VOYAGER PROBING DARK MATTER

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Paris, France

Cargèse - Corsica
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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 (PRL 119, 021103)

MB and M. Cirelli (PRL 122, 041104)

MB, T. Lacroix, M. Stref and J. Lavalle (PRD 99, 061302)

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NewDark

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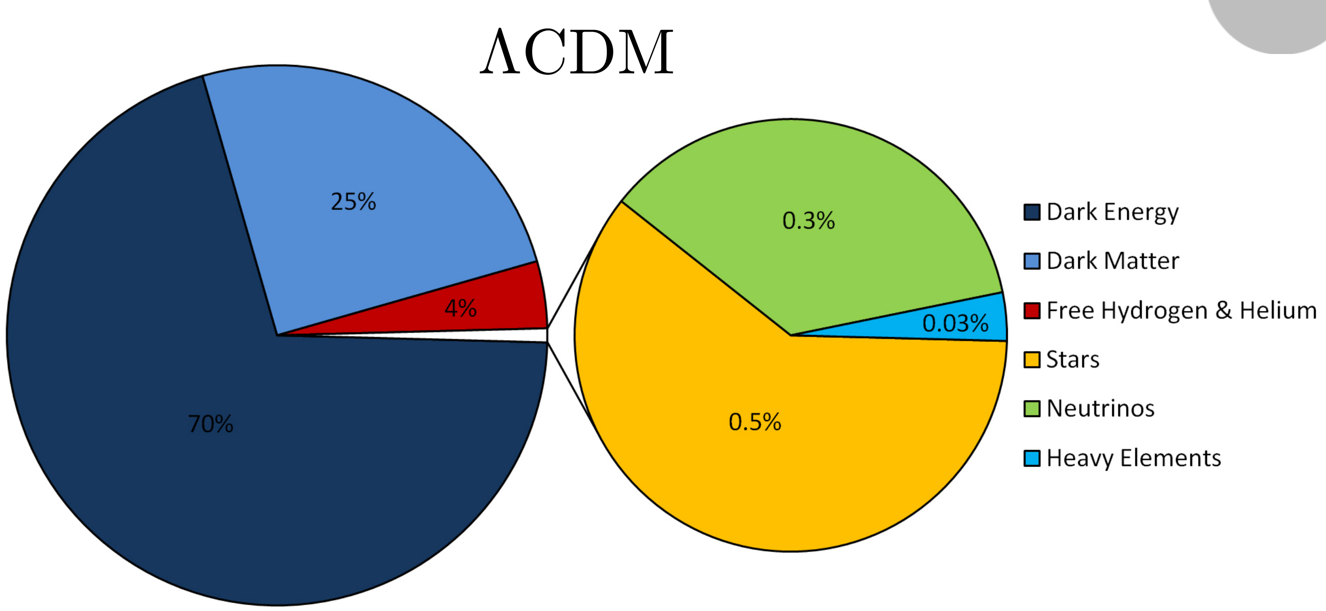
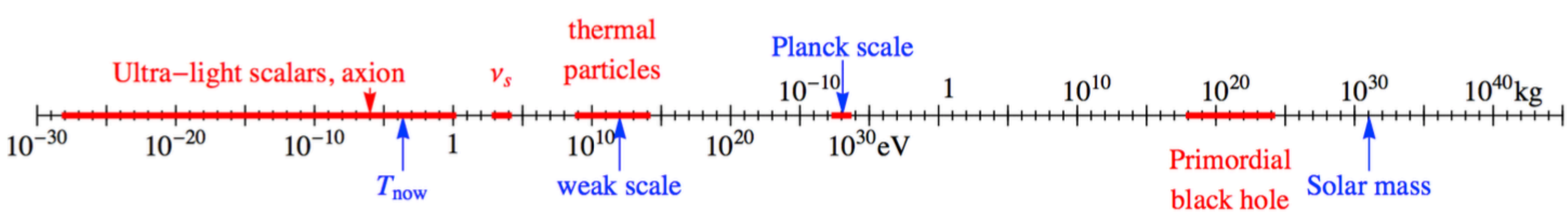
Dark matter: evidences and candidates

Evidences for Dark Matter at different scales:

- spiral galaxies
- galaxy clusters
- cosmology



Bertone & Tait (2018)



Dark matter: evidences and candidates

Evidences for Dark Matter at different scales:

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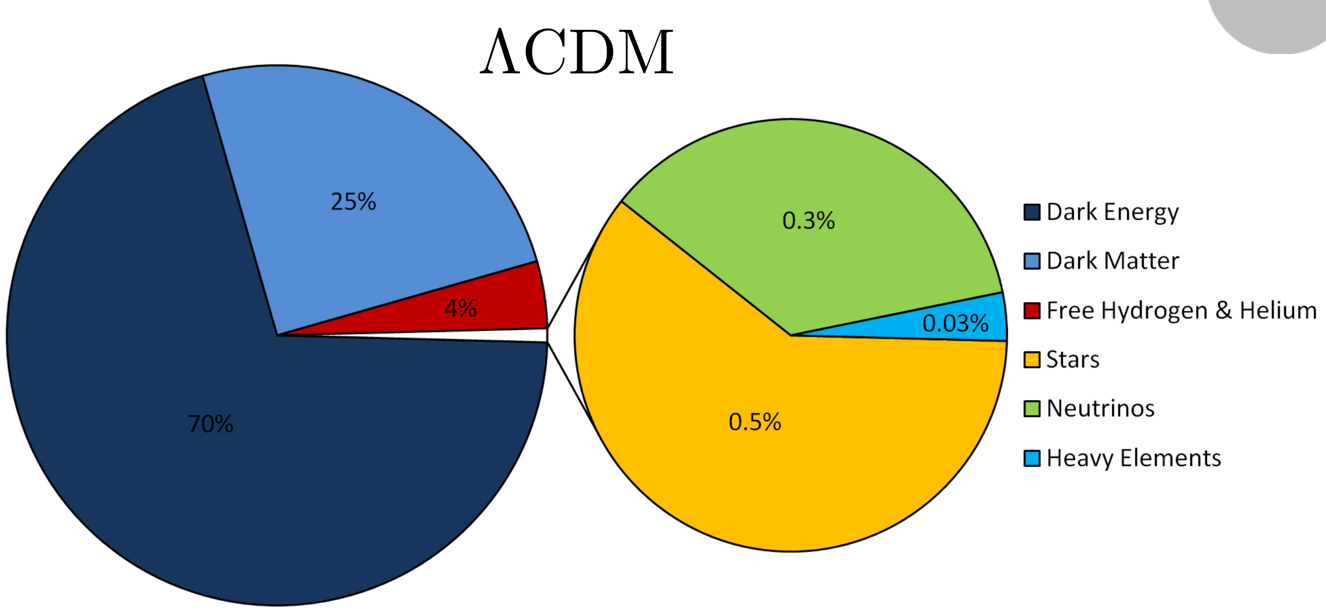
- cosmology



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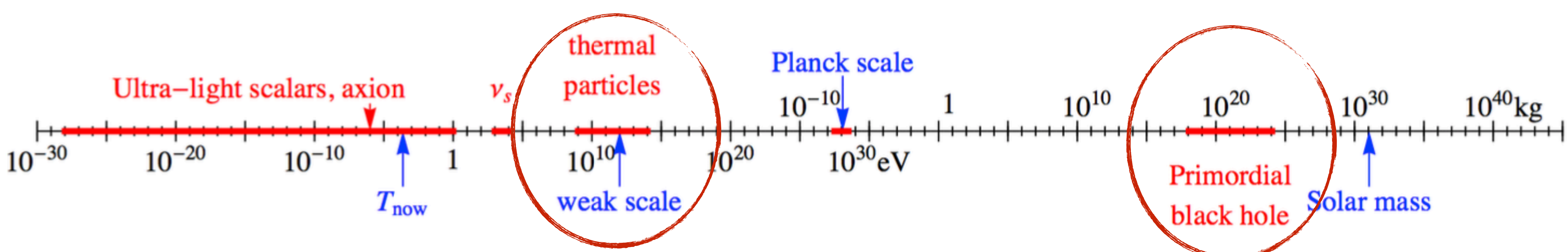
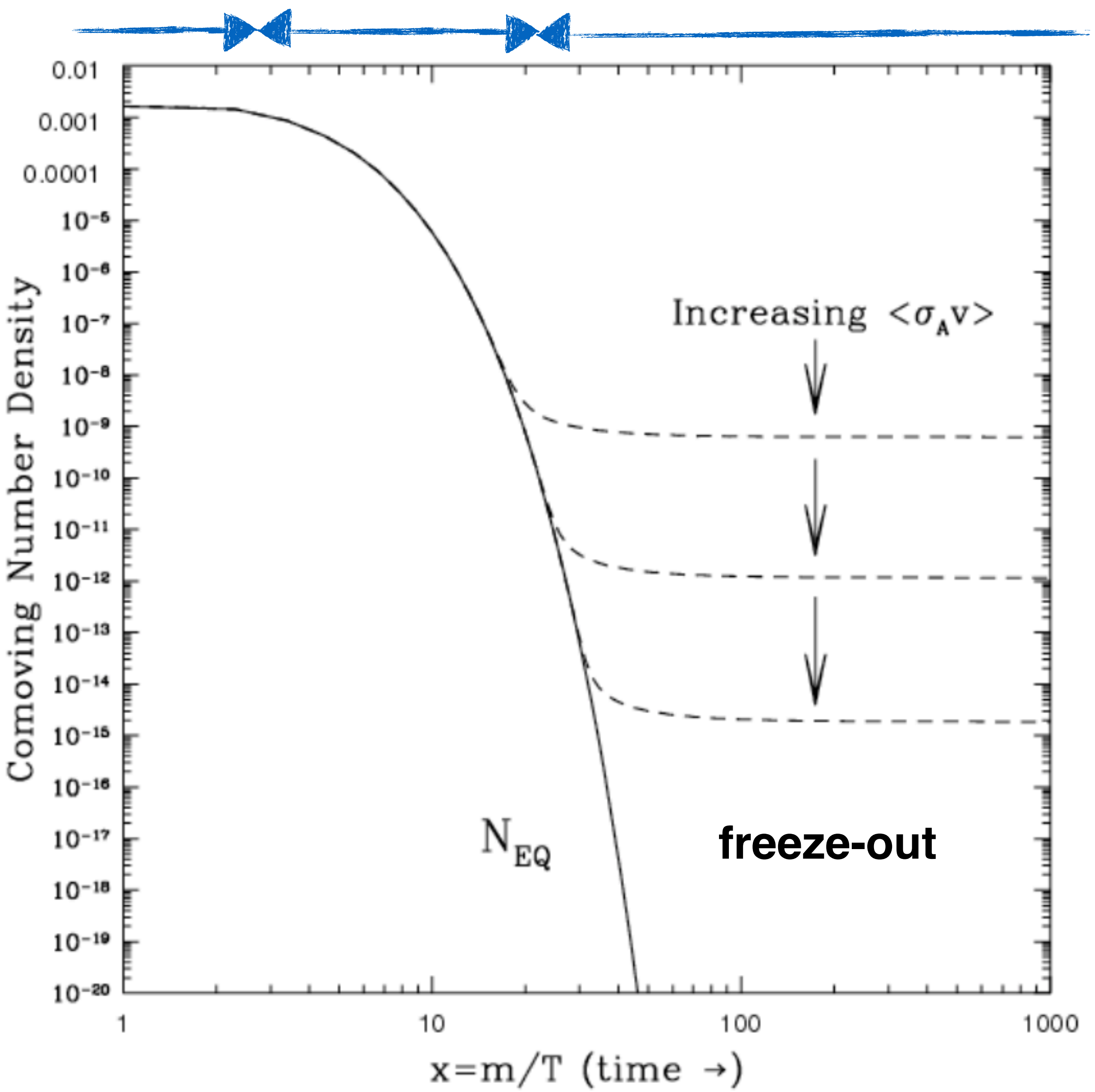


The WIMP paradigm (**W**eakly **I**nteractive **M**assive **P**articles)

If DM particles are thermally produced in the early Universe, they should be:

✓ Neutral ✓ Very long lived ✓ Cold ⟺ massive (≳ keV) ✓ Weakly interactive

$T > m_{\rm DM}$ $T < m_{\rm DM}$ $\Gamma_{\rm ann} < \Gamma_{\rm Hubble}$

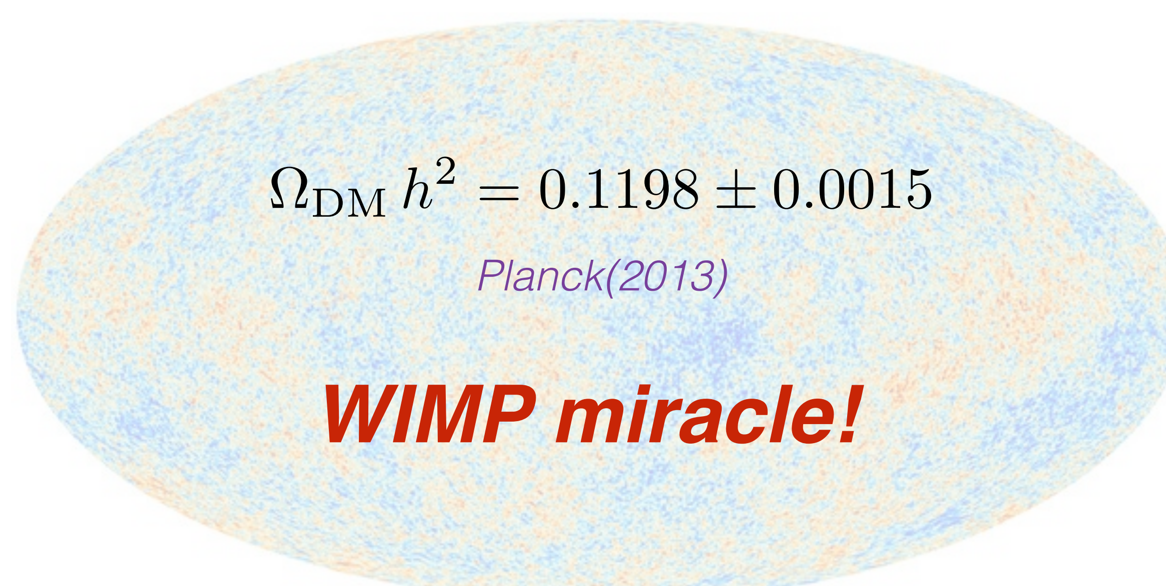


DM relic density

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

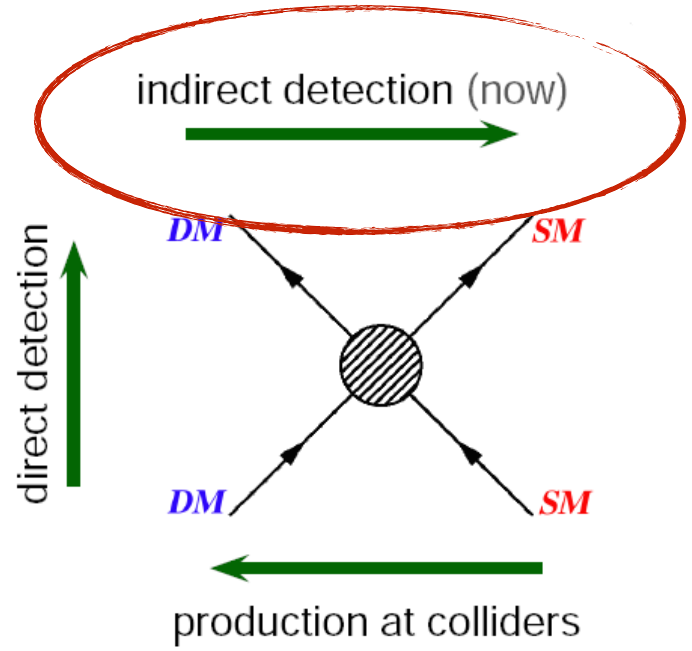
annihilating cross section

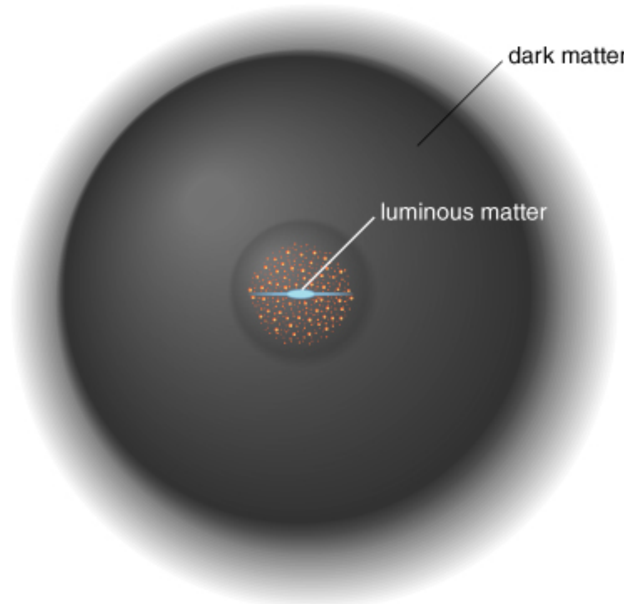
- ***weak***-scale mass (10 GeV - 1 TeV)
- ***weak***-scale interaction $\langle \sigma v \rangle \simeq 3 \times 10^{-26}\ {\rm cm^3\, s^{-1}}$

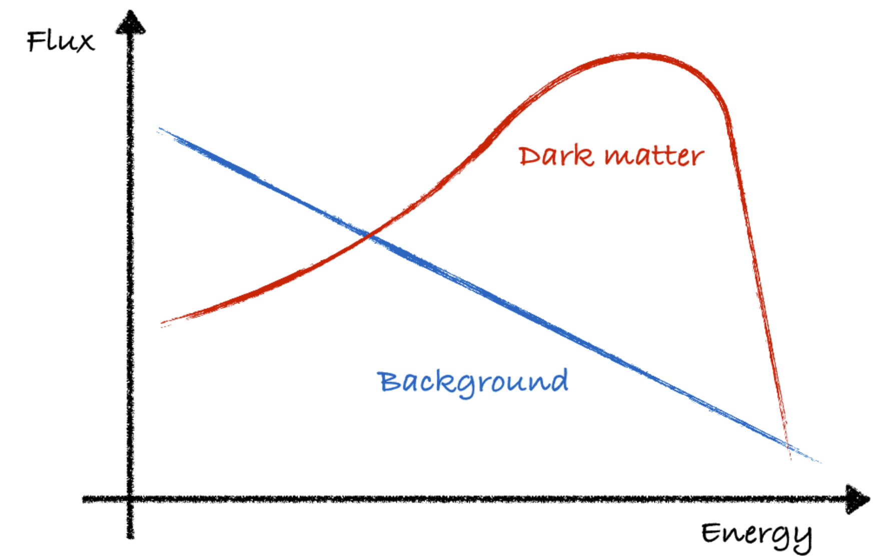


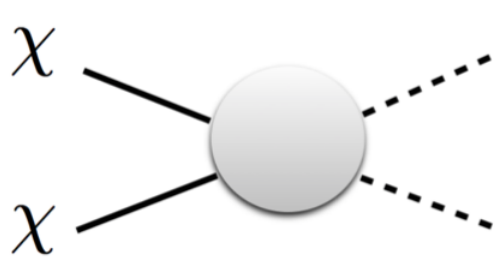
Dark matter indirect detection

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









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

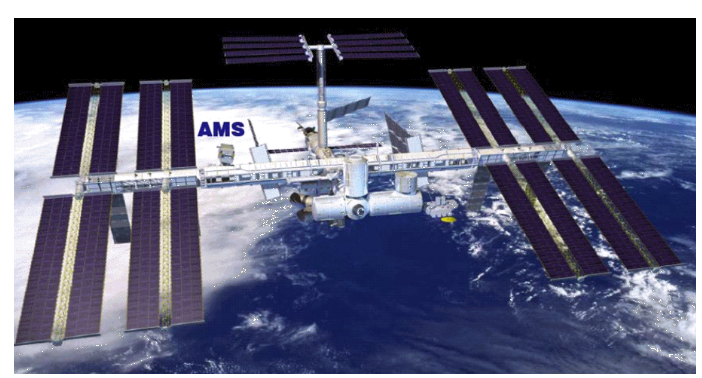
annihilation channel decay final products

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

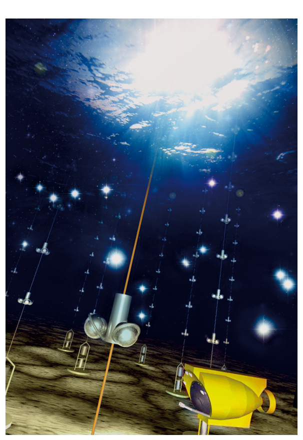
- **Gamma rays**
- **Charged cosmic rays**
- **Neutrinos**

Fermi-LAT

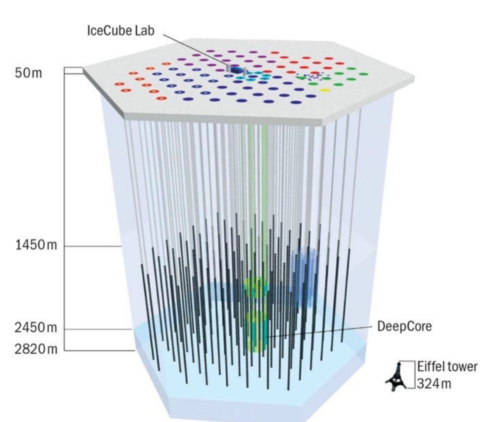
HESS



AMS-02



Antares



IceCube

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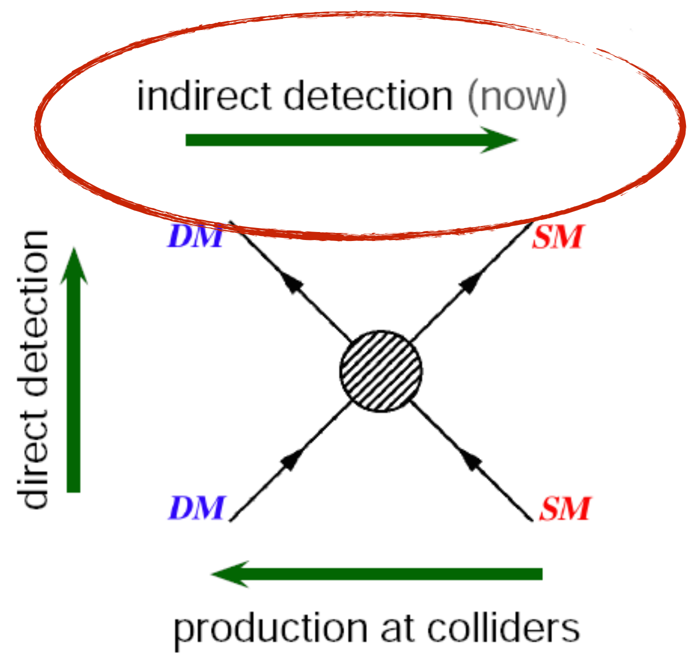
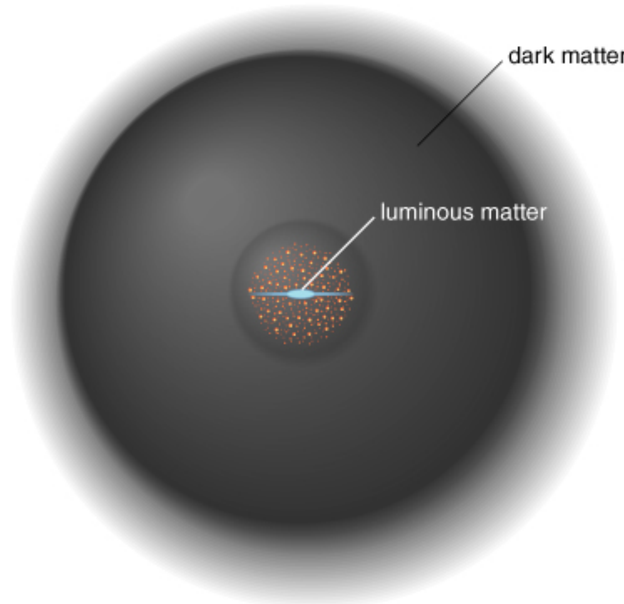
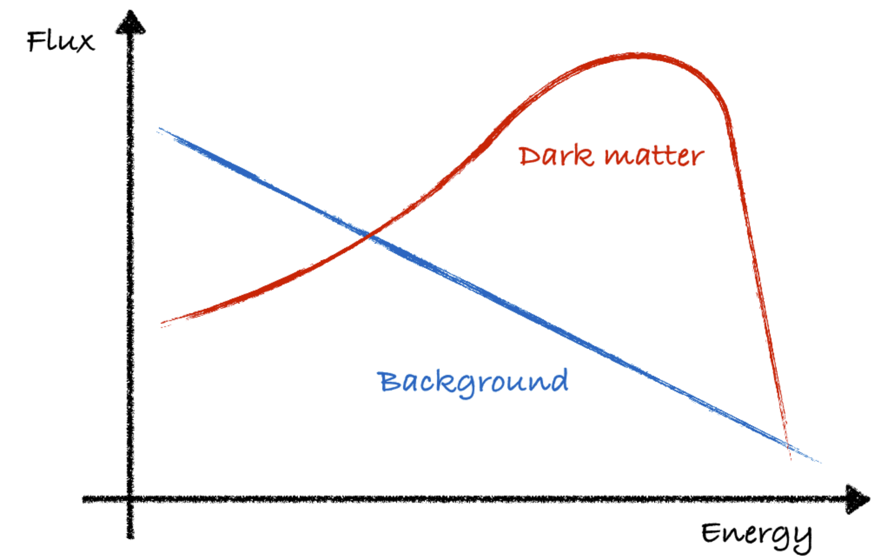
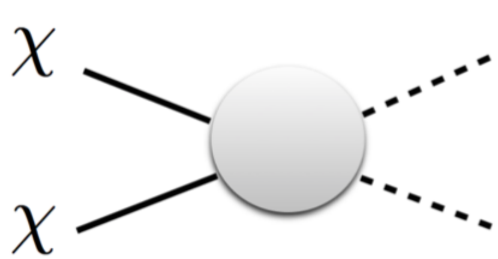








$W^-, Z, b, \tau^-, t, h, \ldots \longrightarrow e^\pm, \overset{(-)}{\nu}, \overset{(-)}{p}, \overset{(-)}{D}, \gamma, \ldots$

annihilation channel   decay   final products

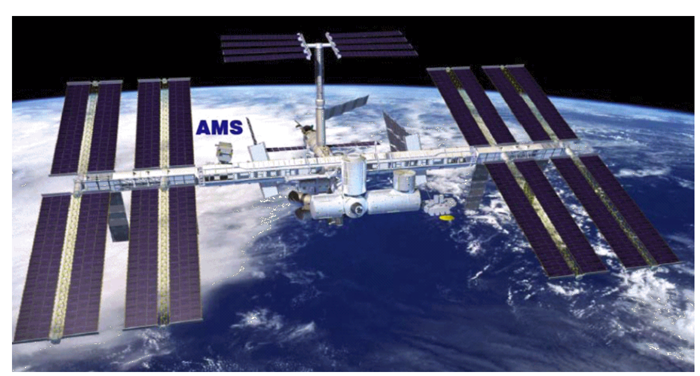
$W^+, Z, \bar{b}, \tau^+, \bar{t}, h, \ldots \longrightarrow e^\mp, \overset{(-)}{\nu}, \overset{(-)}{p}, \overset{(-)}{D}, \gamma, \ldots$

