Dark Matter

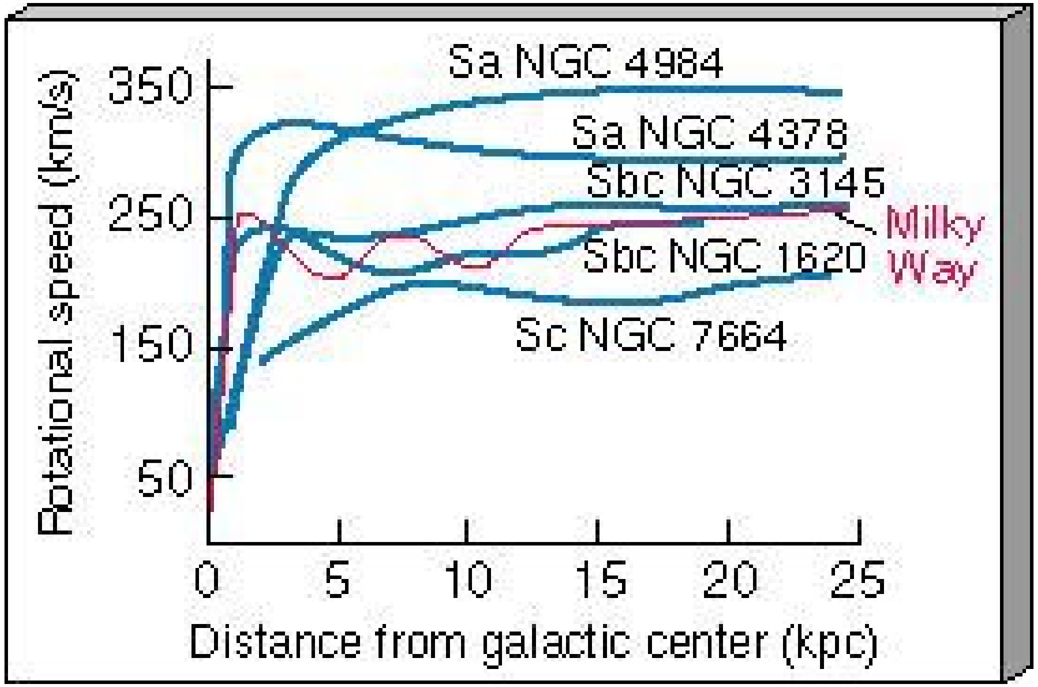
1) Evidences: mini/midi/maxi
2) Cosmology and astrophysics
3) Direct detection?
4) Indirect detection?
5) Production at LHC?

Alessandro Strumia, Roma, May 12, 2011

Evidences for Dark Matter: mini

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

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



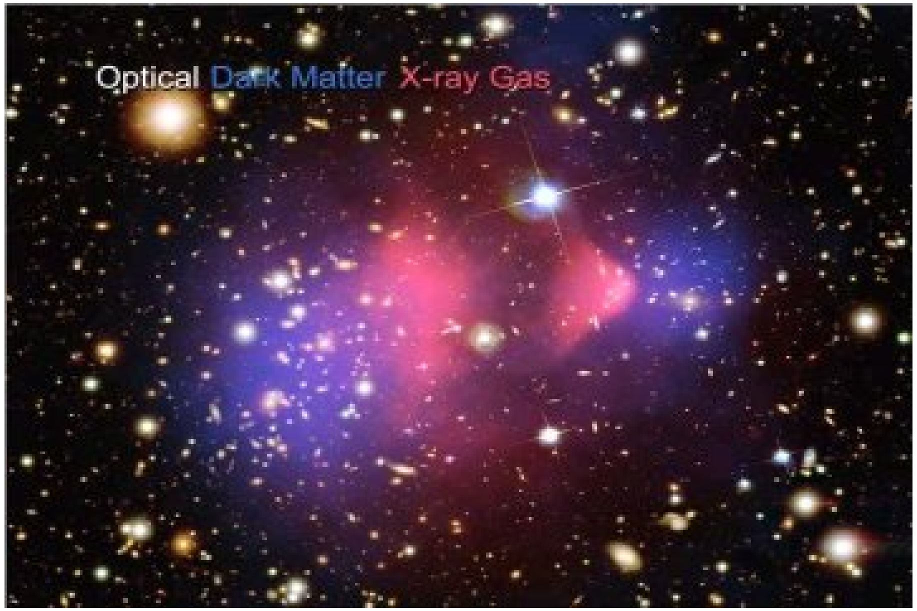
Evidences for Dark Matter: midi

- 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]

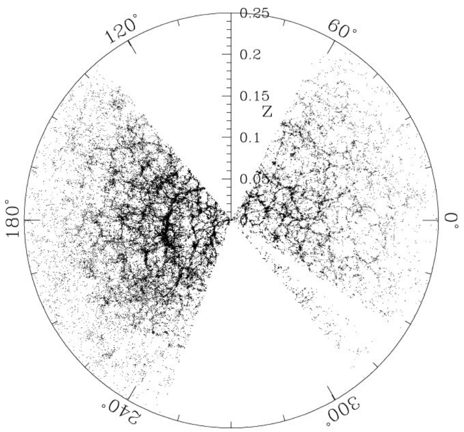


bullet.mpg

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

Evidences for Dark Matter: maxi

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



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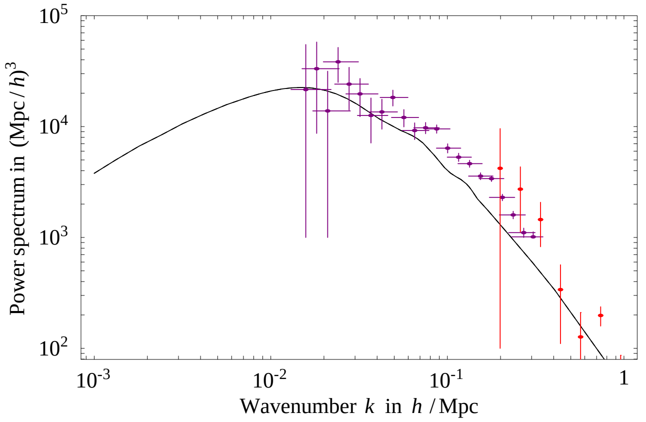
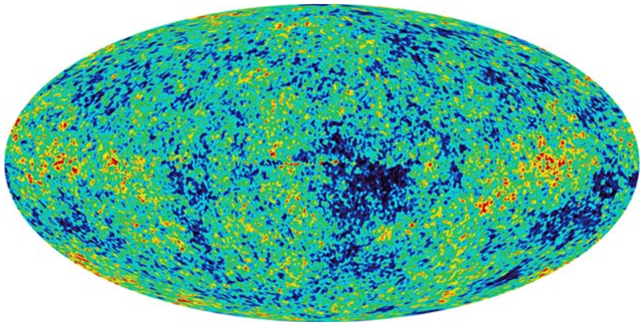


- Pattern of **CMB anisotropies** tell $\Omega_{\text{tot}} \simeq 1$ and discriminate $\Omega_\Lambda/\Omega_{\text{DM}}$



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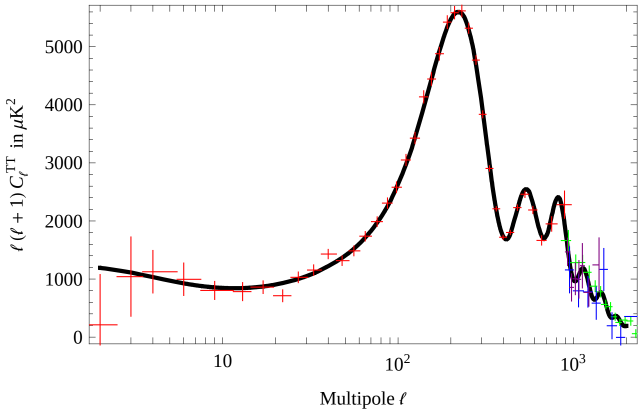
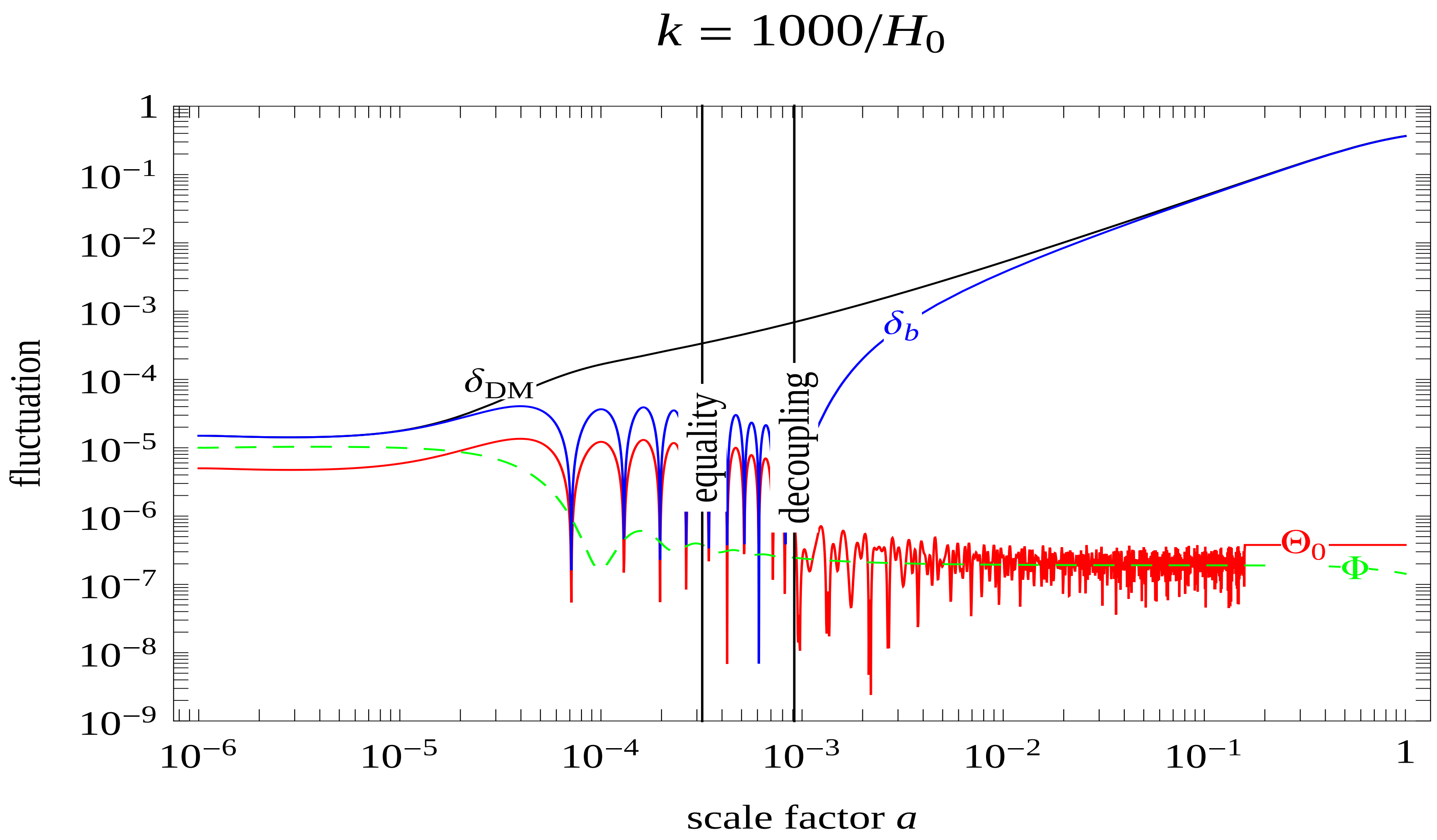


