Dark Matter theory

1) DM as usual
2) PAMELA, ATIC/FERMI

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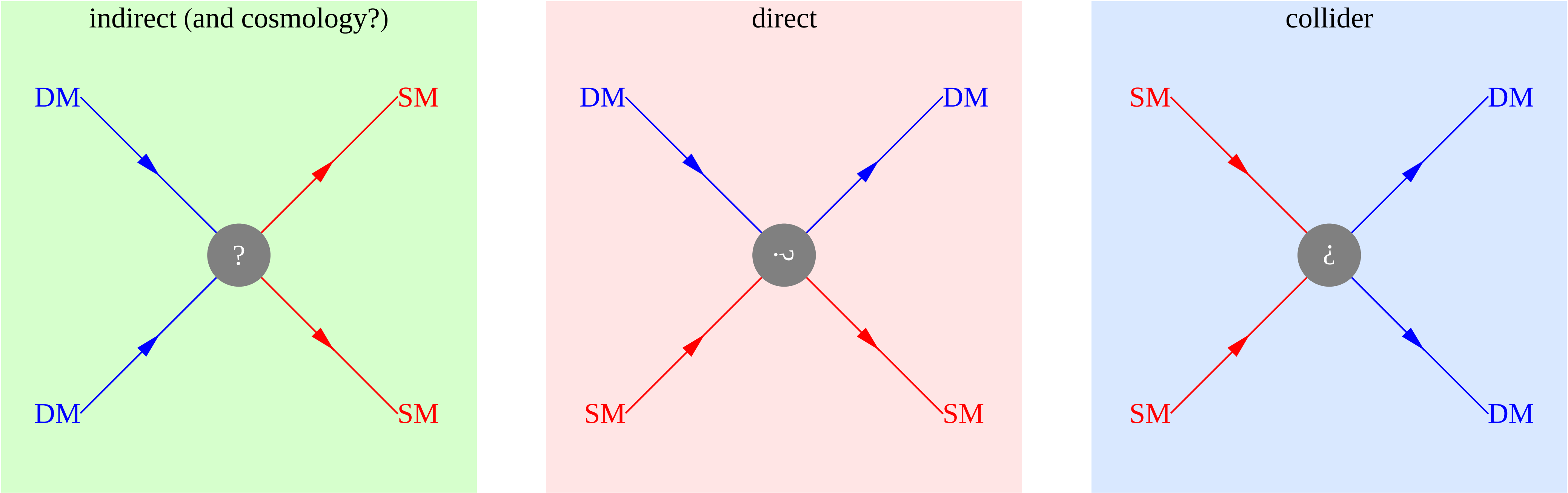
EPS HEP 2009, www.cern.ch/astrumia/DM.pdf

Testing TeV-scale dark matter



best if SM $= W^{\pm}$

best if SM $= q$

DM and cosmology

Thermal DM reproduces the cosmological DM abundance $\Omega_{\rm DM}h^2 \approx 0.11$ for

$$\sigma v \approx 3\times 10^{-26}\frac{\rm cm^3}{\rm sec} \sim \frac{1}{T_0 M_{\rm Pl}} \qquad \text{around freeze-out, i.e. } v\sim 0.2.$$

which is typical of weak-scale particles: precise **TeV** DM masses are obtained assuming that DM is in *one* electro-weak multiplet with *only gauge* interactions:

Quantum numbers $\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	Spin	nick-name	DM mass in TeV	Events at LHC $\int\mathcal{L}\,dt=$100/fb	$\sigma_{\rm SI}$ in $10^{-45}\,\mathrm{cm}^2$
2	1/2	0	sneutrino	0.54	~ 400	0.3
2	1/2	1/2	higgsino	1.2	~ 200	0.3
3	0	0	–	2.5	~ 1	1.3
3	0	1/2	wino	2.7	~ 2	1.3
5	0	1/2	*stable*	9.6	0	12

(co-annihilations and Sommerfeld included)

Dark Matter at LHC?

DM above a TeV is too heavy for LHC and for δm_h^2. DM below a TeV with weak gauge interactions annihilates too much leaving a too low Ω_{DM}, unless:

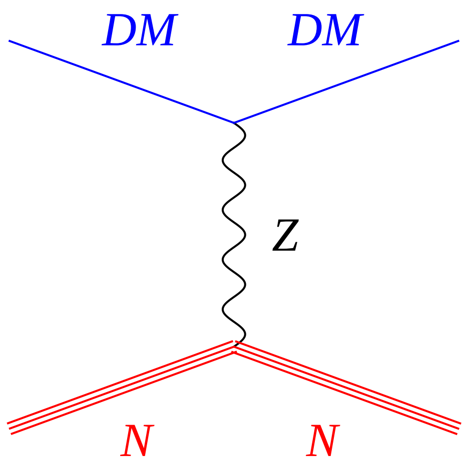
- Extra solution at $M < M_W$ such that too large $\sigma(\text{DM}\,\text{DM} \to W^+W^-)$ is kinematically suppressed. Not fully excluded by LEP. E.g. 'inert doublet'

- Mix interacting ($M \gg v$) with singlets ($M \to 0$): get any intermediate M.

- DM as singlet + extra coupling e.g. bino$_{\text{DM}}$-lepton-slepton Yukawa in SUSY works if sleptons are around or below the LEP bound. Small extra couplings can be resonantly enhanced, e.g. DM DM $\to A \to b\bar{b}$ in SUSY if $M_A = 2M$.

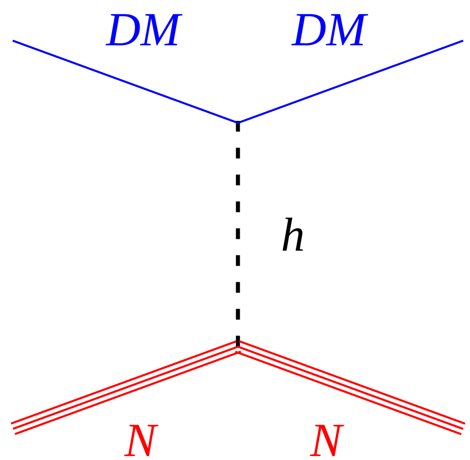
- LHC can make many gluinos that decay into DM, maybe slowly (gravitino).

