The 2011 Hadron Collider Physics Summer School

Dark Matter (1/2)

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Outline

- Introduction:
  Dark Matter, what we know about it...

- The WIMP mechanism/connection
  and how to detect DM particles...

- Some DM models:
  - SUSY DM: sneutrino, neutralino, gravitino
  - SuperWIMPs and decaying DM
  - Axion DM

- Outlook

Dark Matter: Evidence and Properties

DARK MATTER EVIDENCE

CLUSTER SCALES:

The early history of
Dark Matter:
In 1933 F. Zwicky found the first evidence for DM in the velocity dispersion of the galaxies in the COMA cluster...
Already then he called it
DARK MATTER !

DARK MATTER EVIDENCE

CLUSTER SCALES:

Nowadays even stronger result from X-ray emission: the temperature of the cluster gas is too high, requires a factor 5 more matter than the visible baryonic matter...

DARK MATTER EVIDENCE

CLUSTER SCALES:

Systems like the Bullett cluster allow to restrict the self-interaction cross-section of Dark Matter to be smaller than the gas at the level

$$\sigma \leq 1.7 \times 10^{-24} cm^2 \sim 10^9 pb \quad (m = 1\ \mathrm{GeV})$$

[Markevitch et al 03]

One order of magnitude stronger constraint by requiring a sufficiently large core... [Yoshida, Springer & White 00]

Similar bounds from the sphericity of halos...

DARK MATTER EVIDENCE

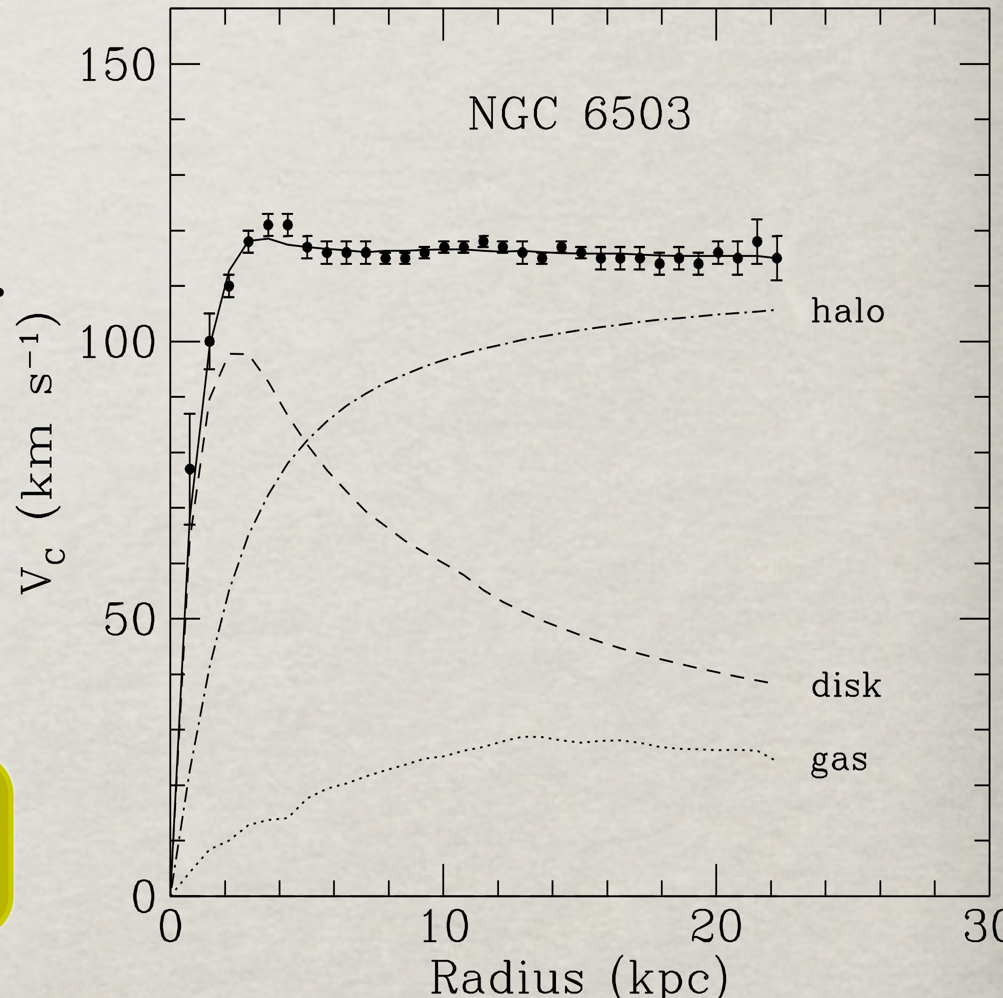
GALACTIC SCALES:

the stars in the outer part of galaxies are faster than expected...

$$v_c^2 \propto G_N \frac{M(r)}{r} \propto \frac{M_{tot}}{r}$$

But instead it is constant ! Need

$$M(r) \propto r, \text{ i.e. } \rho_{DM} \propto r^{-2}$$



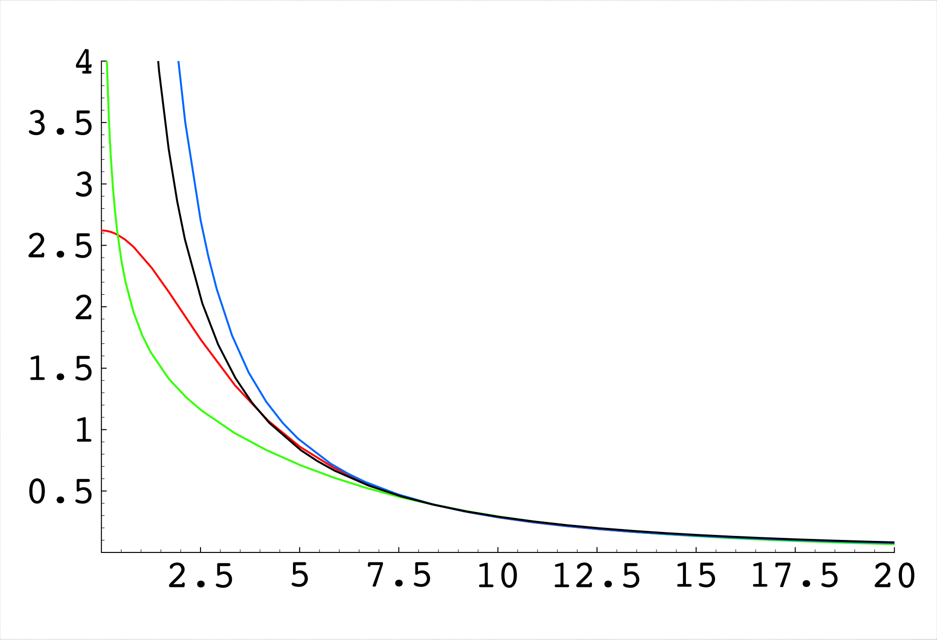
Unfortunately the density in the internal region of the galaxies is much more uncertain...

DARK MATTER EVIDENCE

GALACTIC SCALES:

Many profiles, inpired by data or numerical simulations: Isothermal, NFW, Moore, Kratsov, Einasto, etc....

$$\rho(r) = \frac{\rho_0}{(r/R)^\gamma[1+(r/R)^\alpha]^{(\beta-\gamma)/\alpha}}$$



Critical for indirect detection !

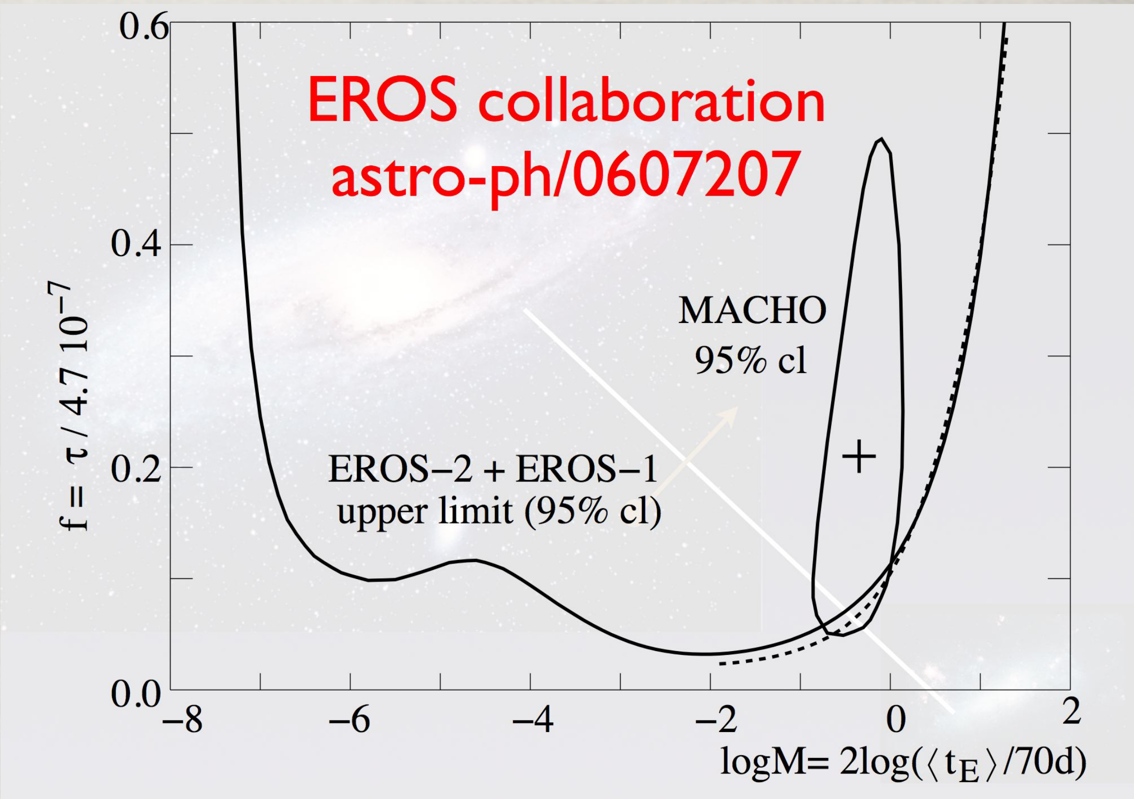
Other important fact: DARK MATTER is still here !
It is either stable or extremely long-lived. The decay into photon or charged particles must have a lifetime above 10^26 s, into neutrinos it can be a couple of orders of magnitude shorter.

DARK MATTER EVIDENCE

GALACTIC SCALES:

Faint planets, MACHOS ?
No evidence from the EROS collaboration between $10^{-7}$and 20 solar masses.

Still clumps of Dark Matter, which are much less concentrated may be there...

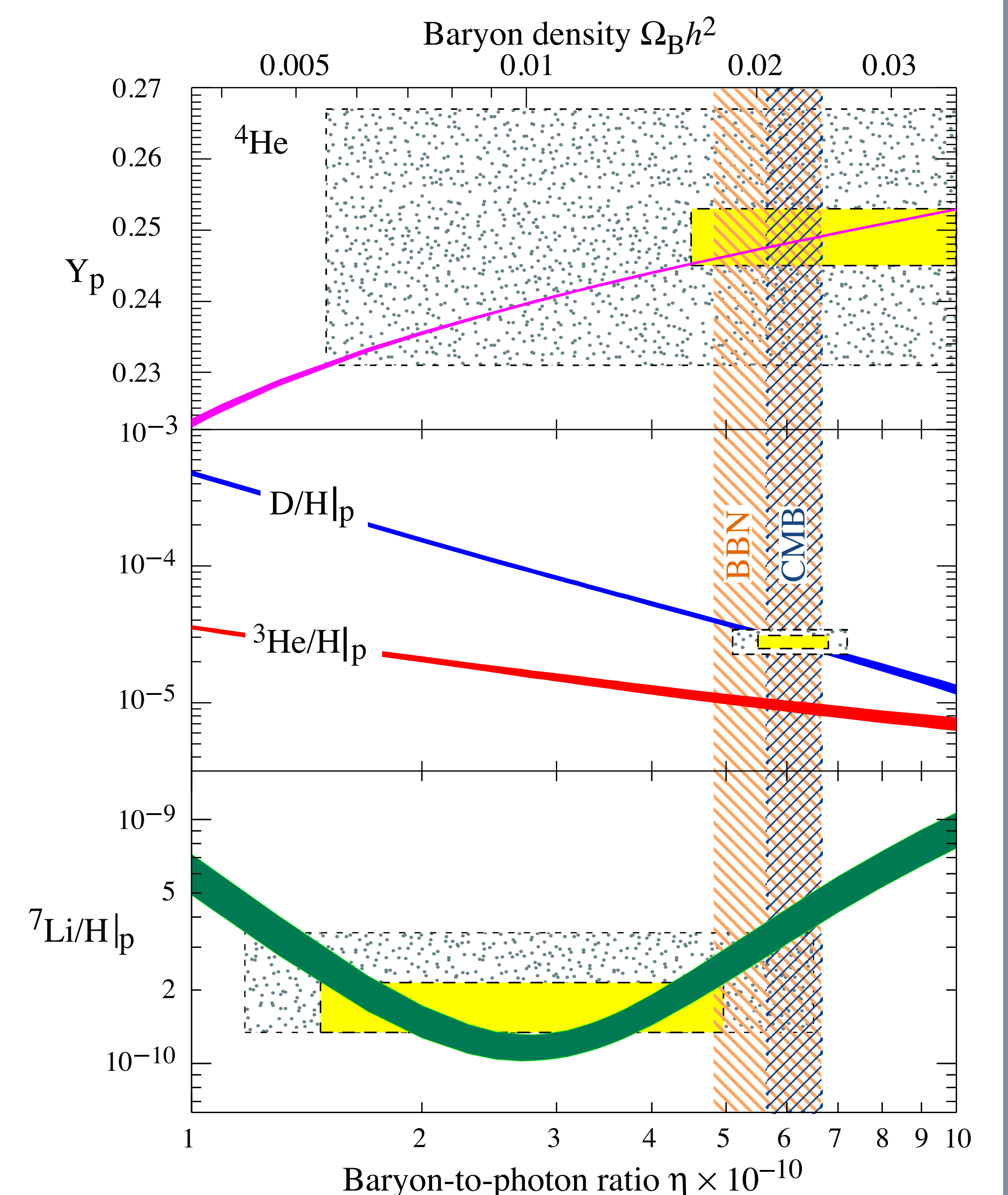


Big Bang Nucleosynthesis

[Fields & Sarkar PDG 07]

- Light elements abundances obtained as a function of a single parameter $\Omega_B h^2$
- Perfect agreement with WMAP determination
- Some trouble with Lithium 6/7

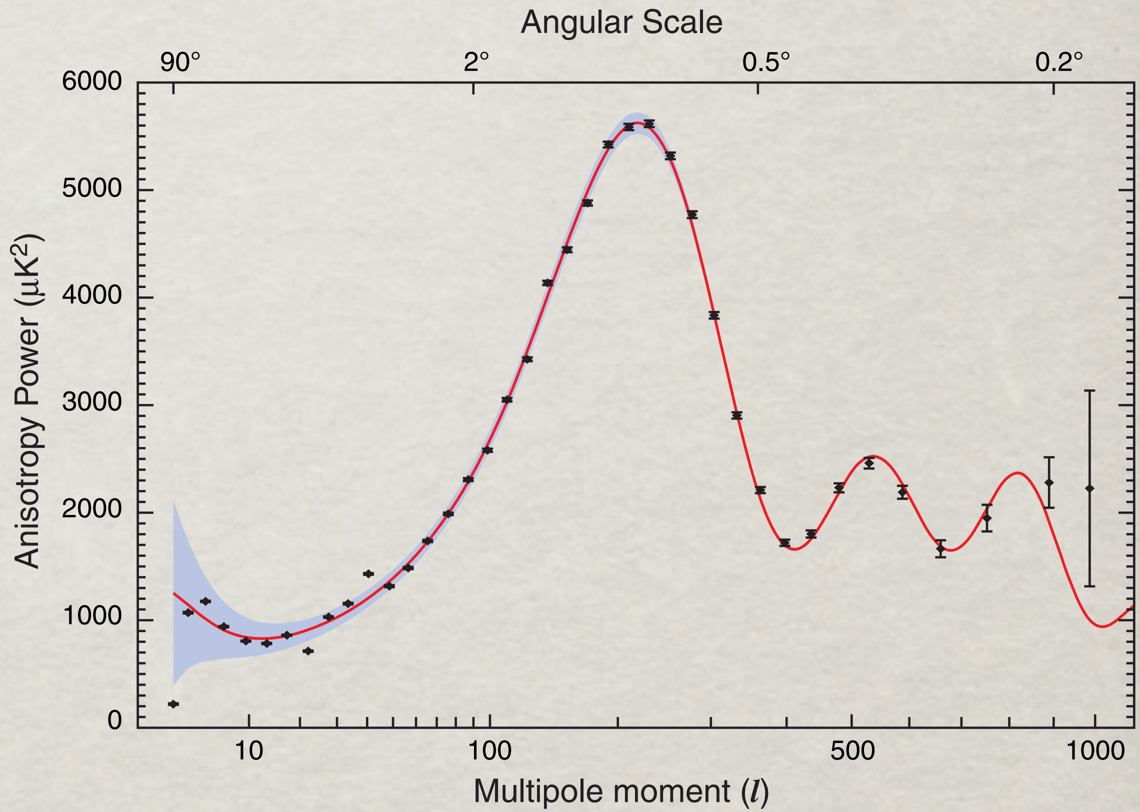
$$\Omega_B h^2 = 0.02 < \Omega_{DM} h^2$$



DARK MATTER EVIDENCE

HORIZON SCALES:

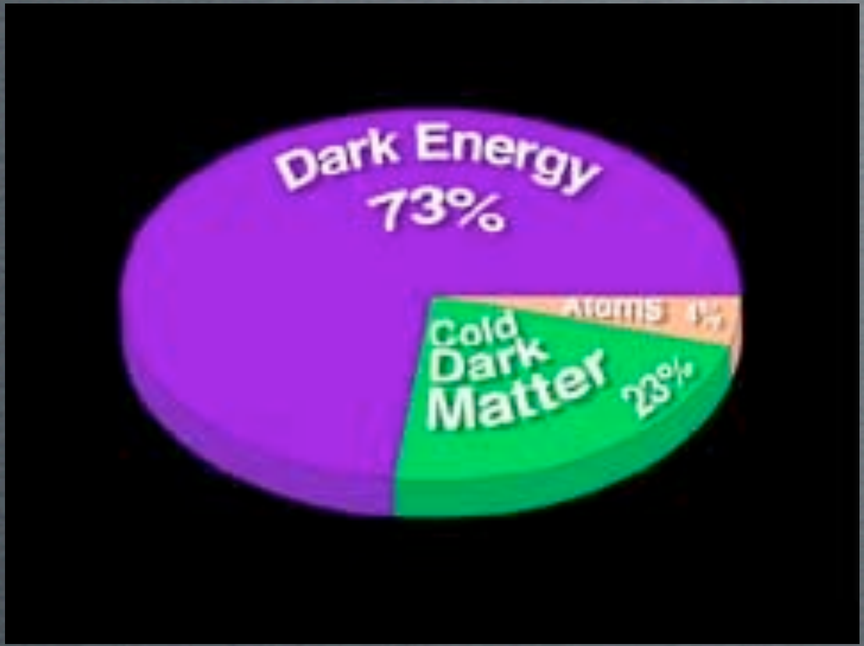
From the position and height of the CMB anisotropy acoustic oscillations peaks we can determine very precisely the curvature of the Universe and other background parameters.



