Dark Matter

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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 rich experimental program under way and insights on the DM problem

Discovery and classical tests

1933: the discovery of DM in galaxy clusters

Fritz Zwicky measures the proper motion of galaxies in the Coma cluster

Credit: NASA, K. Peak

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

Discovery and classical tests

1933: the discovery of DM in galaxy clusters

The existence of DM claimed on the basis of a dynamical mass estimate derived using the Virial Theorem:

$$\langle V \rangle + 2\langle K \rangle = 0 \qquad \text{with:}$$

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

$$\langle V \rangle = -\frac{N^2}{2} G_N \frac{\langle m^2 \rangle}{\langle r \rangle}$$ average potential energy due to $N^2/2$ pairs of galaxies

By measuring the velocity dispersion and the geometrical size, Zwicky estimated the total mass associated to the N galaxies:

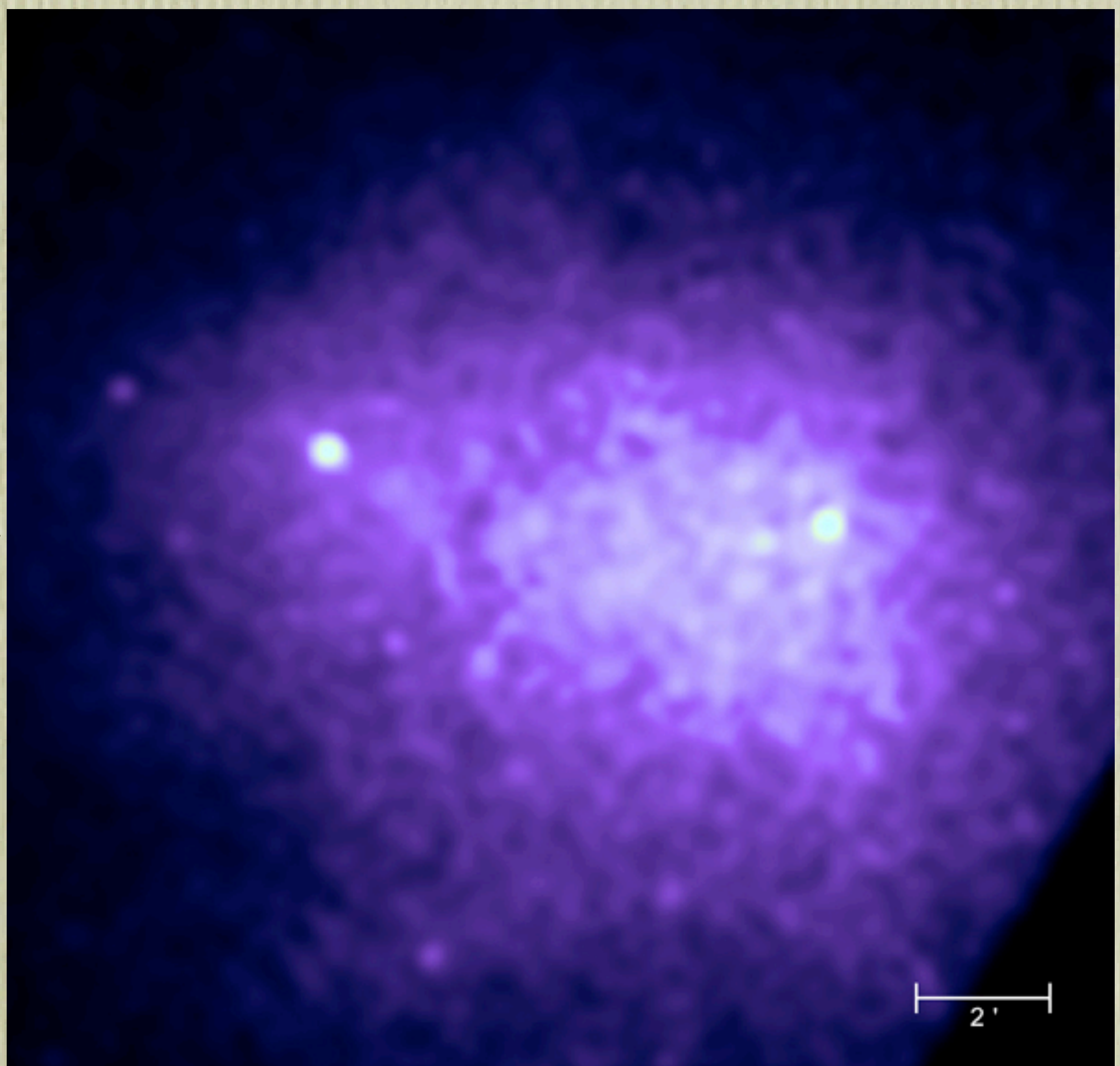
$$M \equiv N \langle m \rangle \sim \frac{2\langle r \rangle \langle v^2 \rangle}{G_N} \quad \Longrightarrow \quad \frac{M}{L} \sim 300h \frac{M_\odot}{L_\odot} \quad \Longrightarrow \quad \Omega_M \simeq 0.2 - 0.3$$

M/L is about the same one obtains with more modern dynamical approaches; in the last step, extrapolating a value for the Universe luminosity, one finds a result in fair agreement with much robust cosmological probes ($\Omega_i \equiv \rho_i / \rho_c$).

DM in clusters:

Actually, rather than in stars, most of the ordinary mass in clusters is in the form of hot gas, which emits at X-ray frequencies:

Credit: NASA, Yikhlinin et al.



X-ray image of the Coma cluster with Chandra telescope

Assume that the system 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)

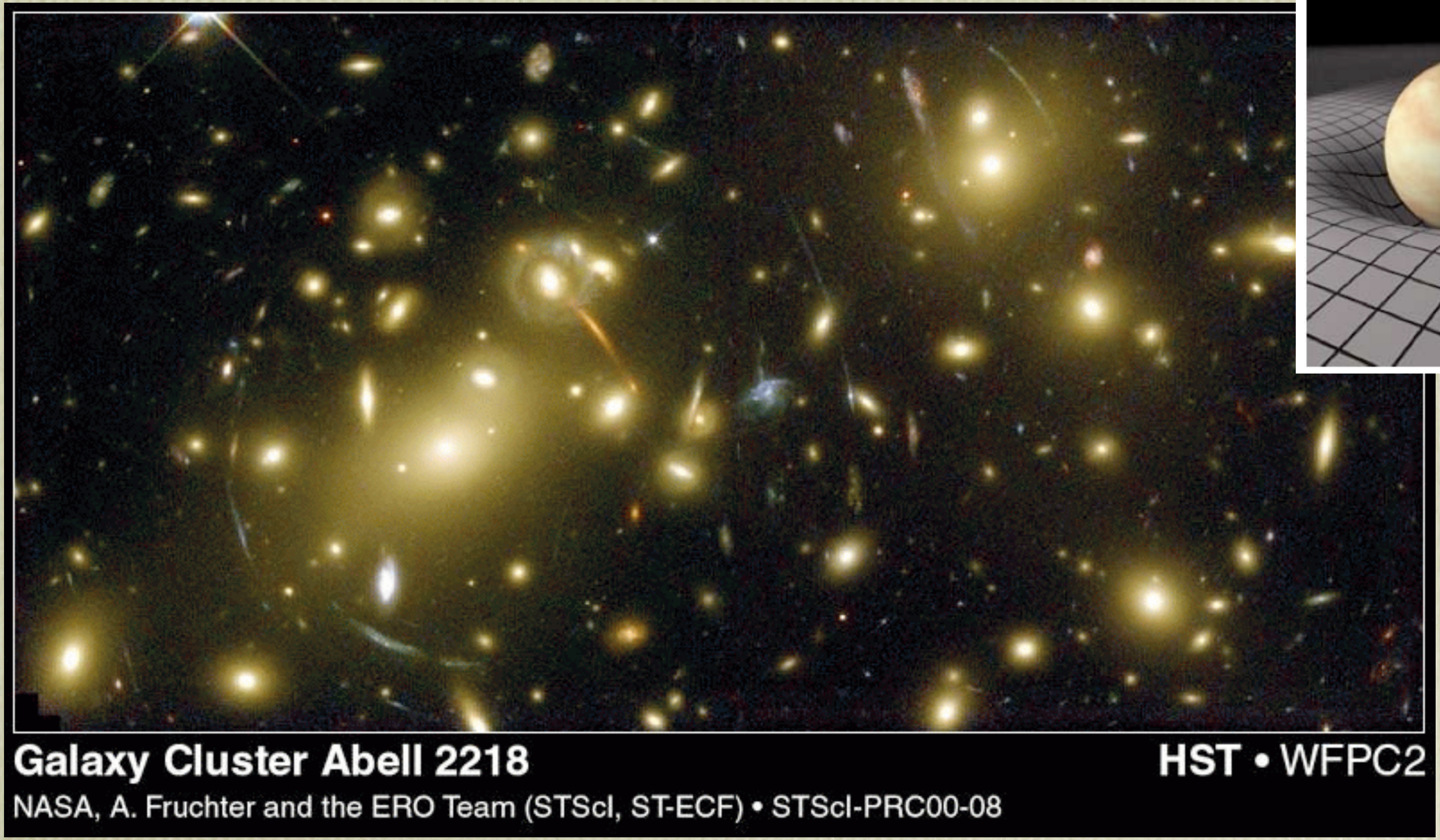
$$M_b/M \equiv f_b \simeq 14\%$$

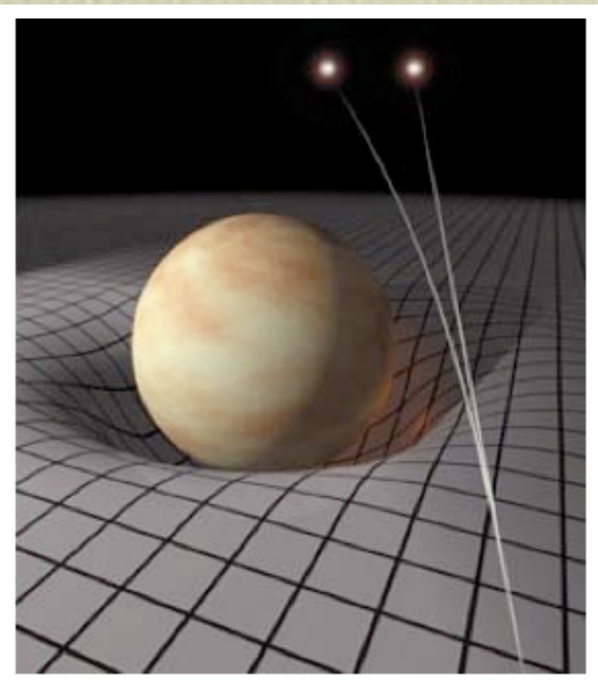
$$\Omega_M \simeq \Omega_b/f_b \simeq 0.29$$

Ω_b from BBN

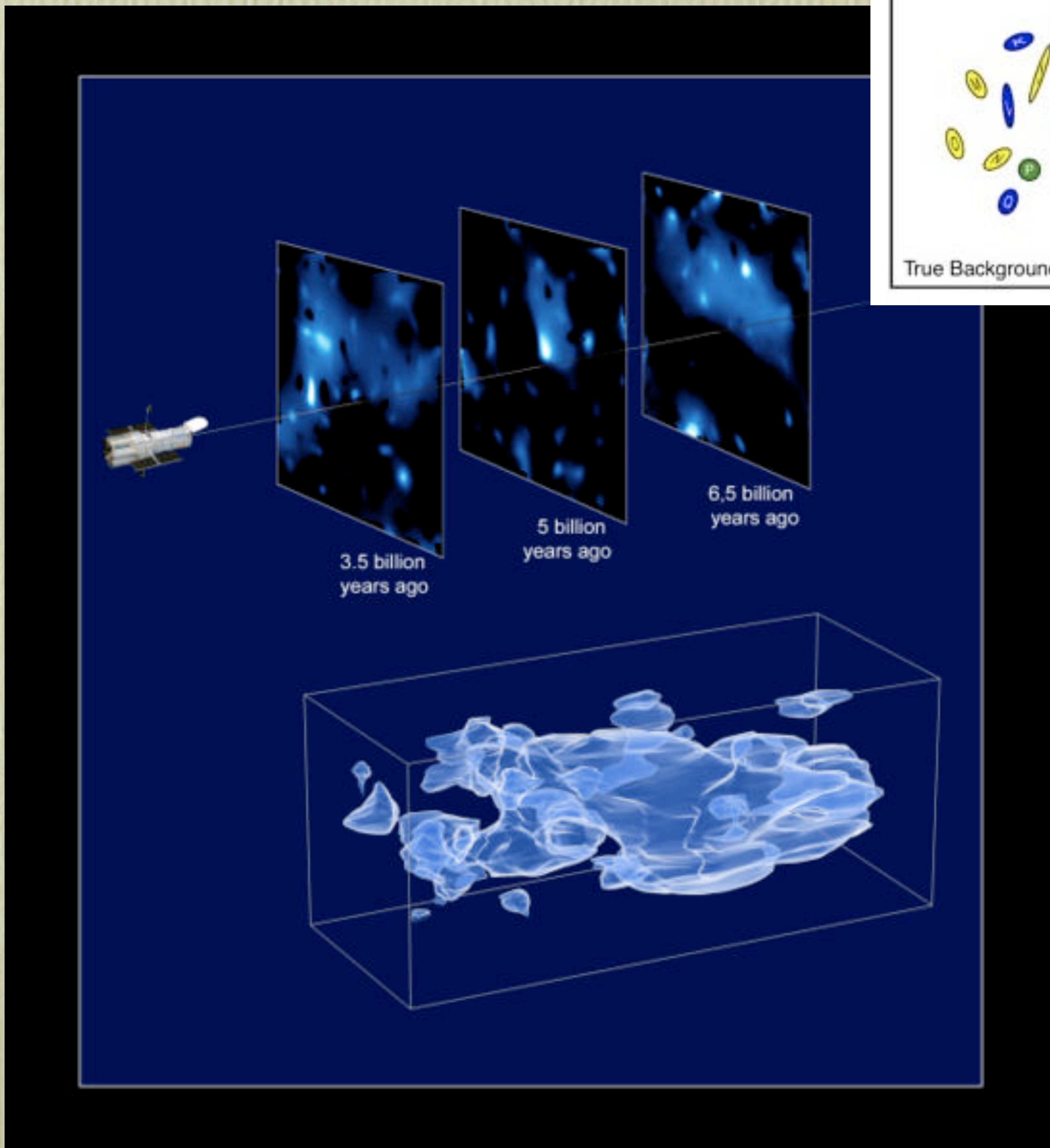
DM in clusters:

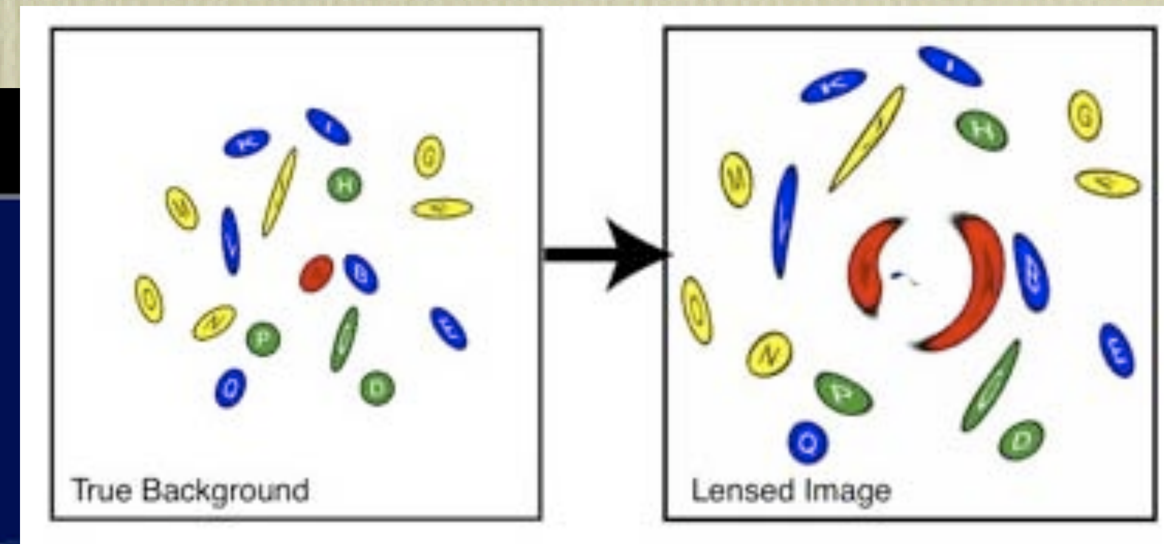
the latest approach is to perform a mass tomography through strong gravitational lensing:





Cosmic web:





weak gravitational lensing map of the large-scale distribution of matter: the result is a loose network of filaments, growing over time, which intersect in massive structures at the location of galaxy clusters.

COSMOS survey, Massey et al. 2007

Discovery and classical tests

1939: the hypothesis of DM in galaxies

Horace Babcock noticed that velocity of stars in the outskirts of the Andromeda galaxy (M31) was unexpectedly high, indicating the presence of a large amount of unseen mass.

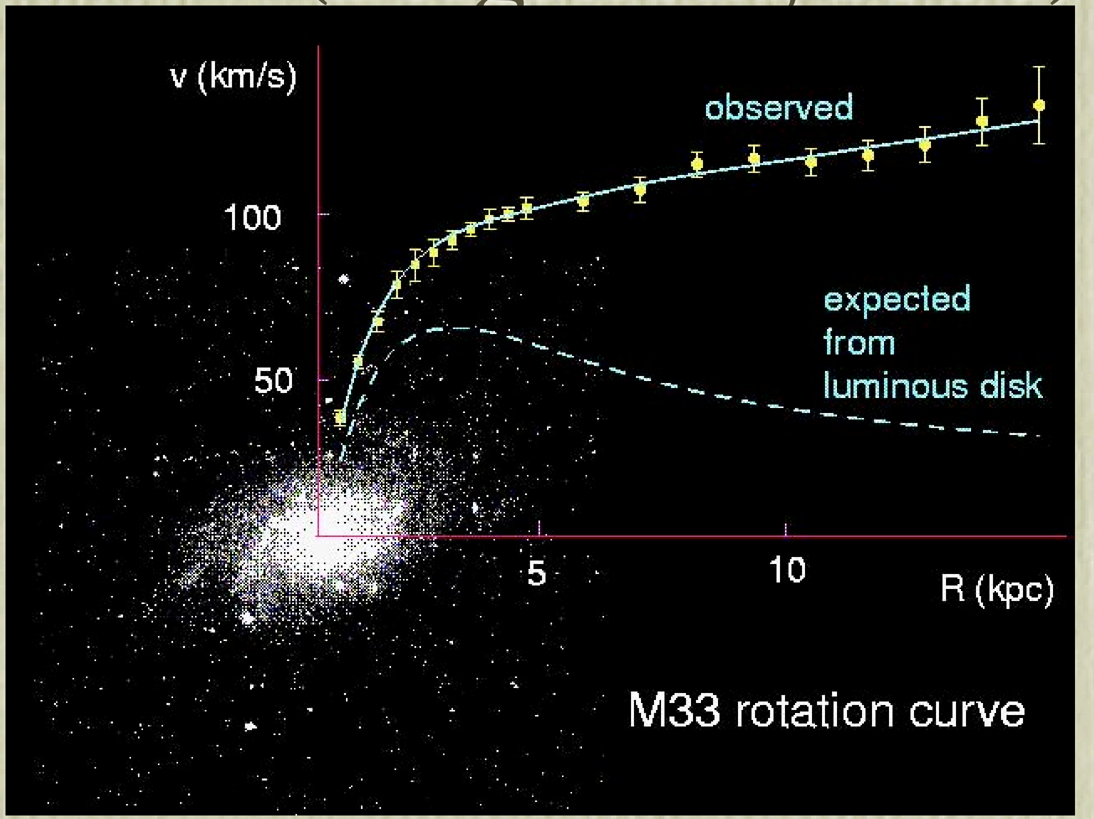
By the 1960s and 1970s a number of refined studies on galactic rotation curves were produced by several researchers including Vera Rubin

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:

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

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

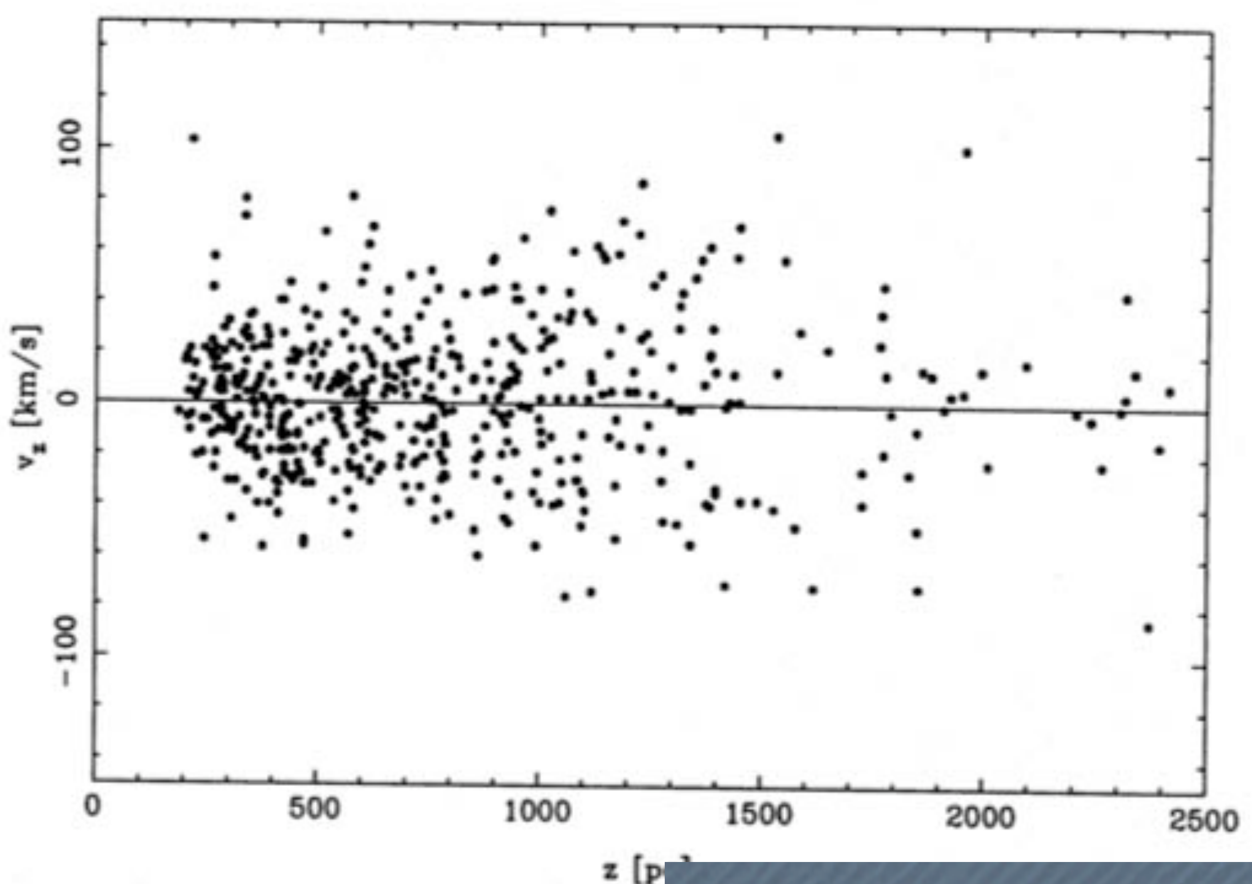
It is a difficult task to build a mass model for the Galaxy, given our biassed perspective on it. However there is such a wealth of complementary dynamical tracers providing relevant informations that we do have to an understanding of some of the features in the DM halo. E.g.:

Determination of the local dark matter halo density

It is possible to combine informations from:

Local surface mass densities:
local star velocity fields to infer the vertical motion of stars in the solar neighborhood

Kuijken & Gilmore, 1991



+ several more!

Determination of the local dark matter halo density

All dynamical tracers compared to a mass model for the Galaxy. The standard approach is to perform a decomposition into into axisymmetric or spherically symmetric terms. E.g.: Catena & P.U., arXiv:0907.0018

$$\rho_d(R,z) = \frac{\Sigma_d}{2z_d} e^{-\frac{R}{R_d}} \operatorname{sech}^2\left(\frac{z}{z_d}\right) \quad \text{with} \quad R < R_{dm}$$

stellar disc

$$\rho_{bb}(x,y,z) = \rho_{bb}(0)\left[s_a^{-1.85}\exp(-s_a) + \exp\left(-\frac{s_b^2}{2}\right)\right]$$

stellar bulge/bar

$$\rho_h(r) = \rho' f\,(r/a_h)$$

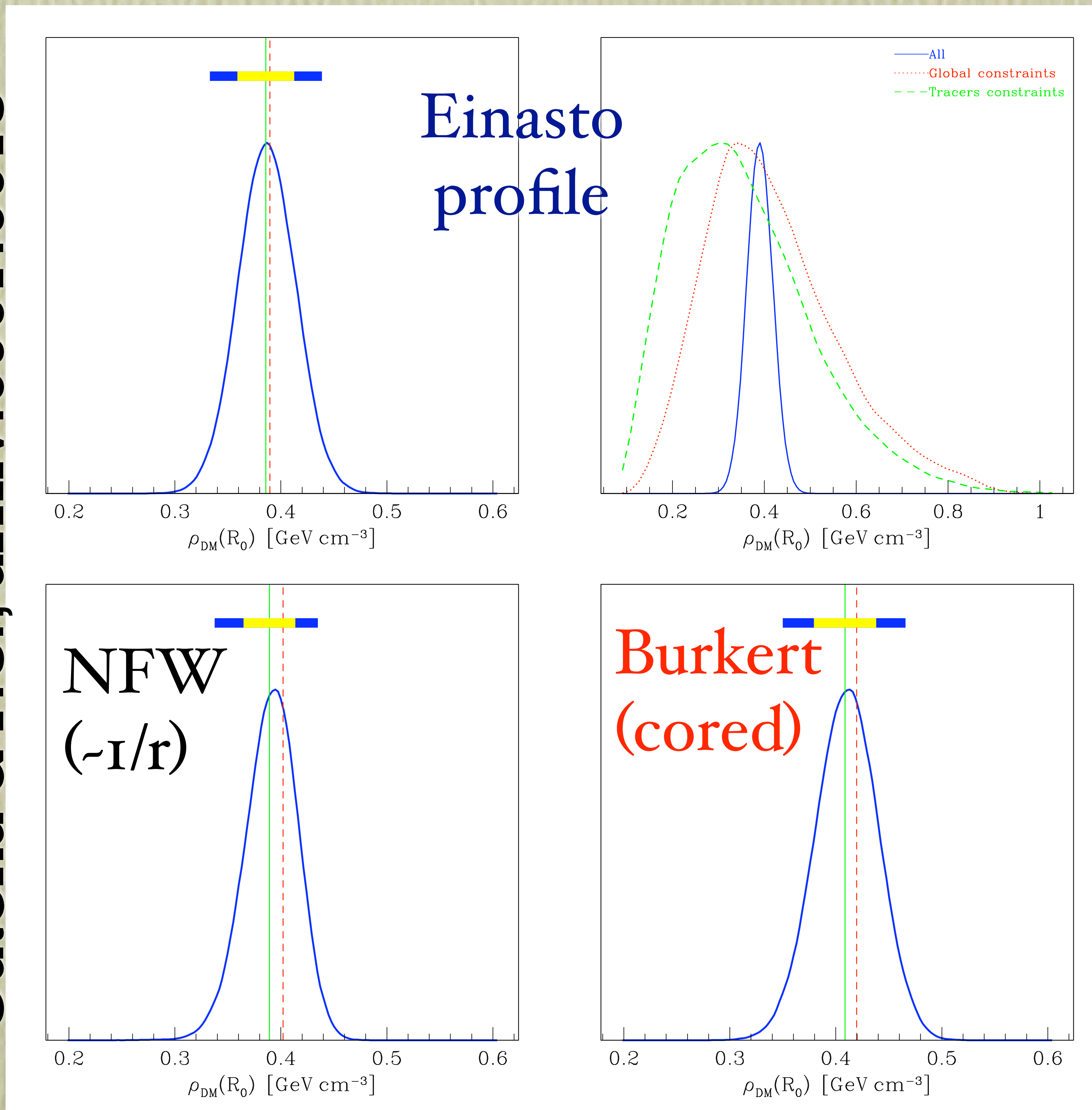
dark matter halo

+ gas disc

a **7 or 8 parameter model**, which, having defined an appropriate likelihood function, is studied in a **Bayesian approach** implementing a Markov chain Monte Carlo method:

Determination of the local dark matter halo density

Catena & P.U., arXiv:0907.0018



Marginal posterior pdf for the local halo density for three different choices of the functional form for the MW DM profile. 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 - slightly different results for halos with some flattening, see, e.g.:

Pato et al., arXiv:1006.1322

Regarding total mass estimates:

$$\mathrm{M_{vir}} = 1.1 \pm 0.2 \times 10^{12} \mathrm{M}_\odot \Leftrightarrow M_{\text{stars+gas}} \simeq 4 \cdot 10^{10} M_\odot$$

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

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:

$$\Omega_{\rm tot} \sim 1 \qquad \Omega_{\rm M} \sim 0.27 \qquad \Omega_{\Lambda} \sim 0.73 \qquad \ldots$$

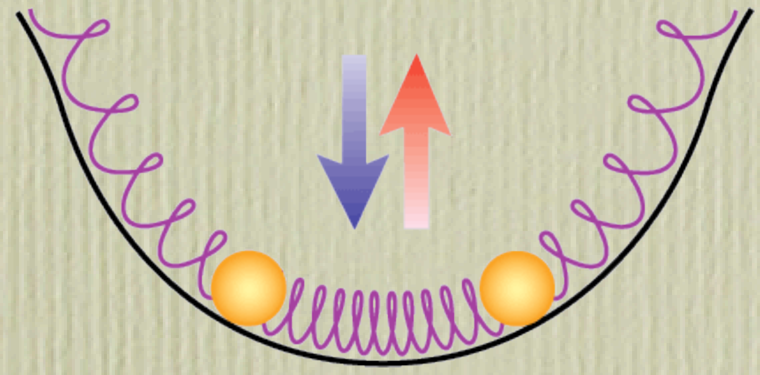
$$\underbrace{\Omega_{\rm DM} \sim 0.23 \qquad \Omega_{\rm b} \sim 0.04}_{\Omega_{\rm M}}$$

$\Omega_{\rm b}$ in remarkable agreement with BBN!

