Lecture 1 (Part II)

Dark matter as a particle: importance of non-gravitational interactions

Outline:

- Thermal production of DM: the WIMP miracle

- Strategies for non-gravitational detection of WIMPs

  i) Indirect detection

  ii) Direct detection

Literature: **(i)** The early Universe, Kolb and Turner, Westview Press, 1994
(ii) Particle Dark Matter: Evidence, Candidates and Constraints, Bertone, Hooper and Silk, 2004, hep-ph/0404175
(iii) Supersymmetry and cosmology, Feng, 2005, hep-ph/0405215,
(iv) Supersymmetric dark matter, Jungman, Kamionkowski and Griest, 1996, Physics Reports, 267, 195
(v) Galaxy formation and evolution, Mo, van den Bosch and White, Cambridge U. Press, 2010

Particle DM: WIMPs

• From the gravitational evidence of the existence of DM, we know that it has a global abundance of $\Omega \sim 0.23$, it doesn't produce electromagnetic radiation at a significant level and it should be compatible with a successful structure formation scenario.

• DM is mostly non-baryonic: CMB and abundance of light elements. The only possibility in the SM of Particle Physics is neutrinos, but given their low mass they would be incompatible with the hierarchical process of structure formation ("hot dark matter", more on this in Lect. 4).

• Particle candidates arise in well-motivated extensions to the SM; among the different possibilities, the so-called WIMPs (Weakly Interacting Massive Particles) are the most studied.

• Most well-known example: the lightest neutralino. Naturally predicted by SUSY: a new symmetry in nature, for each particle in nature there is a "superpartner" with a spin differing by 1/2; since no superpartner has been observed this symmetry is broken allowing the superpartners to be more massive (in minimal models ~1TeV); gives a solution to the hierarchy problem. The LHC has constrained SUSY models (particularly the minimal one).

• There are 4 neutralinos: mass eigenstates (combinations) of the superpartners of the neutral gauge bosons of the theory: neutral Higgs, Z^0 and photon.

• The lightest one is typically the lightest SUSY particle (LSP), neutral, stable, with a mass of ~100GeV and is a Majorana fermion (its own antiparticle: it self-annihilates)

Thermal production of DM: the WIMP miracle

Relic Abundance (freeze-out approximation)
BLACKBOARD!

Thermal production of DM: the WIMP miracle (Summary)

- DM number density evolution given by the Boltzmann equation:

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle\left(n_\chi^2 - \left(n_\chi^{EQ}\right)^2\right)$$

- At early times the solution follows closely the equilibrium solution.
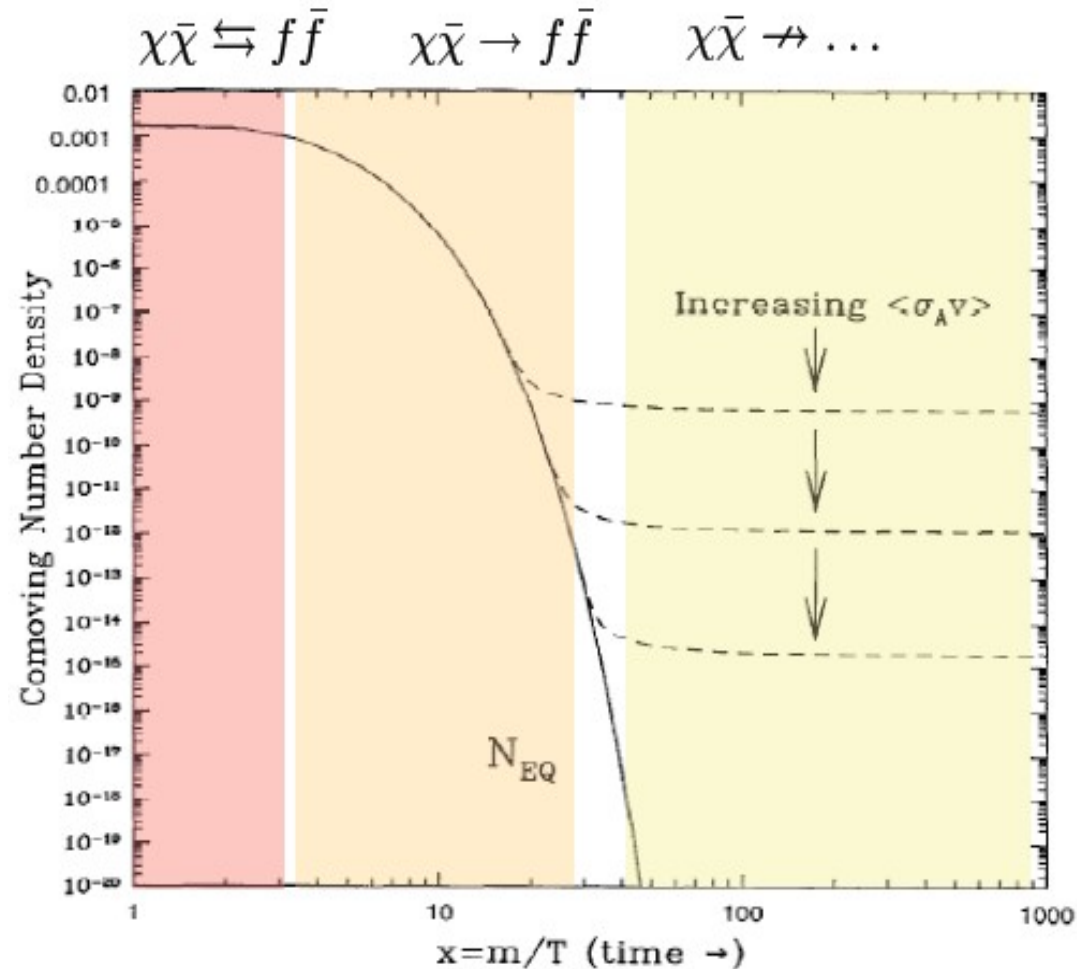
- At a characteristic time ($\Gamma/H=1$), the comoving number density "freezes-out".

$$\Omega_\chi = msY(x=\infty) \sim \frac{10^{-10}\ \mathrm{GeV}^{-2}}{\langle\sigma_A v\rangle}$$

- If mass and self-annihilation cross section are set by the weak scale then we get the correct relic density:

$$m^2 \sim \langle\sigma_A v\rangle^{-1} \sim M_{weak}^2$$

$$\boxed{\Omega_\chi \sim 0.1}$$

$$\chi\bar\chi \leftrightarrows f\bar f \qquad \chi\bar\chi \to f\bar f \qquad \chi\bar\chi \nrightarrow \ldots$$

Increasing $\langle\sigma_A v\rangle$

N_{EQ}

$x = m/T$ (time →)

Comoving Number Density

Thermal cross-section (weak interactions):

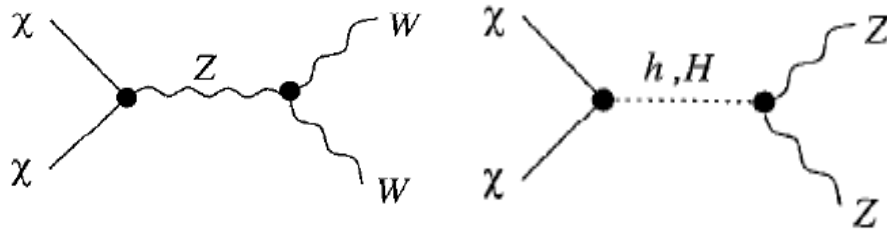$\langle\sigma v\rangle \sim 3\times10^{-26}\ \mathrm{cm}^3\mathrm{s}^{-1}$

A different perspective: observed abundance constrains the DM annihilation cross section

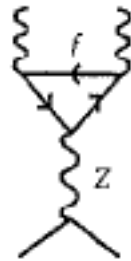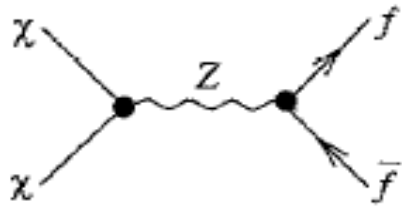# Strategies for non-gravitational detection of WIMPs

