GRAPPA student seminar

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GRAPPA
GRavitation AstroParticle Physics Amsterdam

DM candidates: 90 orders of magnitude in mass

10^{-22} eV

Axion-like particles

1 GeV 1 TeV

10^{19} GeV (10^{-5} g)

10^{57} GeV (10^{33} g)

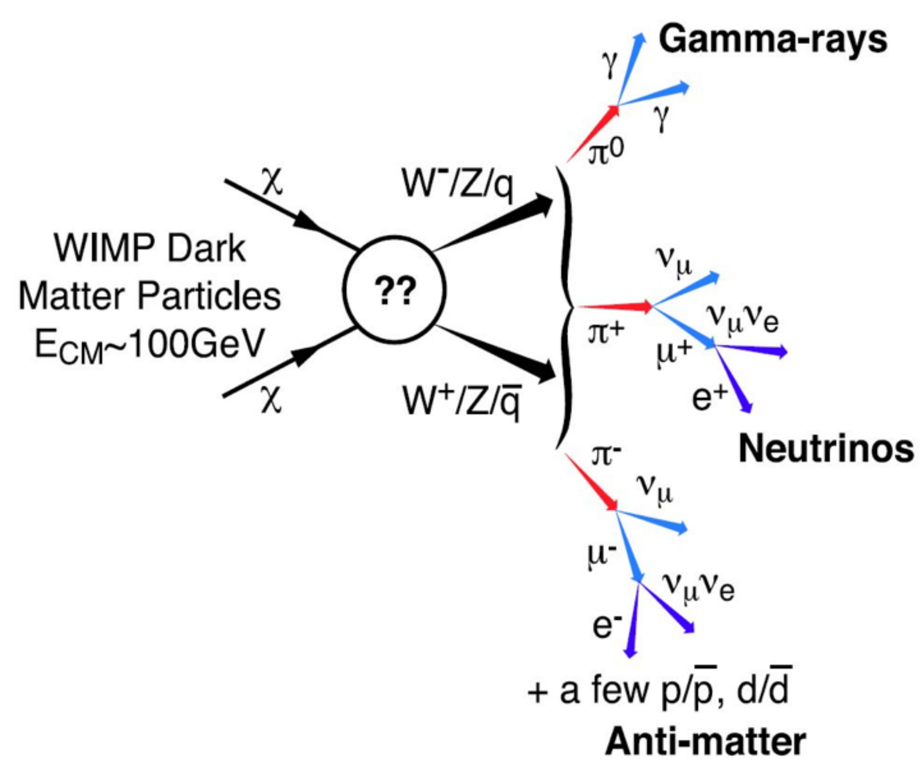
"Fuzzy" Dark Matter

λ_{dB} ~ 1 kpc ~ size of a dSph Galaxy

[Hui, Ostriker, Tremaine, Witten 2016]

Weakly interacting massive particles (WIMPS)

e.g. lightest neutralino state in MSSM



Primordial black holes (PBHs)

[Zeld'ovich and Novikov 1966, Hawking 1971]

many constraints from lensing, wide binaries, Galactic disk stability

became less popular after MACHO and EROS results *[Alcock 2001]*

now reconsidered in the DM community, as we will see

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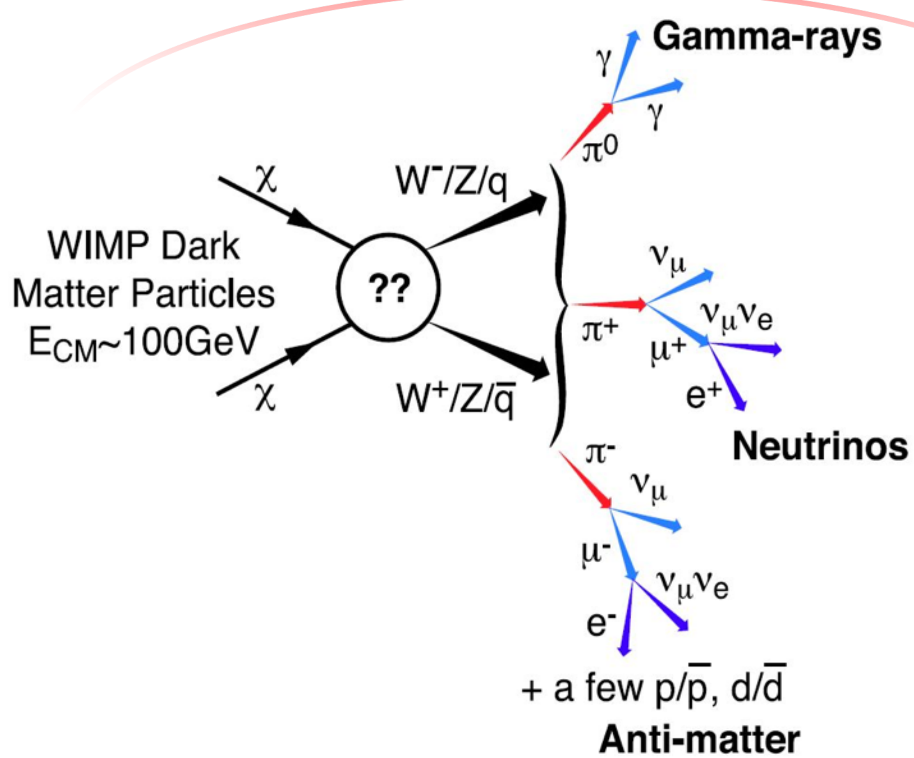

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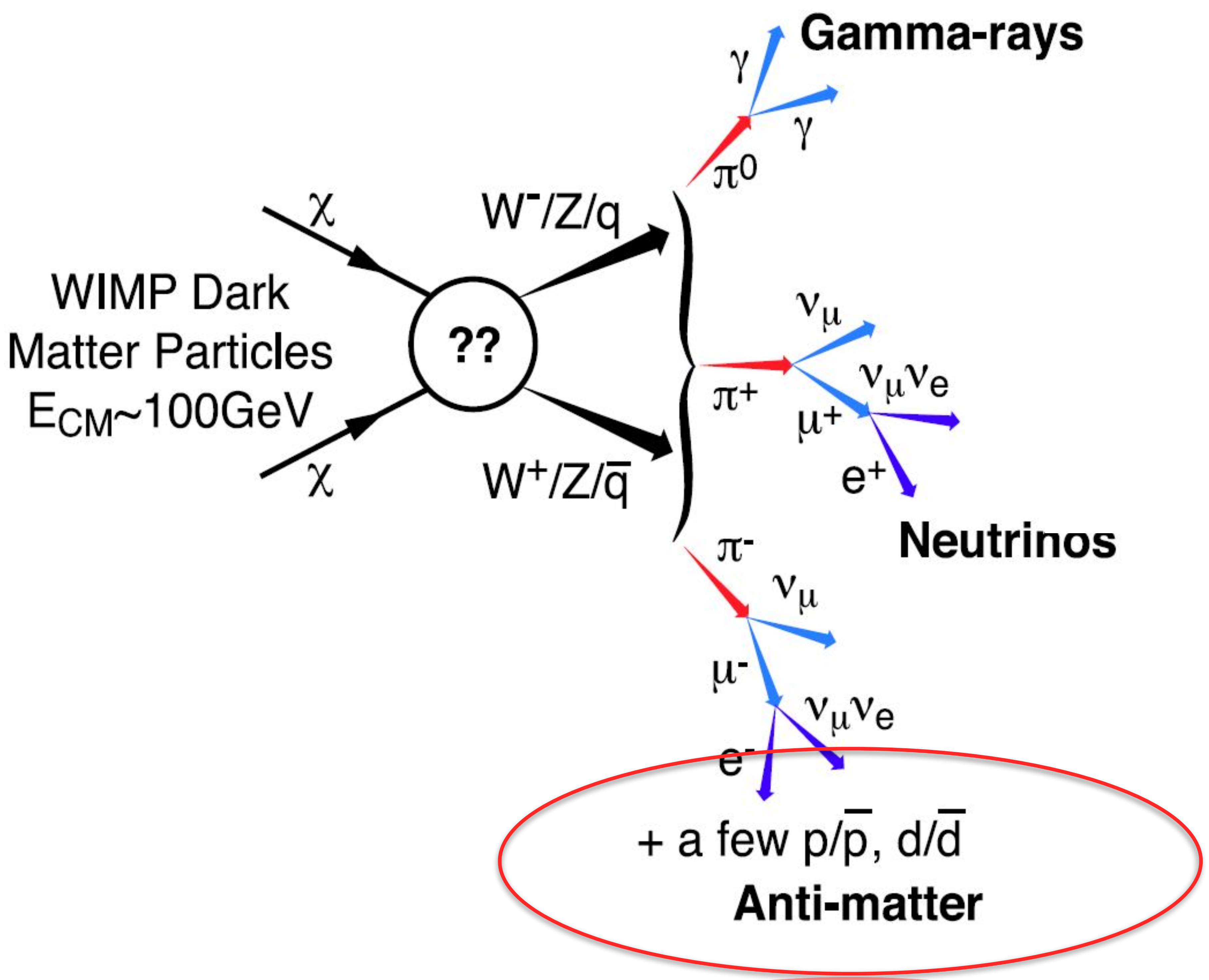
Indirect detection of WIMP DM: The antiparticle channel



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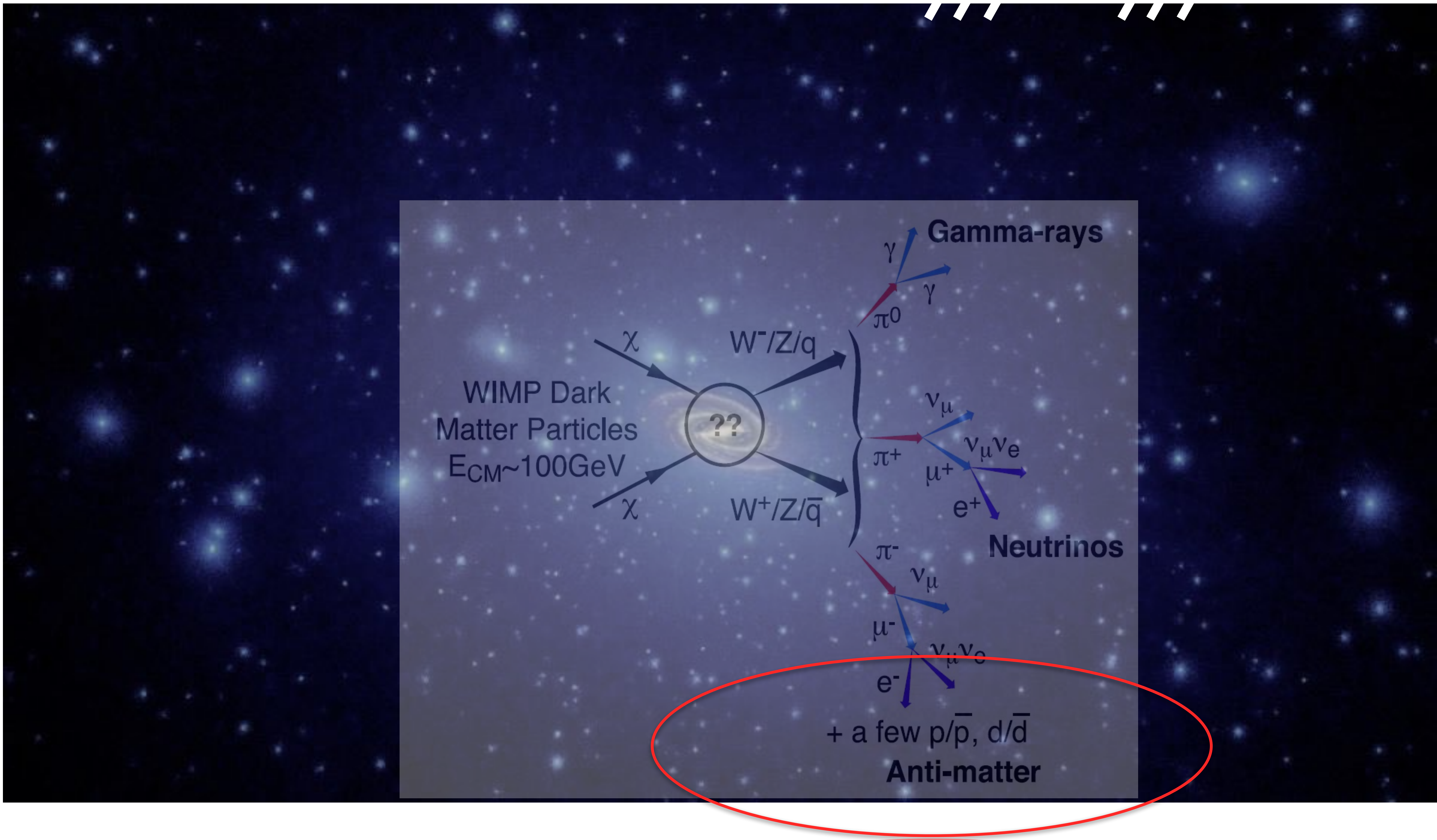
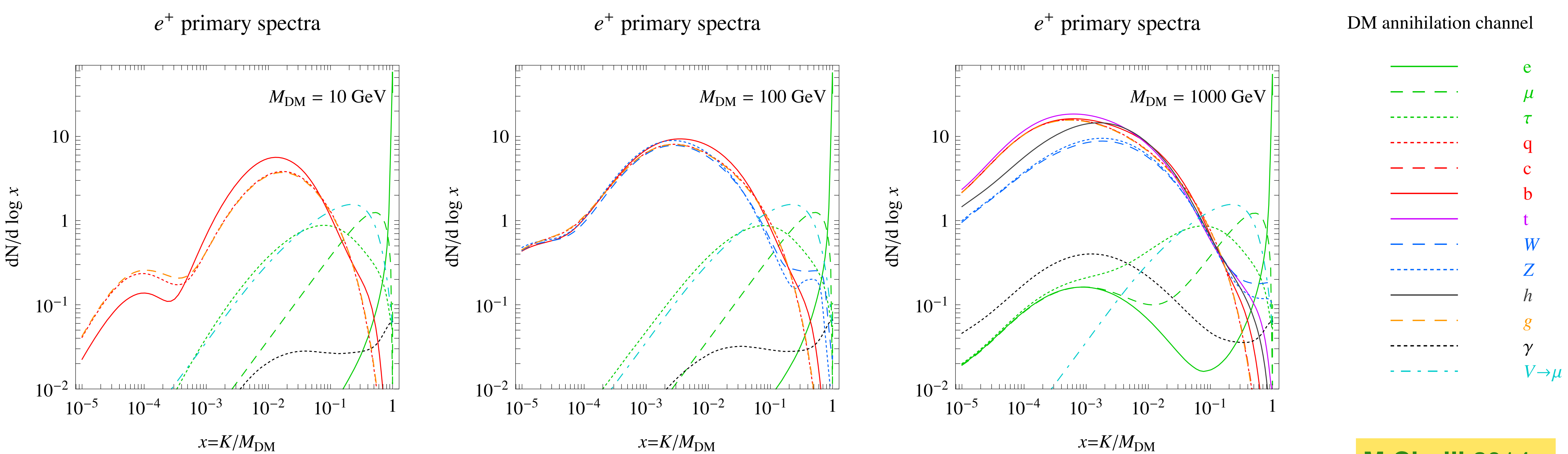


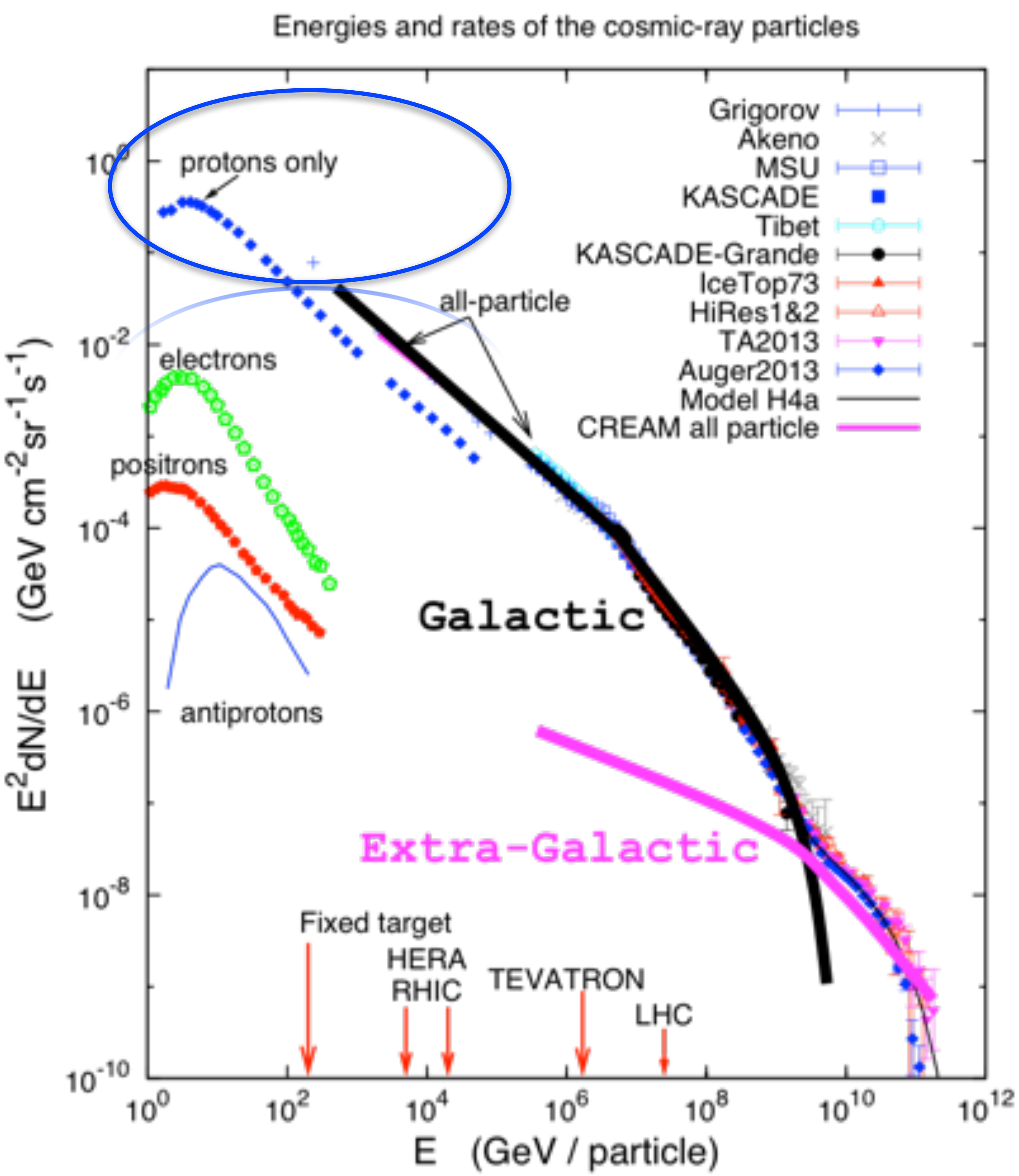
Fluxes of antiparticles

$$Q_{e^\pm}(E) = \underbrace{\frac{1}{2}\left(\frac{\rho_{DM}}{m_{DM}}\right)^2}_{\text{Astrophysics}} \underbrace{\sum_f \left\{ \langle \sigma v \rangle_f \frac{dN^f_{e^\pm}}{dE}(E) \right\}}_{\text{Particle physics}}$$



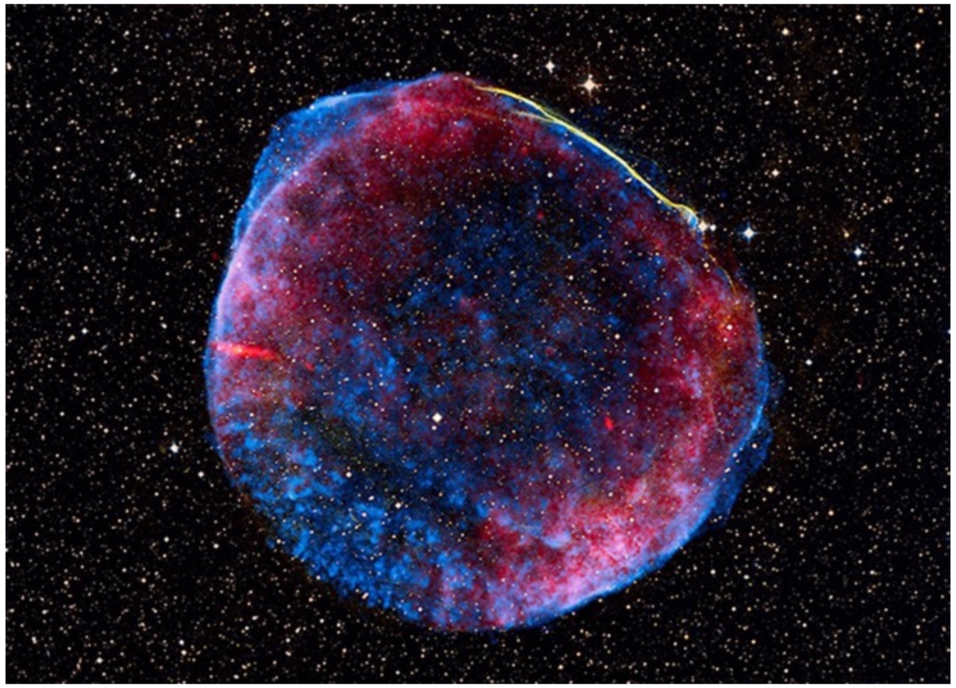
M.Cirelli 2014

Where to look? The CR background



Primary CRs

Protons, most of the nuclei, electrons are directly accelerated at astrophysical shocks (e.g. in Supernova Remnants) via *diffusive shock acceleration* [Blandford & Ostriker 1978; Bell 1978; Axford et al. 1977; Krymskii 1977]



