Dark Matter

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Seminari dei dottorandi del XXIX ciclo

Pisa, 17/09/14

Outline

- Standard Cosmology
- Evidences for Dark Matter
- Freeze out mechanism
- Dark Matter Searches
- Minimal Dark Matter

some references :

- Gorbunov, Rubakov, *Introduction to theory of the early Universe: The Hot Big Bang Theory* (World Scientific);
- Bertone, Hooper, Silk (hep-ph/0404175)
- Cirelli (hep-ph/1202.1454)

...others given during the talk

Standard Cosmology

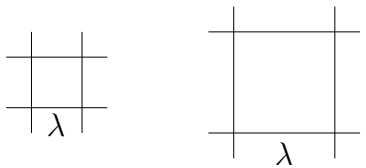
- **Einstein equations**: geometry $\longleftrightarrow$ matter

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu}\mathcal{R} = -\frac{8\pi G}{c^4} T_{\mu\nu} + \Lambda g_{\mu\nu}$$

- **metrics**: symmetries of the problem

  homogeneity and isotropy $\longrightarrow$ RW metric

$$ds^2 = -c^2 dt^2 + a(t)^2 \left(\frac{dr^2}{1 - kr^2} + r^2 d\Omega^2 \right)$$



$$d(t) = a(t)\lambda \Rightarrow H(t) = \frac{\dot{a}(t)}{a(t)}$$

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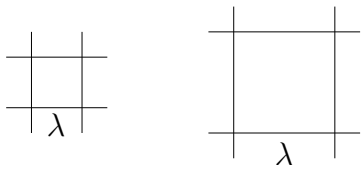

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Friedmann equation

$$H^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho$$

$$\rho_c \equiv \frac{3H^2}{8\pi G} \Rightarrow k = 0$$

flat euclidean space

species abundances $\quad \Omega_i = \dfrac{\rho_i}{\rho_c}$

$$\Omega \equiv \sum_i \Omega_i \;\Rightarrow\; \Omega = 1 + \frac{k}{H^2 a^2}$$

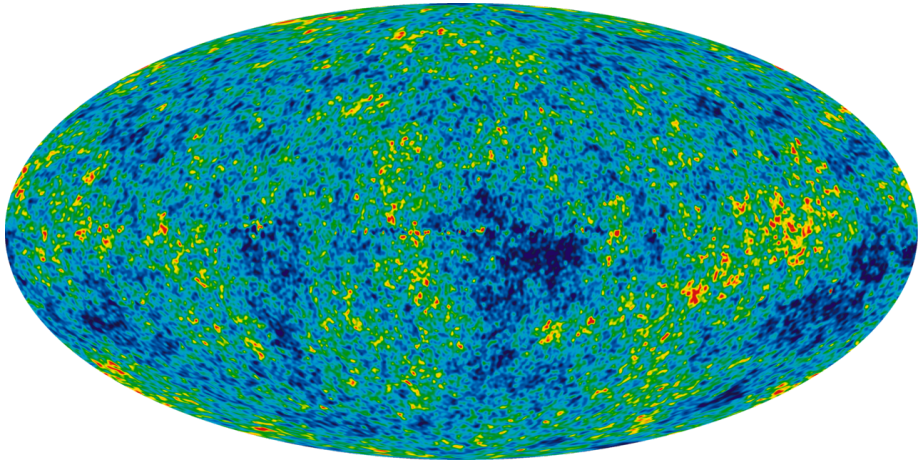
The Universe today

- homogeneous, isotropic and **expanding** : $H_0 = (70.5 \pm 1.3)\,\dfrac{km}{s\,Mpc}$

$$t \sim H_0^{-1} \simeq 1.4 \cdot 10^{10} yrs\,, \quad l \sim c\,H_0^{-1} \simeq 4.3 \cdot 10^3 Mpc$$

