Dark Matter, particle candidates and their detection

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Plan for the lectures

- Evidence for DM from astrophysical and cosmological observations
- Implications for properties of particle DM candidates
- Mechanisms for generating DM particles
- DM models and their detection
- The PAMELA & Fermi rush

Useful reviews:

- Bergström, hep-ph/0002126
- Bertone, Hoper & Silk, hep-ph/0404175

The discovery of DM and classical tests

DM in clusters:

In 1933 Zwicky claimed the existence of DM with a dynamical mass estimate of the Coma cluster:

Optical image of the Coma cluster, about 1000 galaxies within a radius of about 1 Mpc

Credit: Kitt Peak

The discovery of DM and classical tests

DM in clusters:

In 1933 Zwicky claimed the existence of DM with a dynamical mass estimate of the Coma cluster:

Use the virial theorem: $\langle V \rangle + 2\langle K \rangle = 0$

$\langle K \rangle = N \dfrac{\langle m\, v^2 \rangle}{2}$ average kinetic energy due to N galaxies

$\langle V \rangle = -\dfrac{N^2}{2} G_N \dfrac{\langle m^2 \rangle}{\langle r \rangle}$ average potential energy

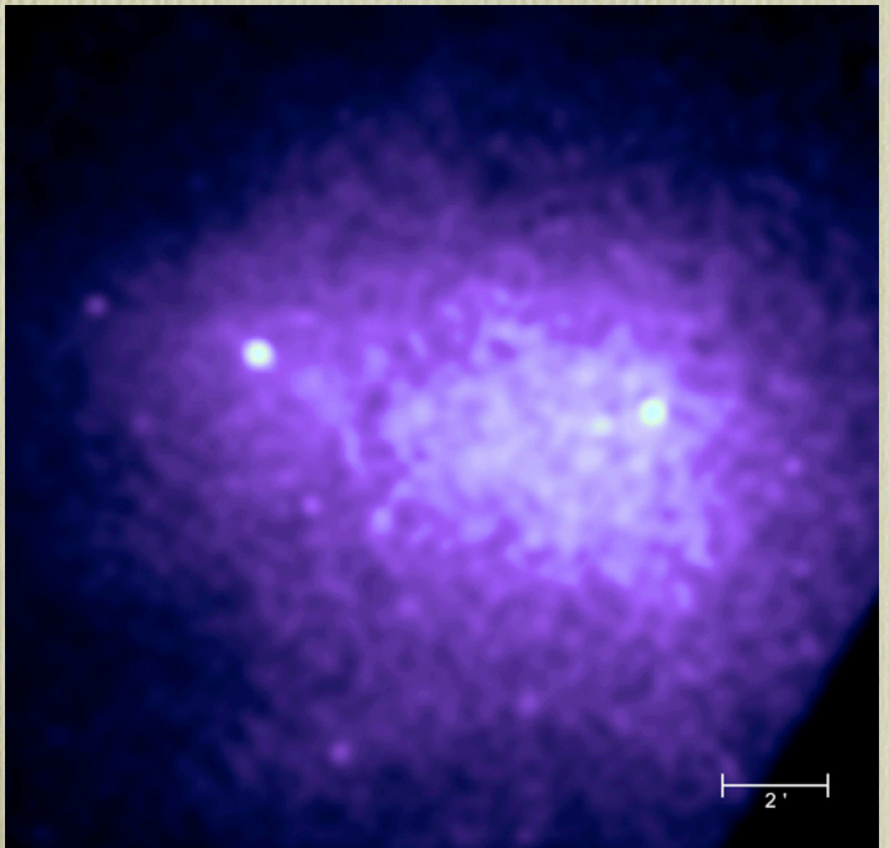
measure the velocity dispersion and geometrical size to get:

$$M \equiv N \langle m \rangle \sim \frac{2\langle r \rangle \langle v^2 \rangle}{G_N} \quad \Longrightarrow \quad \frac{M}{L} \sim 300h \frac{M_\odot}{L_\odot} \quad \Longrightarrow \quad \Omega_M \simeq 0.2 - 0.3$$

i.e. about the same value with more modern dynamical approaches (recall that $\Omega_i \equiv \rho_i / \rho_c$)

DM in clusters: mass estimates with X-ray observations

In clusters most baryonic mass is in the form of hot gas.



X-ray image of the Coma cluster with Chandra telescope

Credit: NASA, Yikhlinin et al.

DM in clusters: mass estimates with X-ray observations

In clusters most baryonic mass is in the form of hot gas.

Assume that it is in thermal equilibrium within the underlying gravitational well. Its density distribution $\rho_g(r)$ and pressure $P_g(r)$ satisfy:

$$\frac{1}{\rho_g}\frac{dP_g}{dr} = \frac{G_N\, M(<r)}{r^2}$$

Gas density maps are obtained from X-ray luminosity, X-ray spectra give temperature maps, i.e. pressure maps.

Example: in Abel 2029 (Lewis et al. 2003)

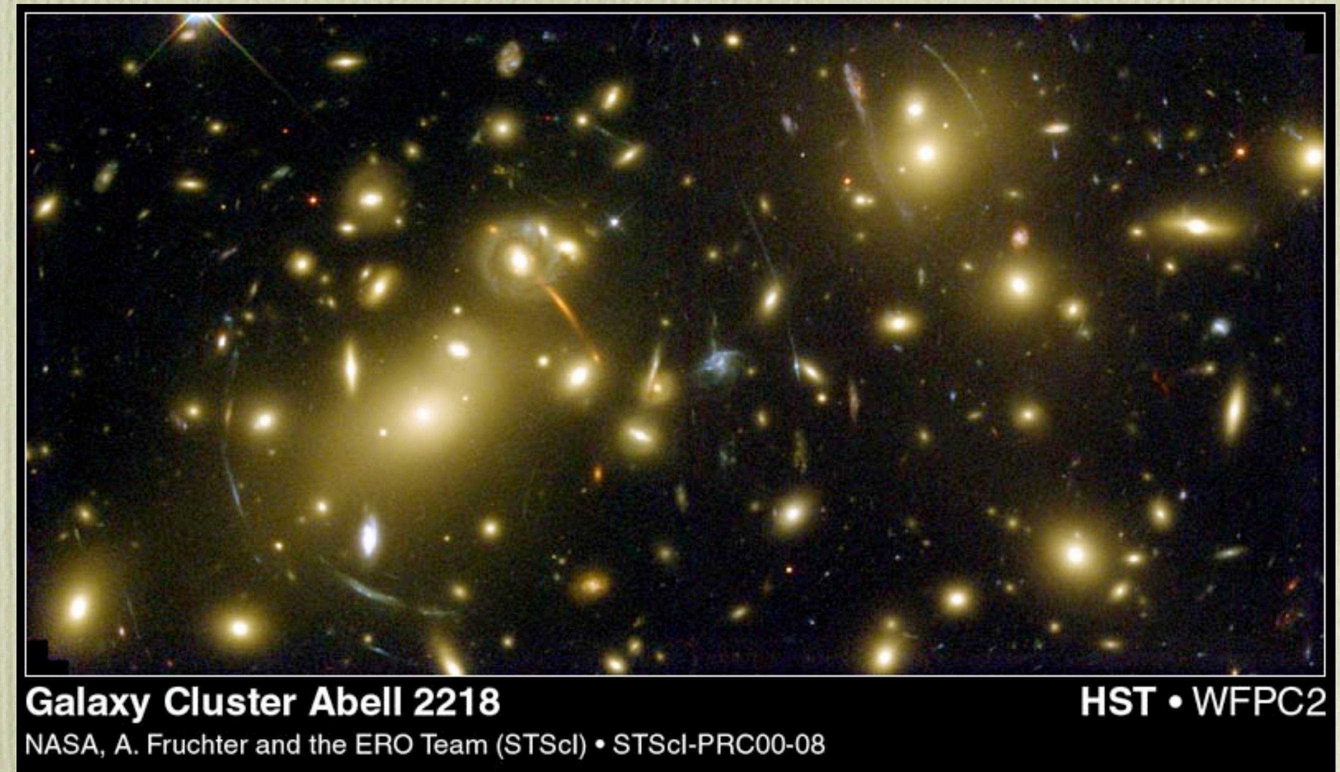
$M_b/M \equiv f_b \simeq 14\%$

$\Omega_M \simeq \Omega_b/f_b \simeq 0.29$

Ω_b from BBN

DM in clusters:

mass tomography through gravitational lensing:

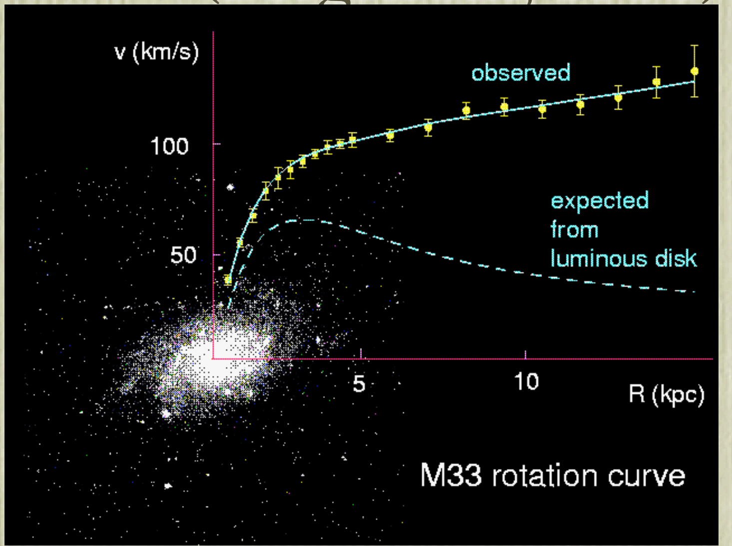


DM in galaxies:

Mismatch in galactic rotation curves (first in '50s & '60s):

(Bergström, 2000)

circular velocity



galacto-centric distance

$$v_{\rm circ} = \sqrt{\frac{G_N\, M(<r)}{r}}$$

outside the body, i.e. at:

$$M(<r) = M_{\rm tot}$$

Keplerian fall-off expected:

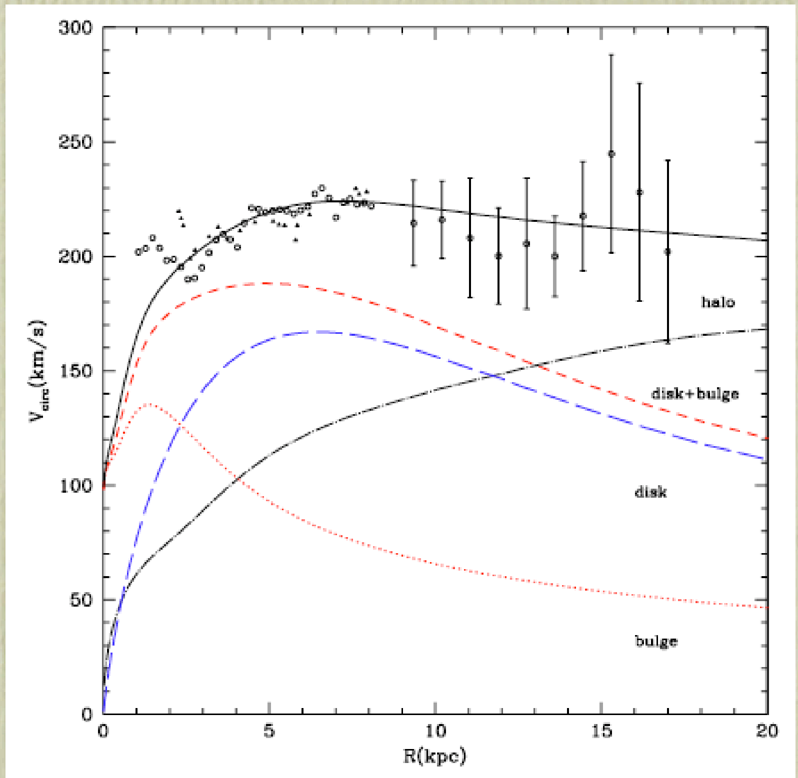
$$v_{\rm circ} \propto \frac{1}{r^{1/2}}$$

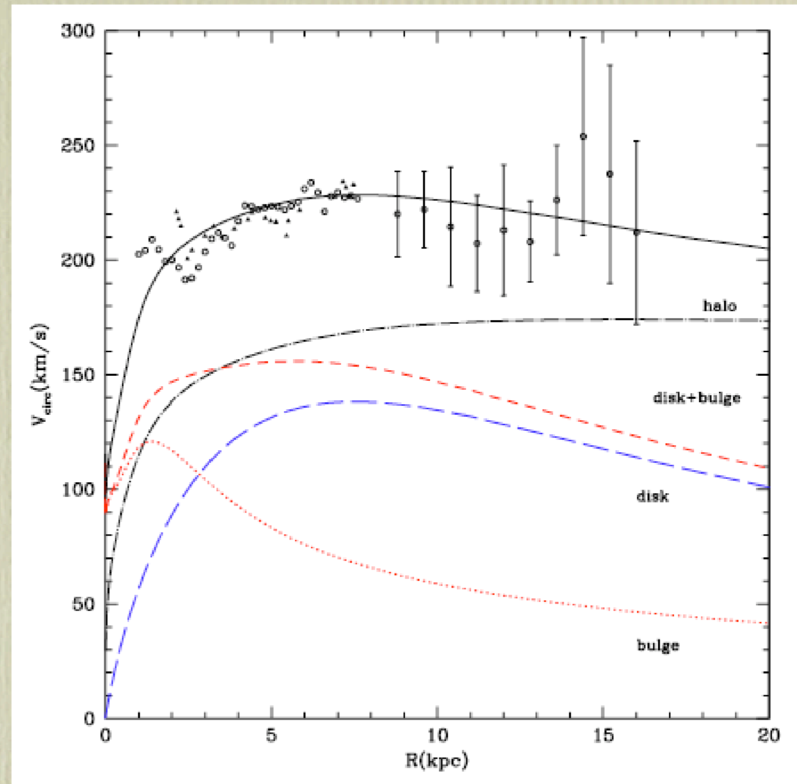
rather than ~ flat:

$$v_{\rm circ} \sim \text{const.} \quad \Longrightarrow \quad M_{DM}(r) \propto r \quad \Longrightarrow \quad \rho_{DM}(r) \propto \frac{1}{r^2}$$

Milgrom: no DM but modify Newton's law introducing a minimum acceleration scale: $a_0 \sim c\, H_0$ (MOND)

Milky Way rotation curve





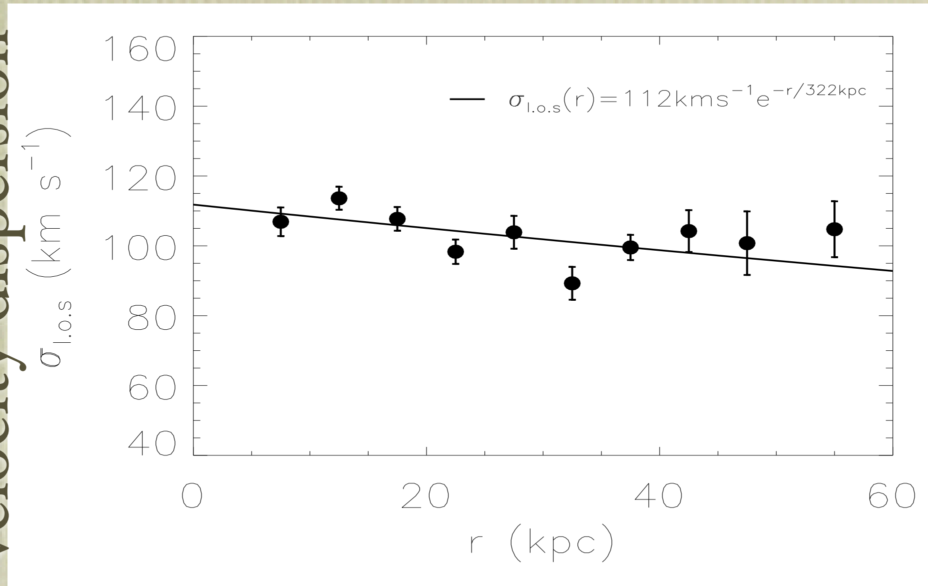
"Maximal" disc

"Minimal" disc

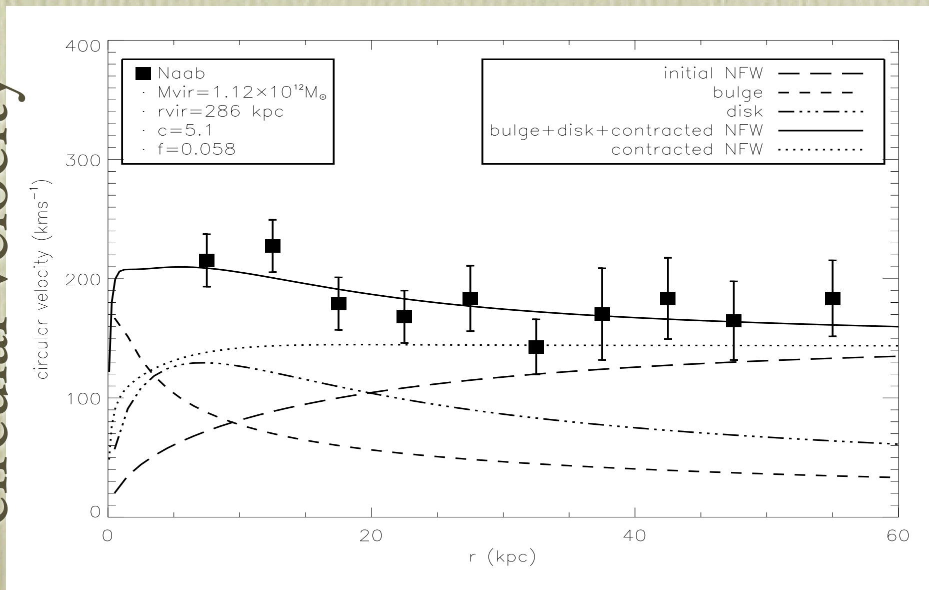
Klypin, Zhao & Somerville, 2001

Mapping the dynamics of the Milky Way with Blue Horizontal Branch stars

velocity dispersion



circular velocity



Xue et al. (SDSS), arXiv:0801.1232

$$\mathrm{M}(<60\,\mathrm{kpc}) = 4.0\pm0.7\times10^{11}\mathrm{M}_\odot$$

$$\mathrm{M_{vir}} = 1.1\pm0.2\times10^{12}\mathrm{M}_\odot$$

$$\Leftrightarrow \quad M_{\mathrm{stars+gas}} \simeq 4\cdot10^{10}M_\odot$$

DM in galaxies: the case for the Milky Way

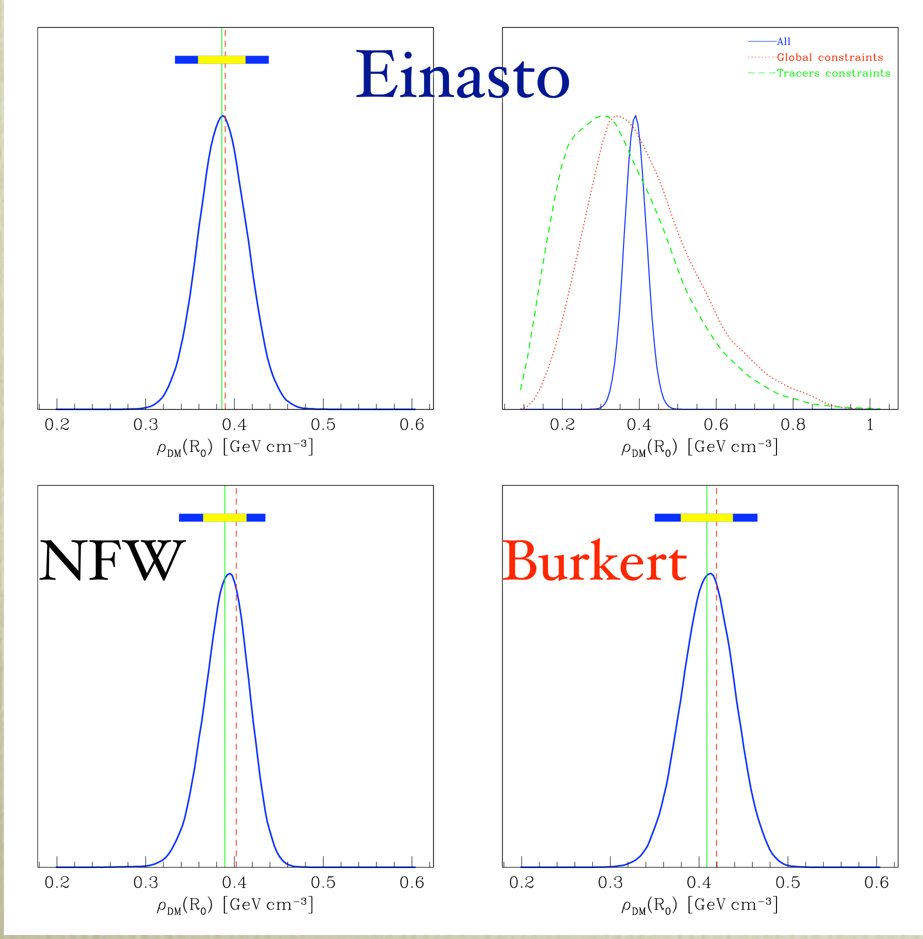
There is evidence for the DM halo to be extended rather than in a disc-like structure:
- tidal tail of the Sagittarius dwarf (e.g., Ibata et al. 2001; Martinez-Delgado et al. 2004)
- thickness of the gas layer in the Galaxy outskirts (Olling & Merrifield, 2002)

Build a self-consistent model, add in further info such as local velocity fields for given population of stars, ect. ect., and find that the mean value for the local DM density is:

$$\rho_{DM}(R_0) \sim 0.01 M_\odot \,\mathrm{pc}^{-3} \sim 0.3\,\mathrm{GeV\,cm}^{-3}$$

For reference: $1\,\mathrm{pc} = 3.08 \cdot 10^{18}\,\mathrm{cm}$ & $1 M_\odot = 1.12 \cdot 10^{57}\,\mathrm{GeV}$

Actually matching the SDSS rotation curve, plus novel determinations of the local circular velocity (Reid et al., 2009) and of the Sun's Galactocentric distance (Gillessen et al. 2009) to the classical dynamical tracers for the Galaxy, the local DM halo density is fairly well constrained:



Marginal posterior pdf for the local halo density for three different choices of the functional form for the MW DM profile. Results obtained with a Markov chain scan of a 7-dimensional parameter space. In all cases the mean value found is about:

$$0.39 \text{ GeV cm}^{-3}$$

with a 1-sigma error bar of about 7%. Spherical symmetry has been assumed for the DM halo profile.

DM in the era of precision cosmology

The Standard Model for cosmology (ΛCDM model) as a minimal recipe, i.e. a given set of constituents for the Universe and GR as the theory of gravitation, to be tested against a rich sample of (large scale) observables: CMB temperature fluctuations, galaxy distributions, lensing shears, peculiar velocities, the gas distribution in the intergalactic medium, SNIa as standard candles, ...

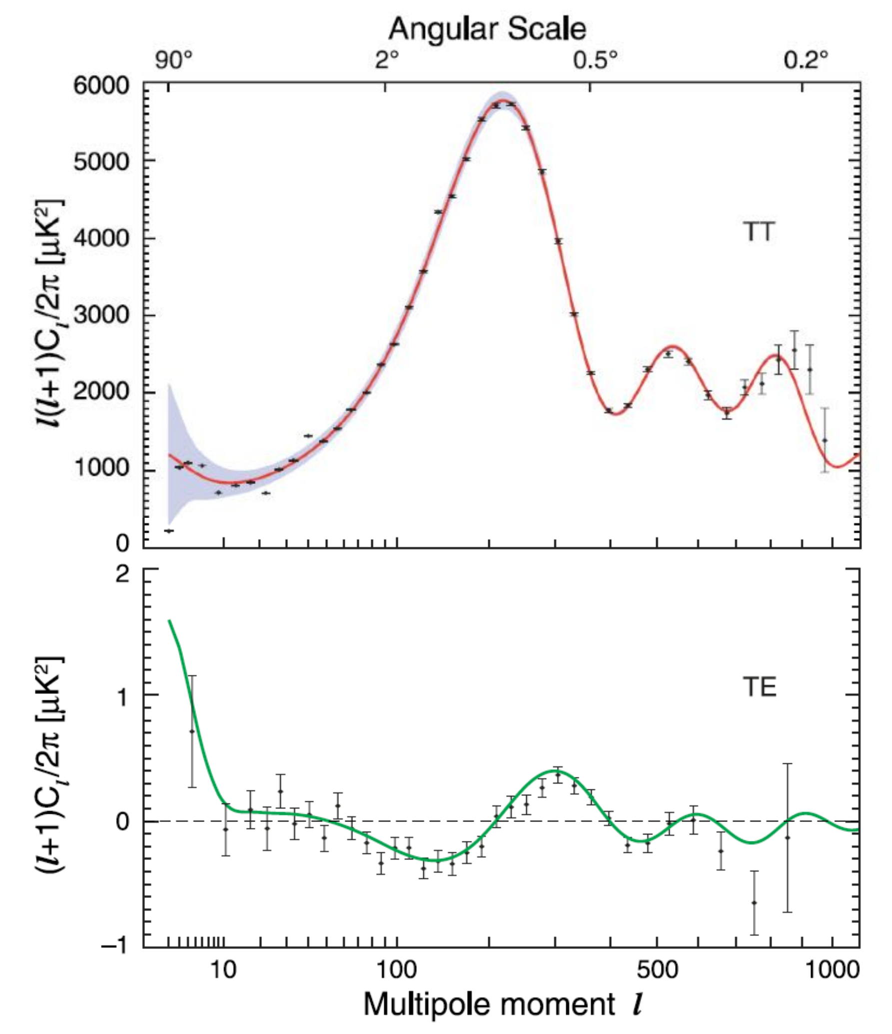
All point to a single "concordance" model:

$$\Omega_{Tot} \sim 1 \qquad \underbrace{\Omega_M \sim 0.24}_{\Omega_{DM} \sim 0.20 \quad \Omega_b \sim 0.04} \qquad \Omega_{DE} \sim 0.76 \qquad \ldots$$

Ω_b in remarkable agreement with BBN!

DM appears as the building block of all structures in the Universe:

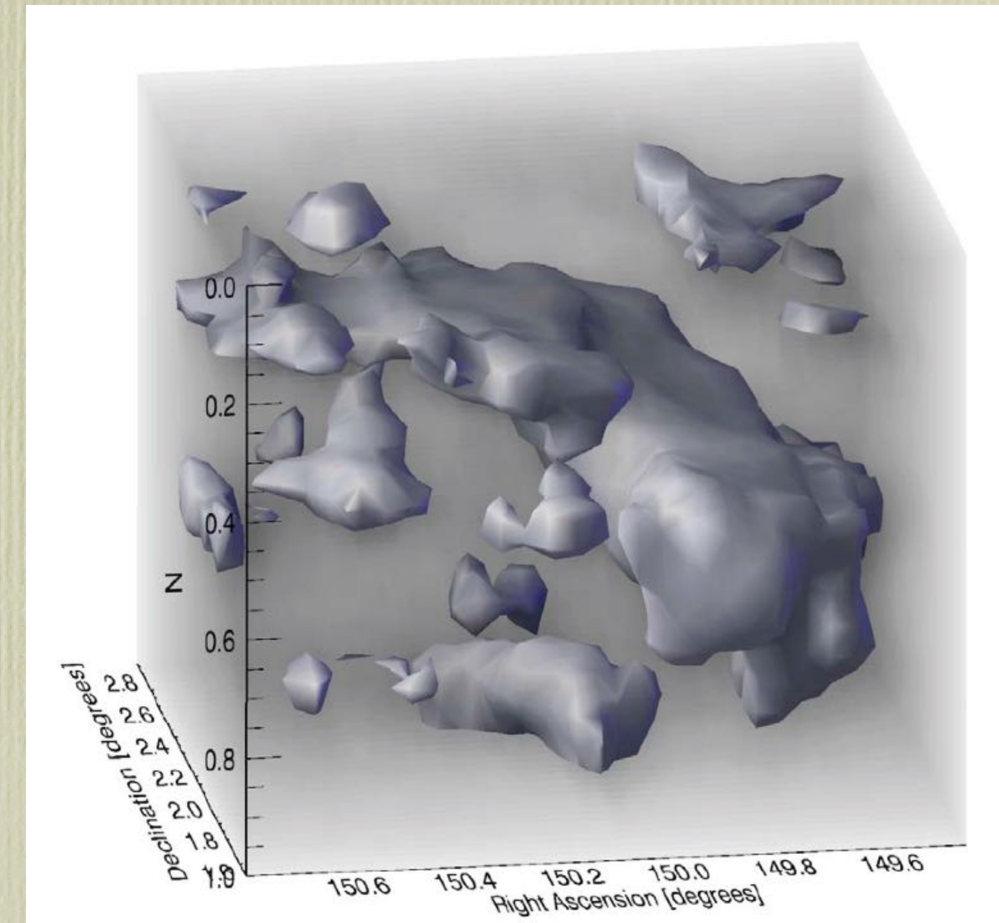
e.g., it accounts for the gravitational potential wells in which CMB baryon acoustic oscillations take place:



(5-yr WMAP, 2009)

The Universe is permeated by a loose network of DM filaments, intersecting in massive structures; gas accumulates therein and forms stars.

gravitational scaffold
as detected in weak
lensing surveys,
Massey et al. 2007



What about giving up on GR as theory of gravitation and trying to avoid introducing dark matter?