Direct DM detection: theory



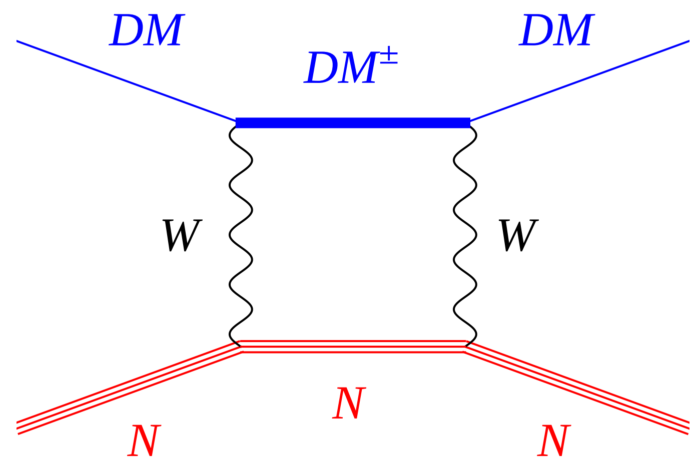
tree, vector

$$\sigma_{\rm SI} \approx \frac{\alpha^2\, m_N^2}{M_Z^4}$$



tree, scalar

$$\sigma_{\rm SI} \approx \frac{\alpha^2\, m_N^4}{M_h^6}$$

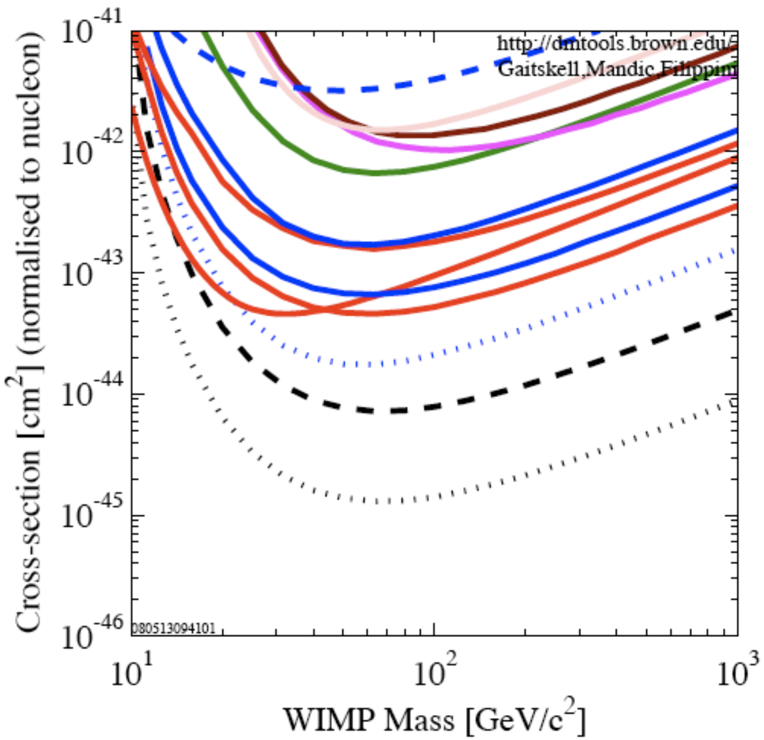


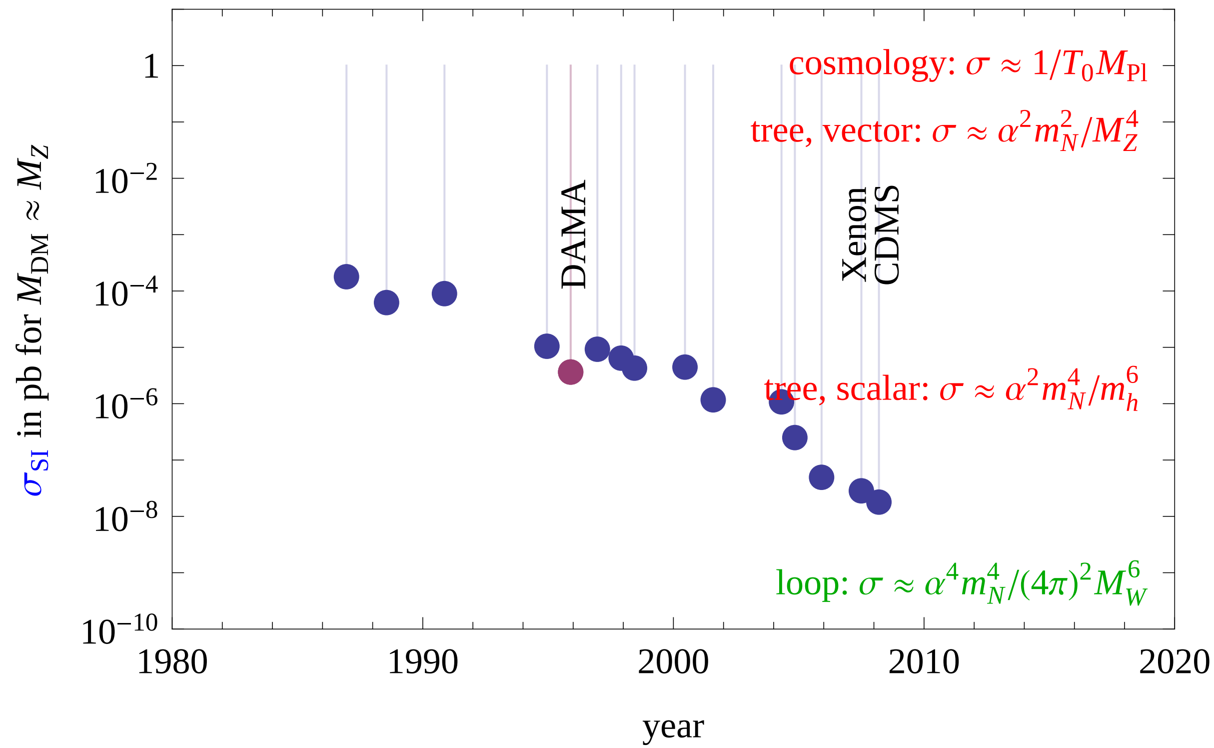
loop

$$\sigma_{\rm SI} \approx \frac{\alpha^4\, m_N^4}{M_W^6}$$

Direct DM detection: experiment

Bounds on the Spin-Independent $\sigma_{\rm SI}$(DM nucleon) parameter:





DM must be neutral under the γ, g and almost neutral under the Z

The vector effect vanishes if DM is real (e.g. a 'neutralino' Majorana fermion)

Inelastic DM $N \to {\rm DM}' N$ can explain DAMA **and** its energy spectrum for $\Delta M \sim 100\,$keV: soon (already?) tested by ZEPLIN, and by LUX and XENON.