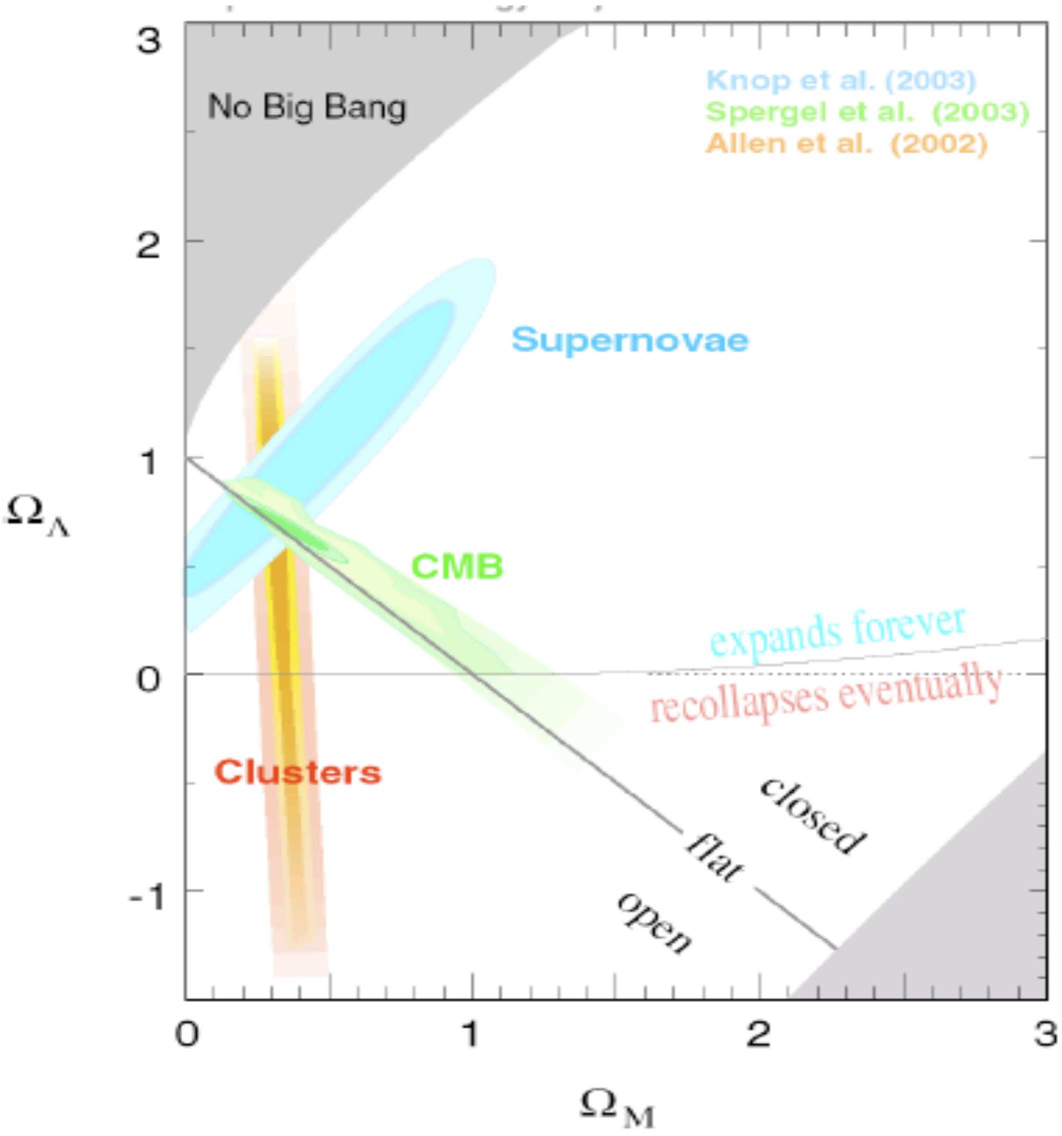
- Hubble diagram with SN shows accelerated expansion: $\Omega_\Lambda \gtrsim \Omega_{\text{DM}}$

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 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:

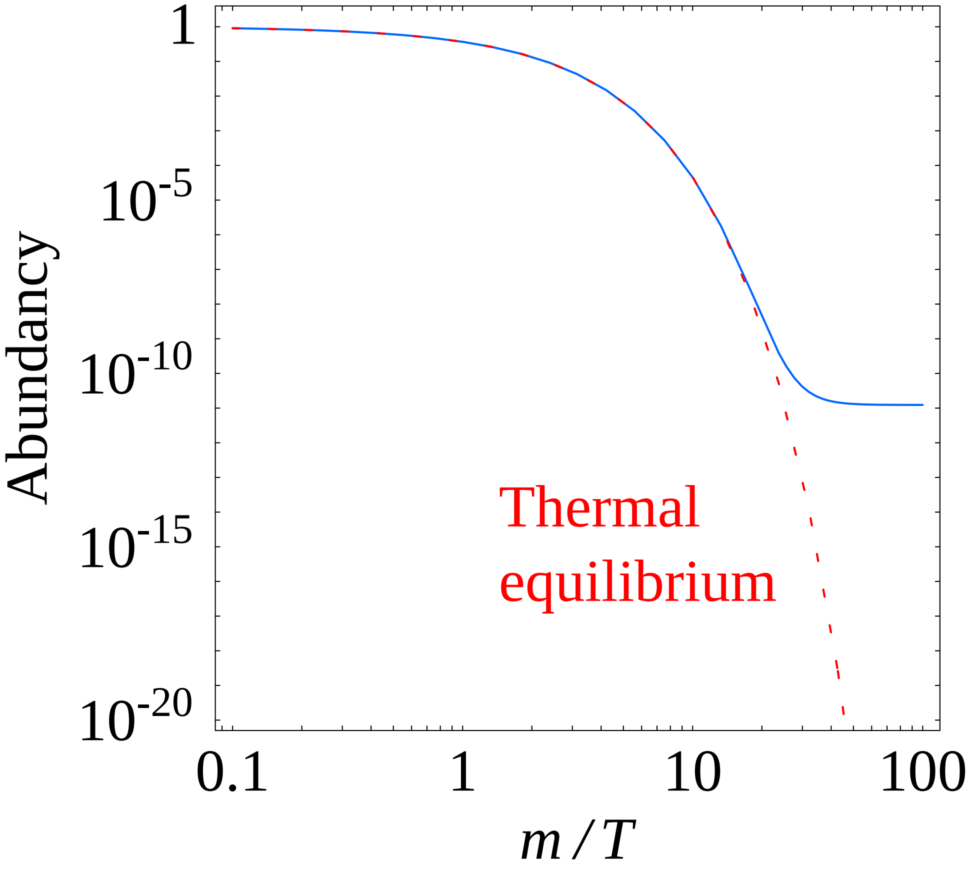
$$\frac{n_{\rm DM}}{n_\gamma} \sim \frac{T^2/M_{\rm Pl}\sigma}{T^3} \sim \frac{1}{M_{\rm Pl}\sigma m}$$

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

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:

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

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

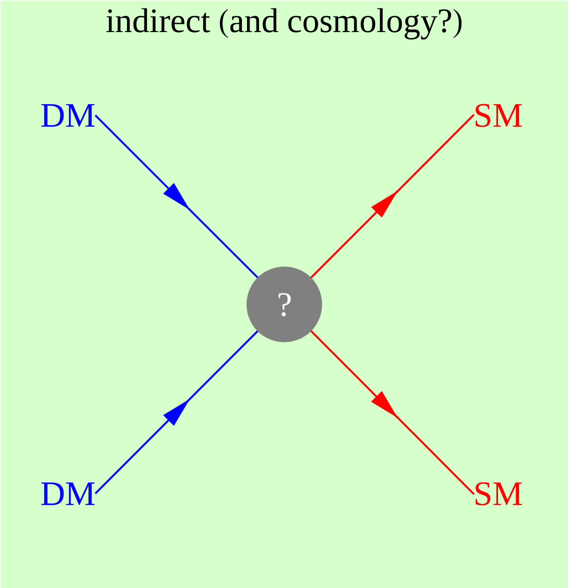
- LHC can make many gluinos that decay into DM, maybe slowly (gravitino).