- Gamma rays

Fermi-LAT

HESS

- **Charged cosmic rays**

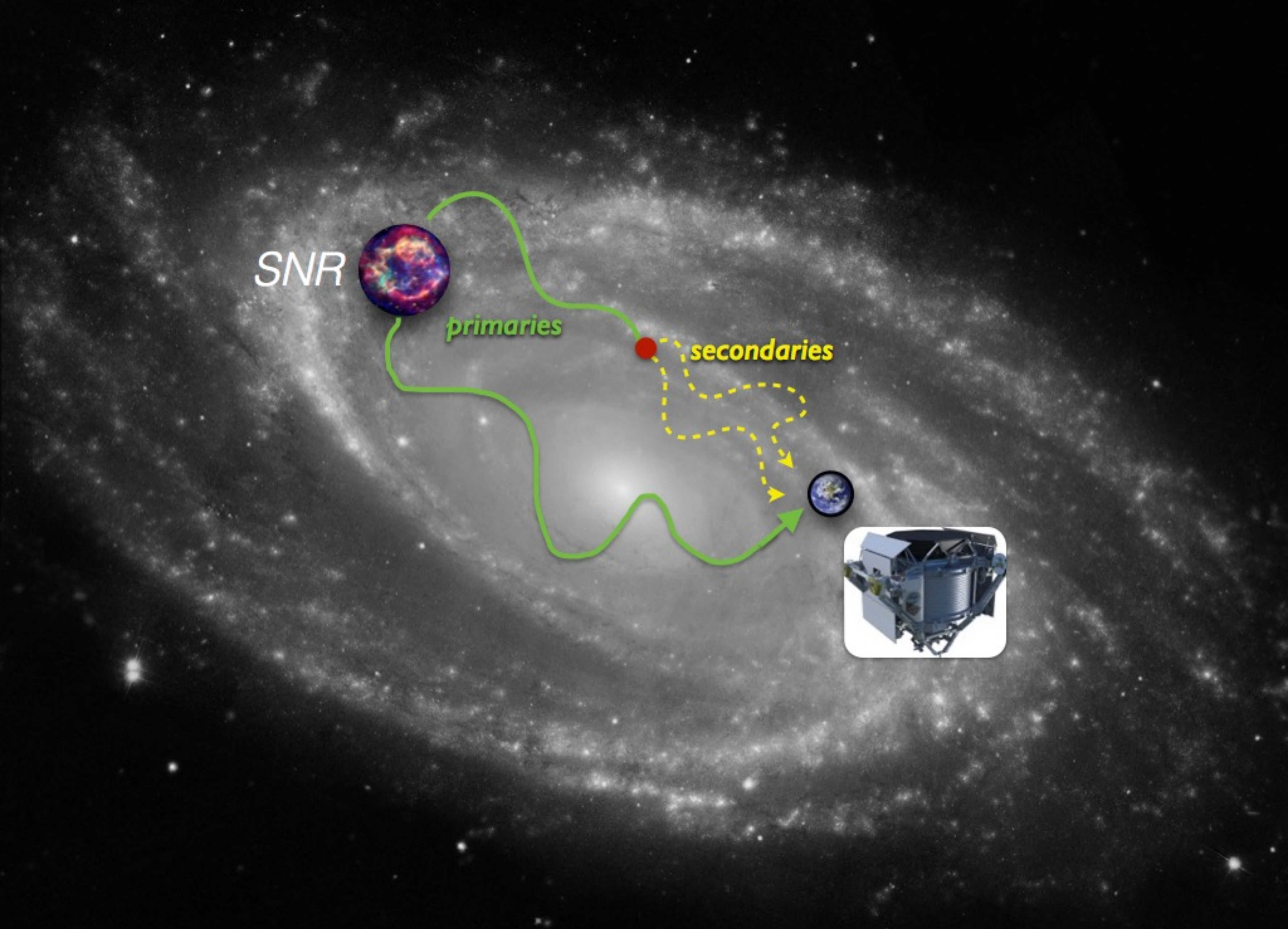


AMS-02

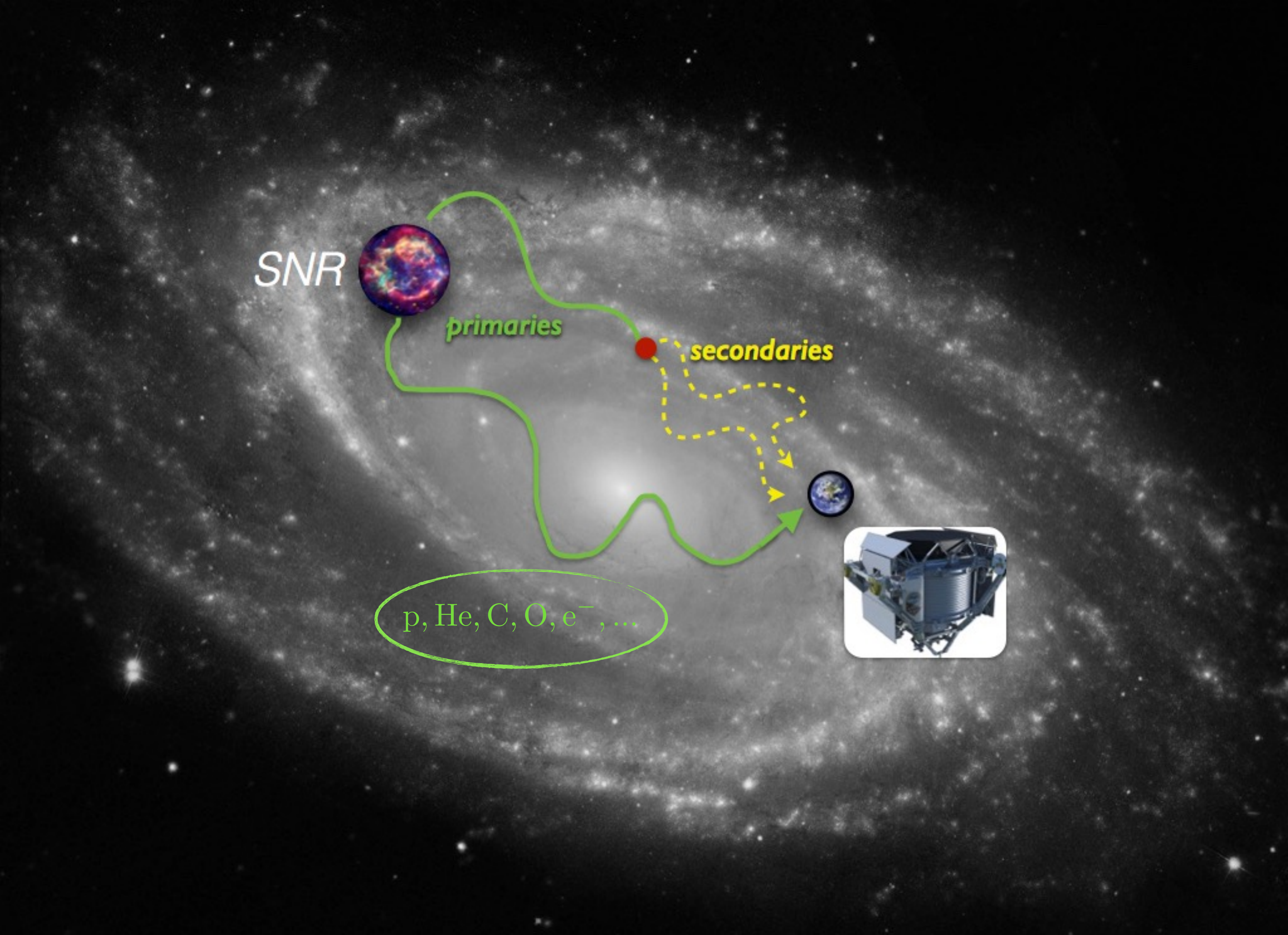
- Neutrinos

Antares

IceCube



Courtesy A. Putze



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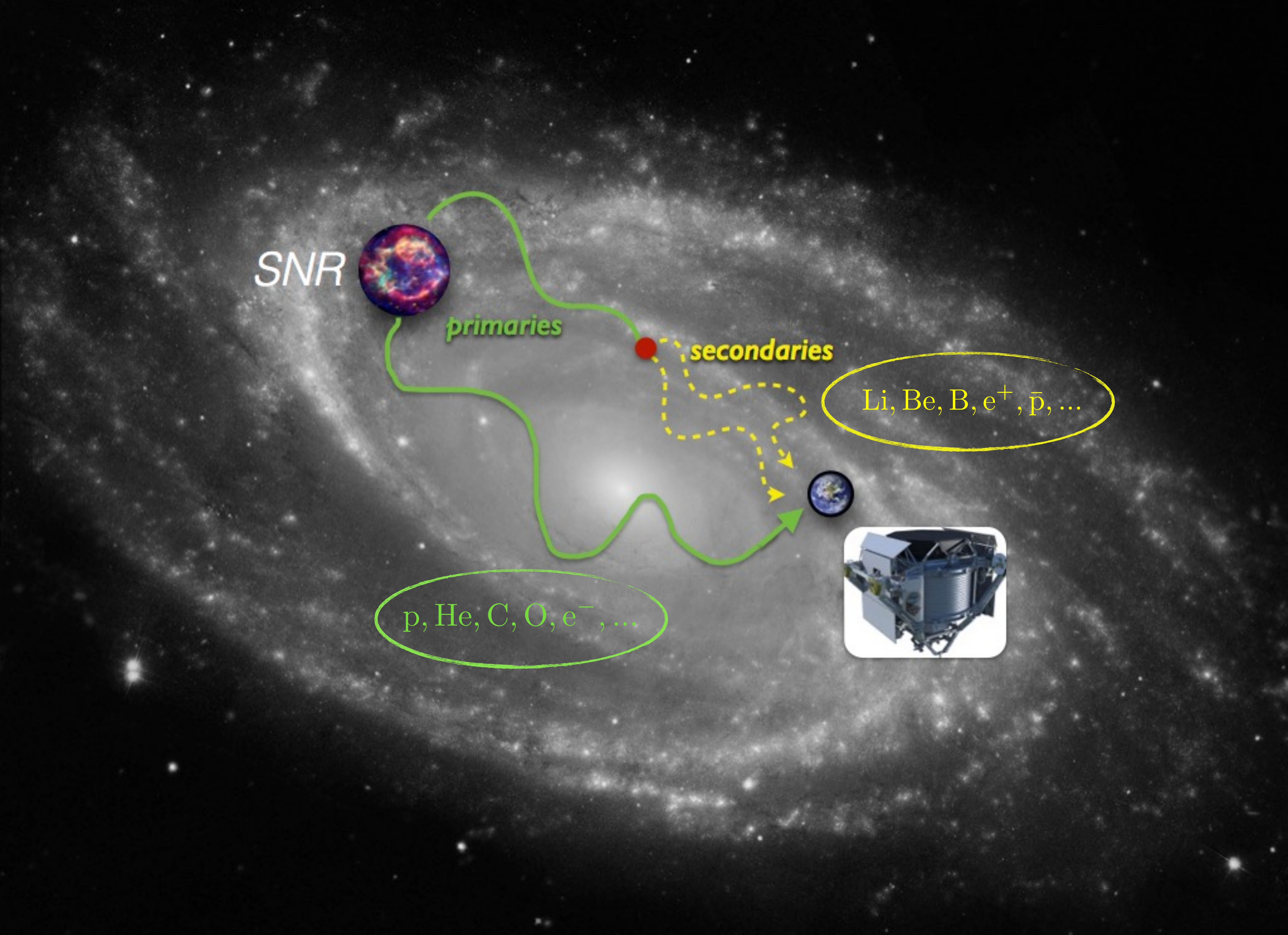

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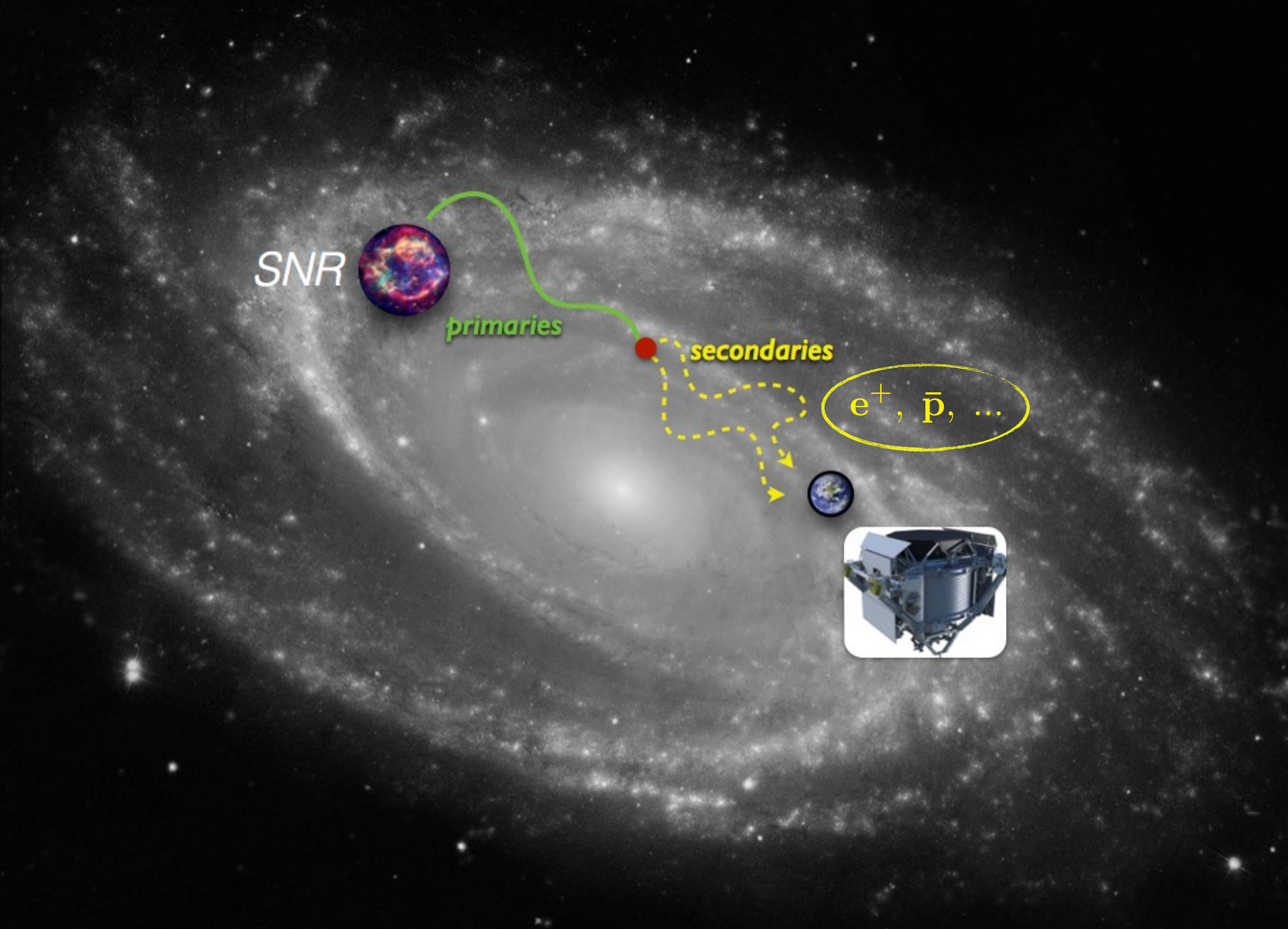

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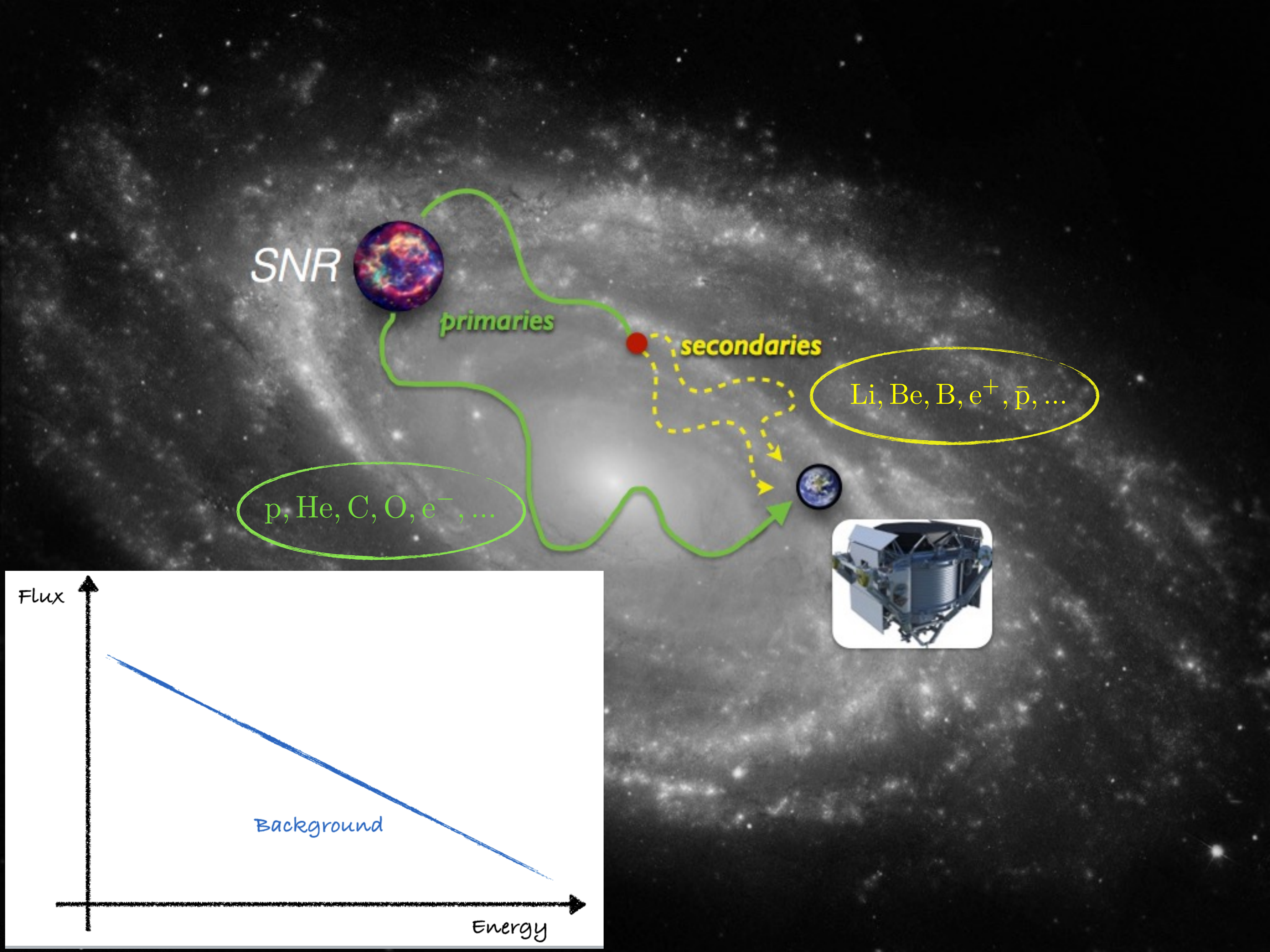
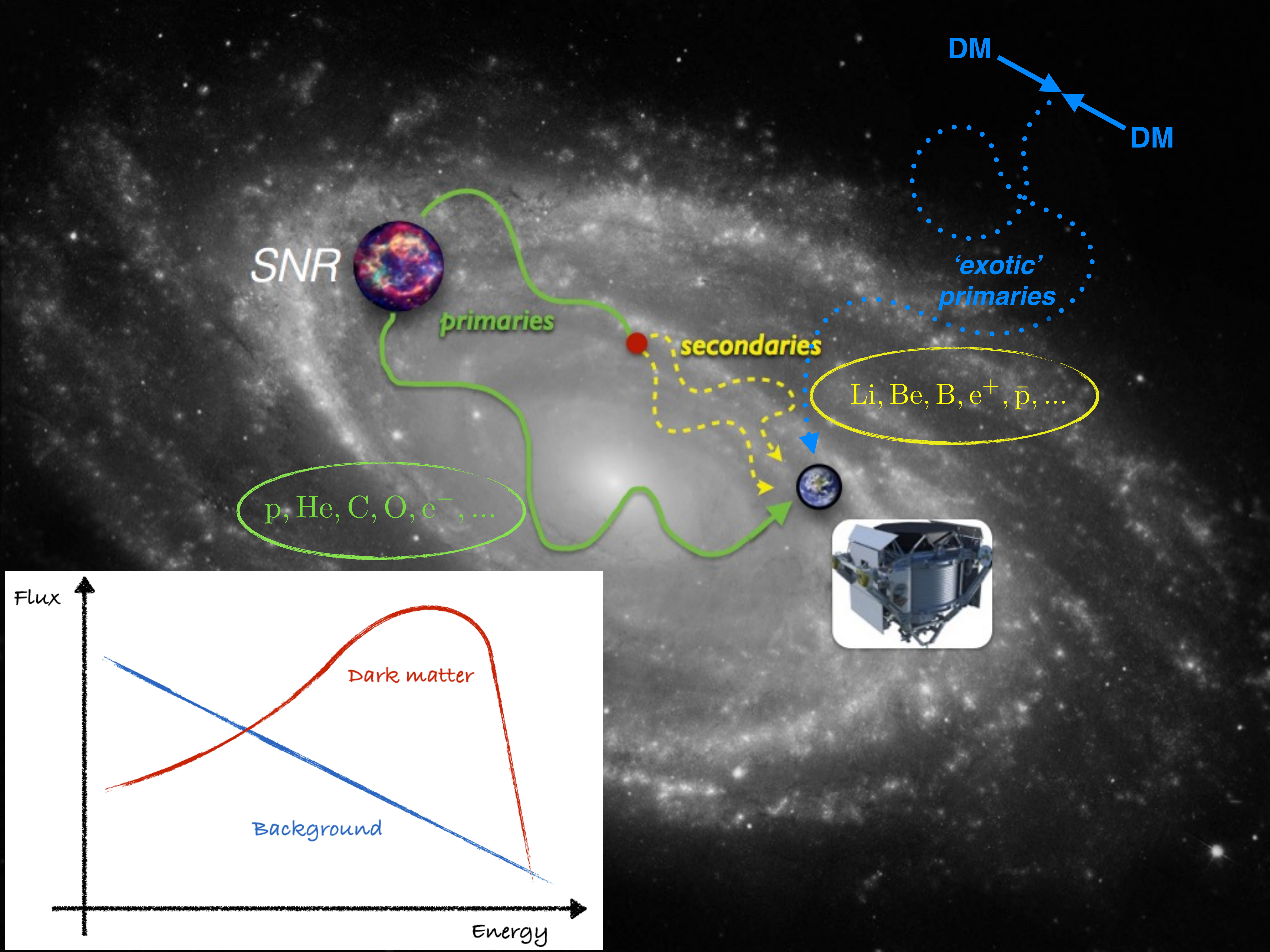

SNR
primaries
secondaries
Li, Be, B, e^{+}, $\bar{p}$, ...
p, He, C, O, e^{-}, ...
Flux
Background
Energy

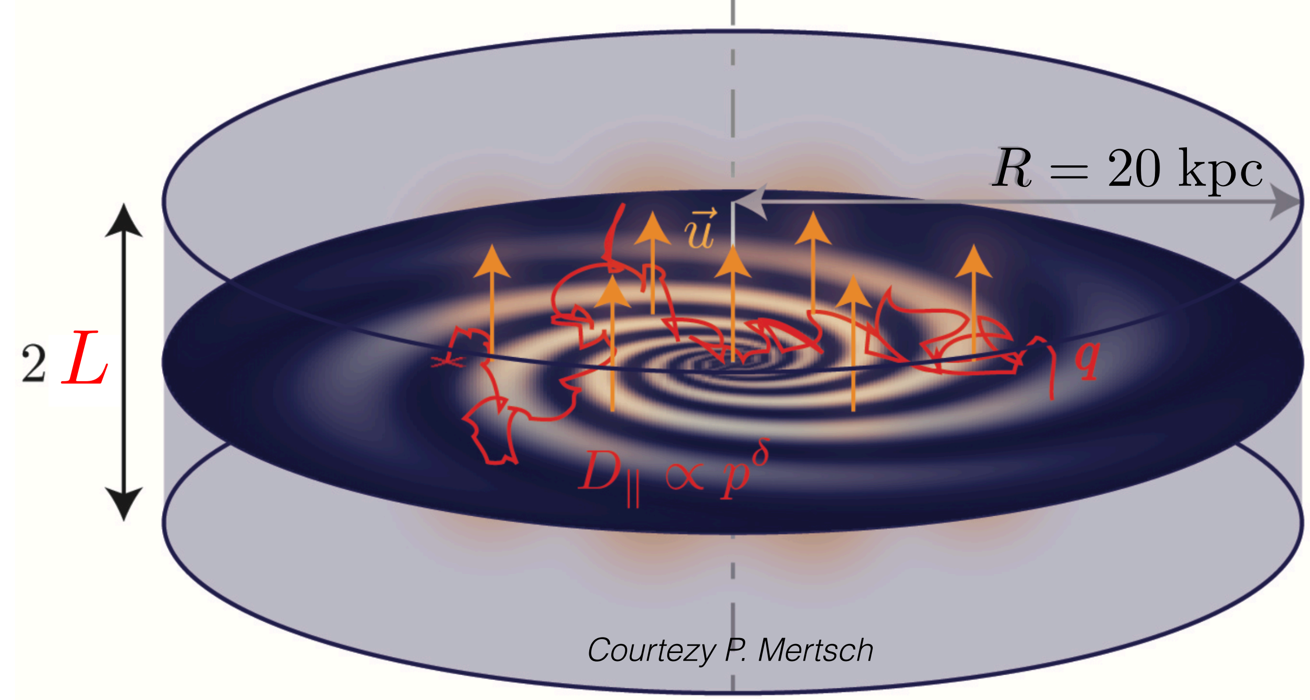


DM
DM
'exotic' primaries
SNR
primaries
secondaries
Li, Be, B, e^+, $\bar{p}$, ...
p, He, C, O, e^-, ...
Flux
Dark matter
Background
Energy

Two-zone diffusion model

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

Magnetic halo - $1 \lesssim L \lesssim 20\ \mathrm{kpc}$
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** $$Q^{sink}(E,\vec{x})$$
  - Interaction with the interstellar medium (ISM)
  - Decay
- **Energy losses** $$b(E,\vec{x})$$
  - Interaction with the ISM (Coulomb, ionisation, bremsstrahlung, adiabatic expansion)
  - Synchrotron emission, inverse Compton scattering (electrons)
- **Diffusive reacceleration** from stochastic acceleration (Fermi II) $$D(E) = \frac{2}{9}\,{V_A}^2\,\frac{E^2\beta^4}{K(E)}$$

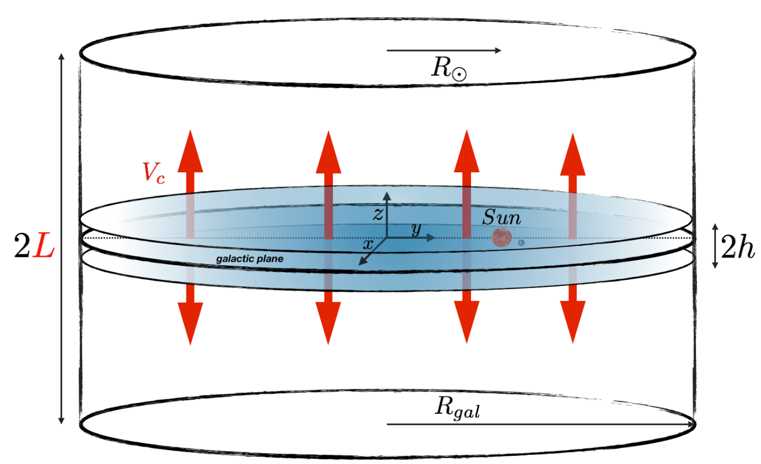
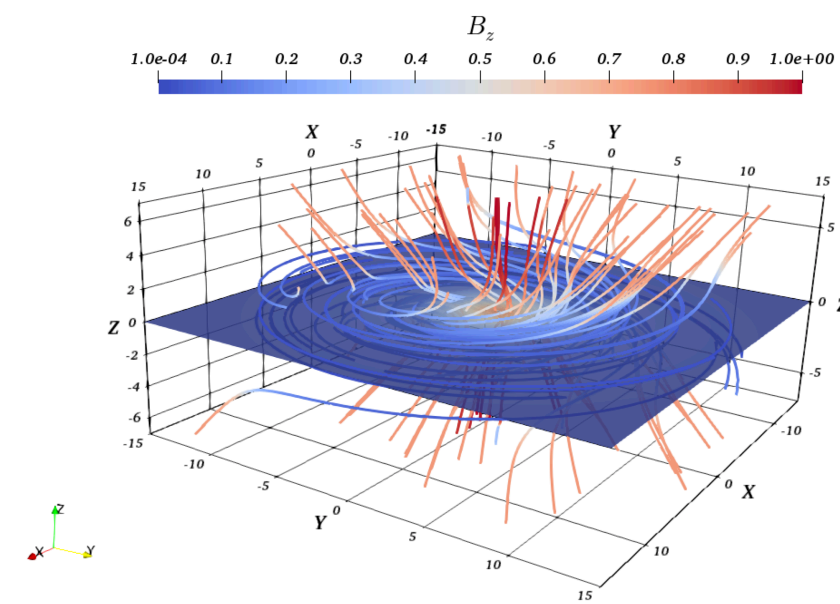
Propagation parameters determined using data of secondary to primary ratios (e.g. B/C)

e.g: Y. Génolini, MB+(2019)

Transport equation

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

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

	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 own code***, *etc.*	*GALPROP, DRAGON, PICARD, etc.*

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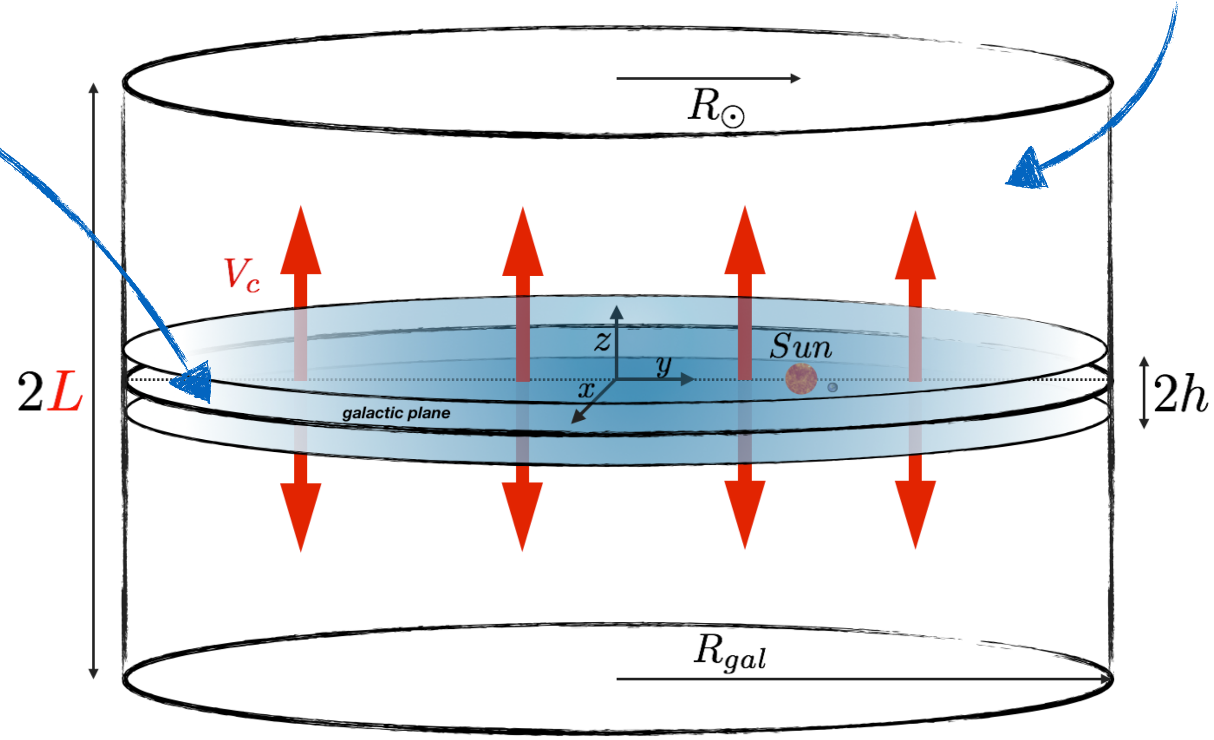
Transport of cosmic rays $e^{\pm}$

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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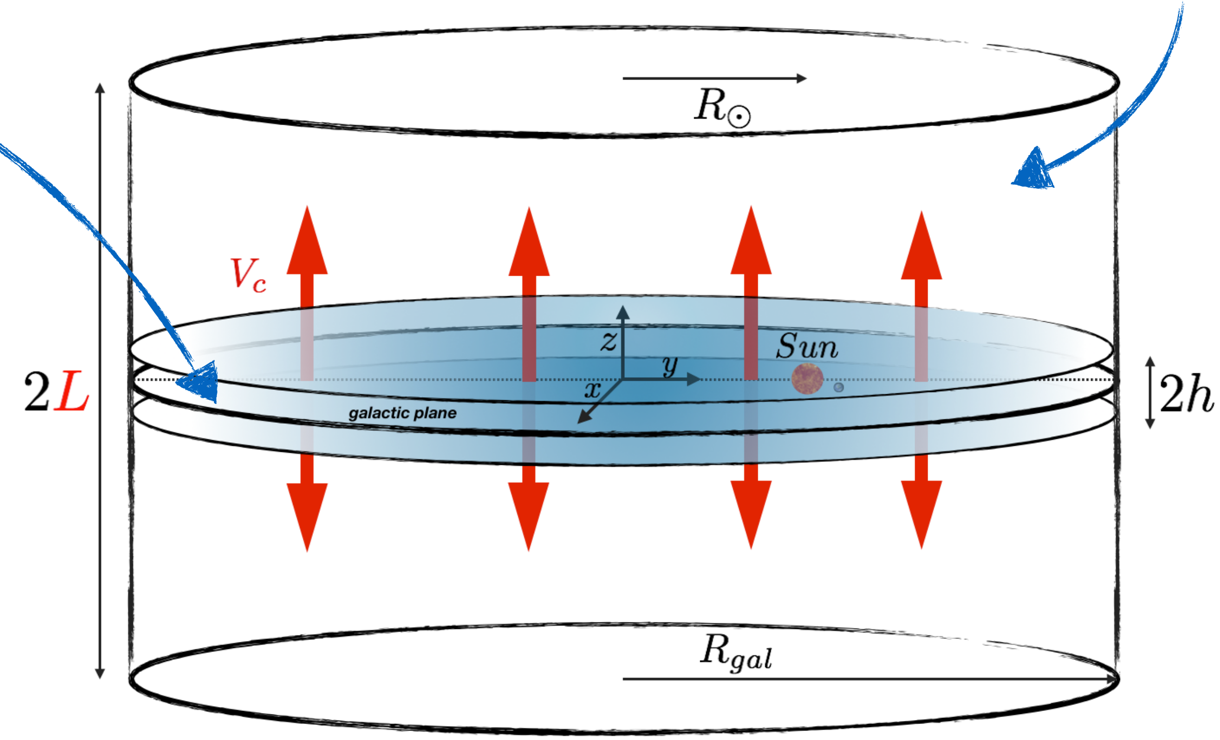

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High energy approximation

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

***E* > 10 GeV**

Transport of cosmic rays *e*±

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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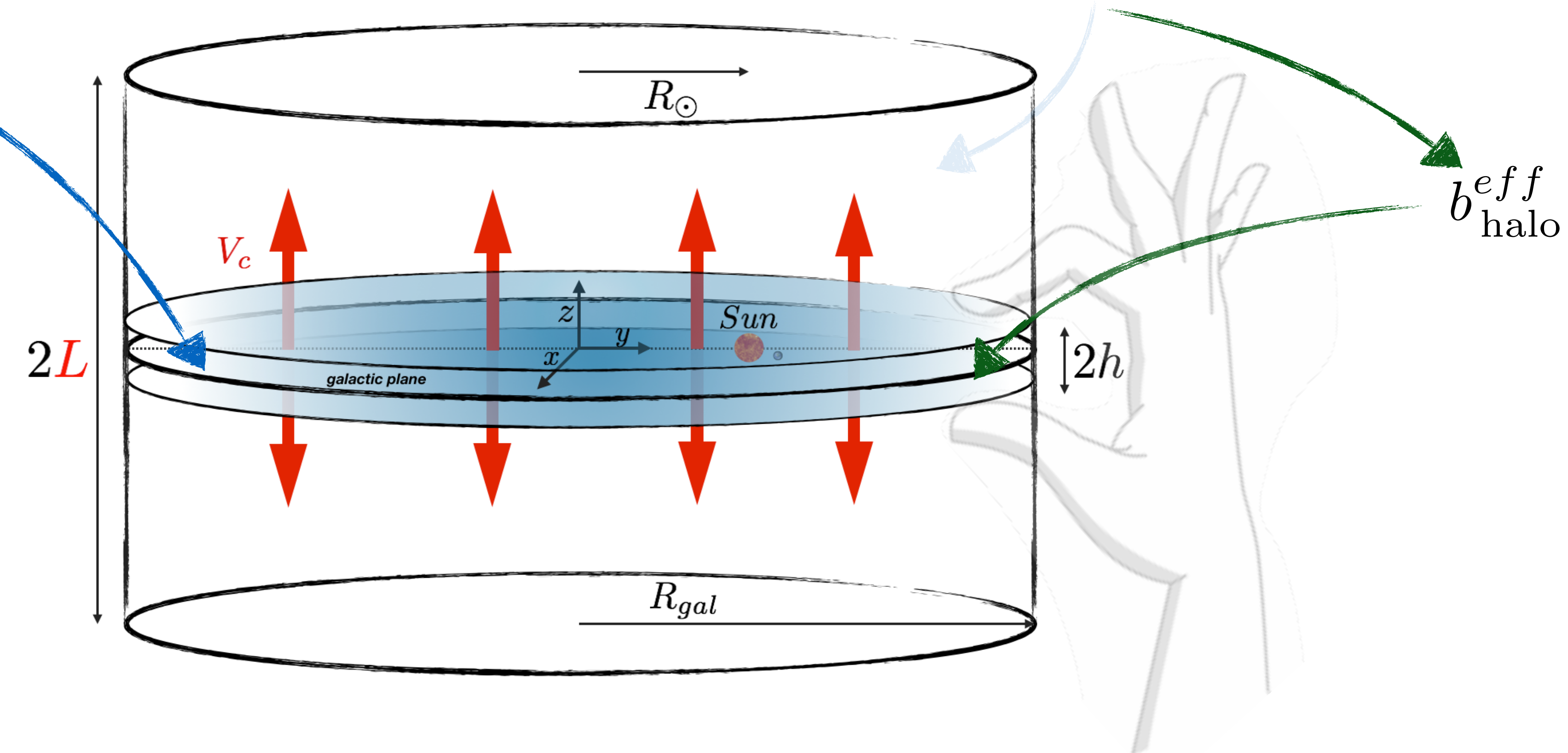


Pinching method

MB+(2016a)

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

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

⟹ **extend** the semi-analytic computation of *e*± interstellar fluxes **down to MeV** energies!

