Voyager probing Dark Matter

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Paris, France

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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 and M. Cirelli (arXiv:1807.03075)

MB, T. Lacroix, J. Lavalle and M. Stref (to appear)

LPTHE
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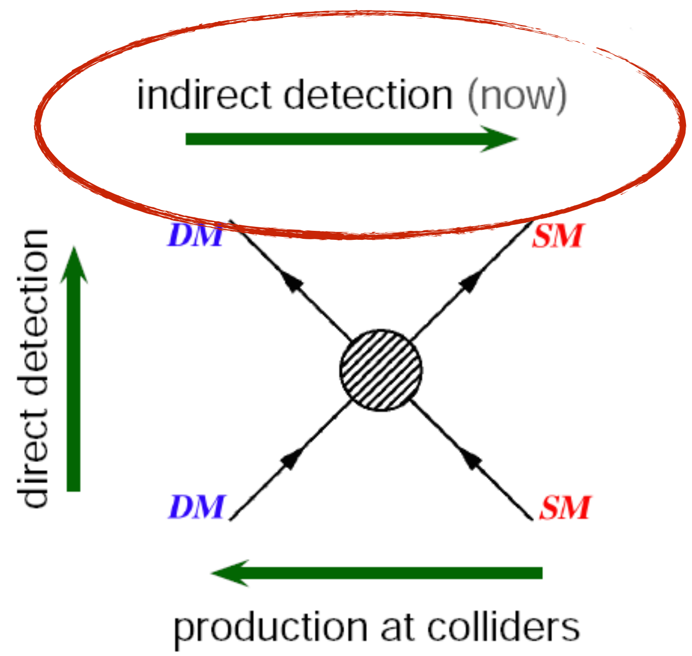
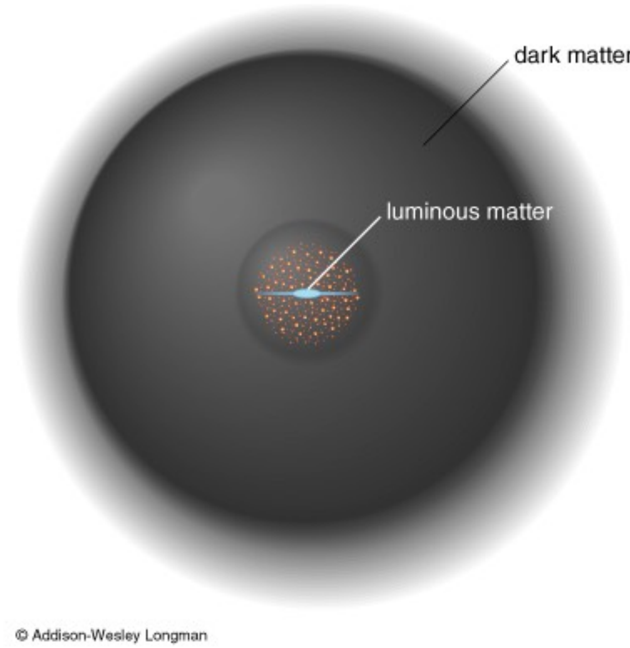
erc NewDark

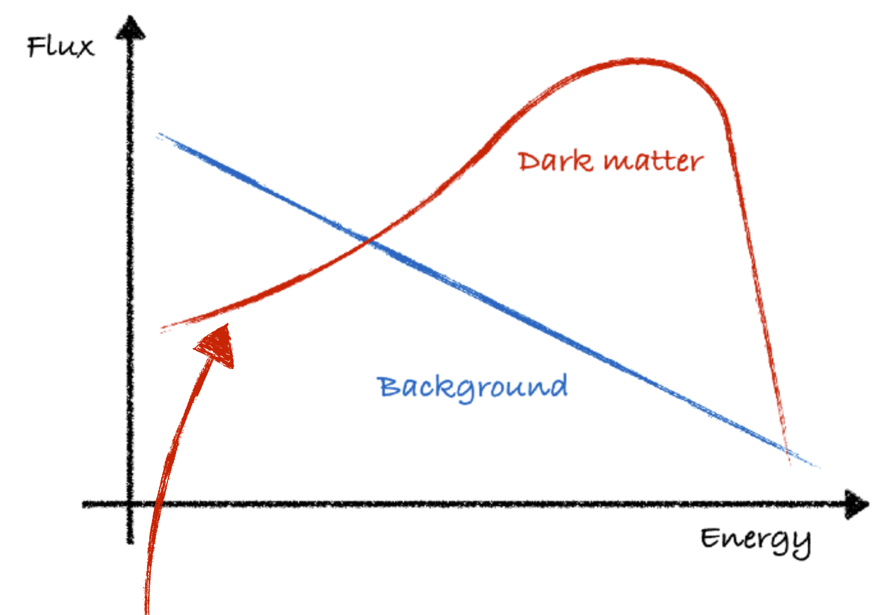
Dark matter indirect detection

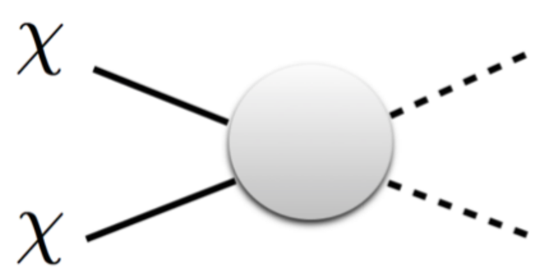
(see talks by F. Calore, M. Stref)

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









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

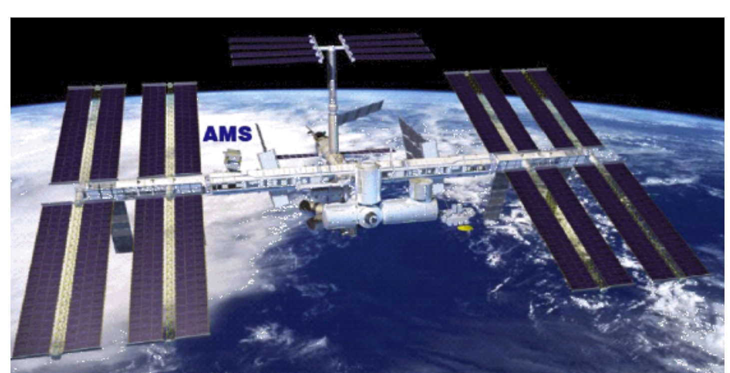
annihilation channel — decay — final products

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

- Gamma rays

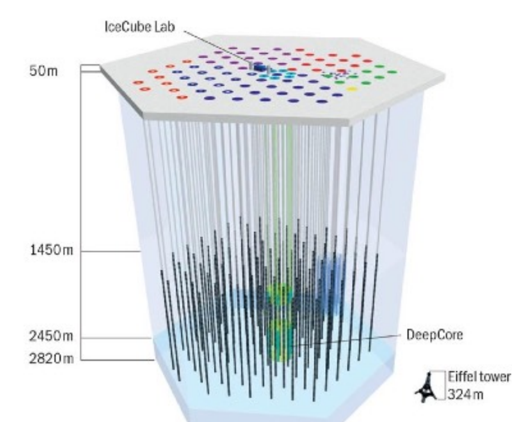
HESS

- Charged cosmic rays



AMS-02

- Neutrinos



IceCube

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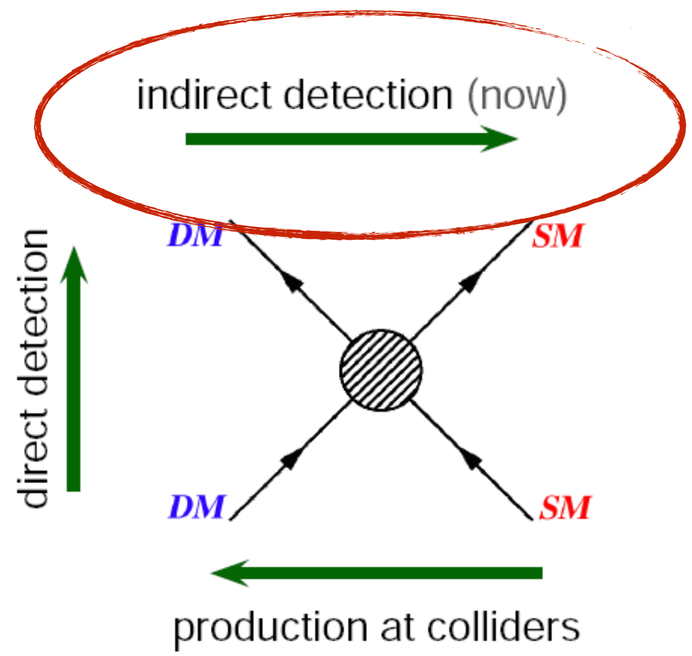

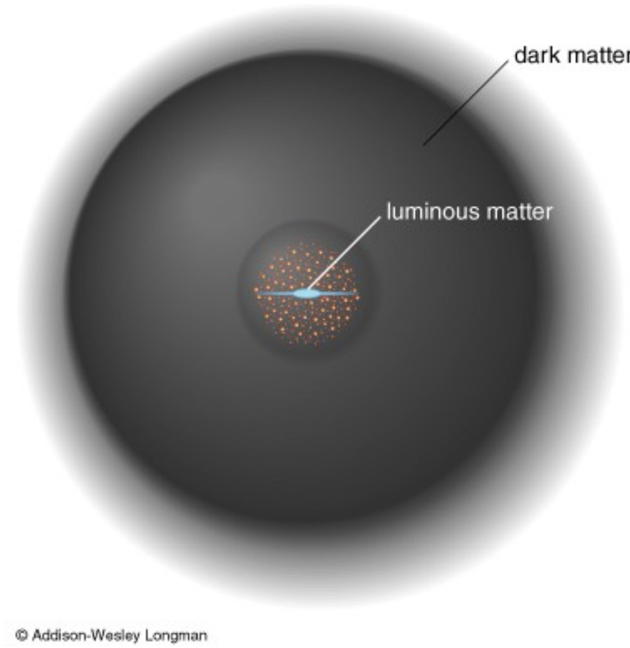

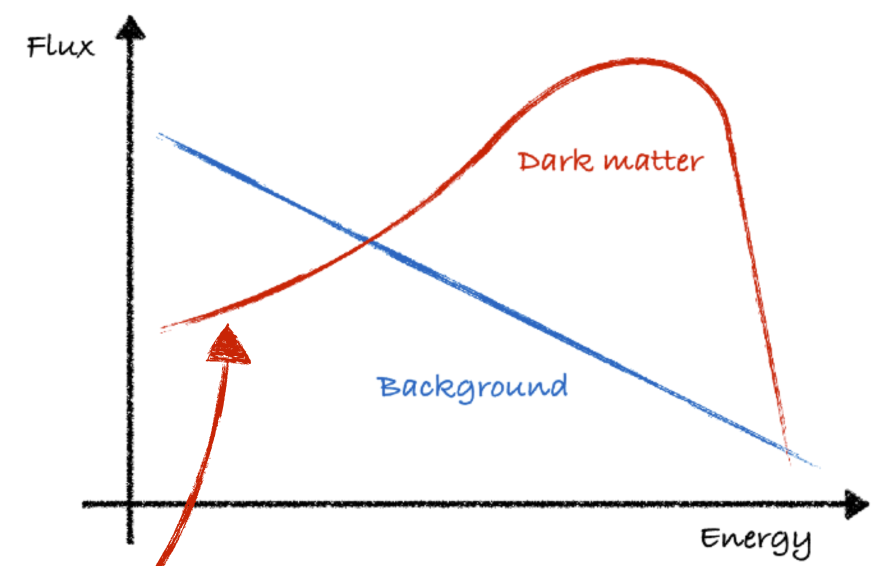

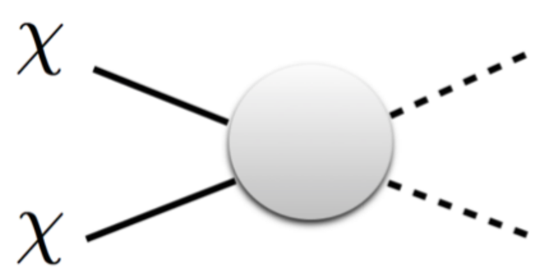

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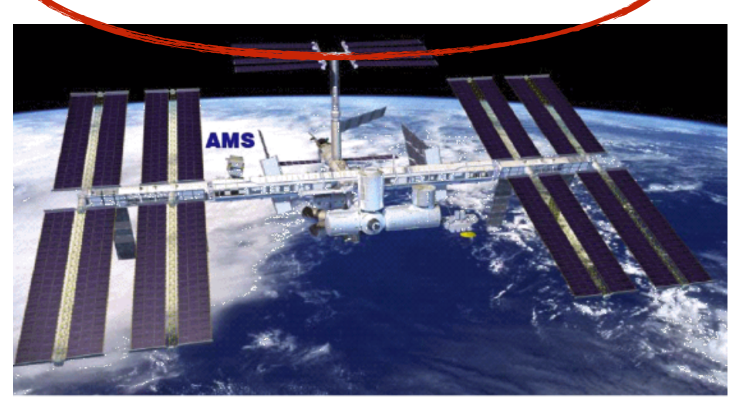

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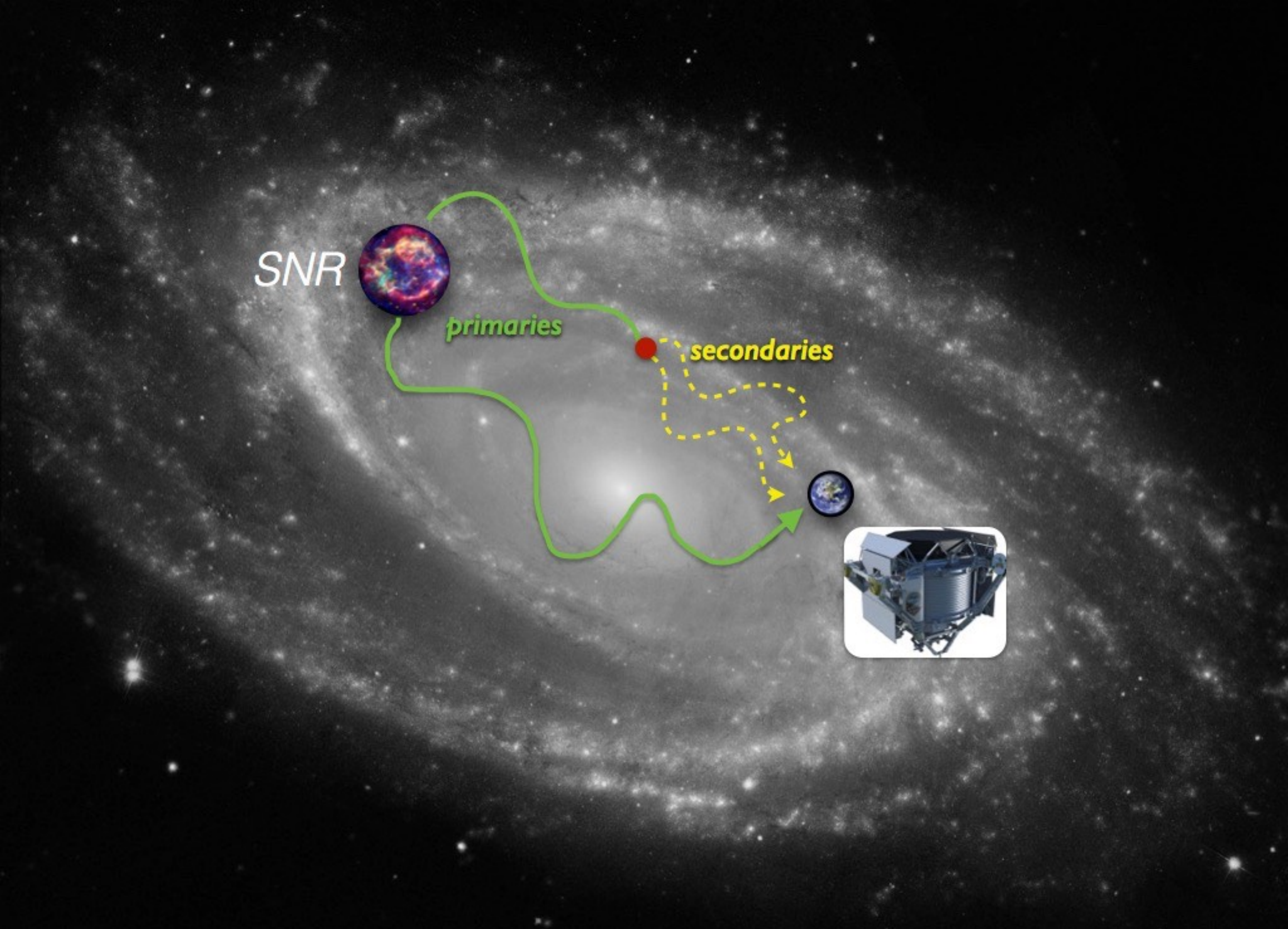
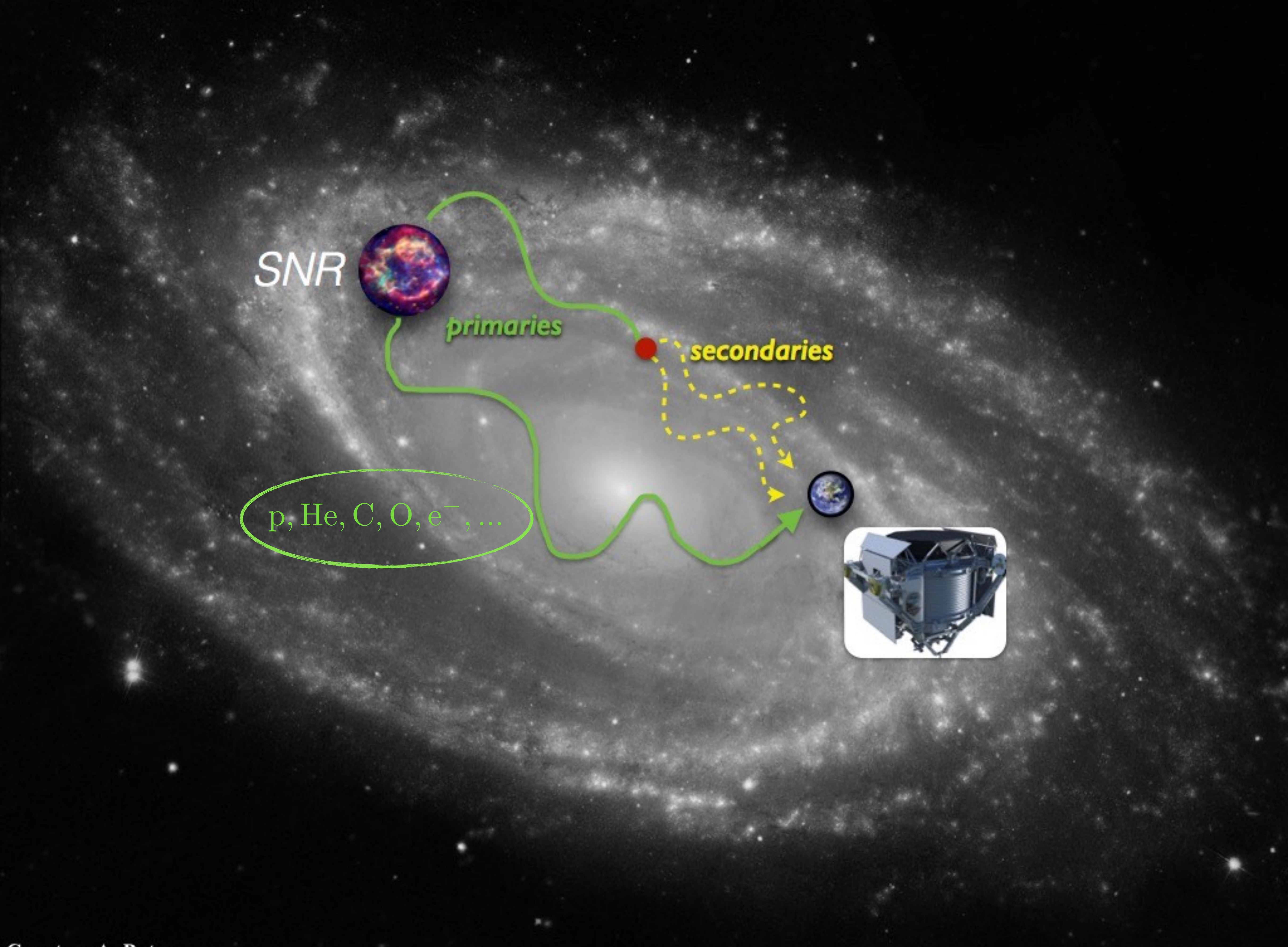


Courtesy A. Putze



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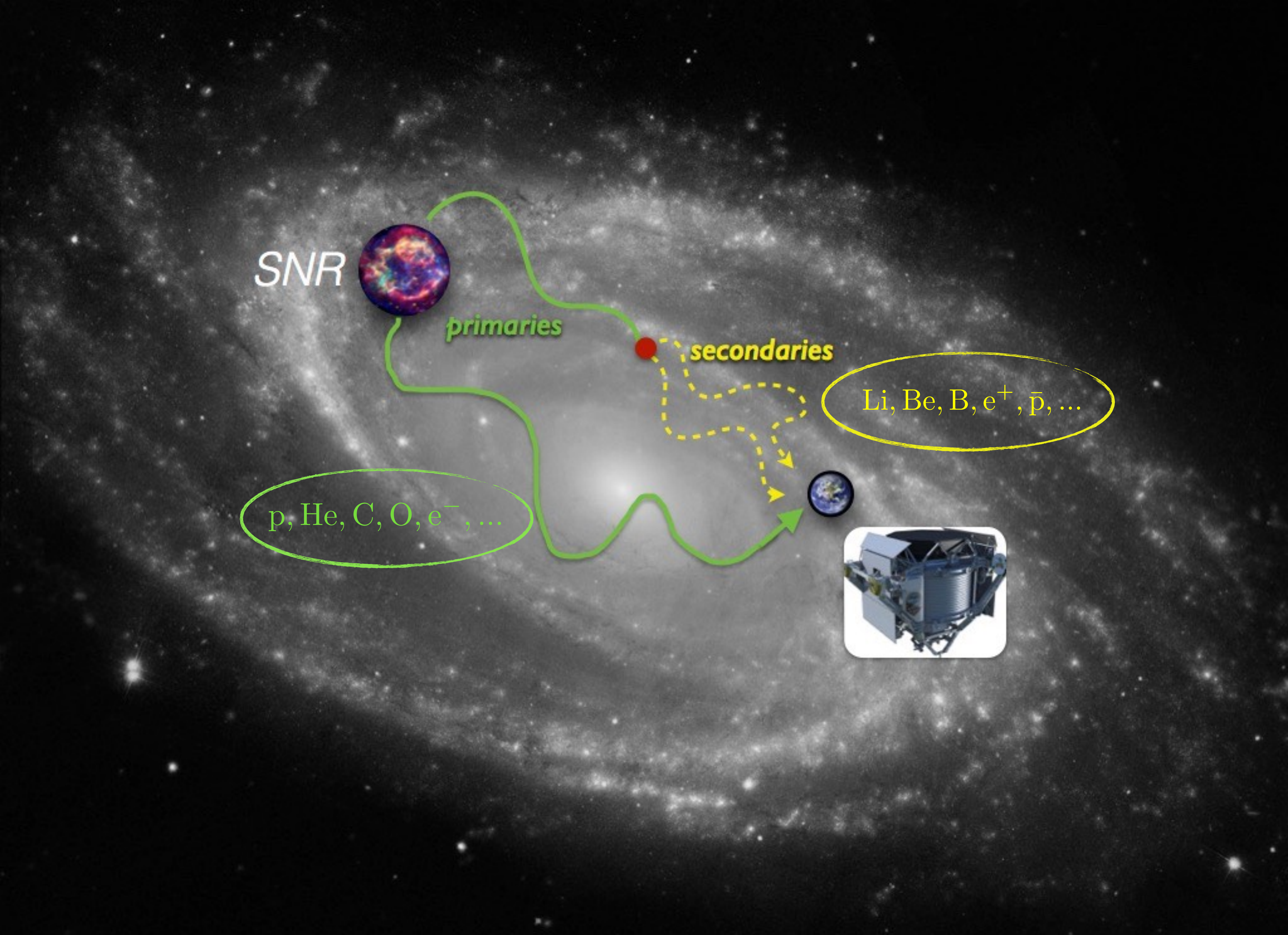

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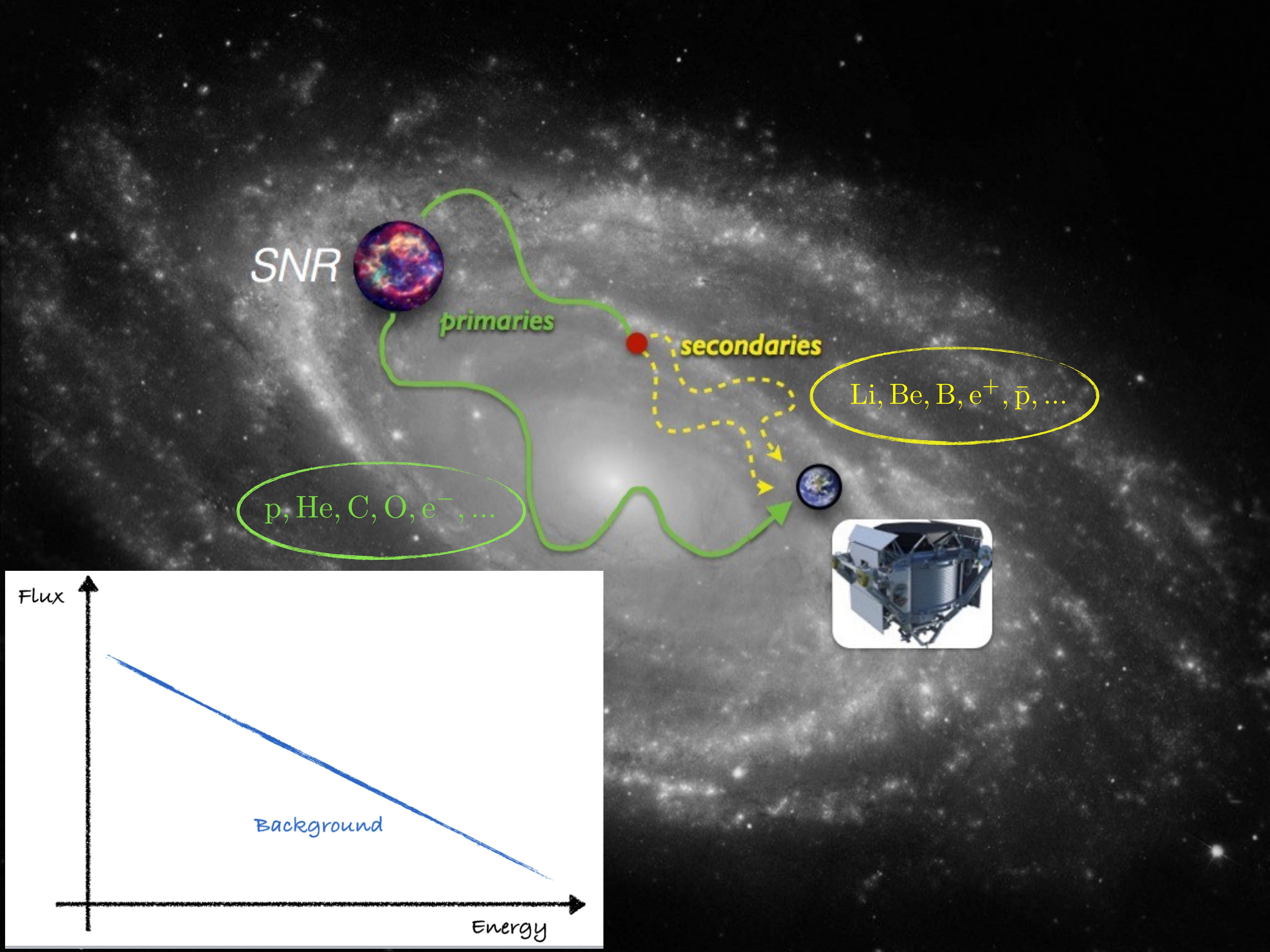
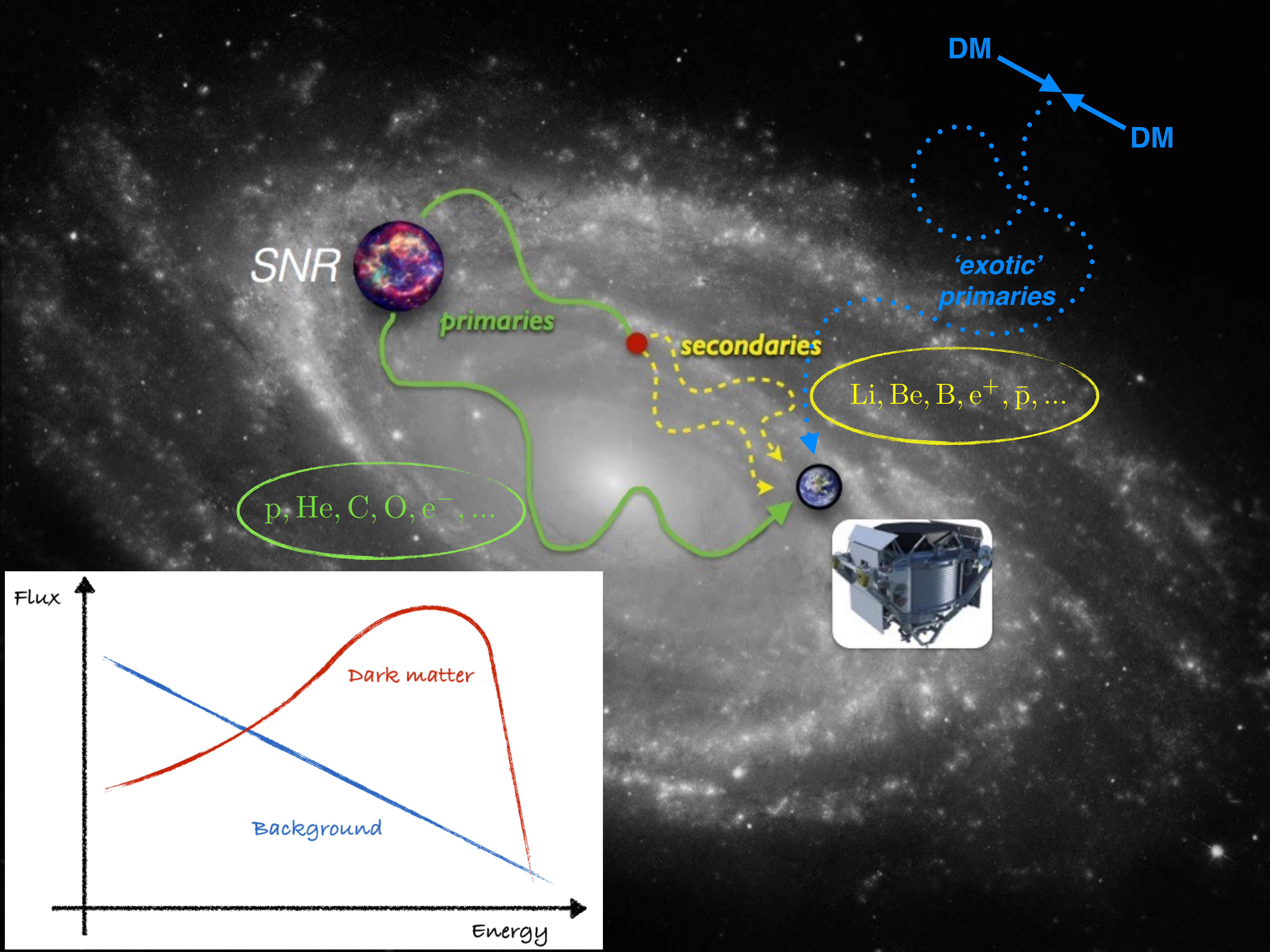
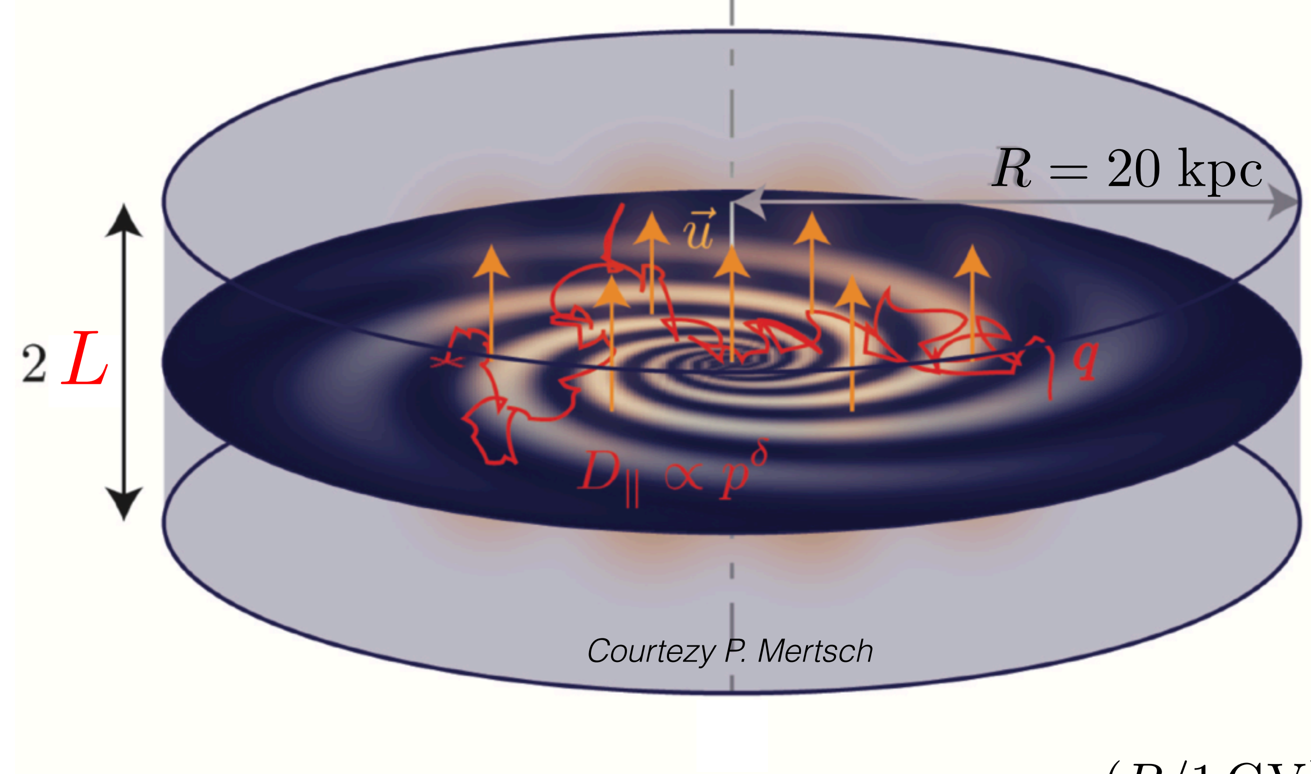

