Dark Matter

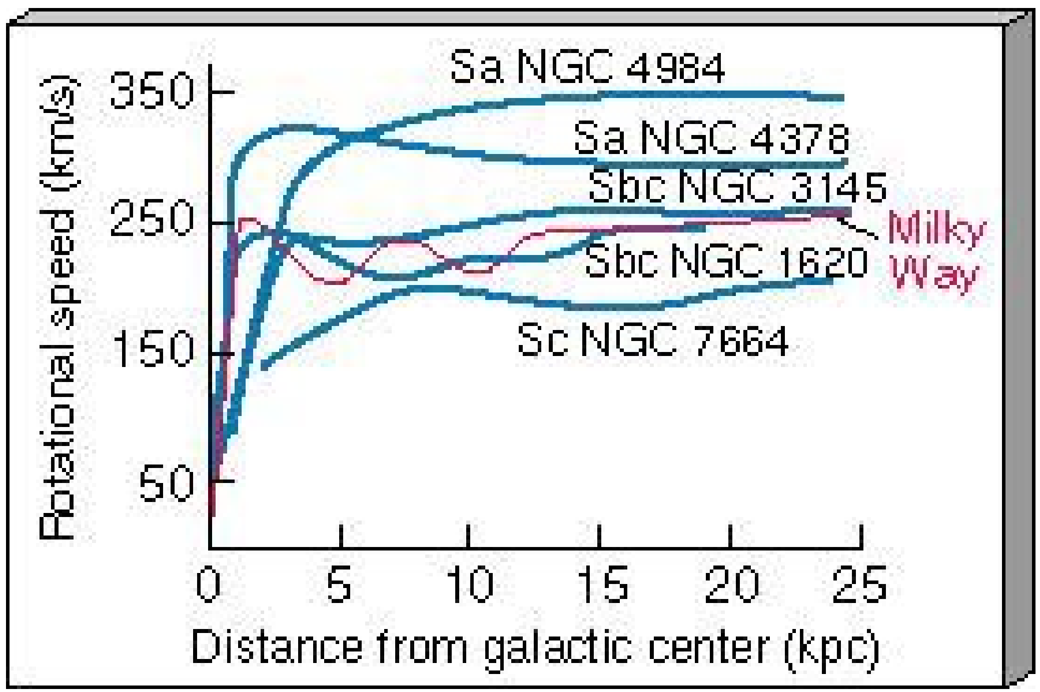
1) Evidences: mini/midi/maxi
2) Cosmology and astrophysics
3) Direct detection?
4) Indirect detection?
5) Production at LHC? [Barr]

Alessandro Strumia, YETI 2010.

Evidences for Dark Matter: mini

DM seen only through its gravity (interactions with SM particles not seen)

Rotation curves of galaxies: $v^2/r > GM_{\text{visible}}/r^2$. (almost all become flat? An accident or Modified Newtonian Dynamics?). [Vera Rubin, 1962, ignored]



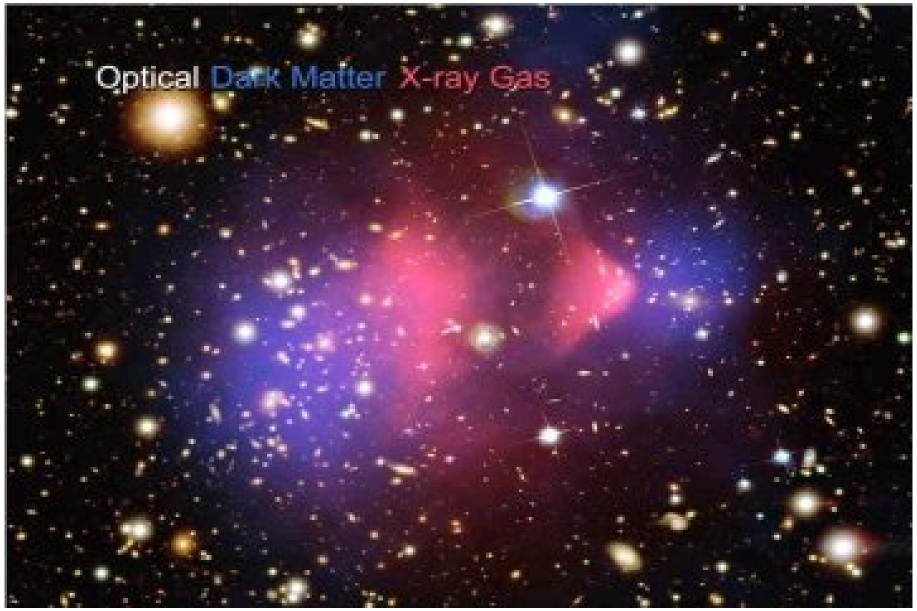
Evidences for Dark Matter: midi

- Velocity dispersion in clusters of galaxies [Fritz Zwicky, 1933, ignored]. The virial theorem $\langle K \rangle = -\langle V \rangle$ tells the mass of N objects at distance r:

$$N\frac{mv^2}{2} = \frac{1}{2}\frac{N(N-1)}{2}\frac{Gm^2}{r} \qquad \Rightarrow \qquad m = \frac{2rv^2}{GN}$$

- Weak Lensing sees more gravity and...

- off-set between gravity and matter in collision of the Bullet cluster [2006]

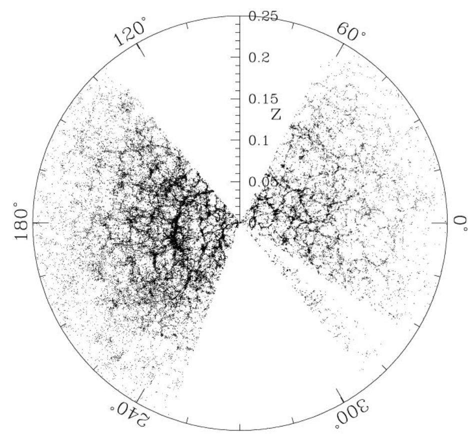


bullet.mpg

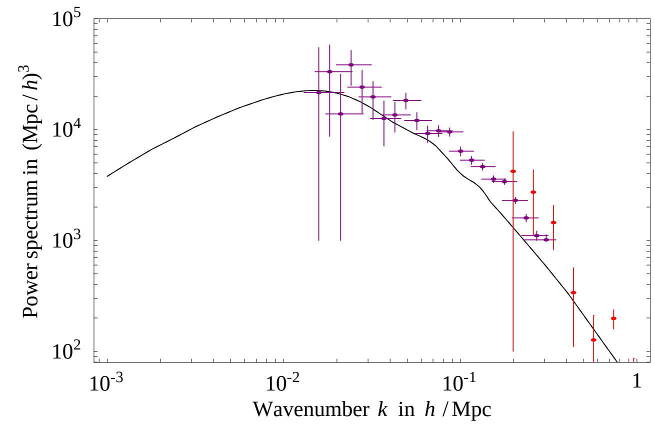
Constraints on DM: $\sigma(\text{DM DM}) \lesssim \sigma_p$, $M_{\text{DM}} > 10^{-22}(30)\,\text{eV}$ if boson (fermion)

Evidences for Dark Matter: maxi

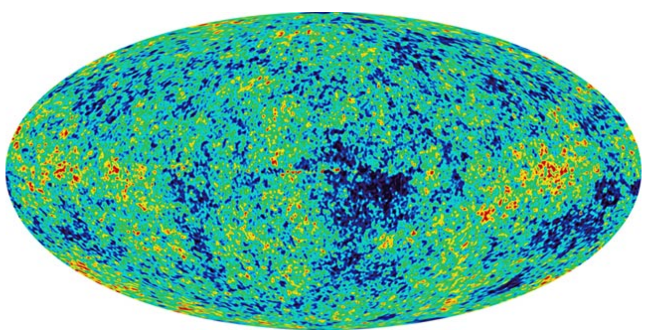
- Pattern of **inhomogeneities in density of galaxies**



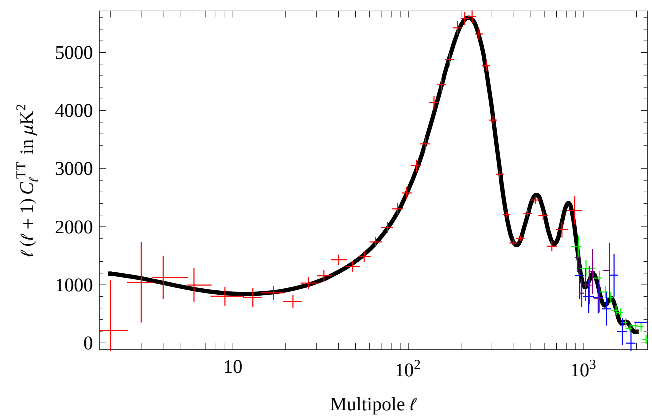
$\leftrightarrow$



- Pattern of **CMB anisotropies** tell $\Omega_{\rm tot} \simeq 1$ and discriminate $\Omega_\Lambda/\Omega_{\rm DM}$