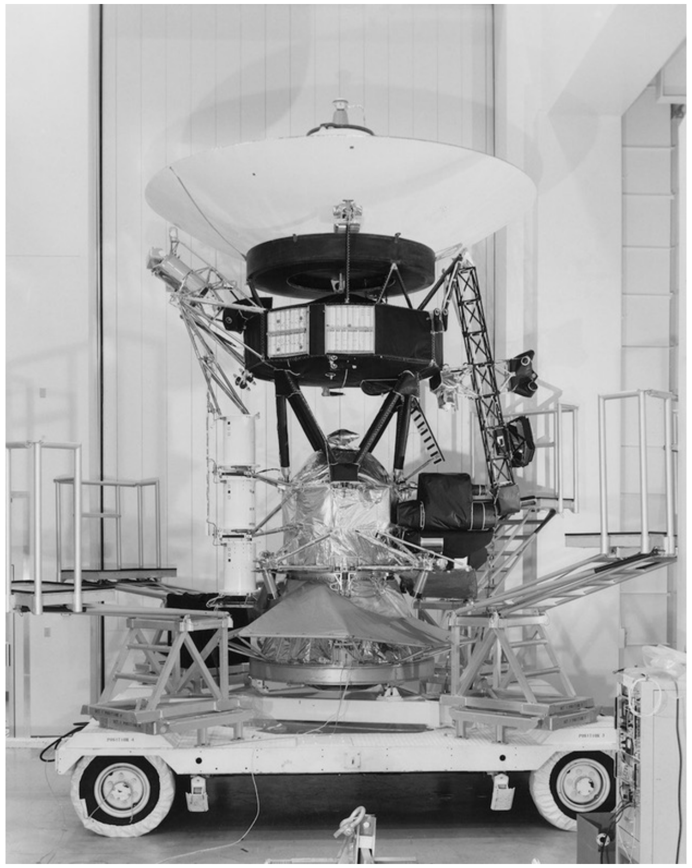
MeV cosmic rays?

🤔

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



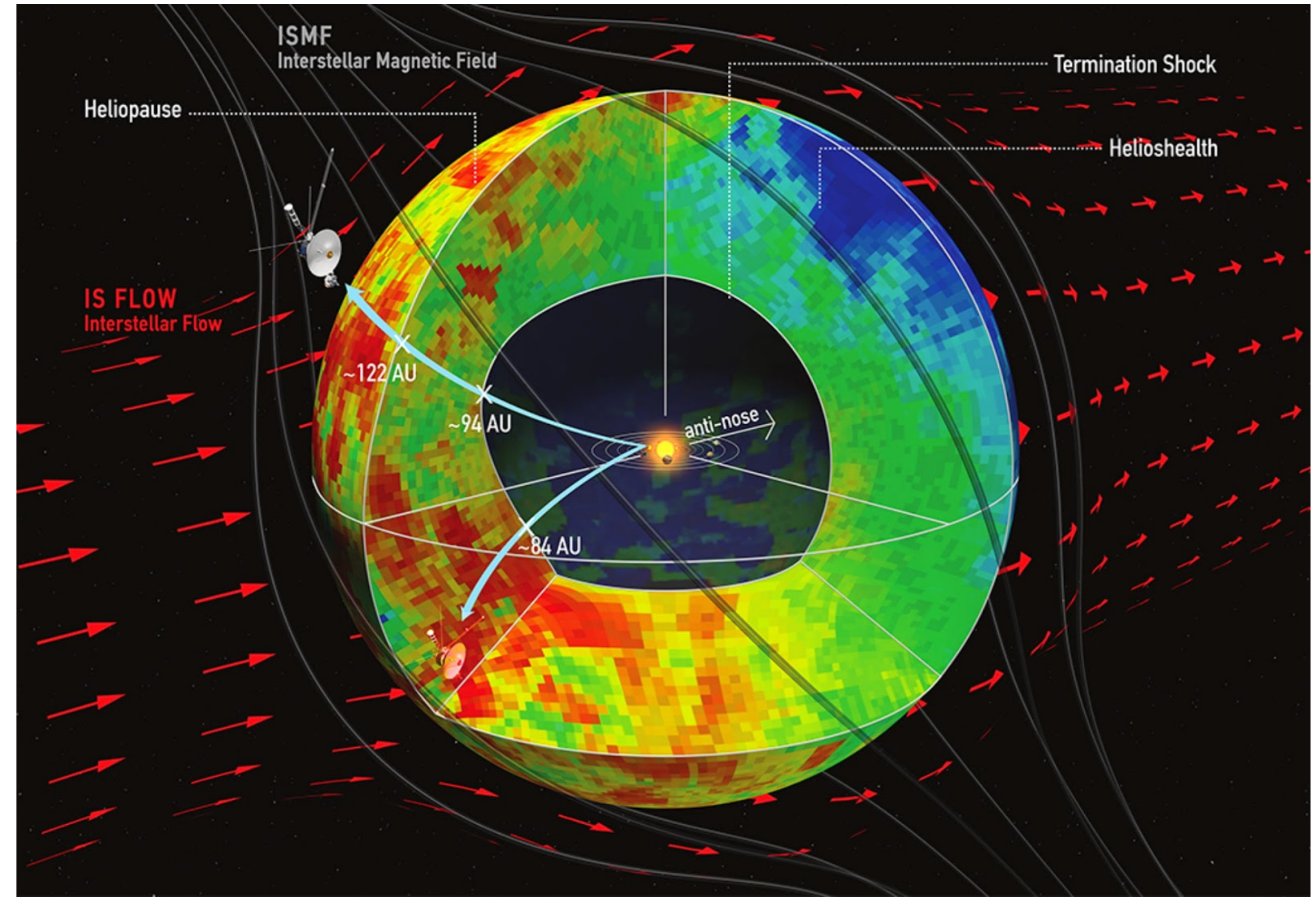
launch:
1977

distance now:
~140 au

direction:
Hercules (solar apex)

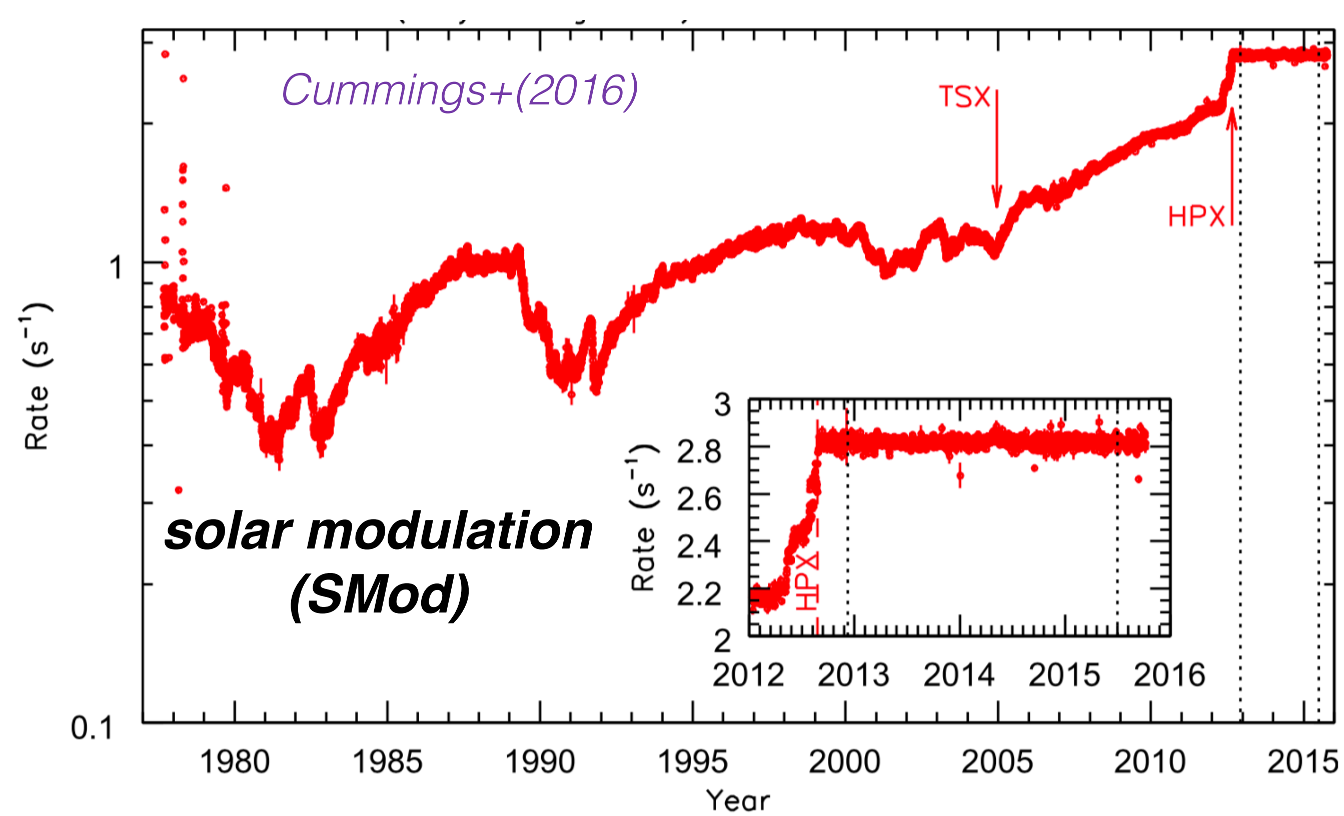
velocity/Sun:
~17 km/s

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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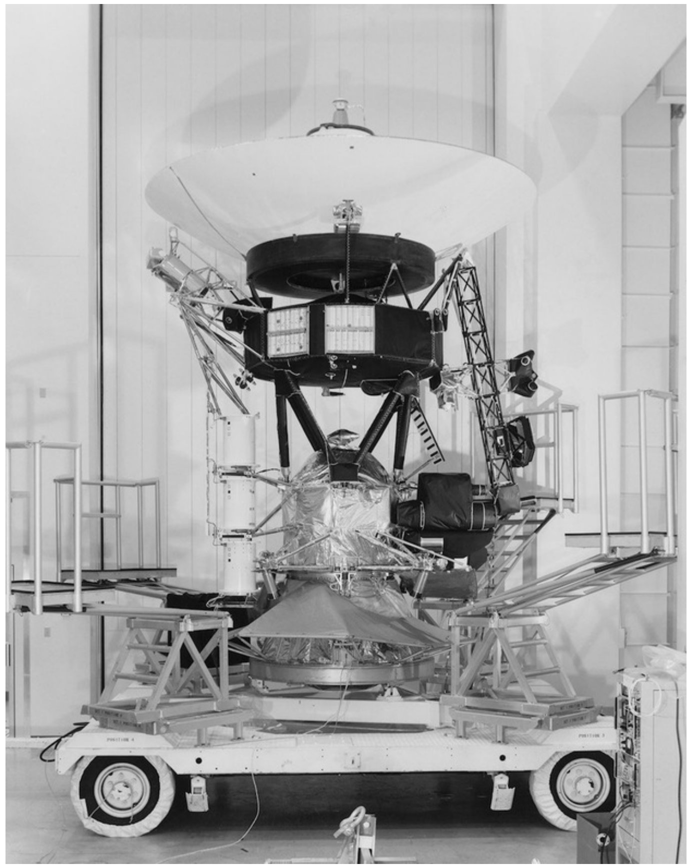

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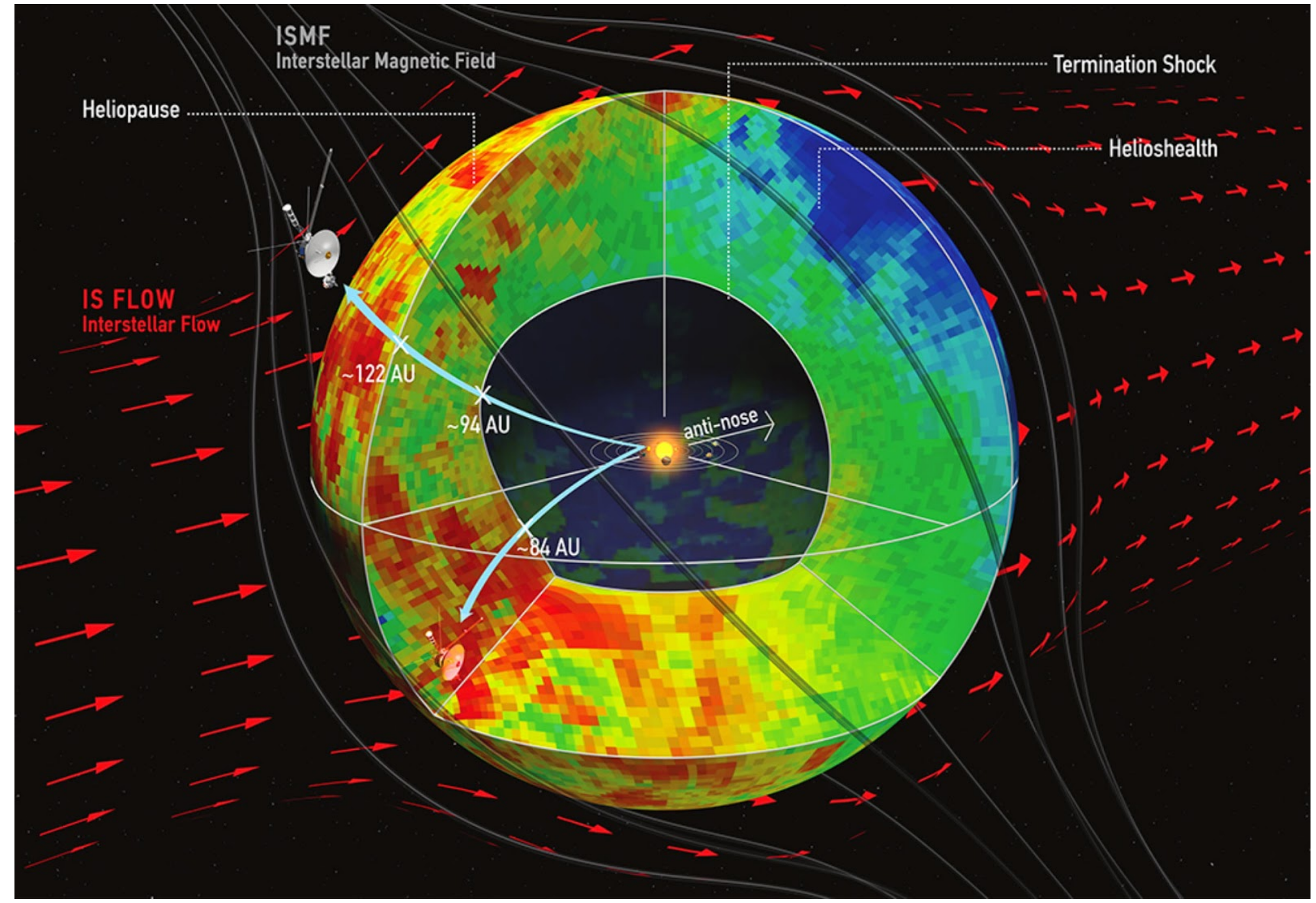

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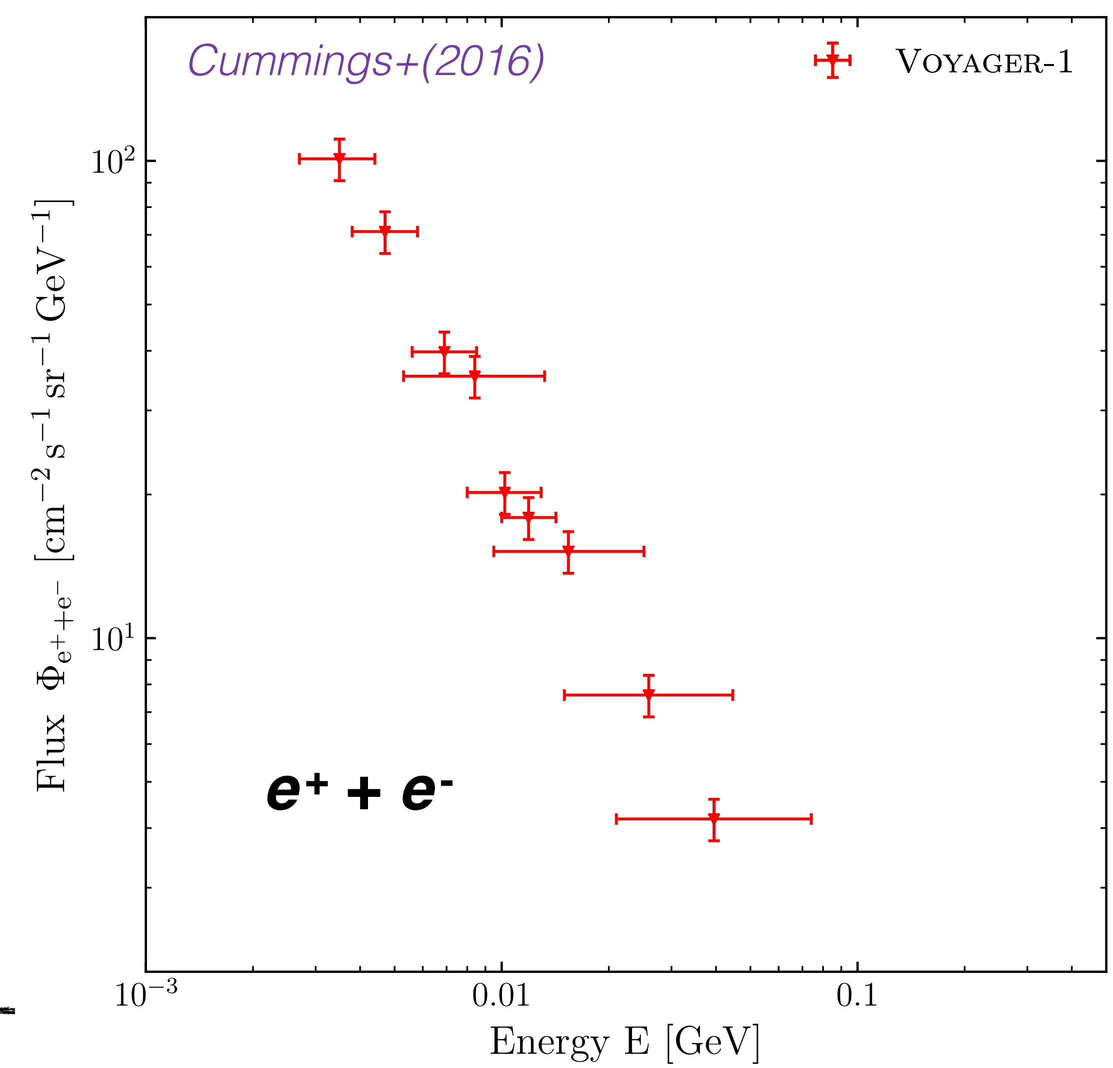

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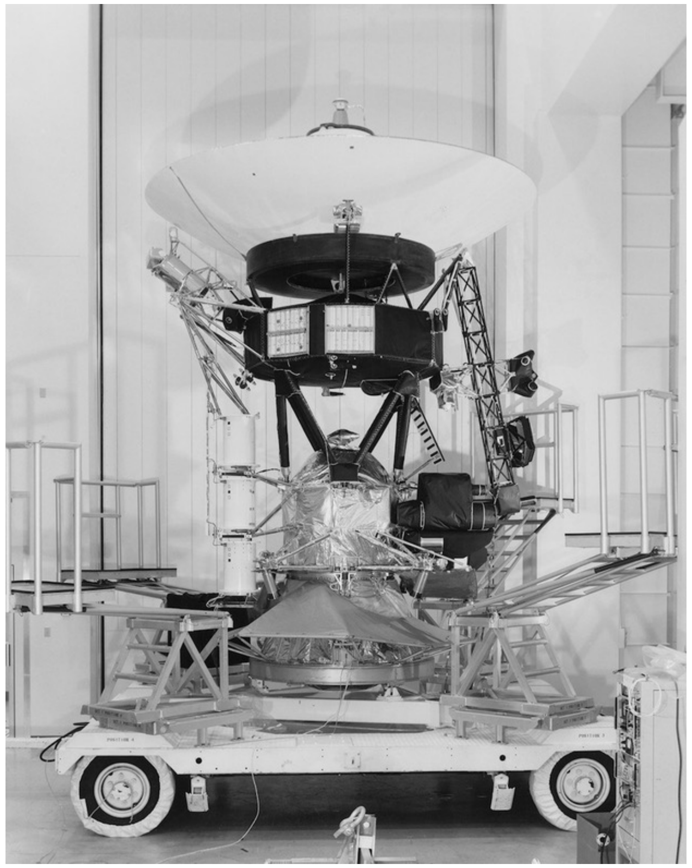

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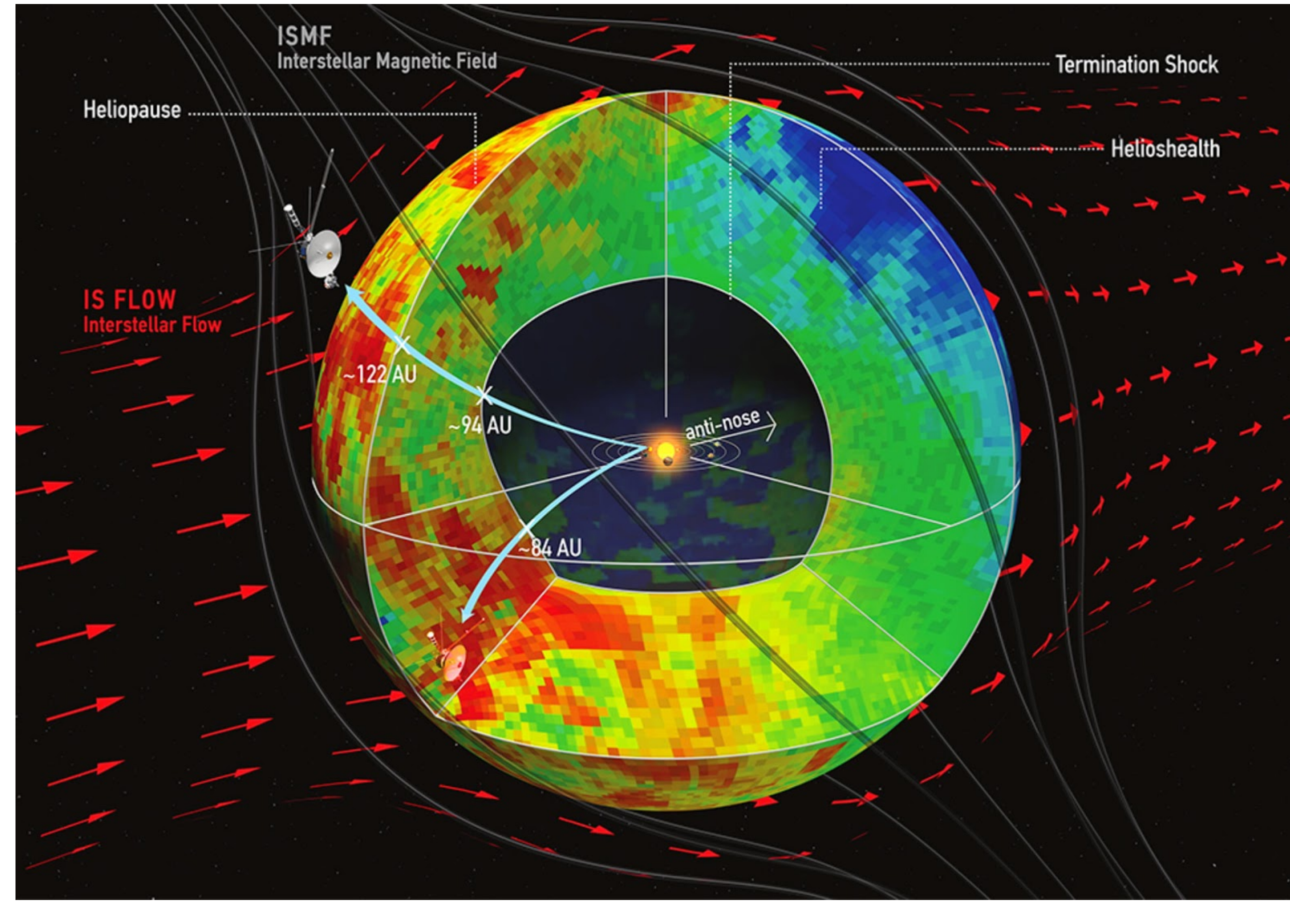

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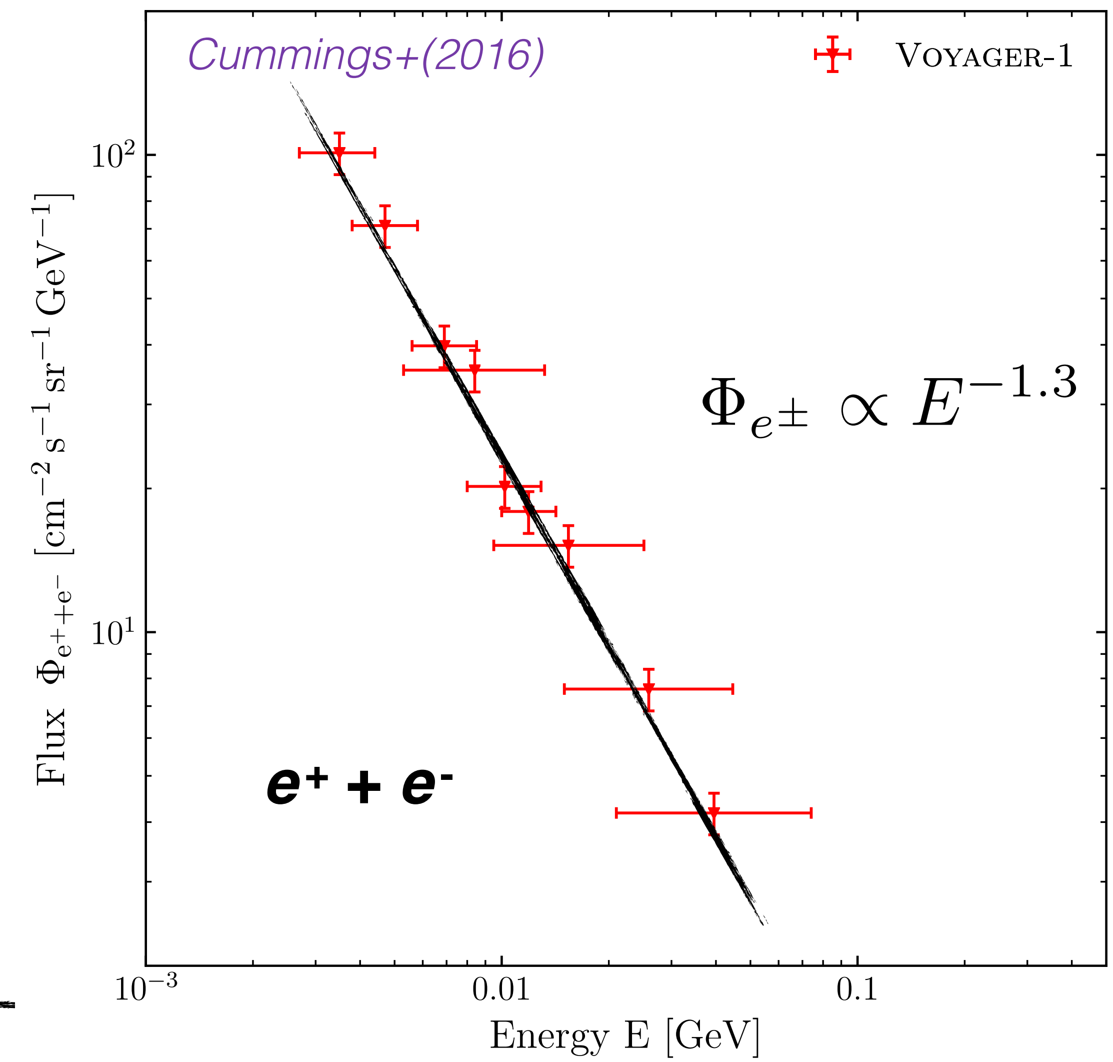

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MB, J. Lavalle and P. Salati (PhysRevLett.119.021103)

and

MB, T. Lacroix, M. Stref and J. Lavalle (Phys. Rev. D 99, 061302)

MeV dark matter particles: motivations

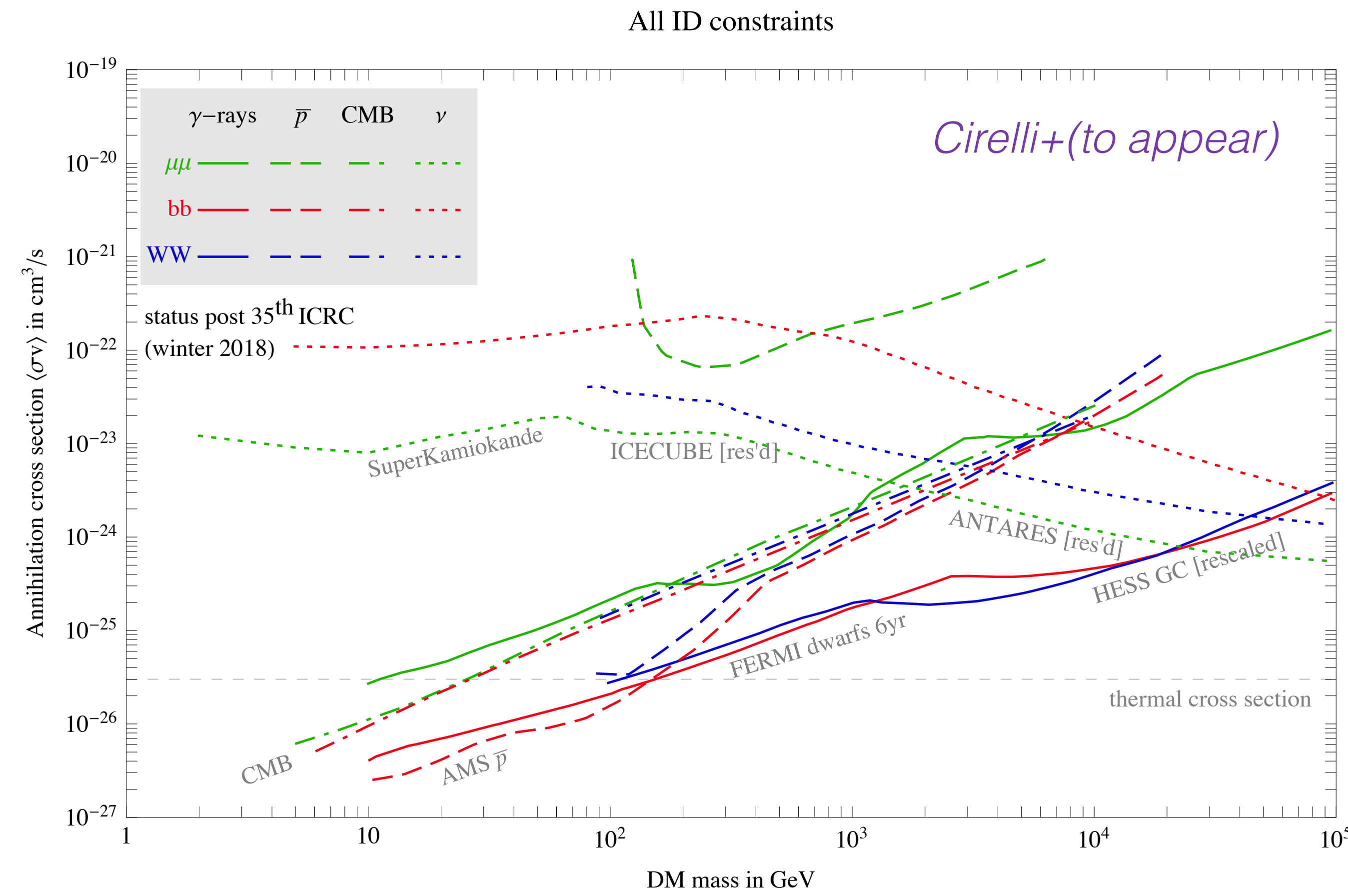
- **No conclusive detection** at the GeV scale

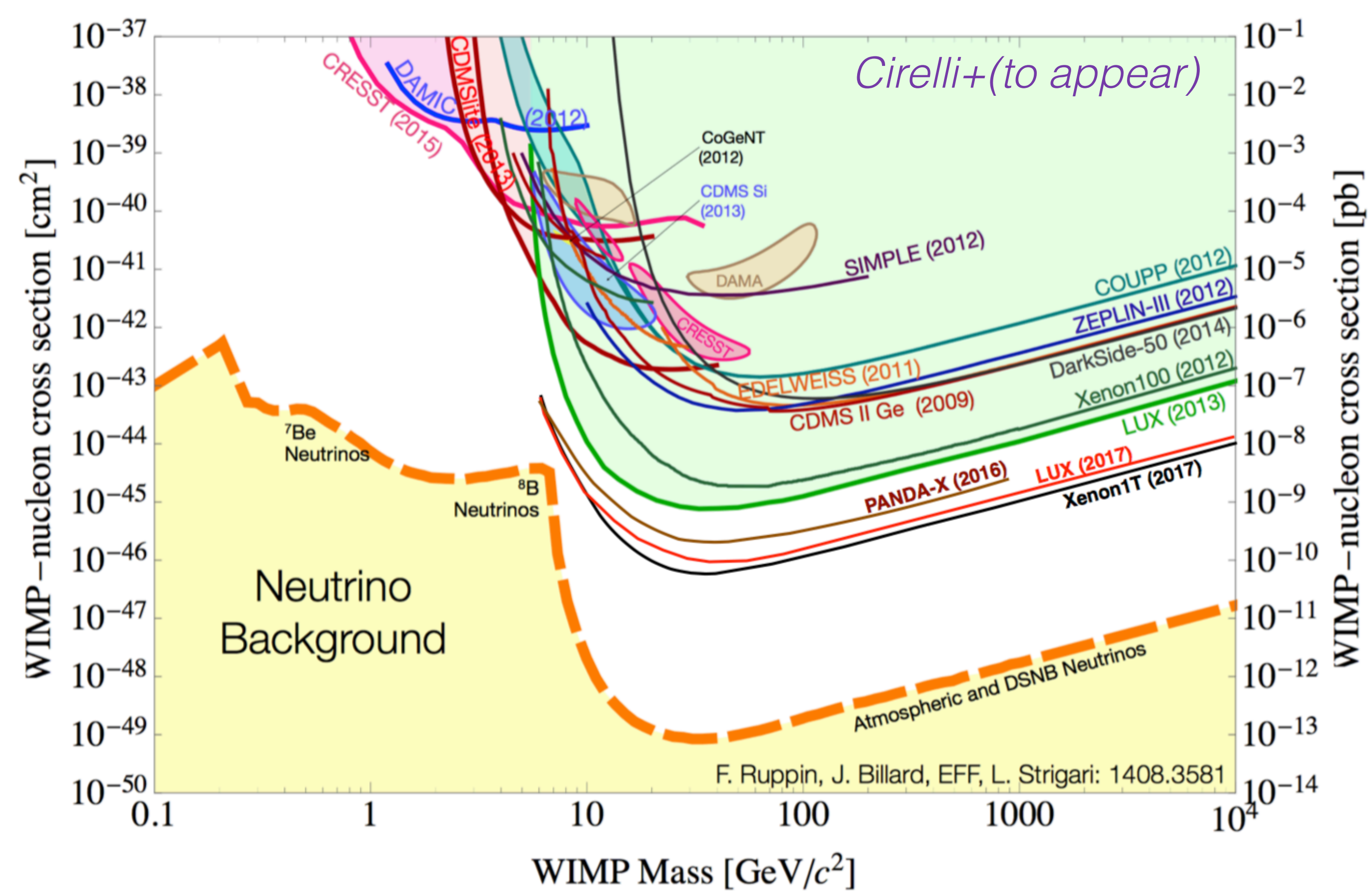
- **Not many annihilation channels kinematically available**
  π (> 140 MeV), μ (> 105 MeV), e, ν, γ
  $\Longrightarrow$ pass the constraints from γ and pbar

- **Difficult to detect in direct detection experiments**
  - too light for nuclear target detectors
  - large uncertainties from the Galaxy escape velocity

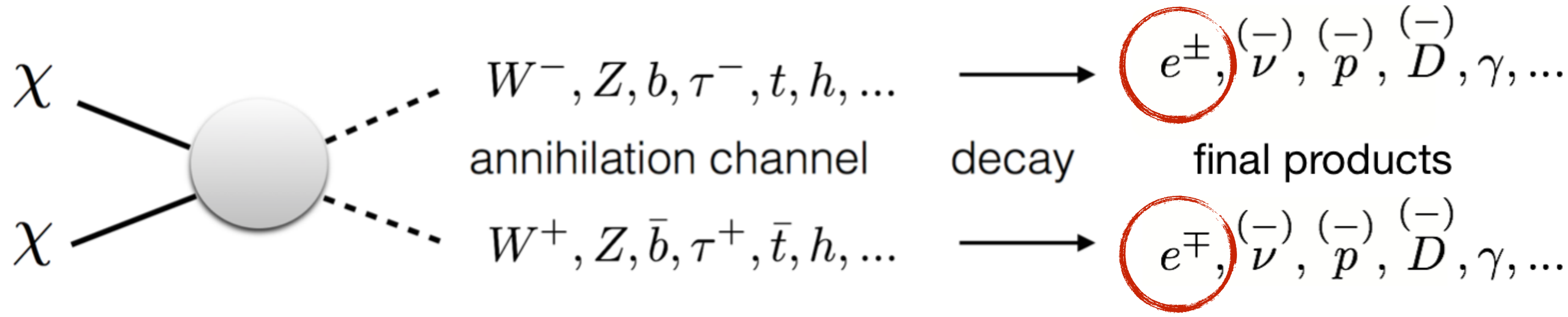
- **Suppression of small scale structures** with masses below ~10^4 to 10^7 $M_\odot$ *(e.g: Boehm+(2014))*
  $\Longrightarrow$ might solve the missing satellites problem?