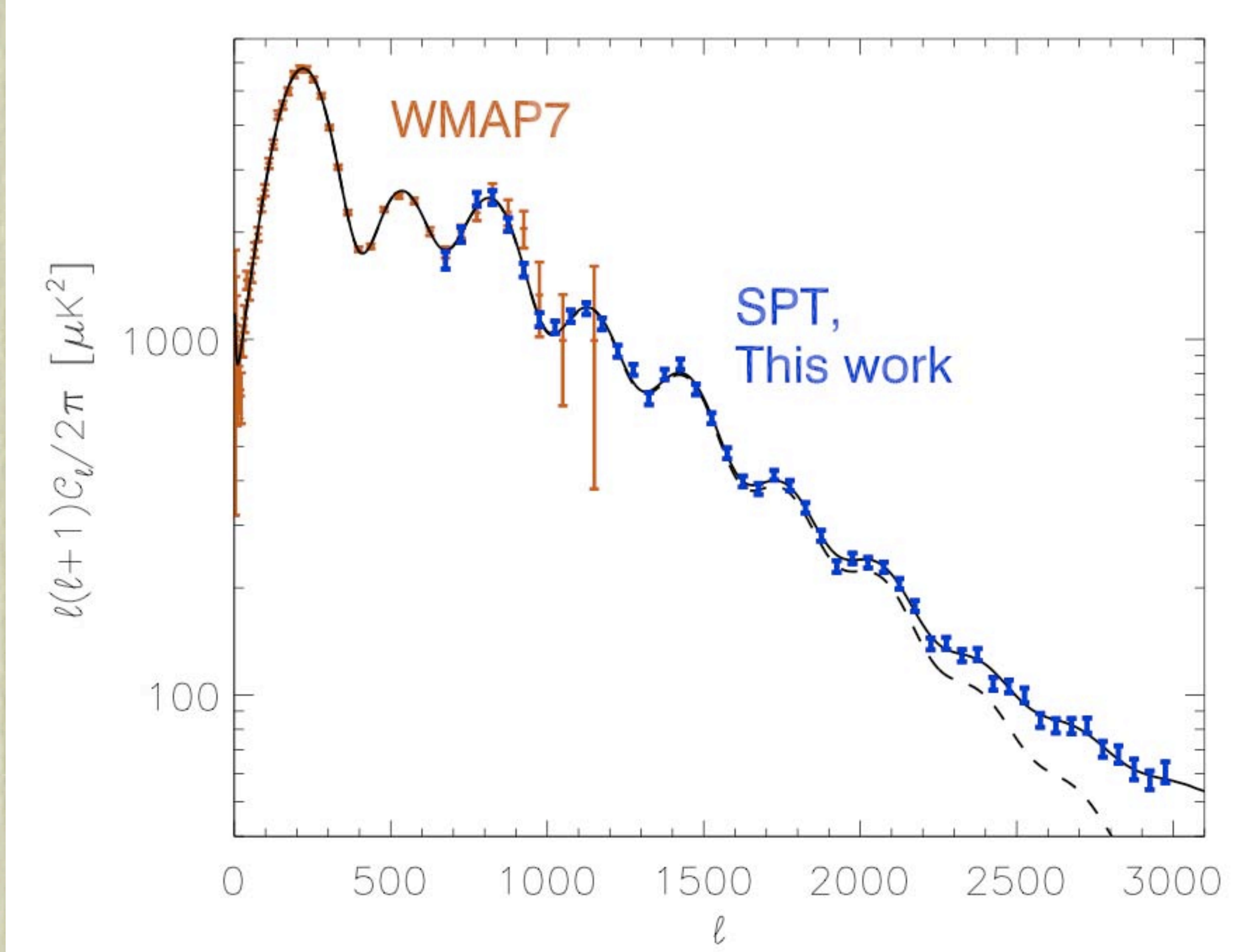
DM appears as the building block of all structures in the Universe:

(7-yr WMAP, 2010 + STP, 2011)

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



Credit: W. Hu website



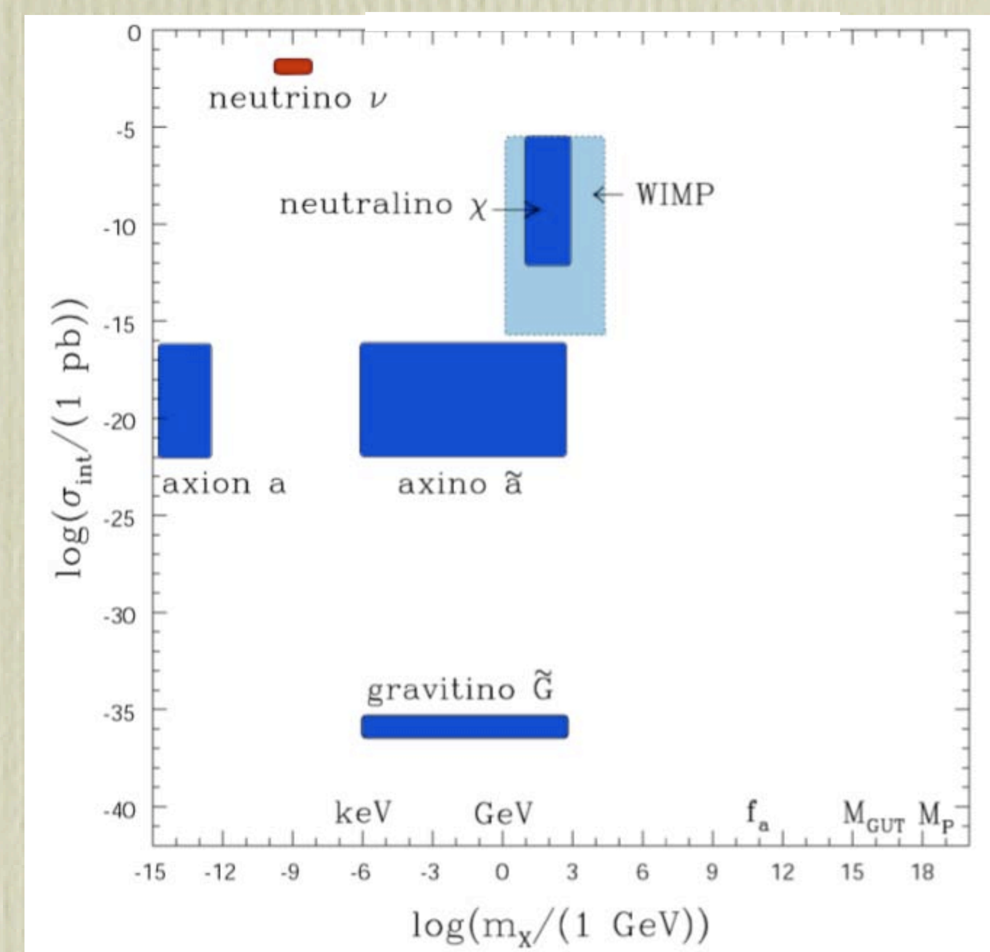
Giving up GR as theory of gravitation to avoid the DM term, introducing a theory (TeVeS?) with MOND-like Newtonian limit, would be an option only if all these observables are addressed. This has not been done systematically, but attempts of this kind typically end up with requiring some form of DM.

DM as a (new) elementary particle (field)

1001 models in 1001 different frameworks...

How to make the jump from the indirect (gravitational) evidence to the identification of the nature of the DM component?

(just a subset)



Credit: L. Roszkowski

We know very little about the mass and interaction strength of DM particles, the properties which are crucial for devising a detection strategy:

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

There are 5 golden rules (i.e. properties that cannot be strongly violated):

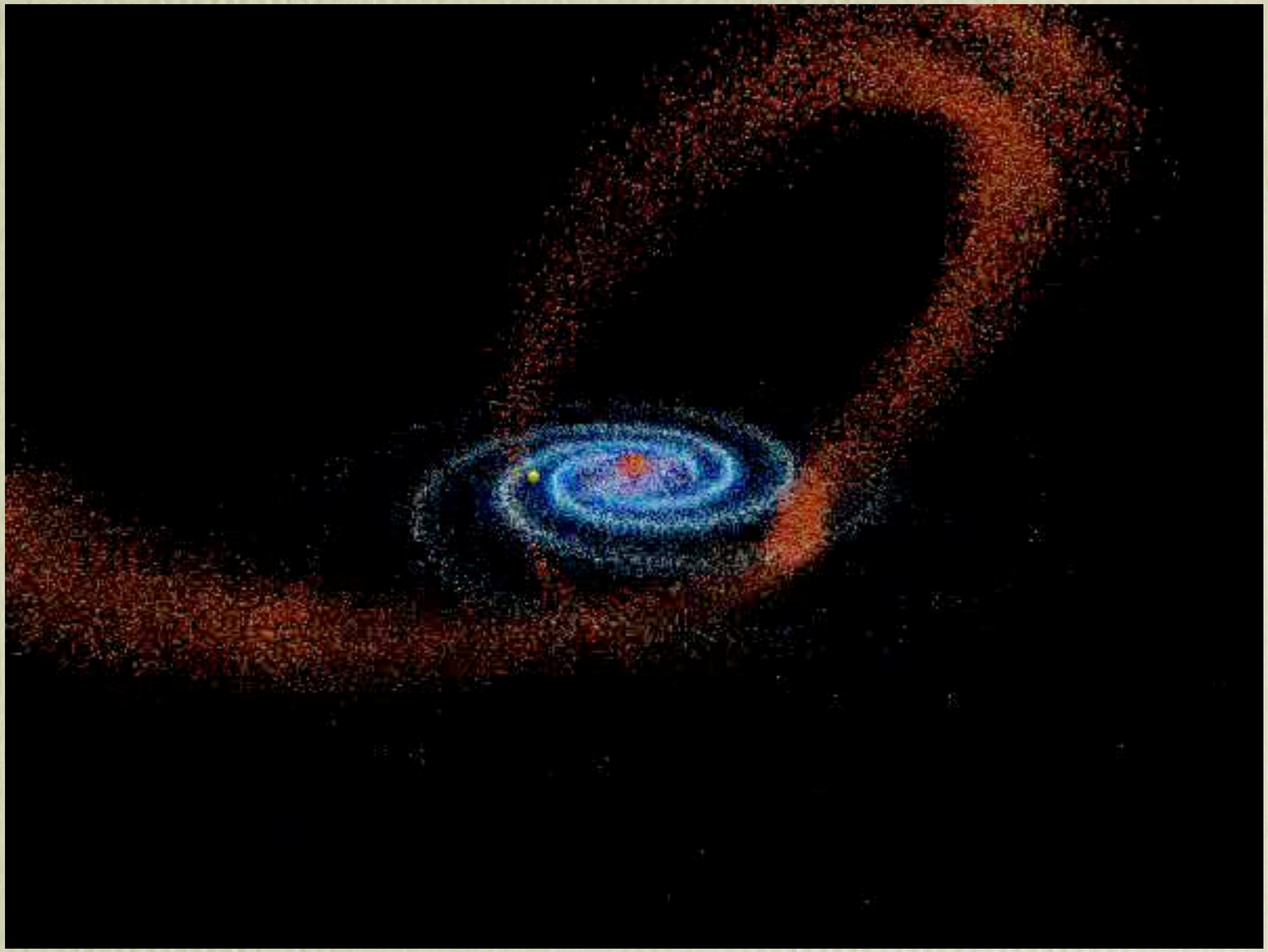
1) DM is **optically dark**: its electromagnetic coupling is suppressed since: a) it is does not couple to photons prior recombination; b) it does not contribute significantly to the background radiation at any frequency; c) it cannot cool radiating photons (as baryons do, when they collapse to the center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

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

1) DM is **optically dark** ⇒ DM is **dissipation-less**

The morphology expected for a spiral galaxy is that the thin stellar disc is embedded in a much more massive and extended spherical (actually triaxial) dark matter halo. This is confirmed by the observation of tidal effects on satellites.

E.g.: the Sagittarius Dwarf in the Milky Way

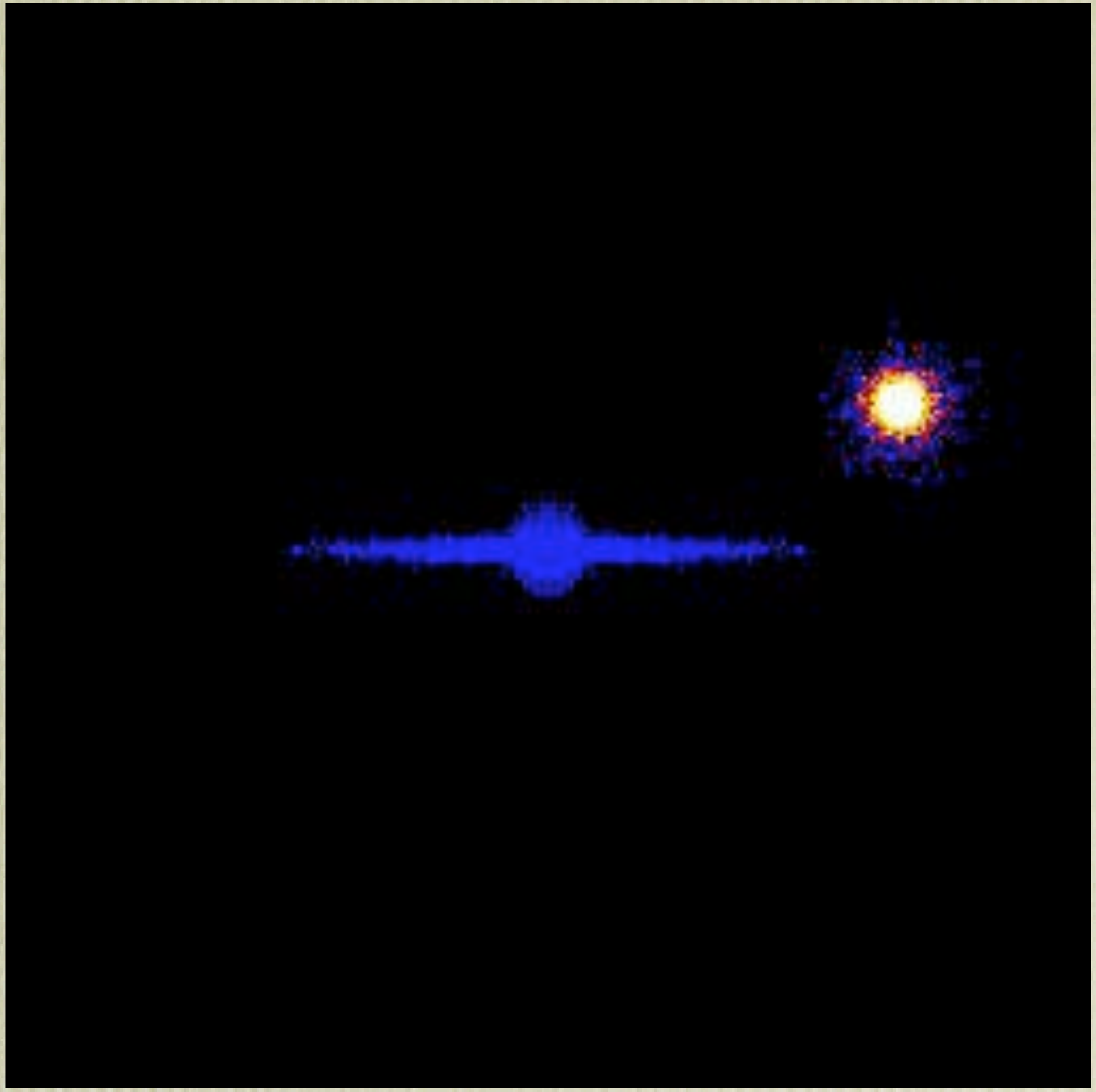


orange dots: M-giant stars as mapped by 2MASS, 2003, credit D. Law.

1) DM is **optically dark** ⇒ DM is **dissipation-less**

E.g.: the Sagittarius Dwarf in the Milky Way

Simulation of the time evolution of the interaction of a Sagittarius-like dwarf with a Milky Way-like halo. The simulations spans approximately 2 billion years in the past through 500 million years in the future.



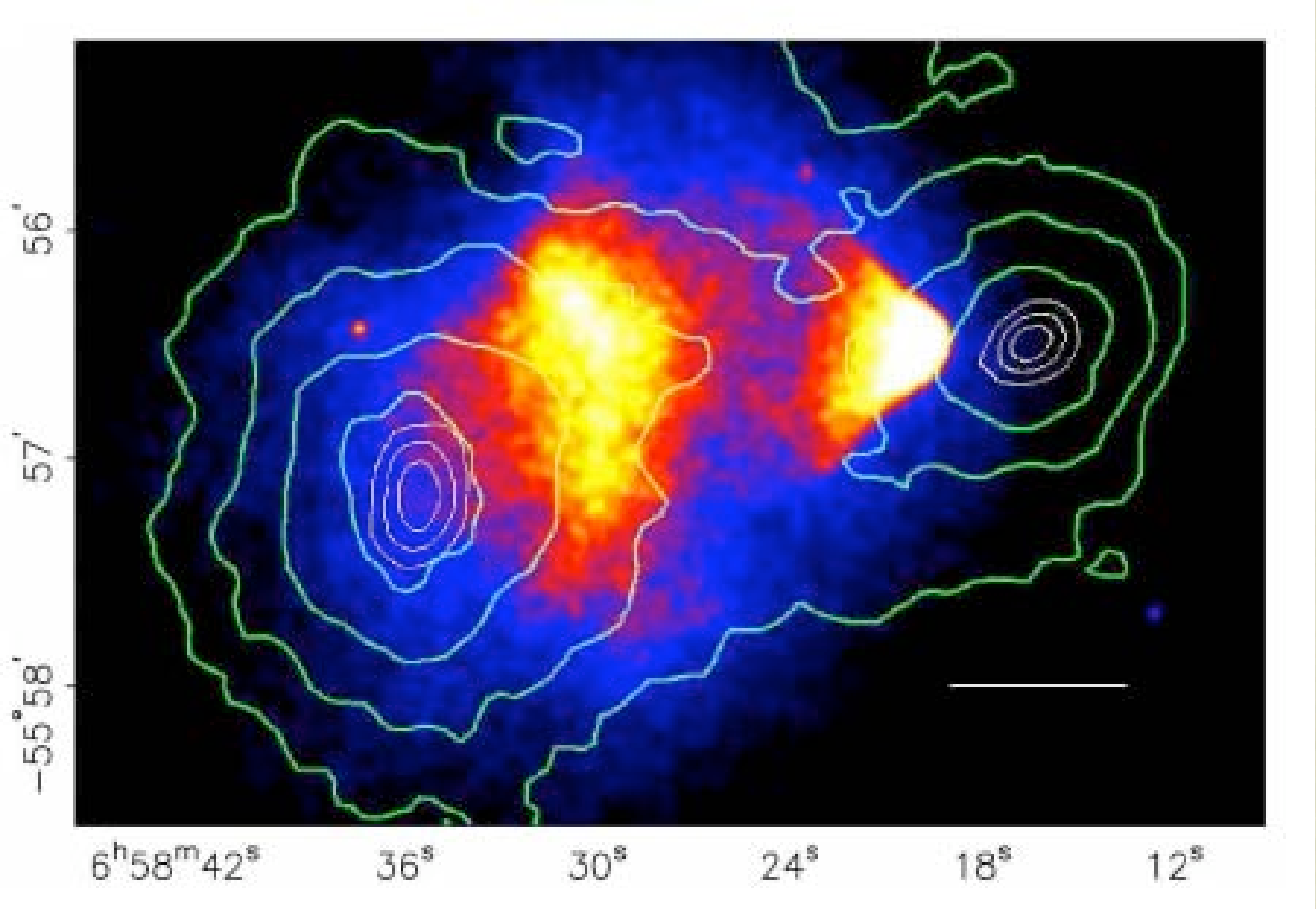
credit: K. Johnston

Of course, it does not matter what is the channel in which energy is dissipated. Mirror baryons as DM suffer from this problem, and one needs to invoke some feedback mechanism to balance against cooling.

2) DM is **collision-less** (or, at least, much less collisional than baryons)

Limits from the fact that you get spherical clusters as opposed to the observed ellipticity in real clusters (e.g. Miralda-Escude, 2000). Stronger evidence for this property from the observation of a galaxy cluster which has undergone a recent merging, the 1E0657-558 cluster ("Bullet" cluster):

Isolevel curves for the mass density as derived from gravitational lensing, superimposed on a X-ray image tracing the hot gas in the system, Clowe et al. 2006

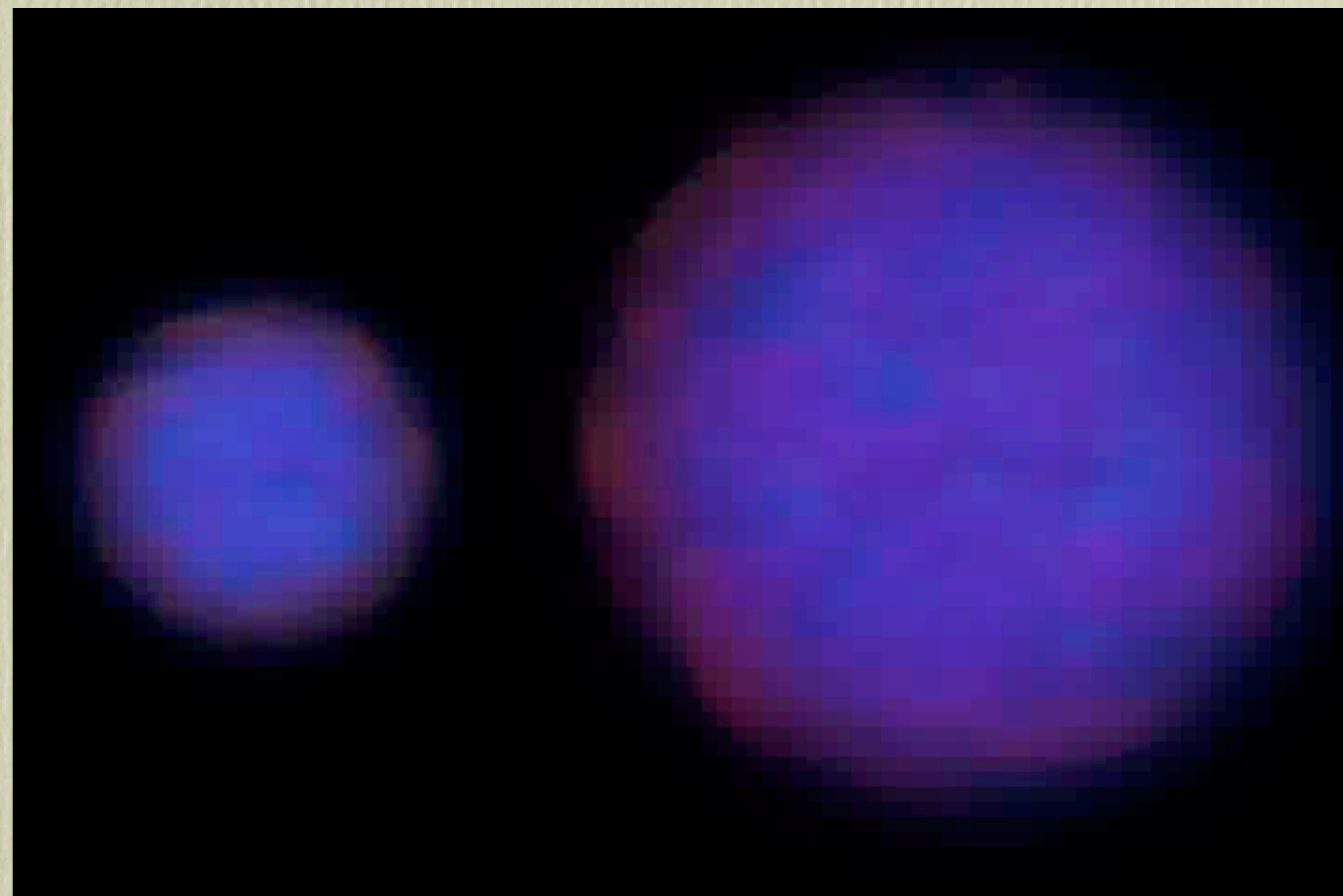


Sketch of the Bullet collision: the hot gas is collisional and experiences a drag force that slows it down and displaces it from the dark matter which is essential insensitive to a high-speed impact:

in red: gas

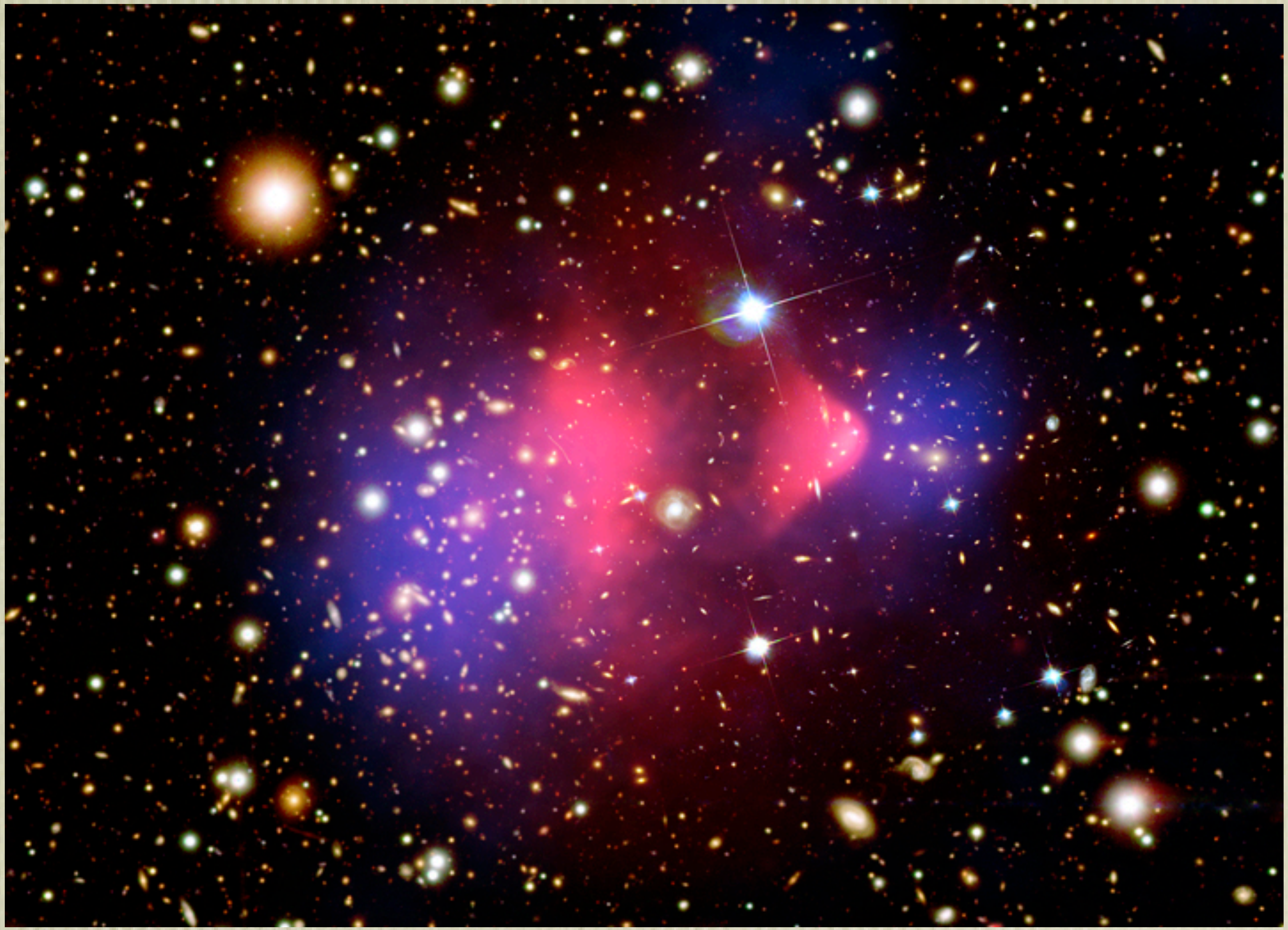
in blue: dark matter

Credit: NASA, M. Weiss



This is one of the examples in which it is very hard to reconcile a framework without DM with observations.

