Astroparticle Physics & Cosmology

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$[q,p]=i\hbar$

Outline Lectures

- Dark Matter, what we know about it...
- The WIMP mechanism/connection
  - SUSY WIMPs: sneutrino, neutralino
- Other (non-WIMP) DM models:
  - Axion DM
  - Asymmetric Dark Matter
- Baryogenesis: - EW baryogenesis
  - Leptogenesis
- 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 Bullet 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:

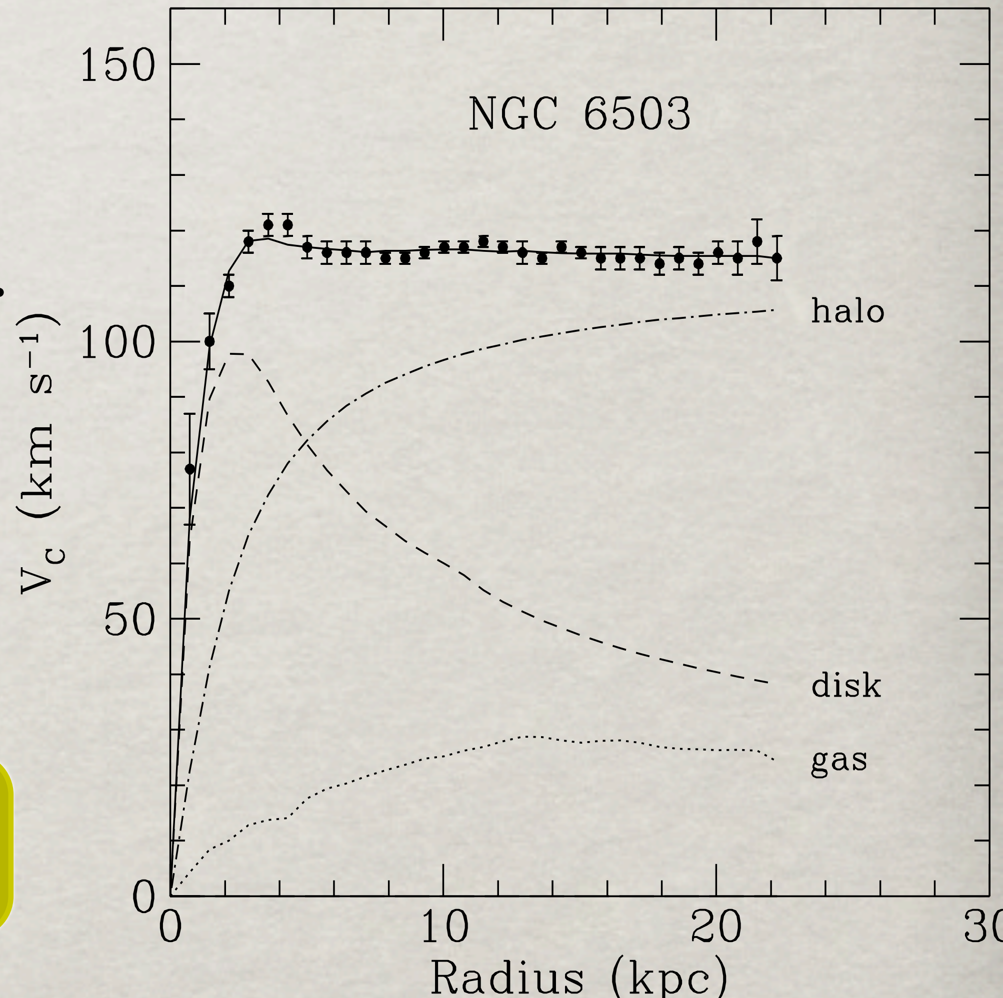
[V. Rubin '70, ...]

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

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

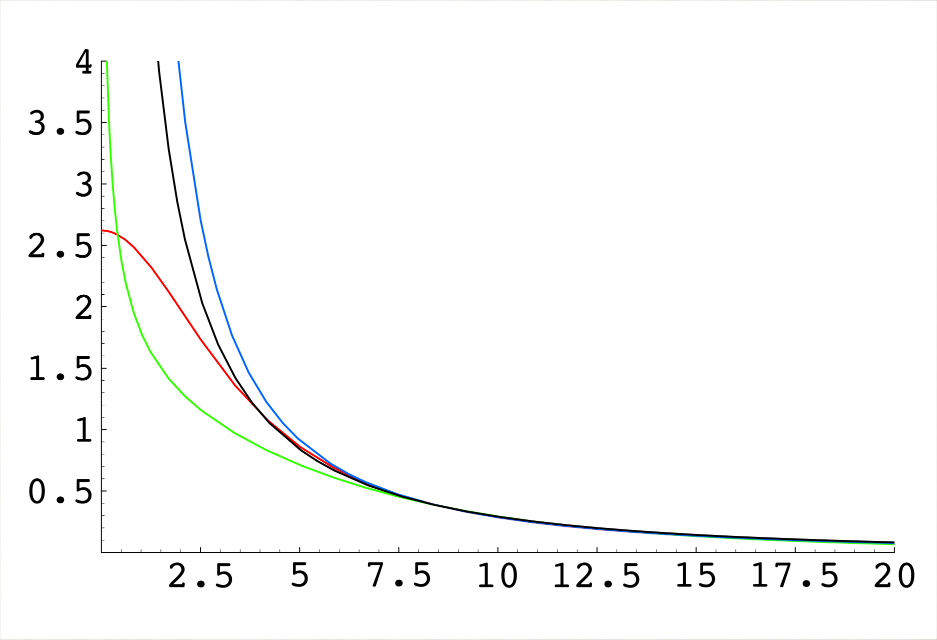


Unfortunately the density in the internal region of the galaxies is much more uncertain...

DARK MATTER EVIDENCE

GALACTIC SCALES:

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



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

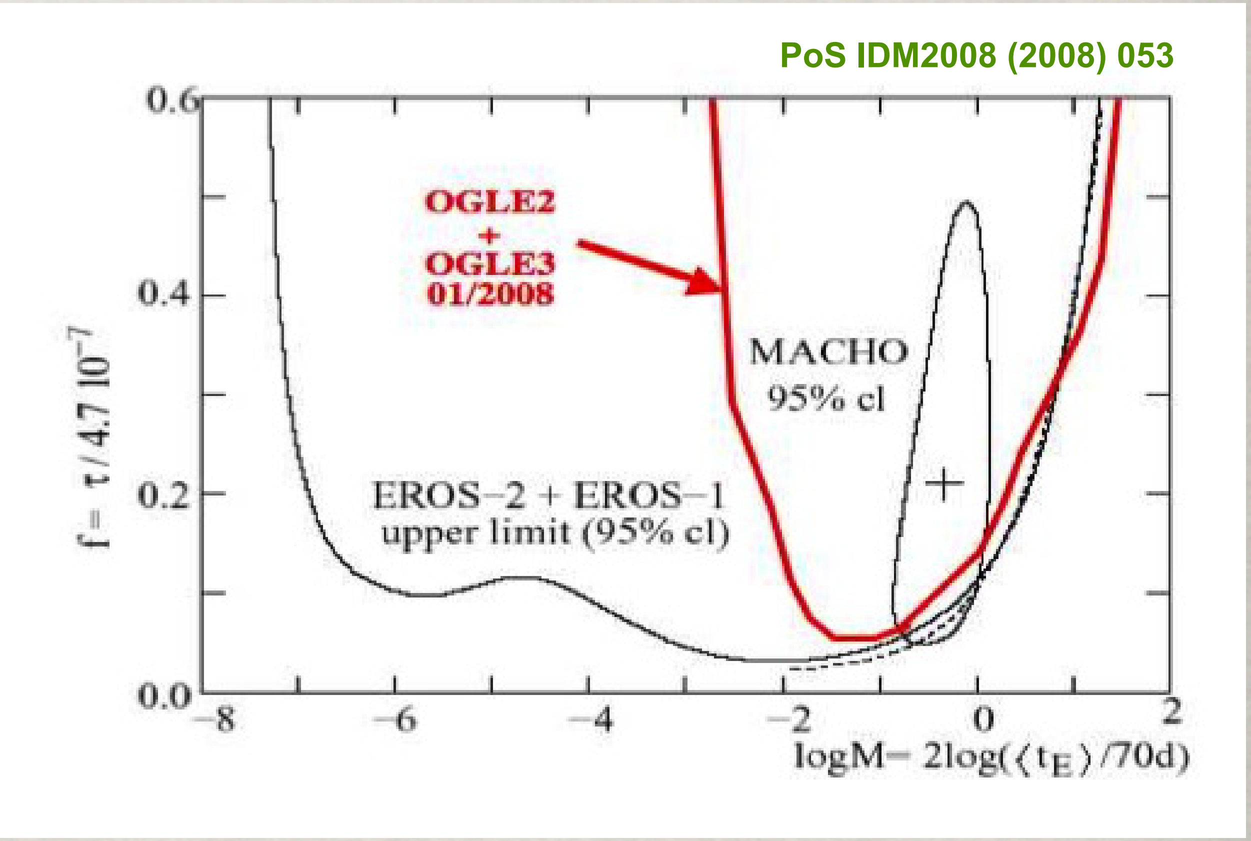
Critical for indirect detection !

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, a.k.a. MAssive Compact Halo ObjectS ?
No evidence from the EROS collaboration between 10^{-7} and 20 solar masses.

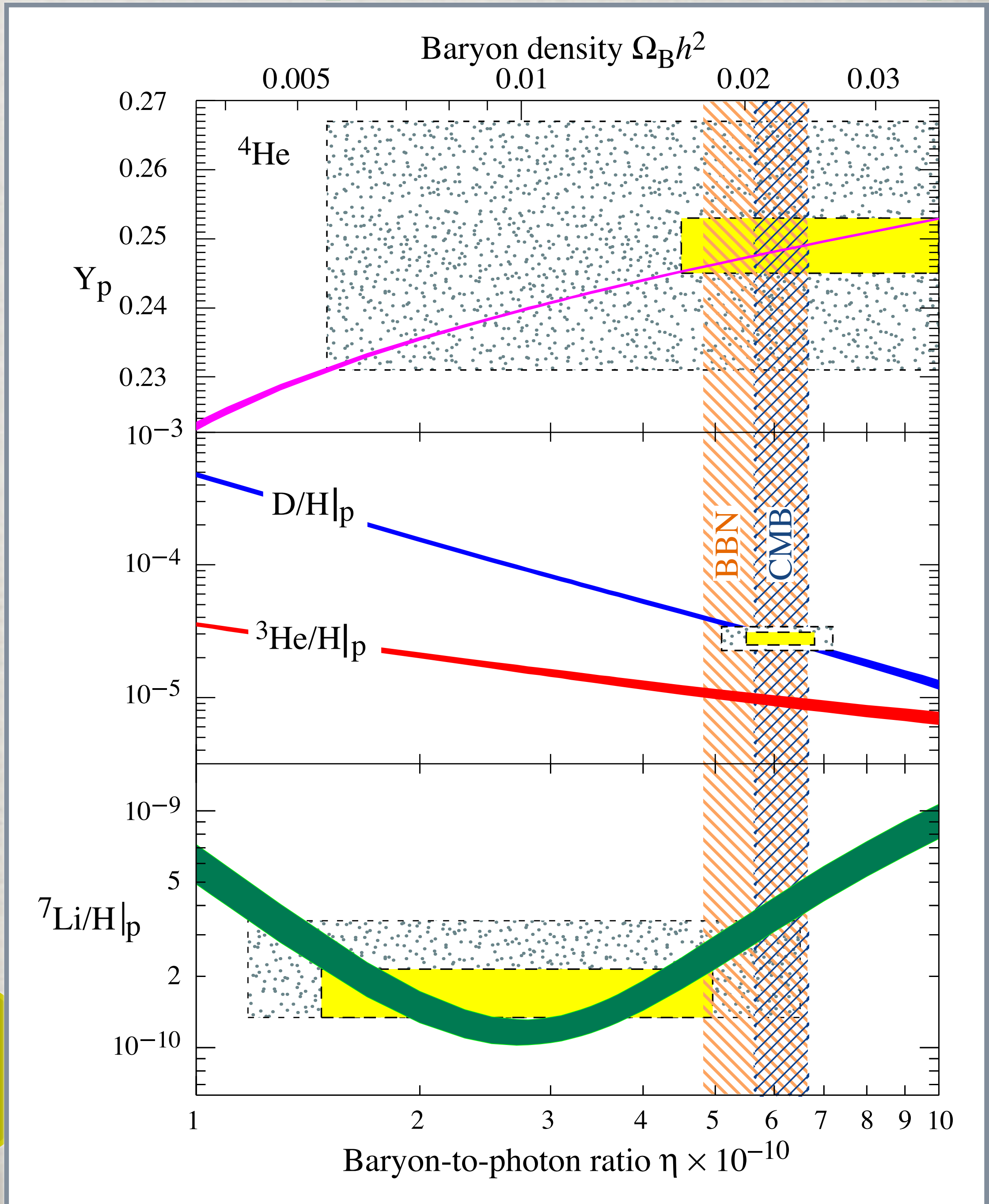


Still clumps of (non baryonic) Dark Matter, which are much less concentrated, may be there...

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

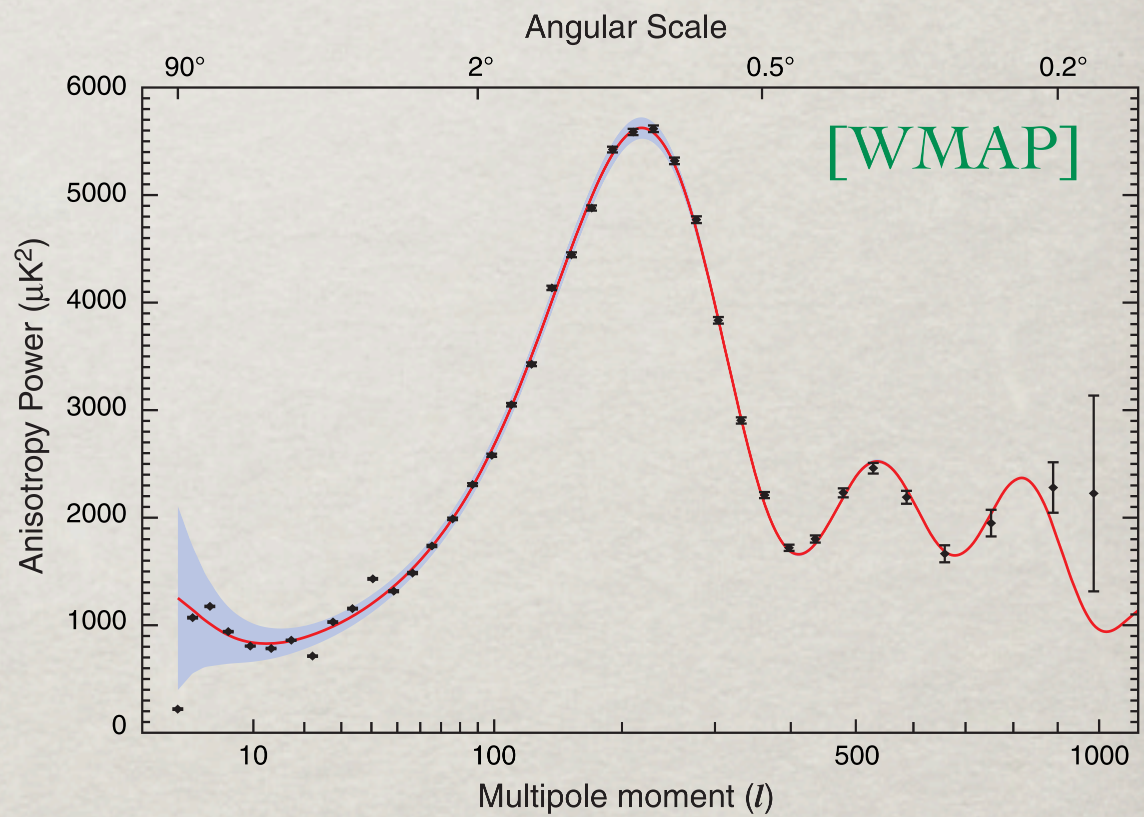


$$\Omega_B h^2 = 0.02 < \Omega_{DM} h^2$$

DARK MATTER EVIDENCE

HORIZON SCALES:

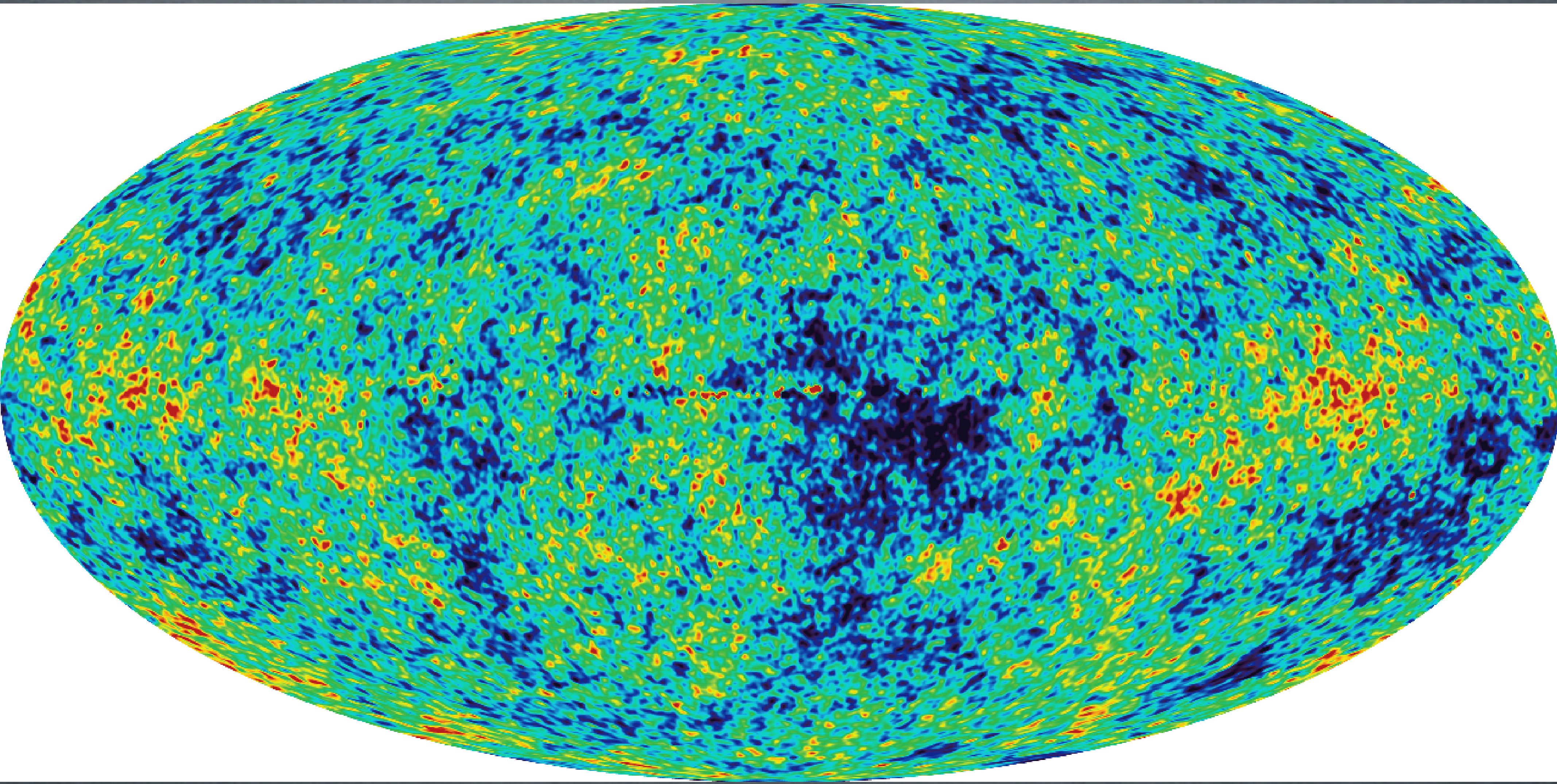
From the position and height of the CMB anisotropy acoustic oscillations peaks we can determine very precisely the curvature of the Universe and other background parameters.



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

DARK MATTER →

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

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

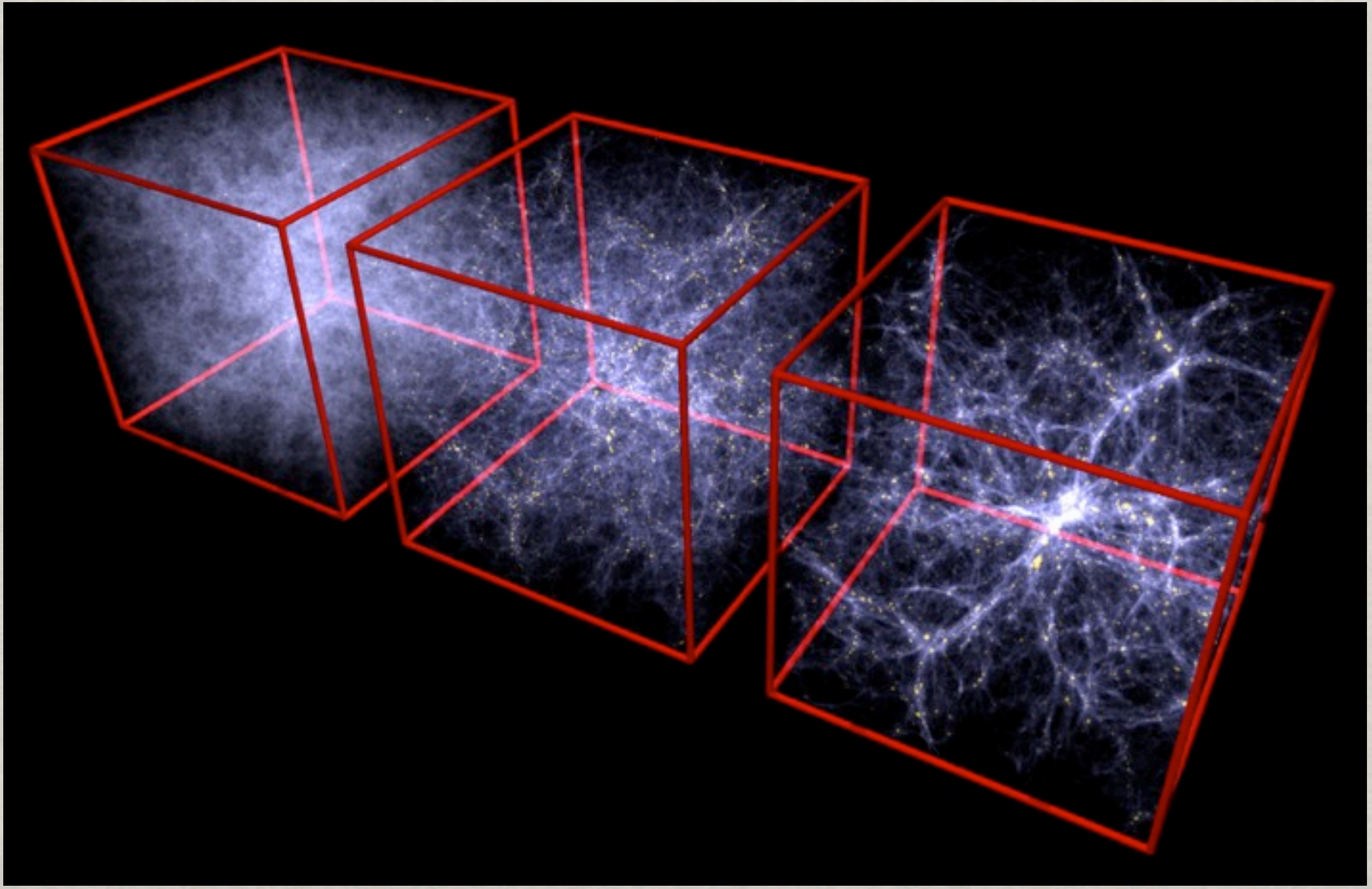
NOTE: much weaker than exponential due to the expansion friction term $\propto H$! Also if the expansion is dominated by radiation, the growth is inhibited and at most only logarithmic in time. We need a long time of matter dominance to make initial fluctuations become large...

Non Linear regime

Structure Formation

V. Springel @MPA Munich

Yoshida et al 03



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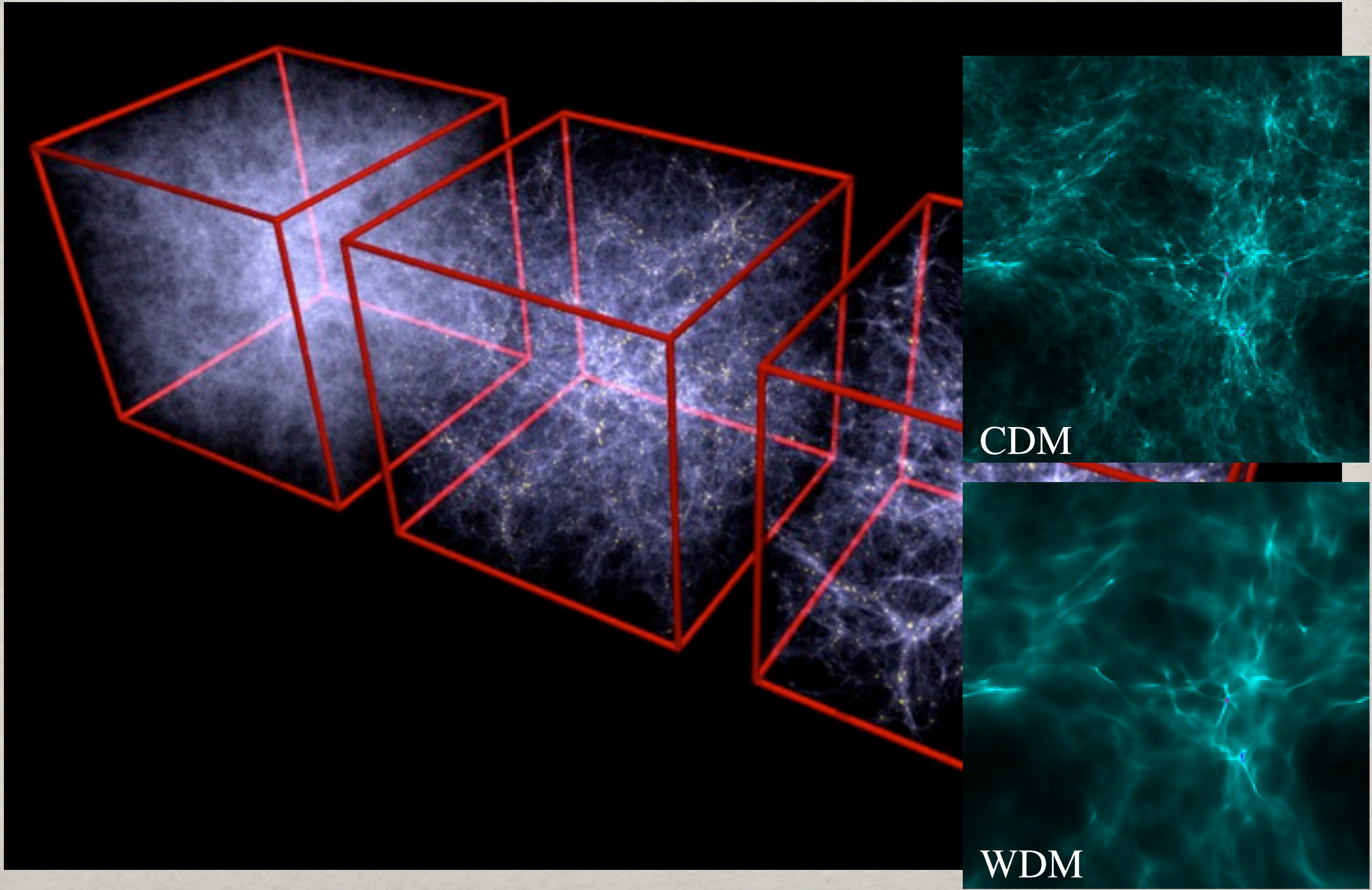
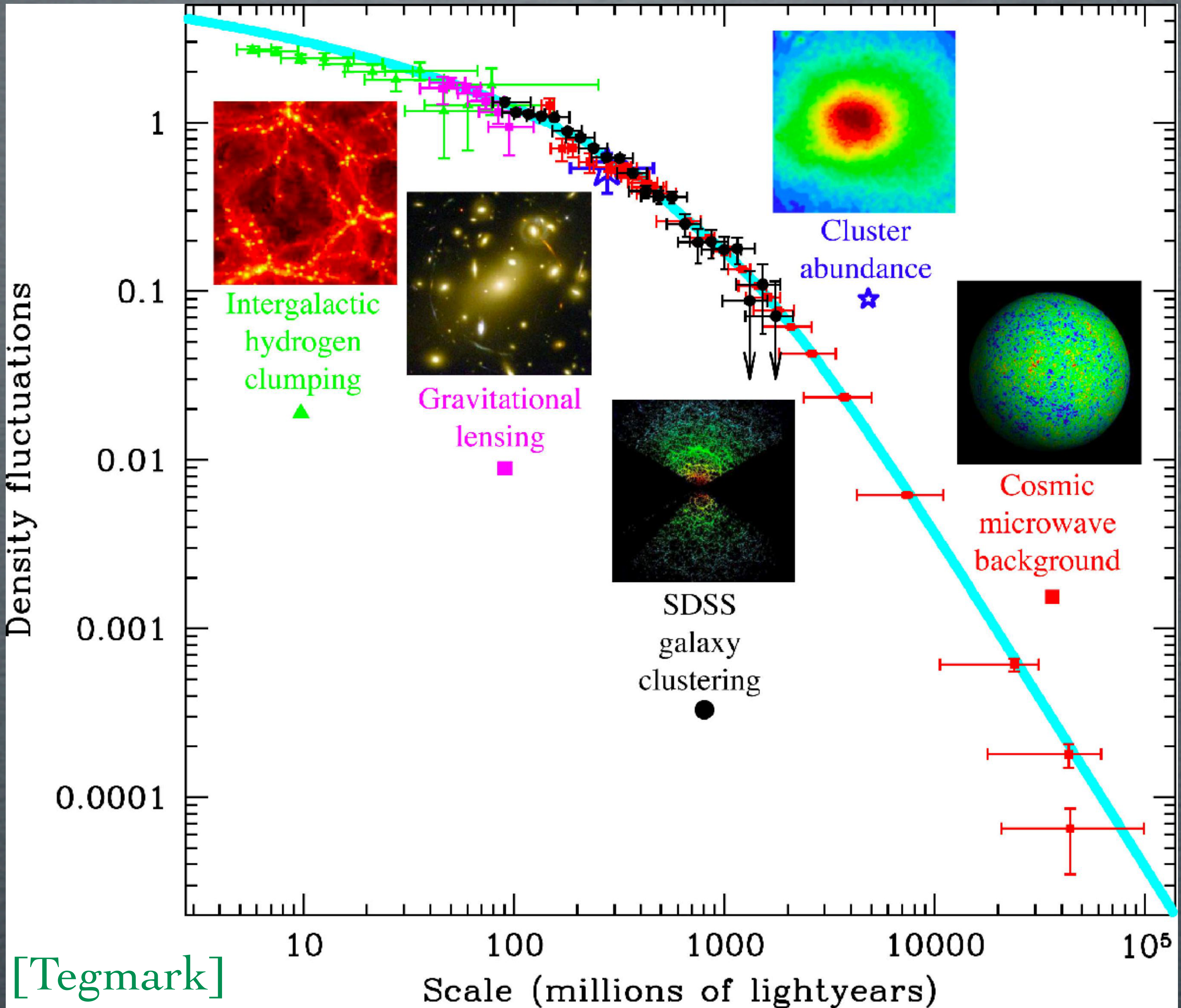


MEASURE FLUCTUATION ON ALL SCALES



[Tegmark]