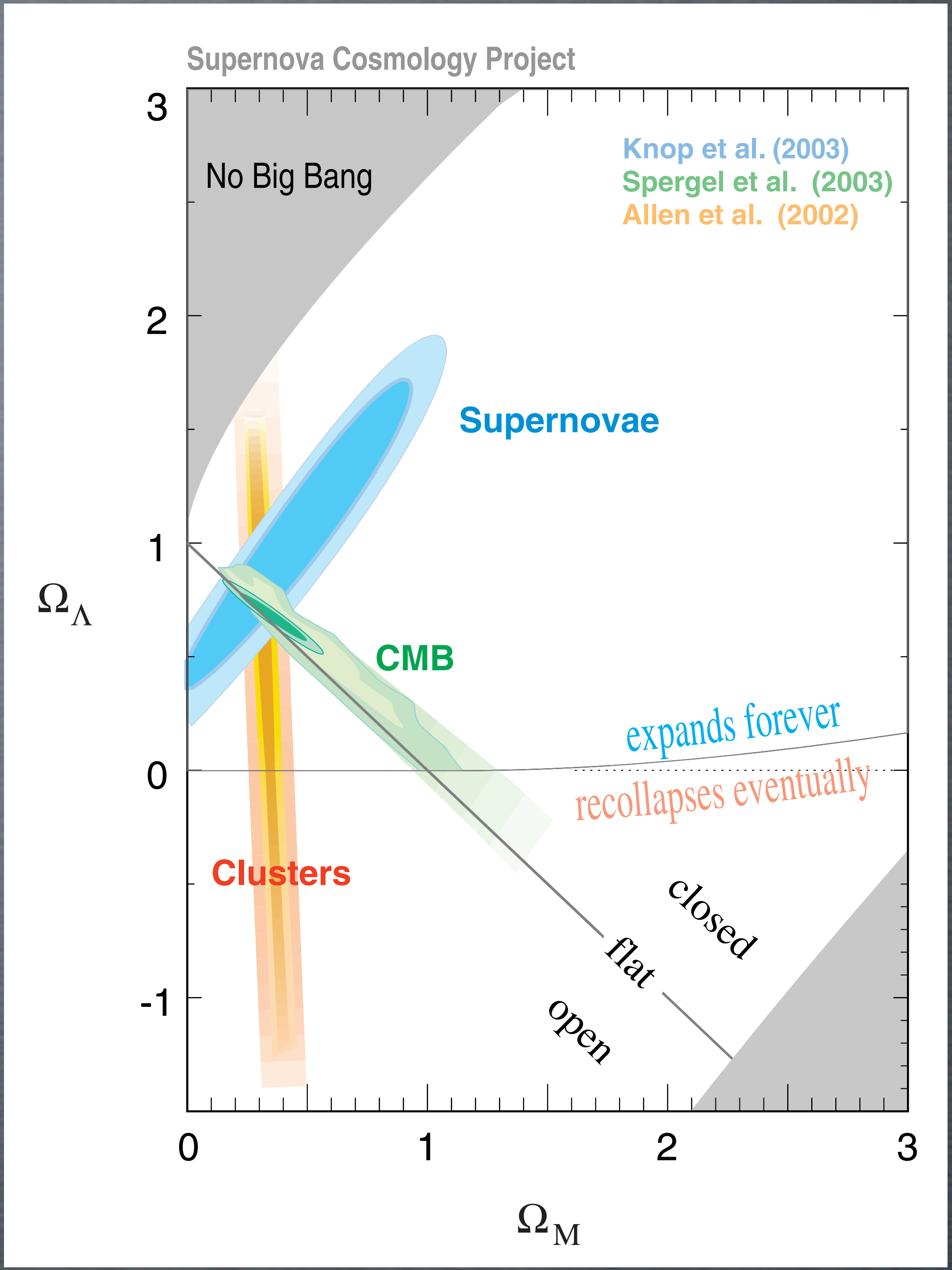
Particles	Ωh^2	Type
Baryons	0.0224	Cold
Neutrinos	< 0.01	Hot
???	0.1-0.13	Cold

DARK MATTER →

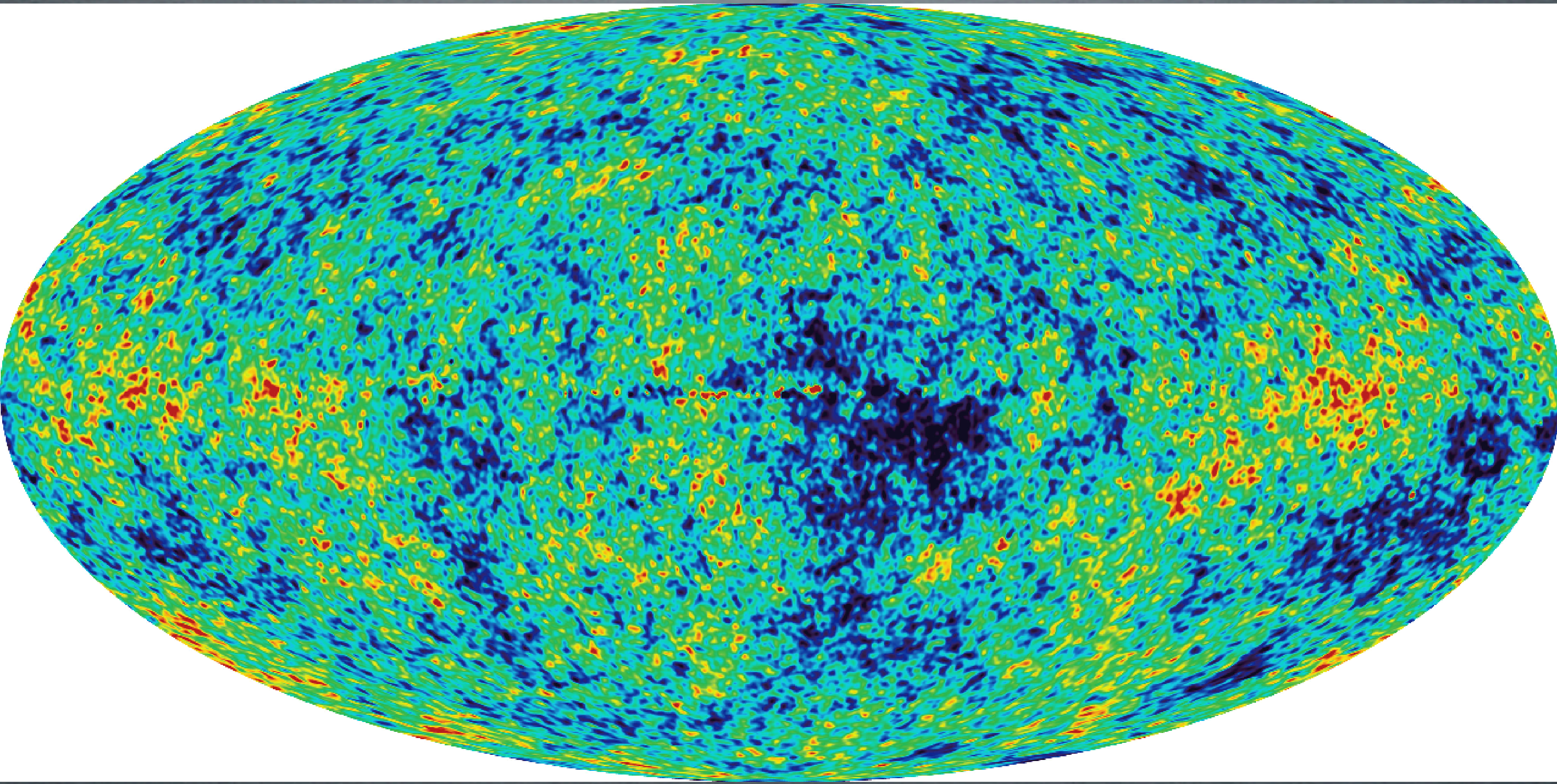
ENERGY CONTENT



with traces of photons, neutrinos & ... ?



More DM evidence from the CMB & WMAP satellite



Tiny ripples on the black body spectrum at level of 0.01%...

How do fluctuations grow ?

What happens after such perturbations "re-enter" the horizon ?

In the Newtonian limit we have for the density perturbations of a matter fluid $\delta = \frac{\delta\rho}{\rho}$

$$\ddot{\delta}_k + 2H\dot{\delta}_k + \left(\frac{{c_s}^2 k^2}{a^2} - 4\pi G\rho\right)\delta_k = 0,$$

where $c_s = \delta p/\delta\rho$ is the sound speed in the plasma. Again a linear equation with a negative "mass" term... The fluctuations with negative mass grow and those have k below k_J ,i.e. a physical wavelength larger than the Jeans length:

$$\lambda_J = \frac{2\pi a}{k} = c_s\sqrt{\frac{\pi}{G\rho}} \simeq \frac{c_s}{H} \quad \text{sound horizon}$$

How strongly do they grow ? The growing solution is

$$\delta_k \sim C_1 H \int \frac{dt}{a^2 H^2} + C_2 H \sim C_1 t^{2/3} + C_2 t^{-1} \quad \text{for matter dominance}$$

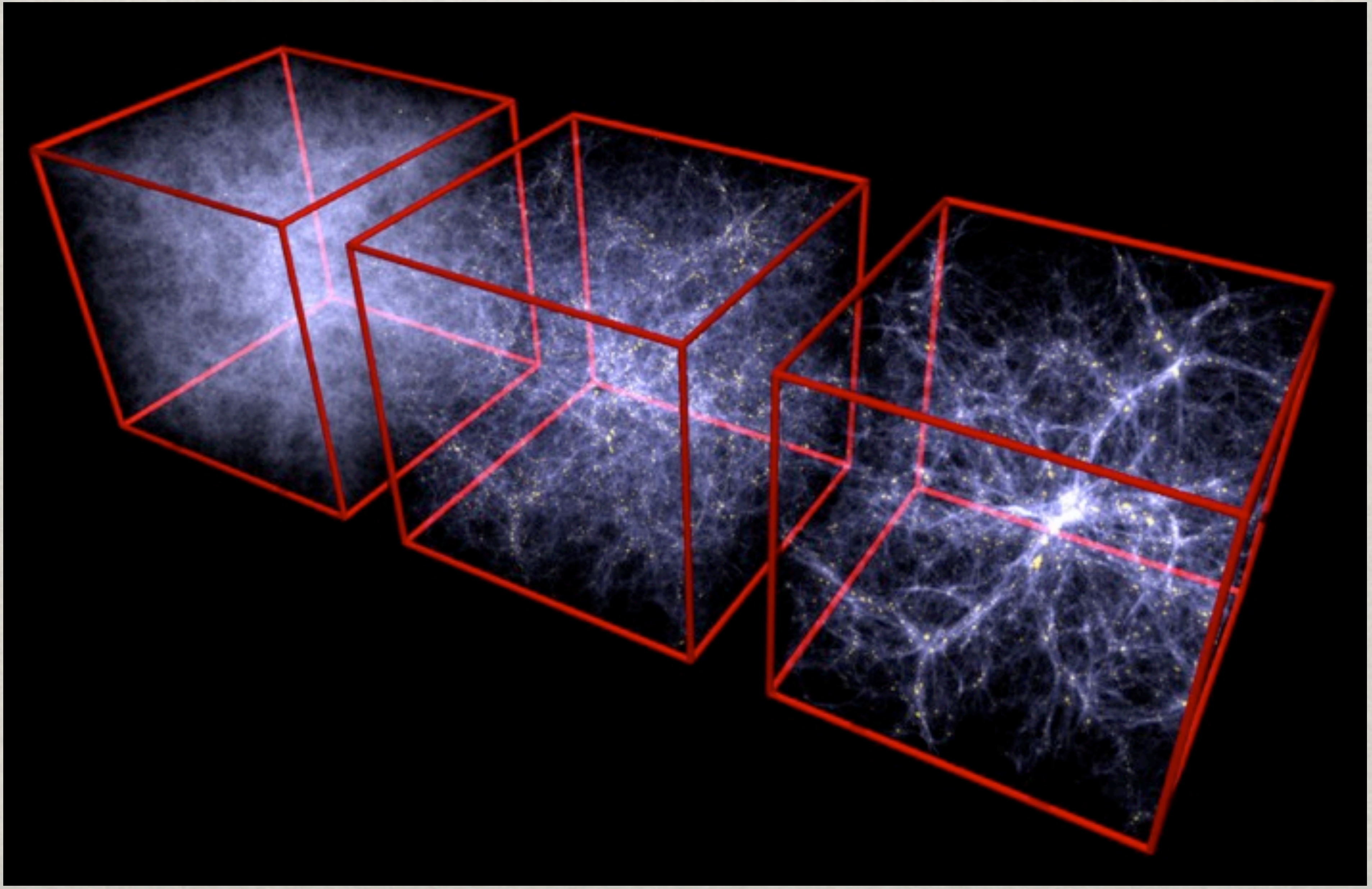
NOTE: much weaker than exponential due to the expansion friction term $\propto H$! Also if the expansion is dominated by radiation, the growth is inhibited and at most only logarithmic in time. We need a long time of matter dominance to make initial fluctuations become large...

Non Linear regime

Structure Formation

V. Springel @MPA Munich

Yoshida et al 03



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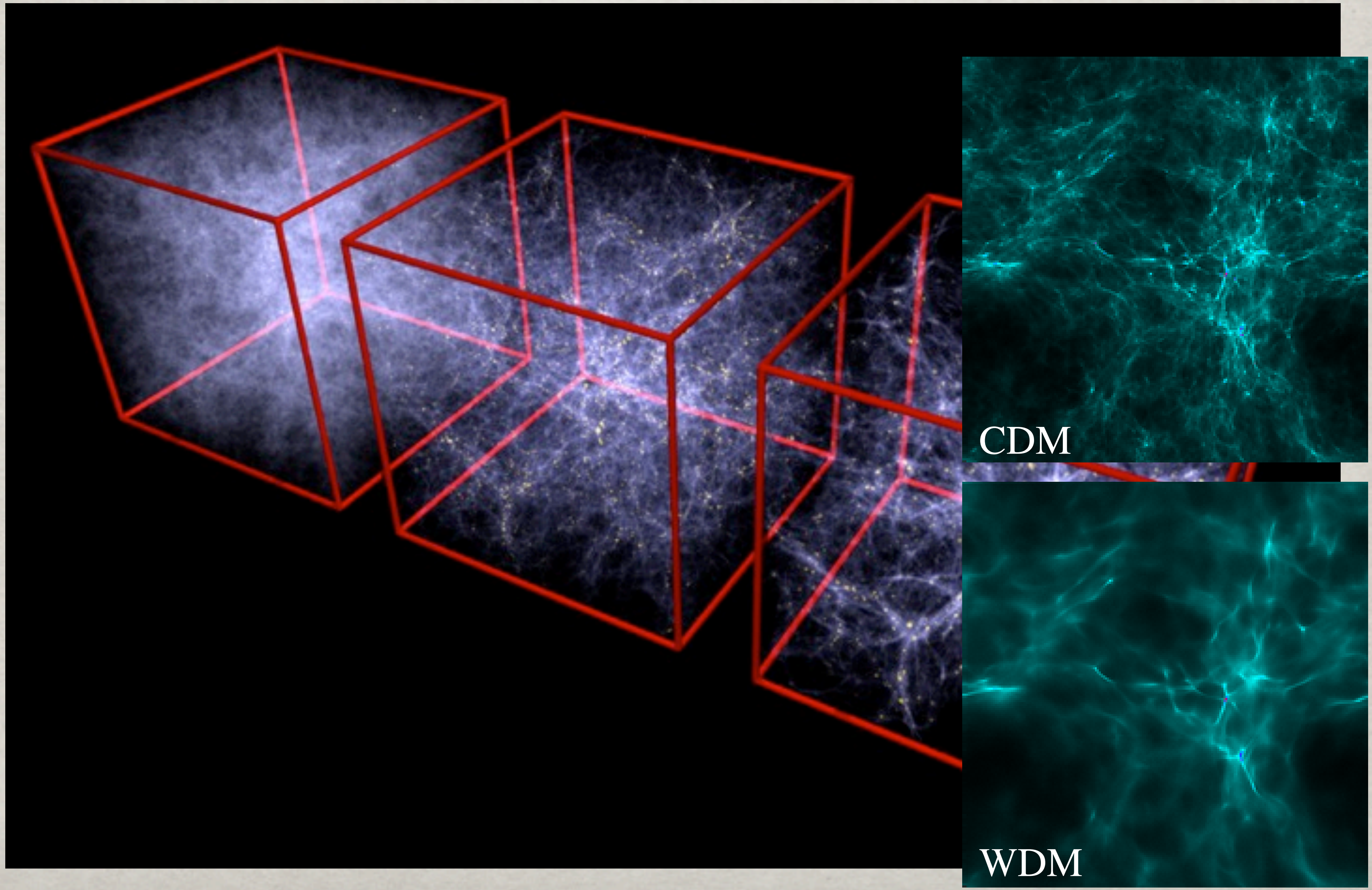
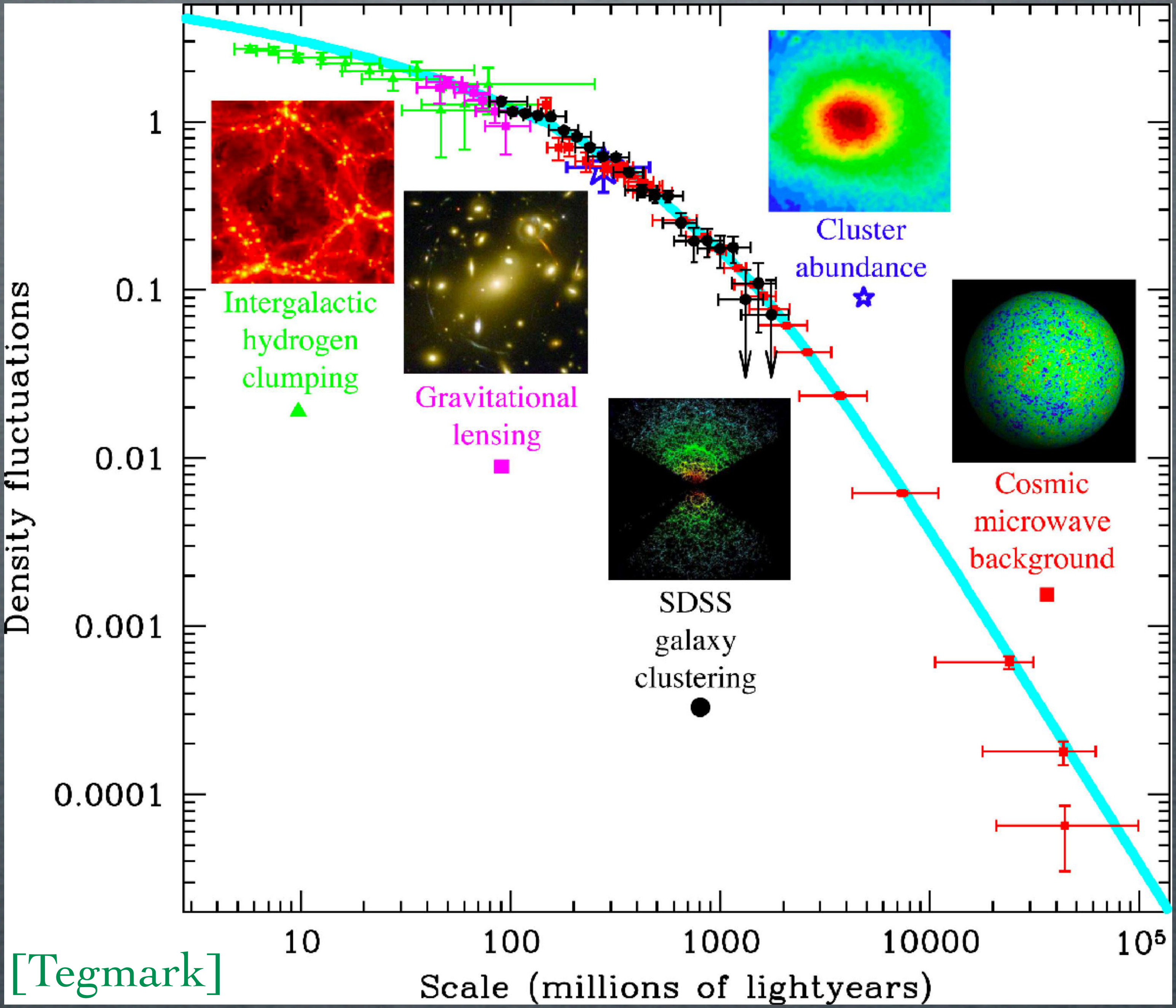


MEASURE FLUCTUATION ON ALL SCALES



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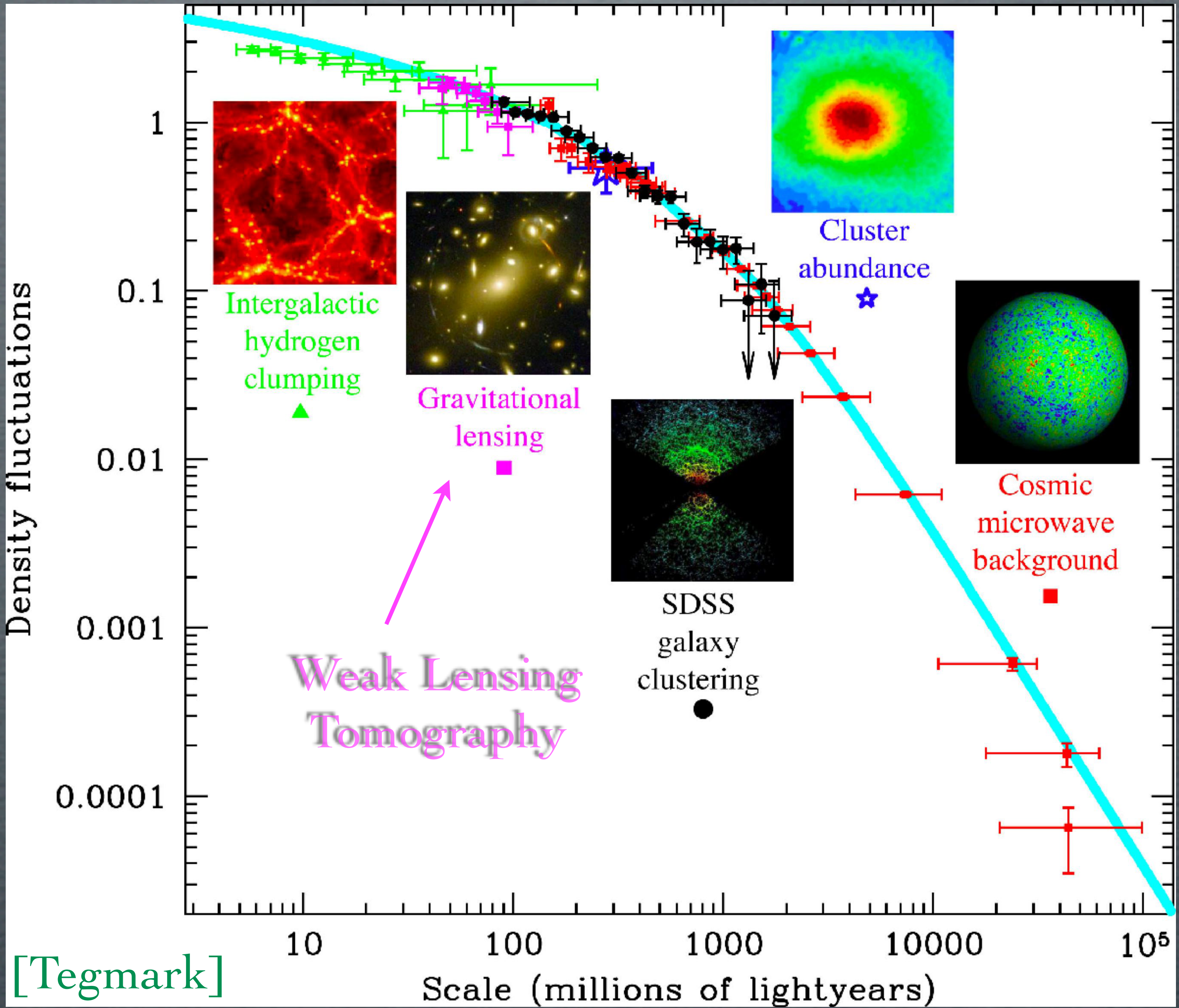
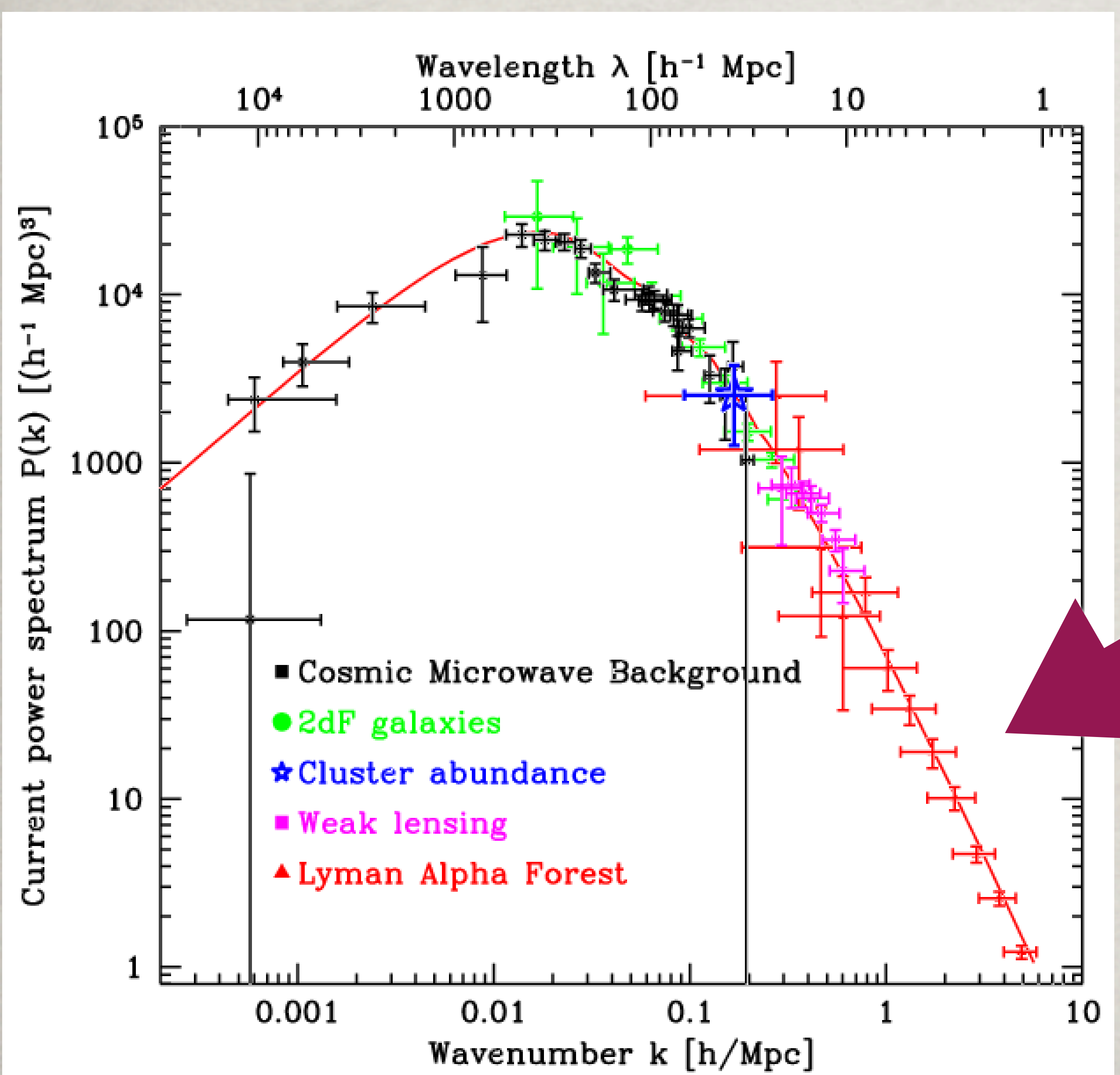


WDM & the Power spectrum



WARM DM suppresses perturbations on scales smaller than its free-streaming length:

$$\lambda_{FS} \sim \mathrm{Mpc}\left(\frac{m_{WDM}}{1\mathrm{keV}}\right)$$

Compare with the data:

$$m_{WDM} > 4\ \mathrm{keV}$$

[Viel et al. '07]

DARK MATTER PROPERTIES

- Interacts very weakly, but surely gravitationally (electrically neutral and decoupled from the primordial plasma !!!)
- It must have sufficiently large density to give a long matter dominated phase and the right density profile to “fill in” the galaxy rotation curves.
- No pressure and small free-streaming velocity, it must cluster & cause structure formation.

