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Dark Matter and Energy - II

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Dark Matter

and Dark Energy

(part II)

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VII School on Non-Accelerator Astroparticle Physics

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Dark energy and particle physics

Consider the field description of a particle.

For simplicity take a scalar particle, defined by:

$$L = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi)$$

Under the assumption of homogeneity,

$$\rho \equiv T_0^0 = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$

$$p \equiv -T_i^i = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

Assume that the field is in a configuration close to the minimum of the potential V_0. If V_0 is large:

$$p = -\rho = -V_0$$

i.e. we find a cosmological constant behavior with Λ given by

$$\frac{\Lambda}{8\pi G} \equiv V_0$$

The cosmological constant is very small compared to energy scales we are familiar with in particle physics:

$$\rho_\Lambda = \frac{\Lambda}{8\pi G} = \Omega_\Lambda \cdot \rho_c(t_0) \simeq 2.5 \cdot 10^{-47} \text{ GeV}^4$$

A huge fine-tuning is usually required

One example in a classical field theory model:

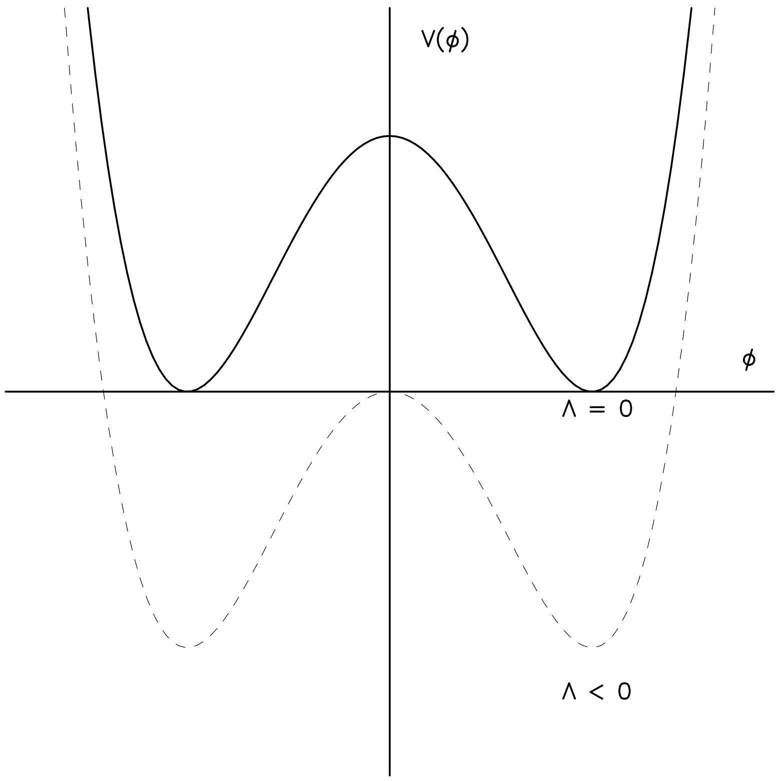
Consider a case of spontaneous symmetry breaking, induced by the transition from a potential with minimum in $\phi = 0$ into the "Mexican hat" potential:

$$V(\phi) = V_0 - \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4$$

with ground states in

$$\phi = +\sigma \text{ or } \phi = -\sigma,$$

where $\sigma = \sqrt{\mu^2/\lambda}$.



If $V_0 = 0$ you get a large negative cosmological constant $V(\phi = \sigma) = -\mu^4/4\lambda$.

You are forced to choose V_0 such that

$$V_0 - \mu^4/4\lambda \simeq 10^{-47}\ \text{GeV}^4.$$

For the Higgs mechanism you expect

$$V_0 \sim (100\ \text{GeV})^4$$

and you are forced to a fine tuning of 1 part in 10^{55}!

In a quantum field theory framework, zero-point vacuum fluctuations have the form:

$$\langle T_{\mu\nu} \rangle = \Lambda g_{\mu\nu}$$

For both fermions and bosons the generated effective cosmological constant is divergent:

$$\rho_{\text{vac}} = \frac{\Lambda}{8\pi G} = \langle T_{00} \rangle_{\text{vac}} \propto \int_0^\infty \sqrt{k^2 + m^2} k^2 dk$$

You need to introduce a UV cutoff:

$$\rho_{\text{vac}} \simeq \frac{k_c^4}{16\,\pi^2}$$

The natural cutoff would be M_{Pl} but then Λ would be 120 orders of magnitude too large!

For theories with unbroken supersymmetry, the fermionic and bosonic contributions to T_{00} cancel out. However our world is not supersymmetric.

Some recent attempts implements models with extra-dimensions.

Coming back to cosmology, models with a ρ_Λ constant in time, as opposed to the matter and radiation components, scaling, respectively, as a^{-3} and a^{-4}, face two kinds of problems:

Coincidence problem: What is the reason why Ω_M and Ω_Λ are of the same order today, and we just started accelerating?

Fine tuning problem: Extrapolating backwards in the Early Universe, the matter (and radiation) term becomes much larger than the cosmological constant. Extreme fine-tuning in the initial conditions.

Dark energy models with time varying equation of state $p(t) = w(t)\,\rho(t)$ try to address the second problem: e.g., dark energy as **quintessence**.

Consider again the scalar field with:

$$\rho \equiv T^0_0 = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$

$$p \equiv -T^i_i = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

but now with ϕ far from the minimum $V_0 = 0$. w can vary between -1 and 1.