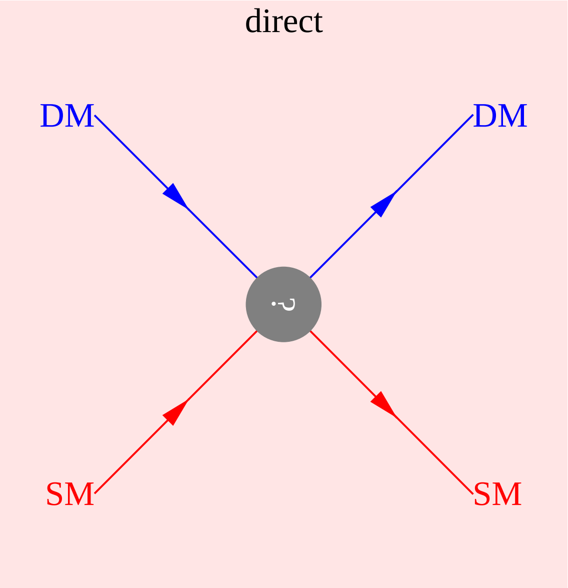
3 paths towards TeV-scale dark matter

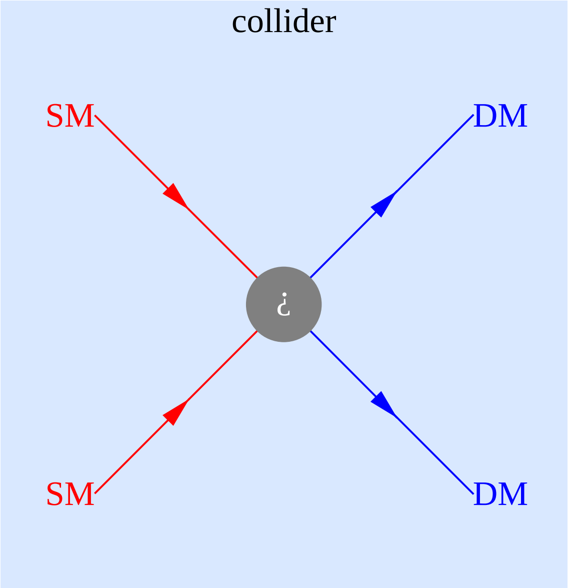
from the sky

from the underworld

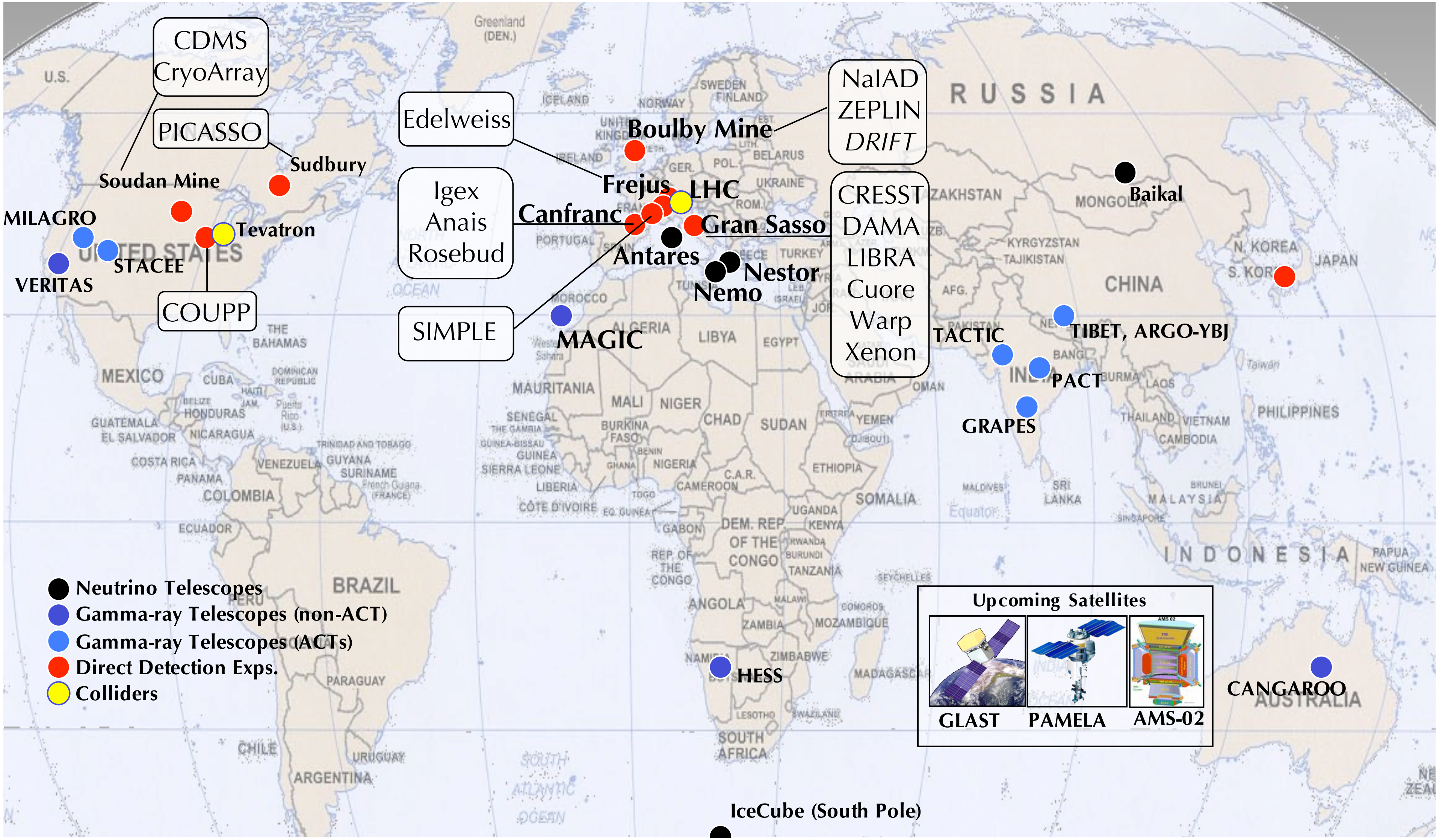
from CERN







DM is. Messianic awaiting for the coming: a few claims/year. Beware to fake Messiahs: “*And they shall turn away their ears from the truth, and shall be turned unto fables*” Timothy 4: 3,4.


CDMS
CryoArray
PICASSO
Sudbury
Soudan Mine
MILAGRO
Tevatron
STACEE
VERITAS
COUPP
Edelweiss
Igex
Anais
Rosebud
SIMPLE
Boulby Mine
Frejus
LHC
Canfranc
Gran Sasso
Antares
Nestor
Nemo
MAGIC
NaIAD
ZEPLIN
DRIFT
CRESST
DAMA
LIBRA
Cuore
Warp
Xenon
Baikal
TIBET, ARGO-YBJ
TACTIC
PACT
GRAPES
HESS
CANGAROO
IceCube (South Pole)
Upcoming Satellites
GLAST
PAMELA
AMS-02
● Neutrino Telescopes
● Gamma-ray Telescopes (non-ACT)
● Gamma-ray Telescopes (ACTs)
● Direct Detection Exps.
○ Colliders

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:

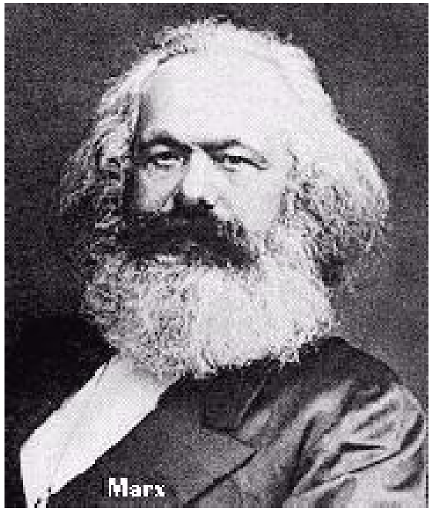
DM velocity: $v \approx 10^{-3}$ from gravitational infall. Boltzmann up to v_{escape}?

The Milky Way DM density profile

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

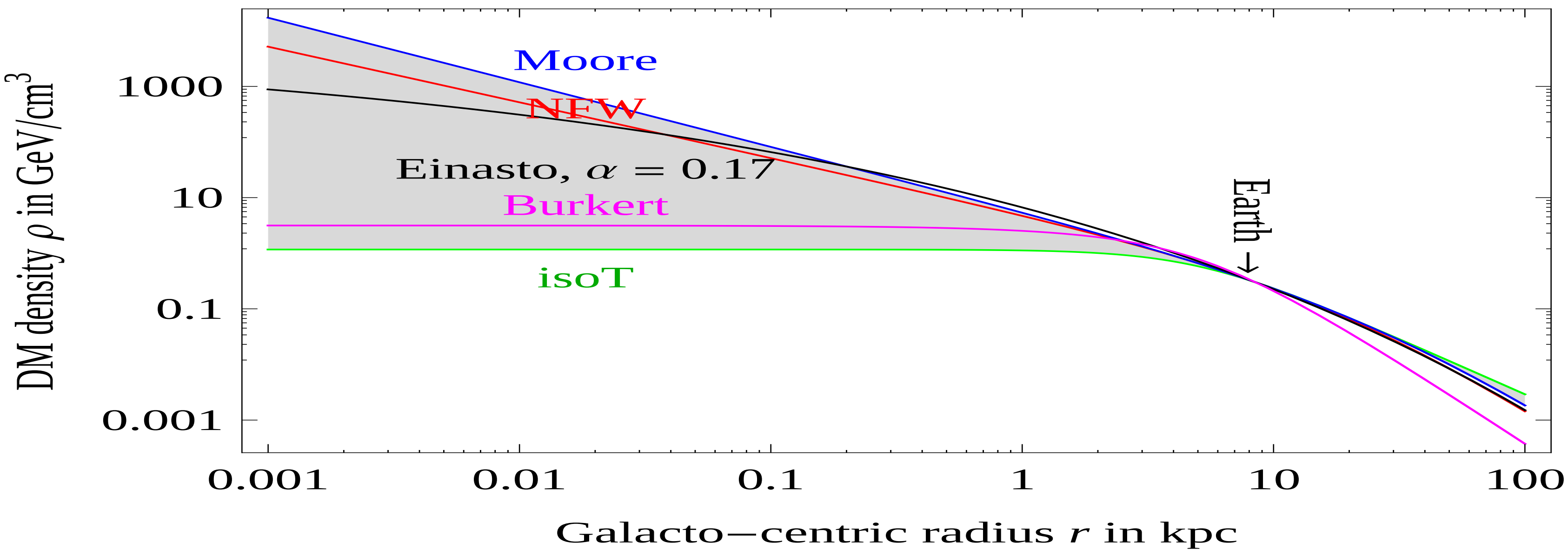
$$\rho_\odot \equiv \rho(r_\odot) \approx (0.3 \pm 0.1)\,\text{GeV}/\text{cm}^3 \approx \text{matter density.}$$

About 10000 times higher than the cosmic average. Closer to the GC matter dominates so observations do not tell ρ. Theory too is 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 $\rho(r)$

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



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.

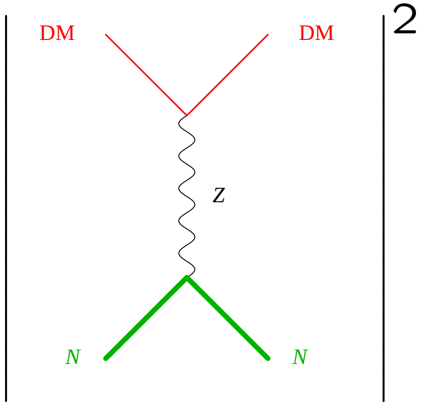
Direct DM detection

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 $M \sim m \sim 100\,\mathrm{GeV}$. Energy of scattered nuclei gives signals: ionization and/or scintillation and/or heat.