$\leftrightarrow$



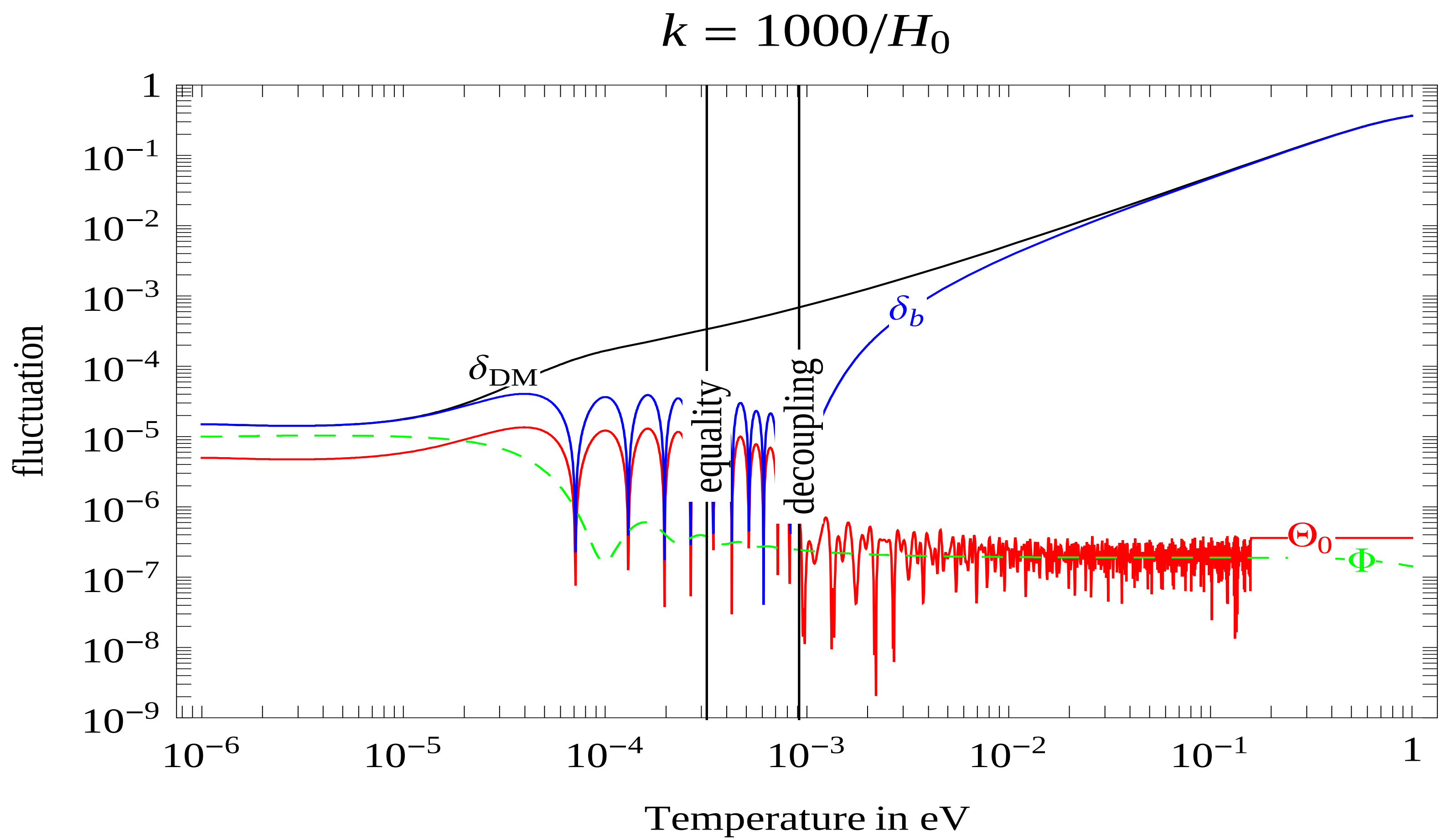
- Hubble diagram with SN shows accelerated expansion: $\Omega_\Lambda \gtrsim \Omega_{\rm DM}$

Dark Matter inhomogeneity in cosmology

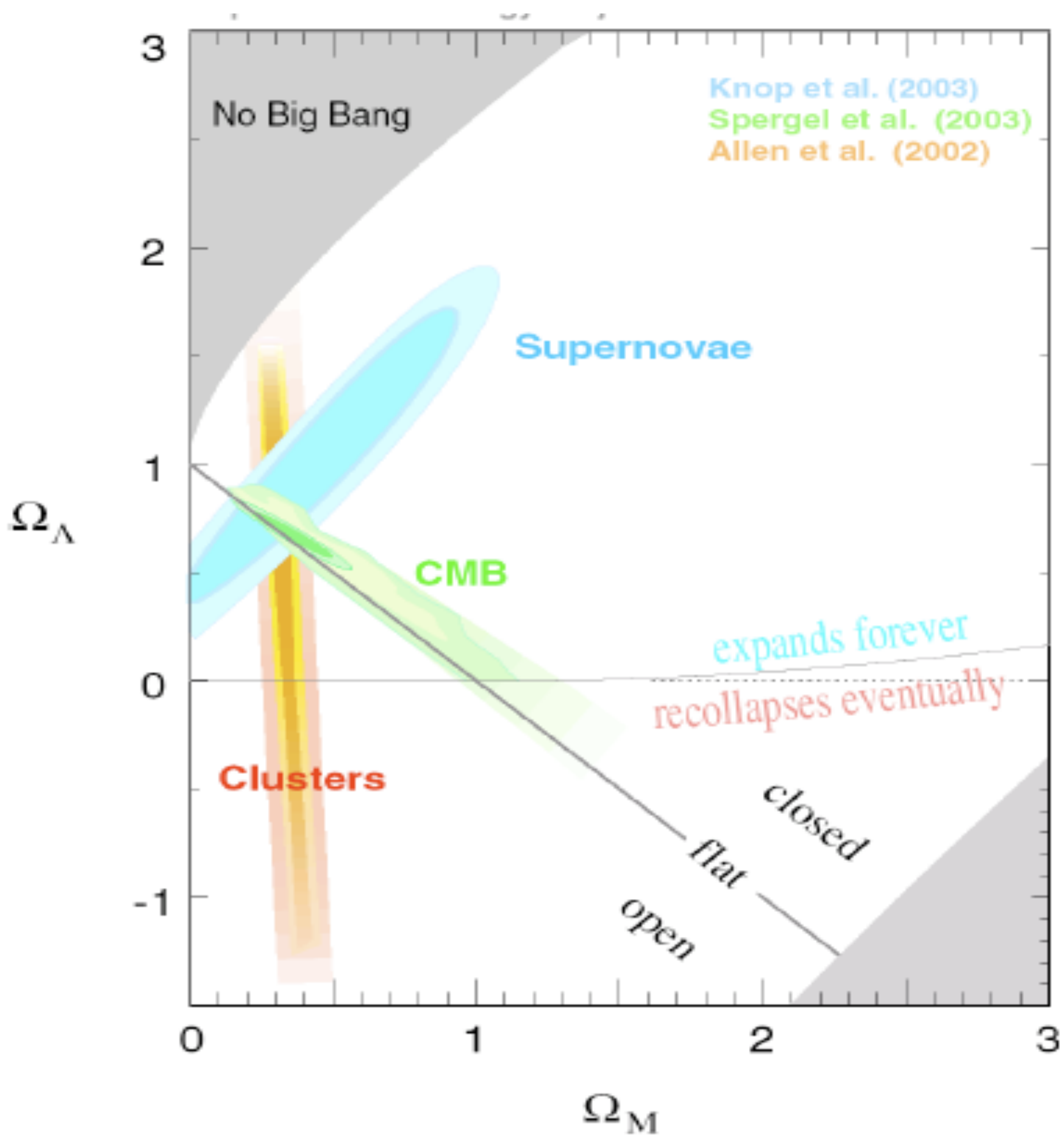
$\rho(x,t) = [1+\sum_k e^{ikx}\delta_k(t)]\rho(t)$ is computable until $\delta_k \ll 1$: $\ddot{\delta}_k + 2H\dot{\delta}_k \simeq 4\pi G \sum \delta_k \rho$

The last term becomes significant after mat/rad equality: DM starts clumping.

Later γ and baryons decouple: matter falls in DM potential, γ remain CMB.



$\Omega_\Lambda \approx 73\%$, $\Omega_{DM} \approx 23\%$, $\Omega_{matter} \approx 4\%$



What Cold Dark Matter is?

DM exists, but so far we have seen only its effects on gravity. Whatever DM is, it couples to gravity via $T_{\mu\nu}$. Seeing some mass does not tell what it is: protons, particles, planets, black holes...

DM is not protons, neutrons, electrons, that interact with photons.

DM is not neutrinos, because cosmology wants Cold DM, $M \gg T_{\rm eq}$, such that it behaves as a pressureless fluid $T_{\mu\nu} \approx \text{diag}(\rho, 0, 0, 0)$ e.g. dust.

Since we do not see it, DM is Dark: negligible interactions with the photon, the gluon, the Z. All SM particles are excluded, even as primordial black holes.

Presumably CDM is some new Matter particle with mass $10\,\text{keV} \lesssim m \lesssim \infty$ and small $\sigma \ll 1/m_p^2$. Whatever particle, cosmology only sees dust.

CDM could be a light coherently oscillating scalar field. Or cold axions...

Cold Dark Matter as thermal relic

What happens to a stable particle at $T < m$?