Indirect signals of Dark Matter

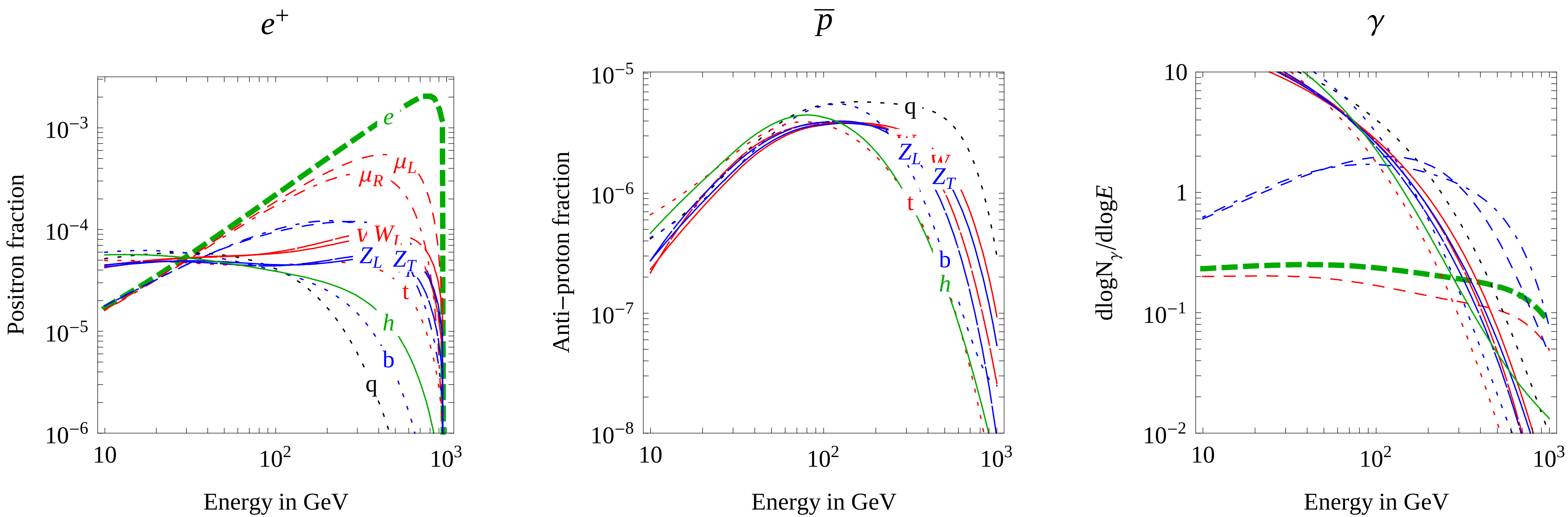
DM DM annihilations in our galaxy might give detectable γ, e^+, $\bar{p}$, $\bar{\mathrm{d}}$, ν.

Model-independent final state spectra

Indirect signals depend on the DM mass M, non-relativistic σv, primary BR:

$$\text{DM DM} \to \left\{ \begin{array}{llll} W^+W^-, & ZZ, & Zh, & hh \\ e^+e^-, & \mu^+\mu^-, & \tau^+\tau^- & \\ b\bar{b}, & t\bar{t}, & q\bar{q} & \end{array} \right. \begin{array}{l} \text{Gauge/higgs sector} \\ \text{Leptons} \\ \text{quarks, } q = \{u, d, s, c\} \end{array}$$

Energy spectra of the stable final-state particles, e, p, ν, γ for $M = 1$ TeV:



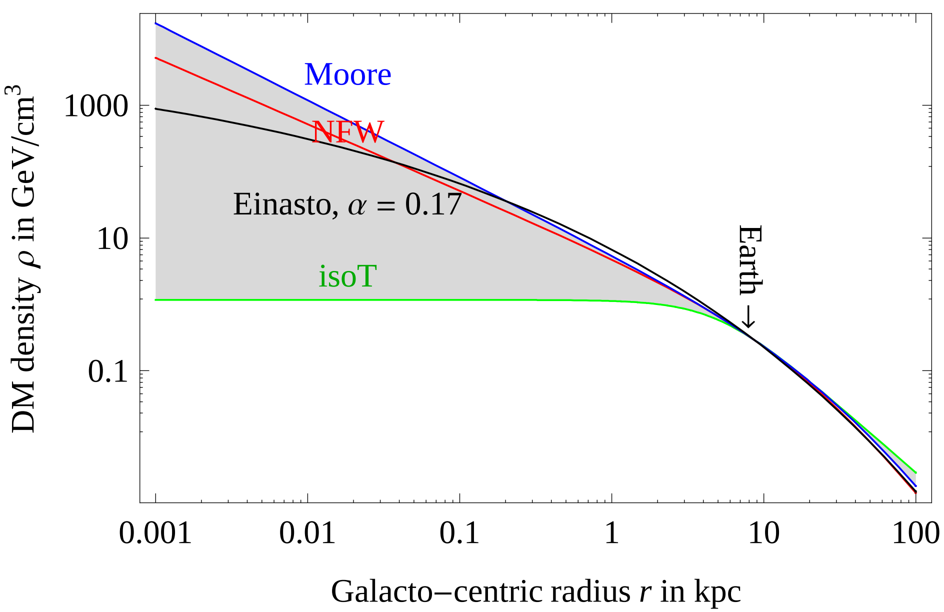
Warning: γ receive extra comparable contributions from 3-body and one-loop.

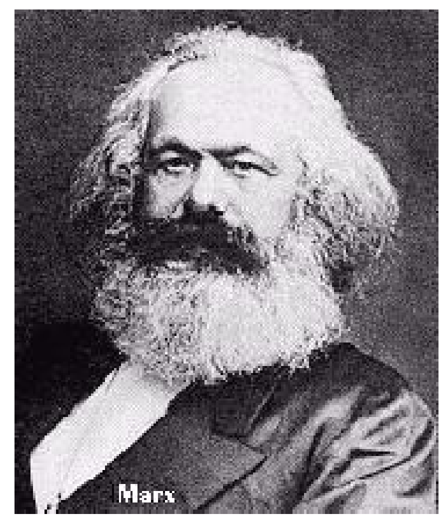
The galactic DM density profile

DM velocity: around the escape velocity $\beta \approx 10^{-3}$.

DM local density: $\rho_\odot \equiv \rho(r_\odot \approx 8\,\mathrm{kpc}) \approx 0.38\,\mathrm{GeV/cm}^3$ from rotation curves.

DM is spherically distributed but its density profile $\rho(r)$ is uncertain. Indeed DM is like capitalism according to Marx: a gravitational system has no ground state so everything is (slowly) collapsing to a point and maybe $\rho(r \to 0) = \infty$.





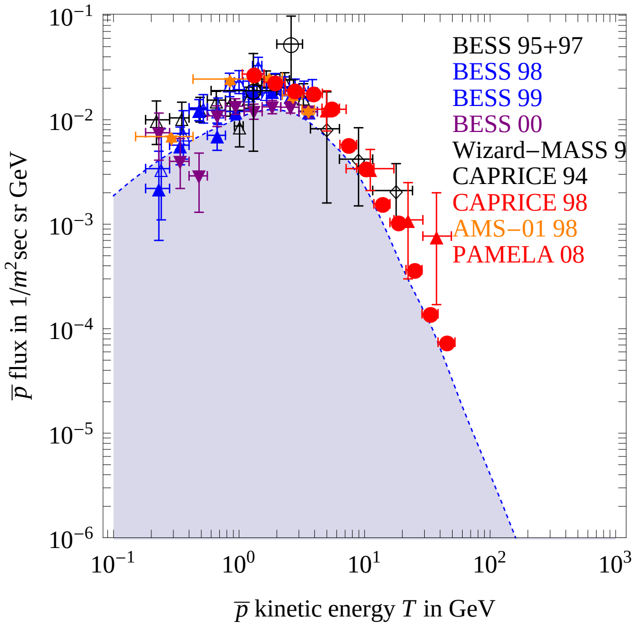
Sub-halos boost the DM DM signal?

