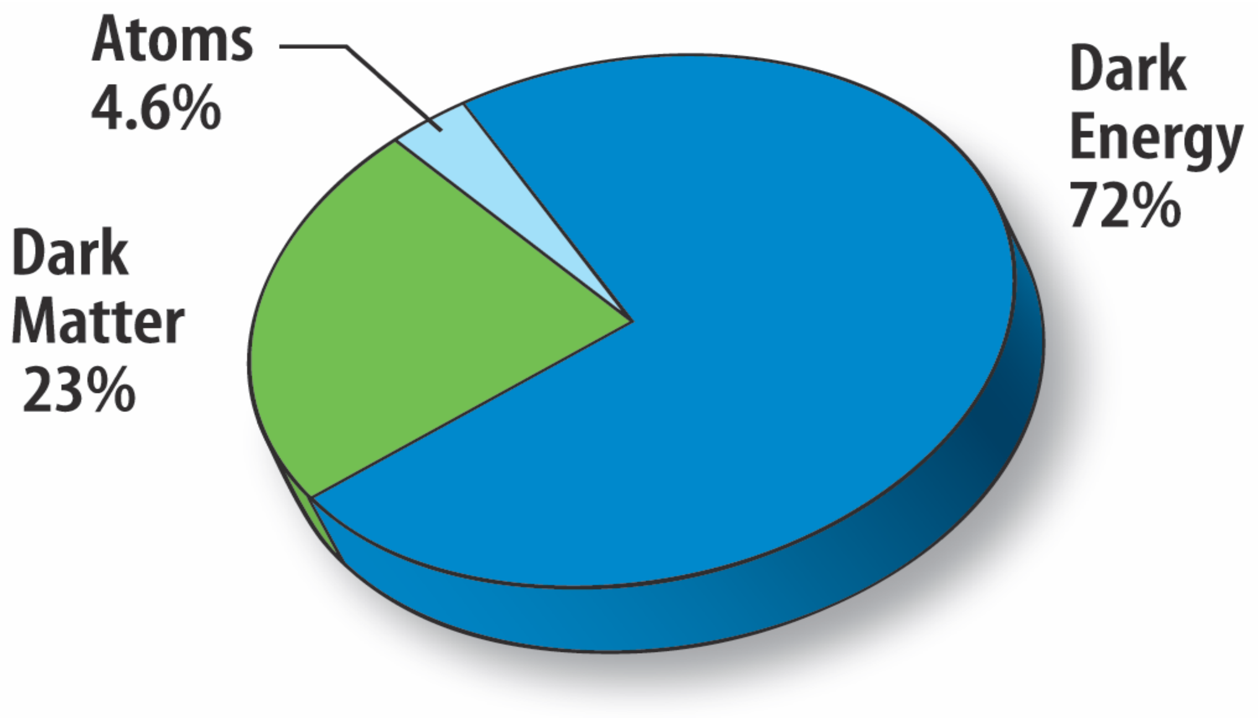
Dark Matter: current and future

Yasunori Nomura

UC Berkeley; LBNL

The universe is mostly dark



… One of the major discoveries in our time

What is the dark energy?

What is the dark matter (DM)? ⇐

Plan

- Evidence of DM
  - Astrophysical observations
  - Cosmology
- DM as a new particle
  - What we do (not) know about DM
  - Candidates for DM
- Experimental probe
  - Direct/indirect detections
  - Colliders
- Hints already?
  - DAMA
  - PAMELA/ATIC

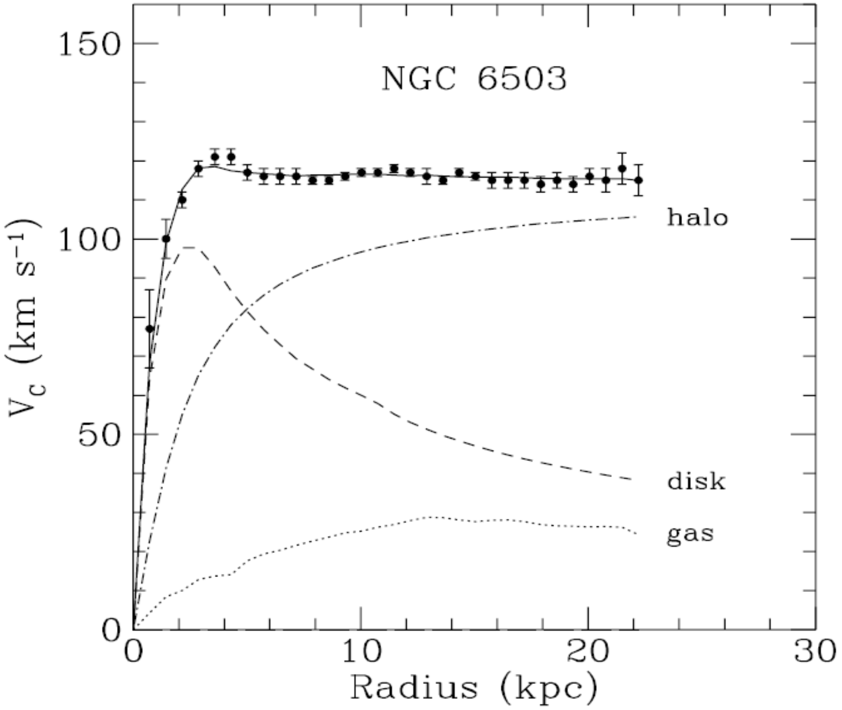
cf.

E. Kolb & M. Turner, "The Early Universe"
G. Bertone, D. Hooper, J. Silk, Phys. Rep. 405, 279 (2005)
M. Taoso, G. Bertone, A. Masiero, JCAP 03, 022 (2008)
and refs therein, ……

Evidence of DM

Rotation curves of galaxies

Rotation curves are typically flat well beyond the edge of visible disks



$$v(r) = \left(\frac{GM(r)}{r}\right)^{1/2}$$

… Need new dark component with $\rho(r) \sim 1/r^2$

(nearly) spherical halo

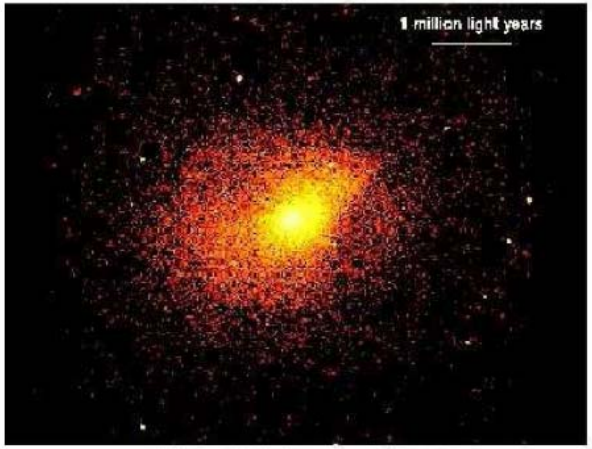
Other Evidences

Gravitational lensing, velocity dispersion of satellite galaxies, …

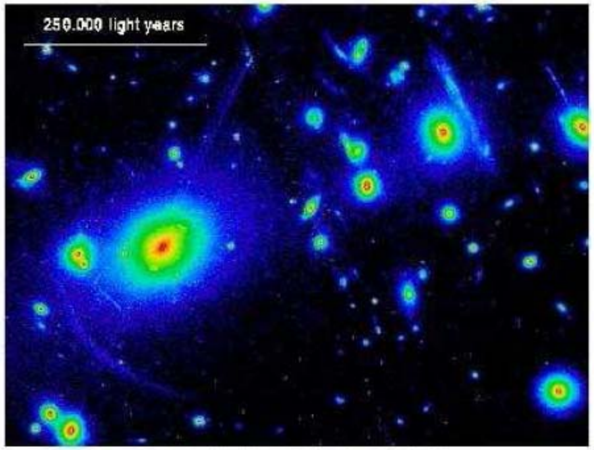
On larger scales

The mass of a cluster of galaxies: Virial theorem, lesnsing, …

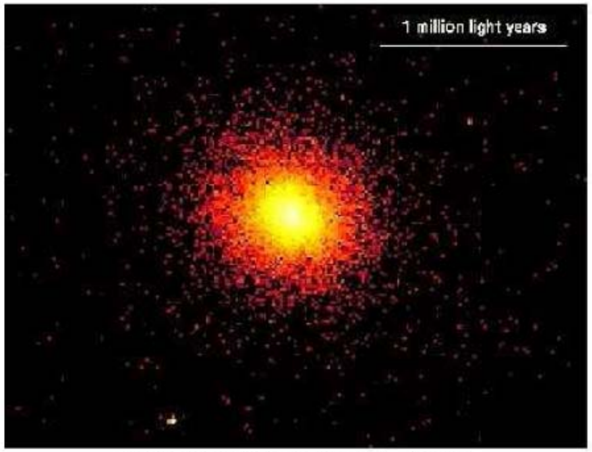
The amount of baryons (gas): X-ray observations, SZ effect…



