Dark Matter and the signatures (II)

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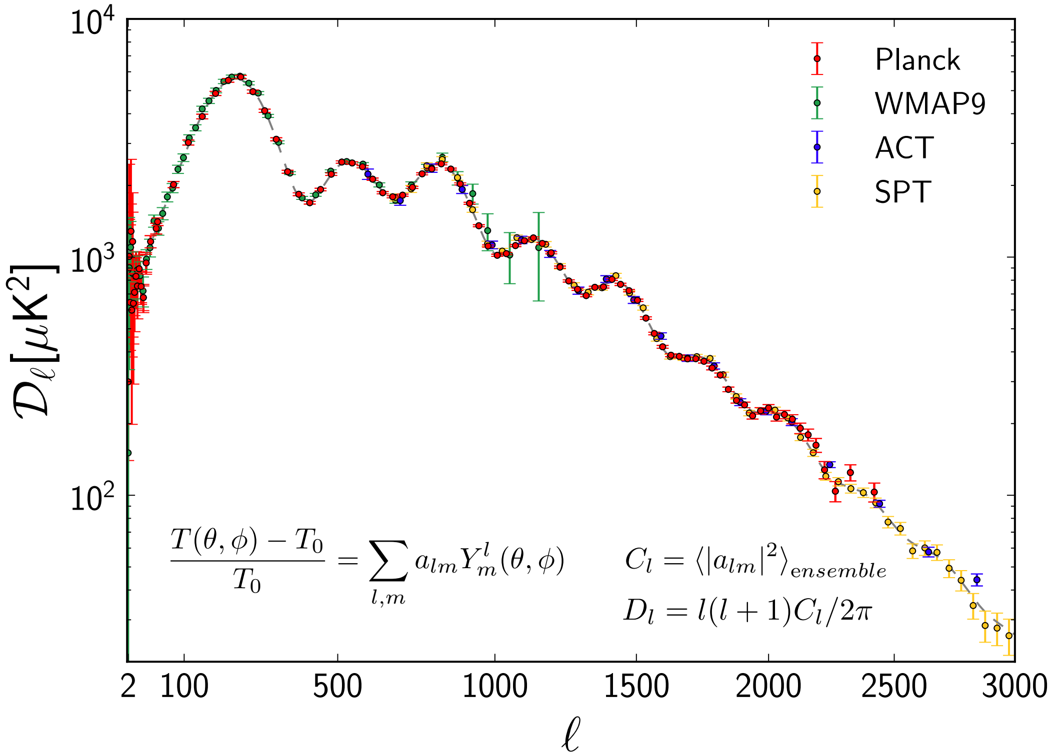
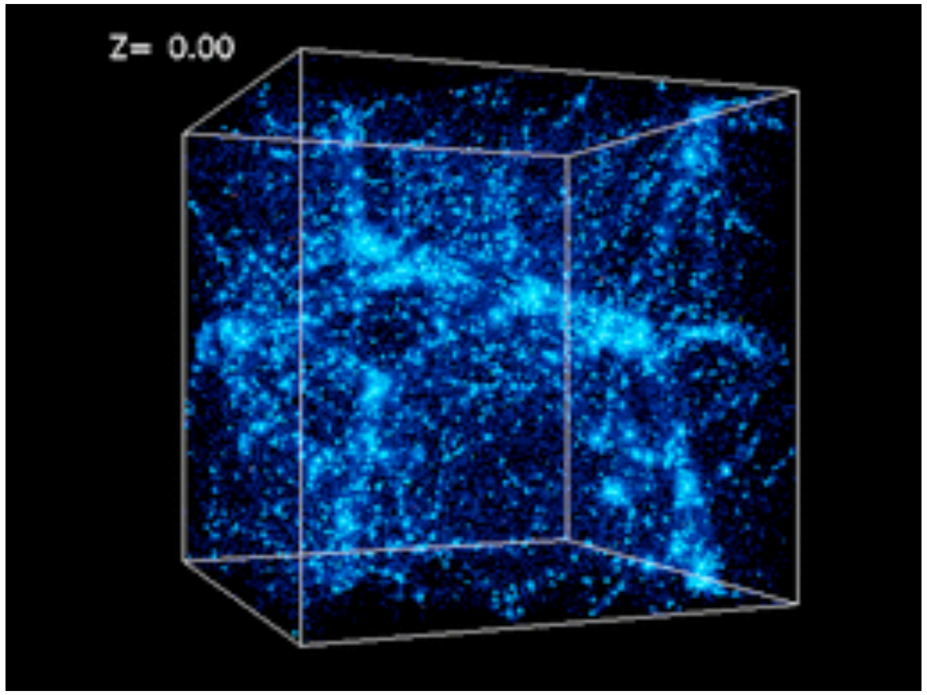
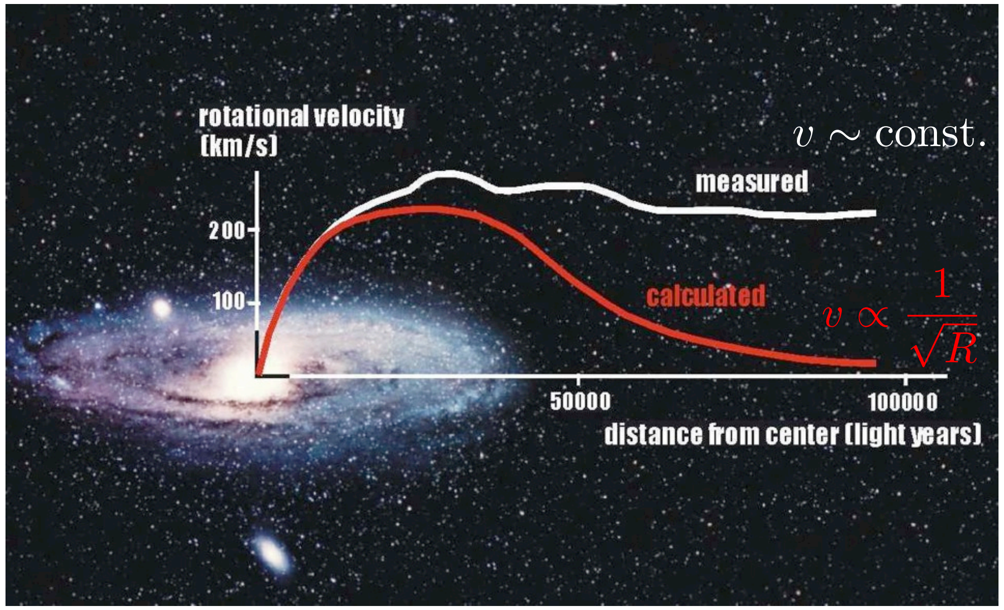
Summer Institute 2013, Jirisan, Korea