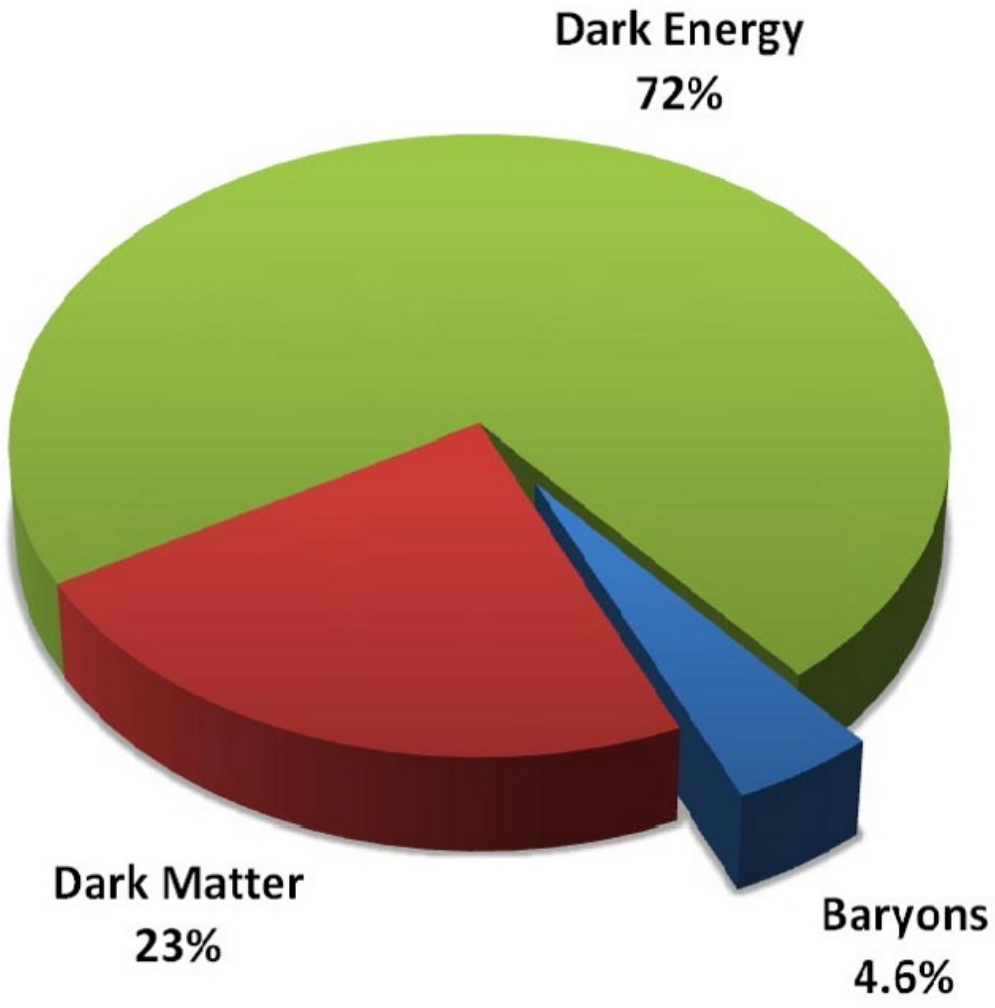
- **C**osmic **M**icrowave **B**ackground (gas of non interacting photons)

$$T_{CMB} \simeq 2.73\,K$$
$$\frac{\delta T}{T} \simeq 10^{-4} - 10^{-5}$$



- **flat** Universe : $\Omega \simeq 1$ (CMB + Type Ia Supernovae)

The dominant part of the energy density is unknown!