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 (Spergel& 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:

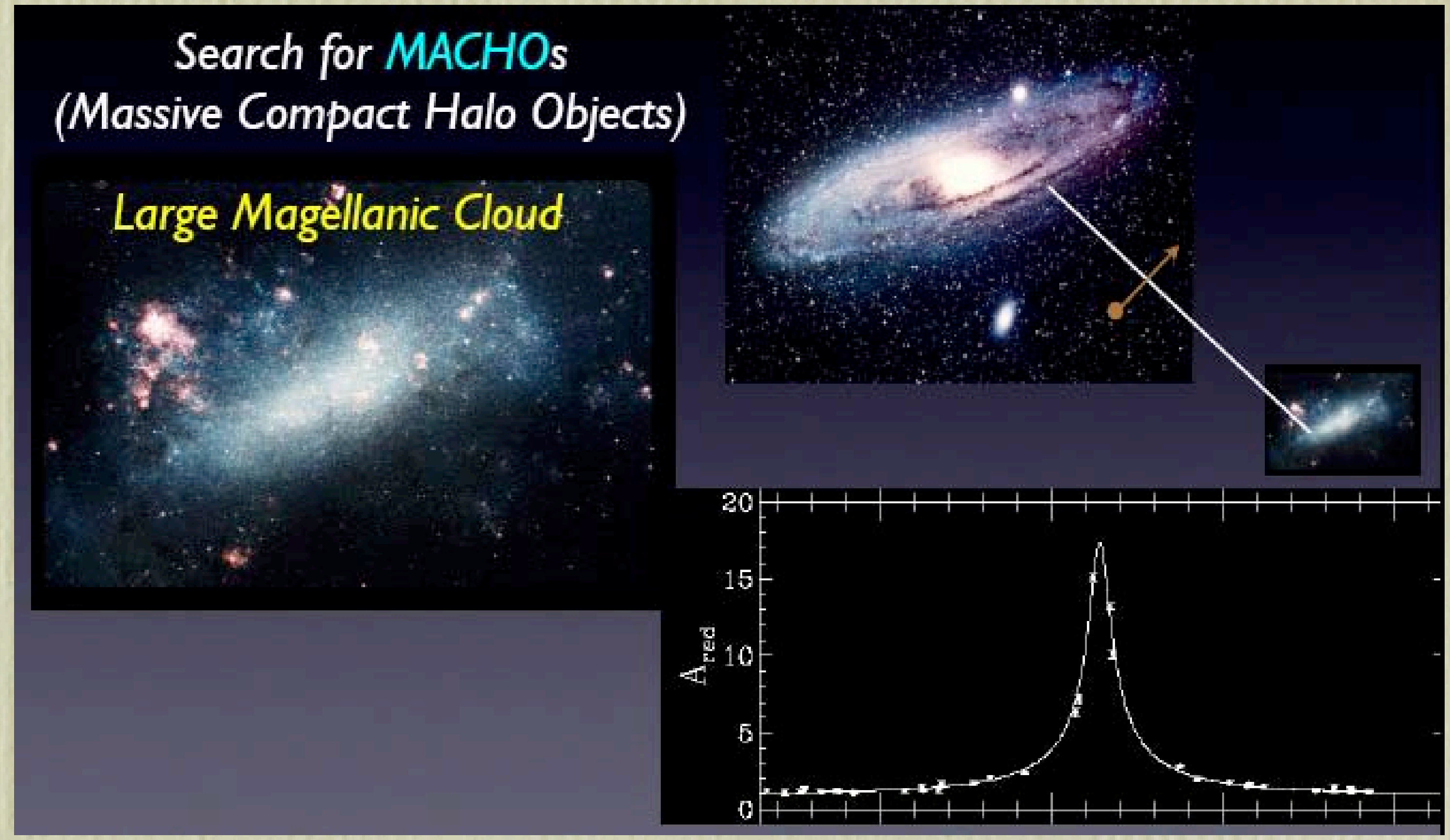
thickness of disks: $M_p < 10^6\ M_\odot$

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

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

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

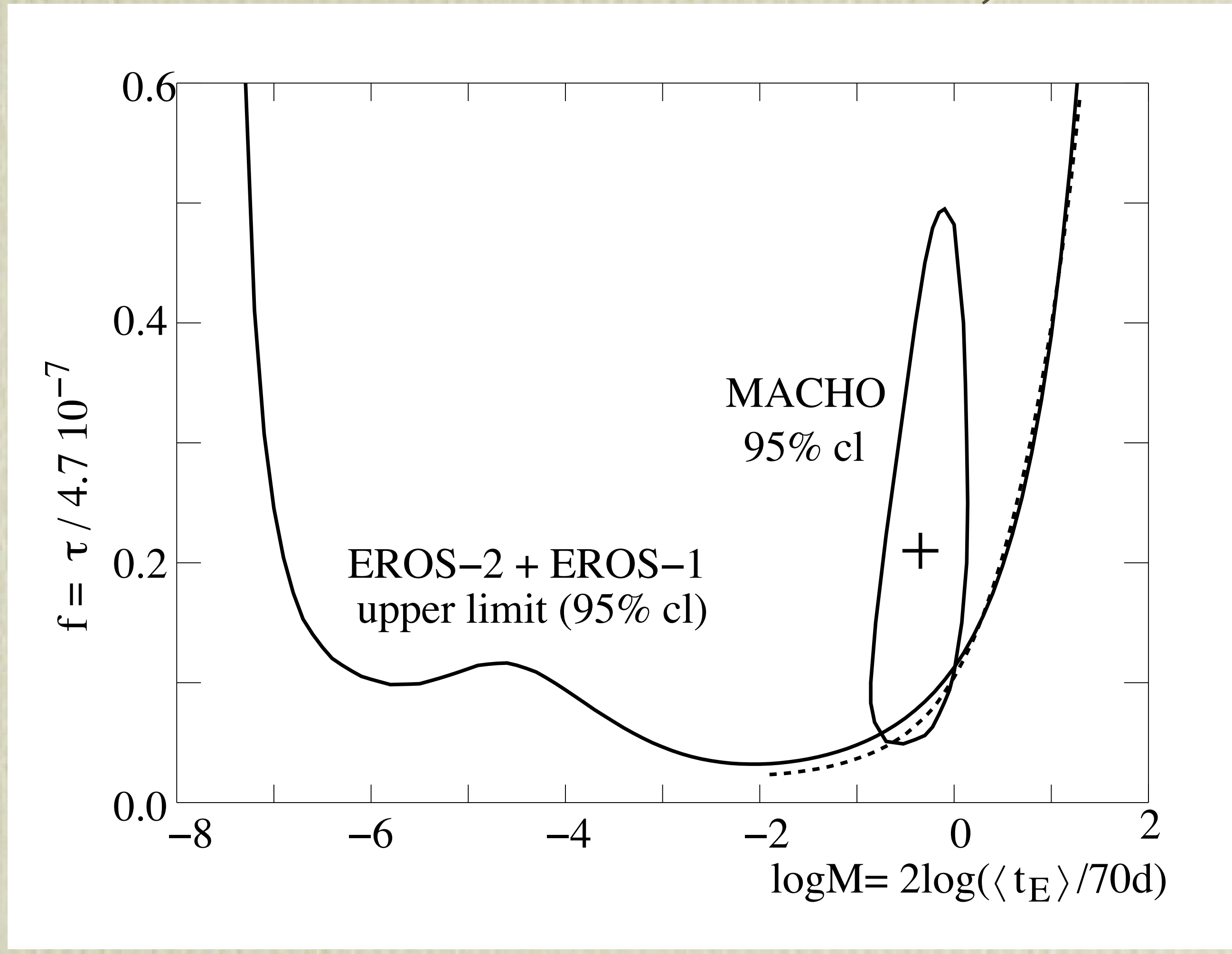
Machos + Eros microlensing seaches exclude MACHOs in the Galaxy in the mass range $(10^{-7} - 10)\ M_\odot$



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

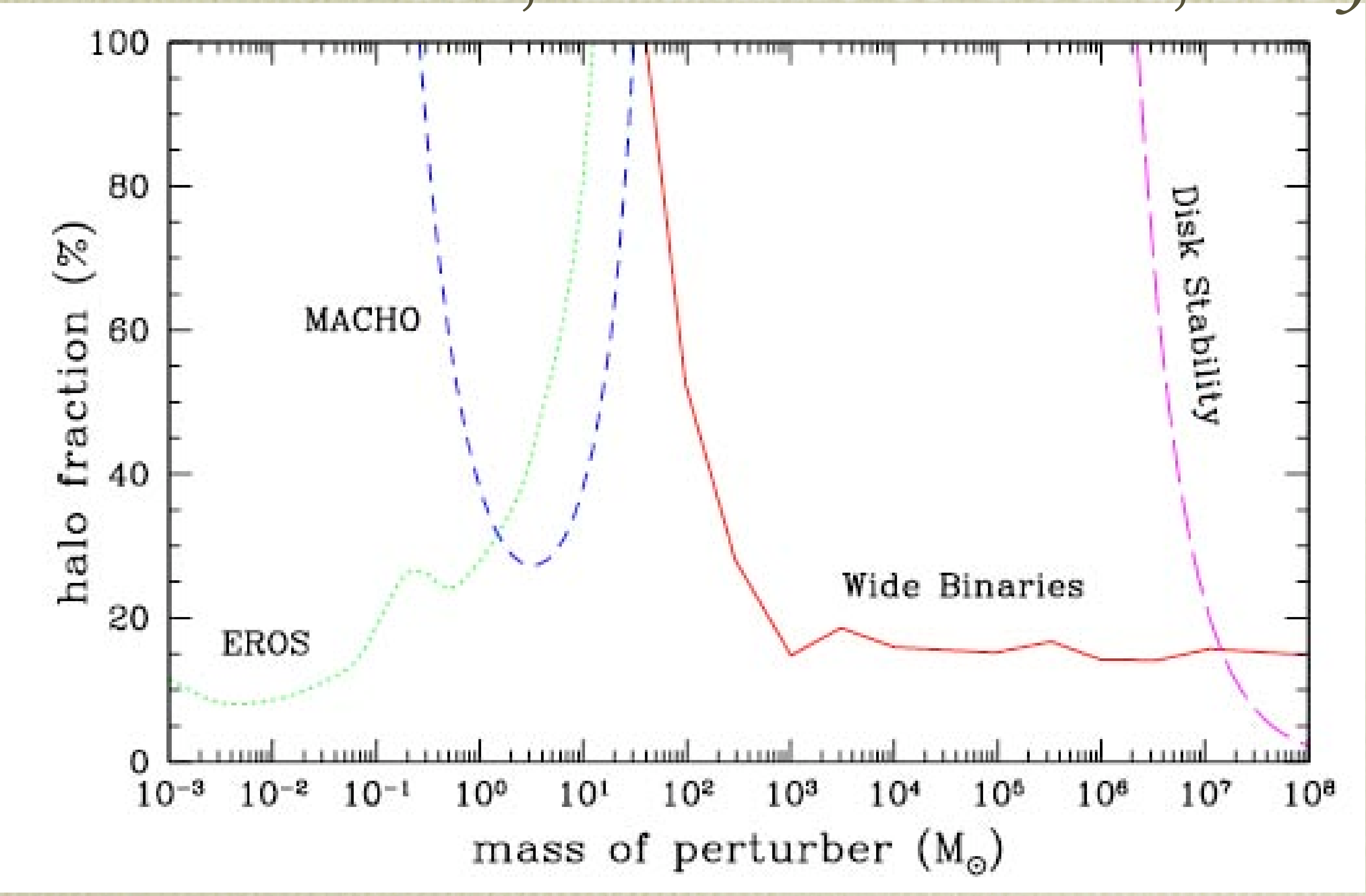
$$\tau_{\rm lmc} = 4.7 f \times 10^{-7}$$

Tisserand et al., 2008



These constraints however are irrelevant when rephrased in terms of DM particle masses:

Yoo, Chaname & Gould, 2003



$$M_p < 10 \; M_\odot \Longrightarrow M_p < 10^{58} \mathrm{GeV}$$

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

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

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

"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: $f^{\rm ini}_{\rm max} = \dfrac{g}{h^3}$

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

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

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

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

$$\rho_0 \sim 1\,{\rm GeV\,cm^{-3}}$$

$$\sigma \sim 100\,{\rm km}\,s^{-1}$$

$\Longrightarrow$ $M_p \gtrsim 35\,{\rm eV}$ (even tighter for dwarf galaxies)

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:

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

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:

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

eq. o. m.

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

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

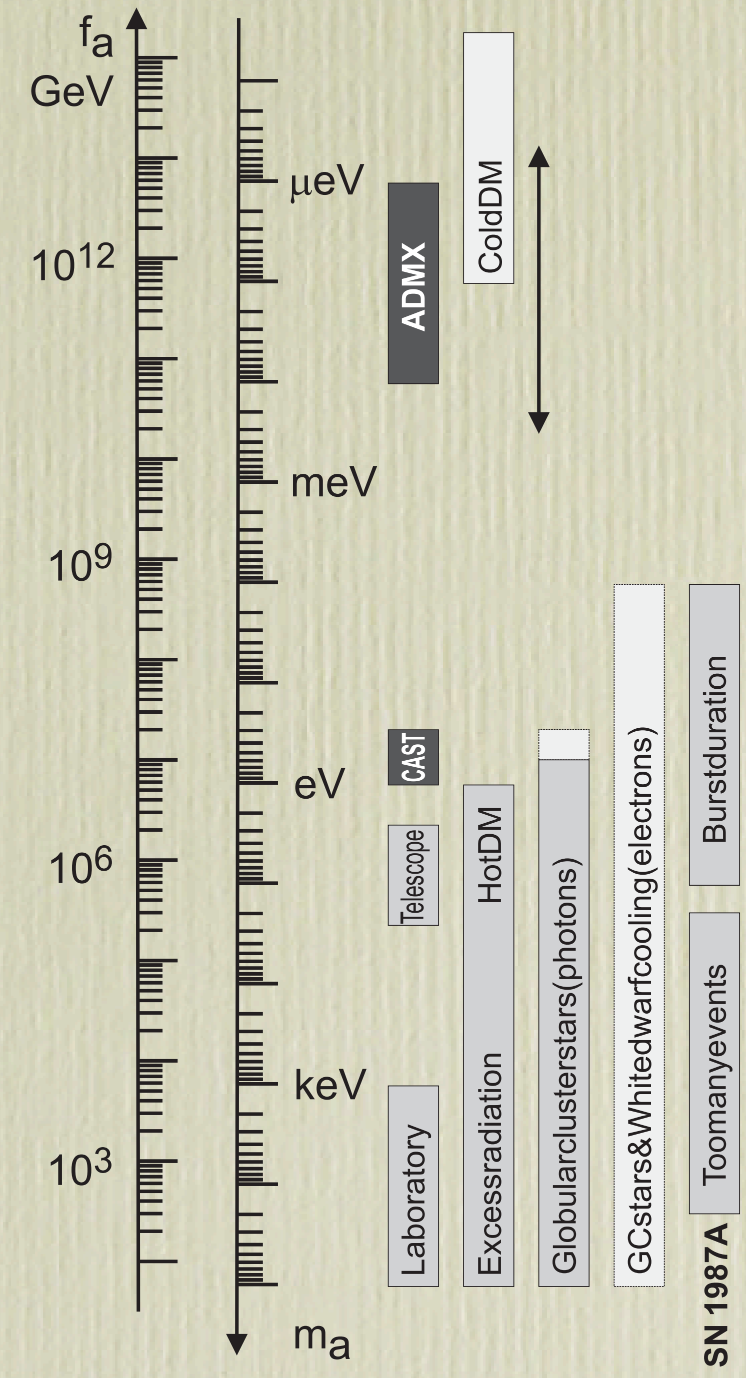
$$m_a \sim 10^{-5}\,\mathrm{eV}$$

$$\updownarrow$$

$$\Omega_a \sim 1$$

(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

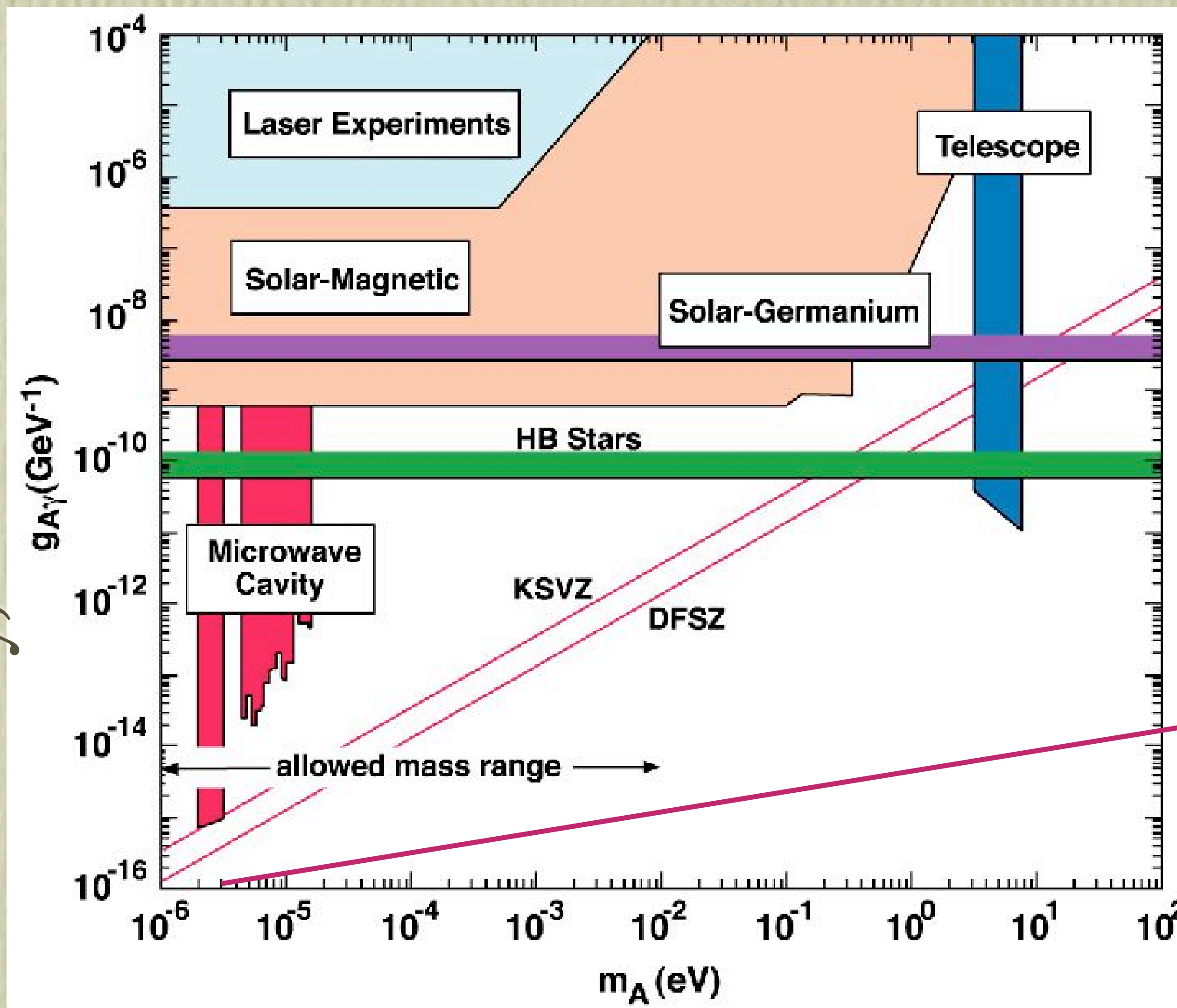
DM detection needs to be considered case by case. For the axion there are generic couplings:

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

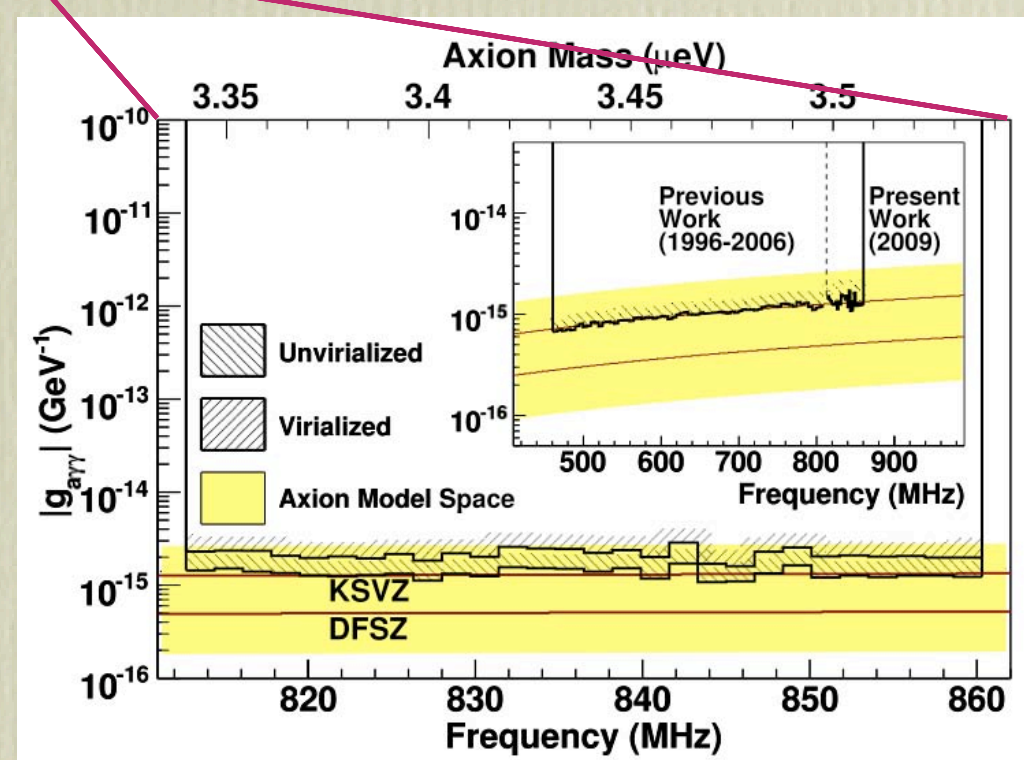
In particular the axion-electromagnetic field coupling has the form:

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

Duffy, et al. 2006



Axion detection through resonant conversion in a microwave cavity



Asztalos, et al. 2009

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

$\chi\bar{\chi} \rightarrow P\bar{P}$

$P\bar{P} \rightarrow \chi\bar{\chi}$

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

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

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

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 $x \equiv M_\chi/T$:

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

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

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

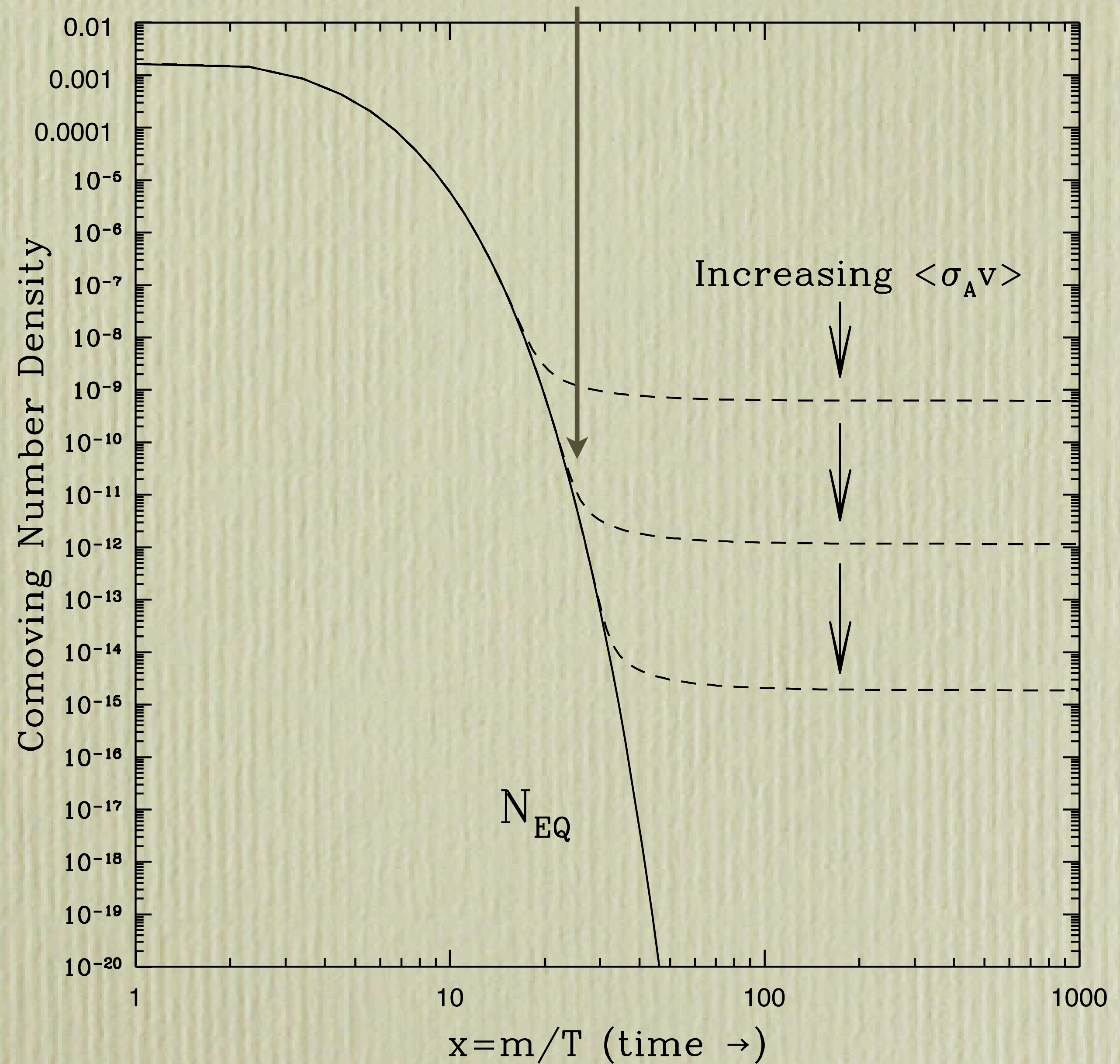
For the freeze-out of a relativistic species $Y_\chi^{eq} \neq Y_\chi^{eq}(T_f)$

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

For neutrinos: $\Omega_\nu h^2 = \frac{\sum m_{\nu_i}}{91\,\mathrm{eV}}$ (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: $M_\chi/T_f \sim 20$

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

→ 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: "minimal" DM (Cirelli et al., hep-ph/0512090), DM in technicolor theories (Gudnason et al., hep-ph/0608055), ...

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.

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.:

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

gravitino production from a SUSY state in thermal 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***, ...

WIMPs as non-thermal DM

The thermal relic picture is valid within an extrapolation of the early Universe from the epoch at which it is well tested, the onset of BBN:

$T_{BBN} \simeq 1\,\mathrm{MeV}$ or: $t(T_{BBN}) \simeq 1\,\mathrm{s}$

assuming that: a) there is no entropy injection, b) the Universe is radiation dominated, and c) there is no extra χ source, up to, at least:

$T_f \simeq M_\chi/20 \sim 5 - 50\,\mathrm{GeV}$ or: $t(T_f) \sim 10^{-7} - 10^{-9}\,\mathrm{s}$

However, all three conditions may be violated in theories containing at heavy states extremely weakly (e.g.: gravitationally) coupled to matter, such as the gravitino or moduli in SUSY theories. These states are not in thermal equilibrium in the early Universe, possibly dominate the Universe energy density prior BBN, are long-lived and may inject a large amount of entropy and/or χ particles.

A perfectly viable scenario as long as their lifetime is:

$\tau_\phi < t(T_{BBN})$

or that Universe is "re-heated" to a temperature:

$T_{RH} > T_{BBN}$

The prediction for the relic density of χ is model dependent, there are however a few definite scenarios. One attractive possibility (e.g., Moroi & Randall, hep-ph/9906527):

There is one heavy modulus, driving the Universe to a matter dominated phase, decaying with a large entropy injection (the number density of early thermal relics is totally diluted) and a non-negligible branching ratio into χ, reheating the Universe at a temperature:

$$T_{RH} \sim \text{few MeV} - 100\,\text{MeV}$$

At the modulus decay the χ number density is comparable to the number density of light SM states, however pair annihilations instantaneously reduce it to the level at which annihilations become inefficient:

$$n_\chi \sim \frac{H(T_{RH})}{\langle \sigma v \rangle}$$

If the annihilation cross-section is not strongly dependent on temperature:

$$\Omega_\chi^{NT} h^2 \sim \Omega_\chi^T h^2 \frac{T_f}{T_{RH}} \sim \frac{3 \cdot 10^{-27}\,\text{cm}^3\,\text{s}^{-1}}{\langle \sigma v \rangle} \frac{T_f}{T_{RH}}$$

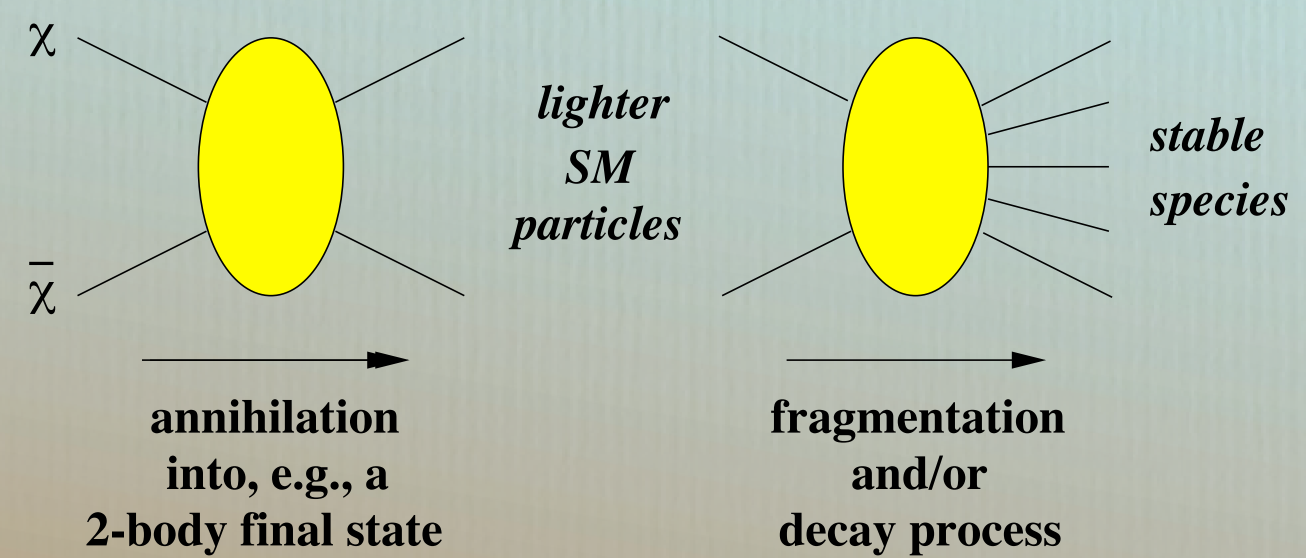
i.e., compared to the thermal relic case, an increase in the annihilation cross-section is needed for χ to match the dark matter density level.

Is this testable at the LHC?