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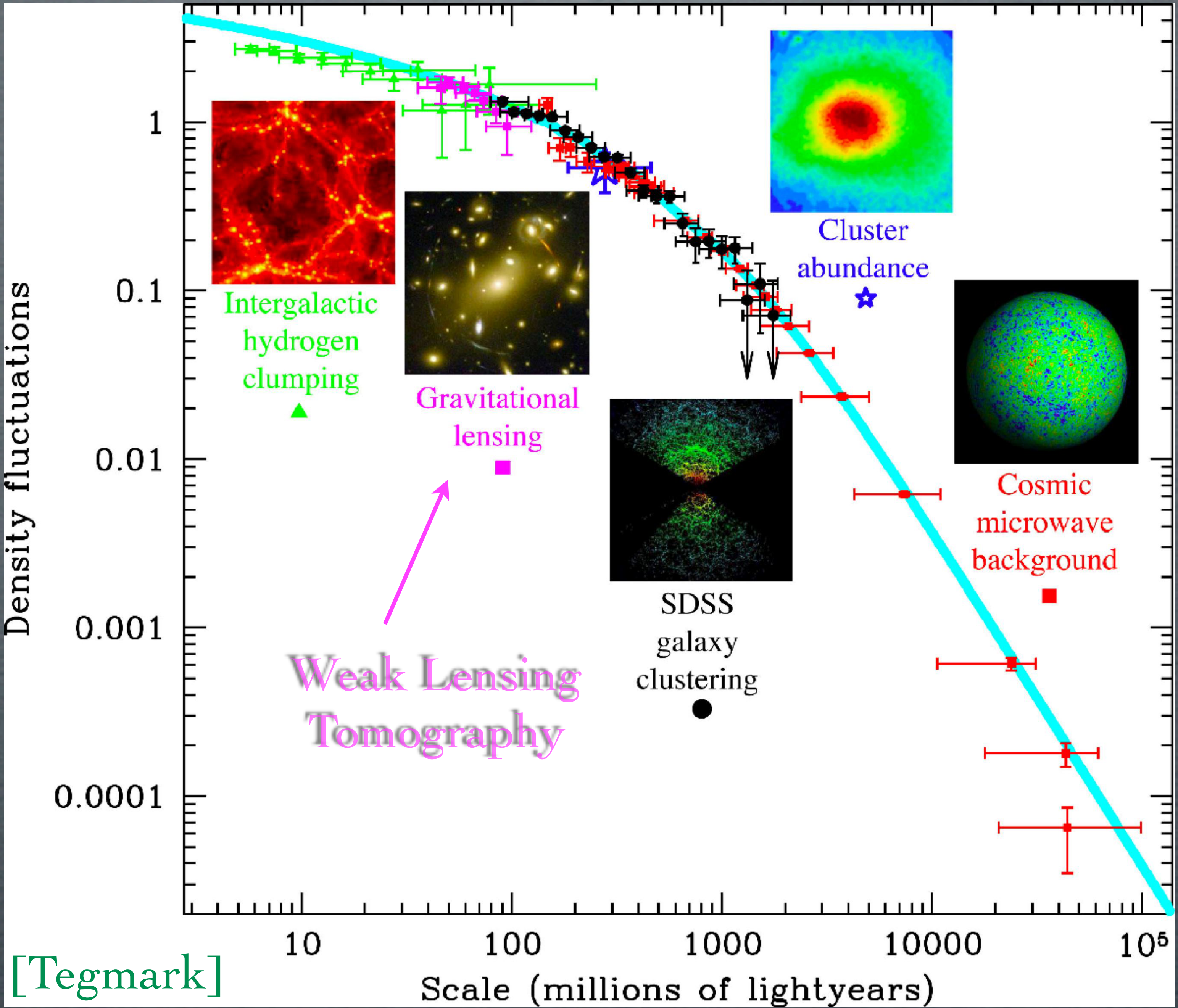
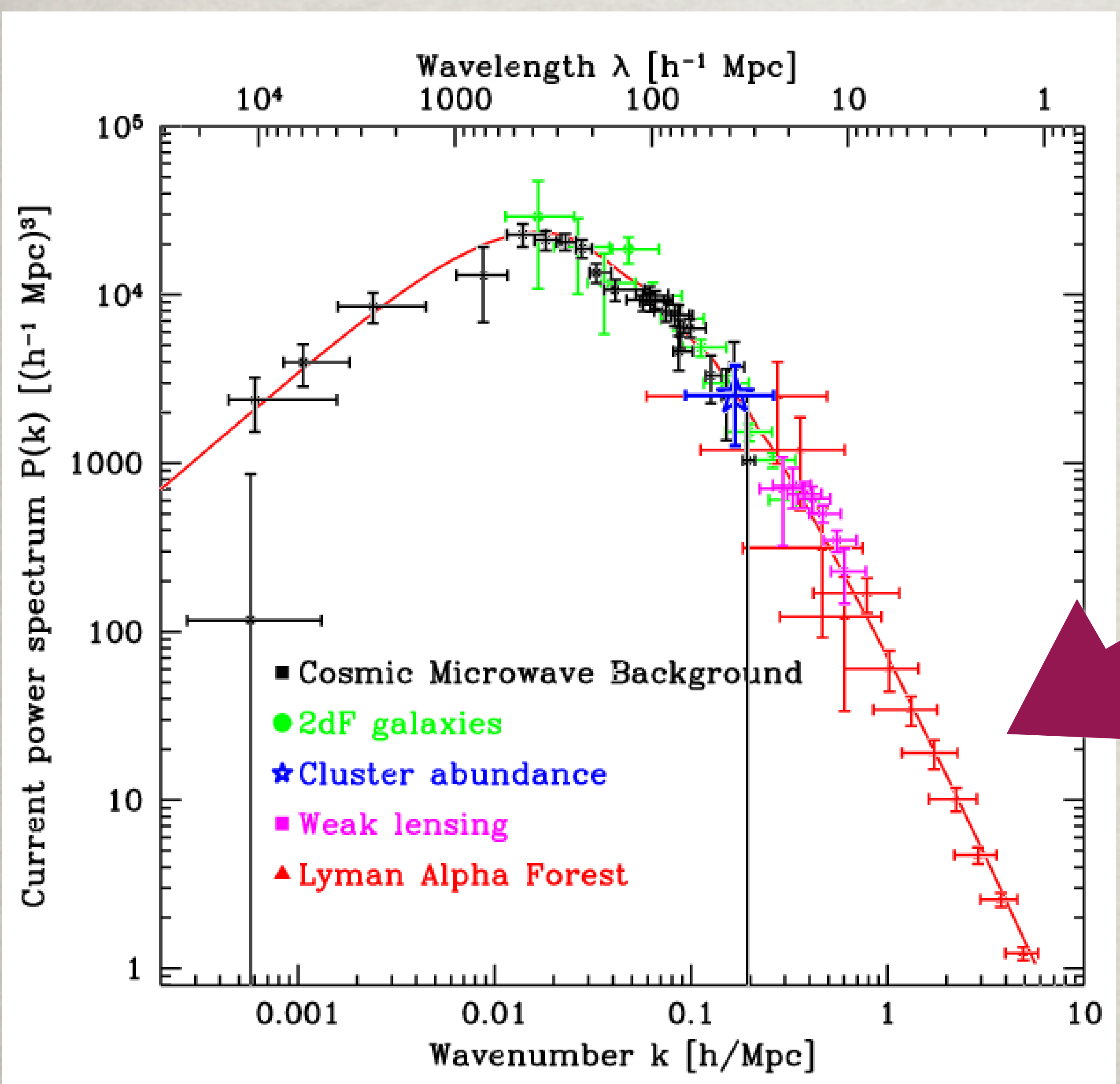


WDM & the Power spectrum



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

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

Compare with the data:

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

[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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Standard Model			
Matter			Forces
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$\boxed{\nu_e}$	$\boxed{\nu_\mu}$	$\boxed{\nu_\tau}$	$\cancel{W^\pm, Z}$
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charged/unstable

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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

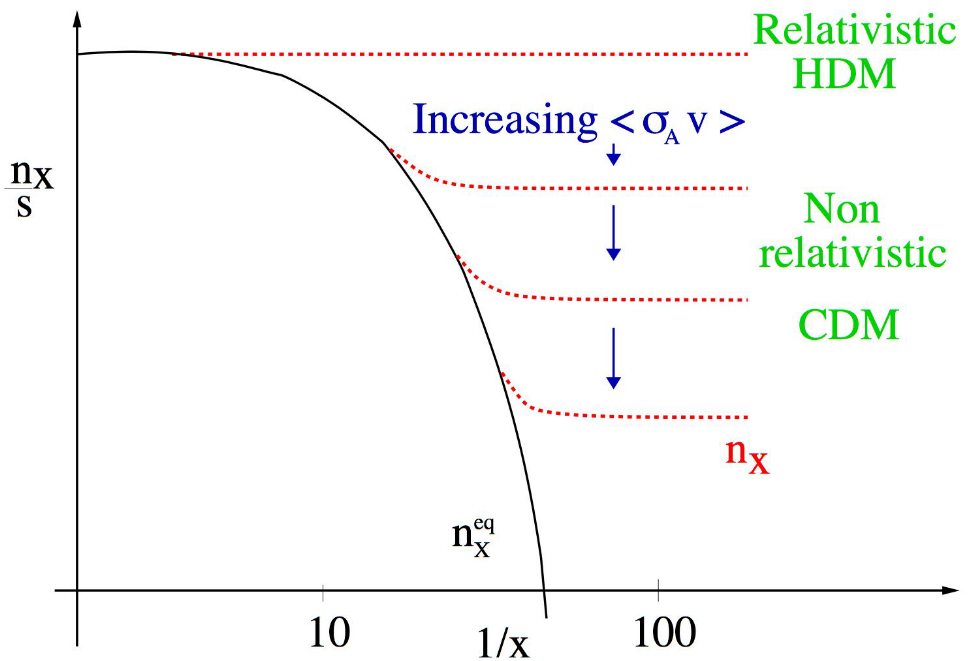
$$\Omega_X = m_X n_X(t_{now}) \quad \propto \quad \frac{1}{\langle\sigma_A v\rangle_{x_f}}$$

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 MECHANISM II

Approximate solution of the Boltzmann equation

Rewrite the equation in terms of $Y = \frac{n}{s}$ and $\frac{d}{dt} = Hx\frac{d}{dx}$ for $x = \frac{m_X}{T}$:

$$\frac{dY_X}{dx} = -\frac{s\langle\sigma(X+X \to \text{anything})v\rangle}{xH}\left(Y_X^2 - Y_{eq}^2\right)$$

Until x_f we have $Y_X = Y_{eq}$, after that we can neglect Y_{eq} that decreases exponentially and then

$$\frac{dY_X}{Y_X^2} = -\frac{s(x)\langle\sigma(X+X \to \text{anything})v\rangle(x)}{xH(x)}dx$$

which has the solution

$$Y_X(x) = \frac{Y_X(x_f)}{1 + Y_X(x_f)\frac{s(m_X)}{H(m_X)}\int_{x_f}^{x}\frac{dx}{x^2}\langle\sigma(X+X \to \text{anything})v\rangle(x)}$$

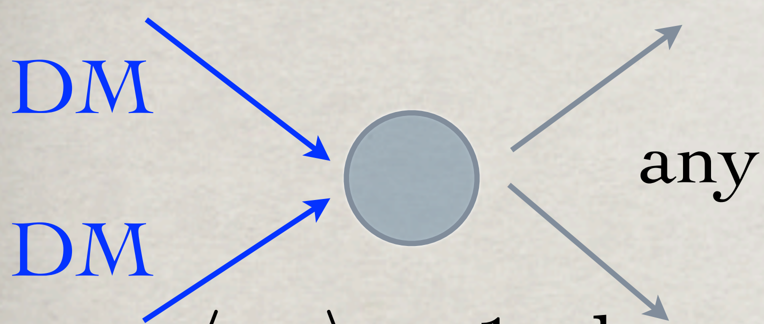
so when σ is sufficiently large after freeze-out

$$Y_X(x) \simeq \frac{1}{\frac{s(m_X)}{H(m_X)}\int_{x_f}^{x}\frac{dx}{x^2}\langle\sigma(X+X \to \text{anything})v\rangle(x)}$$

very weakly dependent on x_f; otherwise $Y_X(x) = Y_X(x_f)$.

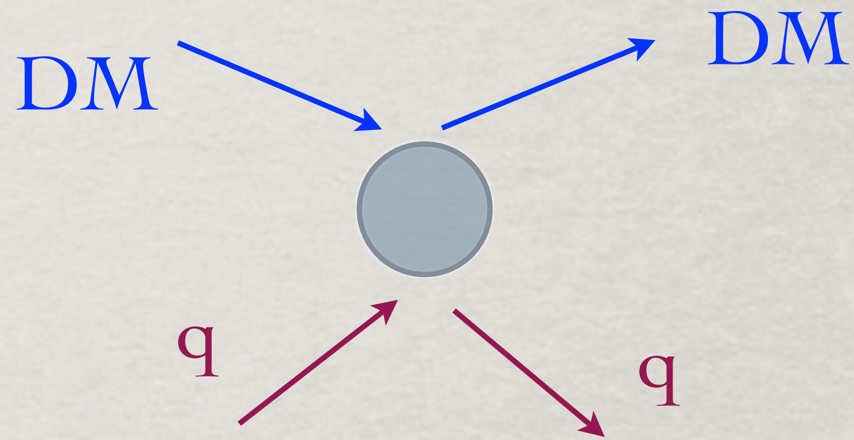
THE WIMP CONNECTION

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

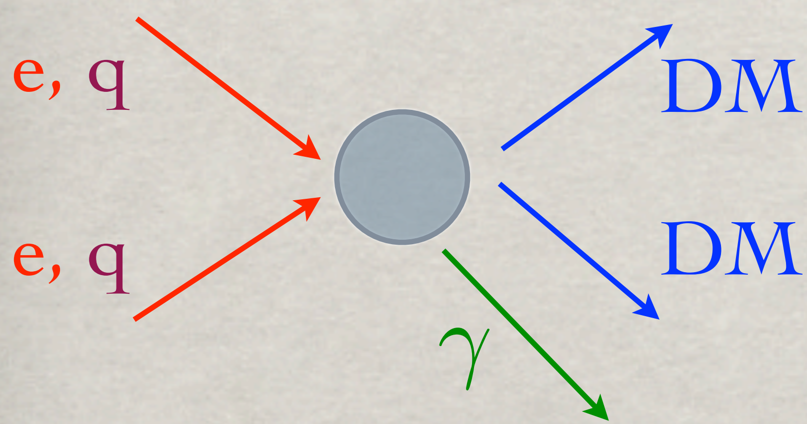


$\langle \sigma v \rangle \sim 1$ pb

Direct Detection:



Colliders: LHC/ILC



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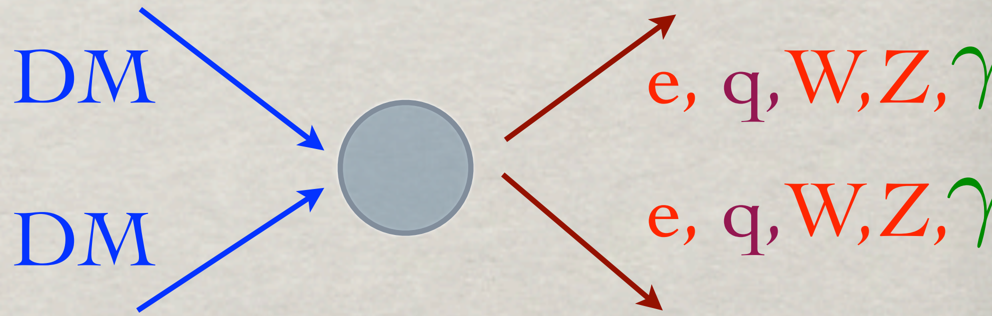

3 different ways to check this hypothesis !!!

THE WIMP CONNECTION

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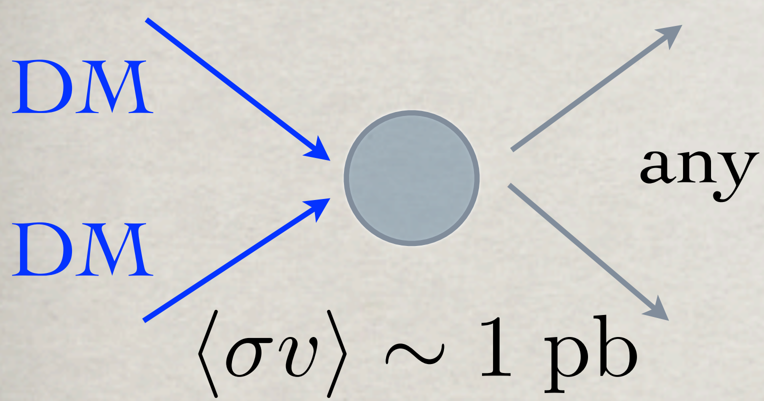

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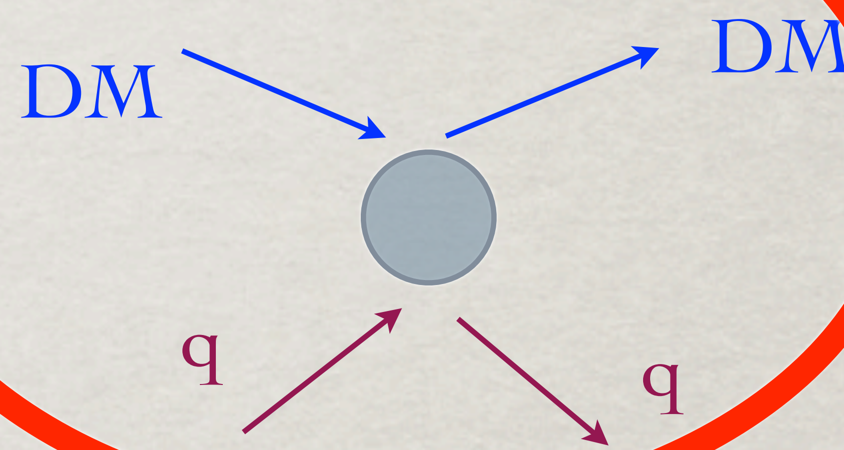

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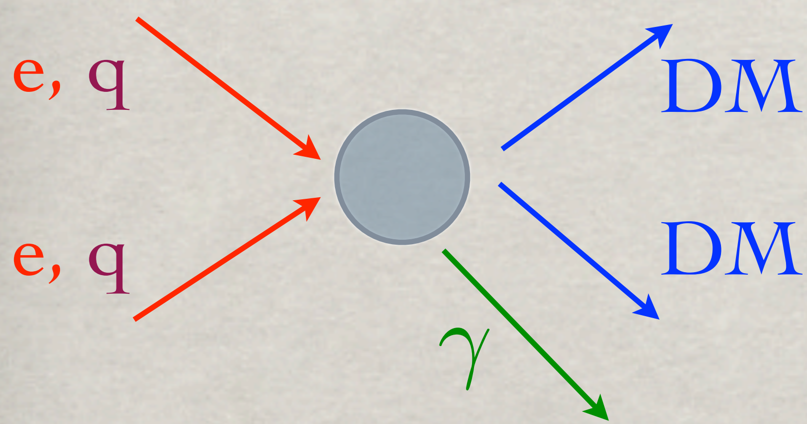

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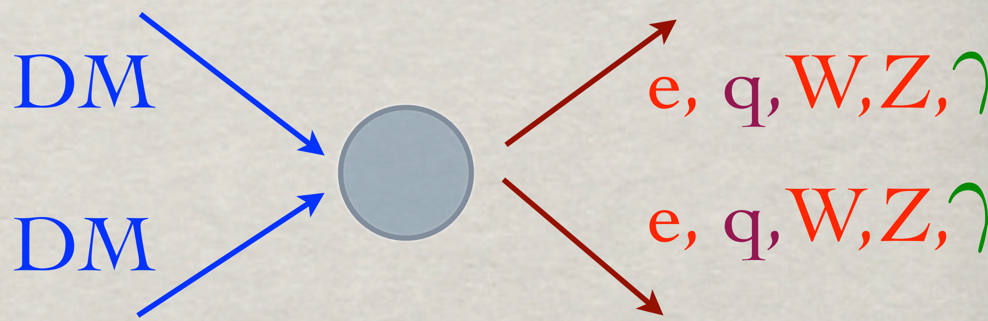
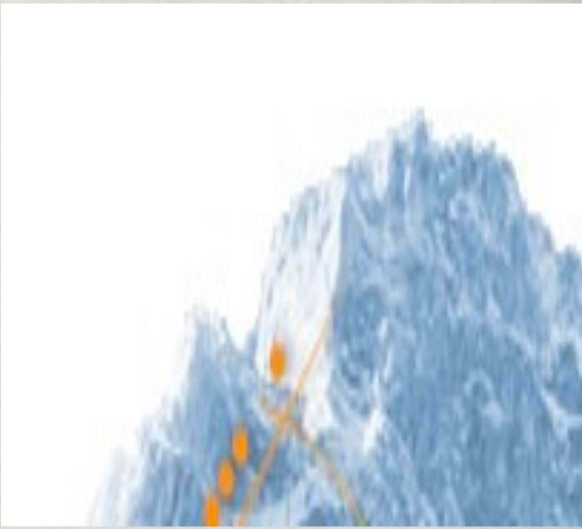
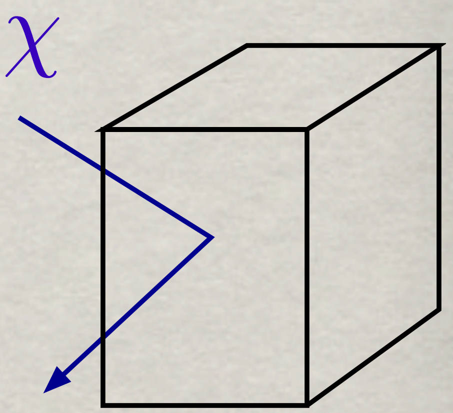


3 different ways to check this hypothesis !!!

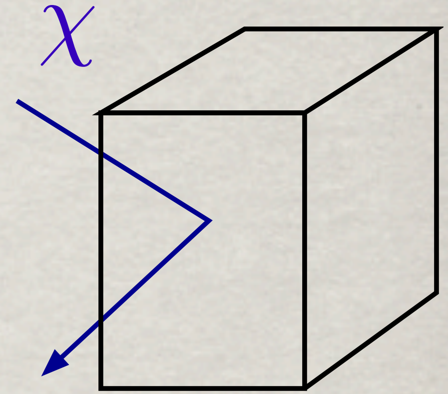
THE HOPE: DETECT DM !



- 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

Rate depends on v in lab frame → annual modulation !

Direct WIMP detection

How large are the cross-sections that we expect from thermal consideration or the exchange of (known) EW particles ?

- Thermal relic cross-section to give $\Omega_{DM} h^2 \sim 0.1$

$$\langle \sigma v \rangle \sim 3 \times 10^{-26} cm^3/s \rightarrow \sigma \sim 10^{-36} cm^2 = 1 \text{ pb}$$

- Exchange of Z boson:

$$\sigma \sim \lambda_{Z\chi}^2 G_F^2 m_p^2 \sim 10^{-38} \lambda_{Z\chi}^2 cm^2 = 10^{-2} \lambda_{Z\chi}^2 \text{ pb}$$

- Exchange of Higgs boson:

$$\sigma_p \sim \lambda_{h\chi}^2 m_p^2 / m_h^4 \sim 10^{-44} \lambda_{h\chi}^2 cm^2 = 10^{-8} \lambda_{h\chi}^2 \text{ pb}$$

BOUNDS ON WIMP DM

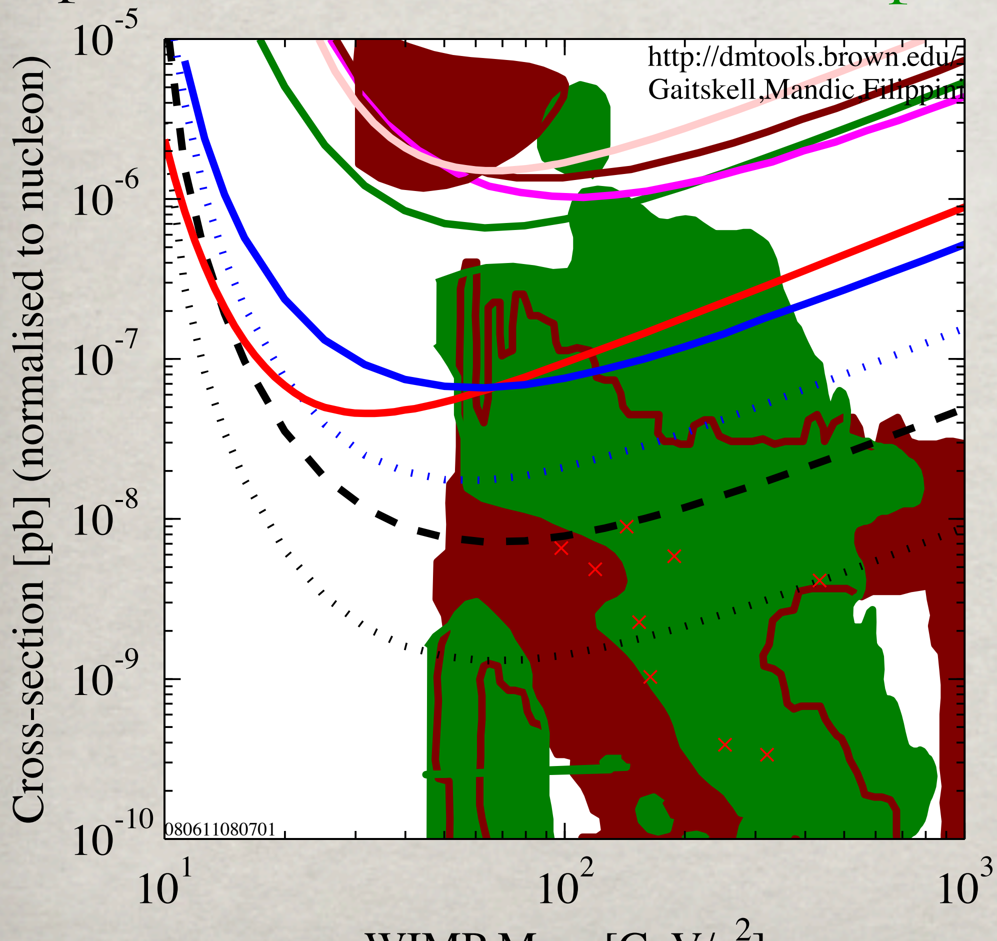
Spin independent:

CDMS (Ge/Si crystal)

XENON-10 (noble gas/liquid)

Super CDMS

WARP, Zeplin II

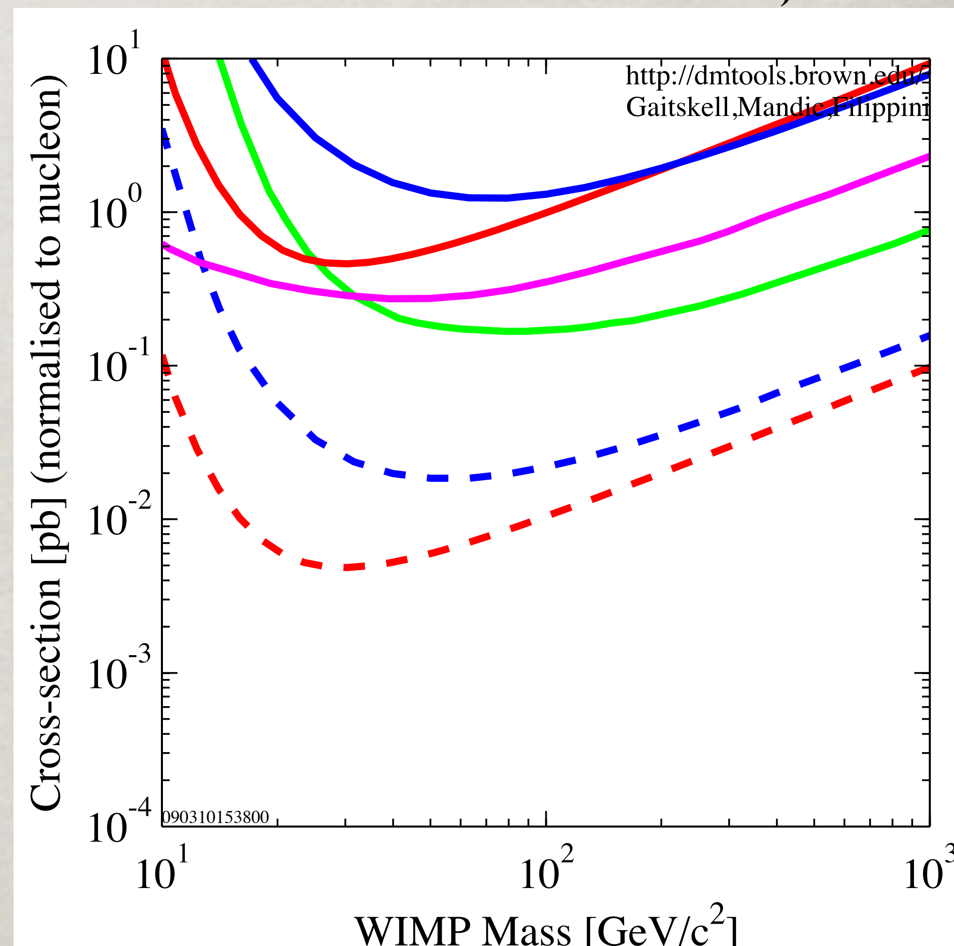


Spin dependent:

proton:

neutron:

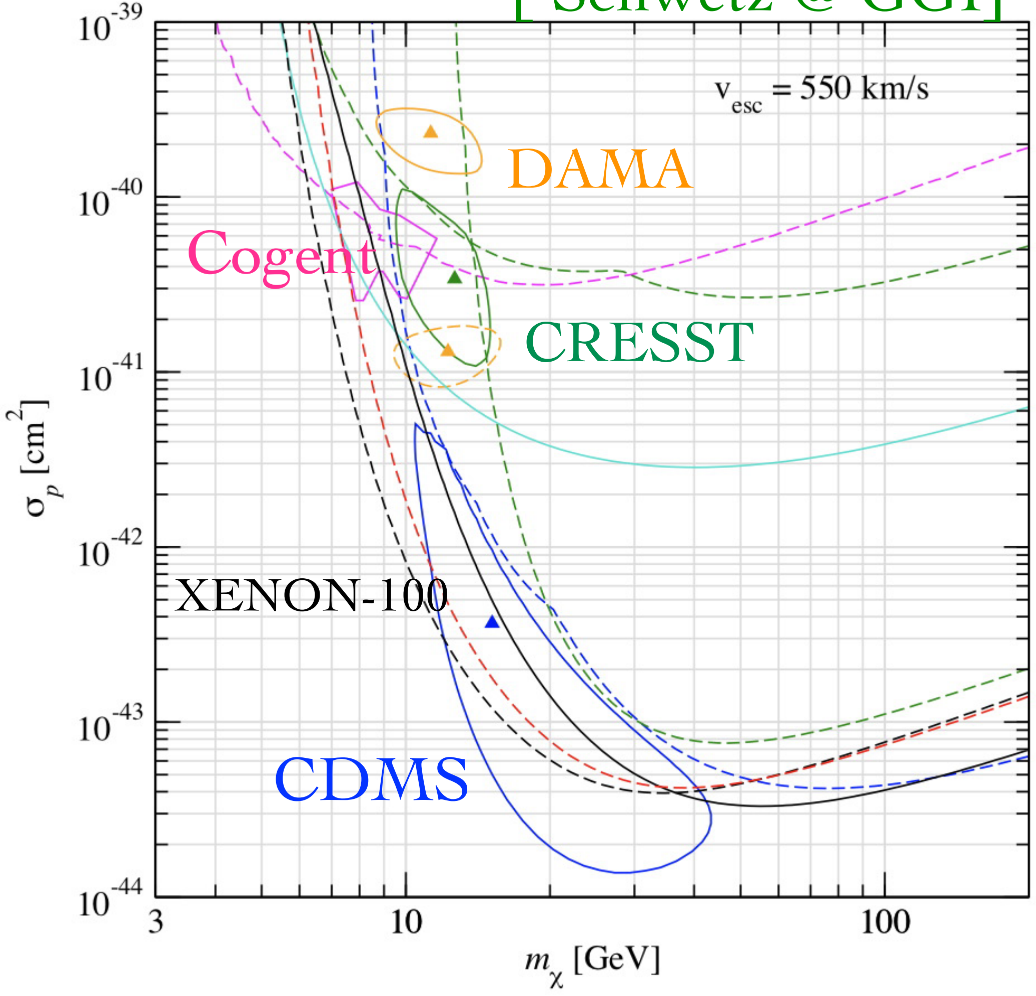
COUPP, KIM



NEWS: SIGNAL(S) OF DM ?

In the last couple of years quite a number of hints appeared in the low mass region... Unfortunately difficult to fit all together and moreover the region is excluded by XENON-100.

[Schwetz @ GGI]



DAMA: annual modulation @ ~9 sigma

Cogent: excess+ann. mod.

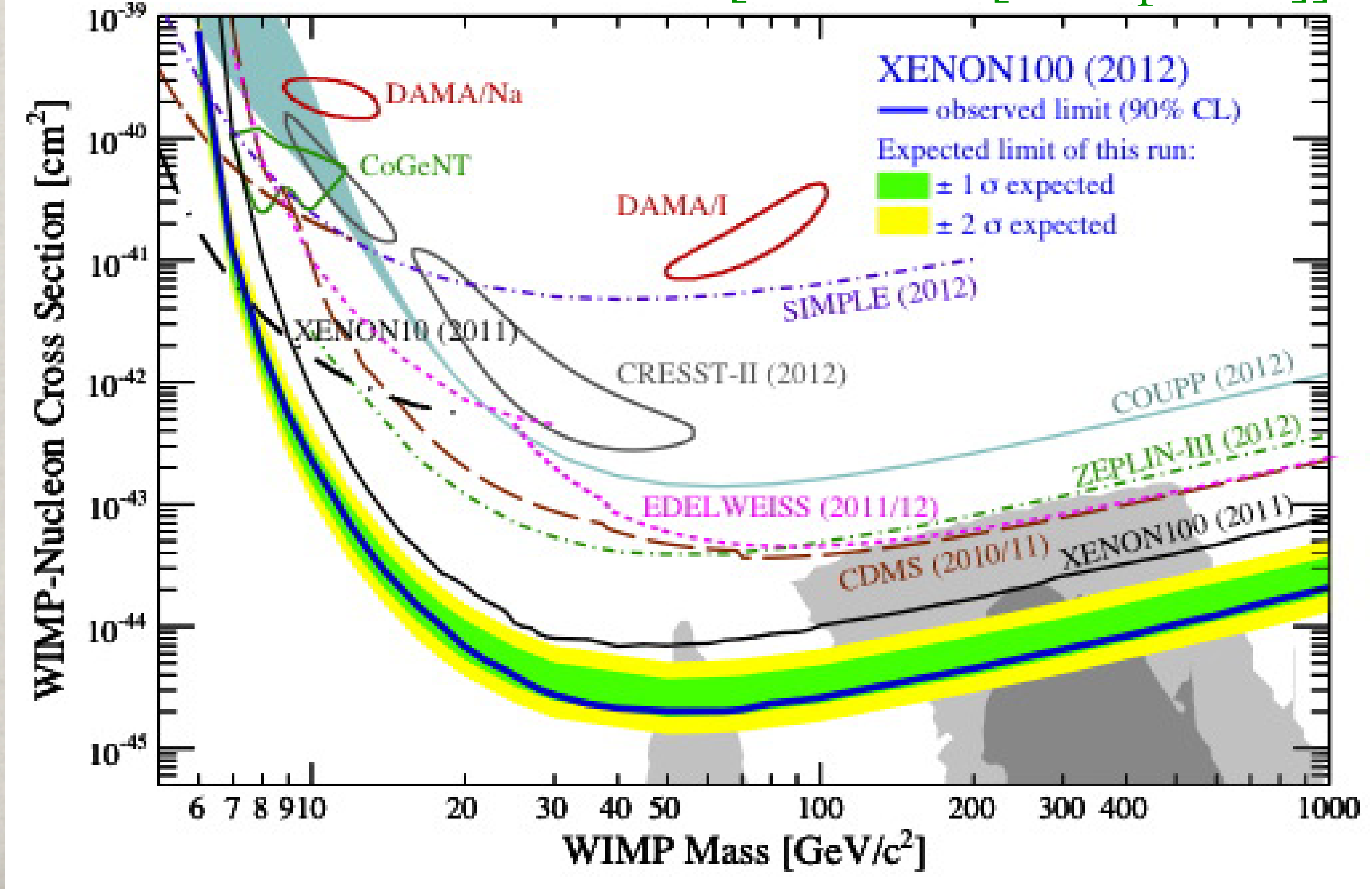
CRESST: 67 events vs 38 bg

CDMS: 2 events vs 0.8 bg
no annual modulation

NEWS: SIGNAL(S) OF DM ?

