6th NeXT PhD Workshop: The Quest for New Physics in the LHC Run II Era

Brighton, 20-23 June 2016

Particle astrophysics & Cosmology

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Outline

- Lecture 1 & 2:
  Standard Cosmology, Inflation and Structure Formation

- Lecture 3:
  Dark Matter & Baryogenesis

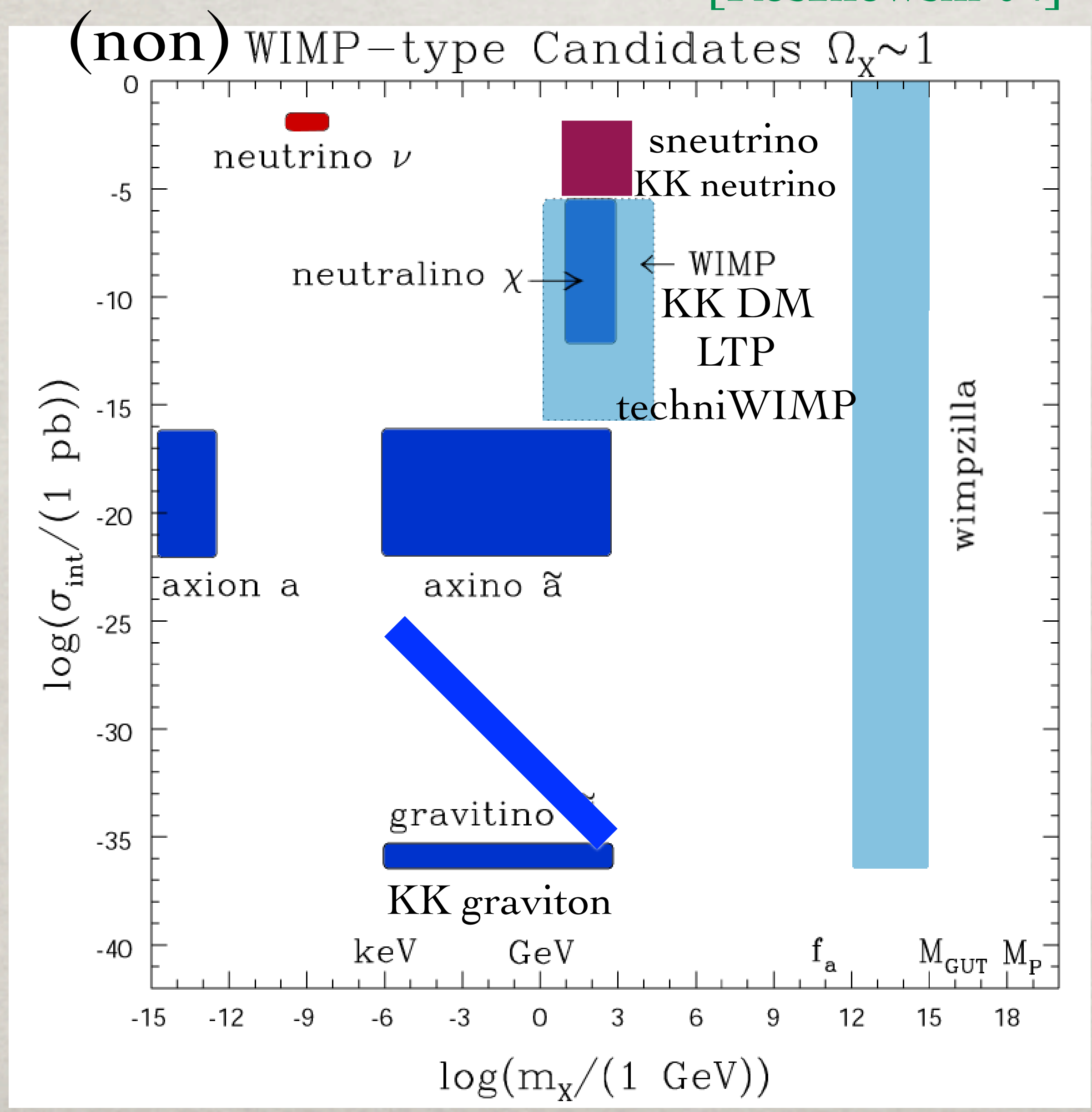
Lecture 3: Outline

- (Some) Dark Matter Candidates and how to detect them
- CP violation in the SM & beyond
- Baryogenesis & the Sakharov conditions
- Mechanisms for baryogenesis
- Conclusions

Dark Matter candidates

DARK MATTER CANDIDATES

[Roszkowski 04]



Too many different candidates...

Standard DM production paradigms:

WIMPs

(i.e. neutralino)

&

"FIMP/ SuperWIMPs"

(i.e. gravitino)

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

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

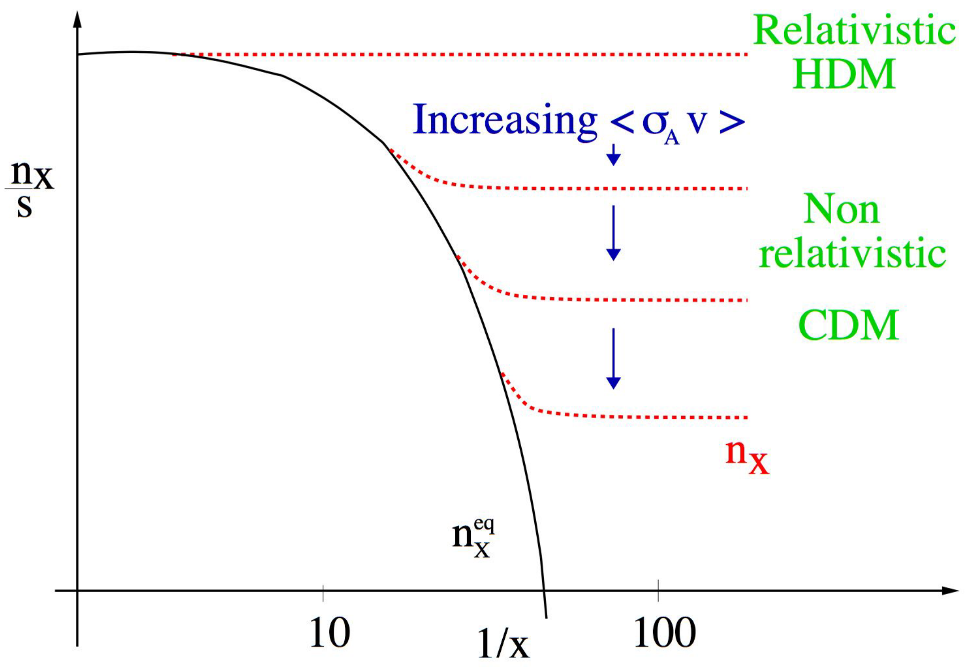
Hubble expansion   Collision integral

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



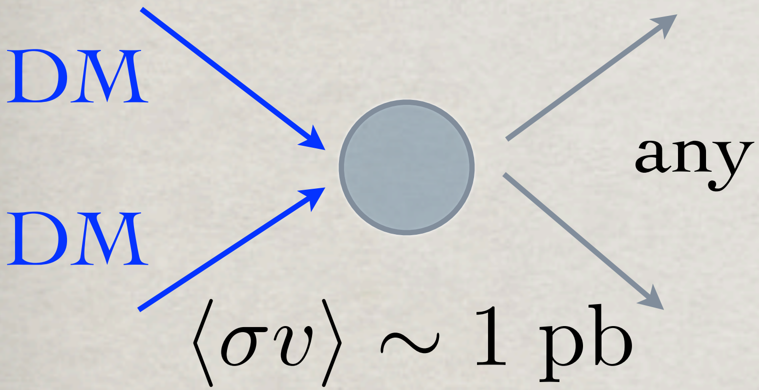
For $m_X \simeq 100$ GeV a WEAK cross-section is needed !

Weakly Interacting Massive Particle

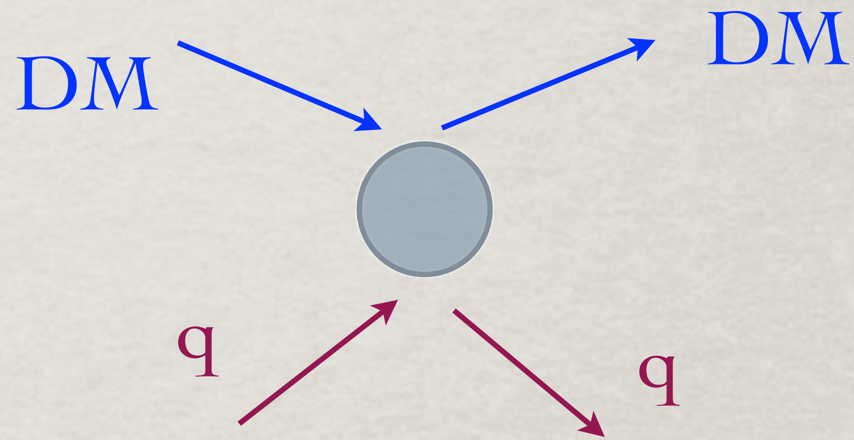
For weaker interactions need lighter masses HOT DM !

THE WIMP CONNECTION

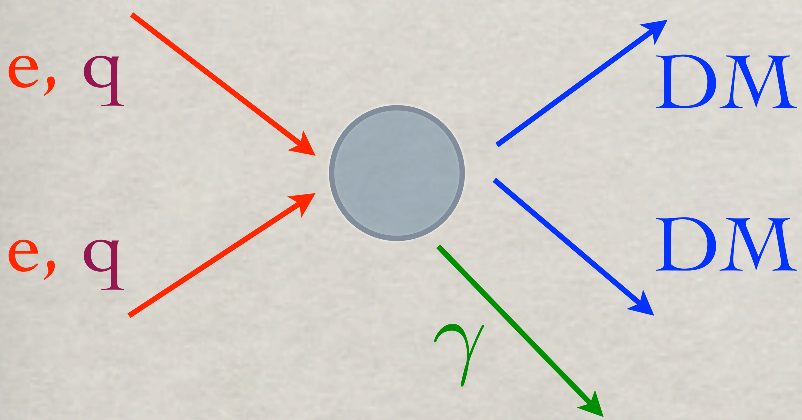
Early Universe: $\Omega_{CDM} h^2$



Direct Detection:



Colliders: LHC/ILC



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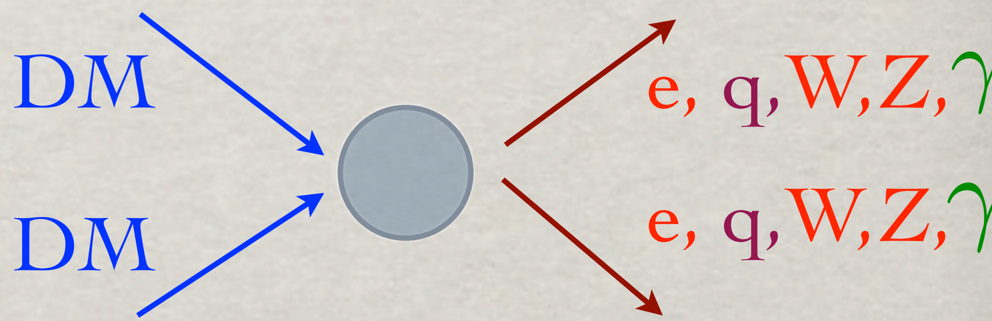


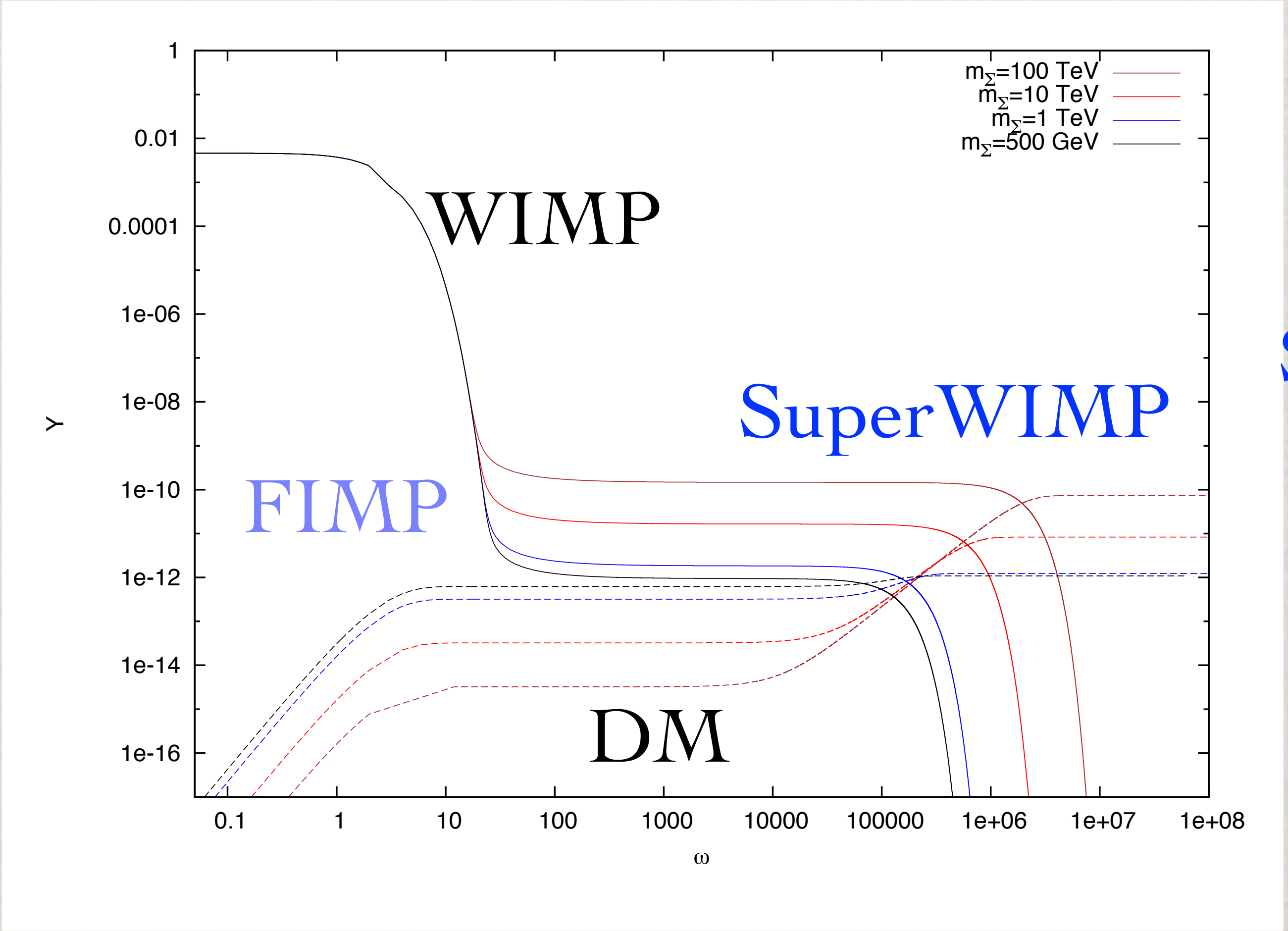
3 different ways to check this hypothesis !!!

SuperWIMP/FIMP paradigms

Add to the BE a small decaying rate for the WIMP into a much more weakly interacting (i.e. decaying !) DM particle:

[Hall et al 10]

FIMP DM produced by WIMP decay in equilibrium



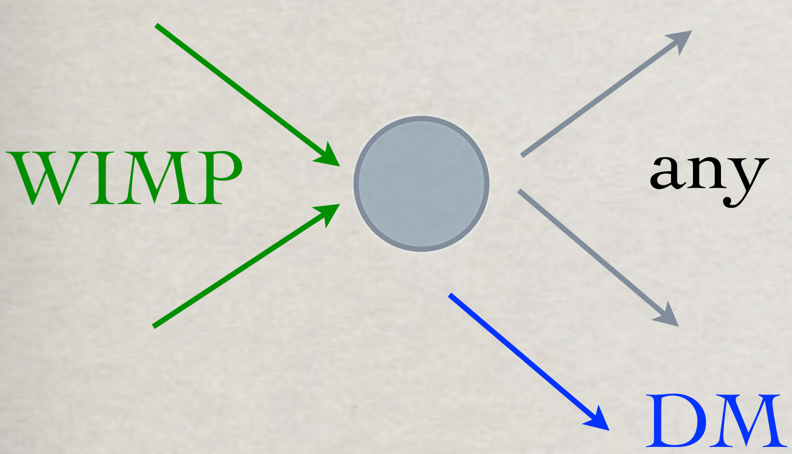
[Feng et al 04]

SuperWIMP DM produced by WIMP decay after freeze-out

Two mechanism naturally giving "right" DM density depending on WIMP/DM mass & DM couplings

F/SWIMP CONNECTION

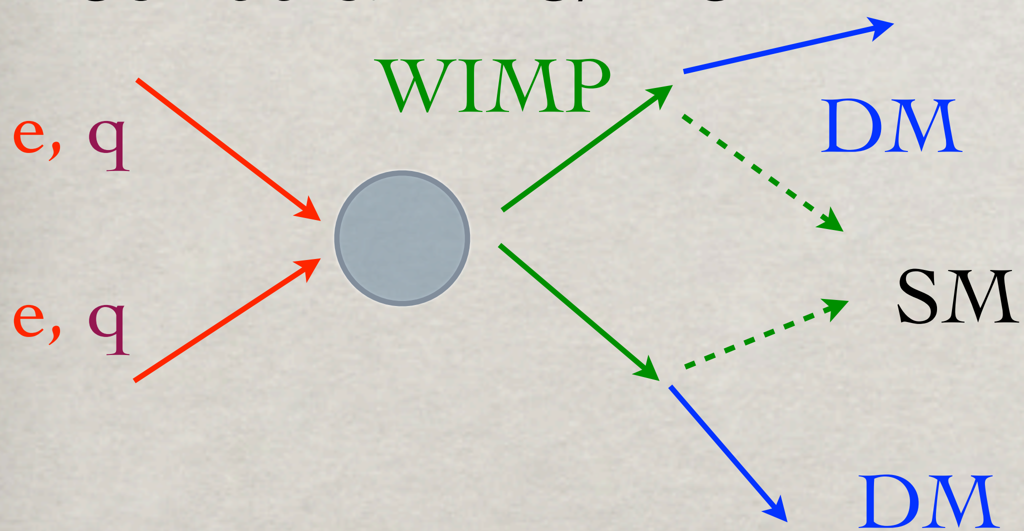
Early Universe: $\Omega_{CDM} h^2$



Direct Detection:

NONE...

Colliders: LHC/ILC



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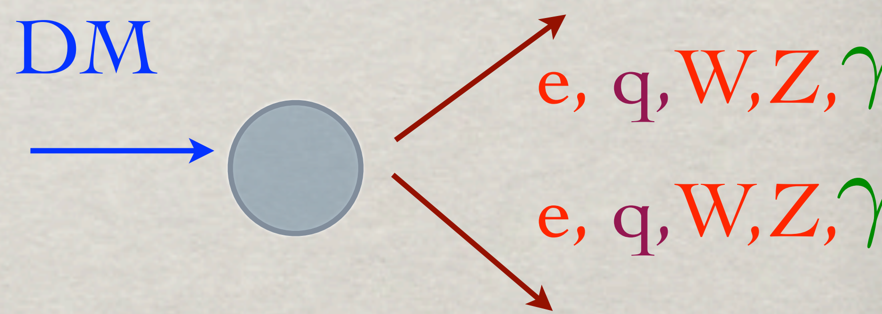

decaying DM !

3 different ways to check this hypothesis !!!

F/SWIMP CONNECTION

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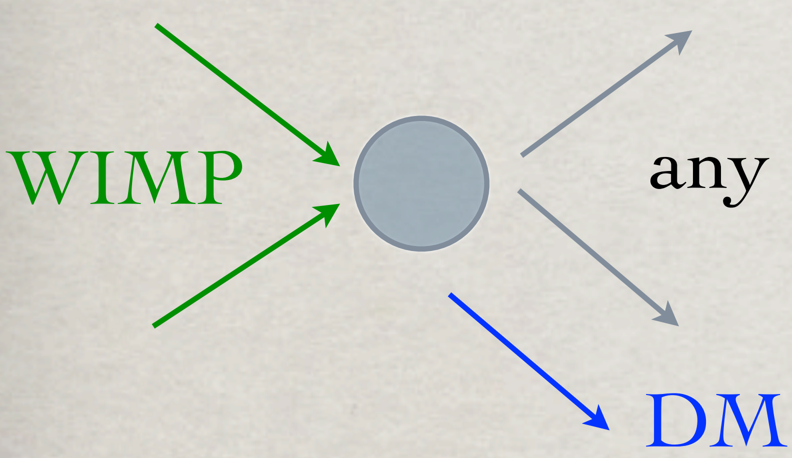
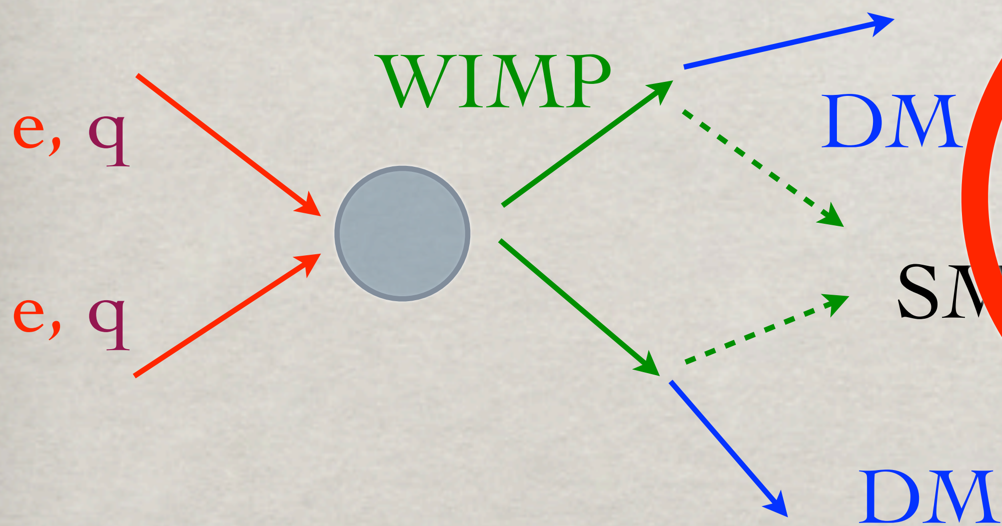


Direct Detection:

NONE...

Colliders: LHC/ILC



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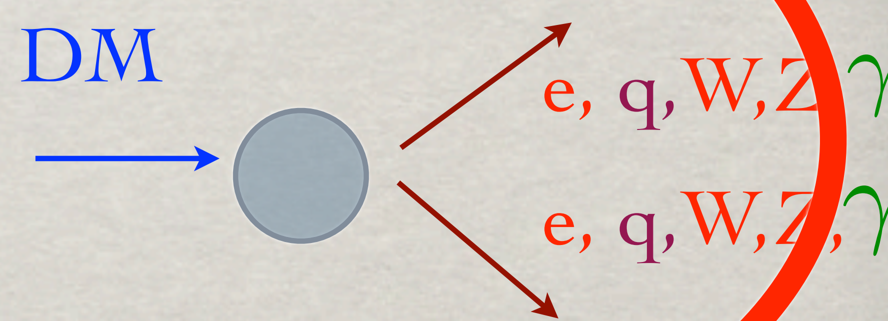


decaying DM !

3 different ways to check this hypothesis !!!

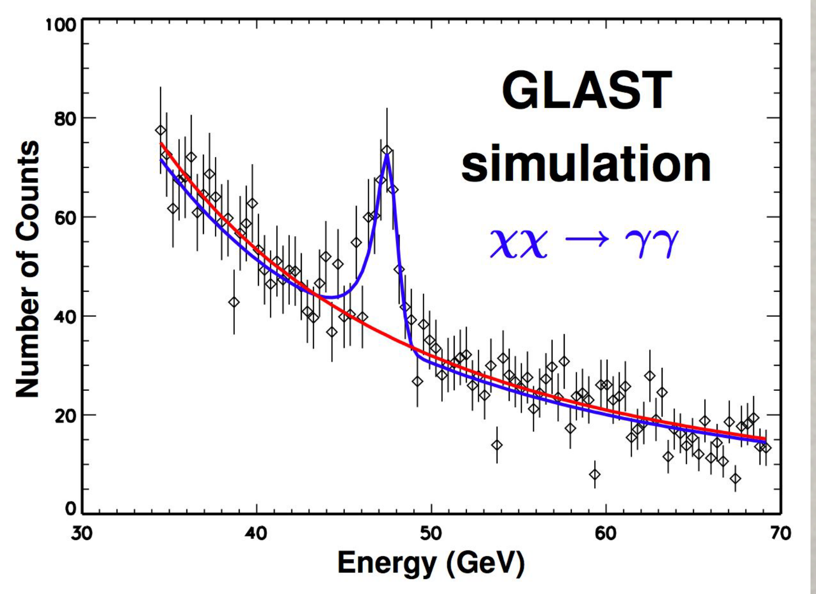
THE HOPE: DETECT DM !

- 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 J(θ)

- Strongly dependent on the halo model/density via J 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.



