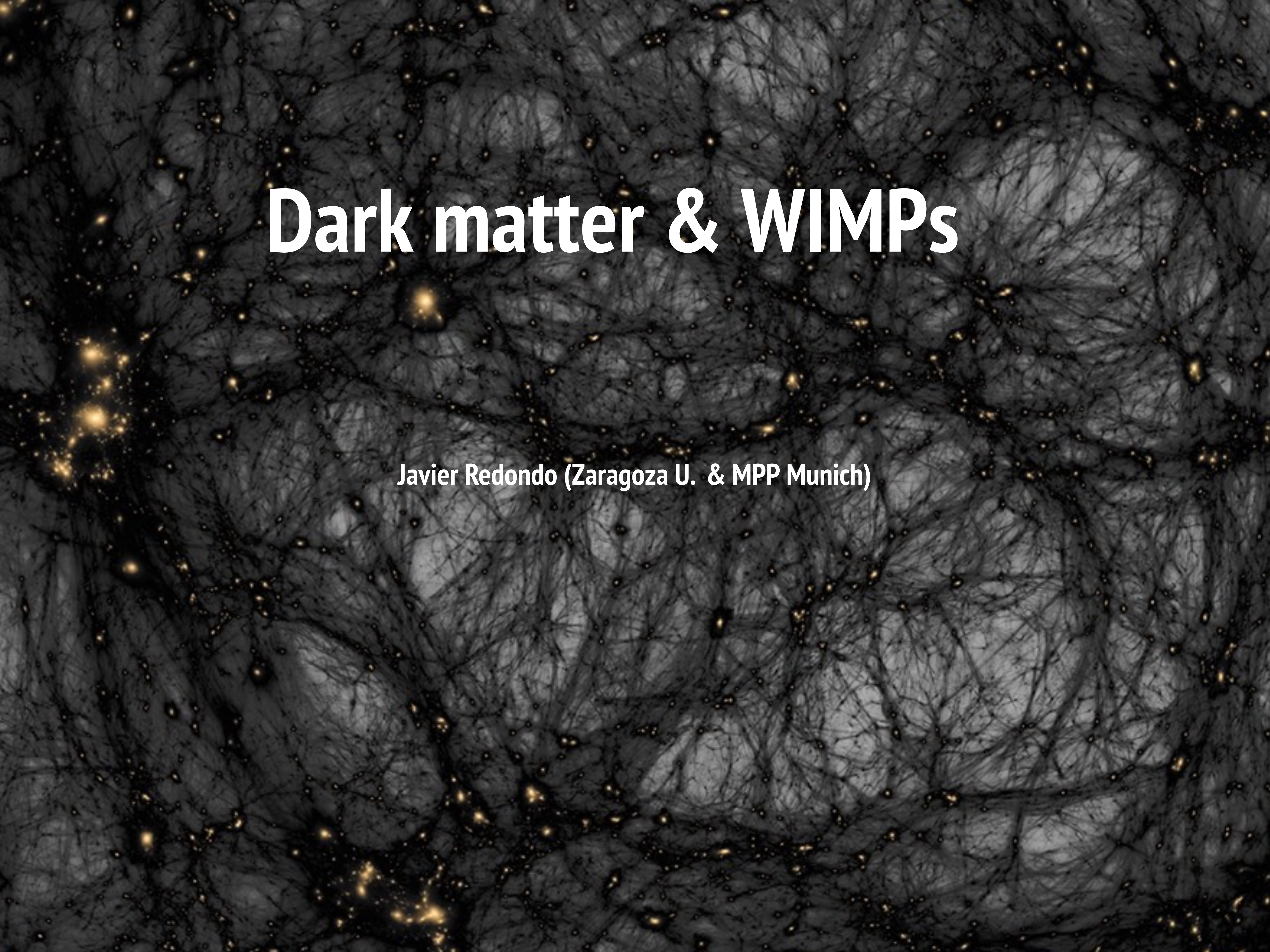
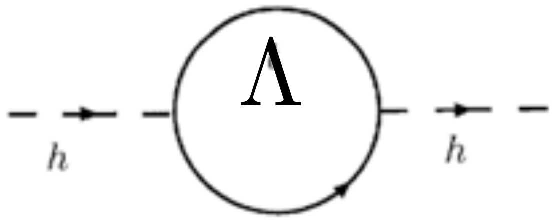


Dark matter & WIMPs

Javier Redondo (Zaragoza U. & MPP Munich)

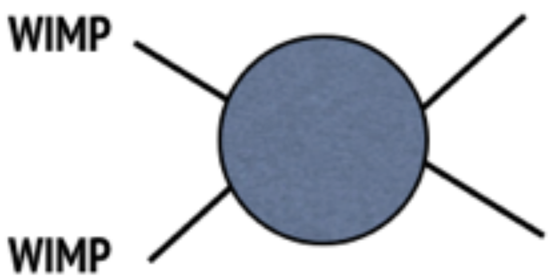
WIMPs : weakly interacting massive particles

- **Hierarchy problem** $m_h \ll M_p \sim 10^{19}\mathrm{GeV}$ **demands new "physics" at the TeV related to weak scale**

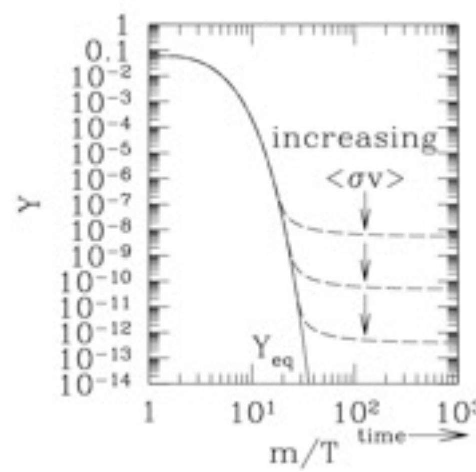


$\Delta m_h \sim \Lambda$ **what makes Higgs mass INSENSITIVE to ultraviolet PHYSICS?**

- **WIMP "miracle" : The big bang produces WIMPs "automatically" with the correct abundance**



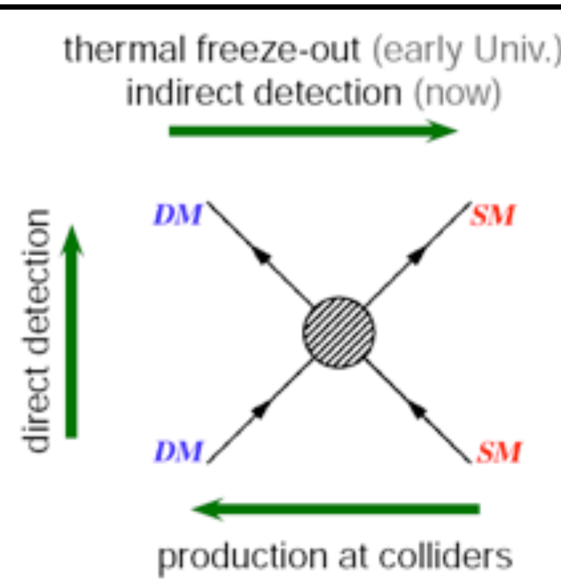
$\sigma \sim \frac{g^4}{M^2}$



$\Omega_{\mathrm{WIMP}} \sim O(1)$

$g \sim O(1), M \sim m_W$

- **Detection complementarity**



relic abundance from FREEZE OUT

- **Postulate <u>new stable particle</u>, related to SM particles can annihilate and be produced in pairs from SM particles**

$$\psi + \bar{\psi} \leftrightarrow \mathrm{SM} + \mathrm{SM}$$

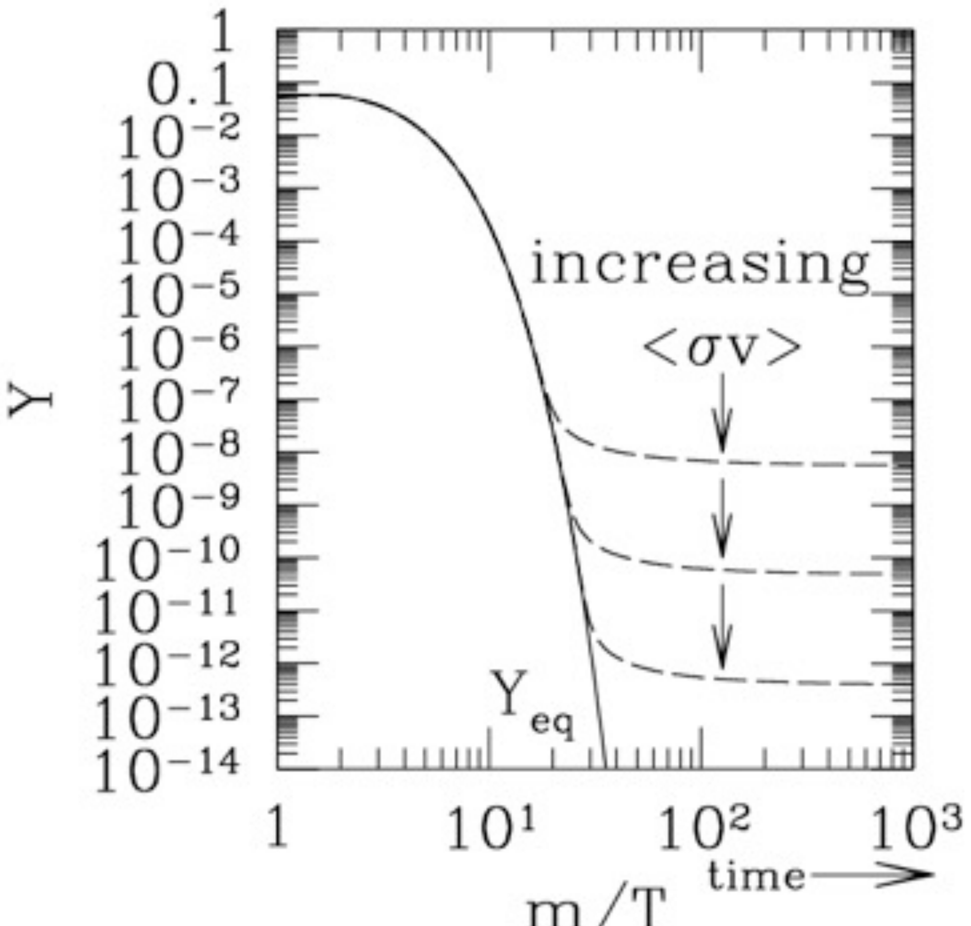
- **Is kept in thermal equilibrium at T>mass**
- **when T<mass, n_eq drops exponentially**
- **but at some point, they are so diluted that they don't find them to annihilate... their number density per comoving volume will be constant (or number/entropy)**

$$Y = n_\psi / s = cons$$

- **Relic density given by Boltzmann equation**

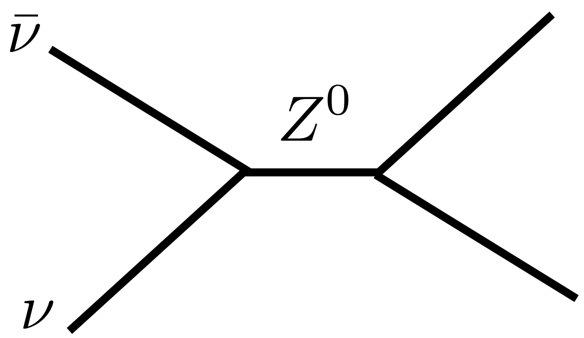
$$\frac{dn_\psi}{dt} + 3Hn = -\langle \sigma v \rangle (n^2 - n_{eq}^2)$$

annihilation **production**



freeze out of a neutrino-like particle

- **Neutrinos annihilate into leptons, quarks through Z exchange**



low Energies

$$\sigma \propto \frac{g^4}{(m_Z^2)^2}\cdots$$

missing energy factors ...

$$\sigma \propto \frac{g^4 E^2}{(m_Z^2)^2}$$ **Relativistic**

$$\sigma \propto \frac{g^4 m^2}{(m_Z^2)^2}$$ **Non-Rel**

- **Freeze-out of abundance/(com. vol) when ...** $$\frac{n_{eq}\langle\sigma v\rangle}{H} \sim O(1) \equiv \frac{n_{\rm Fo}\langle\sigma v\rangle}{H}$$

- **Relic density today** $$\rho_0 \equiv m\, n_0 = m\, Y_0 s_0 = Y_{\rm Fo} s_0 = n_{\rm Fo}\frac{s_0}{s_{\rm Fo}}$$

- **Assume Freeze out happens when N-like particle is <u>non-relativistic</u> ($n_{\rm eq}$ decreases exponentially with T)**

$$\rho \sim m\frac{O(1)H_{\rm Fo}}{\langle\sigma v\rangle}\frac{s_0}{s_{\rm Fo}} \propto m\frac{T_{\rm Fo}^2}{\langle\sigma v\rangle}\frac{1}{T_{\rm Fo}^3} \propto \frac{T_{\rm Fo}}{m}\frac{1}{\langle\sigma v\rangle} \sim \frac{1}{\langle\sigma v\rangle}$$

- Independent of mass

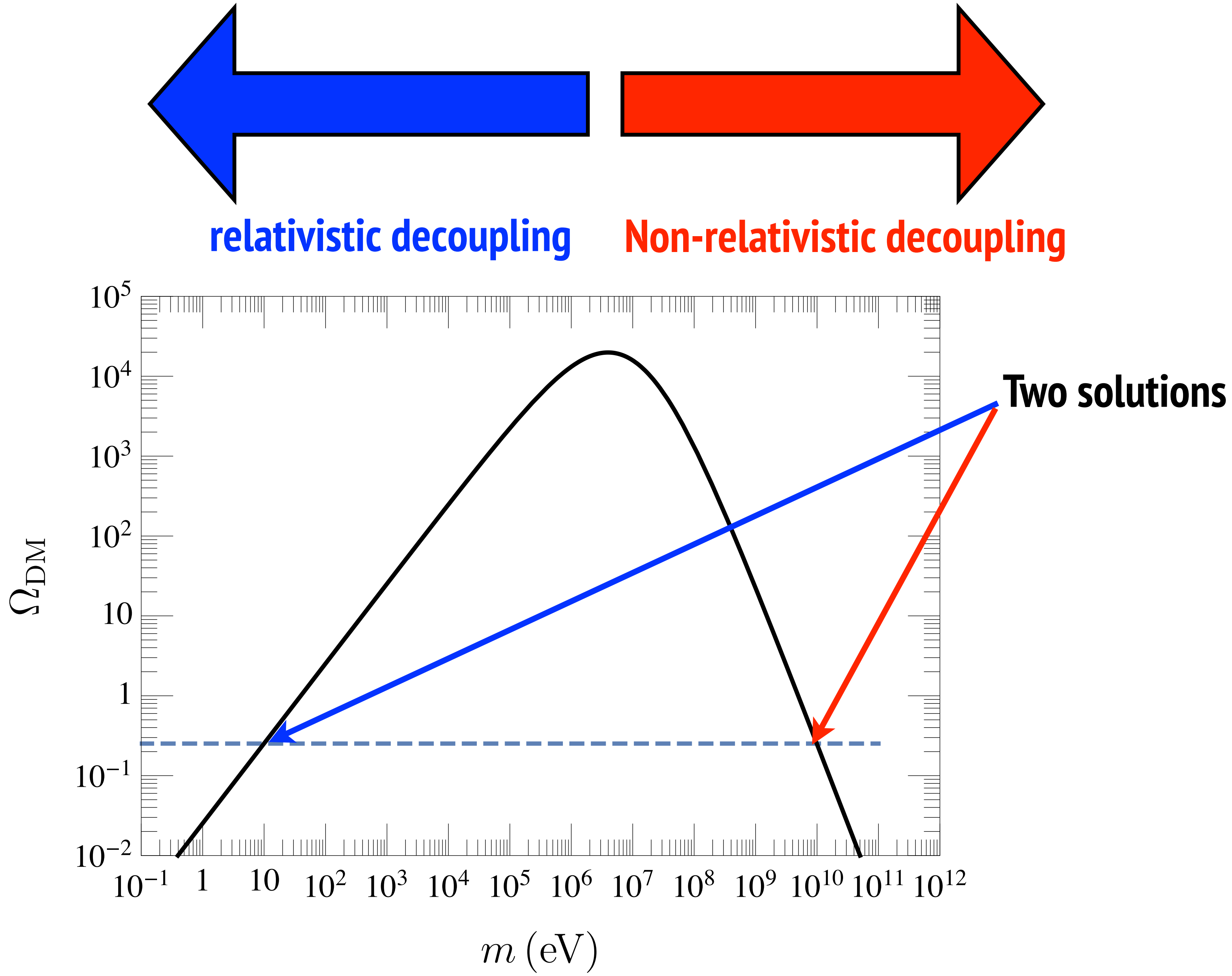
- $T_{\rm Fo}/m \sim \log(\sigma, m\ldots)$

- **Freeze out can happen when the particle is <u>relativistic</u> because of a small cross section** $n_{\rm eq,fo} \sim g T_{\rm fo}^3$

$$\rho \propto m\frac{n_{\rm Fo}}{s_{\rm Fo}} s_0 \propto m\frac{T_{\rm Fo}^3}{g_S(T_{\rm Fo})T_{\rm Fo}^3} \sim m\frac{1}{g_S(T_{\rm Fo})}$$

freeze out of a neutrino-like particle

Lee-Weinberg curve



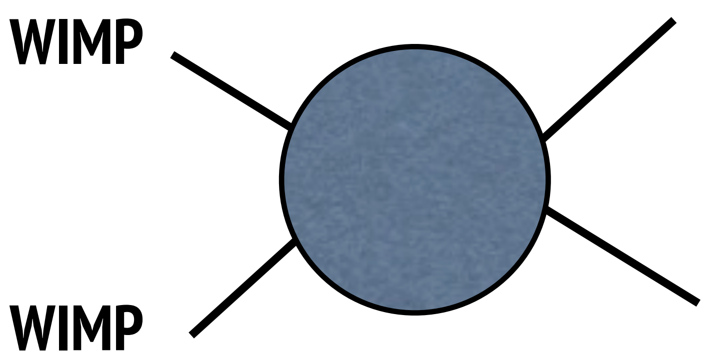
hot and cold dark matter (hot is problematic... free-streaming length!)

The WIMP miracle

Plug in all the numbers

$$\Omega_{\rm cdm} = 0.3 \frac{3\times 10^{-26}{\rm cm}^3/{\rm s}}{\langle \sigma v\rangle}$$

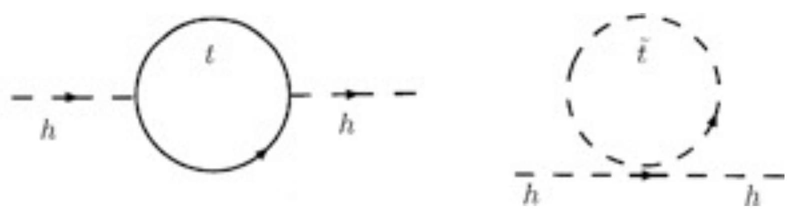
but this is a typical cross section of electroweak interaction size!!!



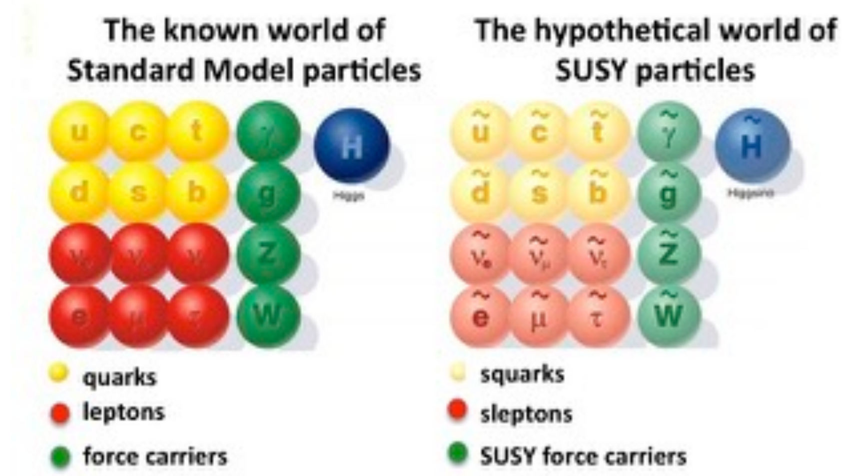
$$\langle \sigma v\rangle \sim \frac{1}{\pi' s}\frac{g^4}{m_{\rm EW}^2} \sim O(3\times 10^{-26}{\rm cm}^3/{\rm s})$$

Super Symmetry

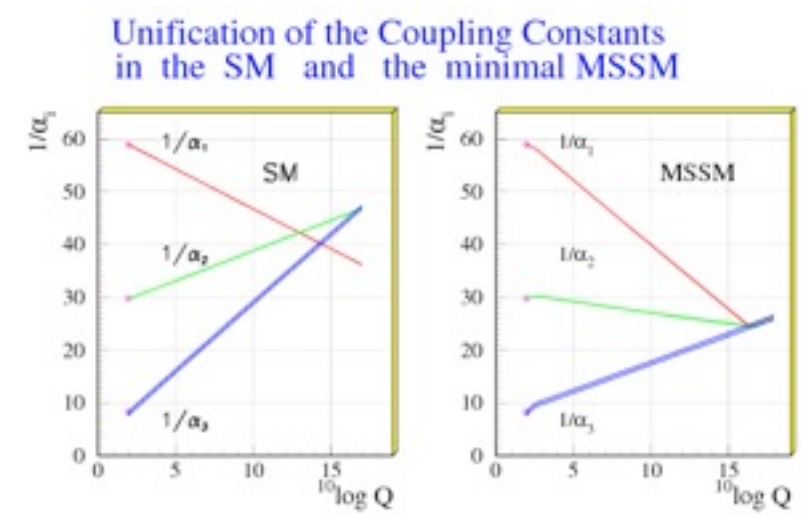
- **Each particle has its own SUSY partner-particle with $\pm 1/2$ spin**



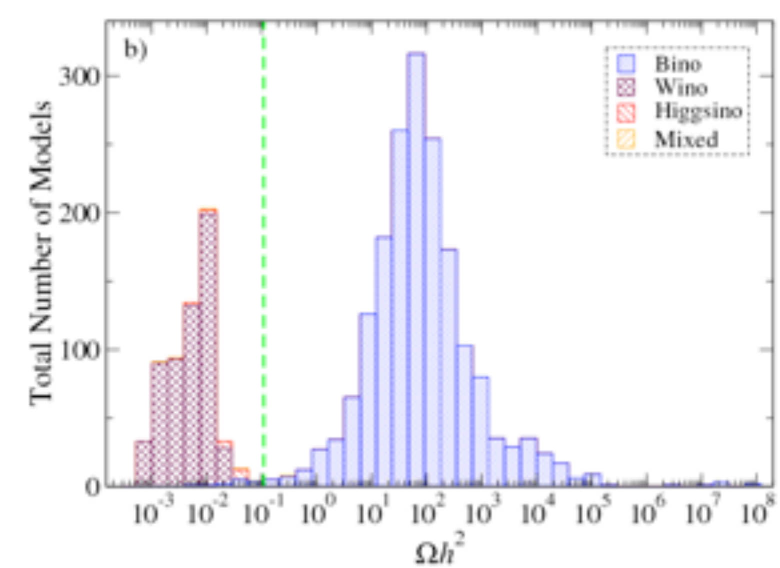
(dangerous Higgs mass corrections cancel by pairs)



- **Stability $\tau \gg 14\,\mathrm{Gyear}$ requires R-parity (SM+, SUSY-)**
- **R-parity -> Lightest SUSY particle stable**
- **Neutralinos (partners of bosons, sneutrinos,…)**
- **With SUSY particles, SM couplings unify at HE! GUT**
- **SUSY is needed in String theory (quantum gravity) (…well)**
- **Huge parameter space (many free parameters)**
- **Detection complementarity (LHC, direct, indirect)**

