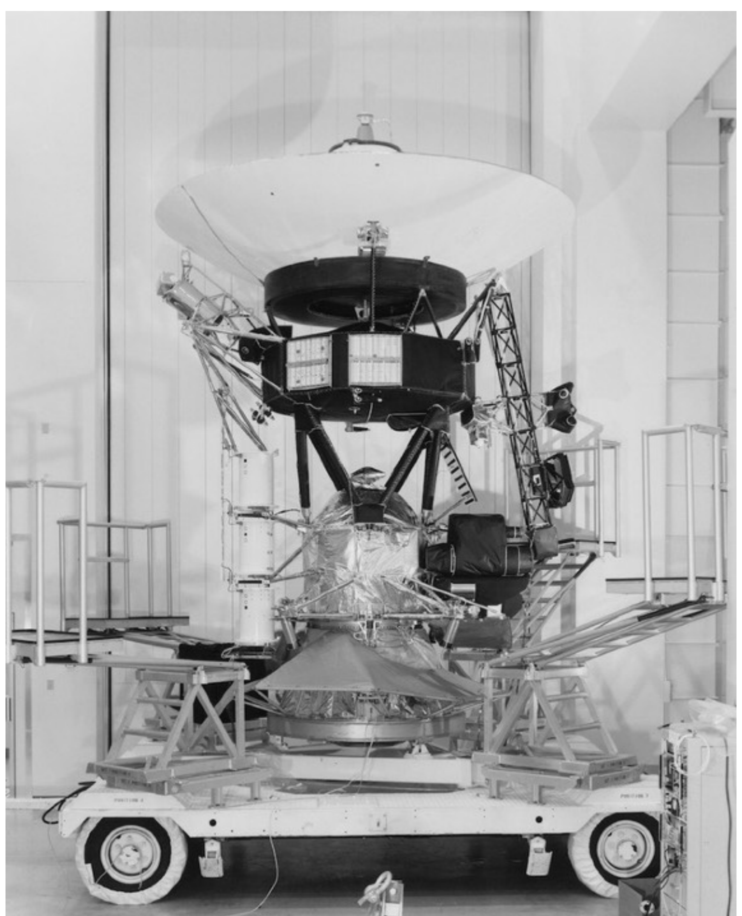
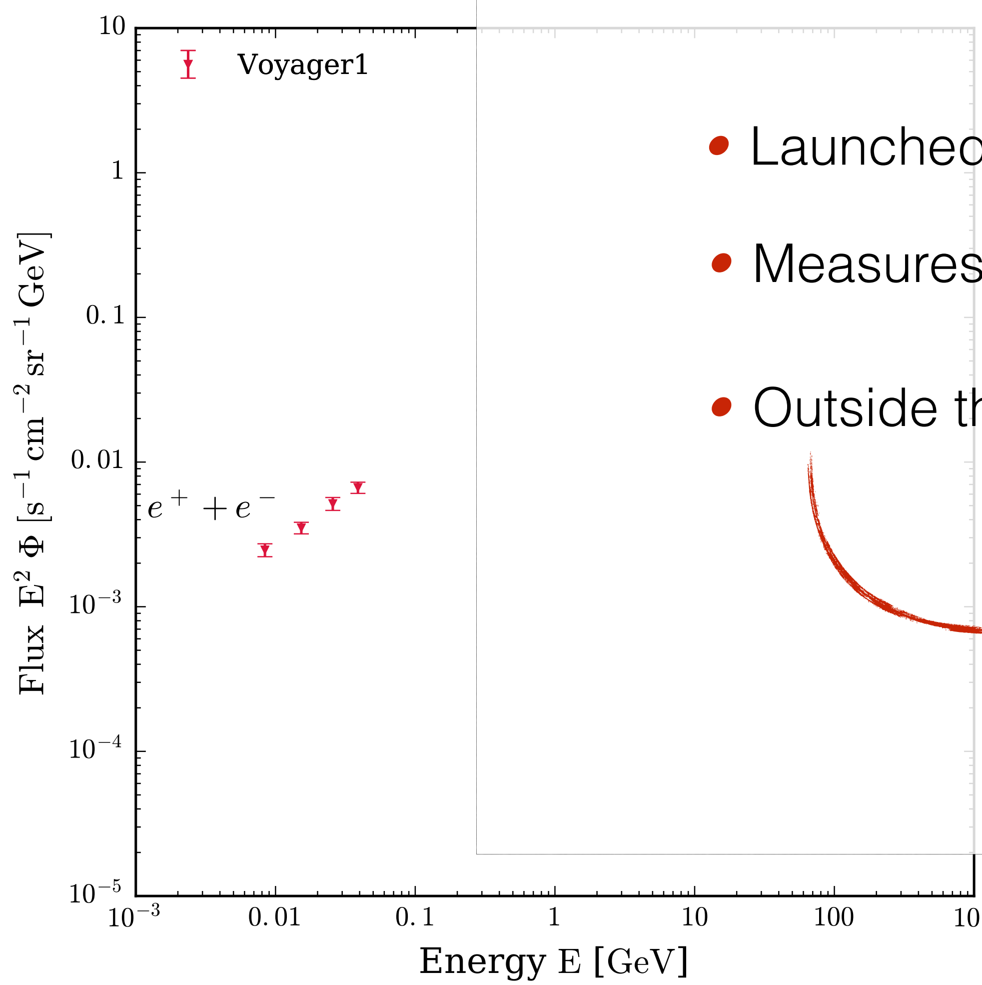
- Interstellar sub-GeV e^- and e^+ are shielded by the solar magnetic field, they cannot reach detectors orbiting the Earth.

✓ **Voyager-1 spacecraft has crossed the heliopause during summer 2012.**

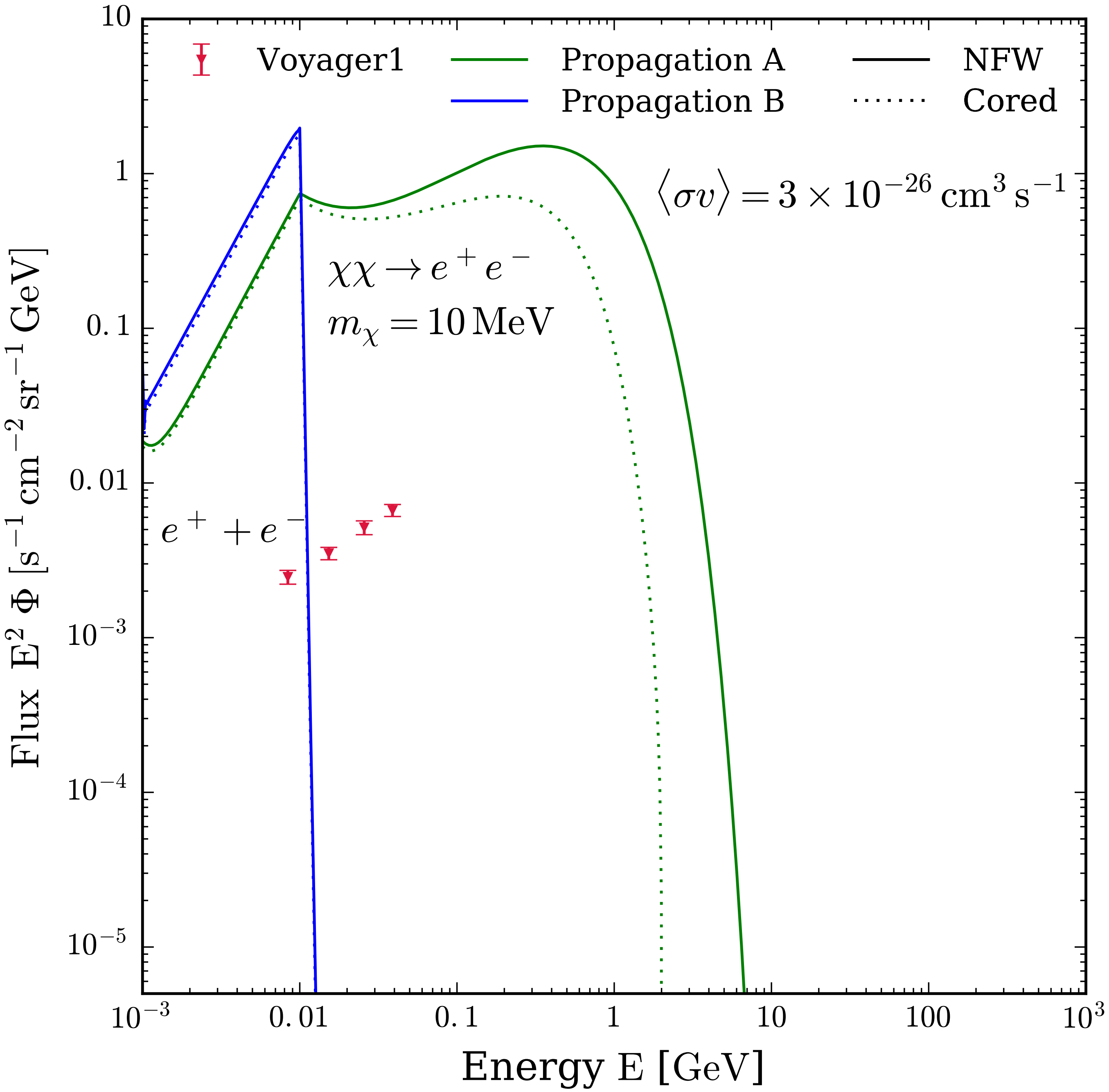




- Launched in 1977
- Measures the flux of **<u>electrons + positrons</u>**
  Stone et al. (2013)
- Outside the heliosphere since august 2012

→ independent of solar effects

Constraints on DM annihilating cross section



- **Model A**: $V_A = 117.6\,\mathrm{km/s}$
- **Model B**: $V_A = 31.9\,\mathrm{km/s}$

$$\chi\chi \longrightarrow e^+e^-$$

Conservative constraints (without background):

$$\Phi^{\mathrm{DM}}_{e^+ + e^-}(E_i) \leq \Phi^{\mathrm{exp}}_{e^+ + e^-}(E_i) + 2\sigma_i$$

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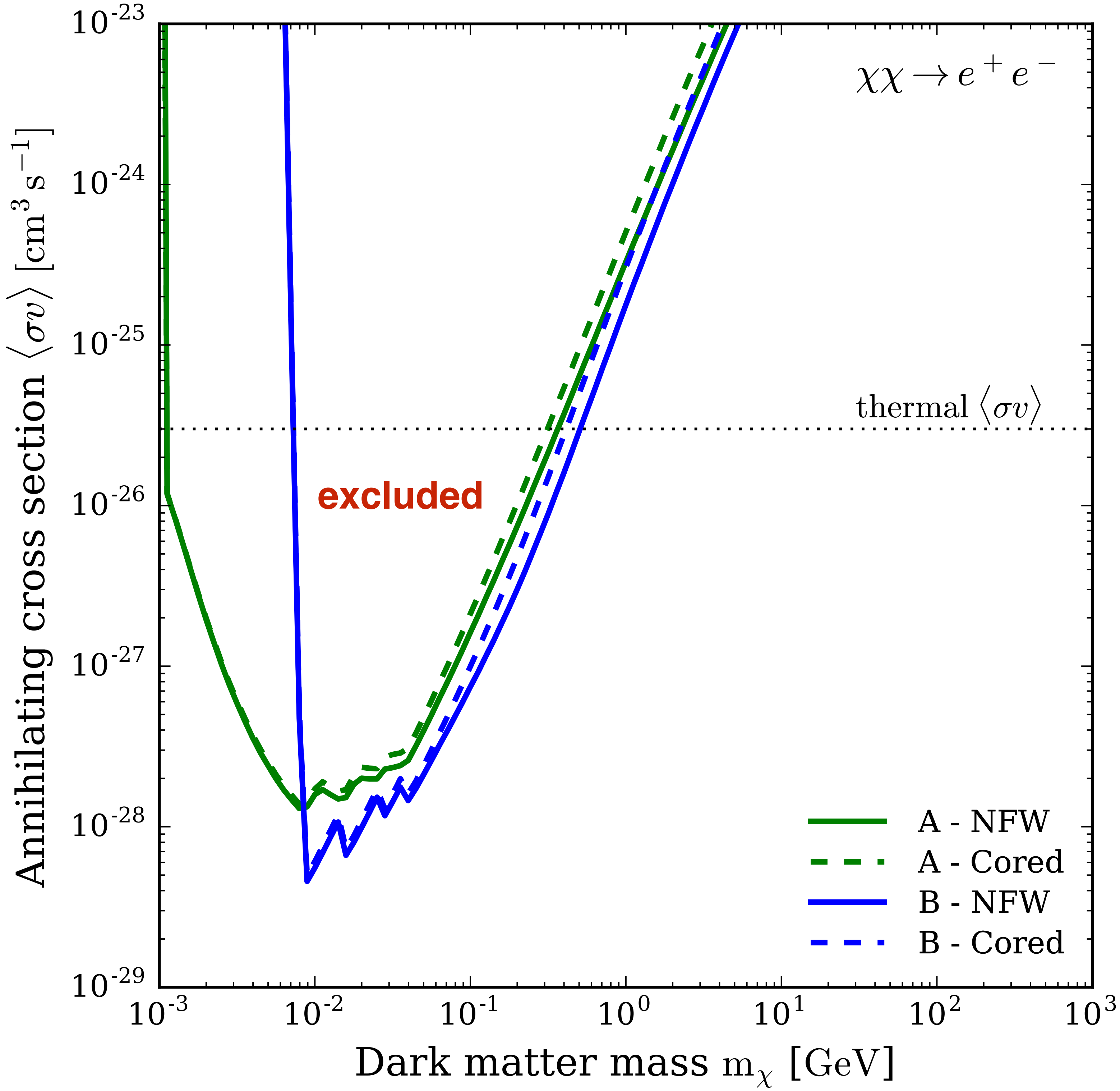

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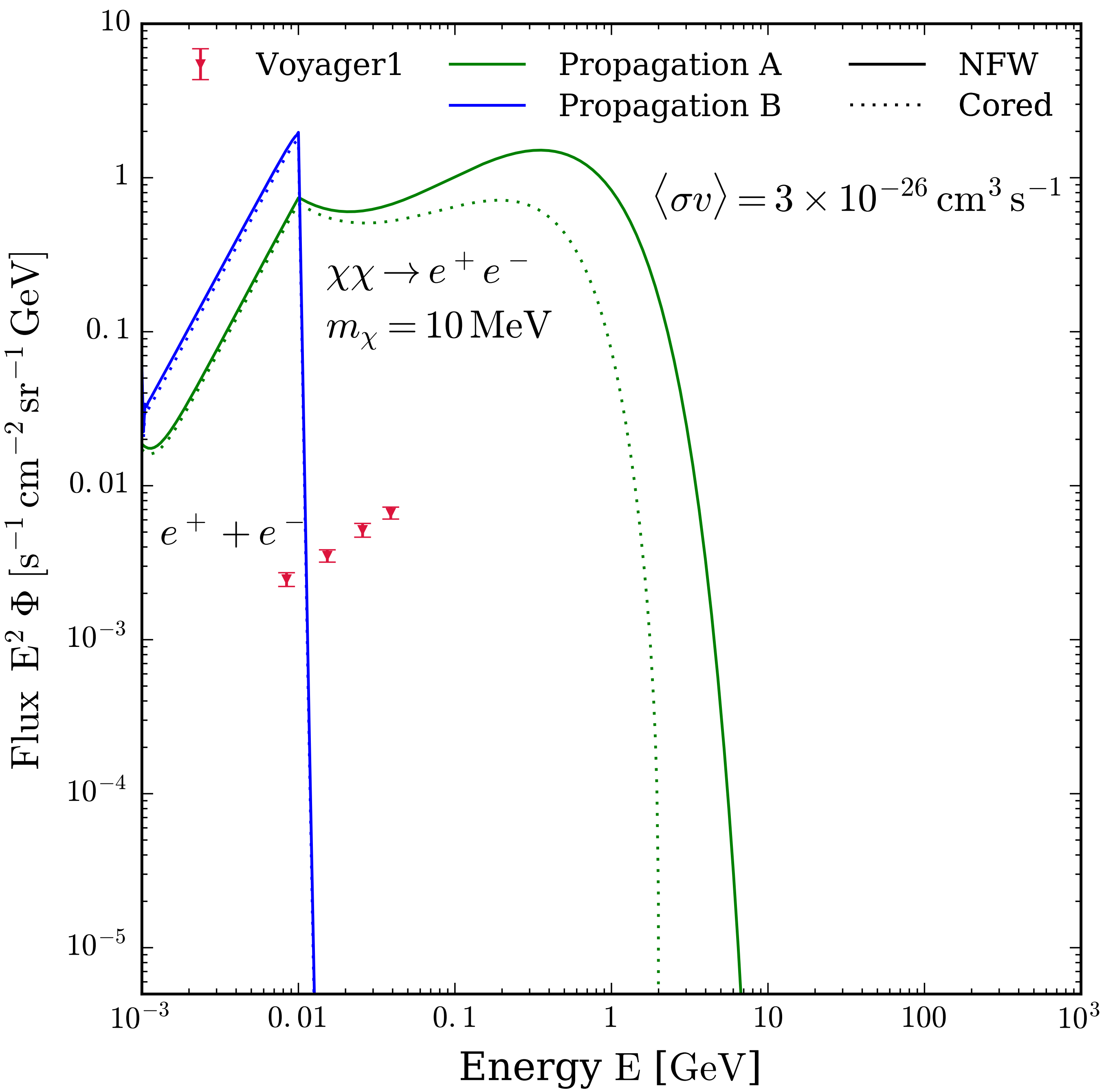

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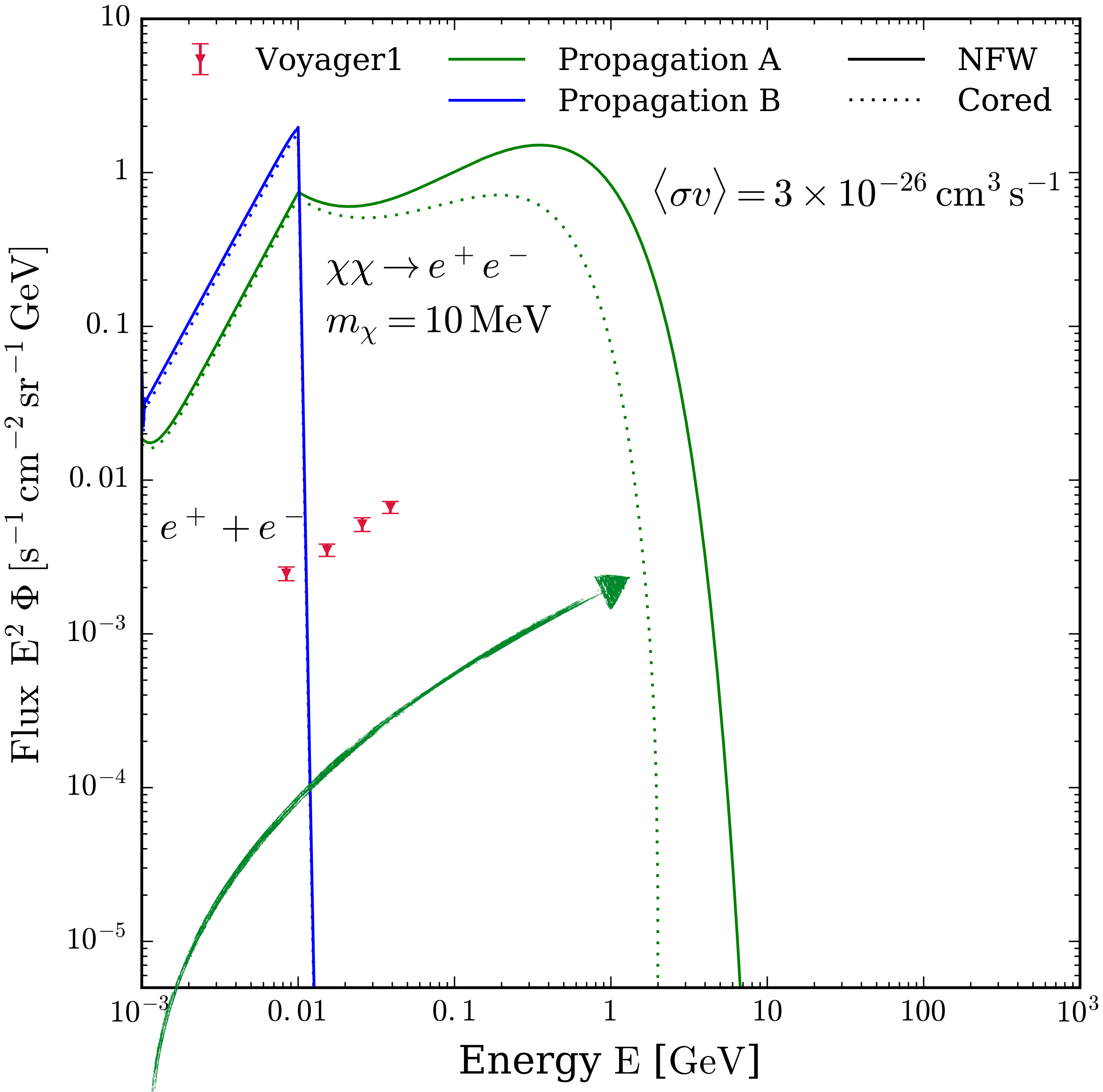

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Models with strong diffusive reacceleration enable to detect positrons **above** the DM mass!

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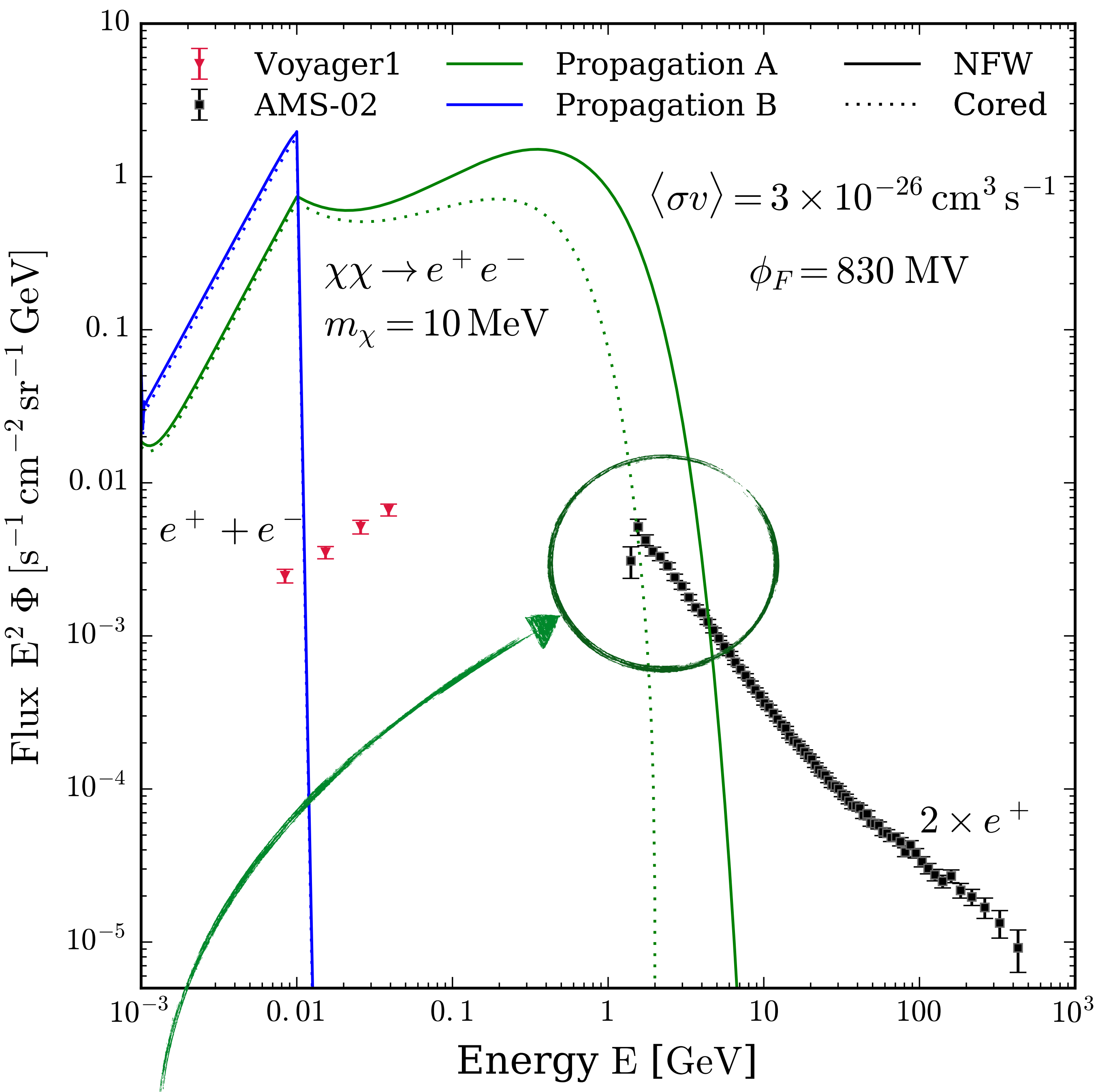

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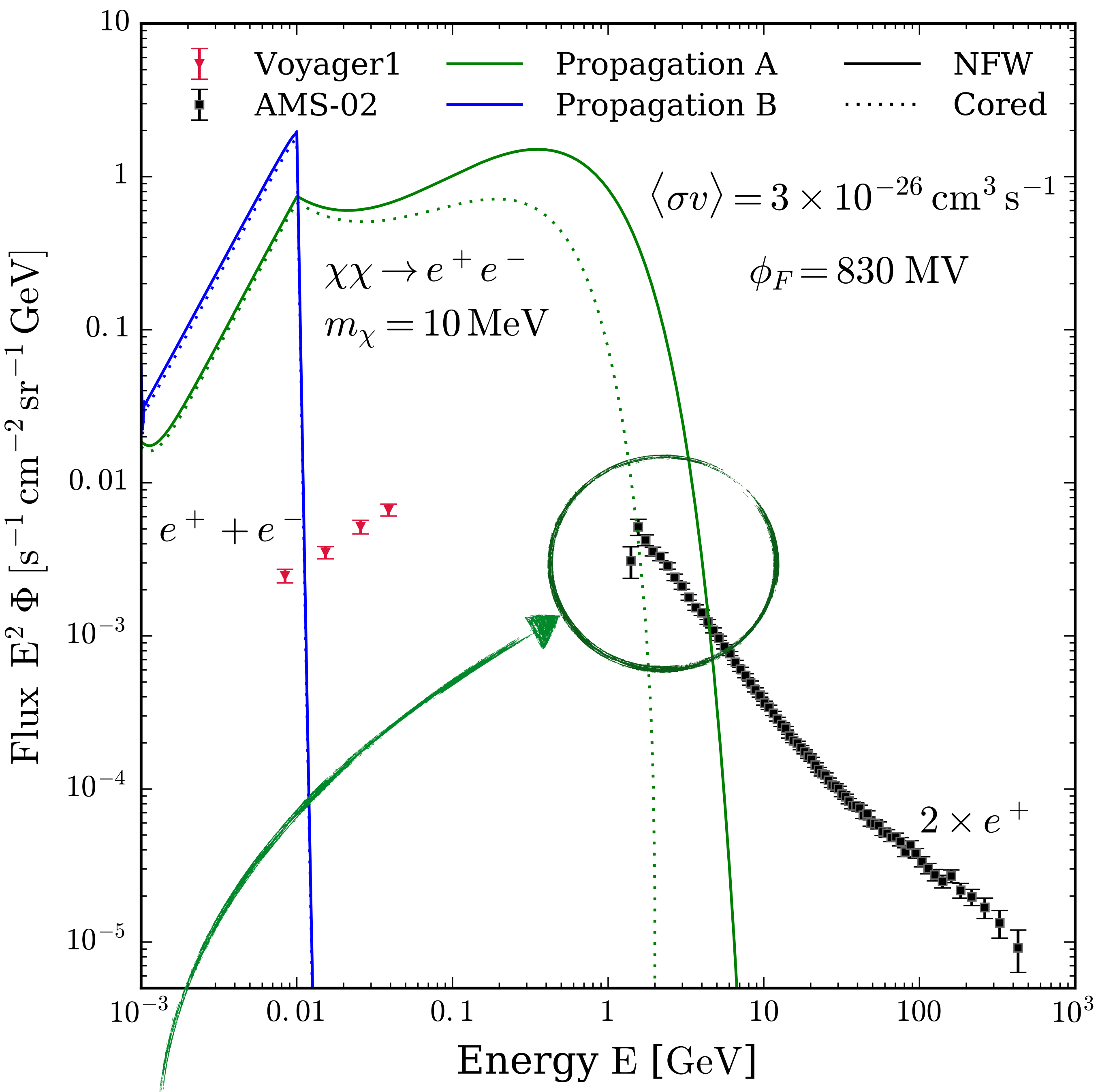

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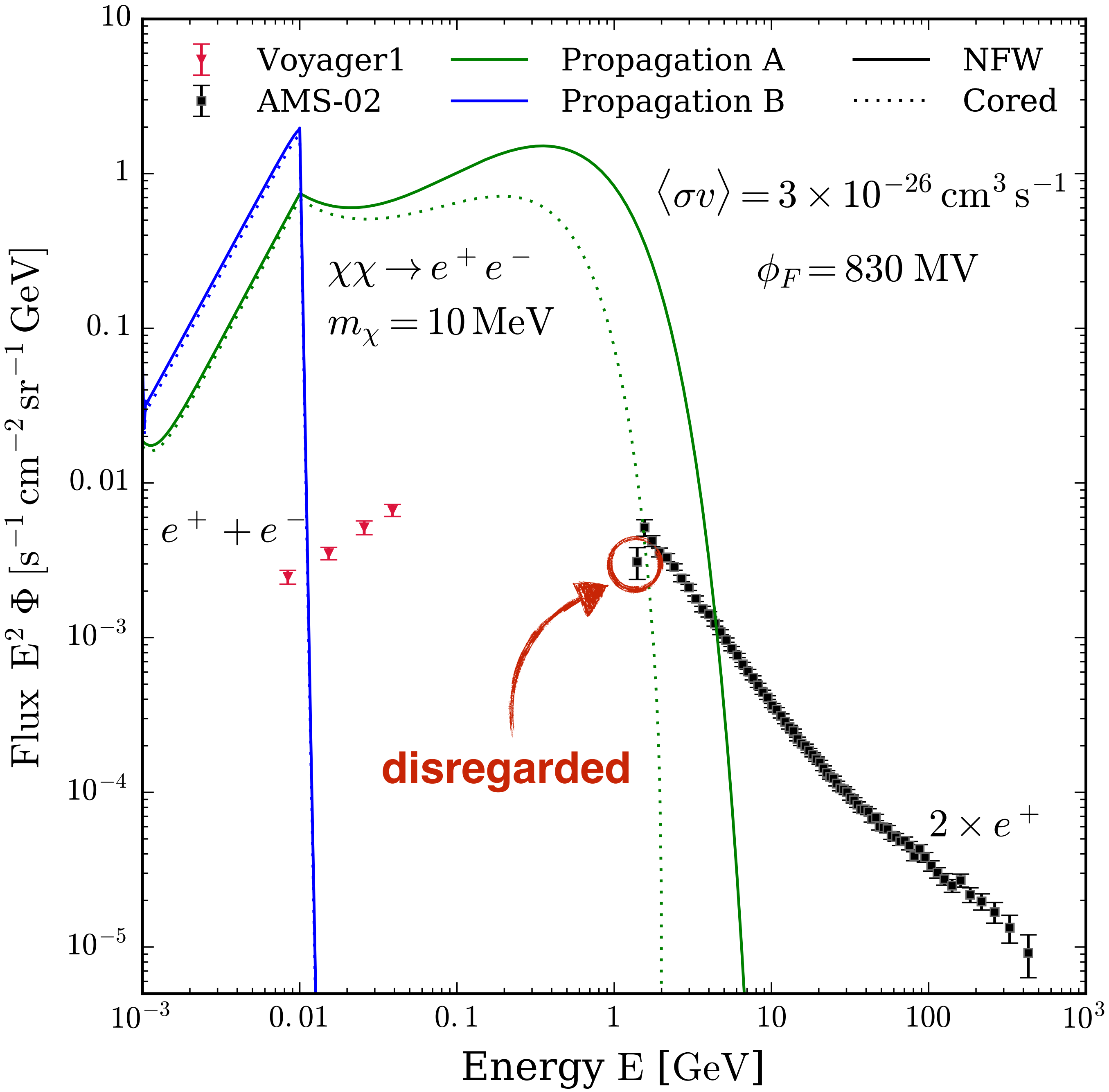

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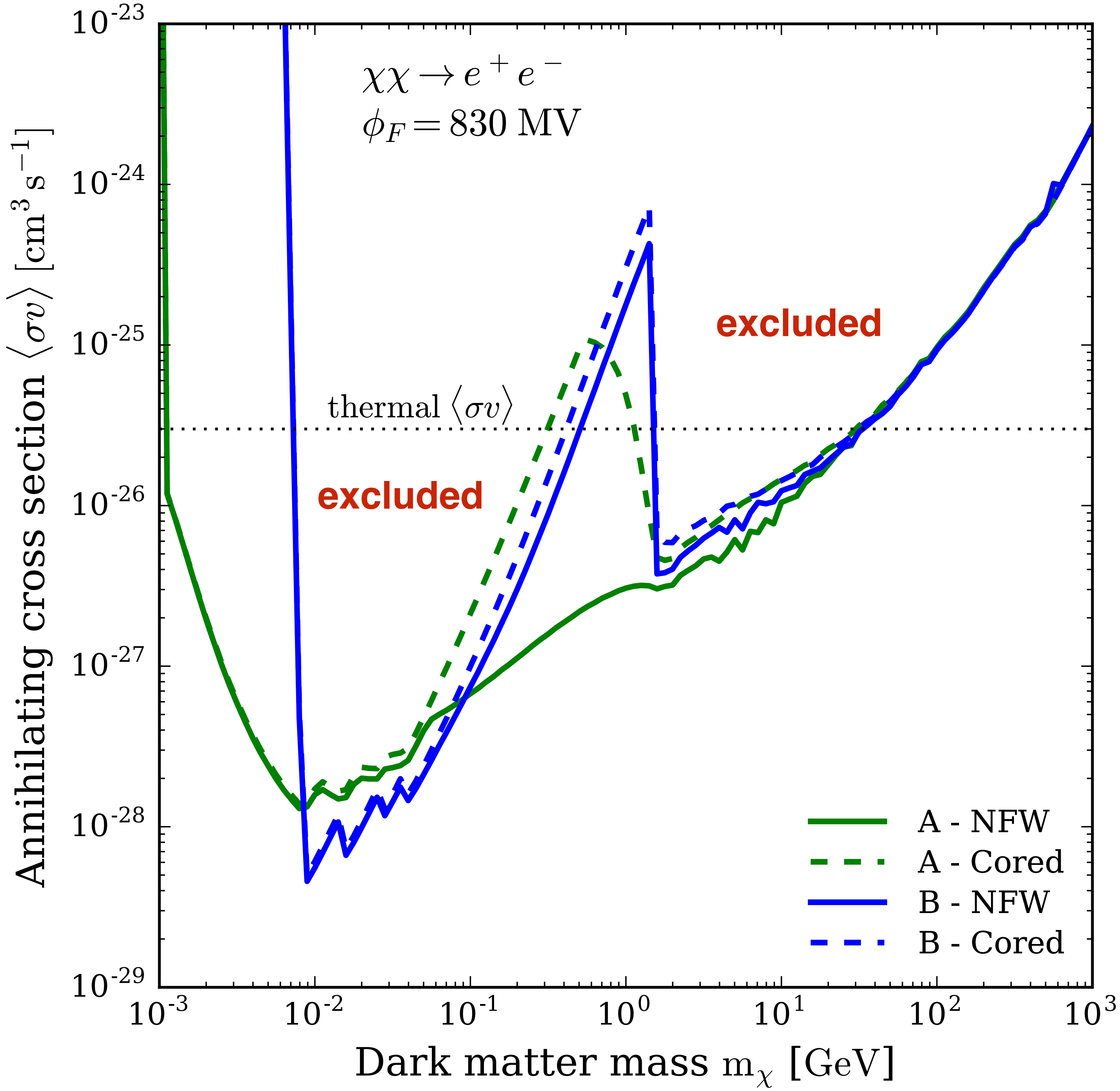

