

VOYAGER PROBING DARK MATTER

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IRN - Annecy
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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)

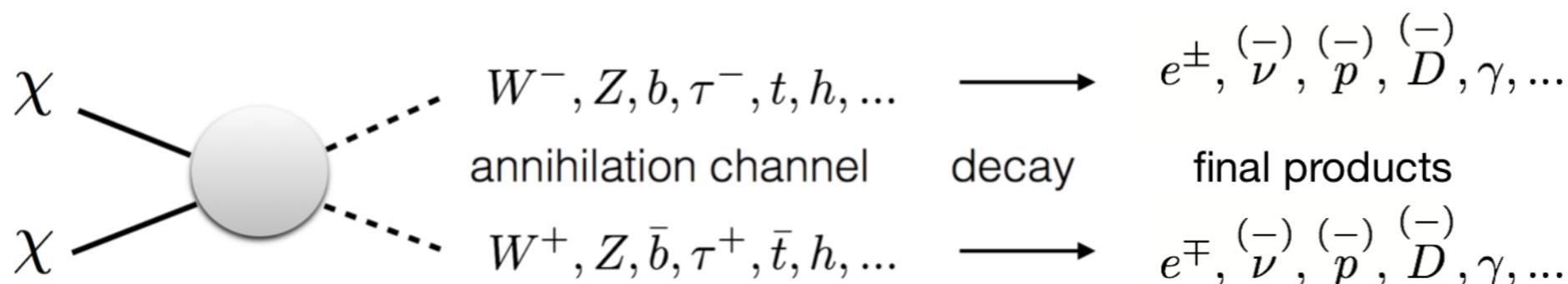
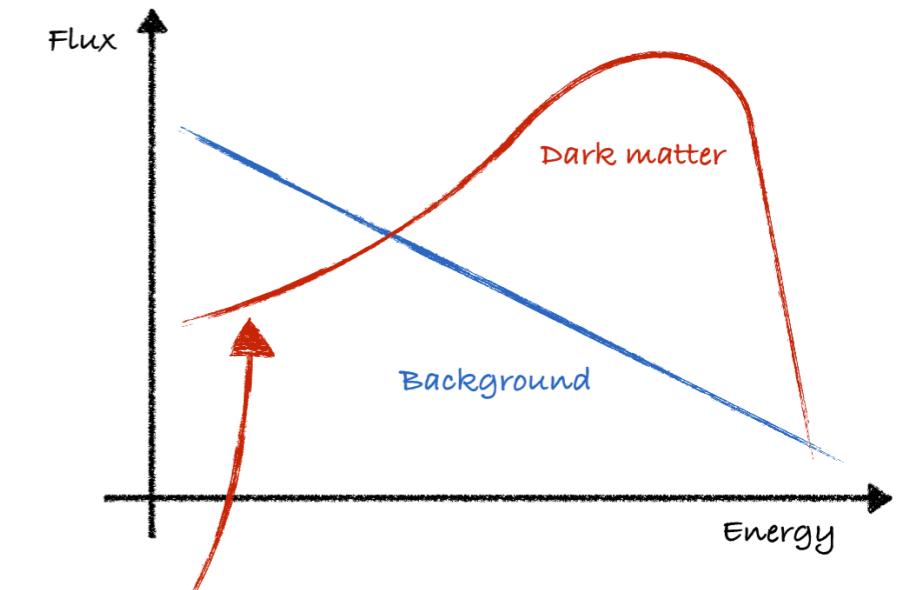
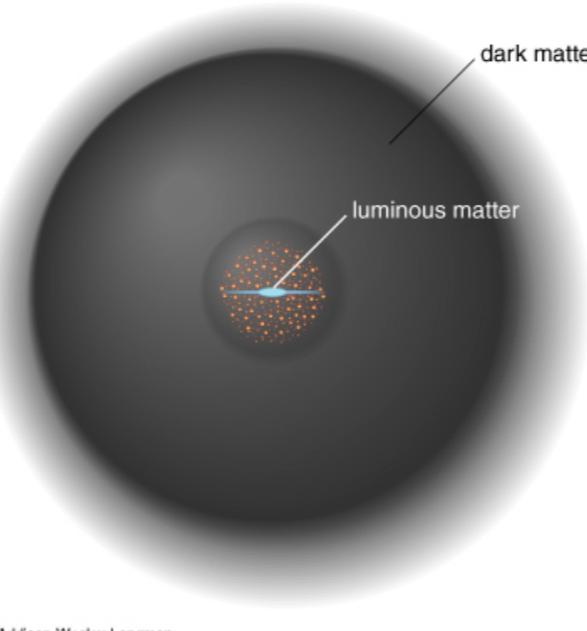
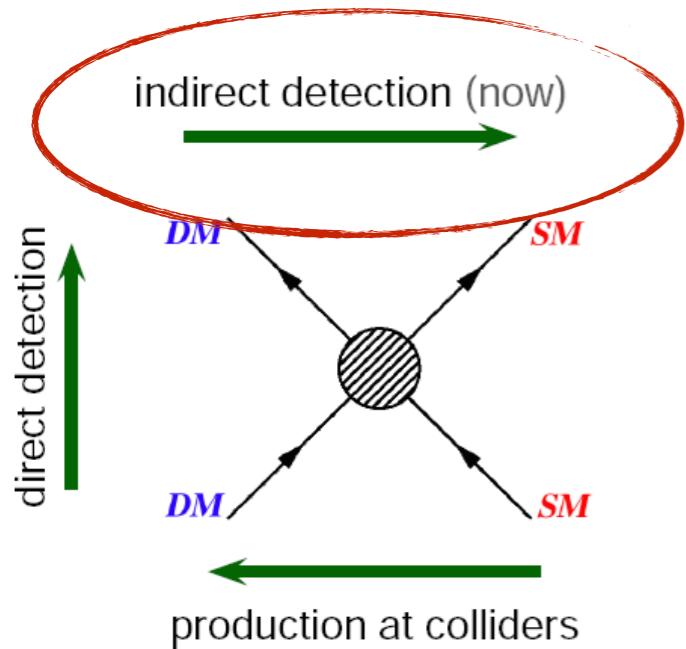


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THEORIQUE ET HAUTES ENERGIES



Dark matter indirect detection

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



- Gamma rays



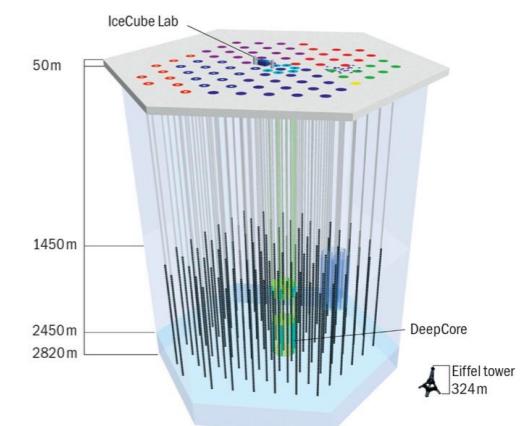
HESS

- Charged cosmic rays



AMS-02

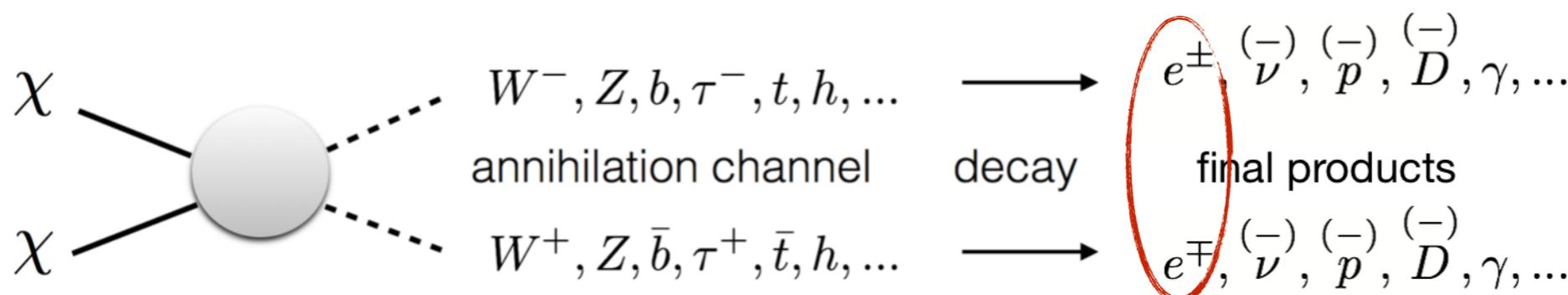
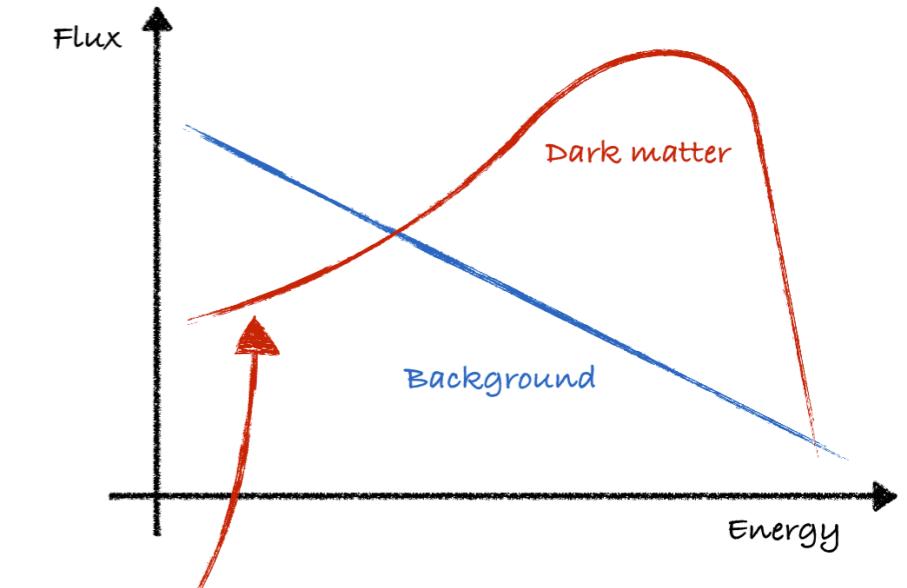
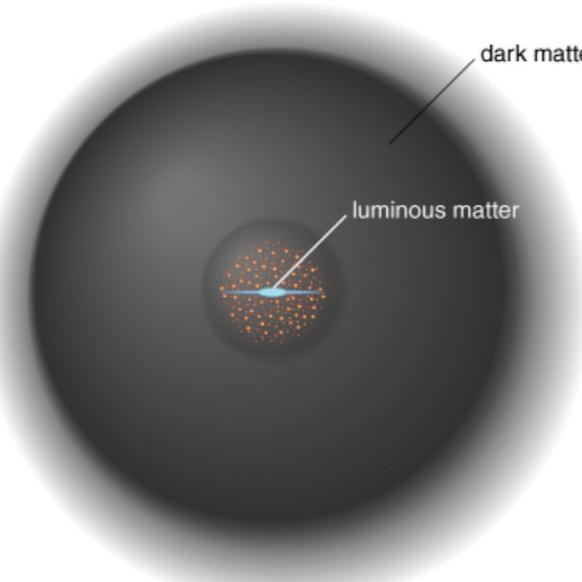
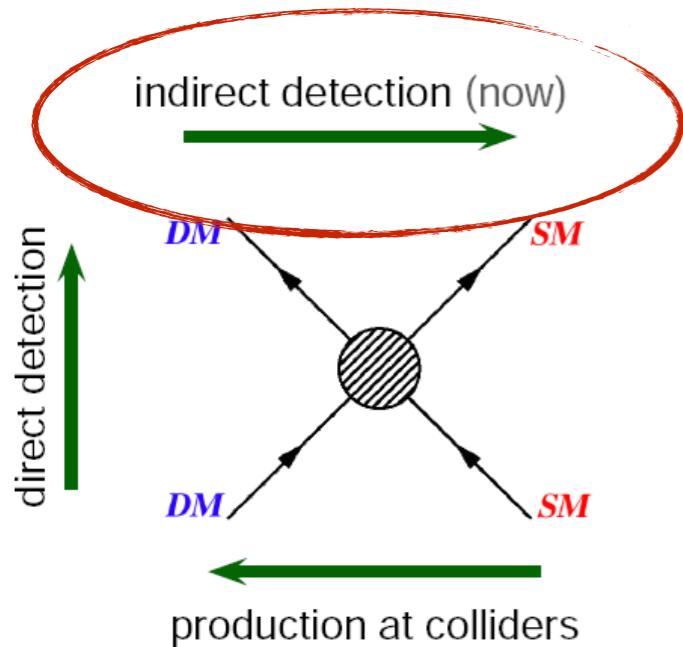
- Neutrinos



IceCube

Dark matter indirect detection

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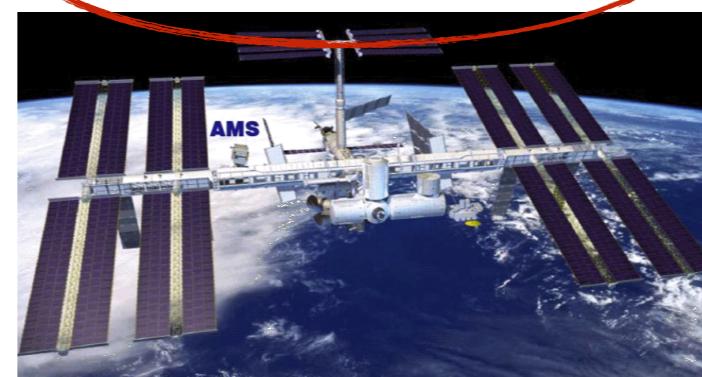


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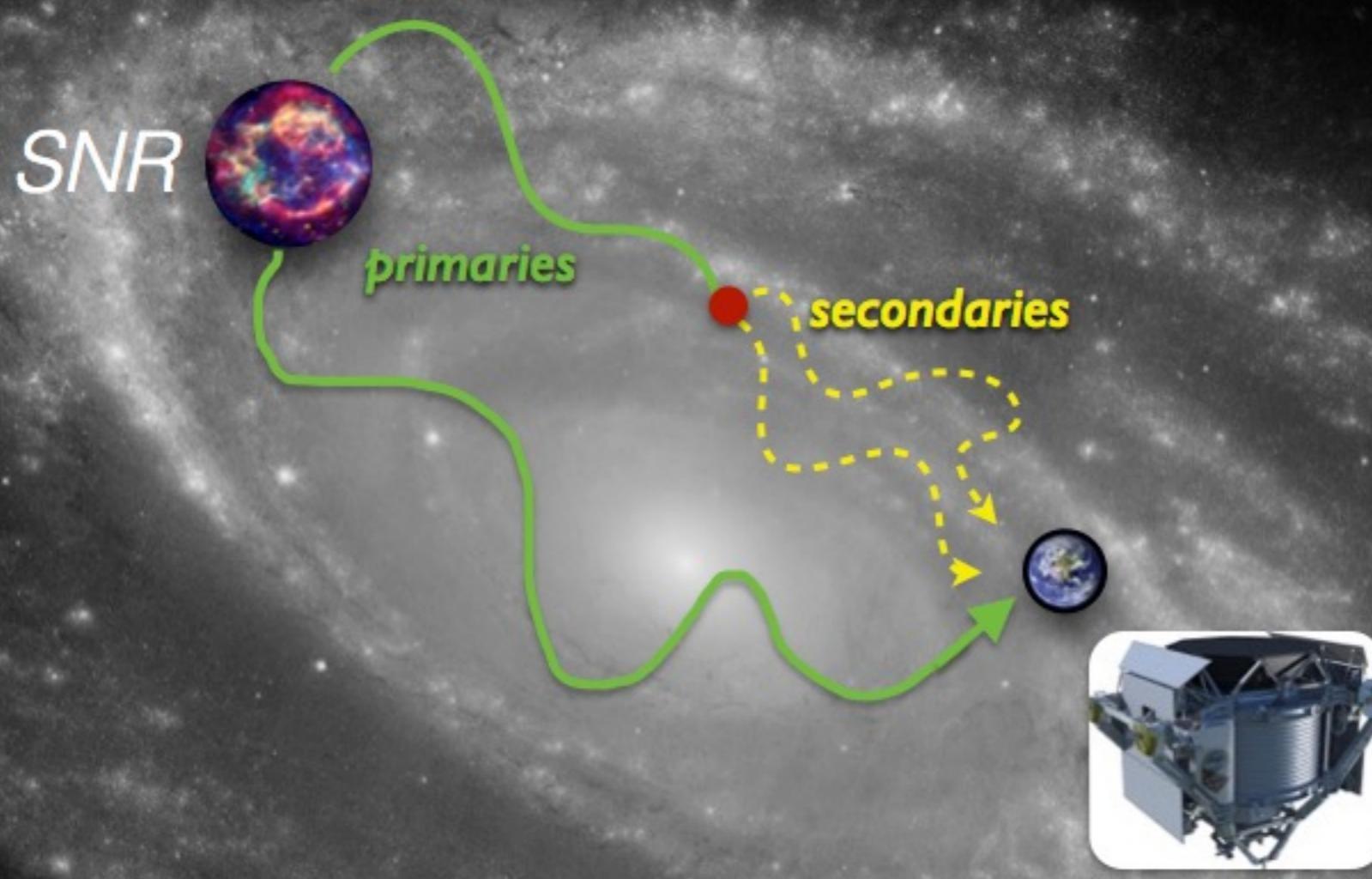


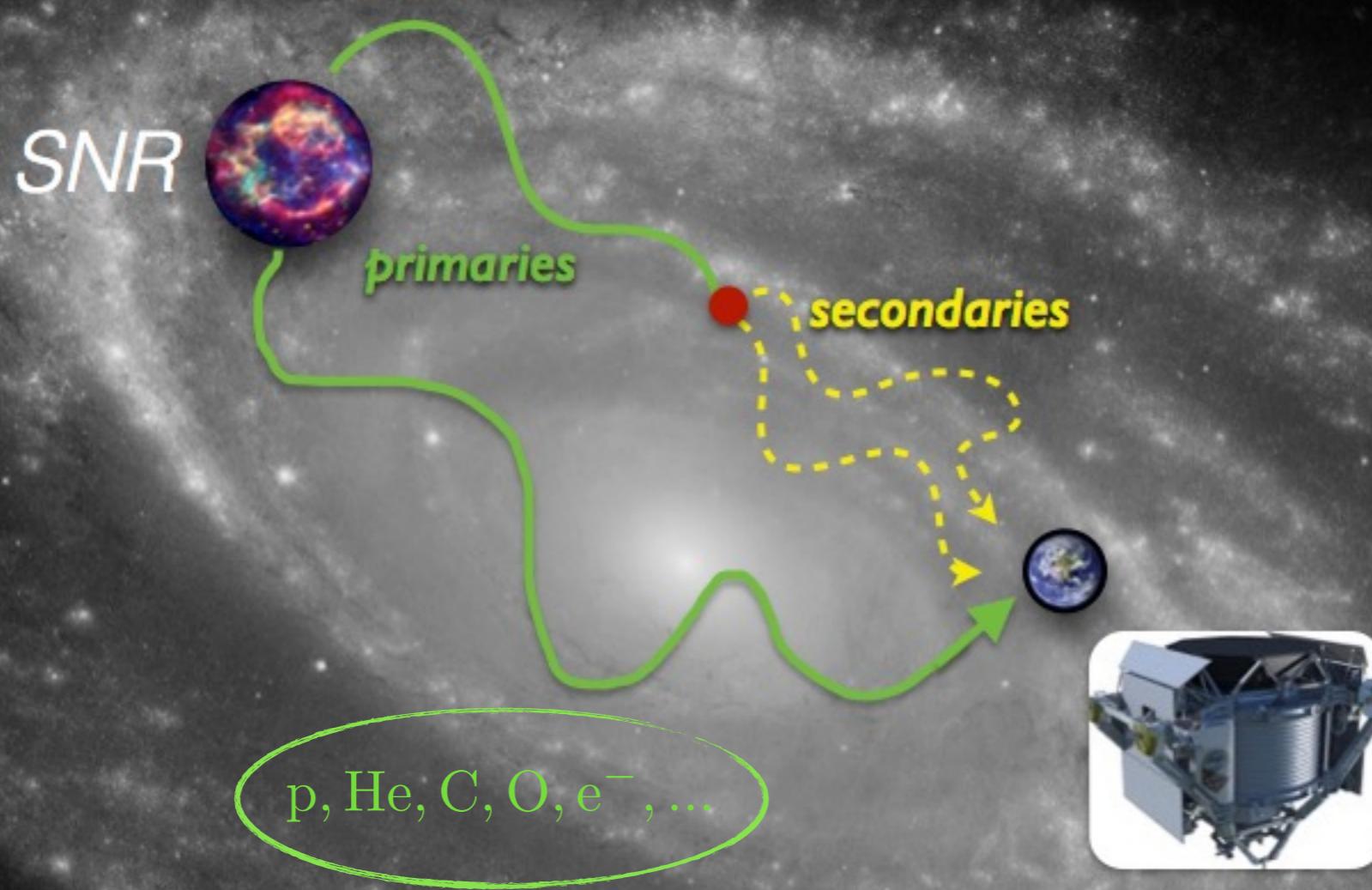
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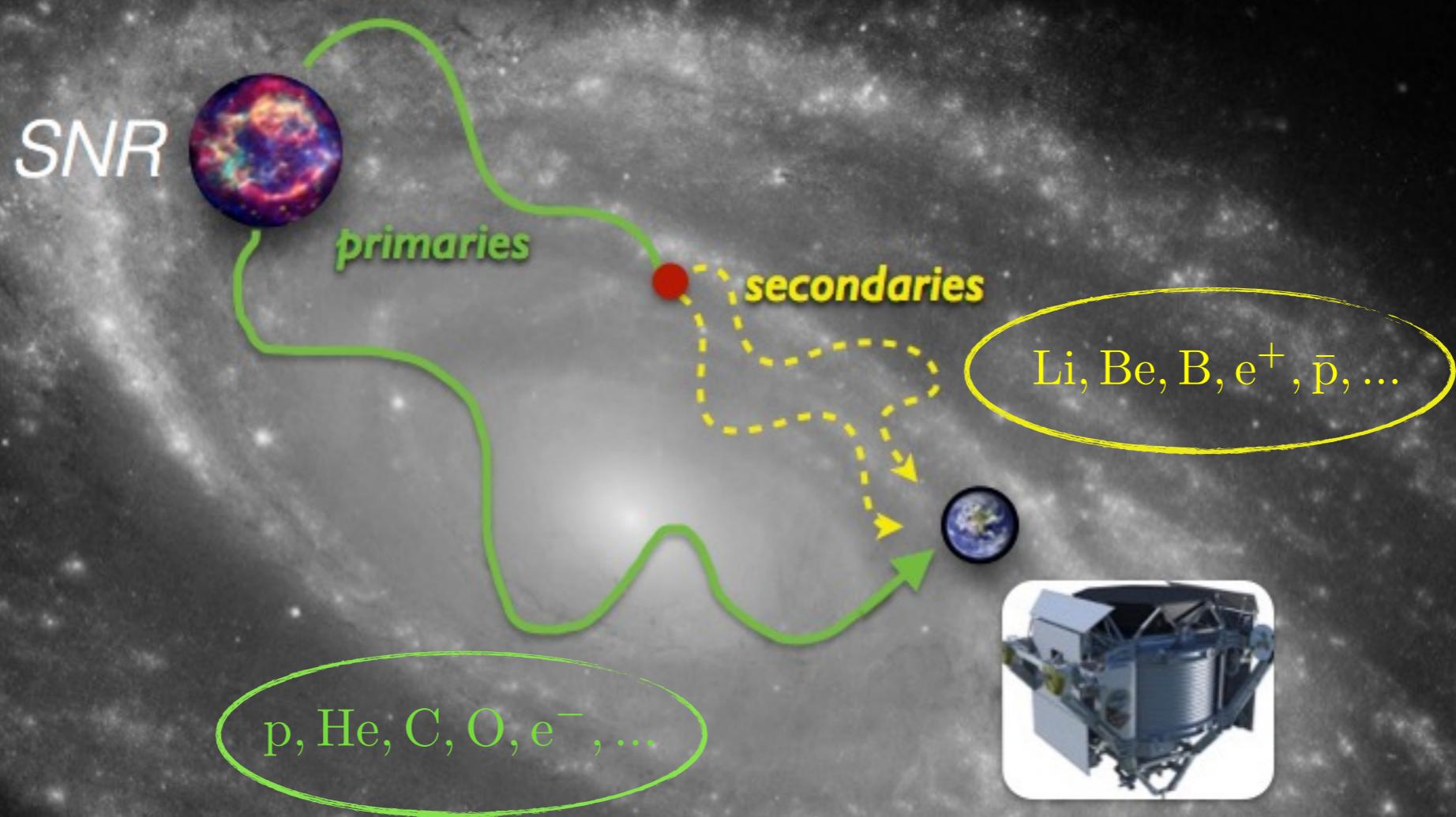
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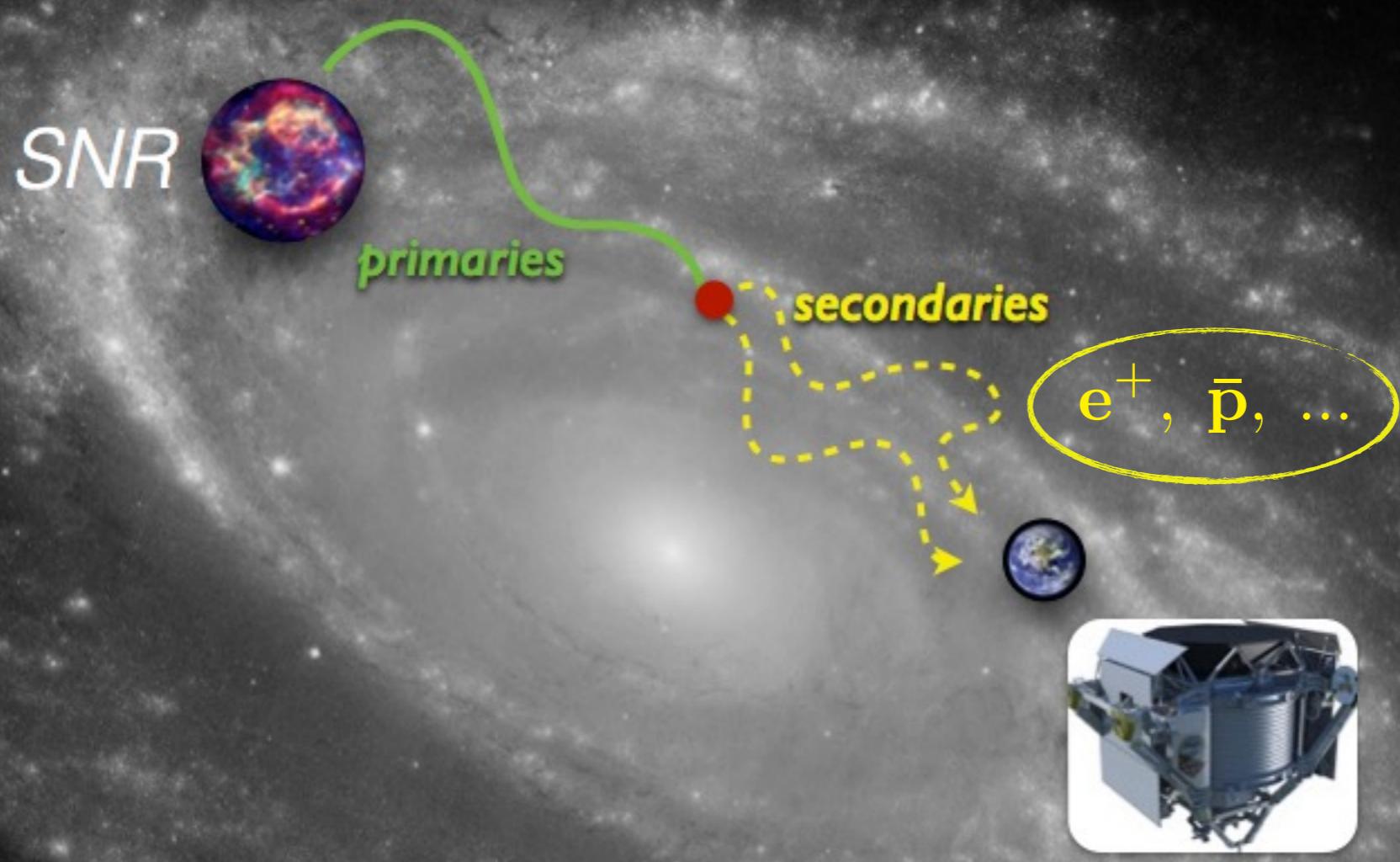