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

$$\sigma(\mathrm{DM}\,\mathcal{N} \to \mathrm{DM}\,\mathcal{N}) =$$



$$\sim \; (G_{\mathrm{F}} m Y_{\mathrm{DM}})^2 \sim 10^{-35}\,\mathrm{cm}^2$$

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

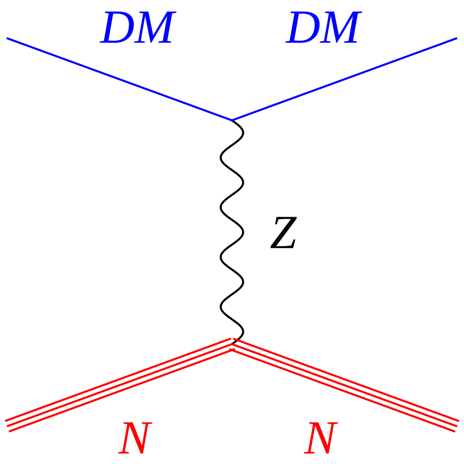
$$\text{events} \sim N\frac{\rho_\odot}{M} v\sigma \sim \frac{1000}{\mathrm{kg}\cdot\mathrm{yr}} \frac{\sigma}{10^{-35}\,\mathrm{cm}^2} \frac{\rho_\odot}{10^{-25}\mathrm{g}/\,\mathrm{cm}^3} \frac{v}{200\,\mathrm{km}/\,\mathrm{sec}} \frac{m}{100\,\mathrm{GeV}}$$

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

Direct DM detection: key parameter

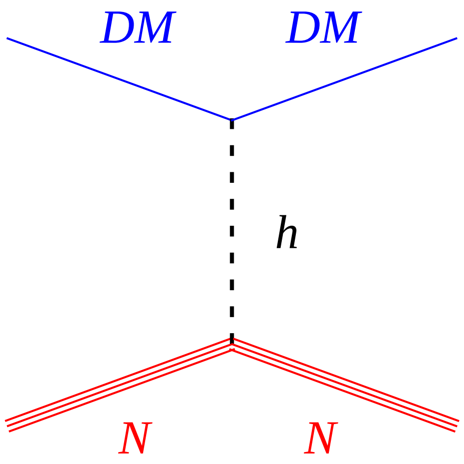
$\sigma_{\rm SI}$ = spin-independent DM/nucleon cross section

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



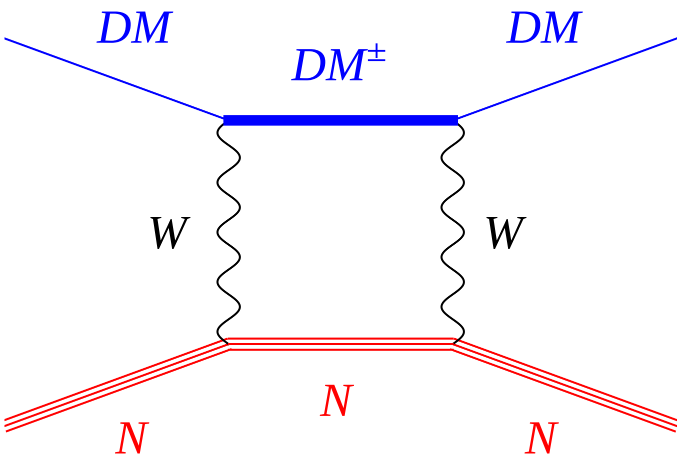
tree, vector

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



tree, scalar

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

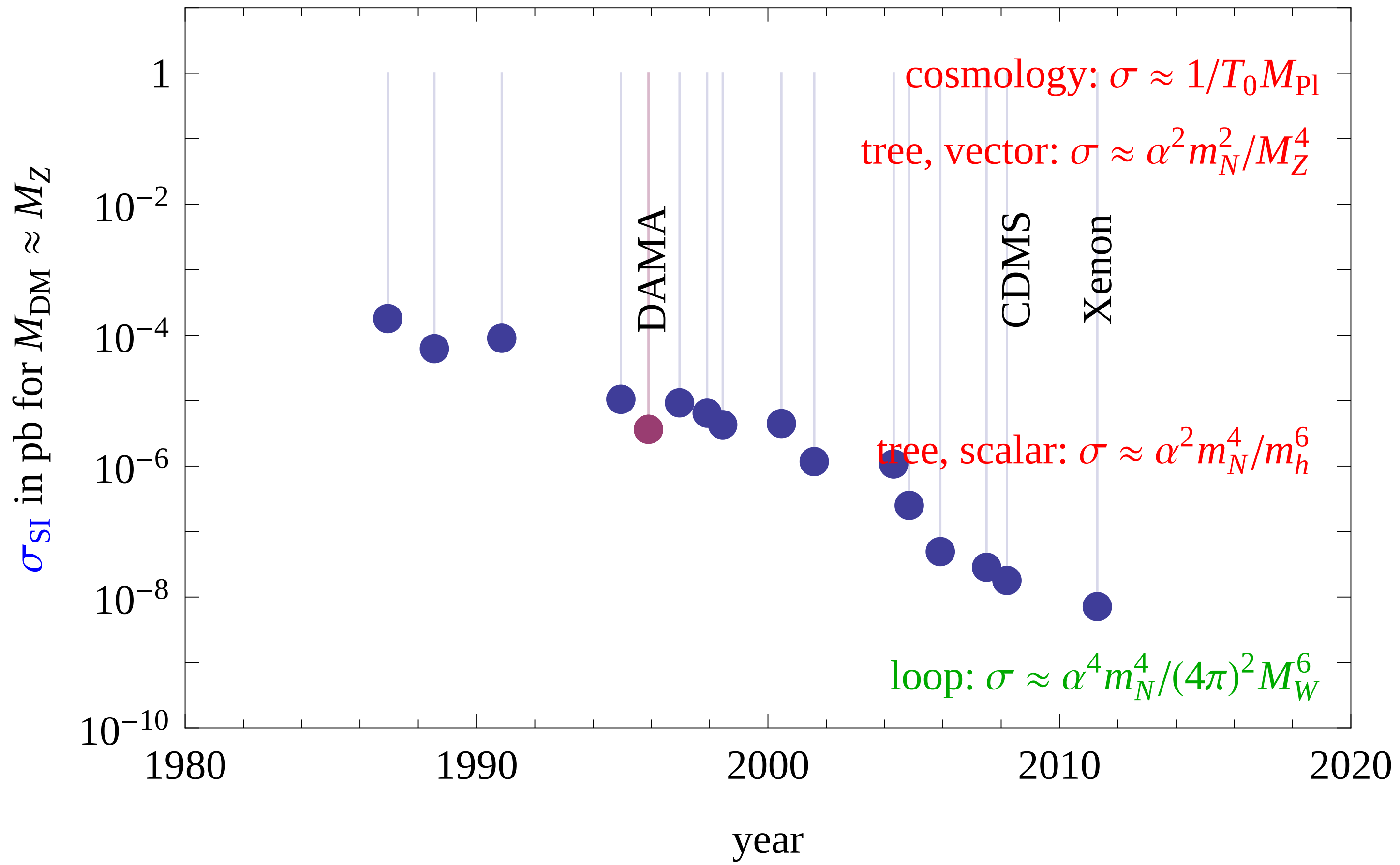


loop

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

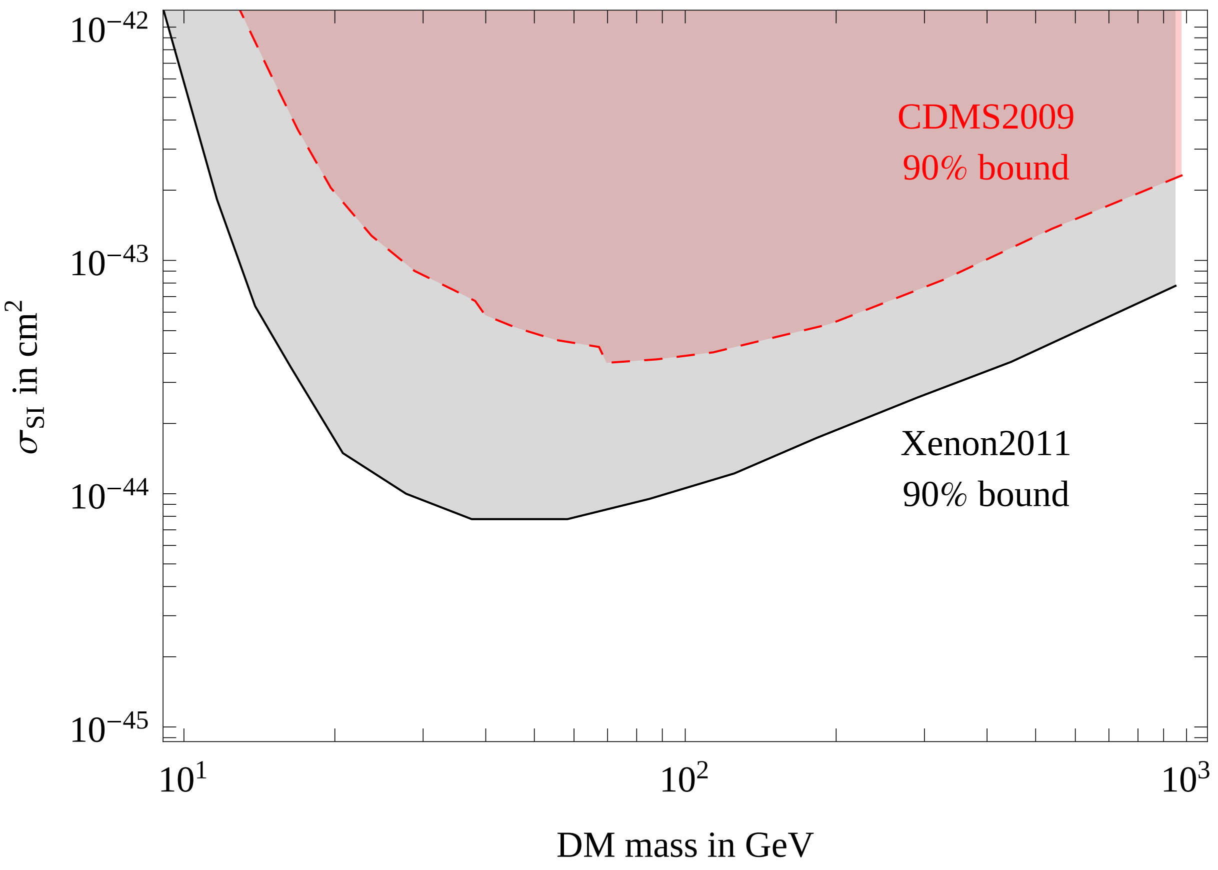
The vector effect vanishes if DM is real (e.g. a Majorana fermion).