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





CRs $e^\pm$ from dark matter



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

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

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

Dark matter distribution in the MW

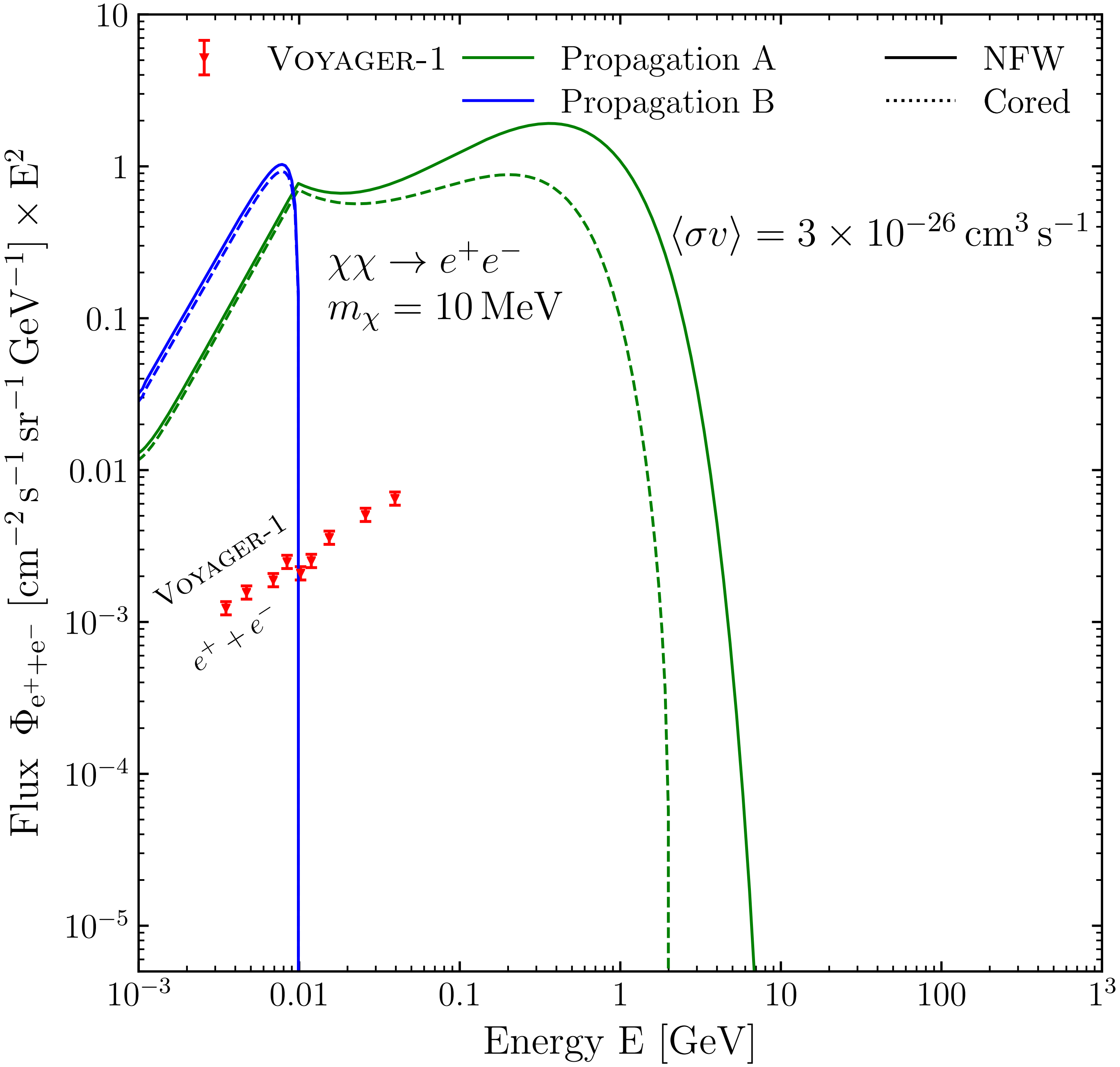
- **NFW** (spike in the GC)
- **Cored** (~ 8 kpc core)

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



- **Propagation A:** strong reacceleration
  $V_A = 117.6\,\mathrm{km/s}$ *Maurin+(2001)*

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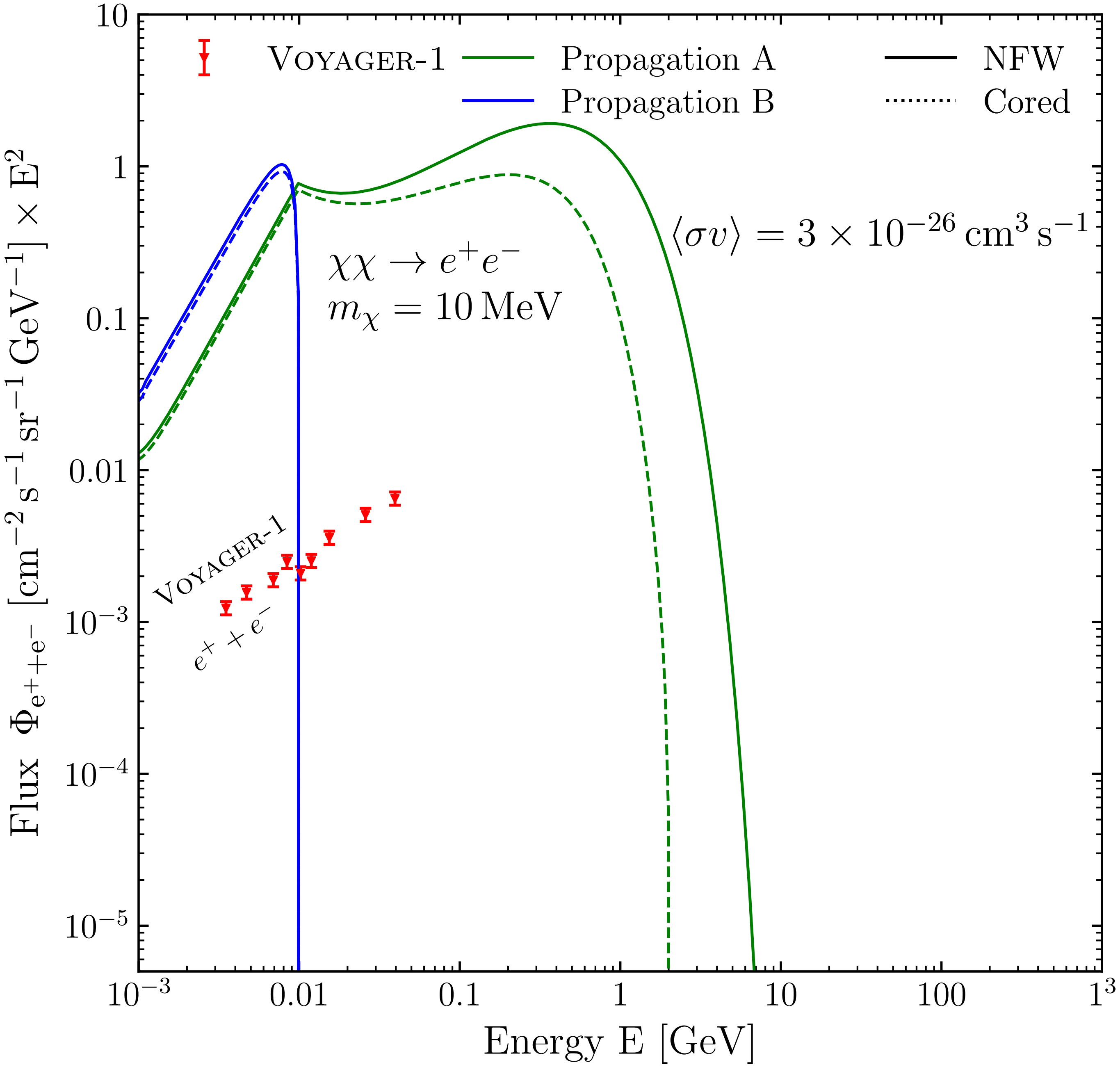
electron channel $\chi\chi \longrightarrow e^+e^-$

Constraints on annihilation cross section



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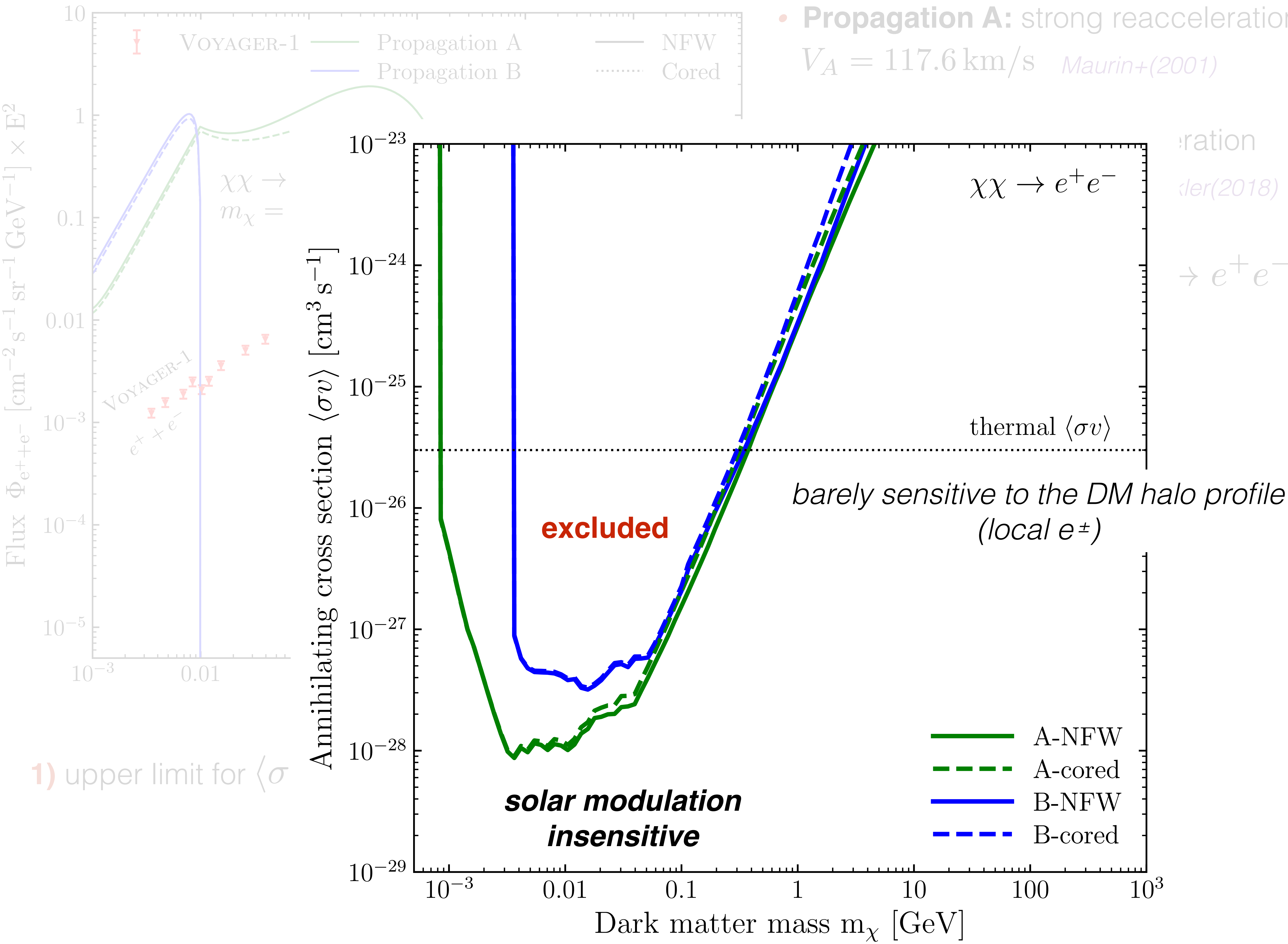

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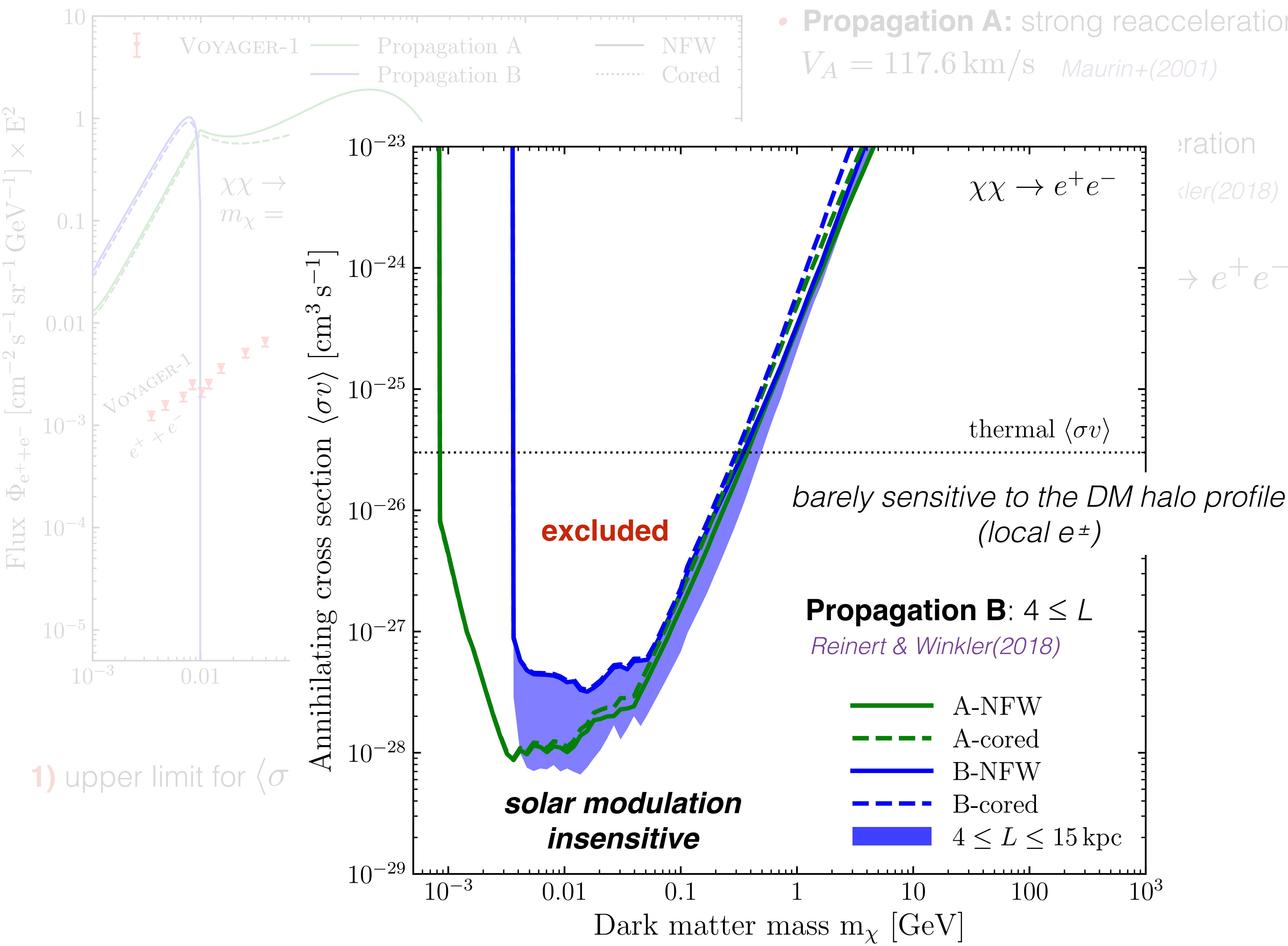

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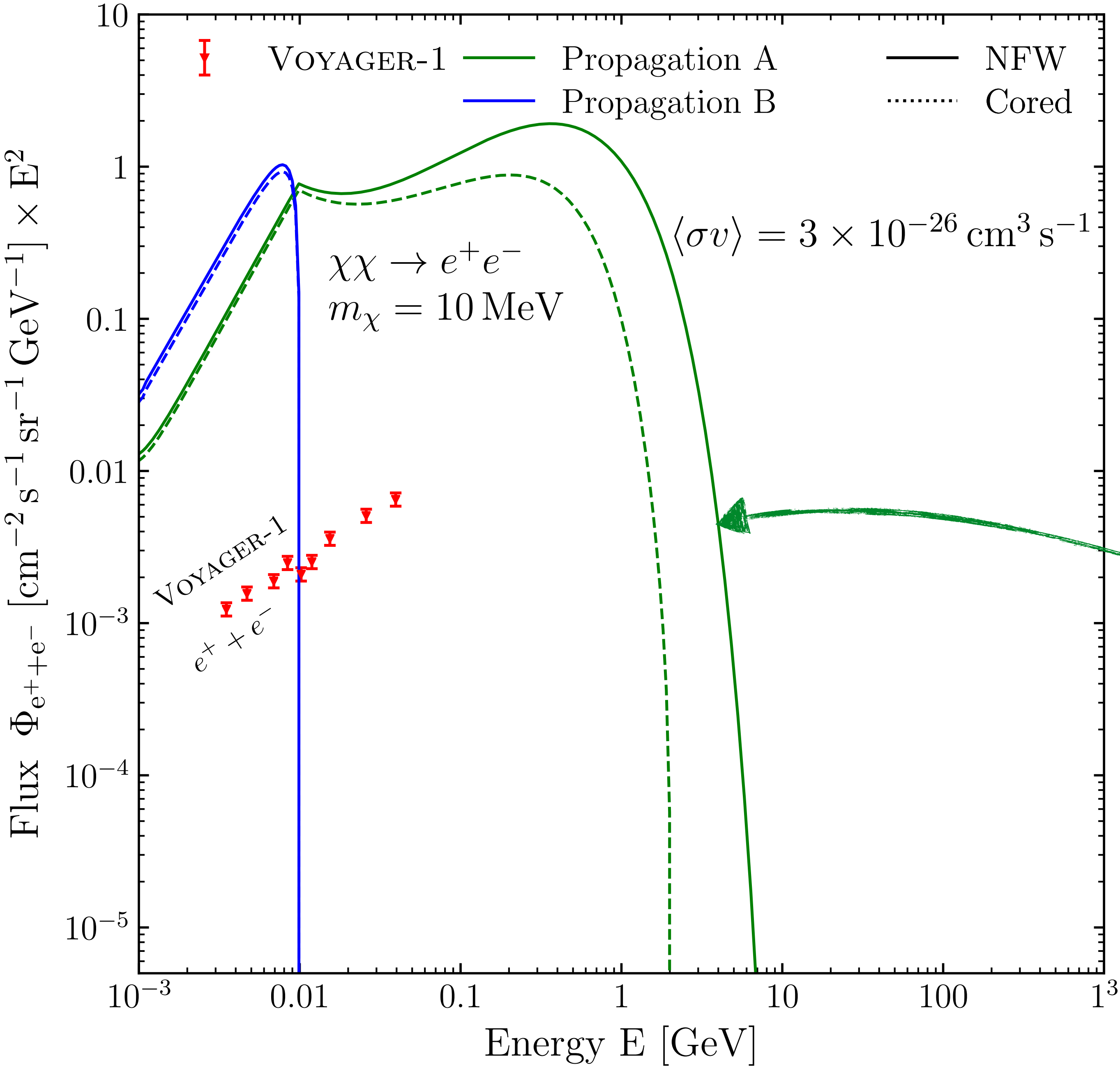

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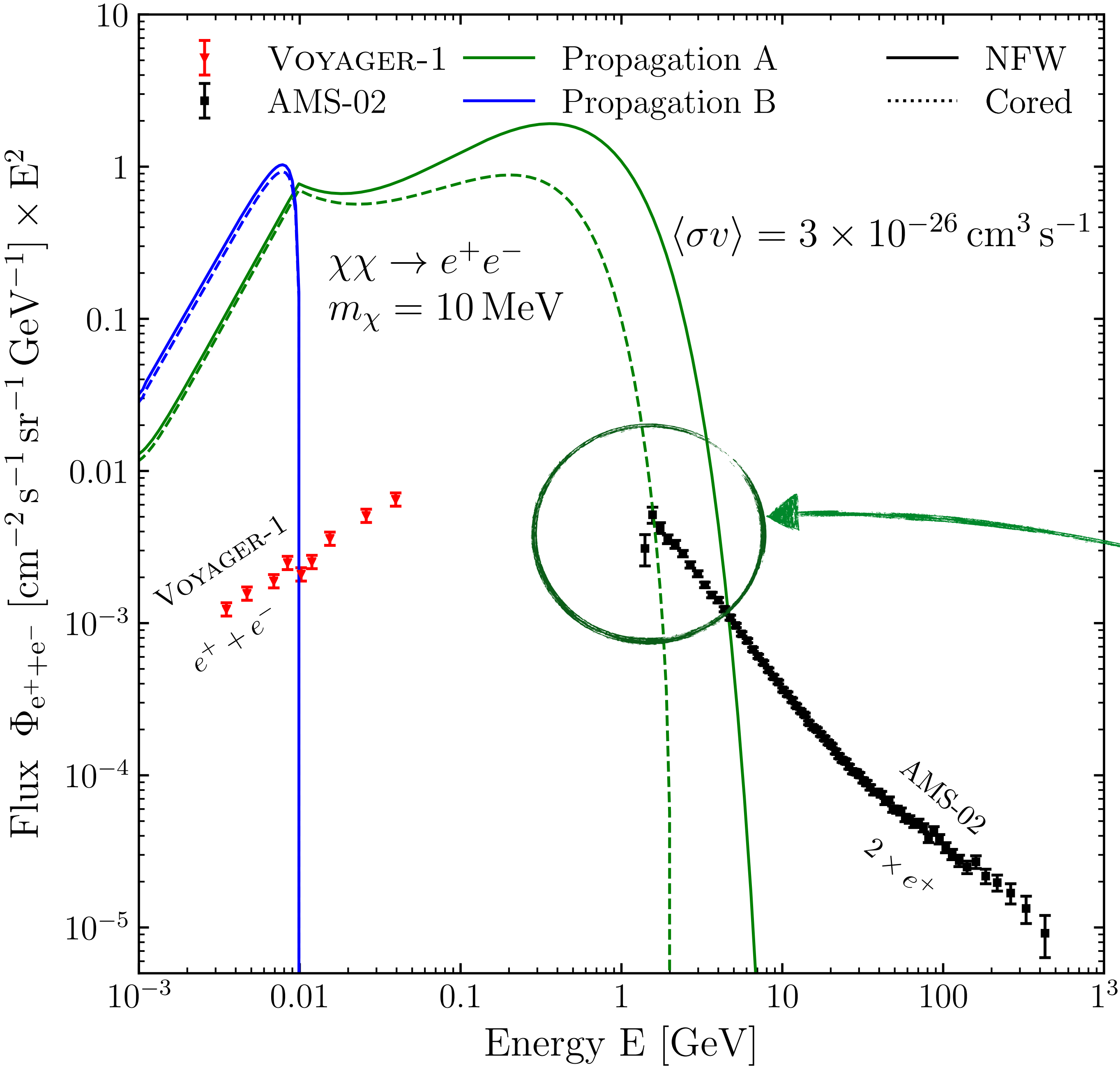

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eleration

Vinkler(2018)

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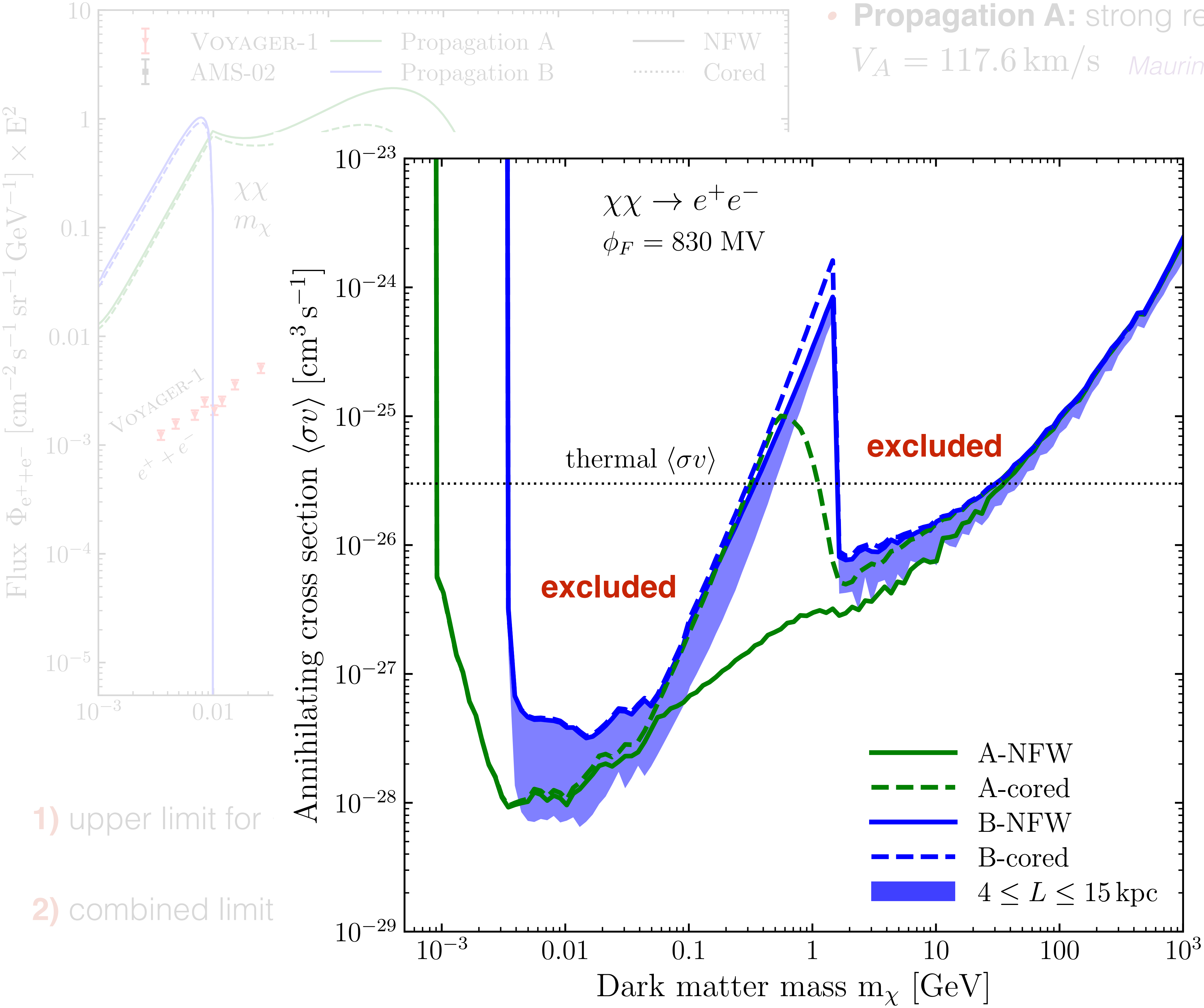
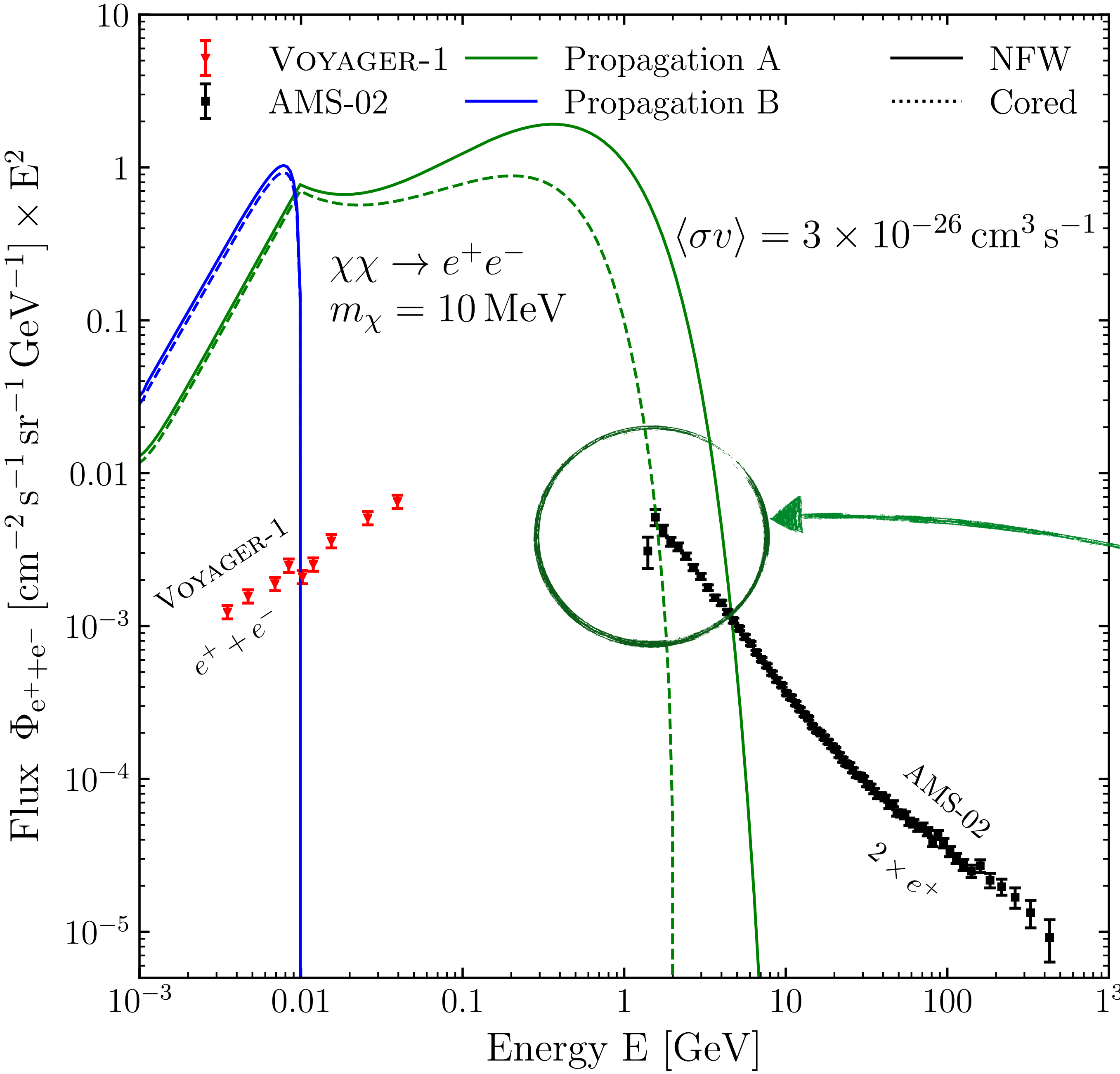