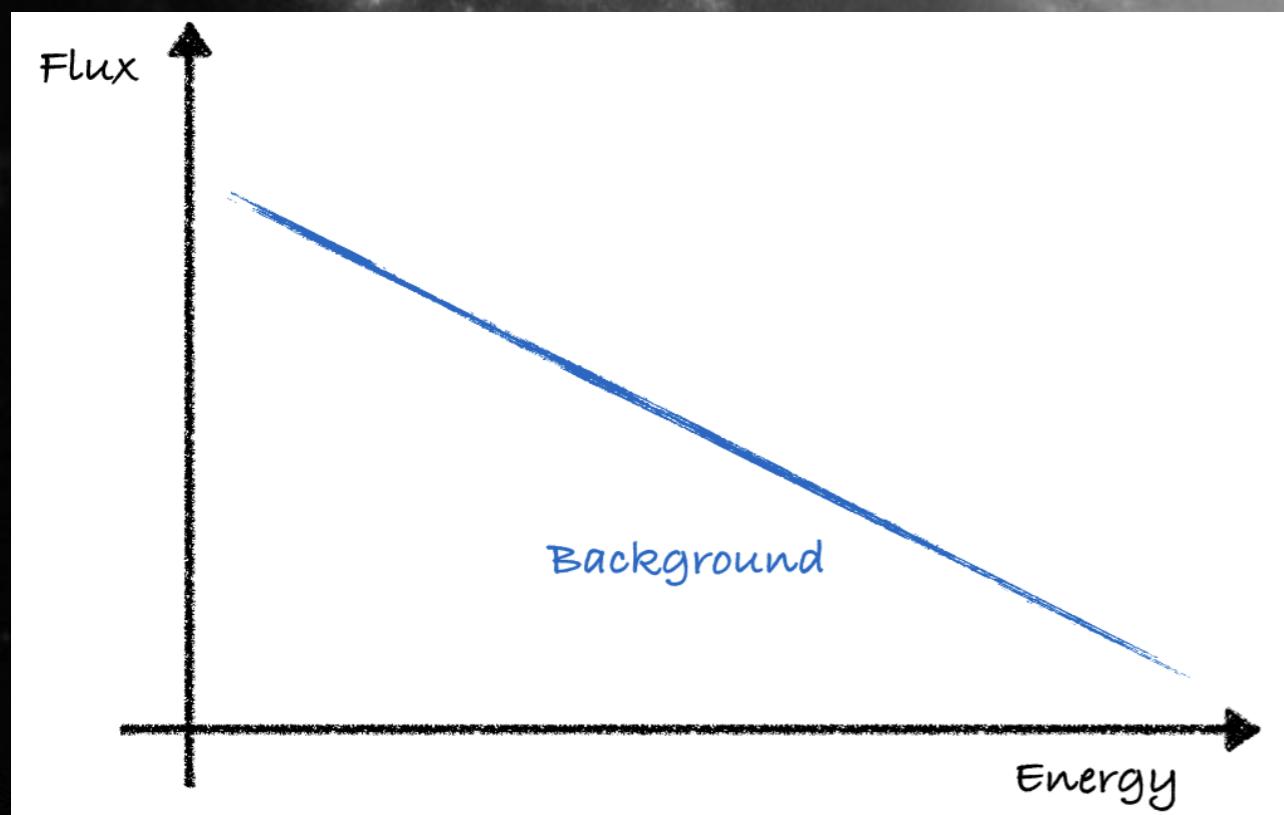
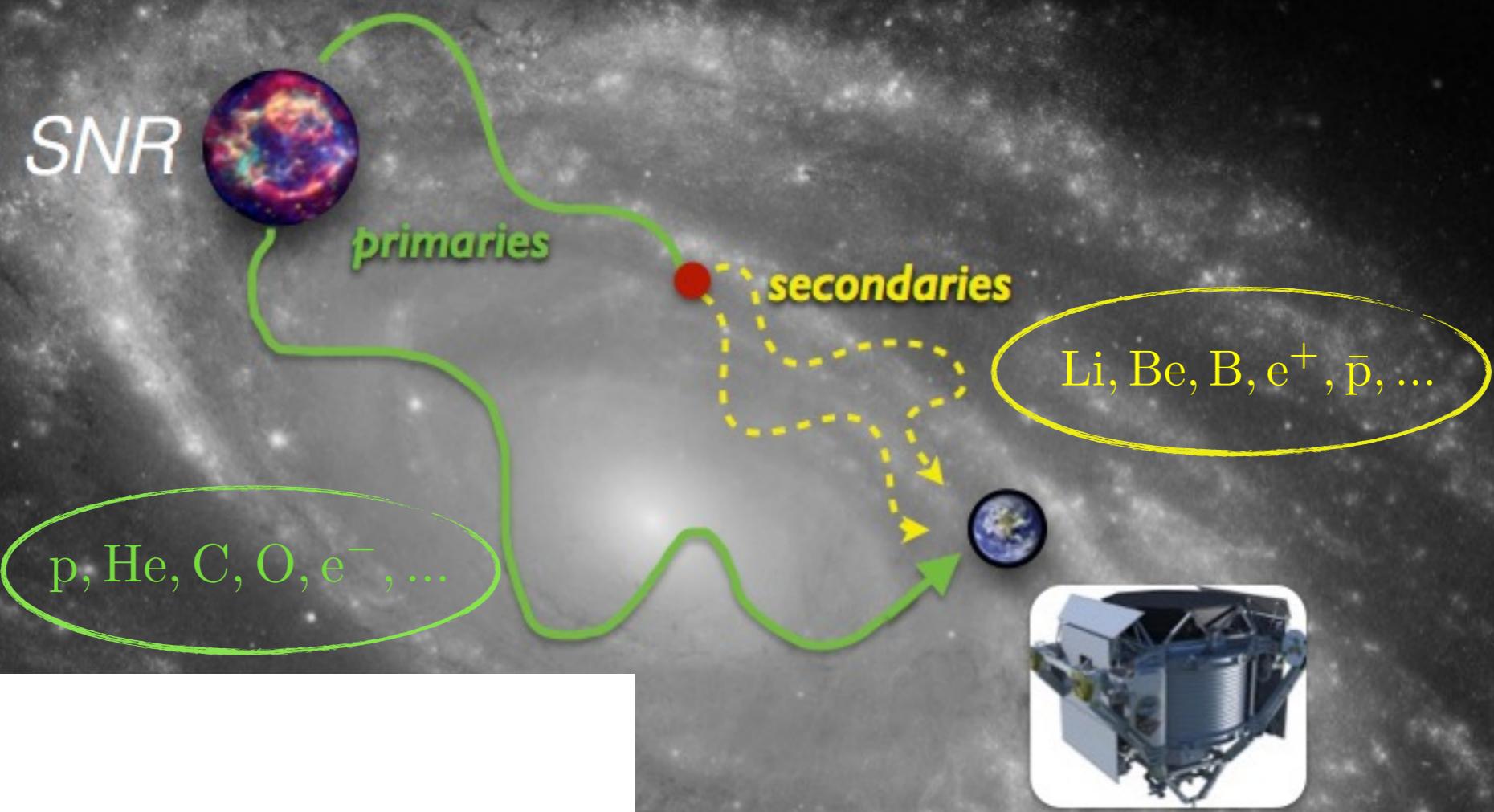
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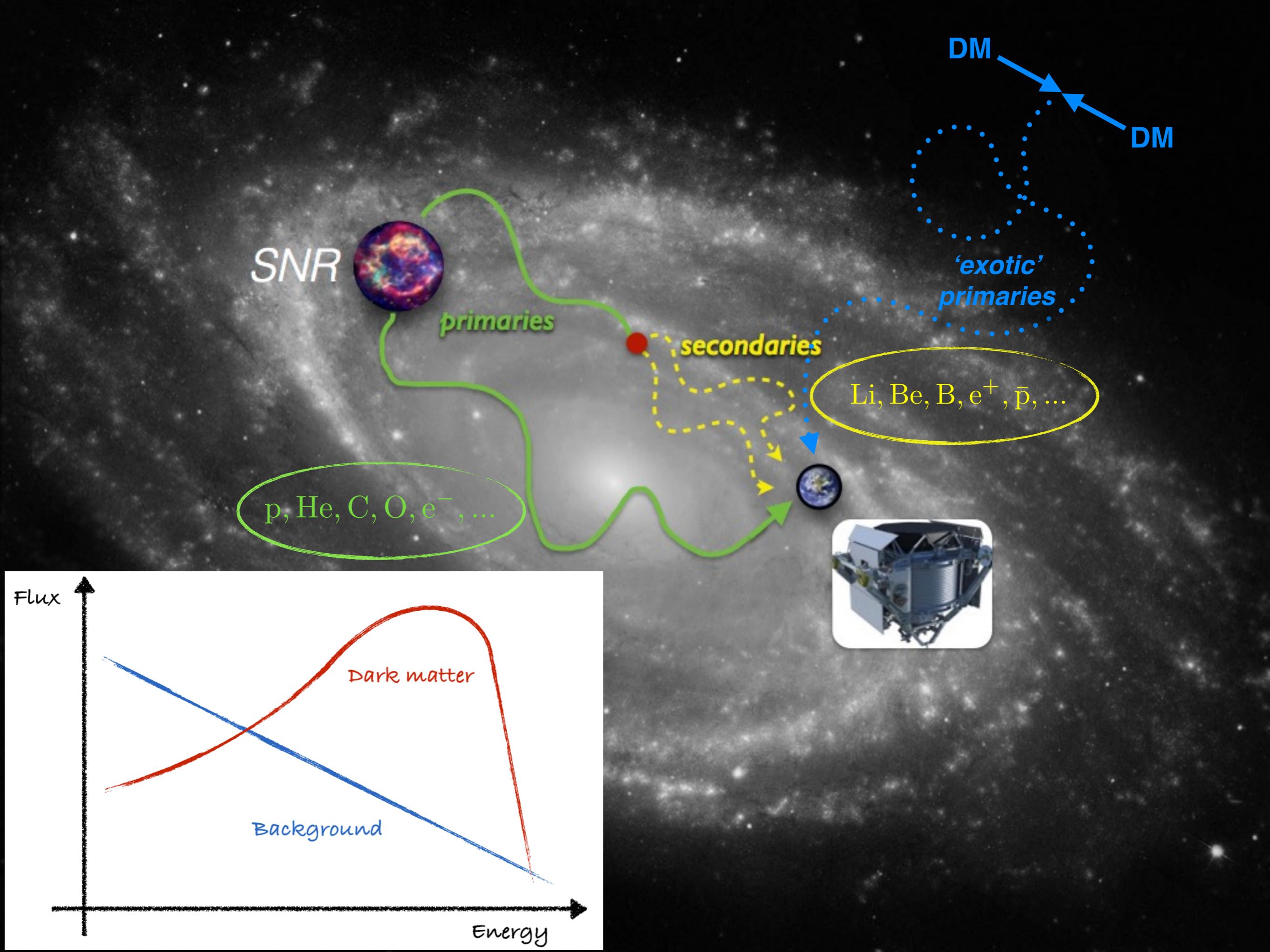








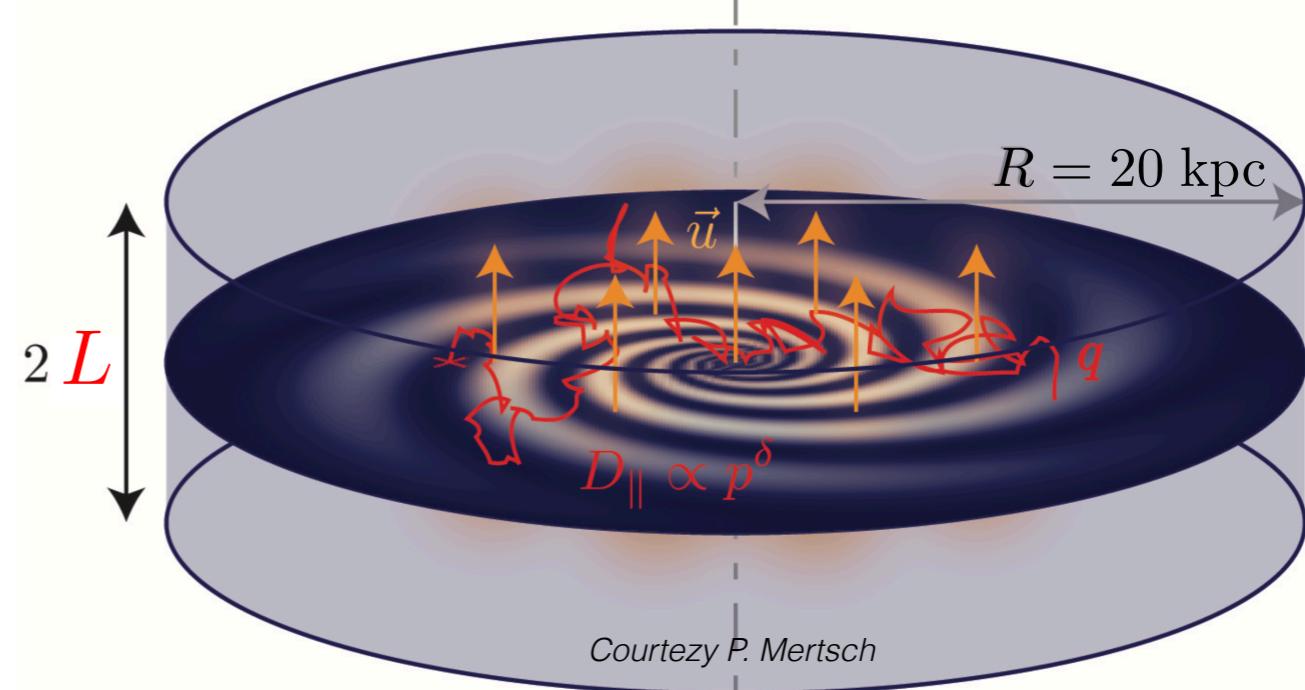




Two-zone diffusion model

Galactic disc - $h \sim 100$ 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
- **Convection** (Galactic wind) from supernovae explosions in the disc
- **Destruction**
 - Interaction with the interstellar medium (ISM)
 - Decay
- **Energy losses**
 - Interaction with the ISM (Coulomb, ionisation, bremsstrahlung, adiabatic expansion)
 - Synchrotron emission, inverse Compton scattering (electrons)
- **Diffusive reacceleration** from stochastic acceleration (Fermi II)

$$K(E) = K_0 \beta \frac{(R/1\text{ GV})^\delta}{\{1 + (R/R_b)^{\Delta\delta/s}\}^s}$$

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

$$Q^{sink}(E, \vec{x})$$

$$b(E, \vec{x})$$

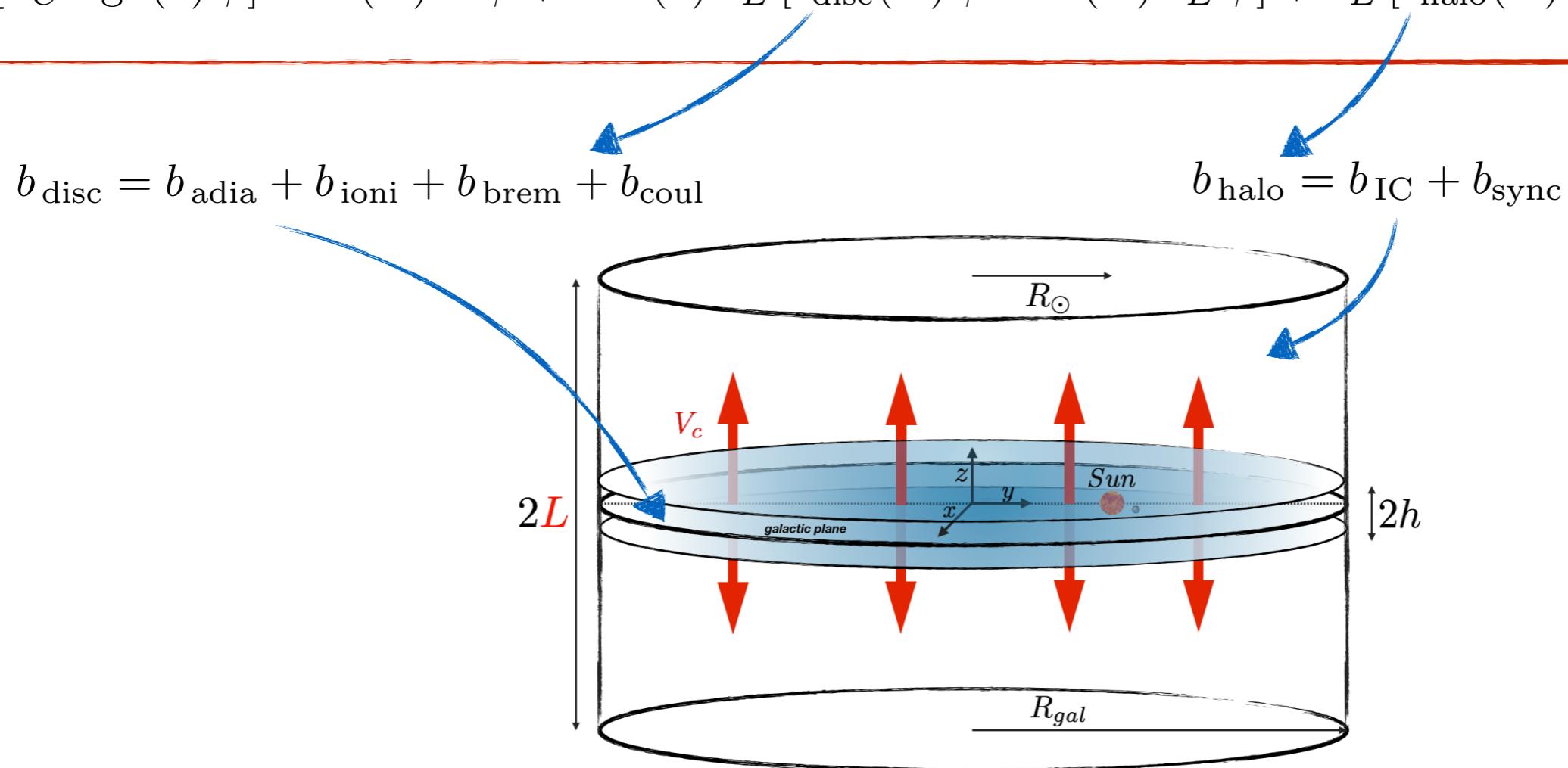
$$D(E) = \frac{2}{9} V_A^2 \frac{E^2 \beta^4}{K(E)}$$

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

Transport of cosmic rays e^\pm

Steady state

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



No analytical solution for this equation

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

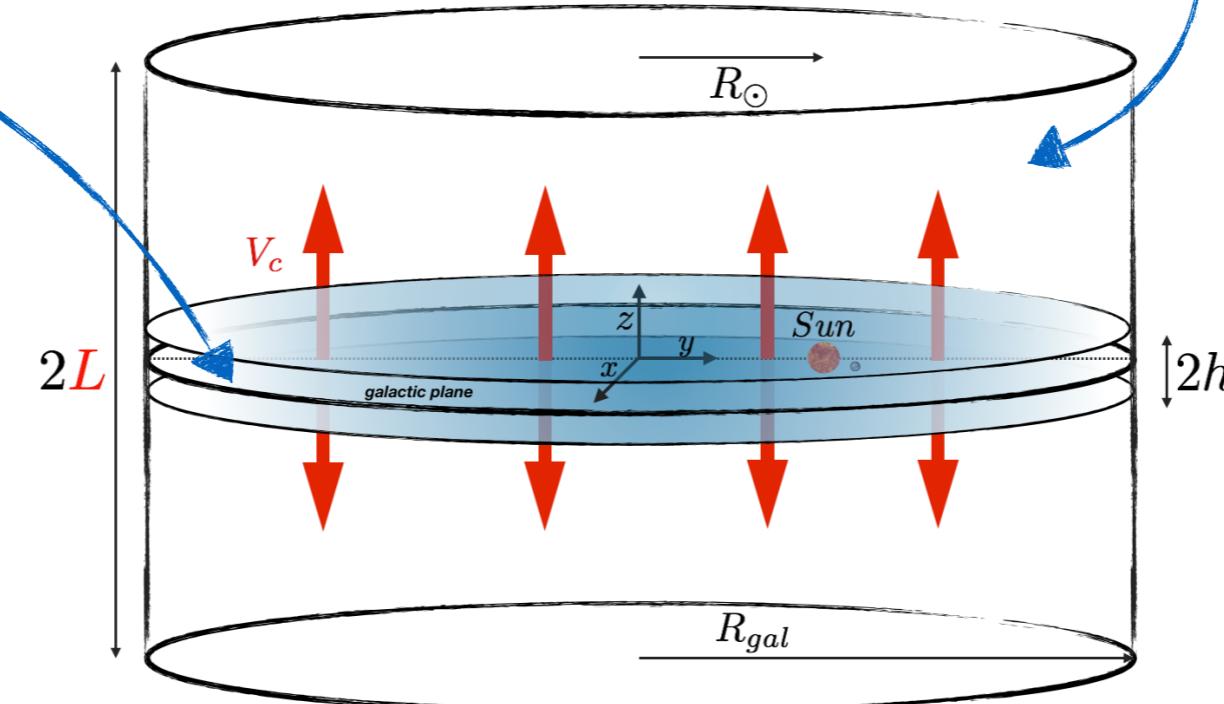
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$$b_{\text{disc}} = b_{\text{adia}} + b_{\text{ioni}} + b_{\text{brem}} + b_{\text{coul}}$$