SNR
primaries
secondaries
Li, Be, B, e$^+$, $\bar{p}$, ...
p, He, C, O, e$^-$, ...
Flux
Background
Energy


DM
DM
'exotic' primaries
SNR
primaries
secondaries
Li, Be, B, e^+, $\bar{p}$, ...
p, He, C, O, e^-, ...
Flux
Dark matter
Background
Energy

The two-zone diffusion model

Galactic disc - *h* ~ 100 pc
stars, gas and dust distributed in the arms

Magnetic halo - $1 \lesssim L \lesssim 20$ kpc
diffusion zone of the model



- **Space diffusion** on the turbulent magnetic field $$K(E) = K_0\,\beta\,\frac{(R/1\,\mathrm{GV})^{\delta}}{\{1+(R/R_{\mathrm{b}})^{\Delta\delta/s}\}^{s}}$$
- **Convection** (Galactic wind) from supernovae explosions in the disc $$\vec{V}_C = V_C\,\mathrm{sign}(z)\,\vec{e}_z$$
- **Destruction**
  - Interaction with the interstellar medium (ISM) $$Q^{sink}(E,\vec{x})$$
  - Decay
- **Energy losses**
  - Interaction with the ISM (Coulomb, ionisation, bremsstrahlung, adiabatic expansion) $$b(E,\vec{x})$$
  - Synchrotron emission, inverse Compton scattering (electrons)
- **Diffusive reacceleration** from stochastic acceleration (Fermi II) $$D(E) = \frac{2}{9}\,{V_A}^2\,\frac{E^2\beta^4}{K(E)}$$

Propagation parameters determined using data of secondary to primary ratios (e.g. B/C)

(see talk by D. Maurin)

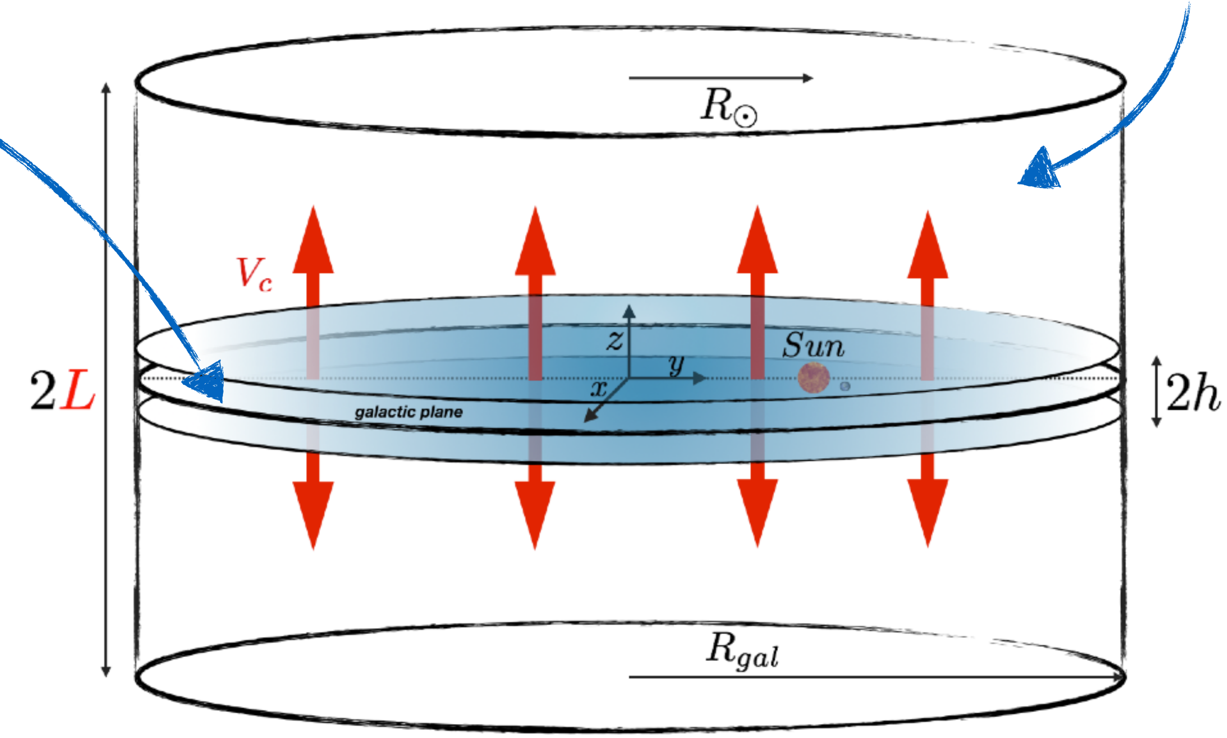
Transport of cosmic rays $e^{\pm}$

Steady state

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

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

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



No analytical solution for this equation

Numerical algorithm (GALPROP, DRAGON, PICARD, etc.) $\Rightarrow$ **prohibitive CPU time**

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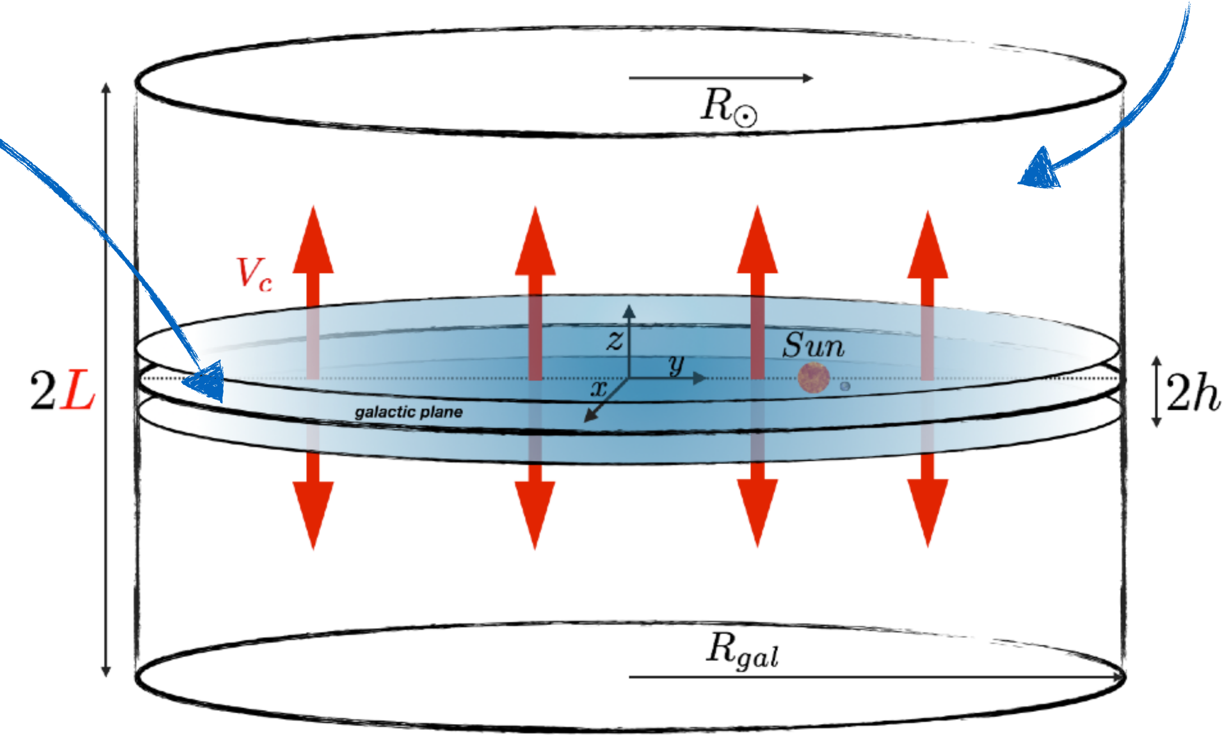

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High energy approximation

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

***E* > 10 GeV**

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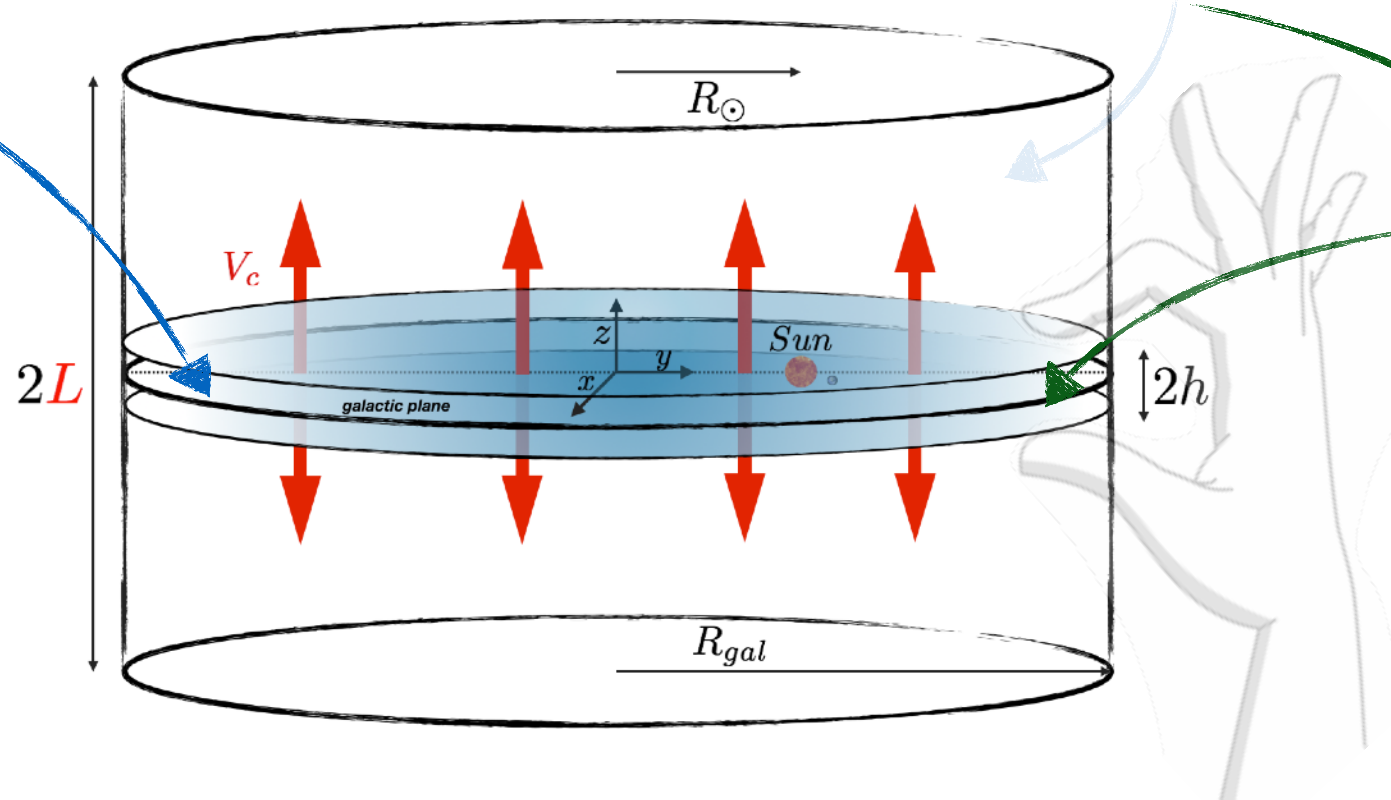
$$b_{\rm disc} = b_{\rm adia} + b_{\rm ioni} + b_{\rm brem} + b_{\rm coul}$$

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

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



Pinching method

MB+(2016a)

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

Semi-analytical computation of e^- *and* e^+ fluxes, **including all propagation effects**

$\Longrightarrow$ **extend** the semi-analytic computation of $e^{\pm}$ interstellar fluxes **down to MeV** energies!

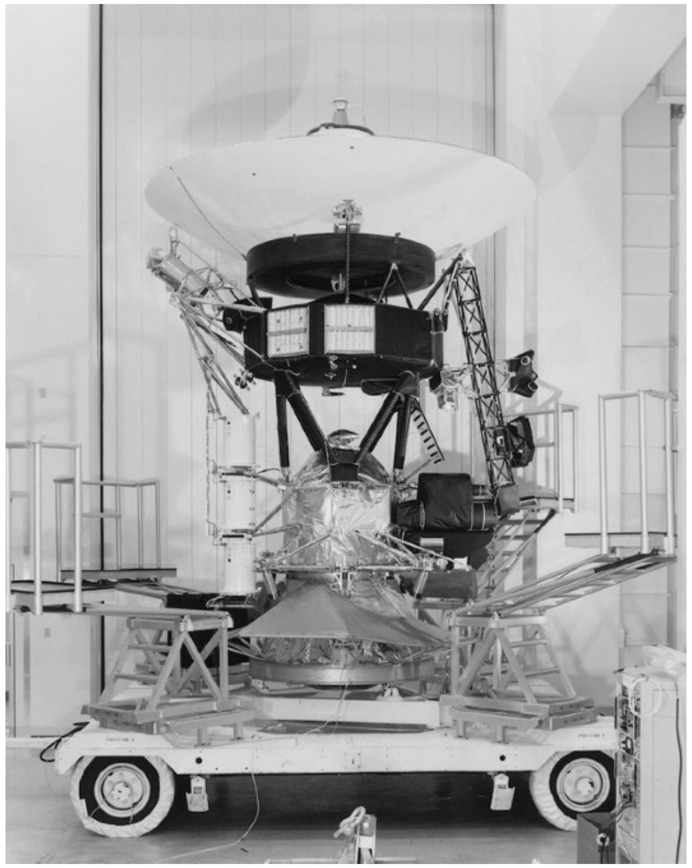
MeV cosmic rays?

🤔

Sub-GeV interstellar CRs cannot reach detectors orbiting the Earth

they are stopped by the heliopause (solar wind)

Voyager-1 crossed the heliopause in 2012



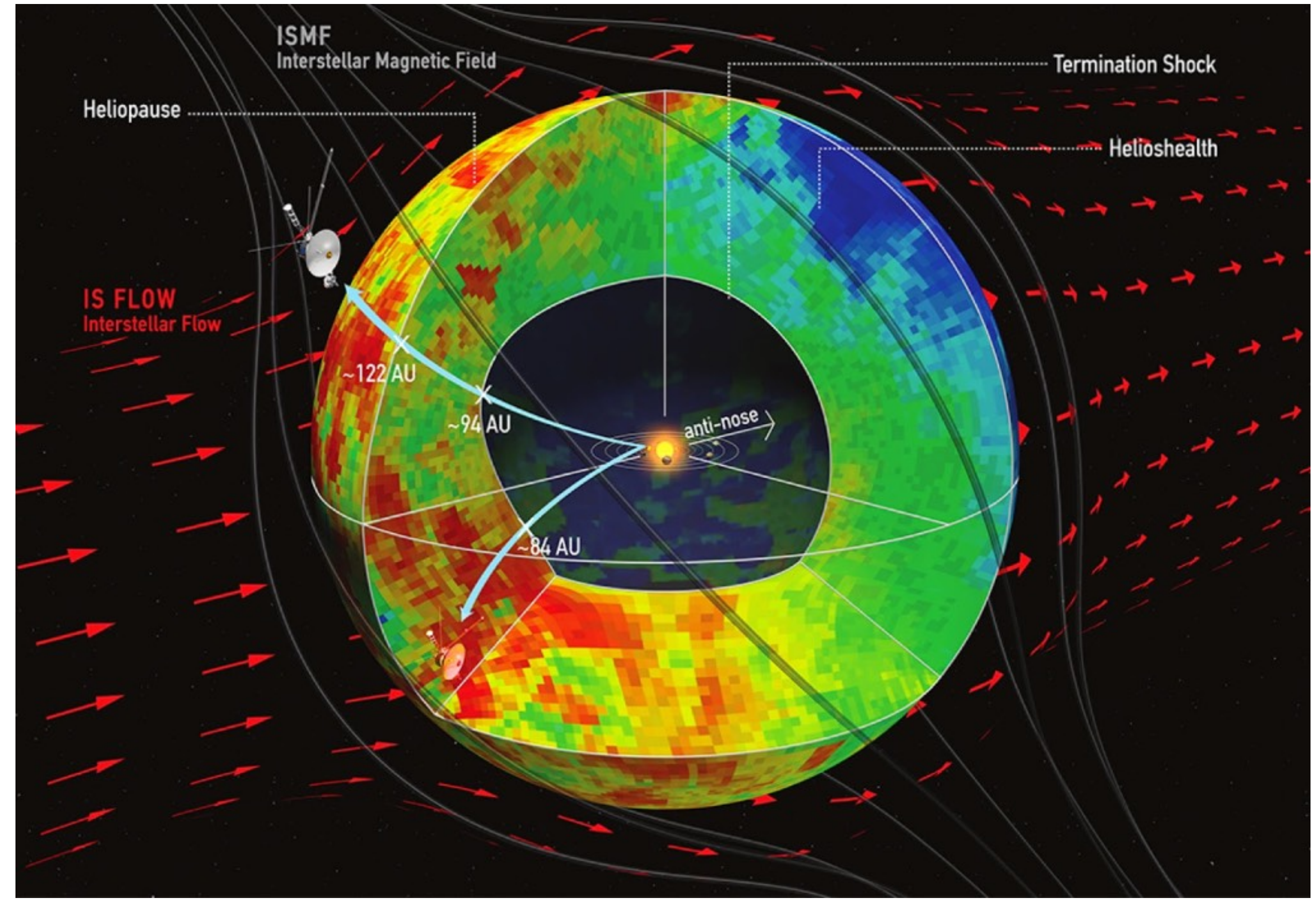
launch:
1977

distance now:
~140 au

direction:
Hercules (solar apex)

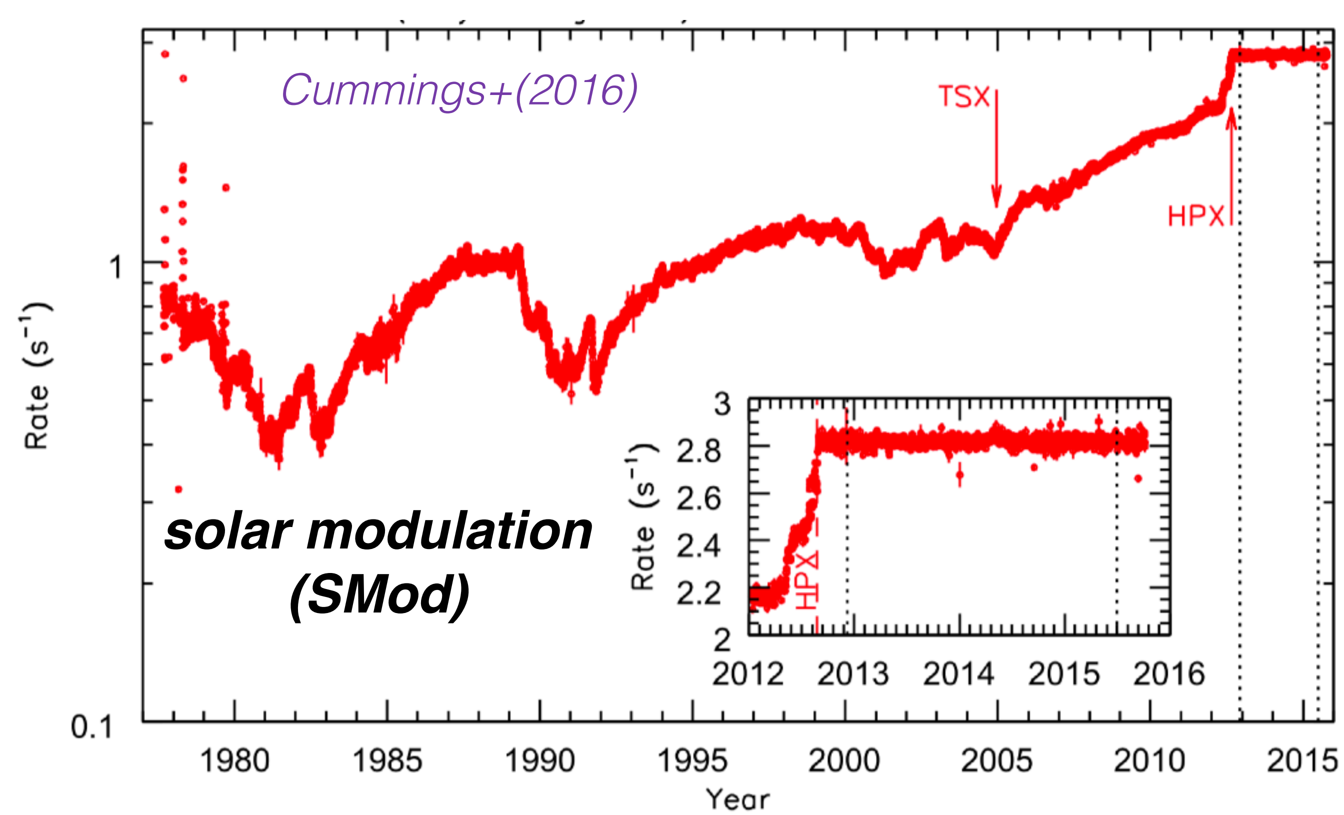
velocity/Sun:
~17 km/s

CRs energy:
$10 \lesssim T_n \lesssim 100$ *MeV/n*



Voyager-1 crossed the heliopause in August 2012
⟹ probes now the local interstellar medium

- First data of interstellar CRs
  ⟹ **independent** of solar effects (modulation)
- First **sub-GeV interstellar** CRs



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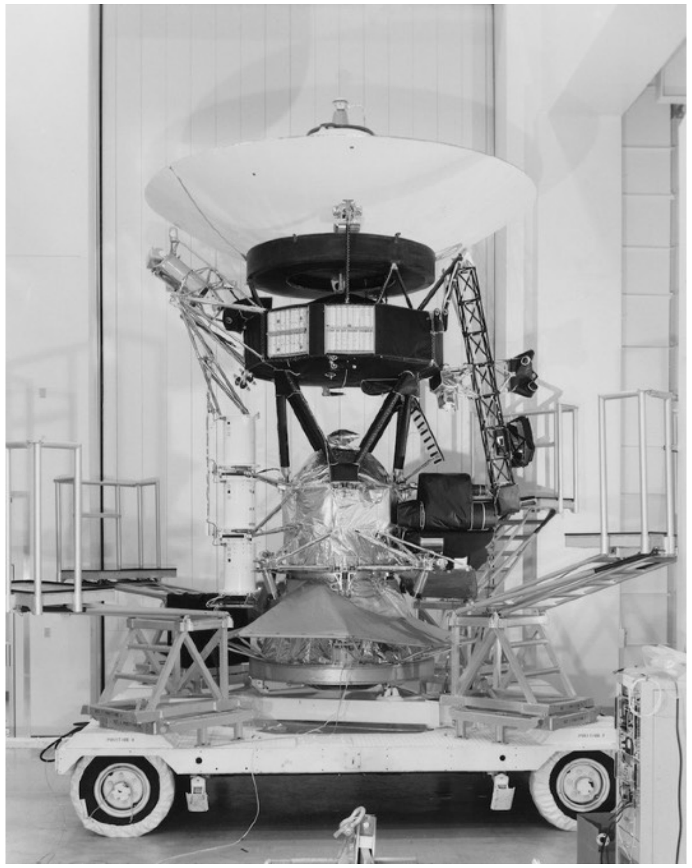

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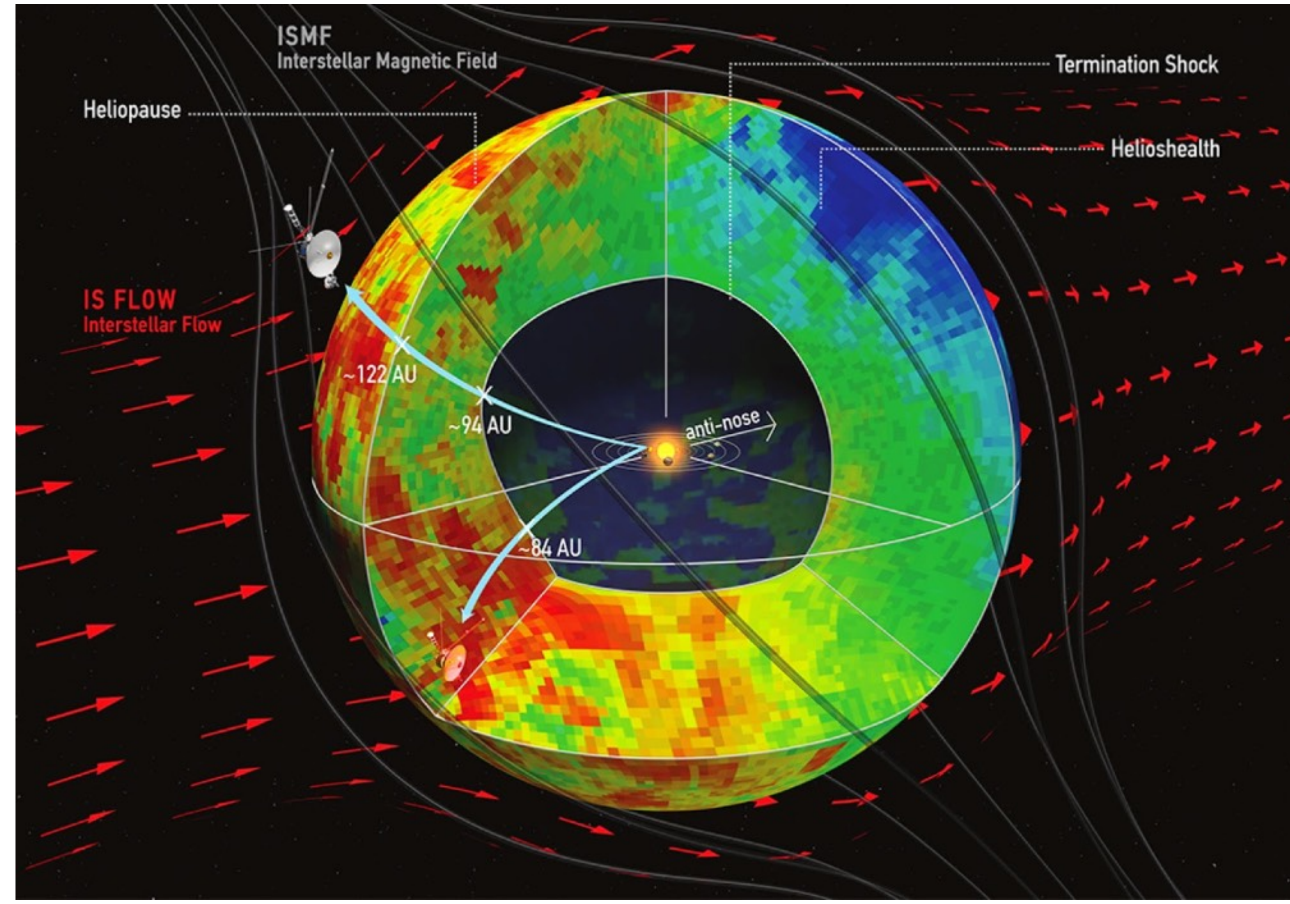

