

Voyager probing Dark Matter

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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 (A&A 605, 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)



LPTHE

LABORATOIRE DE PHYSIQUE
THEORIQUE ET HAUTES ENERGIES



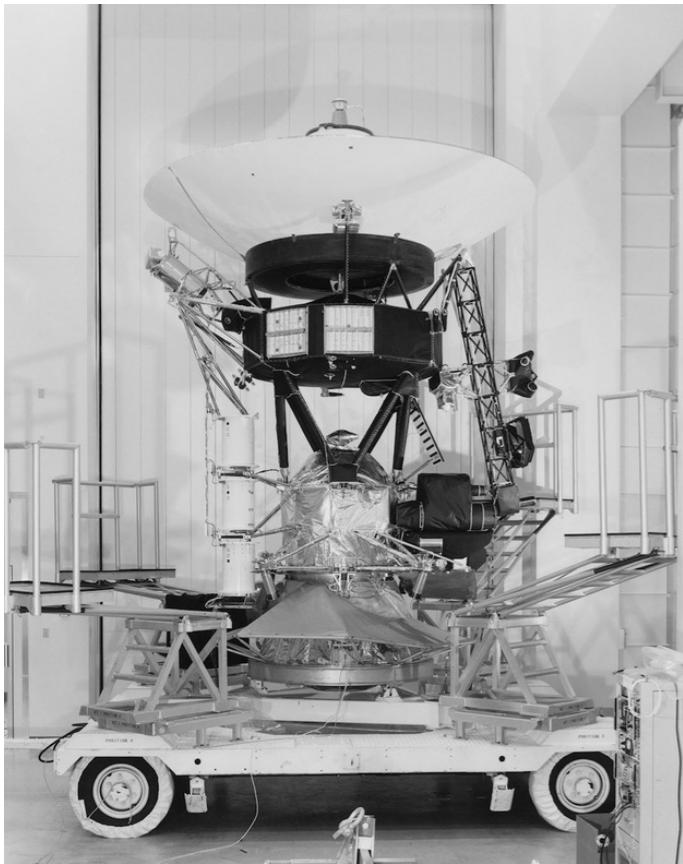
MeV cosmic rays?



Sub-GeV interstellar CRs cannot reach detectors orbiting the Earth

they are stopped by the heliopause

Voyager-1 crossed the heliopause in 2012



launch:

1977

distance now:

~145 au

direction:

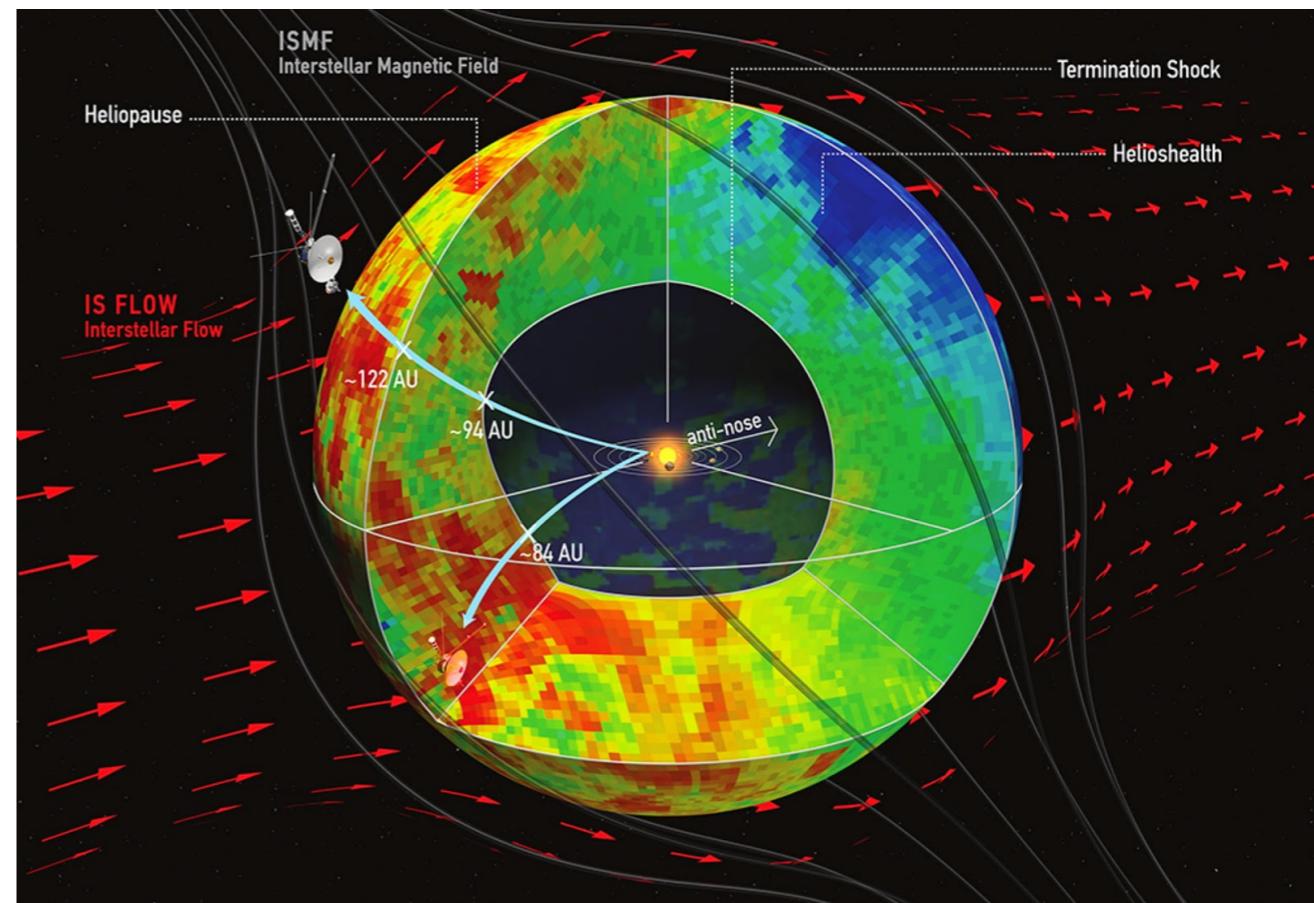
Hercules (solar apex)

velocity/Sun:

~17 km/s

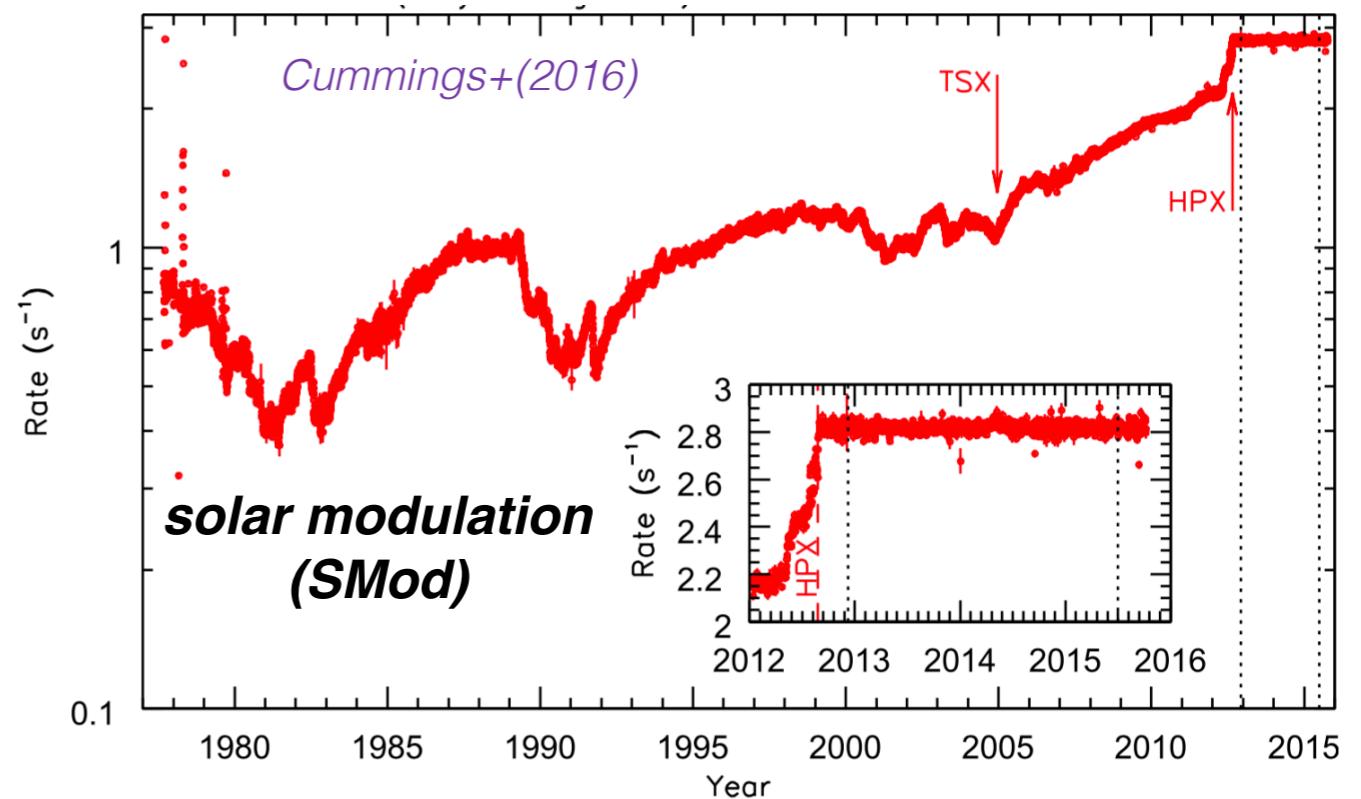
CRs energy:

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

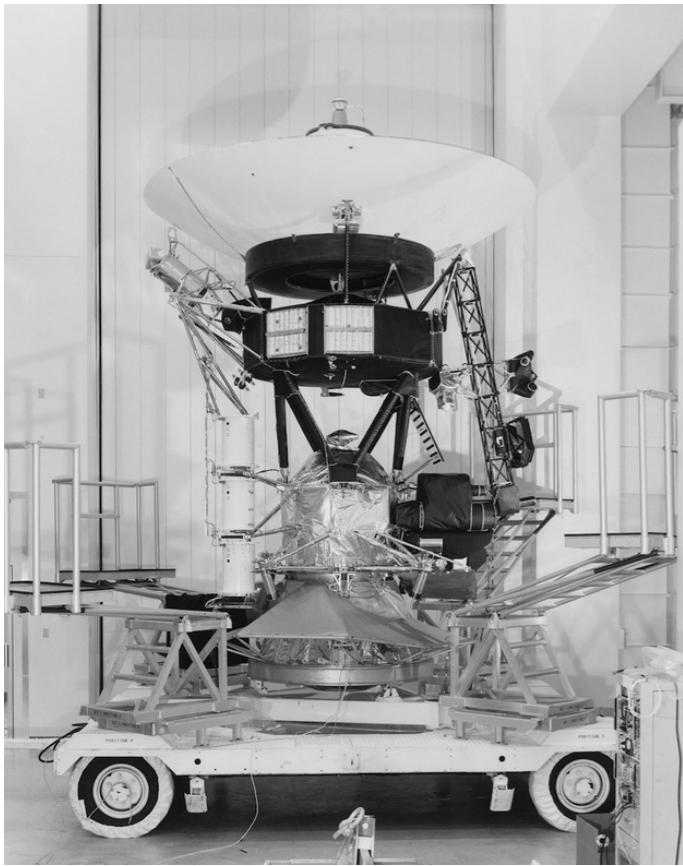


Voyager-1 crossed the heliopause in August 2012
⇒ probes now the local interstellar medium

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



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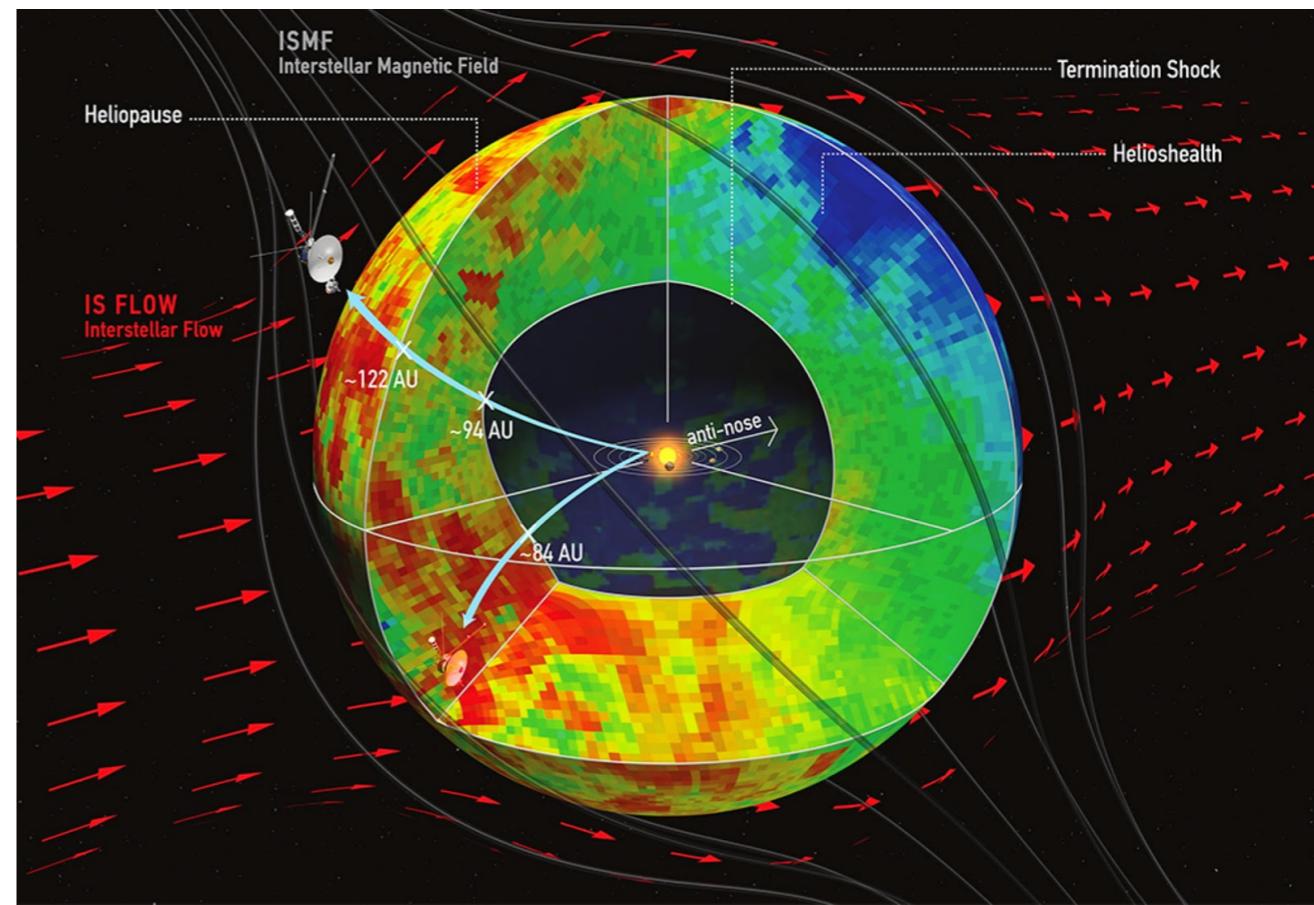
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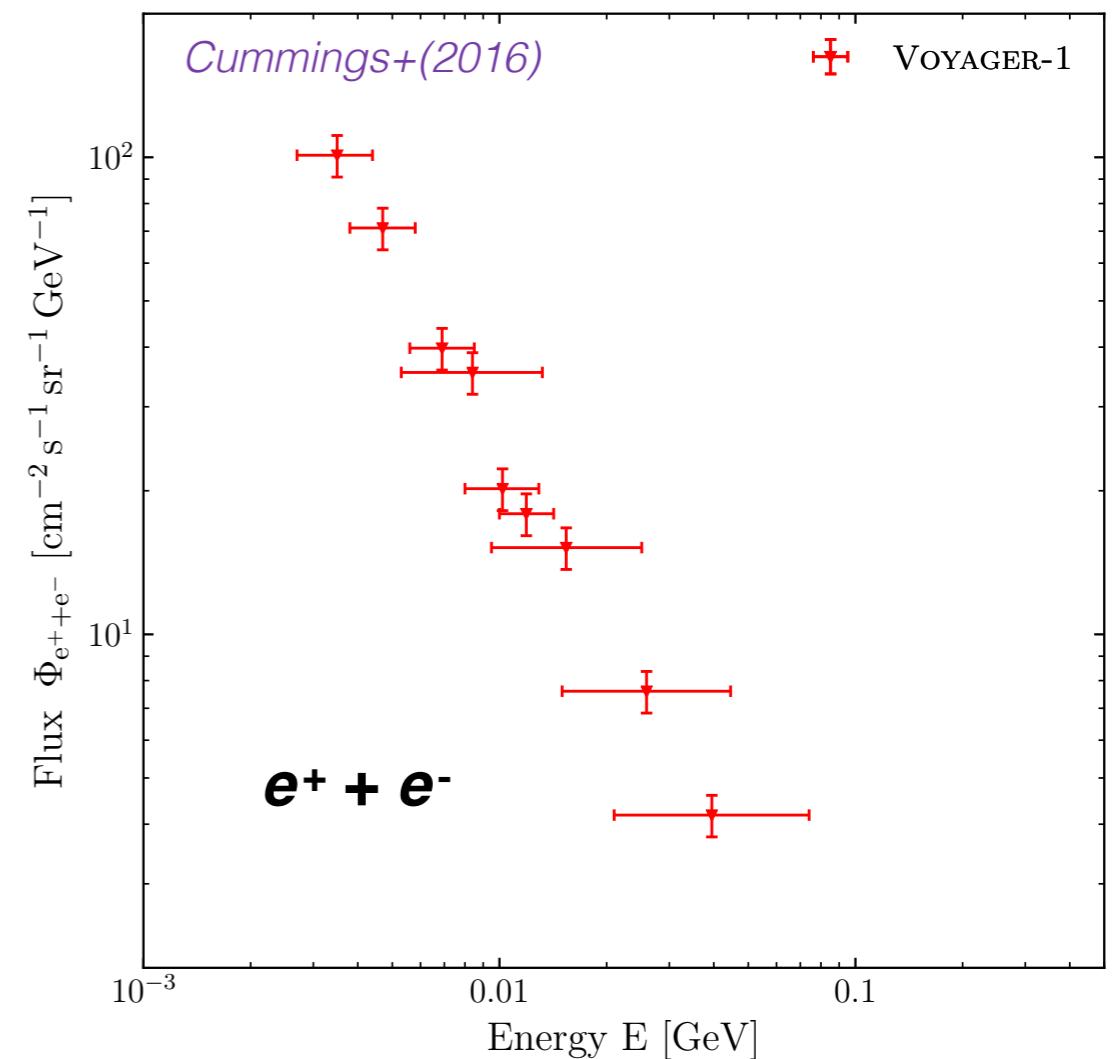
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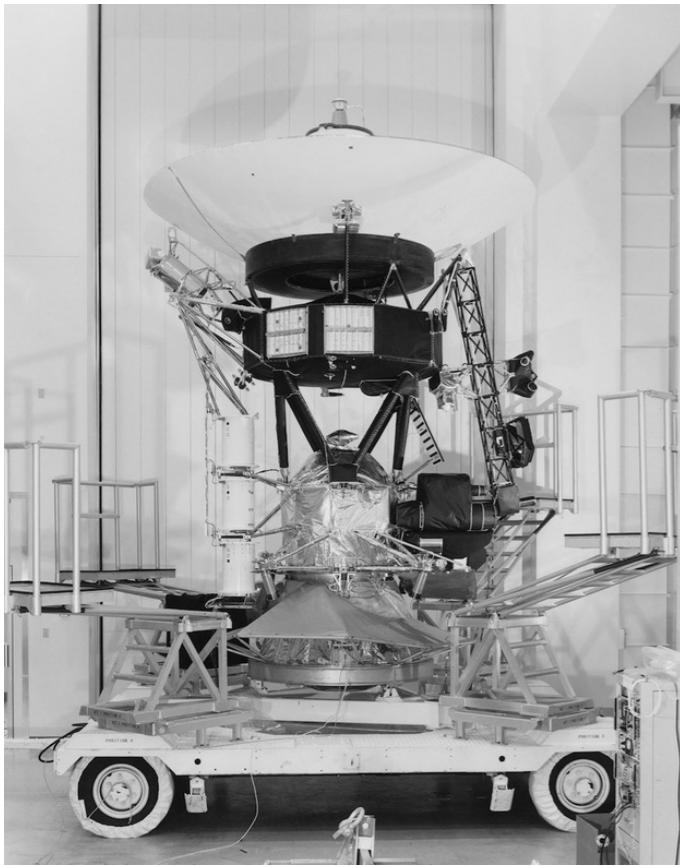