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



No analytical solution for this equation

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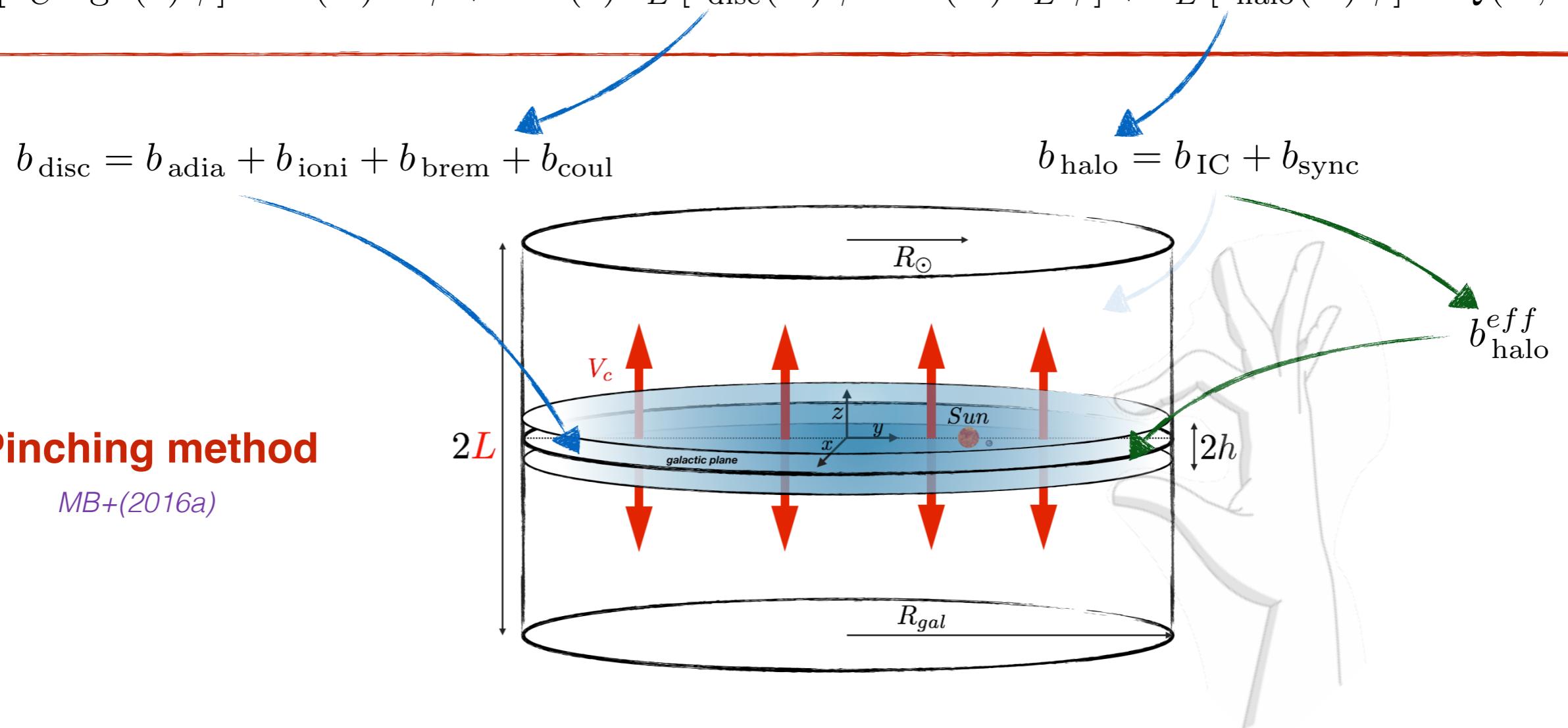
High energy approximation

$$-K(E) \Delta \psi + \partial_E [b_{\text{halo}}(E) \psi] = Q(E, \vec{x}) \quad E > 10 \text{ GeV}$$

Transport of cosmic rays e^\pm

Steady state

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



Pinching method

MB+ (2016a)

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

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

⇒ **extend** the semi-analytic computation of e^\pm interstellar fluxes **down to MeV** energies!

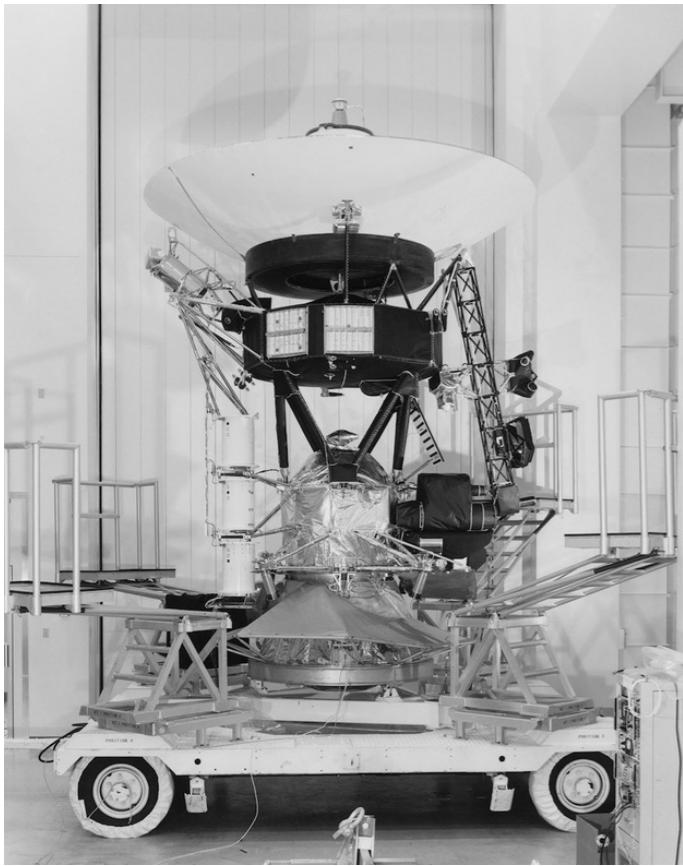
MeV cosmic rays?



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:

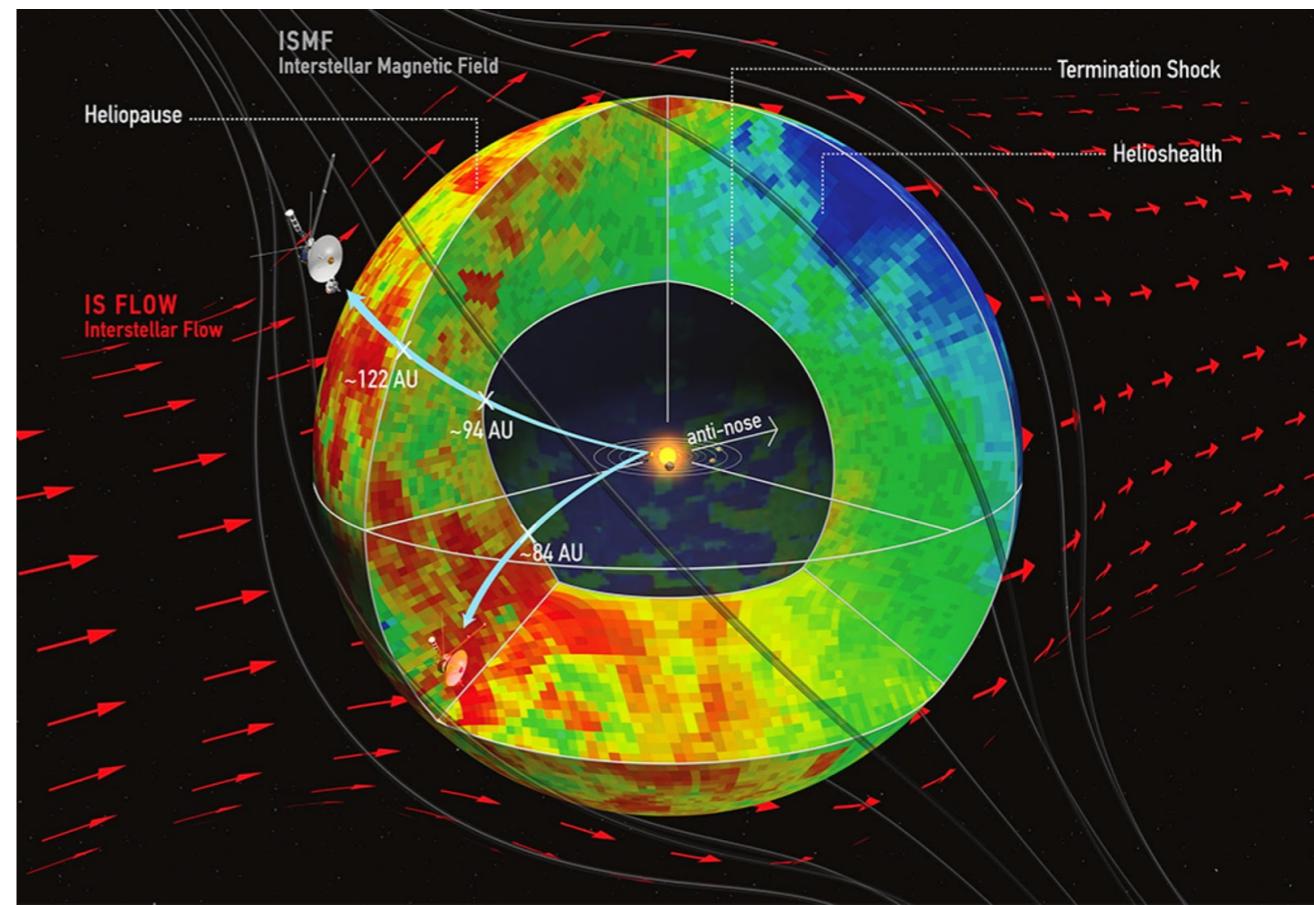
Hercules (solar apex)

velocity/Sun:

~17 km/s

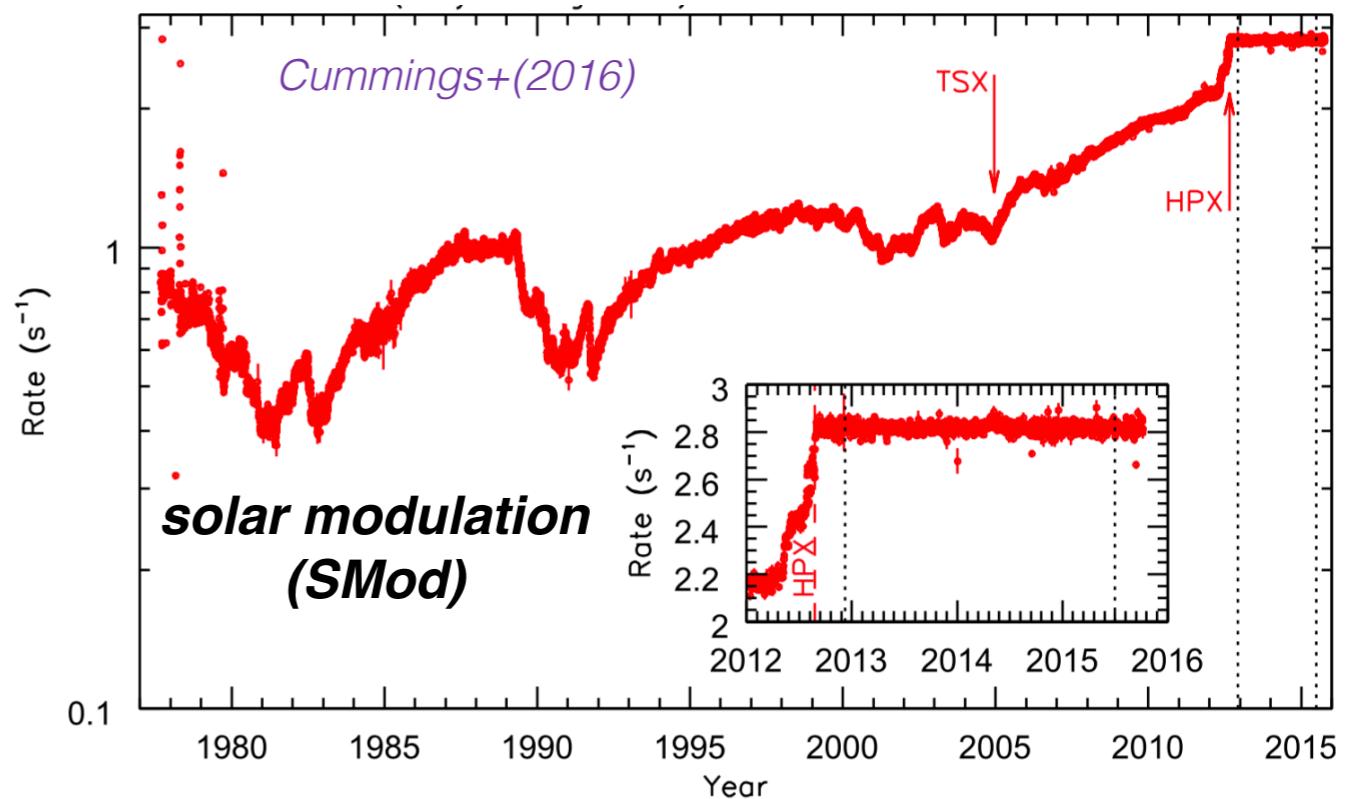
CRs energy:

$10 \lesssim T_n \lesssim 100 \text{ MeV}/n$



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



Voyager-1 crossed the heliopause in 2012



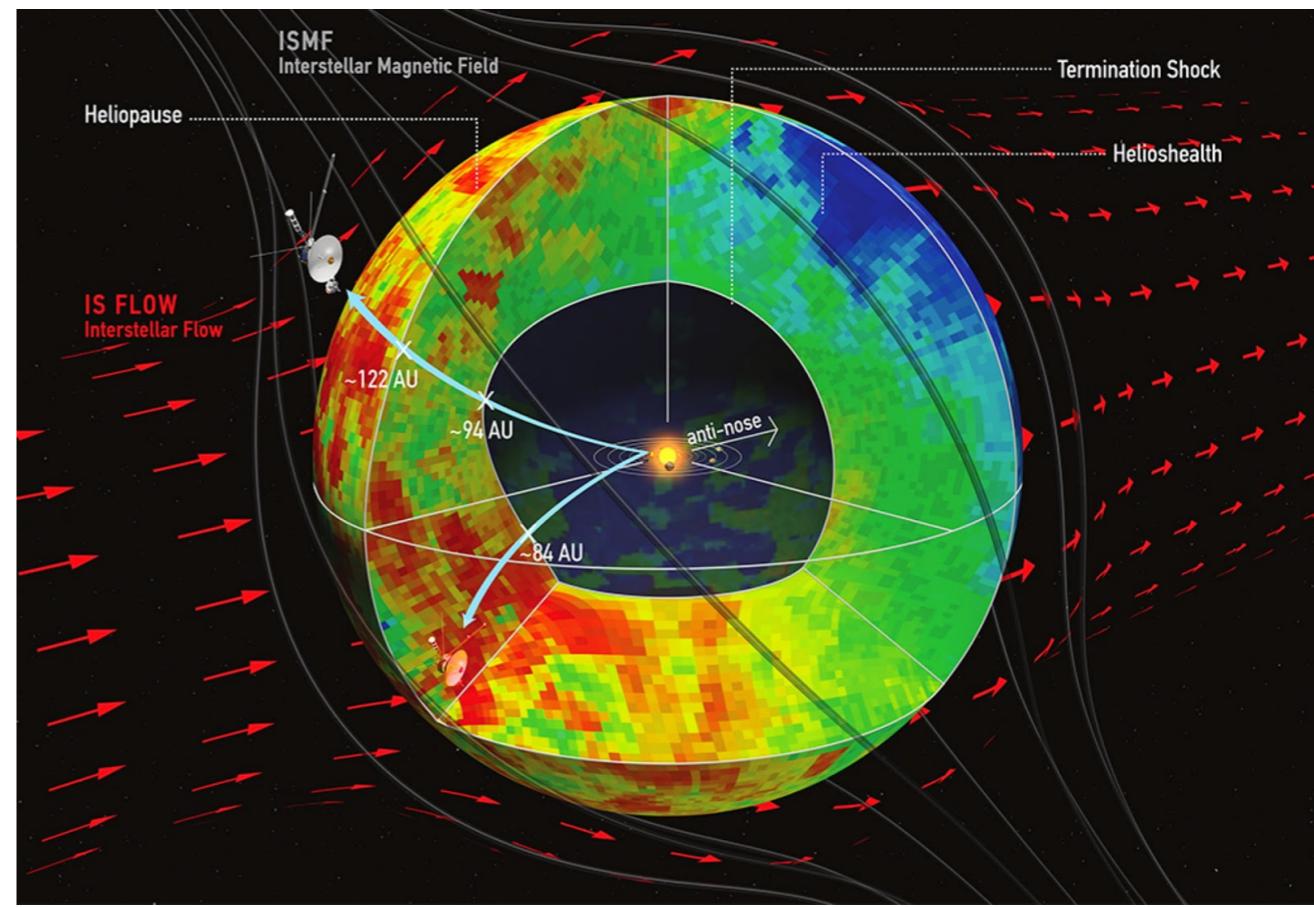
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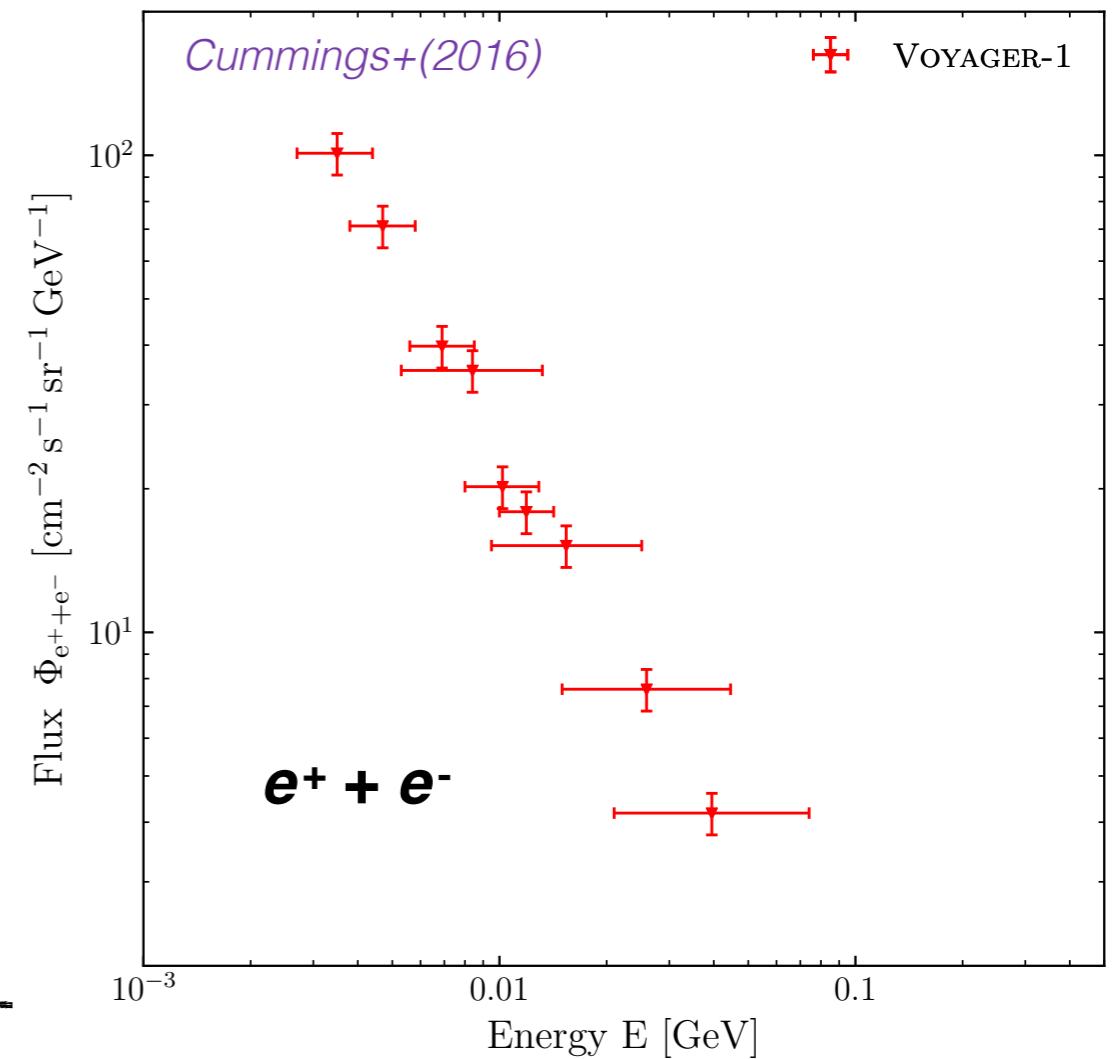
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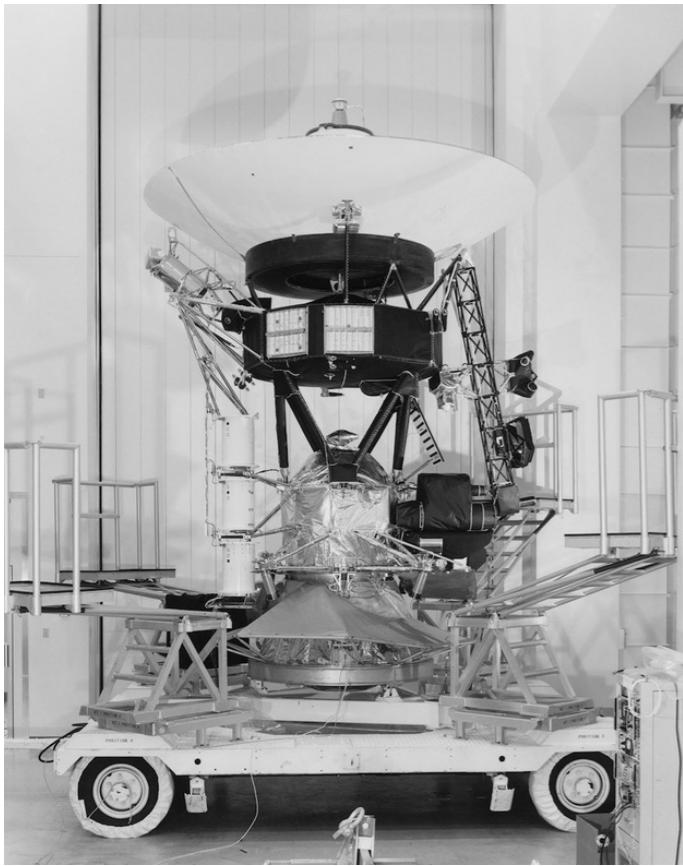


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- Flux of $e^+ + e^-$ (no magnet) from ~3 to ~80 MeV