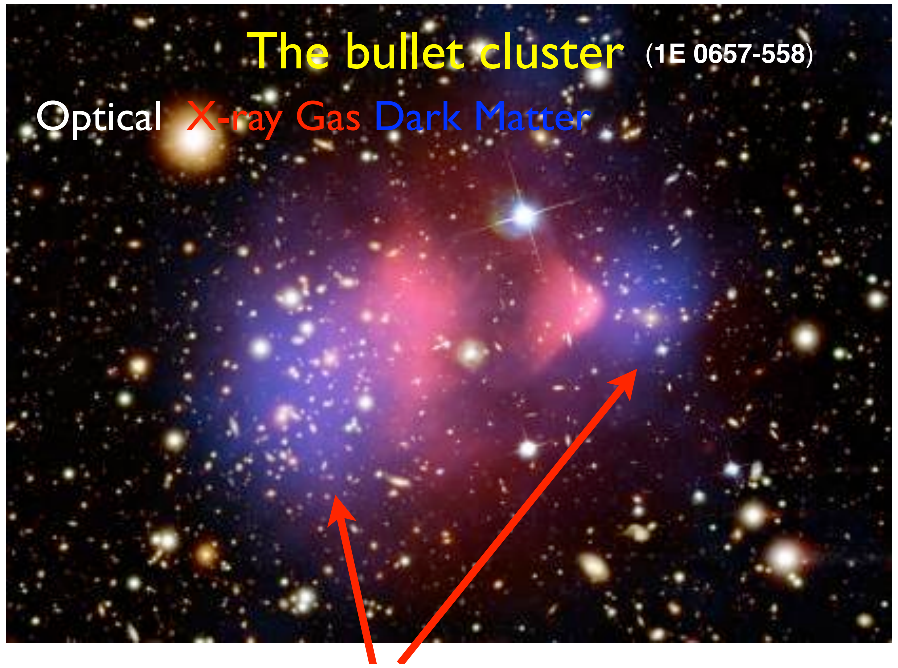
Why do we need dark matter?

