What do Galactic electrons and positrons tell us about Dark Matter?

Mathieu Boudaud

Laboratoire de **P**hysique **T**héorique et **H**autes **E**nergies
Paris, France

IRN Terascale - Marseille
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Based on:

MB, E. F. Bueno, S. Caroff, Y. Genolini, V. Poulin, V. Poireau, A. Putze, S. Rosier, P. Salati and M. Vecchi
(Astron.Astrophys. 605 (2017) A17)

MB, J. Lavalle and P. Salati
(PhysRevLett.119.021103)

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

LPTHE
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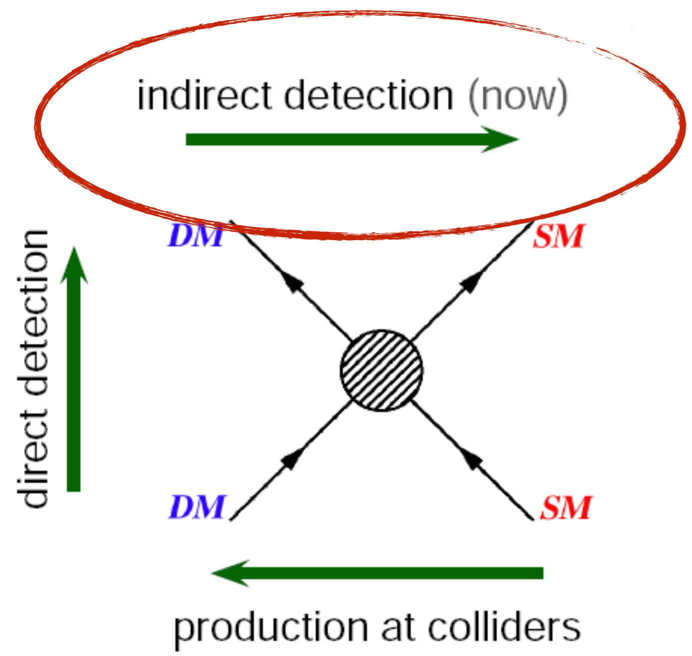
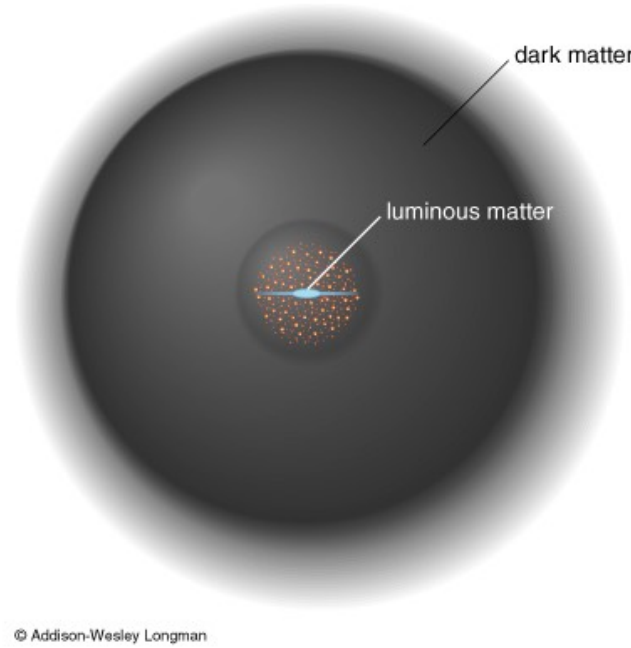
THEORIQUE ET HAUTES ENERGIES

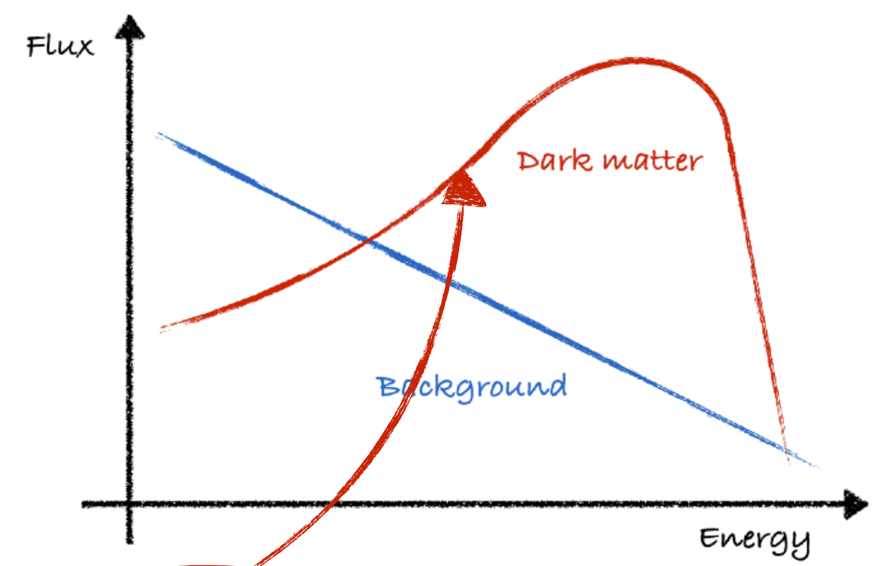
erc
NewDark

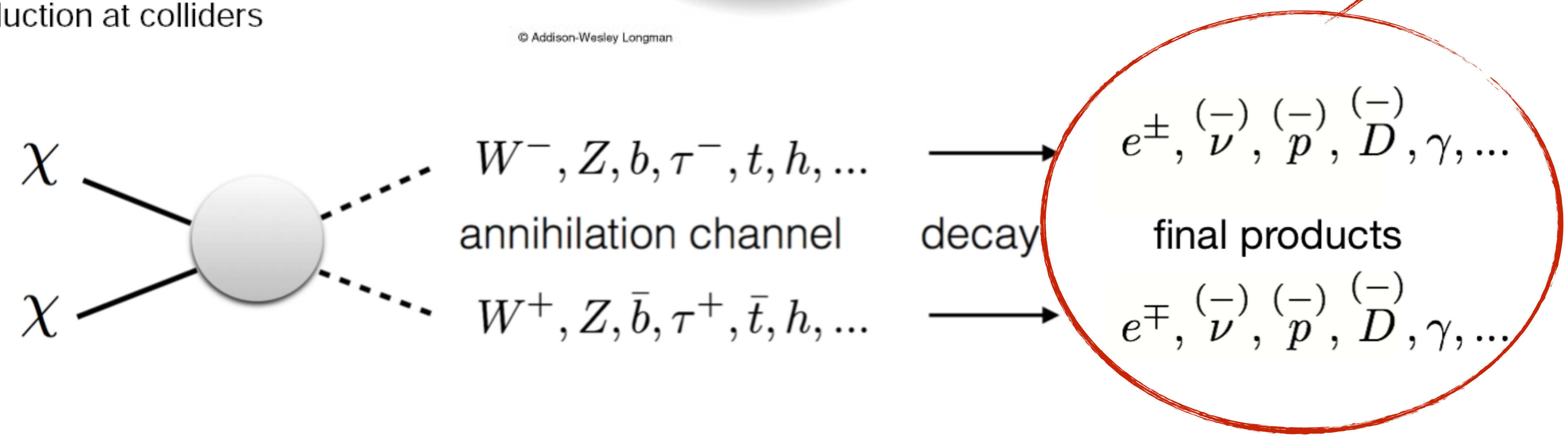
Dark matter indirect detection

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



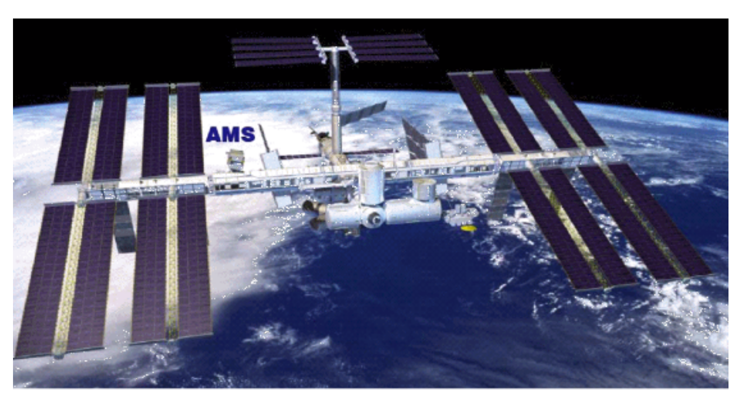




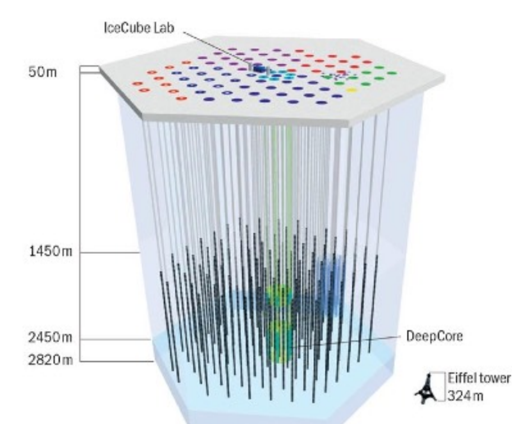


- Gamma rays
- Charged cosmic rays
- Neutrinos

HESS



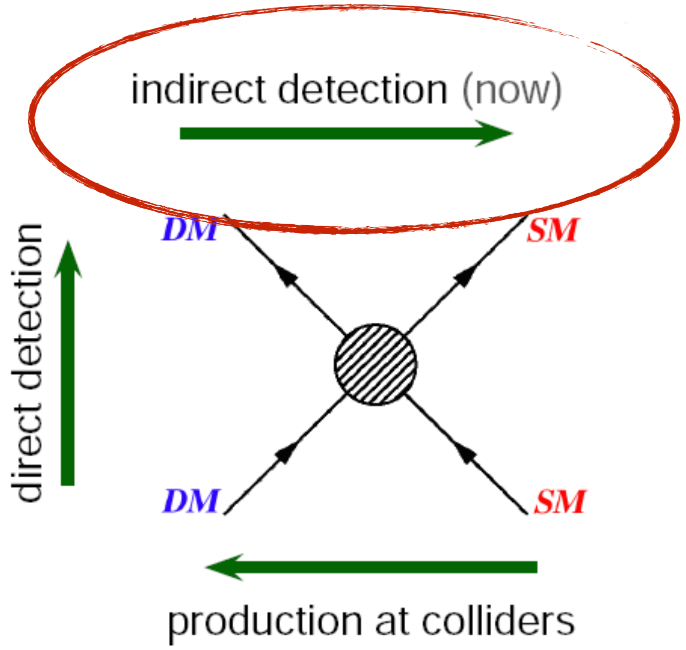
AMS-02

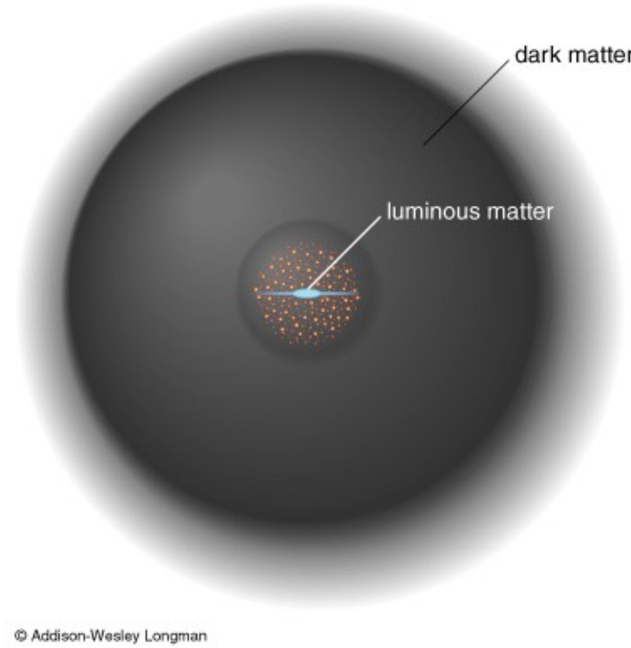


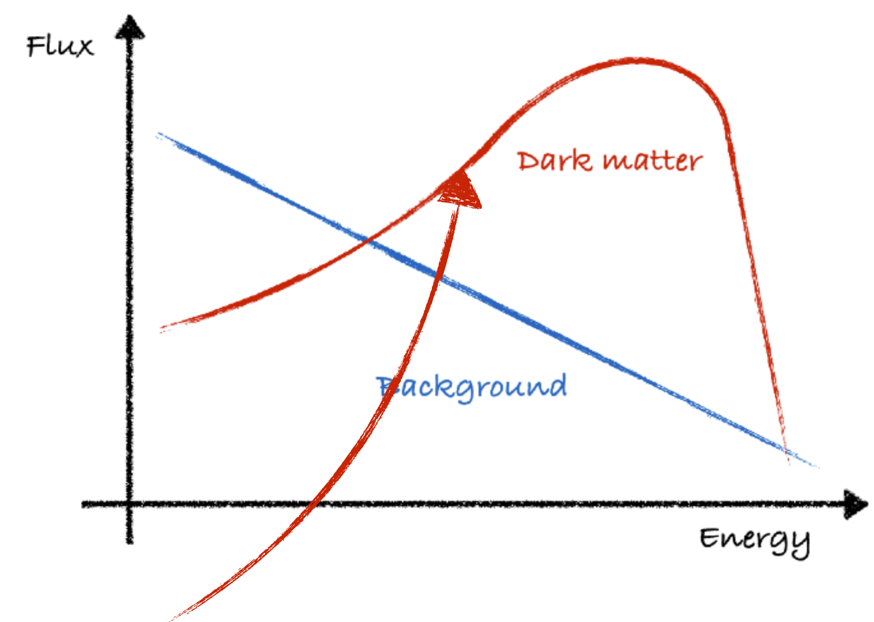
IceCube

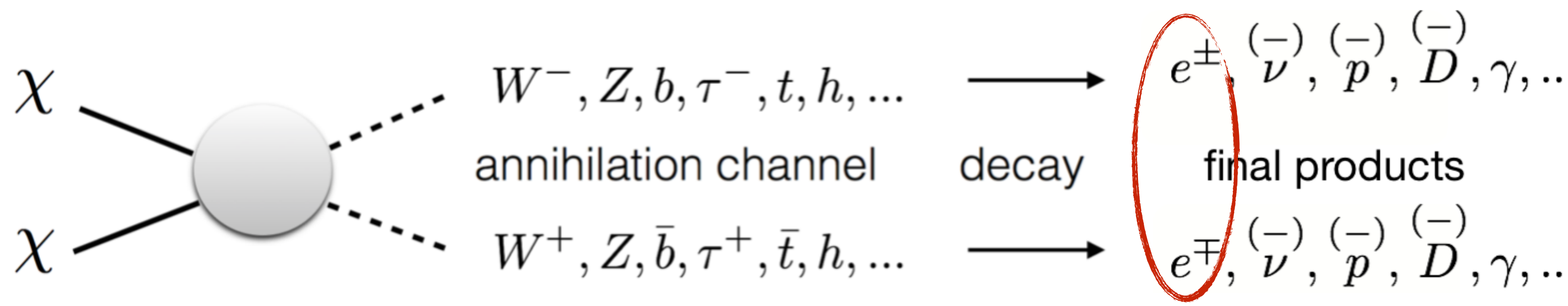
Dark matter indirect detection

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





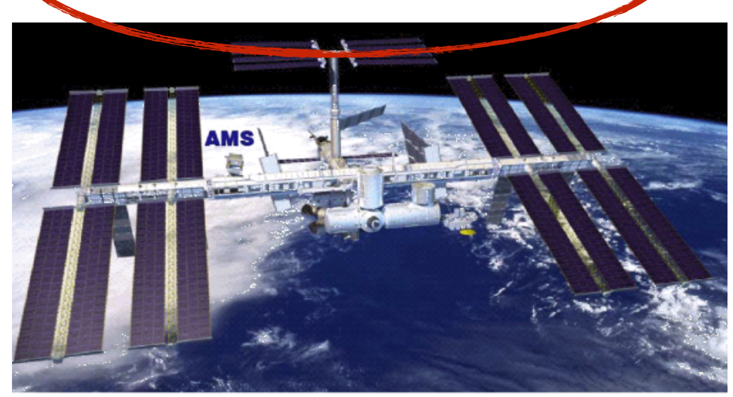




- Gamma rays

HESS

- Charged cosmic rays



AMS-02

- Neutrinos

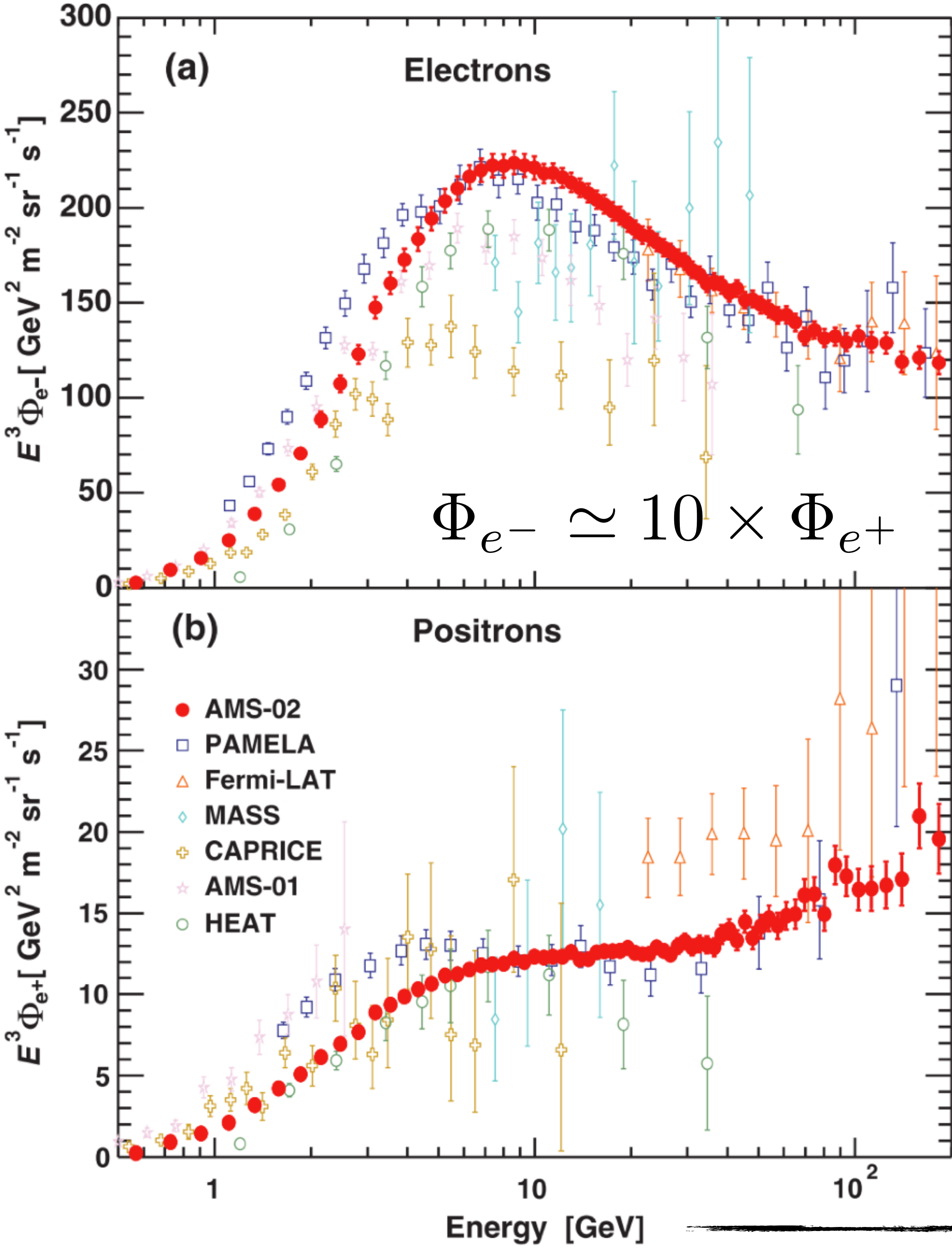
IceCube

AMS-02 e⁺ and e⁻ data

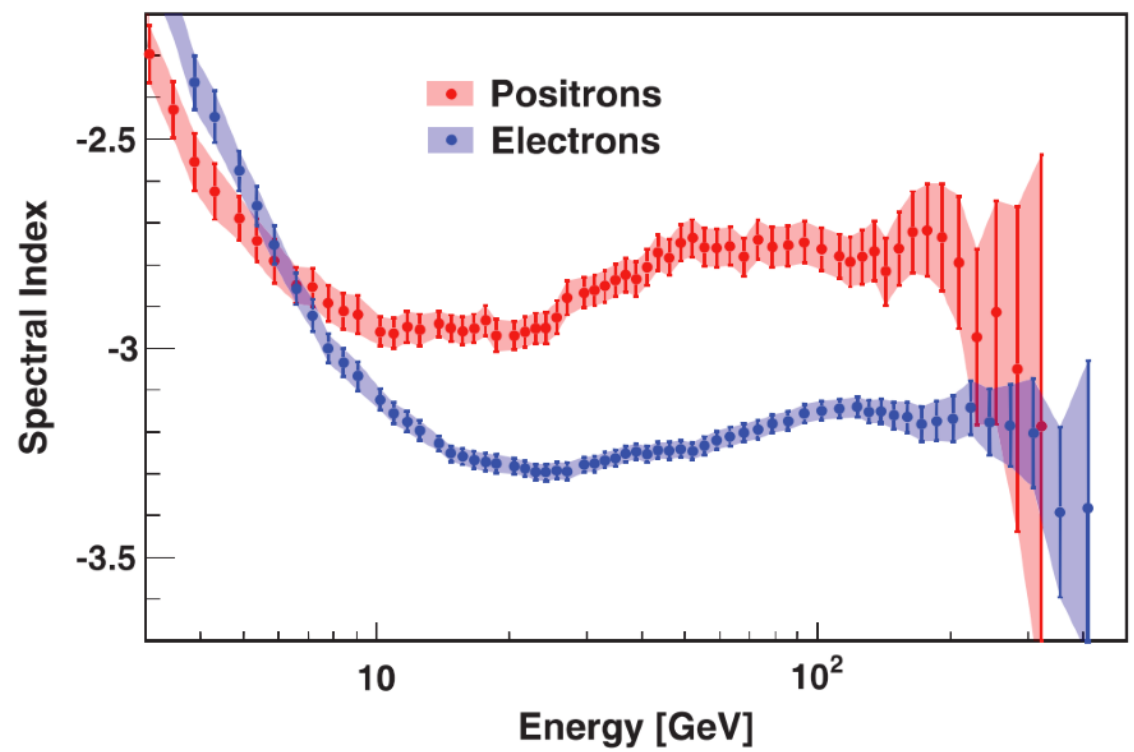
AMS-02 collaboration has measured the electrons, positrons flux and the positron fraction from ~ 0.5 GeV up to ~ 500 GeV with an unprecedented high accuracy.

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

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



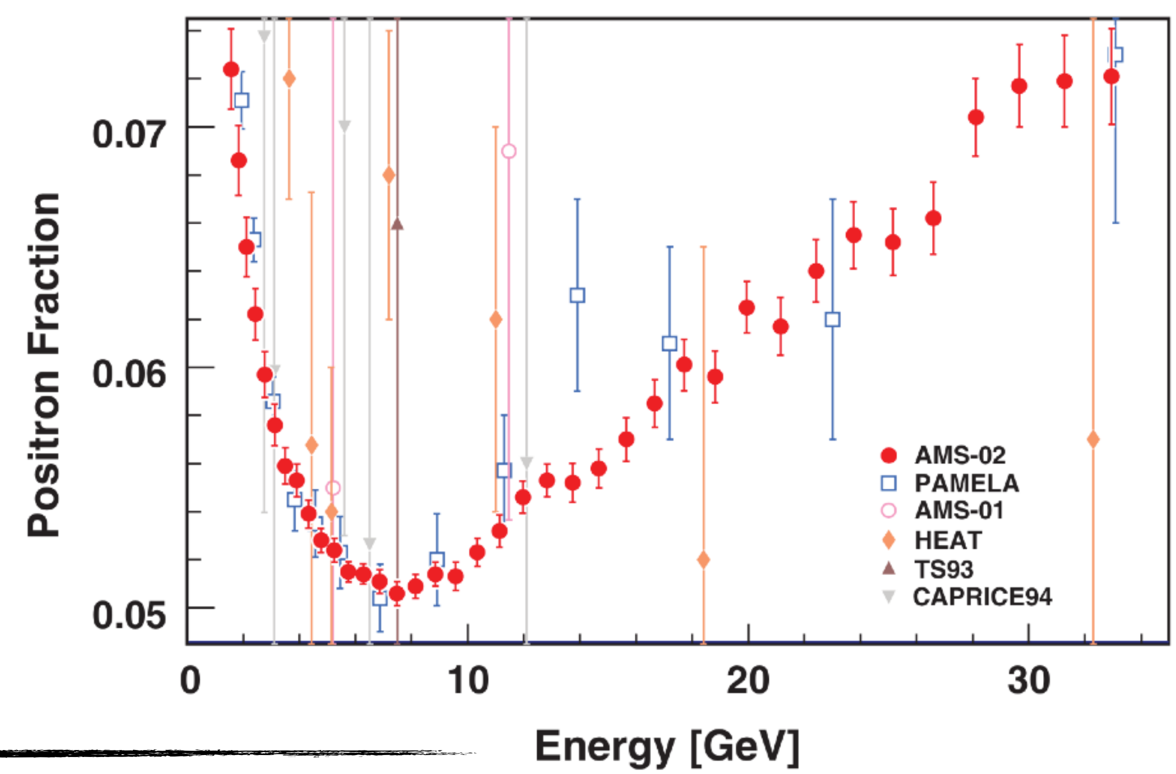
$$\Phi_{e^-} \simeq 10 \times \Phi_{e^+}$$

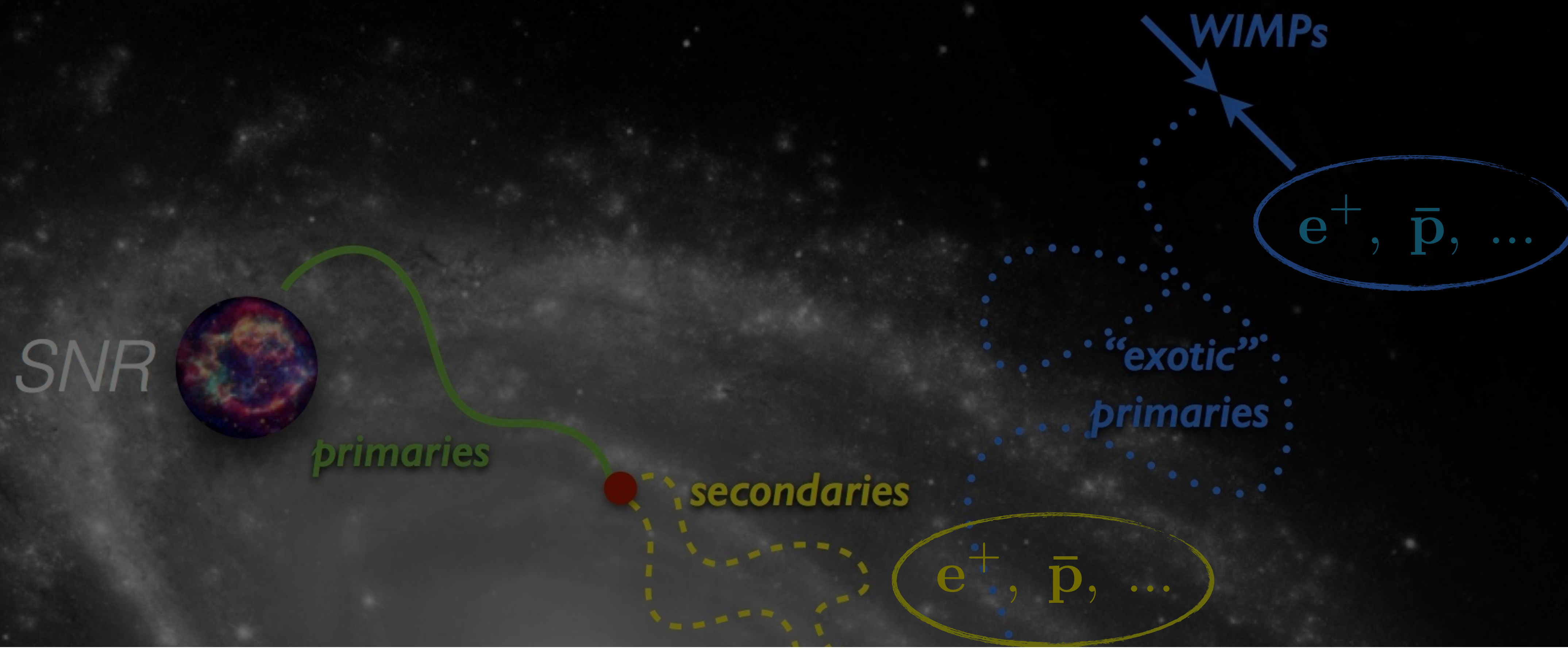


E ~ 100 GeV

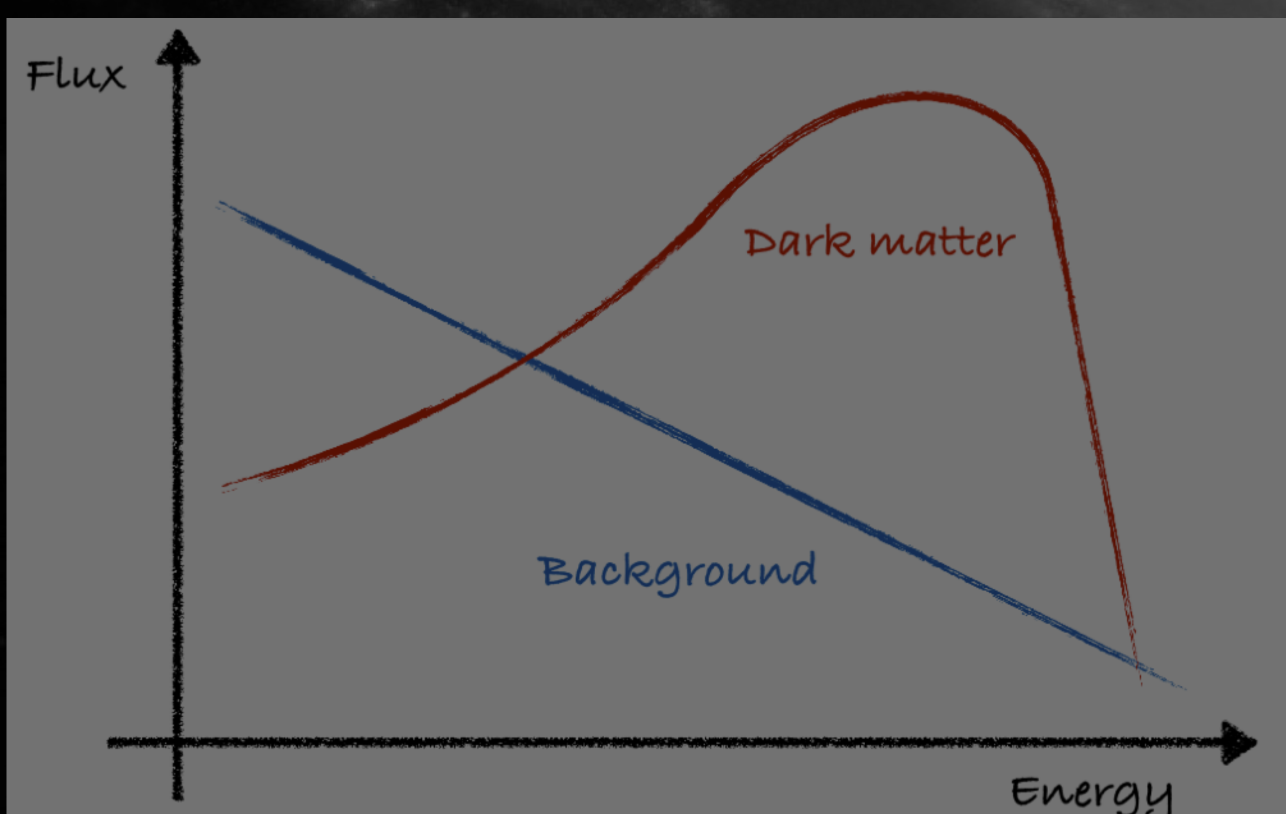
$\gamma_{e^+} \simeq 2.75$

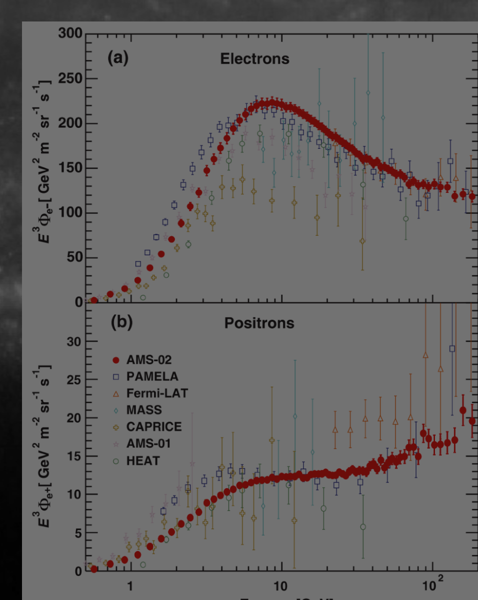
$\gamma_{e^-} \simeq 3.15$

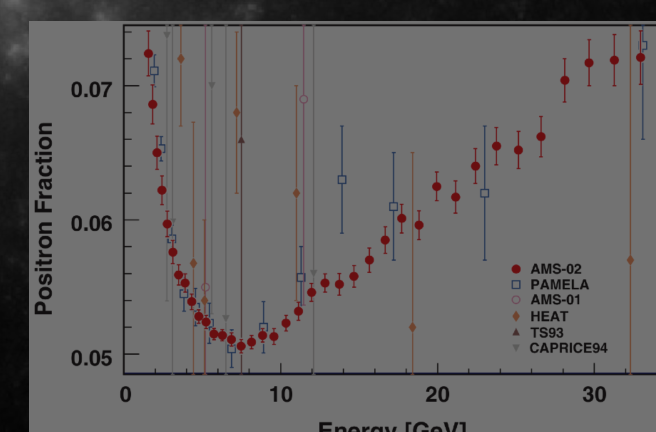




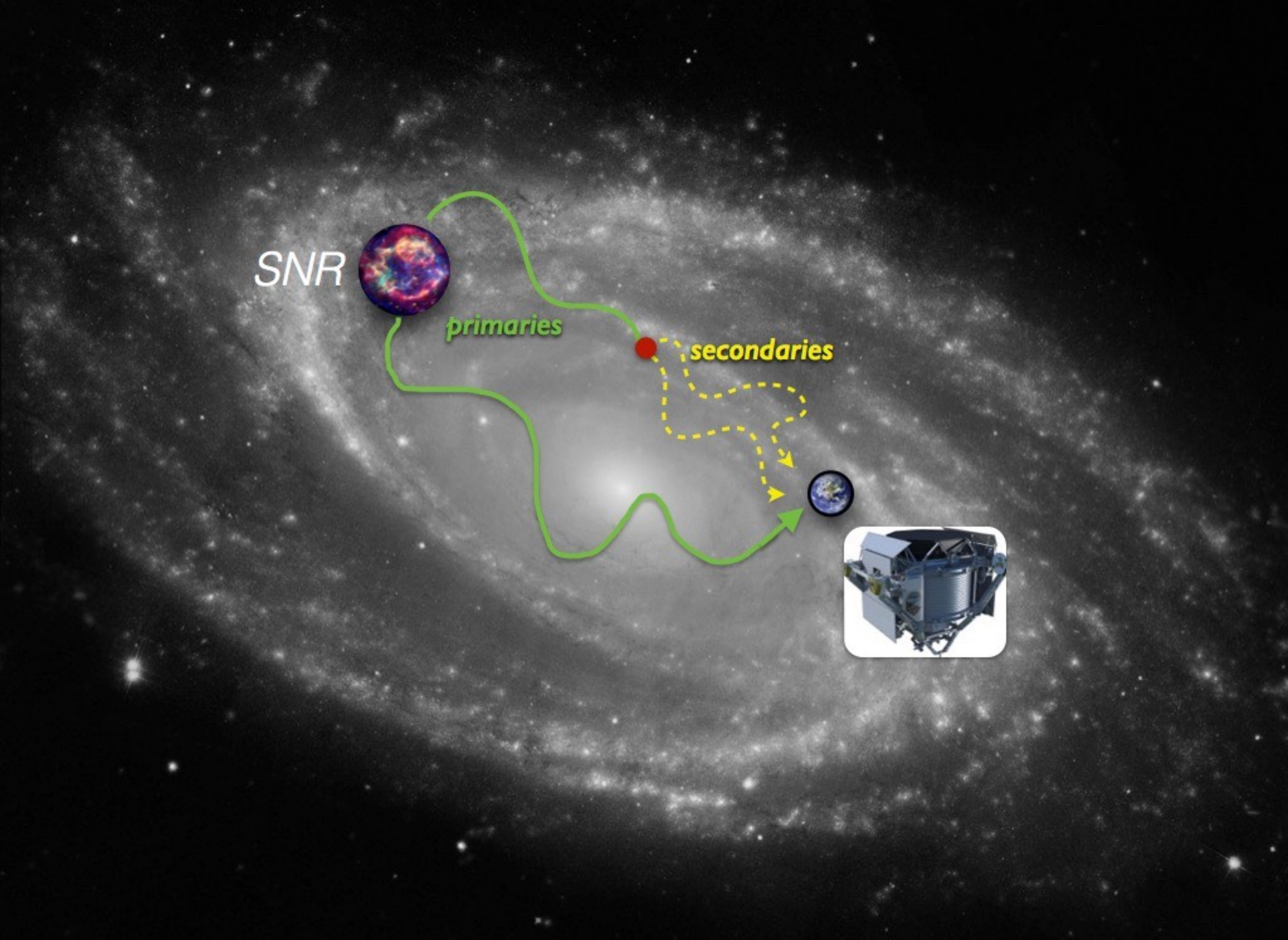
Is there any signal of dark matter in the e⁻ and/or e⁺ data?