MOND is not a theory of gravitation. The formulation of a covariant theory with MOND-like limit is very recent:

TeVeS (tensor-vector-scalar) gravity theory, Bekestein 2004

The theory has not been tested yet against the full set of astrophysical and cosmological observables, still within the available subset, it does not look straightforward to match all observations, without introducing a (small) DM component.

We will stick to the idea that DM is needed, and it is in the form of some elementary particle.

What do cosmology and astrophysics tell us about properties of DM particles?

There are 5 golden rules.

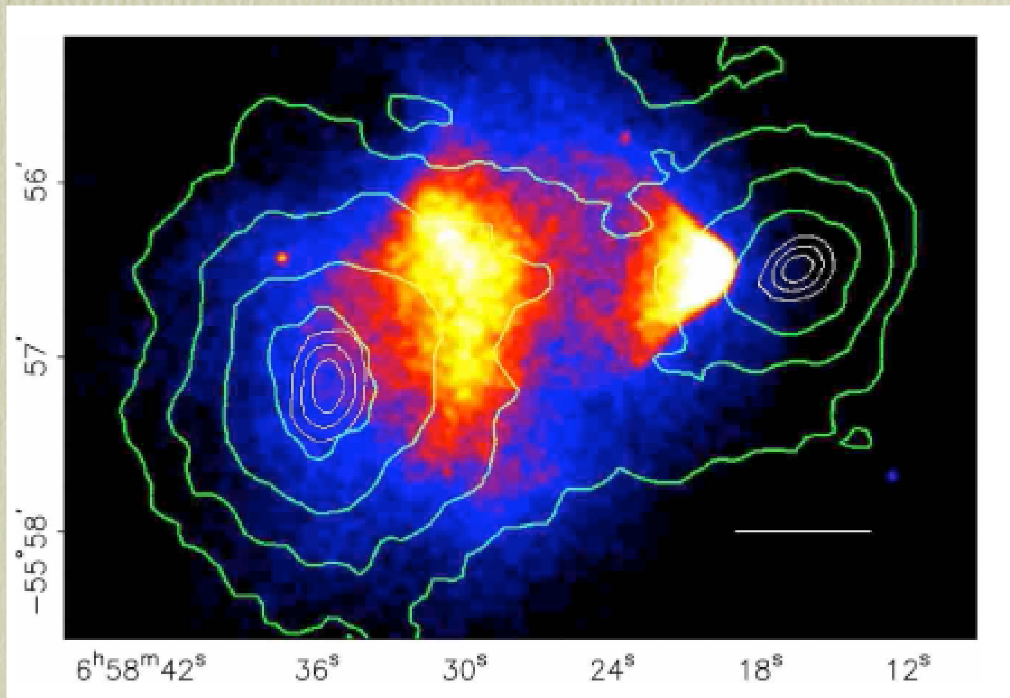
1) DM is **optically dark**: its electromagnetic coupling is suppressed since: a) it is does not couple to photons prior recombination; b) it does not contribute significantly to the background radiation at any frequency; c) it cannot cool radiating photons (as baryons do, when they collapse to the center of galaxies) $\Rightarrow$ DM is **dissipation-less**

Tight limits for particles with a millicharge, or electric/ magnetic dipole moment, see, e.g., Sigurdson et al. 2004

2) DM is **collision-less**:

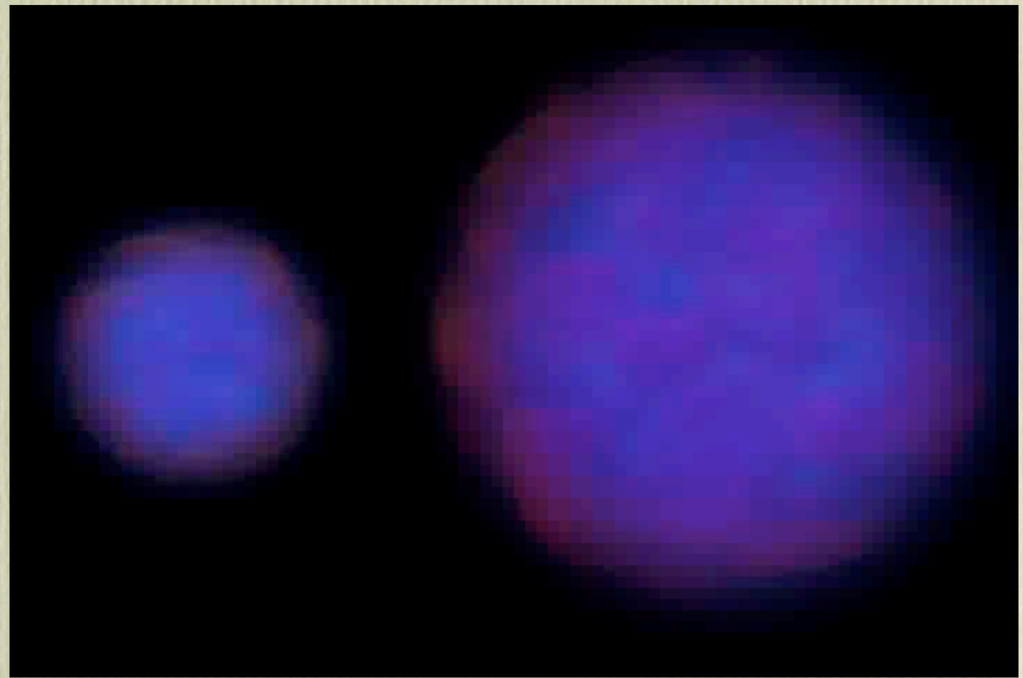
Limits from the fact that you get spherical clusters as opposed to the observed ellipticity in real clusters (e.g. Miralda-Escude, 2000). More recently, limits from the morphology of the recent merging in the 1E0657-558 cluster ("Bullet" cluster):

Lensing map of the cluster superimposed on Chandra X-ray image, Clowe et al. 2006



Sketch of the Bullet collision: the hot gas is collisional and experiences a drag force that slows it down and displaces it from the dark matter which is not slowed by the impact:

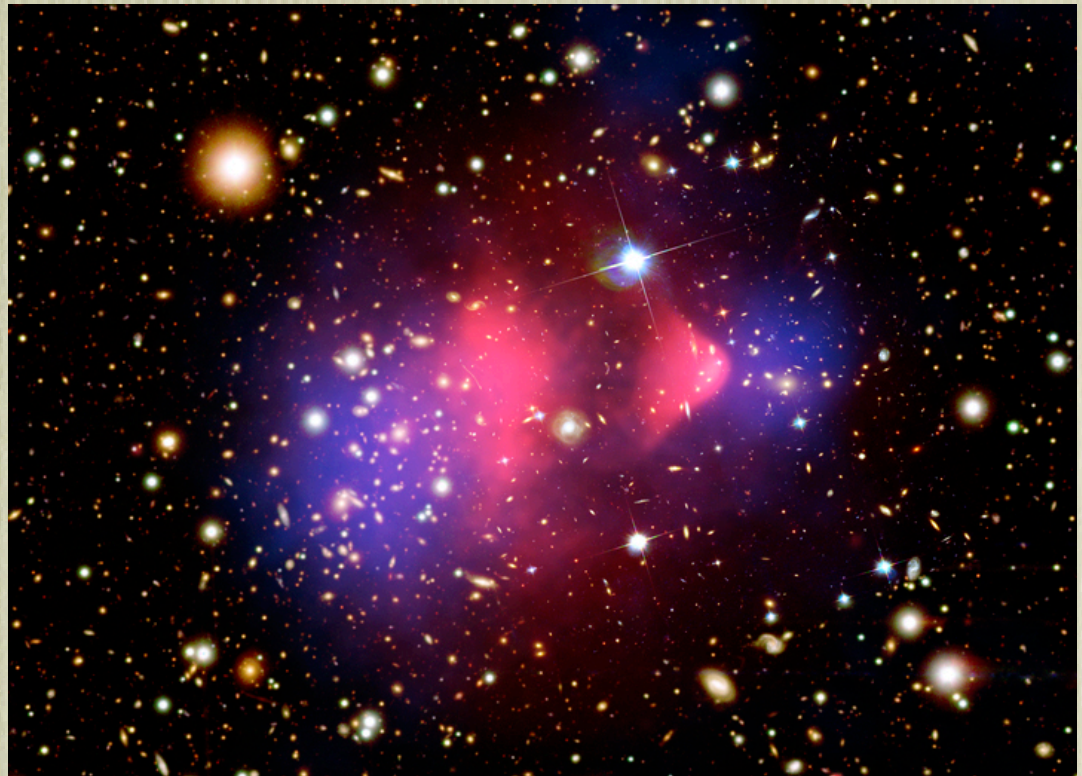
Credit: NASA, M. Weiss



In red: hot gas

In blue: dark matter

Optical, X-ray (pink grading), lensing map (blue grading). Credit: NASA & ESO; M. Markevitch et al. 2006; Clowe et al. 2006.



Inferred limit of the self-interaction cross section per unit mass: $\sigma/m < 1.25 \ \mathrm{cm}^2 \ \mathrm{g}^{-1}$ (Randall et al. 2007) in the range $\sigma/m \sim 0.5 - 5 \ \mathrm{cm}^2 \ \mathrm{g}^{-1}$ claimed for self-interacting DM (Stergel& Steinhardt 2000)

1) + 2) constrain the interaction strength: what about implications for the mass of the dark matter particles?

3) DM is in a **fluid limit**: we have not seen any discreteness effects in DM halos. Granularities would affect the stability of astrophysical systems. Limits from:

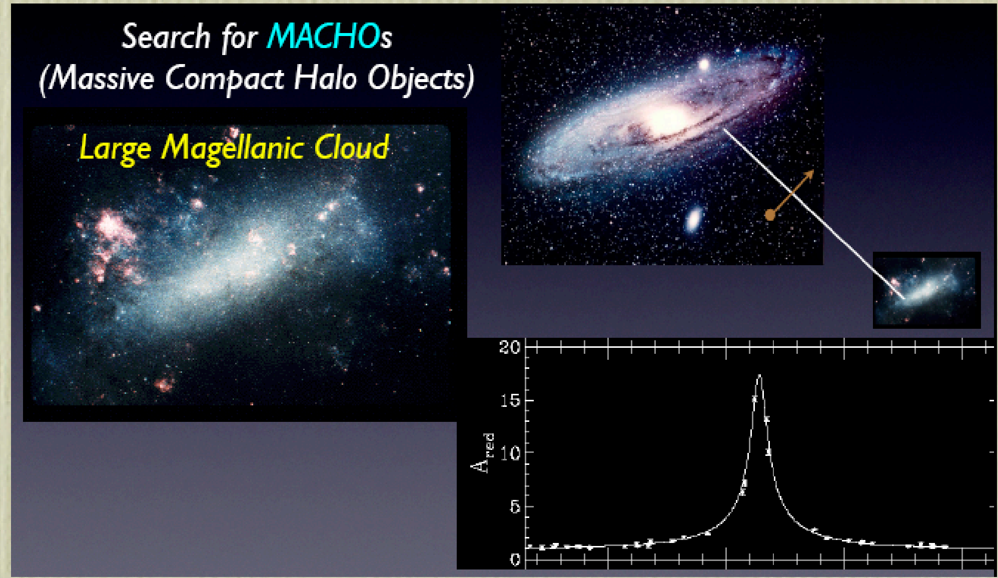
thickness of disks: $M_p < 10^6\, M_\odot$

globular clusters: $M_p < 10^3\, M_\odot$

Poisson noise in Ly-α: $M_p < 10^4\, M_\odot$

halo wide binaries: $M_p < 43\, M_\odot$

Machos + Eros microlensing seaches exclude MACHOs in the Galaxy in the mass range $(10^{-7} - 10)\, M_\odot$

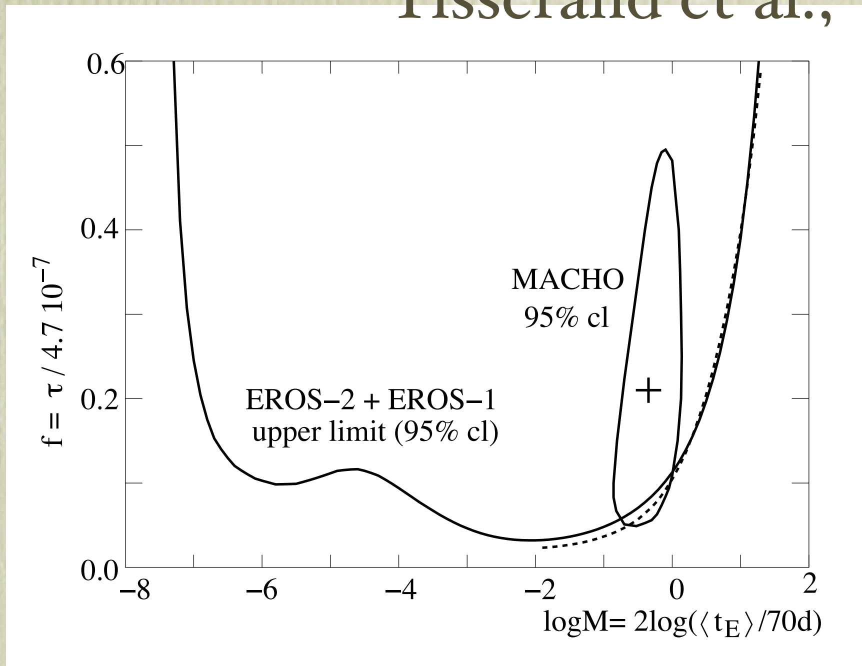


$$\tau = \frac{4\pi G D_s^2}{c^2}\int_0^1 dx\rho(x)x(1-x)$$

$$\downarrow$$

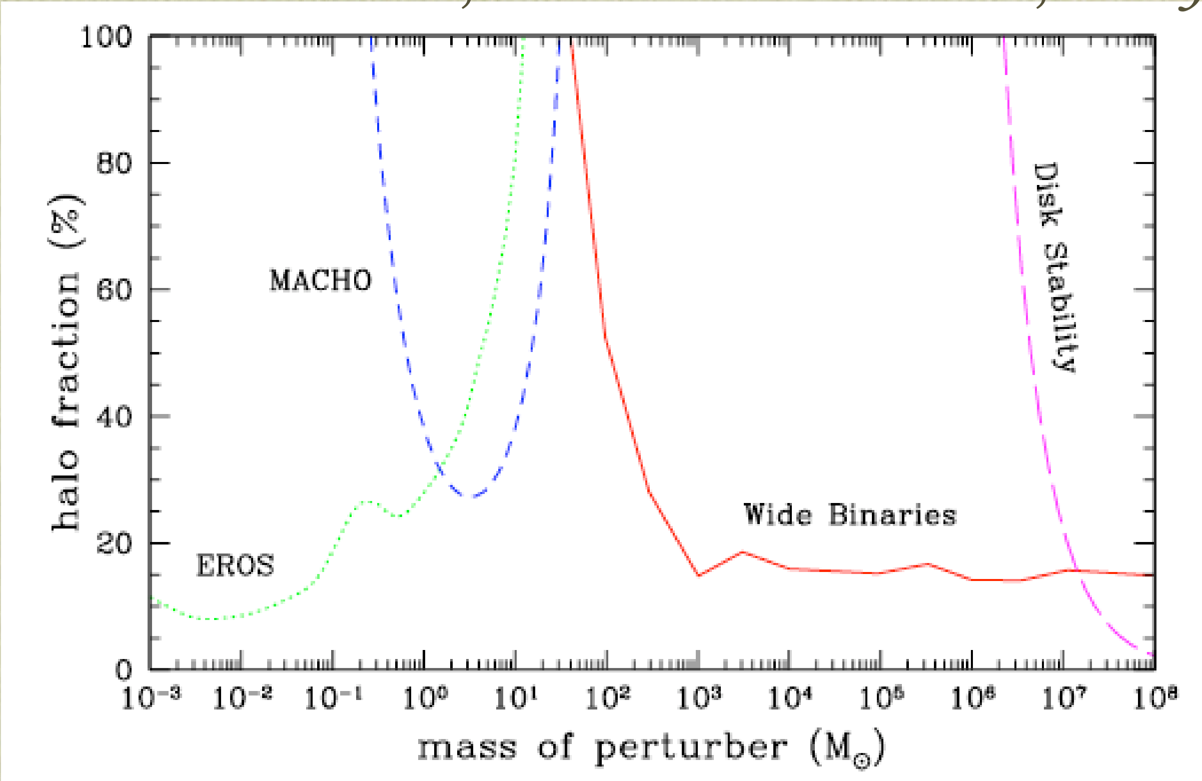
$$\tau_{\rm lmc} = 4.7 f \times 10^{-7}$$

Tisserand et al.,



1) + 2) constrain the interaction strength: what about implications for the mass of the dark matter particles?

Yoo, Chaname & Gould, 2003



Not very tight limits: $M_p < 10\ M_\odot \Longrightarrow M_p < 10^{58}$ GeV

4) DM is **classical**: it must behave classically to be confined on galactic scales, say 1 kpc, for densities ~ GeV cm^{-3}, with velocities ~ 100 km s^{-1}

Two cases:

a) for ***bosons***: the associated De Broglie wavelength

$$\lambda = \frac{h}{p} \simeq 4\,\mathrm{mm}\,\frac{\mathrm{eV}}{M_p} \quad \text{for} \quad v_p \simeq 100\,\mathrm{km}\,s^{-1}$$

$\lambda \lesssim 1\,\mathrm{kpc}$ implies: $\boxed{M_p \gtrsim 10^{-22}\,\mathrm{eV}}$

"Fuzzy" CDM ? Hu, Barkana & Gruzinov, 2000

b) for ***fermions***: Gunn-Tremaine bound (PRL, 1979)

Take DM as some fermionic fluid of non-interacting particles. Start from a (quasi) homogeneous configuration; Pauli exclusion principle sets a maximum to phase space density in this initial configuration: $f_{\rm max}^{\rm ini} = \frac{g}{h^3}$

For a non-interacting fluid: $\frac{df}{dt} = 0$

Fine-grained f versus the coarse-grained $\bar{f}$ which is "observable" and whose maximum can only decrease:

$$\bar{f}_{\rm max} \leq f_{\rm max} \leq f_{\rm max}^{\rm ini}$$

For a DM isothermal sphere: $\bar{f}_{\rm max} = \frac{\rho_0}{M_p^4} \frac{1}{(2\pi\sigma^2)^{3/2}}$

$$\rho_0 \sim 1\,{\rm GeV\,cm}^{-3} \qquad \sigma \sim 100\,{\rm km}\,s^{-1} \quad \Longrightarrow \quad \boxed{M_p \gtrsim 35\,{\rm eV}}$$

5) DM is **cold** (or better it is *not hot*): at matter-radiation equality perturbations need to growth. If kinetic terms dominates over the potential terms, free-streaming erases structures. Defining the free-streaming scale:

$$\lambda_{FS}(t) = \int_{t_i}^{t} \frac{v(t')}{a(t')} \simeq 2\frac{t_{NR}}{a_{NR}}$$

with a large contribution when $v(t) \sim 1$, i.e. up to $t = t_{NR}$ when the species goes non-relativistic, and we assumed radiation domination, $t \propto a^2$

$$T_{NR} \sim M_p/3 \implies t_{NR} \propto M_p^{-2} \implies a_{NR} \propto M_p^{-1}$$

One finds a free-streaming scale:

$$\lambda_{FS} \simeq 0.4\,\mathrm{Mpc}\,(M_p/\mathrm{keV})^{-1}(T_p/T)$$

For a neutrino:

$$\lambda^{\nu}_{FS} \simeq 40\,\mathrm{Mpc}\,(M_{\nu}/30\,\mathrm{keV})^{-1}$$

Top-down formation history excluded by observations, i.e. hot DM excluded. In the cold DM regime λ_{FS} is negligibly small. Warm DM stands in between and needs some particle in the keV mass range (Lyα data place constraints on this range).

The 5 golden rules imply, e.g., that **Baryonic DM and Hot DM are excluded,** and that **Non-baryonic Cold DM is the preferred paradigm**

They also imply that there is **no dark matter candidate in the Standard Model of particle physics**

Still, constraints on particle physics models are rather poor

How do you generate DM?

Further hints on the particle physicist's perspective. The most beaten paths have been:

i) DM as a ***thermal relic product***
(or in connection to thermally produced species);

ii) DM as a ***condensate***, maybe at a phase transition; this usually leads to very light scalar fields;

iii) DM ***generated at large T***, most often at the end of (soon after, soon before) inflation; sample production schemes include gravitational production, production at reheating or during preheating, in bubble collisions, ... Candidates in this category are usually very massive.

CDM as a condensate

Very light scalar created in state of coherent oscillations ~ Bose-condensate.

Consider a scalar $\phi = \phi(t)$ with potential $V(\phi) = \frac{1}{2} m^2 \phi^2$; its eq. of motion is:

$$\ddot{\phi} + 3\,H\,\dot{\phi} + m^2\,\phi = 0$$

When $3\,H < m$ oscillations start with frequency m
$\Rightarrow$ coherent oscillations with modes behaving like matter:

$$\rho = \frac{1}{2}\left[\dot{\phi}^2 + m^2\,\phi^2\right] \Longrightarrow \dot{\rho} = \dot{\phi}\ddot{\phi} + m^2\,\phi\dot{\phi} \Longrightarrow \dot{\rho} = -3\,H\,\dot{\phi}^2$$

eq. o. m.

$$\langle V \rangle = \langle T \rangle = \rho/2 \Longrightarrow \dot{\rho} = -3\,H\,\rho \Longrightarrow \boxed{\rho \propto a^{-3}}$$

coherent oscill.

A slight variant of this picture applies to the axion, pseudo goldstone boson of Peccei-Quinn symmetry introduced to solve the strong CP problem

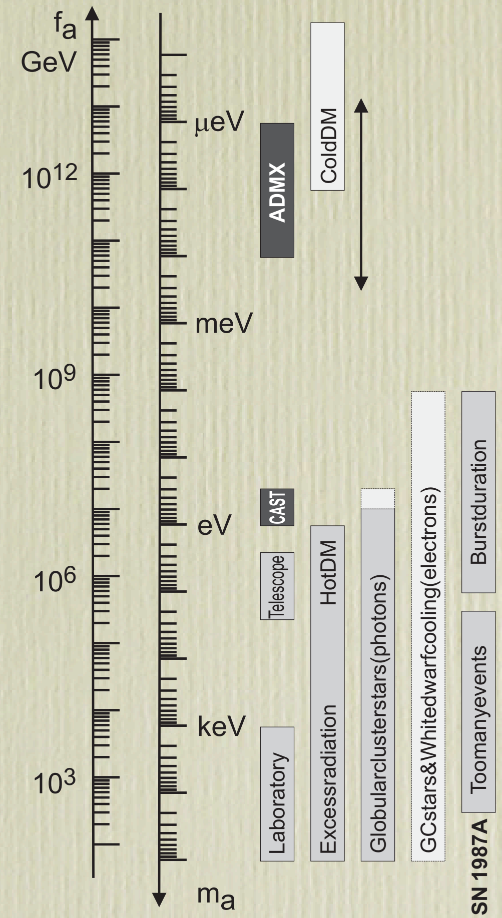
$$m_a \sim 10^{-5}\,\mathrm{eV}$$

$$\updownarrow$$

$$\Omega_a \sim 1$$

(assumes phase average; in case of no averaging or including extra components the mass range is widened)

$1/m_a \propto f_a$ Peccei-Quinn scale



Raffelt, 2006

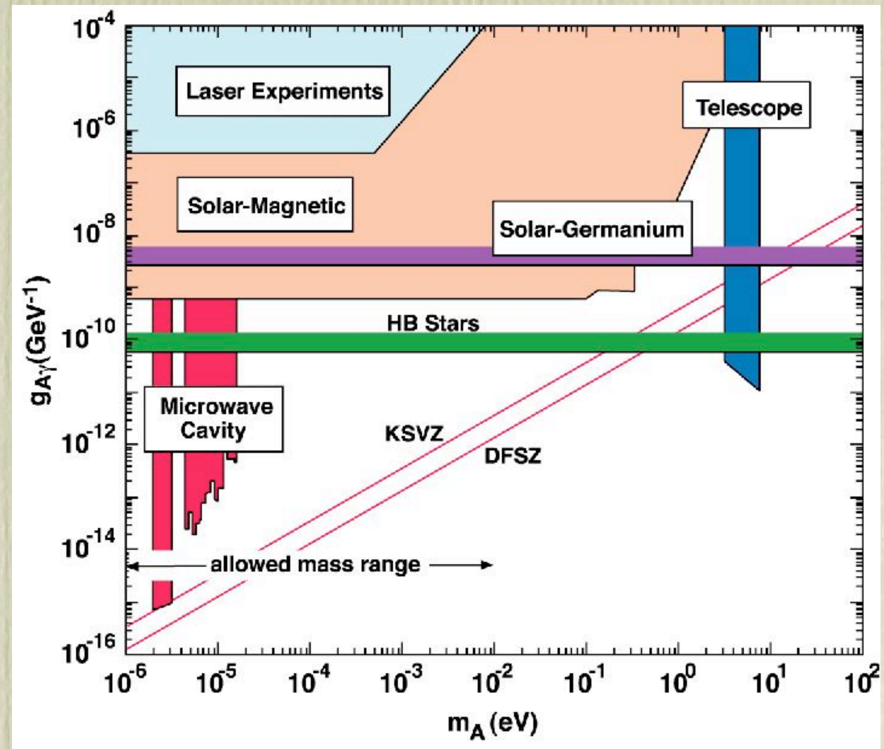
DM detection needs to be considered case by case. For the axion there are generic couplings:

$$g_{aii} \propto \frac{1}{f_a}$$

In particular the axion-electromagnetic field coupling has the form:

$$L_{a\gamma\gamma} = g_{a\gamma\gamma}\, a\, \mathbf{E} \cdot \mathbf{B}$$

Axion detection through resonant conversion in microwave cavities



Duffy, et al. 2006

CDM particles as thermal relics

Let χ be a stable particle, with mass M_χ, carrying a non-zero charge under the SM gauge group. Processes which change its number density take the form:

$$\chi\bar{\chi} \leftrightarrow P\bar{P}$$

with P some lighter SM state in thermal equilibrium.

The evolution of its number density $n_\chi = \frac{g_\chi}{(2\pi)^3}\int f_\chi(p,T)\,d^3p$ is described by Boltzmann eq.:

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma_A v\rangle_T\left[(n_\chi)^2 - \left(n_\chi^{eq}\right)^2\right]$$

dilution by the volume expansion

thermally averaged annihilation cross section

$P\bar{P} \to \chi\bar{\chi}$

$\chi\bar{\chi} \to P\bar{P}$

n_χ^{eq} is the number density in thermal equilibrium:

$$n_\chi^{eq} \propto T^3 \qquad \text{iff} \qquad T \gg M_\chi$$

$$n_\chi^{eq} \propto (M_\chi T)^{3/2} \exp\left(-M_\chi/T\right) \qquad \text{iff} \qquad T \ll M_\chi$$

Rephrase Boltzmann eq. scaling out the dependence on H on the l.h.s. by introducing:

$$Y_\chi \equiv \frac{n_\chi}{s} \quad \text{with the entropy density} \quad s \propto g_{\text{eff}}(T)\, T^3$$

being conserved in a comoving volume $s\, a^3 = \text{const.}$, i.e. $\dot{s} = -3\, s\, H$ (we will ASSUME no late entropy injection); replace also the t dependence with $x \equiv M_\chi/T$:

$$\frac{x}{Y_\chi^{eq}} \frac{dY_\chi}{dx} = -\boxed{\frac{\langle \sigma_A v \rangle_T\, n_\chi^{eq}}{H}} \left[\left(\frac{Y_\chi}{Y_\chi^{eq}} \right)^2 - 1 \right]$$

$$\sim \frac{\Delta Y}{Y}$$

triggered by

χ in thermal equilibrium down to the freeze-out T_f, given, as a rule of thumb, by:

$$\Gamma(T_f) = n_\chi^{eq}(T_f)\langle\sigma_A v\rangle_{T=T_f} \simeq H(T_f)$$

After freeze-out, when $\Gamma \ll H$, the number density per comoving volume stays constant $Y_\chi(T) \simeq Y_\chi^{eq}(T_f)$, i.e. the relic abundance for χ freezes in. The nowadays abundance is given by:

$$\Omega_\chi = \frac{\rho_\chi}{\rho_c} = \frac{M_\chi\, n_0}{\rho_c} = \frac{M_\chi\, s_0\, Y_0}{\rho_c} \simeq \frac{M_\chi\, s_0\, Y_\chi^{eq}(T_f)}{\rho_c}$$

with: $s_0 \simeq 3000\ \mathrm{cm}^{-3}$

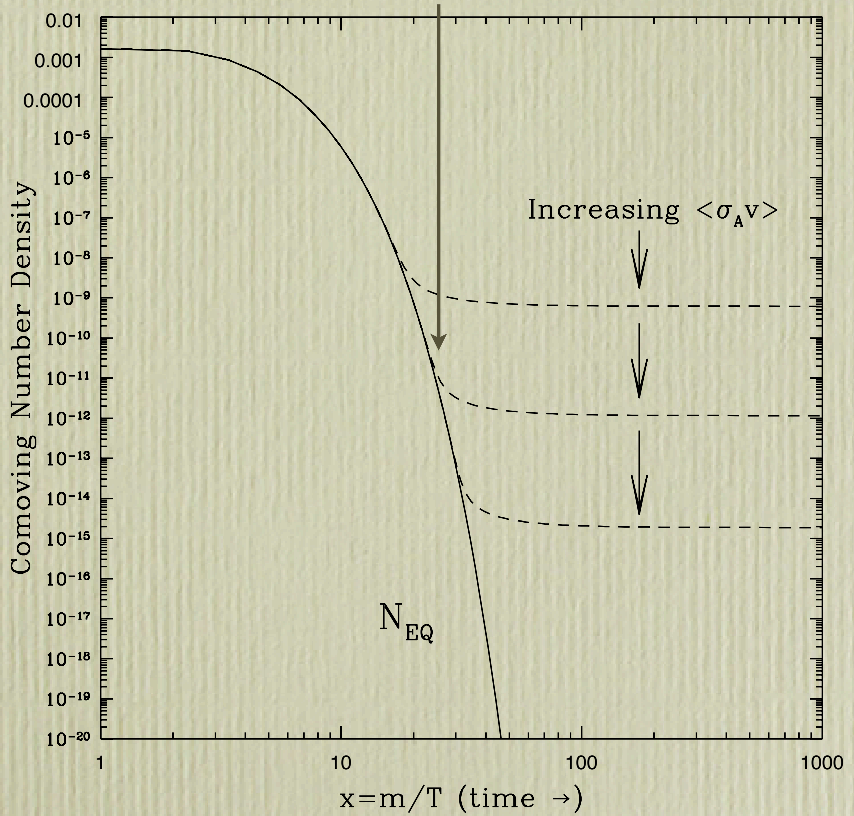
For the freeze-out of a relativistic species $Y_\chi^{eq} \neq Y_\chi^{eq}(T_f)$

$\Omega_\chi \propto M_\chi$ and does not depend on $\langle\sigma_A v\rangle_{T=T_f}$.