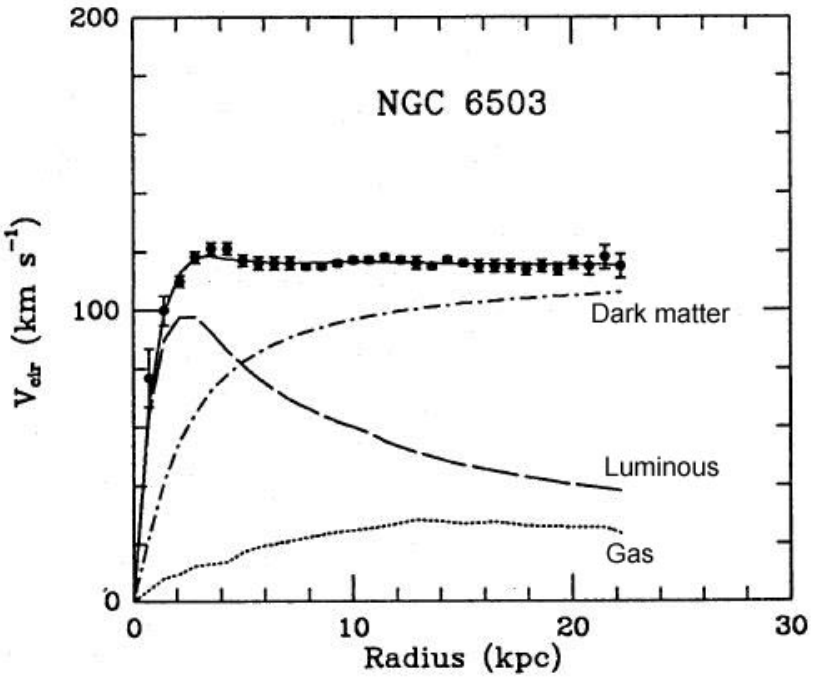
Evidences for Dark Matter

- **Galaxies rotation curves** (galaxy scale)

flat behaviour at large distances

$$v(r) = \sqrt{\frac{GM(r)}{r}}\,,\; M(r) = \int 4\pi r^2 dr \rho(r)$$

$$v(r) \sim \text{const} \;\Rightarrow\; M(r) \propto r\,, \quad \rho(r) \propto 1/r^2$$

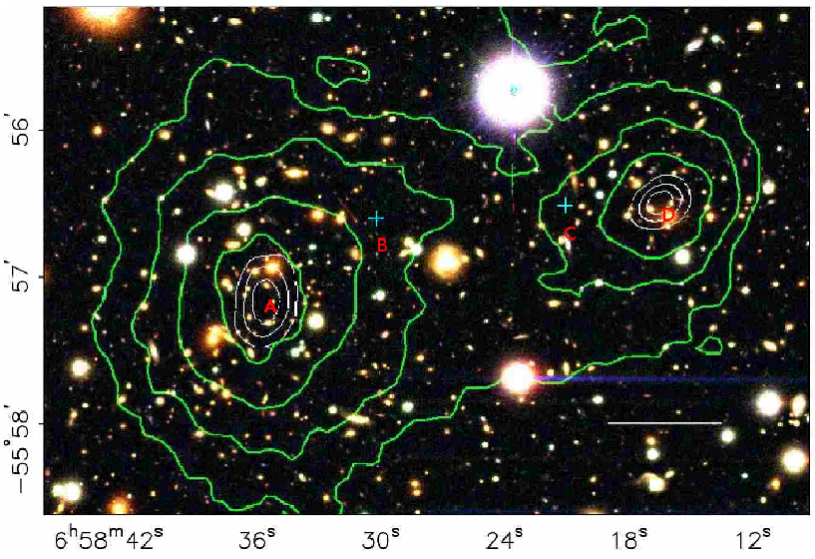


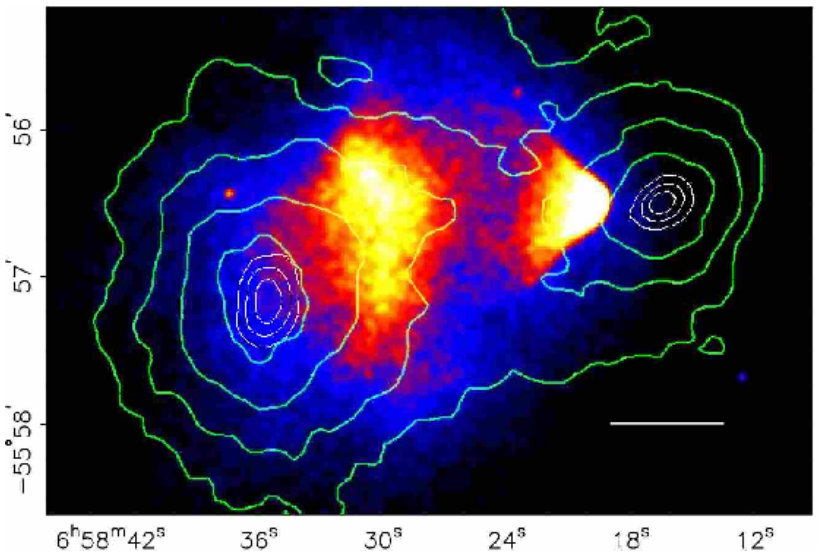
Ordinary matter embedded in a DM cloud : galactic halo