Indirect detection of WIMP dark matter

A chance of detection stems from the WIMP paradigm itself:

Pair annihilations of WIMPs in DM halos (i.e. at T≅0)



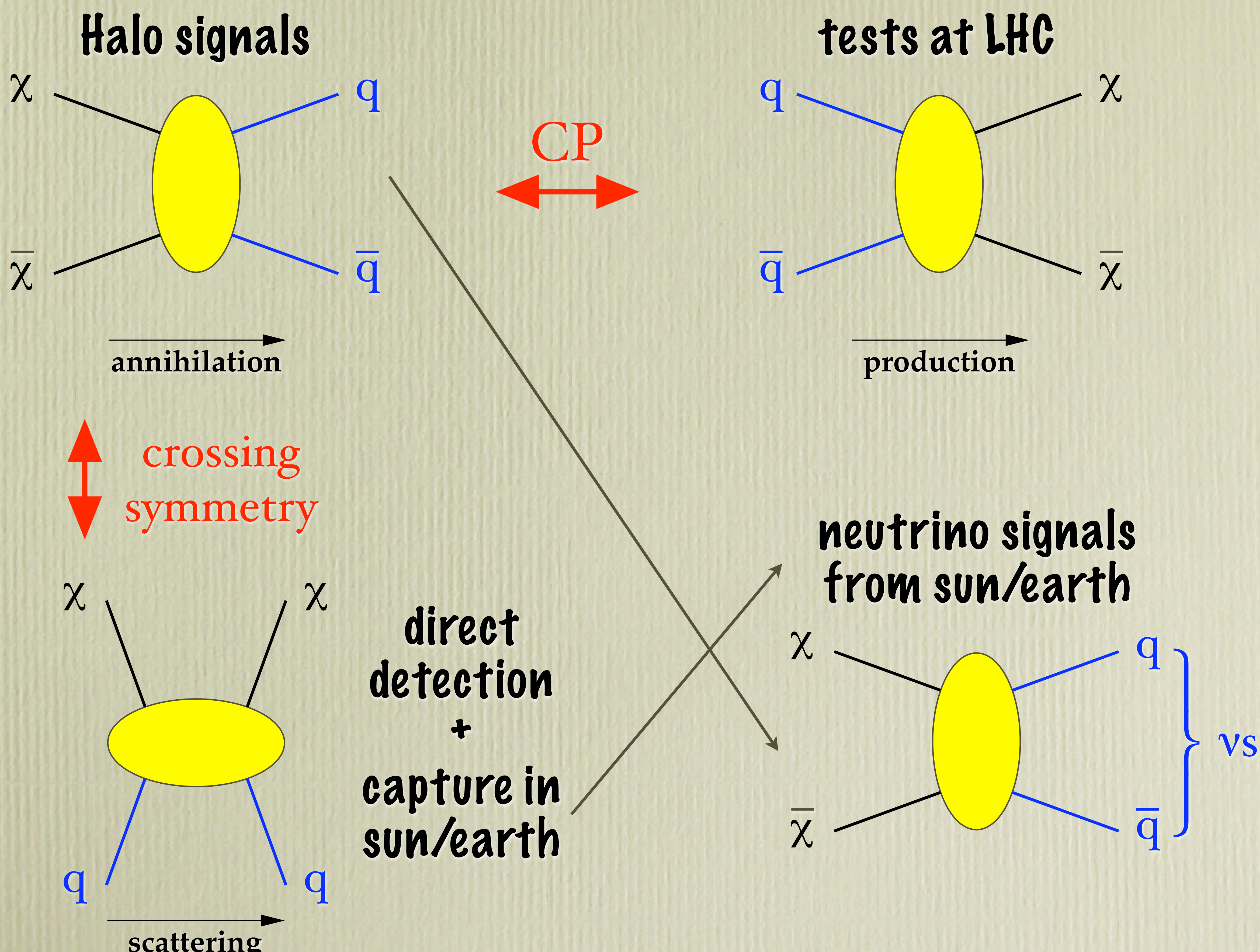
Focus on:
antiprotons,
positrons,
antideuterons,
gamma-rays,
(neutrinos)

- $(\sigma v)_{T\simeq 0} \overset{?}{\sim} \langle \sigma v \rangle_{T=T_f}$
- final state branching ratios
- $N_{\chi-\mathrm{pairs}} \propto [\rho_\chi(r)]^2 \simeq [\rho_{\mathrm{DM}}(r)]^2$

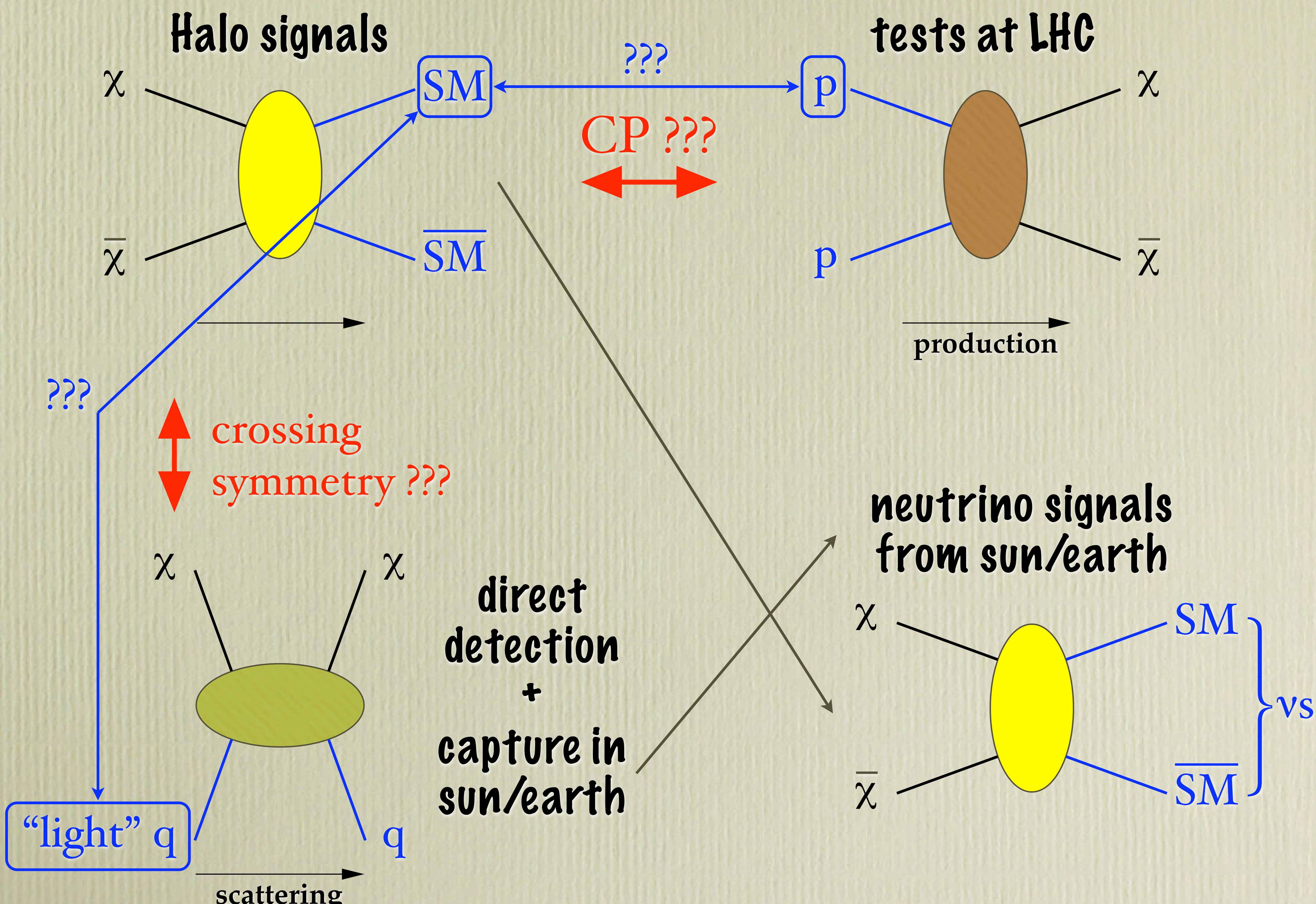
} WIMP DM source function

Dynamical observations (?)/
N-body simulations (?)

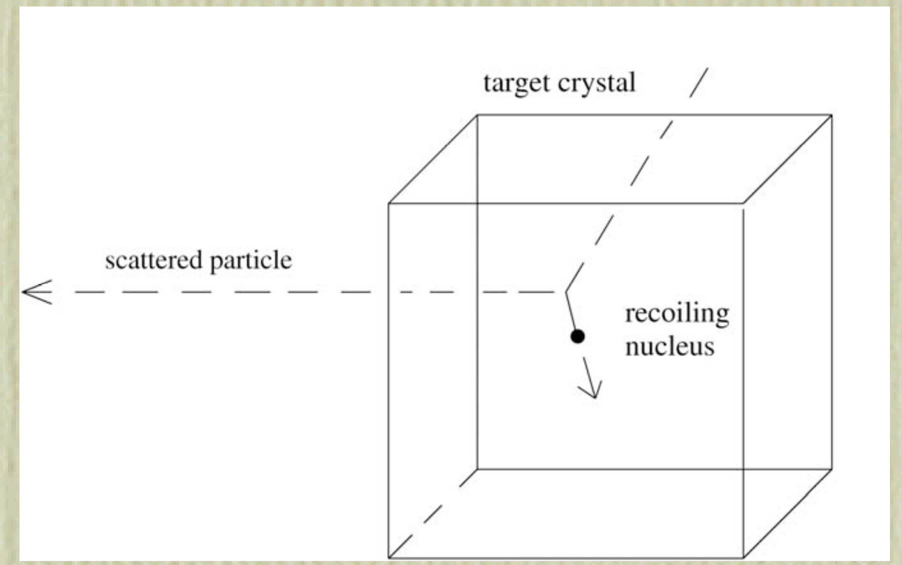
WIMP couplings to ordinary matter



WIMP coupling to ordinary matter ???



Direct detection:



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

The detection rate takes 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

Spin-dependent versus spin-independent

For WIMP DM in the form of Majorana fermions, there are two terms contributing to the scattering cross section in the non-relativistic limit:

not coherent

Axial-vector
(spin-dependent)

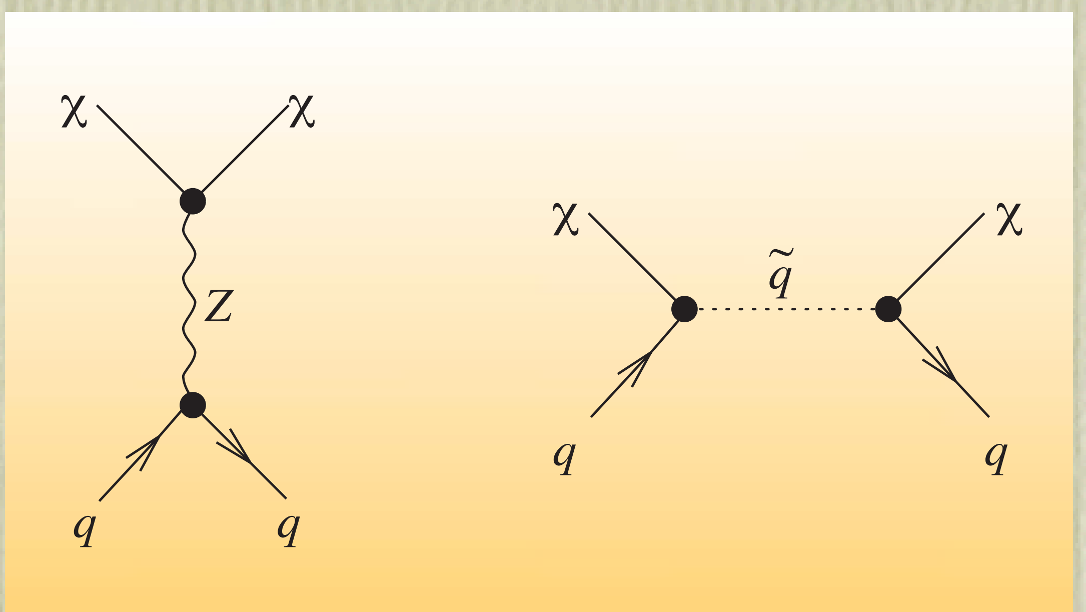
$$\mathscr{L}_A = d_q \; \bar{\chi}\gamma^{\mu}\gamma_5\chi\bar{q}\gamma_{\mu}\gamma_5 q$$

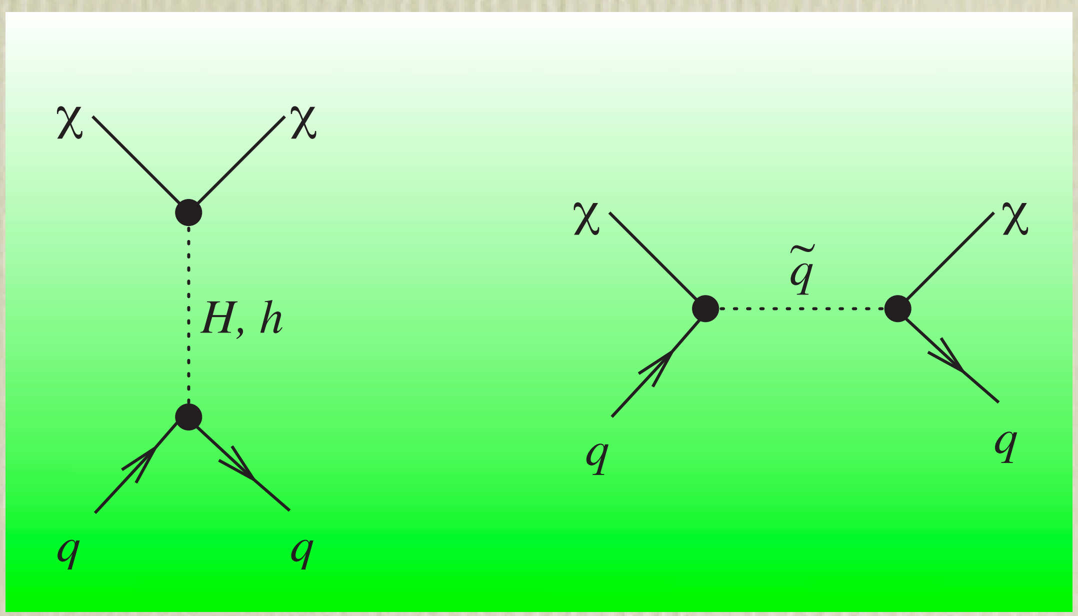
coherent

Scalar
(spin-independent)

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

In case of neutralinos in the MSSM:





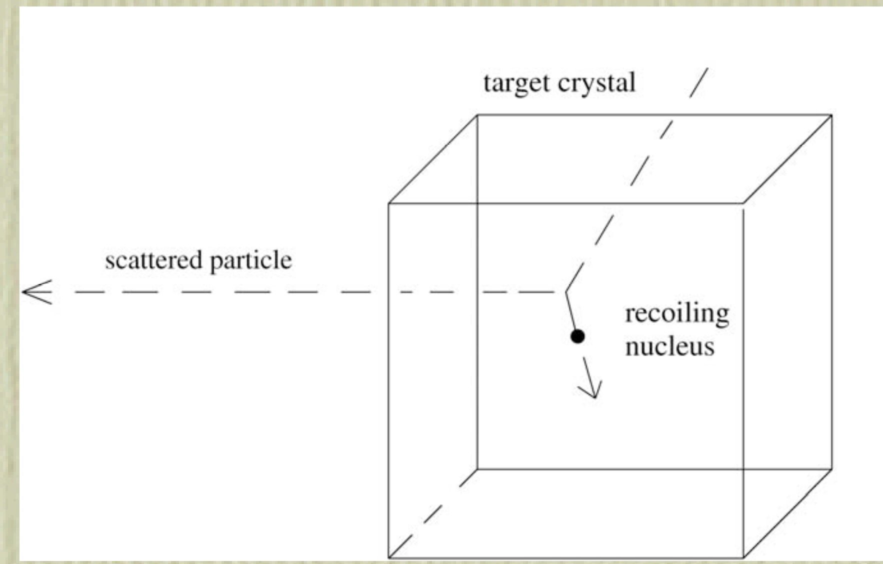
For dirac fermions also:

coherent

$$\text{Vector: } \mathscr{L}^q_{vec} = b_q \; \bar{\chi}\gamma_{\mu}\chi\,\bar{q}\gamma^{\mu}q$$

For spin-0 or spin-1 WIMPs the discussion is analogous.

Direct detection:



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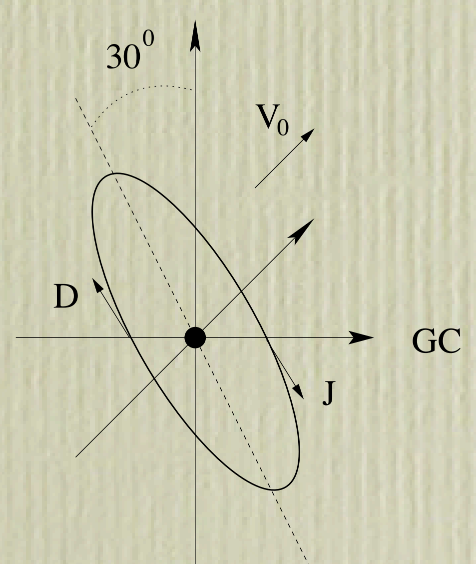
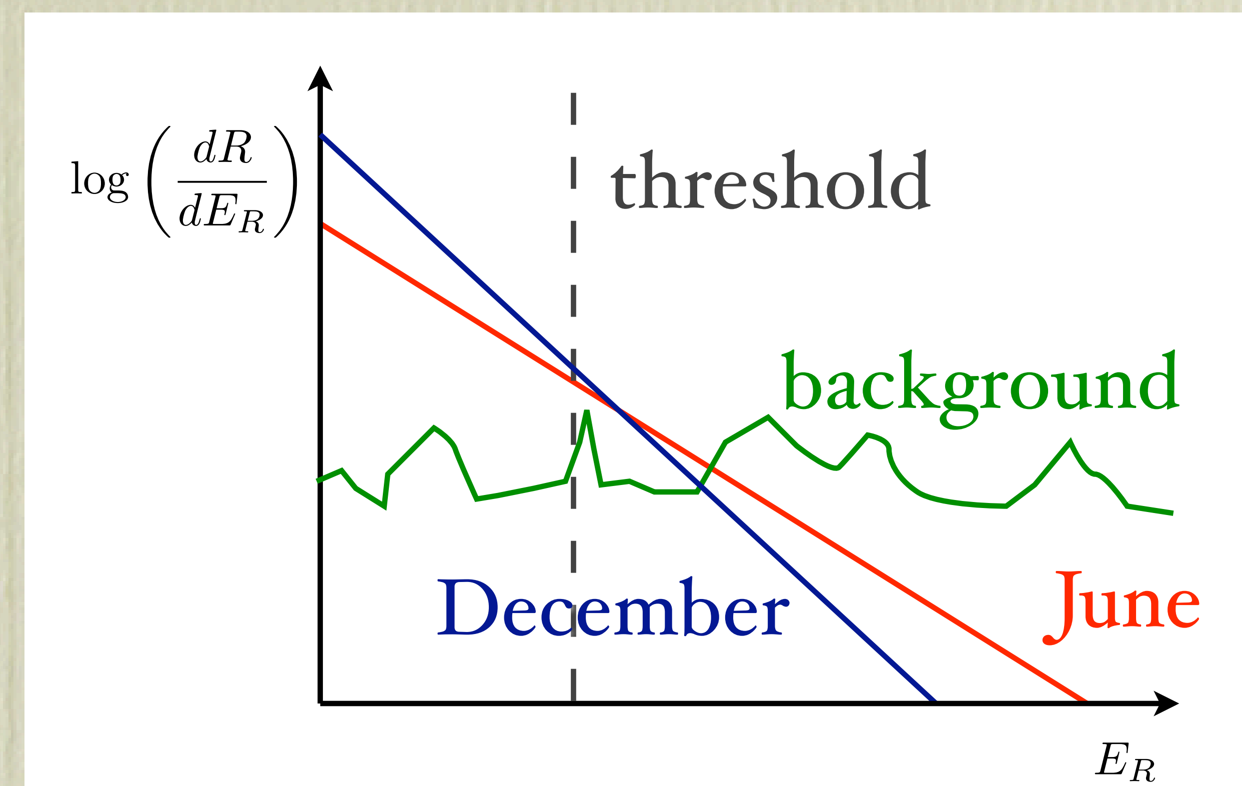
WIMP-nucleus cross section

WIMP DF

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

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

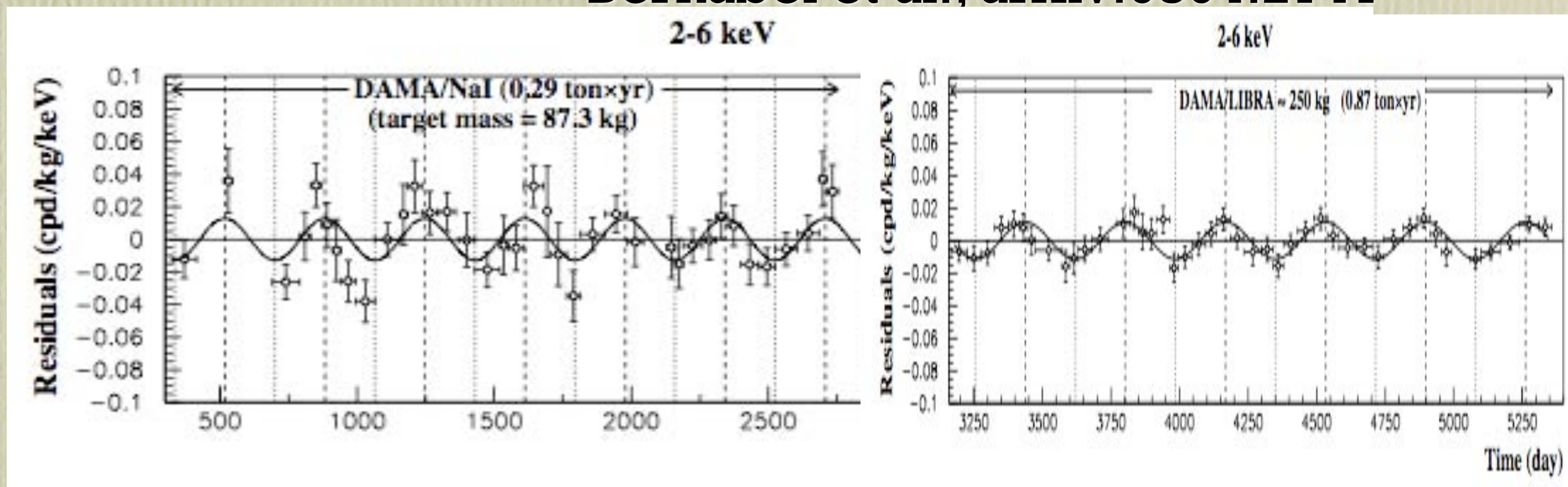




Annual modulation detected by DAMA/LIBRA

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



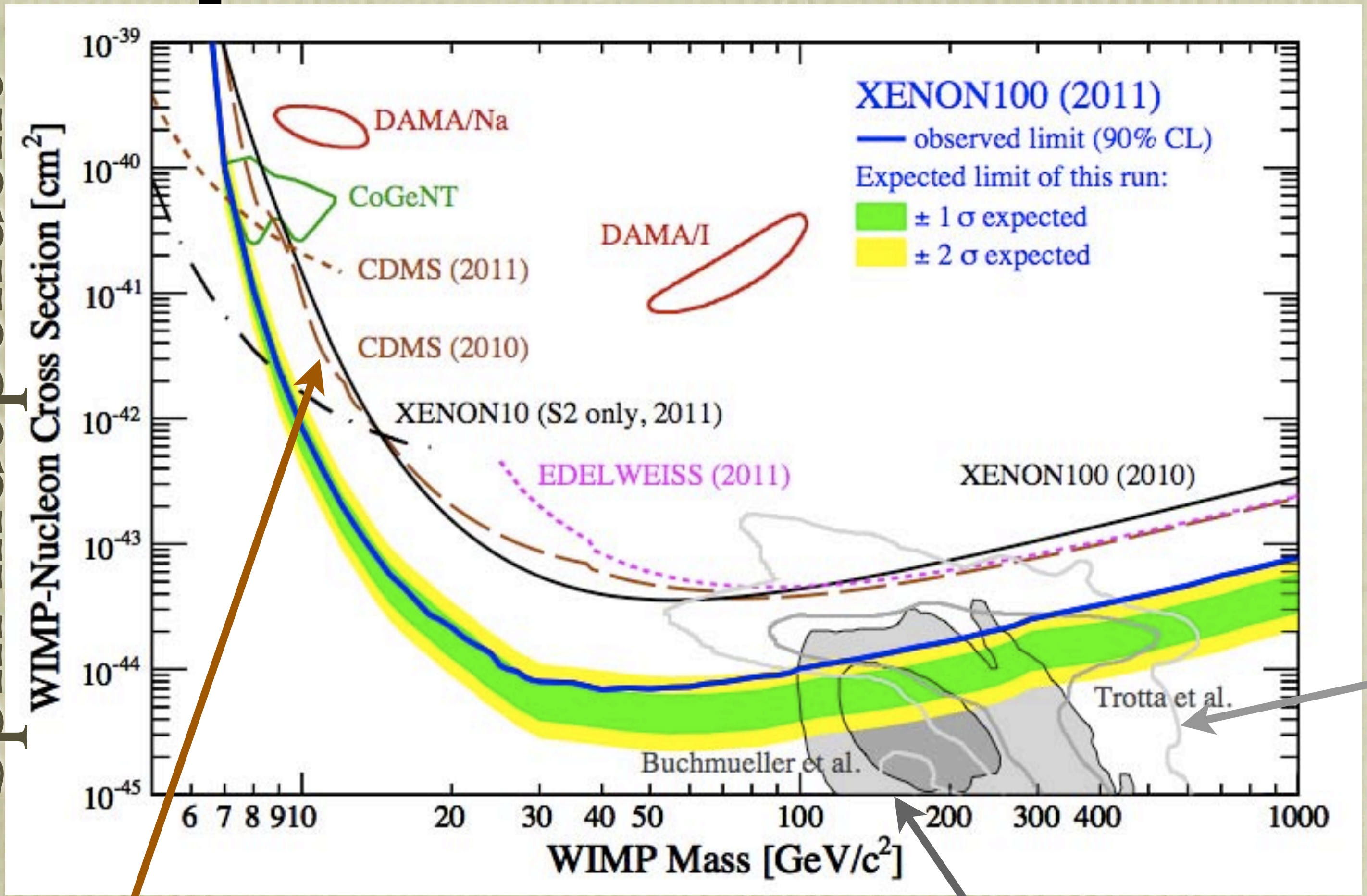
Bernabei et al., arXiv:1002.1028

By now 12 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.

XENON & CDMS II set upper limits:

Aprile et al., arXiv:1104.2549

Spin independent



Background rejection based on multi-channel analyses. The limits are already setting relevant constraints on well-motivated particle physics models, such as:

Neutralino DM within the CMSSM, Trotta et al., arXiv: 0809.3792

Ahmed et al., arXiv:0912.3592

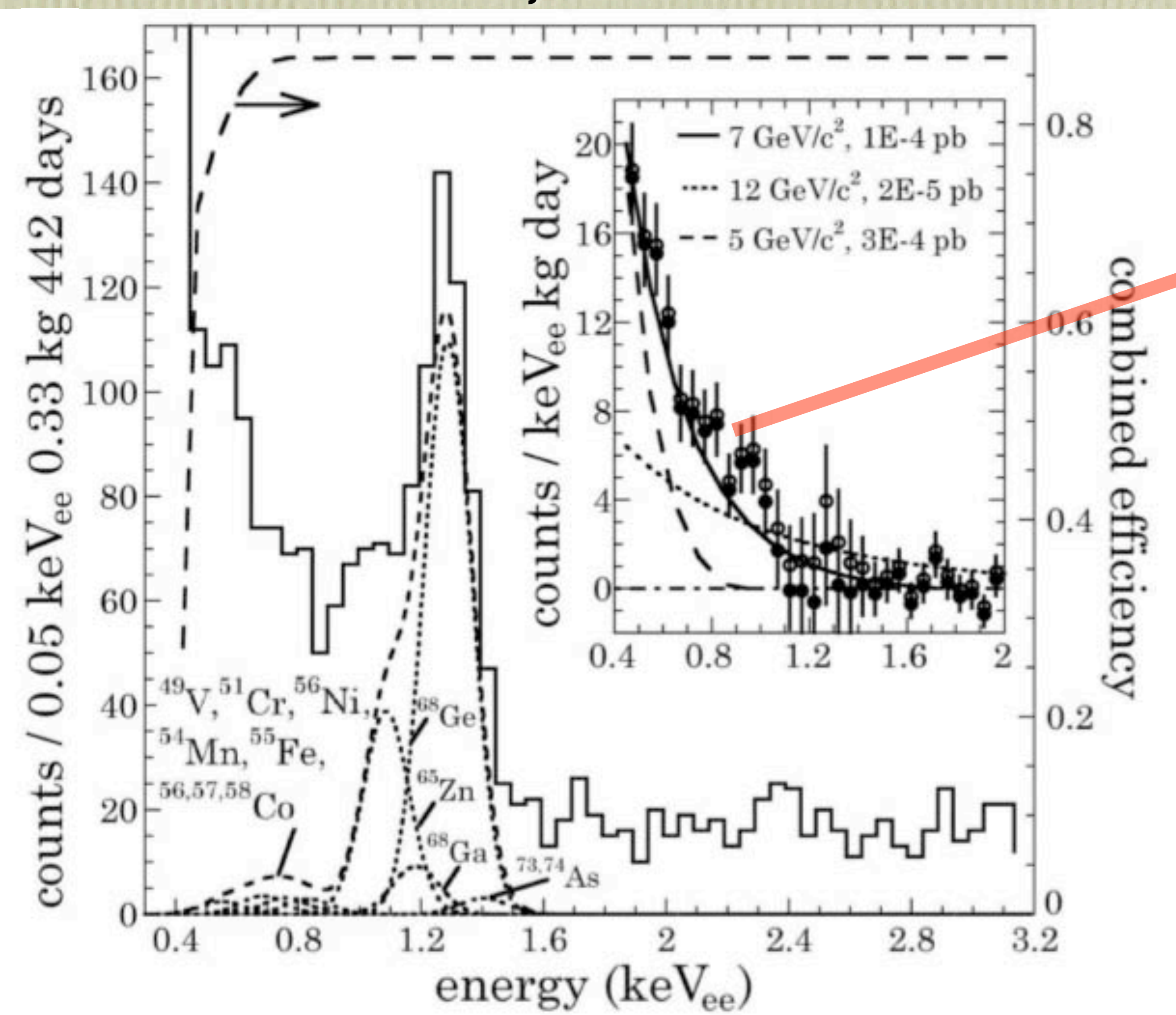
Buchmueller et al., arXiv: 1102.4585 - same model but updated LHC constraints

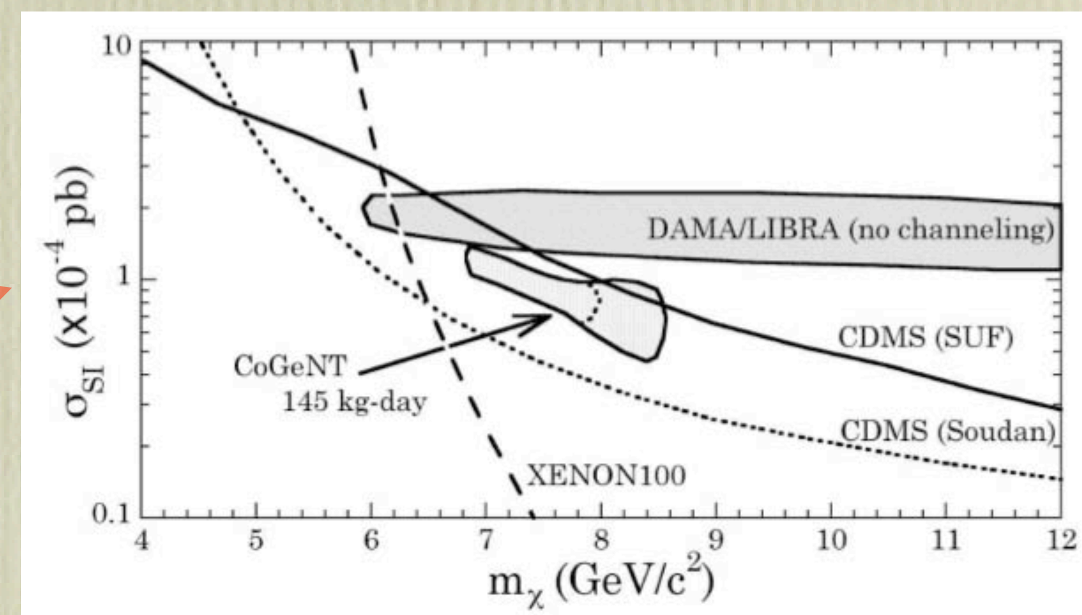
Final goal: ton-scale detectors increasing the present sensitivities of a factor of 100 (1000???)

Recent detection (hints) from CoGeNT & CRESST II:

CoGeNT: Small Ge detector with very low threshold, excellent energy resolution and extremely low noise: an exponential tail not straightforwardly identifiable as background; it is a DM signal ?