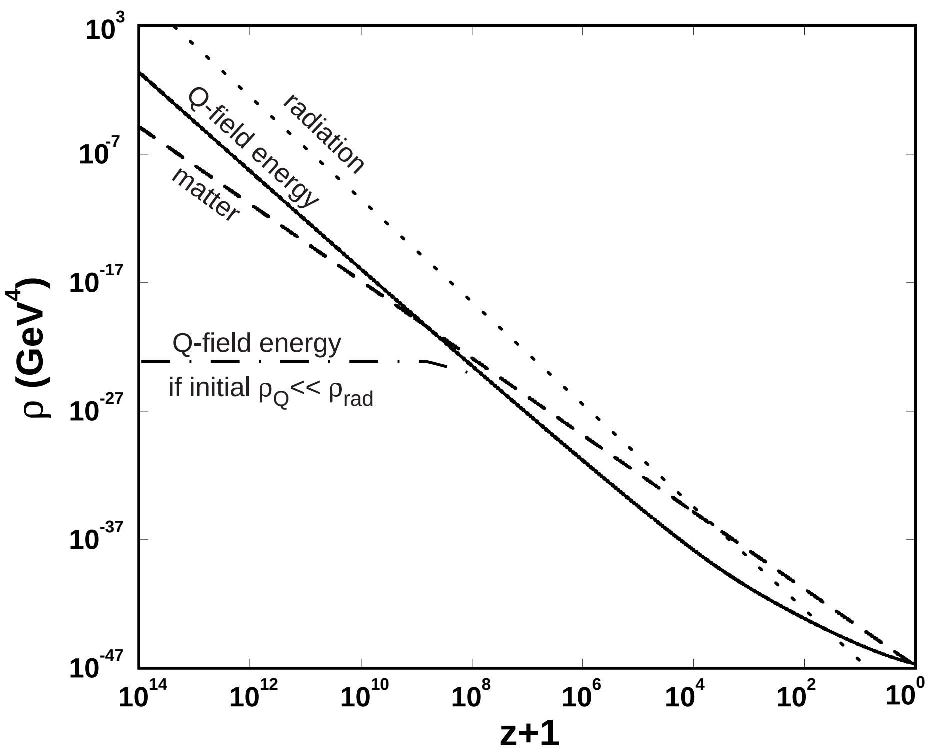
Assume minimal coupling. ϕ starts at a large value, and rolls down V with "friction" due to the expansion of the Universe.

For potentials that are sufficiently steep:

$$\Gamma \equiv \frac{V''V}{(V')^2} \geq 1$$

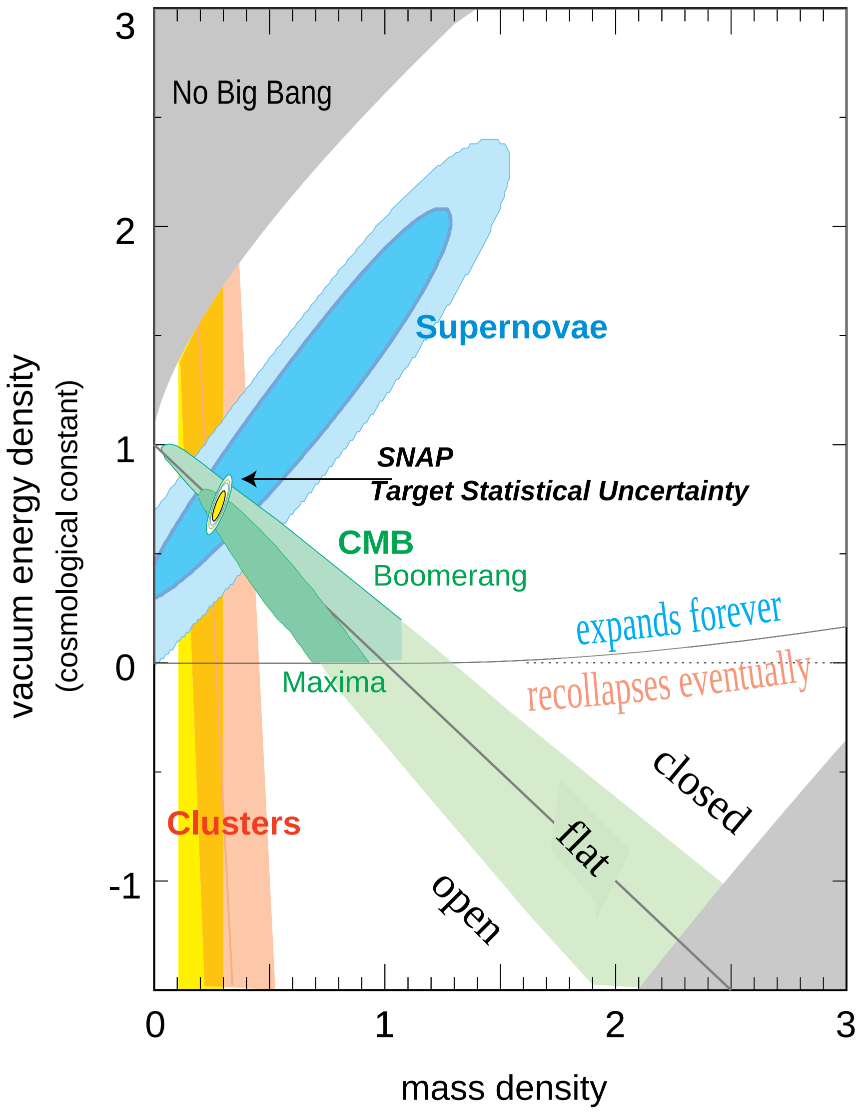
a common evolutionary path, the tracker trajectory, is reached from a wide range of initial conditions.

Example: $V(\phi) = V_0/\phi^\alpha$



Zlatev, Wang & Steinhardt (1999)

Dark energy will be measured which much higher accuracy in the future:



Aldering et al. (2002)

Will evidence for a time evolving w be found as well?

Relic particles as dark matter

Postulate a new stable particle χ, with mass M_χ and non-zero coupling to SM particles.