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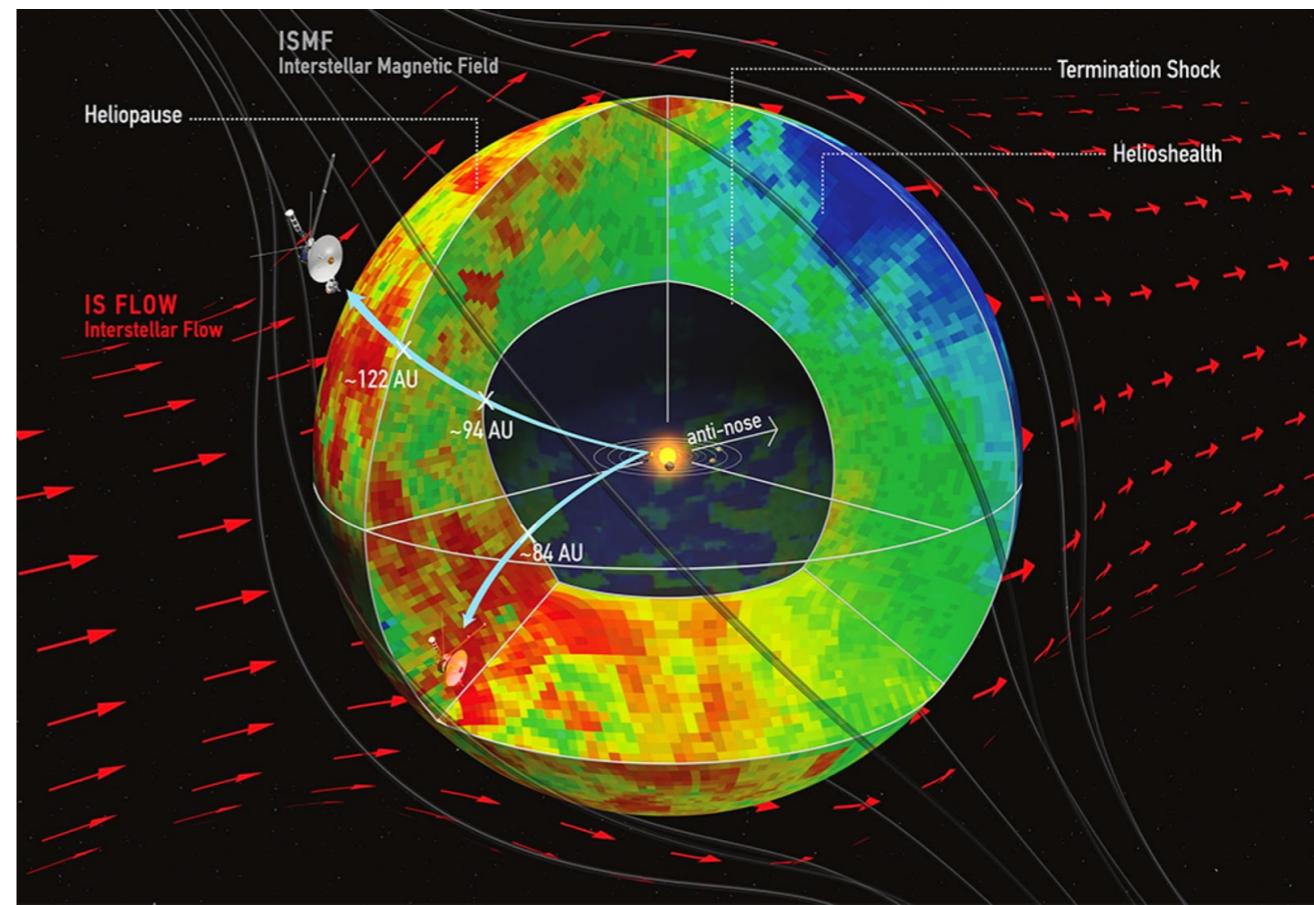
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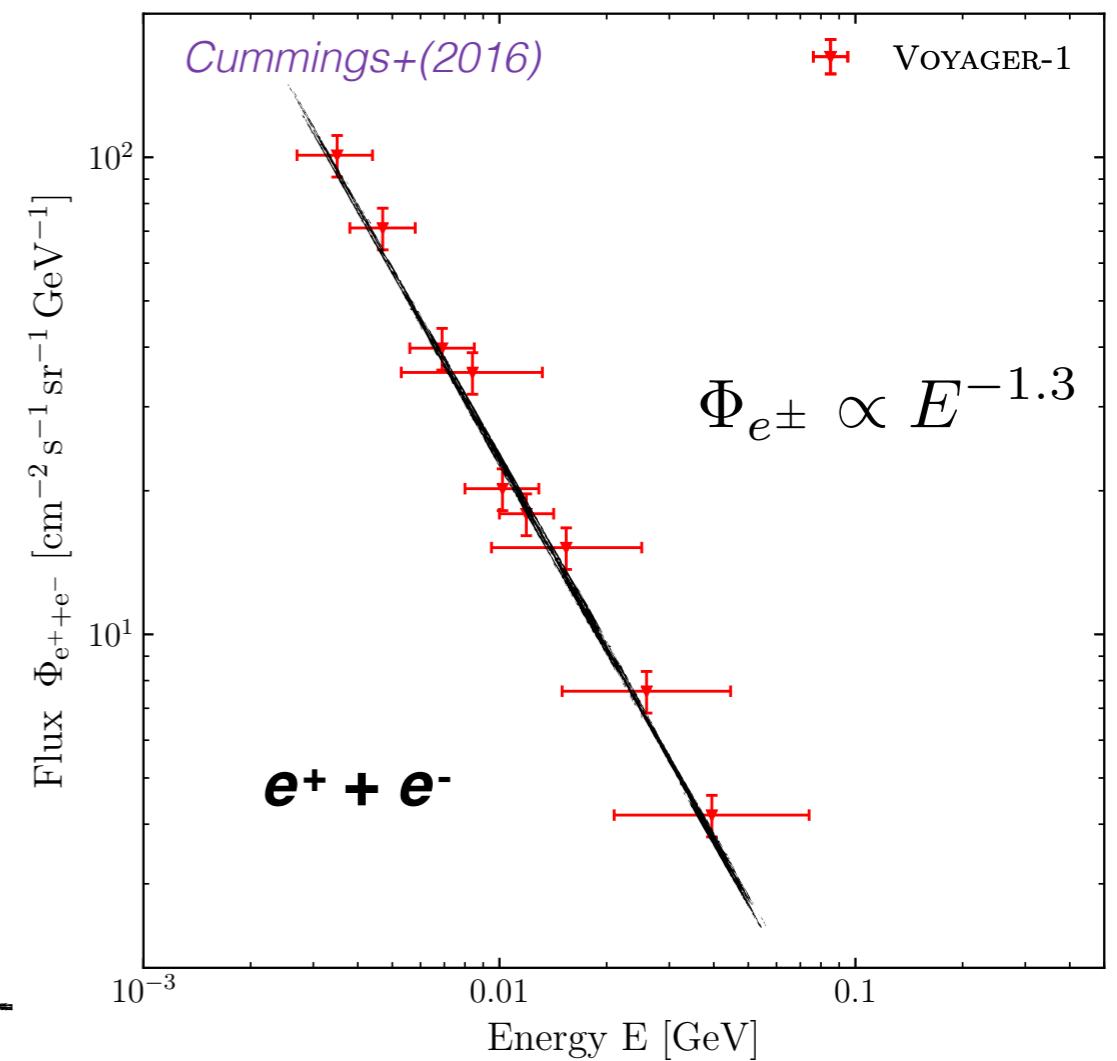
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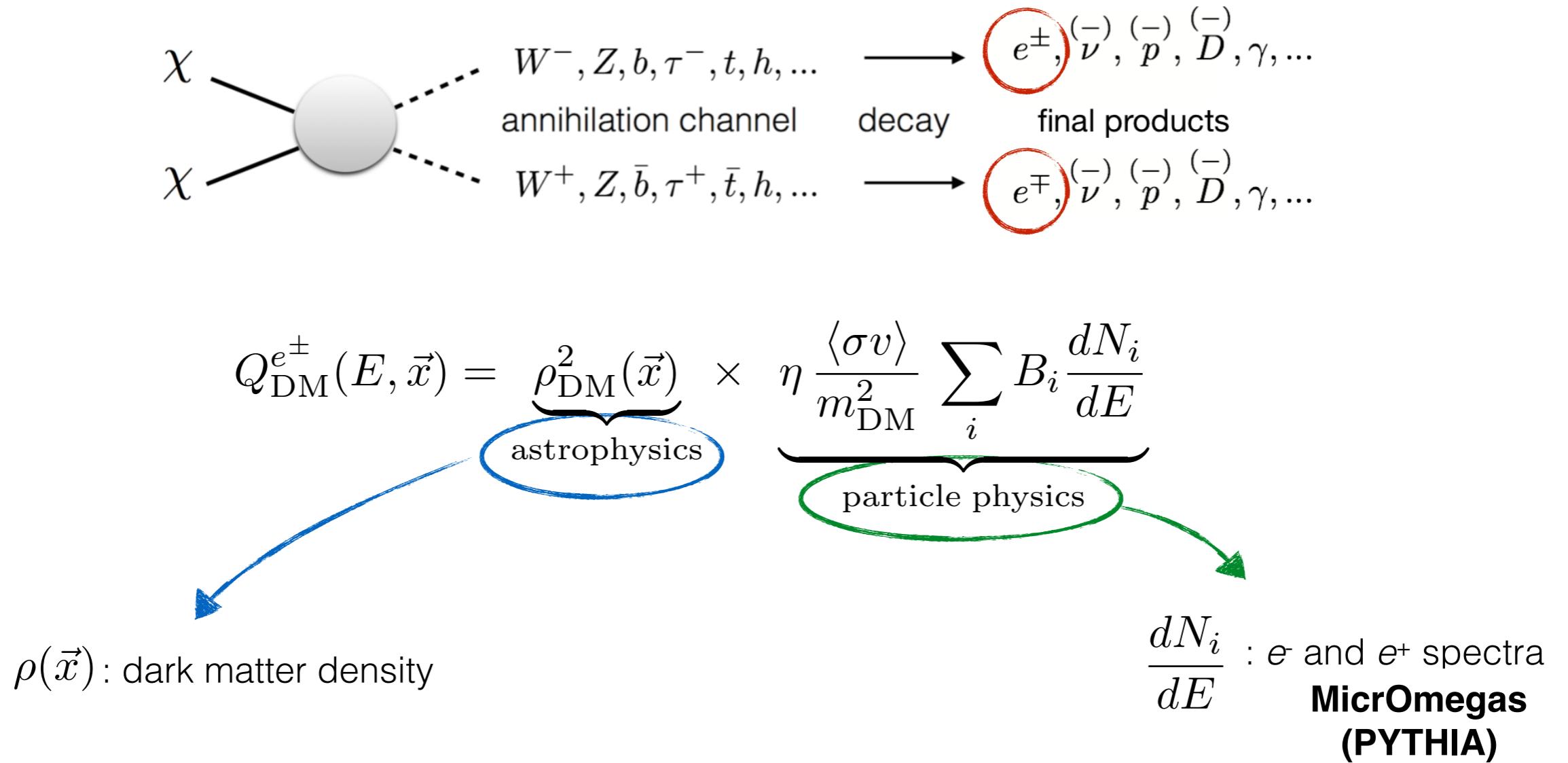
Application 1: MeV dark matter particles

MB, J. Lavalle and P. Salati (PRL119.021103)

and

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

CRs e^\pm from dark matter



Dark matter distribution in the MW

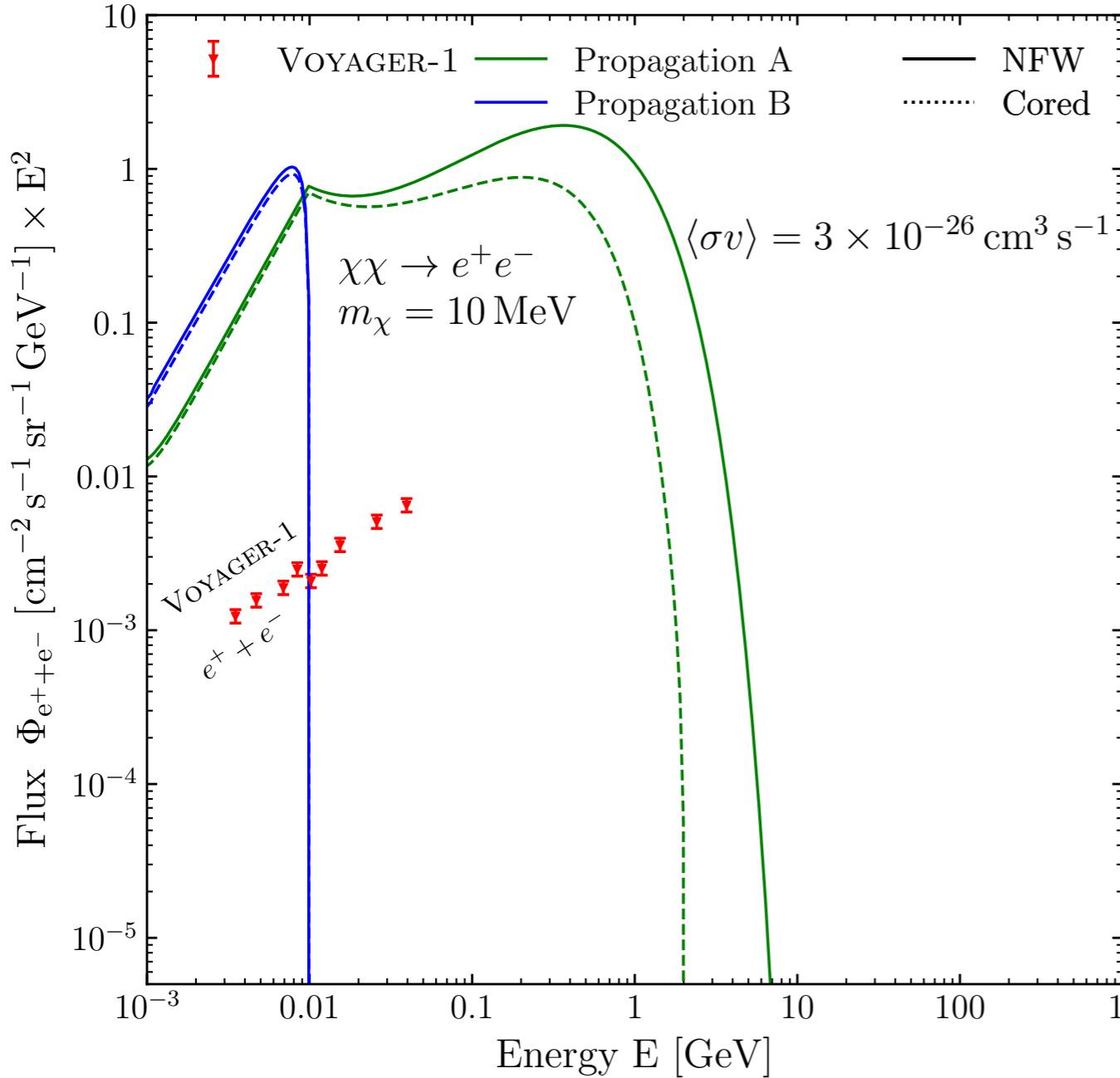
- **NFW** (spike in the GC)
- **Cored** (~ 8 kpc core)

McMillan(2016)

CRs propagation in the Galaxy

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

Constraints on annihilation cross section



- **Propagation A:** strong reacceleration

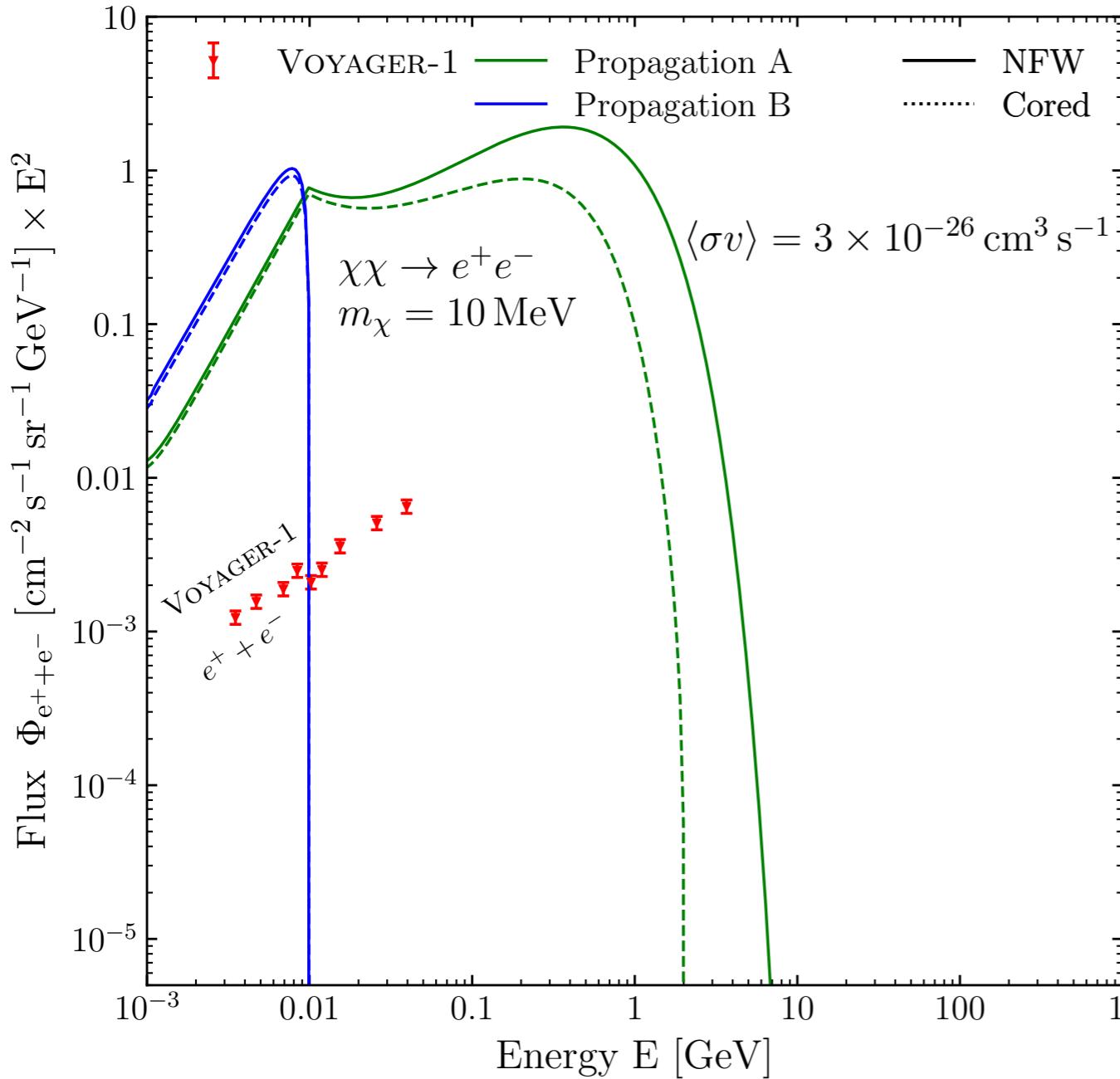
$V_A = 117.6 \text{ km/s}$ Maurin+(2001)

- **Propagation B:** no reacceleration

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

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

Constraints on annihilation cross section



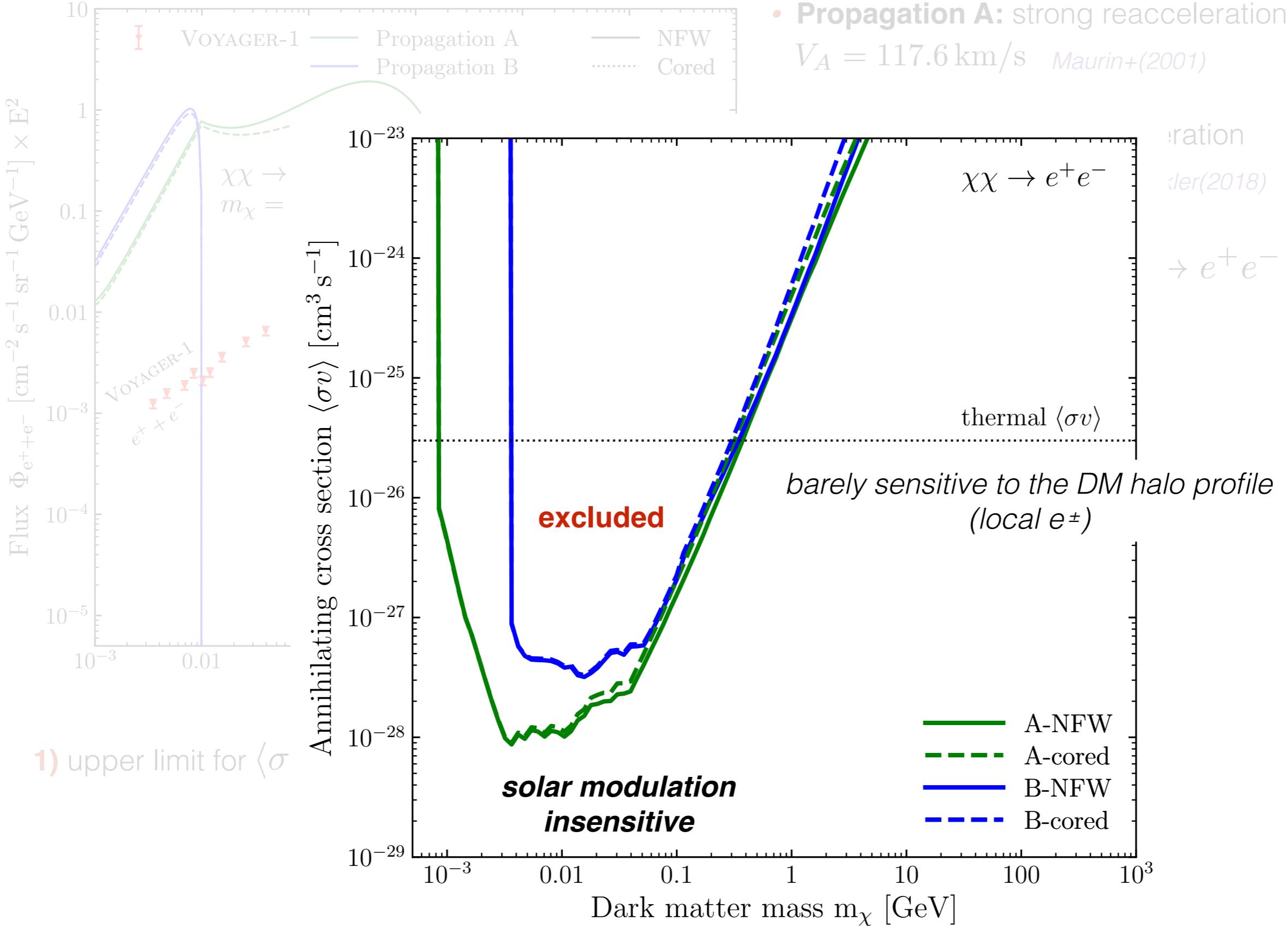
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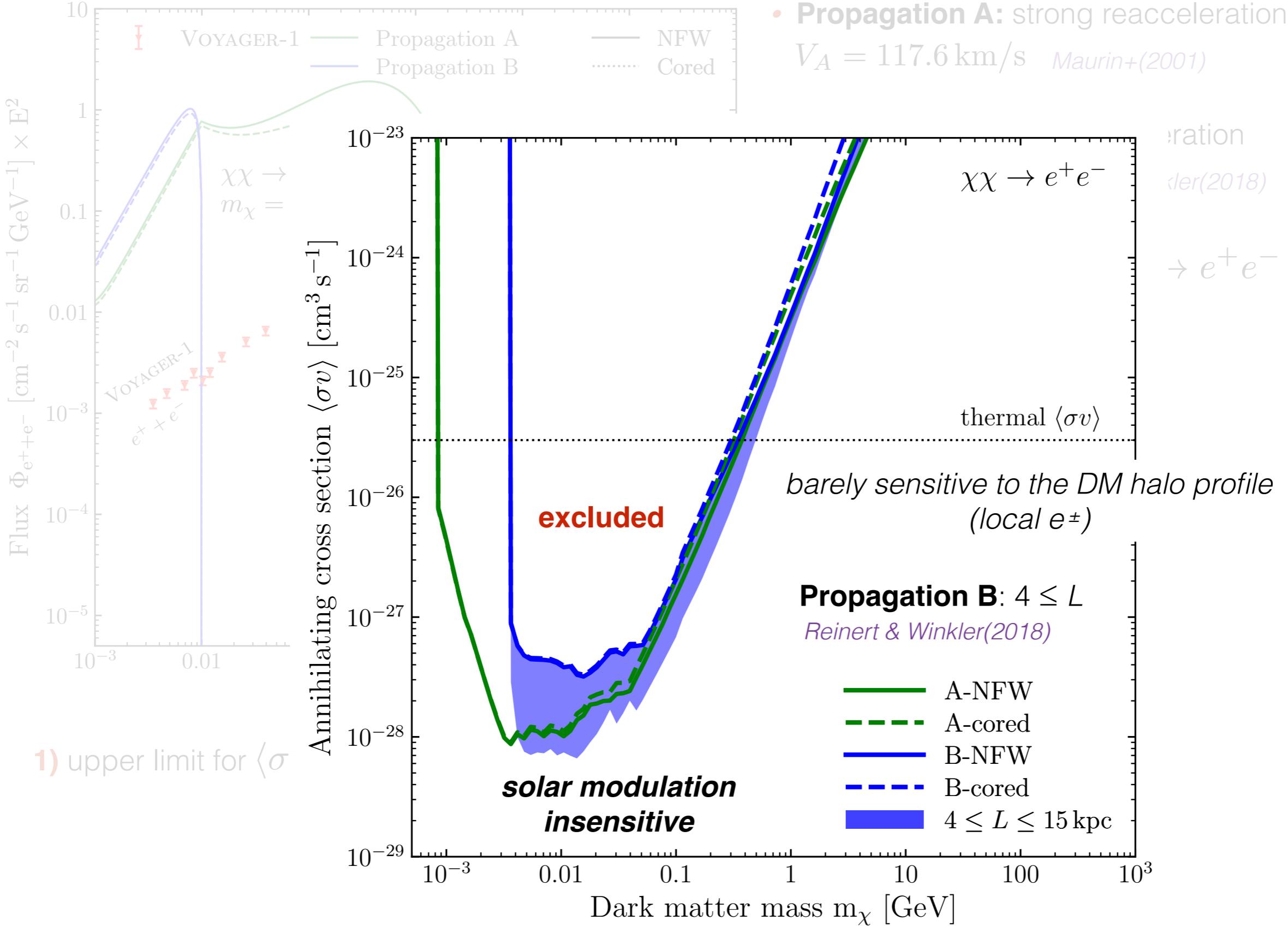
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1) upper limit for $\langle\sigma v\rangle$ from Voyager-1 e^\pm : $\Phi_{e^+ + e^-}^{\text{DM}}(E_i) \leq \Phi_{e^+ + e^-}^{\text{exp}}(E_i) + 2\sigma_i$