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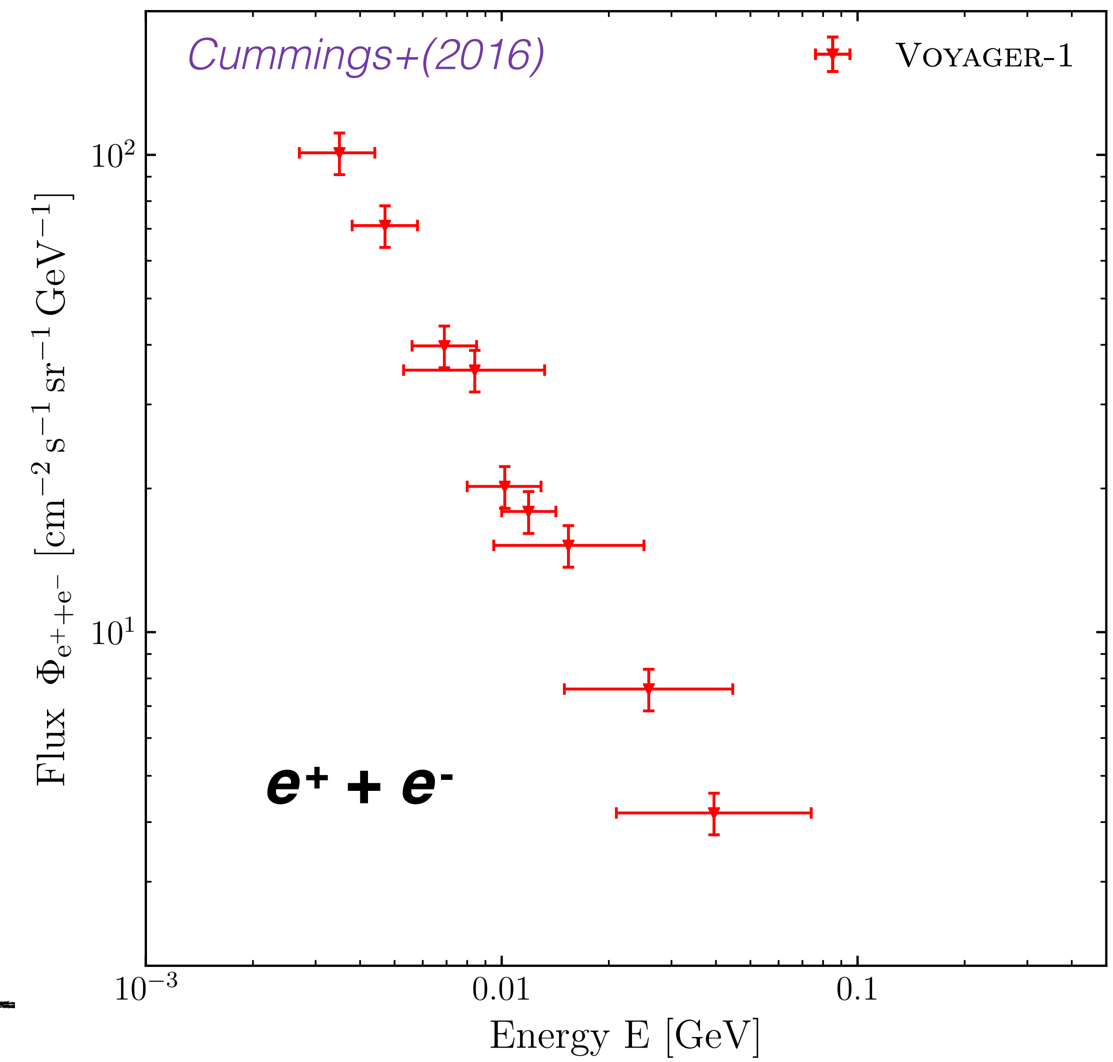

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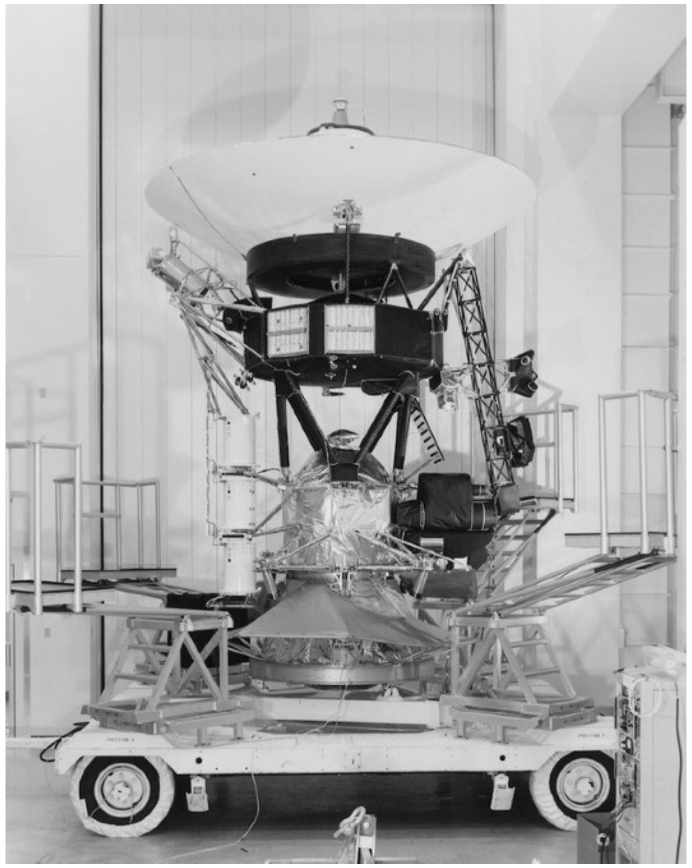

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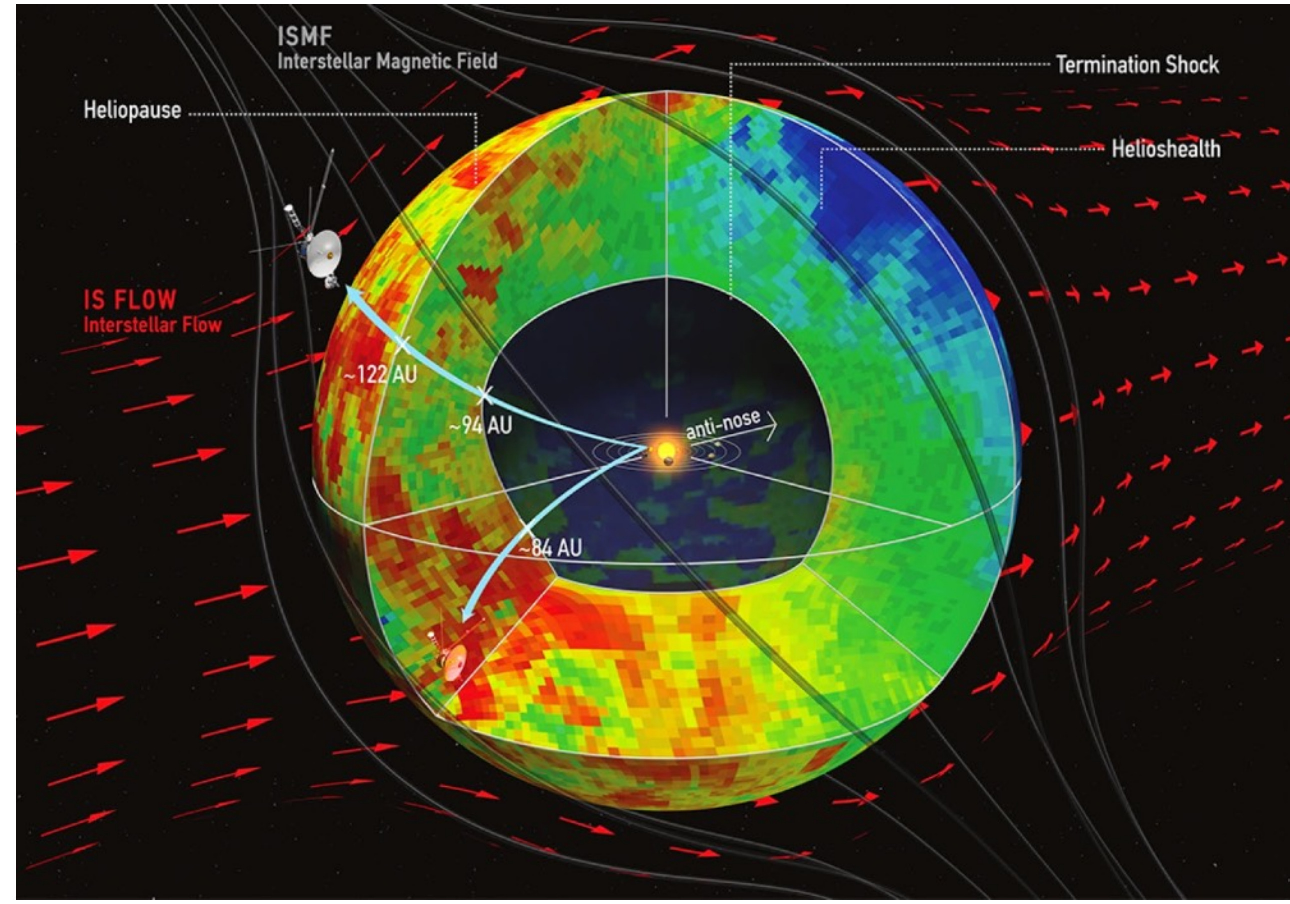

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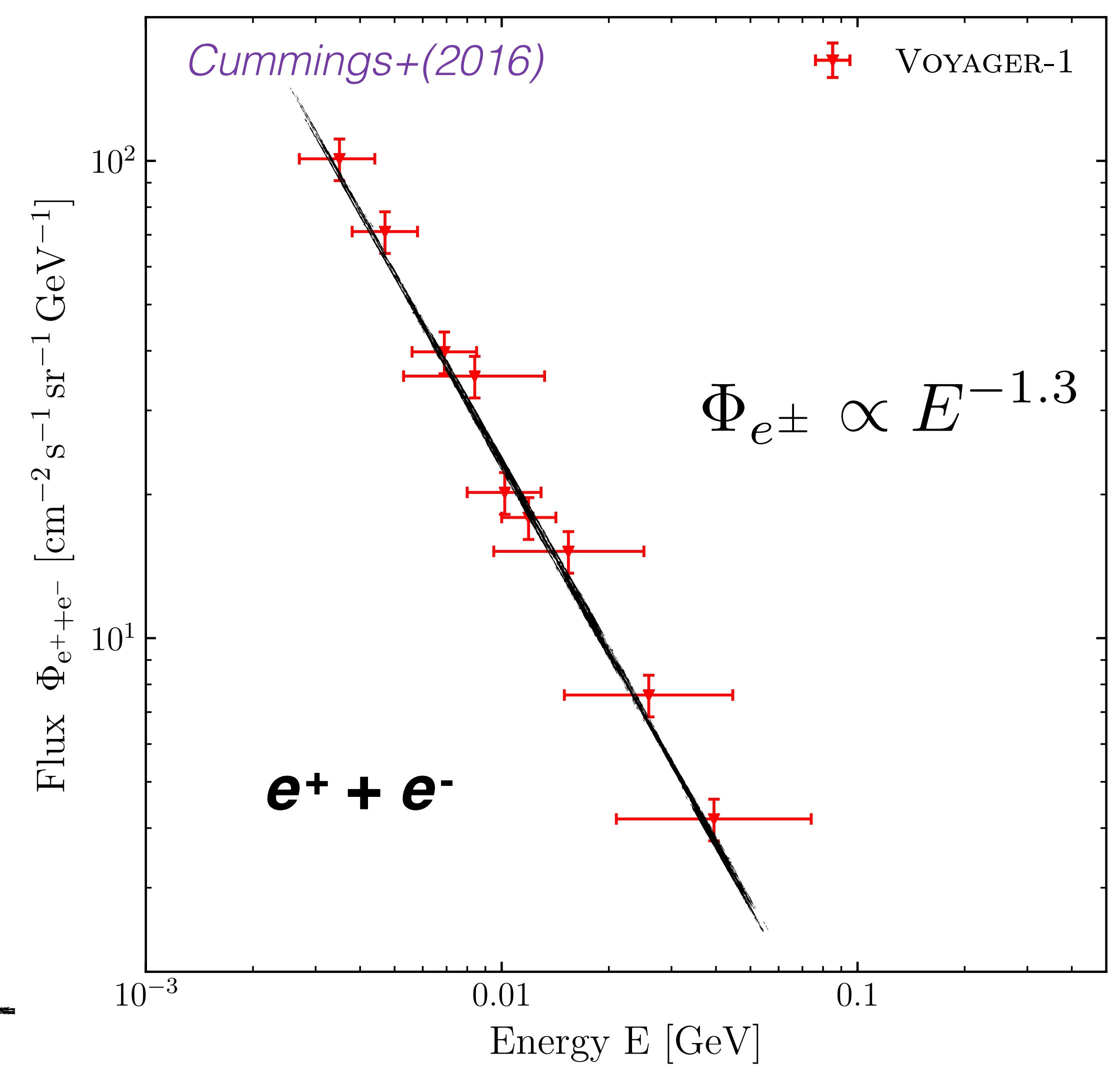
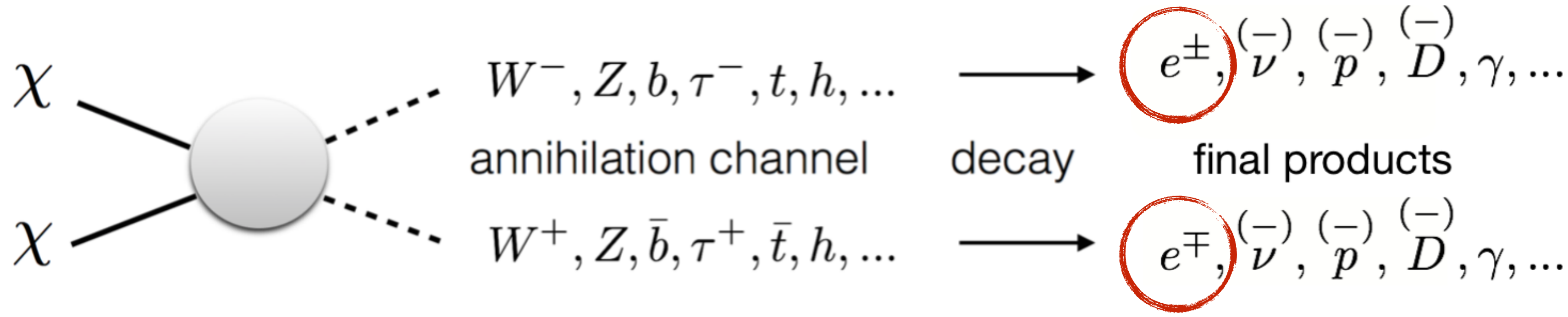


Application 1:

Contraints on MeV dark matter particles

MB, J. Lavalle and P. Salati (PhysRevLett.119.021103)
and
MB, T. Lacroix, M. Stref and J. Lavalle (to appear)

CRs $e^{\pm}$ from dark matter



$$Q_{\rm DM}^{e^{\pm}}(E,\vec{x}) = \underbrace{\rho_{\rm DM}^2(\vec{x})}_{\text{astrophysics}} \times \underbrace{\eta \frac{\langle \sigma v \rangle}{m_{\rm DM}^2} \sum_i B_i \frac{dN_i}{dE}}_{\text{particle physics}}$$

$\rho(\vec{x})$: dark matter density

$\frac{dN_i}{dE}$: e^- and e^+ spectra
MicrOmegas
(PYTHIA)

Dark matter distribution in the MW

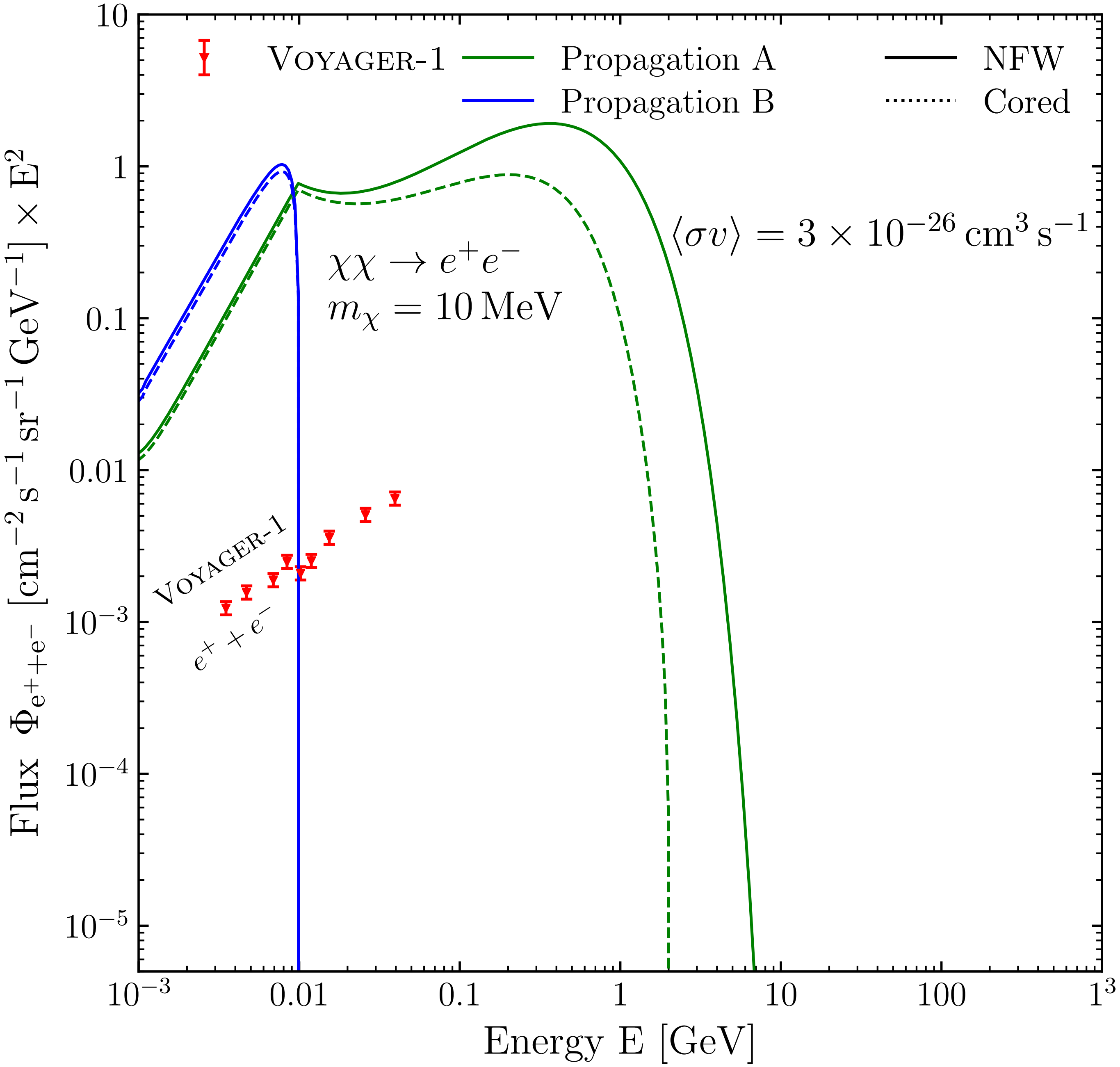
- **NFW** (spike in the GC)
- **Cored** (~ 8 kpc core)

McMillan(2016)

CRs propagation in the Galaxy

- **Propagation A**: MAX from *Maurin+(2001)* (HEAO3 B/C)
  Consistent with AMS-02 positrons and antiprotons
  $V_A = 117.6\,\mathrm{km/s}$ (*strong reacceleration*)
- **Propagation B**: best fit on AMS-02 B/C from *Reinert & Winkler(2018)*
  $V_A = 0\,\mathrm{km/s}$ (*no reacceleration*)

Constraints on annihilation cross section



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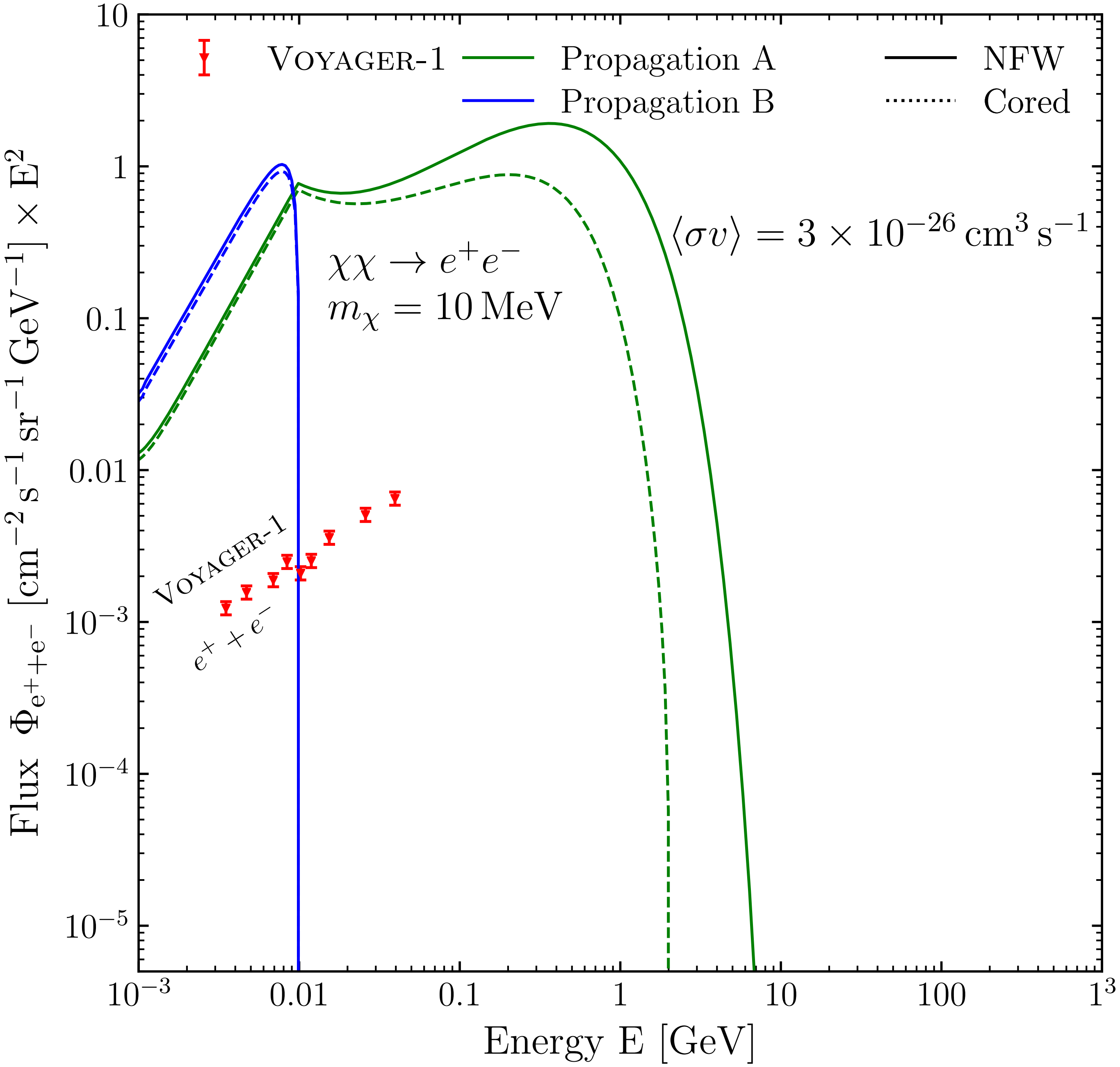

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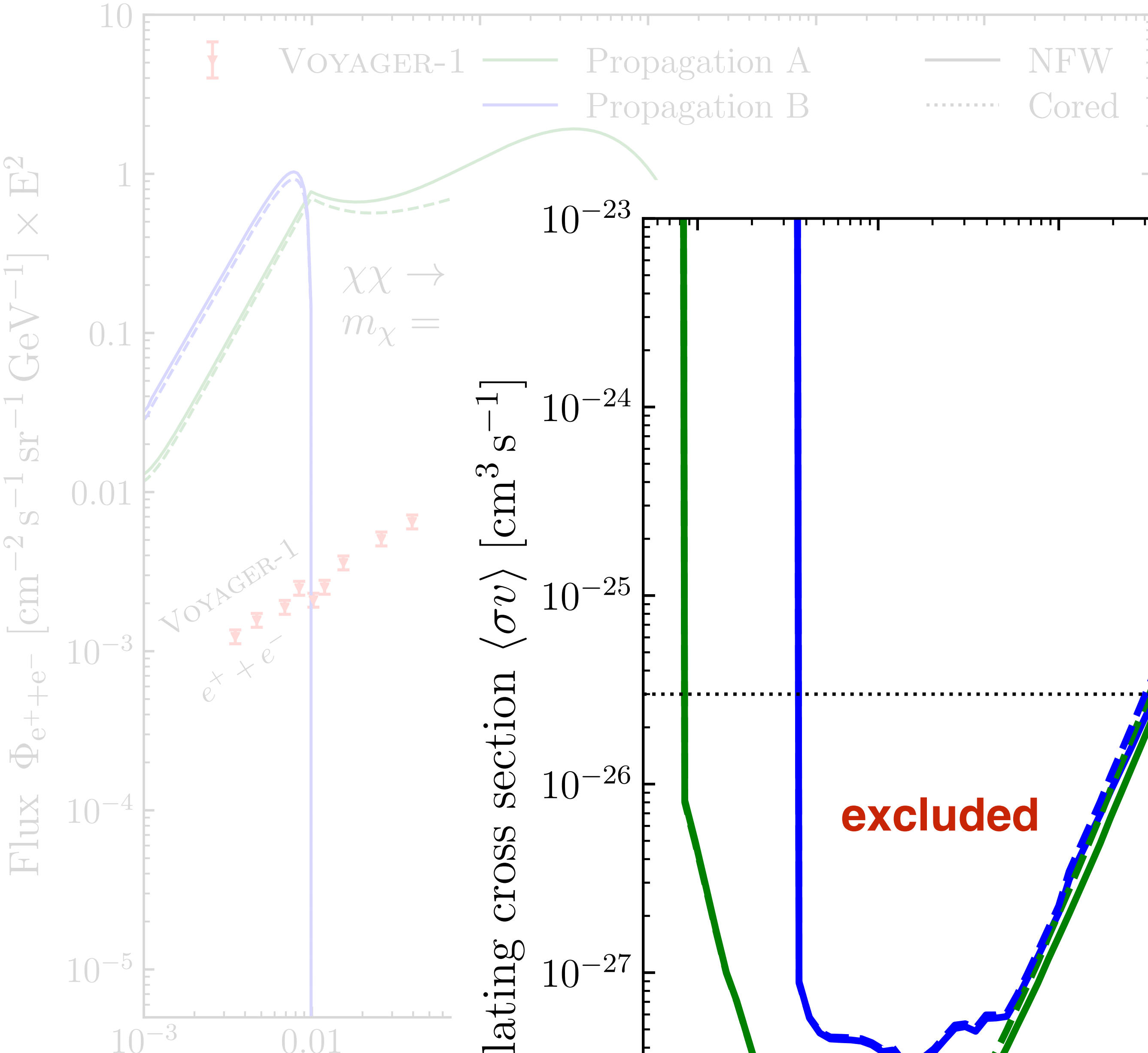

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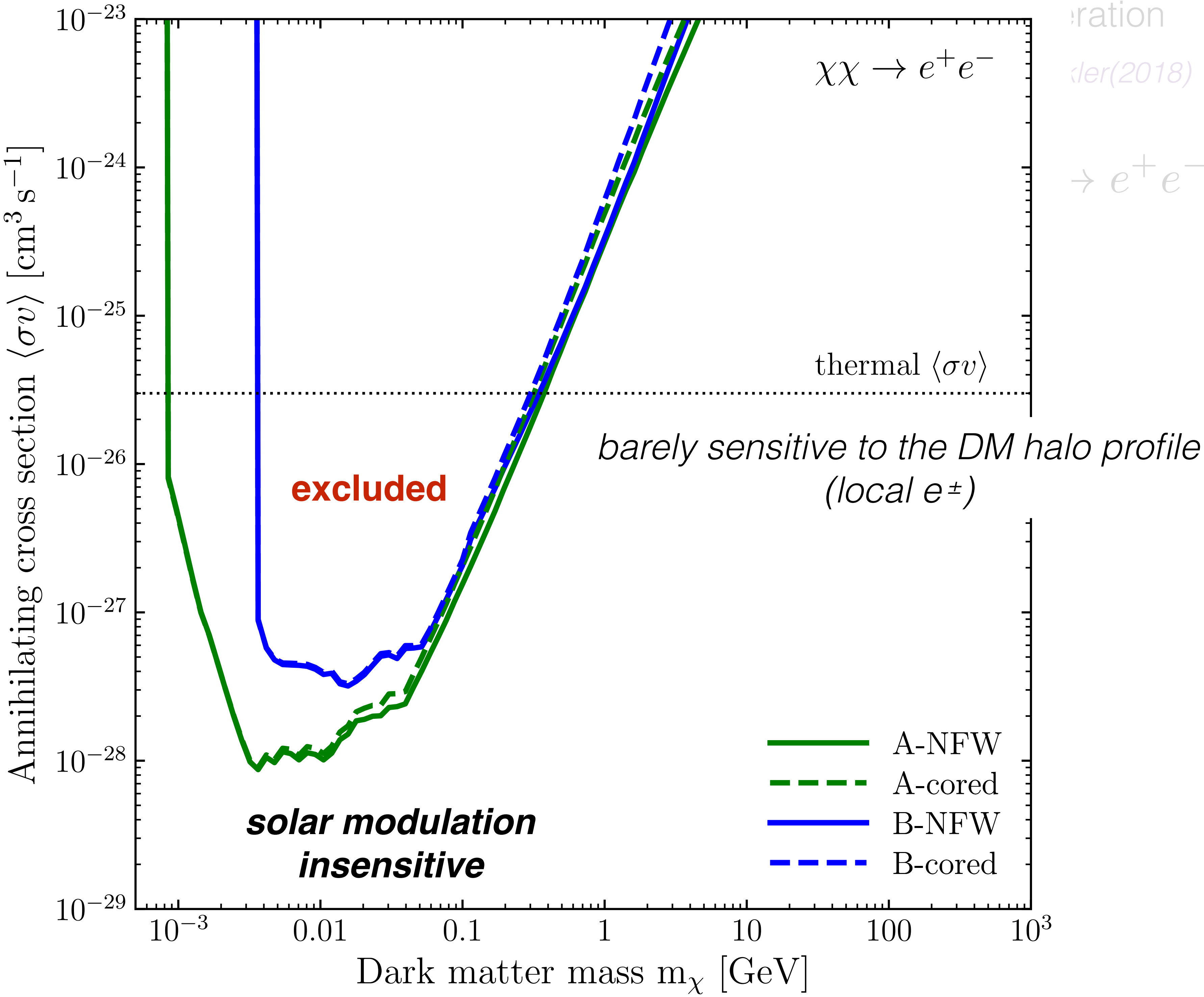

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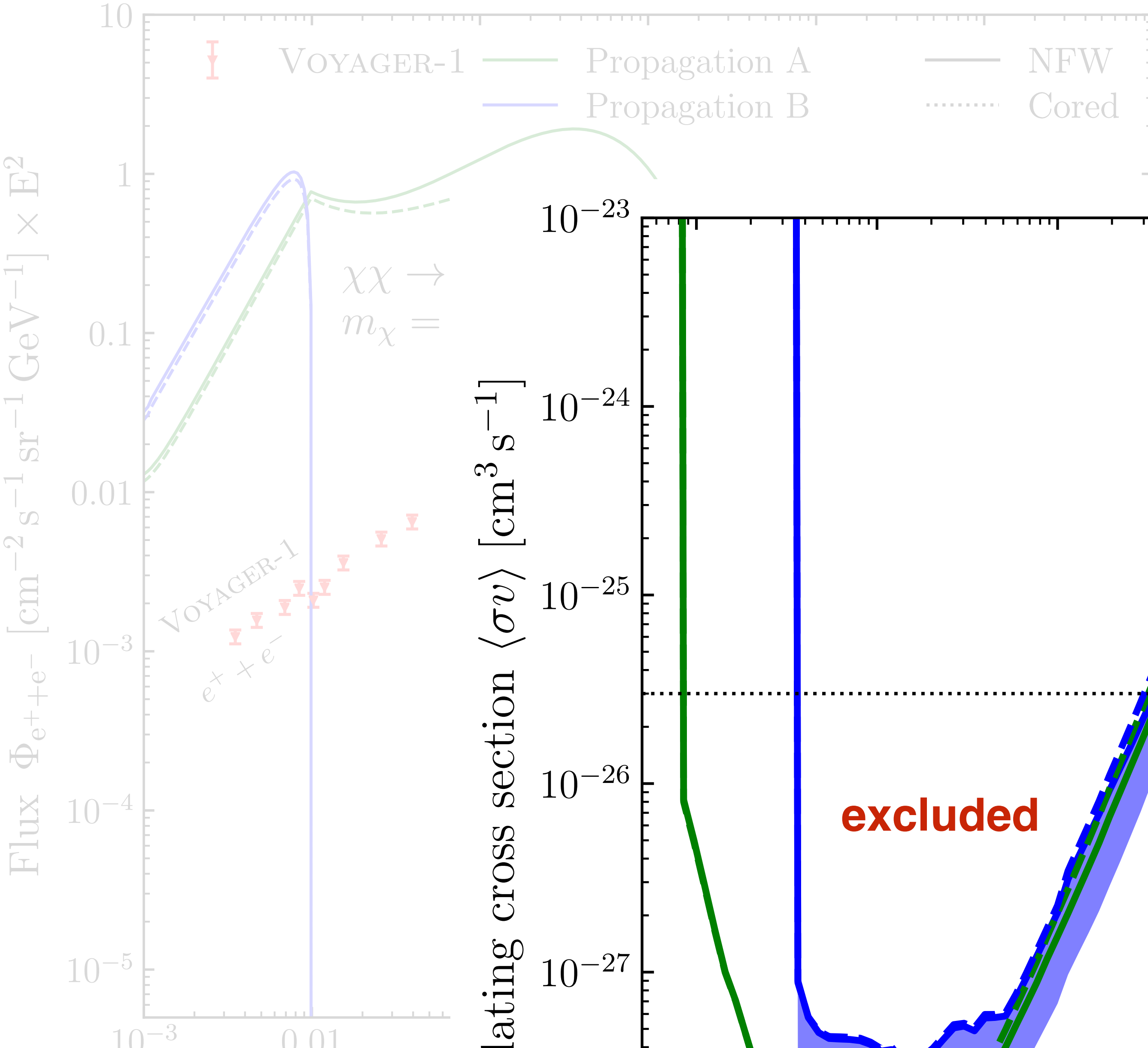