Indirect detection: annihilation channels

Examples of Feynman diagrams for neutralinos
  (Jungman, Kamionkowski and Griest, 1996)

For a generic theory that predicts
  WIMPS we have:

To W bosons:

To fermions and photons

In general the number of Feynman diagrams for each final state is large, there are public numerical codes that perform these calculations (together with a precise computation of the relic density):

DarkSUSY (http://www.physto.se/~edsjo/darksusy/)
MicrOMEGAs (http://lapth.in2p3.fr/micromegas/)
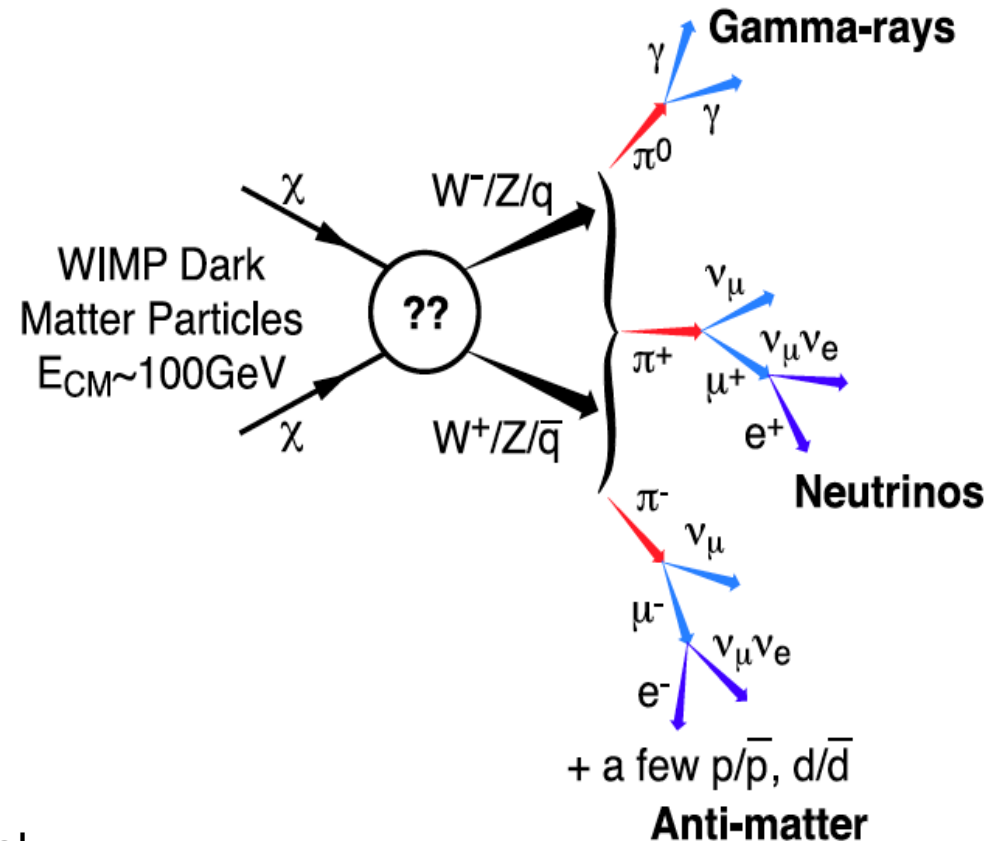

Fig. from Baltz et al. 2003

Indirect detection: annihilation rate

- The volume emissivity of a given annihilation by-product (energy of by-product produced per unit volume, time and energy range):

$$\mathcal{E} = f_{\mathrm{WIMP}}\rho_\chi^2 \qquad f_{\mathrm{WIMP}} = E\left(\frac{dN}{dE}\right)_{\mathrm{SM}}\left(\frac{\langle \sigma v\rangle}{2m_\chi^2}\right)$$

- The density squared dependence is connected to the gravitational interactions of dark matter ("astrophysical factor"). The most natural places to to look for annihilation are the regions with the highest DM densities: GC, nearby galaxies,...

- The properties of DM as a particle are in f_{WIMP}, the by-product spectrum is particularly relevant (e.g. photons).

Secondary Photons (tree level)
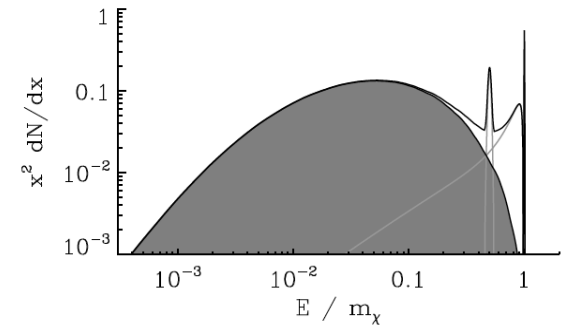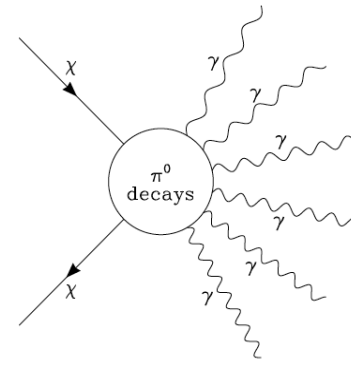
Internal Bremsstrahlung $\mathcal{O}(\alpha)$
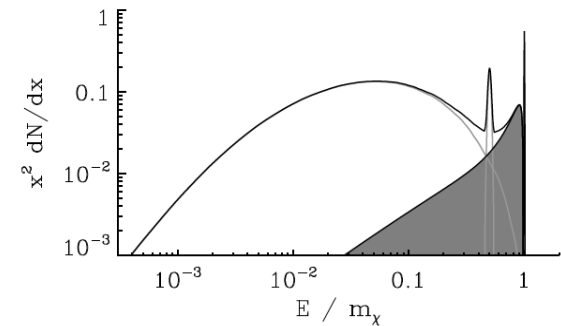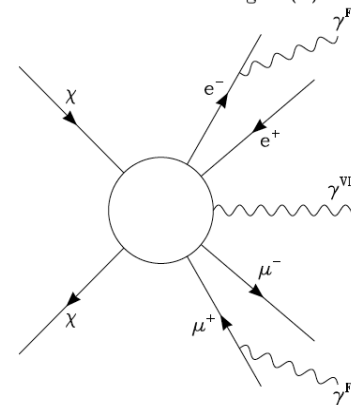
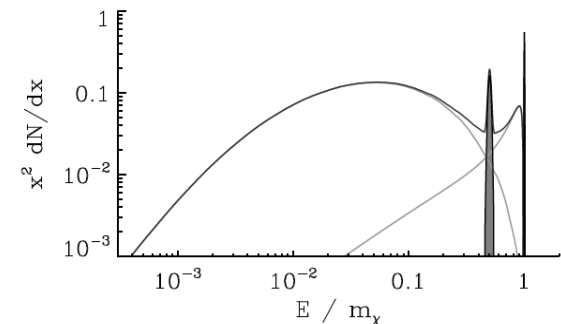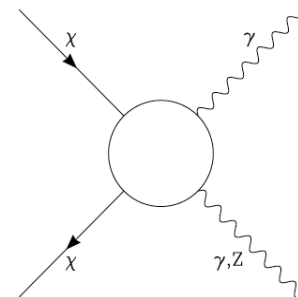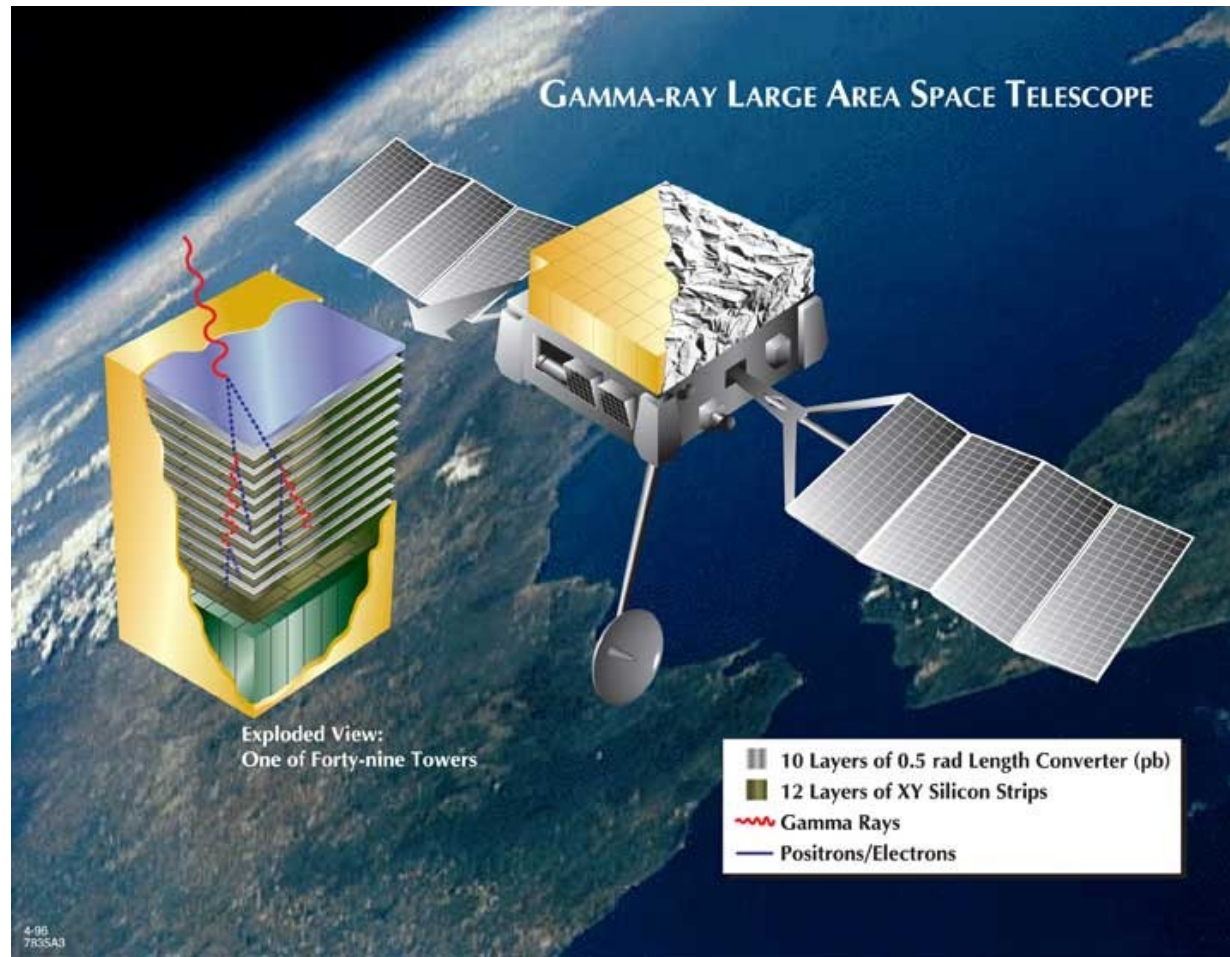Line Signal (loop level $\mathcal{O}(\alpha^2)$)