Aalseth et al., arXiv:1106.0650





again tension with other experiments

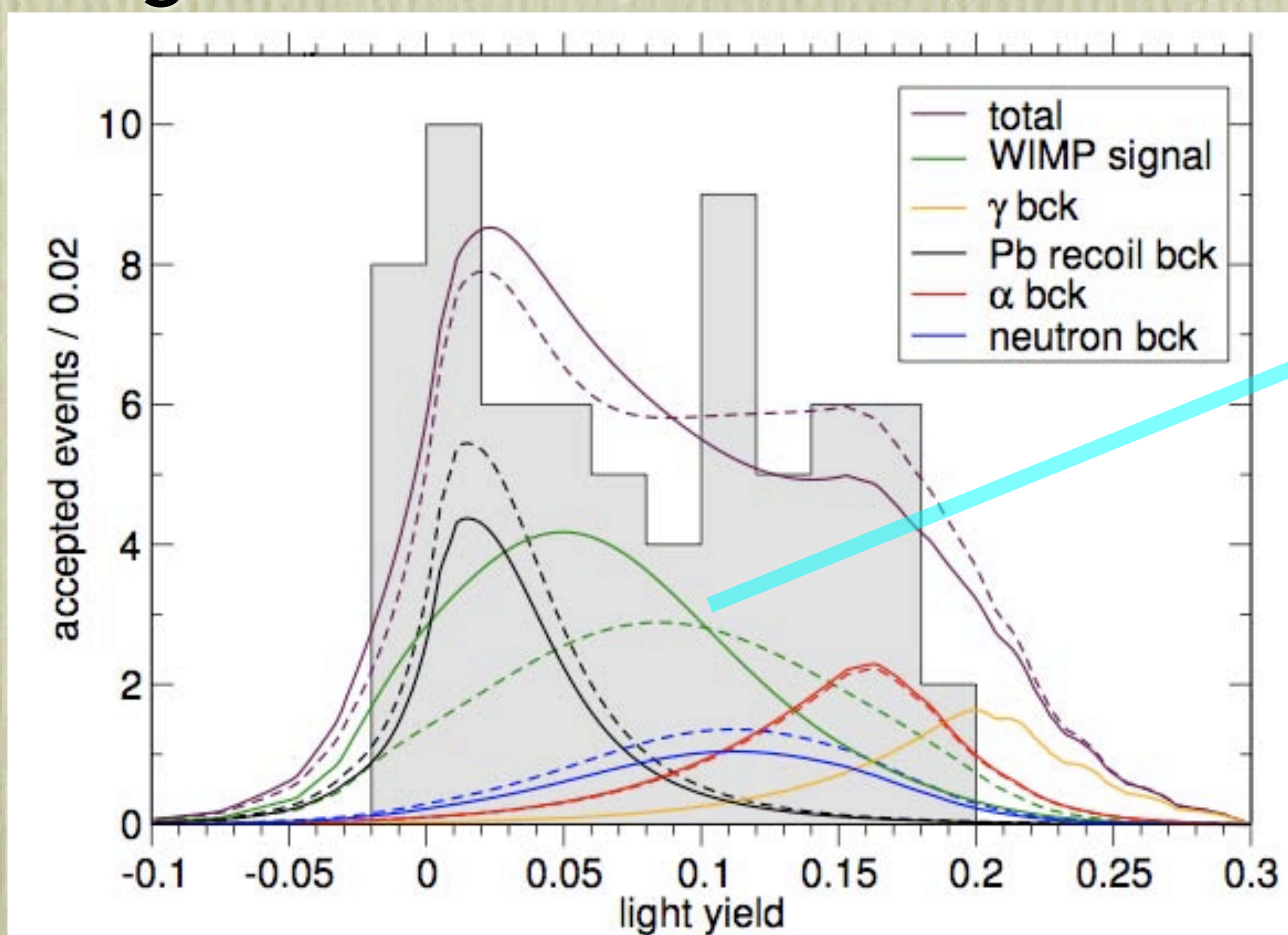
light neutralinos in the MSSM (no gaugino mass unification) (?)

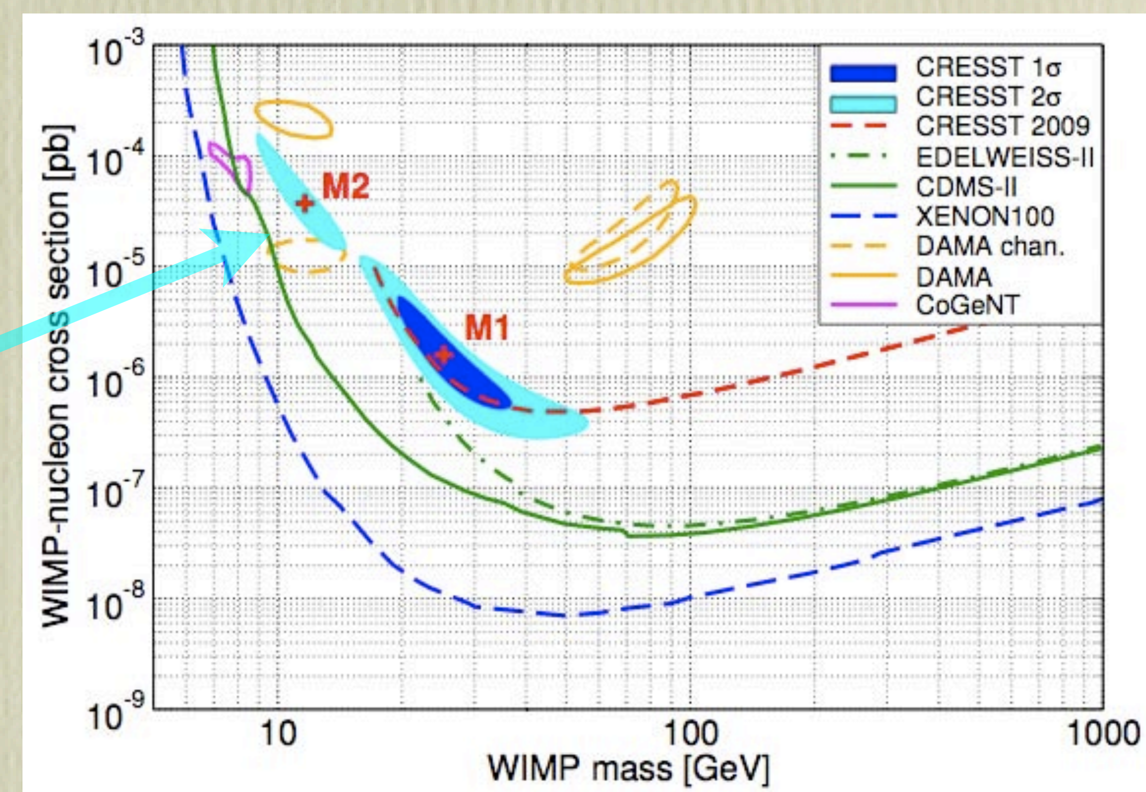
Bottino et al., arXiv:0912.4025

Recent detection (hints) from CoGeNT & CRESST II:

CRESST II: $CaWO_4$ detector with 2-channel readout, found 67 events and estimated with a significance larger than 4 σ that backgrounds cannot explain all of them:

Angloher et al., arXiv:1109.0702





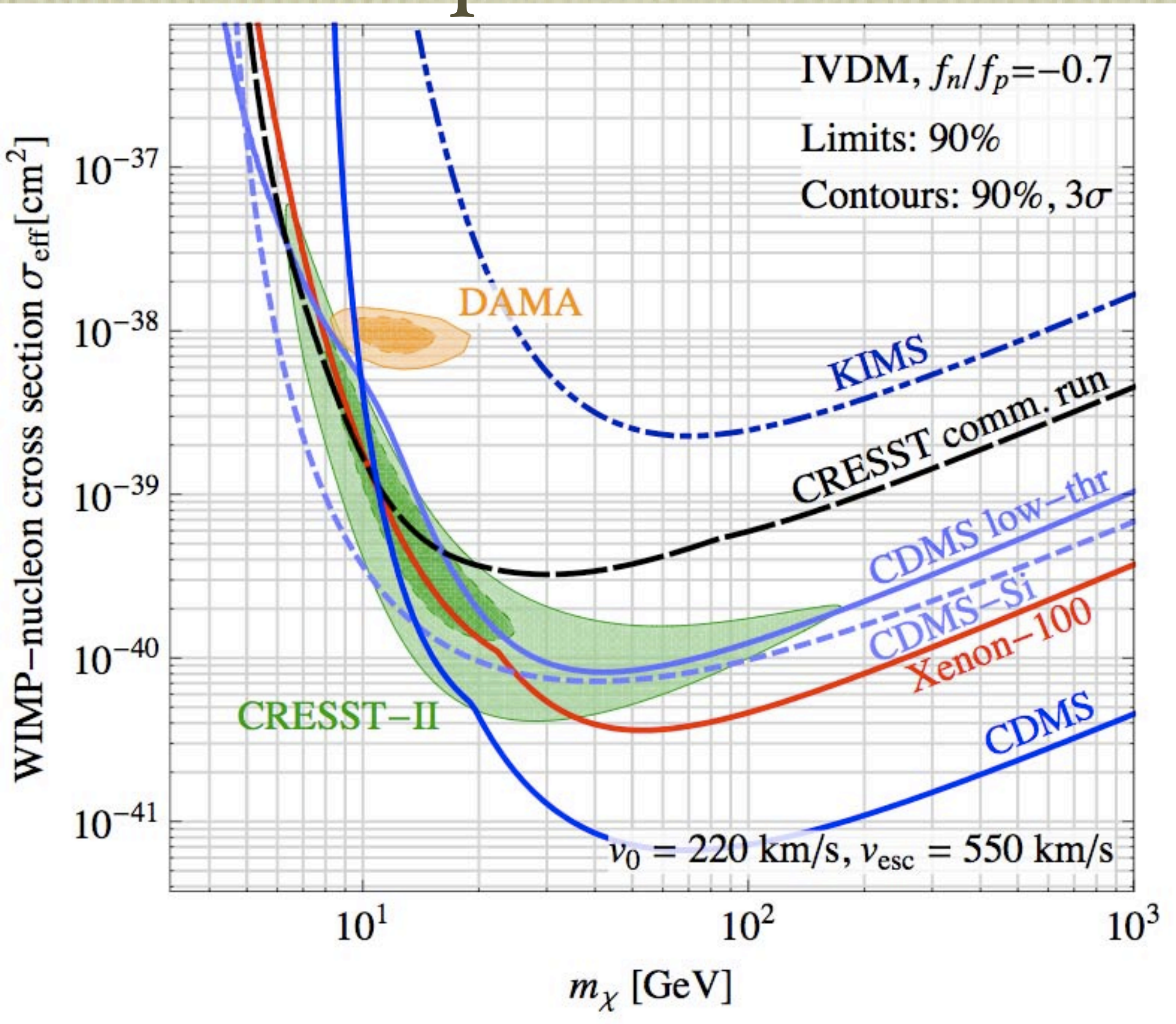
once more tension with other experiments within this interpretation

Putting all within the same WIMP framework:

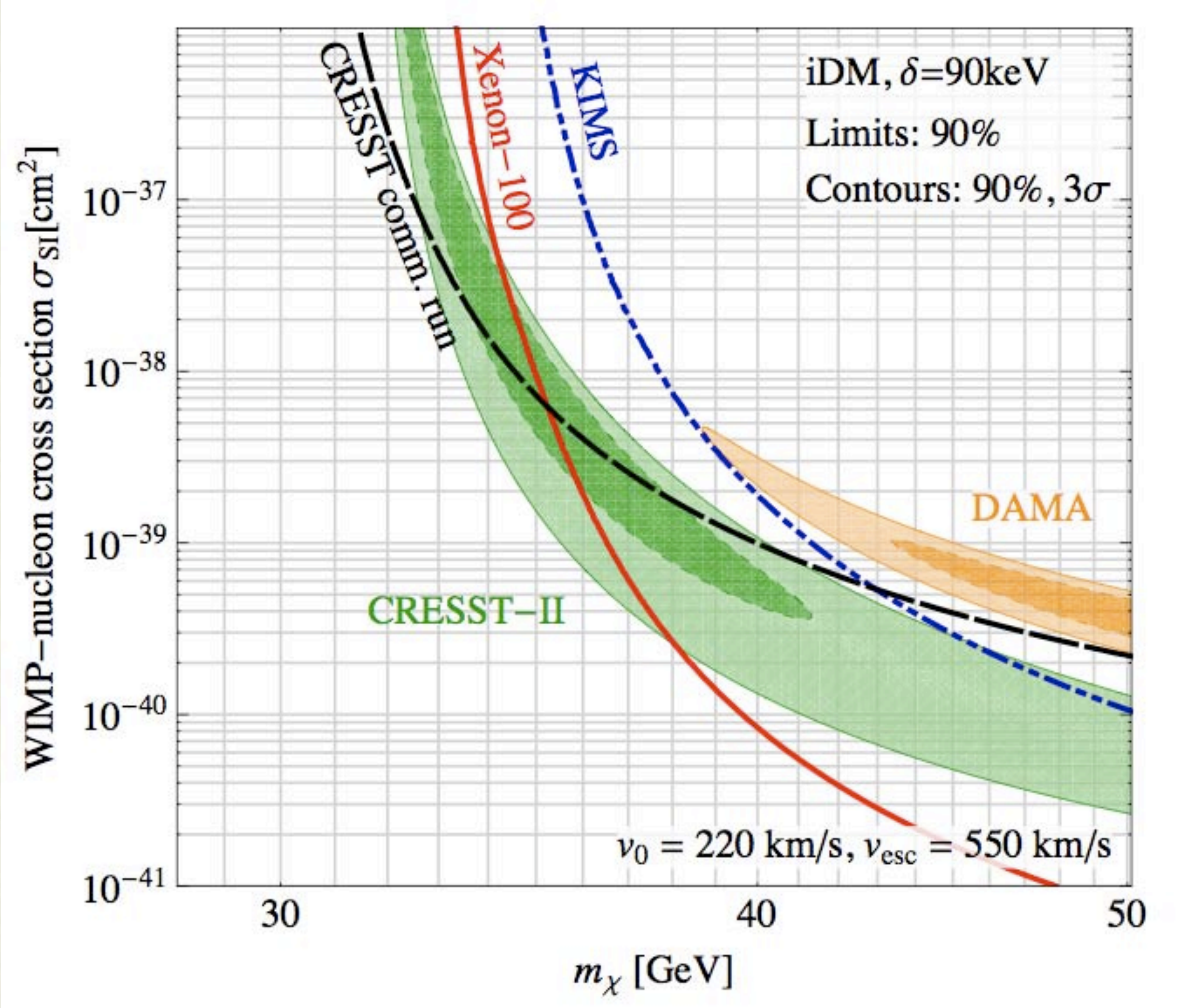
Several recent analyses exploring less standard scenarios and comparing to each detector response (with slightly different results), e.g.:

Kopp et al., arXiv:1110.2721

Isospin Violation



Inelastic scattering



(Very) little room for accommodating one signal, a very hard (maybe impossible) task to reconcile all of them.

Putting all within the same WIMP framework:

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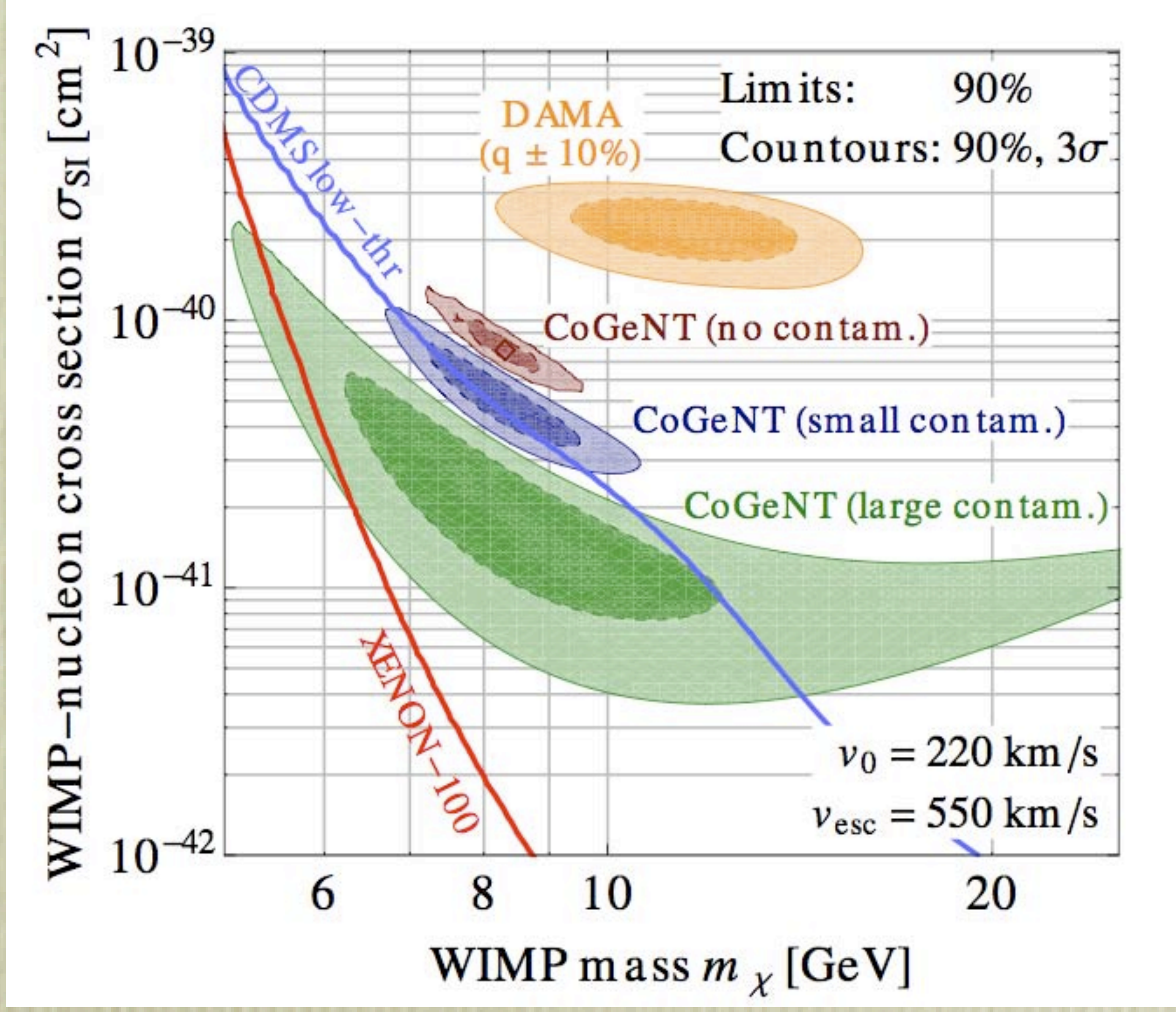
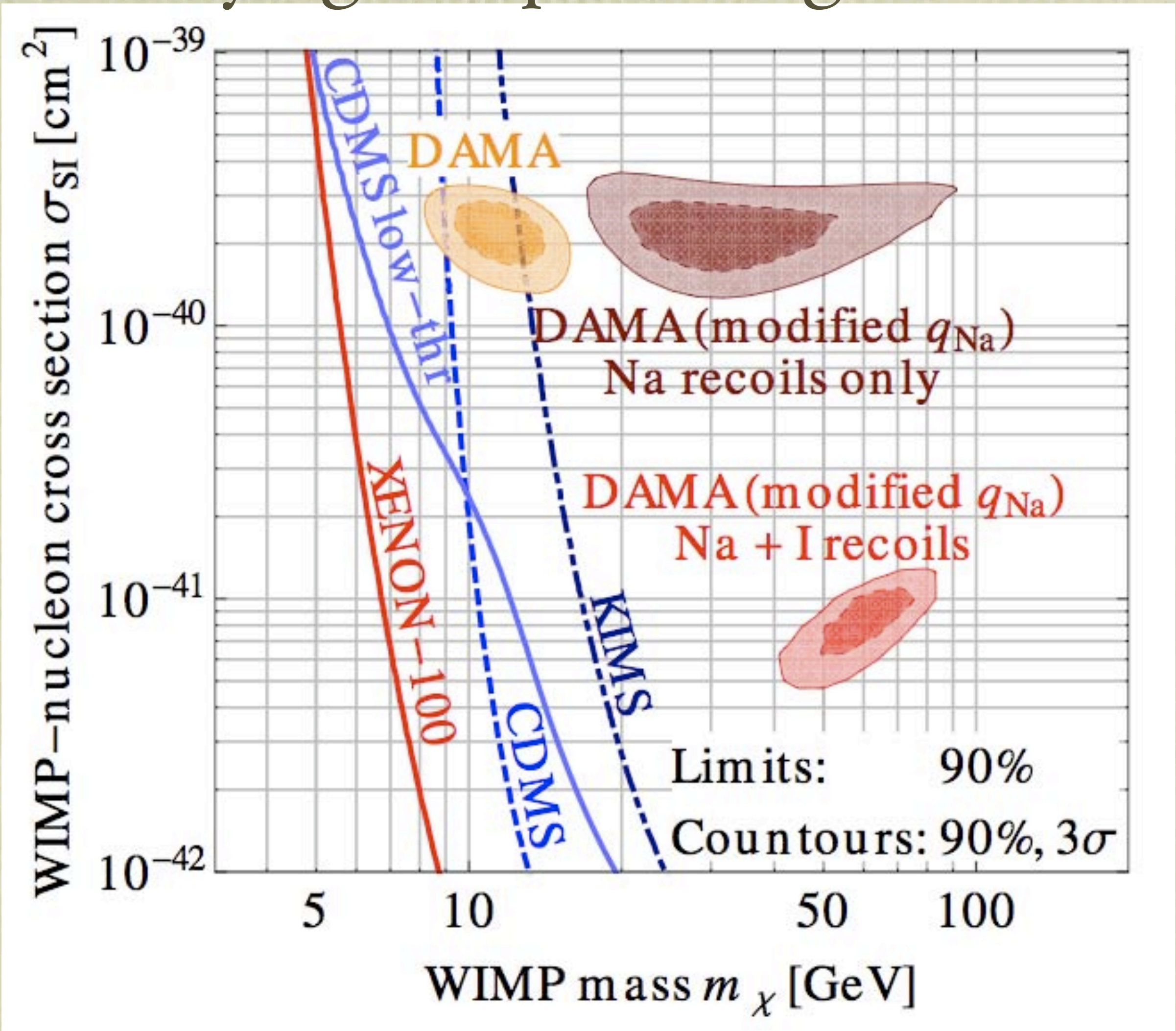
Kopp et al., arXiv:1110.2721

different background in CoGeNT

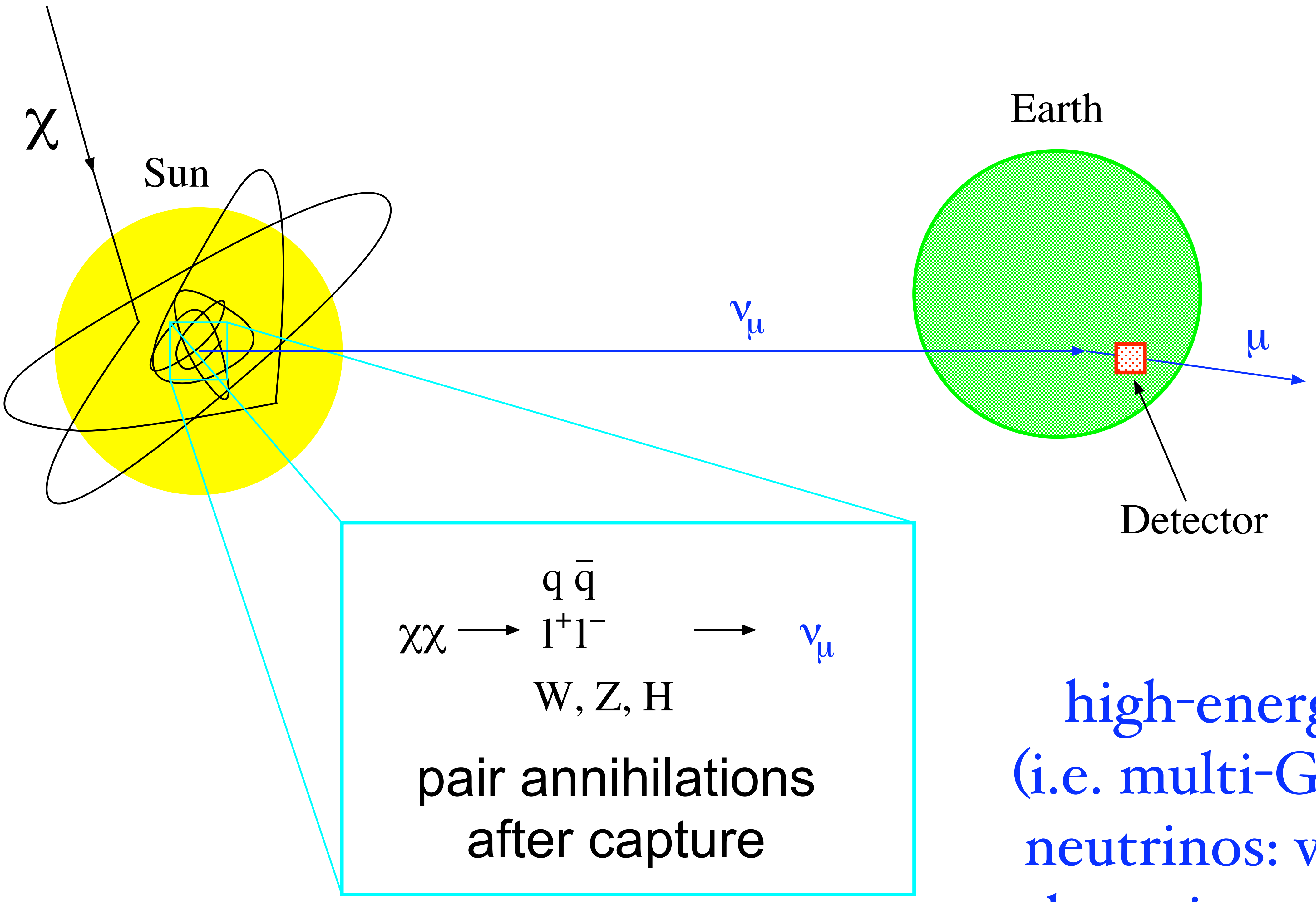


varying Na quenching factor



Should one trust all (any) of the results at phase value?

WIMP searches with neutrino telescopes



high-energy (i.e. multi-GeV) neutrinos: very clean signature!

The WIMP number density inside the Sun/Earth obeys the equation:

$$\frac{dN}{dt} = \underbrace{C_c}_{\text{capture}} - \underbrace{C_a}_{\text{annihilation}} N^2$$

which gives the WIMP annihilation rate:

$$\Gamma_a \equiv \frac{1}{2} C_a N^2 = \frac{1}{2} C_c \tanh^2(t/\tau)$$

with: $t = t_\odot \simeq 4.5 \cdot 10^9$ years & $\tau \equiv 1/\sqrt{C_c C_a}$.