- Dark Matter in the CMB temperature perturbation





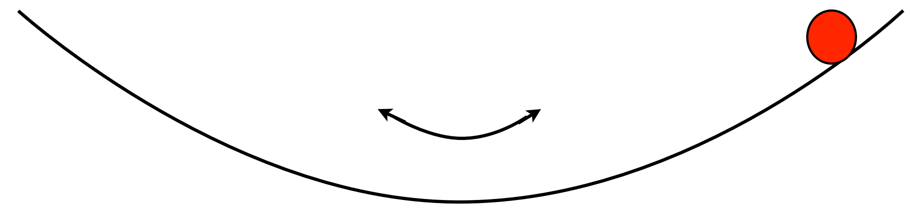


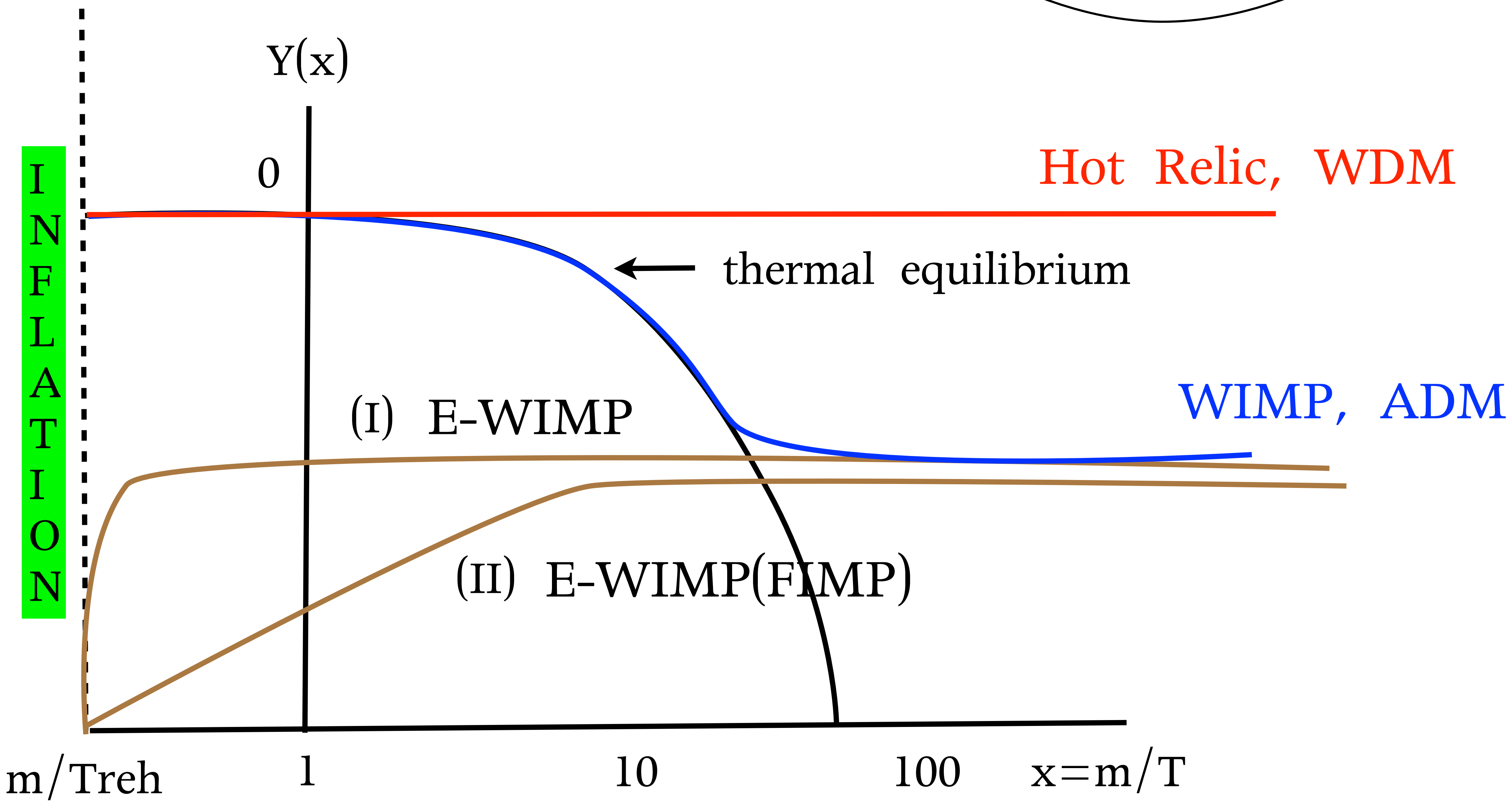


Wednesday, August 21, 13

Production of dark matter

Non-thermal production: Misalignment mechanism





The necessities of Dark Matter all come from the gravitational observation.

Why there is no other signatures of dark matter in the non-gravitational one?

We have many models where DM has weak interactions.
They may show up in the non-gravitational phenomena.
We want to see these signatures if any.