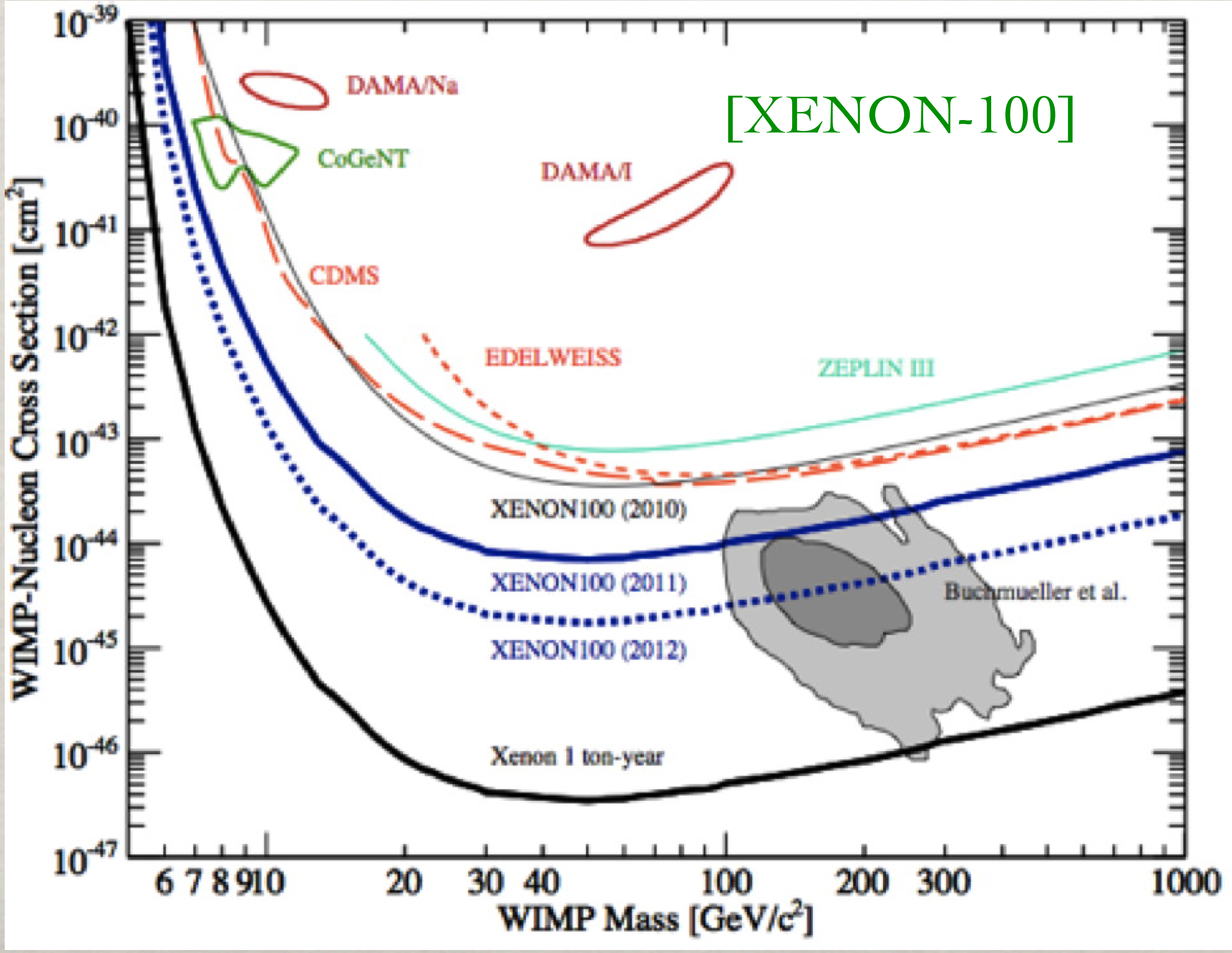
Recent new results by XENON-100 appeared, with two events in the signal region compatible with background, giving the exclusion region below:

[1207.5988[astro-ph.CO]]



Future Prospects

XENON-100 is still running and should get even better statistics in the future and then upgrade to 1 ton...



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

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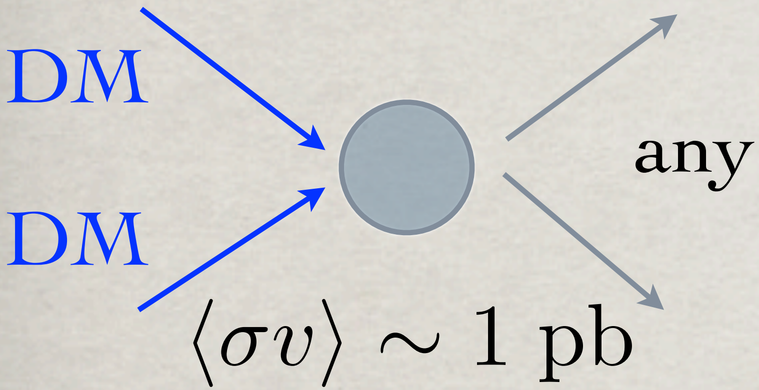

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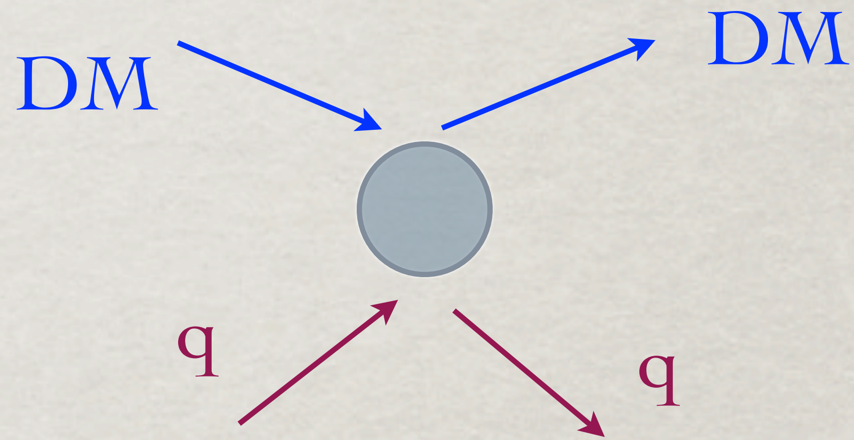
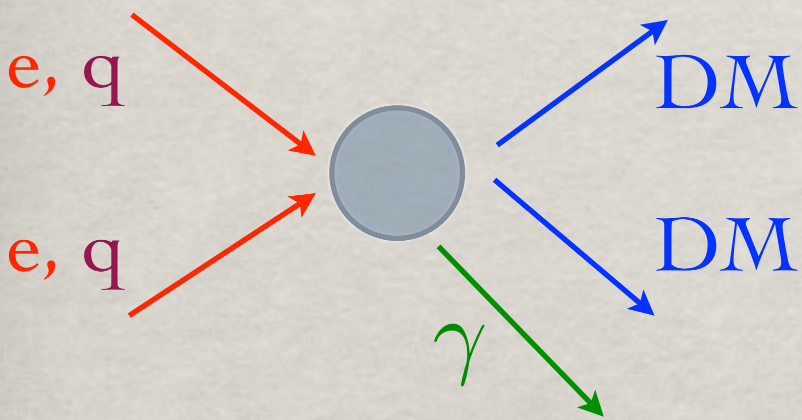
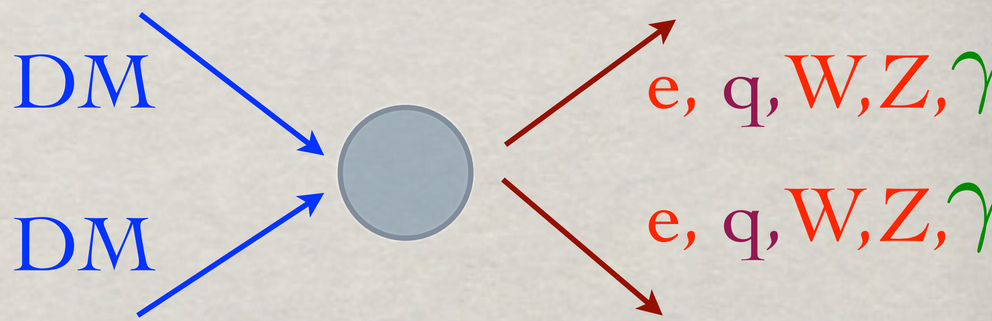


Colliders: LHC/ILC



Indirect Detection:



3 different ways to check this hypothesis !!!

THE WIMP CONNECTION

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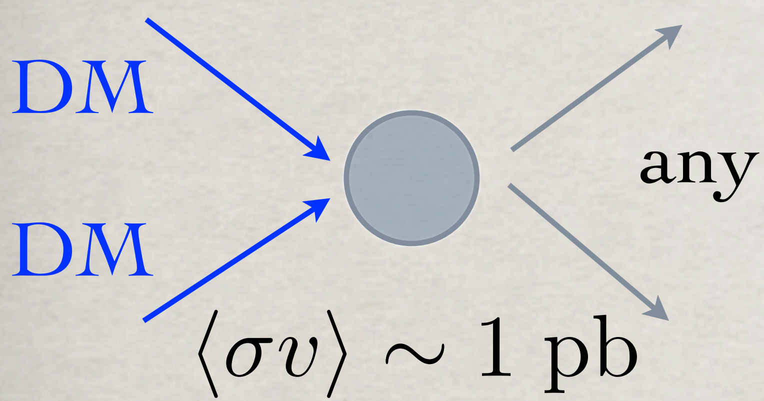

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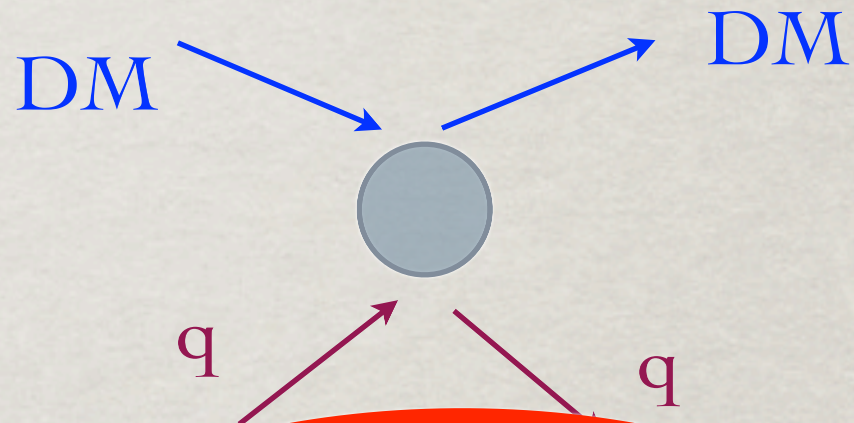

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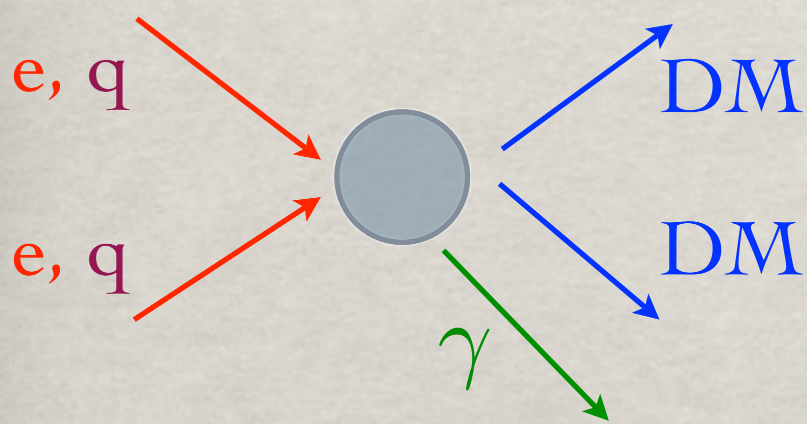

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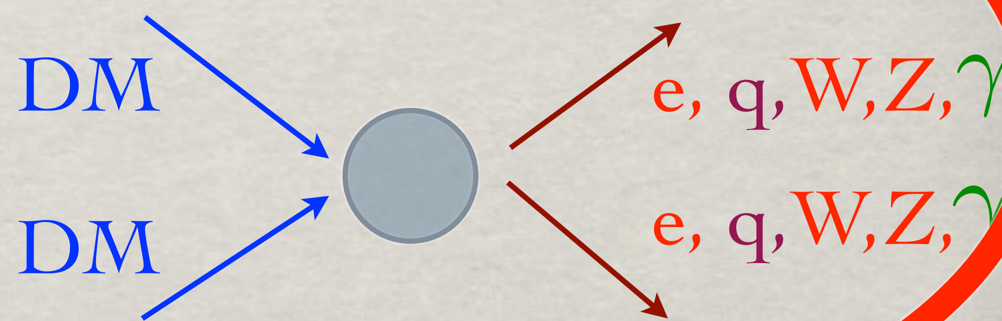
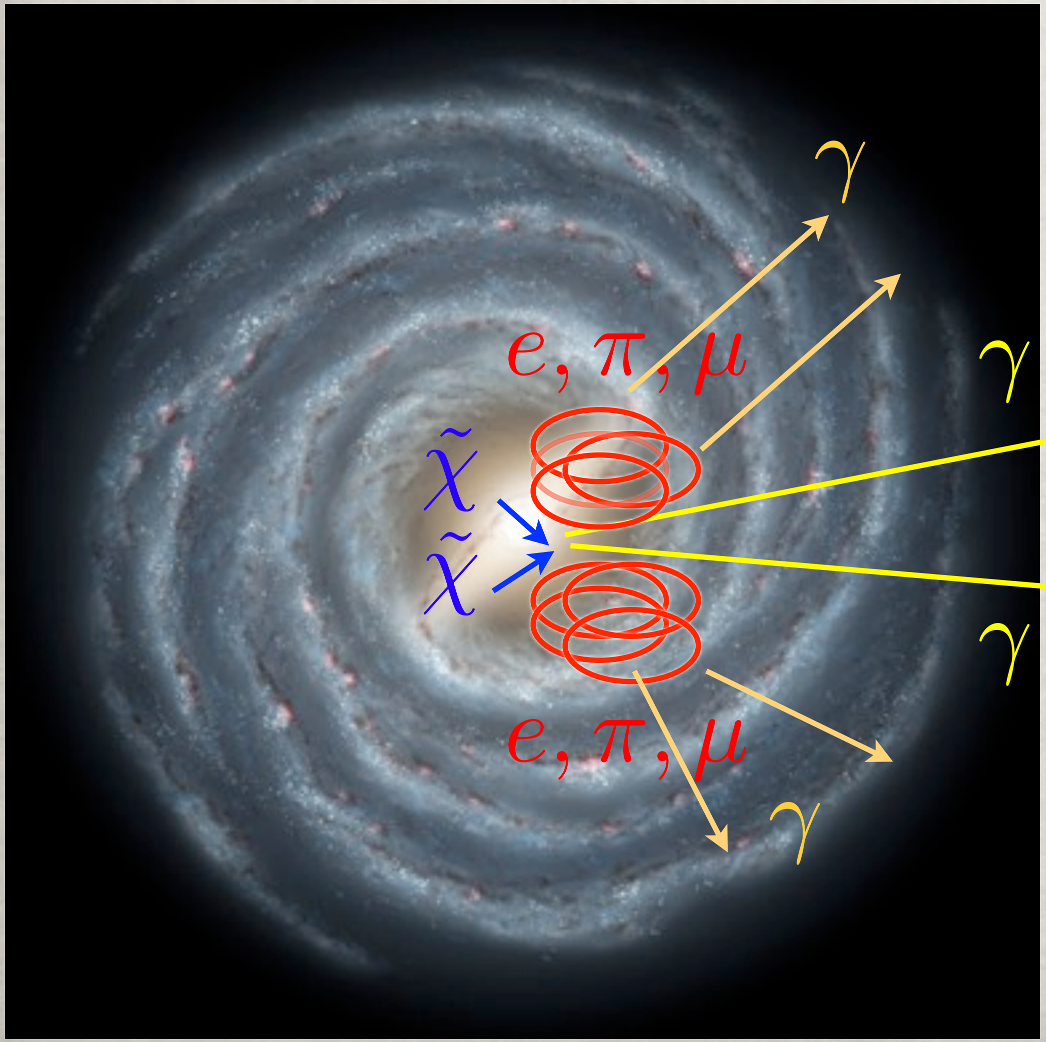


3 different ways to check this hypothesis !!!

THE HOPE: DETECT DM !

- 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

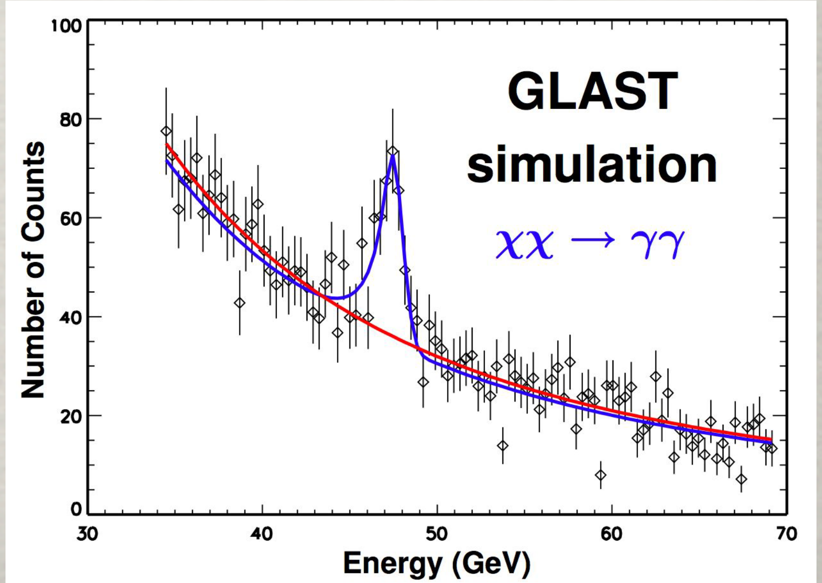
THE HOPE: DETECT DM !

- 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.



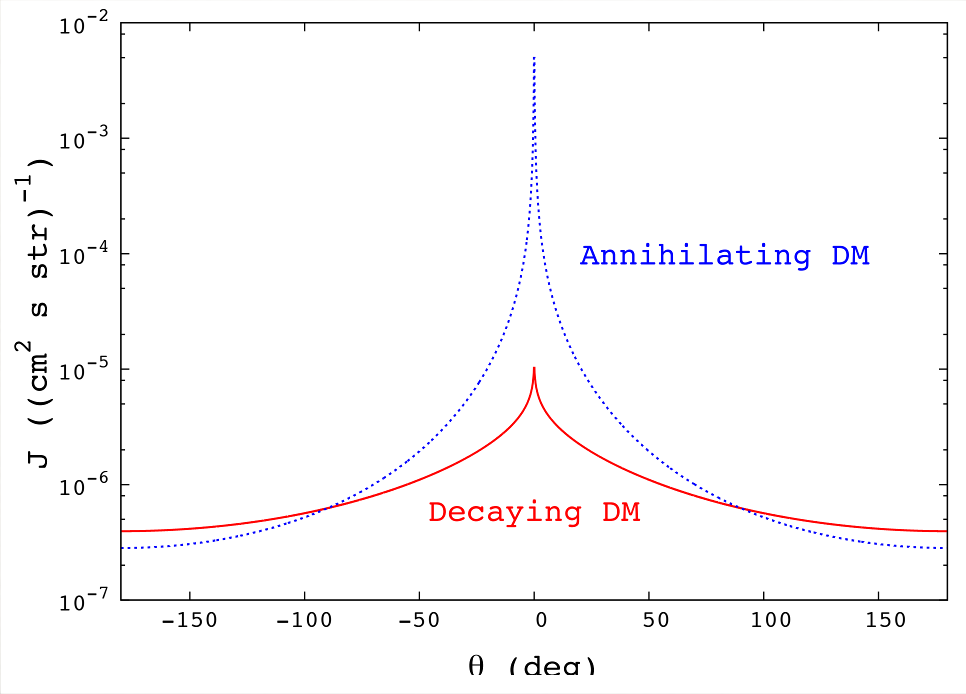
DECAYING DM

- The flux from DM decay in a species i is given by

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

Particle Physics Halo property

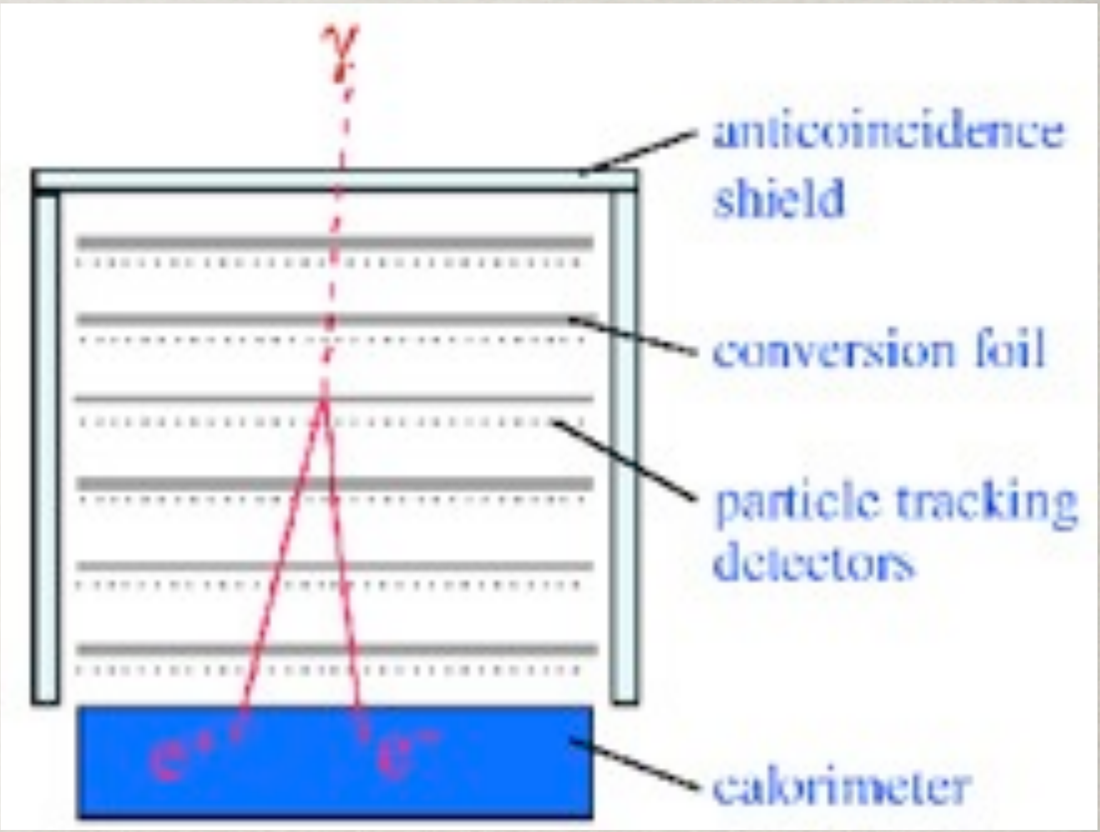
- Very weak dependence on the Halo profile; what matters is the DM lifetime...
- Spectrum in gamma-rays given by the decay channel! Smoking gun: gamma line...
- Galactic/extragalactic signal are comparable...



Satellites for DM: detectors in space !

Gamma-ray Large Area Space Telescope (GLAST) Integrated on the Space Craft at Spectrum Astro Space Systems December 2006

FERMI-LAT



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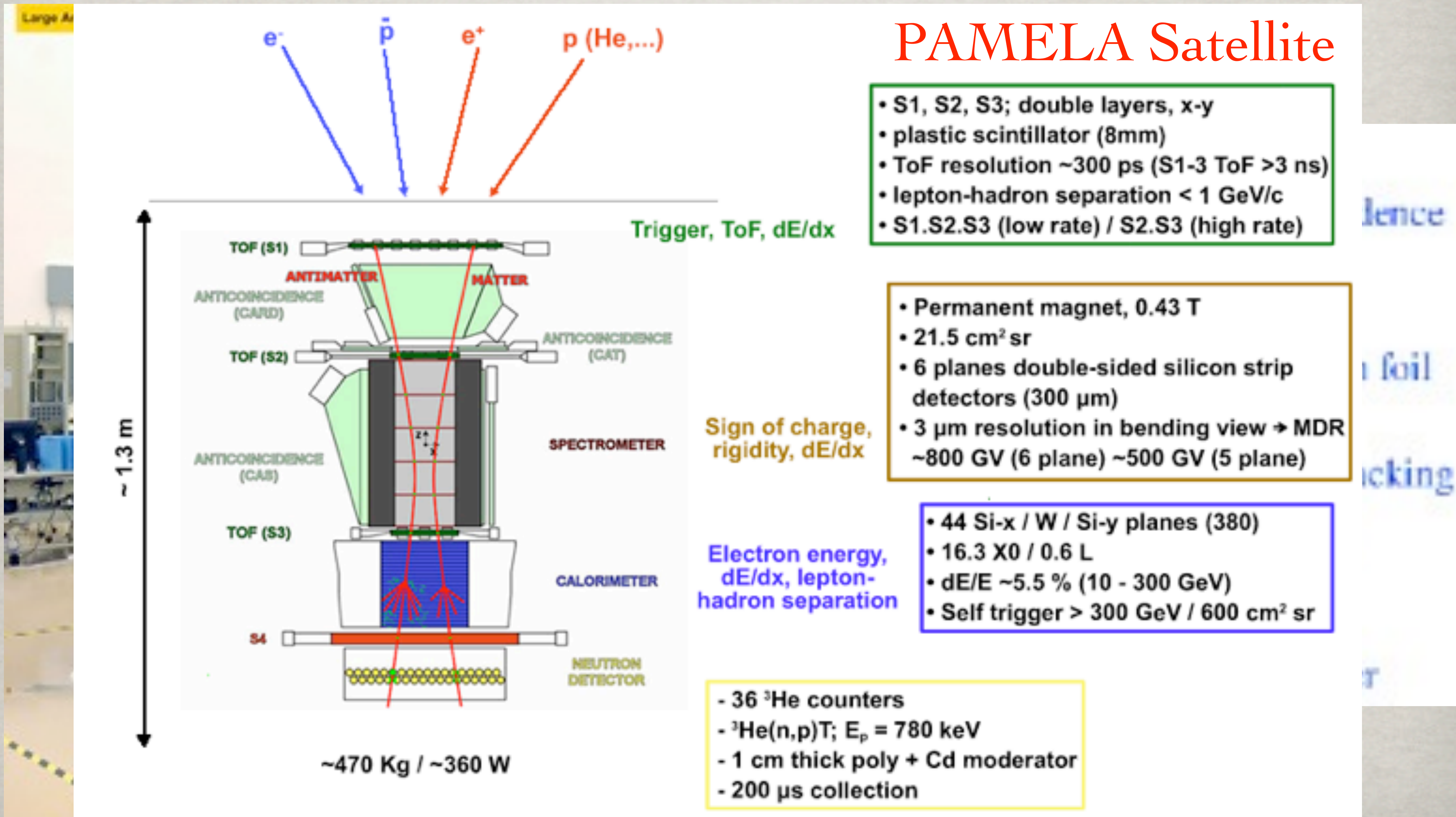
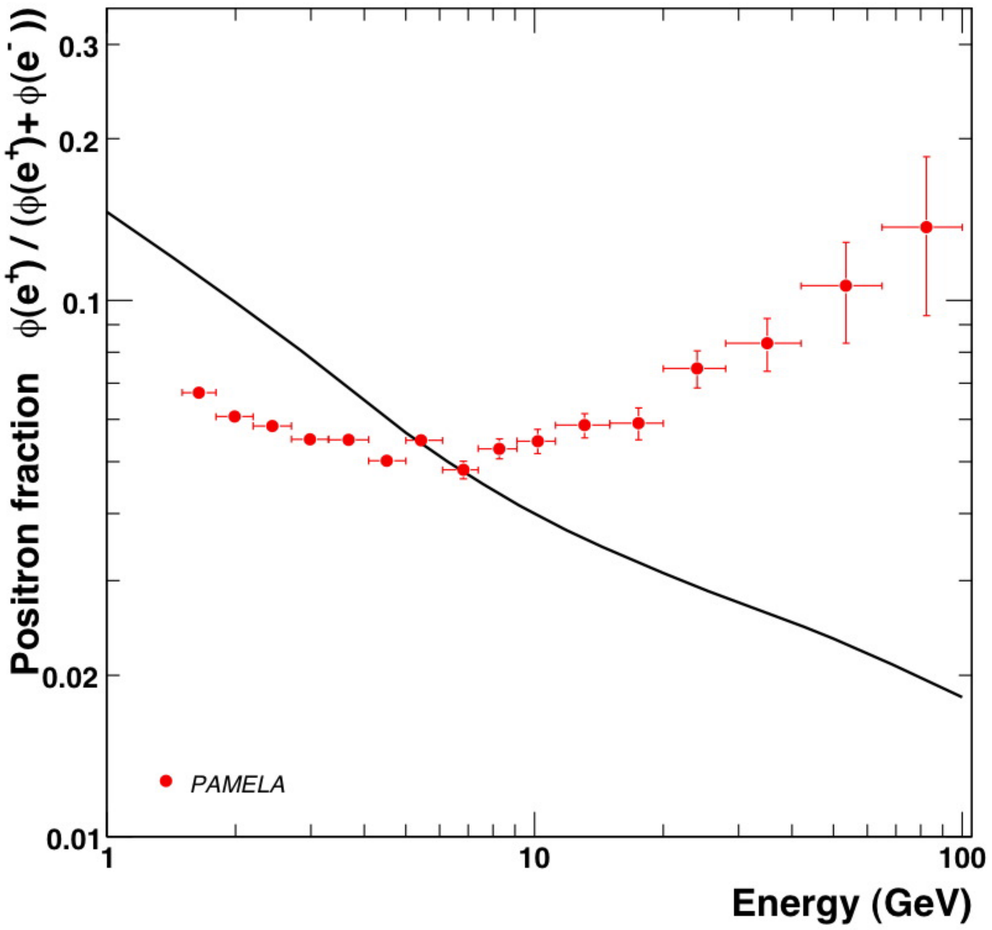


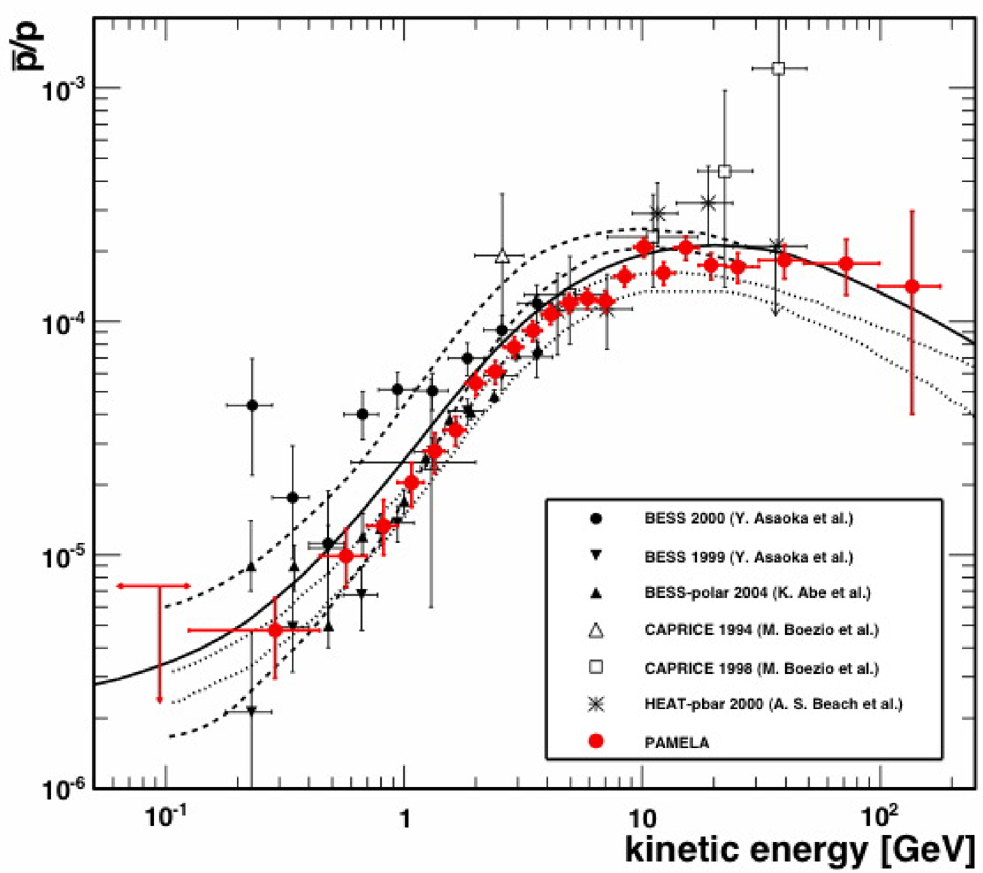
News from the sky I

The PAMELA satellite measures antimatter and released data of positron fraction & antiprotons 4 years ago:

[0810.4995]



[1007.0821]