⬇

COLD DARK MATTER

DARK MATTER PROPERTIES

- Electrically neutral, non-baryonic, possibly electroweak interacting, but could even be only gravitationally interacting.
- It must still be around us: either stable or very very long lived, i.e. it is the lightest particle with a conserved charge (R-, KK-, T-parity, etc...) or its interaction and decay is strongly suppressed !
- If it is a thermal relic, must be sufficiently massive to be cold..., but it may even be a condensate...

⬇

LOOK FOR PARTICLE DM CANDIDATES !

SM and Dark Matter

- Do we have a DM candidate in the SM ???

Standard Model			
Matter			Forces
e	μ	τ	γ
ν_e	ν_μ	ν_τ	$W^\pm, Z$
u	c	t	g
d	s	b	G

- Neutrinos seem the only chance...

SM and Dark Matter

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Matter			Forces
$\cancel{e}$	$\cancel{\mu}$	$\cancel{\tau}$	γ
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charged/unstable

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$\cancel{u}$	$\cancel{c}$	$\cancel{t}$	$\cancel{g}$
$\cancel{d}$	$\cancel{s}$	$\cancel{b}$	$\cancel{G}$

massless

charged/unstable

baryonic

- Neutrinos seem the only chance...

Neutrino as (prototype) DM

- Massive neutrino is one of the first candidates for DM discussed; for thermal SM neutrinos:

$$\Omega_\nu h^2 \sim \frac{\sum_i m_{\nu_i}}{93 \text{ eV}}$$

but $m_\nu \leq 2 \text{ eV}$ (Tritium β decay) so $\Omega_\nu h^2 \leq 0.07$

- Unfortunately the small mass also means that neutrinos are HOT DM... Their free-streaming is non negligible and the LSS data actually constrain

$$m_\nu \leq 0.27 \sim 1 \text{ eV} \Rightarrow \boxed{\Omega_\nu \ll \Omega_{DM}}$$

NEED to go beyond the Standard Model !

WIMP DM

THE WIMP MECHANISM

Primordial abundance of stable massive species

[see e.g. Kolb & Turner '90]

The number density of a stable particle X in an expanding Universe is given by the Bolzmann equation

$$\frac{dn_X}{dt} + 3Hn_X = \langle\sigma(X + X \to \text{anything})v\rangle \left(n_{eq}^2 - n_X^2\right)$$

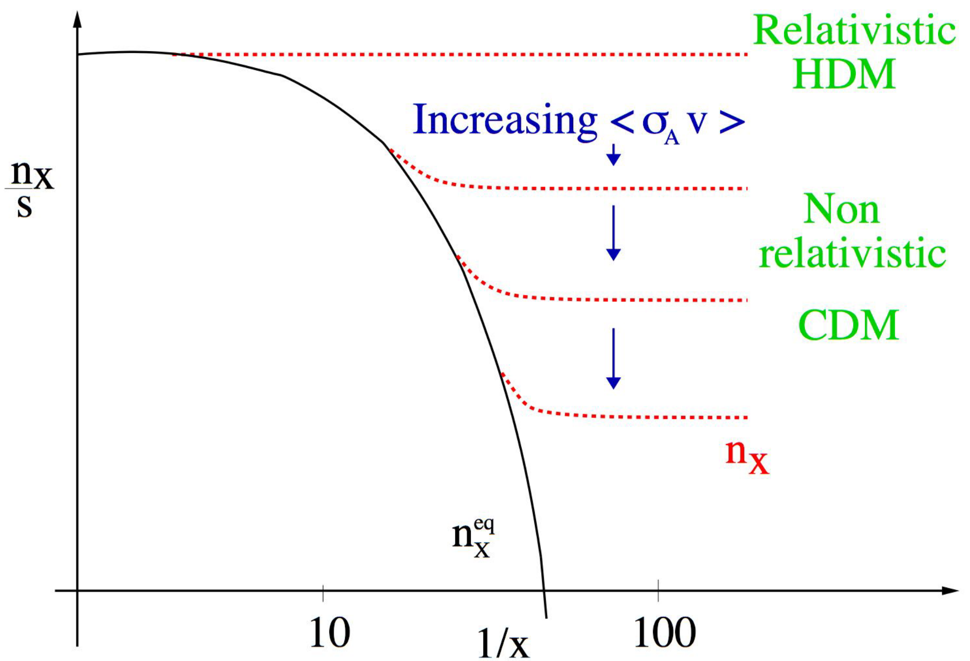
Hubble expansion   Collision integral

The particles stay in thermal equilibrium until the interactions are fast enough, then they freeze-out at $x_f = m_X/T_f$

defined by $n_{eq} \langle\sigma_A v\rangle_{x_f} = H(x_f)$ and that gives

$$\Omega_X = m_X n_X(t_{now}) \quad \propto \quad \frac{1}{\langle\sigma_A v\rangle_{x_f}}$$

Abundance $\Leftrightarrow$ Particle properties



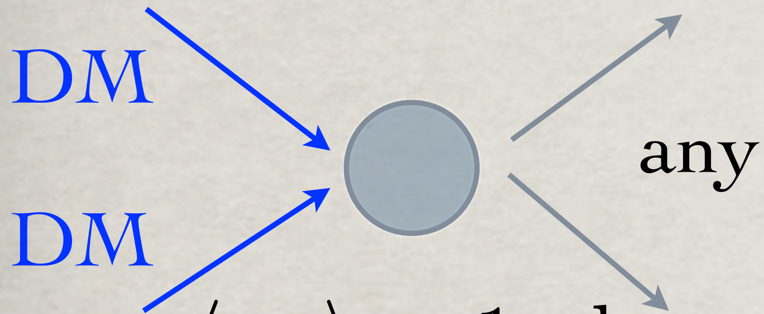
For $m_X \simeq 100$ GeV a WEAK cross-section is needed !

Weakly Interacting Massive Particle

For weaker interactions need lighter masses HOT DM !

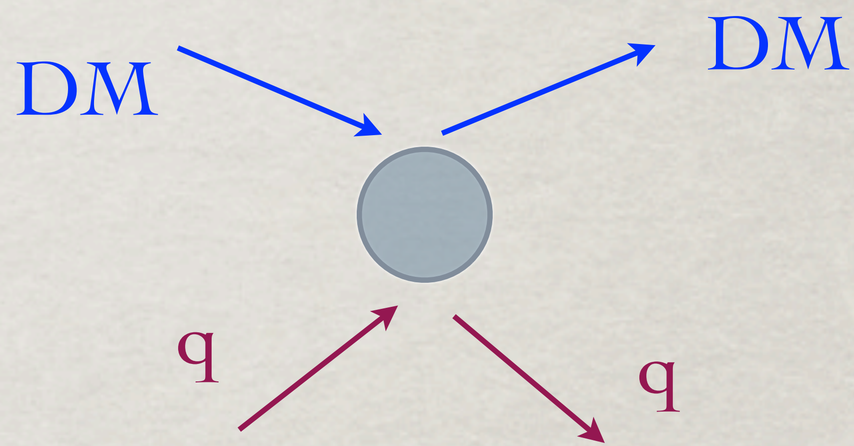
THE WIMP CONNECTION

Early Universe: $\Omega_{CDM}h^2$

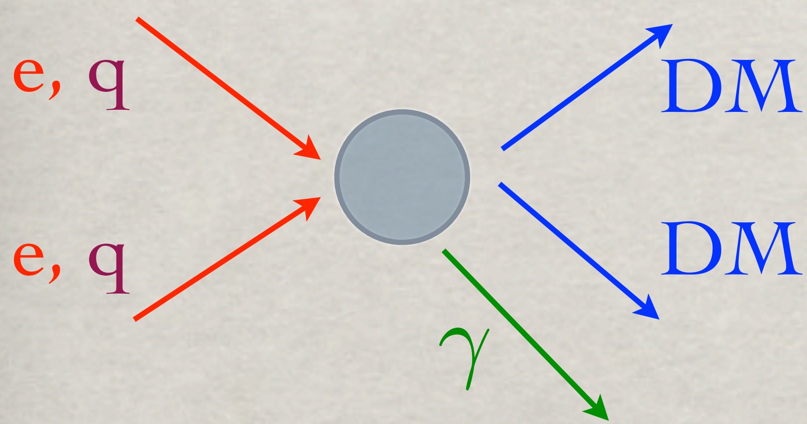


$\langle \sigma v \rangle \sim 1$ pb

Direct Detection:



Colliders: LHC/ILC



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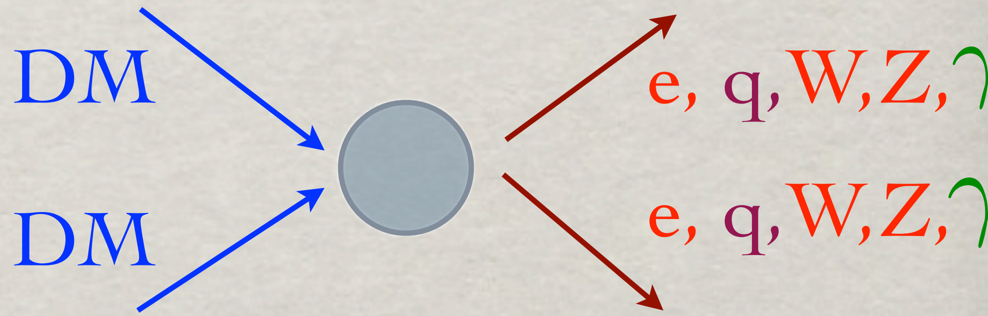

3 different ways to check this hypothesis !!!

THE WIMP CONNECTION

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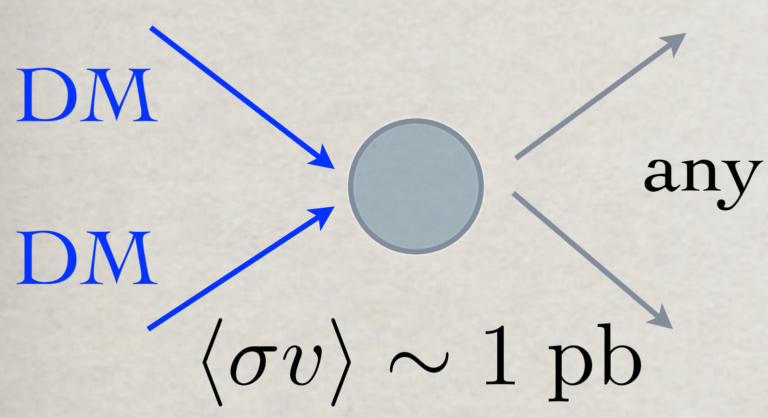

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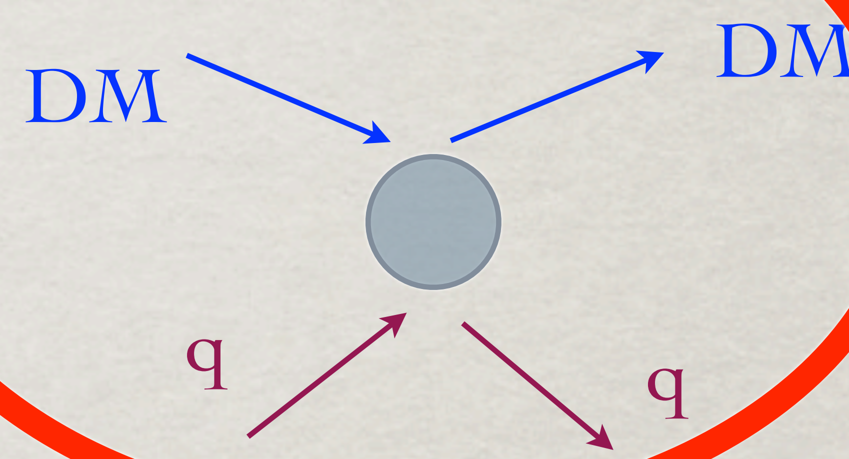

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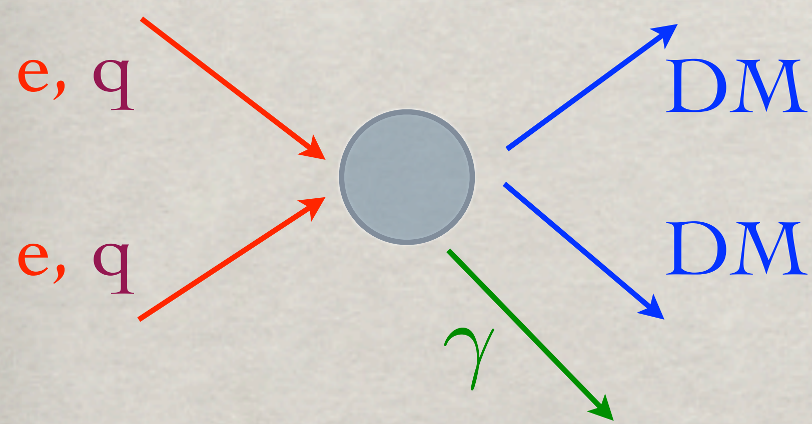

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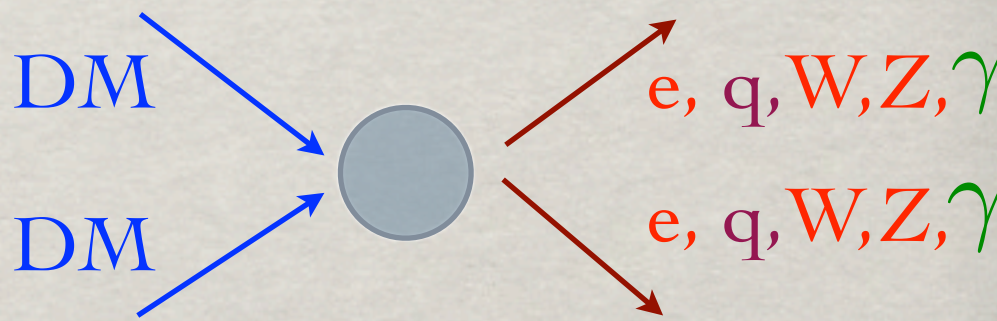
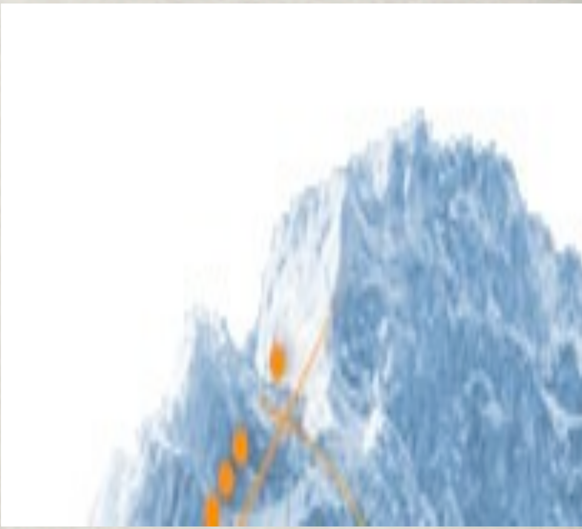
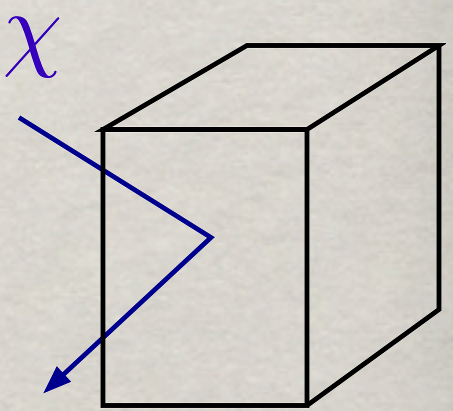


3 different ways to check this hypothesis !!!

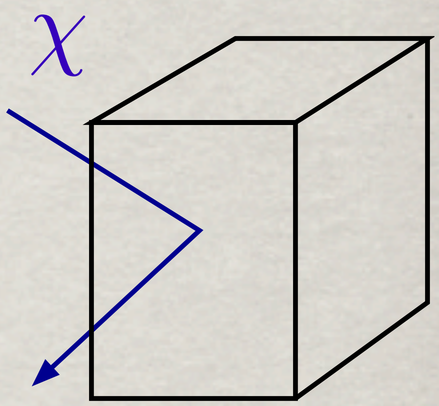
THE HOPE: DETECT DM !



- In direct DM searches in various underground laboratories measuring the “wind” of DM crossing the Earth...
- A WIMP scatters with the nuclei like neutrons, so it is necessary to suppress very strongly the background due to cosmic rays and radioactivity
- To veto electrons/photons the detectors usually measure two different signals, e.g. ionization+phonons (cryogenic detectors) ionization+light (noble gas/liquid detectors)



Direct WIMP detection



- Elastic scattering of a WIMP on nuclei. The recoil energy is in the keV range:

$$\Delta E = \frac{4 m_{DM} m_N}{(m_{DM} + m_N)^2} \, E_{kin}^{DM}$$

with

$$E_{kin}^{DM} \sim \frac{1}{2} m_{DM} v^2 \sim 50 \text{ keV} \frac{m_{DM}}{100\text{GeV}}$$

Need very low threshold !