Evidences for Dark Matter

- **Gravitational lensing** (cluster of galaxies scale)

bullet cluster





90% of baryons in intergalactic gas

the gas is slowered by the collision

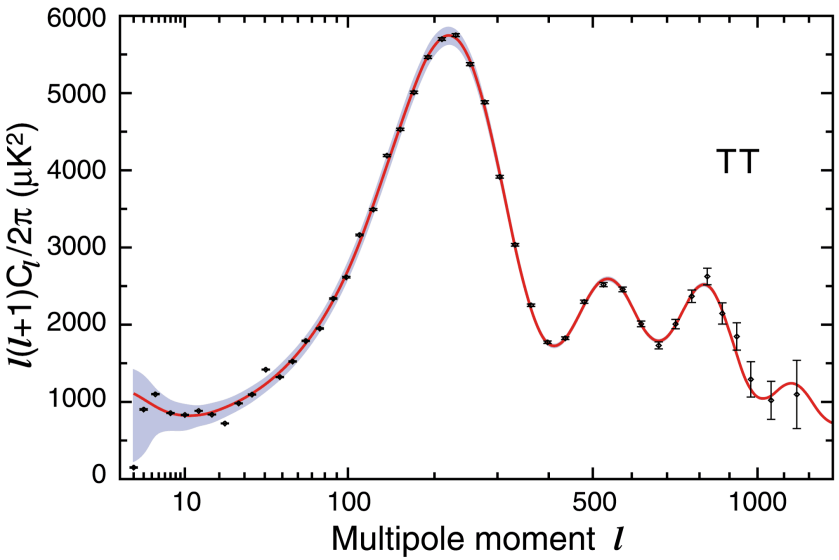
gravitational field mainly produced by DM

Evidences for Dark Matter

- **CMB power spectrum** (cosmological scale)

$$\frac{\delta T}{T}(\theta,\phi) = \sum_{l=2}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\theta,\phi)$$

$$C_l \equiv \frac{1}{2l+1} \sum_{m=-l}^{l} |a_{lm}|^2$$



Informations about the composition of the Universe at decoupling time

good agreement with Big Bang Nucleosynthesis

Dark Matter is there, but...

what is it?

Dark Matter is there, but...

what is it?

Must be **neutral, stable** and **weakly interacting**
none of the SM particles is a good DM candidate:

physics Beyond the Standard Model is required!

Freeze Out mechanism

- X stable particle in thermal equilibrium with the cosmic plasma

$$X\bar{X} \leftrightarrow \text{light particles}$$

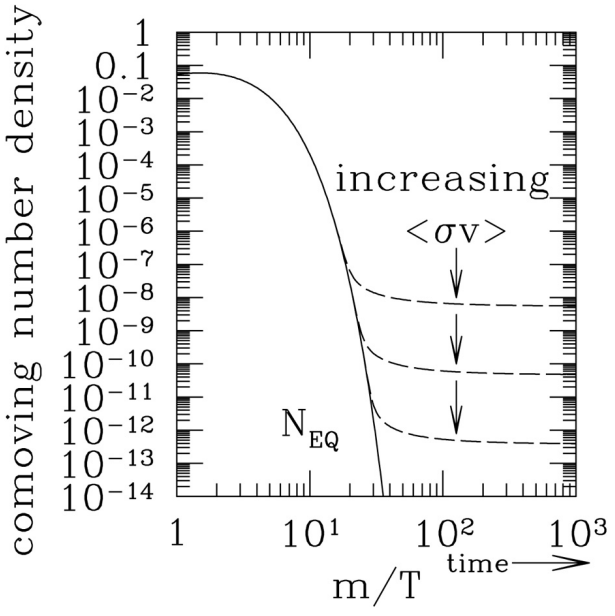
- $T < m_X$

$$n_X^{eq} = g_X \left(\frac{m_X T}{2\pi}\right)^{3/2} e^{-m_X/T}$$

(COLD DM)