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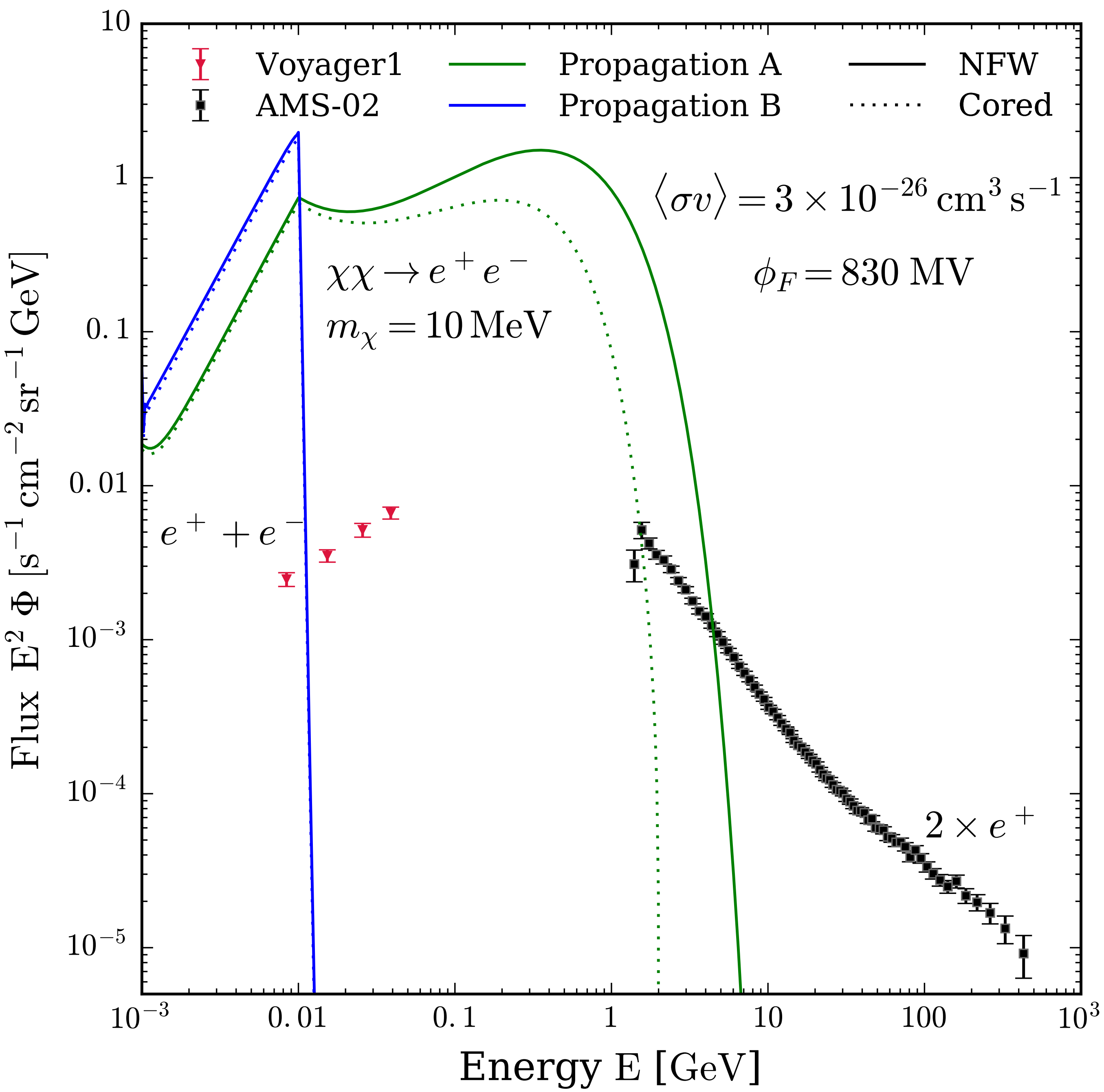

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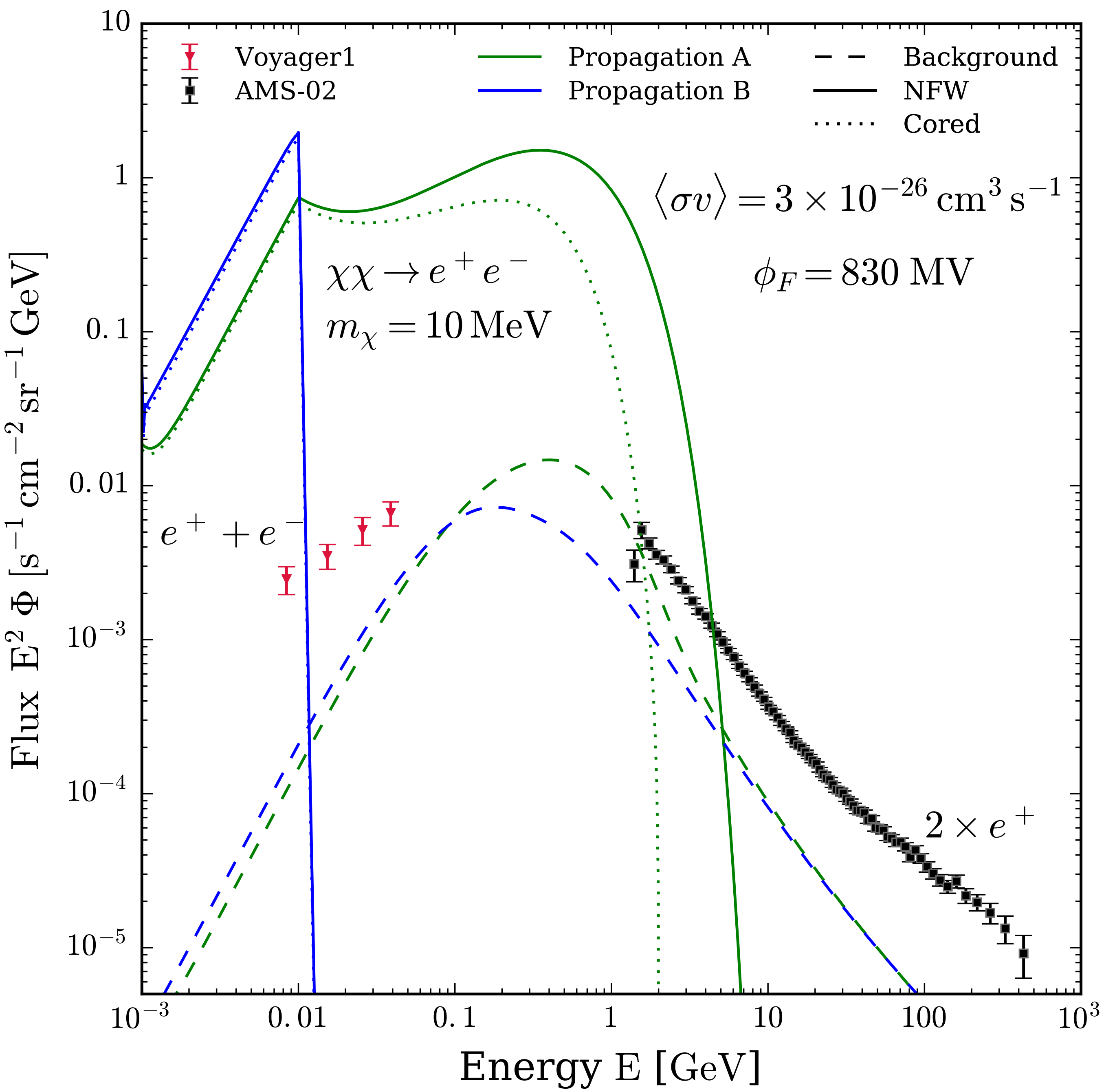

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With astrophysical background of secondary e+:

$$\Phi^{\mathrm{DM}}_{e^+ + e^-}(E_i) \leq \Phi^{\mathrm{exp}}_{e^+ + e^-}(E_i) + 2\sigma_i$$

and

$$\Phi^{\mathrm{DM}}_{e^+}(E_i) + \Phi^{\mathrm{II}}_{e^+}(E_i) \leq \Phi^{\mathrm{exp}}_{e^+}(E_i) + 2\sigma_i$$

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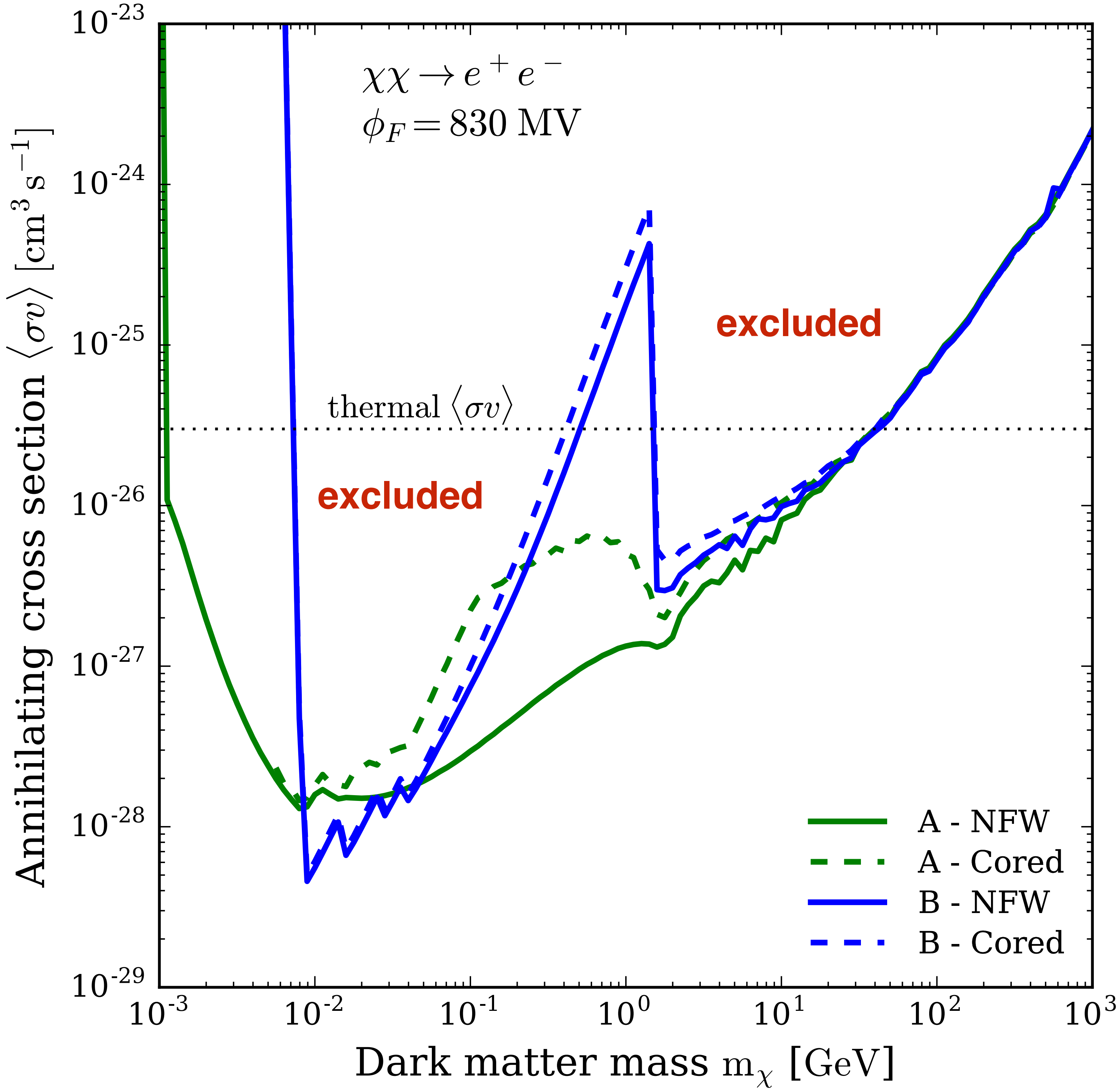
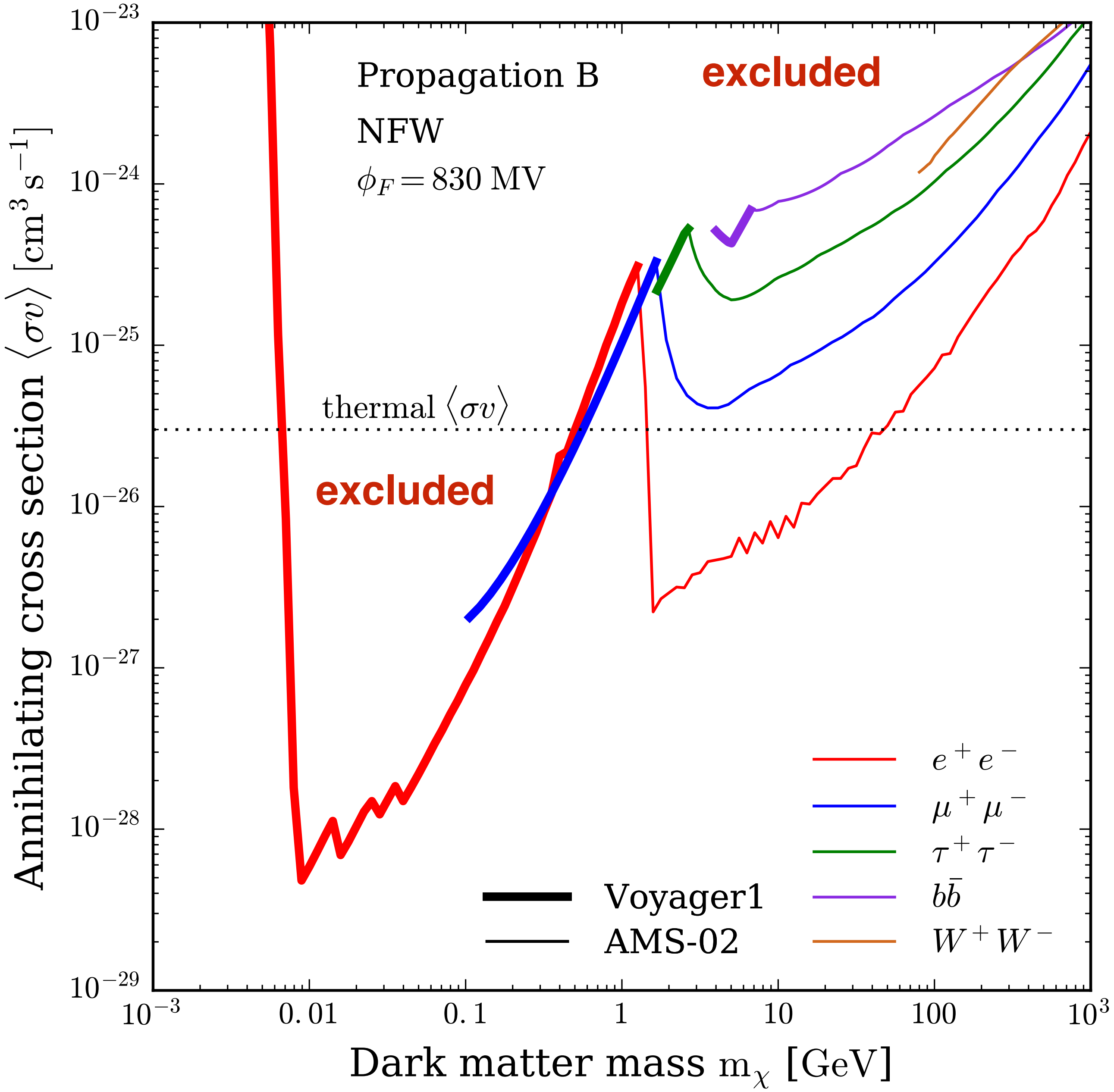
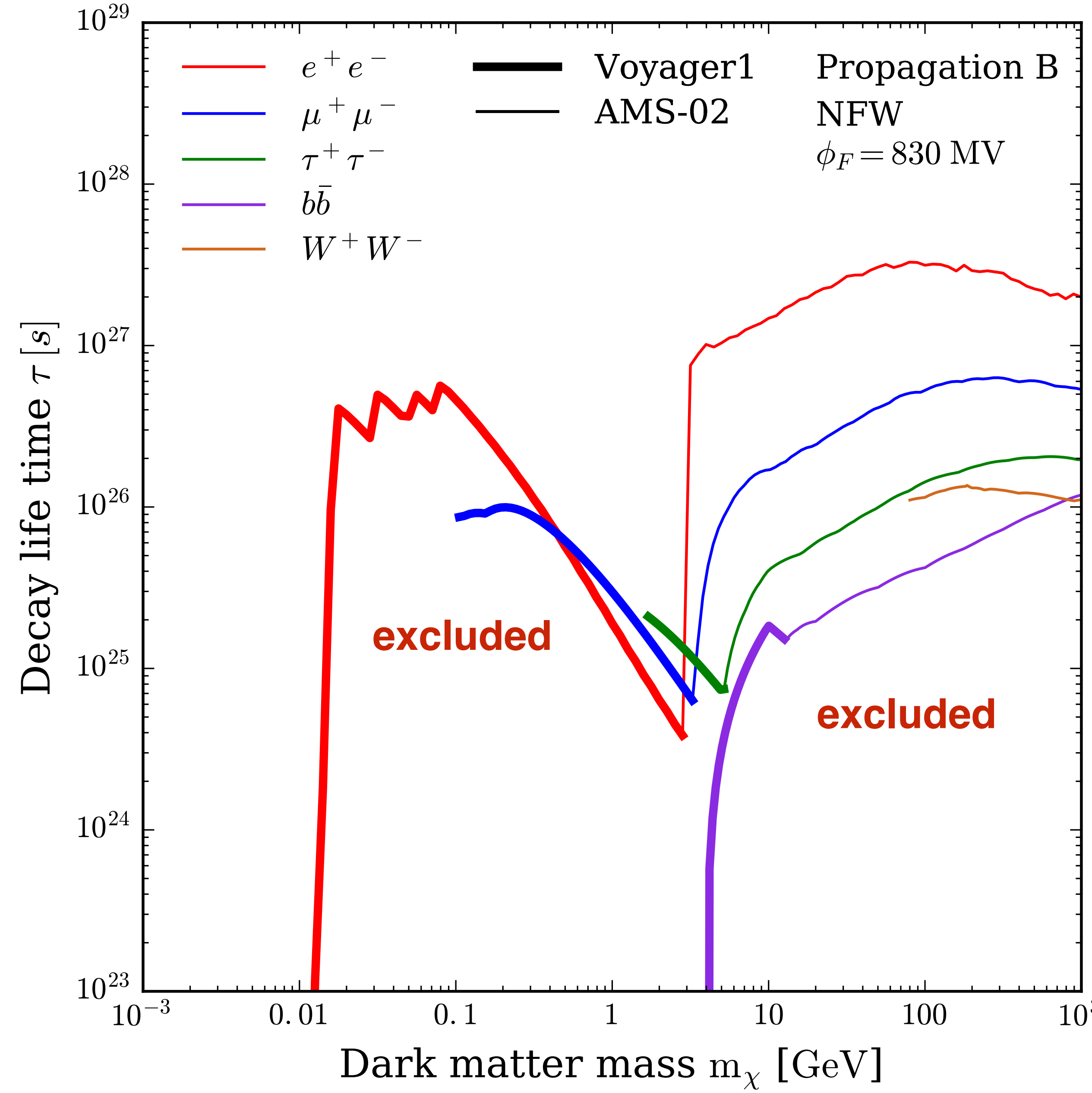
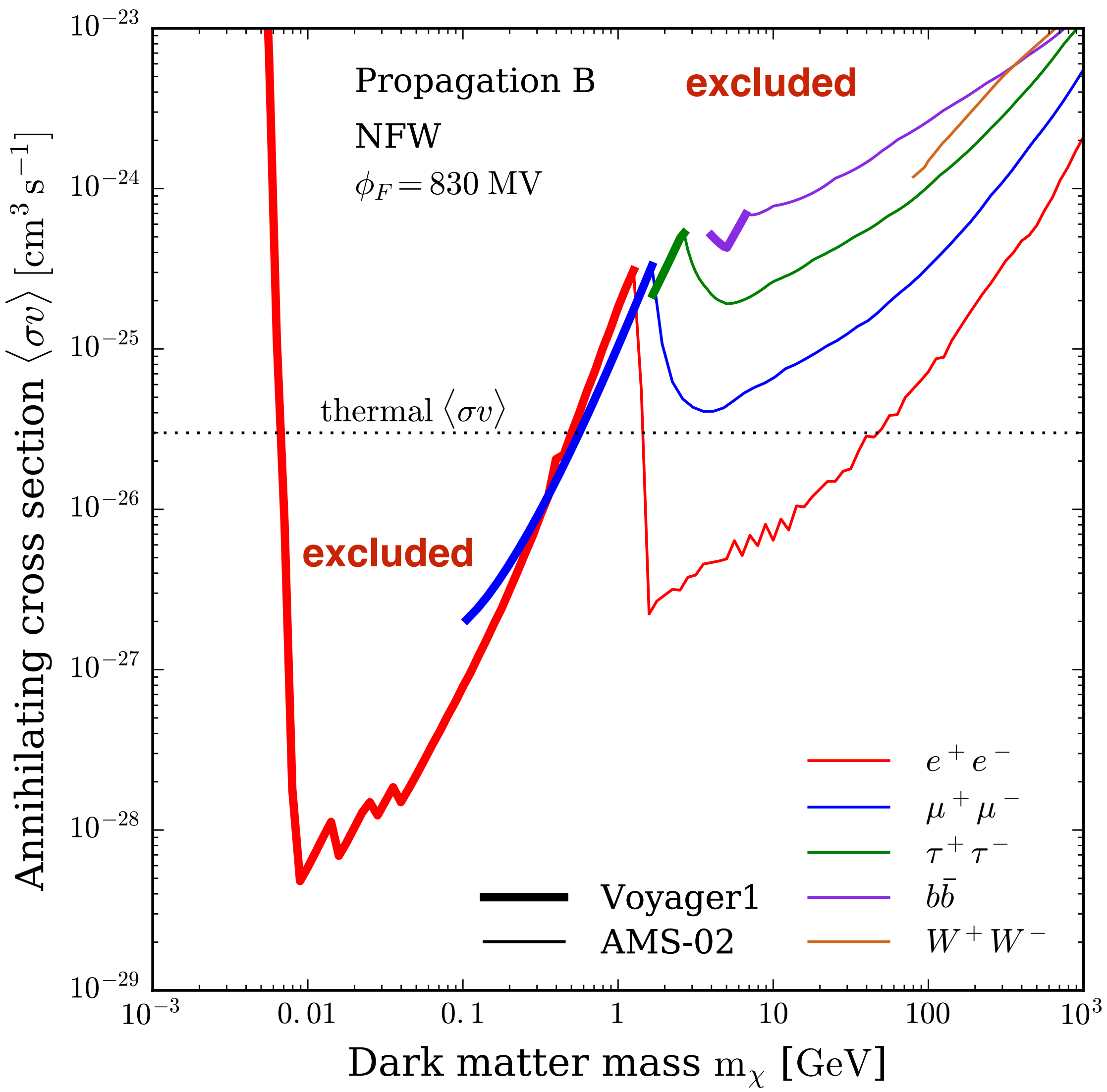


Annihilating Dark Matter *MB+(2016)* **Decaying Dark Matter**





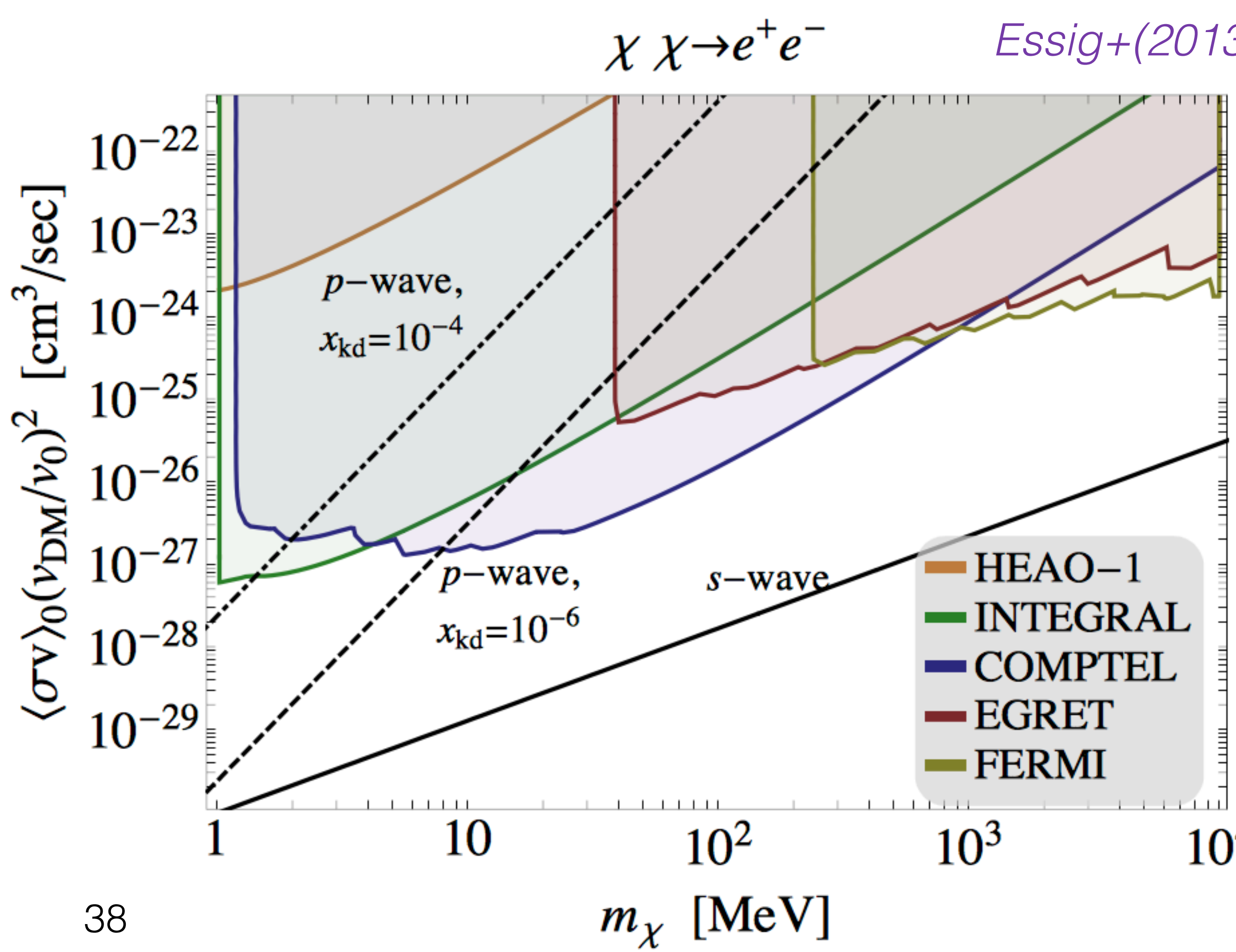
Comparison with other constraints



X-rays and ɣ-rays

- **More** stringent by more than 1 order of magnitude.
- **Less** sensitive to the DM halo shape.

Essig+(2013)



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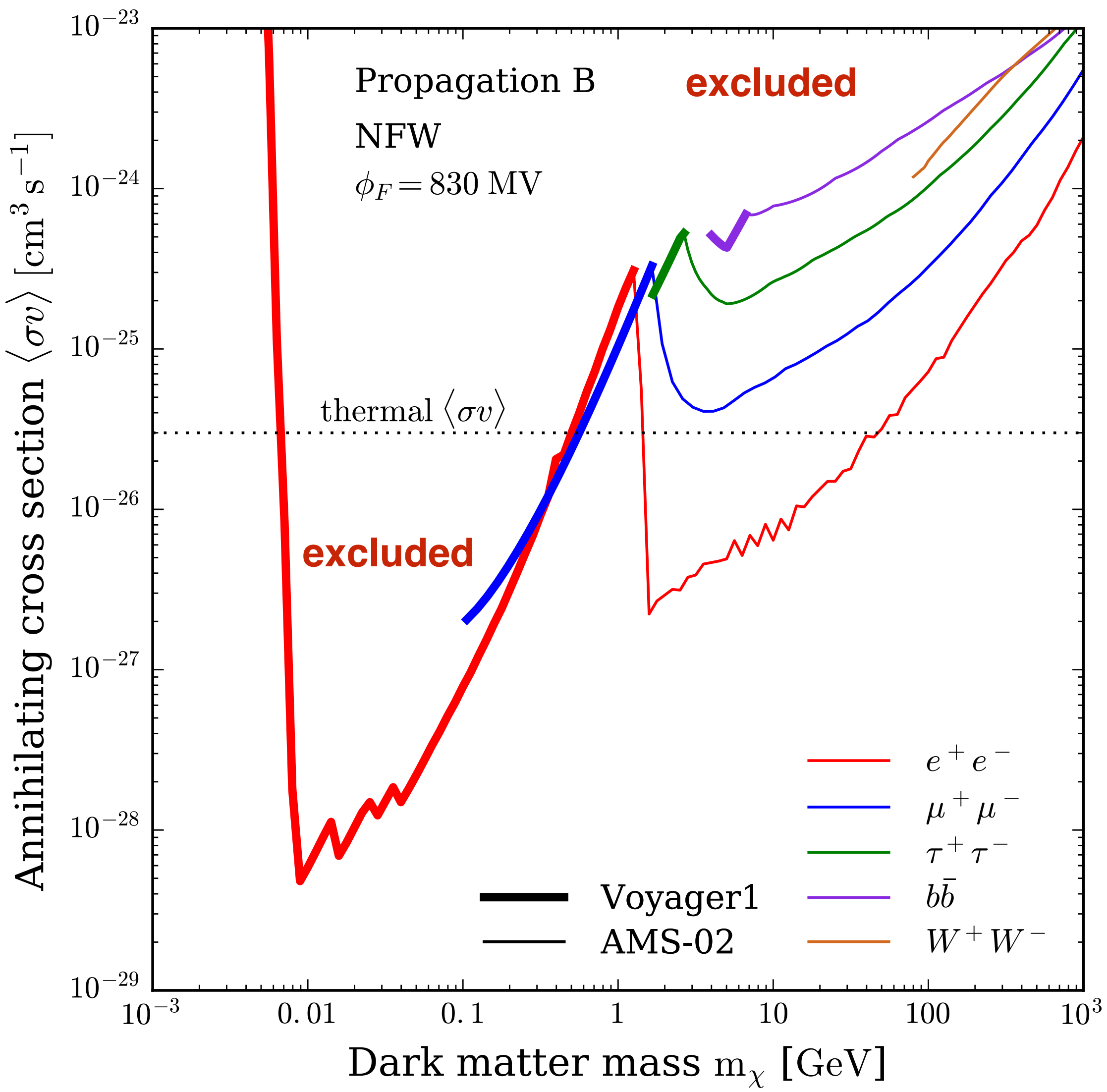
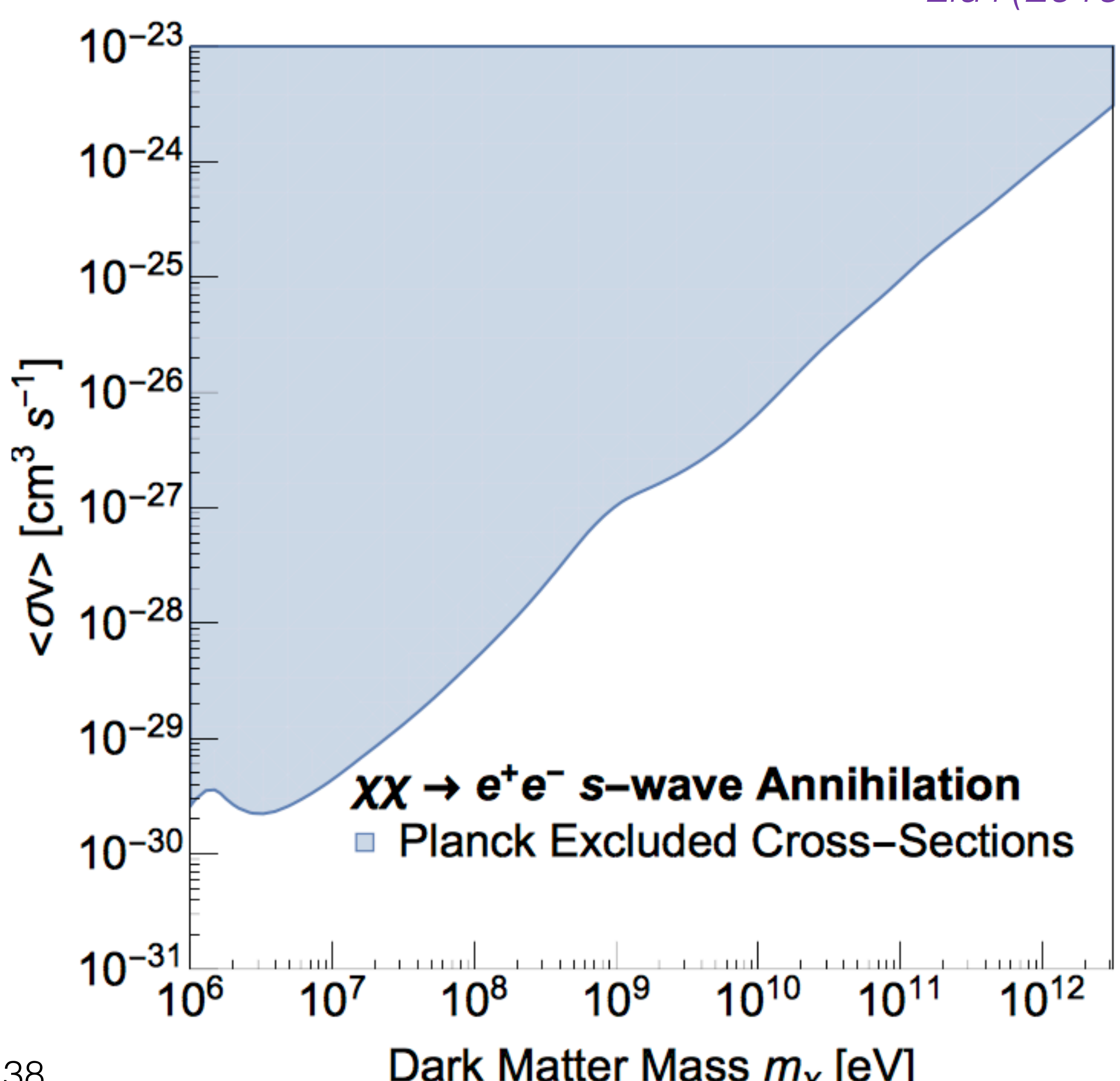


CMB

- **Less** stringent by 1 order of magnitude for s-wave <σv>.