- The rate is given by

$$\frac{dR}{dE_R} \propto \sigma_n F^2(E_R) \, \frac{\rho_{DM}}{m_{DM}} \int_{v_{min}}^{\infty} \frac{dv}{v} f(v)$$

Particle Physics Halo physics

BOUNDS ON WIMP DM

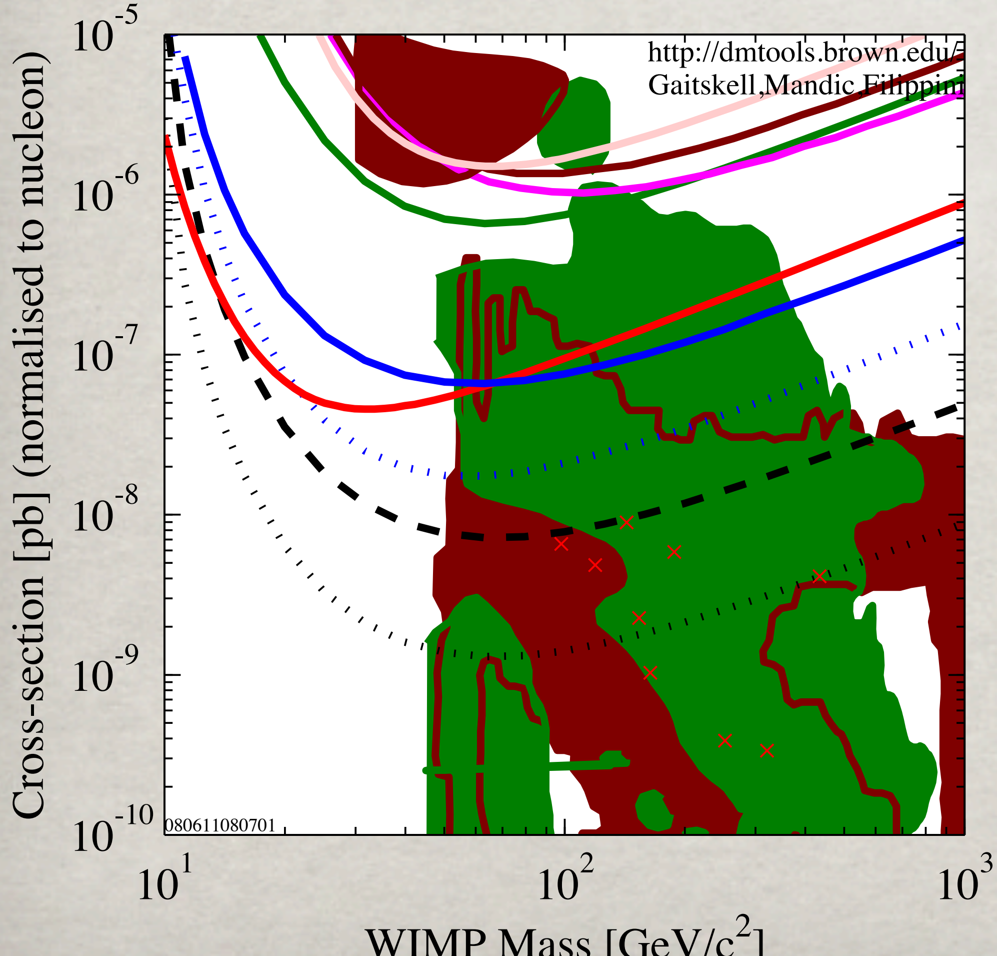
Spin independent:

CDMS (Ge/Si crystal)

XENON-10 (noble gas/liquid)

Super CDMS

WARP, Zeplin II

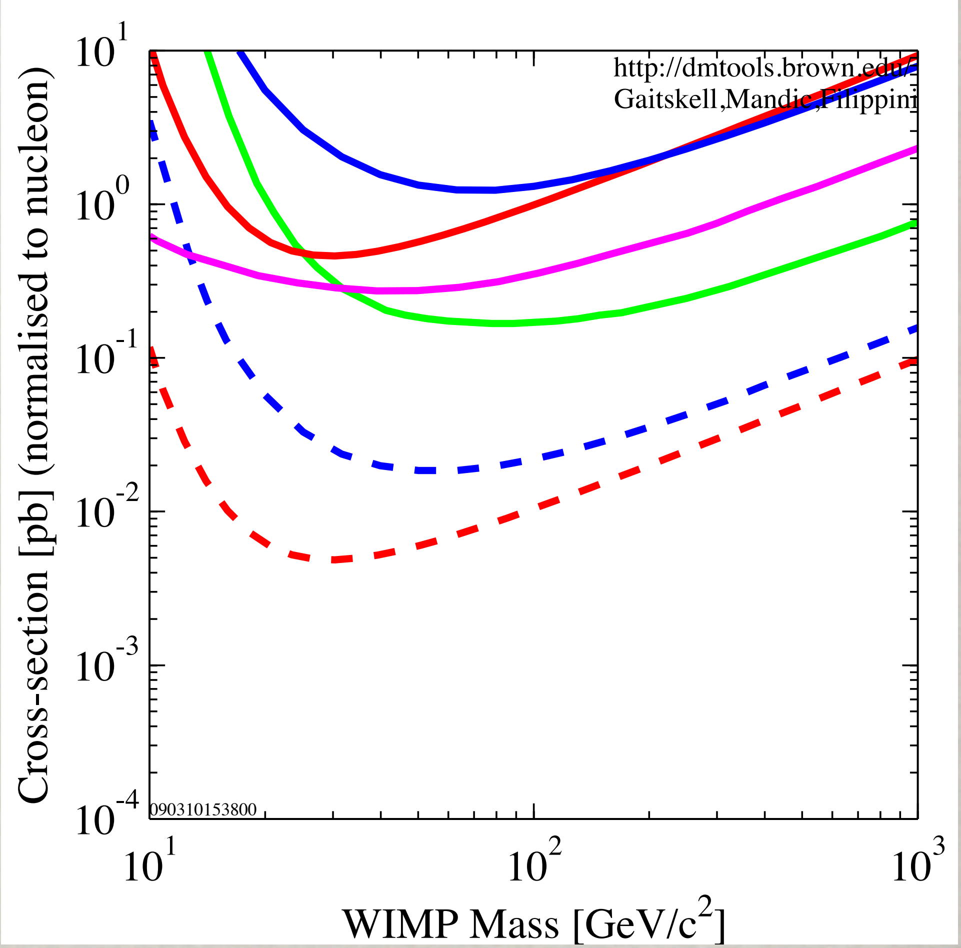


Spin dependent:

proton:

neutron:

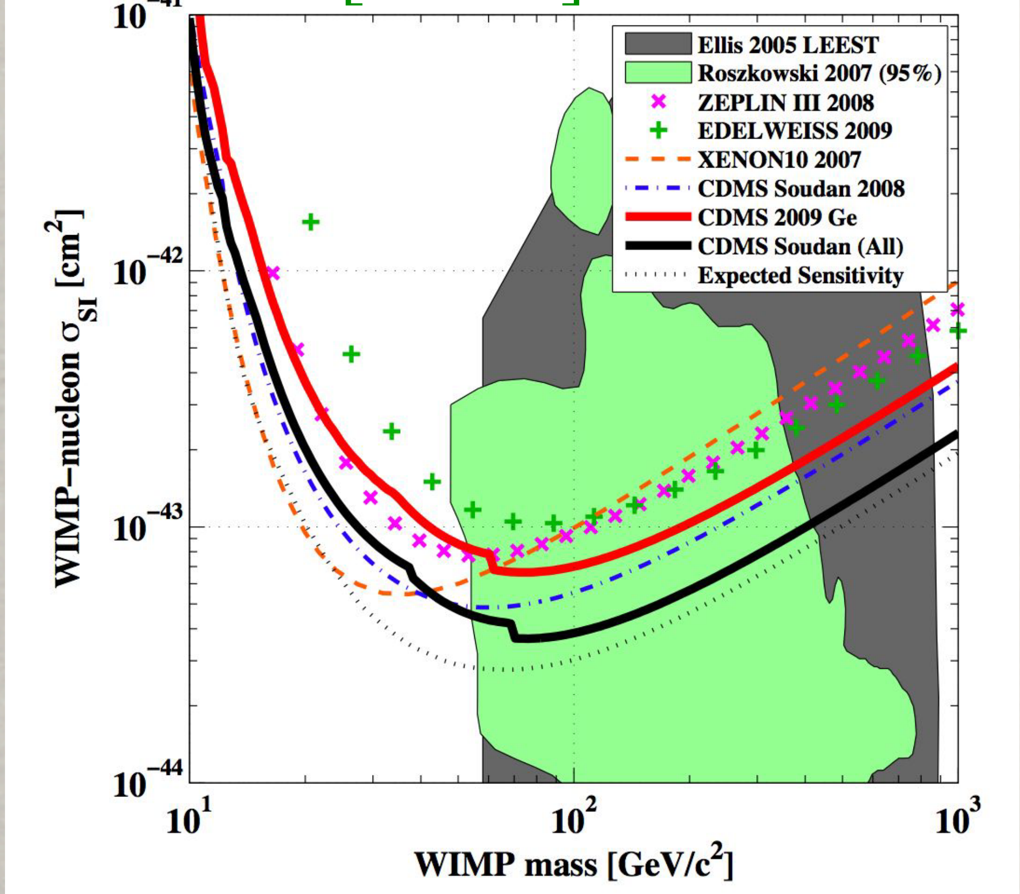
COUPP, KIM



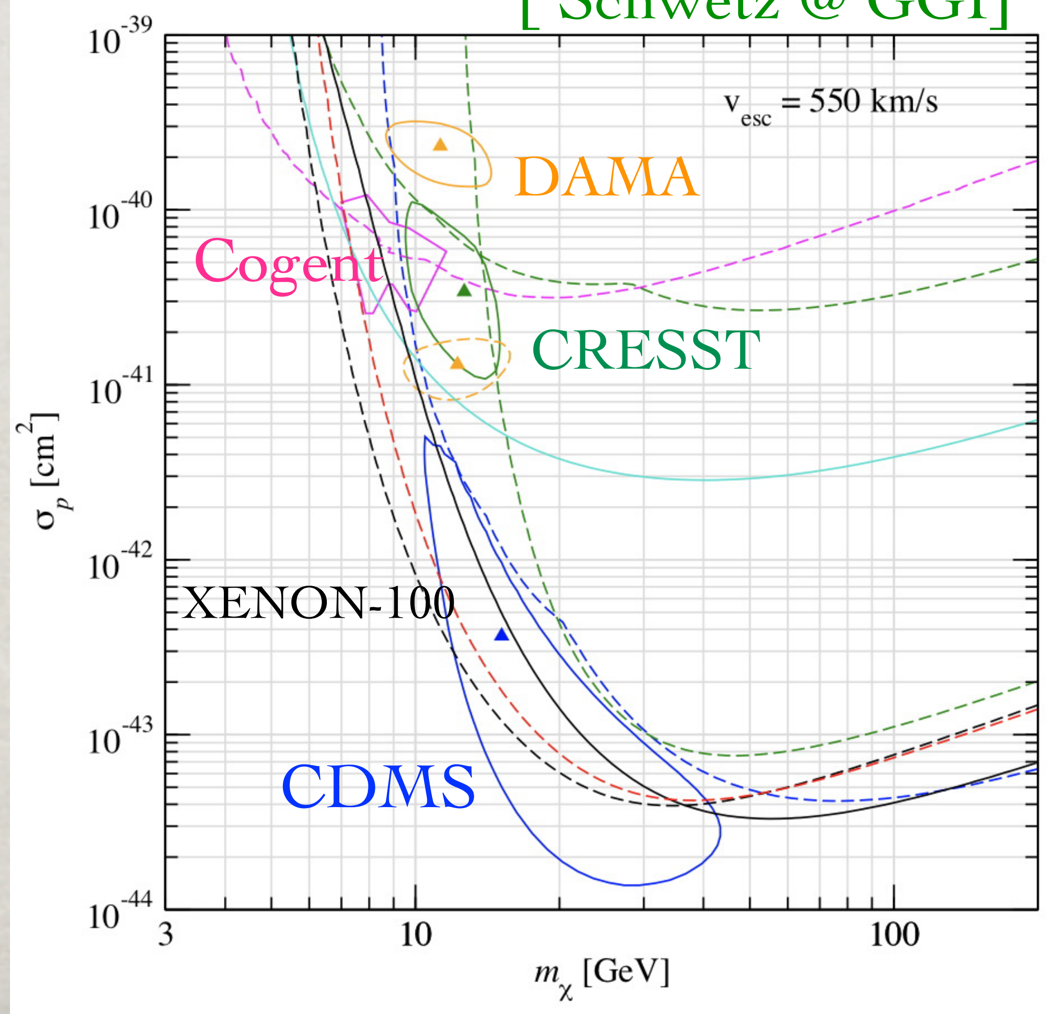
News: signal(s) of DM ?

The latest CDMS analysis of 12/09 finds 2 events in the signal region where they expect only 0.8 background; moreover quite a number of hints in the low mass region...

[CDMS]

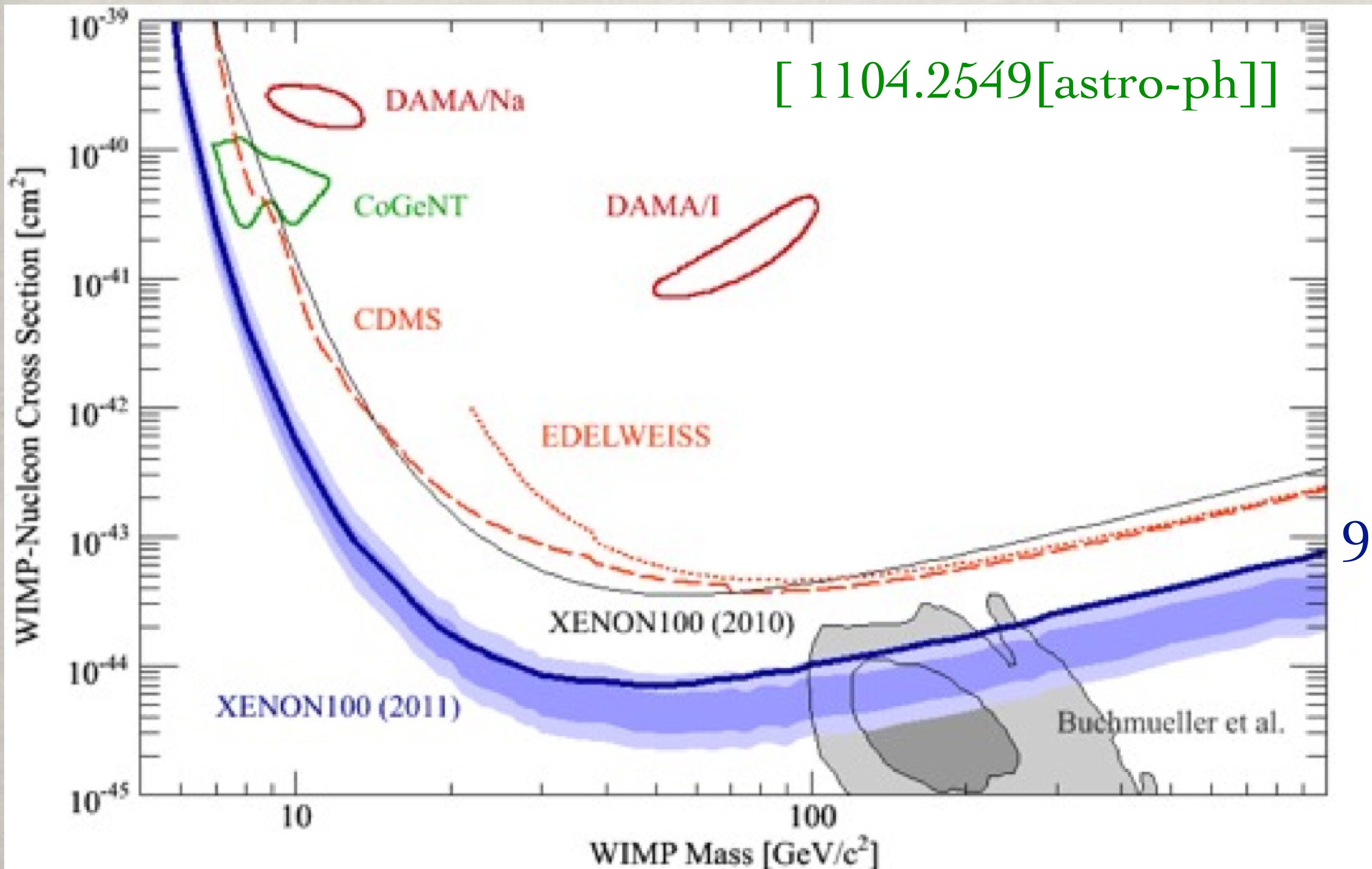


[Schwetz @ GGI]



News: signal(s) of DM ?

Last April a new analysis of XENON-100 appeared, also with an excess: 3 events in the signal region where they expect only ~ 2 background.

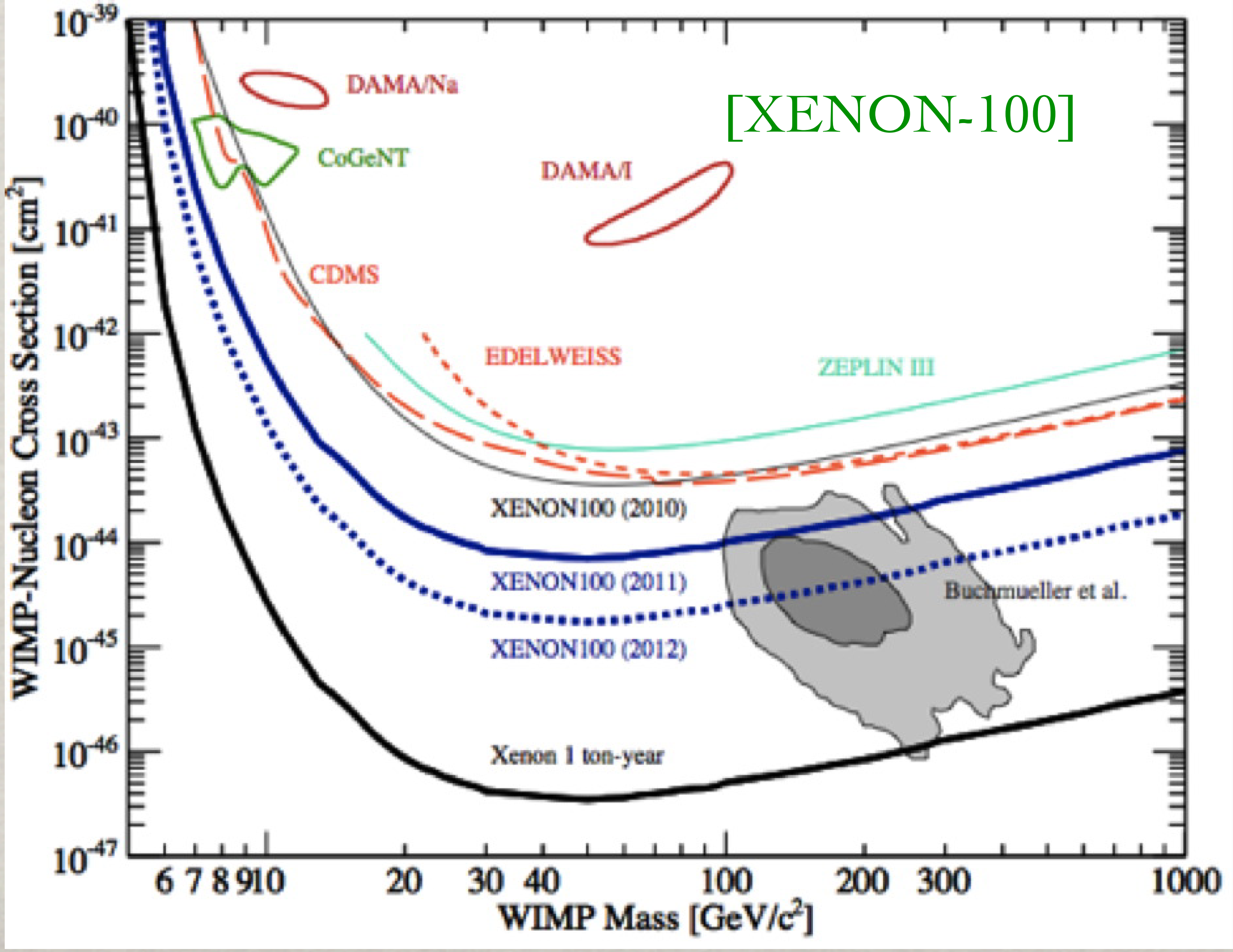


90% CL Bound

Expected Bound 1/2 σ

Future Prospects

XENON-100 is still running and should get better statistics next year if a signal is there...

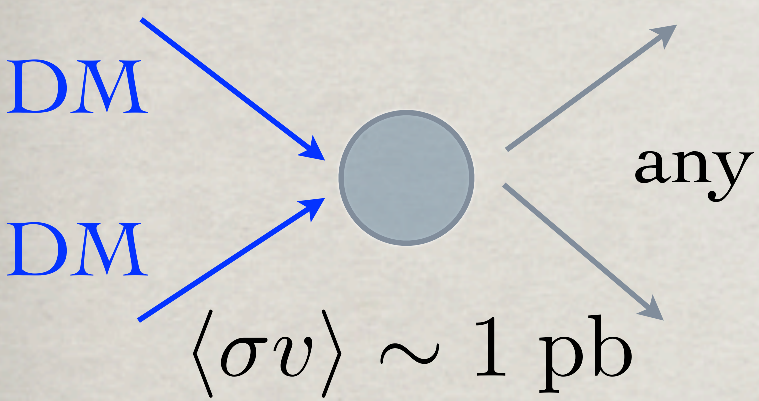


The DM Direct Detection challenge

- Measure the Dark Matter mass: possible if the mass is light and using different detector's materials.
- Determine the halo velocity distribution.
- Disentangle models using spin dependent versus spin independent cross-section...
- Check consistency with LHC/ID signal !

THE WIMP CONNECTION

Early Universe: $\Omega_{CDM} h^2$



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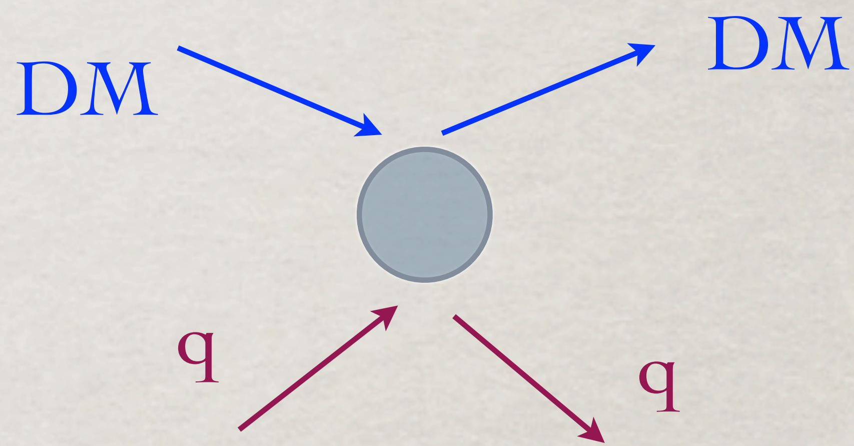
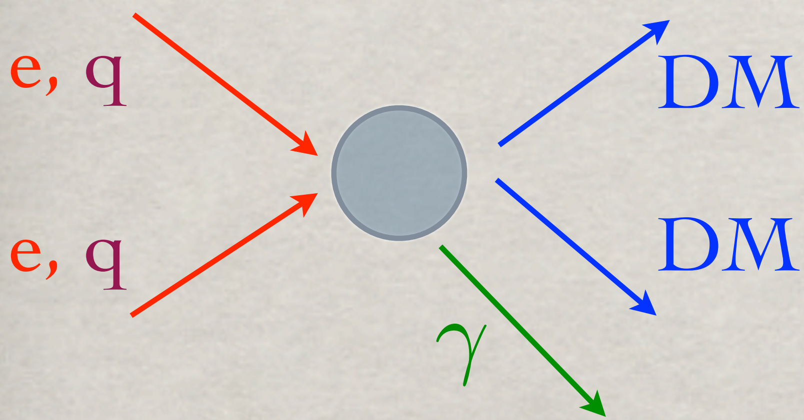


Colliders: LHC/ILC



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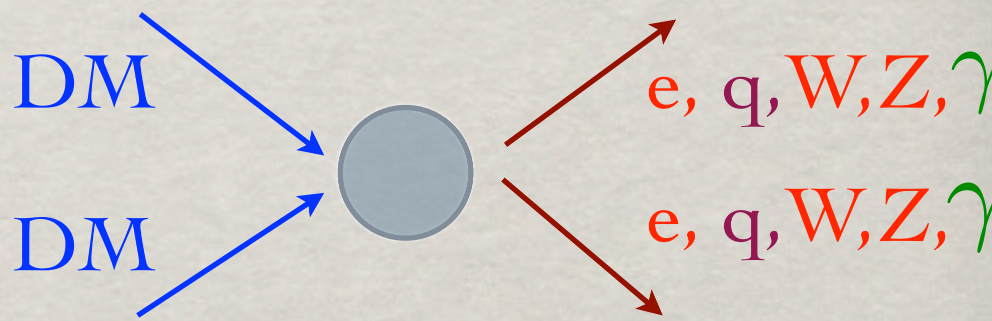

3 different ways to check this hypothesis !!!