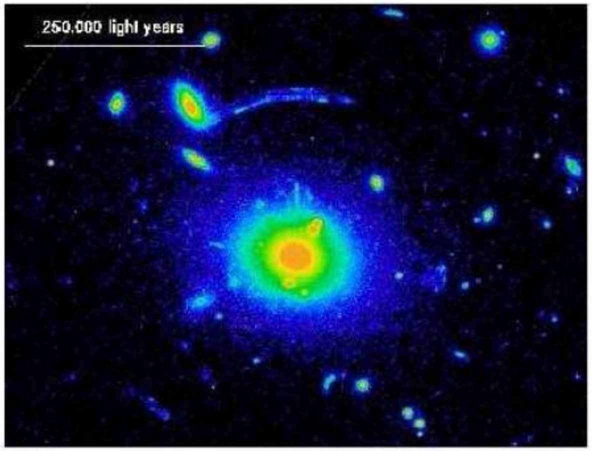
Abell 2390: Chandra (ACIS)



Abell 2390: HST (WFPC2)



MS2137.3-2353: Chandra (ACIS)



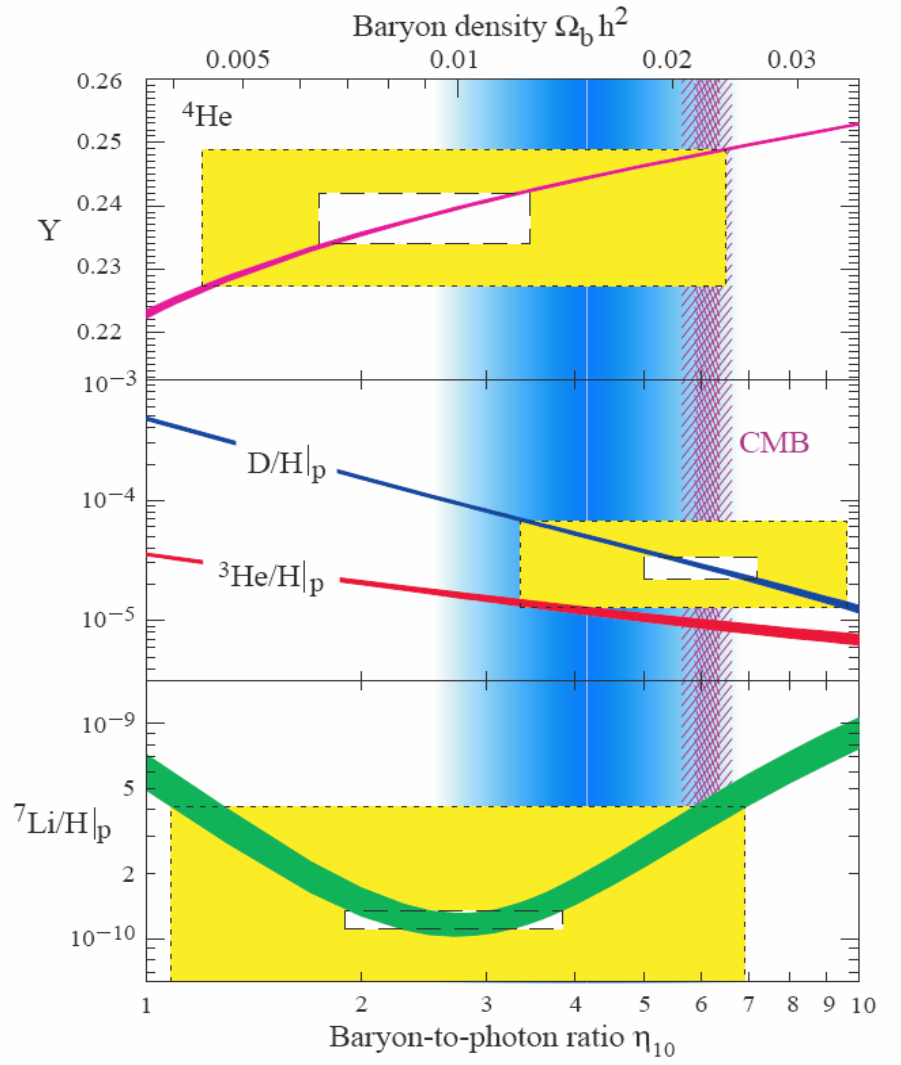
MS2137.3-2353: HST (WFPC2)

$$\frac{M_{total}}{M_{gas}} » 1$$

$$\Omega_{matter} \equiv \frac{\rho_{mass}}{\rho_c} \sim 0.3$$

Why not baryons we just missed?

Big bang nucleosynthesis (BBN)



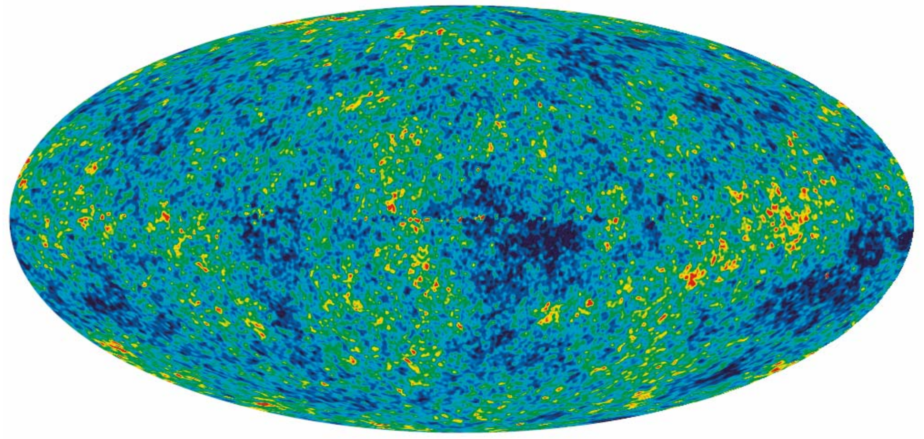
The abundance of light elements depends on the amount of baryons

$\Omega_{baryon} \sim 0.03 – 0.04$

« Ω_{matter} inferred from clusters

Latest cosmology confirms the picture

Cosmic microwave background (CMB)



The power spectrum depends on Ω_b, Ω_M, ..

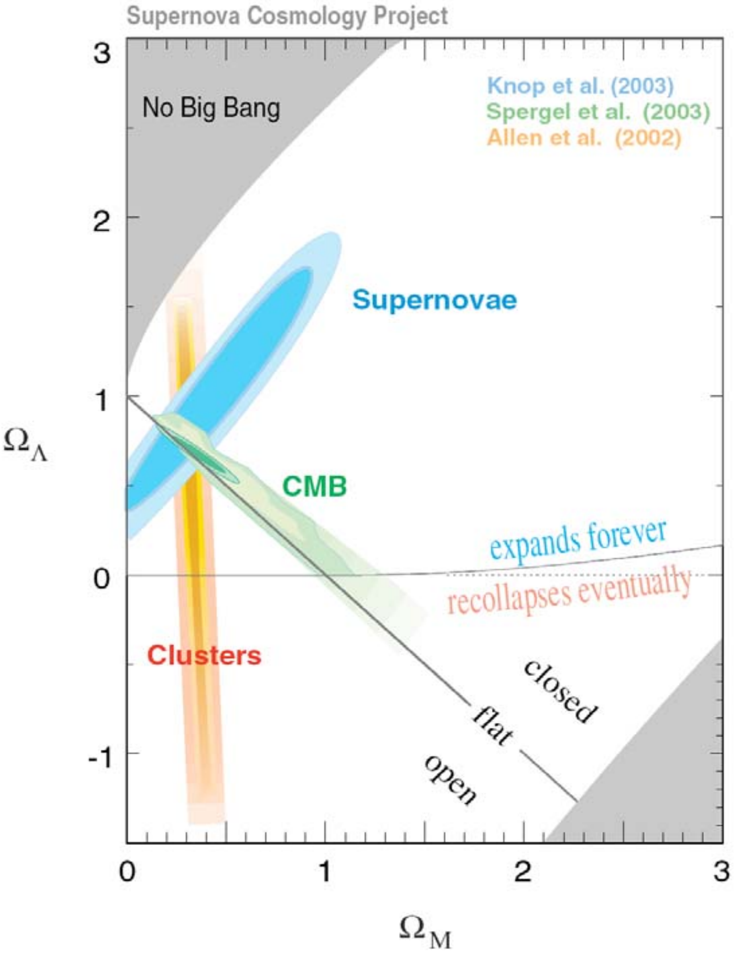
$$\Omega_b h^2 = 0.02273 \pm 0.00062$$

$$\Omega_M h^2 = 0.1099 \pm 0.0063$$

$$(h = 0.719 ^{+0.026}_{-0.027})$$

WMAP only (5 years)