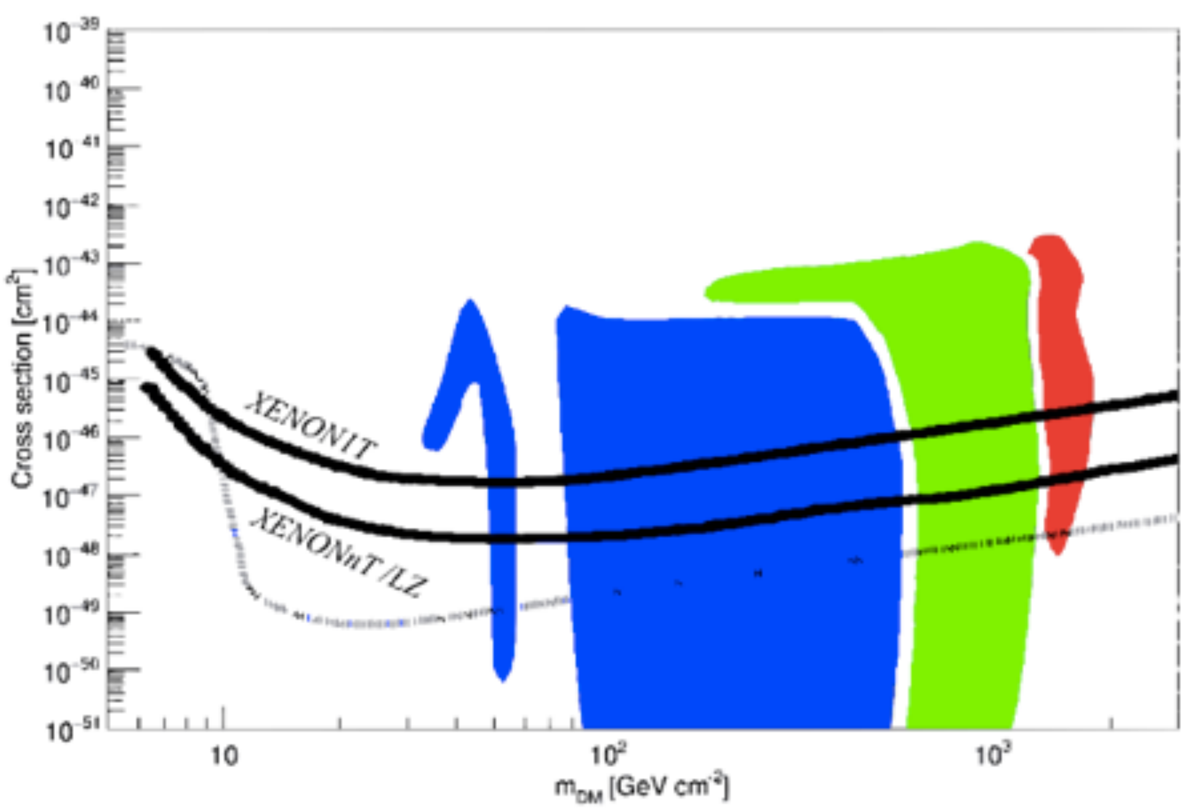


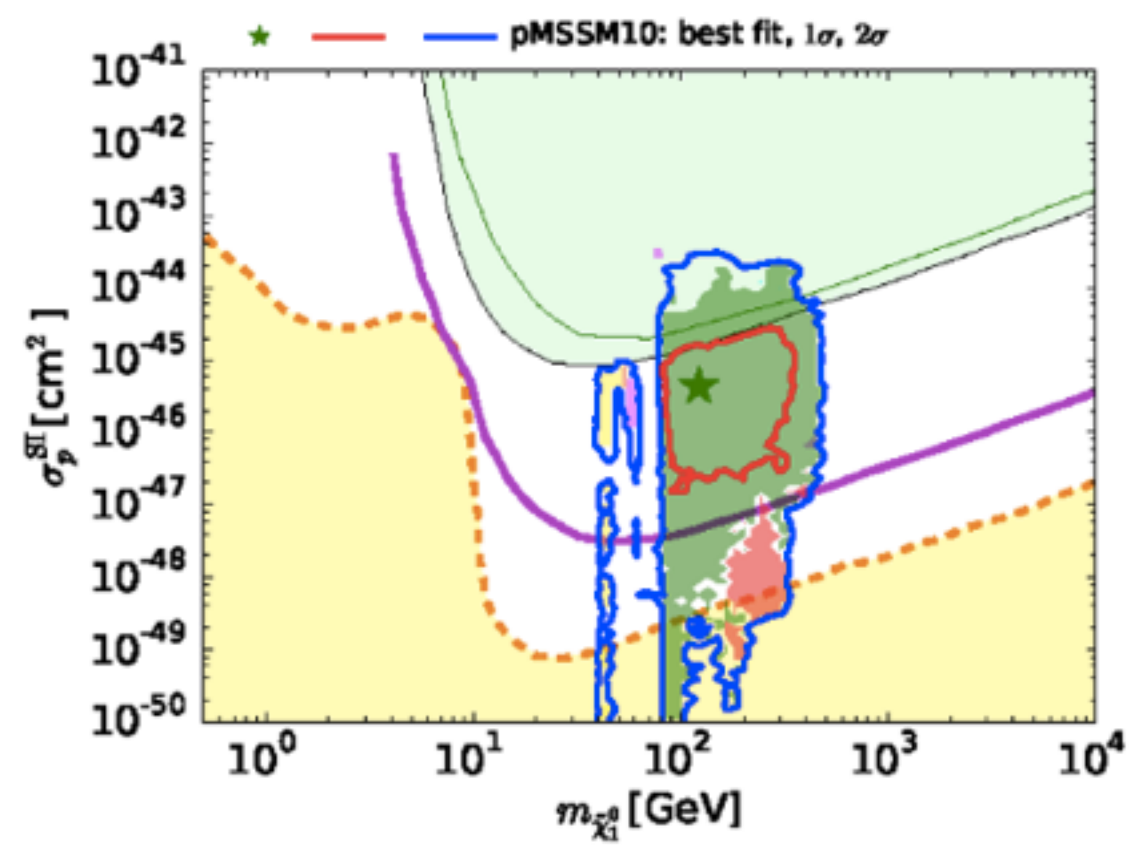
Relic density (a mistuned miracle)



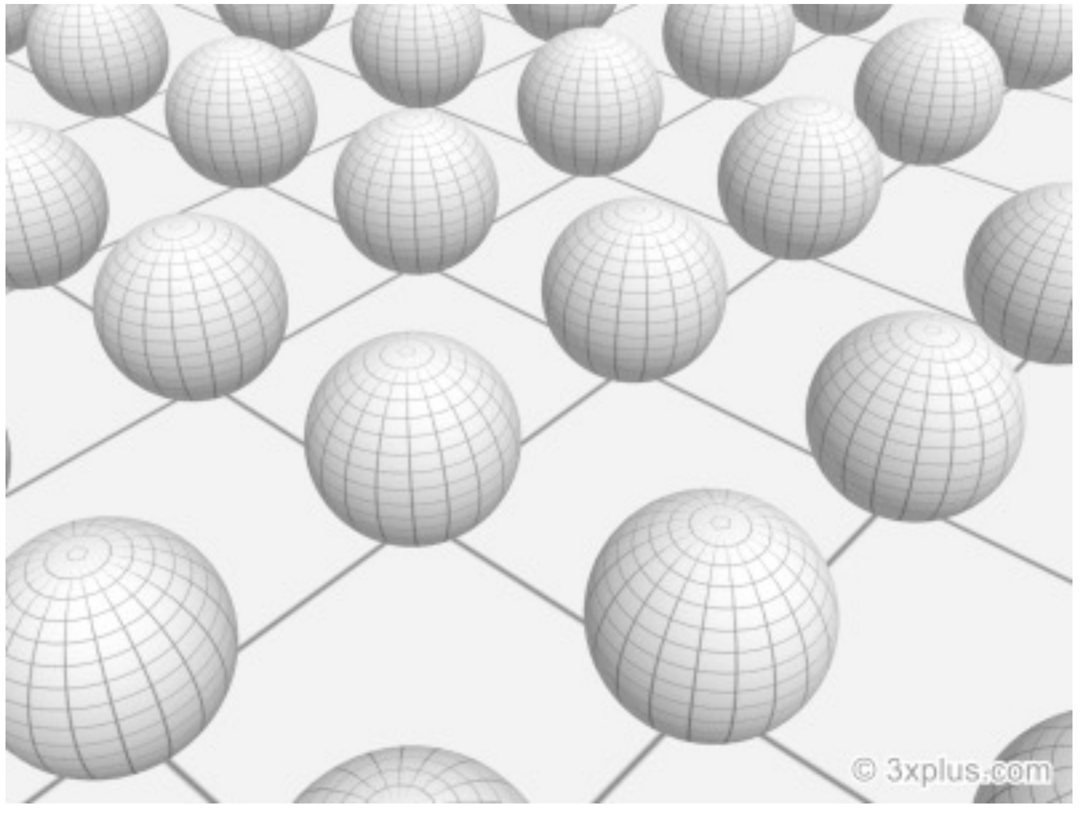
SUSY Dark matter candidates

- Neutralino (mixture of Wino, Bino, Higgsino) Neutral Majorana fermion $\tilde{\chi}_1^0$
- Sneutrino $\tilde{\nu}$
- Beyond Minimal SUSY (MSSM), Next MSSM (extra scalar…)
- Relic density calculation is complicated many channels! (numerical packages DarkSUSY, Micromegas)
- Only relatively simple models explored (mSUGRA, etc…) … huge range of possibilities





Kaluza-Klein Dark matter : extra dimensions



Large Extra dimensions? Kaluza-Klein Dark Matter

- **Alternative solution to the hierarchy problem: gravity scale is not** $M_p = 1.2 \times 10^{19}\mathrm{GeV}$

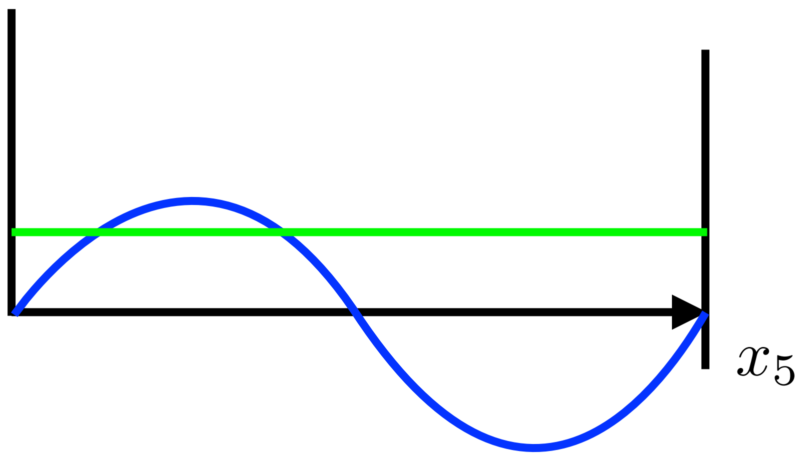
$$S = \int \left(\frac{M_p^2}{8\pi} R + \mathcal{L}_{\mathrm{SM}} \right) \sqrt{-g} d^4 x \quad \Rightarrow \quad S = \int \left(\frac{M_*}{8\pi} R + \mathcal{L}_{\mathrm{SM}} \right) \sqrt{-g} d^{4+n} x$$

- **Large volume of extra dimensions, means effectively weakly coupled gravity in 4D**

$$M_*^2 \int \sqrt{-g} d^n x = M_*^2 \times V = M_p^2$$

- **M_* ~ TeV, no hierarchy problem!**
- **New dimensions ... new "particles" (Kaluza-Klein towers)**
- **momentum in the extra dimension looks like "mass" in 4D**

$$E = \sqrt{m^2 + p_x^2 + p_y^2 + p_z^2 + p_w^2}$$

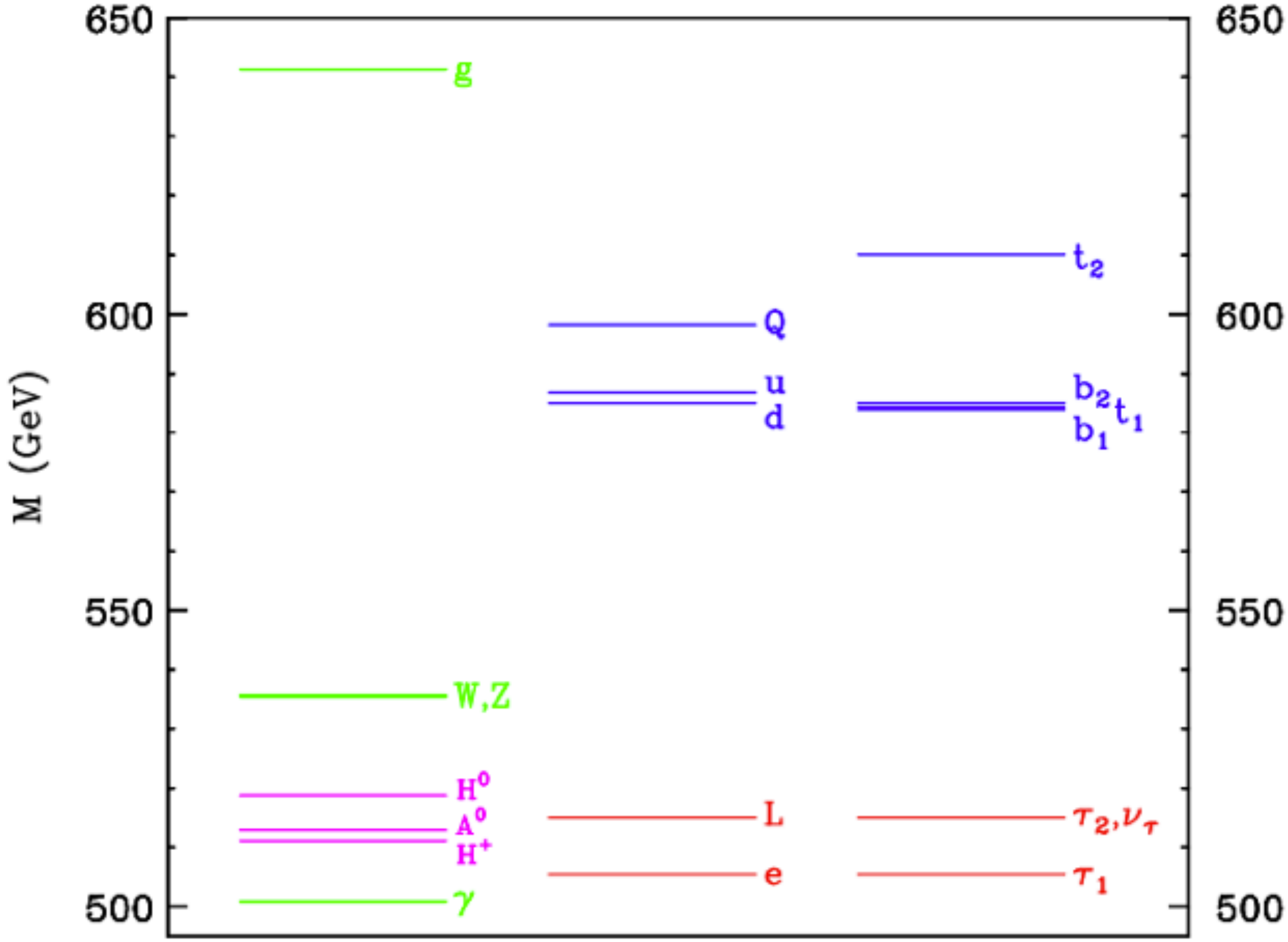


p_w is quantised if 5th dimension is compact $p_w \sim \frac{2\pi}{L_w} \times 0, 1, \ldots$

momentum conservation -> parity, lightest k=1 mode stable!

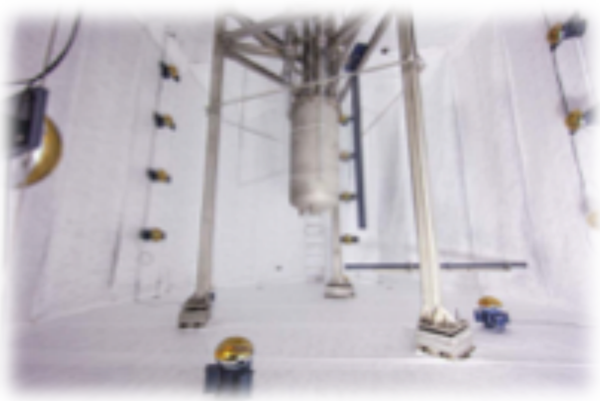
Large Extra dimensions? Kaluza-Klein Dark Matter

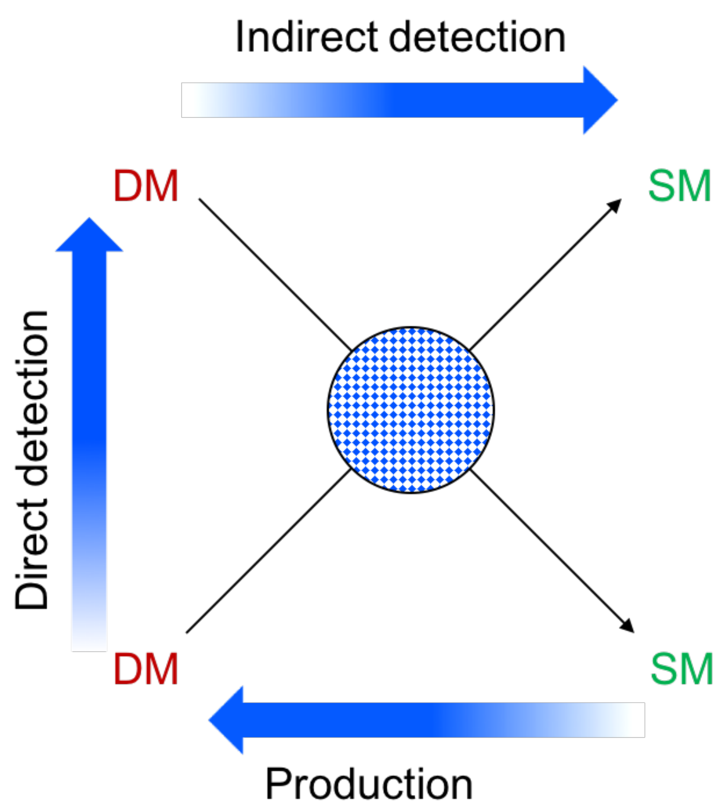
KK particles are copies of the SM, except for a higher "base" mass $M \sim \frac{2\pi}{L_w}$ **(+radiative splitting)**



Detecting WIMPs

XENON
Cresst
Edelweiß
COUP
etc.



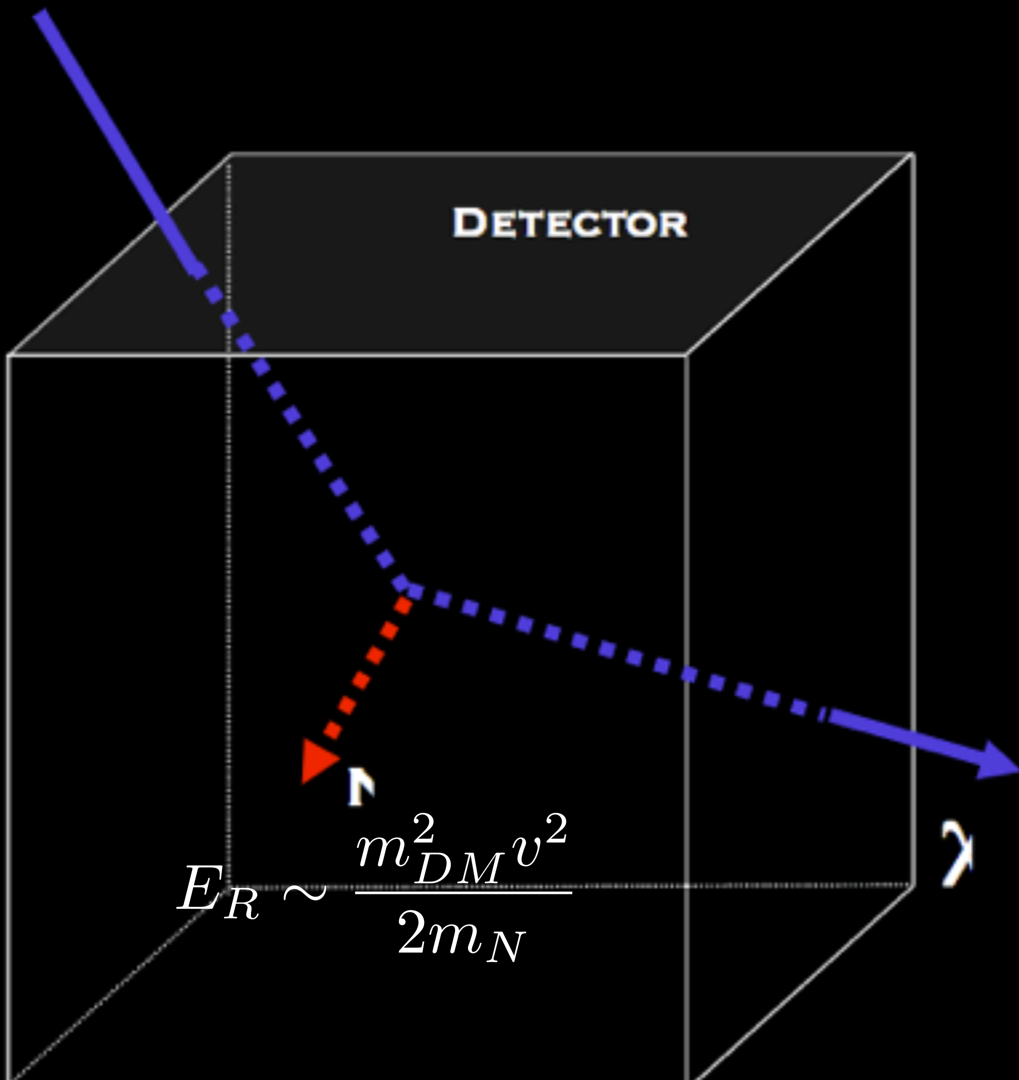


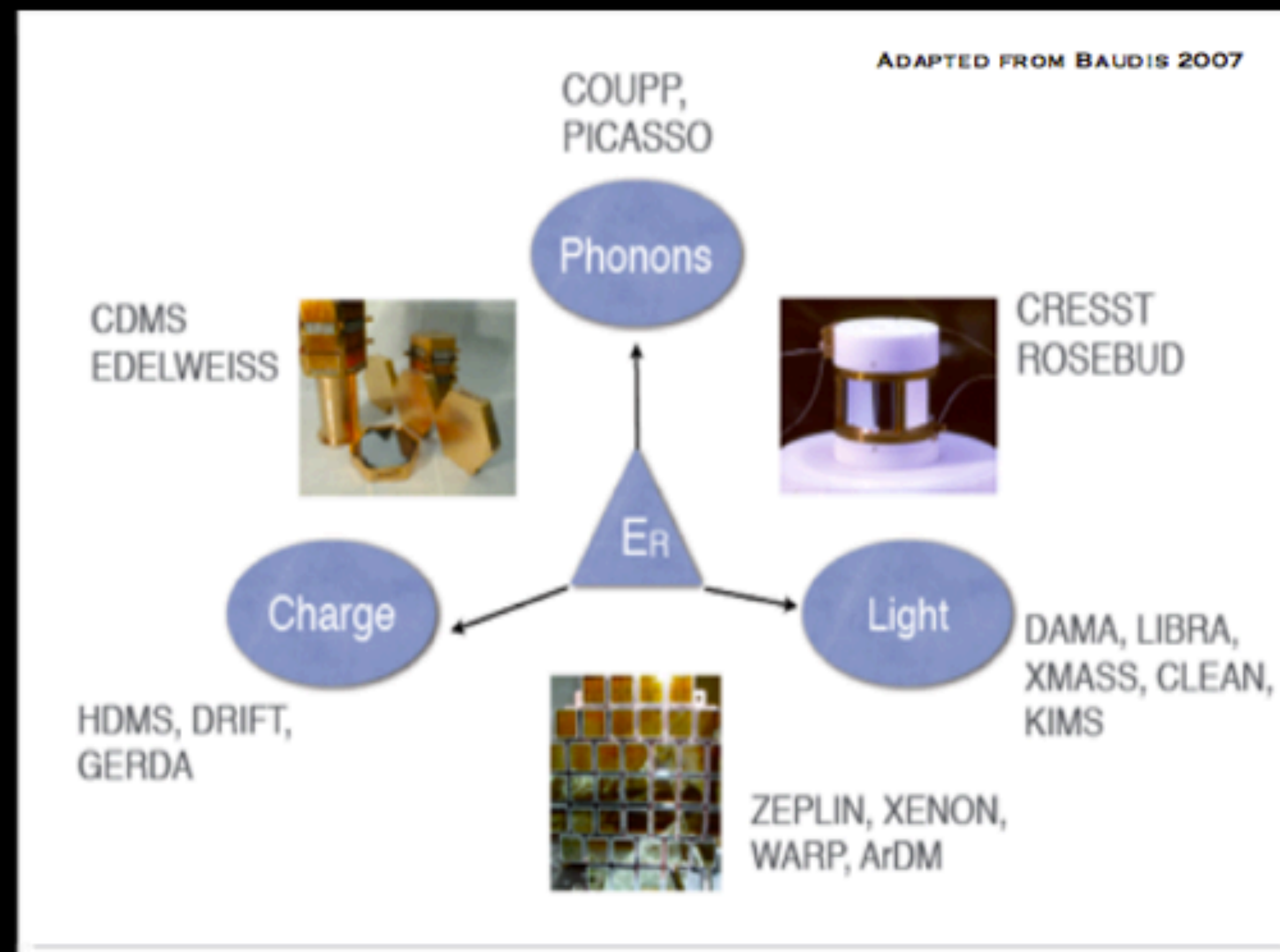
Fermi
AMS
H.E.S.S.
CTA
etc.