Experimental progress



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

Anomaly-free Dark Matter

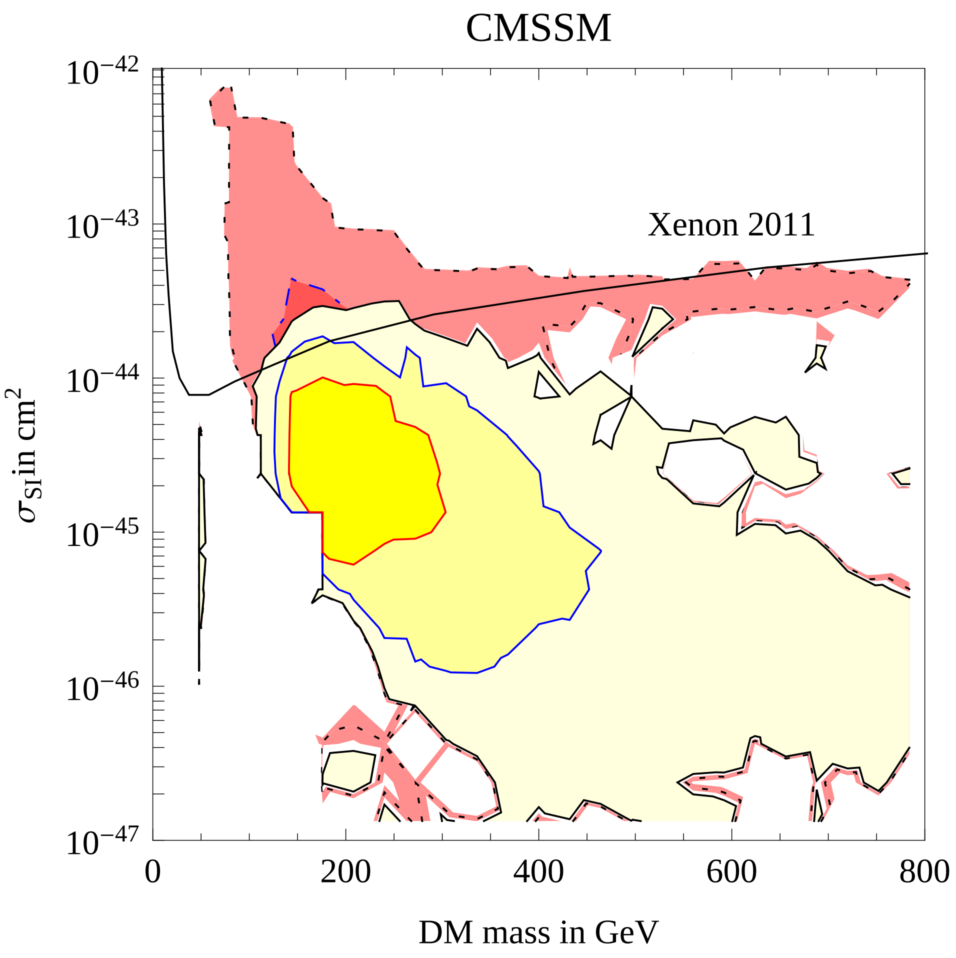


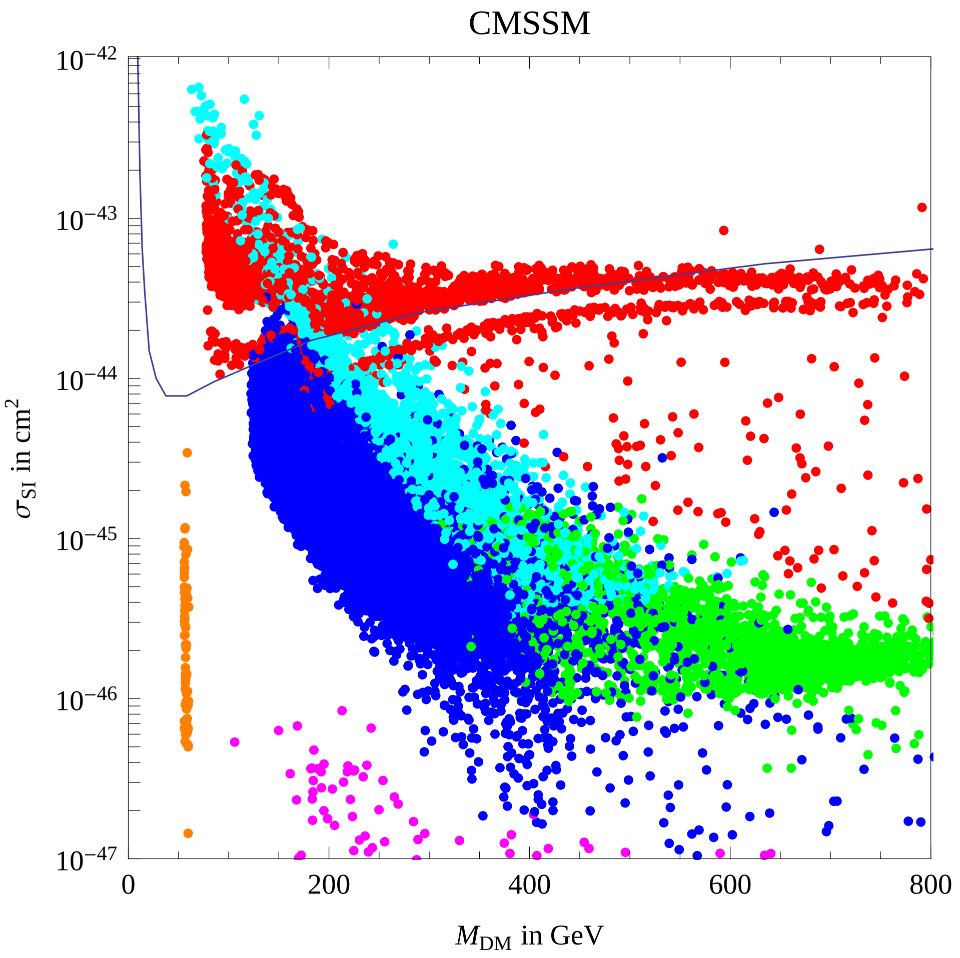
Best sensitivity if $M_{\rm DM} \approx M_N \sim 100\,\mathrm{GeV}$, can reach 10^{-47} in 201?.

For heavier DM $n_{\rm DM} = \rho_{\rm DM}/M_{\rm DM}$ gets smaller and the bound weaker.
For lighter DM the recoil energy is small: the signal goes below backgrounds.
Below a few GeV is $\approx$ terra incognita

SUSY Dark Matter

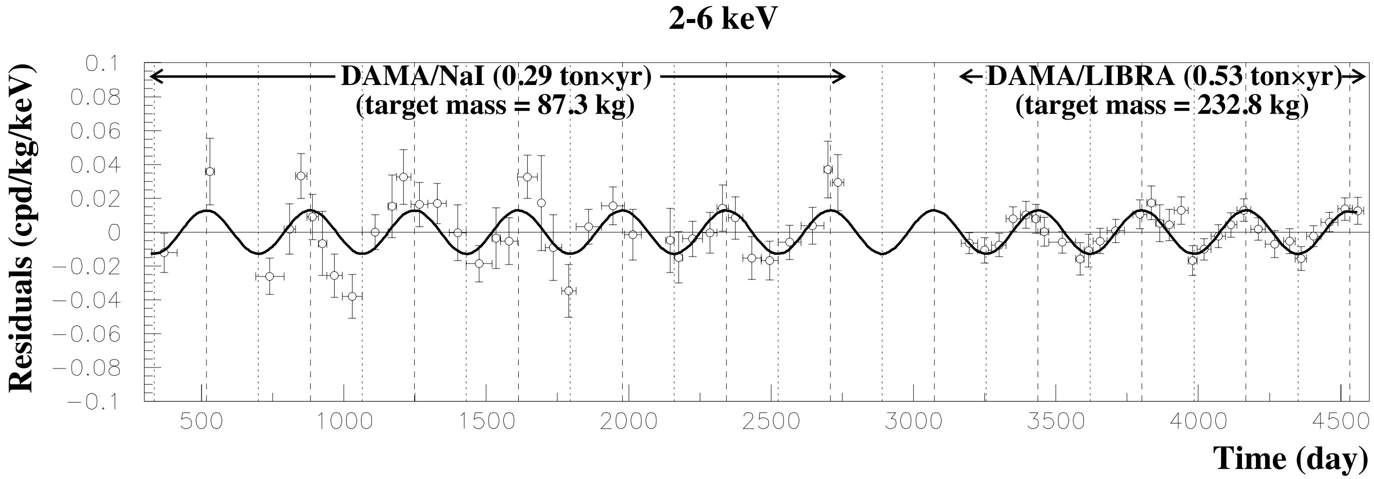
(CMSSM ≈ mSuGra ≈ ZUZY)

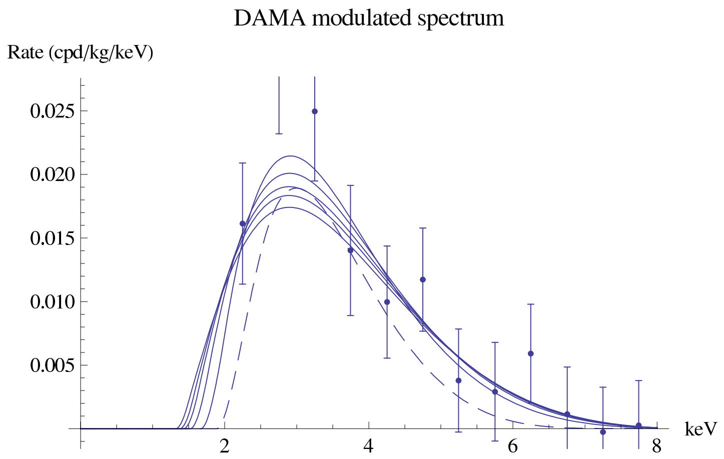




How to get $\Omega_{\rm DM}h^2 \approx 0.11$? Annihilation into light sleptons is now ∼excluded and special mechanisms needed: slepton co-annihilations, well-tempered, h resonance, H, A resonance, h, H, A at large $\tan\beta$, stop co-annihilations