Liu+(2016)



p-wave annihilation

MB, J. Lavalle, T. Lacroix, P. Salati and M. Stref (in process)

In the low velocity limit: $$\langle \sigma v \rangle = s_0 + s_1 \beta^2 + \mathcal{O}(\beta^4)$$

s-wave contribution (s_0) — p-wave contribution ($s_1\beta^2$)

CMB epoch

$$\beta(T_{\rm CMB}) = \beta(T_{\rm FO}) \times \frac{T_{\rm CMB}}{T_{\rm FO}}$$

$$T_{\rm CMB} \simeq 0.1 \text{ eV}$$

$$\beta(T_{\rm CMB}) \simeq 10^{-6} \left(\frac{1\text{GeV}}{m_{\rm DM}} \right)$$

Now in the Milky Way

Assuming a Maxwellian distribution with

$$\sigma^2 \equiv \langle v^2 \rangle$$

$$v_c = \sqrt{2}\, \sigma \qquad v_c \simeq 240 \text{ km}\,\text{s}^{-1}$$

$$\beta_{\rm MW} \simeq 10^{-3}$$

Contraints on p-wave annihilations could be more stringent for local observations than CMB.

p-wave annihilation *MB, J. Lavalle, T. Lacroix, P. Salati and M. Stref (in process)*

In the low velocity limit: $$\langle \sigma v \rangle = s_0 + s_1 \beta^2 + \mathcal{O}(\beta^4)$$

s-wave contribution (s_0) p-wave contribution ($s_1 \beta^2$)

Spherical symmetric distribution of DM particles in the Galaxy:

$$f(\vec{v}, \vec{x}) \equiv \frac{d^6 N}{d^3x \; d^3v} = f(|\vec{v}|, r)$$

$$\langle \sigma v \rangle (r) = K_0(r) \int d^3\vec{v}_1 \int d^3\vec{v}_2 \; f(|\vec{v}_1|, r) f(|\vec{v}_2|, r) \, \sigma \, v_{12}$$

$K_0(r) = \int d^3\vec{v}_1 \int d^3\vec{v}_2 \; f(|\vec{v}_1|, r) f(|\vec{v}_2|, r)$: normalization factor

$v_{12} = |\vec{v}_2 - \vec{v}_2|$: relative velocity

The Eddington formalism:

A method to derive the DM phase space distribution density starting from a Galactic mass model.

Eddington (1916), Binney and Tremaine (1987)

Constraints DM mass models $\rho_{DM}(r)$ $\Longrightarrow$ $f(|\vec{v}|, r)$ $\Longrightarrow$ $\langle \sigma v \rangle (r)$

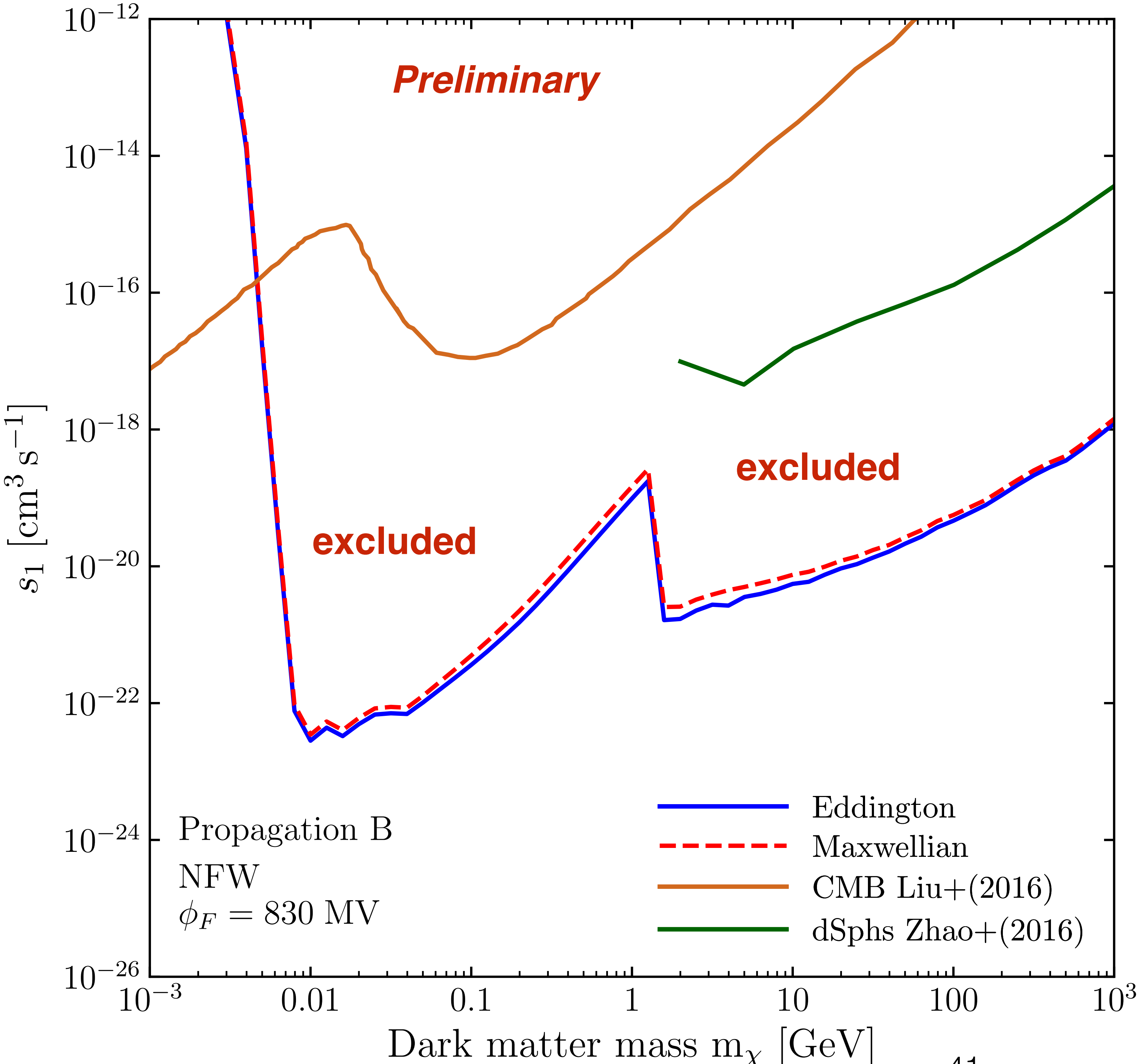
e.g: McMillan (2016), Catena & Ullio (2010)

p-wave annihilation

MB, J. Lavalle, T. Lacroix, P. Salati and M. Stref (in process)

$$Q^{\rm DM}(E,r) = \frac{1}{2} m_\chi^2 \rho^2(r)\langle\sigma v\rangle(r) \frac{dN}{dE}$$

$$\rho^2_{\rm eff}(r) = \rho^2(r)\langle\sigma v\rangle(r)$$



- More stringent by 3 to 8 orders of magnitude than CMB constraints.
- More stringent by 4 orders of magnitude than dSph constraints.

The antiprotons story

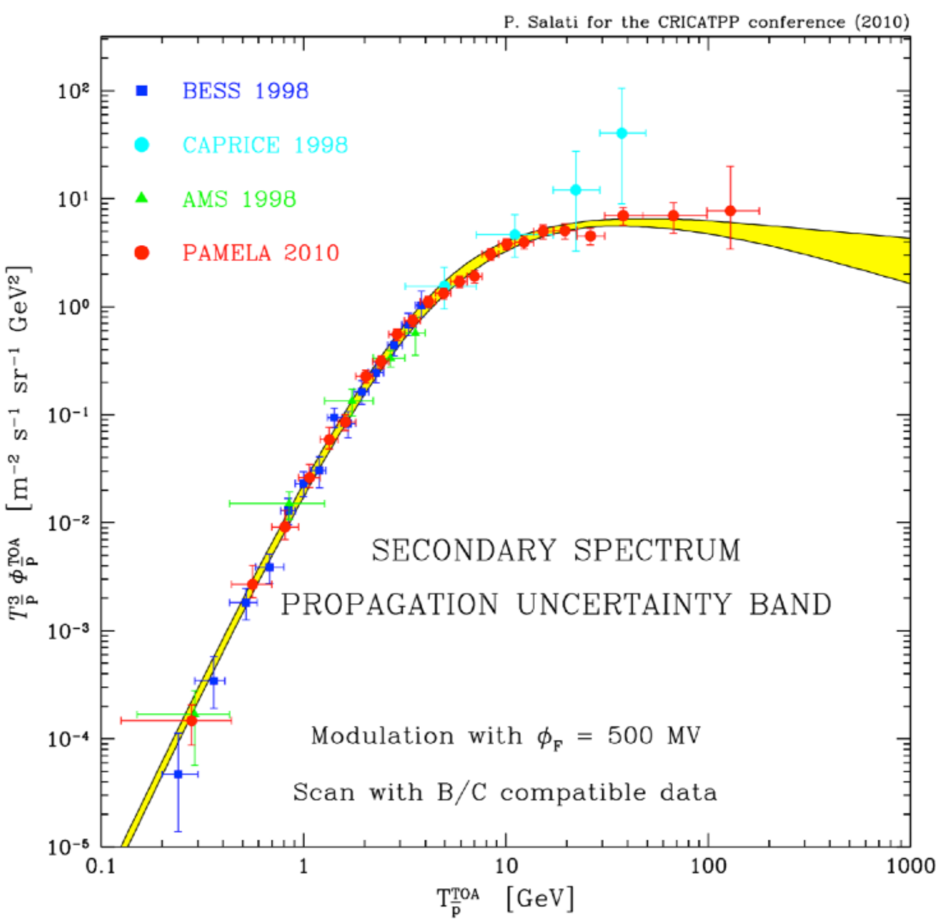
Dark matter searches with PAMELA antiprotons

Launched in 2006

Adriani et al., PRL 105, 121101 (2010)

Adriani et al., JETPL 96, 621 (2013)

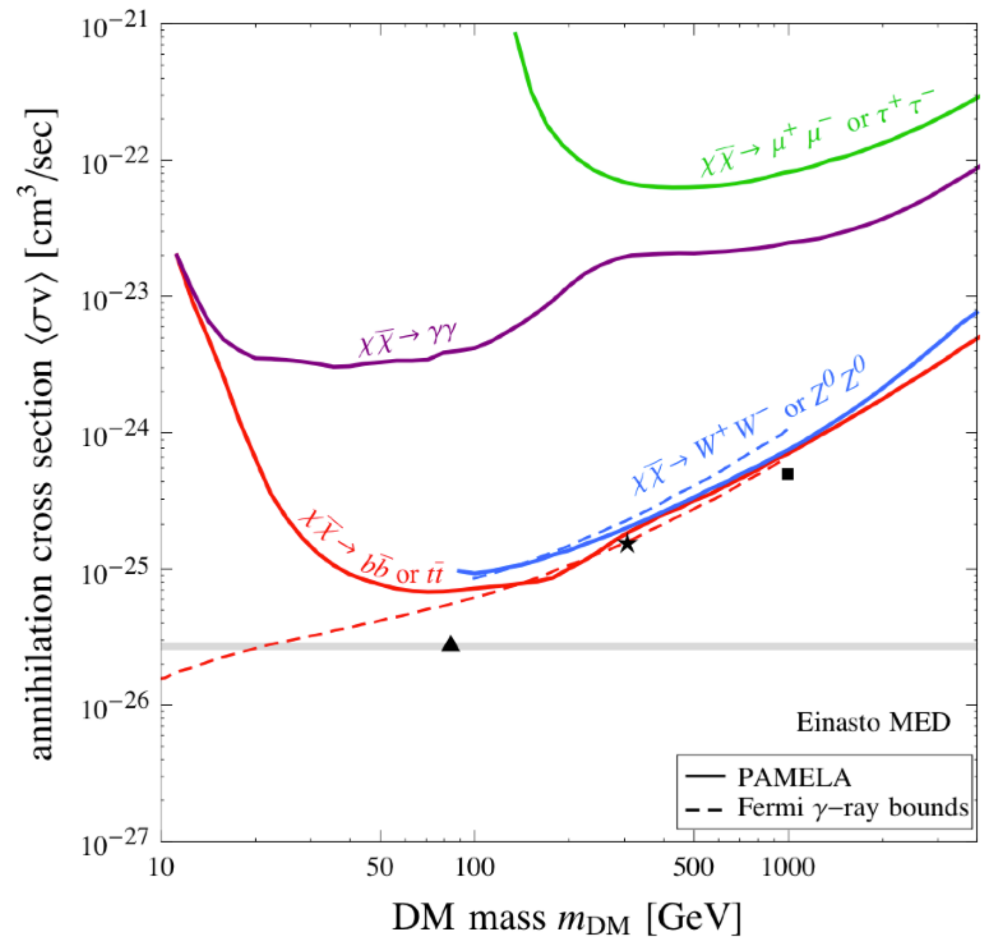
The antiprotons background (secondary component) is consistent with PAMELA data (no excess).



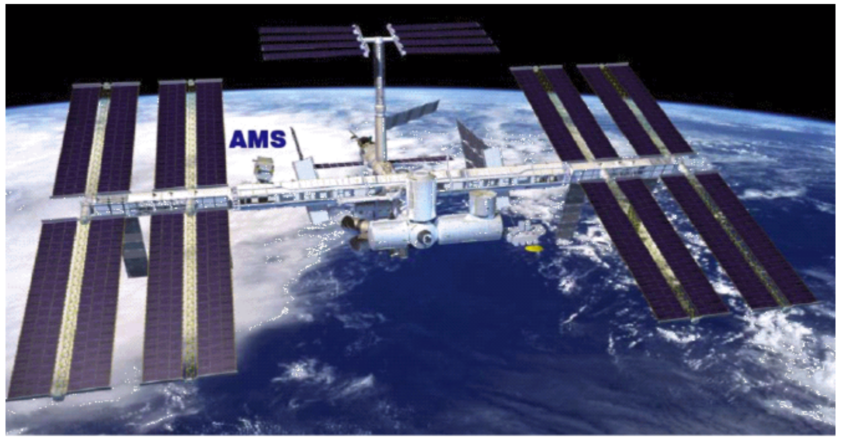
No DM signal

Constraints on the DM annihilation cross section

e.g: G. Giesen & M. Cirelli (2013)

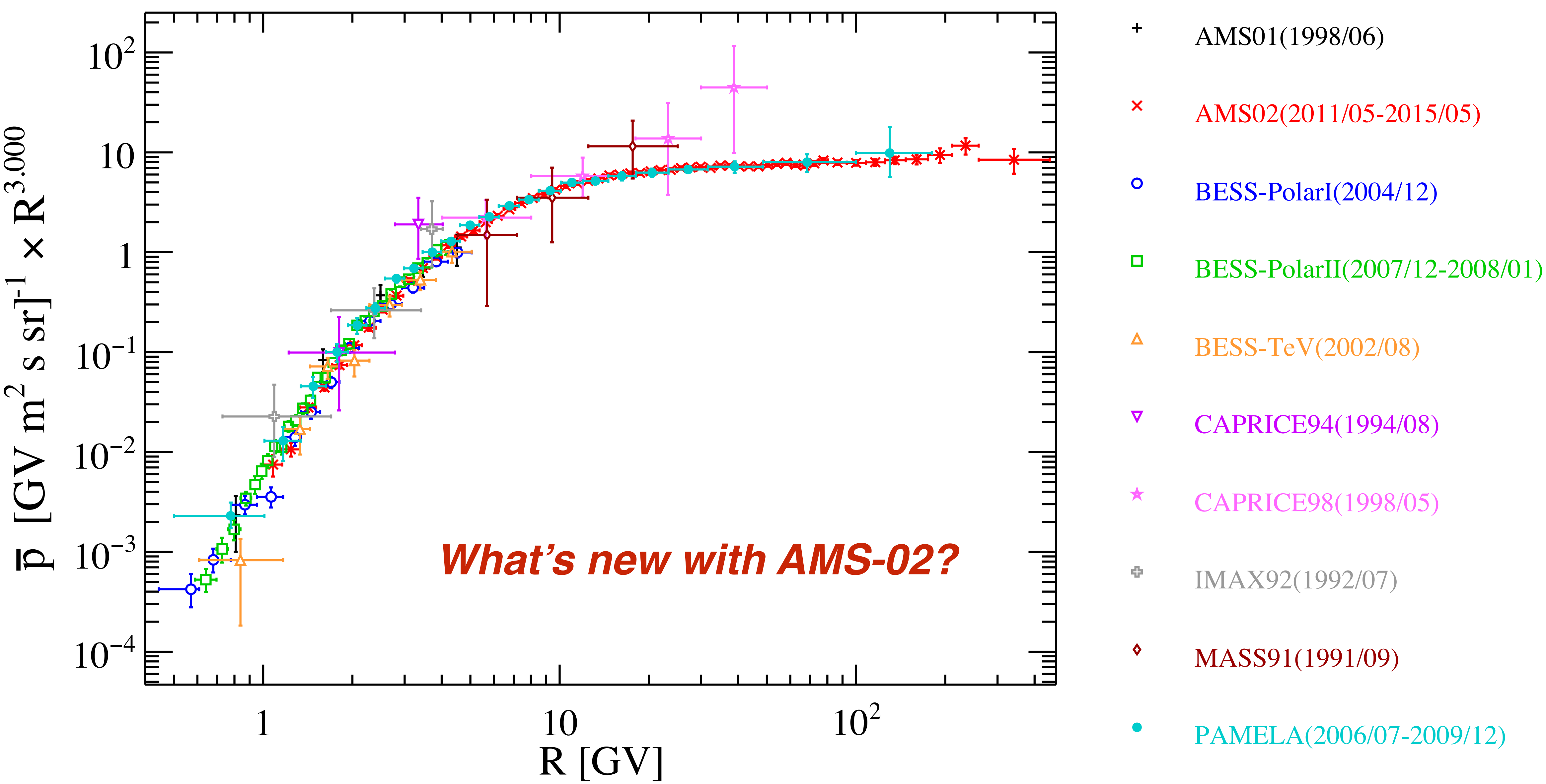


Dark matter searches with AMS-02 antiprotons



Launched in 2011

Aguilar et al., PRL 117, 091103 (2016)

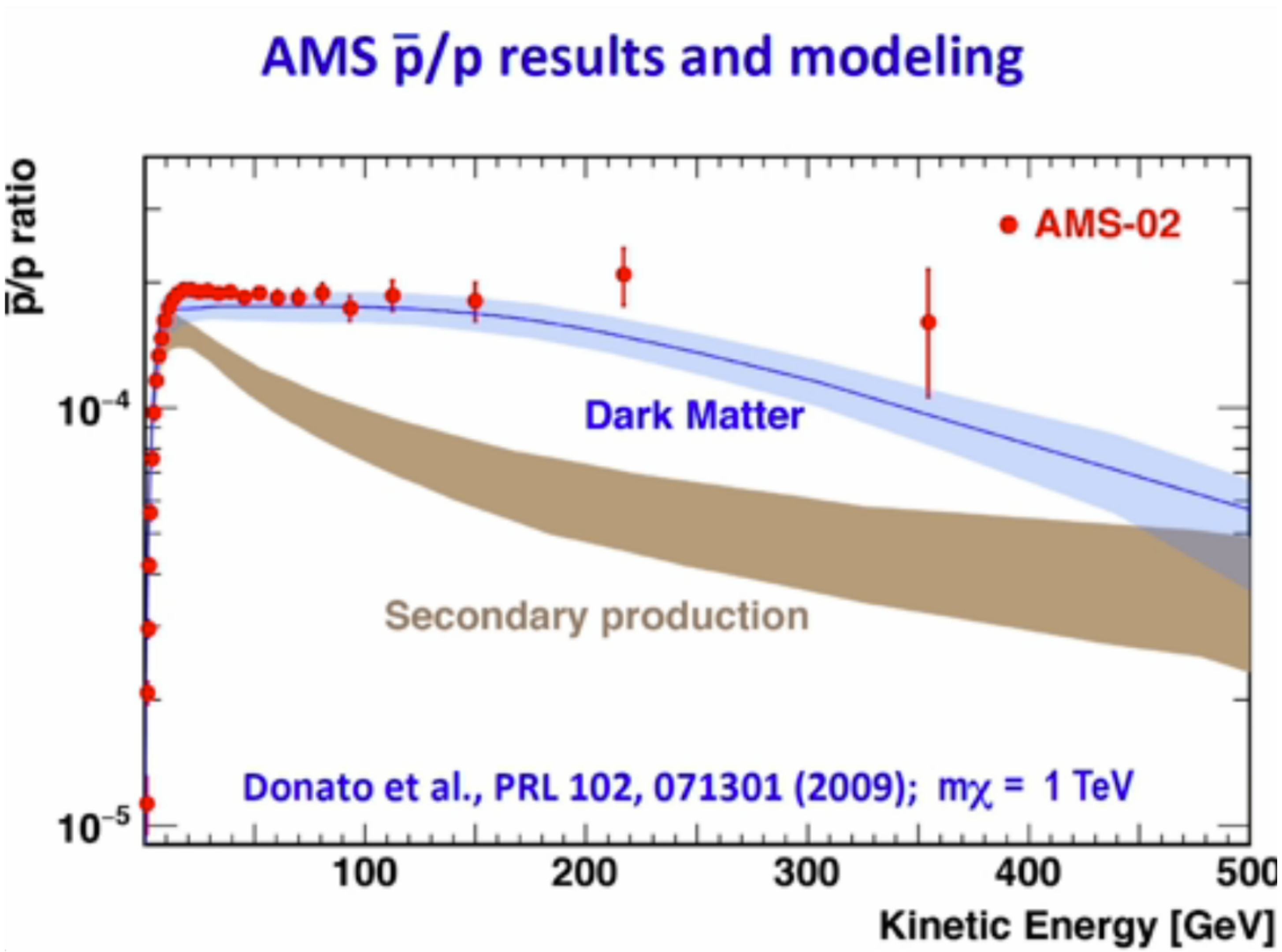


AMS-02 antiproton to proton ratio

$$\bar{p}/p \equiv \frac{\Phi_{\bar{p}}}{\Phi_p}$$

15-04-2015 AMS days at CERN

AMS-02 collaboration presented preliminary results of the $\bar{p}/p$ ratio from ~ 1 GeV up to ~ 500 GeV with an unprecedented high accuracy.



AMS-02 suggested an antiprotons **excess** with respect to the astrophysical background.

Is it the discovery of a dark matter signal?

Let's compute the astrophysical background and its theoretical uncertainties with

- new data for the primary CRs fluxes
- new data for the production X-sections

Secondary antiprotons

$$p\,(\mathrm{CR}) \;+\mathrm{H}\,(\mathrm{ISM}) \;\longrightarrow\; \bar{p} \;+\; X \;\;(\simeq 70\%)$$
$$\alpha\,(\mathrm{CR}) \;+\mathrm{H}\,(\mathrm{ISM}) \;\longrightarrow\; \bar{p} \;+\; X \;\;(\simeq 25\%)$$
$$p\,(\mathrm{CR}) \;+\mathrm{He}\,(\mathrm{ISM}) \;\longrightarrow\; \bar{p} \;+\; X \;\;(\simeq 4\%)$$
$$\alpha\,(\mathrm{CR}) \;+\mathrm{He}\,(\mathrm{ISM}) \;\longrightarrow\; \bar{p} \;+\; X \;\;(\simeq 1\%)$$

Secondary antiprotons

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$$\alpha\,(\mathrm{CR}) \ + \mathrm{H}\,(\mathrm{ISM}) \ \longrightarrow \ \bar{p} \ + \ X \ \ (\simeq 25\%)$$

$$p\,(\mathrm{CR}) \ + \mathrm{He}\,(\mathrm{ISM}) \ \longrightarrow \ \bar{p} \ + \ X \ \ (\simeq 4\%)$$

$$\alpha\,(\mathrm{CR}) \ + \mathrm{He}\,(\mathrm{ISM}) \ \longrightarrow \ \bar{p} \ + \ X \ \ (\simeq 1\%)$$

$$q^{\mathrm{II}}(E,r) = 4\pi \sum_{i=p,\alpha} \ \sum_{j=\mathrm{H,He}} \ \int_{E^0}^{+\infty} dE_i \ \frac{d\sigma_{ij\to\bar{p}X}}{dE}(E_i \to E)\ \phi_i(E_i,r)\ n_j$$

Secondary antiprotons

$$p\,(\mathrm{CR}) \;+\mathrm{H}\,(\mathrm{ISM}) \;\longrightarrow\; \bar{p} \;+\; X \;\;(\simeq 70\%)$$

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- Cross sections for the production of antiprotons.

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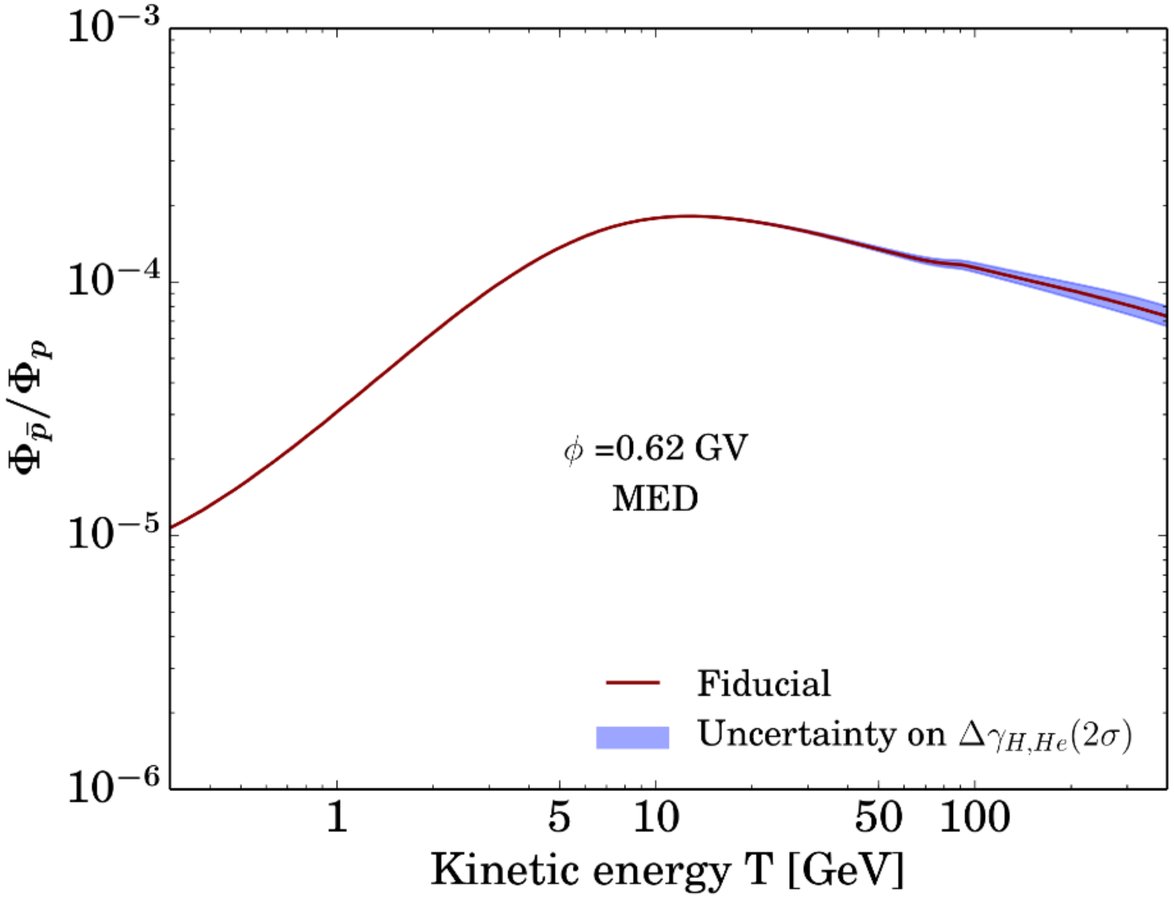
- Cross sections for the production of antiprotons.
- Energy and space distribution of primary CRs everywhere in the Galaxy.