LHC with
CMS and ATLAS

Direct Detection

Principle and Detection Techniques

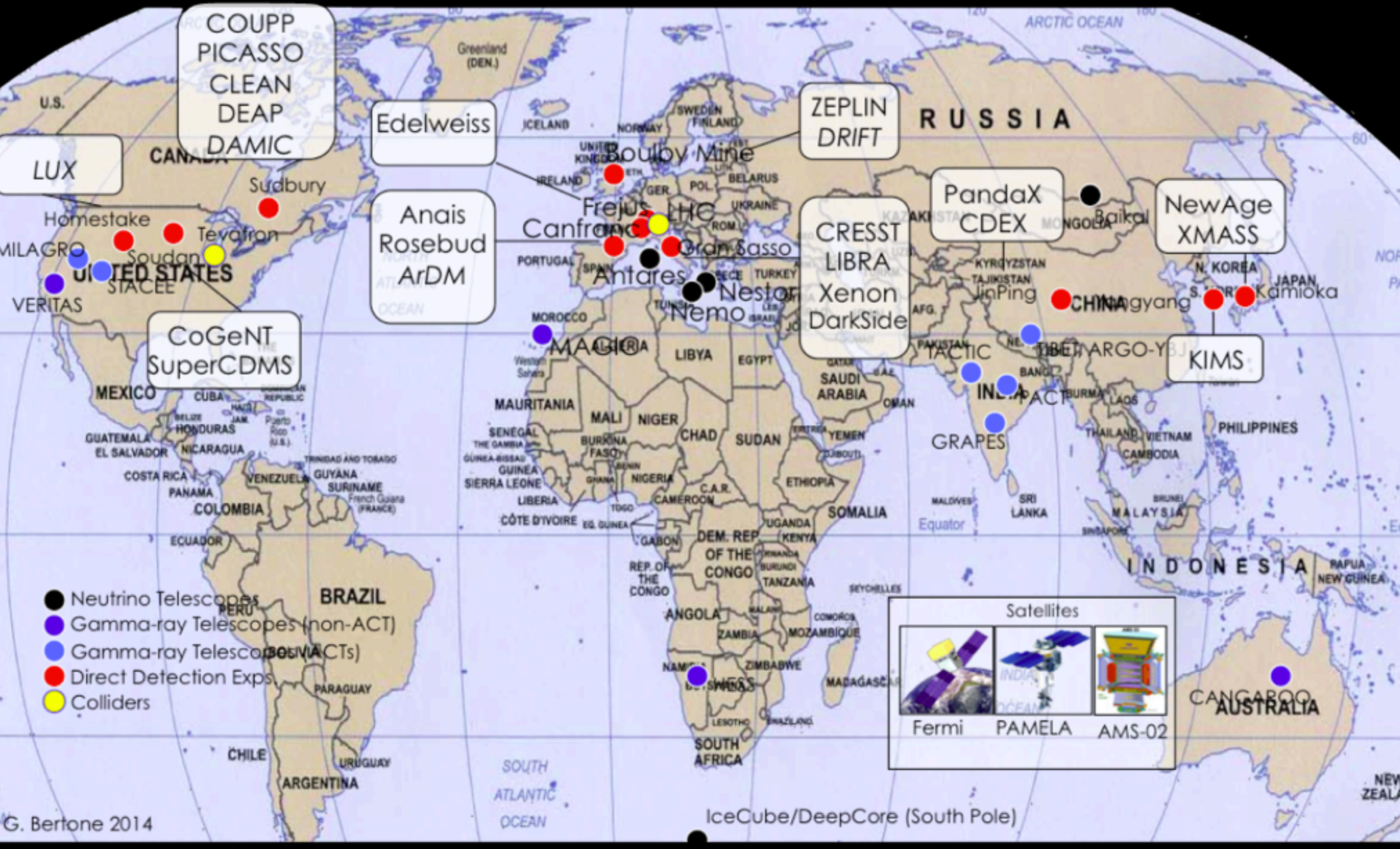




DM SCATTERS OFF NUCLEI IN THE DETECTOR

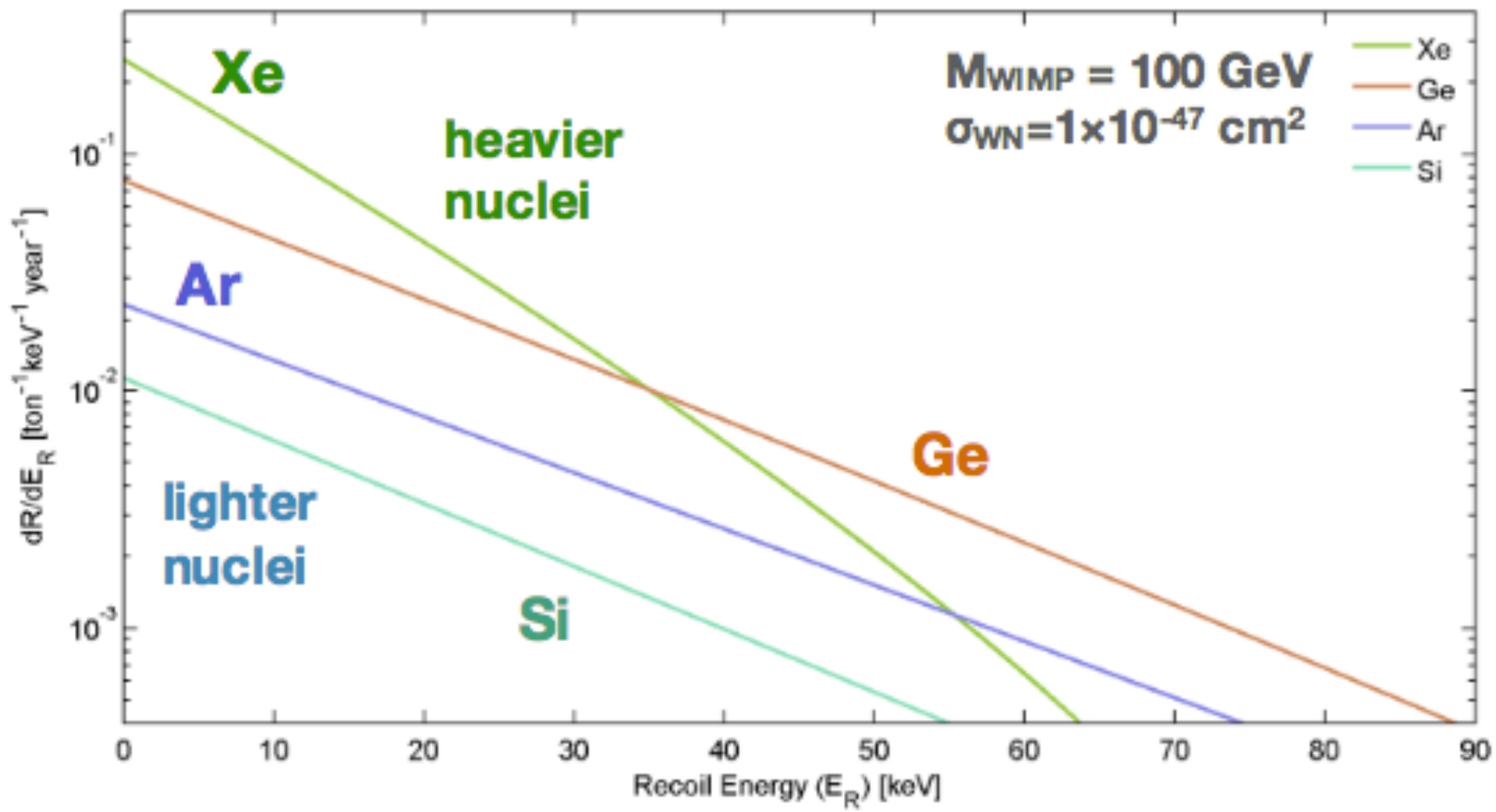
DETECTION OF RECOIL ENERGY VIA IONIZATION (CHARGES), SCINTILLATION (LIGHT) AND HEAT (PHONONS)

The worldwide race



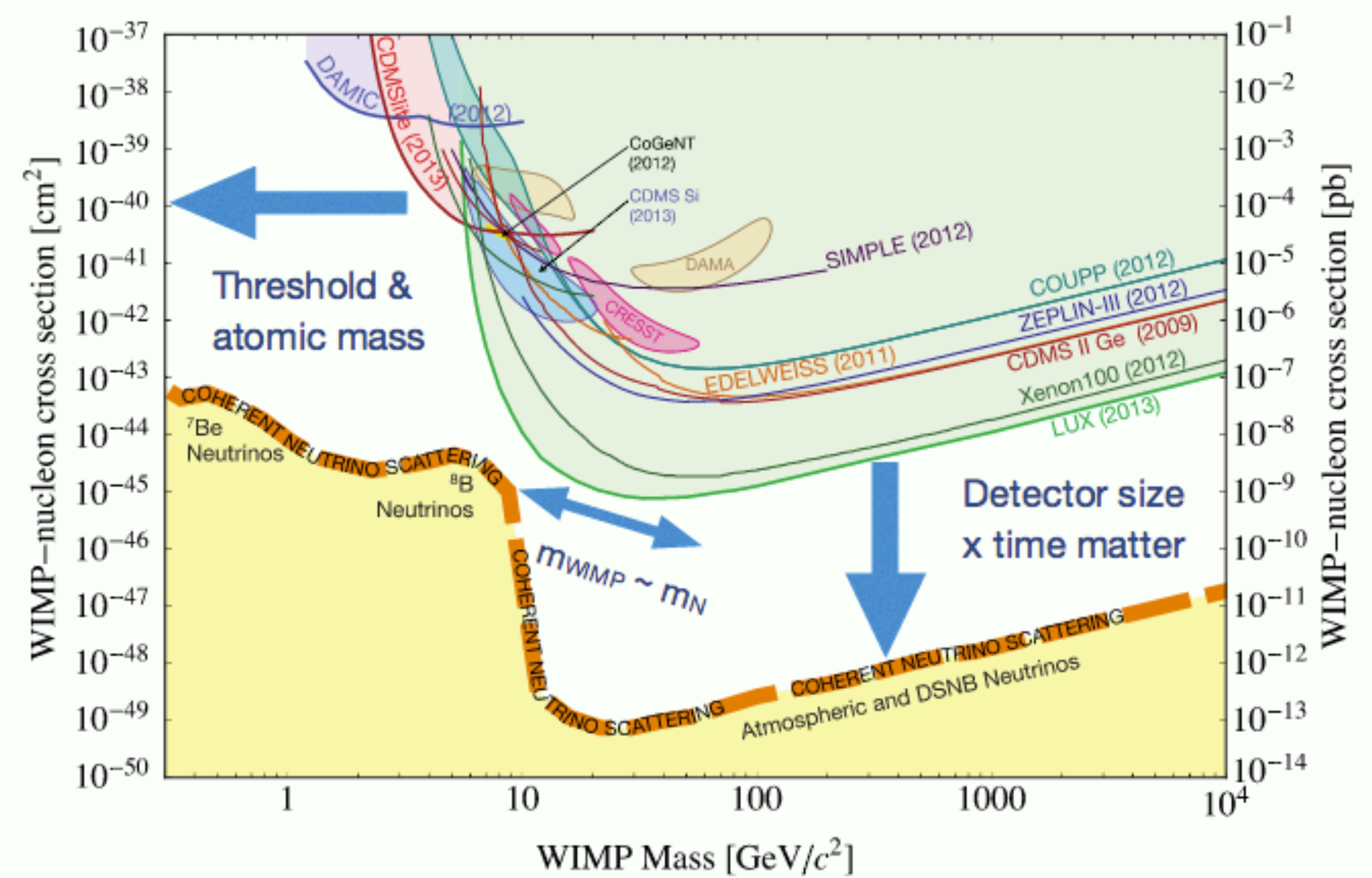
Expected rates

$$R \sim 0.13 \frac{\text{events}}{\text{kg year}} \left[\frac{A}{100} \times \frac{\sigma_{WN}}{10^{-38}\,\text{cm}^2} \times \frac{\langle v \rangle}{220\,\text{km}\,\text{s}^{-1}} \times \frac{\rho_0}{0.3\,\text{GeV}\,\text{cm}^{-3}} \right].$$

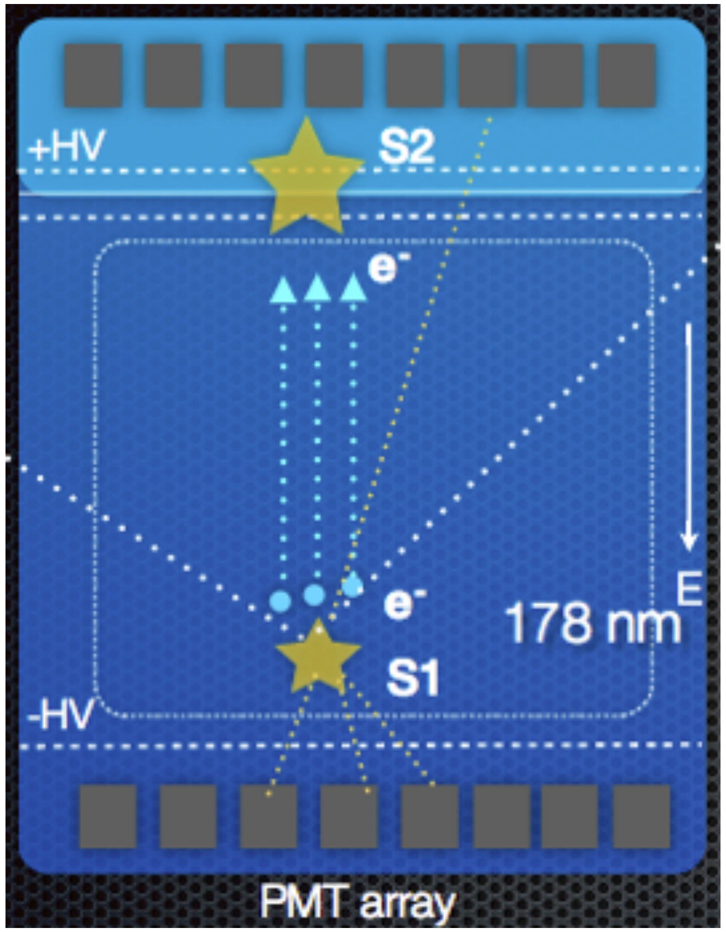


- Extremely low rates peaking at low ER,
- need to control backgrounds to amazing levels

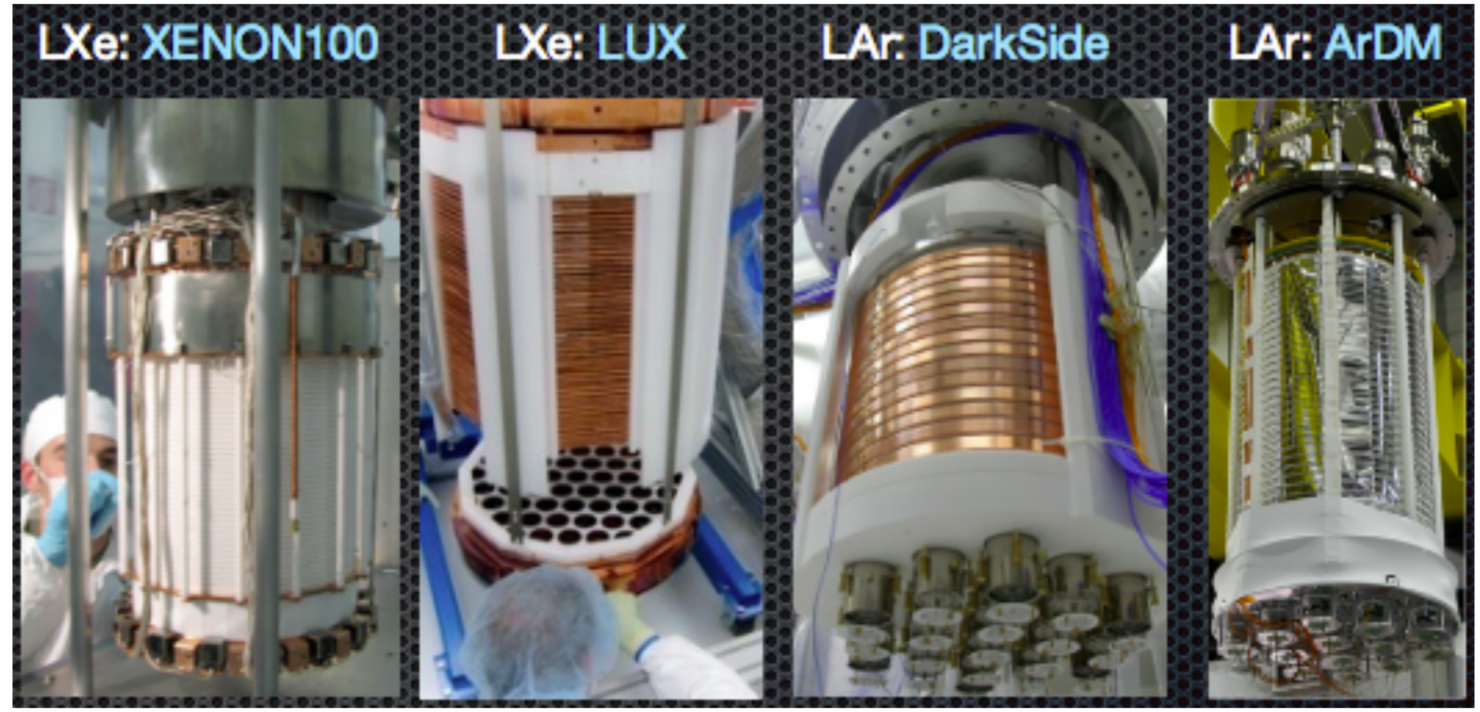
Summary of searches and findings



Noble liquid time projection chambers

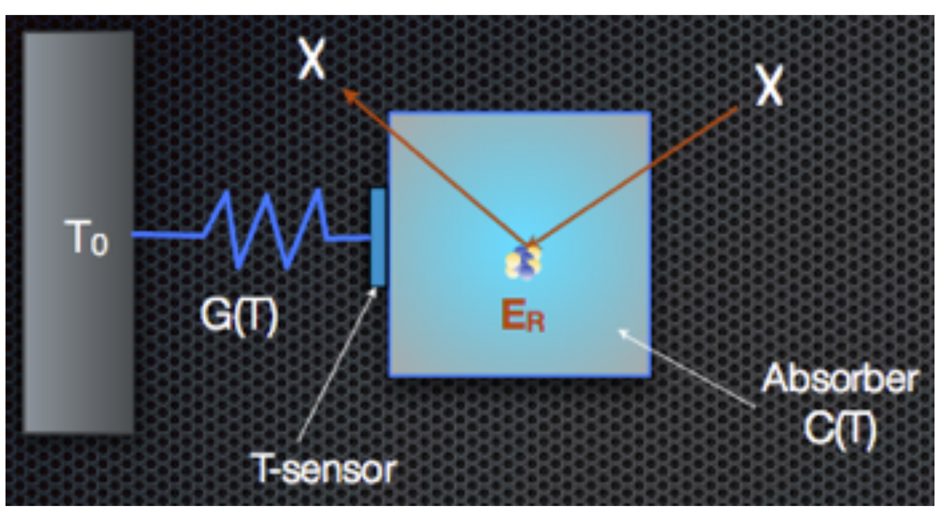


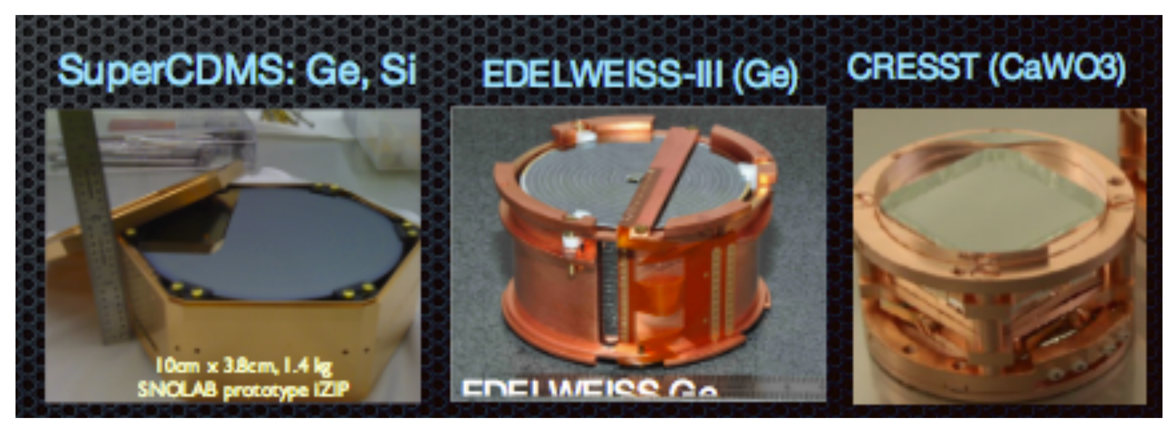
Large mass, self-shielding, low intrinsic background, large A



mK Bolometers

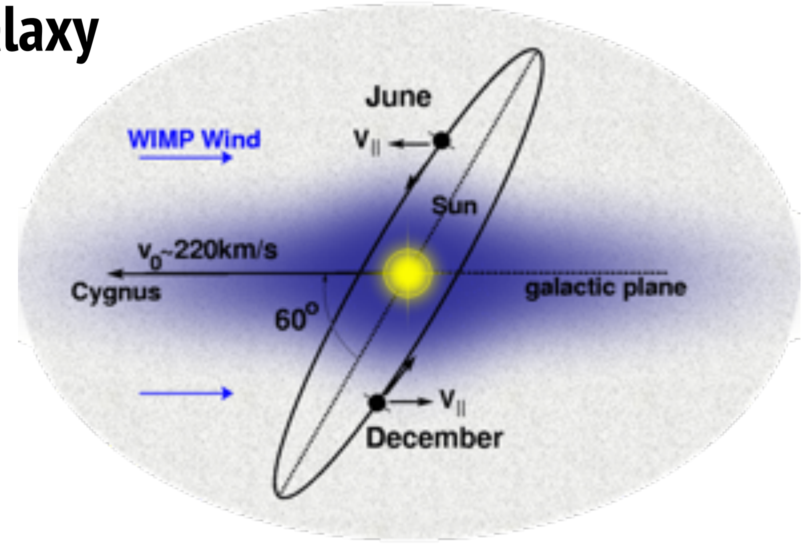
energy resolution, low threshold



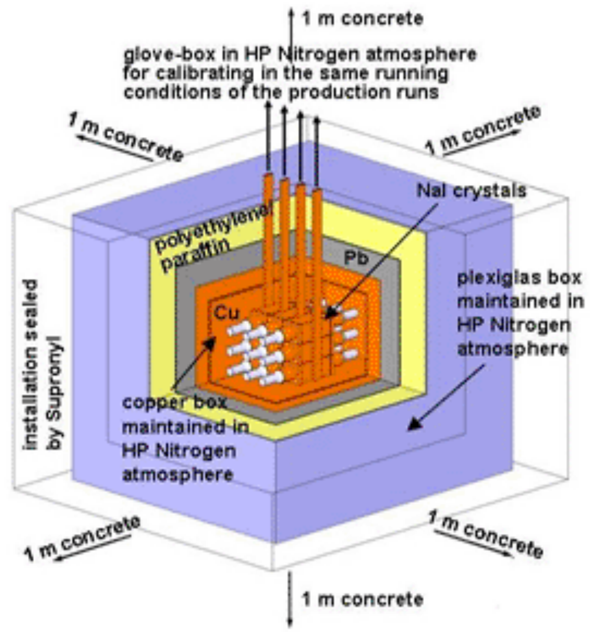


Rate modulation

Earth motion around the Sun around the galaxy
velocity dependence of rate
Max June, min December (~2-10%)