- $\Gamma_{ann} < H$

n_X freezes out at $n_X^{eq}(T_f)$



formally described by Boltzmann Equations

$$\frac{dn_X}{dt} + 3\,n_X H = -\langle\sigma v\rangle\,(n_X^2 - n_{X,eq}^2)$$

$$\Gamma_{ann}(T_f) = n_X^{eq}(T_f)\,\langle\sigma_{ann}v\rangle \simeq H(T_f)$$

$$\sigma_{ann} = \frac{\sigma_0}{v} \quad \text{(s-wave)}\,, \qquad H \sim \frac{T^2}{M_{Pl}} \quad \text{(RD)}$$

$$\Omega_X \;=\; \frac{\rho_{X,0}}{\rho_c} \sim 3\cdot 10^{-10}\,\frac{GeV^{-2}}{\sigma_0}\,\frac{1}{\sqrt{g_{*,f}}}\,\log\left(\frac{g_X\,M_{Pl}m_X\sigma_0}{(2\pi)^{3/2}}\right)\frac{1}{2h^2}$$

- main dependence on σ_0
- only *log* dependence on m_X
- result completely independent on the initial conditions

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$$\Omega_X = \Omega_{DM} \simeq 0.2 - 0.3$$

$$\sigma_0 \sim (0.3 - 1.5)\, 10^{-8}\, GeV^{-2} \sim (1-6)\, 10^{-36}\, cm^2$$

$$\langle\sigma_{ann} v\rangle \sim 3\cdot 10^{-26}\, \frac{cm^3}{s}$$

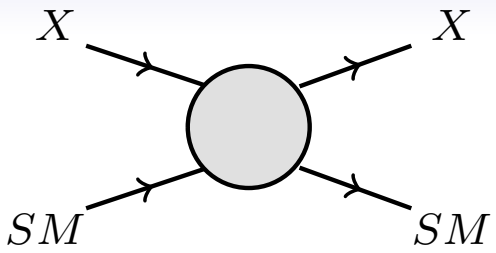
- comparable to weak interaction cross actions

$$\sigma_0 \sim \alpha_X^2/m_X^2 \quad \longrightarrow \quad m_X \sim \alpha_X\, 10\, TeV$$

- **W**eak **I**nteracting **M**assive **P**articles (WIMP): $m_X \sim 100\, GeV - 1\, TeV$

(WIMP miracle)

Direct Detection



$$\rho_X \simeq 0.3 \, \frac{GeV}{cm^3} \, , \, v_X \simeq 10^{-3}$$

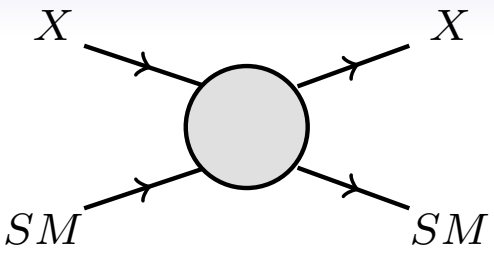
$$\Phi_X \sim 10^7 \, \frac{1}{cm^2 s} \, \frac{GeV}{m_X}$$

$$\mathcal{N}_{ev} \sim \frac{\text{few events}}{\text{year}}$$

$$\Delta E \sim 10 - 100 \, keV$$

DAMA-LIBRA, CoGeNT, CDMS,
CRESST, XENON, LUX...

Direct Detection



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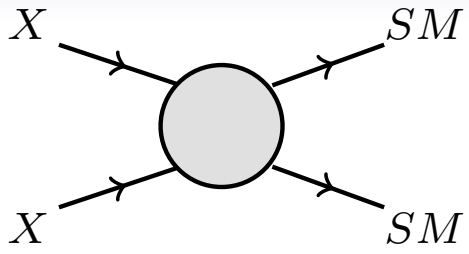


$\bar{p}$, e^+, $\bar{d}$ (PAMELA, FERMI, HESS, AMS)

× no directional infos

× unknown bg

√ e^+ excess → few TeV DM, huge σ_{ann} ?

× no excess on $\bar{p}$ → lepto-philic DM ?