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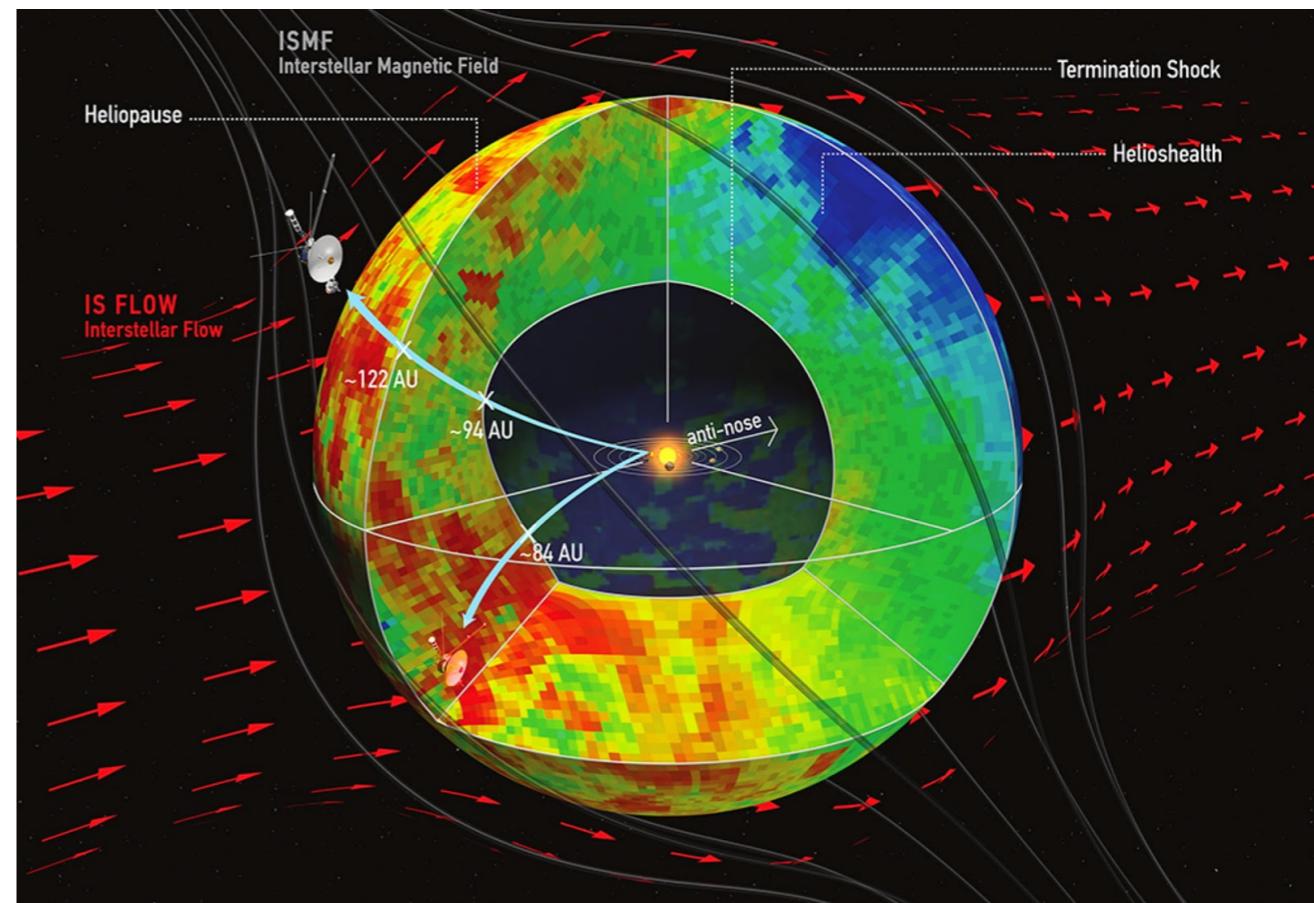
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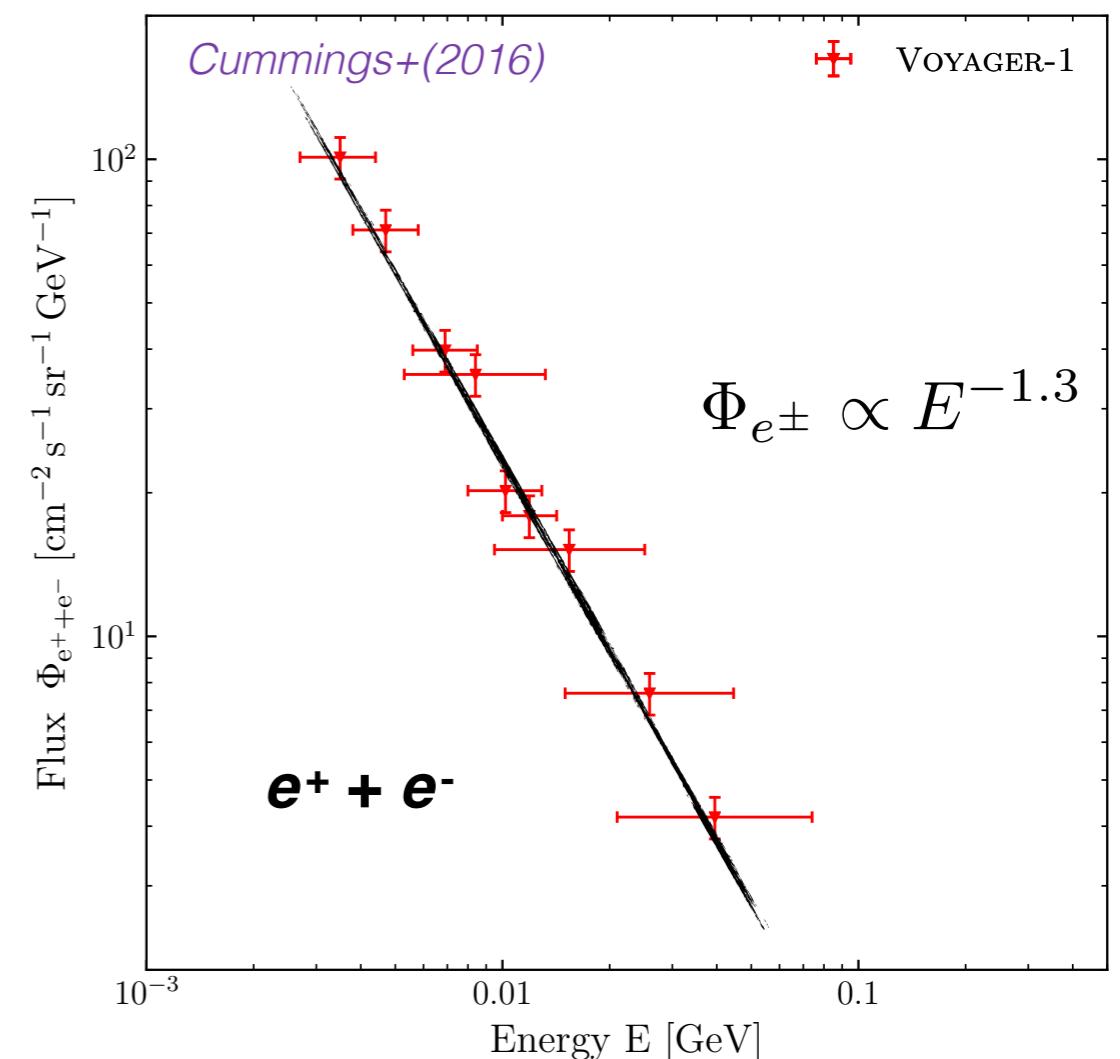
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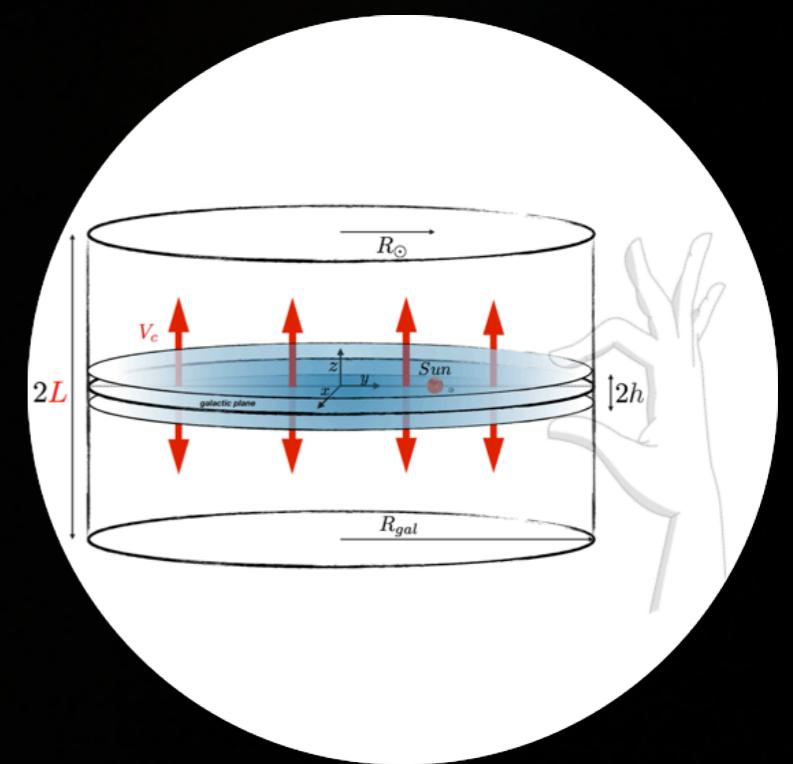






1. Transport of sub-GeV electrons

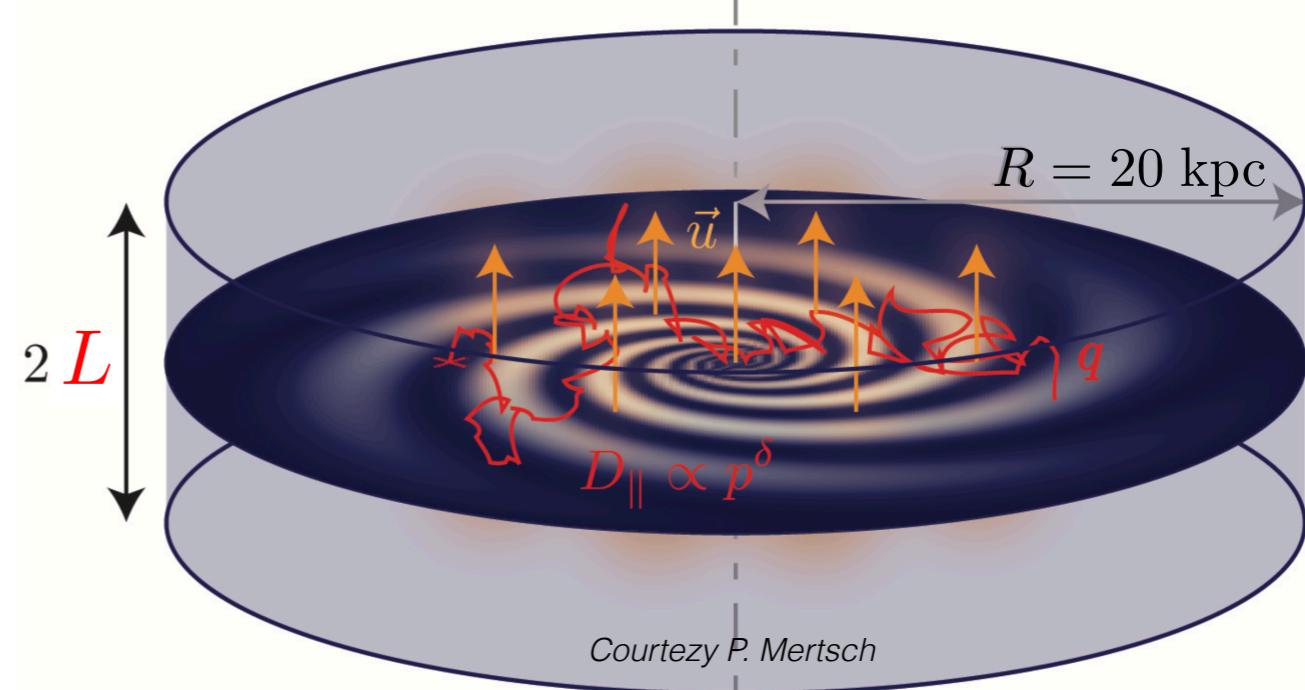
MB, E. F. Bueno, S. Caroff, Y. Genolini, V. Poulin V. Poireau, A. Putze, S. Rosier, P. Salati and M. Vecchi (A&A 605, A17)



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)

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

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

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

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

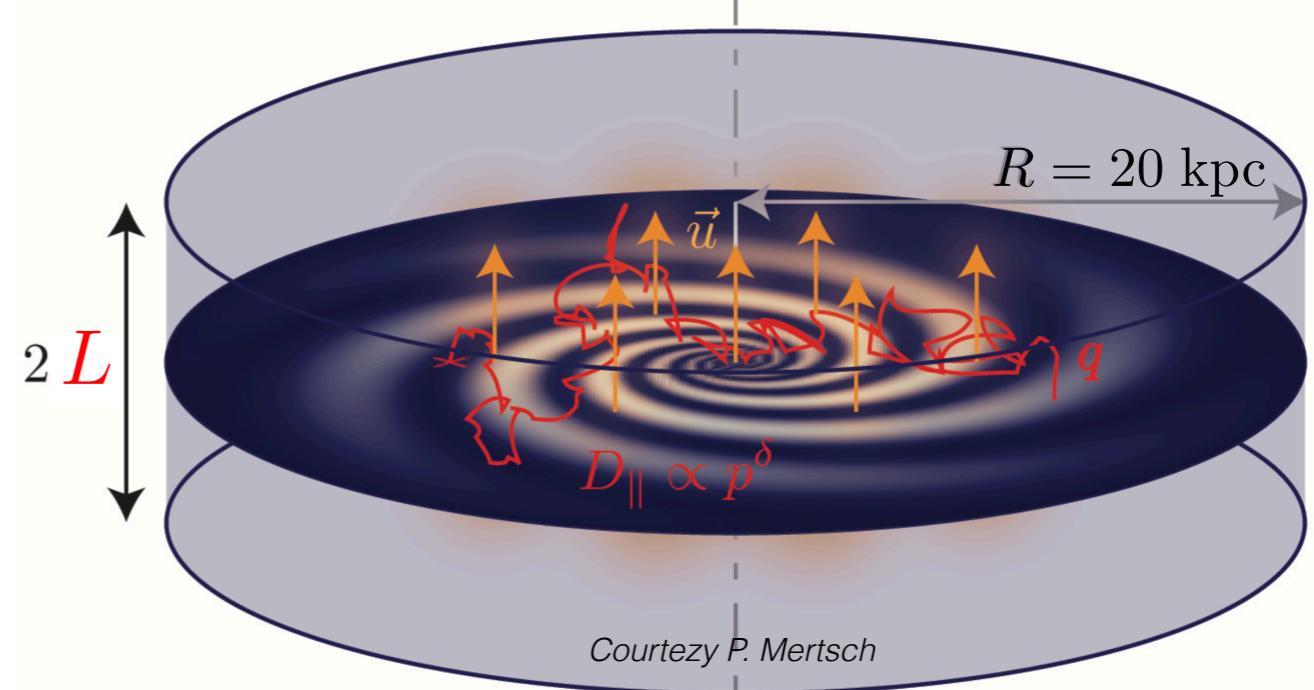
$$D(E) = \frac{2}{9} V_A^2 \frac{E^2 \beta^4}{K(E)}$$

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

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-

See talks by:

Y. Génolini, Mon. 16:30, CRD
L. Derome, Mon. 17:45, CRD
M. Vecchi, Mon. 18:00, CRD

- **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)

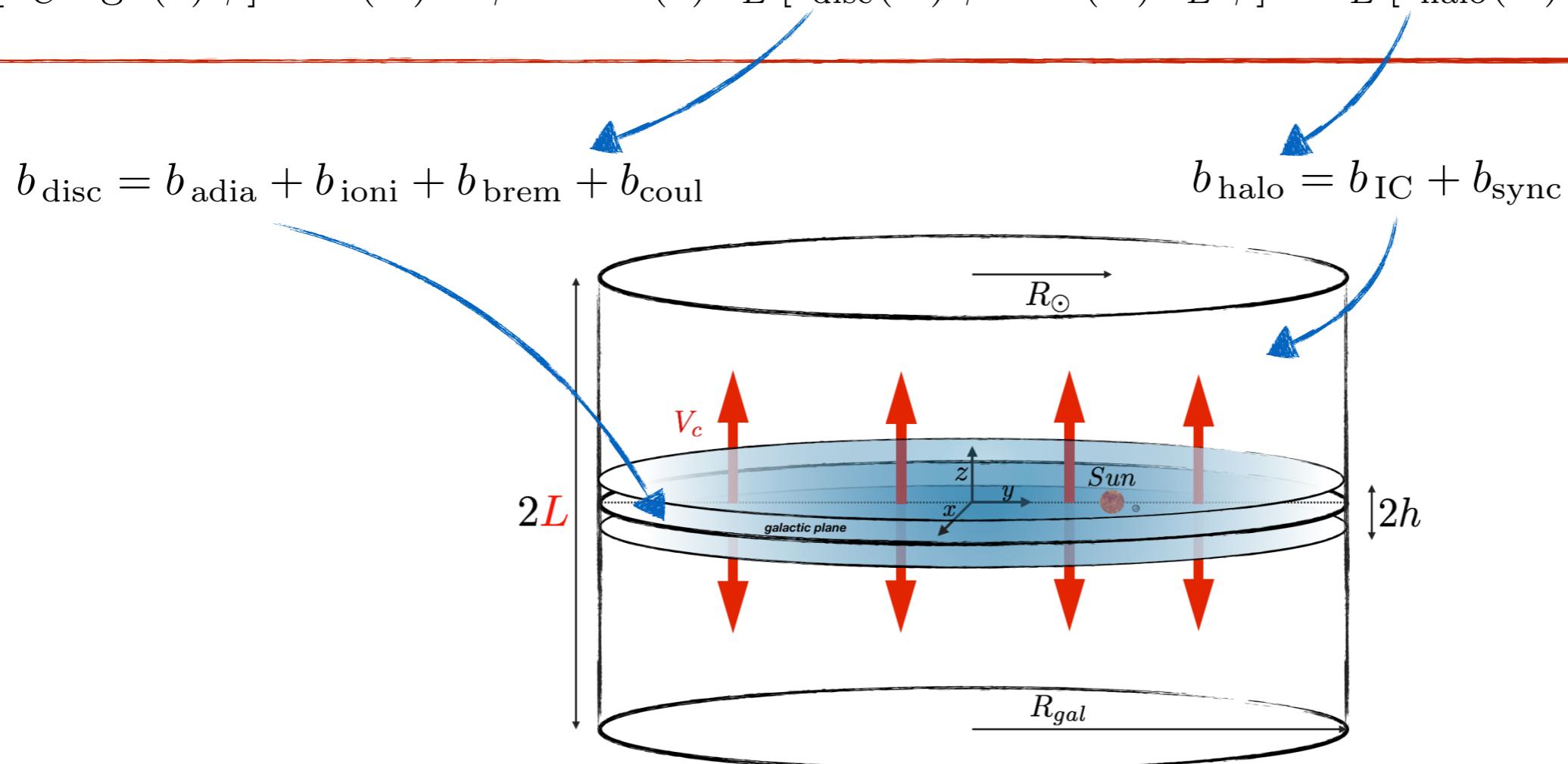
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Propagation parameters determined using data of secondary to primary ratios (e.g. B/C)