In the early Universe, at high T, χ would be in thermal equilibrium:

$\chi\bar{\chi} \leftrightarrow l\bar{l}$ with l some lighter SM particle

Its thermal equilibrium number density is

$$n_\chi^{eq} = \frac{g_\chi}{(2\pi)^3} \int f_\chi(p)\, d^3p$$

with

$$f_\chi(p) = \frac{1}{exp(E/T) \pm 1}$$

where $E = \sqrt{p^2 + M_\chi^2}$ is the energy, and $+$ applies for fermions, while $-$ for bosons.

There are two regimes, respectively for relativistic and non-relativistic particles:

$n_\chi^{eq} \propto T^3$ if $T >> M_\chi$

$n_\chi^{eq} \propto (M_\chi T)^{3/2} \exp\left(-M_\chi/T\right)$ if $T << M_\chi$

χ in equilibrium down to the freeze out temperature T_f, at which, as a rule of thumb,

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

$\Longrightarrow$ after freeze out, when $\Gamma \ll H$, the number density per comoving volume, say

$$Y(T) \equiv \frac{n_\chi(T)}{s(T)}$$

with $s(T)$ the entropy density, remains constant $\simeq Y^{eq}(T_f)$, i.e. the relic abundance of χ freezes in.

The nowadays density follows then from:

$$\left(\frac{n_\chi}{s}\right)_{T=T_0} = \left(\frac{n_\chi}{s}\right)_{T=T_f}$$

where $s_0 \simeq 3000$ cm^{-3} and $s(T) \propto T^3$.

Still two opposite regimes: the case for particles that are relativistic at T_f and that for non-relativistic ones.

Relativistic case

As both n_χ and s scale like T^3, in this regime Y does not depend on temperature!

Assuming $M_\chi > T_0$,

$$\rho_\chi(T_0) = M_\chi \cdot s_0\, Y^{eq}(T_f) = \text{const} \cdot M_\chi$$

Light neutrinos belong to this class of candidates. You find that:

$$\Omega_\nu h^2 = \frac{\rho_\nu}{\rho_c/h^2} = \frac{\sum_i M_{\nu_i}}{94.4\,\text{eV}}$$

Limits from current cosmological data depend on the set of priors one uses. From SDSS and WMAP, in a 7-paramter model Tegmark et al. (2003):

$$\Omega_\nu h^2 < 0.12 \cdot \Omega_{CDM} h^2 \quad \Leftrightarrow \quad \sum_i M_{\nu_i} < 1.7\,\text{eV}$$

Non-relativistic case

Let χ be massive.

In this case Y has a strong (exponential) dipendence on T_f.

Still consider a rule of thumb estimate, and derive $n_\chi^{eq}(T_f)$ from freeze out condition:

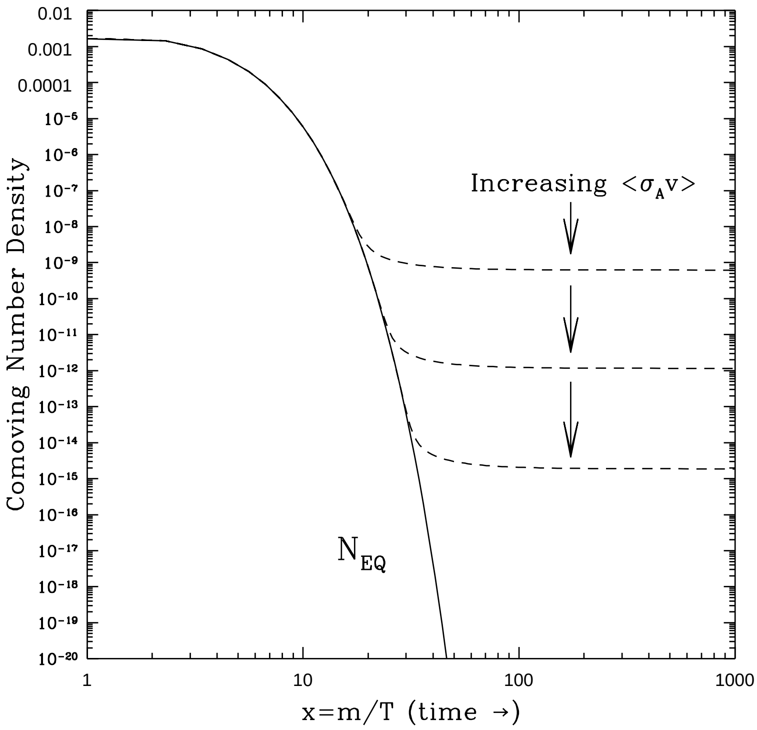
$$n_\chi^{eq}(T_f) \simeq H(T_f)/\langle\sigma_A v\rangle_{T=T_f}$$

Plug in:

- $H = 1.66\, g_*^{1/2}\, T^2/M_{Pl}$,
- $s \simeq 0.4\, g_*\, T^3$,
- $T_f \simeq M_\chi/20$ (a posteriori, from full treatment)

and find:

$$\Omega_\chi h^2 = \frac{M_\chi\, n_{\chi,0}}{\rho_c} \simeq \frac{3 \cdot 10^{-27} \mathrm{cm}^{-3}\mathrm{s}^{-1}}{\langle\sigma_A v\rangle_{T=T_f}}$$



Jungman, Kamionkowski & Griest, Phys. Rep. 267 (1996) 195;

see also, e.g., Kolb & Turner, The Early Universe, chapter 5.

In a more accurate analysis, the Boltzmann eq.