Fig. from Kuhlen 2010

Indirect detection strategies: gamma-rays

The Fermi satellite was launched in 2008 and has expanded our knowledge in gamma-ray astronomy (20MeV < E < 500 GeV; angular resolution ~0.1deg above 10GeV)
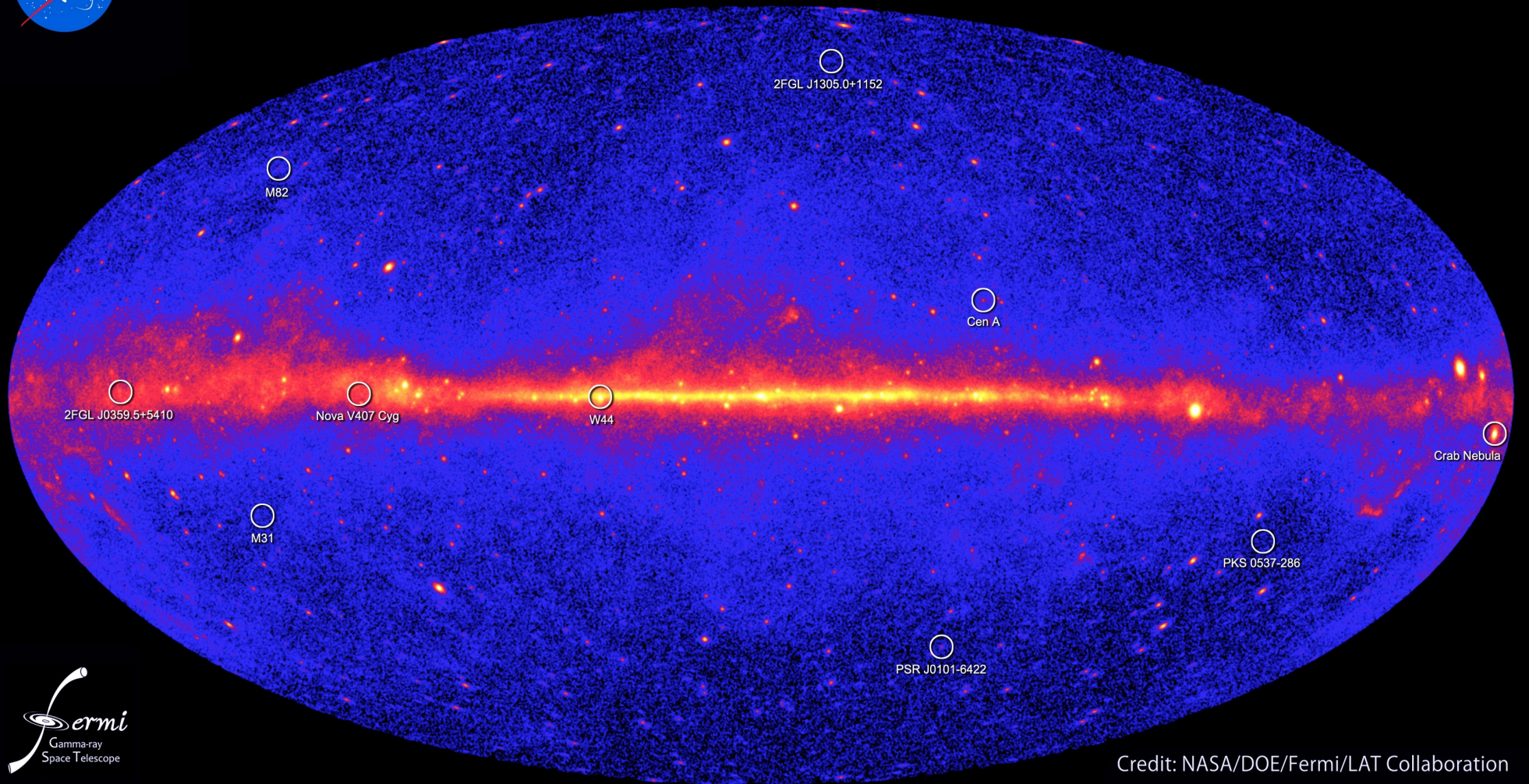
Image credit: NASA

Recall that WIMPs have masses of ~100GeV, so they are expected to produce photons in the gamma-ray energy range