Cosmic concordance



DM as a new particle

What do we know about DM?

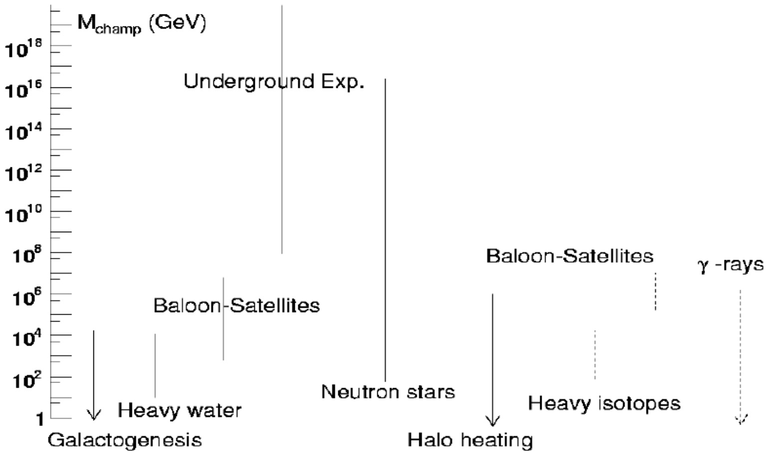
- DM is neutral

  positively charged $X \rightarrow Xe^-$

  (heavy hydrogen)

  negatively charged $X \rightarrow Xp$

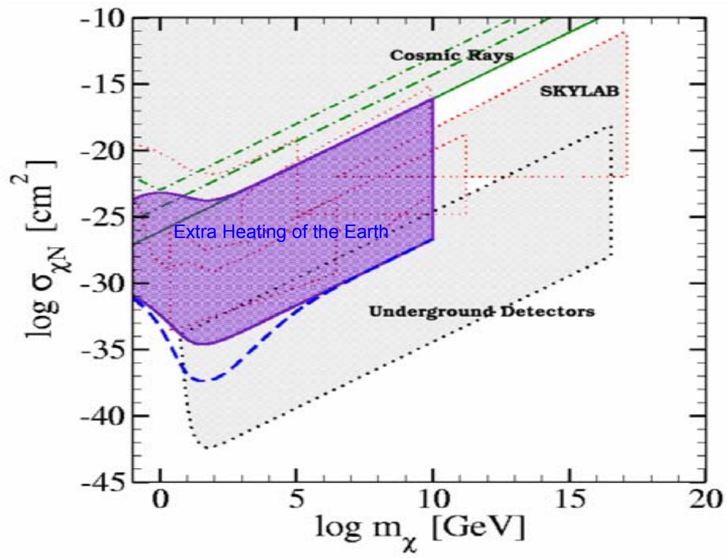
  (heavy "neutron")



- DM is not colored

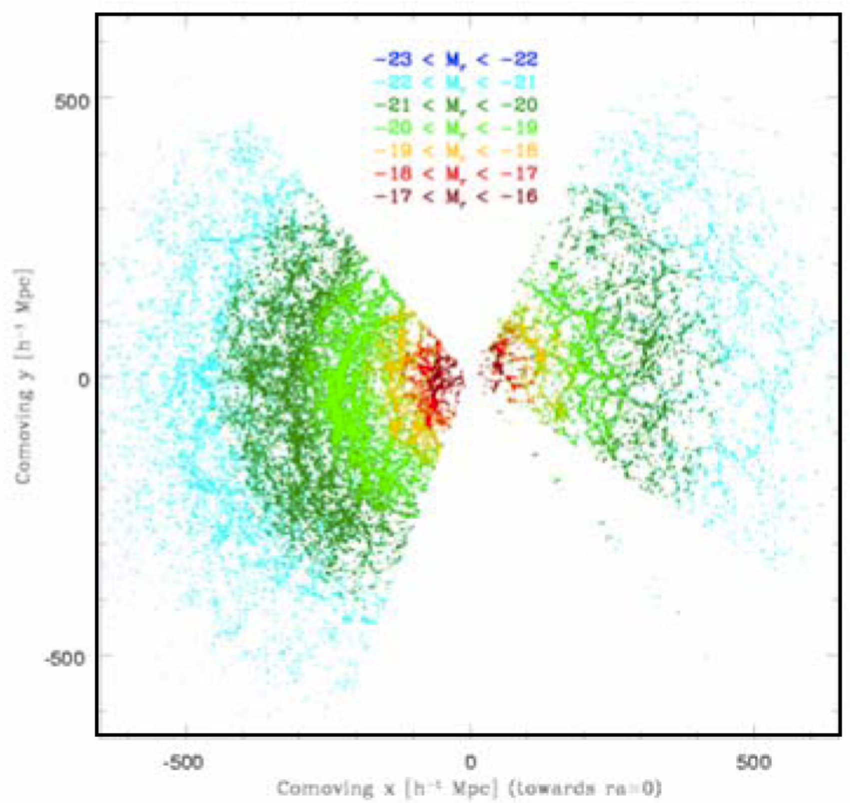
  cloered $X \rightarrow X\bar{q}, Xqq$

  (heavy hadrons)

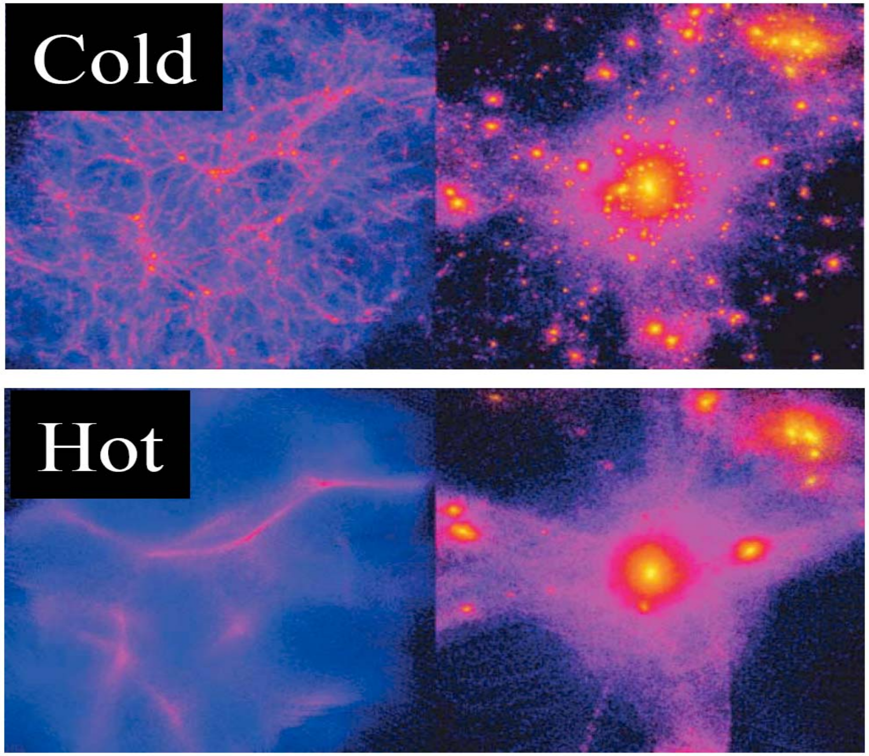


- DM is cold — nonrelativistic at $z \sim 3000$ ($t \sim 10^4$ yrs)