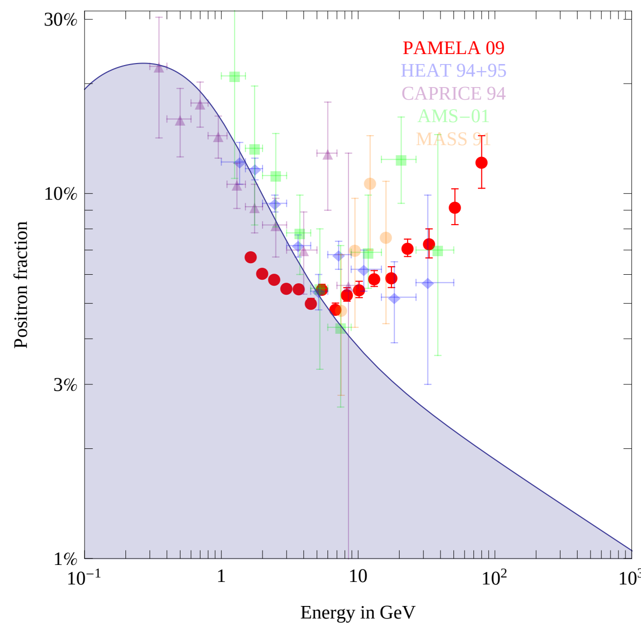
N-body simulations suggest that DM might clump in subhalos:

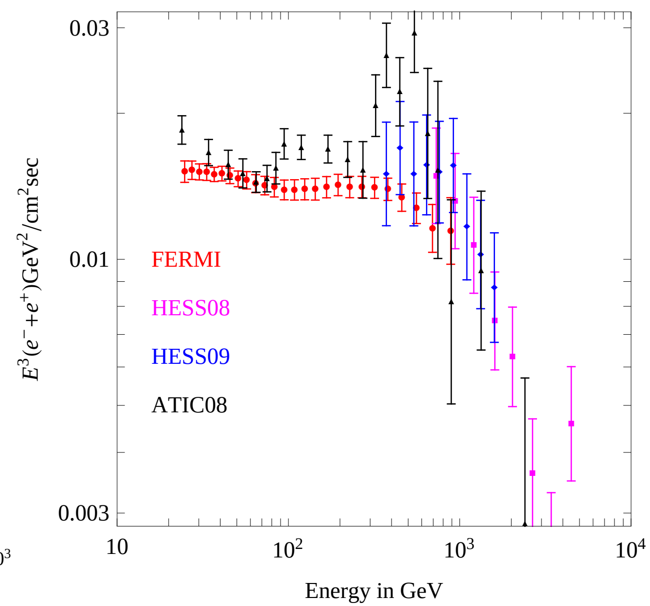
Annihilation rate $\propto \int dV\ \rho^2$ increased by a boost factor $B = 1 \leftrightarrow 100 \sim$ a few

Simulations neglect normal matter, that locally is comparable to DM.

PAMELA, FERMI/ATIC, HESS







$\bar{p}$: consistent with bck

e^+/e^-: excess

$e^- + e^+$: feature?

The $e^{\pm}$ excesses can be unexpected DM

PAMELA e^{+} needs either leptonic DM channels or any channel if $M \gtrsim$ TeV.

PAMELA $\bar{p}$ disfavor non-leptonic channels, unless $M \gtrsim 10\,$TeV.

ATIC or FERMI want leptonic channels and $M \sim 3\,$TeV.

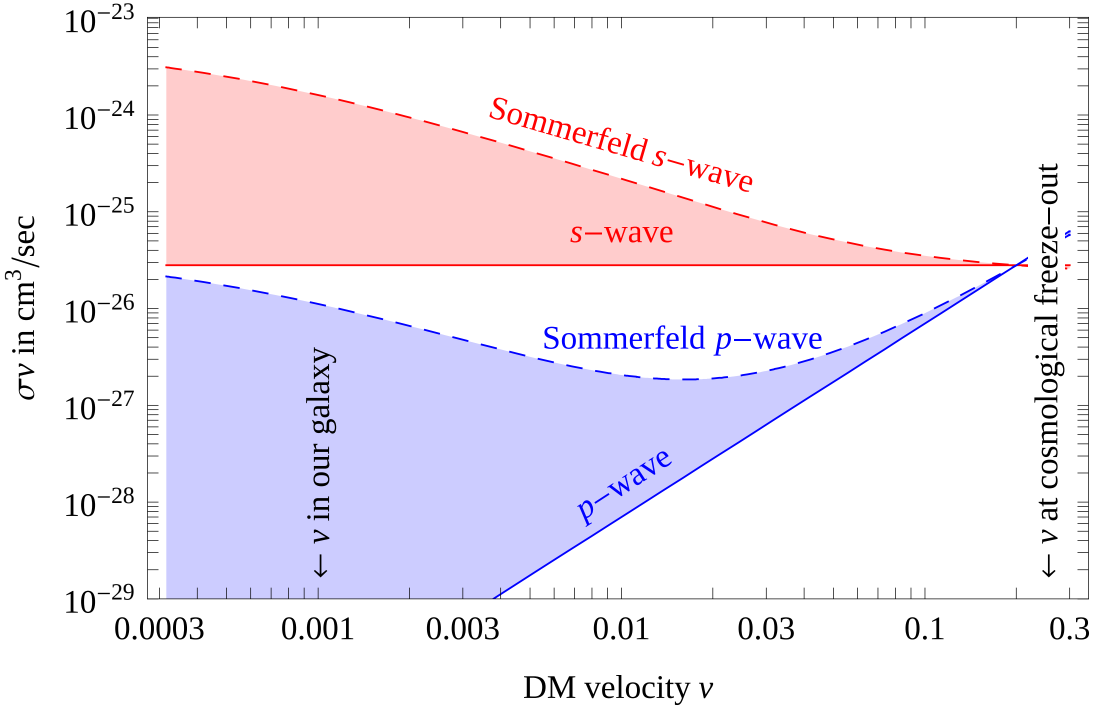
σv a few orders above the value suggested by cosmology or $\tau \sim 10^{26}\,$sec.

(caveats)

σ(PAMELA + FERMI) $\gg$ σ(cosmo)

up to co-annihilations, resonances, sub-clumps, ..., Sommerfeld enhancement: how to extrapolate the cosmological σv at $v \sim 0.2$ down to $v \sim 10^{-3}$?

Usually bad $\sigma v \propto v^0$ (s-wave) or worse $\sigma v \propto v^2$ (p-wave). Classic analogy: the sun attracts slower bodies, enhancing its cross section: $\sigma = \pi R_\odot^2(1+v_{\rm escape}^2/v^2)$. Quantum Sommerfeld effect: $\sigma v \propto 1/v$ if DM is charged under a lighter particle.



Present in the SM if $M \gtrsim M_W/\alpha$, but DM would annihilate into W^+W^-.