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

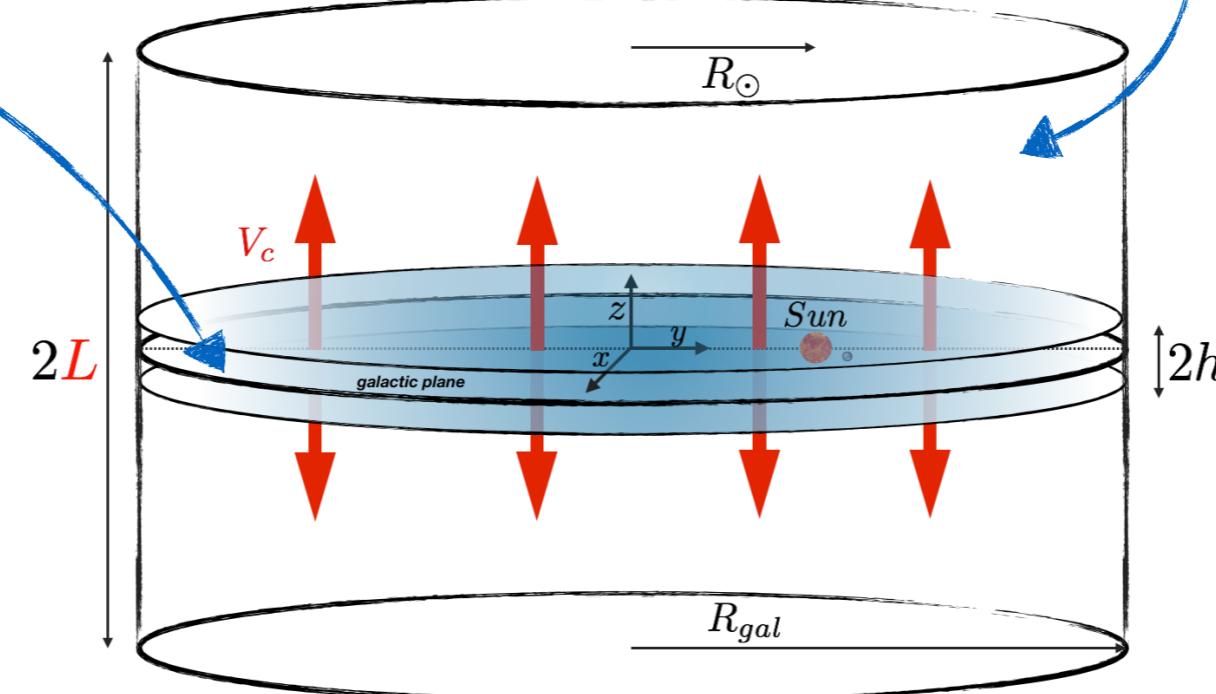
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$$b_{\text{disc}} = b_{\text{adia}} + b_{\text{ioni}} + b_{\text{brem}} + b_{\text{coul}}$$

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



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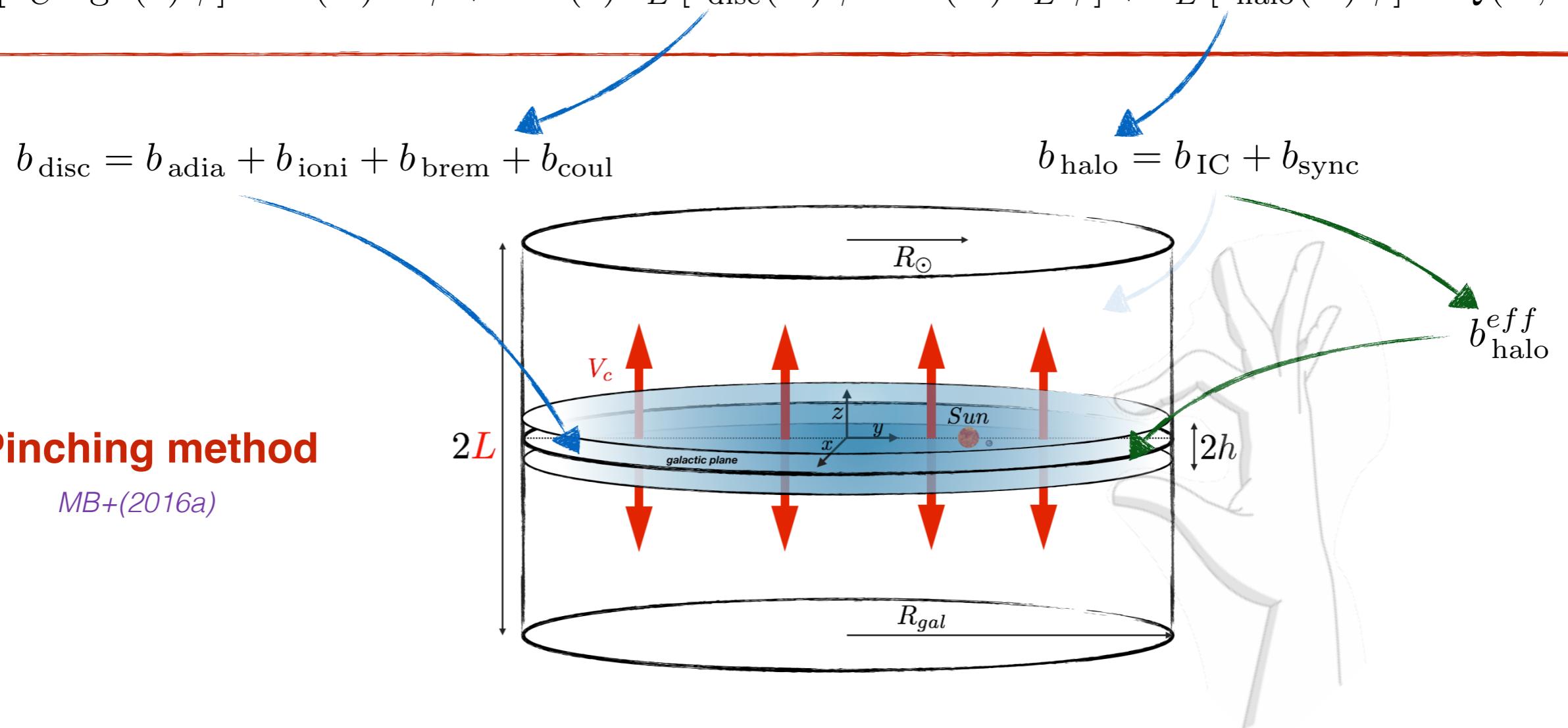
High energy approximation

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

Transport of cosmic rays e^\pm

Steady state

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



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

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!

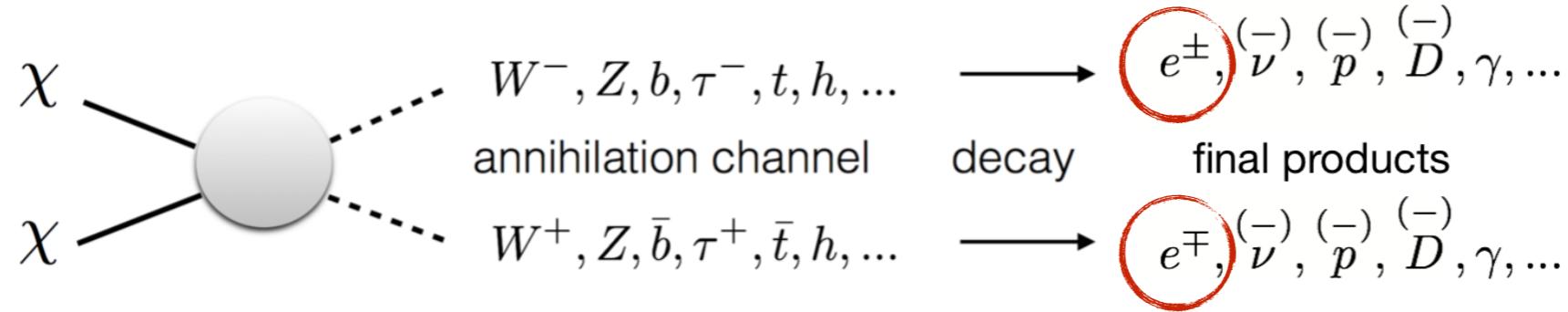
2. Light WIMPs

MB, J. Lavalle and P. Salati (PRL 119, 021103)

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



CRs e^\pm from dark matter



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

$\rho(\vec{x})$: dark matter density $\frac{dN_i}{dE}$: e^- and e^+ spectra
MicrOmegas
(PYTHIA)

Dark matter distribution in the MW

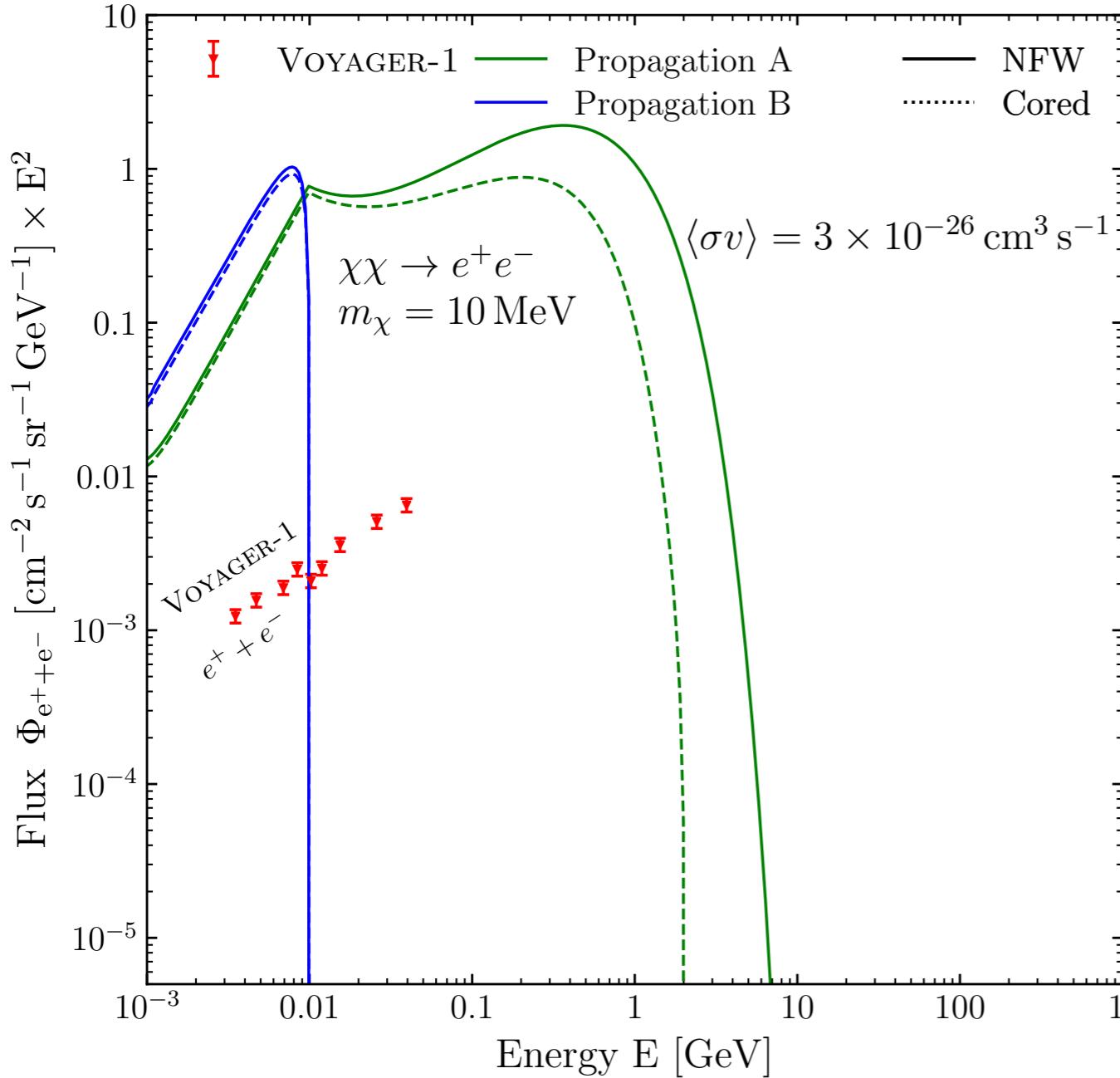
- **NFW** (spike in the GC)
- **Cored** (~ 8 kpc core)

McMillan(2016)

CRs propagation in the Galaxy

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

Constraints



- **Propagation A:** strong reacceleration

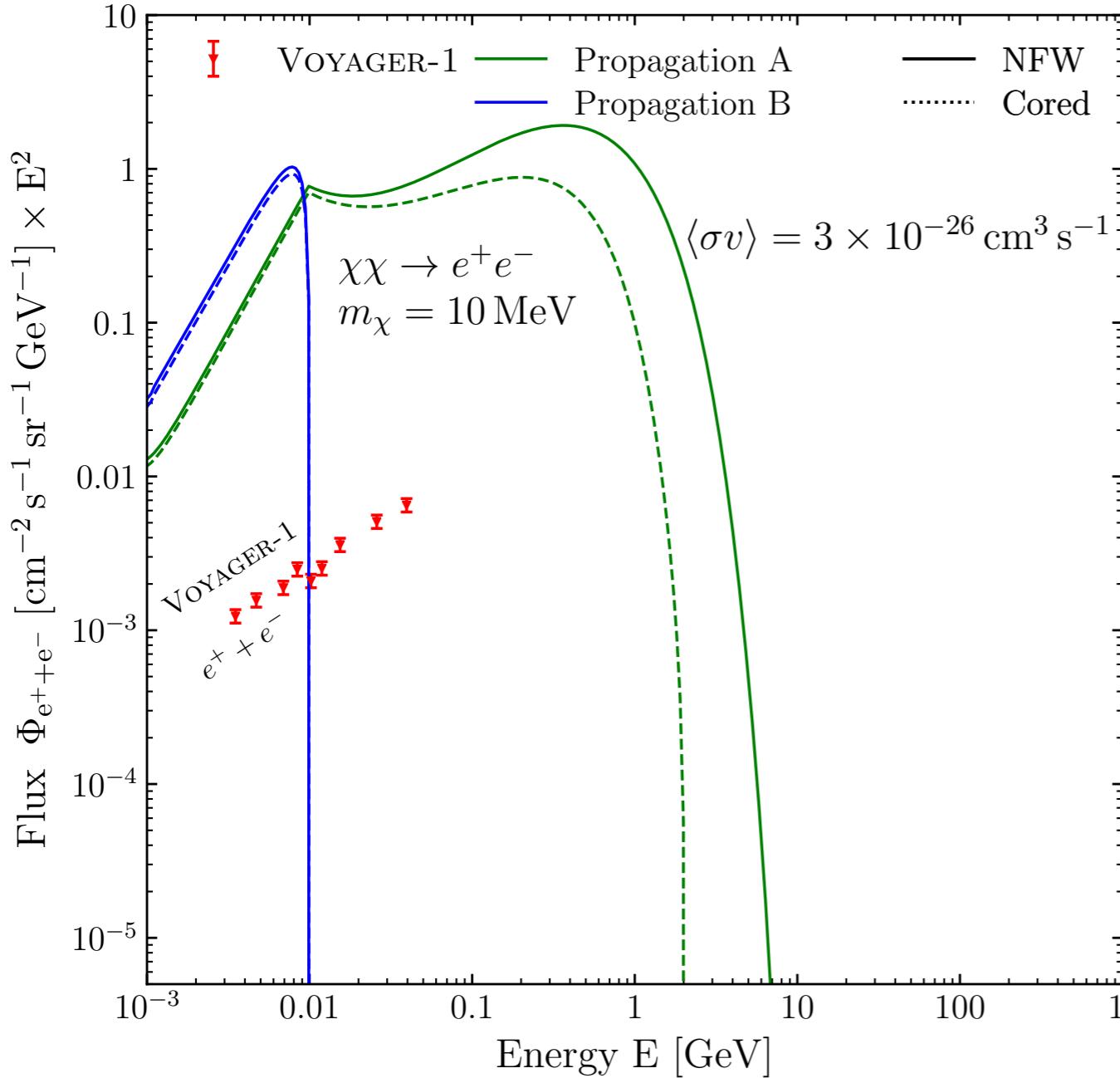
$V_A = 117.6 \text{ km/s}$ Maurin+(2001)