Scatterings try to give thermal equilibrium

$$n_{\rm DM} \propto \exp(-m/T).$$

But at $T \lesssim m$ they become too slow:

$$\Gamma \sim \langle n_{\rm DM}\sigma\rangle \lesssim H \sim T^2/M_{\rm Pl}$$

Out-of-equilibrium relic abundance:

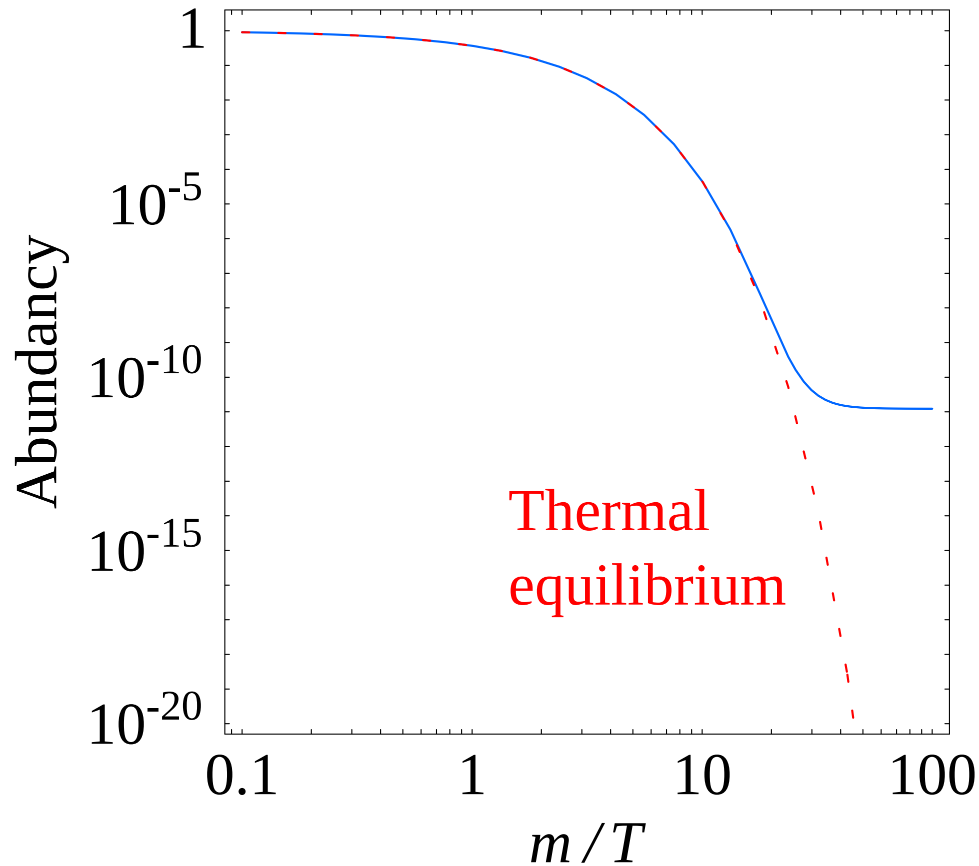
$$\frac{n_{\rm DM}}{n_\gamma} \sim \frac{T^2/M_{\rm Pl}\sigma}{T^3} \sim \frac{1}{M_{\rm Pl}\sigma m}$$

$$\frac{\rho_{\rm DM}}{\rho_\gamma} \sim \frac{m}{T_{\rm now}}\frac{n_{\rm DM}}{n_\gamma} \sim \frac{1}{M_{\rm Pl}\sigma T_{\rm now}}$$

Inserting $\rho_{\rm DM} \sim \rho_\gamma$ and $\sigma \sim g^2/m^2$ fixes

$$m/g \sim \sqrt{T_{\rm now}M_{\rm Pl}} \sim \text{TeV}$$

Testable at LHC + direct + indirect...



The freeze-out DM abundance

Boltzmann equation for $Y = n_{\rm DM}/s$ as function of $z = M/T$:

$$sHz\frac{dY}{dz} = -2(\frac{Y^2}{Y_{\rm eq}^2} - 1)\gamma_{\rm ann}$$

Only the non relativistic limit $v \to 0$ is relevant:

$$\gamma_{\rm ann} \propto \langle \sigma_{\rm ann} v\rangle \to \text{cte } (s\text{-wave}) + v^2 \times \text{cte } (p\text{-wave}) + \cdots$$

The Boltzmann equation simplifies to:

$$\frac{dY}{dz} = -\frac{\lambda}{z^2}(Y^2 - Y_{\rm eq}^2), \qquad \lambda = \left.\frac{\langle \sigma_{\rm ann} v\rangle s}{2H}\right|_{T=M}$$

Approx. solution (weakest wins) in terms of the freeze-out temperature T_f:

$$0.40\frac{\rm eV}{M} \stackrel{?}{=} \frac{n_{\rm DM}(T)}{s(T)} \approx \frac{\sqrt{180/\pi \ {\rm dof}_{\rm SM}}}{M_{\rm Pl}\ T_f \langle \sigma_{\rm ann} v\rangle}, \qquad \frac{M}{T_f} \approx \ln \frac{{\rm dof}_{\rm DM} M M_{\rm Pl} \langle \sigma_{\rm ann} v\rangle}{240\ g_{\rm SM}^{1/2}} \sim 26$$

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 $SU(2)_L$	$U(1)_Y$	Spin	nick-name	DM mass in TeV	Events at LHC $\int \mathcal{L}\,dt = 100$/fb	$\sigma_{\rm SI}$ in $10^{-45}\,{\rm cm}^2$
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 below a TeV

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 $\Omega_{\rm DM}$, unless:

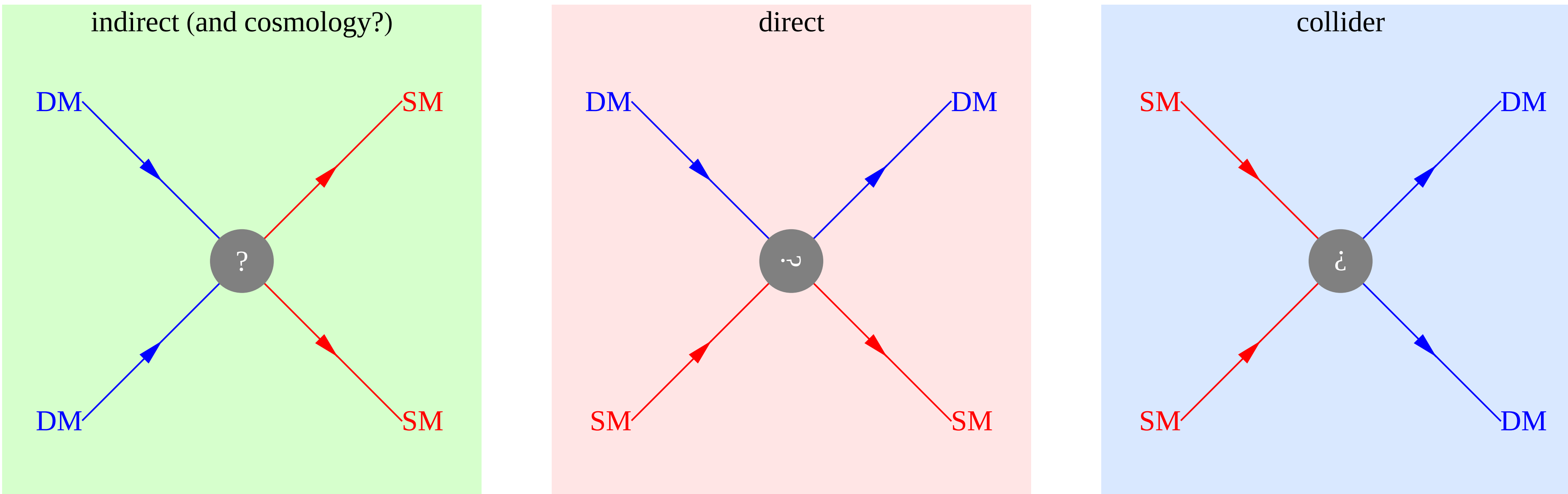
- Extra solution at $M < M_W$ such that too large $\sigma(\text{DM DM} \to W^+W^-)$ is kinematically suppressed. Not fully excluded by LEP. E.g. 'inert doublet'

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

- DM as singlet + extra coupling e.g. bino$_{\rm DM}$-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).

Testing TeV-scale dark matter



Where DM is today?

Matter interacts and cools forming galaxies. DM does not interact and should make a spherical halo, possibly with smaller sub-halos. The local DM density depends on galactic physics. N-body simulations [mpeg] give this sort of results:

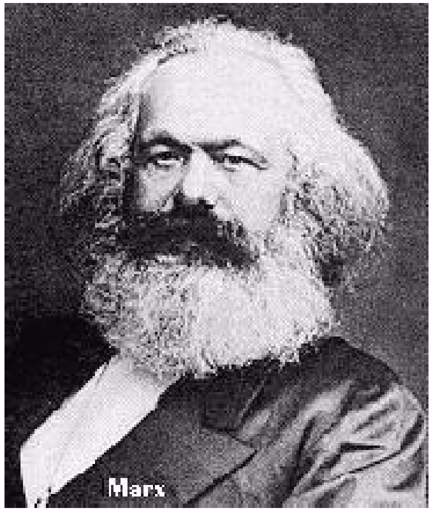
DM velocity: $v \approx 10^{-3}$ from gravitational infall. Boltzmann up to v_{escape}?

