Dark Matter, particle candidates and their detection

Piero Ullio
SISSA & INFN (Trieste)

Mytilene, September 27-28, 2007

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

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: $\langle V\rangle + 2\langle K\rangle = 0$

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

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

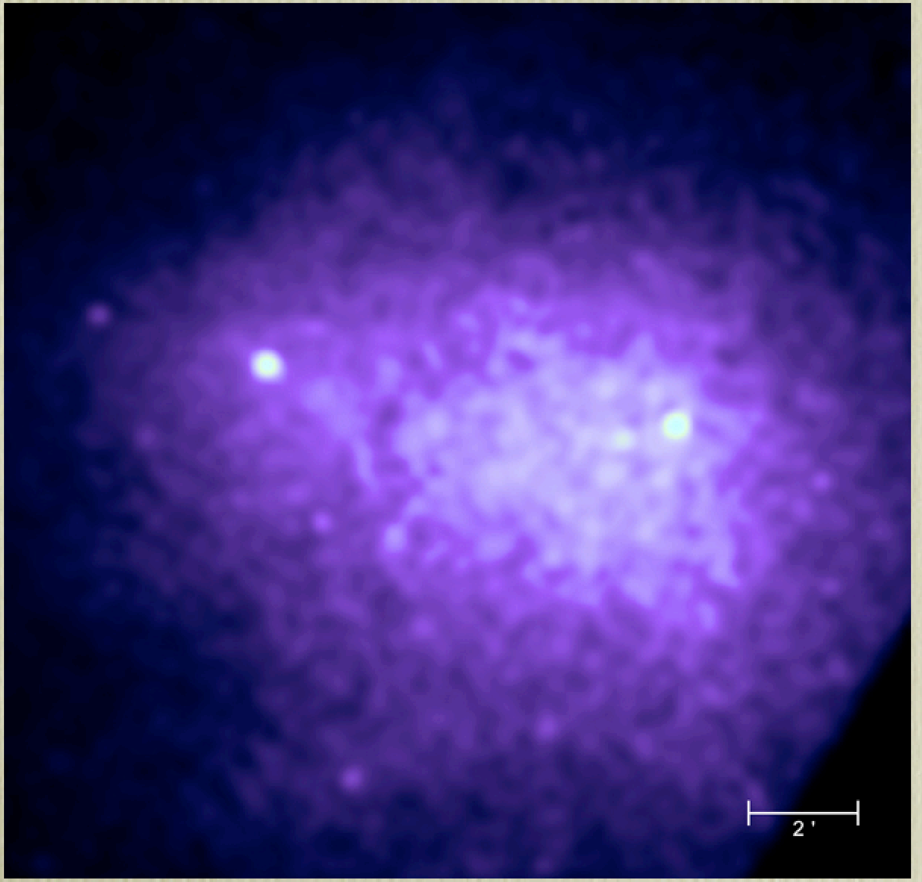
measure the velocity dispersion and geometrical size to get:

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

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)

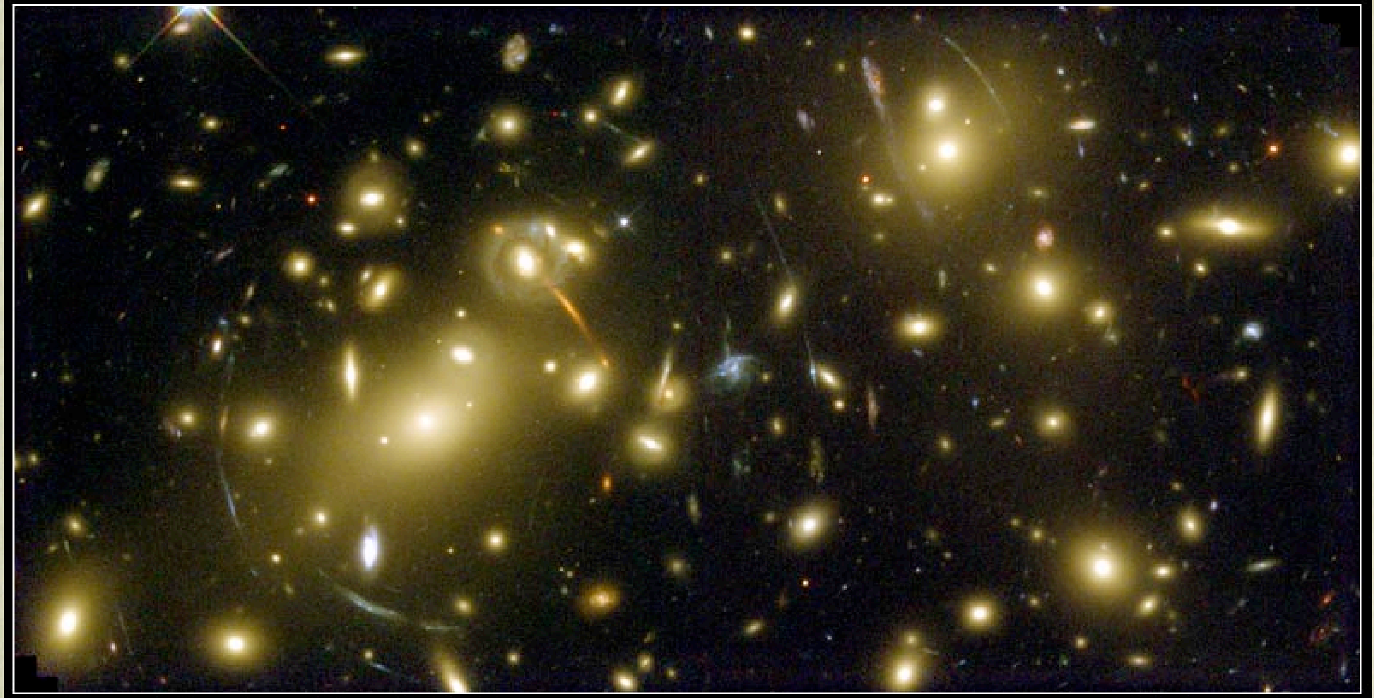
$$M_b/M \equiv f_b \simeq 14\%$$

$$\Omega_M \simeq \Omega_b/f_b \underset{\uparrow}{\simeq} 0.29$$

Ω_b from BBN

DM in clusters:

mass tomography through gravitational lensing:



Galaxy Cluster Abell 2218 HST • WFPC2

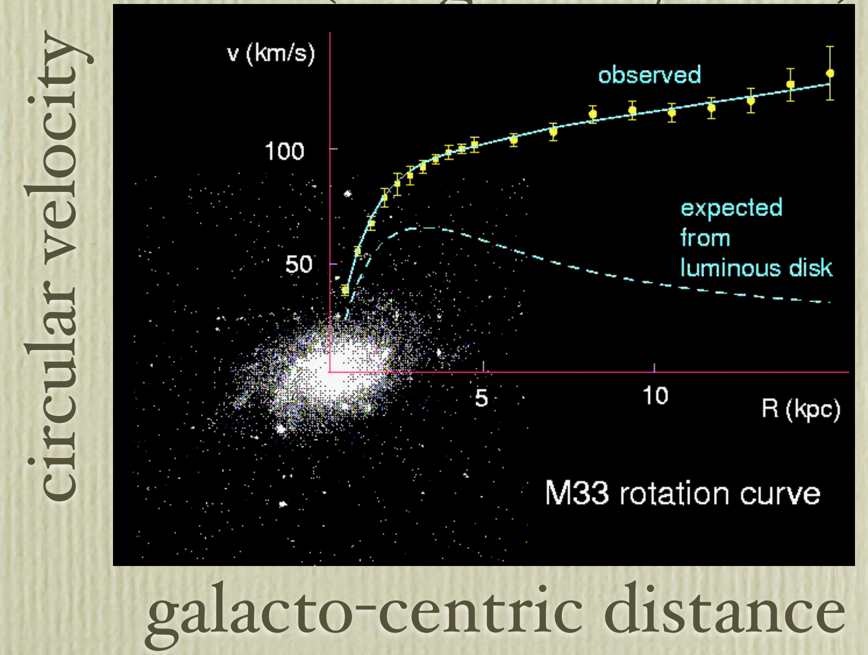
NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08

Other techniques have been applied as well, e.g., mass mapping through Sunyaev-Zeldovich effect

DM in galaxies:

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

(Bergström, 2000)



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

outside the body, i.e. at:

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

Keplerian fall-off expected:

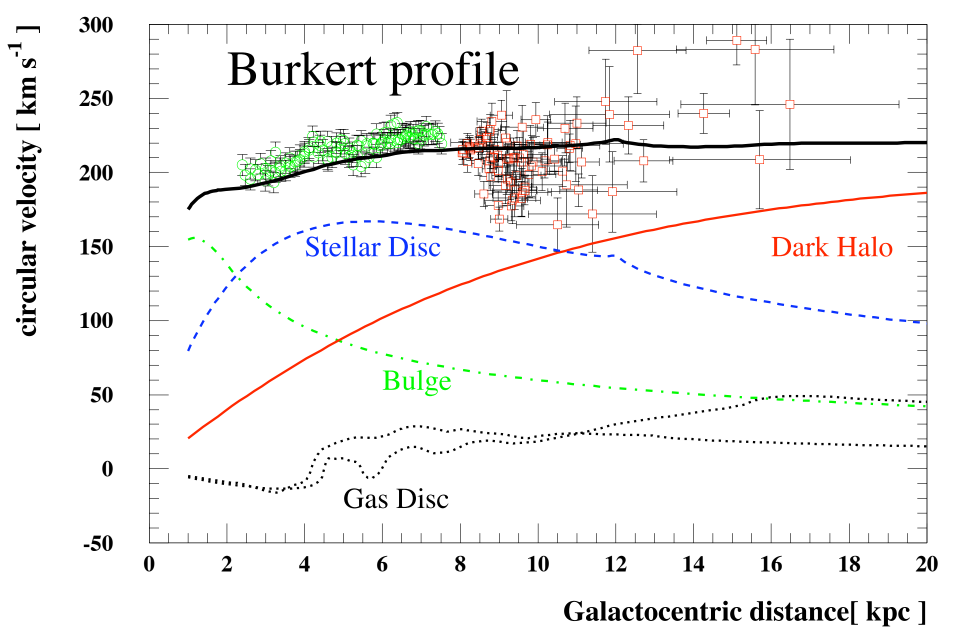
$$v_{\rm circ} \propto \frac{1}{r^{1/2}}$$

rather than ~ flat:

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

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

DM in galaxies: the case for the Milky Way



it is a hard task to measure the MW rotation curve. In maximal-disc models the local DM component can be negligible.

The dynamics of galactic satellites, globular clusters, horizontal branch stars, ..., give:

$$M_{\rm tot}(r < 50{\rm kpc}) \simeq (5.4^{+0.1}_{-0.4}) \cdot 10^{11} M_\odot$$

or: $M_{\rm tot} \simeq M_{\rm vir} \simeq 1 - 2 \cdot 10^{12} M_\odot$

$\Leftrightarrow$ $M_{\rm stars+gas} \simeq 4 \cdot 10^{10} M_\odot$

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

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:

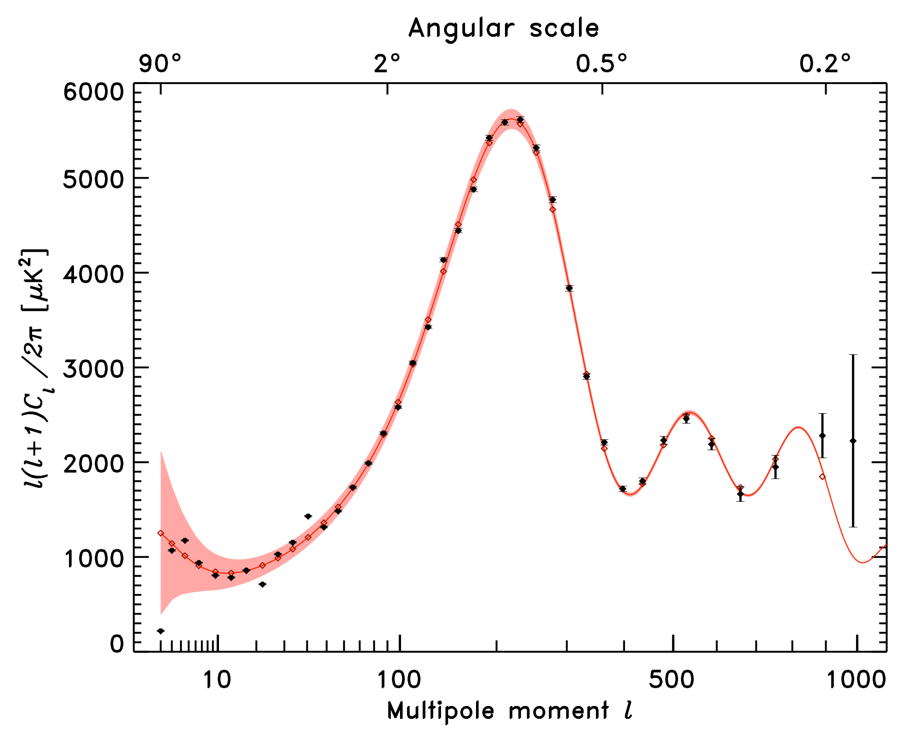
$$\Omega_{Tot} \sim 1 \qquad \underbrace{\Omega_{M} \sim 0.24} \qquad \Omega_{DE} \sim 0.76 \qquad \ldots$$

$$\Omega_{DM} \sim 0.20 \qquad \Omega_{b} \sim 0.04$$

Ω_b in remarkable agreement with BBN!

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

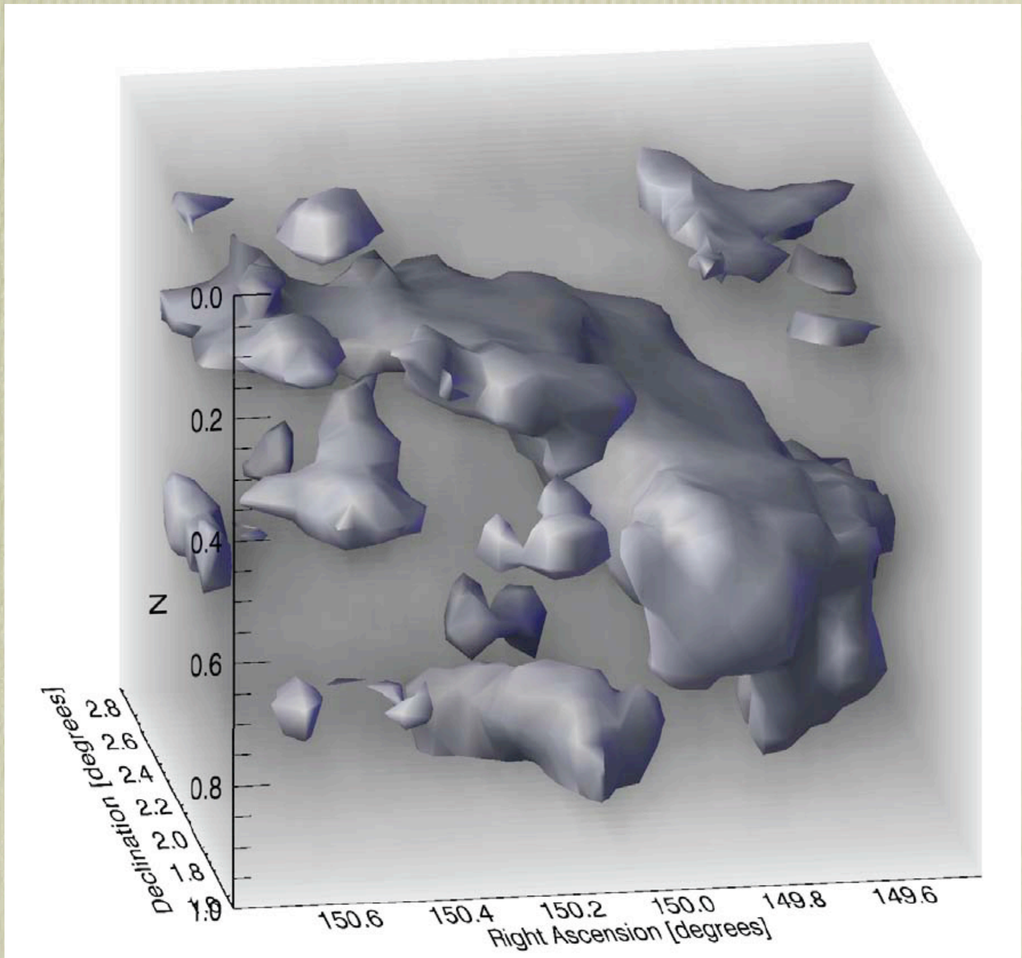
e.g., it accounts for the gravitational potential wells in which CMB baryon acoustic oscillations take place:



(3-yr WMAP, 2006)

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 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.

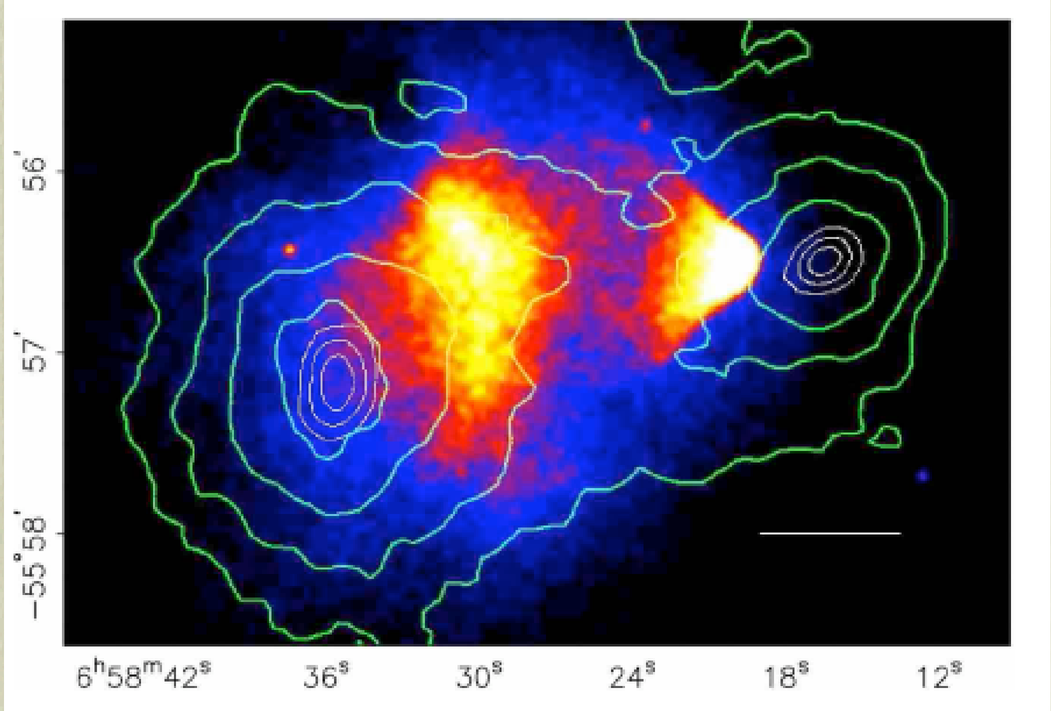
1) DM is **optically dark**: its electromagnetic coupling is suppressed since: a) it is does not couple to photons prior recombination; b) it does not contribute significantly to the background radiation at any frequency; c) it cannot cool radiating photons (as baryons do, when they collapse to the center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