# Indirect detection strategies: the richness of the gamma-ray sky

Fermi two-year all-sky map

Credit: NASA/DOE/Fermi/LAT Collaboration

Indirect detection strategies: the richness of the gamma-ray sky

Ordinary astrophysical sources: Galactic diffuse emission (cosmic rays interacting with the interstellar medium and the interstellar radiation field)
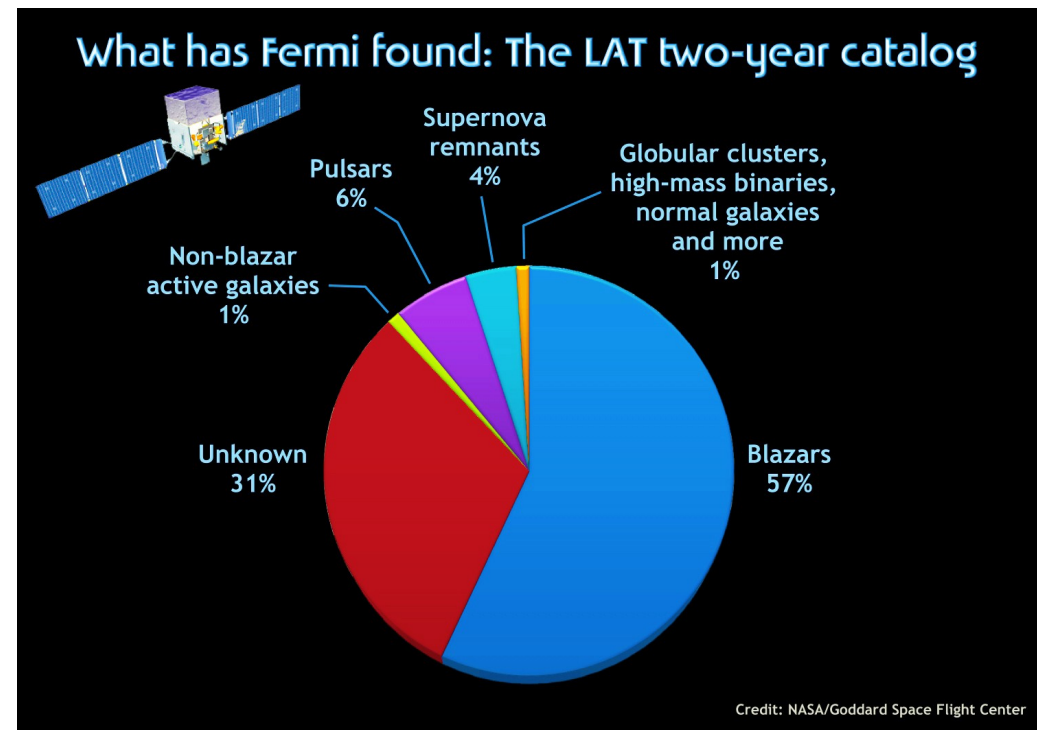
Inverse Compton up-scattering

Bremsstrahlung radiation

proton-proton collisions
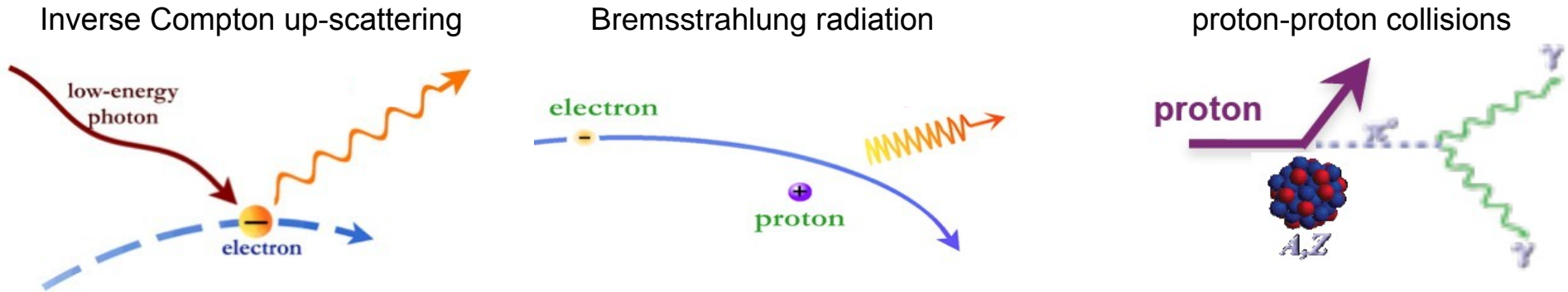
"Point" sources of gamma-rays:

Blazars: AGN with one of its jets pointing towards us (IC with background photons)

Pulsars: highly magnetized rotating neutron star (e.g. γ's from synchrotron radiation of accelerated charged particles)

Supernova remnants: electrons and protons accelerated to >TeV energies in the shock

Our limited knowledge of the different sources creates an uncertainty in DM searches!

What has Fermi found: The LAT two-year catalog

Supernova remnants 4%

Pulsars 6%

Non-blazar active galaxies 1%

Globular clusters, high-mass binaries, normal galaxies and more 1%

Unknown 31%

Blazars 57%

Credit: NASA/Goddard Space Flight Center

DM annihilation constraints from gamma-ray observations

Fermi-LAT collaboration (arXiv:1108.3546)
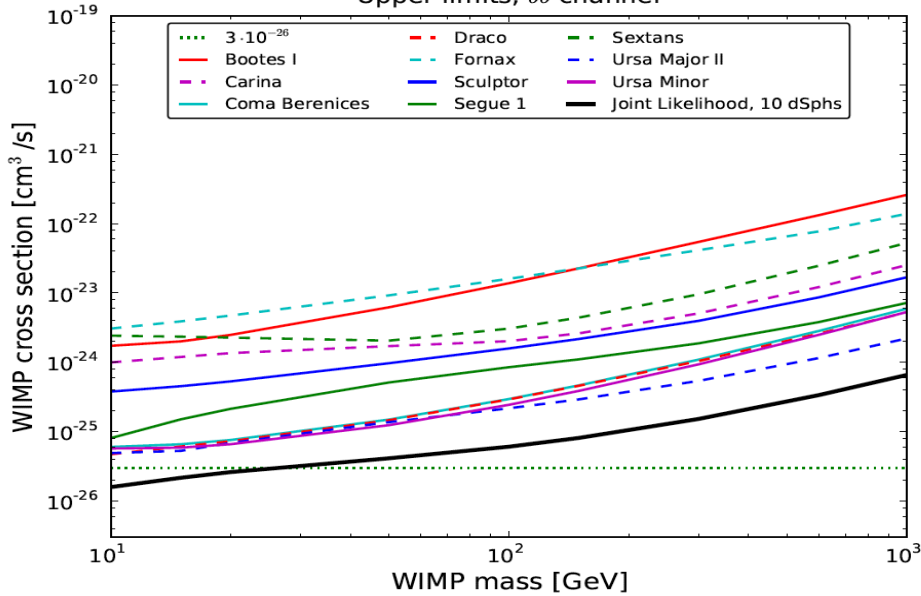
Zavala et al. 2010 (arXiv:arXiv:0908.2428)

MW satellites

Good targets: low astrophysical background (DM-dominated systems M/L>100; low gas and stellar contents)

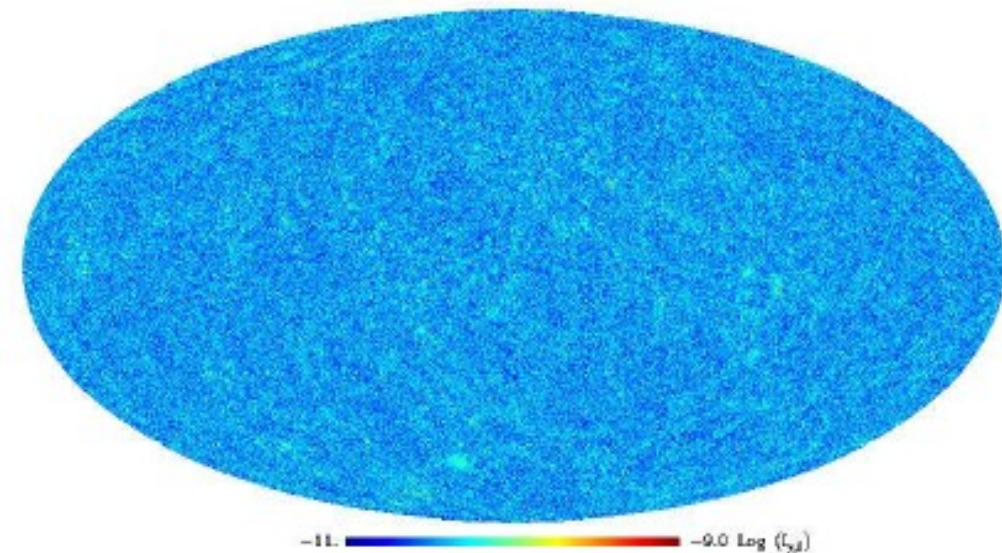Uncertain DM distribution (incomplete phase-space information; see Lect. 3)