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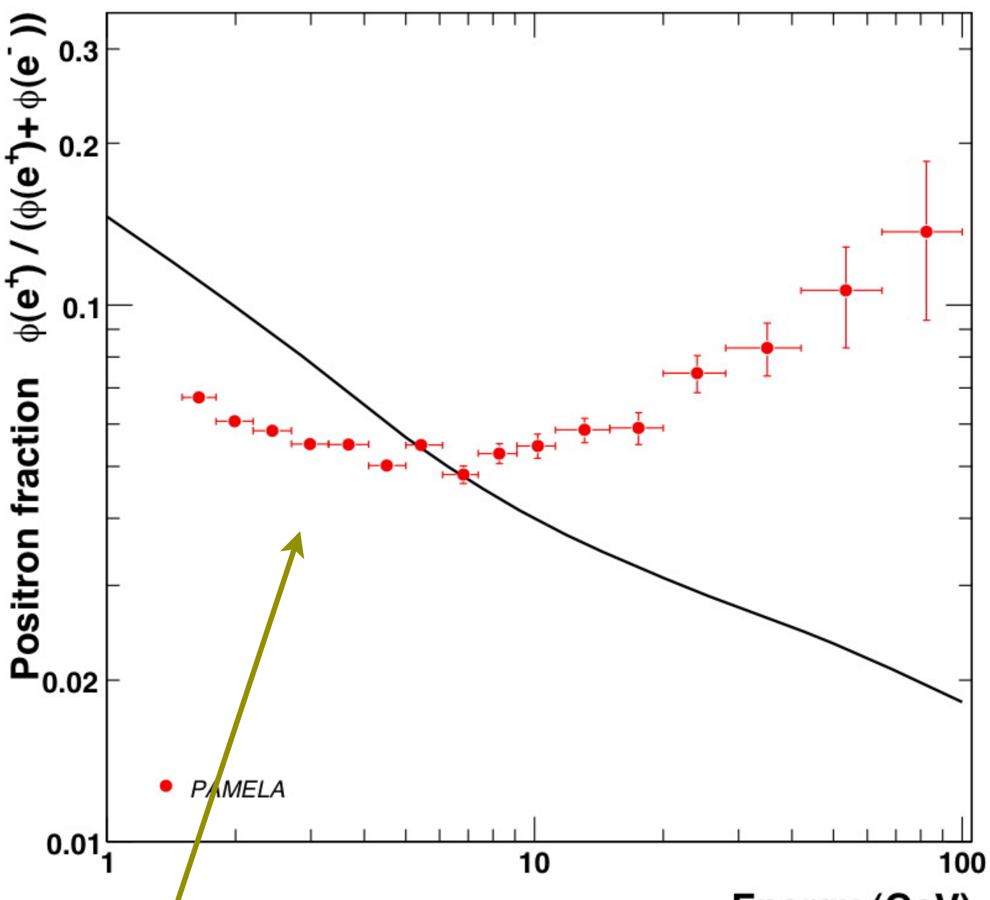
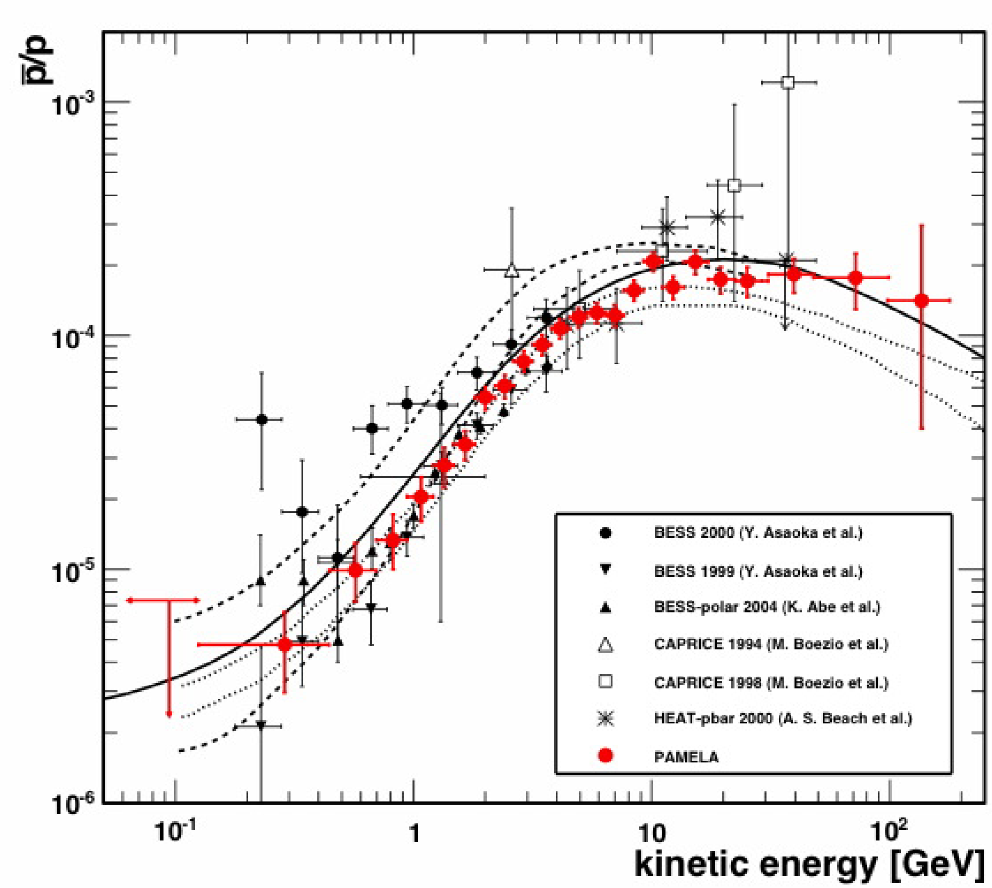


Solar modulation

[1007.0821]



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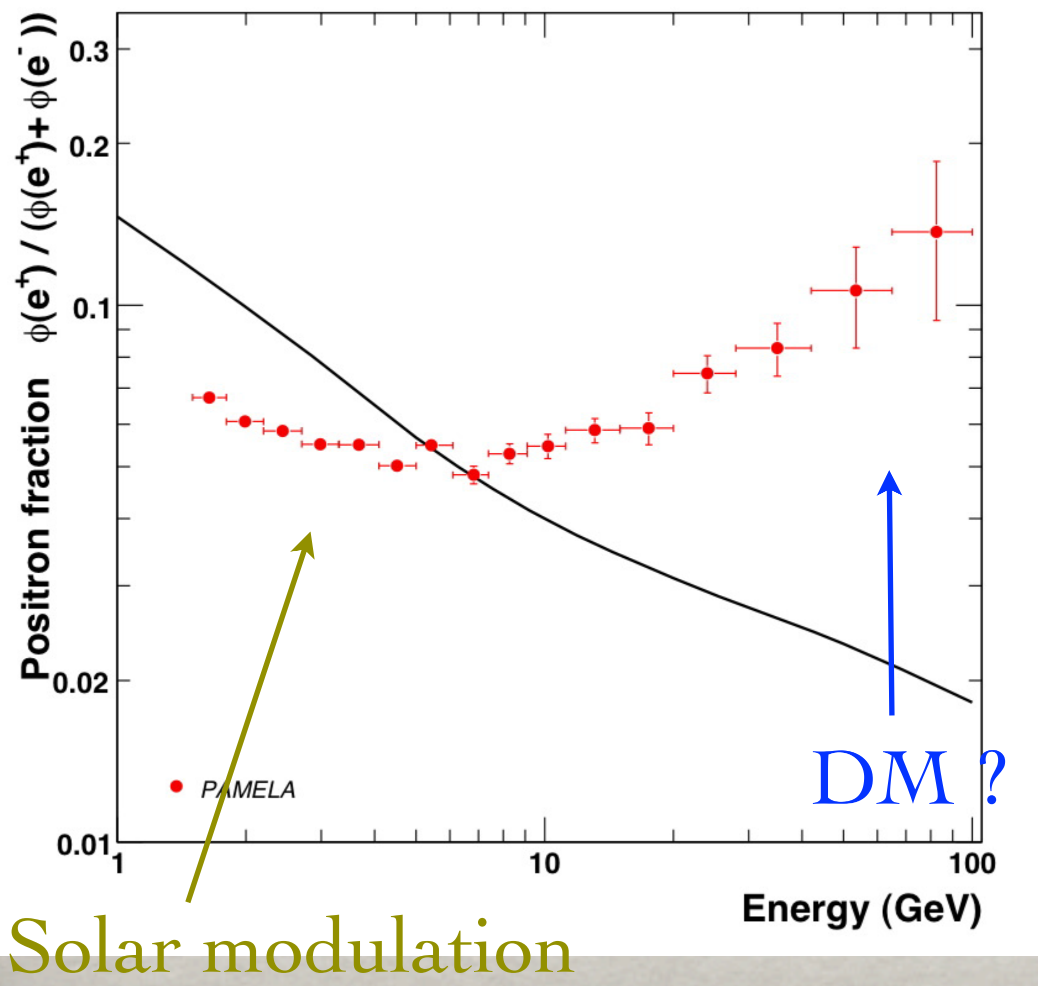
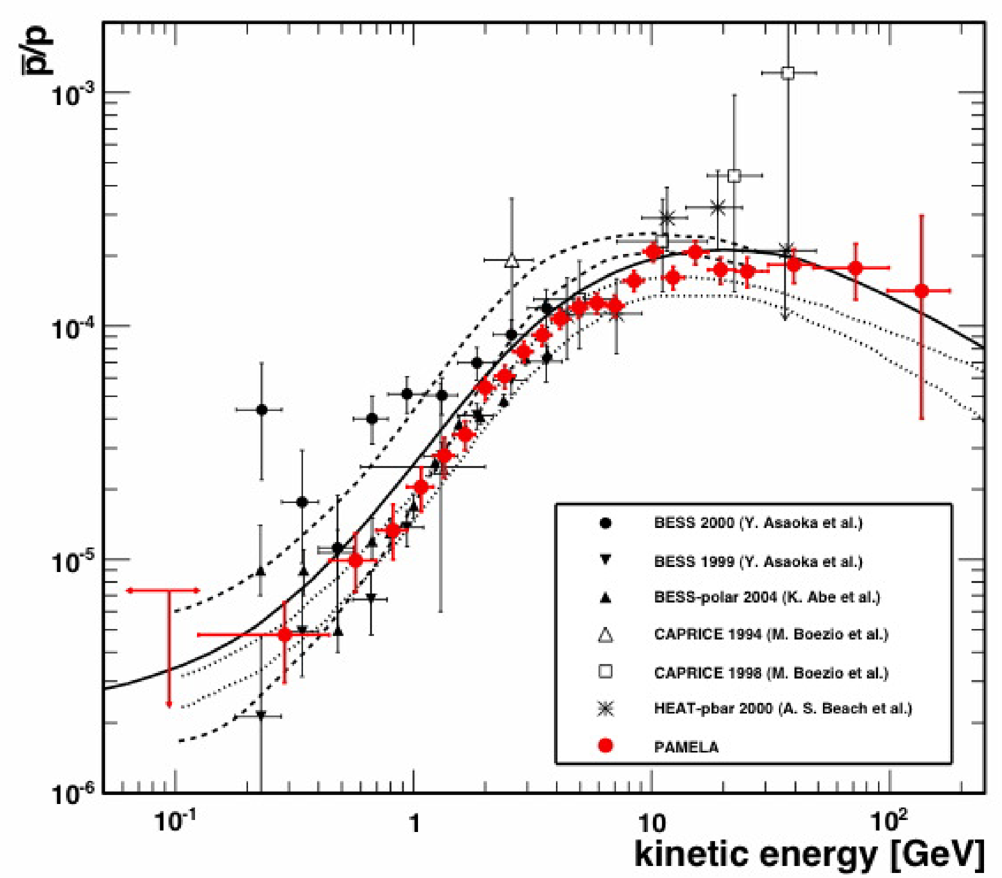


[1007.0821]



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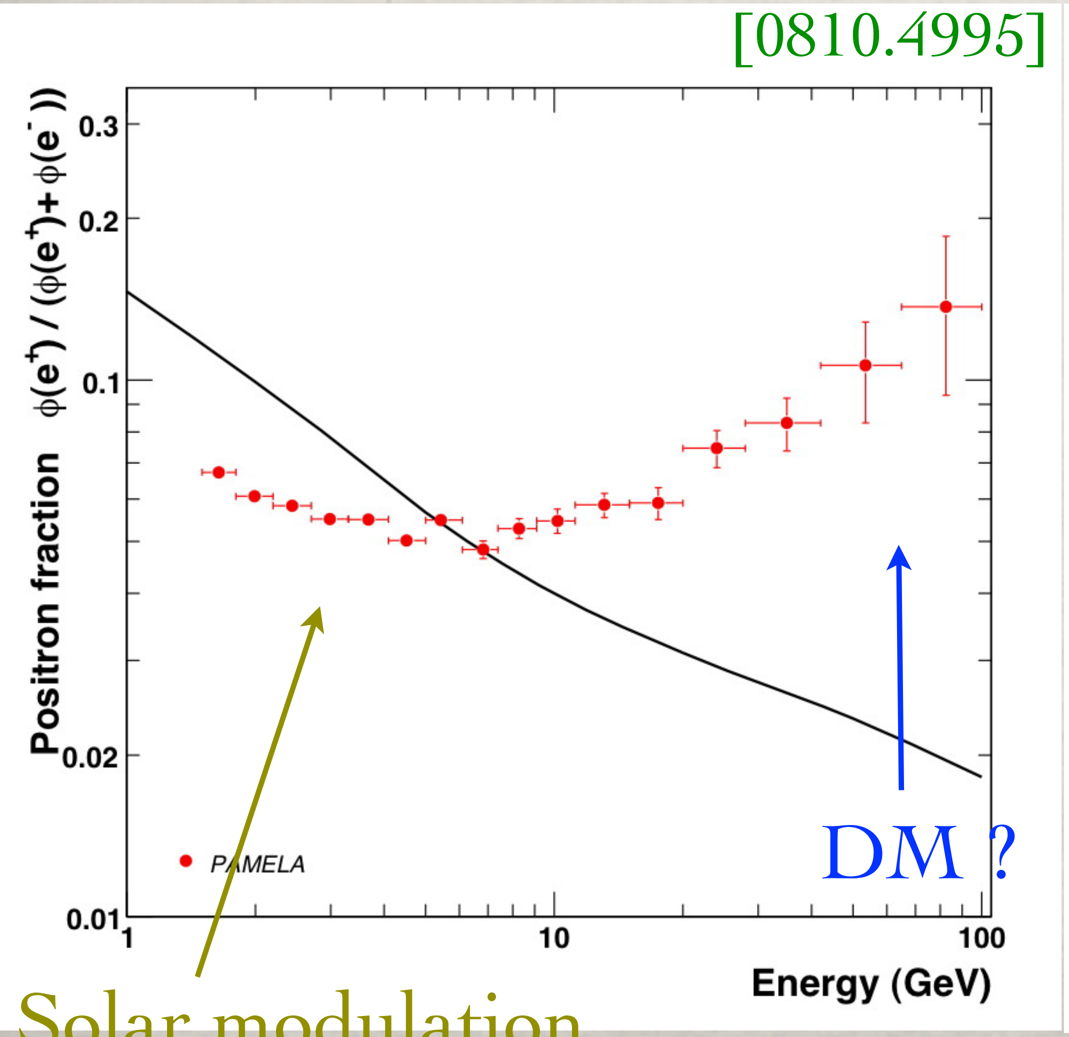

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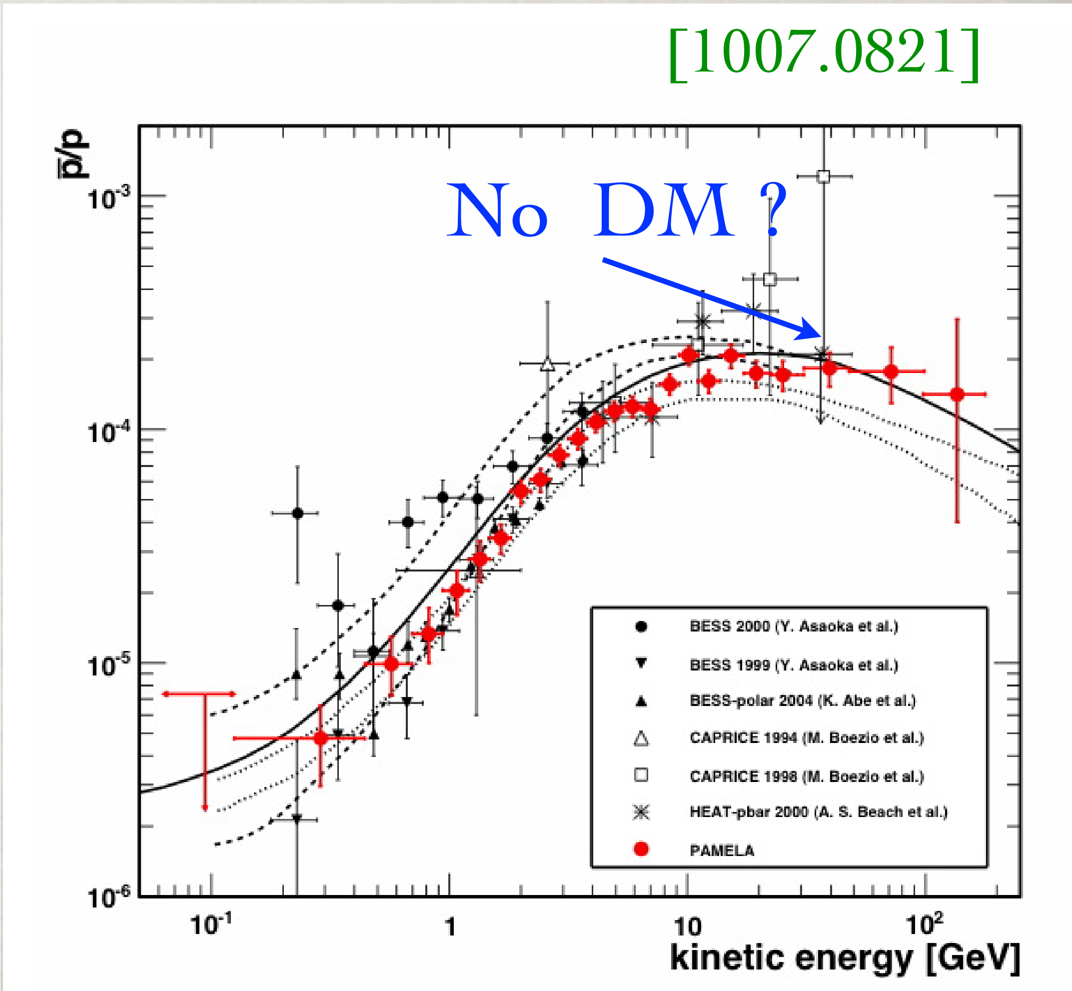
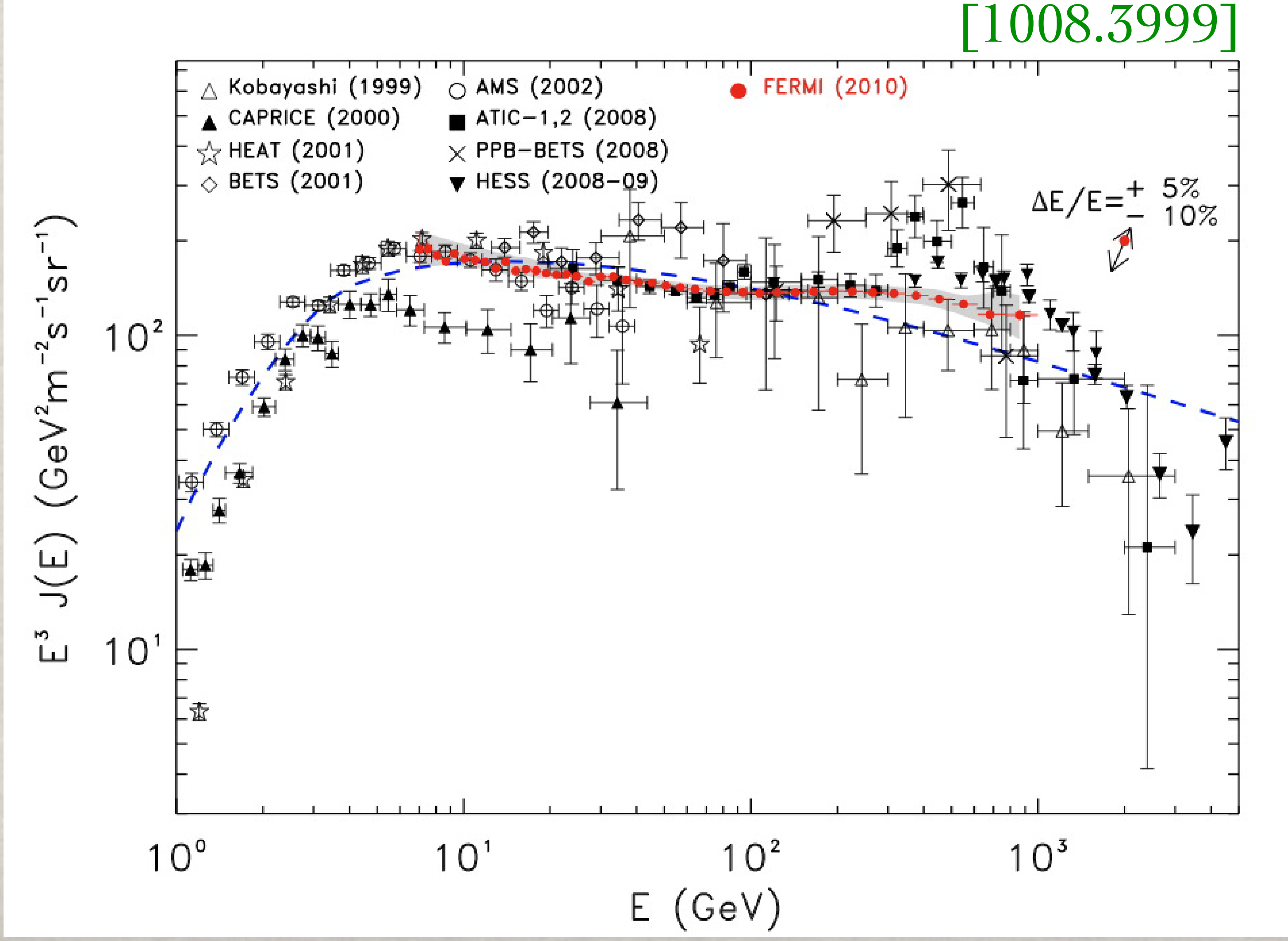


News from the sky II

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



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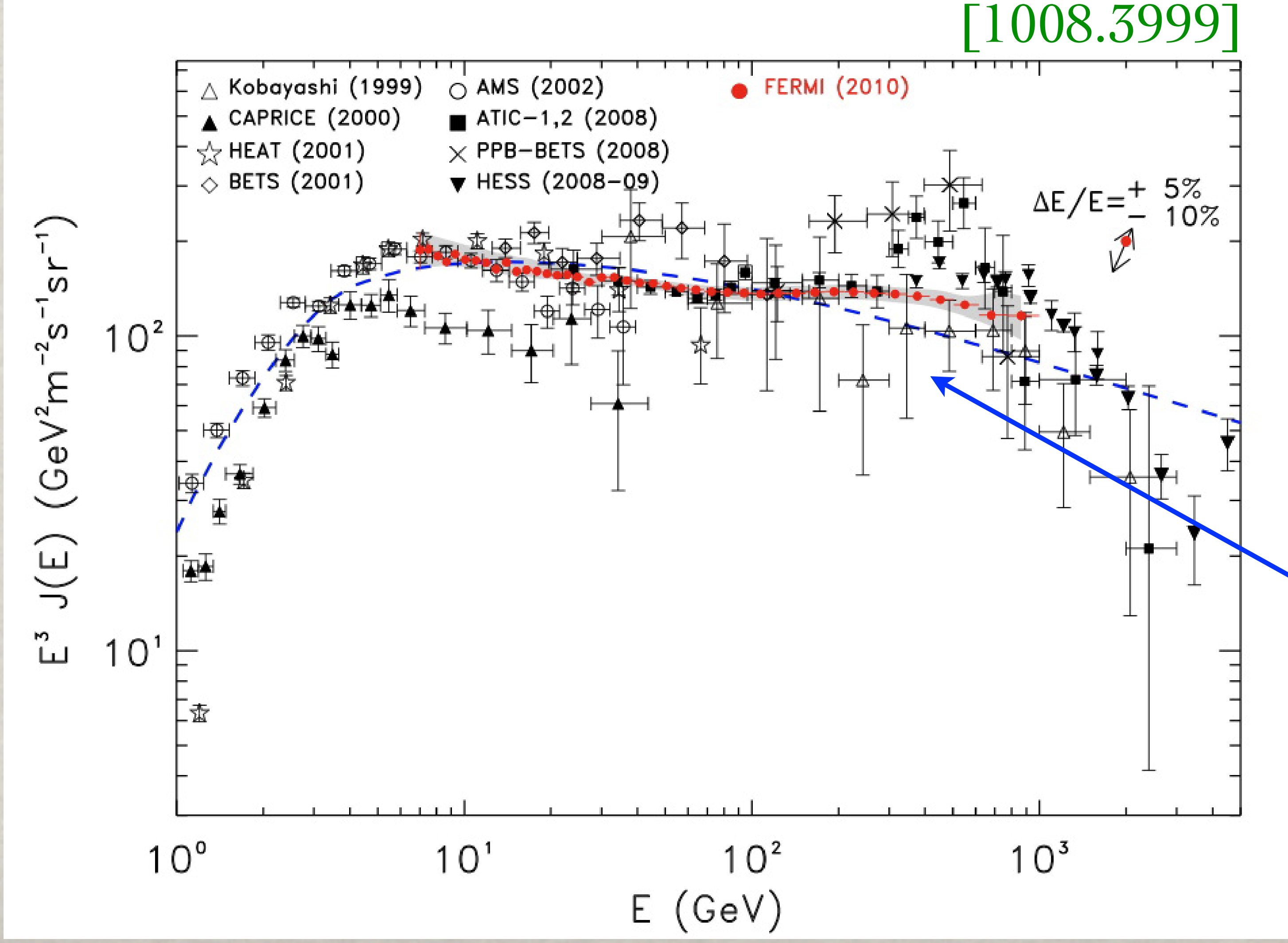
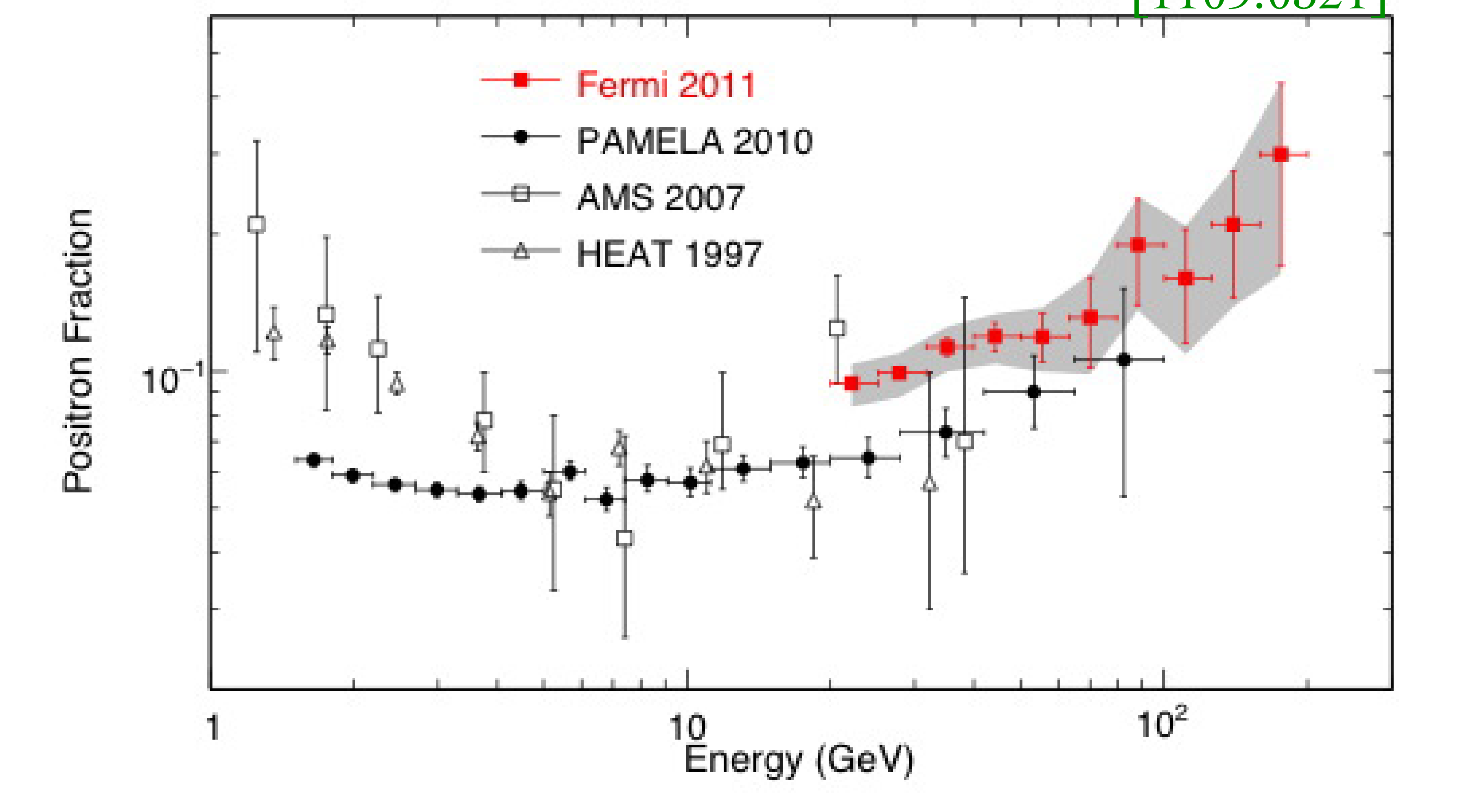


News from the sky II

FERMI did confirm the PAMELA excess using the earth magnetic field to separate the charges:

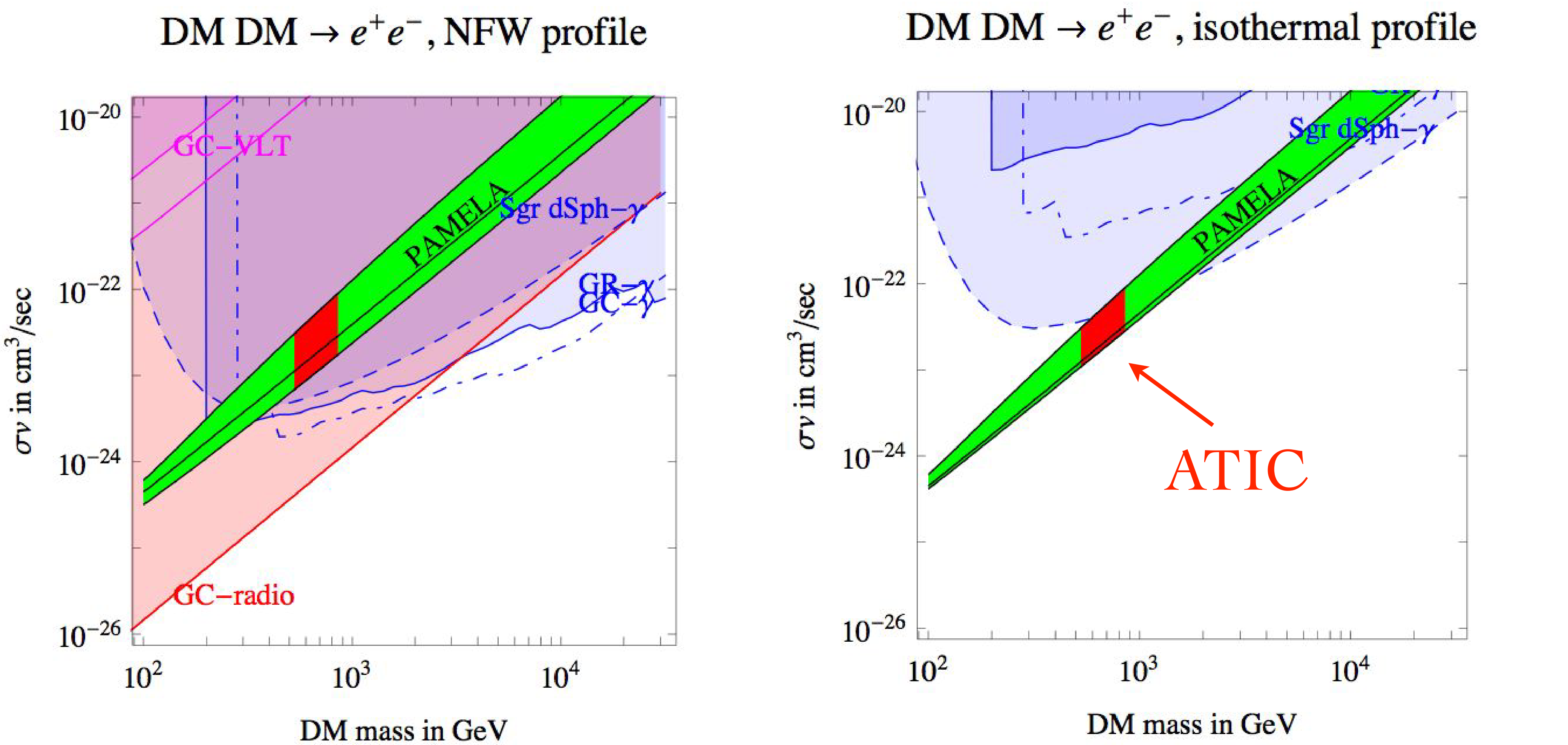
[1109.0521]



WIMP annihilation ???