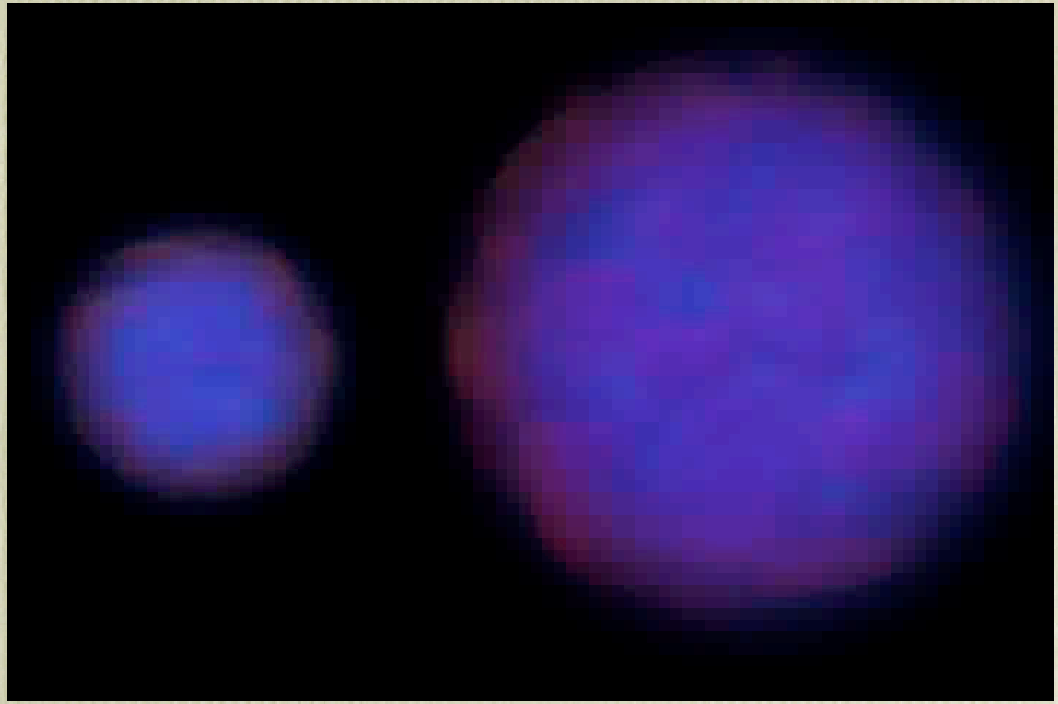
Limits from the fact that you get spherical clusters as opposed to the observed ellipticity in real clusters (e.g. Miralda-Escude, 2000). More recently, limits from the morphology of the recent merging in the 1E0657-558 cluster ("Bullet" cluster):

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:

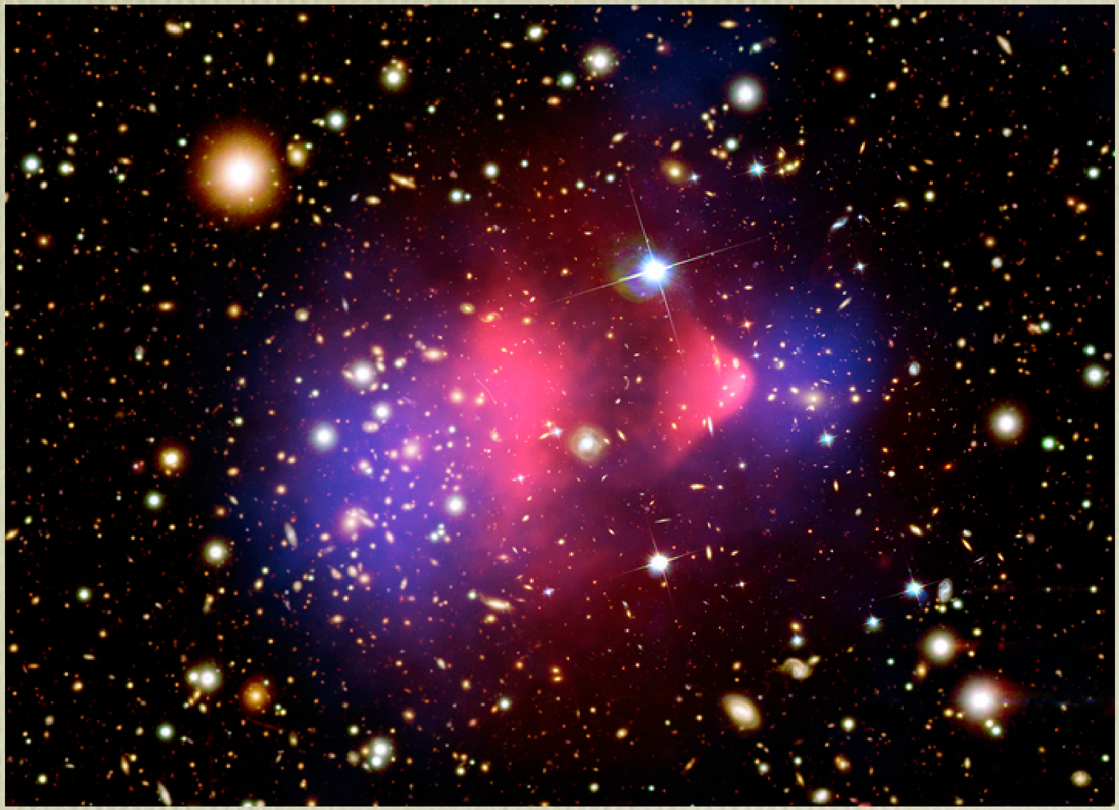
Credit: NASA, M. Weiss



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: $M_p < 10^4\, M_\odot$

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

Not very tight limits: $M_p < 10^3\, M_\odot \Rightarrow M_p < 10^{60}\,\mathrm{GeV}$

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

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

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

"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: $f_{\max}^{\rm ini} = \frac{g}{h^3}$

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:

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

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

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

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, $t \propto a^2$

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

One finds a free-streaming scale:

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

For a neutrino:

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

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
⇒ coherent oscillations with modes behaving like matter:

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

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

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

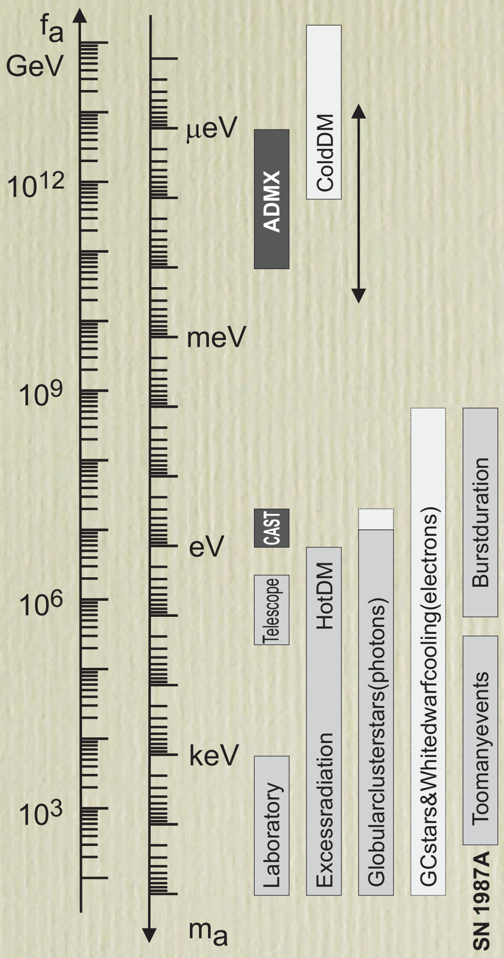
$$m_a \sim 10^{-5}\,\mathrm{eV}$$

$$\updownarrow$$

$$\Omega_a \sim 1$$

(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

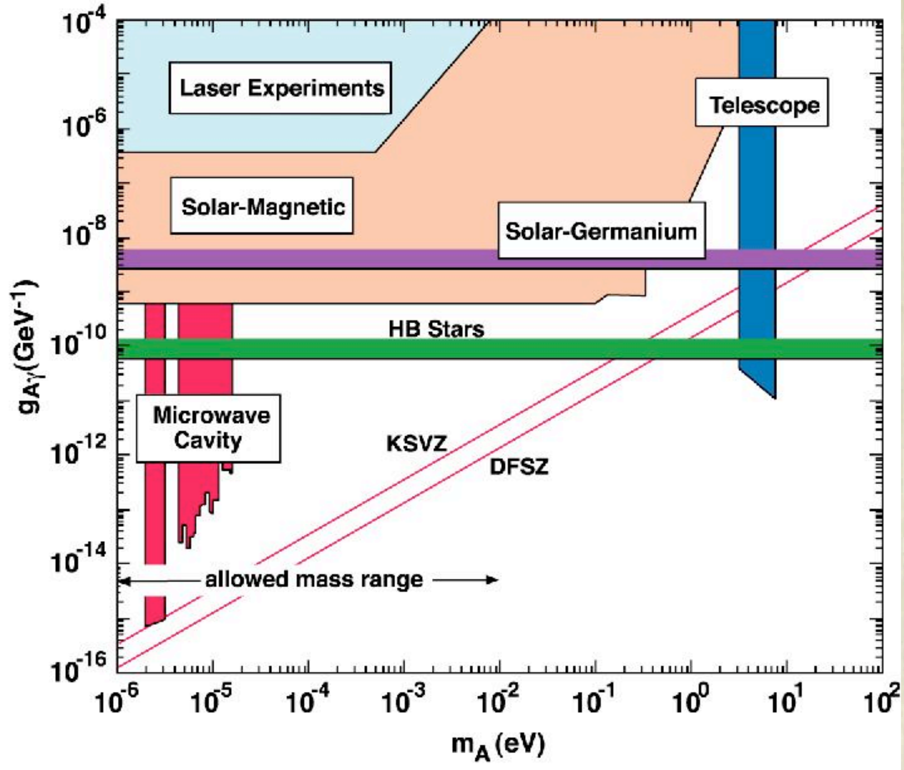
DM detection needs to be considered case by case. For the axion there are generic couplings:

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

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.:

$$\frac{dn_\chi}{dt} + \underbrace{3Hn_\chi}_{\text{dilution by the volume expansion}} = -\underbrace{\langle\sigma_A v\rangle_T}_{\text{thermally averaged annihilation cross section}}\left[\underbrace{(n_\chi)^2}_{\chi\bar{\chi} \to P\bar{P}} - \underbrace{\left(n_\chi^{eq}\right)^2}_{P\bar{P} \to \chi\bar{\chi}}\right]$$

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:

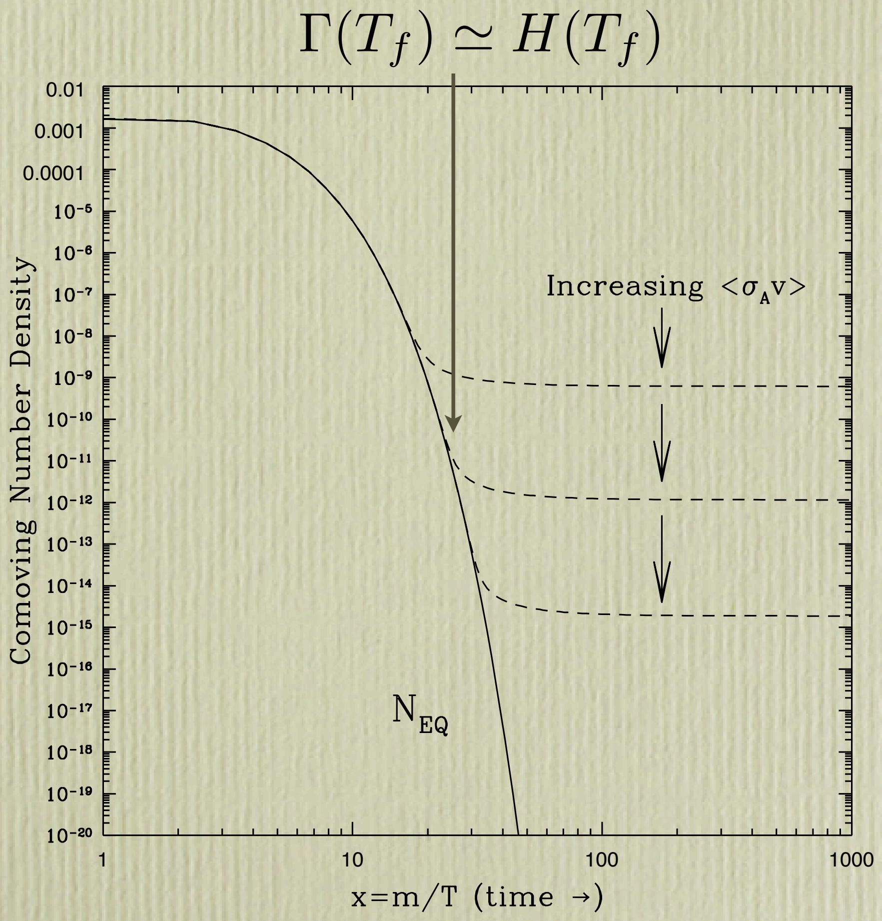
$$\Omega_\chi = \frac{\rho_\chi}{\rho_c} = \frac{M_\chi\, n_0}{\rho_c} = \frac{M_\chi\, s_0\, Y_0}{\rho_c} \simeq \frac{M_\chi\, s_0\, Y_\chi^{eq}(T_f)}{\rho_c}$$

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

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

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



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

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

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

WIMP DM candidates

A recipe which can be easily implemented in most SM extensions on the market:

- Supersymmetry* with R-parity
- Universal Extra Dimensions with KK-parity
- Gauge-Higgs Unification in 5D* with mirror symmetry
- Little Higgs * with T-parity
- ...

DM as a by-product in models mostly introduced to understand the electroweak scale* (not surprisingly since we need electroweak interaction strengths), with discrete symmetries introduced to protect other features.

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):

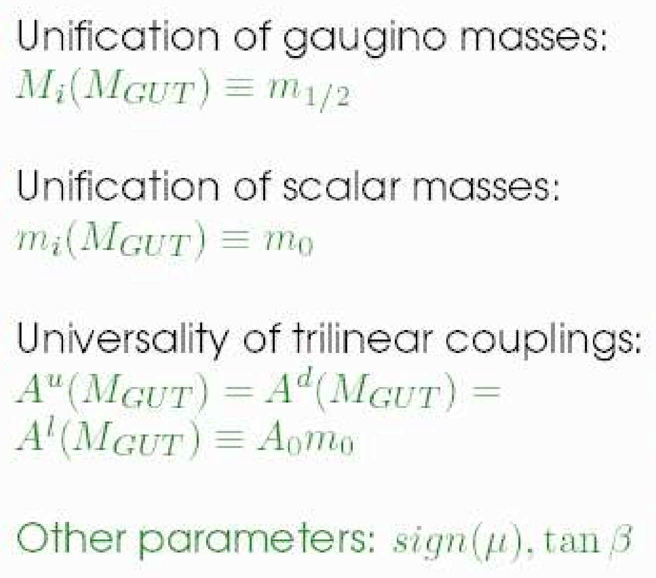
$$\tilde{\chi}^0_1 = N_{11}\tilde{B} + N_{12}\tilde{W}^3 + N_{13}\tilde{H}^0_1 + N_{14}\tilde{H}^0_2$$

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:

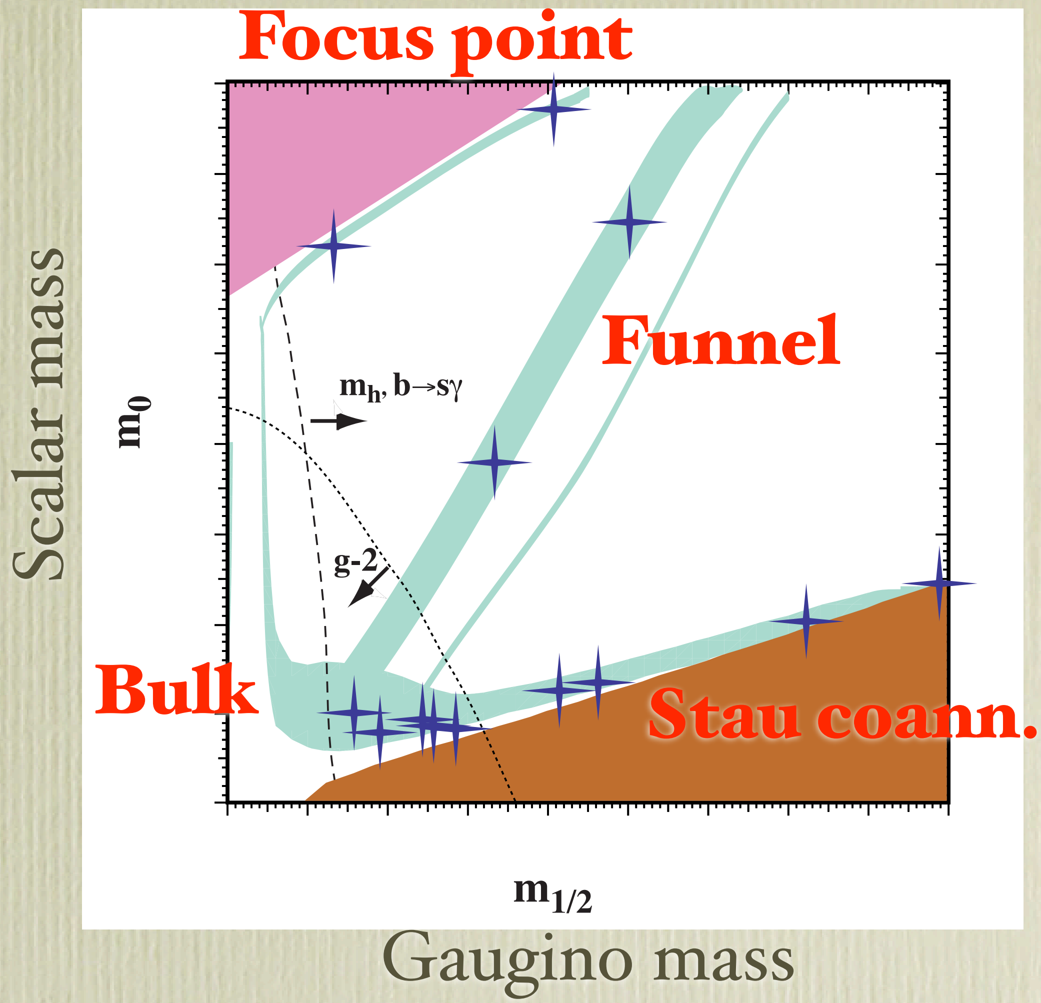


Unification of gaugino masses:
$M_i(M_{GUT}) \equiv m_{1/2}$

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:

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

These annihilations have a helicity-flip suppression:

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

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

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

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:

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

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

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

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

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 $m_1 \le m_2 \le \ldots \le m_N$ and sharing a quantum number. Trace the evolution of densities simultaneously, since all states have comparable densities (and are essentially indistinguishable):

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

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 :

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

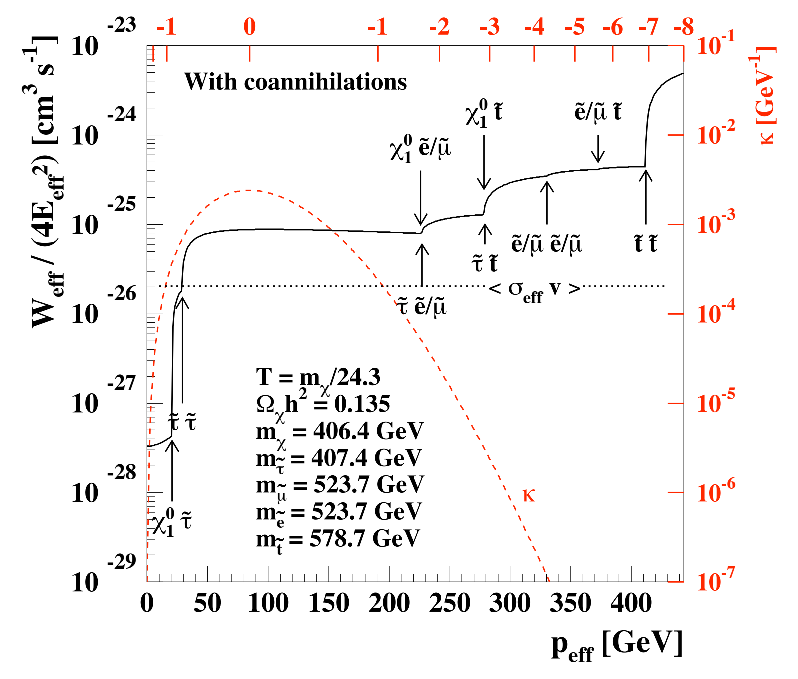
For fast $\chi_i\ X_b^i \leftrightarrow \chi_j\ X_b^f$, one has $\dfrac{n_i}{n} \simeq \dfrac{n_i^{eq}}{n^{eq}}$ and:

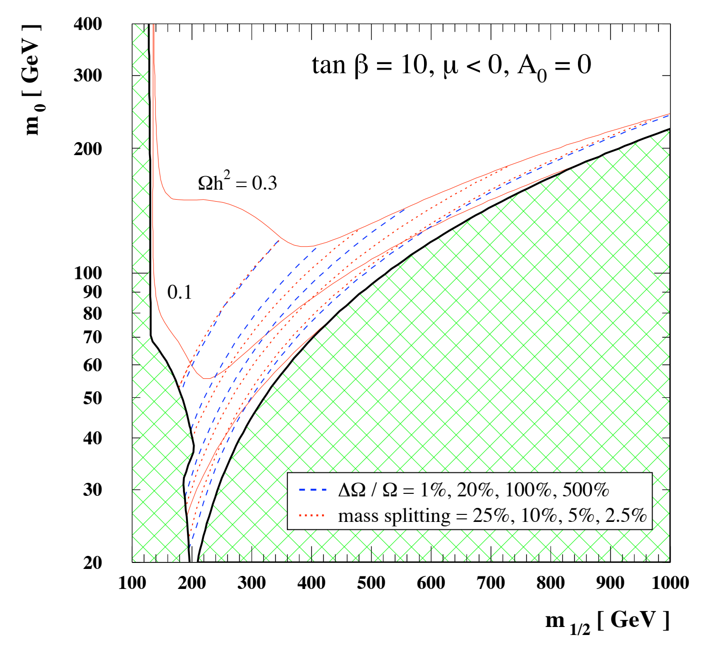
$$\frac{dn}{dt} = -3\,H\,n - \langle \sigma_{eff} v \rangle \left[n^2 - (n^{eq})^2 \right]$$

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

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.