Extragalactic gamma-ray background

Integrated gamma-rays coming from DM structures along the line of sight (up to z~2)
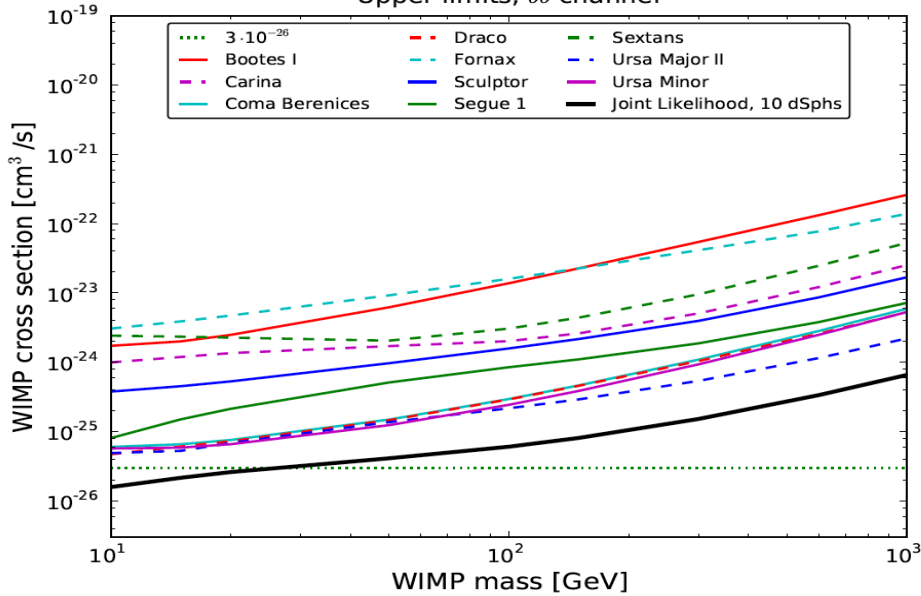
Signal dominated by low-mass structures (devoid of stars/gas). Promising features in statistical properties of anisotropies

Uncertain abundance of low-mass structures (see Lect. 3)

DM annihilation constraints from gamma-ray observations
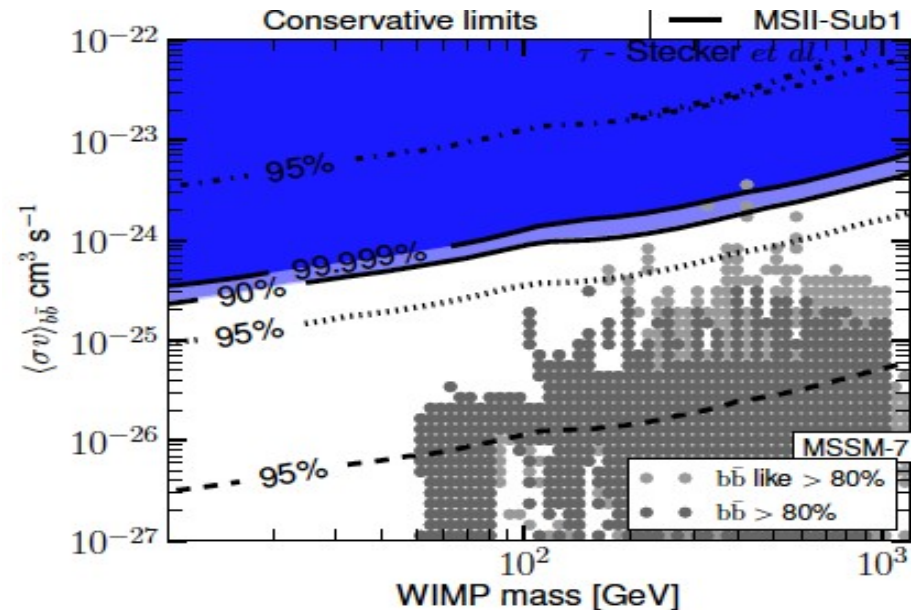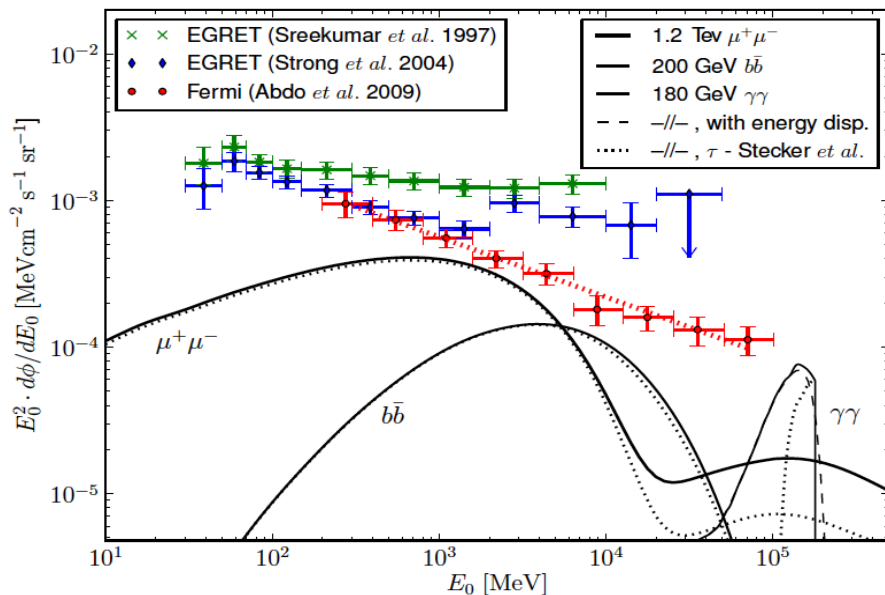
Fermi-LAT collaboration (arXiv:1108.3546)

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Good targets: low astrophysical background (DM-dominated systems M/L>100; low gas and stellar contents)

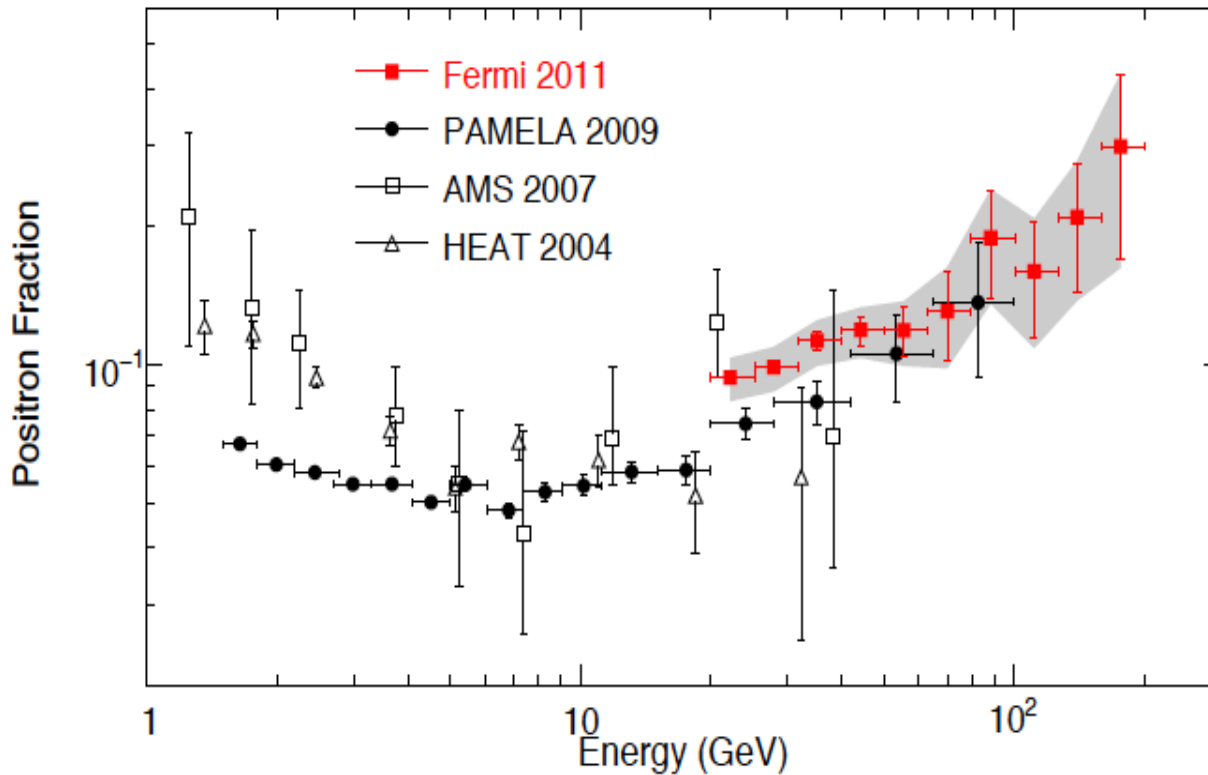Uncertain DM distribution (incomplete phase-space information, see Lect. 4)