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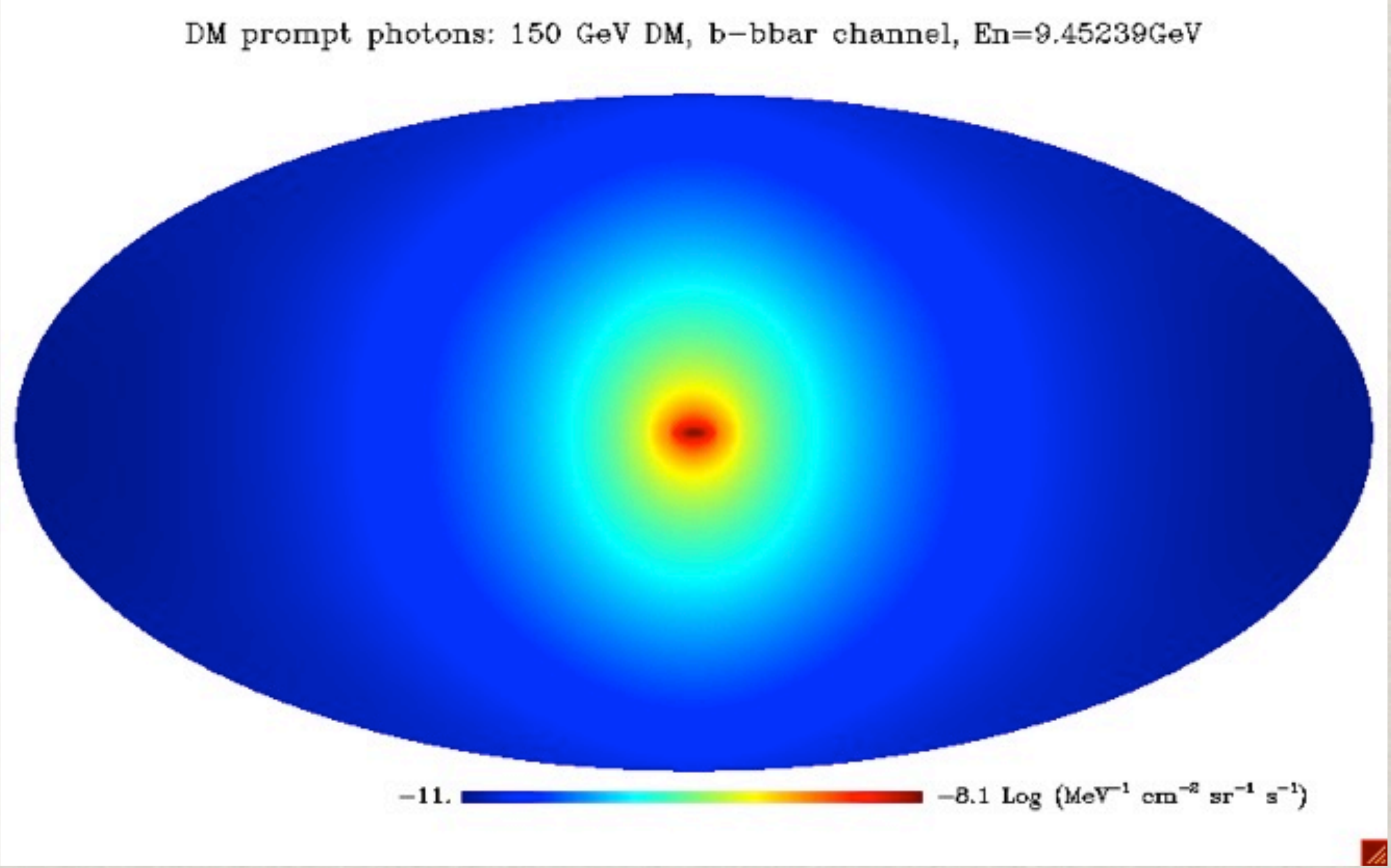

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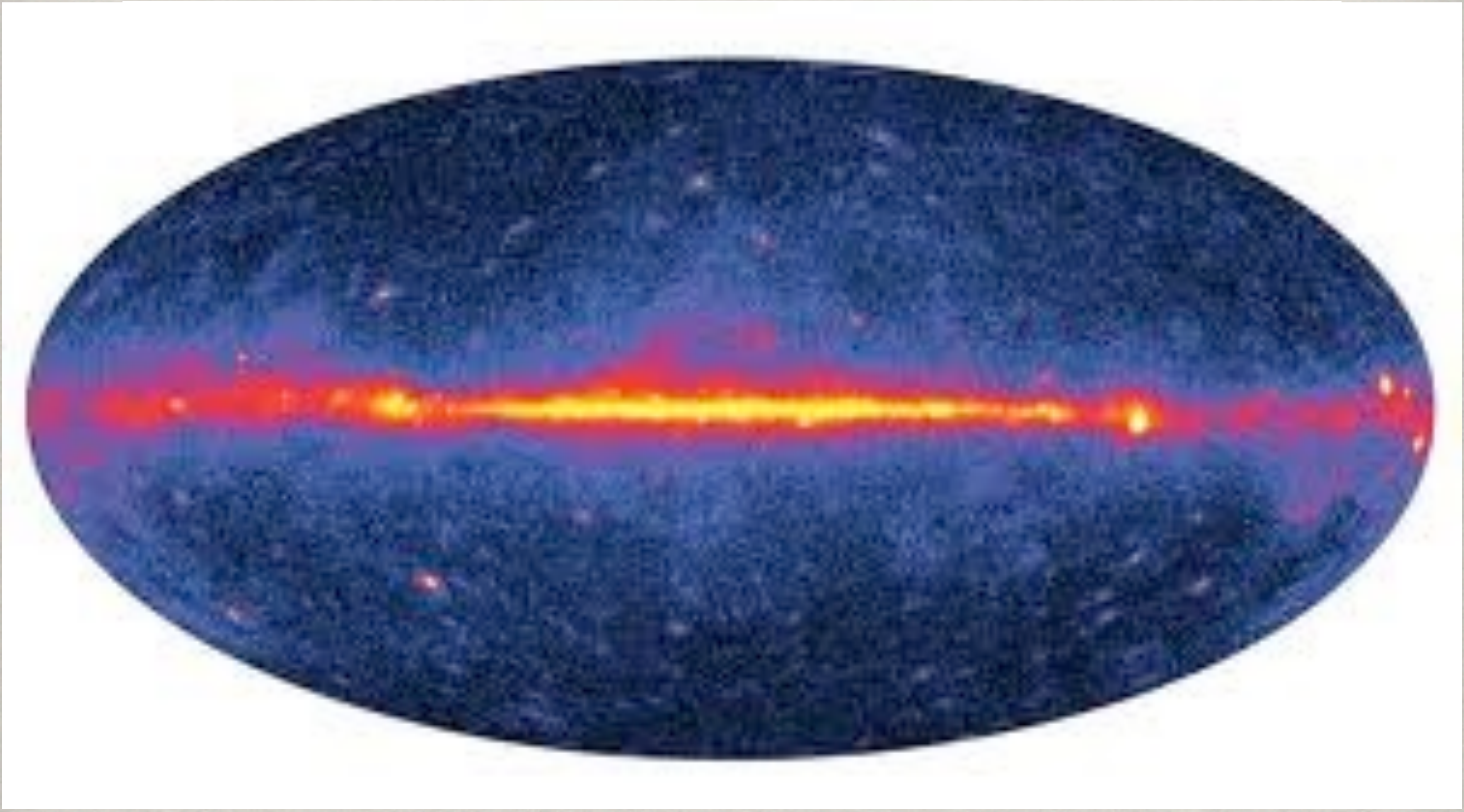


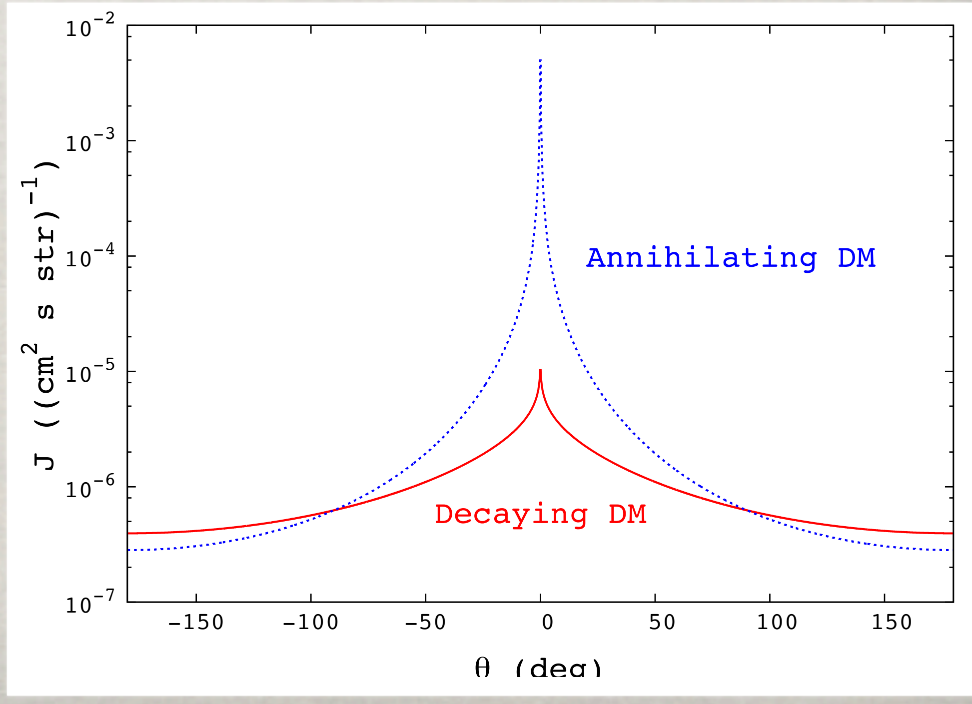
DECAYING DM

- 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 $J(\theta)$

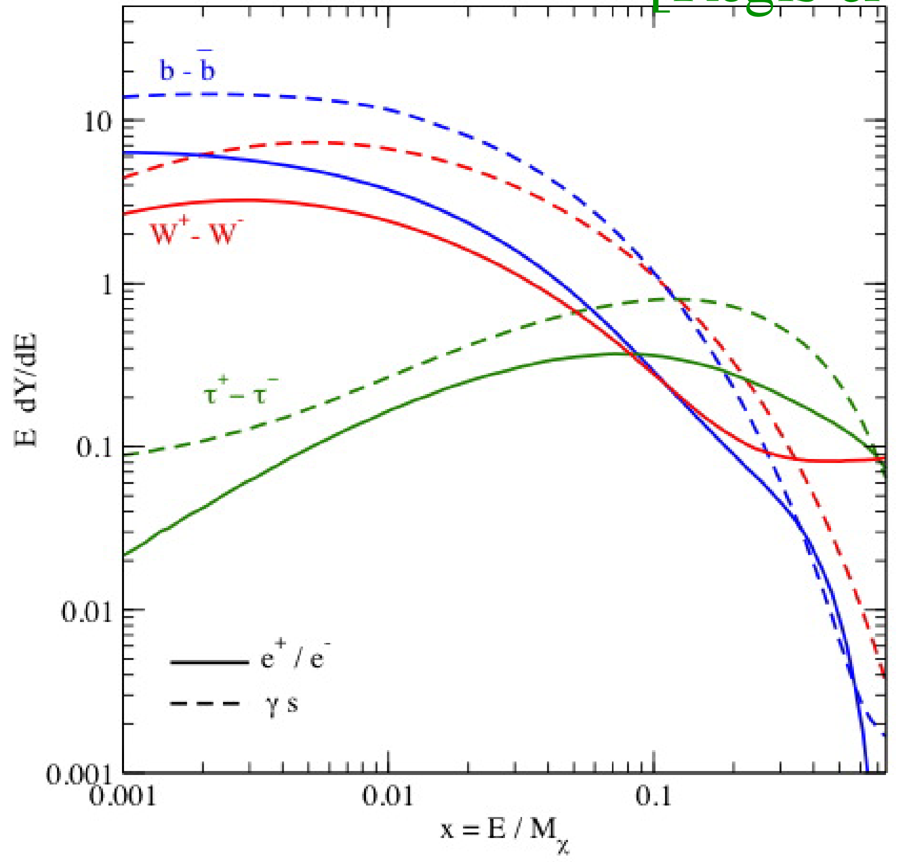
- Very weak dependence on the Halo profile; what matters is the DM lifetime...
- Galactic & extragalactic signals are comparable...
- Spectrum in gamma-rays given by the decay channel! Smoking gun: gamma line...

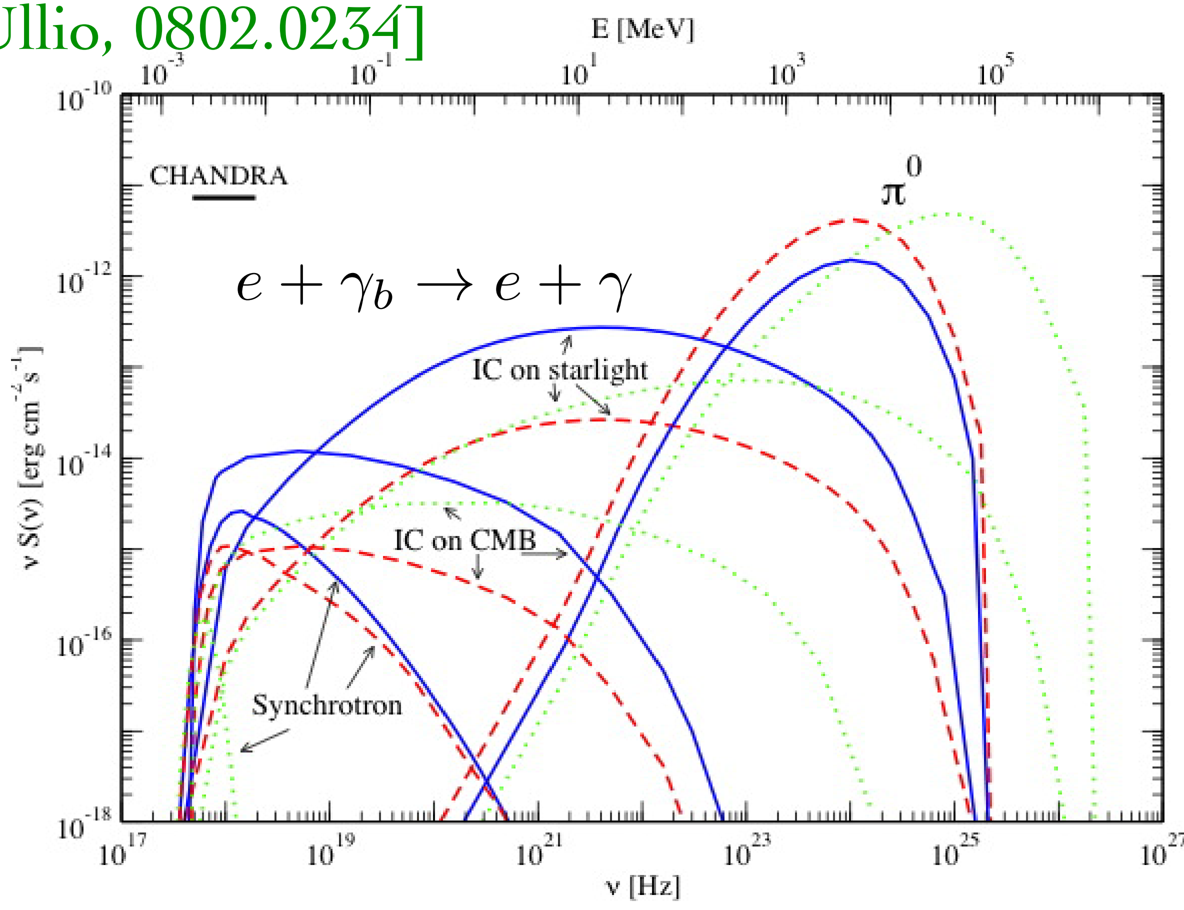


EM Spectrum from DM

Dark Matter annihilation (or decay) can give photons not only directly from the annihilation, but also by many secondary processes, especially if stable charged particles are produced: Synchrotron emission, Inverse Compton scattering

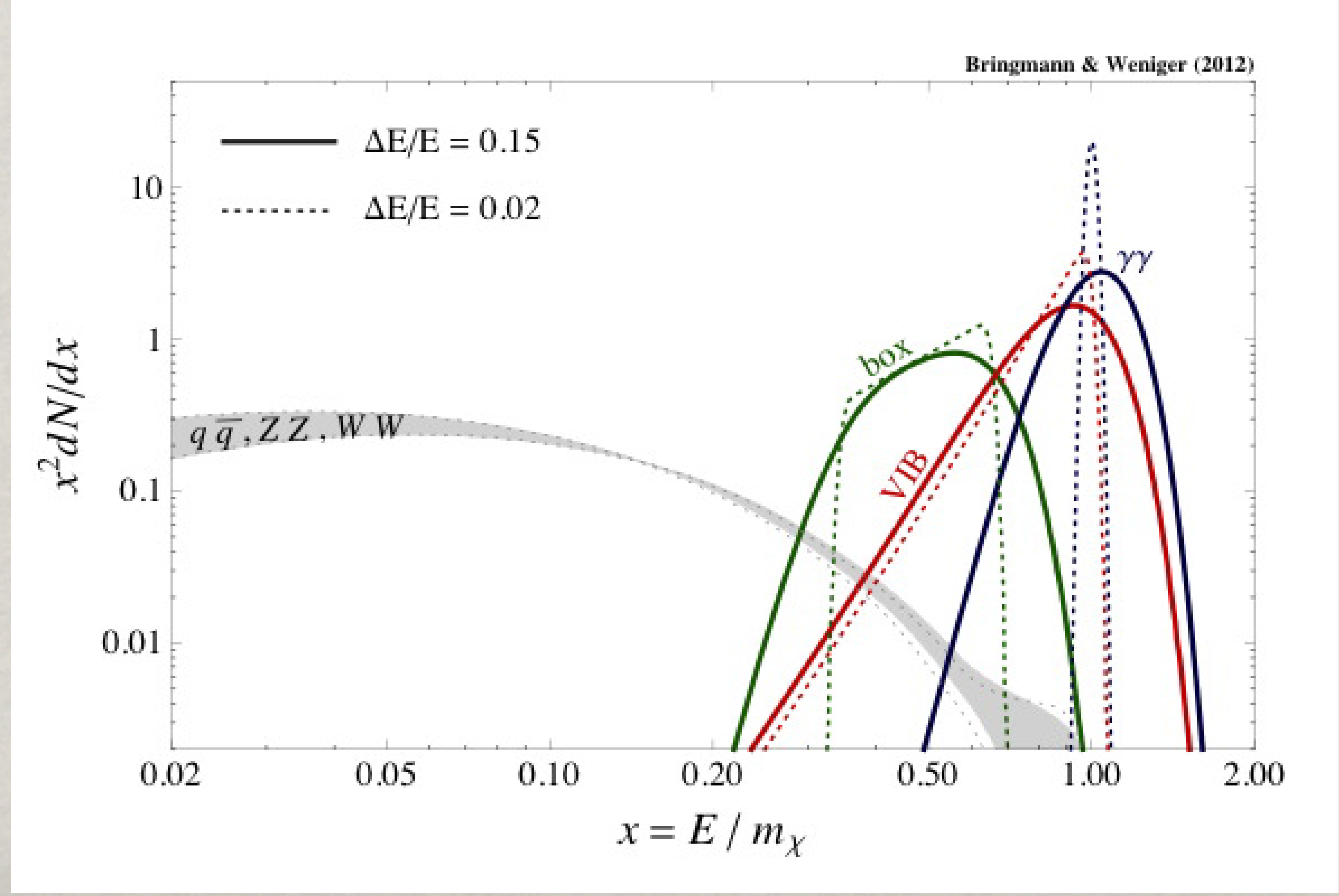
[Regis & Ullio, 0802.0234]





DM Spectral features

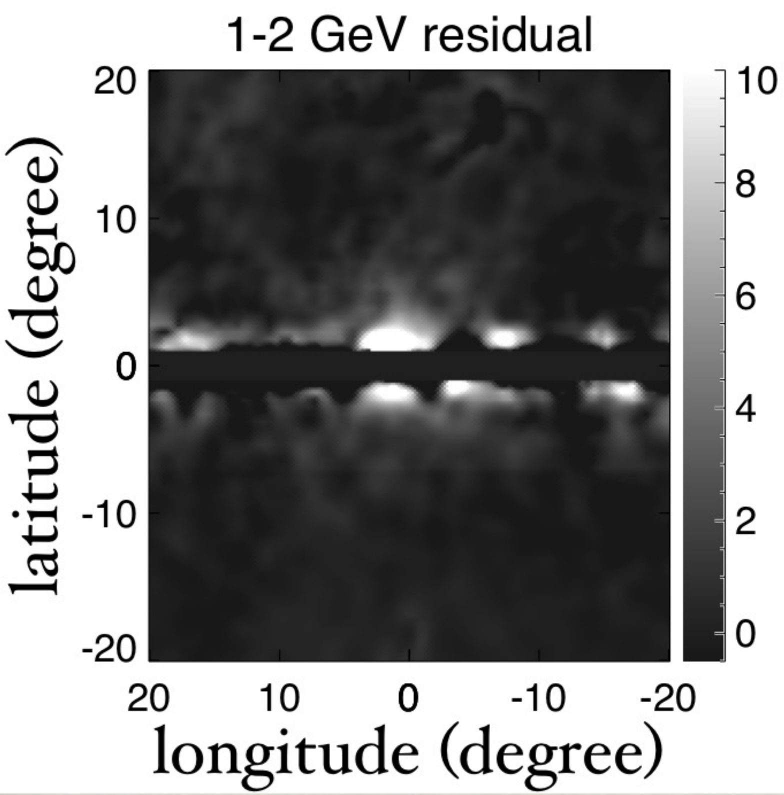
Depending on the model, different features could appear and stick out from the continuum spectrum, helping to see the signal and disentangle the model ! Smoking guns !

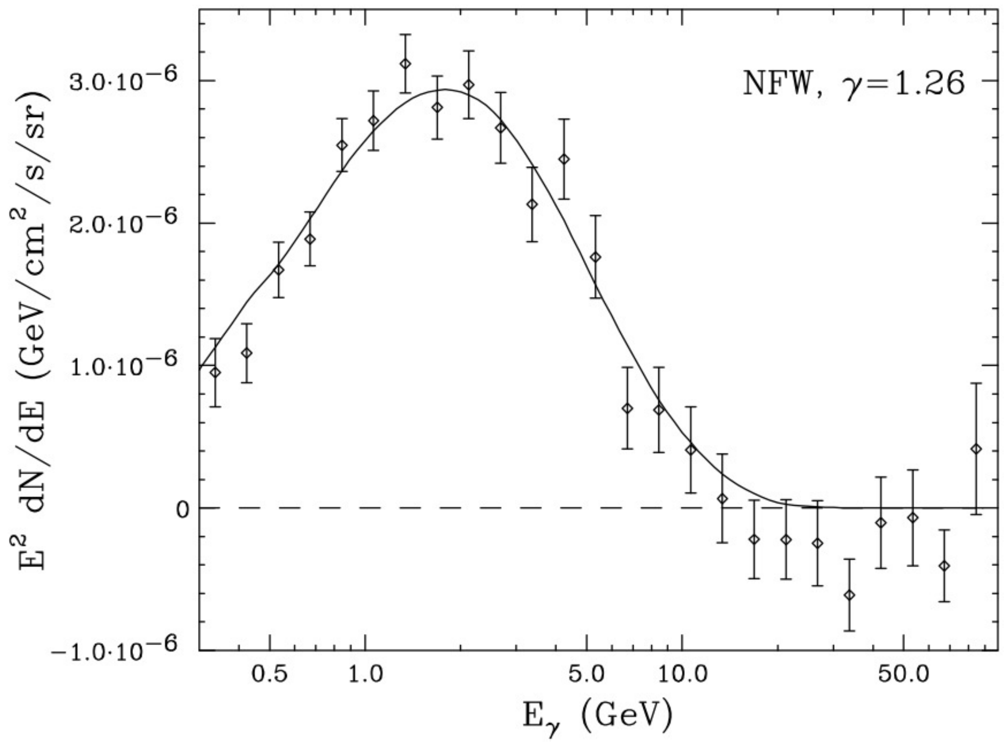


Galactic centre excess

An excess has been found since some years in the FERMI-lat data by Hooper & al. in the direction of the Galactic centre:

[Daylan & al 1402.6703]