DAMA: annual modulation seen at 8.8σ



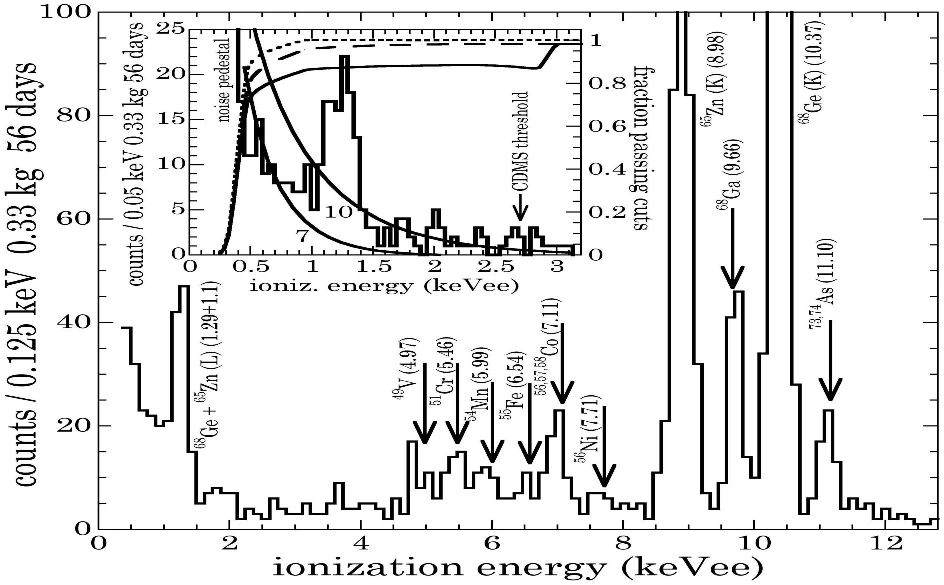


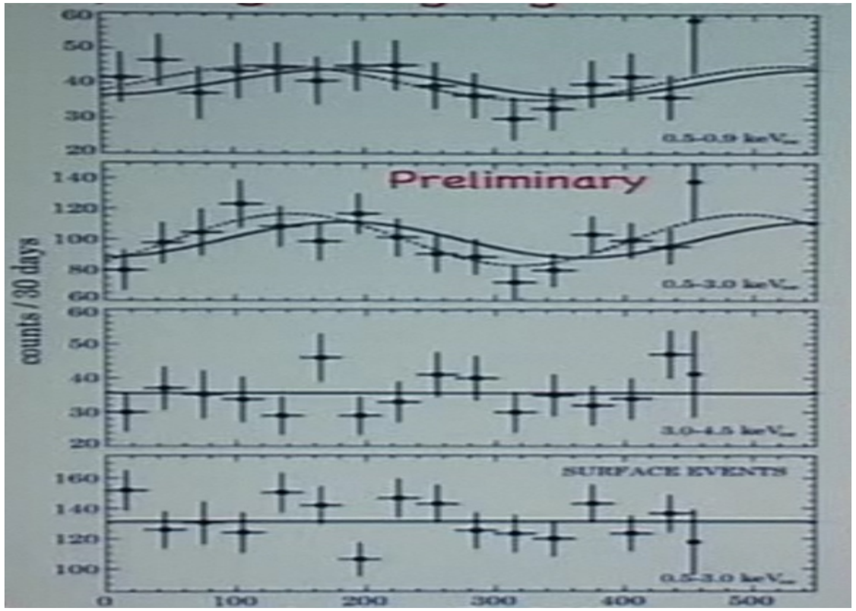
The phase is right: peak on 2 june ± week when $|\vec{v}_{\text{earth/sun}} + \vec{v}_{\text{sun}}|$ is maximal. The energy spectrum of the 5% modulation is not exponential; peak at 3 keV.

- DM form factor: $F_{\text{DM}} \sim q^2$ or q^4 rather than q^0? NO
- Inelastic DM: DM $N \to$ DM$'N$ with $\frac{1}{2}\mu v^2 > M' - M \sim$ keV gave right spectrum. Excluded by Xenon, unless scattering is on heavy thallium impurity
- Magnetic inelastic DM (coupled to large Iodine magnetic dipole)
- DM that makes bound state with NaI. CRAZY
- Luminous DM $\to$ DM$^* \to$ DM γ

CoGeNT

- Excess claimed at low energy. Light DM with large σ and light mediator?
- Almost compatible with DAMA (can be made compatible with partly background / more uncertainties / isospin-dependent / form factor).

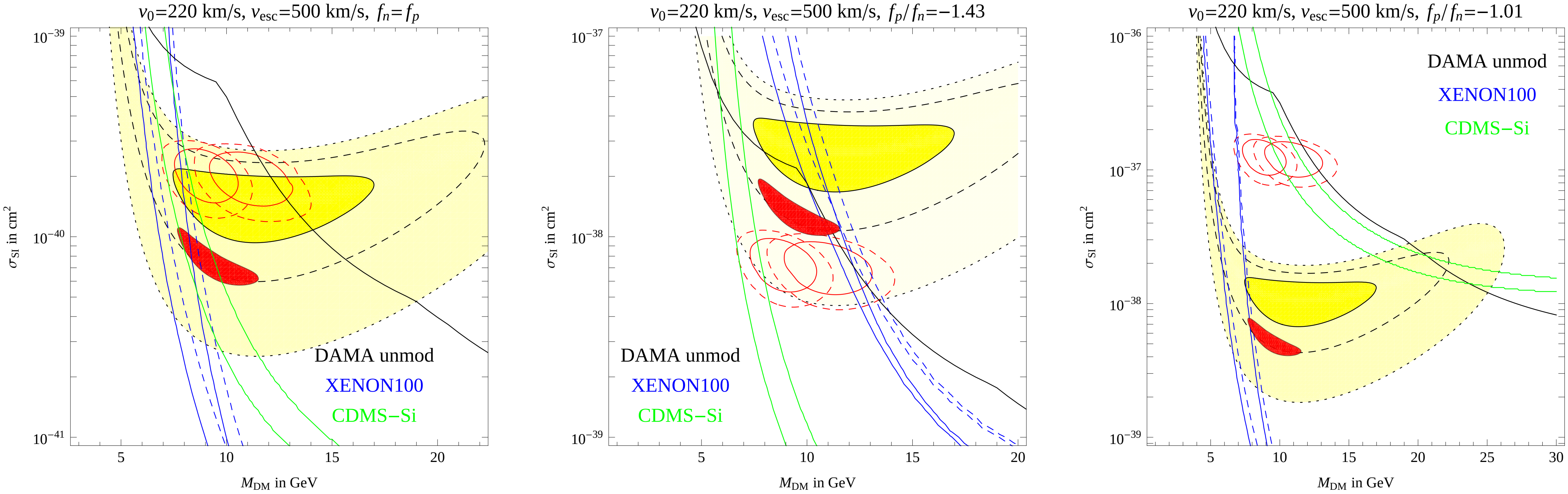




- **2011 breaking news:** $\approx 3\sigma$ **hint for modulation of the CoGent excess**.

- CoGeNT and CDMS are both Ge in the same place. CDMS sees nothing (what about scintillation and its modulation?) 1103.3481 vs 1011.2482

Anomalous Dark Matter



(Thanks to D. Pappadopulo, M. Farina, T Volansky)

Indirect DM detection

Indirect signals of Dark Matter

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

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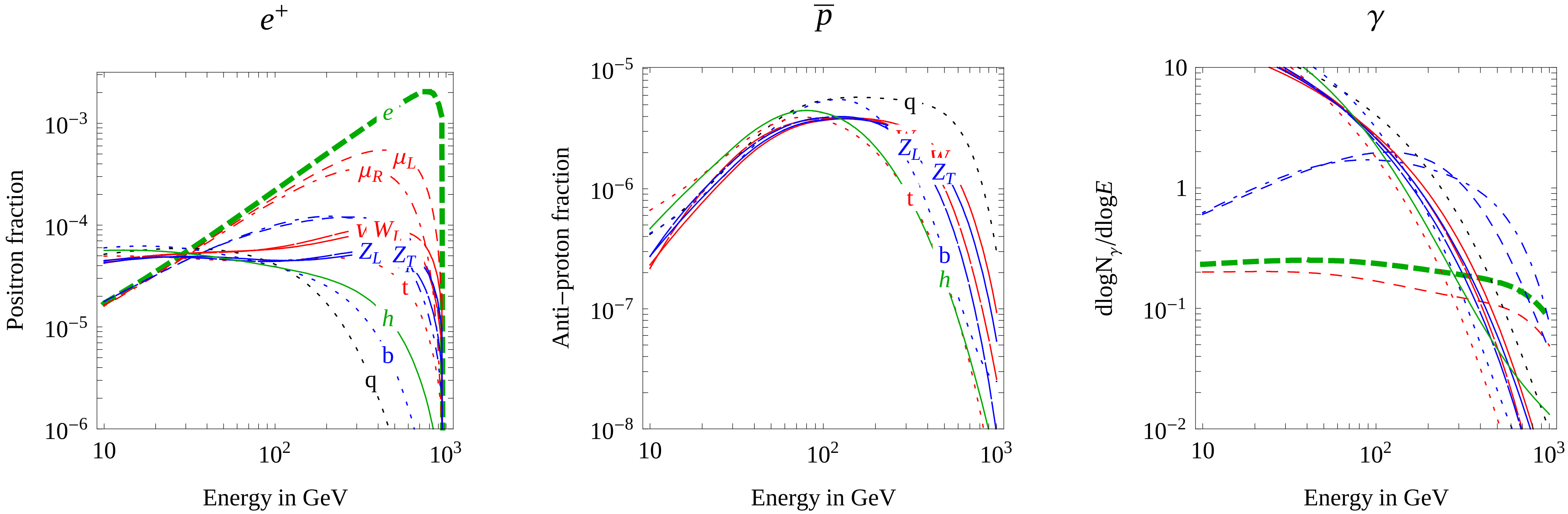
Final state spectra for $M = 1$ TeV

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:



Advertisement

You want to compute all signatures of your DM model in positrons, electrons, neutrinos, gamma rays... but you dont want to mess around with astrophysics?