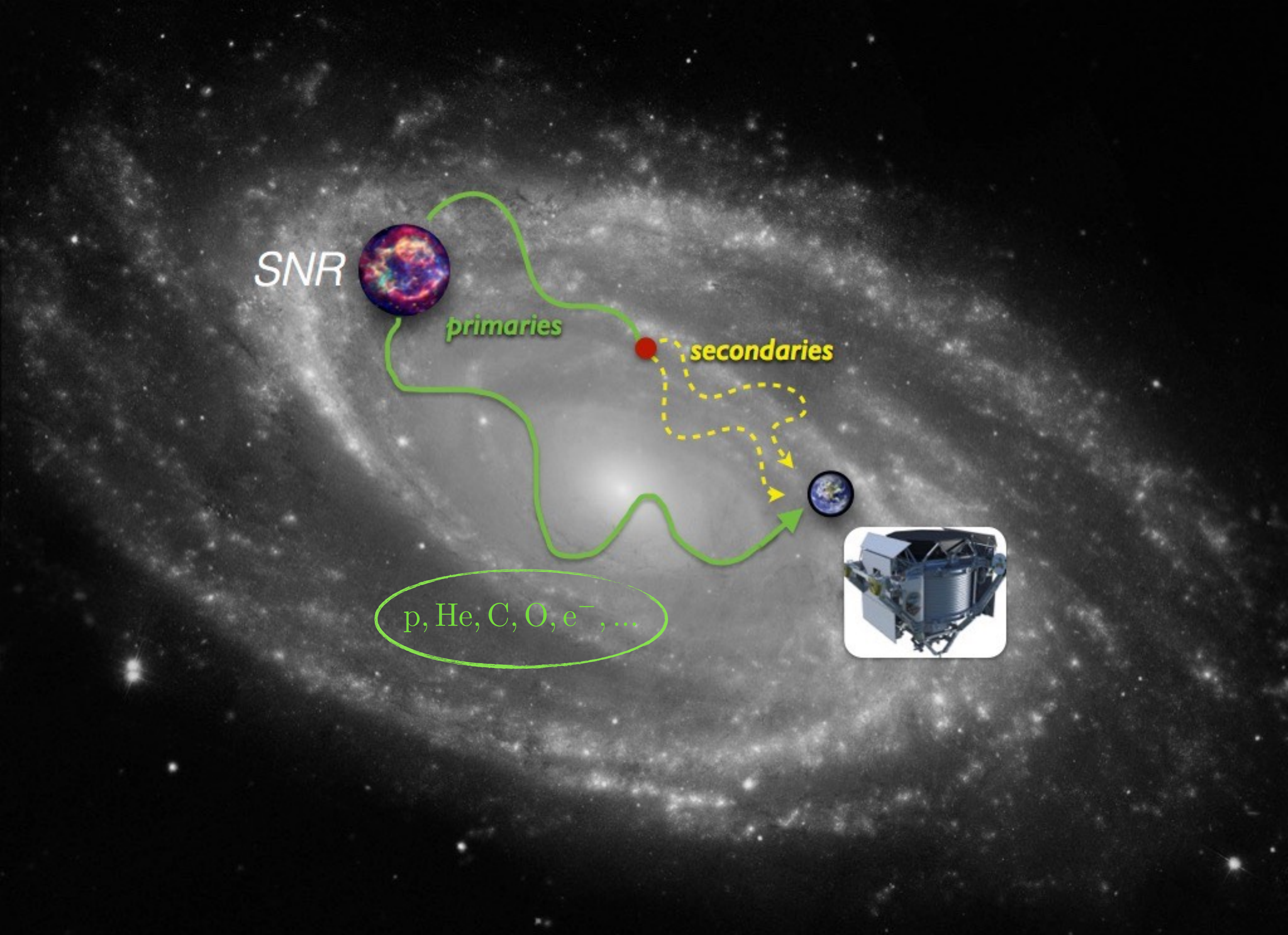




Propagation of cosmic rays: the diffusion model



Courtesy A. Putze



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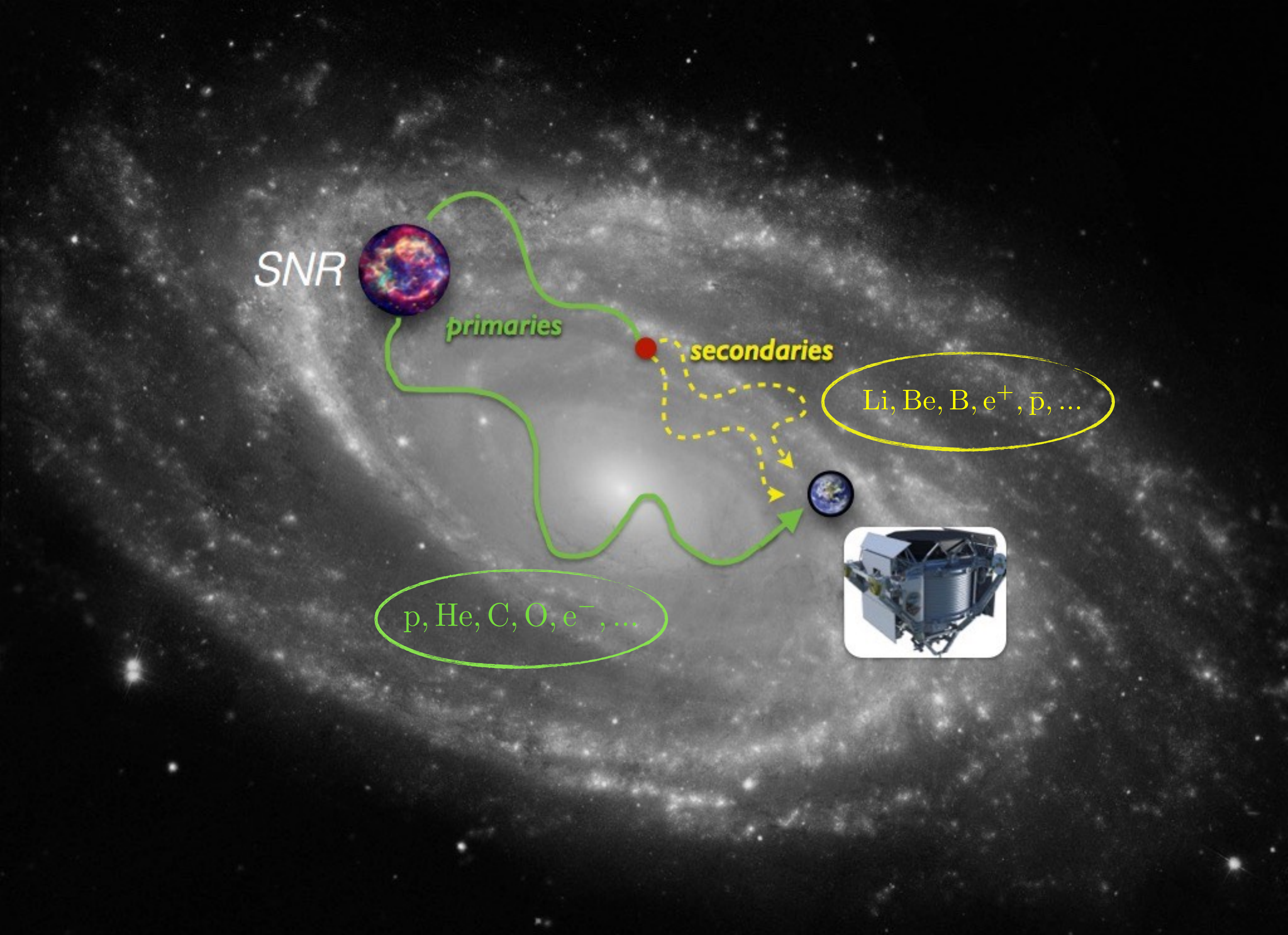

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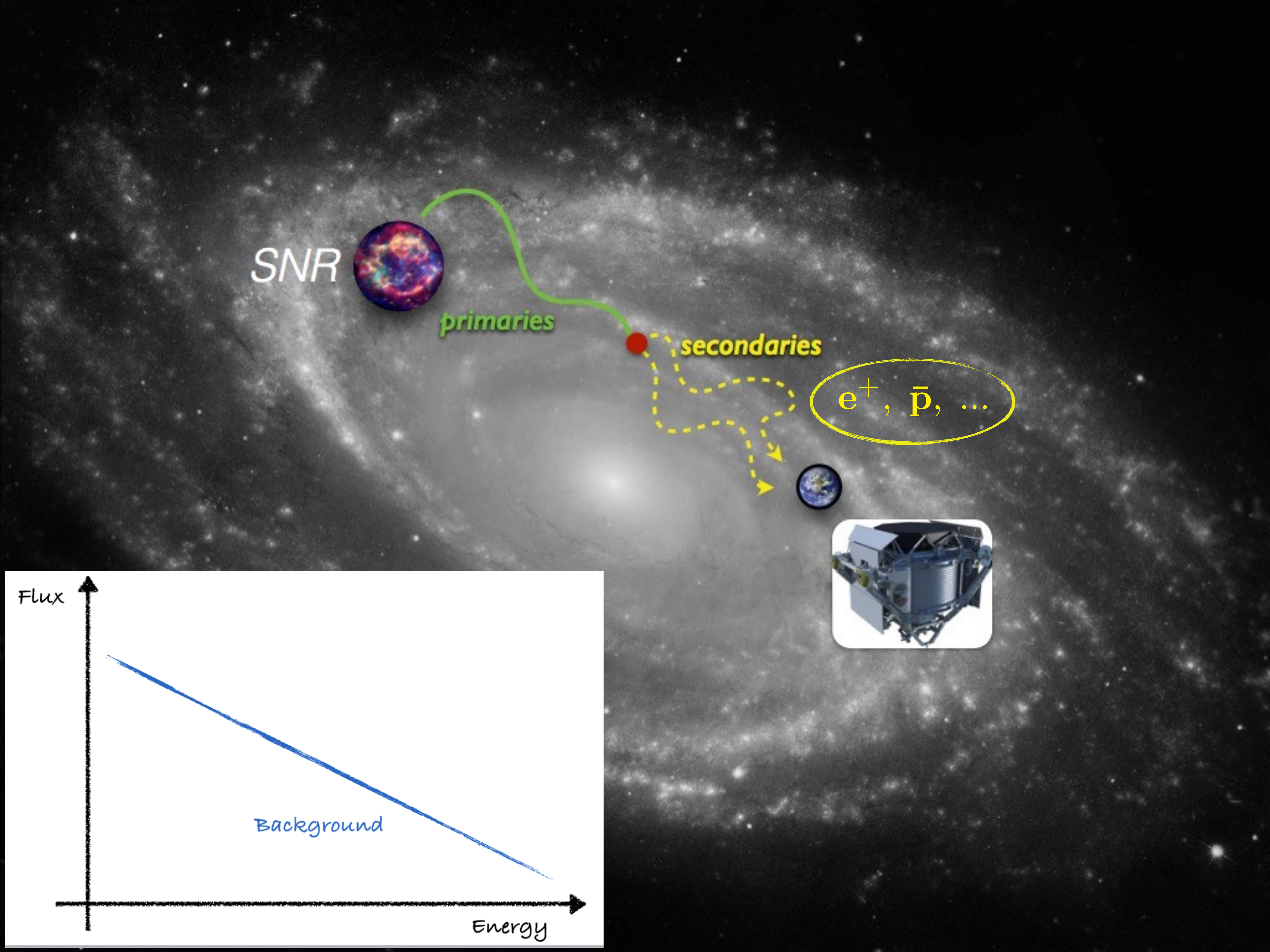
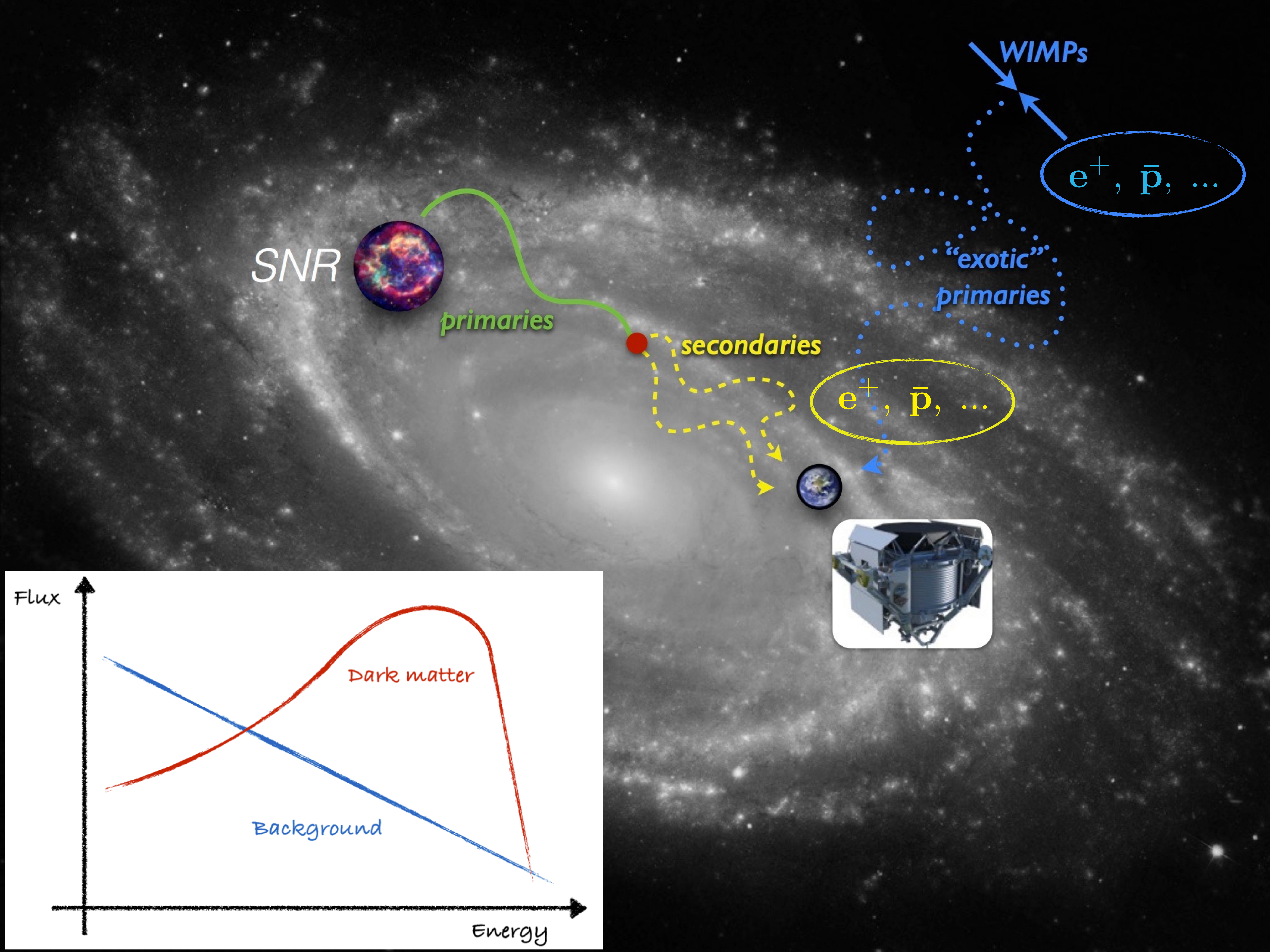

SNR
primaries
secondaries
$e^+, \bar{p}, ...$
Flux
Background
Energy



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

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

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

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

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

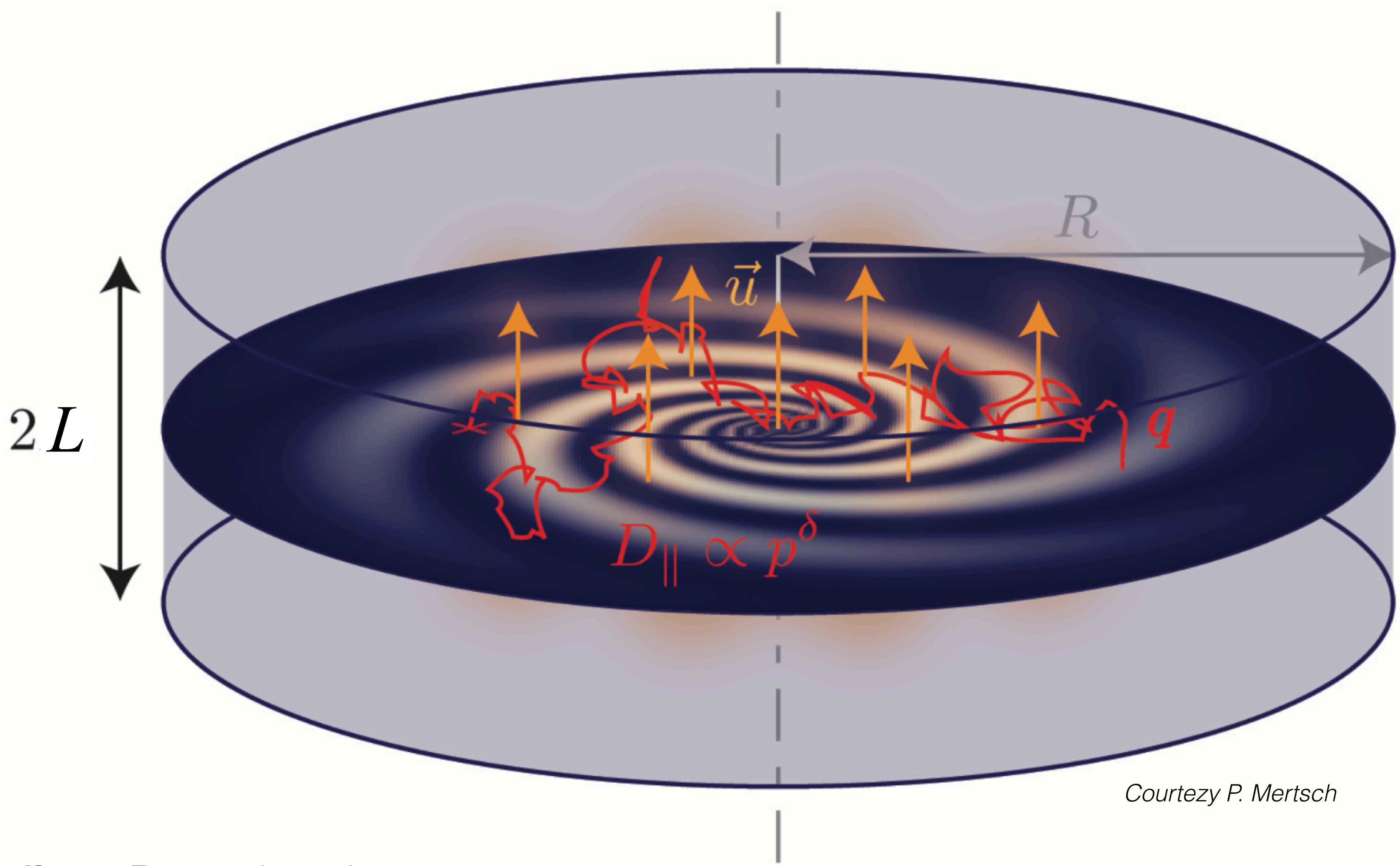
Production

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

Destruction

- Spallation
- Decay
- Annihilation

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.

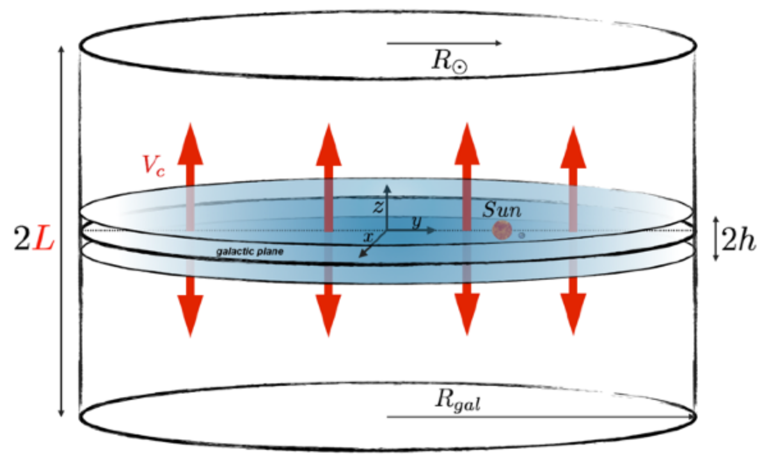
The magnetic halo - *R ~ 20 kpc, 1 ≲ L ≲ 20 kpc*

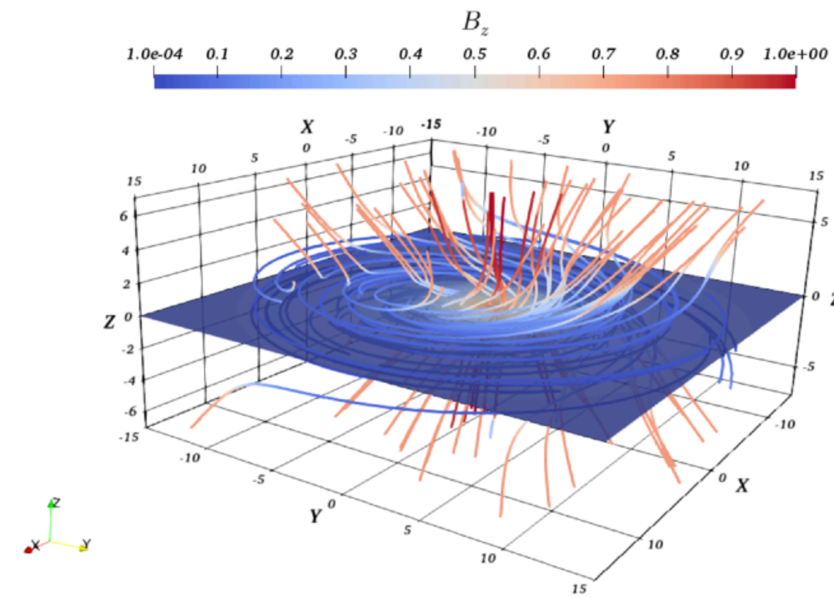
The diffusion zone of the model. Cosmic rays that escape the magnetic halo cannot go back.

Cosmic rays propagation

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

	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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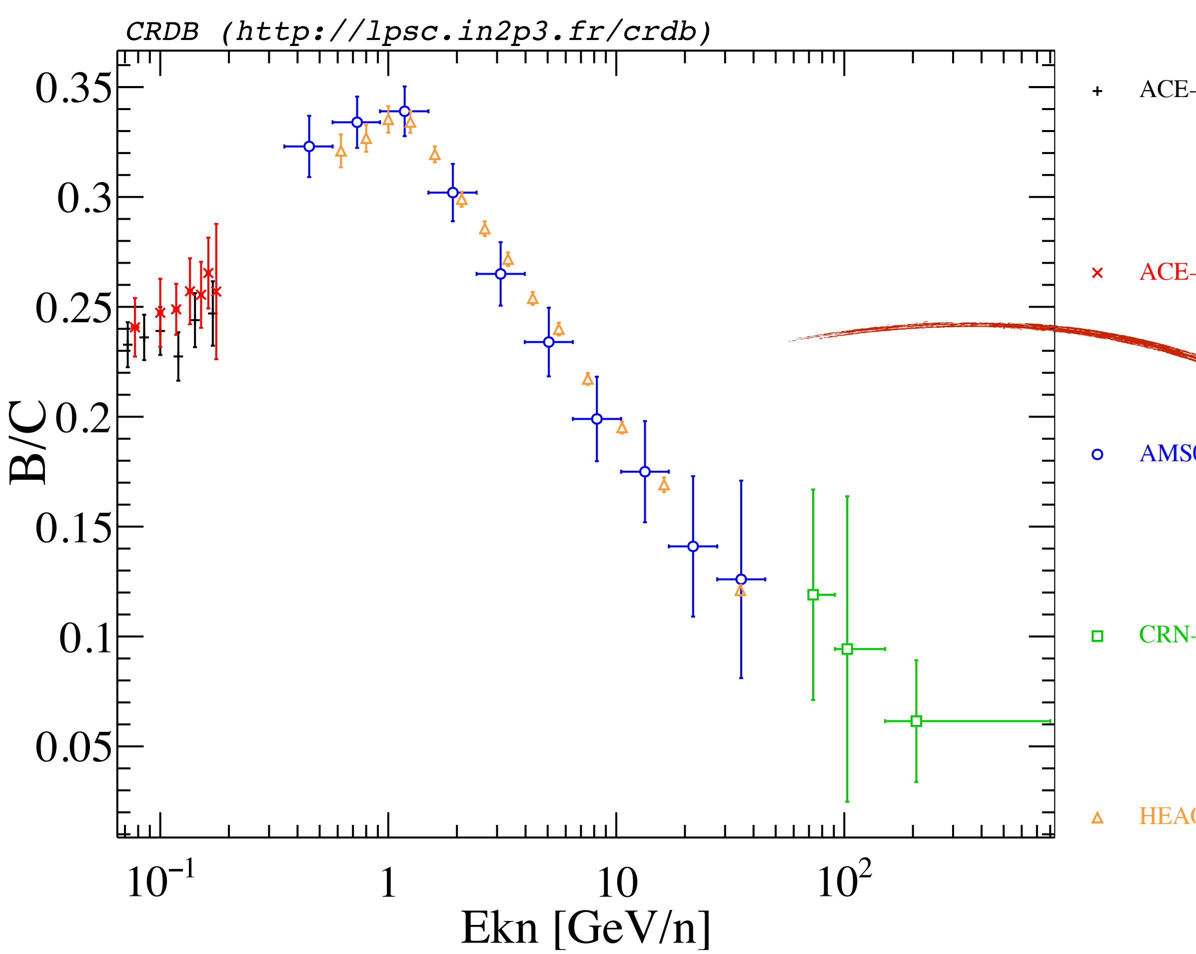
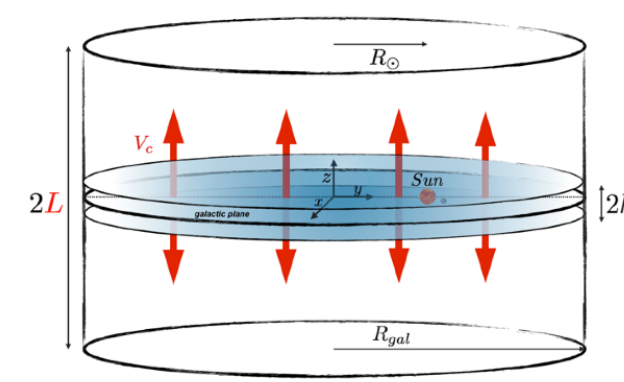


Semi-analytical

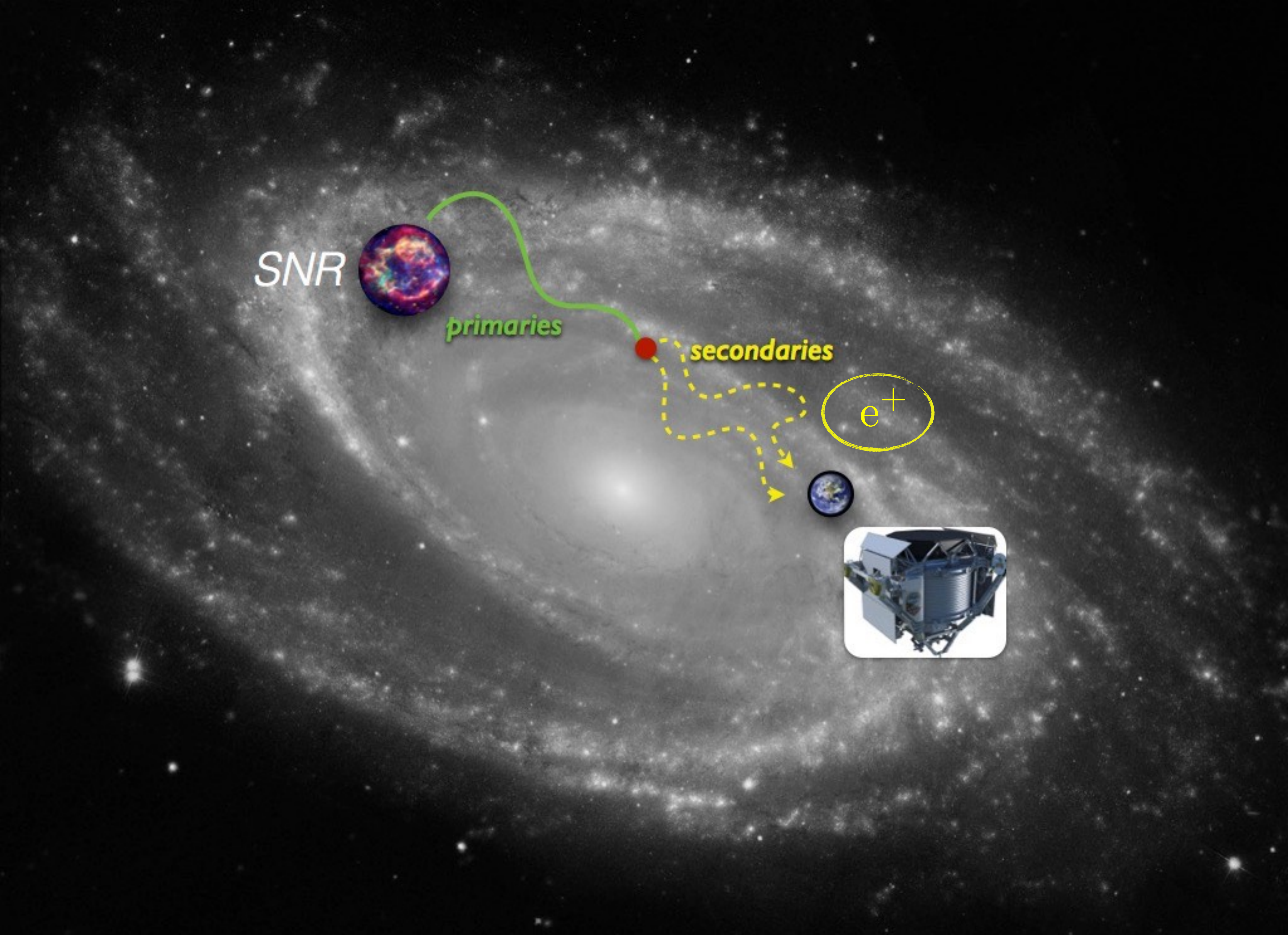
Maurin et al. (2001)

&

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

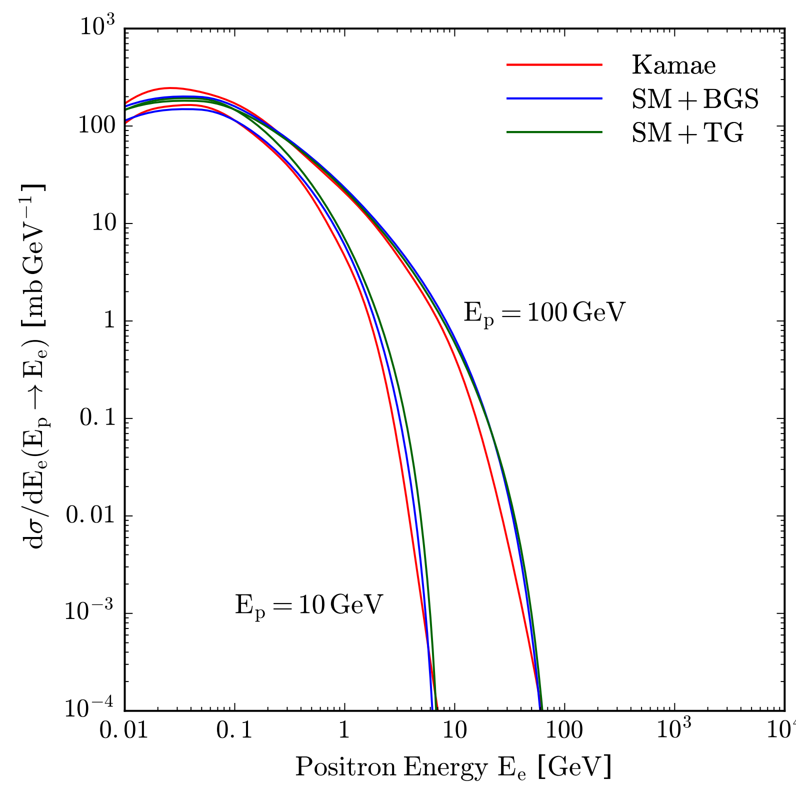


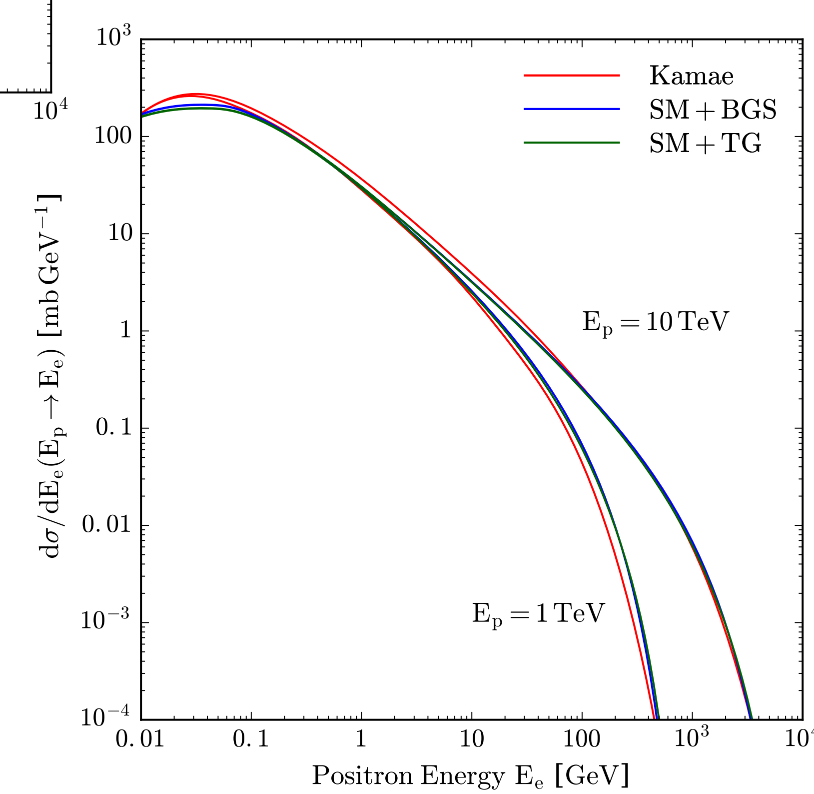
Courtesy A. Putze

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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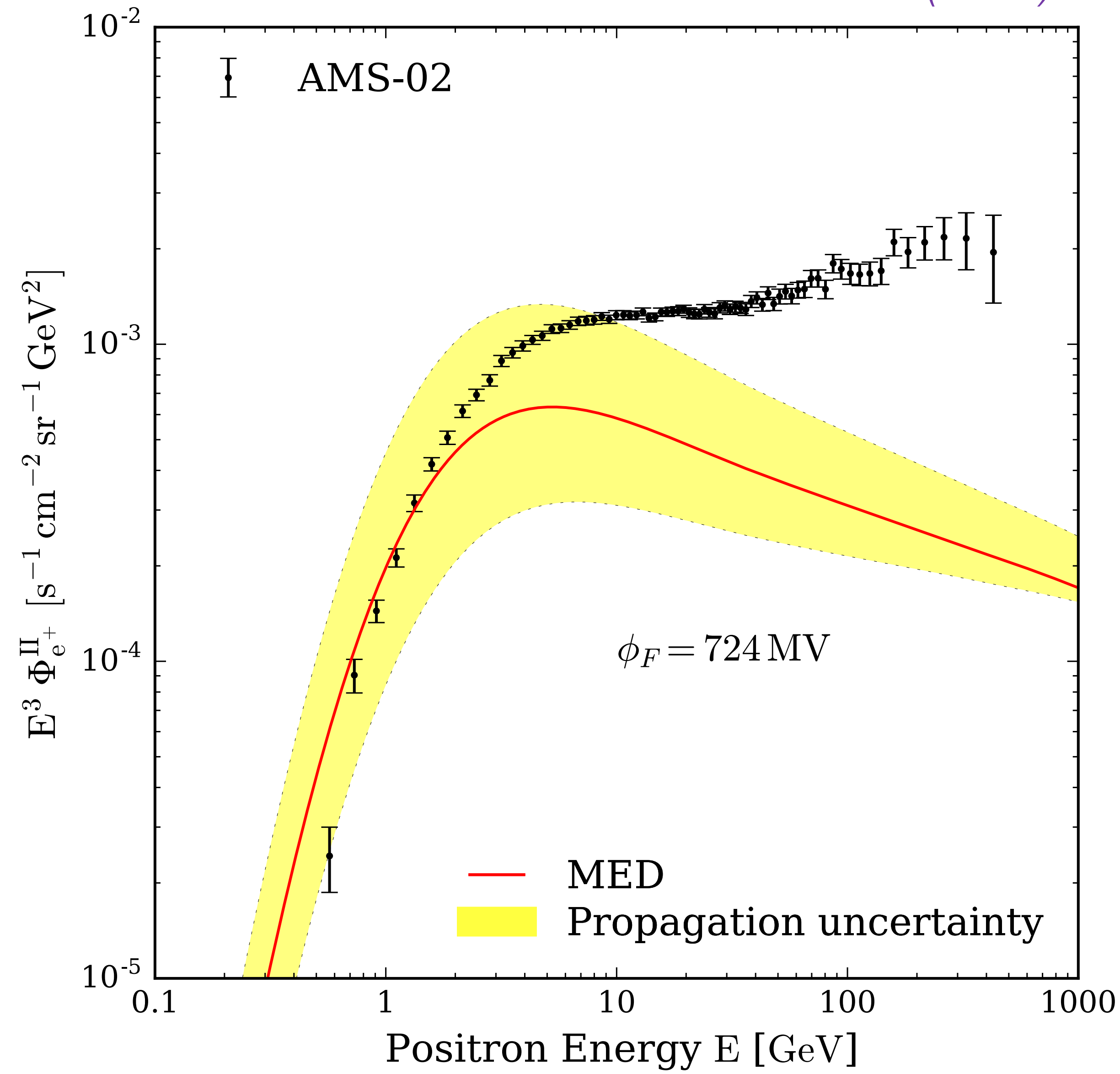
MB+(2014)

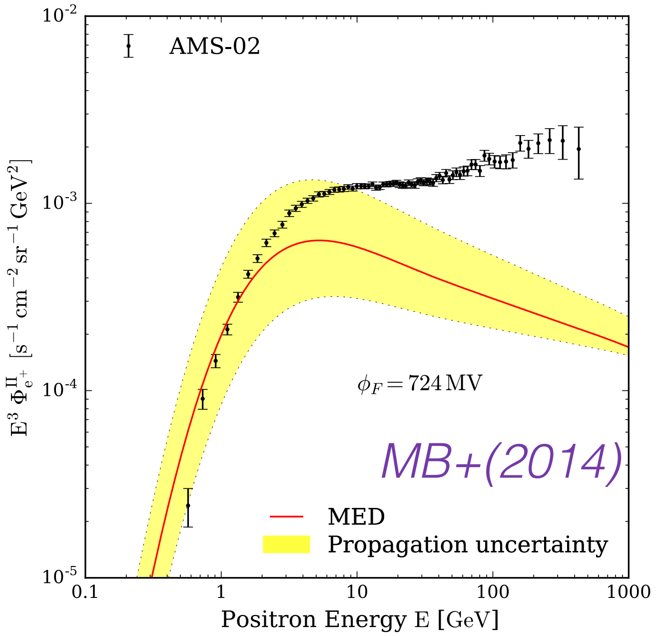


Positron excess above ~ 10 GeV!