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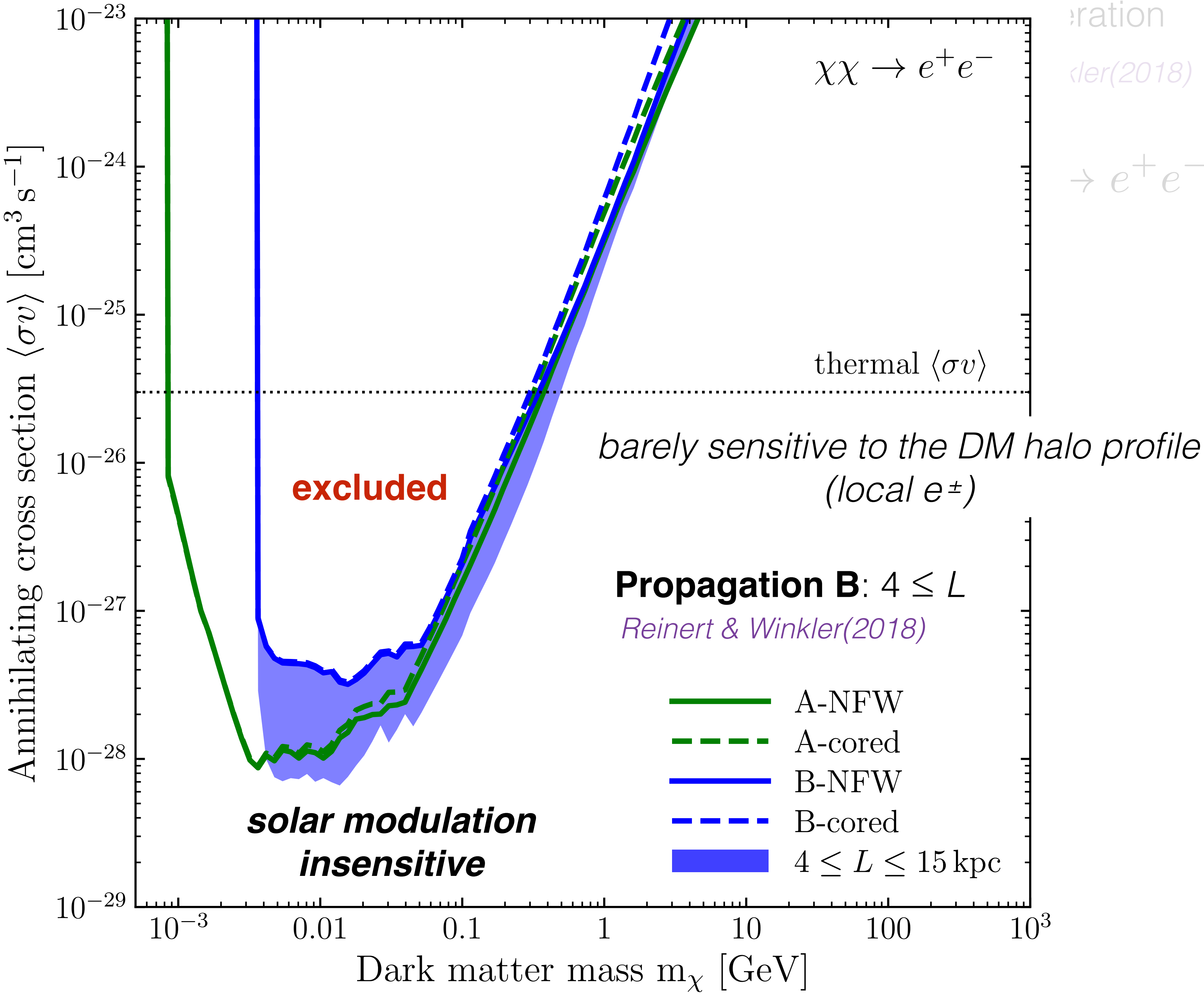

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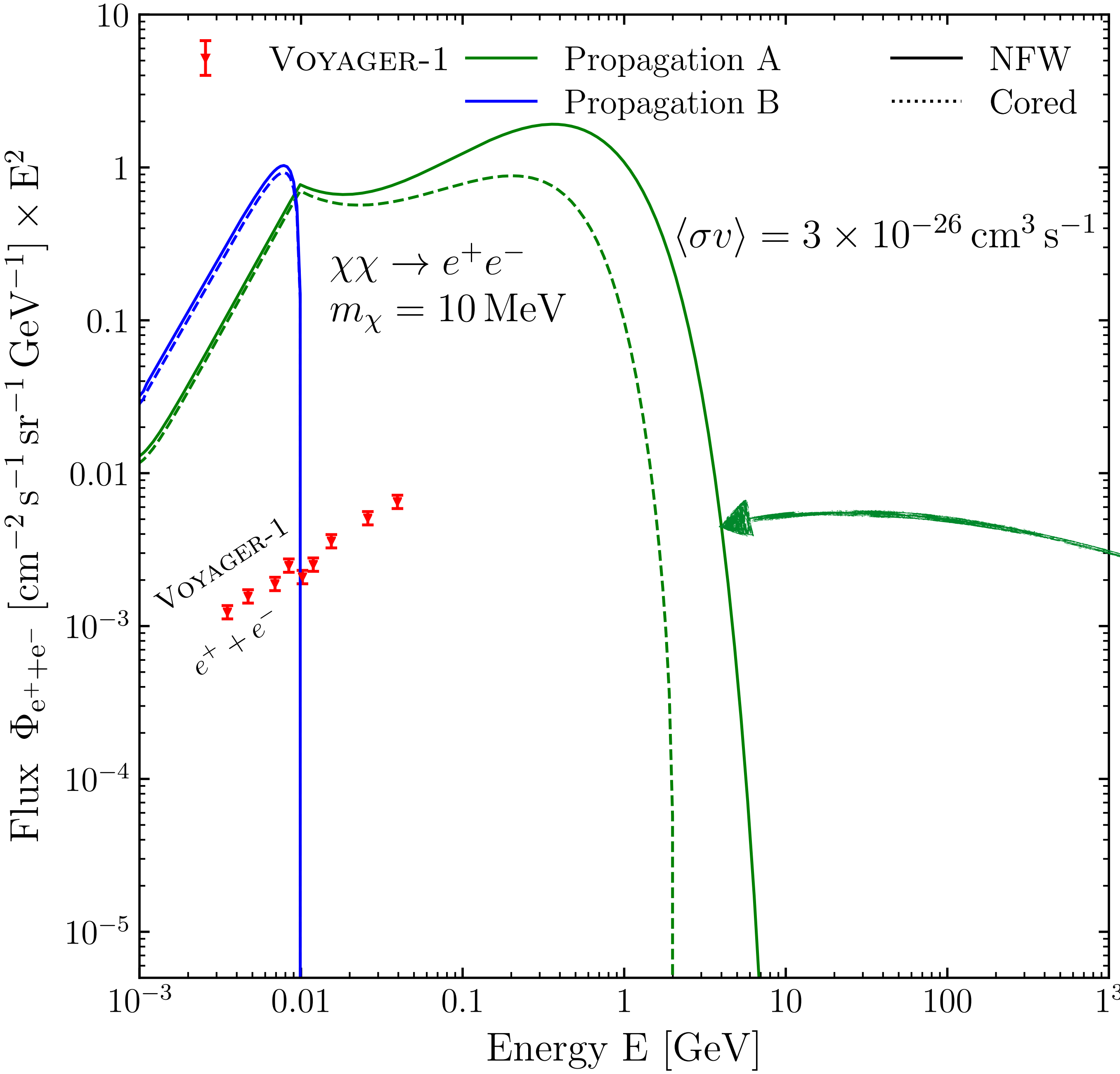

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$\Longrightarrow$ detection of positrons **above** the DM mass!

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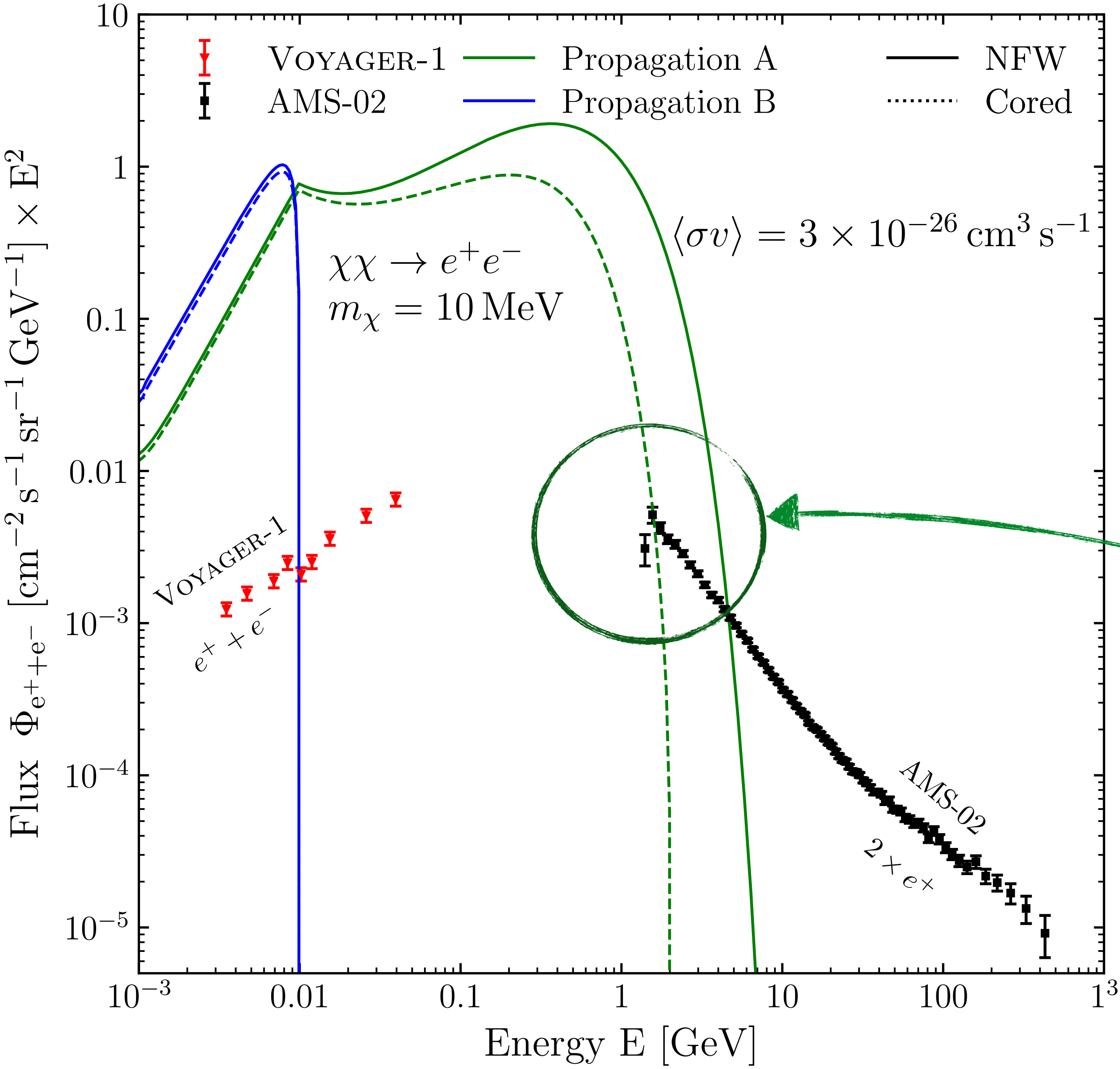

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eleration

Vinkler(2018)

$\longrightarrow e^+e^-$

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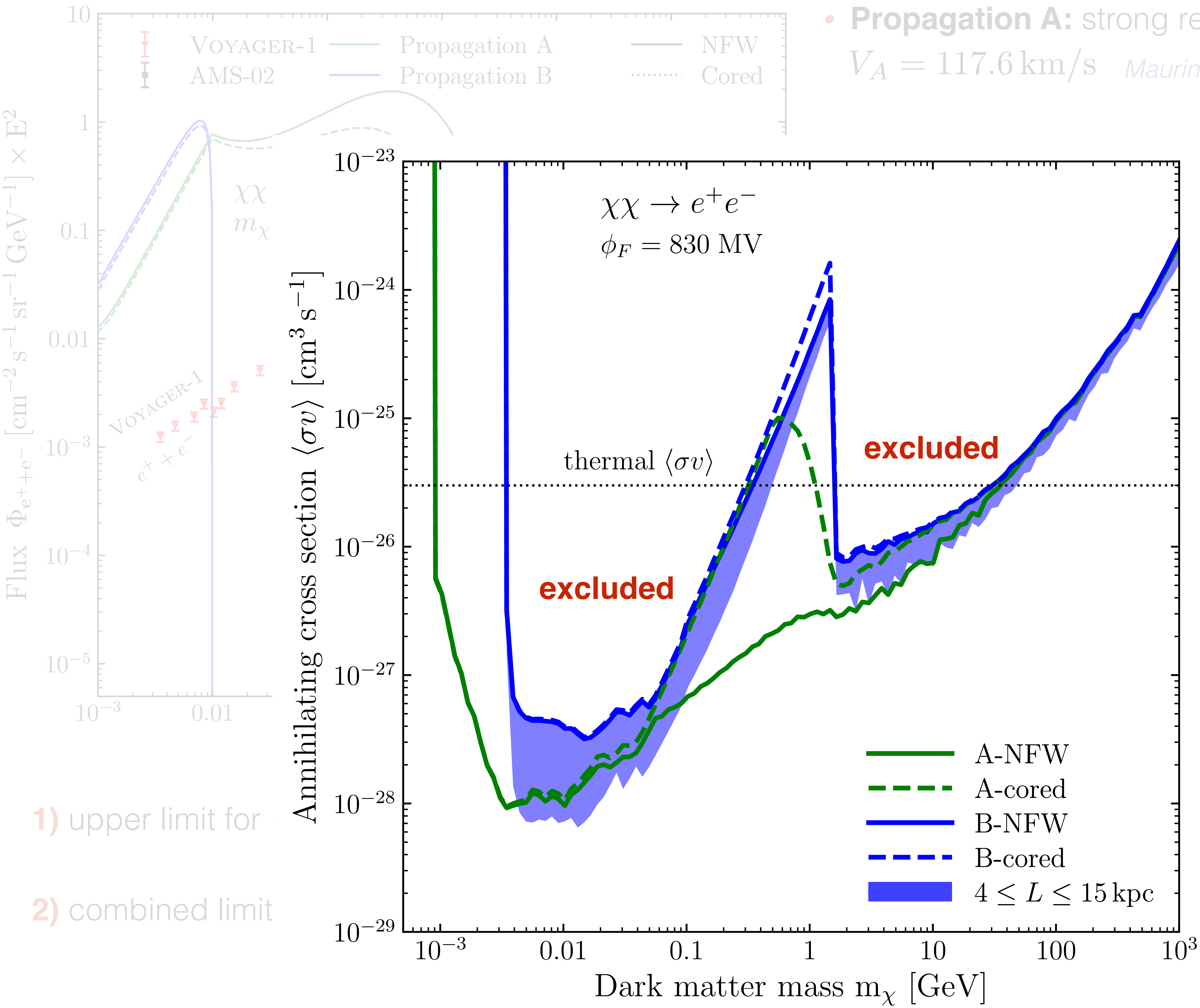

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$\ldots) + 2\sigma_i$

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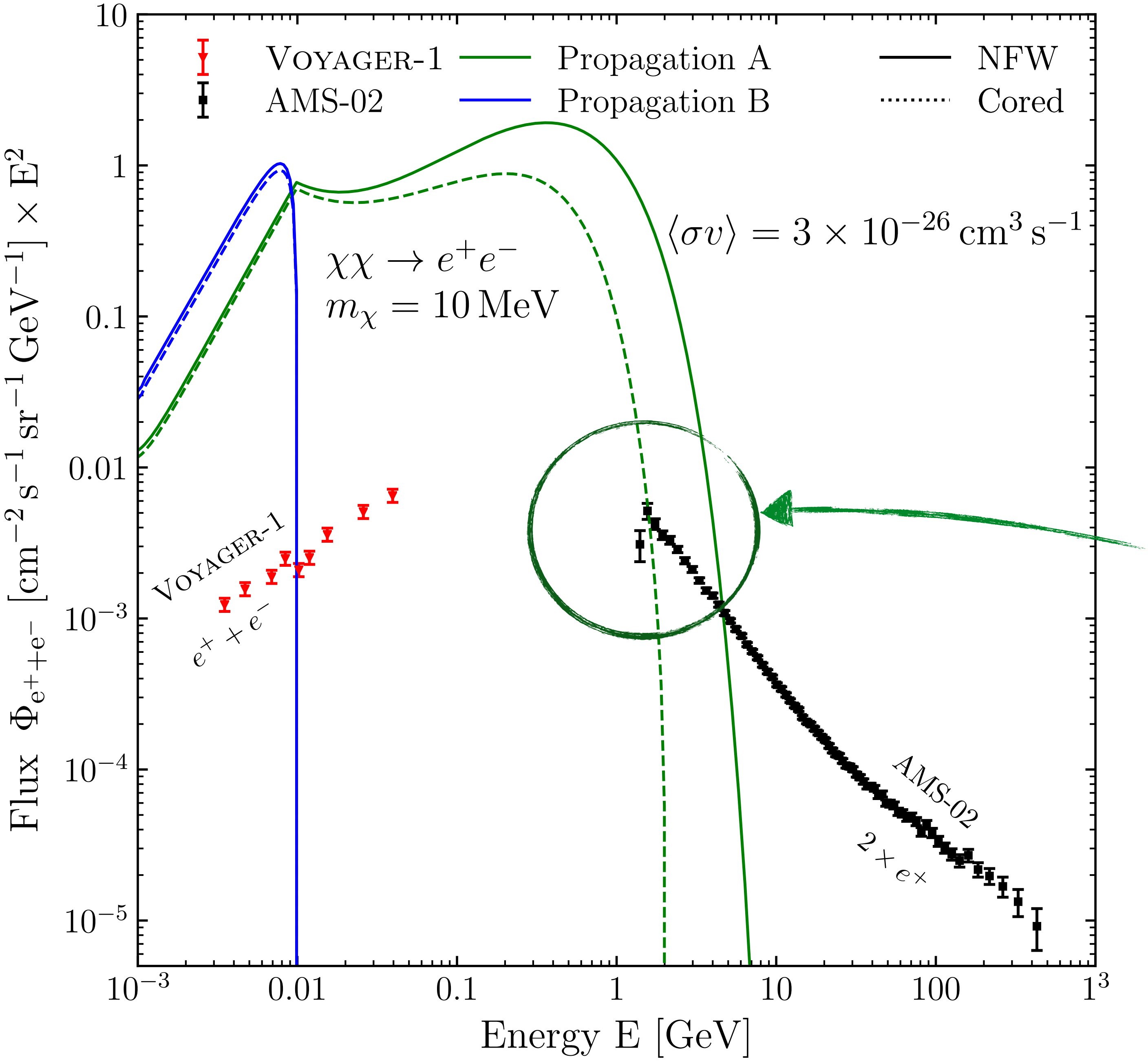

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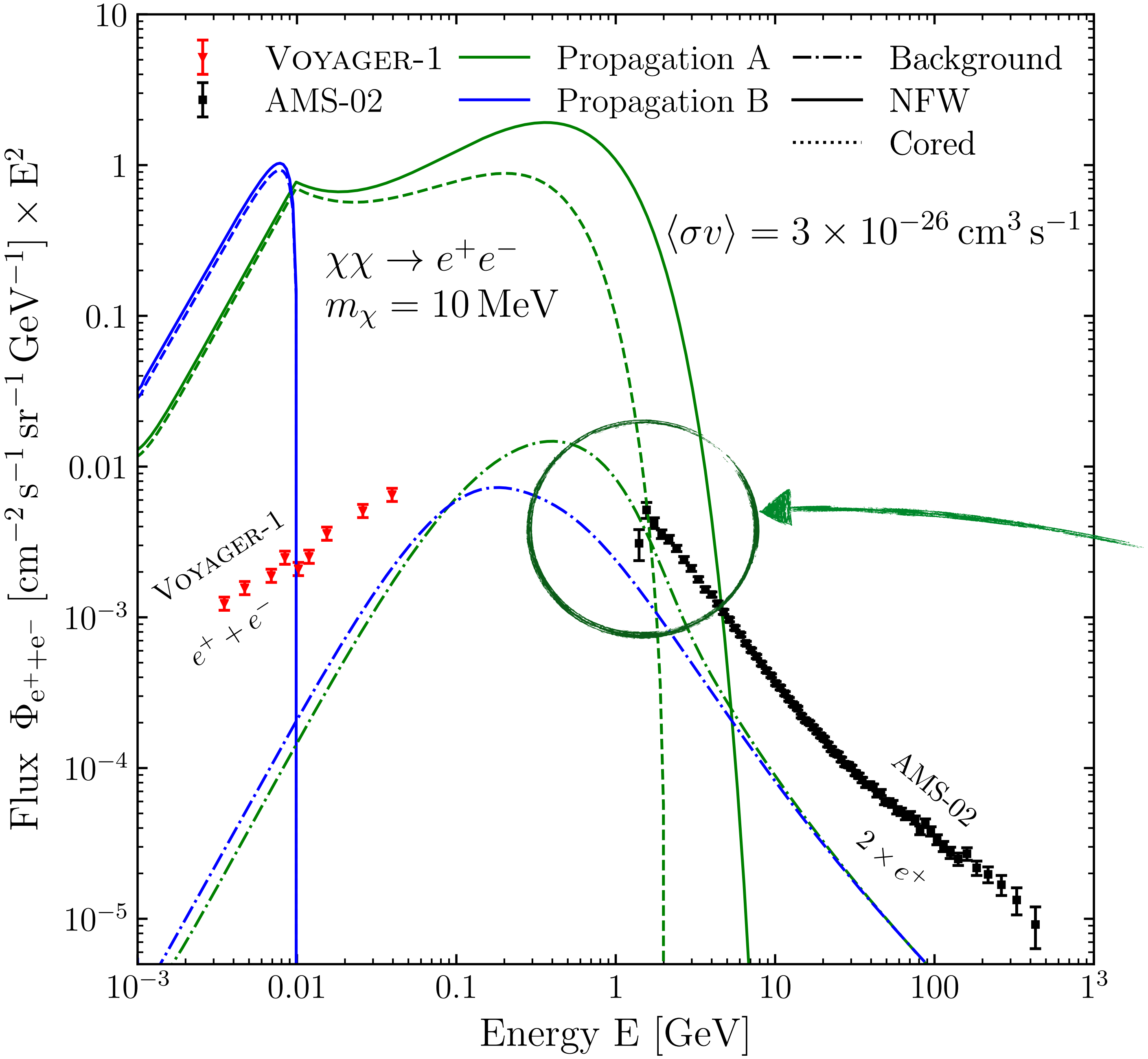
Constraints on annihilation cross section



- **Propagation A:** strong reacceleration
  $V_A = 117.6\,\mathrm{km/s}$ *Maurin+(2001)*
- **Propagation B:** no reacceleration
  $V_A = 0\,\mathrm{km/s}$ *Reinert & Winkler(2018)*

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

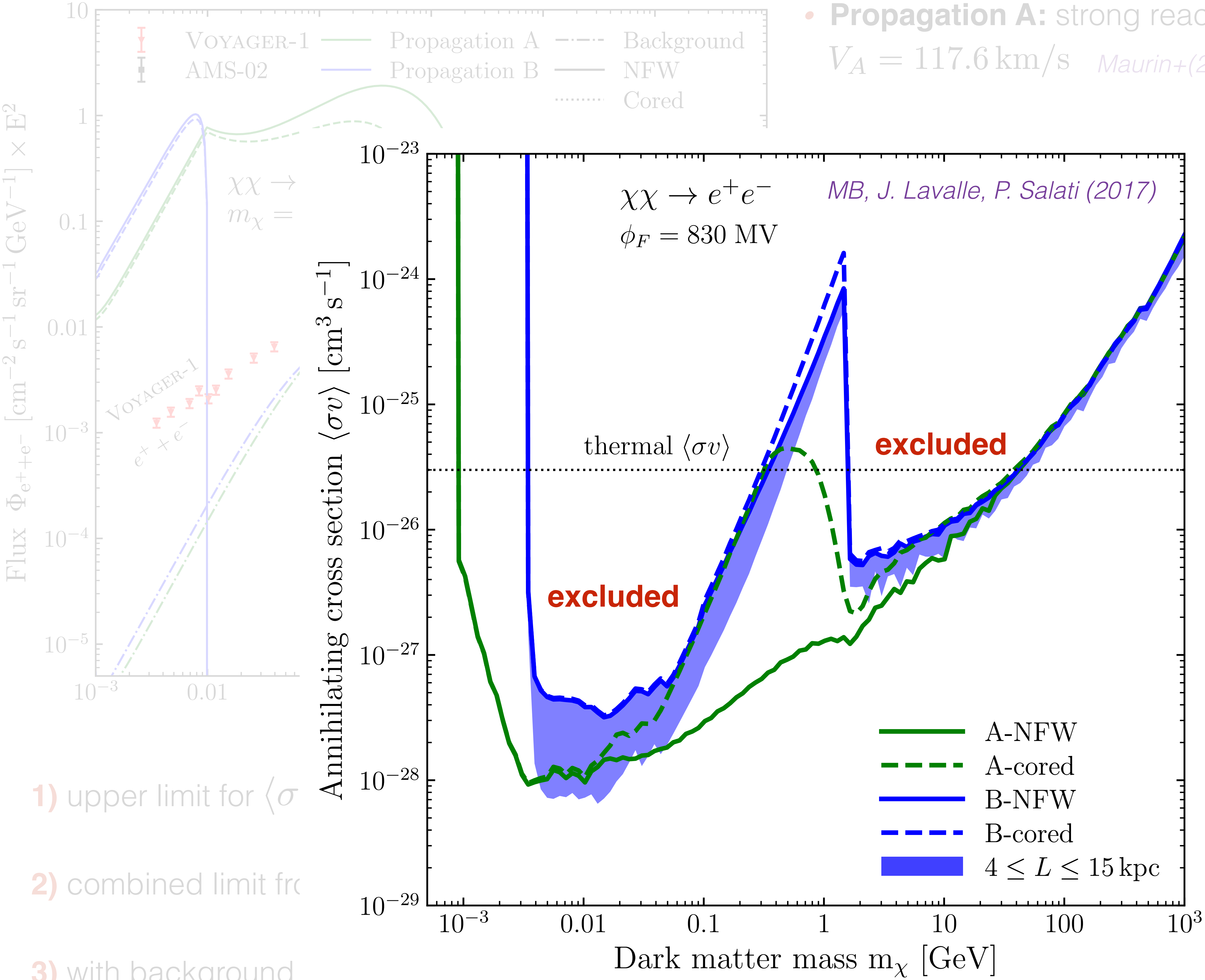
Model **A** with **strong diffusive reacceleration**
$\Longrightarrow$ detection of positrons **above** the DM mass!

1) upper limit for $\langle\sigma v\rangle$ from Voyager-1 $e^\pm$: $\Phi^{\mathrm{DM}}_{e^++e^-}(E_i) \leq \Phi^{\mathrm{exp}}_{e^++e^-}(E_i) + 2\sigma_i$

2) combined limit from Voyager1 $e^\pm$ and AMS-02 e^+: **1)** $+$ $\Phi^{\mathrm{DM}}_{e^+}(E_i) \leq \Phi^{\mathrm{exp}}_{e^+}(E_i) + 2\sigma_i$

3) with background of secondary e^+: **1)** $+$ $\Phi^{\mathrm{DM}}_{e^+}(E_i) + \Phi^{\mathrm{II}}_{e^+}(E_i) \leq \Phi^{\mathrm{exp}}_{e^+}(E_i) + 2\sigma_i$

Constraints on annihilation cross section



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…eration

…ler(2018)

… reacceleration

…ve the DM mass!