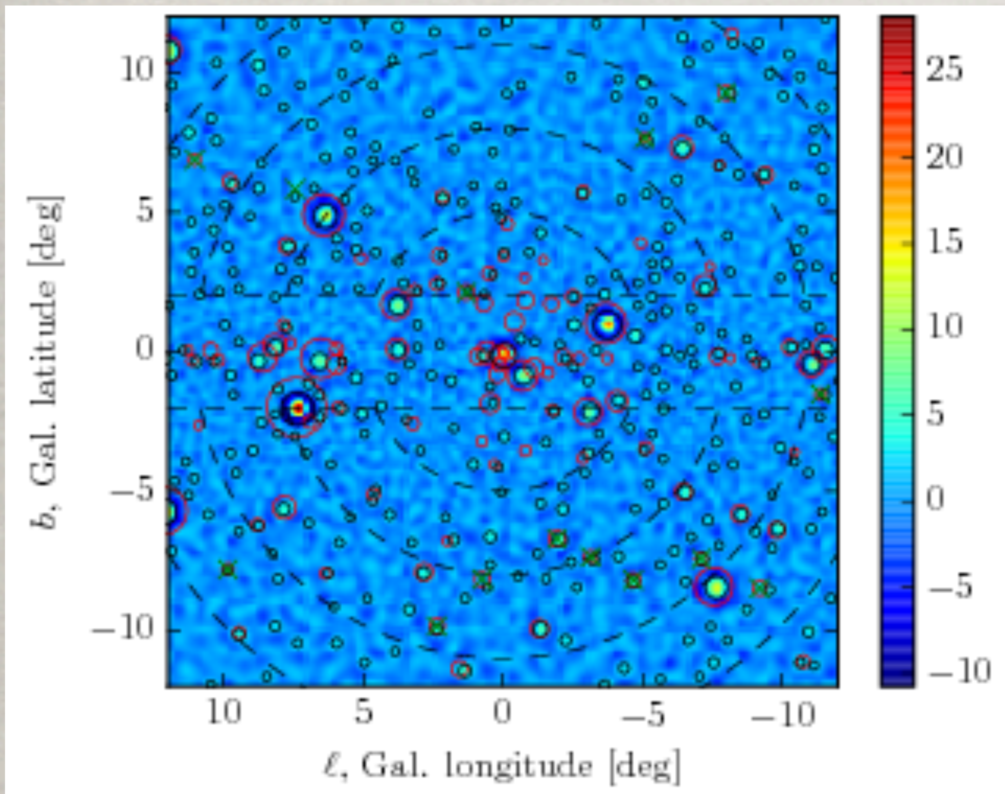


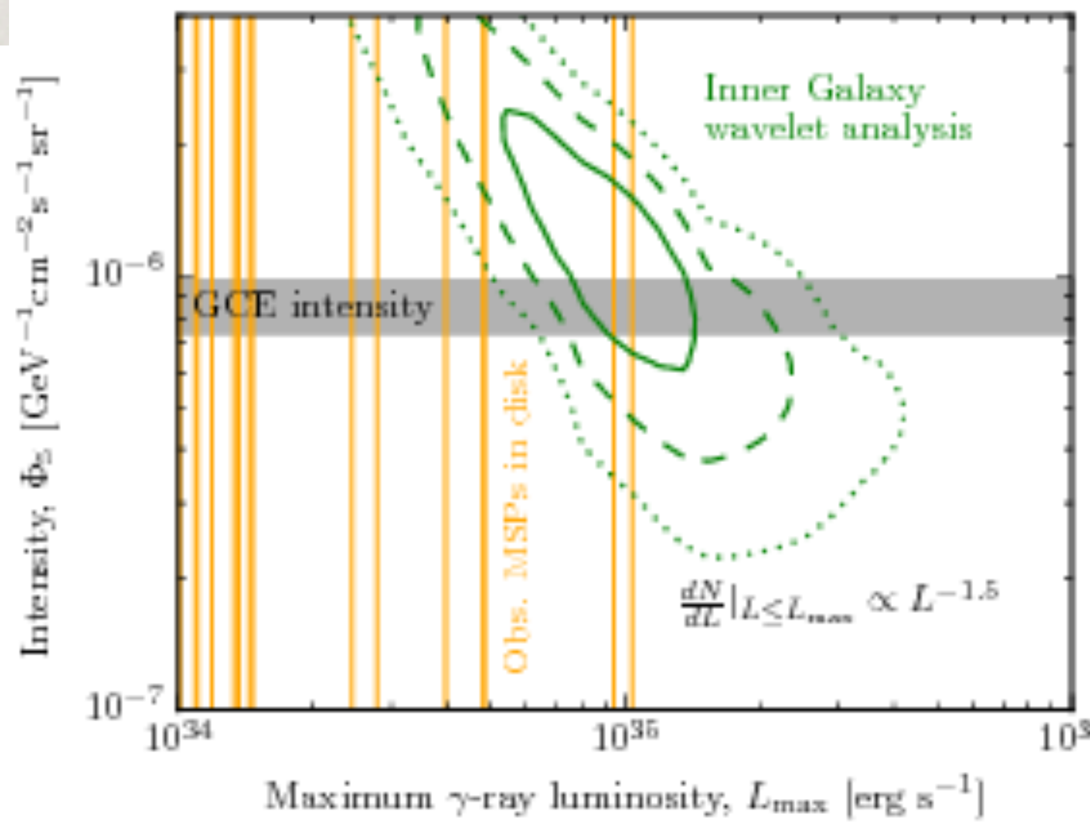
Compatible with a thermal relic annihilating into $b\,\bar{b}, \tau^+\,\tau^-$

Maybe due to millipulsar

A large population of millipulsars at the centre of the galaxy may be below the threshold for point-source detection:

[Bartels, Krishnamurthy & Weniger 16]



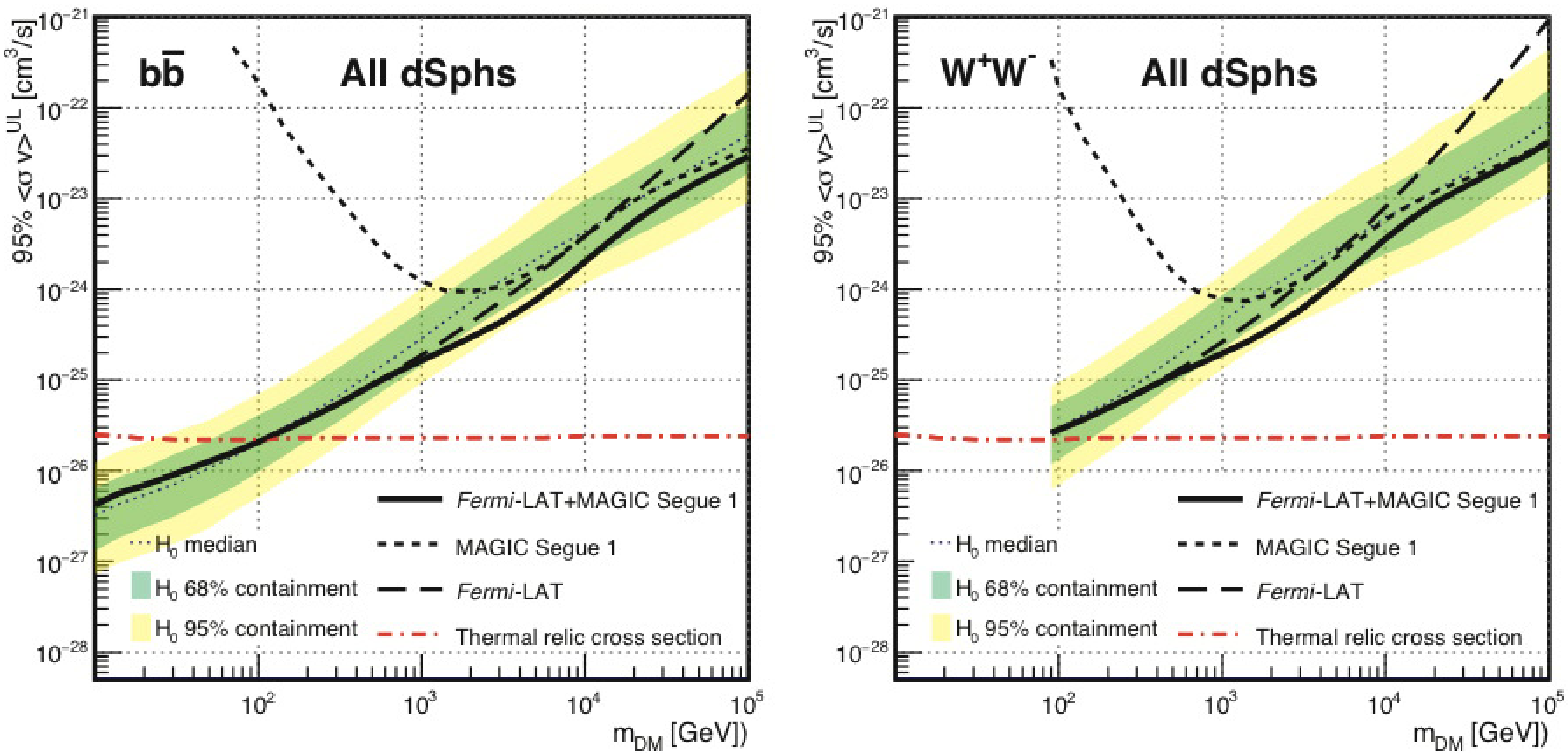


Wavelet analysis seems to find a substantial contribution…

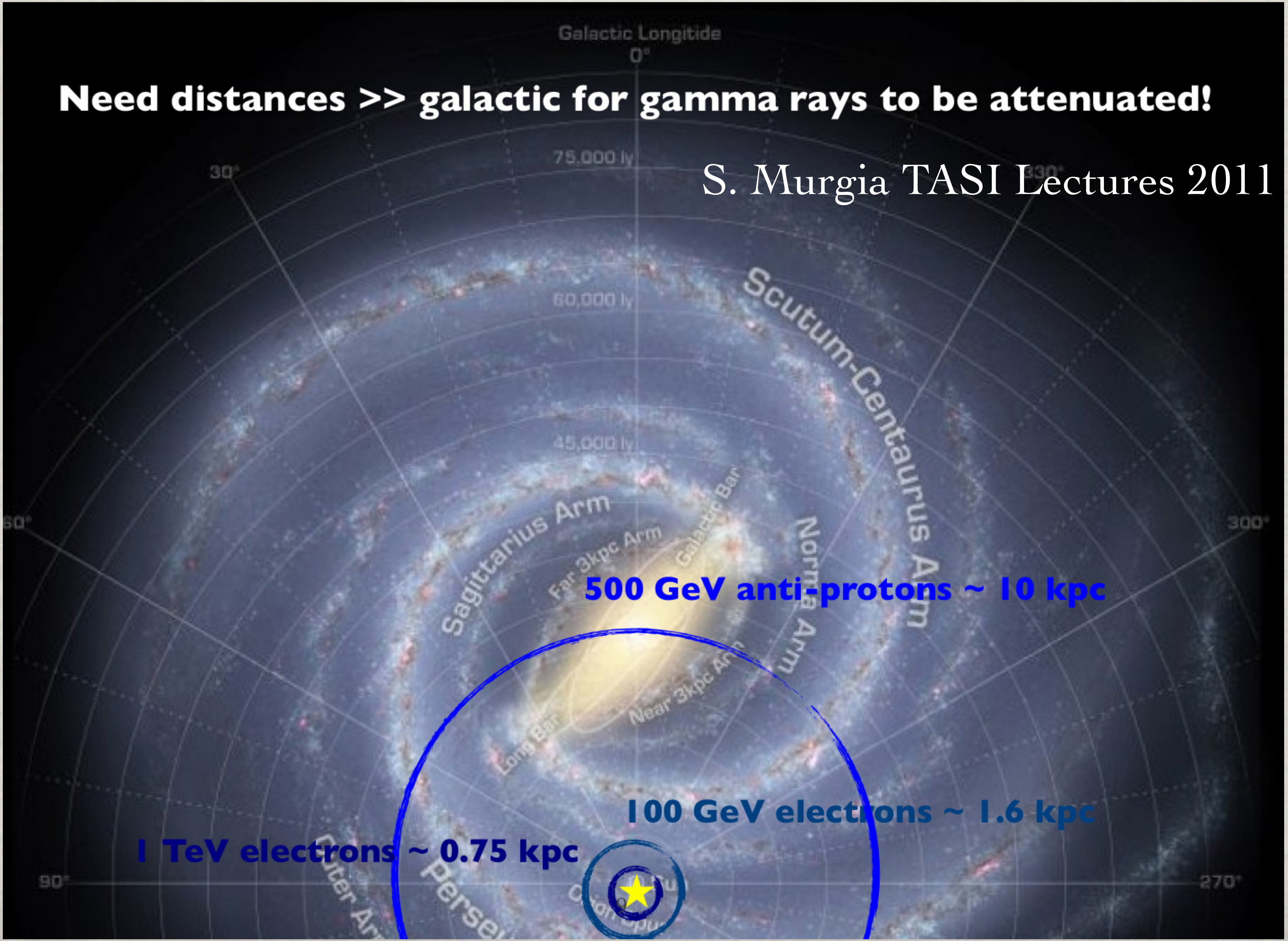
Bounds on WIMP DM

Strong limits are obtained from dwarf satellite galaxies, both from Fermi-LAT and MAGIC:

[Fermi-LAT & MAGIC 1601.06590]

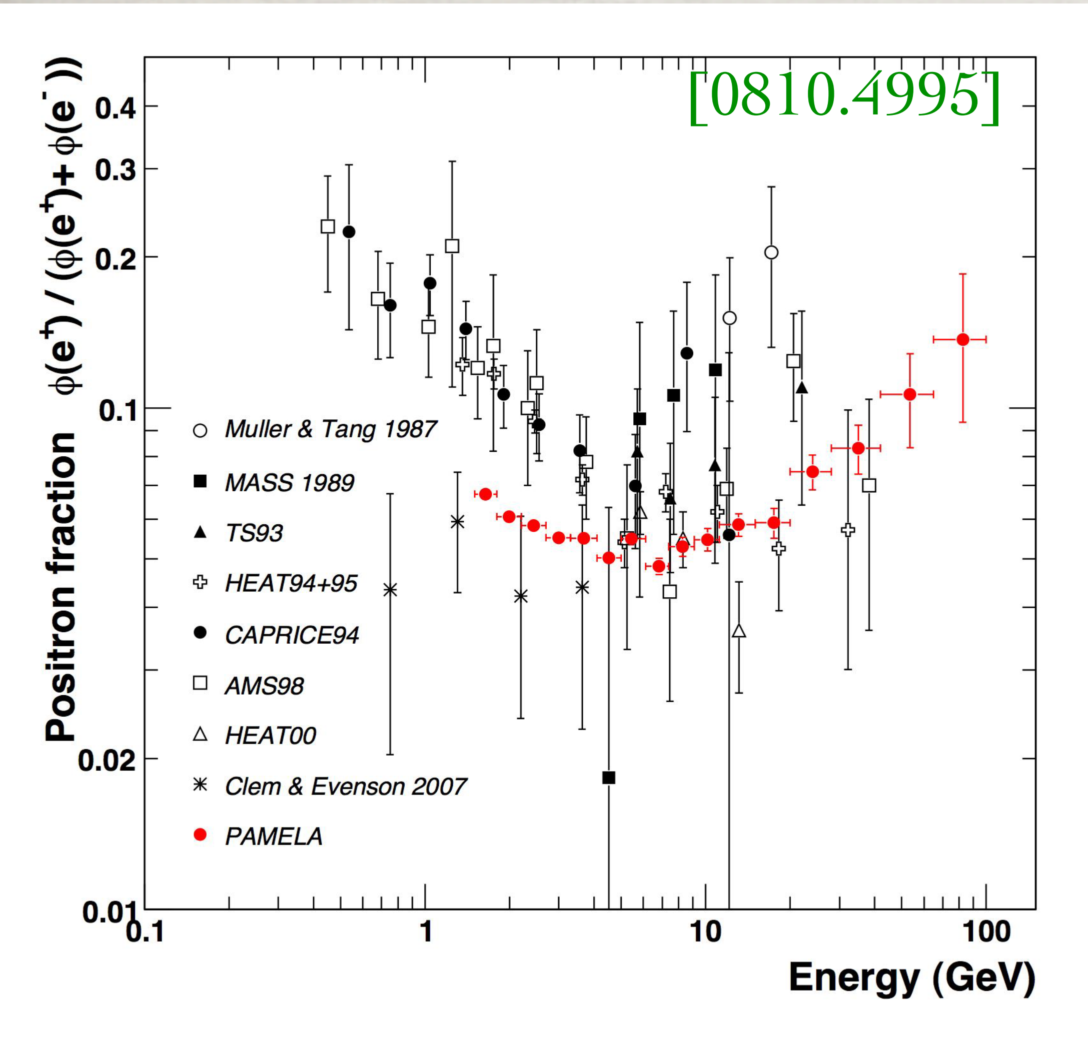


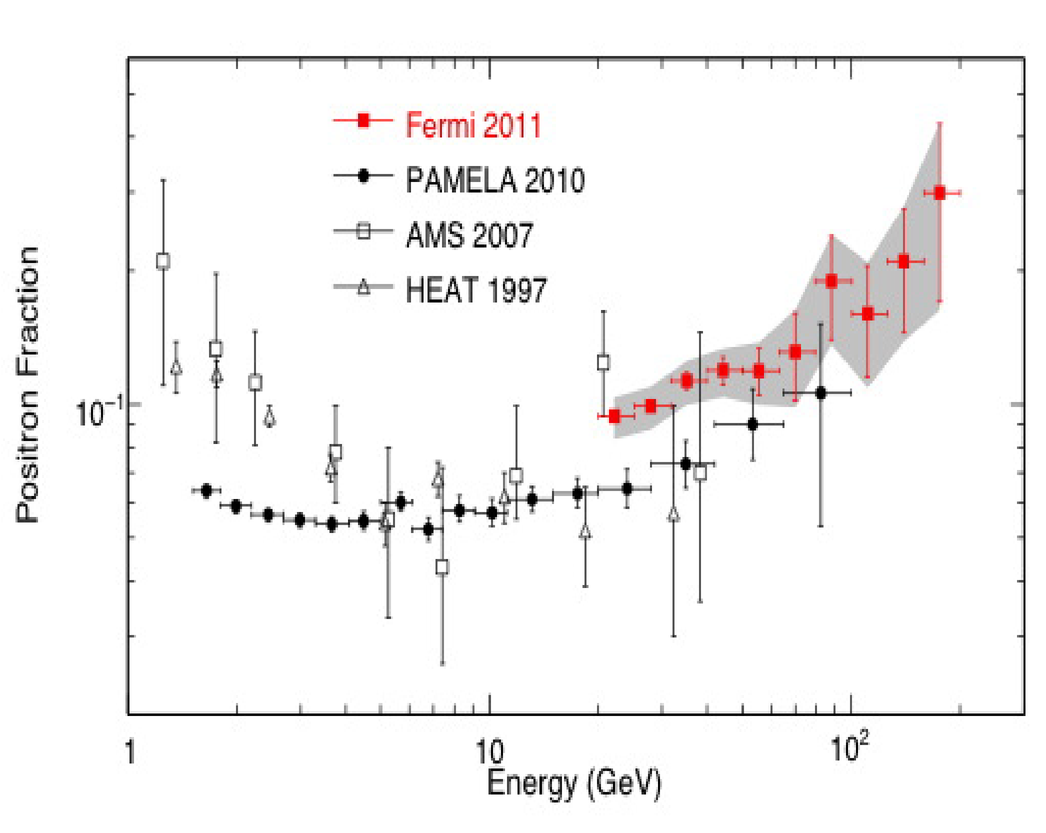
GALACTIC PARTICLE'S RANGES



Antimatter in CR: positrons

In 2008 PAMELA observes a rising positron fraction, later confirmed by FERMI (exploiting Earth magnetic field !):





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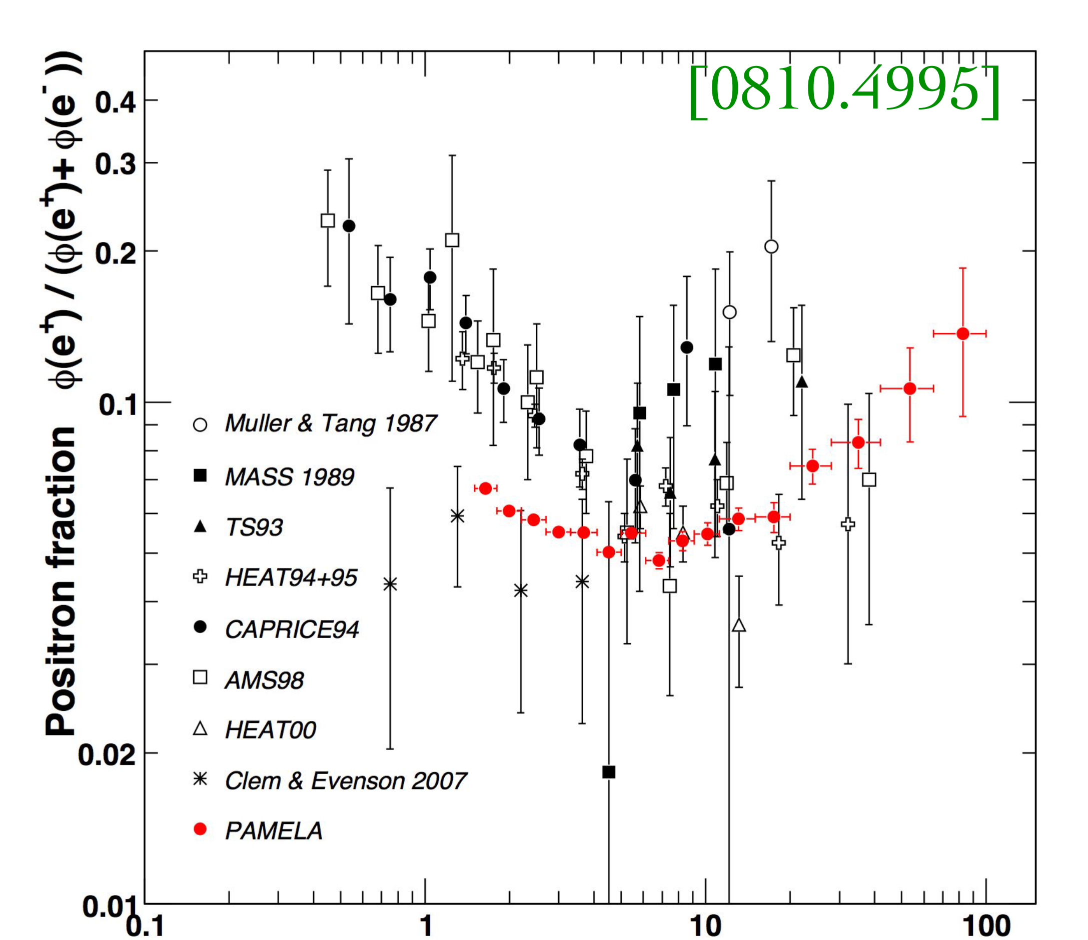