Theoretical uncertainties on the astrophysical antiprotons background



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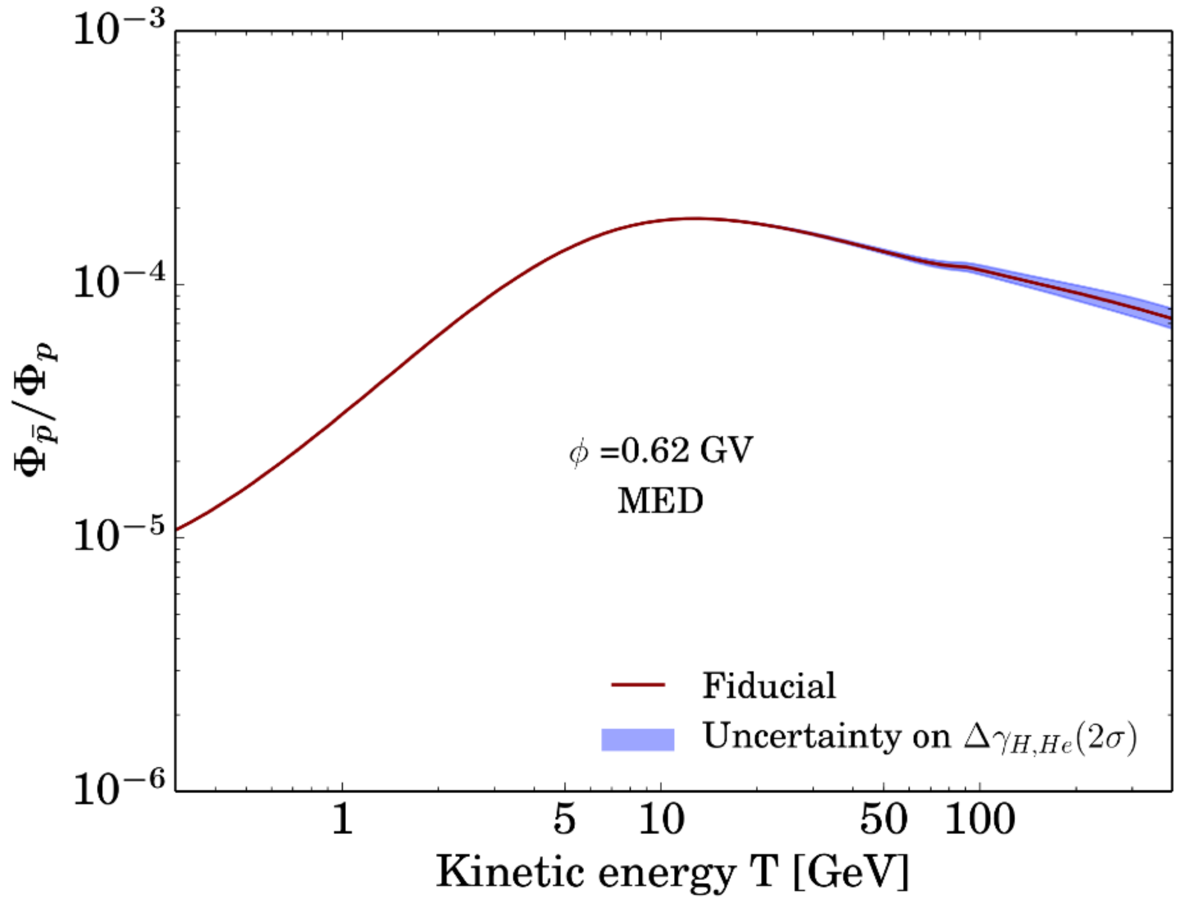

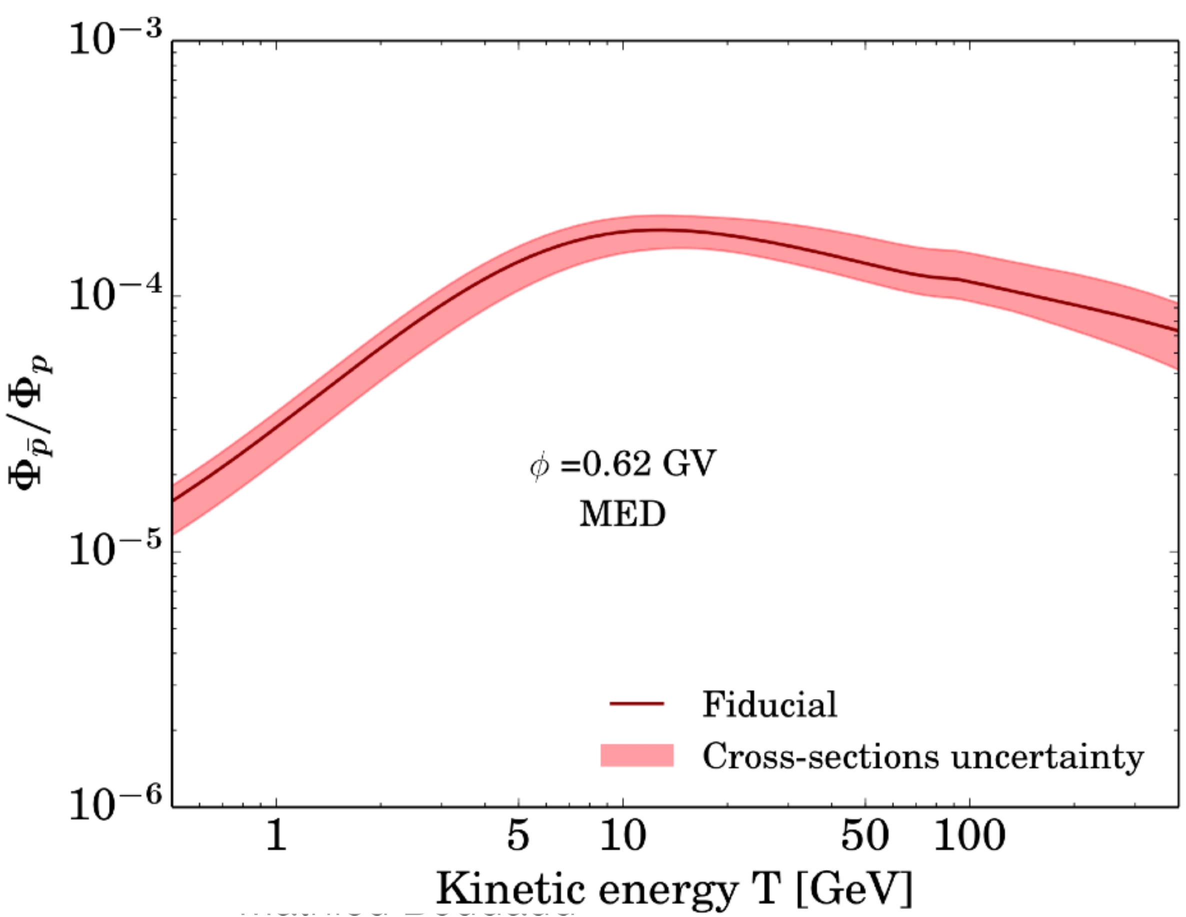

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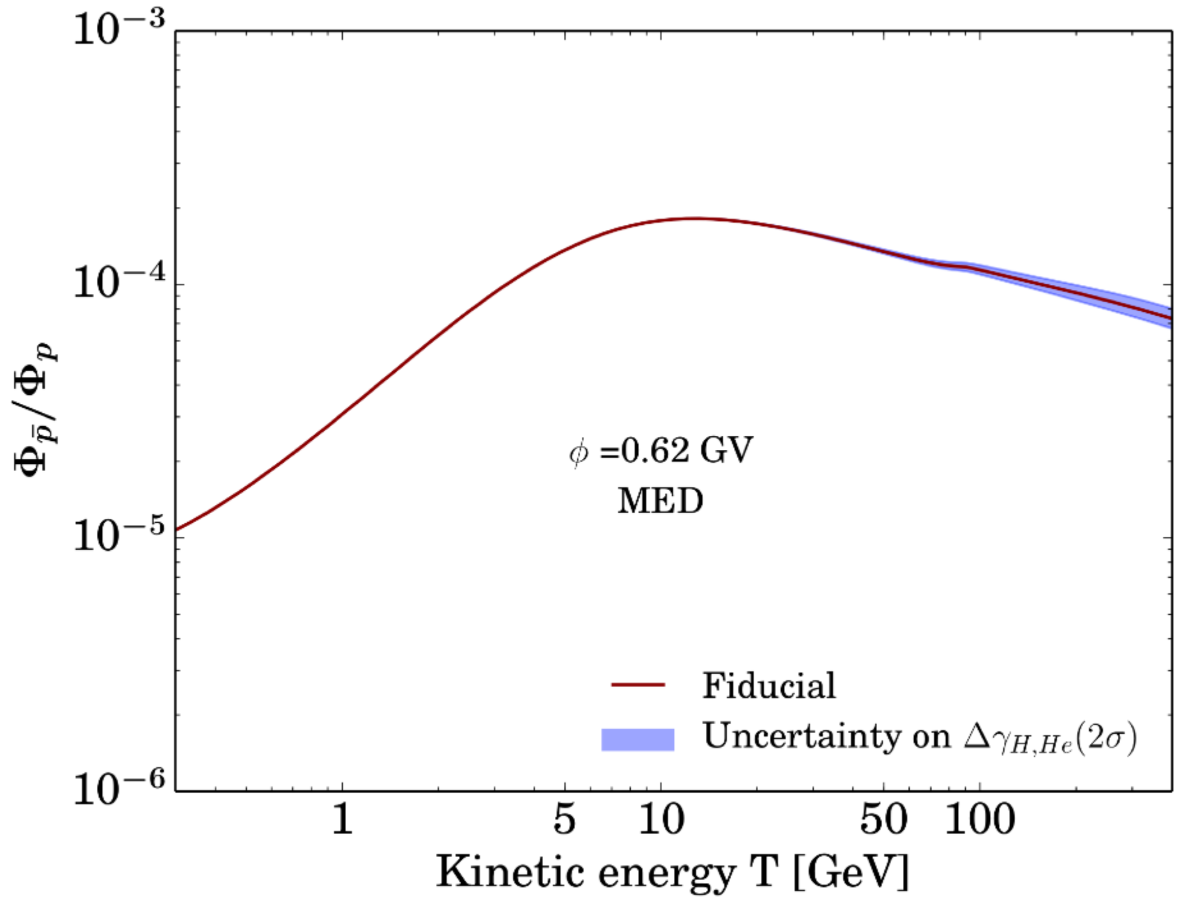

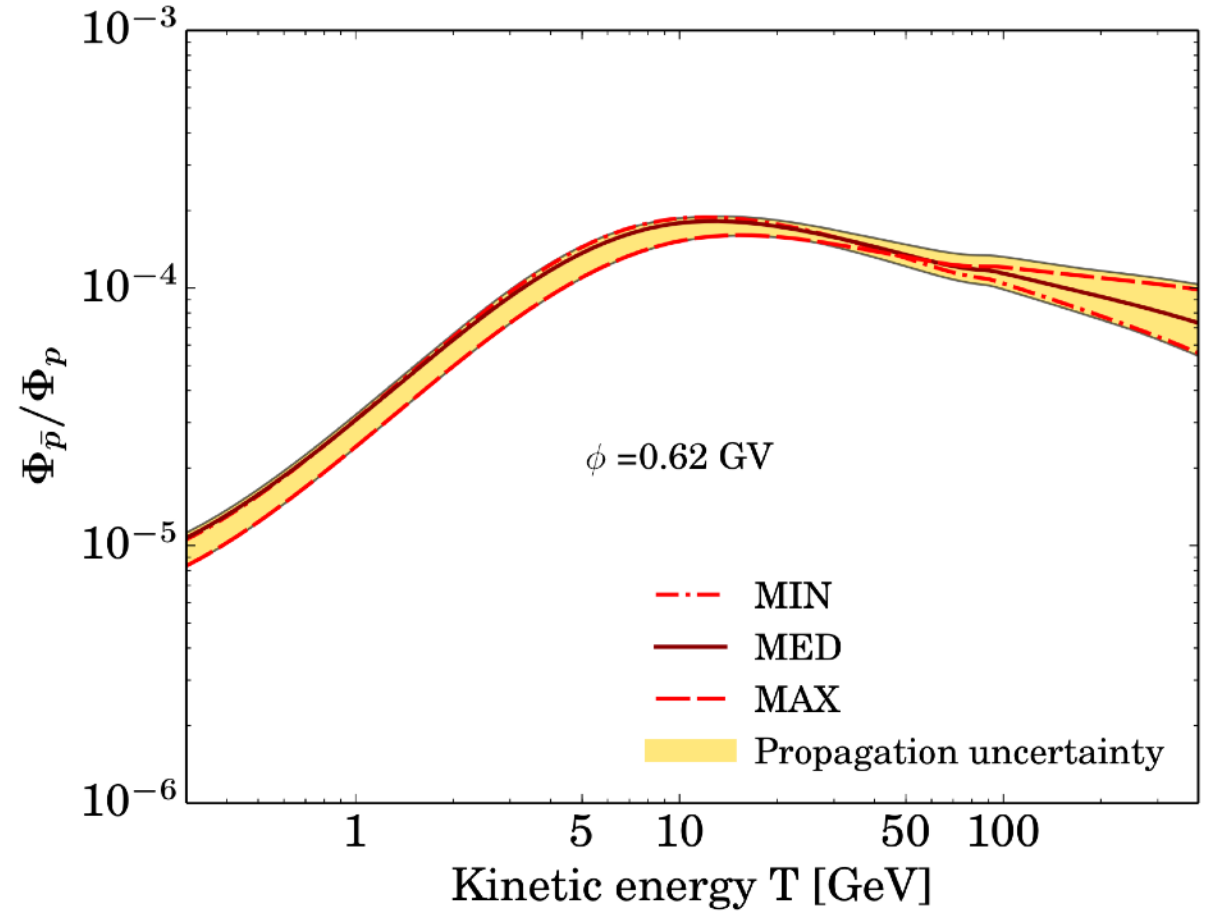

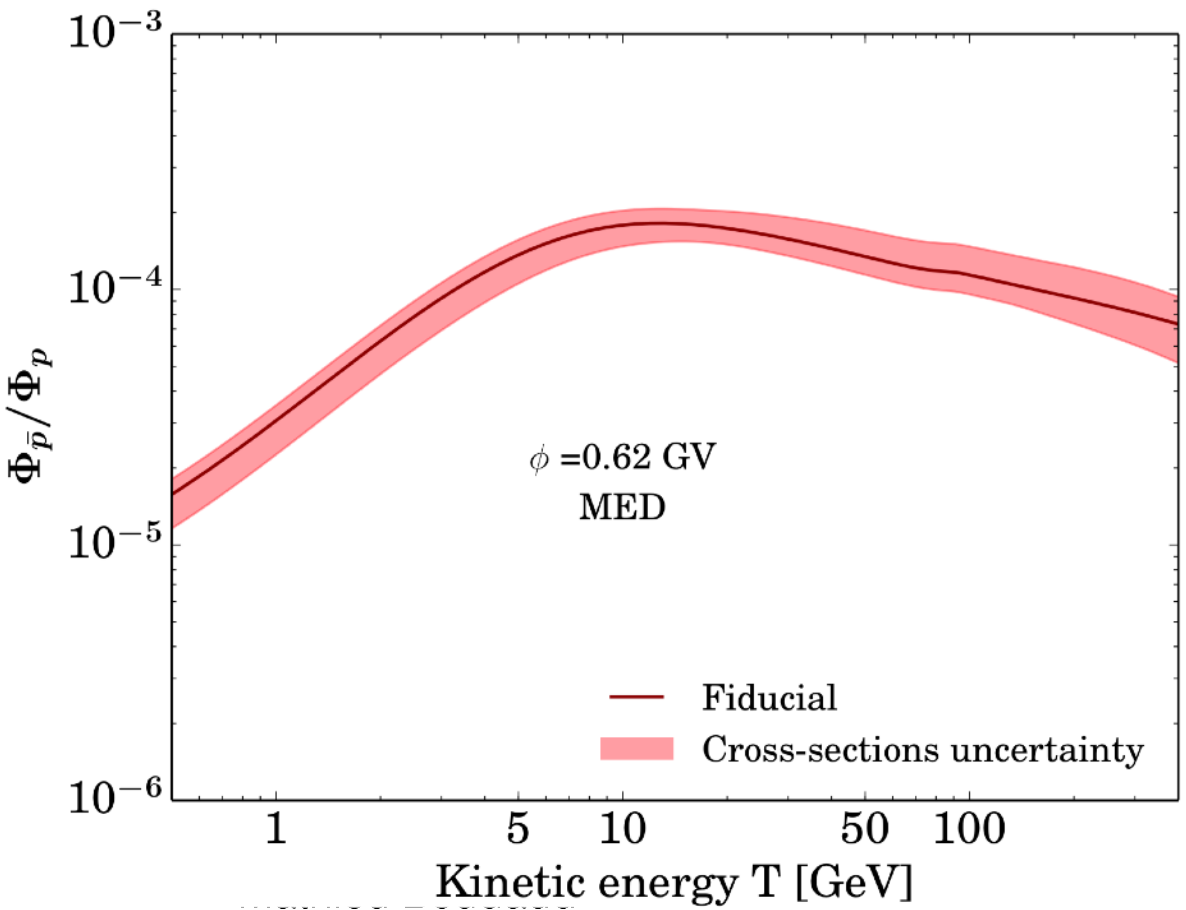

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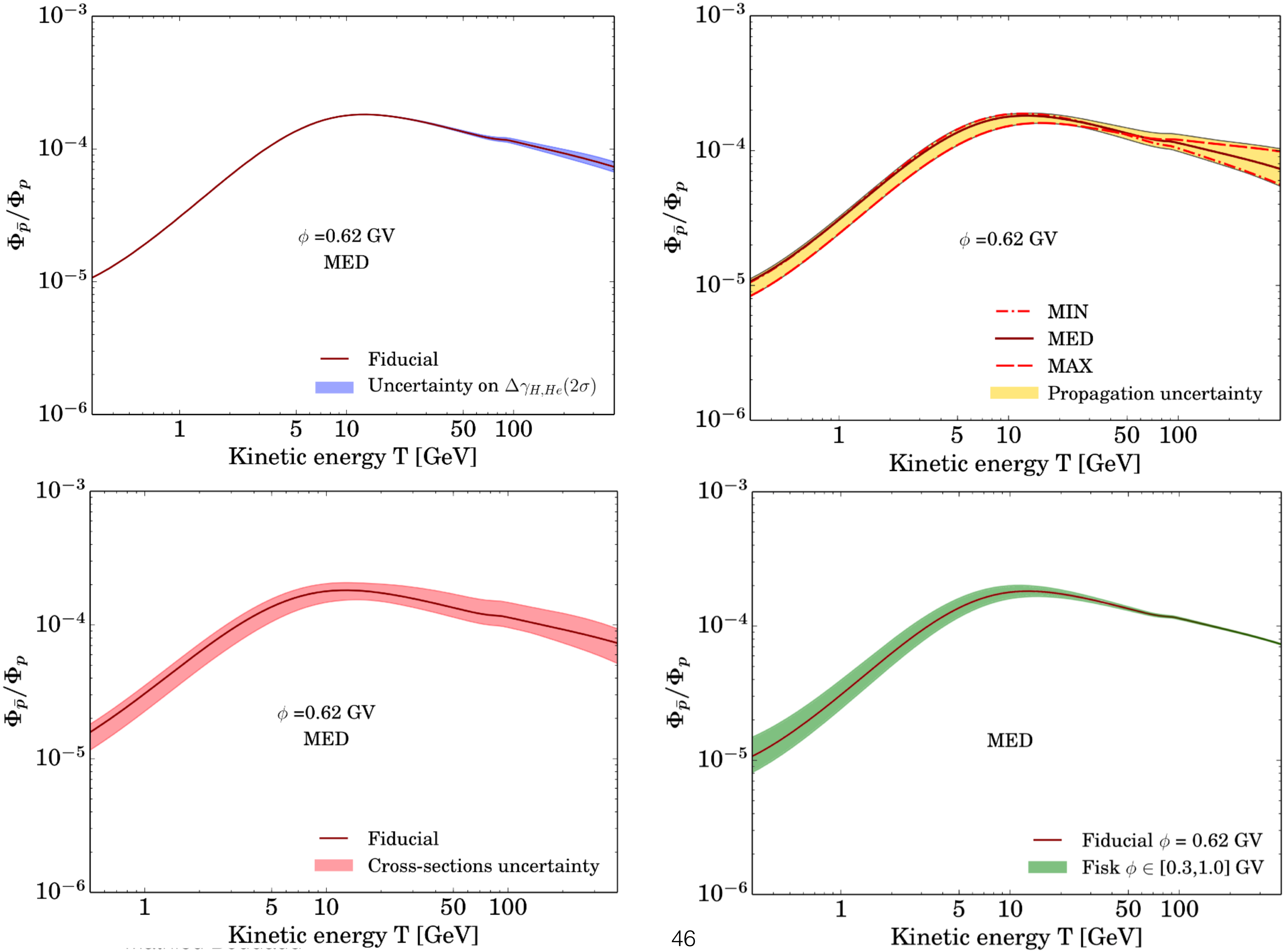

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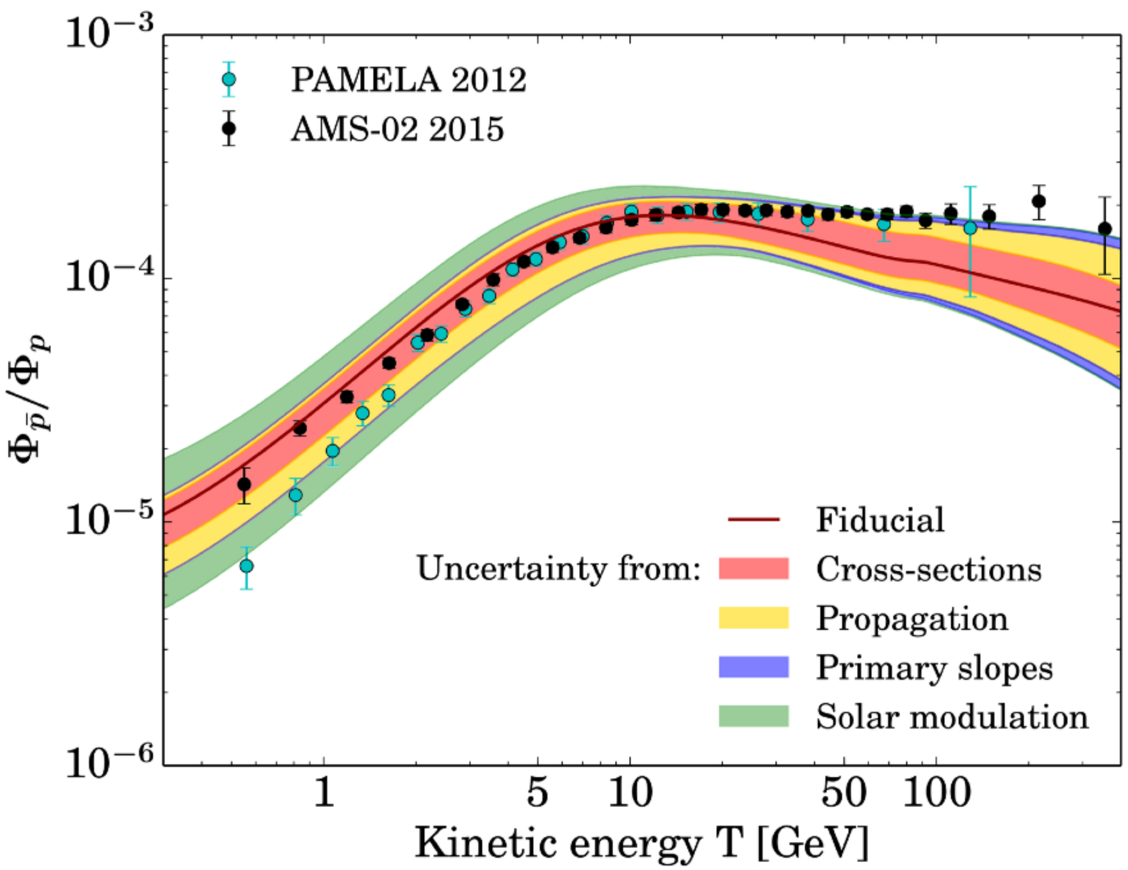
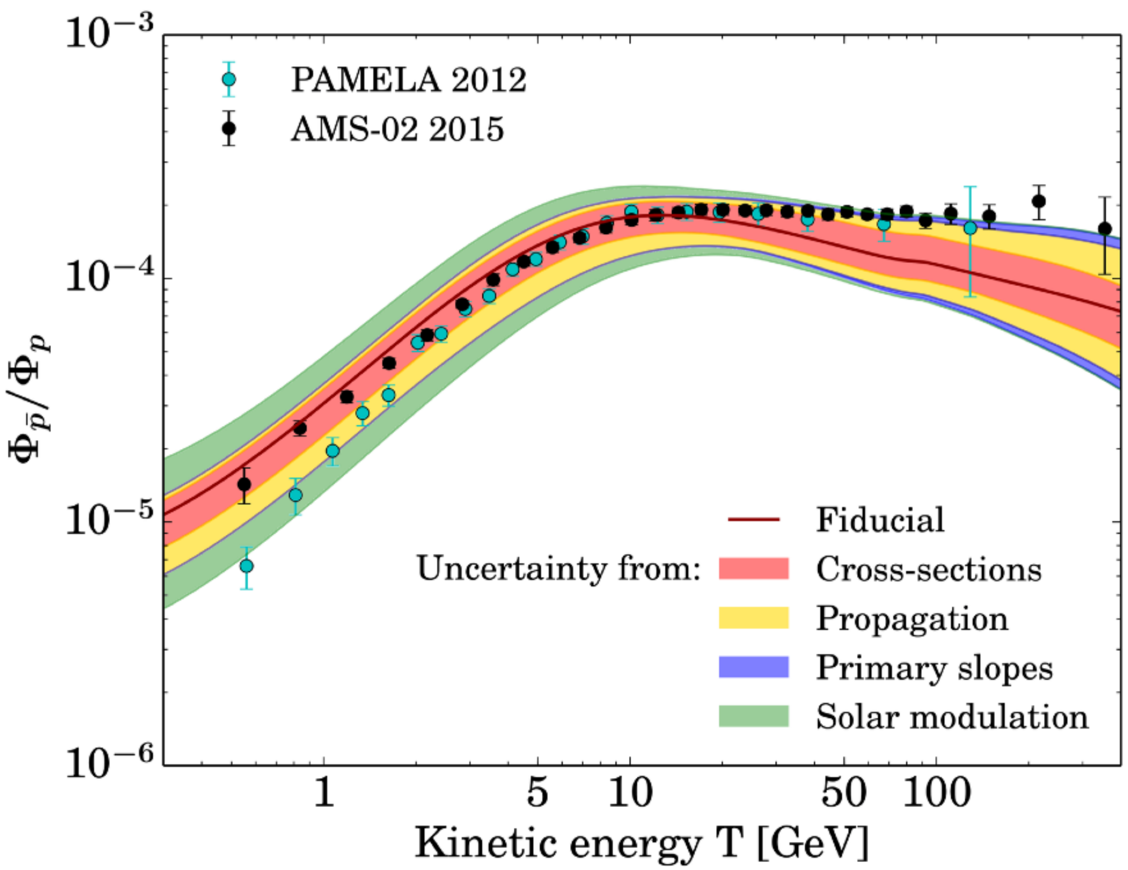


G. Giesen, MB+(2015)

Theoretical uncertainties on the astrophysical antiprotons background



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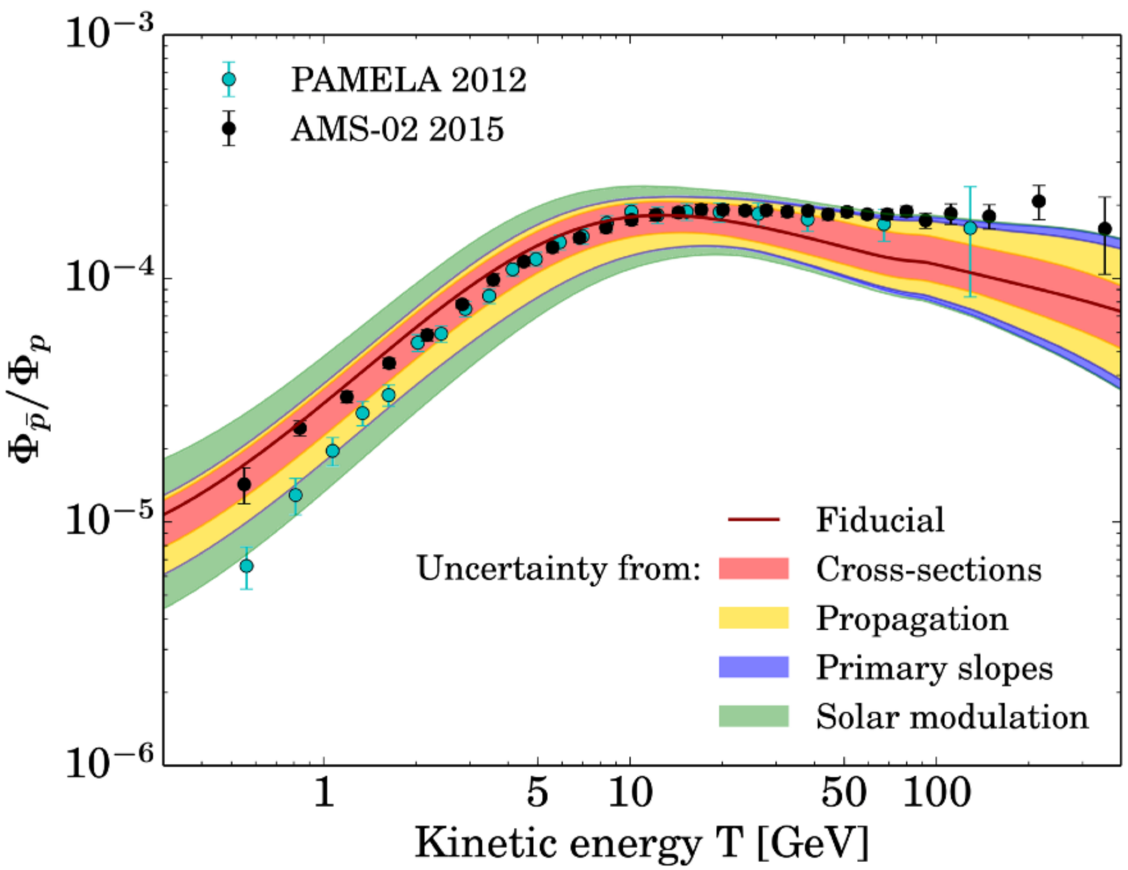

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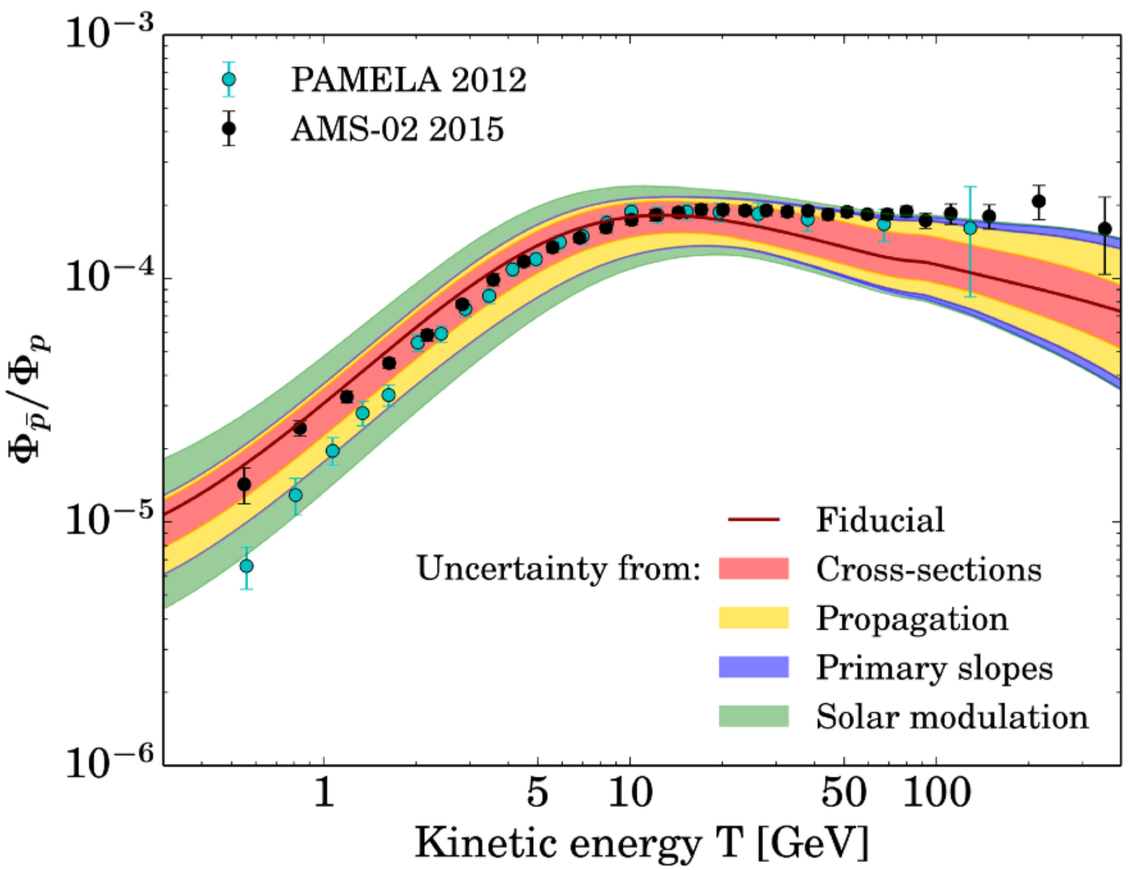
Case	δ	K_0 [kpc^2/Myr]	L [kpc]	V_C [km/s]	V_a [km/s]
MIN	0.85	0.0016	1	13.5	22.4
MED	0.70	0.0112	4	12	52.9
MAX	0.46	0.0765	15	5	117.6

Theoretical uncertainties on the astrophysical antiprotons background



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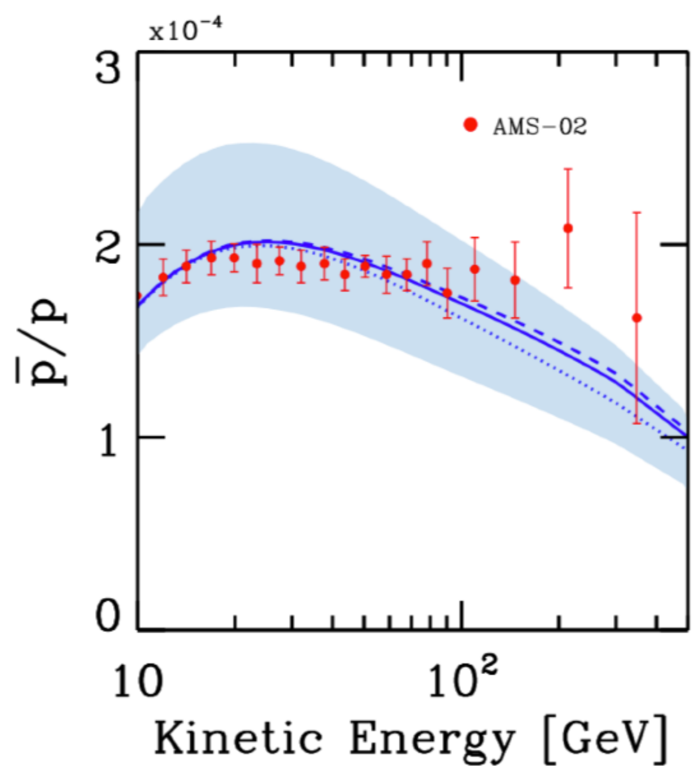
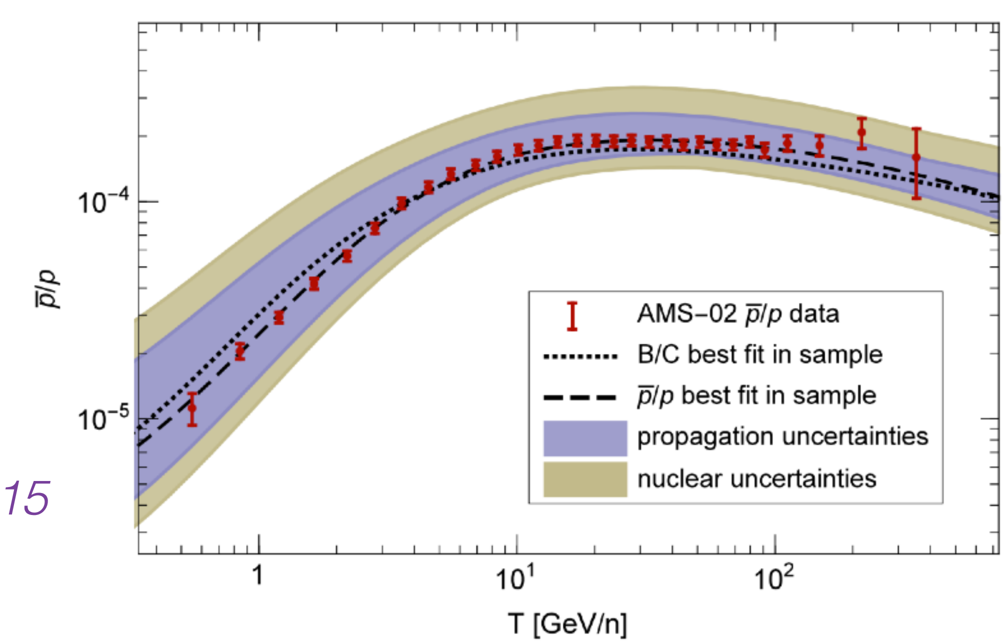
Similar conclusions from independent analysis