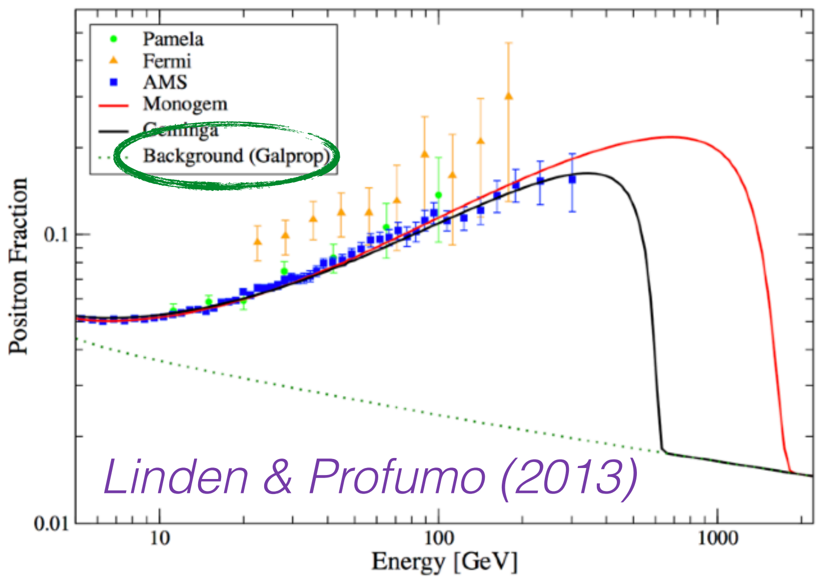
The positron excess

Numerical

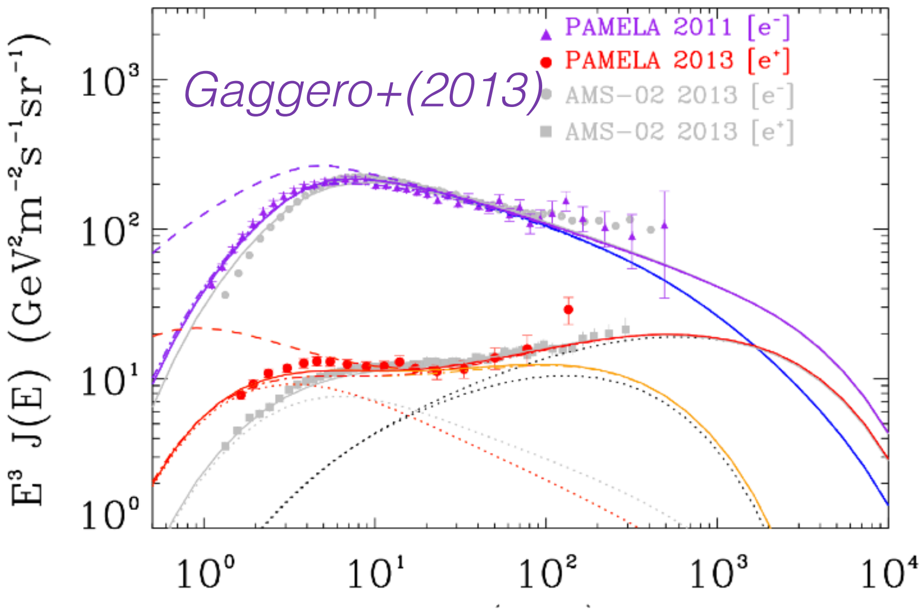
Semi-analytical



(GALPROP)

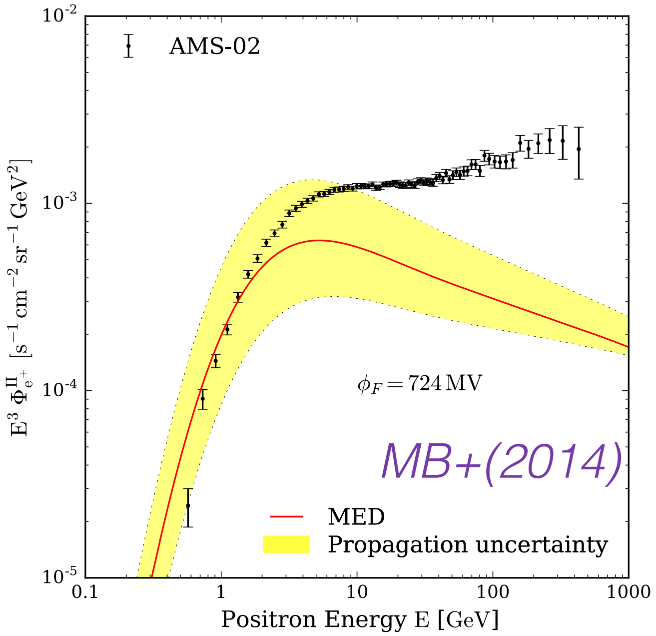


(DRAGON)



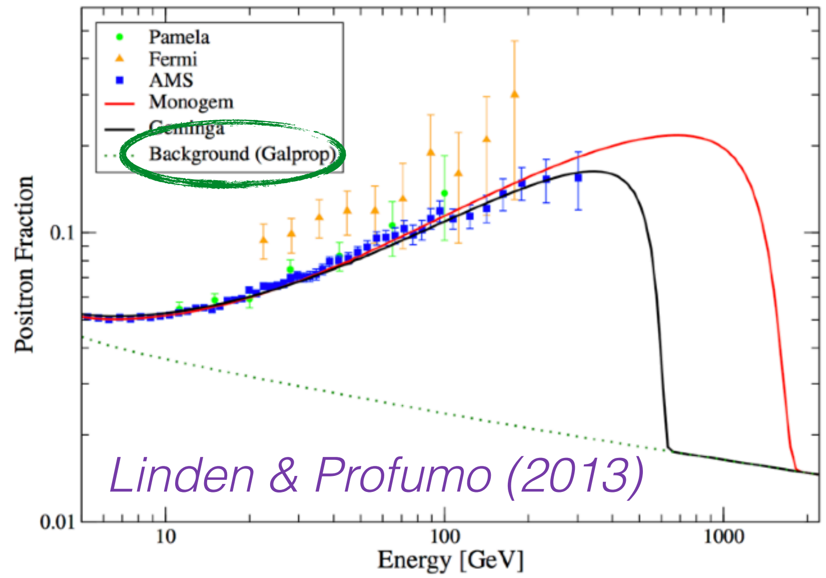
The positron excess

Semi-analytical

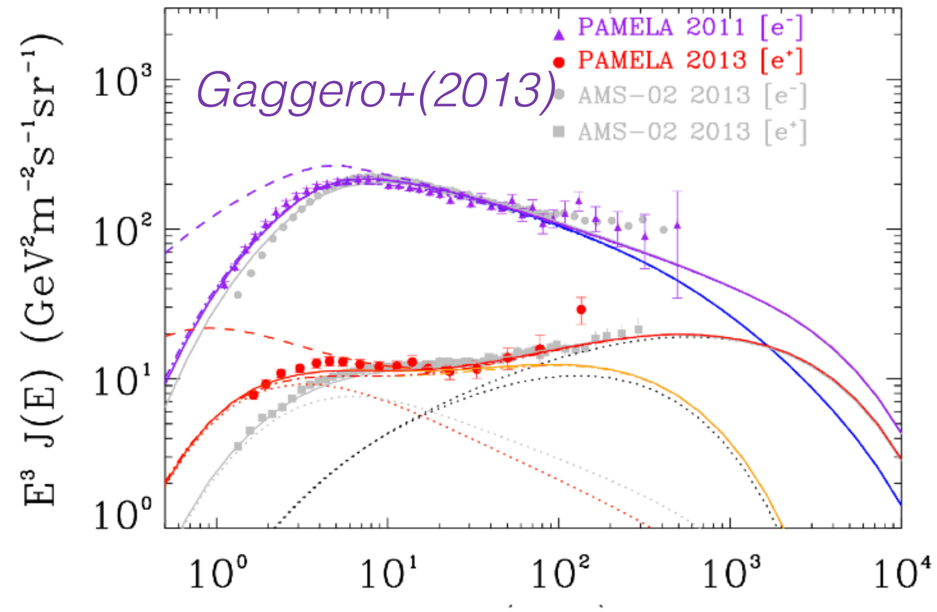


Numerical

(GALPROP)



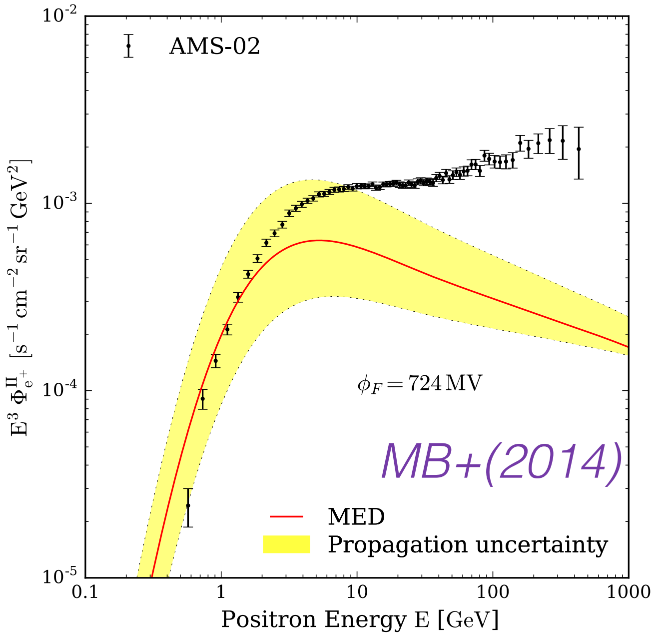
(DRAGON)



- Primary e⁺ produced inside SNRs
  e.g: *Blasi & Serpico (2009)*
  Mertsch & Sarkar (2014)

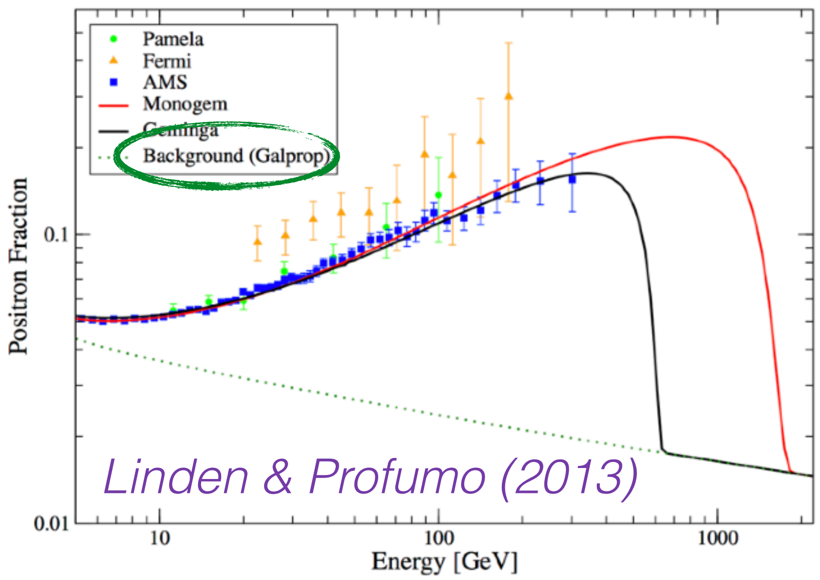
The positron excess

Semi-analytical



Numerical

(GALPROP)



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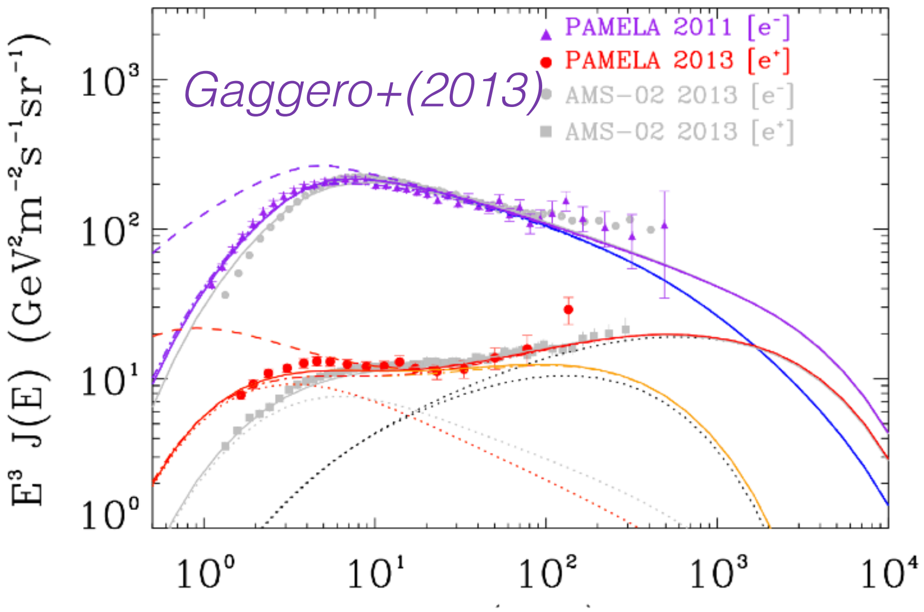

- Primary e+ produced inside SNRs
  e.g: *Blasi & Serpico (2009)*
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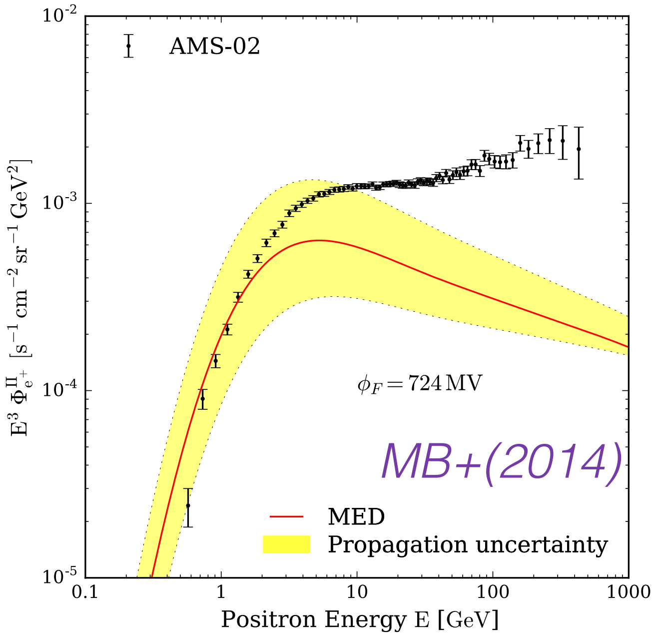
Serious tension with CR nuclei

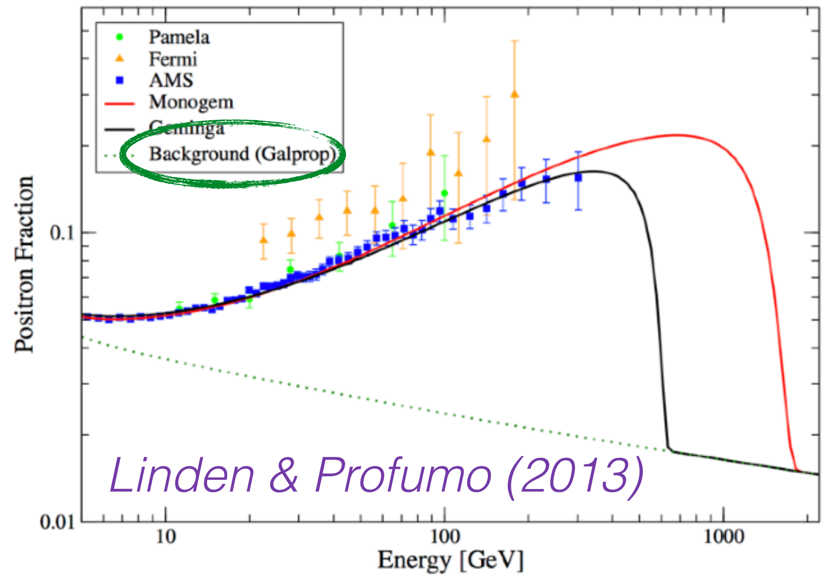
The positron excess

Semi-analytical



Numerical

(GALPROP)



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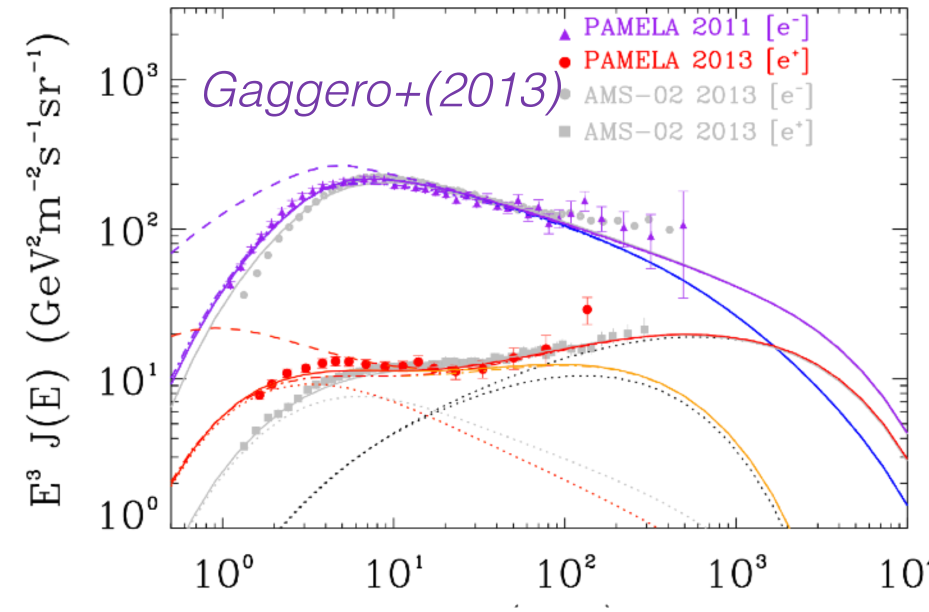

- Primary e^+ produced inside SNRs
  e.g: *Blasi & Serpico (2009)*
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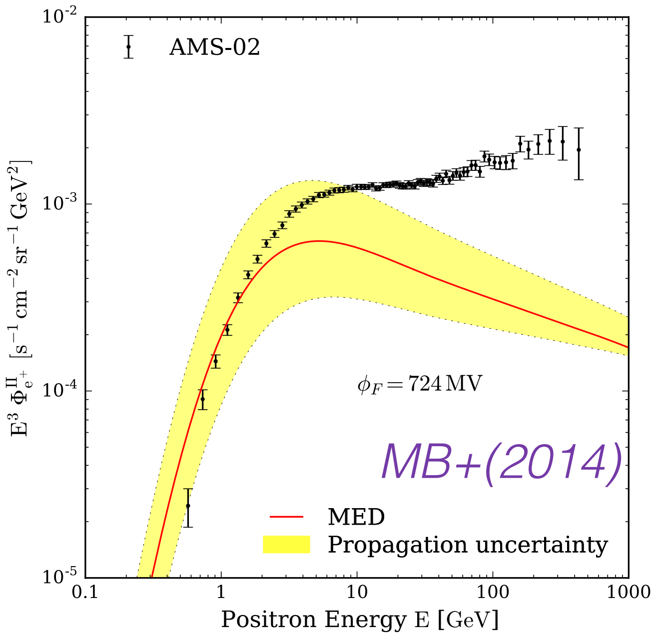
Serious tension with CR nuclei

- Nearby and young PWNe
  e.g: *Linden & Profumo (2013), Gaggero+(2013)*
  Di Mauro+(2014), MB+(2014)

The positron excess

Semi-analytical



Numerical

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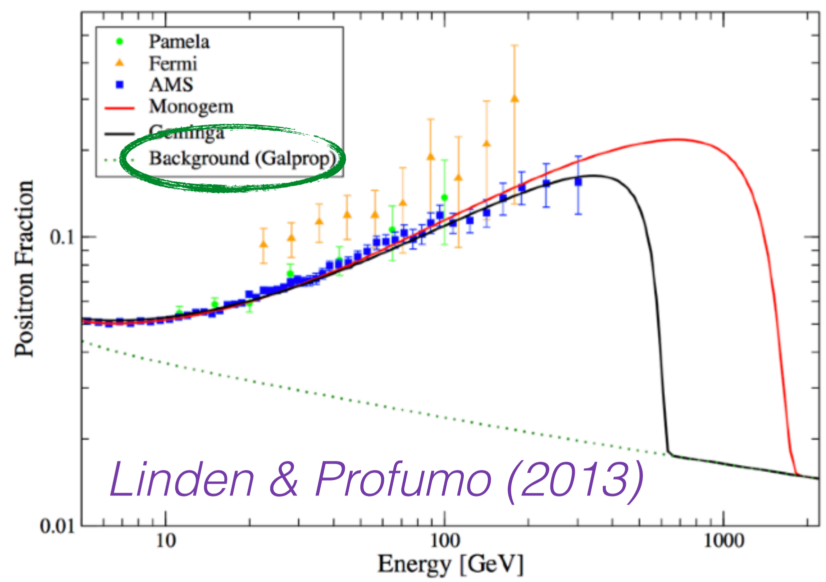
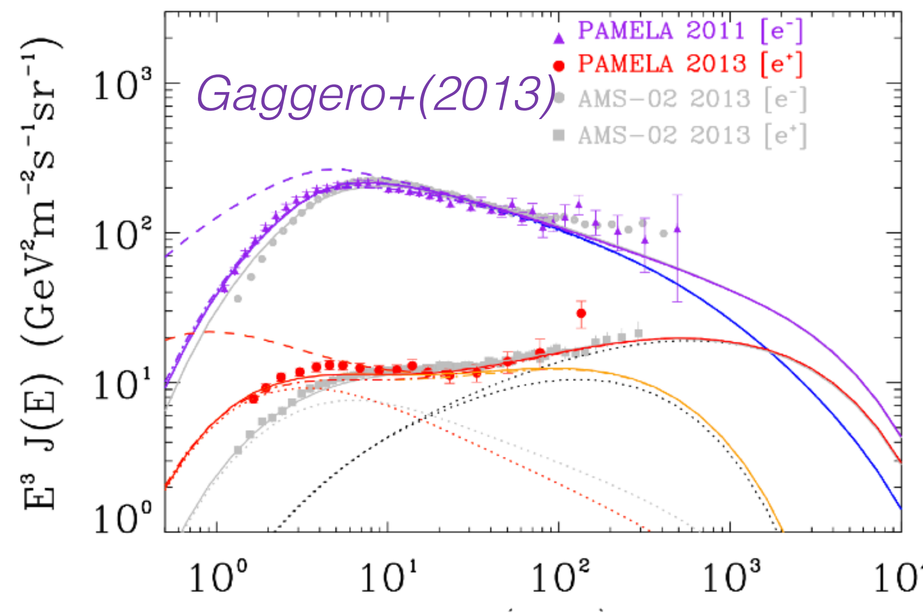


(DRAGON)



- Primary e+ produced inside SNRs
  e.g: *Blasi & Serpico (2009)*
  Mertsch & Sarkar (2014)

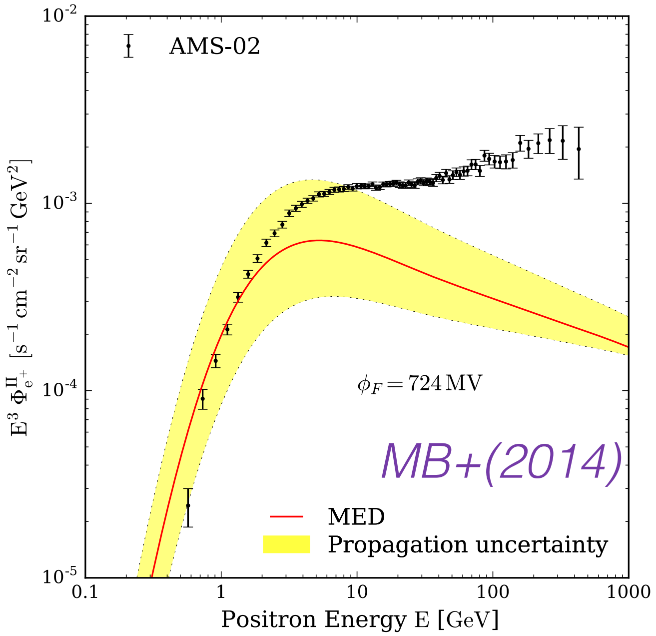
  Serious tension with CR nuclei

- Nearby and ~2-3 Myr old SNR
  e.g: *Kachelriess, Neronov & Semikoz (2017)*

- Nearby and young PWNe
  e.g: *Linden & Profumo (2013), Gaggero+(2013)*
  Di Mauro+(2014), MB+(2014)

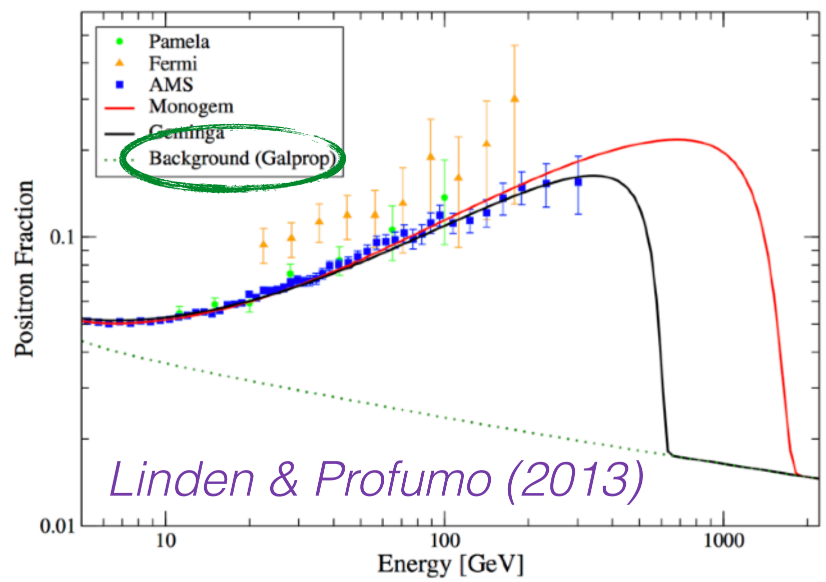
The positron excess

Semi-analytical

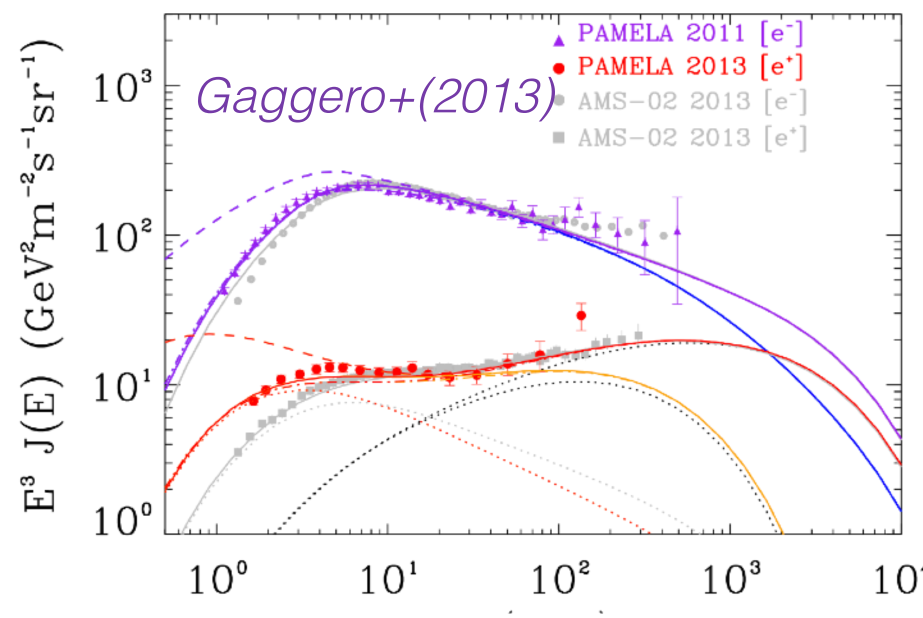


Numerical

(GALPROP)



(DRAGON)



- Primary e⁺ produced inside SNRs
  e.g: *Blasi & Serpico (2009)*
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  Serious tension with CR nuclei

- Nearby and ~2-3 Myr old SNR
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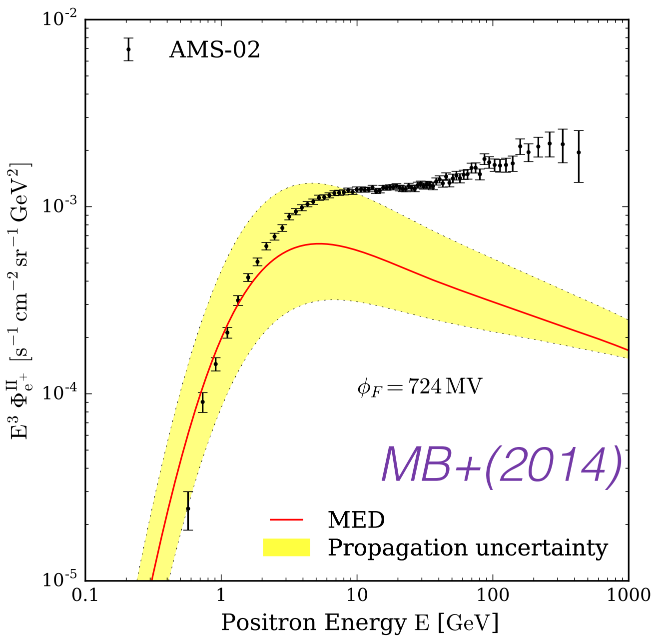
  Unlikely scenario ($p < 0.1\%$)
  Genolini, Salati, Serpico & Taillet (2016)

- Nearby and young PWNe
  e.g: *Linden & Profumo (2013), Gaggero+(2013)*
  Di Mauro+(2014), MB+(2014)

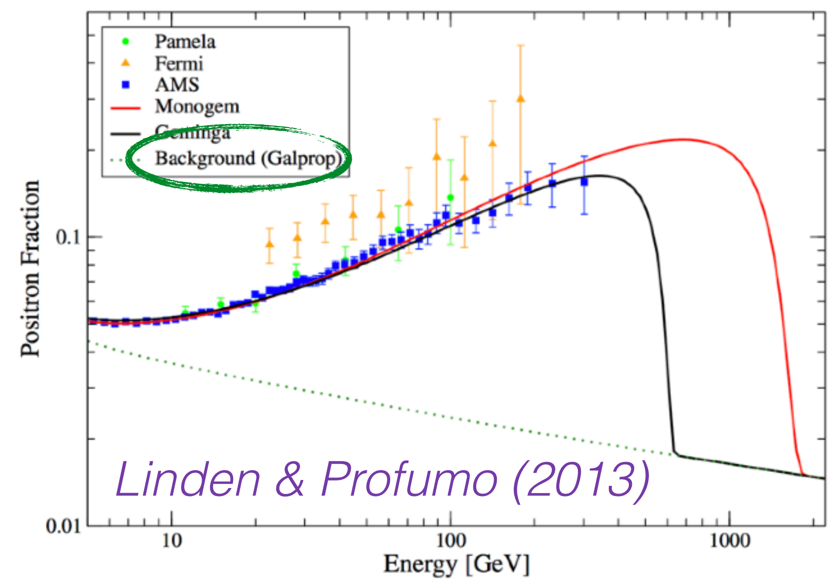
The positron excess

Semi-analytical

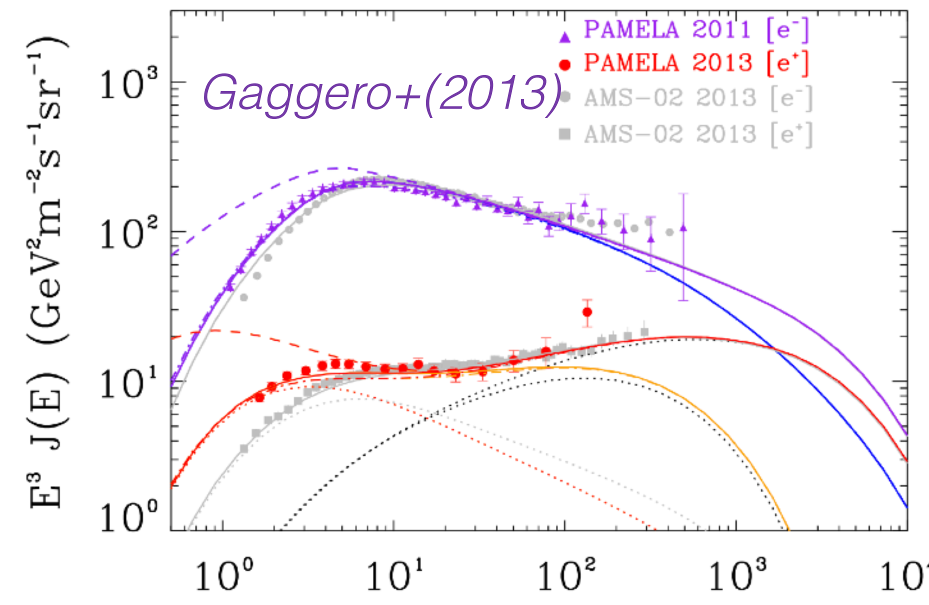


Numerical

(GALPROP)



(DRAGON)



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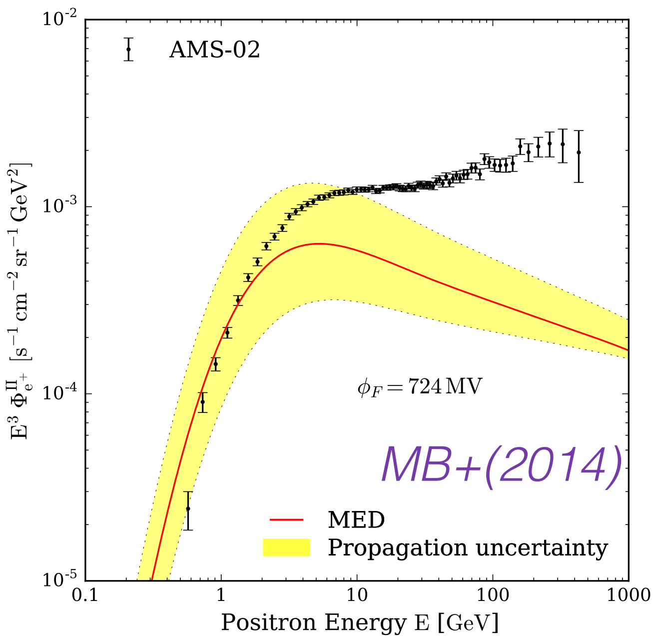
The positron excess

Numerical

Semi-analytical



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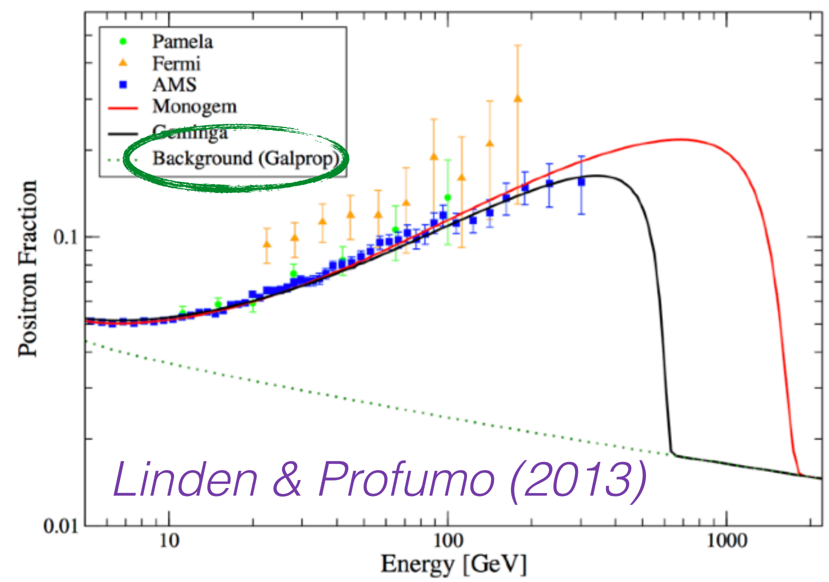
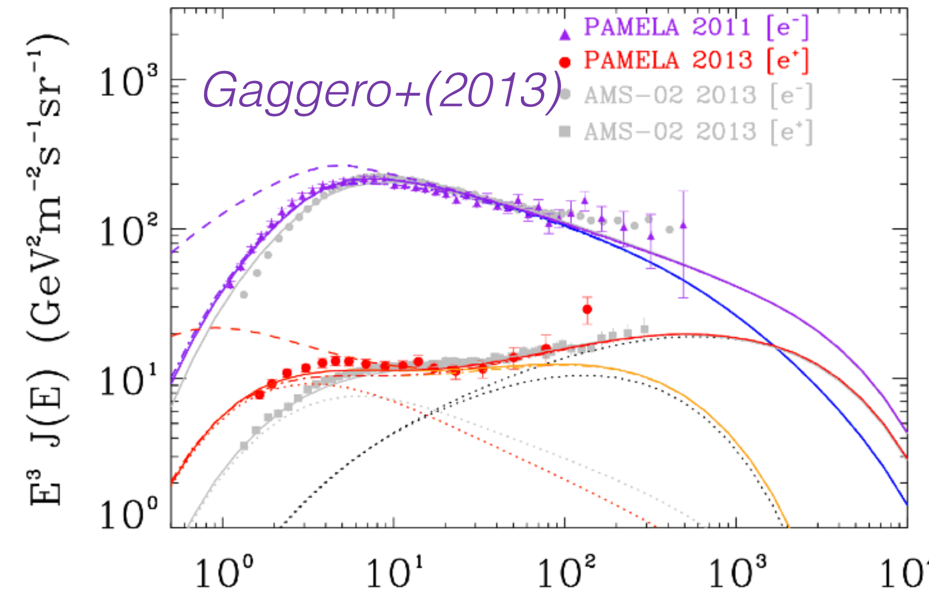


(DRAGON)



- Primary e^+ produced inside SNRs

  e.g: *Blasi & Serpico (2009)*
  Mertsch & Sarkar (2014)

  Serious tension with CR nuclei

- Nearby and ~2-3 Myr old SNR

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- Nearby and young PWNe

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The positron excess

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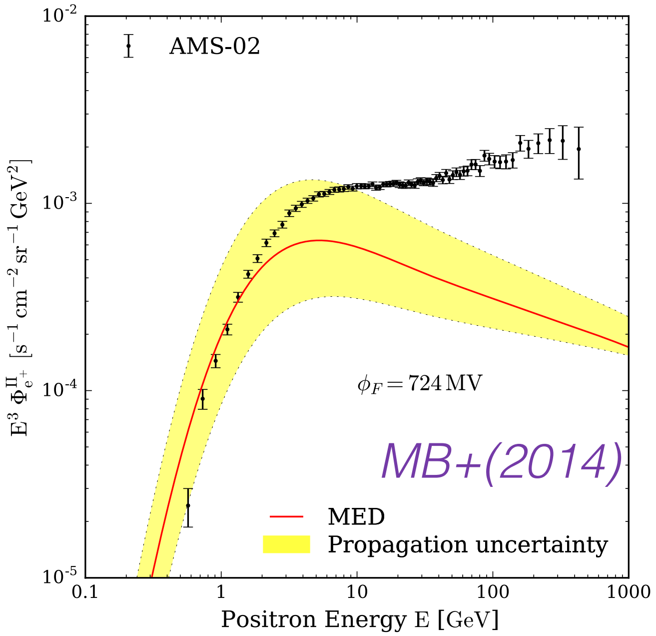