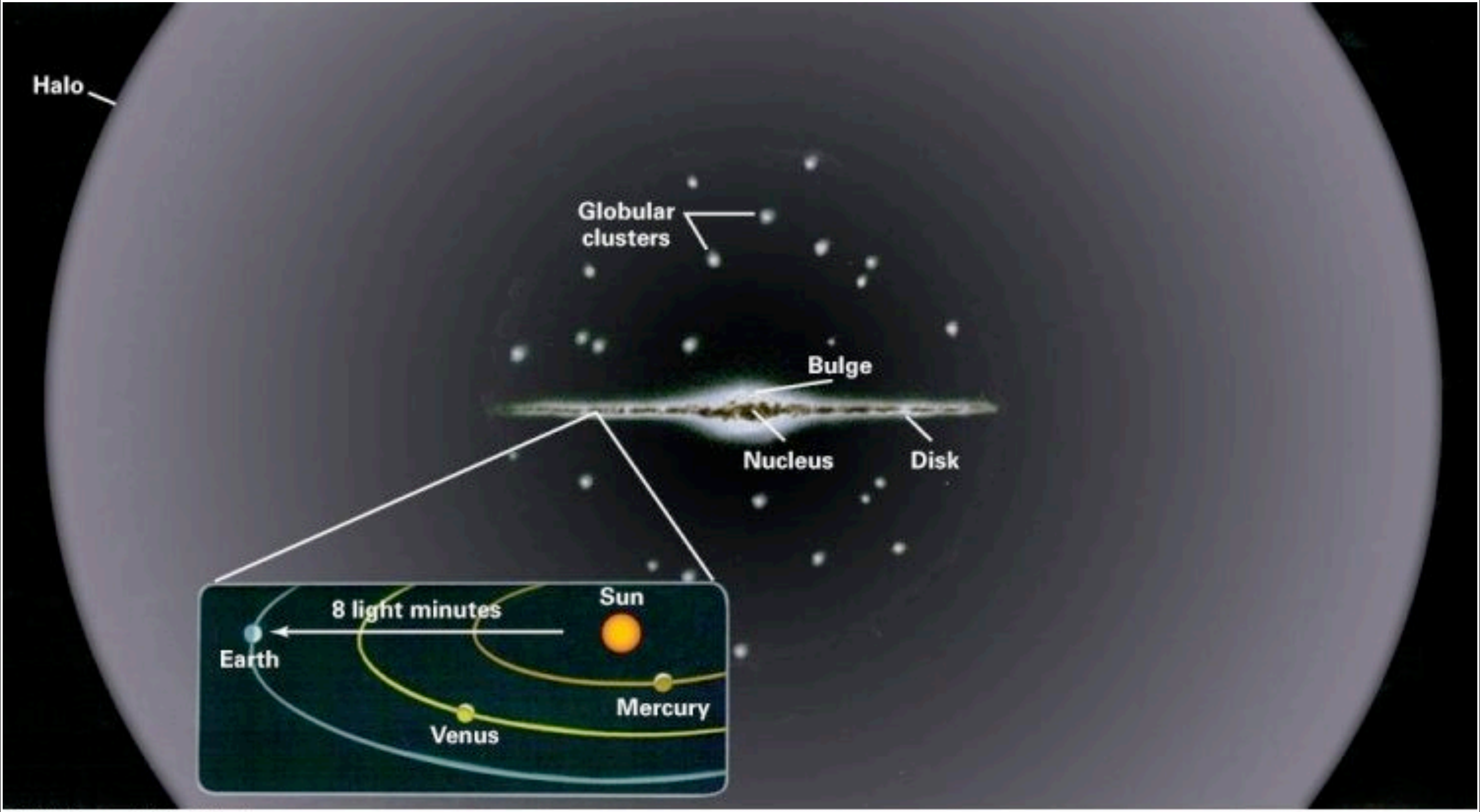
Signatures of Dark Matter

- Direct Detection
- Indirect Detection

Already observed Dark Matter?

- Signals in the direct detection?
- Signals in the gamma ray?
- Signals in the cosmic ray?

• Dark Matters are around us



DM density around Sun

$$\rho_{\rm DM}({\rm Sun}) \sim 0.3 \pm 0.2\,{\rm GeV/\,cm^3}$$
$$\sim 5 \times 10^{-25}\,{\rm gram/\,cm^3}$$

Air density at sea level

$$\rho_{\rm air} \sim 10^{-3}\,{\rm gram/\,cm^3}$$

- Dark Matters are moving around

The velocity distribution of DM is assumed to be Maxwell-Boltzmann corresponding to spherical and isotropic density distribution of $\rho(r) \propto \frac{1}{r^2}$, with velocity dispersion 270 km/sec and truncated to the value for the escape velocity.

$$f(\mathbf{v}) = \frac{1}{\sqrt{2\pi}\sigma_v} \exp\left(-\frac{\mathbf{v}^2}{2\sigma_v^2}\right),$$

with $\sigma_v = \sqrt{3/2}v_c$ $\quad v_c \equiv v(r = R_0) = 220\,\mathrm{km\,s^{-1}}$

Escape velocity $\quad f(\mathbf{v}) = 0$ for $v \geq v_{esc} = 544\,\mathrm{km\,s^{-1}}$

"The local dark matter phase-space density and impact on WIMP direct detection"

[Catena, Ullio, 2010, 2012]

• Earth and Sun are moving around Galaxy

Earth goes around Sun, Sun goes around Galaxy.

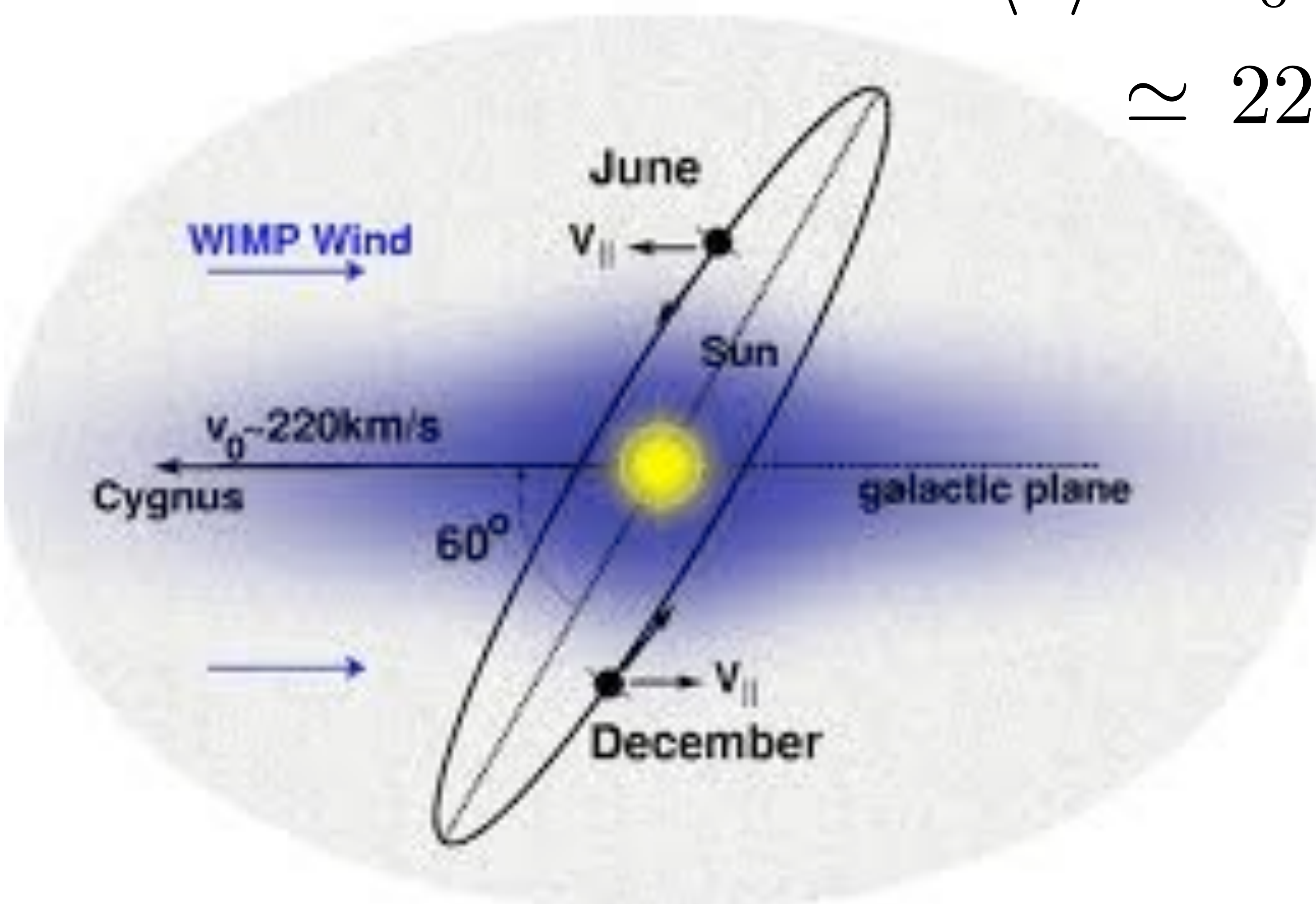
$$f_\oplus(\vec{v}) = f_{\rm gal}(\vec{v} + \vec{v}_\odot + \vec{v}_\oplus)$$