γ (FERMI, HESS, CT)

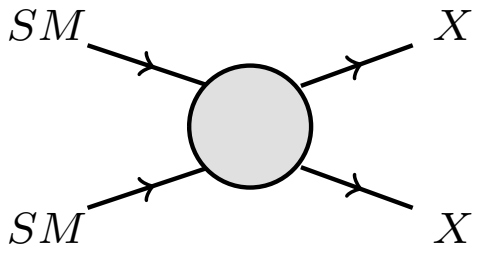
? 130 GeV excess

ν, $\bar{\nu}$ (SK, ICECUBE)

√ bounds on DM cross section

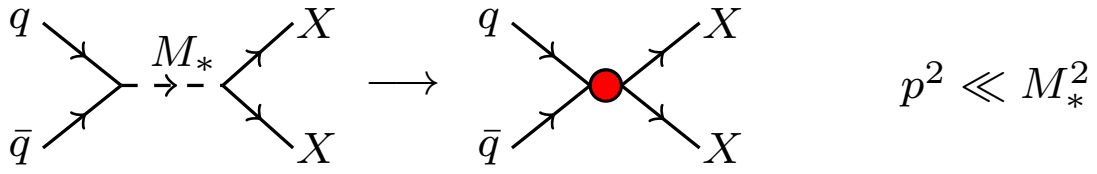
? high energy solar ν, smooking gun for DM

Collider searches



× model dependent searches based on natural EW theories

√ model independent searches based on Effective Field Theories:
monophotons, monojets + MET channels at LHC
describe the unknown interaction DM-SM with effective operators



$$p^2 \ll M_*^2$$

× validity of EFT at LHC is questionable and get worse increasing the energy
Busoni, De Simone, Morgante, Riotto (hep-ph/1307.2253)

? need of new strategies for Dark Matter searches at colliders
De Simone, Giudice, Strumia (hep-ph/1402.6287)

EWSB theories $\longrightarrow$ WIMP candidates

SUSY, Composite Higgs, Extra Dimensional Theories

but

- till now no evidences at LHC
- a lot of free parameters $\longrightarrow$ not clear phenomenolgy
- DM stability imposed by hand (discrete symmetries)

Minimal Dark Matter

Cirelli, Fornengo, Strumia (hep-ph/0512090), Cirelli, Strumia (hep-ph/0903.3381)

SM + DM (X, multiplet of scalars or fermions)

- assume that X has only $SU(2)_L \times U(1)_Y$ gauge interactions with SM particles
- the only new parameter is M_X (fixed by Ω_X)

quantum number assignements that provide a good DM candidate:

- the lightest one is neutral
- lightest component is automatically stable
- still allowed by DM searches

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the best candidate is a fermion quintiplet of $SU(2)_L$ with $Y = 0$

$$M_X \sim 10\,TeV$$

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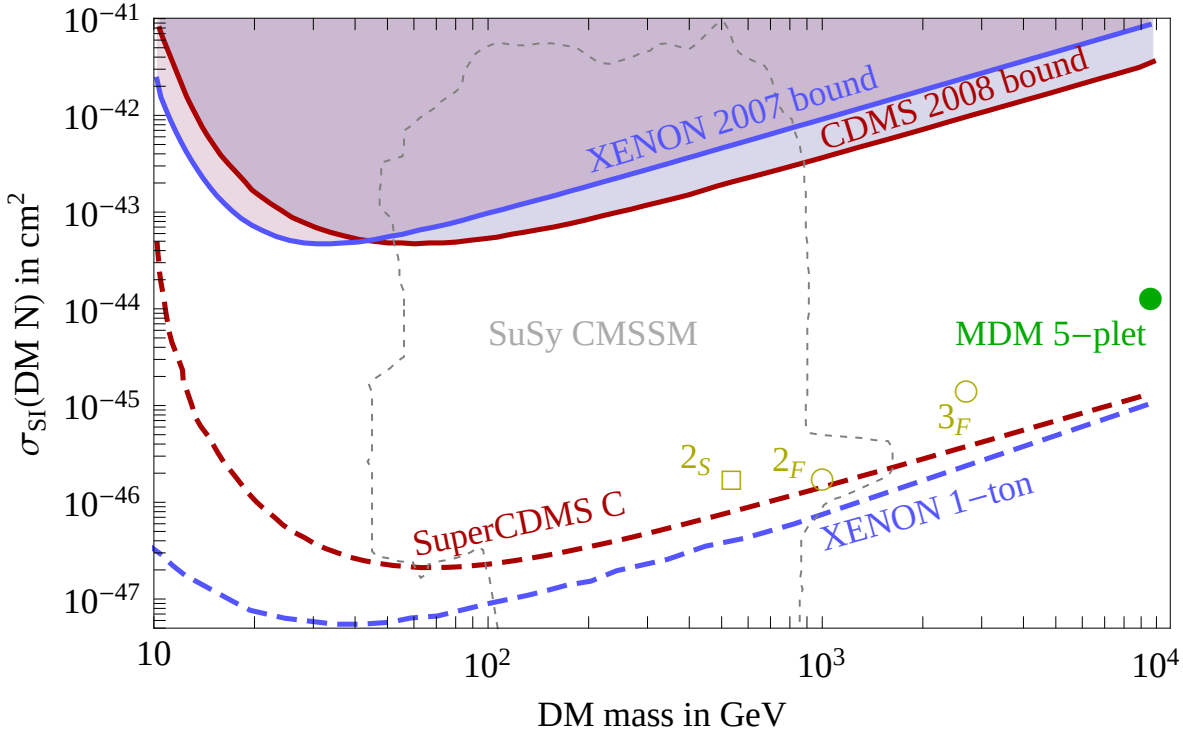
another good candidate is a fermion triplet of $SU(2)_L$ with Y=0