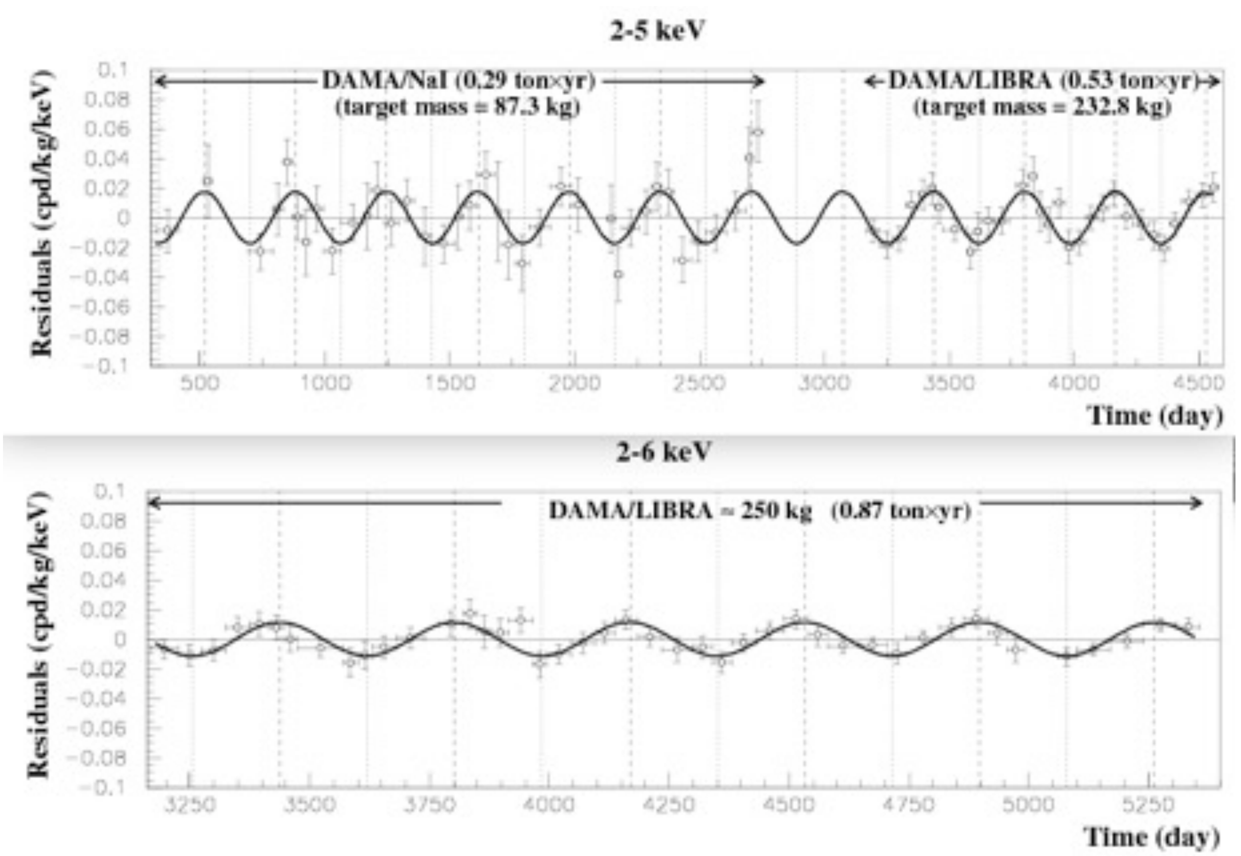


DAMA/LIBRA

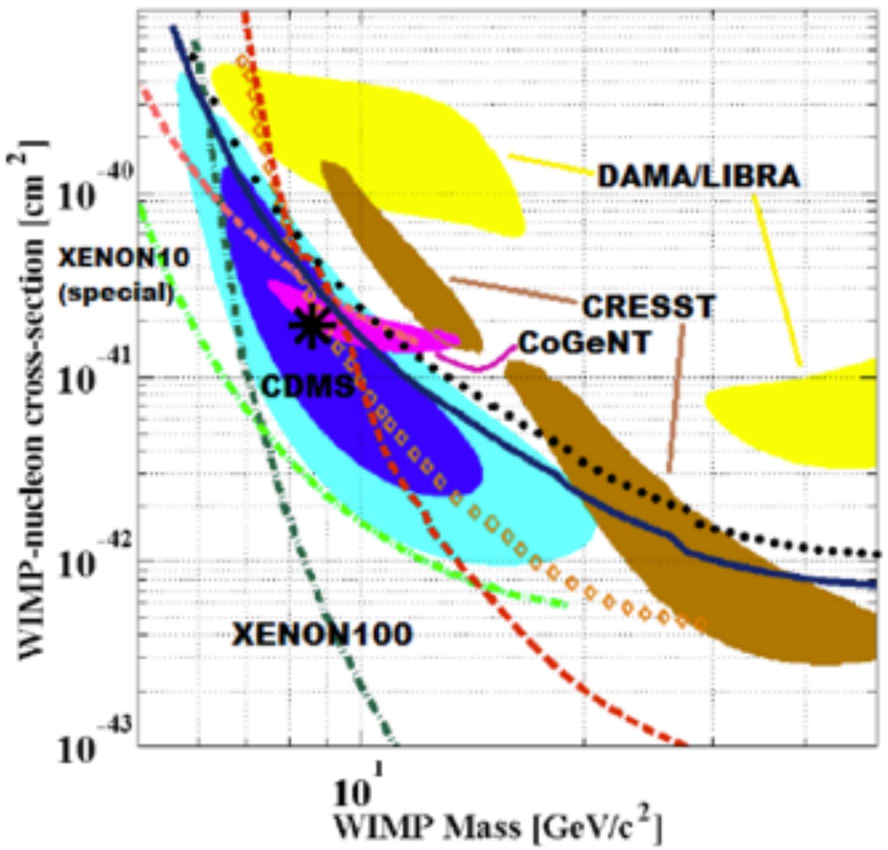


Simplified schema of ~ 100 kg NaI(Tl) set-up

DAMA/LIBRA observed the modulation with NAI crystals

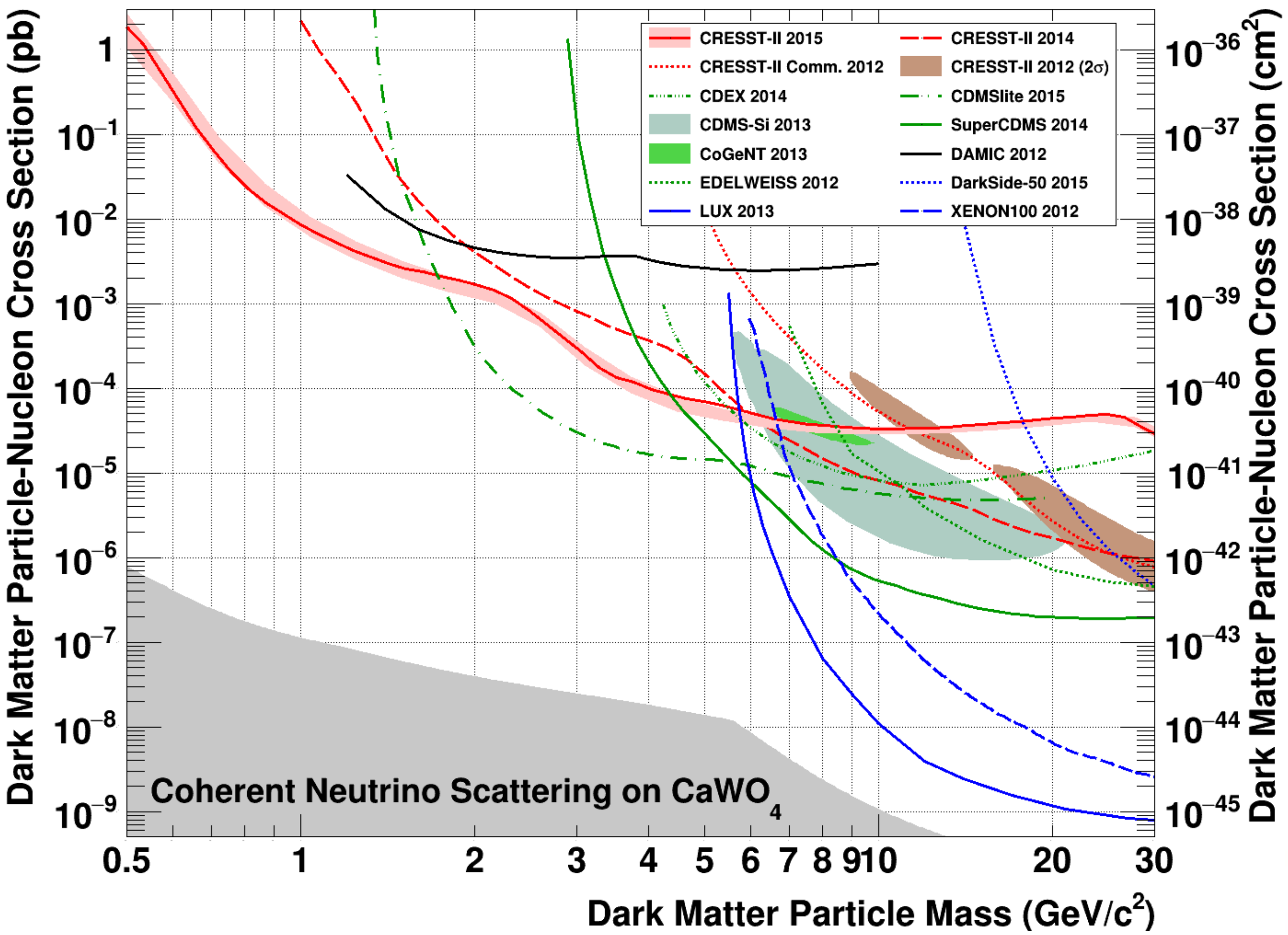


DM interpretation self-consistent, but not with others

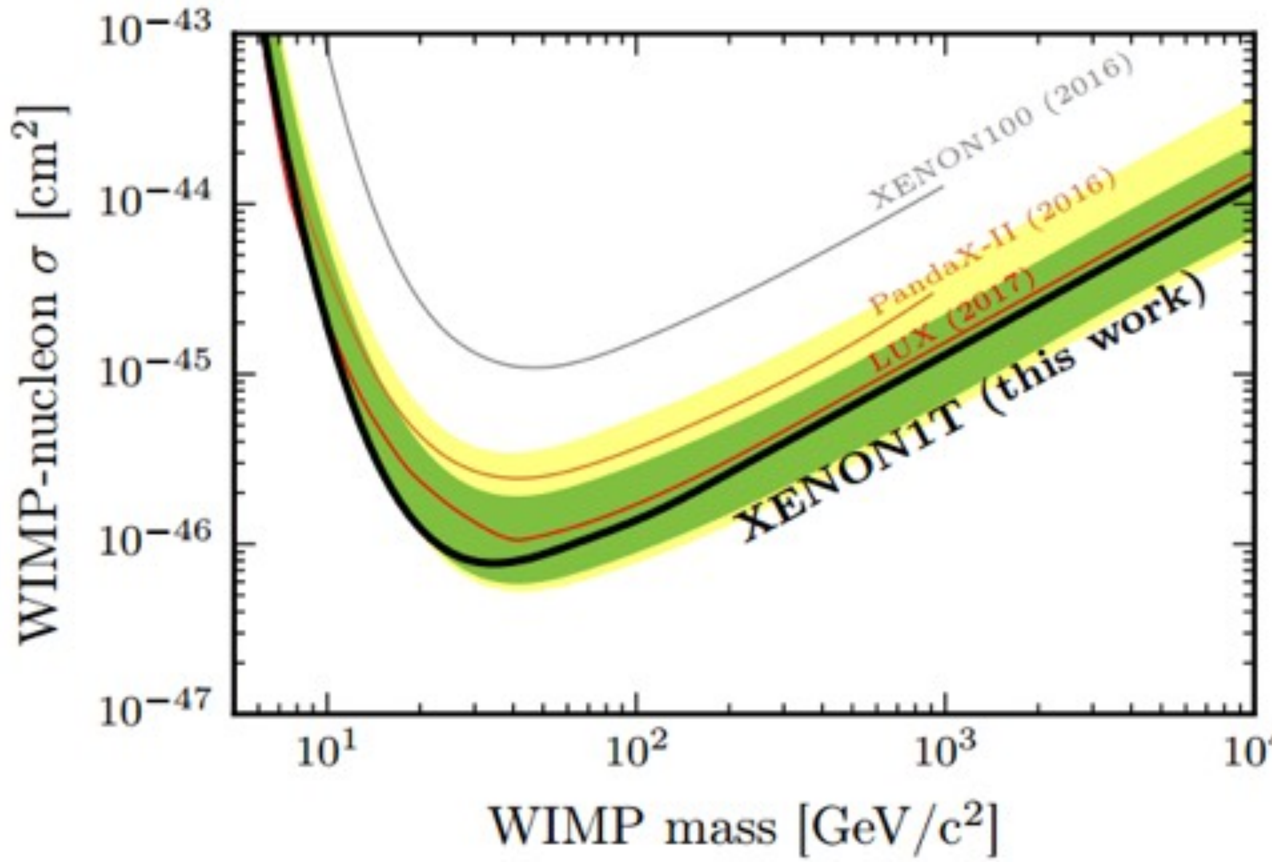


need for other experiments: ANAIS, SABRE

Low WIMP masses

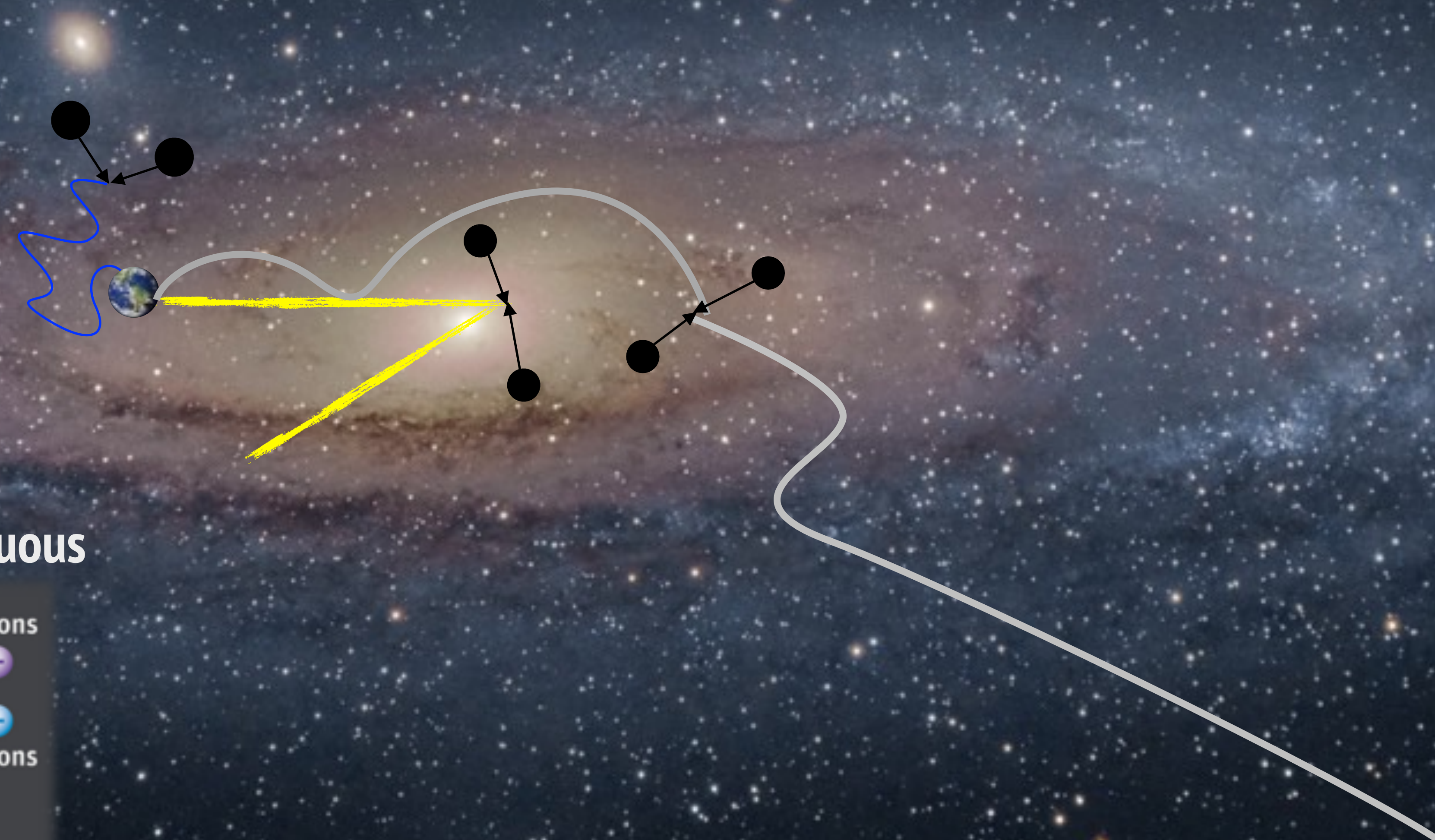


XENON1T last results

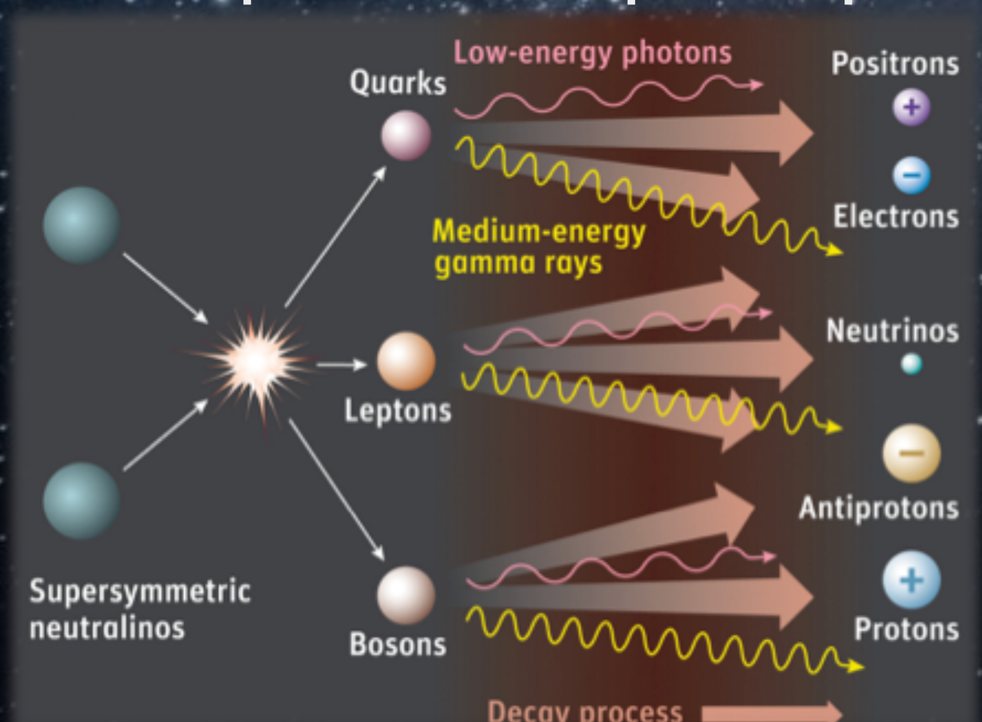


Indirect detection

WIMP abundance froze out (less than 1 annihilation/lifetime ... but there are plenty!)

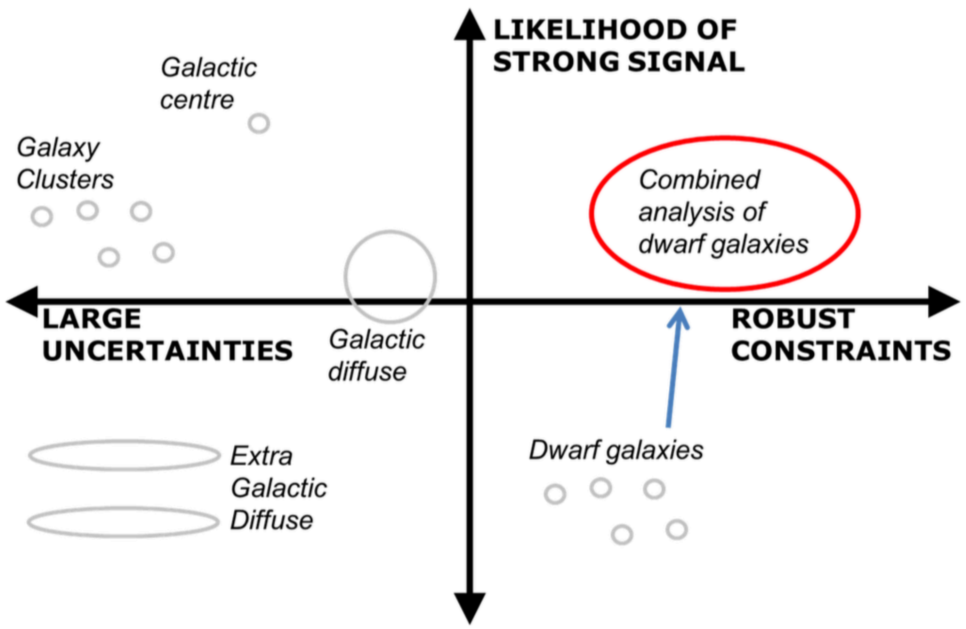


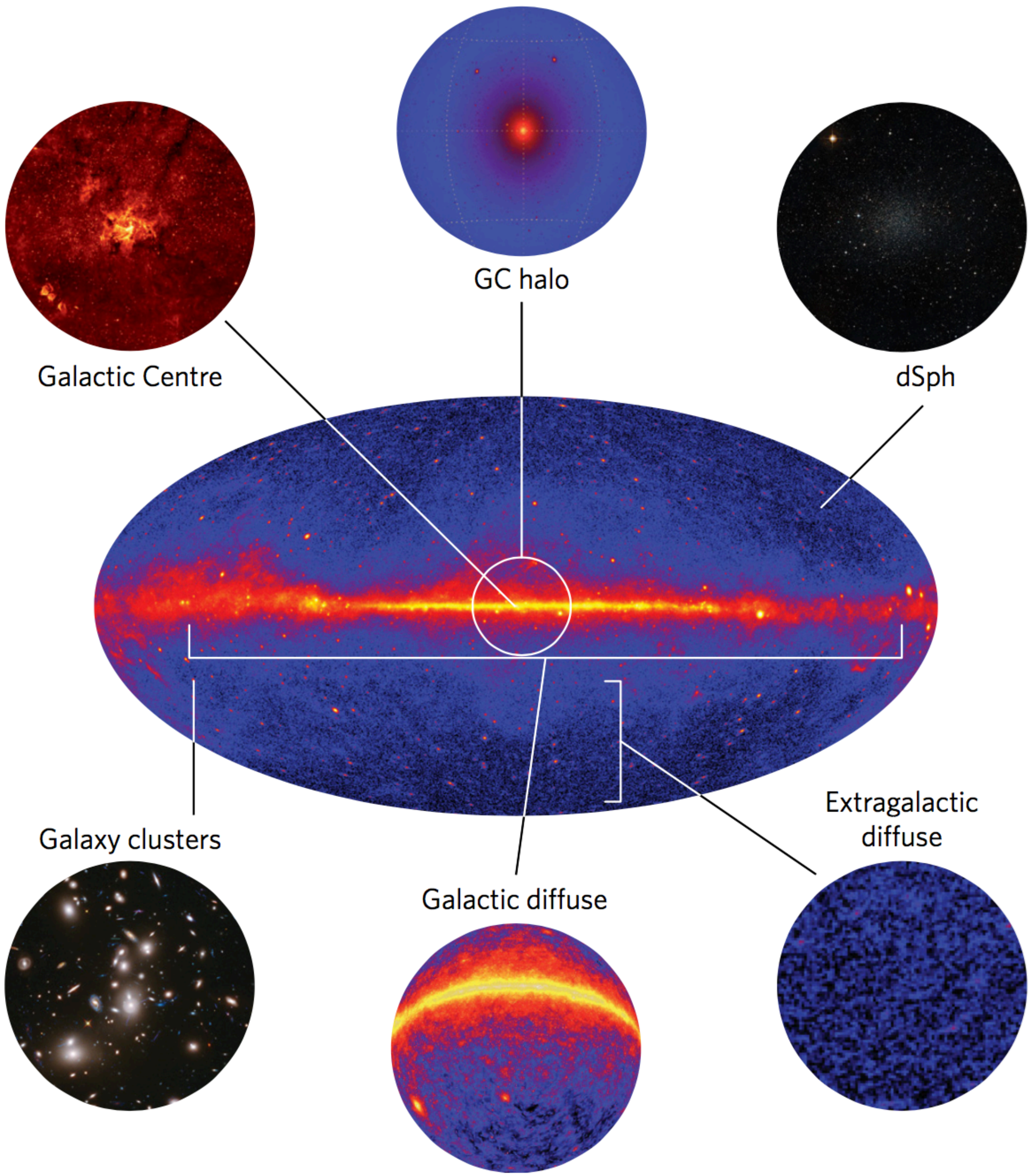
Annihilation products can be quite conspicuous