Evoli et al. 2015

Kappl et al. 2015



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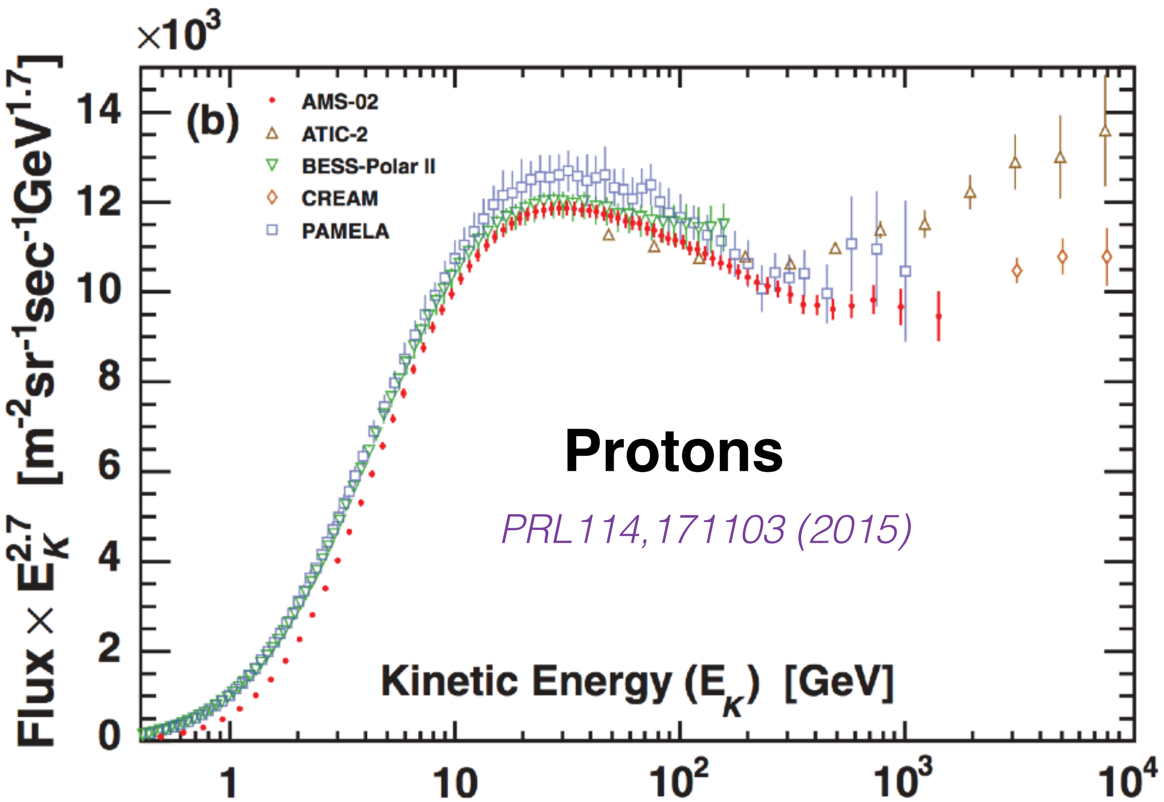
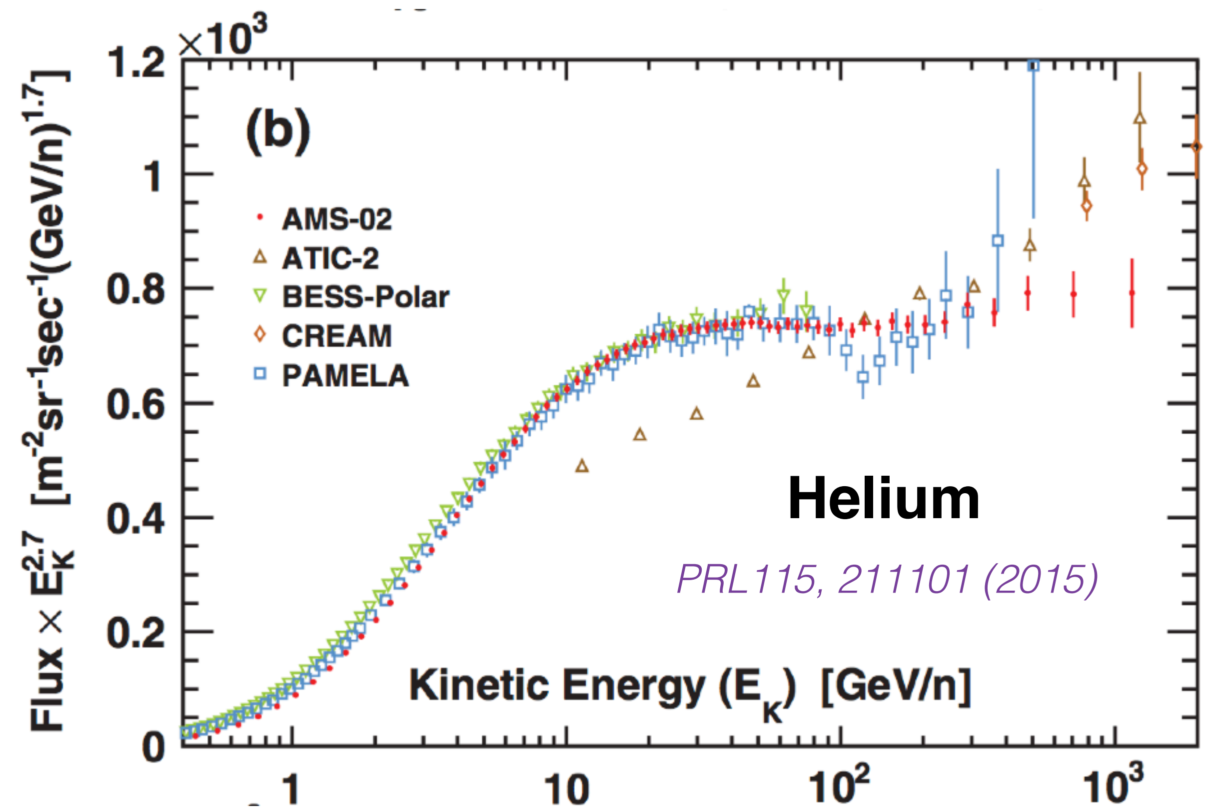
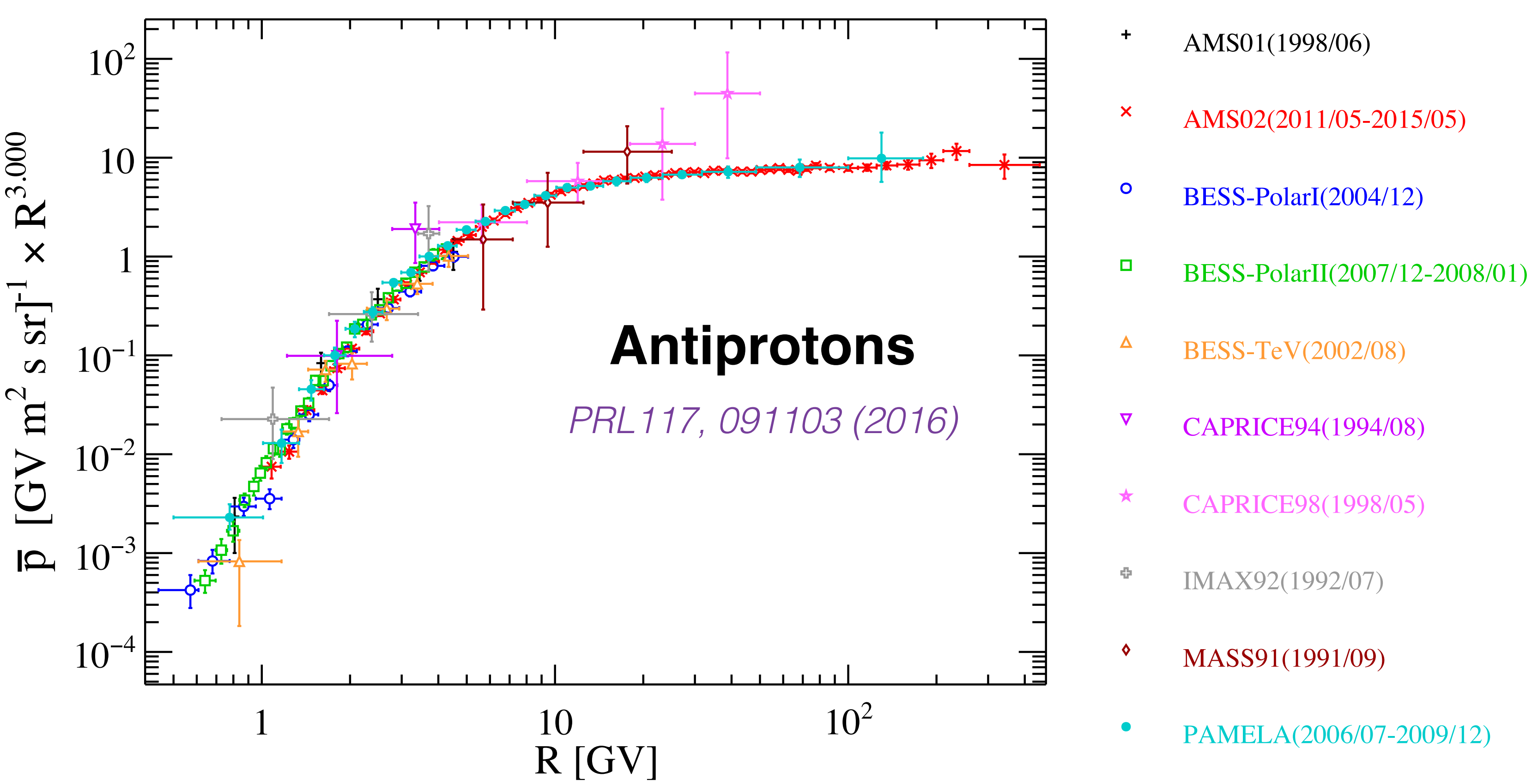
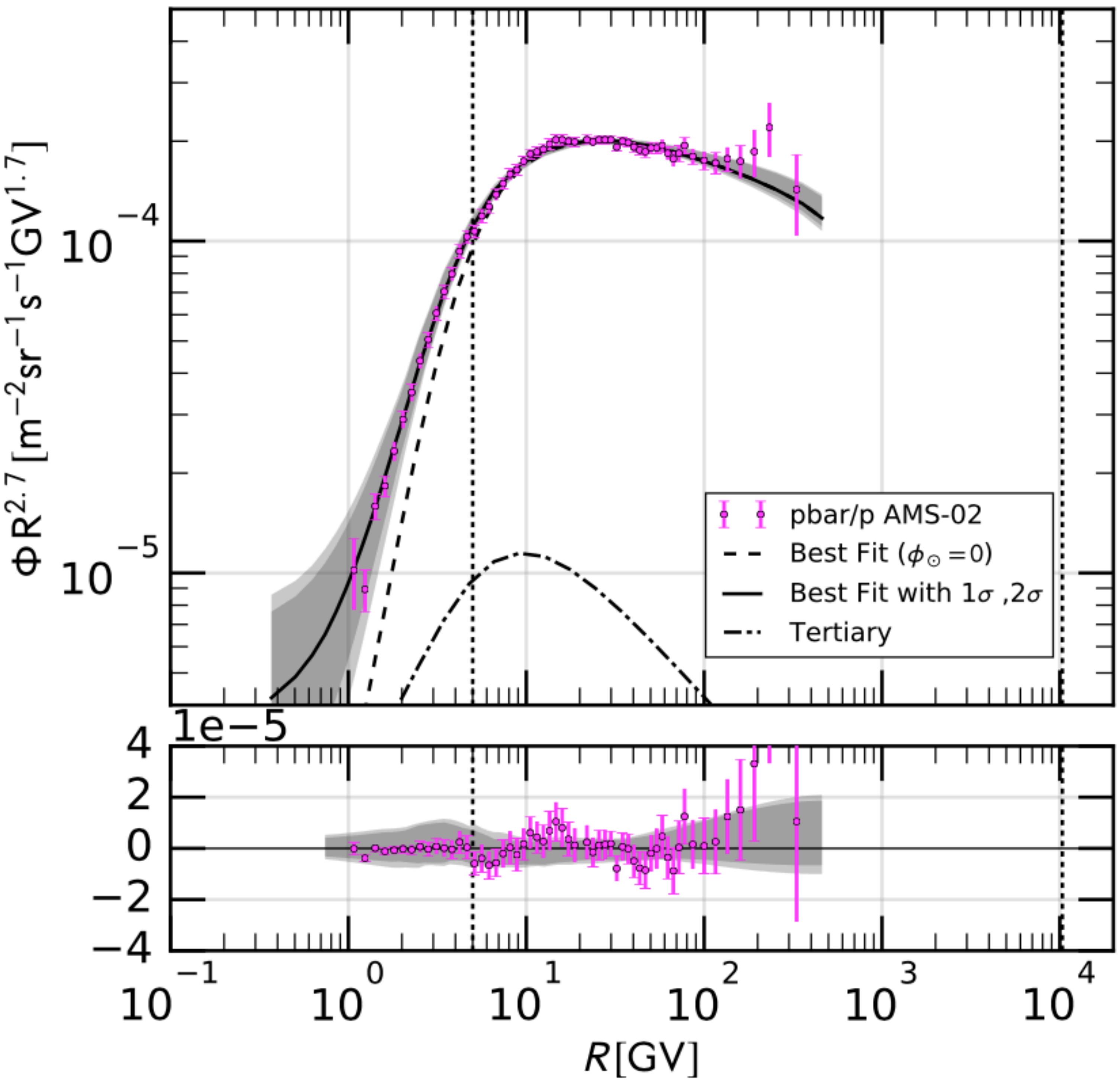






Antiprotons excess at R~10 GV?

Cuoco, Krämer & Korsmeier (2016)



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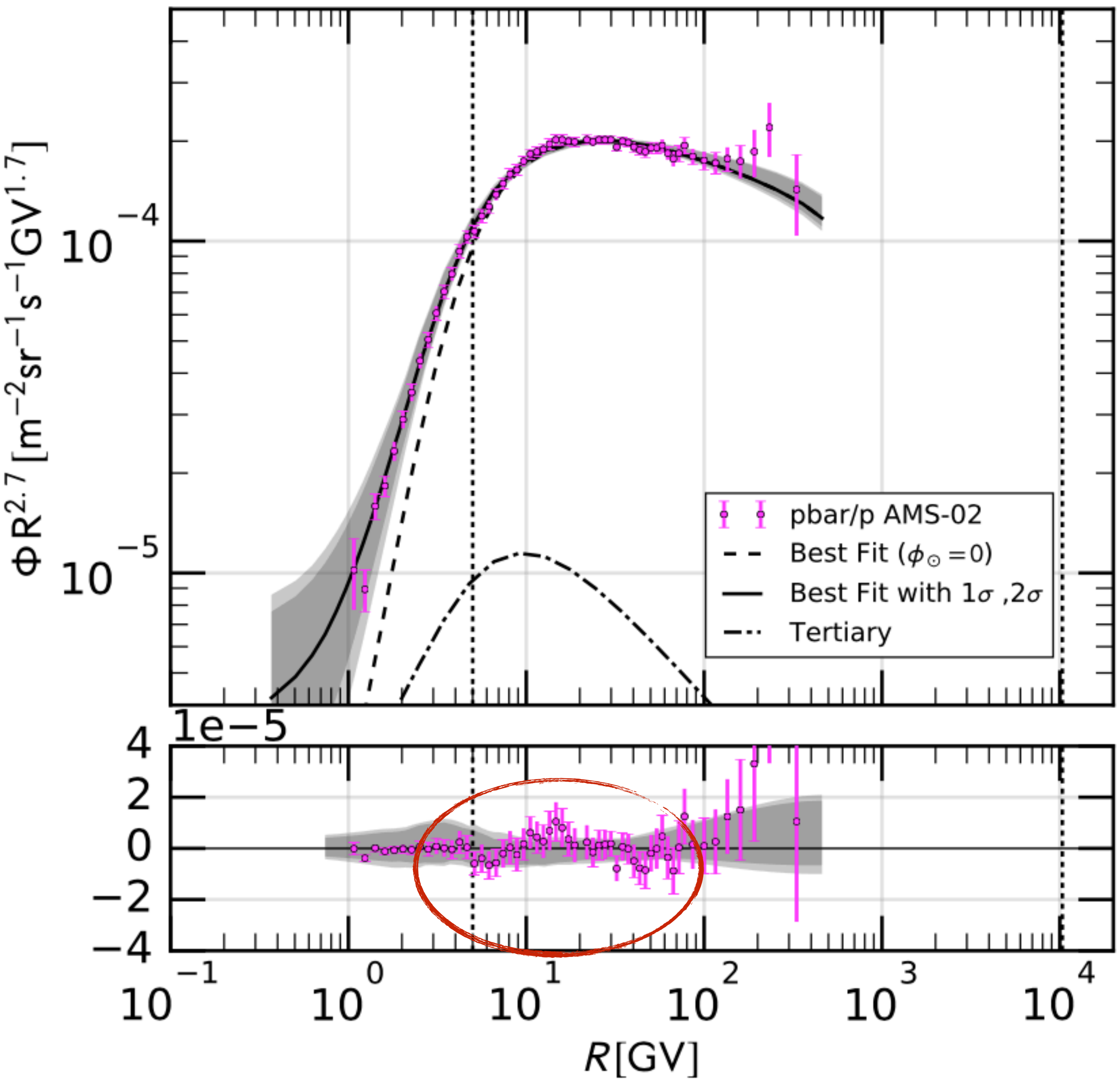

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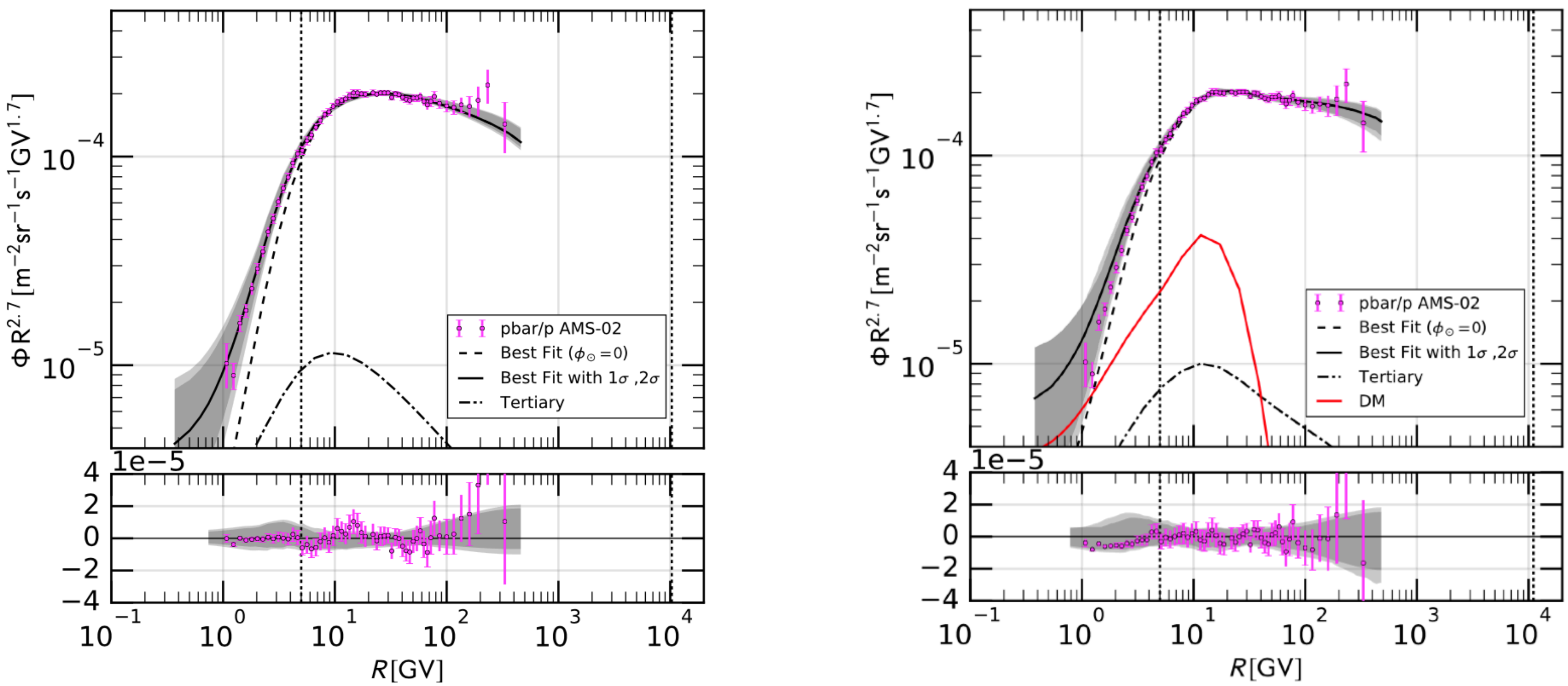
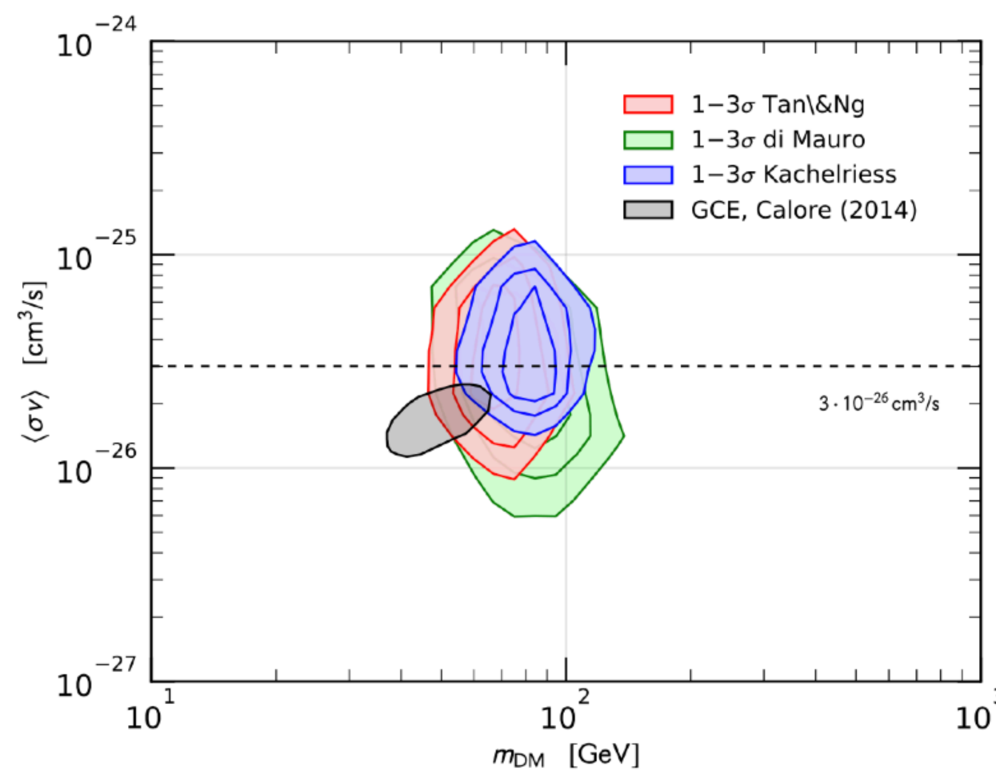


- Dark matter signal at 4.5 σ

$$m_\chi \simeq 80 \text{ GeV}$$

$$\langle \sigma v \rangle \simeq 3 \times 10^{-26} \text{ cm}^3\text{s}^{-1}$$ (Thermal relic!)

- Same DM mass that explains the « Galactic center excess »
Calore+(2014)



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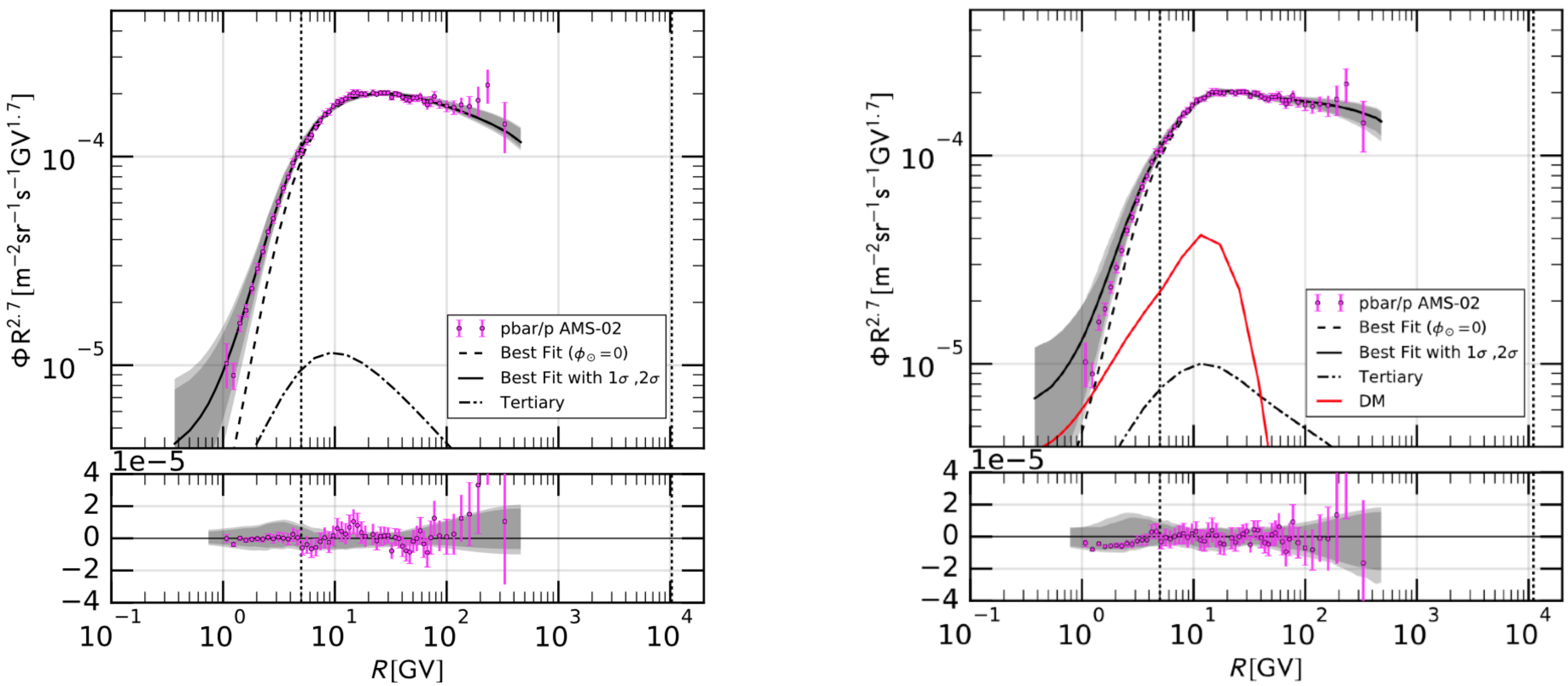


A critical look:

- Propagation parameters are derived from ***p***, **He** and $\bar{p}$ data.

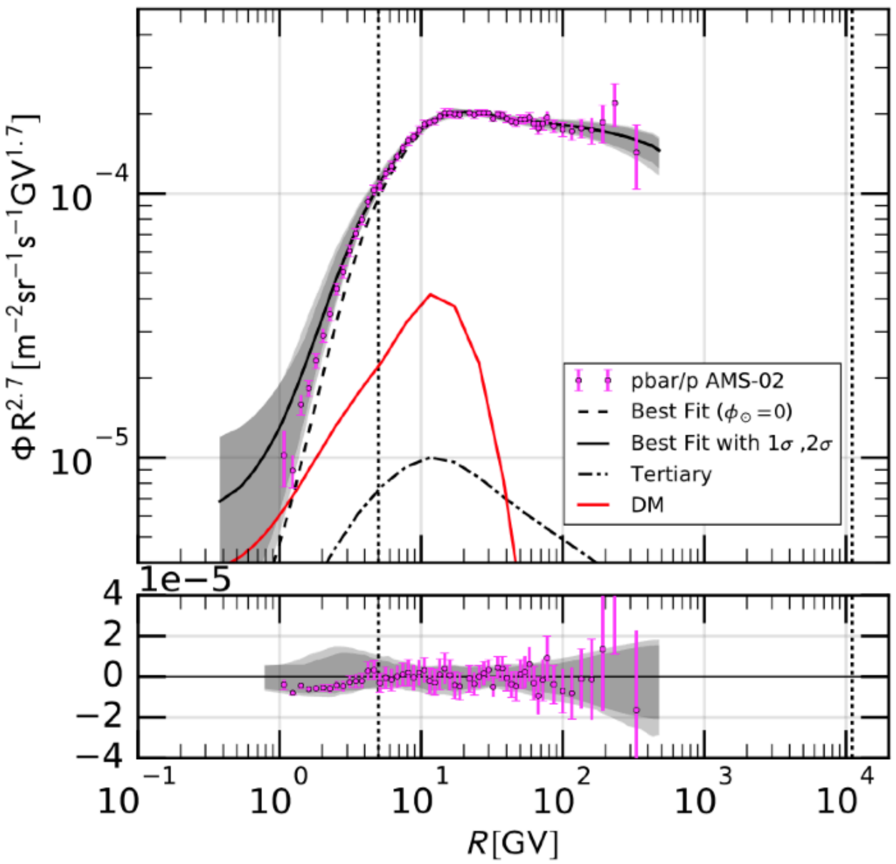
  Background + DM $\Longrightarrow$ δ = 0.24 ***Does not match preliminary B/C measured by AMS-02 with δ ≃ 0.5.***

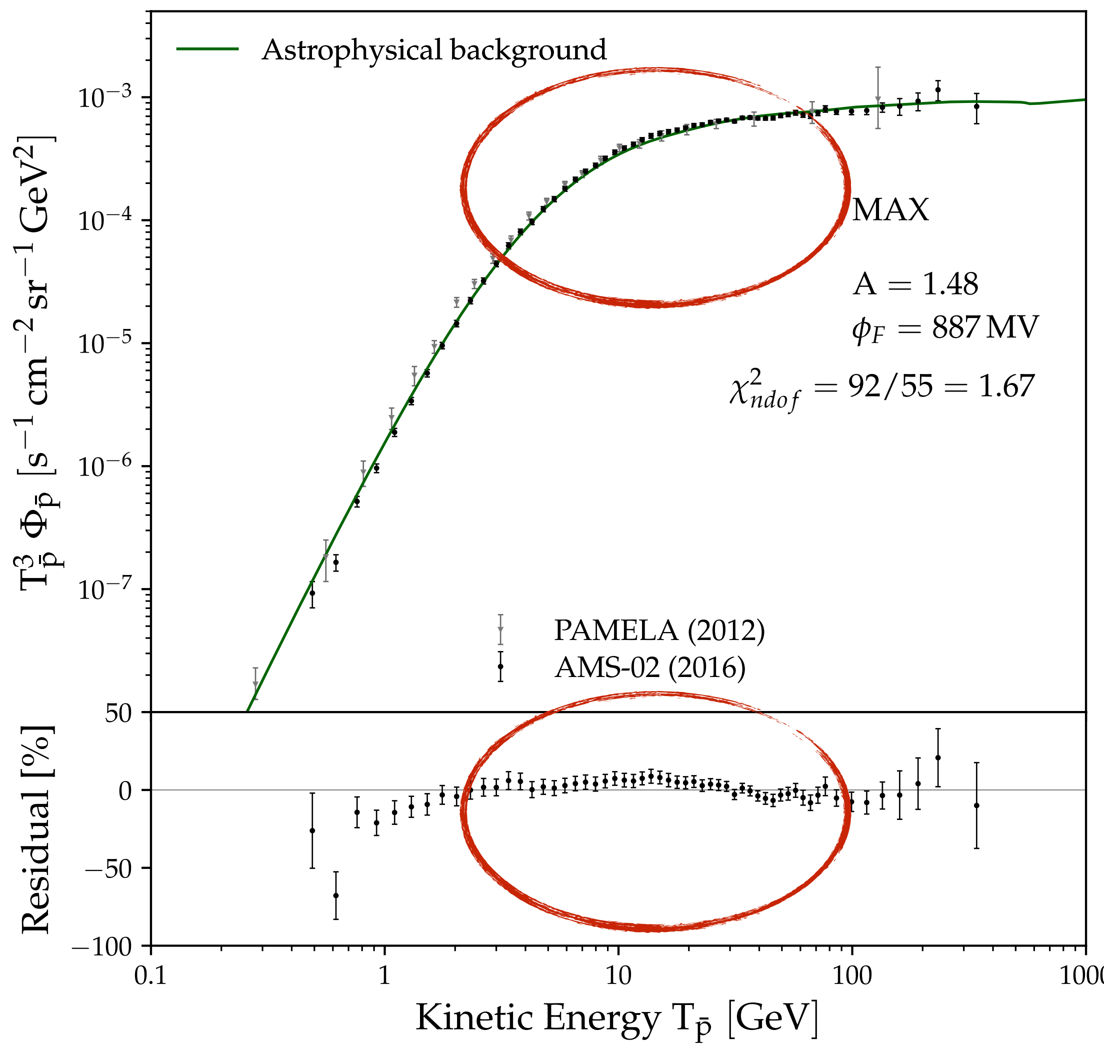
  « While preliminary B/C data from AMS-02 are available, there is, however, evidence that the propagation of heavy nuclei like B and C is different from the propagation of light nuclei like protons and antiprotons [14]. Thus, using B/C data to constrain CR propagation is likely to introduce a bias when analysing antiprotons. »

- The excess disappears if low energy data (R < 5GV) are taken into account in the analysis.

Antiprotons excess at R~10 GV?