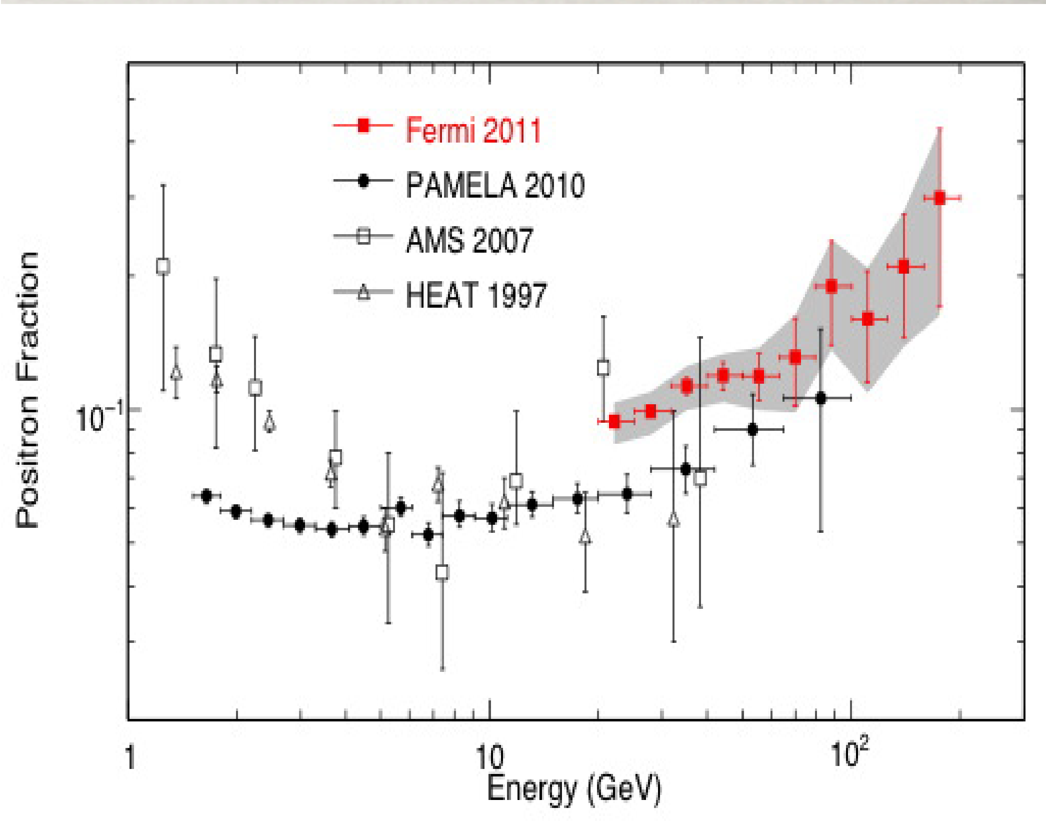

Solar modulation

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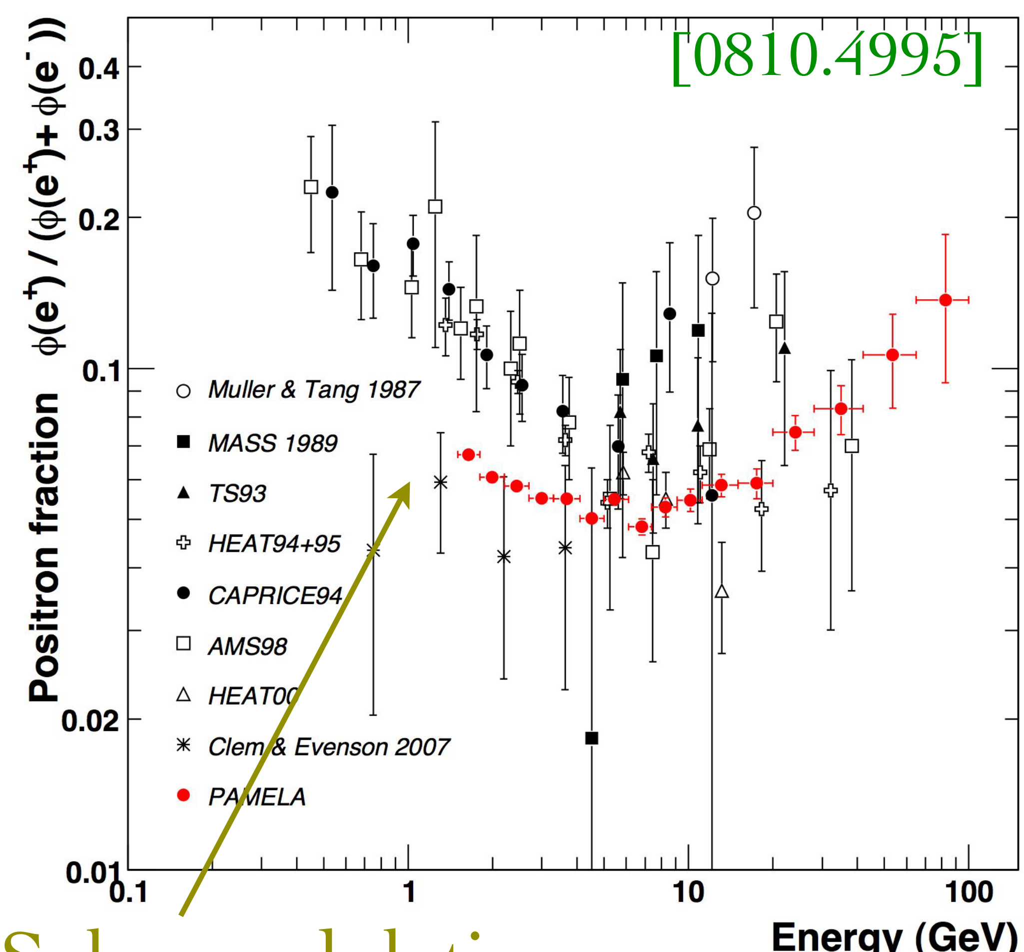
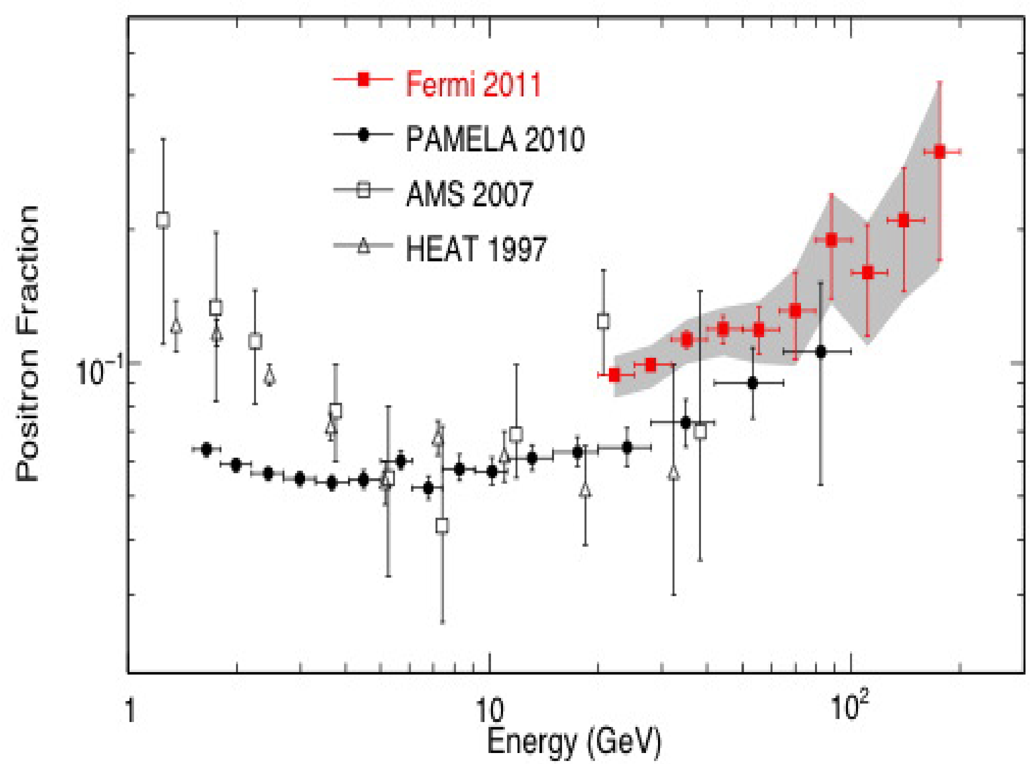
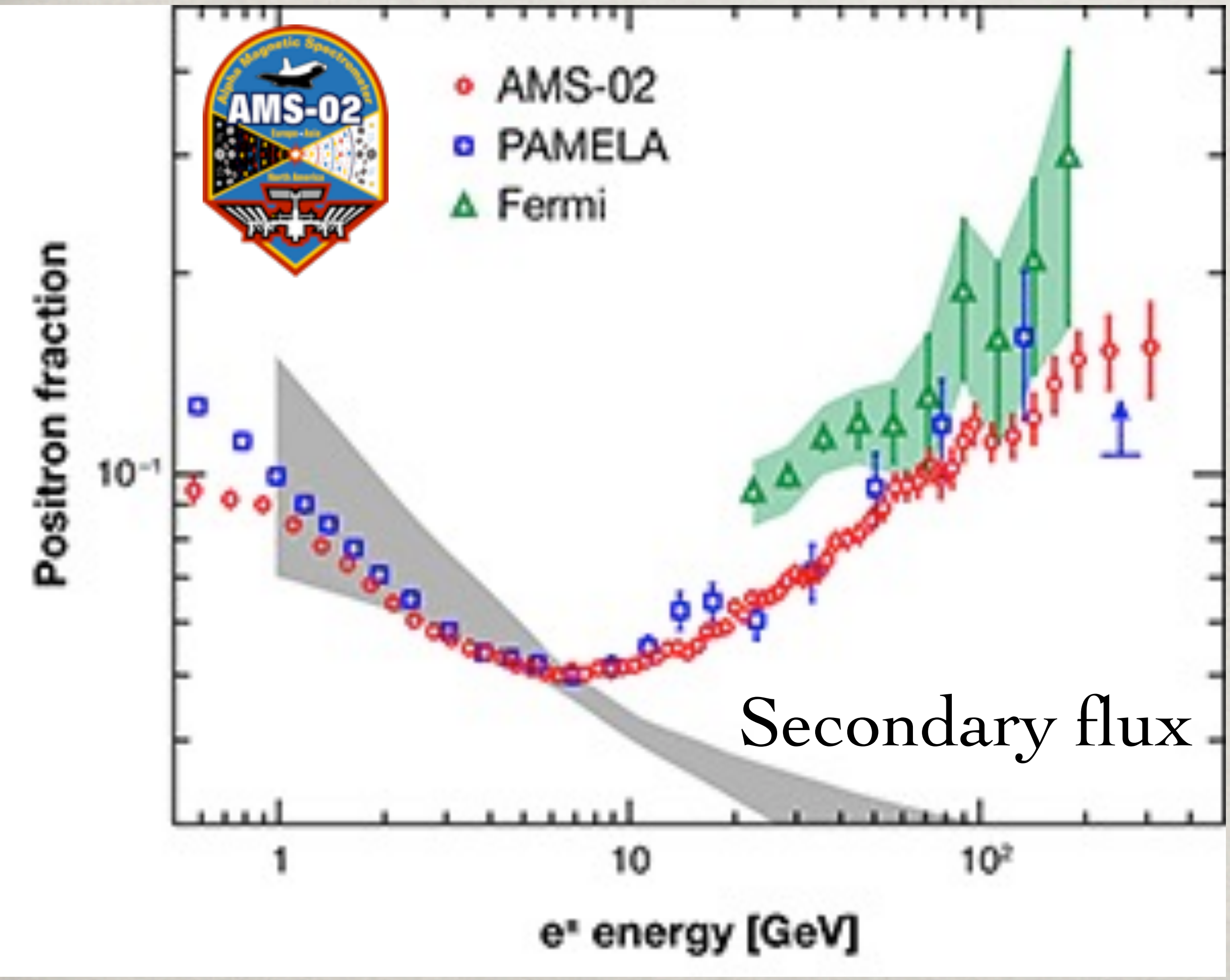


Solar modulation



Antimatter in CR: positrons

News: AMS-02 confirms PAMELA and FERMI !



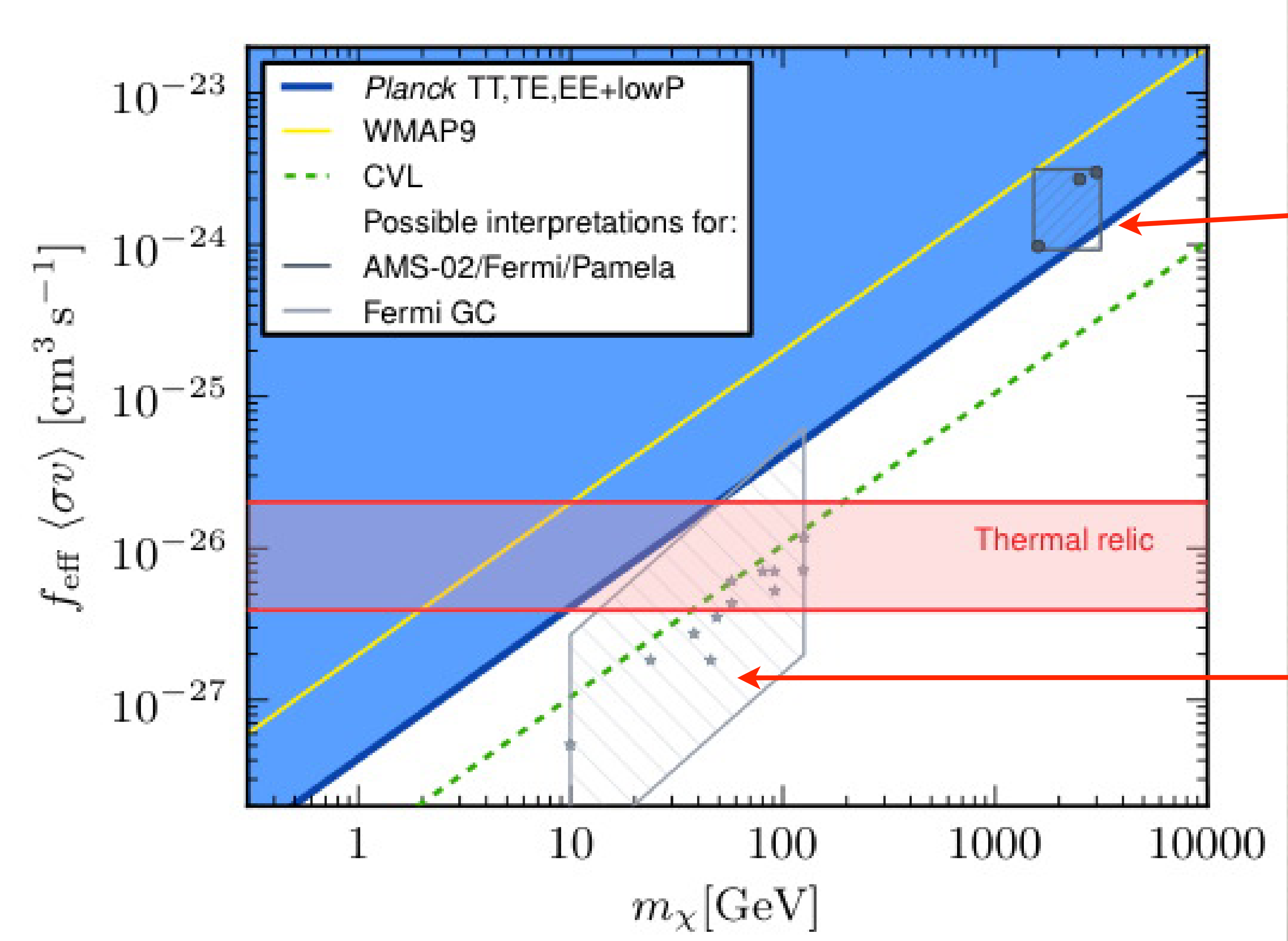
Such a rising spectrum is not explainable by "secondary" positrons produced by CR propagation !

Need a positron source and not too far away...
Dark Matter or astrophysics ?

PLANCK: DM ANNIHILATION

WIMP annihilation also modifies the epoch of recombination due to the release of energy in the primordial plasma and leaves imprints into the CMB ! Planck can now exclude cross-sections as those needed by PAMELA and AMS-02:

[Planck 1502.01589]

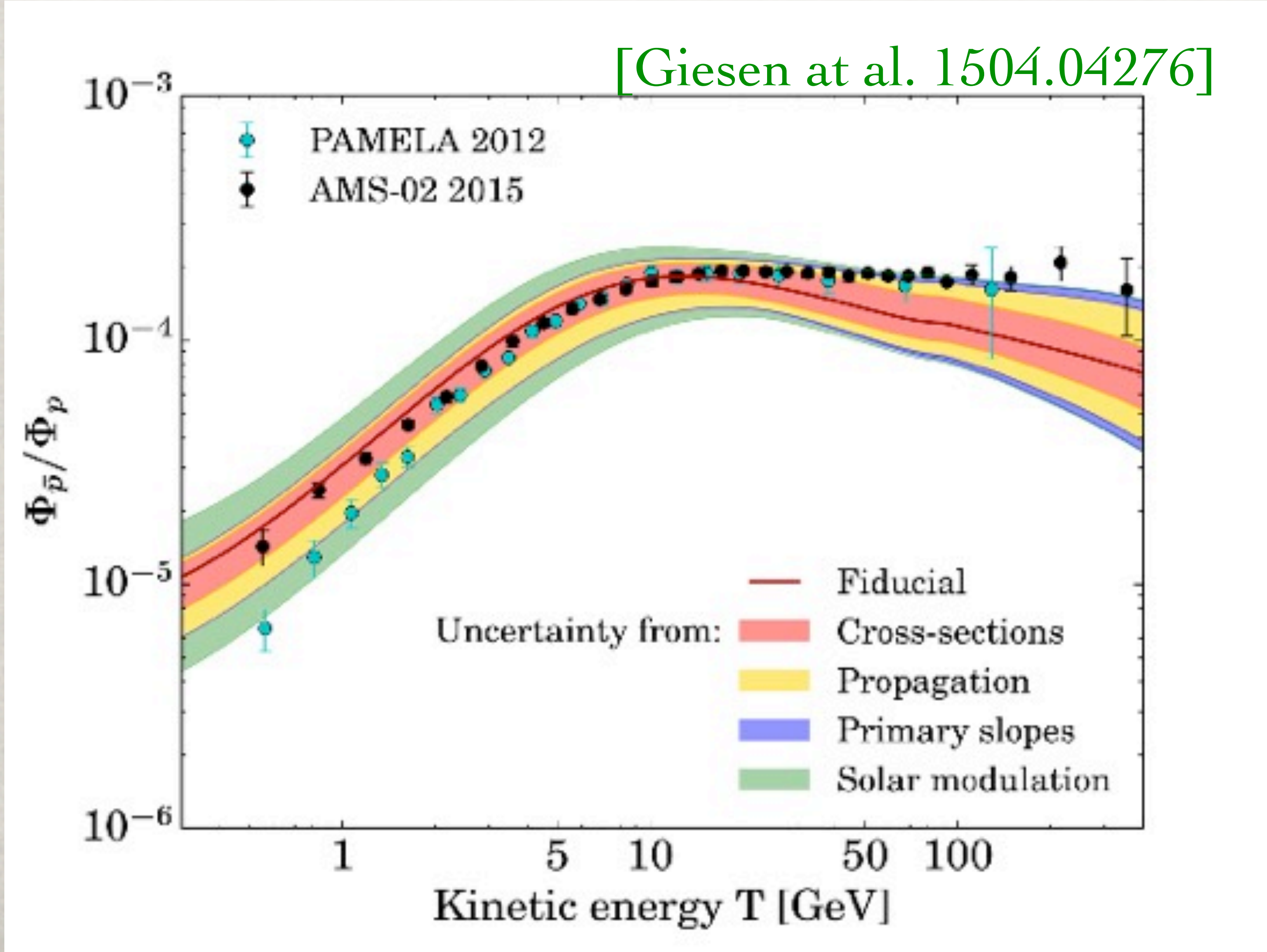


Pamela-inspired DM models

Galactic centre excess

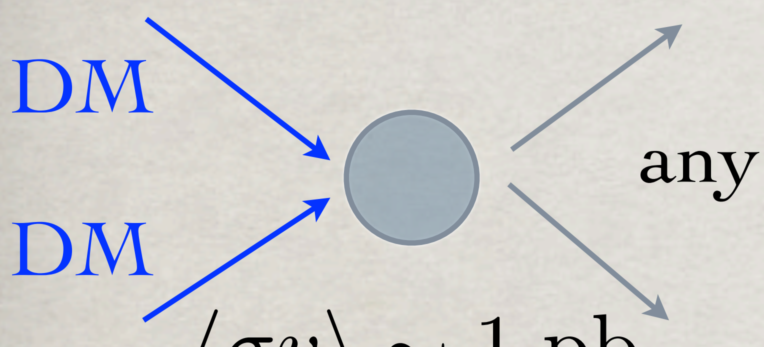
Antimatter in CR: antiprotons

New data from AMS-02 for antiprotons: is there an excess ???



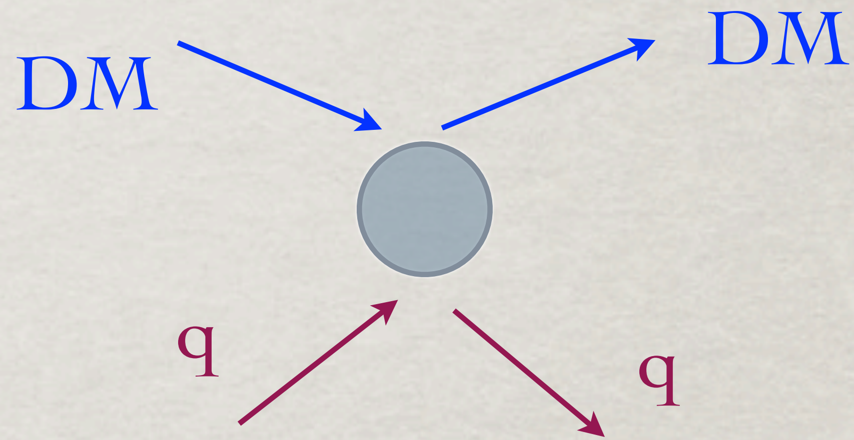
THE WIMP CONNECTION

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

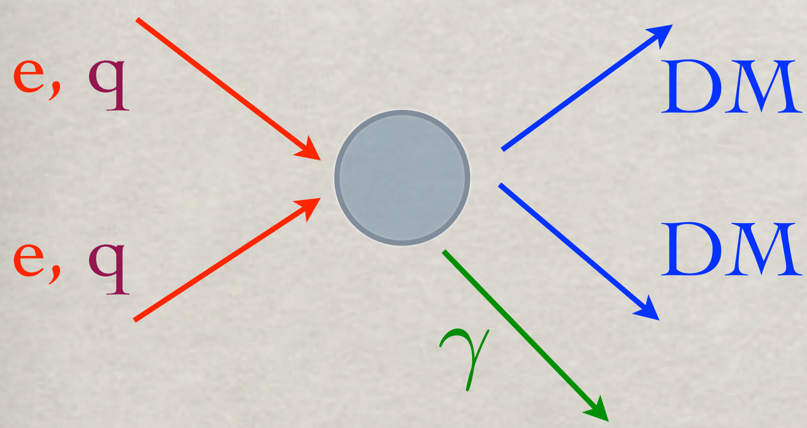


$\langle \sigma v \rangle \sim 1$ pb

Direct Detection:



Colliders: LHC/ILC



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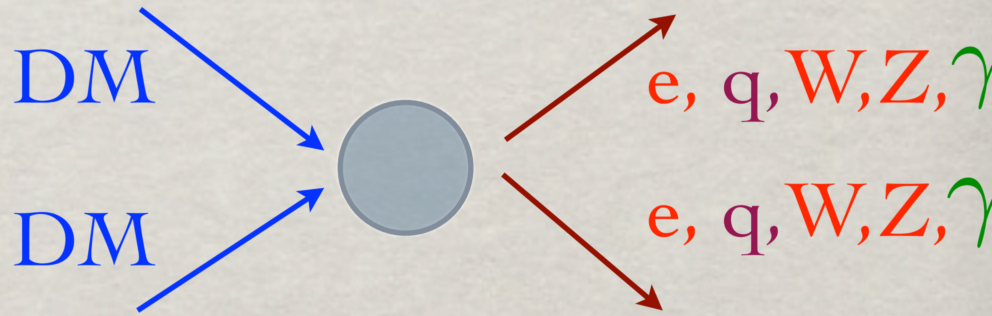

3 different ways to check this hypothesis !!!

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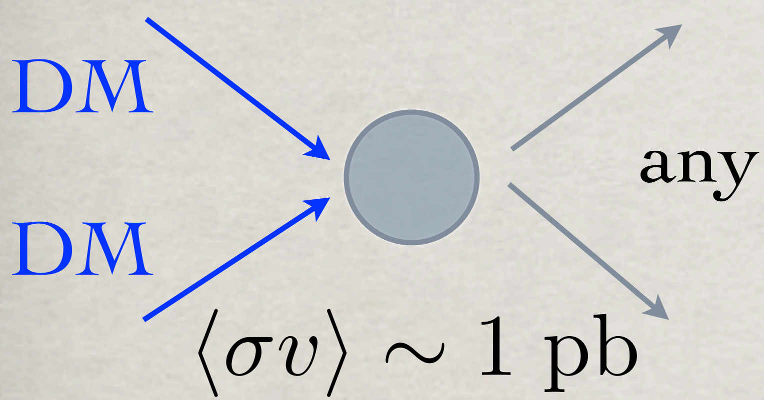

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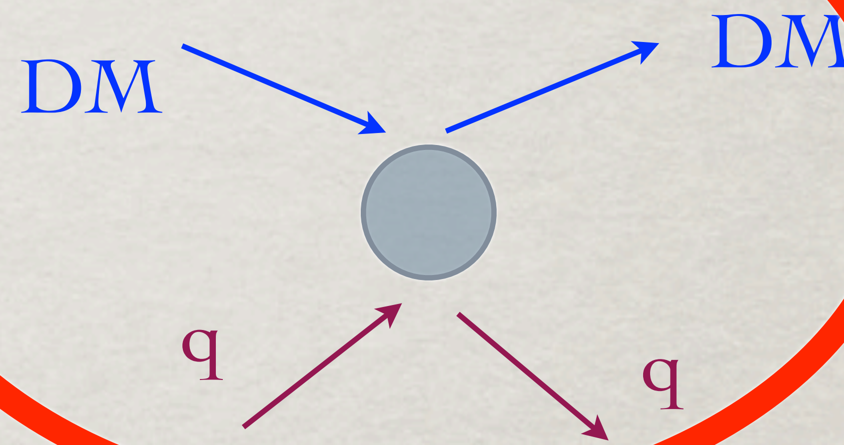

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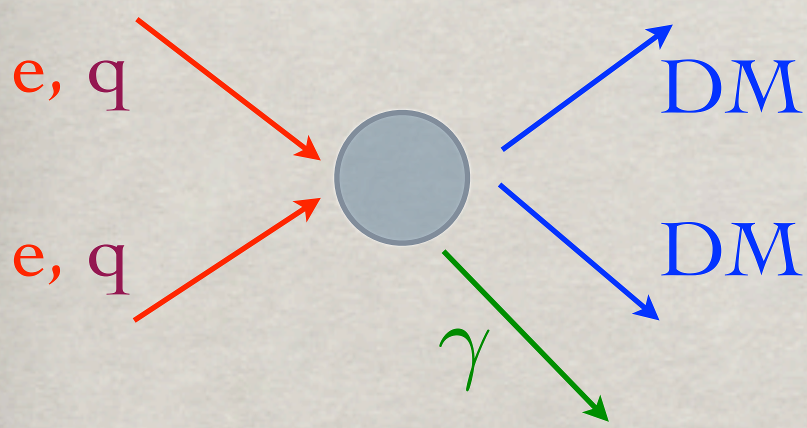

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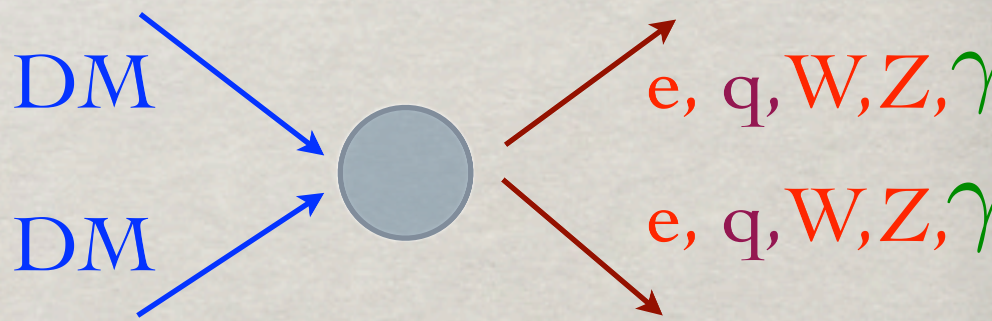

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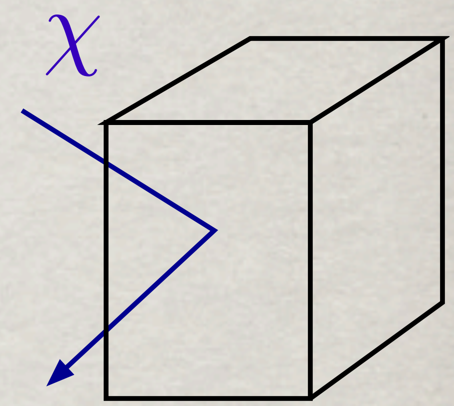
Direct WIMP detection



- 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:

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

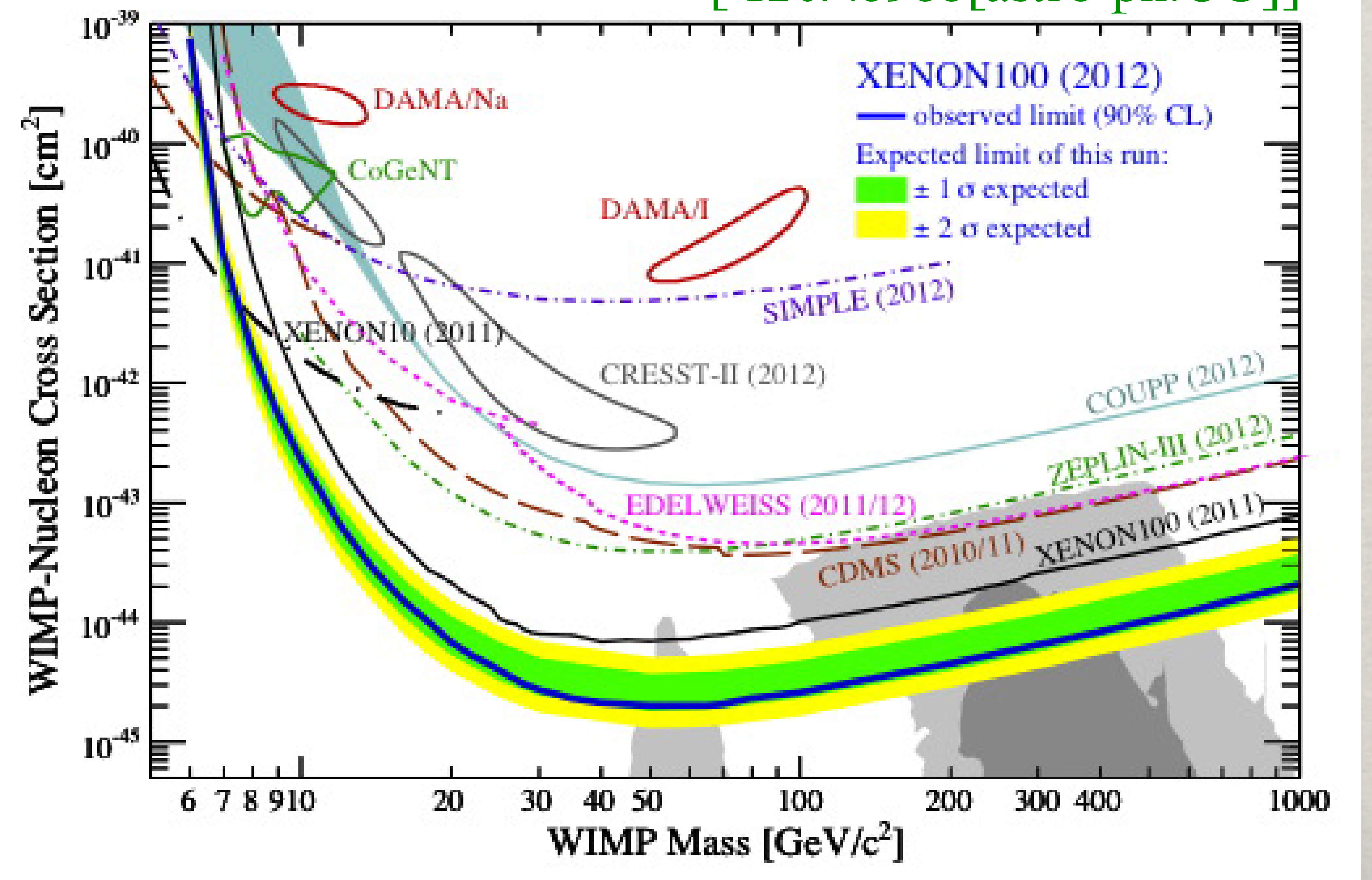
- Exchange of Higgs boson:

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

Direct detection of DM

A large part of parameter space already excluded by searches: Z-type cross-section is out, now we are exploring Higgs-type

[1207.5988[astro-ph.CO]]



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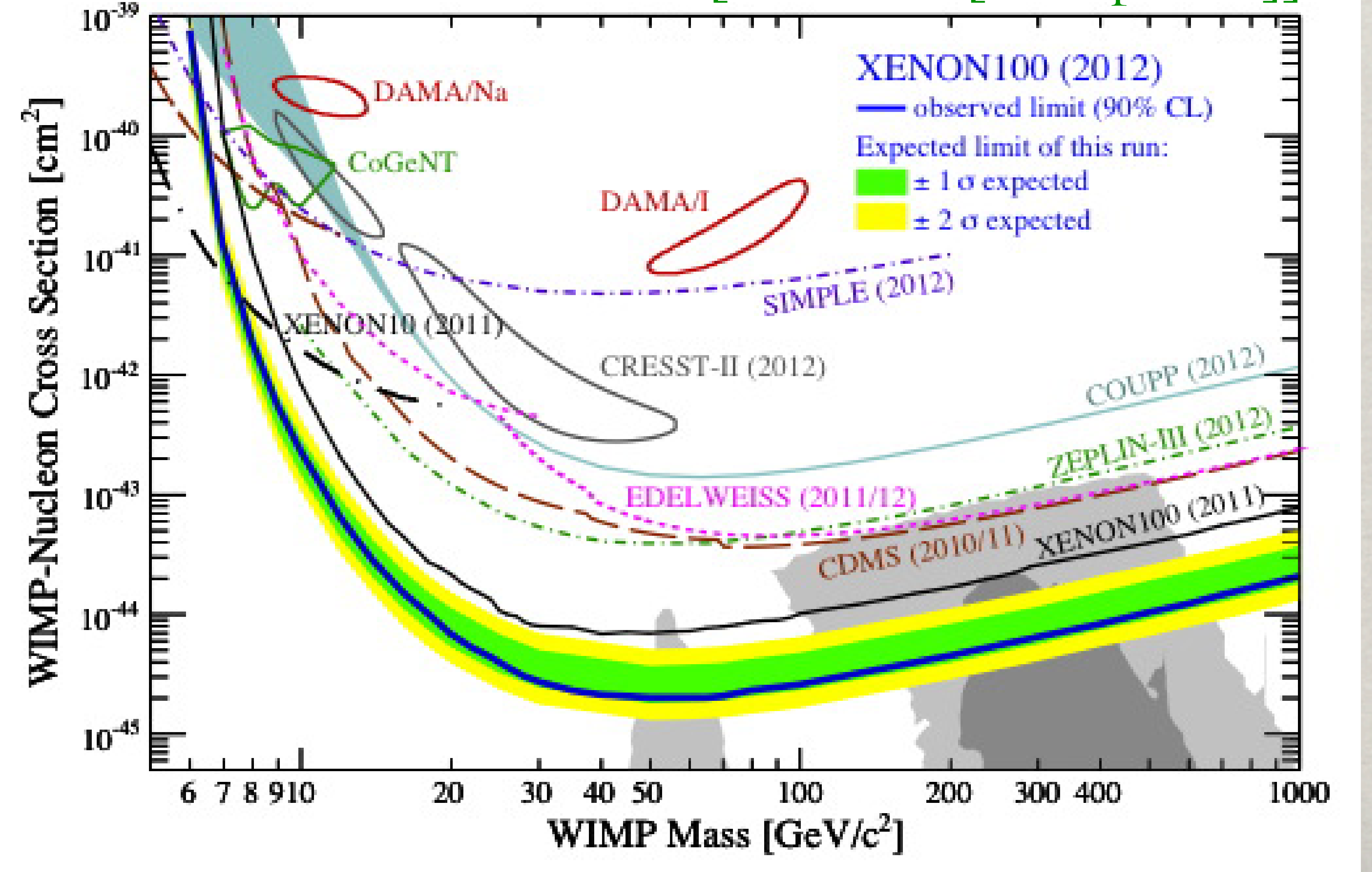

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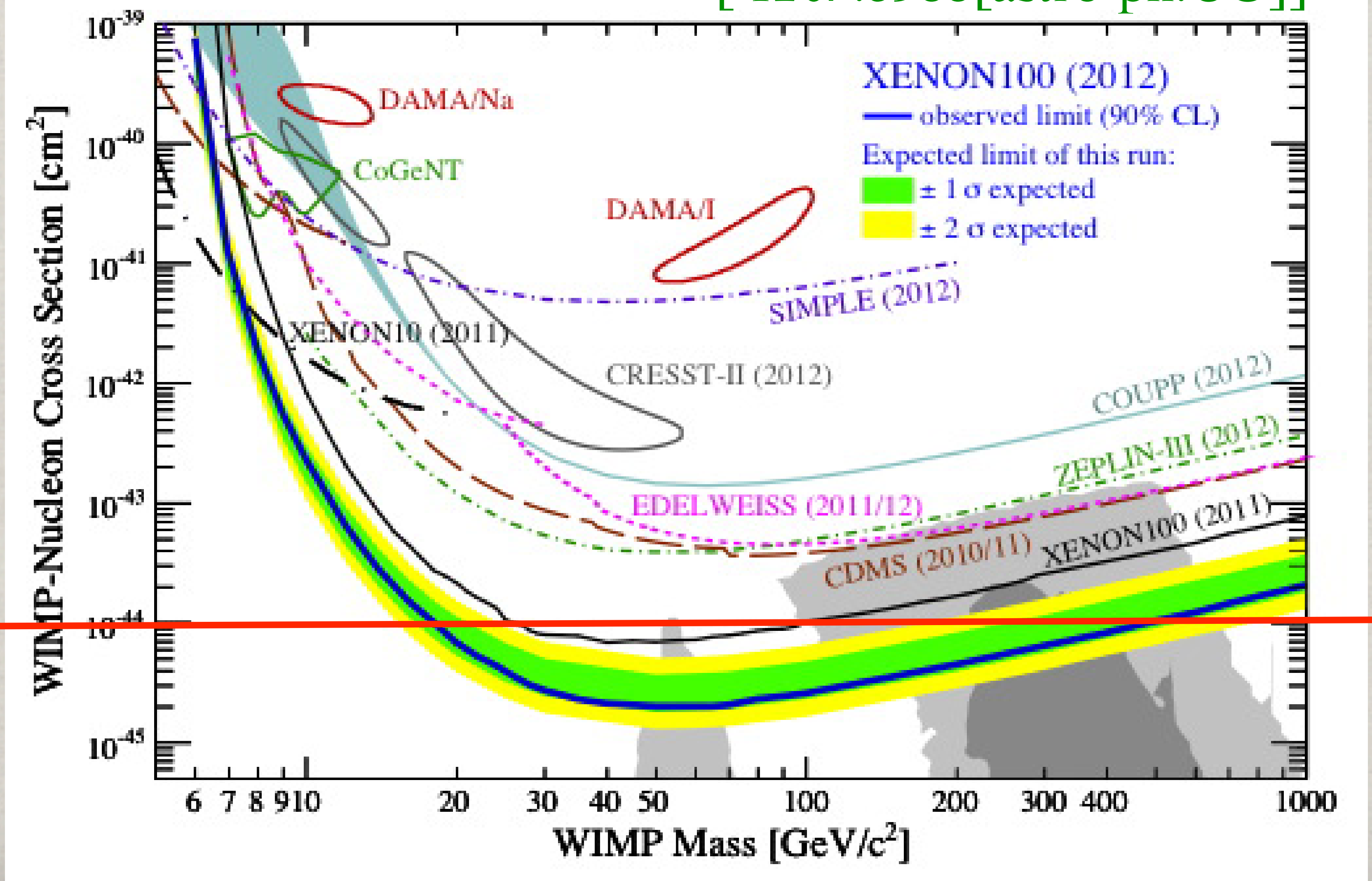
Z

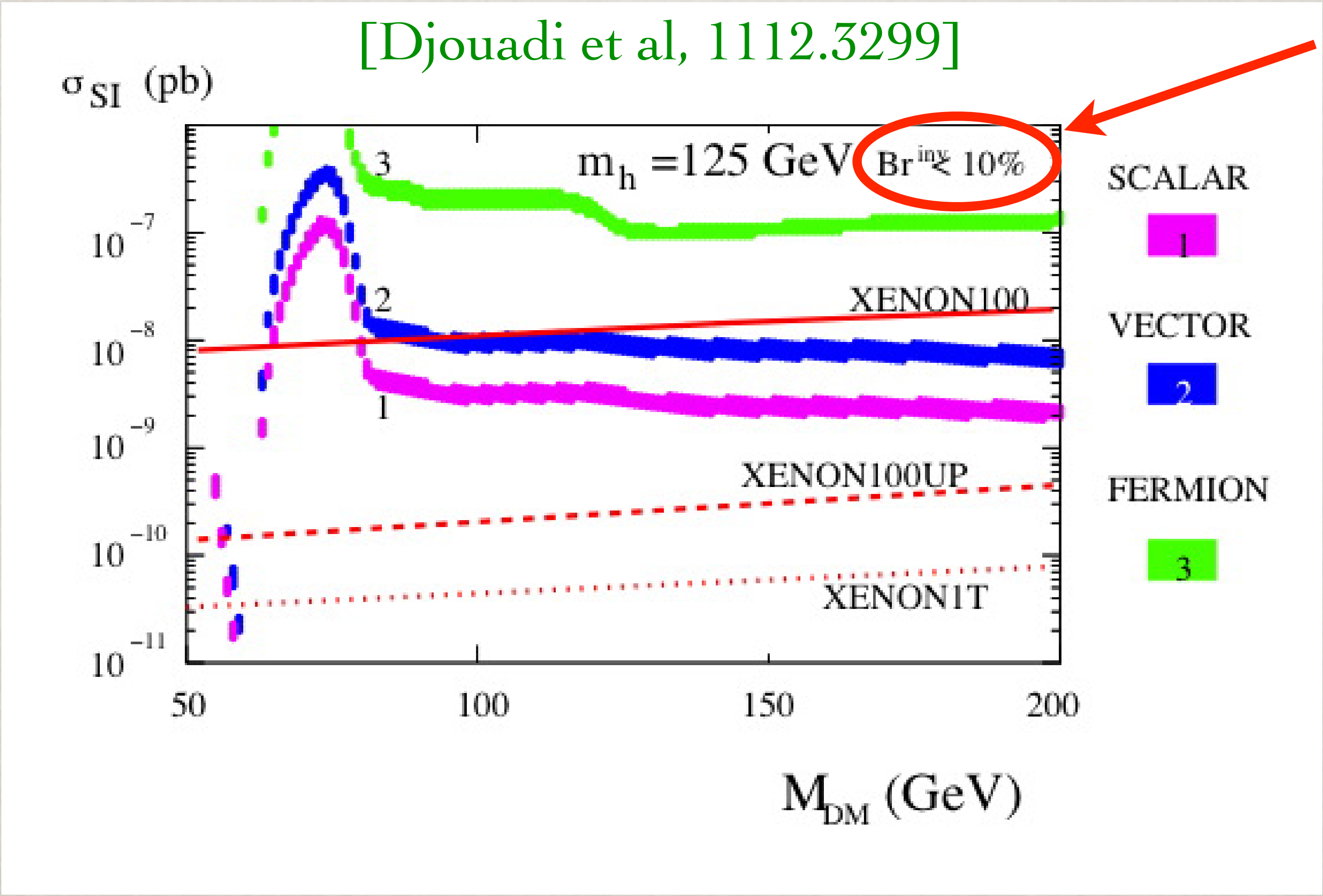
[1207.5988[astro-ph.CO]]

Higgs



Higgs portal DM

If the DM interacts with Higgs via portal interaction, it is already under siege by DD & LHC:

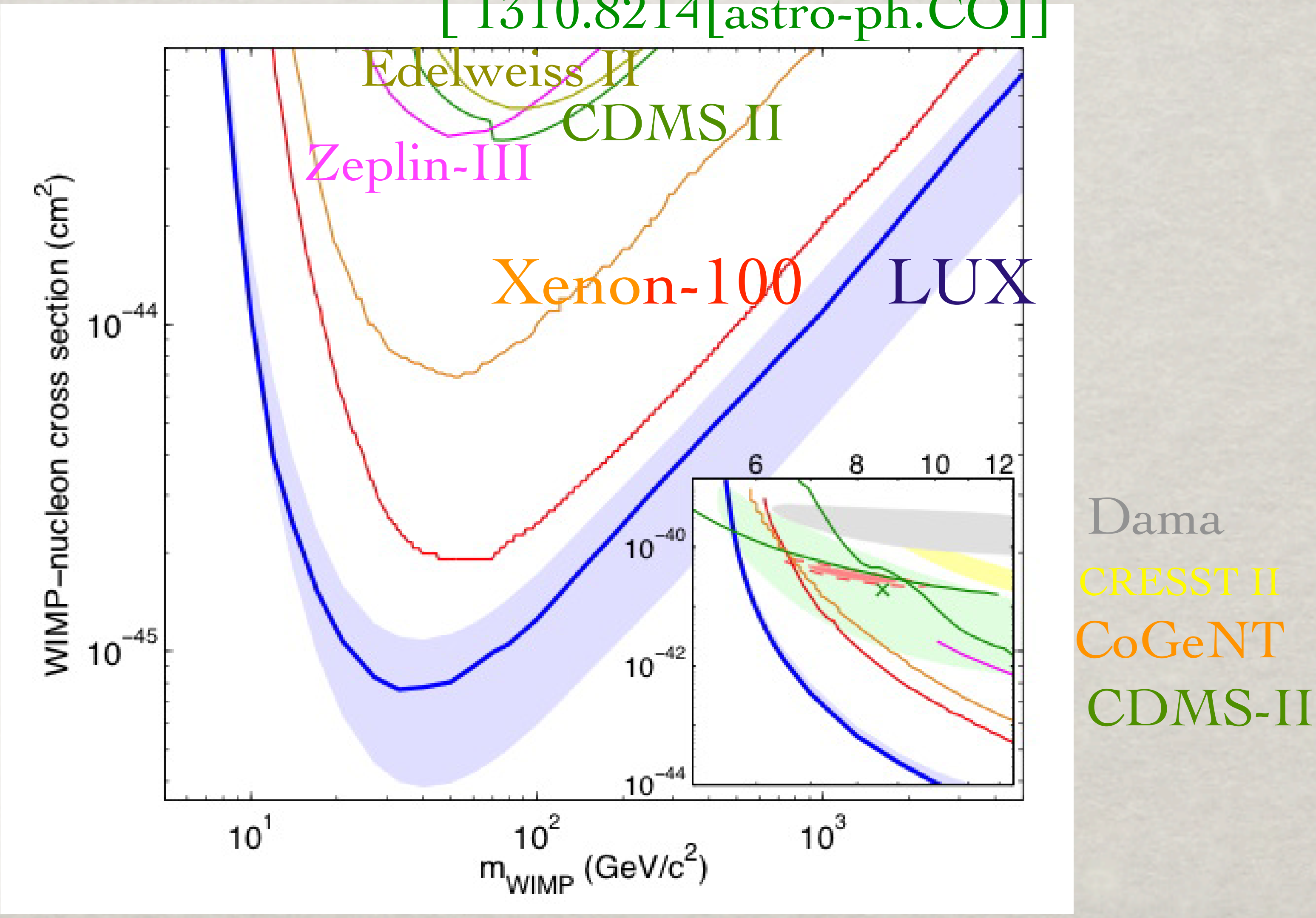


Invisible Higgs decay

NEWS: SIGNAL(S) OF DM ?

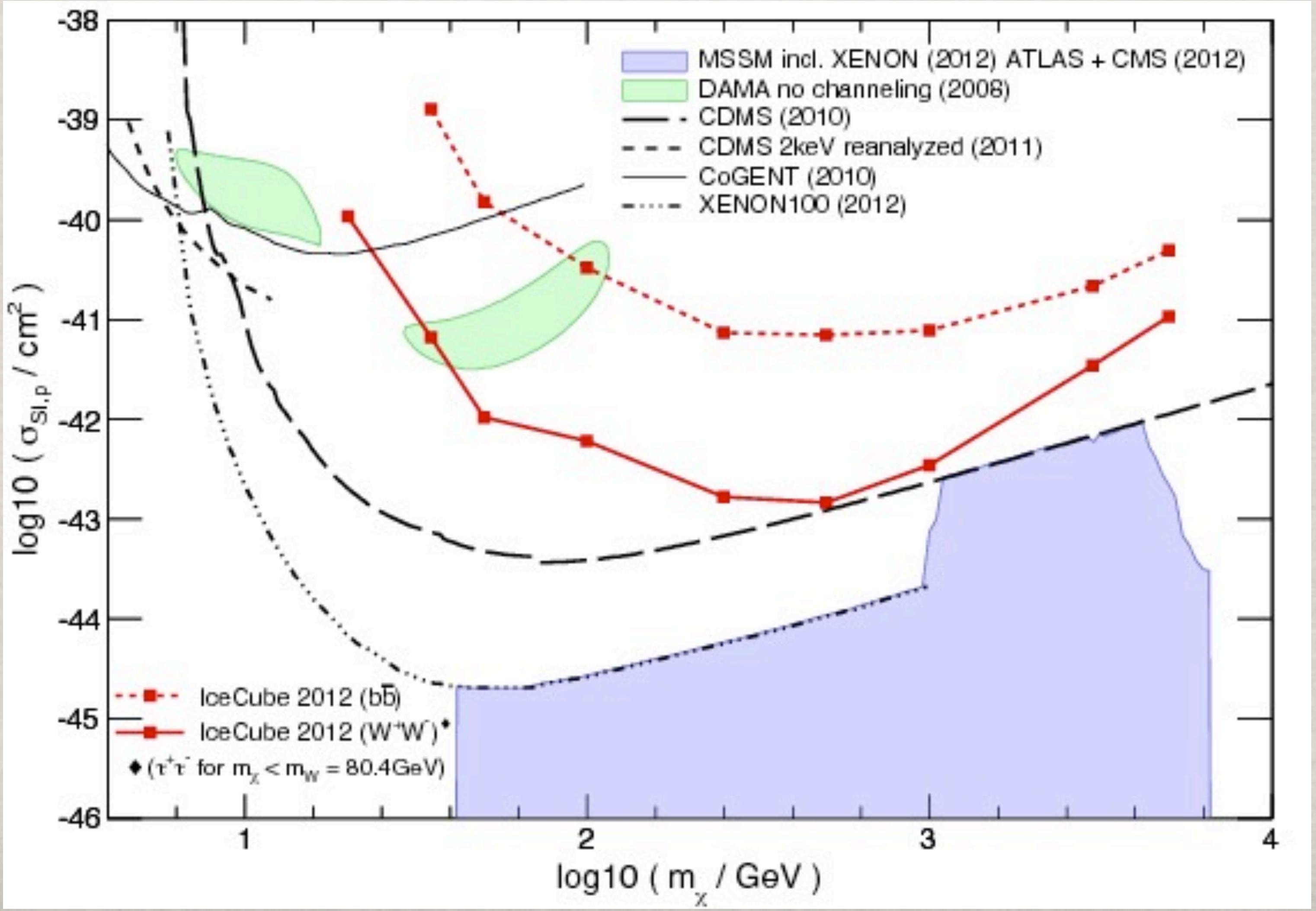
Latest results by LUX with lowest threshold ever !
Again excludes all previous hints

[1310.8214[astro-ph.CO]]



DM signal in neutrinos

DM can accumulate and annihilate in the sun, if it interacts sufficiently strongly with protons; the only particles that can escape the sun environment are neutrinos: Limits from neutrino detectors



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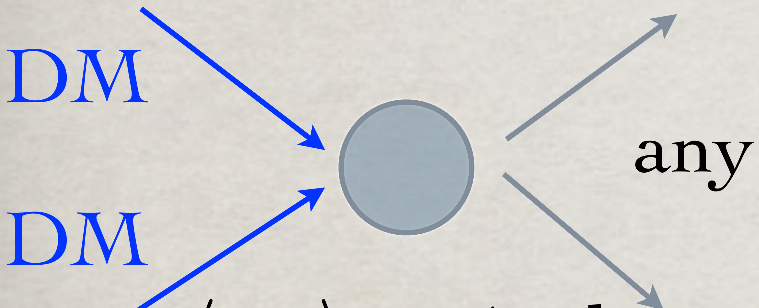
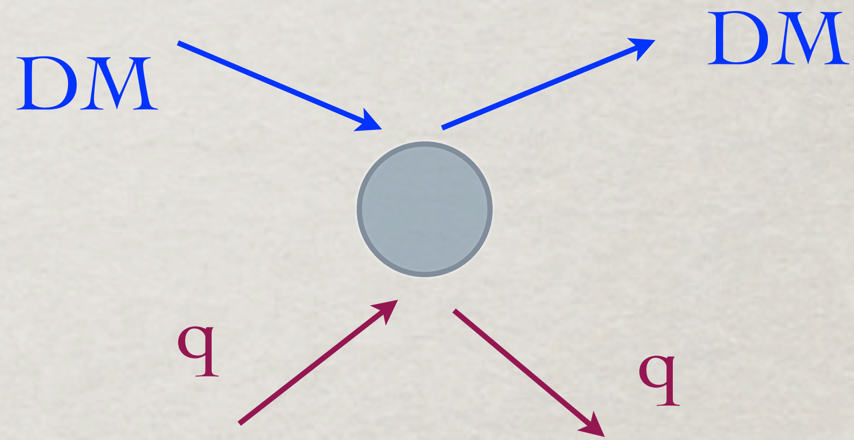


$\langle \sigma v \rangle \sim 1 \text{ pb}$

Direct Detection:



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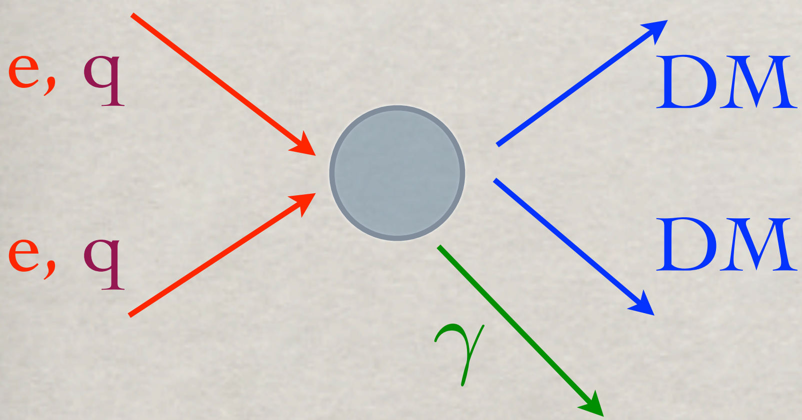
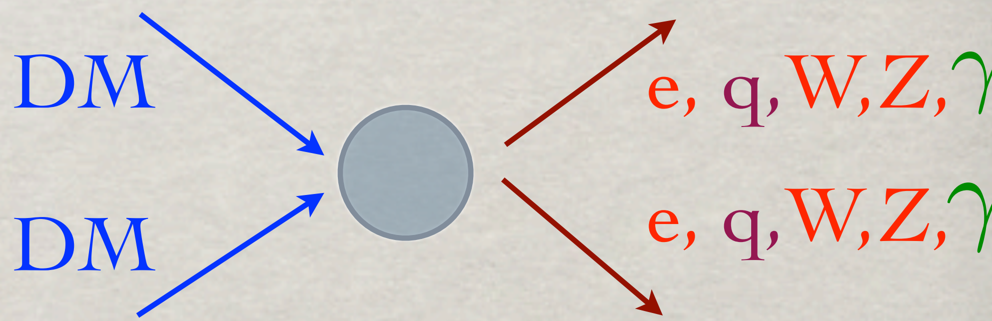


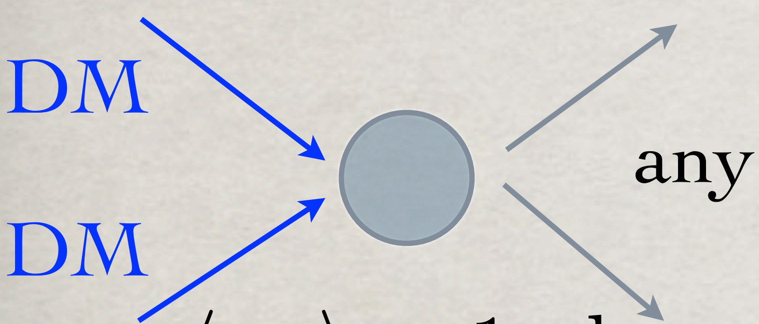
Indirect Detection:



3 different ways to check this hypothesis !!!