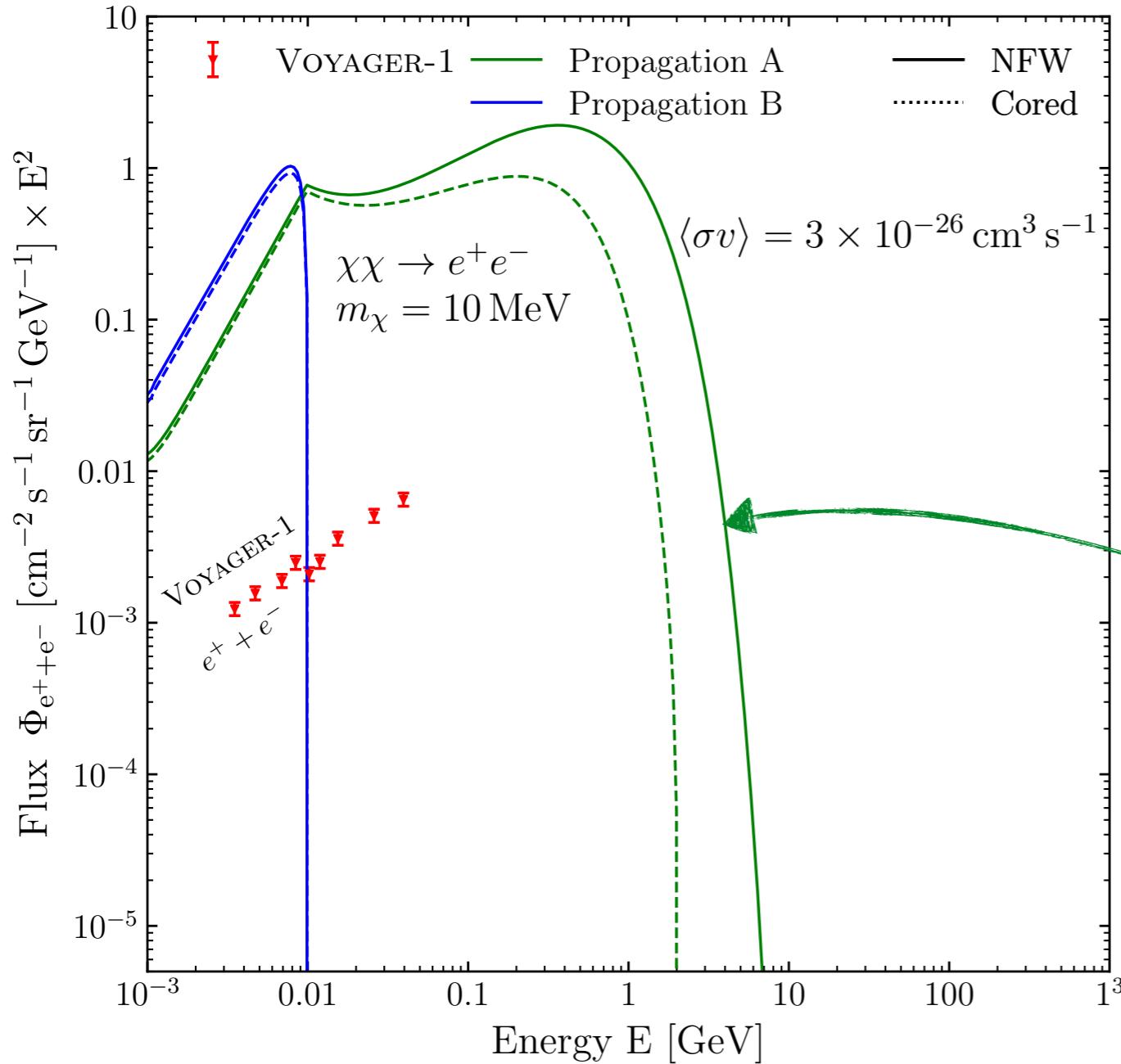
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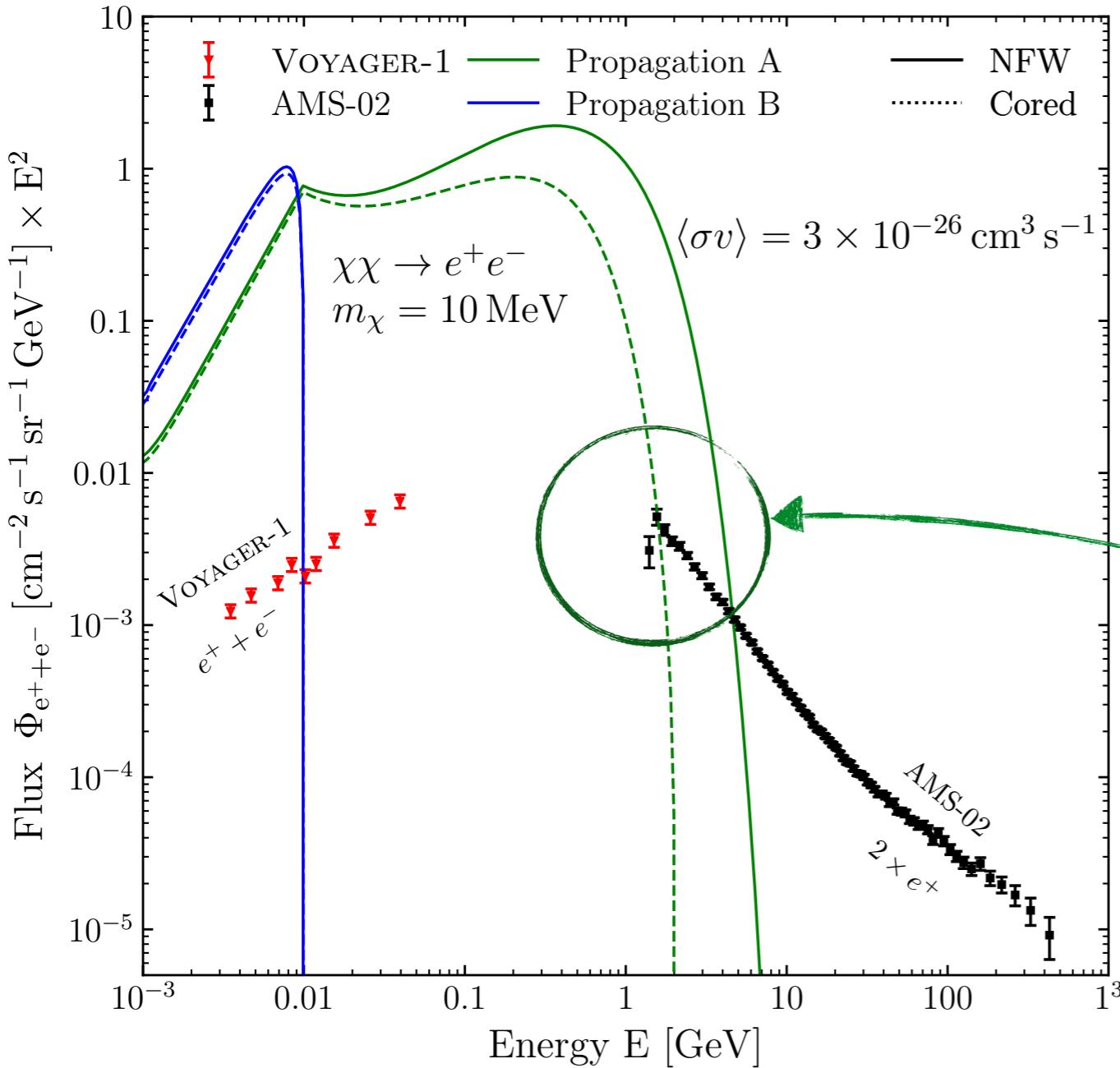
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Model **A** with **strong diffusive reacceleration**
 \Rightarrow detection of positrons above the DM mass!

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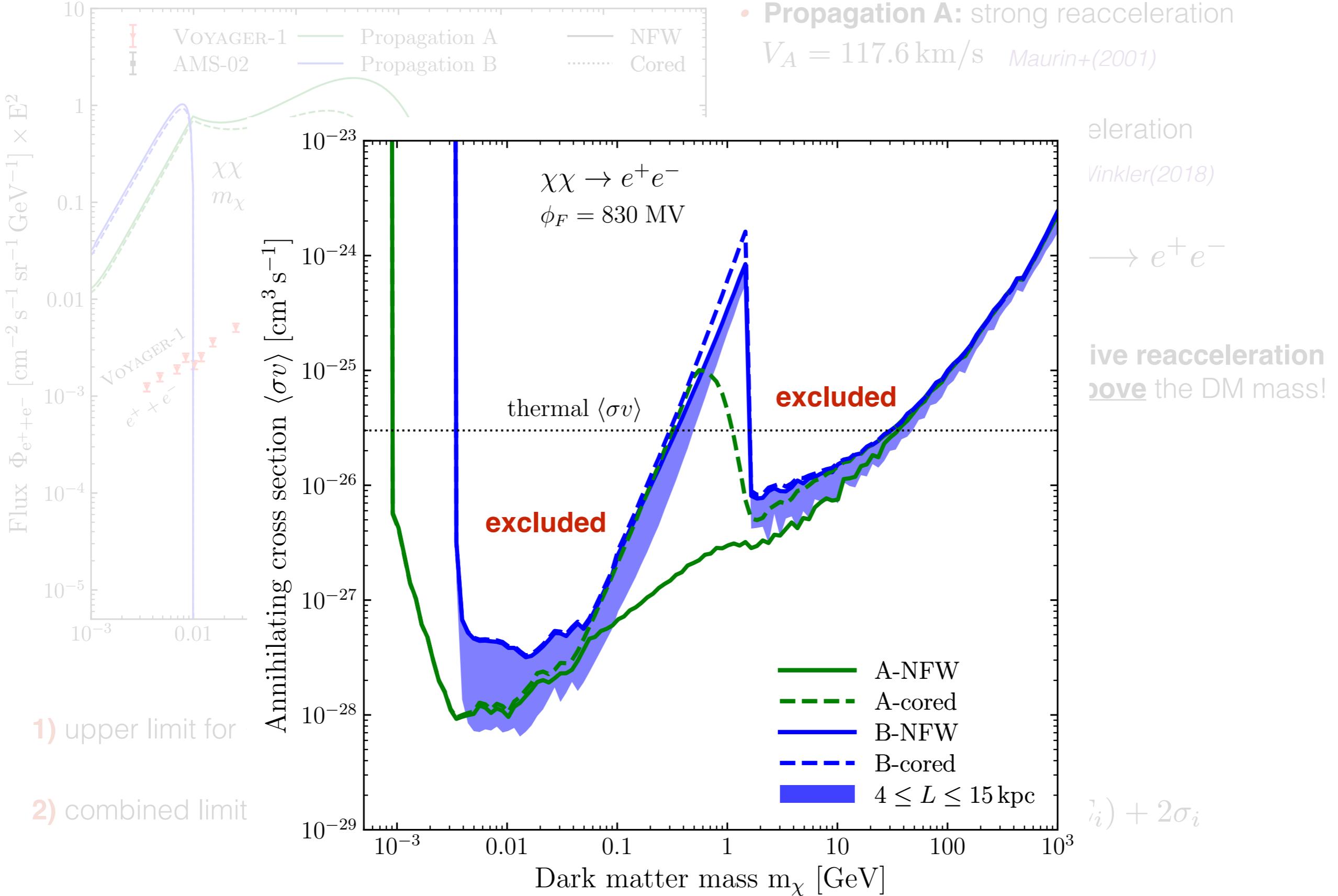
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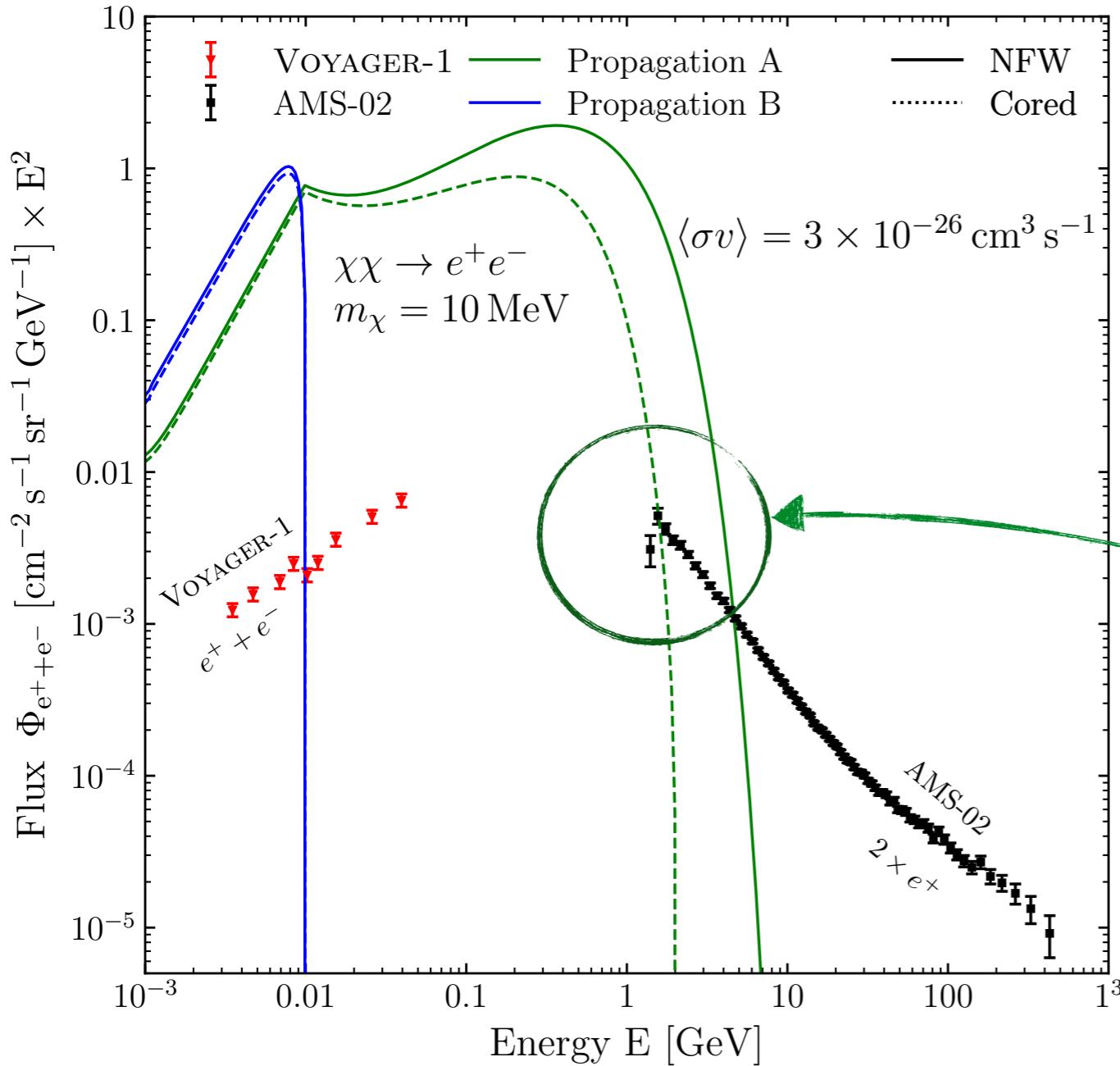
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Constraints on annihilation cross section



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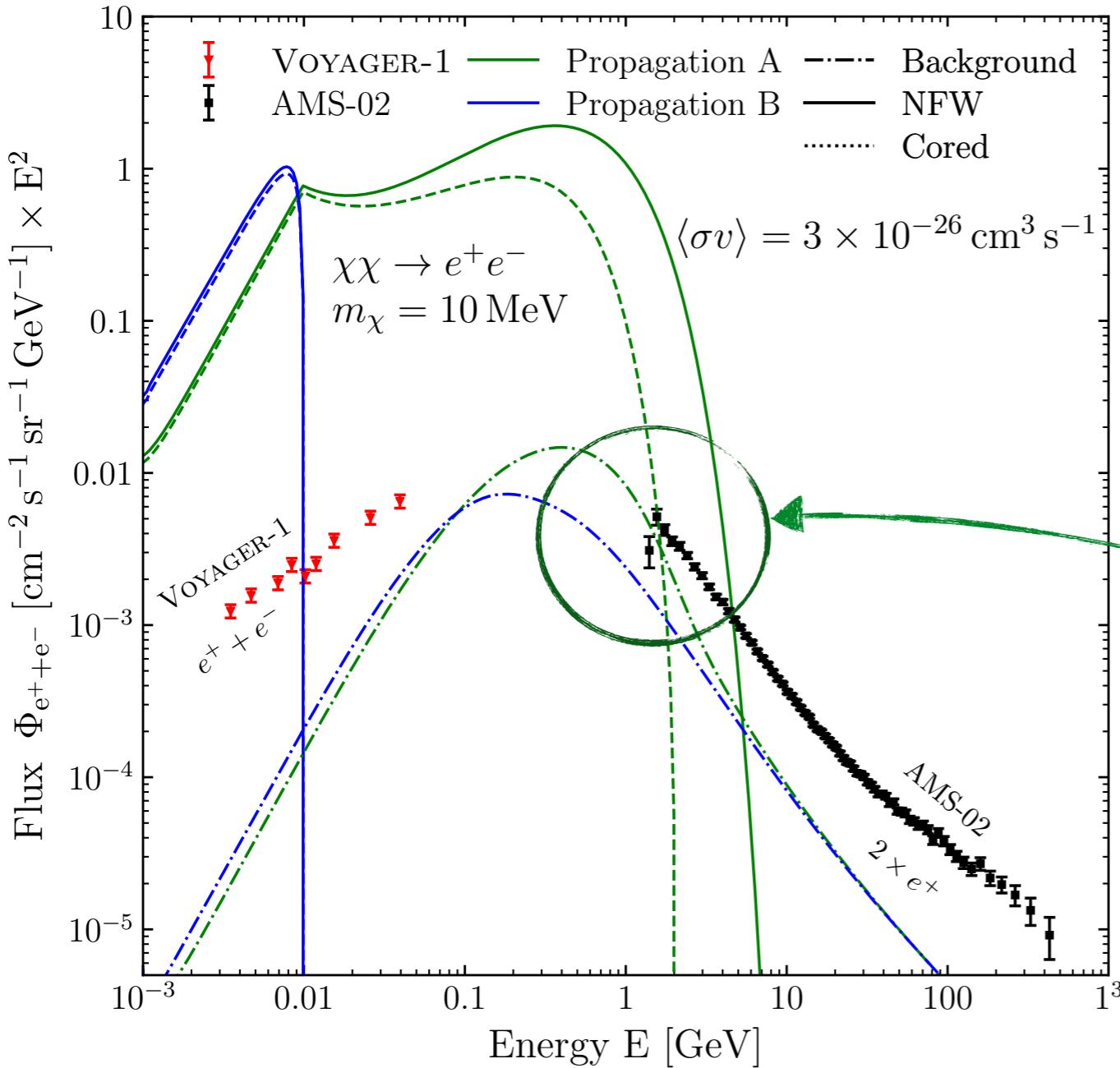
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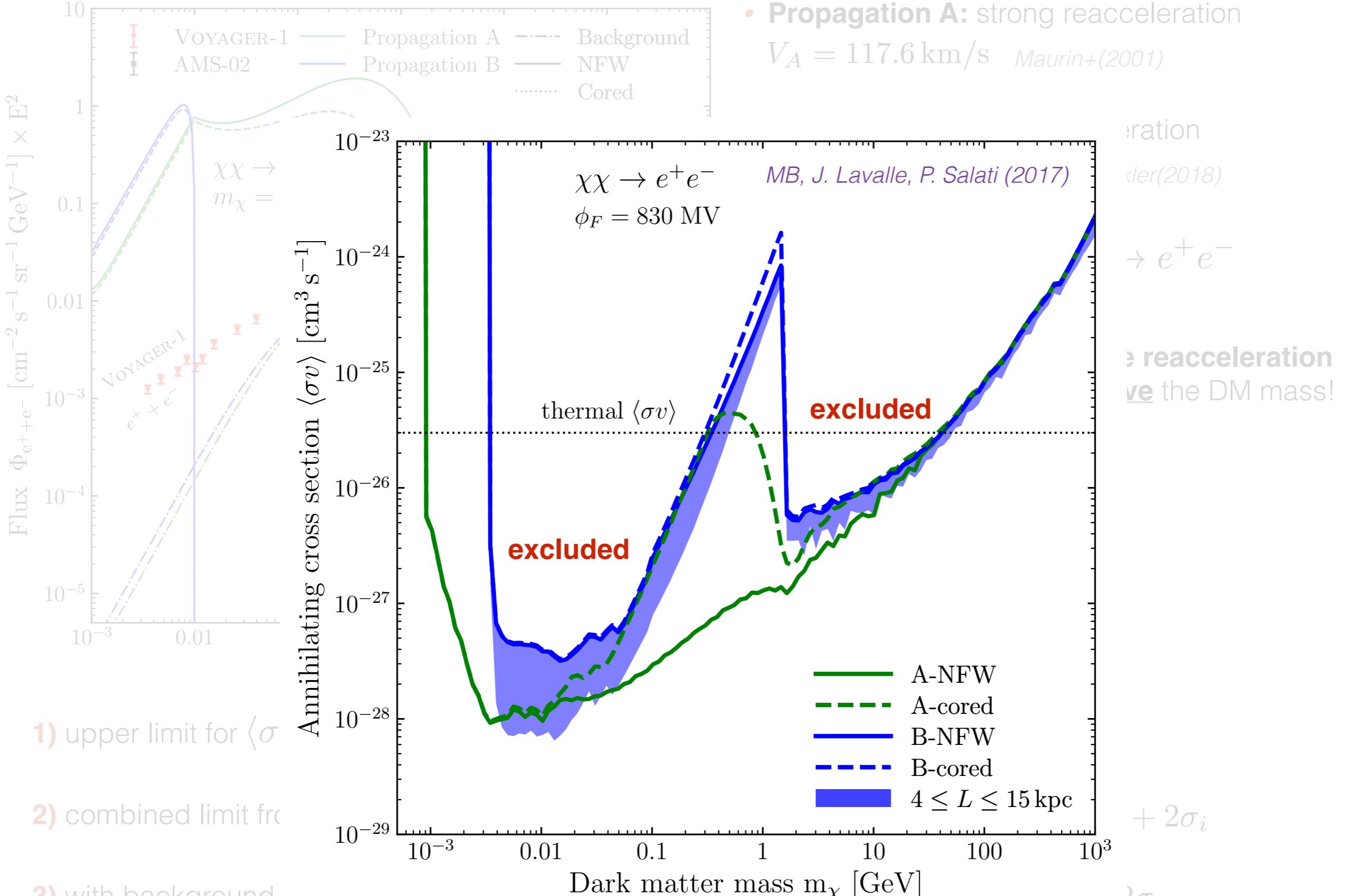
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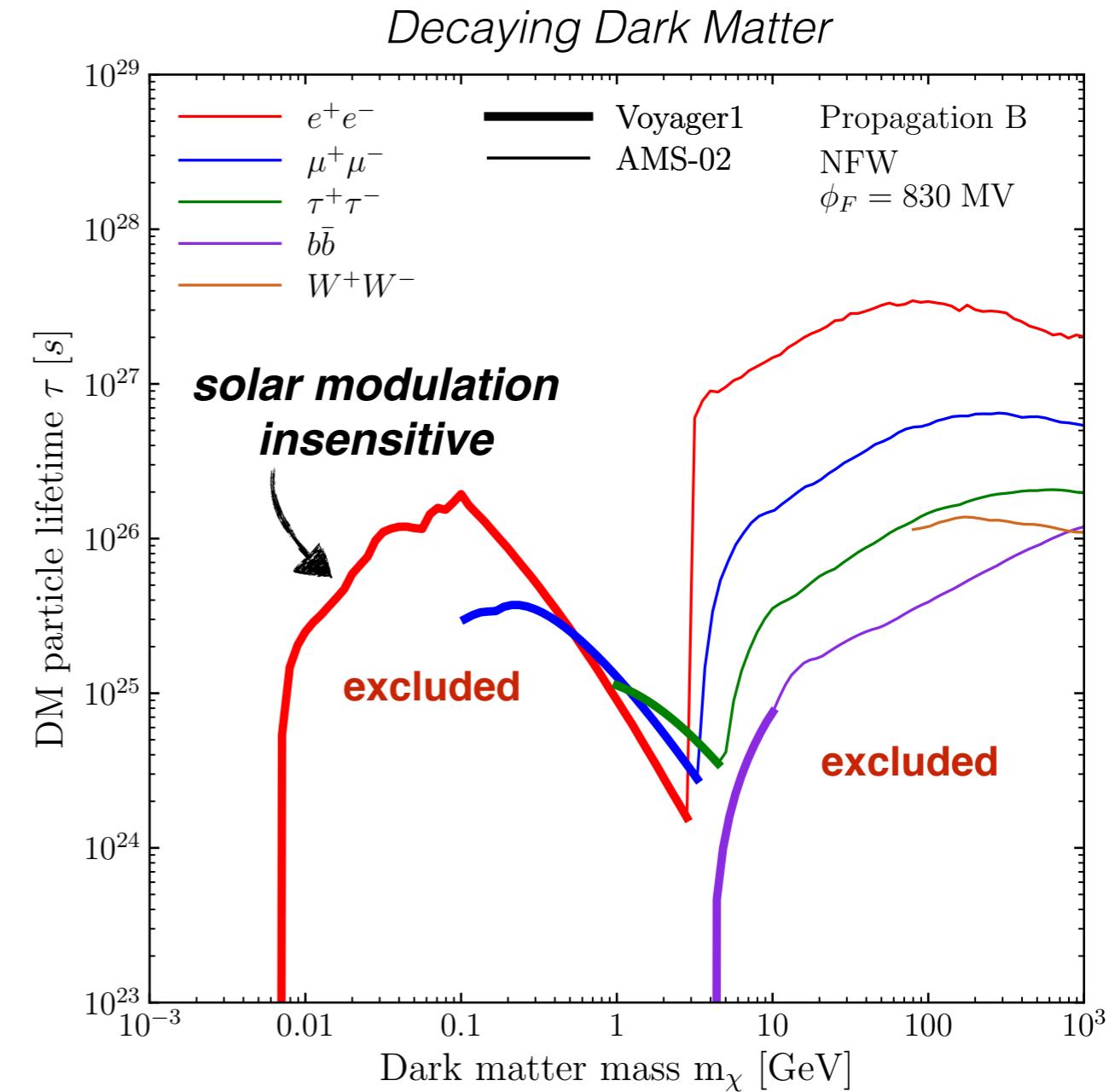
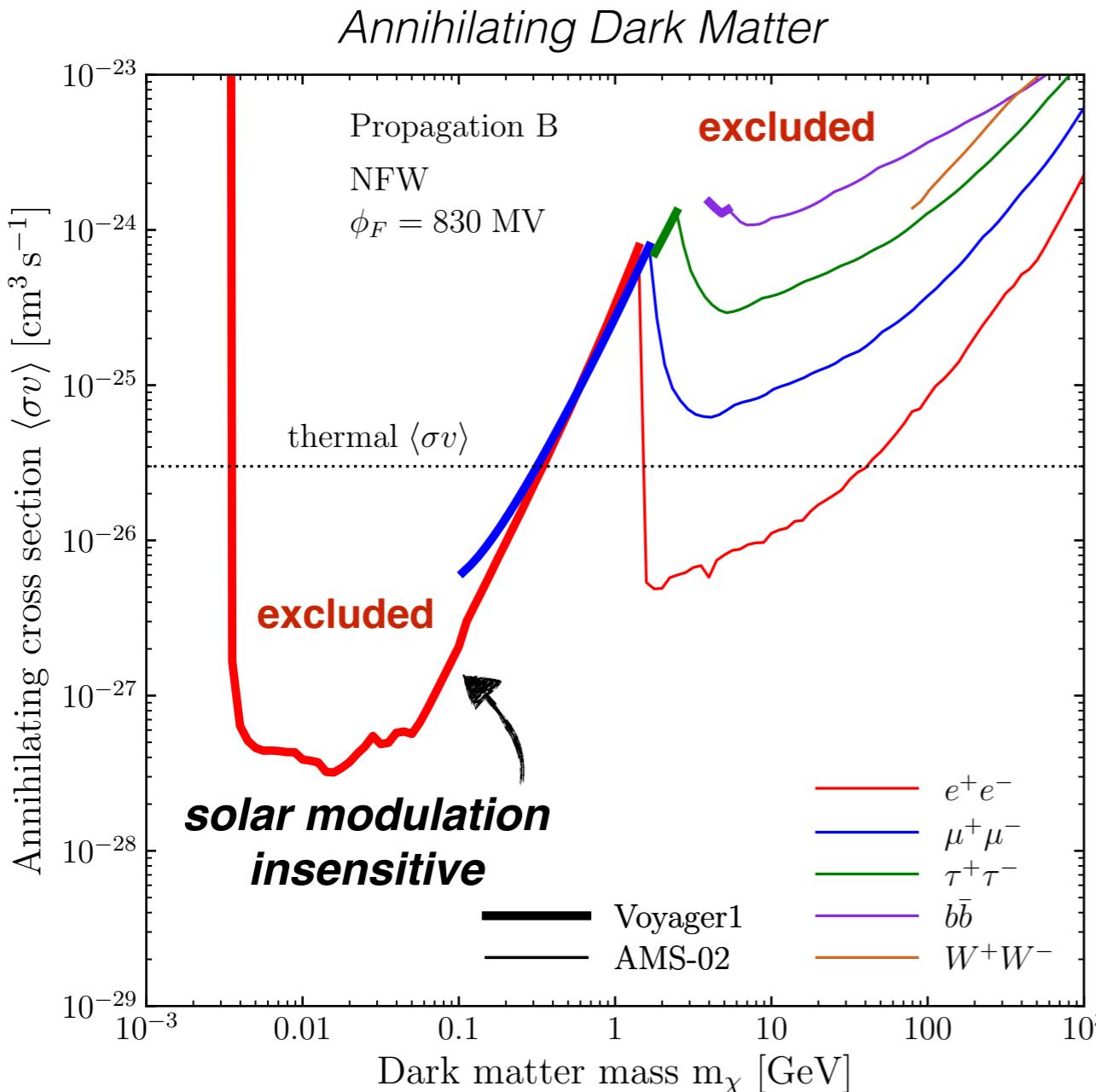
3) with background of secondary e^+ : 1) + $\Phi_{e^+}^{\text{DM}}(E_i) + \Phi_{e^+}^{\text{II}}(E_i) \leq \Phi_{e^+}^{\text{exp}}(E_i) + 2\sigma_i$