For neutrinos: $\Omega_\nu h^2 = \dfrac{\sum m_{\nu_i}}{91\,\mathrm{eV}}$ (but forget about HDM)

Non-relativistic species freeze-out in their Boltzmann tail:

$$\Gamma(T_f) \simeq H(T_f)$$



$$\Omega_\chi h^2 \simeq \frac{M_\chi\, s_0\, Y_\chi^{eq}(T_f)}{\rho_c/h^2}$$

(f.-o. cond. + s conservation)

$$\simeq \frac{M_\chi\, s_0}{\rho_c/h^2}\, \frac{H(T_f)}{s(T_f)\langle\sigma_A v\rangle_{T_f}}$$

(standard cosmology)

$$\simeq \frac{M_\chi}{T_f}\, \frac{g_\chi^\star}{g_{\rm eff}}\, \frac{1\cdot 10^{-27}{\rm cm}^{-3}{\rm s}^{-1}}{\langle\sigma_A v\rangle_{T=T_f}}$$

with: $M_\chi/T_f \sim 20$

$$\Omega_\chi h^2 \simeq \frac{3\cdot 10^{-27}{\rm cm}^{-3}{\rm s}^{-1}}{\langle\sigma_A v\rangle_{T=T_f}} \longrightarrow \text{WIMP}$$

WIMP DM candidates

The recipe for WIMP DM looks simple. Just introduce an extension to the SM with:

i) a new stable massive particle;
ii) coupled to SM particles, but with zero electric and color charge;
ii b) not too strongly coupled to the Z° boson
(otherwise is already excluded by direct searches).

Solve the Boltzmann eq. and find its mass.

Likely, not far from M_W, maybe together with additional particles carrying QCD color: LHC would love this setup!

A recipe which can be implemented in many SM extensions. Maybe the most delicate point is the requirement of stability. You can enforce it via a discrete symmetry:

- R-parity in SUSY models
- KK-parity in Universal Extra Dimension models (Servant & Tait, hep-ph/0206071)
- T-parity in Little Higgs models (Bickedal et al., hep-ph/0603077)
- Z symmetry in a 2 Higgs doublet SM extension (the “Inert doublet model”, Barbieri et al. hep-ph/0603188)
- Mirror symmetry in 5D models with gauge-Higgs unification (Serone et al., hep-ph/0612286)
- ...

or via an accidental symmetry, such as a quantum number preventing the decay: [Mirror DM], DM in technicolor theories (Gudnason et al., hep-ph/0608055), “minimal” DM (Cirelli et al., hep-ph/0512090) , ...

Incomplete list of models and very incomplete list of references!

In most of these, DM appears as a by-product from a property considered to understand or protect other features of the theory.

Neutralino LSP as DM

In the MSSM there are four such states, with mass matrix:

$$\mathcal{M}_{\tilde{\chi}^0_{1,2,3,4}} = \begin{pmatrix} M_1 & 0 & -\frac{g' v_1}{\sqrt{2}} & +\frac{g' v_2}{\sqrt{2}} \\ 0 & M_2 & +\frac{g v_1}{\sqrt{2}} & -\frac{g v_2}{\sqrt{2}} \\ -\frac{g' v_1}{\sqrt{2}} & +\frac{g v_1}{\sqrt{2}} & 0 & -\mu \\ +\frac{g' v_2}{\sqrt{2}} & -\frac{g v_2}{\sqrt{2}} & -\mu & 0 \end{pmatrix}$$

and lightest mass eigenstate (most often the LSP):

$$\tilde{\chi}^0_1 = N_{11}\tilde{B} + N_{12}\tilde{W}^3 + N_{13}\tilde{H}^0_1 + N_{14}\tilde{H}^0_2$$

A very broad framework, which gets focussed on narrow slices in the parameter space once more specific LSP DM frameworks are introduced.

E.g.: neutralino LSP in the CMSSM

Minimal scheme,
but general enough to
illustrate the point.

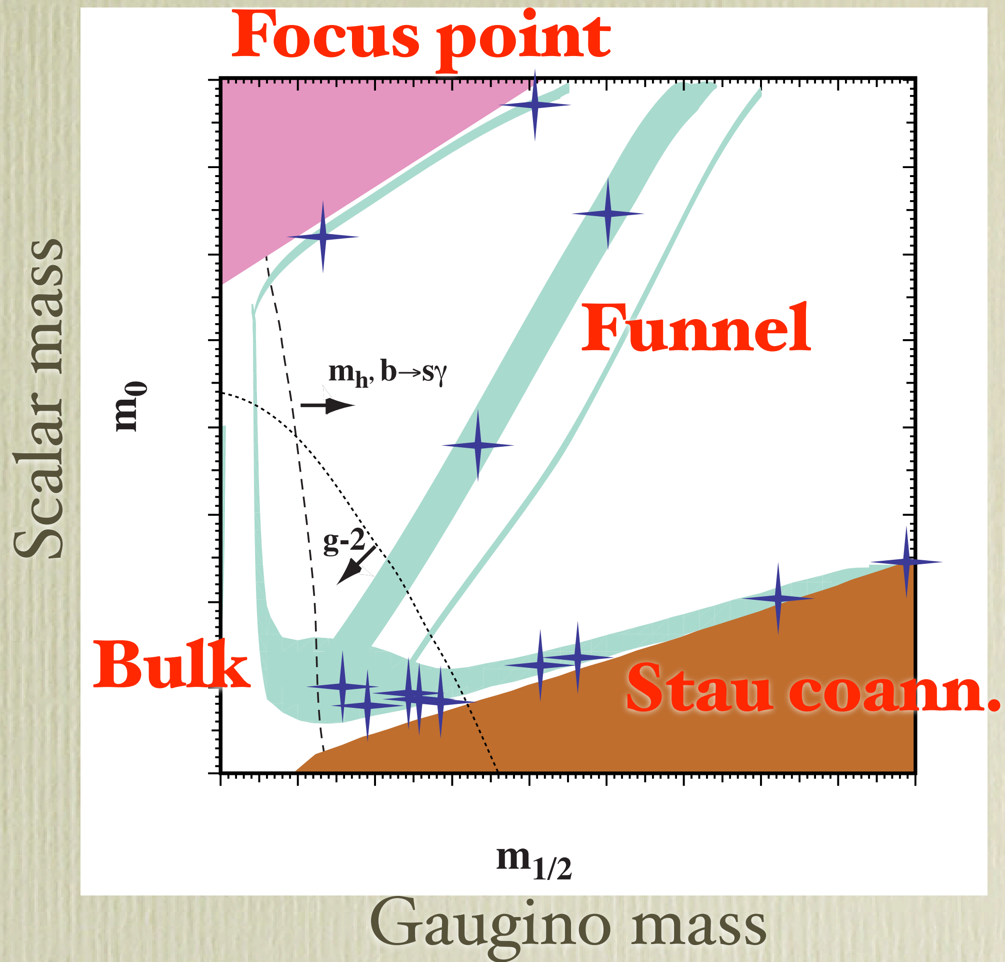
Set of assumptions:

Unification of gaugino masses:
$M_i(M_{GUT}) \equiv m_{1/2}$

Unification of scalar masses:
$m_i(M_{GUT}) \equiv m_0$

Universality of trilinear couplings:
$A^u(M_{GUT}) = A^d(M_{GUT}) = A^l(M_{GUT}) \equiv A_0 m_0$

Other parameters: $sign(\mu), \tan\beta$



Battaglia et al. 2001

Bulk region: the lightest neutralino is Bino-like (since the RGEs give $M_1 \simeq 0.5 M_2$); the thermal relic density is set by pair annihilation processes of the kind:

$\tilde{\chi}_1^0 \, \tilde{\chi}_1^0 \leftrightarrow f \, \bar{f}$ mediated by a $\tilde{f}$ in the t- & u-channels

These annihilations have a helicity-flip suppression:

$$\langle \sigma_A v \rangle_{S-wave} \propto \frac{m_f^2}{[M_{\tilde{\chi}_1^0}^2 + M_{M_{\tilde{\chi}_1^0}^2}^2]^2}$$

The P-wave, which is in general suppressed, takes over:

$$\langle \sigma_A v \rangle_{P-wave} \propto v^2 \propto \frac{T^2}{M_{\tilde{\chi}_1^0}^2}$$

One finds a "light" neutralino, i.e. 100-150 GeV, in a regime barely allowed by accelerator constraints.

Funnel region: you still have a Bino-like neutralino and the thermal relic density is still set by pair annihilations into fermions:

$$\tilde{\chi}^0_1 \, \tilde{\chi}^0_1 \leftrightarrow f \, \bar{f}$$

but these are now driven by a A^0 in a resonant s-channel, i.e. when the amplitude:

$$M \propto \frac{1}{s - m_A^2} \simeq \frac{1}{4 \, M^2_{\tilde{\chi}^0_1} - m_A^2}$$

gets a sharp enhancement in the limit $M_{\tilde{\chi}^0_1} \simeq m_A \, / \, 2$

In the cMSSM, this can happen for large $\tan\beta$ and the mass scale for the lightest neutralino may shift up to ~ 700 GeV

Coannihilation processes?

Suppose that the theory contains a set of N states nearly degenerate in mass $\chi_1, \chi_2, \cdots \chi_N$, with $m_1 \leq m_2 \leq \ldots \leq m_N$ and sharing a quantum number. Trace the evolution of densities simultaneously, since all states have comparable densities (and are essentially indistinguishable):

$$
\begin{aligned}
\frac{dn_i}{dt} &= -3\,H\,n_i - \sum_j \langle \sigma_{ij} v_{ij} \rangle \left(n_i n_j - n_i^{eq} n_j^{eq} \right) \\
&\quad - \sum_{j \neq i} \langle \sigma_{i\to j} v_{i\to j} \rangle \left(n_i - n_j \frac{n_i^{eq}}{n_j^{eq}} \right) \\
&\quad + \sum_{j>i} \Gamma_{j\to i} \left(n_j - n_i \frac{n_j^{eq}}{n_i^{eq}} \right) \\
&\quad - \sum_{j<i} \Gamma_{i\to j} \left(n_i - n_j \frac{n_i^{eq}}{n_j^{eq}} \right),
\end{aligned}
$$

$\chi_i\,\chi_j \leftrightarrow X_a^f$

$\chi_i\,X_b^i \leftrightarrow \chi_j\,X_b^f$

$\chi_j \leftrightarrow \chi_i\,X_c^f$

After freeze-out, all particles decay to the stable state χ_1.
It is sufficient to trace $n = \sum_i n_i$ rather than each n_i :

$$\frac{dn}{dt} = -3\,H\,n - \sum_{i,j} \langle \sigma_{ij} v_{ij} \rangle \left(n_i n_j - n_i^{eq} n_j^{eq} \right)$$

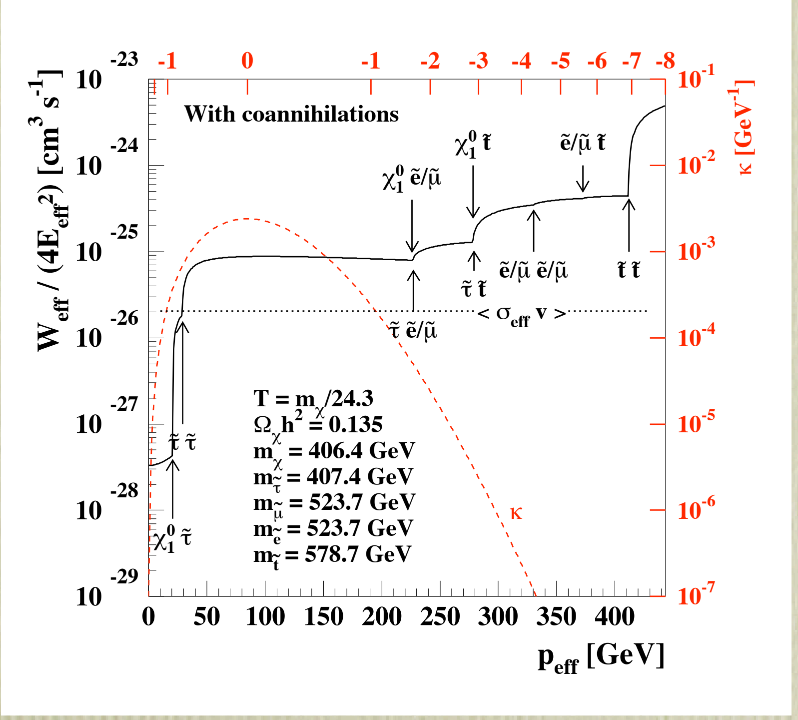
For fast $\chi_i \, X_b^i \leftrightarrow \chi_j \, X_b^f$, one has $\frac{n_i}{n} \simeq \frac{n_i^{eq}}{n^{eq}}$ and:

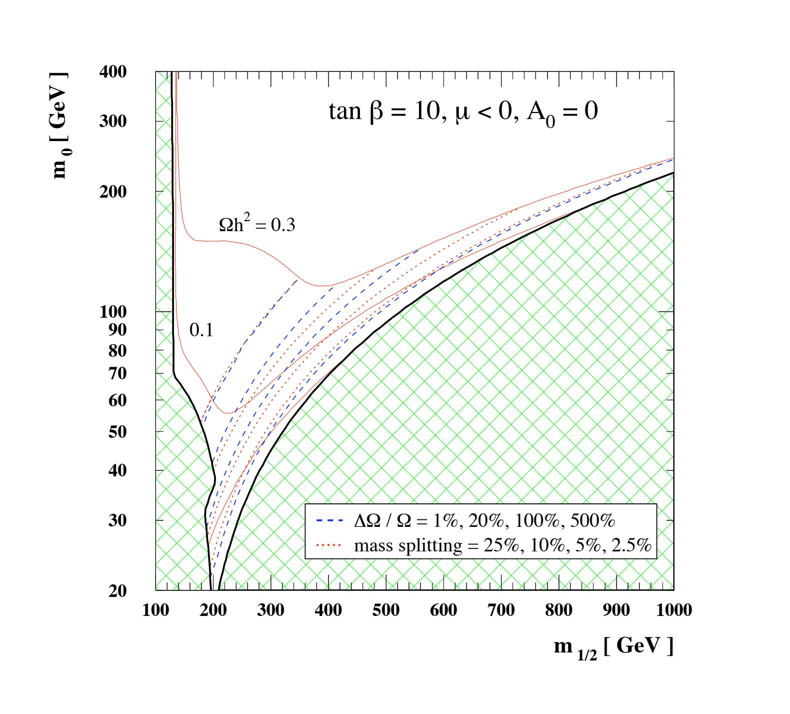
$$\frac{dn}{dt} = -3\,H\,n - \langle \sigma_{eff} v \rangle \left[n^2 - (n^{eq})^2 \right]$$

with $\langle \sigma_{eff} v \rangle = \sum_{i,j} \langle \sigma_{ij} v_{ij} \rangle \frac{n_i^{eq}}{n^{eq}} \frac{n_j^{eq}}{n^{eq}}$

Analogous to the 1-particle case, with the coannihilating species acting as dominant (parasite) degree of freedom if their annihilation rate is larger (smaller) than for the DM species, and a net decrease (increase) in the relic density.

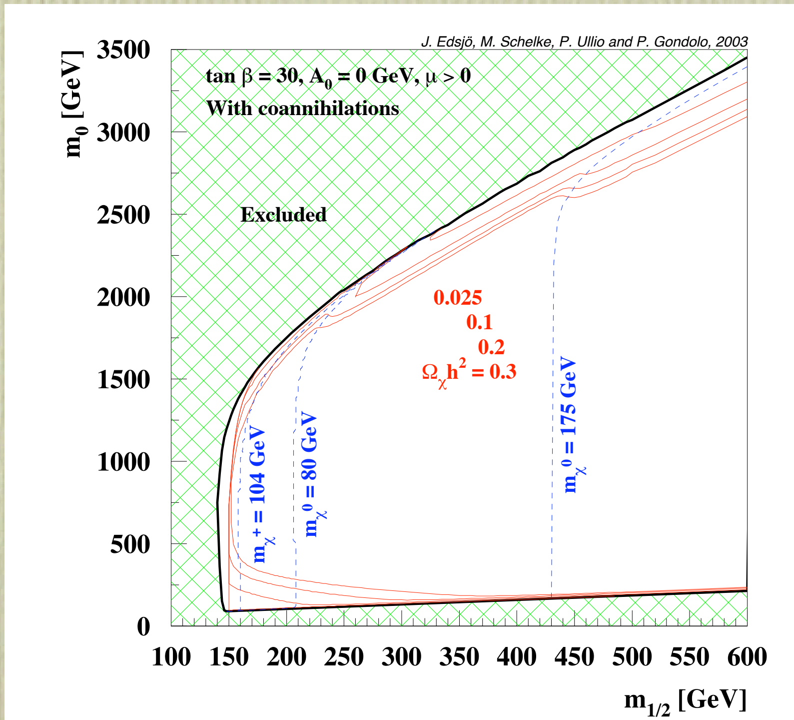
Stau coannihilation region: a Bino-like neutralino is nearly degenerate in mass with a stau and the latter sets the thermal relic density:

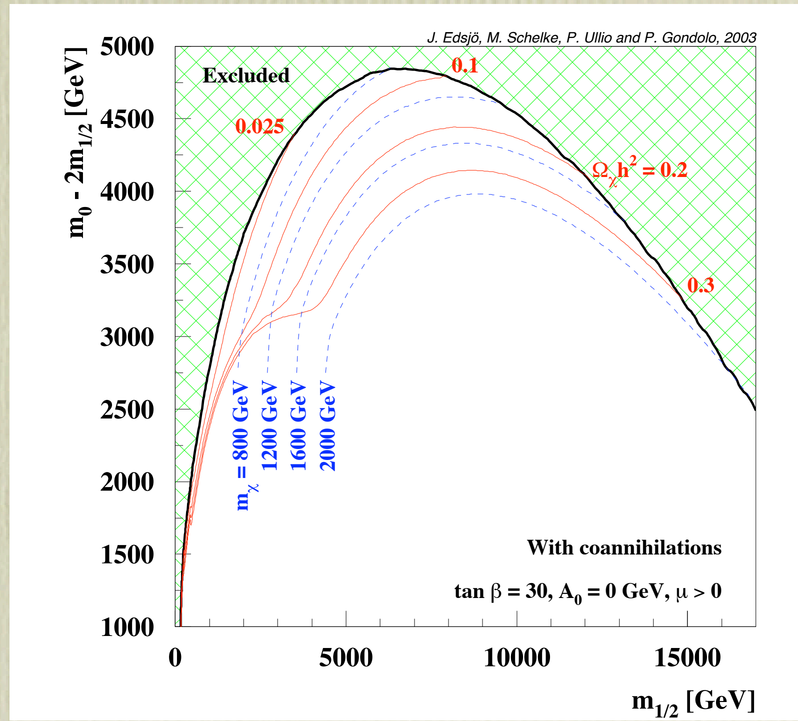




lightest neutralino mass scale up to 300-400 GeV

Focus point region: the parameter μ gets of the order or smaller than gaugino mass parameters; the lightest neutralino is in mixed state or Higgsino-like. The annihilation is driven by gauge boson final states, while sfermions are heavy.



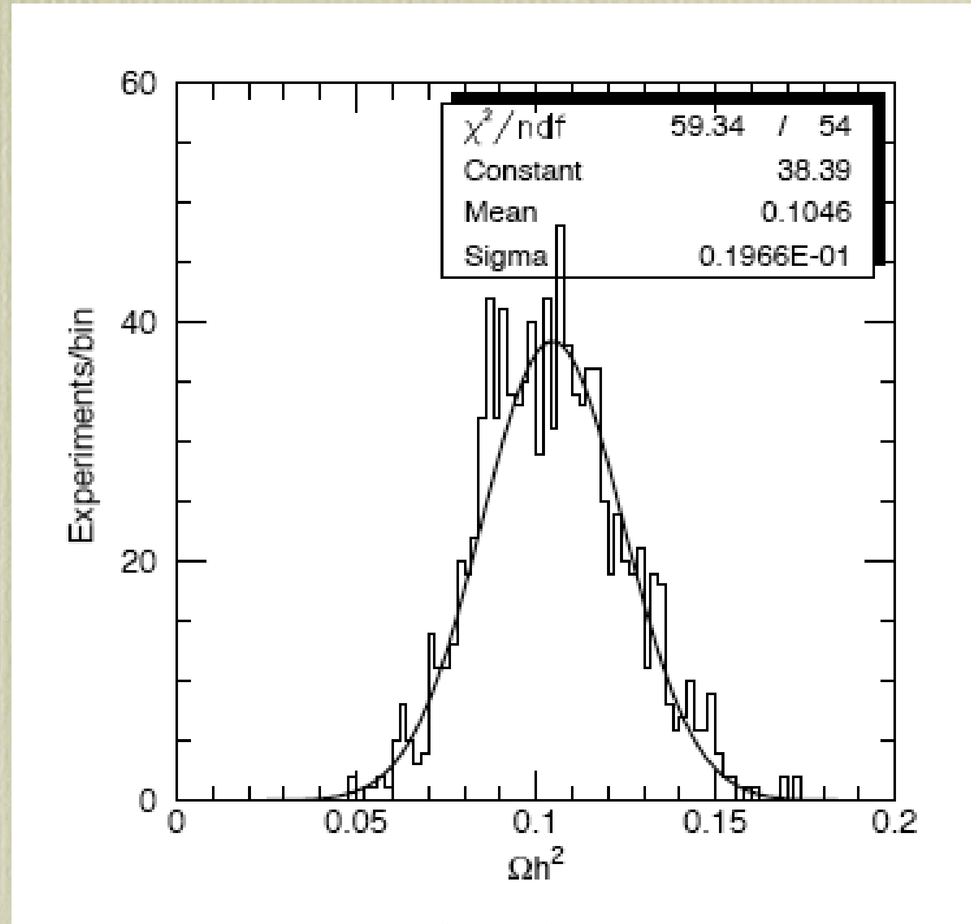


WIMPs at the LHC time. A few possibilities.

There are favourable case, such as for the **bulk region**, in which you would reconstruct the relic density:

Most superpartners are light and detected at LHC (only heaviest stop, stau and neutralino are not seen in example displayed):

fairly accurate prediction for the relic density



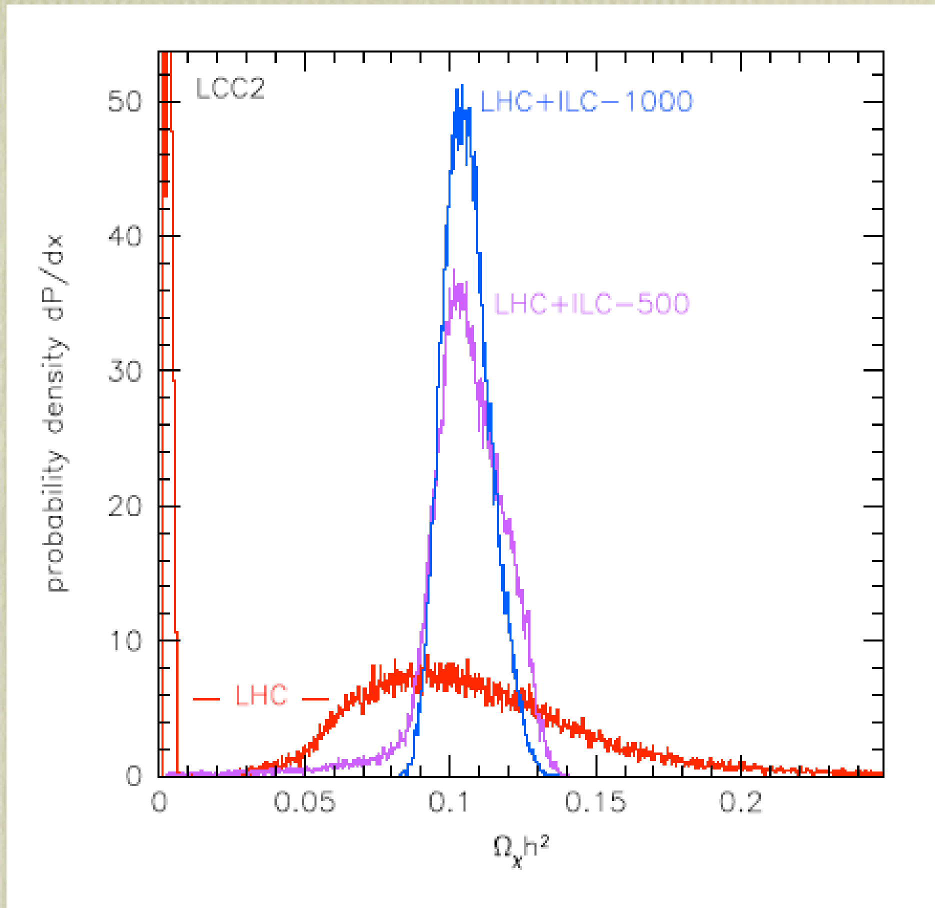
Relic density

Nojiri, Polesello & Tovey, 2006

... and much less favourable cases, such as for the **focus-point region**:

Even assuming a light $M_{1/2}$ (300 GeV), LHC finds only the gluino and 3 neutralinos:

the relic density value is poorly reconstructed



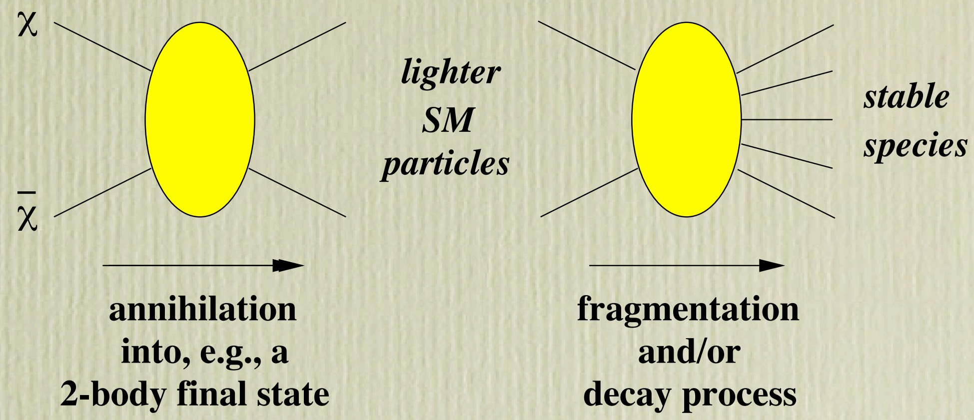
Relic density

Baltz, Battaglia, Peskin & Wizansky, 2006

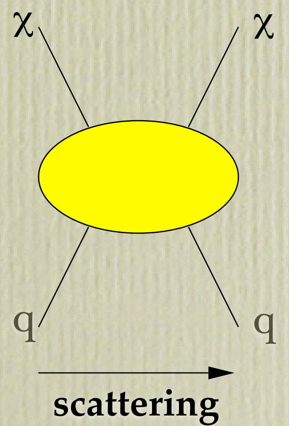
Detection of WIMP DM

A very rich phenomenology expected for WIMPs:

Pair annihilation rate at T=0 (i.e. in today's halos) of the order of the one at freeze-out (?)



By crossing symmetry (?)



i.e. a coupling to ordinary matter, allowing for direct detection or capture into massive bodies (Earth/Sun)

In practice the scheme is much less predictive:

✶the spread in values for the T=0 annihilation rate may be substantial, because of:

- on the particle physics side, e.g., coannihilation, threshold, or resonance (resonance) effects,
- on the cosmological side, e.g., a late entropy release or a Universe expansion rate faster at freeze-out;

✶the crossing symmetry rarely applies;

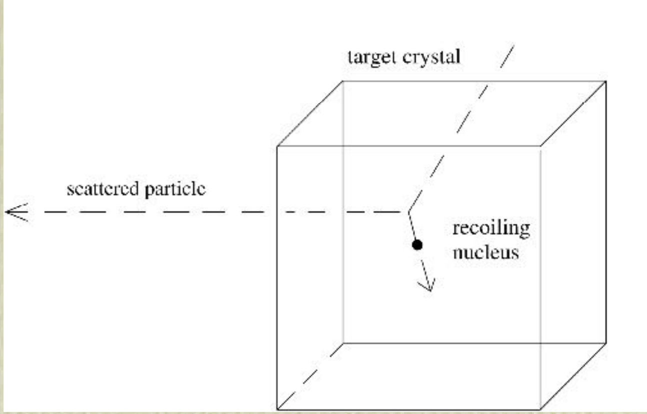
✶particles with color charge are seldom the (light) states setting the thermal relic density.