Cuoco, Krämer & Korsmeier (2016)





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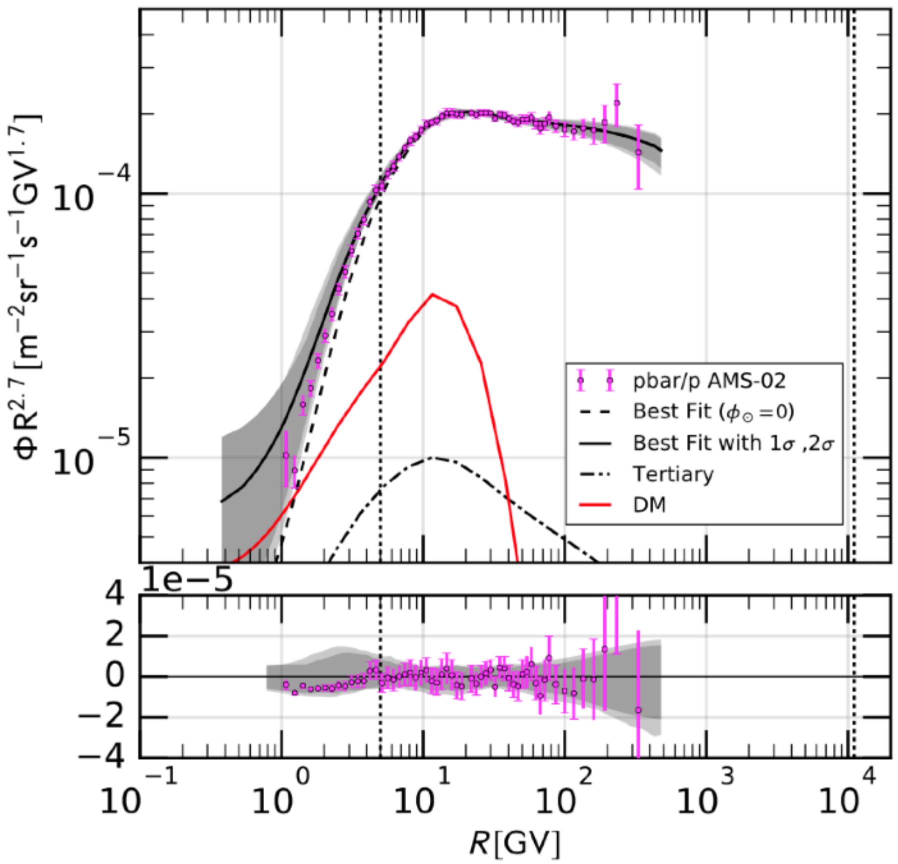

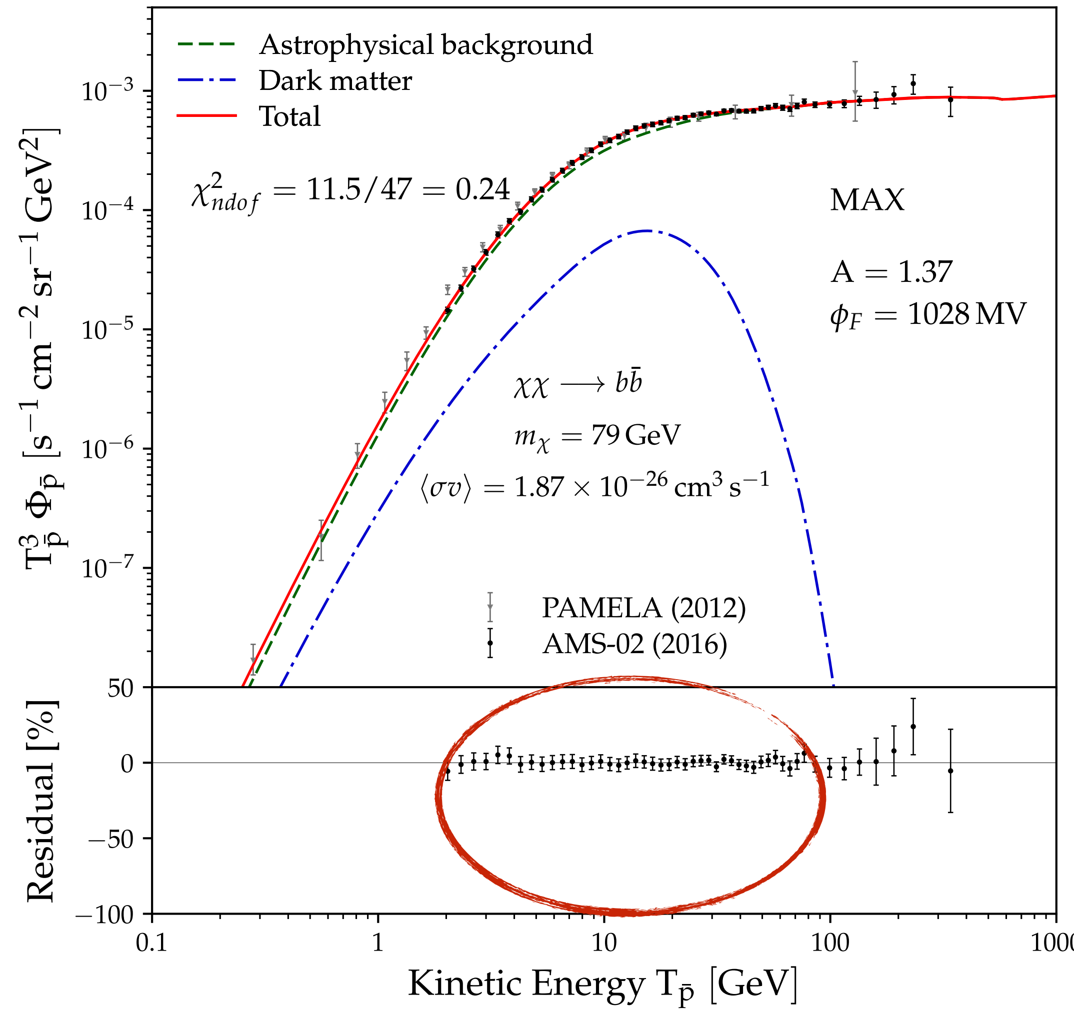

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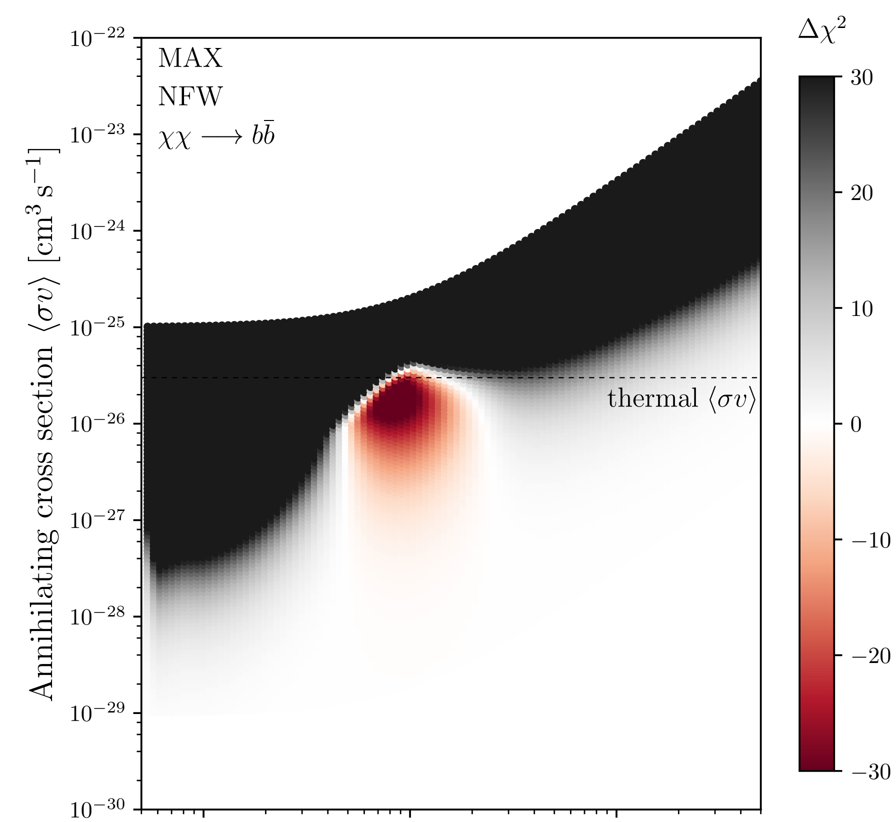
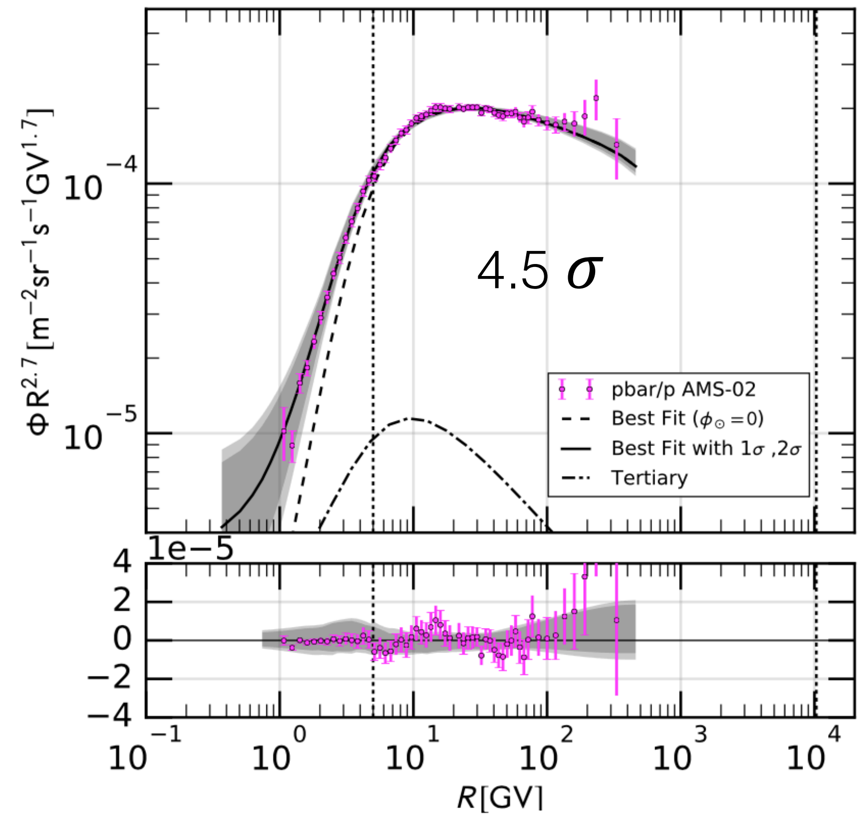
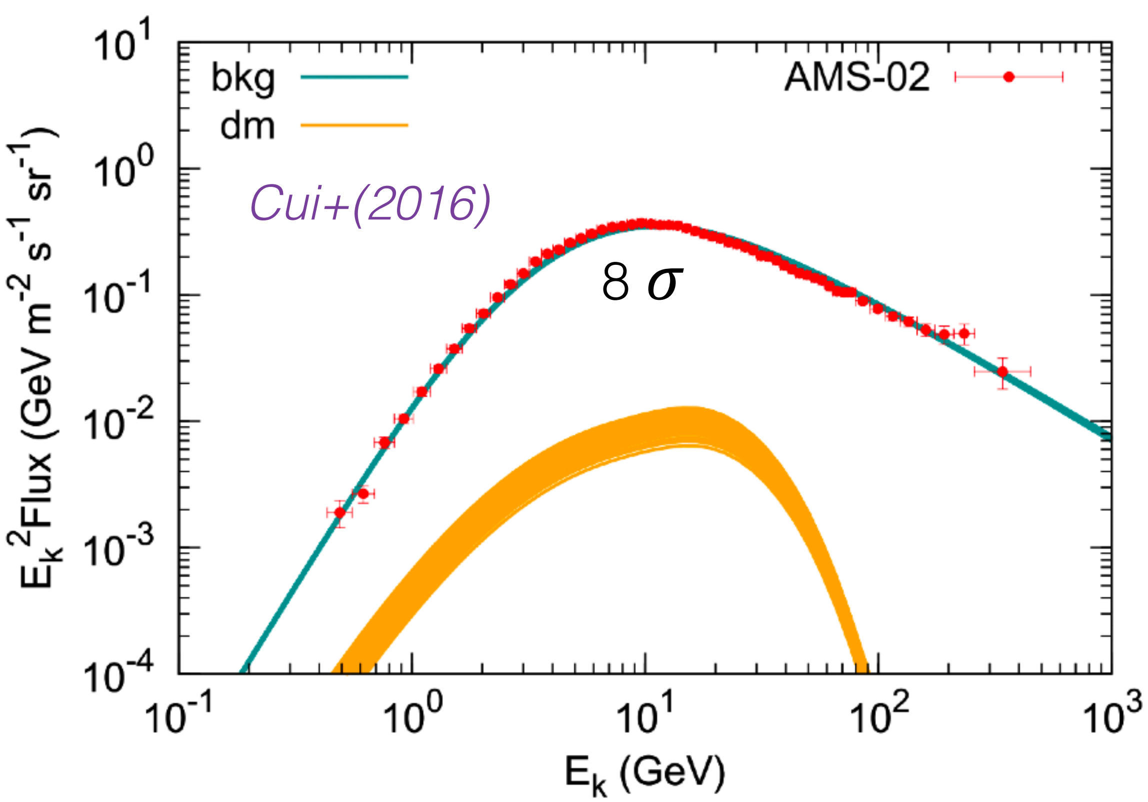


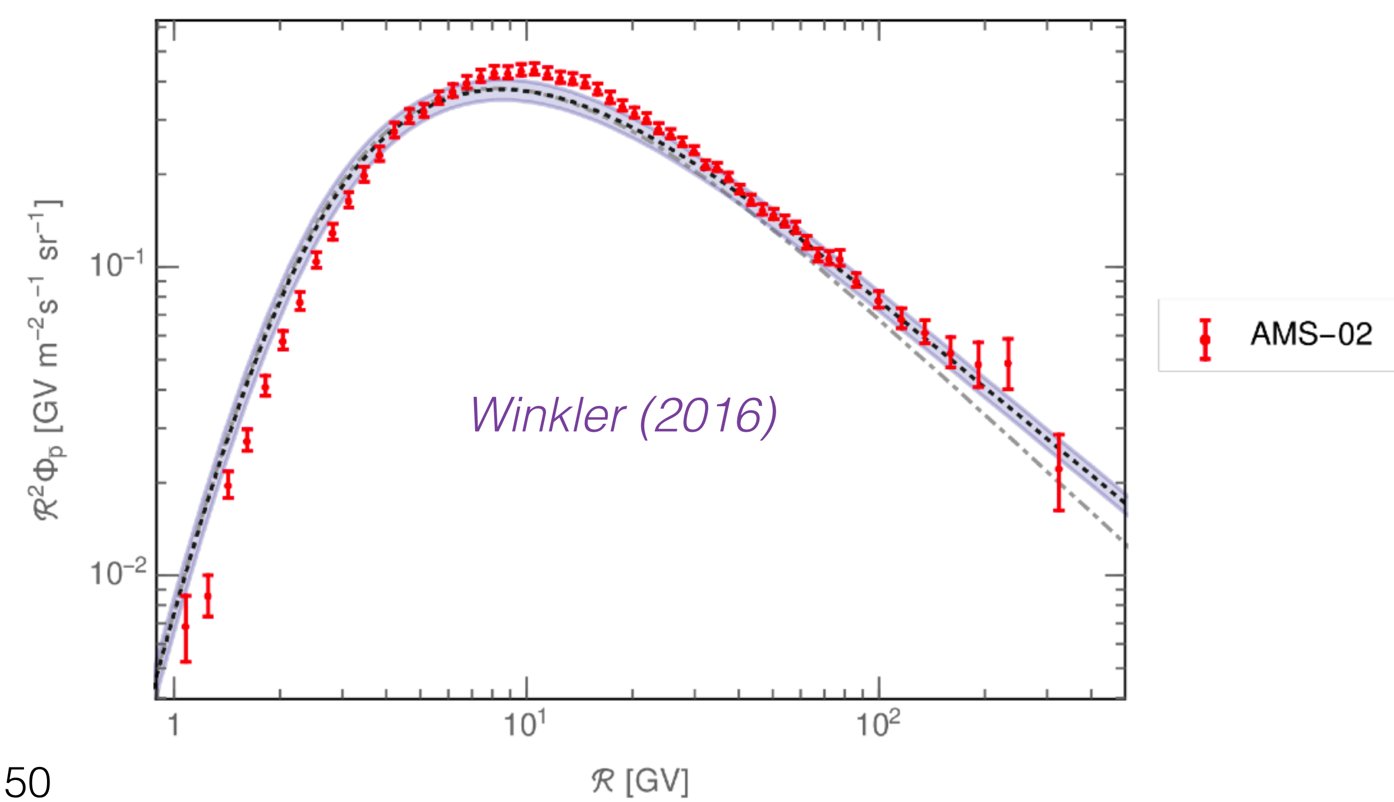
Antiprotons excess at R~10 GV?

A 10 GV excess is found by several independent analysis.

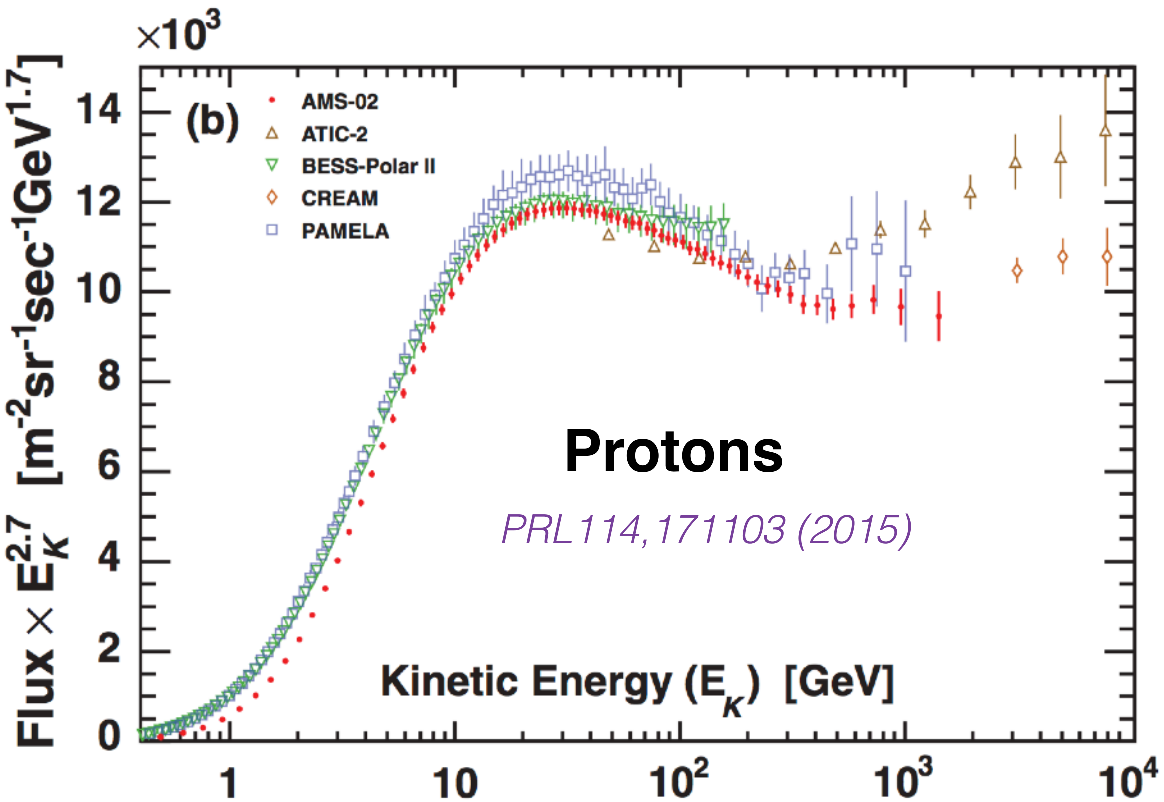
Cuoco, Krämer & Korsmeier (2016)

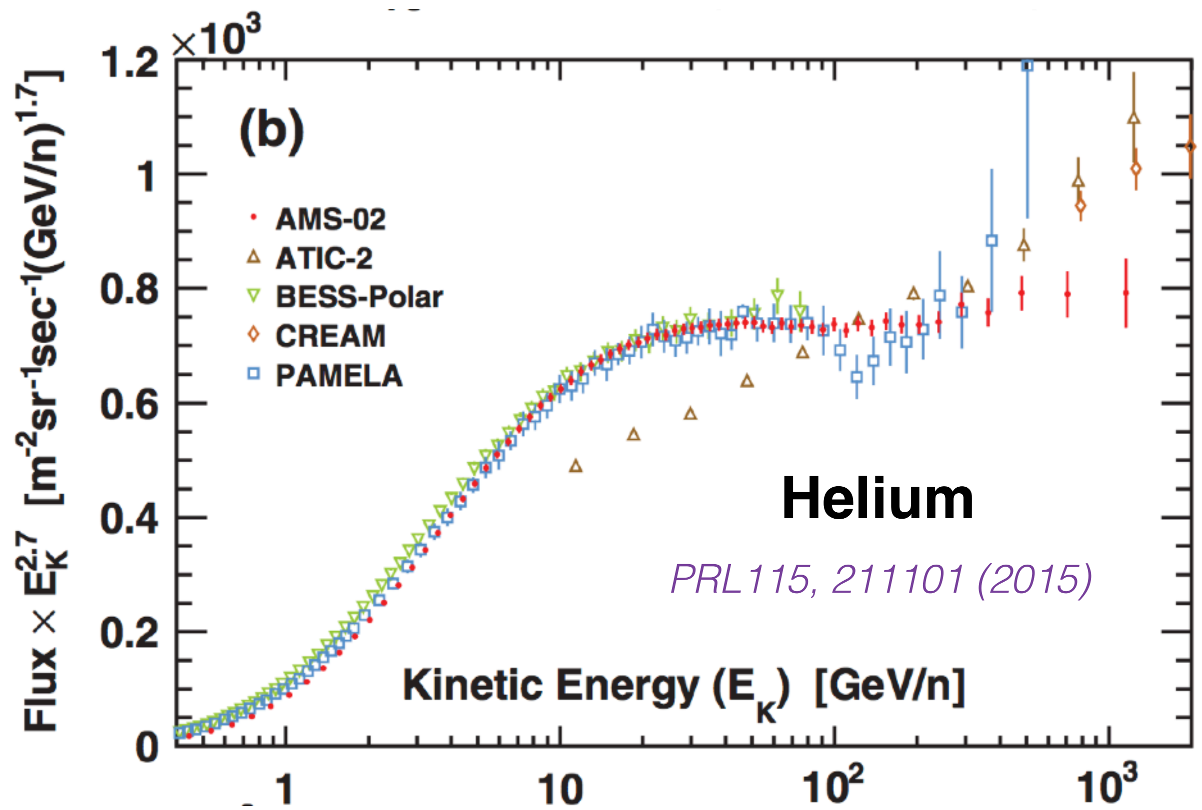


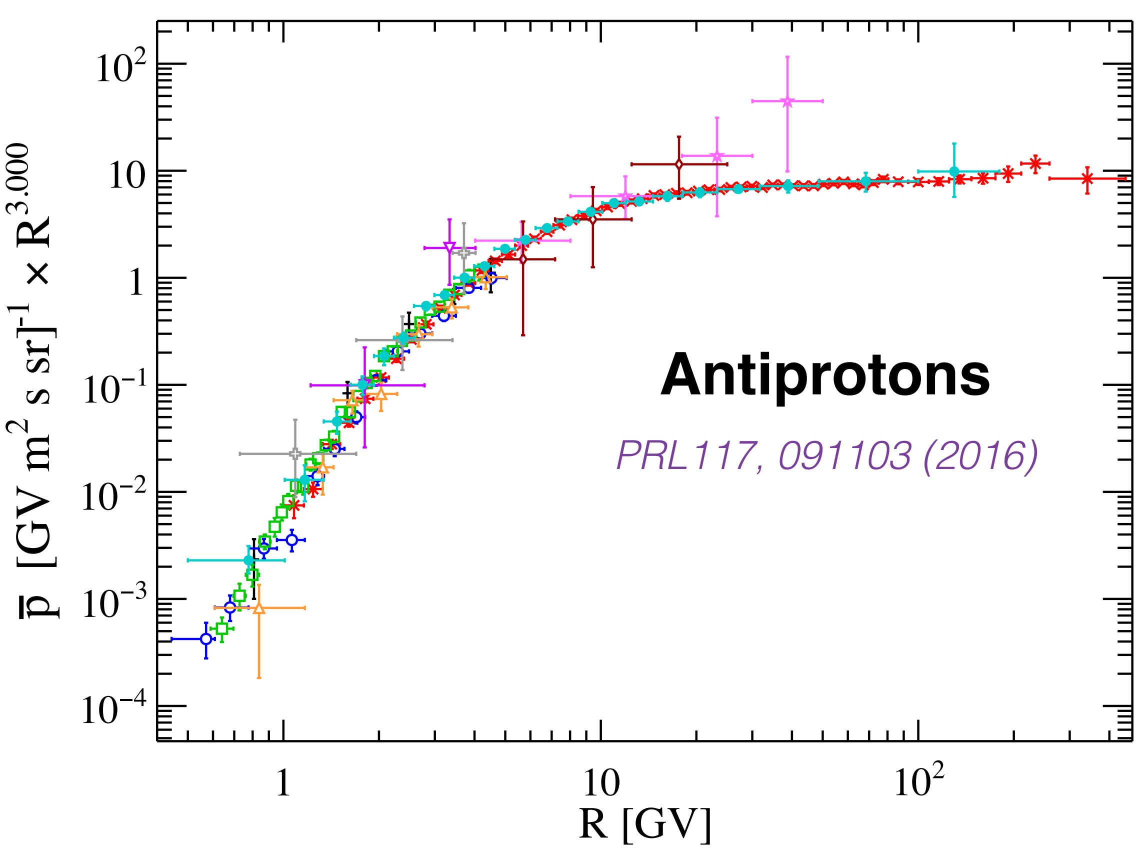


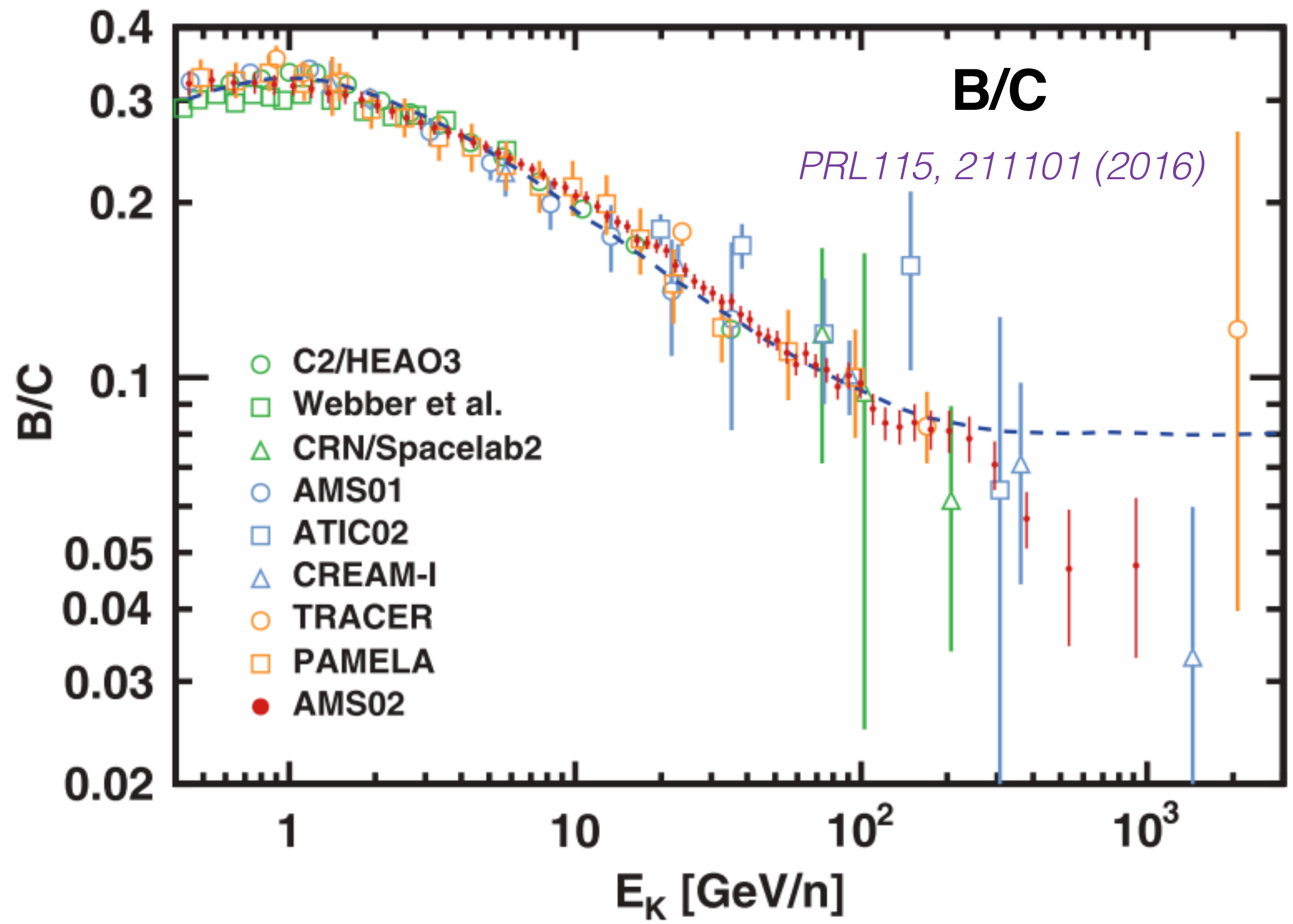


AMS-02 has published the flux of p, He, antiprotons and B/C









Antiprotons excess at ~10 GeV?

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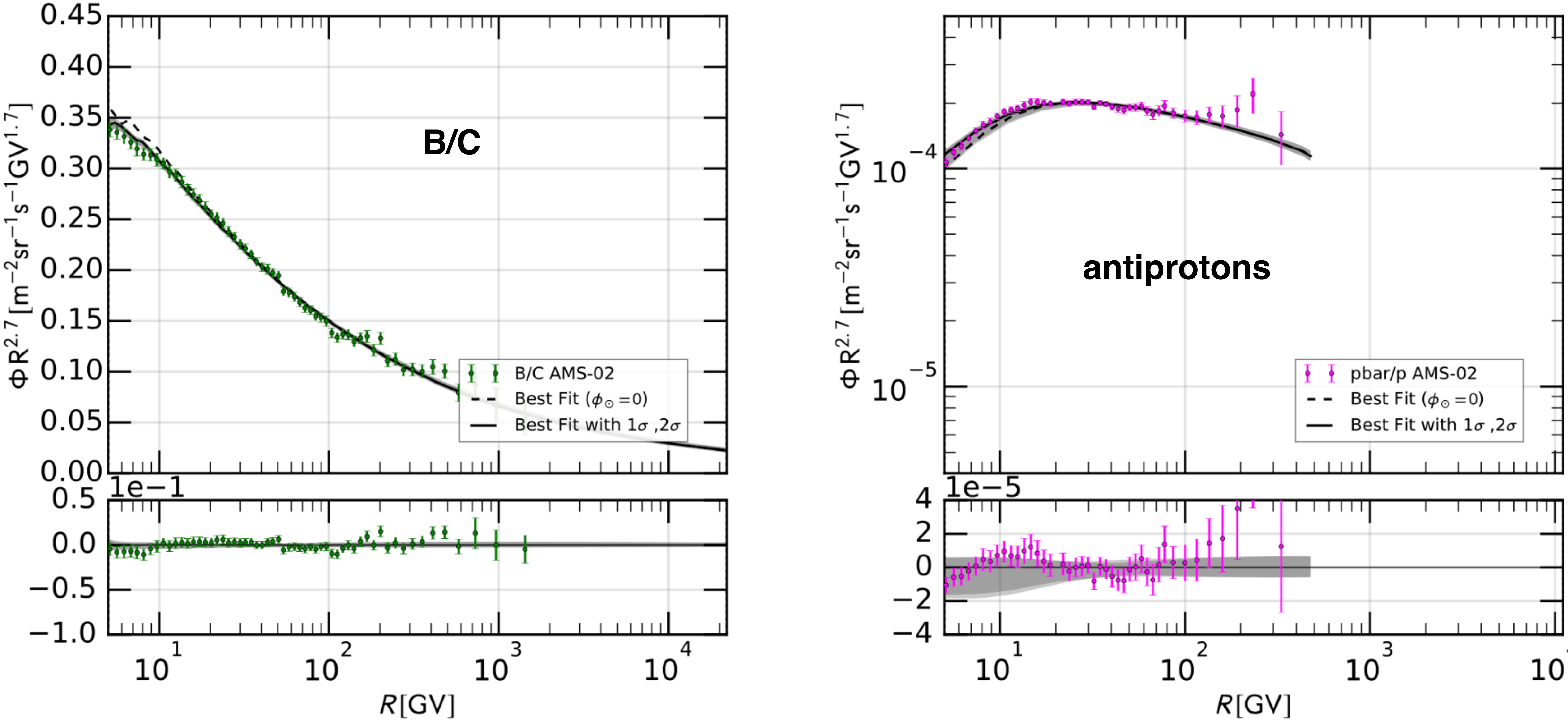


Same feature in B/C and antiprotons data!