1) upper limit for $\langle\sigma$…

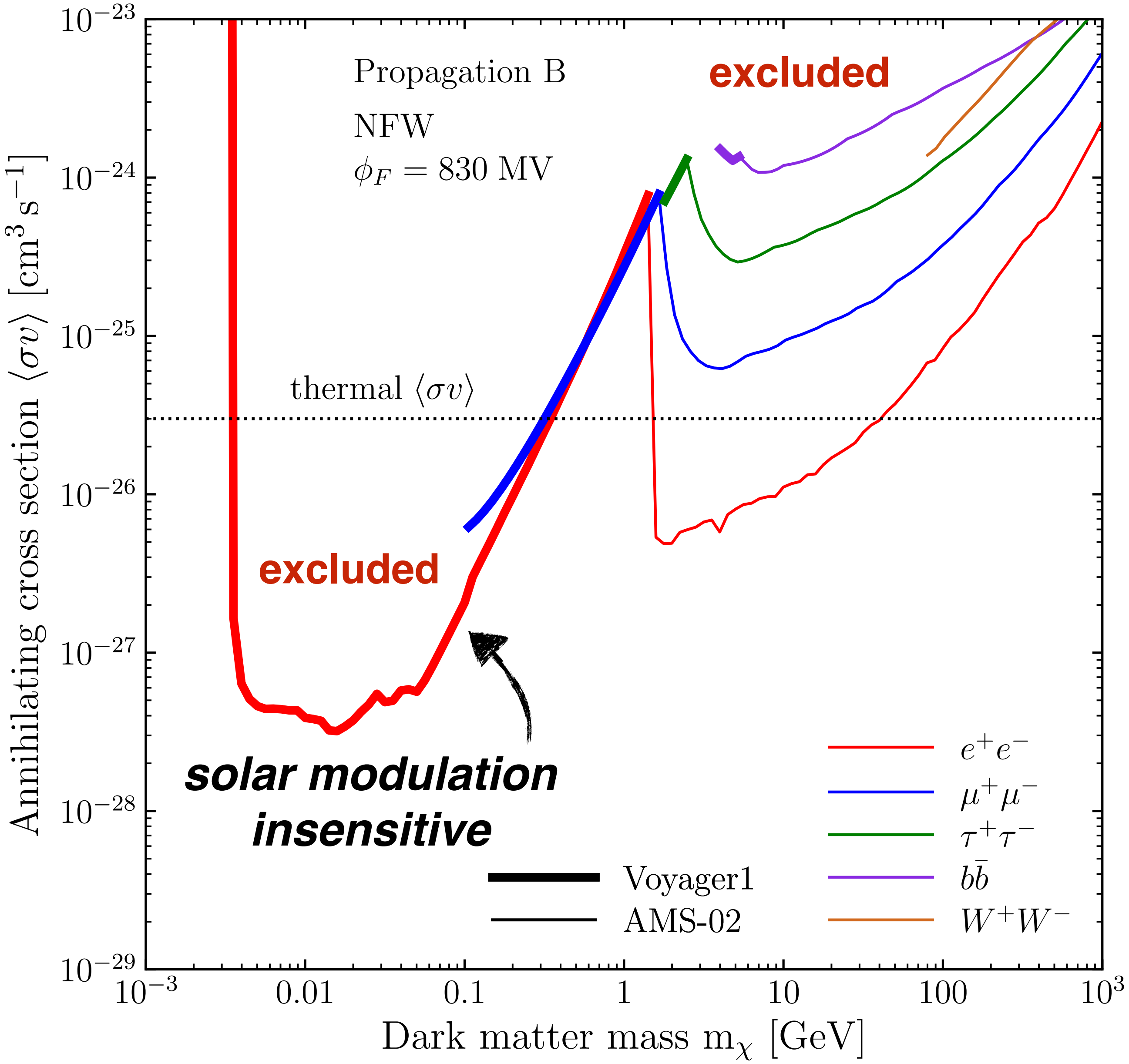
2) combined limit fr…

3) with background

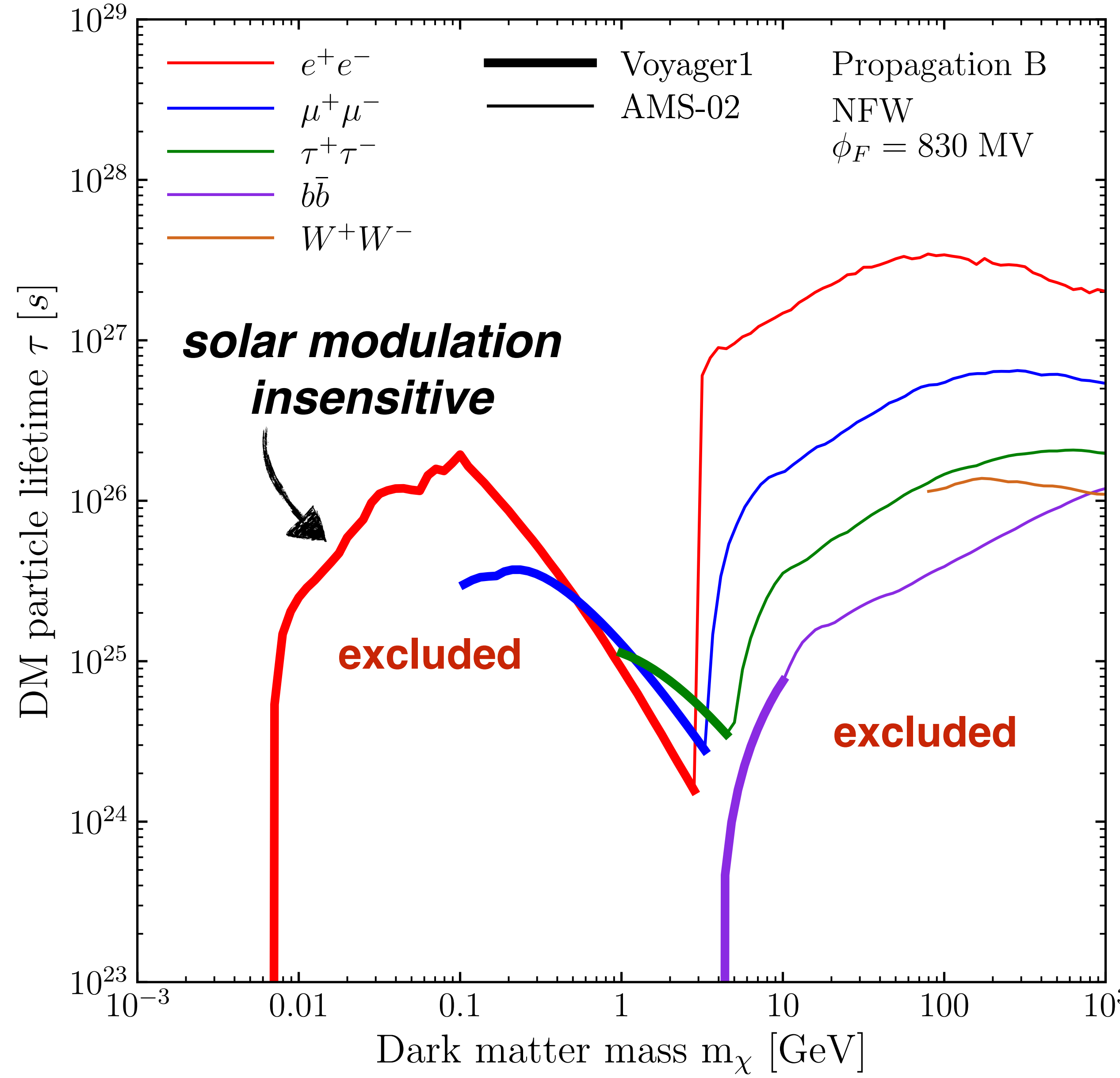
Constraints on DM annihilating cross section

MB, J. Lavalle, P. Salati (2017)

Annihilating Dark Matter



Decaying Dark Matter



X-rays and ɣ-rays *Essig+(2013)*

- **More** stringent (~1 order of magnitude)
- **Less** sensitive to the DM halo shape

Cosmic Microwave Background *Liu+(2016)*

- **Less** stringent

only for s-wave annihilation

Velocity average annihilation cross-section

$$\langle \sigma v \rangle = \sigma_0 \, c + \sigma_1 \, c \, \beta^2 + \mathcal{O}(\beta^4)$$

s-wave, *p-wave*

Srednicki+(1998)

σ_0, σ_1, … rely on the DM model

Velocity average annihilation cross-section

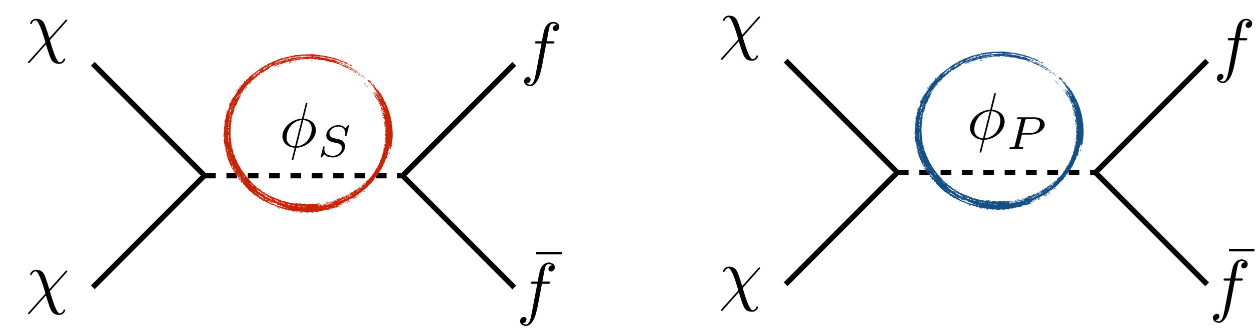
$$\langle \sigma v \rangle = \sigma_0\, c + \sigma_1\, c\, \beta^2 + \mathcal{O}(\beta^4)$$

$\boldsymbol{\sigma}_0$, $\boldsymbol{\sigma}_1$, … rely on the DM model

Srednicki+(1998)

	s-wave	*p-wave*
scalar mediator	✗	✓
pseudo-scalar mediator	✓	✓

e.g:



Assuming $\langle \sigma v \rangle$ constant (velocity independent) is a strong assumption for the DM model

$\Longrightarrow$ better to constrain the $\boldsymbol{\sigma}_i$ coefficients, directly linked to the DM models

Velocity average annihilation cross-section

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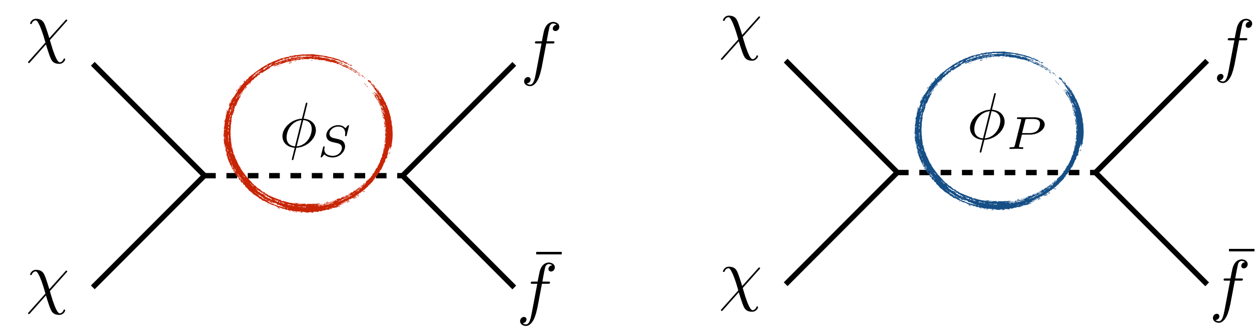
σ_0, σ_1, … rely on the DM model

Srednicki+(1998)

	s-wave (σ_0)	*p-wave* (σ_1)
scalar mediator	✗	✓
pseudo-scalar mediator	✓	✓

e.g:



Assuming $\langle \sigma v \rangle$ constant (velocity independent) is a strong assumption for the DM model
$\Longrightarrow$ better to constrain the σ_i coefficients, directly linked to the DM models

Recombination (CMB)

$$T_{\rm DM}(z_{\rm rec}) = \frac{T_\gamma^2(z_{\rm rec})}{T_{\rm kd}}$$

$$x \equiv \frac{T}{m_\chi}$$

$$\beta^2(z_{\rm rec}) = 10^{-9}\left(\frac{x_{\rm kd}}{1000}\right)\left(\frac{m_\chi}{1\,{\rm MeV}}\right)$$

Now in the Milky Way

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

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

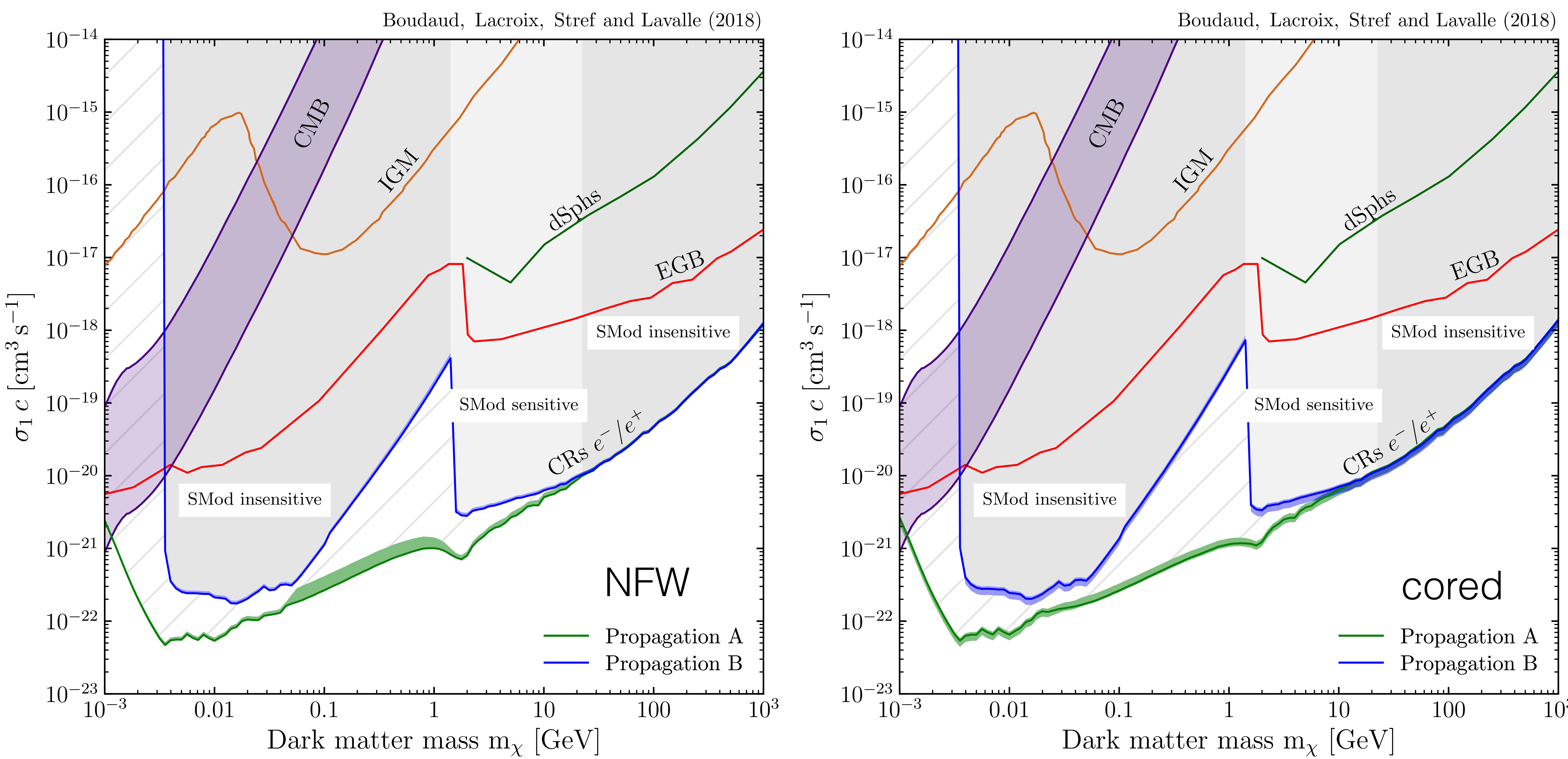
$$\beta^2_{\rm MW} \simeq 10^{-6}$$

Contraints on **p-wave annihilations** (σ_1) should be **more stringent** for local CRs observations than for CMB

Velocity dependent annihilation (p-wave)

MB, T. Lacroix, M. Stref and J. Lavalle (to appear)

$\langle \sigma v \rangle (r)$ from Eddington inversion method *T. Lacroix, M. Stref and J. Lavalle (2018)*



- **more stringent** (orders of magnitude) than other constraints *Liu+(2016), Zhao+(2016)*
- **barely sensitive** to the DM halo profile to the velocity anisotropy of the DM particles
- **insensitive** to the solar modulation below ~1 GeV and above ~20 GeV

Application 2:

Contraints on primordial black holes (PBHs) as dark matter

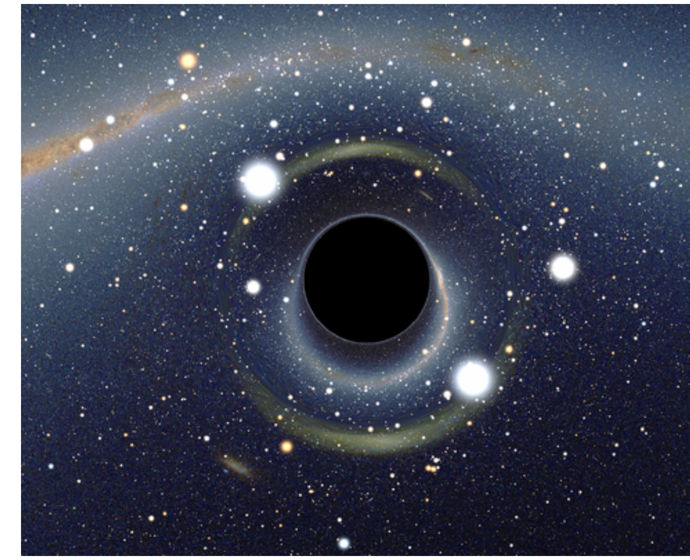
MB & M. Cirelli (arXiv:1807.03075)

Primordial black holes as dark matter

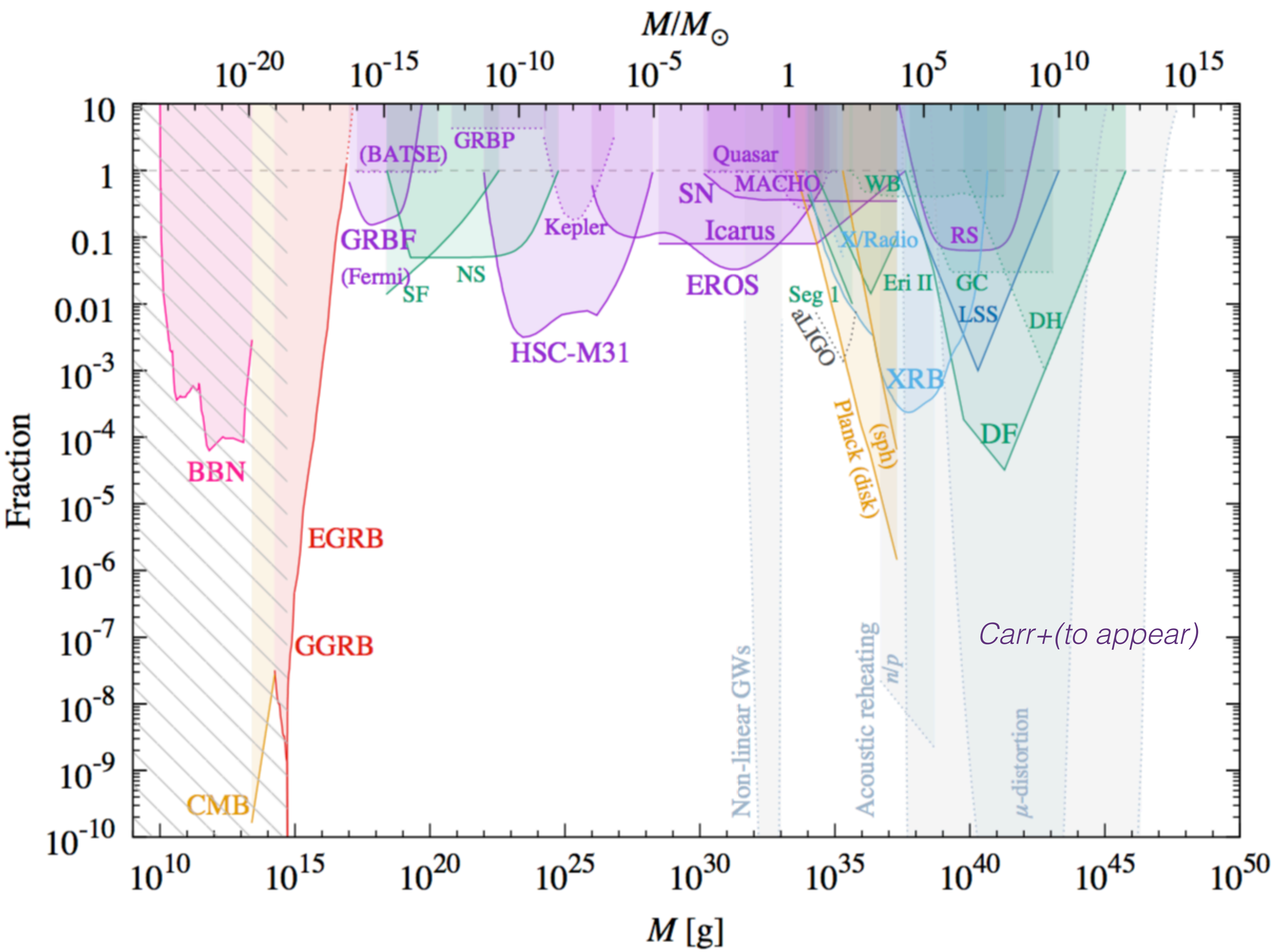
Produced from cosmological fluctuations during inflation

$$M \sim 10^{15} \left(\frac{t}{10^{-23}\,\mathrm{s}} \right) \mathrm{g}$$

fraction of DM in PBHs: $f = \frac{\rho_{\mathrm{PBH}}}{\rho_{\mathrm{DM}}}$



Lensing, **dynamical**, **accretion**, **cosmological** and **Hawking radiation** limits



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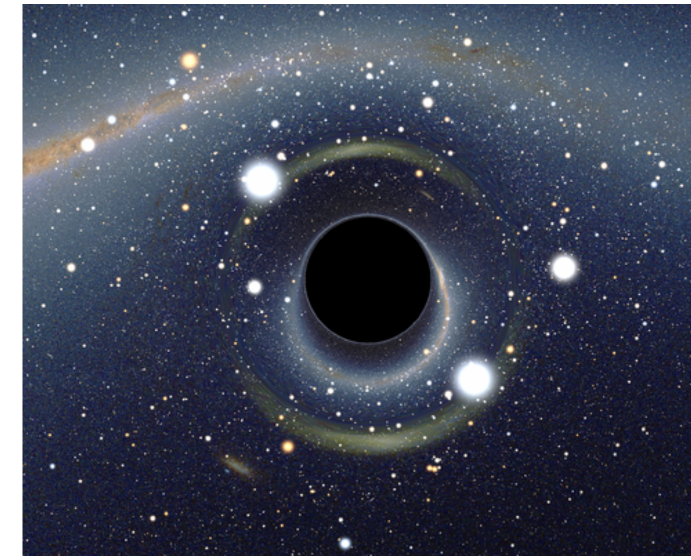
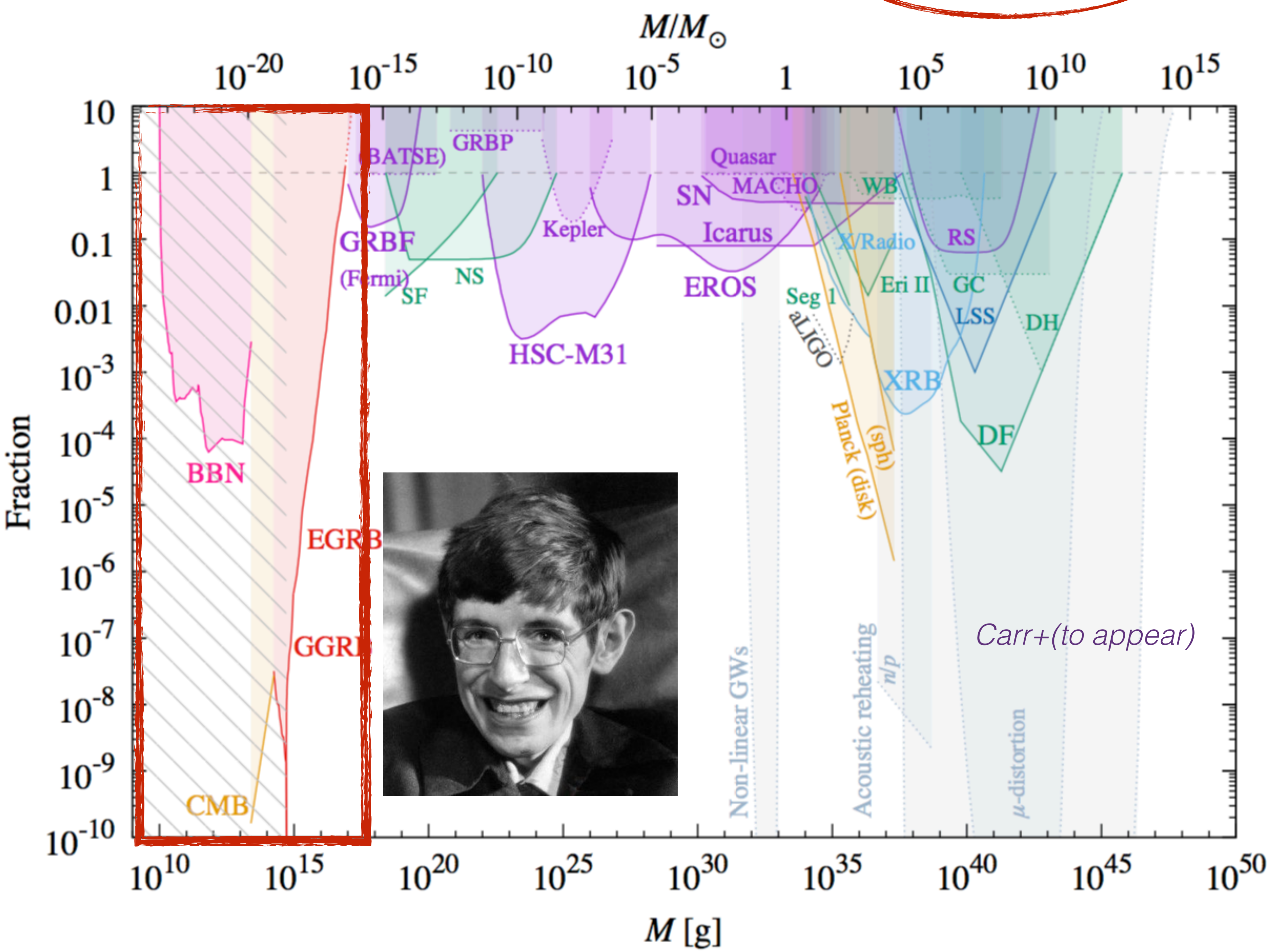


Lensing, **dynamical**, **accretion**, **cosmological** and **Hawking radiation** limits



Microscopic BHs

$$M \in [10^{15}, 10^{17}]\ \mathrm{g}$$

$$M = 10^{16}\mathrm{g} = 10\ \mathrm{GT}$$

(asteroid / small mountain)

$$R = \frac{2\,GM}{c^2} \simeq 15 \times 10^{-15}\,\mathrm{m}$$

(nucleus size)

$$\rho_\odot^{\mathrm{DM}} = 0.4\,\mathrm{GeV cm^{-3}}$$

$$d \sim 1\ \mathrm{au}$$

Hawking radiation of electrons and positrons

BH temperature from classical thermodynamics

$$S \propto \mathcal{A} = 4\pi R^2$$

$$dU = T dS \implies T = \frac{\hbar c^3}{2\pi G k_B M}$$

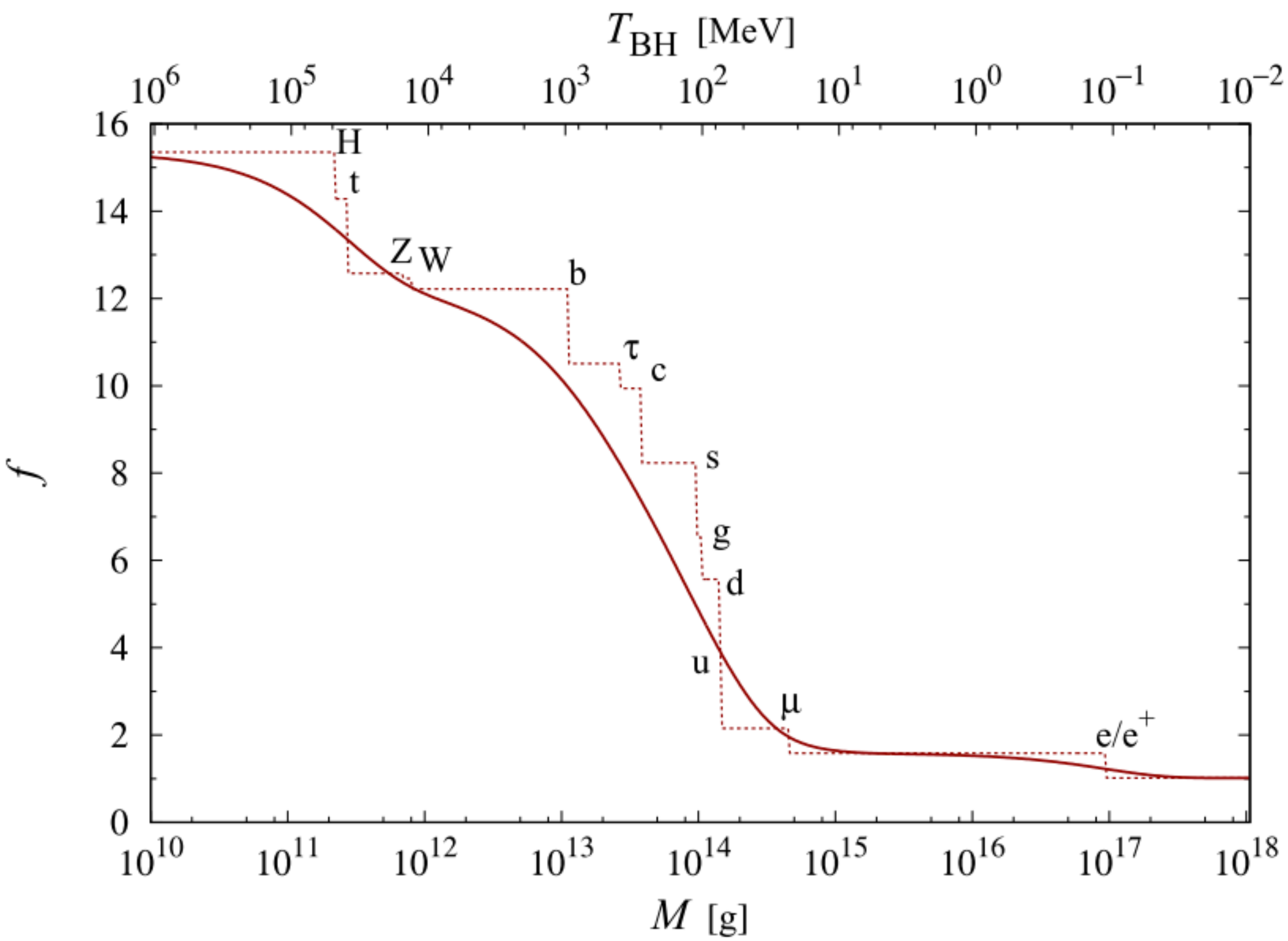
Hawking temperature from QFT in curved spacetime

$$T = \frac{\hbar c^3}{8\pi G k_B M}$$

BHs lose mass radiating particles with the rate:

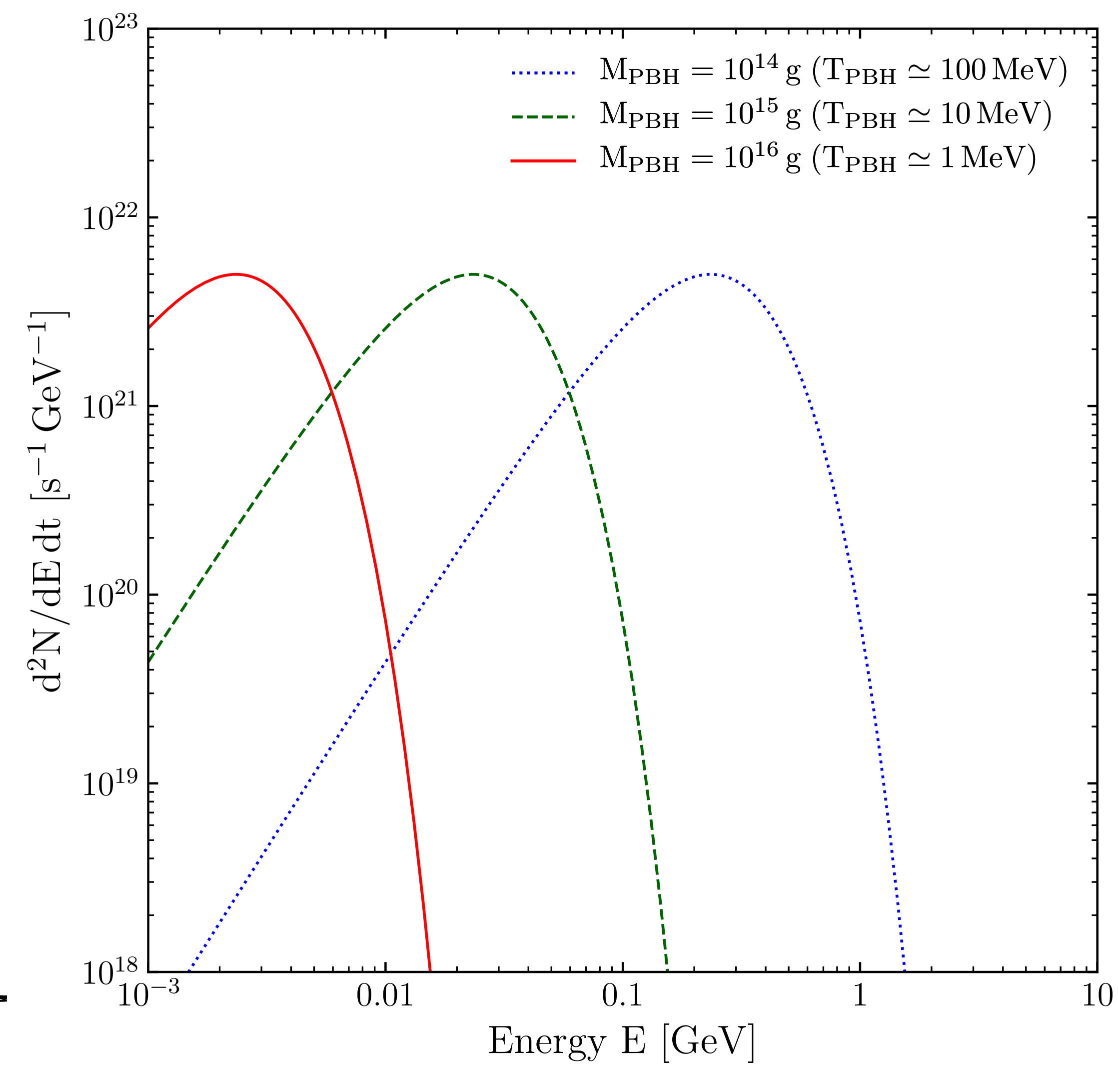
$$\frac{dM}{dt} \simeq -5.25 \times 10^{25} f(M) \left(\frac{g}{M}\right) g\, s^{-1}$$