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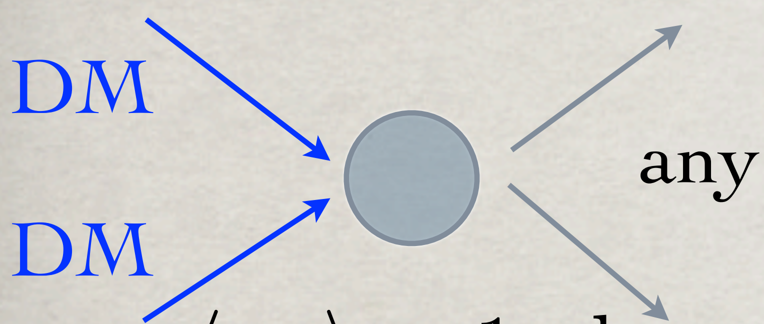

$\langle \sigma v \rangle \sim 1 \text{ pb}$

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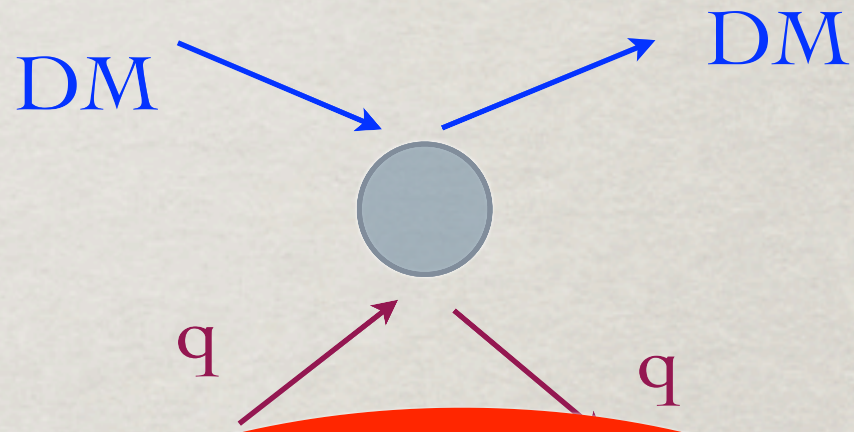

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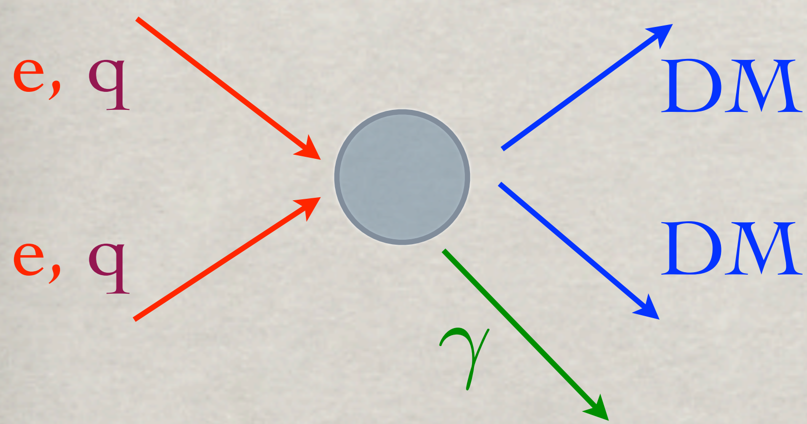

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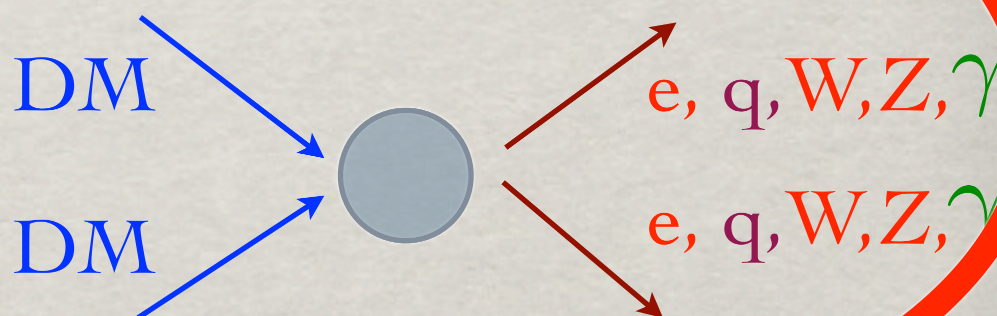
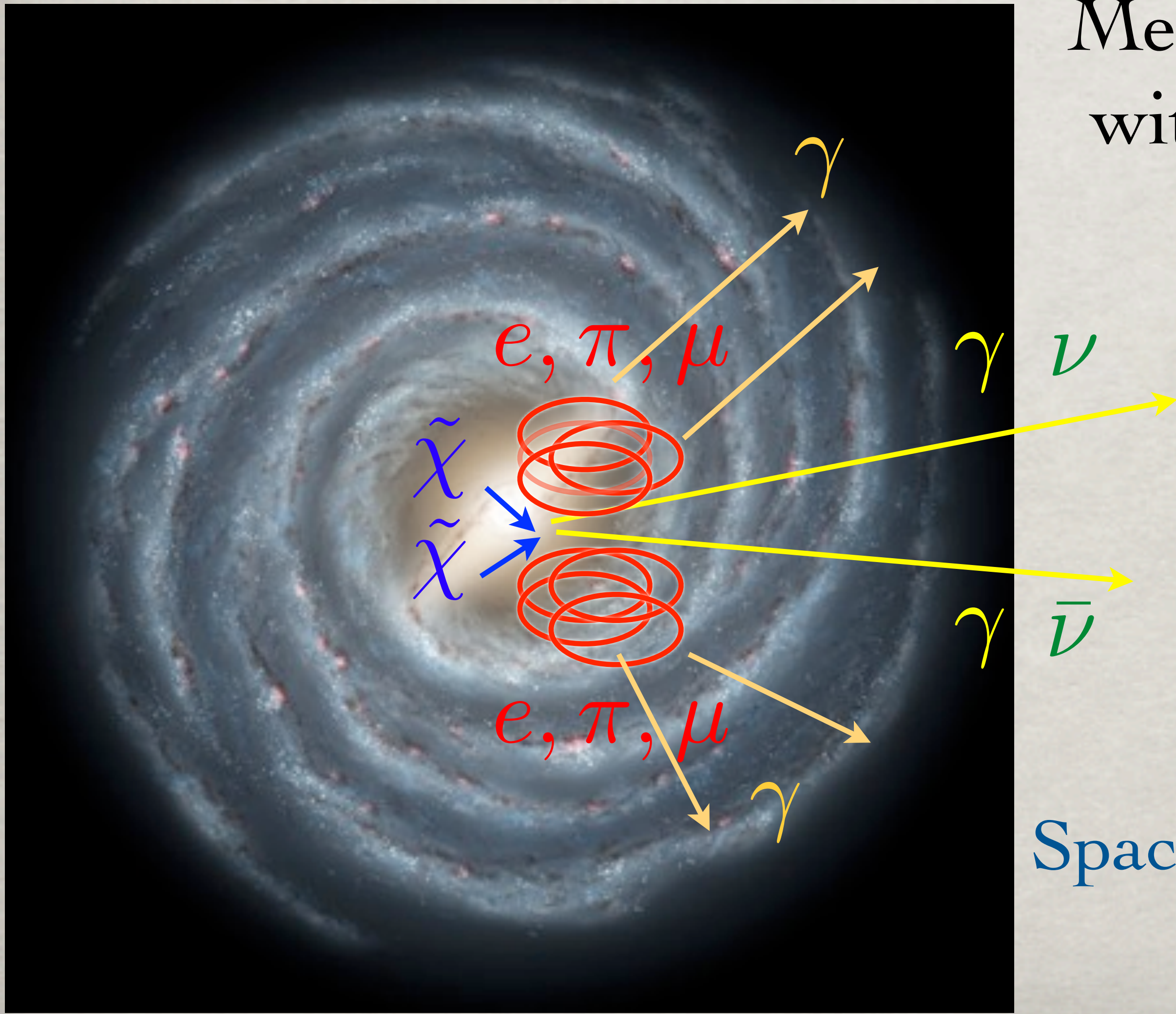


3 different ways to check this hypothesis !!!

THE HOPE: DETECT DM !

- Look for annihilation signals from the region where the density is large: centre of the Milky Way, other galaxies, clumps of DM, etc...



Measure the decay products with balloons or satellites !

Space: FERMI GRST, PAMELA, AMS-02

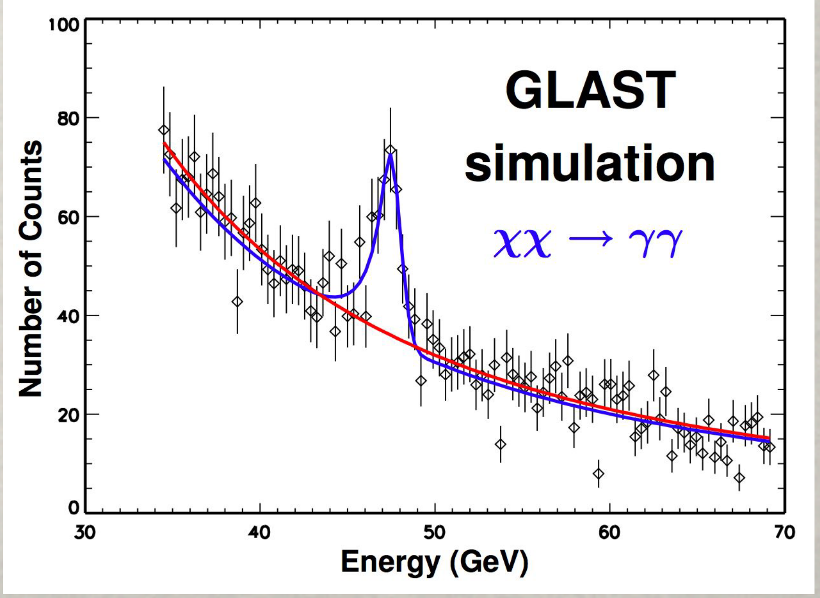
THE HOPE: DETECT DM !

- The flux in a species i is given by

$$\Phi(\theta, E) = \sigma v \, \frac{dN_i}{dE} \, \frac{1}{4\pi m_{DM}^2} \int_{l.o.s.} ds \, \rho^2(r(s,\theta))$$

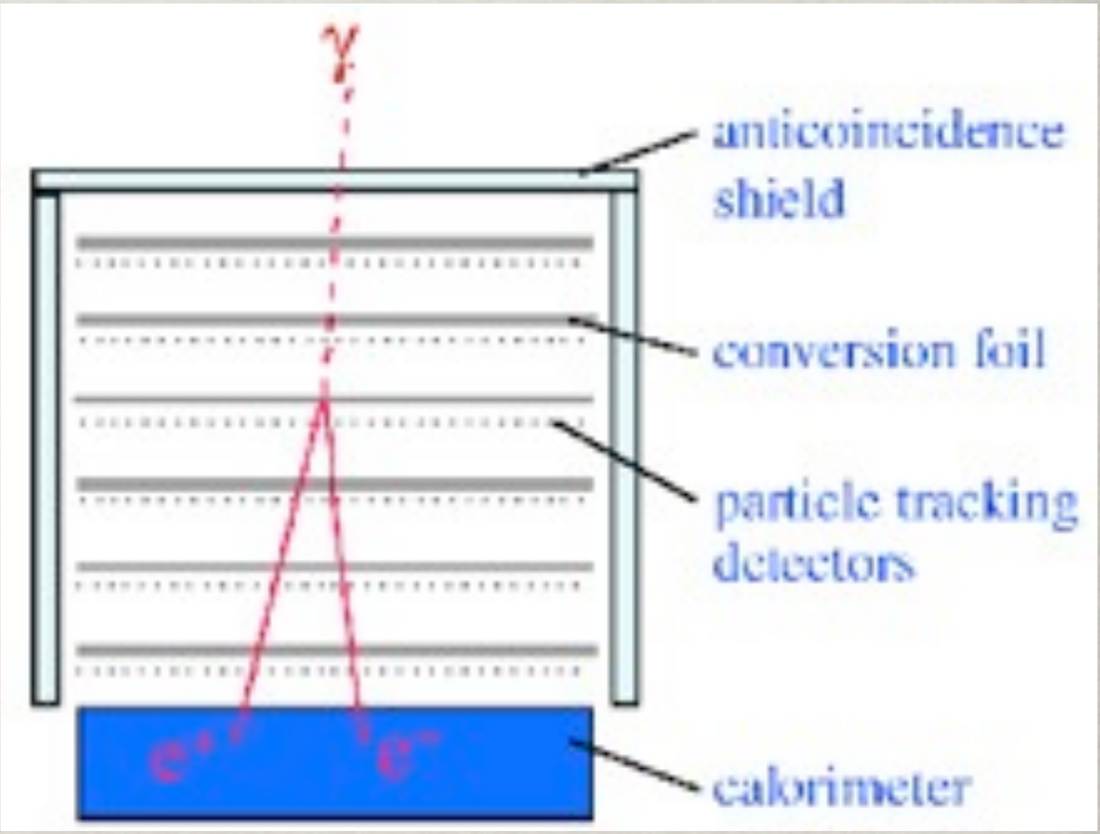
Particle Physics Halo property

- Strongly dependent on the halo model/density and the DM clumping: BOOST factor !
- Spectrum in gamma-rays determined by particle physics ! Smoking gun: gamma line...
- For other species also the propagation plays a role.

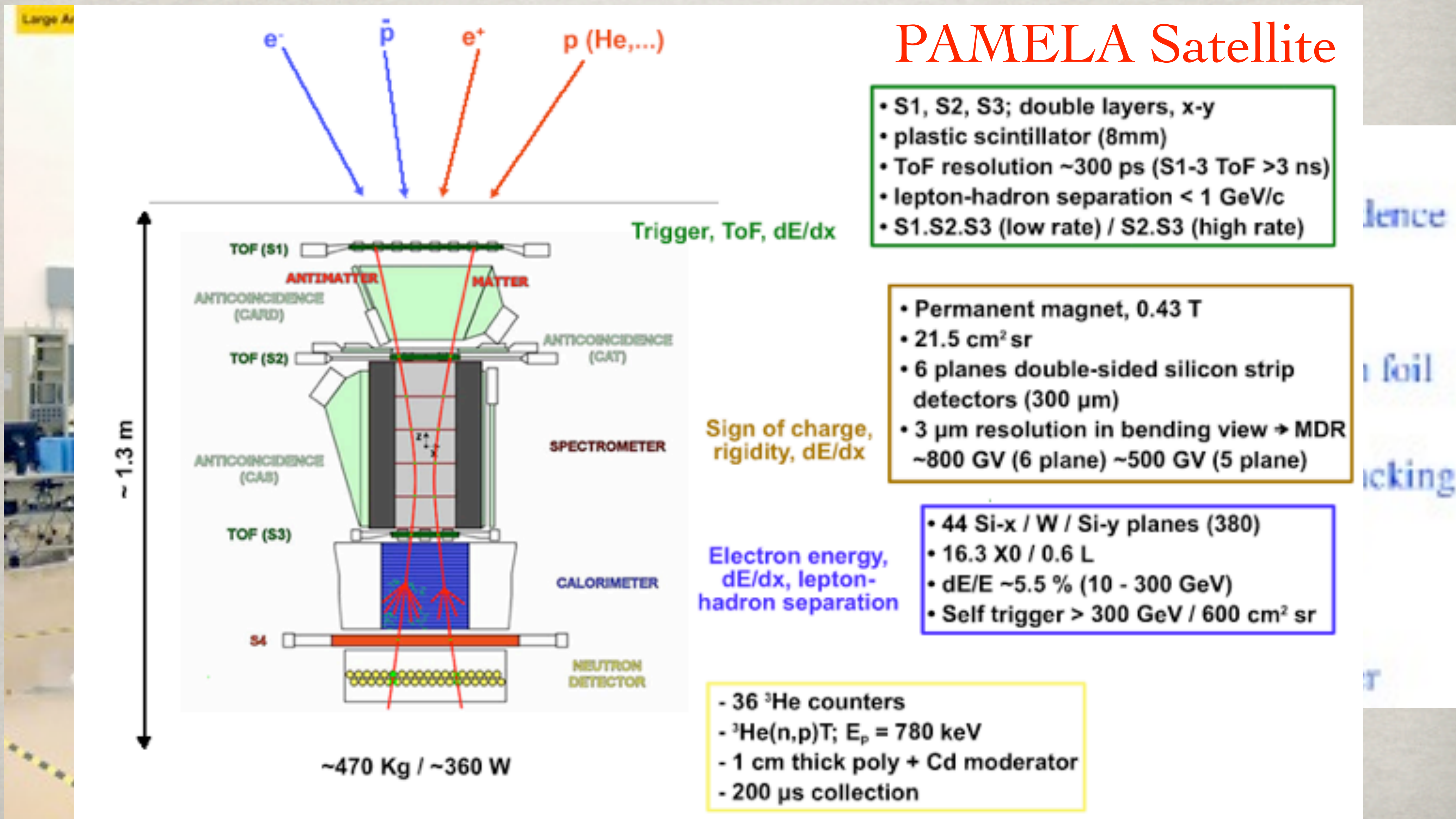


Satellites for DM: detectors in space !

FERMI-LAT



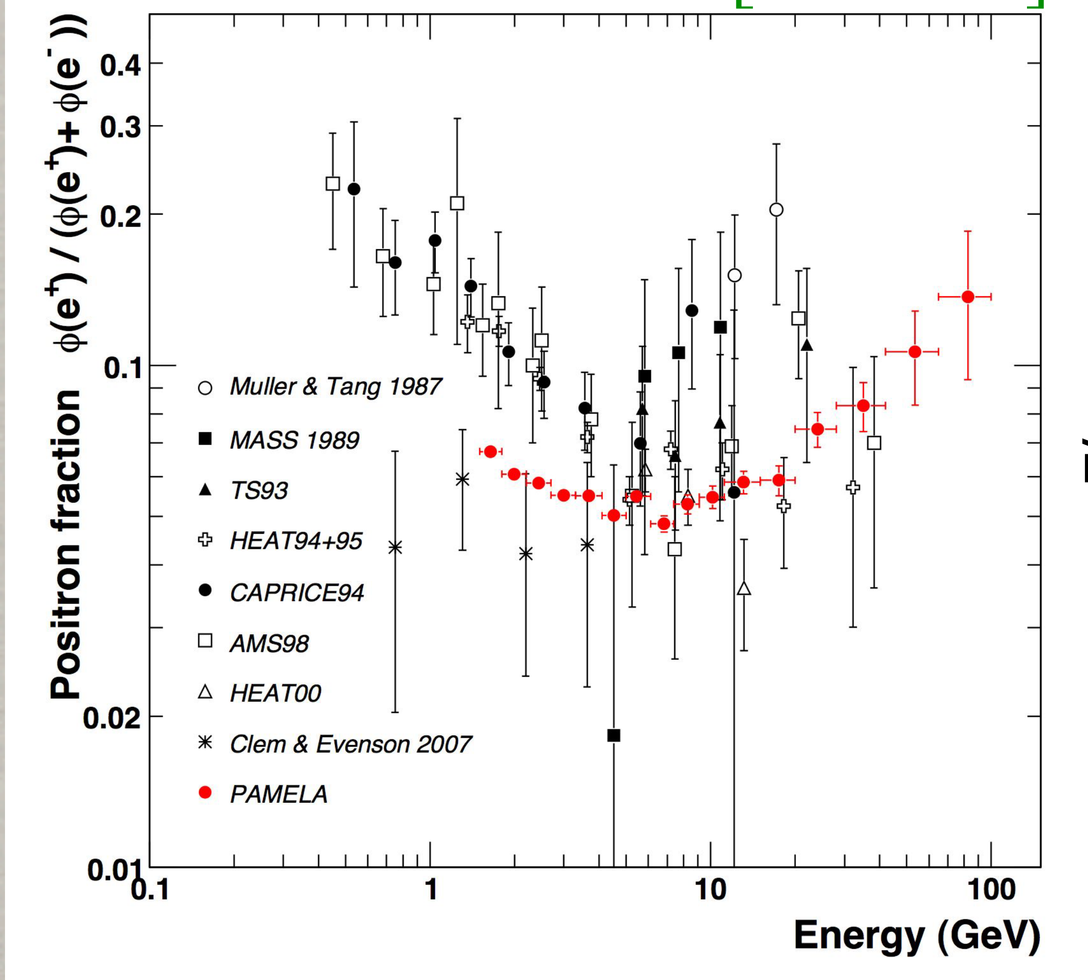
Satellites for DM: detectors in space !