$$v_\odot \sim 220\,{\rm km/\,sec}$$

$$v_\oplus \sim 30\,{\rm km/\,sec}$$

The velocity has annual and diurnal modulation.

$$\langle v \rangle = v_0 \pm v_\oplus$$
$$\simeq\ 220\,{\rm km/\,sec}\ \pm 30\,{\rm km/\,sec}$$



$$E_{\rm kin} \simeq (1 - 10)\,{\rm keV}$$

for (10-100) GeV DM.

Direct Detection

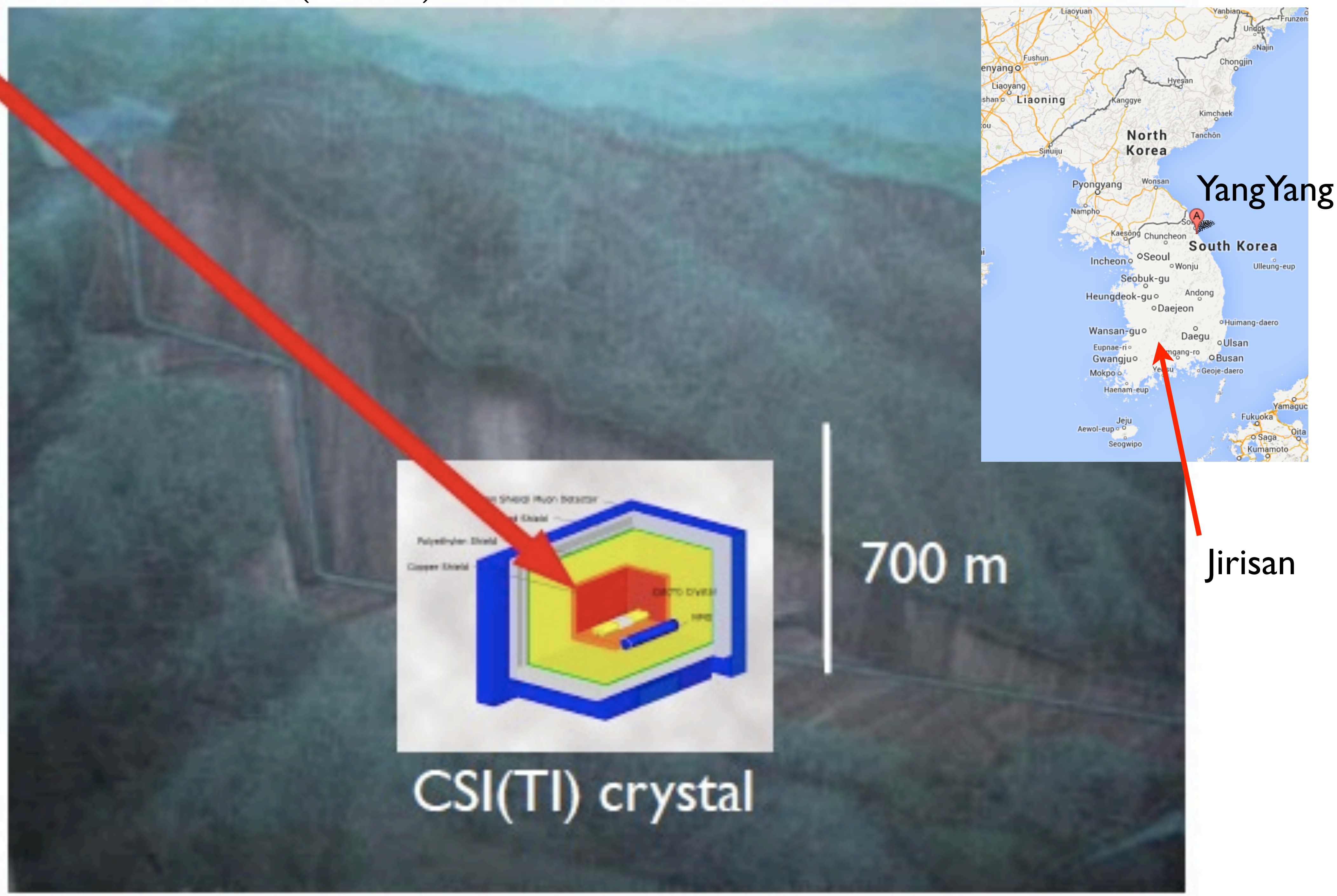
• Direct Detection

WIMP

$$n = \frac{\rho}{m} \sim 0.3\,\mathrm{cm}^{-3}\left(\frac{1\,\mathrm{GeV}}{m}\right)$$

Mt. JeomBong

$E_{\mathrm{kin}} \simeq (1-10)\,\mathrm{keV}$



KIMS (Korea Invisible Mass Search) : Yang Yang Lab.