Secondary B

$$\mathrm{C, O} + (\mathrm{H, He})_{\mathrm{ISM}} \rightarrow \mathrm{B} + \mathrm{X}$$

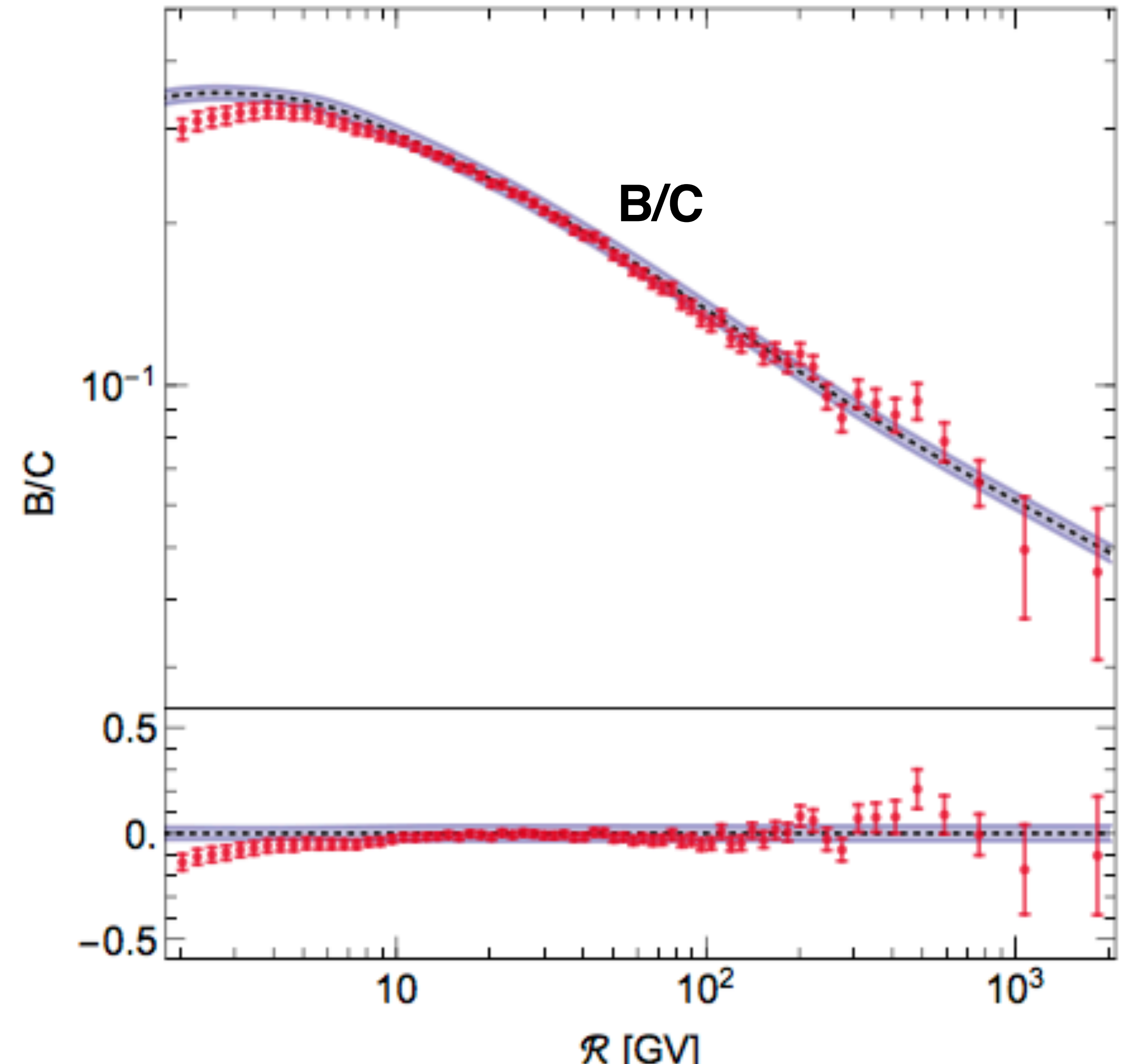
Secondary $\bar{p}$

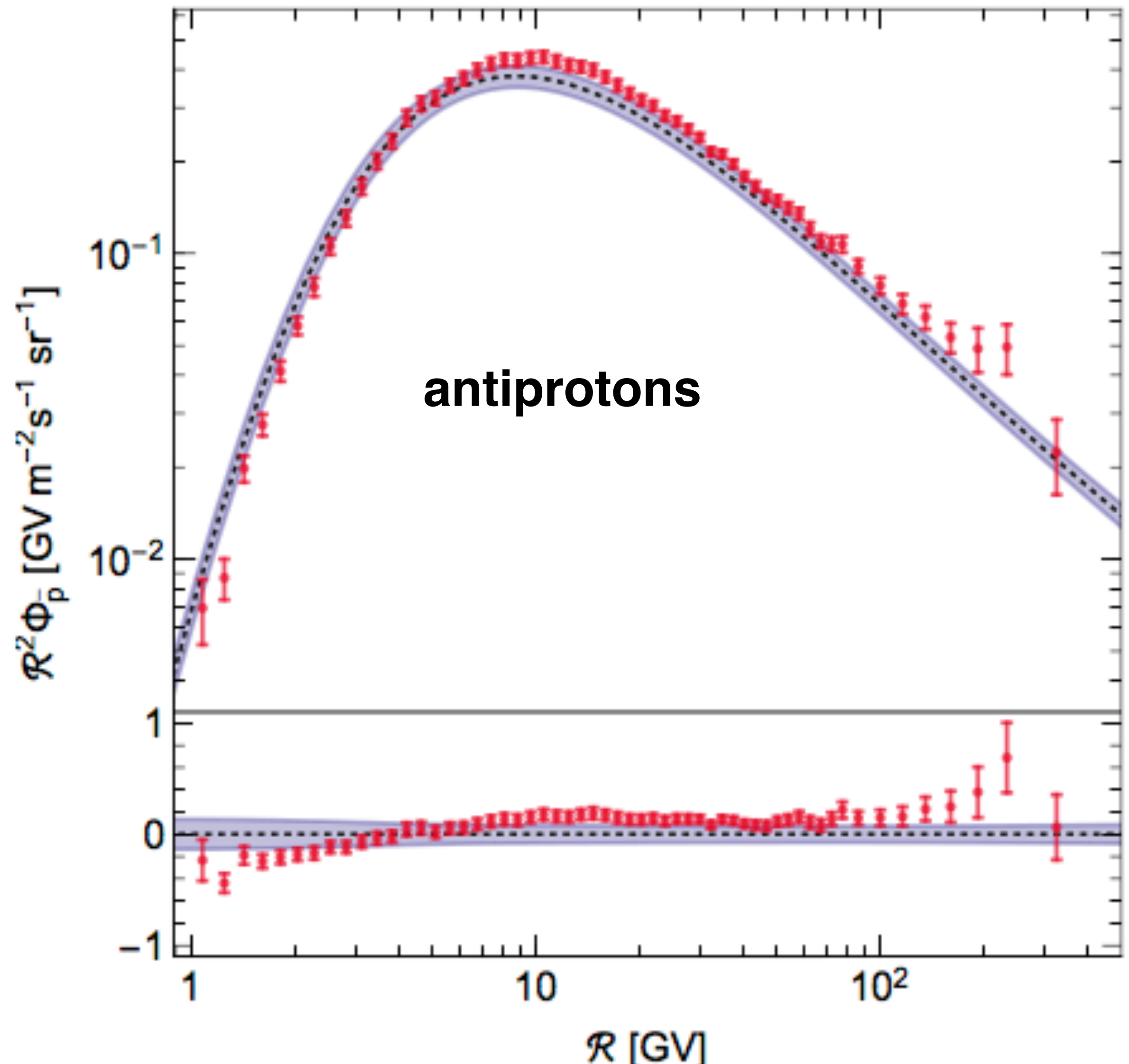
$$p, \alpha + (\mathrm{H, He})_{\mathrm{ISM}} \rightarrow \bar{\mathrm{p}} + \mathrm{X}$$

Does this feature come from the propagation model?

Antiprotons excess at ~10 GeV?

Reinert & Winkler (2017)





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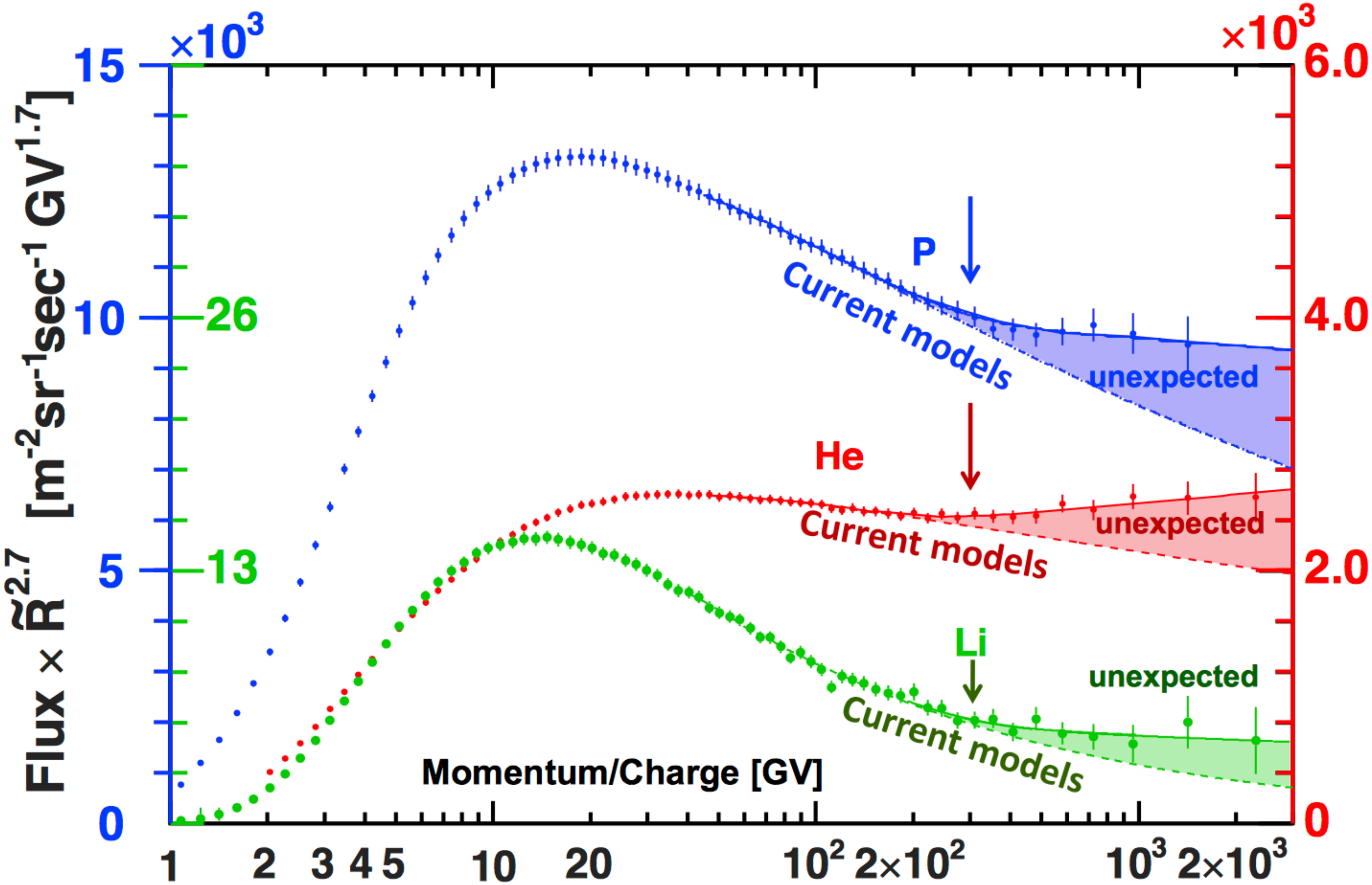
A universal break in the spectra of cosmic ray nuclei?

Pointed by PAMELA and confirmed by AMS-02: an universal kink at R ≃ 200 GV?

$$\Delta_{\text{kink}} \simeq 0.13$$



This feature is not predicted by the conventional propagation models!

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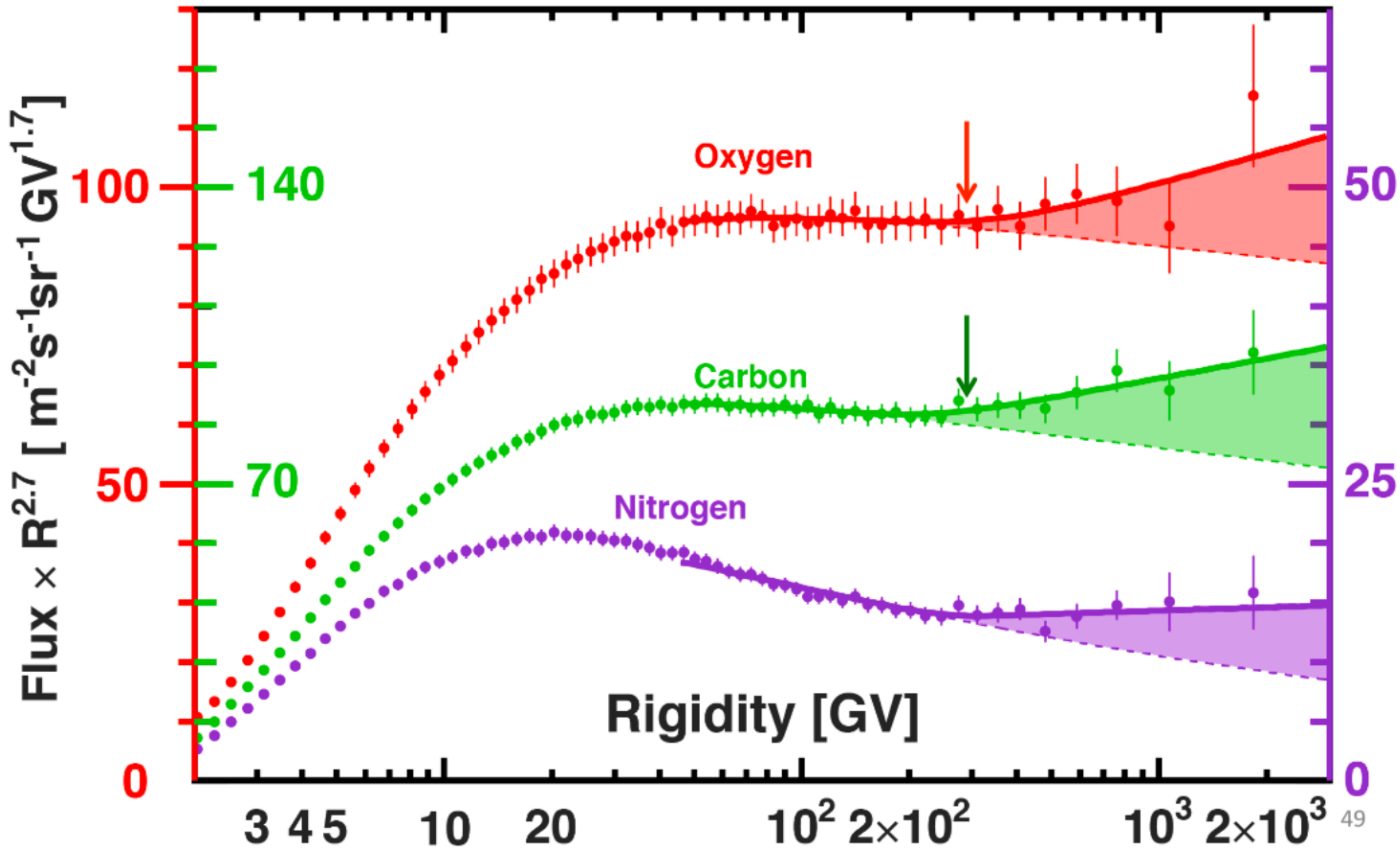

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A universal break in the spectra of cosmic ray nuclei?

In the high energy regime $R \gtrsim 100\ \mathrm{GV}$

Primary cosmic rays

$$\Phi_{\mathrm{I}}(R) \propto q_{\mathrm{I}}(R) \times \frac{1}{K(R)}$$

Acceleration in SNRs   Propagation in the Galaxy

Where do come from the hardening?
Acceleration or **propagation** in the Galaxy?

Secondary cosmic rays

$$\Phi_{\mathrm{II}}(R) \propto \frac{1}{K(R)} \times \left\{ q_{\mathrm{II}}(R) \propto \frac{q_{\mathrm{I}}(R)}{K(R)} \right\}$$

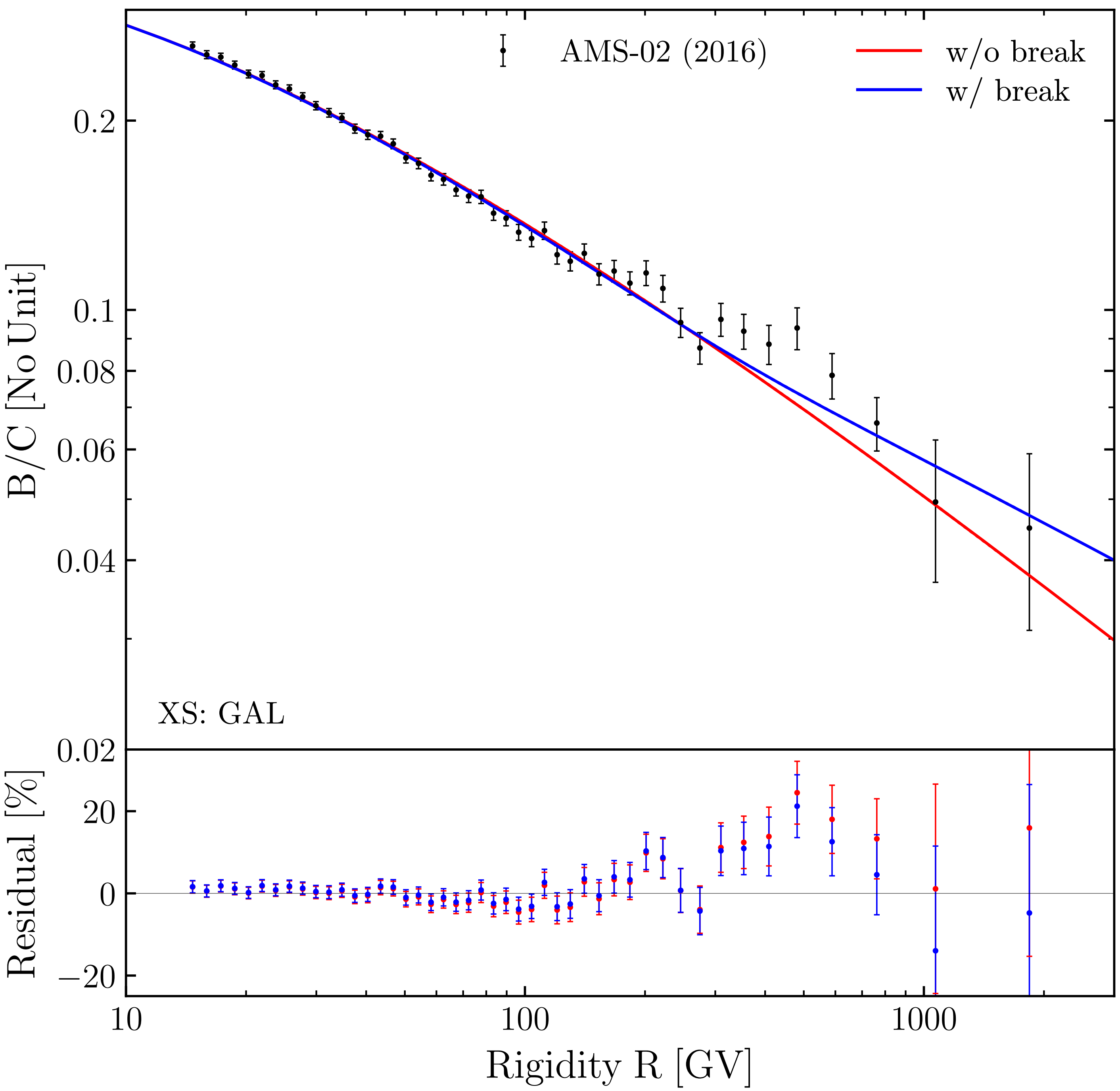
Secondary to primary ratios

$$\frac{\Phi_{\mathrm{II}}}{\Phi_{\mathrm{I}}}(R) \propto \frac{1}{K(R)}$$

- If the hardening comes from propagation, we should observe it in the secondary to primary ratios.
- In addition, the hardening of secondaries should be two times the one of primaries.

$$\Delta^{\mathrm{II}}_{\mathrm{kink}} = 2 \times \Delta^{\mathrm{I}}_{\mathrm{kink}}$$

A universal break in the spectra of cosmic ray nuclei?



$$K(E) = K_0\,\beta^\eta \left(\frac{R}{1\,\mathrm{GV}}\right)^\delta$$

$$\Delta\chi^2 = 11$$

Decisive evidence! (Bayesian terms)

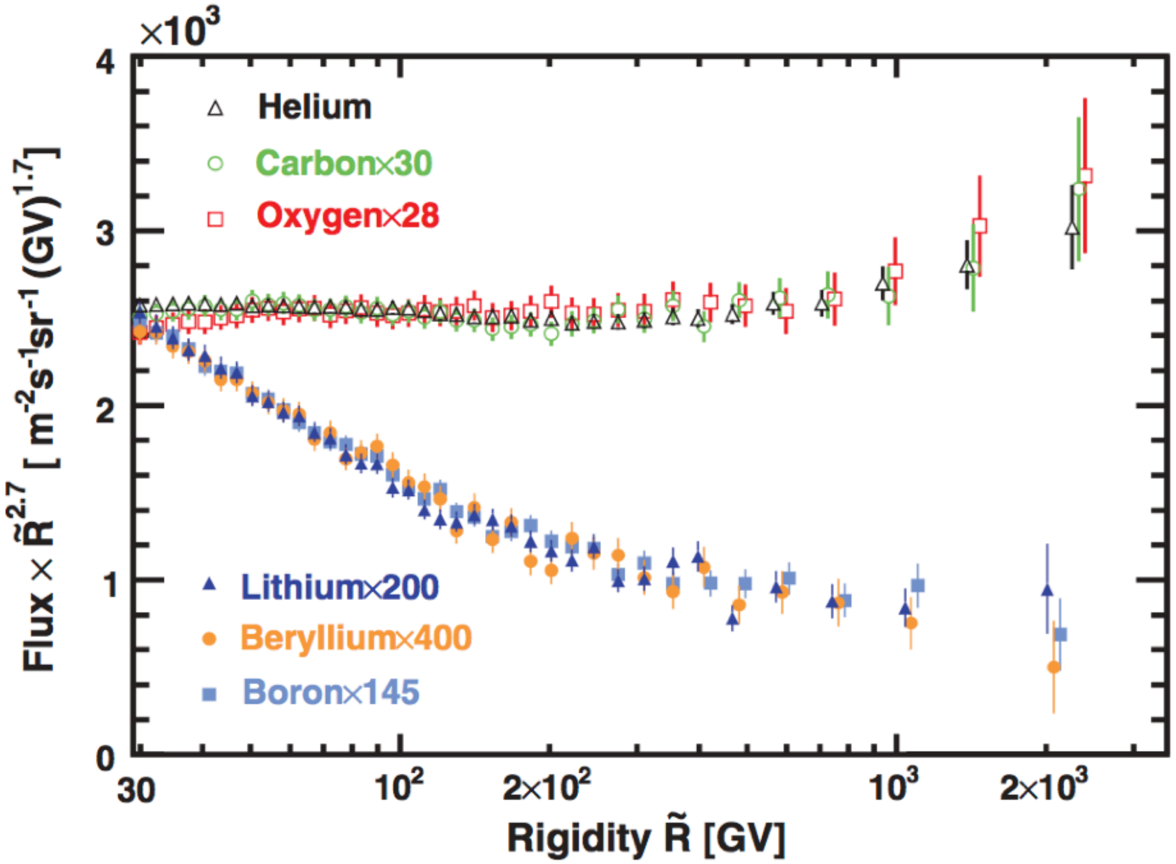
$$K(E) = K_0\,\beta^\eta \frac{(R/1\,\mathrm{GV})^\delta}{\left\{1 + (R/R_b)^{\Delta\delta/s}\right\}^s}$$

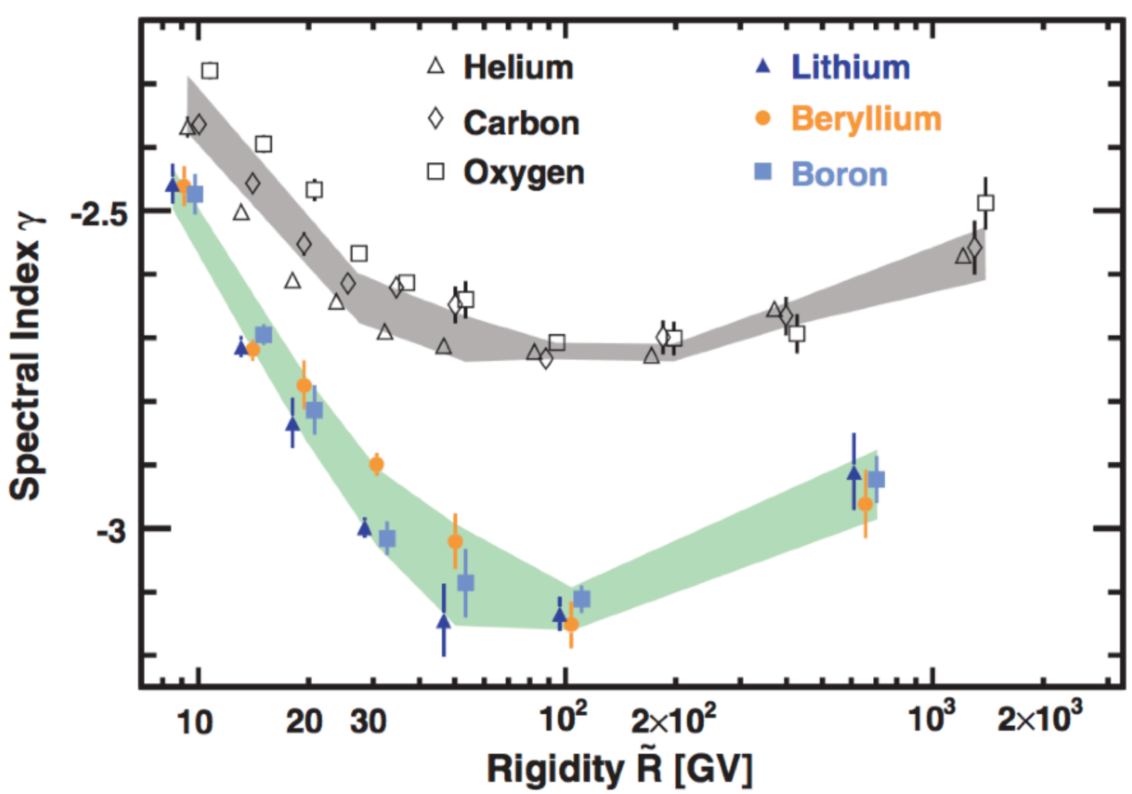
The break at ~200 GV is most likely due to propagation effects!

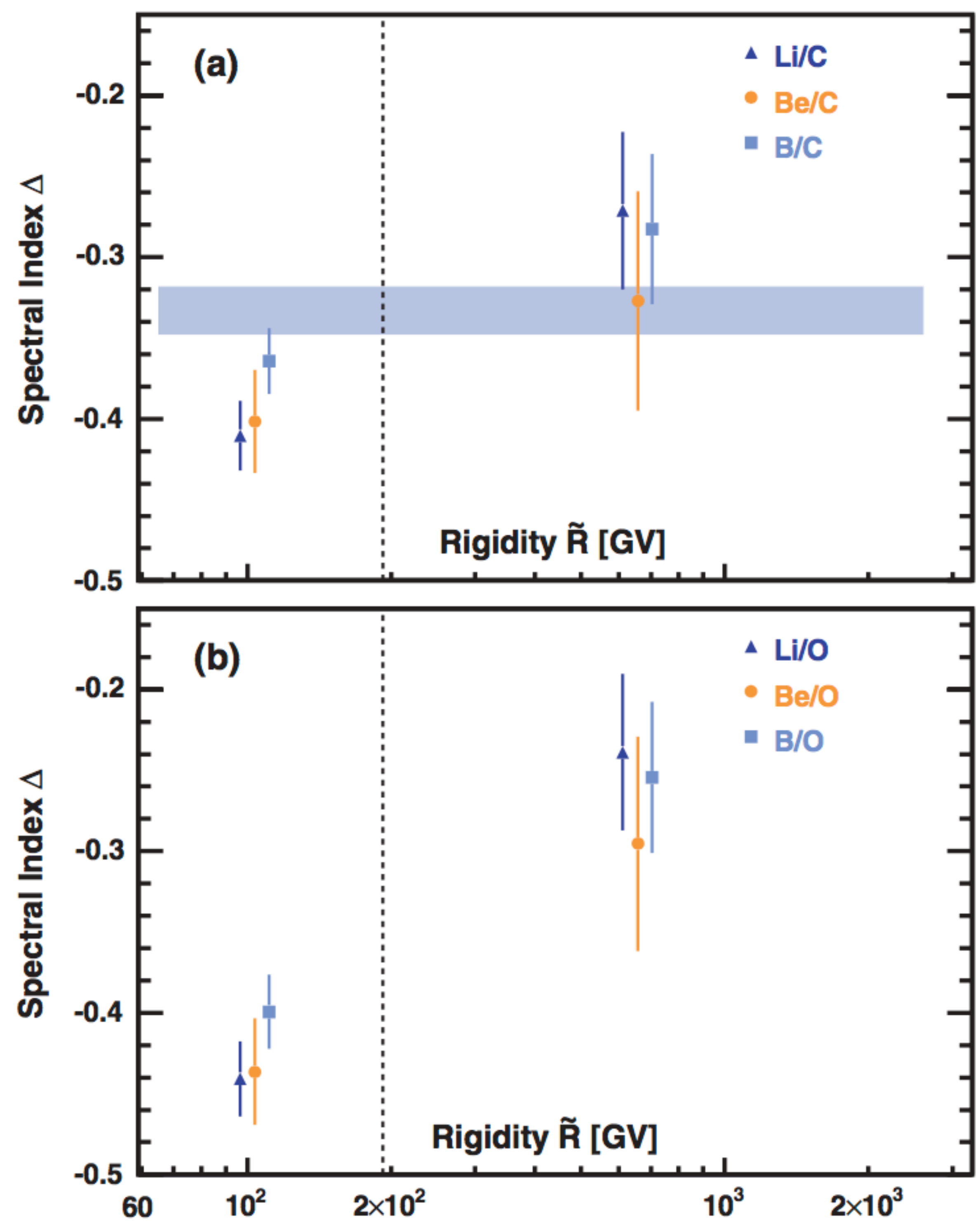
Y. Genolini, P. Serpico, MB, S. Caroff, V. Poulin, L. Derome, J. Lavalle, D. Maurin, V. Poireau, S. Rosier-Lee, P. Salati, and M. Vecchi (2017)

A universal break in the spectra of cosmic ray nuclei?

The propagation origin of the hardening is confirmed by the recent AMS-02 release *PRL, 12, 011102, (2017)*







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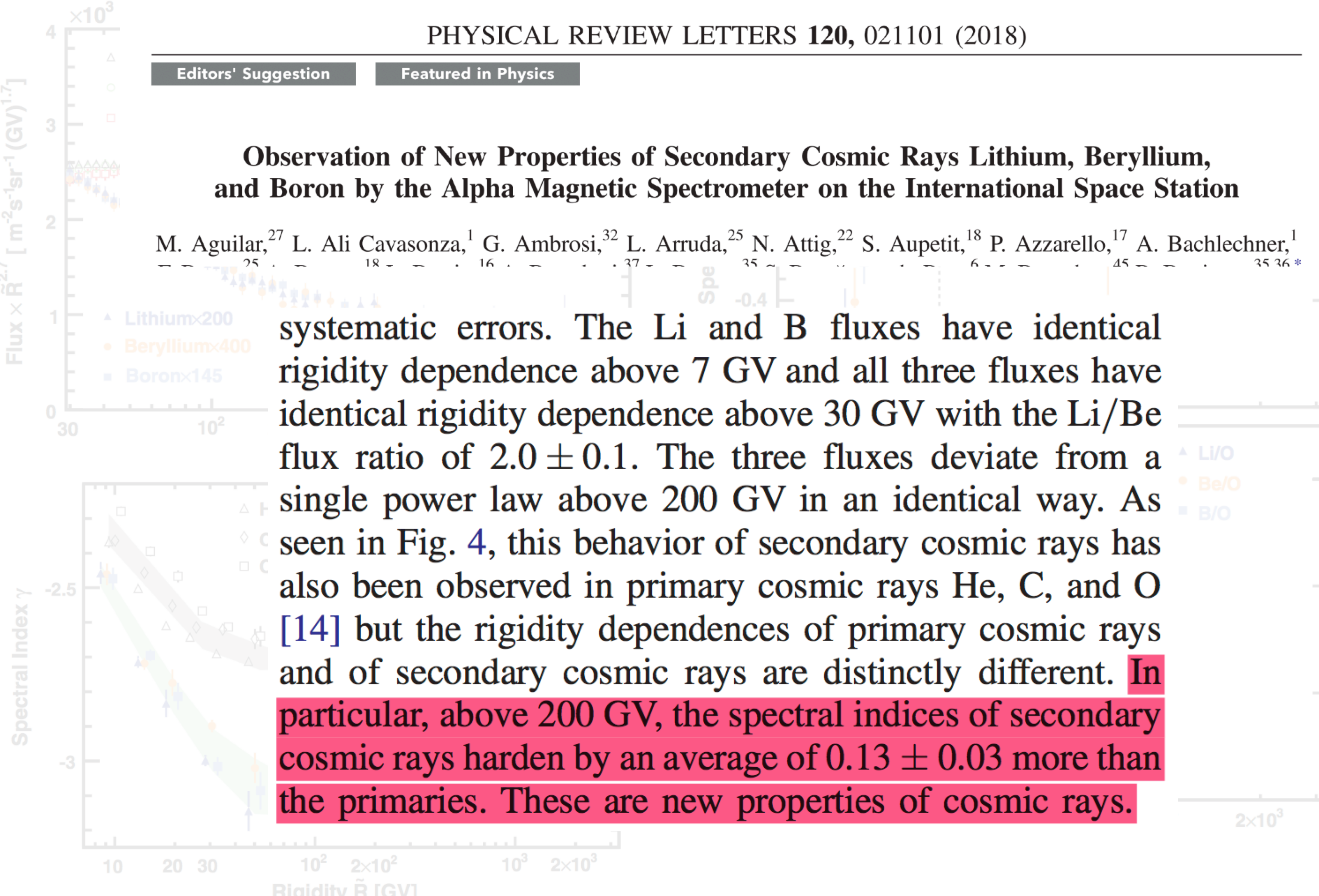

PHYSICAL REVIEW LETTERS **120,** 021101 (2018)

Editors' Suggestion | Featured in Physics

Observation of New Properties of Secondary Cosmic Rays Lithium, Beryllium, and Boron by the Alpha Magnetic Spectrometer on the International Space Station

M. Aguilar,[27] L. Ali Cavasonza,[1] G. Ambrosi,[32] L. Arruda,[25] N. Attig,[22] S. Aupetit,[18] P. Azzarello,[17] A. Bachlechner,[1]

systematic errors. The Li and B fluxes have identical rigidity dependence above 7 GV and all three fluxes have identical rigidity dependence above 30 GV with the Li/Be flux ratio of 2.0 ± 0.1. The three fluxes deviate from a single power law above 200 GV in an identical way. As seen in Fig. 4, this behavior of secondary cosmic rays has also been observed in primary cosmic rays He, C, and O [14] but the rigidity dependences of primary cosmic rays and of secondary cosmic rays are distinctly different. In particular, above 200 GV, the spectral indices of secondary cosmic rays harden by an average of 0.13 ± 0.03 more than the primaries. These are new properties of cosmic rays.

A universal break in the spectra of cosmic ray nuclei?