Legend

In blue: effect making detection harder
In red: larger rates expected

Direct detection:

The attempt to measure the recoil energy from elastic scattering of local DM WIMPs with underground detectors (cosmic-ray shielded).



A WIMP halo particle of mass M_χ and velocity v scatters on a target nucleus of mass M_N under a CM angle θ, giving a recoil energy:

$$Q = \frac{|\vec{q}|^2}{2\,M_N} = v^2 \frac{M_\chi^2 M_N}{(M_\chi + M_N)^2}(1 - \cos\theta)$$

E.g., for: $N = {}^{76}Ge\,, \quad M_\chi \sim 100\,\mathrm{GeV}\,, \quad v \sim 200\,\mathrm{km\,s^{-1}}$ $\longrightarrow$ $Q_{max} \sim 20\,\mathrm{keV}$

The expected rate is about the product of the # of target nuclei per unit mass, the WIMP flux and the WIMP-nucleon scattering cross section:

$$R \simeq N_T\, F\, \sigma_{\chi N} \simeq N_T\, \frac{\rho_\chi}{M_\chi}\,\langle v\rangle\,\sigma_{\chi N} \simeq \frac{4\,\mathrm{events}}{\mathrm{kg\,day}}\,\frac{\rho_\chi^{0.3}}{M_\chi^{100}}\langle v_{200}\rangle\left(\frac{\sigma_{\chi N}^{1\,\mathrm{pb}}}{A}\right)$$

More precisely the event rate, as a function of the LAB recoil energy is in the form:

$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \int_{vmin}^{v_{max}} d\vec{v} f(\vec{v}) |\vec{v}| \frac{d\sigma(\vec{v}, E_R)}{dE_R}$$

WIMP-nucleus cross section

WIMP DF

Integral on the WIMP velocity in the detector frame

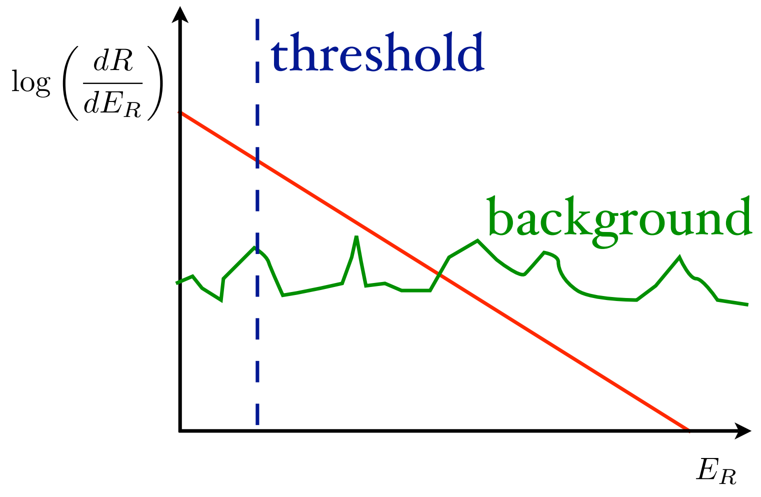
For standard velocity distributions, one finds approximately:

$$\frac{dR}{dE_R} \simeq \frac{R_{tot}}{r\, E_R^0} \exp\left(-\frac{E_R}{r\, E_R^0}\right)$$

with

$$r = \frac{4\, M_\chi\, M_N}{(M_\chi + M_N)^2}$$

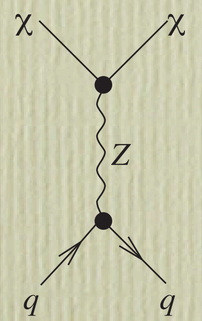
and E_R^0 the most probable recoil energy.

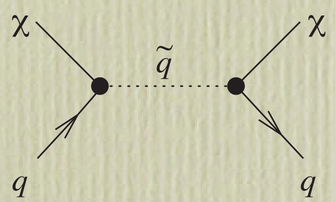


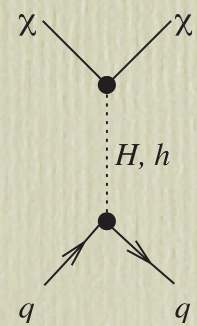
For WIMP DM in the form of Majorana fermions, there are two contributions to the cross section:

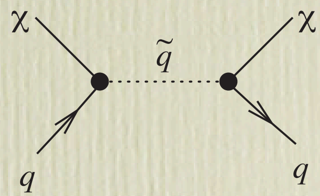
Axial-vector (spin-dependent)	scalar (spin-independent)
$\mathscr{L}_A = d_q \; \bar{\chi}\gamma^\mu\gamma_5\chi\bar{q}\gamma_\mu\gamma_5 q$	$\mathscr{L}_{\text{scalar}} = a_q \bar{\chi}\chi\bar{q}q$

In case of neutralinos:









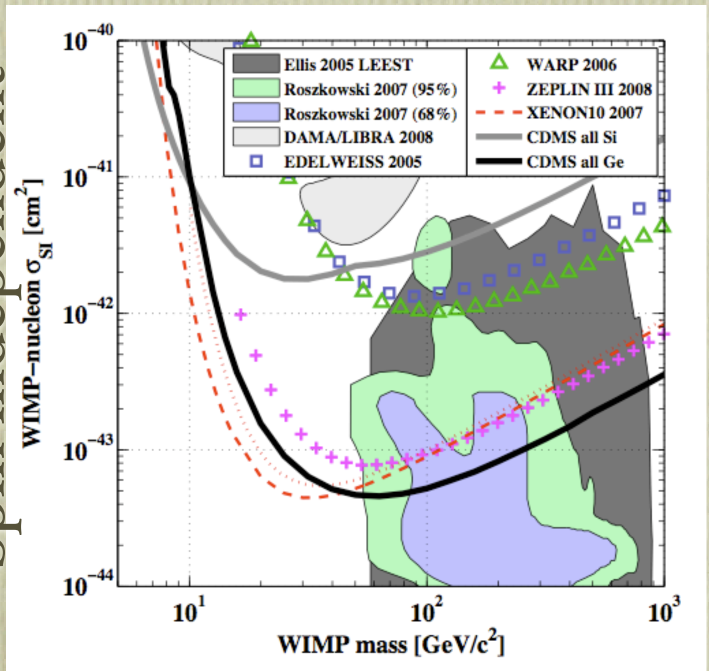
For Dirac fermions you have also: $\mathscr{L}^q_{vec} = b_q \; \bar{\chi}\gamma_\mu\chi\,\bar{q}\gamma^\mu q$

N.B.: a 4-th generation heavy neutrino or sneutrinos interact too strongly and are already excluded.

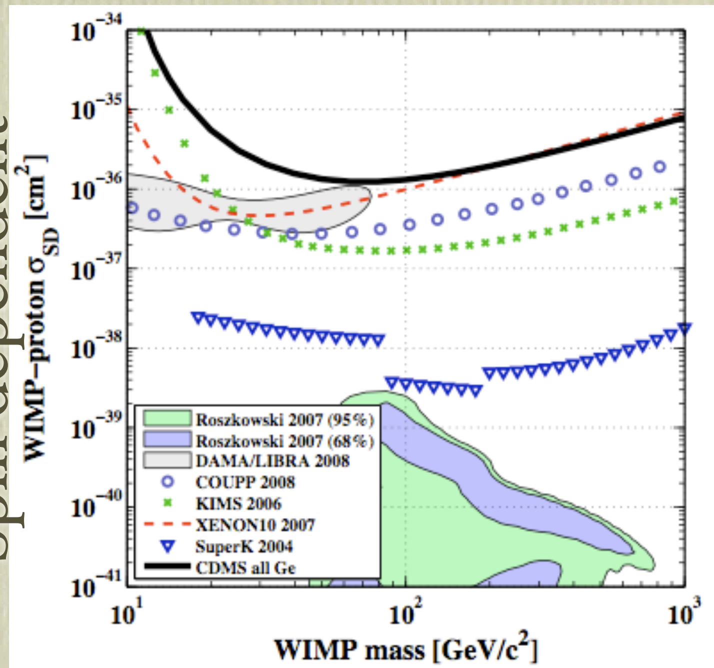
Experimental status versus models:

Very intense experimental efforts in the last decade. Several experiments have published upper limits, improving of a factor of (a) few every year (final goal: ton-scale detectors increasing the present sensitivity of 100 (1000???))

Spin independent



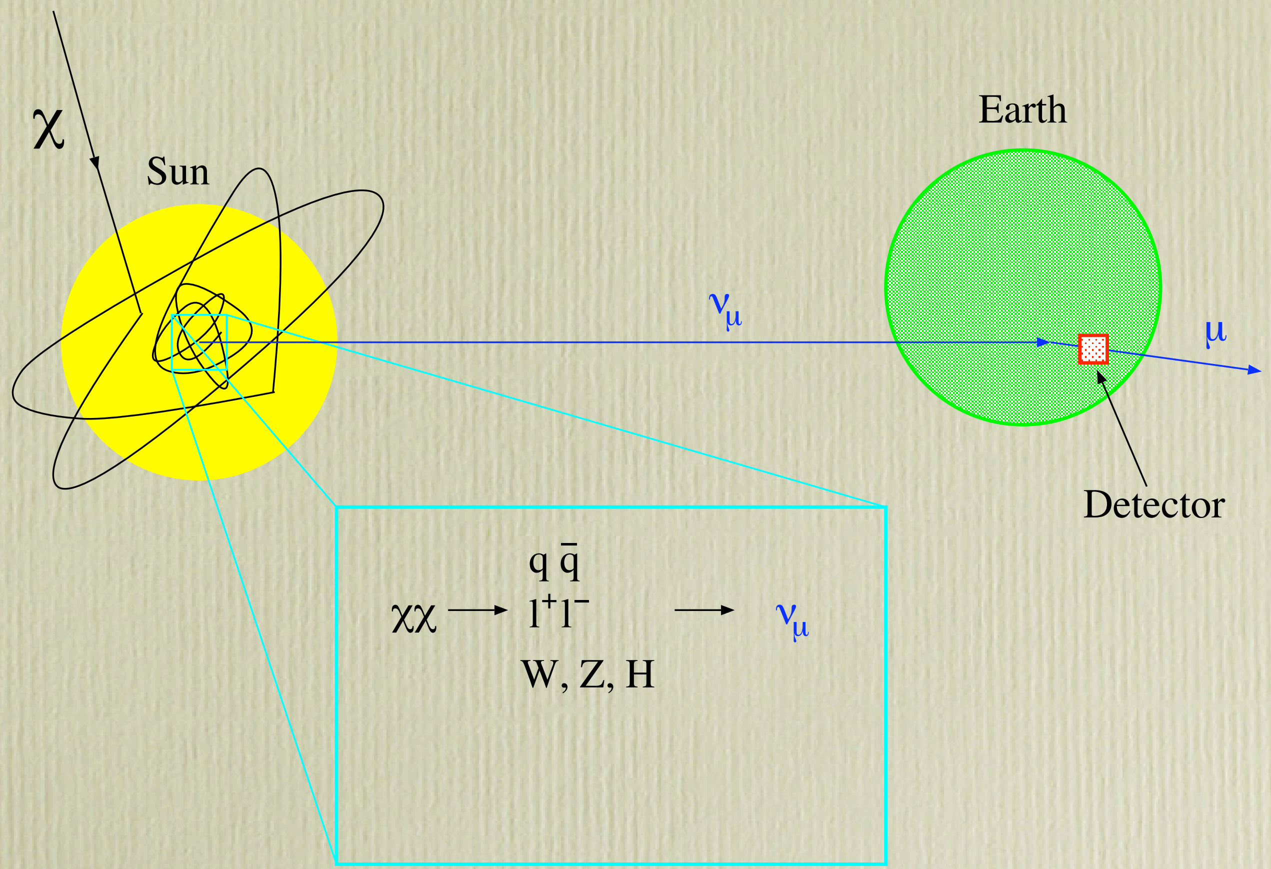
Spin dependent



data compilation by J. Filippini, 2009

The MSSM neutralino DM parameter is being probed by spin-independent limits; less sensitive to spin-dependent effects.

Searches with neutrino telescopes



extra-clean signature!

Searches with neutrino telescopes

Significant limits at present (Baikal, Super-K, Amanda) large sensitivity improvements for the future (IceCube, Antares, Nemo, KM3Net, ect.).

The DM signal is at a detectable level when the capture in the Sun/Earth is efficient, at (or close to) equilibrium between capture rate and annihilation rate.

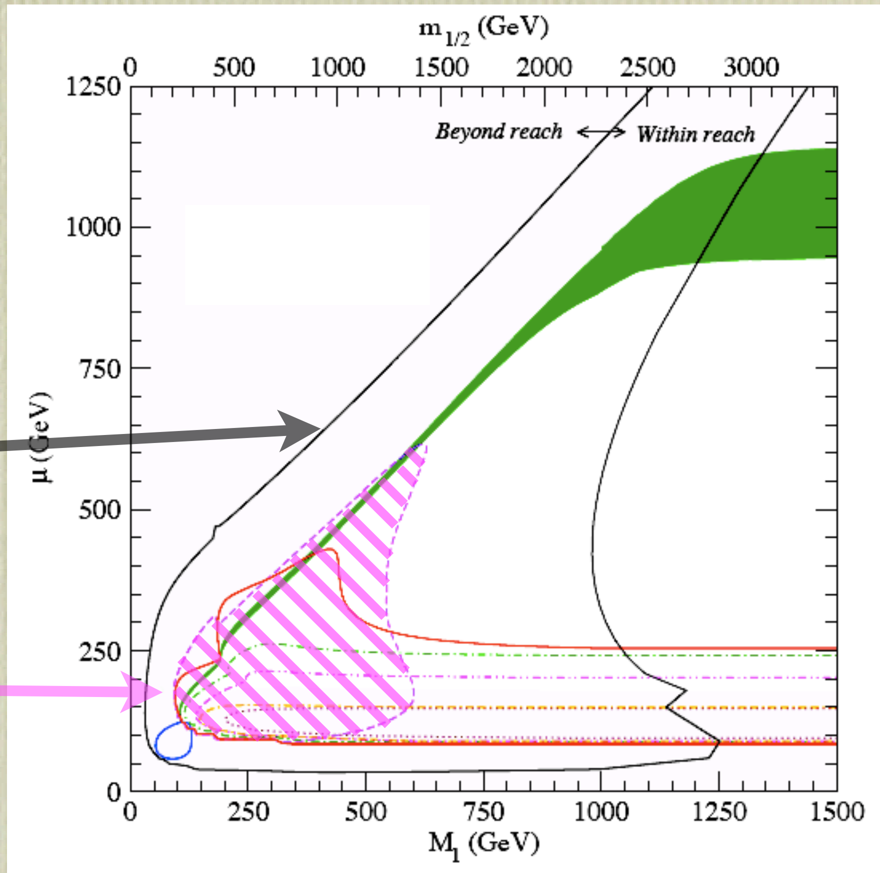
For the Earth, *spin-independent* coupling matters: under standard assumptions for the WIMP distribution in the DM halo, direct detection sets stronger limits.

Capture in the Sun is mainly driven by the *spin-dependent* term; ν-telescopes probe this regime more efficiently than direct detection (in case of standard annihilation modes).

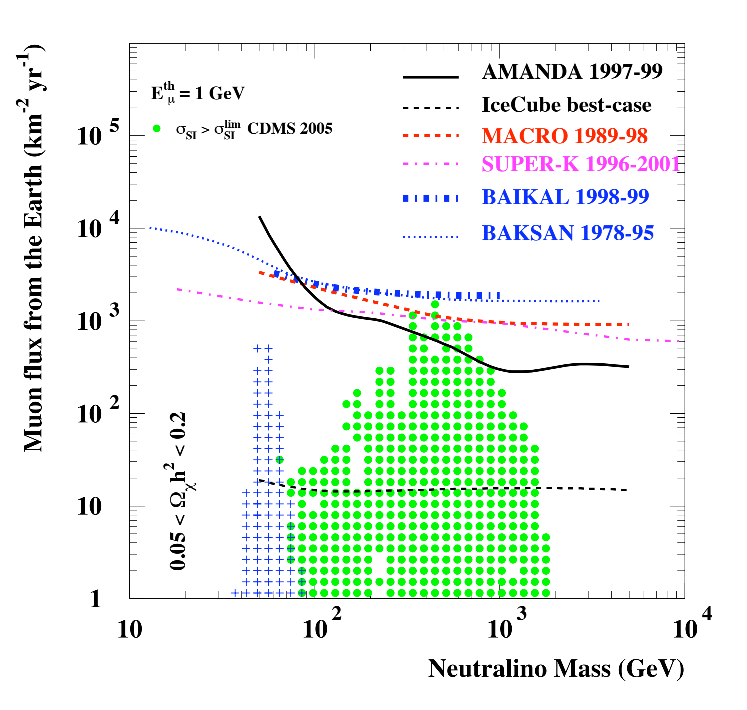
SI versus SD?
the standard lore is
that SI wins

1-ton
detector

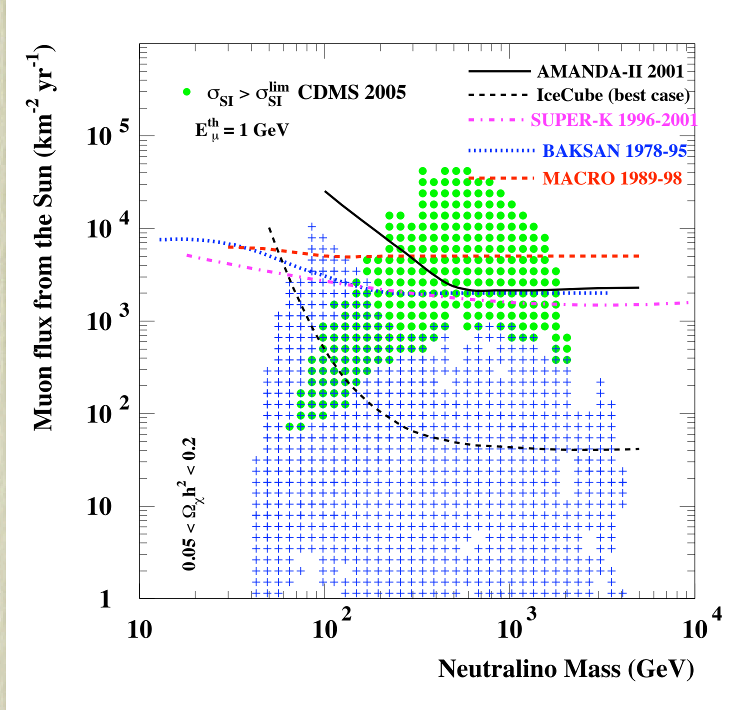
IceCube



More generic MSSM scans, current limits and Icecube discovery potentials:



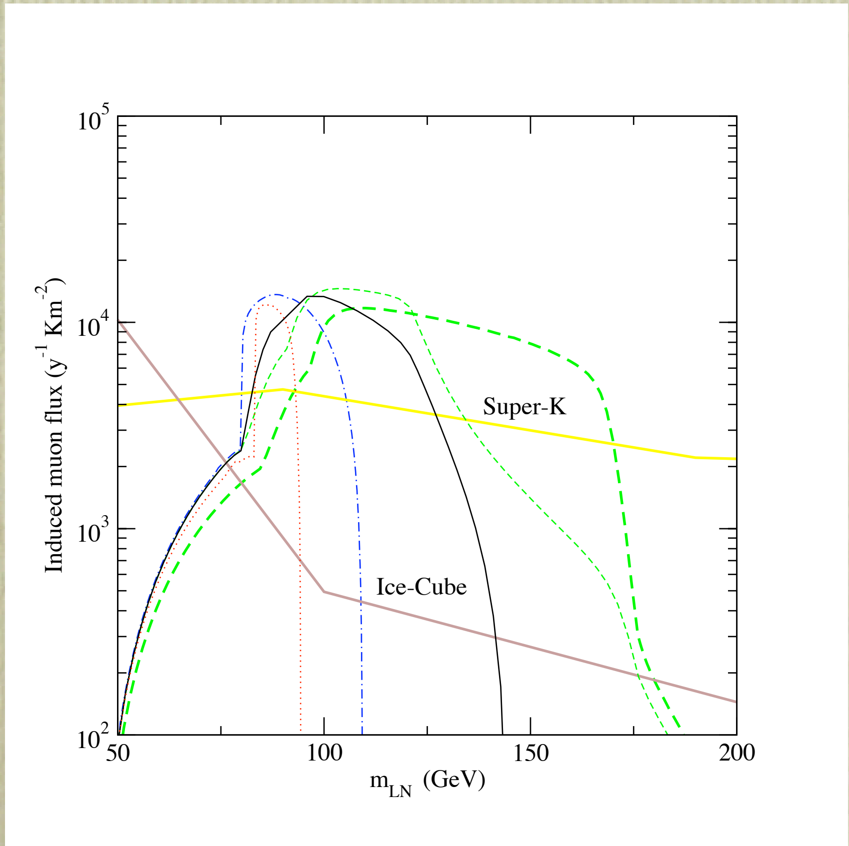
Flux from the Earth



Flux from the Sun

Icecube Coll. + DarkSUSY, 2007

There can be cases in which this pattern is reversed, see, e.g., a model with large Yukawas introduced in EW baryogenesis context:



Tightest limits on the model, direct detection is not excluding any region of the parameter space

Provenza, Quiros & P.U., 2005

Back to direct detection: signatures

In the formula for the detection rate:

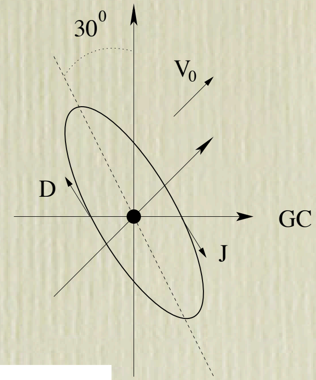
$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \int_{vmin}^{v_{max}} d\vec{v} f(\vec{v}) |\vec{v}| \frac{d\sigma(\vec{v}, E_R)}{dE_R}$$

WIMP-nucleus cross section

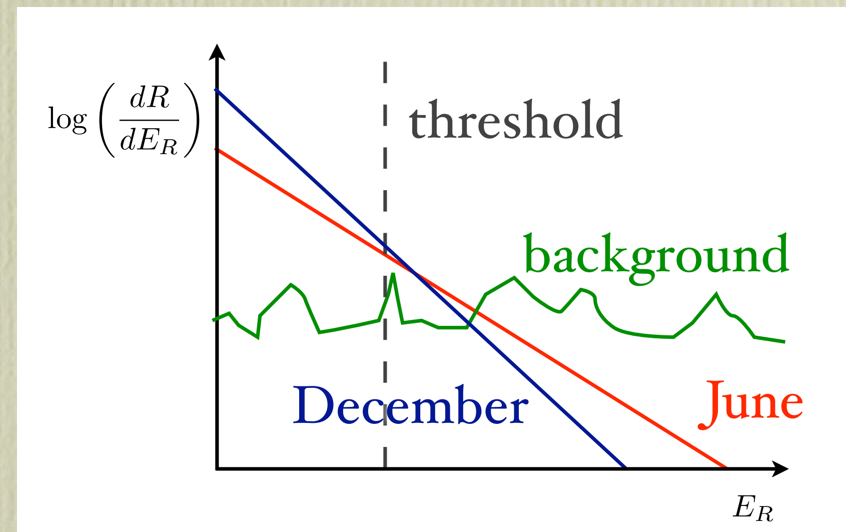
Integral on the WIMP velocity in the detector frame → directional signals & temporal modulation effects

WIMP DF

Annual Modulation:

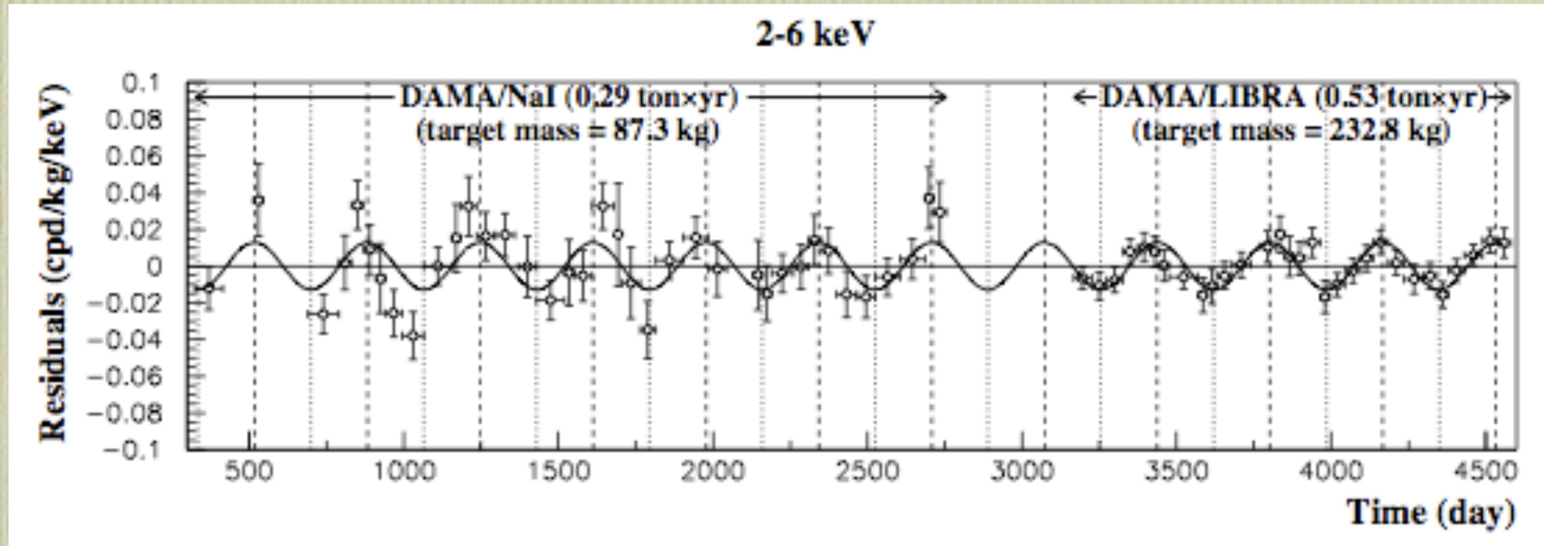


an effect on the total event rate of few % (depending on the WIMP DF)



Annual modulation detected by DAMA/LIBRA

Large mass NaI detector, not discriminating between background and signal events but looking at temporal variation of the total event rate in different energy bins:

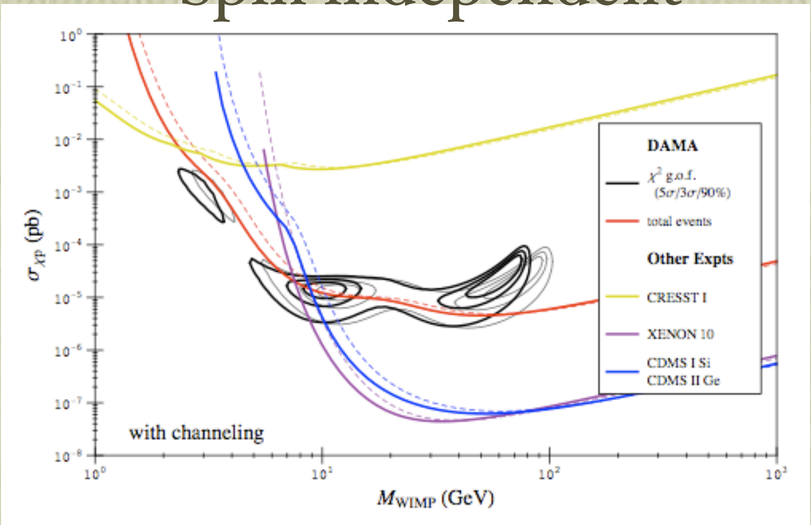


Bernabei et al., arXiv:0804.2741

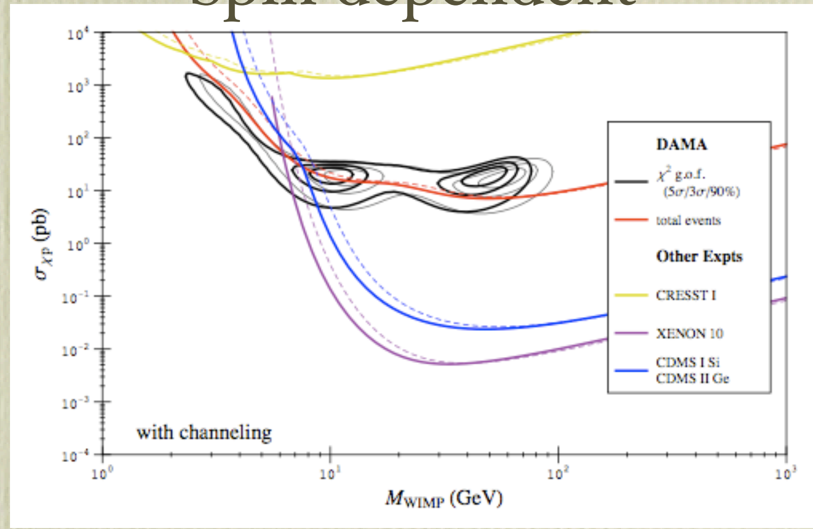
By now 10 annual cycles, huge statistics and modulation effect solidly detected. Regarding its interpretation, the phase of the modulation and its amplitude are compatible and suggestive of WIMP DM scatterings; however converting the effect into a WIMP event rate, there is tension with other direct detection experiments.