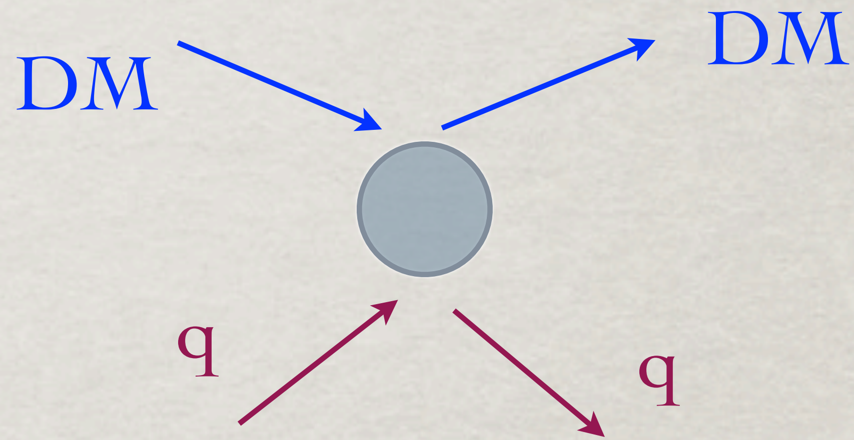
THE WIMP CONNECTION

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

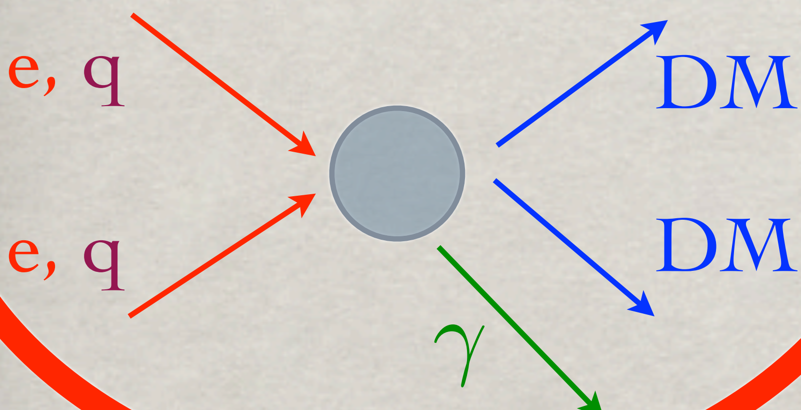


$\langle \sigma v \rangle \sim 1 \text{ pb}$

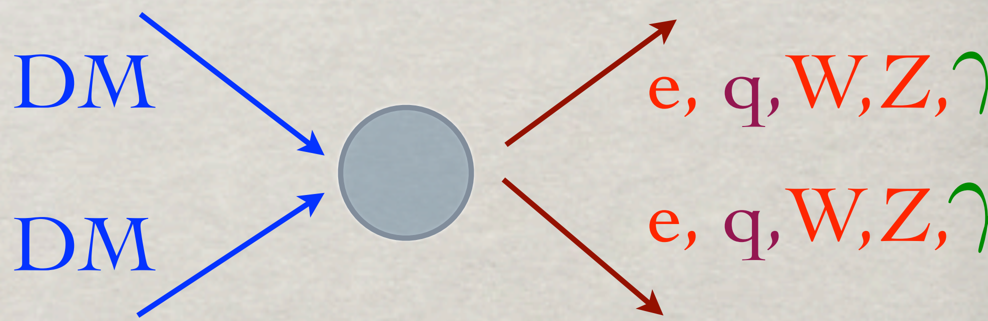
Direct Detection:



Colliders: LHC/ILC



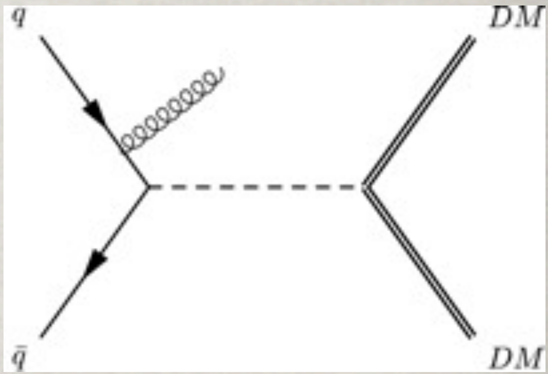
Indirect Detection:

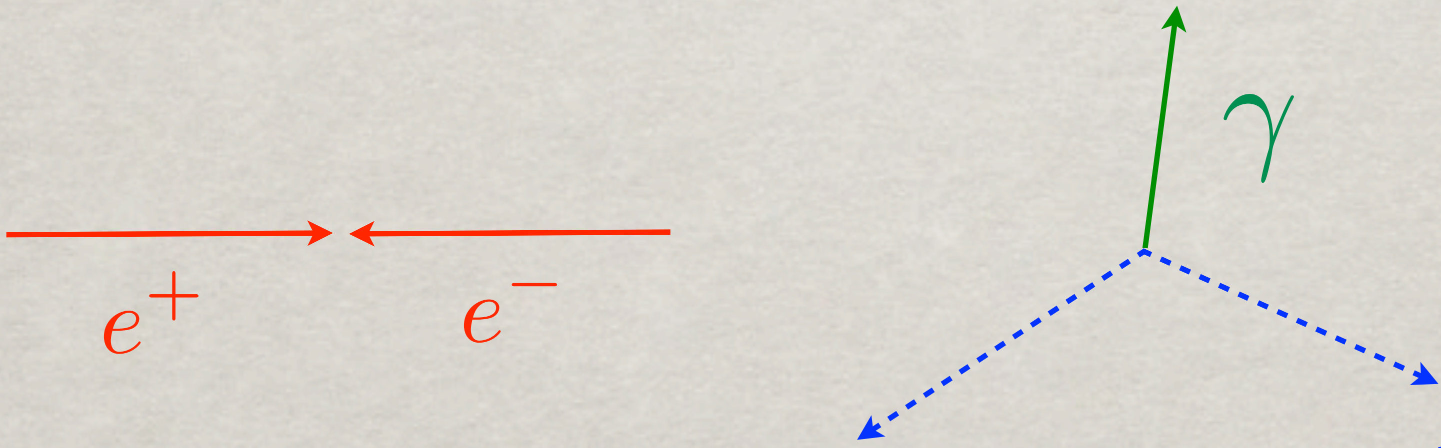


3 different ways to check this hypothesis !!!

Missing energy signature

- The direct production of two DM particles in a collider gives unfortunately no signal !
  The energy just disappears...
- How is it possible to tag such events:
  Thanks to Initial State Radiation !
  i.e. either a single photon or gluon emitted by the initial parton, recoiling against the DM particle(s)



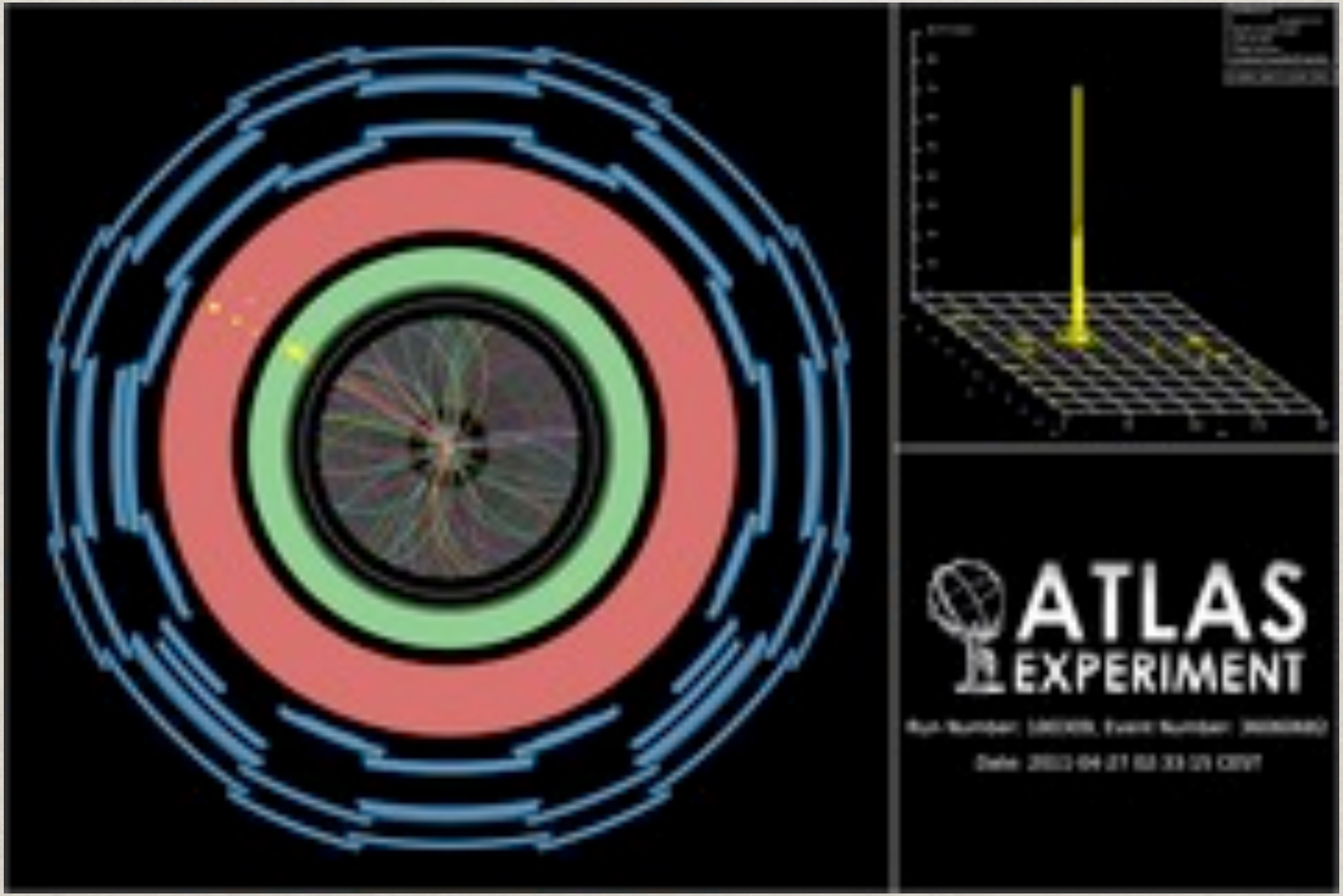


Dark Matter:
Missing energy signature

Trouble: need sufficient rate of DM production...

LHC: Monojets ?

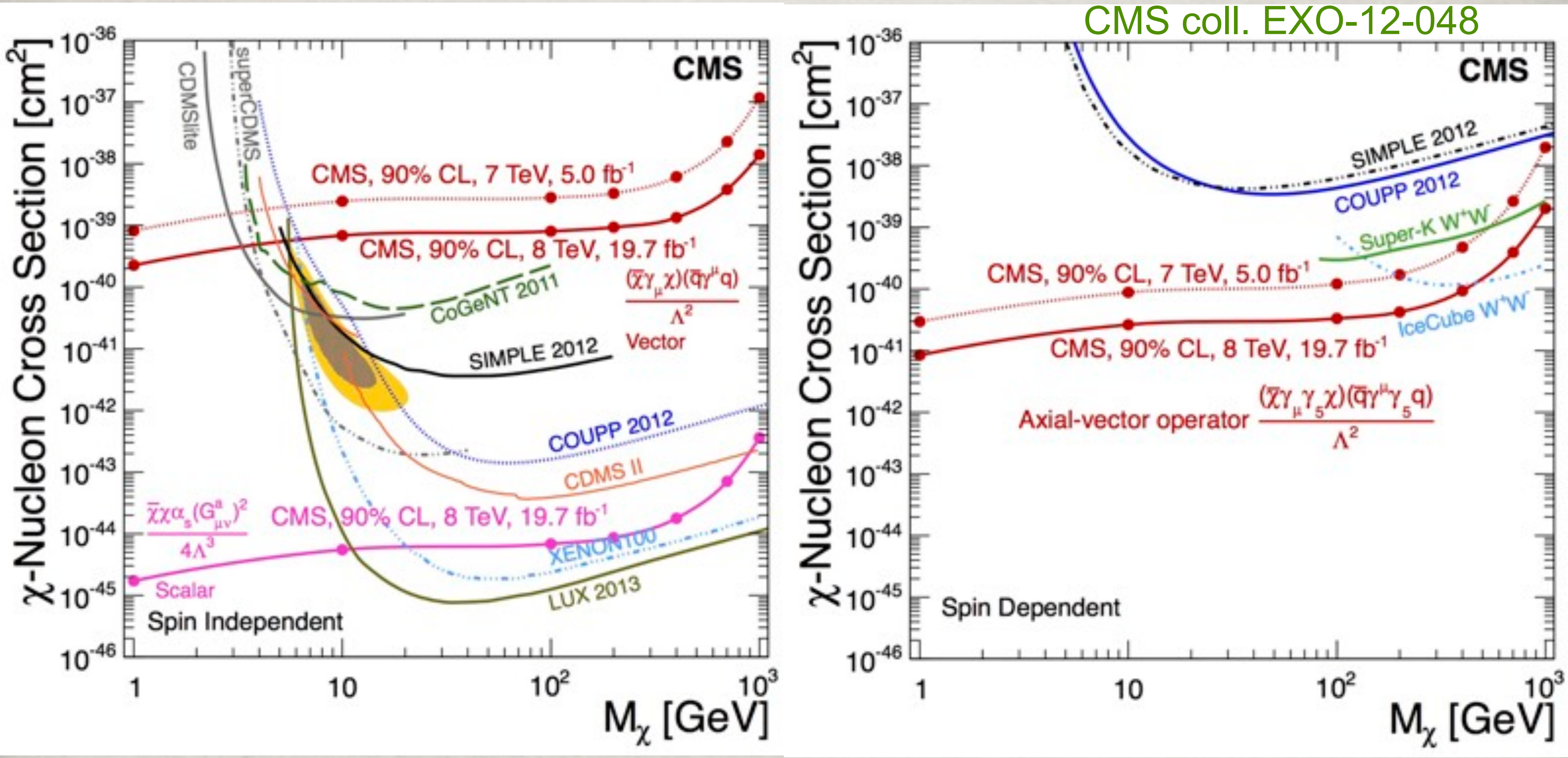
The gluon ISR channel has already being measured at LHC...



Monojet candidate event !

COLLIDER BOUNDS

ATLAS & CMS have performed monojet/monophoton analysis for DM:

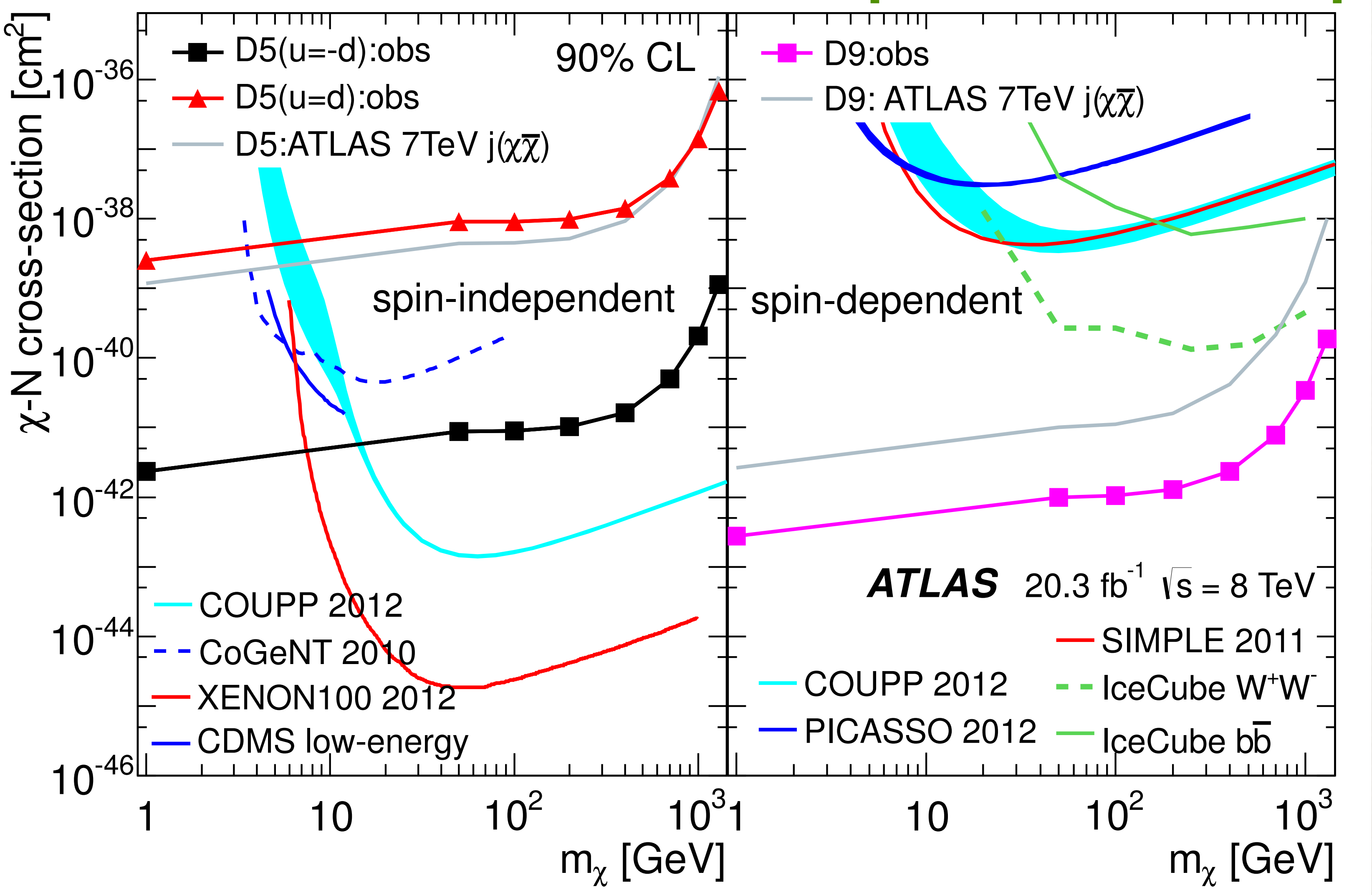


Strongest bound for low mass and for spin dependent case !

COLLIDER BOUNDS

Recently also bounds for mono-W or mono-Z have appeared:

[ATLAS coll. 1309.4017]



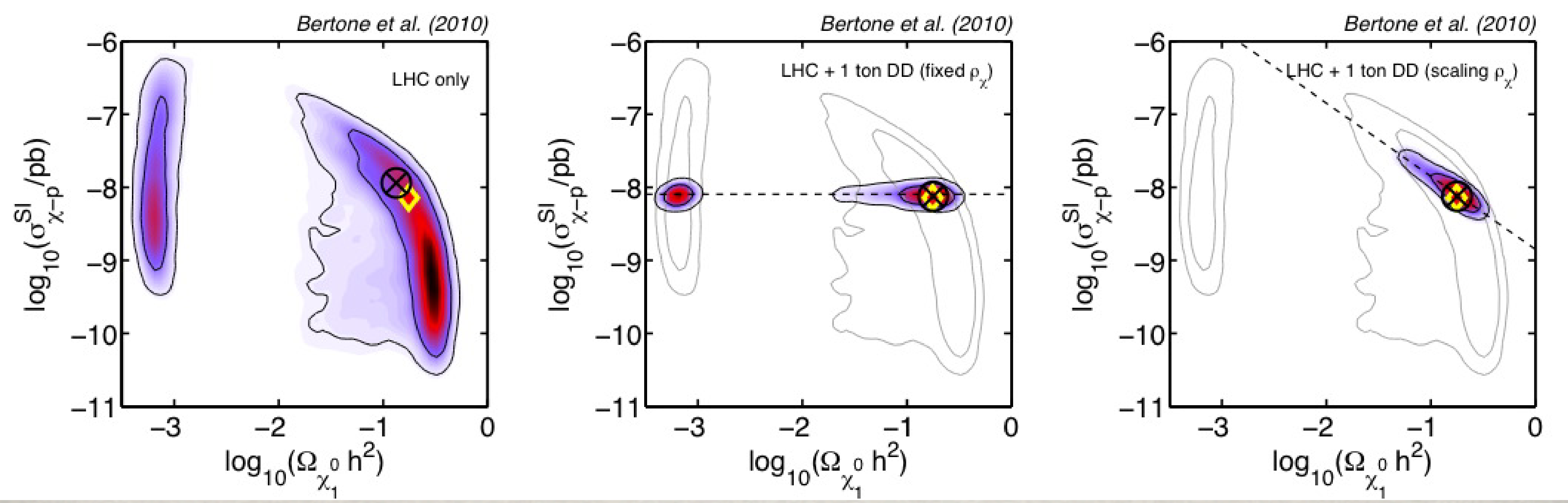
The bounds depend strongly on the operator considered !

LHC-D/ID complementarity

- DD and especially ID have a much more extended mass reach than a collider, even if the sensitivity decreases for large masses since the number density becomes lower...
- A missing energy signal at LHC does not guarantee that the escaping particle is DM or even a thermal relic. We need also a detection signal at ID or DD to be sure that we are seeing the DM particle !
- Goal is also checking the consistency with the WIMP mechanism from measures @ collider (not so simple).

LHC-D/ID complementarity

Even reconstructing its density from the couplings can be difficult since degenerate solutions may appear, e.g. in SUSY.