1) upper limit for

2) combined limit

Constraints on annihilation cross section



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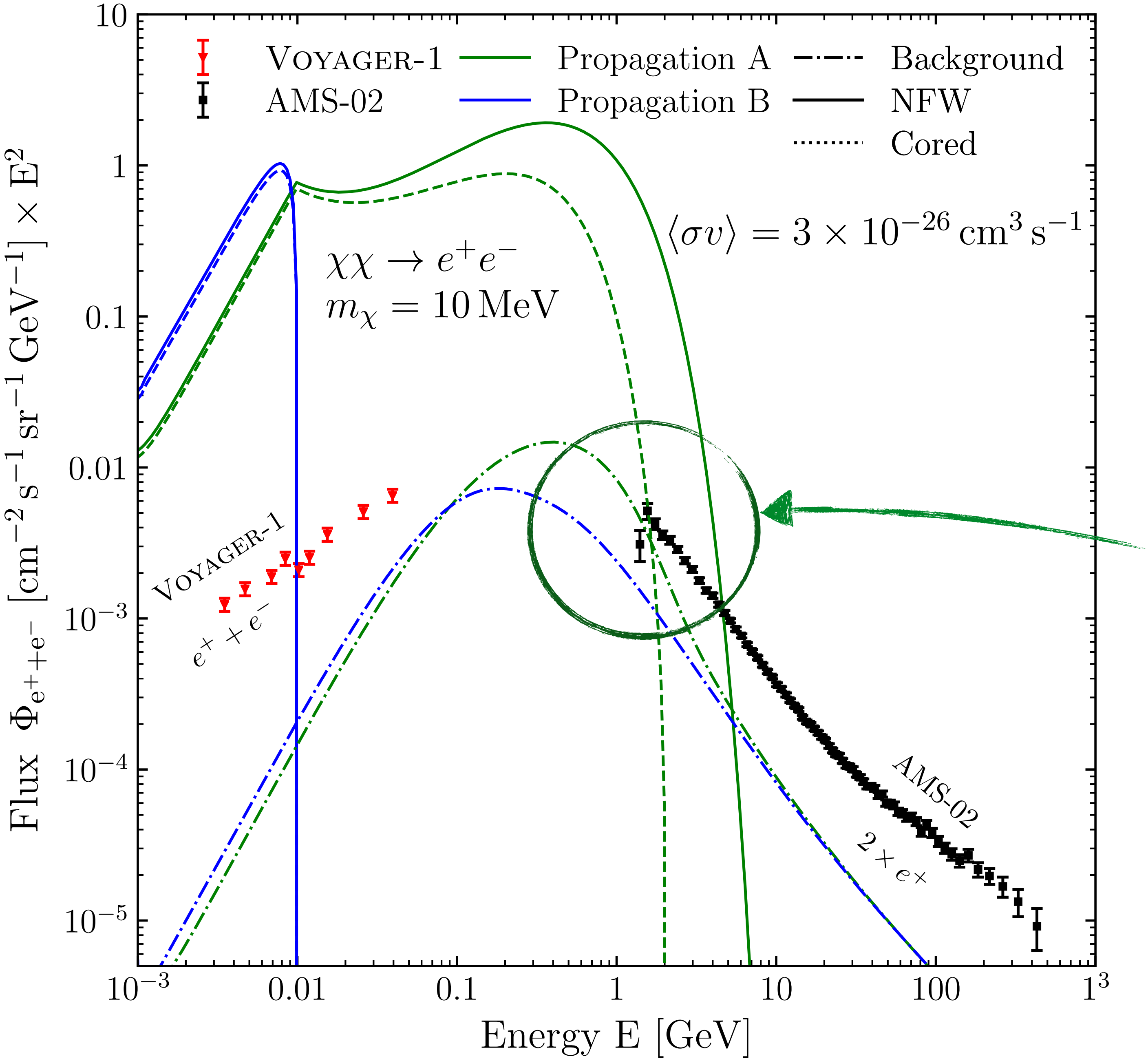

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3) with background of secondary e^+: **1)** + $\Phi^{\mathrm{DM}}_{e^+}(E_i) + \Phi^{\mathrm{II}}_{e^+}(E_i) \leq \Phi^{\mathrm{exp}}_{e^+}(E_i) + 2\sigma_i$

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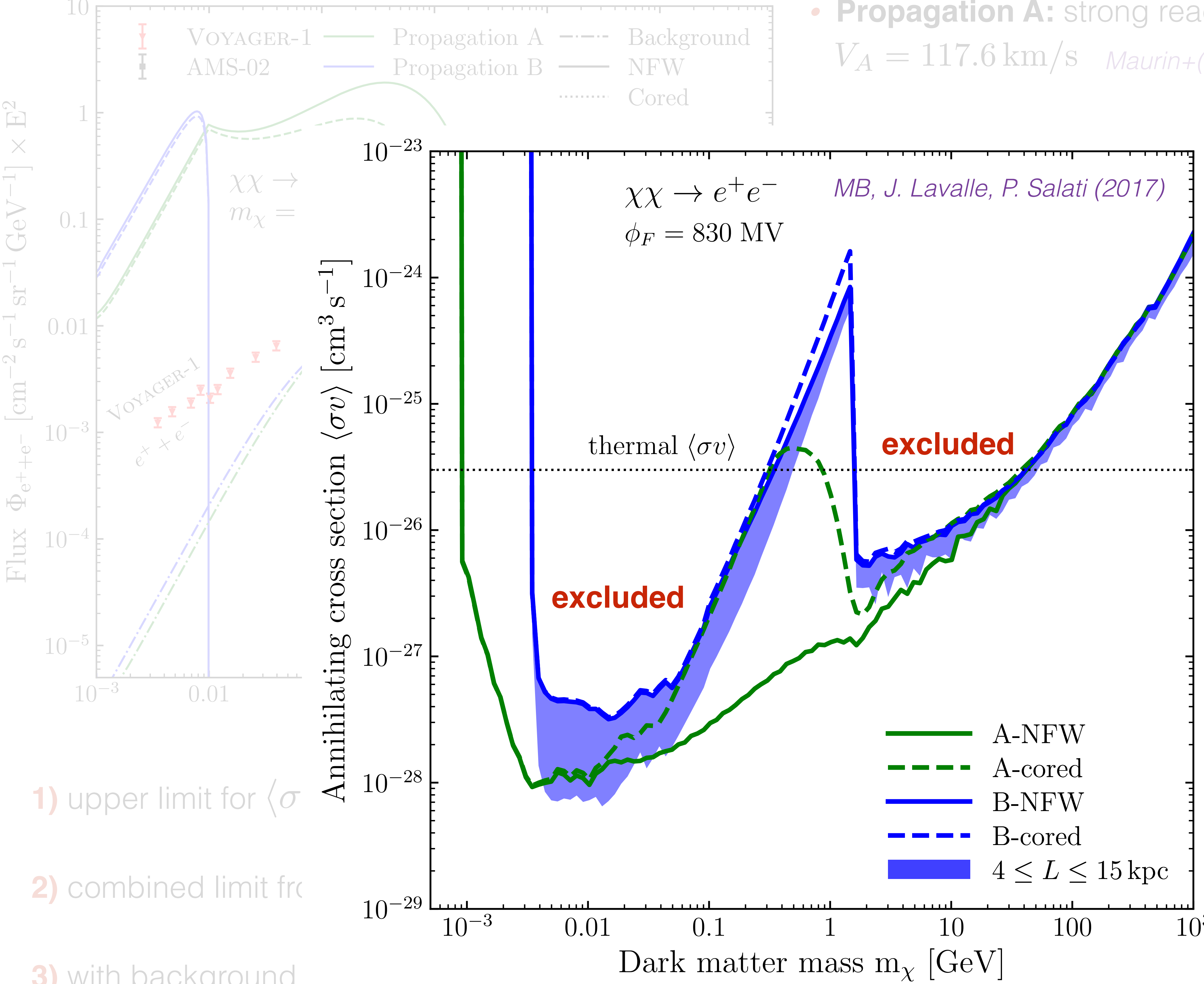


ration

ler(2018)

$\to e^+e^-$

e reacceleration

ve the DM mass!

1) upper limit for $\langle\sigma$

2) combined limit fr

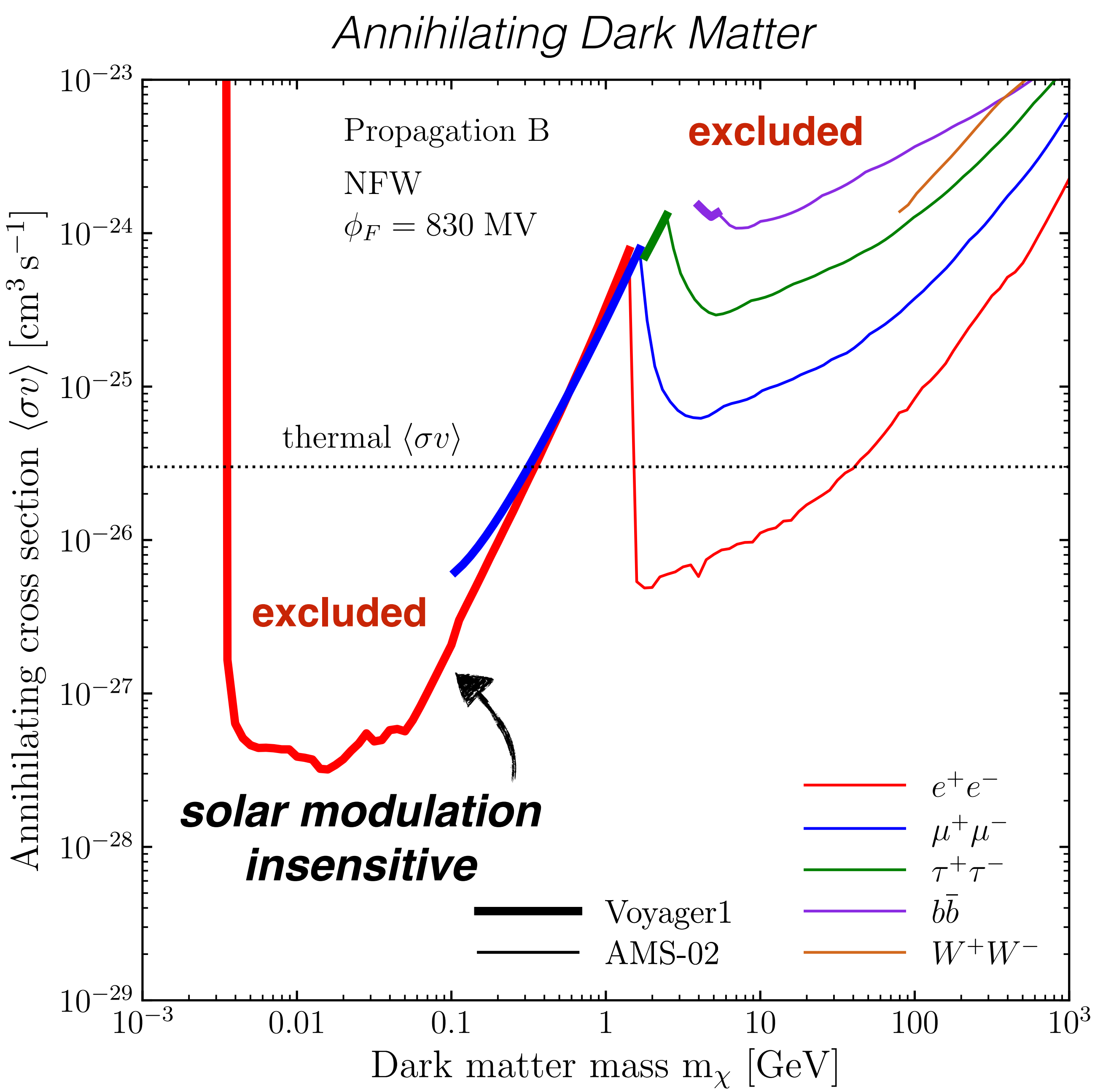
$+ 2\sigma_i$

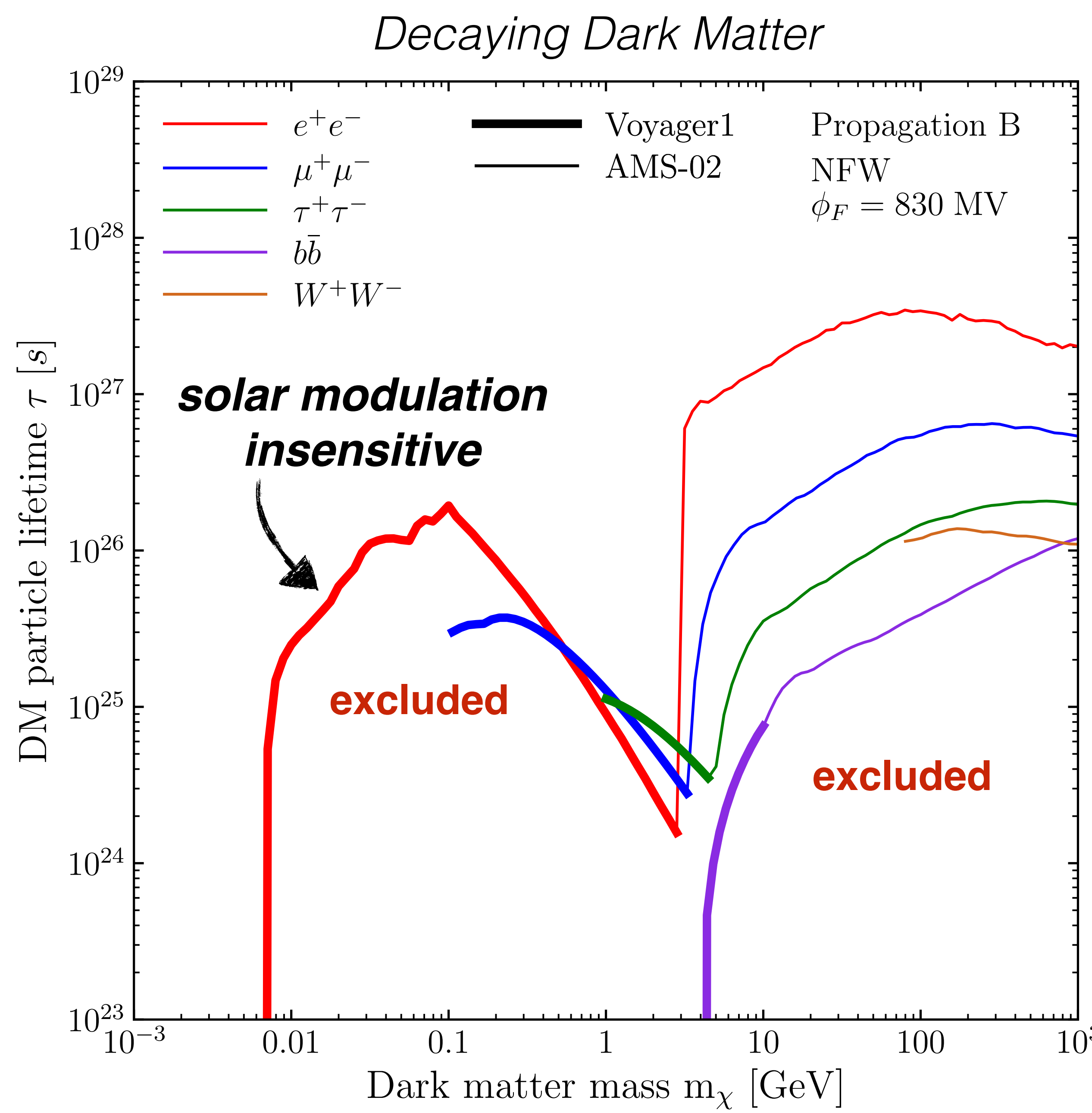
3) with background

$2\sigma_i$

Constraints on DM annihilating cross section

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





X-rays and γ-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

$$\langle \sigma v \rangle = \underbrace{\sigma_0\, c}_{\textit{s-wave}} + \underbrace{\sigma_1\, c\, \beta^2}_{\textit{p-wave}} + \mathcal{O}(\beta^4)$$

σ_0, σ_1, … rely on the DM model

Srednicki+(1998)

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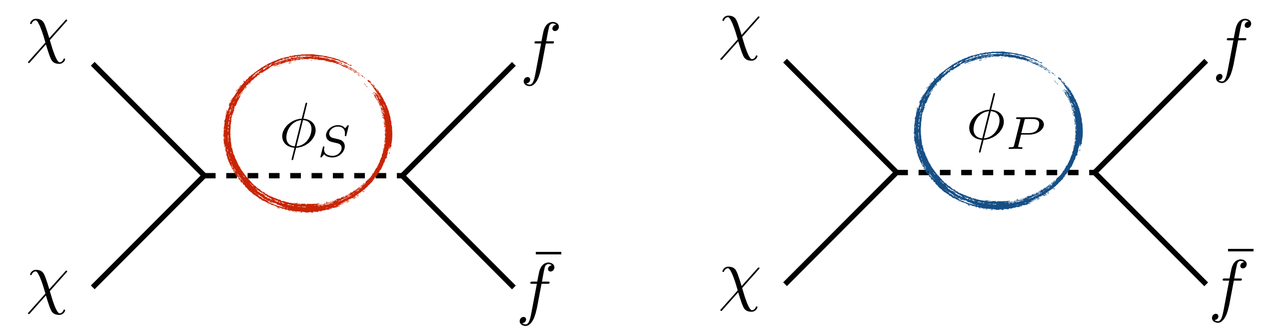
Srednicki+(1998)

	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

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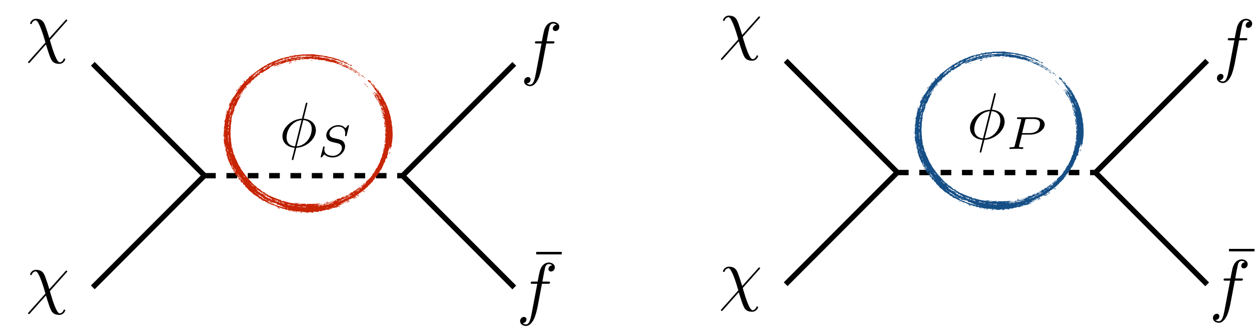

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Recombination (CMB)

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

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

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

Now in the Milky Way

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

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

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

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

Beyond the Maxwell-Boltzmann distribution

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

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

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

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

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Maxwell-Botzmann distribution (Standard Halo Model): $f(\vec{v}) = \dfrac{1}{v_c^3 \pi^{3/2}} \exp\left[- \left(\dfrac{\vec{v}}{v_c} \right)^2 \right]$

$\boxed{\textbf{Oversimplification}}$

- Isothermal sphere
- Infinite system (no bound)
- Ad hoc truncation at v_{esc}

Not a self-consistent model to describe the Galaxy

Need to go beyond the Standard Halo Model

$\Longrightarrow$ **Eddington inversion method (1916)**

Eddington inversion method

Observationally constrained Galactic mass model: $\rho_{\rm tot}(\vec{x}) = \rho_{\rm bar}(\vec{x}) + \rho_{\rm DM}(\vec{x})$ *McMillan (2016)*

Jeans' theorem + Poisson equation (spherically symmetric systems) $\Delta\Phi(r) = 4\pi\, G\, \rho_{\rm tot}(r)$

$\downarrow$ *Eddington (1916), Binney and Tremaine (1987)*

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Lacroix, Stref & Lavalle(2018)

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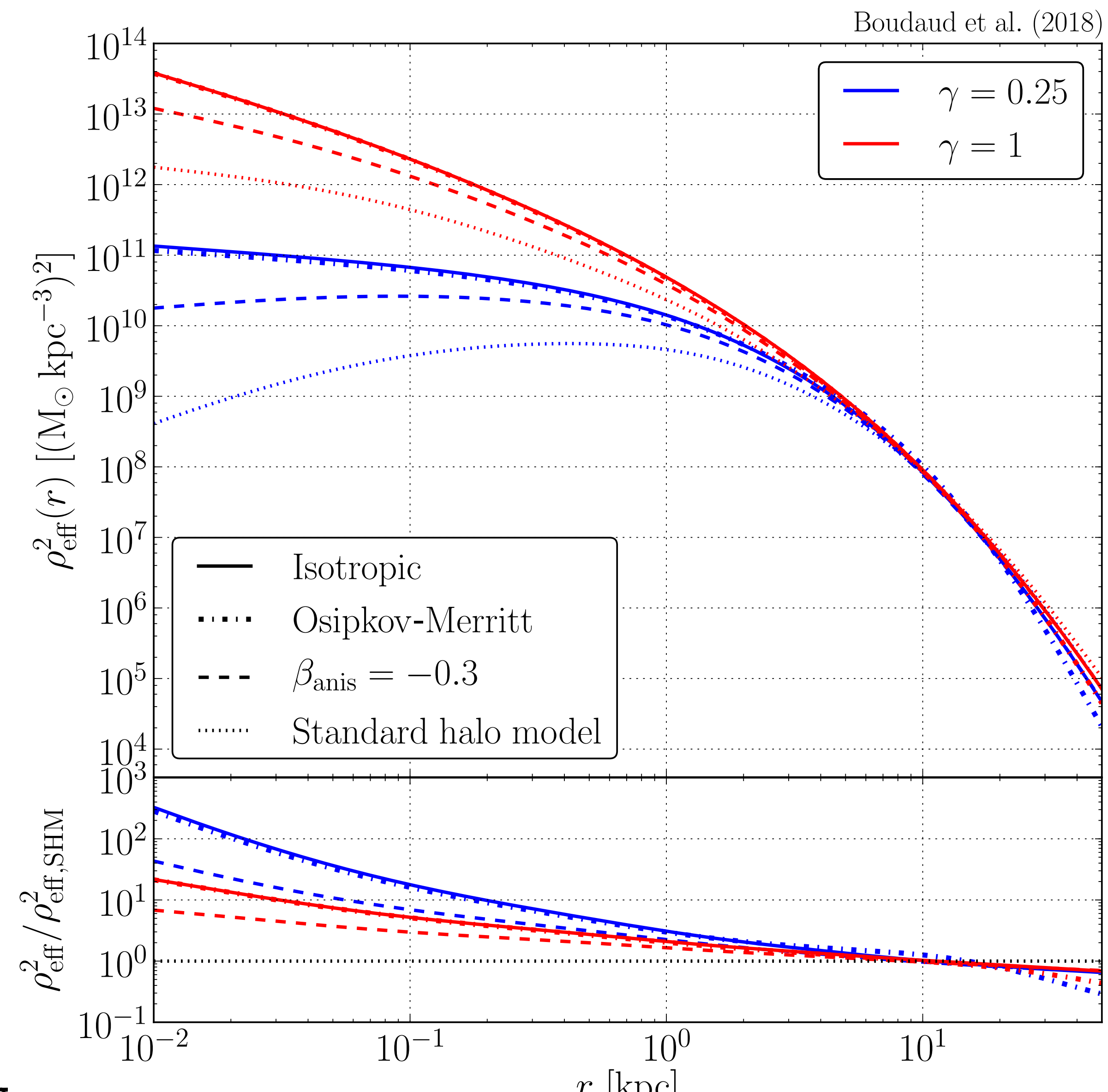
$$\langle \sigma v\rangle(r) = K_0(r) \int d^3\vec{v}_1 \int d^3\vec{v}_2\; f(|\vec{v}_1|, r) f(|\vec{v}_2|, r)\, \sigma\, v_{12}$$

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

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

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

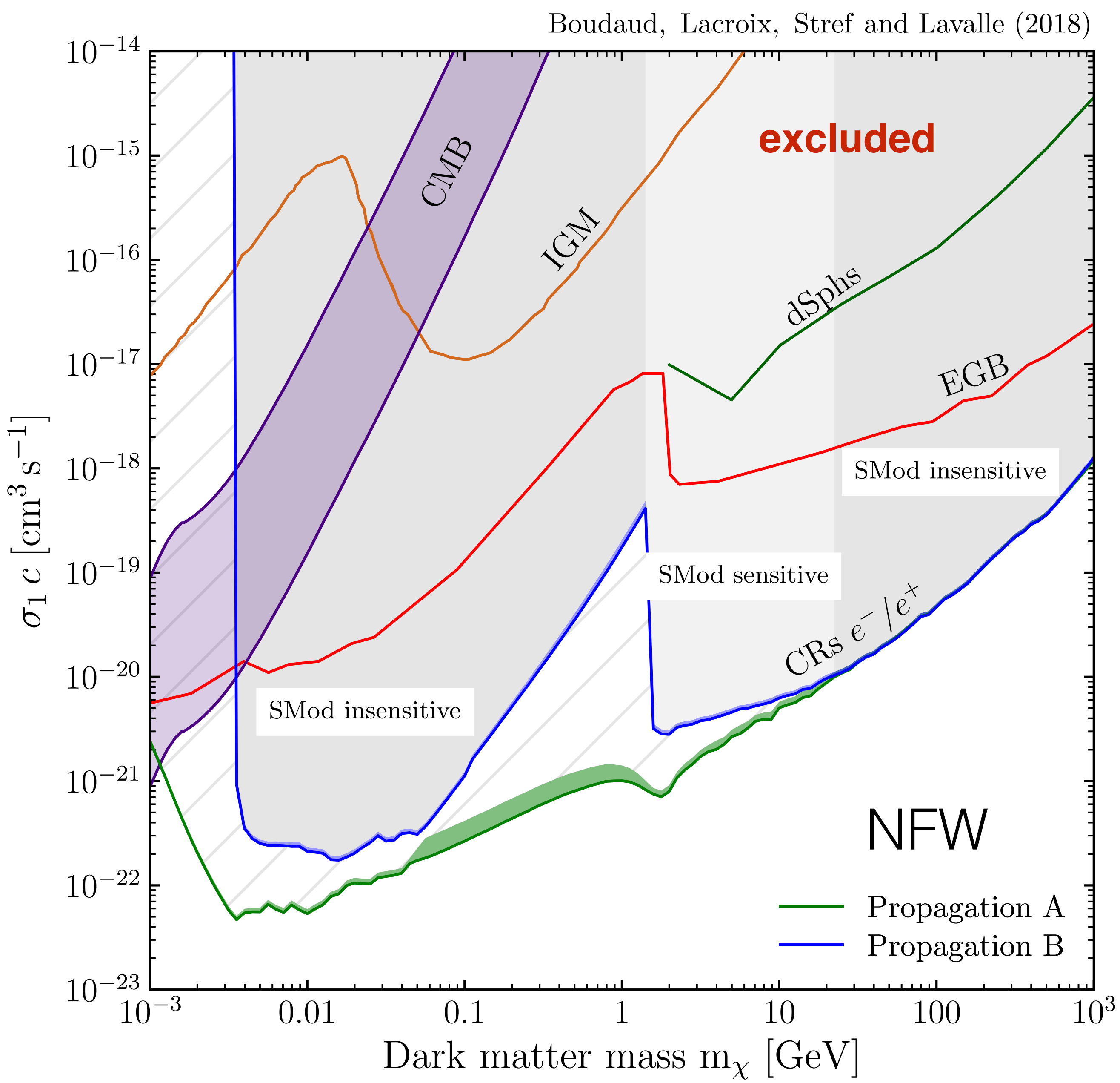
$$\rho^2_{\rm eff}(r) \equiv \rho^2_{\rm DM}(r)\langle\sigma v\rangle(r)$$

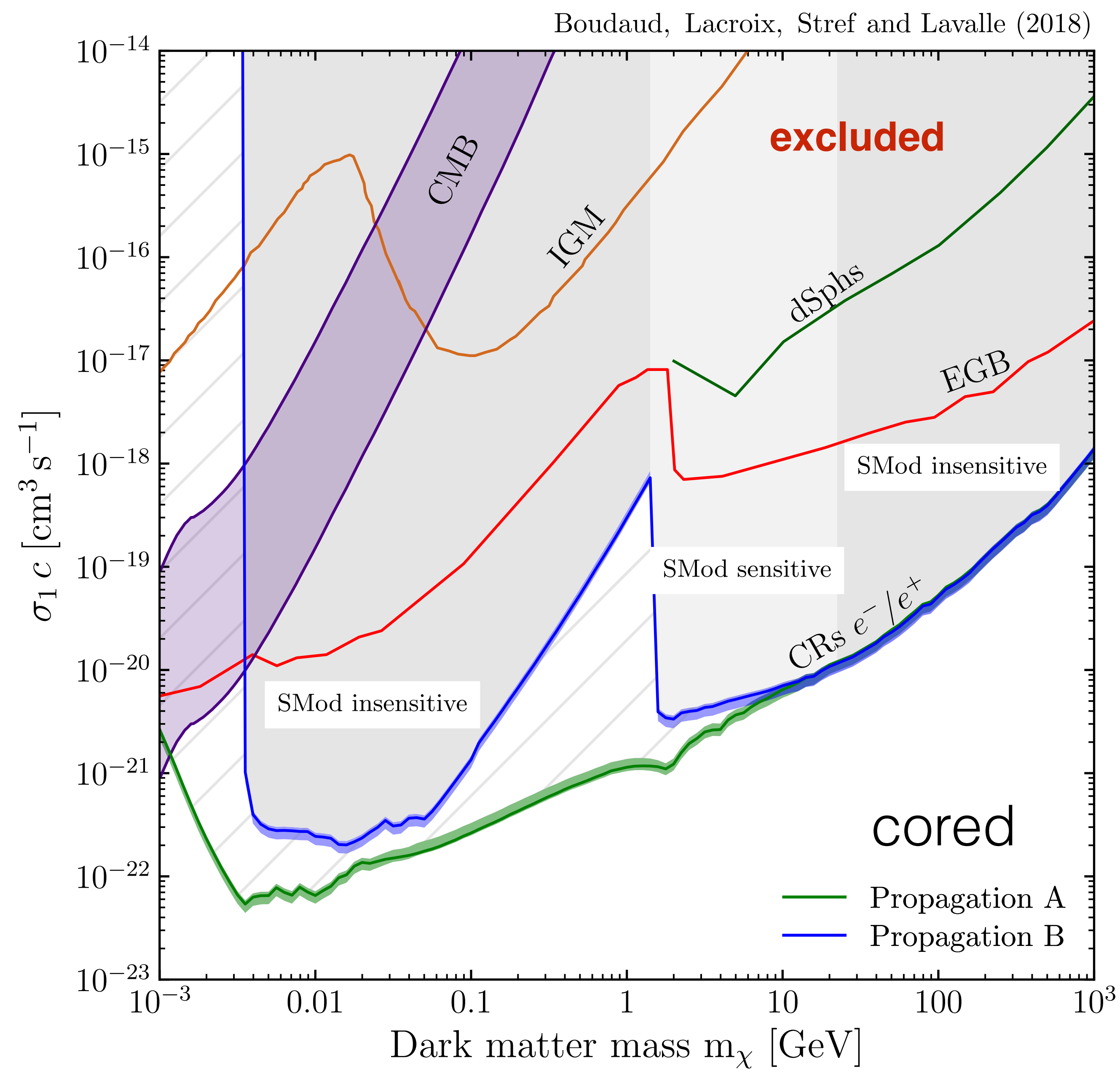


Velocity dependent annihilation (p-wave)