- **Propagation B:** no reacceleration

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

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

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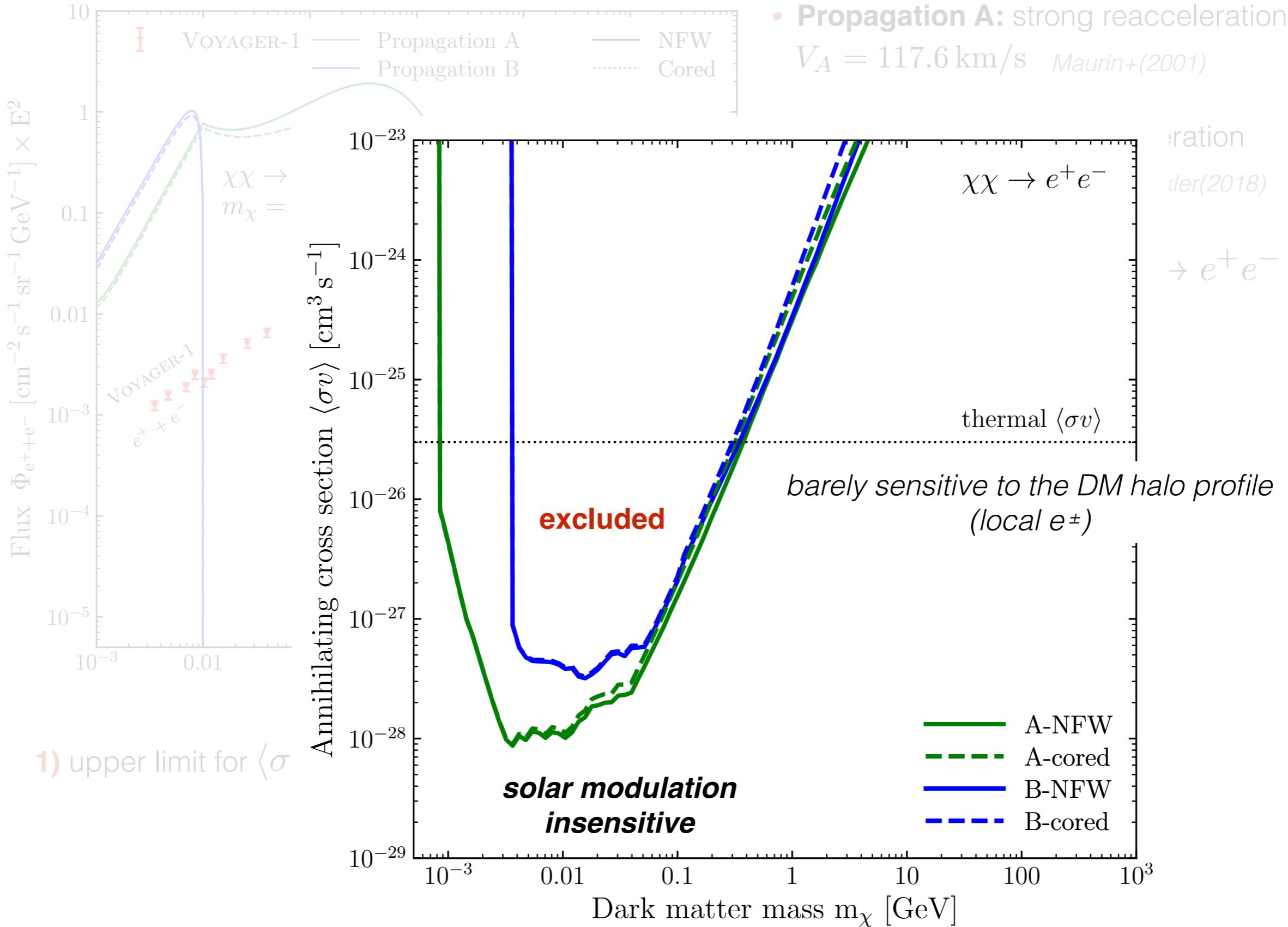
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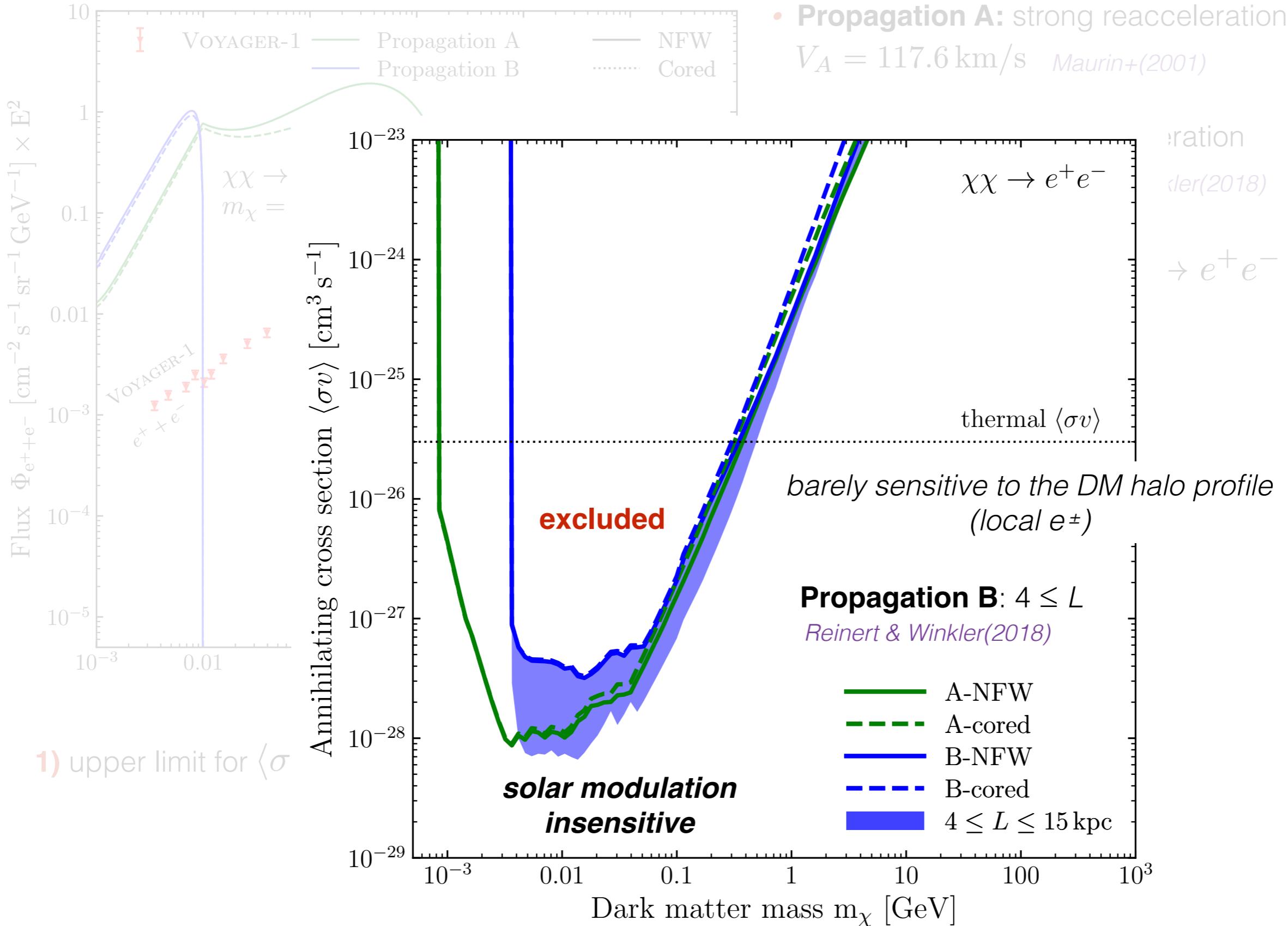
1) upper limit for $\langle\sigma v\rangle$ from Voyager-1 e^\pm : $\Phi_{e^+e^-}^{\text{DM}}(E_i) \leq \Phi_{e^+e^-}^{\text{exp}}(E_i) + 2\sigma_i$

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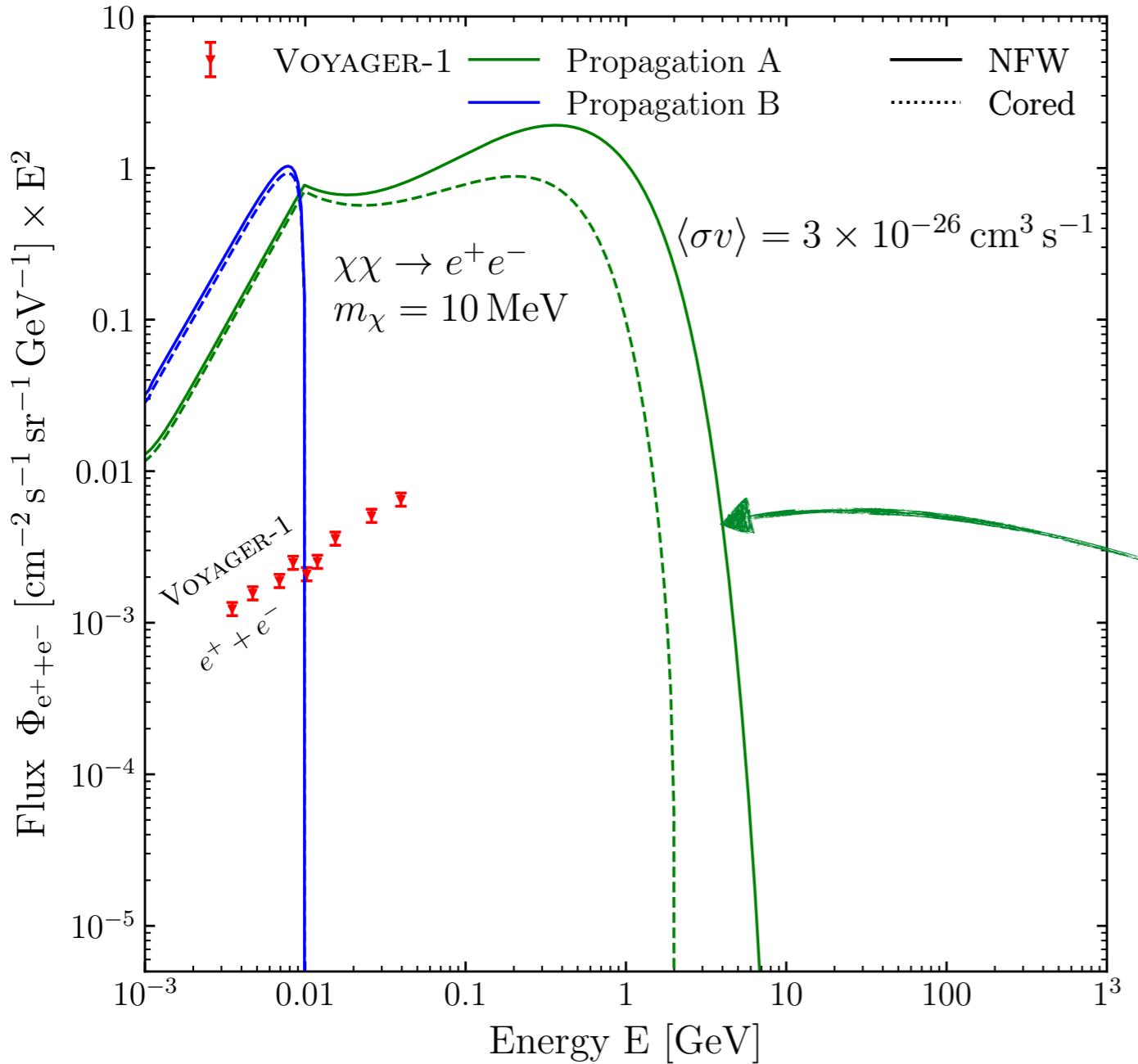


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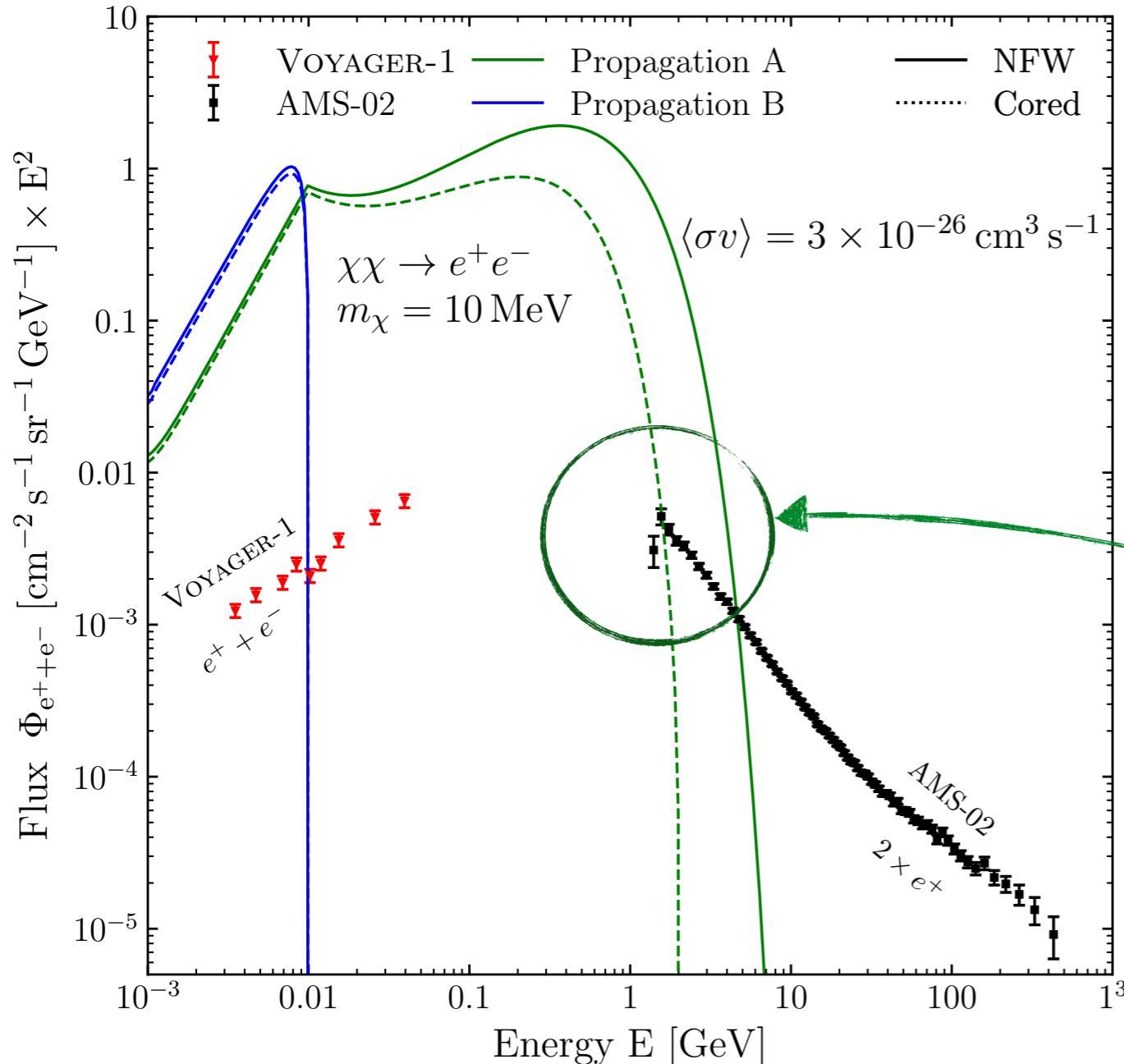
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Model **A** with **strong diffusive reacceleration**
 \implies detection of positrons above the DM mass!

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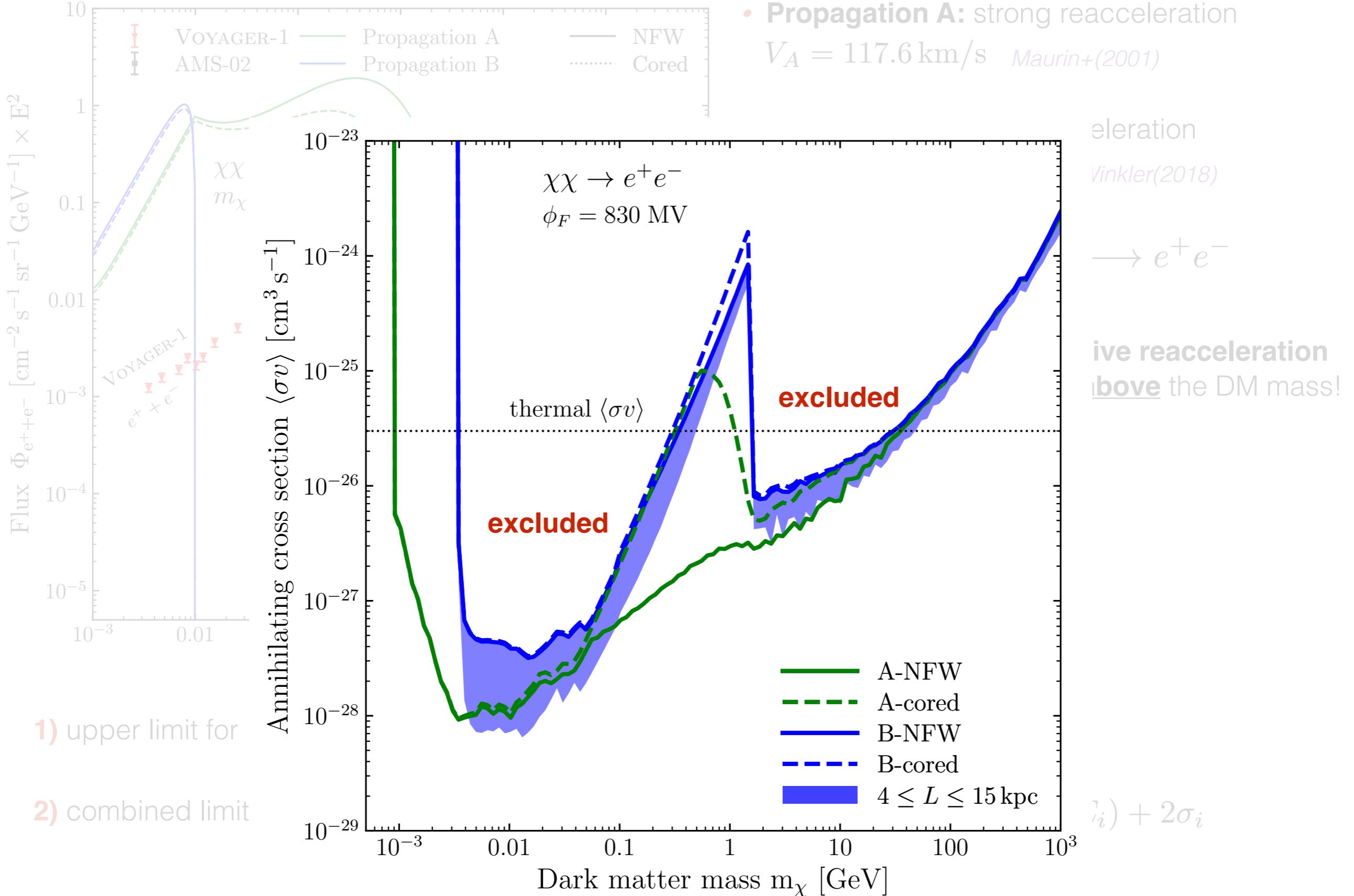
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2) combined limit from Voyager1 e^\pm and AMS-02 e^+ : 1) + $\Phi_{e^+}^{\text{DM}}(E_i) \leq \Phi_{e^+}^{\text{exp}}(E_i) + 2\sigma_i$

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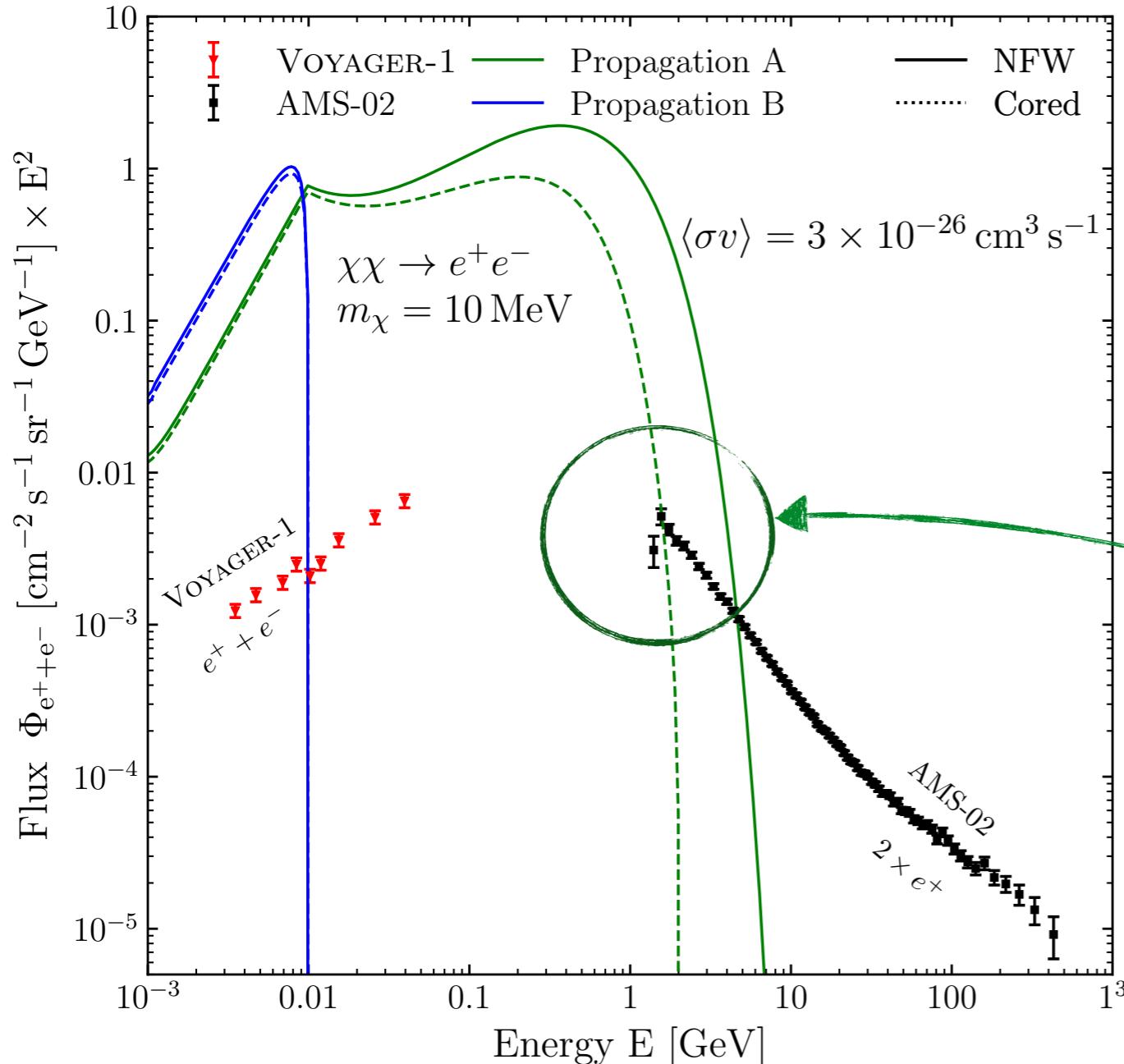


1) upper limit for

2) combined limit

- **Propagation A:** strong reacceleration
 $V_A = 117.6$ km/s Maurin+(2001)
- **Propagation B:** moderate reacceleration
 $V_A = 117.6$ km/s Vinkler(2018)
- **Annihilation:** $\chi\chi \rightarrow e^+e^-$
- **Reacceleration:** above the DM mass!