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

is solved, taking into account

- threshold / resonance effects
- coannihilations

WIMP dark matter candidates

In the simplified treatment, we found:

$$\Omega_\chi h^2 = \frac{M_\chi \, n_{\chi,0}}{\rho_c} \simeq \frac{3 \cdot 10^{-27}\text{cm}^{-3}\text{s}^{-1}}{\langle \sigma_A v \rangle_{T=T_f}}$$

If the coupling of χ to lighter particles has the

weak interaction strength, then:

$$\langle \sigma_A v \rangle \sim \frac{\alpha^2}{(100\,\text{GeV})^2} \sim 10^{-25}\text{cm}^{-3}\text{s}^{-1} \quad \text{for } \alpha \sim 10^{-2}$$

$$\Downarrow$$

a WIMP is naturally a good dark matter candidate

Reversing the argument, if we require that thermal relic particles provide a CDM density of about

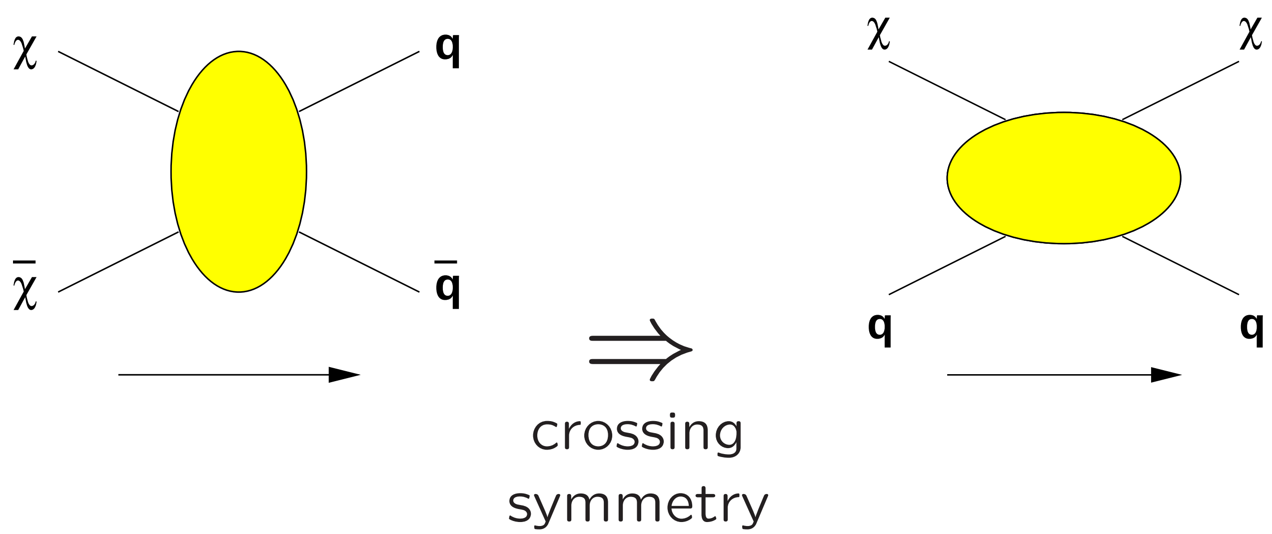
$$0.081 < \Omega_{CDM} h^2 < 0.125$$

(SDSS + WMAP range, in a 9-parameter model, Tegmark et al. (2003)), then a weak interaction scale is required for $\langle \sigma_A v \rangle_{T=T_f}$ (and $\sigma_A v|_{T=0}$ is in most cases of the same order).

WIMP dark matter identification

Direct detection

WIMP elastic scattering with ordinary material:



Goodman & Witten, Phys. Rev. D 31 (1986) 3059

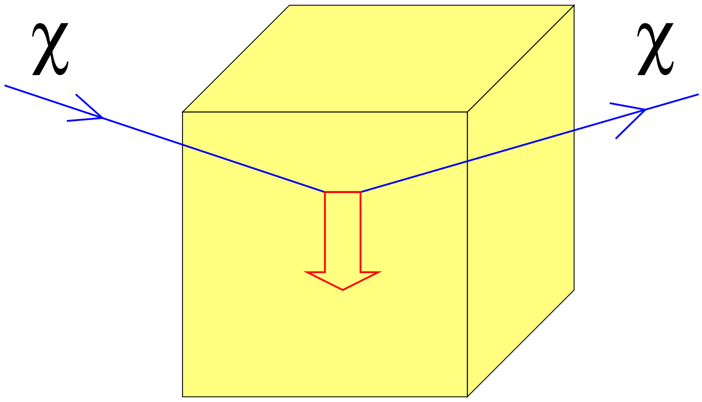
Indirect detection with ν telescopes

Search for energetic neutrinos produced by the annihilation of WIMPs that have accumulated at the center of the Sun and/or the Earth.

Silk, Olive & Srednicki, Phys. Rev. Lett. 55 (1985) 257; Krauss et al., ApJ 299 (1985) 1001; Freese, Phys. Lett. B 167 (1986) 295.

Direct detection

In Ge, NaI, Xe, Ar, ...



Differential rate ($Q =$ energy deposited):

$$\frac{dR}{dQ} = N_T \frac{\rho_\chi^{loc}}{M_\chi} \int_{v_{min}}^{v_{max}} d^3\vec{v}\, f_\chi(\vec{v})\, |\vec{v}|\, \frac{d\sigma}{dQ}$$

σ for Majorana fermions (such as neutralinos) = axial-vector (spin-dependent) term + scalar (spin-independent or coherent, $\propto A^2$) term.