The Milky Way DM density profile

We live at $r_\odot = 8.5\,\mathrm{kpc}$ from the Galactic Center. Rotation curves tell

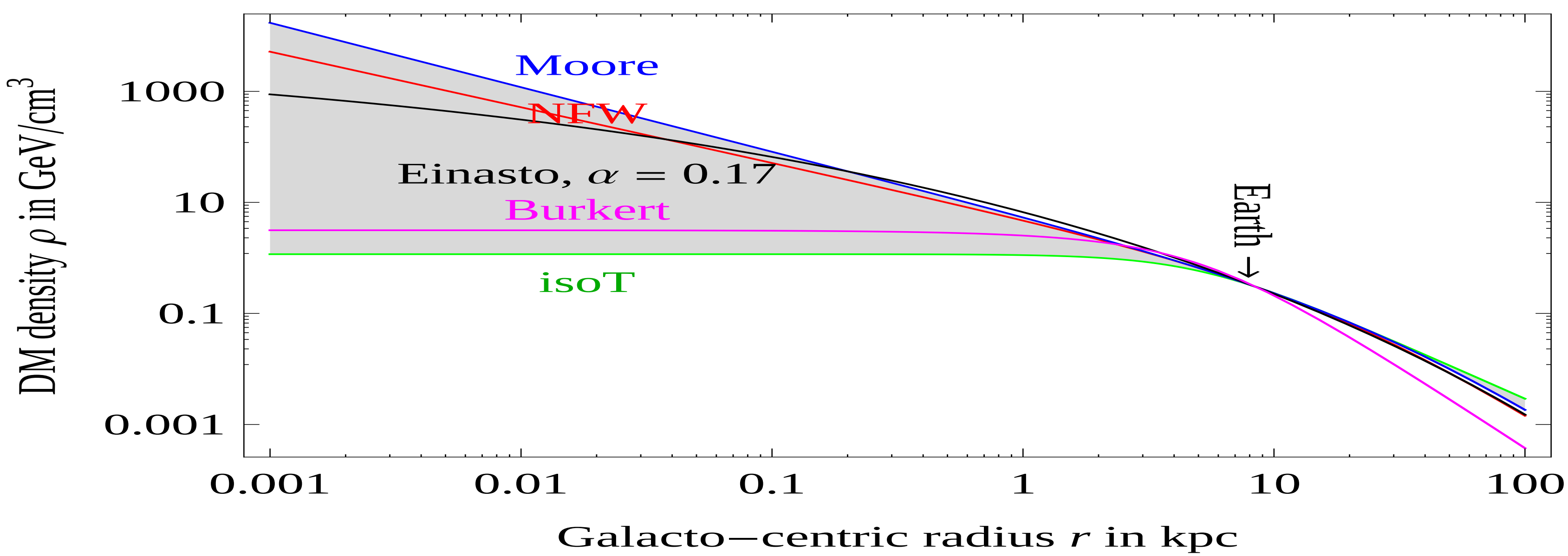
$$\rho_\odot \equiv \rho(r_\odot) \approx (0.3 \pm 0.1)\,\mathrm{GeV/cm^3} \approx \text{matter density.}$$

About 10000 times higher than the cosmic average. Closer to the GC matter dominates so observations do not tell ρ. Theory is also uncertain, because DM is like capitalism according to Marx: a gravitational system has no ground state so everything is (slowly) collapsing to a point and maybe $\rho(r \to 0) = \infty$.



Guesses for the DM density profile $\rho(r)$

$$\frac{\rho(r)}{\rho_\odot} \stackrel{?}{=} \begin{cases} (1+r_\odot^2/r_s^2)/(1+r^2/r_s^2) & \text{isothermal, } r_s = 5\,\text{kpc} \\ \hookrightarrow \cdot(1+r_\odot/r_s)/(1+r/r_s) & \text{Burkert, } r_s = 5\,\text{kpc} \\ \exp(-2[(r/r_s)^\alpha - (r_\odot/r_s)^\alpha]/\alpha) & \text{Einasto, } r_s = 20\,\text{kpc, } \alpha = 0.17, \\ (1+r_\odot/r_s)^2/(1+r/r_s)^2(r_\odot/r) & \text{Navarro-Frenk-White, } r_s = 20\,\text{kpc} \\ (1+r_\odot/r_s)^2/(1+r/r_s)^2(r_\odot/r)^{1.16} & \text{Moore, } r_s = 30\,\text{kpc} \end{cases}$$



Einasto or NFW are favored by N-body simulations, at least at $r >$ kpc.
Burkert is possibly favored by rotation curves of other galaxies.
Moore (isoT) profiles allow to get large (small) DM signals from the GC.

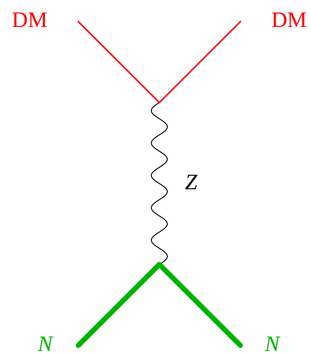
Direct DM detection

Direct DM detection

DM collides with nuclei $\mathcal{N}$ of mass $m = Am_N$ giving them an energy $\sim \mu v^2 \sim$ keV where $\mu = mM/(m+M)$ is the reduced mass: best if $M \sim m \sim 100\,\text{GeV}$. Scattered nuclei can be seen by underground calorimeter or charge or phonons.

keV is low enough that the cross section is coherently enhanced:

$$\sigma(\text{DM}\,\mathcal{N} \to \text{DM}\,\mathcal{N}) = \Bigg|$$



$$\Bigg|^2 \sim \ (G_{\text{F}} m Y_{\text{DM}})^2 \sim 10^{-35}\,\text{cm}^2$$

Seems testable with kg-scale detectors ($N \sim 10^{26}$ nucleons):

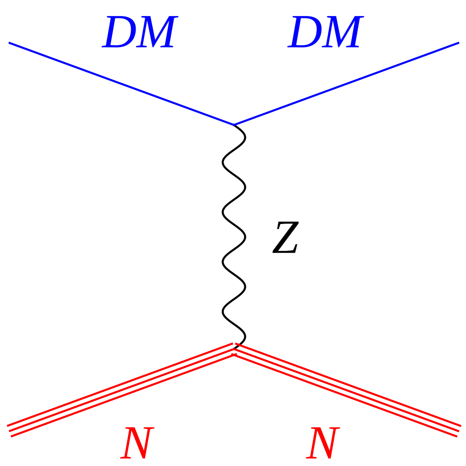
$$\text{events} \sim N\frac{\rho_\odot}{M} v\sigma \sim \frac{1000}{\text{kg}\cdot\text{yr}}\frac{\sigma}{10^{-35}\,\text{cm}^2}\frac{\rho_\odot}{10^{-25}\text{g}/\,\text{cm}^3}\frac{v}{200\,\text{km}/\,\text{sec}}\frac{m}{100\,\text{GeV}}$$

$$\frac{dN_{\text{ev}}}{dE} = \frac{\sigma}{2\mu^2}\frac{\rho_\odot}{M}|F_{\text{nuc}}(E)|^2 \int_{v_{\text{min}}(E)}^{\infty} \frac{dN_{\text{DM}}/dv}{v} dv \sim \exp(-E/E_*)$$

Direct DM detection: key parameter

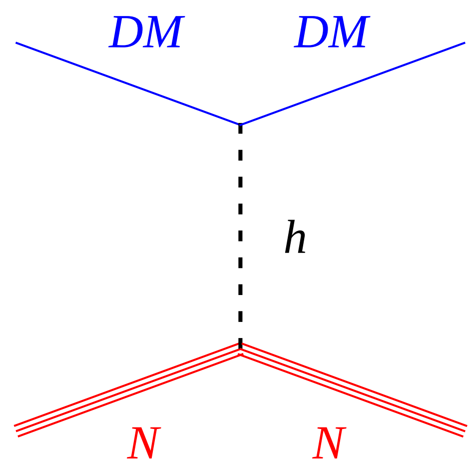
$\sigma_{\rm SI}$ = spin-independent DM/nucleon cross section

allows to compare theory with experiments: DM/nucleus cross section $= A^2\sigma_{\rm SI}$.