Bounds on DM from γ and ν

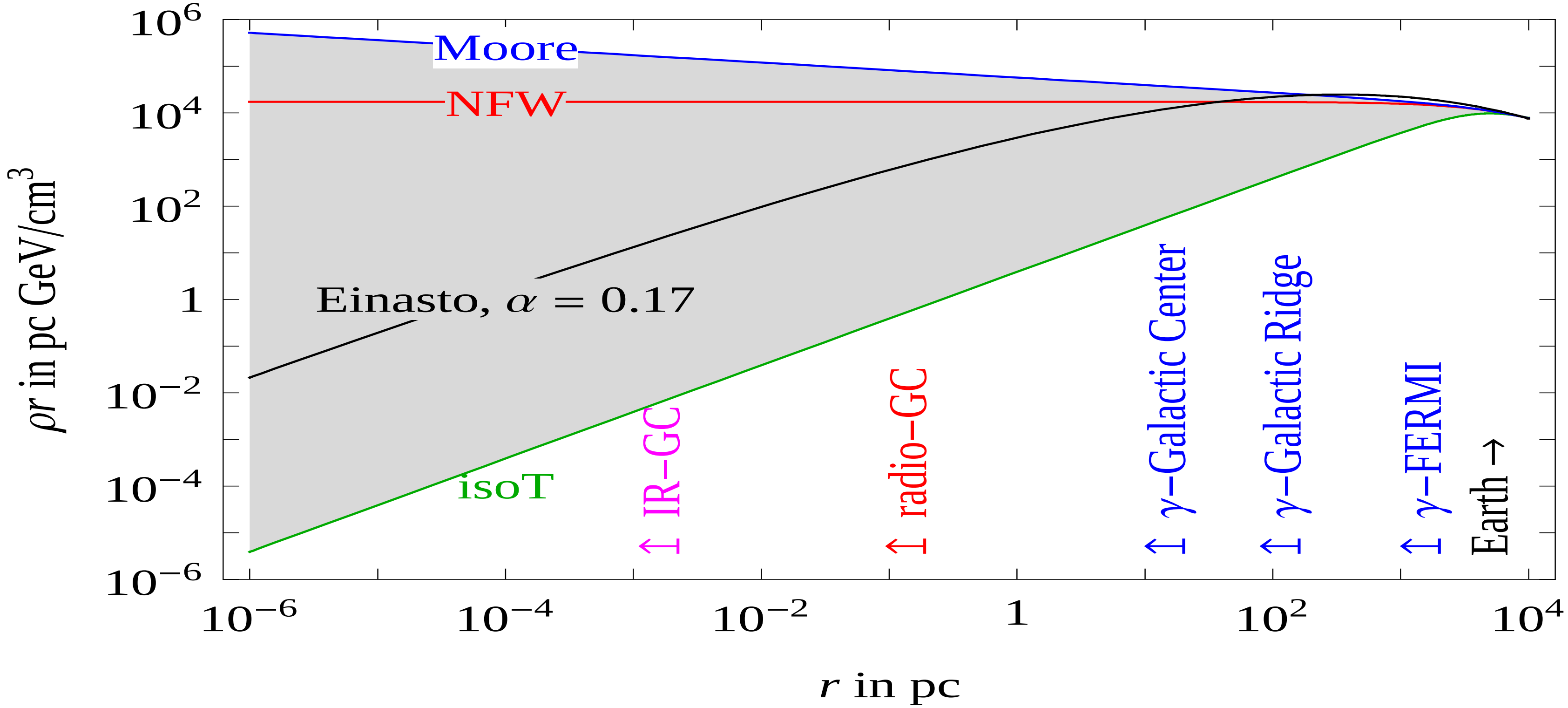
DM DM $\to \ell^+\ell^-$ is unavoidably accompanied by photons:

- **Brehmstralung** from $\ell^\pm$ (if $\ell = \tau$ also $\tau \to \pi^0 \to \gamma\gamma$).
  Largest $E_\gamma \sim M_{\rm DM}$, probed by HESS.

- **Inverse Compton**: $e^\pm\gamma \to e^\pm\gamma'$ scatterings on CMB and star-light: $\dot{E} \propto u_\gamma$.
  Intermediate $E_{\gamma'} \sim E_\gamma(E_e/m_e)^2 \sim 10\,\text{GeV}$ probed by FERMI, that so far only released γ below 10 GeV at $10^\circ < |b| < 20^\circ$ (EGRET not confirmed).

- **Synchrotron**: $e^\pm$ in the galactic magnetic fit: $\dot{E} \propto u_B = B^2/2$.
  Small $E_\gamma \sim 10^{-6}\,\text{eV}$, probed by radio-observations: Davies, VLT, WMAP.