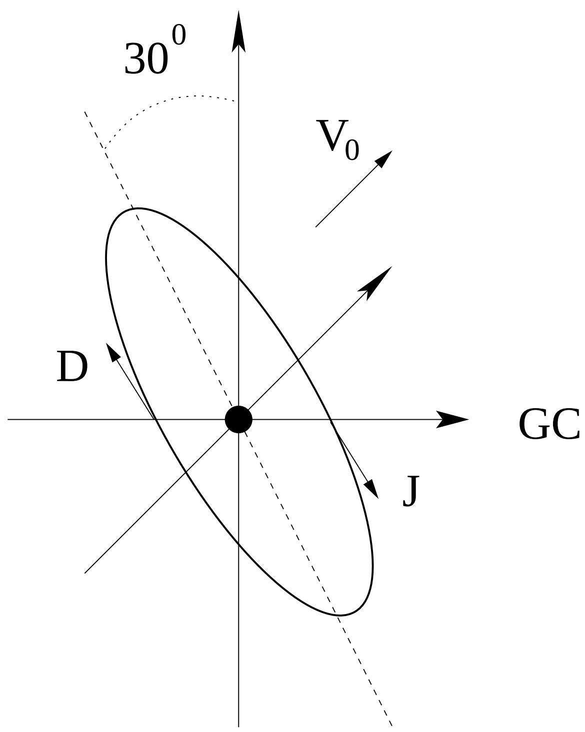
$f_\chi(\vec{v})$ = local χ distribution in momentum space $\Rightarrow$ SIGNATURE to discriminate against the background.

Drukier, Freese & Spergel (1986); Freese, Frieman & Gould (1988).

Signatures for direct detection

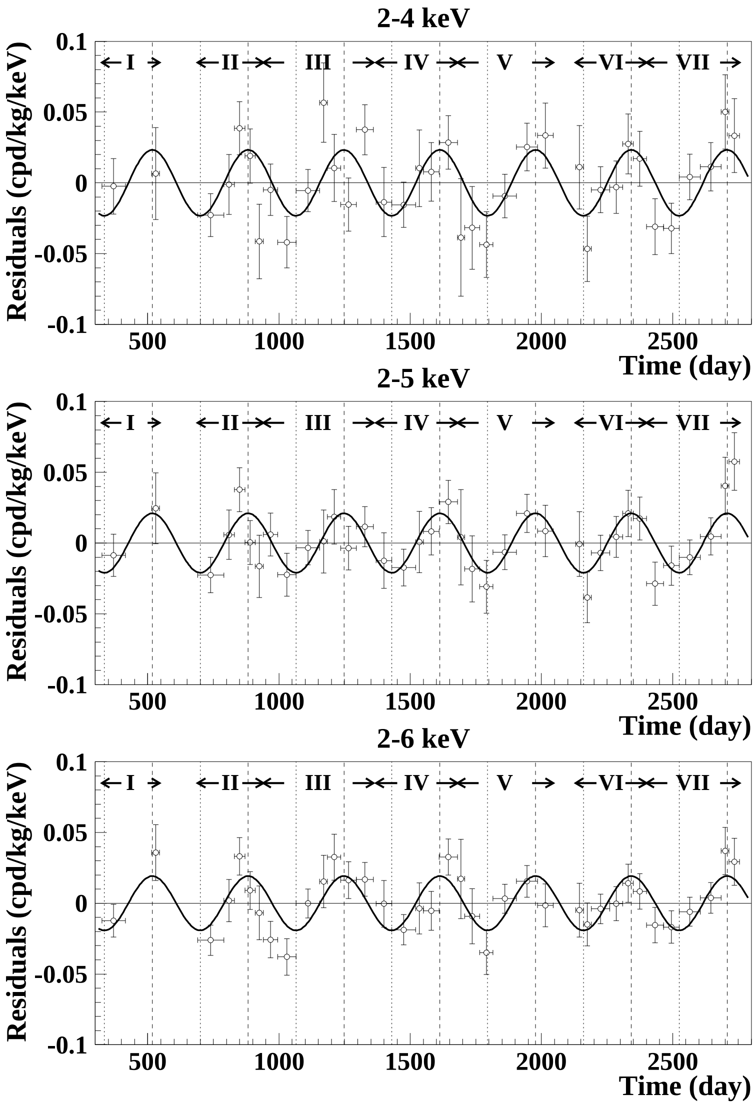
• Use a detector which can identify the direction of the incident WIMP and apply angular discrimination to tell signal from background: in 2003, there is only one experiment, DRIFT, at the R&D stage.

• Search for a modulation in the total event rate (signal + background) to extract the signal: daily modulation (rather small) or annual modulation (at the level of about 5% of the signal)