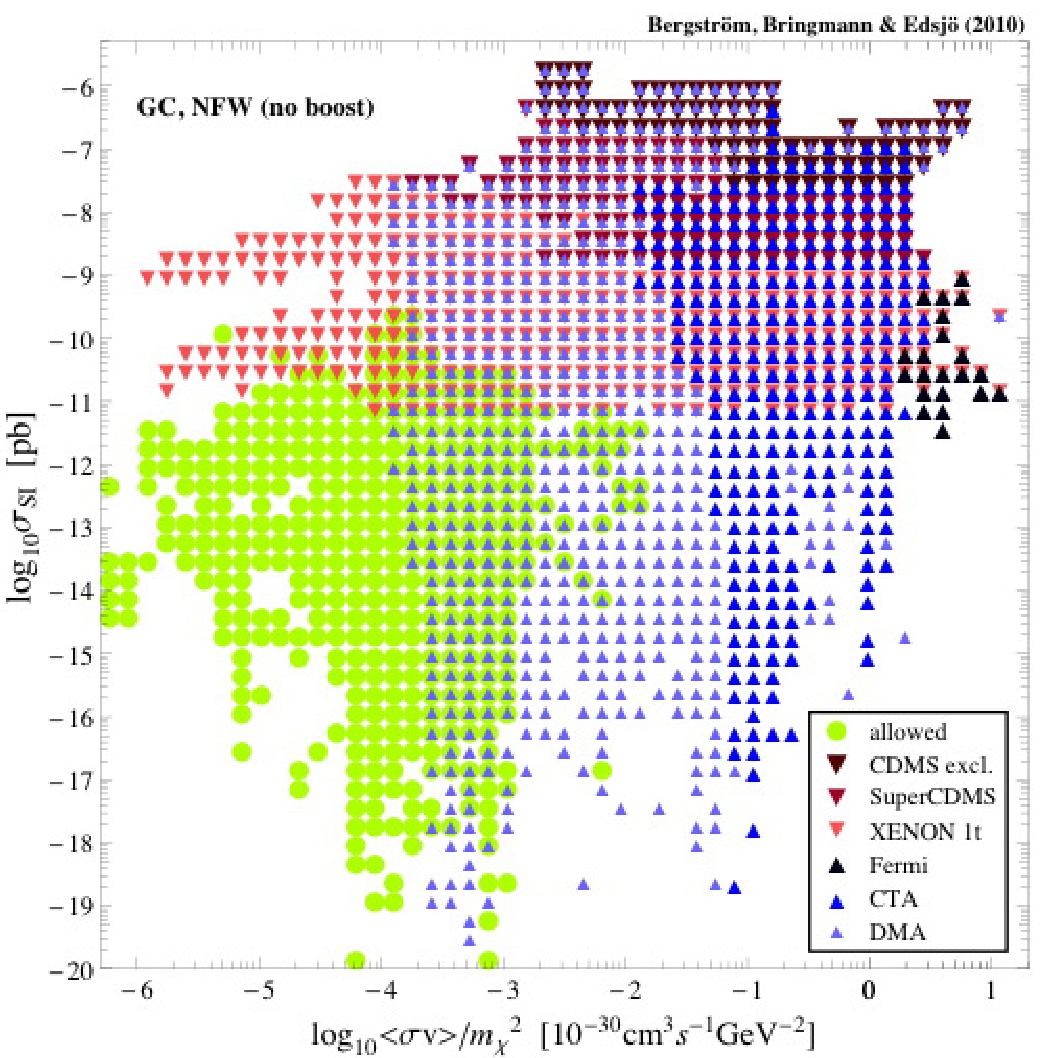


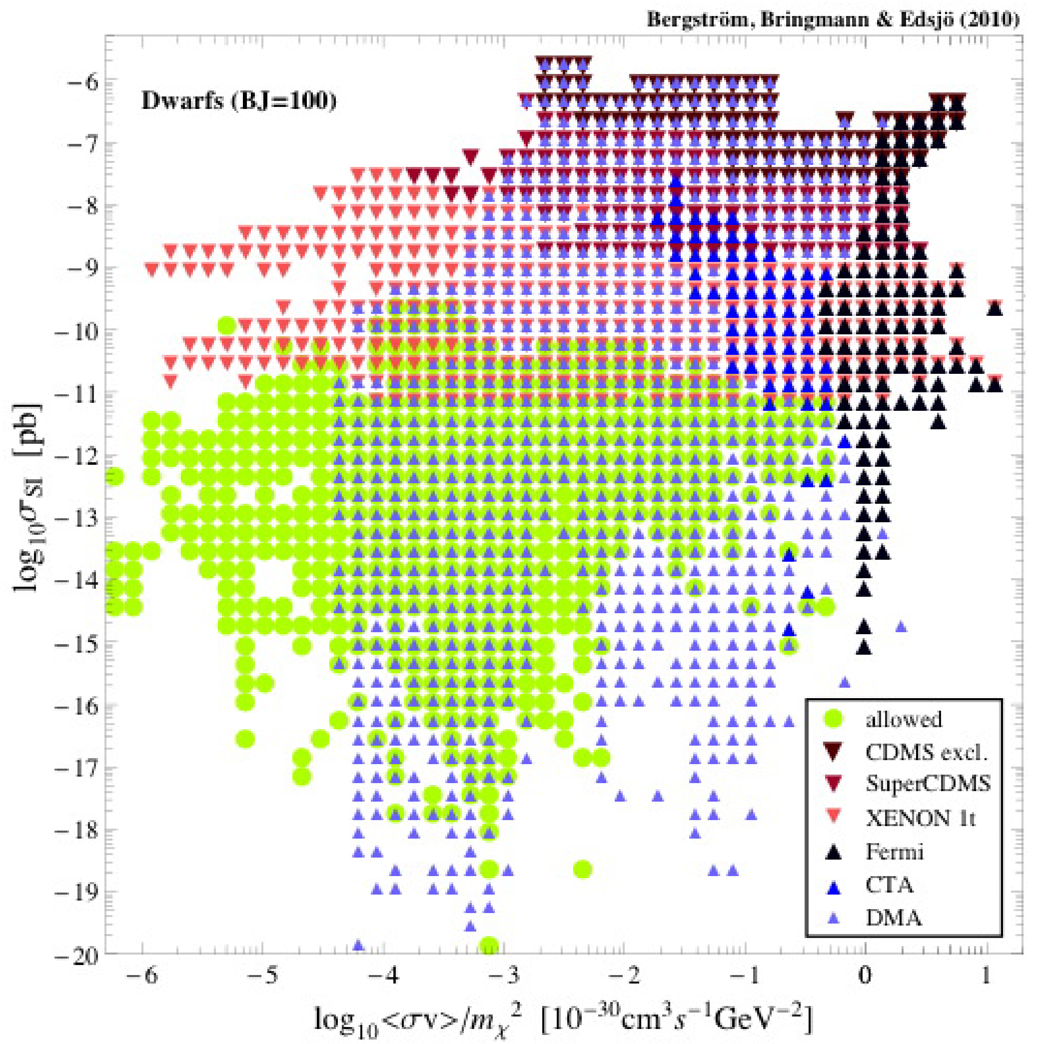
The inclusion of direct detection data in the analysis can lift degeneracies and single out the right solution...
In the best case one would like to have three agreeing signals as a cross-check for the WIMP paradigm !

ID-DD complementarity

ID and DD probe different part of the parameter space e.g. in supersymmetric models !

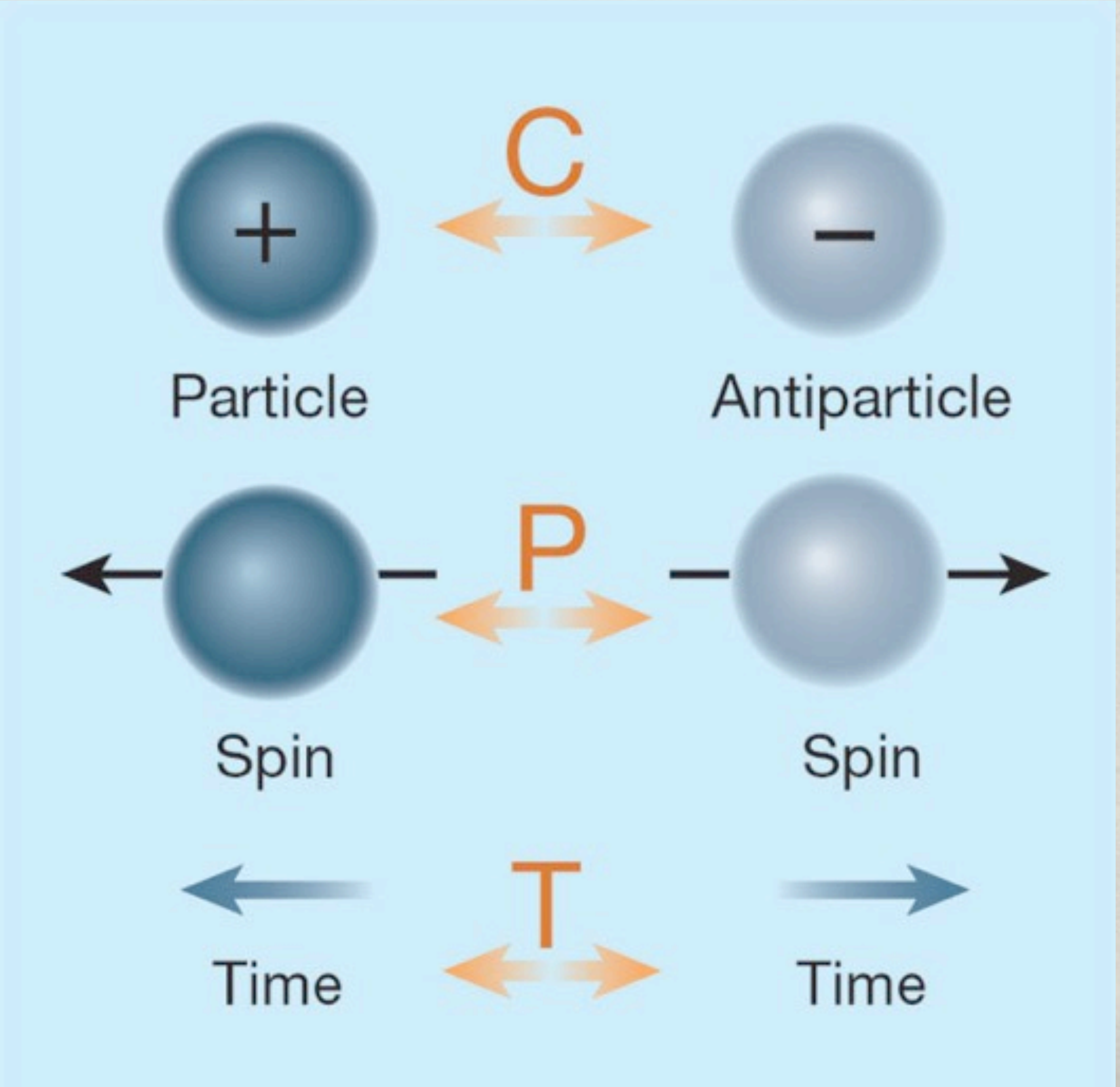
[Bergström, Bringmann & Edsjö-2010]





CP violation in the SM & beyond

C, P, & T symmetries



CPT THEOREM

A Lorentz-invariant QFT with an hermitian Hamiltonian cannot violate the CPT symmetry !

[Lueders & Pauli 1954]

CP violation $\longleftrightarrow$ T violation

Consequence of CPT theorem and locality: particle and antiparticle have the same mass !

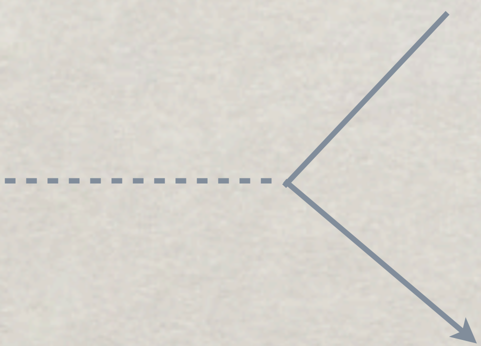
But not the same decay rate or scattering rate in the full quantum theory...

CP violation is quantum

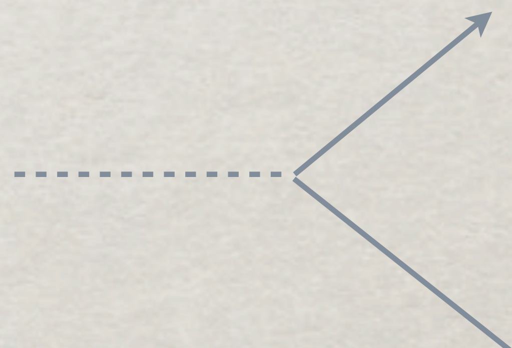
A theory violates CP if complex couplings are present, i.e.

$$\lambda \, h\bar{q}u + \lambda^* \; h^*\bar{u}q$$

If $\lambda \neq \lambda^*$ particle and antiparticle have to start with different couplings, but since $|\lambda| = |\lambda^*|$ the effect reveals itself only via quantum loops !



$i\,\lambda$



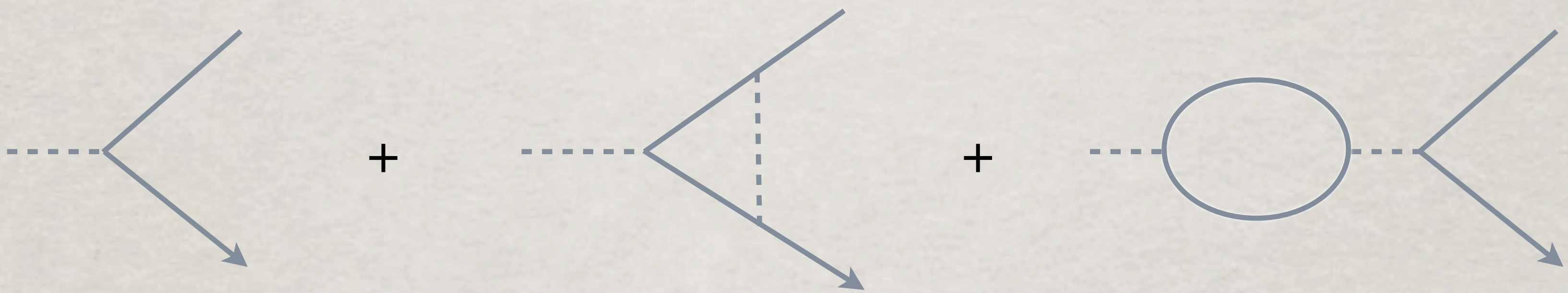
$i\,\lambda^*$

At Born level the matrix element for both decays is

$\mathcal{M} \propto |\lambda|^2 = |\lambda^*|^2$ No CP violation at tree level !

CP violation is quantum

At one loop level first signs of CP violation can appear, the most dominant usually the interference effect between tree-diagram and one-loop-diagrams



$$i\,\lambda \qquad\qquad i\,\lambda\, i\,\lambda^* i\,\lambda \qquad\qquad i\,\lambda\;\; i\,\lambda^*\, i\,\lambda$$

So we have for particle & antiparticle:

$$\mathcal{M} \propto |\lambda|^2 + 2Re\left[\lambda\lambda^*\lambda\lambda^*\; L(x)\right] + \ldots$$

$$\overline{\mathcal{M}} \propto |\lambda^*|^2 + 2Re\left[\lambda^*\lambda\lambda^*\lambda\; L(x)\right] + \ldots$$

$$\Delta\mathcal{M} \propto 2Re\left[\lambda\lambda^*\lambda\lambda^*\; L(x) - \lambda^*\lambda\lambda^*\lambda\; L(x)\right] + \ldots$$

$$\Delta\mathcal{M} \propto -4\, Im\left[\lambda\lambda^*\lambda\lambda^*\;\right] Im[L(x)] + \ldots$$

NB: Vanishing for a single coupling, need flavour dependence !

Unitarity relation

We can obtain the same result and the interpretation of the imaginary part of a loop function from the unitarity relation for the scattering matrix & CPT: $S = I - i\,T$

From unitarity: $S^\dagger S = I = I - i(T - T^\dagger) + T^\dagger T$

$$\longrightarrow \quad T = T^\dagger - i\,T^\dagger T$$

Therefore if we square the amplitude we get

$$|T_{fi}|^2 = |T^*_{if}|^2 + 2Im\left[(T^\dagger T)_{fi} T_{if}\right] + |(T^\dagger T)_{fi}|^2$$

From CPT we obtain $T_{if} = T_{\bar{f}\bar{i}}$ and so

$$\boxed{|T_{if}|^2 - |T_{\bar{f}\bar{i}}|^2 = 2\;Im\left[(T^\dagger T)_{fi} T_{if}\right] + |(T^\dagger T)_{fi}|^2}$$

CP violation is SMALL

CP violation in particle physics arises as a quantum effect from the interference of tree-level and loop diagrams. For these reasons it is multiply suppressed:

- It is higher order in the couplings, e.g.
  $\Delta\mathcal{M} \propto |\lambda|^4$ compared to $\mathcal{M} \propto |\lambda|^2$
- It contains a loop suppression factor
  $$L(x) \propto \frac{1}{4\pi^2} \sim 0.025$$
- It often needs a non-trivial flavour structure and it is therefore even more suppressed in presence of small mixing between generations.

CabibboKobayashiMaskawa Matrix

The CKM matrix is a unitary 3x3 matrix and can in principle contain up to 3 mixing angles and 6 complex phases (recall for nxn: $n(n-1)/2$ angles $n(n+1)/2$ phases), but 5 (2n-1) phases can be reabsorbed in the definition of the fermions, so that only one ($(n-1)(n-2)/2$) phase is physical.

[Wolfenstein 1983]

$$V_{CKM} = \begin{pmatrix} 1 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

The parameter η determines the CP violation and in the SM it is not small ! The area of the unitarity triangles is given by the Jarlskog invariant, measured in K/B decays:

$$J \sim \lambda^6 A^2 \eta \sim 10^{-6}$$

Neutrino masses

The neutrinos are neutral and do not carry a conserved (local) charge, therefore in their case we can also write down a Majorana mass term in addition to the Dirac mass term.

e.g. dimension 5 Weinberg operator:

$$\frac{y}{M_P}\, H^* \bar{\ell}^c H \ell \quad \longrightarrow \quad \frac{y v_{EW}^2}{2 M_P}\, \bar{\nu}_L^c \nu_L$$

A Majorana mass matrix is symmetric and can be diagonalized by an orthogonal rotation, leaving more physical phases !

Pontecorvo-Maki-Nakagawa-Sakata mixing matrix with one Dirac phase δ and two Majorana phases α, β:

$$U_{PMNS} = P \begin{pmatrix} c_{13}c_{12} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - s_{23}c_{12}s_{13}e^{i\delta} & c_{23}c_{12} - s_{23}s_{12}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}c_{12}s_{13}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{12}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

with P = $\mathrm{diag}(e^{i\alpha}, e^{i\beta}, 1)$ $\qquad s_{ij}, c_{ij} = \sin\theta_{ij}, \cos\theta_{ij}$

Baryogenesis & the Sakharov conditions

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

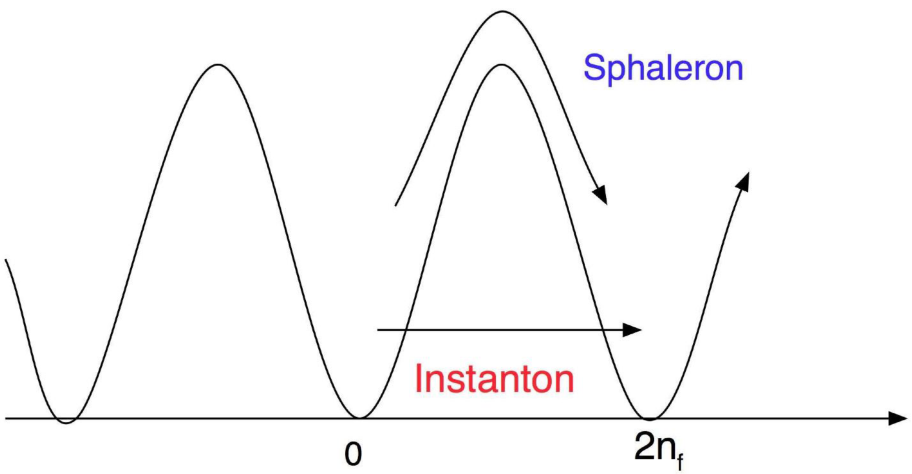
Sakharov studied already in 1967 the necessary conditions for generating a baryon asymmetry from a symmetric state:

- B violation: trivial condition since otherwise B remains zero...
- 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 !

Sakharov Conditions II

For the Standard Model actually we have instead:

- B-L violation: B+L violation 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: present in the CKM matrix, but unfortunately quite small ! Possibly also additional phases needed...

- Departure from thermal equilibrium: phase-transition or particle out of equilibrium ?

Mechanisms for baryogenesis

Sakharov conditions for SM

Let us check the Sakharov conditions for the SM:

- B violation: OK
  Sphaleron processes violating B+L

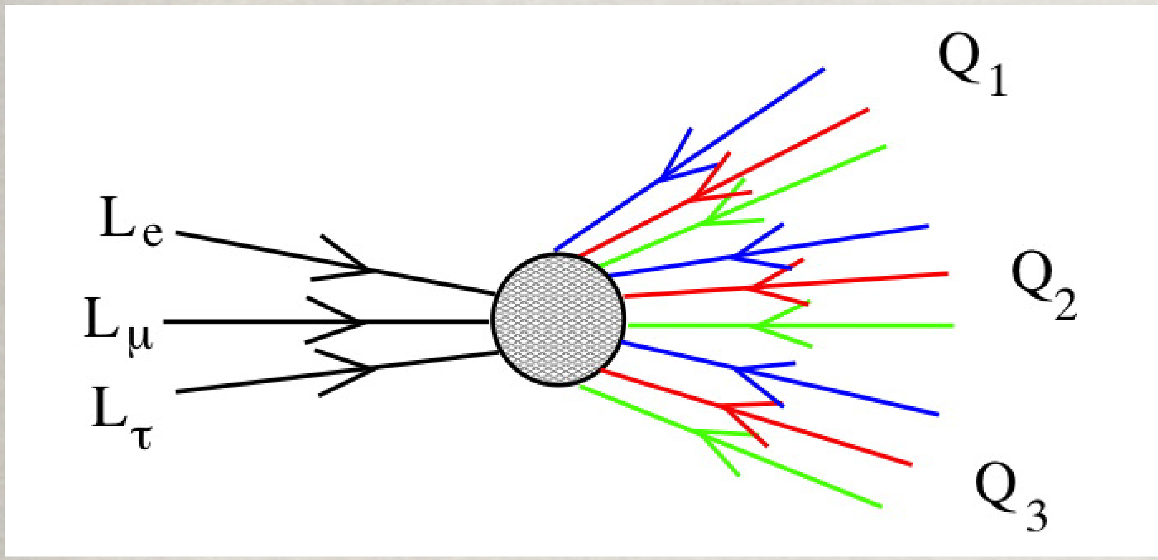
- C and CP violation: OK
  Weak interaction and Yukawa couplings

- Departure from thermal equilibrium: OK
  the electroweak (first order) phase transition

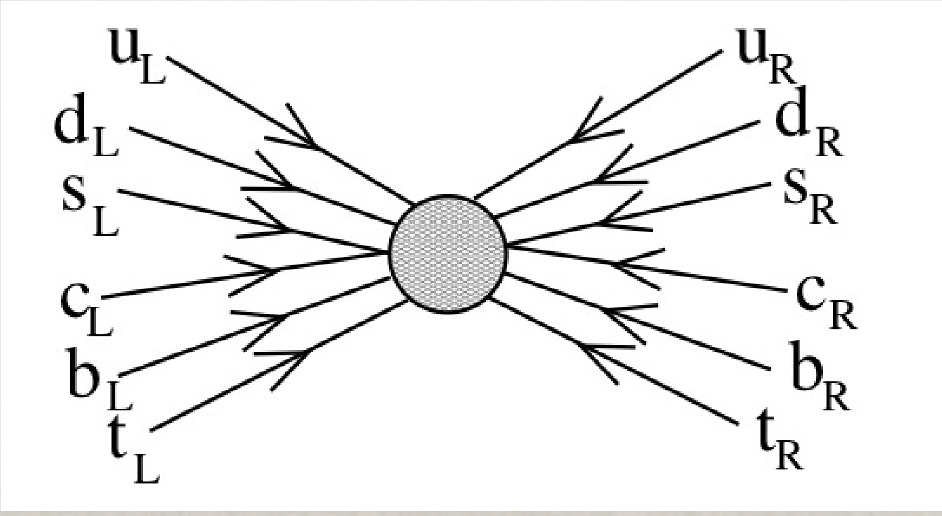
Possible to generate the BAU at the electroweak scale !

[Kuzmin, Rubakov & Shaposhnikov 1985]

Spaleron Processes

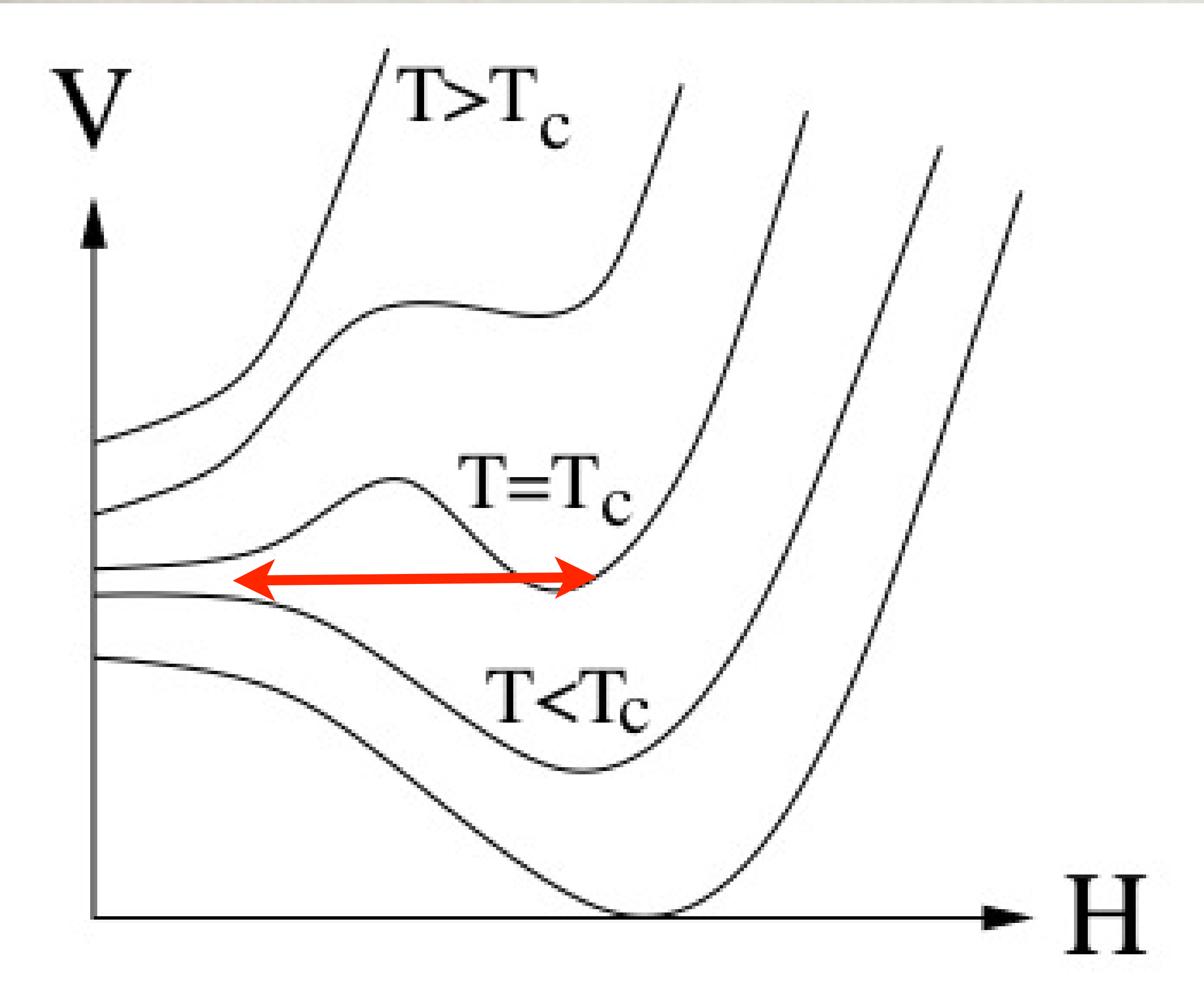


EW Sphaleron:
B and L both change
by -3 units, for n=1
change in Chern-Simons
(winding) number,
while B-L is conserved



QCD Sphaleron:
chirality charge Q_5
changes by $2n_f$ units

1st order transition



At the critical temperature the two vacuum are degenerate. After that temperature, the phase transition proceeds through a tunnelling process from the unstable vacuum at H=0 to the true vacuum with non-zero v.e.v.