Constraints on annihilation cross section



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

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

$\sigma_0, \sigma_1, \dots$ rely on the DM model

Srednicki+(1998)



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Srednicki+(1998)



scalar
mediator

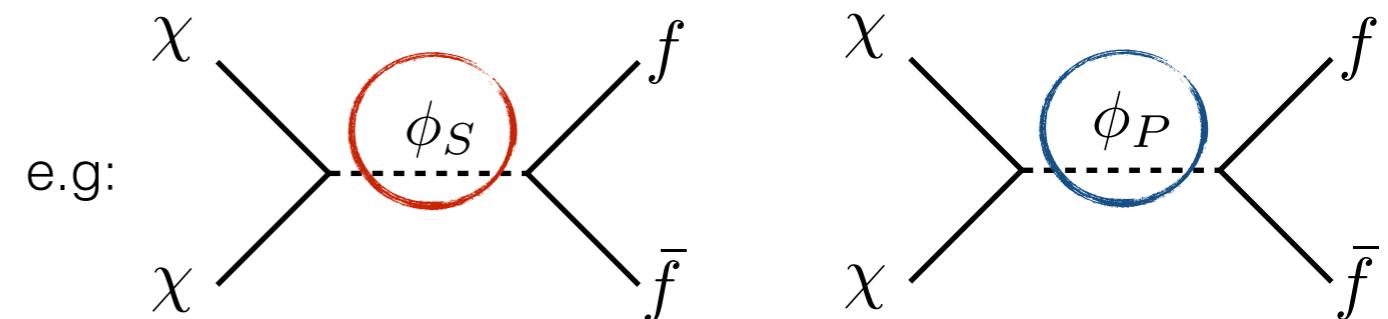
X

pseudo-scalar
mediator

✓

✓

✓

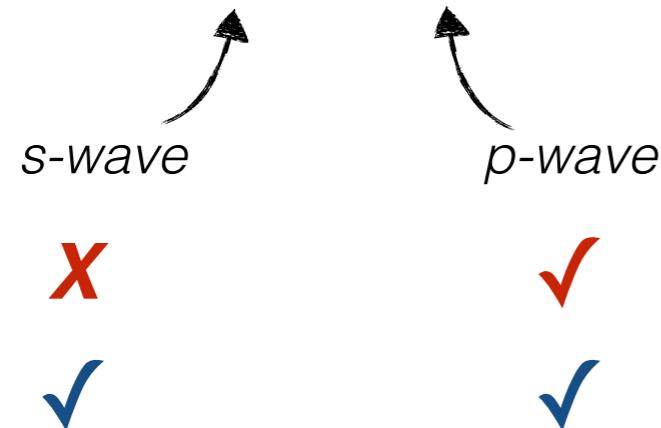


Assuming $\langle \sigma v \rangle$ constant (velocity independent) is a strong assumption for the DM model
⇒ better to constrain the σ_i coefficients, directly linked to the DM models

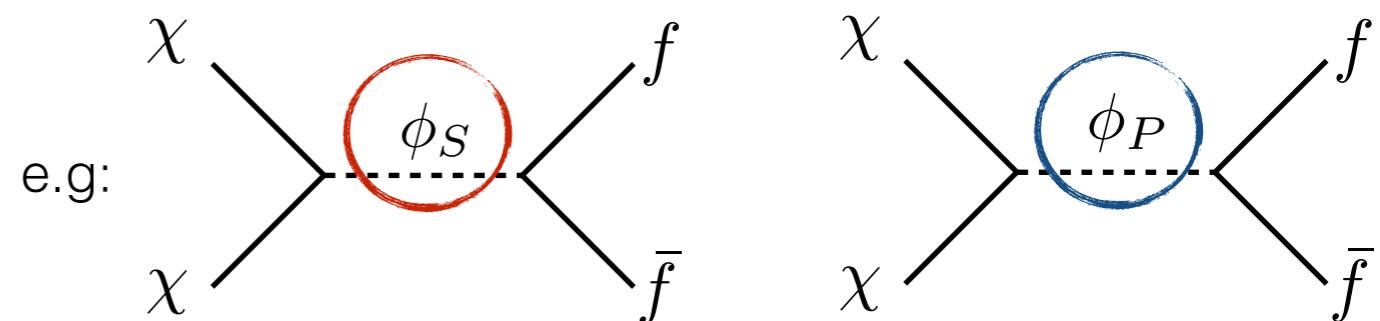
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Recombination (CMB)

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

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

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

Now in the Milky Way

Maxwellian distribution

$$v_c = \sqrt{2} \sigma$$

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

$$v_c \simeq 240 \text{ km s}^{-1}$$

$$\beta_{\text{MW}}^2 \simeq 10^{-6}$$

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

Eddington inversion method

Observationally constrained Galactic mass model:

$$\rho_{\text{tot}}(\vec{x}) = \rho_{\text{bar}}(\vec{x}) + \rho_{\text{DM}}(\vec{x}) \quad \text{McMillan (2016)}$$

Jeans' theorem + Poisson equation
(spherically symmetric systems)

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

Eddington (1916), Binney and Tremaine (1987)

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

Lacroix, Stref & Lavalle(2018)

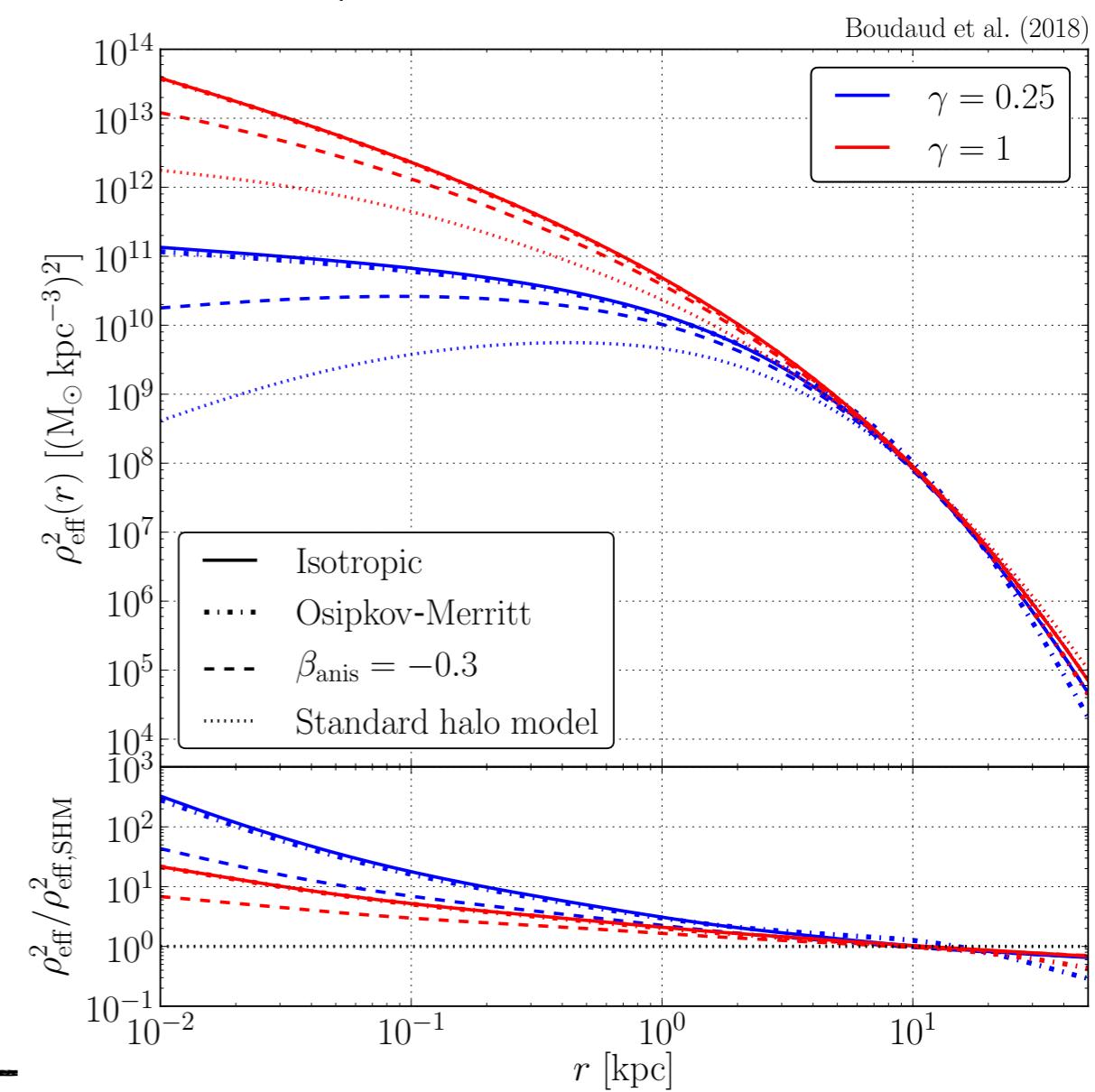
$$\langle \sigma v \rangle(r) = K_0(r) \int d^3 \vec{v}_1 \int d^3 \vec{v}_2 f(|\vec{v}_1|, r) f(|\vec{v}_2|, r) \sigma v_{12}$$

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

$v_{12} = |\vec{v}_2 - \vec{v}_1|$: relative velocity

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

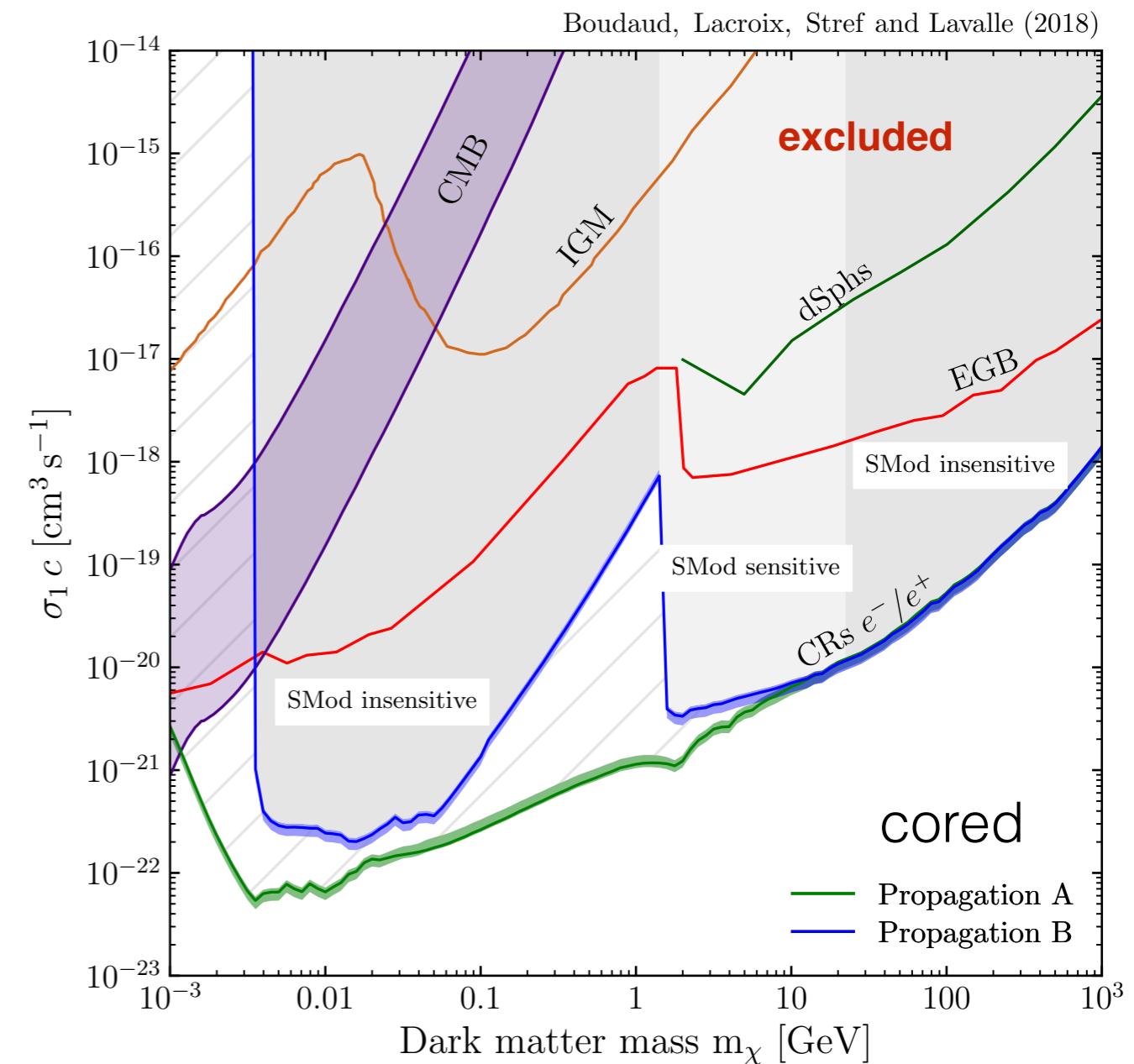
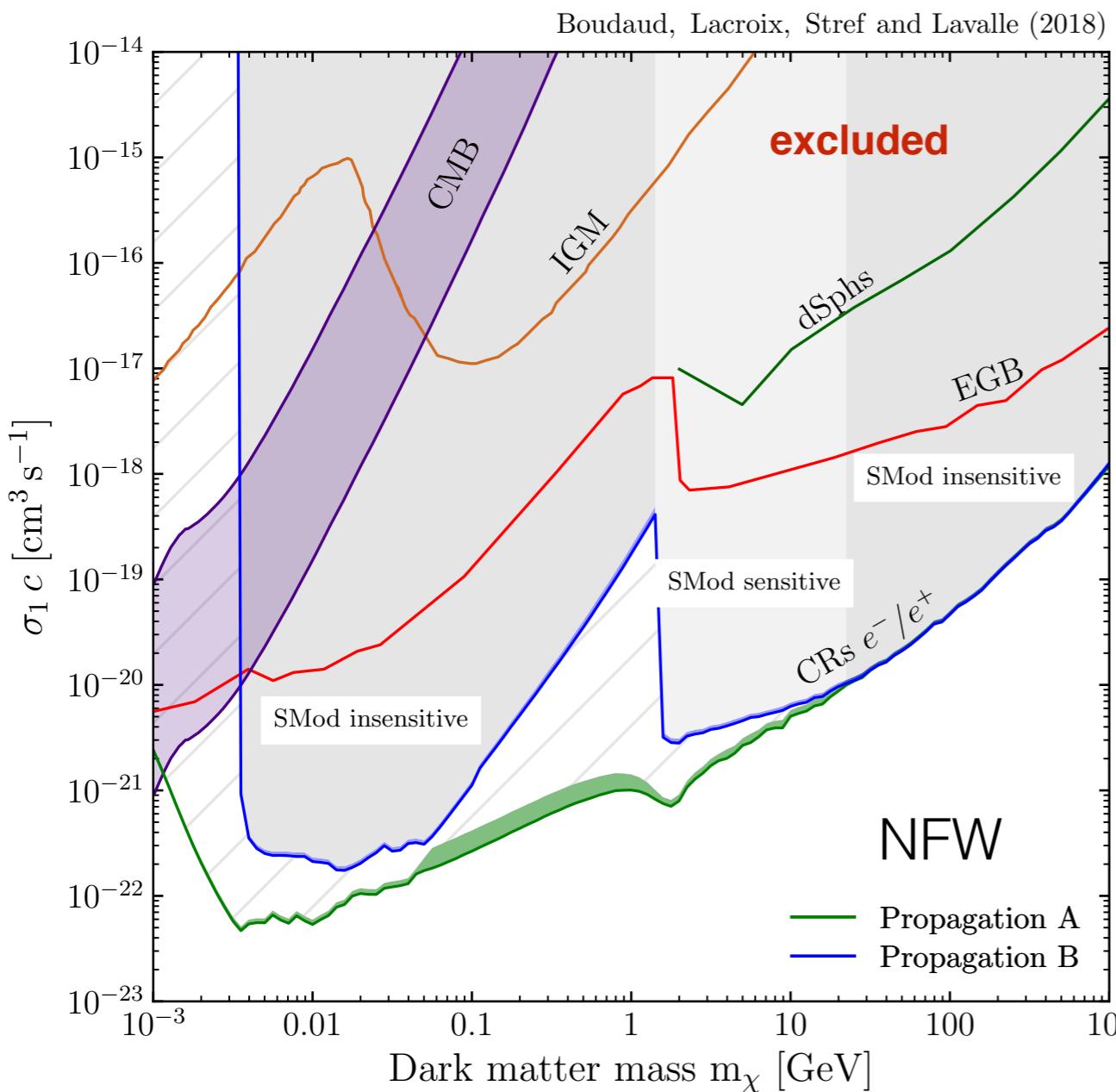
$$\rho_{\text{eff}}^2(r) \equiv \rho_{\text{DM}}^2(r) \langle \sigma v \rangle(r)$$



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



Application 2: Primordial Black Holes

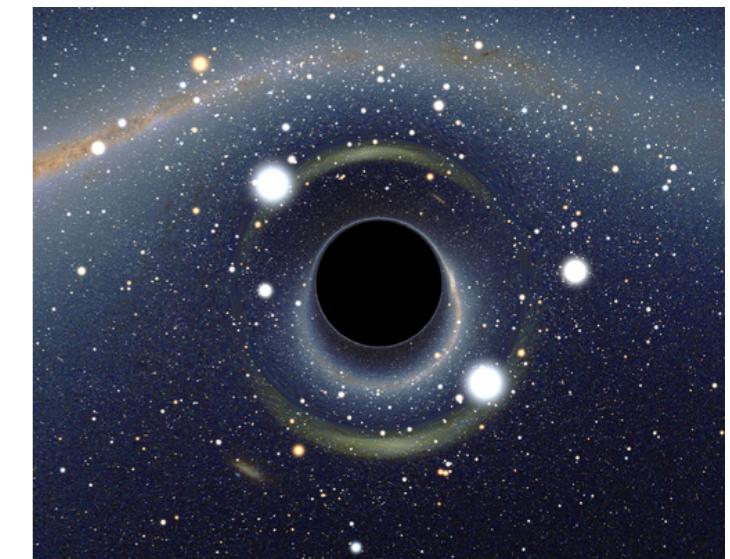
MB and M. Cirelli (PRL 122, 041104)