Constraints



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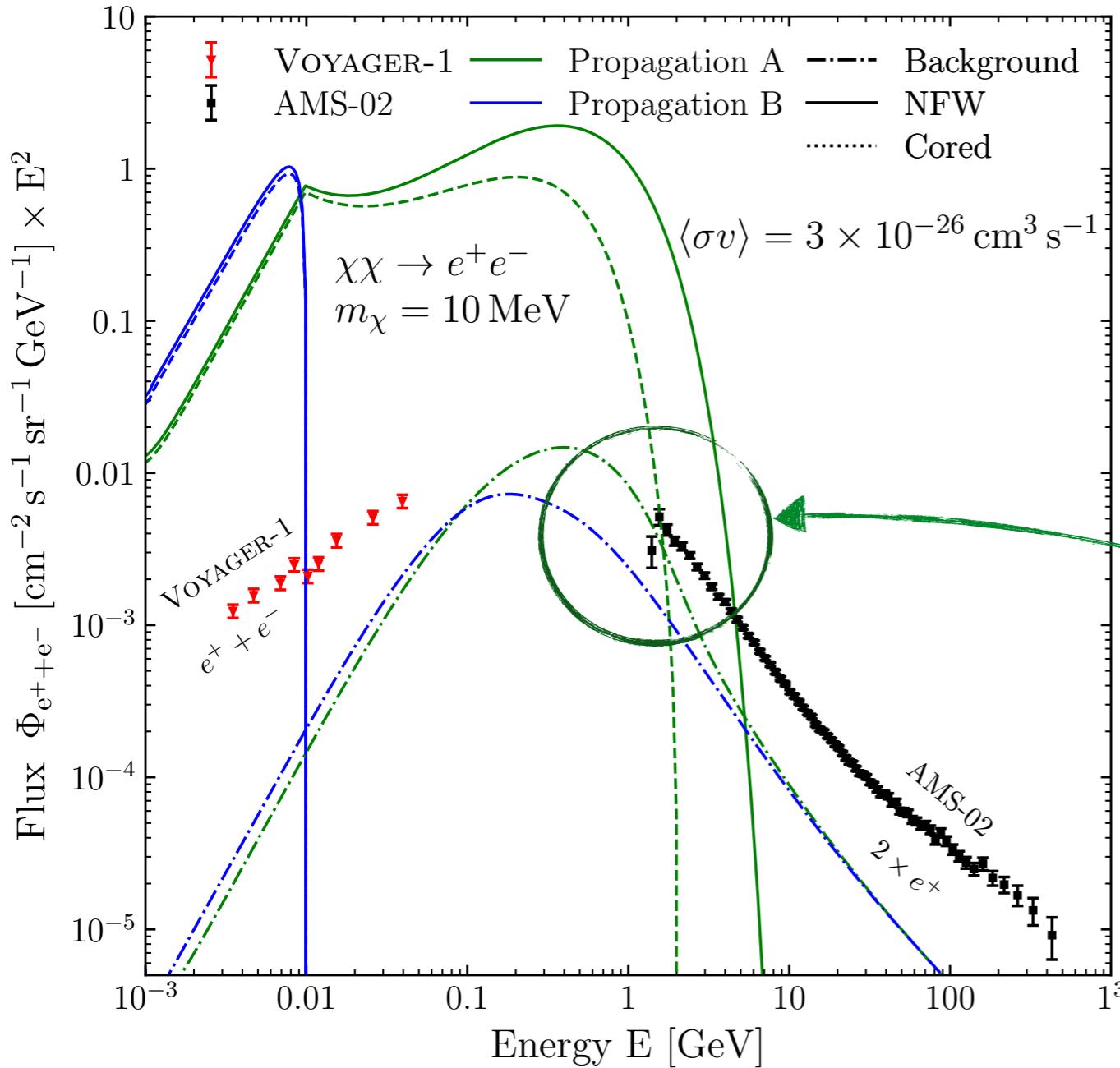
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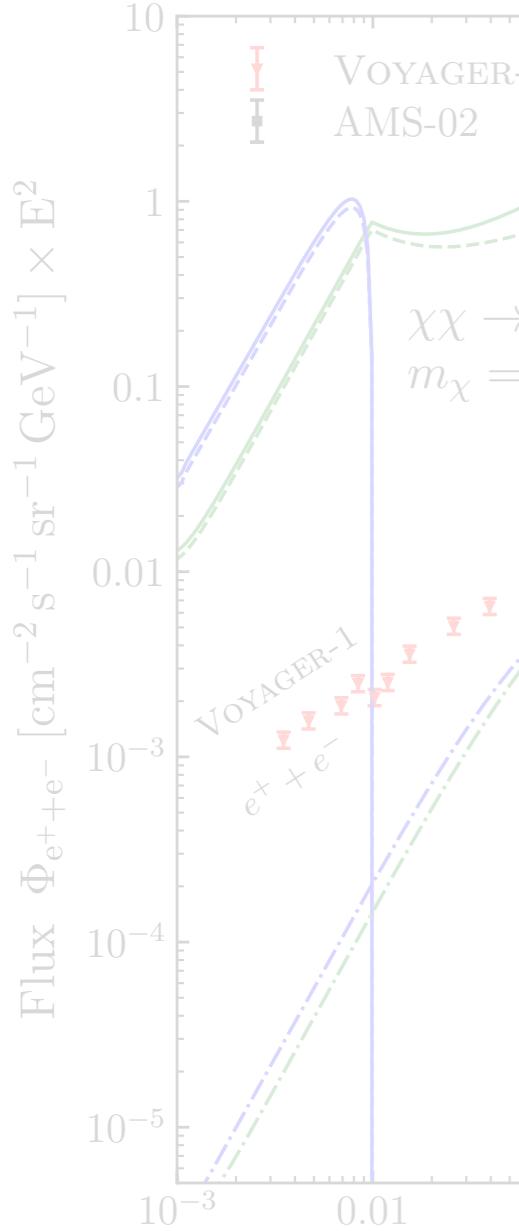
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3) with background of secondary e^+ : 1) + $\Phi_{e^+}^{\text{DM}}(E_i) + \Phi_{e^+}^{\text{II}}(E_i) \leq \Phi_{e^+}^{\text{exp}}(E_i) + 2\sigma_i$

Constraints

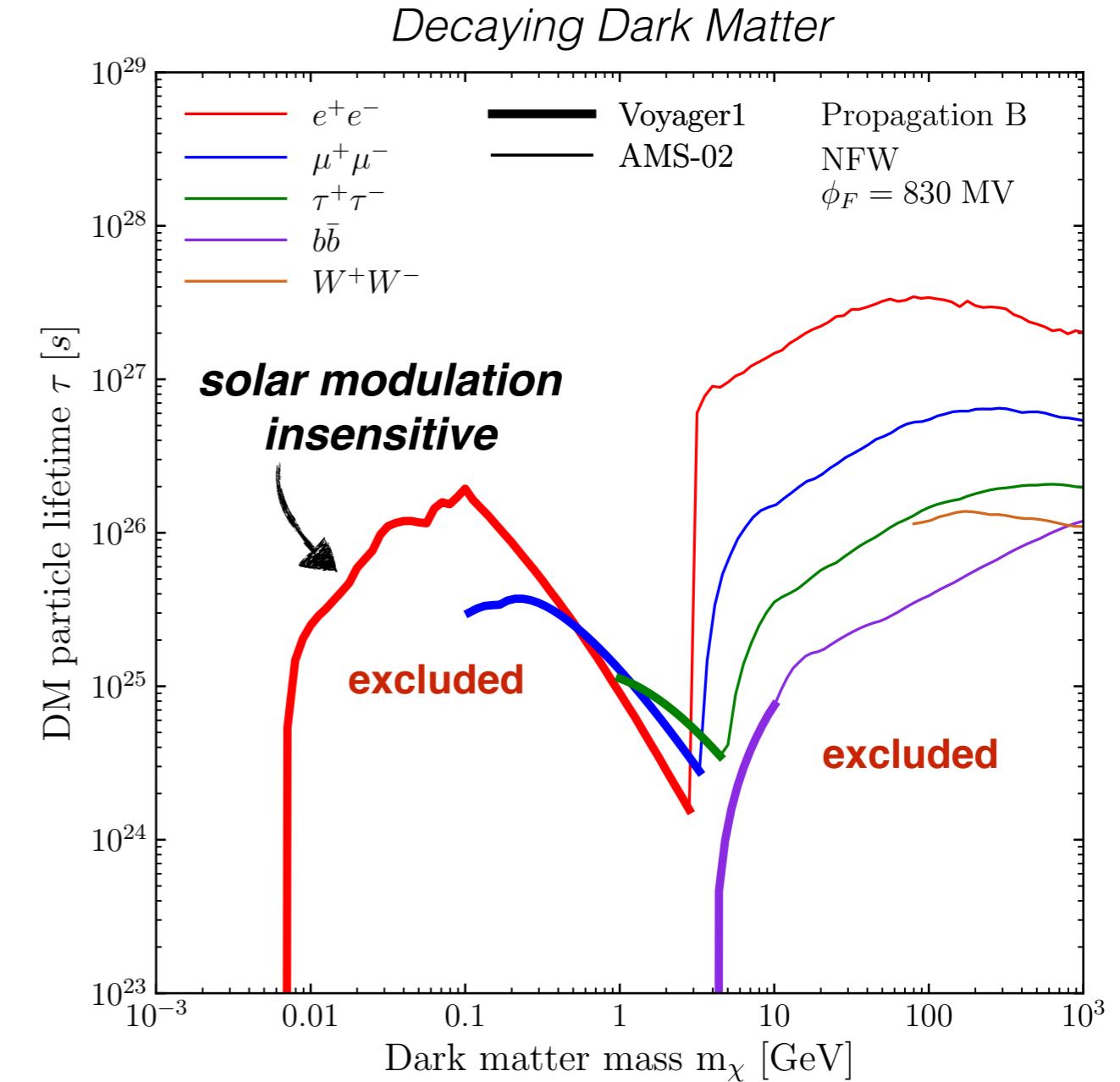
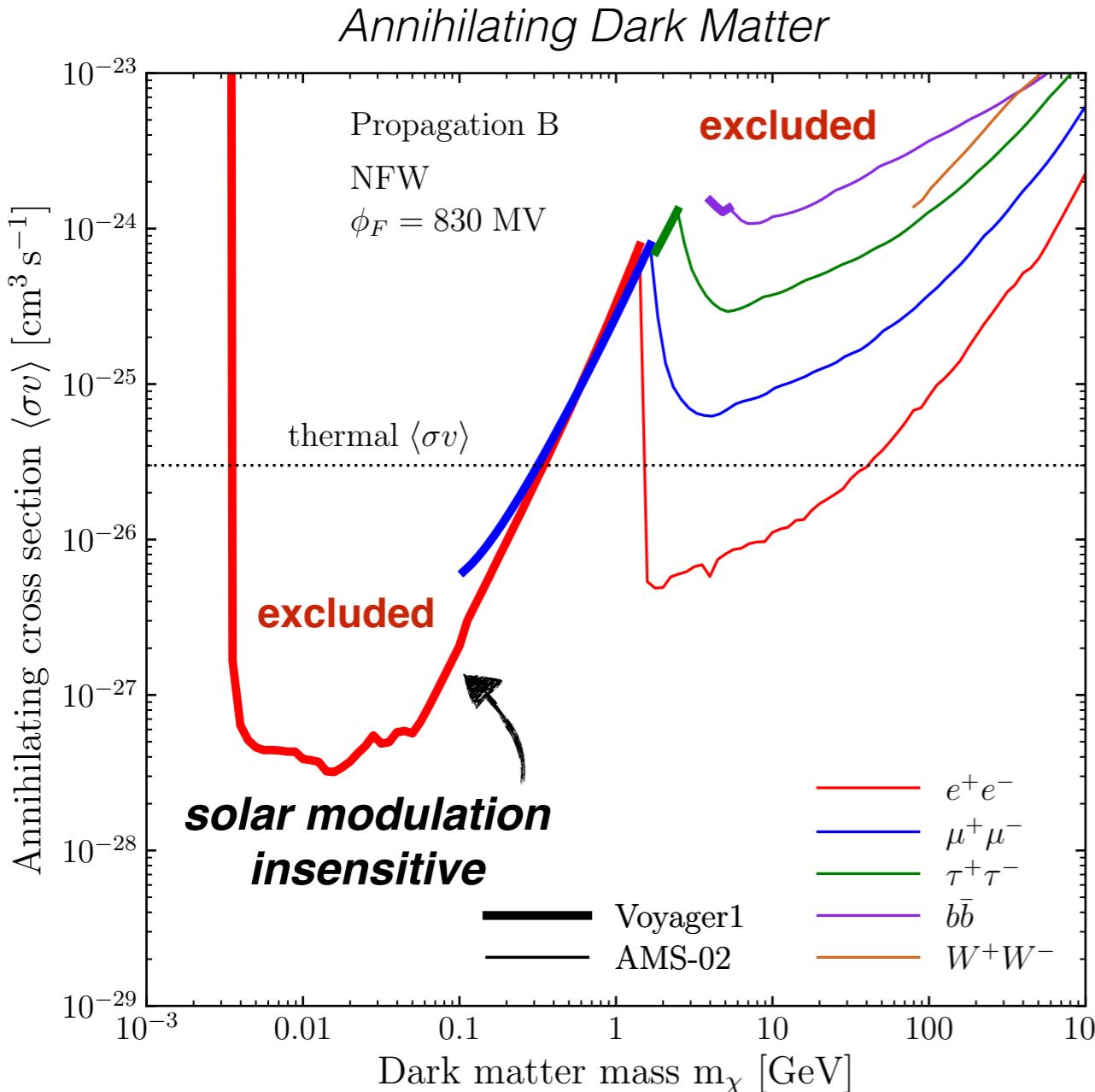


- 1) upper limit for $\langle\sigma v\rangle$
- 2) combined limit fr
- 3) with background

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

reacceleration
→ e^+e^-
→ reacceleration
above the DM mass!

$+ 2\sigma_i$
 $2\sigma_i$



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)*

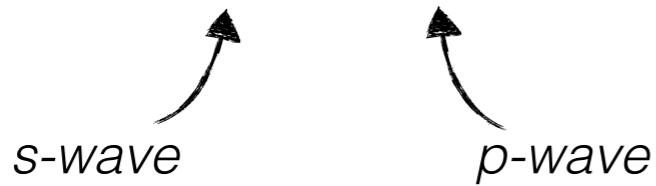
- **Less** stringent

only for s-wave annihilation

s-wave vs p-wave

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

Srednicki+(1998)



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

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scalar
mediator

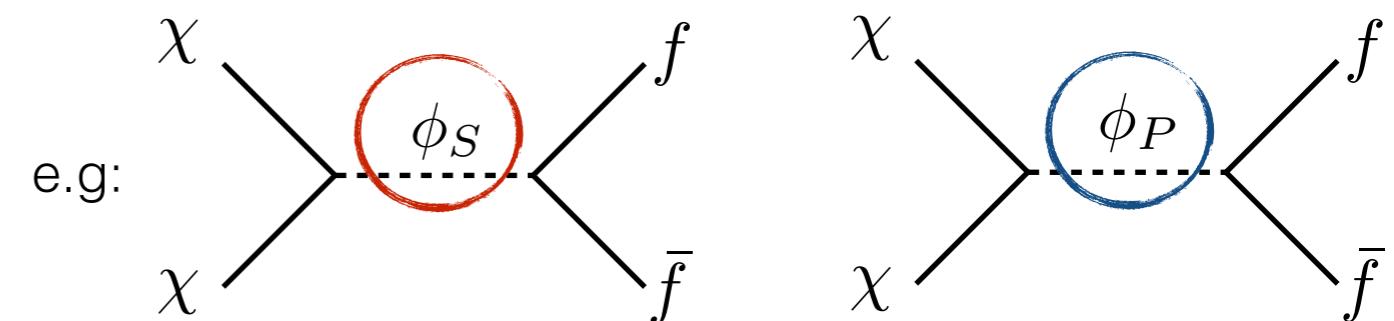
X

✓

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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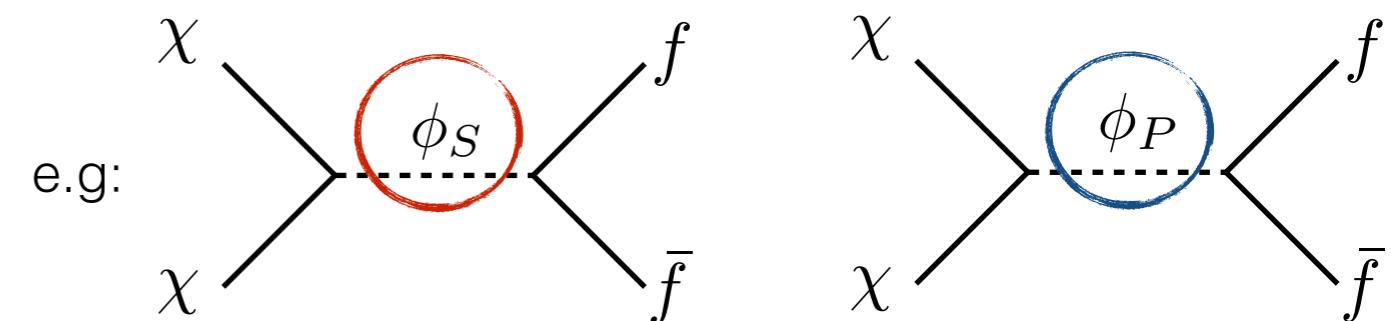
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✓

pseudo-scalar mediator

✓

✓



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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) must be **more stringent** for local CRs observations than for CMB

Dark matter phase space distribution

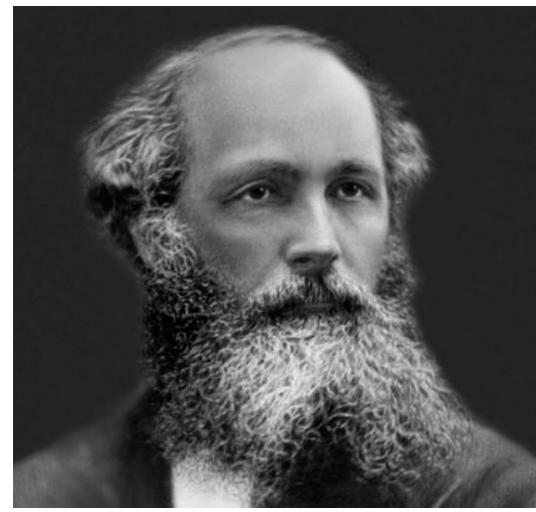
$$\langle \sigma v \rangle(r) = K_0(r) \int d^3\vec{v}_1 \int d^3\vec{v}_2 f(|\vec{v}_1|, r) f(|\vec{v}_2|, r) \sigma v_{12}$$

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

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Maxwell-Boltzmann (Standard Halo Model)

$$f(\vec{v}) = \frac{1}{v_c^3 \pi^{3/2}} \exp \left[- \left(\frac{\vec{v}}{v_c} \right)^2 \right]$$

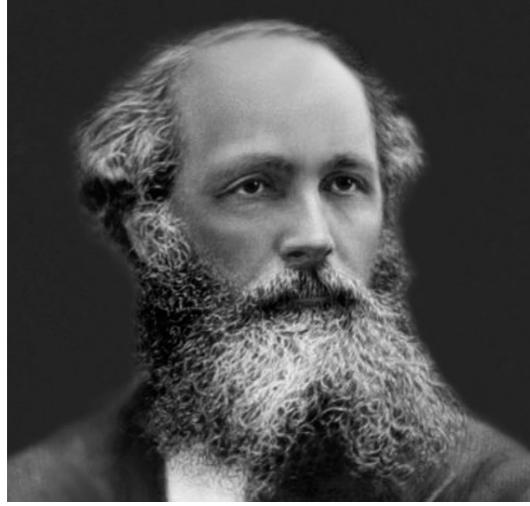
- isothermal sphere
- infinite system (no bound)
- ad hoc truncation at v_{esc}

Not self-consistent

Dark matter phase space distribution

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- isothermal sphere
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Not self-consistent