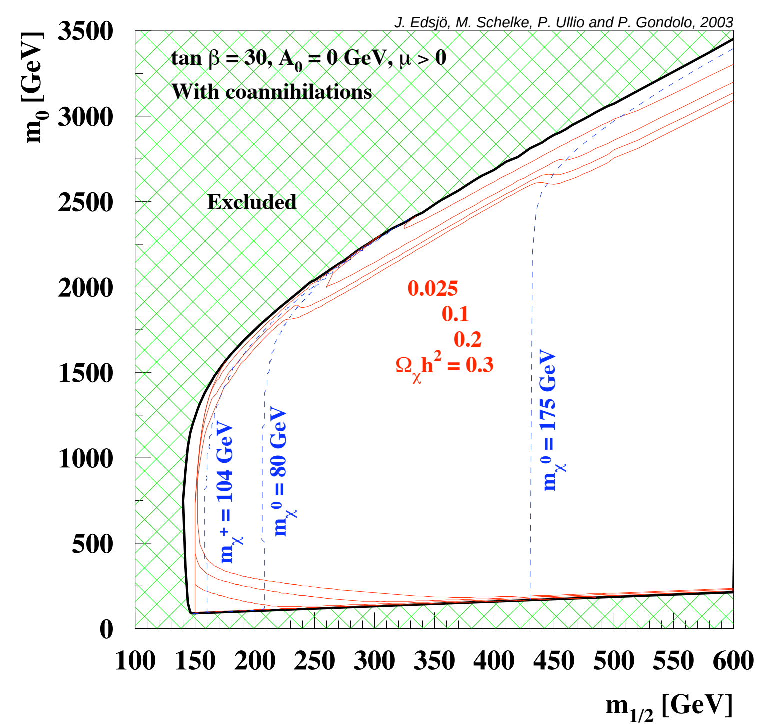
Stau coannihilation region: a Bino-like neutralino is nearly degenerate in mass with a stau and the latter sets the thermal relic density:

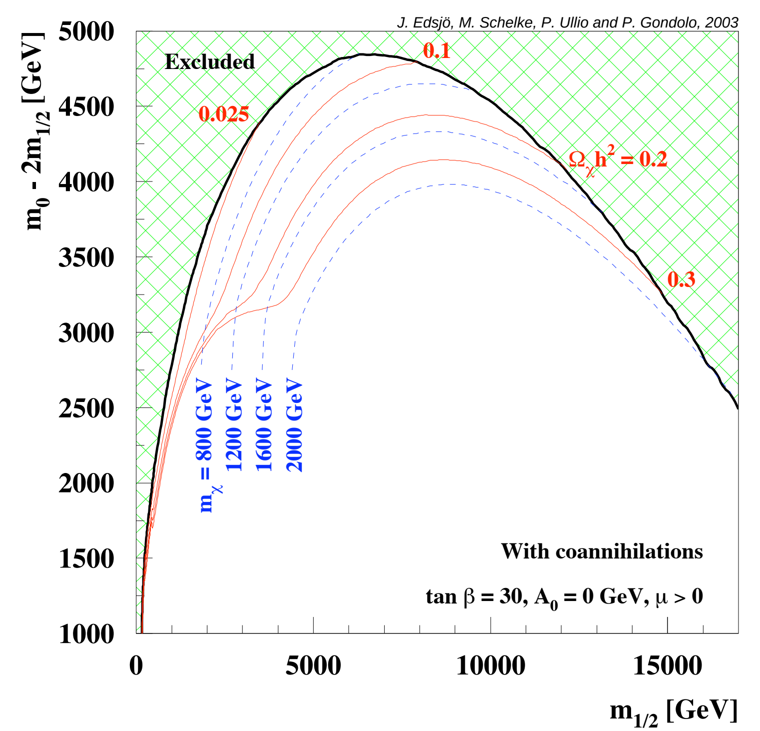




lightest neutralino mass scale up to 300-400 GeV

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.


J. Edsjö, M. Schelke, P. Ullio and P. Gondolo, 2003


J. Edsjö, M. Schelke, P. Ullio and P. Gondolo, 2003

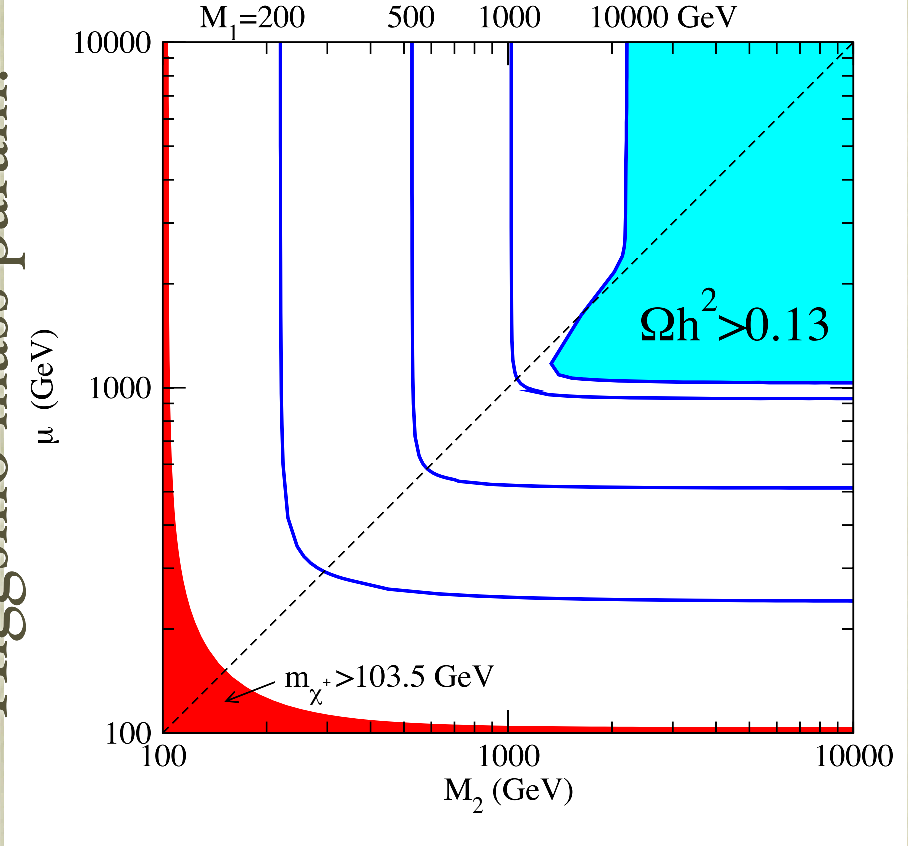
An analogous picture is found in **SPLIT SUSY**

Arkani-Hamed & Dimopoulos, 2004;
Giudice & Romanino, 2004

Scalars decoupled at a high scale; DM constraints prevent gauginos and/or higgsinos from being very heavy as well

bino mass param.

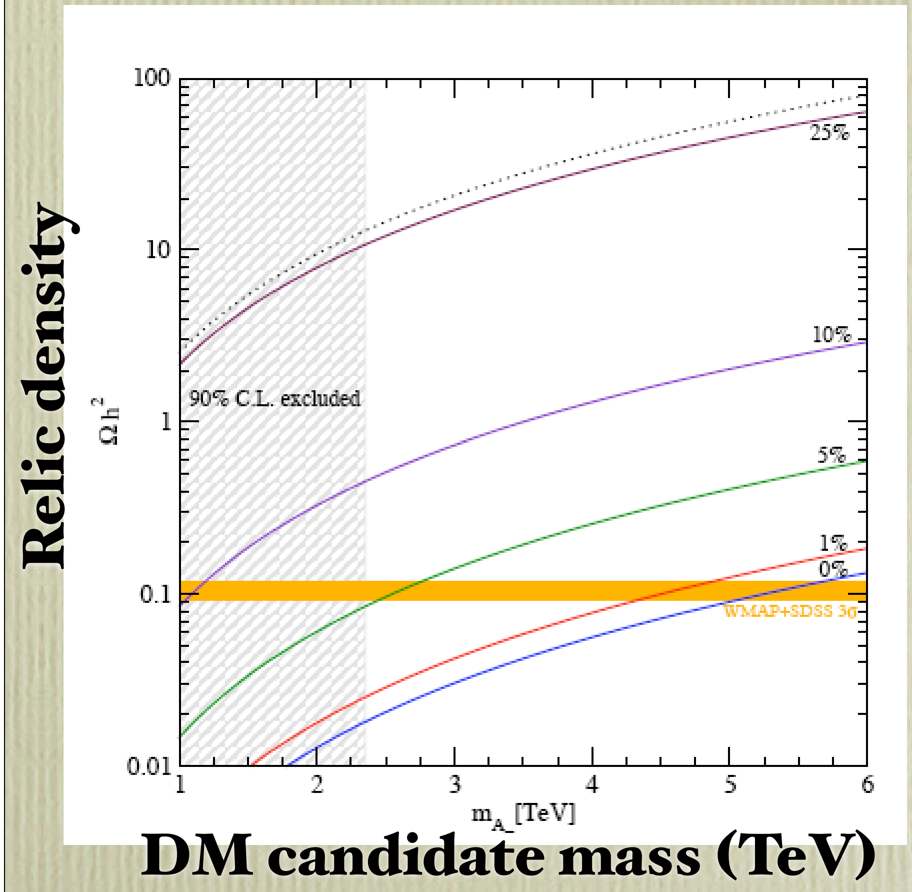
Higgsino mass param.

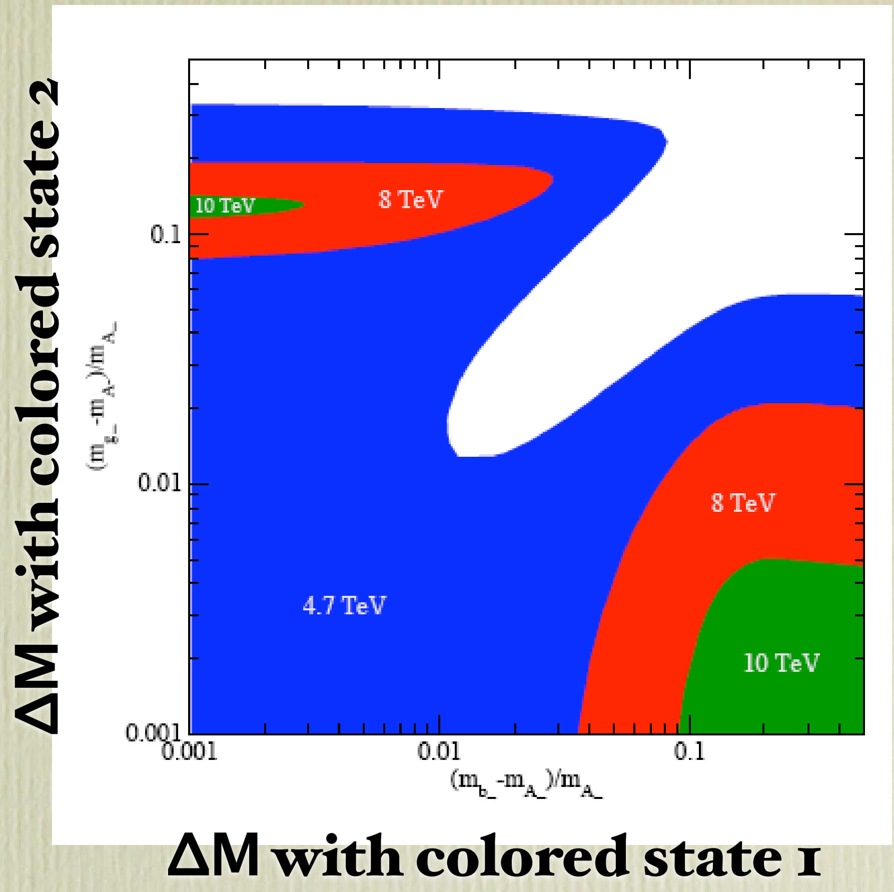


wino mass param.

Masiero, Profumo & P.U., 2004

An extreme case for coannihilations: **LKP in 5D theory with gauge-Higgs unification**





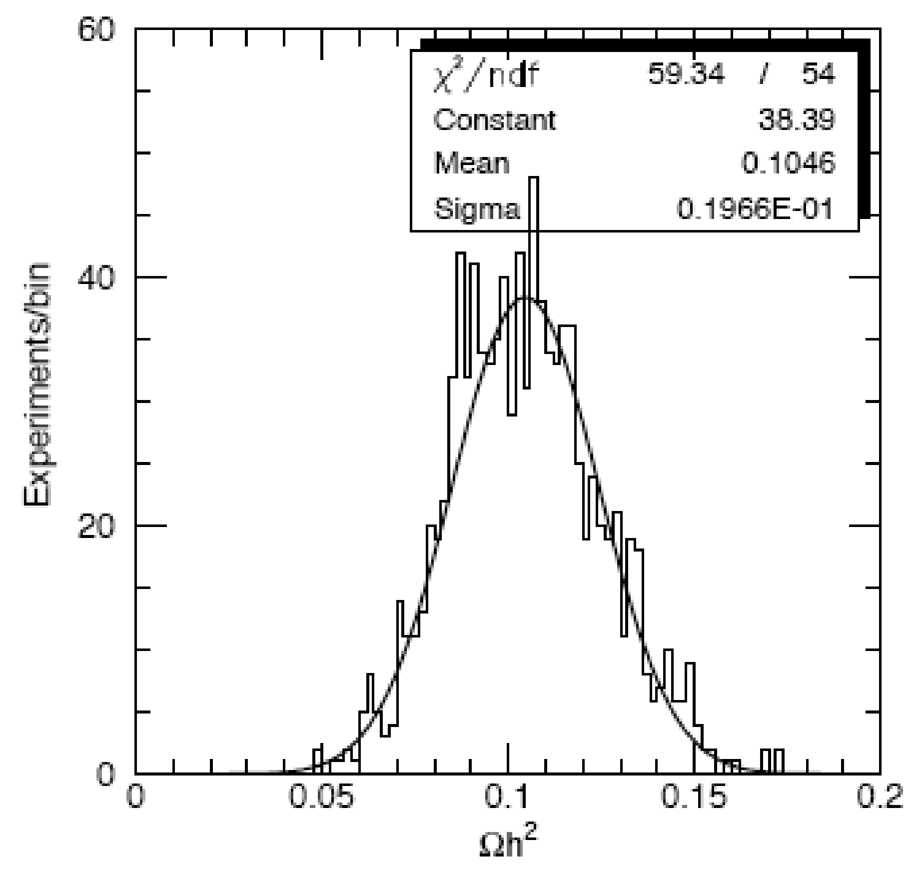
Coannihilations with strongly-interacting states may shift the DM scale in the multi-TeV range,
Regis, Serone & P.U. 2007.

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



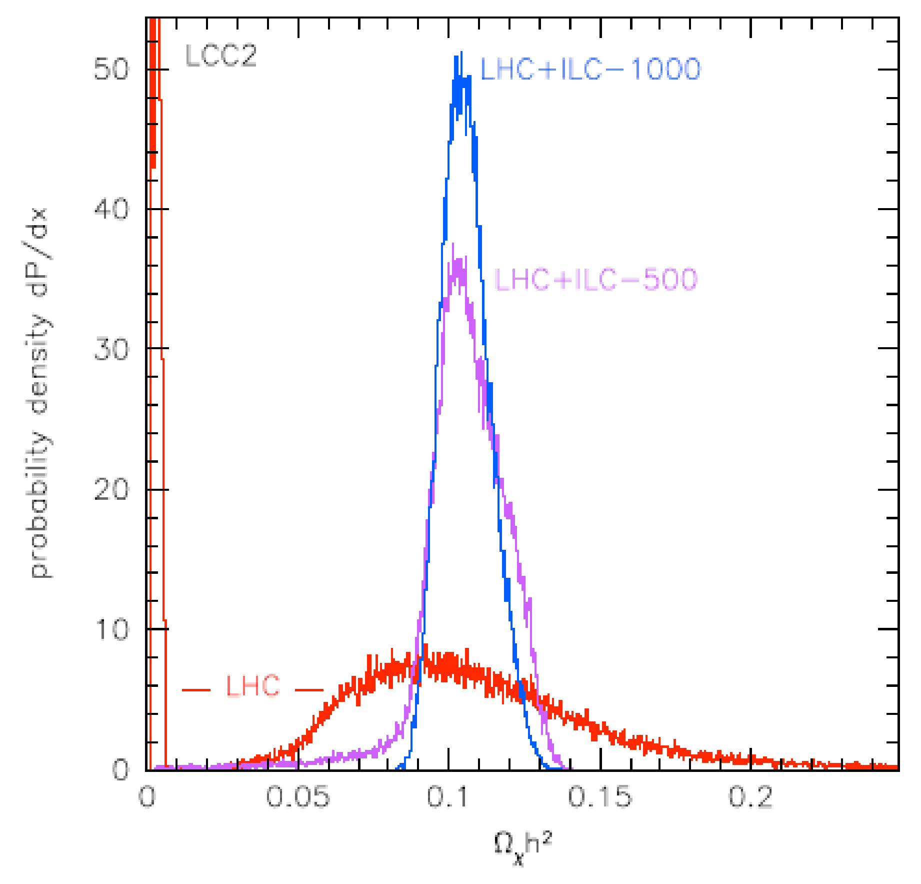
Relic density

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



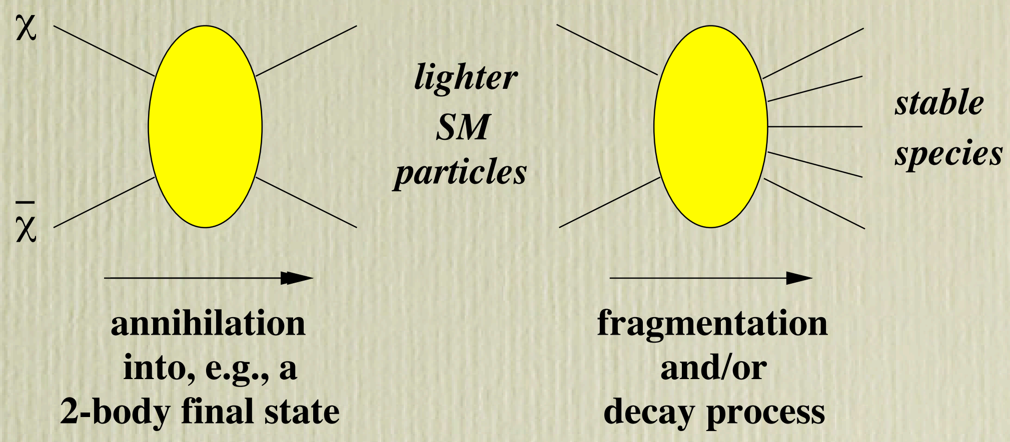
Relic density

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 (?)