$$M_X \sim 3\,TeV$$ Cirelli, Sala, Taoso (hep-ph/1407.7058)

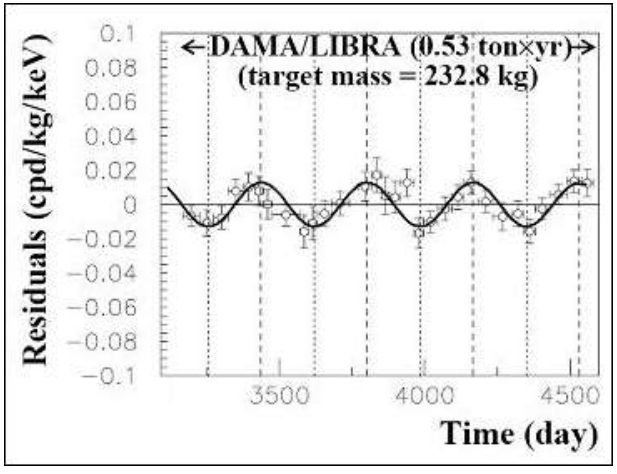

10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
σ_{SI}(DM N) in cm^2
10
10^2
10^3
10^4
DM mass in GeV
XENON 2007 bound
CDMS 2008 bound
SuSy CMSSM
MDM 5−plet
3_F
2_S
2_F
SuperCDMS C
XENON 1−ton

Conclusions

- waiting for new results fron direct detection experiments (Super-CDMS, XENON 1-ton) and indirect detection experiments (AMS-02)
- need of new strategies of model independent searches at LHC-14 and future colliders
- lots of WIMP candidates from EWSB theories: many free parameters
- Minimal Dark Matter: no free parameters, very clear phenomenology

Thanks for your attention!

Hints of Dark Matter?



? annual modulation compatible with the motion of the Earth

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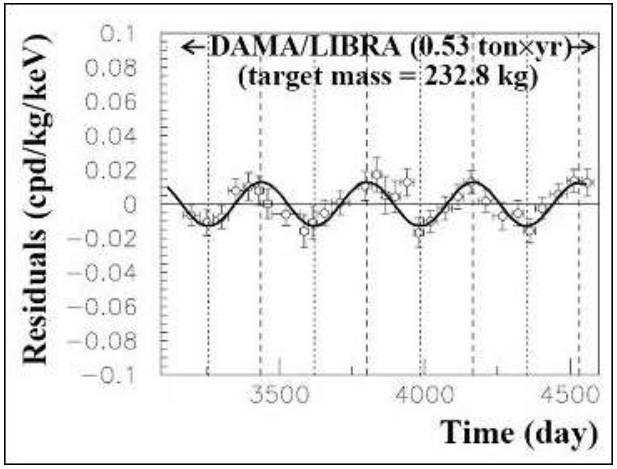