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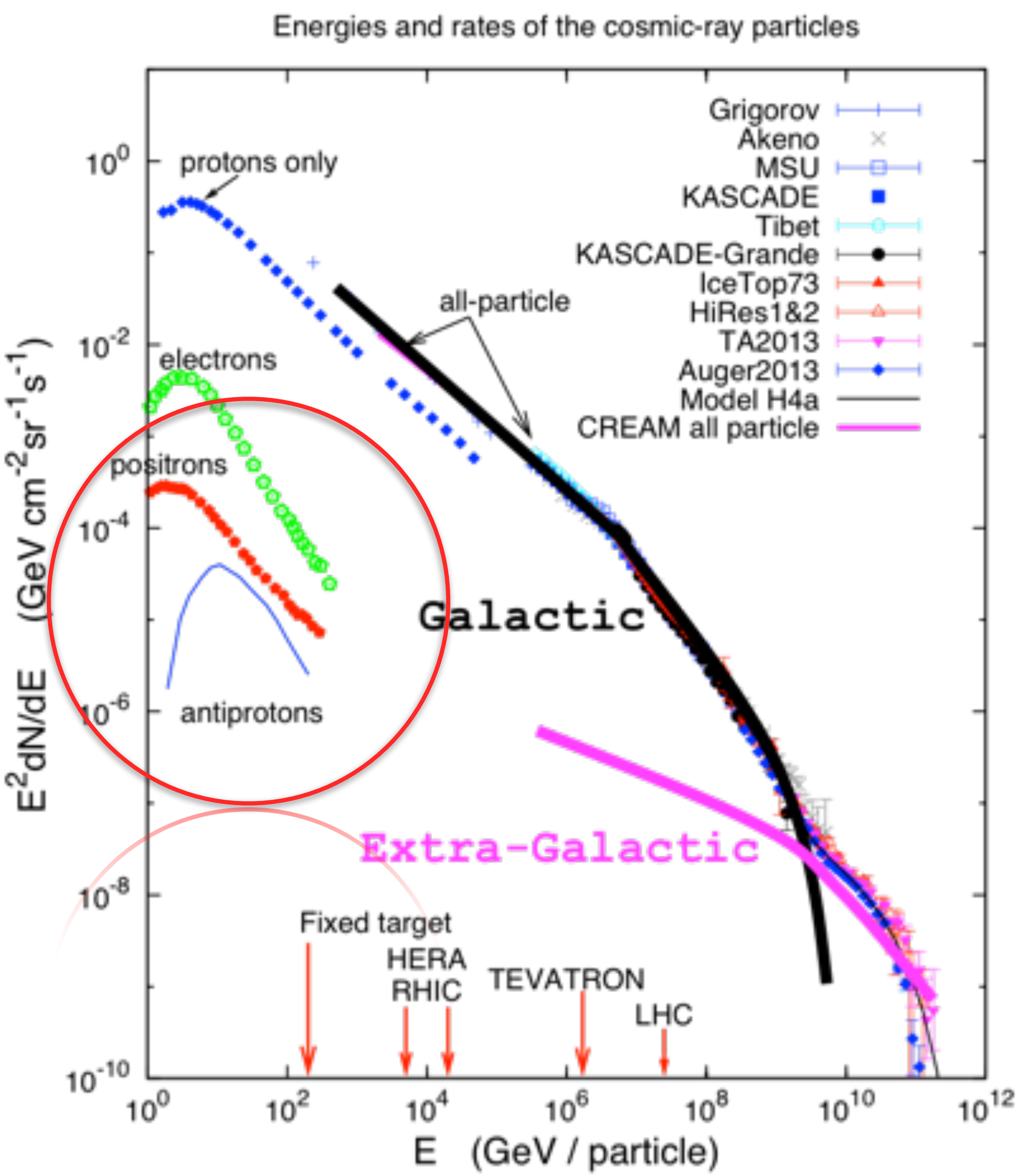
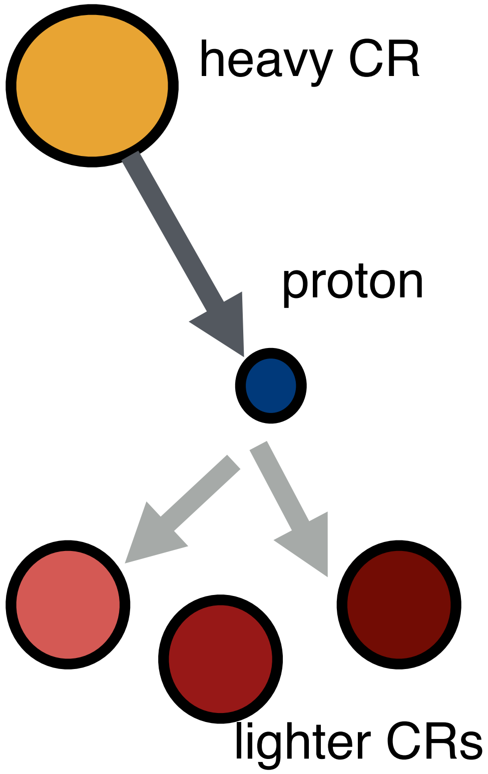


Secondary CRs

Antiparticles, antinuclei and some light nuclei are produced "in flight" by CRs, while they random walk across the Galaxy, via *spallation*



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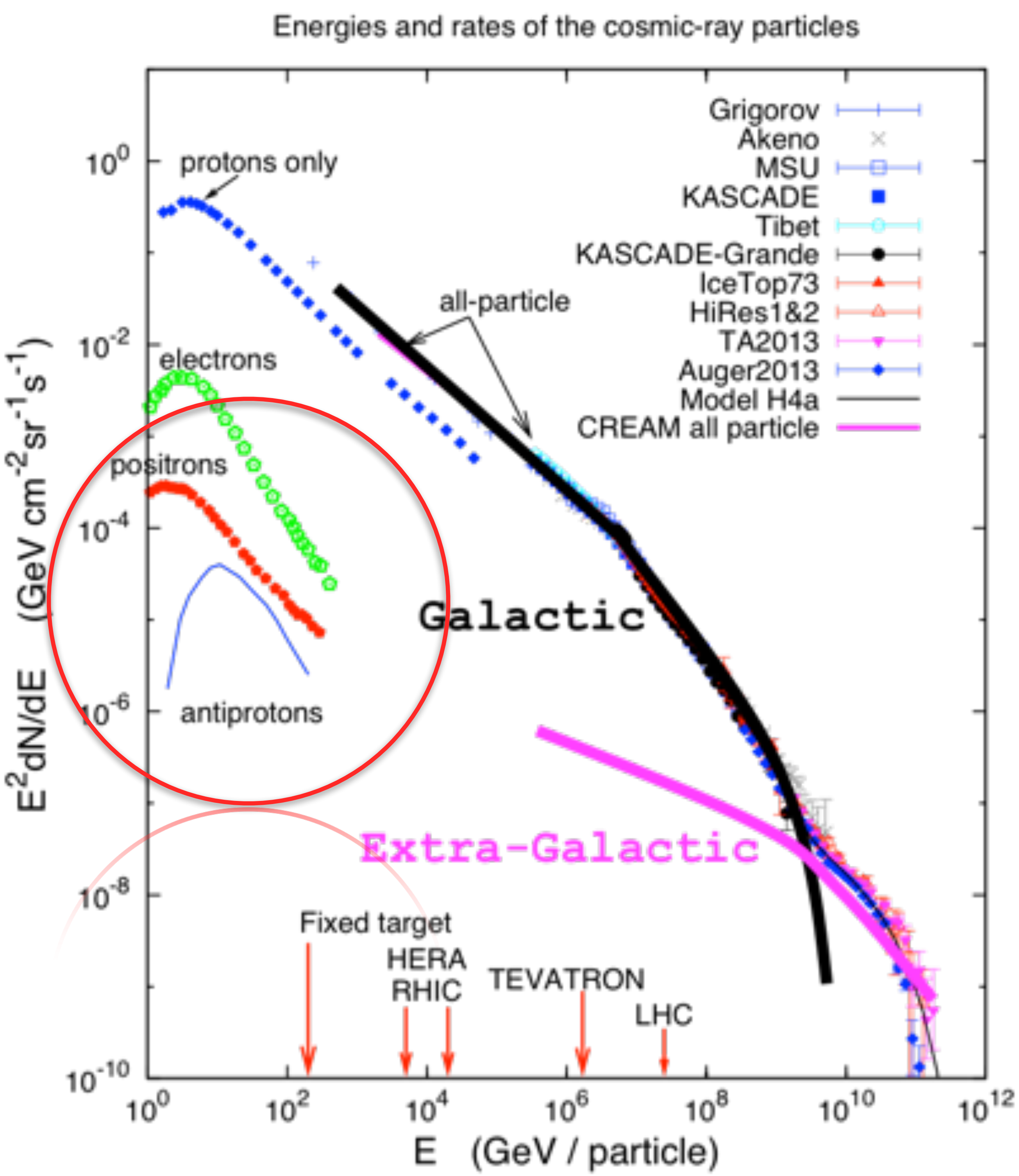

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$$p + \mathrm{H} \rightarrow p + \Delta^+ \rightarrow \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases}$$

$$p + \mathrm{H} \rightarrow \begin{cases} X + \pi^{0,\pm} \\ X + K^\pm \end{cases}$$

$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu \rightarrow e^\pm + \nu_e + 2\nu_\mu$$

Where to look? Energy budget

- The power injected in the Galaxy by DM annihilation is comparable with the power associated to the secondary CR flux [convince yourselves]

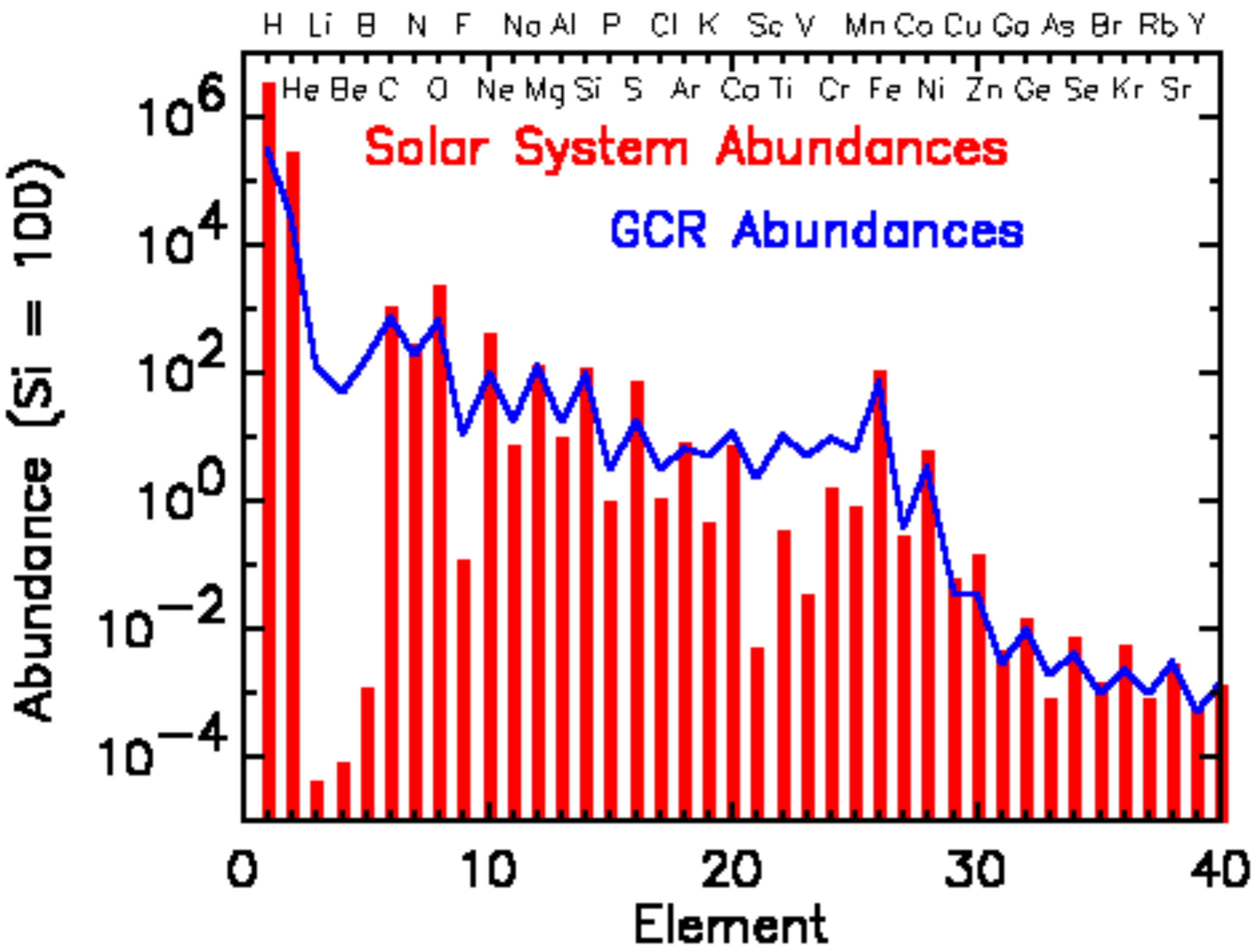
$$L_p = 0.01 \cdot E_{SN} R_{SN} = \frac{V \rho_{N_p}}{\tau_{\rm esc}} \sim 10^{41} \, \frac{\rm erg}{\rm s}$$

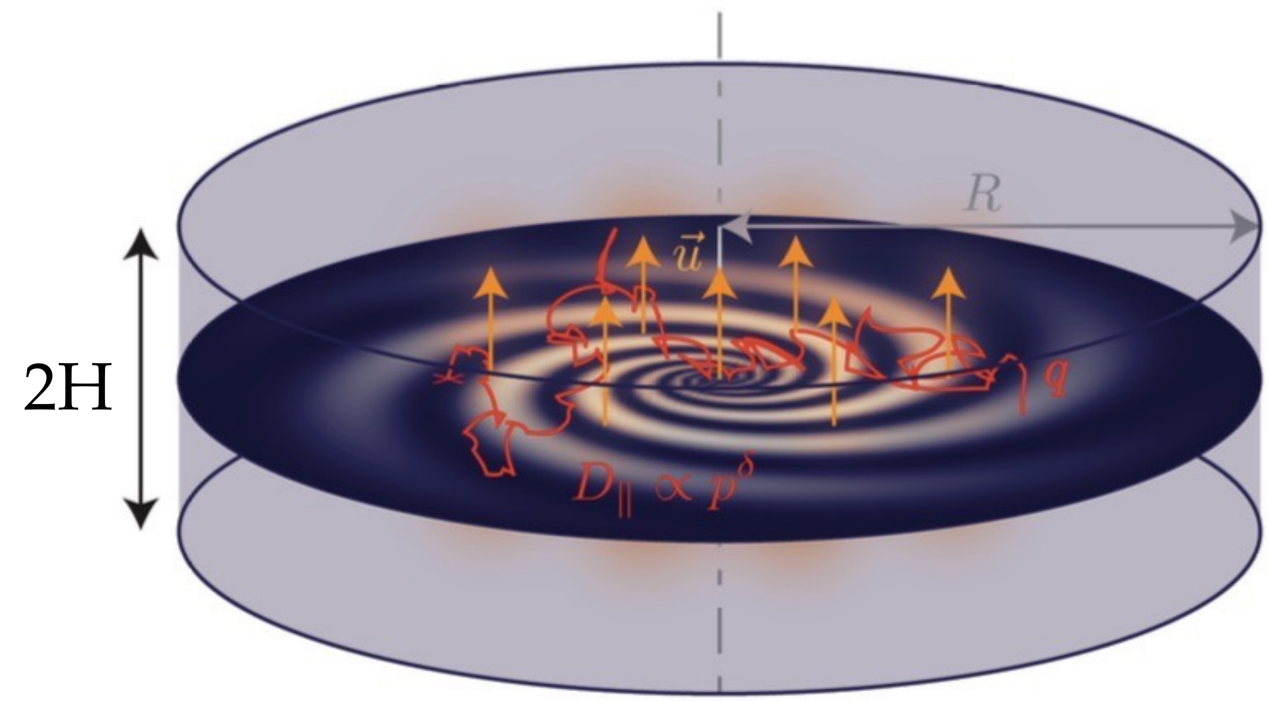
$$L_s \sim 10^{37} \, \frac{\rm erg}{\rm s}$$

$$L_{DM} \sim \frac{\int (\rho^2(\vec{x}) {\rm d}^3 x) \cdot \langle \sigma v \rangle}{m_{DM}} \sim 10^{37} \, \frac{\rm erg}{\rm s}$$

CR propagation: Diffusive halo

- Abundances of light elements in CRs suggest the presence of a large diffusive halo around the Galaxy where charged particles are confined for ~10 Myr

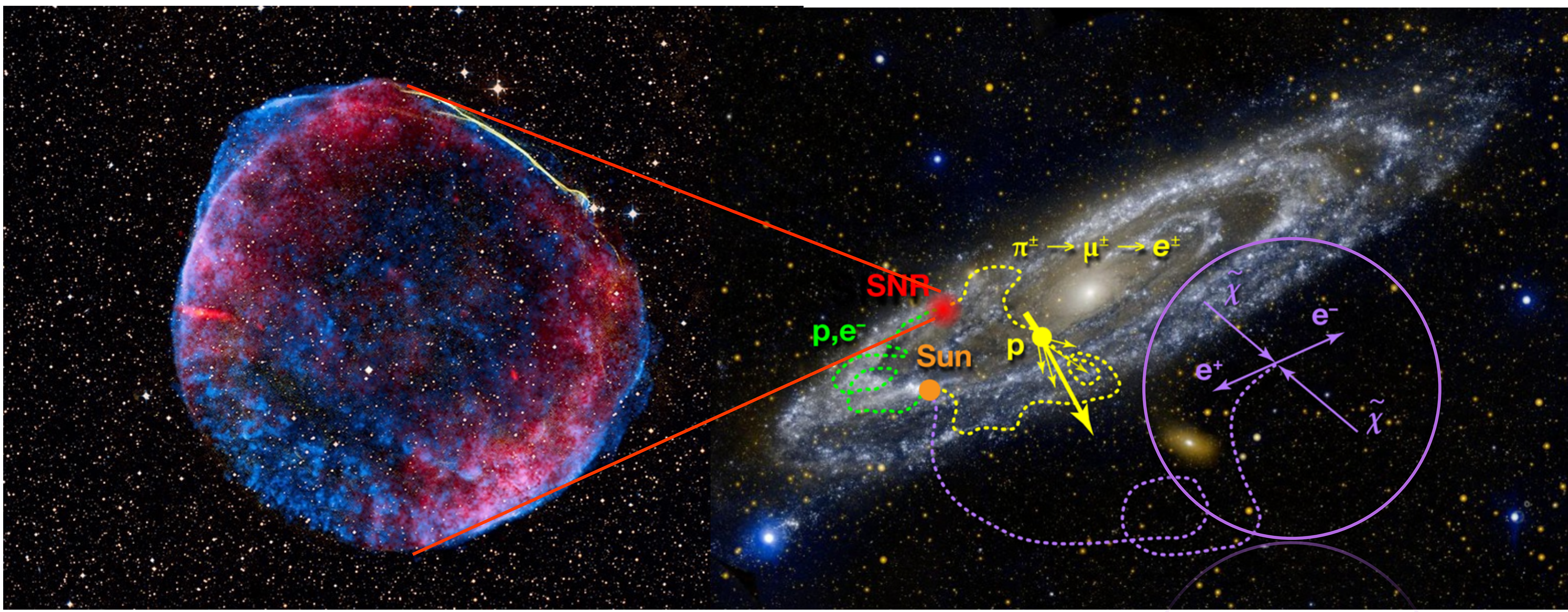




Credit: P. Mertsch

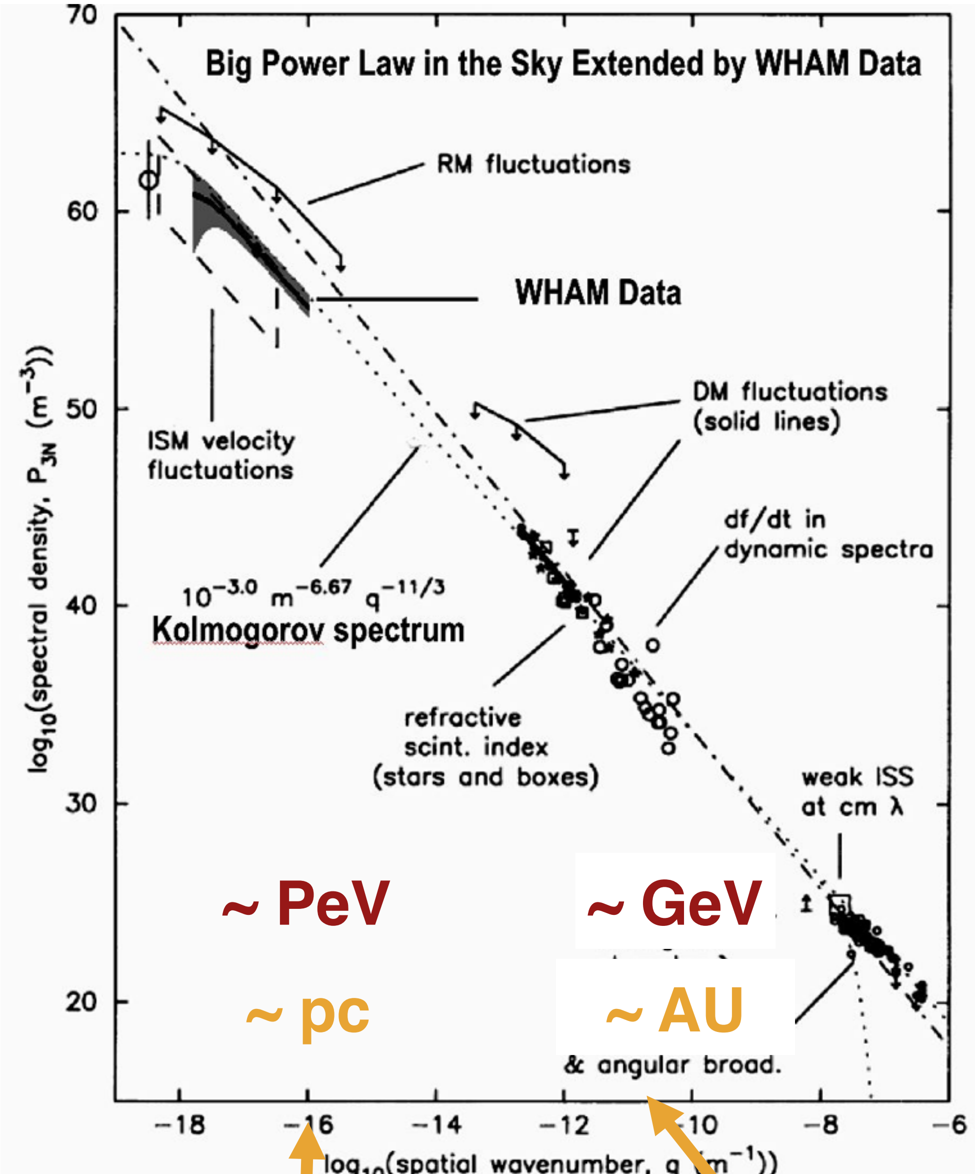
The complete picture

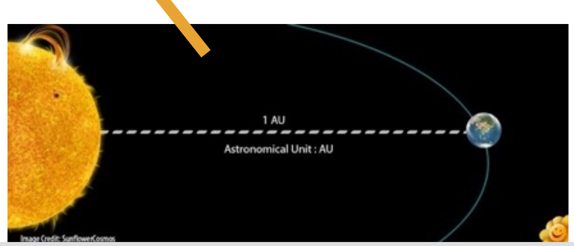
- Both (hypothetical) DM WIMPs and conventional astrophysical accelerators (e.g. SNRs) can inject charged particles in the ISM. These particles random walk through the Galaxy and are detected at Earth