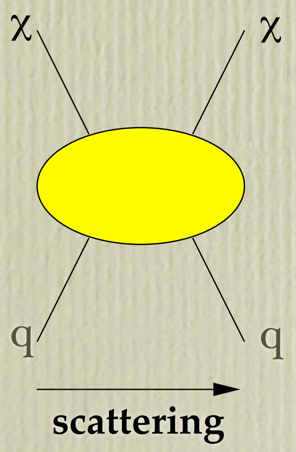
lighter SM particles

stable species

annihilation into, e.g., a 2-body final state

fragmentation and/or decay process

By crossing symmetry (?)



scattering

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:

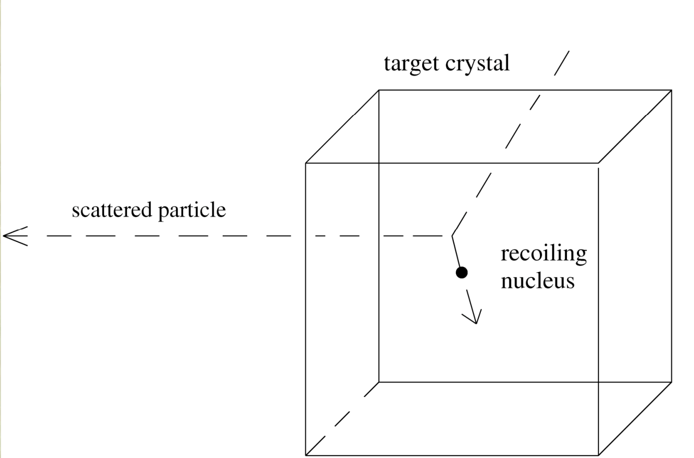
- on the particle physics side, e.g., coannihilation, threshold, or resonance (resonance) effects,
- on the cosmological side, e.g., a late entropy release or a Universe expansion rate faster at freeze-out;

✶ 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

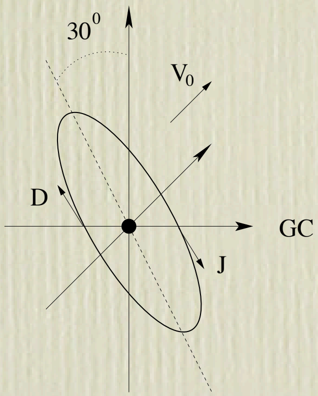
$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \int_{vmin}^{v_{max}} d\vec{v}\, f(\vec{v}) |\vec{v}| \frac{d\sigma(\vec{v}, E_R)}{dE_R}$$

WIMP-nucleus cross section

WIMP DF

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

Annual Modulation:



Direct detection: controversial experimental results

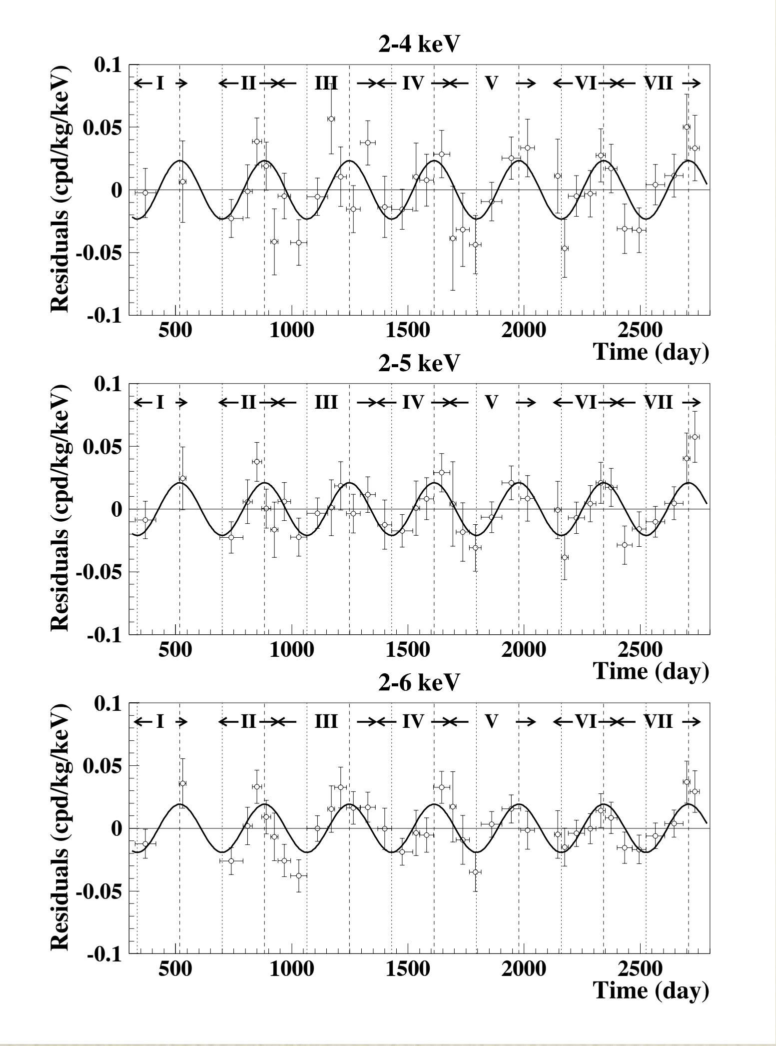
DAMA annual modulation final result, Bernabei et al., 2003:

Seven years, exposure ~ 60000 kg × day,

6.3 σ C.L. for a sinusoidally modulated rate;

LIBRA taking data at present, with analogous but larger setup.

(Signal + background) - t const. term



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

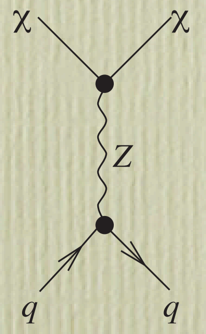
Axial-vector
(spin-dependent)

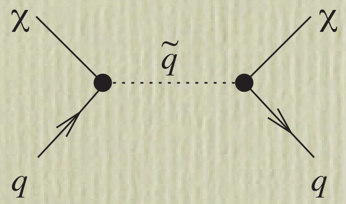
$$\mathscr{L}_A = d_q \; \bar{\chi}\gamma^\mu\gamma_5\chi\bar{q}\gamma_\mu\gamma_5 q$$

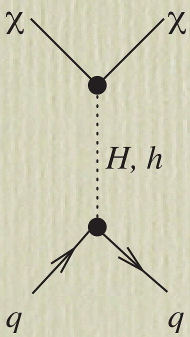
scalar
(spin-independent)

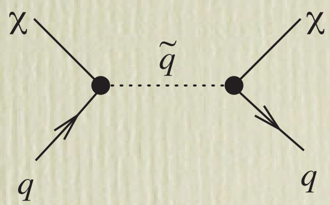
$$\mathscr{L}_{\text{scalar}} = a_q\bar{\chi}\chi\bar{q}q$$

In case of neutralinos:







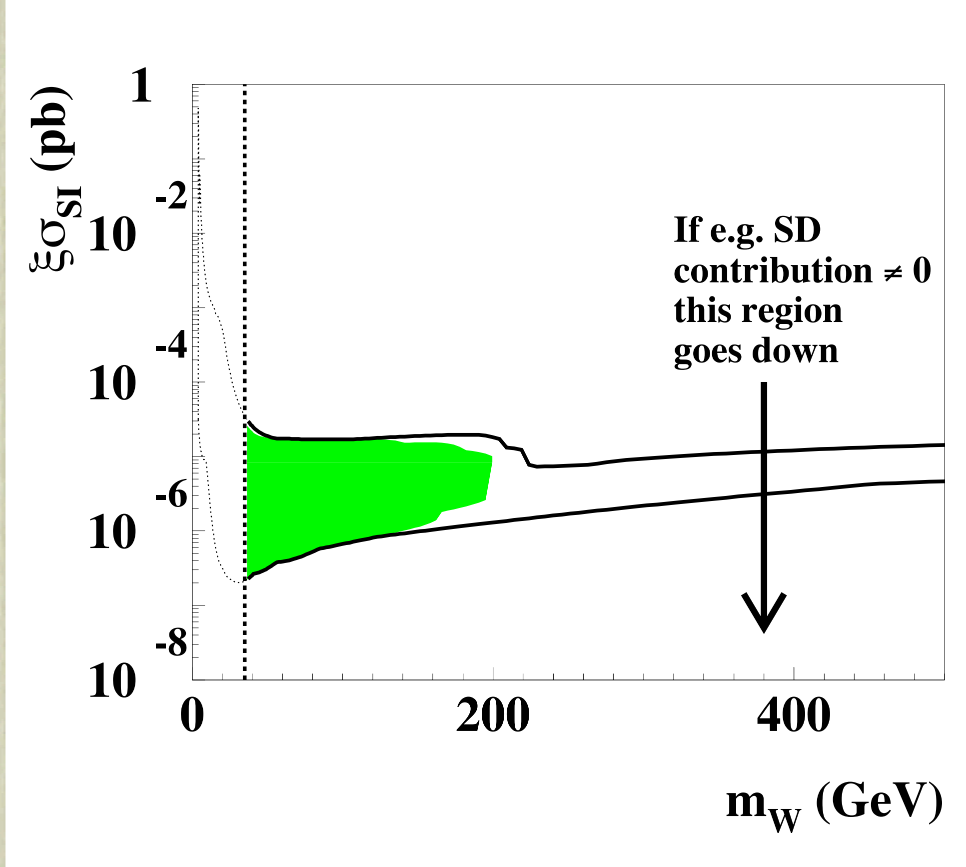


For Dirac fermions you have also: $\mathscr{L}^q_{vec} = b_q \; \bar{\chi}\gamma_\mu\chi\,\bar{q}\gamma^\mu q$

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

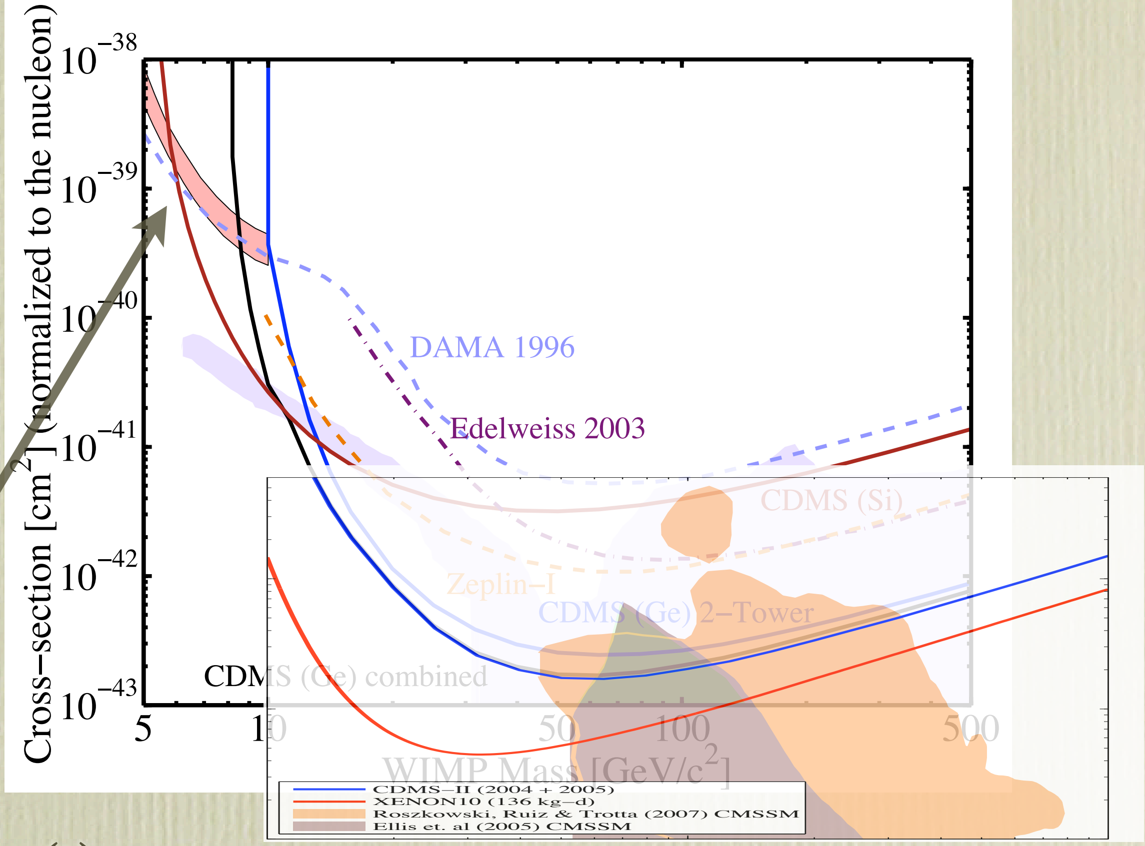
Interpretation of DAMA effect in terms of spin-independent couplings:

DAMA final result, Bernabei et al., 2003:



… not confirmed by competing experiments:

CDMS data, 2005

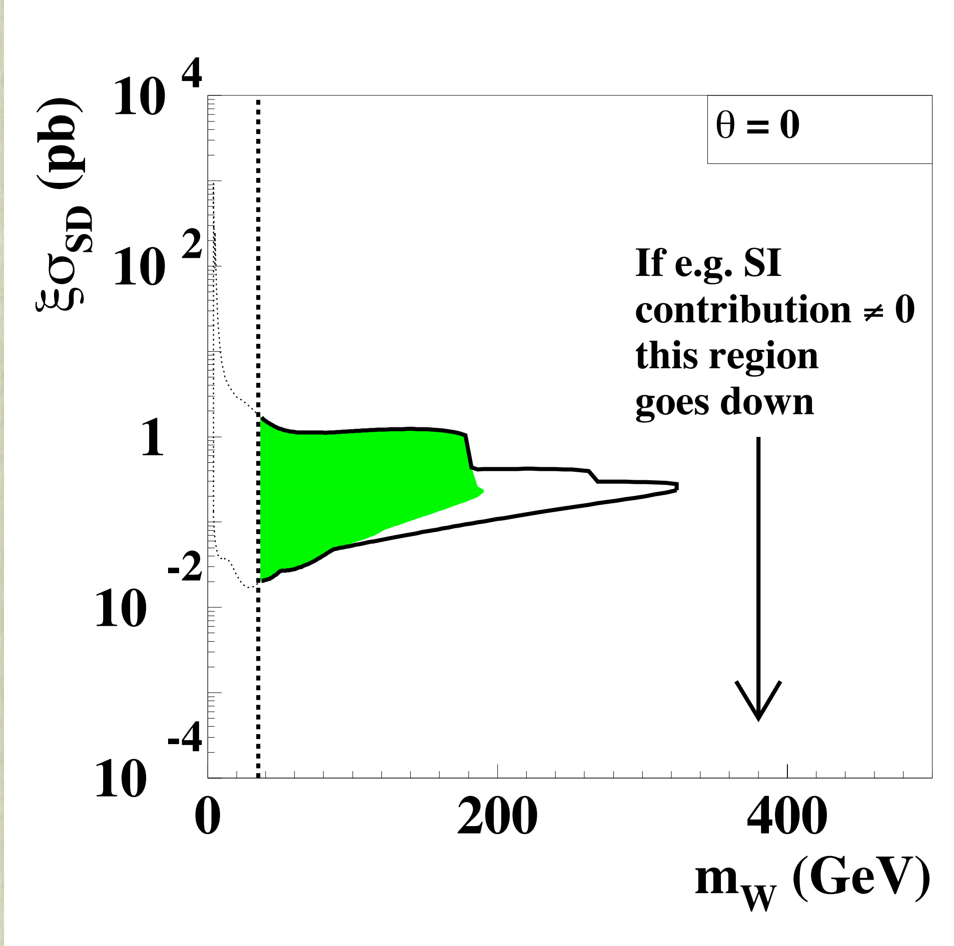


Low-mass loophole (?), Gondolo & Gelmini, 2005

Xenon-10 data, 2007

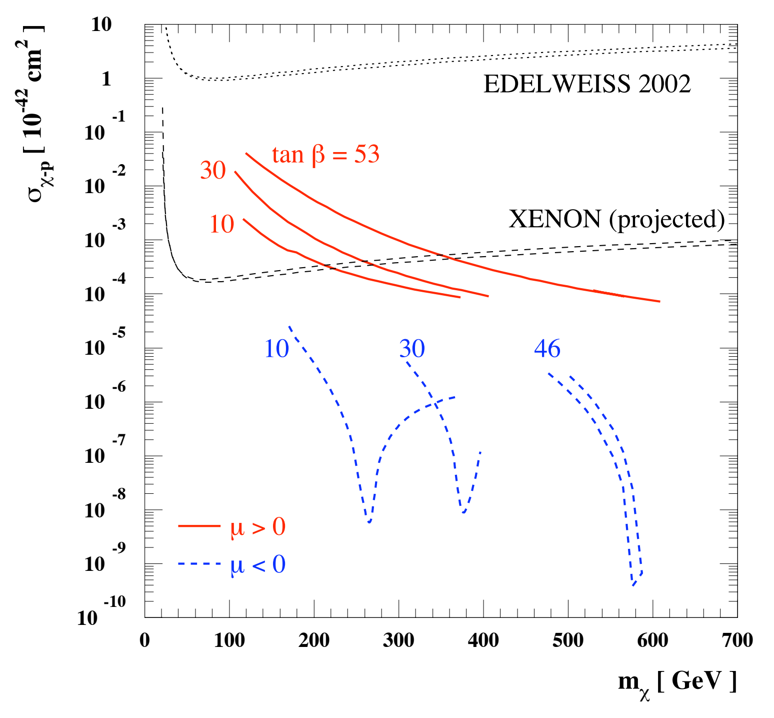
… maybe pointing to a spin-dependent contribution:

DAMA final result,
Bernabei et al., 2003:

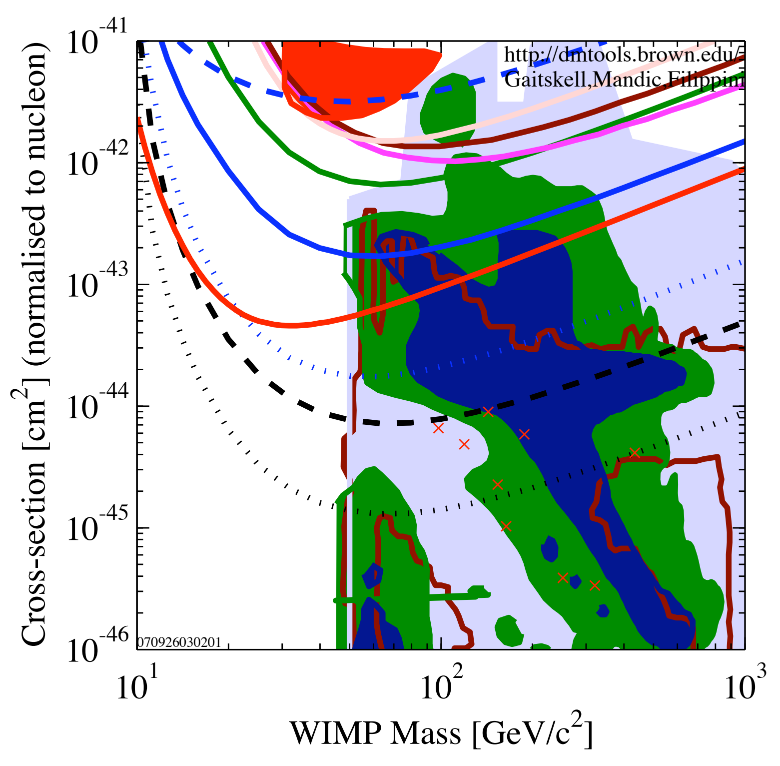


or maybe you need to refer to some other unconventional scenario (or some subtle issue)