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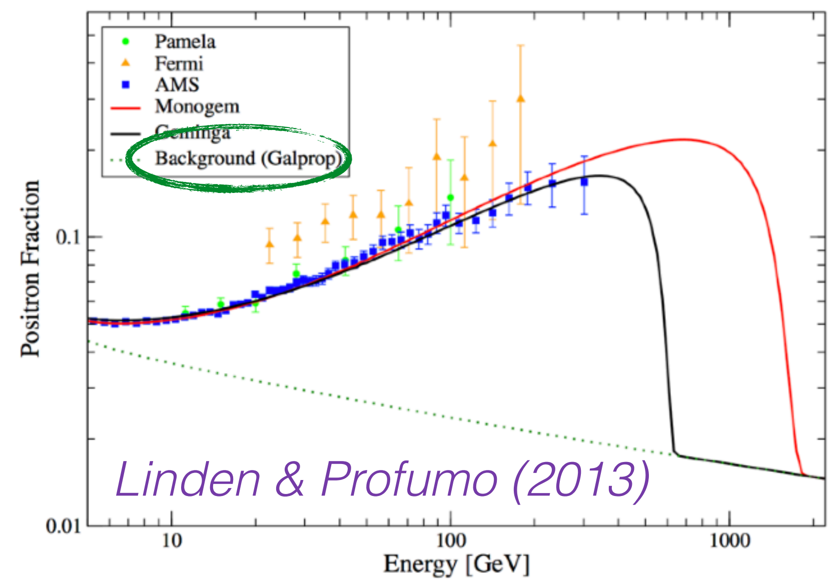

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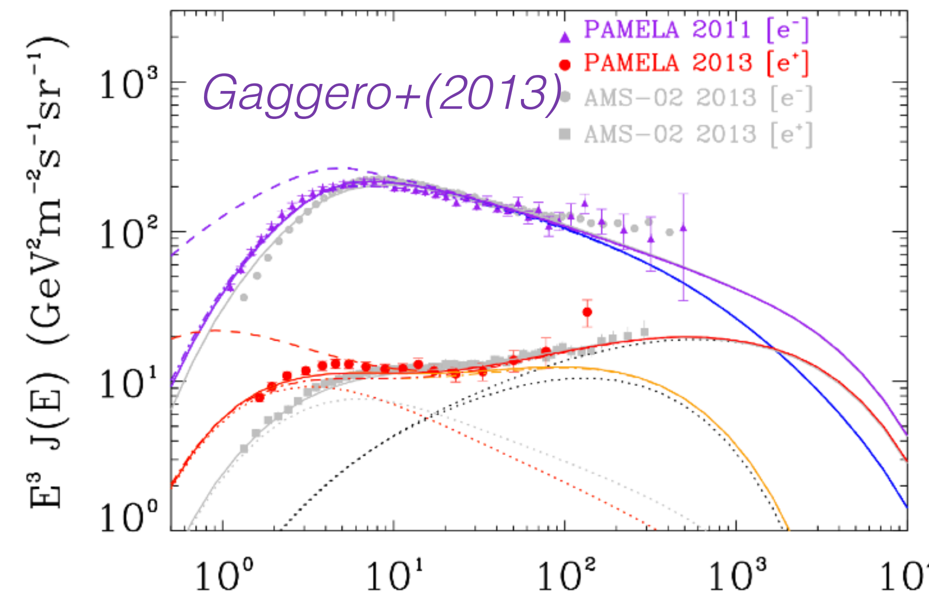

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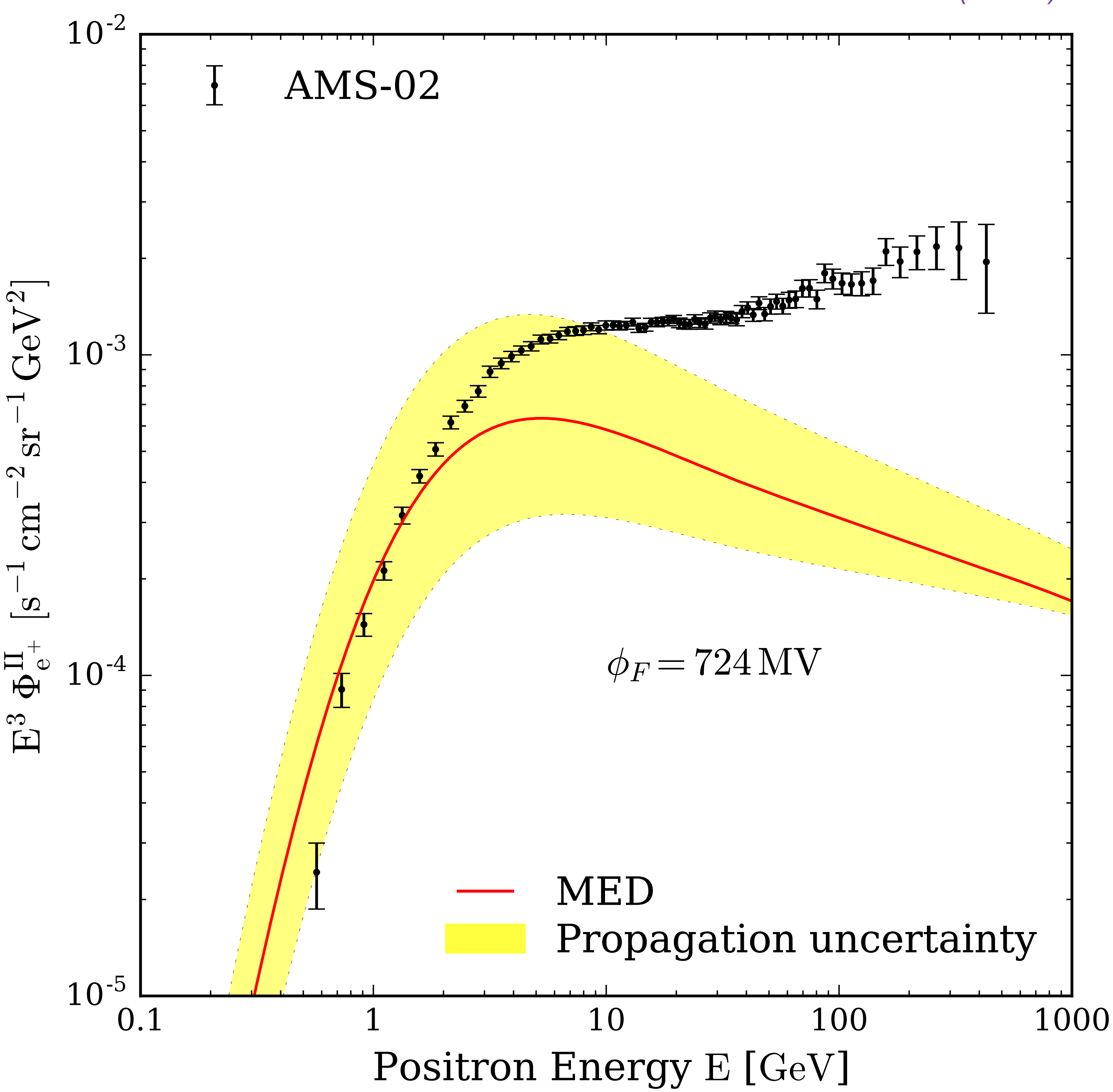
  e.g: *Lipari (2017), Blum, Sato & Waxman (2017)*
  Inconsistent with energy losses, CR nuclei

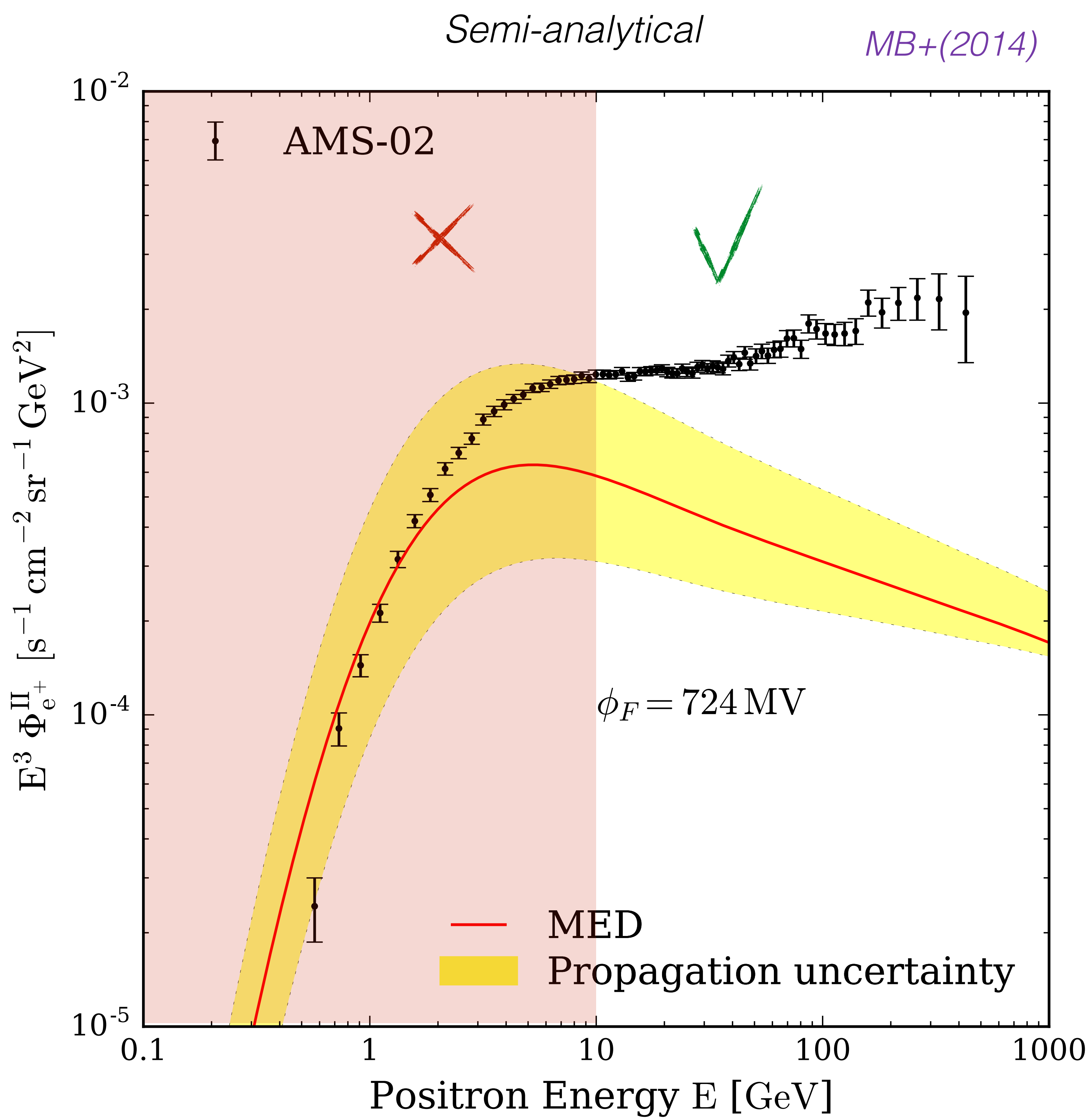
- Primary e⁺ from dark matter
  e.g: *Silk and Srednicki (1984), Baltz & Edsjö (1998), Cirelli & Strumia (2008), MB+(2014)*

The positron excess

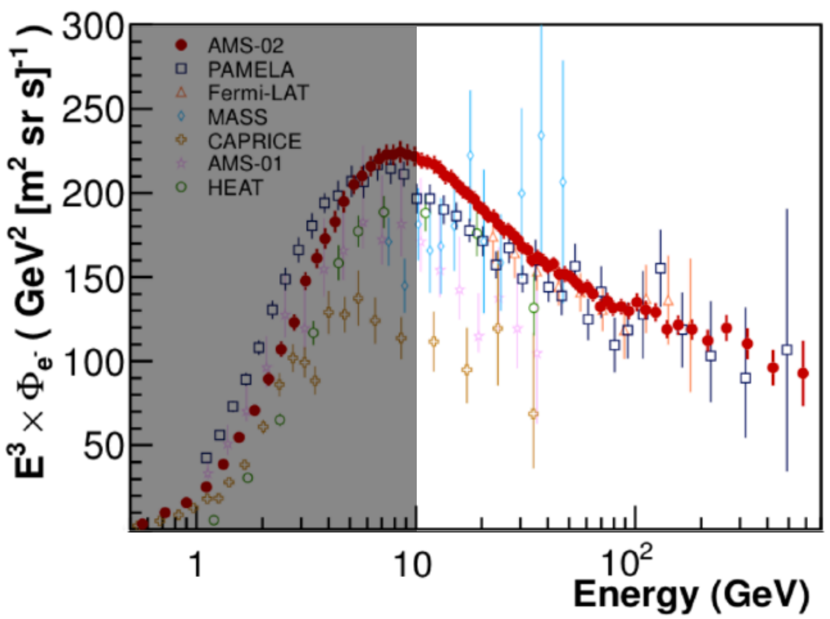
Semi-analytical

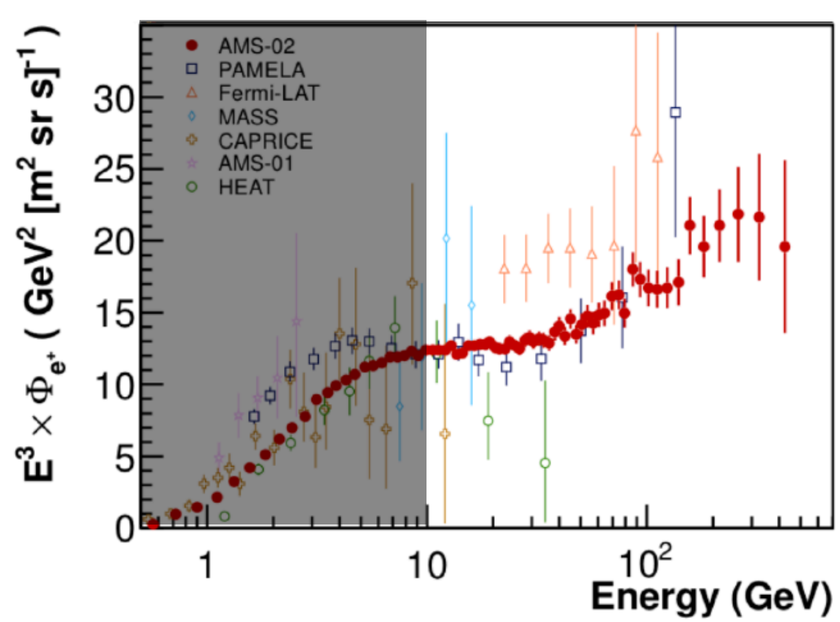


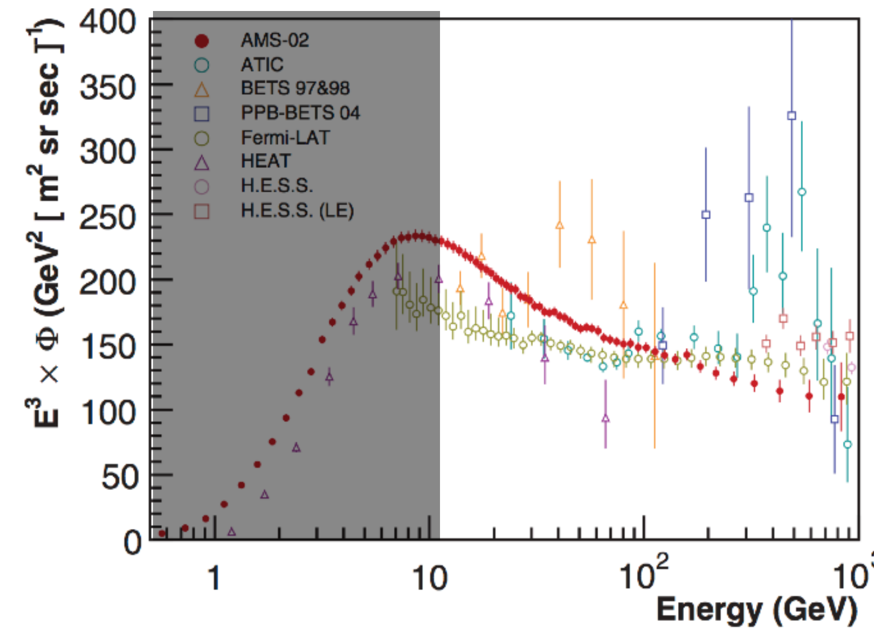
The positron excess



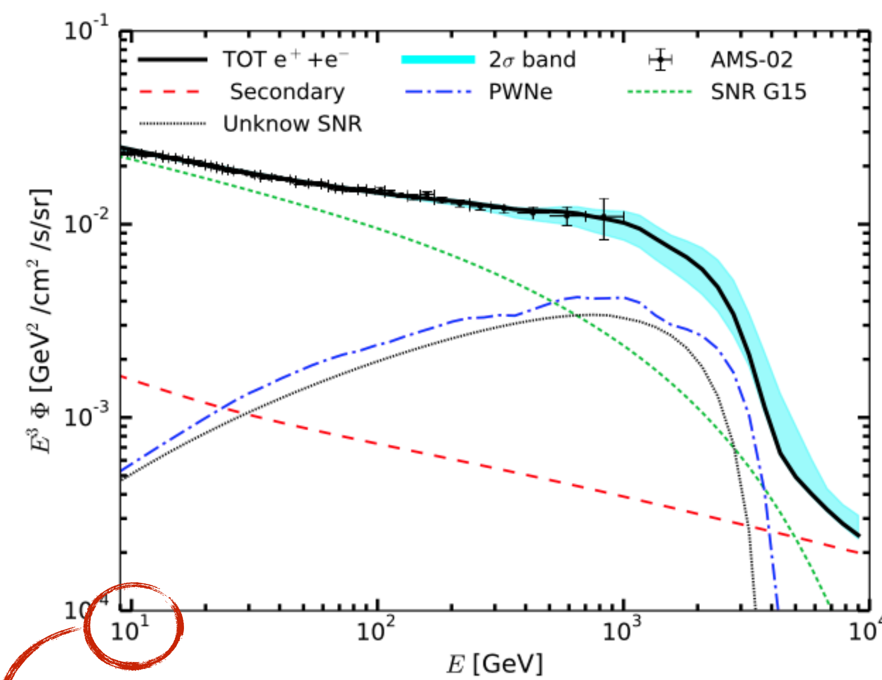
Interpretation of AMS-02 e+/e- data

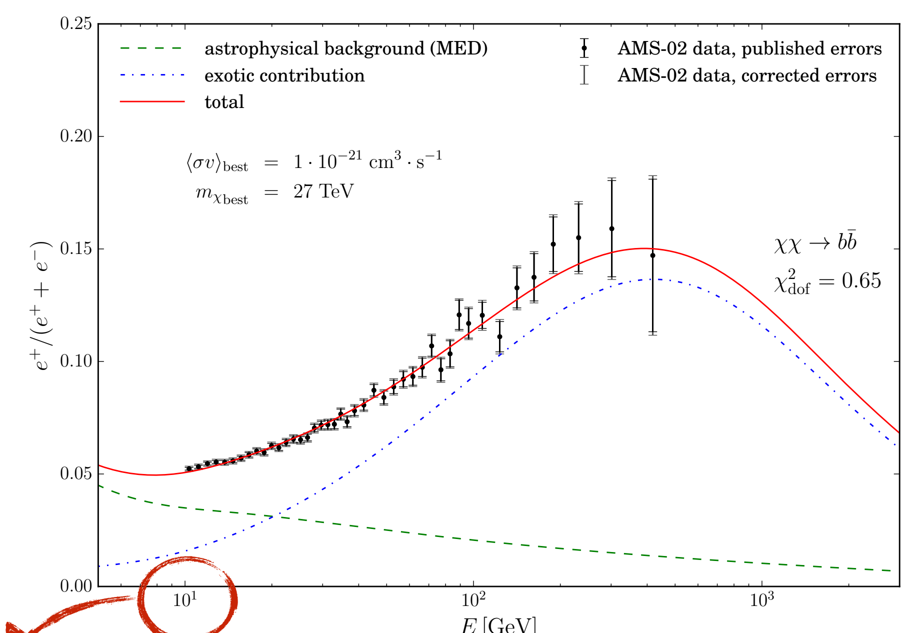






Semi-analytic method analysis e.g.:





10 GeV

Di Mauro+(2016)

10 GeV

MB+(2014)

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

The *pinching method* for low energy e^- and e^+

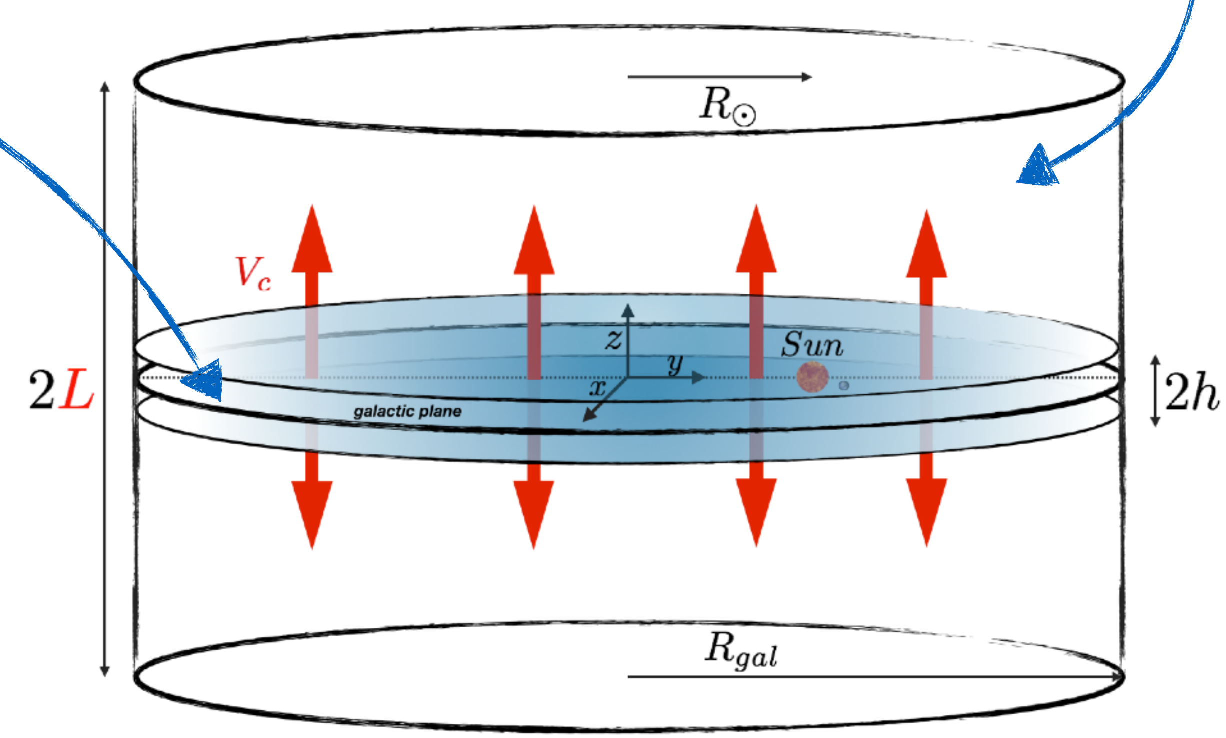
Semi-analytic method for cosmic ray e- and e+

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.)

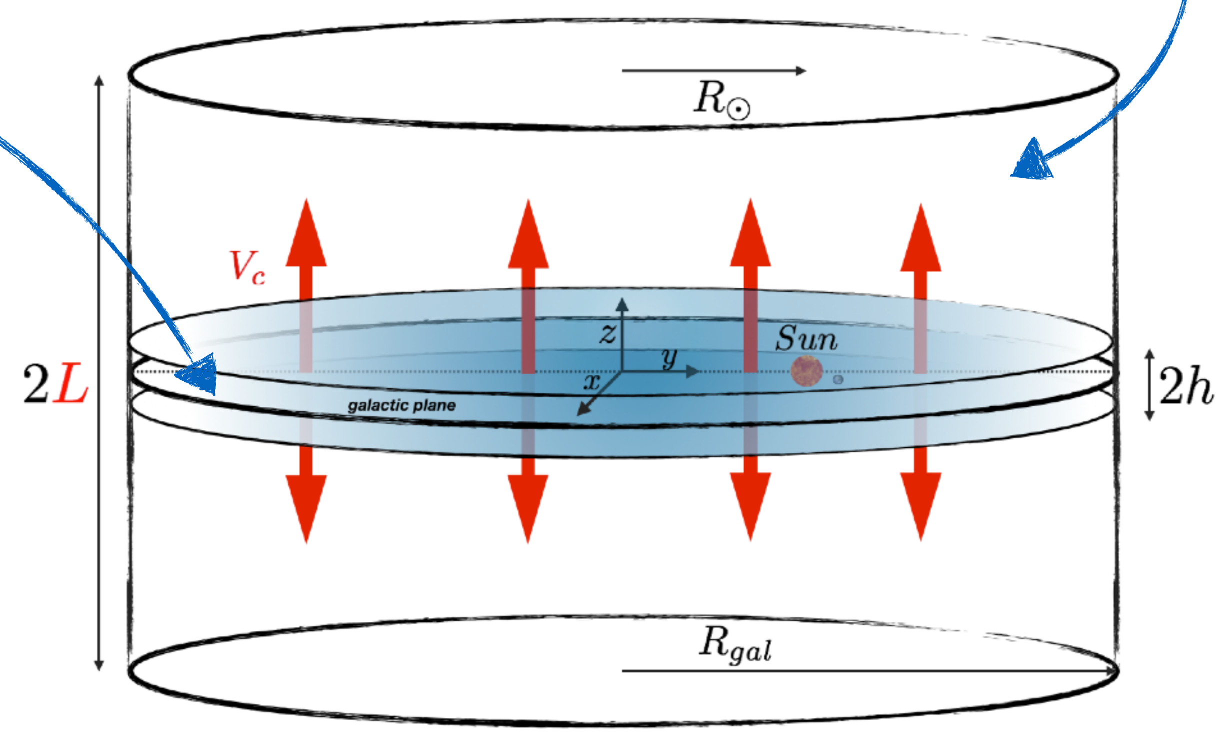
Electrons and positrons: the high-energy approximation

Cosmic rays transport equation (steady state)

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

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

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



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)
Di Mauro+(2014)
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)

Semi-analytic method for cosmic ray e- and e+

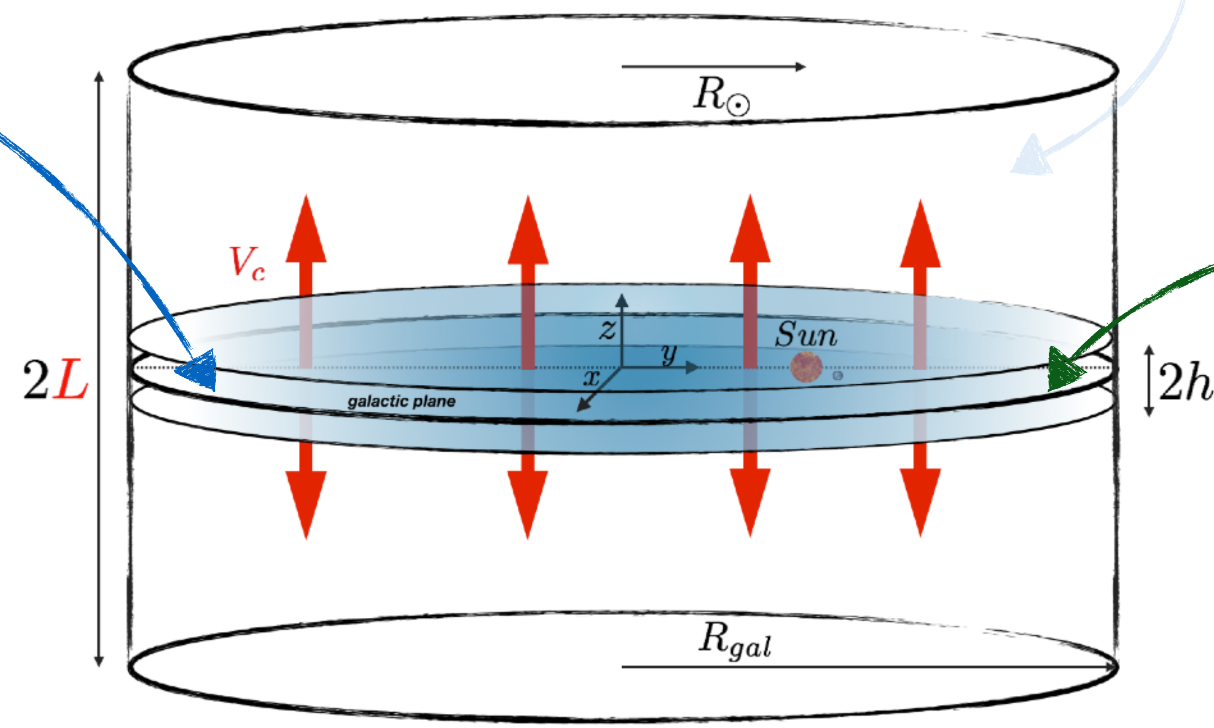
Cosmic rays transport equation (steady state)

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

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

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

b^{eff}_{halo}



The pinching method

MB+(2016a)

Semi-analytic method for cosmic ray e- and e+

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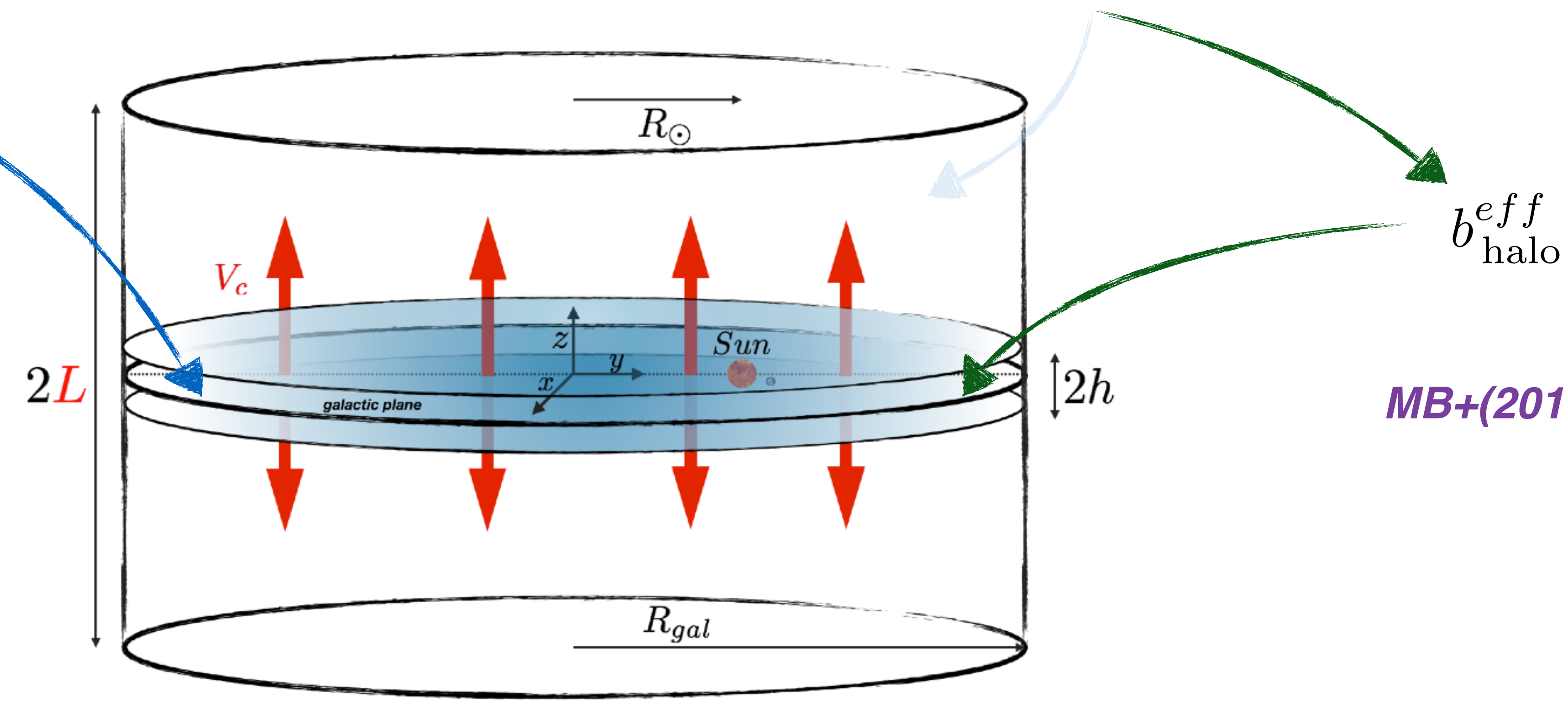

The pinching method

MB+(2016a)

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

The pinching method

MB+(2016a)

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

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

pinching factor

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

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

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

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

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

Semi-analytic method for cosmic ray e$^-$ and e$^+$

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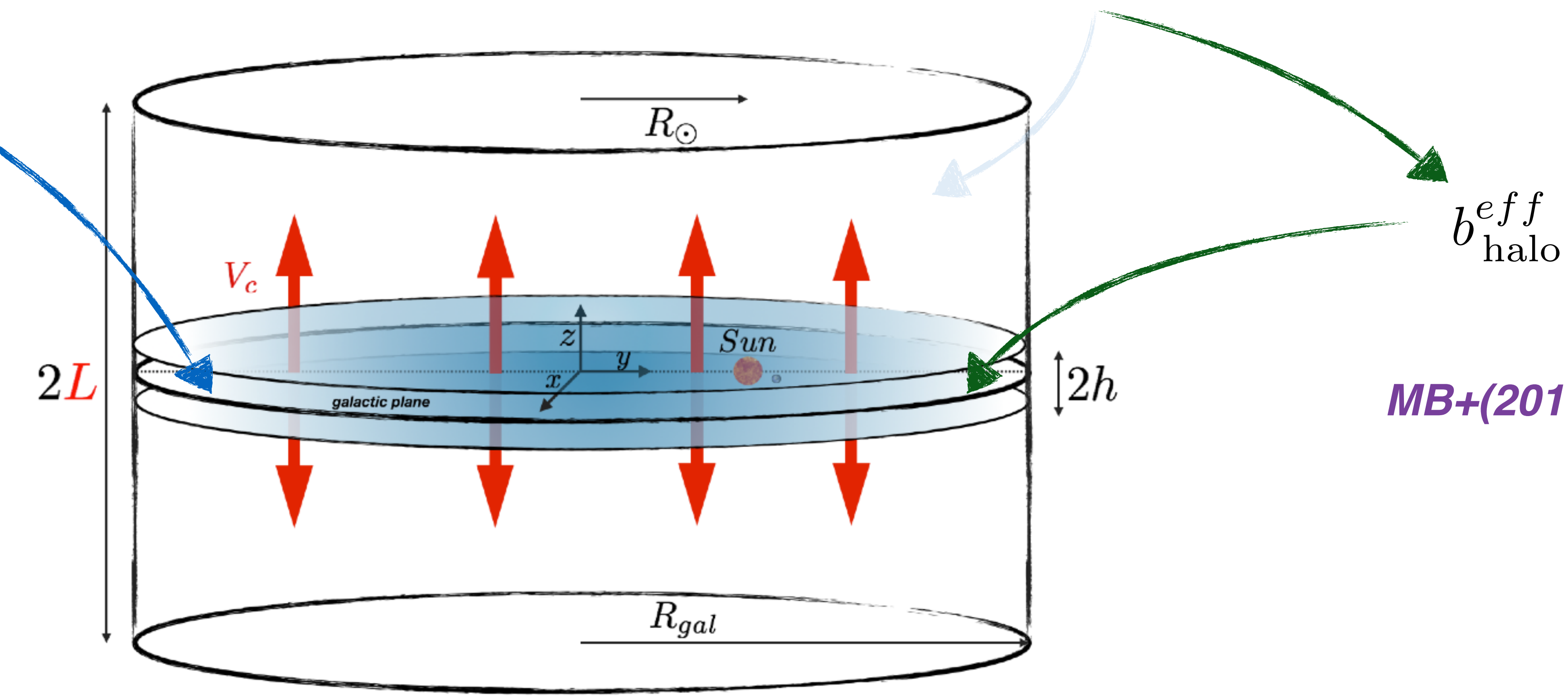
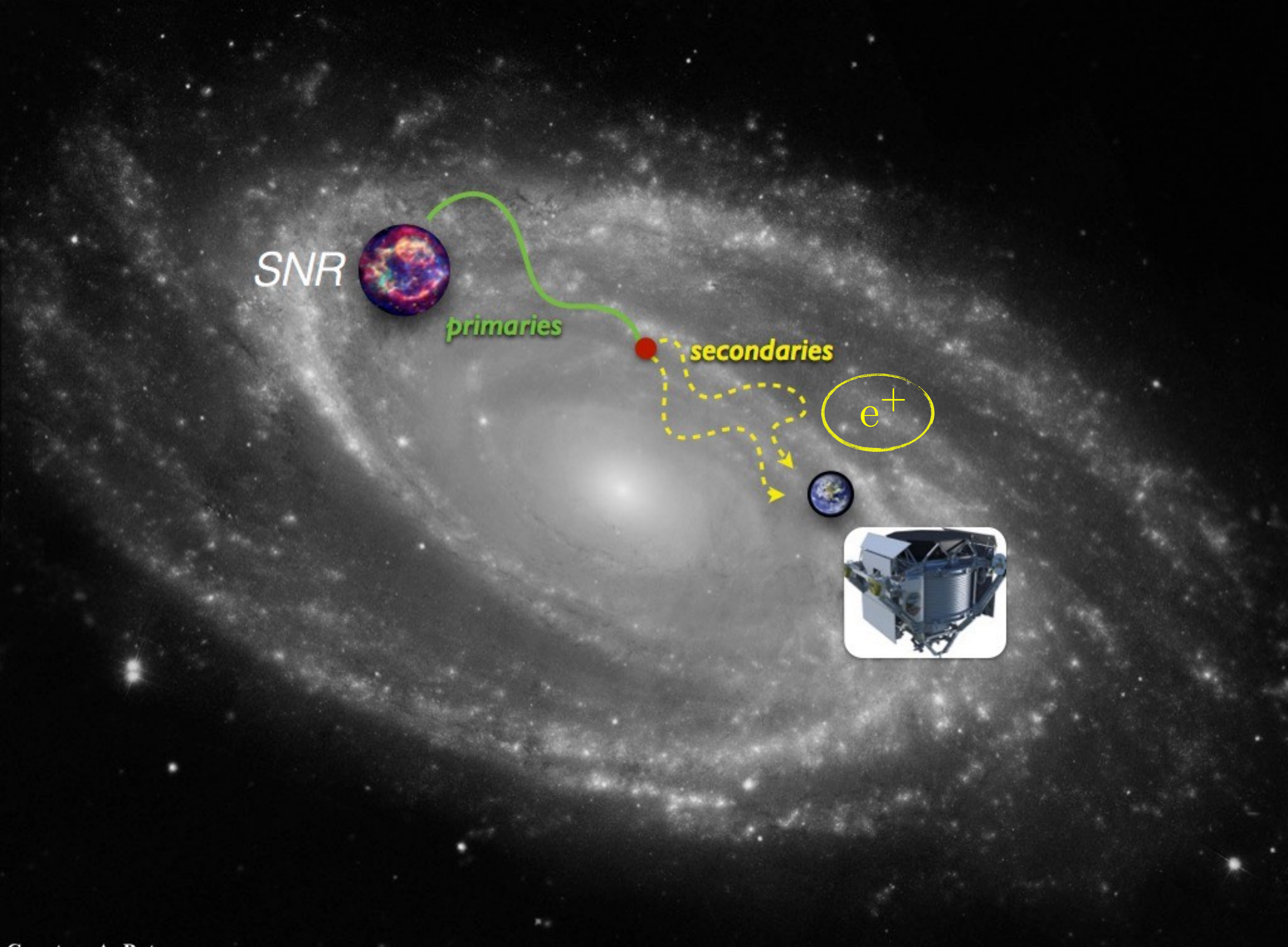