Need a very large boost factor ~ 1000 to fit the PAMELA signal but then the rate seems in contrast with the radio signal from the galactic centre for a NFW profile

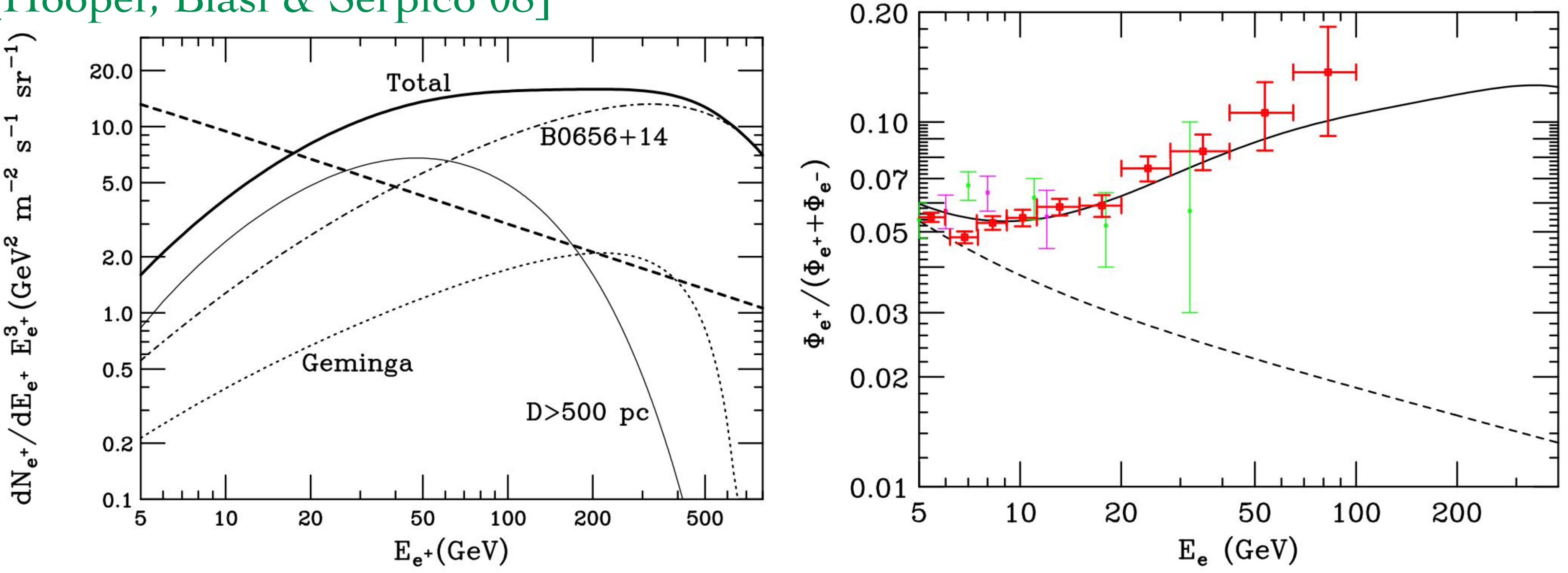
[Bertone, Cirelli, Strumia & Taoso 08]



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]

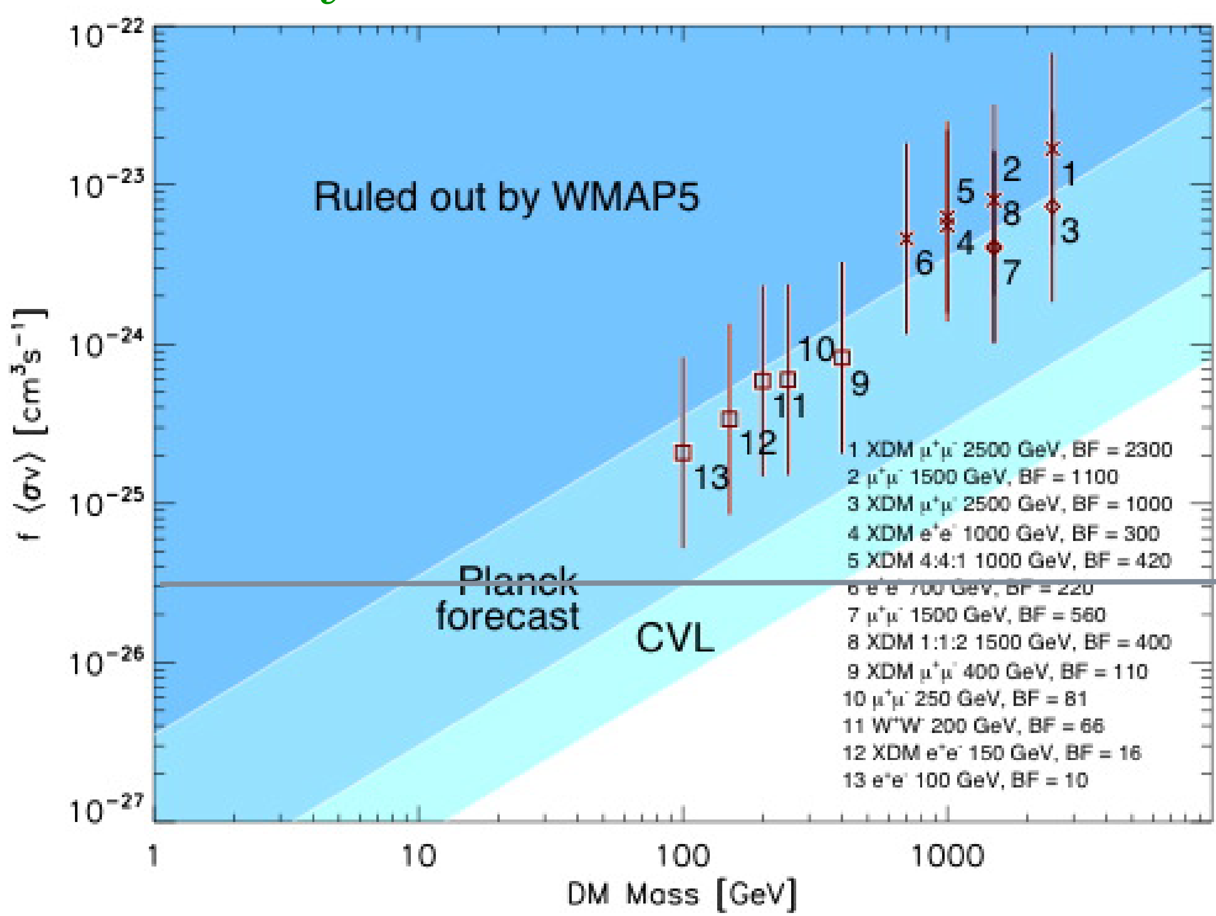


Differences from DM signal: exponential cut-off and some small anisotropy, but of the order 0.05-0.1 %

PLANCK MAY TELL...

WIMP annihilation also modifies the epoch of recombination due to the release of energy in the primordial plasma and leave imprints into the CMB ! WMAP already puts some constraints, but Planck will reach cross sections needed by PAMELA

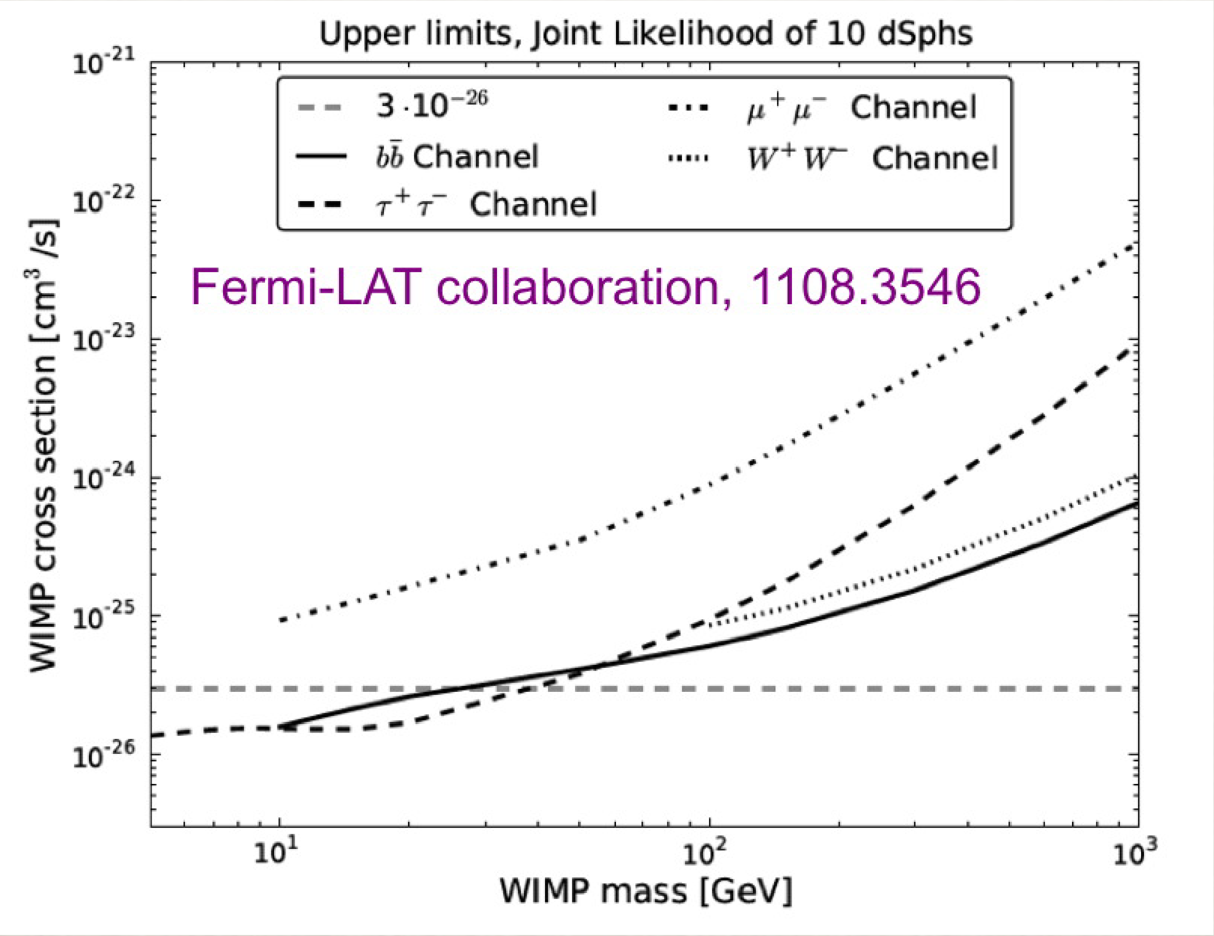
[Slatyer, Padmanabhan& Finkbeiner 09]



Thermal cross-section

News from the sky III

The FERMI satellite has new combined bounds on the gamma-ray emissions from satellite dwarf-galaxies



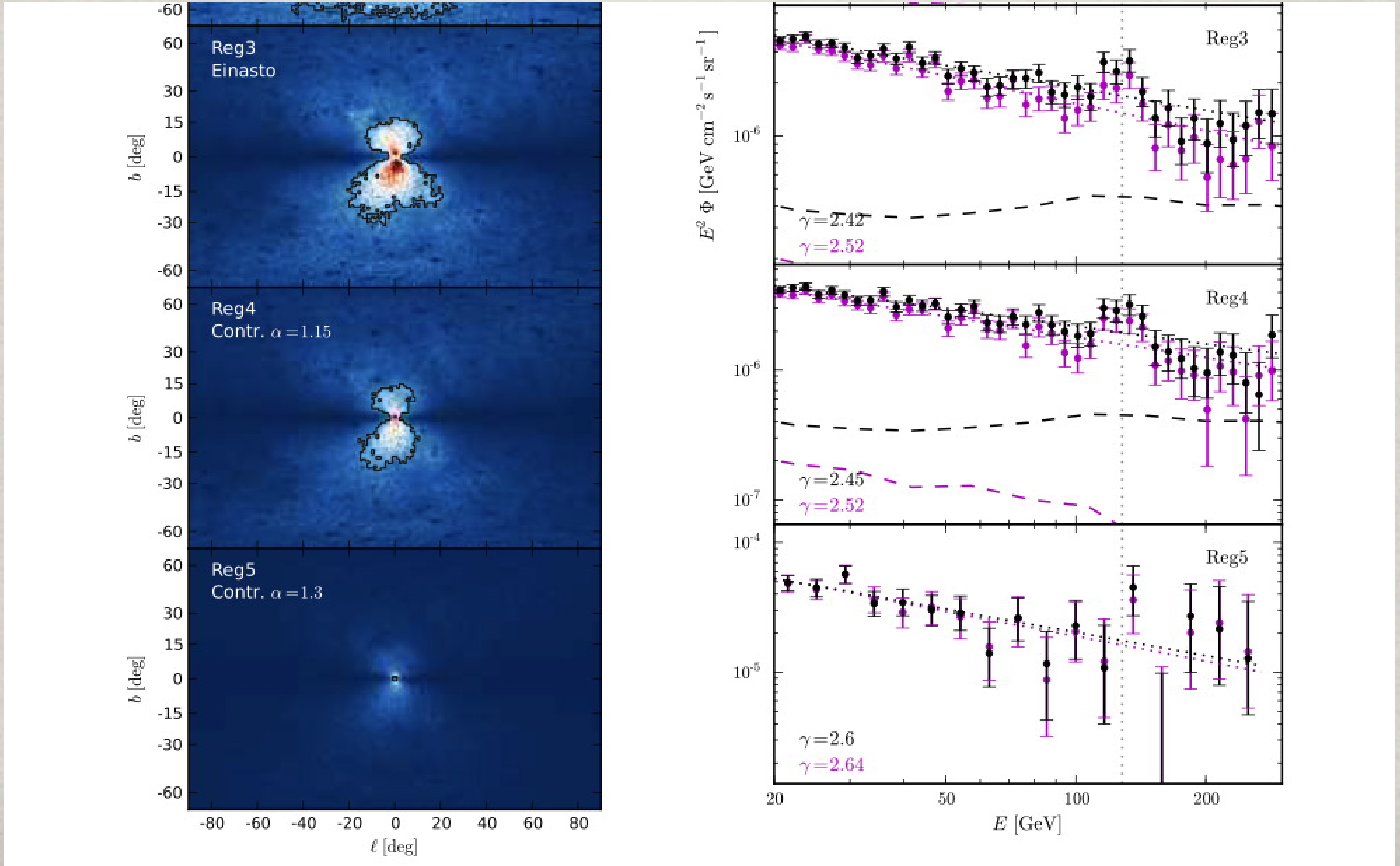
Thermal cross-section

Low mass WIMPs annihilating in bottom quarks/tau leptons are excluded up to ~ 30-40 GeV !

News from the sky IV

But possibly the FERMI collaboration missed a line signal ?

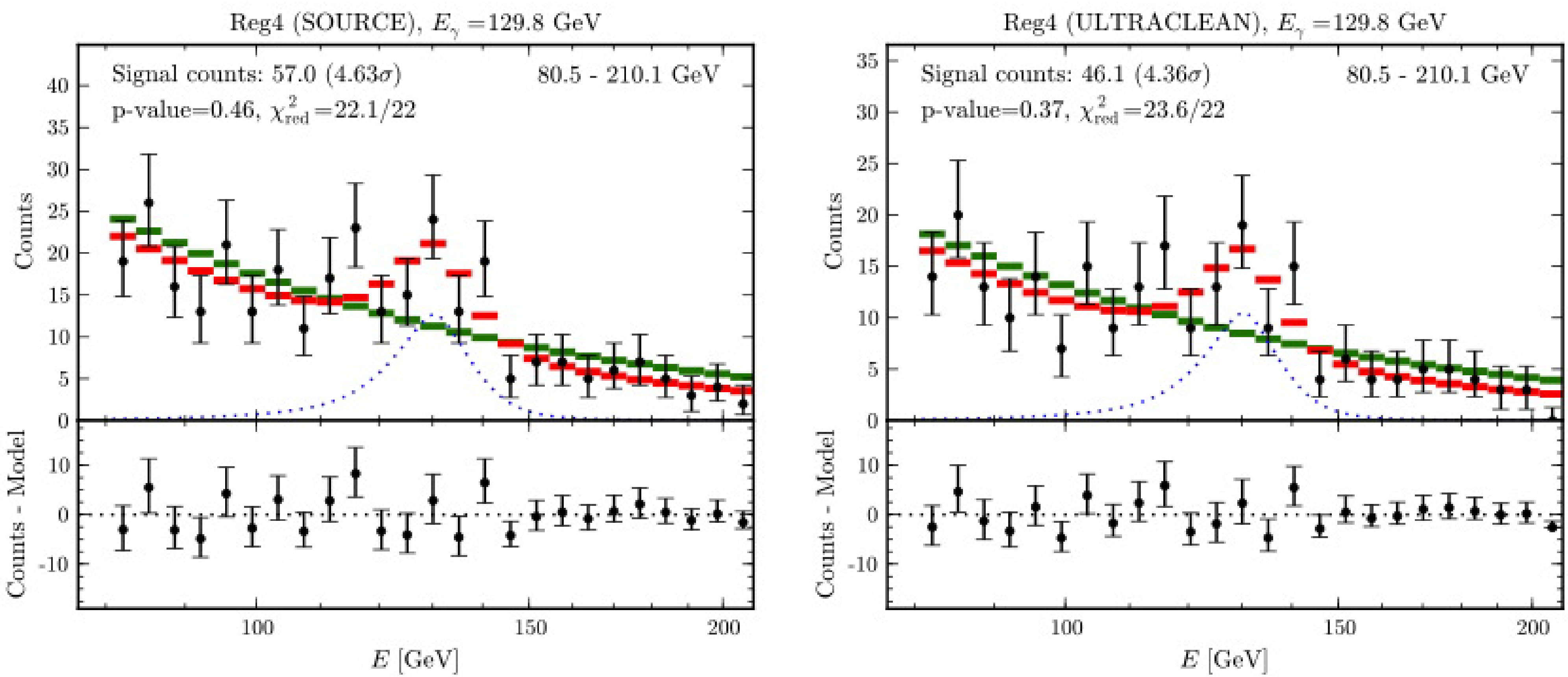
Choose optimized regions in the sky: [Ch. Weniger, 1204.2797]



News from the sky IV

In regions 3-4 the best significance in both FERMI data sets

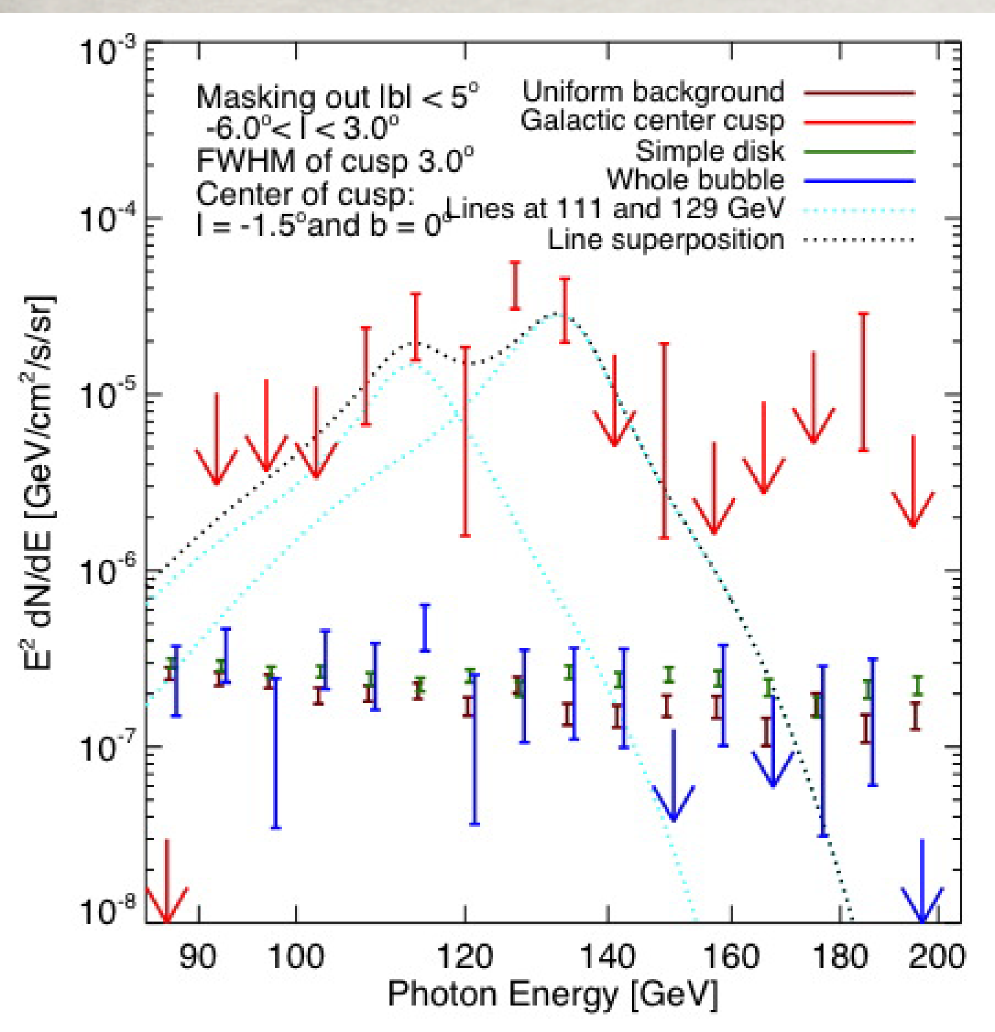
[Ch. Weniger, 1204.2797]



Local significance more than 4 sigma, taking into account the look elsewhere effect it gives 3.2 sigma

News from the sky IV

Actually the data are compatible also with two line, but...



[Finkbeiner & Su, 1206.1616]

News from the sky IV

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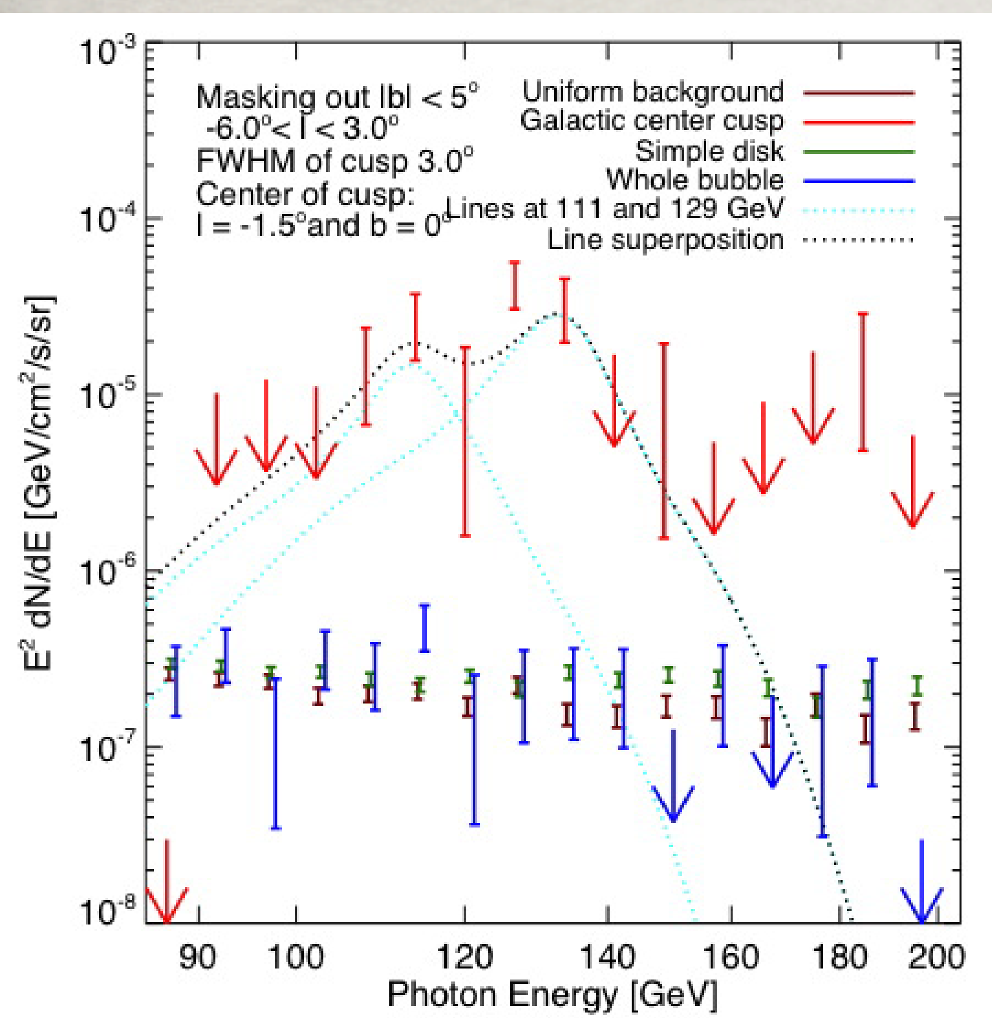
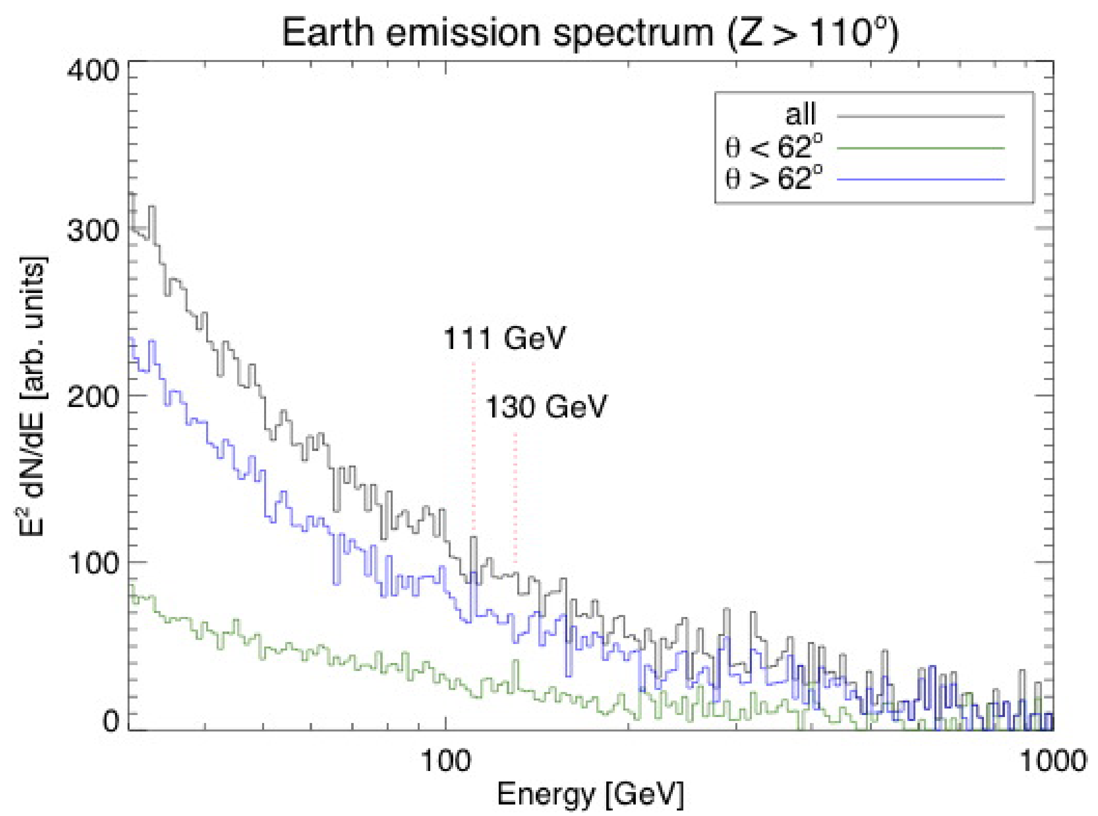


[Finkbeiner & Su, 1206.1616]

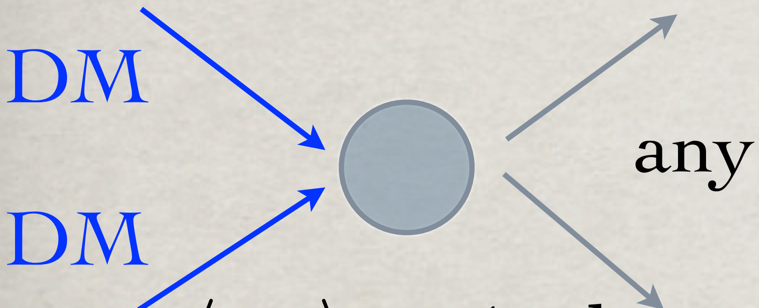


...the same lines appear also in the earth emission spectrum...

Let us wait for the FERMI analysis !

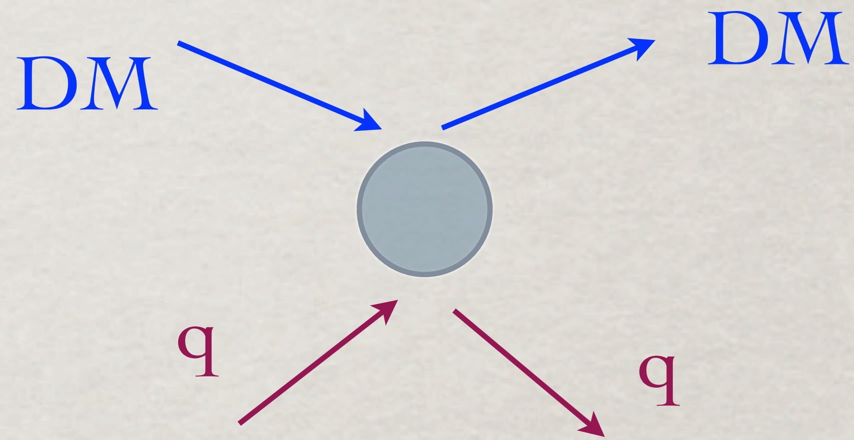
THE WIMP CONNECTION

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

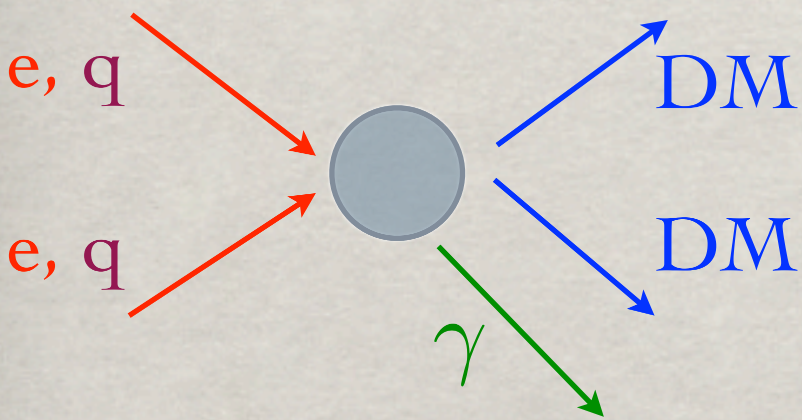


$\langle \sigma v \rangle \sim 1 \text{ pb}$

Direct Detection:



Colliders: LHC/ILC



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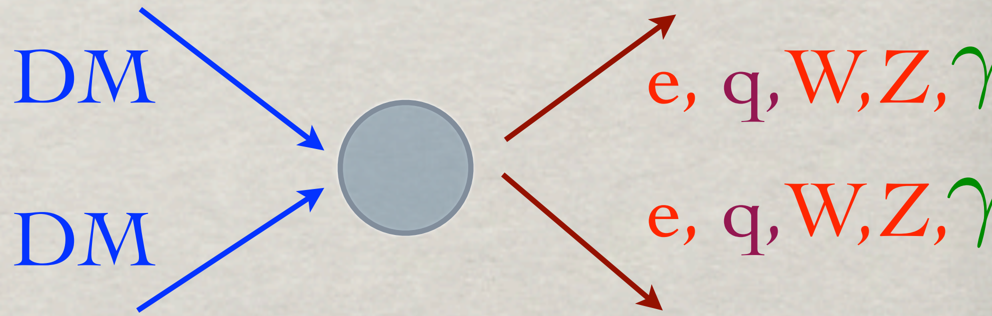

3 different ways to check this hypothesis !!!

THE WIMP CONNECTION

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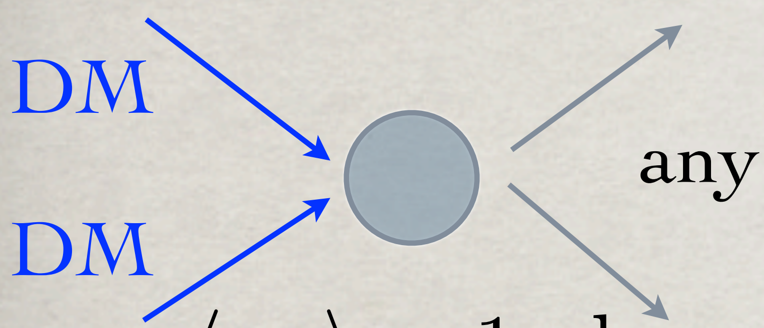

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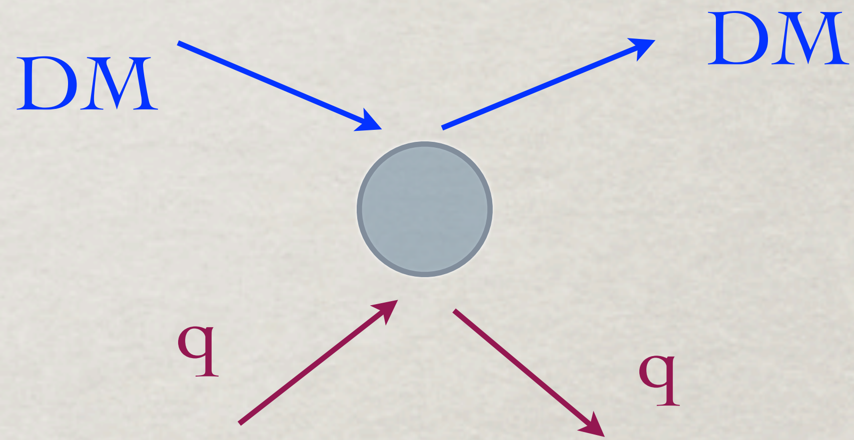

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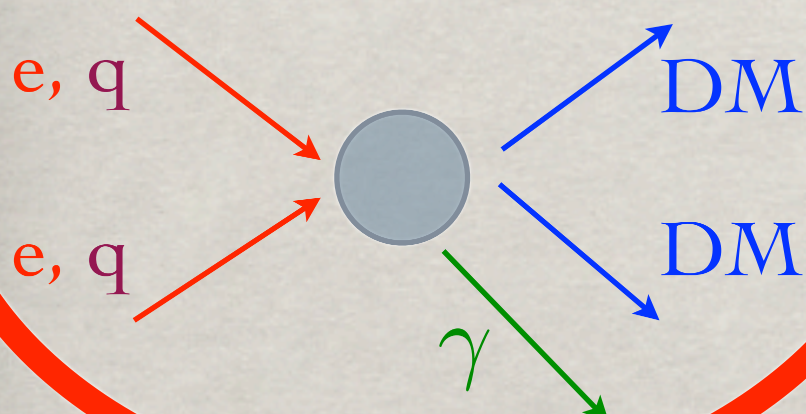
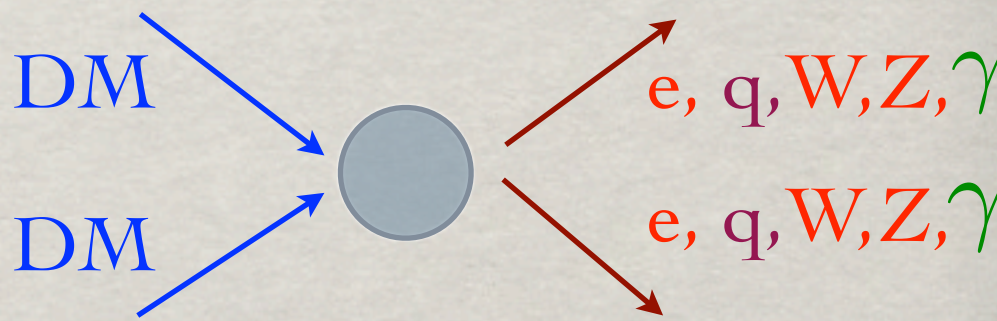


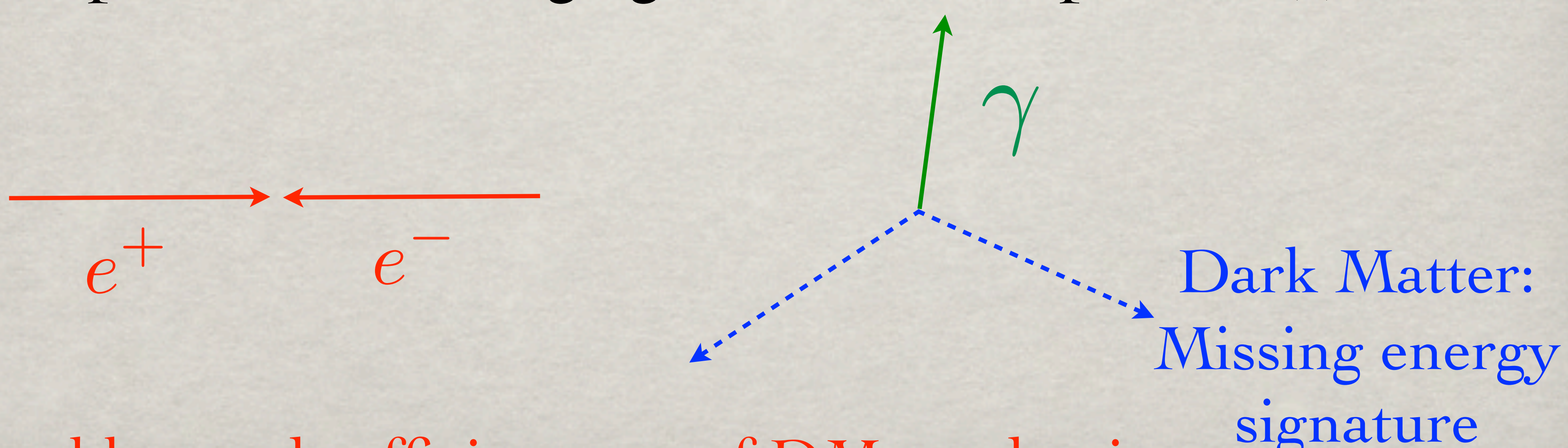
Indirect Detection:



3 different ways to check this hypothesis !!!