Theory of CR transport

Resonant pitch-angle scattering on Alfvénic turbulence
[Morrison 1957; Jokipii ApJ **146** 1966; Jokipii&Parker PRL **21** 1968]

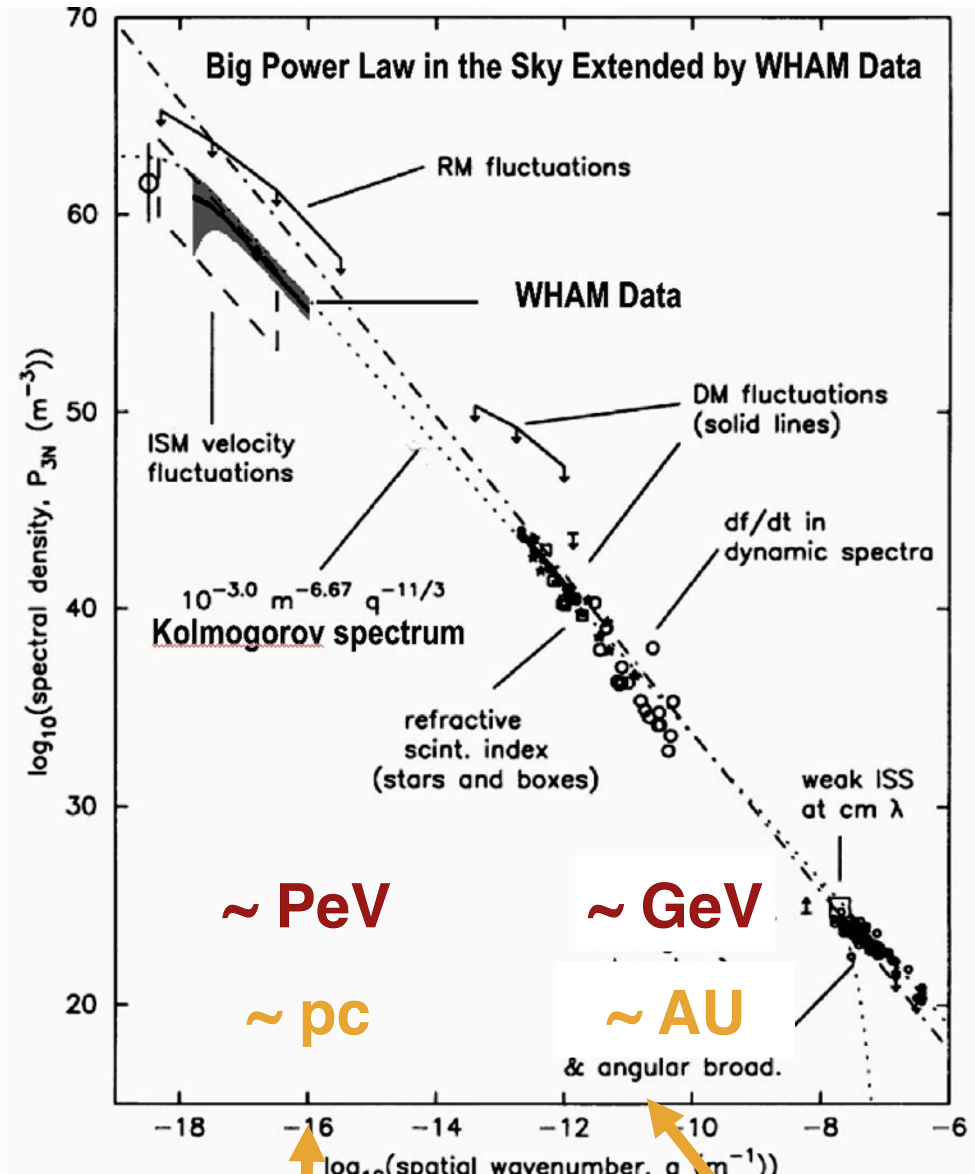


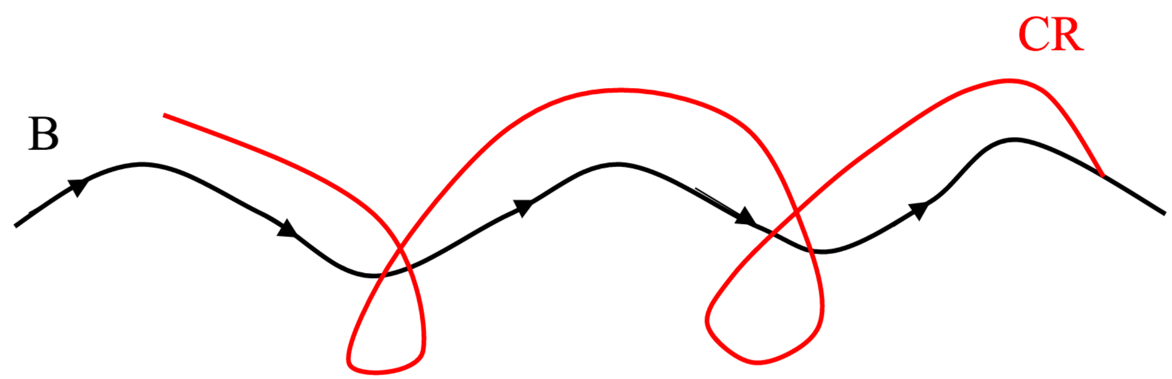


- The ISM is **magnetized** and **turbulent** over a wide inertial range; energy injection at large scales (~100 pc), e.g. by supernova explosions
- **Pitch-angle scattering:** A resonant interaction between Alfvén waves that make up the turbulent cascade and charged CRs
- A CR interacts with an Alfvén wave: If the **resonance condition** is satisfied, its pitch angle randomly changes. This stochastic process eventually results in a mostly **parallel spatial diffusion** w.r.t. the regular field

Resonant pitch-angle scattering on Alfvénic turbulence

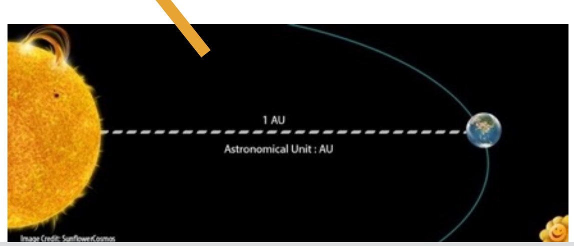
[Morrison 1957; Jokipii ApJ **146** 1966; Jokipii&Parker PRL **21** 1968]





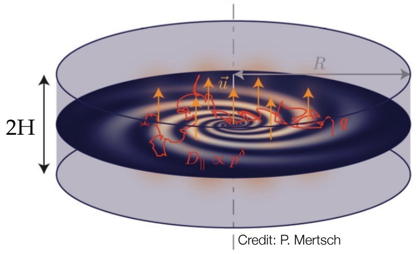
$$D(p) = \frac{1}{3} r_L(p) v(p) \frac{1}{k_{res} W(k_{res})} \qquad k_{res} = \frac{1}{r_L(p)}$$

$$\int_{k_0}^{\infty} dk \; W(k) = \eta_B = \frac{\delta B^2}{B_0^2}$$



Phenomenology of CR transport

Phenomenological description of the processes involving CR transpor
[Morrison, Olbert, Rossi 1954; Ginzburg&Syrovatskii 1964; Berezinskii et al. 1990]



- Primary CR production
- Secondary CR production via *spallation*

- *Rigidity-dependent* diffusion: Usually modeled as an isotropic and homogeneous rigidity-dependent coefficient

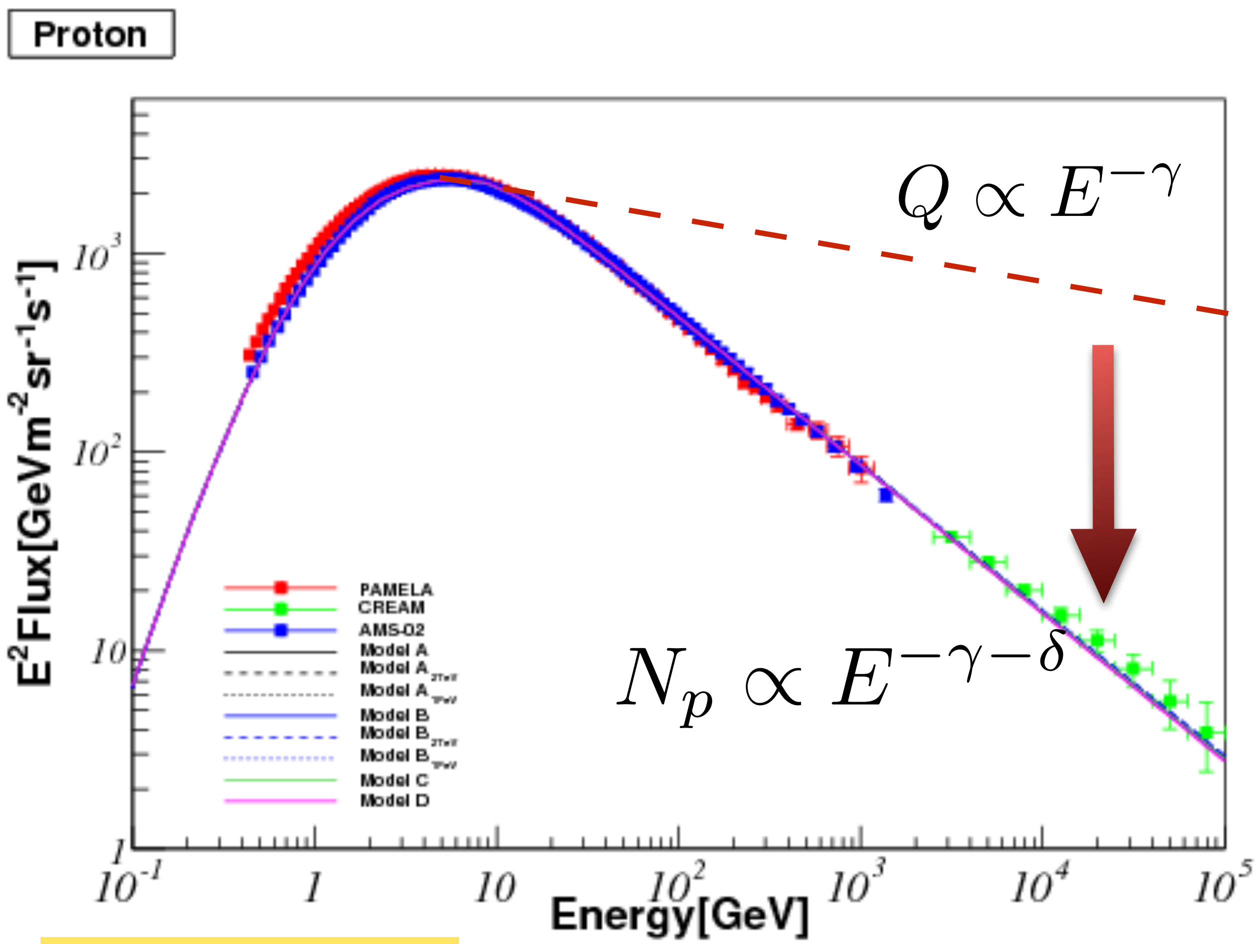
- *Rigidity-independent* advection, energy losses, etc.

$$\nabla \cdot (\vec{J}_i - \vec{v}_w N_i) + \frac{\partial}{\partial p}\left[p^2 D_{pp}\frac{\partial}{\partial p}\left(\frac{N_i}{p^2}\right)\right] - \frac{\partial}{\partial p}\left[\dot{p}N_i - \frac{p}{3}\left(\vec{\nabla}\cdot\vec{v}_w\right)N_i\right] =$$

$$Q + \sum_{i<j}\left(c\beta n_{\rm gas}\,\sigma_{j\to i} + \frac{1}{\gamma\tau_{j\to i}}\right)N_j - \left(c\beta n_{\rm gas}\,\sigma_i + \frac{1}{\gamma\tau_i}\right)N_i$$

$$J_i = -D_{ij}\nabla_j N \longrightarrow D = D_0\left(\frac{p}{p_0}\right)^{\delta}$$

Impact on primary spectra



AMS collaboration, proton spectrum

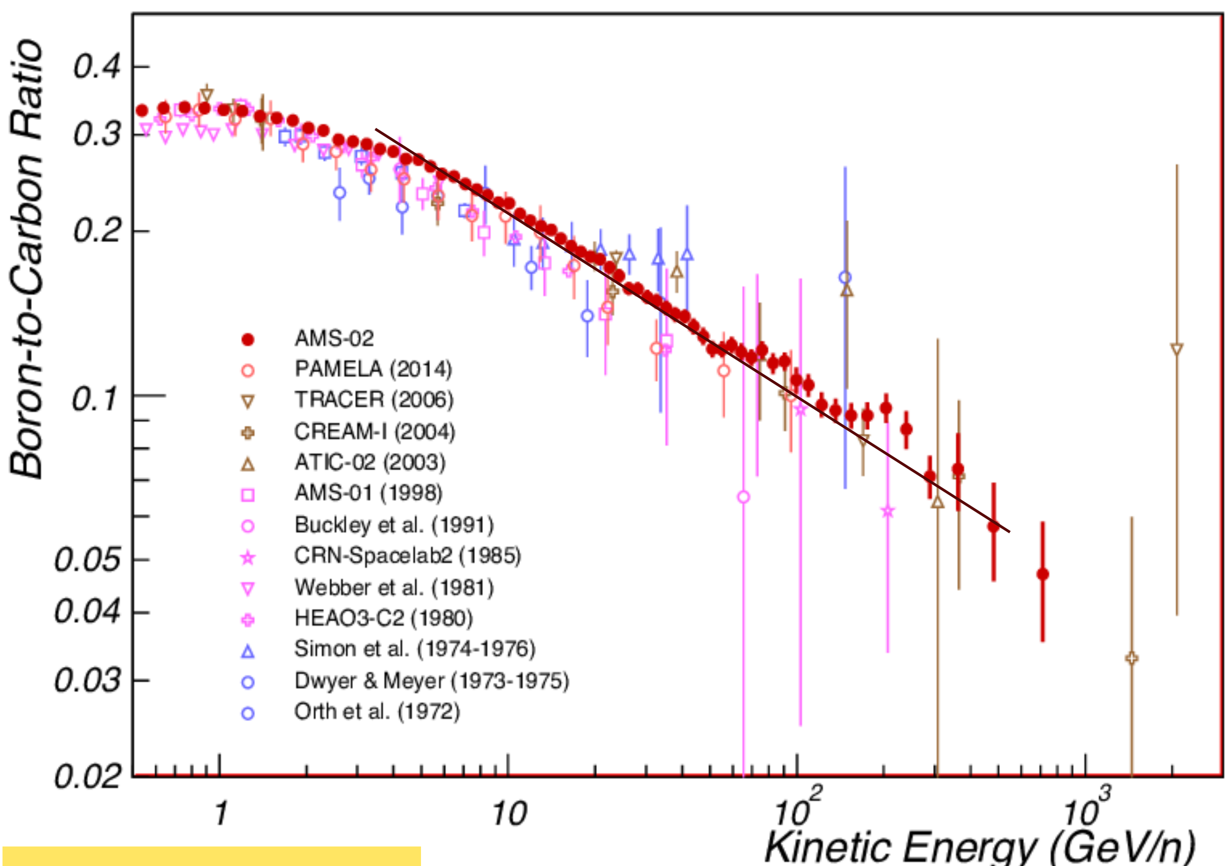
$$\frac{\partial N_p(p)}{\partial t} = 0 = Q_p(p) - \frac{N_p(p)}{\tau_{\rm esc}(p)}$$

$$Q_p = Q_0 \left(\frac{p}{p_0}\right)^{-\gamma}$$

$$\tau_{\rm esc}(p) = \frac{H^2}{D(p)} = \tau_0 \left(\frac{p}{p_0}\right)^{-\delta}$$

$$N_p(p) = \left(\frac{p}{p_0}\right)^{-\gamma-\delta}$$

Secondary-over-primary ratios



AMS collaboration,
B/C spectrum

$$\frac{\partial N_s(p)}{\partial t} = 0 = Q_s(p) - \frac{N_s(p)}{\tau_{\rm esc}(p)}$$

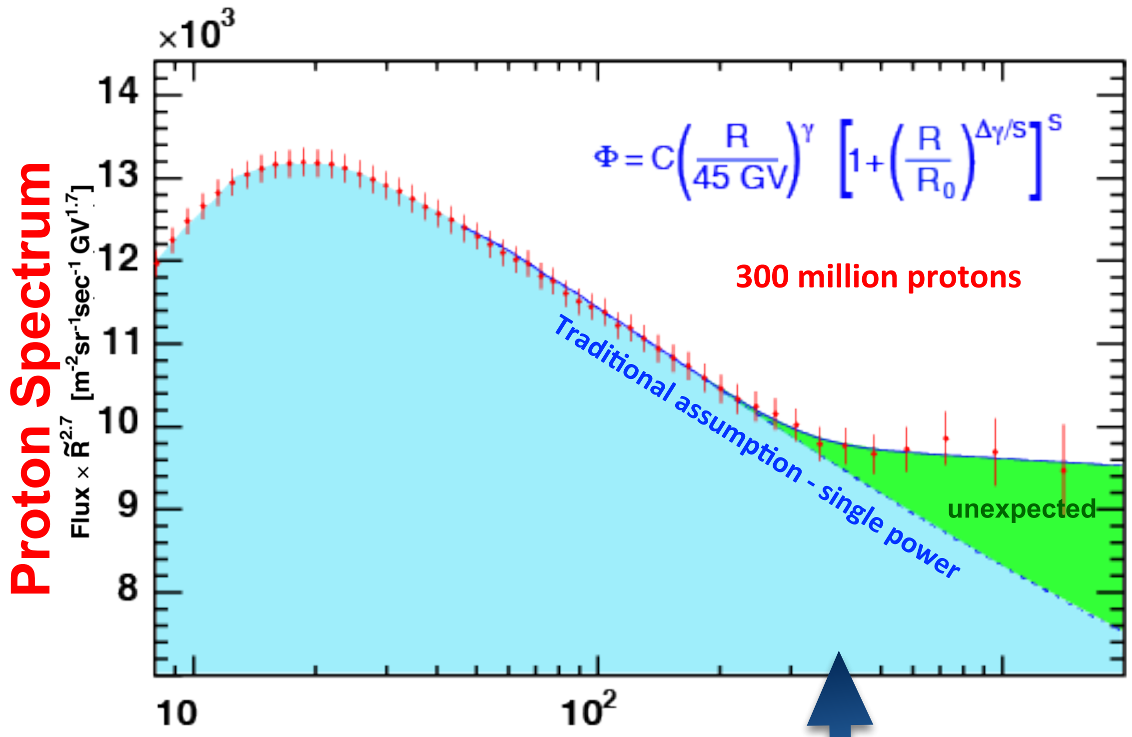
$$Q_s \propto N_p \sigma n_{\rm gas}$$

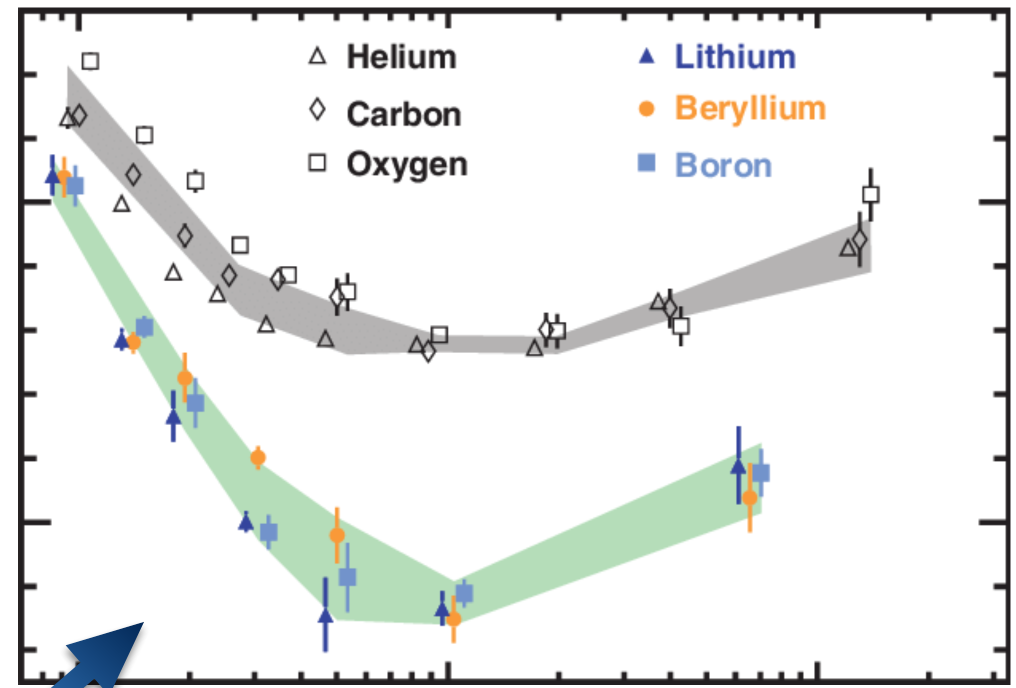
$$\tau_{\rm esc}(p) = \frac{H^2}{D(p)} = \tau_0 \left(\frac{p}{p_0}\right)^{-\delta}$$