The order parameter v jumps from zero to a finite value !

EW baryogenesis

Broken phase

$$\Gamma_{sph} \sim 0$$

$$\frac{v_c}{T_c} > 1$$

Strong 1st order PT

B > 0

$\not{CP}$

$\not{CP}$

v_W

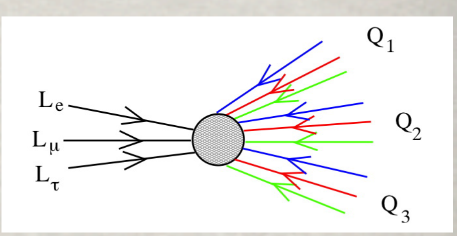
L_W

$\not{CP}$

$\not{CP}$

Unbroken phase

$$\Gamma_{sph} > H$$



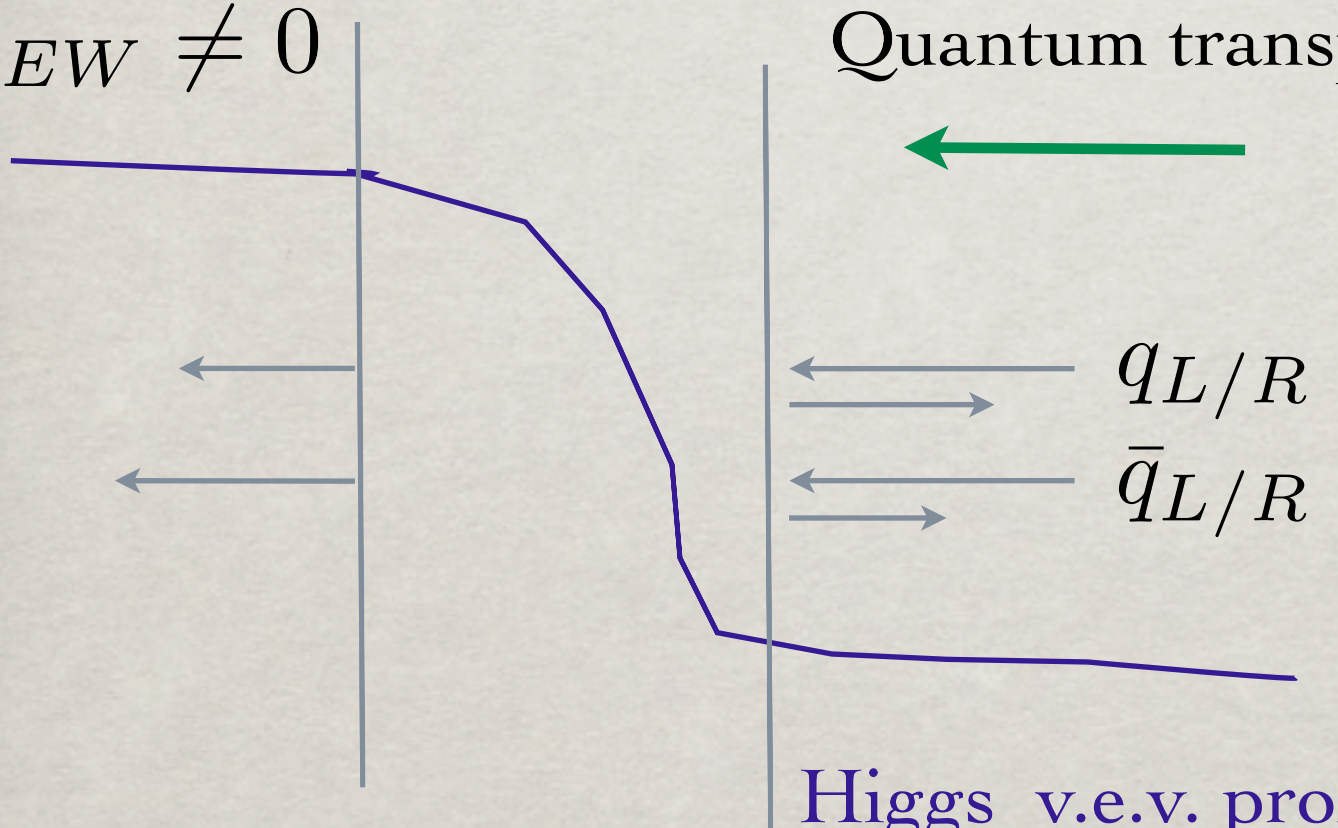
B=0

EW Baryogenesis

The bubble wall corresponds to a non-trivial v.e.v. profile. C, CP violation is provided by the different reflection/ transmission probabilities across the bubble wall.

$v_{EW} \neq 0$

Quantum transport equation



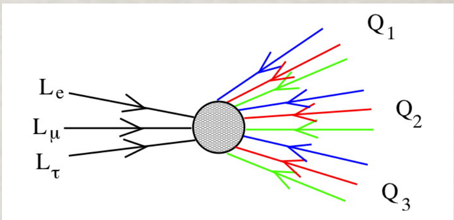
$q_{L/R}$

$\bar{q}_{L/R}$

Higgs v.e.v. profile

$v_{EW} = 0$

Bubble Wall at rest



EW sphalerons translate the CP asymmetry into BAU that then drifts into bubble

EW Phase Transition in SM

Compute the effective potential at finite temperature:

$$V(H,T) = m^2(T)H^2 - E(T)H^3 + \lambda(T)H^4$$

The cubic term determines mostly the presence of a barrier

Bosonic Loops contribute to E(T), increasing the strength of the phase transition

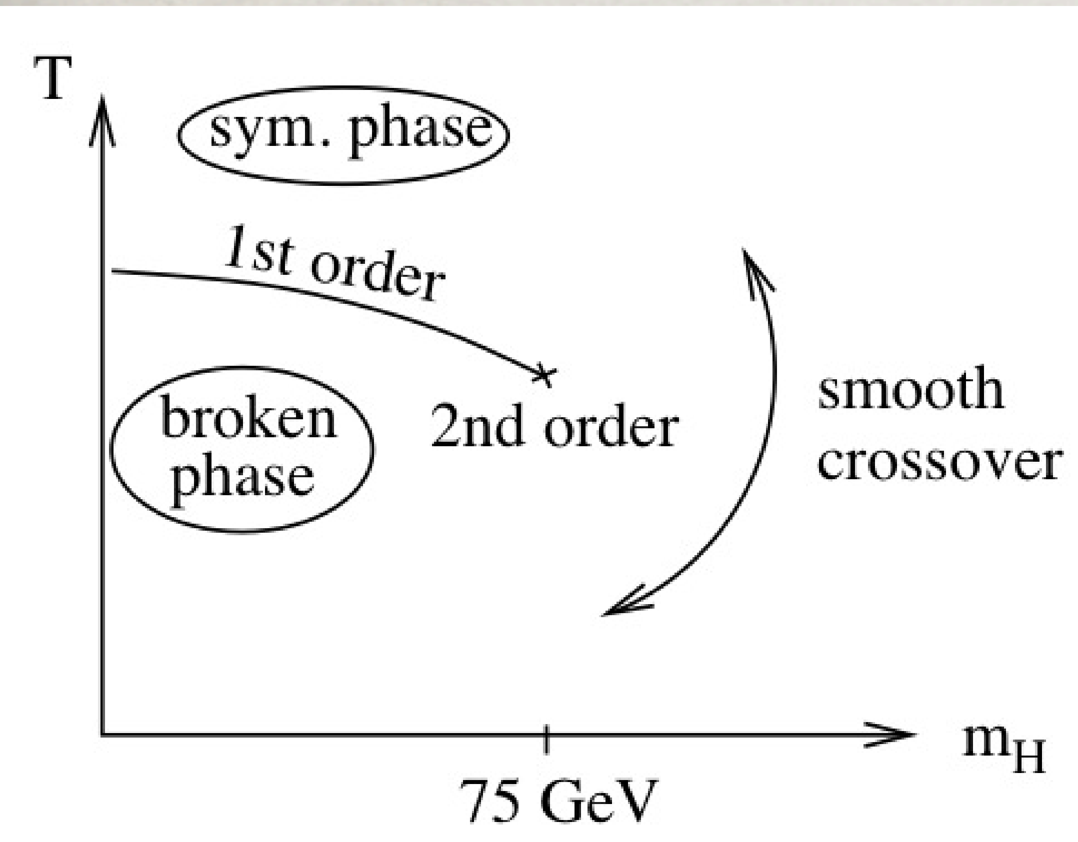
Caveat: perturbative computation is not trustworthy at the critical temperature

$\longrightarrow$ Lattice computations

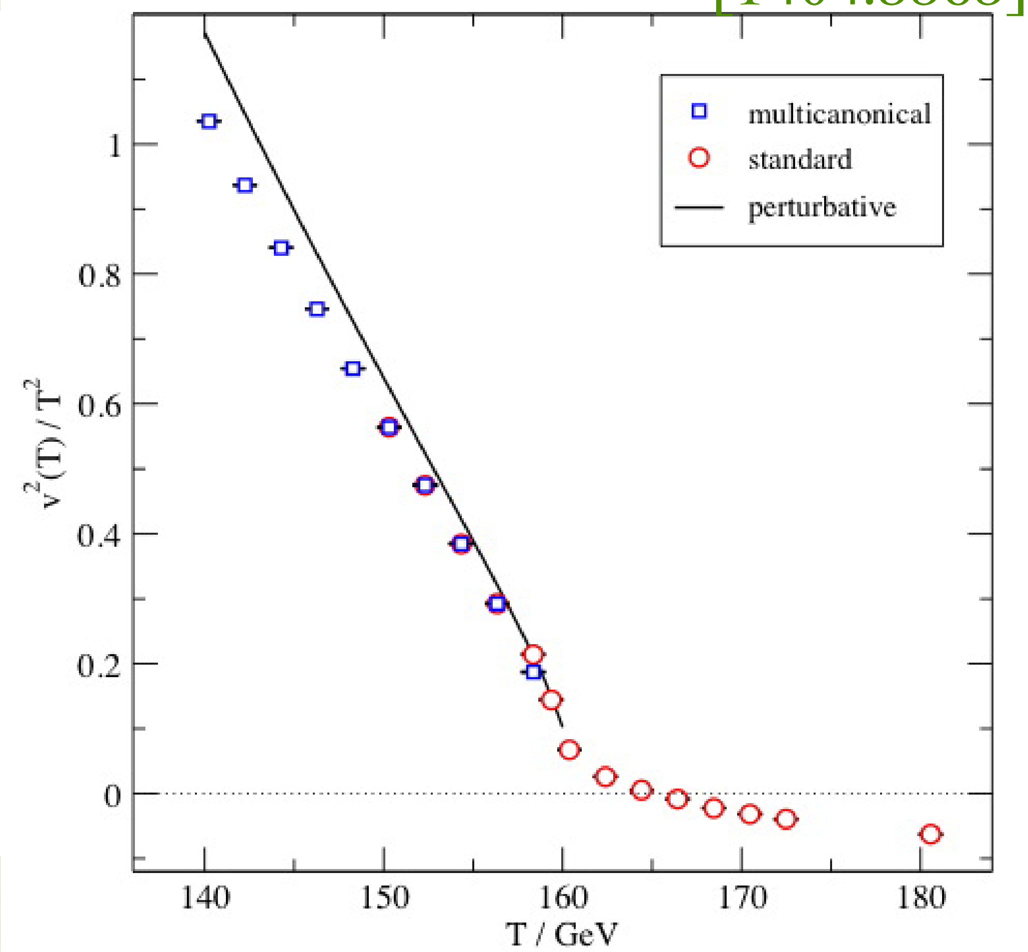
Only if the transition is sufficiently strong, i.e. $\dfrac{v_c}{T_c} > 1$ EW baryogenesis can work !

EW Phase Transition in SM

Compute the phase diagram for the EW phase transition:
for the physical Higgs mass it is a smooth cross-over !



[1404.3565]



NO EW baryogenesis in the SM !

Sakharov conditions for SM

Let us check the Sakharov conditions for the SM:

- B violation: OK
  Sphaleron processes violating B+L
- C and CP violation: OK, but not clear if sufficient
  Weak interaction and Yukawa couplings
- Departure from thermal equilibrium: NO !
  the electroweak phase transition is a cross-over...

Not possible to generate the BAU at the electroweak scale in the Standard Model !

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 Phase Transition BSM

Again compute the effective potential at finite temperature:

$$V(H,T) = m^2(T)H^2 - E(T)H^3 + \lambda(T)H^4$$

The cubic term determines mostly the presence of a barrier

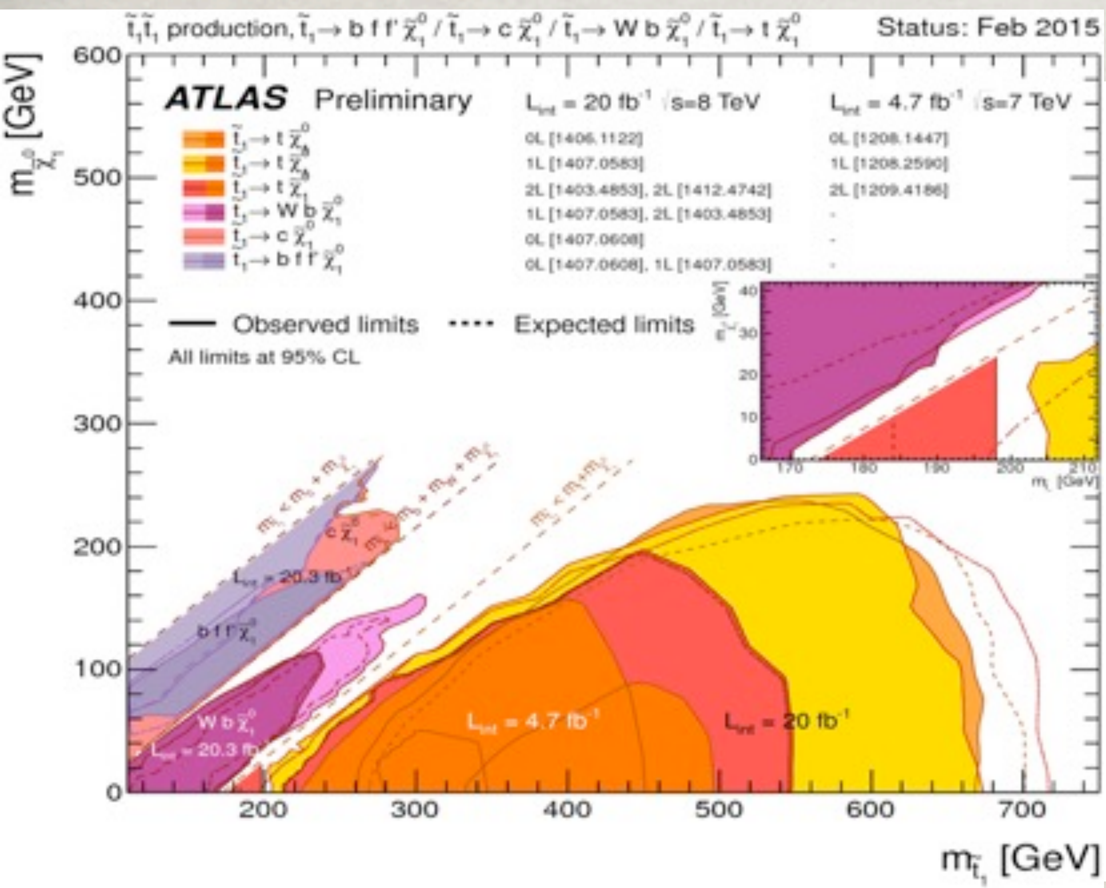
Bosonic Loops contribute to E(T), increasing the strength of the phase transition, so in order to make it first order increase the number of bosons in the model !

Many different possibilities, the simplest ones are:

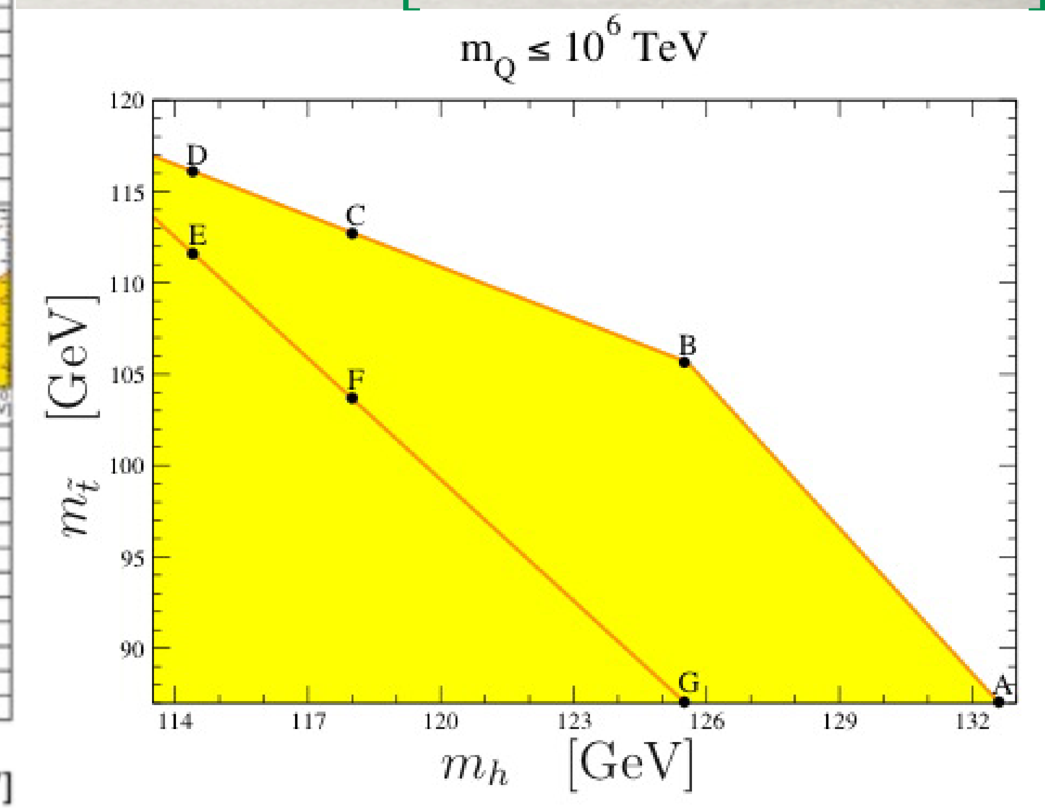
- extend the scalar/Higgs sector of the SM;
- add supersymmetry;
- add higher dimensional operators.

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.

$$W = Y_\nu L H N + \frac{1}{2} M_R N N \quad \rightarrow \quad \text{see-saw}$$

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

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

Both channel are possible due Majorana nature of N !

Neutrino masses & seesaw

[Minkowski 77, Gell-Mann, Ramond & Slanski 79, Yanagida 80]

Try to explain why the neutrino masses are so small: via the mixing with a very heavy state, the RH neutrino N !

$$W = Y_\nu L H N + \frac{1}{2} M_R N N$$

After the EW symmetry breaking we have a mixing between the LH neutrino and N and a Majorana mass term:

$$m_{N\nu} = \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix}$$

Eigenvalues:

$$m_\nu = -\frac{m_D^2}{M_R}, \; m_N = M_R$$

→ see-saw mechanism The larger M_R the smaller m_ν

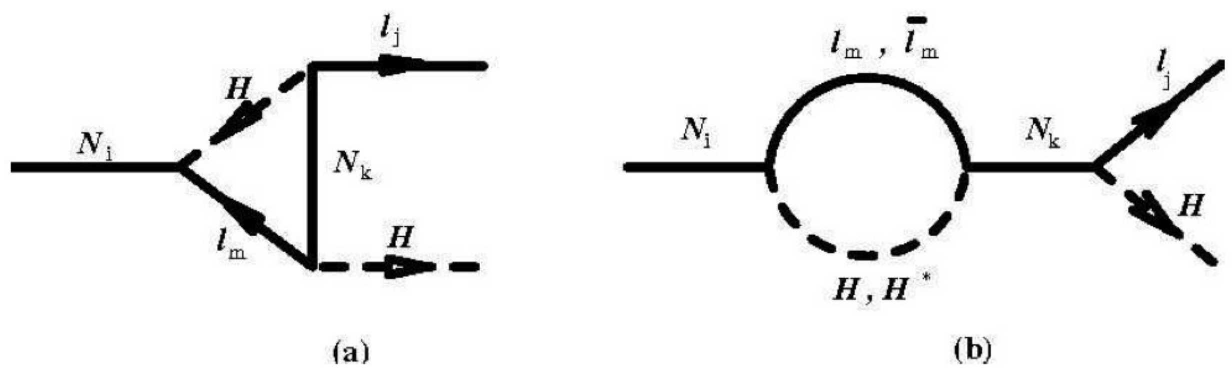
For $m_D \sim m_t$ need $M_R \sim 10^{15}\mathrm{GeV}$

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

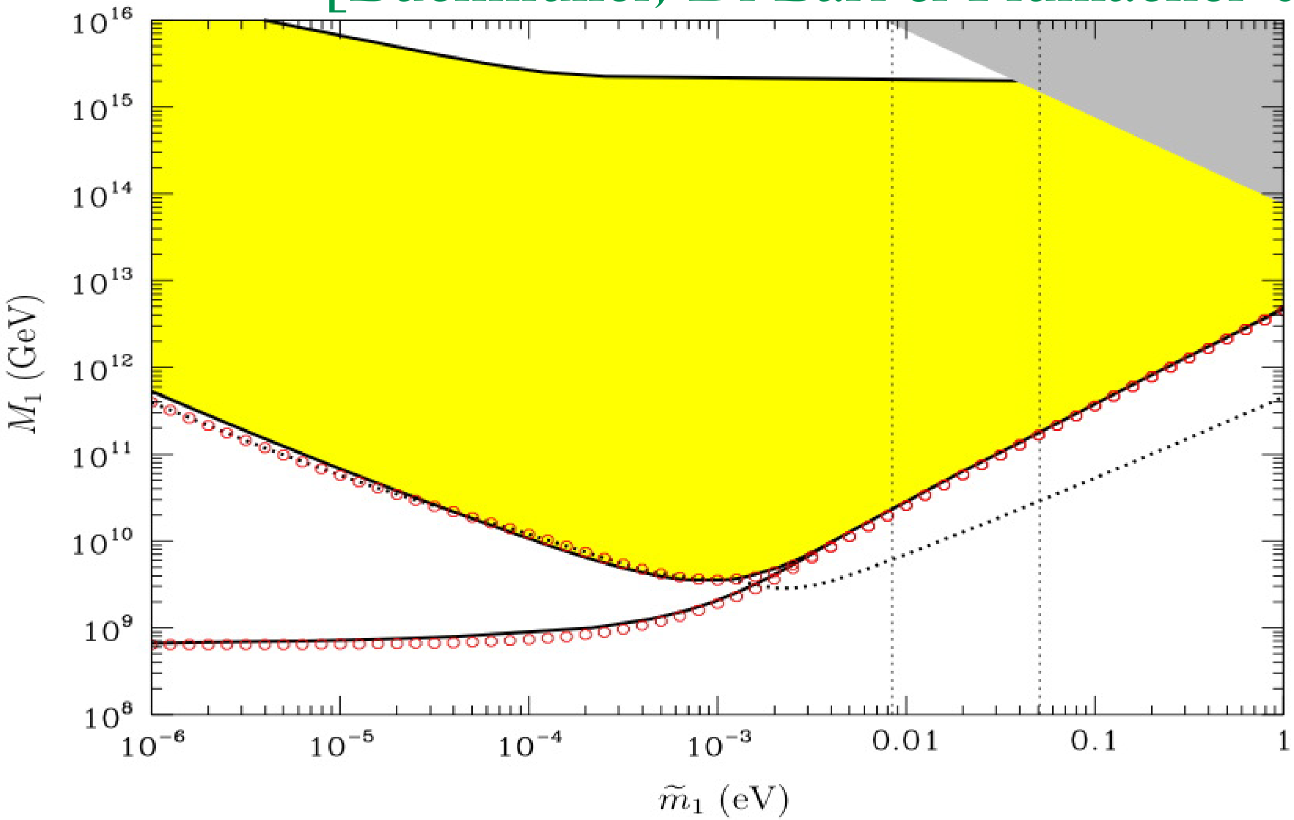
$$\frac{n_L}{s} = \frac{n_{B-L}}{s} = \frac{135\zeta(3)g}{8\pi^4 g_S}\epsilon_1 \simeq 4 \times 10^{-3}\epsilon_1 \quad \rightarrow \frac{n_B}{s} \sim -1.5 \times 10^{-3}\epsilon_1$$

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

Thermal Leptogenesis

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...

Low E vs high E CP ?

One important question is if the low energy leptonic CP violation observables are related to the CP violation in leptogenesis... Unfortunately not directly !

Simple parameter counting:

the 3x3 Majorana (low energy) mass matrix contains 9 real parameters, i.e. 3 masses, 3 mixings and 3 phases (1 Dirac & 2 Majorana phases), while the (high energy) Yukawa matrix & RH neutrino mass matrix amount instead to 18 real parameters.

In general the measurable low-energy Dirac phase in the neutrino sector is given by a complicated of the high energy parameters ! Nevertheless in specific models definite predictions are possible, e.g. 2 RH neutrino case or some flavoured leptogenesis cases...

Conclusions & Outlook

- Cosmology and astroparticle physics still provides a lot of puzzles to solve !
  Still unclear are the nature of the Inflaton and Dark Matter and the mechanism for Baryogenesis, but they mostly require to go Beyond the Standard Model !
- Some classes of models/mechanisms are being probed already by astrophysical observations and particle physics experiments.
- Unification of two Standard Models still missing

Lots of OPEN QUESTIONS remain...