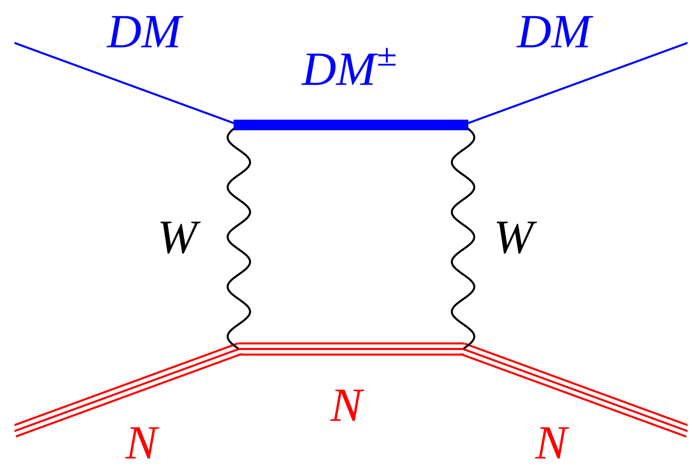
tree, vector

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



tree, scalar

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

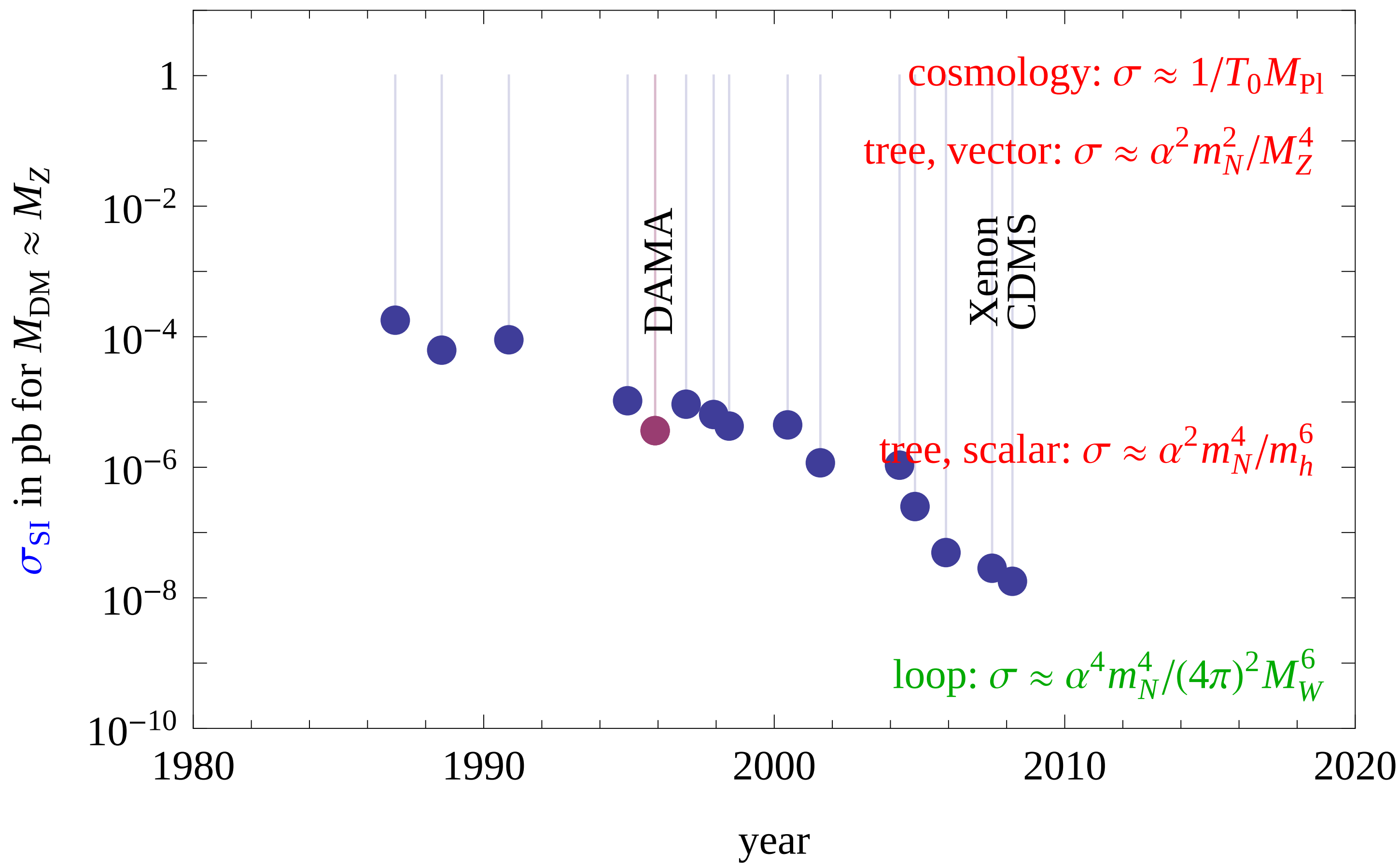


loop

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

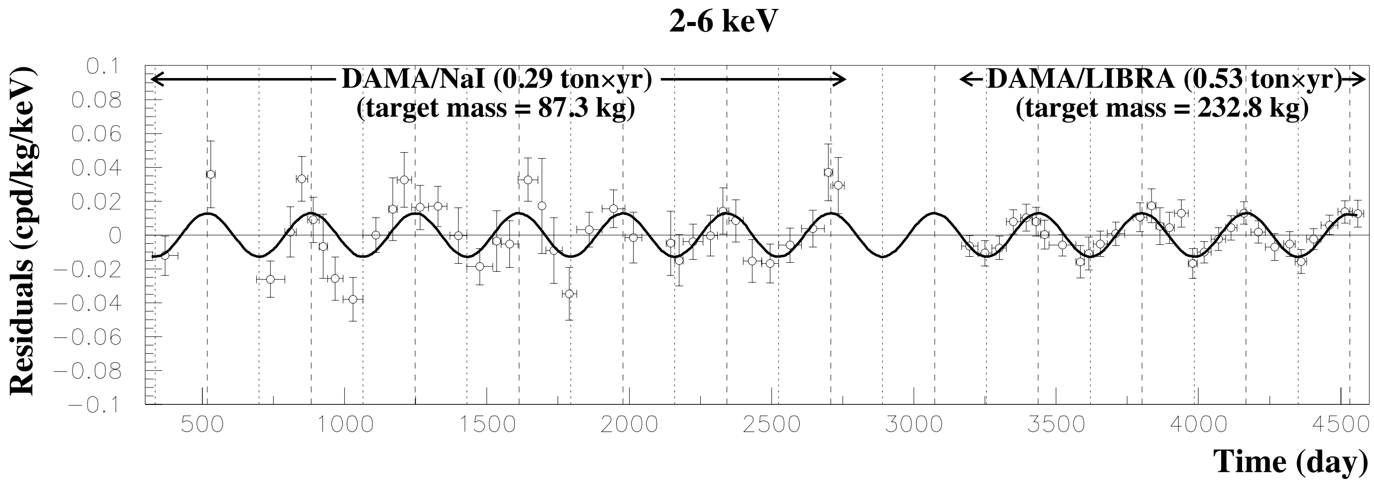
The vector effect vanishes if DM is real (e.g. a Majorana fermion).

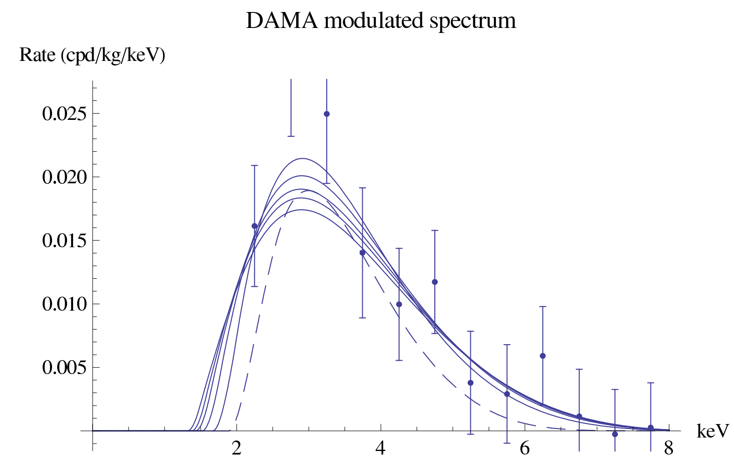
Experimental progress



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

DAMA: annual modulation seen at 8σ





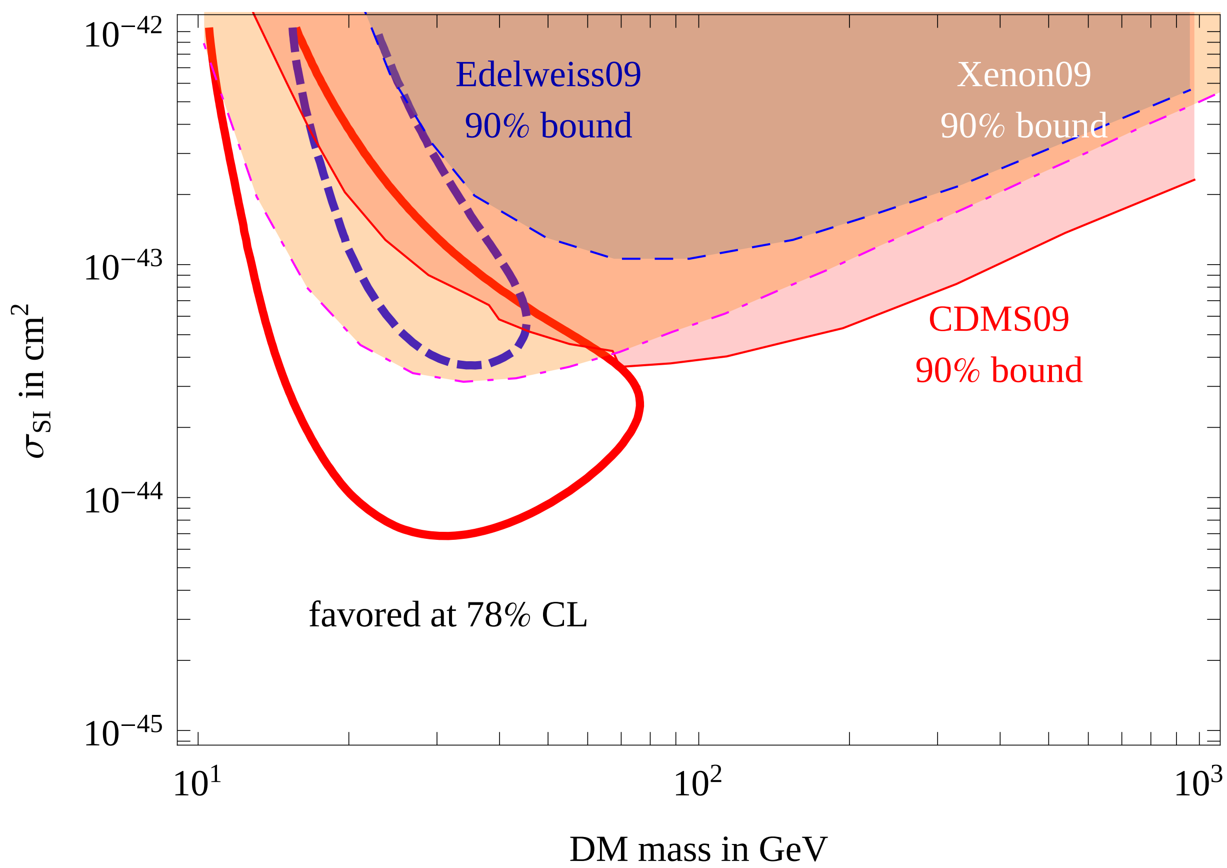
The phase is right: peak on 2 june when $|\vec{v}_{\text{earth/sun}} + \vec{v}_{\text{sun}}|$ is maximal.
The energy spectrum of the 5% modulation is not exponential; peak at 3 keV.