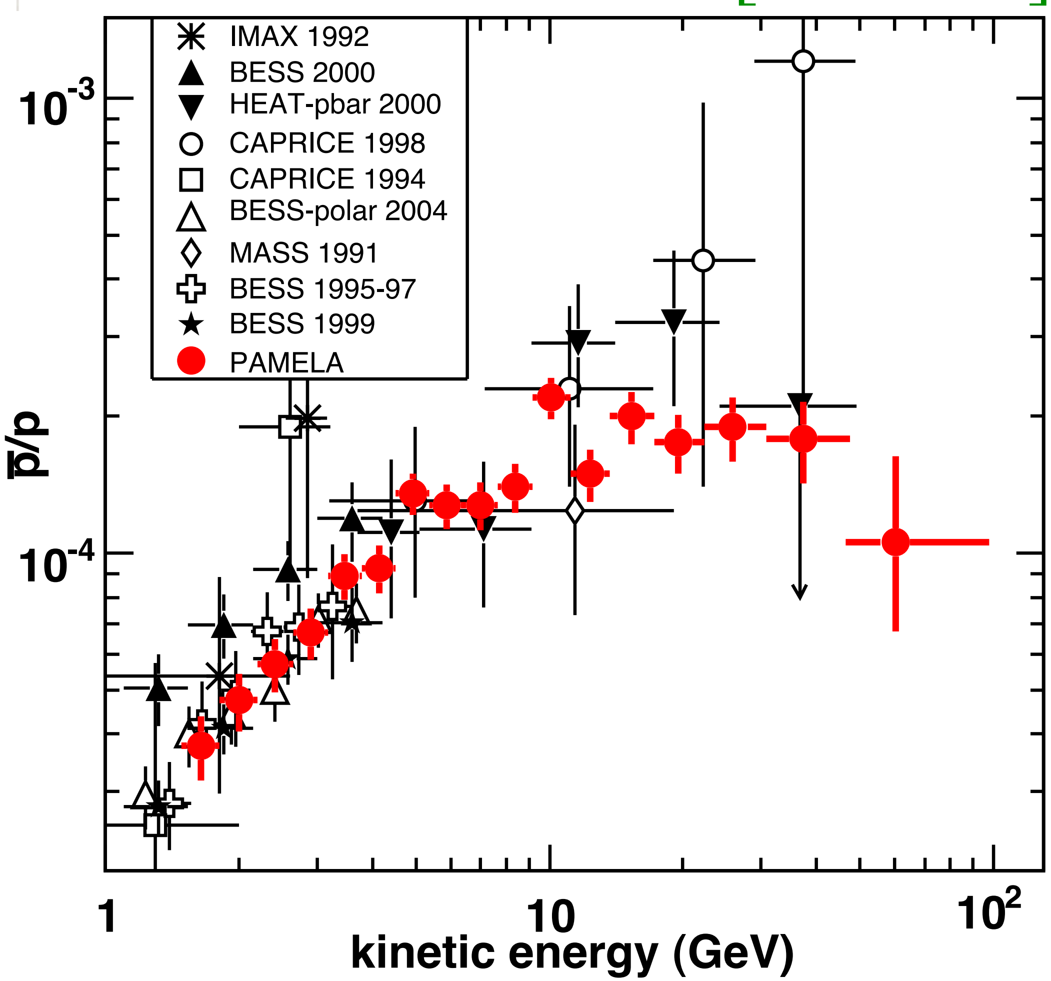
News from the sky I

The PAMELA satellite measures antimatter and released data of positron fraction & antiprotons >2 years ago:

[0810.4995]



[0810.4994]



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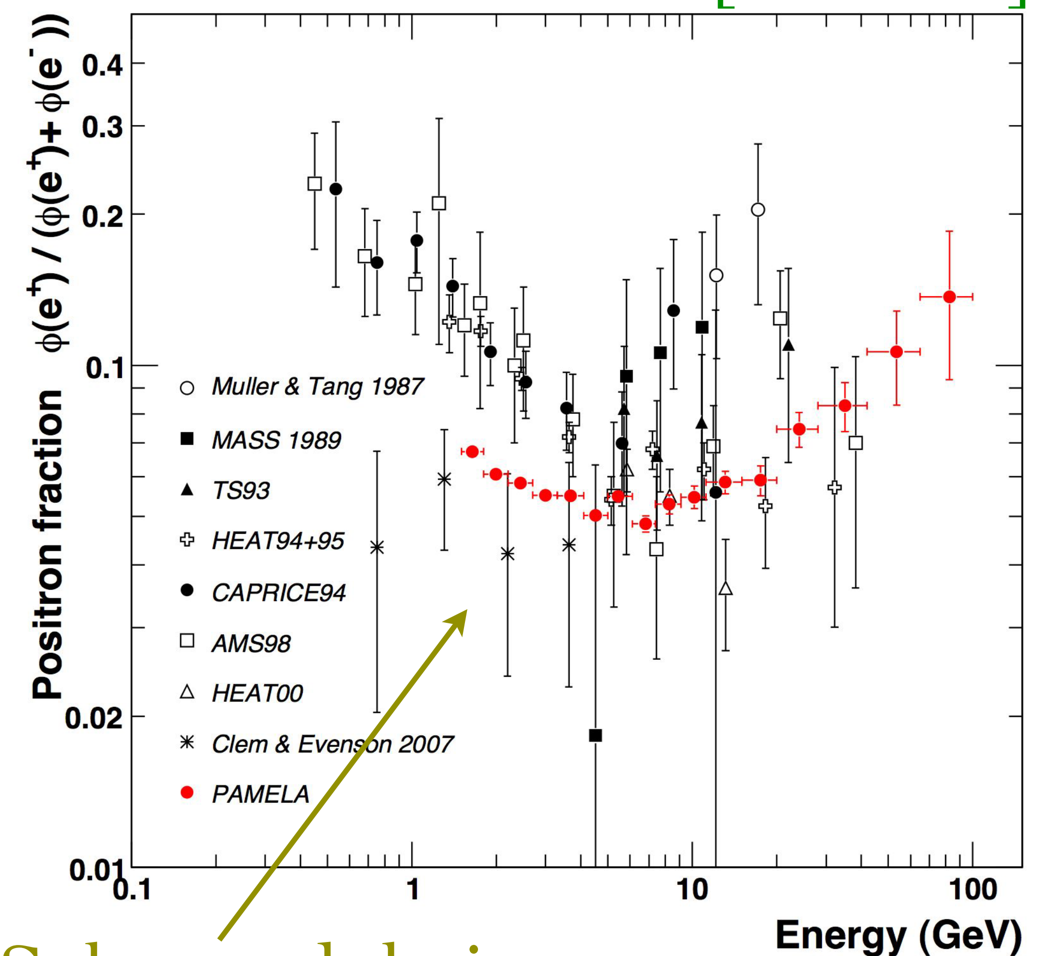
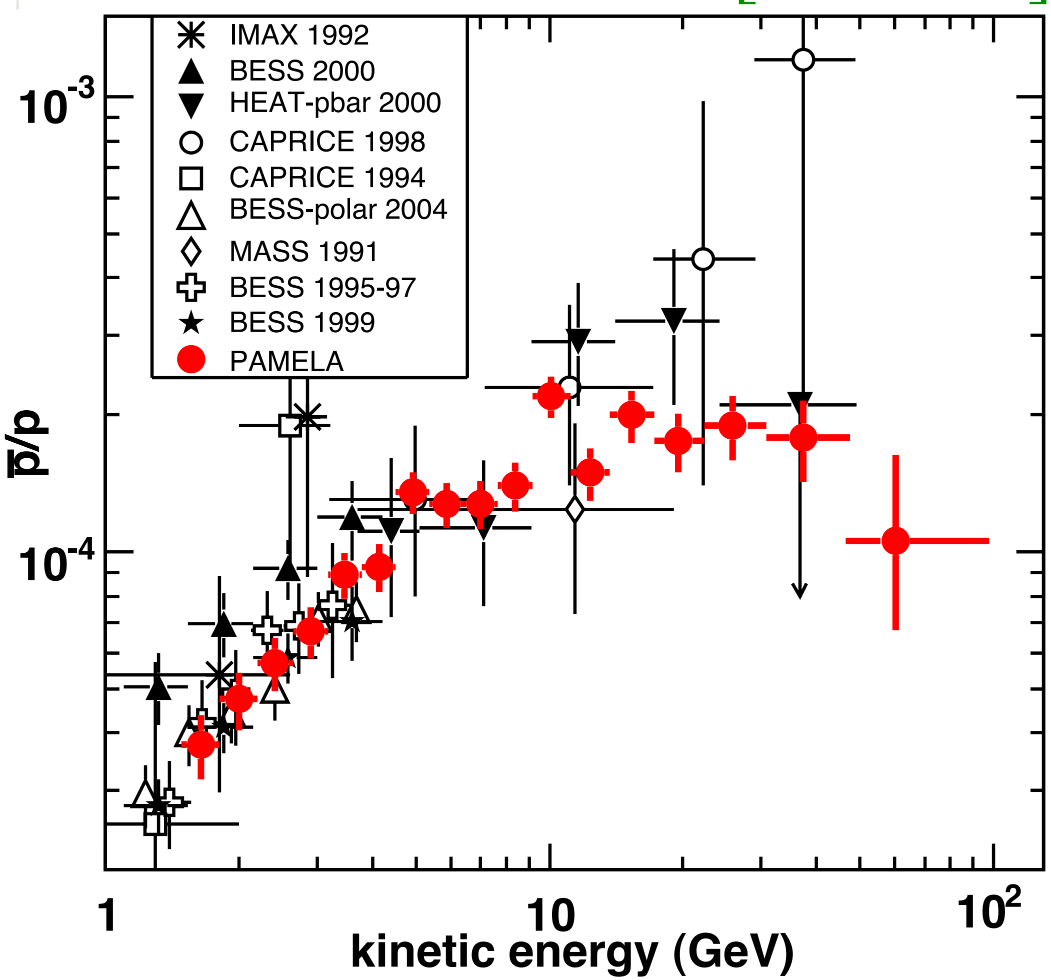


Solar modulation

[0810.4994]



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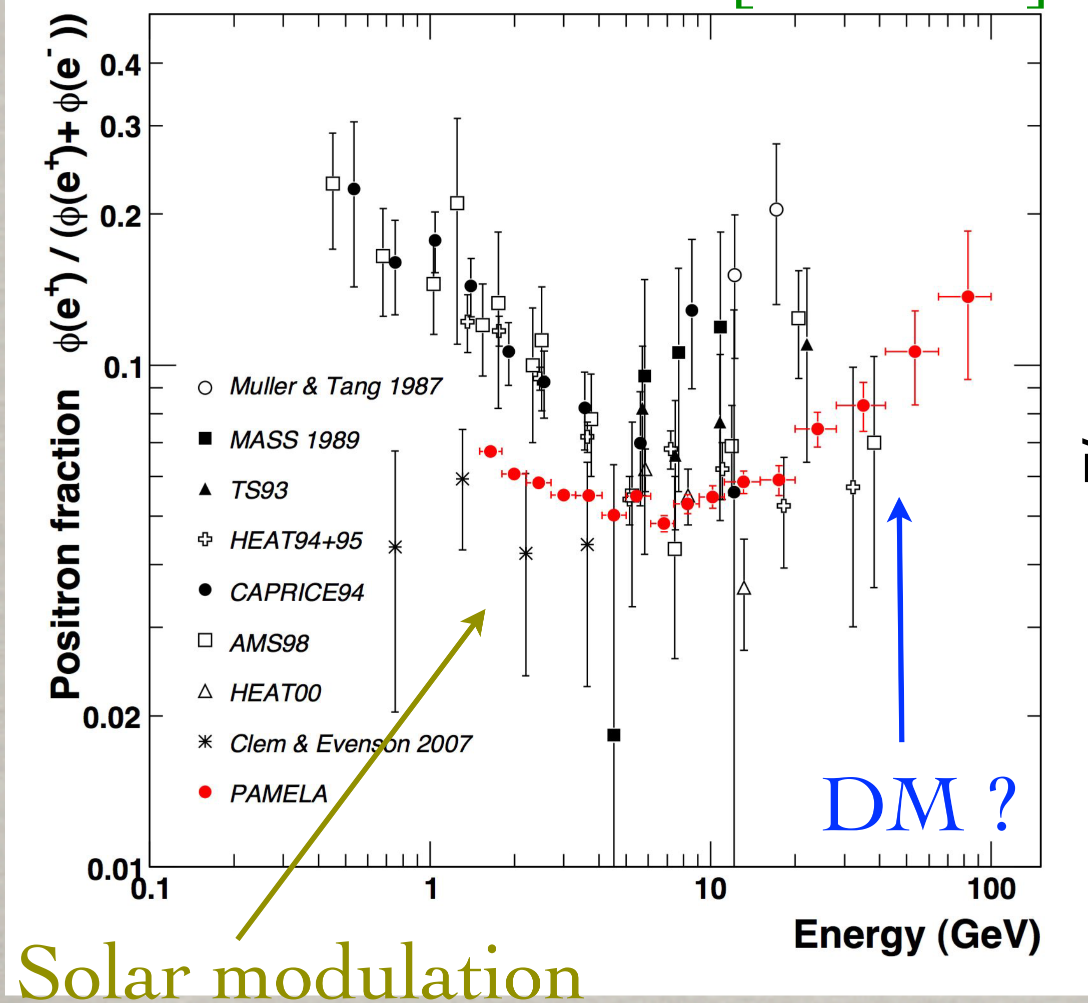

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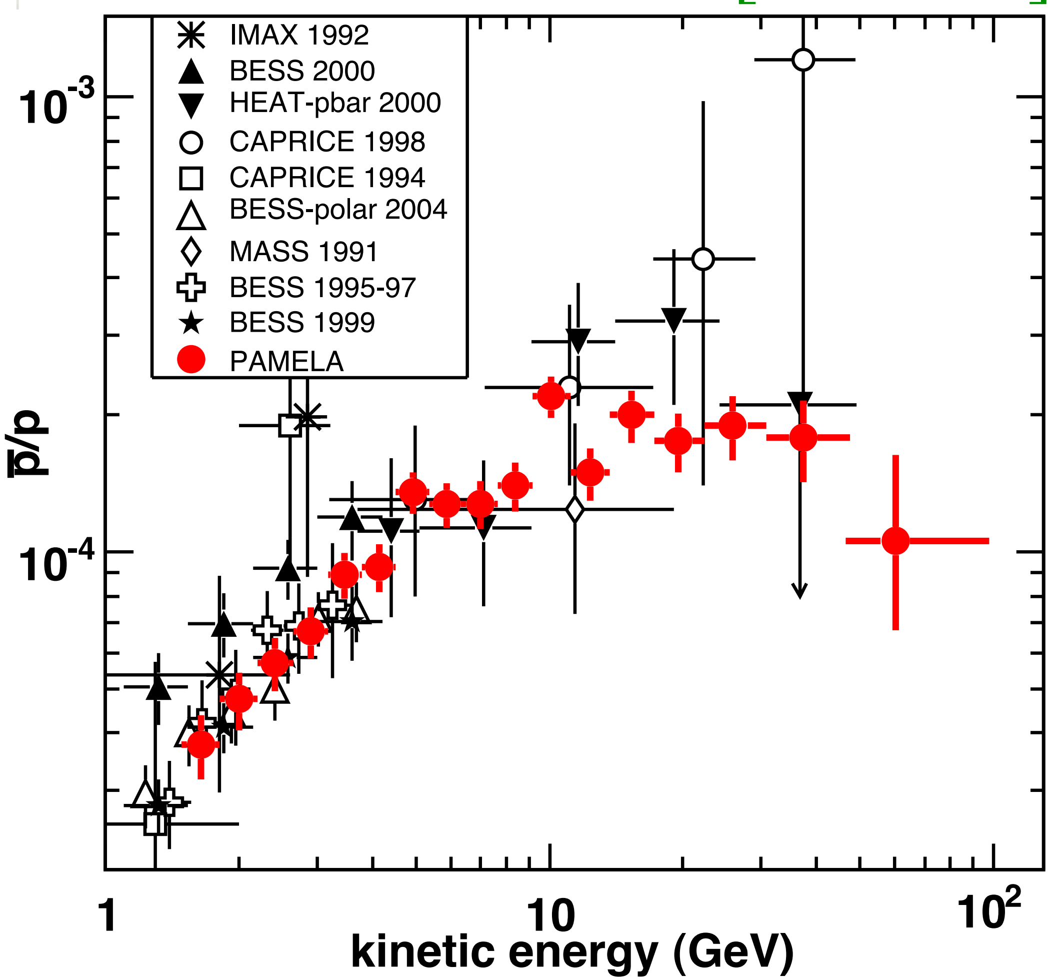

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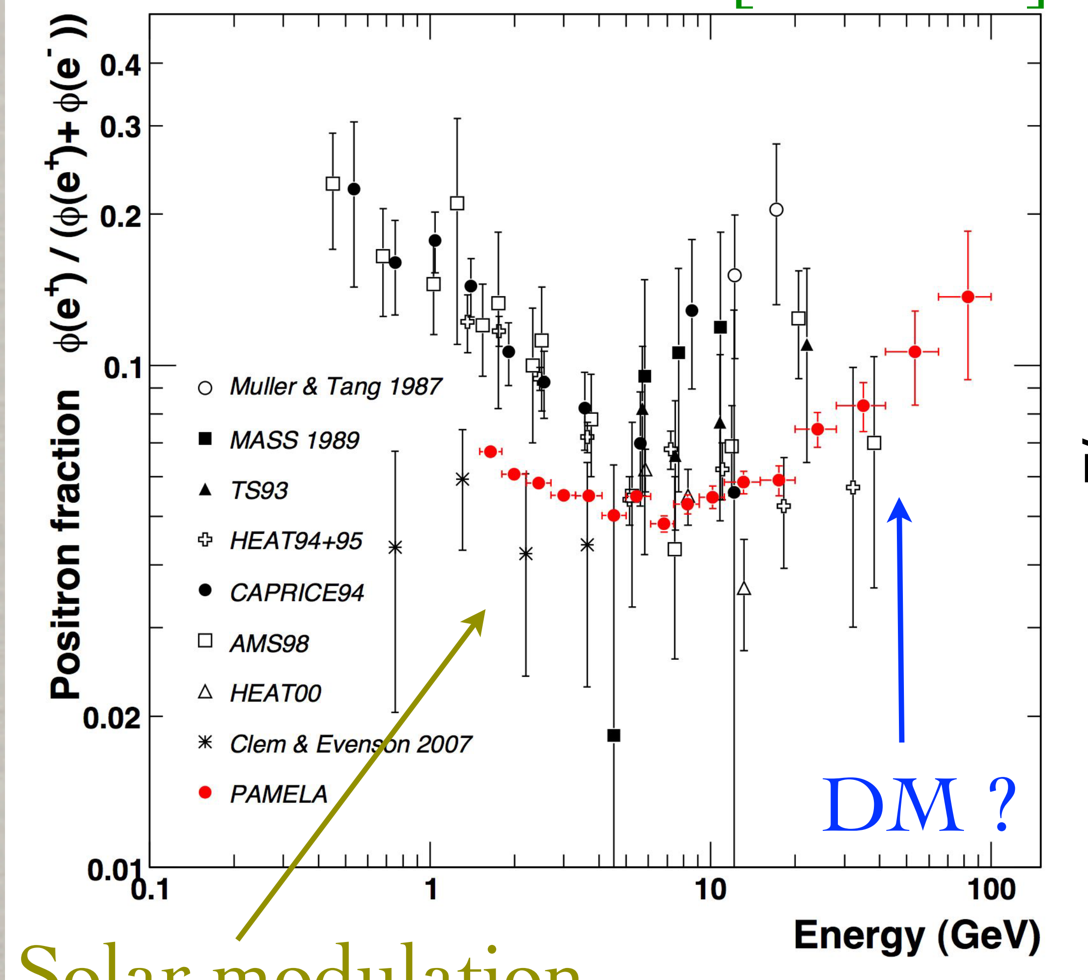

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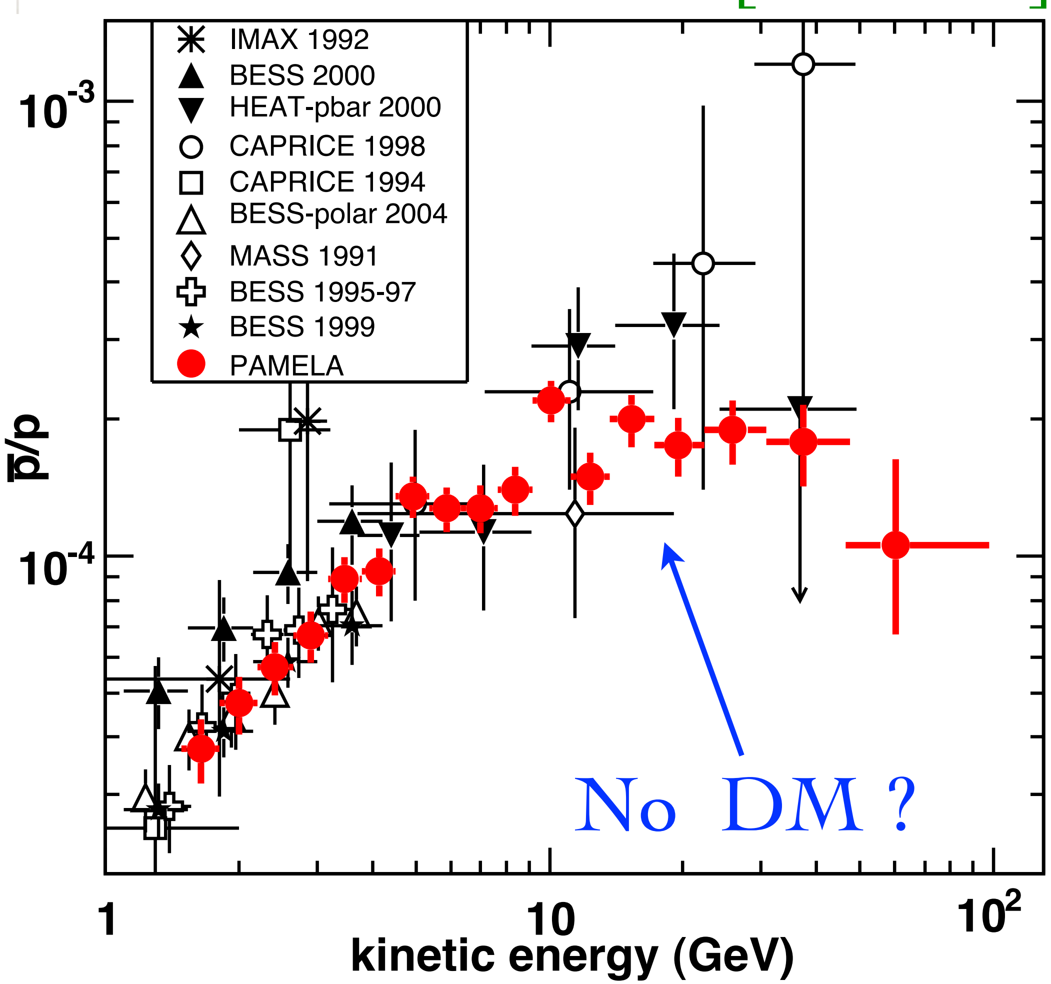
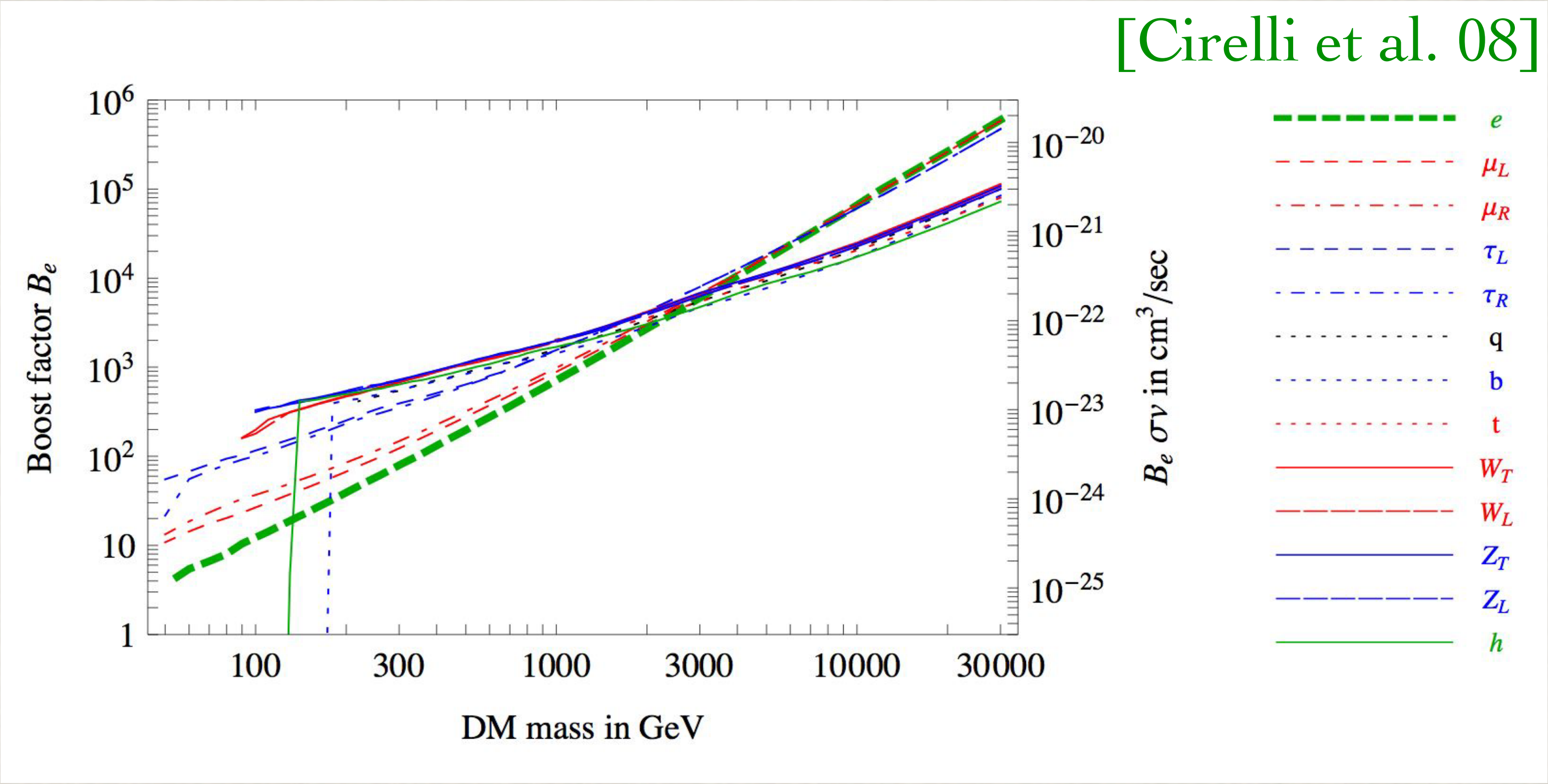


WIMP ANNIHILATION ?