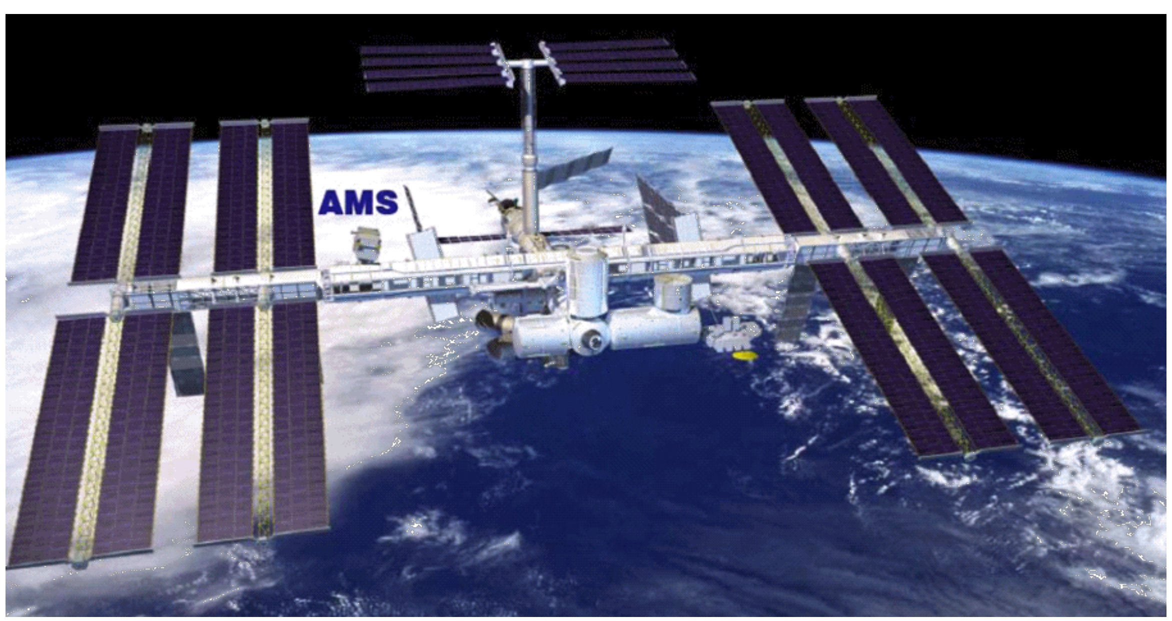
$$N_s(p) = N_p \sigma\, n_{\rm gas} \left(\frac{p}{p_0}\right)^{-\delta}$$

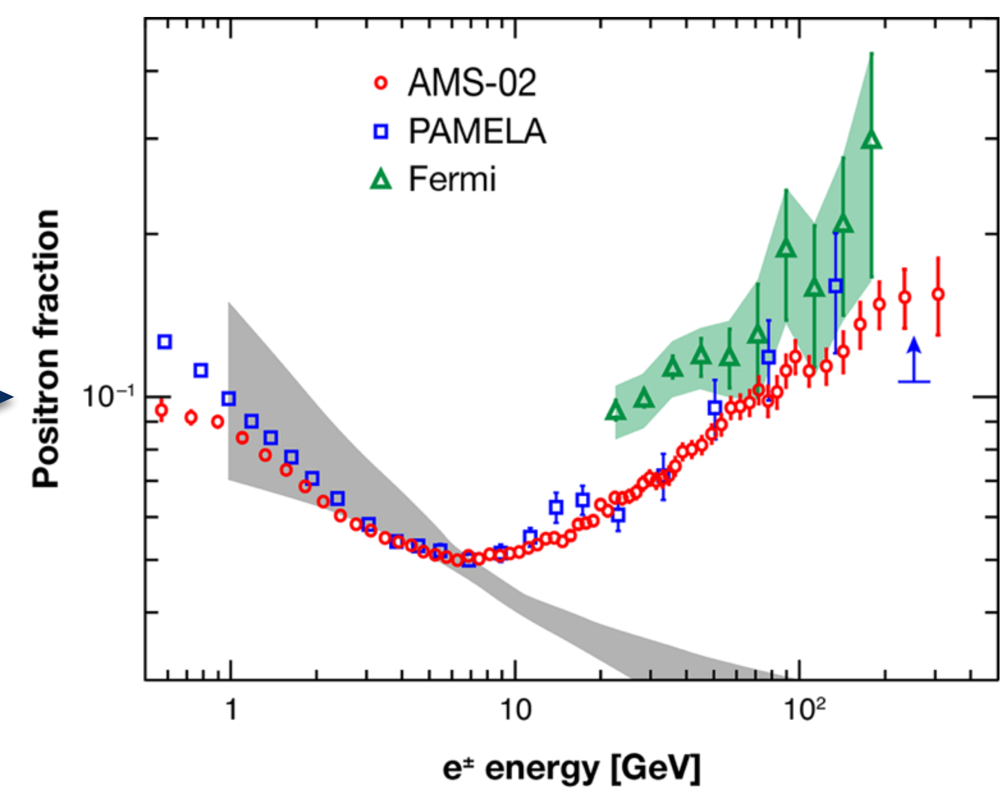
$$\frac{N_s}{N_p} = \sigma n_{\rm gas} \left(\frac{p}{p_0}\right)^{-\delta}$$

Anomalies in charged CR fluxes

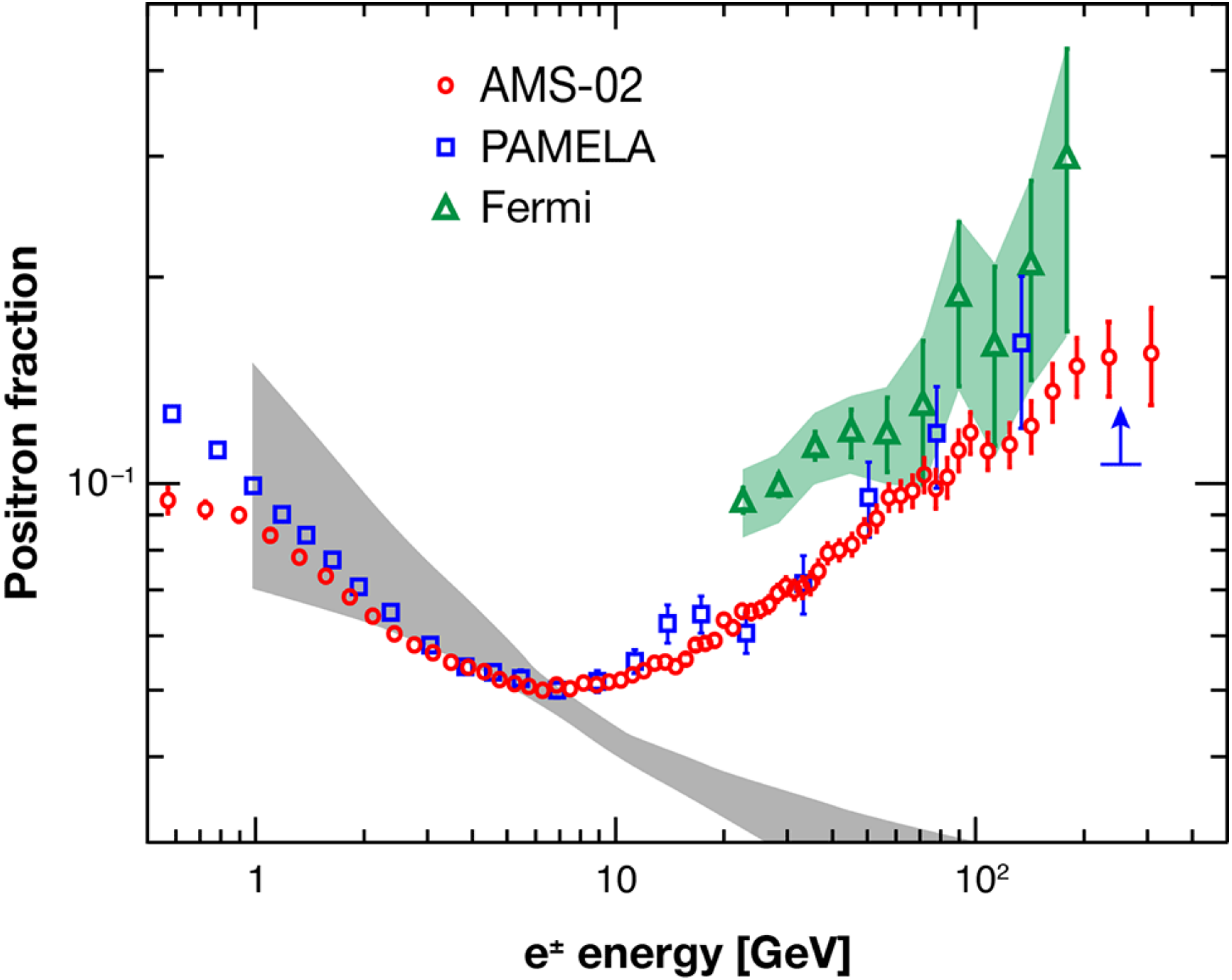






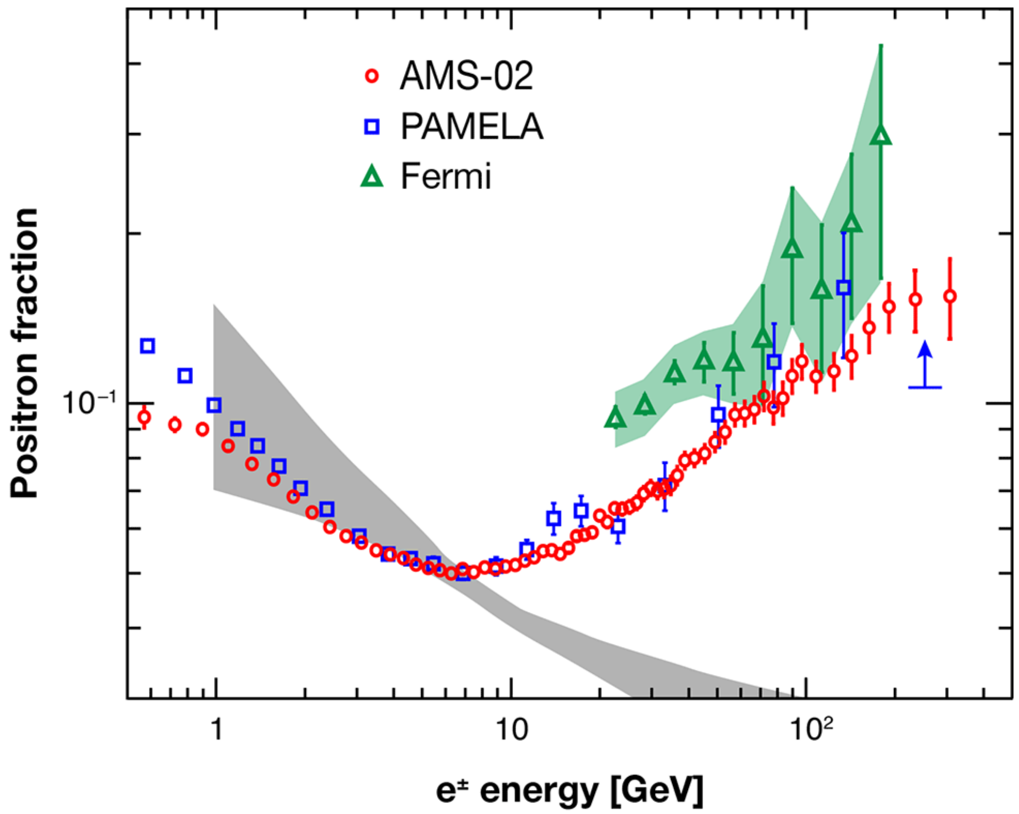


The positron anomaly



The positron anomaly

$$f(E) \equiv \frac{\Phi_{e^+}}{\Phi_{e^+} + \Phi_{e^-}}$$



- **Grey band:** expectations from the conventional scenario in which positron are secondary products of proton spallation, and therefore have a steeper spectrum

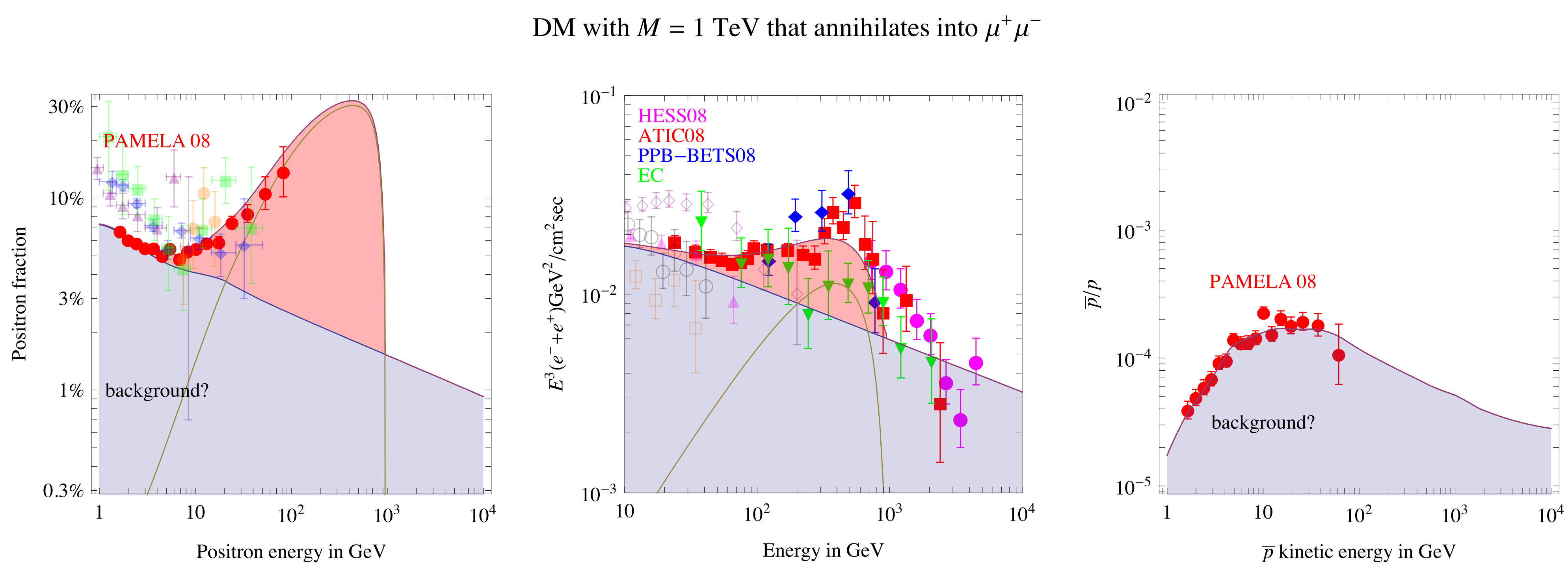
$$N_{e^+} \propto E^{(-\alpha_p - \delta) - \delta - l}$$

$$N_{e^-} \propto E^{(-\alpha_e) - \delta - l}$$

- **Data** suggest an extra *primary population* of positrons with hard spectrum!

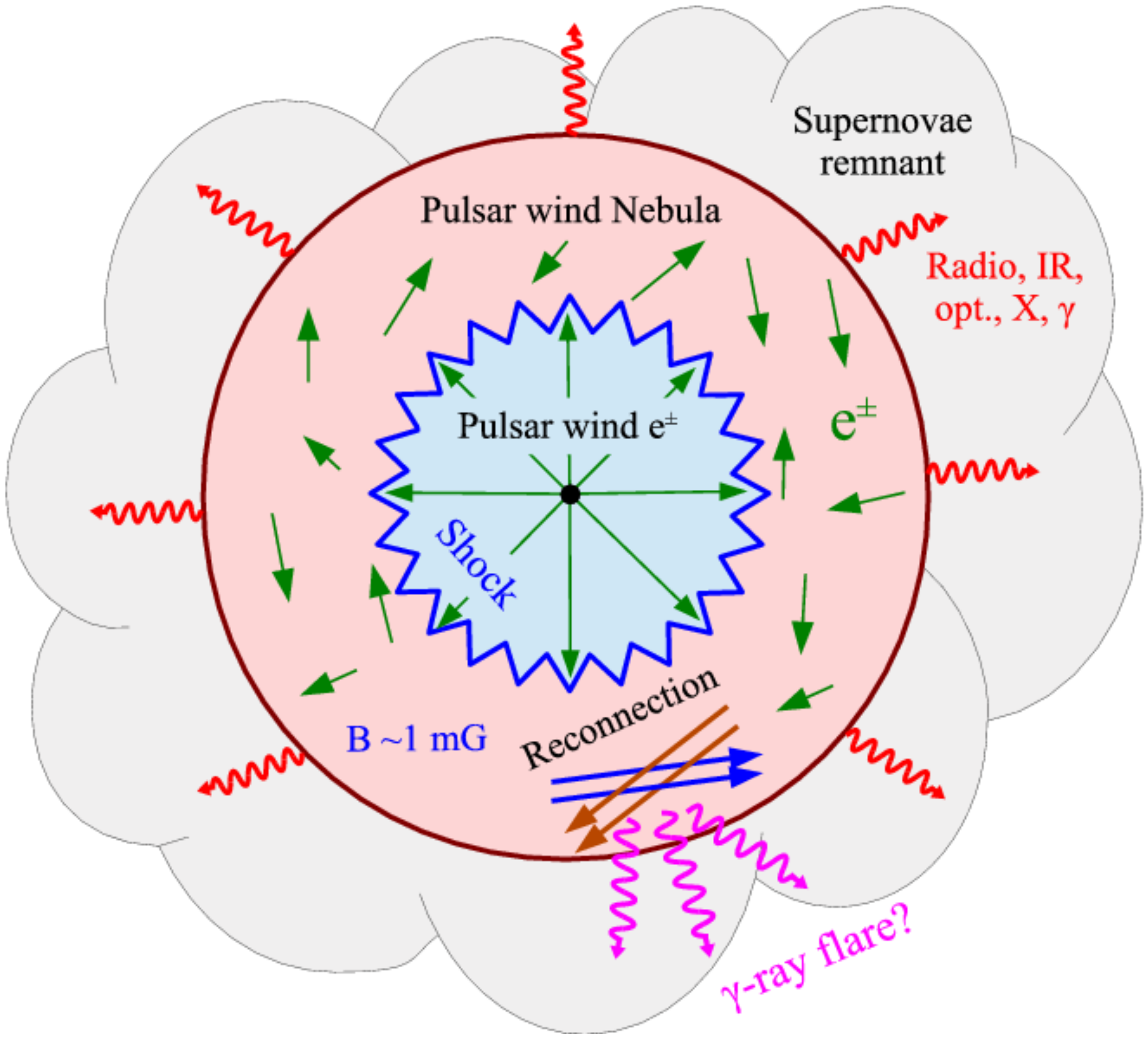
The positron anomaly: DM interpretations

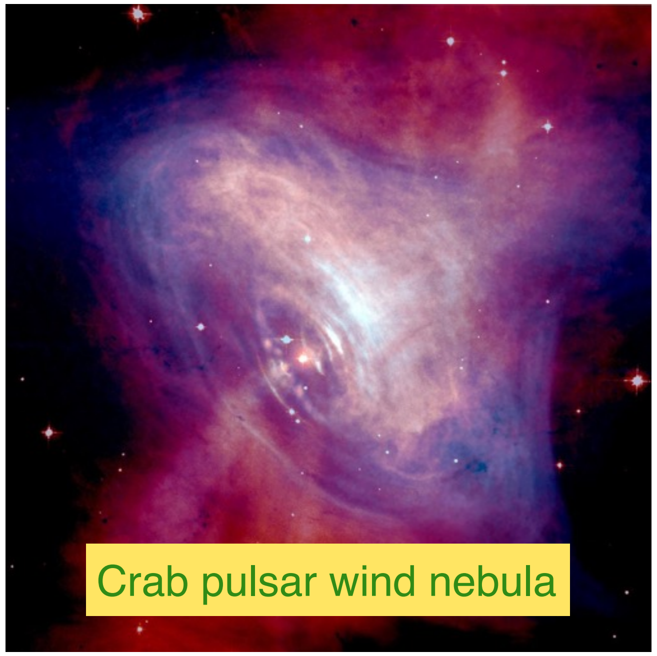
- Interpreting the positron excess as DM annihilation is challenging
- **Constraints** from other channels? [convince yourselves]
- Lepto-philic DM needed? [convince yourselves]
- **Large cross section** compared to the naive expectations (thermal relic freeze-out) [convince yourselves]