MB, Lacroix, Stref & Lavalle (2018)

$\langle \sigma v \rangle (r)$ from Eddington inversion method





- **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

Table of contents

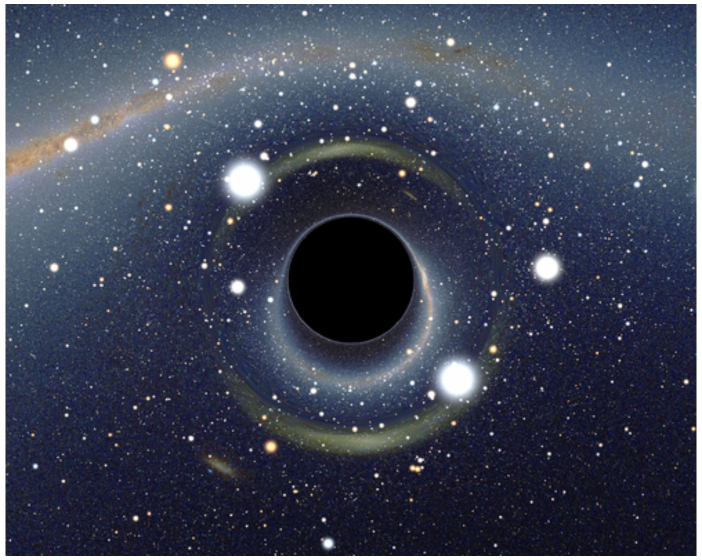
MB and M. Cirelli (PRL 122, 041104)

Primordial black holes as dark matter

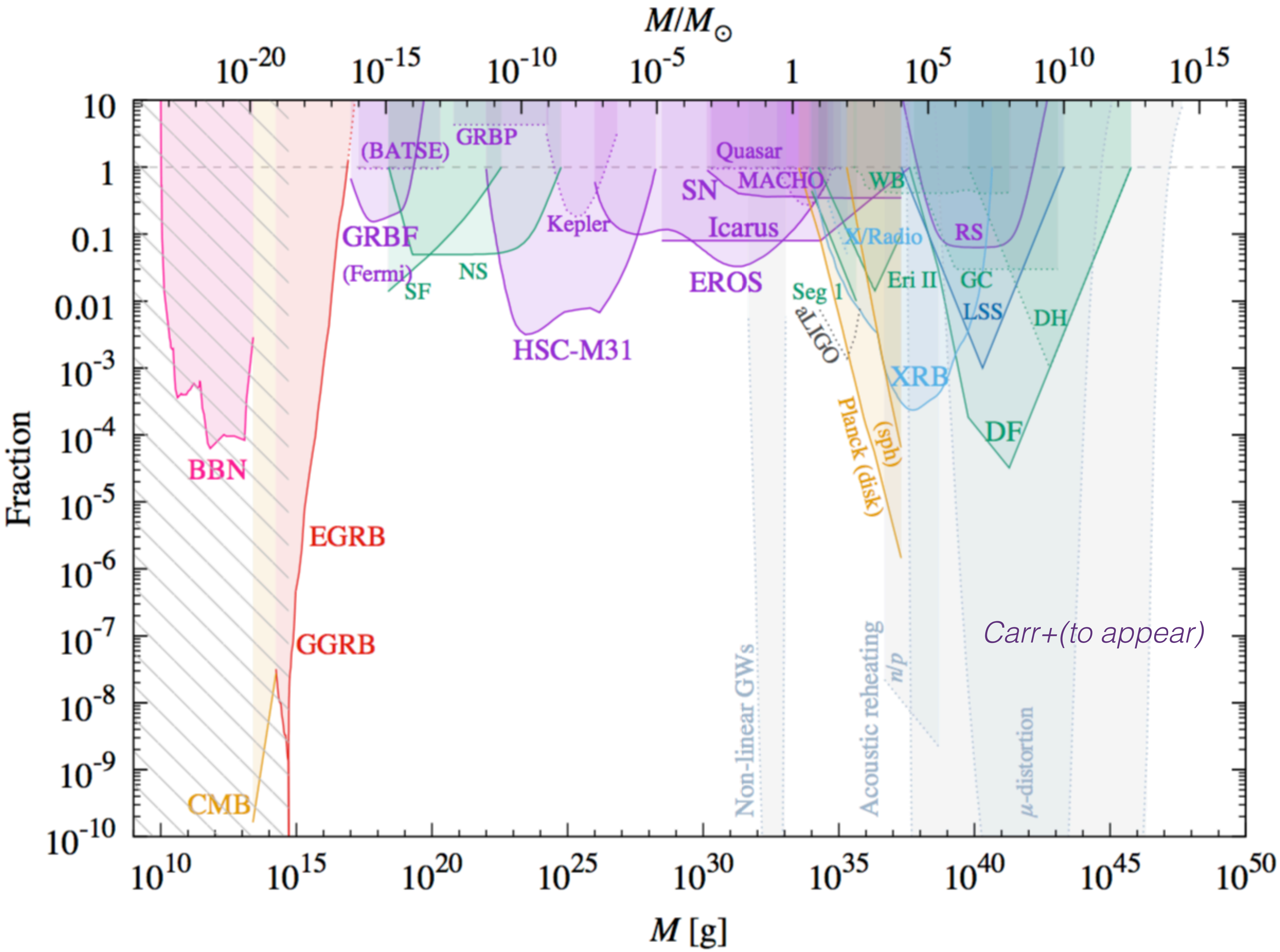
Produced from quantum fluctuations before inflation

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

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



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



Carr+(to appear)

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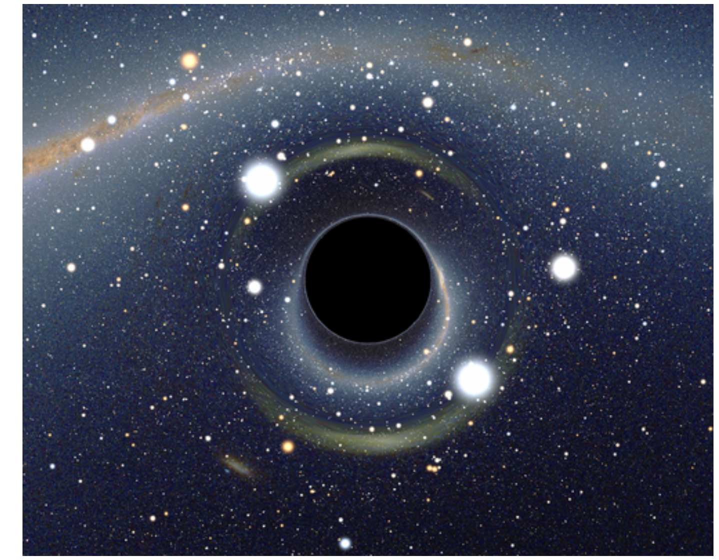

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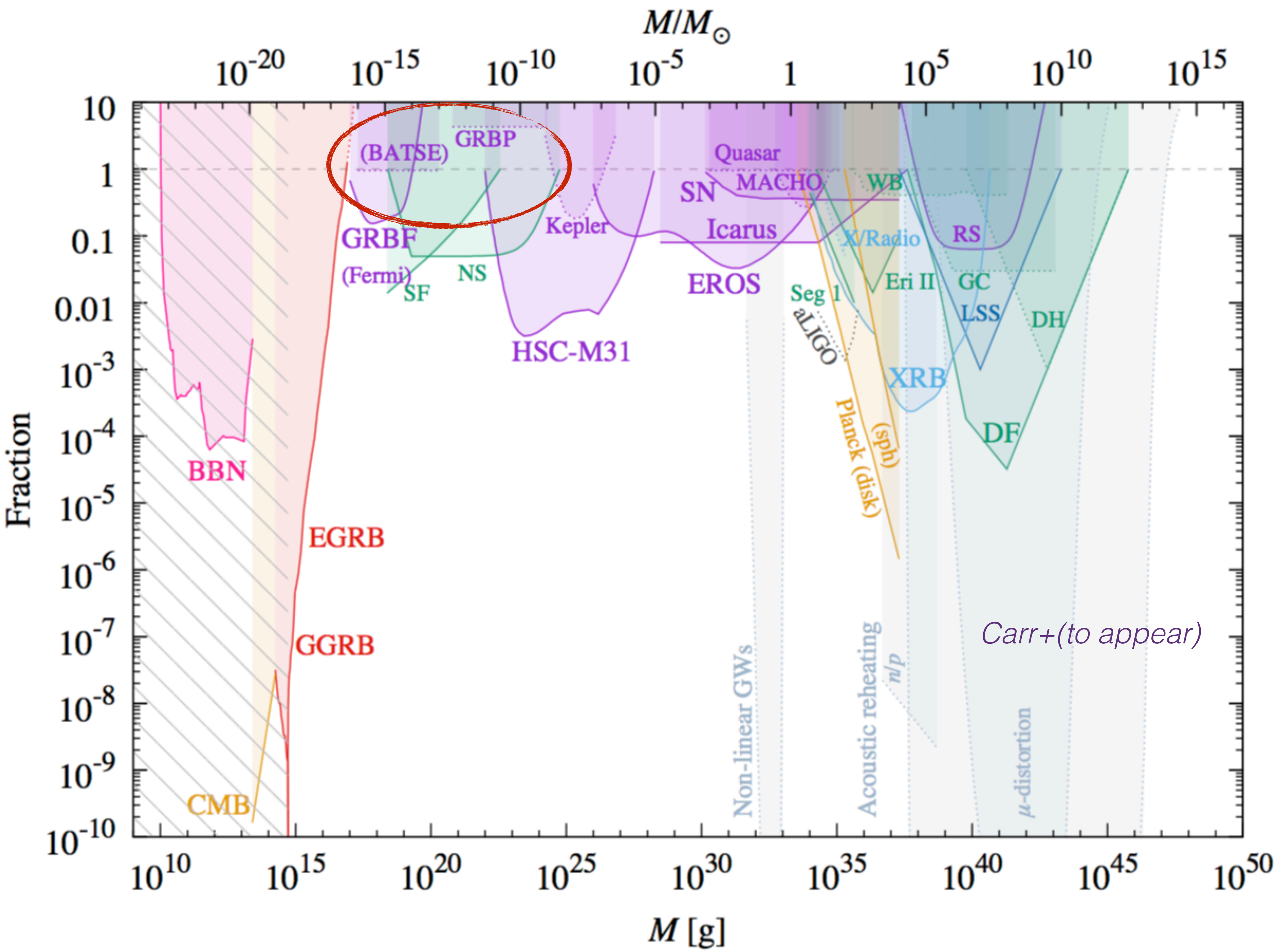

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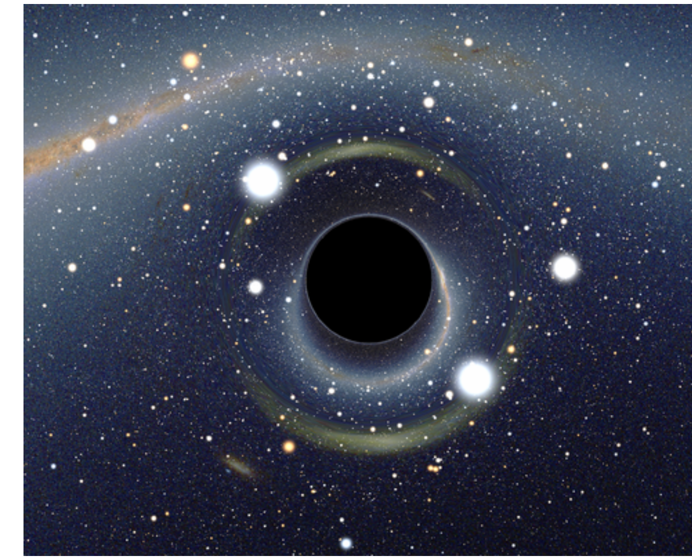

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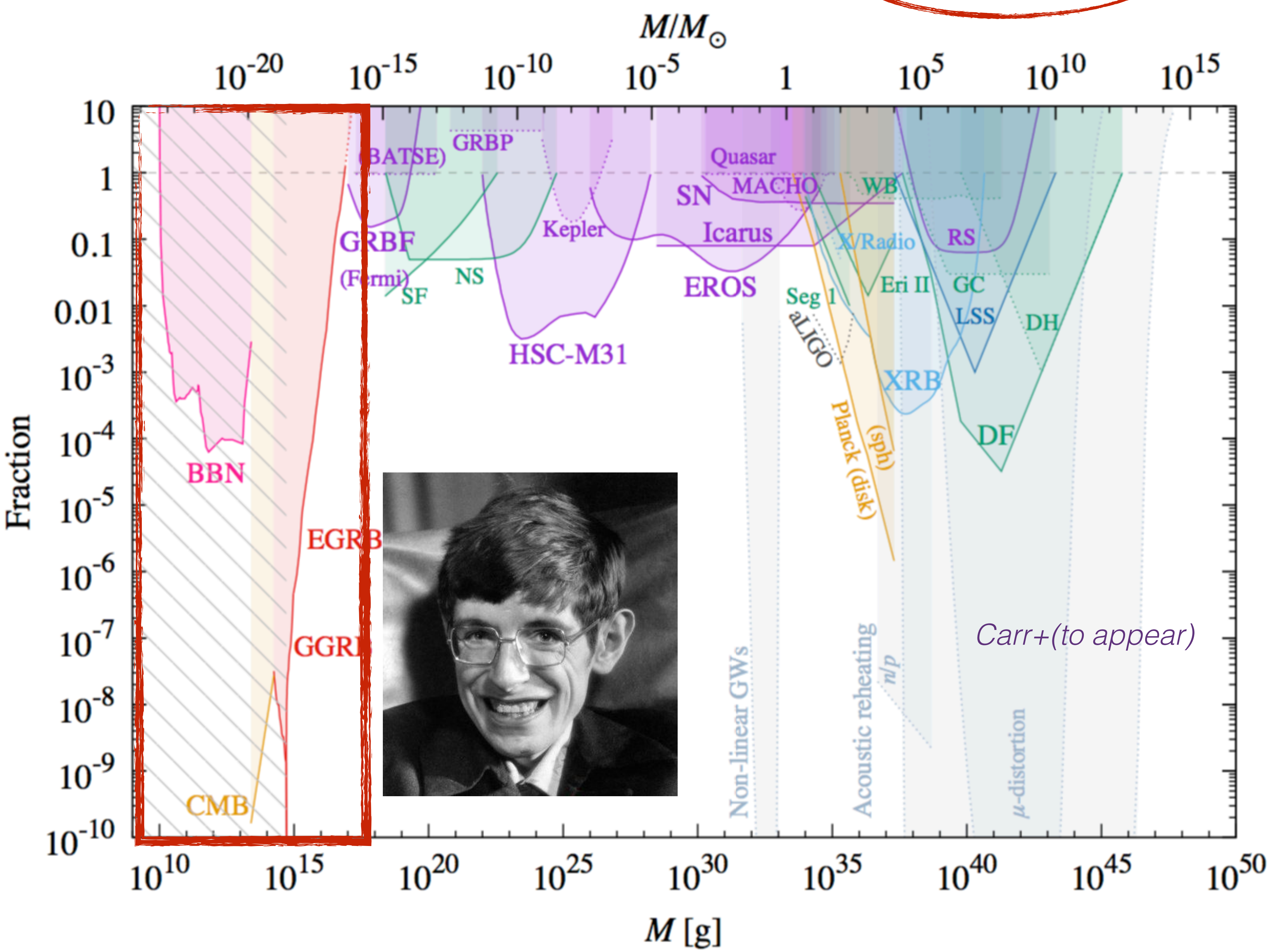


Microscopic BHs

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

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

(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

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

$$dU = T dS \implies T \propto \frac{\hbar\, c^3}{G\, k_\mathrm{B}\, M}$$

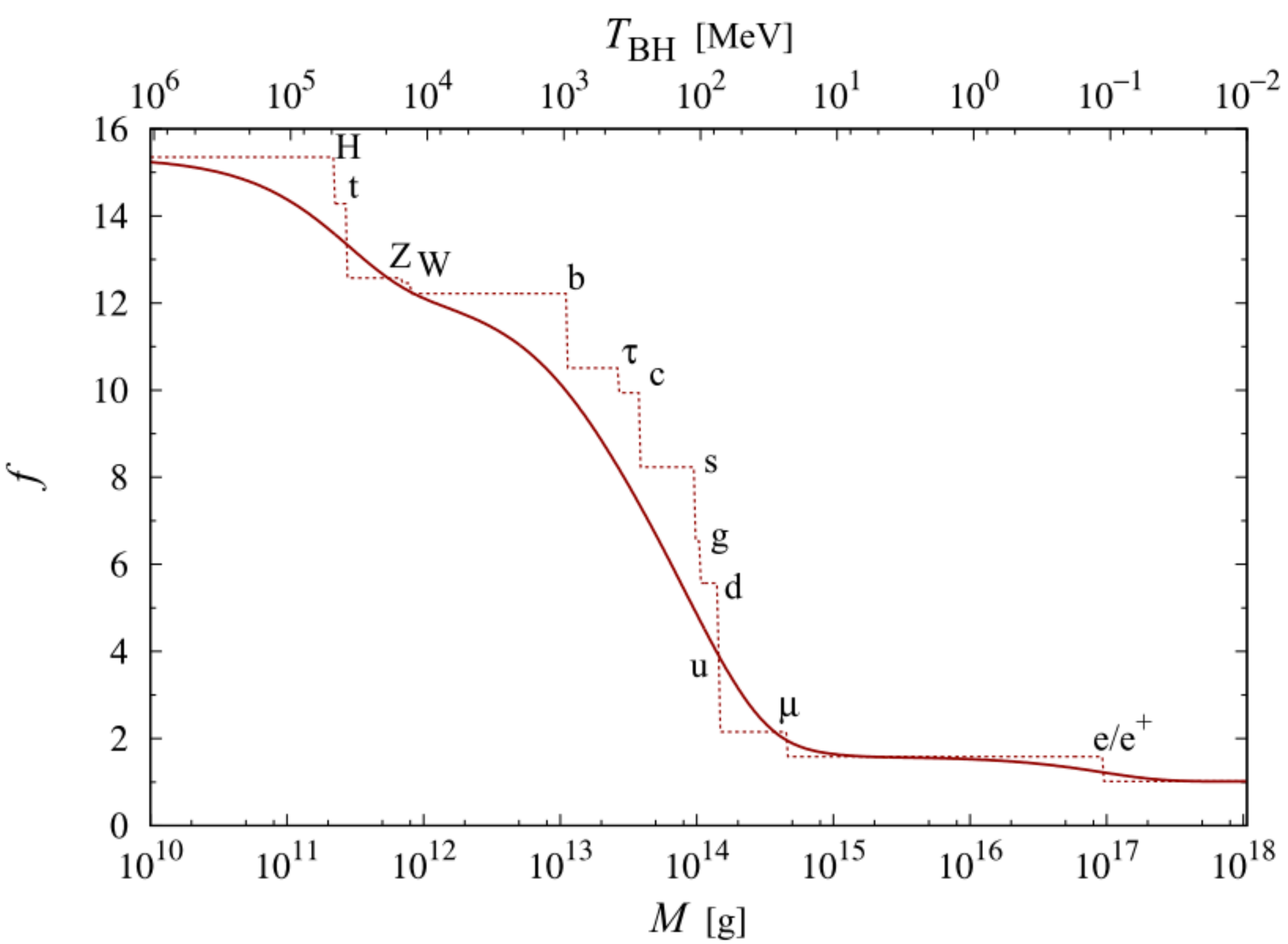
Hawking temperature from QFT in curved spacetime

$$T = \frac{\hbar\, c^3}{8\pi\, G\, k_\mathrm{B}\, M}$$

BHs lose mass radiating particles with the rate:

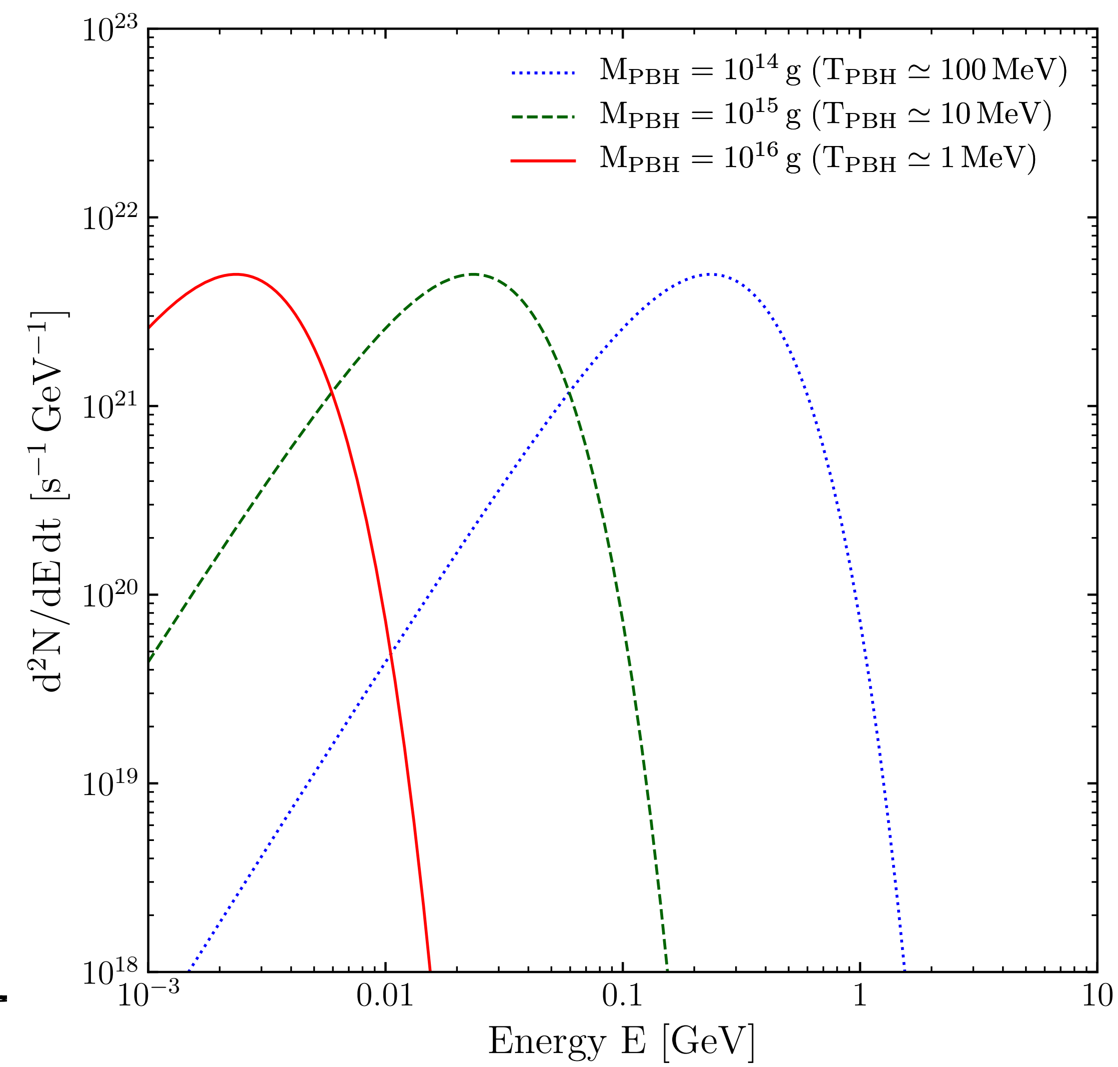
$$\frac{dM}{dt} \simeq -5.25 \times 10^{25} f(M) \left(\frac{\mathrm{g}}{M}\right) \mathrm{g\,s^{-1}}$$

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

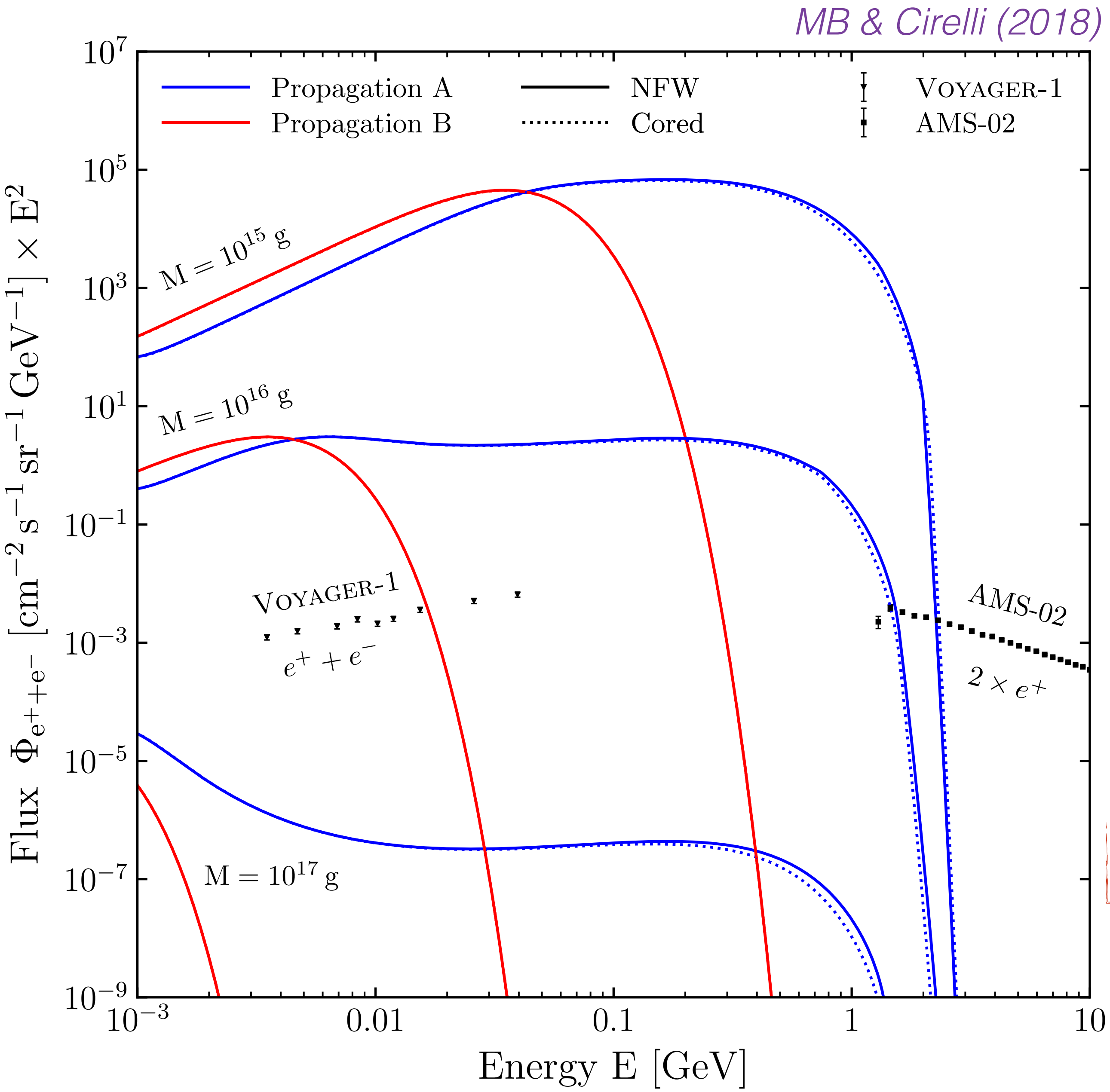


quasi-black body (grey) emission of $e^\pm$

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



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



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

Propagation B: no reacceleration

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

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

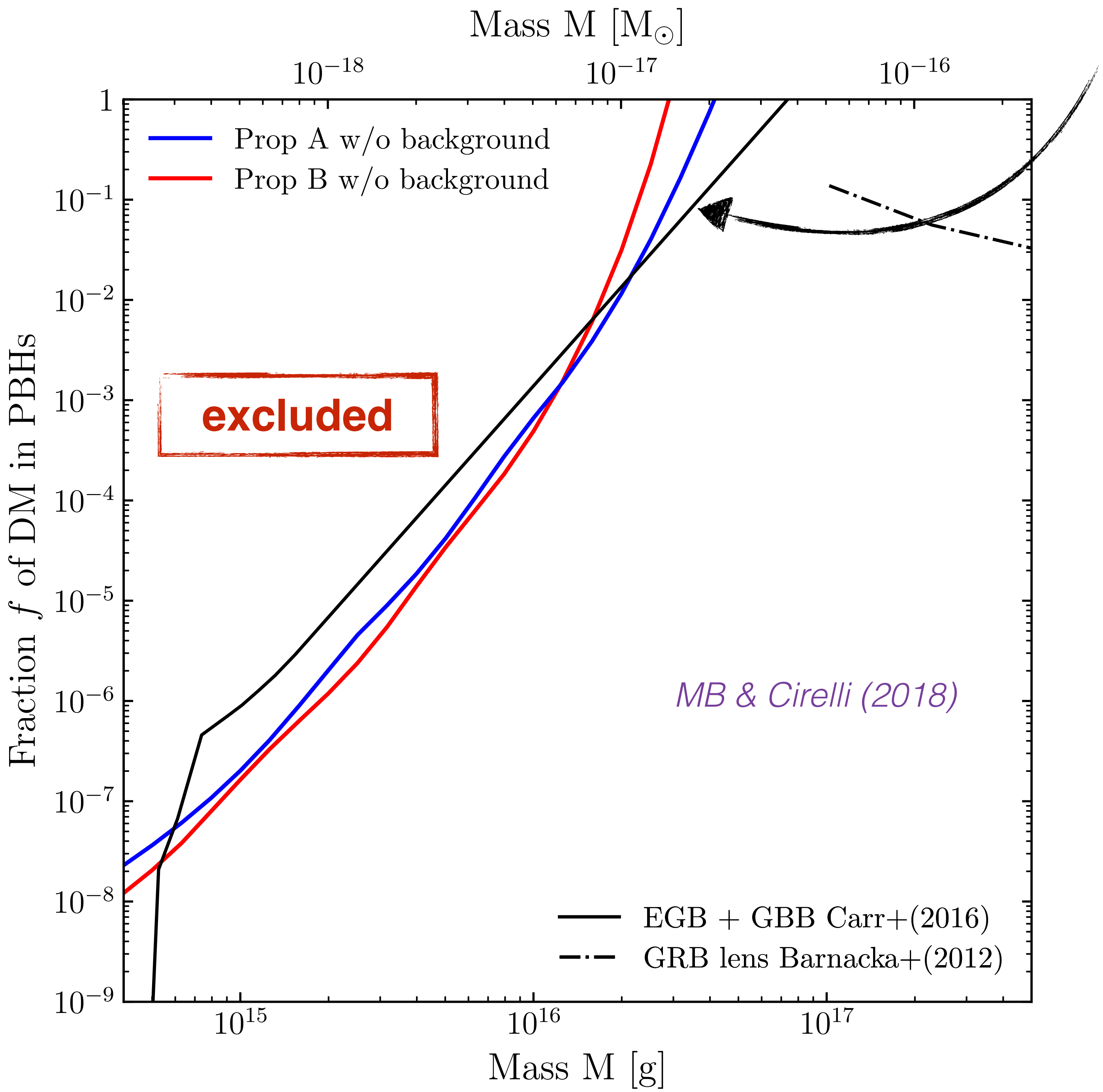
$$\rho_{\odot}^{\mathrm{DM}} = 0.4\,\mathrm{GeV cm^{-3}}$$