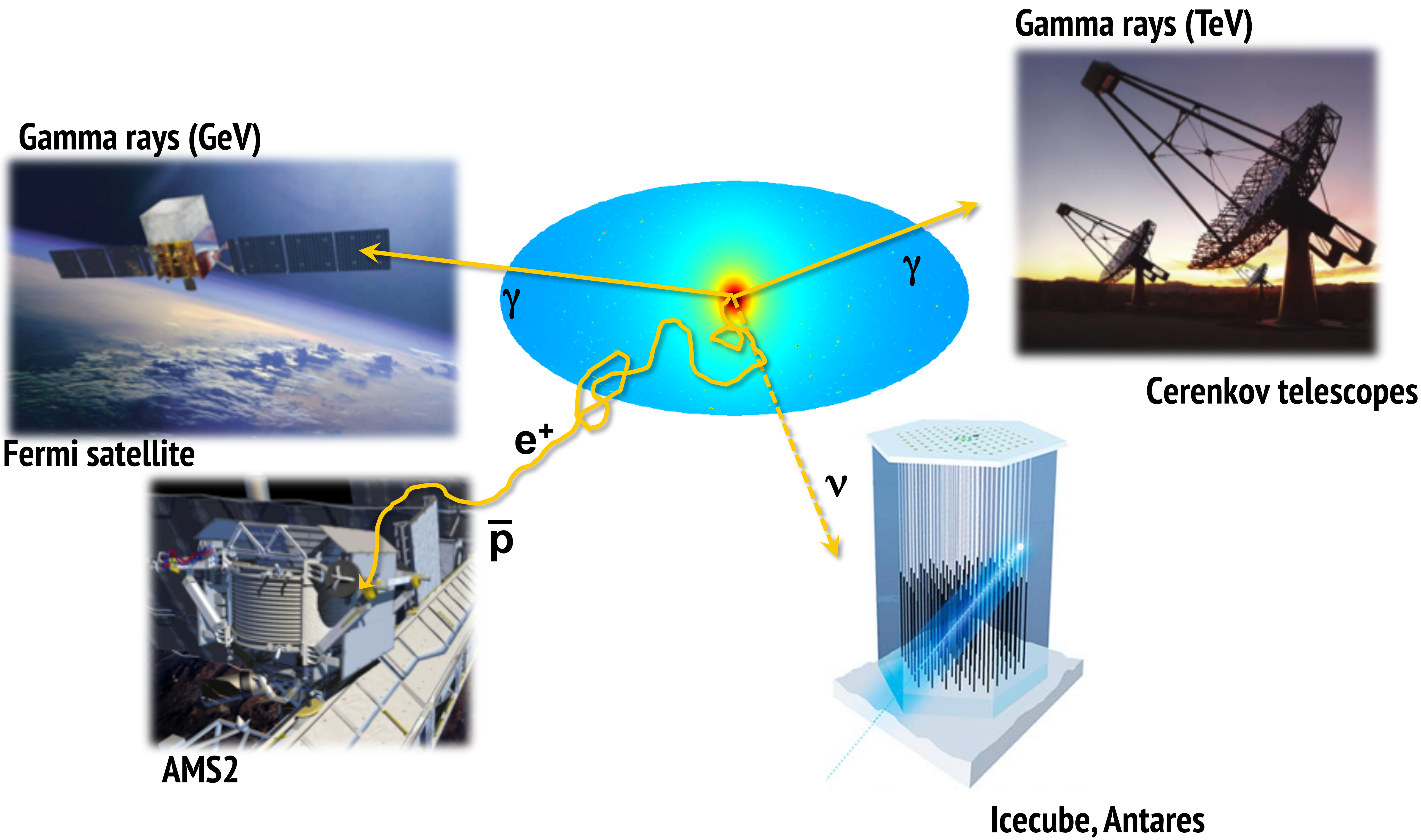
Sources

Signals vs uncertainties

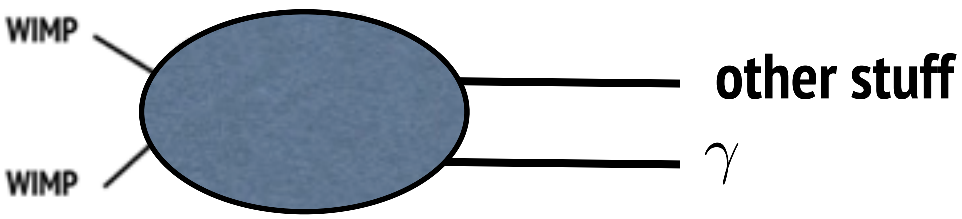


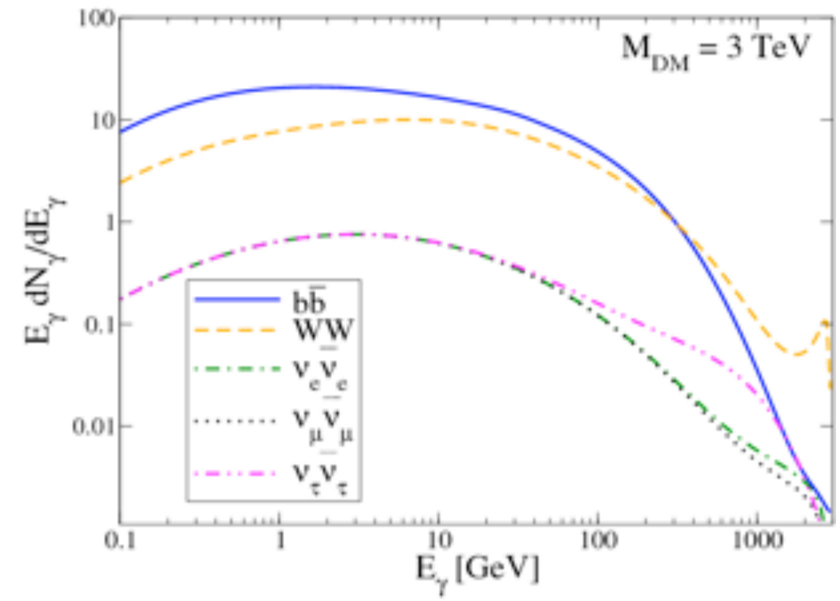


Channels and detectors

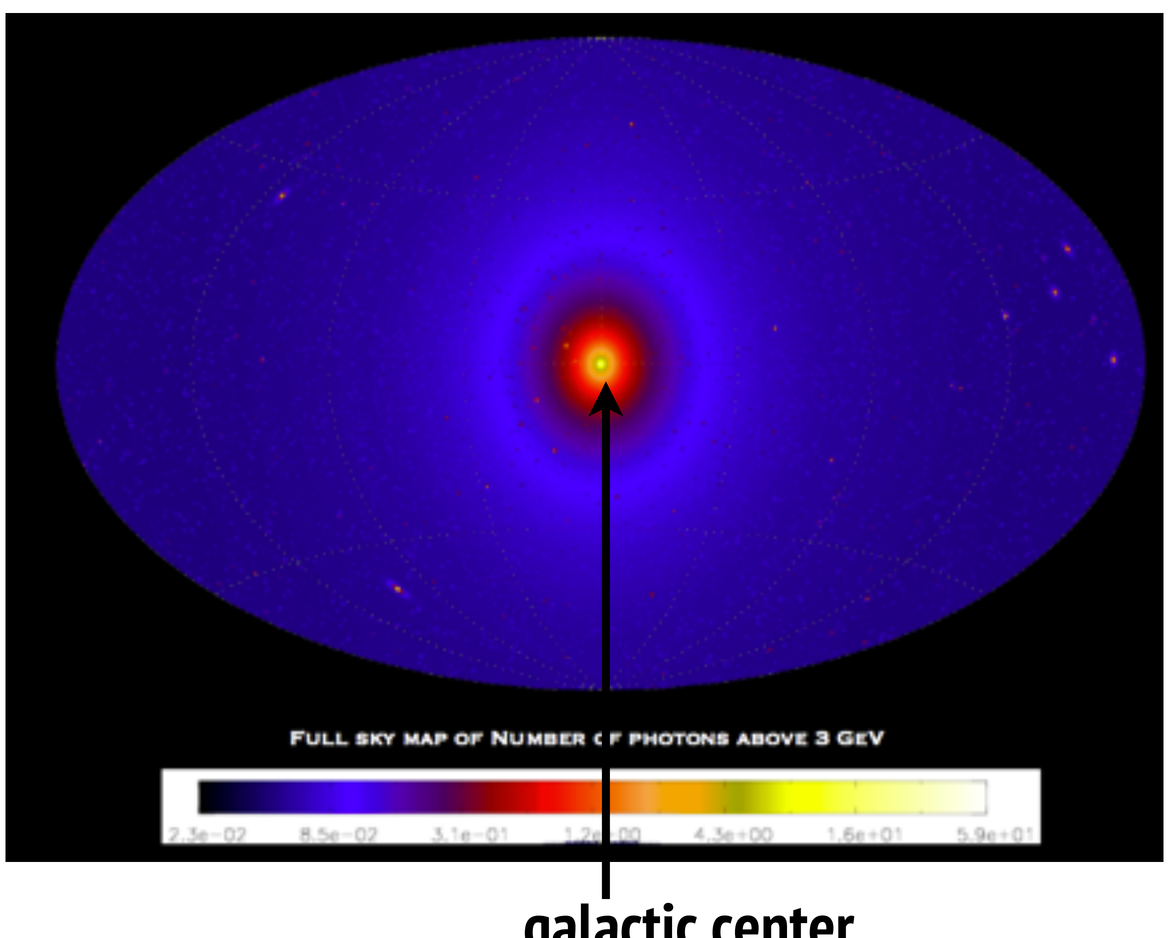


Gamma rays

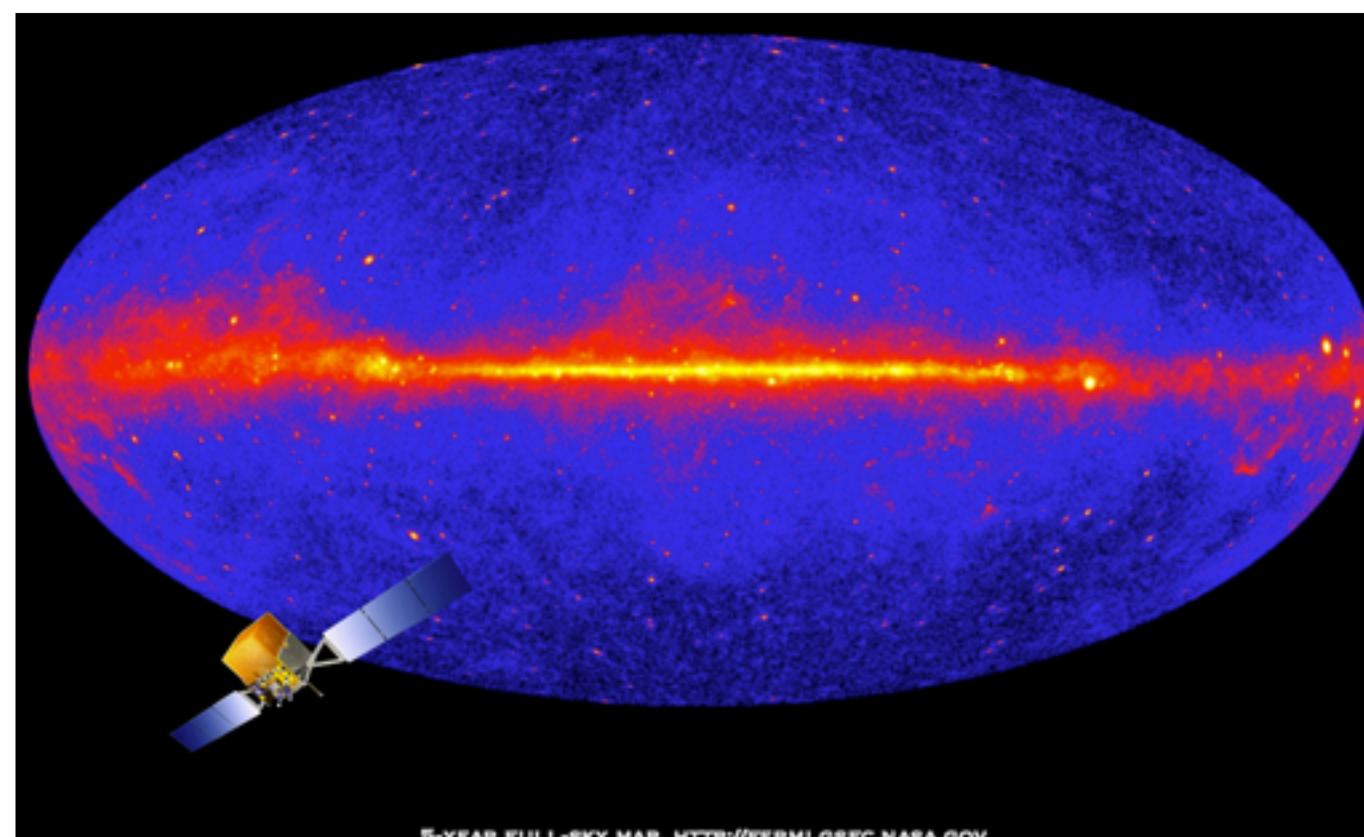




halo simulation + cross section -> signal map

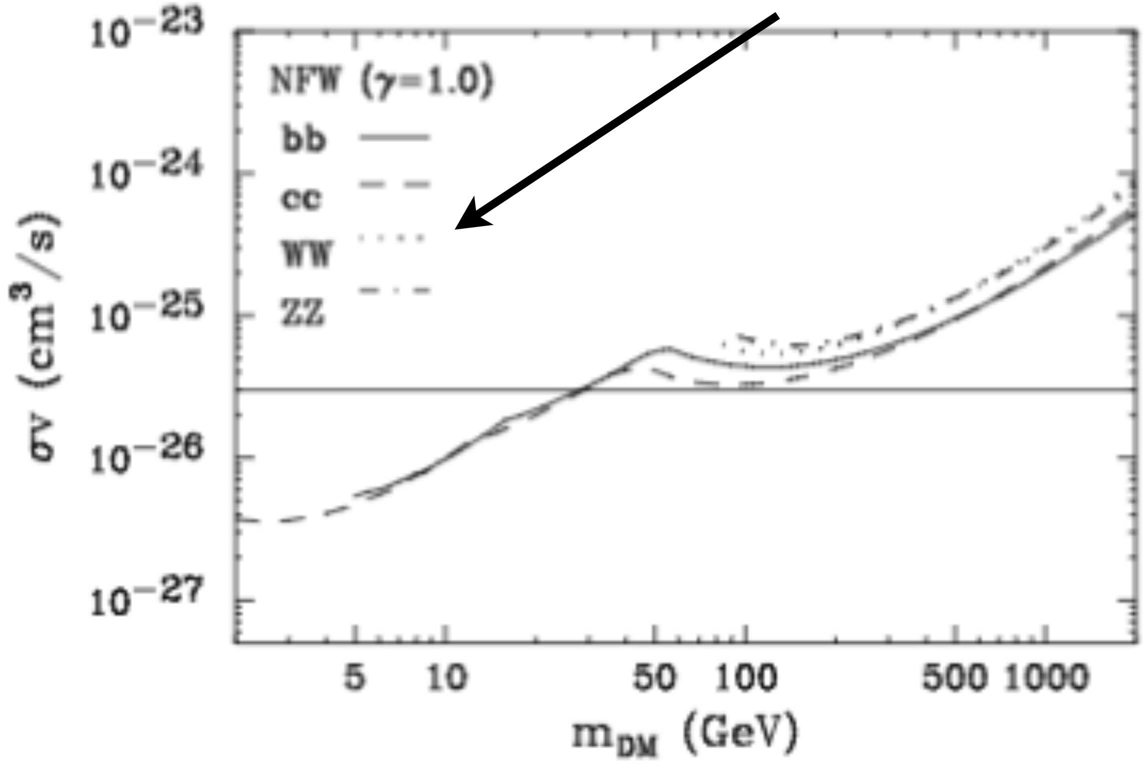


compare with Fermi-LAT measurements



Non observation over background -> constraints

annihilation channel



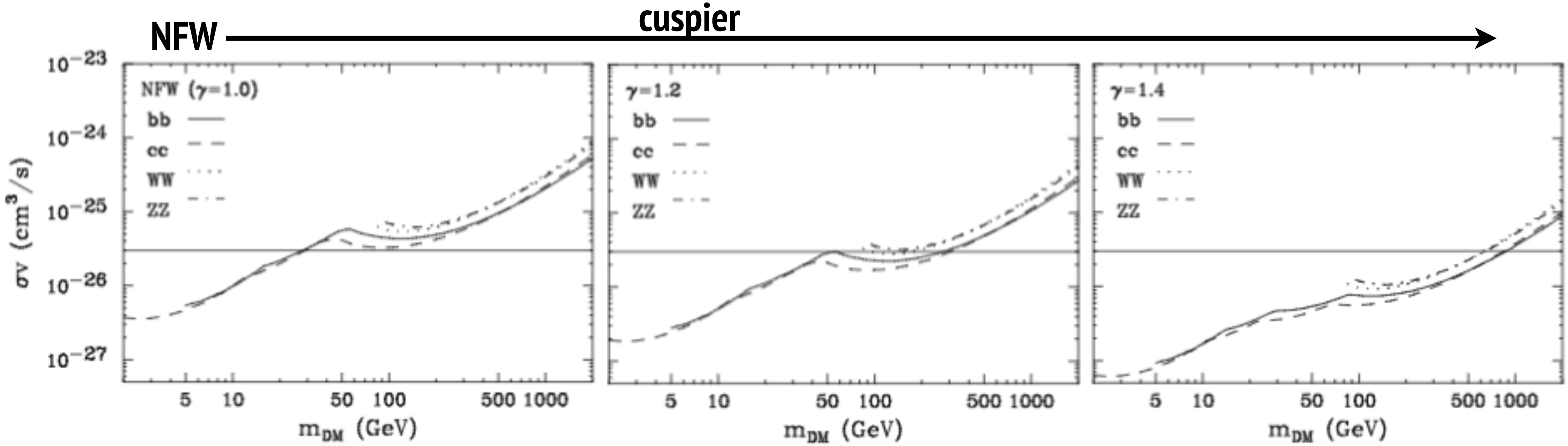
Thermal relic cross section

DM particle mass

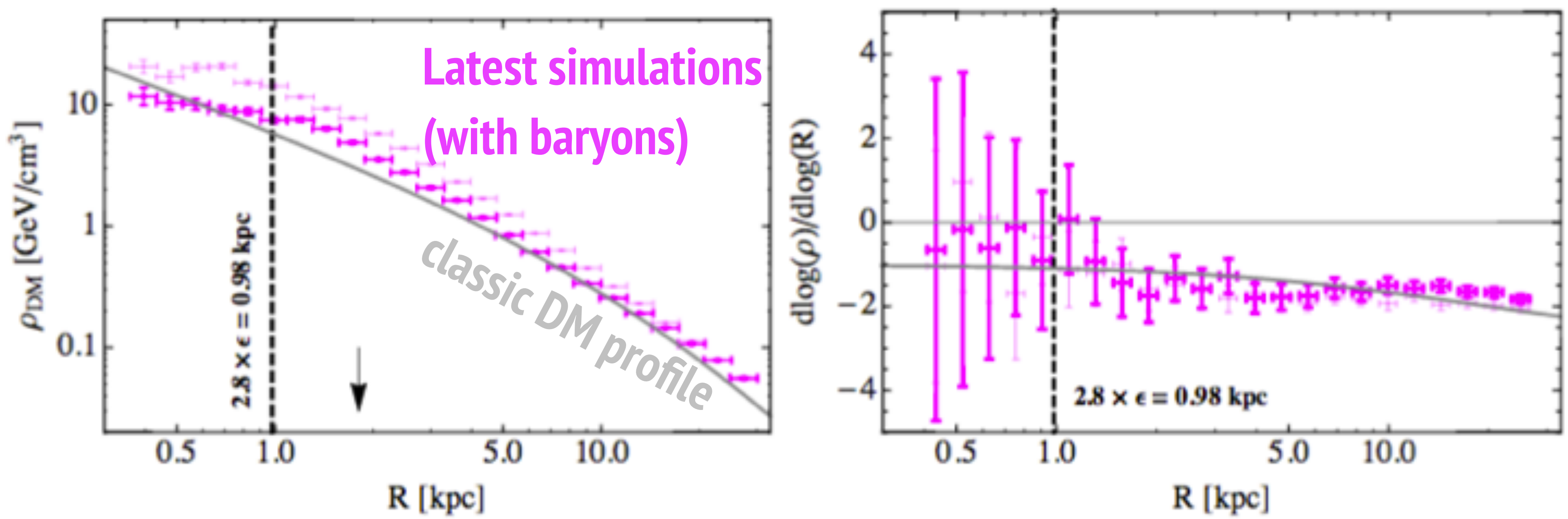
Dependence on Halo DM profile $\rho \propto r^{-\gamma}$

Signal amplifies the uncertainties

$$\frac{d\Phi_\gamma}{dE} = \frac{\langle \sigma v \rangle}{8\pi\, m_\chi^2} \frac{dN_\gamma}{dE} \int_{\rm l.o.s.} ds\, \rho^2(r(s,\psi))\,.$$