Cirelli et al. 0809.2409

The positron anomaly: Astrophysical interpretations





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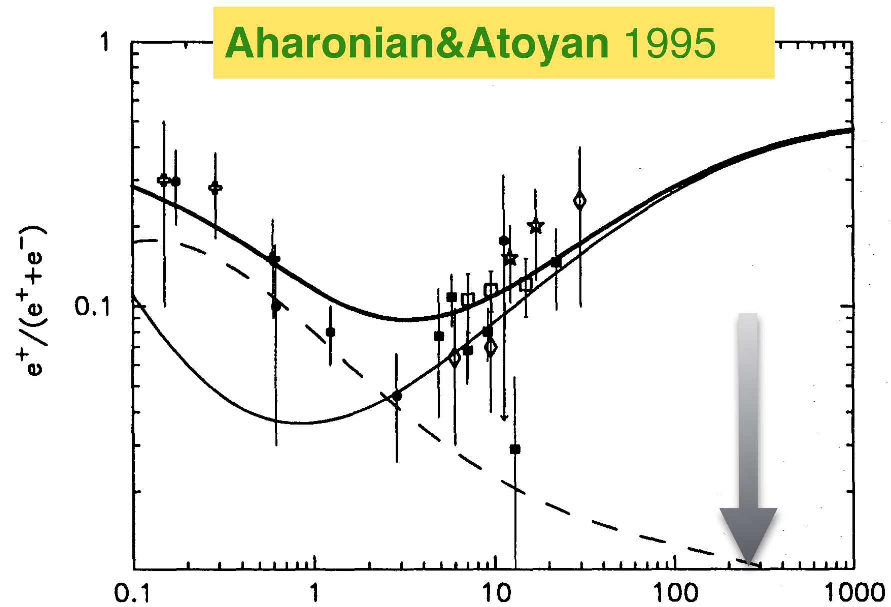
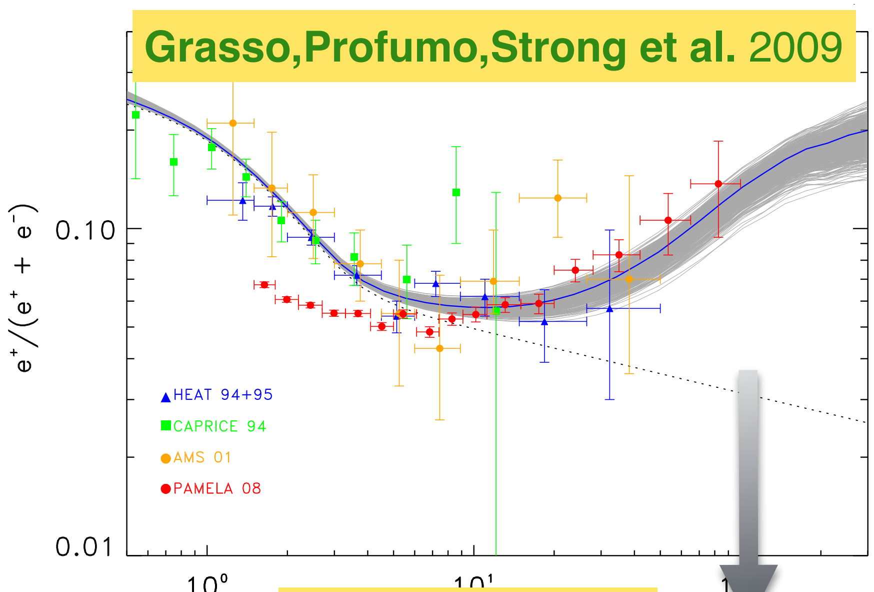
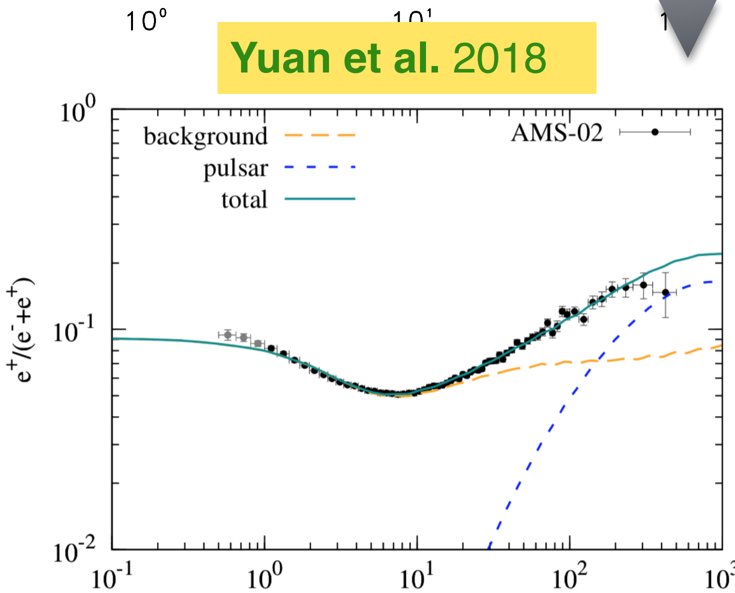
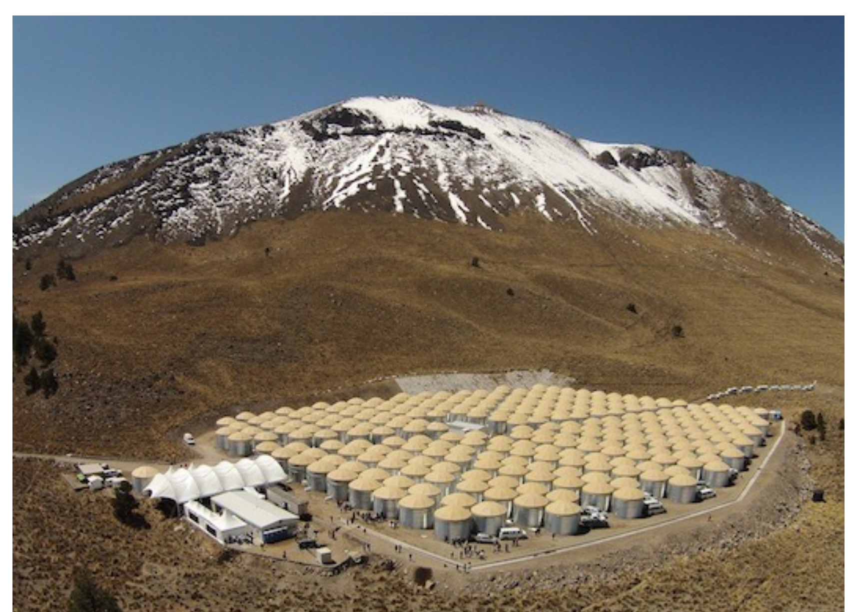
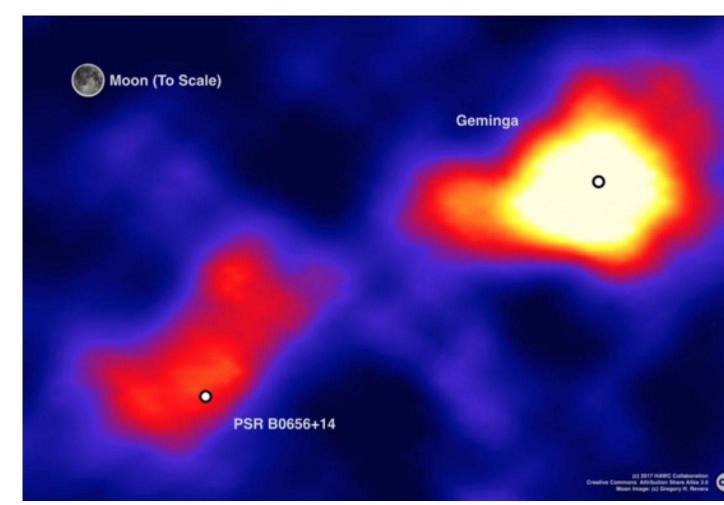






- Pulsars can accelerate electron+positron pairs with hard spectrum
- A natural explanation of the excess, already discussed in the 1990s before accurate data from PAMELA and AMS
- Recently, the HAWC collaboration has detected TeV IC emission around Geminga: possible signature of *freshly accelerated leptons escaping the pulsar*



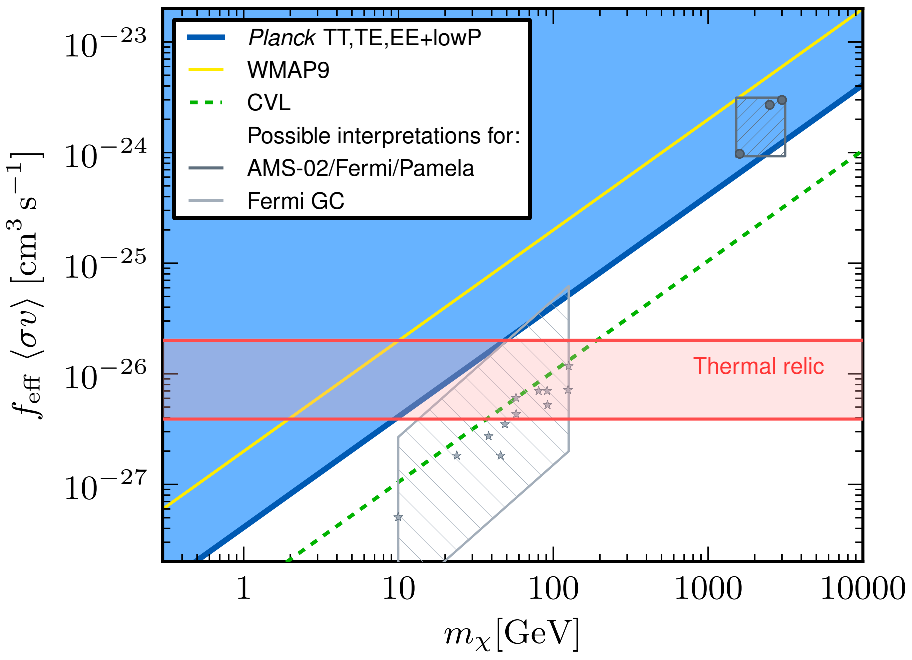


The positron anomaly: Discussion

- Pros and cons of the **pulsar scenario** VS **DM scenario** [see e.g. arXiv:0810.4846, arXiv:0905.0636] [*review* arXiv:1802.00636]

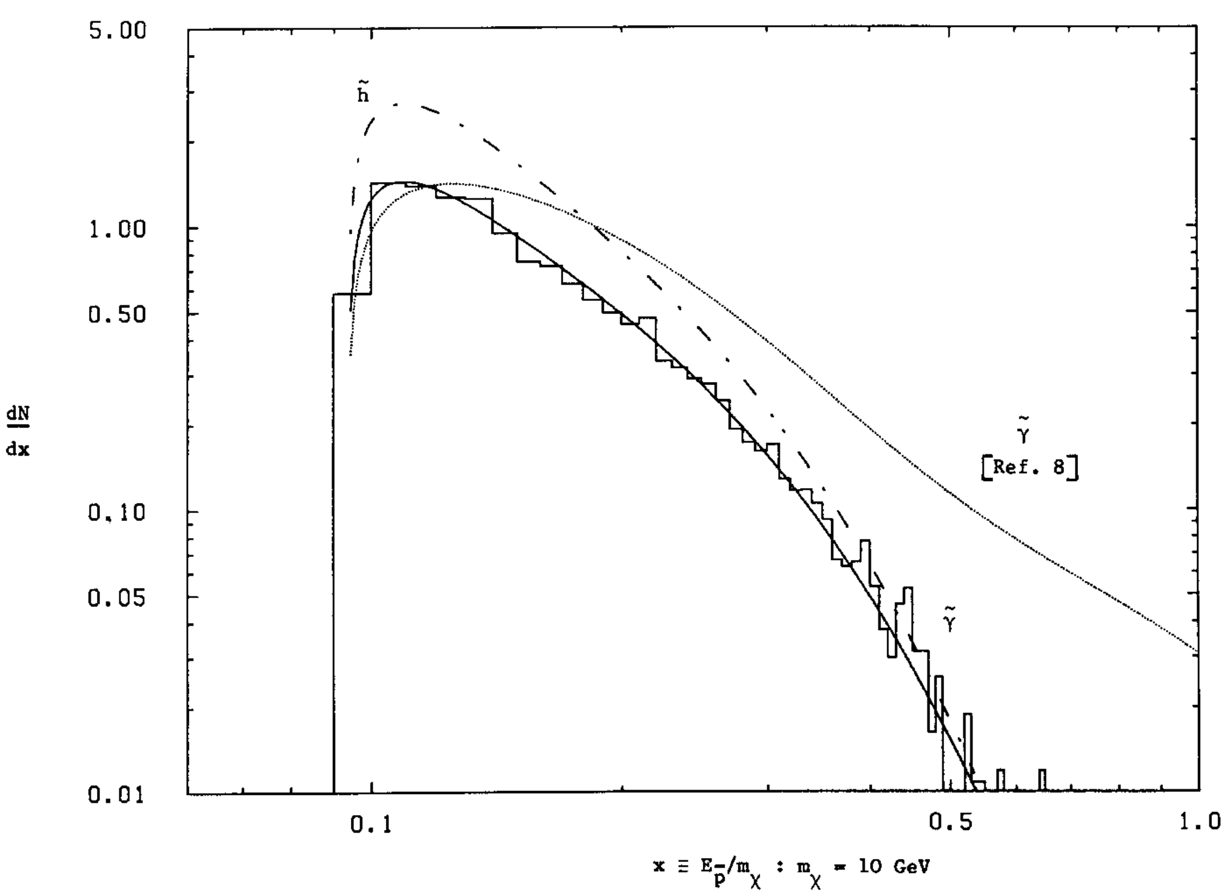
- Other possible interpretations of the excess? [arXiv:0903.2794]

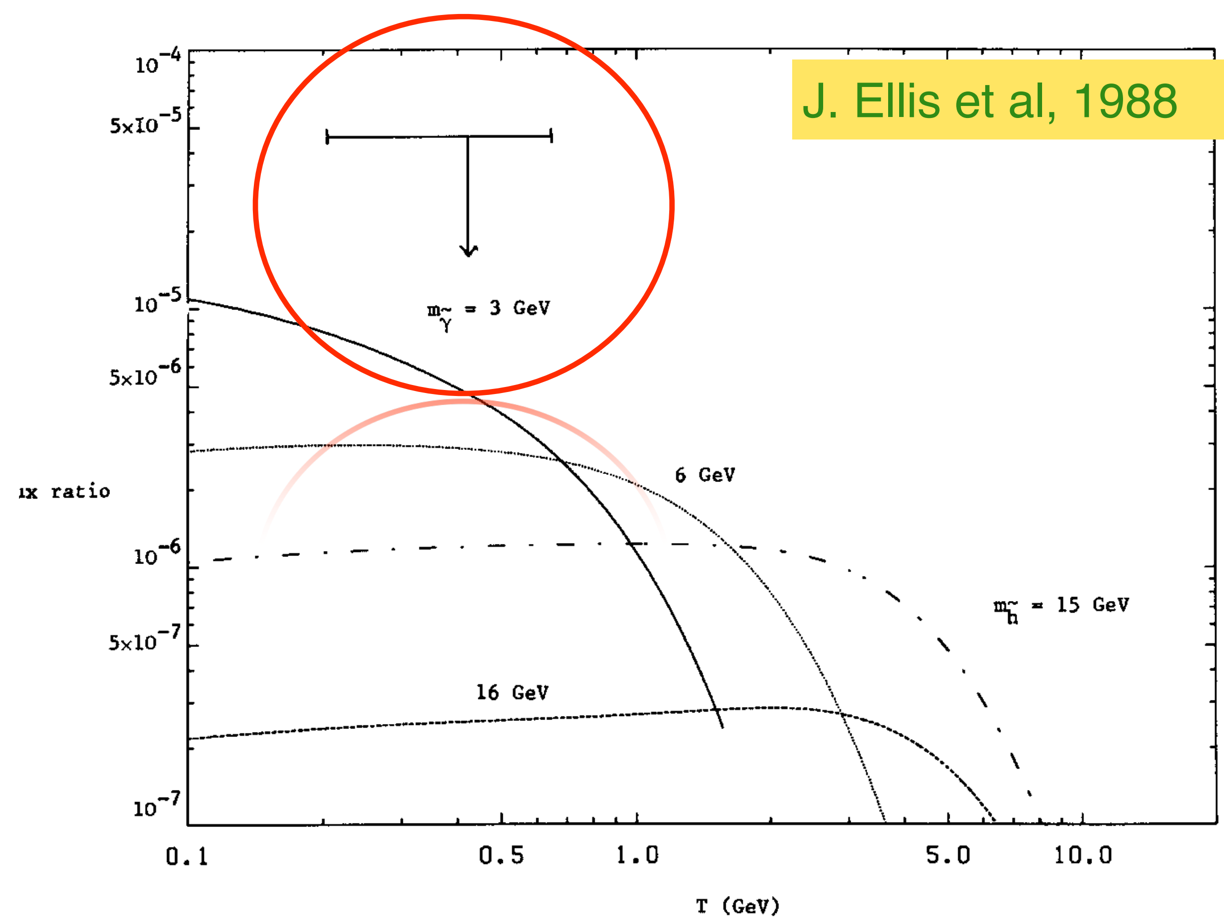
- CMB constraints on DM scenario? [arXiv:1502.01589]



The antiproton channel

- The idea of detecting *secondary antiprotons from DM annihilation* was put forward in pioneering papers already in the 1980s
- However, data were not constraining at all at the time, due to small fluxes and low statistics of the experiments.

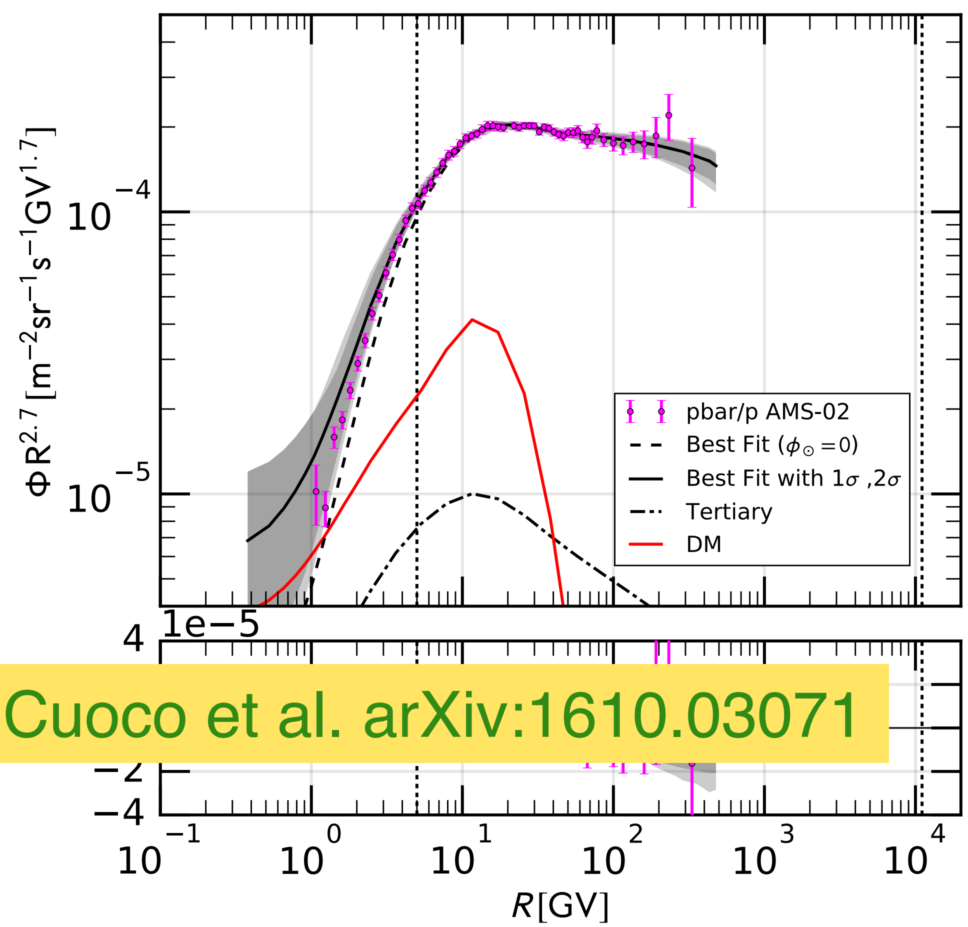




J. Ellis et al, 1988

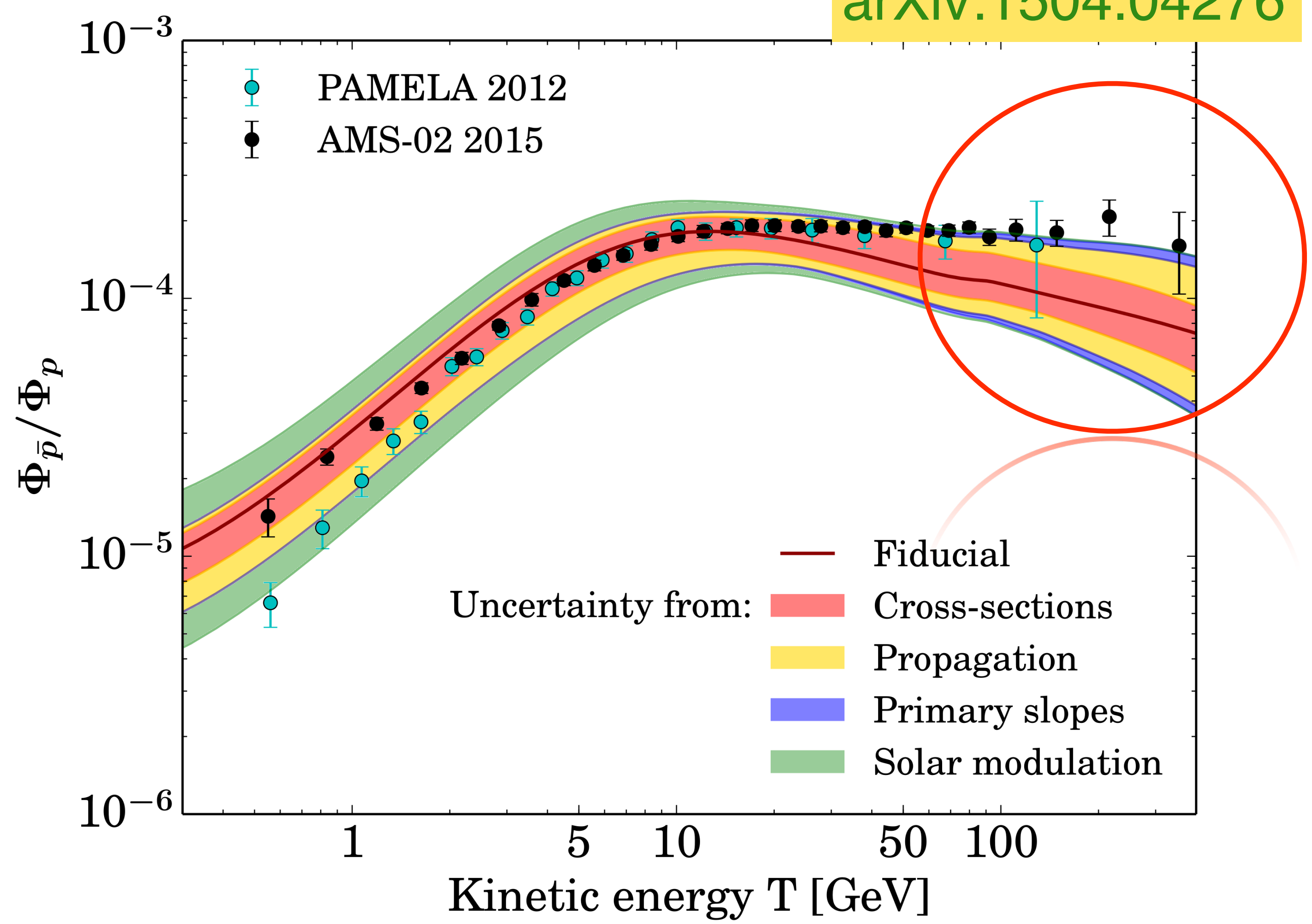
The antiproton channel: Current status

- Nowadays, AMS is providing extremely accurate data up to ~300 GeV
- No striking evidence of anomalies
- Small 2σ hint of excess above 100 GeV
- Extra contribution at low energy currently under debate