Several analyses on the WIMP elastic scattering interpretation in the latest years, comparing different experiments (not totally trivial since DAMA is the only NaI detector, competitors run with Ge, Si, Xe, Ar, ...). Lately the discussion has been on ion channeling or not channeling, and different circular velocities for the Sun.

Spin independent



Spin dependent



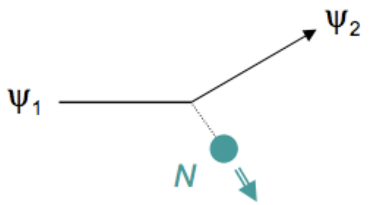
Savage et al., arXiv:0901.2713

There is (very little) room for a solution in case of light WIMPs (masses between, say, 2 and 10 GeV)

... or explain DAMA out of the WIMP framework:

Inelastic dark matter
Smith, Weiner ('01)

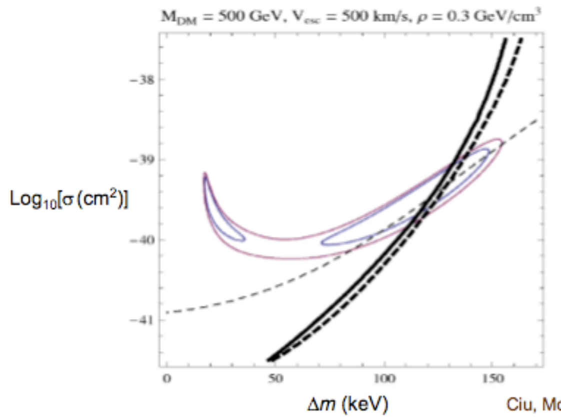
Two dark states with $\Delta m \sim O(100\,\text{keV})$



... scatters (only) inelastically

The minimum velocity depends on nuclei

$$v_{\min} \simeq \frac{1}{\sqrt{2 m_N E_R}} \left(\frac{m_N E_R}{\mu} + \Delta m \right)$$



Ciu, Morrissey, Poland, Randall

Naturally obtained via symmetry breaking

e.g. $\mathcal{L} = M\psi\bar{\psi} + m(\psi\psi + \bar{\psi}\bar{\psi})$ $\quad m \ll M$

WIMP indirect detection via halo annihilation signals

Search for those terms with small (or well-constrained) conventional (i.e. background) astrophysical components. Either as prompt yields

antimatter gamma-rays (neutrinos)

or from interactions/back-reaction of yields (mostly electrons and positrons) on background radiation/fields:

radiative photon emission (synchrotron, inverse Compton, Bremsstralung)

S-Z effect

Heating

Signatures:

I) in energy spectra: One single energy scale in the game, the WIMP mass, rather then sources with a given spectral index; edge-line effects?

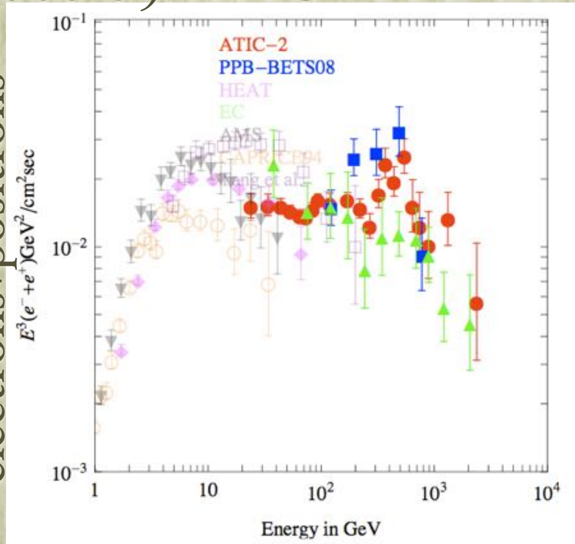
II) angular: flux correlated to DM halo shapes and with DM distributions within halos: central slopes, rich substructure pattern.

A fit of a featureless excess may set a guideline, but will be inconclusive.

The focus on electrons and positrons because of recent experimental results:

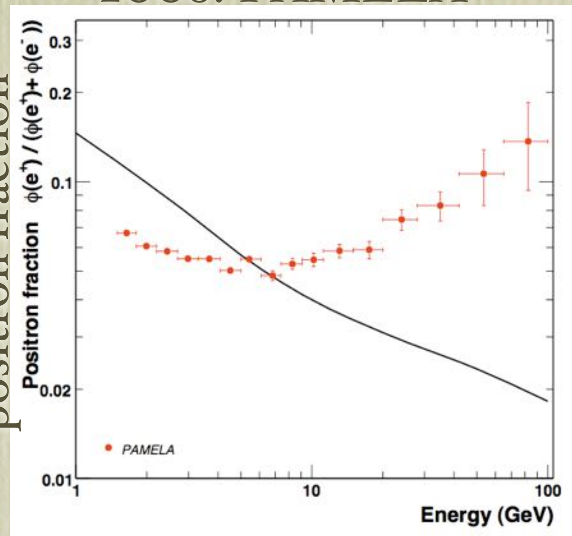
2008-09: ATIC + PPB-BETS

electrons+positrons



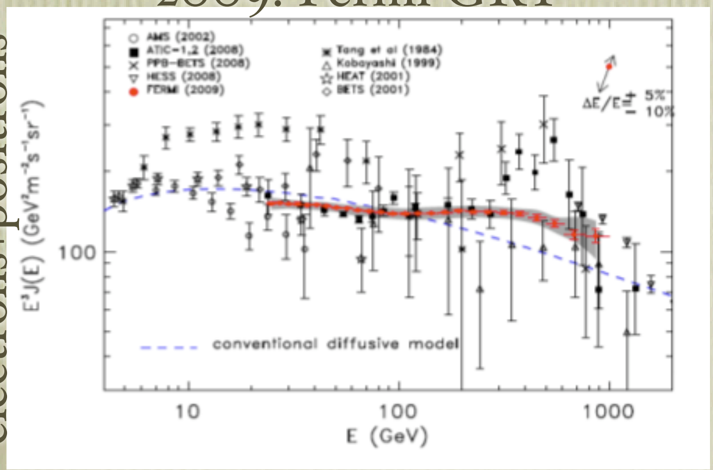
2008: PAMELA

positron fraction



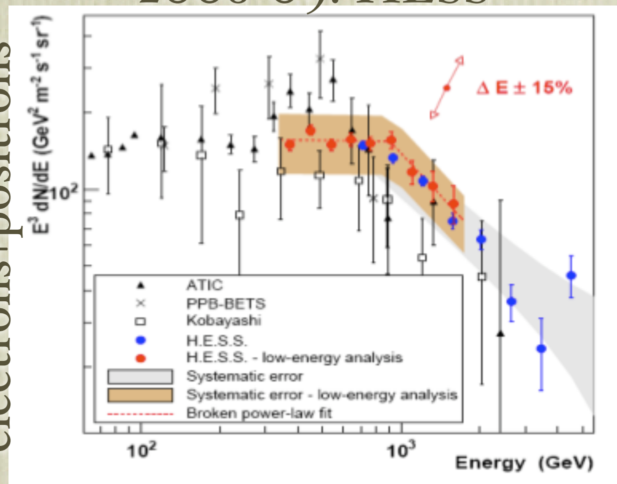
2009: Fermi GRT

electrons+positrons



2008-09: HESS

electrons+positrons



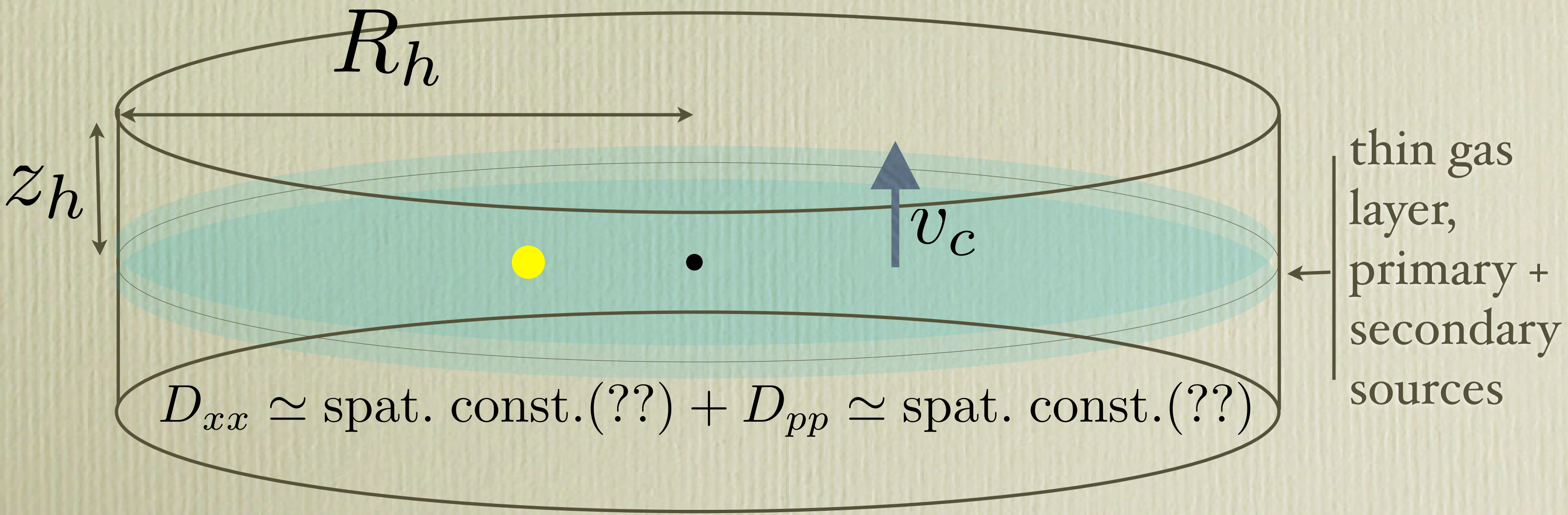
Charged particles in the Galaxy

A random walk (maybe with a preferred drift direction) in turbulent & regular magnetic fields, modeled through a diffusion equation:

$$\frac{\partial n_i(\vec{r},p,t)}{\partial t} = \vec{\nabla}\cdot\left(D_{xx}\vec{\nabla} n_i - \vec{v}_c\, n_i\right) + \frac{\partial}{\partial p}\, p^2 D_{pp}\, \frac{\partial}{\partial p}\, \frac{1}{p^2}\, n_i - \frac{\partial}{\partial p}\left[\dot{p}\, n_i - \frac{p}{3}\,(\vec{\nabla}\cdot\vec{v}_c)\, n_i\right] + q(\vec{r},p,t) + \frac{n_i}{\tau_f} + \frac{n_i}{\tau_r}$$

spatial diffusion — reacceleration — energy loss — convection — source — decay, fragmentation

usually solved in steady state (l.h.s. put to zero) and applied to some schematic picture of the Galaxy :



What are the main sources of galactic cosmic rays?

Some simplified argument (close to numerology):

The energy density in CRs is about: $w_{CR} \simeq 0.5\,\mathrm{eV\,cm^{-3}}$

The total energy stored in the confinement volume is then about: $W_{CR} \simeq w_{CR} V_{conf} \simeq 2 \cdot 10^{55}\,\mathrm{erg}$

Dividing by the CR confinement time, you find the required CR luminosity: $L_{CR} \simeq \frac{W_{CR}}{\tau_{conf}} \simeq 5 \cdot 10^{40}\,\mathrm{erg s^{-1}}$

Compare with the typical Supernova luminosity (rate times injected energy): $L_{SN} = R_{SN} E_{SN} \simeq 3 \cdot 10^{41}\,\mathrm{erg s^{-1}}$

SNe are the CR sources
if the efficiency is about 10-20%

Start with primary nucleon species:

At “high energy” (say, above 10-GeV), energy losses and reacceleration are small:

$$\frac{\partial n_i(\vec{r},p,t)}{\partial t} = \vec{\nabla}\cdot\left(D_{xx}\vec{\nabla}n_i - \cancel{\vec{v}_c n_i}\right) + \cancel{\frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}n_i} - \frac{\partial}{\partial p}\left[\cancel{\dot{p}\, n_i} - \cancel{\frac{p}{3}\left(\vec{\nabla}\cdot\vec{v}_c\right)n_i}\right] + q(\vec{r},p,t)$$

Neglect for the moment also convection; spatial diffusion is the term setting the confinement time:

$\tau_{conf} \propto 1/D_{xx}$ with $D_{xx}(p) \propto p^{\alpha}$ and (??)

$\alpha = 1/3$	Kolmogorov
$\alpha = 1/2$	Kraichnan

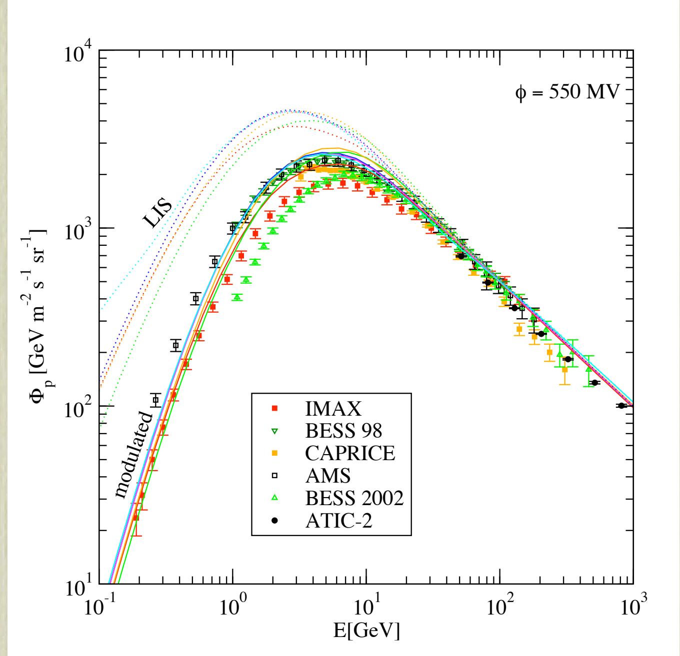
Consider, e.g., primary protons. The source function is in the form:

$q_p \propto p^{-\beta_{inj,p}}$ with $\beta_{inj,p} \simeq 2$ (strong shock limit)

Solving the propagation eq. and comparing the result to the local proton flux:

$\phi_p \propto q_p \cdot \tau_{conf} \propto p^{-\beta_{obs,p}}$ with $\beta_{obs,p} \simeq 2.7$

In fair agreement with the prediction: $\beta_{obs,p} = \beta_{inj,p} + \alpha$



Apply the same to secondary nucleon species:

"Secondaries" are particles generated in the interaction of primary species with the interstellar medium in "spallation" processes. Example: secondary Boron from the primary Carbon. The Boron source function proportional to the Carbon flux (after propagation):

$$q_B \propto \phi_C \propto p^{-\beta_{obs,C}}$$

The Boron flux (after propagation) is in the form:

$$\phi_B \propto p^{-\beta_{obs,B}}$$

predicting:

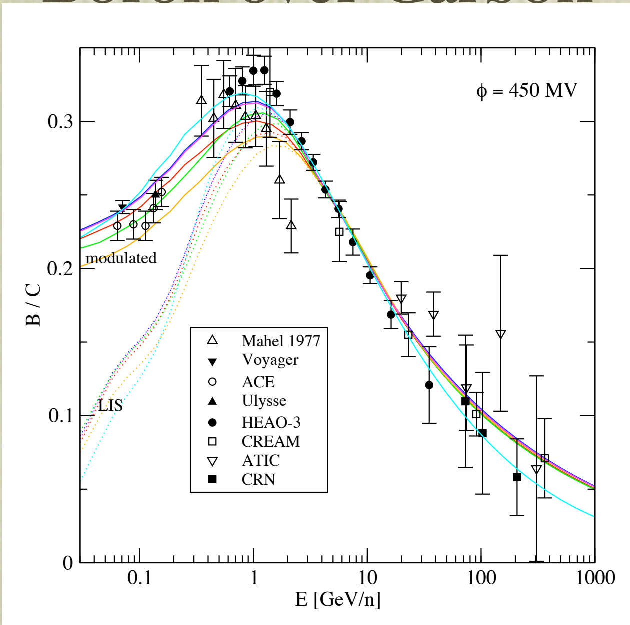
$$\beta_{obs,B} = \beta_{obs,C} + \alpha$$

i.e., the secondary to primary ratio:

$$\phi_B/\phi_C \propto p^{-\beta_{obs,B}+\beta_{obs,C}} = p^{-\alpha}$$

is predicted to be independent of the (unknown) Carbon injection index.

Boron over Carbon



compare against observations and find α (plus a combination of other parameters in the full propagation model)

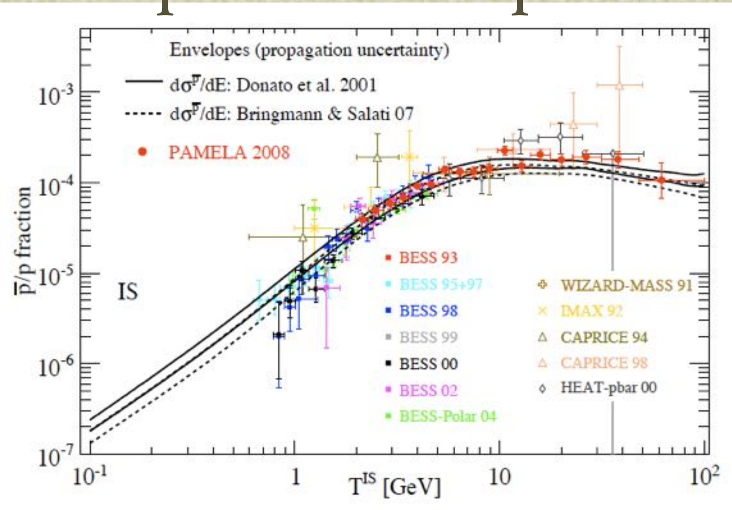
The picture for antiprotons is totally consistent:

Antiprotons are generated in the interaction of primary proton and helium cosmic rays with the interstellar gas (hydrogen and helium), e.g., in the process:

$$p + H \to 3\,p + \bar{p}$$

Use the parameter determination from the B/C ratio, to extrapolate the prediction for the $\bar{p}/p$ ratio: excellent agreement for secondaries only!

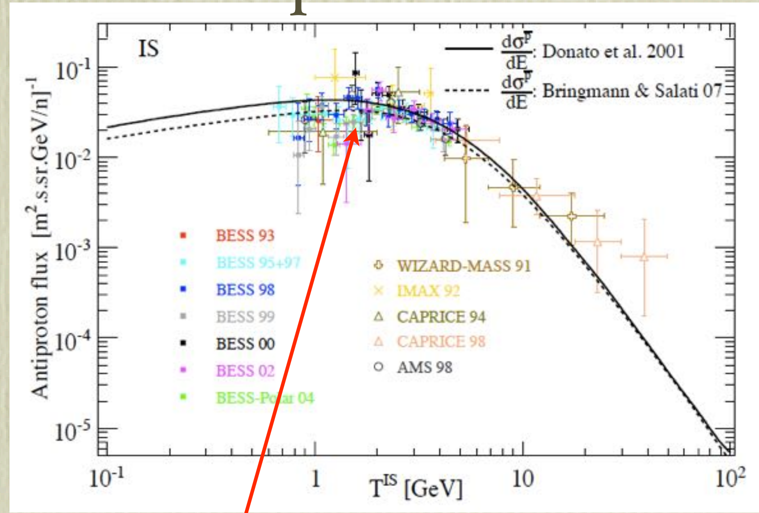
Antiproton over proton



Donato et al., arXiv:0810.5292

Latest Pamela data: Adriani et al., arXiv:0810.4994

Antiproton flux



kinematic peak expected for secondaries, not for a primary component

Coming to electrons and positrons:

Energy losses cannot be neglected (at any energy) for electrons/positrons:

$$\frac{\partial n_i(\vec{r},p,t)}{\partial t} = \vec{\nabla}\cdot\left(D_{xx}\vec{\nabla} n_i - \cancel{\vec{v}_c n_i}\right) + \frac{\partial}{\partial p}\,\cancel{p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}}\,n_i - \frac{\partial}{\partial p}\left[\dot{p}\,n_i - \cancel{\frac{p}{3}\left(\vec{\nabla}\cdot\vec{v}_c\right)}\,n_i\right] + q(\vec{r},p,t)$$

The main effects are due to synchrotron emission on the galactic magnetic fields and inverse Compton emission on the CMB and starlight:

$\dot{p} \propto p^2$ setting a new timescale: $\tau_{loss} \simeq \frac{p}{\dot{p}} \propto p^{-1}$

The solution to the diffusion equation becomes (approximately):

$$\phi_{e^-} \propto q_{e^-}\cdot \min\left[\tau_{loss},\tau_{conf}\right] \propto p^{-\beta_{inj,e}-\delta}$$

with $\delta=1$ for energy losses or $\delta=\alpha$ for diffusion.
Secondary electron/positrons are produced, e.g., through:

$$\begin{aligned} p + H \rightarrow \ldots \rightarrow \pi^{\pm} &+ \ldots \\ &\hookrightarrow \mu^{\pm} + \nu_\mu \\ &\qquad \hookrightarrow e^{\pm} + \nu_e + \nu_\mu \end{aligned}$$

The secondary electron/positron source function is proportional to the proton flux (after propagation), i.e. it scales like:

$$q_{e^\pm} \propto \phi_p \propto p^{-\beta_{inj,p}-\alpha}$$

with the induced flux, predicted to be about:

$$\phi_{e^\pm} \propto q_{e^\pm} \cdot \min\left[\tau_{loss}, \tau_{conf}\right] \propto p^{-\beta_{inj,p}-\alpha-\delta}$$

Looking at the ratio between the (secondary only) positron flux to the (mostly primary) electron flux, you expects it to scale like:

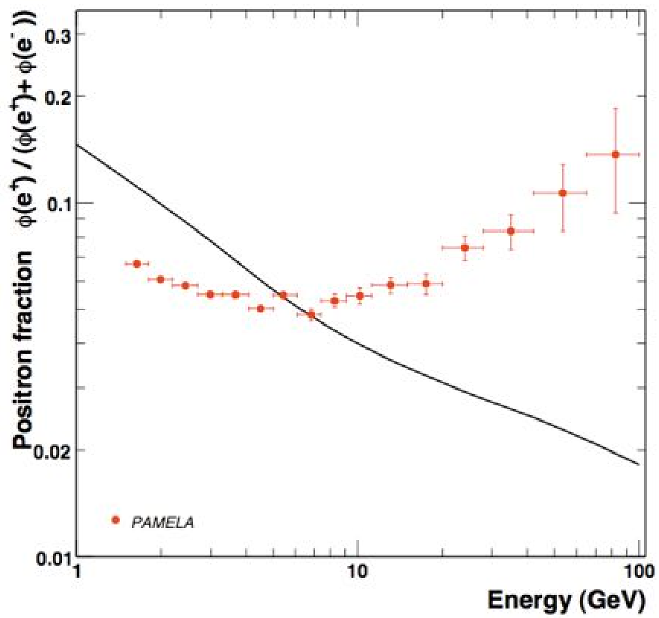
$$\frac{\phi_{e^+}}{\phi_{e^-}} \propto p^{-(\beta_{inj,p}-\beta_{inj,e}+\alpha)}$$

i.e. decreasing with energy since it would be hard to find a scheme in which:

$$\beta_{inj,p} - \beta_{inj,e} + \alpha$$

is negative.

PAMELA measured a rising positron fraction



Adriani et al., arXiv:0810.4995

How to explain a rising positron fraction?

- The propagation model is wrong: there are extra energy-dependent effects which affect secondary positrons (or primary electrons) but not the secondary to primary ratios for nuclei (at least at the measured energies), e.g.: Piran et al., arXiv:0905.0904; Katz et al., arXiv: 0907.1686

- There is production of secondary species within the CR sources with a mechanism giving a sufficiently hard spectrum (reacceleration at SN remnants?), e.g.: Blasi, arXiv:0903.2794; Mertsch & Sarkar, arXiv: 0905.3152

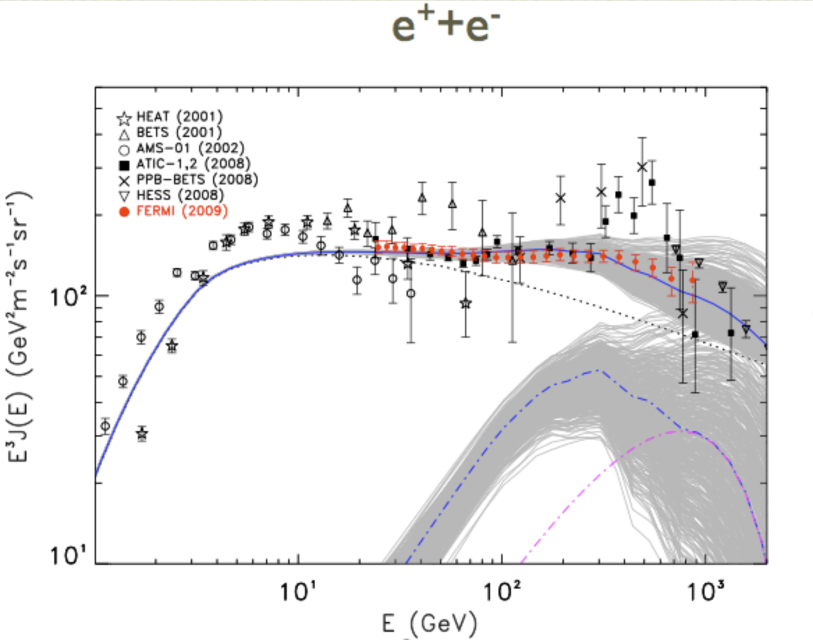
- There are additional astrophysical sources producing primary positrons and electrons: pulsars are the prime candidate in this list.

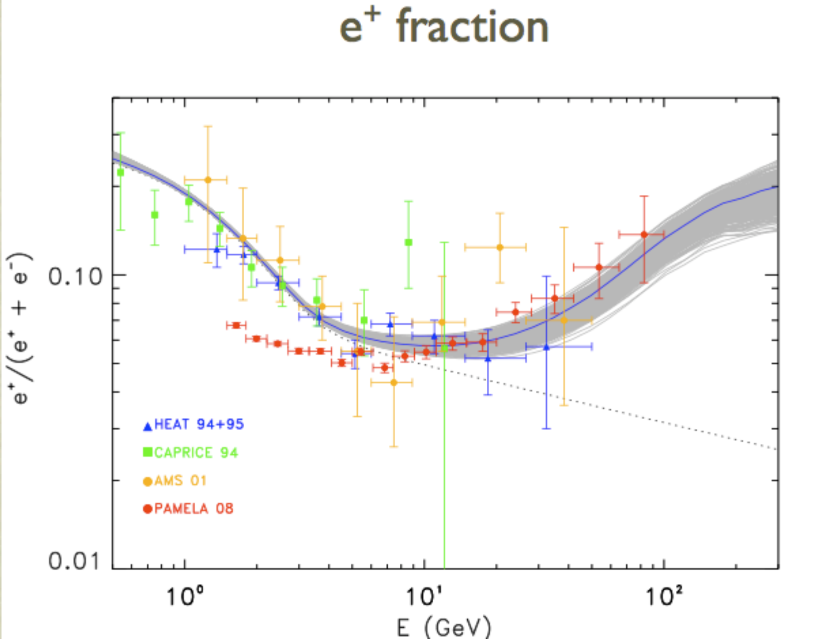
- There is an exotic extra source of primary positrons and electrons: dark matter sources are the most popular in this class.

- ...

Few words on the pulsar interpretation:

There are a few nearby pulsars (Geminga is at only 100 pc) within which electron/positron pair production could be efficient enough. Take a phenomenological approach and fit the data, e.g.:





Grasso et al., arXiv:0905.0636

Successful fits but with a few caveats, e.g.: you need extremely hard source spectra, $\beta \approx 1.5$-1.7; you need to get e^-/e^+ out of the source keeping such hard spectra; the deduced properties of nearby pulsars should be consistent with what you deduce from CRs and photons elsewhere in the Galaxy.