MB+(2016a)

The pinching method

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

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



Courtesy A. Putze

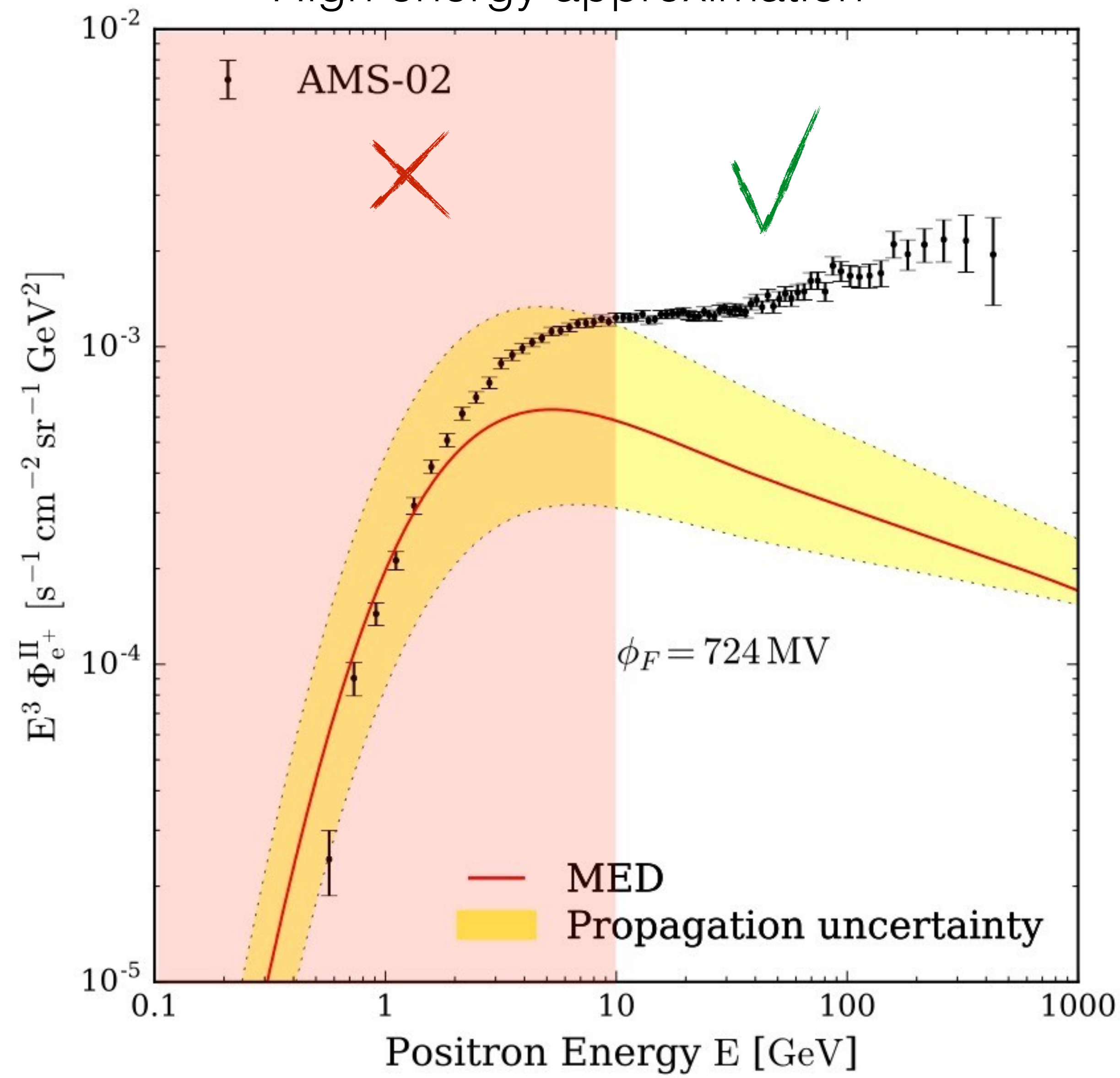
Astrophysical secondary positrons

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

$p + p \longrightarrow$

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

High energy approximation



Astrophysical secondary positrons

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

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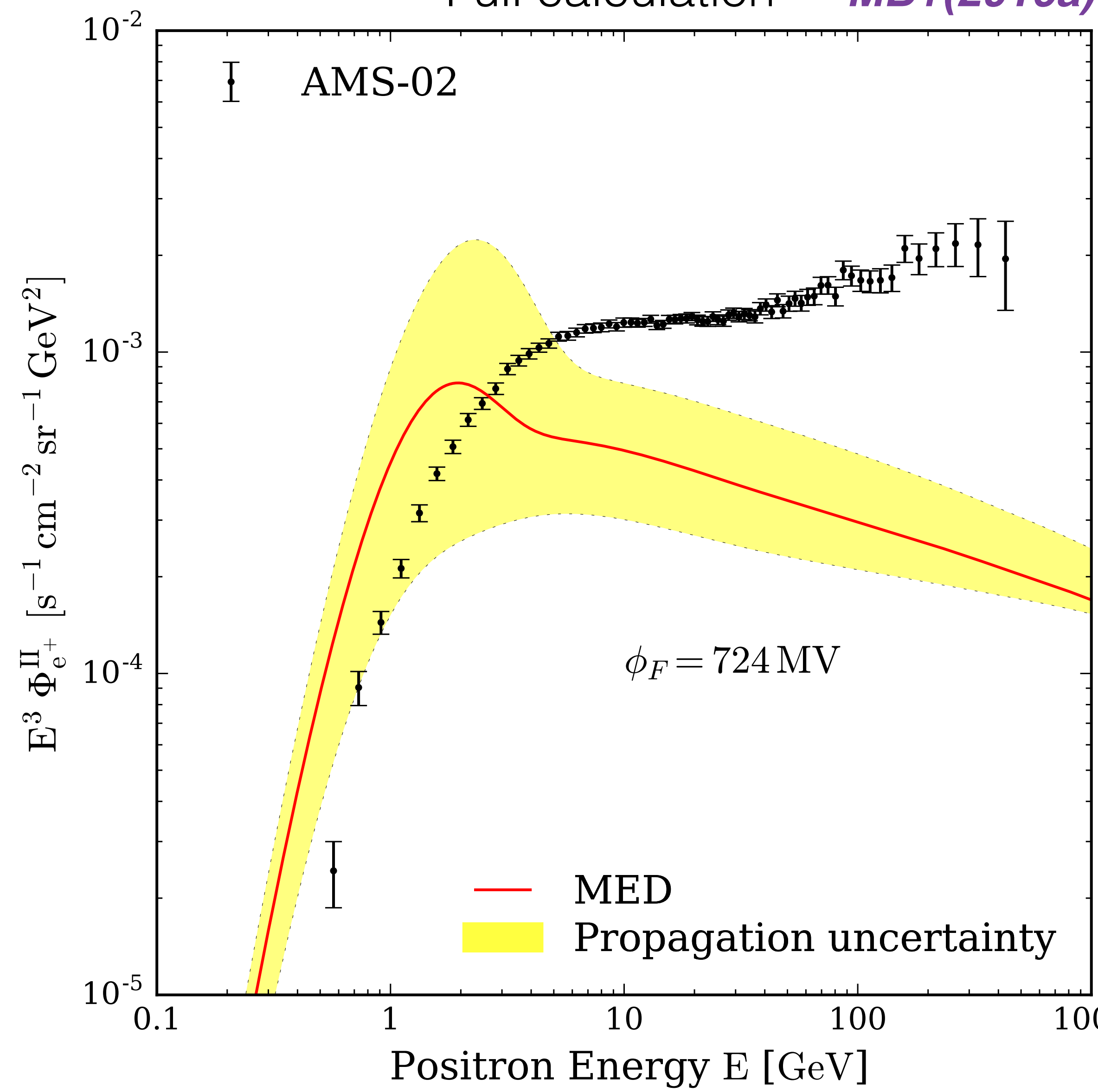
    - $\mu^+ \longrightarrow \bar{\nu}_\mu + \nu_e + e^+$

Full calculation **MB+(2016a)**



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

Astrophysical secondary positrons

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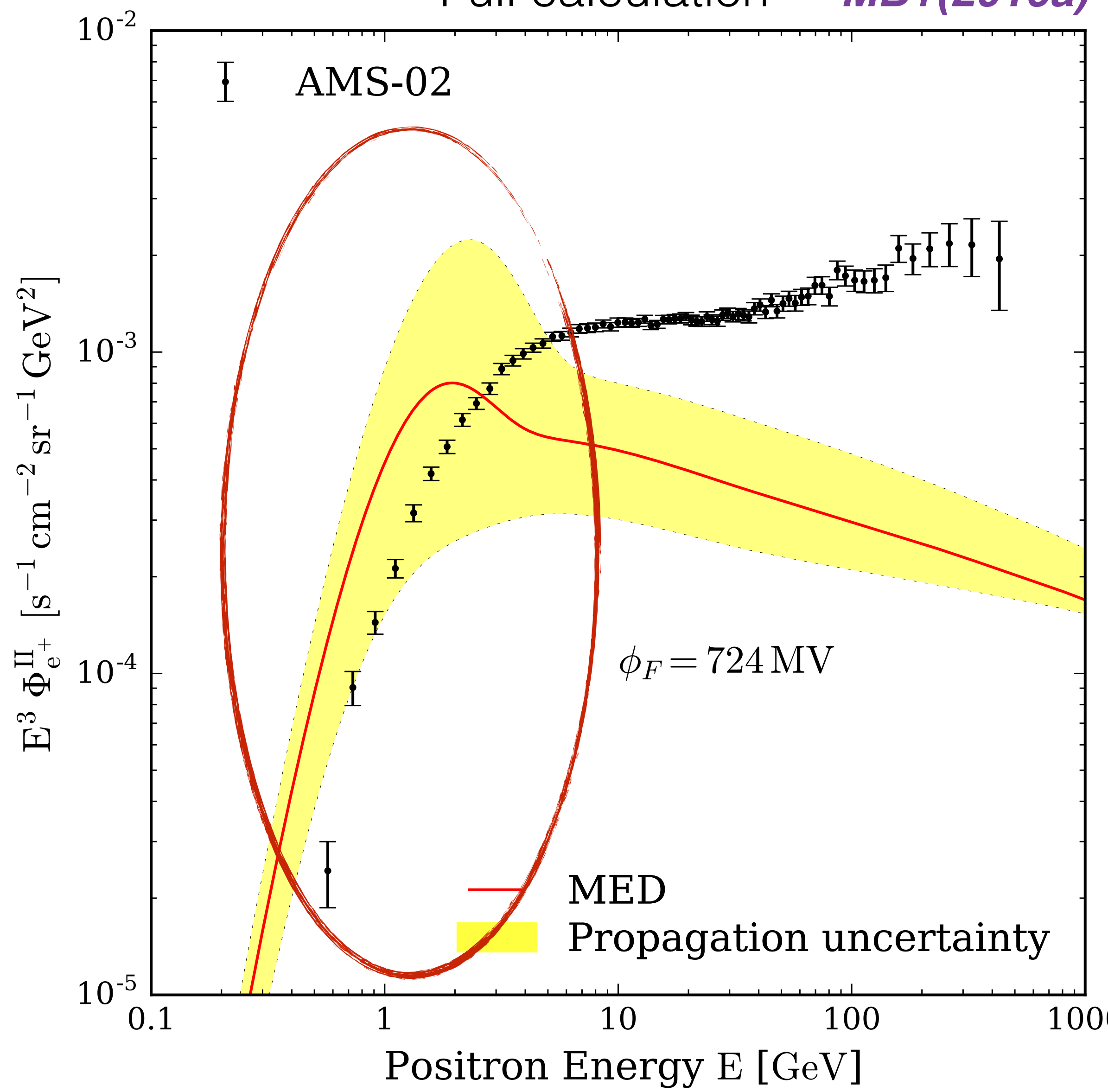
Full calculation **MB+(2016a)**



Astrophysical secondary positrons

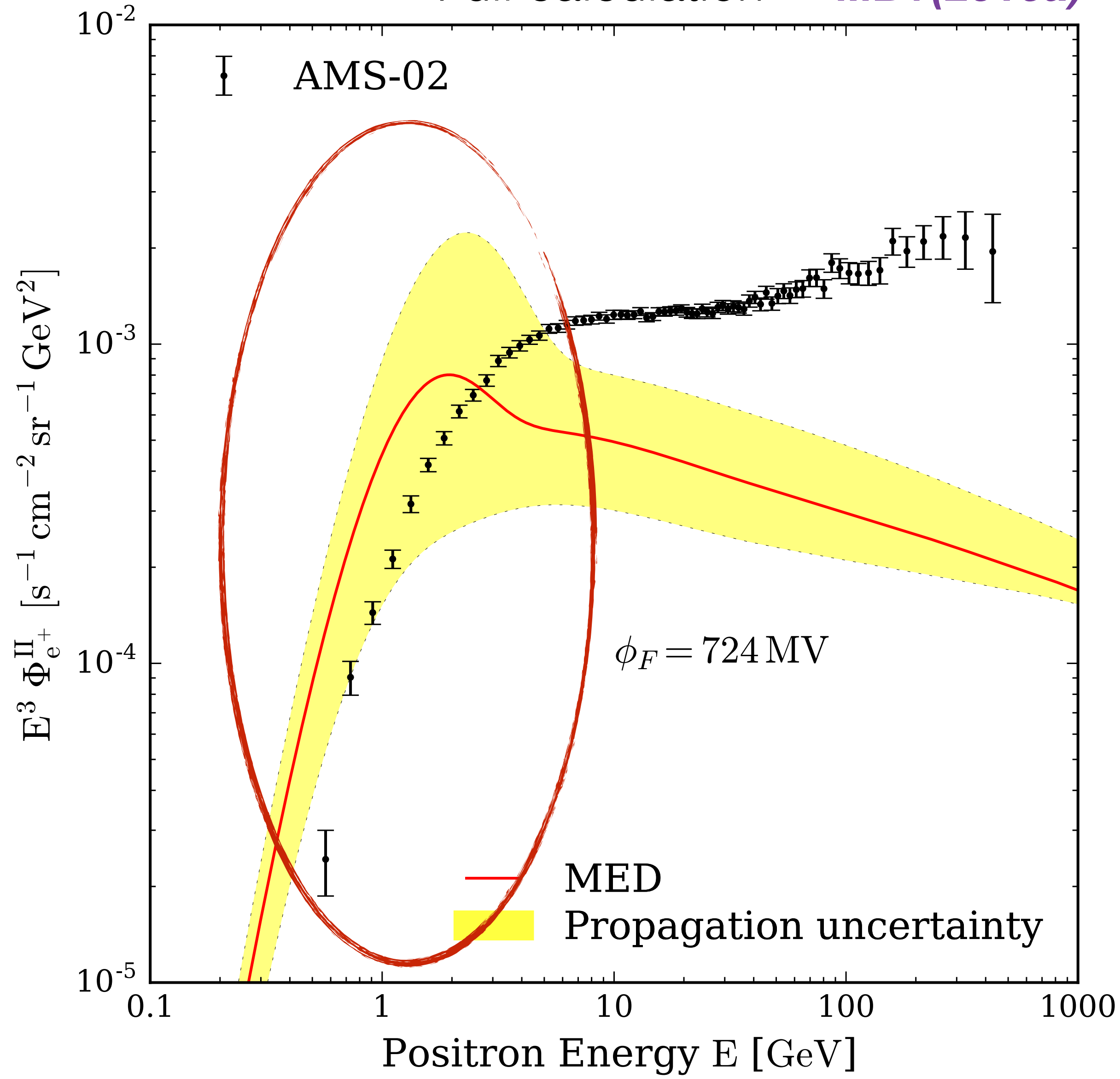
$$Q^{\mathrm{II}}(E,\vec{x}) = 4\pi \sum_{i=p,\alpha} \sum_{j=H,He} n_j \int_{E_0}^{+\infty} dE_i\, \phi_i(E_i,\vec{x})\, \frac{d\sigma}{dE_i}(E_j \to E) \qquad \begin{cases} i = projectile \\ j = target \end{cases}$$

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+(2016a)*



Astrophysical secondary positrons

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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)

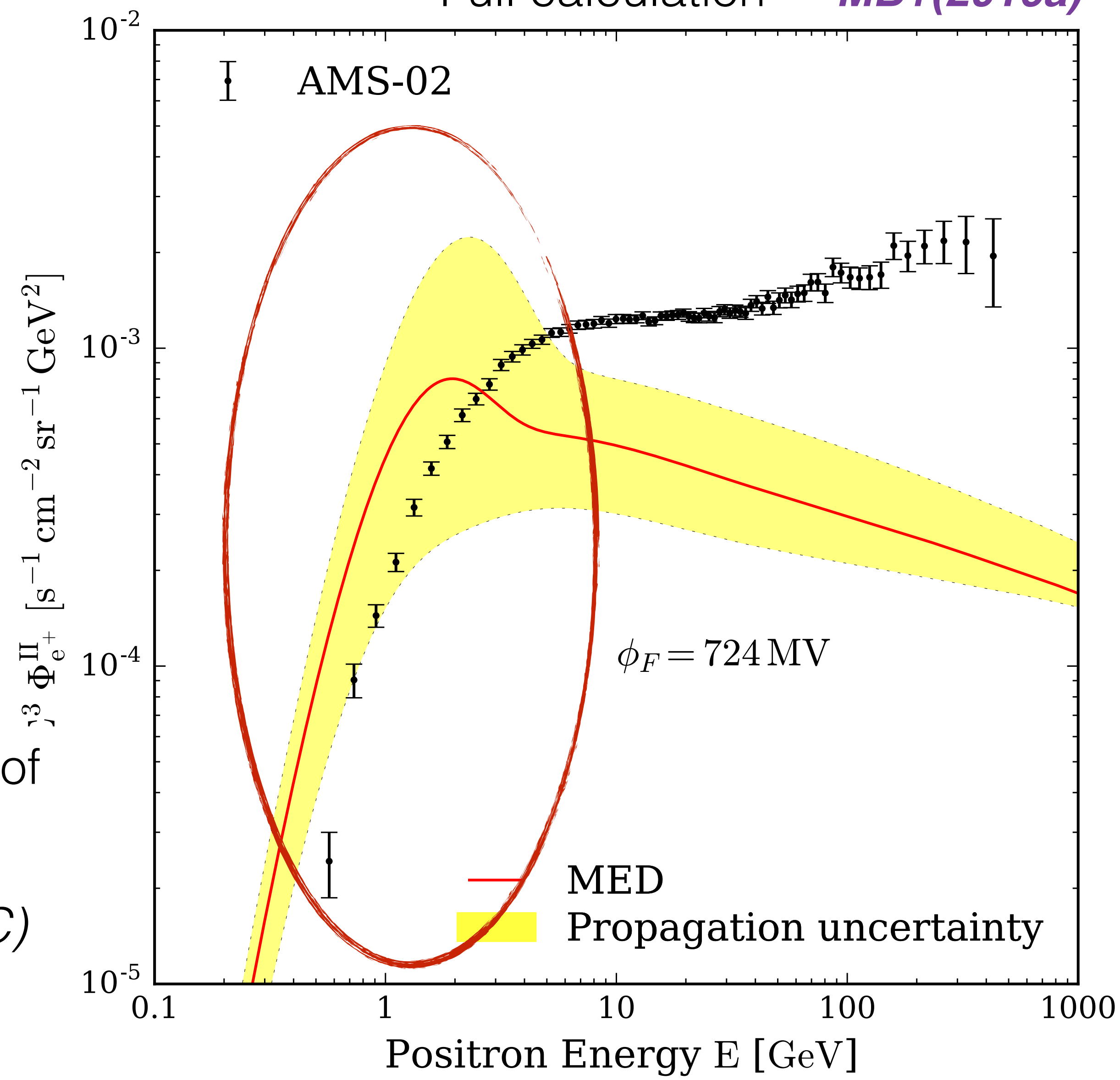
Case	δ	K_0 [kpc²/Myr]	L [kpc]	V_C [km/s]	V_a [km/s]
MIN	0.85	0.0016	1	13.5	22.4
MED	0.70	0.0112	4	12	52.9
MAX	0.46	0.0765	15	5	117.6

Ruled out!

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

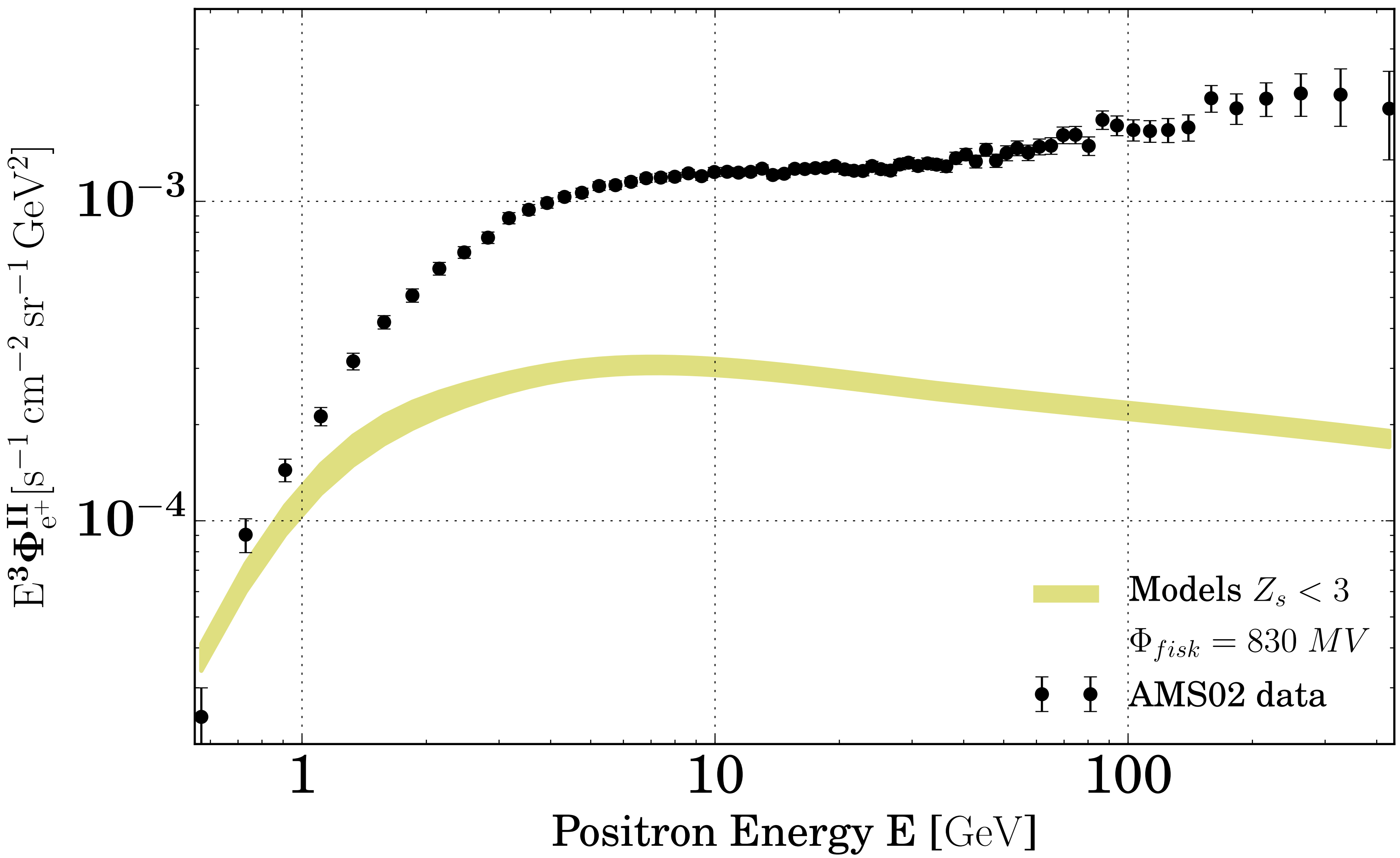
(result confirmed by AMS-02 antiprotons and recent B/C)

Full calculation ***MB+(2016a)***



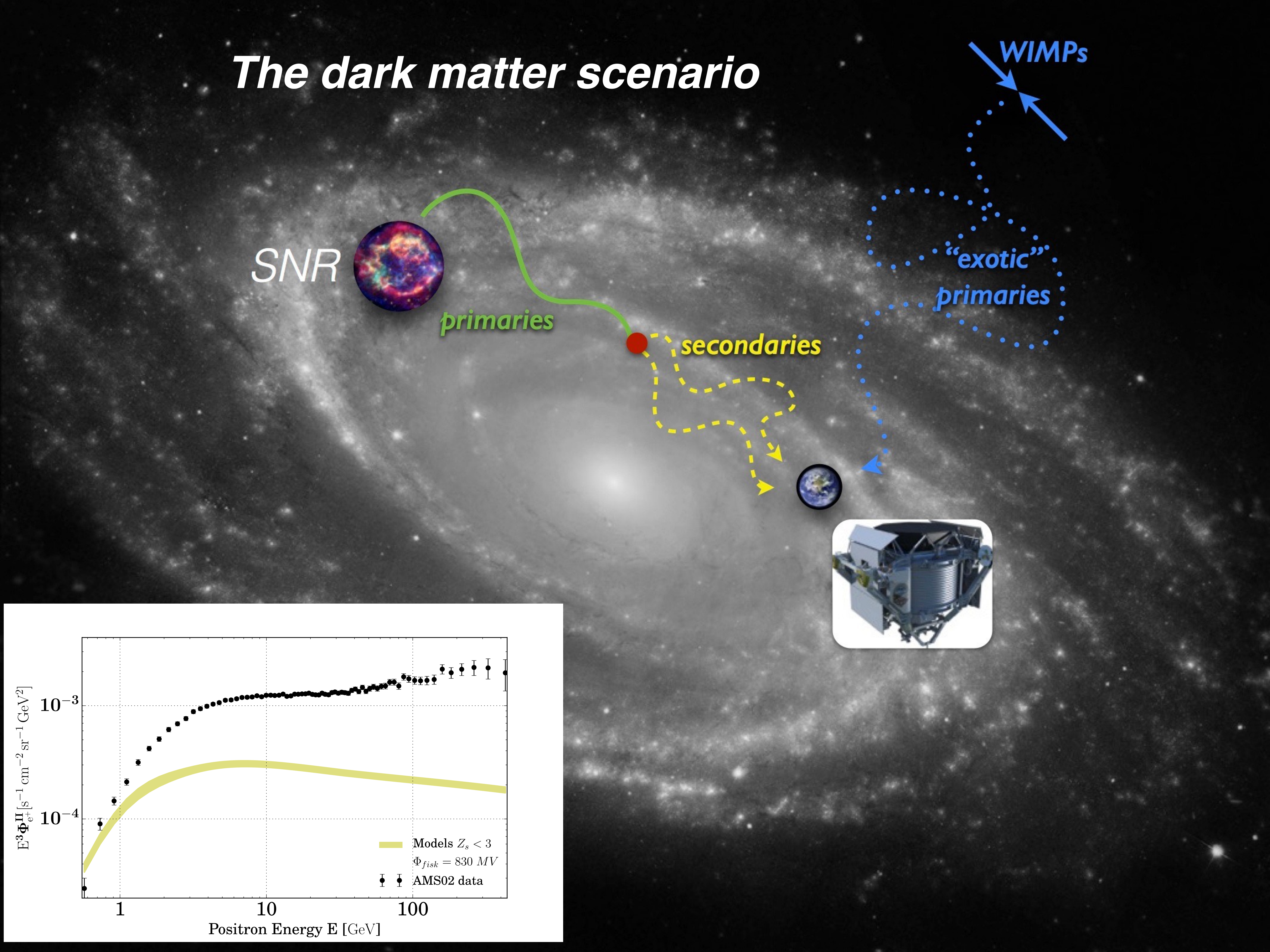
Astrophysical secondary positrons

MB+(2016a)

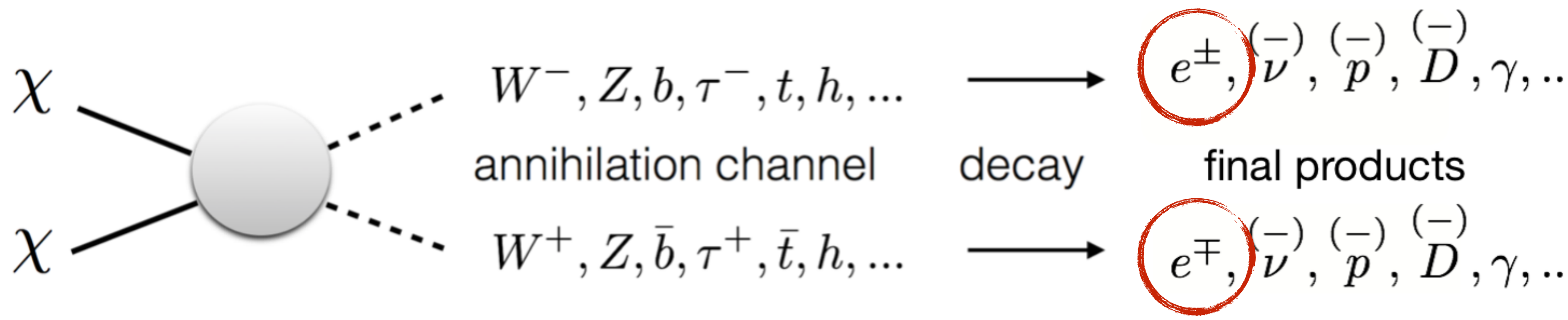


- The uncertainty band for the e $^+$ is now very narrow.
- The positron excess appears now from ~1 GeV.
- Where do come from the remaining positrons?
- We need another component(s) to explain the positron data **from ~1 GeV to ~500 GeV**.

Implications for dark matter searches


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

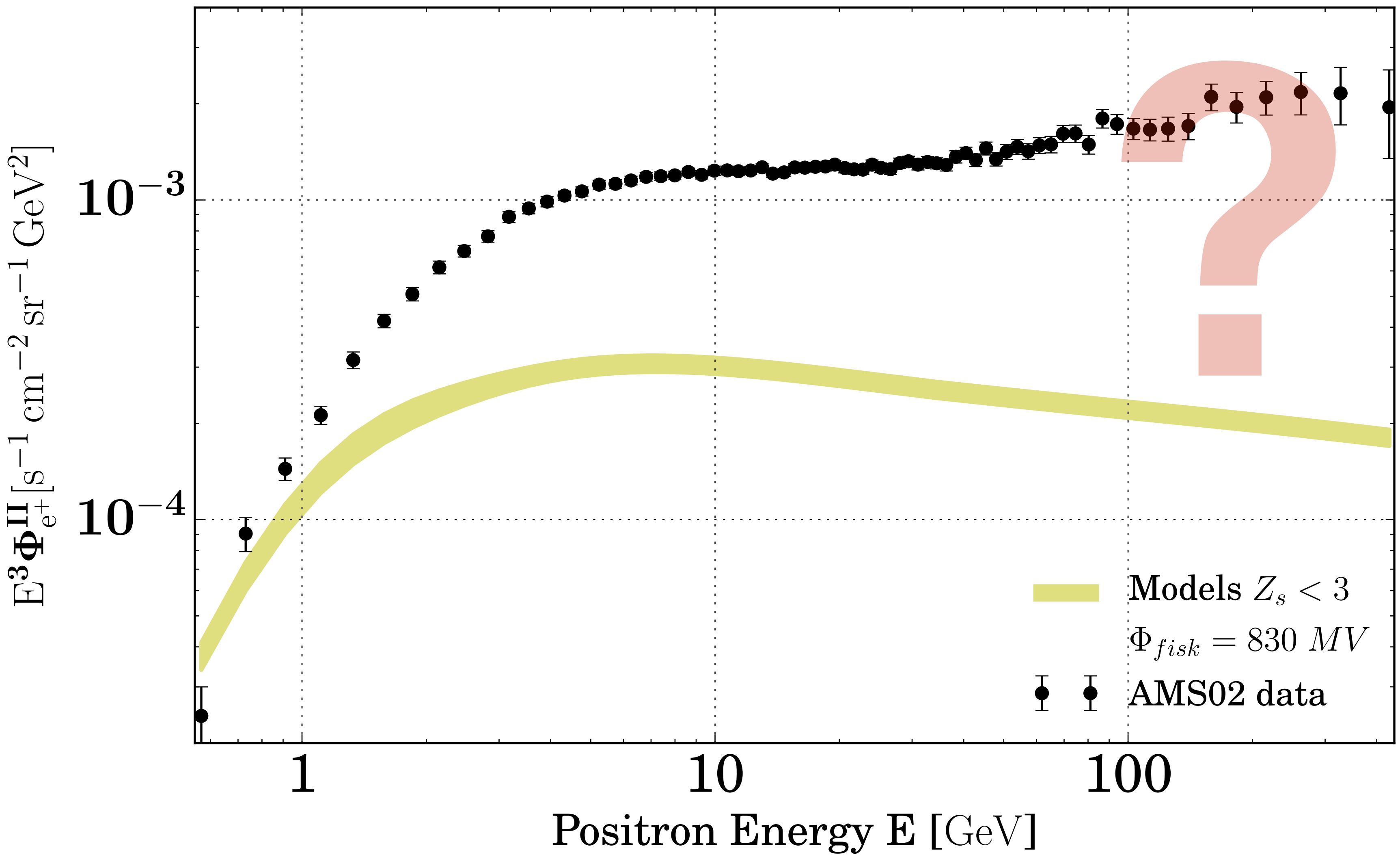
  The mass m_χ

  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?



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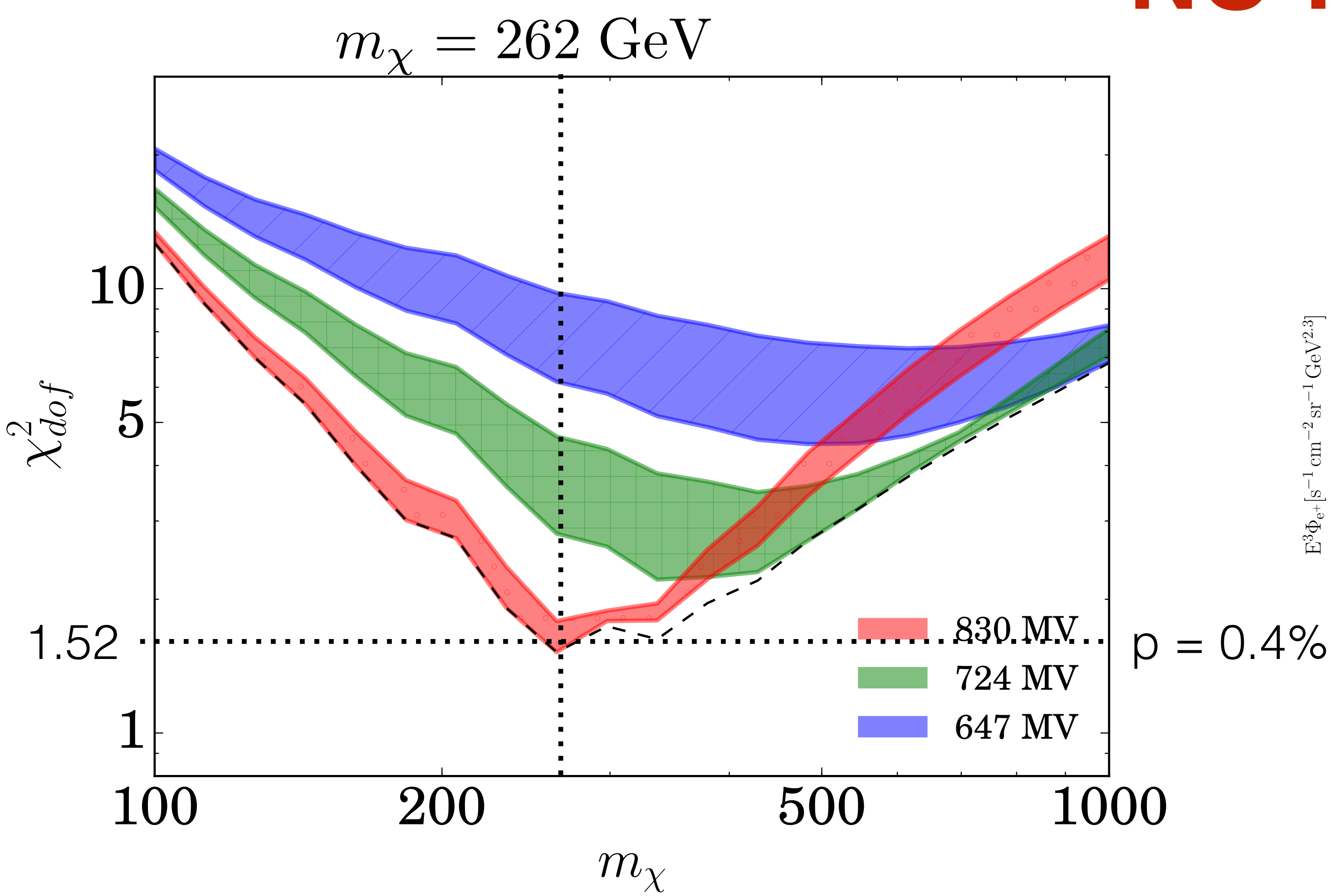
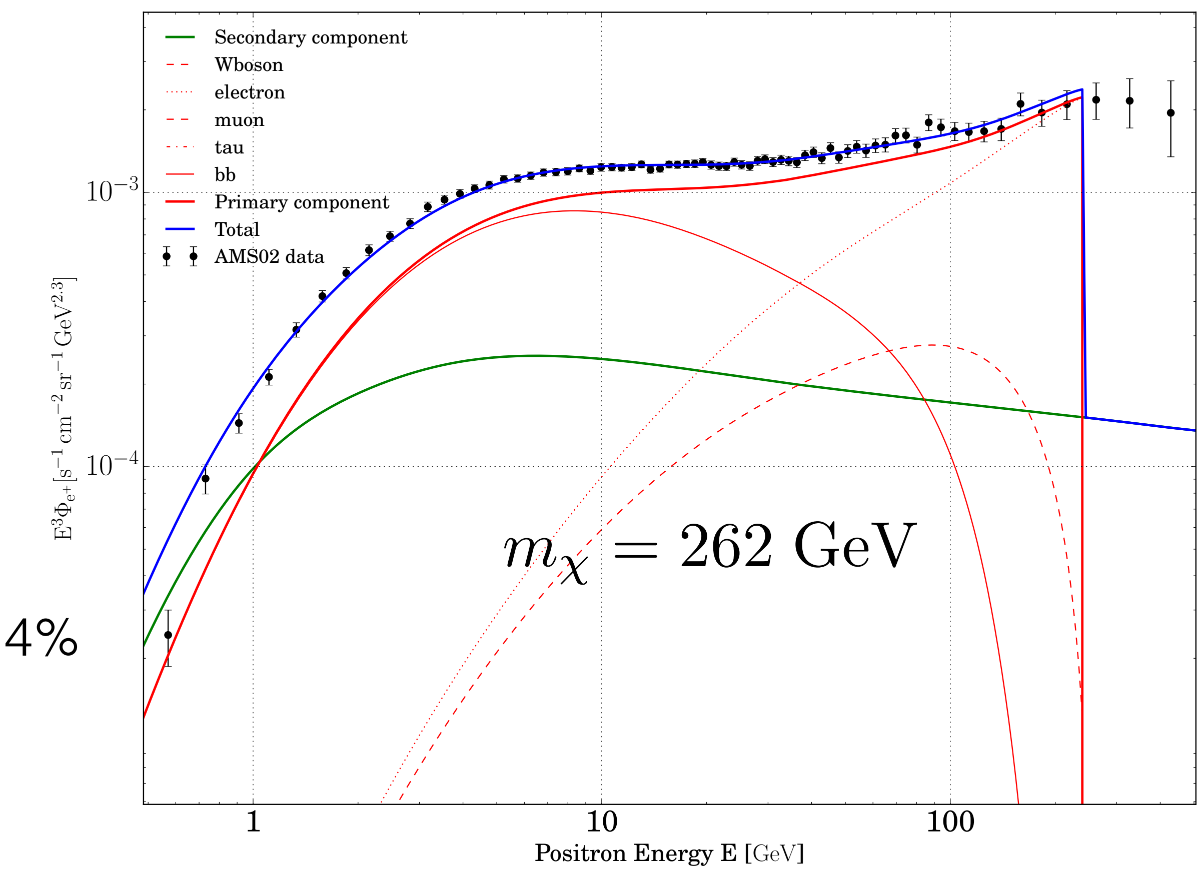


MB+(2016a)



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.