For SUSY WIMPs, predictions for the coherent term look promising (while SD effects are usually negligible):

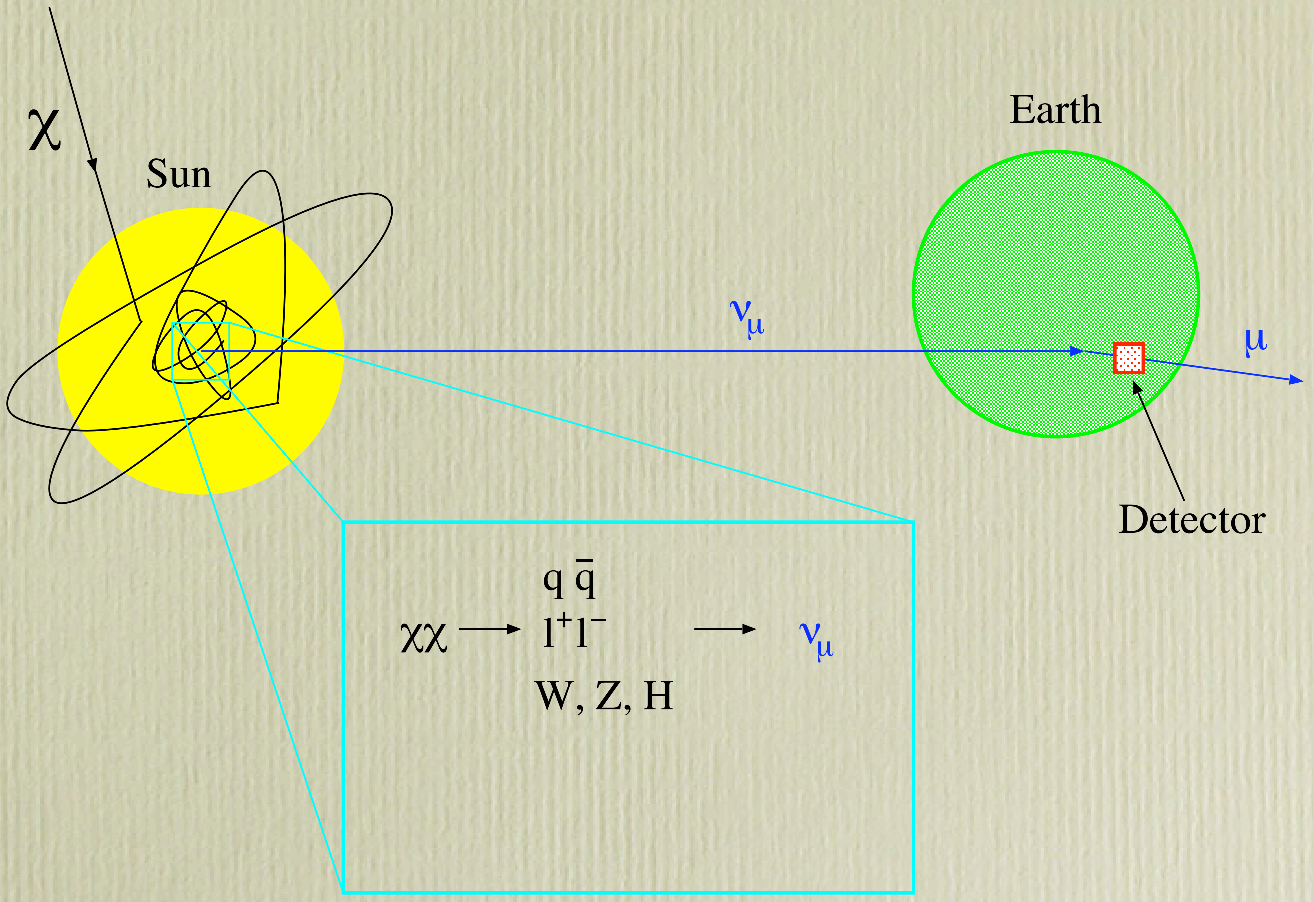


CMSSM, Edsjo, Schelke & P.U., 2004



MSSM, current + projected sensitivies

Searches with neutrino telescopes



extra-clean signature!

Searches with neutrino telescopes

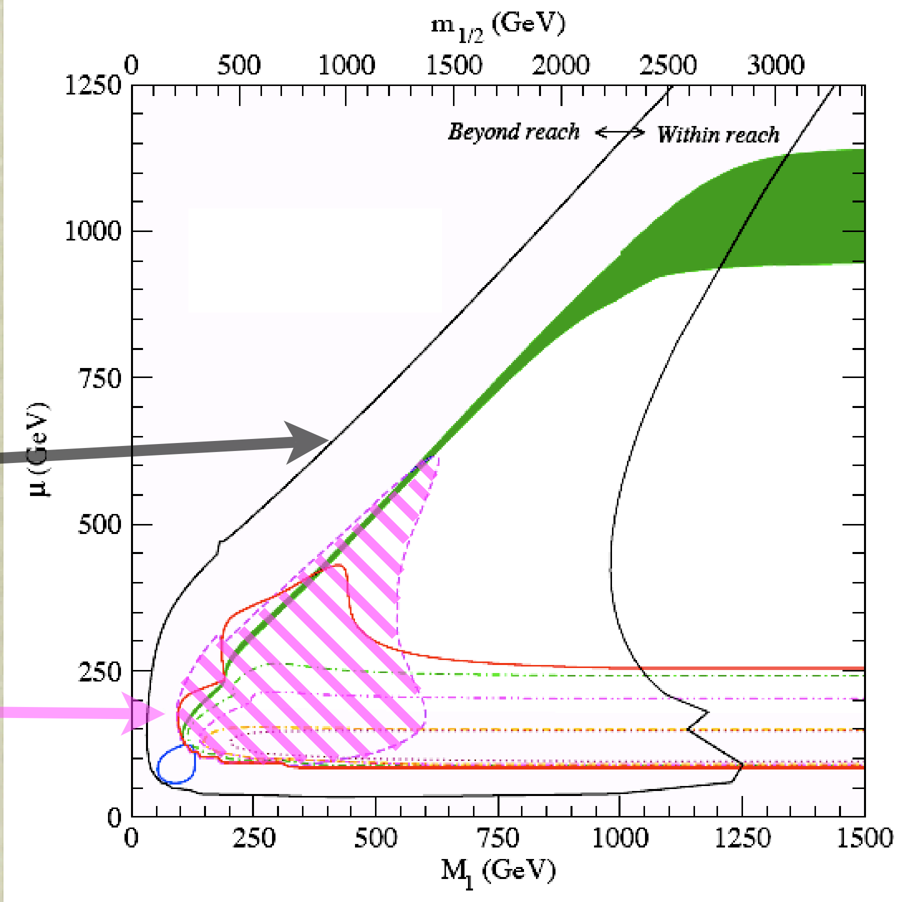
Significant limits at present (Baikal, Super-K, Amanda) large sensitivity improvements for the future (IceCube, Antares, Nemo, KM3Net, ect.).

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).

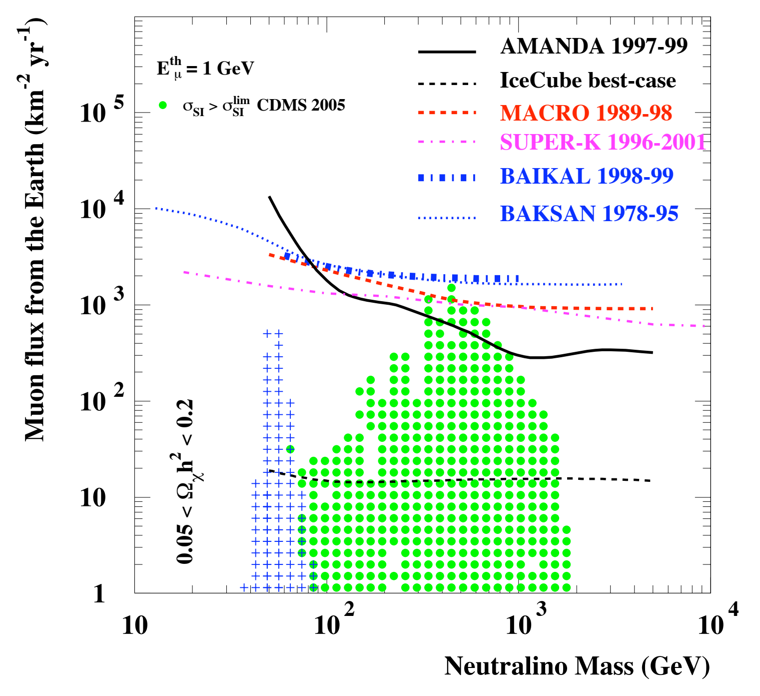
SI versus SD?
the standard lore is
that SI wins



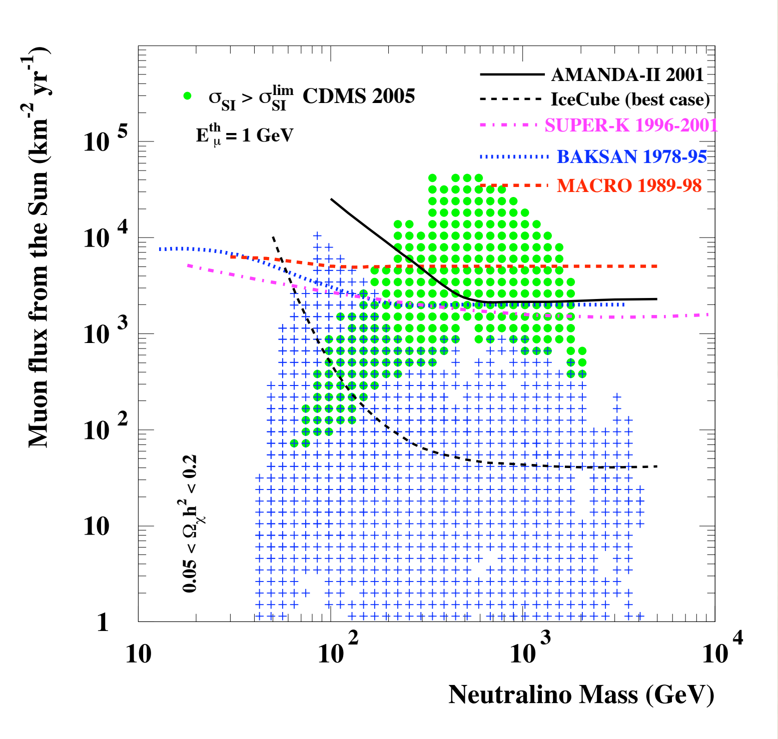
1-ton
detector

IceCube

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



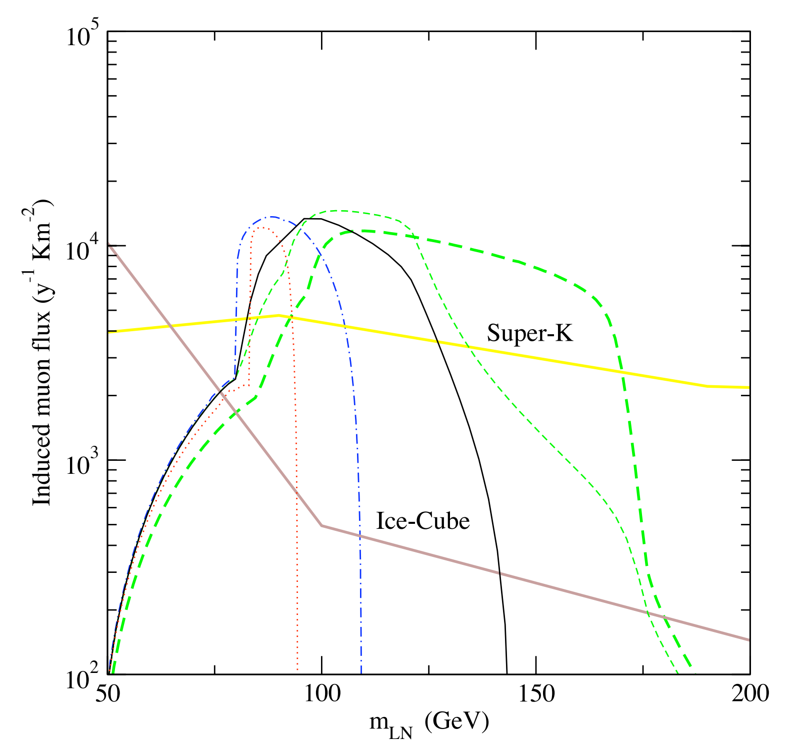
Flux from the Earth



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

Annihilations in DM halos:

search for those terms with small (or well-constrained) conventional (i.e. background) astrophysical components:

as prompt yields:

antimatter gamma-rays neutrinos

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

Synchrotron Inverse Compton

Bremsstralung

S-Z effect Heating

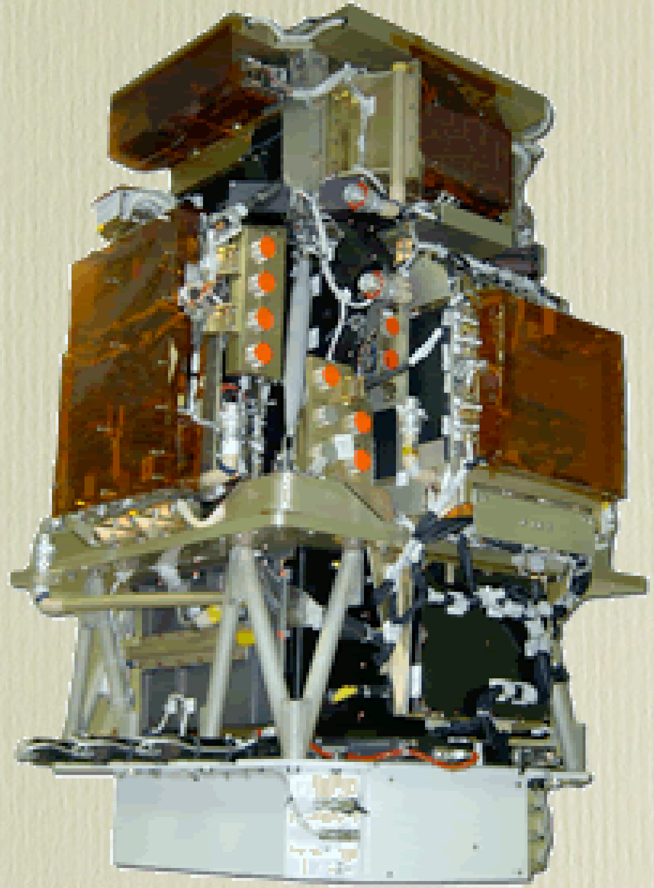
Signatures:

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

Fitting a featureless excess (a few attempts appeared in the last few years) may set a guideline, but is not conclusive.

Antimatter Searches



Pamela on orbit since
July 2006

in 3 yr:
* > 3×10^4 antiprotons
* > 3×10^5 positrons
* p, e^-, He, light nuclei

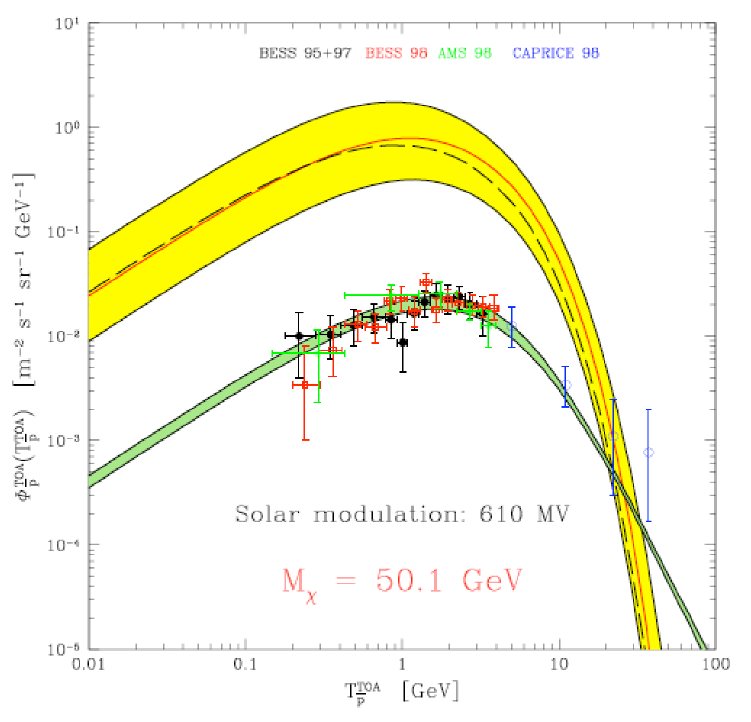
+ balloon experiments + AMS

Antiprotons

Uncertainties on the background and no clear excess in current data; larger data sample may improve the situation.

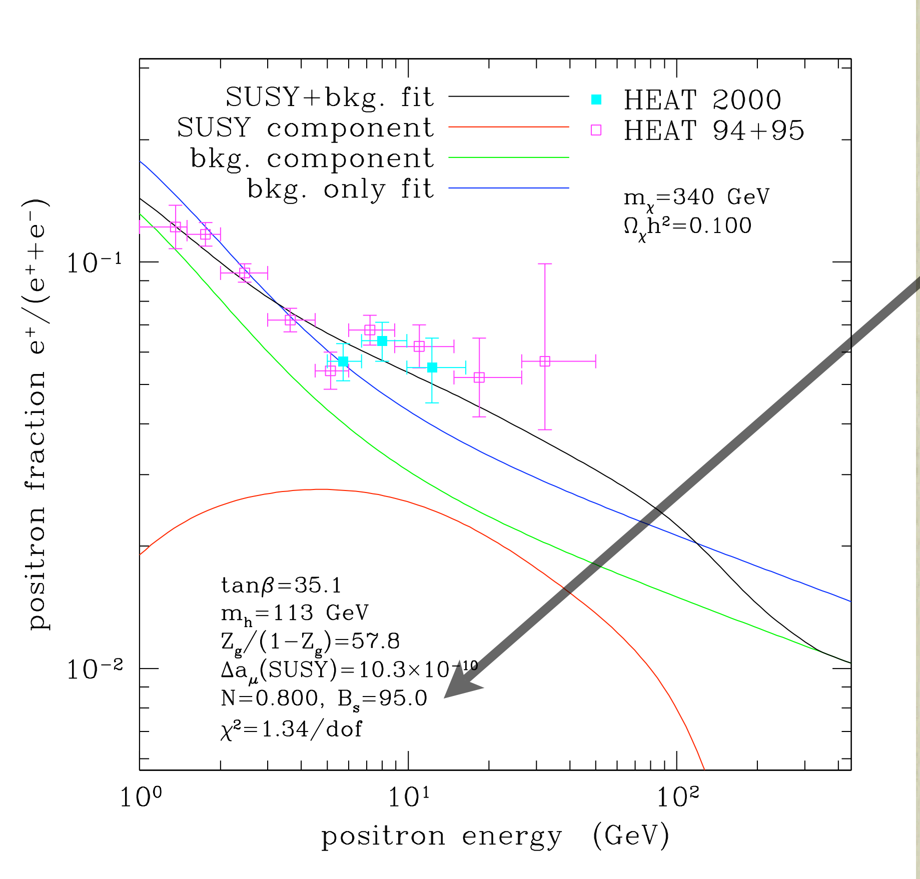
In a vanilla WIMP model (bulk LSP?), it is the channel with largest signal/background ratio: do not forget about it when stretching your model to fit other datasets!