PBHs with a mass M < ~10^{15} g have been evaporated today

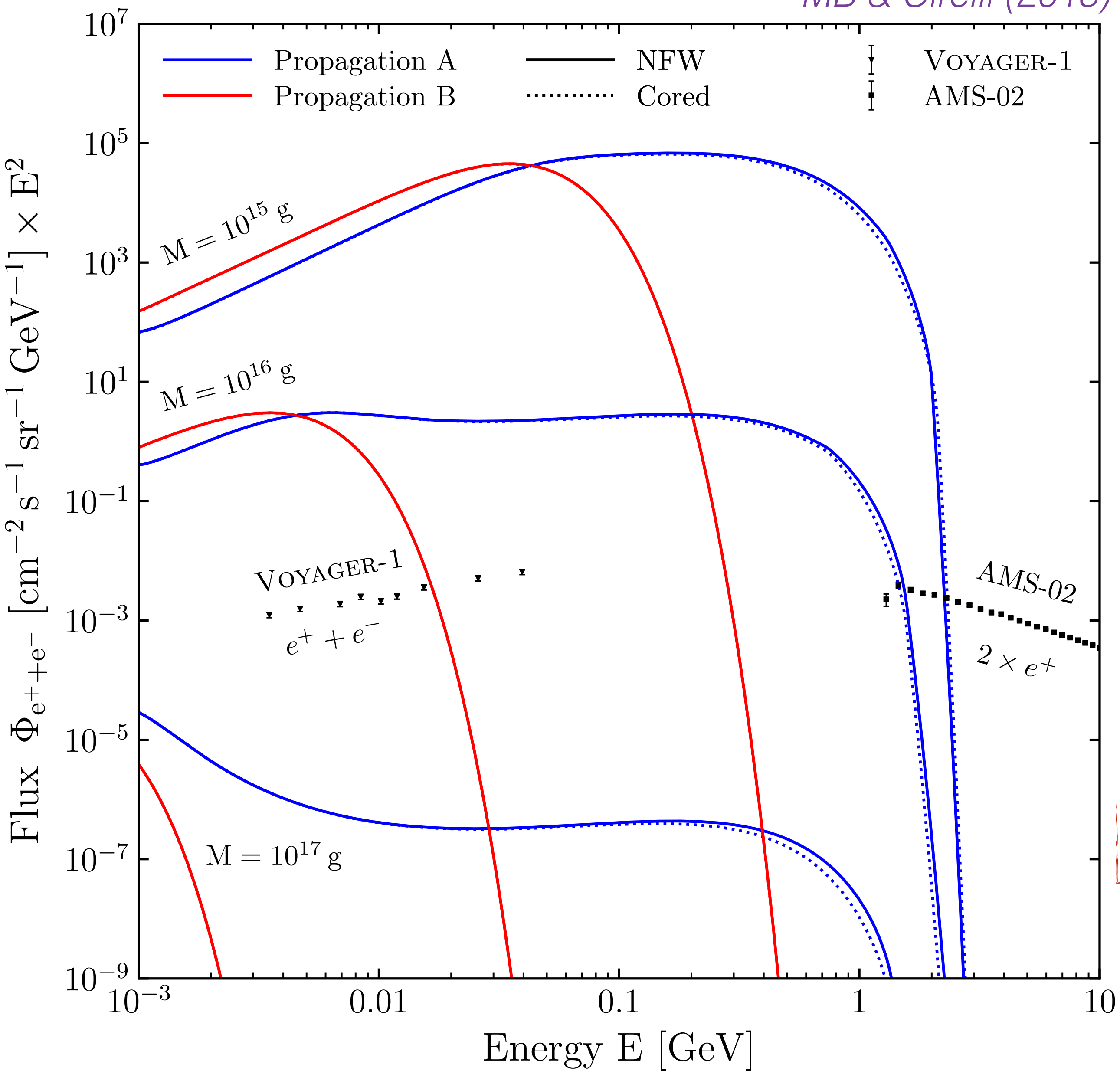


quasi-black body (grey) emission of $e^\pm$

$$\frac{dN}{dt\,dE} = \frac{27}{128}\frac{\hbar^2 c^6}{\pi^3}\frac{x^2}{e^x + 1} \qquad x = \frac{E}{T}$$



CRs $e^{\pm}$ from PBHs radiation



Propagation A: strong reacceleration

$V_A = 117.6\,\mathrm{km/s}$ *Maurin+(2001)*

Propagation B: no reacceleration

$V_A = 0\,\mathrm{km/s}$ *Reinert & Winkler(2018)*

DM distribution from *McMillan(2016)* (**NFW/cored**)

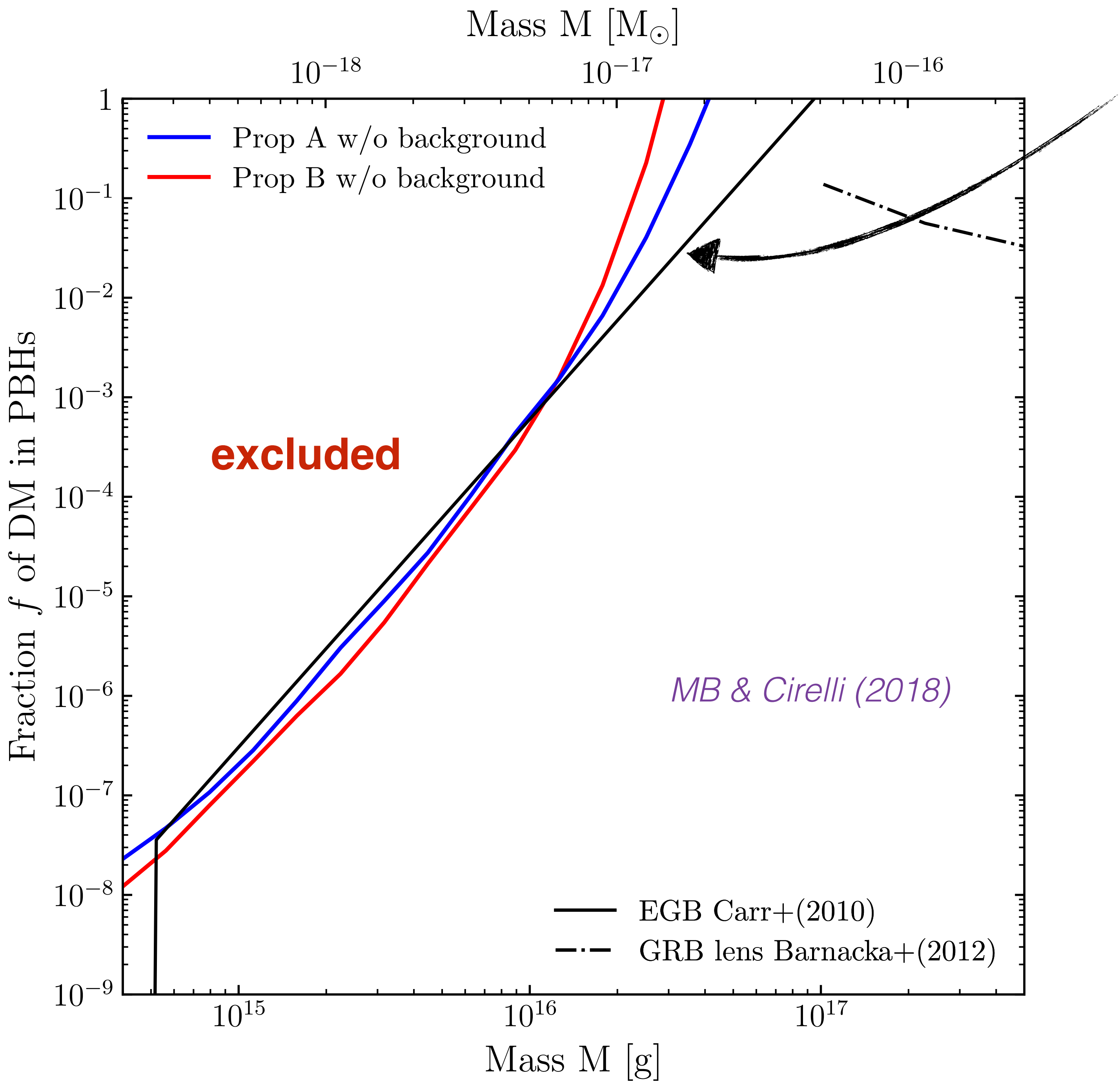
$$\rho_{\odot}^{\mathrm{DM}} = 0.4\,\mathrm{GeV\,cm^{-3}}$$

Voyager-1 probes PBHs with mass up to ~10^{17} g

- Voyager-1 is sensitive local PBHs (~1kpc) because of $e^{\pm}$ energy losses (ISM ionisation)
  $\Longrightarrow$ signal **not sensitive** to the DM halo profile
- strong reacceleration (**A**) enables to detect a signal above 1 GV
  $\Longrightarrow$ AMS-02 probes PBHs with $M < 10^{16}$ g

Voyager-1 data $\Longrightarrow$ upper limit for f = ρ_{PBH}/ρ_{DM}

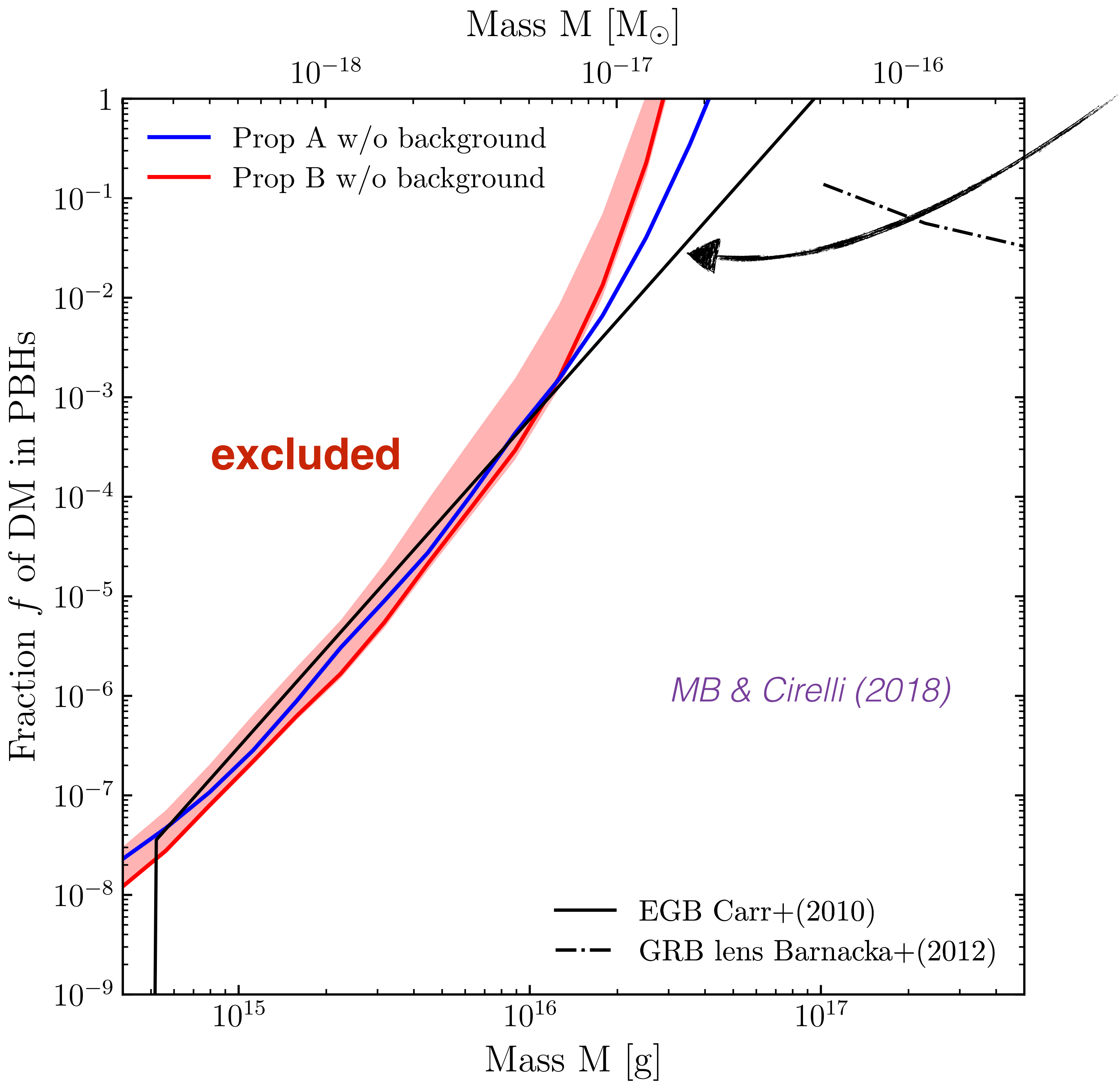
Constraints on the fraction of DM in PBHs



- competitive with EGB limits (Fermi-LAT) up to 10^{16} g

Carr+(2012)

Constraints on the fraction of DM in PBHs



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Carr+(2012)

- red band: uncertainty on the magnetic halo size

$4 < L < 20$ kpc *Reinert & Winkler(2018)*

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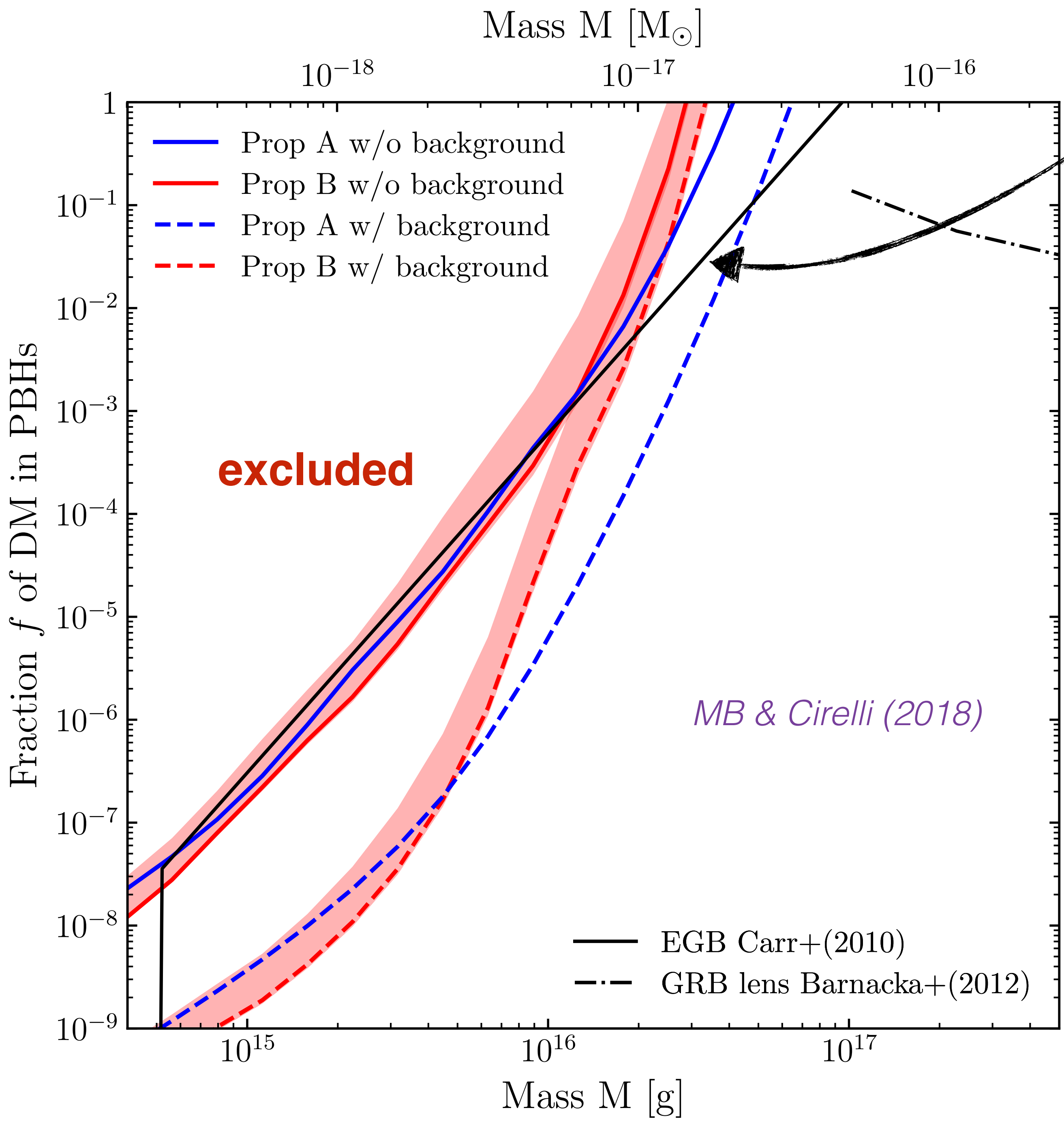


- competitive with EGB limits (Fermi-LAT) up to 10^{16} g

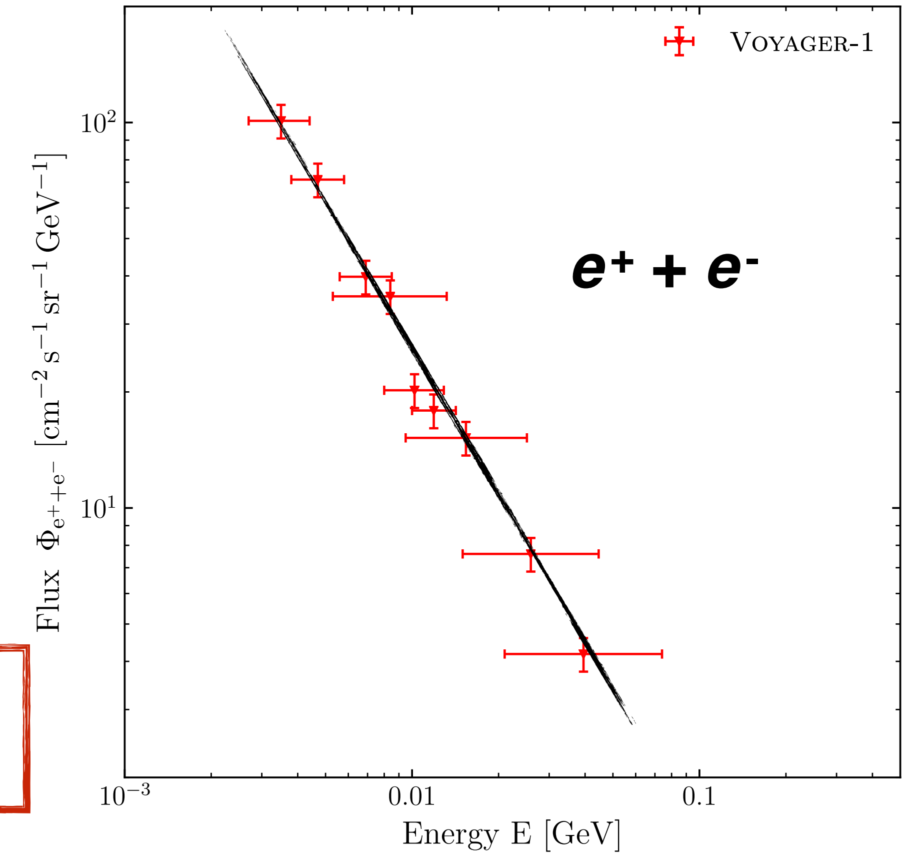
Carr+(2012)

- red band: uncertainty on the magnetic halo size

$4 < L < 20$ kpc *Reinert & Winkler(2018)*

- even better assuming a background for Voyager-1 data (SNRs e^-)

$$\Phi_{e^-}(E) \propto E^{-1.3}$$



local constraints (1~kpc), **no** cosmological assumptions
⟹ **complementary** to cosmological constraints (EGB, CMB, EDGES)

Conclusions and outlook

- The **pinching method** allows to compute **semi-analytically** the flux of $e^{\pm}$ below 10 GeV taking into account **all propagation effects** ***soon in USINE (code for the propagation of Galactic CRs)***

Maurin (2018)

- **Voyager-1** and **AMS-02** $e^{\pm}$ data are used to derive limits on **MeV DM particles**
  - s-wave annihilation (velocity independent)

    More stringent (and less uncertainties) than X-rays and ɣ-rays, **less stringent** than CMB,
  - p-wave annihilation (velocity dependent)

    Eddington inversion to compute properly the velocity average annihilation cross section

    Much more stringent than all existing constraints

- **Voyager-I** (AMS-02) $e^{\pm}$ data are used to derive **local limits** on fraction of DM in **PBHs**
  - **Competitive** with **EGB** for $M < 10^{16}\,M_{\odot}$
  - **Local** constraints, **no** cosmological assumptions

Thank you for your attention!

Questions?

Voyager Golden Record: the Sounds of Earth

Back up

Pinching method

$$-K\Delta\psi + \partial_E\left[b\,\psi\right] = Q \quad\longrightarrow\quad -K\Delta\psi + 2h\,\delta(z)\partial_E\left[b^{eff}_{\text{halo}}\,\psi\right] = Q$$

$$b^{eff}_{\text{halo}}(E,r) = \bar{\xi}(E,r)\,b_{\text{halo}}(E)$$

pinching factor

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

$$J_i(E_S) = \frac{1}{h}\int_0^L dz_S\,\mathcal{F}_i(z_S)\,Q_i(E_S,z_S)$$

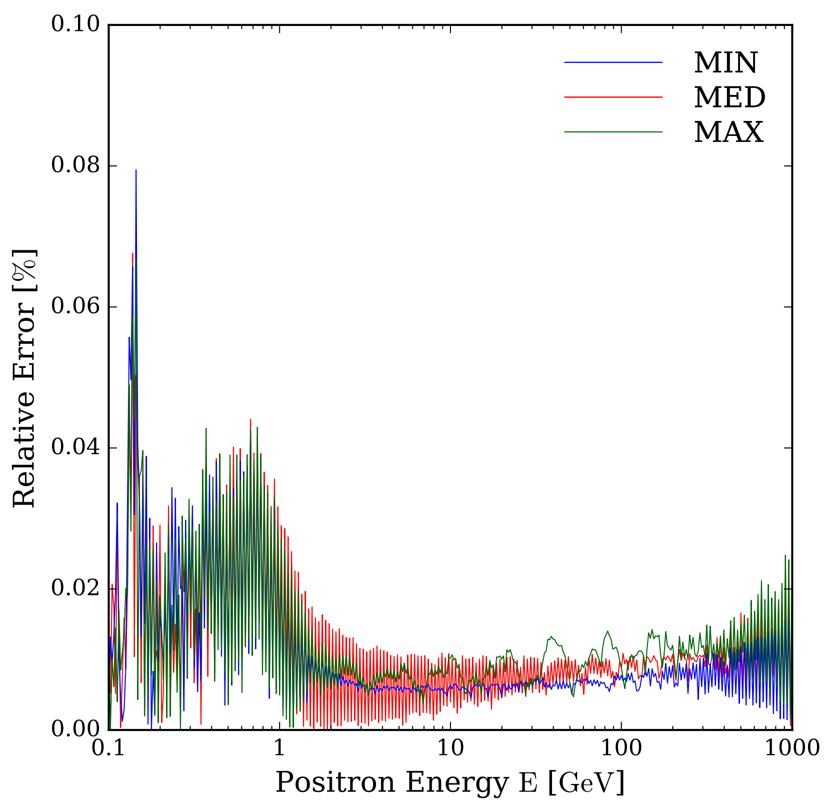
$$\bar{\xi}_i(E) = \frac{\int_E^{+\infty} dE_S\left[J_i(E_S) + 4k_i^2\int_E^{E_S} dE'\,\frac{K(E')}{b(E')}\,B_i(E',E_S)\right]}{\int_E^{+\infty} dE_S\,B_i(E,E_S)}$$

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

$$Q_i(E,z) = \frac{2}{R^2J_1^2(\alpha_i)}\int_0^R dr\,r\,J_0(\xi_i)\,Q(E,r,z)$$

$$C_{i,n} = \frac{1}{4}\left[\left(\frac{\alpha_i}{R}\right)^2 + (nk_0)^2\right]$$

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



- The error averaging the pinching factor **is smaller than 0.1%**
- The more important low energy effects (convection, disc energy losses, DR), the less precise the pinching factor, but, the less precise it has to be!

Astrophysical background of secondary positrons

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

$p + p \longrightarrow$

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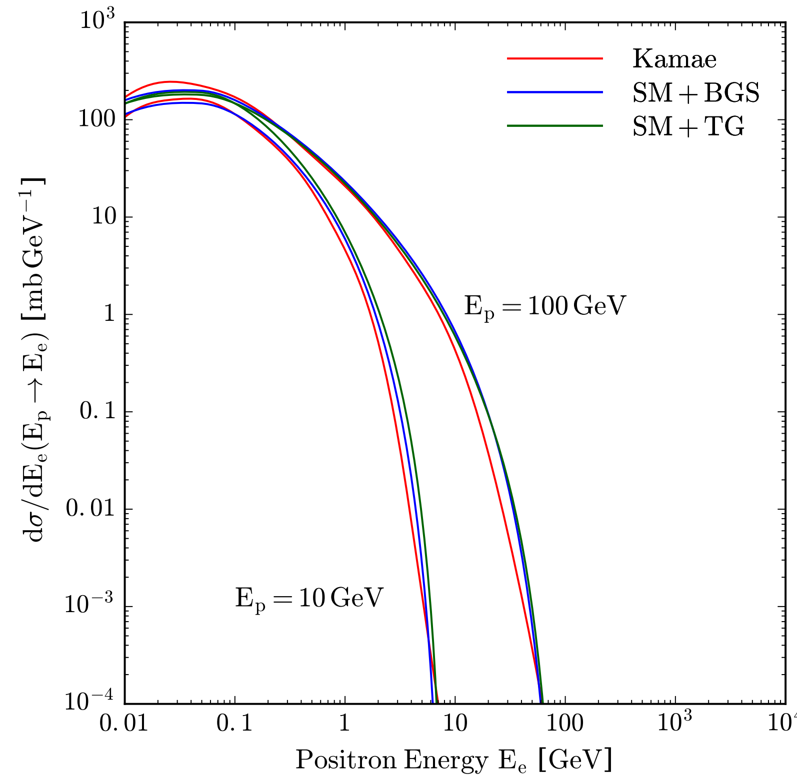

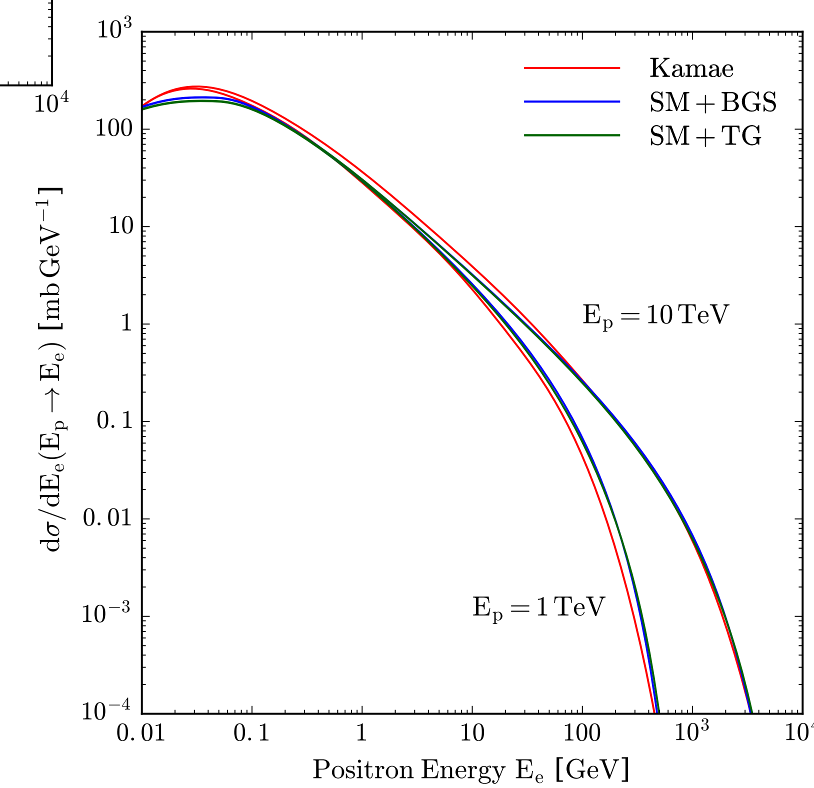

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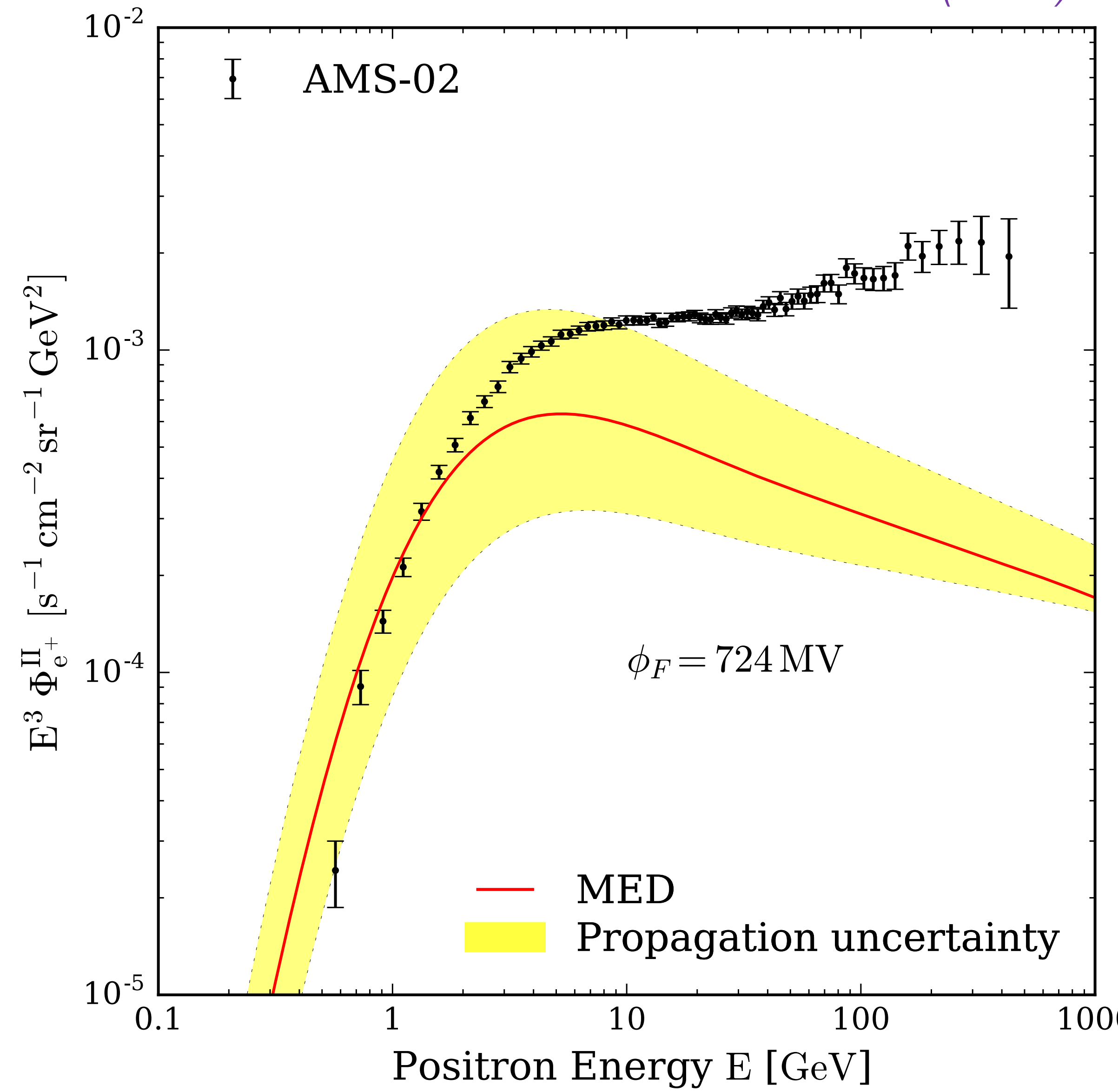
MB+(2014)