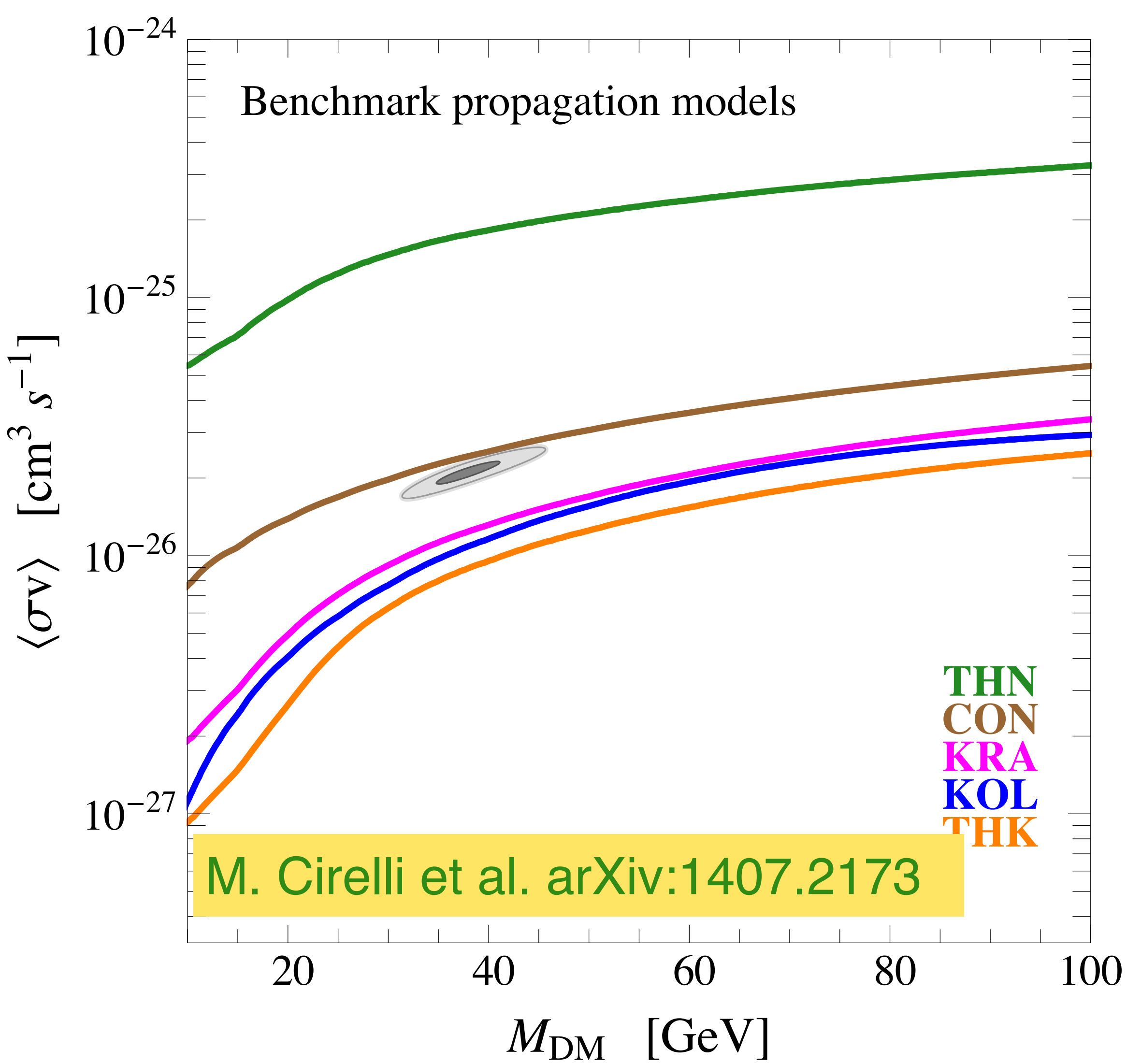
A. Cuoco et al. arXiv:1610.03071

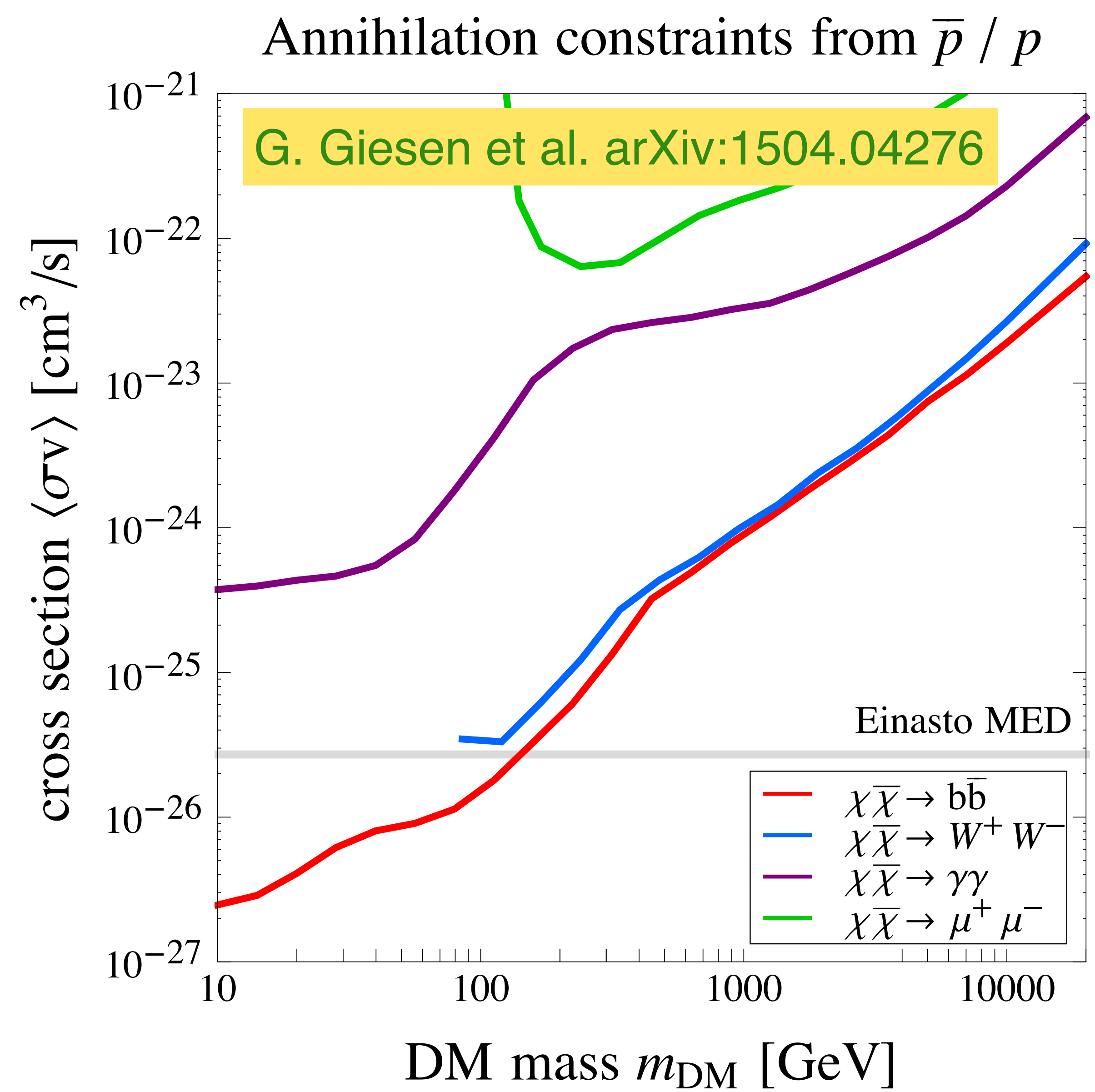
G. Giesen et al. arXiv:1504.04276



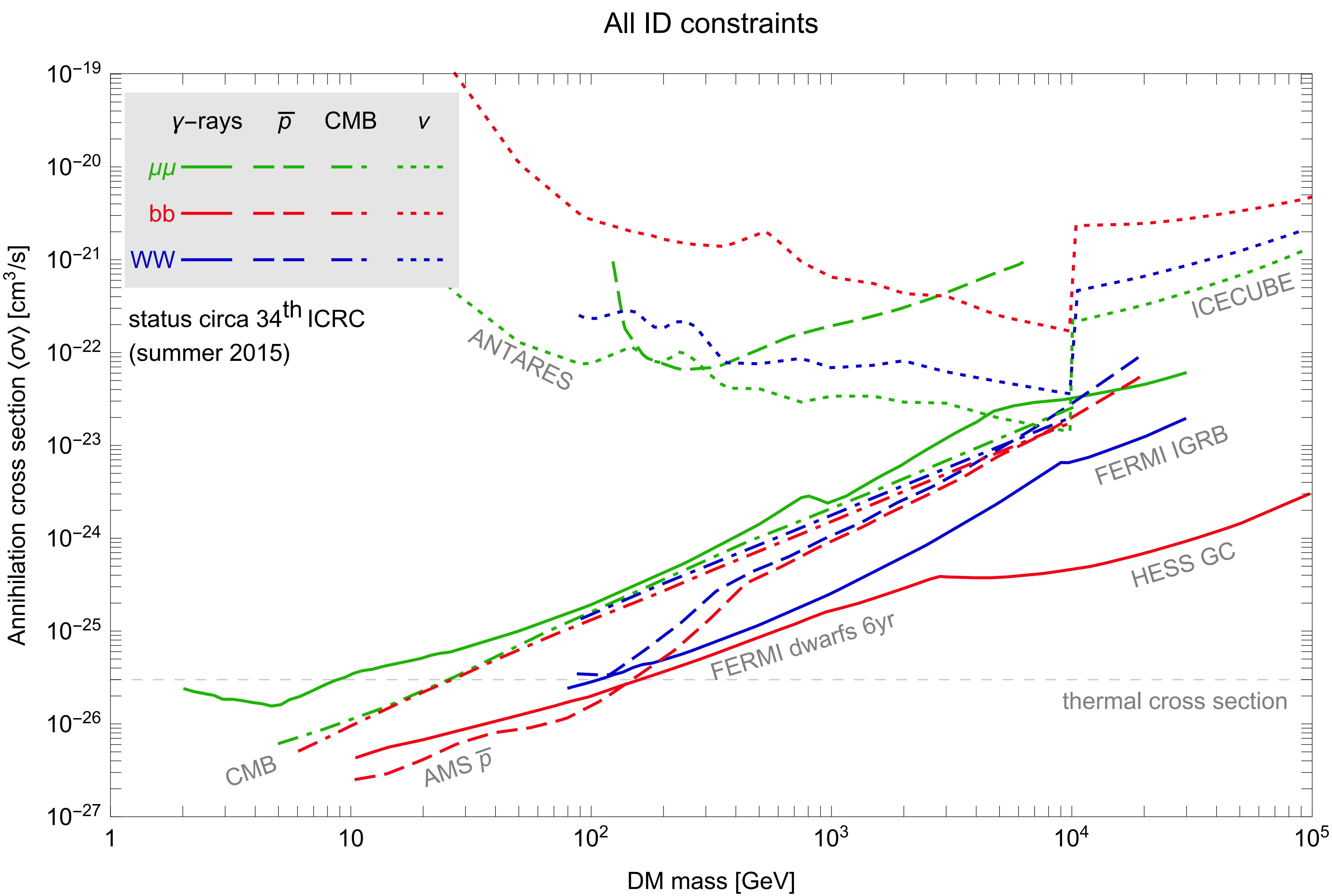
The antiproton channel: Constraints

- Given the high statistics, antiprotons provide stringent constraints on the WIMP annihilation cross section.



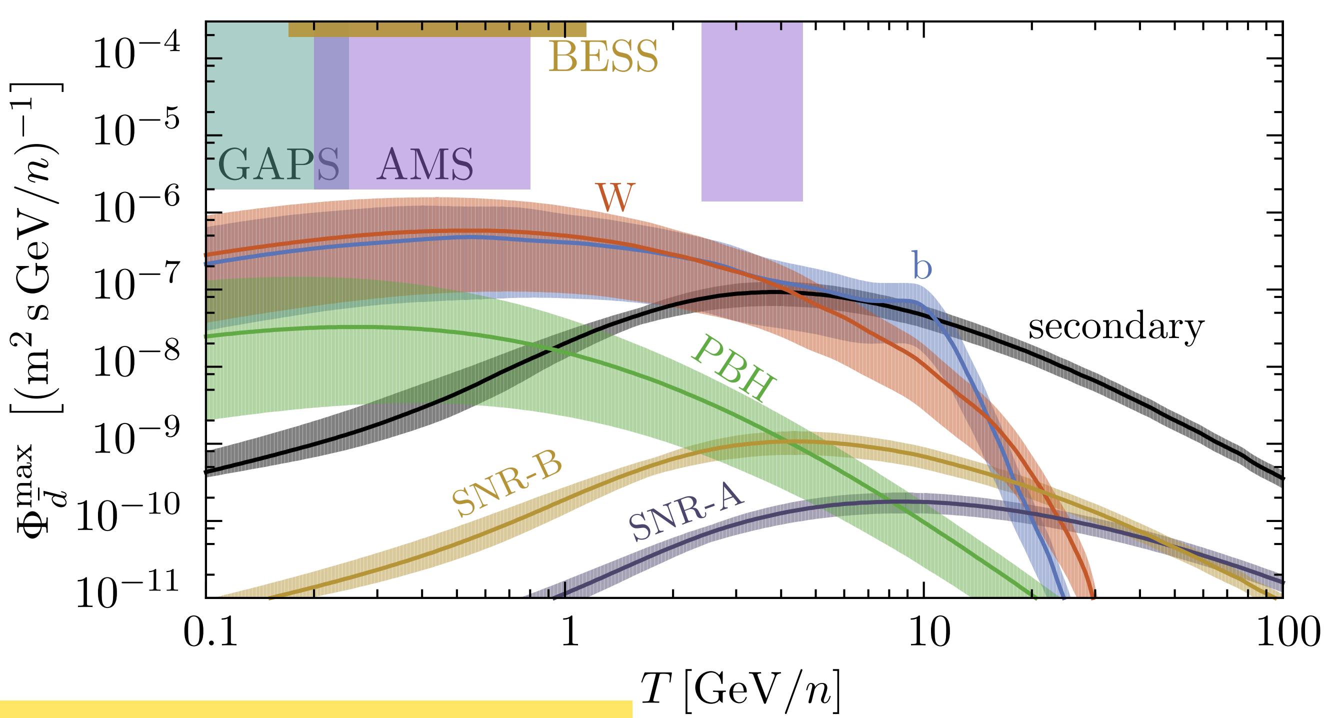


Indirect detection constraints: A comparison

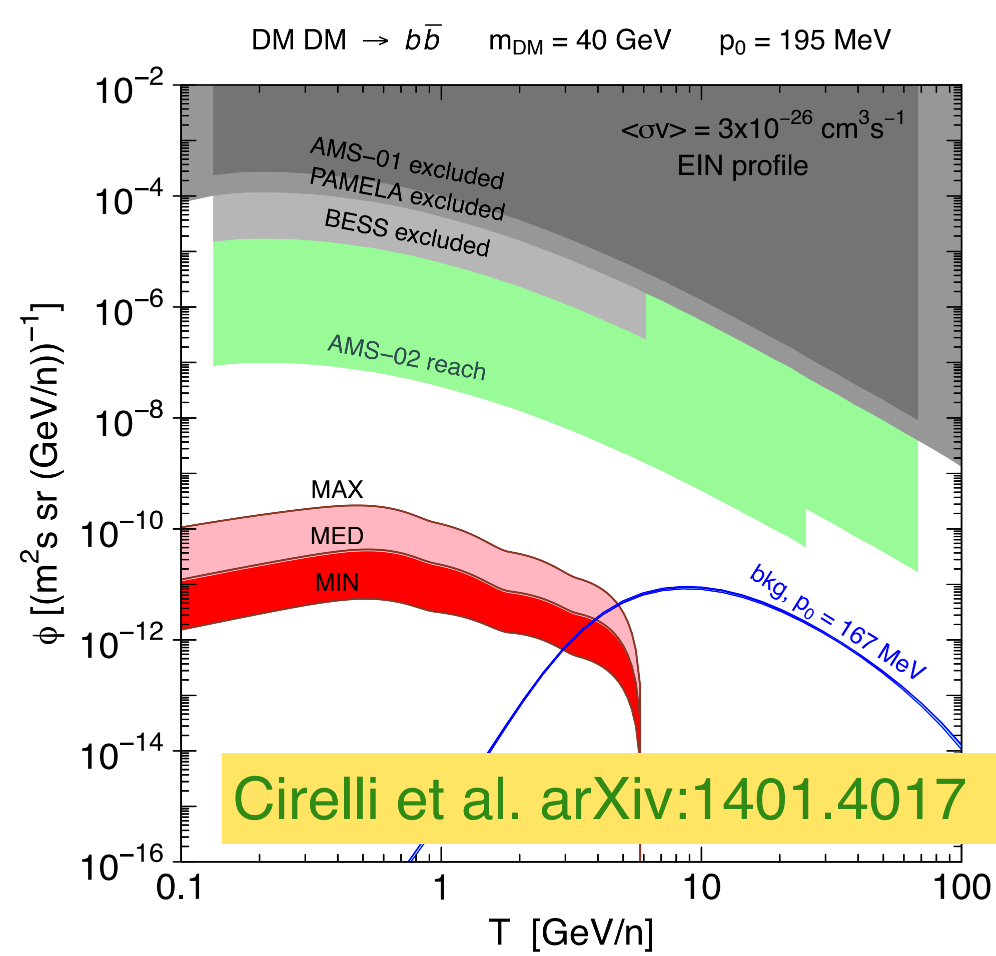


Antinuclei

- Antideuteron and anti-helium can be produced by DM annihilation and CR spallation
- Due to the large threshold for production via spallation, signal and background are better separated in energy
- However, fluxes are very low: Measurement is very challenging



Herms et al. arXiv: 1610.00699



Cirelli et al. arXiv:1401.4017

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[Hui, Ostriker, Tremaine, Witten 2016]

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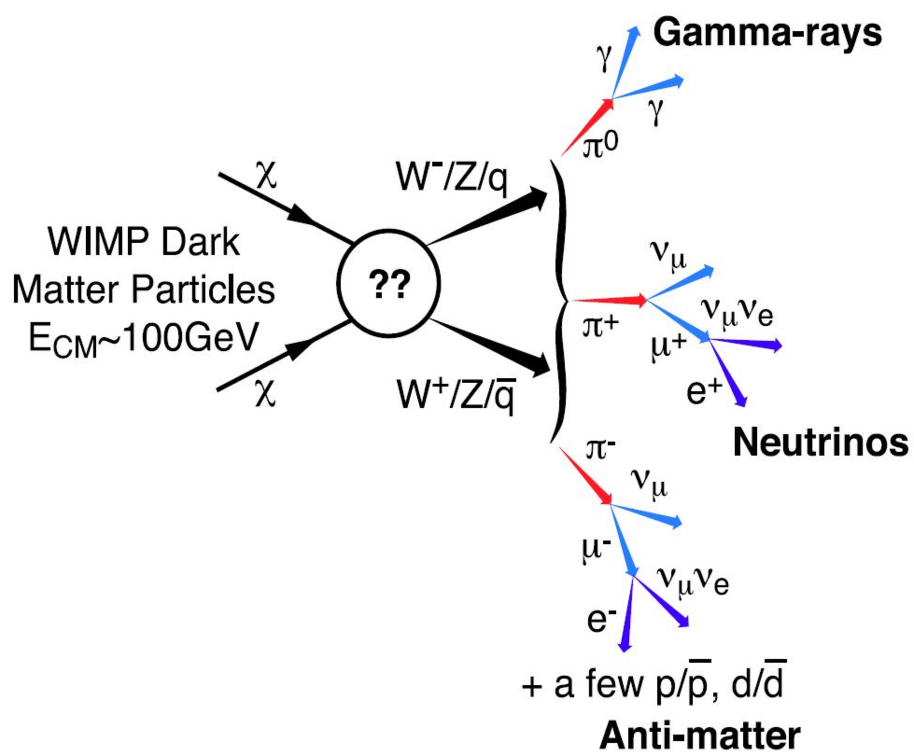

Primordial black holes (PBHs)

[Zeld'ovich and Novikov 1966, Hawking 1971]

many constraints from lensing, wide binaries, Galactic disk stability

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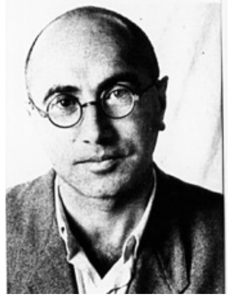
Primordial black hole basics



- Primordial black holes first proposed by Zel'dovich and Novikov [*Y. B. Zel'dovich and I. D. Novikov, Soviet Astronomy 10, 602 (1967)*]

- Hawking proposed that early-Universe density fluctuations could lead to the formation of PBHs with masses *down to the Planck mass* [*S. Hawking*, Mon. Not. R. Astron. Soc. 152, 75 (1971); *Carr and Hawking*, MNRAS 168 (1974)]

density:
$$\rho_S = 10^{18} \left(\frac{M}{M_\odot}\right)^{-2} \frac{\mathrm{g}}{\mathrm{cm}^3}$$

compare to early-Universe density:
$$\rho_C = 10^{6} \left(\frac{t}{\mathrm{s}}\right)^{-2} \frac{\mathrm{g}}{\mathrm{cm}^3}$$

- **The early universe (t < 1 s) is an ideal environment for black hole formation:** The Jeans length scale and the Schwarzschild length scale are comparable

- **Black holes of primordial origin can form from large-amplitude small-scale density fluctuations produced during inflation**
[*Garcia-Bellido, Linde, Wands PRD 1996; Sasaki, Suyama, Tanaka, Yokoyama 2018*]

Primordial black hole basics

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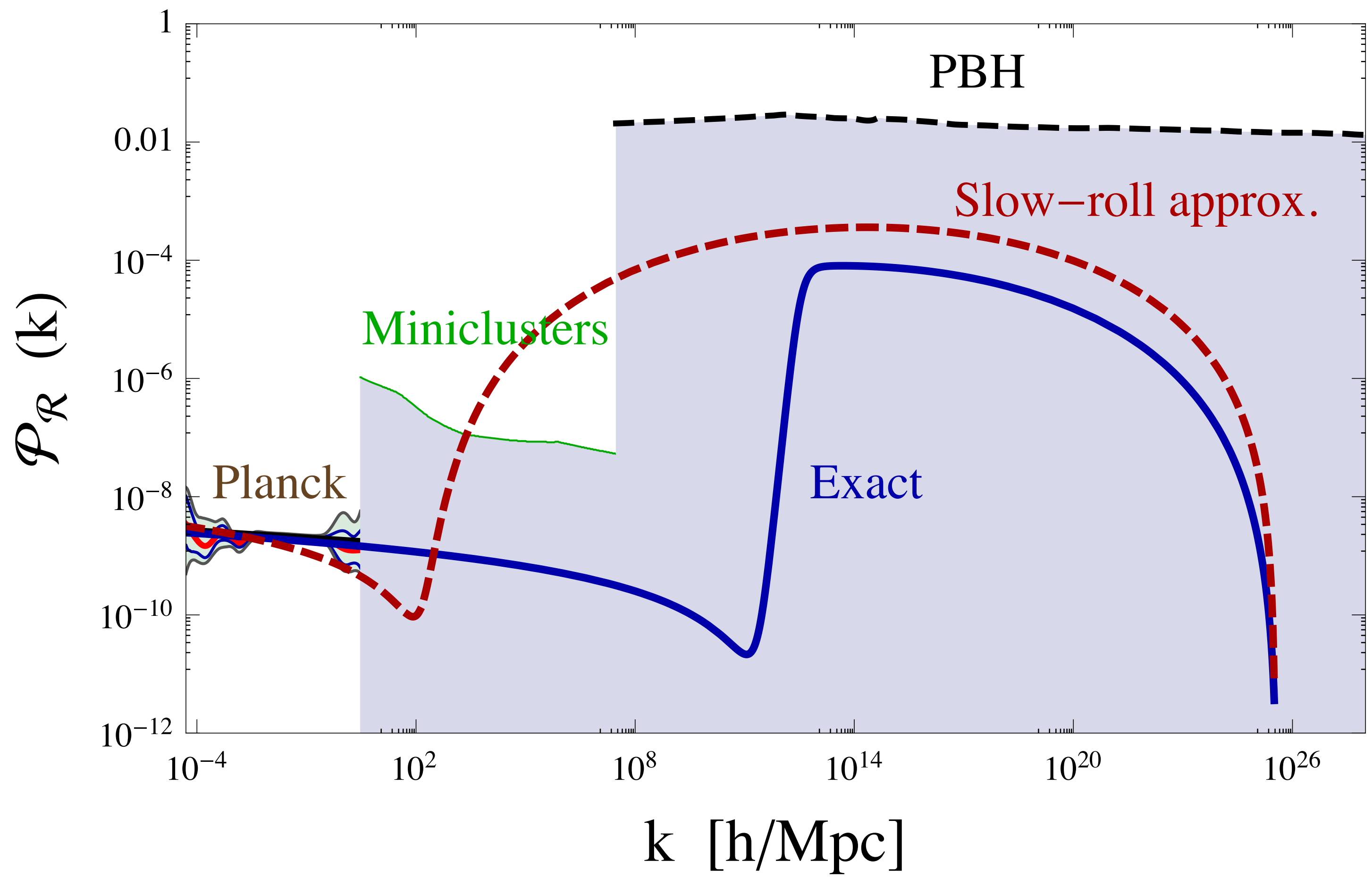