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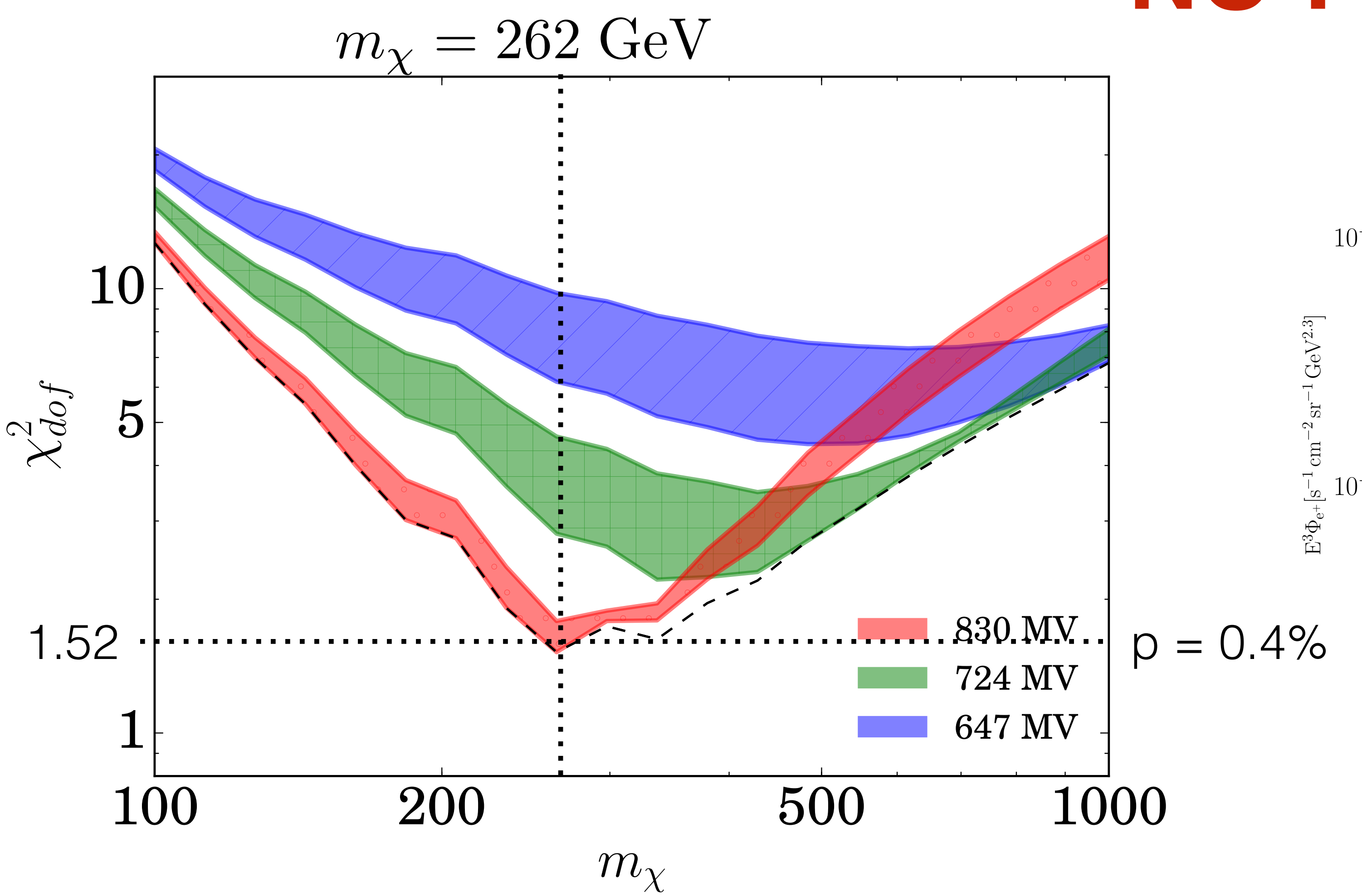

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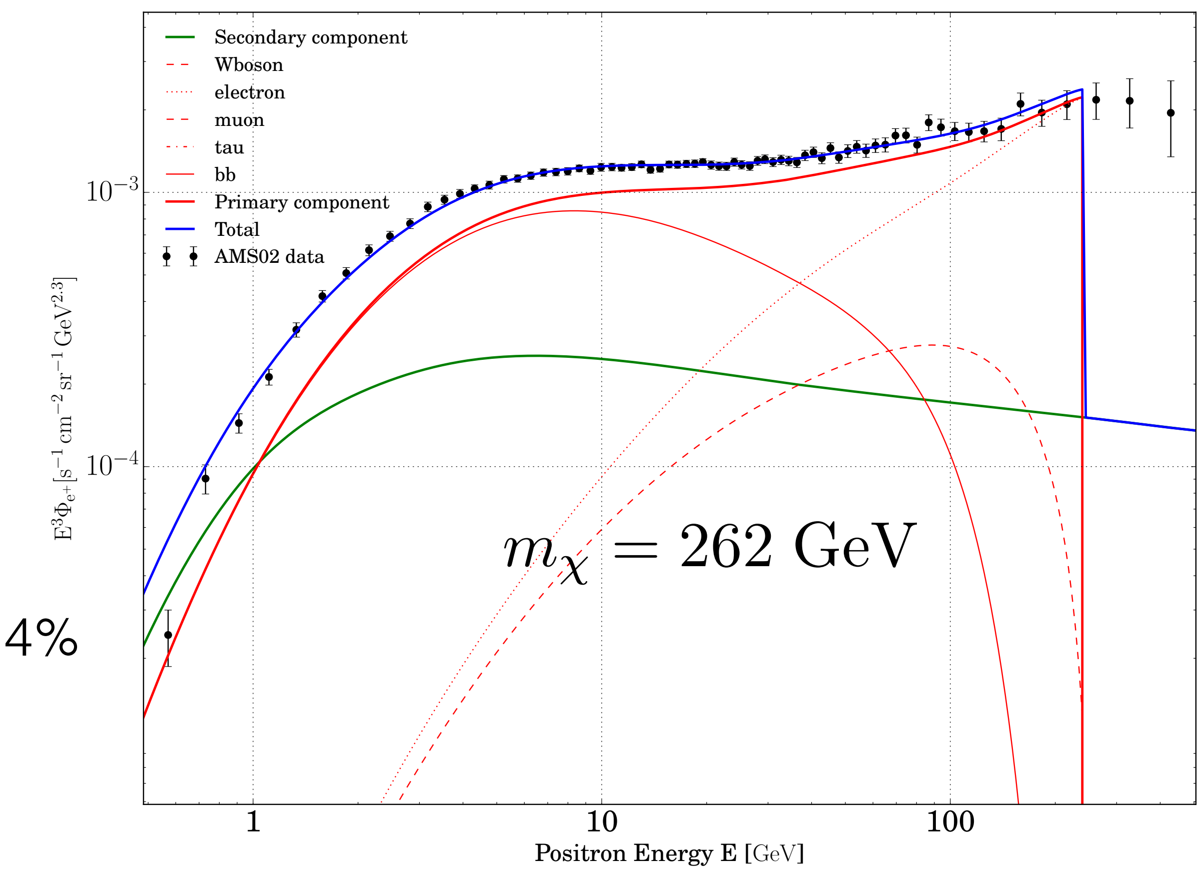

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The poor quality of the fit disfavours a pure DM explanation for the positron excess!

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

Implications for dark matter searches

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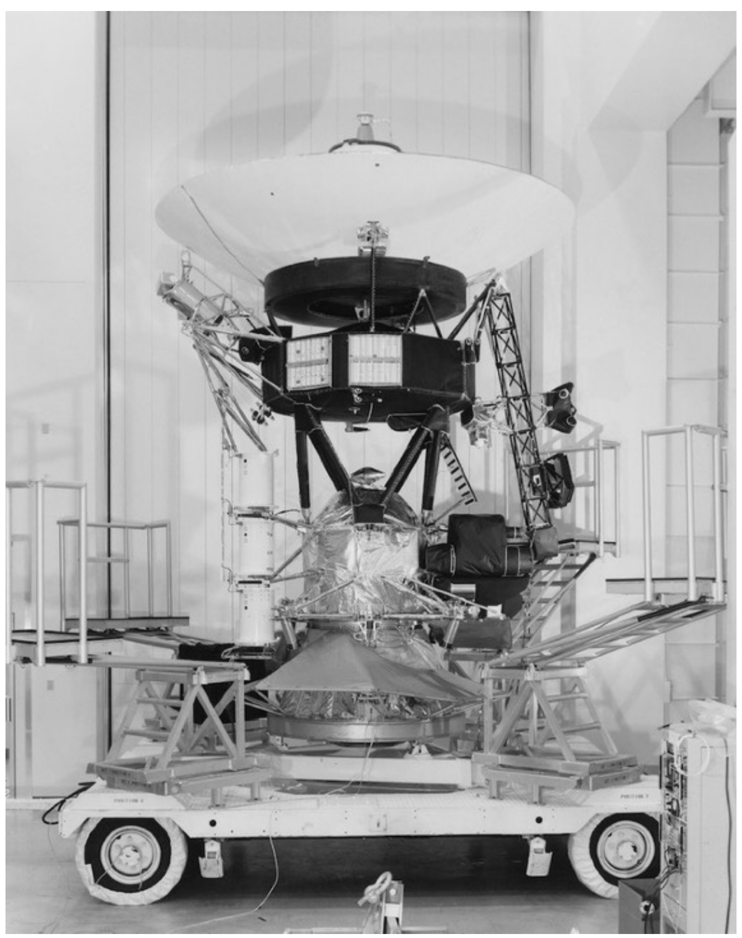
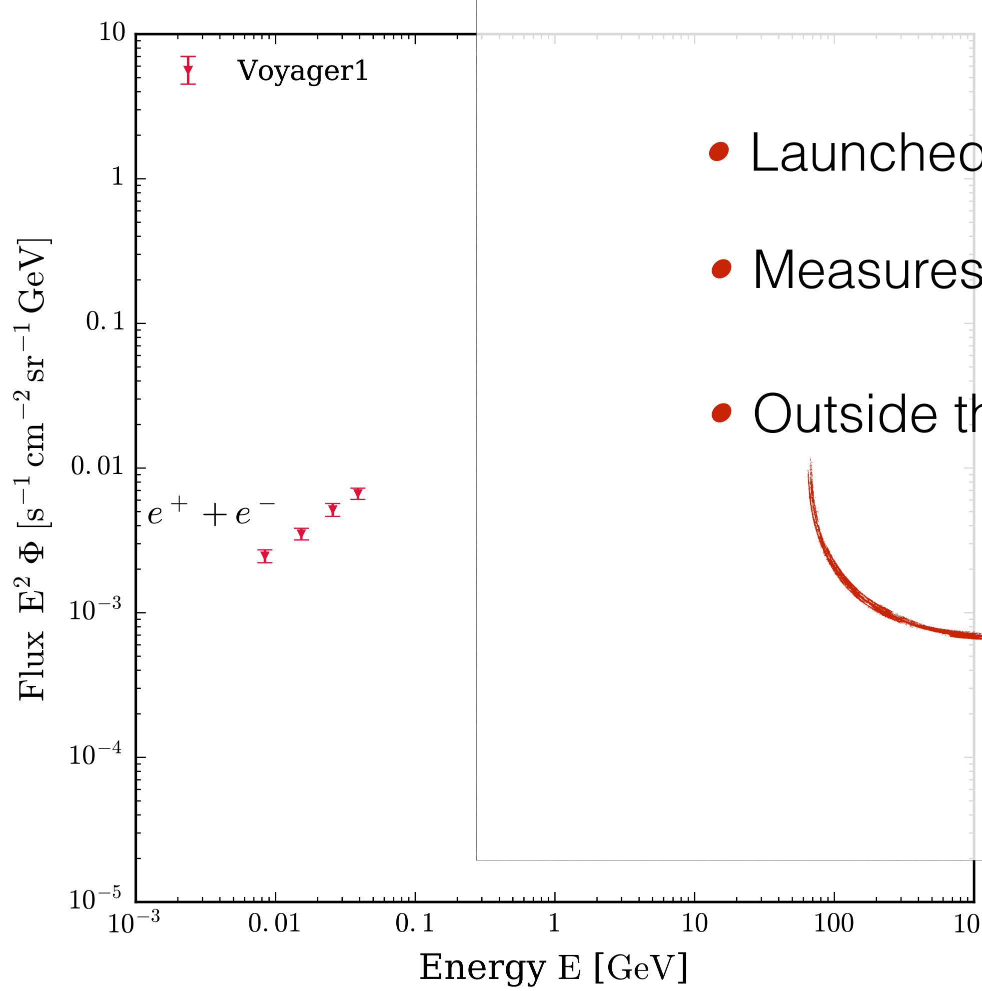
✓ **Voyager-1 spacecraft has crossed the heliopause during summer 2012.**

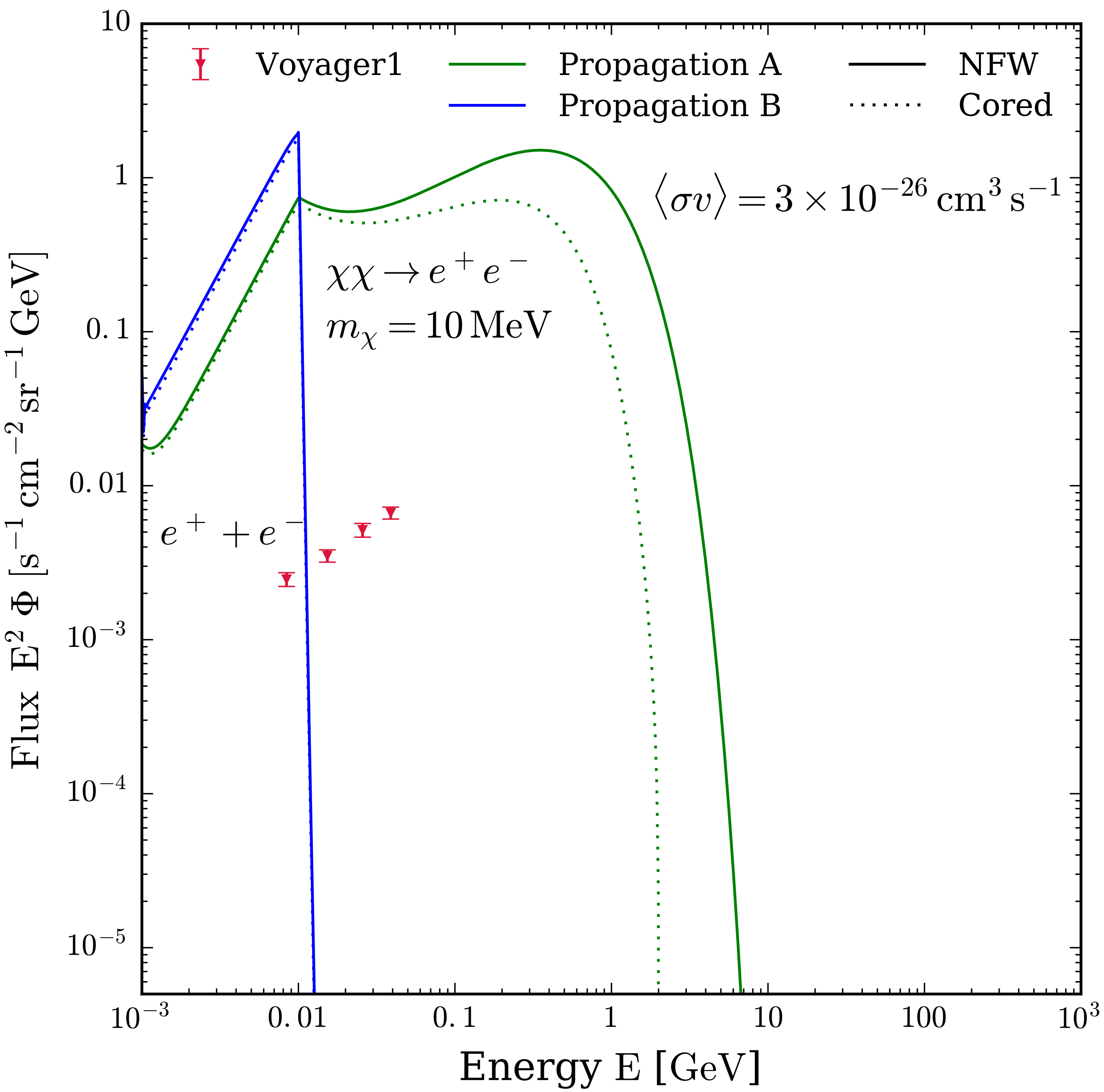




- Launched in 1977
- Measures the flux of **<u>electrons + positrons</u>**
  Stone et al. (2013)
- Outside the heliosphere since august 2012

→ independent of solar effects

Constraints on DM annihilating cross section



- **Model A**: $V_A = 117.6\,\mathrm{km/s}$
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$$\chi\chi \longrightarrow e^+ e^-$$

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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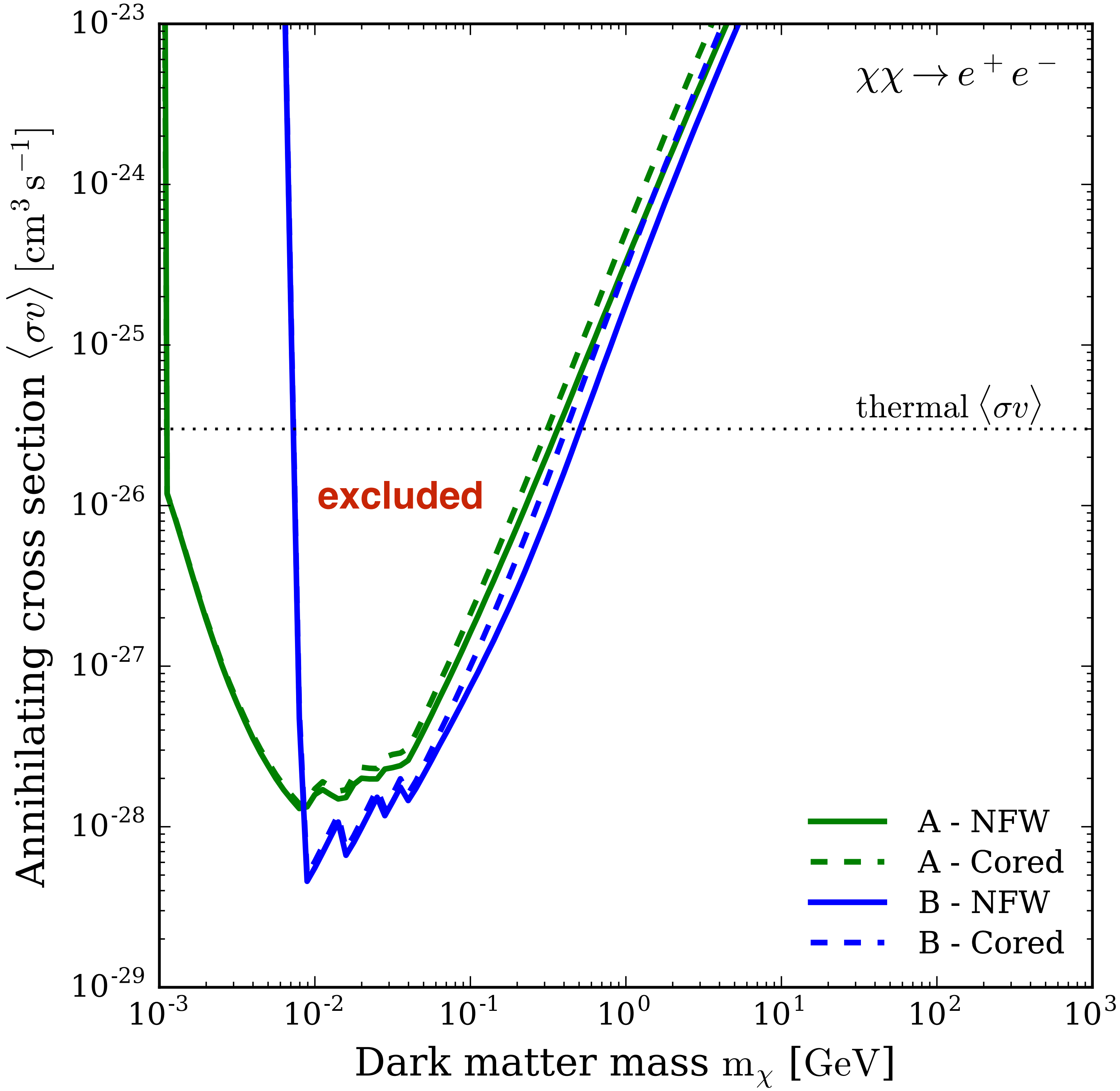

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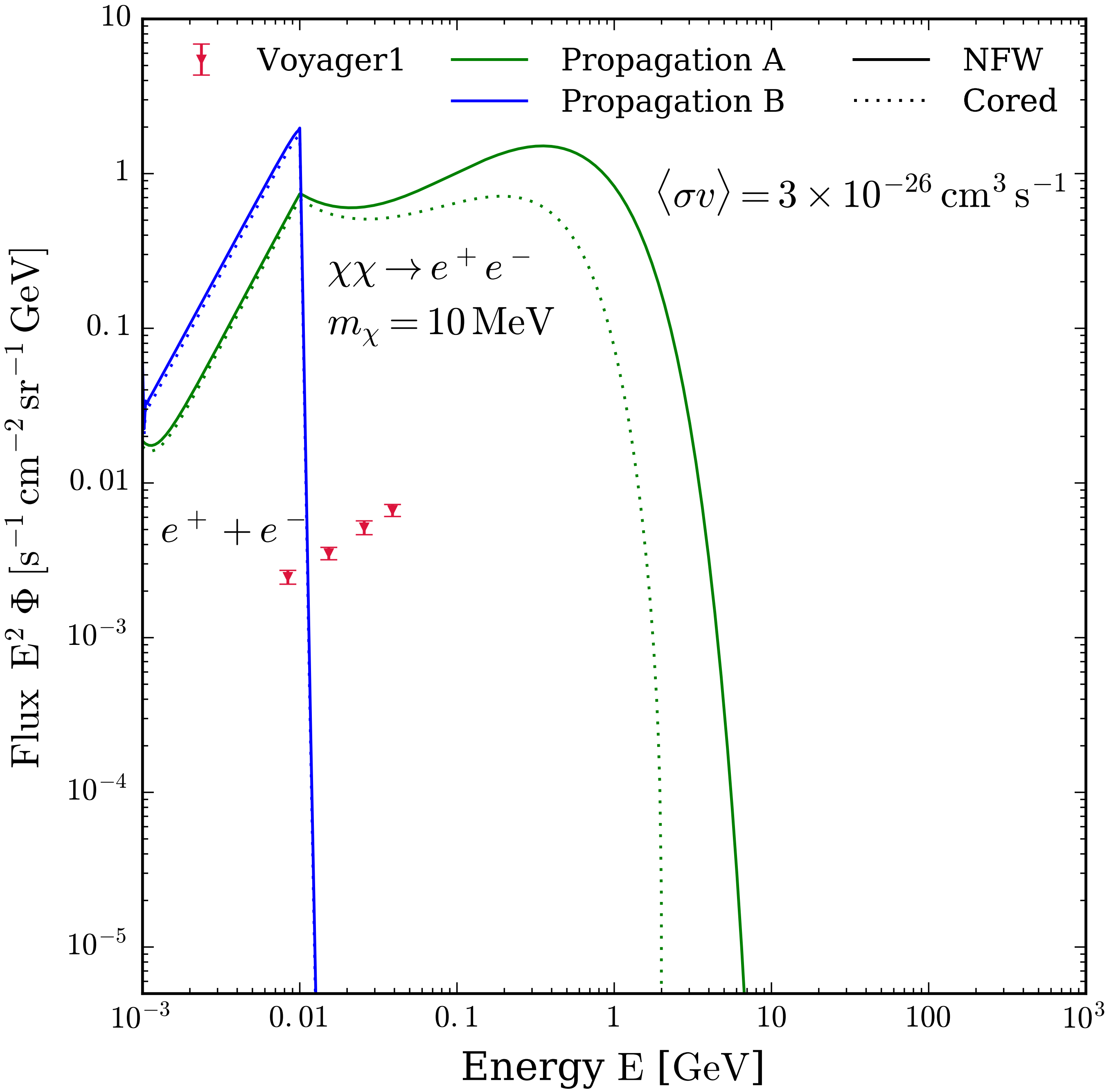

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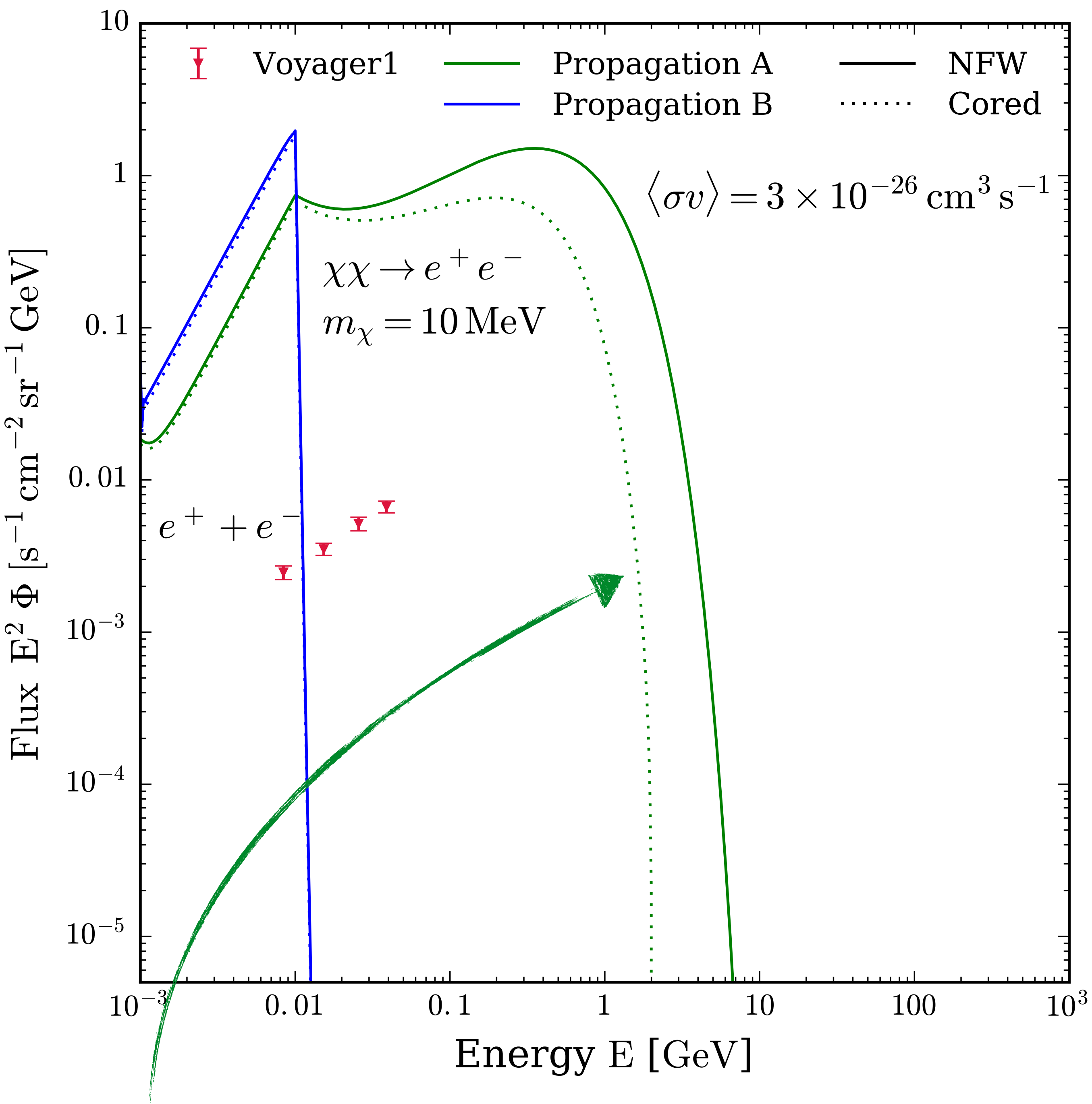

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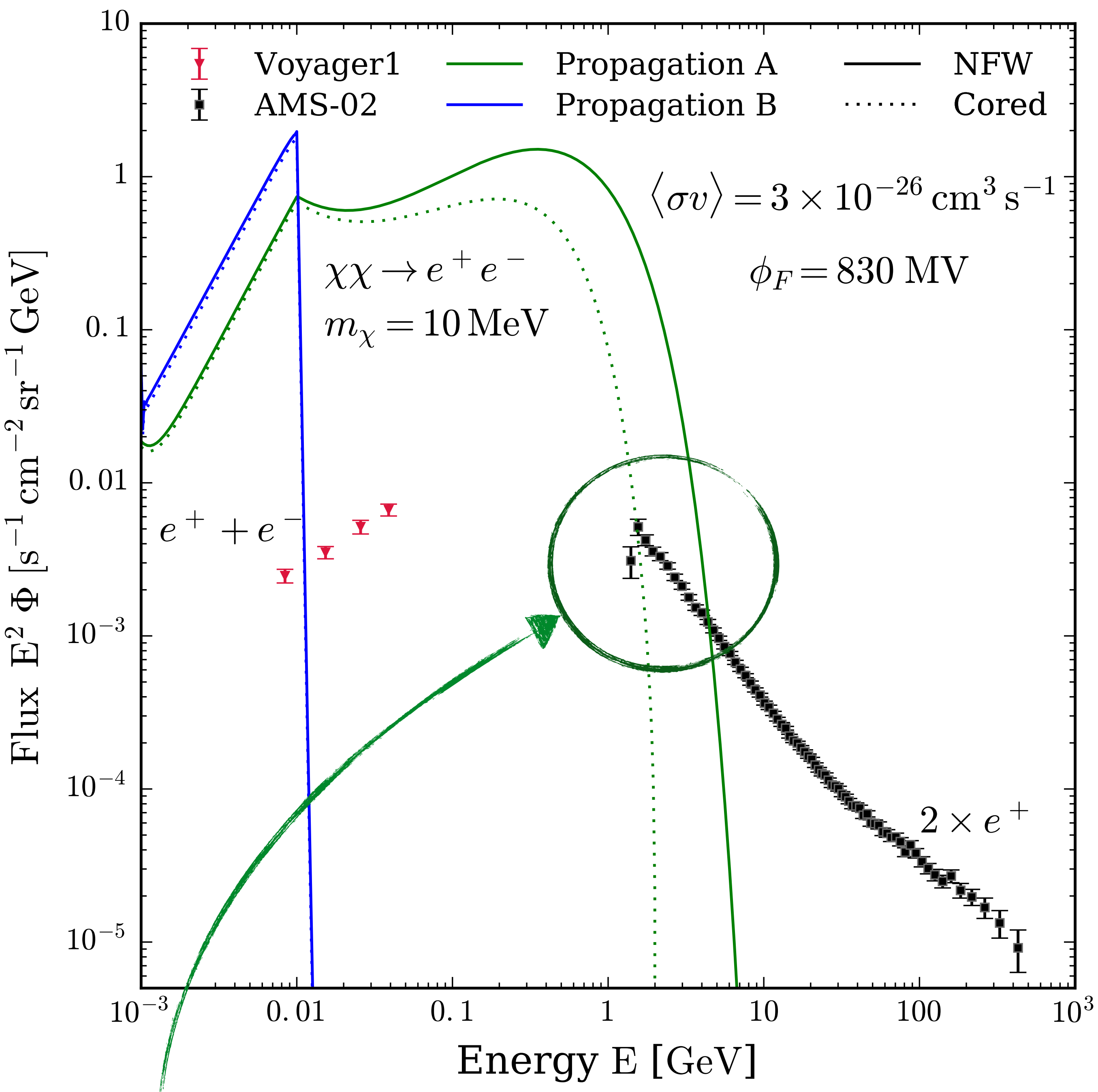

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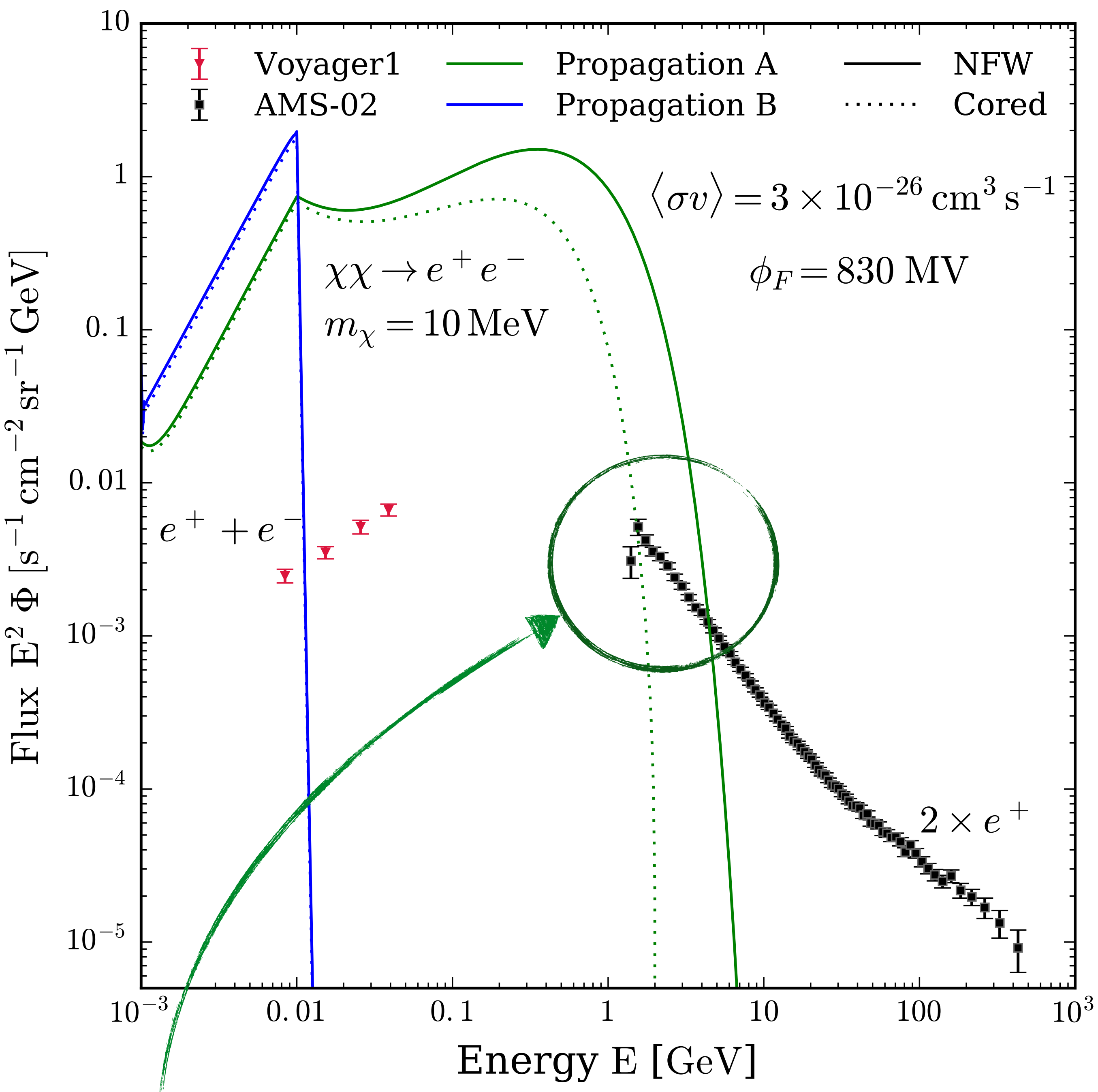

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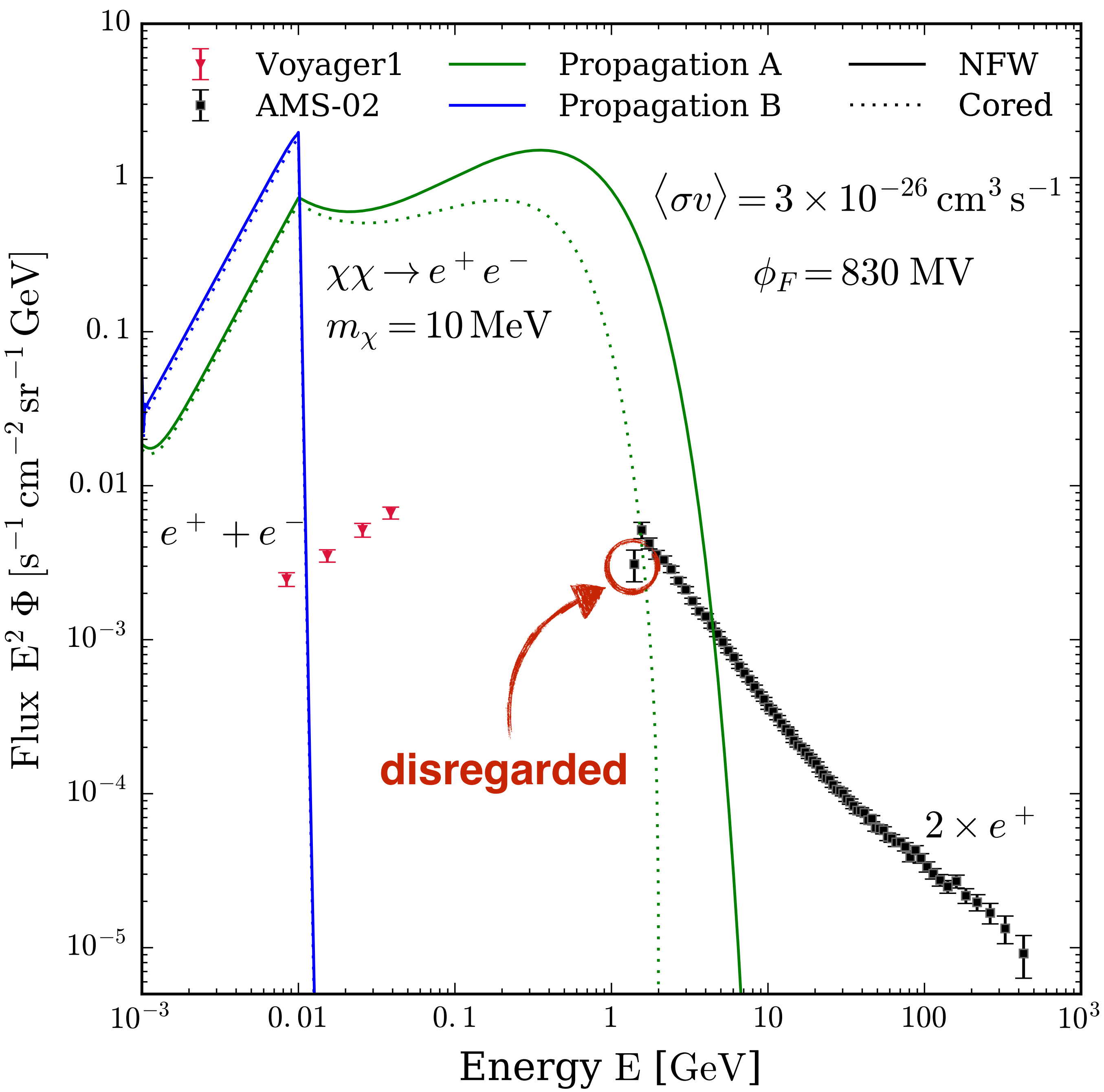