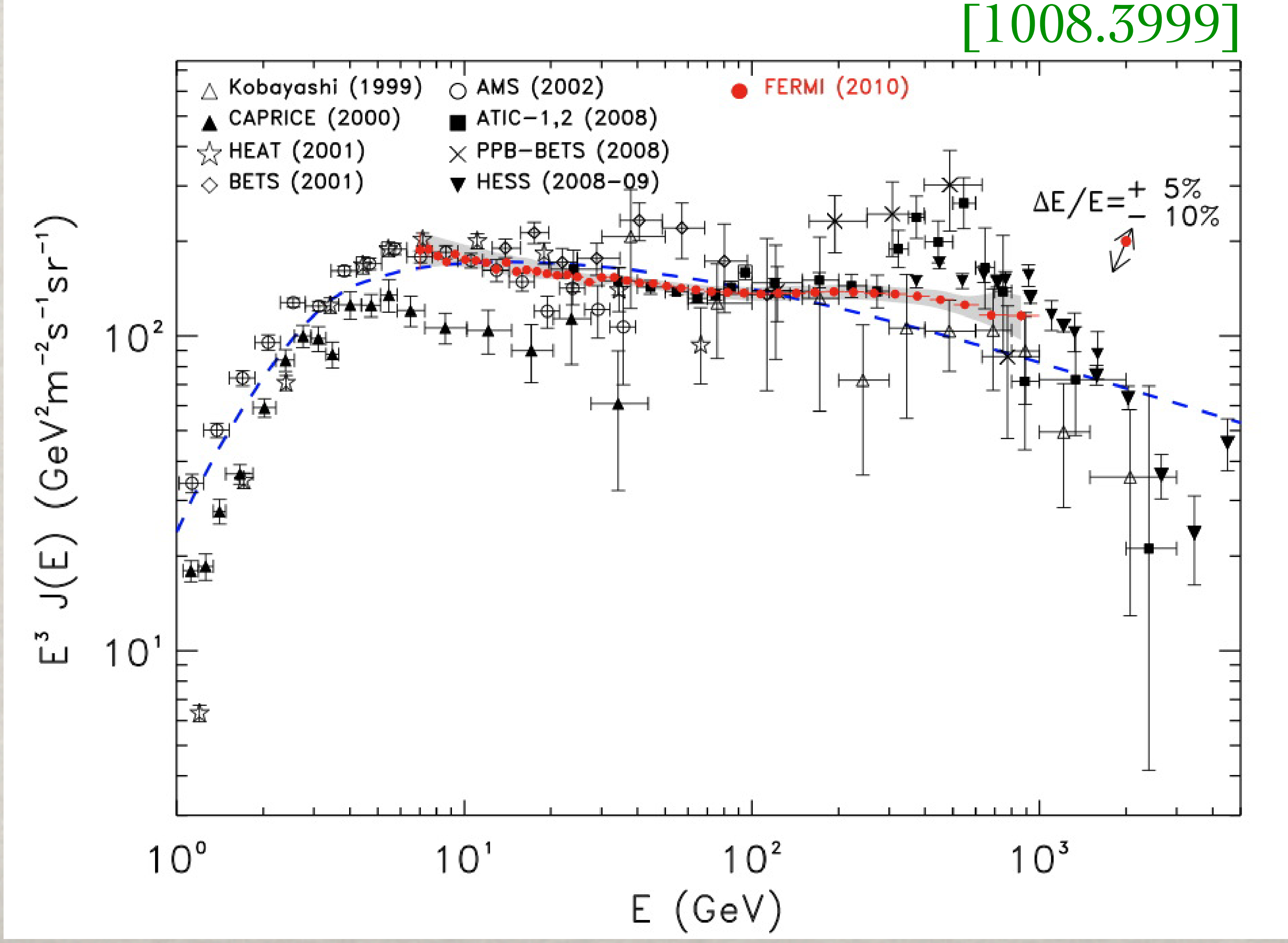
Need a large boost factor or an enhancement of the annihilation cross-section to be consistent with the WIMP mechanism.



Thermal relic annihilation cross-section corresponds to B=1...
Difficult to obtain B > 10-100 from halo models...
Perhaps easier to enhance the annihilation cross-section ?

News from the sky II

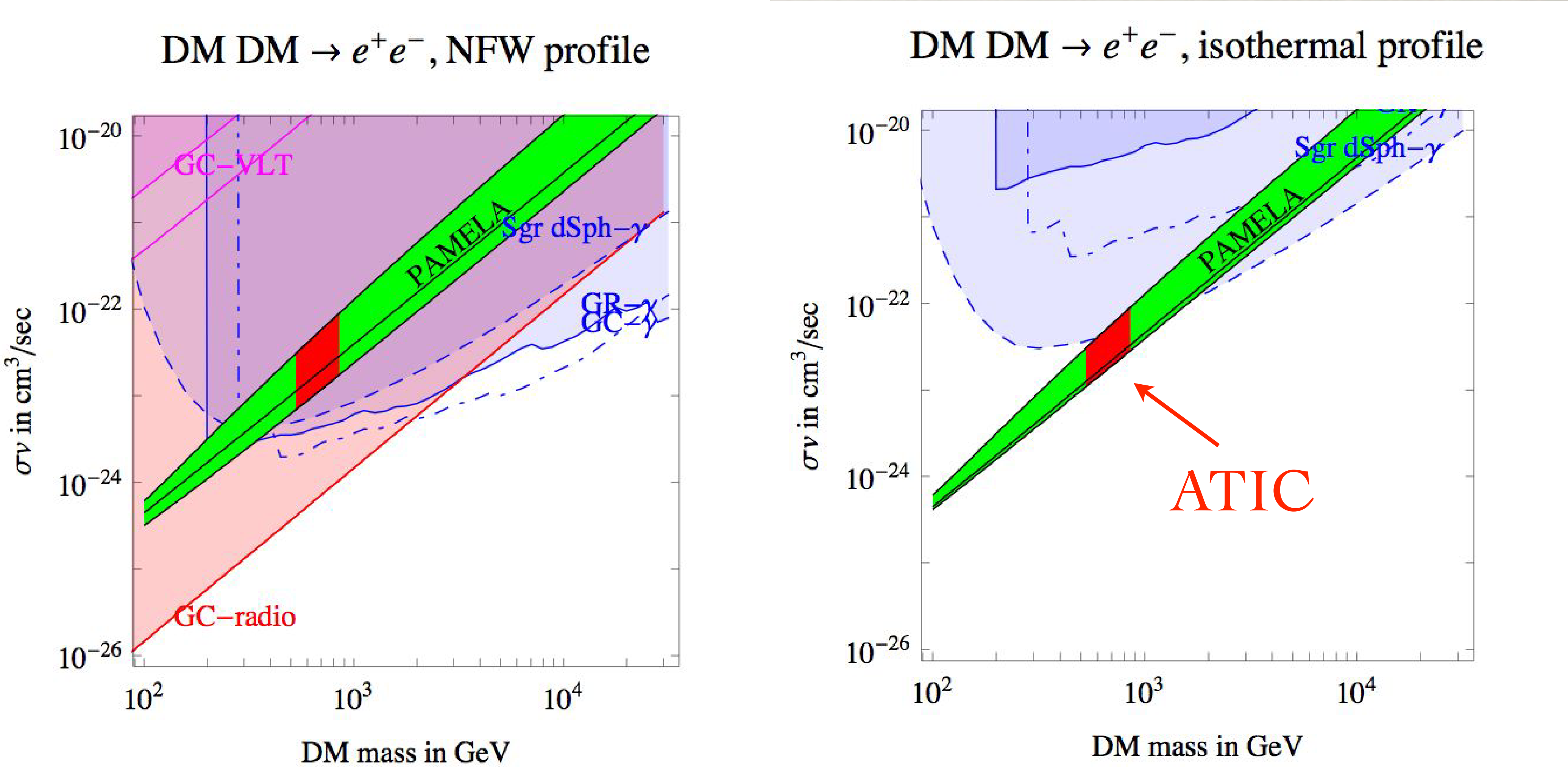
FERMI does not see any spectral feature:
quite "flat" hard electron+position spectrum from 7 GeV up:



WIMP annihilation ???

But note that the signal in leptons seems in contrast with the radio signal from the galactic centre for a NFW profile

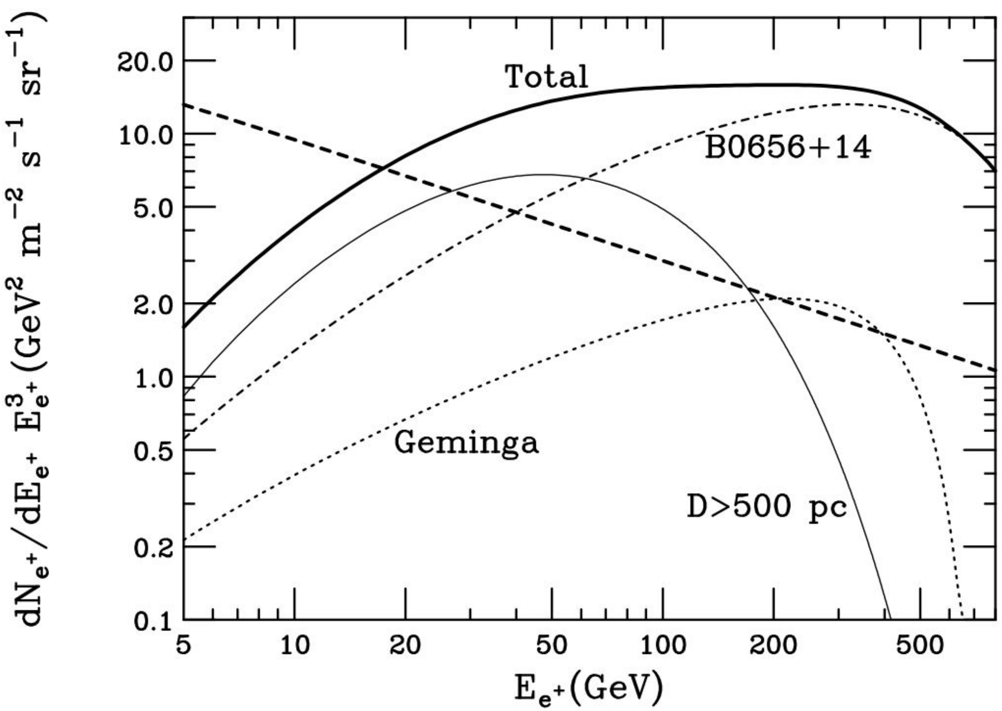
[Bertone, Cirelli, Strumia & Taoso 08]

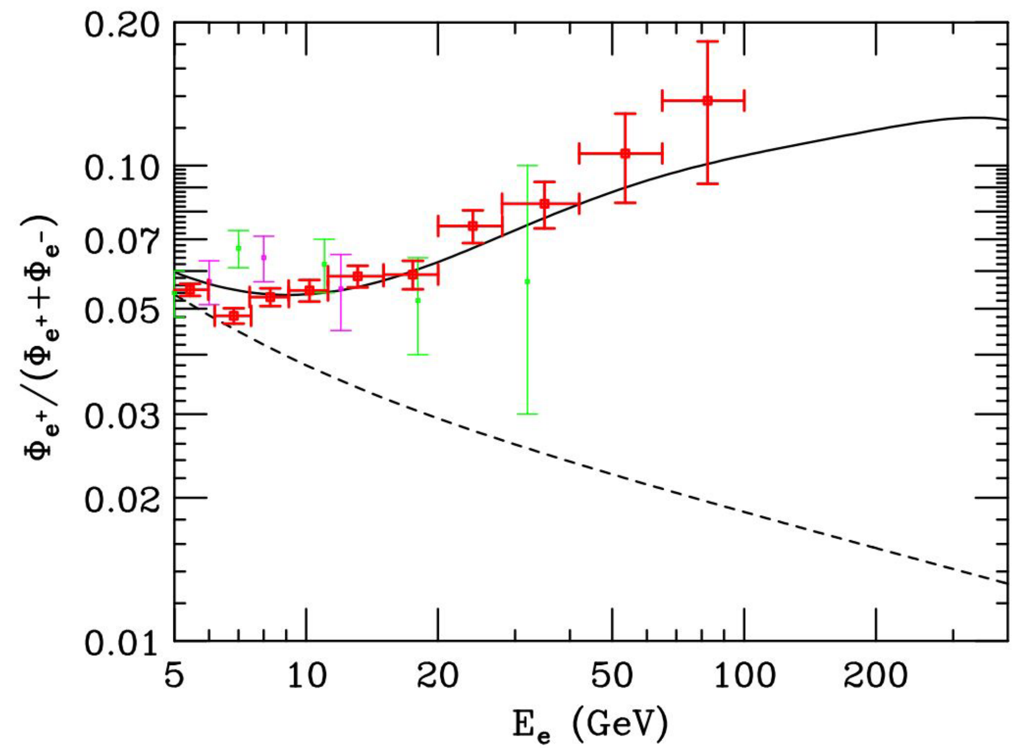


Or is it a pulsar ?

One or more local pulsars may also give the PAMELA signal, producting $e^{+}e^{-}$ pairs from their energetic gammas

[Hooper, Blasi & Serpico 08]



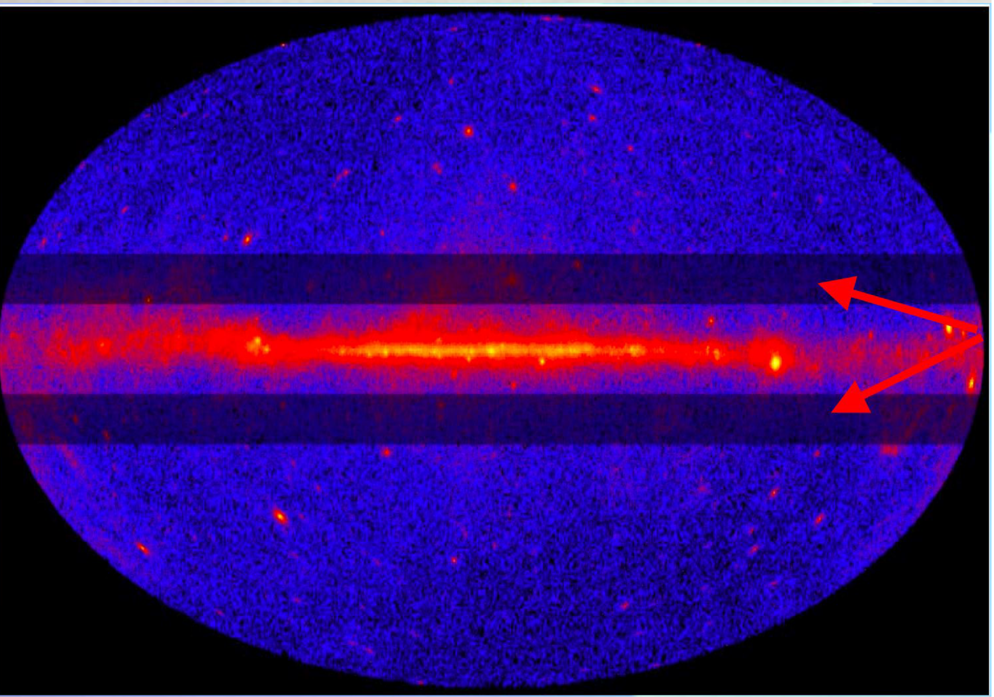


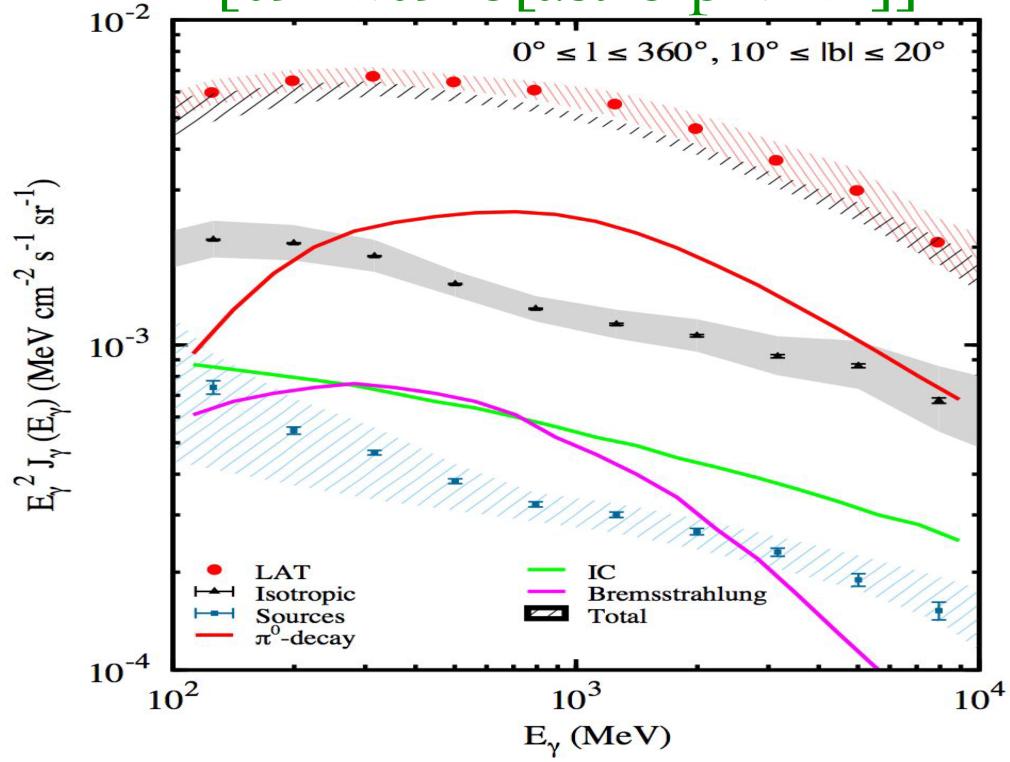
Differences from DM signal: exponential cut-off and some small anisotropy, but of the order 0.05-0.1 %

News from the sky III

The FERMI satellite has new results on the gamma-ray emissions around the galactic centre in the strip |b|=10-20

[0912.0973[astro-ph.HE]]



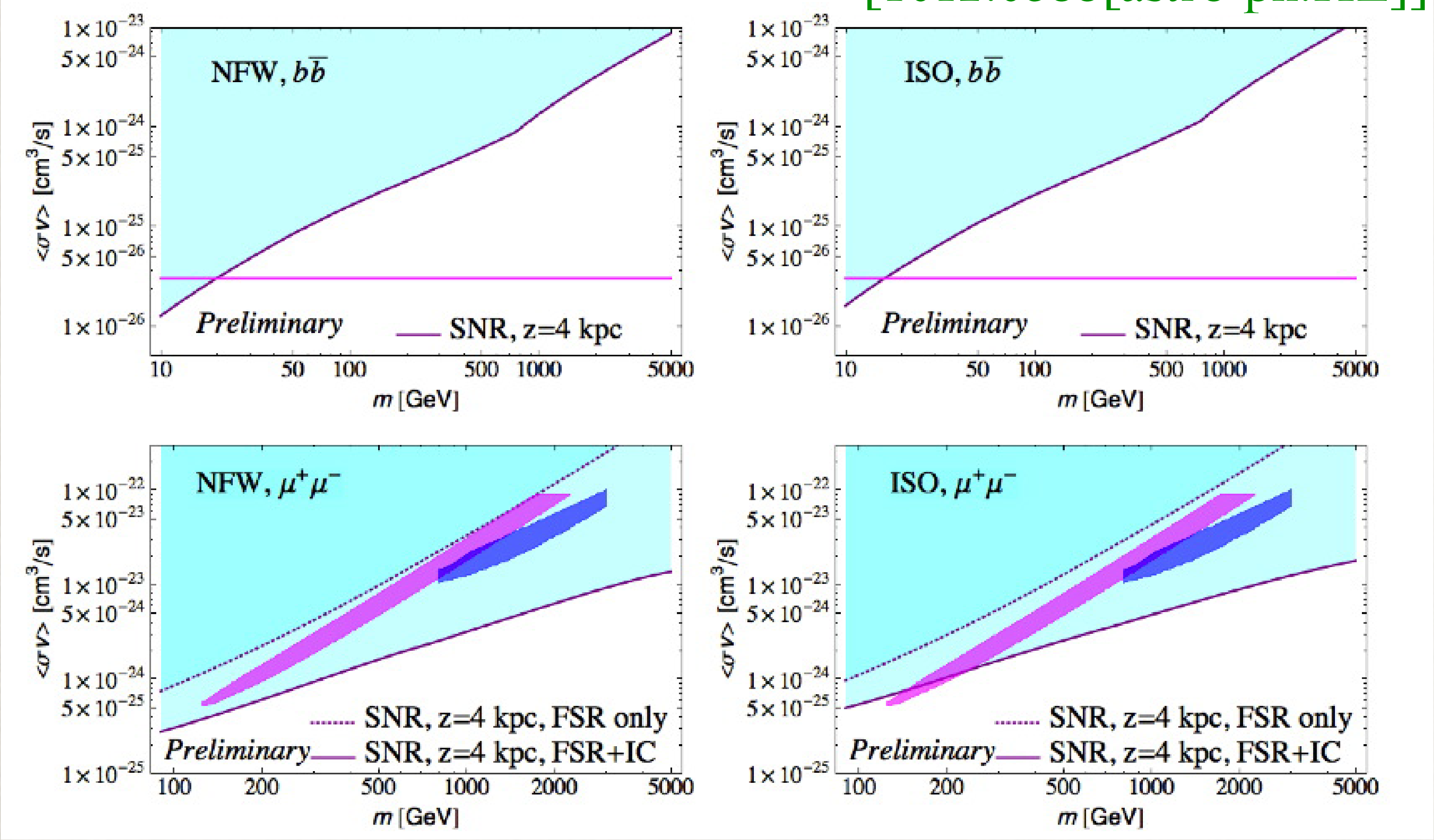


The spectrum seems perfectly consistent with the background, no need of any DM signal there, nor in extra-galactic part. Also recently no lines found between 30-200 GeV...