- observationally constrained Galactic mass model
McMillan (2016)
- spherically symmetry

- Jeans' theorem + Poisson equation

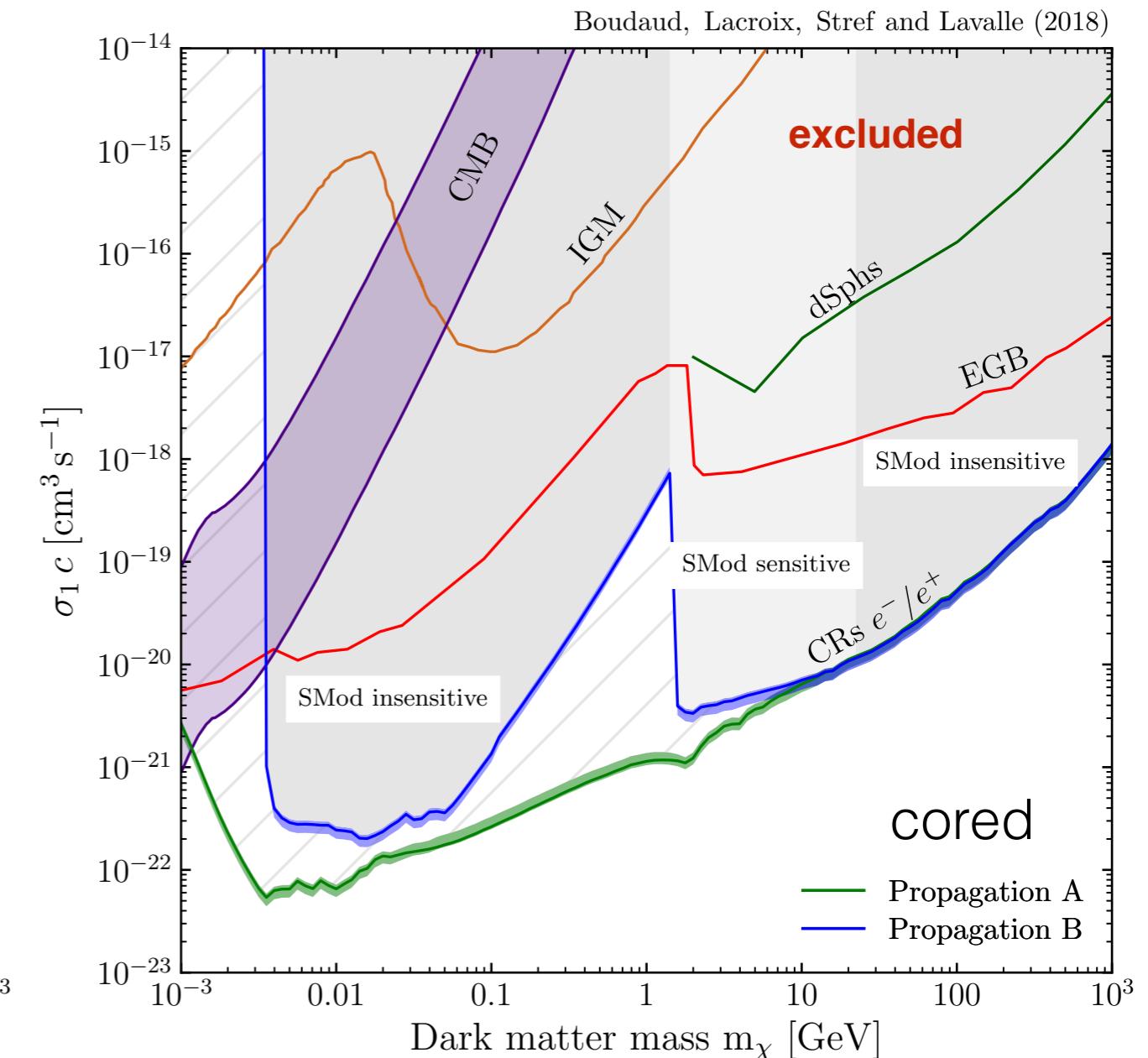
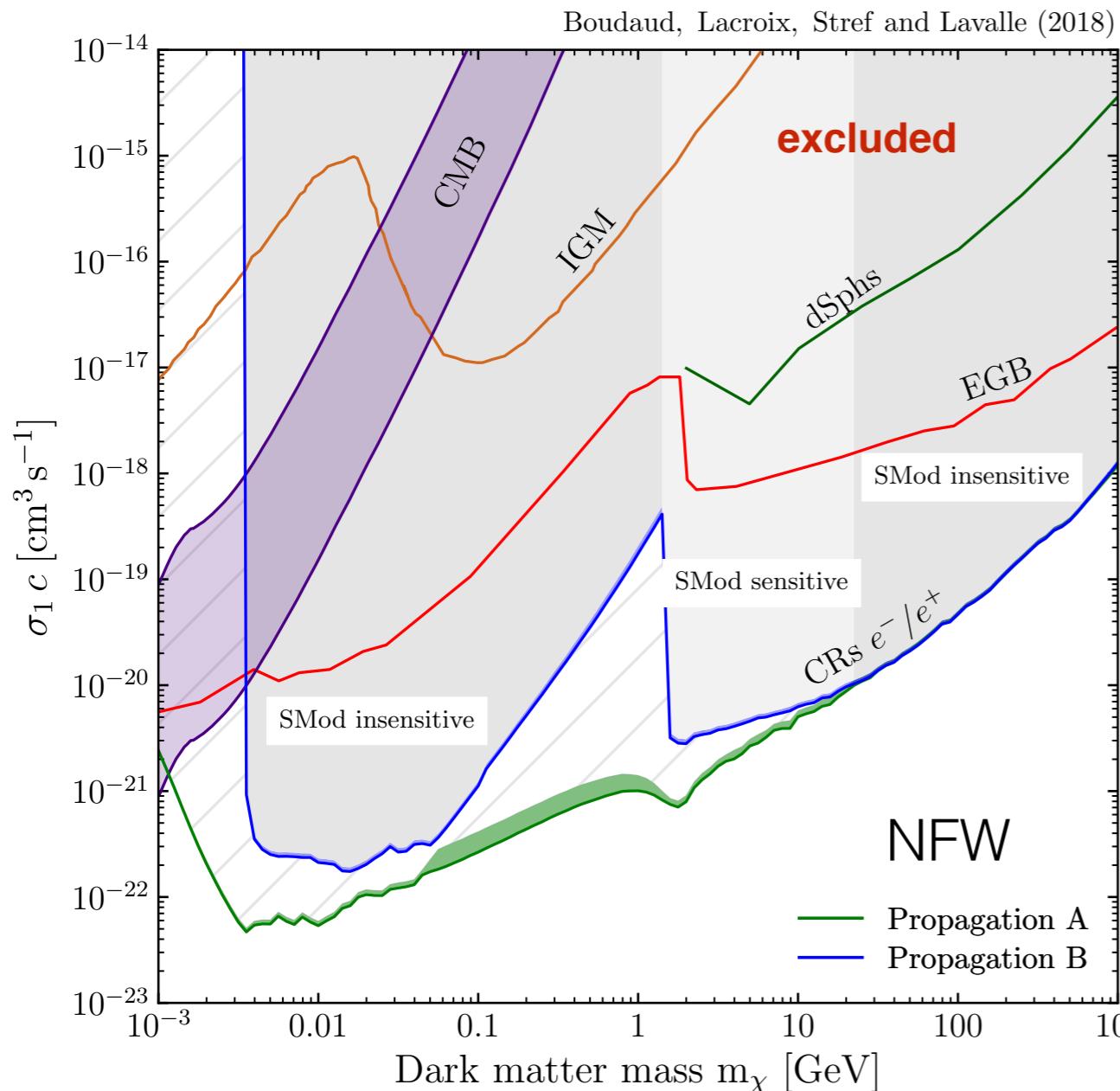
$$\Rightarrow f(\vec{v}, r)$$

Eddington (1916)
Binney & Tremaine (1987)
Lacroix, Stref & Lavalle(2018)

- velocity anisotropy (constant, Osipkov-Merritt)

Velocity dependent constraints (p-wave)

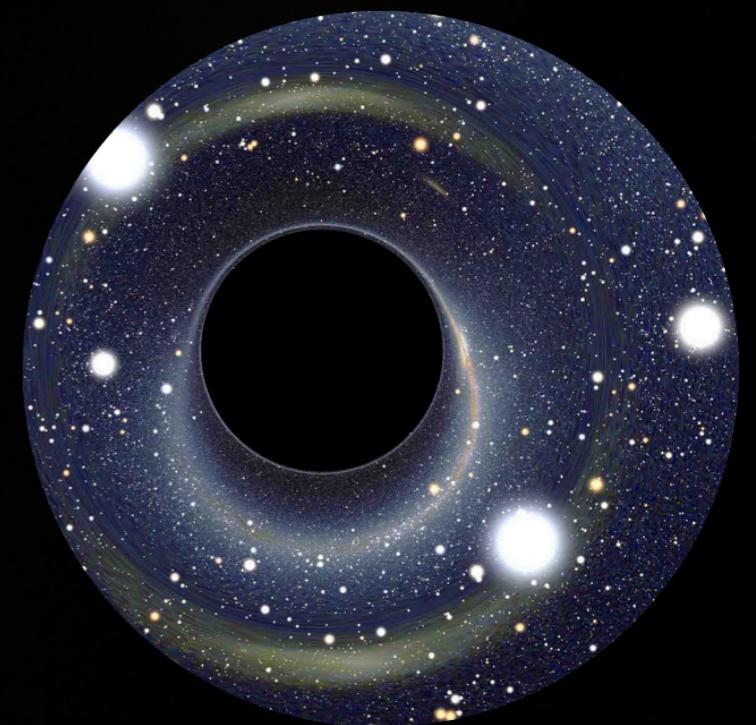
MB, Lacroix, Stref & Lavalle (2018)



- **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 $\sim 1 \text{ GeV}$ and above $\sim 20 \text{ GeV}$

3. Primordial black holes

MB and M. Cirelli (PRL 122, 041104)

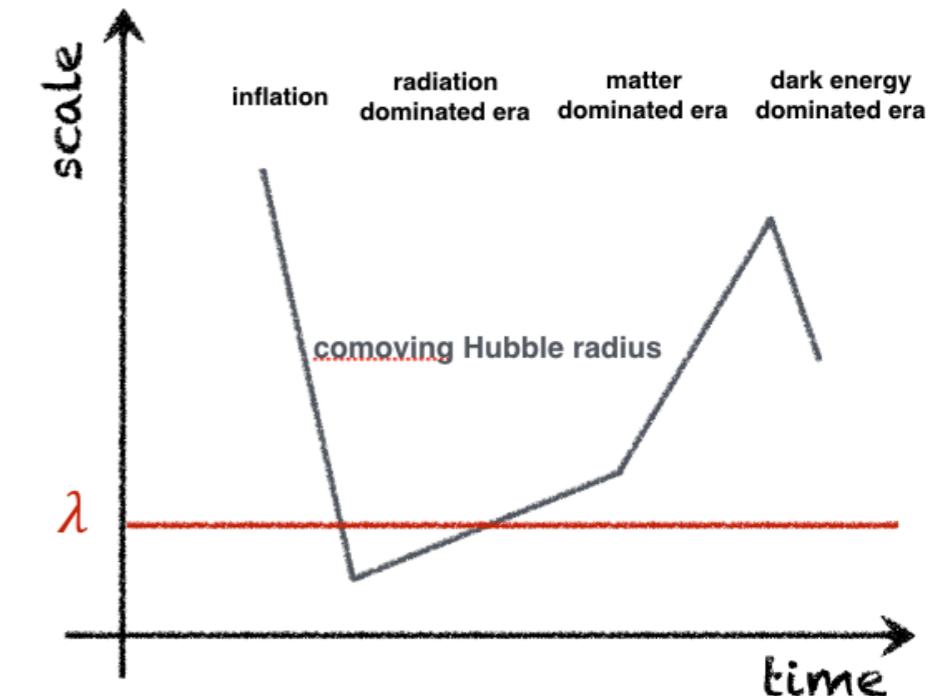


Primordial black holes

Carr & Hawking (1975)

Produced from quantum fluctuations during inflation

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



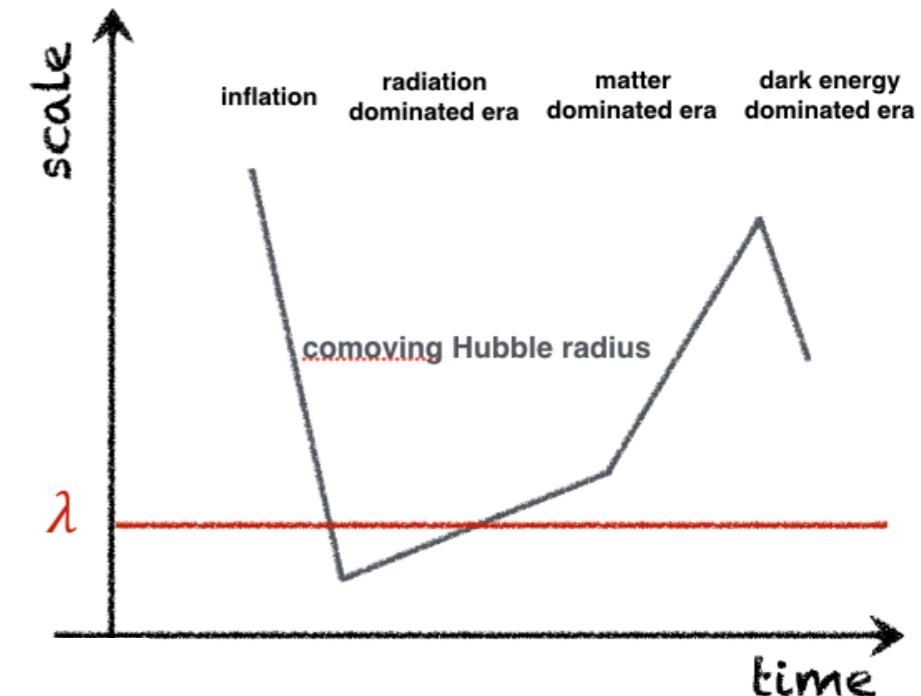
Primordial black holes

Carr & Hawking (1975)

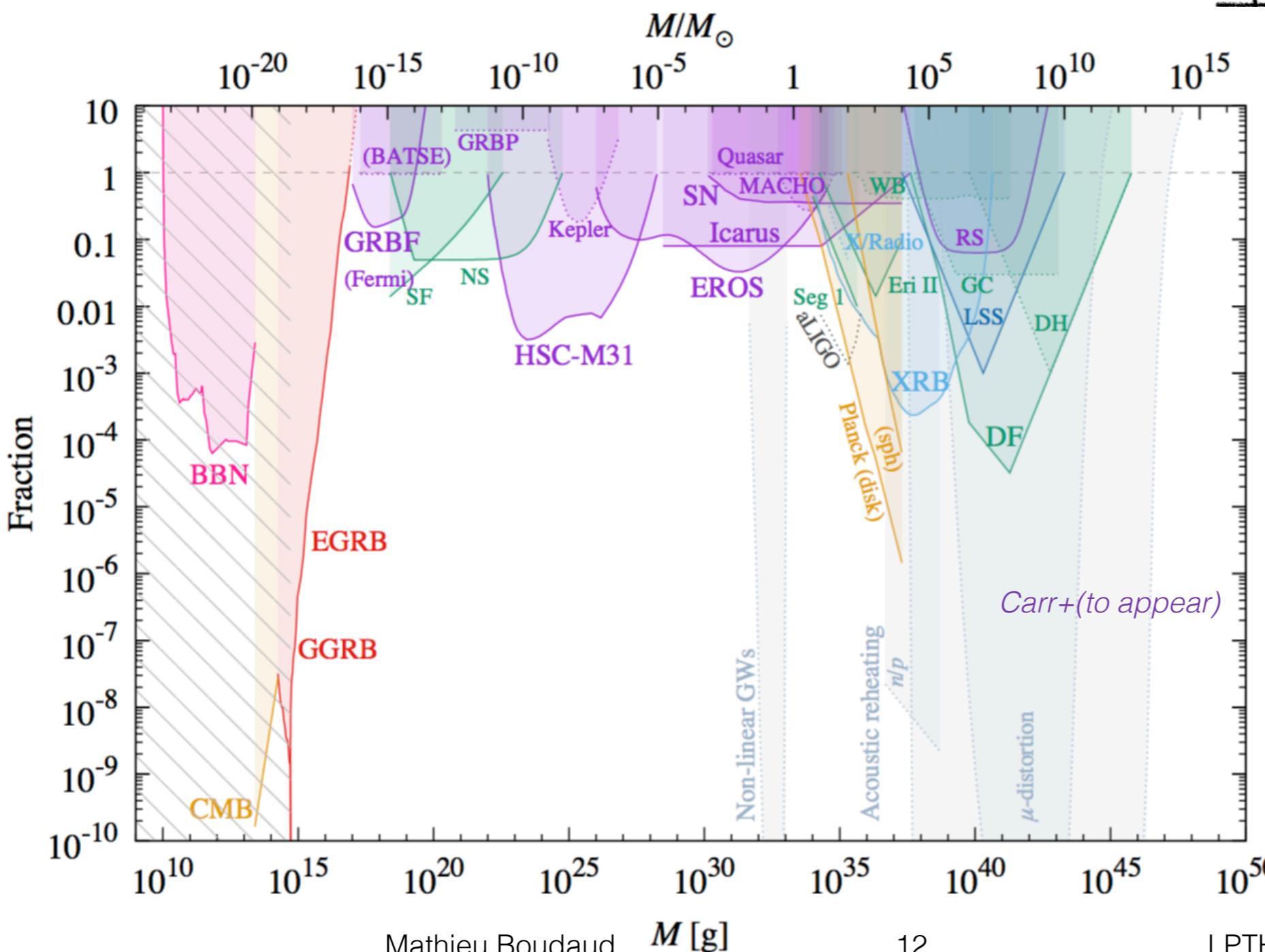
Produced from quantum fluctuations during inflation

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

$$f = \frac{\rho_{\text{PBH}}}{\rho_{\text{DM}}}$$



Lensing, dynamical, accretion, cosmological and Hawking radiation



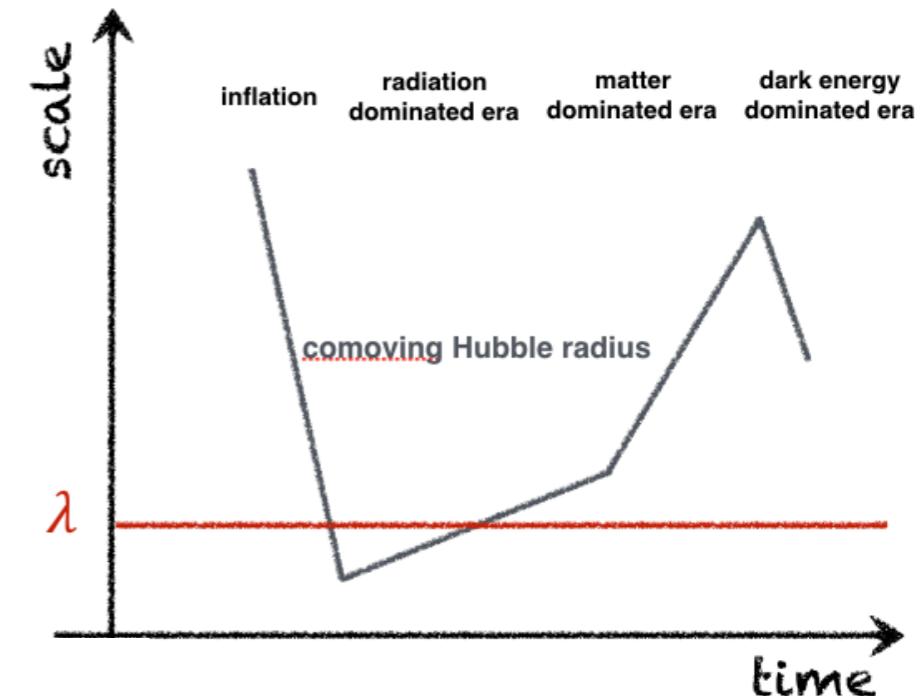
Primordial black holes

Carr & Hawking (1975)