Primordial black holes as dark matter

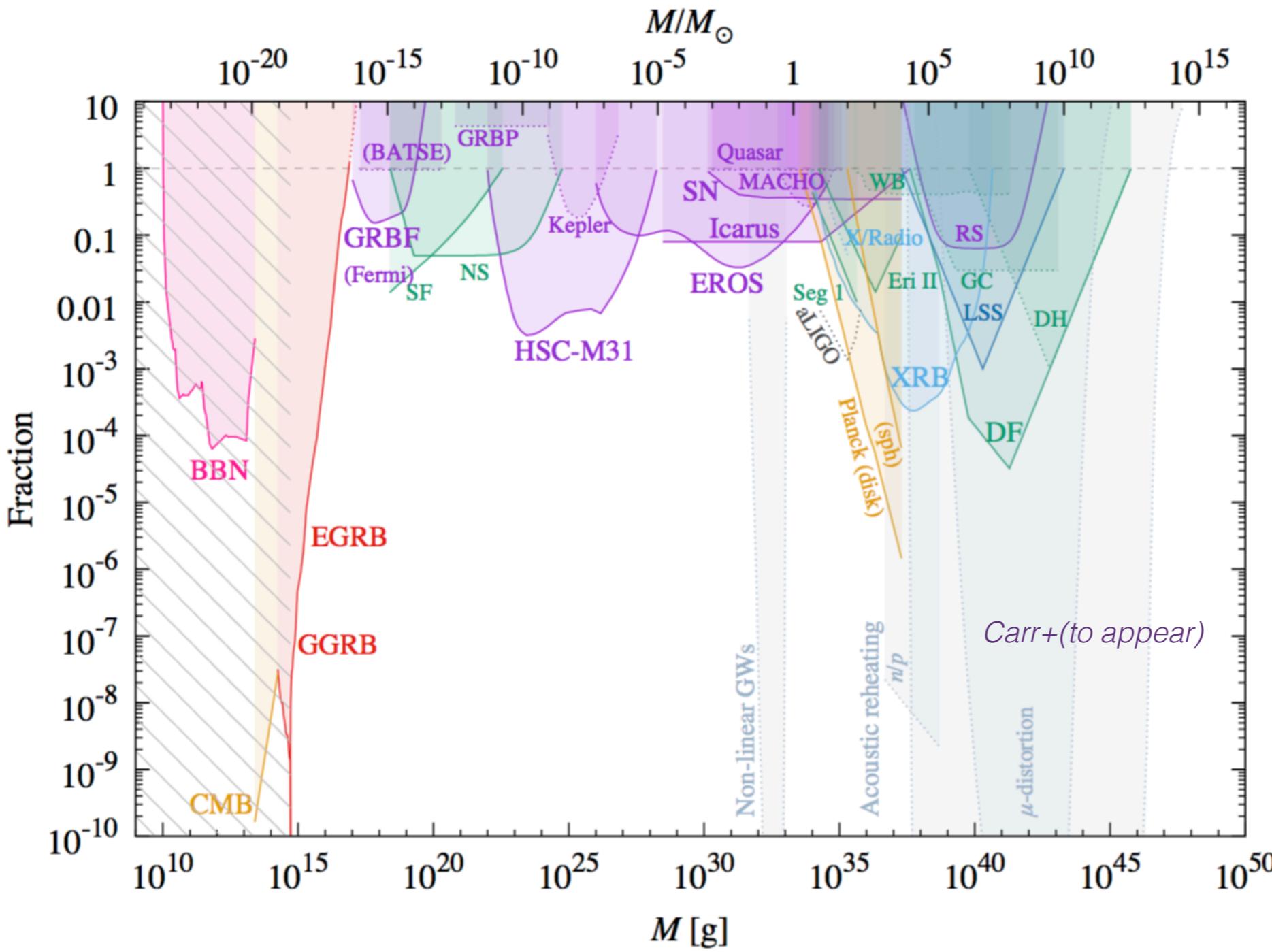
Produced from quantum fluctuations before inflation

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

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



Lensing, dynamical, accretion, cosmological and Hawking radiation limits

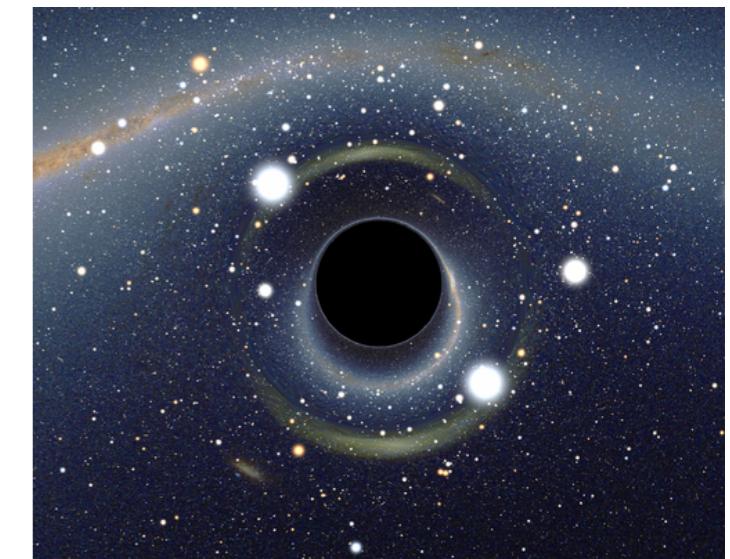


Primordial black holes as dark matter

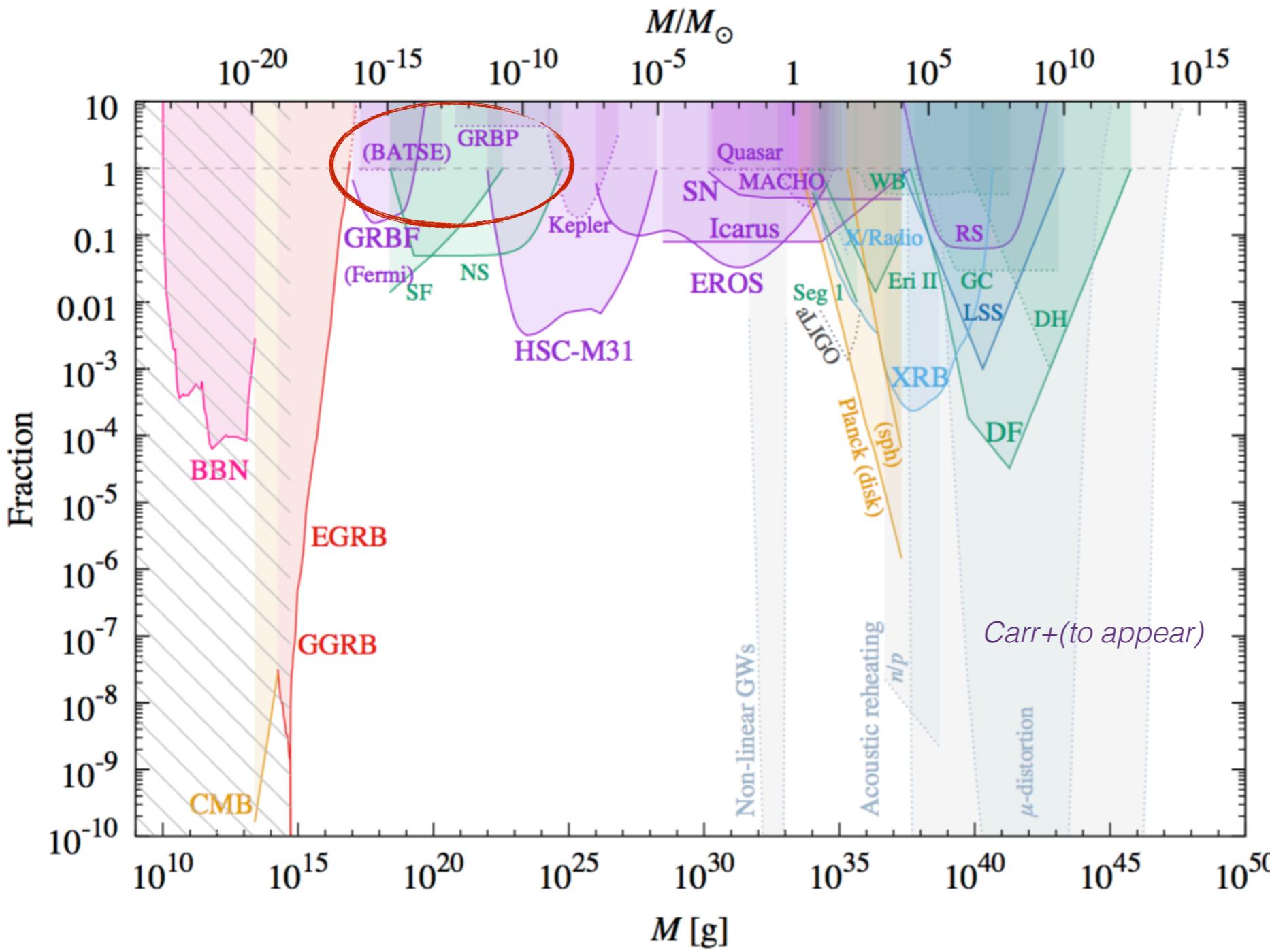
Produced from quantum fluctuations before inflation

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

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



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



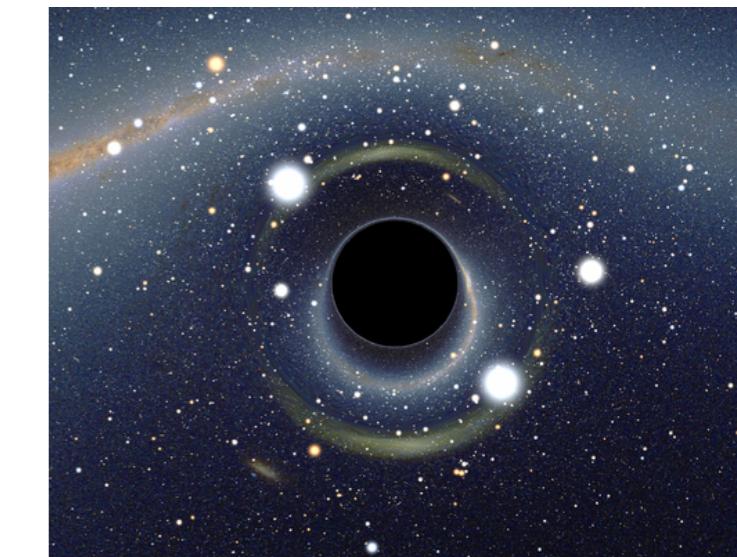
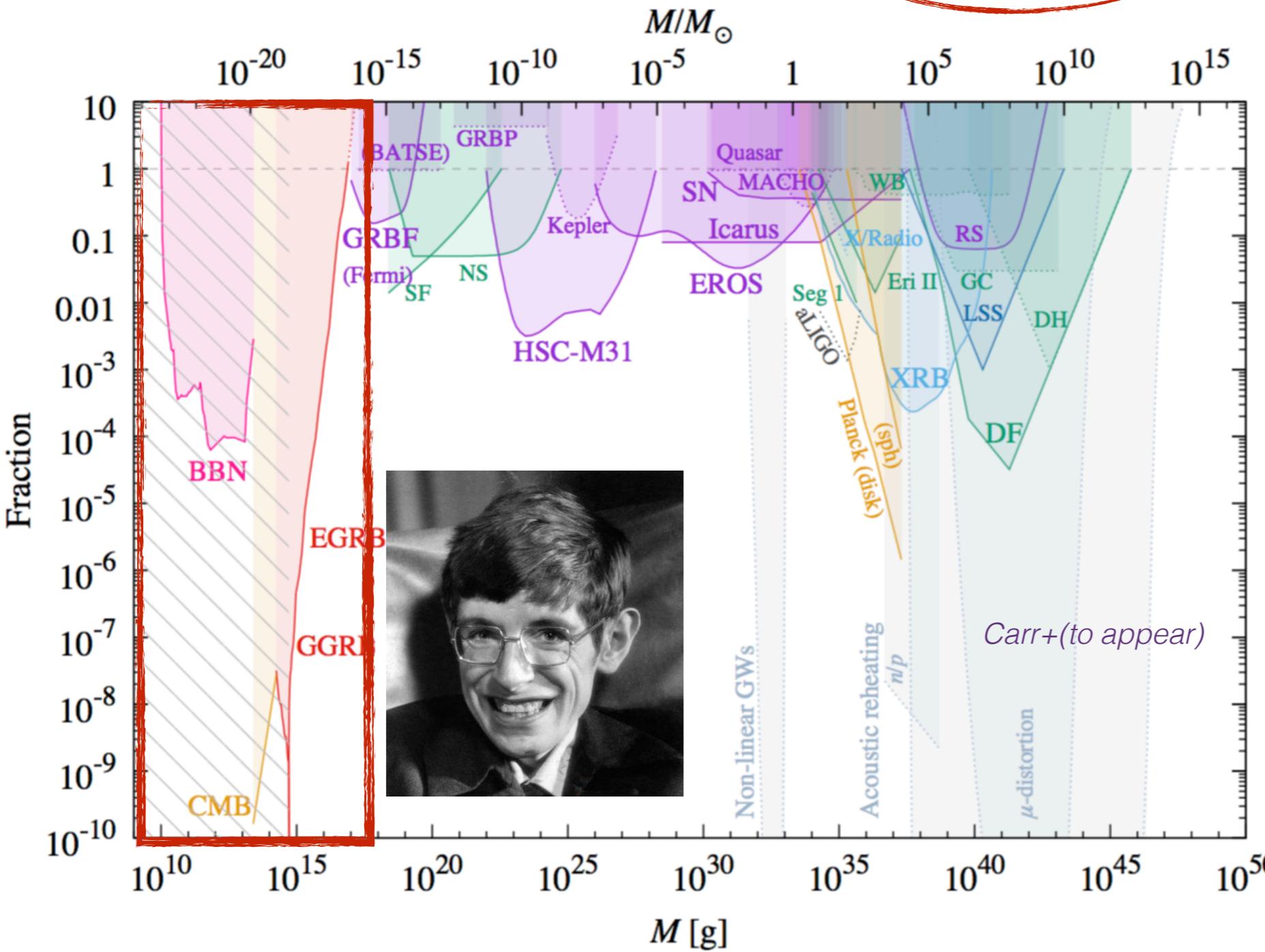
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Lensing, dynamical, accretion, cosmological and **Hawking radiation** limits



Microscopic BHs

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

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

(asteroid / small mountain)

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

(nucleus size)

$$\rho_{\odot}^{\text{DM}} = 0.4 \text{ GeVcm}^{-3}$$

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

Hawking radiation of electrons and positrons

BH temperature from classical thermodynamics

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

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

Hawking temperature from QFT in curved spacetime

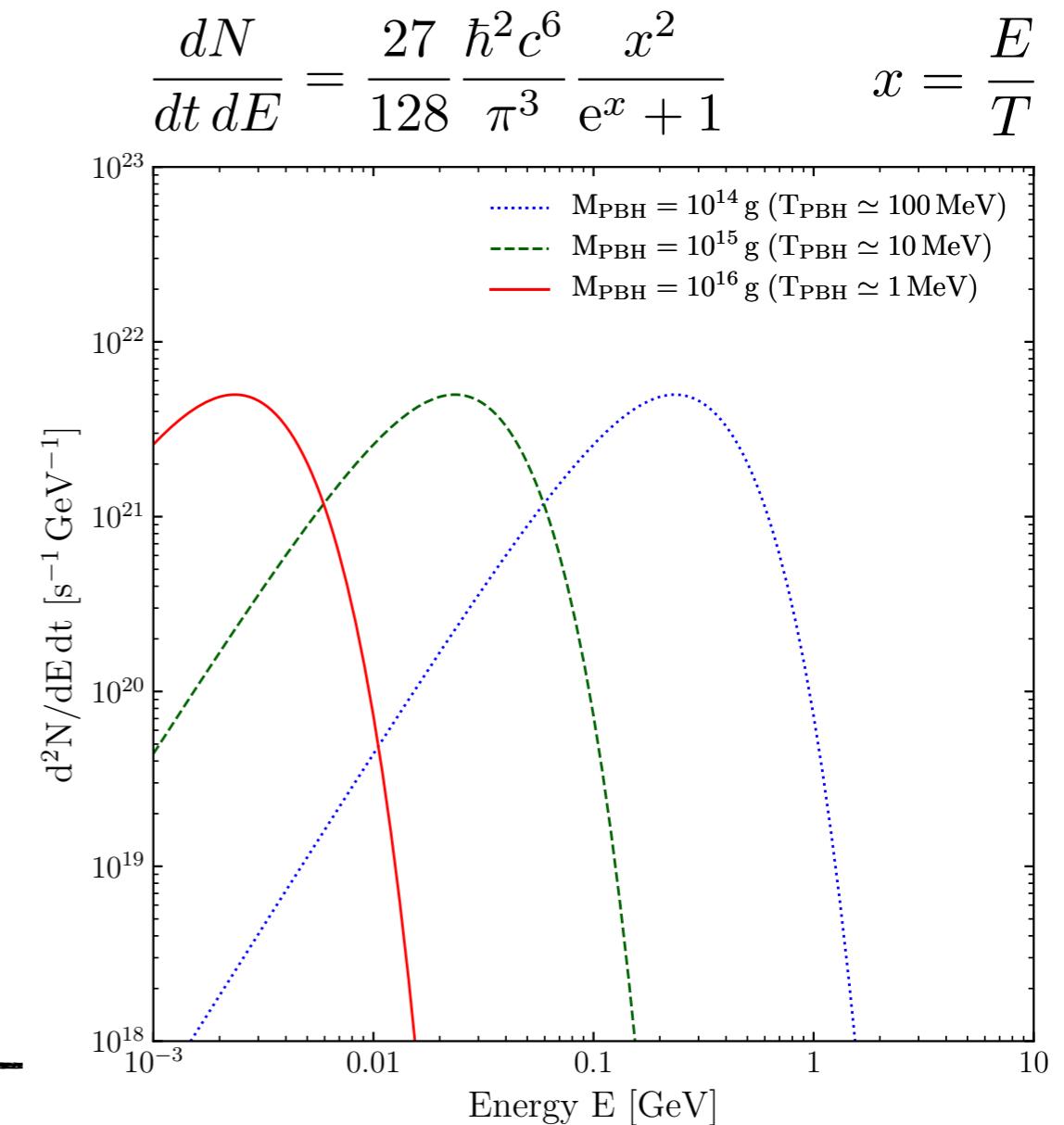
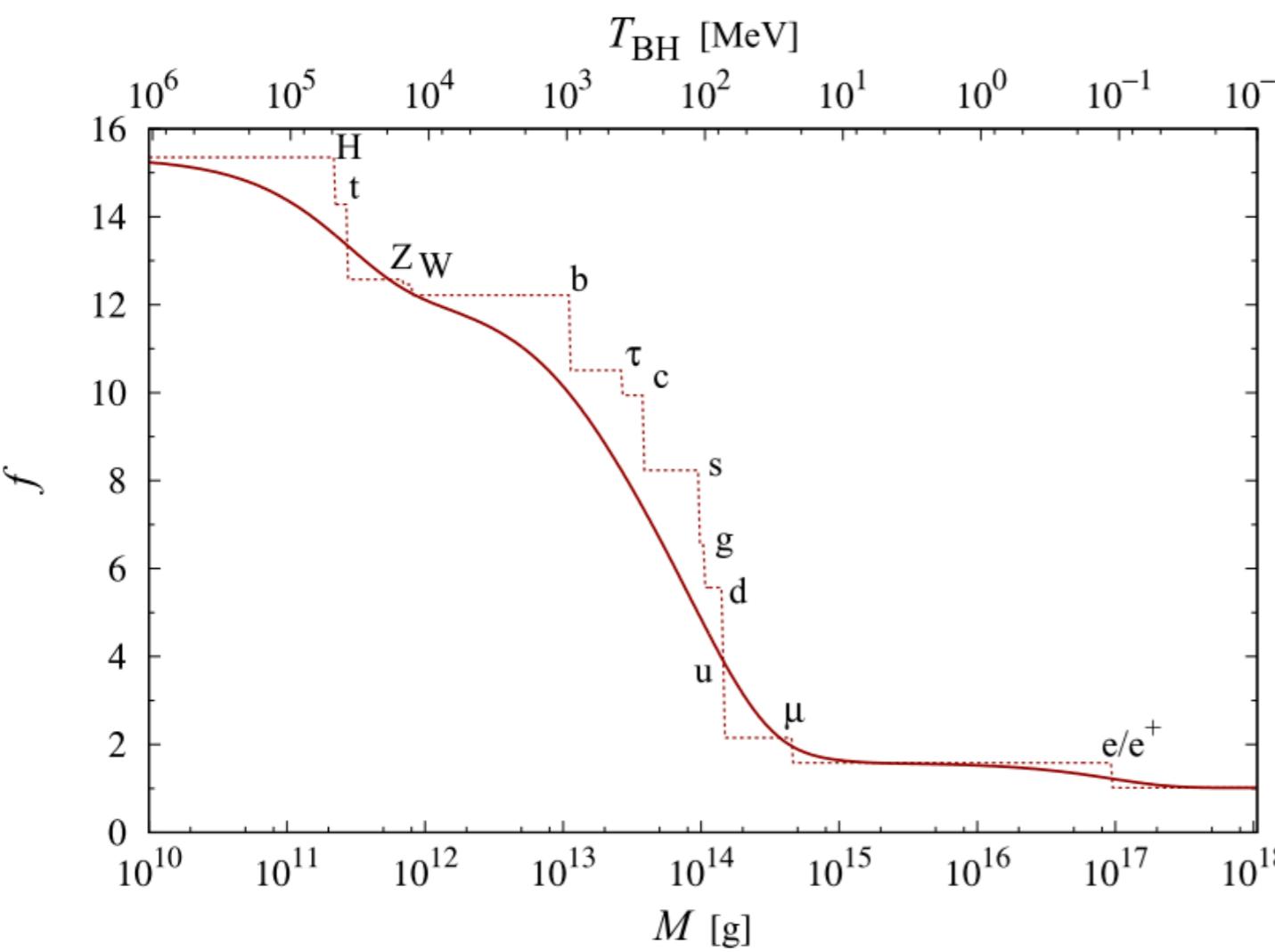
$$T = \frac{\hbar c^3}{8\pi G k_B M}$$

BHs lose mass radiating particles with the rate:

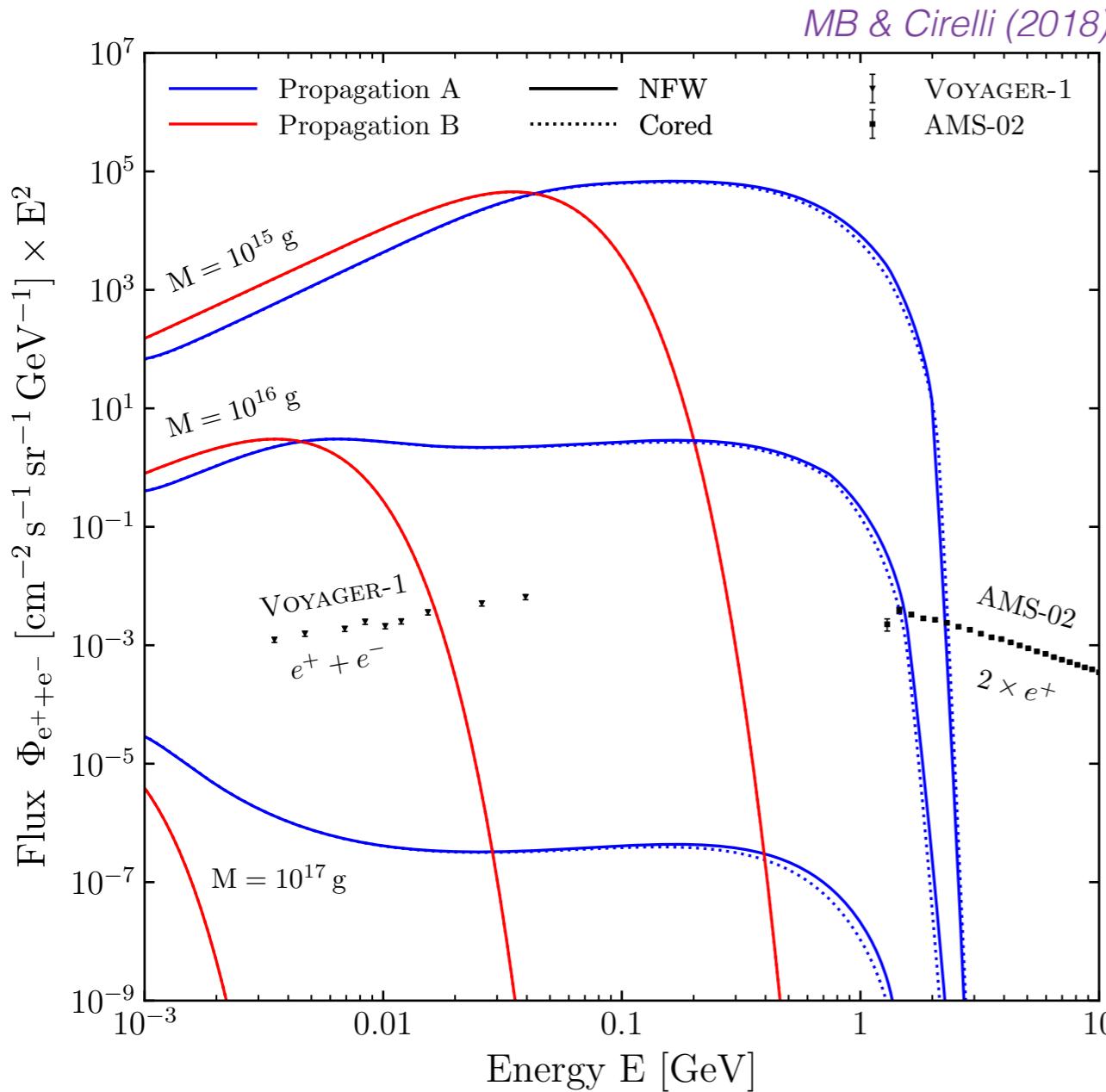
$$\frac{dM}{dt} \simeq -5.25 \times 10^{25} f(M) \left(\frac{g}{M} \right) g s^{-1}$$

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

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



CRs e^\pm from PBHs radiation



Propagation A: strong reacceleration

$V_A = 117.6 \text{ km/s}$ Maurin+ (2001)

Propagation B: no reacceleration

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

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

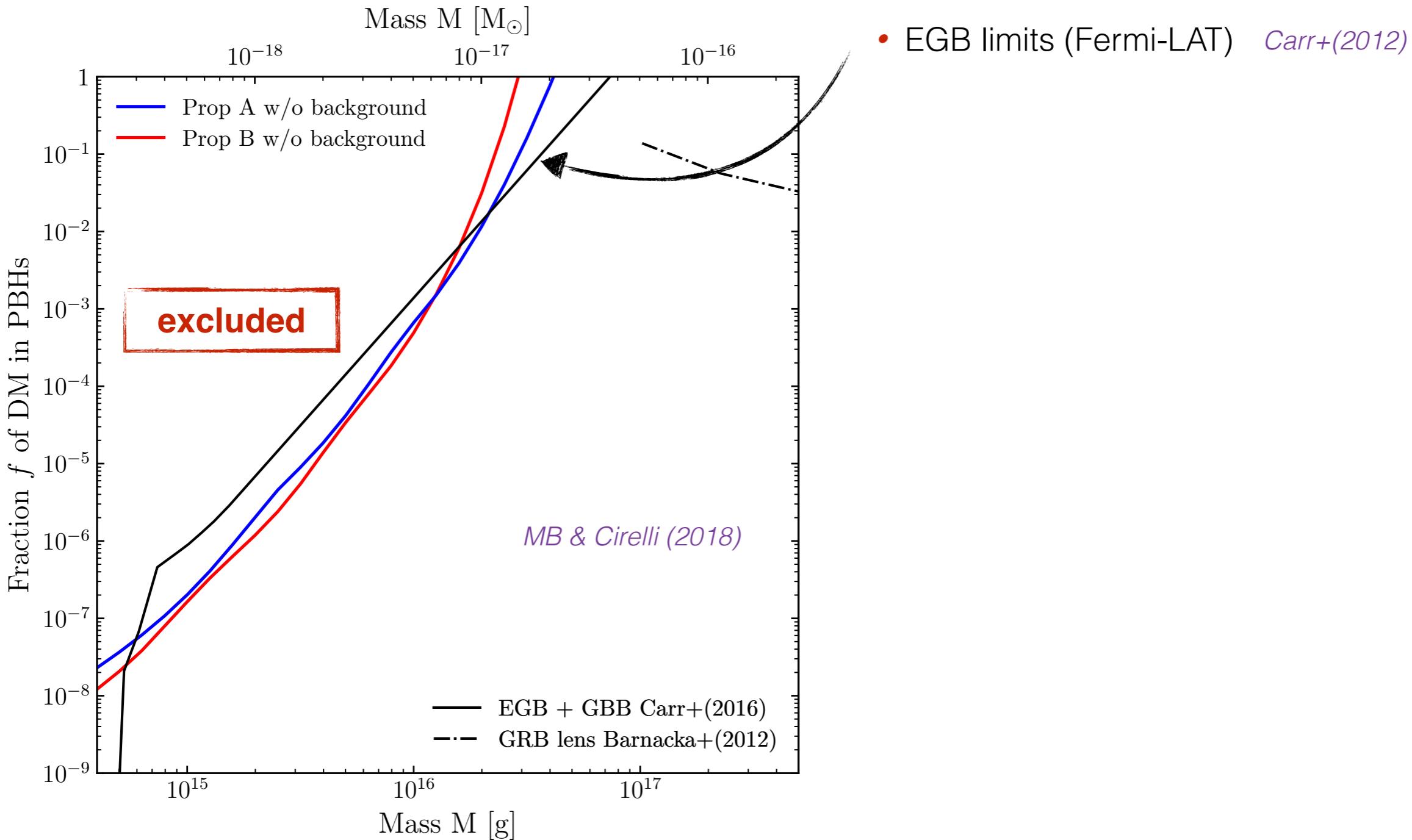
$$\rho_\odot^{\text{DM}} = 0.4 \text{ GeV cm}^{-3}$$

Voyager-1 probes PBHs with mass up to $\sim 10^{17} \text{ g}$

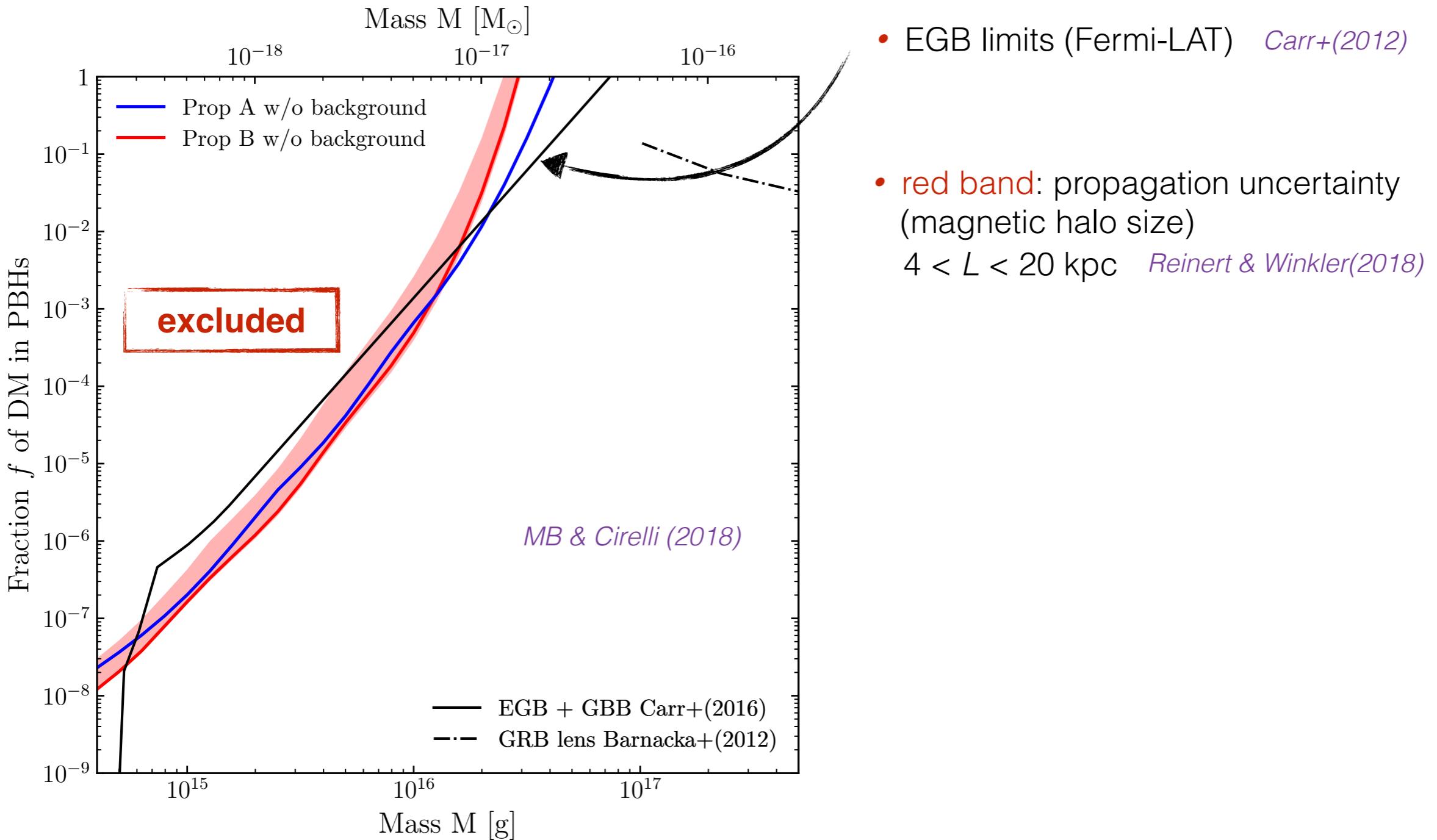
- Voyager-1 is sensitive local PBHs ($\sim 1\text{kpc}$) because of e^\pm energy losses (ISM ionisation)
⇒ signal **not sensitive** to the DM halo profile
- strong reacceleration (**A**) enables to detect a signal above 1 GV
⇒ AMS-02 probes PBHs with $M < 10^{16} \text{ g}$

Voyager-1 data ⇒ upper limit for $f = \rho_{\text{PBH}} / \rho_{\text{DM}}$

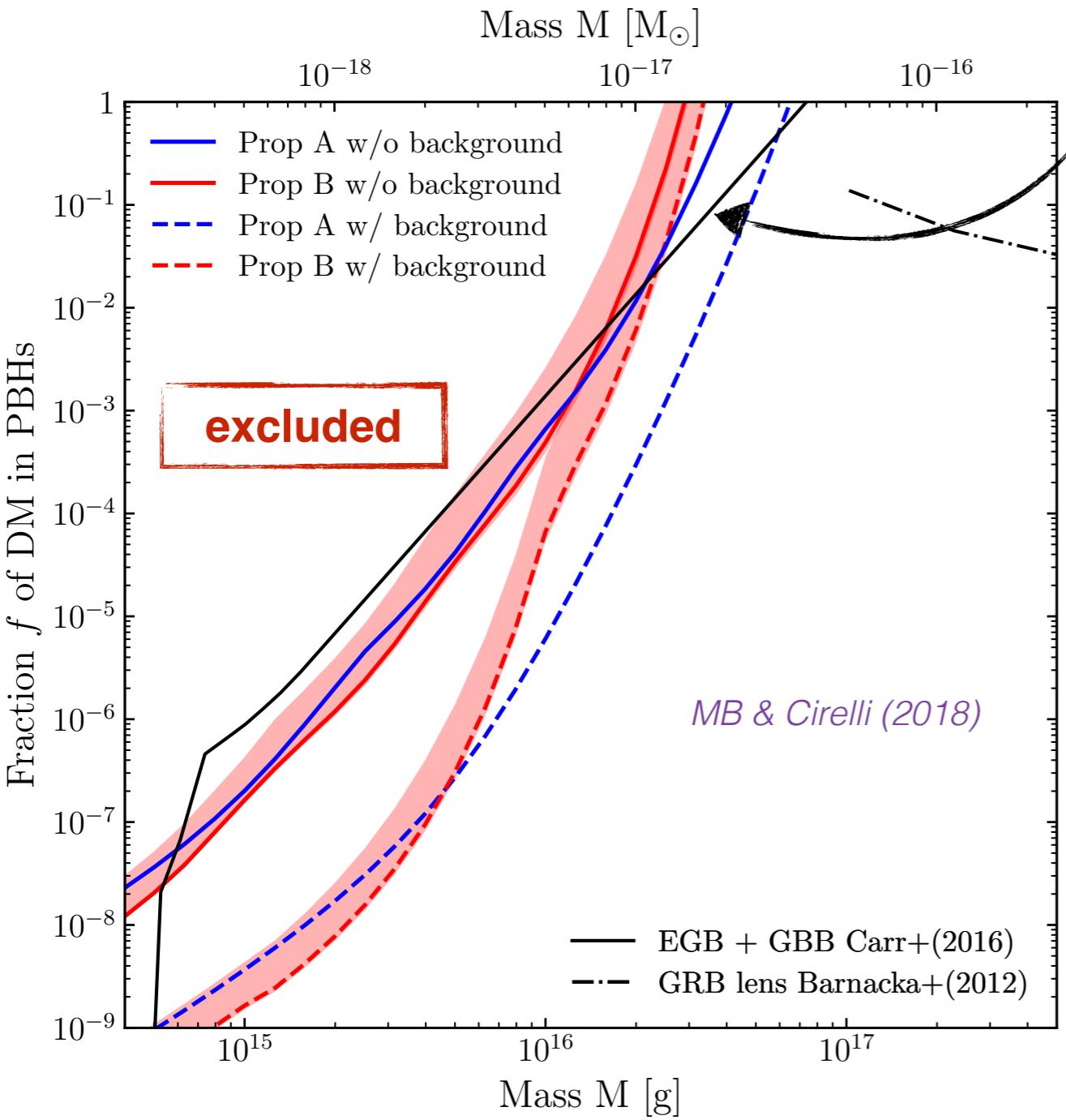
Constraints on the fraction of DM in PBHs



Constraints on the fraction of DM in PBHs

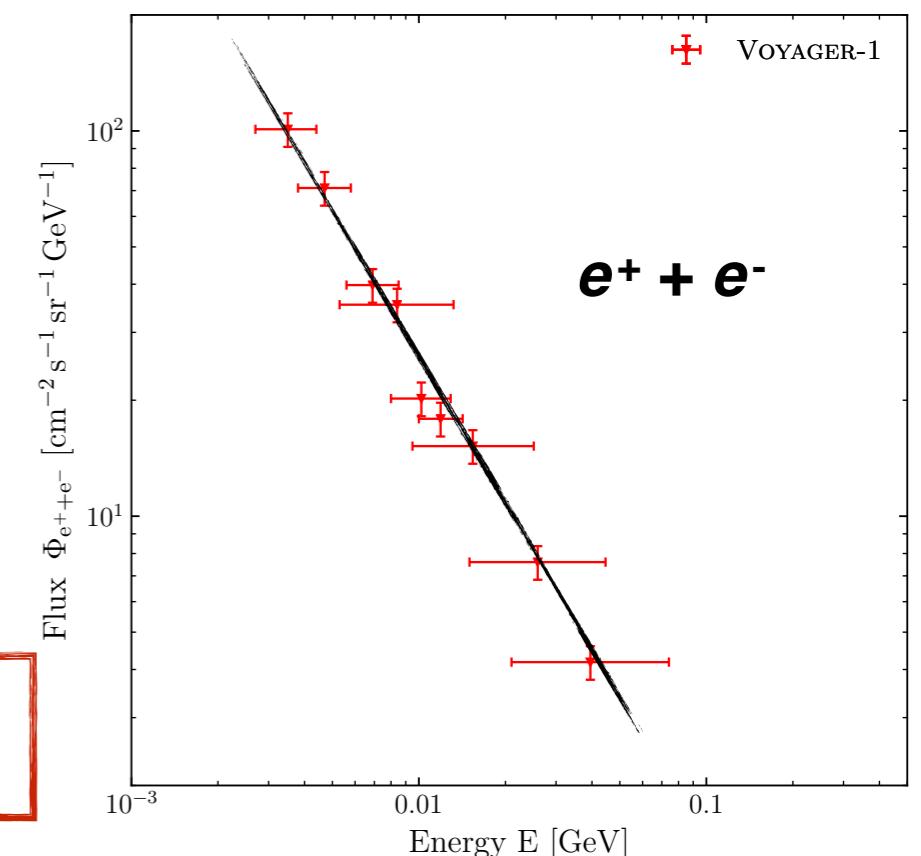


Constraints on the fraction of DM in PBHs



- 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^-)

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



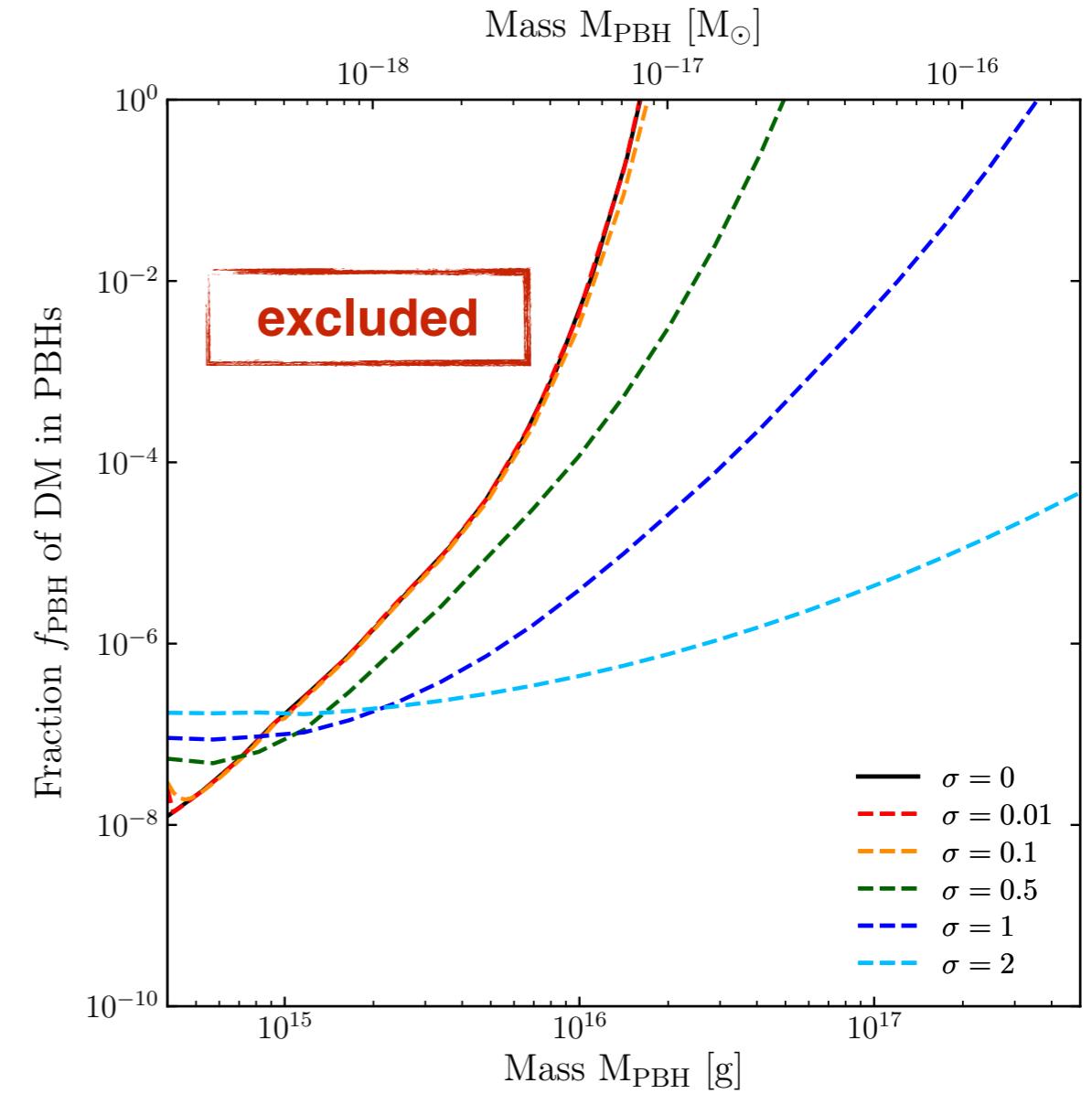
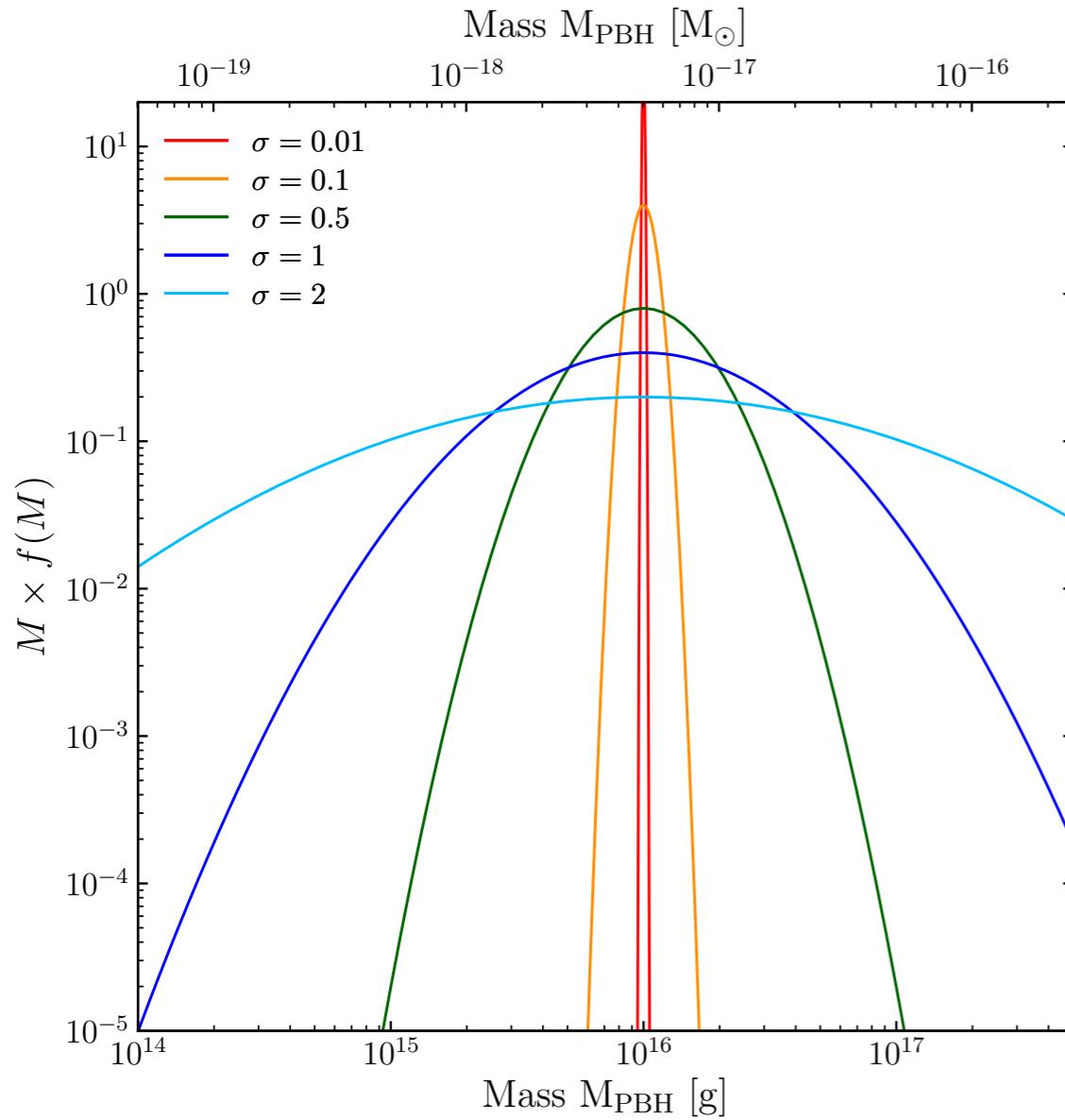
local constraints ($1\sim\text{kpc}$), **no** cosmological assumptions
⇒ complementary to cosmological constraints (EGB, CMB, EDGES)

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)

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



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 γ -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