SDSS data



Simulation



Relativistic DM at $z \sim 3000$ (hot DM) erases small scale structures

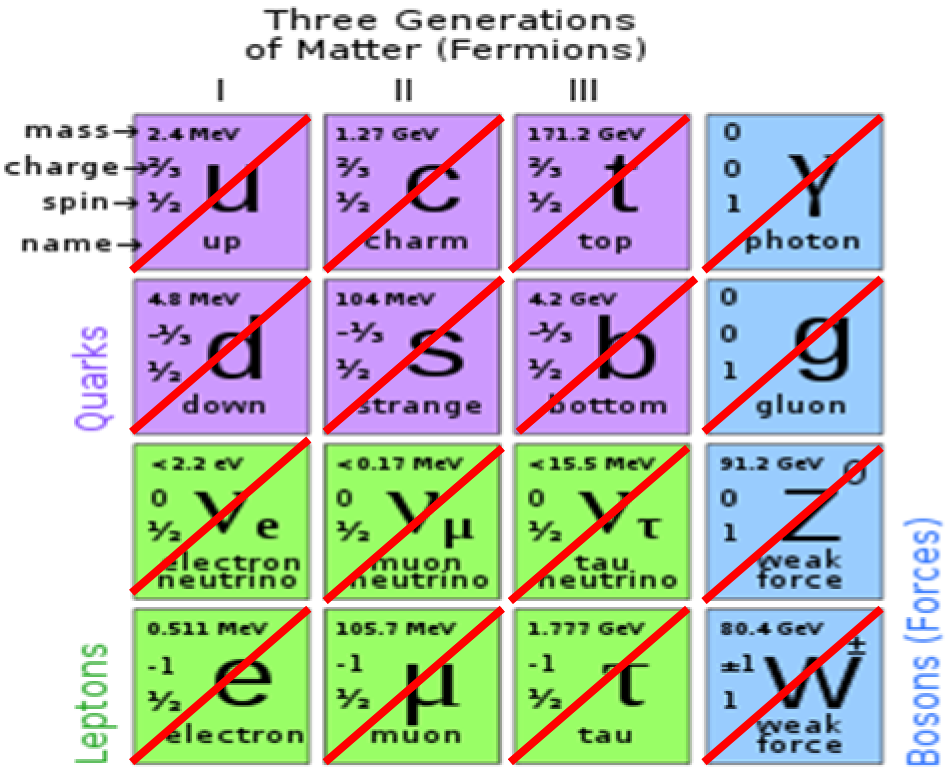
For SM neutrinos $\Omega_\nu h^2 = \dfrac{m_\nu}{90\ \text{eV}}$

free-streaming length: $\lambda_{FS} \sim 20 \left(\dfrac{30\ \text{eV}}{m_\nu}\right)\ \text{Mpc}$

(small mixture of hot DM allowed; $\Sigma m_\nu < 0.2\,\text{eV}$)

Standard model particles?

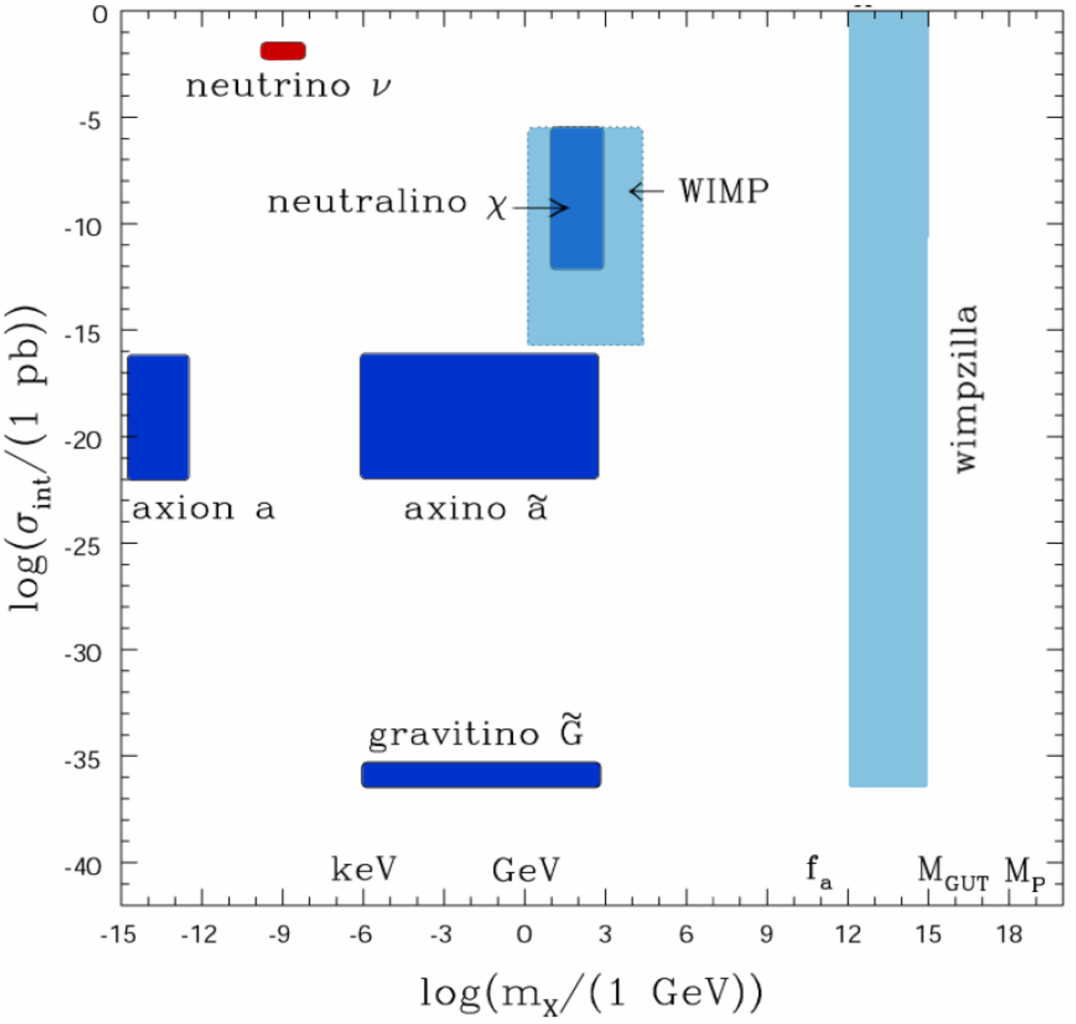
Stable particles — electrons, photons, neutrinos, protons



None of them qualifies

→ New physics beyond the standard model

Know more? — not much



Roszkowski

Huge range of mass and cross section allowed

(and considered)

Some "model-independent" constraints

Bullet cluster

colliding galaxies

$\Longrightarrow$ $\sigma_{\text{self scattering}}/m_{\text{DM}} \lesssim 1\,\text{cm}^2\text{g}^{-1}$

Quantum mechanical effect

$$\lambda_{\text{de Broglie}} \sim \frac{1}{m_{\text{DM}} v} \sim \frac{1}{m_{\text{DM}} r\,(G\rho_{\text{DM}})^{1/2}}$$

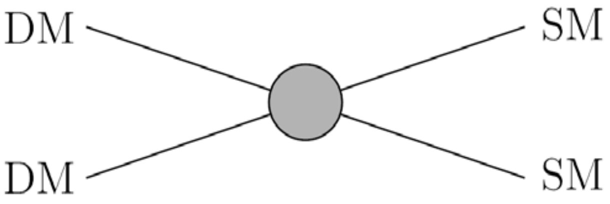
$$\lambda_{\text{de Broglie}} \sim r \quad \rightarrow \quad r_{\text{Jeans}} \sim \frac{1}{m_{\text{DM}}{}^{1/2}(G\rho_{\text{DM}})^{1/4}}$$ below which no instability