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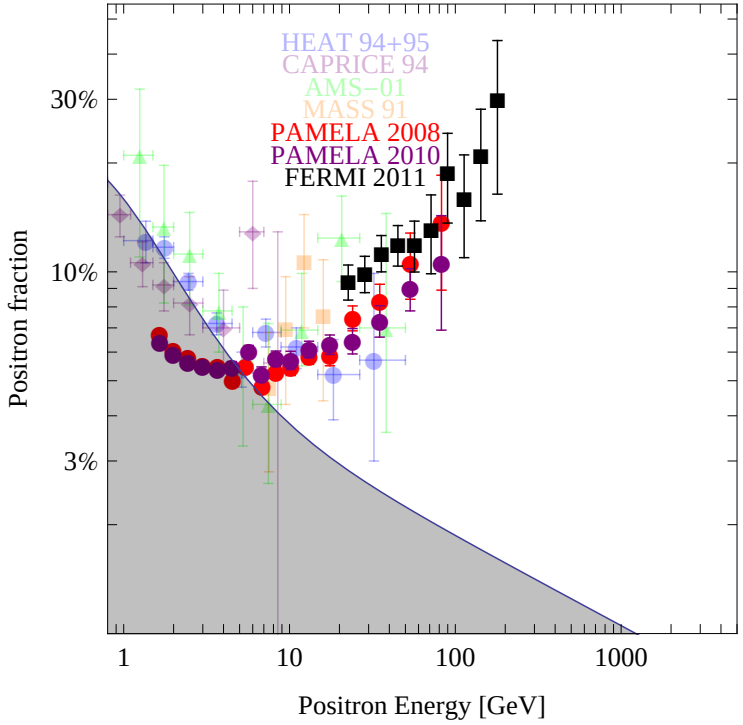

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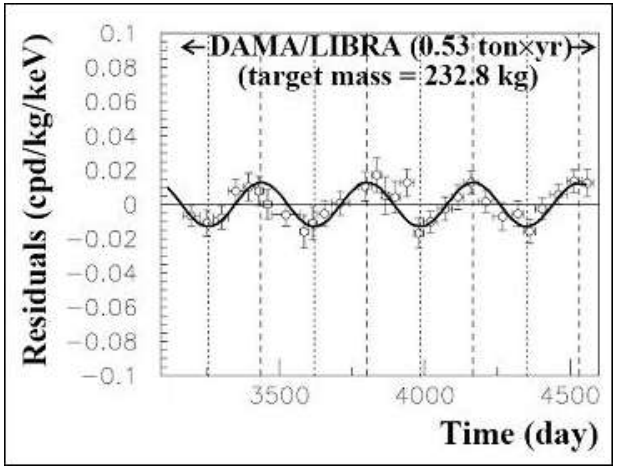

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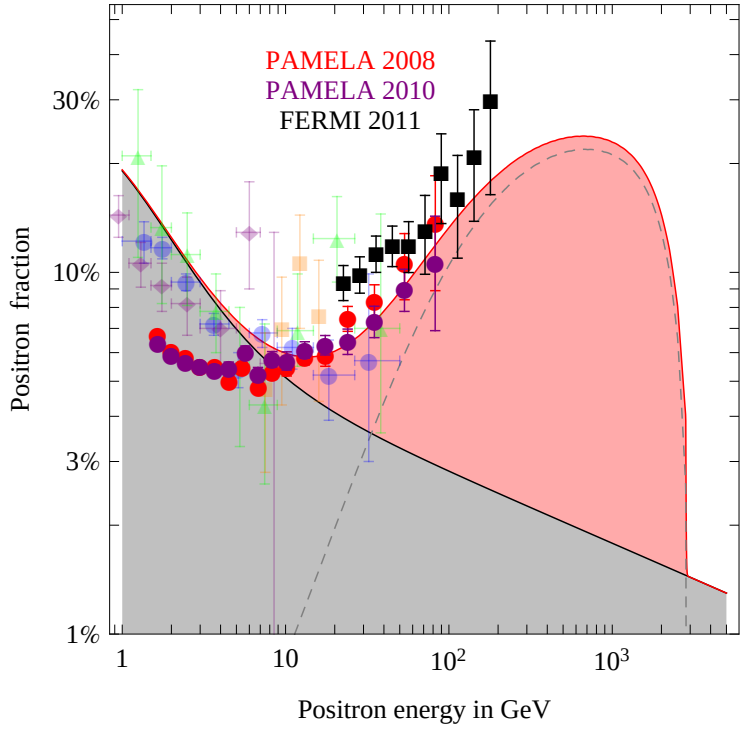

? fitted by a $3\,TeV$ DM candidate with huge cross section $\langle \sigma v \rangle \sim 10^{-23}\,\frac{cm^3}{s}$