Fermi-LAT collaboration (arXiv:1002.4415)

Extragalactic gamma-ray background

DM annihilation signals? Cosmic Ray anomalies

Other CR "anomalies":
- INTEGRAL/SPI 511 keV line (Weidenspointner et al. 2006)
- "WMAP Haze" (Dobler and Finkbeiner 2008)
- "Fermi Haze" (Dobler et al. 2010)

DM annihilation signals? Cosmic Ray anomalies
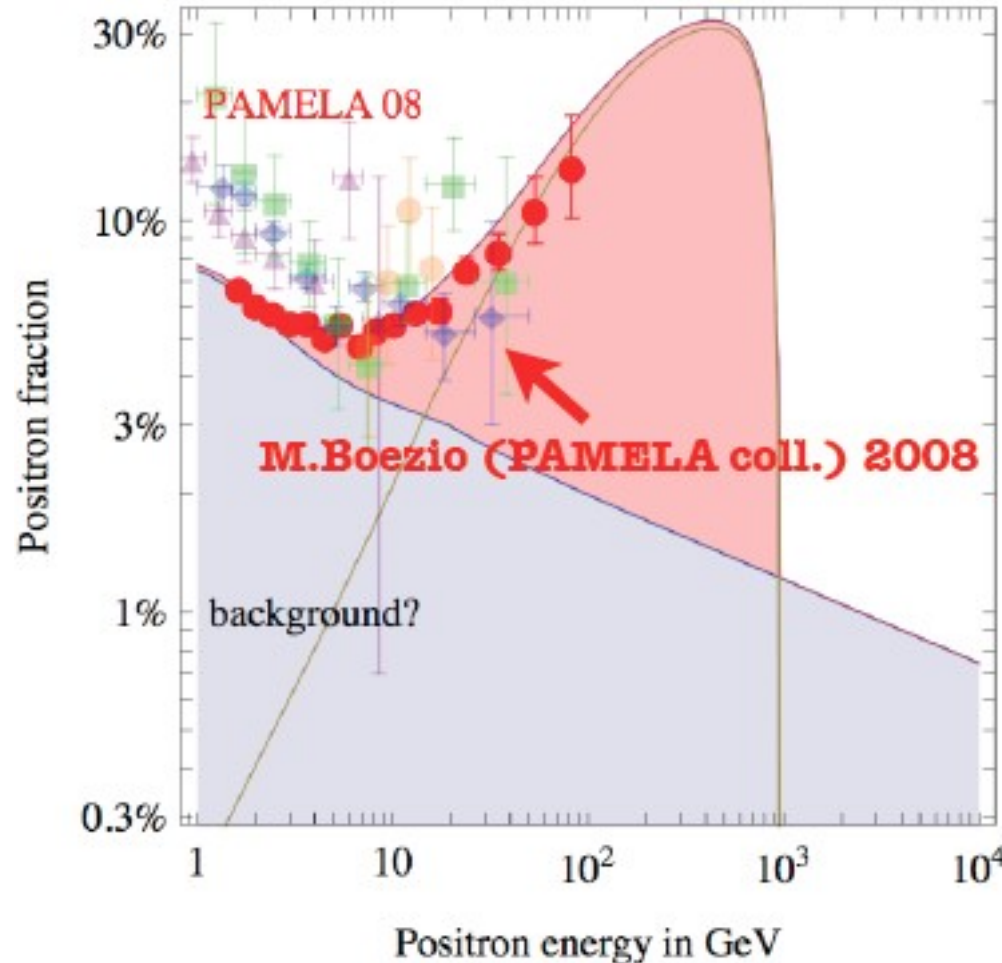
The case for DM annihilation

- WIMP annihilation can explain cosmic ray anomalies but: large cross section, ~100 times larger than the thermal relic value: $3\times10^{-26}cm^3s^{-1}$ (e.g. Bergström et al. 2009), possible in certain DM models that introduce a new force in the DM sector (see Lect. 4)

DM annihilation signals? Gamma-ray lines

~130 GeV gamma-ray line in the direction of the GC: Bringmann et al. 2012, Weniger 2012, Su and Finkbeiner 2012

Analysis of Fermi data (~4yrs), low photon statistics, residual = Map(120-140) – average Map(80-180)

Compatible with a ~130 WIMP annihilating into $\gamma\gamma$ and γZ
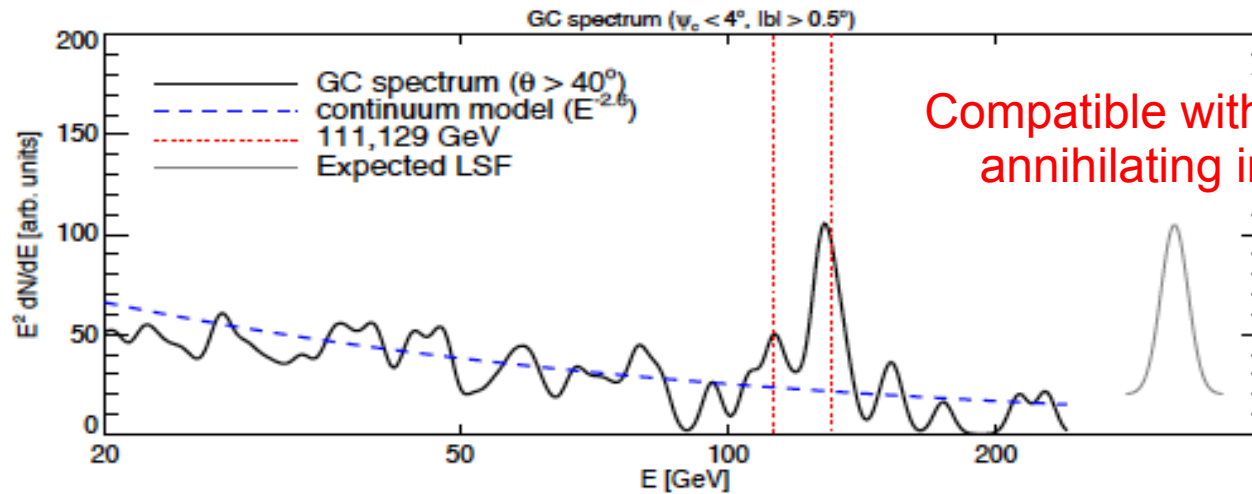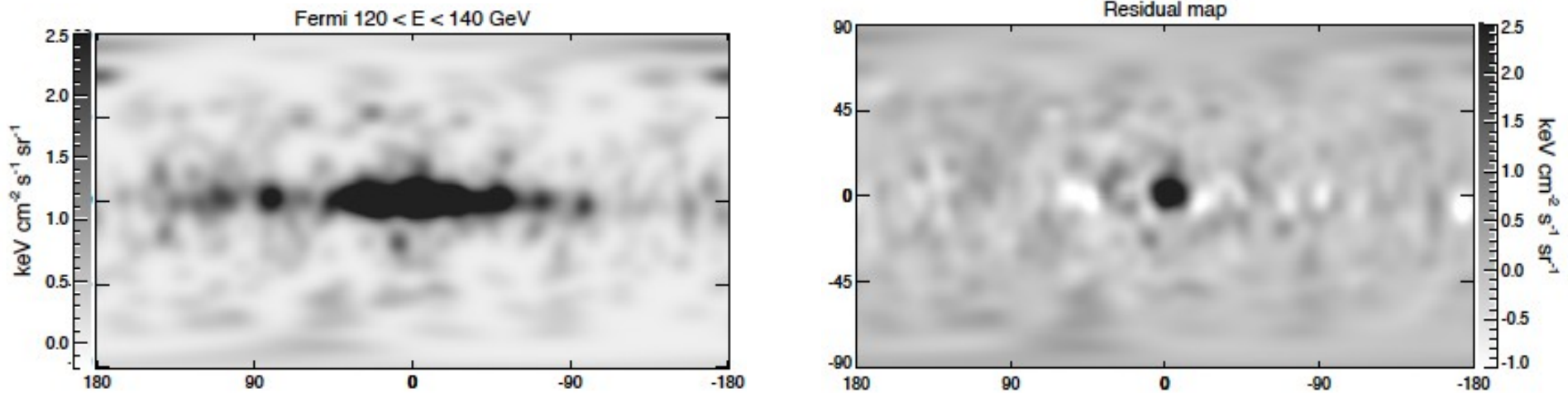
Main issue with DM annihilation interpretation: region of emission is off-center (~200 pc); it might be possible through resonant interactions (gravitational) between DM particles and the Galactic bar (Kuhlen et. al 2012)