EAGLE simulations



The galactic center GeV excess

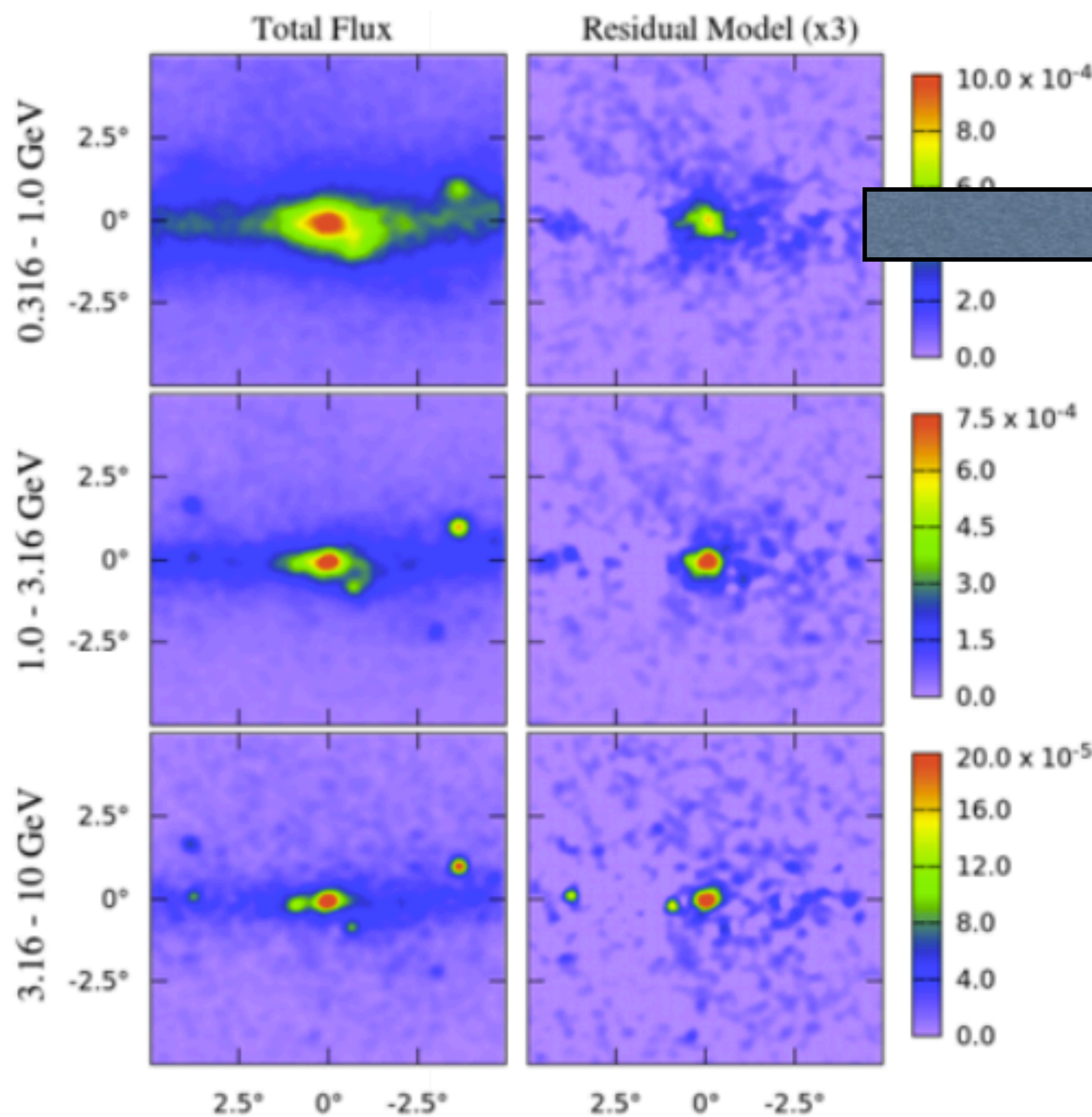
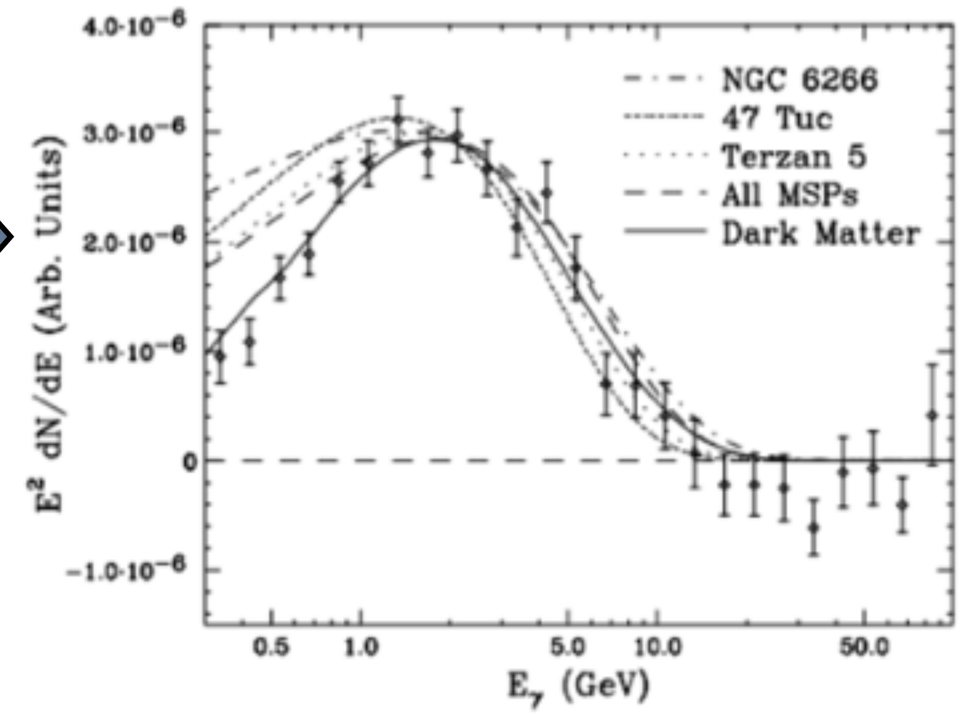
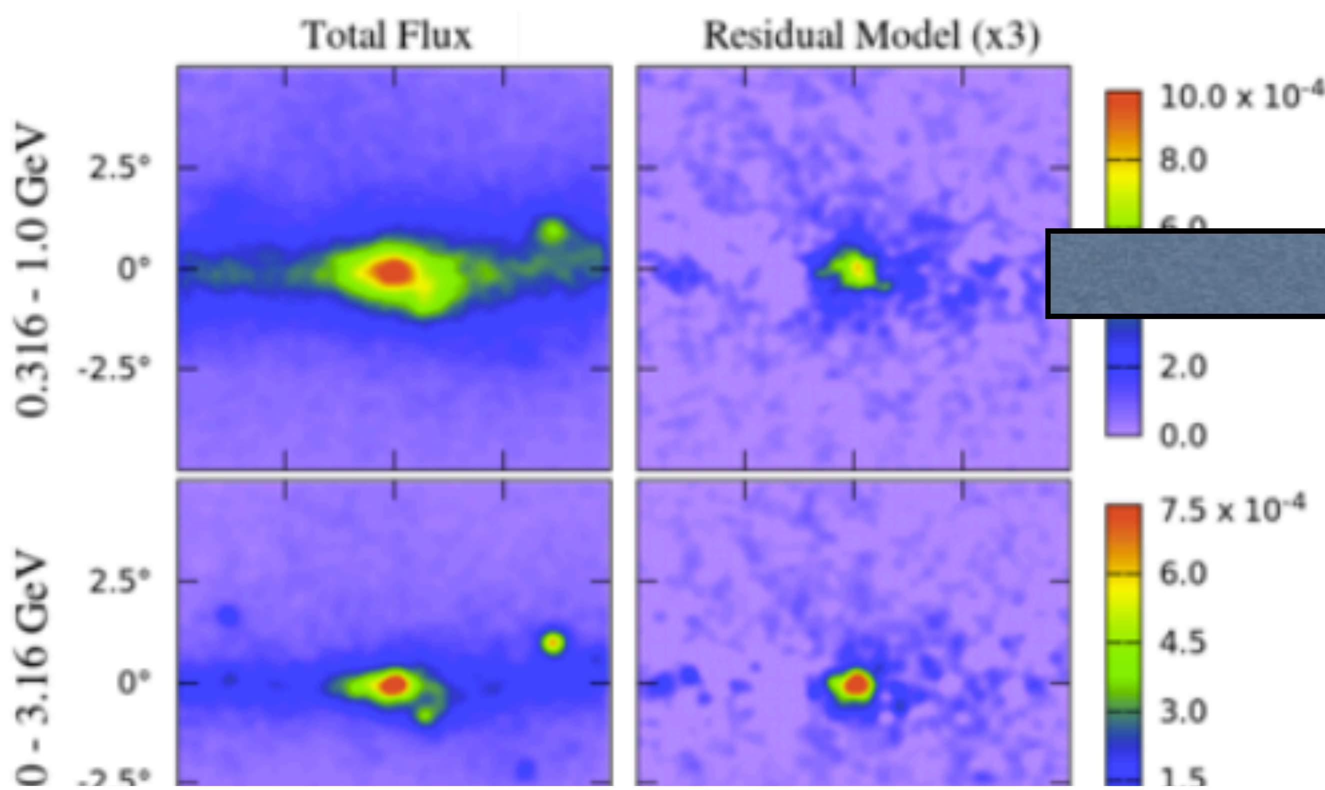
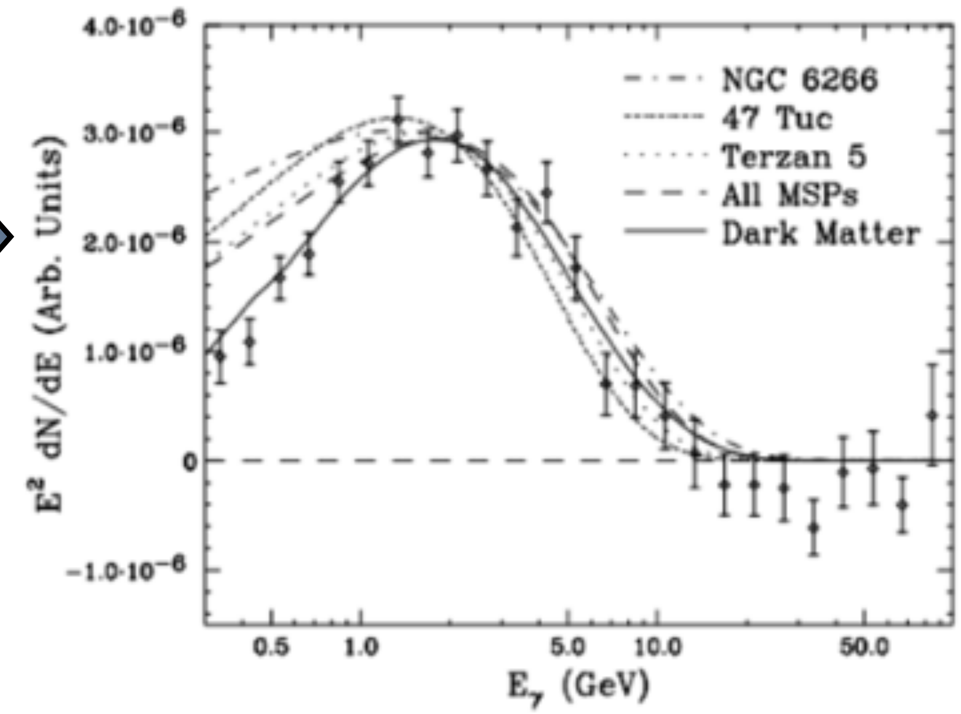


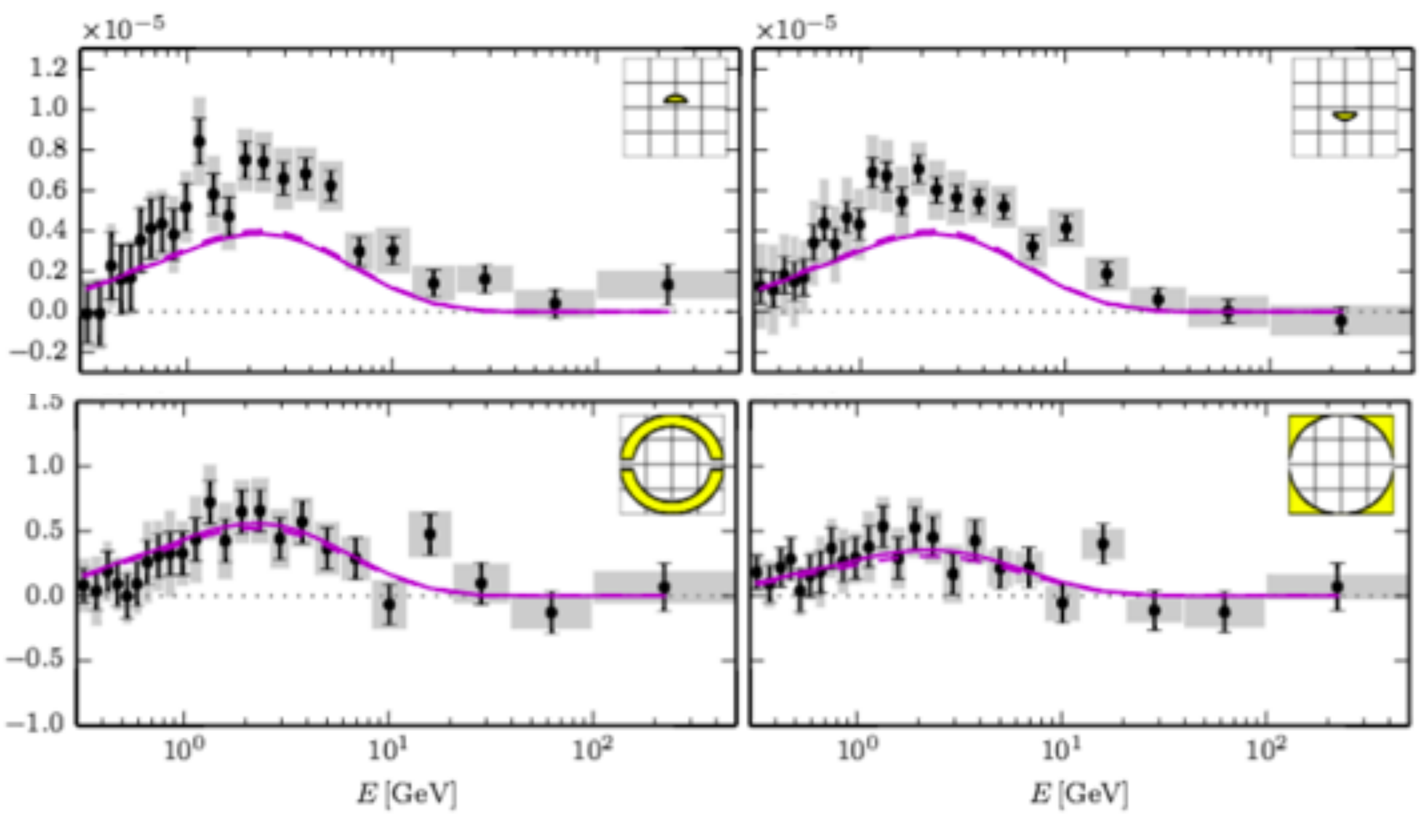
FIG. 9: The raw gamma-ray maps (left) and the residual maps after subtracting the best-fit Galactic diffuse model, 20 cm template, point sources, and isotropic template (right), in units of photons/cm^2/s/sr. The right frames clearly contain a significant central and spatially extended excess, peaking at ~1-3 GeV. Results are shown in galactic coordinates, and all maps have been smoothed by a 0.25° Gaussian.



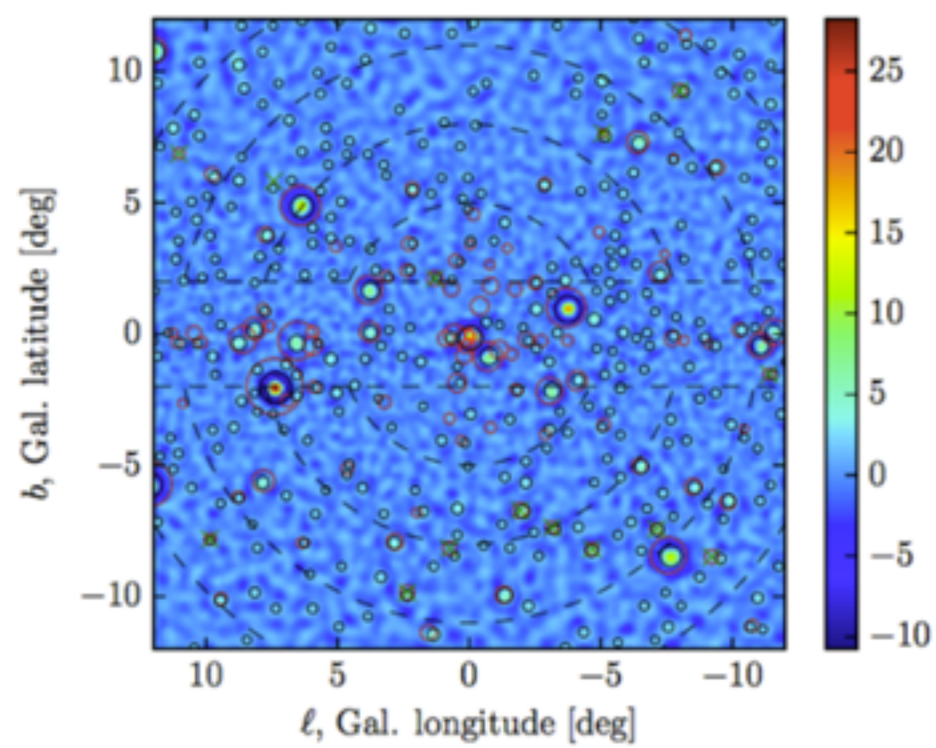
The galactic center GeV excess







millisecond pulsars?

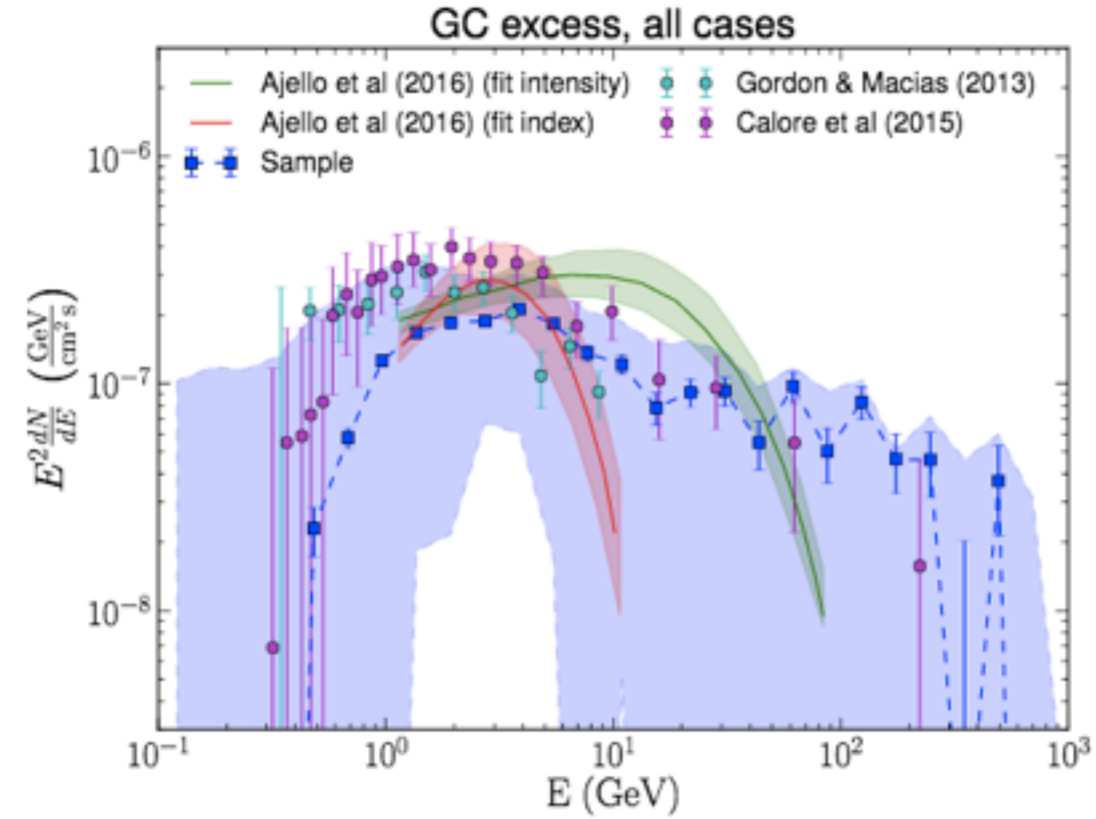


EAGLE profiles http://arxiv.org/pdf/1509.02164.pdf

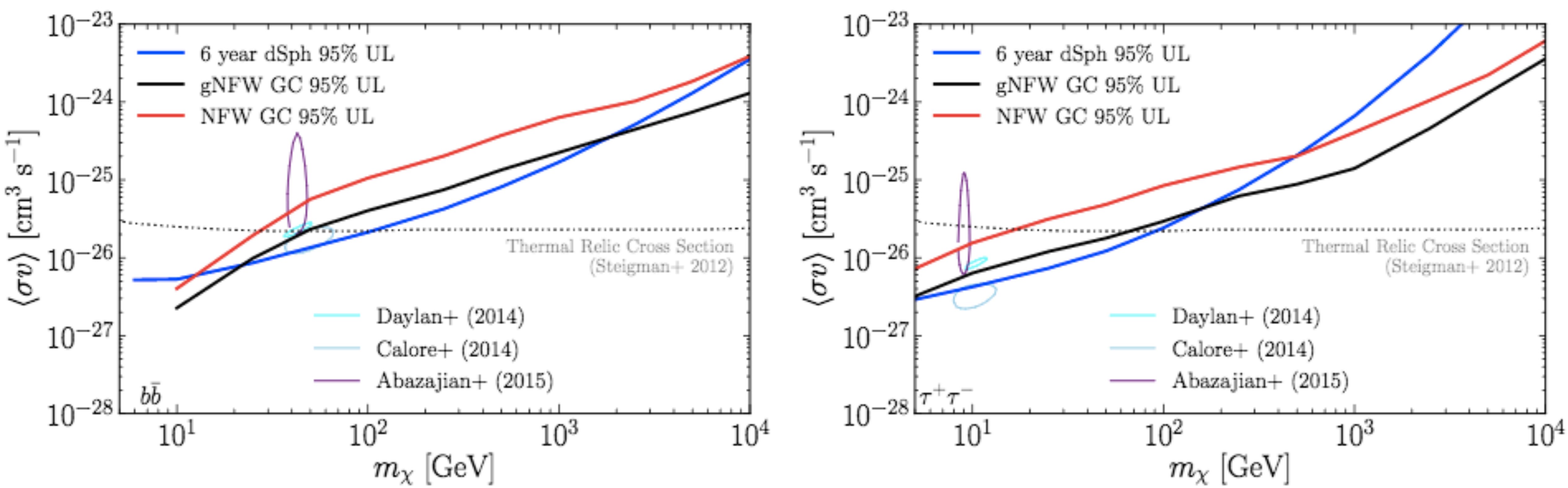
Fermi on the GC excess

1704.03910

- Extensive examination of uncertainties in 6.5 y of P8 data
- Excess in the GC is found in all cases
- different astrophysical model assumptions give ~ 3 uncertainty i
- other comparable S/N excesses are found in Galactic plane
- Possible explanations...
    - leak from Fermi bubbles?
    - CRs from resolved sources?
    - unresolved sources? (millisecond pulsars)



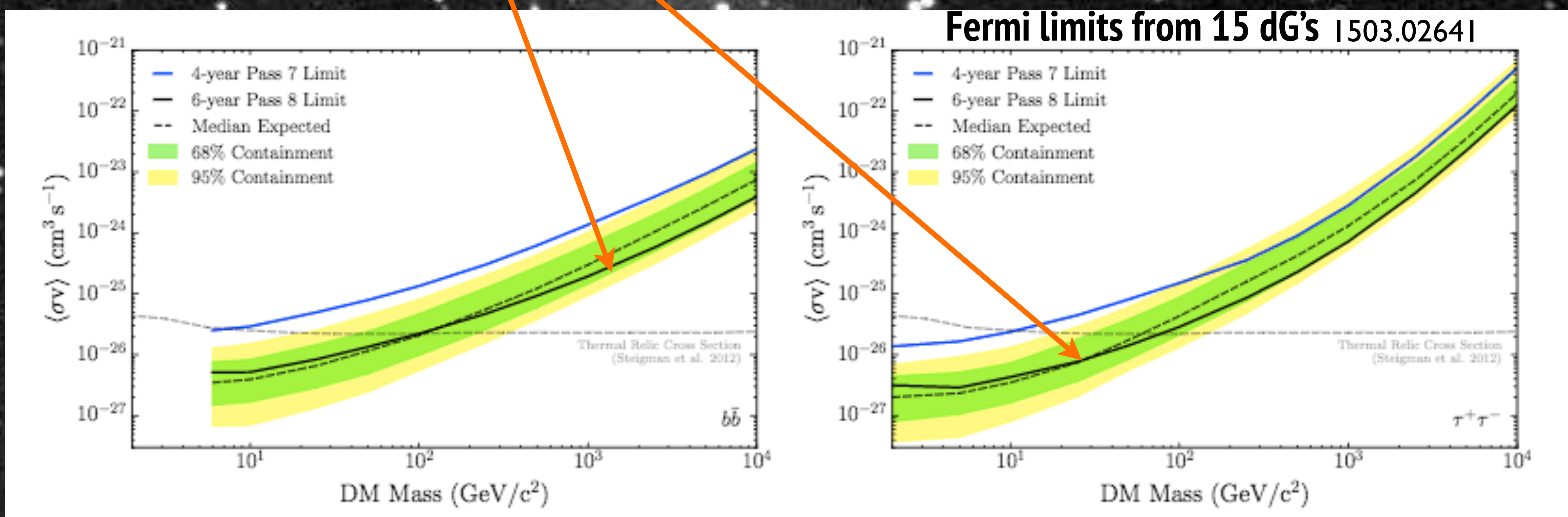
New constraints ... signal not as clear as desired to claim discovery!