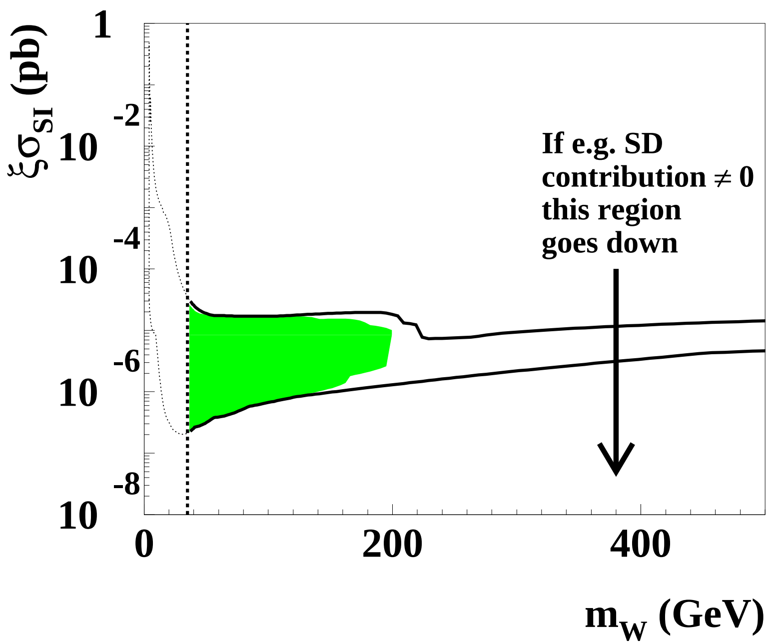
Annual modulation signal in DAMA

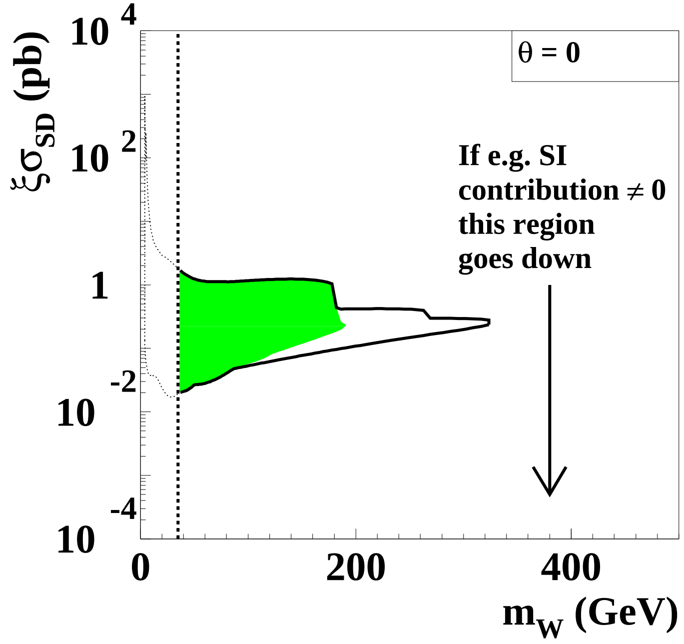
Seven years, exposure $\sim$ 60000 kg $\times$ day, 6.3 σ C.L. for a sinusoidally modulated rate, $7 \cdot 10^{-4}$ probability for an unmodulated rate:



R. Bernabei et al., Riv. N. Cim. 26 (2003) 1, astro-ph/0307403

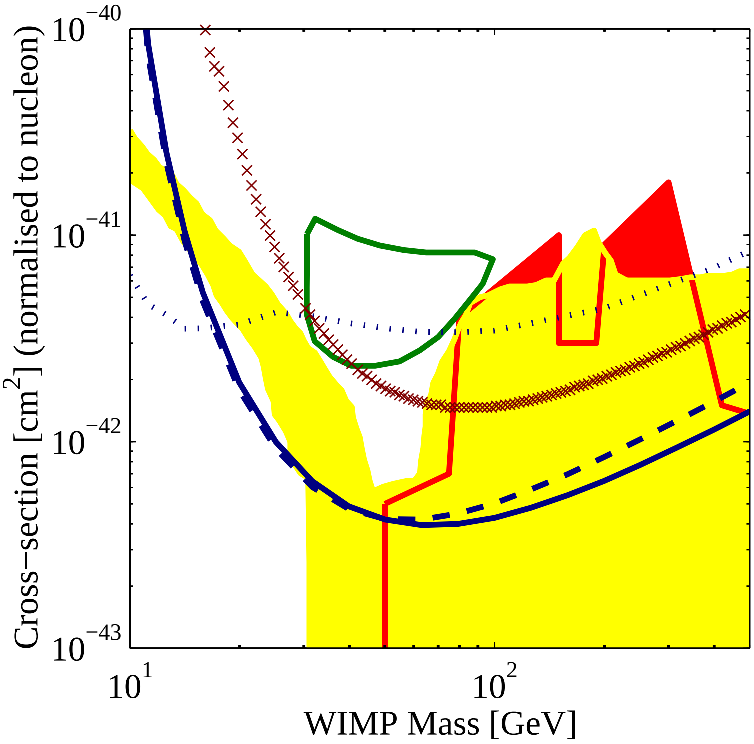
Interpretation as WIMP SI or SD interactions





R. Bernabei et al., Riv. N. Cim. 26 (2003) 1, astro-ph/0307403

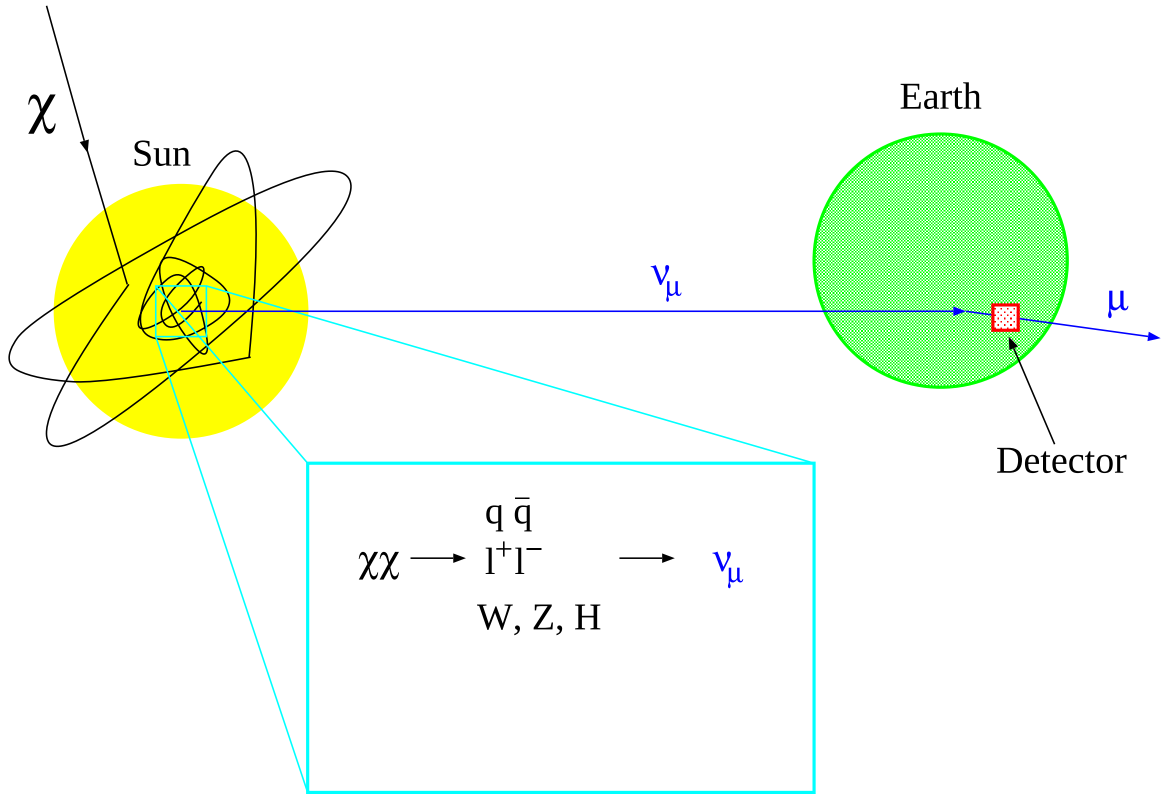
The interpretation as WIMP SI interactions has not been confirmed by competing experiments (which, so far, did not find any evidence for a signal and hence produced exclusion plots)