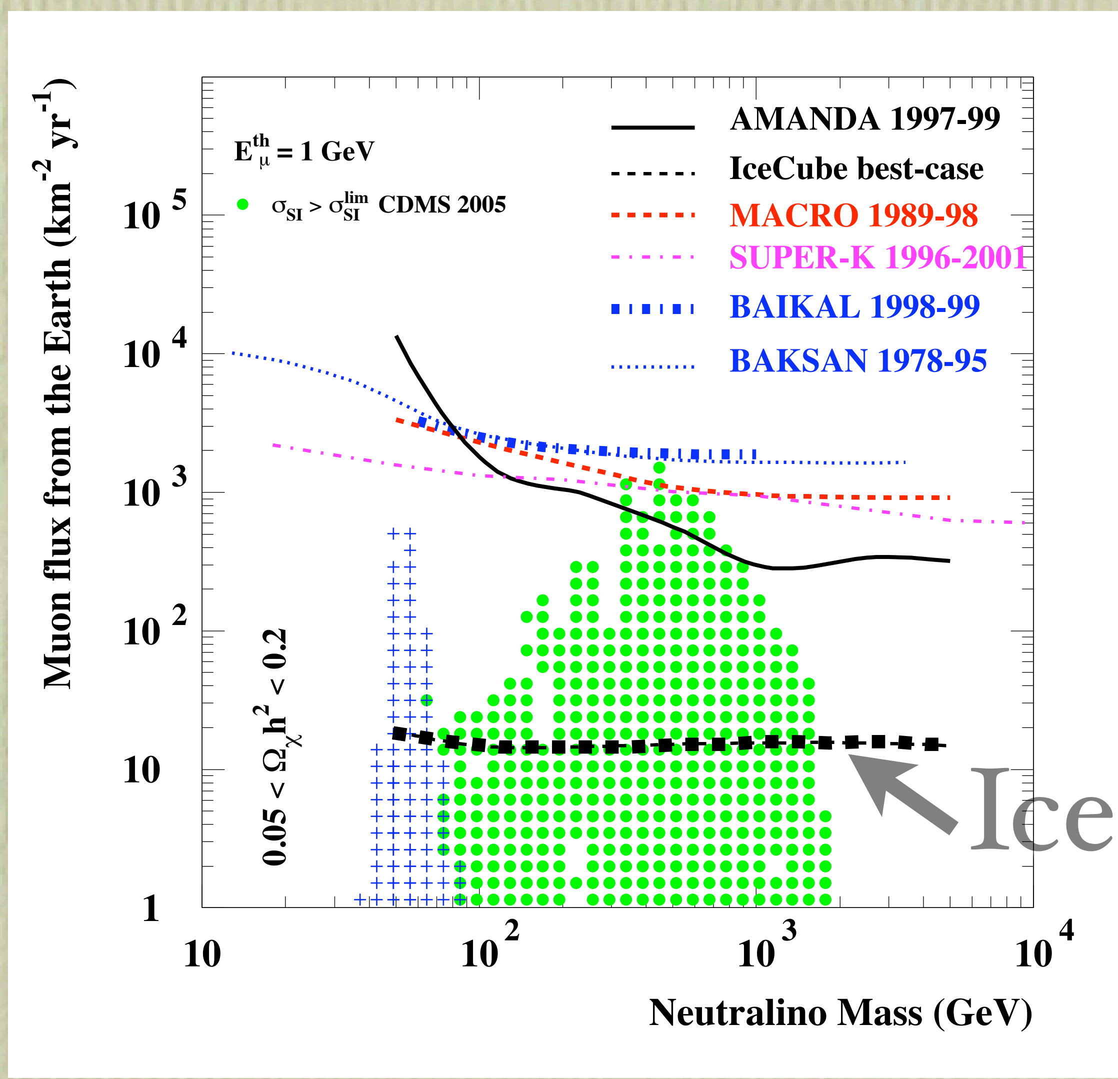
For $\tau \ll t_\odot$ capture and annihilation have reached equilibrium:

$$\Gamma_a = \frac{1}{2} C_c \longrightarrow \Phi_\mu \begin{cases} \underset{\sim}{\propto} \ \sigma^{SD}_{\chi\, p} & \text{Sun} \\ \propto \ \sigma^{SI}_{\chi\, p,n} & \text{Earth} \end{cases}$$

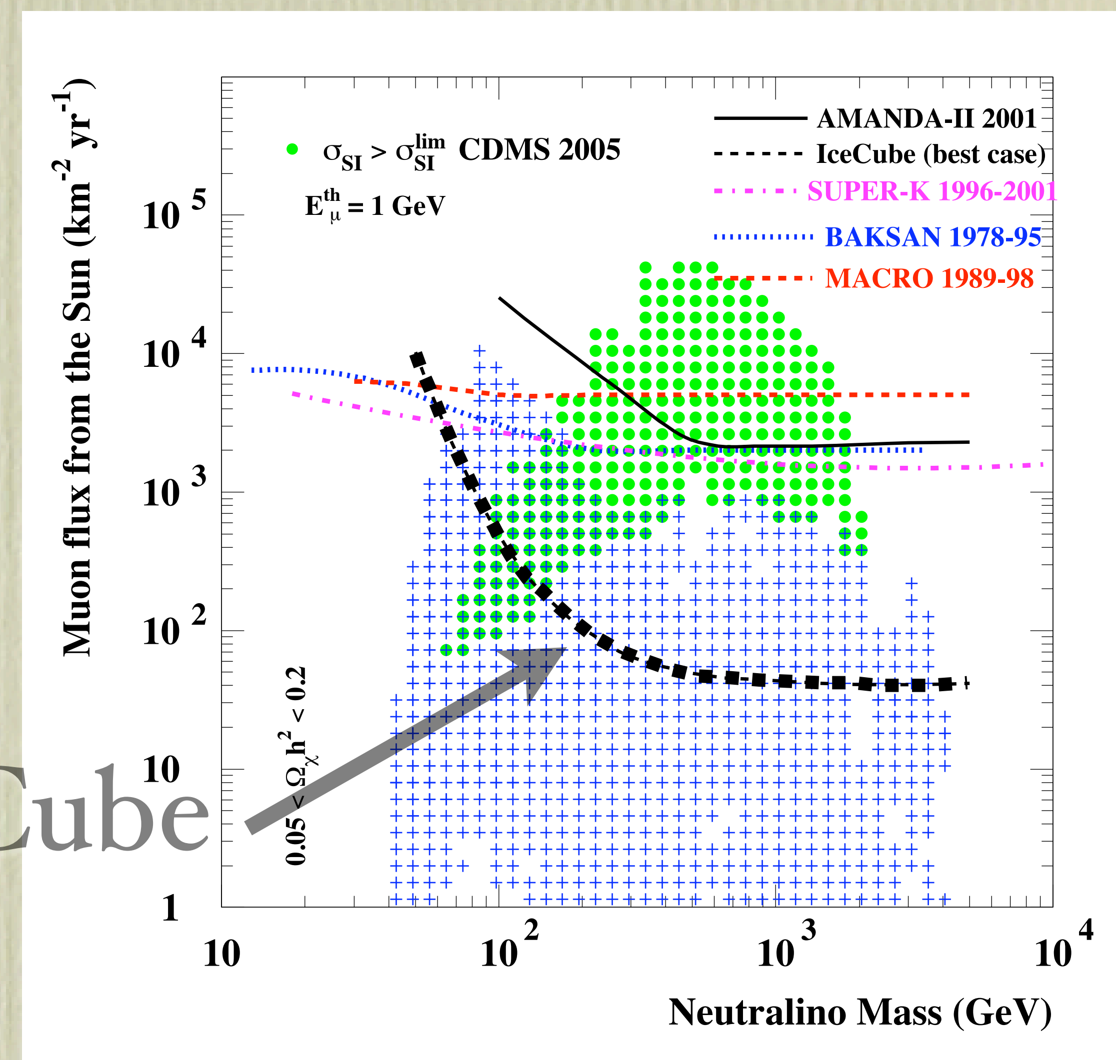
(??? - rarely in equilibrium)

The ν signal from the Earth versus the ν signal from the Sun, keeping in mind direct detection results: the standard lore is that the Sun wins. E.g. a general scan for neutralino dark matter candidates within the MSSM:

Flux from the Earth



Flux from the Sun



IceCube

● model excluded by the 2005 CDMS SI limit

Icecube Collaboration & DarkSUSY, 2007

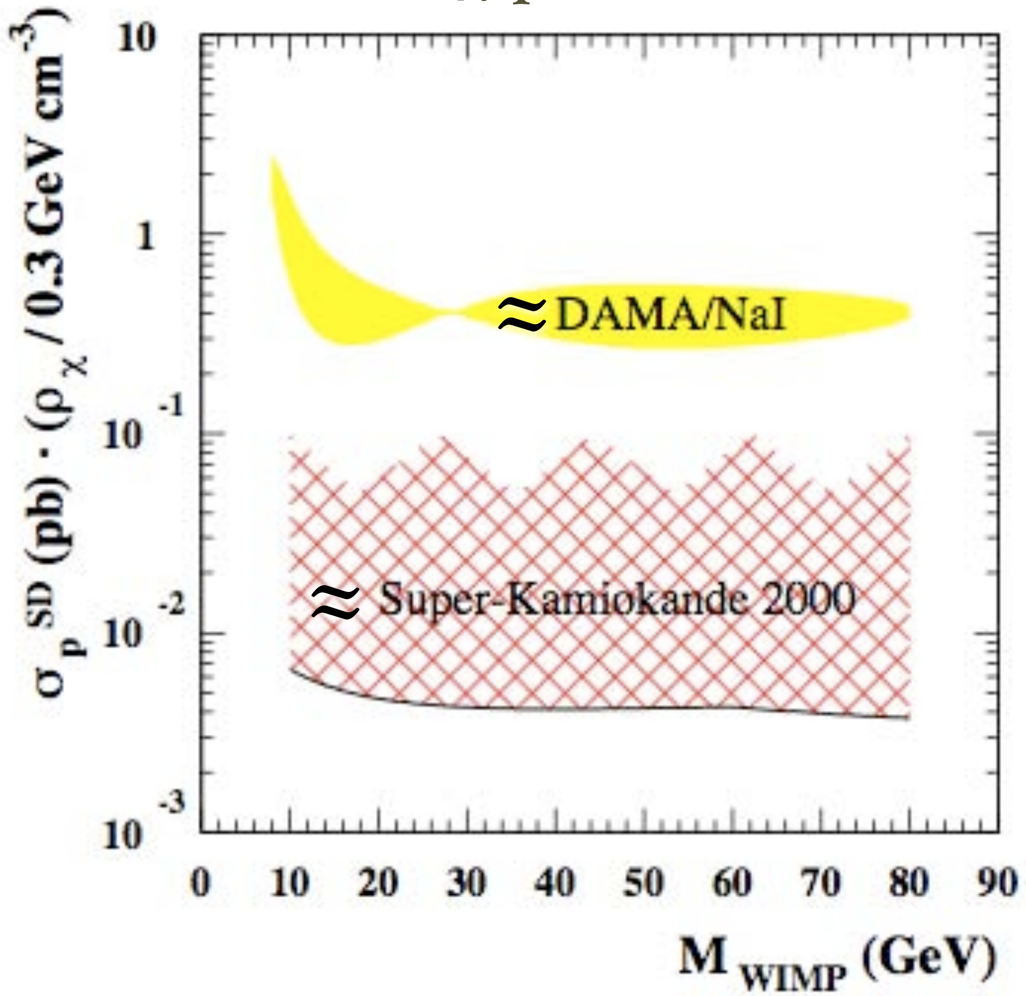
Direct detection versus neutrino telescopes

Test a given a positive signal in a direct detection experiment searching for a ν signal from the Sun, assuming (**Kamionkowski et al., 1995**):

I) equilibrium between capture and annihilation in the Sun;

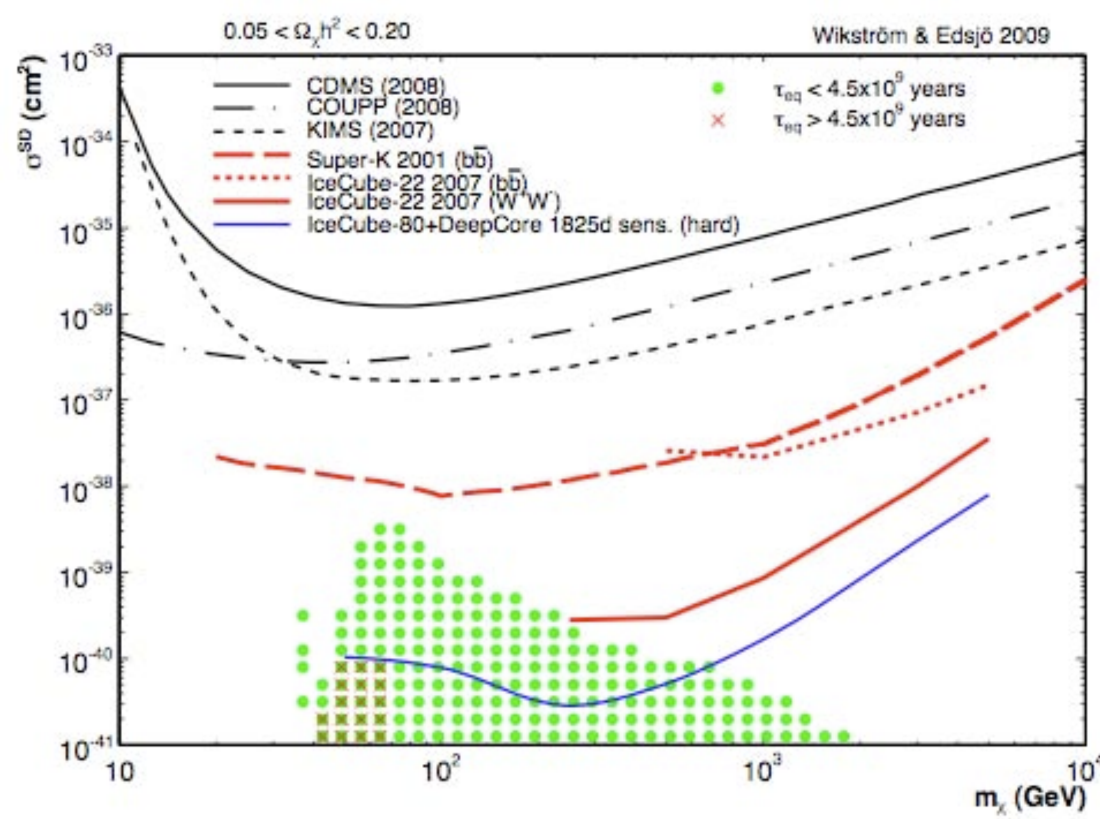
II) WIMP annihilation modes for which the ν yield is not suppressed.

DAMA/LIBRA annual modulation effect and χ-p SD interactions



P.U., Kamionkowski & Vogel,2001

comparison with recent χ-p SD searches



Wikström & Edsjo, 2009

WARNING: there are loopholes in these arguments

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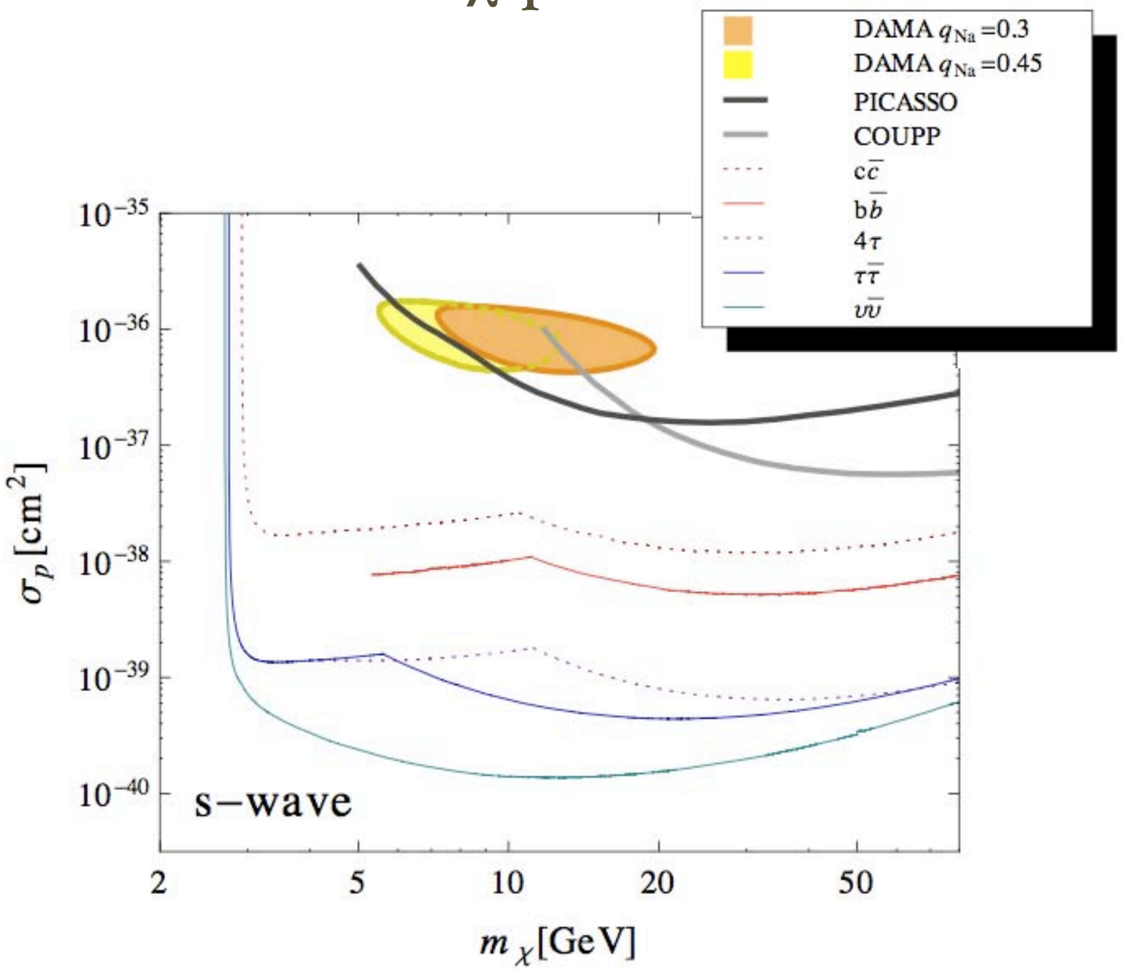

Knappl & Winkler, 2011

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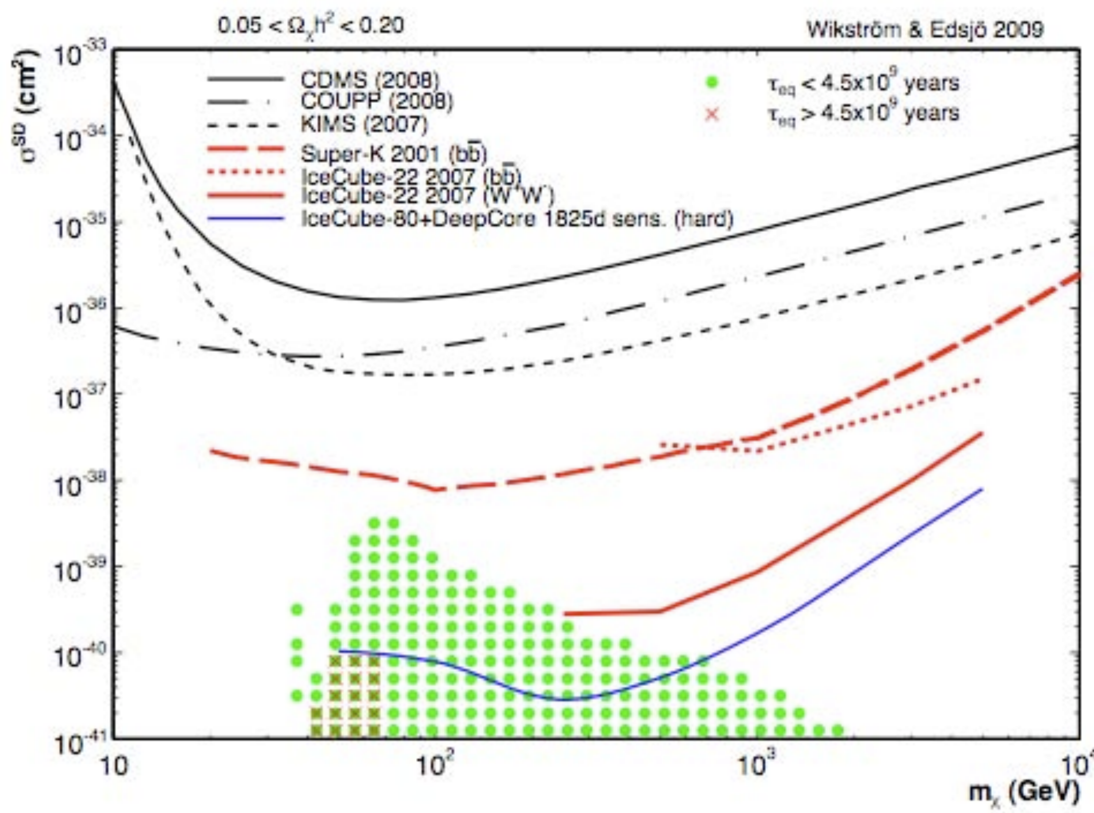

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Indirect detection of WIMP dark matter

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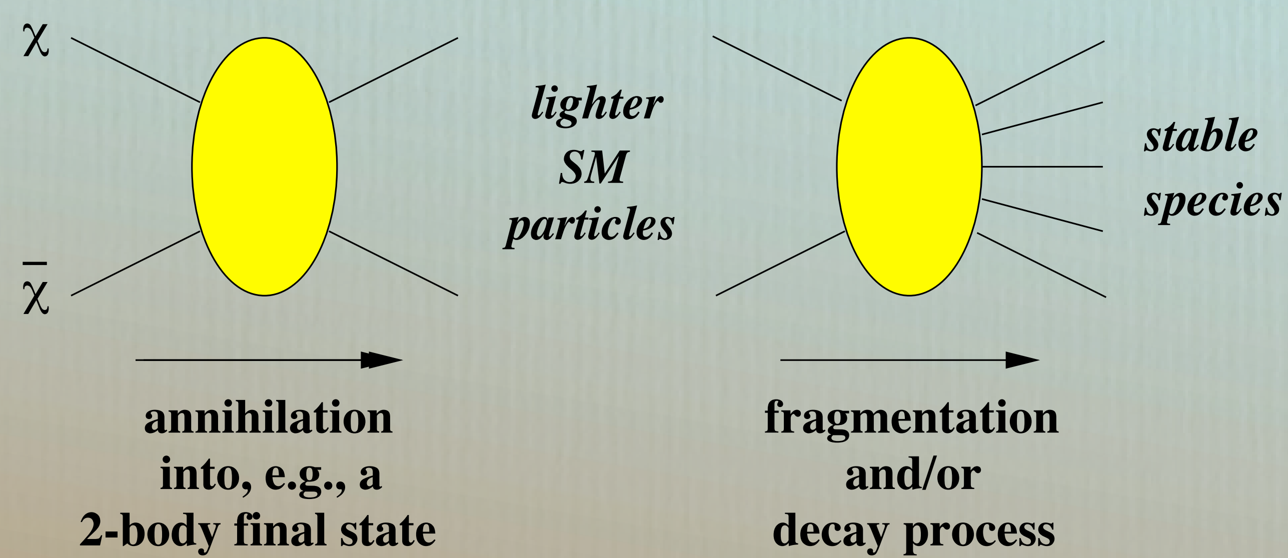
Pair annihilations of WIMPs in DM halos (i.e. at T≅0)



Focus on: antiprotons, positrons, antideuterons, gamma-rays, (neutrinos)

Search for the species with low or well understood backgrounds from other known astrophysical sources.

For "standard" annihilation rates, final states and DM density profiles, the ratio signal over background is the largest for antiprotons (antideuterons), can be sizable for gamma-rays, is fairly small for positrons and very small for neutrinos.

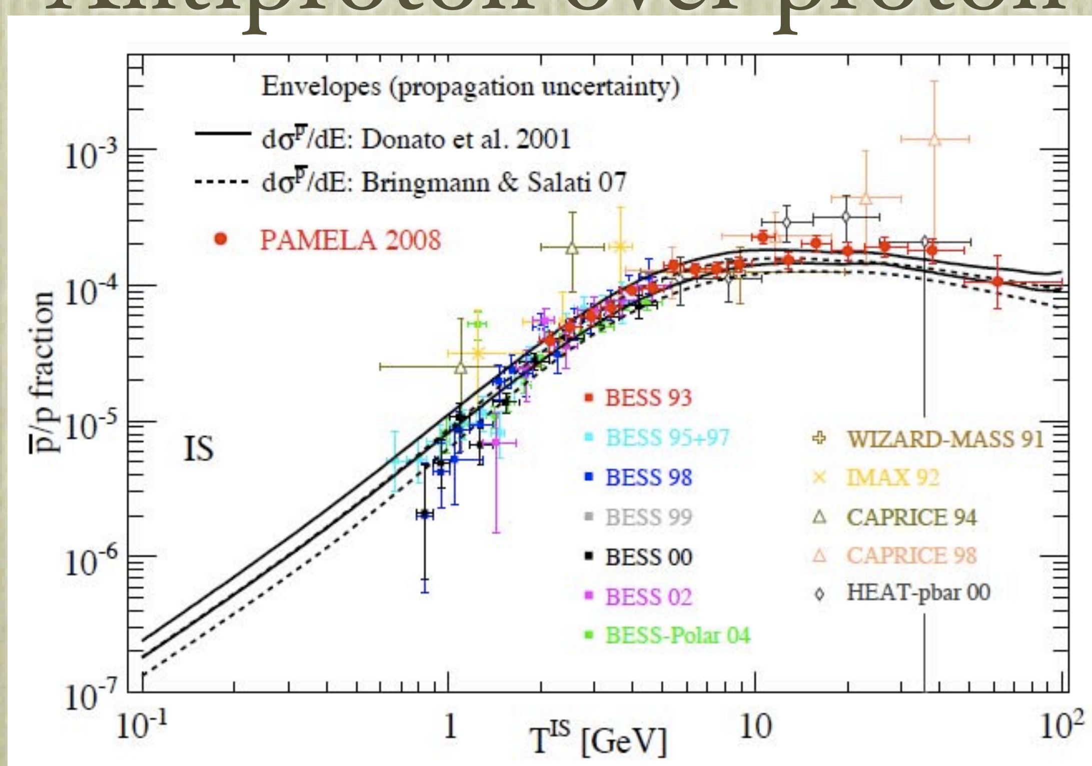
The p̄ measurements are consistent with secondaries:

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:

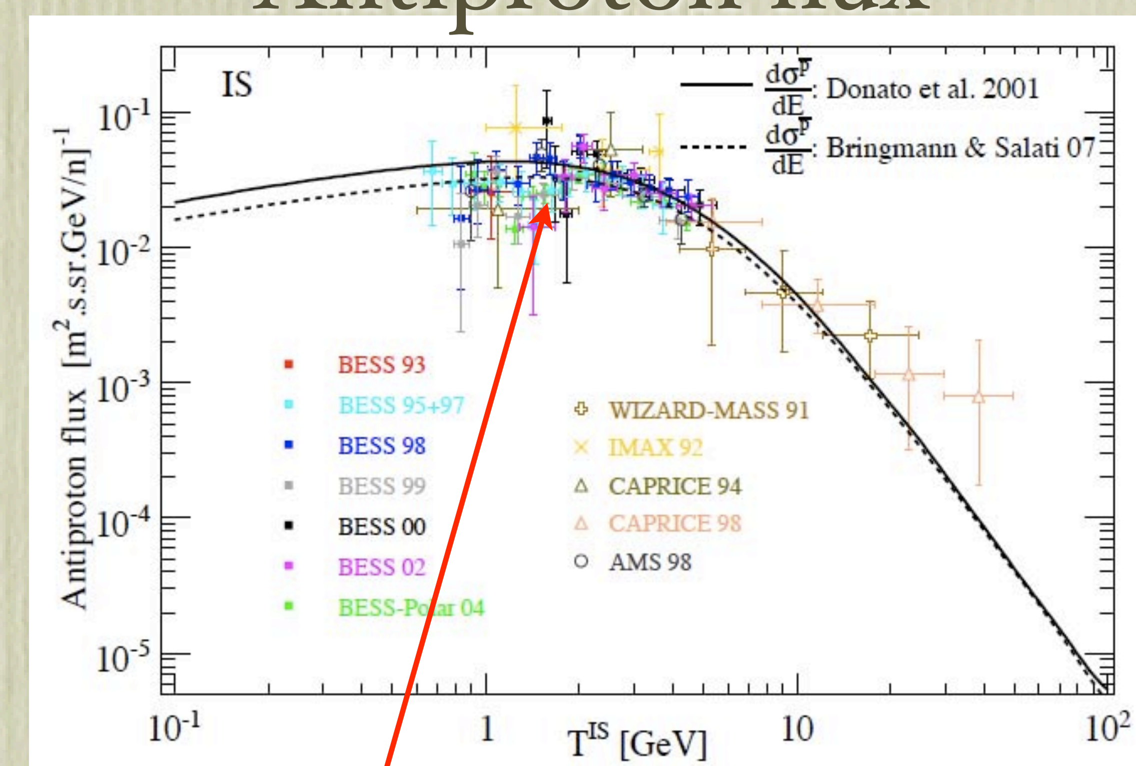
$$p + H \rightarrow 3\,p + \bar{p}$$

Use the parameter determination from the B/C ratio, to extrapolate the prediction for the p̄/p ratio: excellent agreement for secondaries only!

Antiproton over proton



Antiproton flux



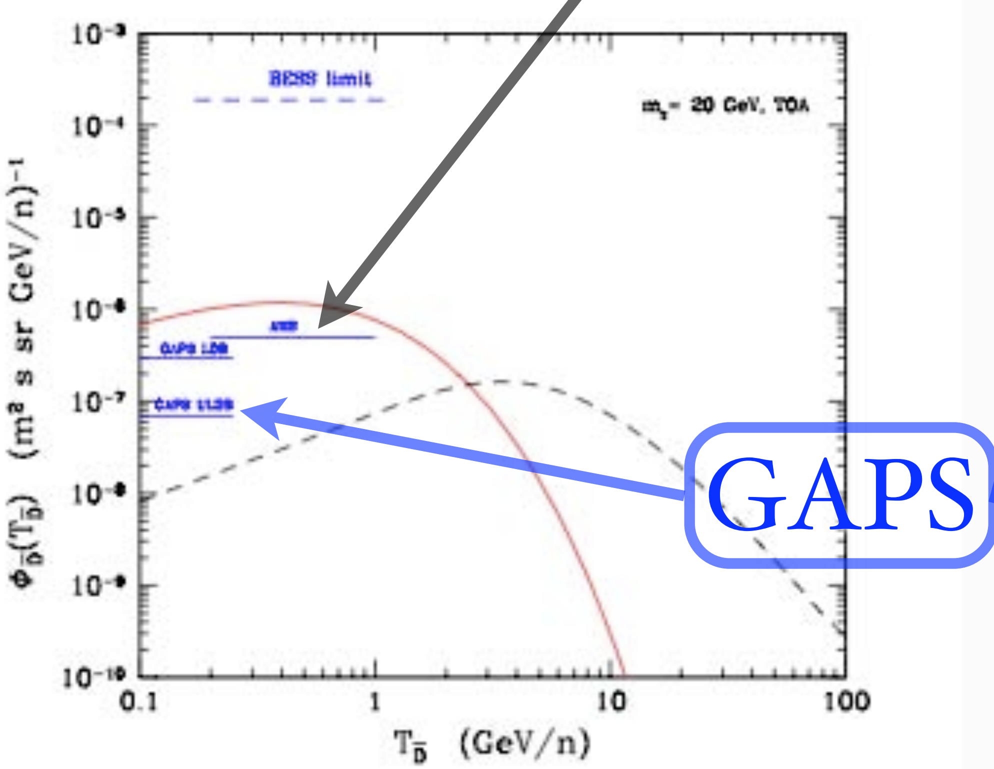
kinematic peak expected for secondaries, not for a primary component

Donato et al., arXiv:0810.5292

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

Antideuteron fluxes (& direct detection)

E.g., for light neutralinos in the MSSM (no gaugino mass unification) large $\bar{D}$ fluxes and a tight correlation with direct searches - this is not fully general.