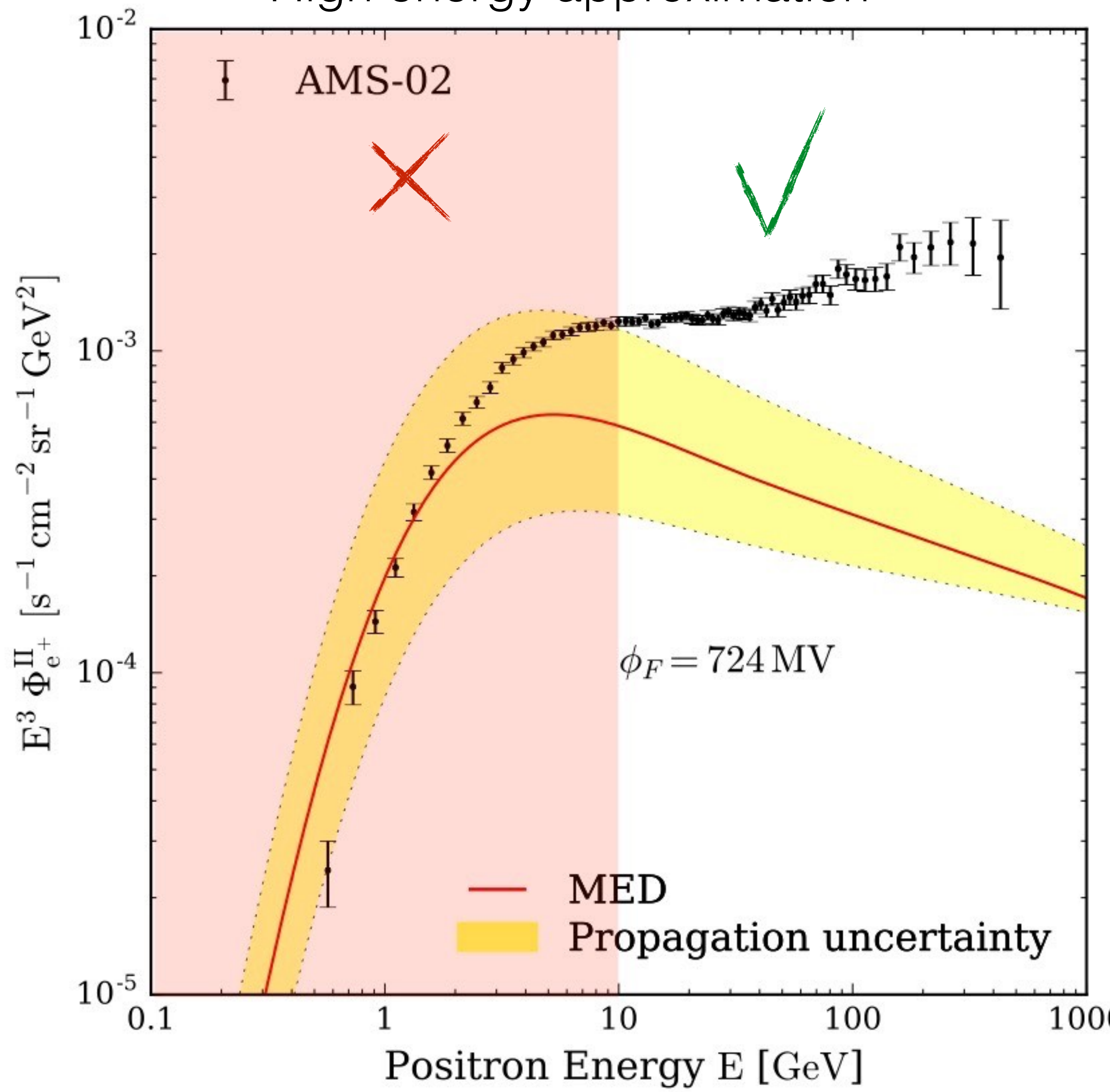
Positron excess above ~ 10 GeV!

Astrophysical secondary positrons

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

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

High energy approximation



Astrophysical secondary positrons

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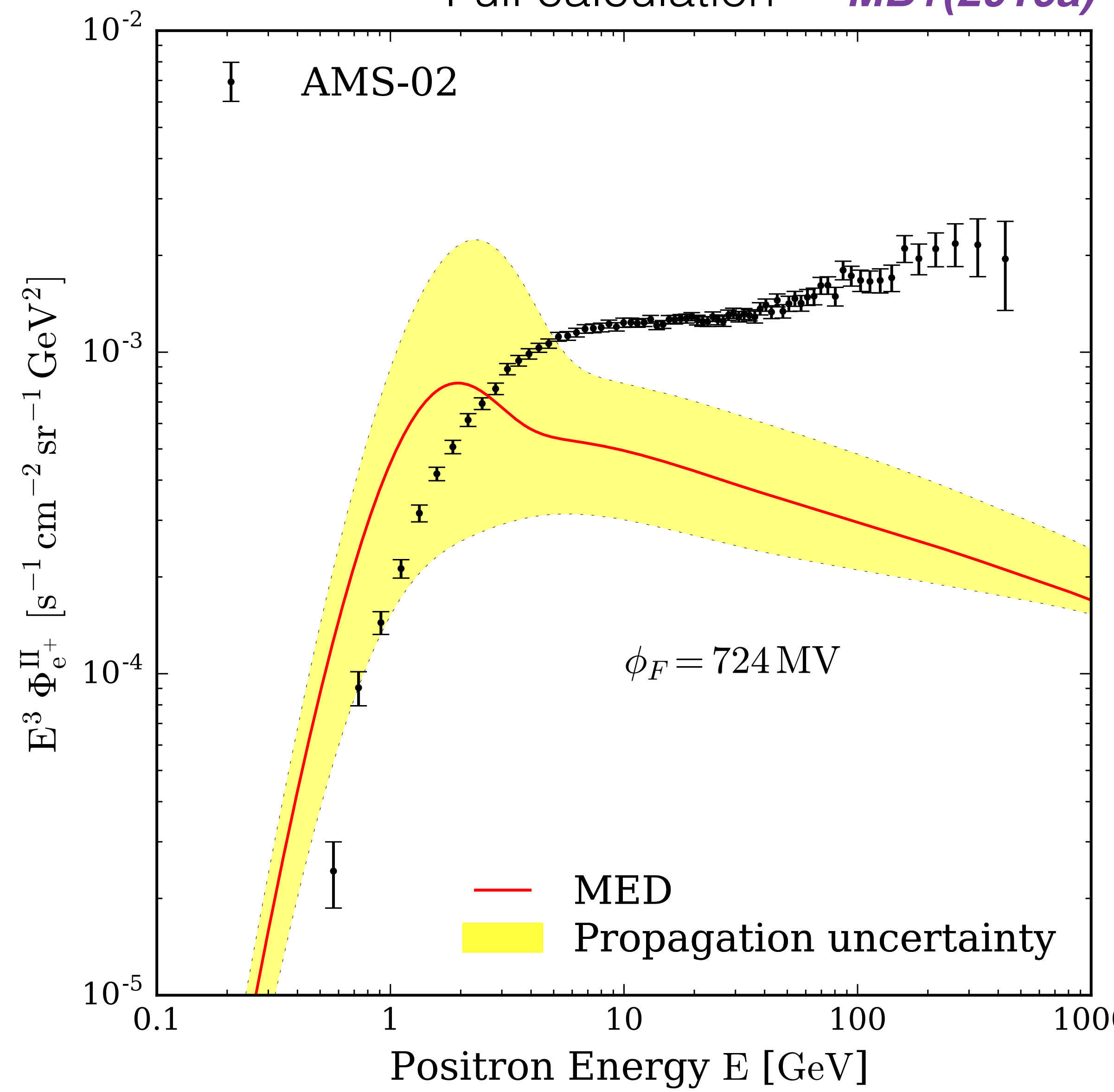
Full calculation **MB+(2016a)**



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

Astrophysical secondary positrons

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

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

The degeneracy between K_0 and L can be lifted!

Lavalle+(2014)

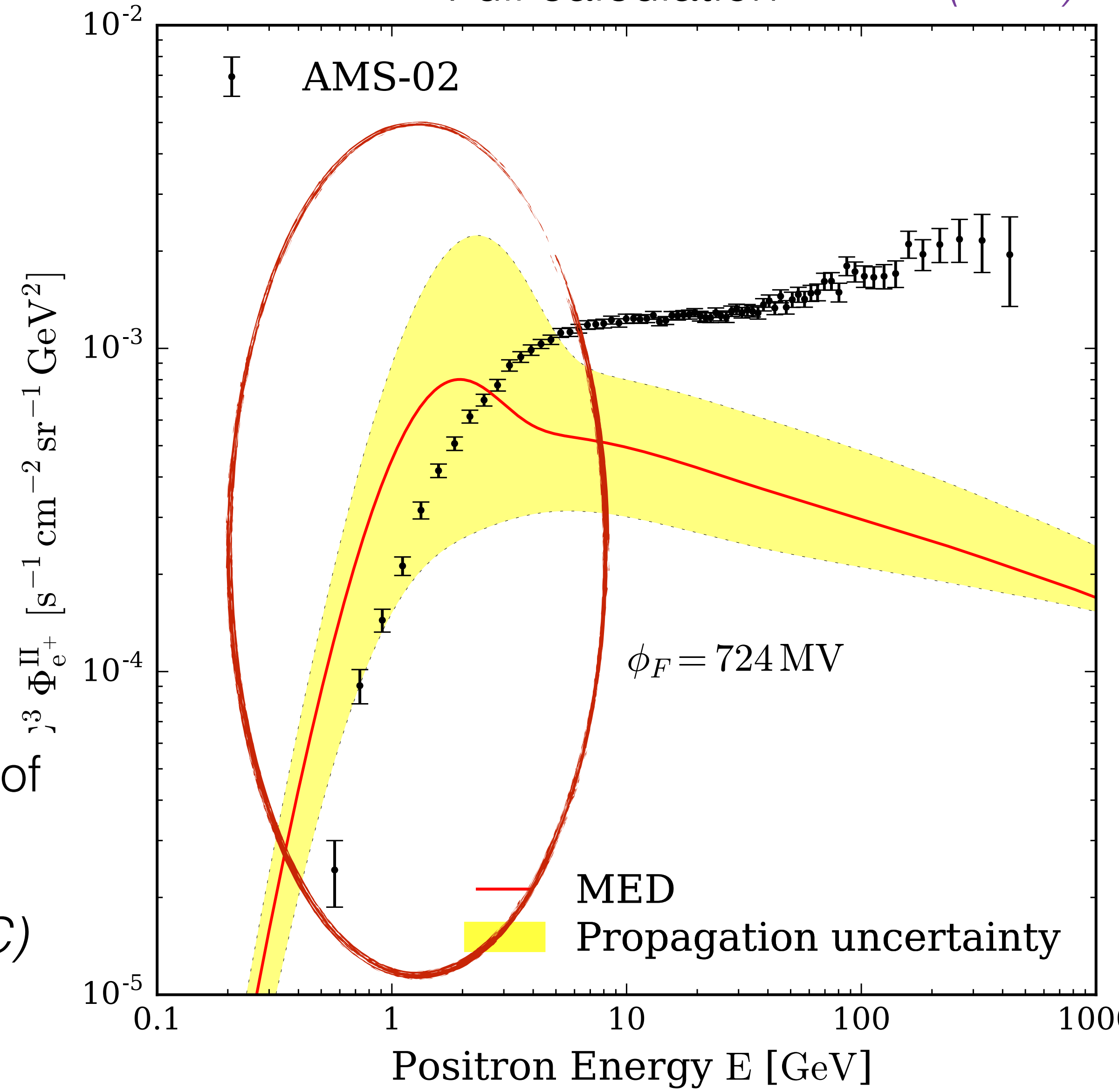
Case	δ	K_0 [kpc^2/Myr]	L [kpc]	V_C [km/s]	V_a [km/s]
MIN	0.85	0.0016	1	13.5	22.4
MED	0.70	0.0112	4	12	52.9
MAX	0.46	0.0765	15	5	117.6

Ruled out!

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

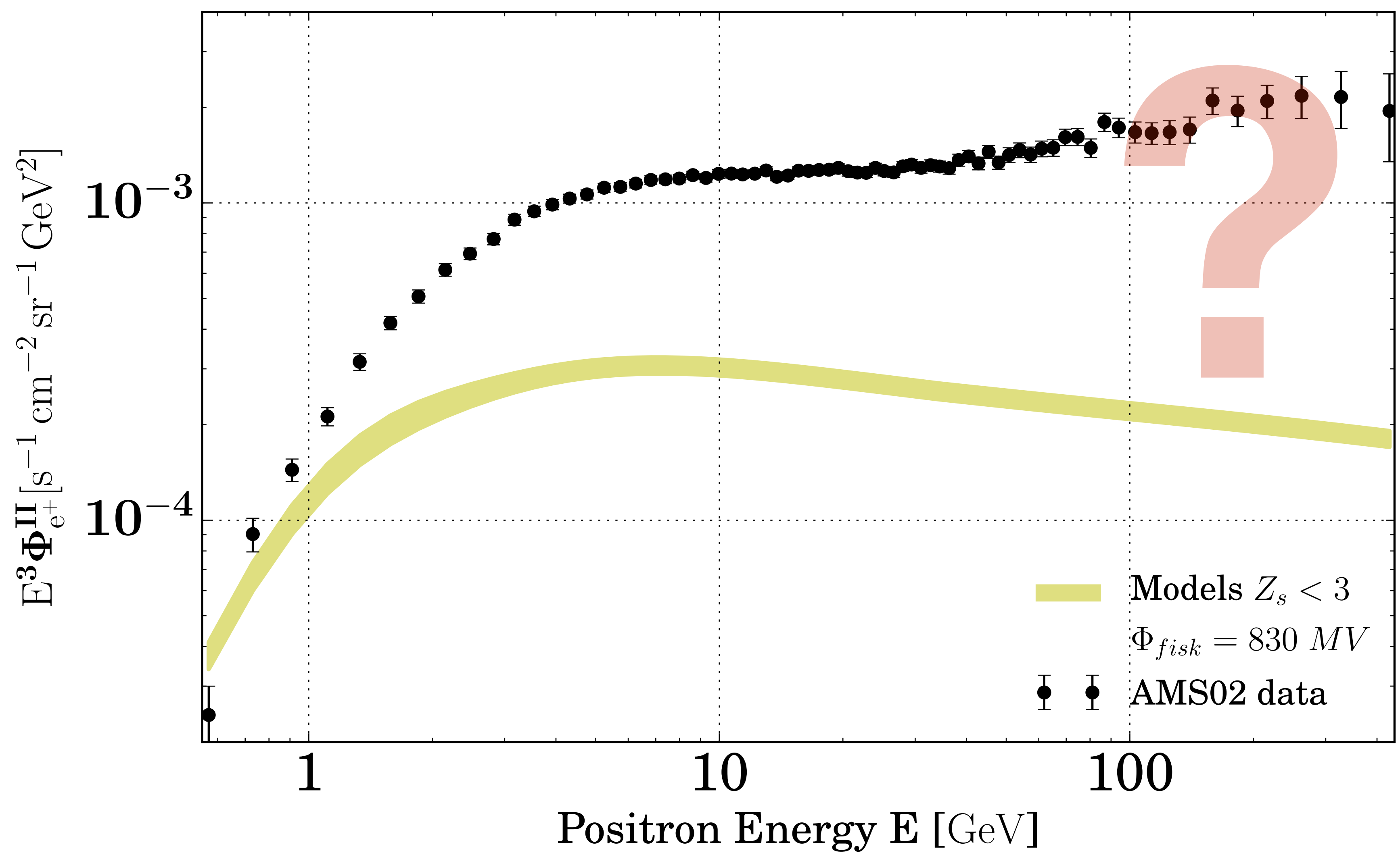
(result confirmed by AMS-02 antiprotons and recent B/C)

Full calculation *MB+(2016)*



The Dark Matter scenario

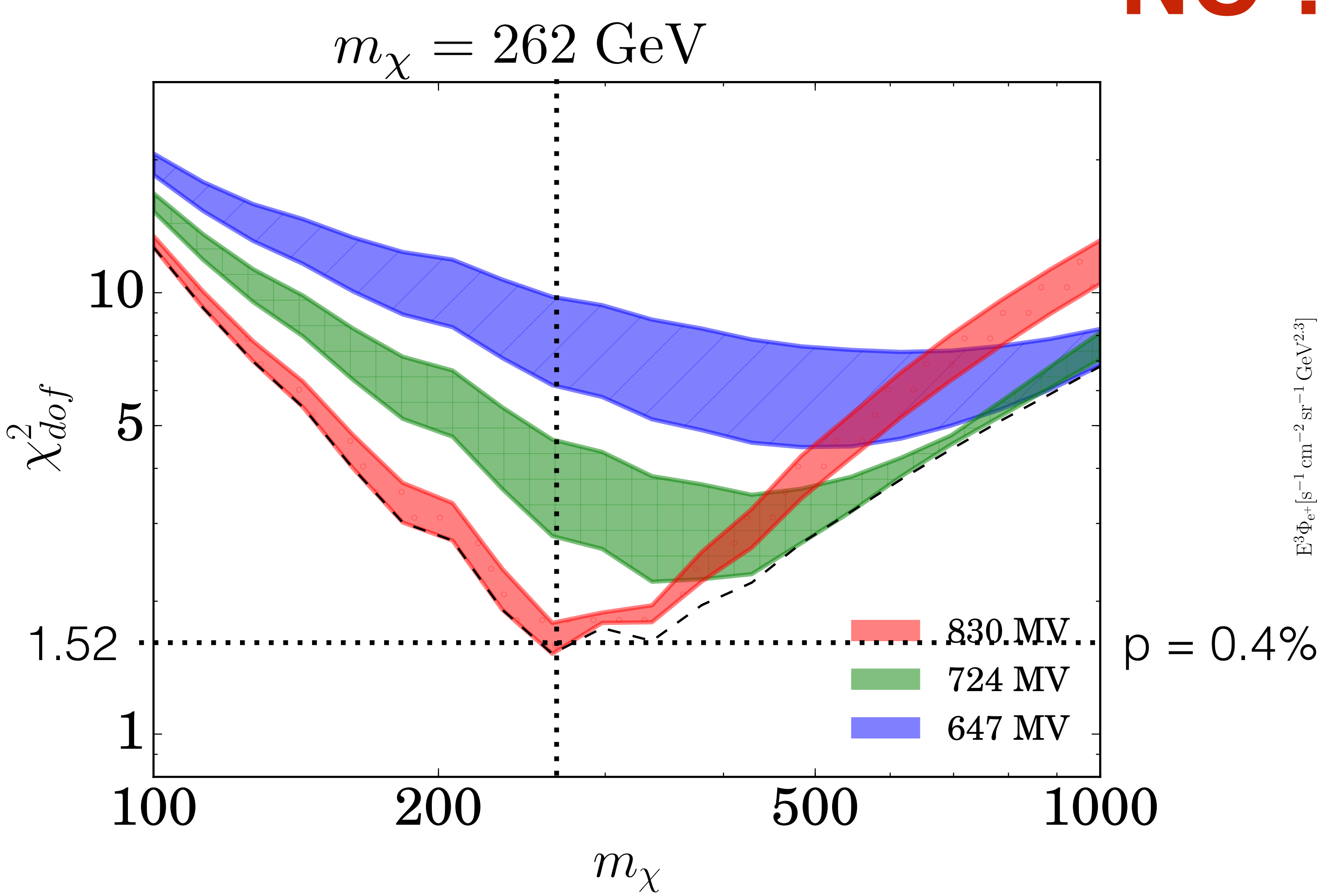
Is it possible to obtain a satisfactory fit to the AMS-02 data?



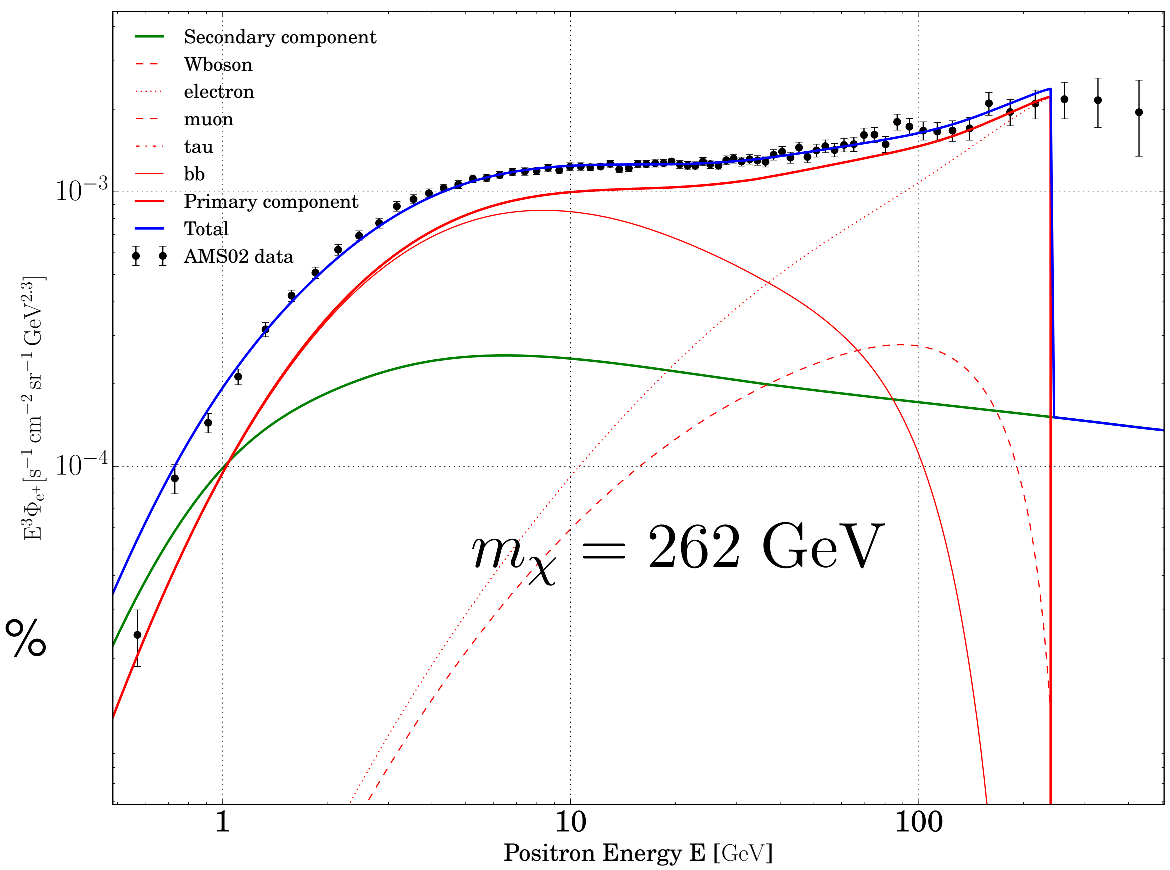
The Dark Matter scenario

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

NO !



MB+(2016a)



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

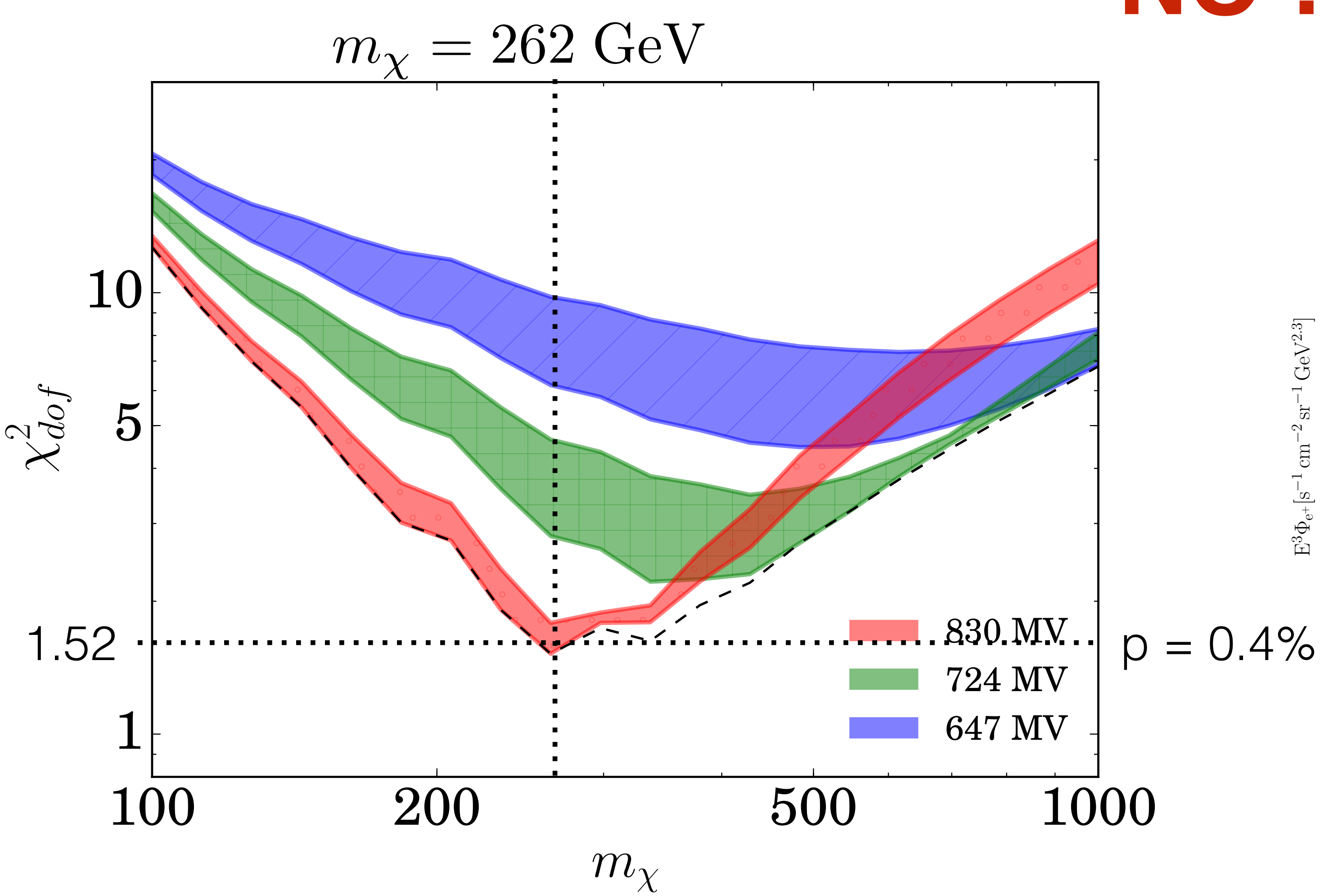
The positron flux produced by DM is restricted « around » the DM mass.

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

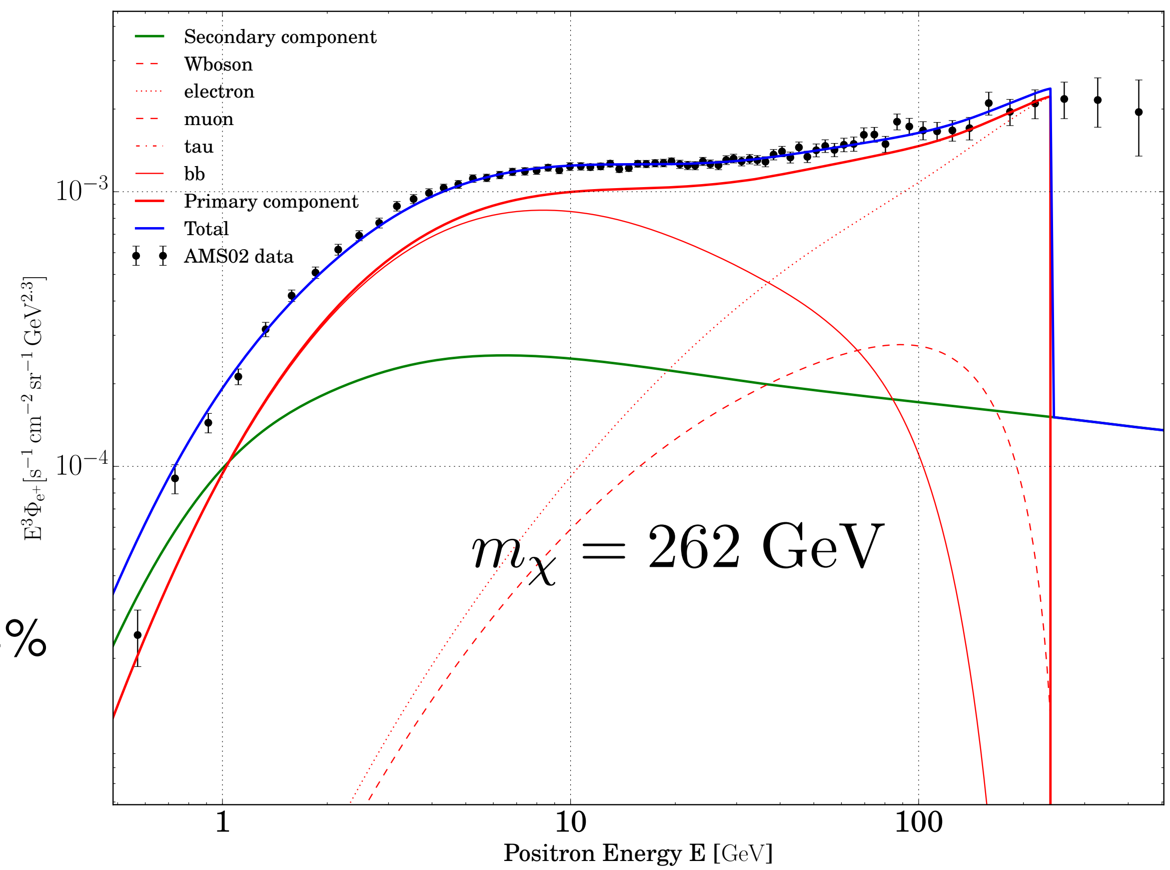
The Dark Matter scenario

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

NO !



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.