The Poor Particle Physicist Cookbook for Dark Matter Indirect Direction

`www.marcocirelli.net/PPPC4DMID.html`

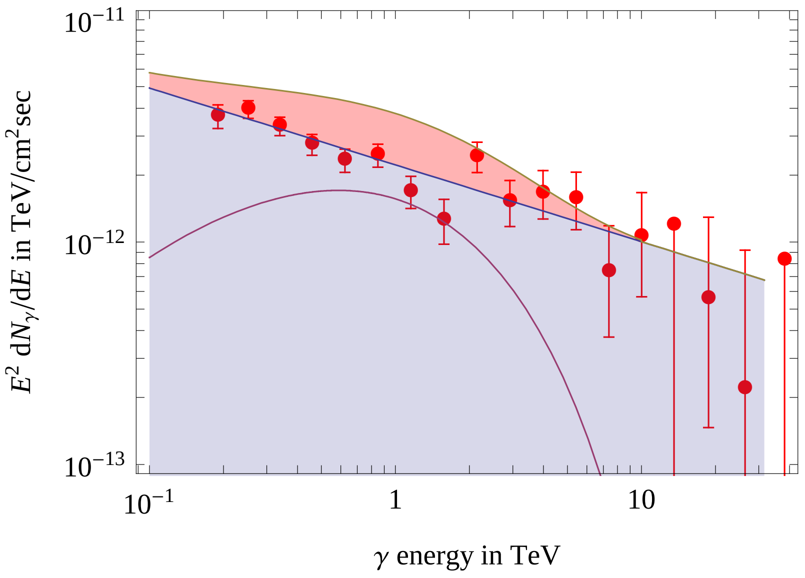
We provide ingredients and recipes
for computing signals of TeV-scale
Dark Matter annihilations and decays
in the Galaxy and beyond.
arXiv:1012.4515

Indirect detection: γ

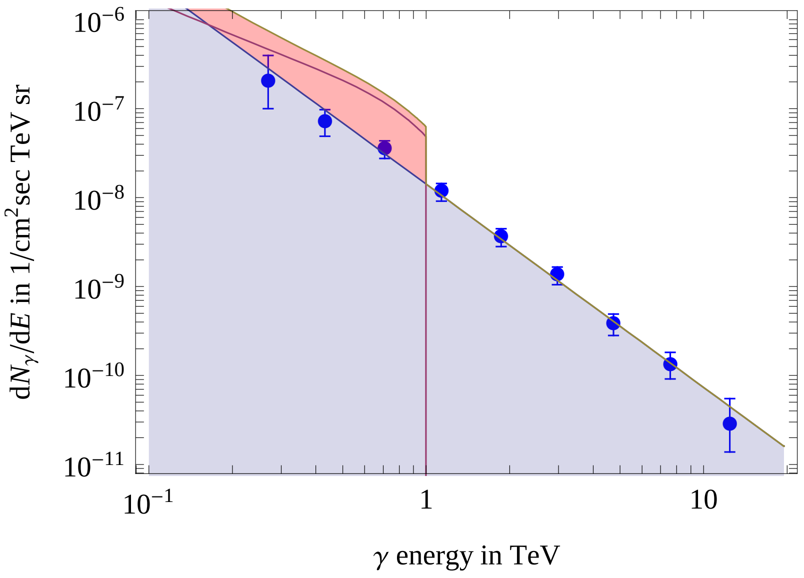
$$\Phi_\gamma = \frac{c}{8\pi}\frac{\rho_\odot^2}{M_{\rm DM}^2}J\langle\sigma v\rangle\frac{dN_\gamma}{dE},\qquad J=\int_\Omega d\Omega\int_{\text{line}-\text{of}-\text{sight}}\frac{ds}{r_\odot}\left(\frac{\rho}{\rho_\odot}\right)^2$$

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, $\sigma v = 10^{-23}\,\text{cm}^3/\text{sec}$):

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

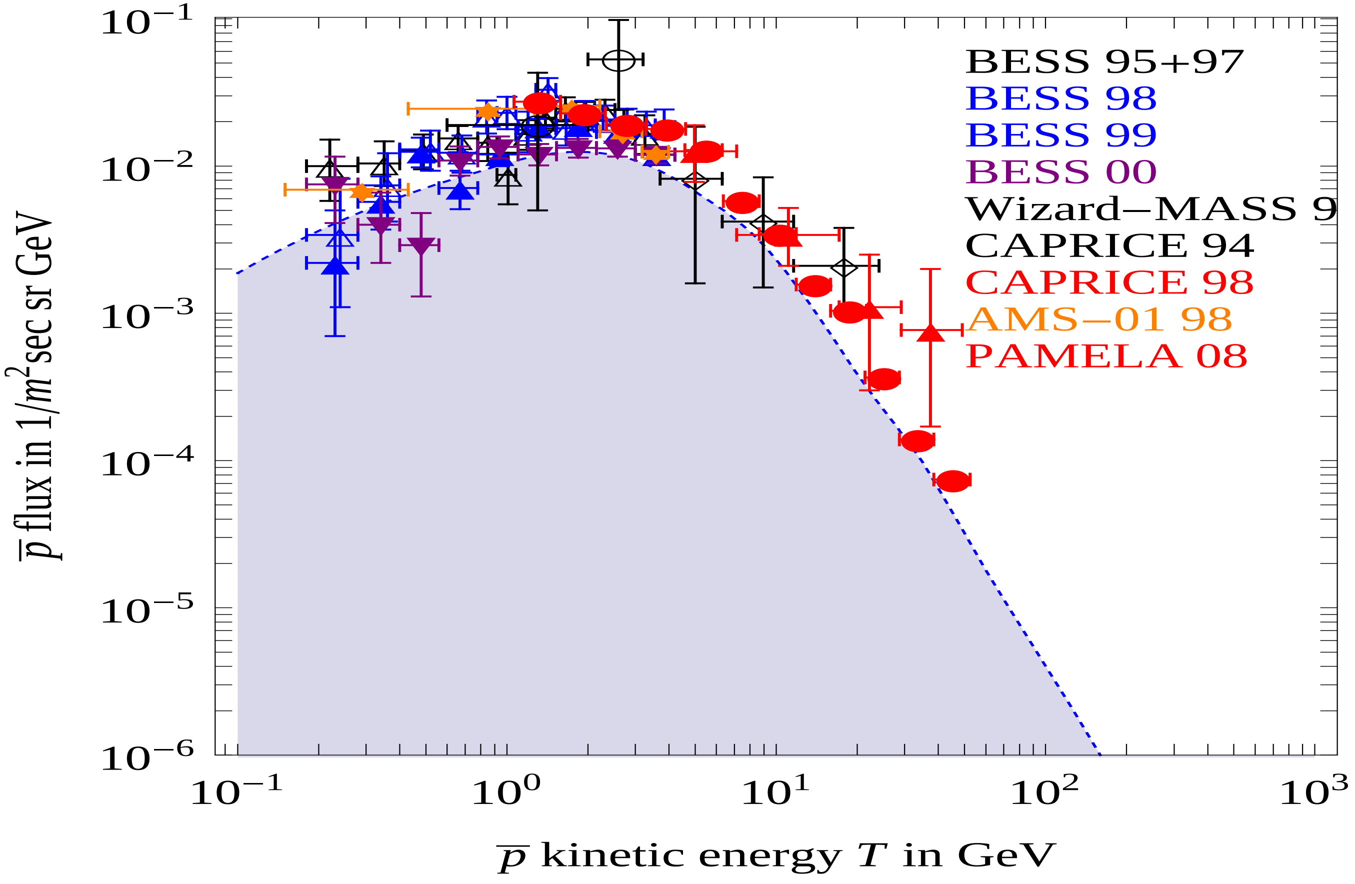


b) M = 1 TeV into $\mu^-\mu^+$, Galactic Ridge



Indirect detection: PAMELA $\bar{p}$

Consistent with background

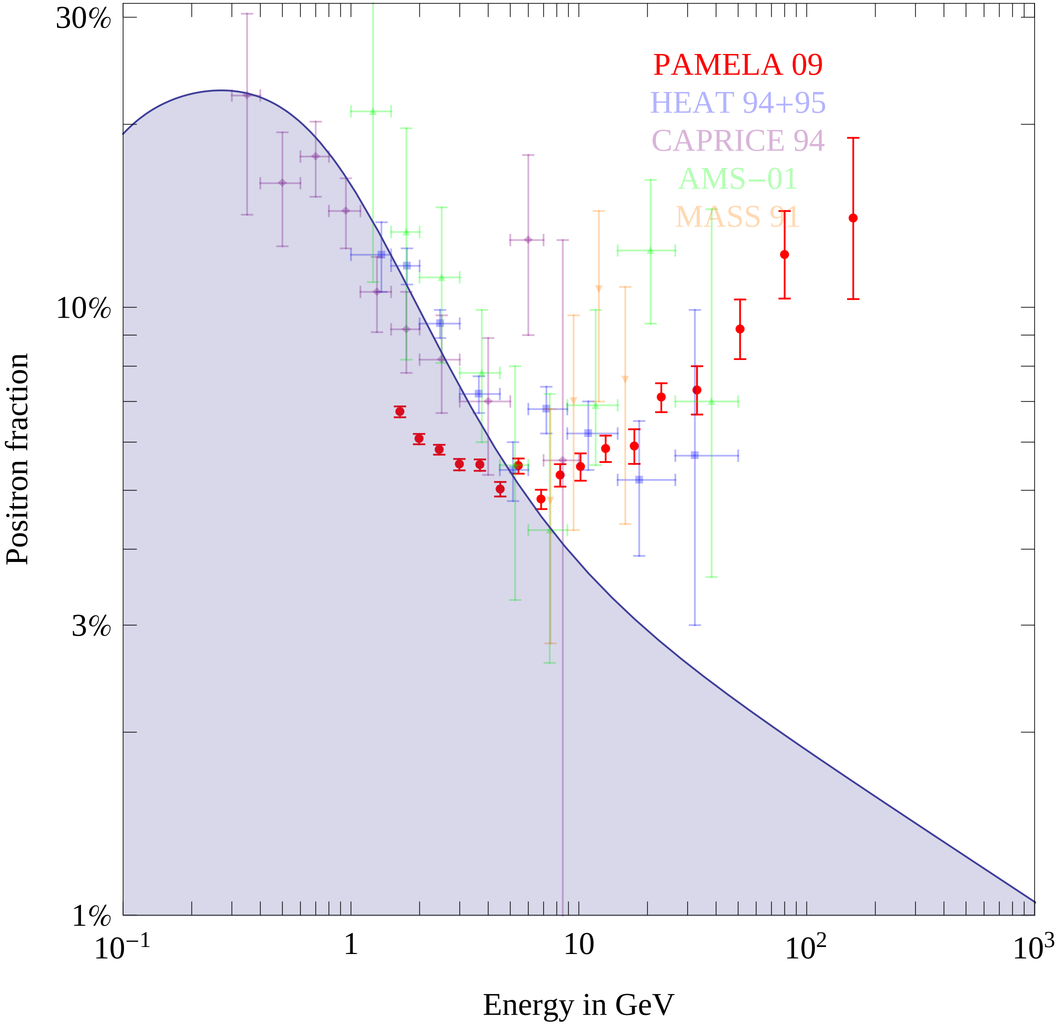


Next big experiment, AMS, will be launched in a few days

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.