Primordial black holes as DM candidate

In general, **PBHs can span an extremely large mass range**

- collapse at Planck time (10^{-43} s) -> Planck mass (10^{-5} g),
- collapse at ~1 s -> $10^5\ M_\odot$

If the mass is too low, the PBHs have enough time to evaporate (Hawking-Bekenstein radiation)

$$t_{\mathrm{evaporation}}[\mathrm{s}] = 10^{71}\left(\frac{M}{M_\odot}\right)^3$$

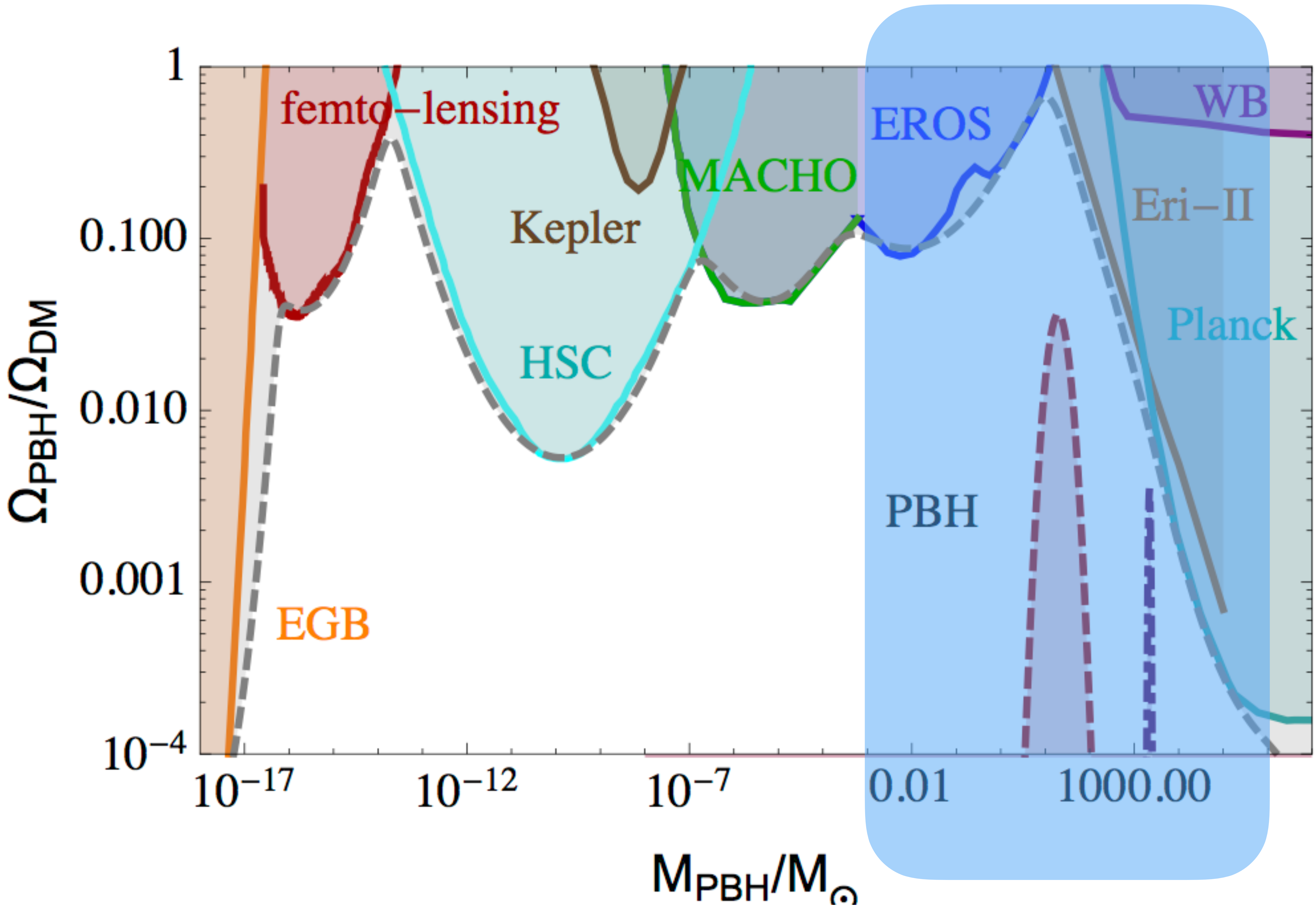
- Chapline was among the first to suggest PBHs as a DM candidate [G. F. Chapline, Nature **253**, 251 (1975)]

- **Typical ranges** for a PBH as DM candidate:

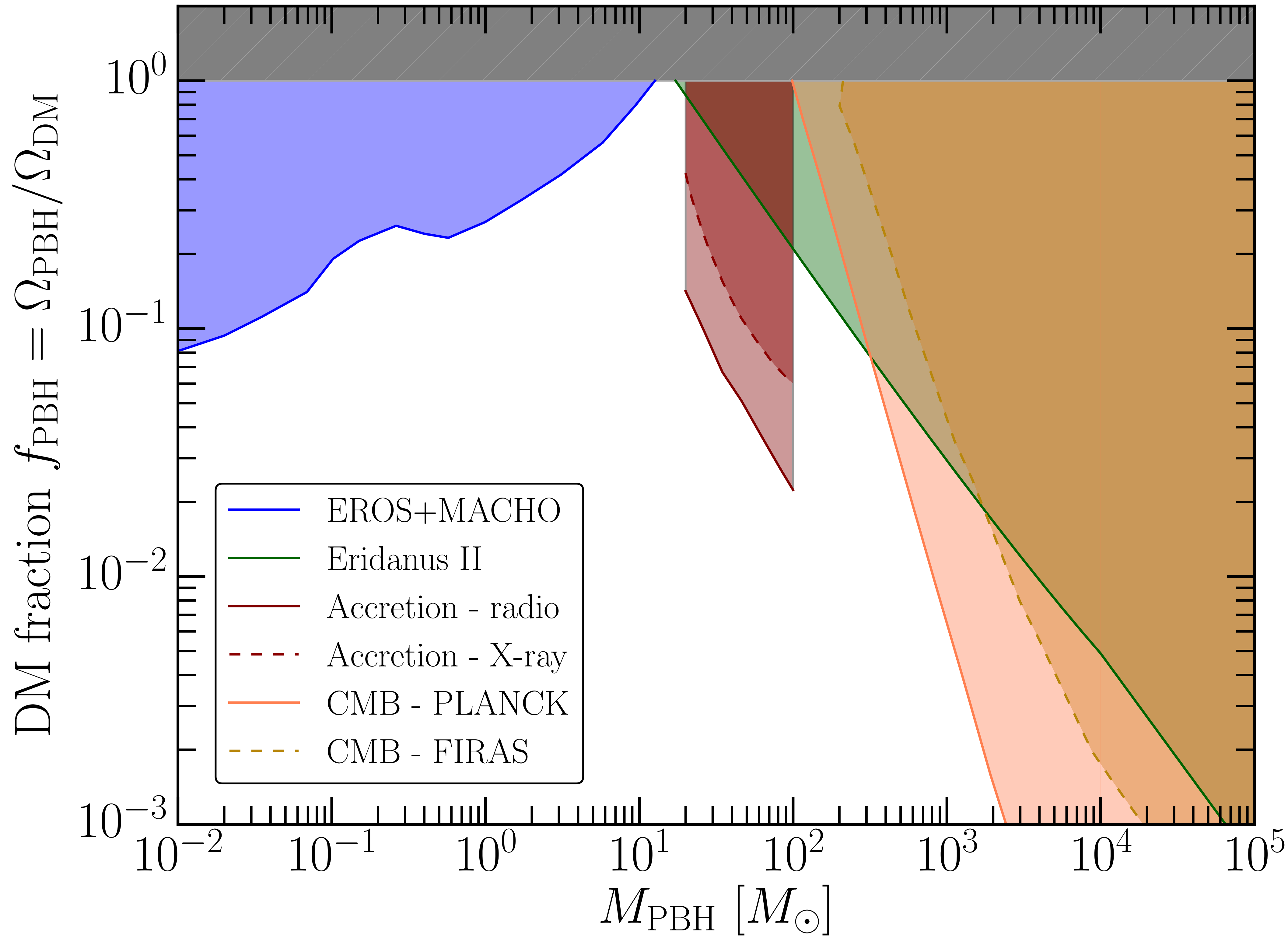
M ~ 10^{16} g ($10^{-17}\ M_\odot$) — 10^{39} g ($10^5\ M_\odot$)
Size ~ 10^{-13} cm — 10^{10} cm
Number in our Galaxy ~ 10^{29} — 10^6

Looking for PBHs

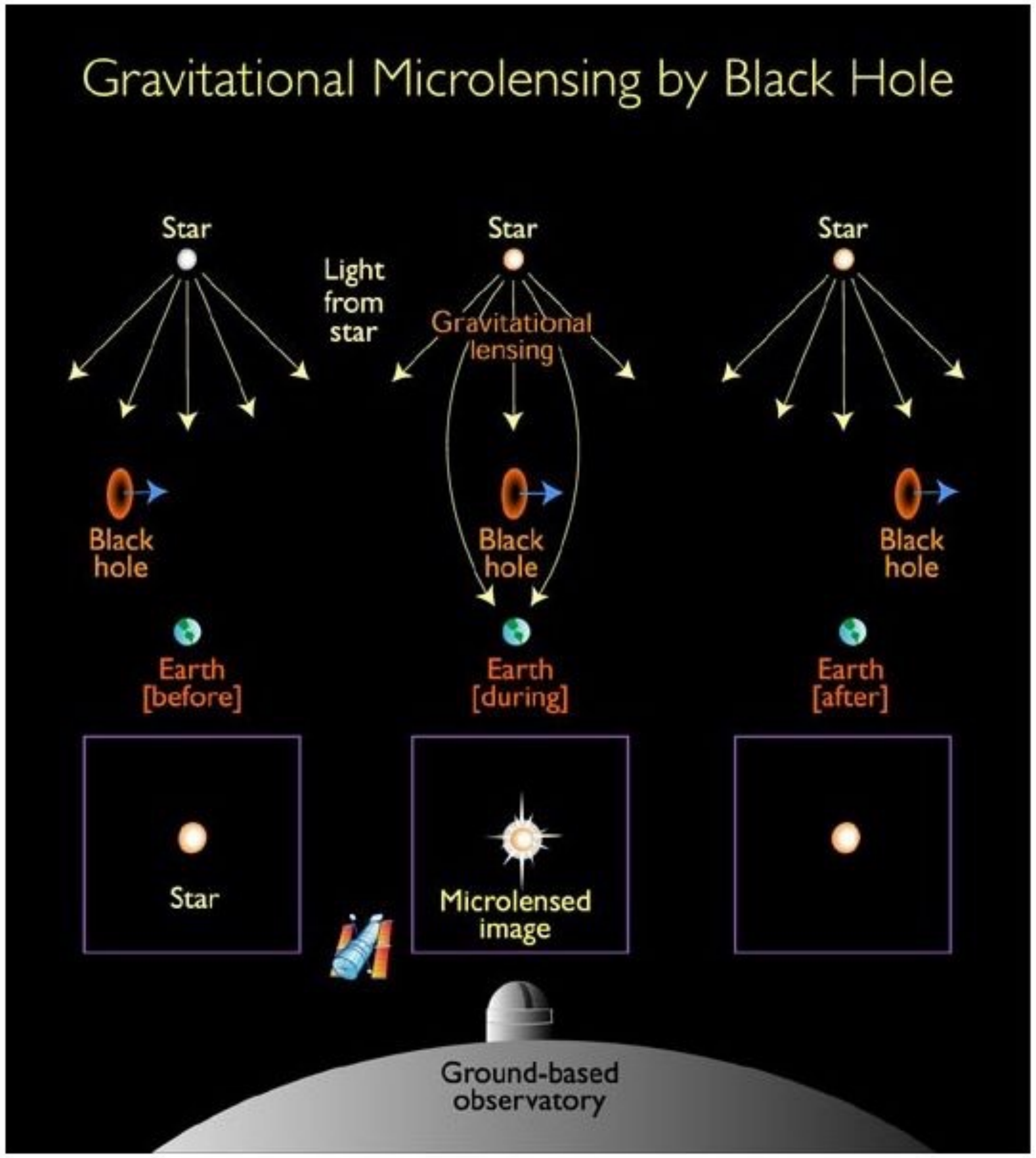
Looking for PBHs: Current constraints



Looking for PBHs: Current constraints: A zoom



Looking for PBHs: Lensing (10^{-17} — 10 M_{Sun})

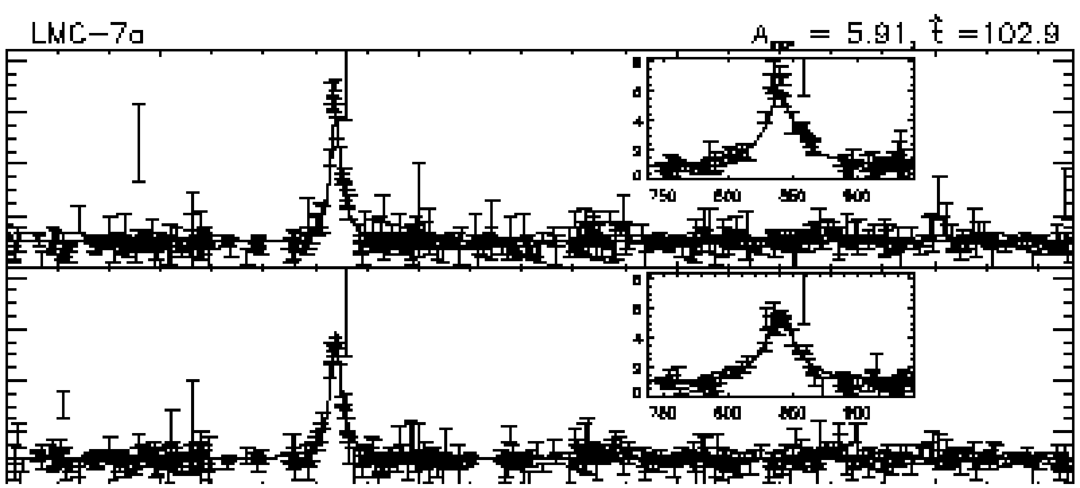


Looking for PBHs: Lensing (10^{-17} — $10\ M_{Sun}$)

- Femto-lensing [*arXiv:1204.2056*] —> Search for events towards GRBs. Schwarzchild radius ~ Photon wavelength: Mass range 10^{-17} - $10^{-10}\ M_{Sun}$

- MACHO project [arXiv:0001272] —> Optical search for micro-lensing events towards the Large Magellanic Cloud: 13-17 short-duration events reported
- No long-duration (> 150 days) events: Constraints up to 30 Msun.

- Hints from Andromeda [arXiv:1711.10458]? This channel offers opportunity of detection!



Looking for PBHs: Radio / X-ray (1 — 1000 M_{Sun})

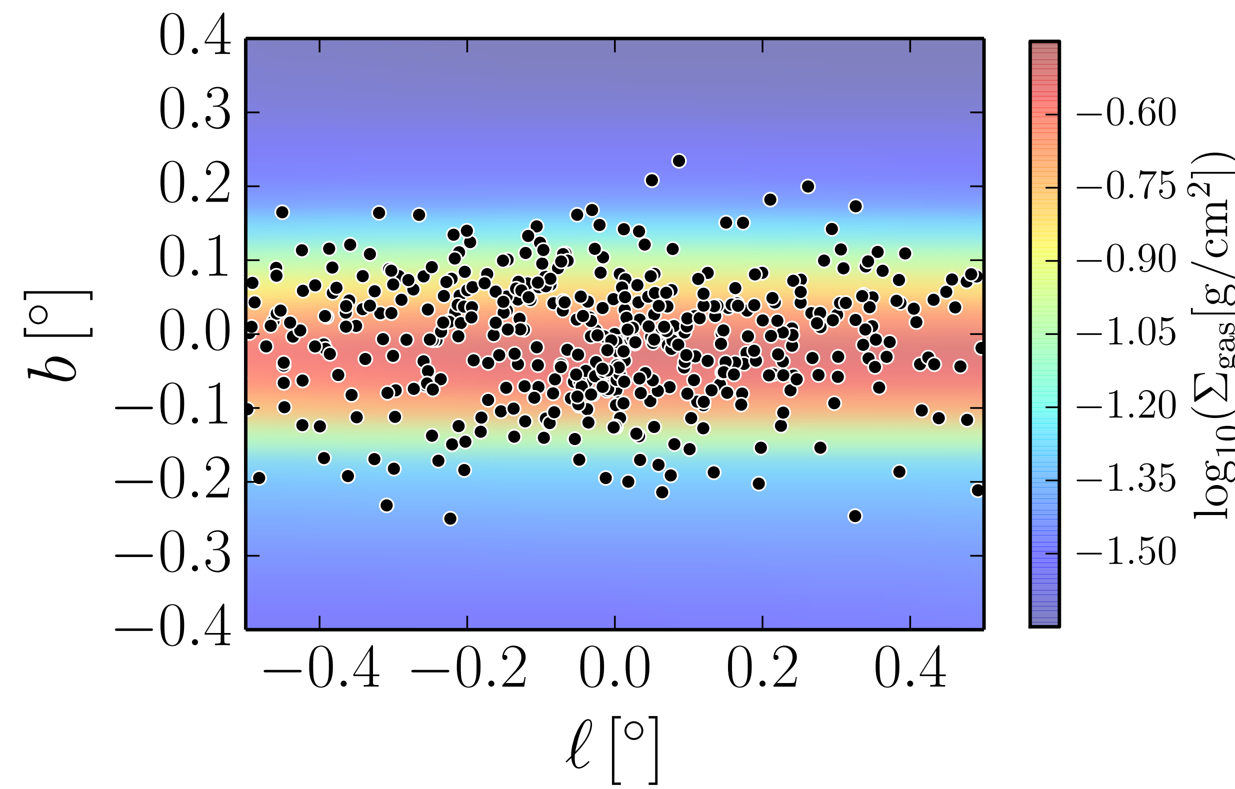
- If ~10$M_\odot$ PBHs are the DM —> **~10^{11} objects of this kind in the Milky Way, and ~10^8 in the Galactic bulge**.