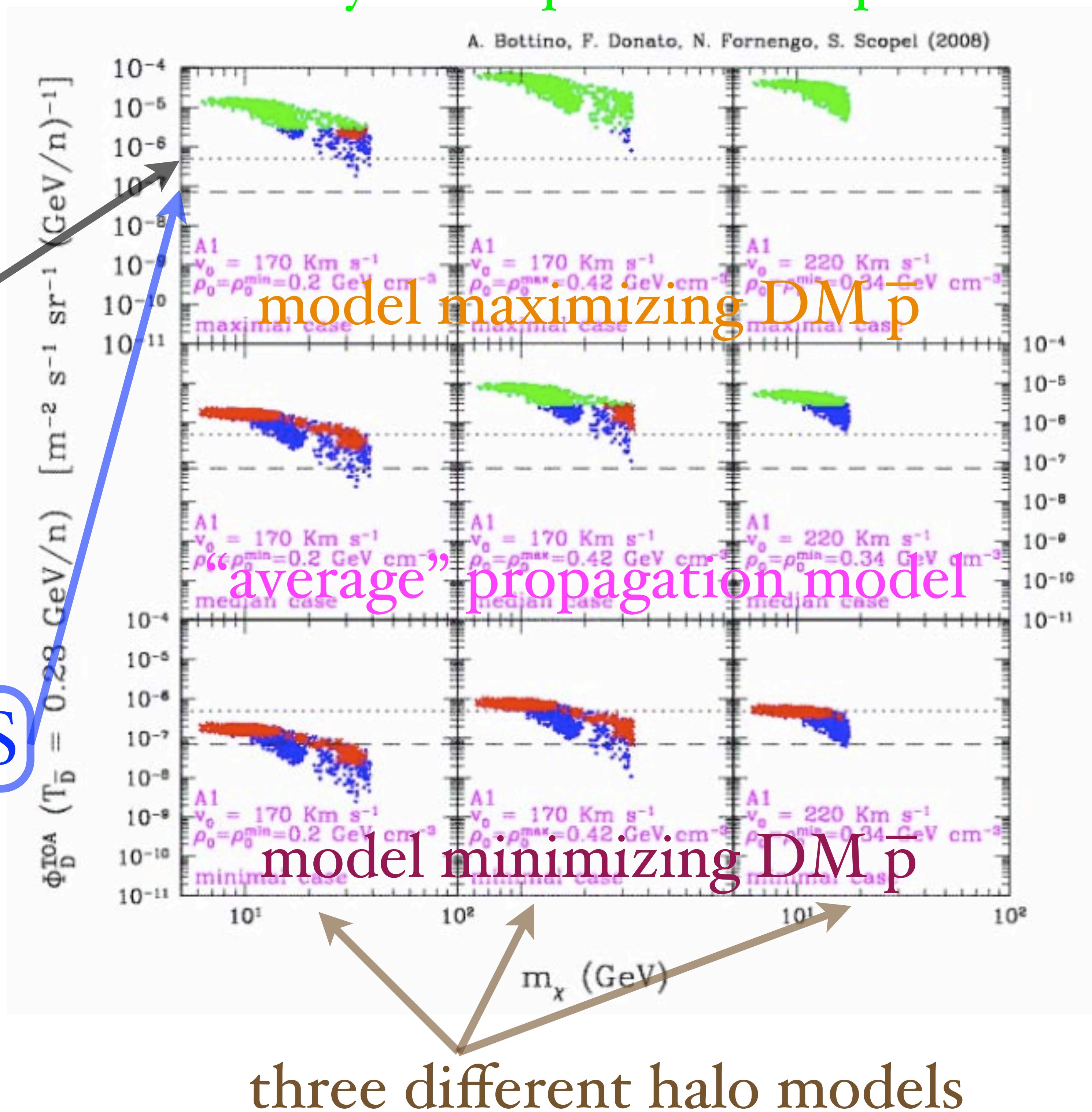


NOTE: much cleaner signature compared to $\bar{p}$

Red: compatible with DAMA and WMAP

Blue: compatible with DAMA but low Ω

Green: already incompatible with $\bar{p}$



Bottino, Donato, Fornengo & Scopel, 2008

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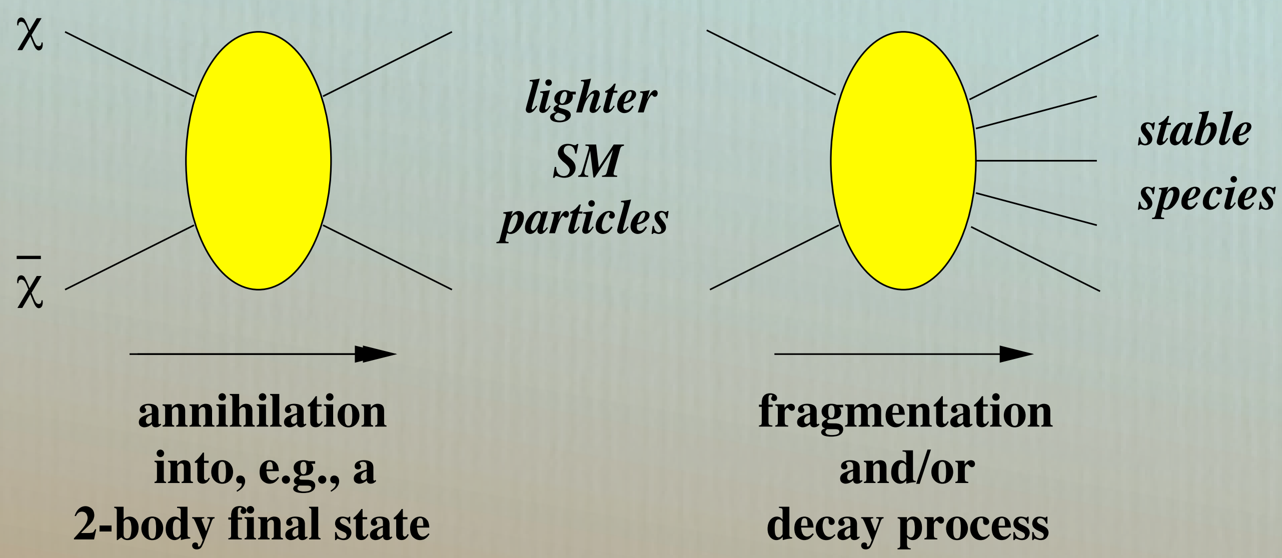


Focus on: antiprotons, positrons, antideuterons, gamma-rays, (neutrinos)

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?

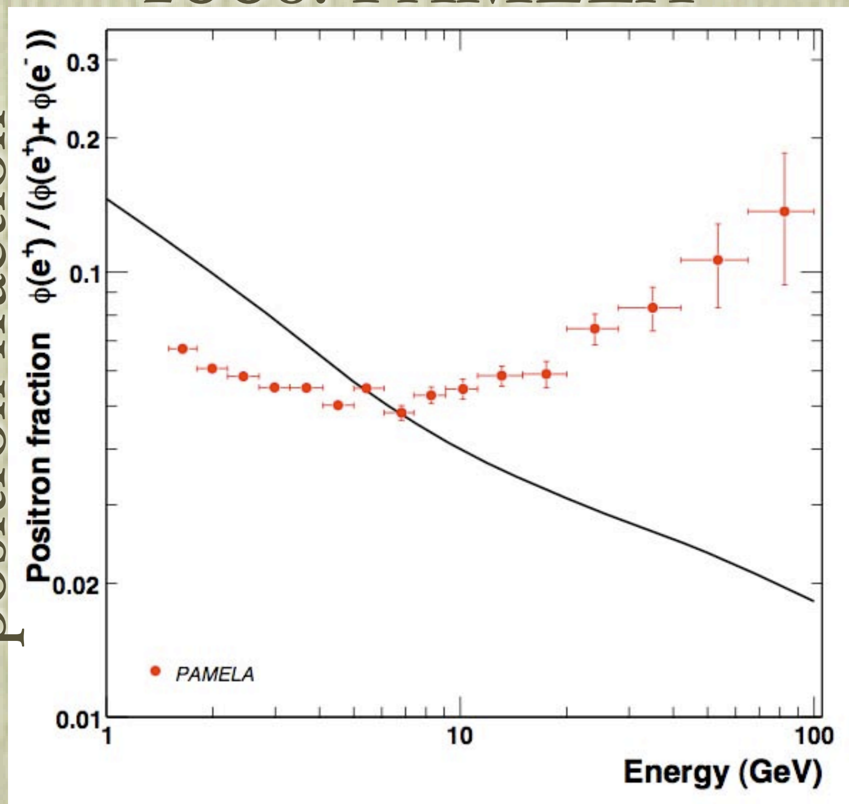
II) angular: flux correlated to DM halo shapes and with DM distributions within halos: central slopes, rich substructure pattern.

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:

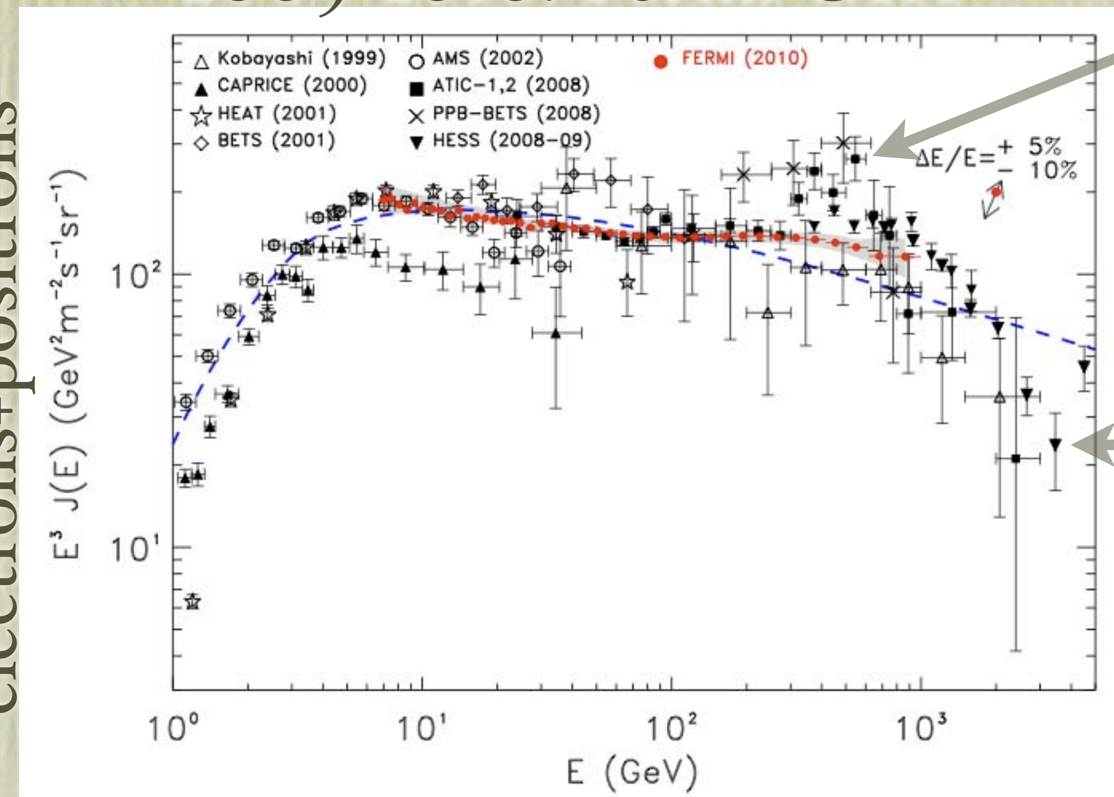
2008: PAMELA

positron fraction



2009-2010: Fermi GRT

electrons+positrons

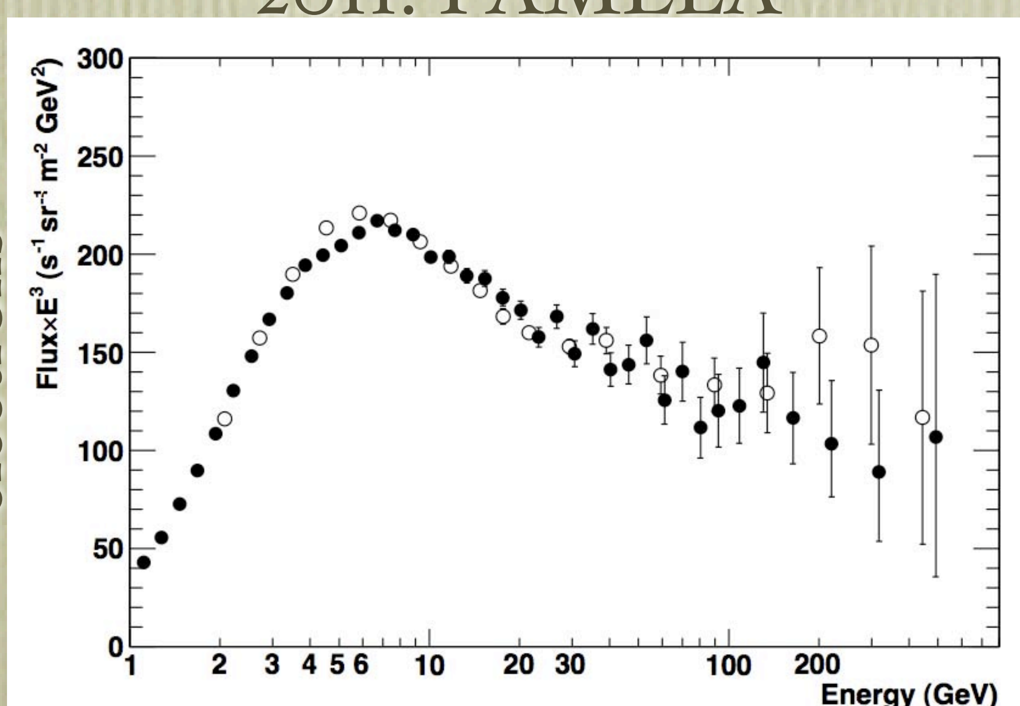


2008: ATIC

2008/9: HESS

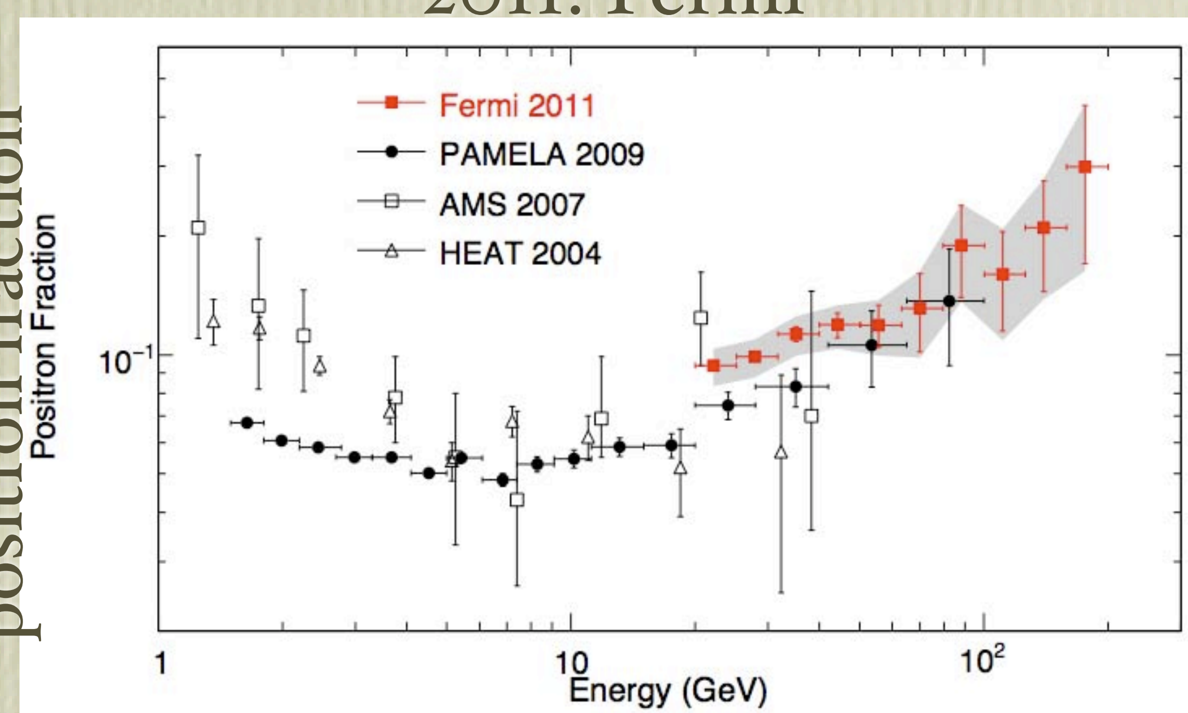
2011: PAMELA

electrons



2011: Fermi

positron fraction



Electrons/positrons and the standard CR lore:

"Primary" CRs from SNe, "secondary" CRs generated in the interaction of primary species with the interstellar medium in "spallation" processes. Example: secondary Boron from the primary Carbon. Experimental data used to tune cosmic propagation parameters such as the spatial diffusion coefficient: $D_{xx}(p) \propto p^{\alpha}$

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

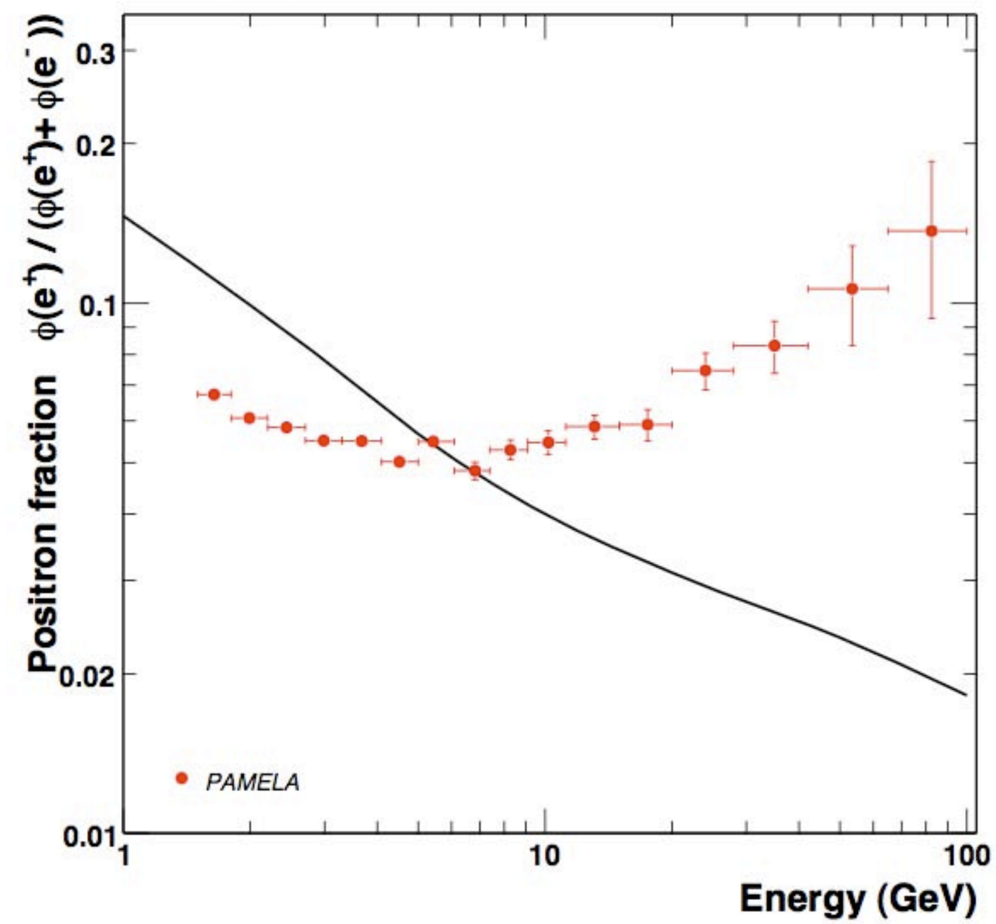
$$\frac{\phi_{e^+}}{\phi_{e^-}} \propto p^{-(\beta_{inj,p}-\beta_{inj,e}+\alpha)}$$

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

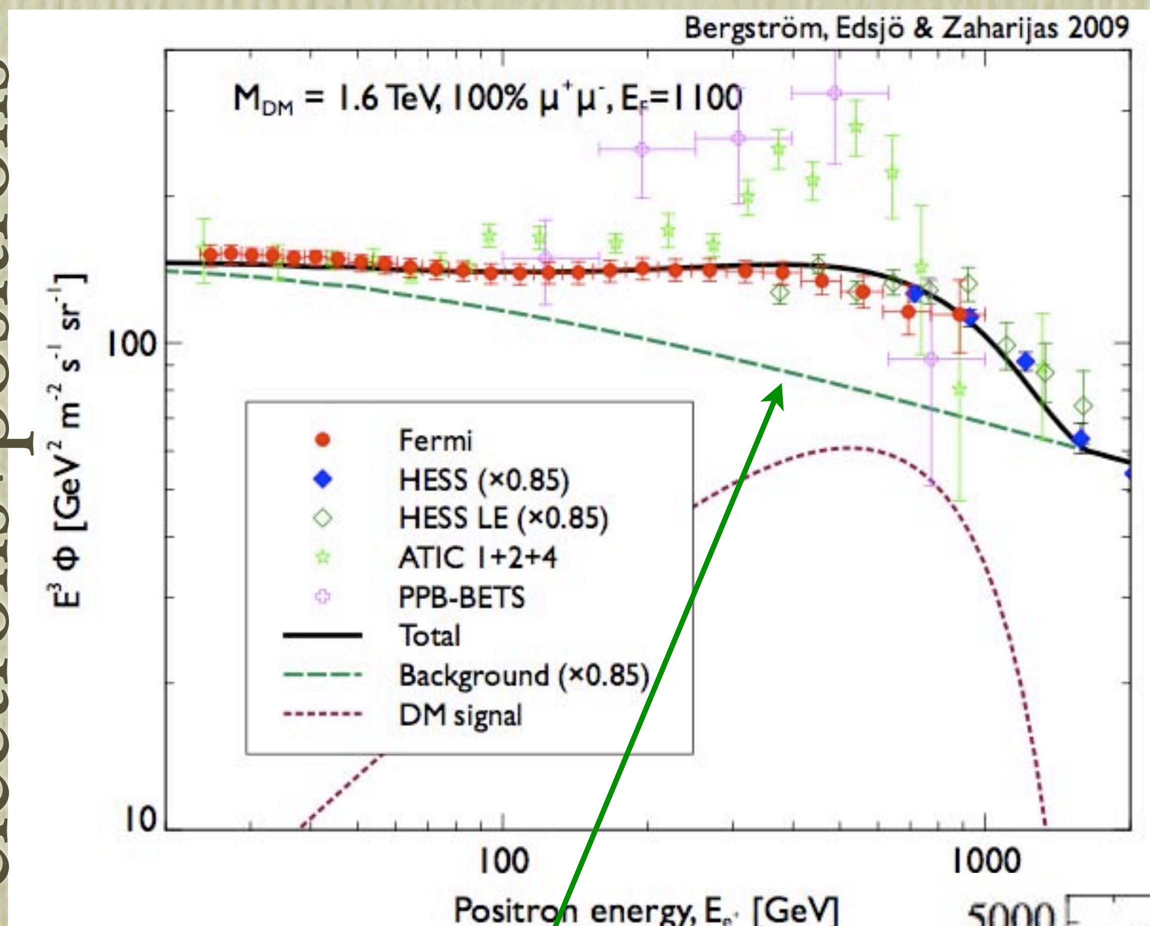
- There is production of secondary species within the CR sources with a mechanism giving a sufficiently hard spectrum (reacceleration at SN remnants?), e.g.: Blasi, arXiv:0903.2794; Mertsch & Sarkar, arXiv:0905.3152

- There are additional astrophysical sources producing primary positrons and electrons: pulsars are the prime candidate in this list, e.g.: Grasso et al., arXiv:0905.0636

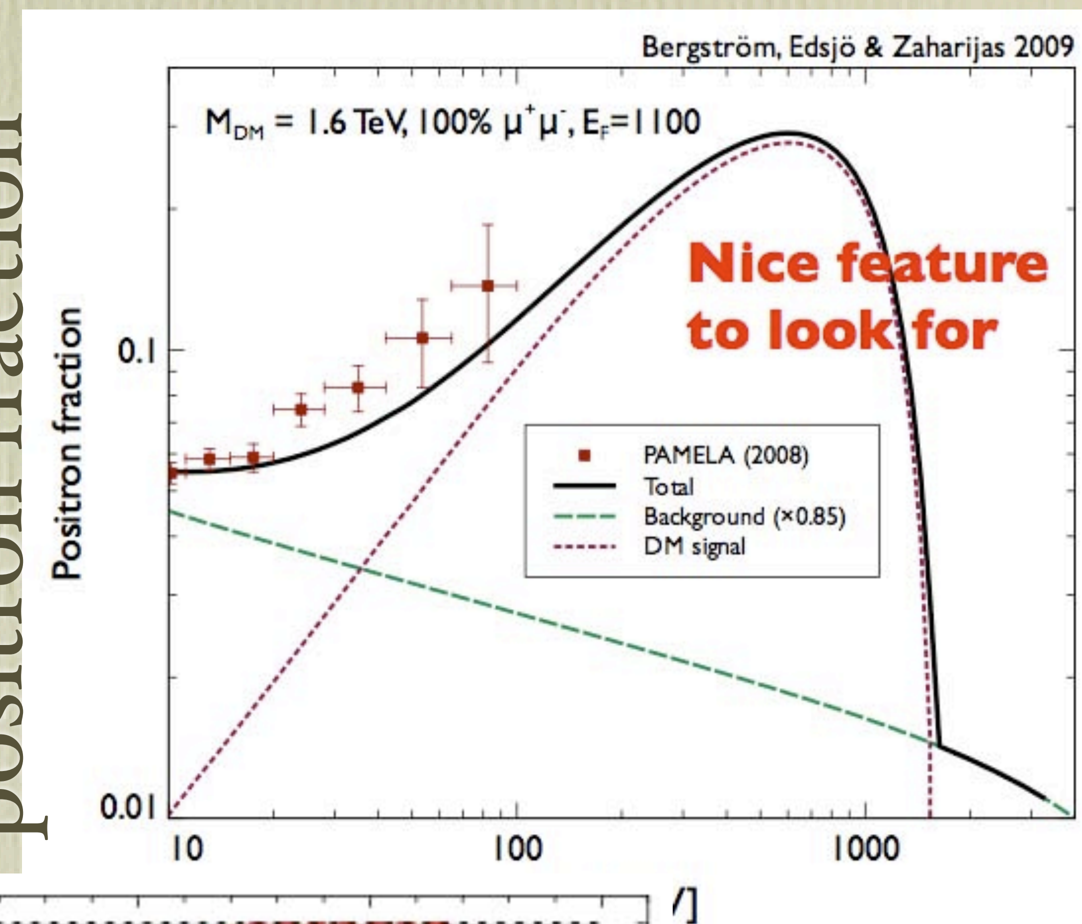
- There is an exotic extra source of primary positrons and electrons: a dark matter source is the most popular option in this class.

Blind fit of the Pamela/Fermi positron/electron data with a generic WIMP model (defined by WIMP mass and dominant annihilation channel), taking into account limits, e.g., from antiproton data:

electrons+positrons

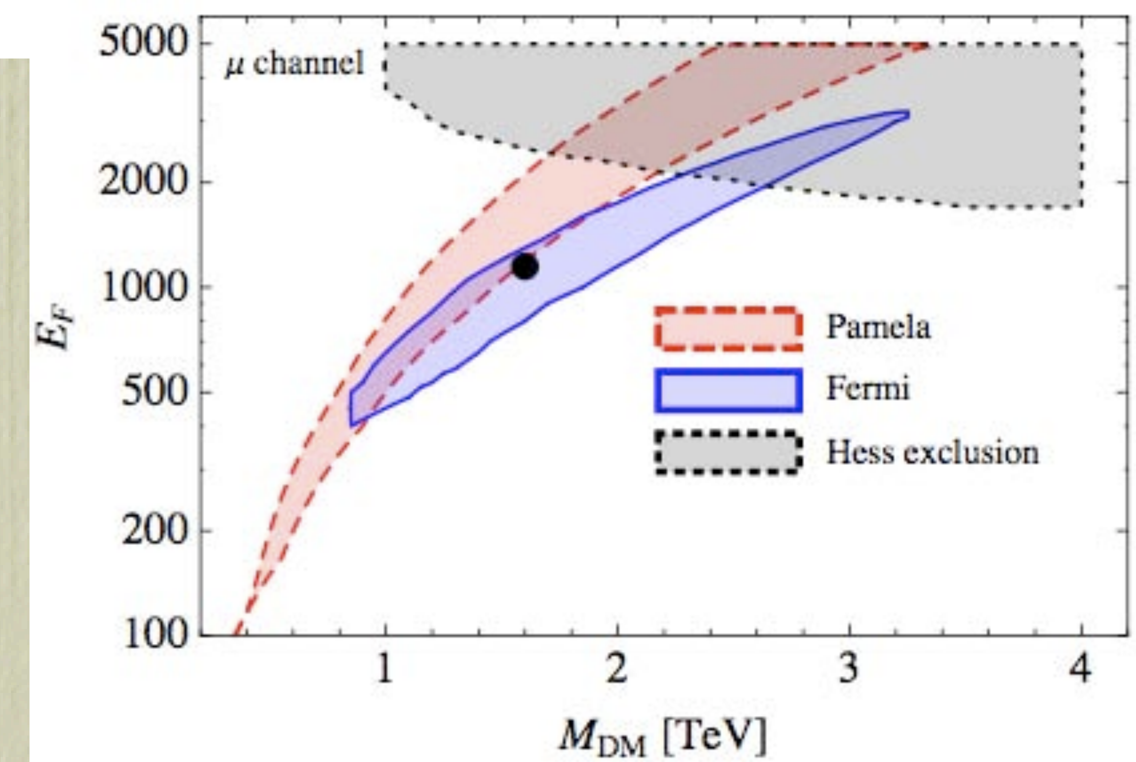


positron fraction



Bergström et al., arXiv:0905.0333

background ?!?



This "solution":

annihilation into muons, heavy WIMPs, large "enhancement factors"

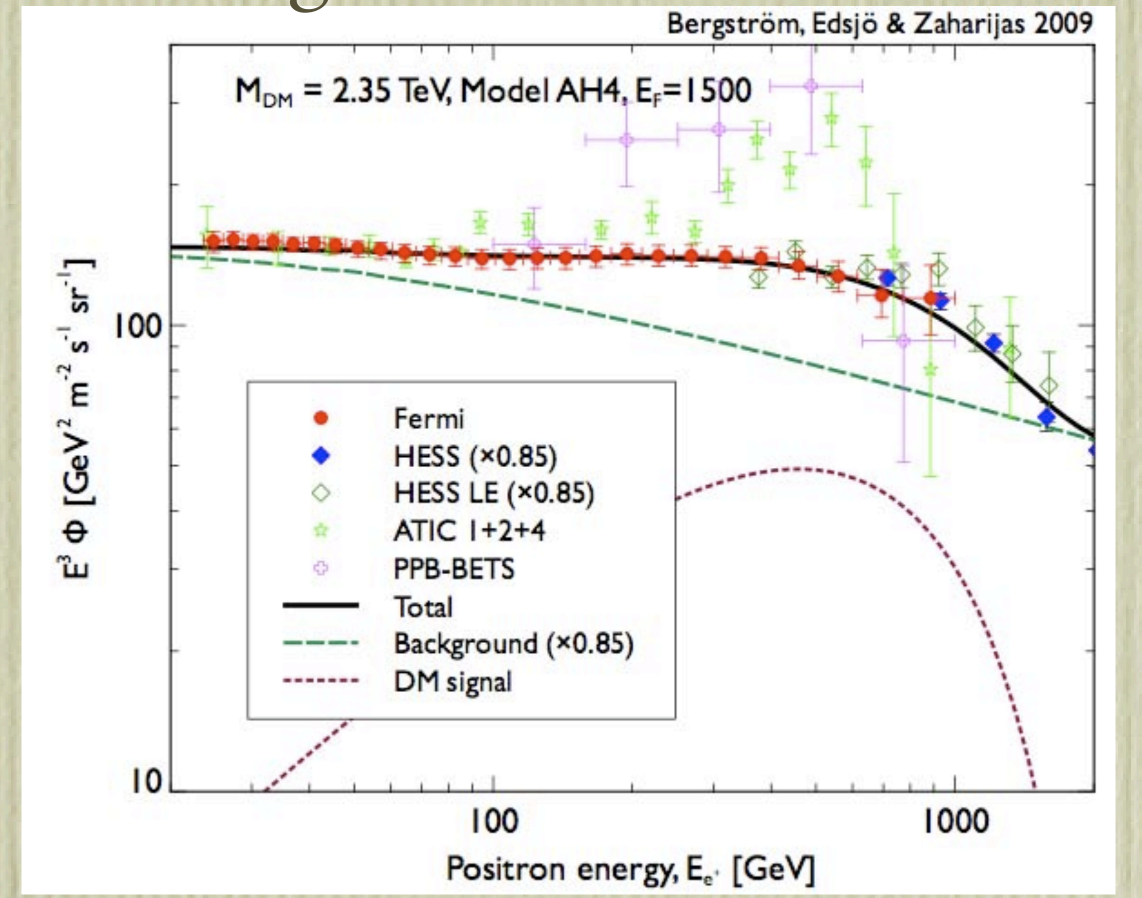
Slightly different results among the numerous fits to the recent data, but convergence on models which are very different from "conventional" WIMP models (e.g. neutralinos in the MSSM). DM seems to be:

- **heavy**, with WIMP masses above the 1 TeV scale;
- **leptophilic**, i.e. with pair annihilations with hard spectrum and into leptons only, or into light (pseudo)scalars which for kinematical reasons can decay into leptons only (there is very little room to accommodate a hadronic component which would manifest in the antiproton data - this point has been disputed by, e.g., Grajek et al., arXiv:0812.4555);
- with a **large** (order 1000 or more) **"enhancement factor"** in the source function, either: i) in the annihilation rate because $\langle \sigma v \rangle_{T_0} \gg \langle \sigma v \rangle_{T_{f.o.}}$ (non-thermal DM or decaying DM? Sommerfeld effect? a resonance effect?); or: ii) in the WIMP pair density because $\langle \rho_\chi^2 \rangle \gg \langle \rho_\chi \rangle^2$.