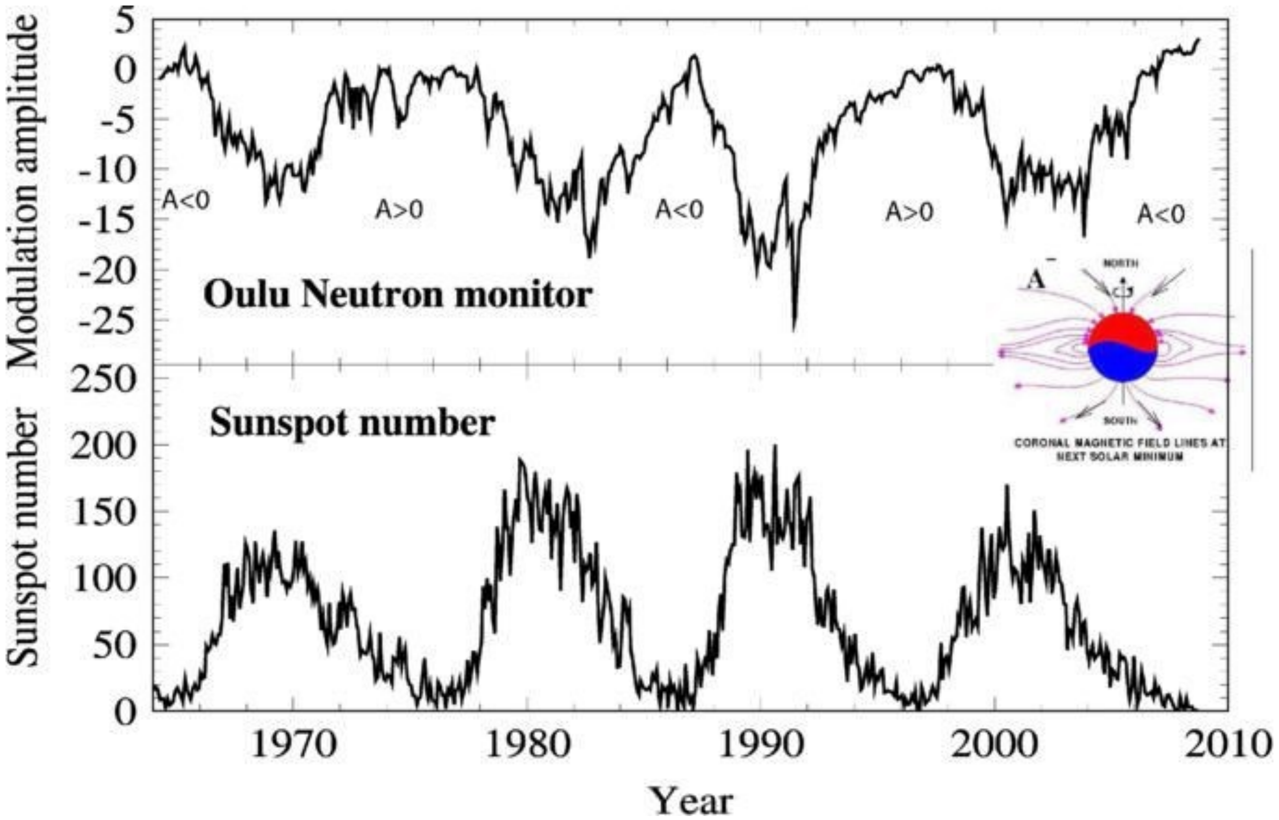
The poor quality of the fit disfavours a pure DM explanation for the positron excess!

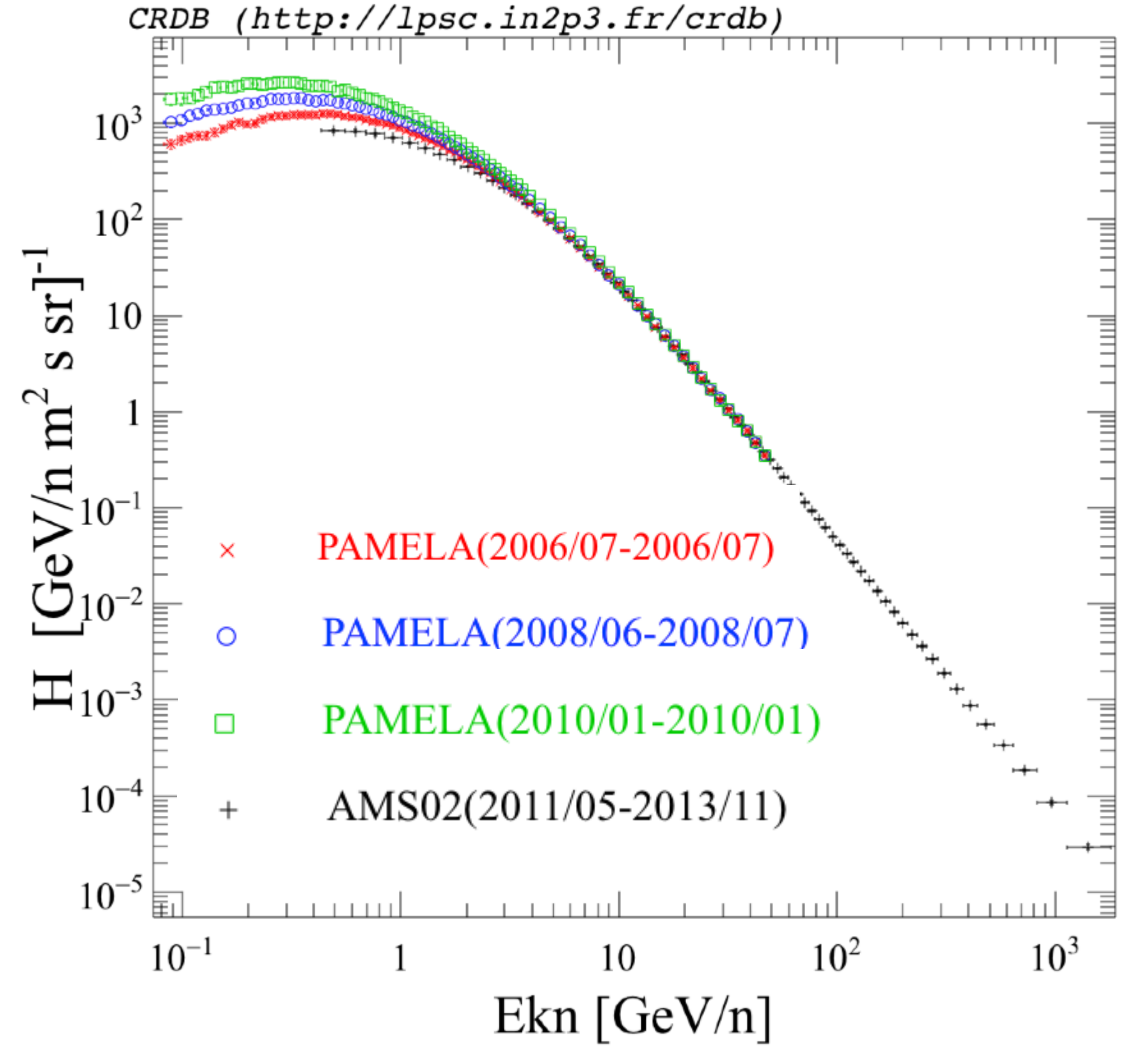
This conclusion is based only on the positron data and does not require constraints from other channels (gamma rays, antiprotons, CMB, etc.)

Solar effect on cosmic rays (solar modulation)

CRs lose energy when enter the heliosphere (solar wind)

- spectra affected for energies ≲ 10 GeV
- time-dependent effect ⟹ « solar modulation »



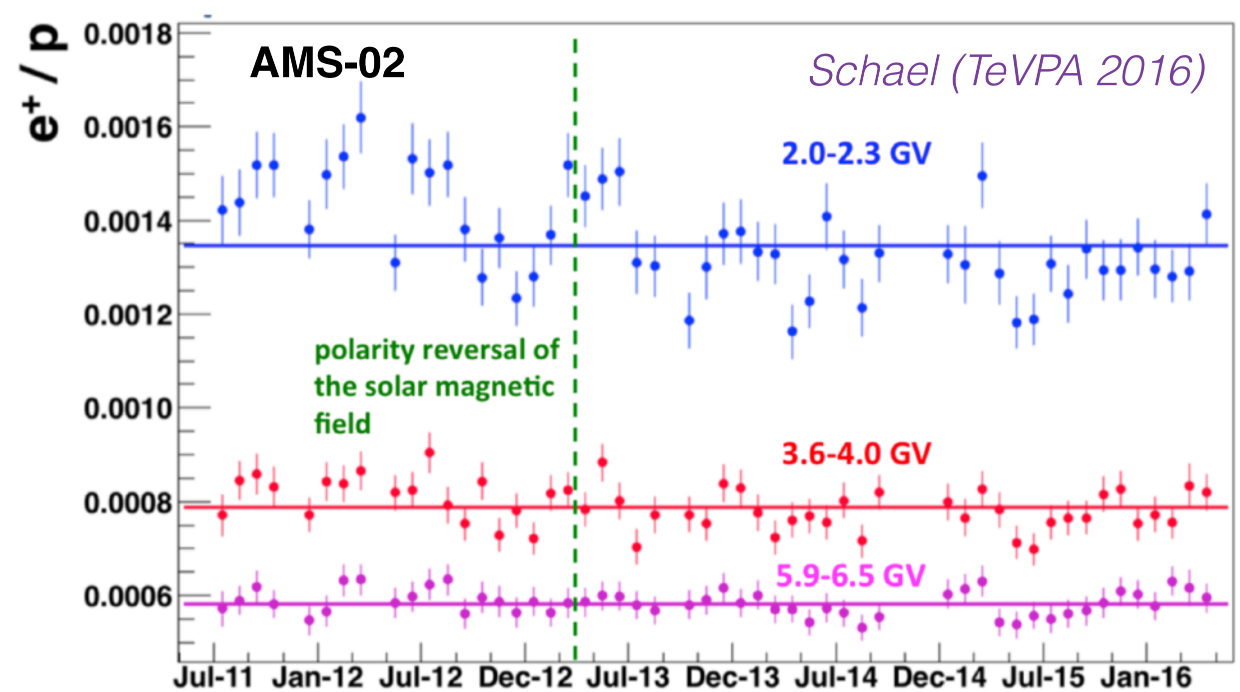


The forced-field approximation (FFA)

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

AMS-02 data (2011/05 to 2013/11): $650 \lesssim \phi_F \lesssim 830\,\mathrm{MV}$

Ghelfi+(2015)

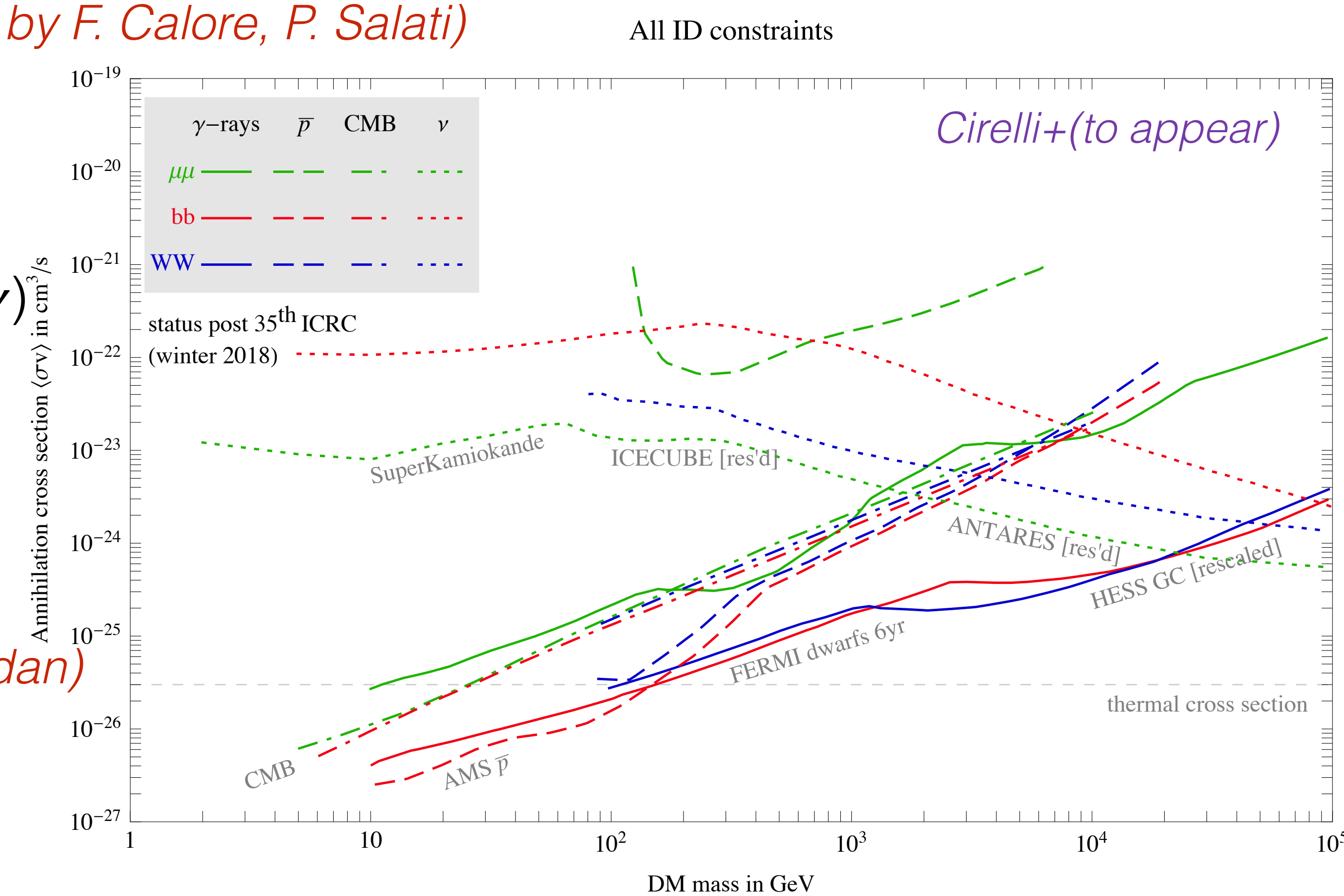


Flat positron-to-proton ratio ⟹ same effect of the solar wind on *p* and e^+

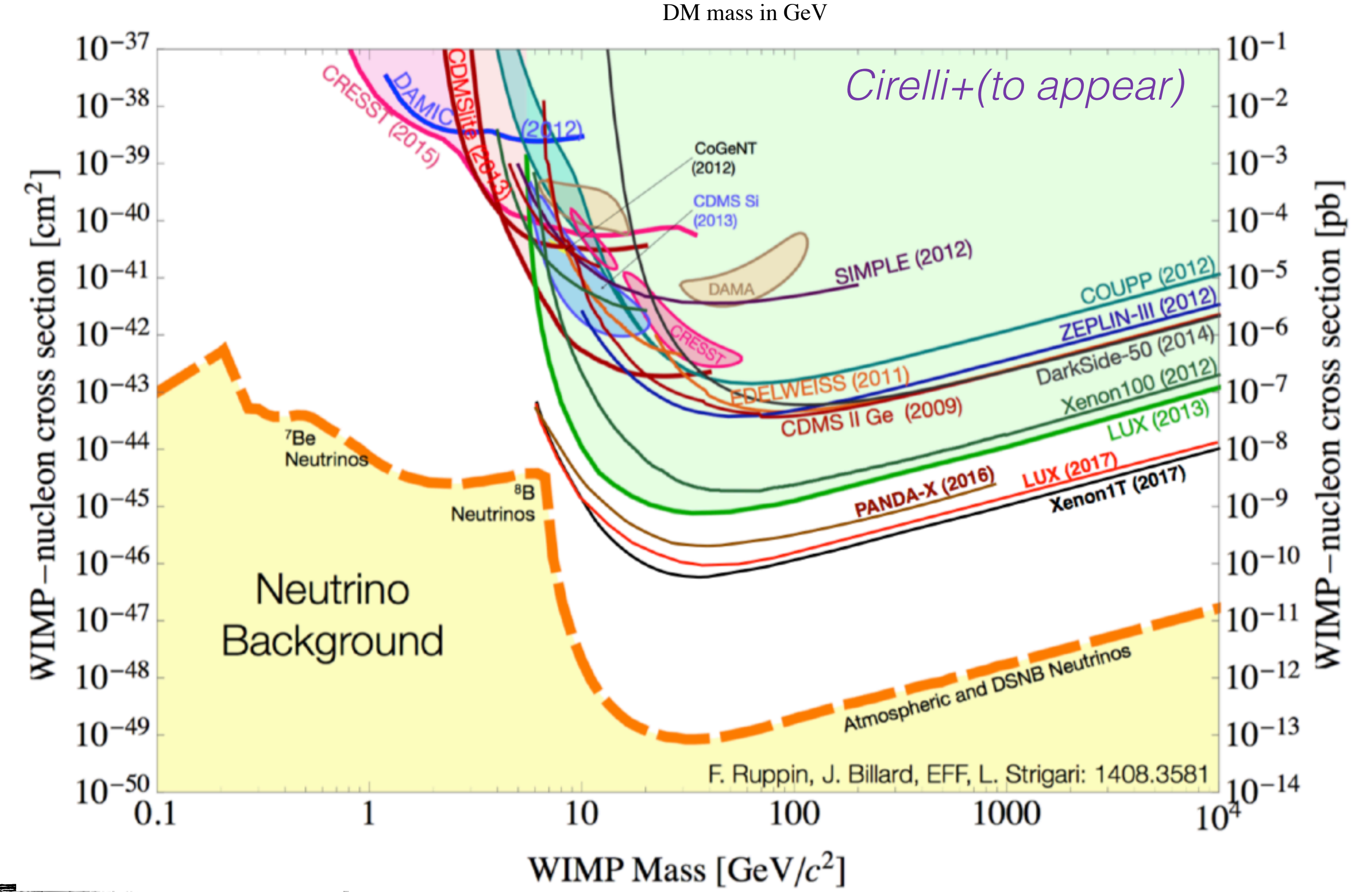
MeV dark matter particles: motivations

- **No conclusive detection** at the GeV scale *(see talks by F. Calore, P. Salati)*

- **Not many channels kinematically available** for annihilation (π (> 140 MeV), μ (> 105 MeV), e, ν, γ)
  $\Longrightarrow$ pass the constraints from γ and pbar



- **Difficult to detect in direct detection experiments** *(see talk by T. Morrodan)*
  - too light for nuclear target detectors
  - large uncertainties from the Galaxy escape velocity



- **Suppression of small scale structures** with masses below ~10^4 to 10^7 $M_\odot$ *(e.g: Boehm+(2014))*
  $\Longrightarrow$ might solve the missing satellites problem?

- **Annihilation into e+/e-**
  $\Longrightarrow$ 511 keV line toward the Galactic center?
  ($m_{DM} \lesssim 3$ MeV *Beacom & Yuksel (2006)*)

Velocity dependent annihilation (p-wave)

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

$f(\vec{v}, \vec{x}) \equiv \frac{d^6 N}{d^3x \, d^3v} = f(|\vec{v}|, r)$: phase space distribution function

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

(see talk by T. Lacroix)

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

Eddington inversion (spherical symmetry) *Eddington (1916), Binney and Tremaine (1987)*

Observationally constrained Galactic mass model $\rho_{DM}(r)$

McMillan (2016)

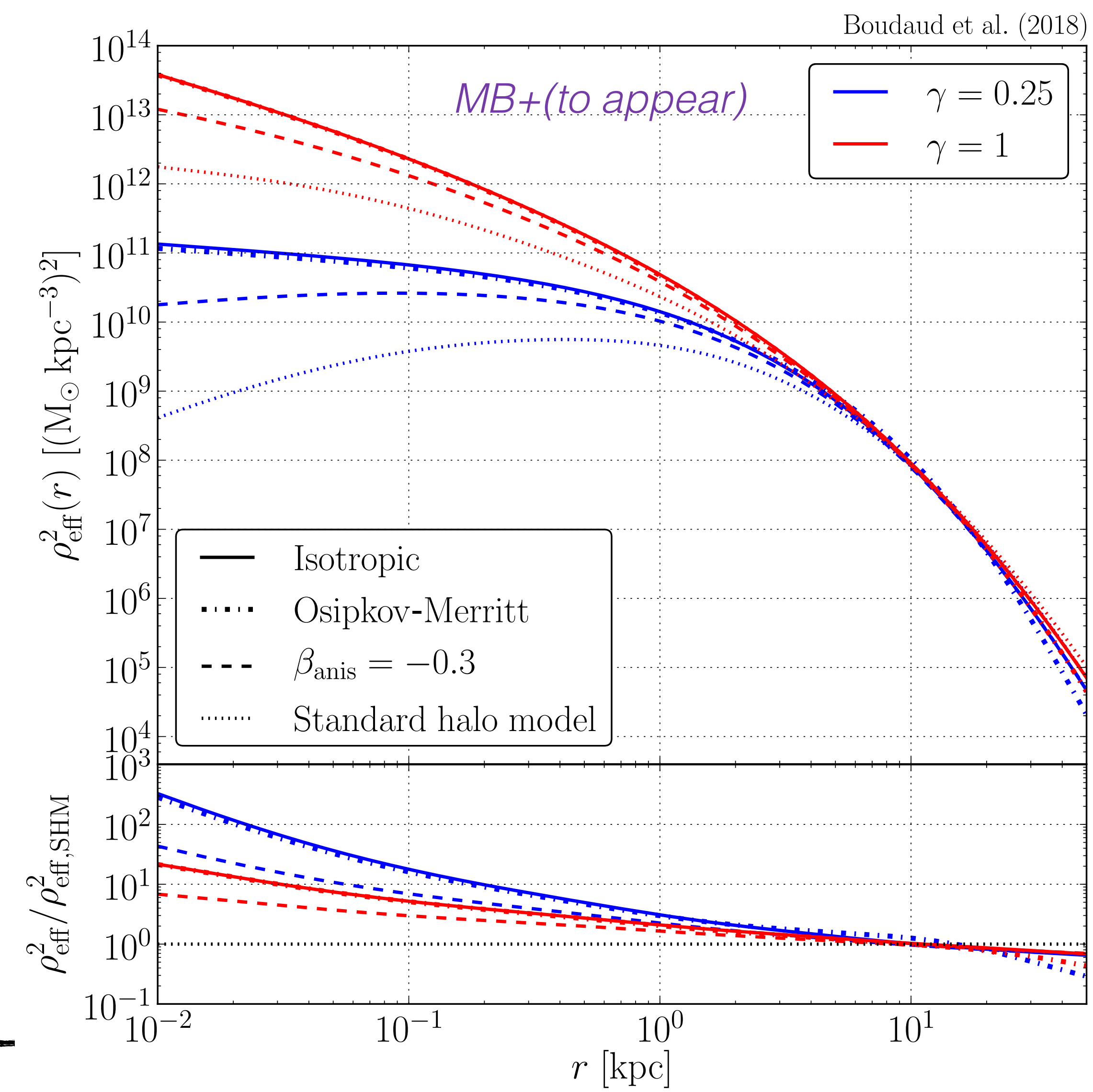
$$\Delta \Phi(r) = 4\pi \, G \, \rho_{\rm tot}(r)$$

Eddington inversion *Lacroix, Stref & Lavalle(2018)*

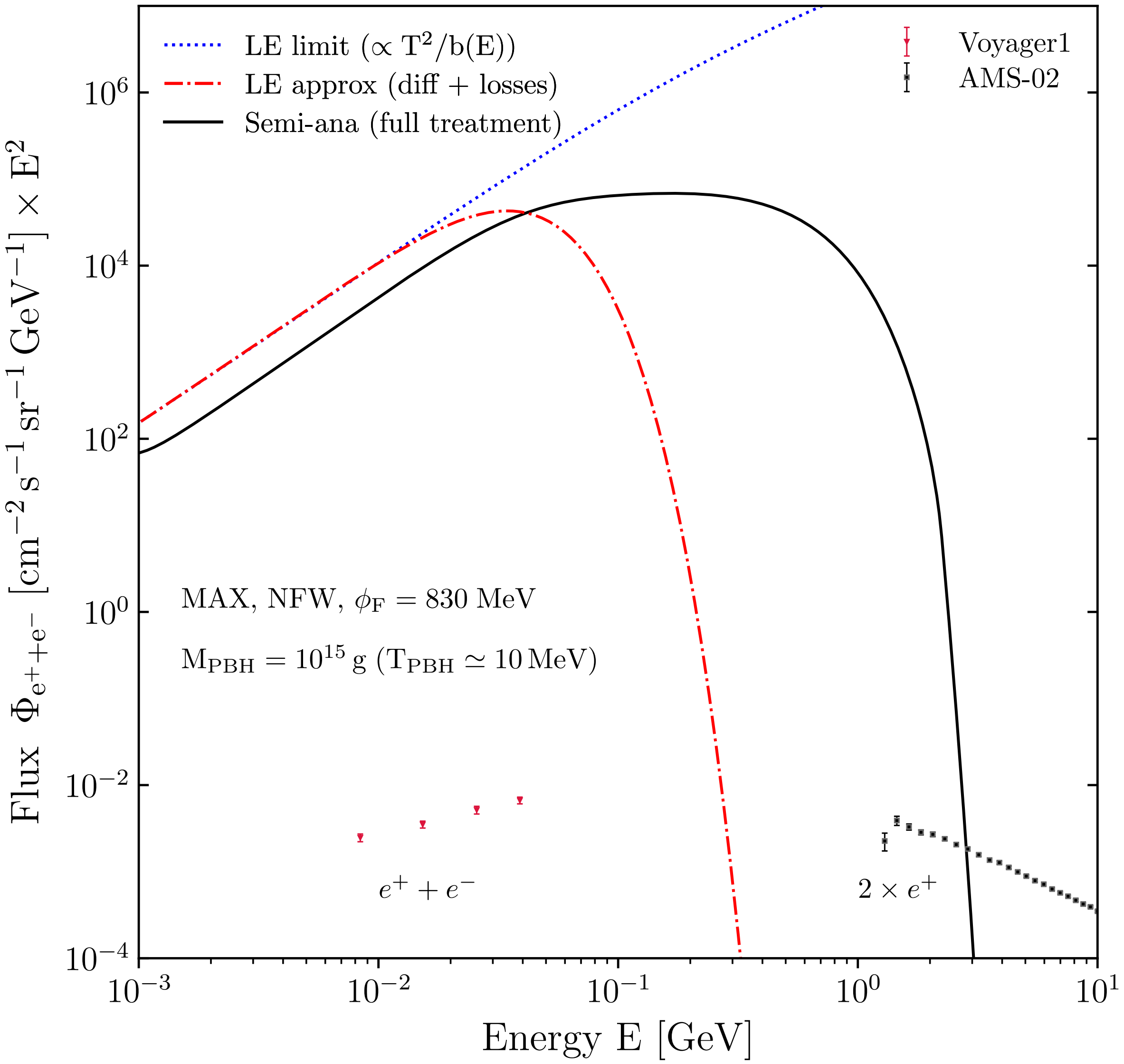
$$f(|\vec{v}|, r) \longrightarrow \langle \sigma v \rangle (r)$$

$$Q_{\rm DM}^{e^\pm}(E, r) = \rho_{\rm DM}^2(r) \langle \sigma v \rangle (r) \frac{\eta}{m_{\rm DM}^2} \sum_i B_i \frac{dN_i}{dE}$$

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



Electrons ans positrons spectrum from PBHs radiation



- **Model A**: MAX from *Maurin+(2001)* (HEAO3 B/C)

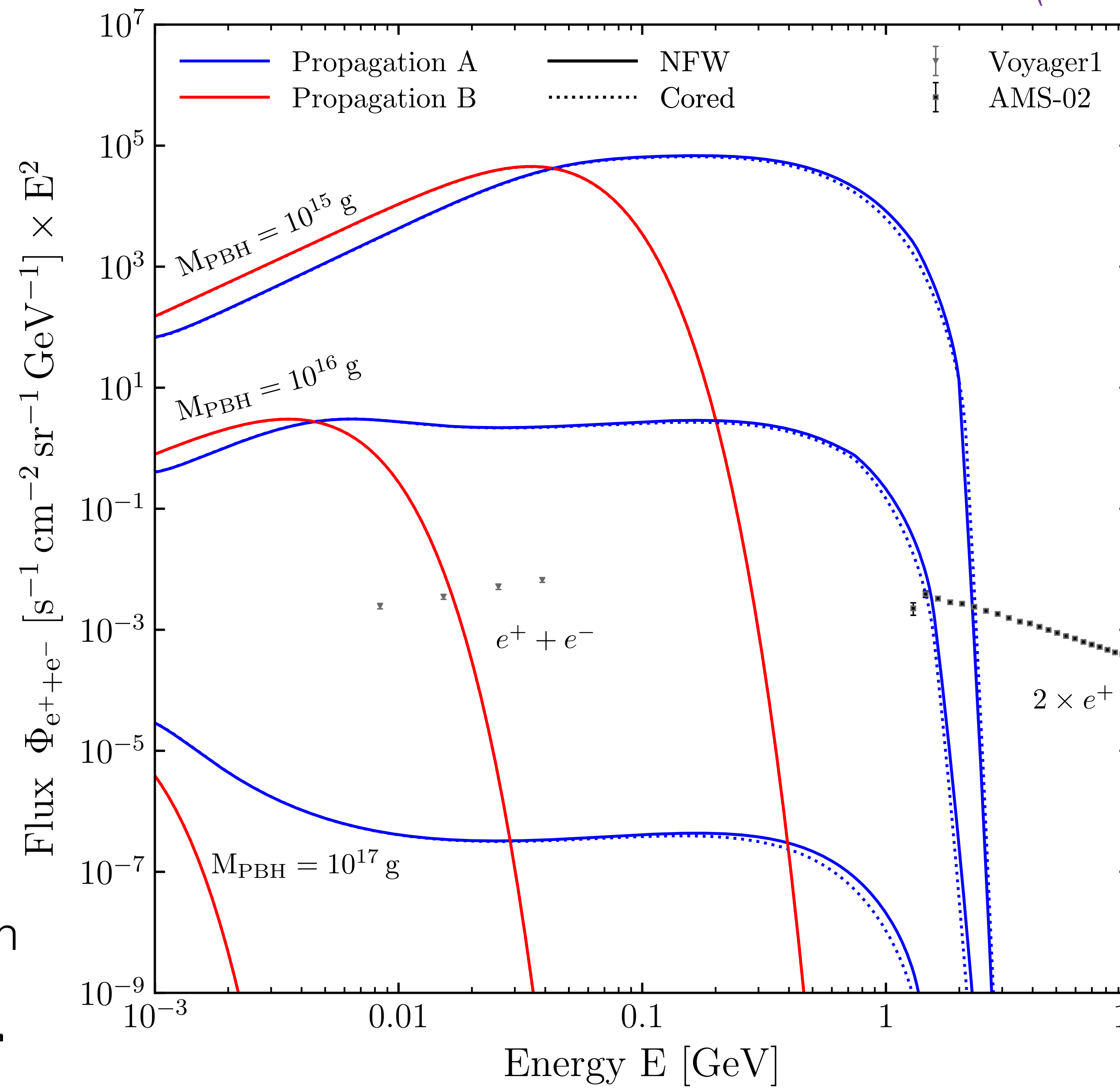
$$V_A = 117.6\,\mathrm{km/s}$$

- **Model B**: best fit from *Reinert&Winkler(2018)* (AMS-02 B/C)

$$V_A = 0\,\mathrm{km/s}$$

DM distribution from *McMillan(2016)* (NFW/cored)

MB & Cirelli(2018)



- Voyager probes PBHs with $M < 10^{17}\,M_\odot$
- AMS-02 probes PBHs with $M < 10^{16}\,M_\odot$ if strong diffusive reacceleration
- Voyager is sensitive to **local** PBHs (a few kpc)

  The signal is not sensitive to the DM distribution in the Galaxy.

Constraints on the fraction of DM in PBHs for a lognormal mass function

Inflation models predict a mass distribution for PBHs, often similar to a lognormal distribution

$$f(M) = \frac{1}{\sqrt{2\pi}\sigma M}\exp\left(-\frac{\log^2(M/M_c)}{2\sigma^2}\right)$$