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



- EGB limits (Fermi-LAT) *Carr+(2012)*

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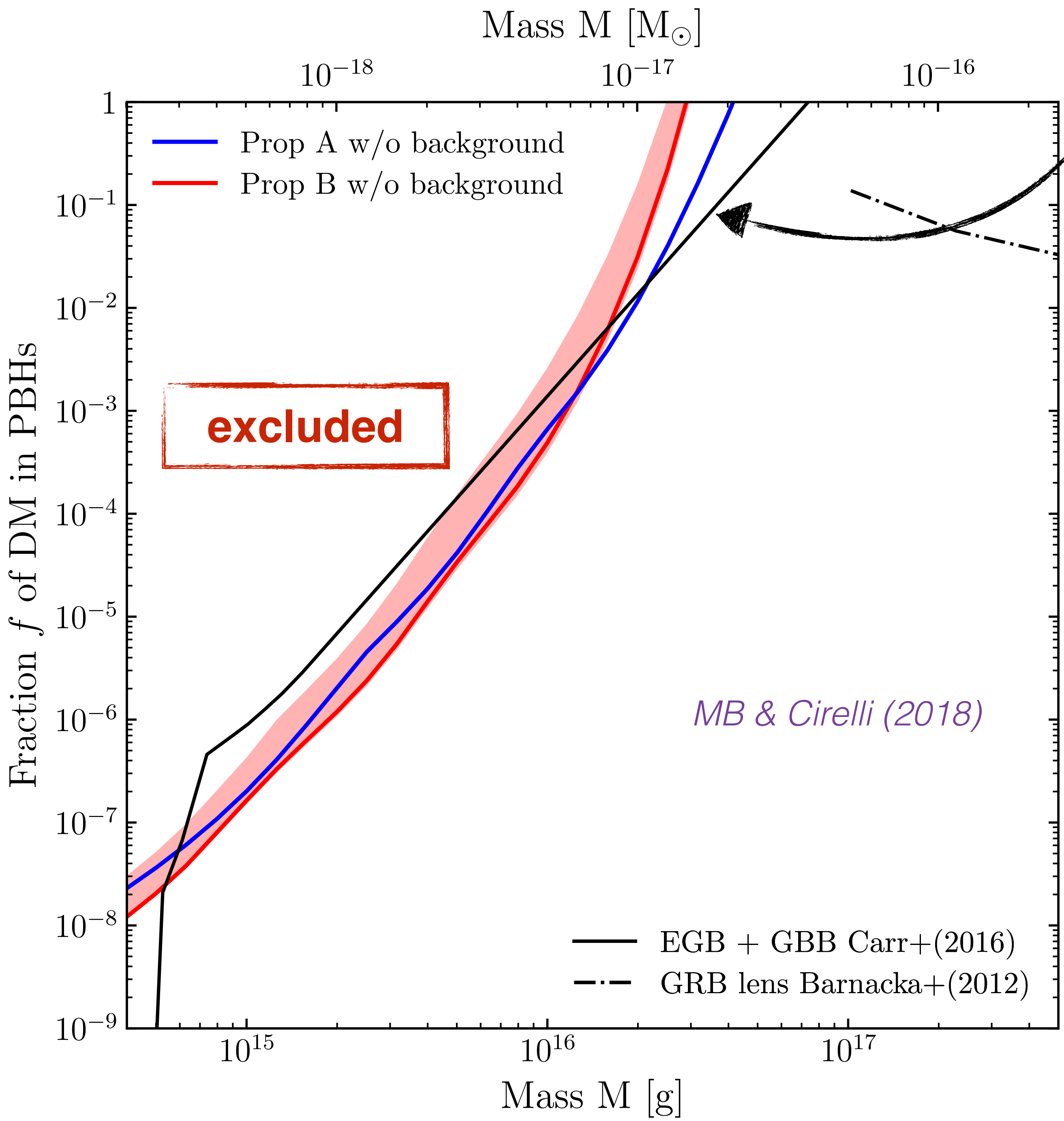

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- red band: propagation uncertainty (magnetic halo size) $4 < L < 20$ kpc *Reinert & Winkler(2018)*

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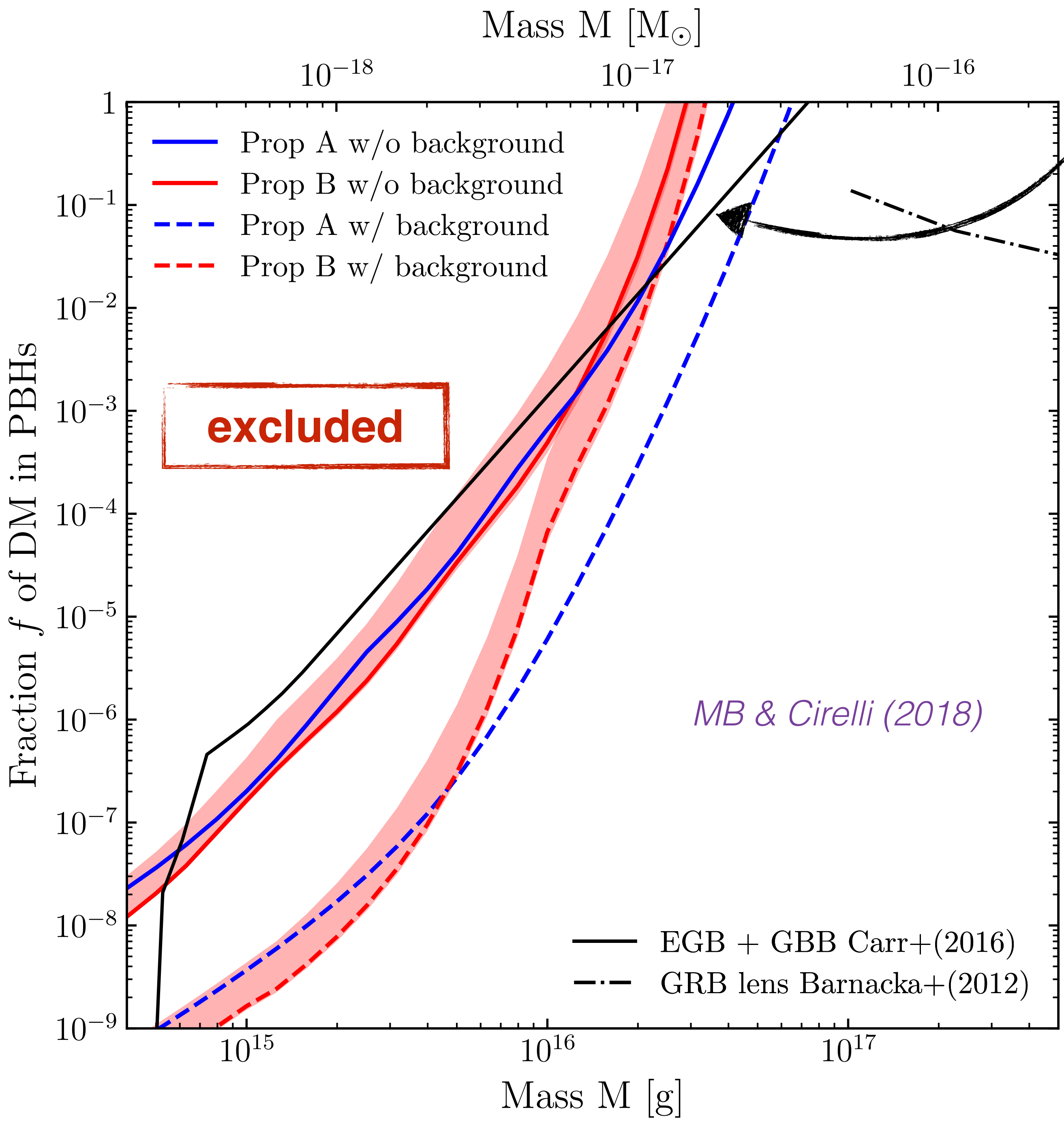
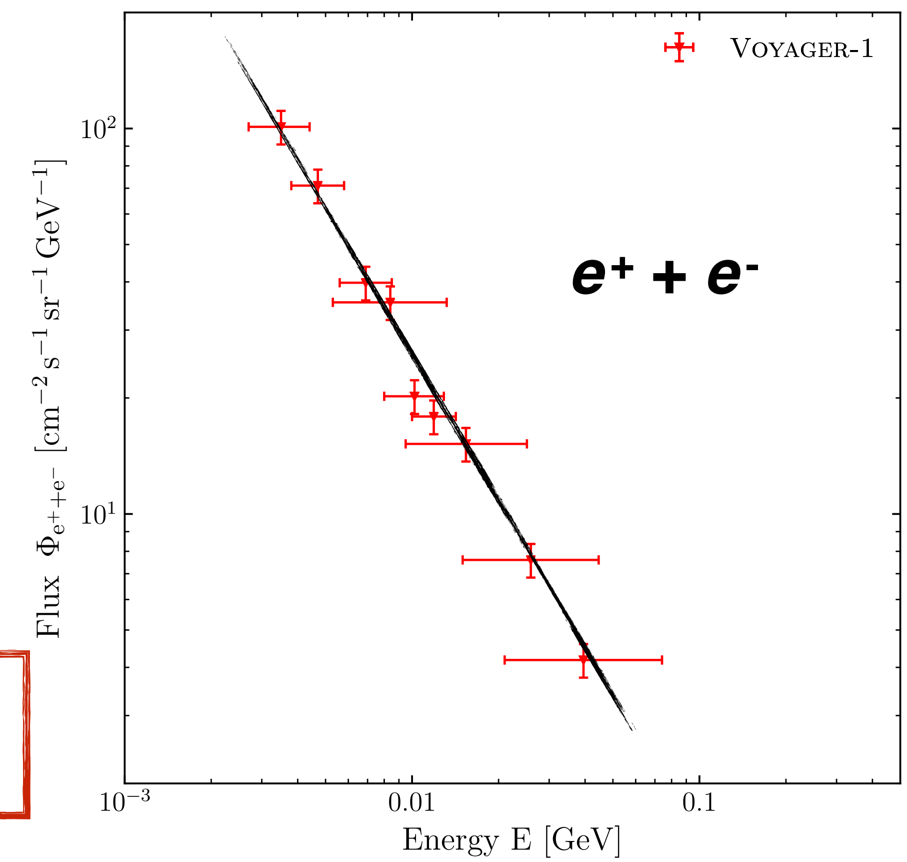


- EGB limits (Fermi-LAT) *Carr+(2012)*
- red band: propagation uncertainty (magnetic halo size)
  $4 < L < 20$ kpc *Reinert & Winkler(2018)*
- even better assuming a background for Voyager-1 data (SNRs e^-)

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



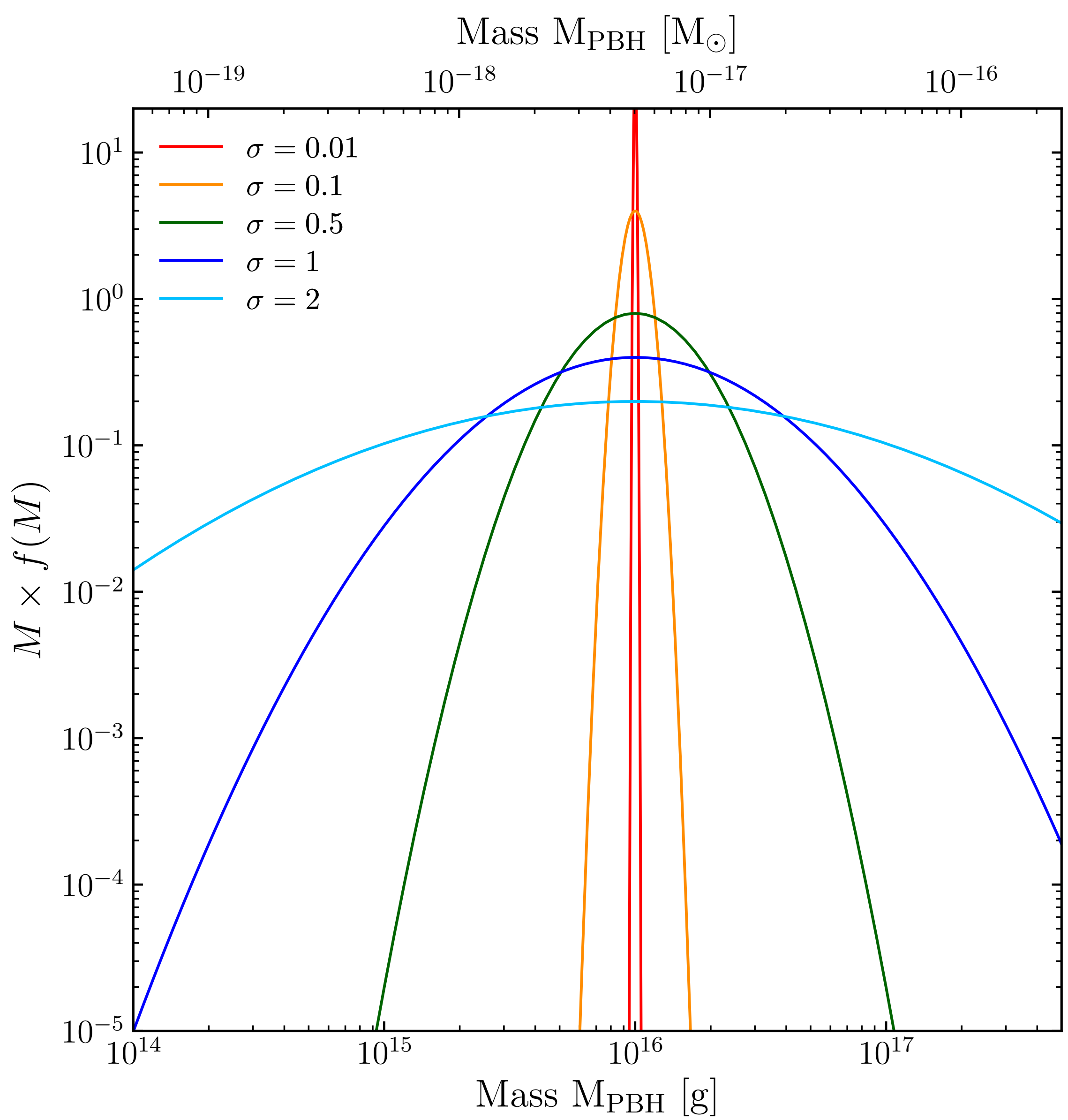
local constraints (1~kpc), **no** cosmological assumptions
$\Rightarrow$ **complementary** to cosmological constraints (EGB, CMB, EDGES)

Constraints for a lognormal mass function

PBHs production models most of the time similar to a lognormal distribution

e.g: Carr+(2017), Kanike+(2018), Calcino+(2018)

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



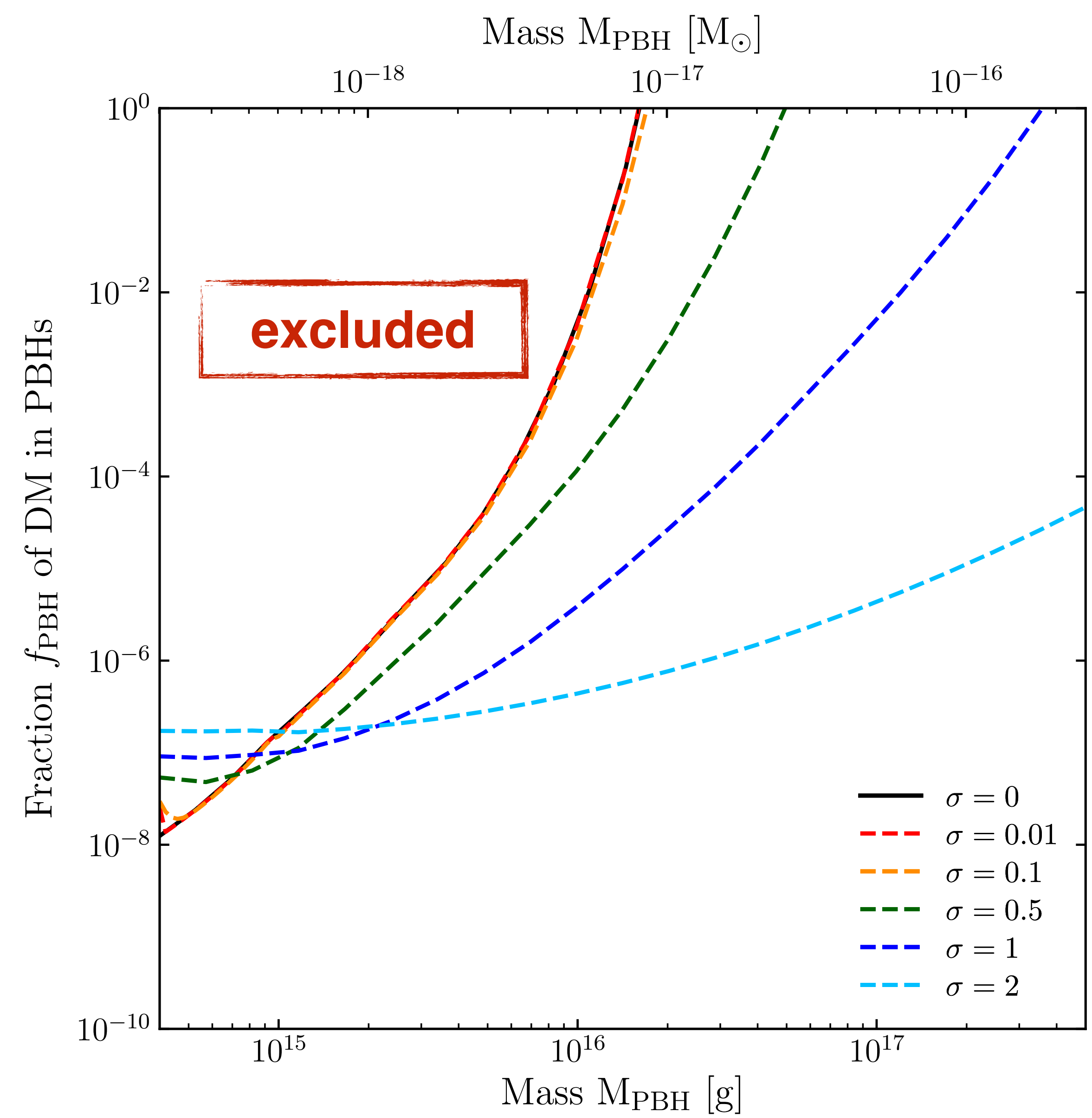


Table of contents

Summary

- The **pinching method** allows to compute **semi-analytically** the flux of $e^{\pm}$ below 10 GeV taking into account **all propagation effects**

- **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 the 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

The pinching method

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

The pinching method

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

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

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

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

pinching factor

The pinching method

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

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

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

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

pinching factor

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

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

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

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

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

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

$$C_{i,n} = \frac{1}{4} \left[\left(\frac{\alpha_i}{R} \right)^2 + (n k_0)^2 \right]$$

The pinching method

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

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

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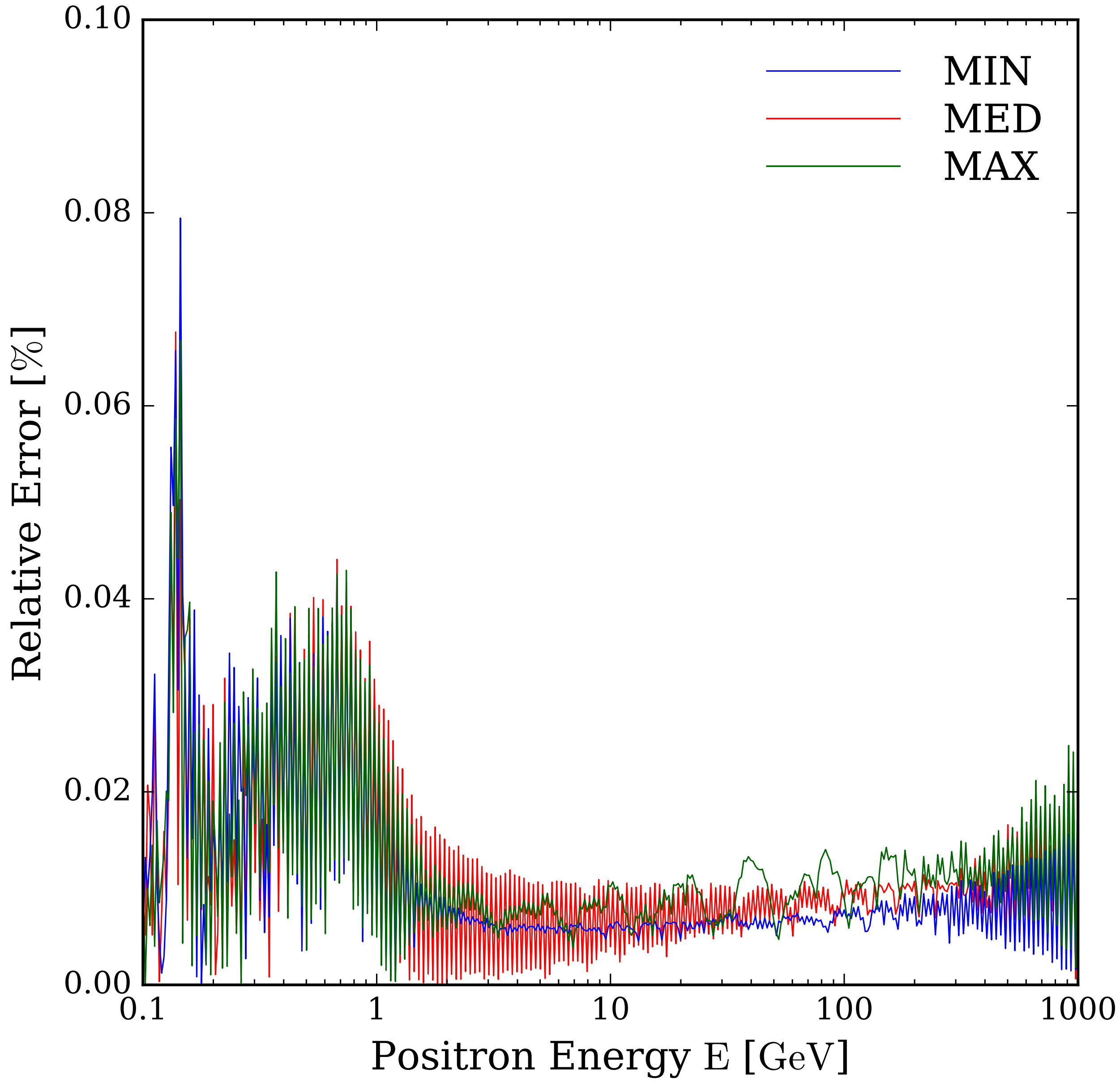
$$b^{eff}_{\mathrm{halo}}(E, r) = \bar{\xi}(E, r)\, b_{\mathrm{halo}}(E)$$

pinching factor

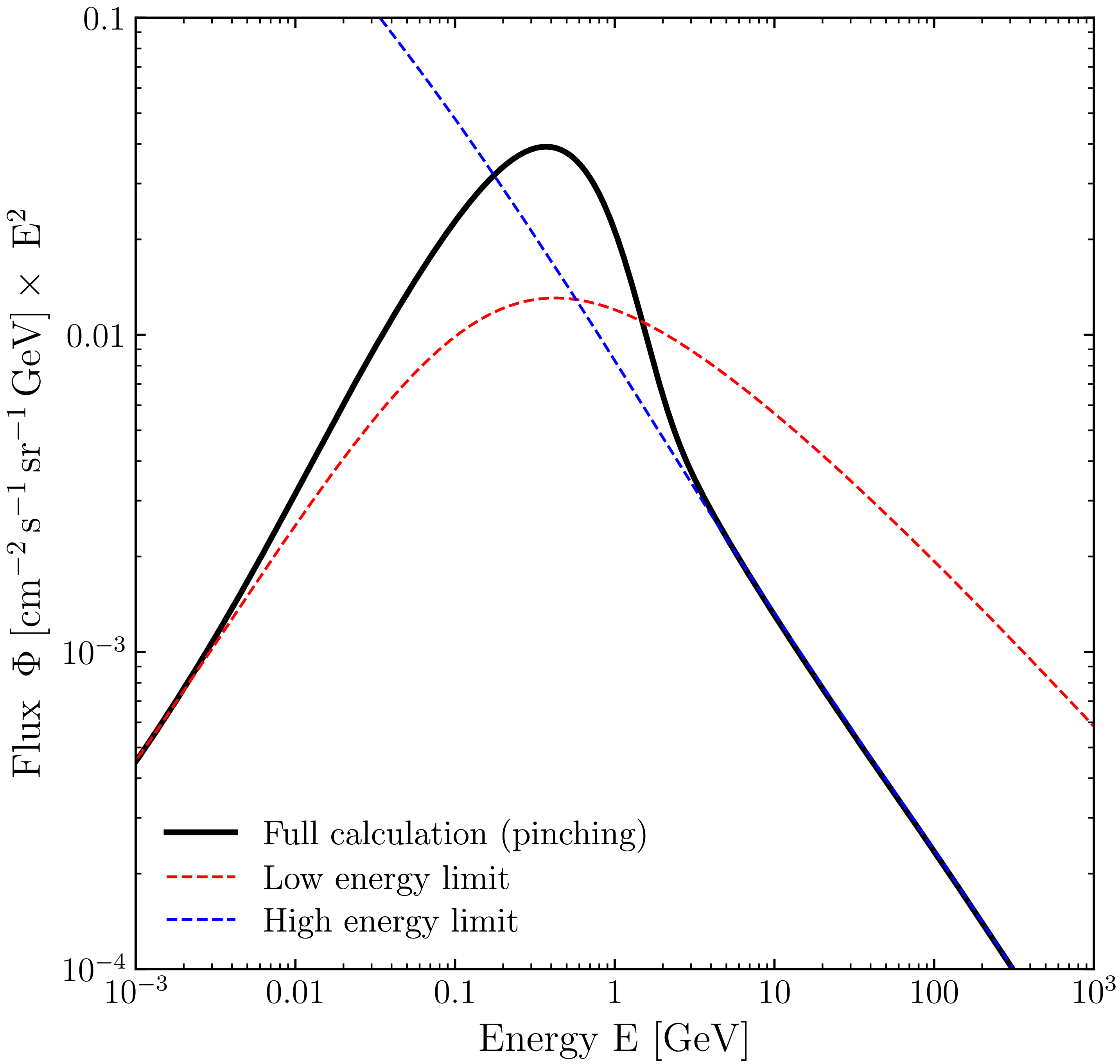


The error we commit « pinching » the halo energy losses is smaller than 0.1%

The pinching method

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

Including all propagation effects
e.g: electrons:



Mathieu Boudaud

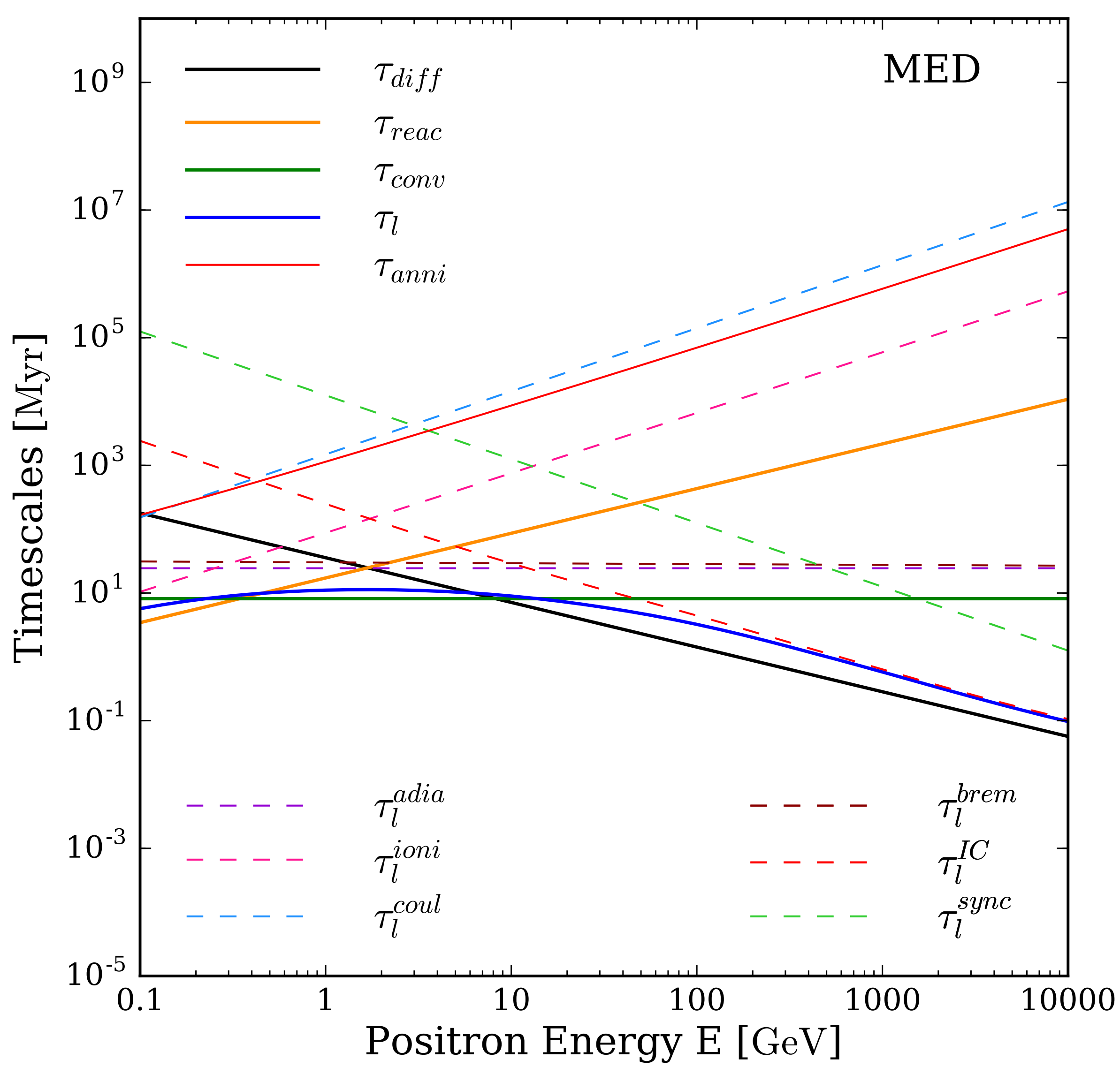
The pinching method

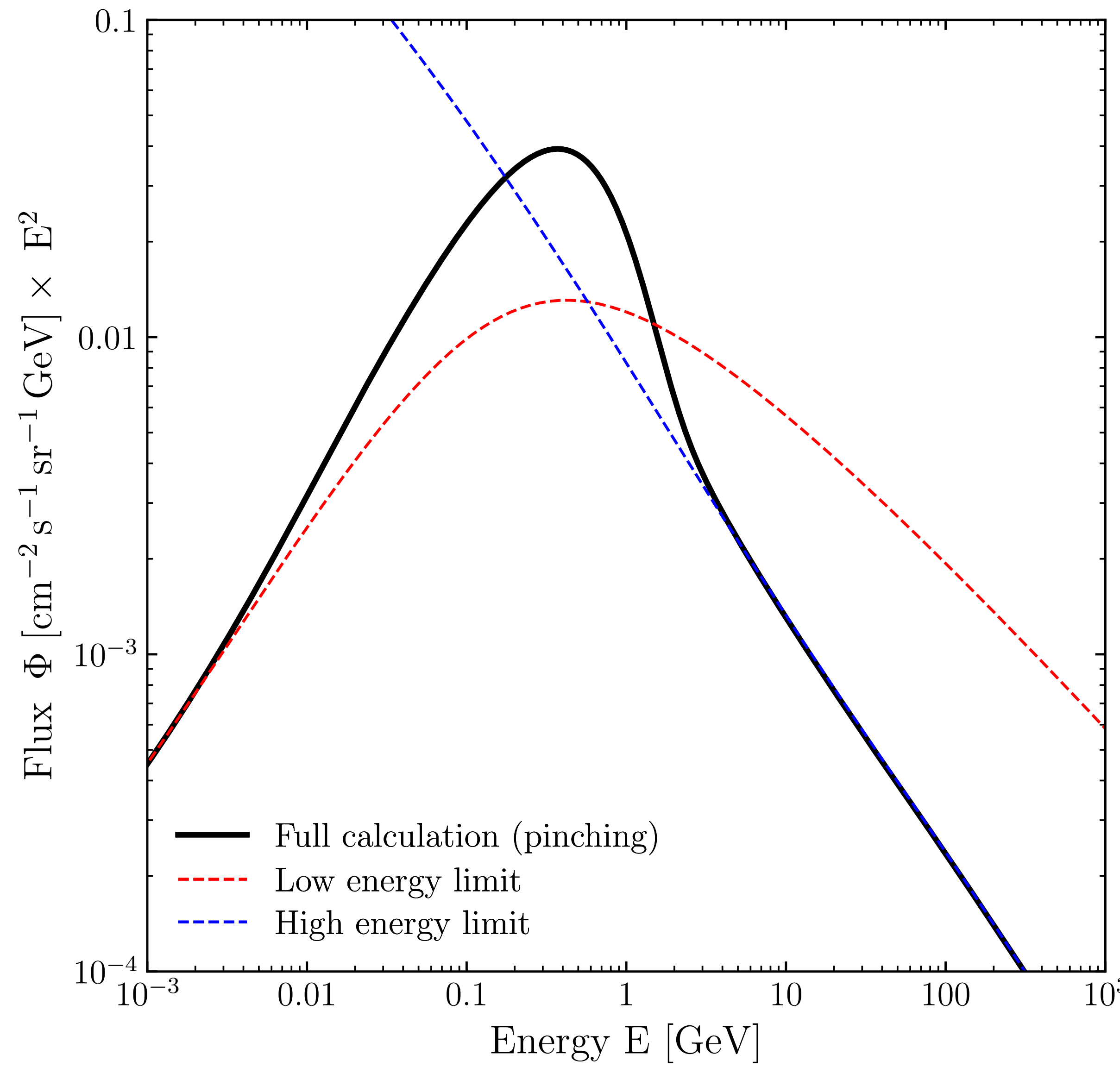
$$\partial_z[V_C\,\mathrm{sign(z)}\,\psi] - K(E)\,\Delta\,\psi + 2h\,\delta(z)\,\partial_E\left\{\left[b_{\rm disc}(E) + b^{eff}_{\rm halo}(E)\right]\,\psi - D(E)\,\partial_E\,\psi\right\} = Q(E,\vec{x})$$

Corrections on b^{eff}_{halo} below a few GeV are needed

Below a few GeV b^{eff}_{halo} is subdominant compared to the other processes

We are safe! 😊





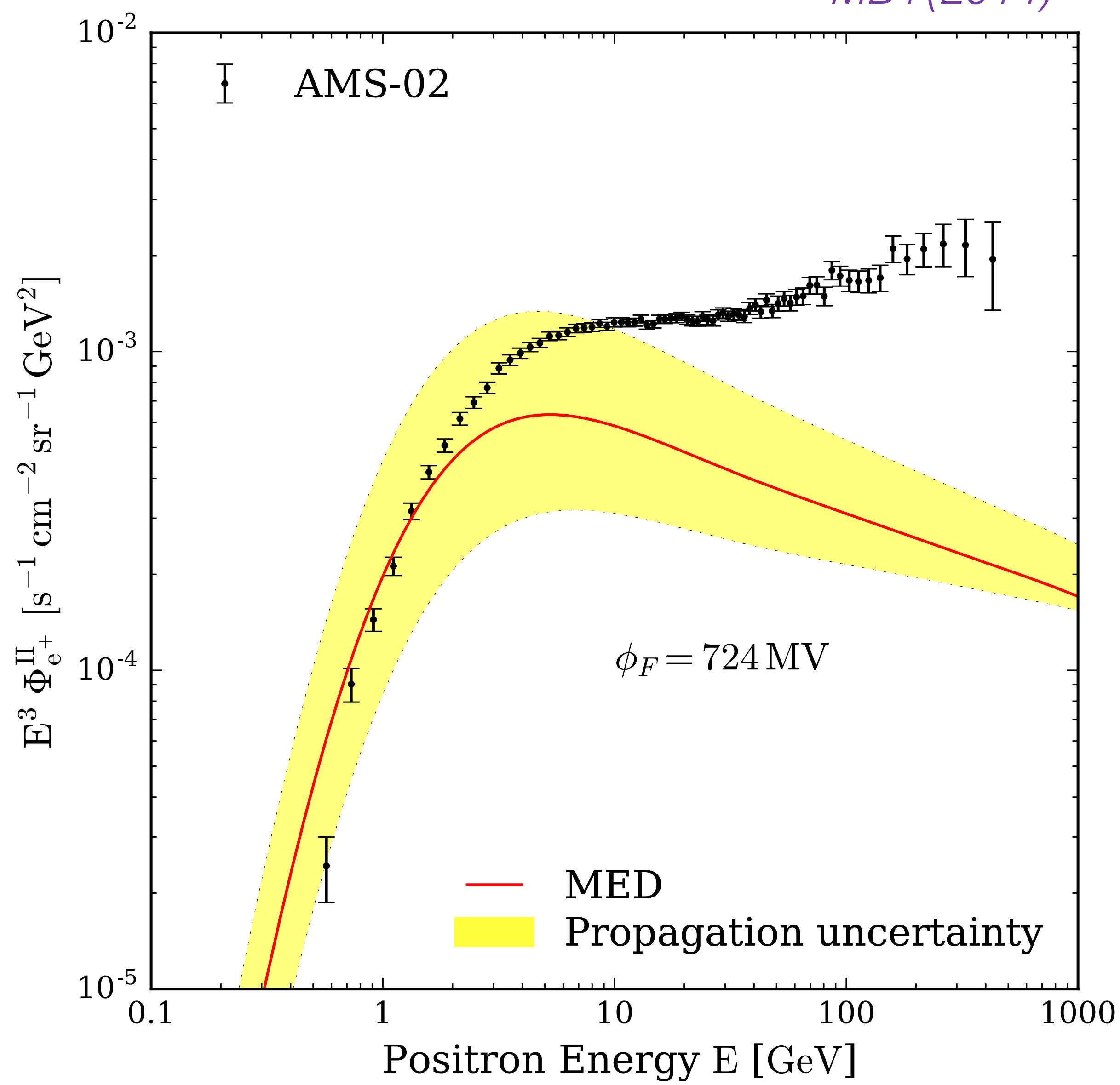
Mathieu Boudaud

Astrophysical background of secondary positrons

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

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

MB+(2014)



Positron excess above ~ 10 GeV!