Roughly the DM flux is for $m_W = 100\,\mathrm{GeV}$

$$\phi_0 = n_0 \times \langle v \rangle = \frac{\rho_0}{m_W} \times \langle v \rangle = 6.6 \times 10^4 \ \mathrm{cm}^{-2}\mathrm{s}^{-1}.$$

Those give the rate per kg per year, for $\sigma_{WN} \sim 10^{-38}\mathrm{cm}^2$,

$$R \sim N_N \times \phi_0 \times \sigma_{WN} = \frac{N_A}{A} \times \frac{\rho_0}{m_W} \times \langle v \rangle \times \sigma_{WN} \sim 0.13\,\mathrm{events\ kg}^{-1}\mathrm{year}^{-1},$$

N_A is the Avogadro number

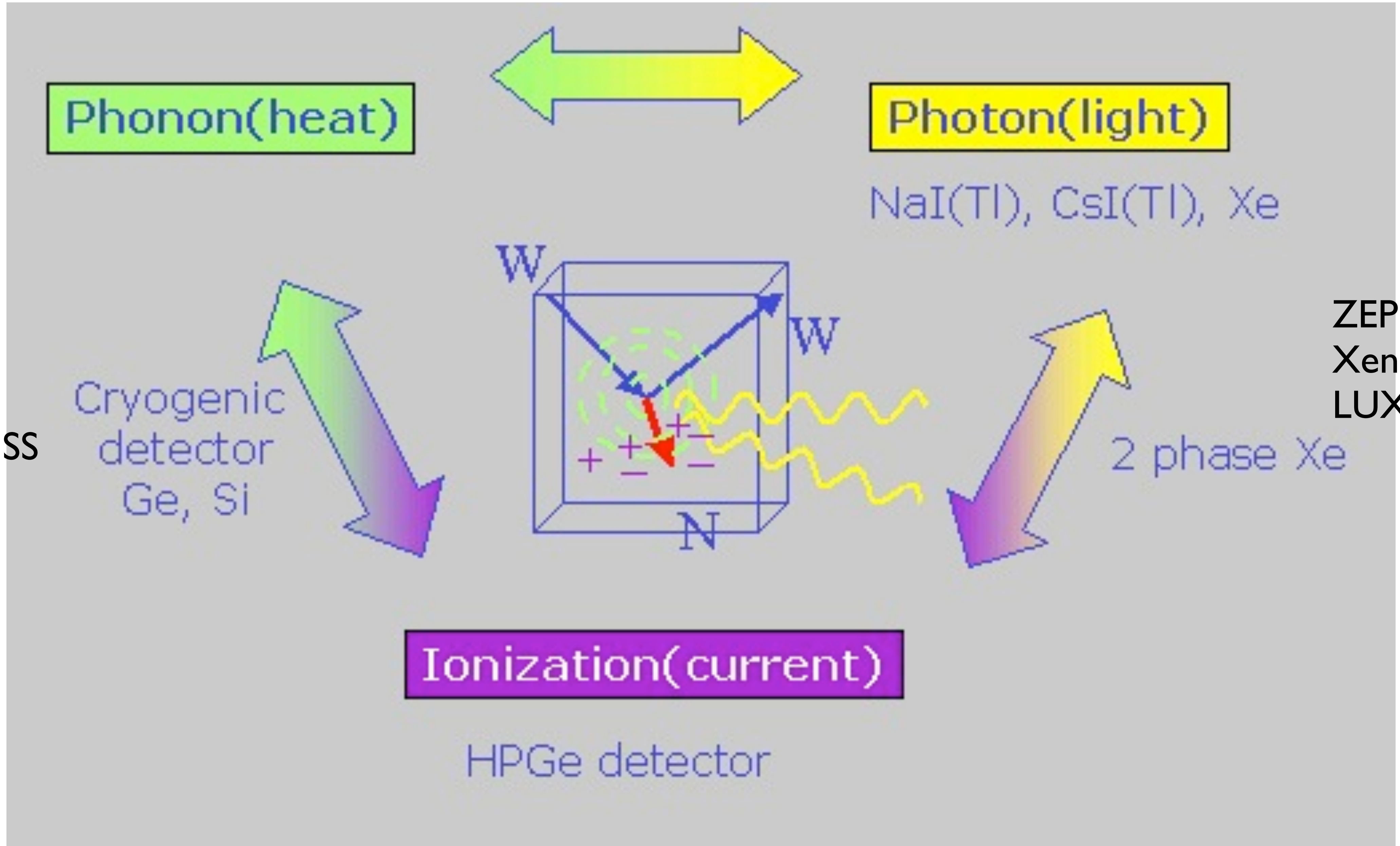
A is the atomic mass of the target nucleus.