Primary electrons/positrons from DM WIMPs:

The relevant process is the pair annihilations of non-relativistic WIMPs in the DM halo, proceeding mostly through two-body final states:

$$\chi\bar{\chi} \to f\bar{f}$$

(the energy of f is equal to the WIMP mass) corresponding to the source function:

$$Q_i(r,E) = \langle\sigma v\rangle_0 \sum_f \boxed{\frac{dN_i^f}{dE}(E)} B_f\, \mathcal{N}_{\text{pairs}}(r)$$

total rate

branching ratio into f

density of WIMP pairs

e^+/e^- energy spectra of two kinds:

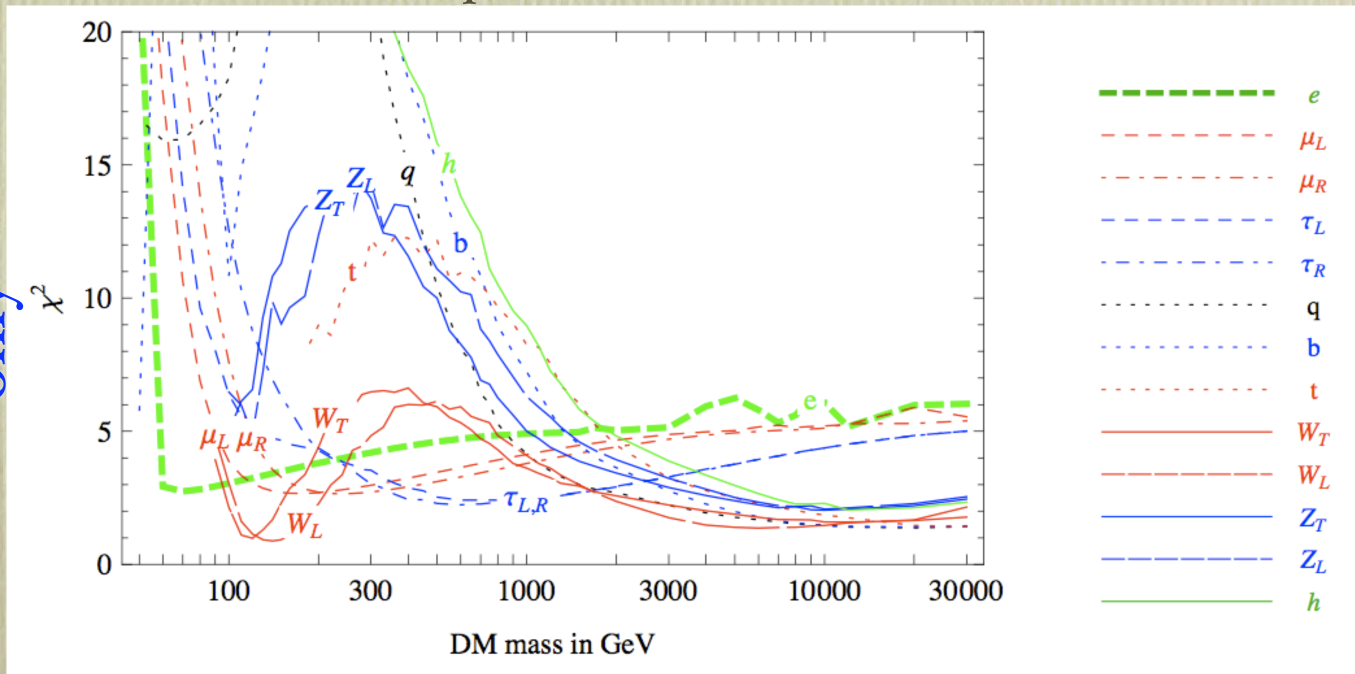
Soft spectra from, e.g., quark final states which produce charged pions decaying into leptons;

Hard spectra from, e.g., lepton or gauge boson final states, in which electrons and positrons are produced promptly or in a short decay chain.

Propagate this extra source in analogy to standard primary and secondary astrophysical components (only caveat: this source is not located in the gas disc, as the astrophysical sources, but spread out in the full diffusive halo).

Different strategies. One possibility is to take again a phenomenological approach and adjust a generic WIMP model (defined by WIMP mass and dominant annihilation channel) to the data (i.e. find, for a given WIMP density, find the annihilation cross section). E.g.: start only with the fit of the PAMELA excess in the positron ratio:

Positron ratio only

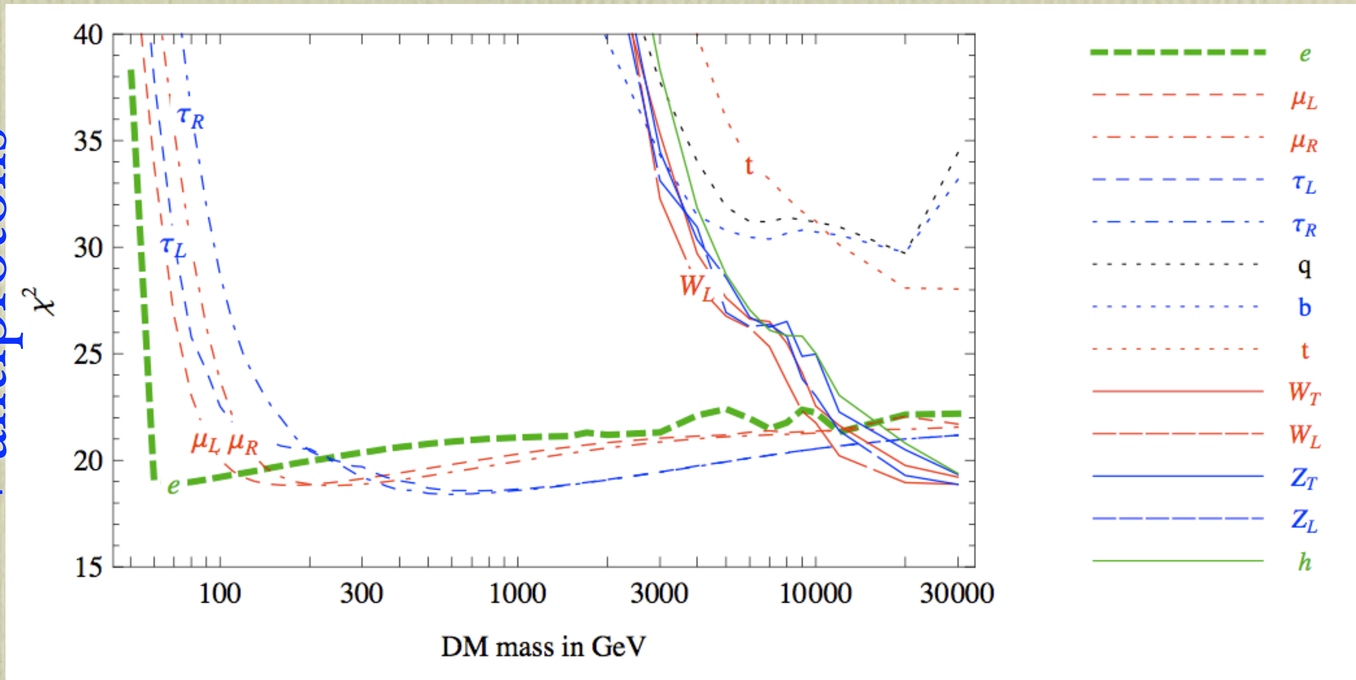


Cirelli et al., arXiv:0809.2409

either very massive WIMPS, or lighter WIMPs but hard annihilation spectra (leptons or W-bosons)

... then cross correlate, for the same WIMP model, other signals. The comparison with antiprotons is very powerful, since there is very little room for an exotic component in that channel:

Positron ratio + antiprotons

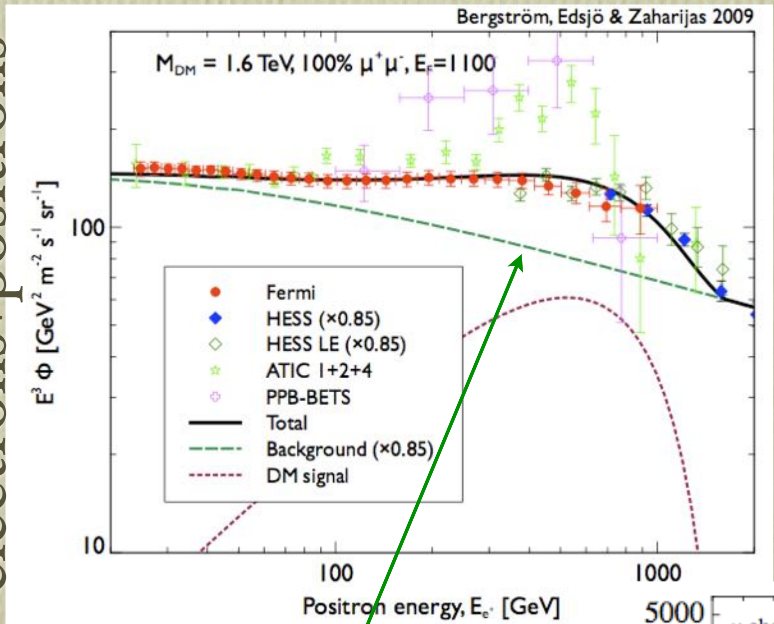


Cirelli et al., arXiv:0809.2409

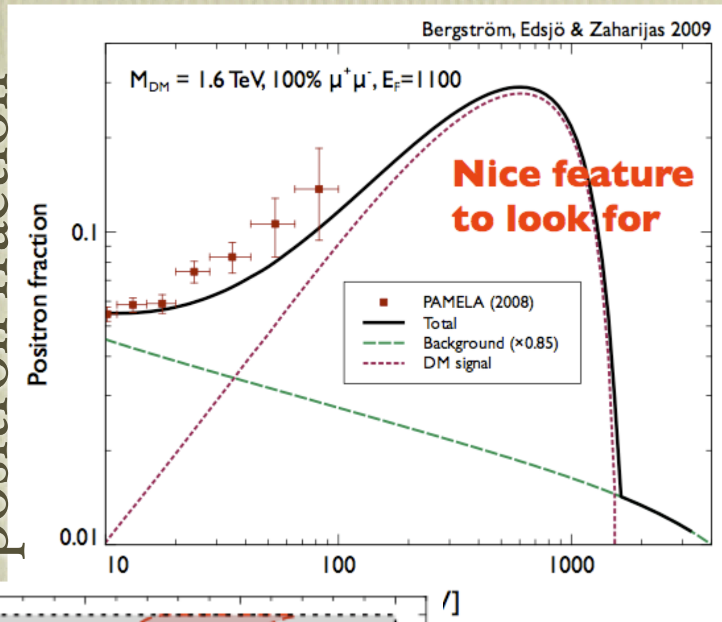
The W-boson annihilation channel has an antiproton yield which is large and inconsistent with antiproton data for WIMPs lighter than 10 TeV or so; leptonic channels are unaffected (they do not give rise to a positron yield).

... add in the recent measurement of the electron+positron flux by FERMI (and disregard previous claims by ATIC and PPB-BETS):

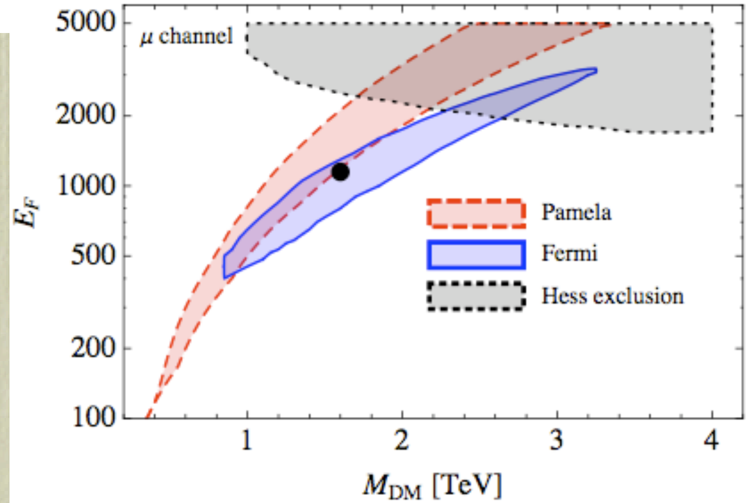
electrons+positrons



positron fraction



background ?!?



This “solution”:

annihilation into muons, heavy WIMPs, large “enhancement factors”

Bergström et al., arXiv:0905.0333

Slightly different results among the numerous fits to the recent data, but convergence on models in which DM is:

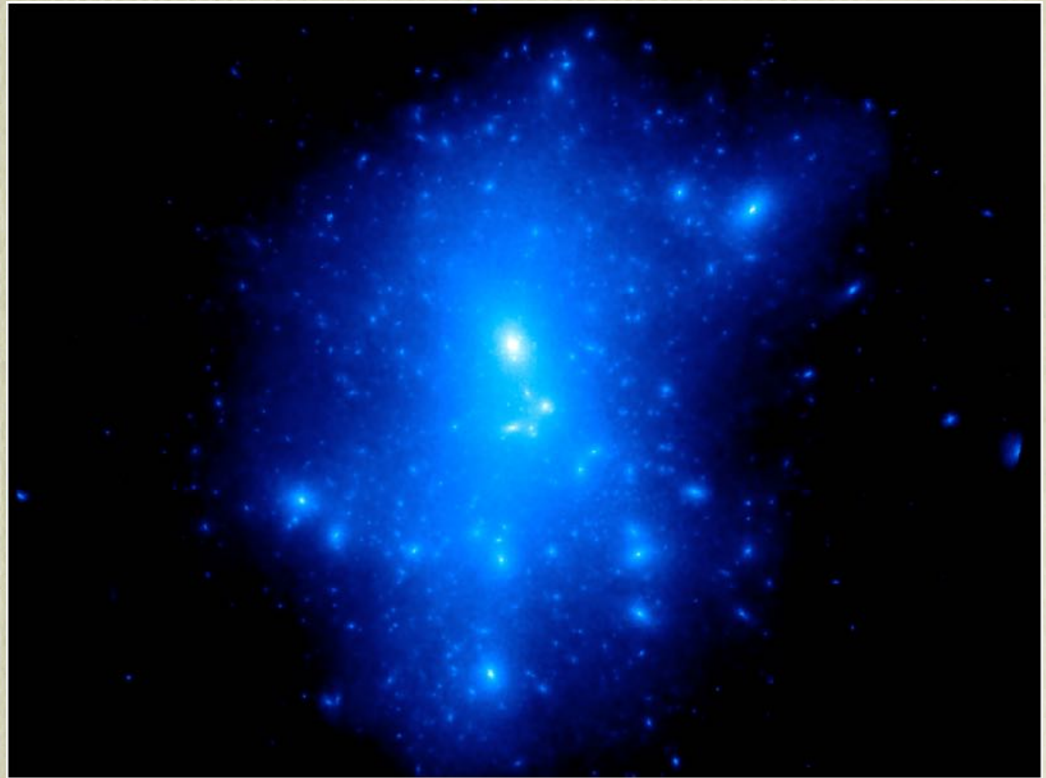
- leptophilic, i.e. with pair annihilation into leptons only, or into light (pseudo)scalars which for kinematical reasons can decay into leptons only (for this second class, see, e.g.: Arkani-Hamed et al., arXiv:0810.0713; Nomura & Thaler, arXiv:0810.5397);

- heavy, with WIMP masses above the 1 TeV scale;

- with a large (order 1000 or more) "enhancement factor" in the source function, either in the annihilation rate because $\langle \sigma v \rangle_{T_0} \gg \langle \sigma v \rangle_{T_{f.o.}}$ (or there is a resonance effect, or DM is simply non-thermal) or in the WIMP pair density because $\langle \rho_\chi^2 \rangle \gg \langle \rho_\chi \rangle^2$.

Enhancements in the indirect detection DM signals are often invoked in connection to substructures within the Galaxy, as simply stems from: $\langle \rho^2 \rangle \gg \langle \rho \rangle^2$

In hierarchical structure formation, small dense structures collapse first, merging then into larger and less dense objects, with a substructure population partially surviving tidal disruption in the merging:

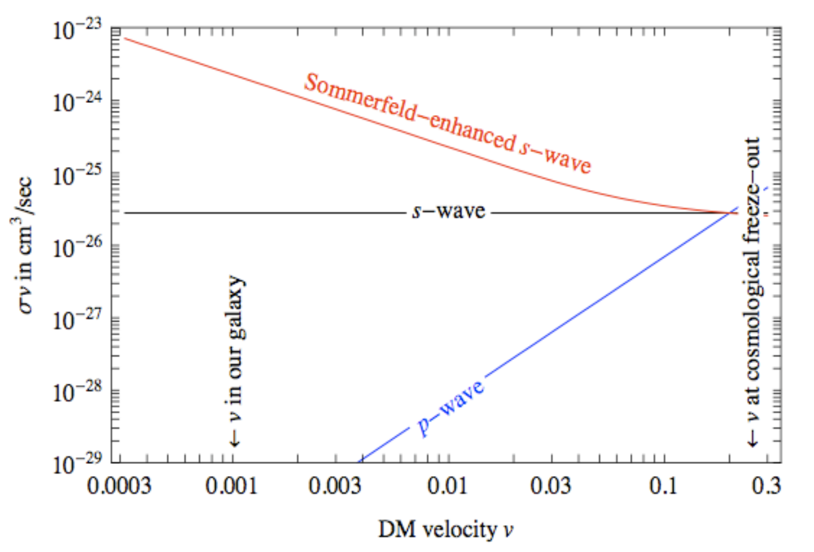


On average, gaining a factor 2 to 10 (or maybe 100) in signals.

Sommerfeld enhancement in the cross section:

Different possibilities for extrapolating the cross section from the early Universe:

Hisano, Matsumoto & Nojiri, (2003); e.g.: Cirelli et al., arXiv:0809.2409



DM is charged under a (new) gauge force, mediated by a “light” boson: this sets a non-perturbative long-range interaction, analogously to Coulomb interaction for positronium:

$$V(r) = -\frac{\alpha}{r}$$

gives the enhancement in the cross section:

$$S = \left|\frac{\psi(\infty)}{\psi(0)}\right|^2 = \frac{\pi\,\alpha/v}{1-e^{-\pi\,\alpha/v}} \xrightarrow{v \ll \alpha} \frac{\pi\,\alpha}{v}$$

The same 1/v enhancement is obtained for a Yukawa potential. In a DM context, first studied in the MSSM for pure very massive Winos or Higgsinos and weak interaction as gauge force (light W boson limit).

Example: a new (sub-)Gev scale dark sector:

Arkani-Hamed et al., arXiv:0810.0713

DM ψ is charged under new gauge force mediated by X^{μ}

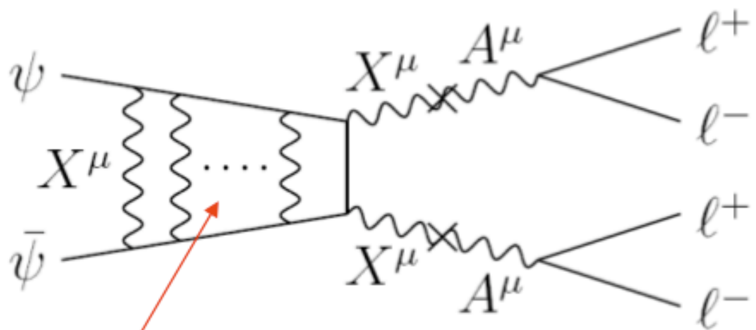
$$m_{\psi} \sim 100\,\mathrm{GeV} - 1\,\mathrm{TeV}, \quad m_X \sim 100\,\mathrm{MeV} - 1\,\mathrm{GeV}$$

existence of new sub-GeV dark sector

Dark gauge field X^{μ} mixes with photon A^{μ}

$$\mathcal{L} = \frac{\varepsilon}{2} X^{\mu\nu} F_{\mu\nu}$$

(ε naturally $O(10^{-3})$)



Nonperturbative enhancement

Leptonic final states

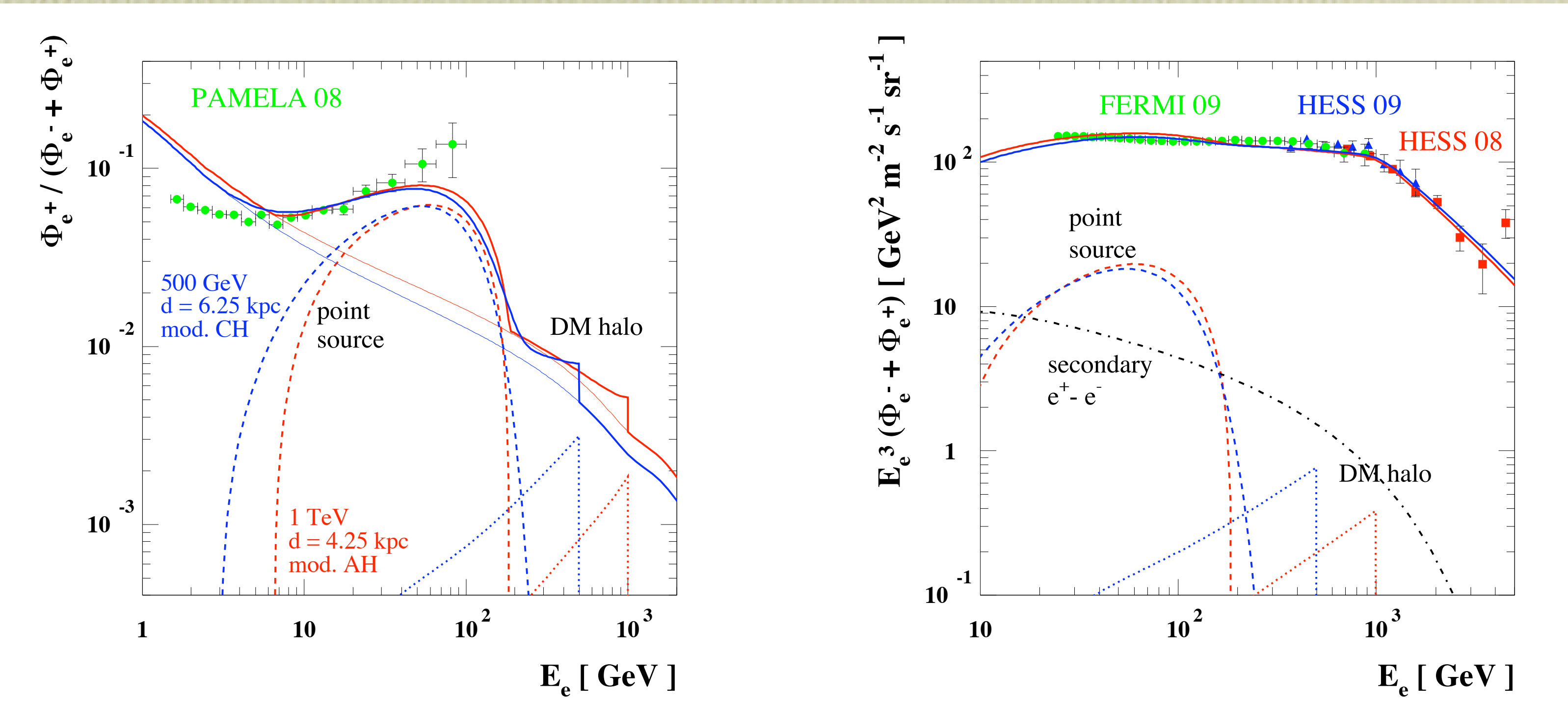
$m_{\phi} \lesssim 2m_{\mu}$: e^+e^-

$2m_{\mu} \lesssim m_{\phi} \lesssim 2m_{\pi}$: 50% e^+e^-, 50% $\mu^+\mu^-$

$2m_{\pi} \lesssim m_{\phi} \lesssim$ GeV: 40% e^+e^-, 40% $\mu^+\mu^-$, 20% $\pi^+\pi^-$

Hovewer do not assume this is the final word ...

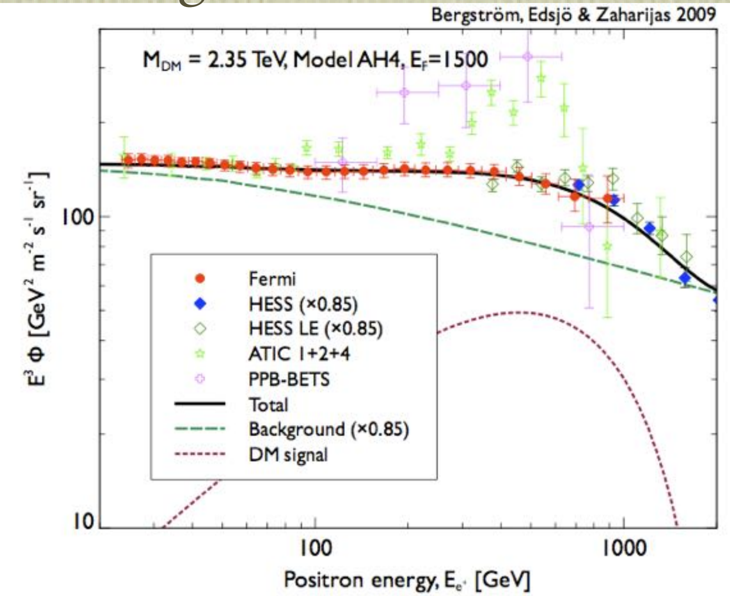
Sample fit to the PAMELA & Fermi electron/positron data, assuming the DM signal is dominated by one single substructure, moving along a sample orbit, with a sample velocity, as well as for a sample WIMP model (mass and annihilation channel), only searching for the optimal distance:



Hardly any correlation between the point source contribution and the contribution from the smooth DM halo component (which in all studies displayed so far was scaled by by the "enhancement factor")

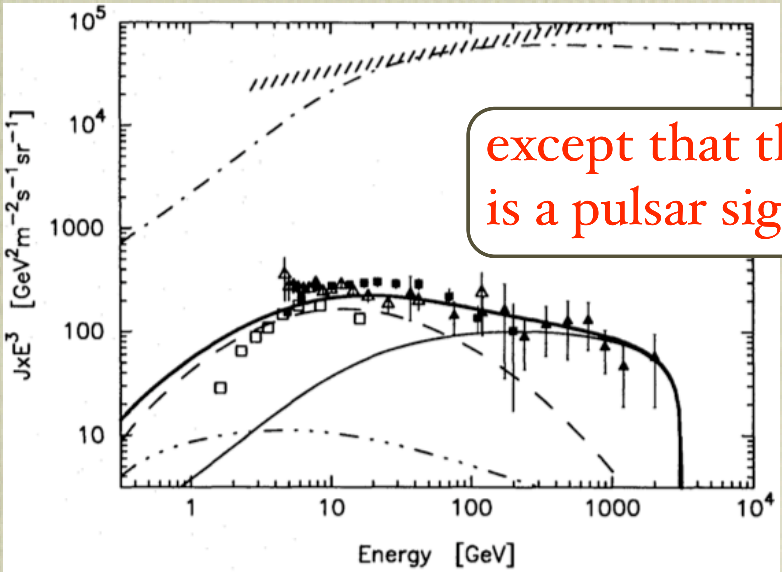
... and do not forget that we may have seen a DM signal, but have not seen a DM signature.

The sample fit of the data with a DM signal:



Bergström et al. on model by Arkani-Hamed et al.

is analogous to the signal foreseen in models of more than a decade ago:



except that this is a pulsar signal

Aharonian et al., 2005

Cleaner spectral features in upcoming higher statistics measurements (???). Insist with cross correlations to other DM detection channels.