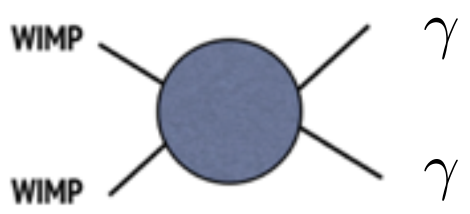
Dwarf galaxies

- Similar size than globular clusters, ~ 10^7 solar mass
- Small signal (
- but large ratio of DM / Luminous mass,
- far from the violent environment of our galactic center

- No excess is observed ... upper limits



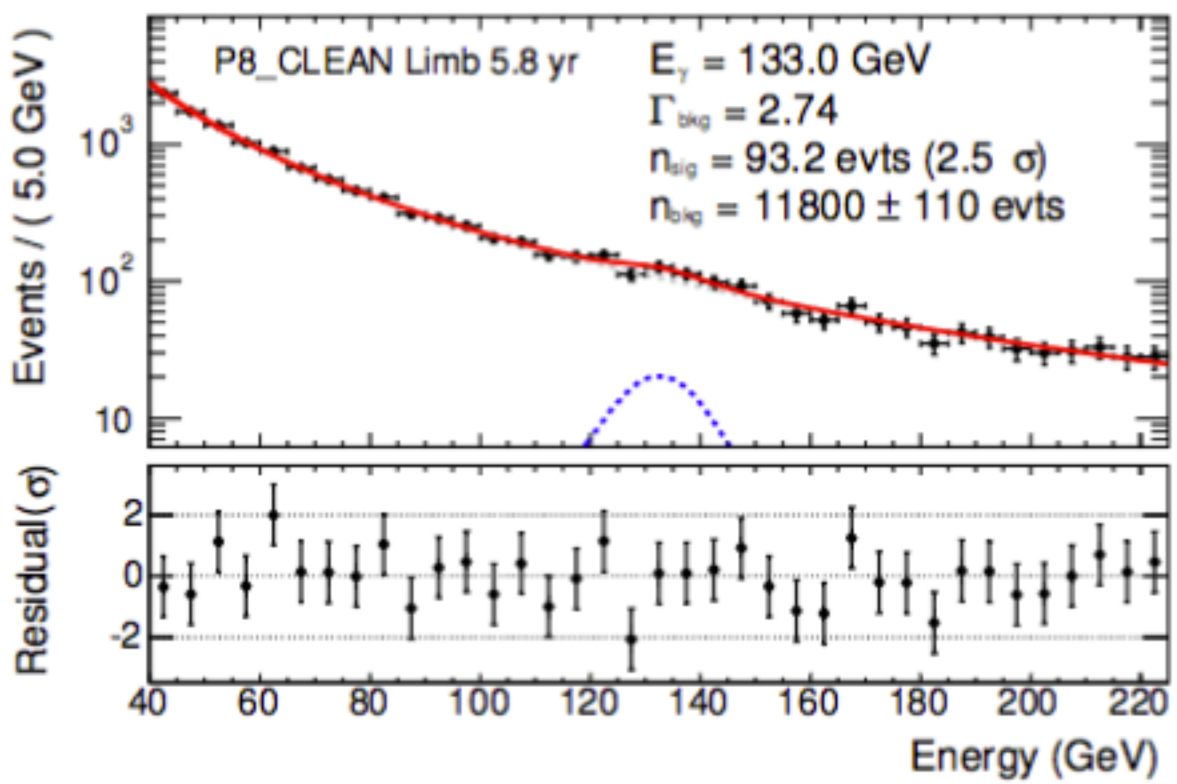
Gamma-ray lines

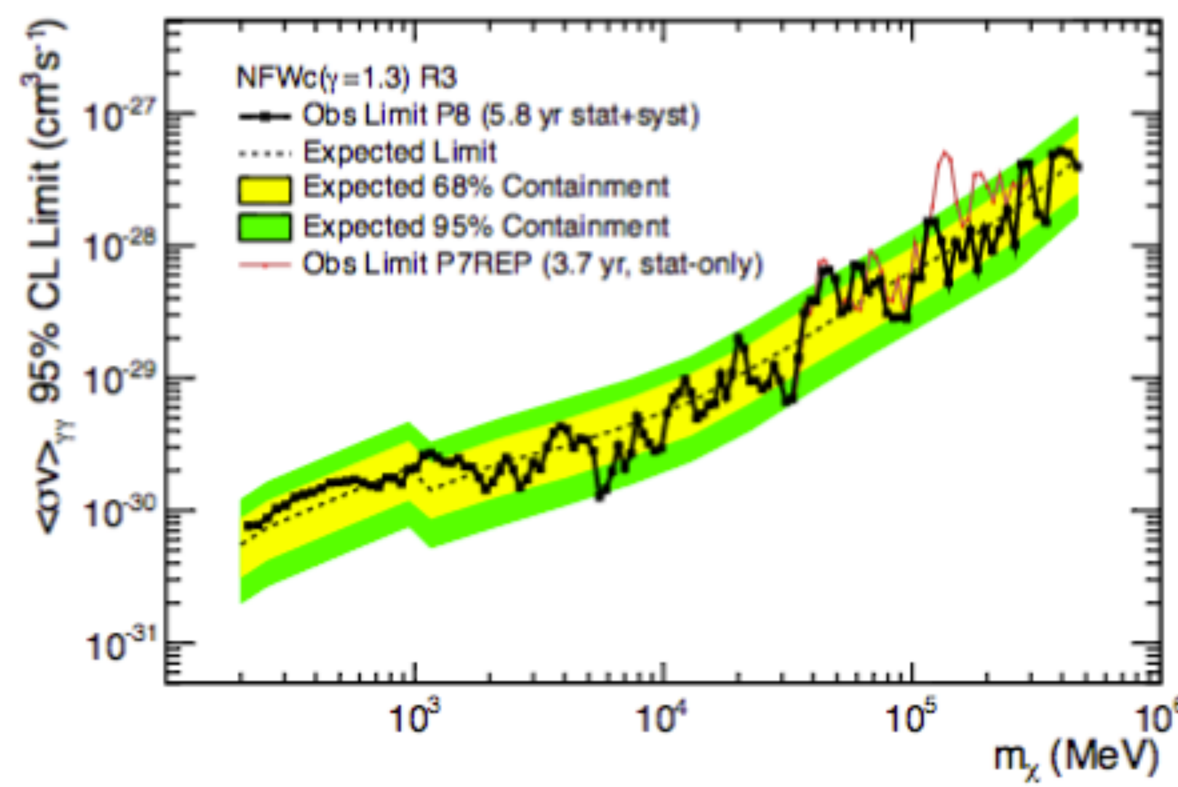


Cross section typically suppressed $\sim \alpha/4\pi \sim 10^{-3}$

But signal is monochromatic! and backgrounds are continuous

FERMI analysis http://arxiv.org/pdf/1506.00013v1.pdf





A hint

Fermi LAT Search for Internal Bremsstrahlung Signatures from Dark Matter Annihilation

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A Tentative Gamma-Ray Line from Dark Matter Annihilation at the Fermi Large Area Telescope

arXiv:1204.2797v2 [hep-ph] 8 Aug 2012

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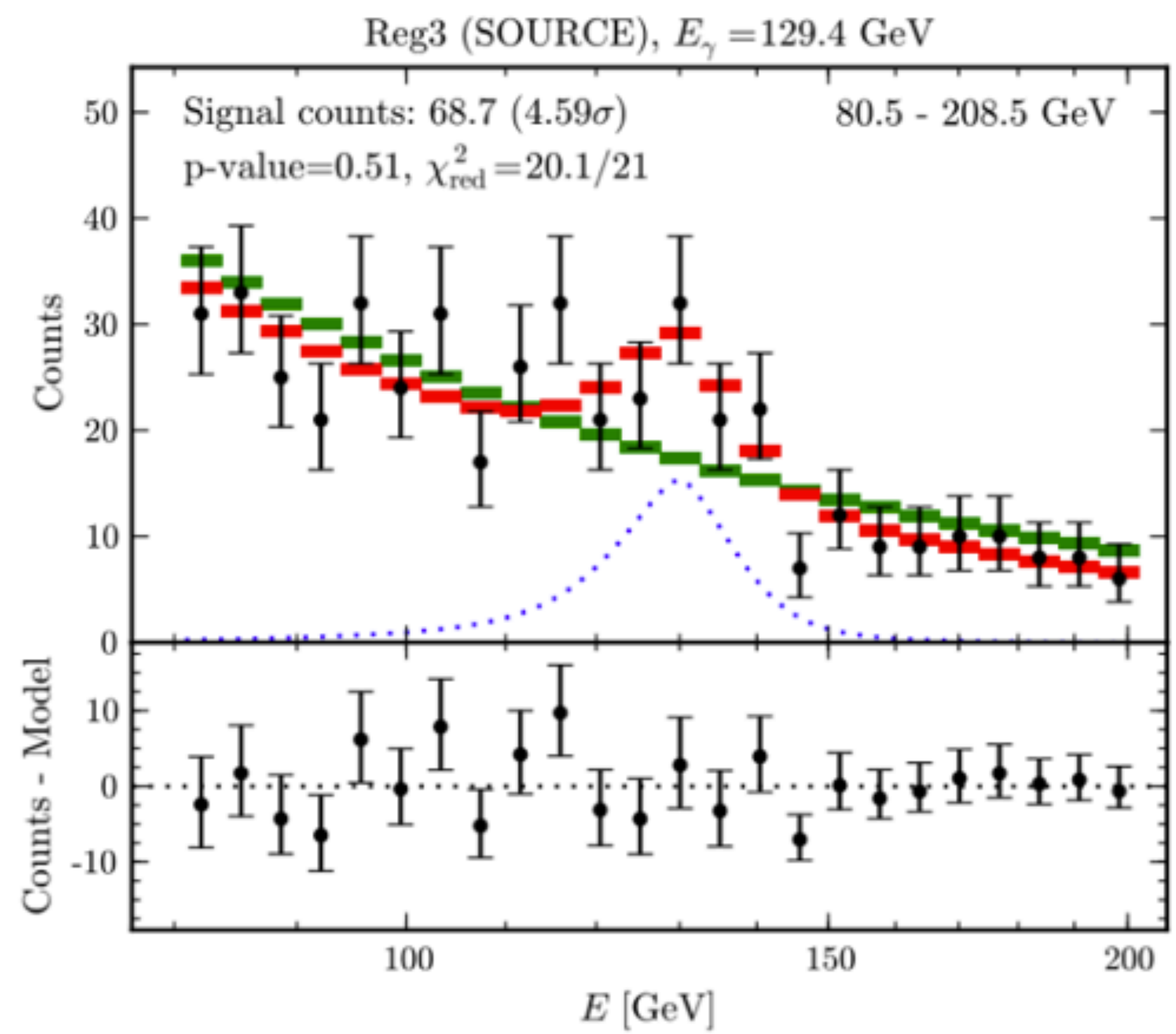
Abstract. The observation of a gamma-ray line in the cosmic-ray fluxes would be a smoking-gun signature for dark matter annihilation or decay in the Universe. We present an improved search for such signatures in the data of the Fermi Large Area Telescope (LAT), concentrating on energies between 20 and 300 GeV. Besides updating to 43 months of data, we use a new data-driven technique to select optimized target regions depending on the profile of the Galactic dark matter halo. In regions close to the Galactic center, we find a 4.6σ indication for a gamma-ray line at $E_\gamma \approx 130$ GeV. When taking into account the look-elsewhere effect the significance of the observed excess is 3.2σ. If interpreted in terms of dark matter particles annihilating into a photon pair, the observations imply a dark matter mass of $m_\chi = 129.8 \pm 2.4^{+7}_{-13}$ GeV and a partial annihilation cross-section of $\langle\sigma v\rangle_{\chi\chi\to\gamma\gamma} = (1.27 \pm 0.32^{+0.18}_{-0.28}) \times 10^{-27}\ \mathrm{cm^3\,s^{-1}}$ when using the Einasto dark matter profile. The evidence for the signal is based on about 50 photons; it will take a few years of additional data to clarify its existence.



unfortunately, it didn't survive statistics and careful E-calibration

an aside (Sterile neutrino DM)

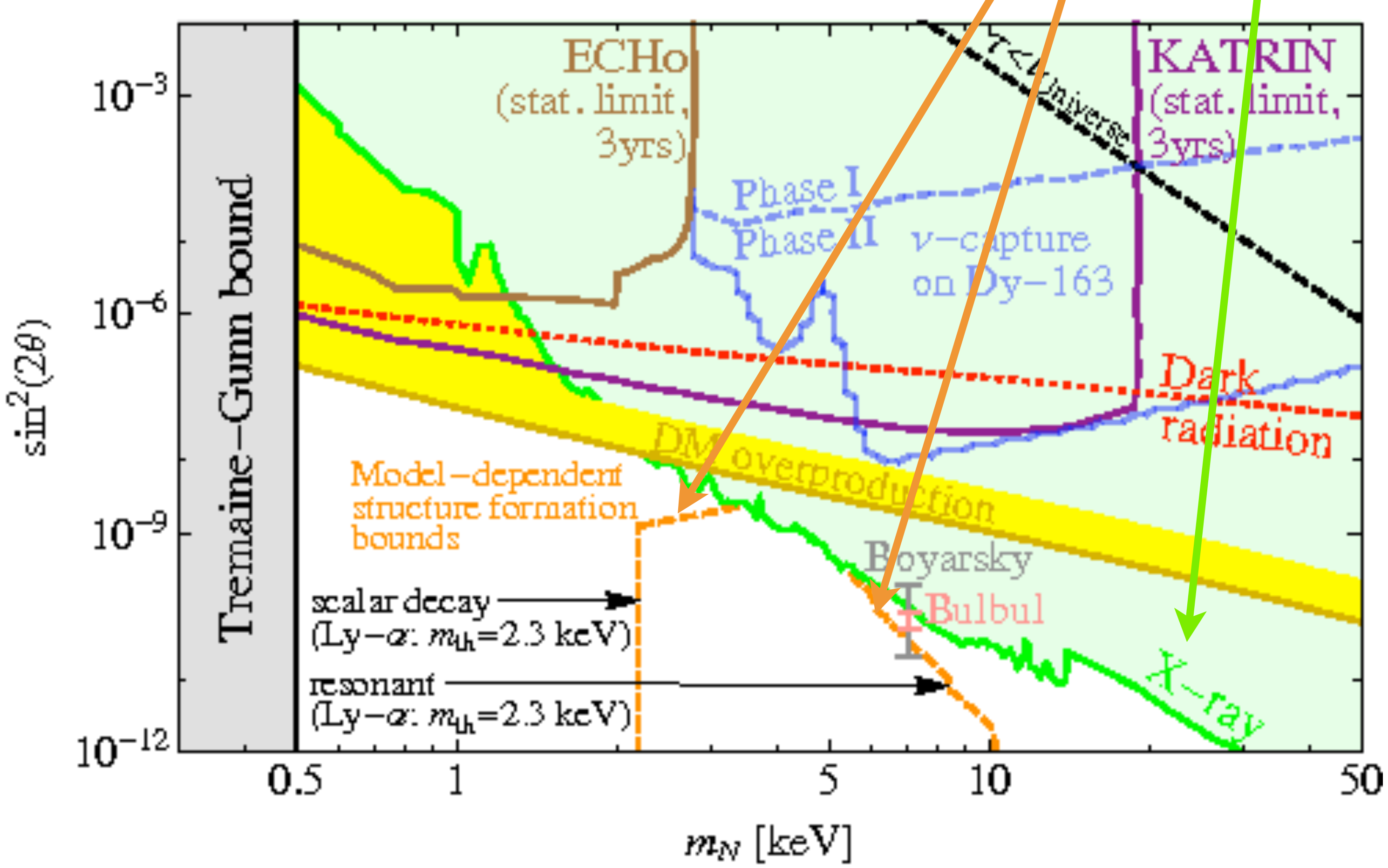
- **Sterile neutrino** mass ~ keV

- Production via oscillations, decay of other particles in the Early Universe,...

- Possibly Warm dark matter but depends on the production mechanism

- Mixing with standard neutrinos allows long-lifetime decays $\nu_s \to \nu\gamma$

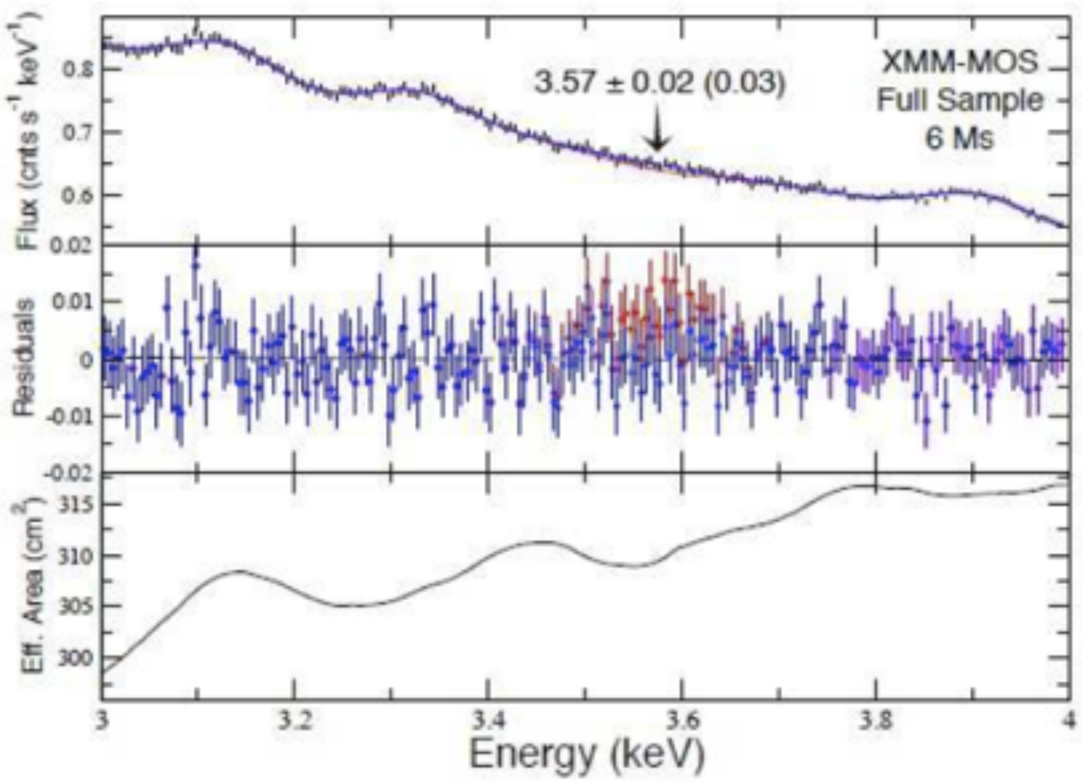
Mixing^2



Sterile neutrino mass [keV]

3.55 keV line

3.55 keV candidate in Galaxy clusters



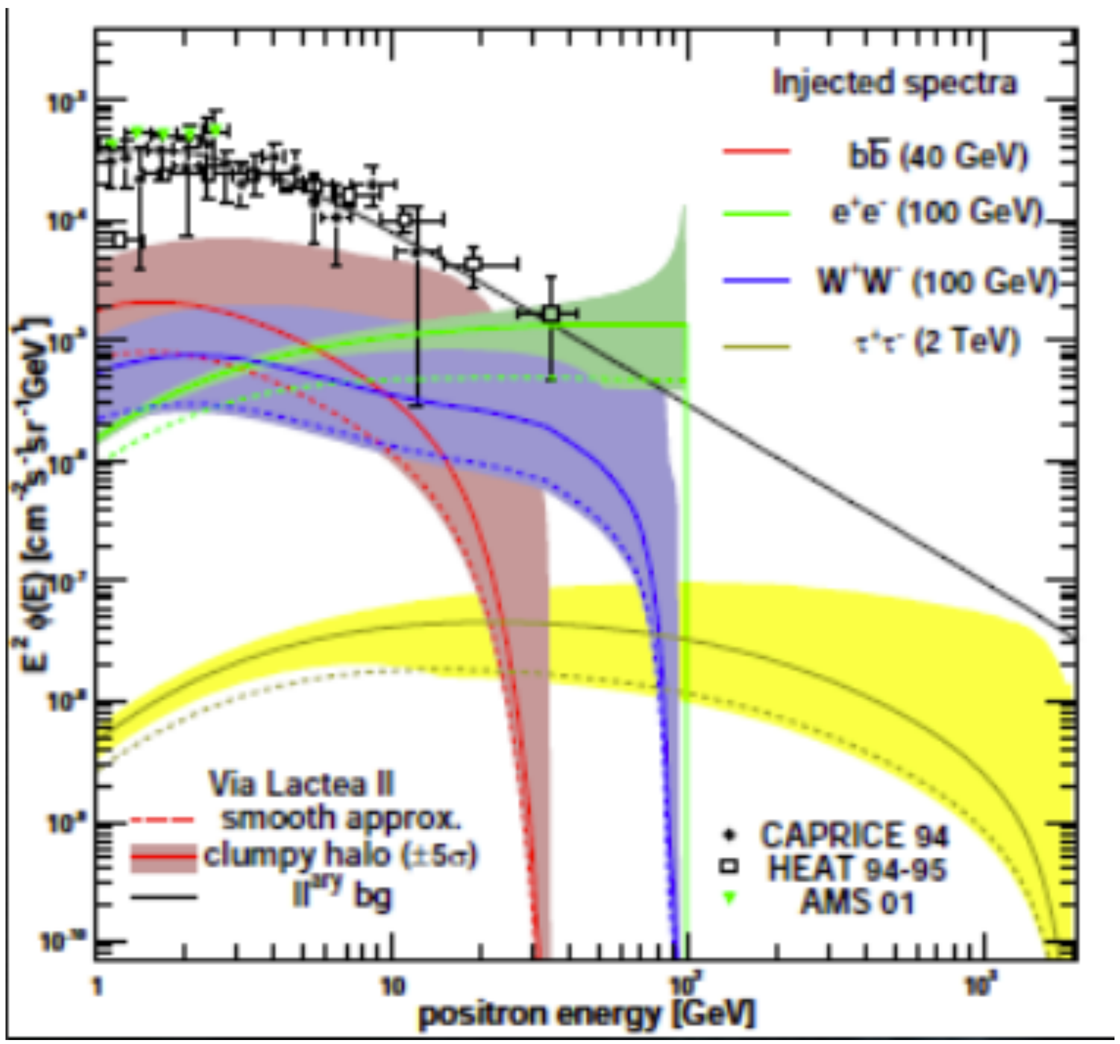
Many observations... but not compatible with each other

Sample	Instrument	$\sin^2 2\theta$ $\times 10^{-11}$
All others stacked (69 clusters)	XMM-MOS	$6.0^{+1.1}_{-1.4}$
All others stacked (69 clusters)	XMM-PN	$5.4^{+0.8}_{-1.3}$
Perseus	XMM-MOS	$23.3^{+7.6}_{-8.9}$
Perseus	XMM-PN	< 18 (90 %)
Coma + Centaurus + Ophiuchus	XMM-MOS	$18.2^{+4.4}_{-5.9}$
Coma + Centaurus + Ophiuchus	XMM-PN	< 11(90%)
Perseus	Chandra ACIS-I	$28.3^{+11.8}_{-12.1}$
Perseus	Chandra ACIS-S	$40.1^{+14.5}_{-13.7}$
M31 on-centre	XMM-Newton	2–20
Stacked galaxies	XMM-Newton	< 2.5 (99%)
Stacked galaxies	Chandra	< 5 (99%)
Stacked dwarves	XMM-Newton	< 4 (95%)

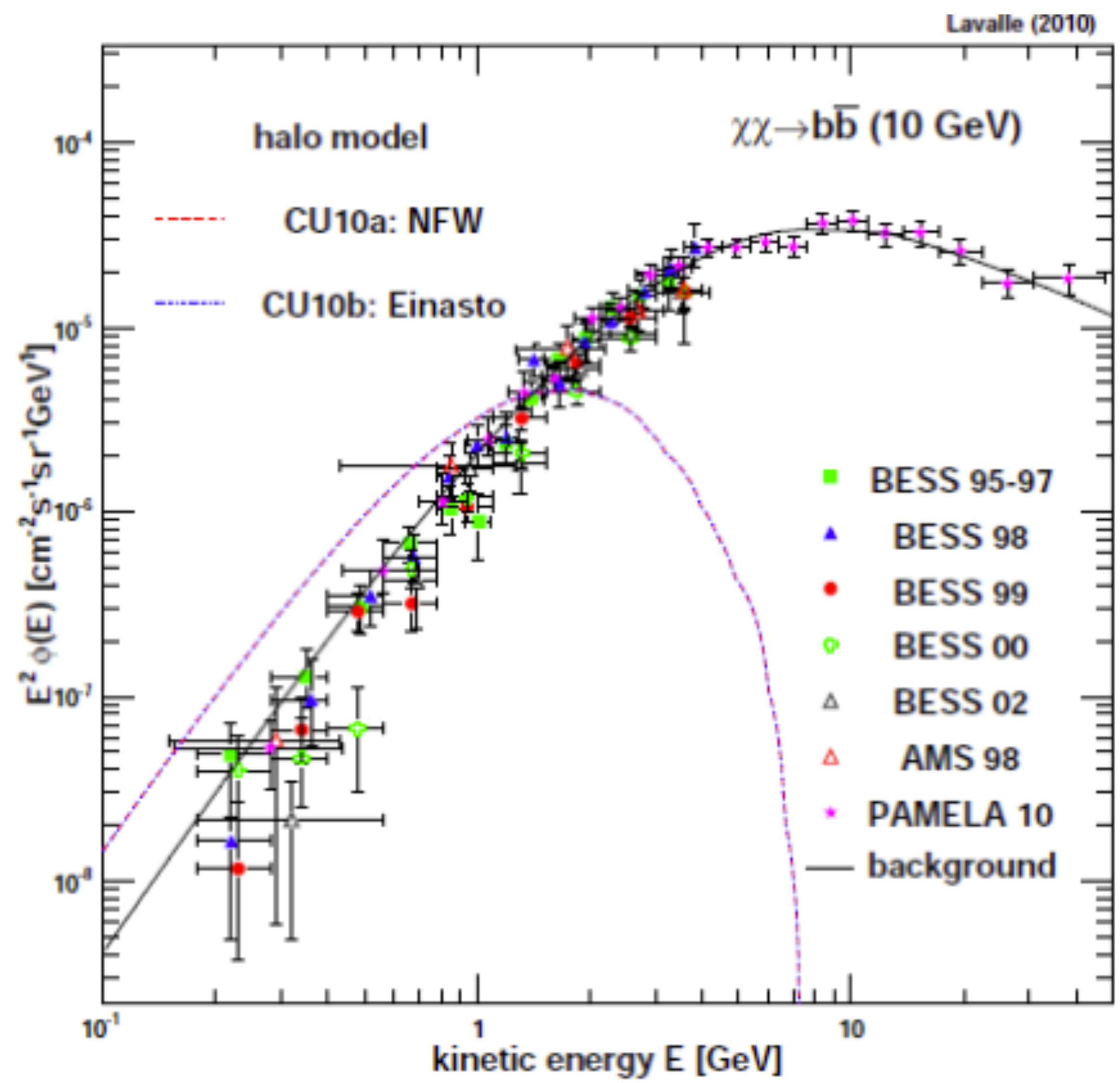
Antimatter

rare ... not produced during big bang ... but cosmic rays collisions produce some