News from the sky III

The FERMI galactic flux gives bounds on the annihilation cross-section, depending on the channels/DM profile:

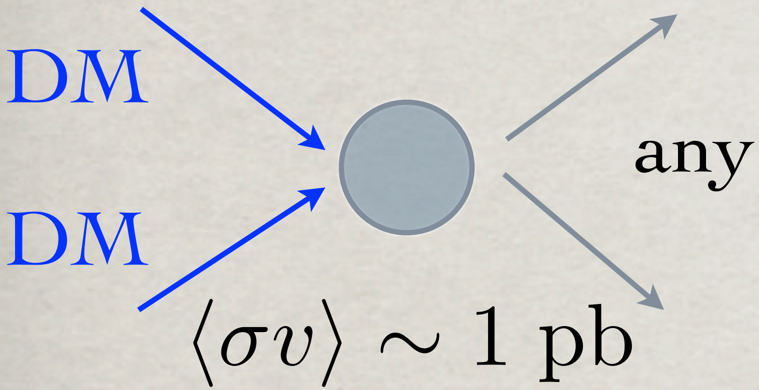
[1012.0588[astro-ph.HE]]



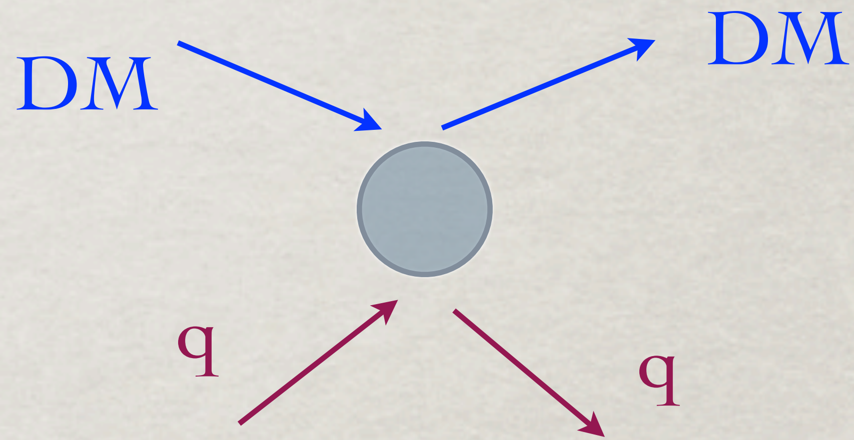
Weaker bounds from other targets: Dwarf galaxies, extragal, ...

THE WIMP CONNECTION

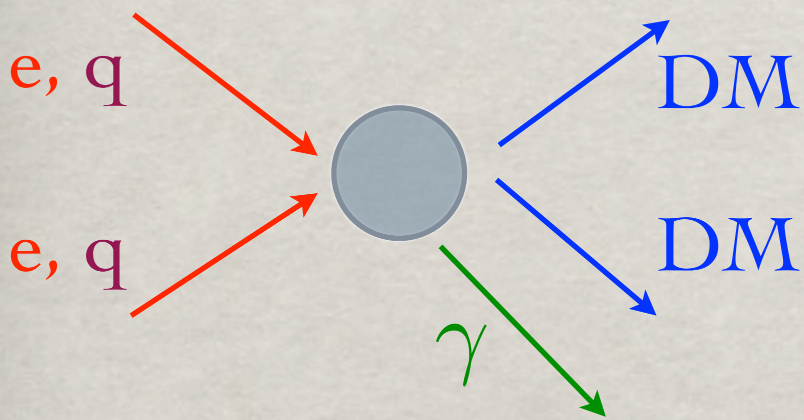
Early Universe: $\Omega_{CDM} h^2$



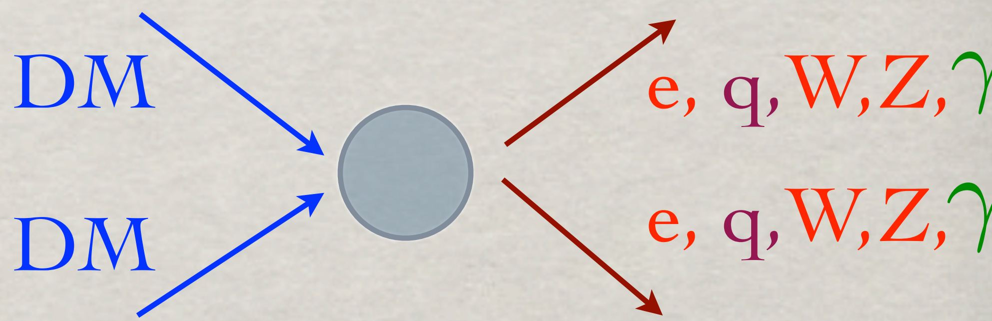
Direct Detection:



Colliders: LHC/ILC



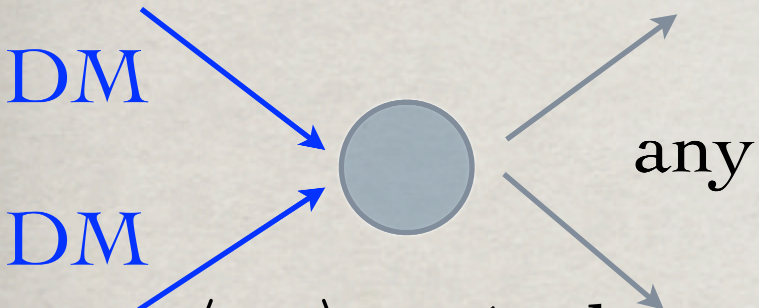
Indirect Detection:



3 different ways to check this hypothesis !!!

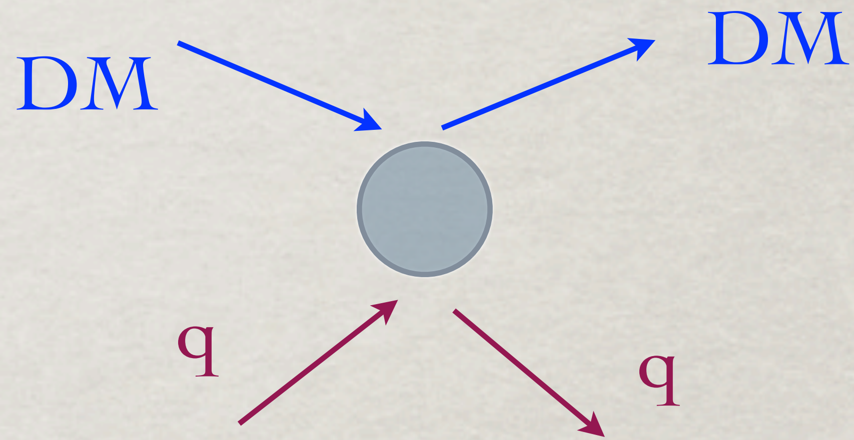
THE WIMP CONNECTION

Early Universe: $\Omega_{CDM} h^2$



$\langle \sigma v \rangle \sim 1$ pb

Direct Detection:



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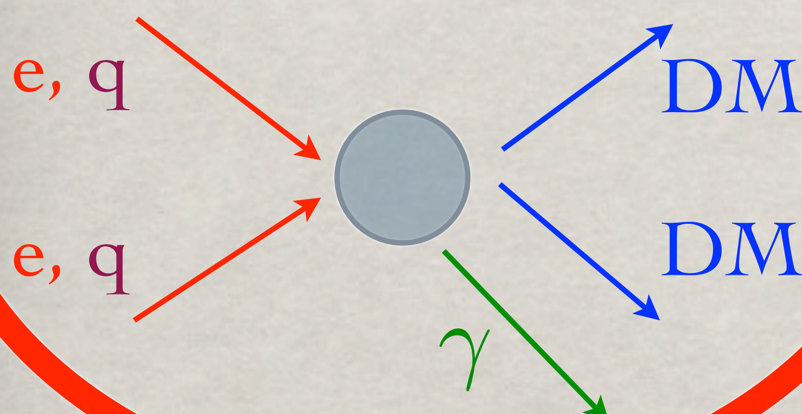
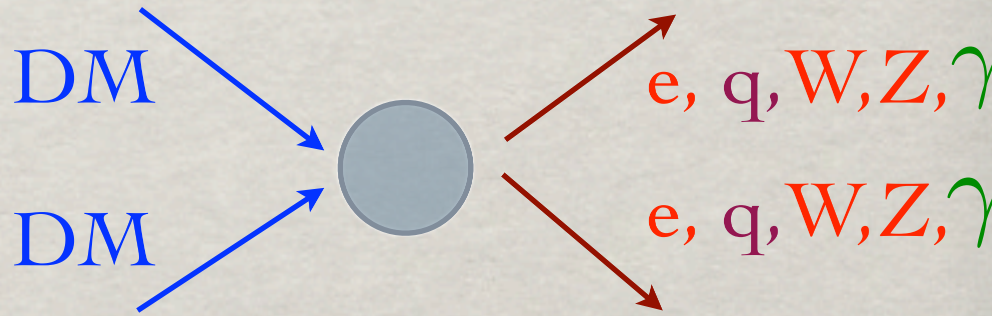


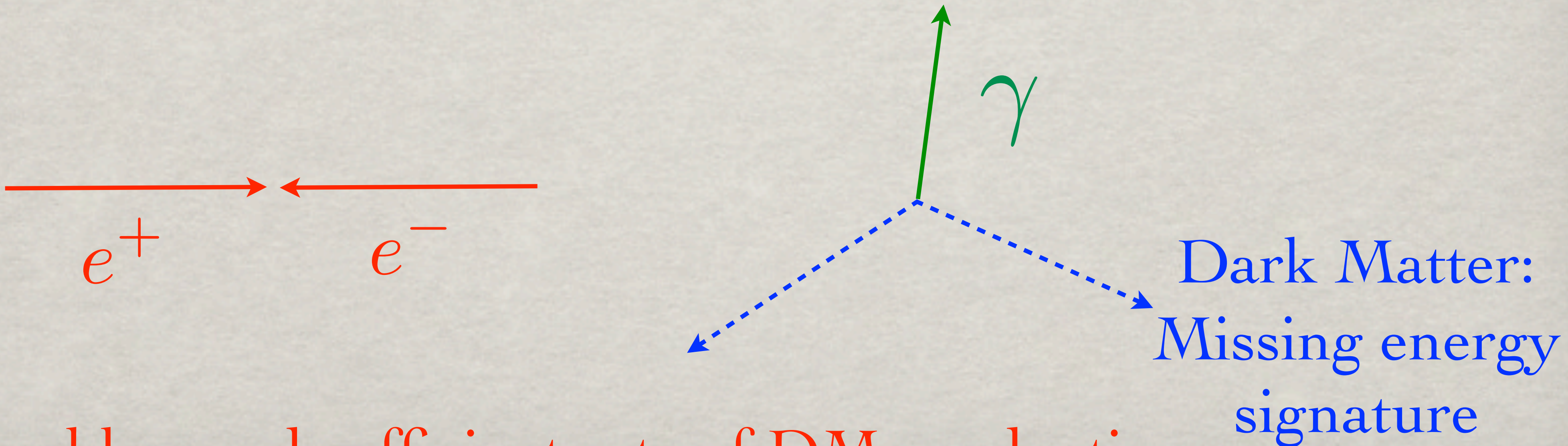
Indirect Detection:



3 different ways to check this hypothesis !!!

Missing energy signature

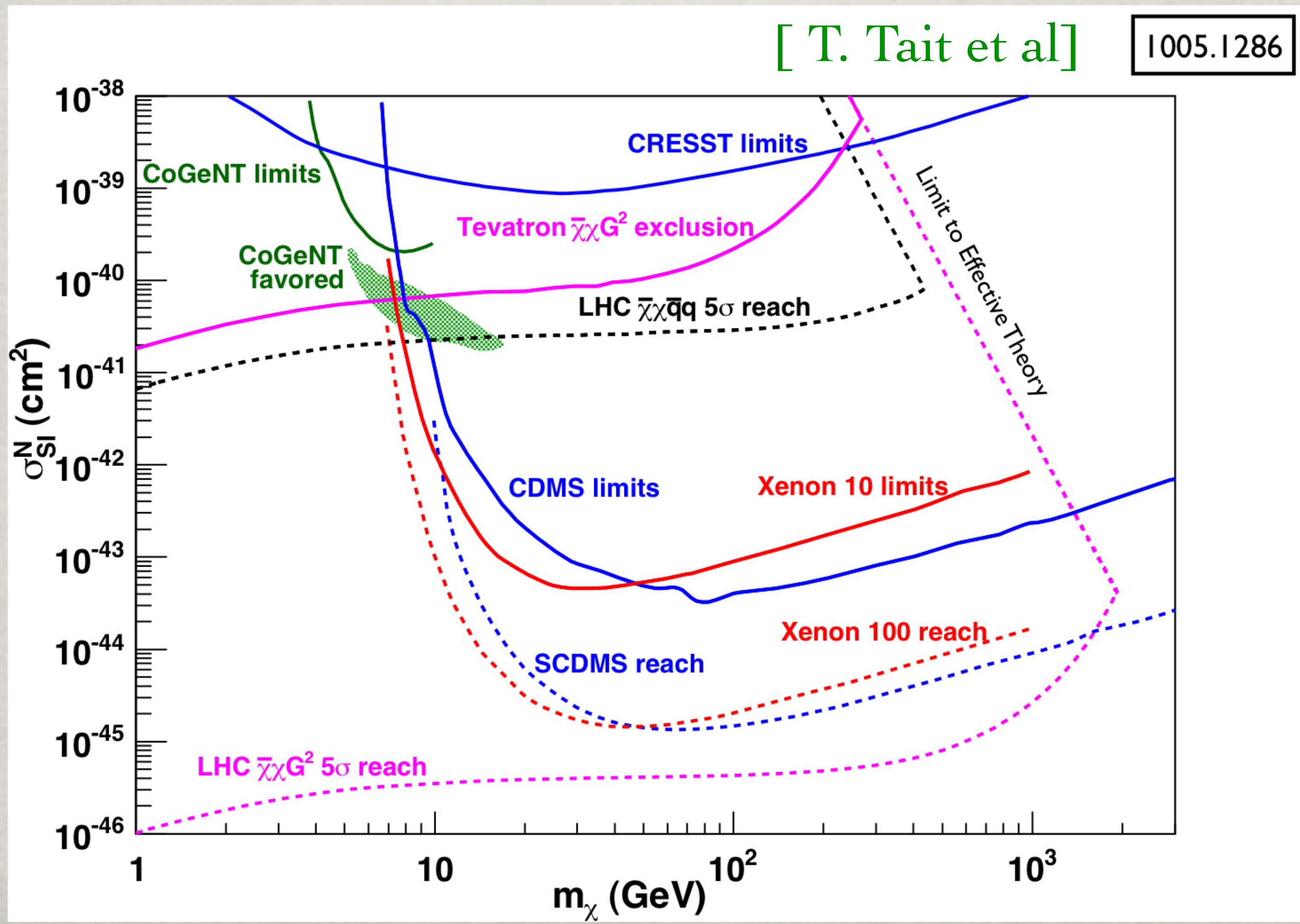
- The direct production of two DM particles in a collider gives unfortunately no signal ! The energy just disappears without trace...
- How is it possible to tag such events: Thanks to Initial State Radiation ! i.e. either a single photon or a gluon emitted by the initial partons, recoiling against the DM particle(s)



Trouble: need sufficient rate of DM production...

COLLIDER BOUNDS

From a model-independent analysis considering dimension 6 effective operators, from the Tevatron stringent limits appear:



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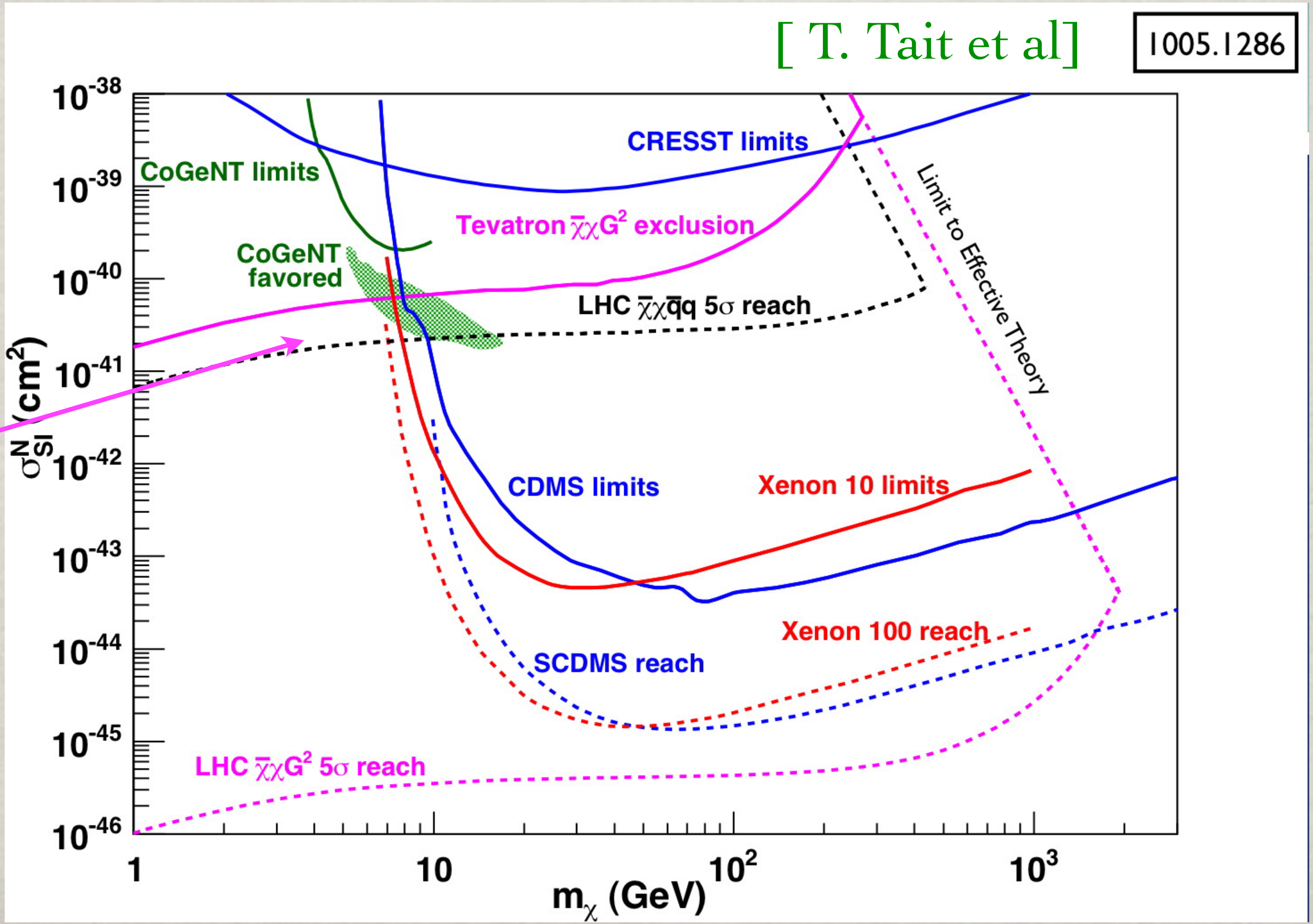
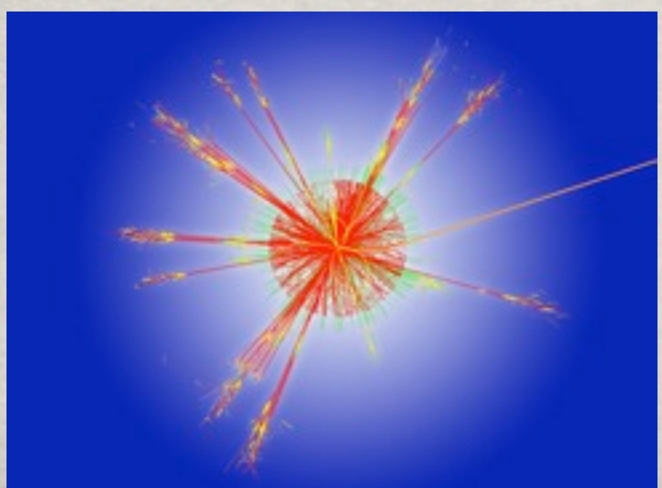
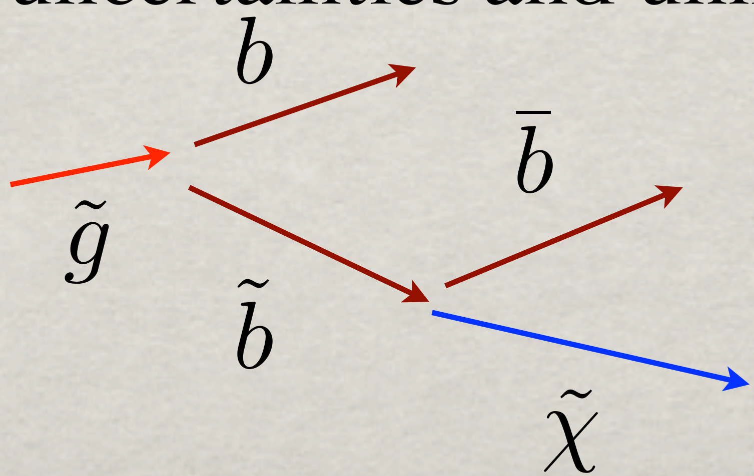


Stronger bound at low mass !

Missing energy signature

- In some cases the DM is produced in cascade decays
- The missing energy can be measured only in the transverse plane and ALL the other particles have to be precisely reconstructed.
- Of course when neutrinos are produced, they give rise to a missing energy background...
- But also hadronic channels without neutrinos suffer from other uncertainties and unknowns.





Dark Matter: Missing energy signature

Outlook

Conclusions & Outlook

- Dark Matter is still an unsolved puzzle: mostly we know what is NOT: no baryon,
  no neutrino, no SM particle, not Hot/Warm...
  It does interact gravitationally, and not via EM/QCD, but anything inbetween is possible.

- If Dark Matter is a WIMP, we should see it at colliders, in direct detection experiments and in indirect detection...   Consistency check !
  DATA are coming in all 3 fields: exciting time !

- But DM may also not be a WIMP...