DM and gamma-ray fluxes:

The source function has exactly the same form as for positrons:

$$Q_i(r, E) = \langle \sigma v \rangle_0 \sum_f \boxed{\frac{dN_i^f}{dE}(E)} B_f \mathcal{N}_{\text{pairs}}(r)$$

total rate

branching ratio into f

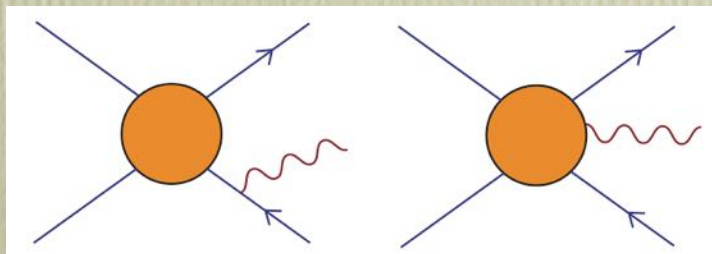
density of WIMP pairs

Energy spectra for the following components:

I) Continuum: i.e. mainly from $f \to \ldots \to \pi^0 \to 2\gamma$

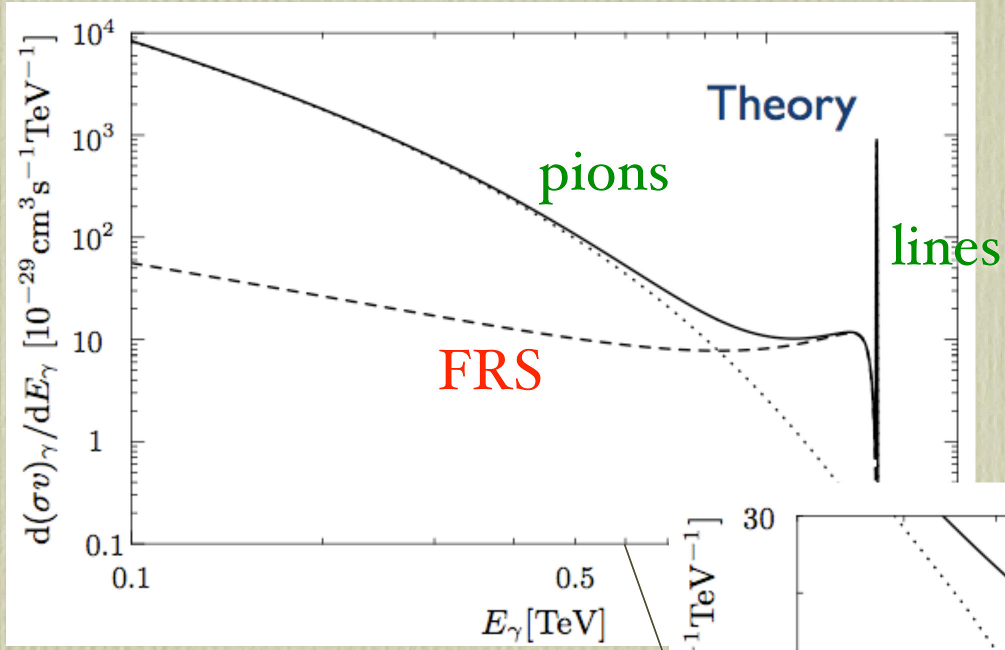
II) Monochromatic: i.e. the 1-loop induced $\chi\chi \to 2\gamma$ and $\chi\chi \to Z^0\gamma$ (in the MSSM, plus eventually others on other models)

III) Final state radiation (internal Bremsstralungh)

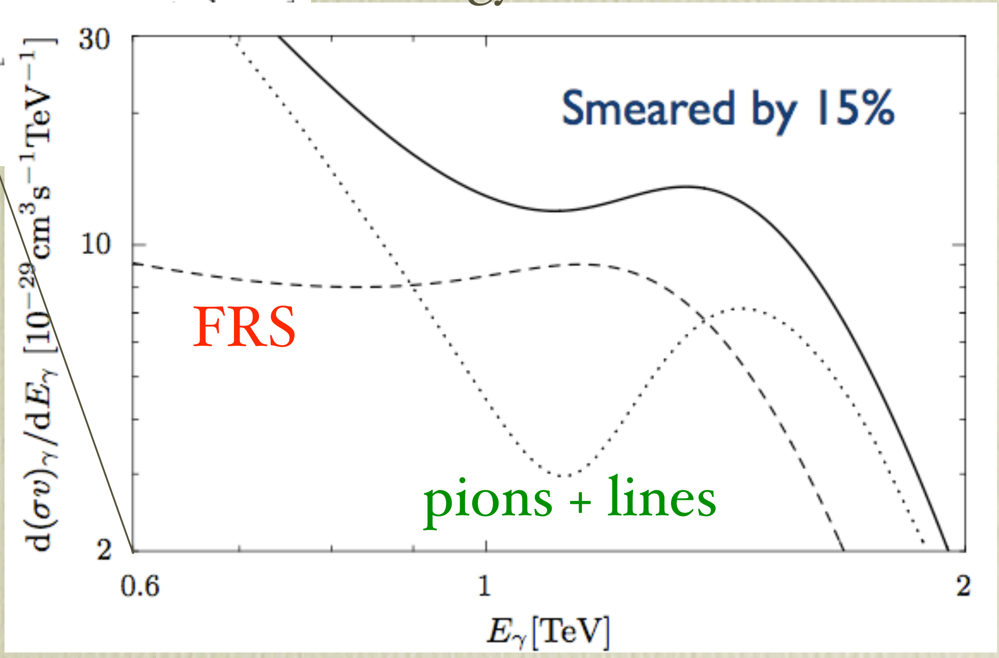


especially relevant for:
$\chi\chi \to l^+ l^- \gamma$
for Majorana fermions

Then for a model for which all three are relevant (e.g. pure Higgsino)The source function has exactly the same form as for positrons:



including a typical detector energy resolution



Bergström et al., astro-ph/0609510

The induced gamma-ray flux can be factorized:

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\theta,\phi) = \frac{1}{4\,\pi}\boxed{\frac{\langle\sigma v\rangle_{T_0}}{2\,M_\chi^2}\sum_f \frac{dN_\gamma^f}{dE_\gamma}B_f}\cdot\boxed{\int_{\Delta\Omega(\theta,\phi)} d\Omega' \int_{l.o.s.} dl\;\rho_\chi^2(l)}$$

Particle Physics DM distribution

Targets which have been proposed:

- The Galactic center (largest DM density in the Galaxy)
- The diffuse emission from the full DM Galactic halo
- Dwarf spheroidal satellites of the Milky Way
- Single (nearby?) DM substructures without luminous counterpart
- Galaxy clusters
- The diffuse extragalactic radiation
- ...

A number of “excesses” claimed in recent years; the Fermi GRT has collected over one year of data by now and will allow for much firmer statements. Preliminary results on DM searches have been presented in summer conferences, unfortunately reporting on upper limits only.

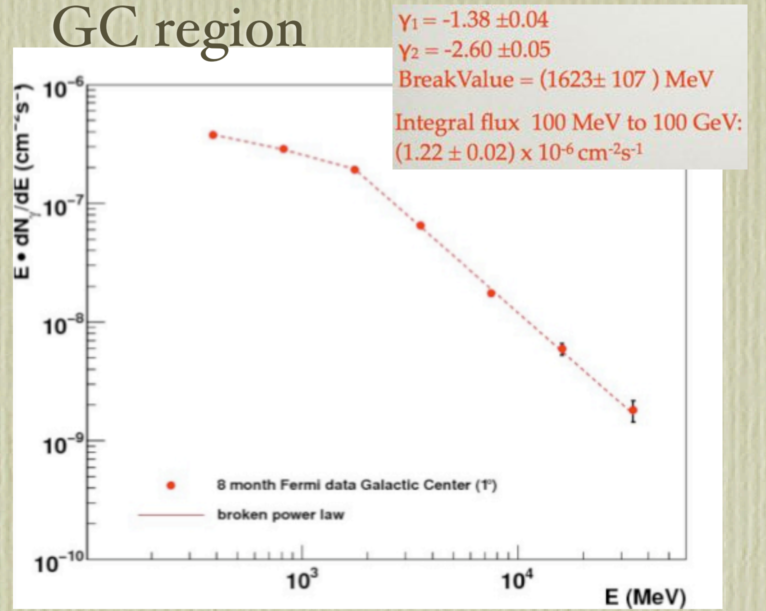
E.g.: S. Murgia, TeV Particle Astrophysics 09

- No evidence for a WIMP contribution within 1° of the GC;
- The diffuse Galactic emission at intermediate and $E > 1$ GeV is lower then from EGRET data, consistent with the background;
- A set of upper limits have been inferred for dwarfs and clusters;
- Upper limits on monochromatic emission from the Galaxy
- No evidence for extended sources without luminous counterpart;
- The diffuse extragalactic can be simply fitted by a single power law.

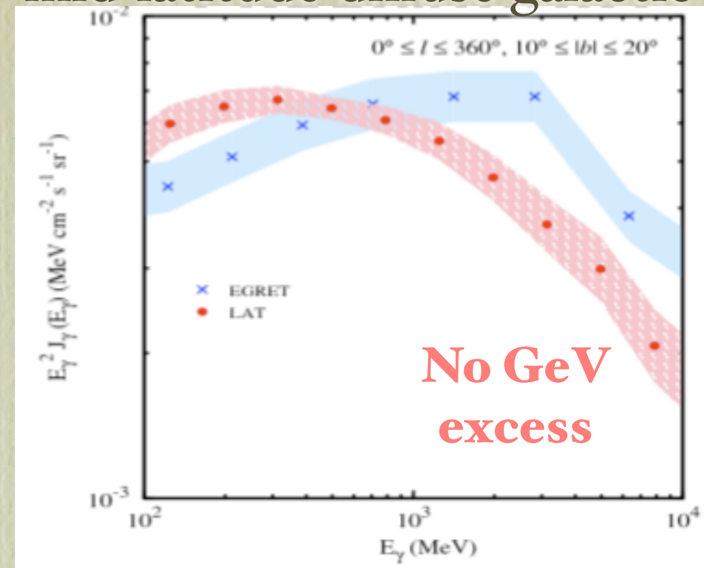
PRELIMINARY

PRELIMINARY

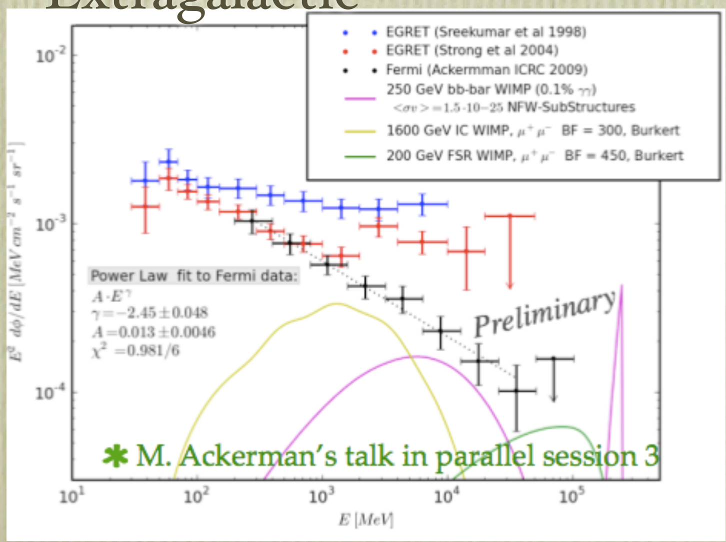
GC region



mid-latitude diffuse galactic

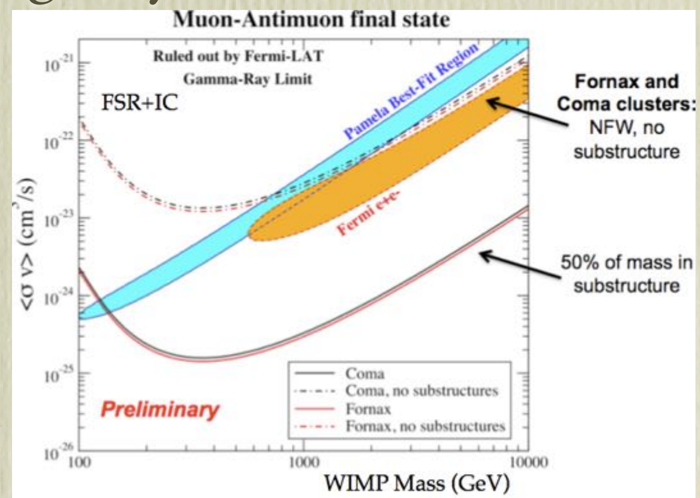


Extragalactic



PRELIMINARY

galaxy clusters



Multifrequency spectra

WIMP CDM in DM halos:

$$\chi\,\chi$$

$$\downarrow \quad (\sigma v)_{T=0} \sim \langle \sigma v \rangle_{T=T_f}$$ and this matching:

$$\Omega_\chi h^2 \simeq \frac{3\cdot 10^{-27}\mathrm{cm}^{-3}\mathrm{s}^{-1}}{\langle \sigma_A v \rangle_{T=T_f}}$$

1-loop states

$$\mathrm{SM}_1\ \mathrm{SM}_2$$

$$\boxed{\gamma\gamma \quad \gamma X^0}$$

(γ-lines)

$\Downarrow$ hadronization and/or decay

$$\overbrace{\ldots \quad \pi^0 \quad \pi^\pm}\ \longrightarrow e^\pm + \ldots$$

$$\pi^0 \downarrow 2\gamma$$

(γs with continuum spectrum)

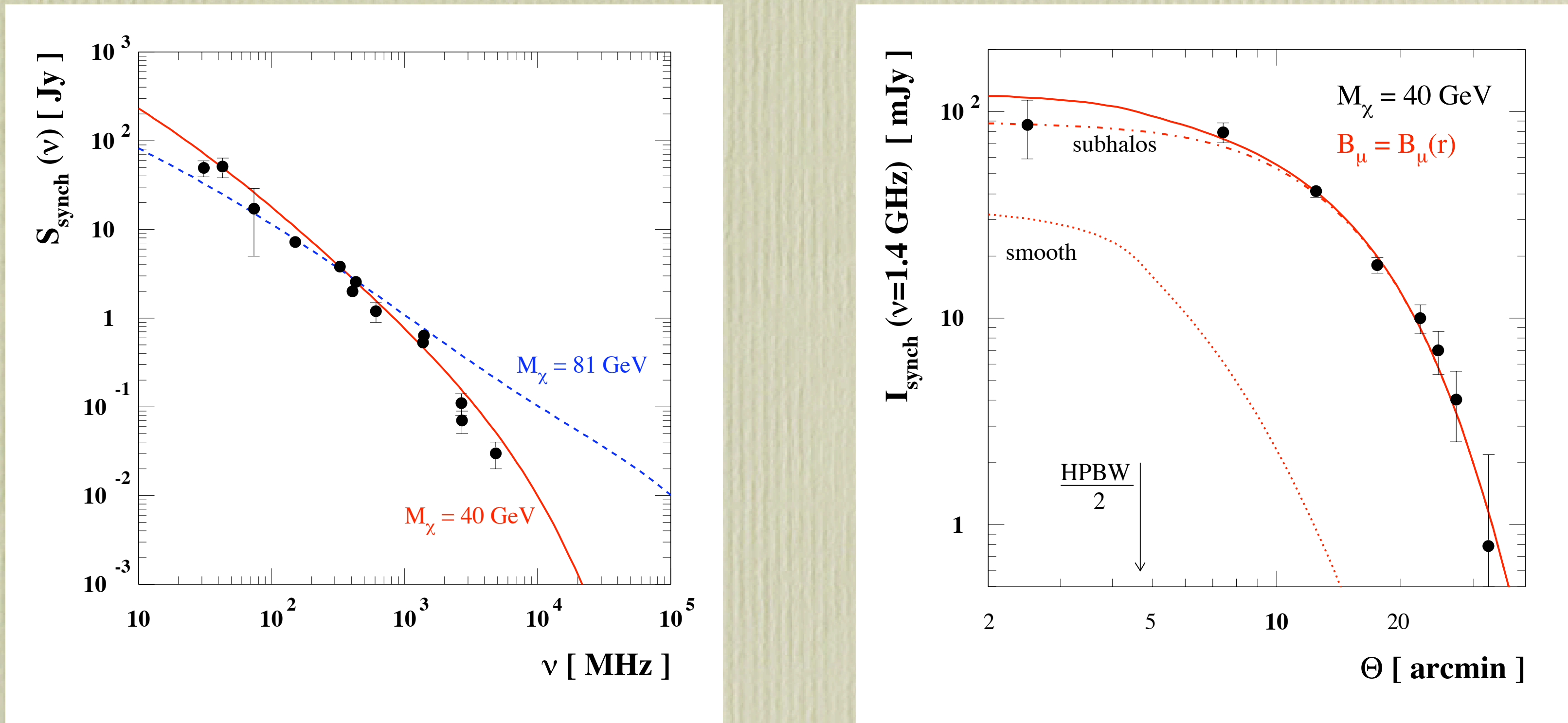
ambient backgrounds and fields

- Synchrotron
- Inv. Compton
- Bremstrahlung
- Coulomb
- Ionization

- radio
- IR
- X-rays
- γs

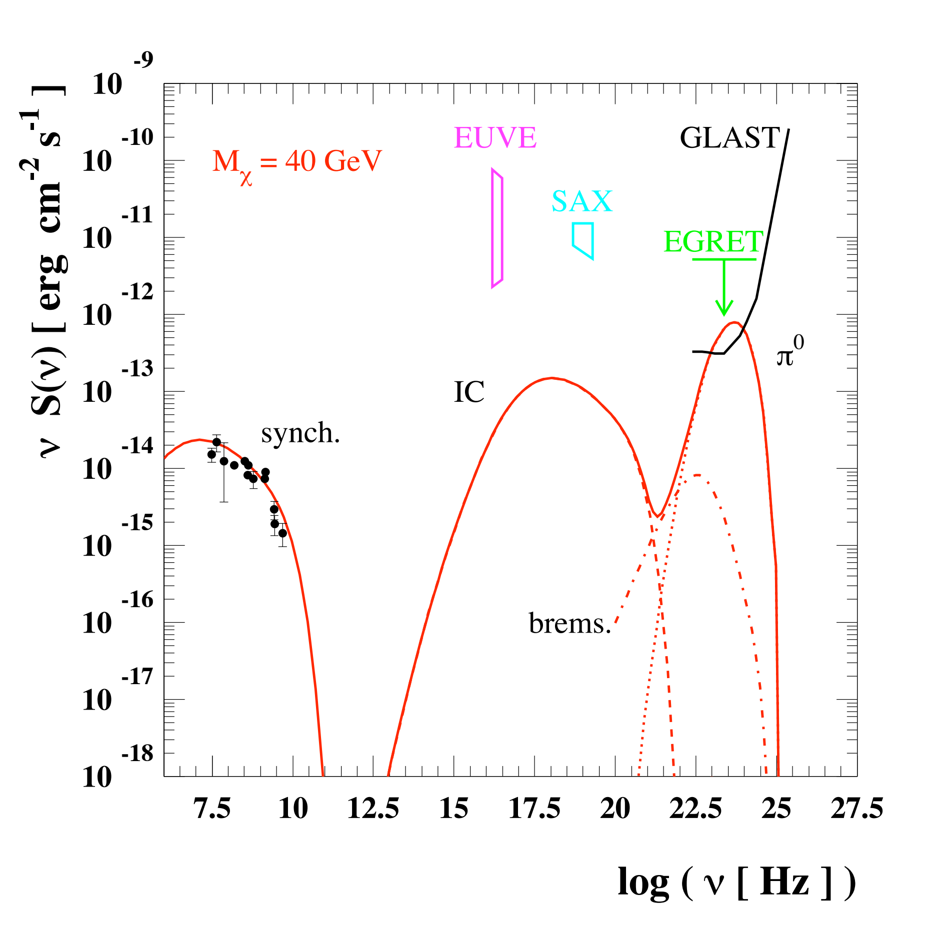
Example: multiwavelength signal from the Coma cluster

E.g., the Coma radio halo can be fitted in spectrum and angular surface brightness by a DM induced component:



Colafrancesco, Profumo & P.U., 2006

but actually this corresponds to a full seed, extending from the radio to the gamma-ray band:

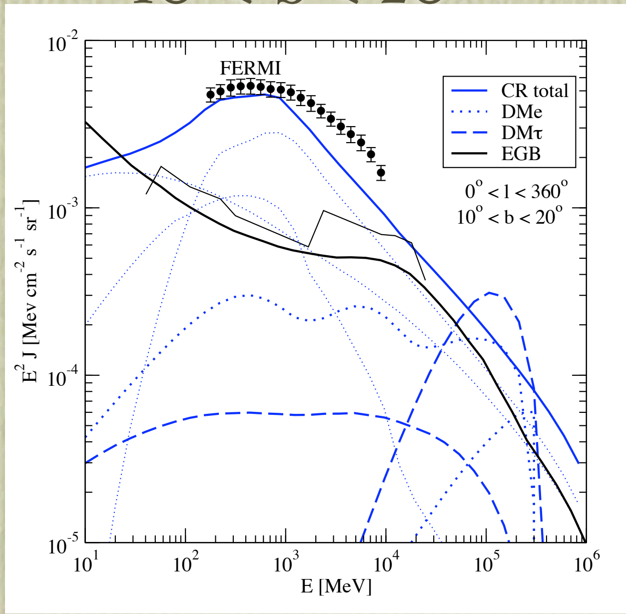


the associated gamma-ray flux within the sensitivity reach of Fermi in the next few years

Multifrequency approach to test local e^+/e^- excesses:

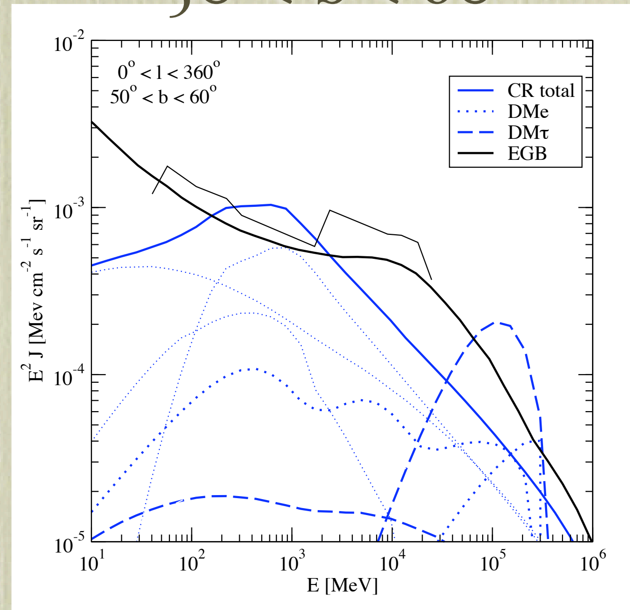
An excess from standard astrophysical sources would be confined to the galactic disc, one from DM annihilation would be spread out to a much larger scale, leading to different predictions for the IC radiation.
IC terms (plus FSR or pion terms) for two sample (leptophilic) models fitting the Pamela excess in the positron ratio:

$10^\circ < b < 20^\circ$



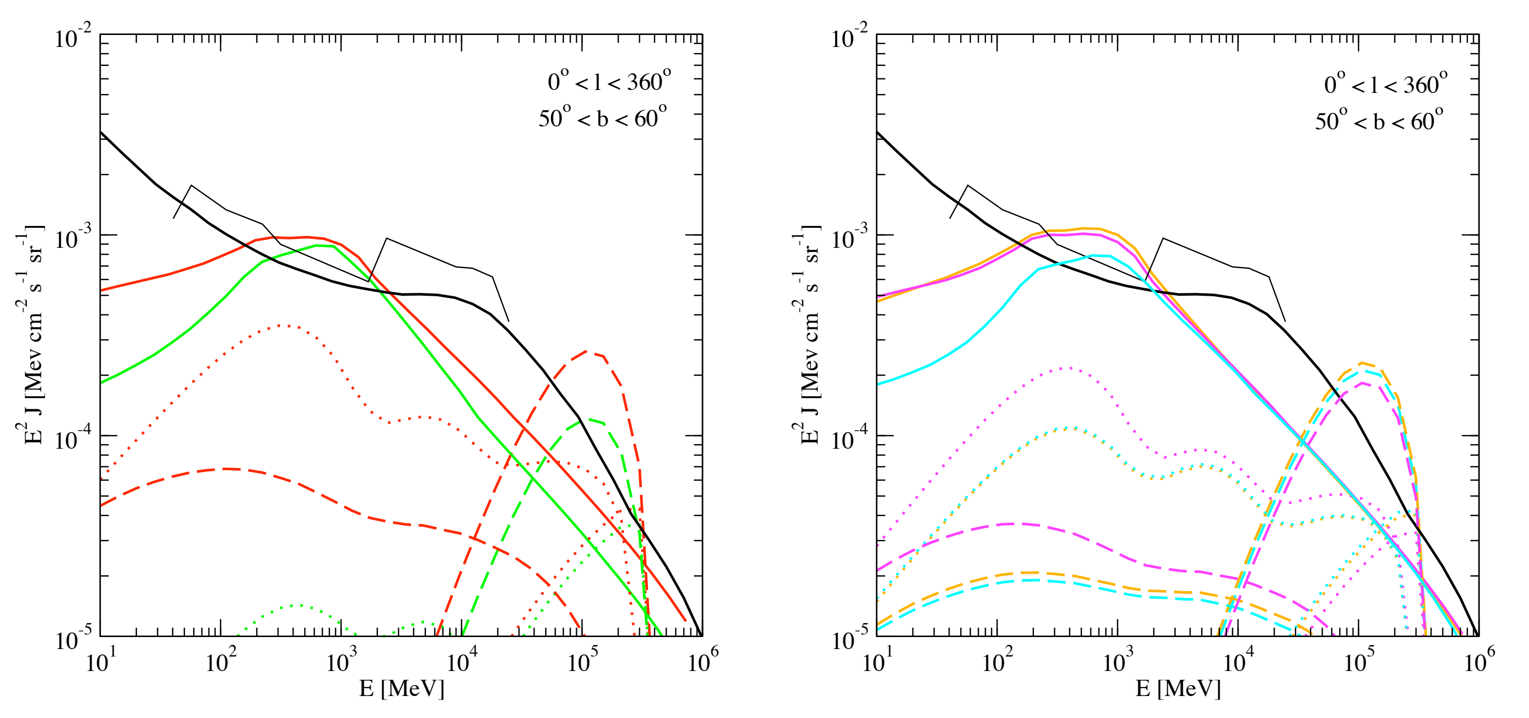
cross checked against Fermi preliminary data at intermediate latitudes

$50^\circ < b < 60^\circ$



a more solid prediction when looking at high latitudes ...

A result which is solid against uncertainties in the propagation model: the previous model extrapolated to a few sample setups consistent with B/C



Note also: the prediction is insensitive to the halo model (since it is well away from the GC), and to whether it is related to annihilating or decaying DM (since it is normalized to the locally measured electron/positron flux)

SuperWIMPs (or E-WIMPs, or ...)

Suppose the lightest particle odd under some descrite symmetry (hence stable) interacts super-weakly rather than weakly. It is NOT in thermal eq. in the early Universe, still it is not totally blind with respect to the thermal bath. E.g.: a ***gravitino*** in the gauge-mediated SUSY breaking scheme, LSP and with gravitational coupling only.

Boltzmann eq.:

$$\frac{dn_{\tilde{G}}}{dt} + 3\,H\,n_{\tilde{G}} = \sum_{\tilde{i},j} \langle \sigma(\tilde{i} + j \rightarrow \tilde{G} + k) v \rangle_T \, n_{\tilde{i}}^{eq} \, n_j^{eq} + \sum_{\tilde{i}} \Gamma(\tilde{i} \rightarrow \tilde{G} + h) n_{\tilde{i}}$$

gravitino production from a SUSY state in therm bath:

scattering of a SM state in therm bath

decaying

Rewrite Boltzmann eq. as:

$$\frac{dY_{\tilde{G}}}{dT} \simeq -\frac{\sum_{\tilde{i},j} \langle \sigma(\tilde{i}+j \to \tilde{G}+k) v \rangle_T \, n_{\tilde{i}}^{eq} \, n_j^{eq}}{T \, H \, s} - \sum_{\tilde{i}} \Gamma(\tilde{i} \to \tilde{G}+h) \frac{Y_{\tilde{i}}}{T \, H}$$

integral over T:

$$\propto T_{\rm RH} \qquad\qquad \propto \frac{1}{T^2}$$

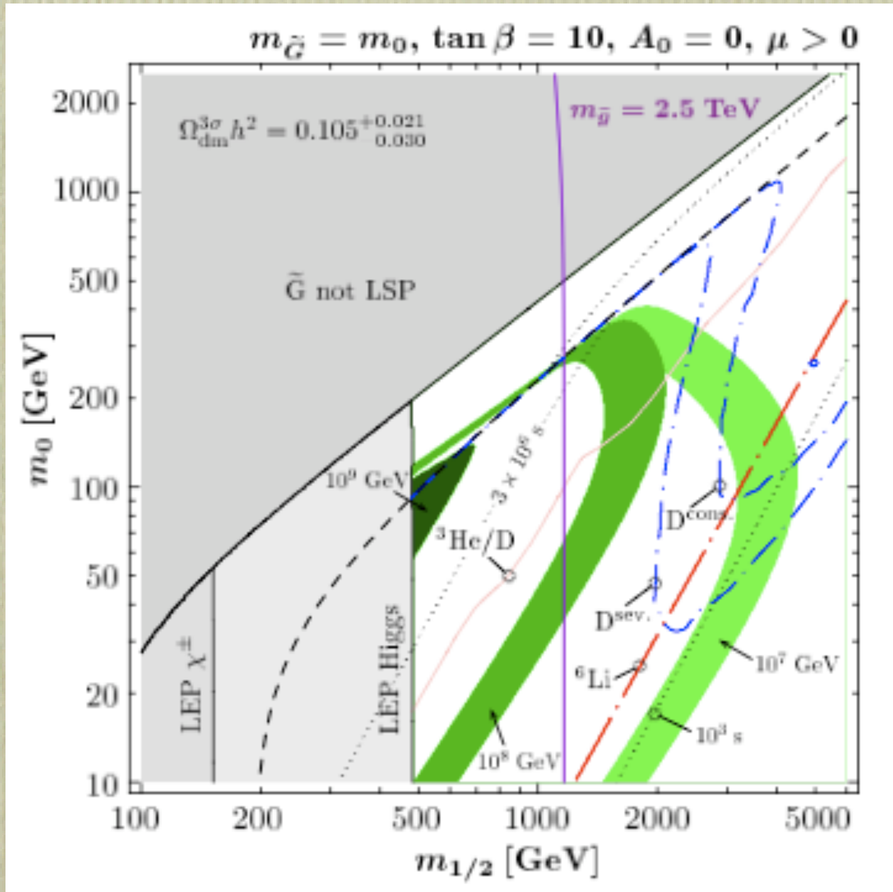
$$\Omega^{TH}_{\tilde{G}} h^2 \simeq 0.2 \left(\frac{100\text{GeV}}{m_{\tilde{G}}} \right) \left(\frac{m_{\tilde{g}}}{1\text{TeV}} \right)^2 \left(\frac{T_R}{10^{10}\text{GeV}} \right)$$

On top of this you may have a relevant thermal relic component for the NLSP and its off-eq. decay into the LSP:

$$\Omega_{LSP} \simeq \frac{M_{LSP}}{M_{NLSP}} \Omega_{NLSP}$$

Analogously for the ***axino***, ***right-handed sneutrino*** , ***KK-graviton***, ***KK right-handed neutrino***, ...

E.g.: CMSSM and the shift in the allowed parameter space, e.g. in the stau coannihilation region:

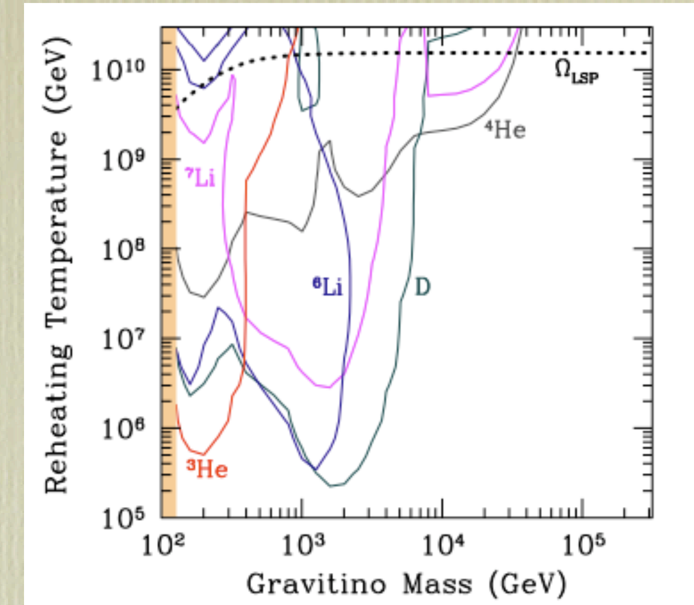


Pradler & Stffen, arXiv: 0710.4548

Accelerator signature of this scenario: the NLSP is **long-lived** and (possibly) charged!