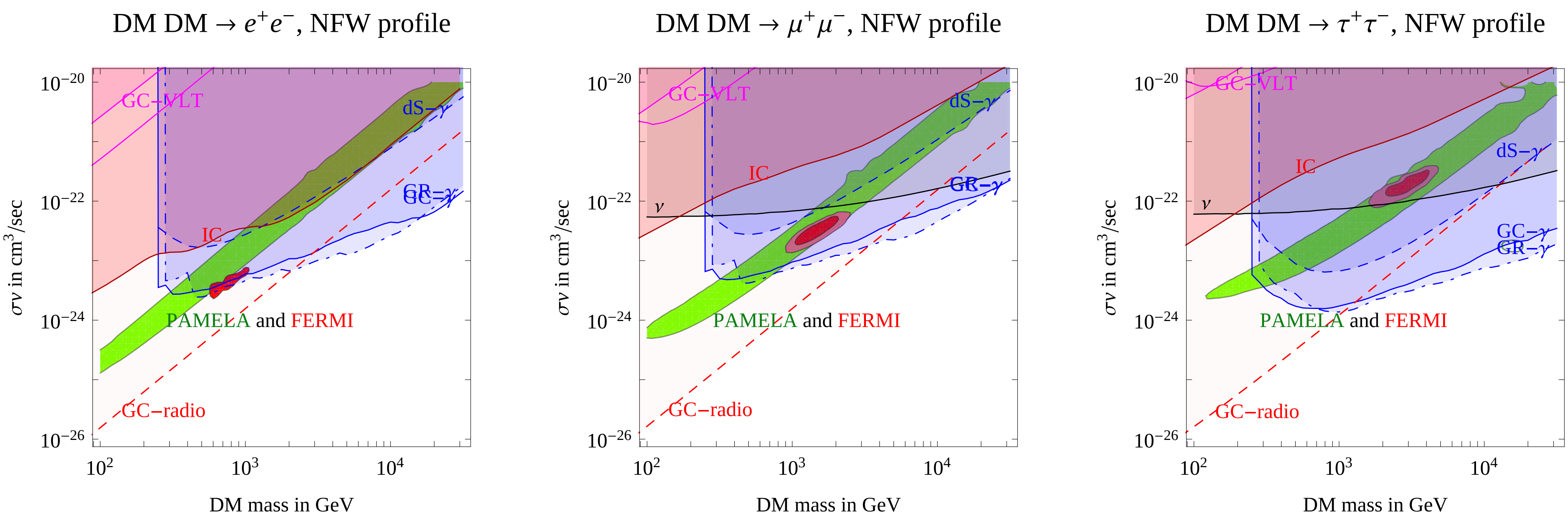
γ observations



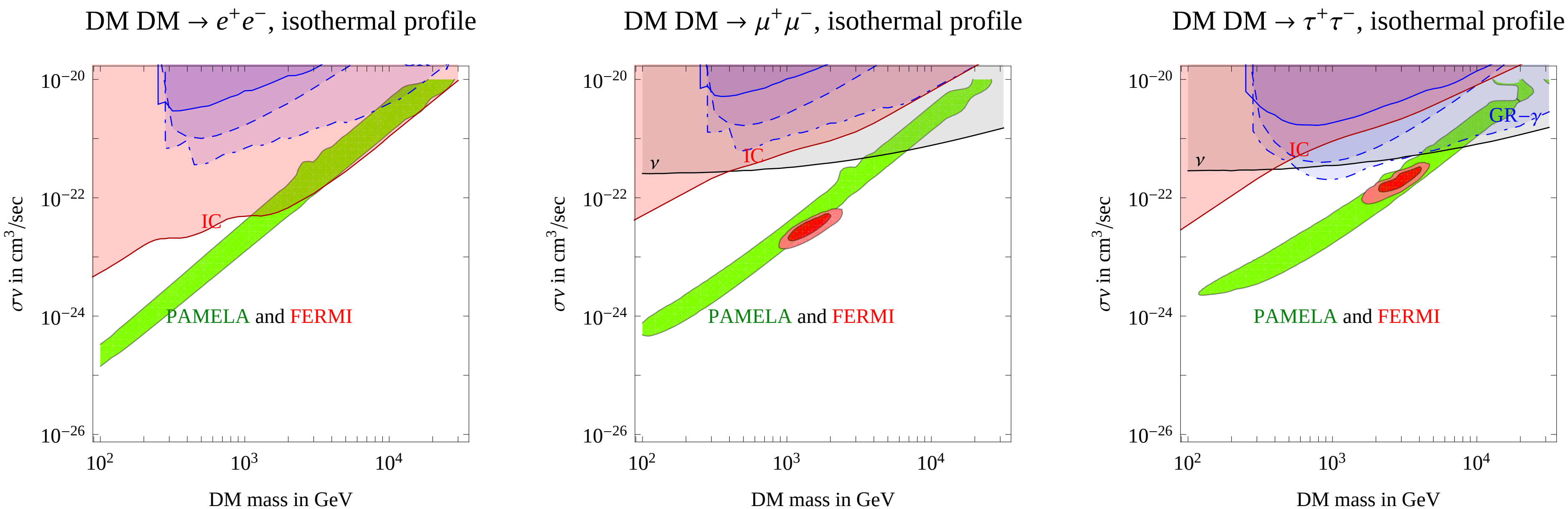
Bounds from Galactic Center observations depend on its unknown DM ρ

$e^{\pm}$ excesses vs γ, ν bounds

Assuming NFW, **conservative** bounds from γ observations of the Galactic Center, Galactic Ridge, Spherical Dwarfes and from radio and ν observations exclude the green (allowed by PAMELA) and the red region (+FERMI):



$e^{\pm}$ excesses can be DM if ρ is isothermal



The Inverse Compton bound is **robust**; today weaker but Fermi is taking data...

New DM theories

DM is charged under a dark gauge group, to get the Sommerfeld enhancement.

DM annihilates into the new vector. If light, $m \lesssim$ GeV, it can only decay into the lighter leptons. Large $\sigma(\text{DM DM} \to \ell^+\ell^+\ell^-\ell^-)$ obtained.

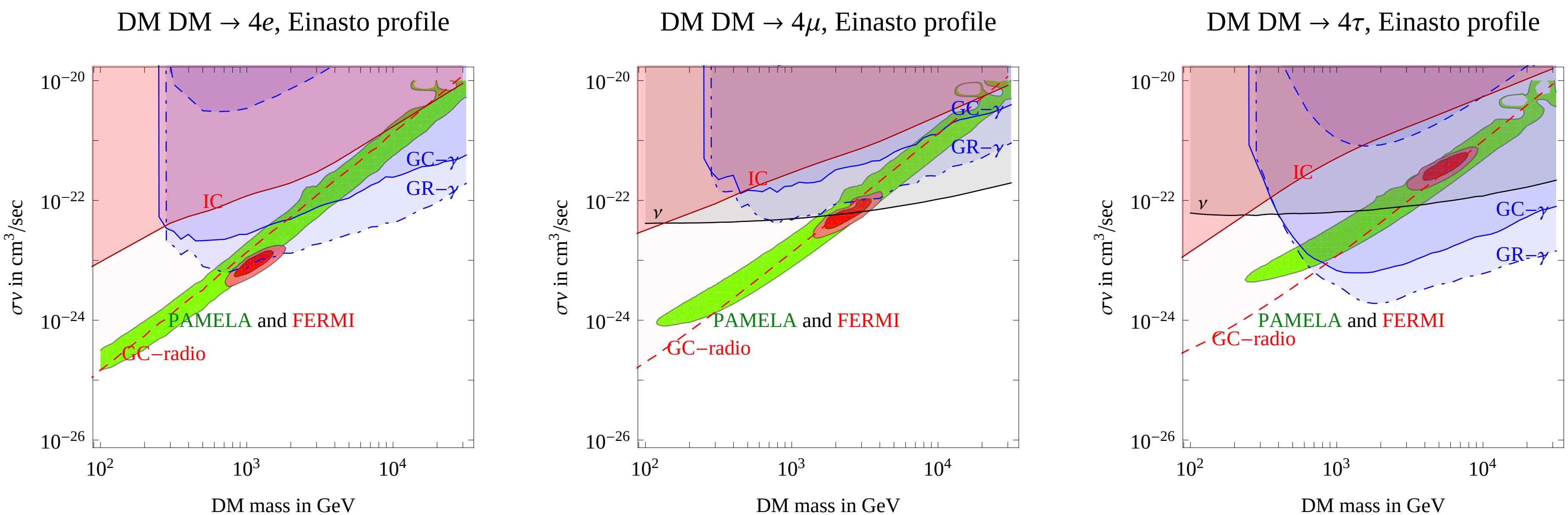
γ has a mixing θ with the new light vector, giving a too large elastic $\sigma_{\rm SI}$.

If the DM gauge group is non abelian and DM has multiple components with 100 keV ($\stackrel{?}{\sim} \alpha_H m$) mass splittings, one can instead get an inelastic σ for DAMA.

Sensitivity to θ, m can be best improved by e beam-dump experiments.

... and 100 other DM models, mostly with DM $\neq$ neutralino!