E.g.:
Bergström et al. ruling out de Boer et al. "fit" of EGRET "excess" in the galactic ϒ-ray flux



Positrons

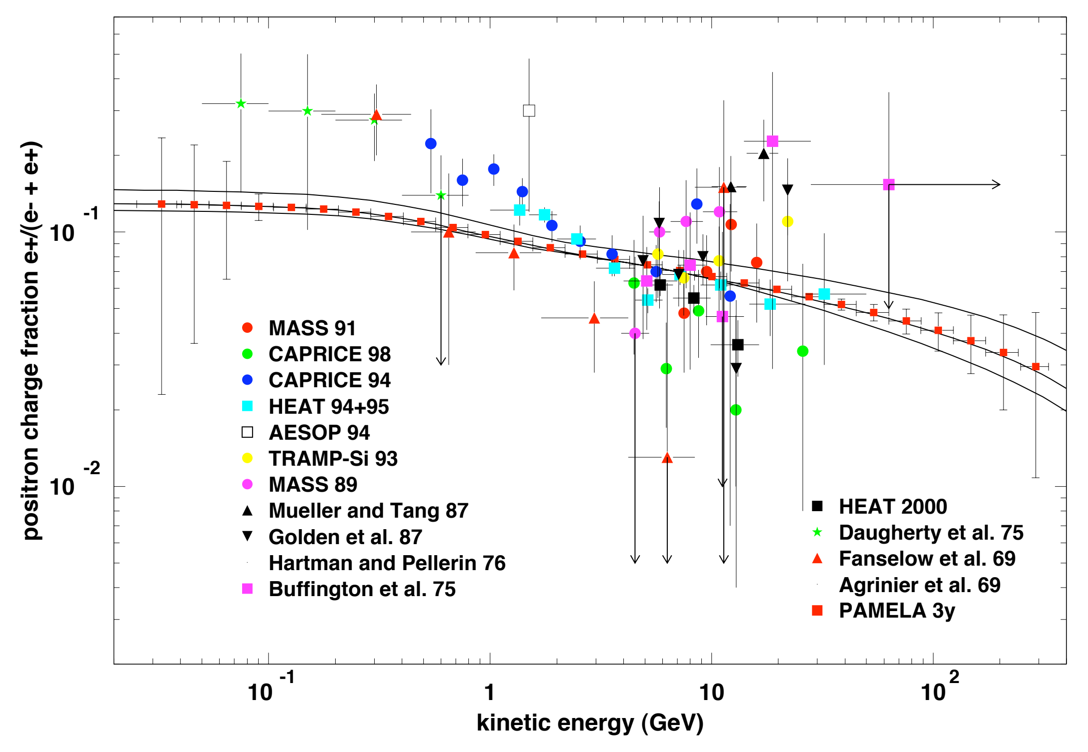
HEAT excess



"Boost factor" from substructures (?)
see more recent analyses,
e.g., Lavalle et al.,
2006 & 2007

In KK DM models
this channel is
particularly interesting

(see also AMS-02) fit by SUSY DM,
e.g., Baltz et al., 2002



Much better statistics with PAMELA,
Lionetto, Morselli & Zdravković, 2005

Searches with gamma-ray telescopes

The next-generation of space-based telescopes is almost ready for launch:

GLAST

launch on
february 5, 2008

+ Agile (in orbit and working), AMS (...)

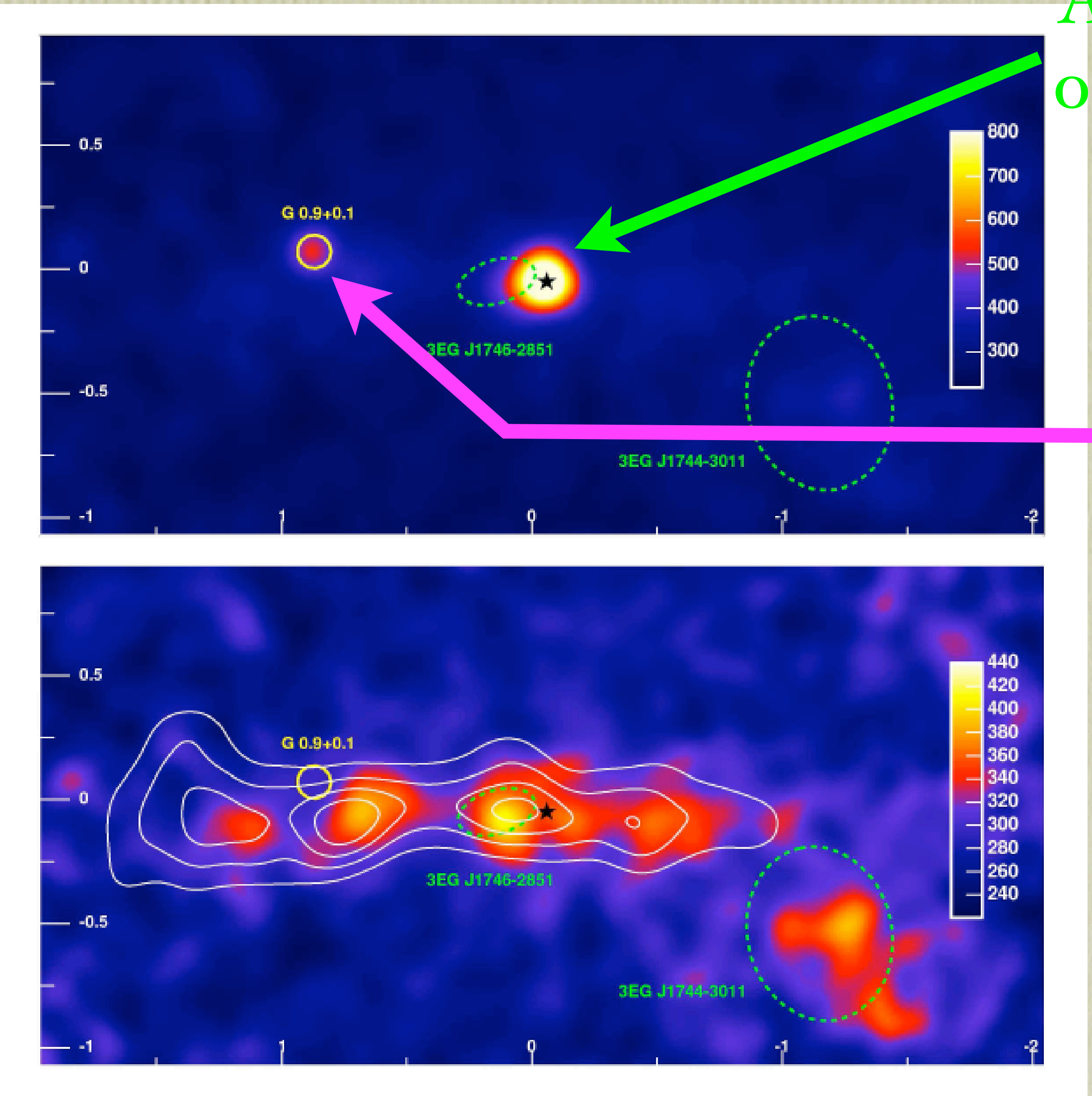
The new era of gamma-ray astronomy with ground-based telescopes has already produced spectacular results:

HESS telescope in Namibia, fully operative since 2003

+ Magic, Stacee, Veritas, ...

Tens of new TeV sources reported in the latest years, compared to the 12 sources known up to 2003

First VHE map of the Galactic Center by HESS:

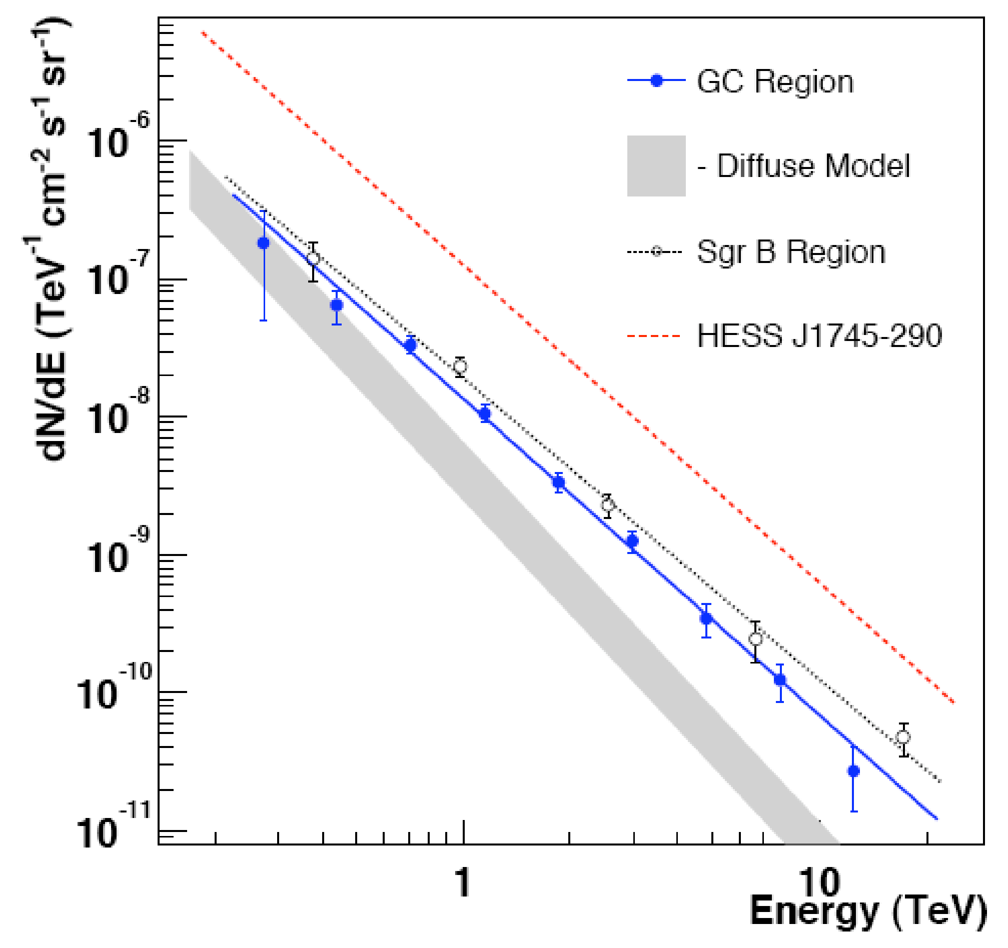


A source at the position of the central BH, Sgr A*

A new plerion discovered

+ diffuse emission from the GC region

Spectral features of central source/excess:



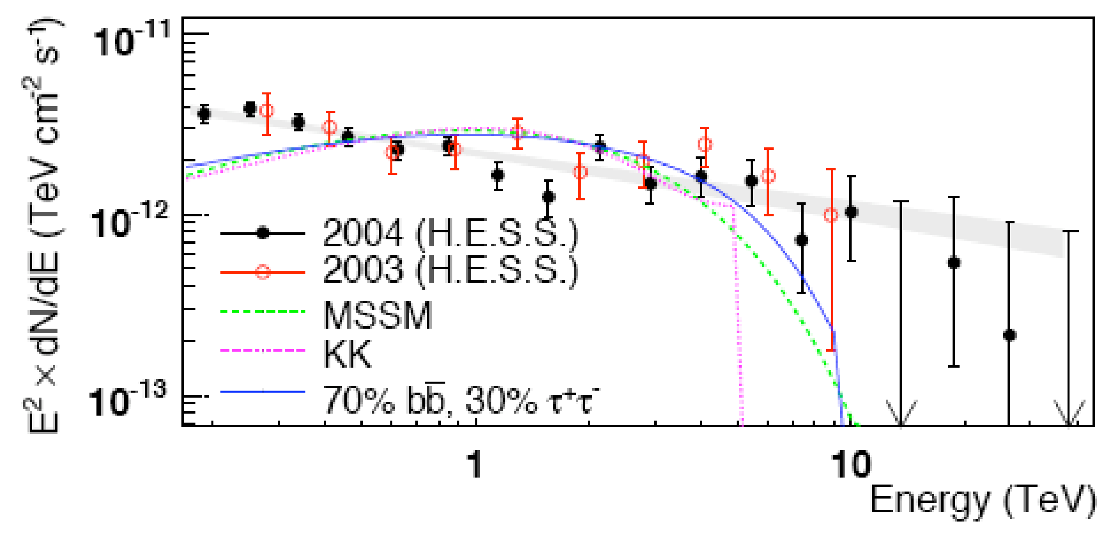
Aharonian et al, 2006

Single power law
(Γ ~ 2.2) from

~150 GeV to ~30 TeV

Tentatively:
the central source is a
Sn remnant and the
diffuse emission from
in the central region is
due to protons injected
in the explosion

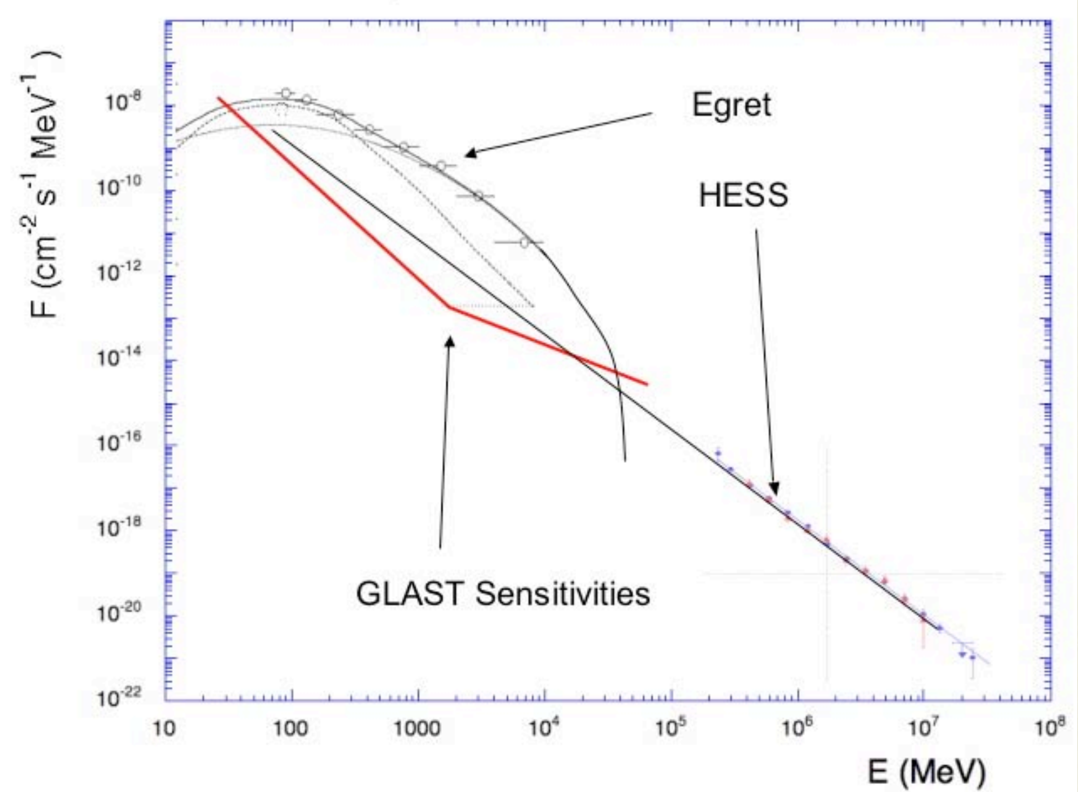
The GC may not be any longer the best bet for indirect dark matter detection!



Aharonian et al., 2007

it is ***very hard*** to support the hypothesis that the central source detected by HESS & MAGIC is due to WIMP annihilations: a standard astrophysical source, i.e. large background for an eventual WIMP component!

it might still be that a DM component could be singled out, e.g. the EGRET GC source (?):



a DM source can fit the EGRET data; GLAST would detect its spectral and angular signatures and identify without ambiguity such DM source!

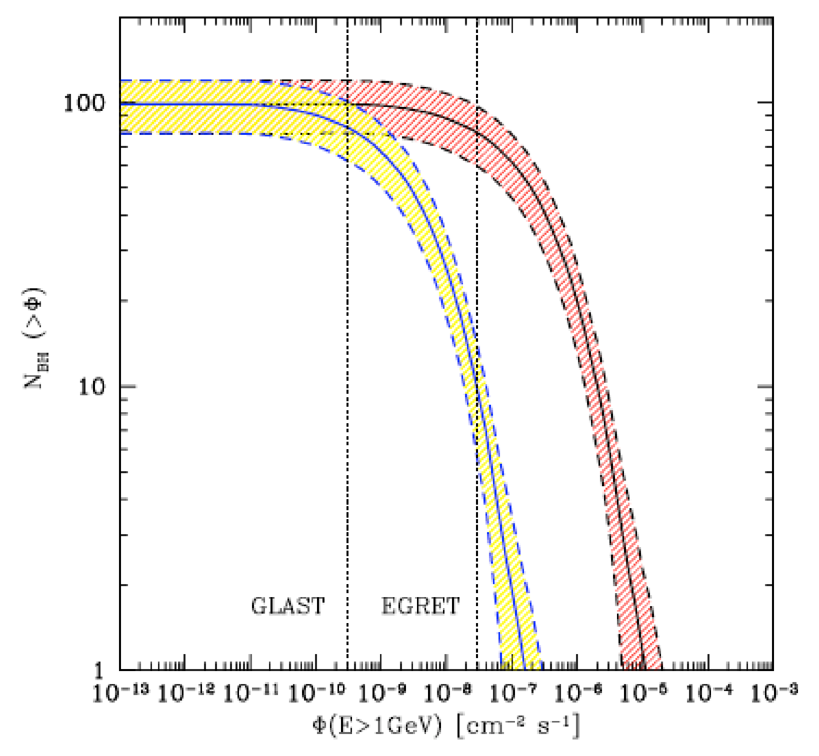
Morselli 2005; analysis in Cesarini, Fucito, Lionetto, Morselli & P.U., 2004

... or we may have to rely on alternative targets; recent proposals include:

Intermediate-mass BHs, carrying mini-spikes

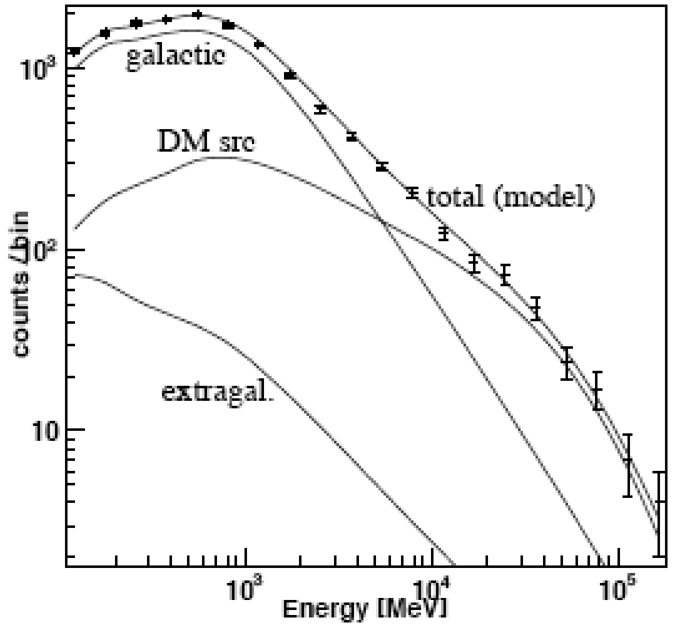
Tens of sources with identical spectrum!

Cross-correlate also with other detection channels.