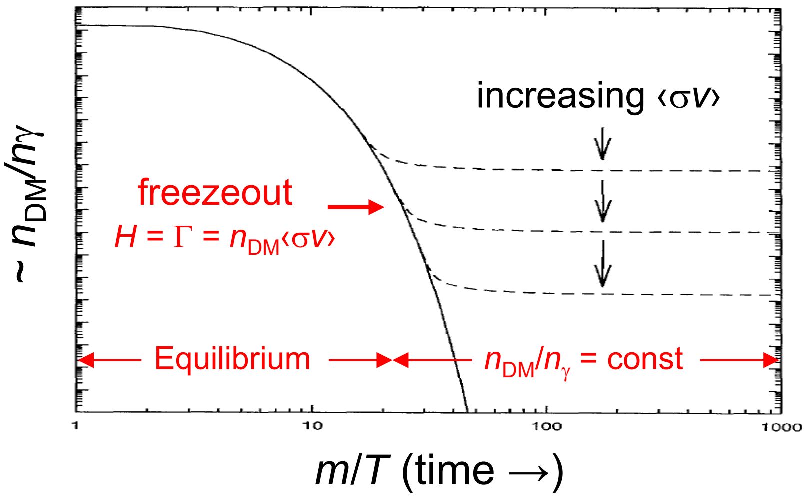
$r_{\text{Jeans}} \lesssim \text{kpc}$ $\Longrightarrow$ $m_{\text{DM}} \gtrsim 10^{-22}\,\text{eV}$

… not strong

Connection to particle physics?

DM as a thermal relic of the early universe





Annihilation cross section determined

$$\Omega_{\rm DM} h^2 \simeq \frac{3\times10^{-27}\,{\rm cm^3\,s^{-1}}}{\langle\sigma v\rangle} \Longrightarrow \langle\sigma v\rangle \sim \frac{g^2}{8\pi}\,\frac{1}{(\mathrm{TeV})^2}$$

weak interaction strength

… Weakly Interacting Massive Particle (WIMP)

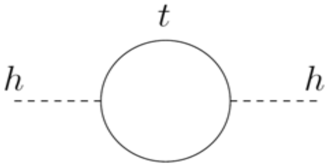
TeV — the most important scale in particle physics

The standard model of particle physics

… contains only a single mass scale:

the scale of electroweak symmetry breaking (EWSB)

stability of the
Higgs potential



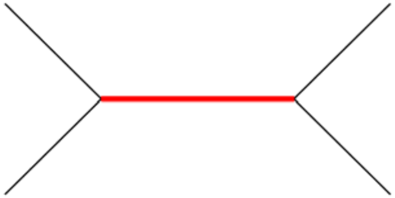
⟹ New physics at ~ TeV?

The lightest particle in the new sector can easily be stable

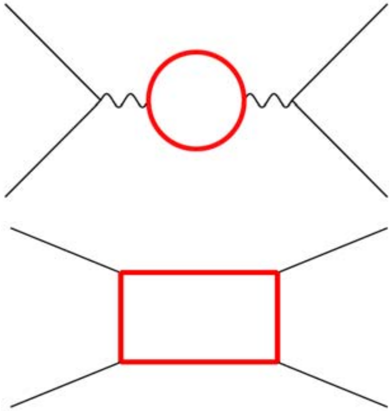
… (approximate) conserved quantum number

cf. QED, QCD, …

Such a quantum number most likely needed



bad for LEP



OK (extra loop factor)

ex. Supersymmetry with R parity

SM (R_p+)		Superparticle (R_p–)	
Quarks	u_i	Squarks	$\tilde{u}_i$
	d_i		$\tilde{d}_i$
Leptons	ν_i	Sleptons	$\tilde{\nu}_i$
	e_i		$\tilde{e}_i$
Gauges	g	Gauginos	$\tilde{g}$
	W		$\widetilde{W}$
	B		$\widetilde{B}$
Higgses	$h_{u,d}$	Higgsinos	$\tilde{h}_{u,d}$
Graviton	G	Gravitino	$\widetilde{G}$

DM candidates:

$\tilde{\nu}_i$, $\widetilde{W}^0$, $\widetilde{B}$, $\tilde{h}_{u,d}^0$, $\widetilde{G}$

only special case
(direct detection)

if the lightest
supersymmetric particle (LSP)

ex. Kaluza-Klein DM

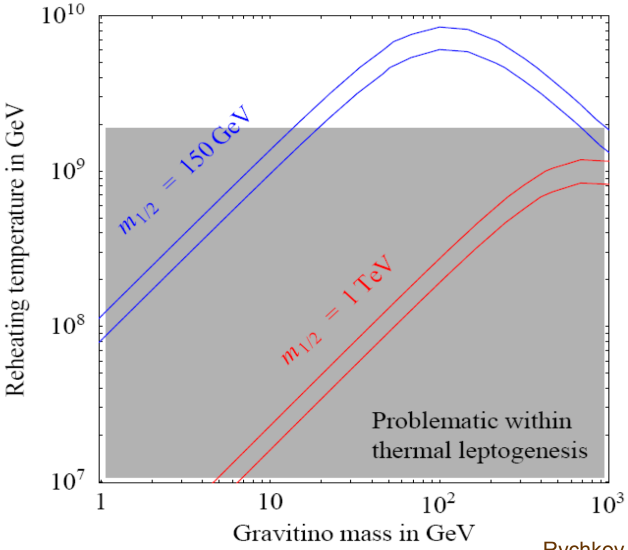
certain special cases in theories with extra dimensions,
although not solving the hierarchy problem

Caveats

- Production of DM may be nonthermal

e.g. Gravitino

- scattering after inflation



Rychkov, Strumia

- decay of the next-to-lightest supersymmetric particle (NLSP)

$$\Omega_{\tilde{G}} = \frac{m_{\tilde{G}}}{m_{\text{NLSP}}} \Omega_{\text{NLSP}}$$

$\Longrightarrow$ Cross section may be very small

e.g. Wino/Higgsino

decay of heavy (*e.g.* moduli) particles

$\Longrightarrow$ Cross section may be larger

- DM may have asymmetry

$$\Omega_X \sim \frac{(n_X - n_{\bar{X}})/s}{10^{-11}} \frac{m_X}{30 \text{ GeV}}$$

related with $(n_B - n_{\bar{B}})/s \sim 10^{-11}$?

non-WIMP example — axion

The symmetries of the standard model allows the term

$$\mathcal{L} = \frac{\theta}{64\pi^2} \varepsilon^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma}$$

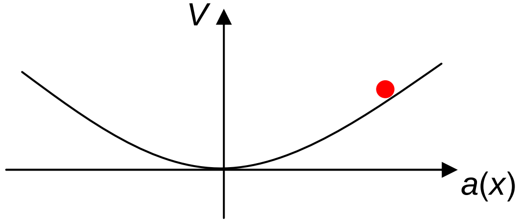
leading to unwanted EDMs for neutron, …

(strong CP problem)

$\longrightarrow$ $|\theta| \lesssim 10^{-9}$ … why?

If $\theta \rightarrow a(x)$ arising from spontaneous breaking of some symmetry (Peccei-Quinn symmetry) at a scale f_a,

$\langle a(x) \rangle$ adjusts $\theta_{\text{eff}} = 0$

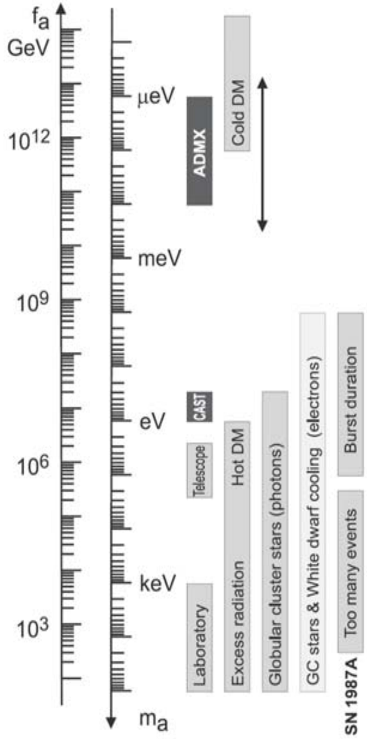


Coherent oscillation of $a(x)$ contributes to Ω_M

$\rightarrow$ cold DM

Astrophysical / terrestial constraints: $f_a \gtrsim 10^9$ GeV

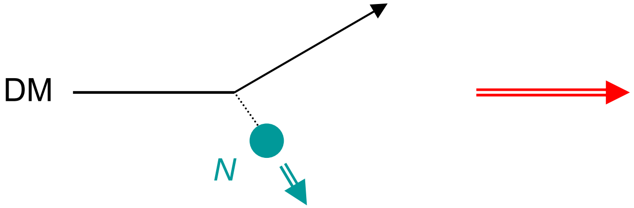
Very weakly coupled, ~$1/f_a$, light ($m_a \sim \Lambda_{QCD}^2/f_a$) state