Direct detection

From Jungman, Kamionkowski and Griest 1996:

> By crossing symmetry, the amplitude for WIMP annihilation to quarks is related to the amplitude for elastic scattering of WIMPs from quarks. Therefore, a WIMP that solves the dark-matter problem is generically expected to have some small, but non zero, coupling to nuclei (through the coupling to quarks). As a result, we expect there to be finite (although small) detection rates in generic models.

Crossing symmetry (typical example): Compton scattering and e+e- annihilation

"Local" WIMPs are expected to elastically scatter (momentum and kinetic energy are conserved) off nuclei in targets, producing nuclear recoil

$$E_{recoil}^{max} = \frac{2m_\chi^2 m_N}{(m_\chi + m_N)^2} v^2$$

~ 10 keV for Xenon (A=54); m_X~100GeV; v~5x10^{-4}c (150km/s)

Scattering rate(number of scattering events per unit time per unit mass of detector):
dN = dn$_X$(σ_{scat}<v>)/m$_N$; WIMPs have a certain speed velocity distribution

$$\frac{dN}{dE_r} = \frac{\sigma_0 \rho_\chi}{2\mu^2 m_\chi} F^2(q) \int_{v_{min}}^{v_{esc}} \frac{f(v)}{v} dv$$

μ is the reduced mass

Threshold energy of the detector

uncertain local velocity distribution!

Direct detection: possible signals?

If the detector is at rest with respect to the galactic DM halo, and the WIMP speed distribution is Maxwellian with velocity dispersion v_0 ($R=N, m_r=\mu$):

$$\frac{dR}{dE_r} \propto \exp\left(-\frac{m_N E_r}{2 m_r^2 v_0^2}\right)$$

No striking feature, exponential spectrum could be produced by different backgrounds

CoGeNT: "irreducible" background with exponential-like energy spectrum

keVee (keV electron equivalent) is used to quantify a measured signal from the detector in terms of the energy of an electron recoil that would be required to generate it

CoGeNT collaboration, 2011

1 barn=10^{-24} cm^2
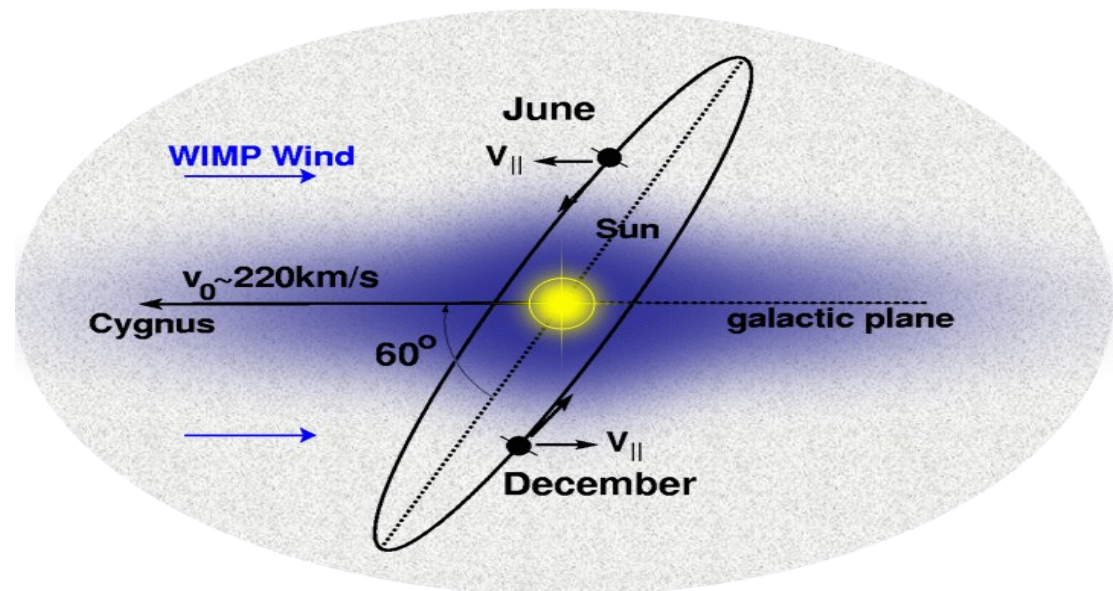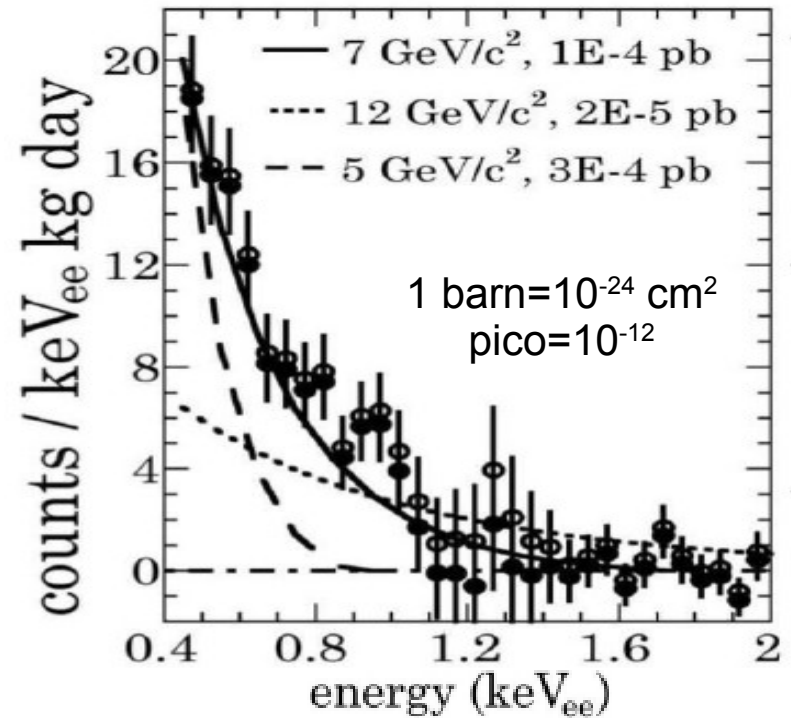pico=10^{-12}

Annual modulation

Correct velocity distribution due to the relative motion of the Earth and the WIMPs wind

$$v_e = v_0 (1.05 + 0.07 \cos \omega t)$$

$$\omega = 2\pi/1 \text{ year}$$

Direct detection: possible signals?