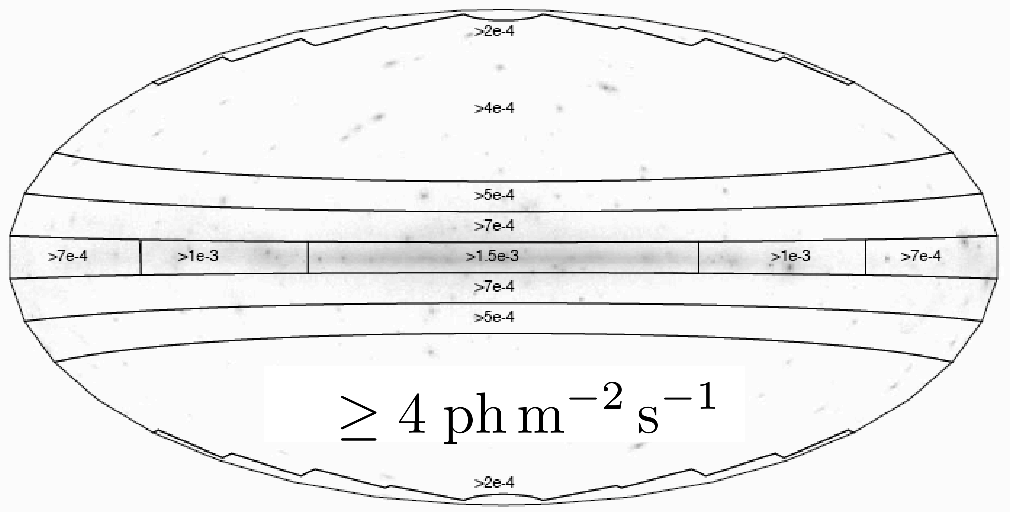
Bertone, Zenter & Silk, 2005

GLAST and DM point sources:



(b)$\phi = 2 \times 10^{-2}$ ph m^{-2} s^{-1},
m_χ = 150GeV, $b\bar{b}$, (l, b)=(50, 0)

Spectral discrimination



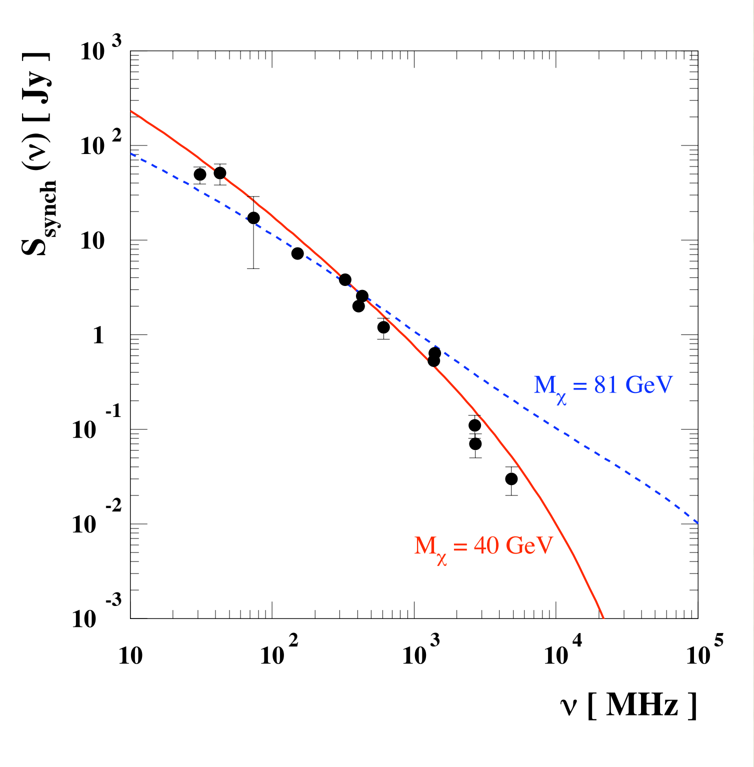
$\geq 4\,\mathrm{ph\,m^{-2}\,s^{-1}}$

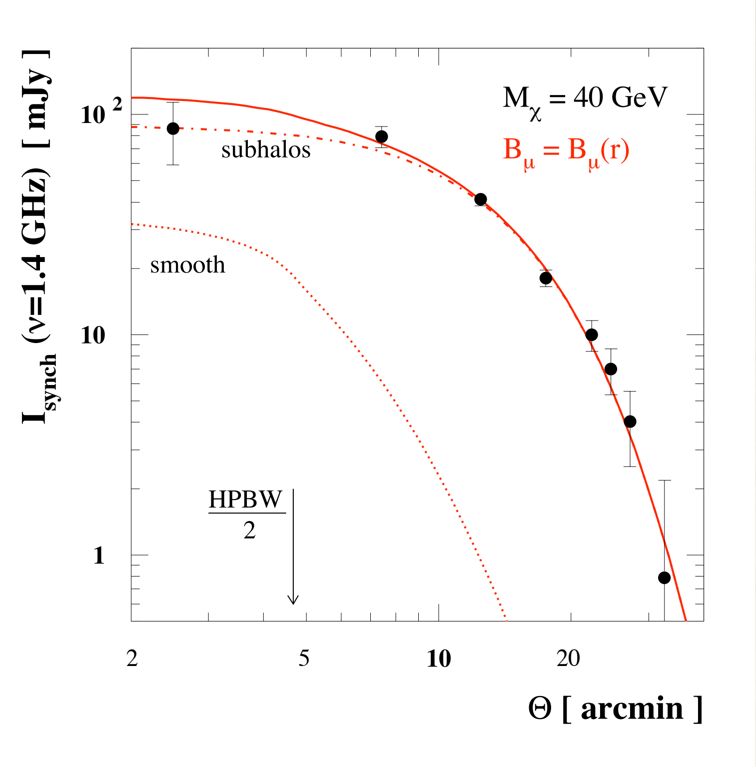
Sensitivity map
(flux above 20 MeV)

Bertone et al., 2007

Multiwalength detection of DM:

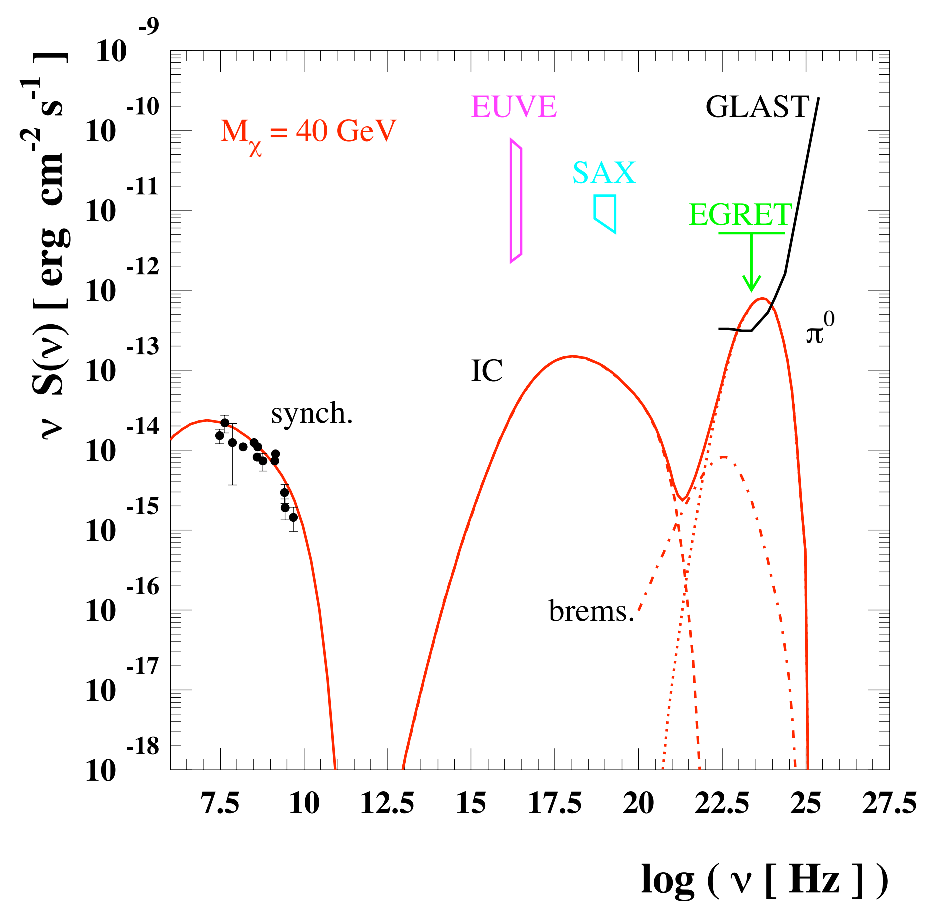
E.g., the Coma radio halo can be fitted in spectrum and angular surface brightness by a DM induced component:





Colafrancesco, Profumo & P.U., 2006

and in these given setups we predict also:



an associated gamma-ray flux within the sensitivity of GLAST

What about tracing WIMP annihilations through the Sunyaev-Zel'dovich Effect?

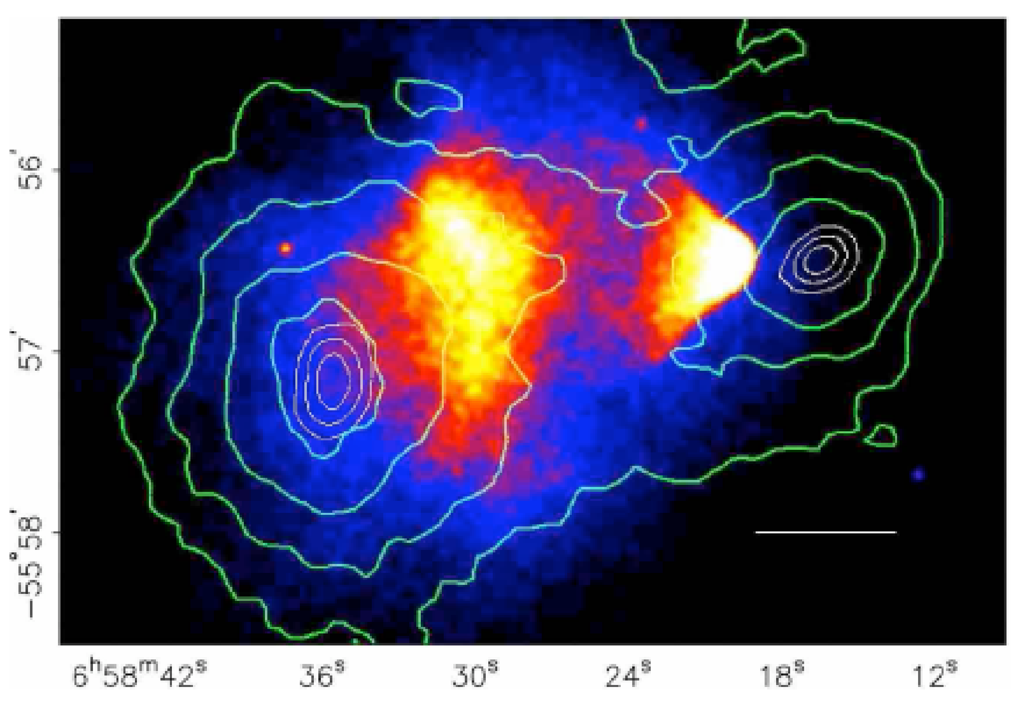
Colafrancesco, 2004

SZ: Compton scattering of CMB photons on the electron/positron populations in clusters. Net effect: low energy photons are "kicked up" to higher energy, hence there is a low frequency decrement and high frequency increment in the CMB spectrum.

In general, a large SZ effect is expected (and detected) in connection to the thermal gas in clusters, it may be hard to fight against this "background" in standard system.

What about systems having gone through a recent merging, with thermal components being displaced from the DM potential wells?

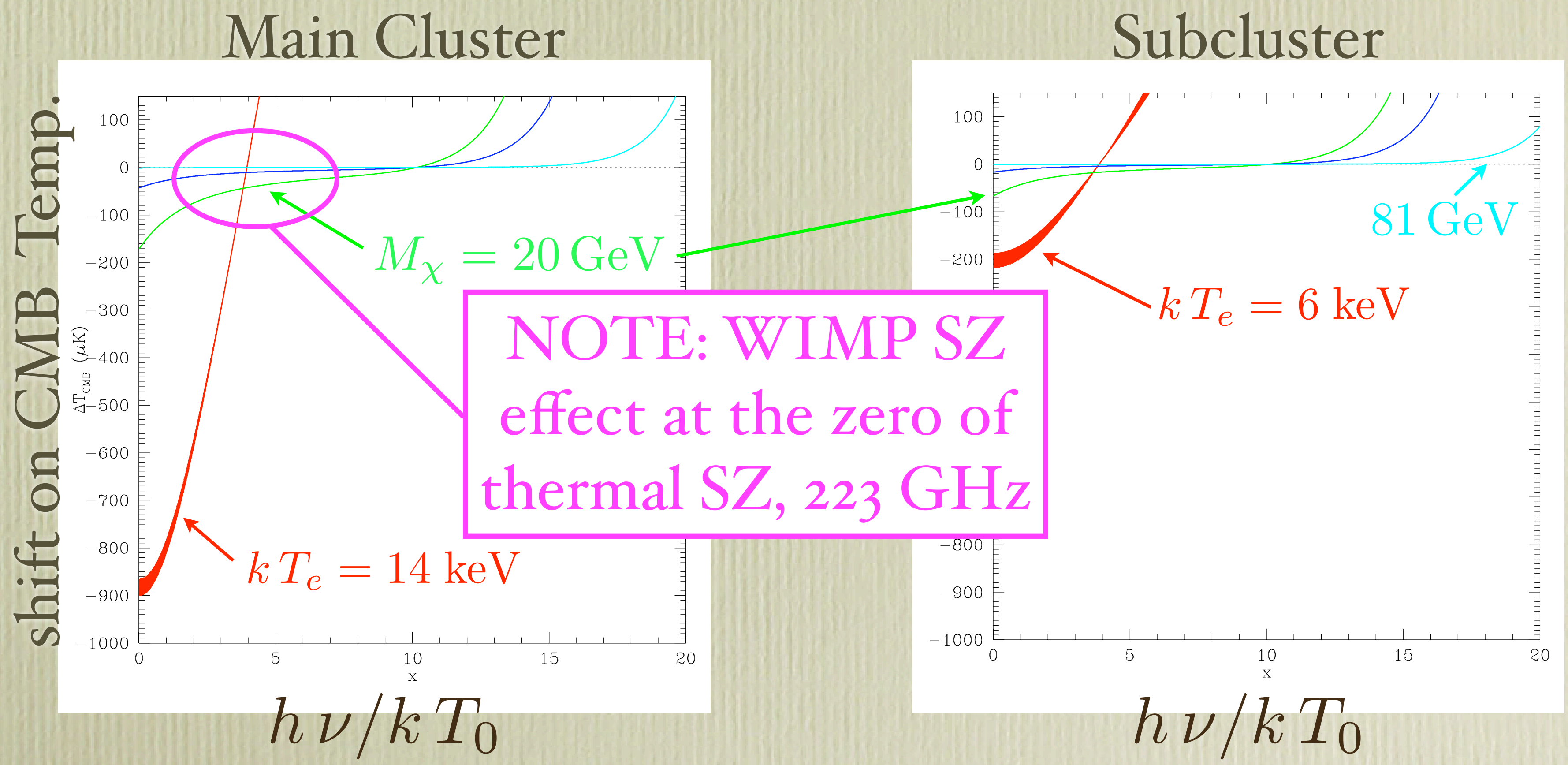
Colafrancesco, de Bernardis, Masi, Polenta & P.U., 2007 a remarkable example of this kind: 1E0657-558 (the Bullet Cluster, see the talk by D. Clowe) at z=0.296



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

A supersonic cluster merger occuring nearly in the plane of the sky, with clean evidence for the separation of the collisionless DM from the collisional hot gas.

SZ effect in the simplified picture with two spherical DM halos (NFW profile) plus two isothermal gas components of given temperature (shock front neglected):