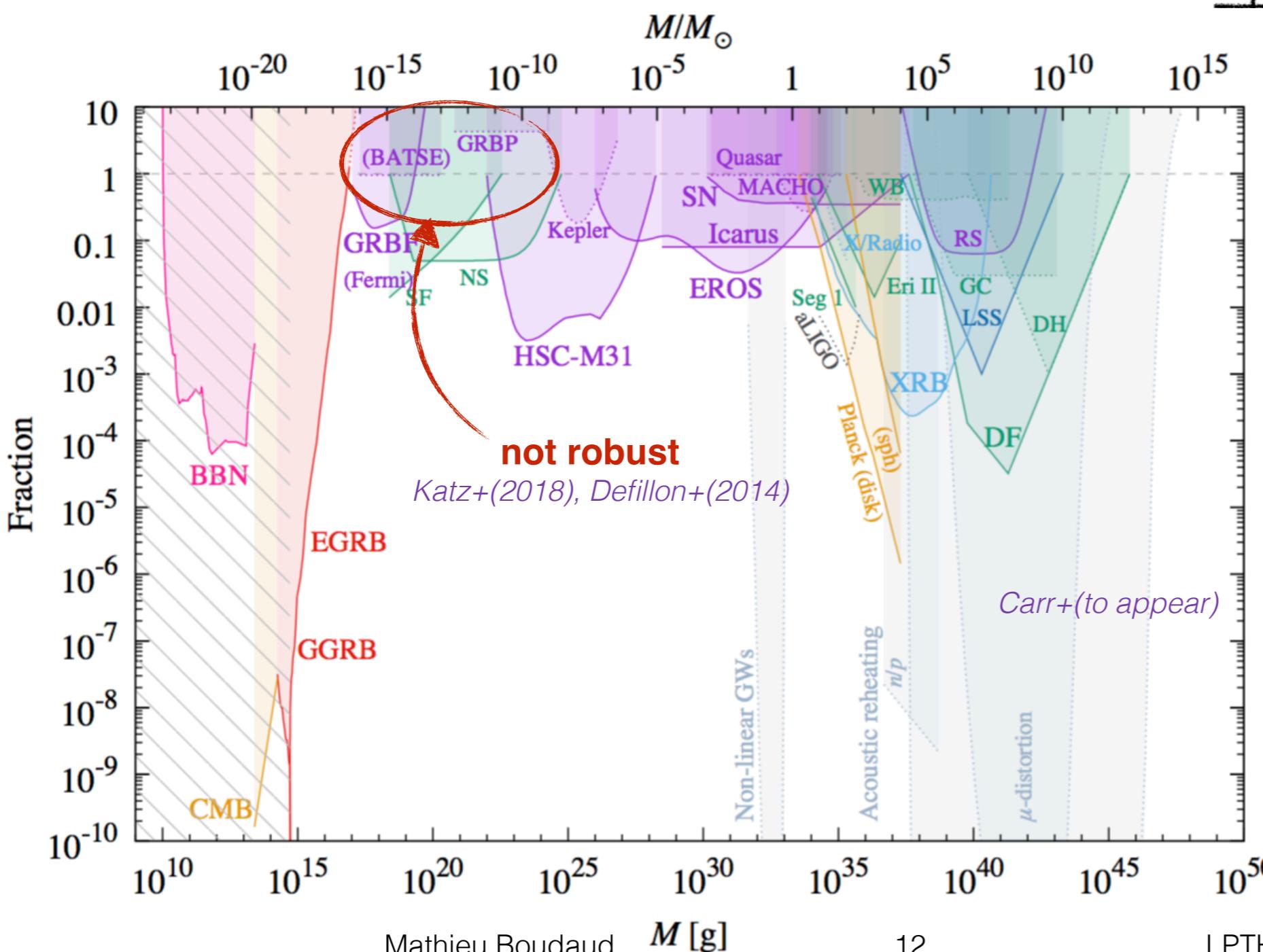
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Lensing, dynamical, accretion, cosmological and Hawking radiation



Primordial black holes

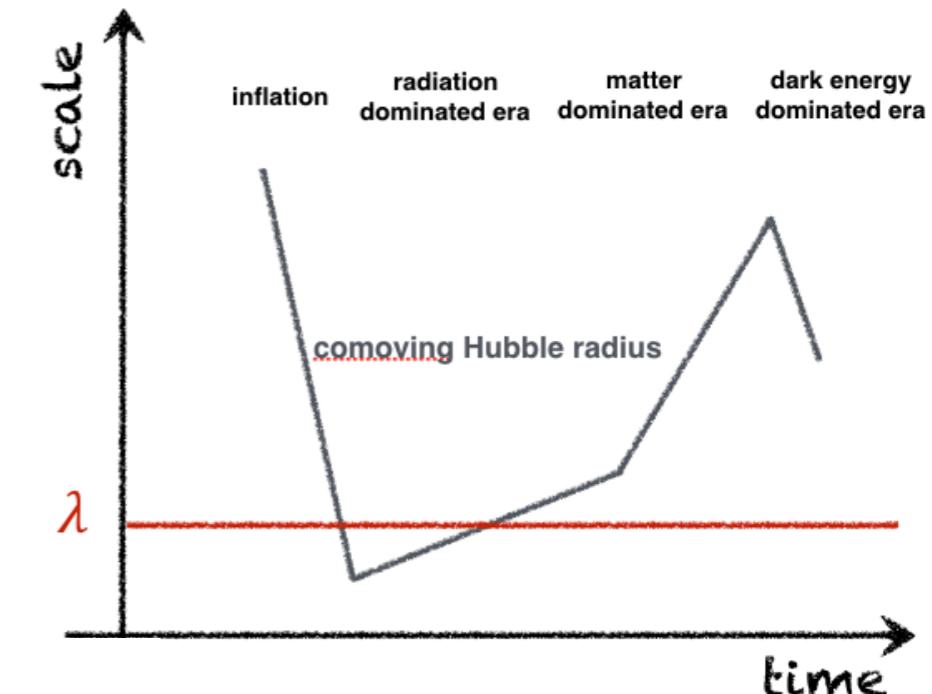
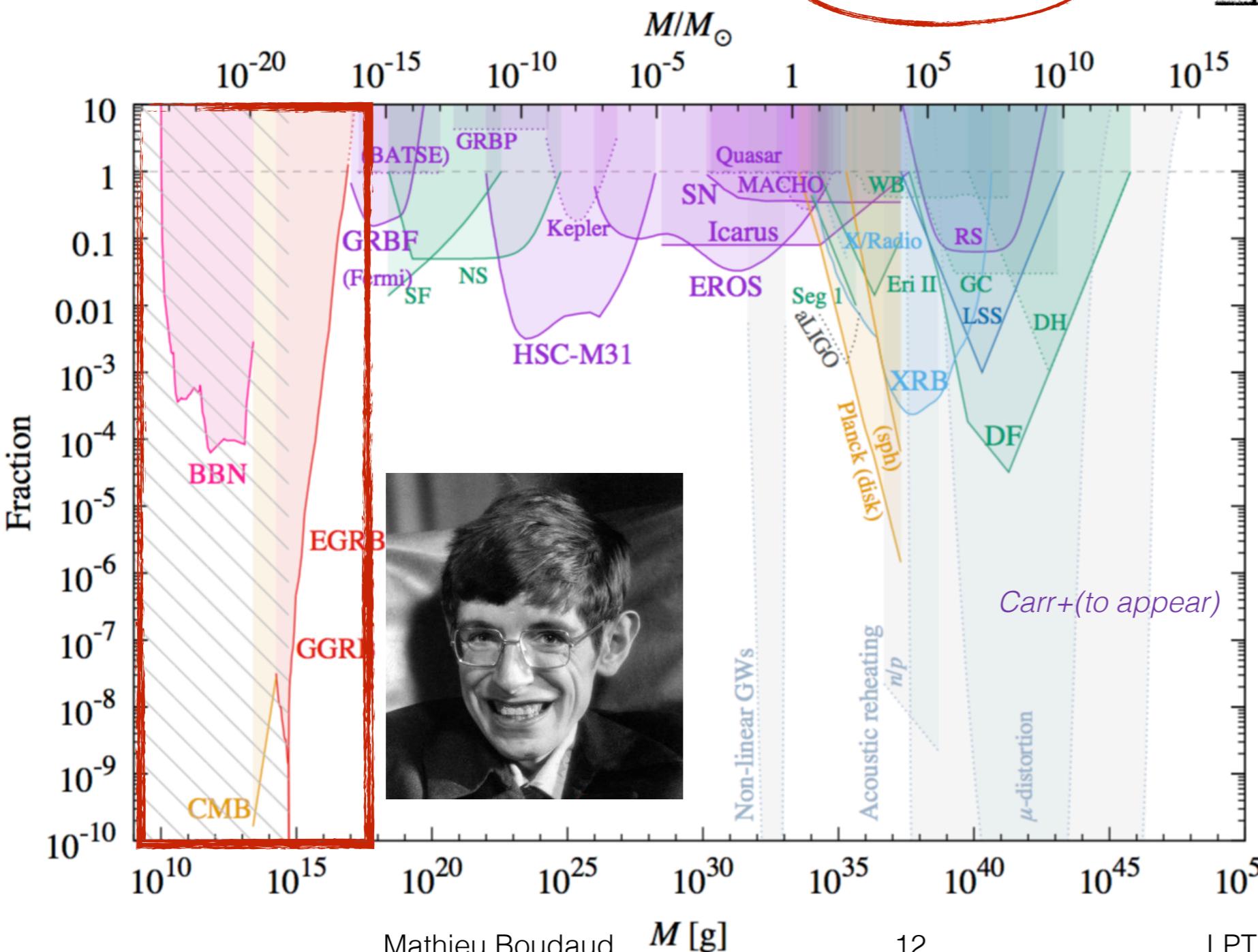
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$$f = \frac{\rho_{\text{PBH}}}{\rho_{\text{DM}}}$$

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



Hawking radiation of e^\pm

Hawking (1975)

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

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

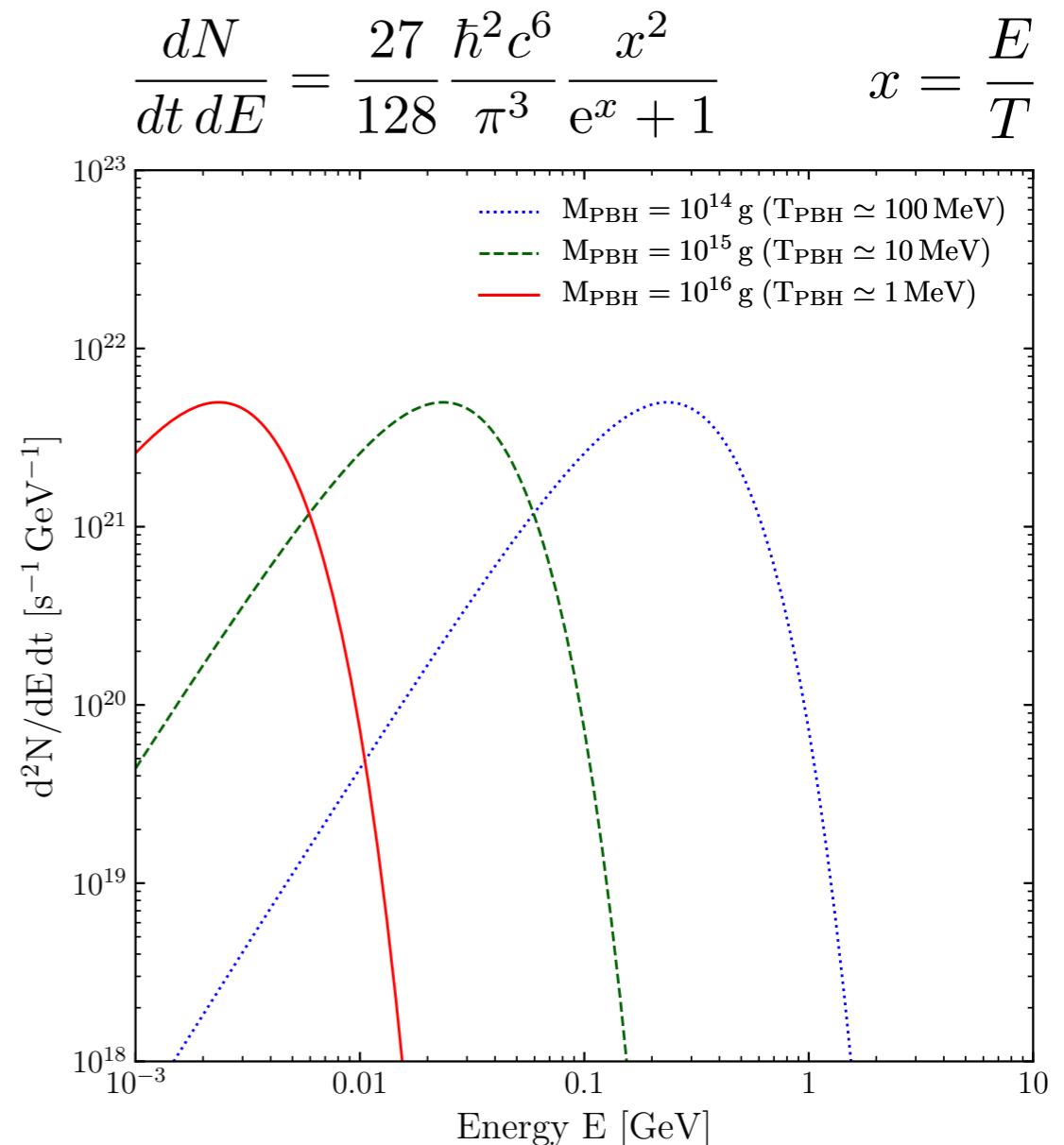
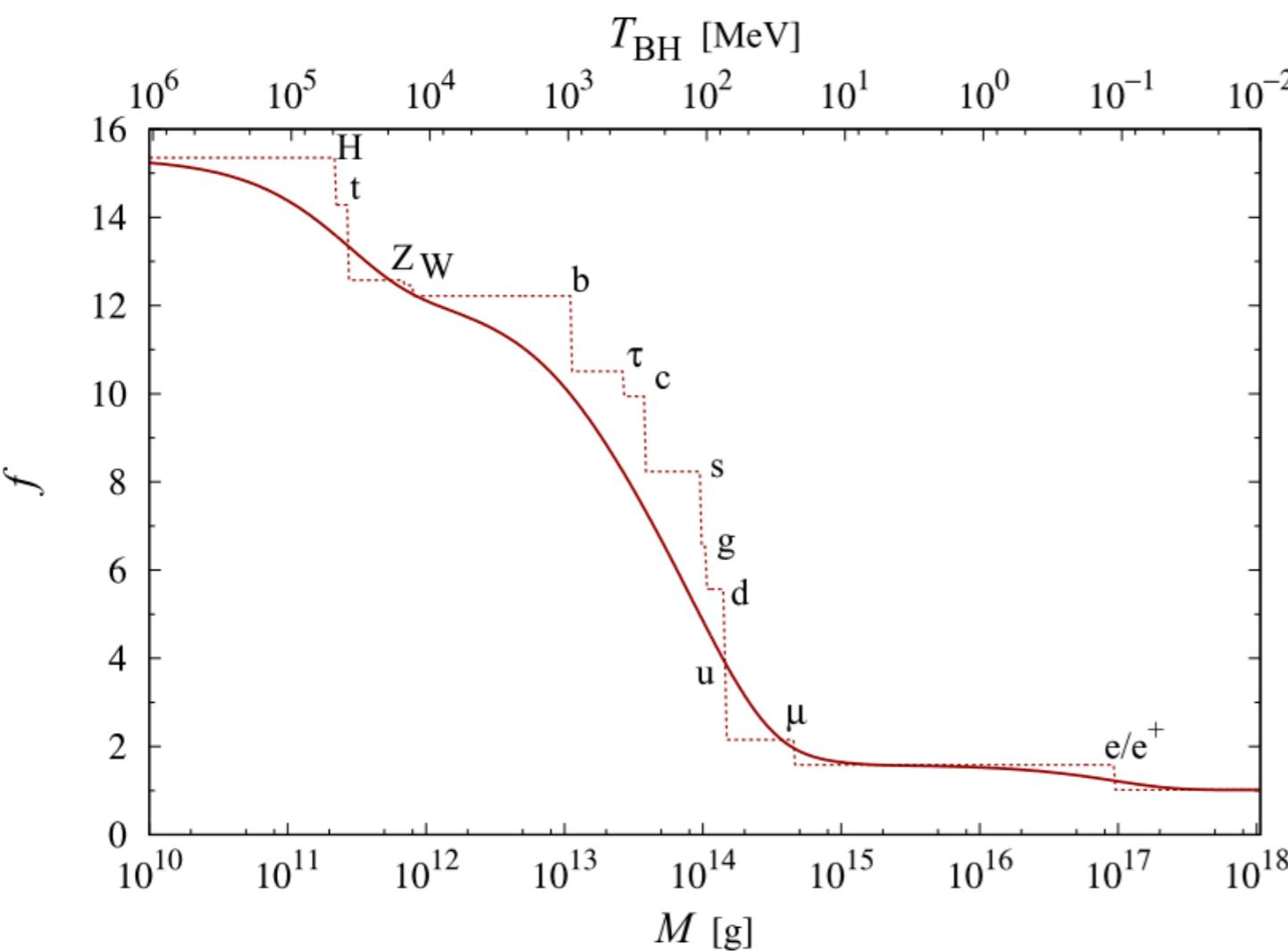


BHs lose mass radiating particles with the rate:

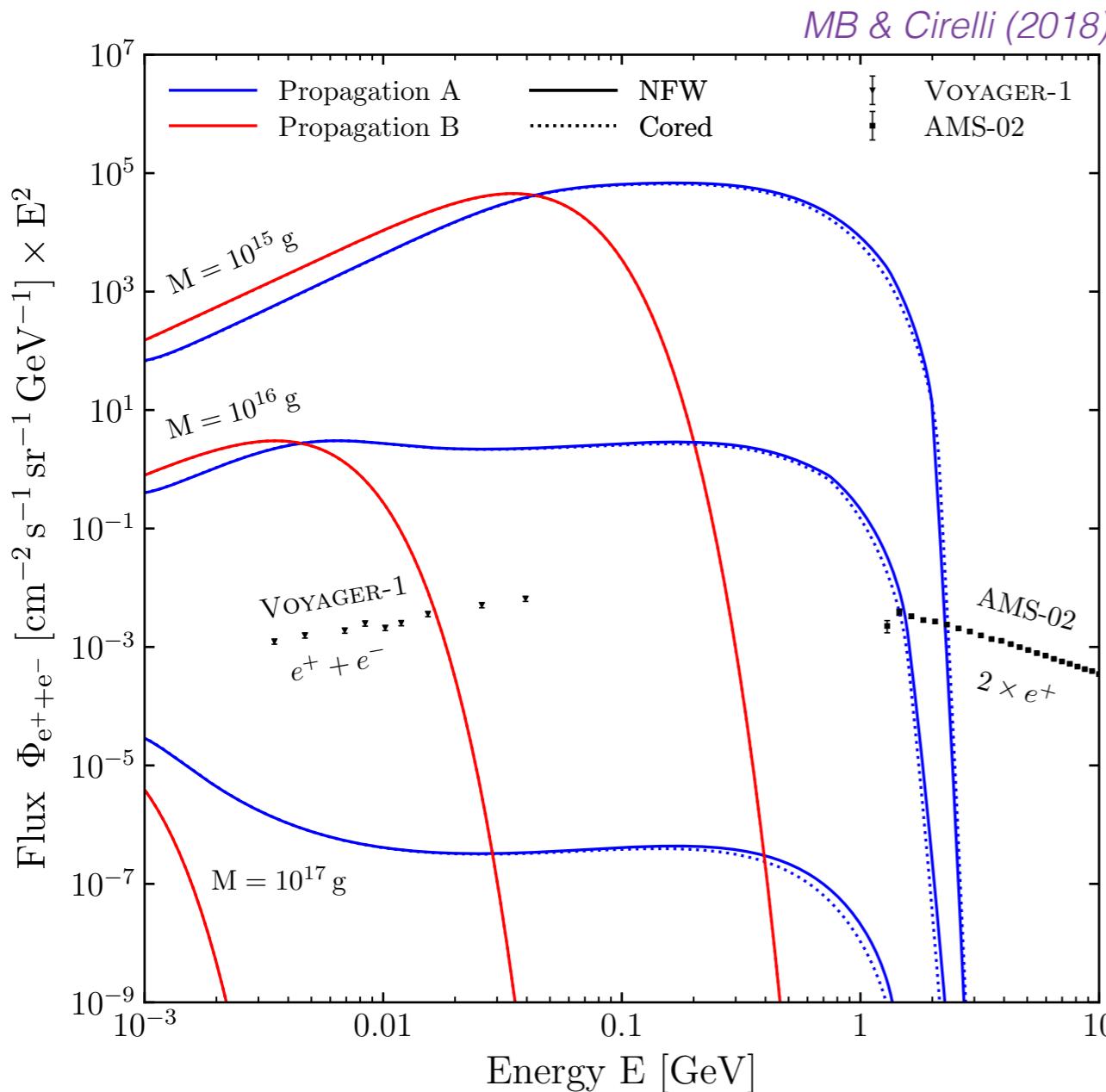
$$\frac{dM}{dt} \simeq -5.25 \times 10^{25} f(M) \left(\frac{g}{M} \right)^2 g s^{-1}$$