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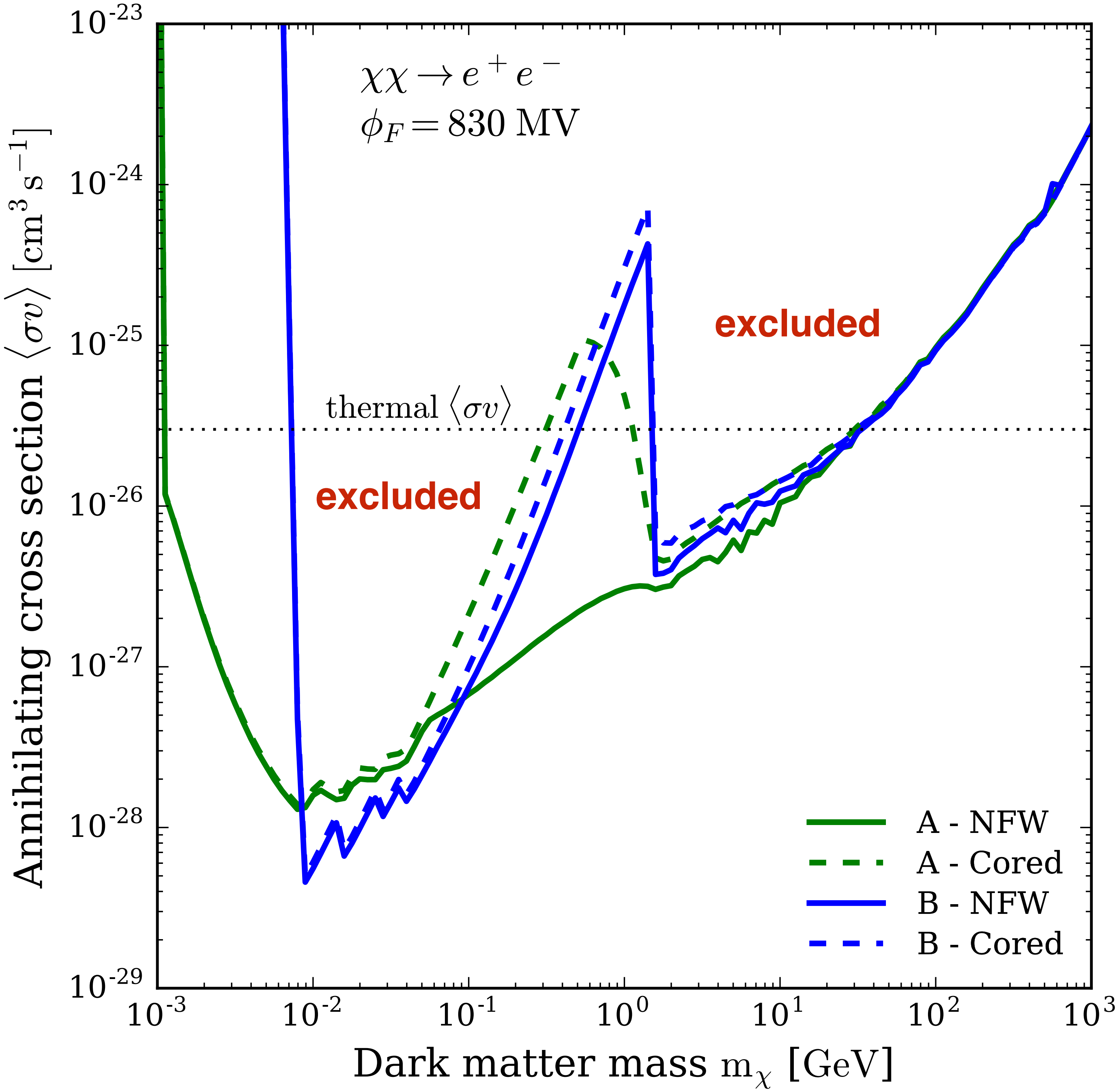

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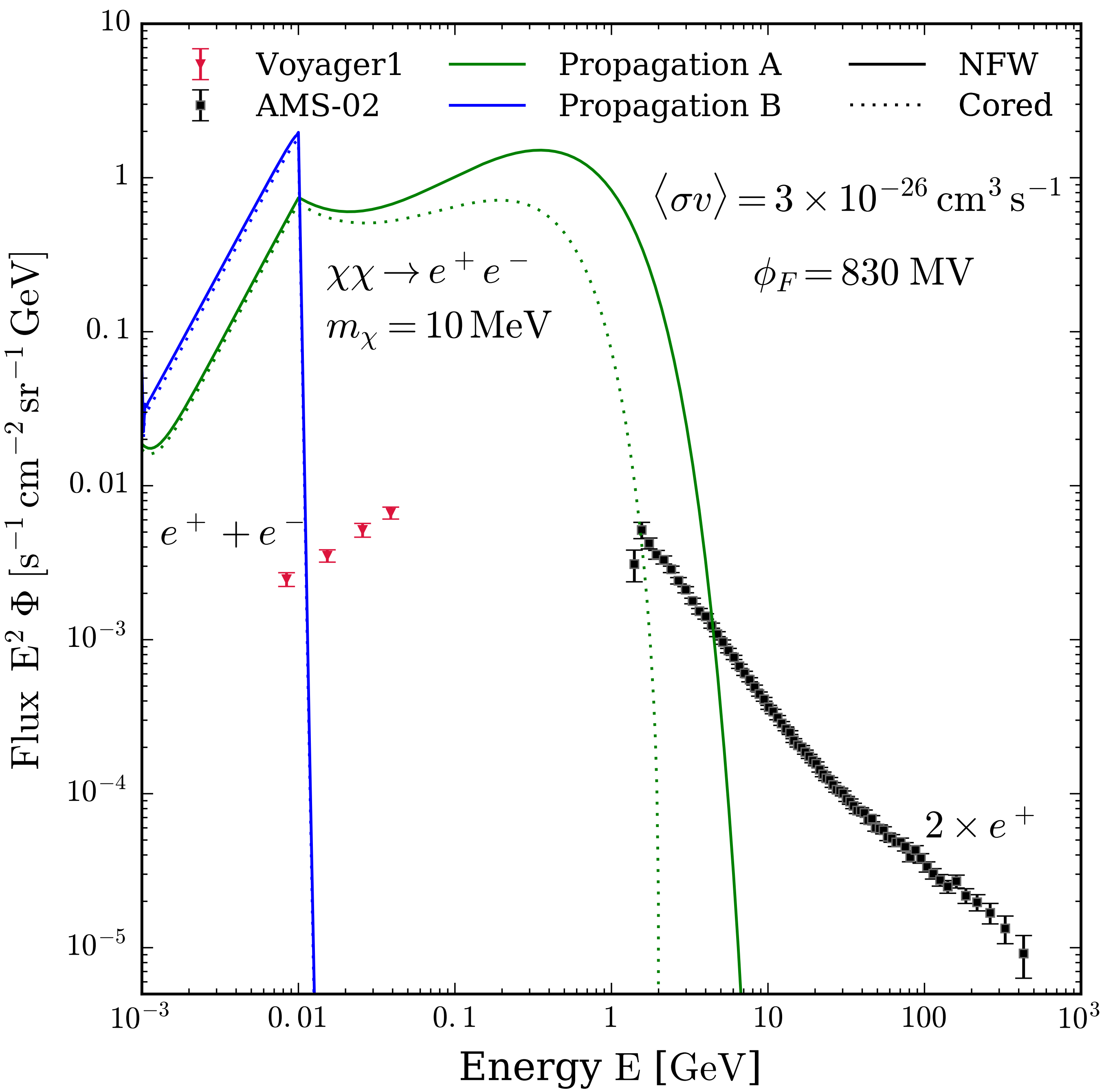

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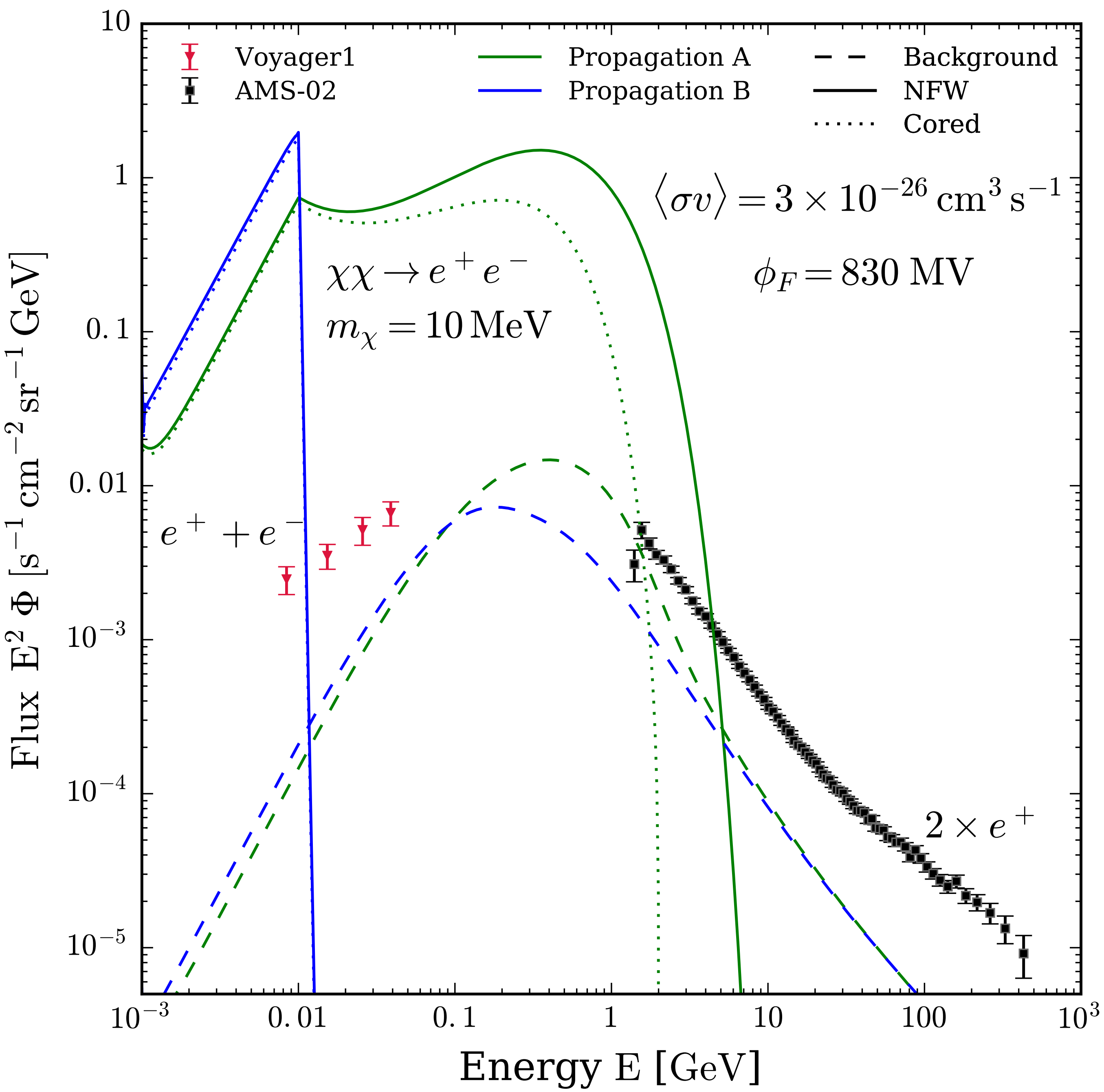

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With astrophysical background of secondary e⁺:

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

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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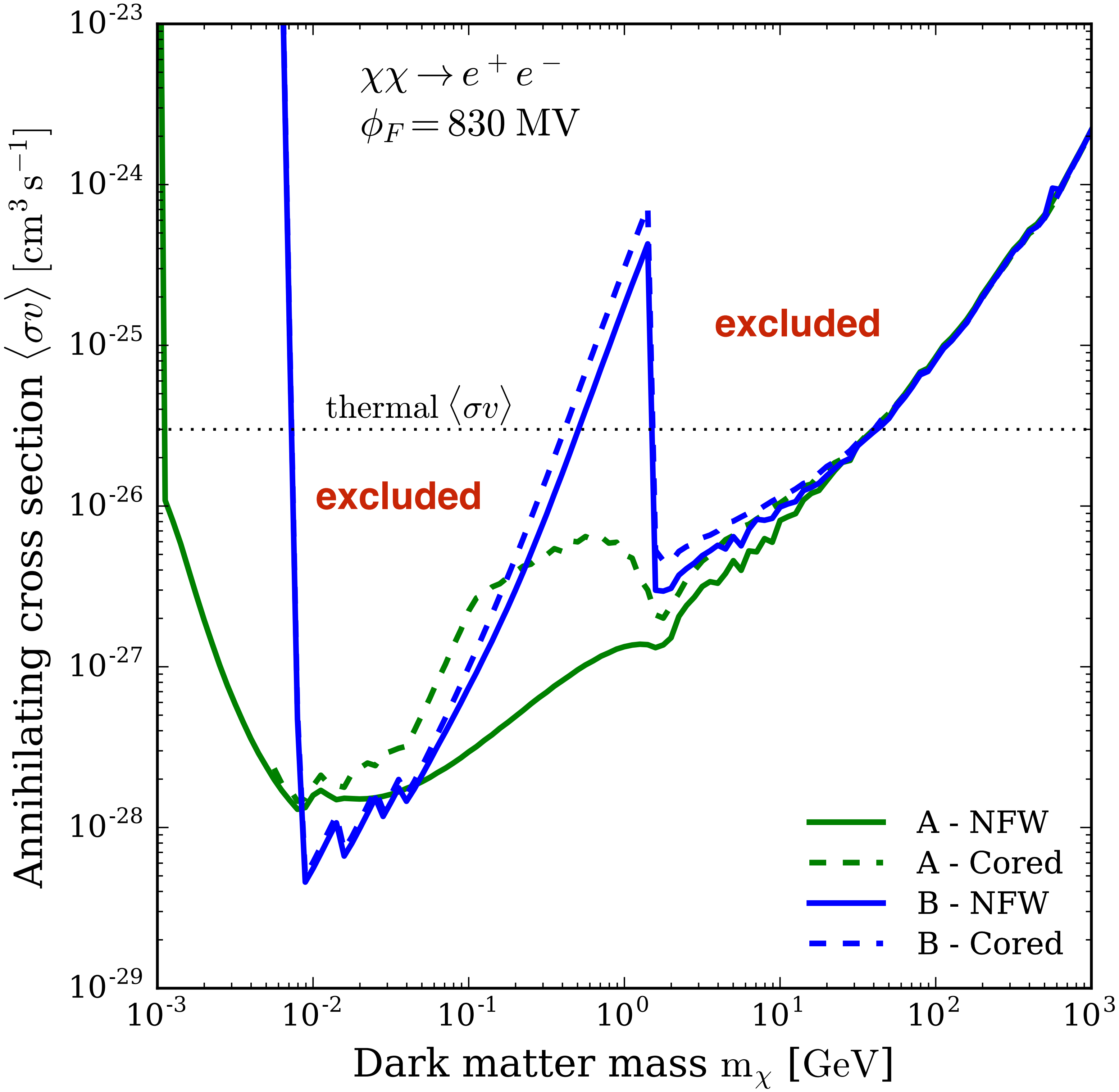
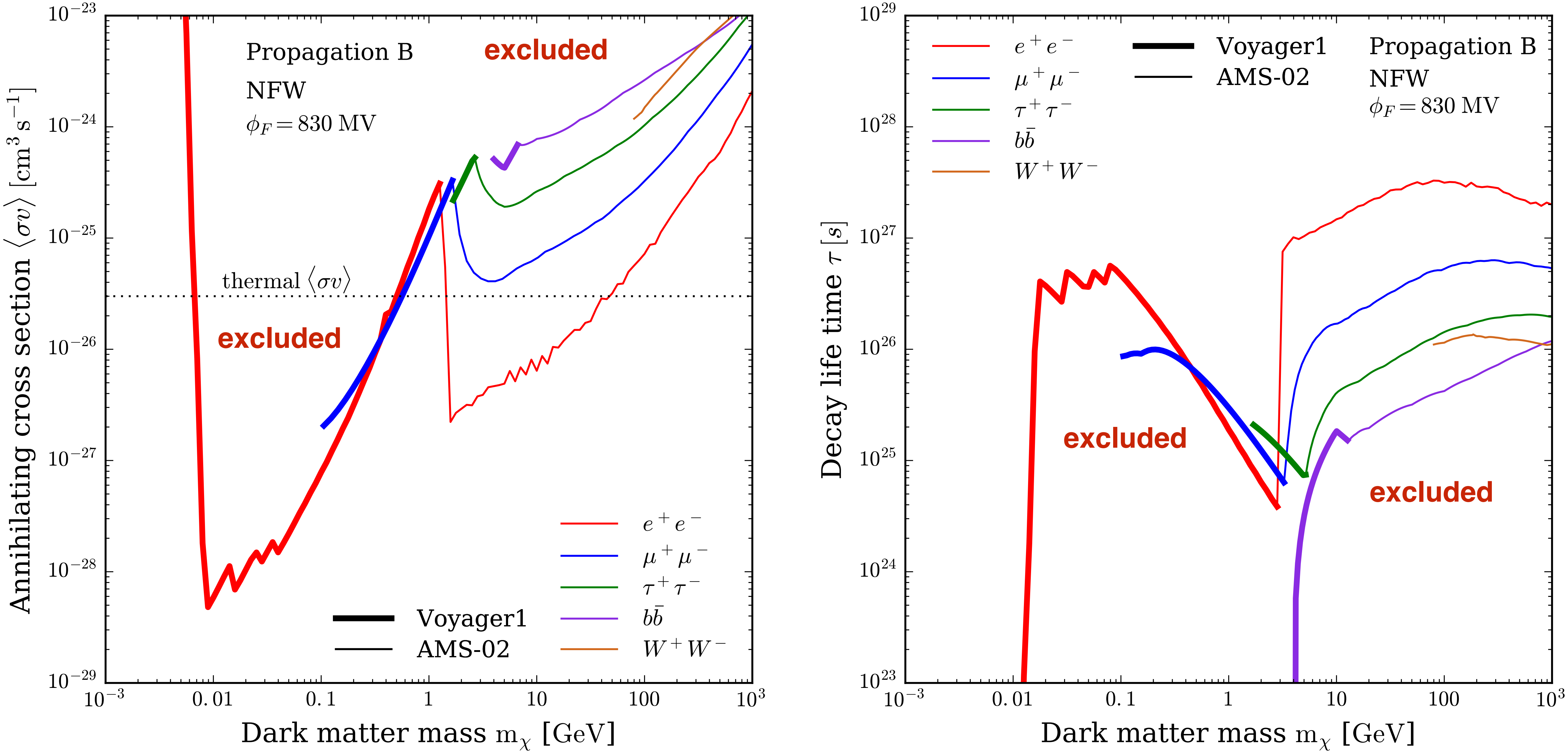
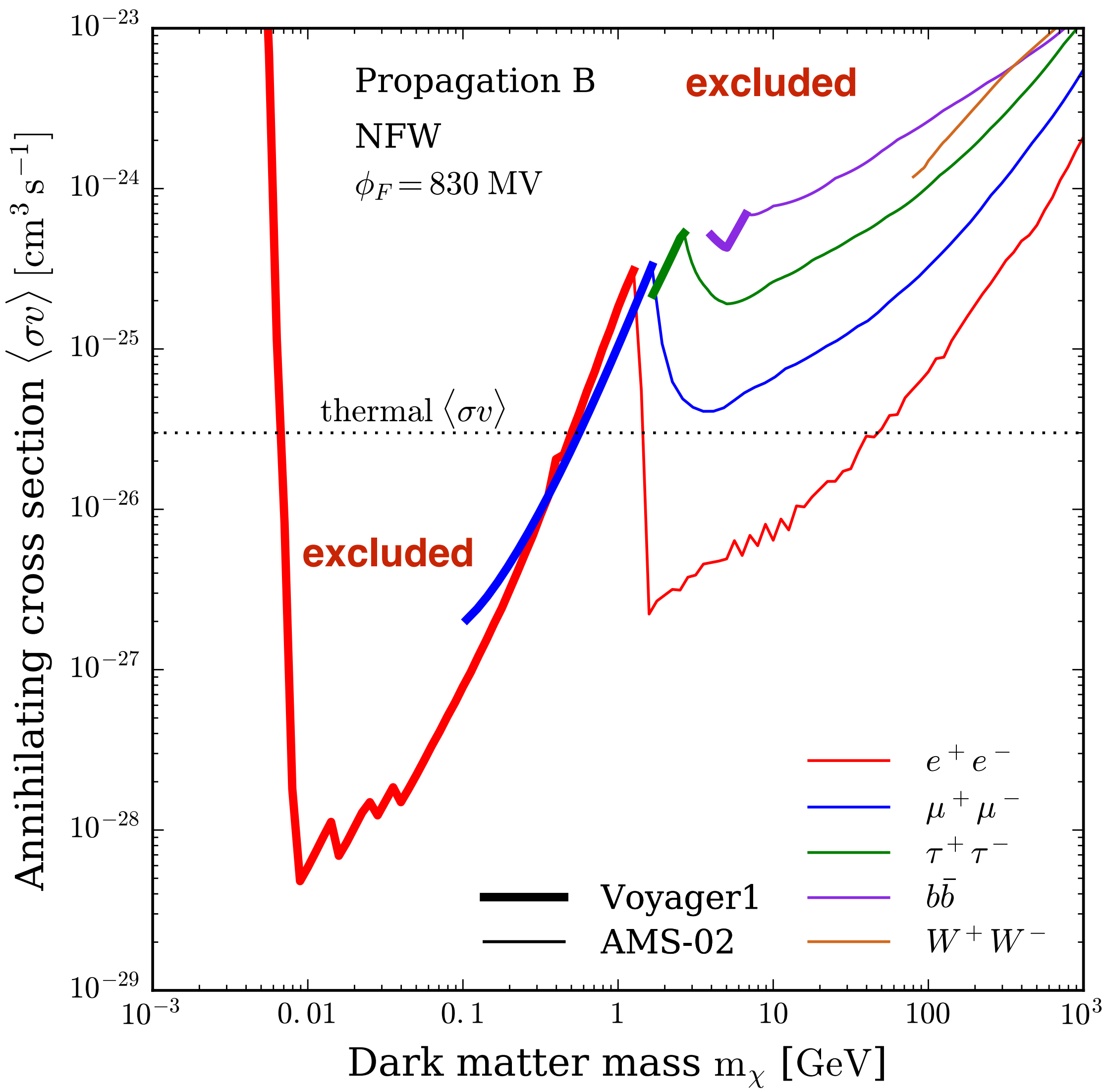


Annihilating Dark Matter ***MB+(2016b)*** **Decaying Dark Matter**

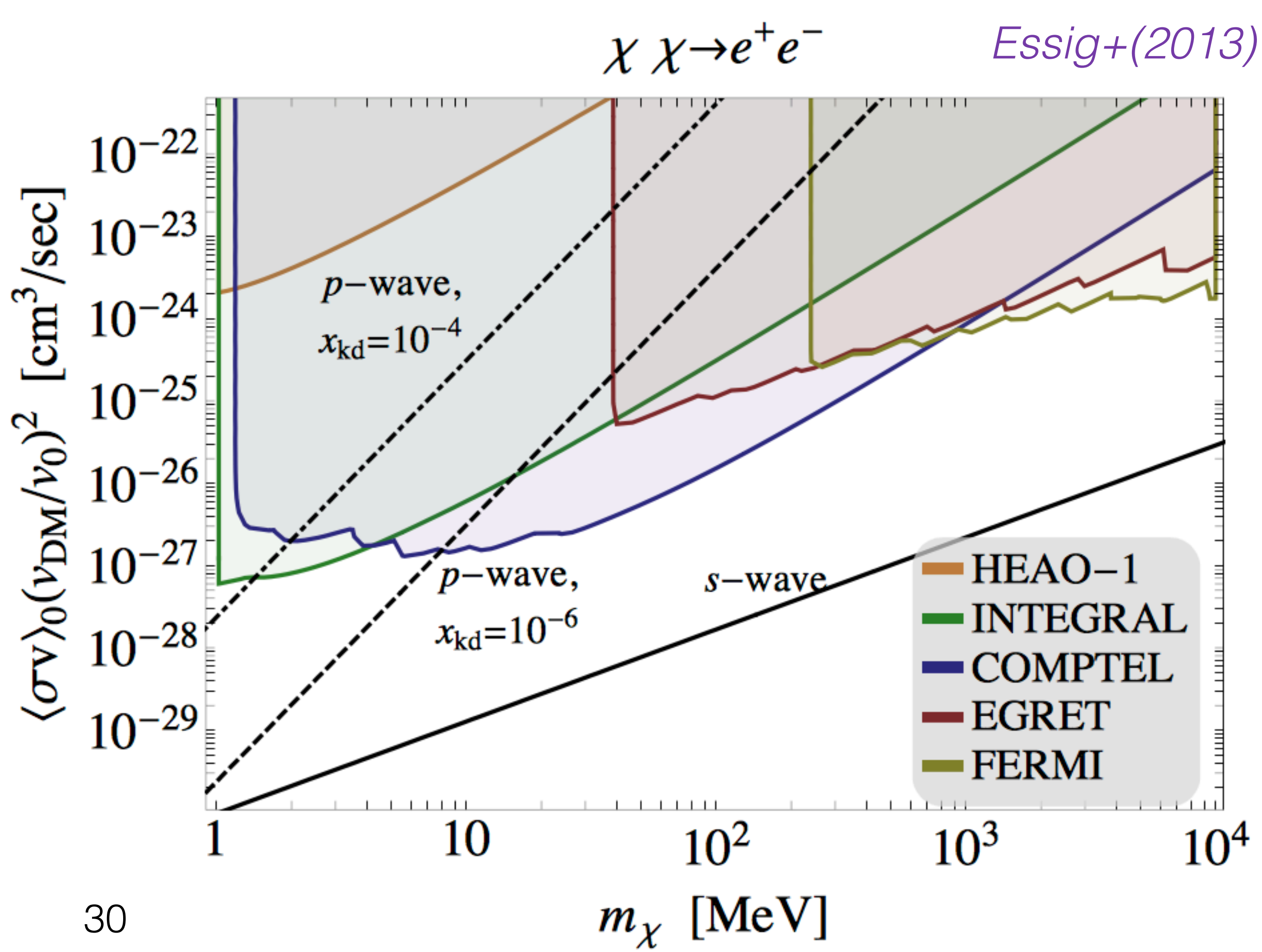


Comparison with other constraints



X-rays and γ-rays

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



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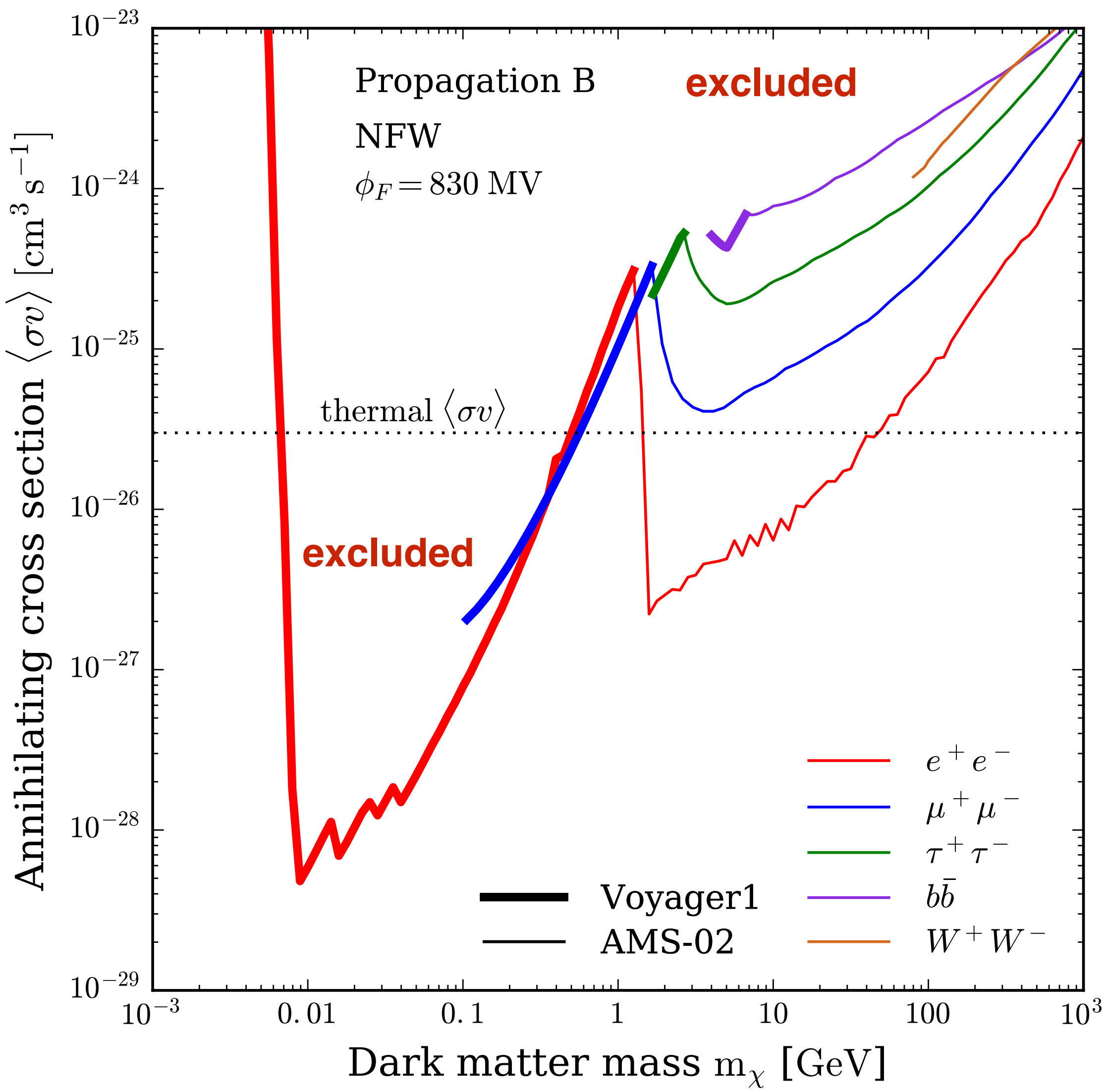
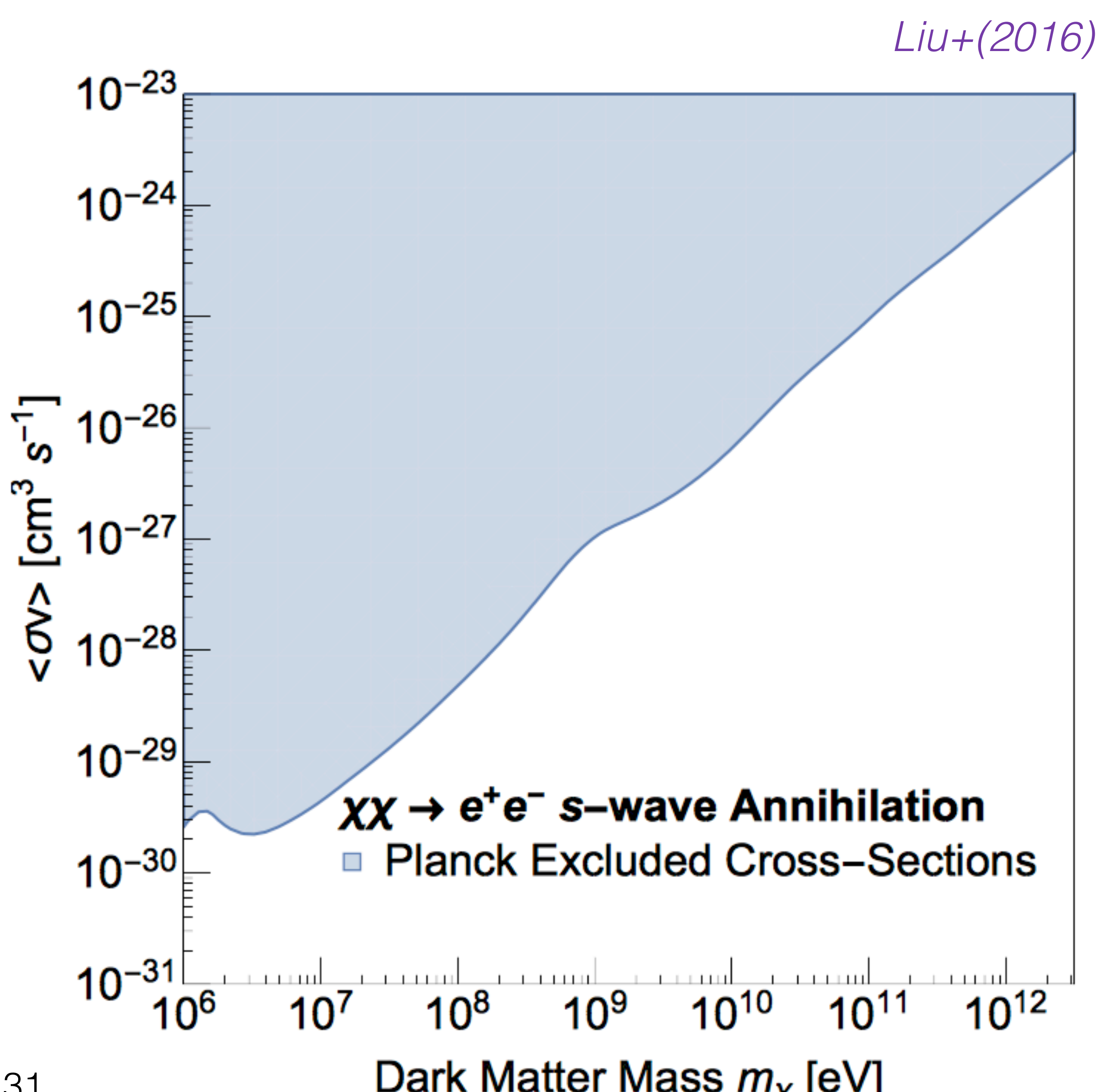


CMB

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



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

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

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

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

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

p-wave annihilation

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

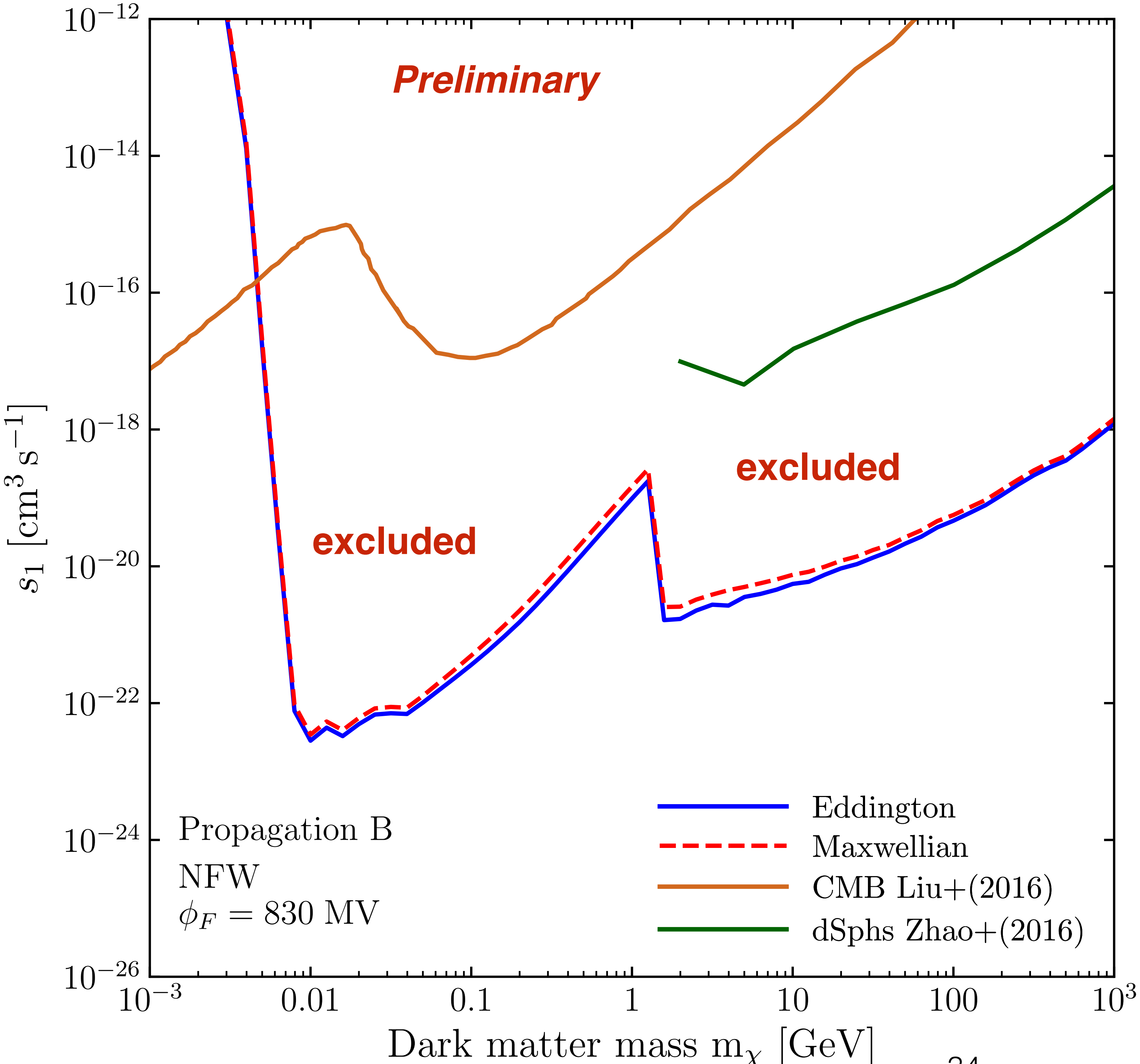
e.g: McMillan (2016), Catena & Ullio (2010)

p-wave annihilation

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

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

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



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

Conclusions and outlook

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- Low energy positrons enables to reduce 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**.