- Could be due to DM form factor: $F_{\text{DM}} \sim q^2$ or q^4 rather than q^0.

- or to DM inelasticity: DM $N \to$ DM$'N$ with $\frac{1}{2}\mu v^2 > M' - M \sim$ keV.

Hardly compatible with all other experiments, although channeling might help.
Suspect: the DAMA total rate also peaks at 3 keV: probably due to ^{40}K contamination in NaI crystals. Borexino could shield ^{40}K, DAMA forbids.

Present status



CDMS has 2 events: **1.4σ excess** over the expected bckg of 0.8 events
Edelweiss has 1 event: **1.4σ excess** over the expected bckg of 0.15 events
The energy spectrum of the 2+1 events (!) favors lighter DM.

Indirect DM detection

Indirect signals of Dark Matter

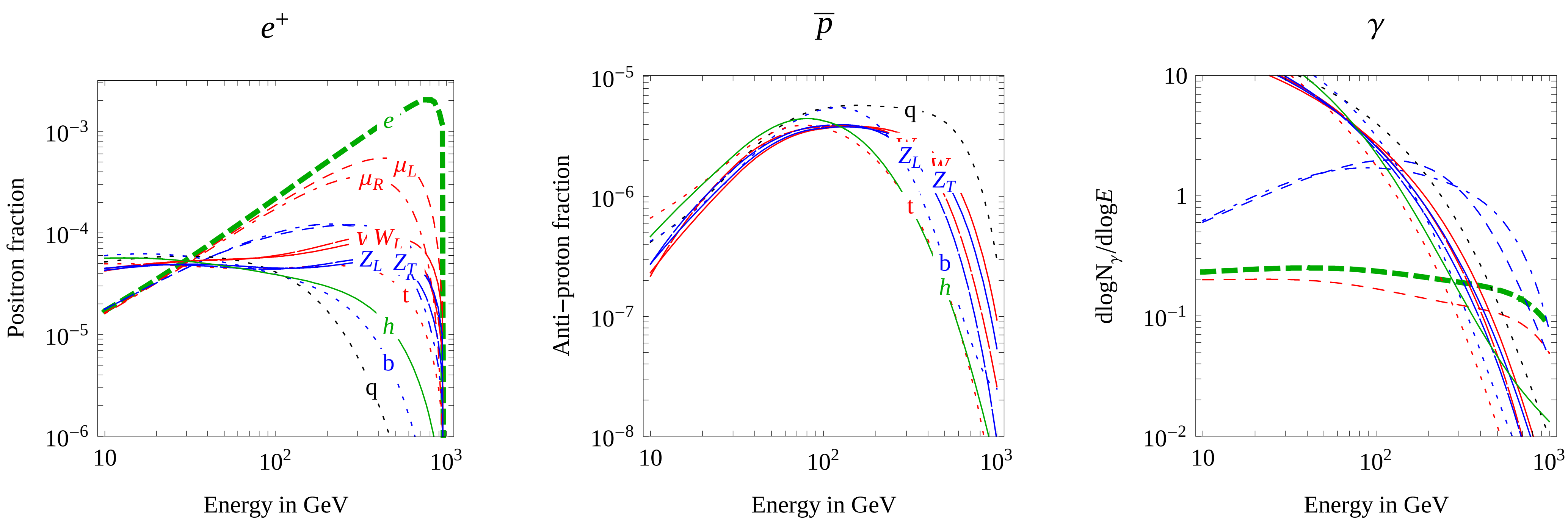
DM DM annihilations in our galaxy might give detectable γ, e^{+}, $\bar{p}$, $\bar{\mathrm{d}}$.

Final state spectra for $M = 1$ TeV

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

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

Energy spectra of the stable final-state particles:

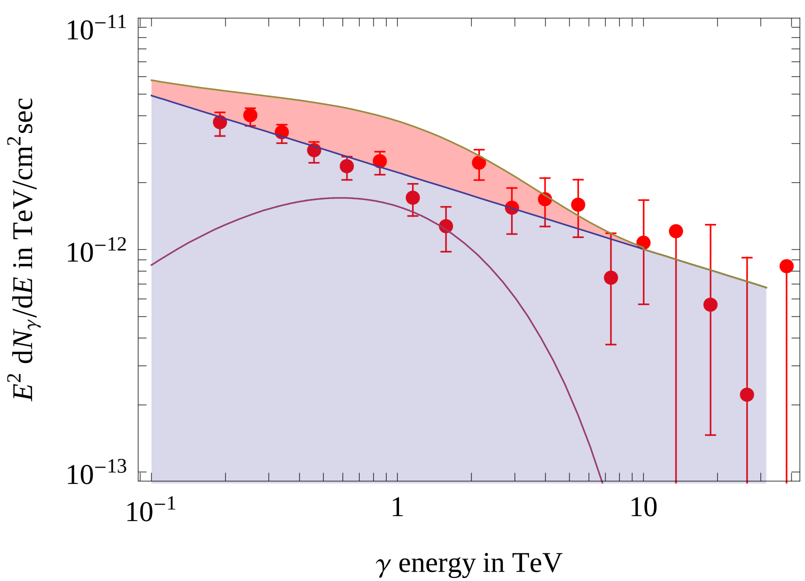


Indirect detection: γ

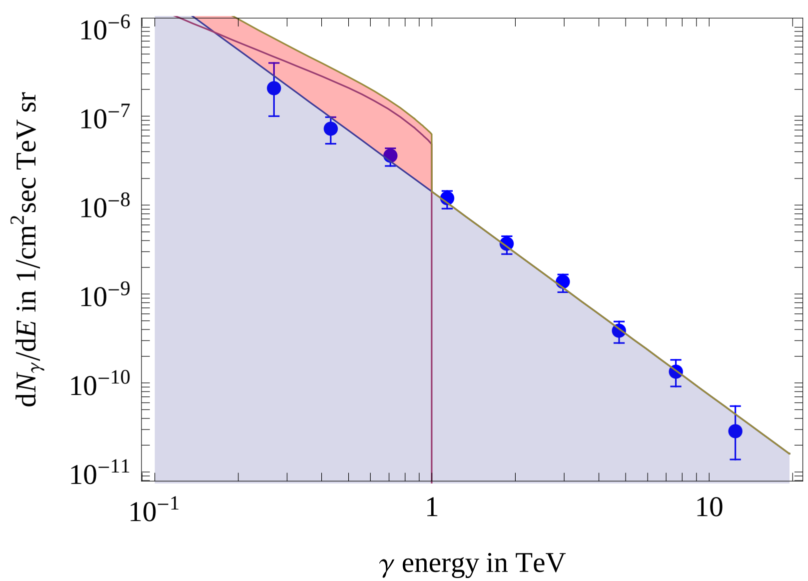
$$\Phi_\gamma = \frac{c}{8\pi}\frac{\rho_\odot^2}{M_{\rm DM}^2} J \langle\sigma v\rangle \frac{dN_\gamma}{dE}, \qquad J = \int_\Omega d\Omega \int_{\rm line-of-sight} \frac{ds}{r_\odot}\left(\frac{\rho}{\rho_\odot}\right)^2$$

The uncertain J encodes astrophysics: for the Galactic Center with $\Omega = 10^{-3}$ it equals $J = 13.5$ (isoT) or 1380 (NFW). DM γ energy spectrum: a continuum plus a line at $E = M$ from DM DM $\to \gamma\gamma$. Photons observed up to 20 TeV by HESS look like astrophysical background (NFW, $\sigma v = 10^{-23}\,{\rm cm}^3/{\rm sec}$):