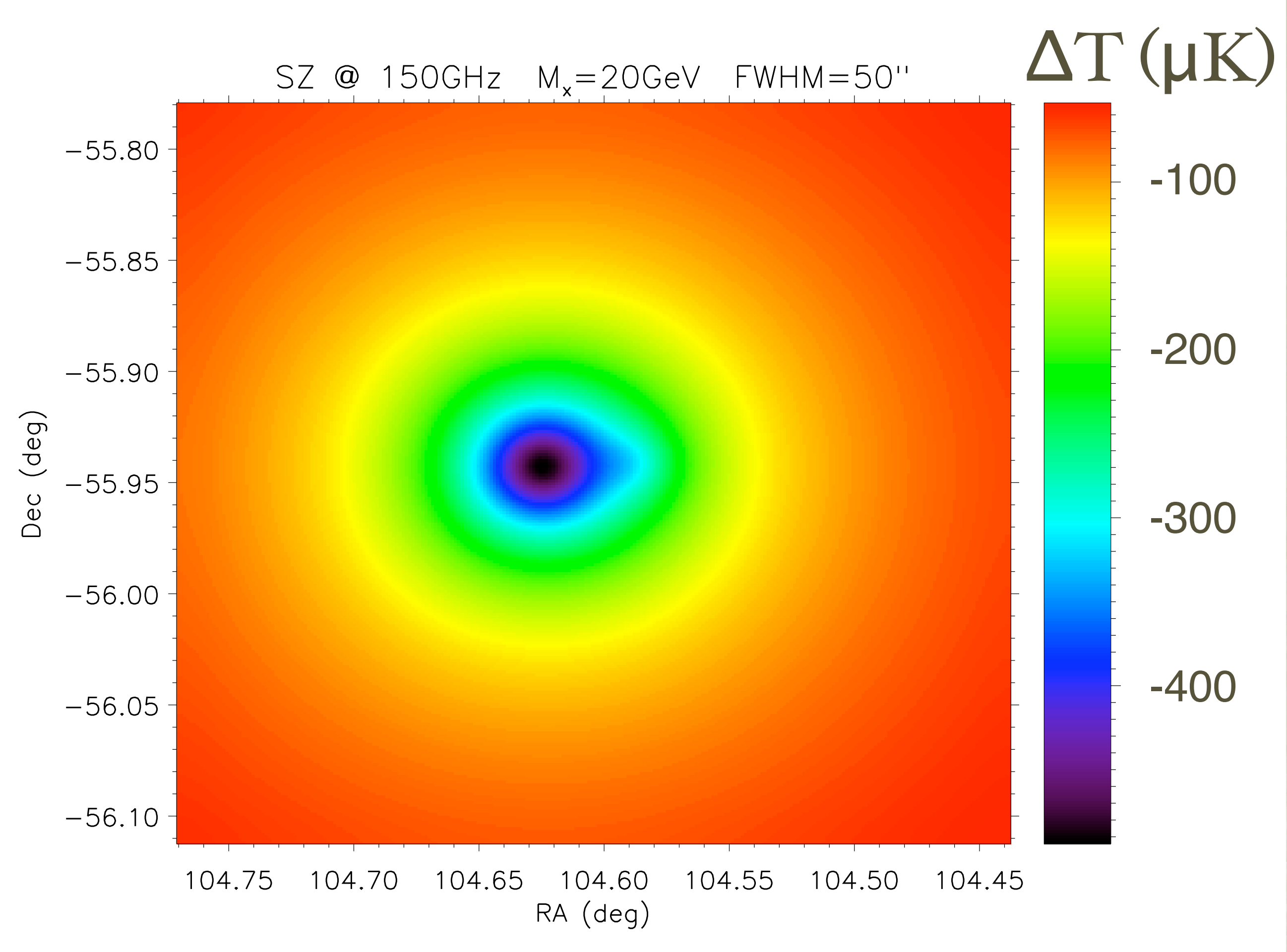
Main Cluster

Subcluster

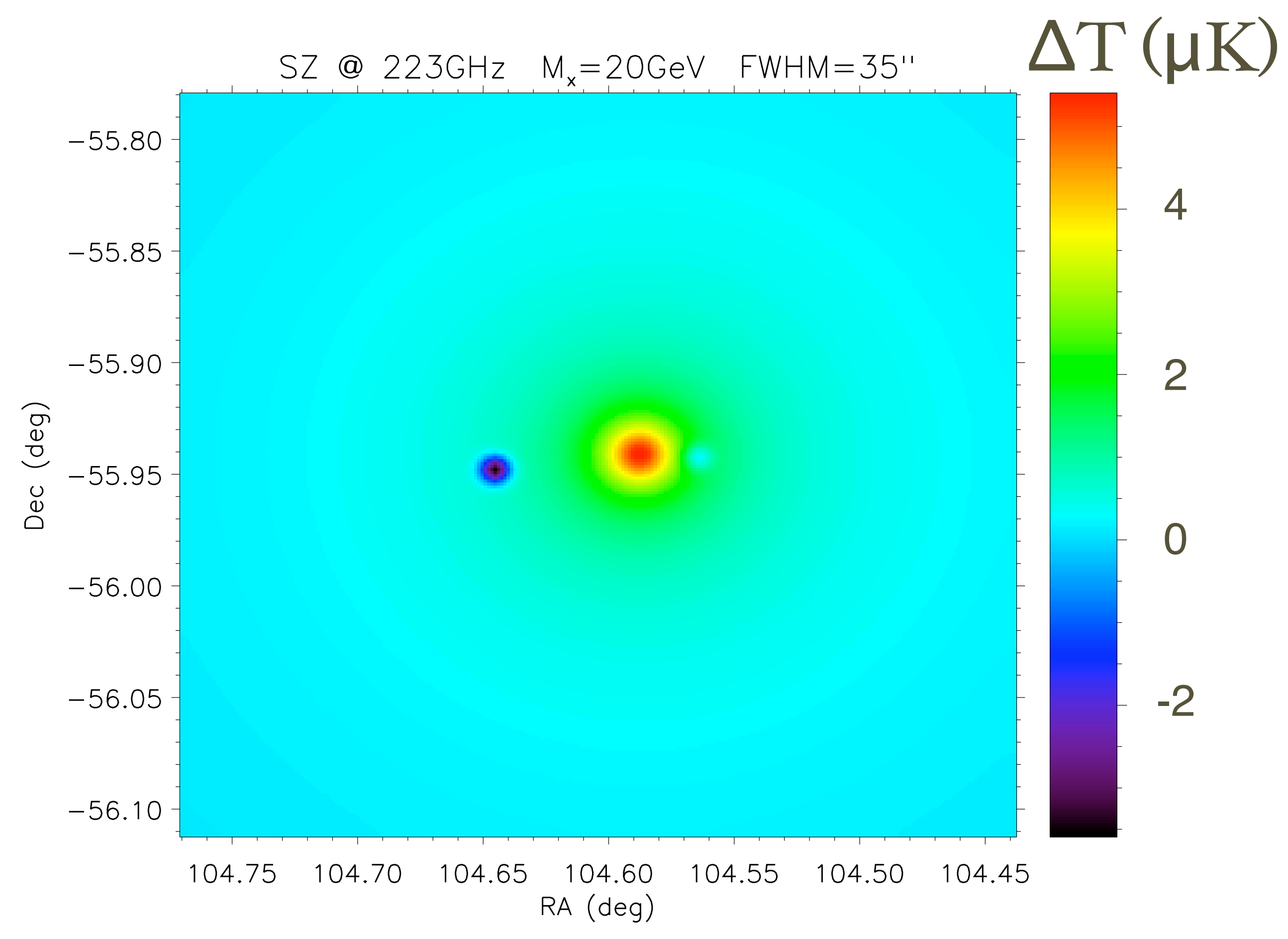
NOTE: WIMP SZ effect at the zero of thermal SZ, 223 GHz

Colafrancesco, de Bernardis, Masi, Polenta & P.U., 2007

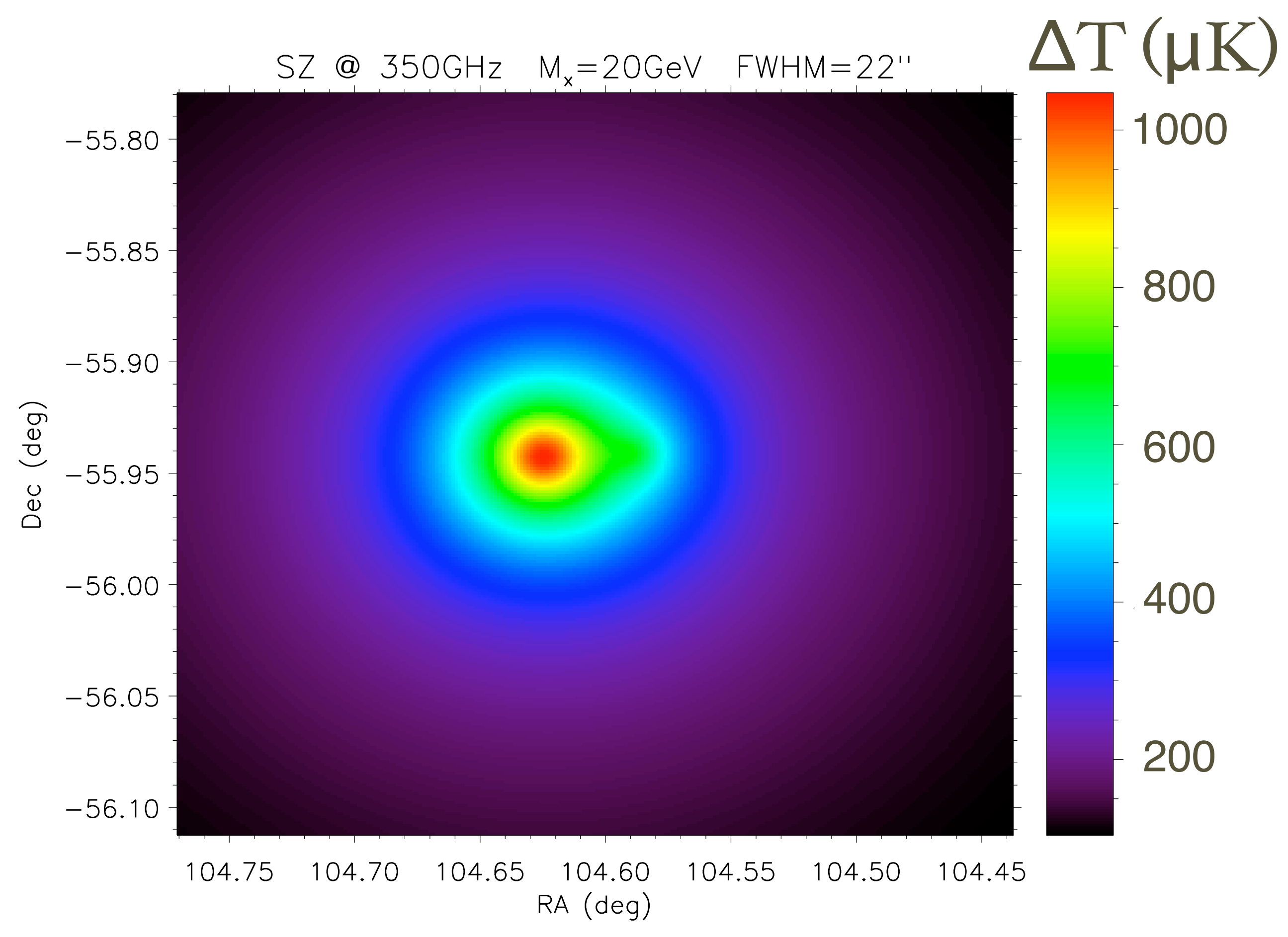
SZ map at 150 GHz:



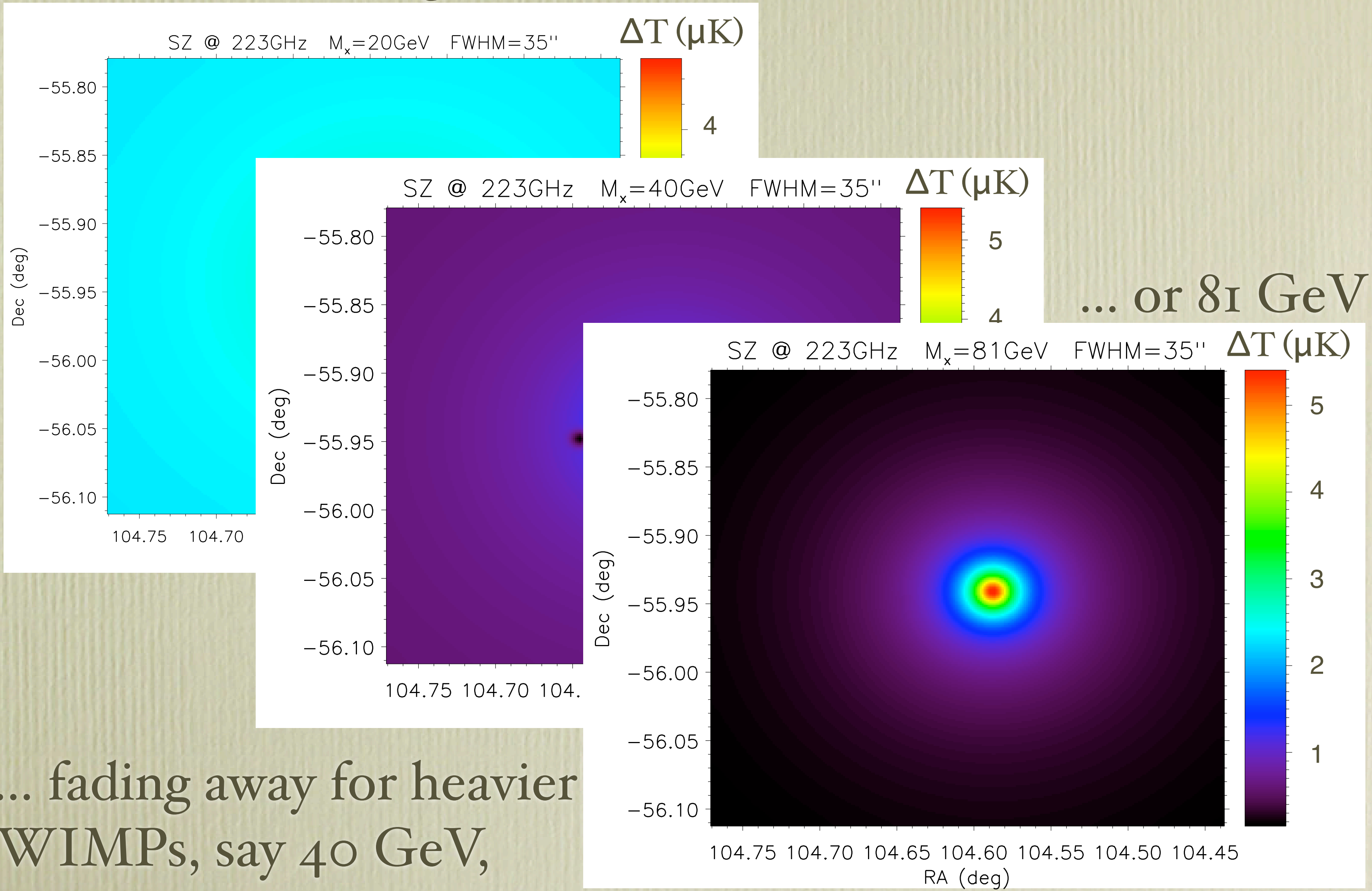
SZ map at 233 GHz:



SZ map at 350 GHz:



A light WIMP, say 20 GeV, gives a detectable (though small) effect:



... fading away for heavier WIMPs, say 40 GeV,

... or 81 GeV

In case of light WIMP DM, we propose this as a (tough) target for OLIMPO, maybe for the South Pole Telescope, the Atacama Cosmology Telescope, APEX, ...

To achieve detection a number of issues needs to be addressed: *contamination, bias and/or noise*, from CMB anisotropies, emission of galaxies and AGNS along the line of sight, temperature distributions in the hot gas, kinematic SZ, atmospheric noise ...

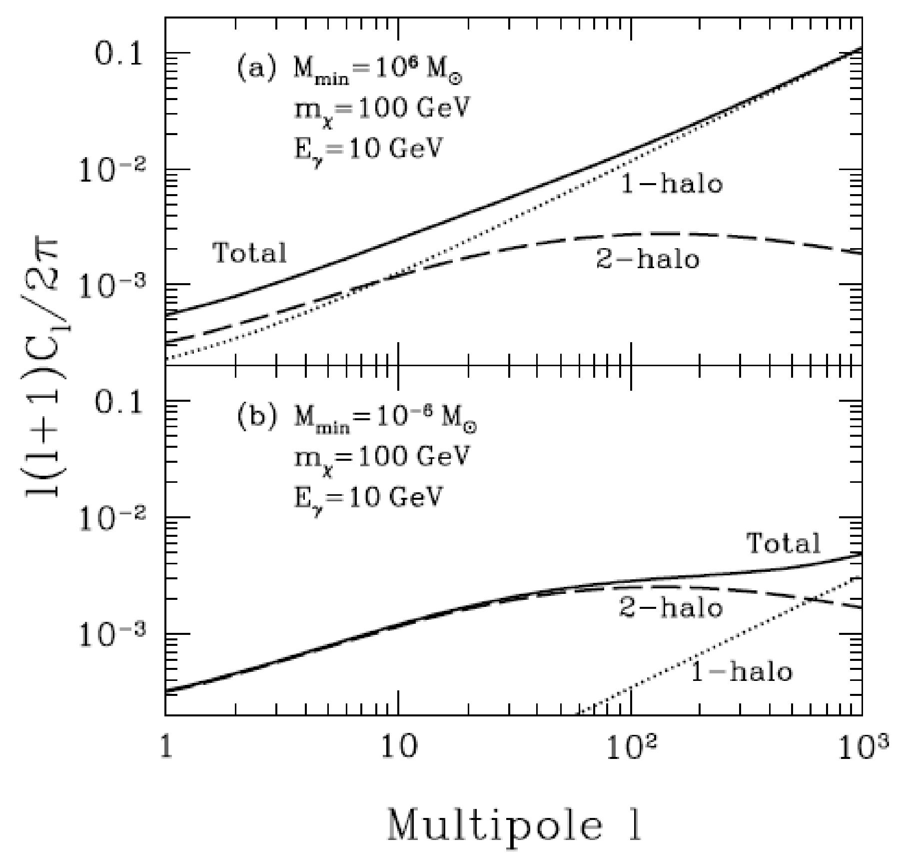
... not to mention uncertainties in the estimate for the signal. *Still, this is possibly a unique probe of the nature of DM, deserving further investigations.*

The Bullet cluster is too far away for a detection with GLAST, while the radio flux could be marginally detectable with LOFAR. Are there any such systems at lower z and thus suitable for a multifrequency study?

Anisotropy in the gamma-ray background:

WIMP contribution
to the extragalactic
gamma-ray background

Characteristic anisotropy
pattern which GLAST
could identify

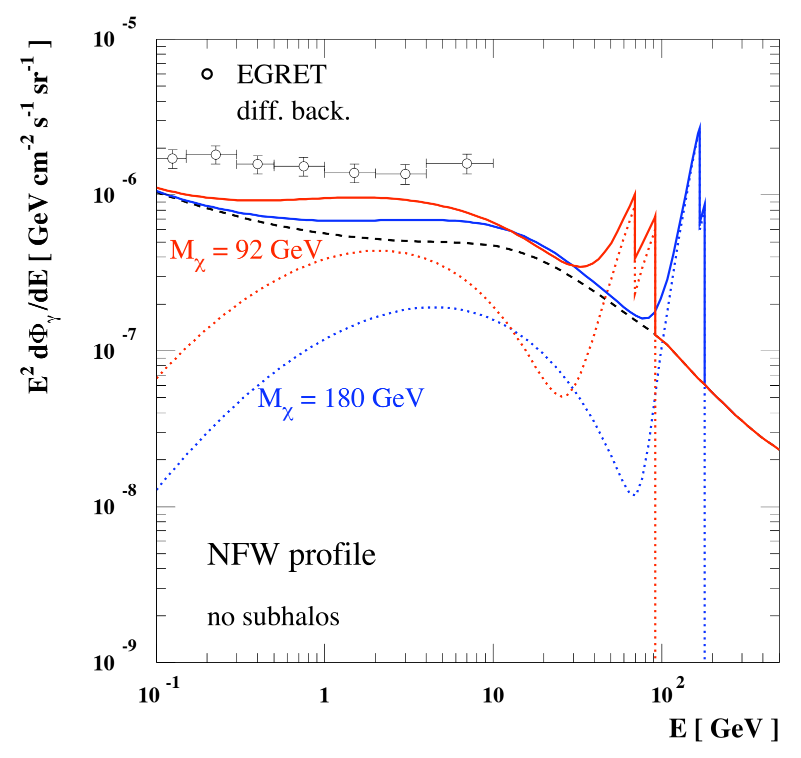


Ando & Komatsu, 2006

Last but not least, the Holy Grail for indirect detection:

the monochromatic gamma-ray signal

e.g., in the
extragalactic γ-ray
background;
P.U., Bergström,
Edsjö & Lacey, 2002



Smoking-gun signature, as well as direct measurement of the WIMP mass.

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.:

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

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

over T:

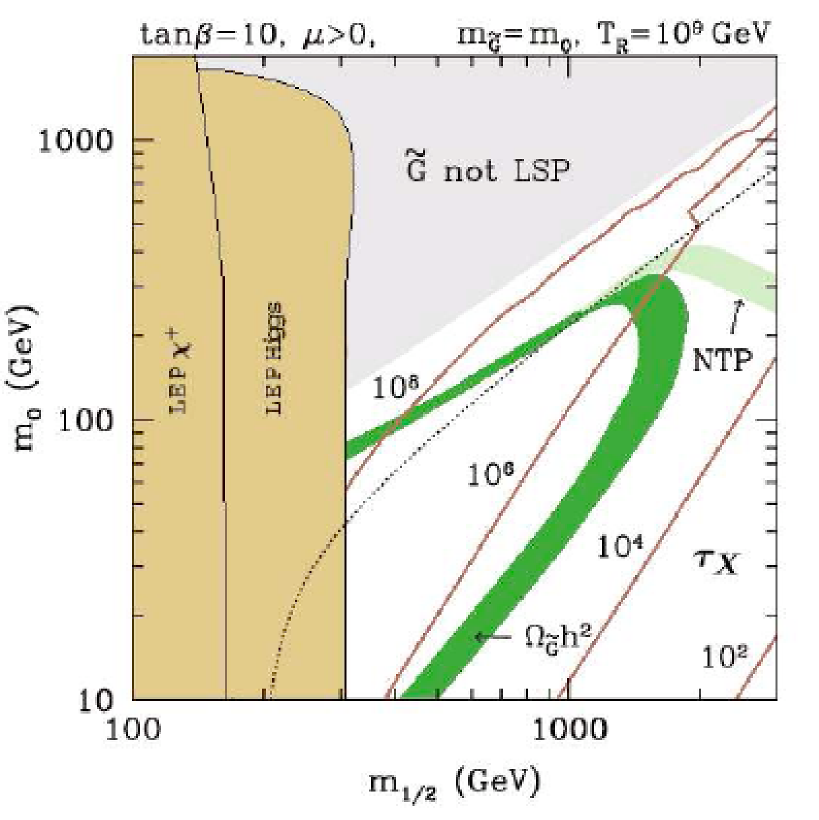
$$\Omega_{\tilde{G}}^{TH} h^2 \simeq 0.2 \left(\frac{100\text{GeV}}{m_{\tilde{G}}} \right) \left(\frac{m_{\tilde{g}}}{1\text{TeV}} \right)^2 \left(\frac{T_R}{10^{10}\text{GeV}} \right)$$

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:



Cerdeno, Choi, Jedamzik, Roszkowski, & Ruiz de Austri, 2006

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

Conclusions

The identification of dark matter is one of the most pressing targets in Science today.

The picture from astrophysical and cosmological observations is getting more and more focussed.

There is a variety of DM candidates on the market, pointing unfortunately in orthogonal directions.

In a (fair) subset of the viable DM scenarios detection look feasible in the near future,
with numerous and complementary techniques on the market.