Astrophysical background of secondary antiprotons

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

- Production XS of antiprotons

$$p\,(\mathrm{CR}) \;+\mathrm{H}\,(\mathrm{ISM}) \longrightarrow \bar{p} + X \;(\simeq 70\%)$$
$$\alpha\,(\mathrm{CR}) \;+\mathrm{H}\,(\mathrm{ISM}) \longrightarrow \bar{p} + X \;(\simeq 25\%)$$
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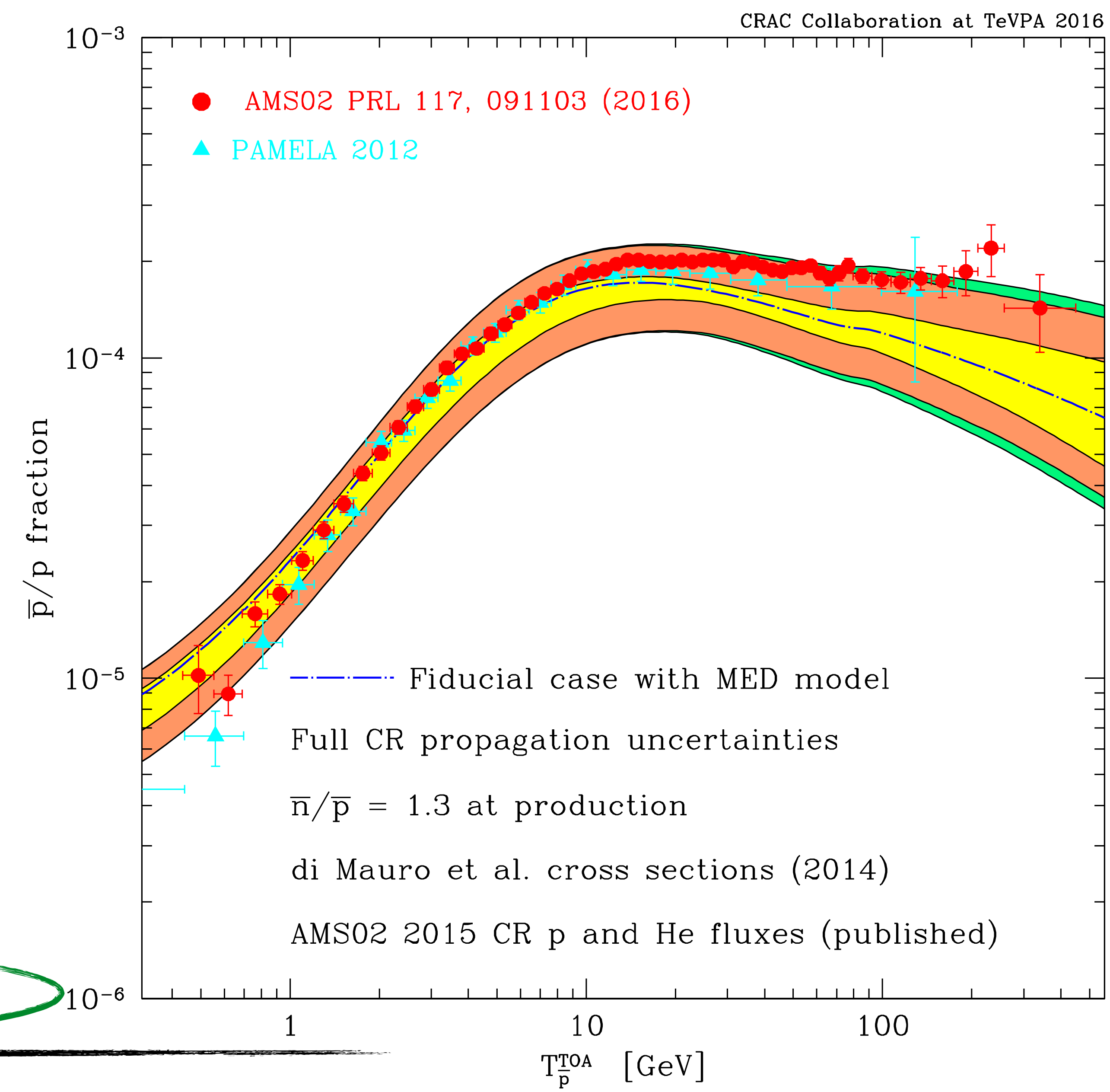
- Energy and space distribution of primary CRs (H, He)

- **AMS-02 data are consistent with the antiproton astrophysical background.**
- **The data prefer a MAX-type set of propagation parameters.**

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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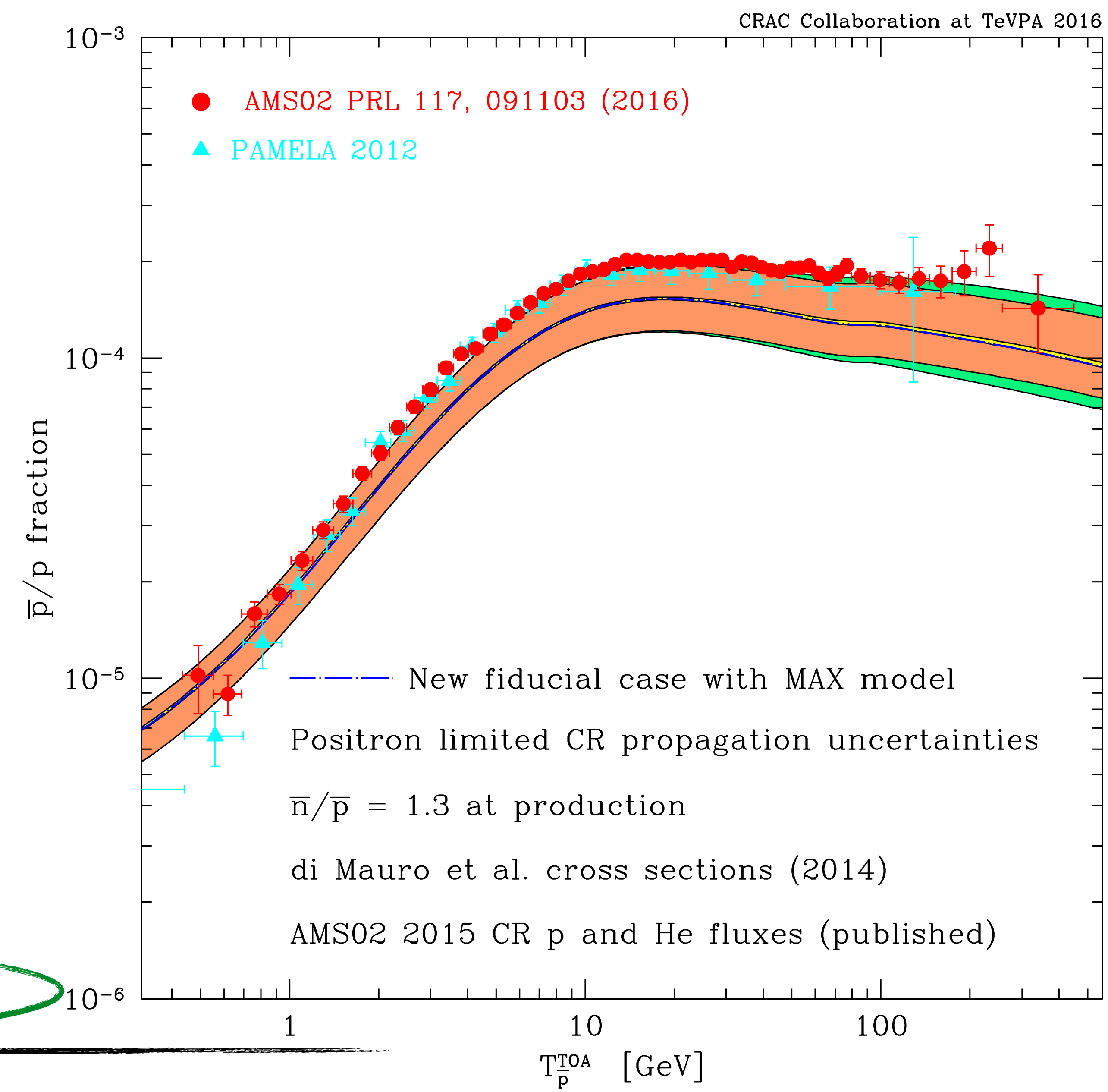

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- We derive constraints on **MeV** Dark Matter using **Voyager-I** and **AMS-02 data**. Our constraints are competitive with X-rays and γ-rays ones as well as CMB ones.

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

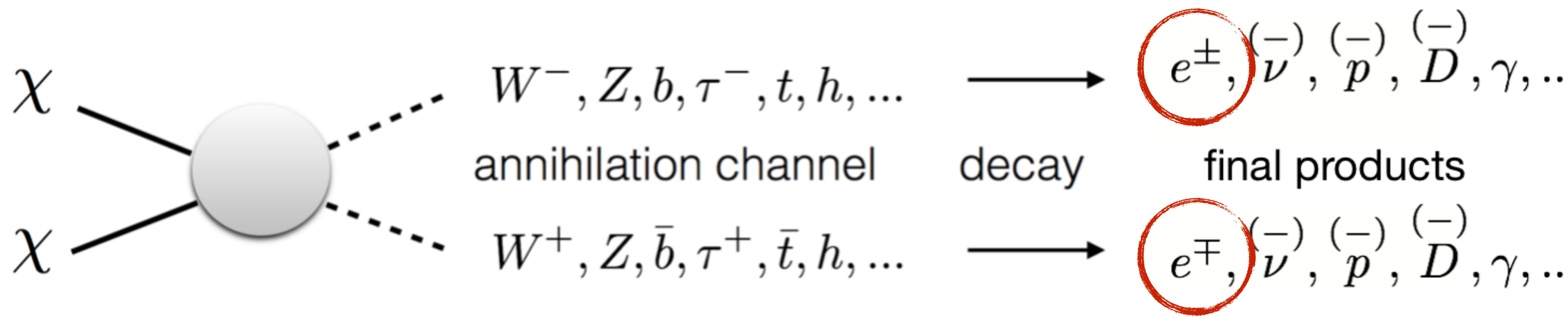
  Less (more stringent) compared to CMB constraints for s-wave (p-wave) $\langle \sigma v \rangle$.

Thank you for your attention!

Questions?

Back up

The dark matter scenario



A very generic class of models

$$\chi\chi \longrightarrow \phi\phi \longrightarrow 2B_e\, e^+e^- + 2B_\mu\, \mu^+\mu^- + 2B_\tau\, \tau^+\tau^-$$

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  The mass m_χ

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

  The branching ratios B_τ, B_μ, B_e

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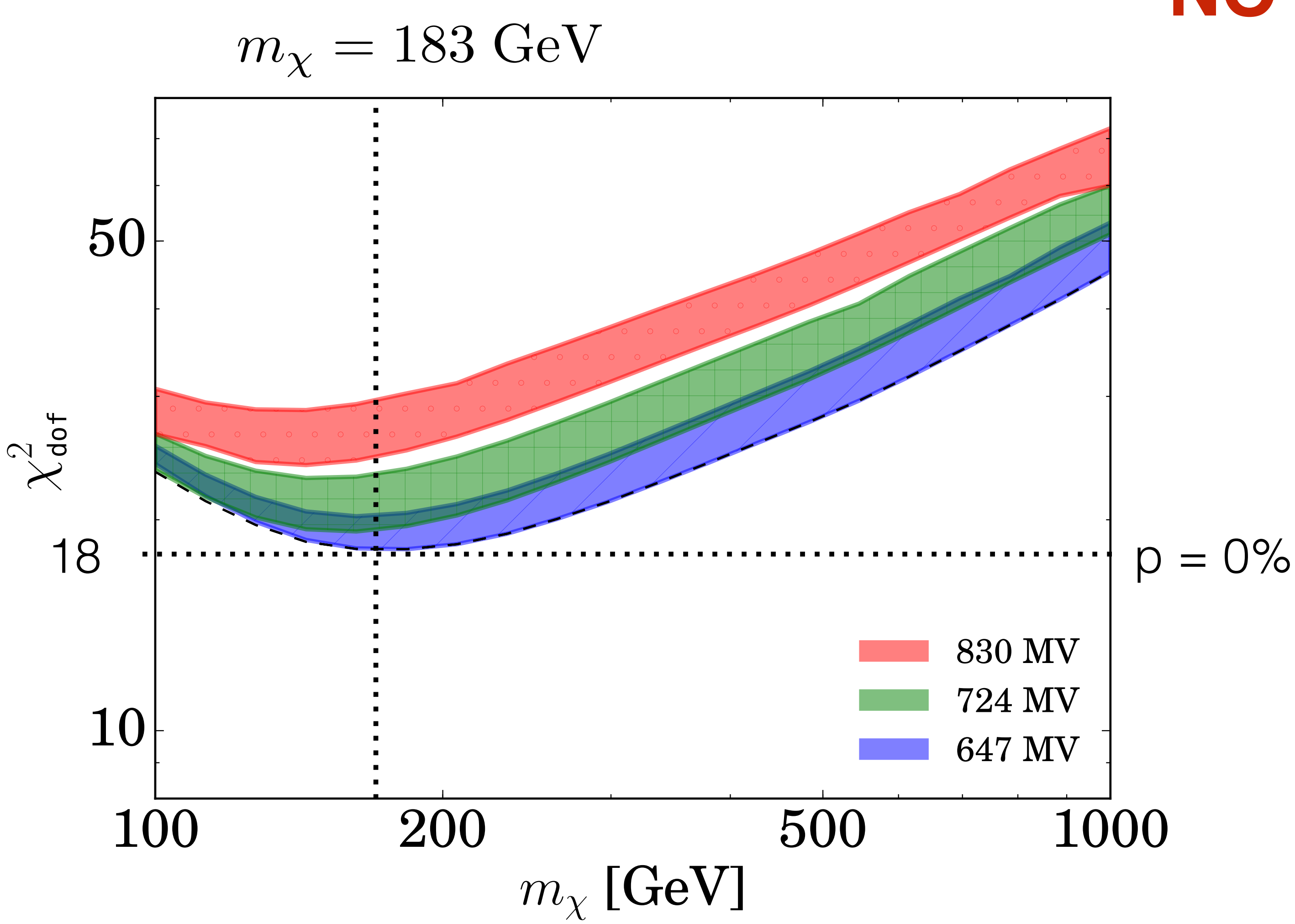
Is it possible to obtain a satisfactory fit to the AMS-02 data?

NO !



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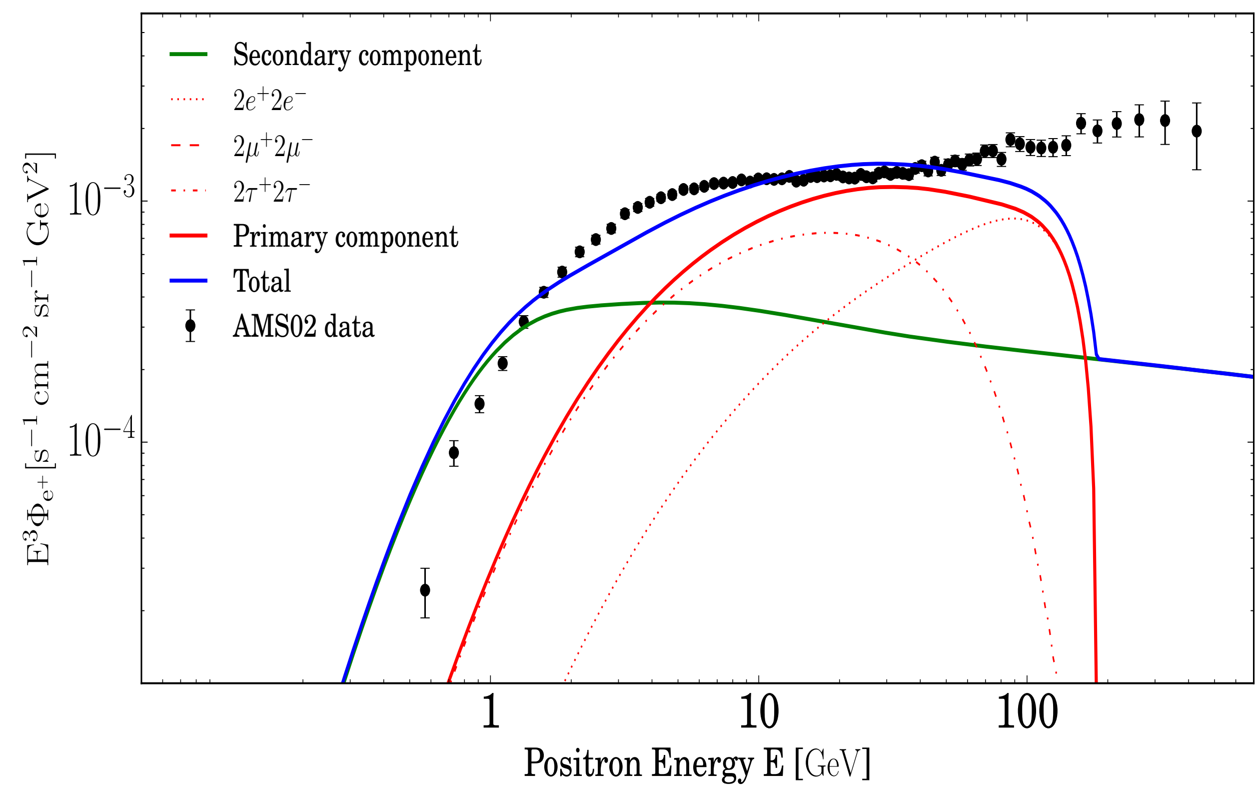

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The positron flux produced by DM is restricted « around » the DM mass.

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.)

Astrophysical background of secondary antiprotons

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

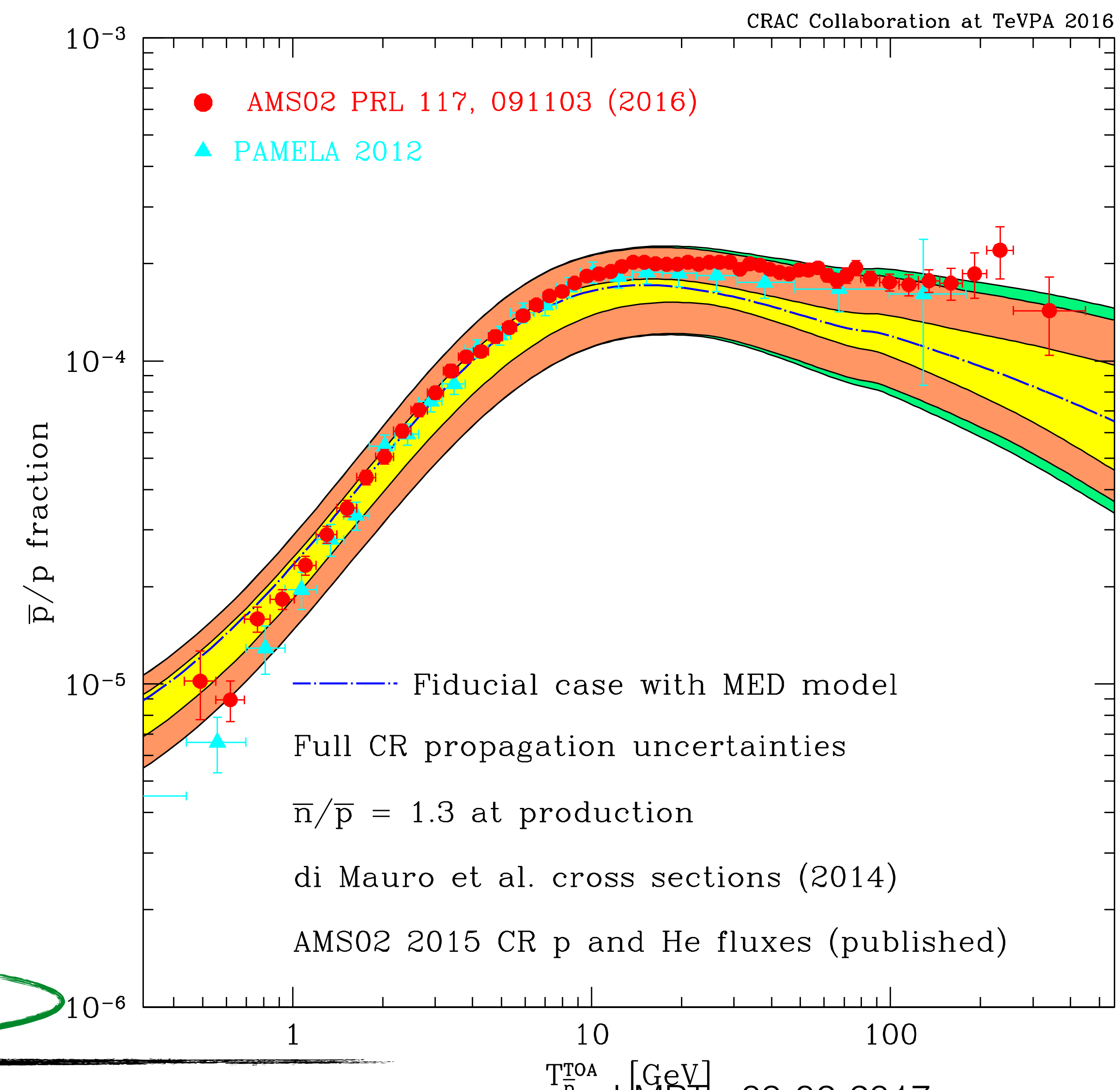
- Production XS of antiprotons

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

- Energy and space distribution of primary CRs (H, He)

- **AMS-02 data are consistent with the antiproton astrophysical background.**
- **The data prefer a MAX-type set of propagation parameters.**

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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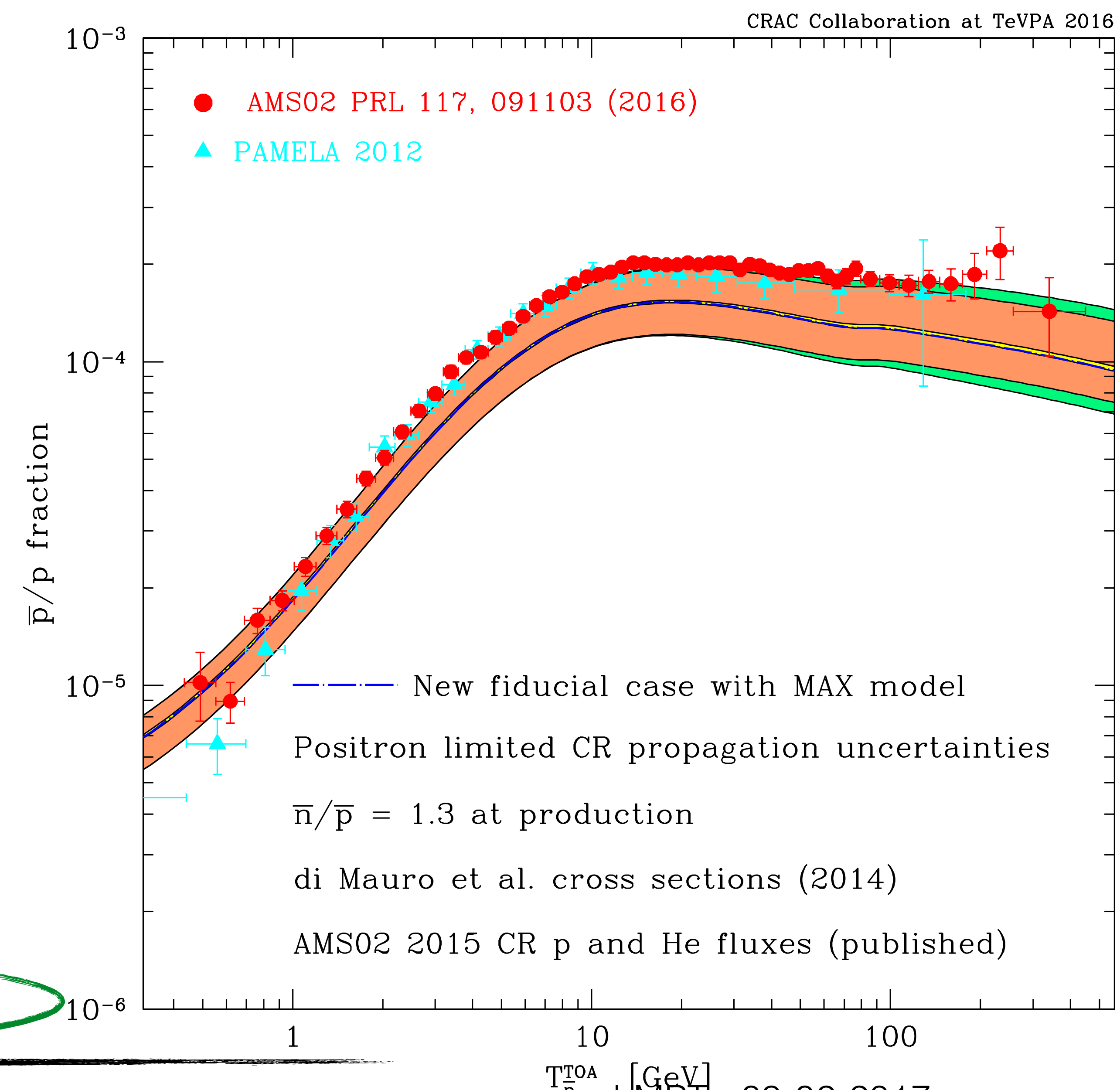
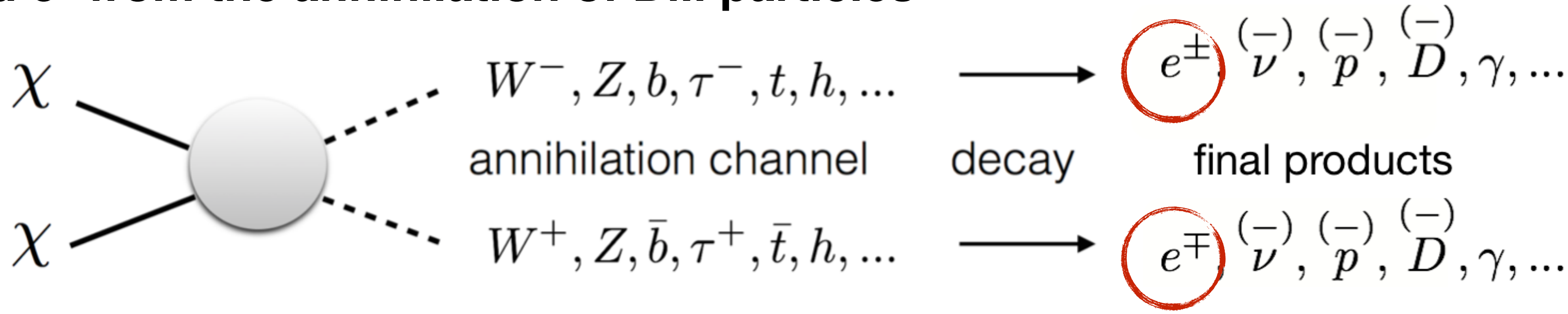


e$^-$ and e$^+$ from the annihilation of DM particles



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

$\rho(\vec{x})$: DM density profile

NFW *McMillan(2016)*

Cored *McMillan(2016)*

$\frac{dN_i}{dE}$: e$^-$ and e$^+$ spectrum at source

MicrOmegas

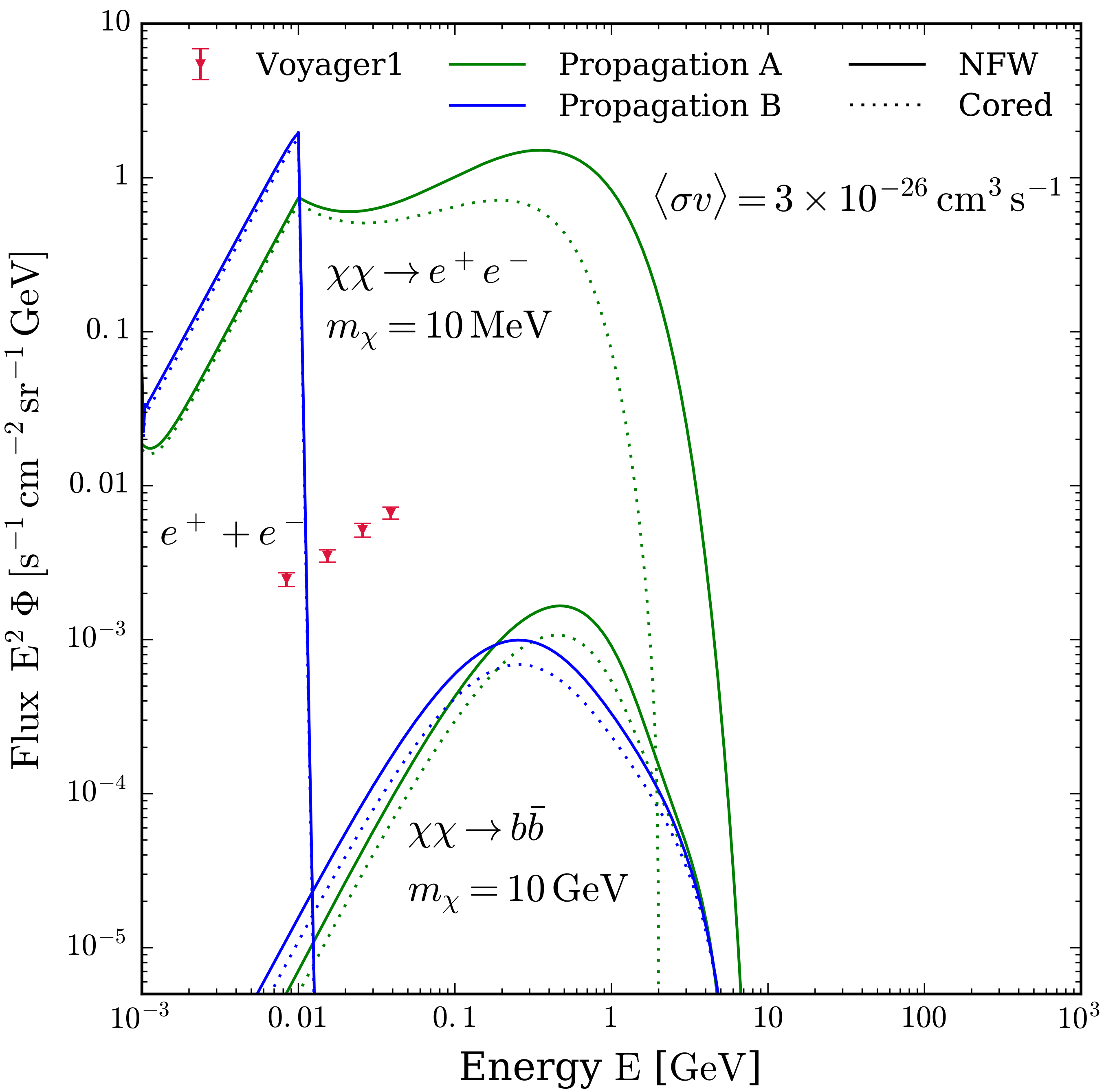
Cosmic rays propagation paramaters

- **Model A**: MAX from B/C analysis of *Maurin+(2001)* consistent with AMS-02 positrons and antiprotons data.
- **Model B**: best fit model of *Kappl+(2015)* on preliminary AMS-02 B/C data.

$V_A = 117.6\,\mathrm{km/s}$

$V_A = 31.9\,\mathrm{km/s}$

Constraints on DM annihilating cross section



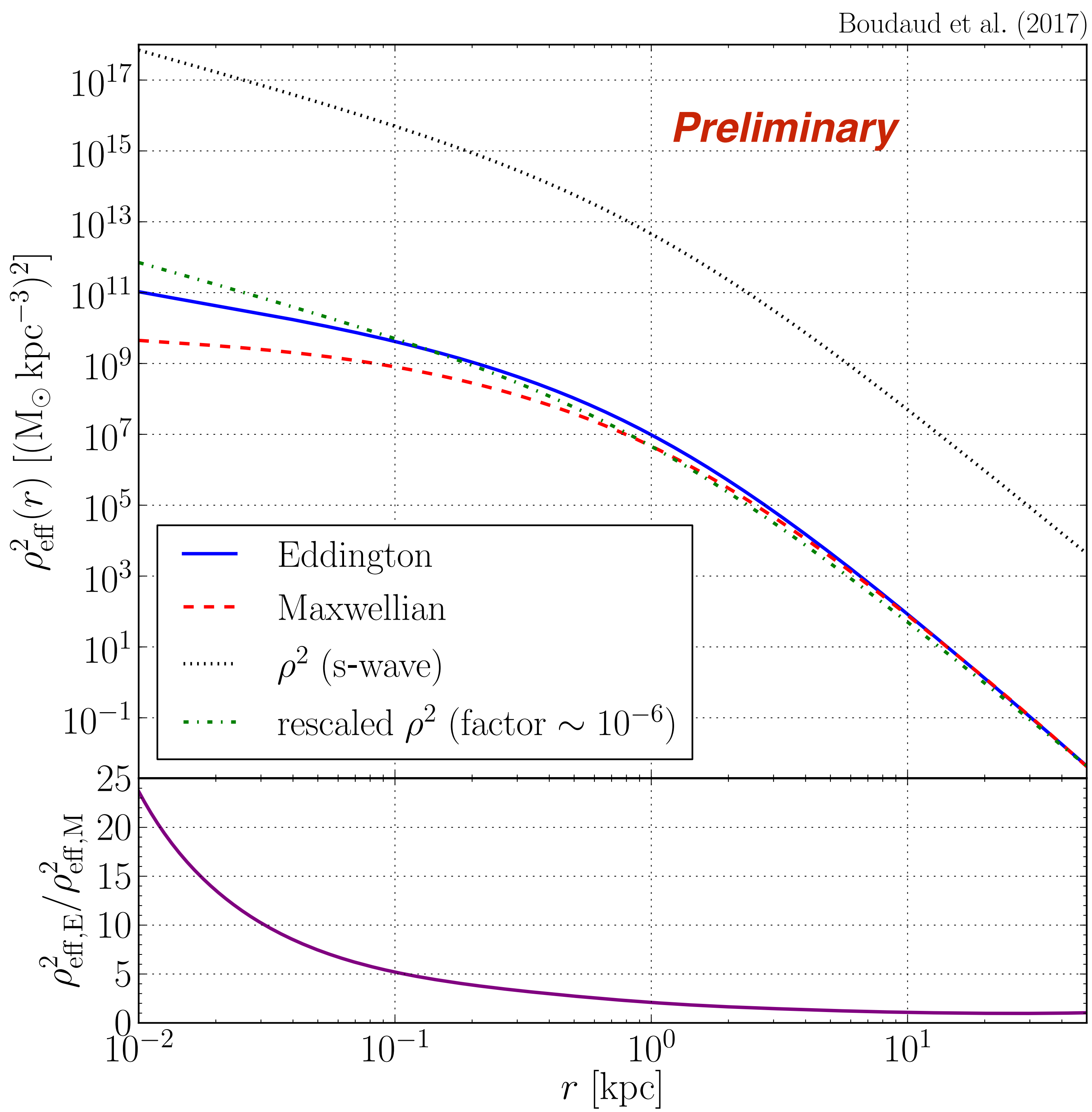
- **Model A**: $V_A = 117.6\,\mathrm{km/s}$
- **Model B**: $V_A = 31.9\,\mathrm{km/s}$

p-wave annihilation

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

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

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

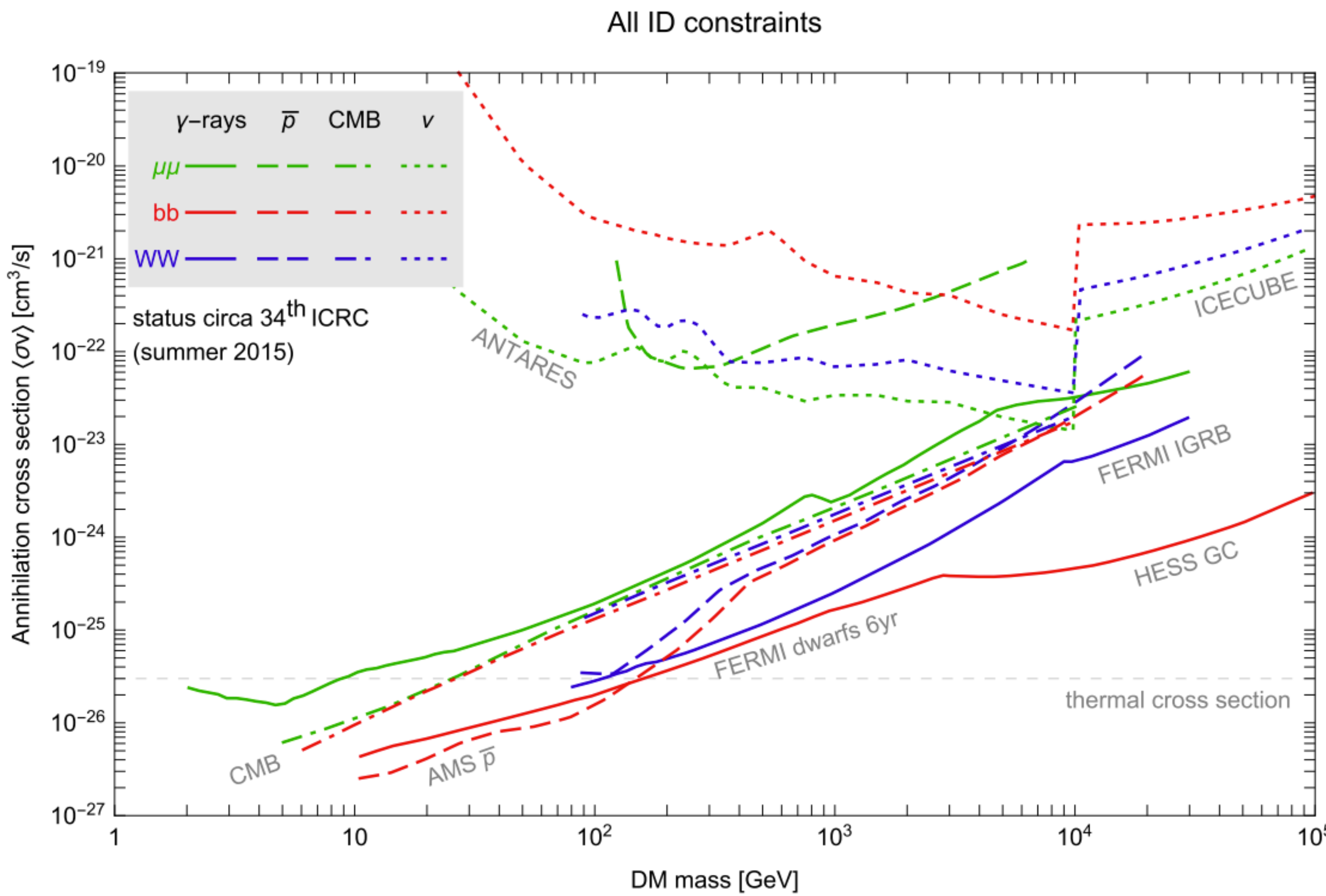


- e.g. NFW from McMillan (2016)

More than one order of magnitude different from the commonly used Maxwellian distribution nearby the GC (10 pc).

Dark matter indirect detection

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



Thermal cross section