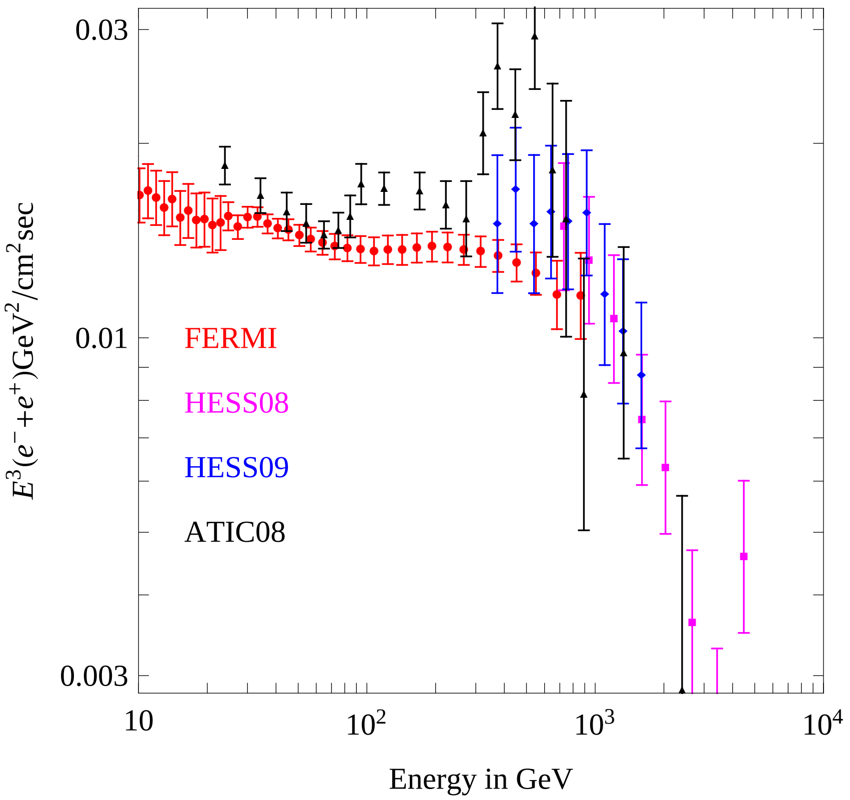
Growing excess above 10 GeV



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.



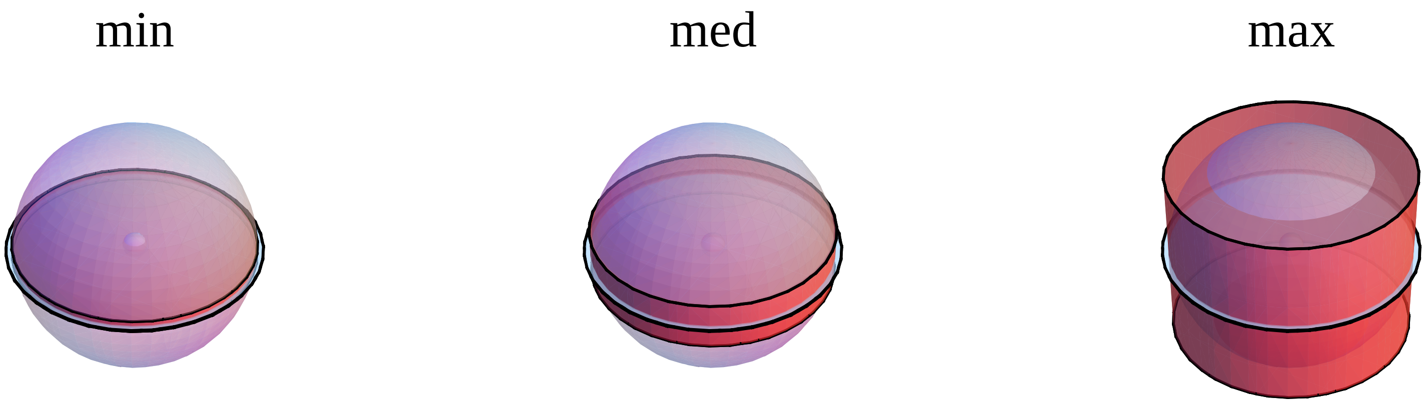
Hardening at 100 GeV and softening at 1 TeV

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 $R = 20\,\text{kpc}$ and height $2L$.

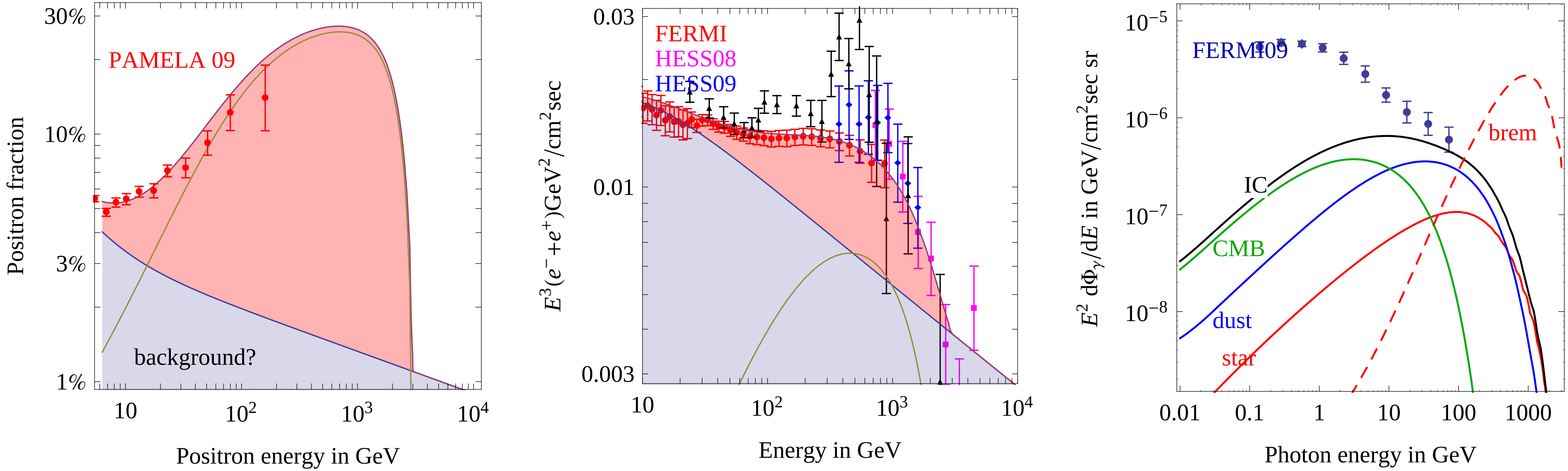
Propagation model	δ	K_0 in kpc^2/Myr	L in kpc	V_{conv} in km/s
min	0.85	0.0016	1	13.5
med	0.70	0.0112	4	12
max	0.46	0.0765	15	5



Explaining the $e^{\pm}$ excesses

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

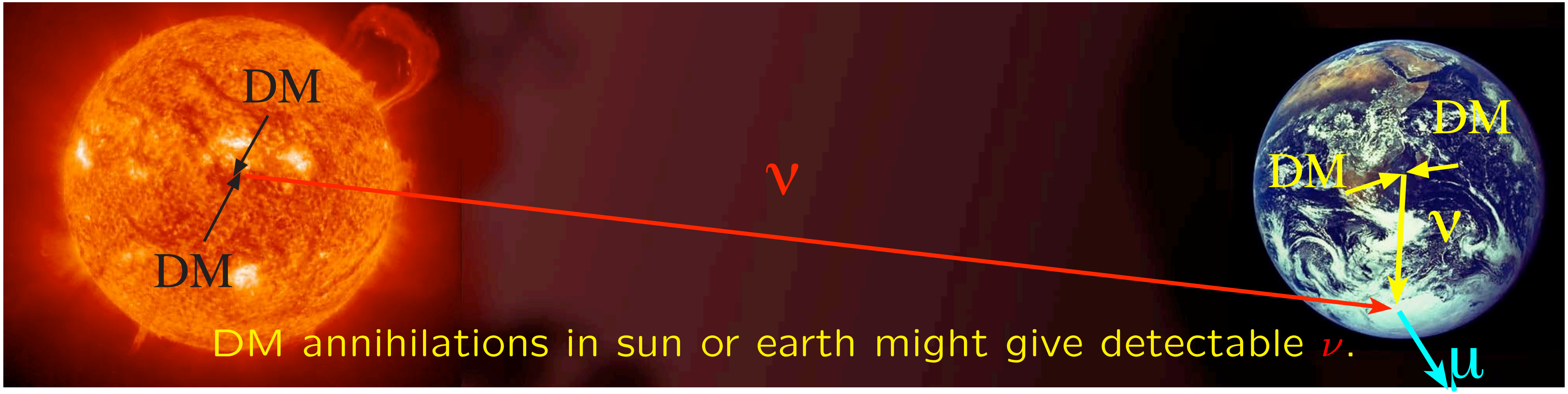
DM with $M = 3.$ TeV that annihilates into $\tau^+\tau^-$ with $\sigma v = 1.8 \times 10^{-22}$ cm^3/s



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

Present status: if $e^{\pm}$ are due to DM, their ICγ must be a significant fraction of γ observed by FERMI. Difficult to discriminate from astro background.

DM accumulated also in the sun and in the earth



DM annihilations in sun or earth might give detectable ν.

Indirect detection: ν

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

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

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

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

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 $\Gamma_{\rm capt} \propto m^{-2}_{\rm DM}$

- 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, what signal?

- DM is probably stable thanks to a Z_2 symmetry: **DM produced in pairs**.

- DM behaves like ν: DM carries away **missing transverse momentum** $\not{p}_T$.

Simplest case: only DM is produced, an initial state jet allows to see $\not{p}_T + j$

Plausible case: DM could be the lightest of a new set of particles (like in SUSY), one has bigger QCD cross sections and $\not{p}_T$ + hard jets or leptons or...

Possible case: DM is not the lightest SUSY particle is not DM, that might be charged and decay into “gravitinos” or “axino” DM with life time $\tau \gtrsim$ m.

etc etc etc