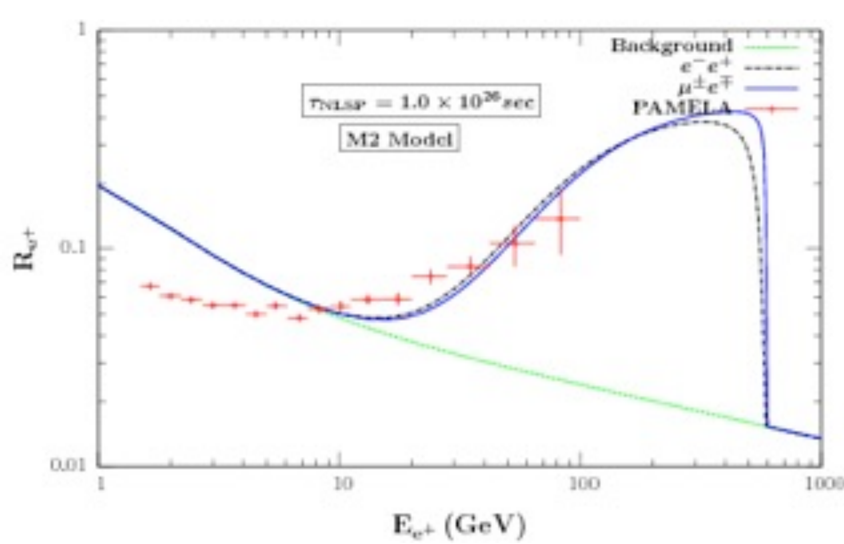
positrons



antiprotons



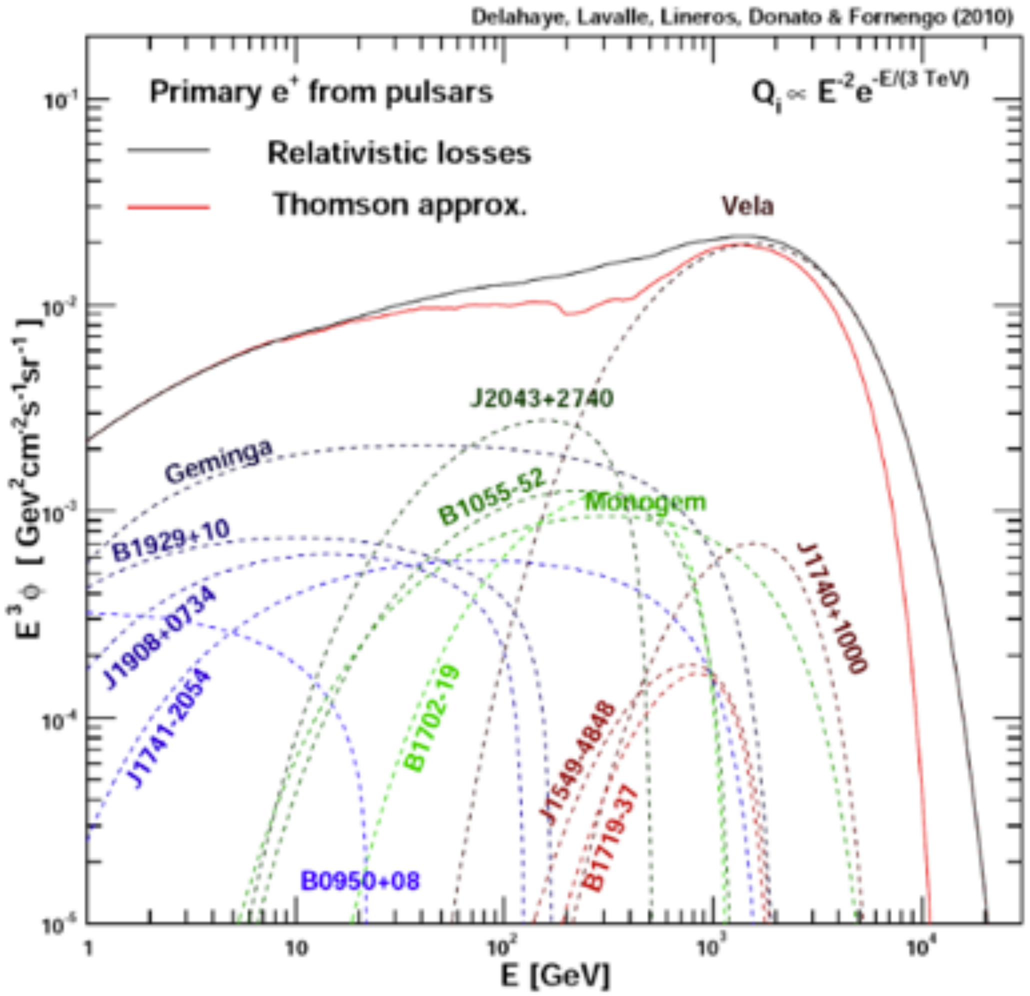
PAMELA excess

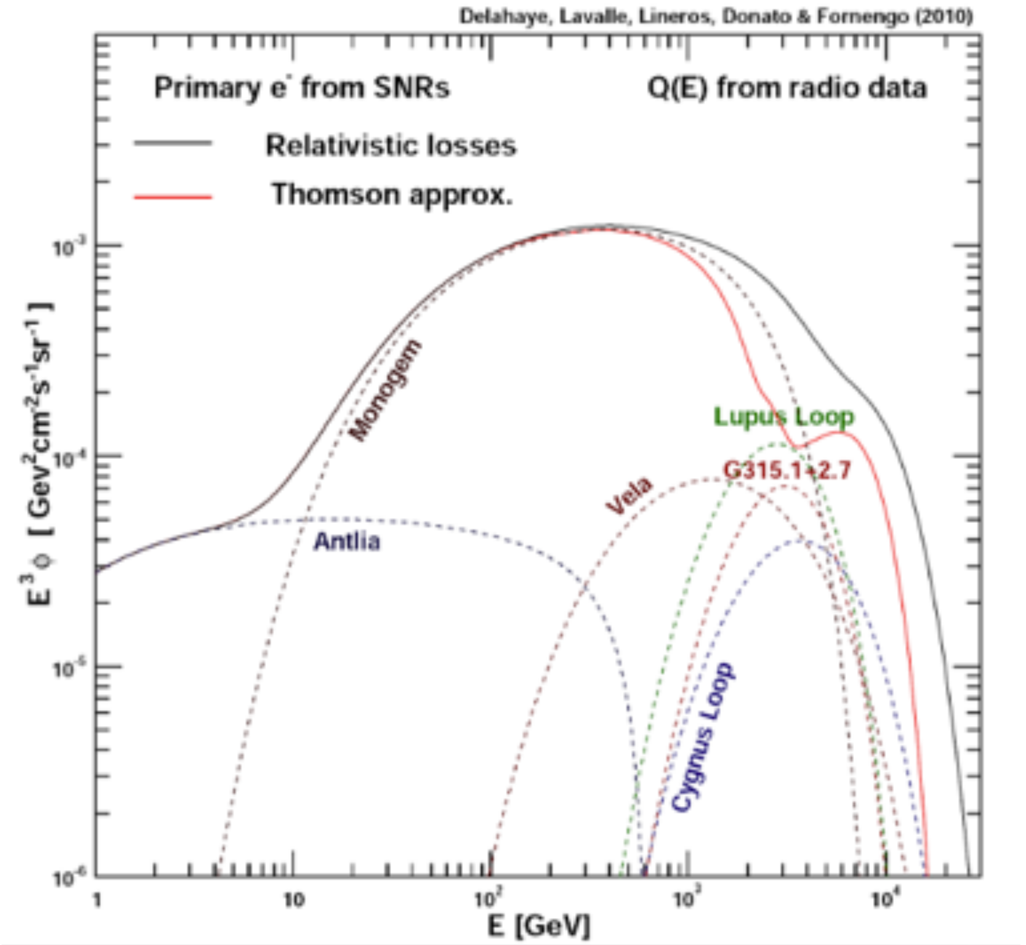


Positrons

HE positrons, mostly from nearby sources (standard or DM)

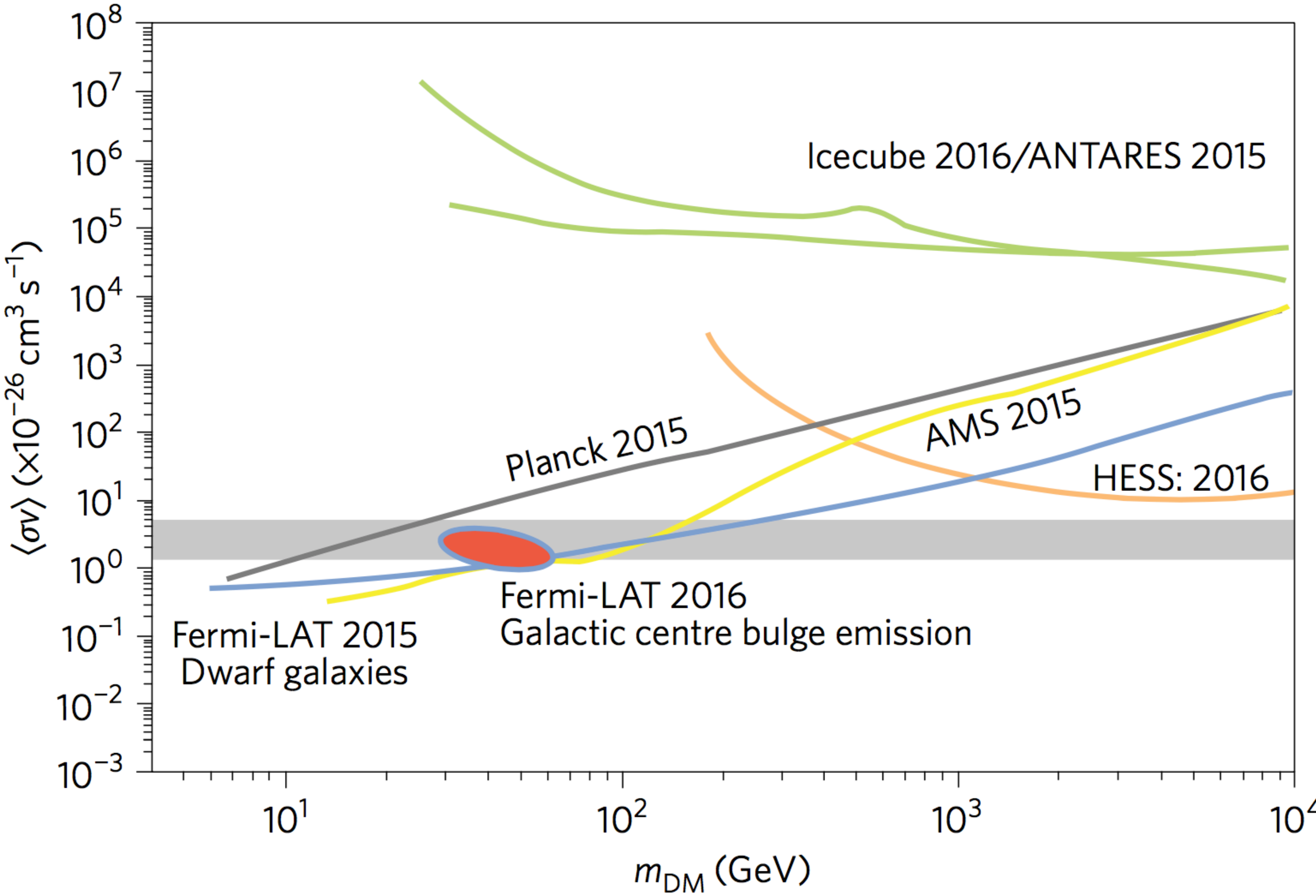
Pulsars, supernova remnants ... are difficult backgrounds





Pulsars, supernova remnats ... are difficult backgrounds

Summary



Neutrinos

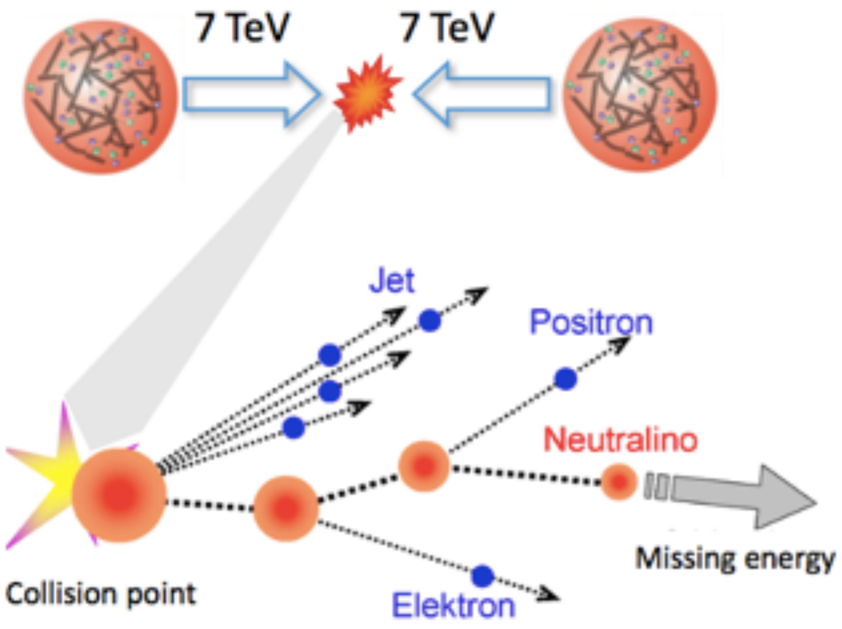
Antimatter

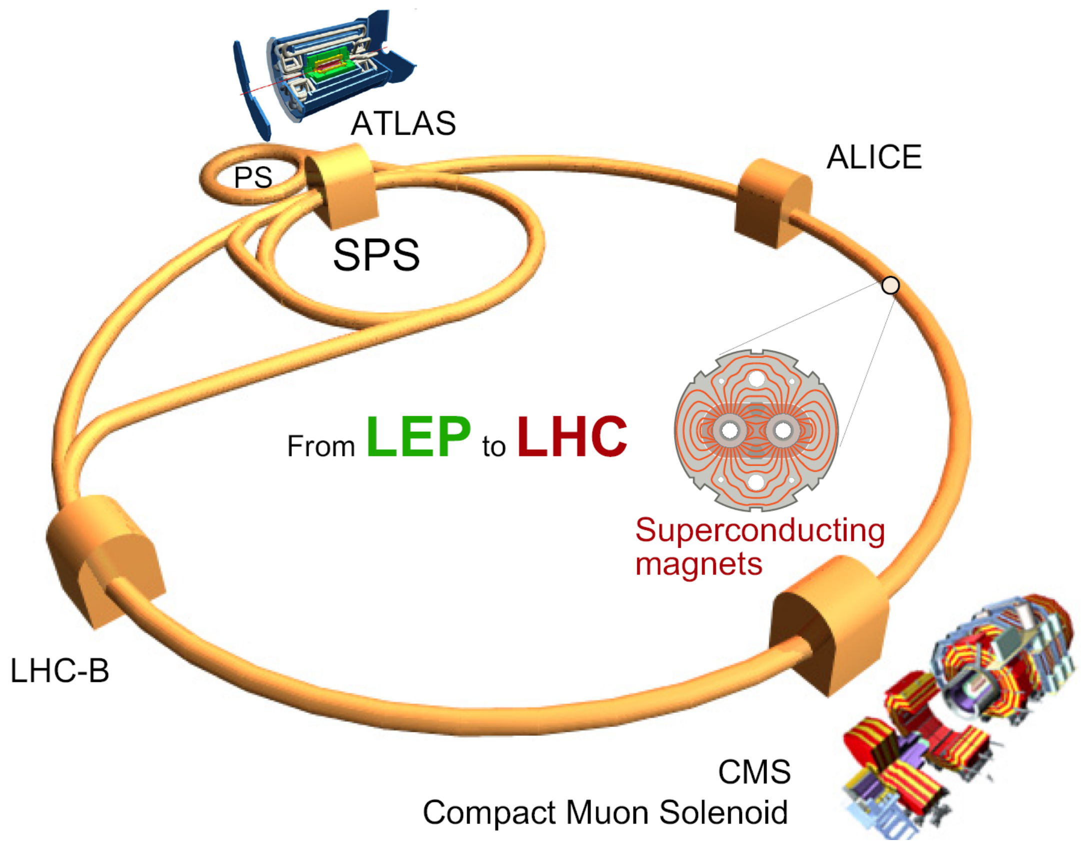
Cerenkov … but

https://www.nature.com/nphys/journal/v13/n3/pdf/nphys4049.pdf

Collider Searches

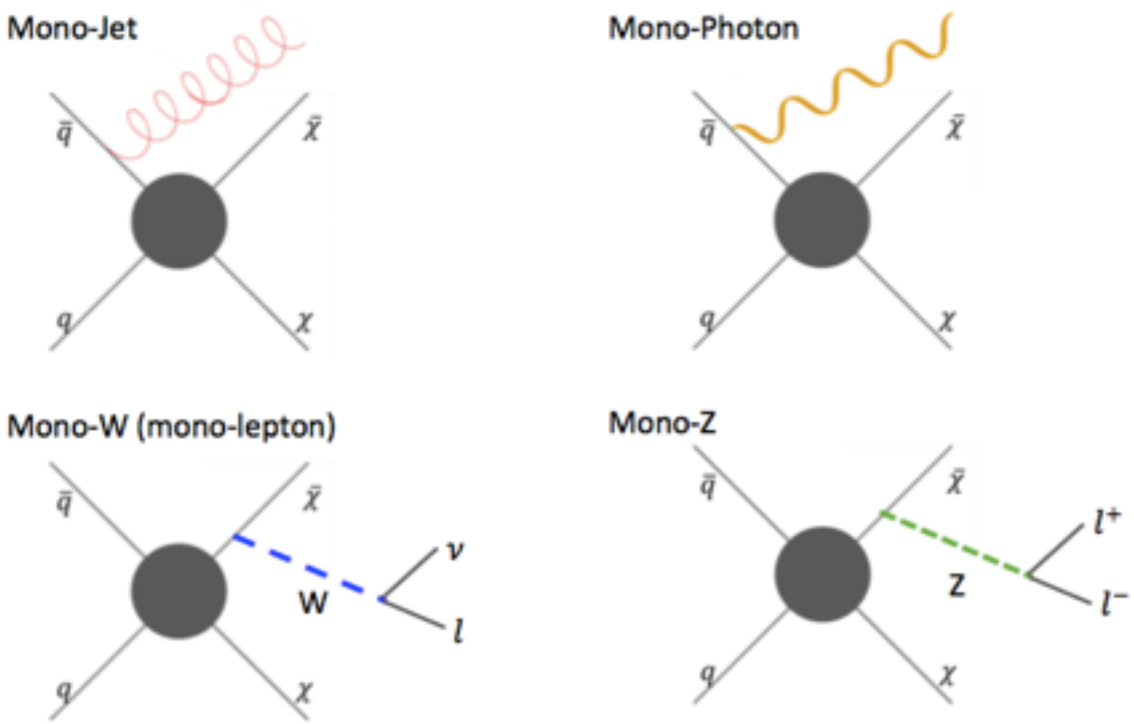
stable and weakly-interacting ... Typical signature ... missing!



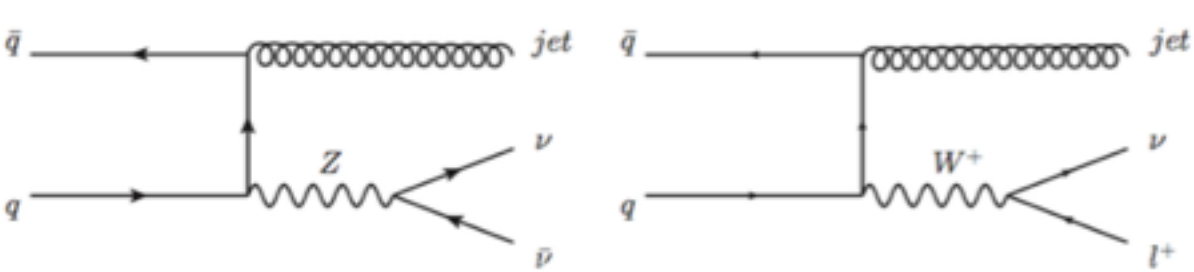


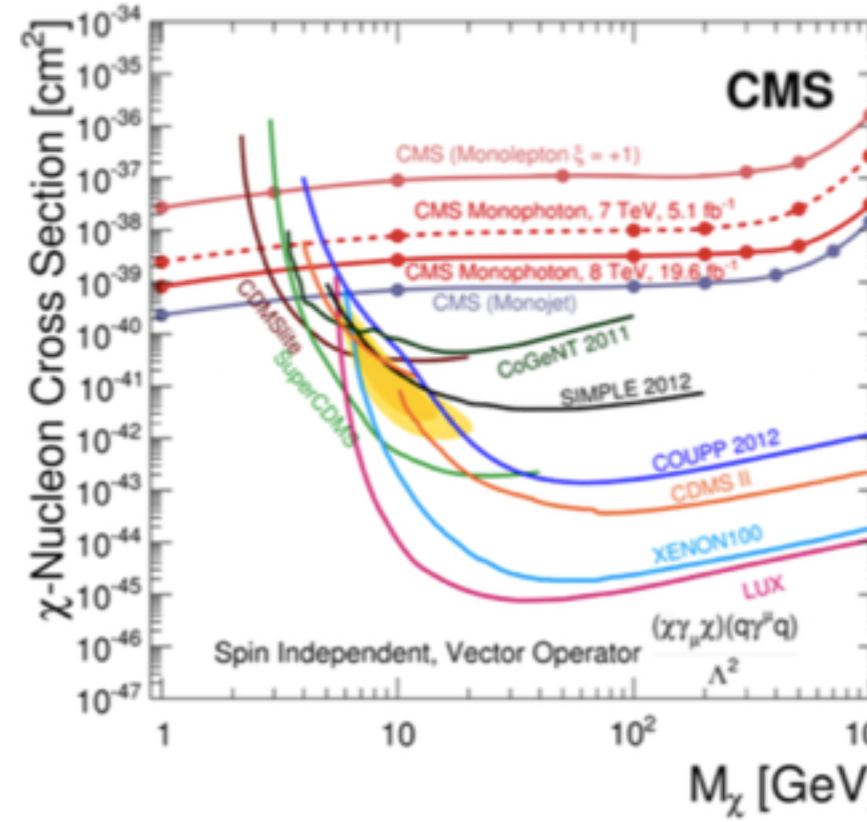
Model independent searches

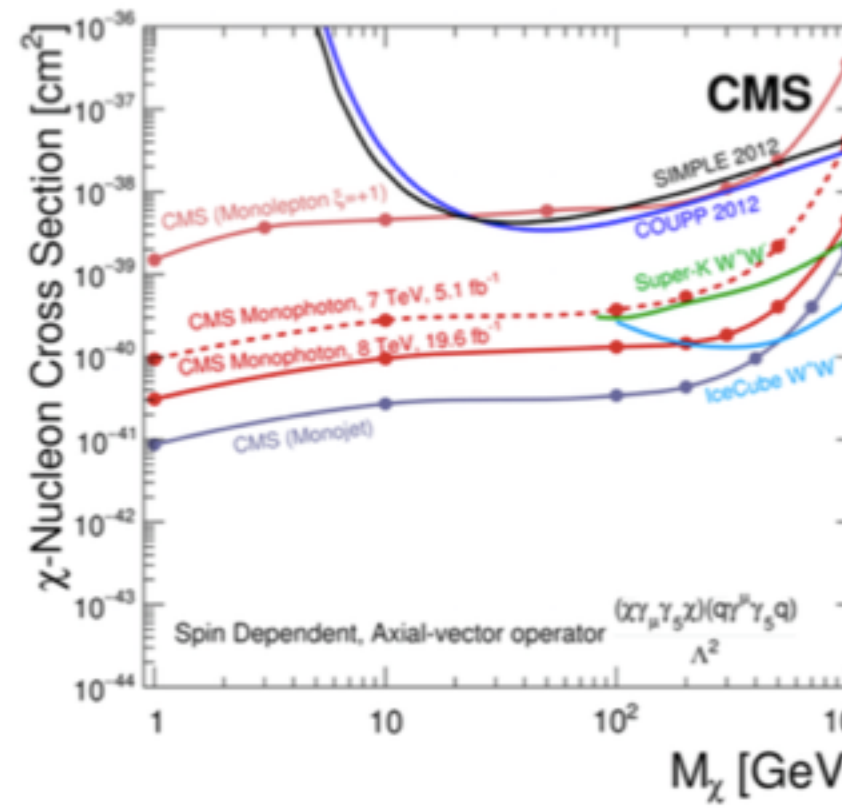
Initial or final radiation of high pT SM particle



Standard model backgrounds are non-negligible







Complementarity