D.S. Akerib et al., astro-ph/0405033

Possible caveats in the comparison, see the lectures by Rita Bernabei.

ν telescopes

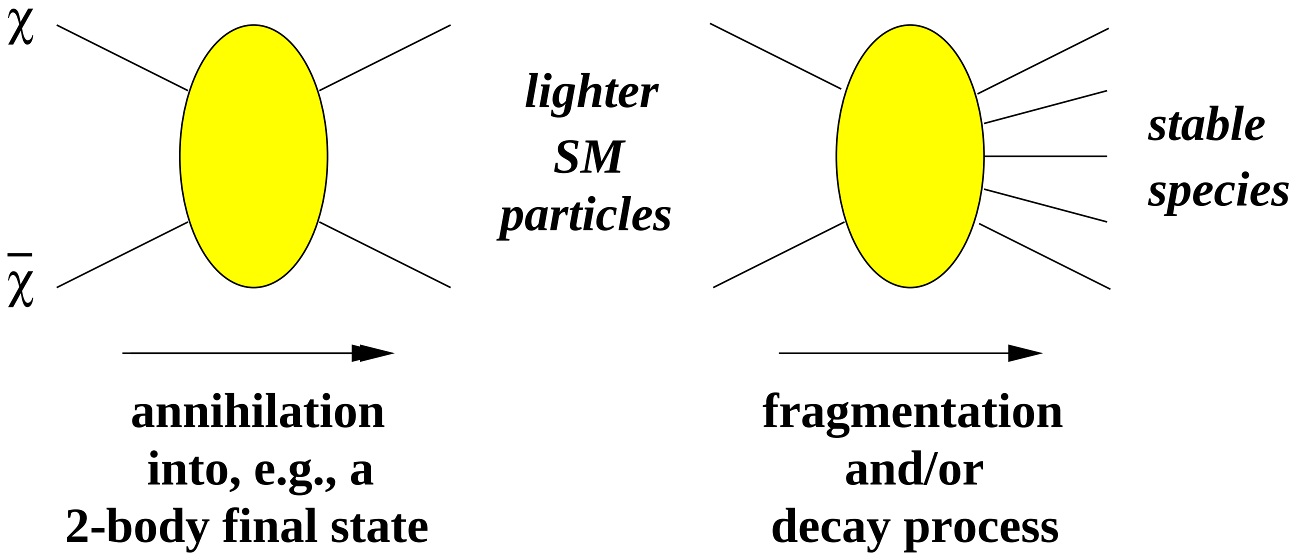


No signal so far, km^3 telescopes under construction

Indirect detection through the search for exotic cosmic rays

Suppose WIMPs form the dark halo of the Galaxy.

Their mean density is much smaller than in the early Universe, or in the center of massive bodies, but pair annihilation can still take place:

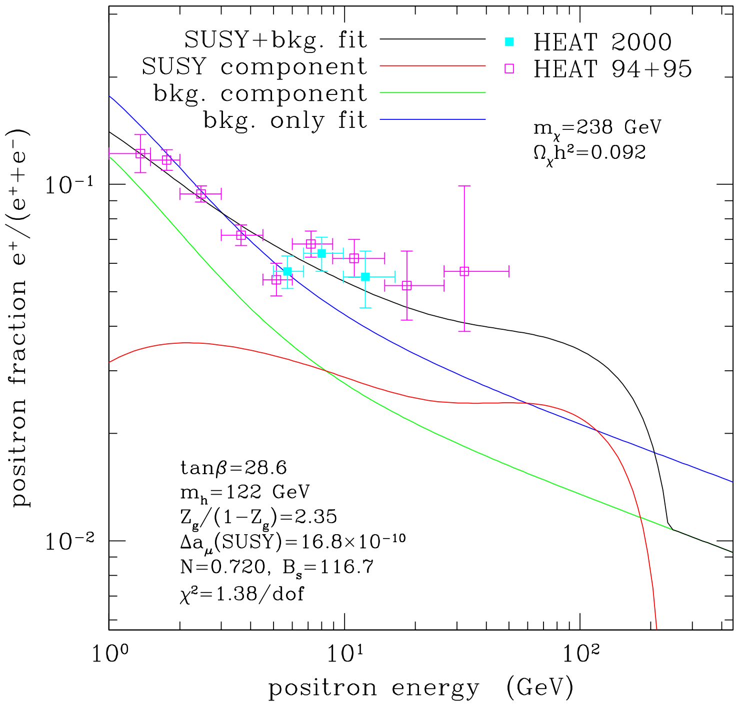


Look at those cosmic ray species with low and/or well-determined conventional (i.e. background) cosmic ray fluxes:

antimatter	photons
$\bar{p}$, $\bar{D}$, e^+	γ-ray, X-rays, radio

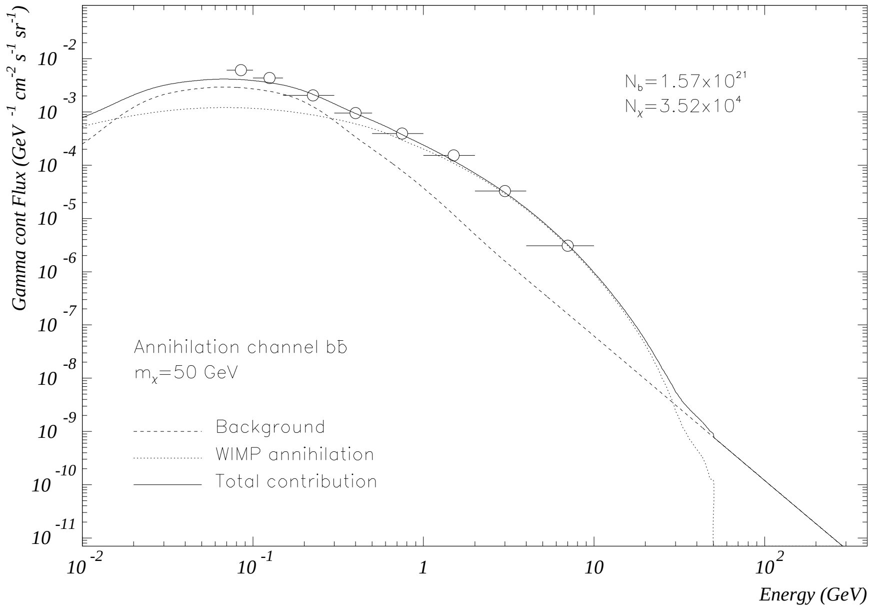
(Very) weak hints of signals in current data

positron "excess"



Baltz et al. (2002)

GC γ-ray excess



Cesarini et al. (2003)

WIMP detection through monochromatic γ-rays

$$\chi\,\chi \to \gamma\,X^0$$

is forbidden at tree-level but allowed at 1-loop level

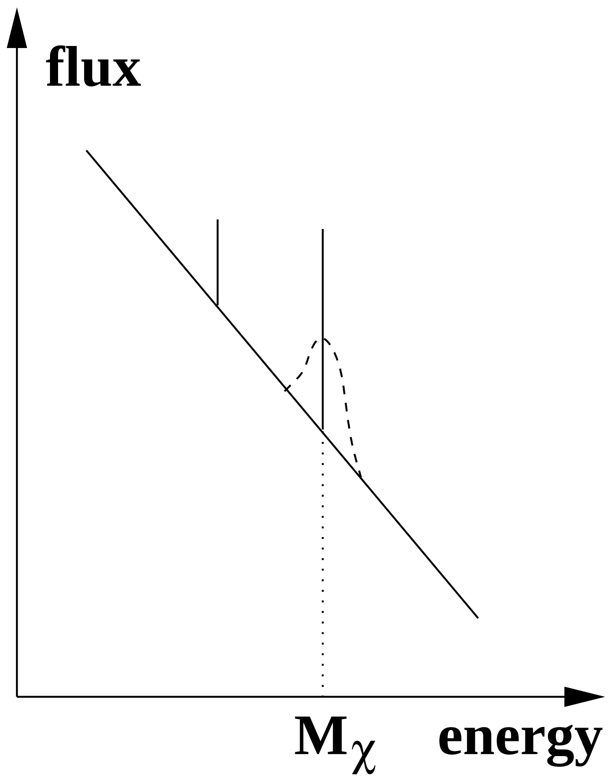
χs in the galactic halo are non-relativistic

$\Downarrow$

γ in the final state is nearly monochromatic

$\Downarrow$

no plausible astrophysical background



Bergström & Snellman, Phys. Rev. D 37 (1988) 3737

Candidates in the WIMP framework

The leading WIMP dark matter candidate is the lightest supersymmetric particle (LSP), plausibly the lightest neutralino χ_1^0.

In the minimal supersymmetric extension to the standard model (MSSM), χ_1^0 is a mixture of the supersymmetric partners of γ, Z boson and neutral part of two Higgs doublets.

It is massive (in the range between few GeV to few TeV), weakly interacting (it has zero electric and color charges) and stable (in R-parity conserving SUSY models).

In the MSSM it is quite natural to find models with cosmologically relevant relic abundance (i.e. this happens in large portions of the huge MSSM parameter space).

Detection prospects vary with SUSY models, but, most notably, different detection techniques are complementary. At the same time, some viable models might be found at future accelerators, some only with dark matter searches (and some are just hopeless for both).

Other WIMP candidates are, e.g.:

• the lightest Kaluza-Klein particle in models with universal large extra dimensions;
• LIMPs, i.e WIMPs just coupled to leptons

WIMPs are just one possibility

The WIMP idea is neat but needs not to be the right one. There are as well plenty of non-thermal dark matter candidates, e.g.:

• the axion, introduced to solve the problem of weakness of CP violation in strong interactions
• "wimpzillas", super-heavy relics from the early Universe
• "Q-balls", topological, extended objects (super-symmetric or not)
• gravitinos, the SUSY partner of the graviton
• mirror matter
• ...

They do not fall any more in a class of models, hence detection techniques have to tuned in each scenario (and some are kind of discouraging, such as for particles which interact just gravitationally).

Conclusions

- Evidence for non-baryonic dark matter and dark energy stronger than ever.

- We are still far from having a comprehensive understanding of the dark side of the Universe in a particle physics contest.

- For what concerns dark energy, some roots have been explored, but something fundamental is still missing. Help may come from future more refined cosmological observations.

- For what concerns dark matter, interesting ideas have been put forward and are being tested; are there already indications that we are on the right track?