- WIMP direct detection techniques (Typical recoil energy is keV)

CRESST
ROSEBUD

CDMS
EDELWEISS

ZEPLIN II, III
Xenon
LUX



Signal from DM scattering ~ one event/year/ton for $\sigma \sim 10^{-45}\,\mathrm{cm}^{-2}$

Background ~ one per day

(alpha particle, electron, photon : electron recoil neutron : nuclear recoil)

The differential rate for WIMP elastic scattering off nuclei

$$\frac{dR}{dE_R} = N_N \frac{\rho_0}{m_W} \int_{v_{\rm min}}^{v_{\rm max}} d\mathbf{v}\, f(\mathbf{v})\, v\, \frac{d\sigma}{dE_R}\,,$$

where N_N is the number of the target nuclei,

E_R is the energy transferred to the recoiling nucleus

$$E_R = \frac{p^2}{2m_N} = \frac{m_{\rm r}^2 v^2}{m_N}(1-\cos\theta),$$

p : momentum transfer

θ : scattering angle in the CM frame

$$\rightarrow \quad v_{\rm min} = \sqrt{\frac{m_N E_R}{2m_r^2}}$$

$$m_r = \frac{m_N \cdot m_W}{m_N + m_W}$$

: WIMP-Nucleus reduced mass

For small DM mass, $m_W \lesssim m_N$

$$v_{\rm min} \simeq \frac{m_N}{m_W}\sqrt{\frac{E_R}{2m_N}}$$

For large DM mass, $m_W \gtrsim m_N$

$$v_{\rm min} \simeq \sqrt{\frac{E_R}{2m_N}}$$

The differential rate for WIMP elastic scattering off nuclei

$$\frac{dR}{dE_R} = N_N \frac{\rho_0}{m_W} \int_{v_{\rm min}}^{v_{\rm max}} d\mathbf{v}\, f(\mathbf{v})\, v\, \frac{d\sigma}{dE_R}\,,$$

WIMP-nucleus differential cross section

$$\frac{d\sigma_{WN}}{dE_R} = \frac{m_N}{2m_r^2 v^2}\left[\sigma_{SI} F_{SI}^2(E_R) + \sigma_{SD} F_{SD}^2(E_R)\right],$$

F_{SI} and F_{SD} : nuclear form factors

Spin-Independent $$\sigma_{SI} = \frac{4m_r^2}{\pi}\left[Z f_p + (A-Z) f_n\right]^2,$$

Spin-Dependent $$\sigma_{SD} = \frac{32 m_r^2}{\pi} G_F^2 \frac{J+1}{J}\left[a_p \langle S_p\rangle + a_n \langle S_n\rangle\right]^2,$$

with f_p, f_n and a_p, a_n : effective WIMP couplings to protons and neutrons in the SI and SD case

The differential rate for WIMP elastic scattering off nuclei

$$\frac{dR}{dE_R} = N_N m_N \frac{\rho_0}{m_W} \frac{\sigma_0 F^2}{2m_r^2} \int_{v_{\min}} \frac{f(\mathbf{v})}{v} d\mathbf{v}$$

velocity distribution : Maxwell-Boltzmann distribution

$$\int_{v_{\min}} \frac{f(\mathbf{v})}{v} d\mathbf{v} \propto \exp(-v_{\min}^2/2\sigma_v^2)$$

For small DM mass,

$$m_r \simeq m_W \qquad v_{\min} \simeq \frac{m_N}{m_W}\sqrt{\frac{E_R}{2m_N}}$$

$$\frac{dR}{dE_R} \propto \frac{\sigma_0}{m_W^3} \exp(-a_0/m_W^2)$$

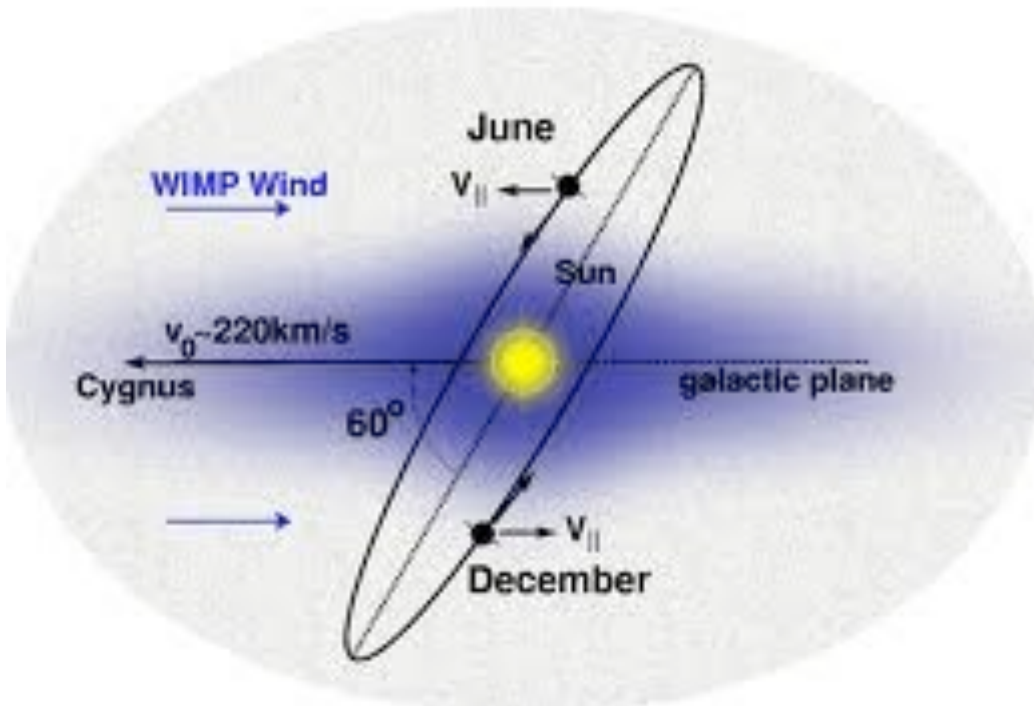
For large DM mass,

$$m_r \simeq m_N \quad v_{\min} \simeq \sqrt{\frac{E_R}{2m_N}}$$

$$\frac{dR}{dE_R} \propto \frac{\sigma_0}{m_W}$$

Maximum recoil rate is when the DM mass is around the nucleus mass.