If the detector is at rest with respect to the galactic DM halo, and the WIMP speed distribution is Maxwellian with velocity dispersion v_0 (R=N, m_r=μ):

$$\frac{dR}{dE_r} \propto \exp\left(-\frac{m_N E_r}{2 m_r^2 v_0^2}\right)$$

No striking feature, exponential spectrum could be produced by different backgrounds

CoGeNT: "irreducible" background with exponential-like energy spectrum

keVee (keV electron equivalent) is used to quantify a measured signal from the detector in terms of the energy of an electron recoil that would be required to generate it

CoGeNT collaboration, 2011

- 7 GeV/c², 1E-4 pb
- 12 GeV/c², 2E-5 pb
- 5 GeV/c², 3E-4 pb

1 barn=10^{-24} cm²
pico=10^{-12}

Annual modulation

DAMA experiment reports an annual modulation signal at high significance
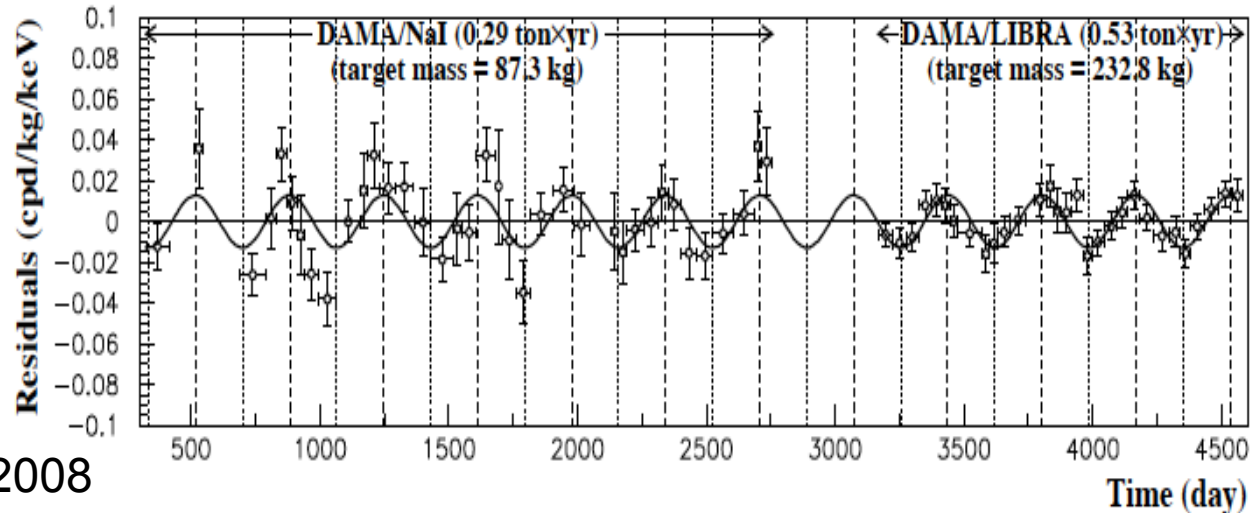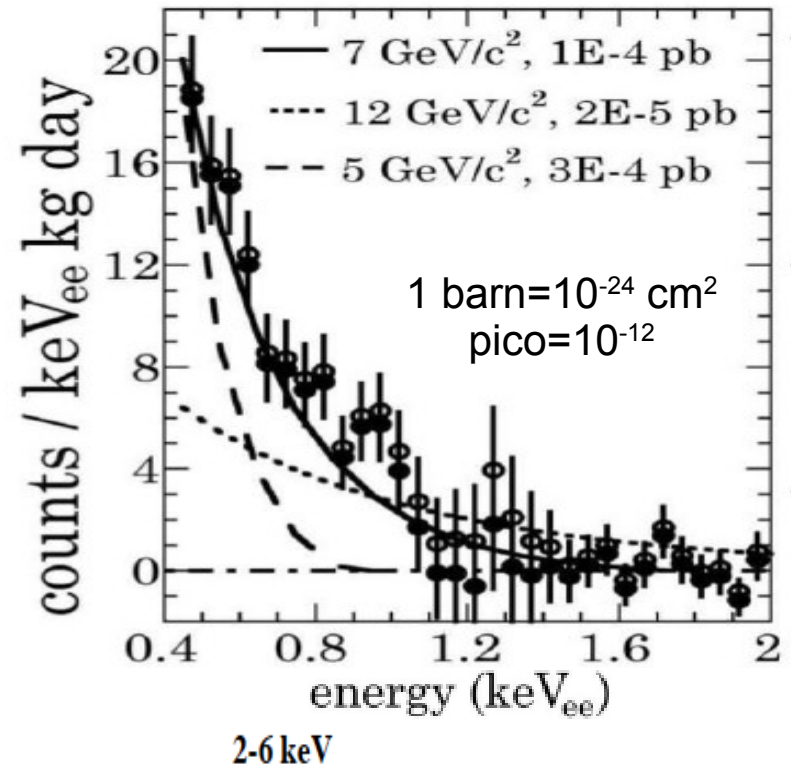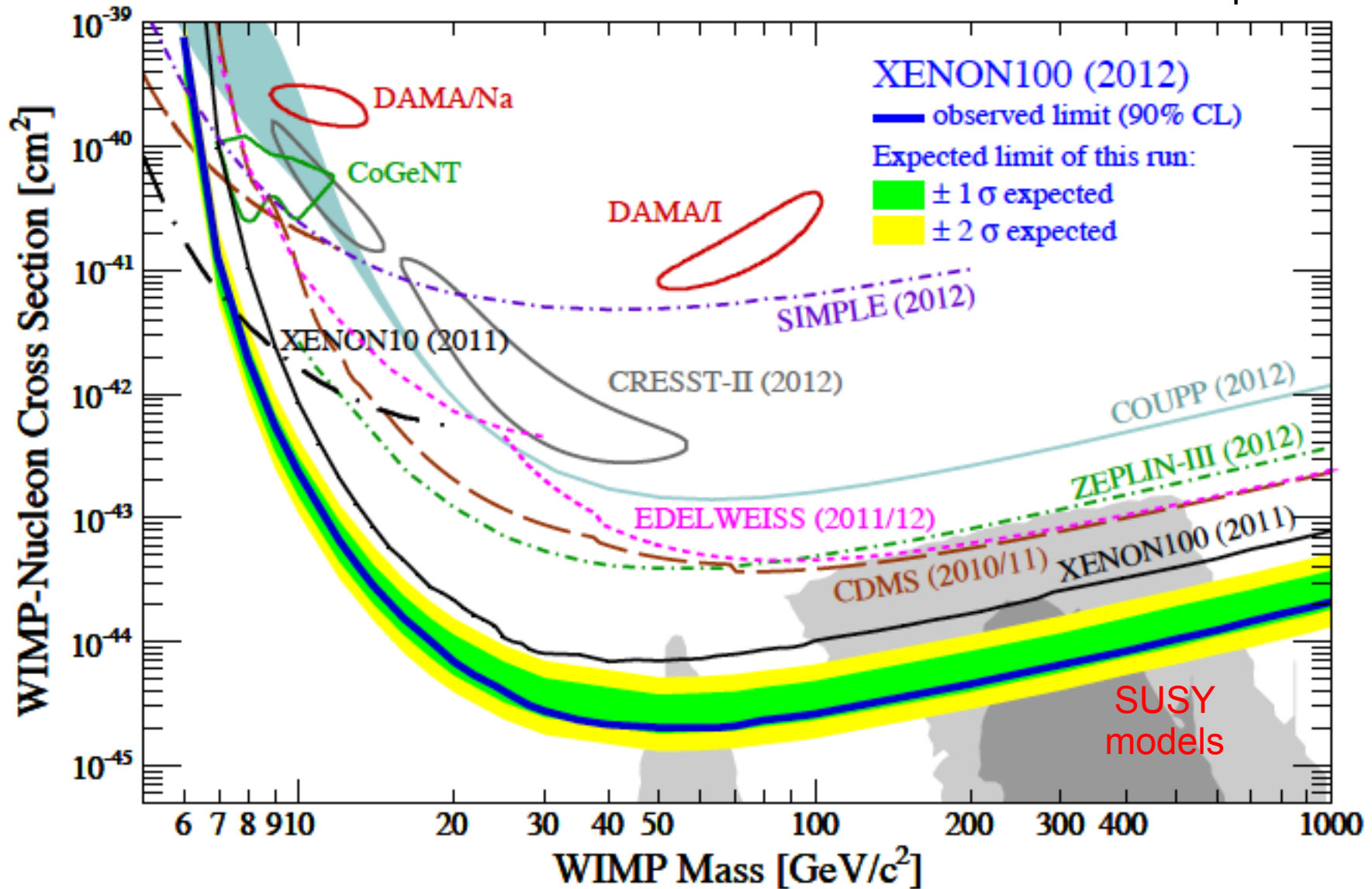

DAMA collaboration, Bernabei et al. 2008

Direct detection: current constraints the "zeptobarn" scale

zepto=10^{-21}

The Xenon100 collaboration, 2012, arXiv:1207.5988