Missing energy signature

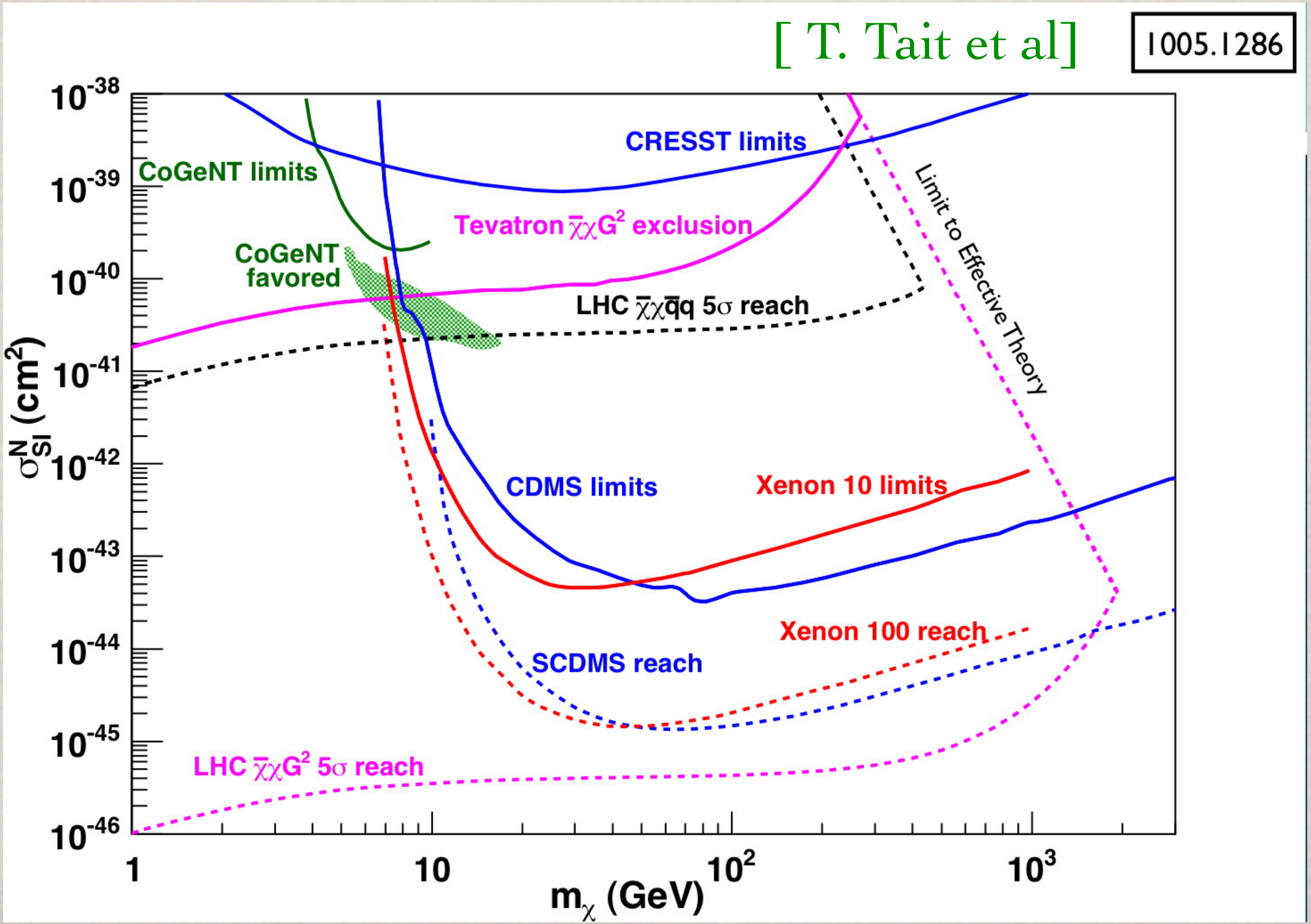
- The direct production of two DM particles in a collider gives unfortunately no signal ! The energy just disappears without trace...
- How is it possible to tag such events: Thanks to Initial State Radiation ! i.e. either a single photon or a gluon emitted by the initial partons, recoiling against the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



Trouble: need sufficient rate of DM production...

COLLIDER BOUNDS

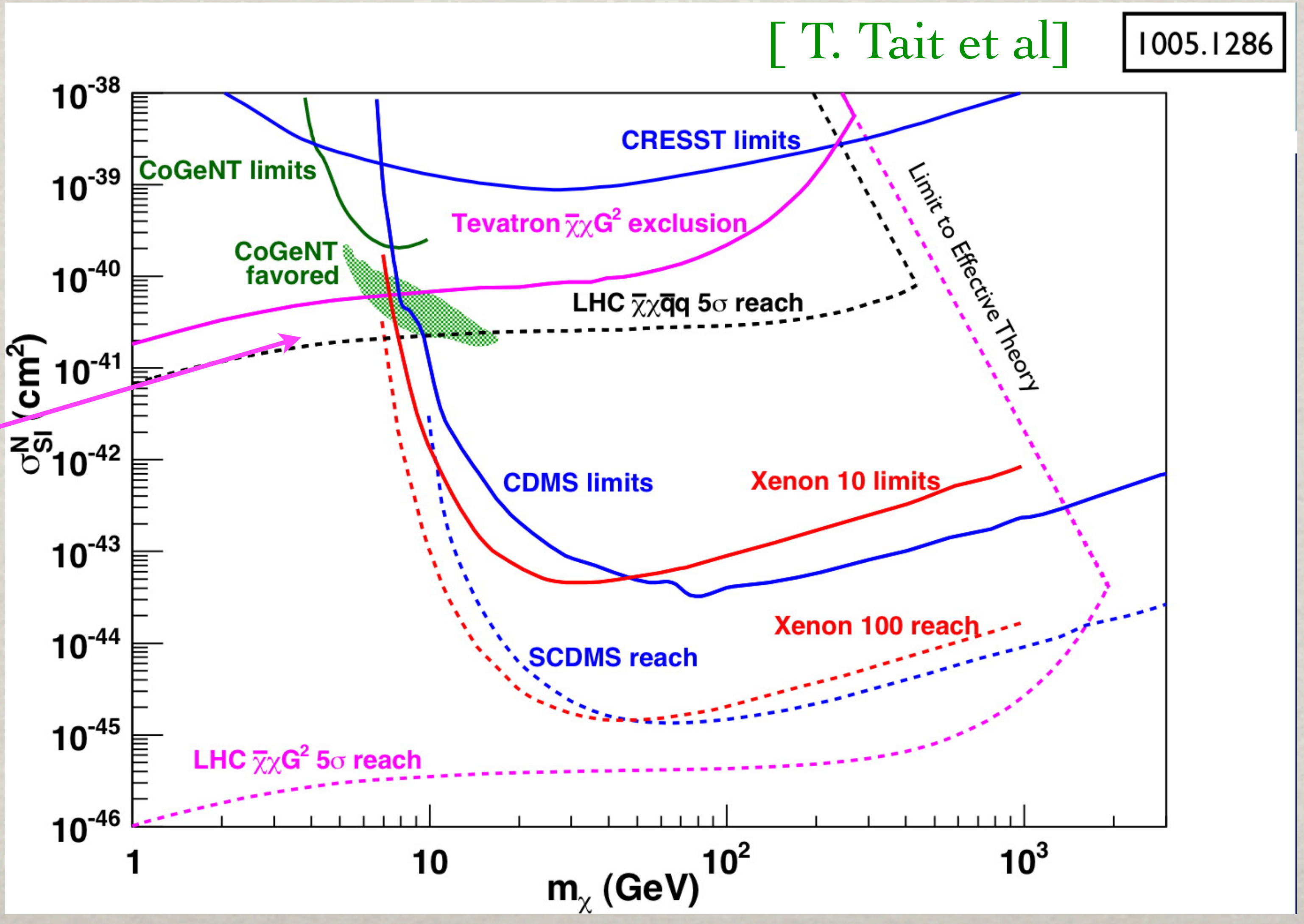
From a model-independent analysis considering dimension 6 effective operators, from the Tevatron stringent limits appear:



COLLIDER BOUNDS

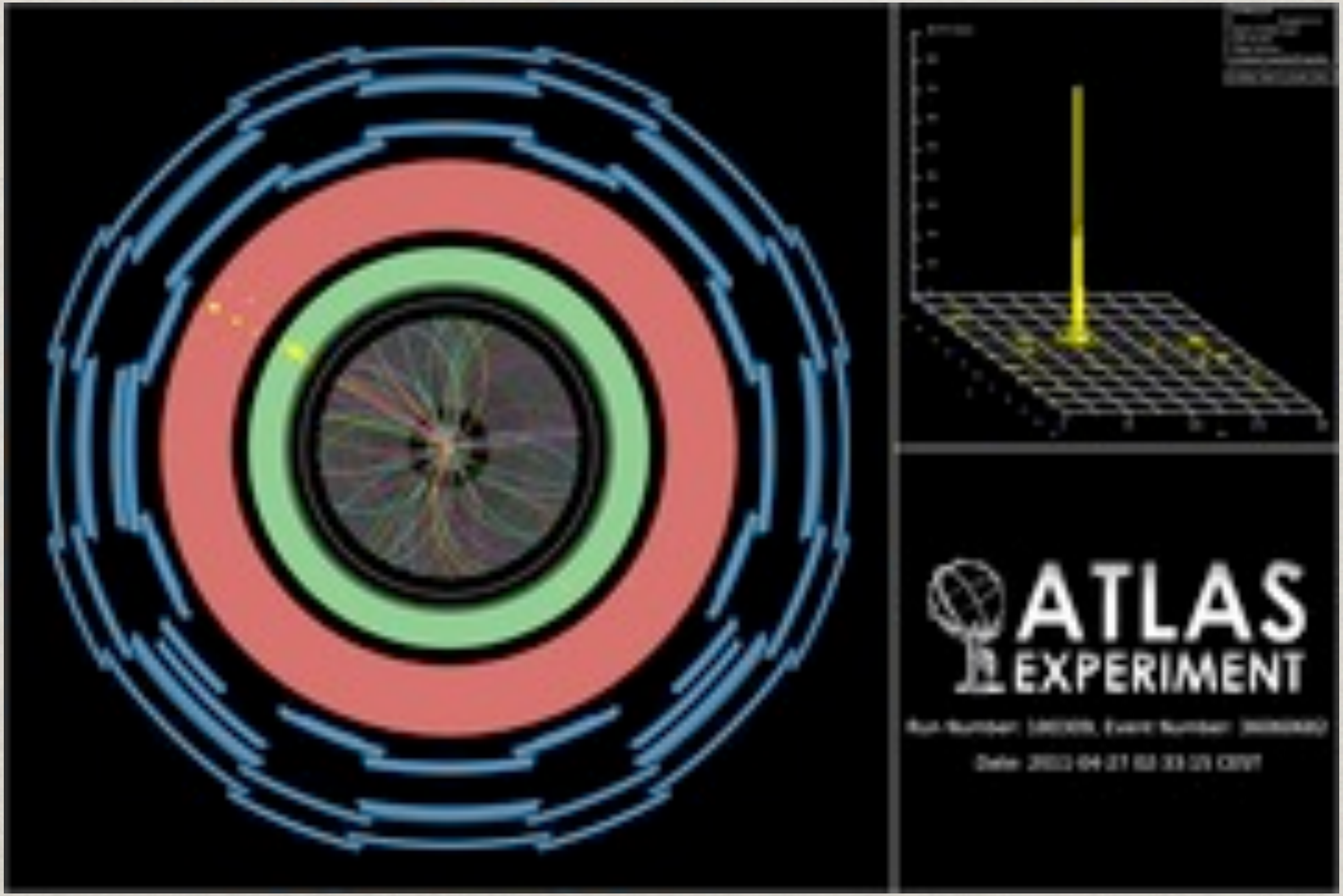
From a model-independent analysis considering dimension 6 effective operators, from the Tevatron stringent limits appear:

Stronger bound at low mass !



LHC: Monojets ?

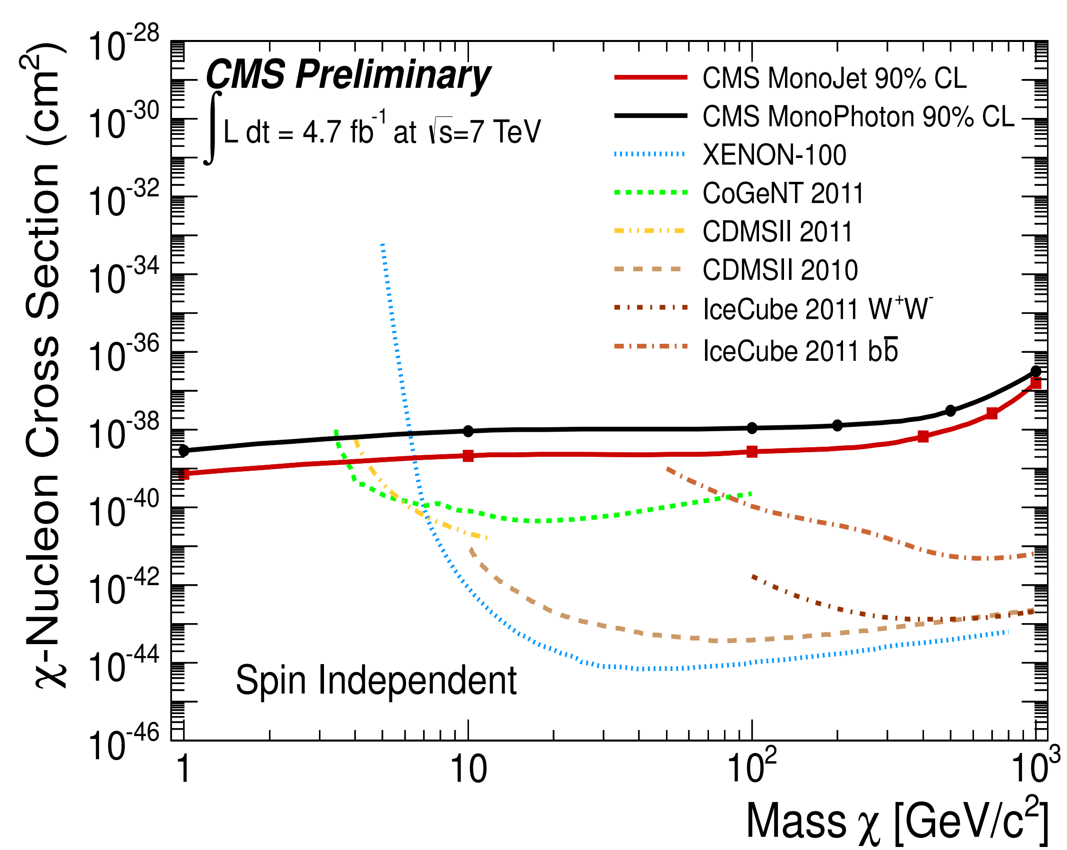
The gluon ISR channel is already being tested at the LHC...

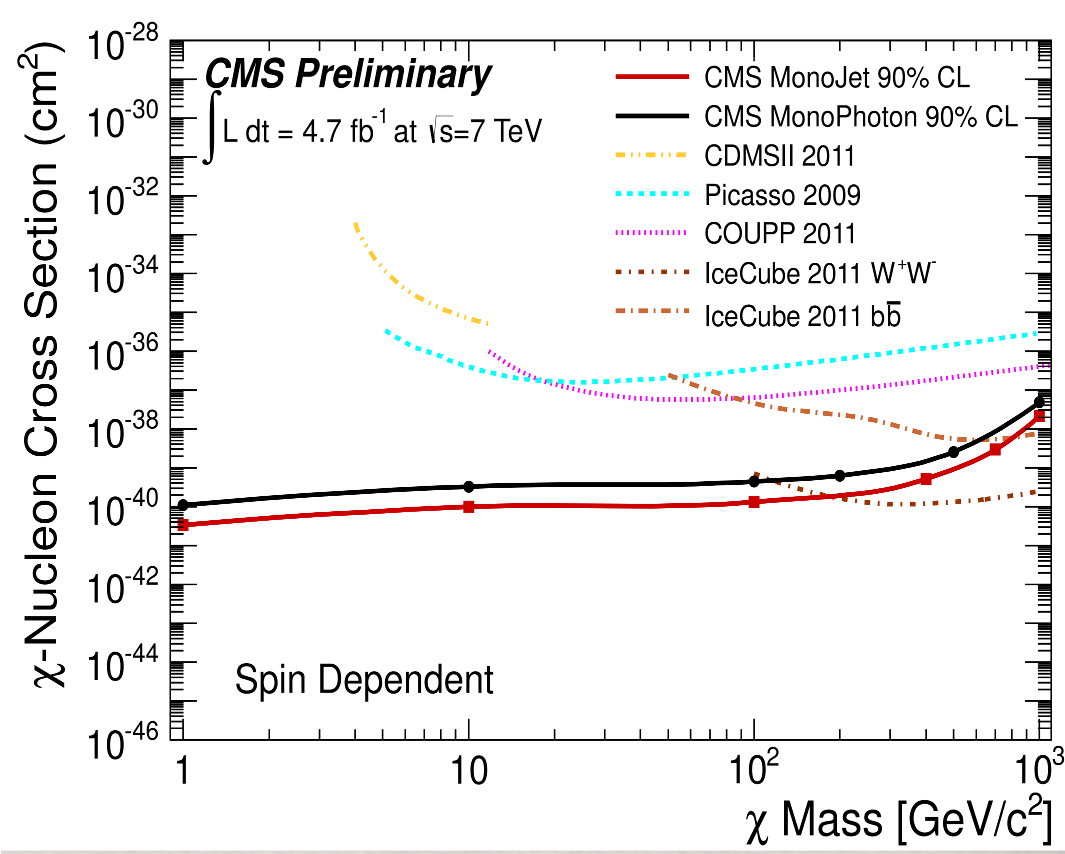


Monojet candidate event !

COLLIDER BOUNDS

Now CMS has performed a monojet/monophoton analysis for DM:

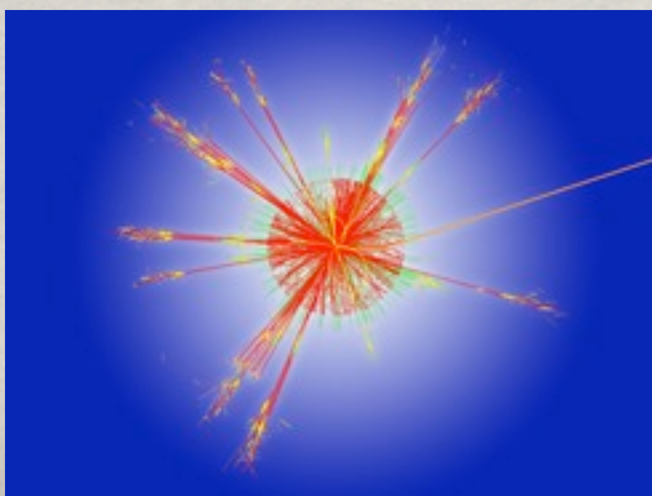


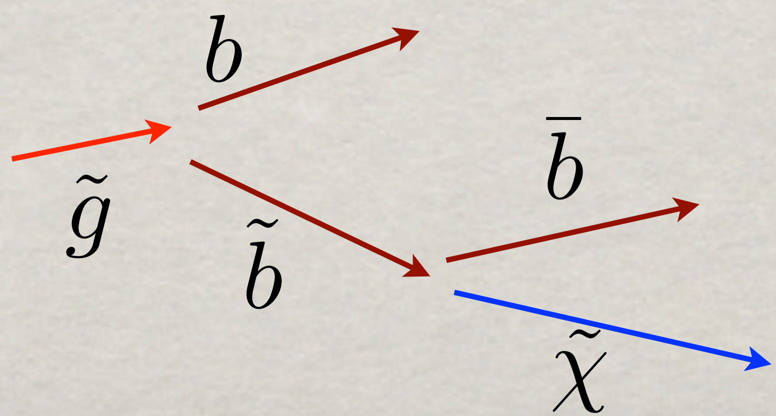


Strongest bound for low mass and for spin dependent case !

Missing energy signature

- In models with a conserved parity and colored states, DM is produced at the end of each cascade decay.
- The missing energy can be measured only in the transverse plane and ALL the other particles have to be precisely reconstructed.
- Of course neutrinos give rise to a background...
- Still one needs confirmation from direct/indirect detection that such particles are really Dark Matter...

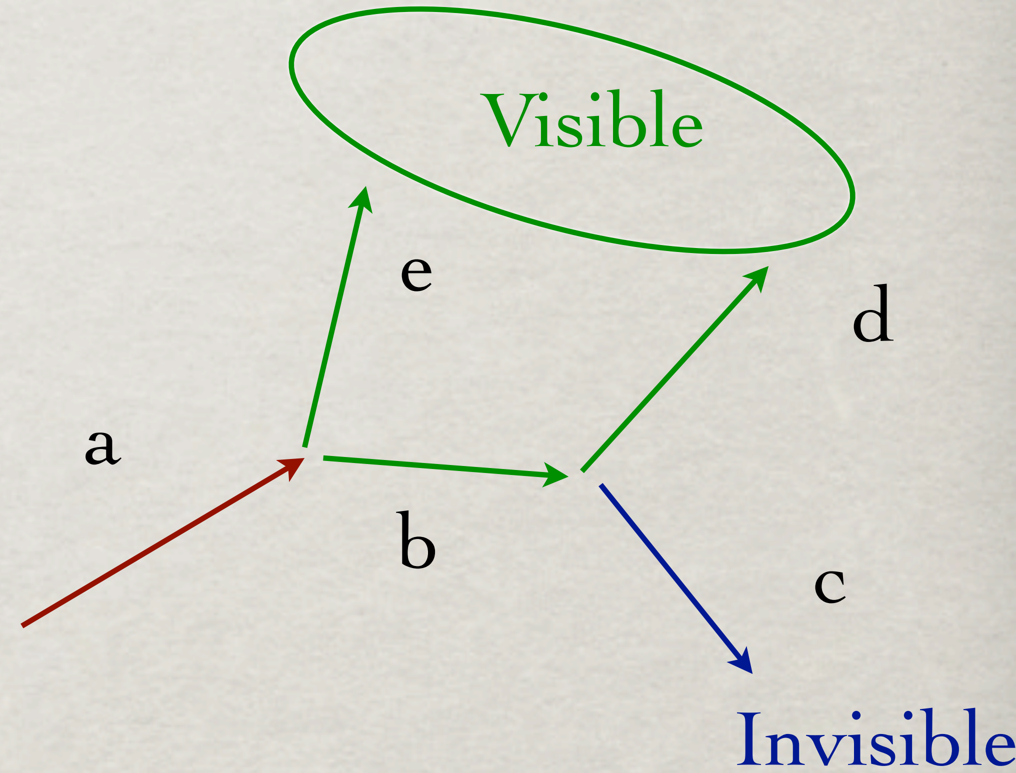




Dark Matter: Missing energy signature

Edge Mass measurement

- Compute the invariant mass distribution of the visible particles e,d
- The maximal value is given when by



$$(m_{de}^{max})^2 = \frac{(m_a^2 - m_b^2)(m_b^2 - m_c^2)}{m_c^2}$$

Mass differences !

Longer chains give more constraints !

NB: assumes 2-body decay chain and no degenerate masses

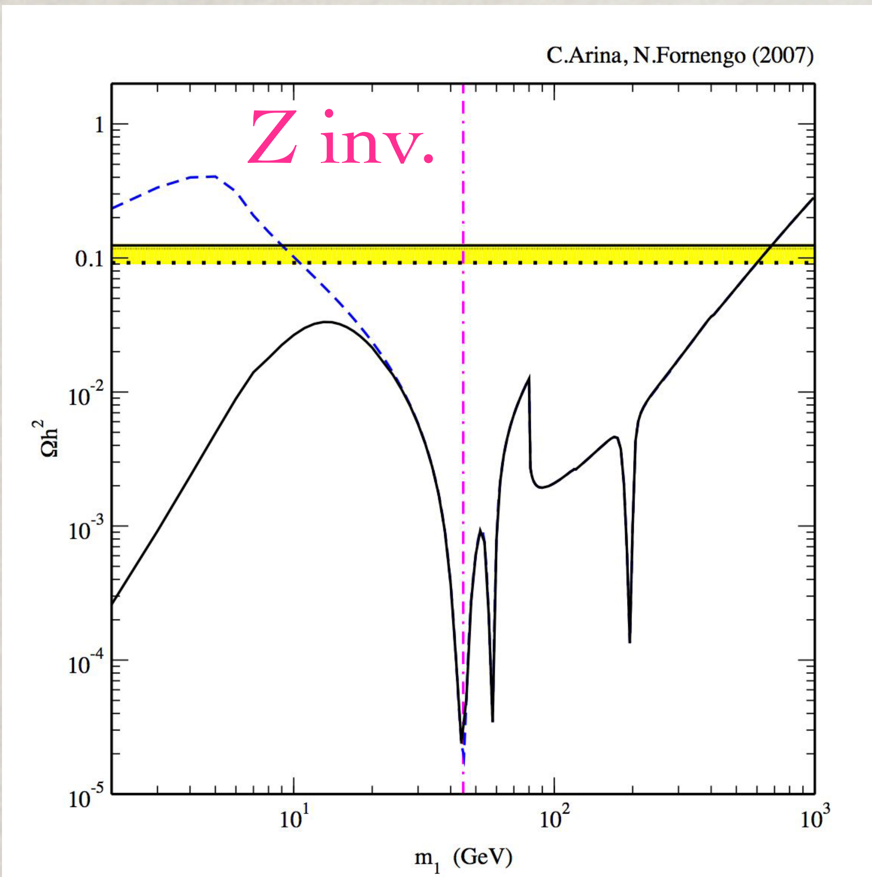
LHC DM CHALLENGE

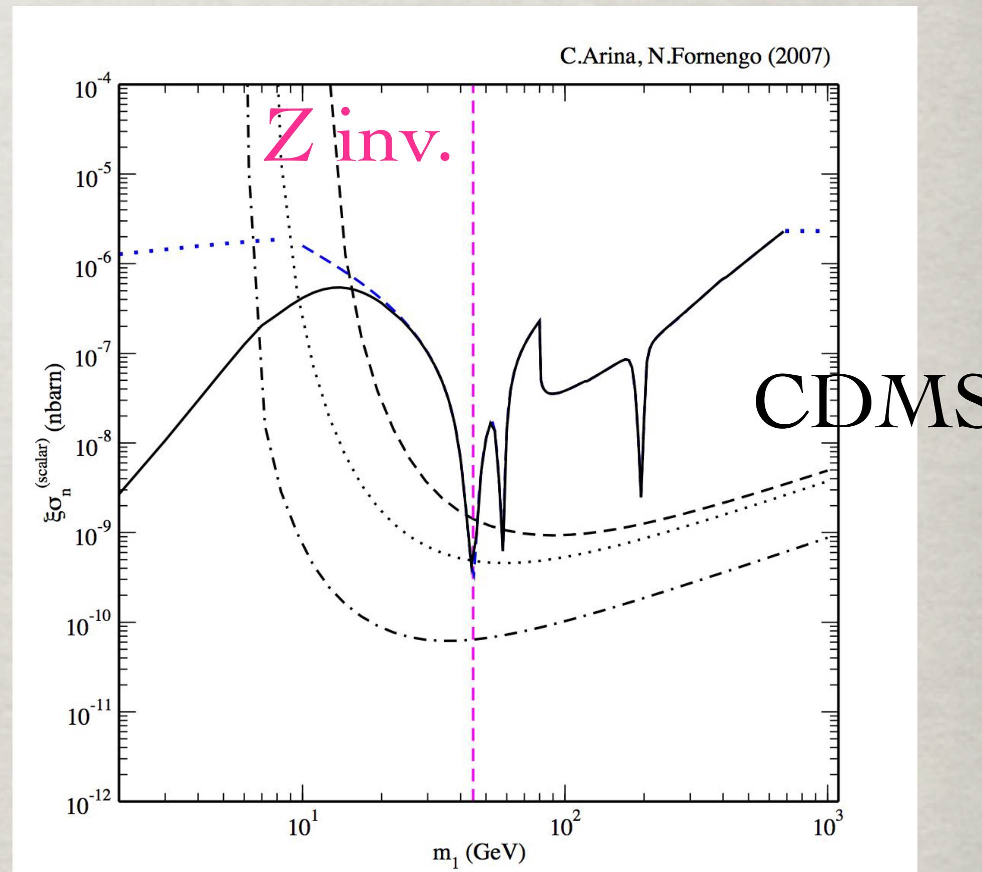
- Find events with large missing transverse energy with the same topology and final state
- Try to measure the masses in different decay chains using invariant mass edges and/or possibly also the shape of the distributions
- Reconstruct the mass differences (~ 1% error) between the new particles in this way and from the frequency of certain chains restrict as well some of the couplings. The DM candidate mass only determined up to ~ 10% error...

EXAMPLE: SUSY WIMPs

SNeutrino as a WIMP

Only two neutral SM superpartners: the sneutrino and the neutralino, superpartner of neutral gauge & Higgs bosons. After the neutrino the sneutrino seems an obvious choice...

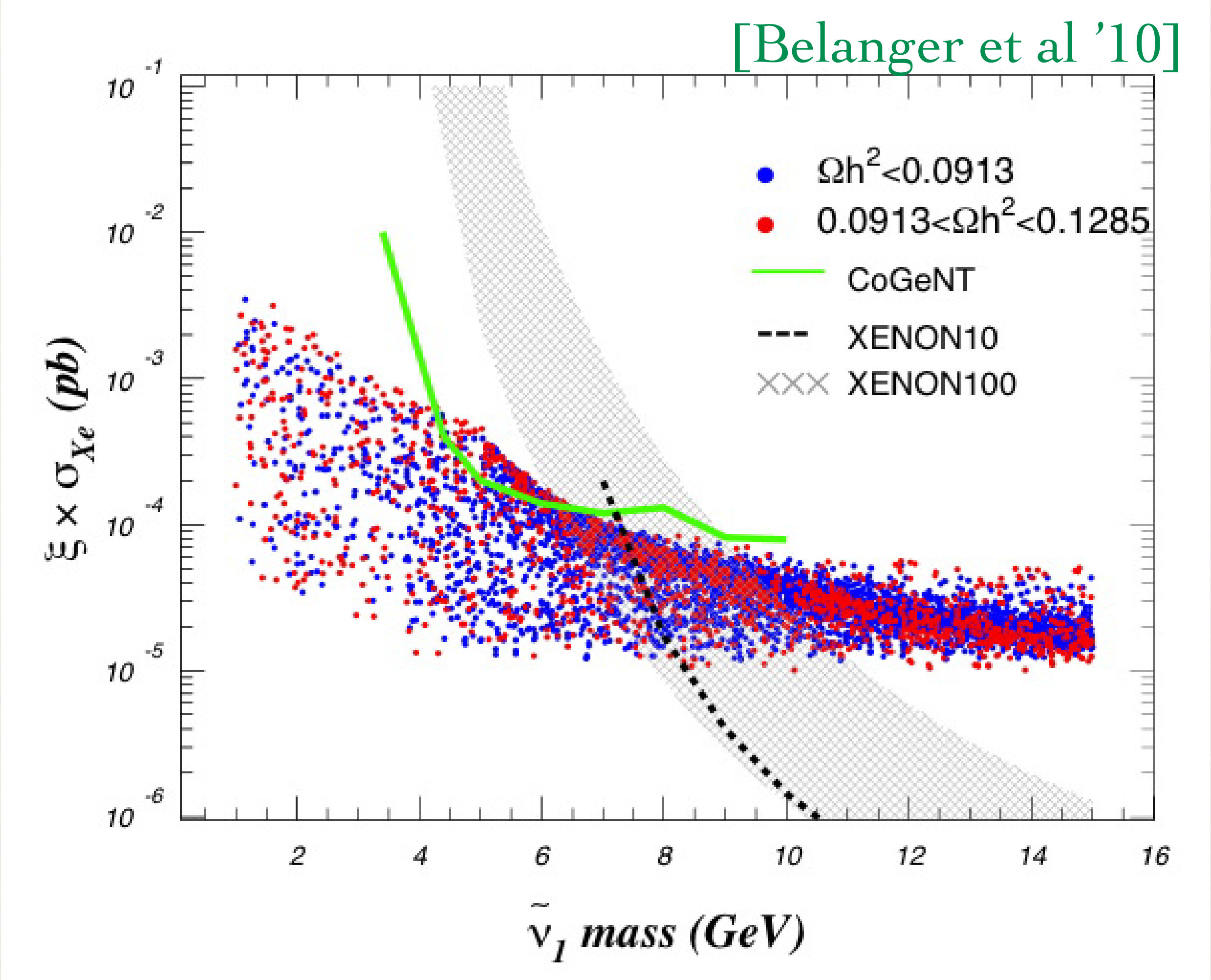




Unfortunately the LH sneutrino interacts too strongly with the Z boson: not a WIMP & also already excluded by DD exps.