Status of DM DM $\to \ell^+\ell^-\ell^+\ell^-$

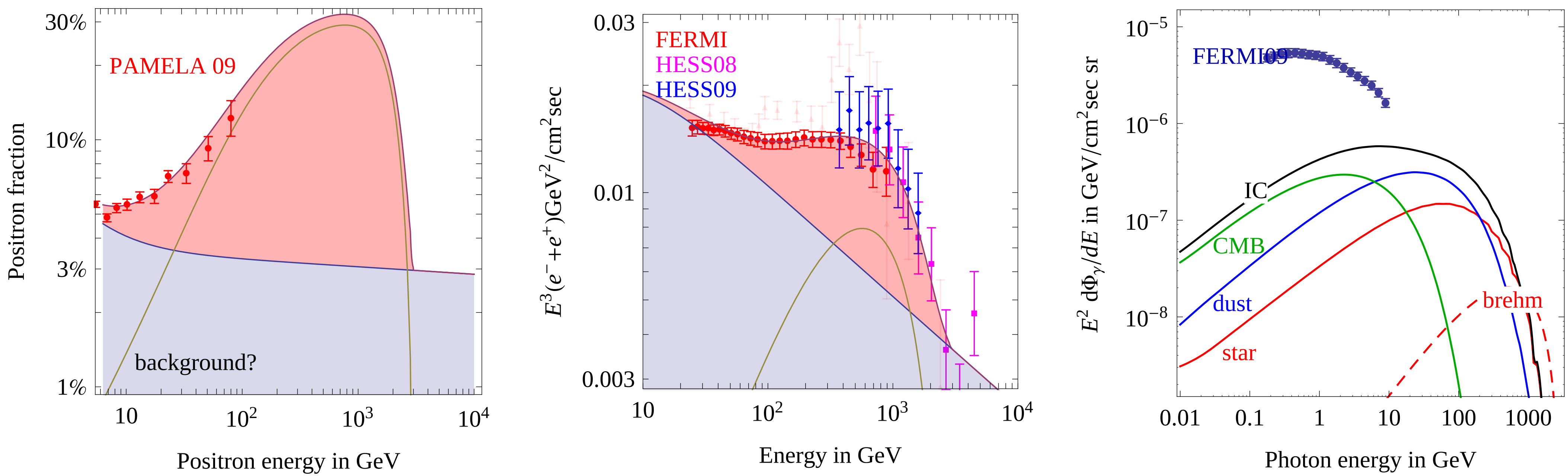


Smoother $e^{\pm}$ spectrum good for FERMI

γ brehmstralung reduced from $\ln M/m_\ell$ to $\ln m/m_\ell$

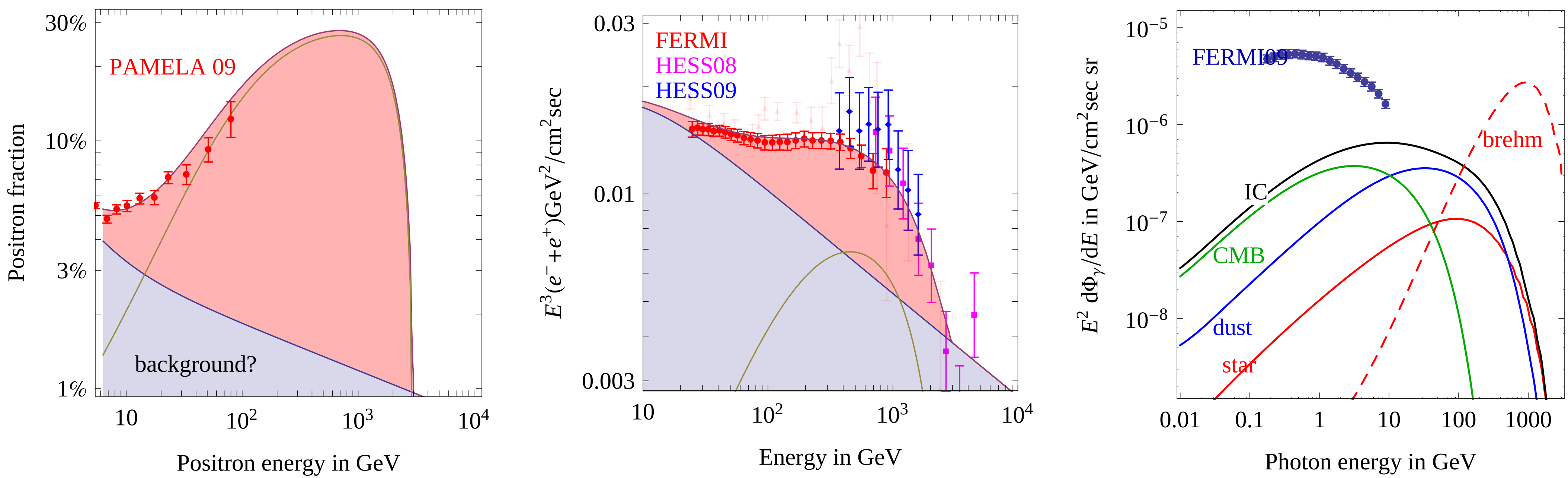
New Dark Matter best fit

DM with $M = 3.$ TeV that annihilates into 4μ with $\sigma v = 8.4 \times 10^{-23}\ \mathrm{cm}^3/\mathrm{s}$



Standard Dark Matter best fit

DM with $M = 3.$ TeV that annihilates into $\tau^+\tau^-$ with $\sigma v = 1.9 \times 10^{-22}$ cm^3/s



(Inverse Compton depends only on the $e^\pm$ spectrum)

Bounds from cosmology

DM annihilation rate $\propto \rho^2$ is enhanced in the early universe: its products can

1. affect BBN at $T \sim$ MeV fragmenting ^{4}He, D, ^{3}He...
   Their primordial abundances are not safely known.