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

grey body emission of e^\pm



Hawking radiation of e^\pm



Propagation A: strong reacceleration

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

Propagation B: no reacceleration

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

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

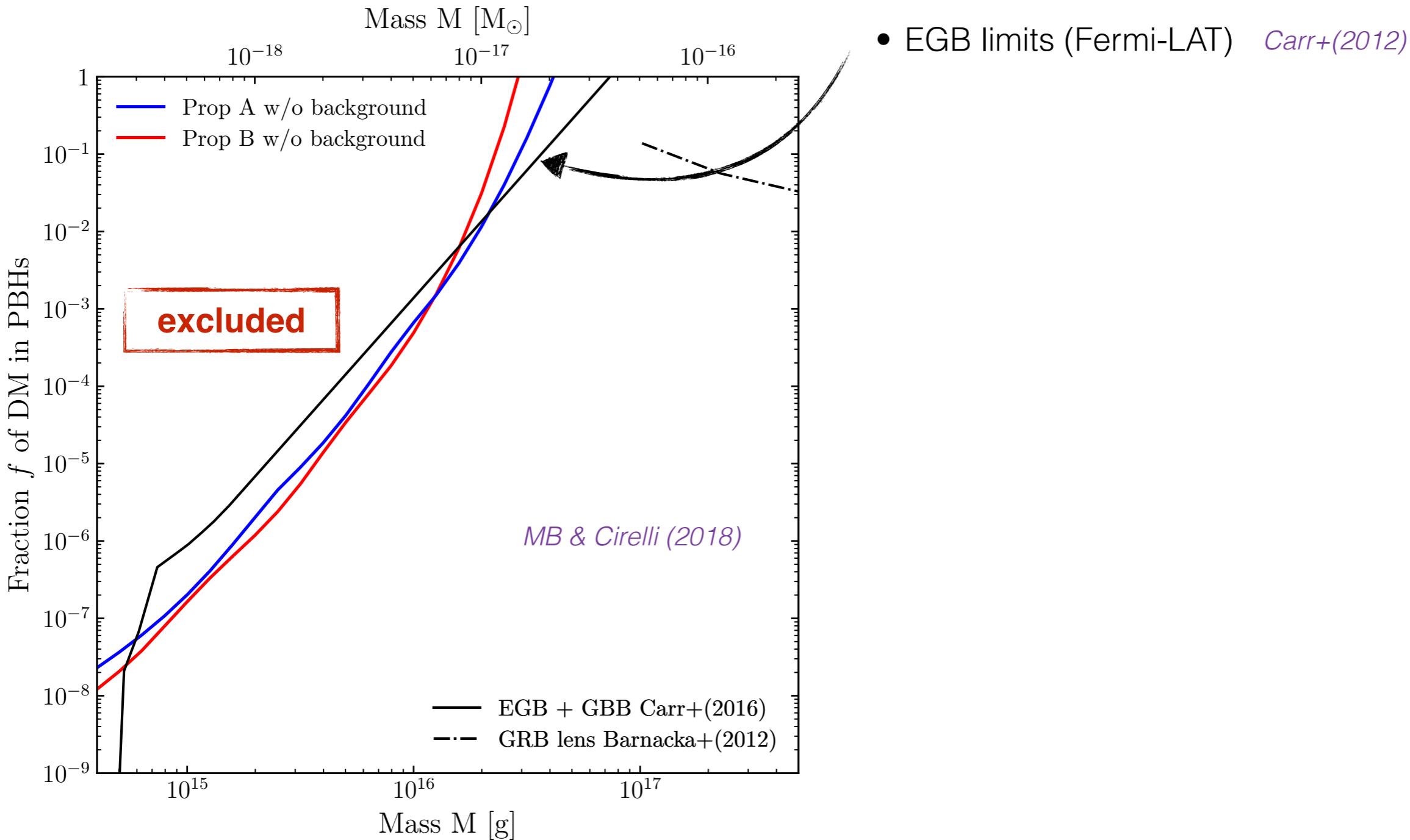
$$\rho_\odot^{\text{DM}} = 0.4 \text{ GeV cm}^{-3}$$

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

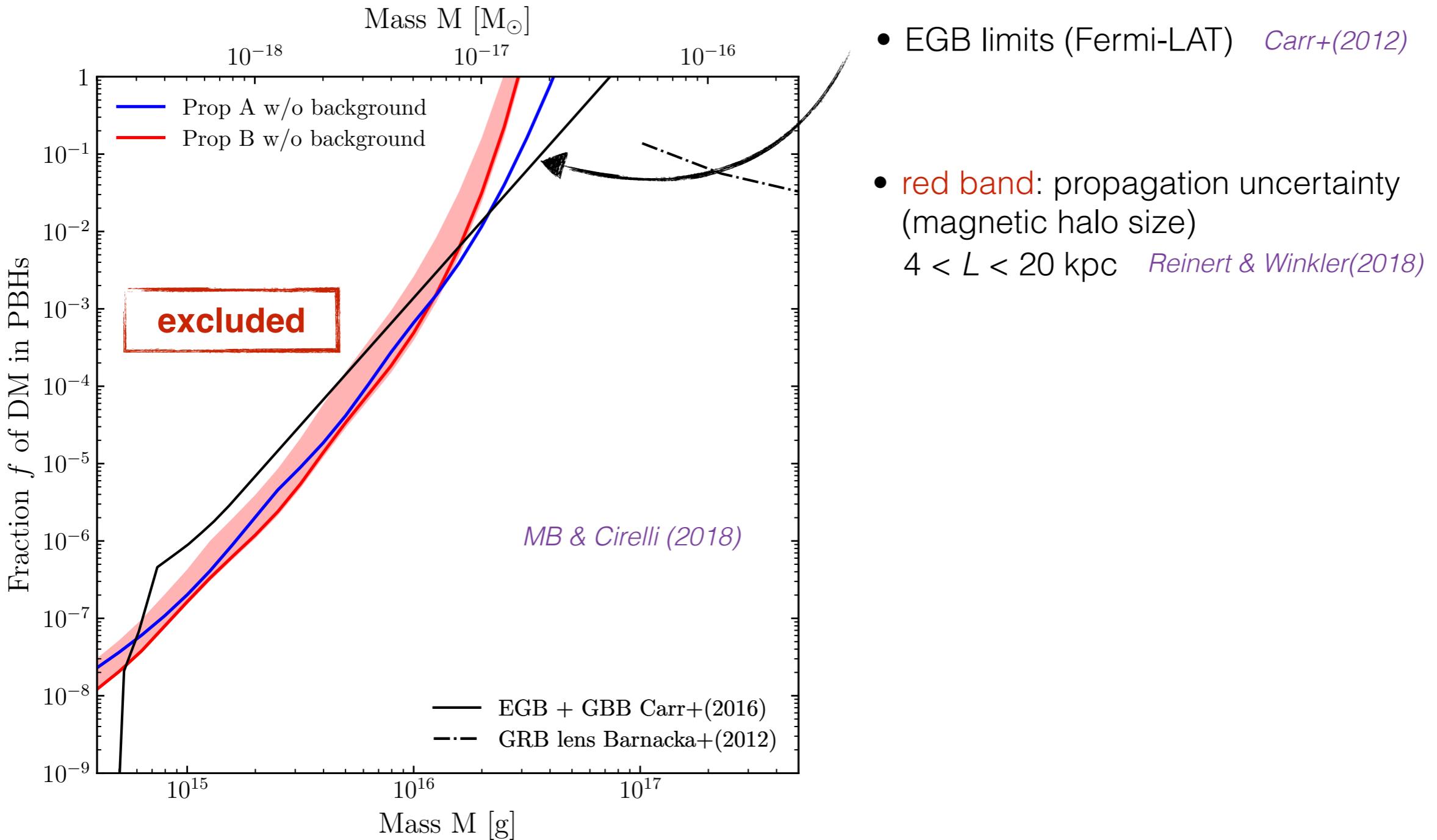
- Voyager-1 is sensitive local PBHs ($\sim 1\text{kpc}$) because of e^\pm energy losses (ISM ionisation)
 \Rightarrow signal **not sensitive** to the DM halo profile
- strong reacceleration (**A**) enables to detect a signal above 1 GV
 \Rightarrow AMS-02 probes PBHs with $M < 10^{16} \text{ g}$

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

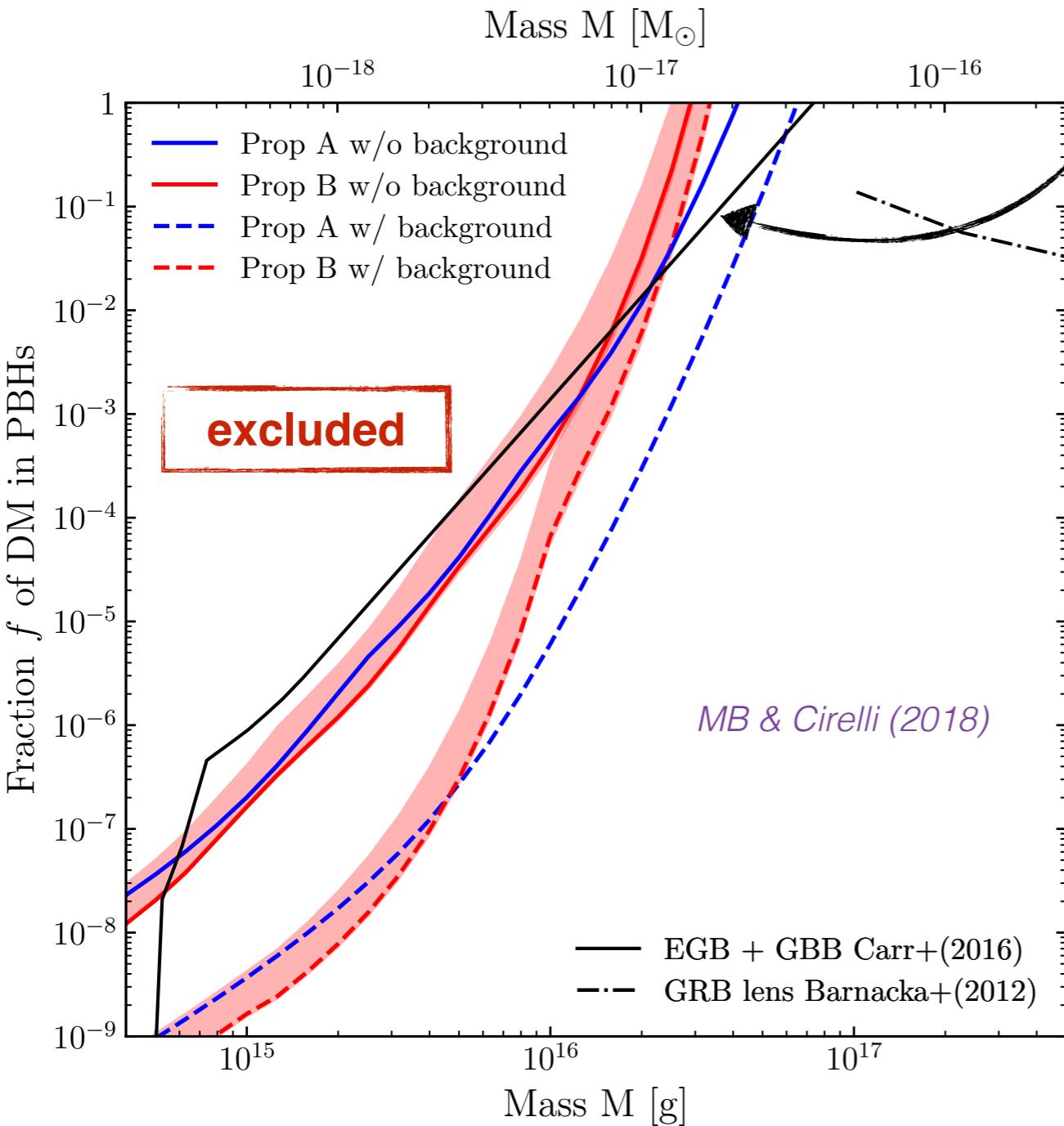
Constraints on the fraction of DM in PBHs



Constraints on the fraction of DM in PBHs

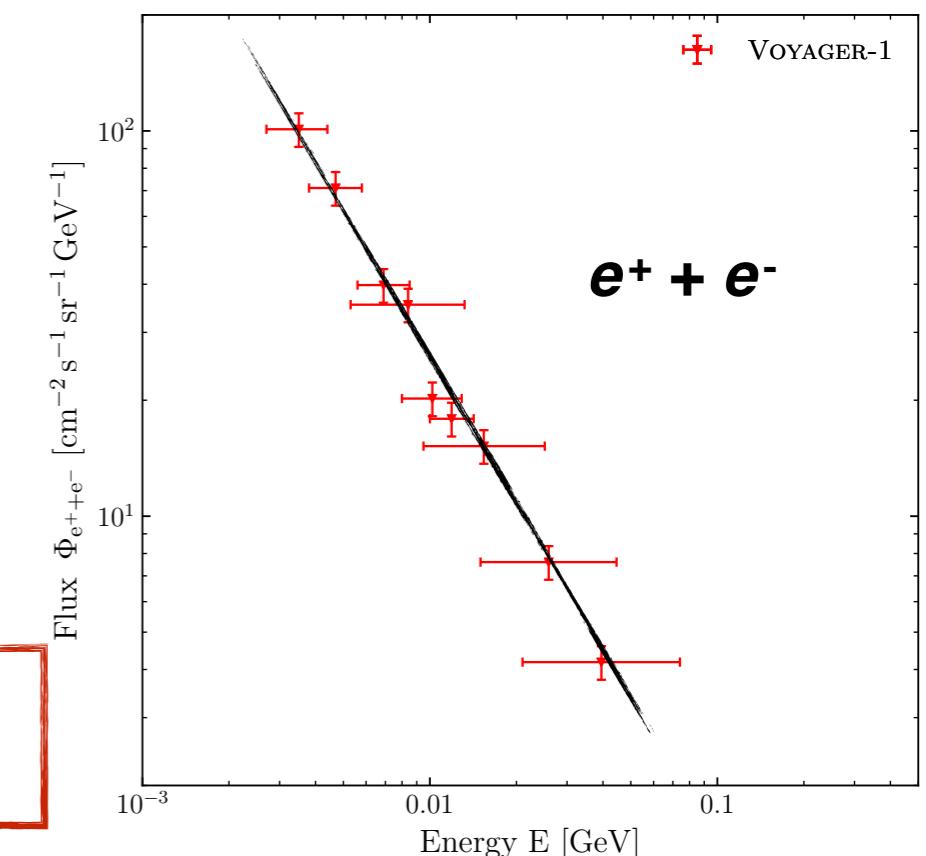


Constraints on the fraction of DM in PBHs



- 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~kpc), **no** cosmological assumptions
⇒ complementary to cosmological constraints (EGB, CMB, EDGES)

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

Back up

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)

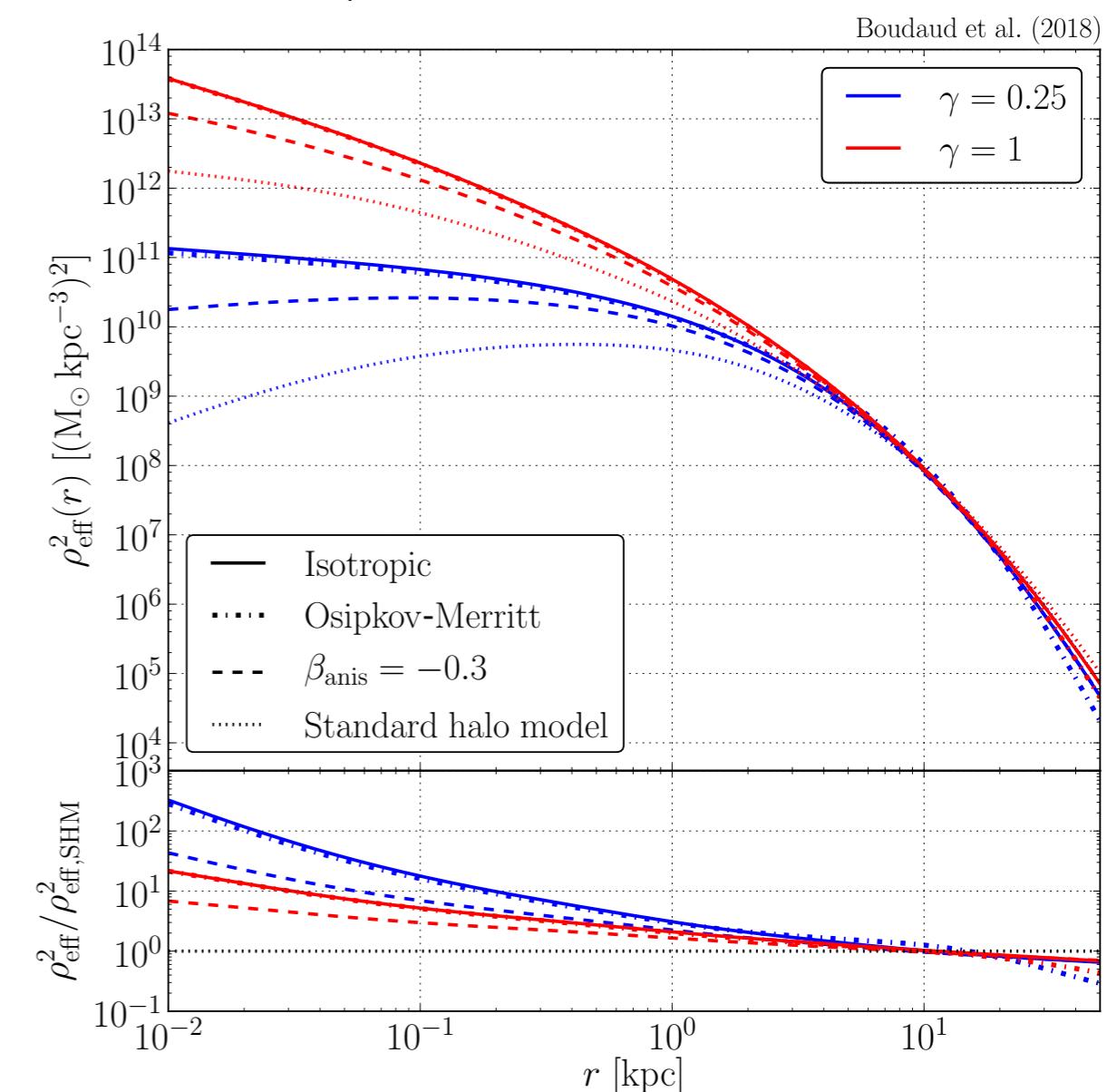
$$\langle \sigma v \rangle(r) = K_0(r) \int d^3 \vec{v}_1 \int d^3 \vec{v}_2 f(|\vec{v}_1|, r) f(|\vec{v}_2|, r) \sigma v_{12}$$

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

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

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

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



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)

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