Mixed sneutrino DM

A mixed sneutrino can be also very light and still have the right thermal density... But also regions at large mass are open.



Similar region and more also for mixed sneutrino in NMSSM

[Cerdeno et al '09]

Neutralino as a WIMP

The neutralino is a natural WIMP, but its mass and couplings change strongly depending on the SUSY breaking parameters: its density can span 5-6 orders of magnitude.

In general the Bino neutralino has a too large density for 100 GeV mass, while the Higgsino and the Wino too low...

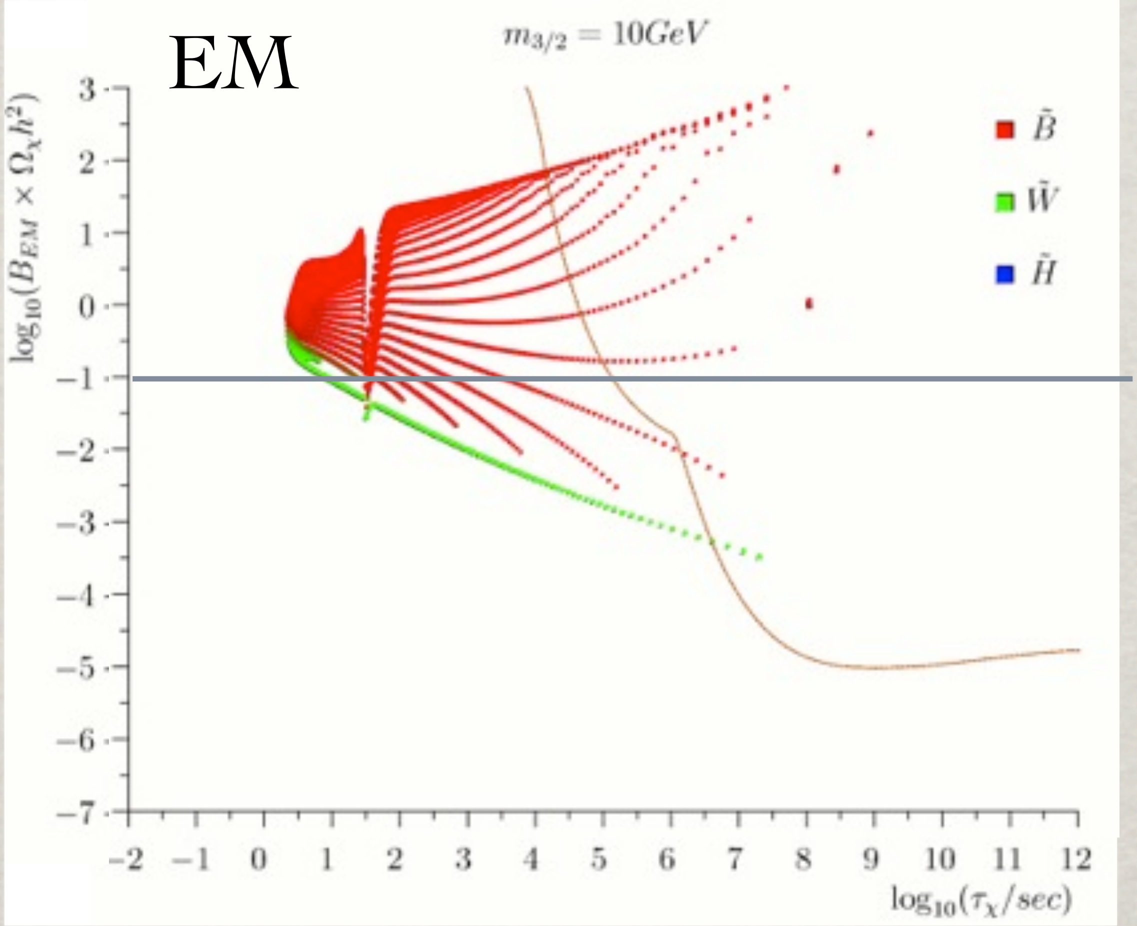
Due to the limits obtained at LEP on the sparticles masses, the natural "bulk" region of parameters (CMSSM) is excluded.

An enhancement is needed for the annihilation cross-section:

- Coannihilation with another SUSY particle;
- Resonance in the annihilation;
- Large coupling with W (higgsino component)

Bino-Wino neutralino

[LC, Hasenkamp, Roberts & Pokorski 09]

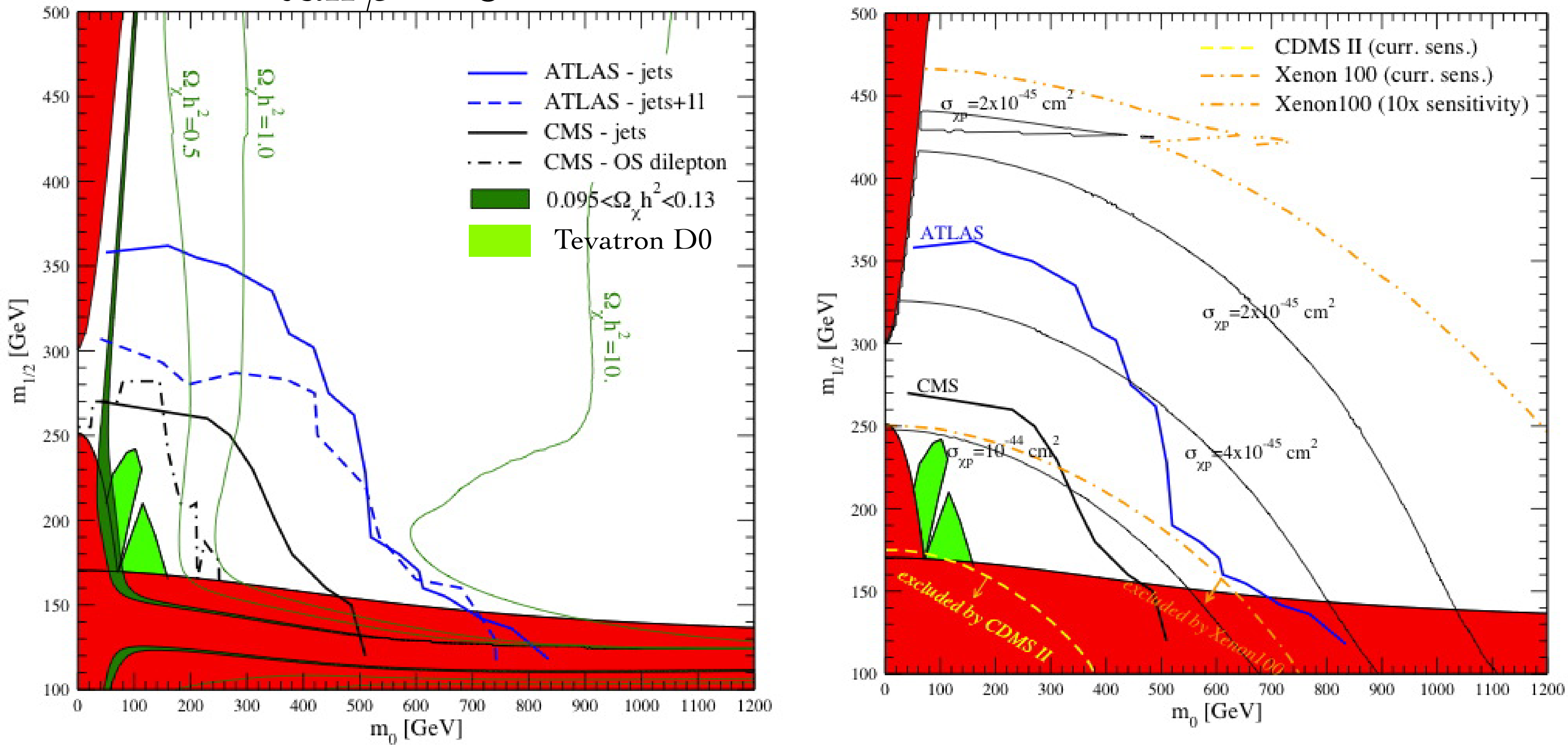


$\Omega_{CDM} h^2 \sim 0.1$

Large dependence on the neutralino composition...; consider instead a simplified model with few parameters, i.e. unified masses for spin 0 and 1/2 particles.

CMSSM NEUTRALINO 2011

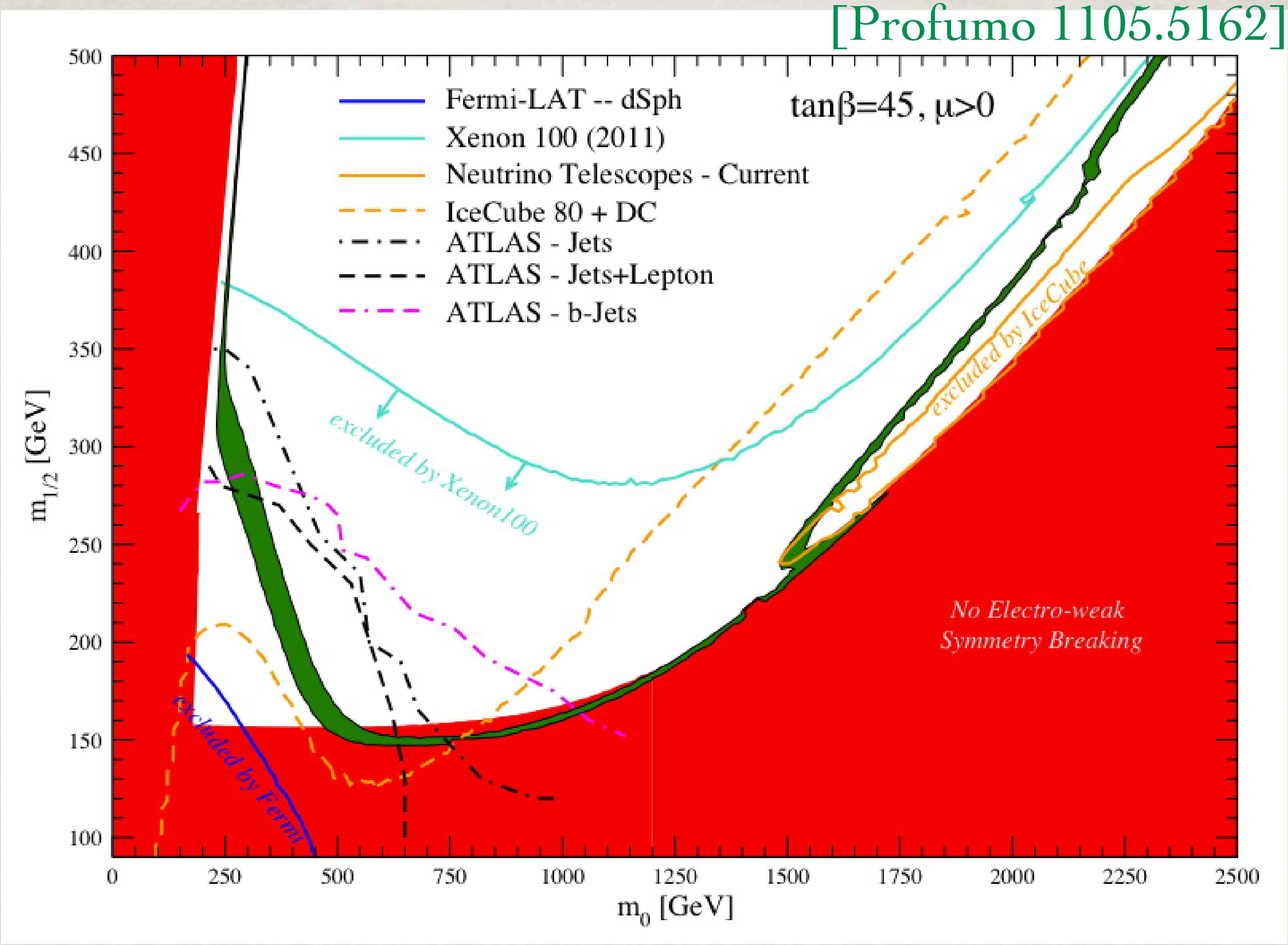
$\tan\beta = 3$ [Profumo 1105.5162]



Indirect detection not yet competitive...

Bino-stau co-annihilation funnel at low m_0 still allowed.

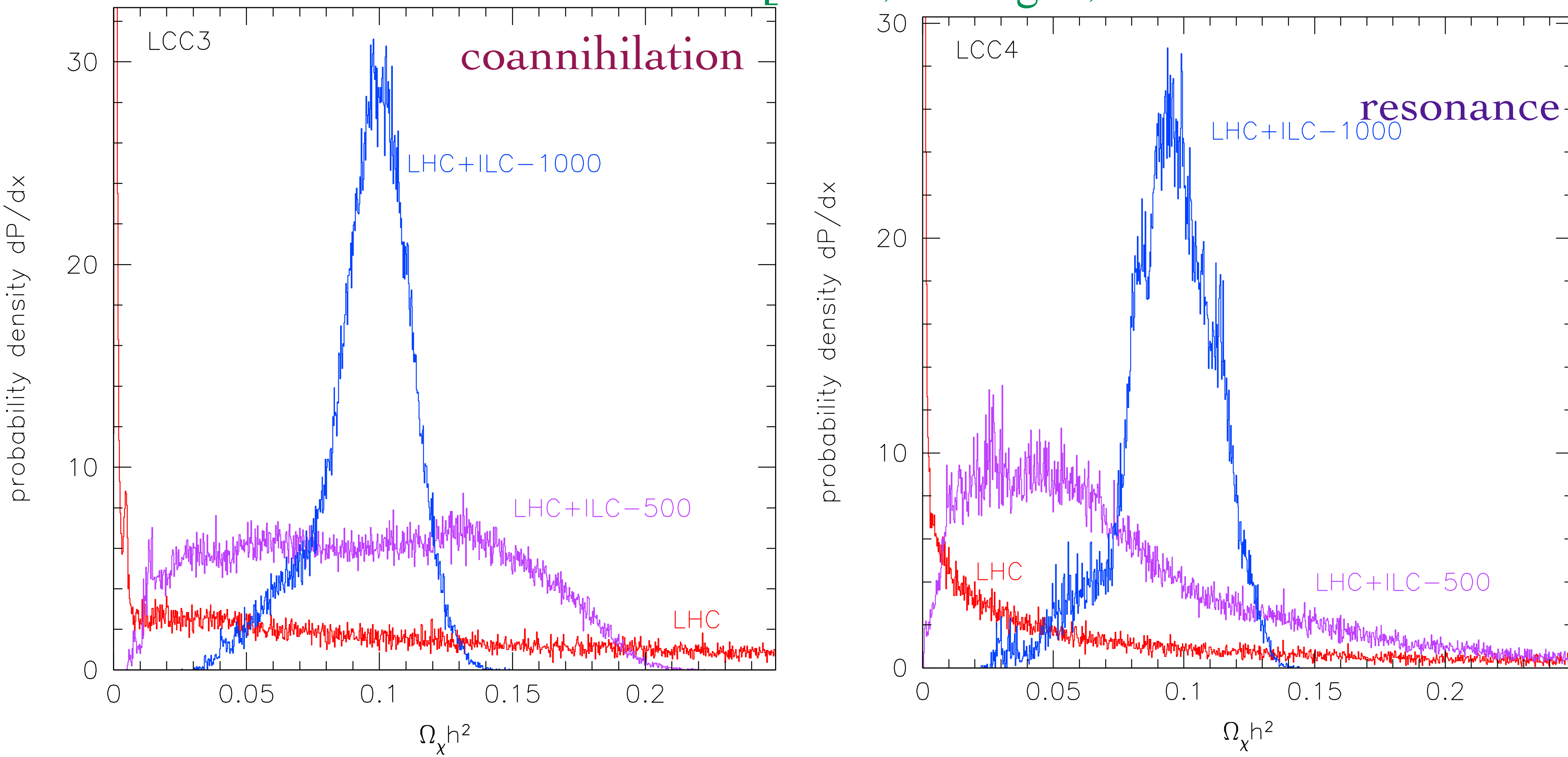
CMSSM NEUTRALINO 2011



For large $\tan\beta$ the direct and indirect detection are more important and give the stronger constraints.

RECONSTRUCTING $\Omega_{DM} h^2$

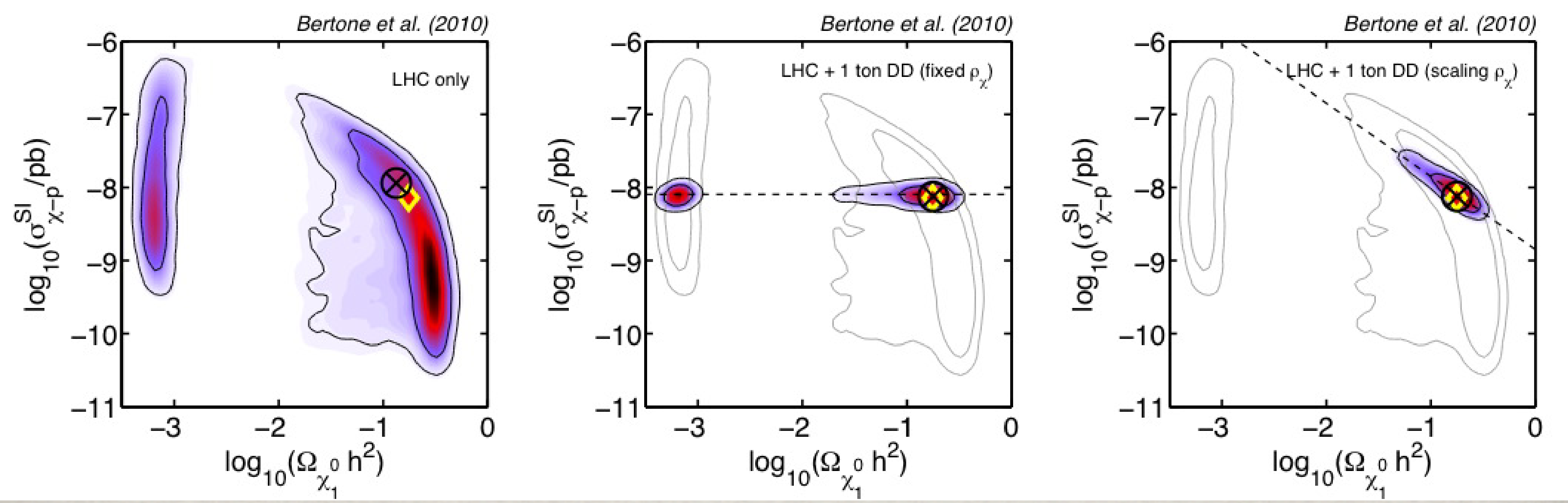
[Baltz, Battaglia, Peskin & Wizanski '06]



Pretty difficult by LHC alone in coannihilation/resonance case; still possible perhaps to improve when data are coming...

Reconstructing $\Omega_{DM}h^2$

In some cases even multiple peaks in the likelihood arise...,
not clear if the escaping particle can be DM or a thermal relic.



The inclusion of direct detection data in the analysis can lift degeneracies and single out the right solution...

In such analysis it can also be checked if the DM is a thermal relic or if other production mechanisms must be at work.

Axion
Dark Matter

Strong CP & the Axion

The QCD vacuum has a non trivial structure, as a superposition of different topological configurations, giving rise to strong CP problem from the term:

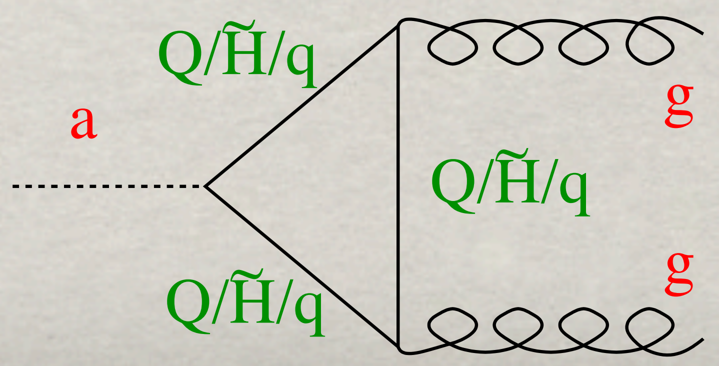
$$\mathcal{L} = \theta \; \frac{\alpha_s}{8\pi} F^b_{\mu\nu} \tilde{F}^{\mu\nu}_b$$

['t Hooft 76]

But from the bounds on neutron el. dipole moment $\boxed{\theta < 10^{-9}}$

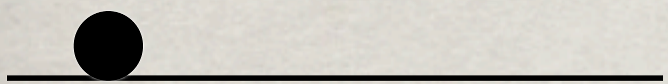
Peccei-Quinn solution: add a chiral global U(1) and break it spontaneously at f_a, leaving the axion, a pseudo-Goldstone boson, interacting as

$$\mathcal{L}_{PQ} = \frac{\alpha_s}{8\pi f_a} a F^b_{\mu\nu} \tilde{F}^{\mu\nu}_b$$



Axions as Dark Matter

The axion is also a very natural DM candidate, but in this case in the form of a condensate, e.g. generated by the misalignment mechanism:



Before the QCD phase transition the potential for the axion is flat

After the QCD phase transition a potential is generated

$$V(a) = \Lambda^4_{QCD}\left(1 - \cos\left(\theta + \frac{a}{f_a}\right)\right)$$

by instantons effects and the axion starts to oscillate coherently around the minimum:

zero momentum particles >> CDM !

Axions as Dark Matter

Their energy density by misalignment is

$$\Omega_a h^2 = 0.5 \left(\frac{f_a}{10^{12}\mathrm{GeV}} \right)^{7/6} \theta_i^2$$

Axions can contribute to star/SN cooling and so

$$0.5 \times 10^{10}\mathrm{GeV} \leq f_a \leq 10^{12}\mathrm{GeV}$$

[Raffelt 98]

Therefore the mass for axion DM is very small:

$$m_a = \Lambda_{QCD}^2 / f_a \sim 6 \times 10^{-5}\mathrm{eV} \left(\frac{f_a}{10^{11}\mathrm{GeV}} \right)^{-1}$$

AXION DM SEARCHES

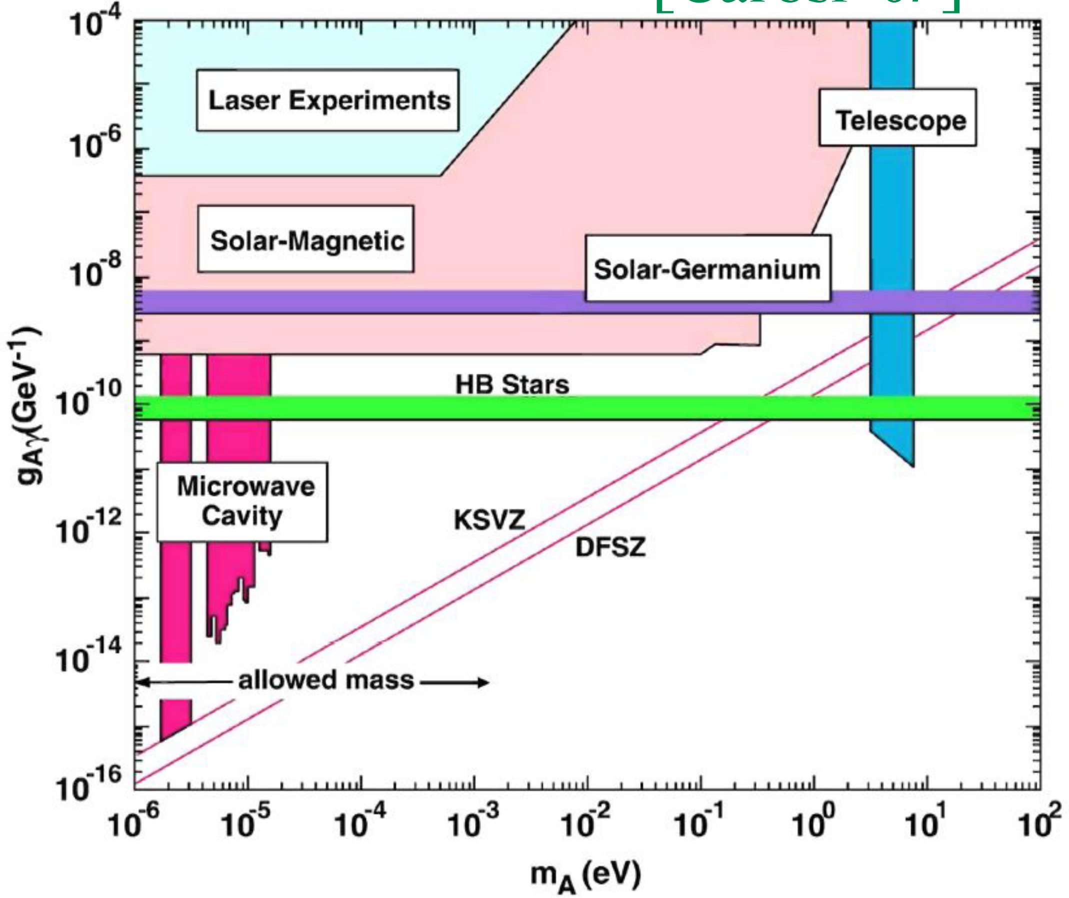
The right abundance can be obtained if the Peccei-Quinn scale is of the order of 10^{11-12} GeV and the mass in the μ eV.

ADMX is finally touching the expected region.

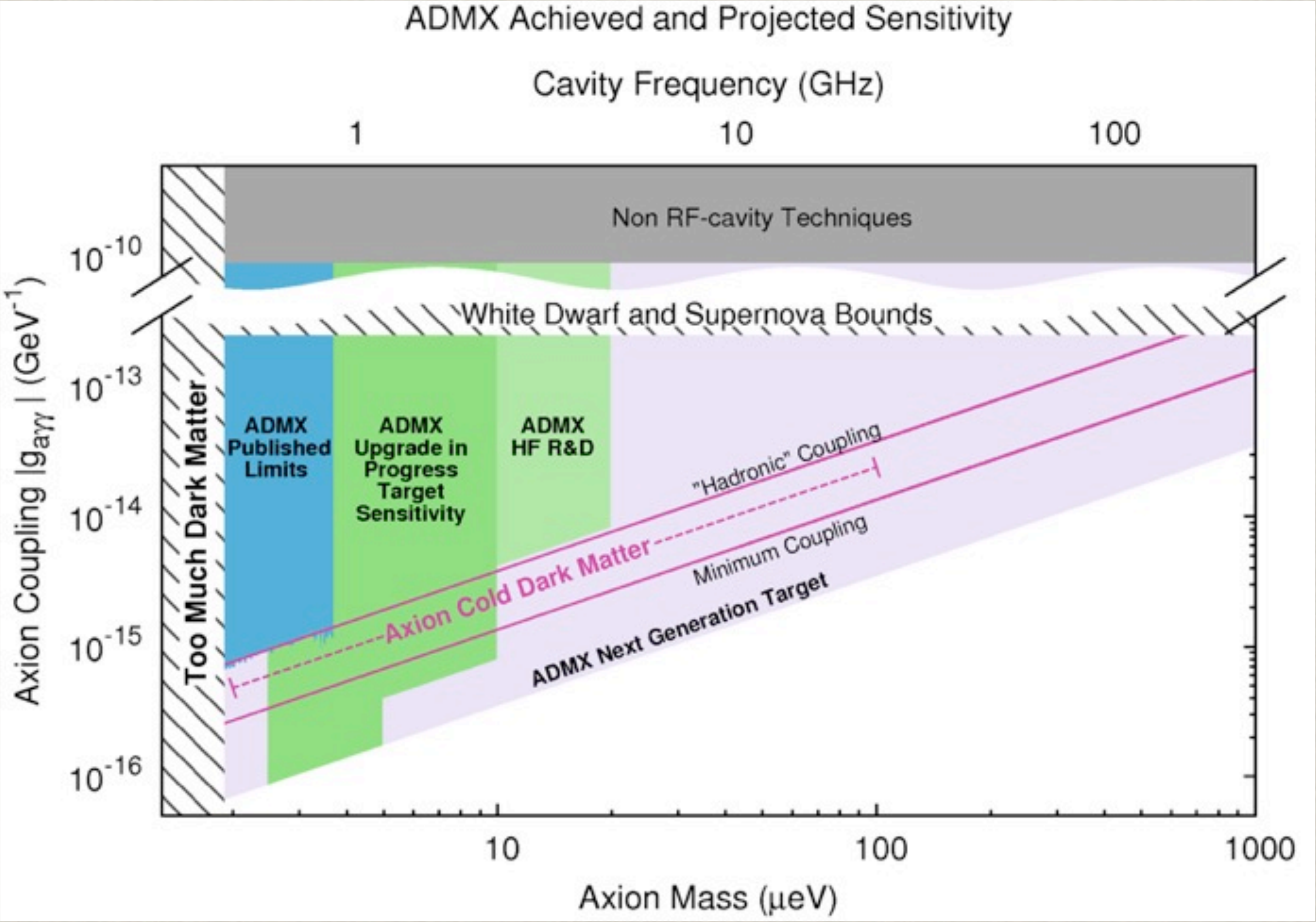
But it could be much wider for non-standard cosmologies...

[Gondolo et al 09]

[Carosi '07]



AXION DM SEARCHES



http://www.phys.washington.edu/groups/admx/home.html

Other evidence of axion DM?

- Axion DM may give rise to a different caustics shapes as Cold DM due to the BEC rotational properties... [Sikivie et al. 07, 08]

- Axion DM is a decaying DM candidate !!!
The axion decays to 2 photons like the pion, but unfortunately the lifetime is beyond reach $\tau_a \geq 10^{46} s$ and the photon energy very low ...

- In the axion/axino mixed DM case, some collider signal are expected, see e.g. [Baer et al. 08, 09,...]

- Other condensates are also possible, but need to be so long-lived and not overclose the universe...

Asymmetric Dark Matter

Asymmetric Dark Matter

[Griest & Seckel '87, Kaplan, Luty &Zurek 90, ...]

Assume instead that there is an asymmetry stored in DM as in baryons: DM asymmetry generated as the baryon asymmetries..

It may also be generated with the baryon asymmetry and then it is natural to expect

$$n_{DM} \sim n_b \rightarrow \Omega_{DM} \sim 5\,\Omega_b$$

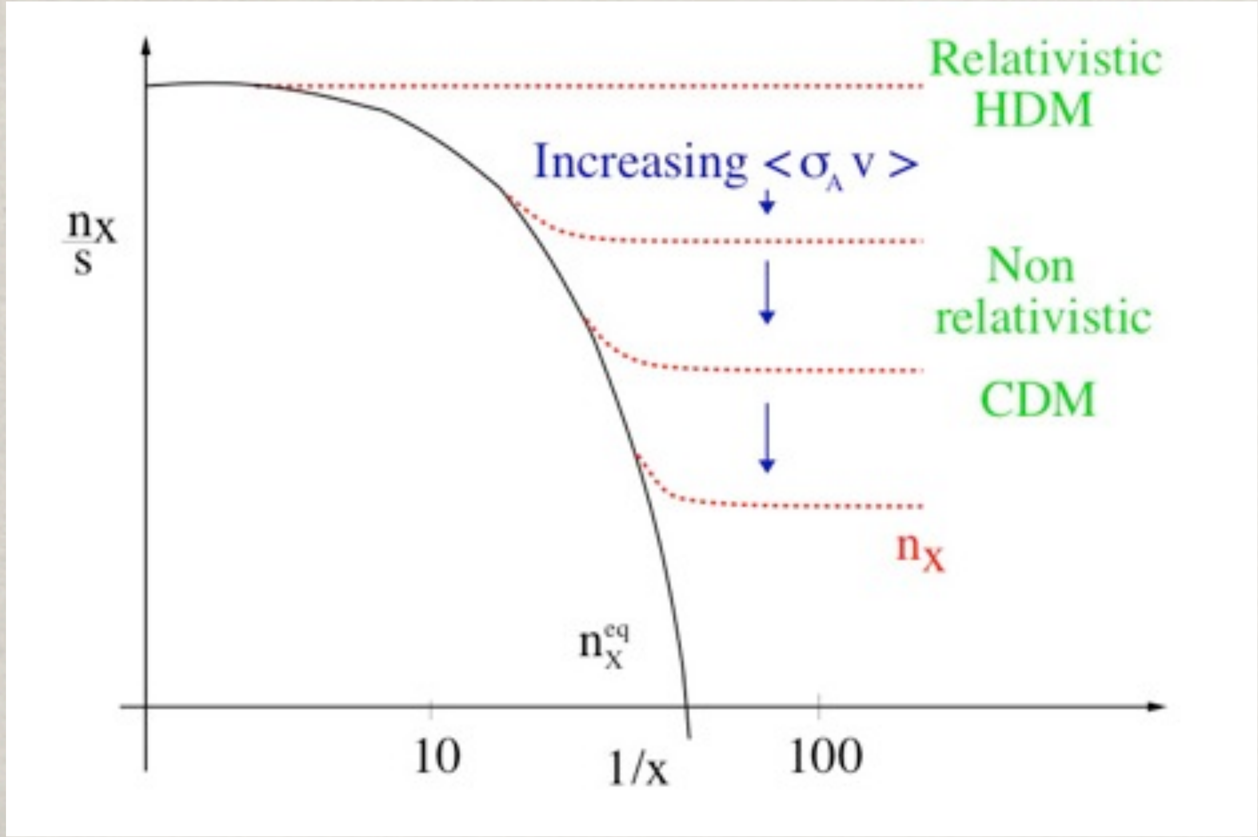
$$\text{for}\; m_{DM} \sim 5\, m_p = 5\,\mathrm{GeV}$$

Simple mechanism to generate such case: out-of-equilibrium decay of a particle producing both B-L, then reprocessed into DM/B/L or even direct asymmetric decay X -> DM + B...

All other coupling exchanging DM/B frozen out !

Asymmetric Dark Matter

DM must annihilate sufficiently strongly to erase the symmetric DM component, so it may also interact more strongly than a WIMP with normal matter...