a) M = 10 TeV into W^+W^-, Galactic Center



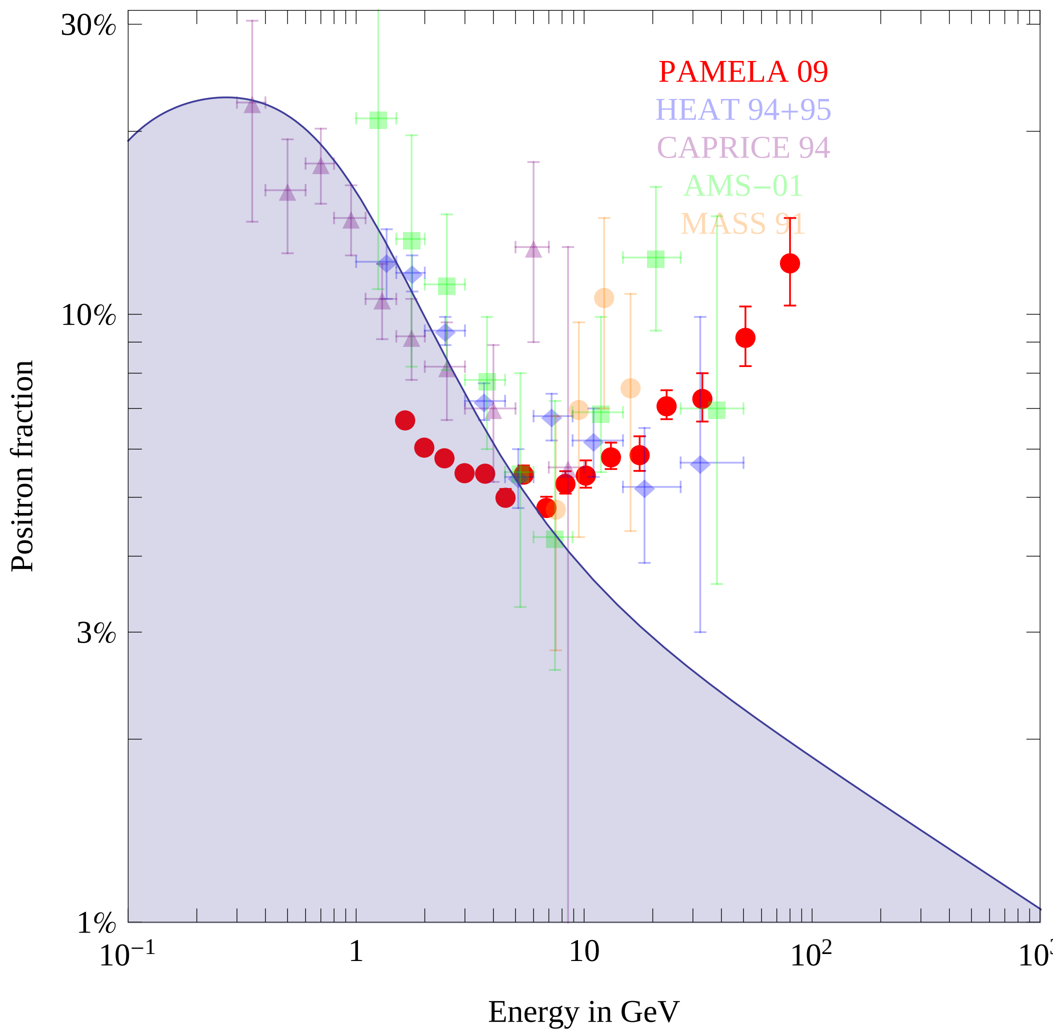
b) M = 1 TeV into $\mu^-\mu^+$, Galactic Ridge



Indirect detection: PAMELA $e^+/(e^+ + e^-)$

PAMELA is a spectrometer + calorimeter sent to space. It can discriminate $e^+, e^-, p, \bar{p}, \ldots$ and measure their energies up to 100 GeV. Below 10 GeV the flux depends on solar activity. Astrophysical backgrounds should give a positron fraction that decreases with energy, unless there is a nearby pulsar.

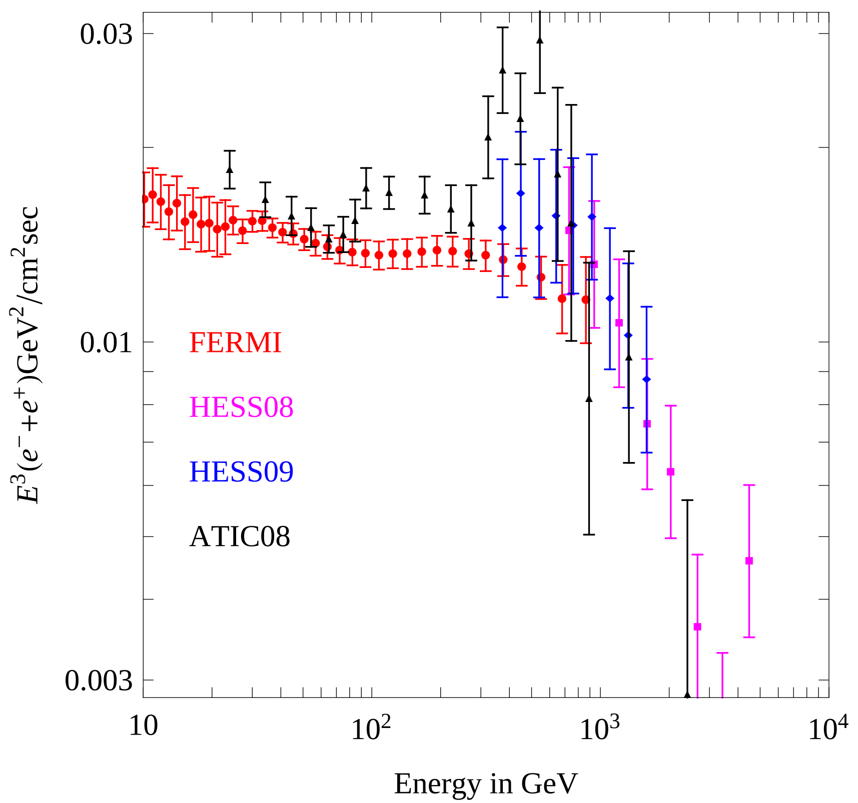
Growing excess above 10 GeV



The PAMELA excess suggest that it might manifest in other experiments: if e^+/e^- continues to grow, it reaches $e^+ \sim e^-$ around 1 TeV...

$e^+ + e^-$: FERMI and HESS

These experiments cannot discriminate e^+/e^-, but probe higher energy.



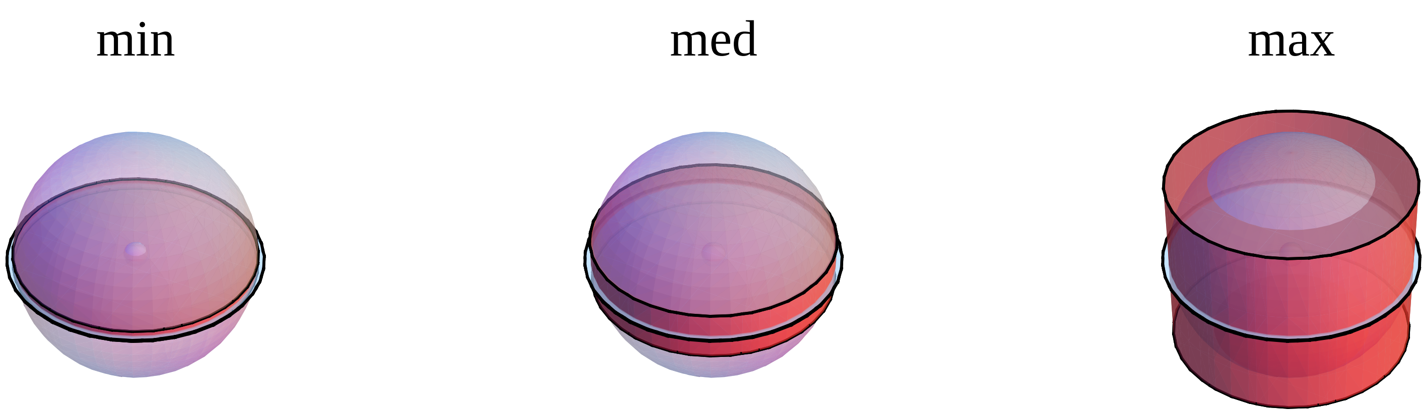
Hardening at 100 GeV and softening at 1 TeV

Propagation of $e^{\pm}$ in the galaxy

$\Phi_e = v_e f/4\pi$ where $f = dN/dV\, dE$ obeys: $-K(E)\cdot\nabla^2 f - \frac{\partial}{\partial E}(\dot{E} f) = Q$.

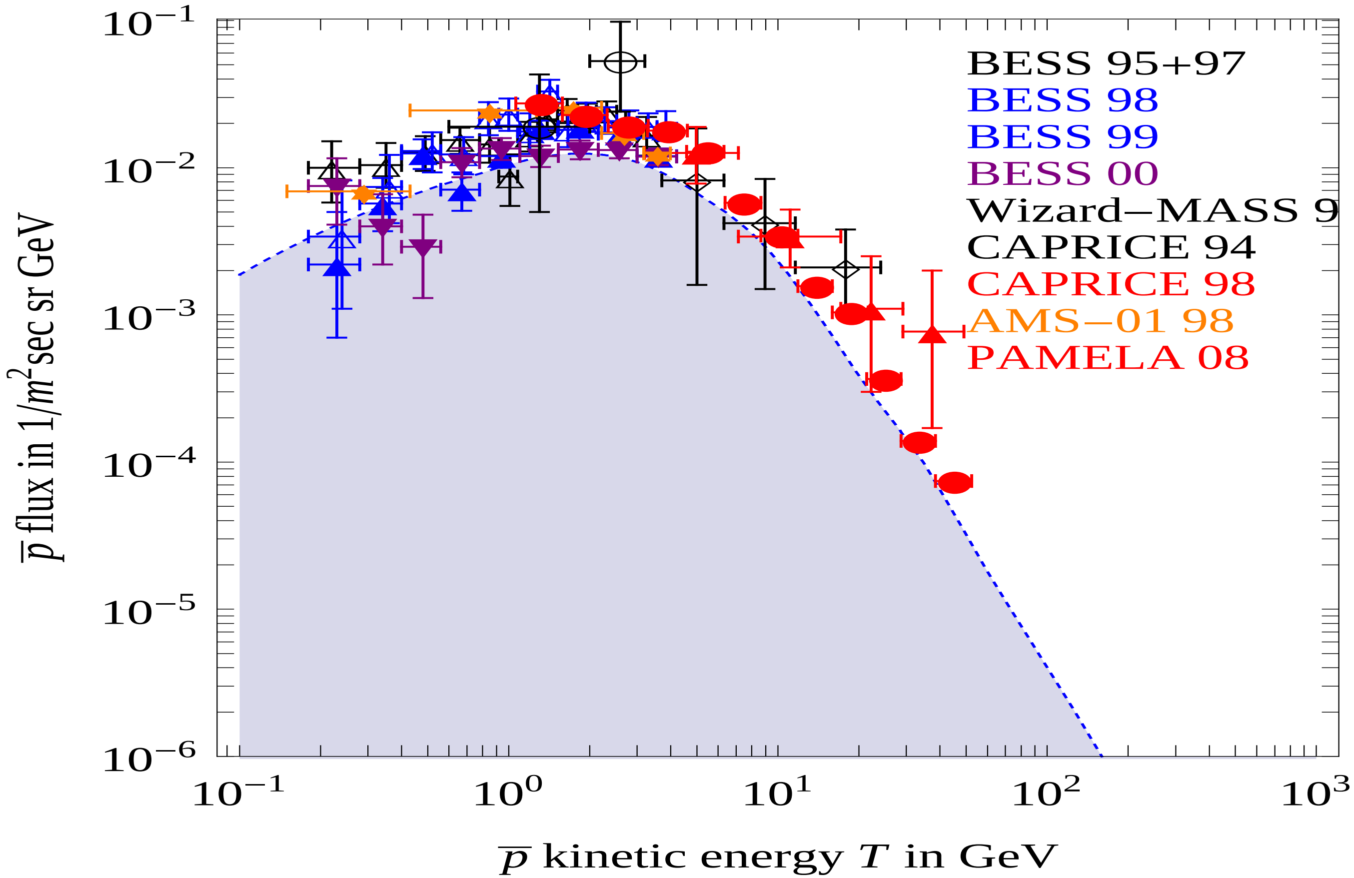
- **Injection**: $Q = \frac{1}{2}\left(\frac{\rho}{M}\right)^2 \langle\sigma v\rangle \frac{dN_e}{dE}$ from DM annihilations.
- **Diffusion** coefficient: $K(E) = K_0(E/\,\text{GeV})^\delta \sim R_{\text{Larmor}} = E/eB$.
- **Energy loss** from IC + syn: $\dot{E} = E^2 \cdot (4\sigma_T/3m_e^2)(u_\gamma + u_B)$.
- **Boundary**: f vanishes on a cylinder with radius $R = 20\,$kpc and height $2L$.