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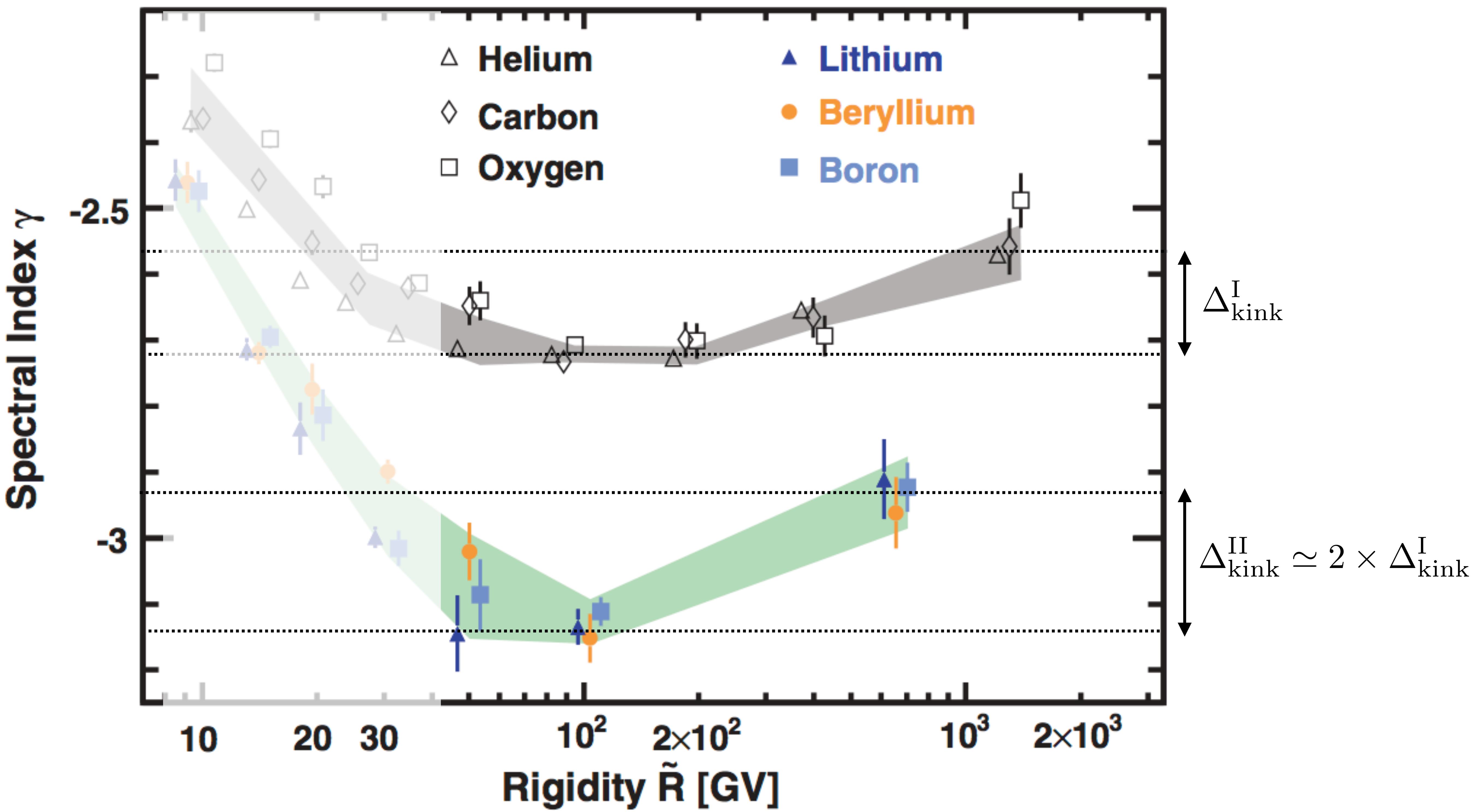
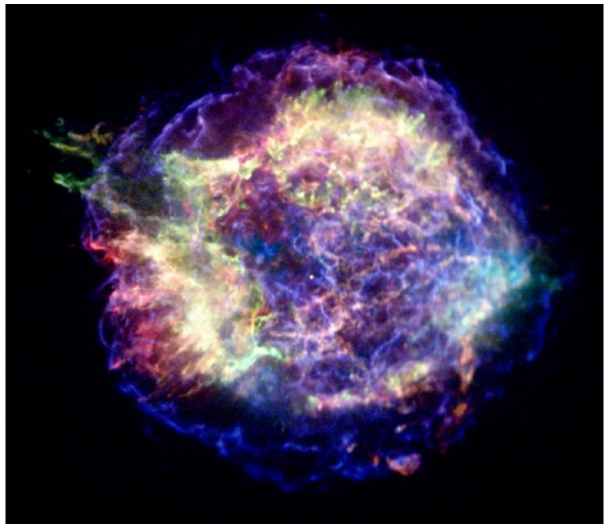


Primary antiprotons?

Primary antiprotons = production in the shocks of supernova remnants (SNRs)



1- Antiprotons are produced close to the shock $p + \mathrm{H} \to \bar{p} + X$

2- Antiprotons are accelerated in the shock by diffusive stochastic acceleration (DSA)

Blasi & Serpico (2009), Mertsch & Sarkar (2014)

Common belief: secondaries from propagation are much more abundant since the grammage in the ISM is much larger than in the source.

$R \sim 100\ \mathrm{GV}$

Secondaries

$\tau_{\mathrm{esc}} \sim 10^7\ \mathrm{yr}$

$n_{\mathrm{ISM}} \simeq 1\ \mathrm{cm}^{-3}$

$\langle \rho_{\mathrm{halo}} \rangle \sim 10^{-26} \mathrm{g\,cm}^{-3}$

$\lambda_{\mathrm{II}} \sim 1\ \mathrm{g\,cm}^{-2}$

Primaries

$\tau_{\mathrm{SNR}} \sim 10^4\ \mathrm{yr}$

$n_{\mathrm{SNR}} = (r \leq 4) \times n_{\mathrm{ISM}}$

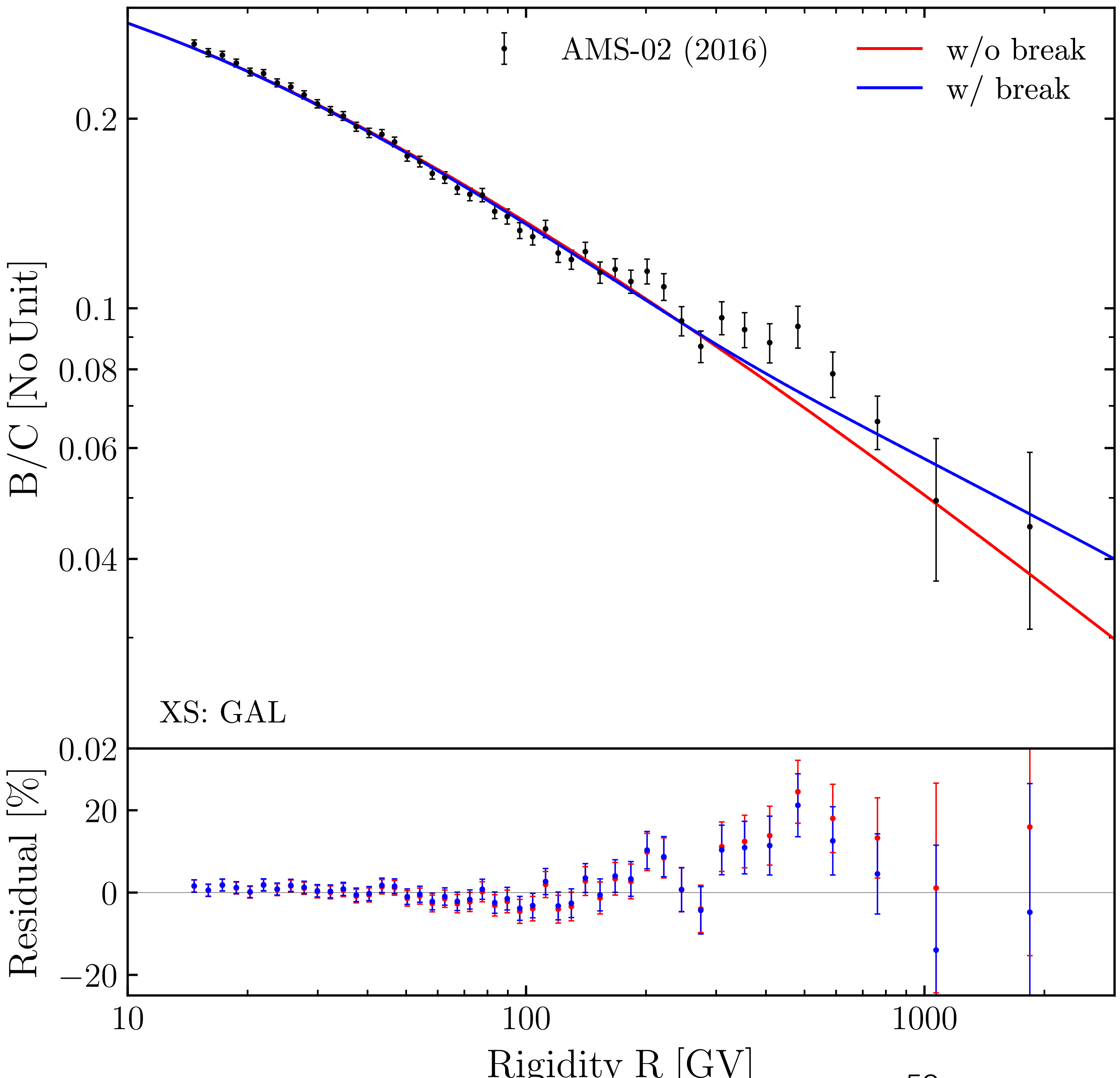
$\langle \rho_{\mathrm{SNR}} \rangle \sim 10^{-24} \mathrm{g\,cm}^{-3}$

$\lambda_{\mathrm{I}} \sim 0.01\ \mathrm{g\,cm}^{-2}$

We expect ~1% of primary B and antiprotons

Antiprotons excess at ~10 GeV?

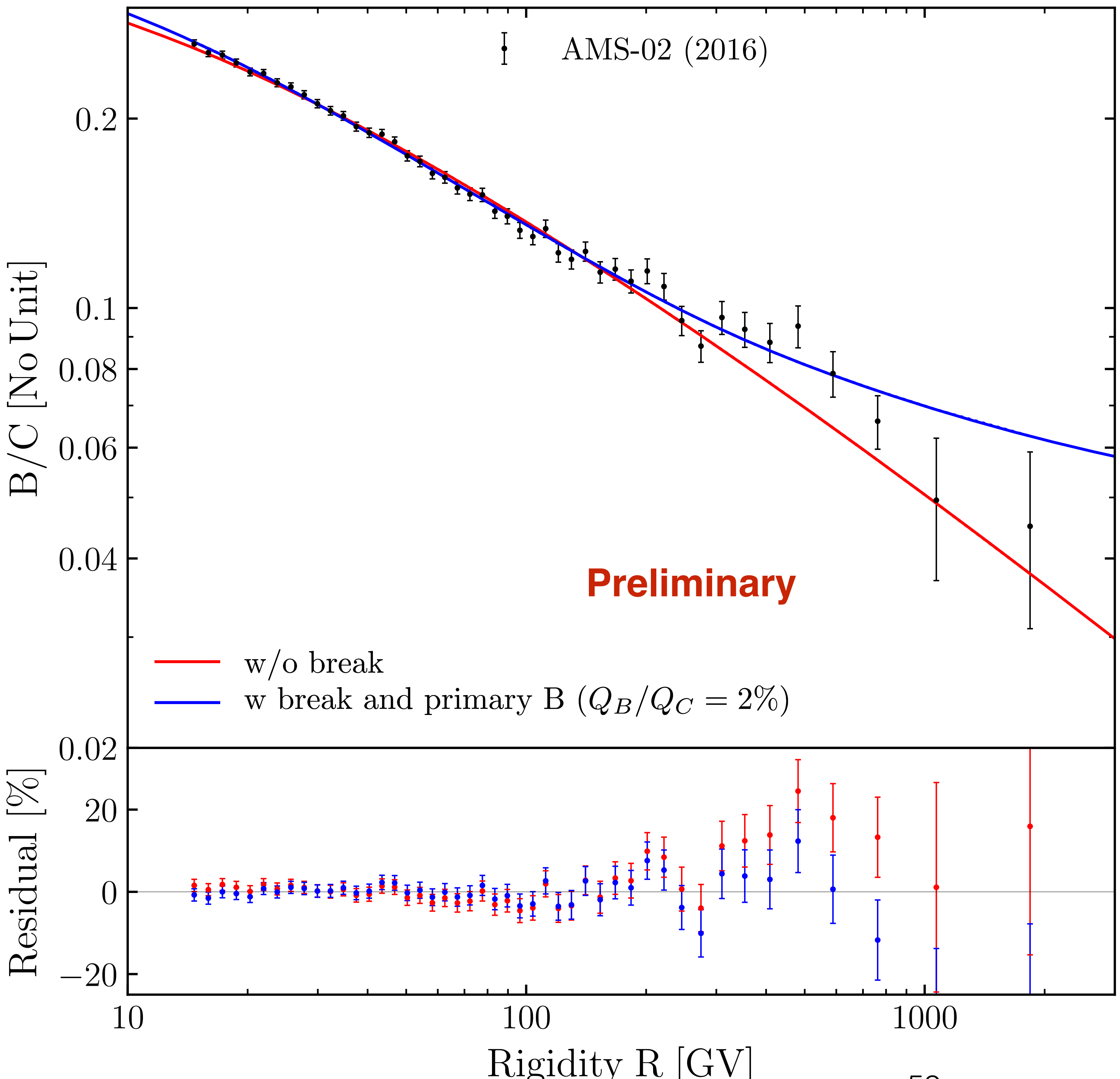
- Break in the diffusion coefficient K(E) from B/C ratio



- standard (w/o break) χ^2_{dof} = 62/41
- w/ break χ^2_{dof} = 50/41

Antiprotons excess at ~10 GeV?

- Break in the diffusion coefficient K(E) from B/C ratio
- Primary B and antiprotons produced in SNRs: Q_B/Q_C = 2% (in a simplified model)



- standard (w/o break) χ^2_{dof} = 62/41
- w/ break χ^2_{dof} = 50/41
- w/ break + Q_B/Q_C = 2%: χ^2_{dof} = 37/41

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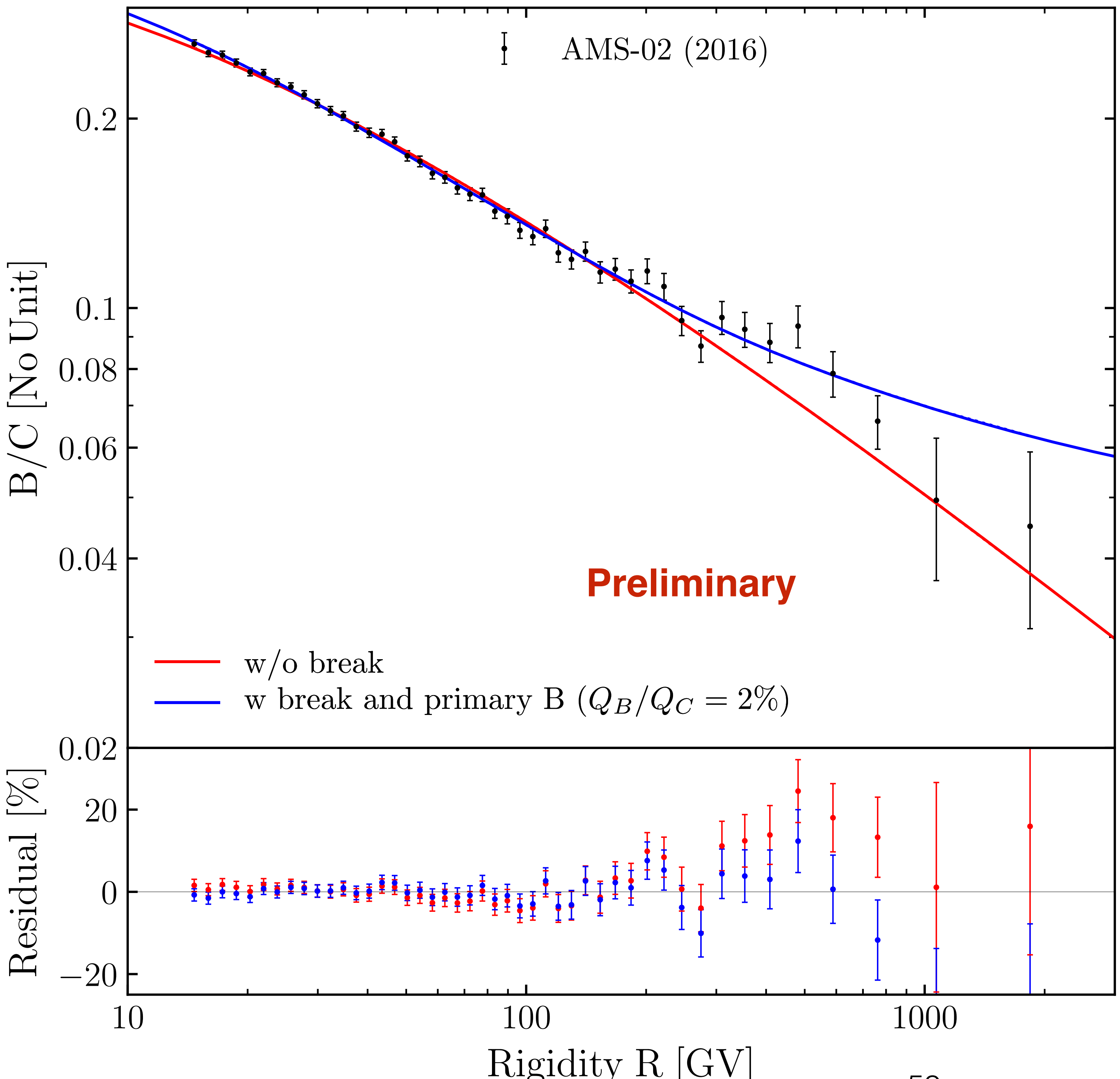


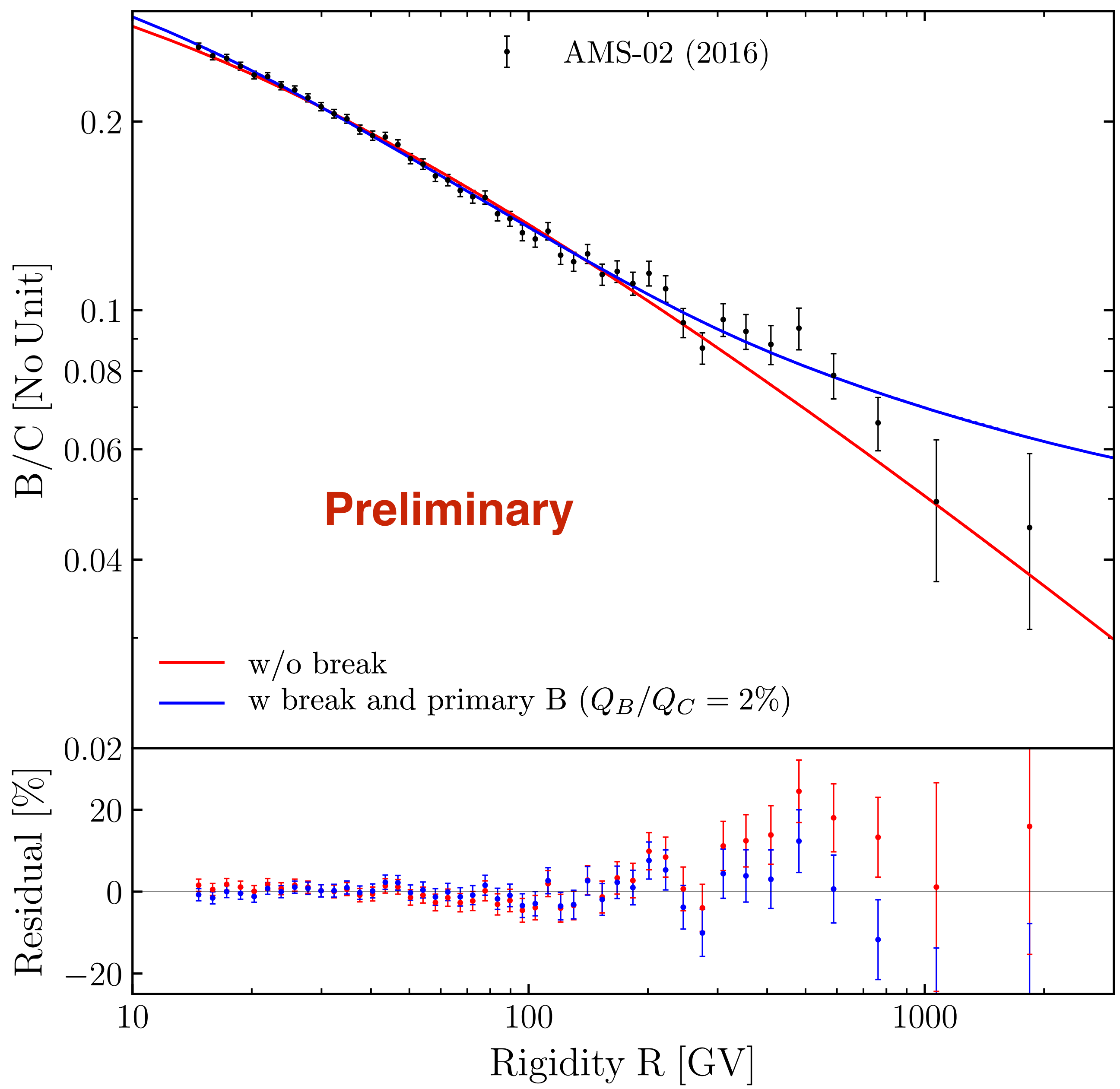
- standard (w/o break) χ^2_{dof} = 62/41
- w/ break χ^2_{dof} = 50/41
- w/ break + Q_B/Q_C = 2%: χ^2_{dof} = 37/41

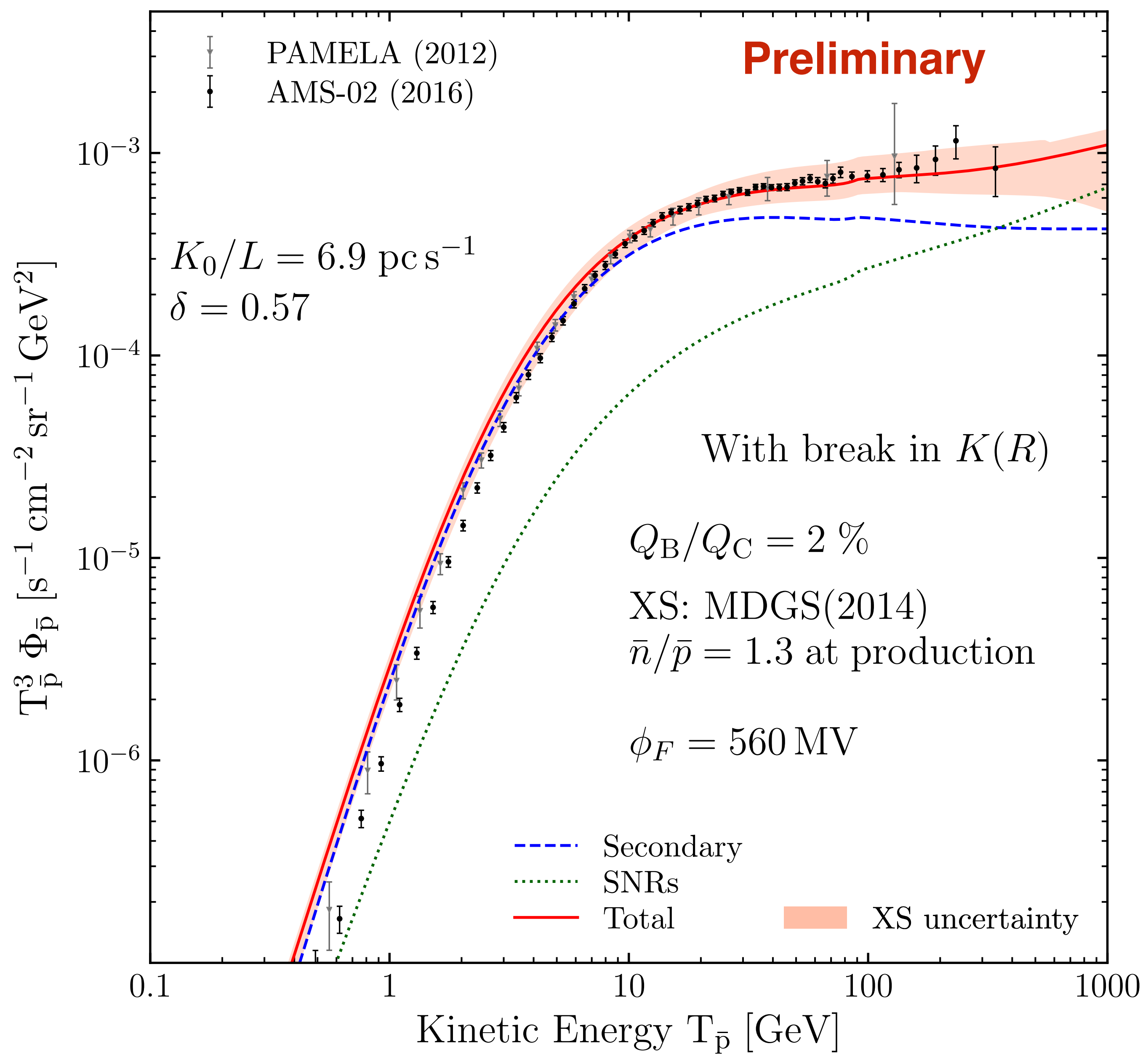
If B nuclei are produced in SNRs, all secondary species too!

Including antiprotons!

Antiprotons excess at ~10 GeV?

- Break in the diffusion coefficient K(E) from B/C ratio
- Primary B and antiprotons produced in SNRs: Q_B/Q_C = 2% (in a simplified model)

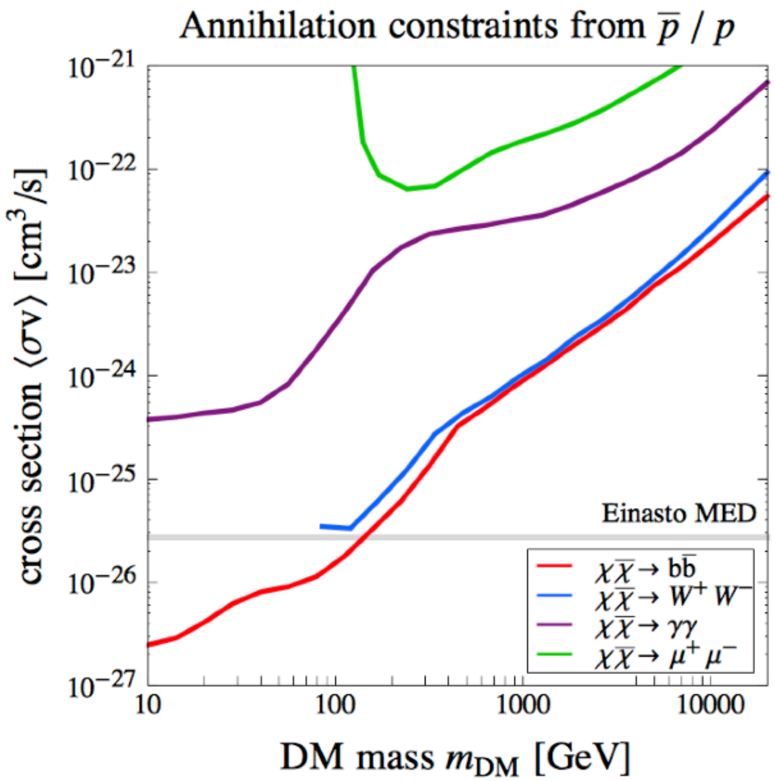




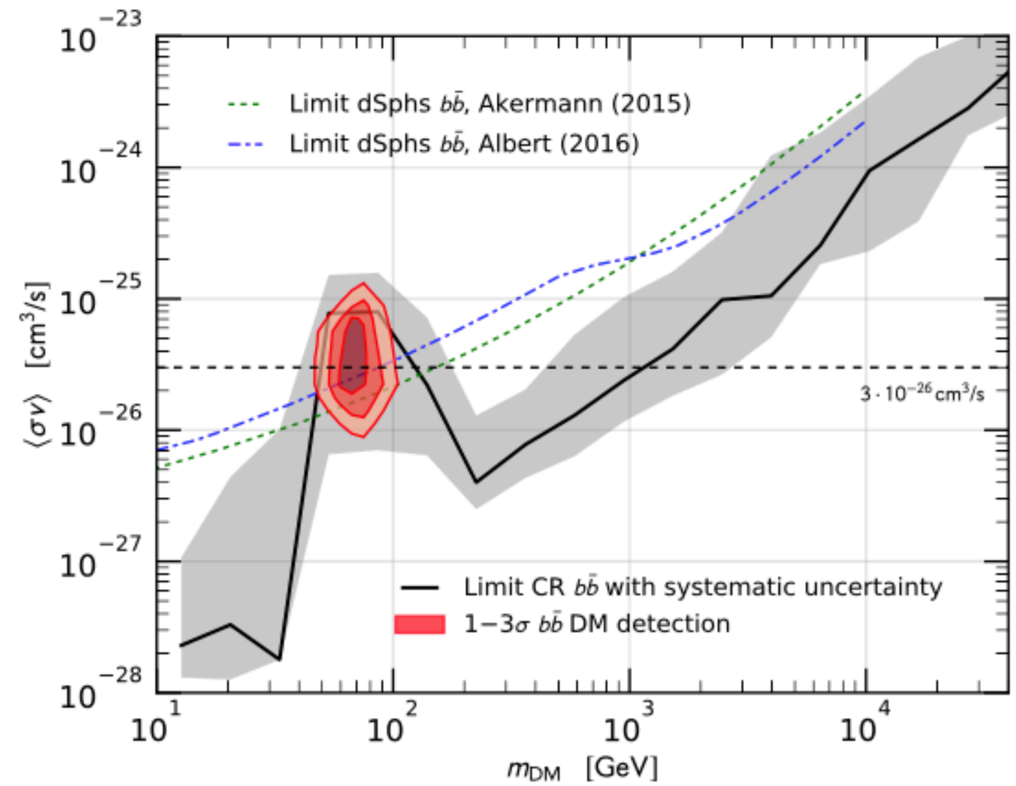
Are AMS-02 data sensitive to the production of antiprotons in SNRs?

Dark matter constraints

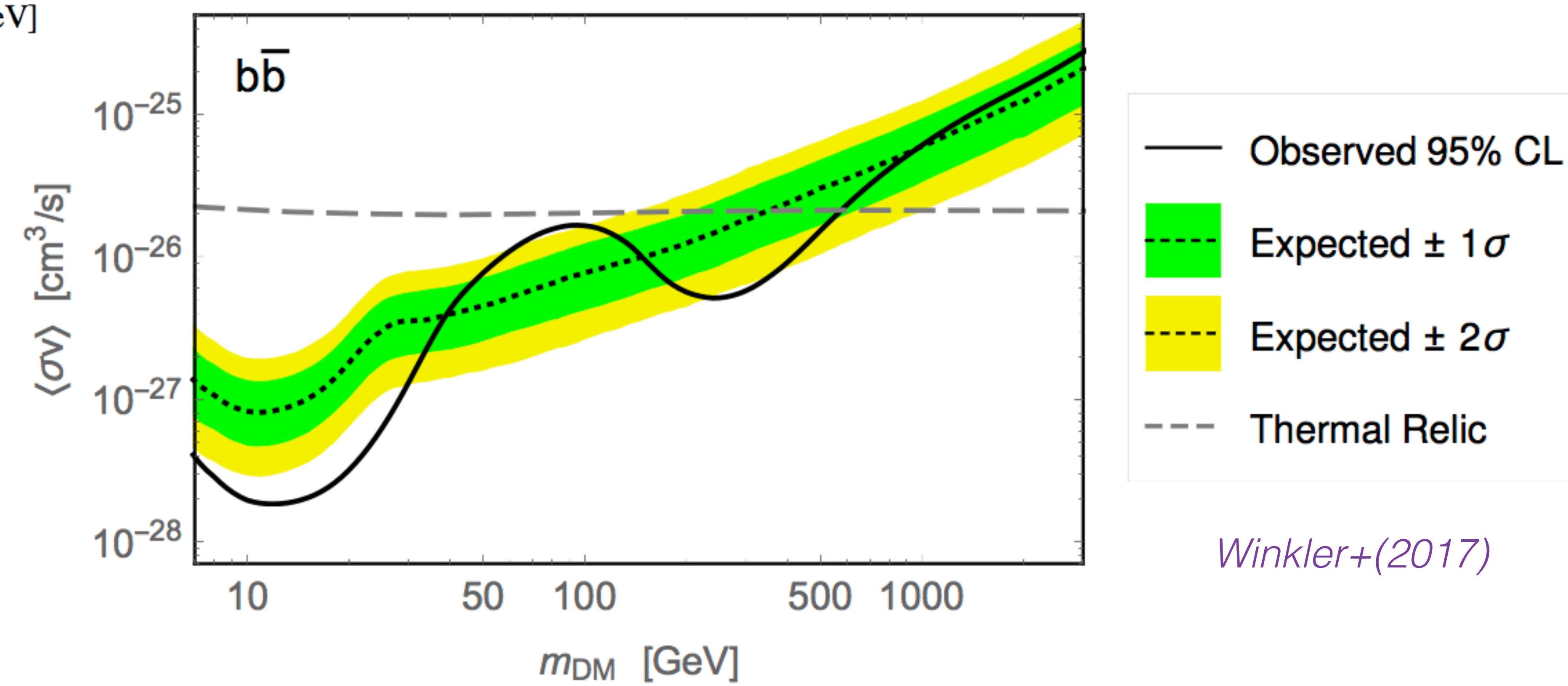
Still, antiprotons provide strong constraints on the DM annihilating cross-section, excluding thermal WIMPs with $m_\chi \lesssim 500\ \mathrm{GeV}$



Giesen+(2015)



Cuoco+(2016)



Winkler+(2017)

Conclusion and outlook

Positrons and electrons

- The **pinching method** enables to compute **analytically** the electrons and positrons flux below 10 GeV taking into account all propagation effects.

- Low energy positrons enables to shrink the space of propagation parameters. The data prefer a **MAX-type** set of propagation parameters with large values of **L** and small values of **δ**.

- The positron excess appears from 1 GeV.

- The **pure DM** scenario is **disfavoured** by the data.

  The spectrum of e^+ from DM annihilations cannot account for the shape of the data.

  This conclusion does not require other constraints (gamma rays, antiprotons or CMB).

- The **single pulsar** scenario provides a **valid** alternative to the DM scenario.

- We derive constraints on **MeV** Dark Matter using **Voyager-I** and **AMS-02 data**. Our constraints are competitive with X-rays and ɣ-rays ones as well as CMB ones.

  The constraints are more stringent than the one obtained from X-rays and ɣ-rays.

  Less (more stringent) compared to CMB constraints for s-wave (p-wave) $\langle\sigma v\rangle$.

Antiprotons

- Cosmic rays antiprotons are interesting for **DM searches** since not many processes are able to produce them
- Theoretical uncertainties (cross section, propagation) are still **larger** than AMS-02 errors
- **Excess** at ~10 GeV with respect to the recent **AMS-02 data**. (*With the standard propagation model*)
- Anomalies for **all cosmic ray nuclei** with respect to the **standard model of propagation**

Necessity to better understand the physics of Galactic cosmic rays (production and propagation)

Break in the diffusion coefficient? *Production of secondary CRs in SNRs?*

- Antiprotons provides **strong constraints** on the DM annihilating cross-section in the **GeV-TeV range**.

Thank you for your attention!

Questions?