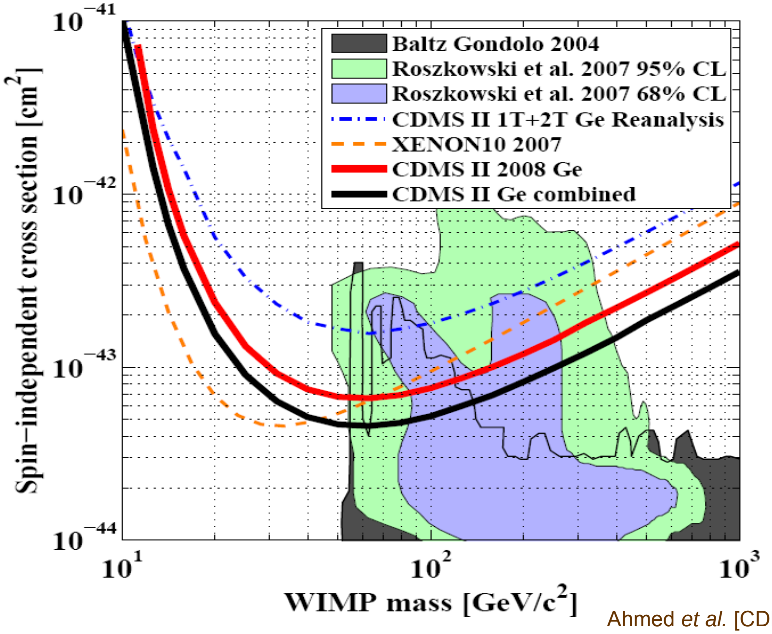
Experimental probe

WIMP has cross sections of weak interaction strength

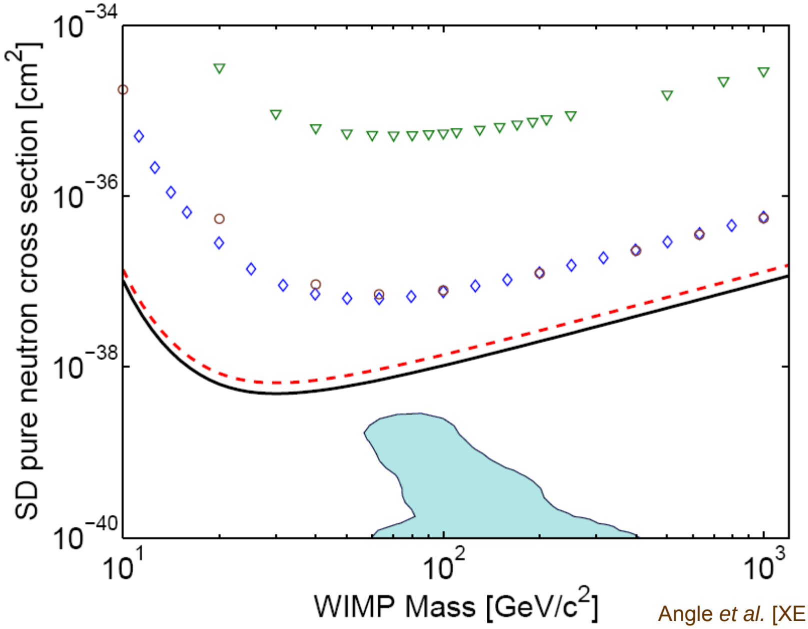
Direct detection experiments



spin independent
spin dependent



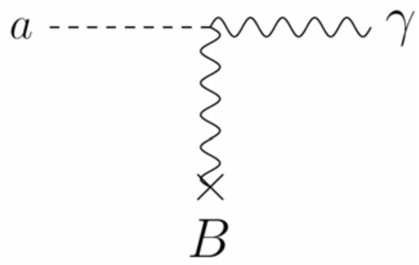
Ahmed *et al.* [CDMS coll.]

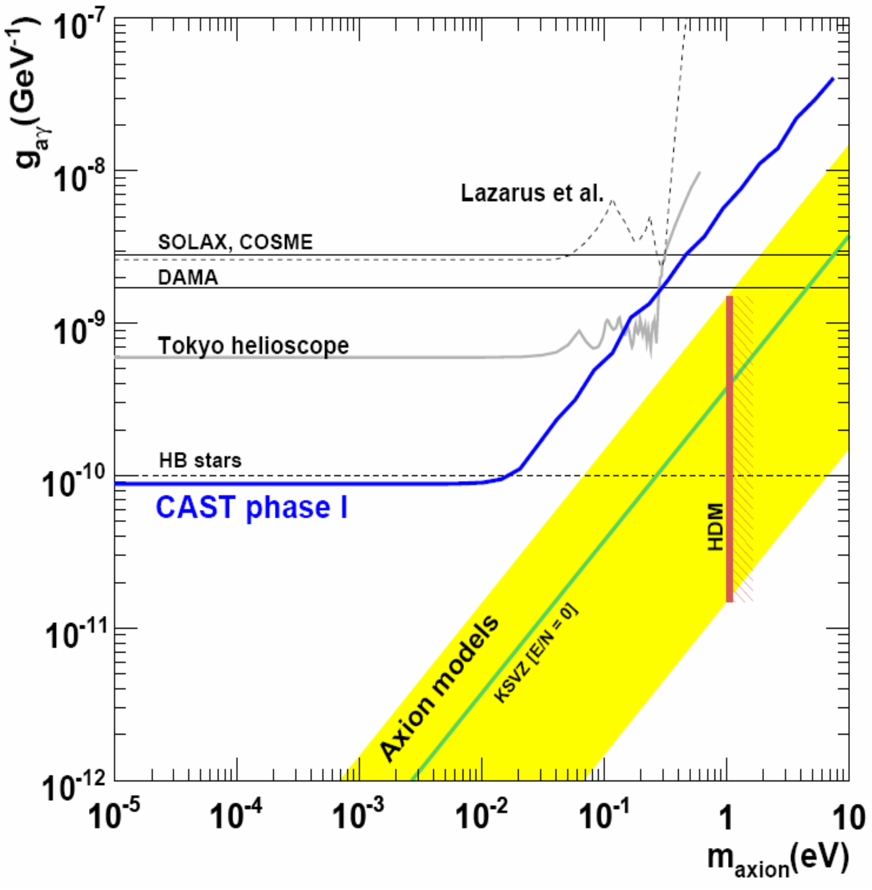


Angle *et al.* [XENON10 coll.]

Axion search

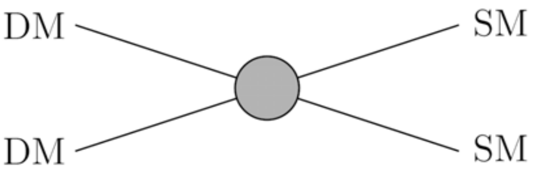
Primakoff effect:



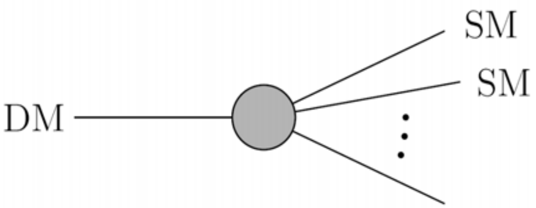


Andriamonje *et al.* [CAST collab.]