Propagation model	δ	K_0 in kpc^2/Myr	L in kpc	V_{conv} in km/s
min	0.85	0.0016	1	13.5
med	0.70	0.0112	4	12
max	0.46	0.0765	15	5



Indirect detection: PAMELA $\bar{p}$

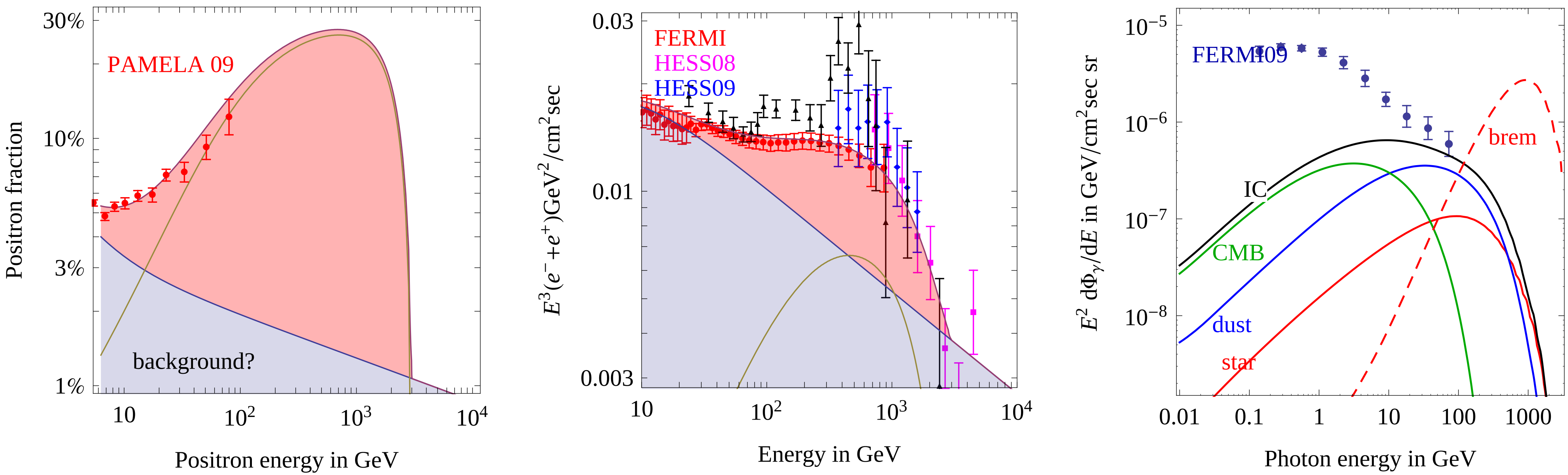
Consistent with background



Explaining the $e^{\pm}$ excesses

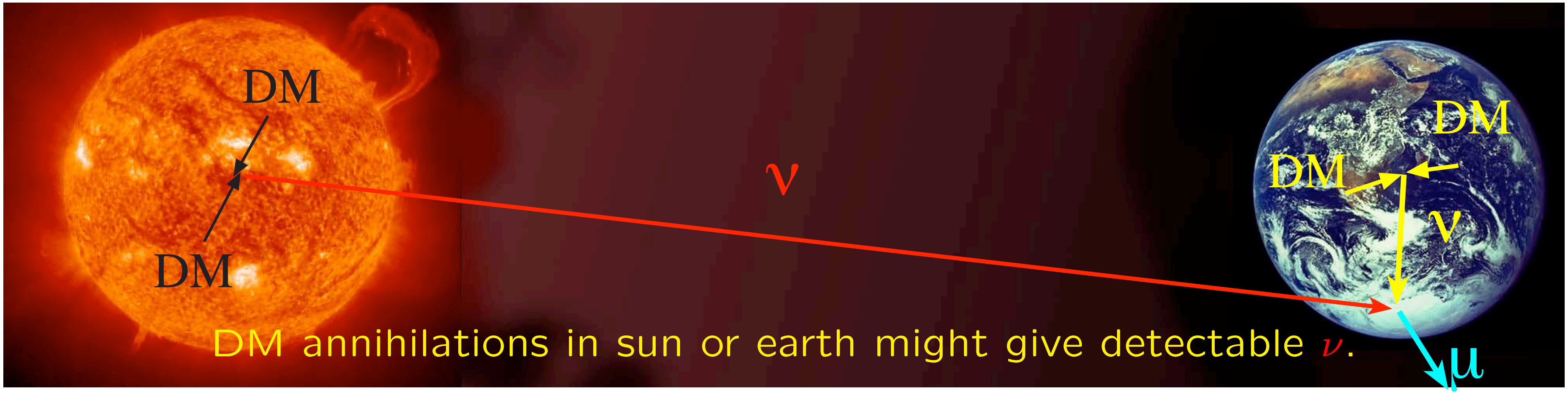
Due to DM? Only if DM annihilates or decays into leptons:

DM with $M = 3.$ TeV that annihilates into $\tau^+\tau^-$ with $\sigma v = 1.8 \times 10^{-22}$ cm^3/s



and if $\rho(r)$ is quasi-constant, otherwise the DM solution is excluded by GC γ

DM accumulated also in the sun and in the earth



Indirect detection: ν

Once captured, DM fall thermalized around the center of the earth and sun:

$$N_{\rm DM}(r) \propto e^{-r^2/R_{\rm DM}^2}, \qquad R_{\rm DM} = \sqrt{\frac{100\,\text{GeV}}{m_{\rm DM}}} \times \begin{cases} 0.08 R_{\rm earth} \\ 0.01 R_{\rm sun} \end{cases}$$

$$\dot N_{\rm DM} = \Gamma_{\rm capt} - \Gamma_{\rm ann} N_{\rm DM}^2$$

$$\Gamma_{\rm ann}^{\rm sun} \approx \frac{\langle \sigma_{\rm DM\,DM} v\rangle}{17 R_{\rm DM}^3} \qquad \Gamma_{\rm capt}^{\rm sun} \approx \frac{10^{28}}{\rm yr}\frac{\sigma_{{\rm DM}\,N}}{10^{-6}\,\text{pb}}\frac{\rho_{\rm DM}}{0.3\frac{\rm GeV}{\rm cm^3}}\left(\frac{270\,\frac{\rm km}{\rm sec}}{v_{\rm DM}}\right)^3\left(\frac{100\,\text{GeV}}{m_{\rm DM}}\right)^2$$

Equilibrium $\dot N_{\rm DM} = 0$ is reached after $t \gtrsim (\Gamma_{\rm capt}\Gamma_{\rm ann})^{-1/2}$ (often ok in the sun)

Then the DM annihilation rate equals $\Gamma_{\rm capt} \propto m_{\rm DM}^{-2}$

- Astrophysical uncertainties (mainly $v_{\rm DM}$, $\rho_{\rm DM}$): $\sim$ one order of magnitude.
- The earth is closer, the sun is bigger: both could be good DMν sources.
- SUSY scatter plots: rate $\sim [10^{-6} \div 100] \times$ (present bounds).
- IceCUBE will improve by 10^2, down to atmospheric and solar backgrounds.

DM at colliders

DM at LHC

DM is probably stable thanks to a Z_2 symmetry: produced in couples.

DM behaves like ν: carries away missing transverse energy $> 2M$.

If only DM is produced, nothing allows to tag the event.

If DM is the lightest of a new set of particles (SUSY), one has bigger cross sections and some tag.

Another possibility is "gravitino DM": the lightest SUSY particle is not DM, might be charged, and decay into "gravitinos" with life time $\tau \gtrsim$ m.