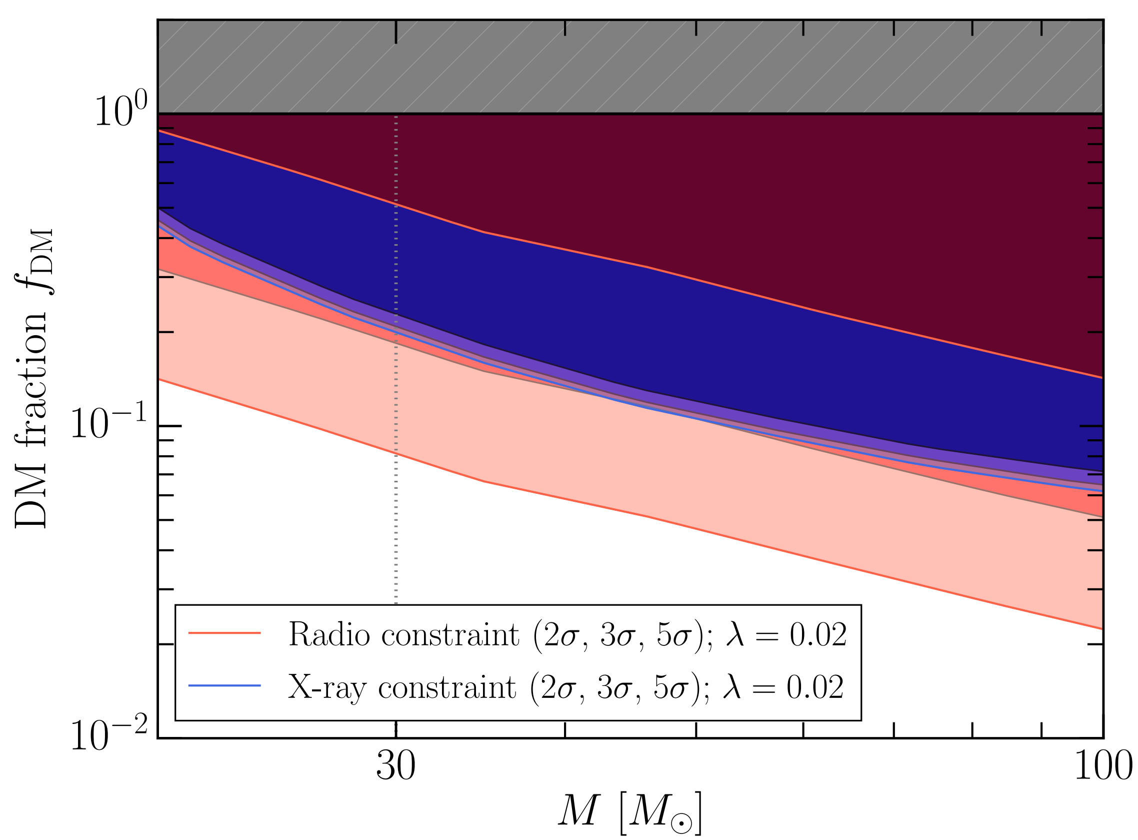
  compare to ~10^8 astrophysical stellar-mass black holes in our Galaxy [Fender et al. arXiv:1301.1341]

- A portion of them is expected to accrete gas in the interstellar medium, and show up as radio/X-ray source in the sky

- The next generation of radio telescopes (SKA project) will have the opportunity for a discovery

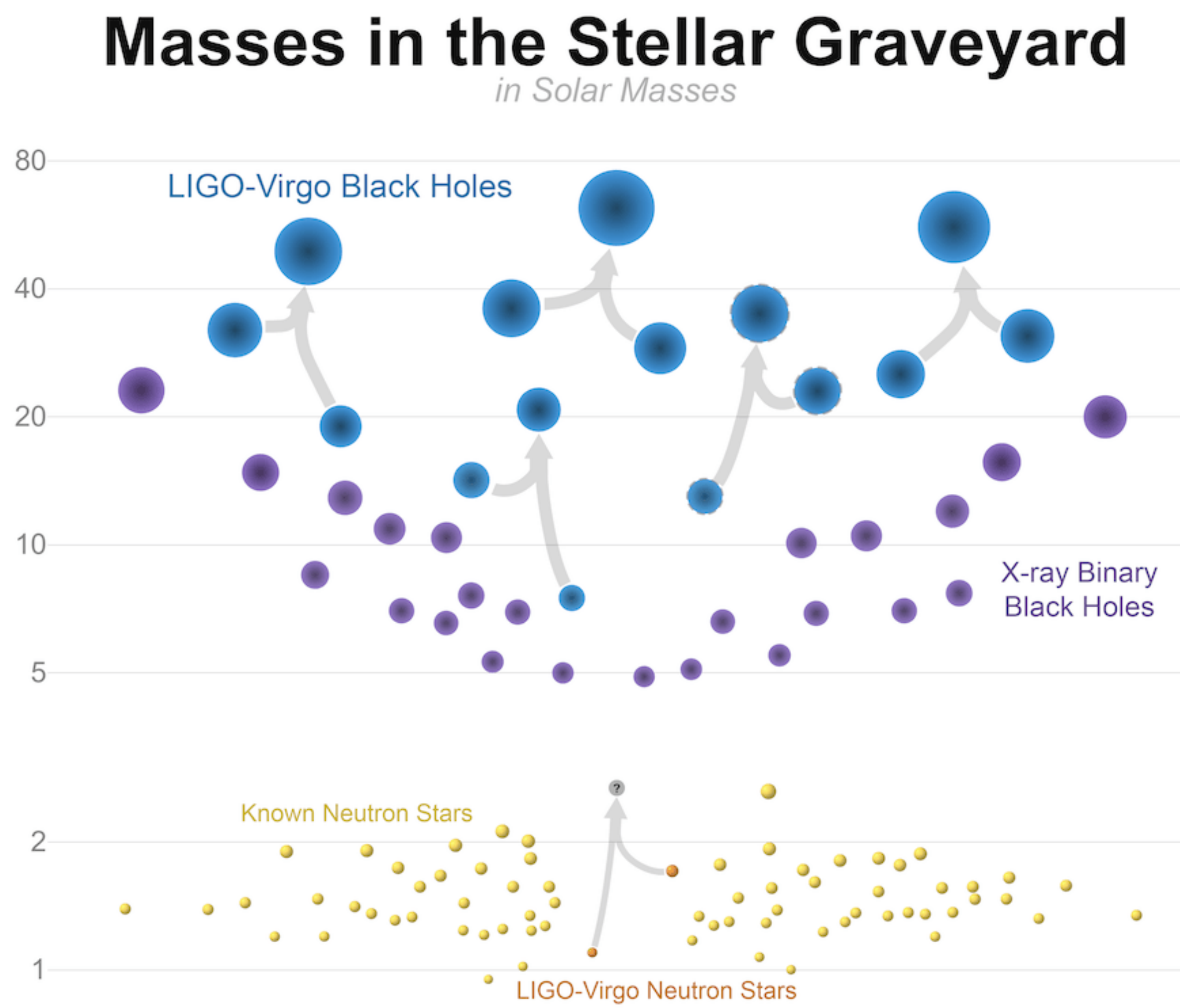
- Comparison with existing catalogues already allow to put a bound on the PBH abundance in this mass range [arXiv:1612.00457]

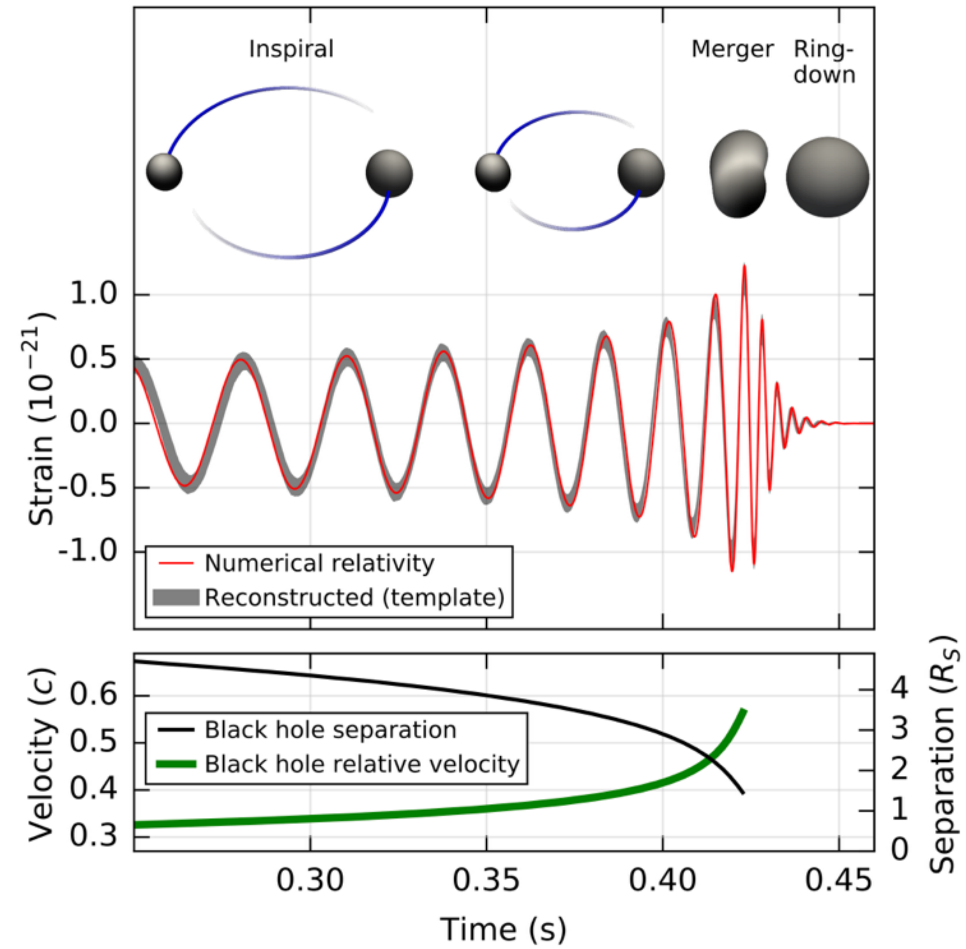




Merger rate and the LIGO/Virgo connection

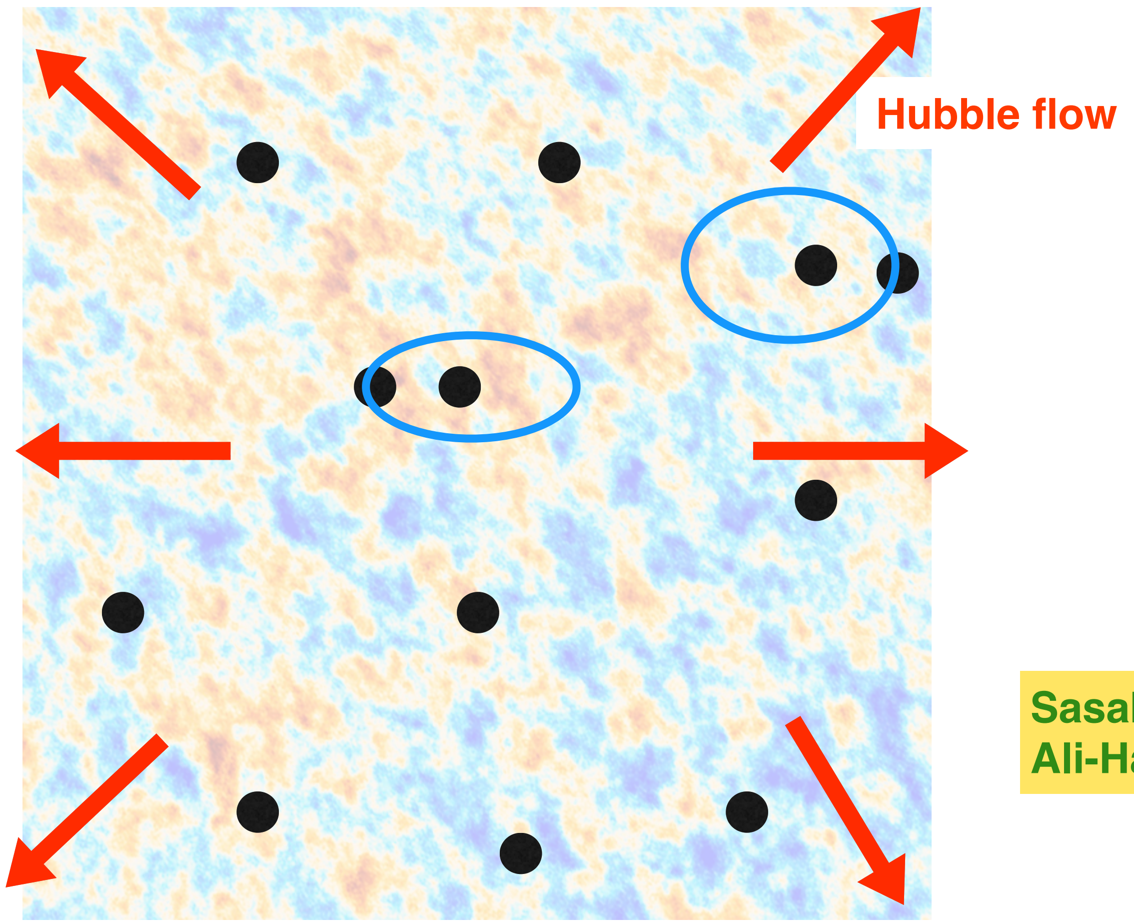
- LIGO and Virgo detected gravitational wave signals from several mergers of massive binary-black hole systems.
- Merger rate in the 10 - 100 M_{Sun} window: $\mathcal{R} = 10 - 200\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$
- Is this rate compatible with a primordial origin?





Merger rate and the LIGO/Virgo connection

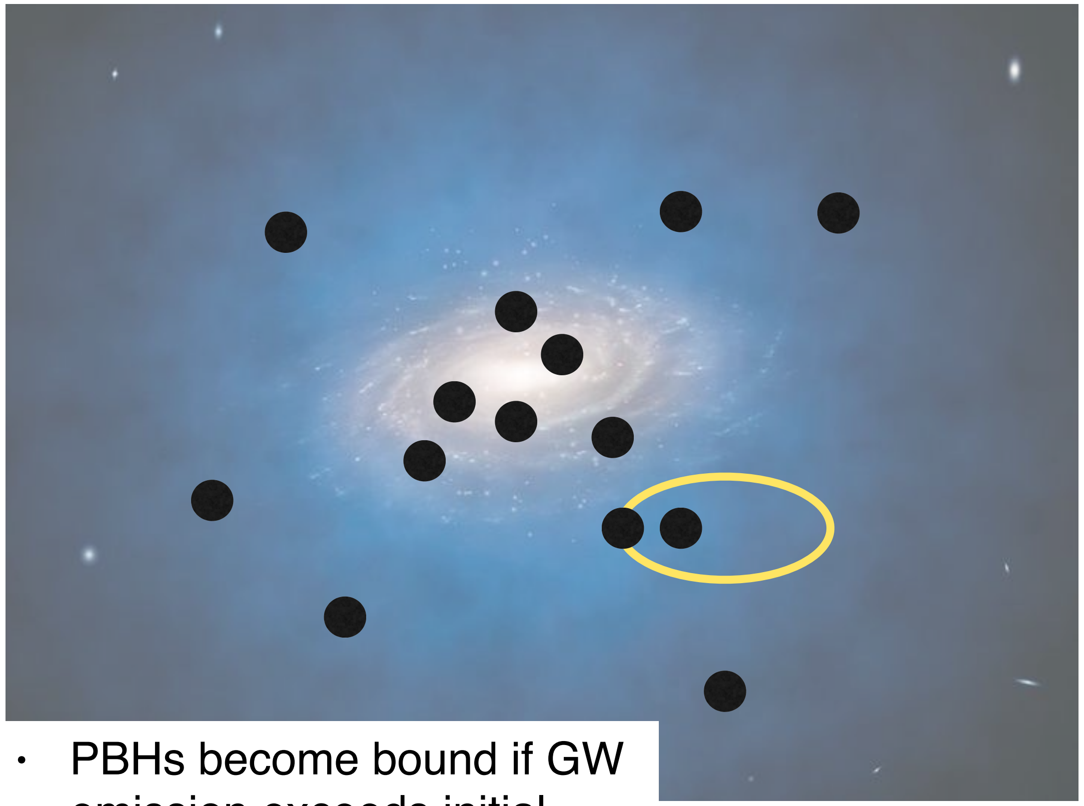
A) Binaries formed in the early Universe



Sasaki+ PRL 2017
Ali-Haimoud+ 2017

- If most of the DM is made of PBHs, **most pairs decouple from the Hubble flow** and form a binary deep in the radiation era.
- If f < 0.01, only **rare pairs with small separation form binary systems**.

B) Binaries formed after close encounters within a DM halo



- PBHs become bound if GW emission exceeds initial kinetic energy

$$\sigma = \pi \left(\frac{85\,\pi}{3}\right)^{2/7} R_s^2 \left(\frac{v_{\rm pbh}}{c}\right)^{-18/7}$$
$$= 1.37 \times 10^{-14}\, M_{30}^2\, v_{\rm pbh-200}^{-18/7}\, {\rm pc}^2$$

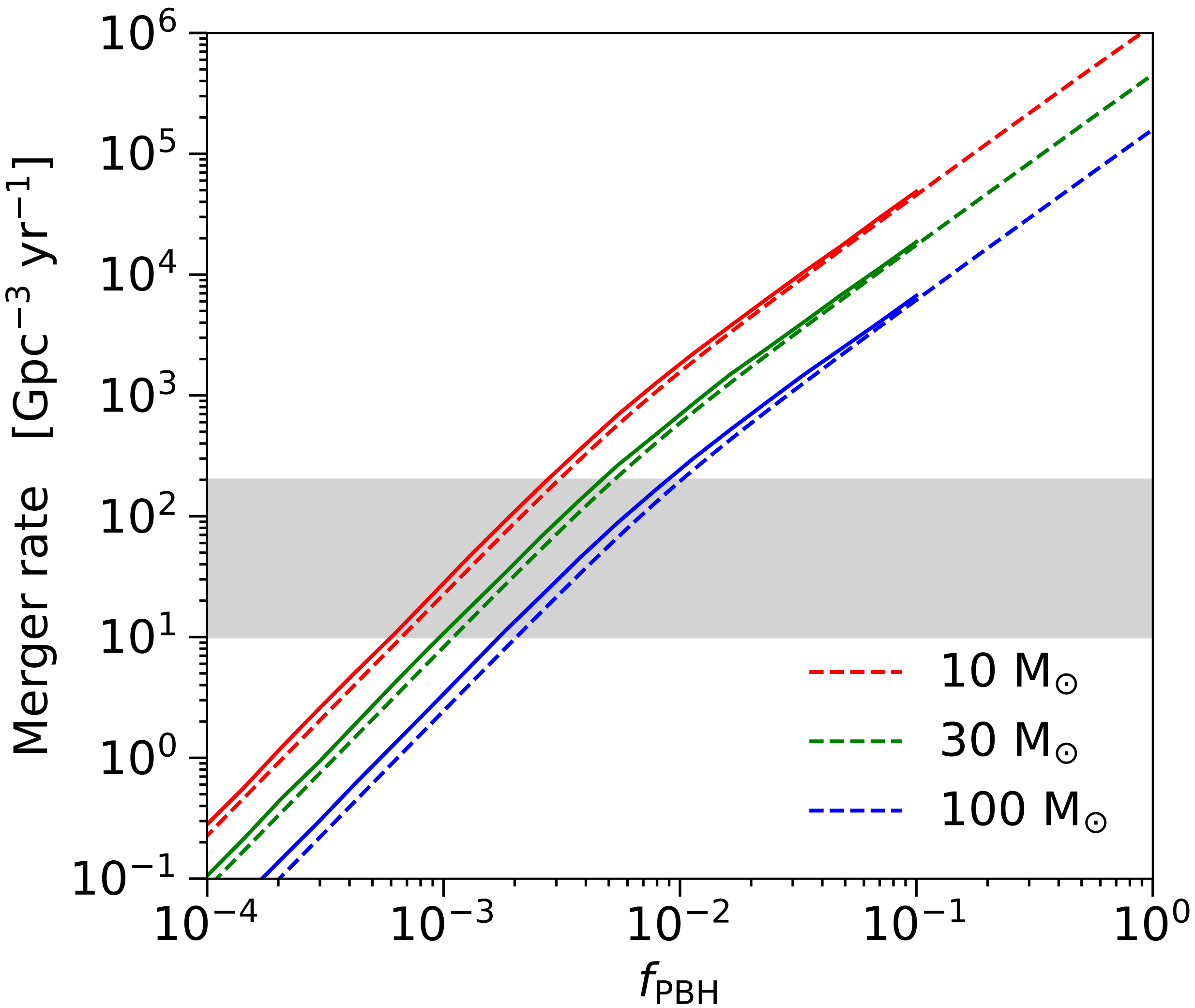
$$\mathcal{R} = 4\pi \int_0^{R_{\rm vir}} r^2 \frac{1}{2} \left(\frac{\rho_{\rm nfw}(r)}{M_{\rm pbh}}\right)^2 \langle \sigma v_{\rm pbh} \rangle \, dr$$

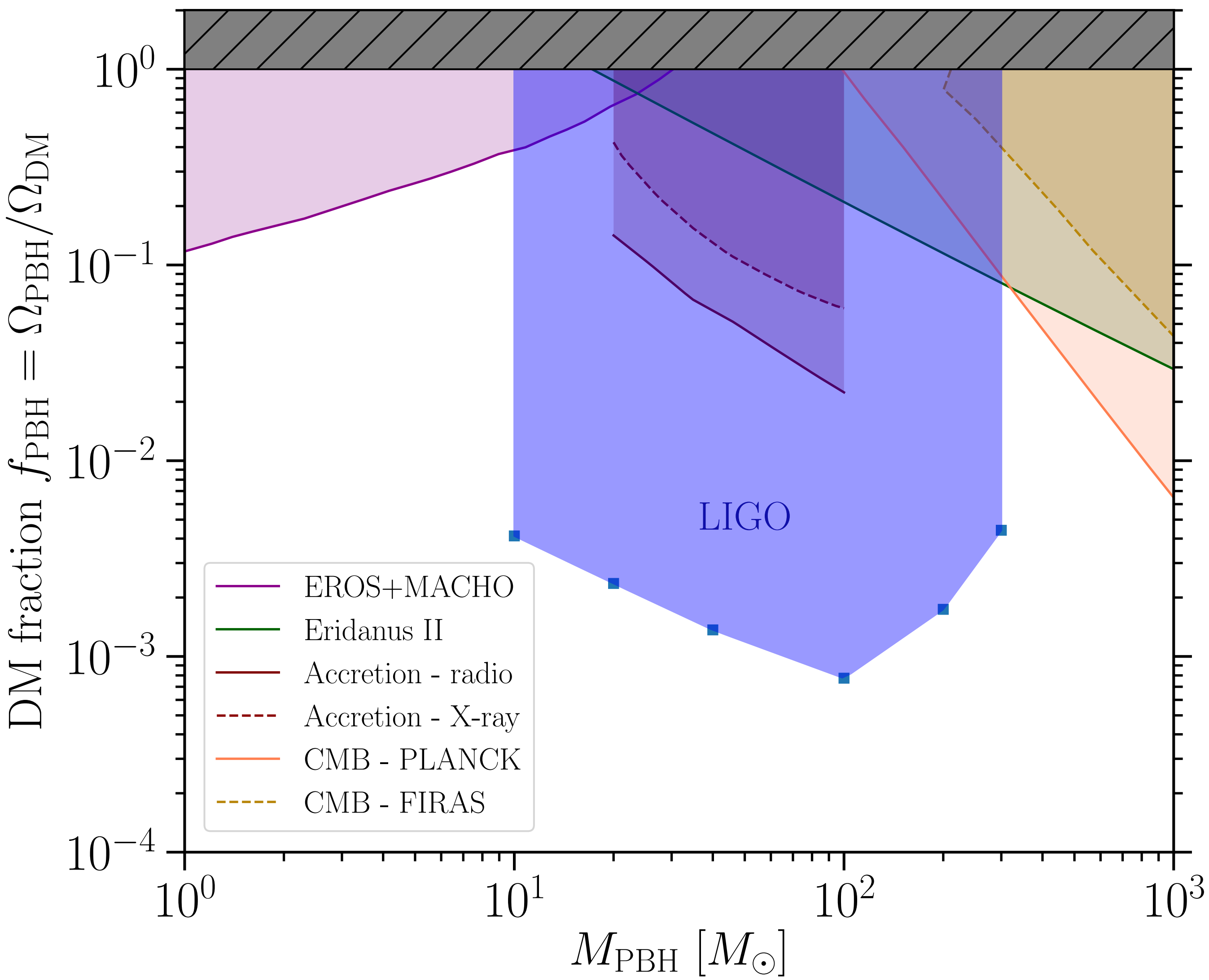
Bird+ PRL 2017

Merger rate: Latest results

- The merger rate from PBH binaries formed in the early Universe is much larger than the one inferred by the LIGO/Virgo collaboration

[Bird+ arXiv:1603.00464, Sasaki+ arXiv:1603.08338, Ali-Haimoud+ arXiv:1709.06576, Kavanagh+ arXiv:1805.09034]





Summary of the discussion points

- **DM indirect detection: positron channel**: DM vs pulsar interpretation.
- **DM indirect detection: antiprotons**: Hint for excesses, constaints.
- **DM indirect detection: antinuclei**: Pros and cons, future prospects.

- **Primordial black holes:** Lensing searches
- **Primordial black holes:** Radio/X-ray searches
- **Primordial black holes:** Merger rates