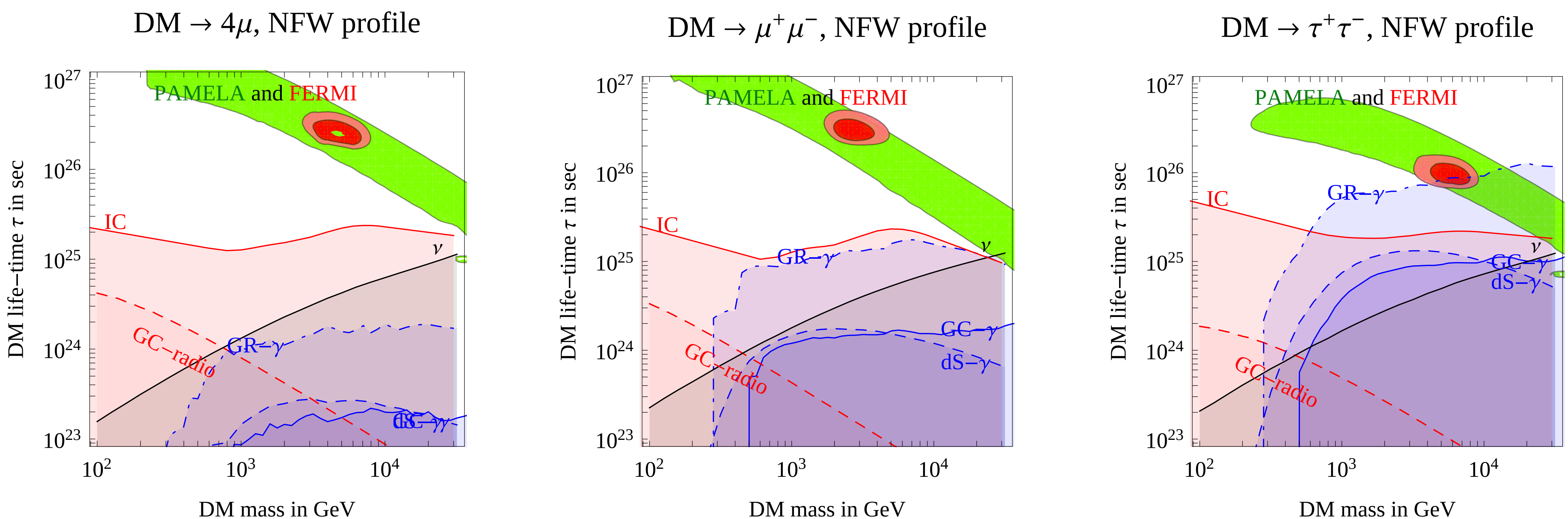
2. affect CMB reionizing H after matter/radiation decoupling, $z \lesssim 1000$.

3. heat gas after structure formation $z \sim 10$.
   Depends on unknown non-linear small-scale DM clustering.

1, 2 and 3 give comparable constraints at the PAMELA-level, $\sigma v \sim 10^{-23}\,\mathrm{cm}^3/\mathrm{sec}$.
2 is stronger and robust and can be improved by PLANCK.

PAMELA/FERMI as DM decays?

Not constrained by cosmology; compatible with all $\rho(r)$ because $\rho^2 \frac{\sigma v}{2M^2} \to \frac{\rho^1}{M\tau}$:



- GUT-suppressed dimension 6 operators give the needed $\tau \sim \frac{M_{\text{GUT}}^4}{M^5} \sim 10^{26}\,\text{s}$

- $M \sim 3\,\text{TeV}$ gives the cosmological Ω_{DM} if DM is a baryon-like asymmetry kept in thermal equilibrium by weak sphalerons down to $T_{\text{dec}} \sim 200\,\text{GeV}$.

Conclusions

The PAMELA, FERMI-ATIC, HESS $e^{\pm}$ excesses attracted most attention. They could be due to astrophysics or to unexpected DM as follows:

- 3 TeV DM that annihilates in $\tau^+\tau^-$ if the DM density $\rho(r)$ is quasi-constant.
- 3 TeV DM that annihilates in 4μ, better if ρ_{eff} is quasi-constant.
- DM that decays mostly into μ or τ, whatever $\rho(r)$ is.
- sub-TeV DM and many other DM possibilities cannot fit the $e^{\pm}$ excesses.

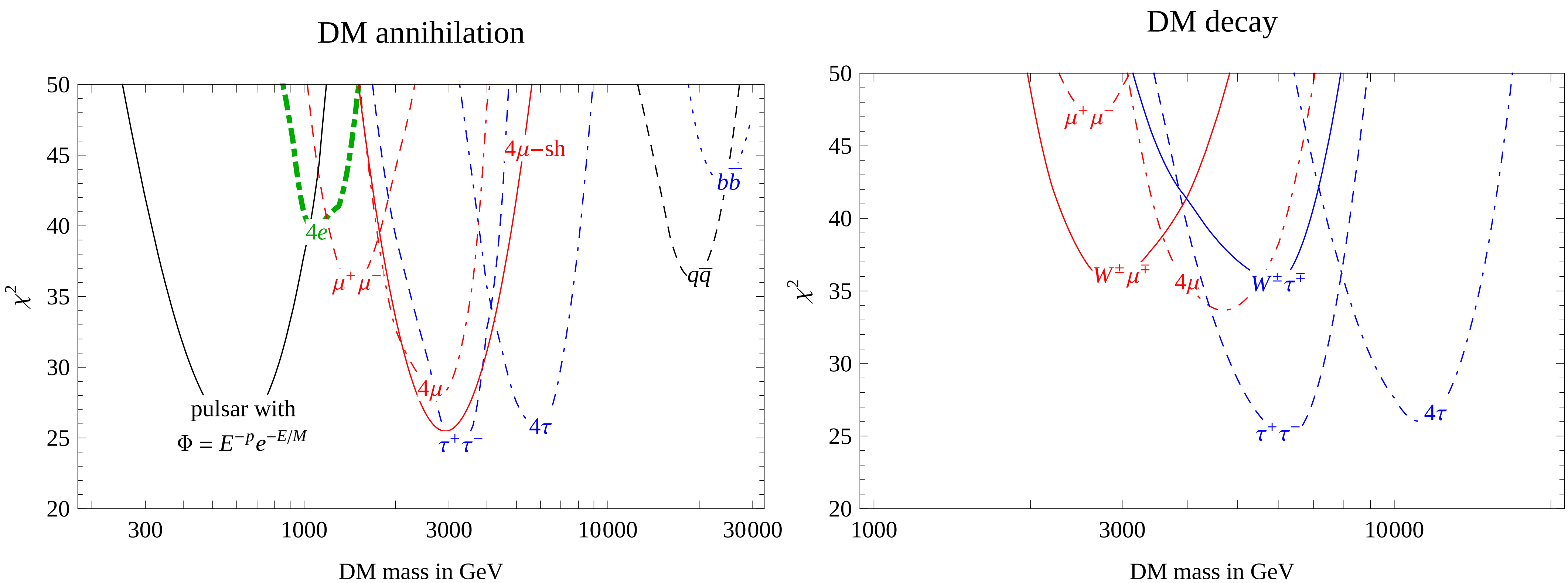
Byproduct: model-independent DM phenomenology and DM models. Next:

- **DM predicts that e^+/e^- continues to grow at higher energies**
  PAMELA up to 270 GeV finds [redacted]. Later AMS.
- **Is an excess present in $\bar{p}$ at higher energies?**
  No, in the extra PAMELA09 preliminary bin. Later AMS up to 1 TeV?
- **IC (and maybe FSR) must give a γ excess**: FERMI on 12 August 09.

After FERMI γ data

Nothing in γ Nothing in $\bar{p}$ Astrophysics in e^+ **Game over?!**	or	DM in e^+ and e^- DM in γ Nothing in $\bar{p}$: **leptophilic DM!?**	?

‘Fitting’ PAMELA and FERMI



Miscellanea DM theory news

Automatically stable DM candidates: weak 5-plet, vectors of extra SU(2).

DM quasi-degenerate to a DM$^\pm$: could form stable bound states with *heavy* enough nuclei: $E_B(\text{DM}^\pm B) \sim Z\alpha^2\mu > \Delta M$.

γ from 3-body annihilations computed in the MSSM.