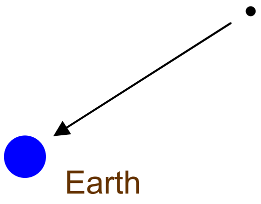
Indirect detection experiments



or

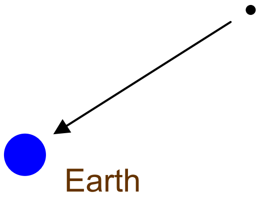


- Photon signals (gamma ray, *X* ray, radio, …)
  - Galactic center region
  - Dwarf galaxies
  - Extra galactic



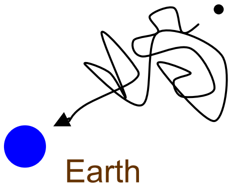
WMAP, EGRET,
H.E.S.S., FERMI, …

- Neutrino signals
  - Galactic center region
  - Center of the sun
  - Center of the earth



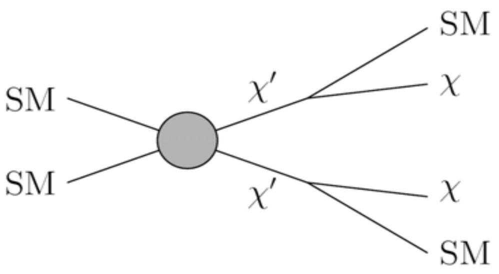
Super-Kamiokande,
IceCube, …

- Antiparticle signals (e^+, $\bar{p}$, …)
  - Galactic halo

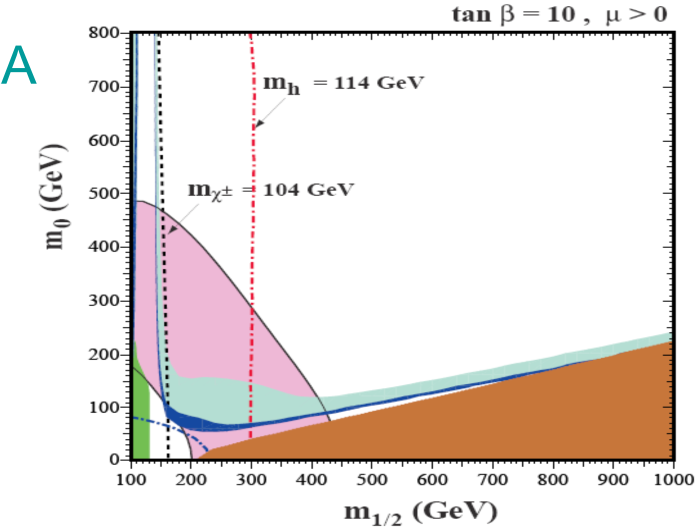


PAMELA, BESS,
ATIC, …

Colliders (LHC, …)



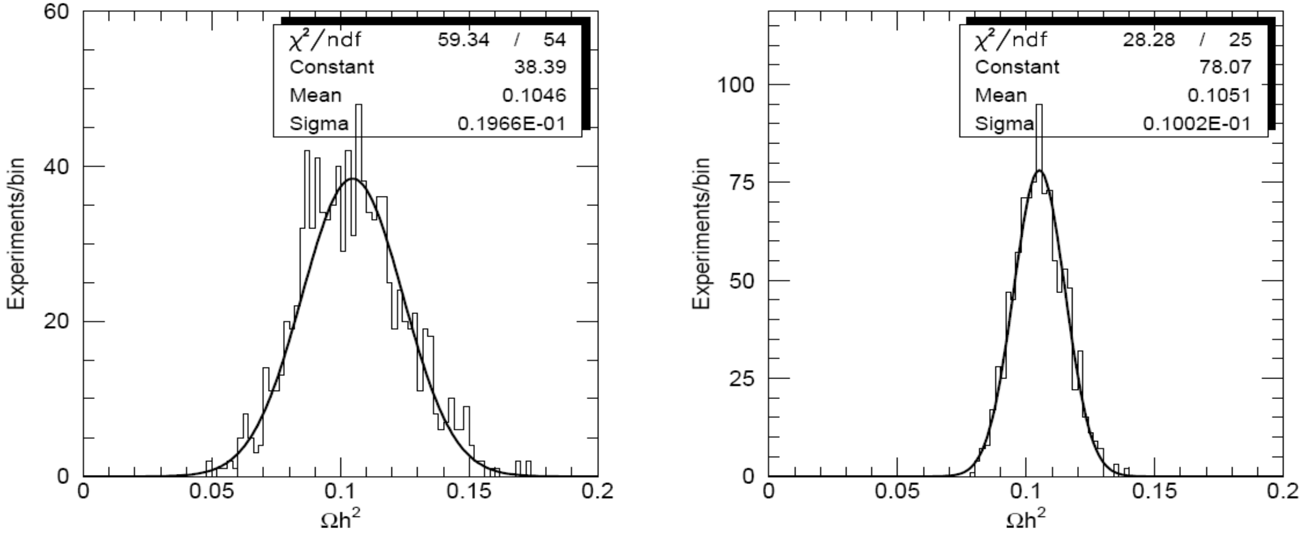
e.g. mSUGRA



Ellis, Olive, Santoso, Spanos

… SM + $\not{E}_T$ signals

Ω_M determination possible at the LHC



$m_0 = 70$ GeV, $m_{1/2} = 250$ GeV, $A_0 = -300$ GeV, $\tan\beta = 10$, $\mu > 0$

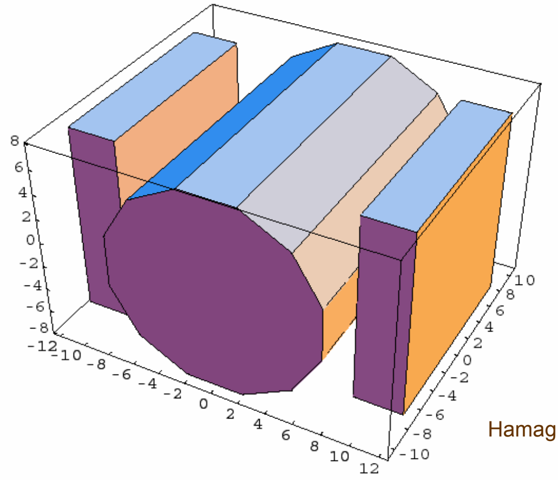
Nojiri, Polesello, Tovey

What if DM is superweakly interacting?

e.g. Gravitino

- NLSP → $\tilde{G}$ (wide range of possibilities for the lifetime)
  - – χ NLSP → γ + $\cancel{E}_T$, …
  - – $\tilde{\tau}$ NLSP → stable charged track, …
  - – …