Hard to extrapolate a connection between this scenario and the direct detection picture. A multi-component dark matter?

Caveat: 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.**

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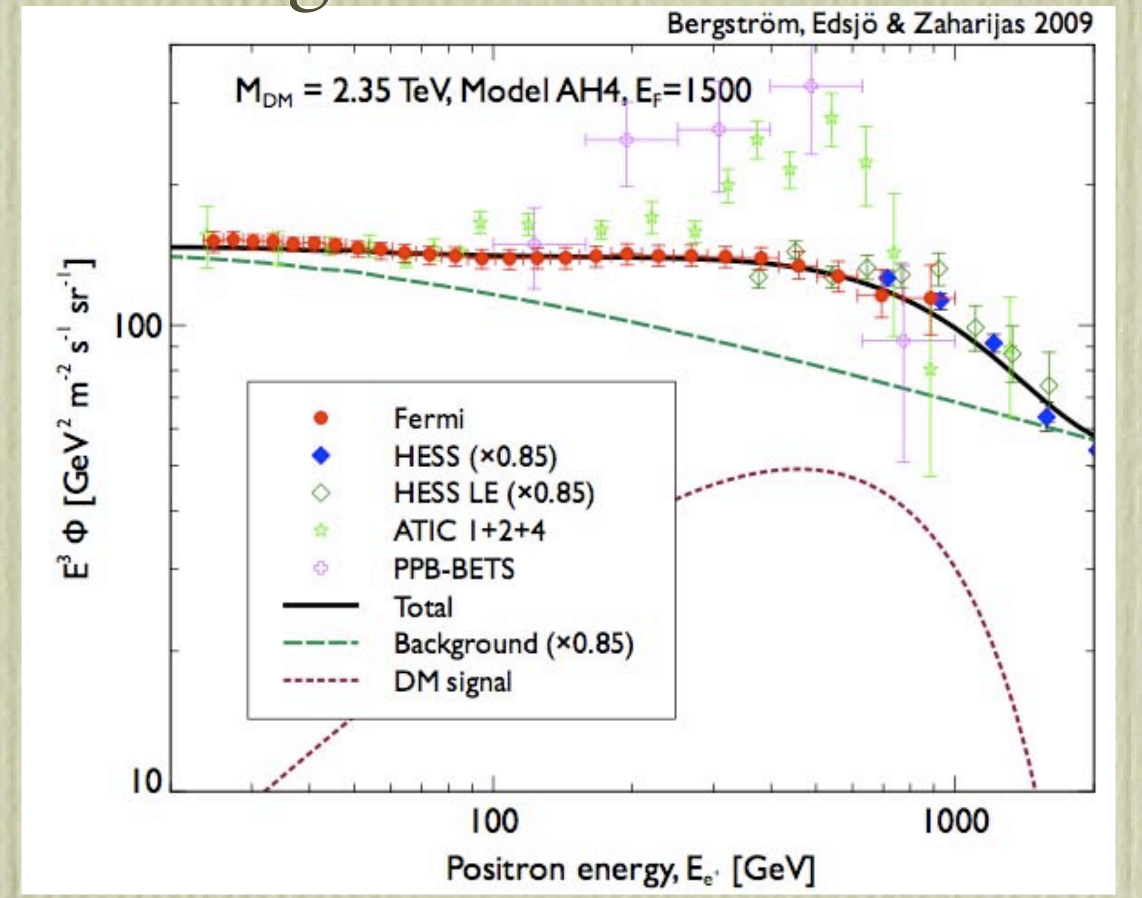
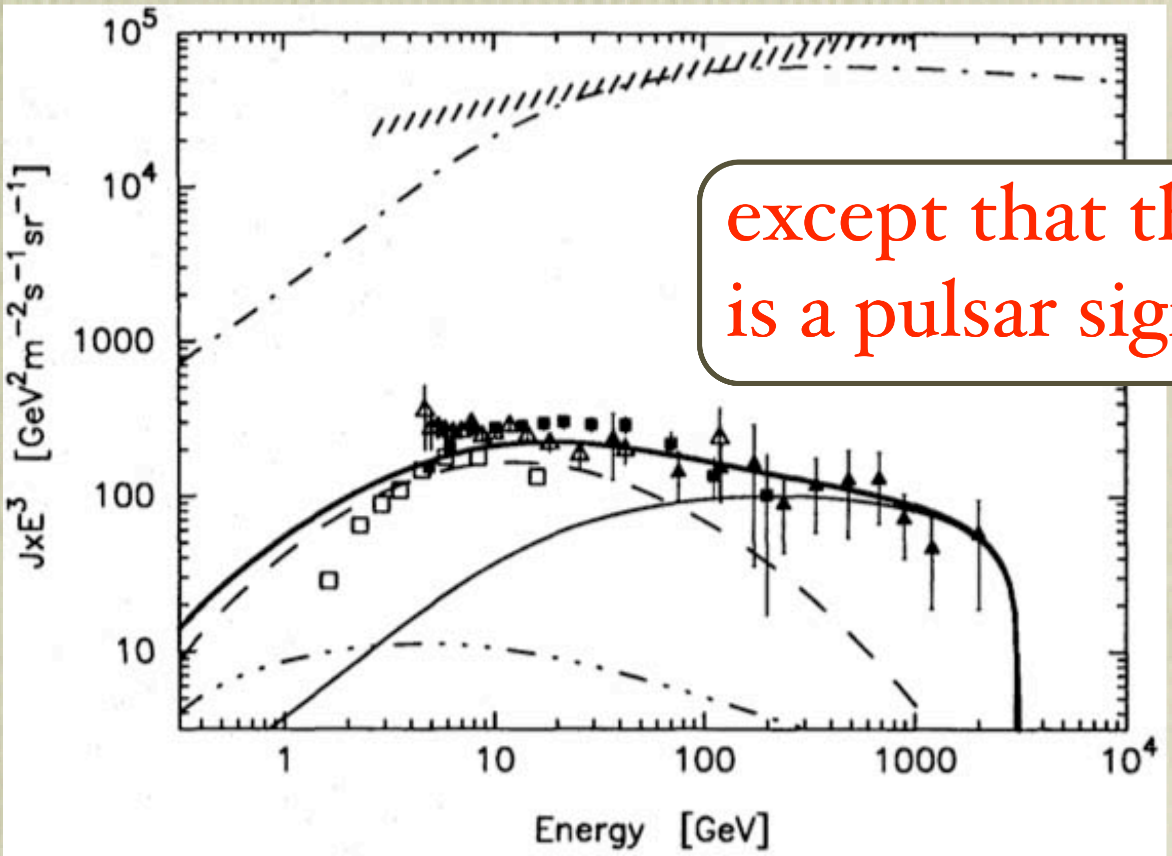


Bergström et al. on model by **Arkani-Hamed et al.**

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



except that this is a pulsar signal

Aharonian et al., 1995

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

E.g.: a DM point source accounting for the PAMELA excess would be detected by the Fermi GST looking at the associated γ-ray flux

DM annihilations and gamma-ray fluxes:

Prompt emission of γ-rays associated to three components:

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

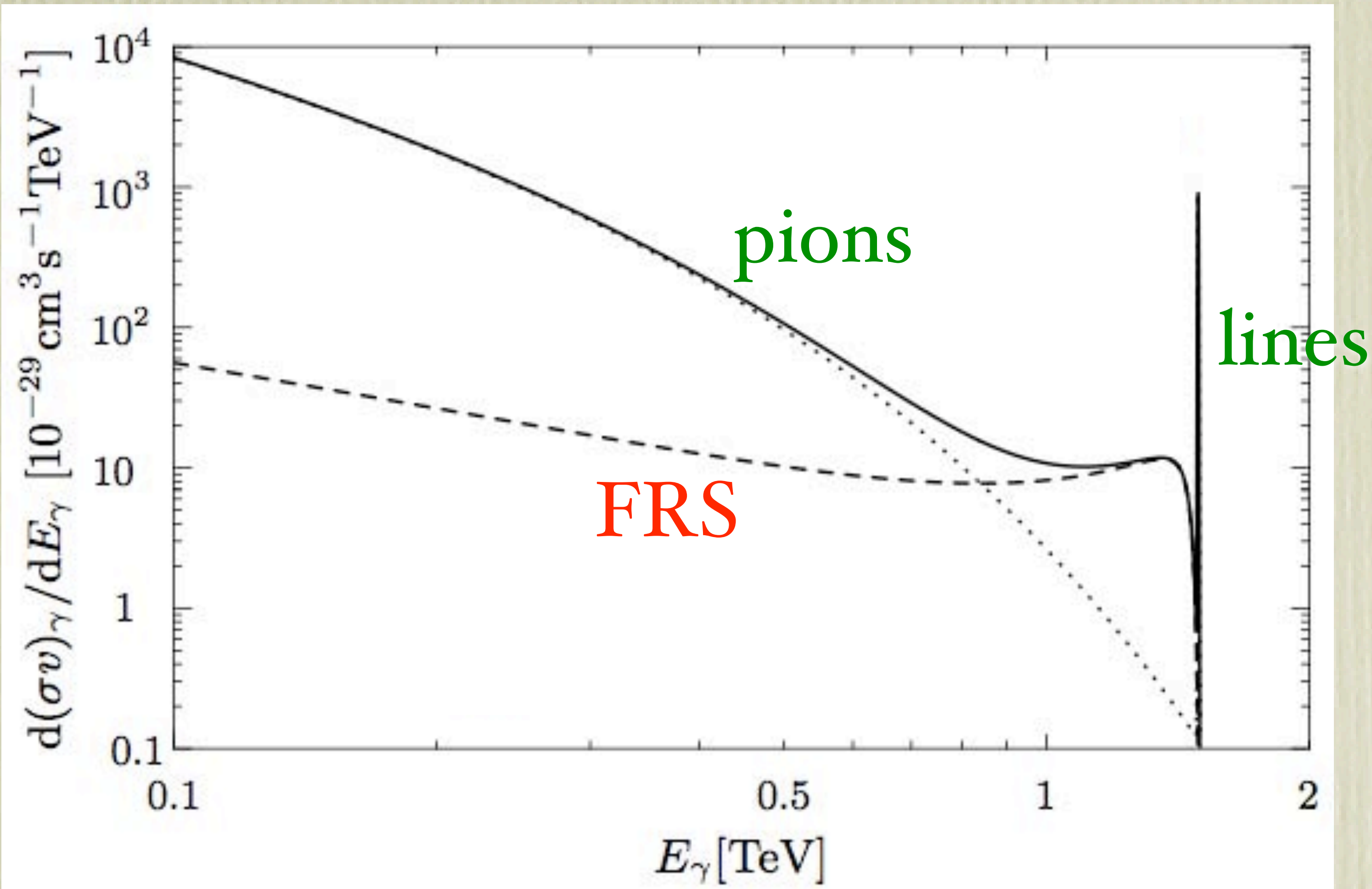
II) Monochromatic: i.e. the 1-loop induced $\chi\chi \to 2\gamma$ and $\chi\chi \to Z^0\gamma$ (in the MSSM, plus eventually others on other models)

III) Final state radiation (internal Bremsstralungh), especially relevant for:

$$\chi\chi \to l^+ l^- \gamma$$

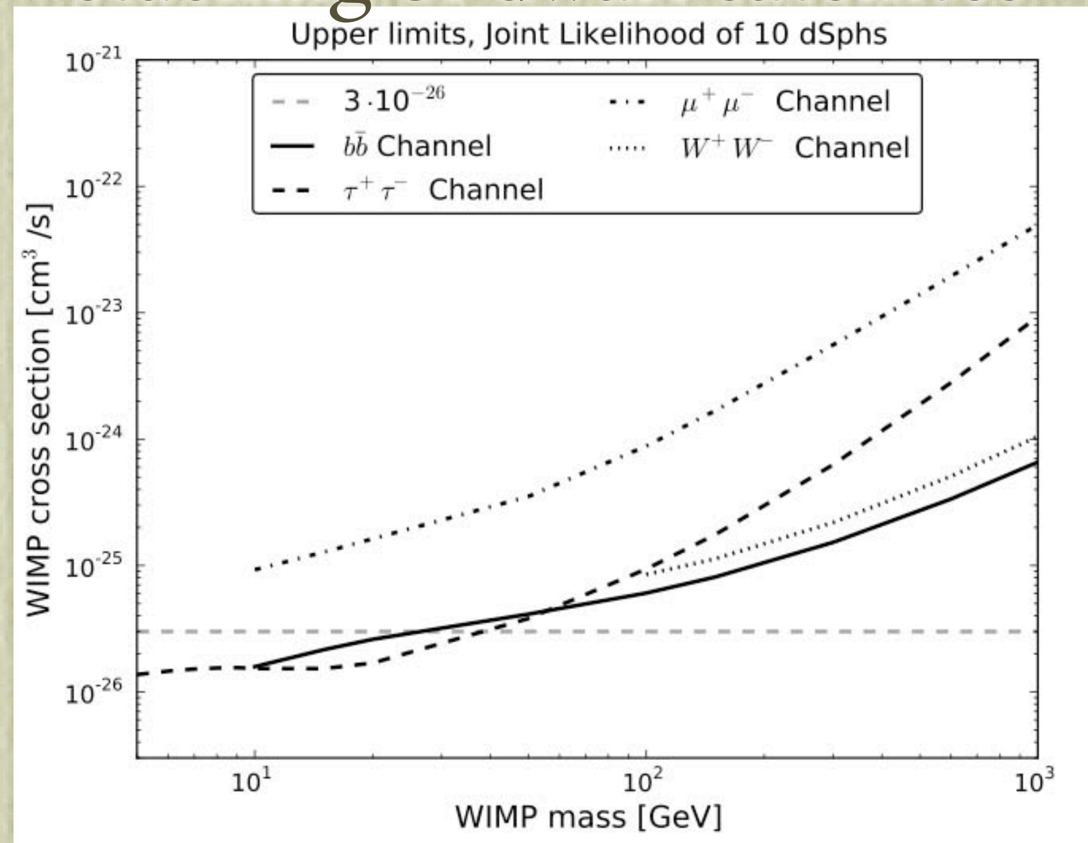
For a model for which all three are large (e.g. pure Higgsino):

Bergström et al., astro-ph/0609510



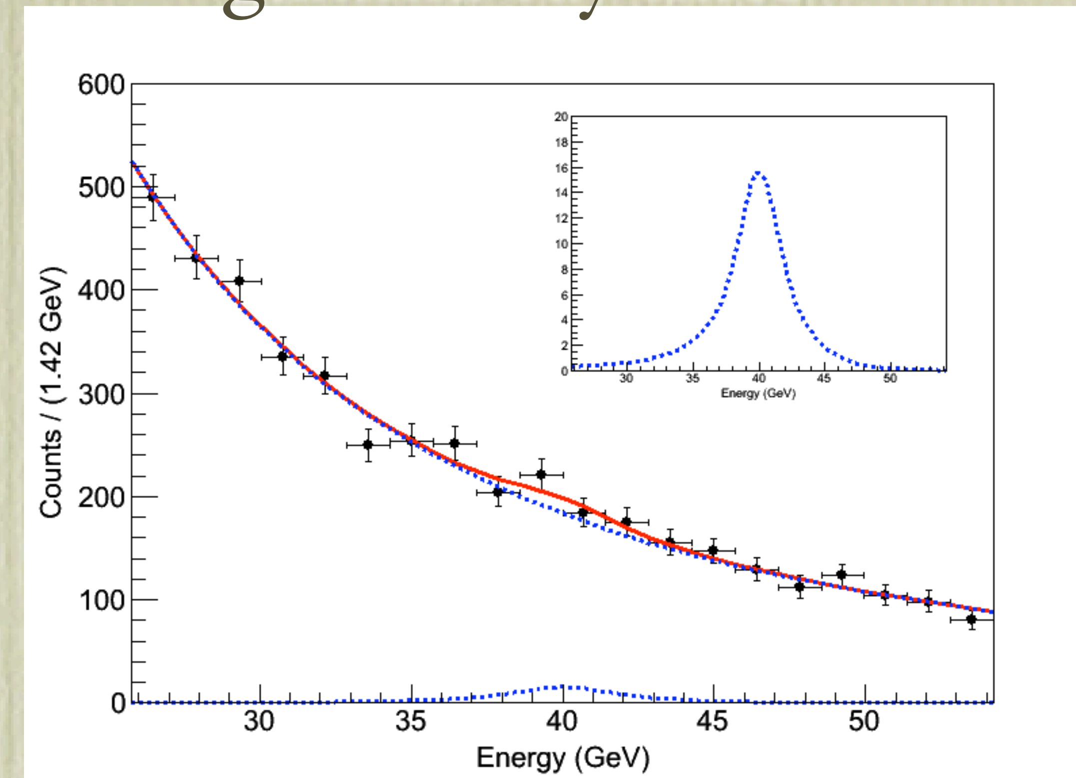
The first upper limits on DM gamma-ray fluxes from Fermi, e.g.:

stacking of dwarf satellites



arXiv: 1108.3546

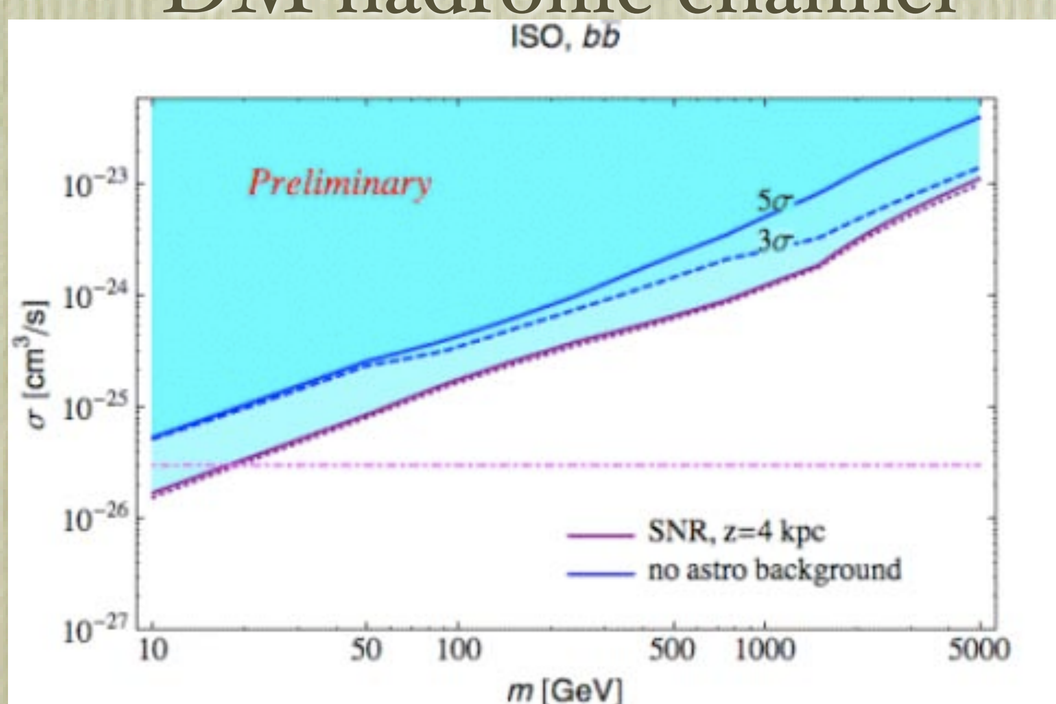
gamma-ray lines



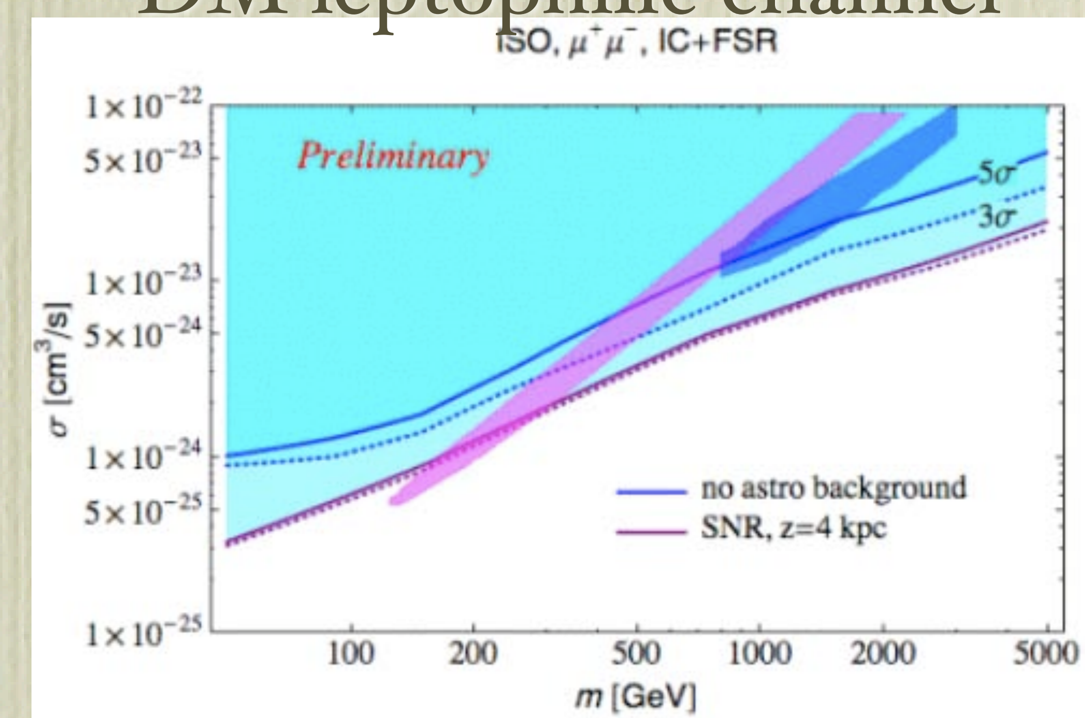
arXiv: 1001.4836

galactic diffuse emission for:

DM hadronic channel



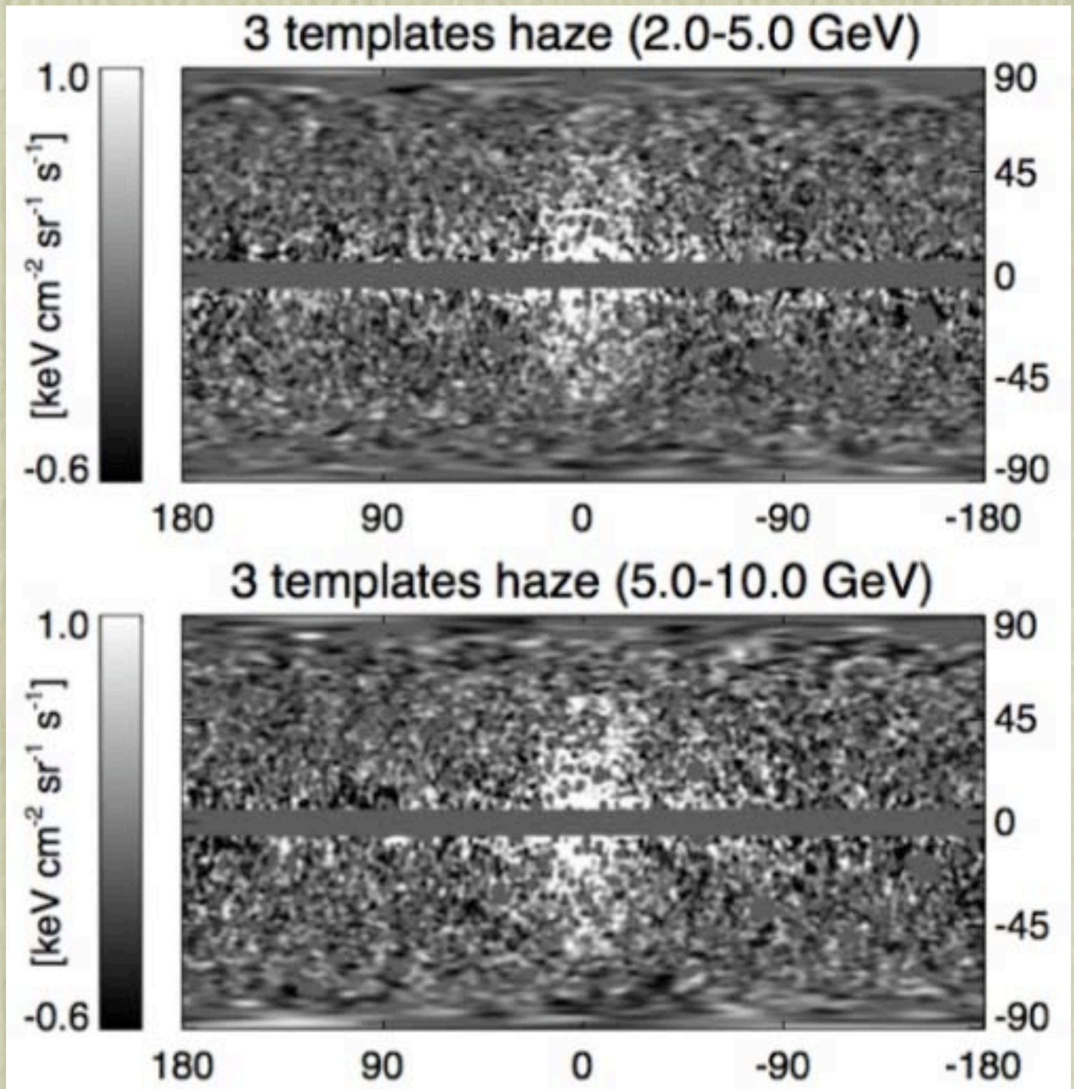
DM leptophilic channel



arXiv: 1012.0588

The first detection claims of DM gamma-ray fluxes from Fermi (following previous claims based on data from EGRET, Integral, ... , which however faded away), e.g.:

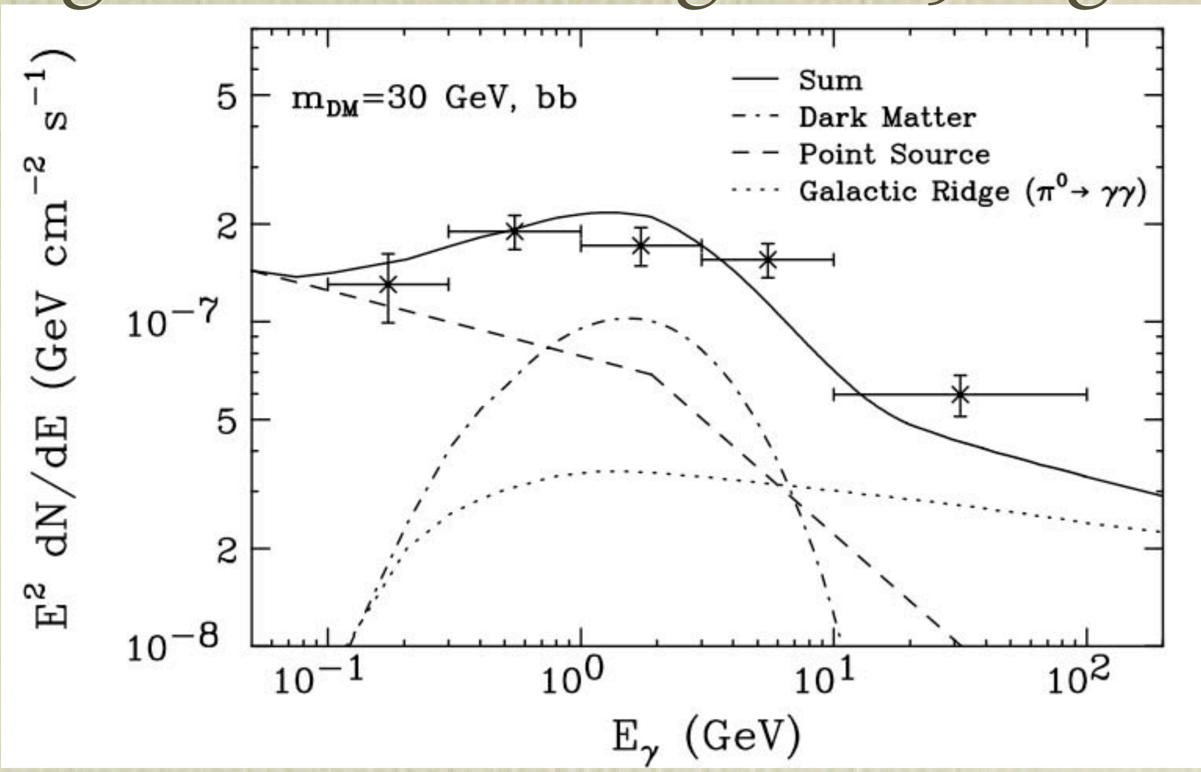
FERMI haze ($\overset{?}{\Leftrightarrow}$WMAP haze)



Dobler et al., arXiv:1102.5095

FERMI & WMAP hazes can be fitted with leptophilic DM with 1.2 TeV mass and EF of 30

galactic center region (<5 deg)



Hooper & Linden, arXiv:1110.0006

Caveat: additional astrophysical sources and of variants to the CR propagation model may provide alternative explanations

More ideas on the market, e.g.:

- Multi-wavelength studies to trace DM annihilations into non-thermal electrons through their radiative emissions (synchrotron, IC, bremsstrahlung, ...) on ambient background and fields, generating a spectrum spanning from the radio to the gamma-ray band.
- Tracing DM annihilations as they heat and ionize baryons during the "dark ages" ($z \sim 100$-1000) leaving an imprint on CMB.
- Looking at the angular power spectrum of the extra-galactic gamma-ray background to search for pattern specific for DM annihilations (and as opposed to those for other plausible contributions to the EGB) .
- Look at DM annihilations in stars and check check their impact on stellar evolution (can you make proto-stars burning DM?)
- ....