Astrophysical secondary positrons

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

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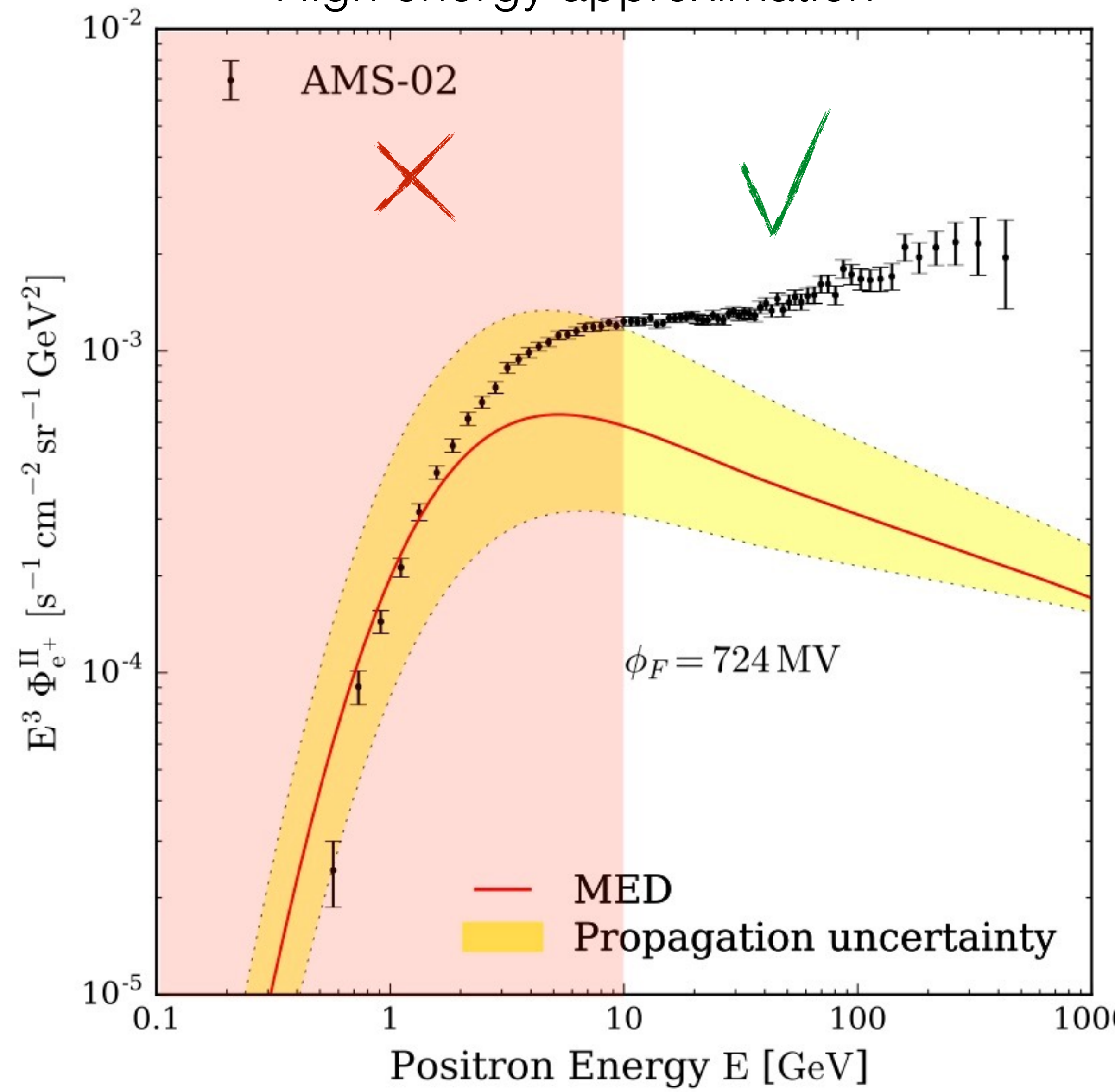
High energy approximation



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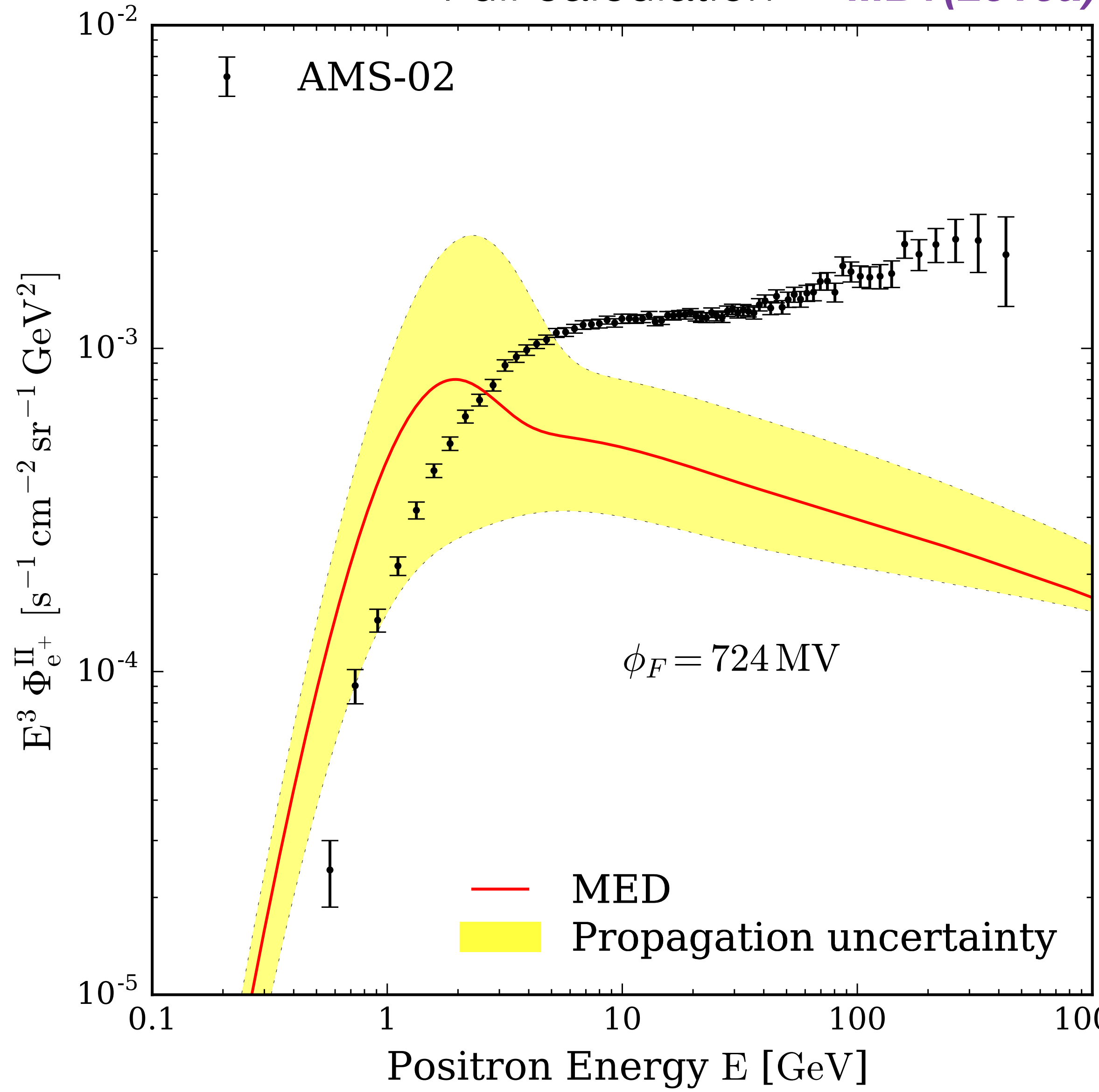
Full calculation ***MB+(2016a)***



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.

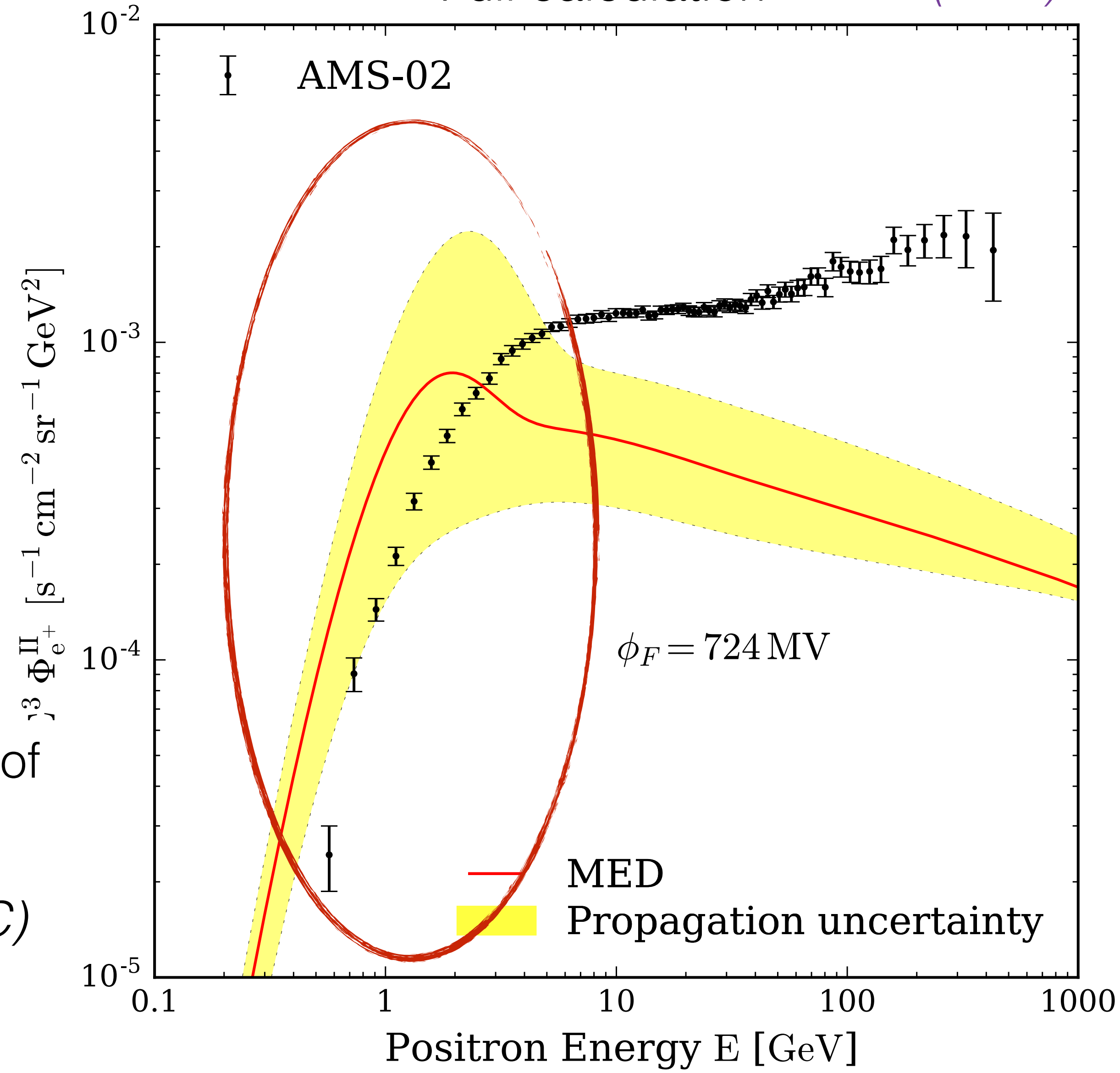
The degeneracy between K_0 and L can be lifted!

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!

Full calculation *MB+(2016)*

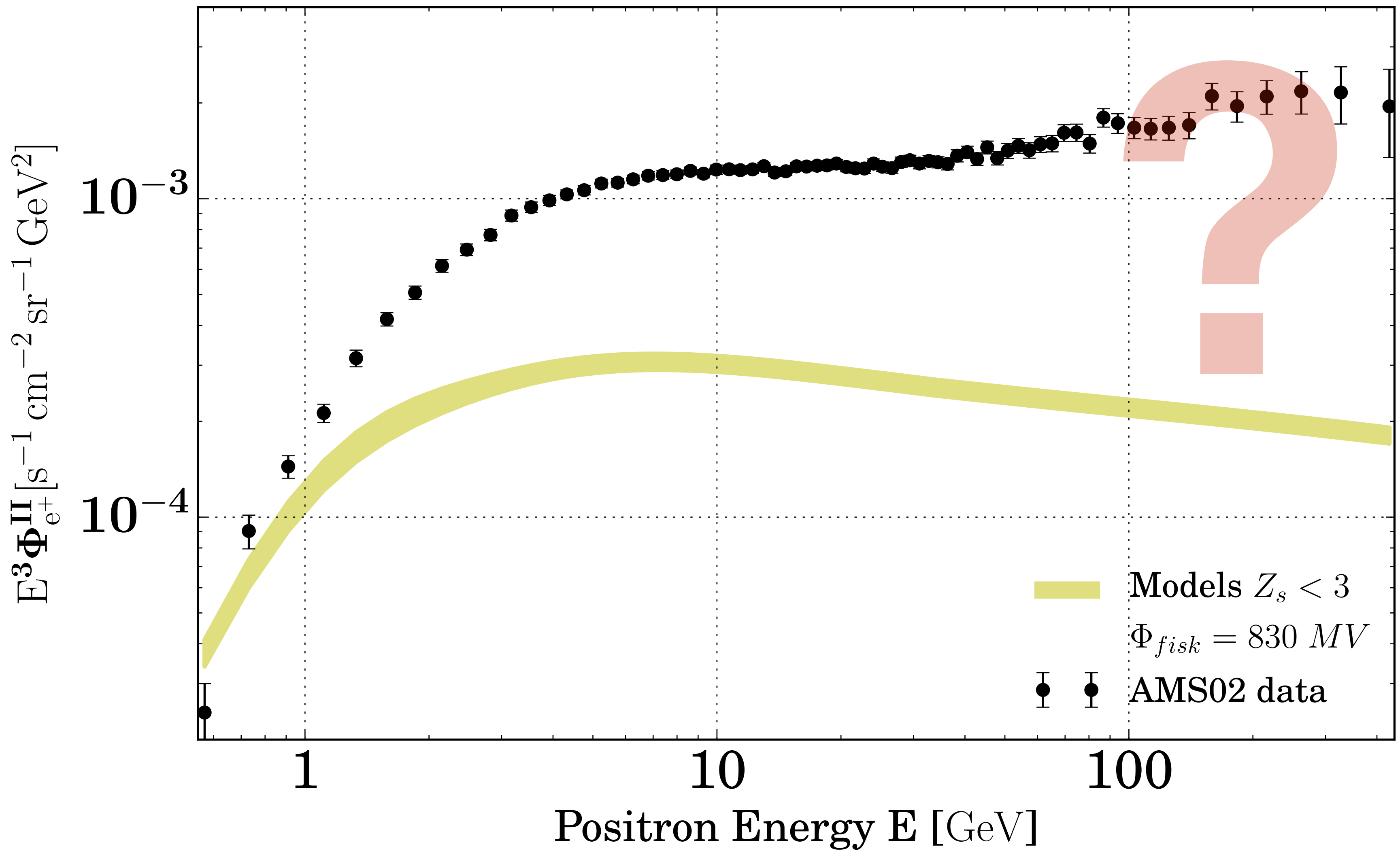


The AMS-02 positrons data favour the **MAX-type** sets of propagation parameters.

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

The Dark Matter scenario

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

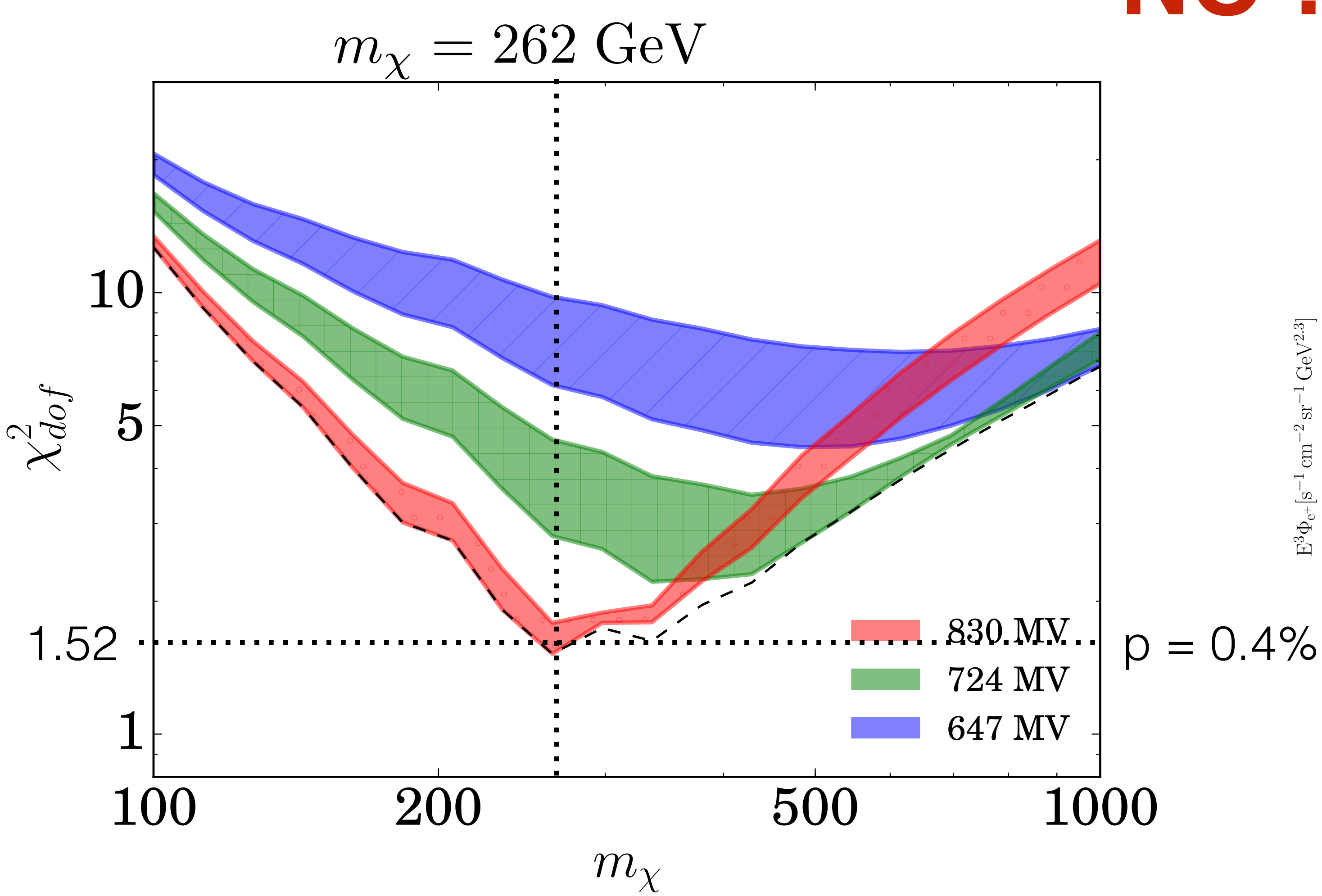


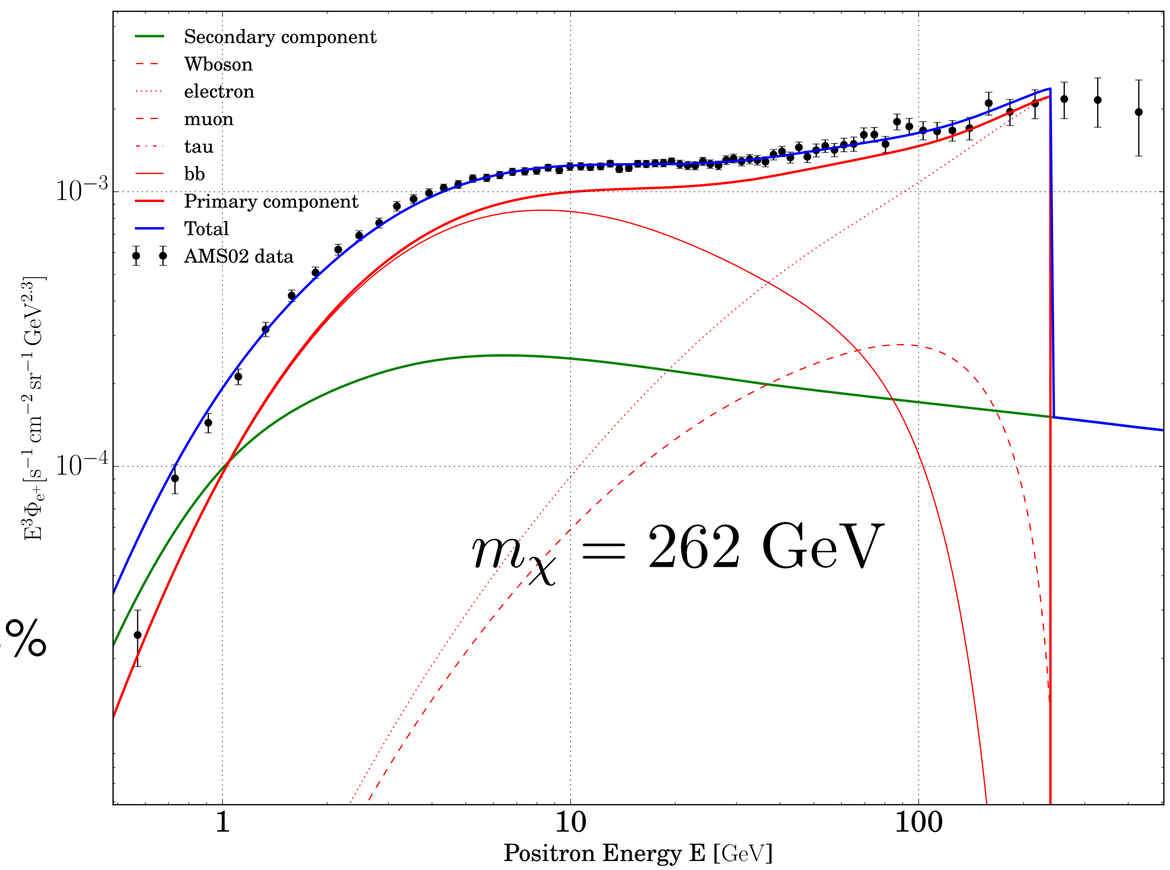
The Dark Matter scenario

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

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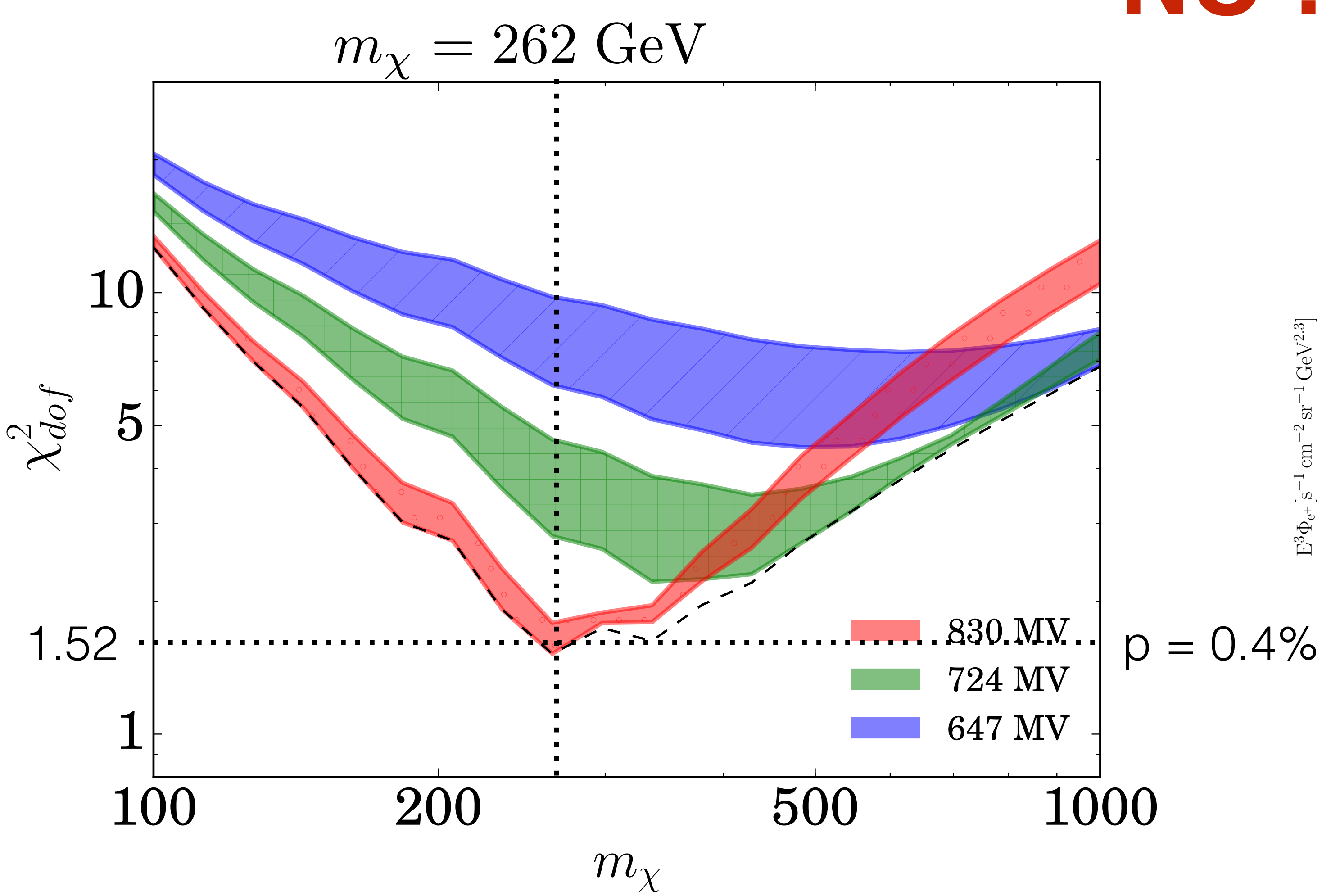
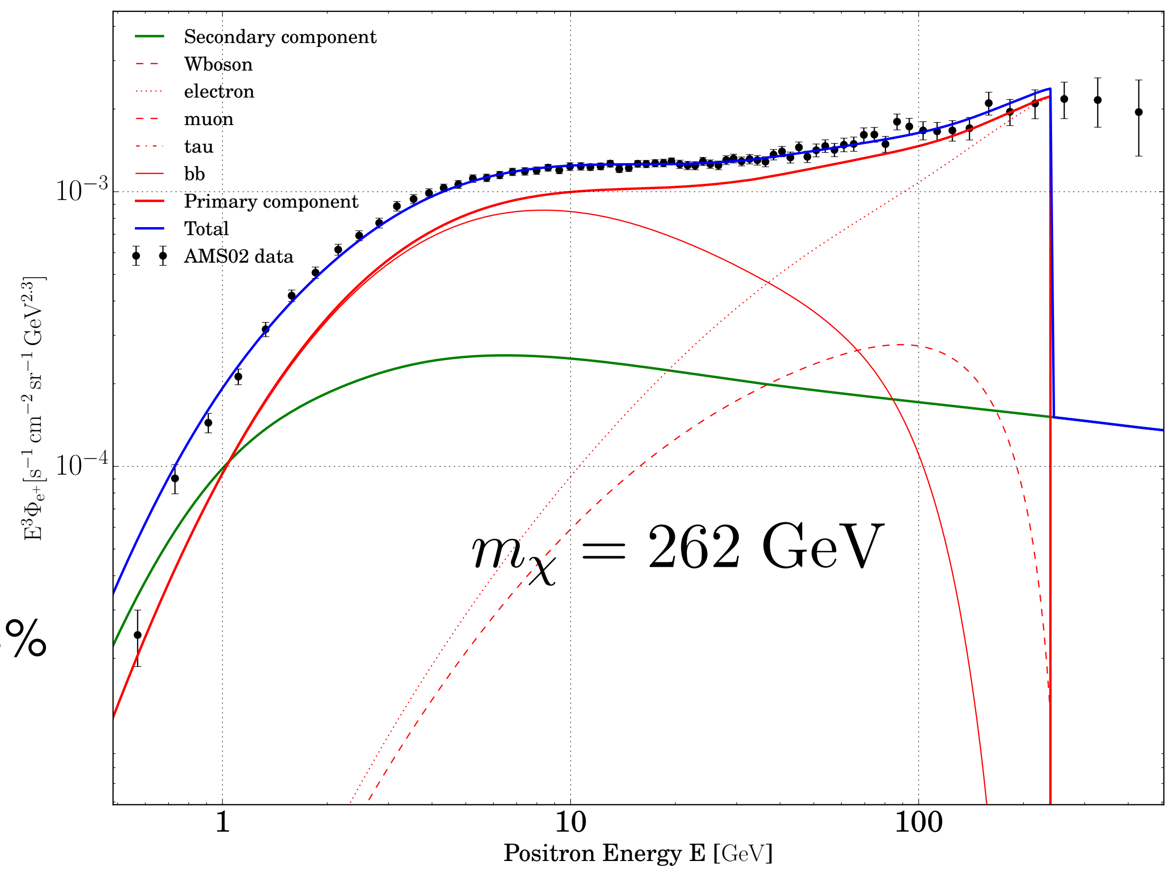
NO !



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.)