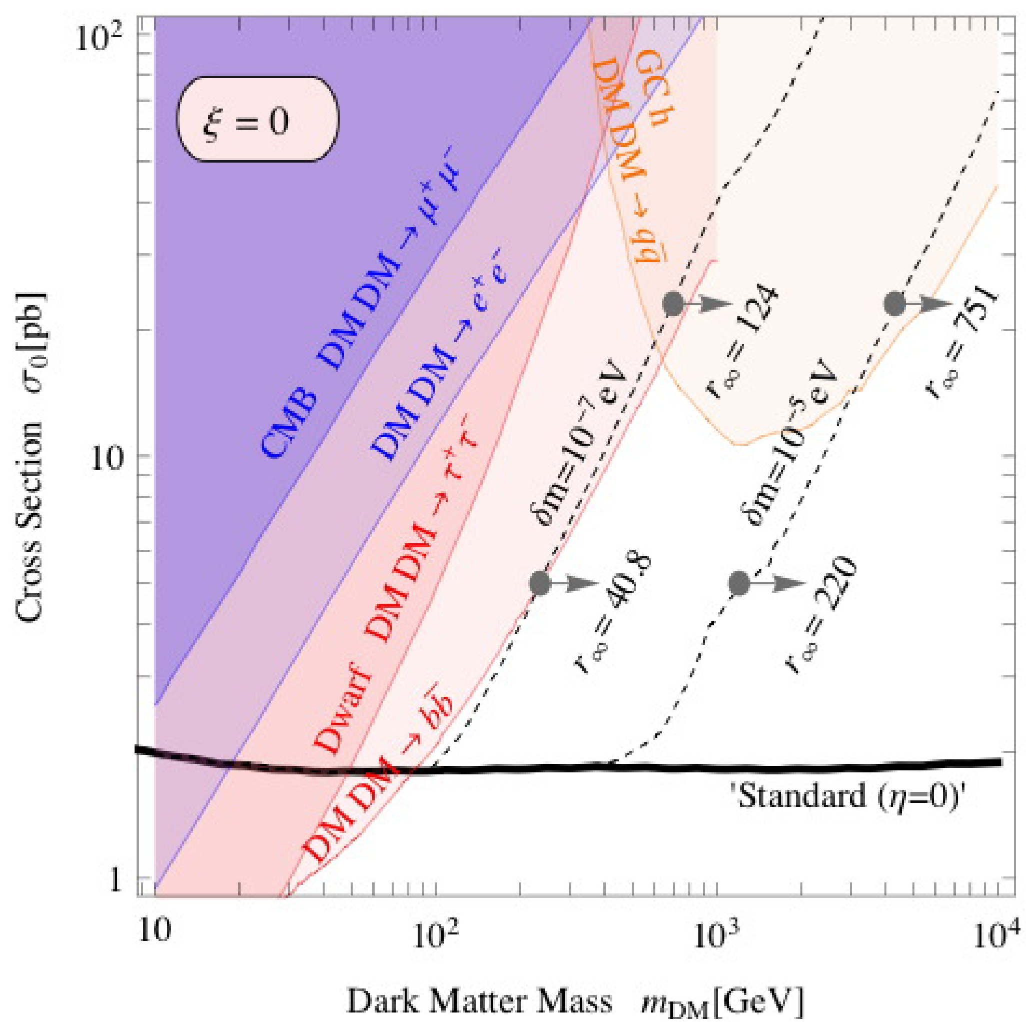
Strong coupling...
...like baryons !

It may accumulate in stars and change the star evolution...

Asymmetric Dark Matter

Some limits including also the possibility of DM-antiDM oscillation...

[Cirelli, Panci, Servant & Zaharijas 11]



ADM @ LHC ?

Strongly model dependent...

Possible to produce ADM if it interacts with colored states as possible in SUSY models, or even produce it directly if the coupling with baryons is large.

In some models ADM is connected to EW symmetry breaking, e.g. Technicolor ADM, and then a more direct influence to EW sector is also viable.

Baryogenesis

Baryogenesis

- The CMB data and BBN both require $\Omega_B \sim 0.05$
- Can it be a relic of thermal decoupling from a symmetric state ? NO ! Decoupling "a la WIMP" give a value $\Omega_B \sim 10^{-10}$, way too small...
- Are we living in a matter patch ??? No evidence of boundaries between matter/antimatter in gammas or antinuclei in cosmic rays... Our patch is as large as the observable Universe !
- No mechanism know can create such separation... The Universe is asymmetric !

Sakharov Conditions

Sakharov studied already in 1967 the necessary conditions for generating a baryon asymmetry from a symmetric state:

- B violation: actually need B-L violation since B+L is violated by the chiral anomaly

$$\partial_\mu J^\mu_{B+L} = 2n_f \frac{g^2}{32\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

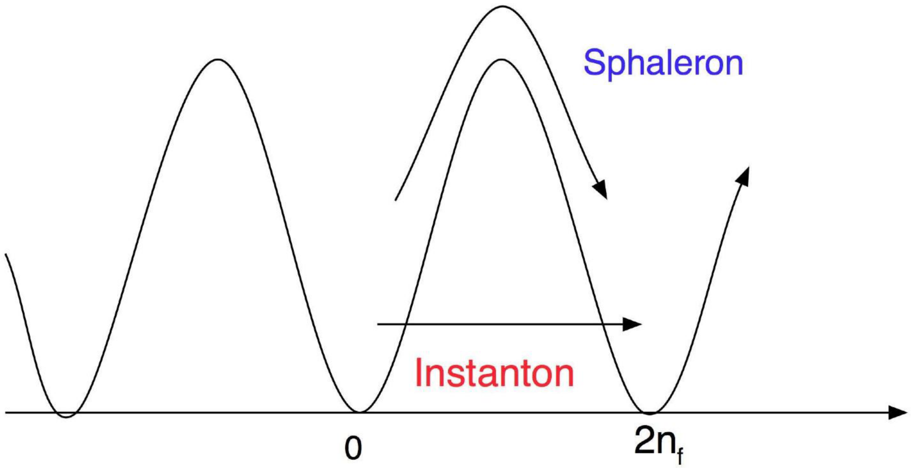
- C and CP violation: otherwise matter and antimatter would still be annihilated/created at the same rate

- Departure from thermal equilibrium: the maximal entropy state is for B = 0, or for conserved CPT, no B generated without time-arrow...

Sphaleron Processes

$B + L$ violation in the Standard Model

In the SM the global $U(1)_{B+L}$ is anomalous. This is related to the complex vacuum structure of the theory, which contains vacua with different configurations of the gauge fields and different topological number. Non-perturbative transitions between the vacua change $B + L$ by $2n_f$.



– $T = 0$: tunneling and is suppressed by $e^{-\frac{4\pi}{\alpha_W}} \ll 1$

$\rightarrow B$ & L practically conserved!

– $T > 0$: the transition can happen via a sphaleron

with rate $\Gamma_{sph}(T) \sim \left(\frac{M_W}{\alpha_W T}\right)^3 M_W^4 e^{-E_{sph}/T}$

So at temperatures $T \geq 100$ GeV sphaleronic transitions are in equilibrium in the Universe $\rightarrow B + L$ erased if $B - L = 0$, otherwise

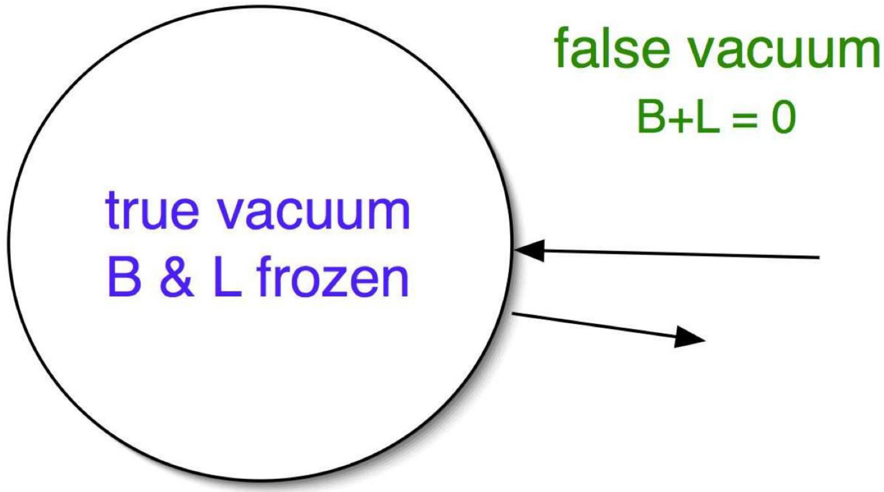
$$B = \frac{8n_f + 4n_H}{22n_f + 13n_H}(B - L)$$

A $B - L$ number is reprocessed into B number !

Is it possible to have baryogenesis in the SM ???

We have B violation via sphalerons, C and CP are present due to the phase in the CKM matrix, what about departure from thermal equilibrium ??? This also happens in the SM if the electroweak phase transition is strongly 1^{st} order. [Kuzmin, Rubakov & Shaposhnikov 85] $\longrightarrow$ Bubble nucleation !

Electroweak baryogenesis



The strength of the transition depends on the height of the barrier between the true and false vacua v/T_c and so on the Higgs mass. Lattice studies have shown that the phase transition in the SM is first order only for masses $m_H \leq 40$ GeV, while now we know that $m_H \geq 114$ GeV: the mechanism does not work in the Standard Model !!! Still it could in the MSSM and extended model:

- stronger phase transition: 1^{st} order until $m_H \sim 120$ GeV for one light stop;
- more CP violating phases, while in SM $J \sim 10^{-20}$ perhaps too small.

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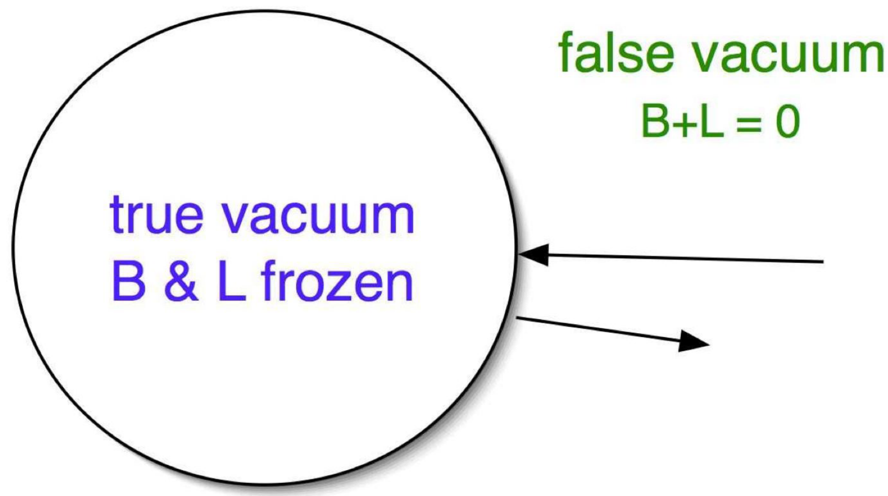

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Baryogenesis mechanisms

Again need to go beyond the Standard Model :

- EW baryogenesis in extensions of the SM with: more scalars, more CP violations... This is possible in Supersymmetry, but also without.

- Leptogenesis: generate first L via decay of heavy Majorana neutrinos -> connection to the see-saw mechanism and neutrino masses.

- Affleck-Dine baryogenesis: store baryon number in a scalar condensates and transfer it to particles when the condensate decays. Mostly studied in SUSY !

EW Baryogenesis in BSM

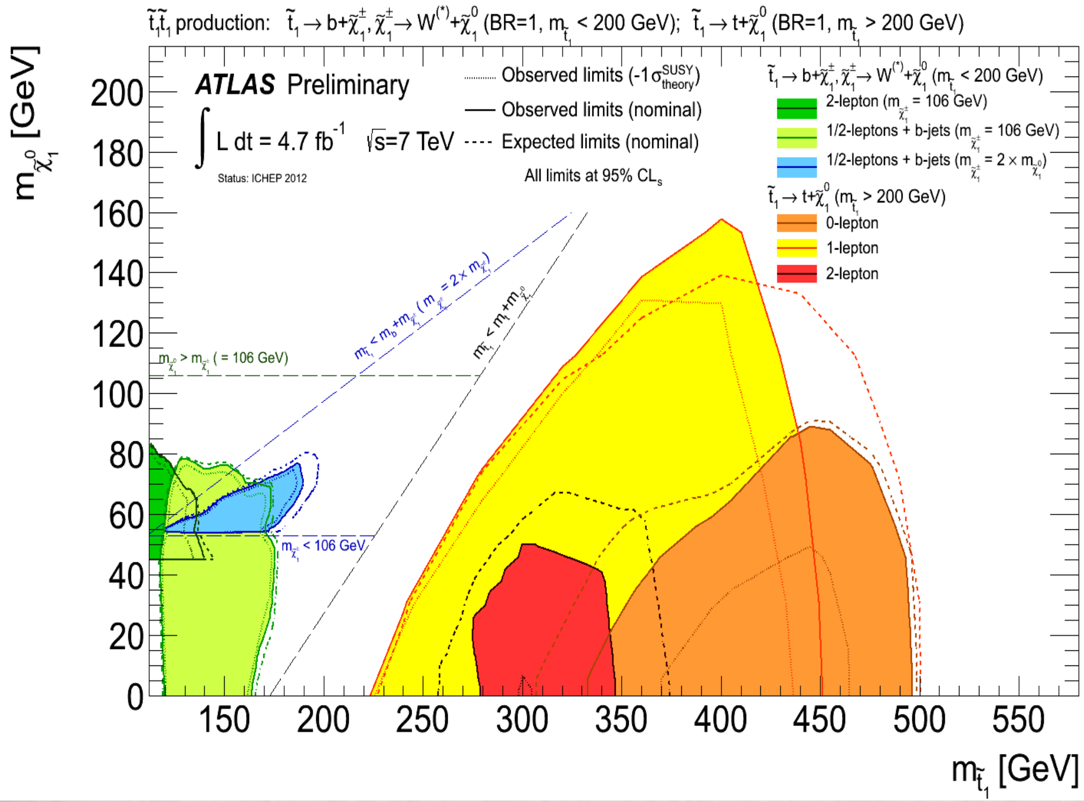
In extensions of the SM EW baryogenesis is possible if

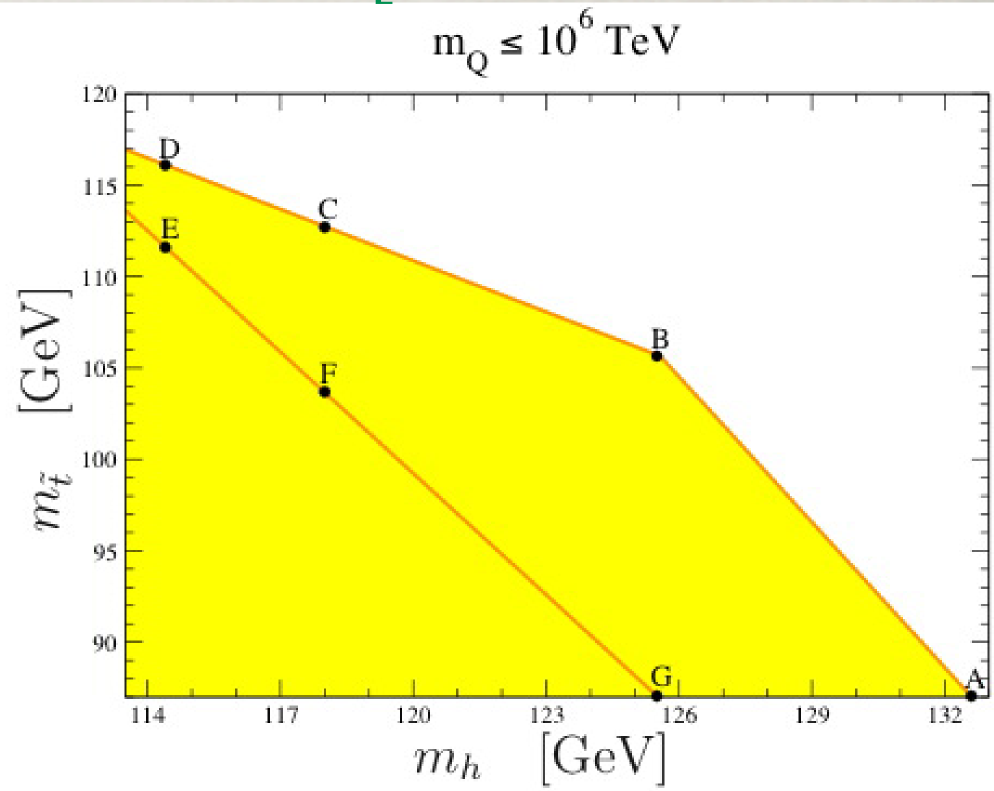
- The phase transition is stronger: e.g. by enhancing the cubic term in the Higgs potential thanks to (light) scalars, e.g. in SUSY stops or singlets !
- There are additional CP violating phases to increase the amount of CP violation.
- Still the Higgs has to be light... in MSSM EW baryogenesis ~ 120 GeV with one stop state below the top... Is it possible with a 125 GeV Higgs ?

EW Baryogenesis in SUSY

In the MSSM a 125 GeV Higgs is still OK for heavy squarks. Still the light stop should be lighter than the top, some region of parameters is already probed by LHC...

[Carena et al 1207.6330]





On the other hand, the light stop enhances ALL higgs-VV couplings and seem not to be what LHC finds for the Higgs...

Baryogenesis via Leptogenesis

[Fukugita & Yanagida '86]

Produce the baryon asymmetry from an initial lepton asymmetry reprocessed by the sphaleron transitions. Naturally possible in the case of see-saw mechanism for generating the neutrino masses.

$$W = Y_\nu LHN + \frac{1}{2} M_R NN \quad \longrightarrow \quad \text{see-saw}$$

Moreover the RH Majorana neutrino can generate a lepton asymmetry via decay if the rate also violates CP

$$N \to \ell \, H \qquad N \to \bar{\ell} \, H^\star$$

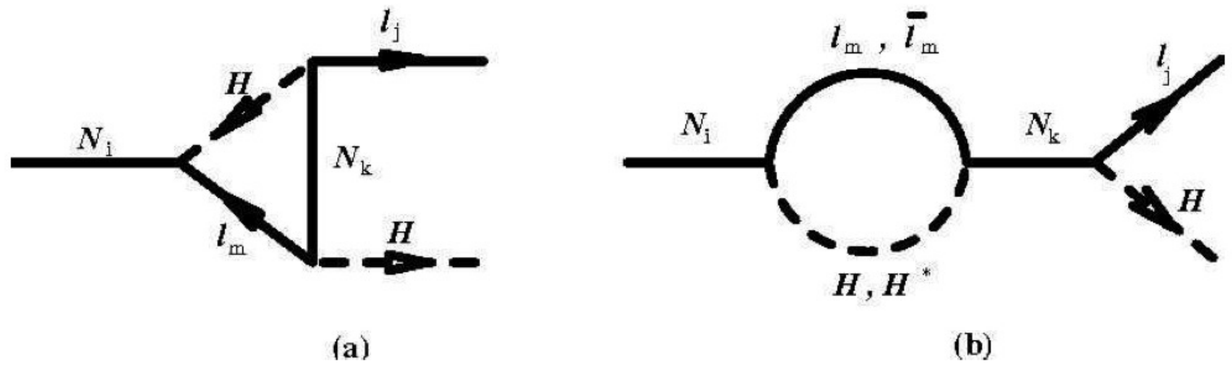
Both channel are possible due Majorana nature of N !

Thermal Leptogenesis

CP violation in N decay

We have CP in the decay of N if the couplings are complex.

CP violation always arises from an interference: tree + one-loop diagrams



We can define

$$\epsilon_i = \frac{\Gamma(N_i \to L) - \Gamma(N_i \to \bar{L})}{\Gamma(N_i \to L) + \Gamma(N_i \to \bar{L})} = -\frac{3}{16\pi} \sum_{i \neq j} \frac{M_i}{M_j} \frac{\Im[(Y_\nu^\dagger Y_\nu)^2_{ji}]}{(Y_\nu^\dagger Y_\nu)_{ii}} \text{ for } M_i \ll M_j$$

It is bounded ! $\rightarrow$relation to neutrino masses via Y_ν...

$$\epsilon \leq 10^{-6} \left(\frac{M_1}{10^{10}\ \mathrm{GeV}} \right) \frac{m_{atm}}{m_1 + m_3}$$ [Davidson & Ibarra 02]

Thermal Leptogenesis

The "back of the envelope" computation:

Out of equilibrium decay

To generate the lepton asymmetry we need also departure from thermal equilibrium: out of equilibrium decay of the lightest N. This happens if $\Gamma_1 \leq H$ at $T \sim M_1$.

$$\Gamma_1 = \frac{(Y_\nu^\dagger Y_\nu)_{11}}{16\pi} M_1 \leq H = \sqrt{\frac{\pi^2 g_*}{90}} \frac{M_1^2}{M_P}$$

$\Rightarrow M_1 \geq \sqrt{\frac{90}{\pi^2 g_*}} \frac{(Y_\nu^\dagger Y_\nu)_{11}}{16\pi} M_P$, i.e. the RH neutrino have to be sufficiently massive. Or one can refrase it as

$$\tilde{m}_1 = \frac{(Y_\nu^\dagger Y_\nu)_{11} v^2}{M_1} \leq \sqrt{\frac{\pi^2 g_*}{90}} \frac{v^2}{M_P} \sim 10^{-3}\text{eV}$$

If this condition is satisfied, then it is trivial to see that every N gives an ϵ amount of lepton number and the final asymmetry is simply

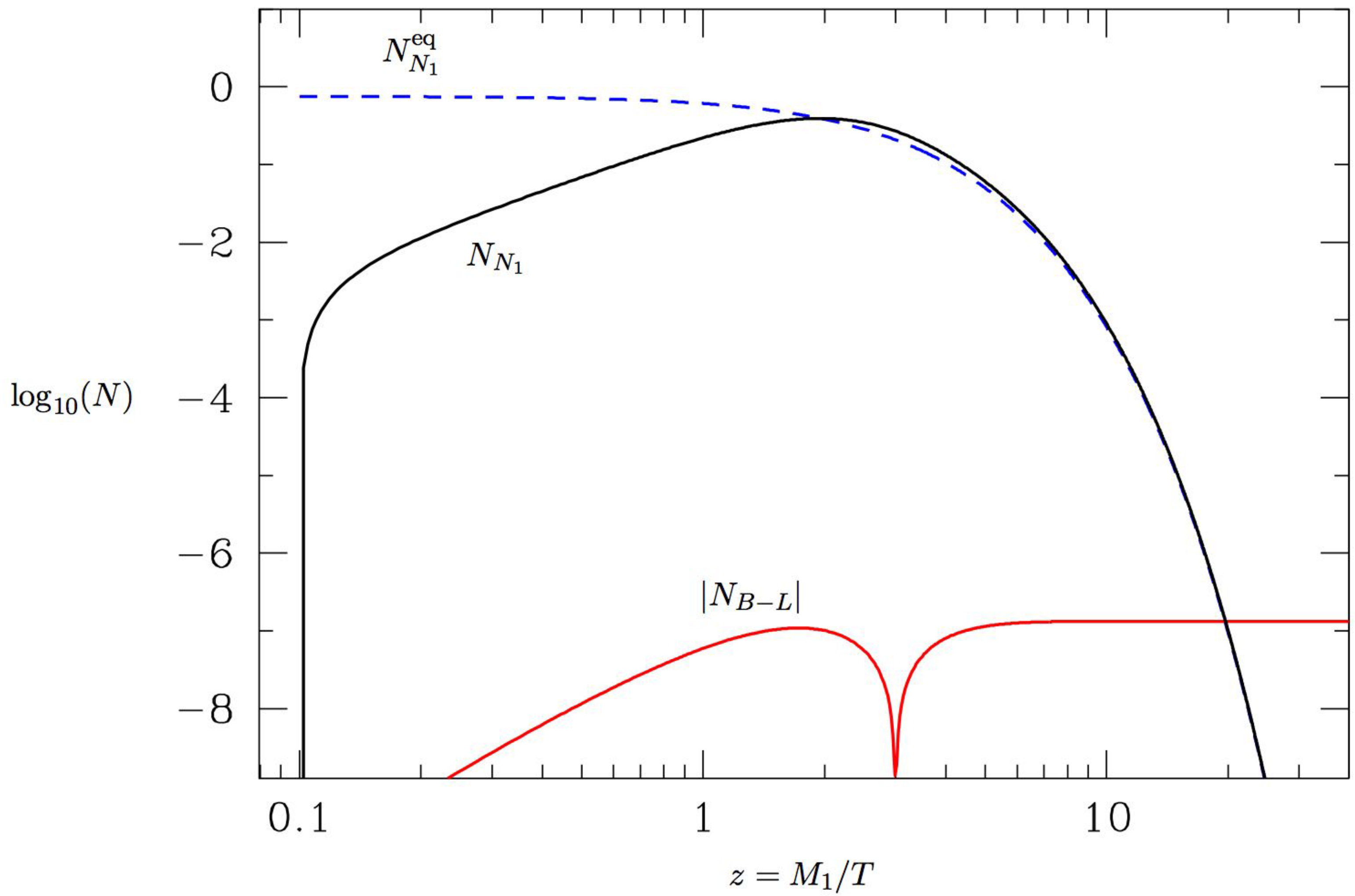
$$\frac{n_L}{s} = \frac{n_{B-L}}{s} = \frac{135\zeta(3)g}{8\pi^4 g_S}\epsilon_1 \simeq 4 \times 10^{-3}\epsilon_1 \quad \rightarrow \frac{n_B}{s} \sim -1.5 \times 10^{-3}\epsilon_1$$

Otherwise one has to solve a couple of Boltzmann equations...

Thermal Leptogenesis

The solution of the coupled Boltzmann equations:

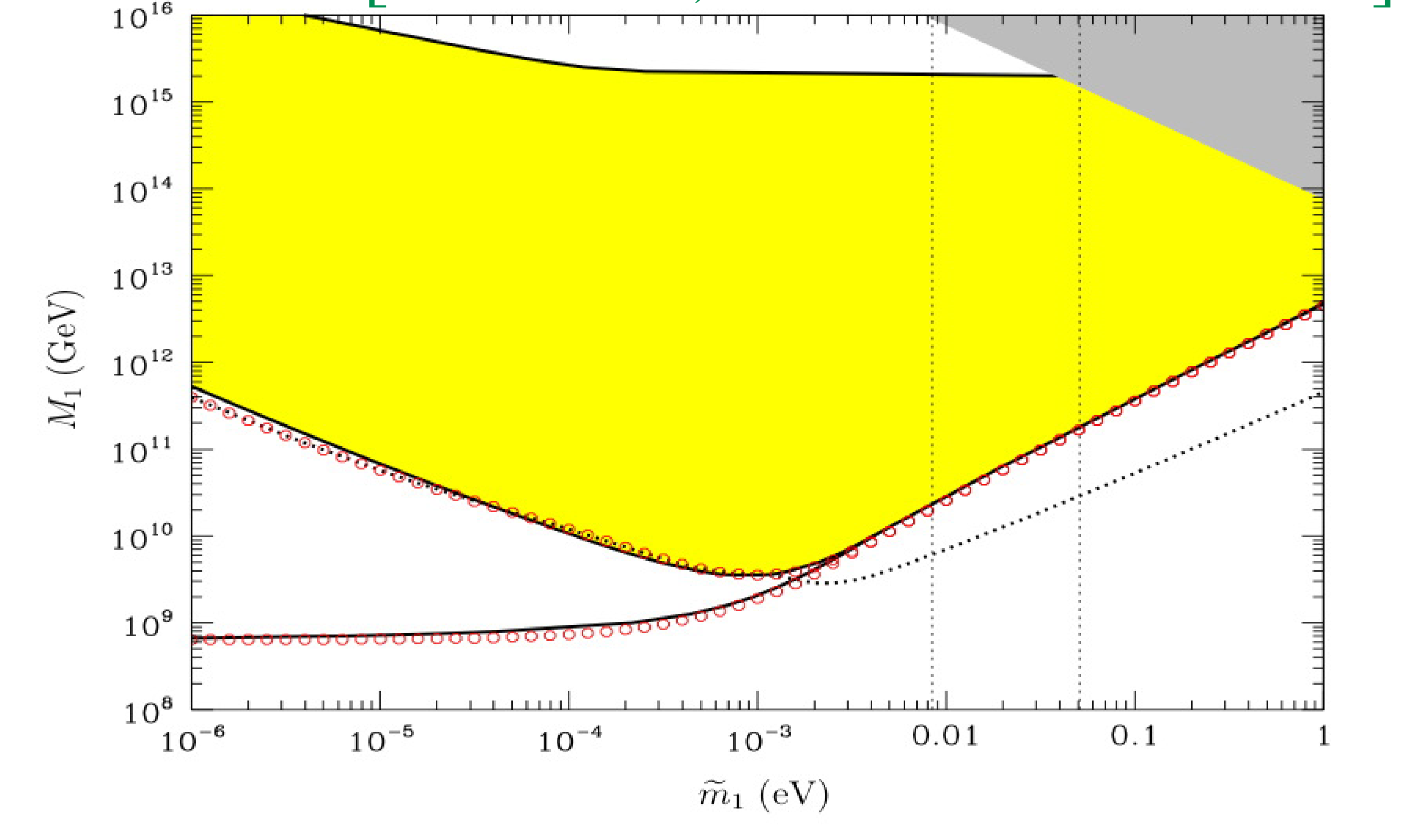
[Buchmüller, Di Bari & Plümacher '04]



Thermal Leptogenesis

M_1 must be large enough to generate the baryon asymmetry, for small M_1 the CP violation is just too small. Need large T_{RH} to produce the RH neutrino...

[Buchmüller, Di Bari & Plümacher 04]



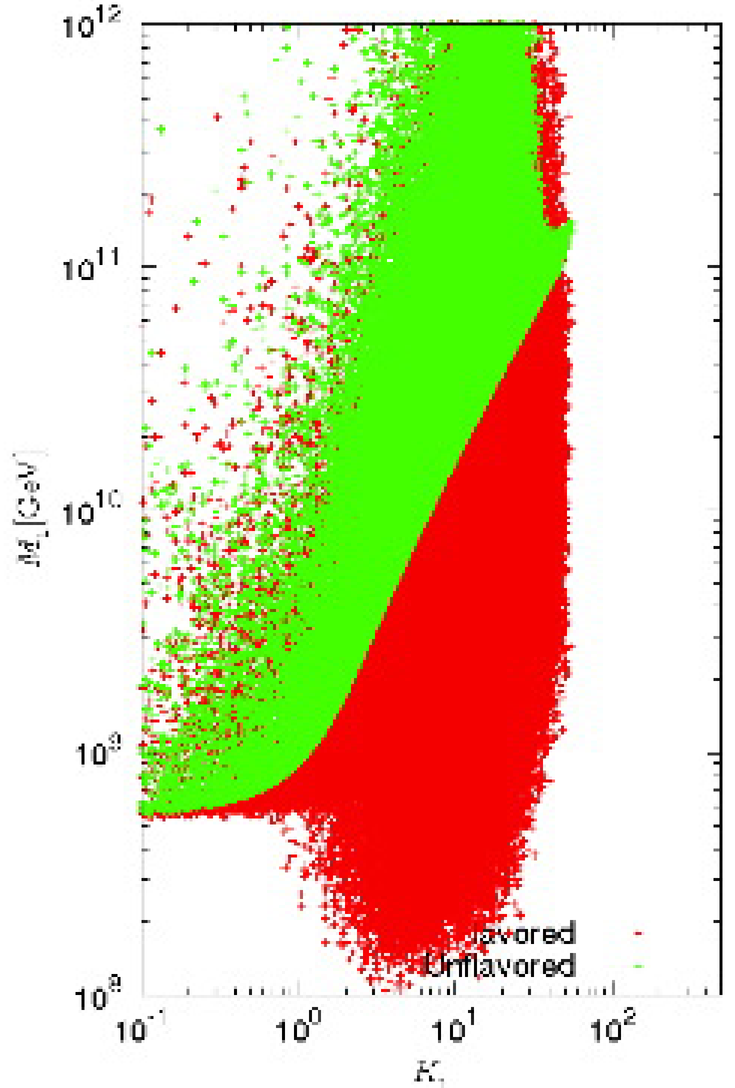
Ways out: enhanced CP violation due to degenerate N's, non-thermal leptogenesis, etc...

Thermal Leptogenesis

[Abada et al, Nardi et al '06, Simone et al '07....]

- Flavoured leptogenesis: add the evolution of the single lepton flavours since they have different Yukawa & so (for RH state) equilibration time. Then it is possible to store L into one/two flavours and relax a bit the constraints..., but not much unfortunately !

[Di Bari 1206.3168]

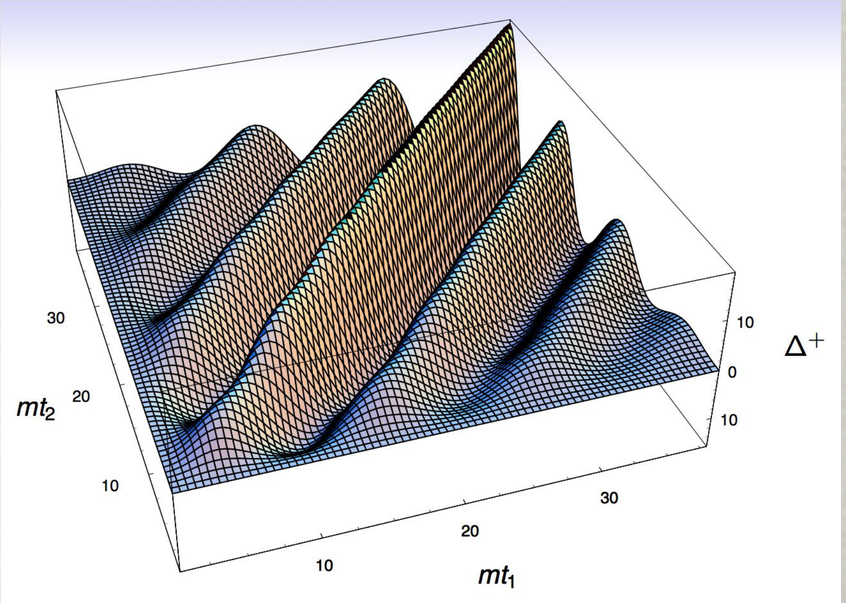


Thermal Leptogenesis

[Buchmüller et al, Garbrecht et al, Garny et al, Drewes et al....]

- Quantum leptogenesis:
  Full quantum mechanical description of the process using Kadanov-Baym equations (2nd order) instead than Boltzmann equations... More effects in principle possible !

- Different statistical/spectral propagators depending on two time variables and solutions include full particle width and memory effects...



Outlook

Conclusions & Outlook

- Dark Matter is still an unsolved puzzle, but we have already excluded some candidates: baryons, neutrinos, Hot DM, sneutrinos...
- If Dark Matter is a WIMP, we should see it at colliders, in direct detection experiments and in indirect detection:Important consistency check !
- If Dark Matter is not a WIMP, there are still chances of a signal, but it depends on the model.
- For baryogenesis: EW is being tested by LHC, leptogenesis is more difficult to check...

Lots of OPEN QUESTIONS remain..., luckily more data are expected soon !