Astrophysical / cosmological implications as well as strong constraints if the decay NLSP →LSP happens after BBN

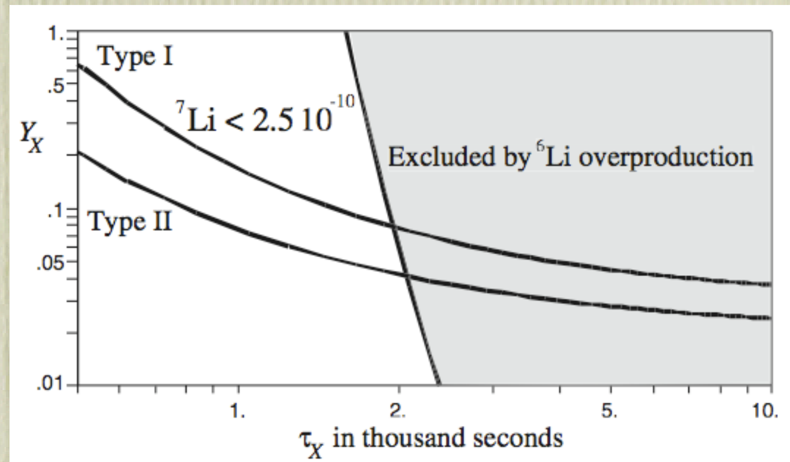
Constraints from NLSP → gravitino LSP due to the injection in the plasma of (non-thermal): photons or electrons (photo-dissociation of D), hadrons (changing the n, p budget an affecting He and/or D). This is the counterpart of the cosmological gravitino problem, i.e. relic gravitinos decaying into (neutralino???) LSP at late times:



Kawasaki et al., 2008

+ novel idea to constrain the models with charged NLSP, since the presence of these relics at the BBN time would catalyze some BBN reactions otherwise suppressed, such as:

$$({}^4\mathrm{He}X^-) + \mathrm{D} \to {}^6\mathrm{Li} + X^-$$



Pospelov et al., 2008

Very strong constraints since $^6\mathrm{Li/H}|_{\mathrm{obs}} \lesssim 10^{-11} - 10^{-10}$

Emergency exit:

Recent idea: avoid the constraints from late decay of the NLSP by ... speeding up the decay via R-parity violation (Buchmüller et al., hep-ph/0702184). Introduce:

$$W_{\Delta L=1} = \lambda_{ikj} l_i e^c_j l_k + \lambda'_{kji} d^c_i q_j l_k$$

You need the gravitino to be sufficiently long lived:

$$\tau_{3/2} \sim 10^{26}\mathrm{s} \left(\frac{\lambda}{10^{-7}}\right)^{-2} \left(\frac{m_{3/2}}{10 \text{ GeV}}\right)^{-3}$$

and the NLSP decaying fast enough:

$$\tau_{\mathrm{NLSP}} \simeq 10^{3}\mathrm{s} \left(\frac{\lambda}{10^{-14}}\right)^{-2} \left(\frac{m_{\mathrm{NLSP}}}{100 \text{ GeV}}\right)^{-1}$$

Twist the model little further and require the gravitino lifetime to match the value required to get the level of yields in todays halo to reproduce the PAMELA excess, Fermi signals, ect. ect. (Ibarra et al., 2008-2009)

Just one example of the several models on the market for decaying DM.

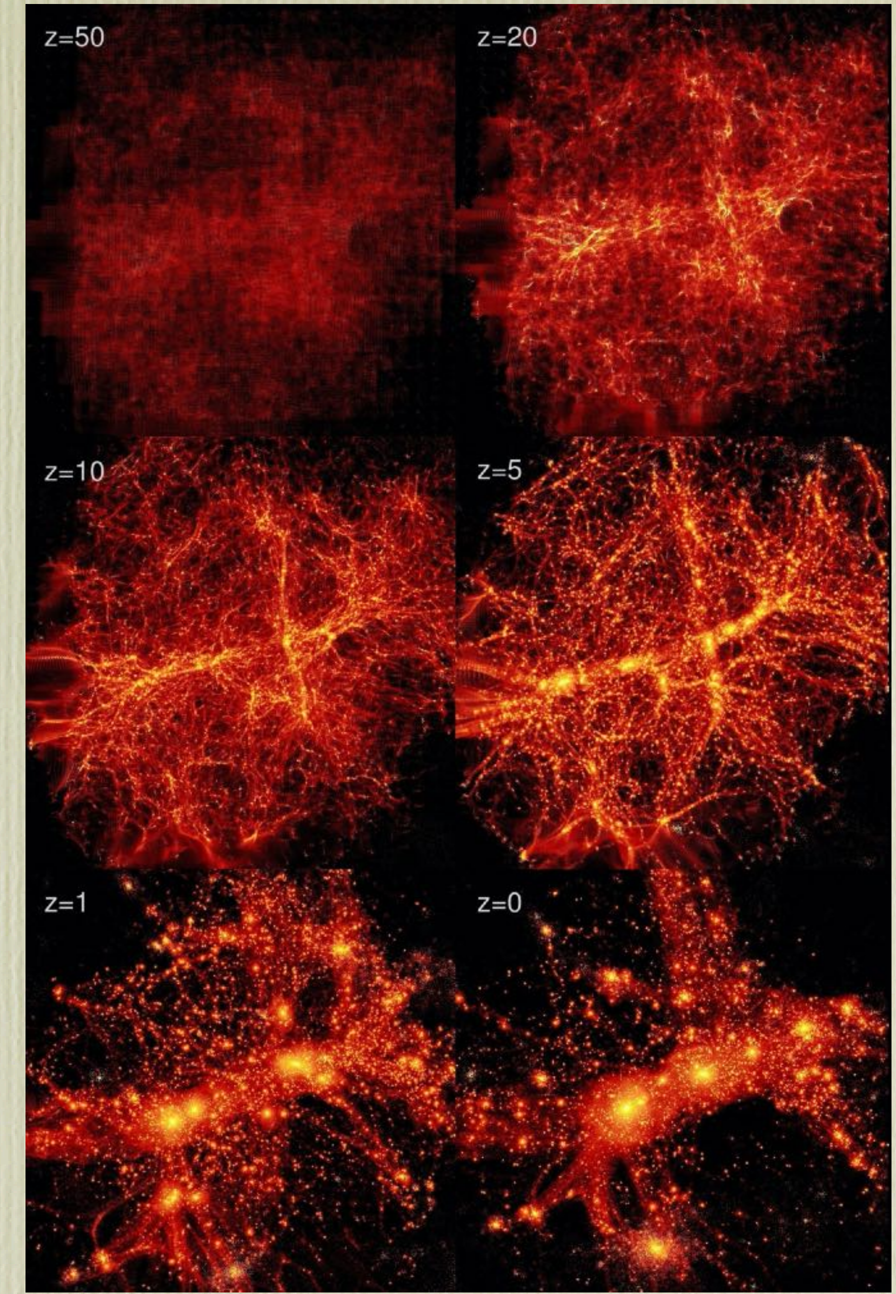
extra slides

Numerical N-body simulations:

following primordial density perturbations in the non-linear regime

Sketch of the formation of the local group:

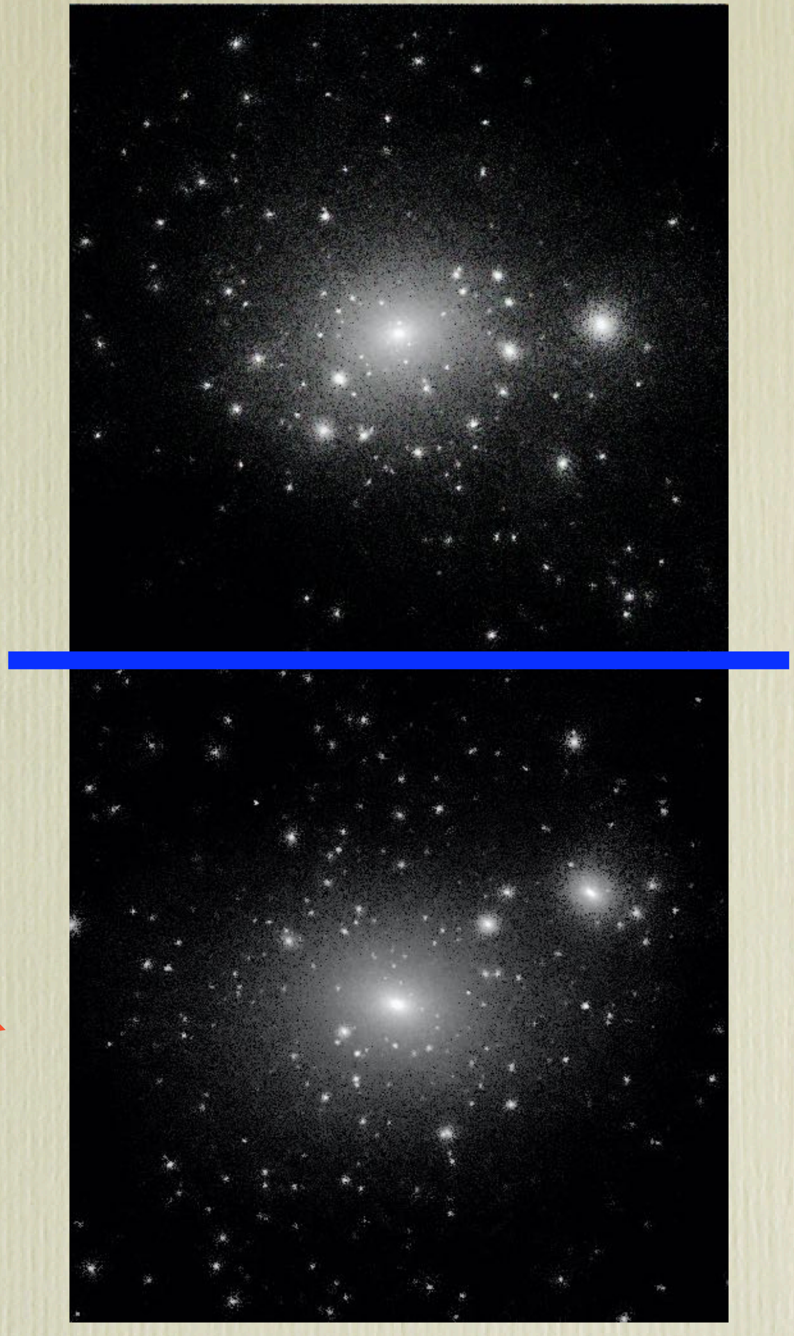
Moore et al., 2005



Self-similarity of structures on different mass scales:

Galaxy $\sim 10^{12}\, M_\odot$

Cluster of galaxies $\sim 10^{15}\, M_\odot$



Moore et al., 2005

Two main features deduced for the simulations:

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A UNIVERSAL DENSITY PROFILE FROM HIERARCHICAL CLUSTERING

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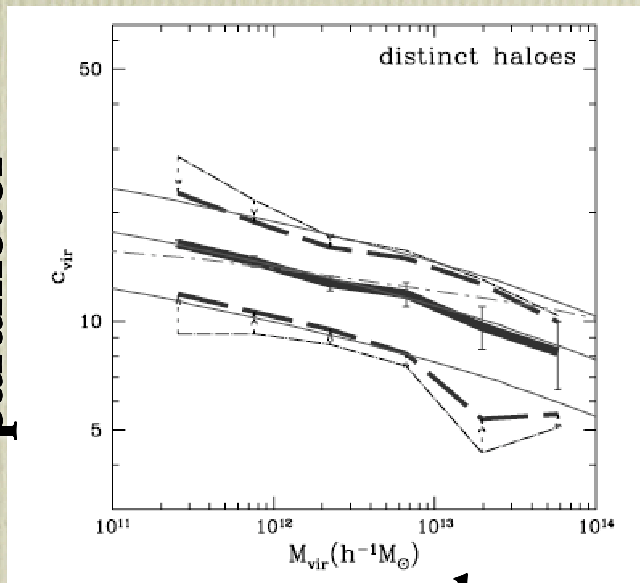
$$\frac{\rho(r)}{\rho_{\rm crit}} = \frac{\delta_c}{(r/r_s)(1 + r/r_s)^2}$$

Correlation between the two parameters in the model:

concentration parameter



mass scale

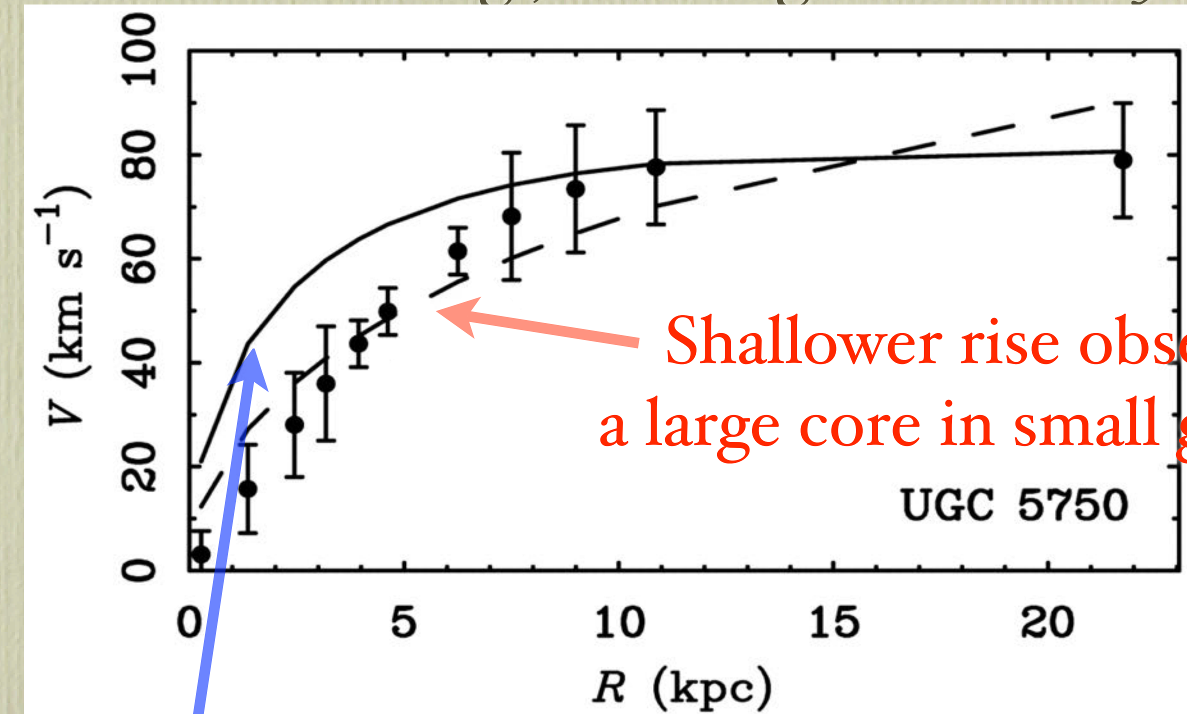
Is the ΛCDM model facing a crisis?

There are possible areas of disagreement between theory (more exactly numerical N-body simulations of the theory in the non-linear regime) and observations:

- ✶Morphology of galaxies, luminosity functions, age of stellar populations, disk sizes, and possibly other “baryonic observables”; most likely all these are in connection with our poor understanding of star and/or galaxy formation;
- ✶Dark matter distribution on small scales, and in particular the shape of DM profiles towards the center of galaxies, and the abundance of substructures in DM halos.

Friction between the measured rotation curve of low mass galaxies and ΛCDM profiles:

e.g., McGaugh et al. 2003

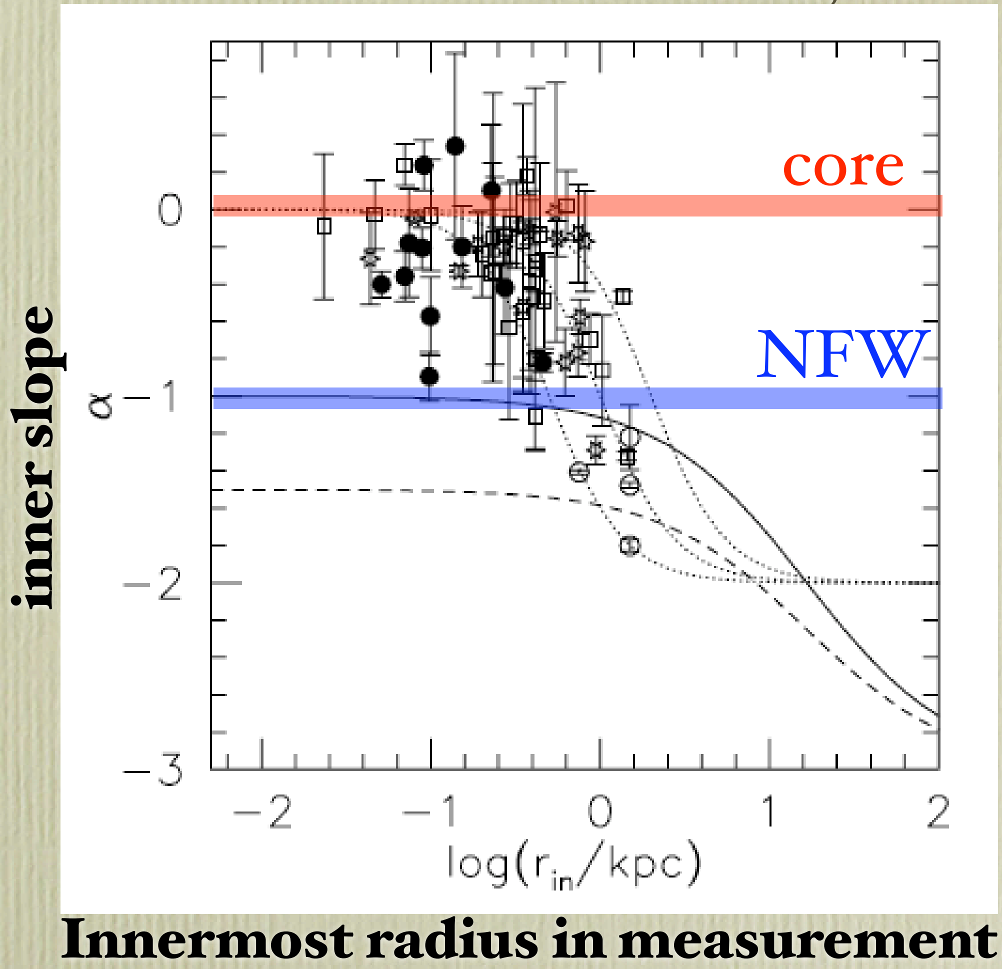


Shallower rise observed:
a large core in small galaxies?

$$\rho_{NFW} \propto \frac{1}{r\,(r+a)^2}$$

Theory predicts
cusp and concentration

de Blok & Bosma, 2002

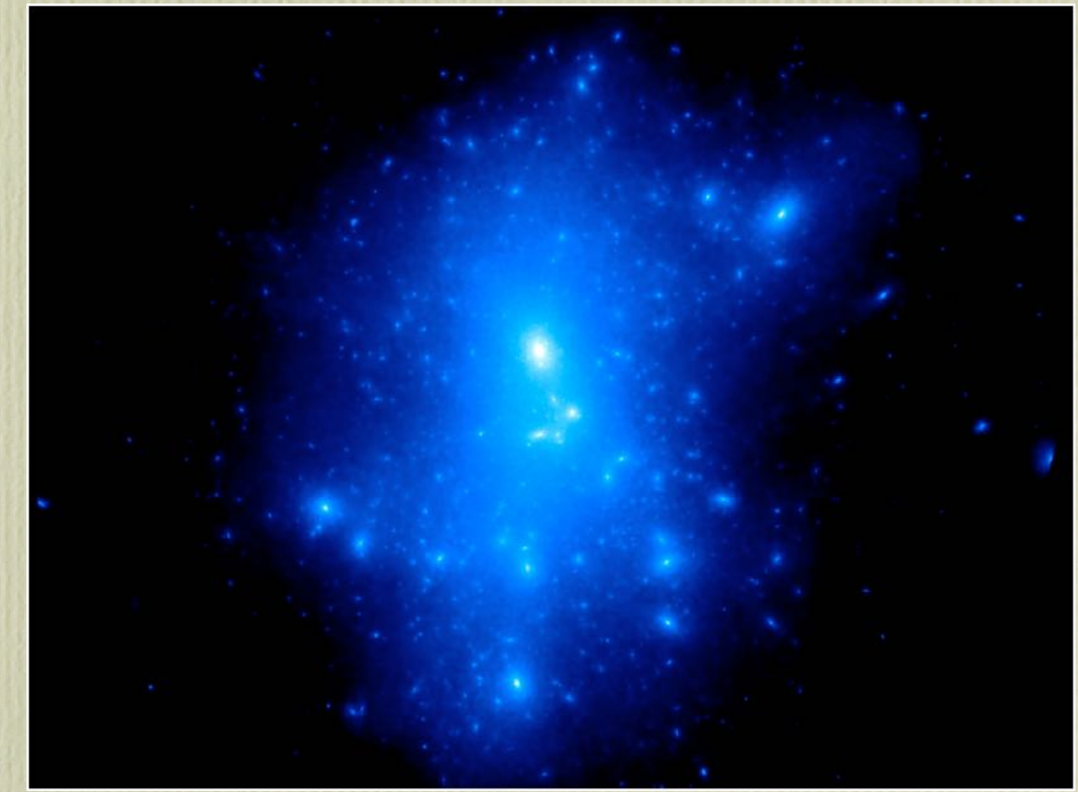


Claim: there is no case in which the dynamical models favor the "theoretical" model (even in smoother versions than NFW) over "phenomenological" cored profiles

Problem, or theoretical and/or observational bias?

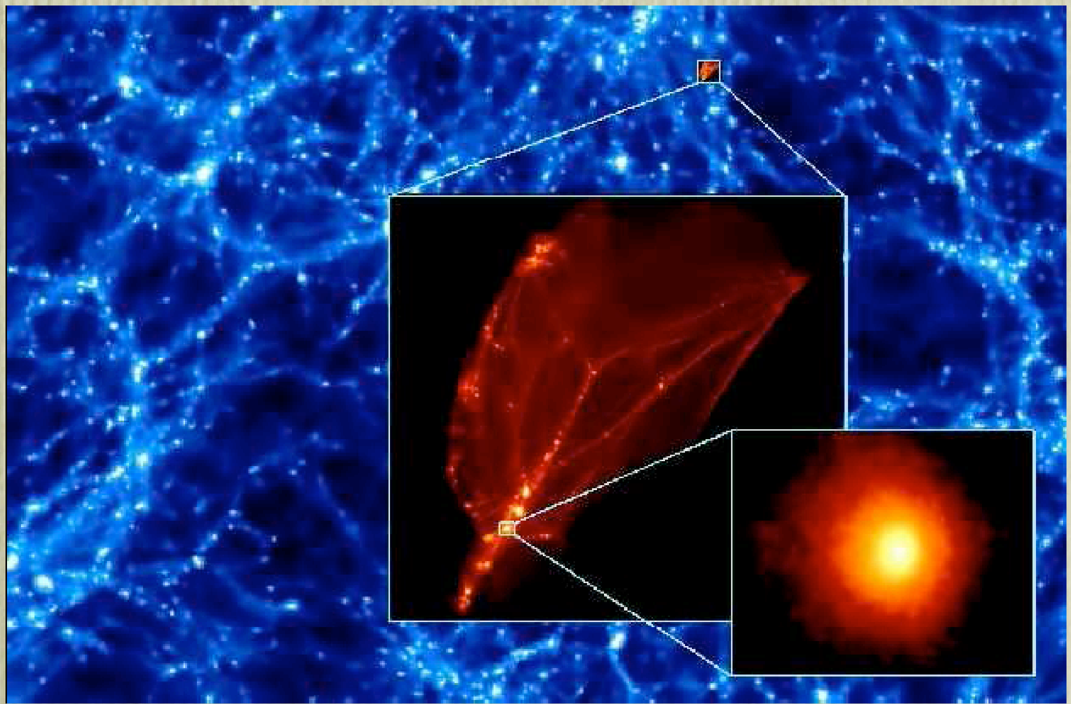
In a ΛCDM cosmology, a typical sketch of a dark matter halo from N-body simulations is:

Moore et al, 2005



a large fraction of the total mass is bound in dark **substructures** with masses ...

... down to the WIMP free-streaming scale, $\sim 10^{-6} M_\odot$, Green, Hofmann & Schwartz, 2004 (or as high as $10^2 M_\odot$, Profumo, Sigdurson & Kamionkowski, 2006) :

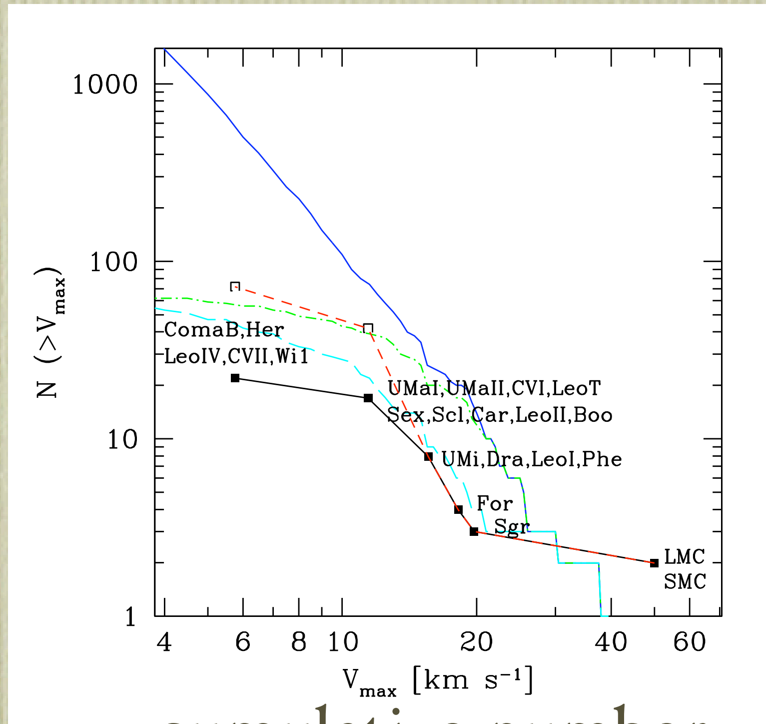


0.024 pc

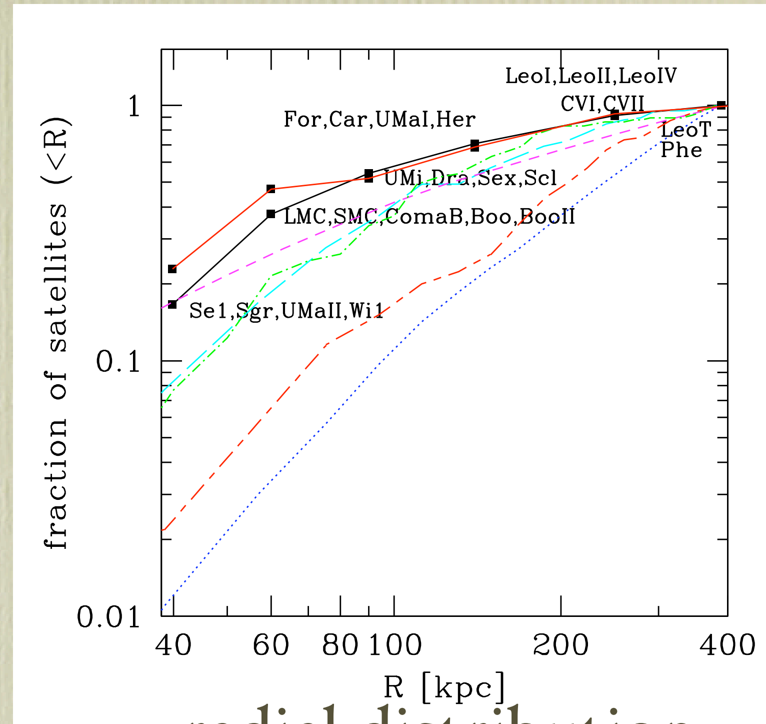
Numerical simulation, z=26

Diemand, Moore & Stadel, 2005

Cumulative number of satellites in simulations versus the number of observed satellites in the Galaxy:



cumulative number



radial distribution

Madau, Diemand & Kuhlen, 2006

Again: real problem or simply an astrophysical mechanism being overlooked ?

Need for a particle physics solution?

Goal: start with a scale invariant CDM power spectrum and then remove power on small scales.

Mechanism: introduce a model mildly (i.e. at level of current bounds) violating one of the 5 main ingredients usually assumed for standard CDM:

1) ~~Dissipation-less~~: e.g., DM with a electric/magnetic dipole moment, Sigurdson et al. 2004

2) ~~Collision-less~~: self interacting DM, Spergel & Steinhardt 2000

3) ~~Fluid limit~~: ...

4) ~~Classical~~: fuzzy DM, Hu, Barkana & Gruzinov 2000

5) ~~Cold~~: warm DM, Hogan & Dalcanton 2000