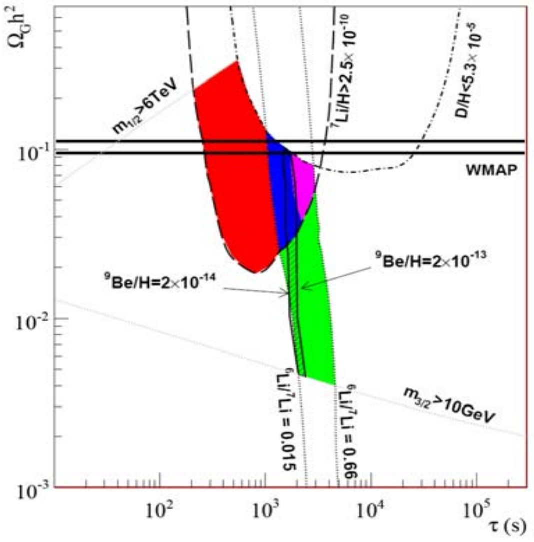
stopper detector



Hamaguchi, Nojiri, de Roeck

measure lifetime, M_{Pl}, …

may affect BBN



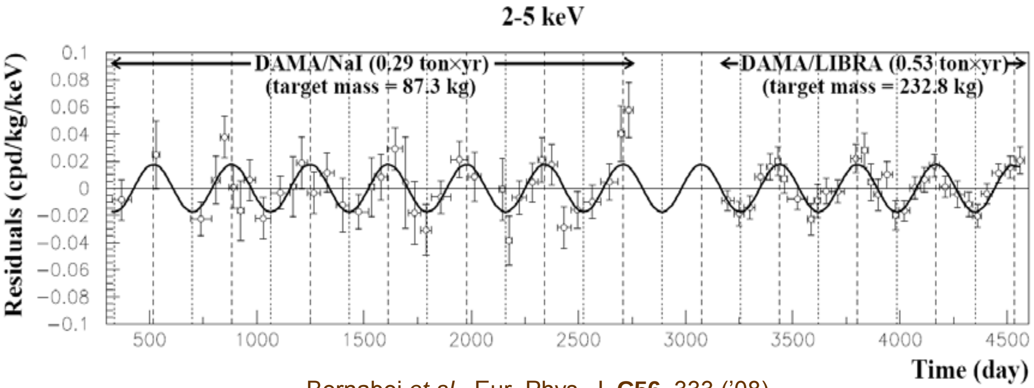
$\tilde{\tau}$ NLSP

Bailly, Jedamzik, Moultaka

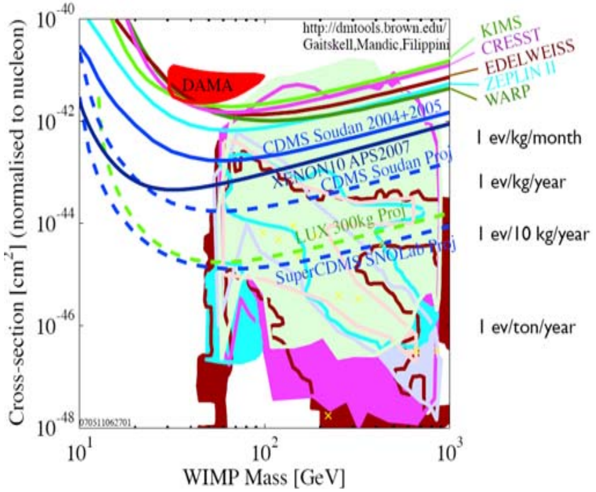
- may slowly decay (indirect detection)

Hints already?

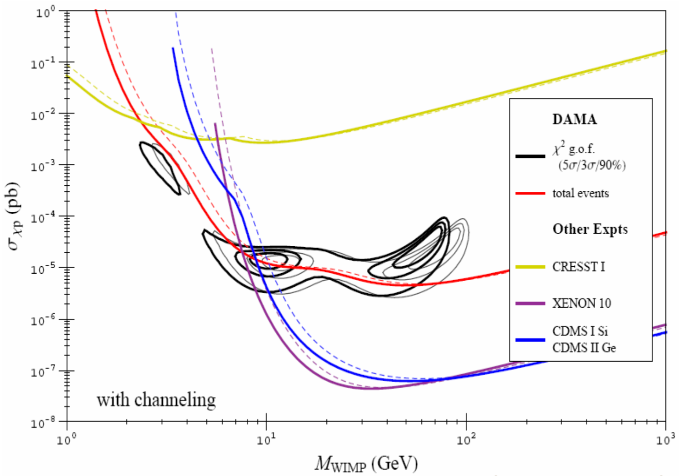
DAMA annual modulation



Bernabei *et al.*, Eur. Phys. J. **C56**, 333 ('08)



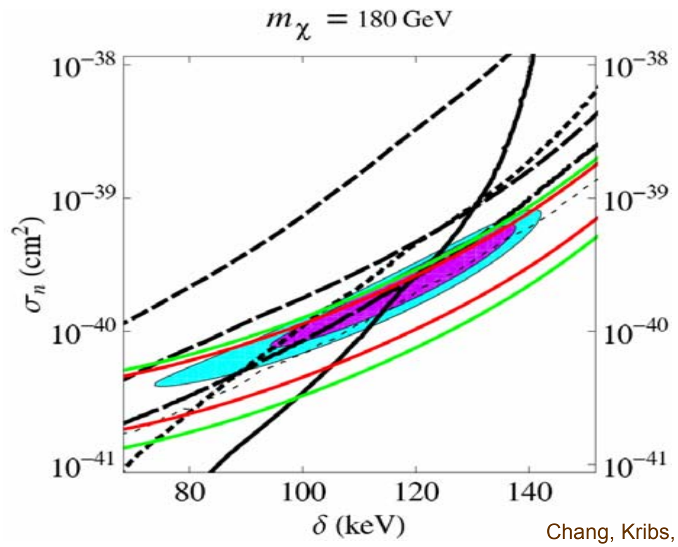
a few GeV WIMP



marginal

Savage, Freese, Gondolo, Spolyar

inelastic DM



tension with CRESST

Chang, Kribs, Tucker-Smith, Weiner

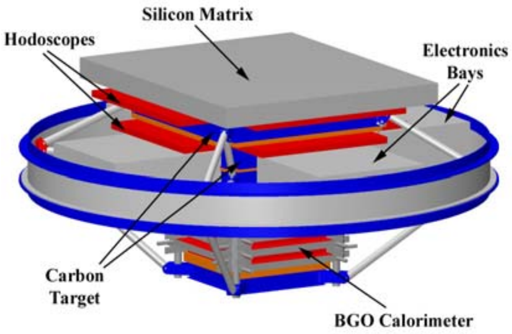
PAMELA / ATIC excesses

PAMELA:

Payload for Antimatter
Matter Exploration
and Light-nuclei
Astrophysics

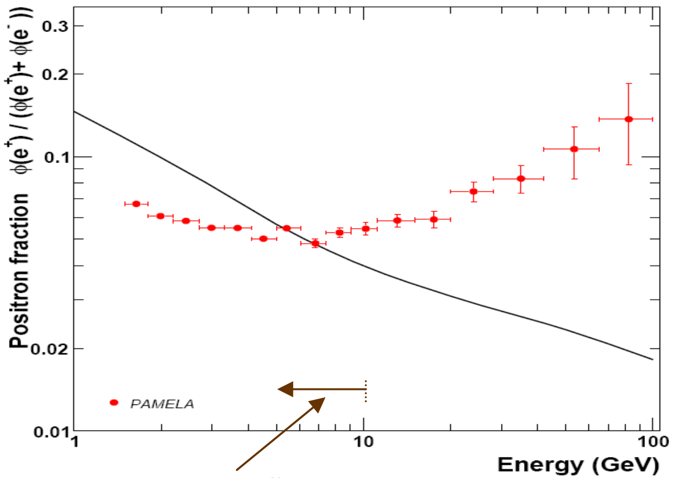
ATIC:

Advanced
Thin
Ionization
Calorimeter



"Anomalies" in $e^{\pm}$ cosmic rays

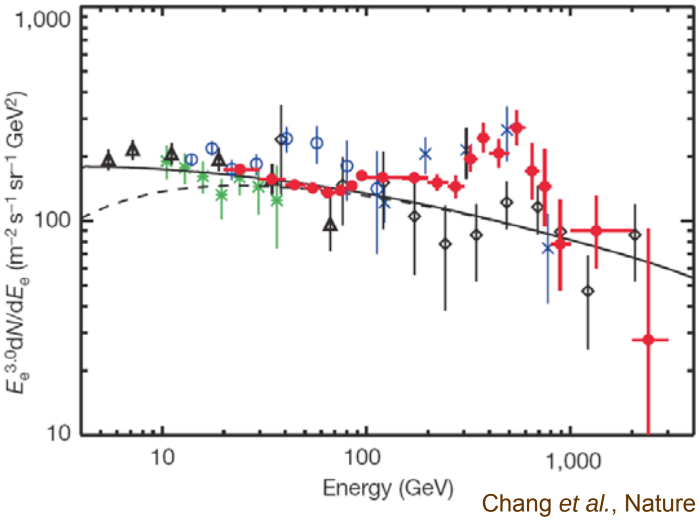
clear rise of the positron fraction
above ~ 10 GeV



solar modulation effect

Adriani *et al.*, arXiv:0810.4995

bump around several hundred GeV
in $e^{+}+e^{-}$ data



Chang *et al.*, Nature **456**, 362 ('08)

Possible interpretations

- Astrophysical sources (pulsars, …)
- Dark matter decay
- Dark matter annihilation

… seems to suggest not "minimal" WIMP

– antiproton consistent with BG

→ leptonic final states

– larger rate than $\langle \sigma v \rangle_{\text{freezeout}}$

→ enhanced $\langle \sigma v \rangle_{\text{galaxy}}$

– large mass scale ~ TeV

… future observations will clarify

cf. Talk by Y.N. on next Wednesday:
Feb. 11, 3:10 - 4:10 pm, 402 Old Le Conte

Conclusions

- Evidence of DM is solid

  → Physics beyond the standard model

- Identity of DM (very) unknown

- Various experiments can (potentially) probe
  - Direct detection
  - Indirect detection
  - Colliders
  - Astrophysical / cosmological observations
  - …

Future experiments will give us further insights