Annual modulation



$$\langle v \rangle = v_0 \pm v_{\oplus}$$
$$\simeq 220\,\text{km}/\,\text{sec} \pm 30\,\text{km}/\,\text{sec}$$

$$\frac{dR}{dE_R}(E_R, t) \simeq \frac{dR}{dE_R}(E_R)\left[1 + \Delta(E_R)\cos\frac{2\pi\,(t - t_0)}{T}\right]$$

where T $= 1$ year and the phase is $t_0 = 150\,\text{d}$.

No signal in the Direct Detection gives upper limit on the scattering cross section.

$$\frac{dR}{dE_R} = N_N m_N \frac{\rho_0}{m_W} \frac{\sigma_0 F^2}{2m_r^2} \int_{v_{\min}} \frac{f(\mathbf{v})}{v} d\mathbf{v} \quad < \frac{dR}{dE_R}\bigg|_{\mathrm{exp.limit}}$$

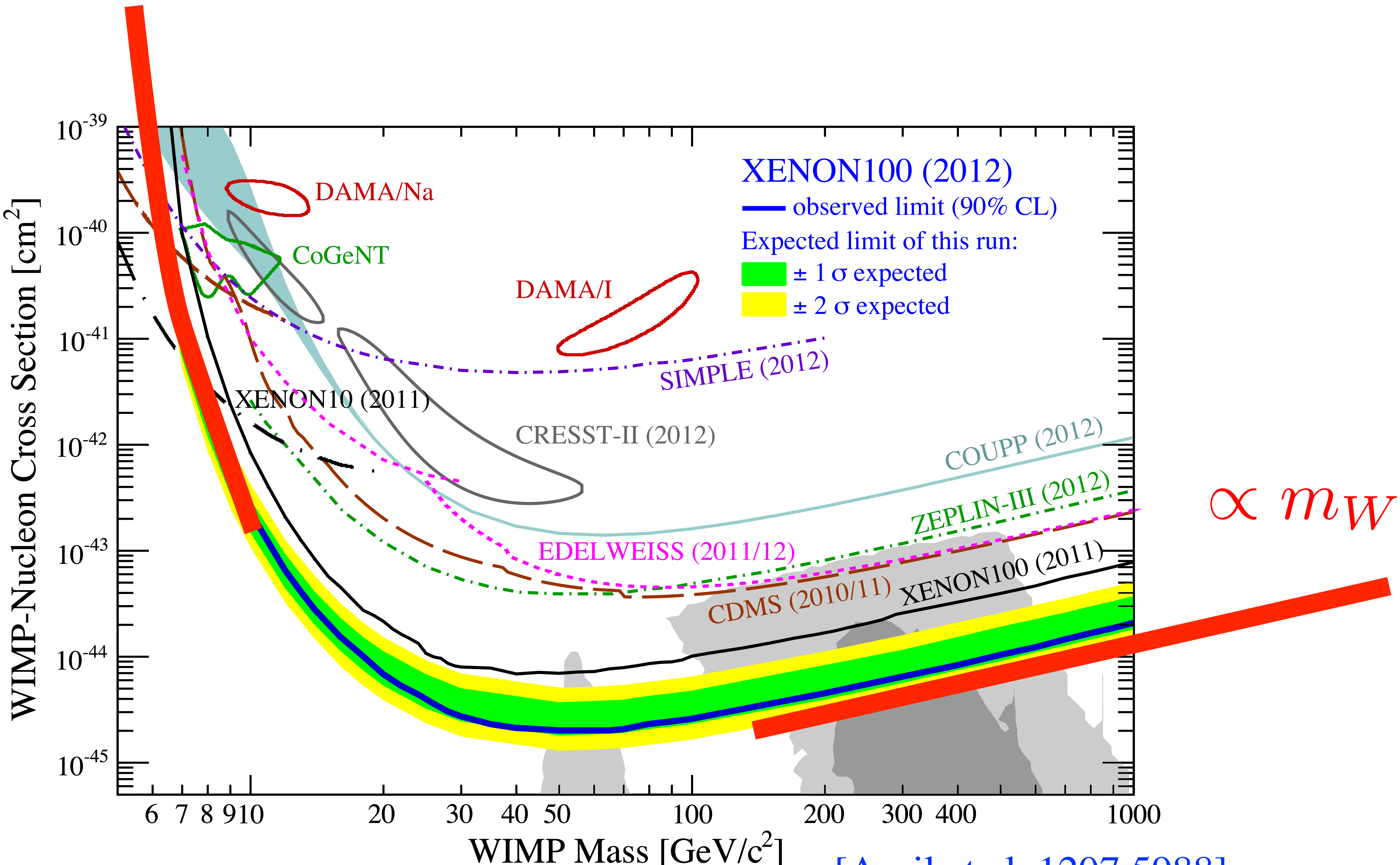
For small DM mass,

$$\frac{dR}{dE_R} \propto \frac{\sigma_0}{m_W^3} \exp(-a_0/m_W^2)$$

For large DM mass,

$$\frac{dR}{dE_R} \propto \frac{\sigma_0}{m_W}$$

$\propto m_W^3 \exp(a_0/m_W^2)$



$\propto m_W$

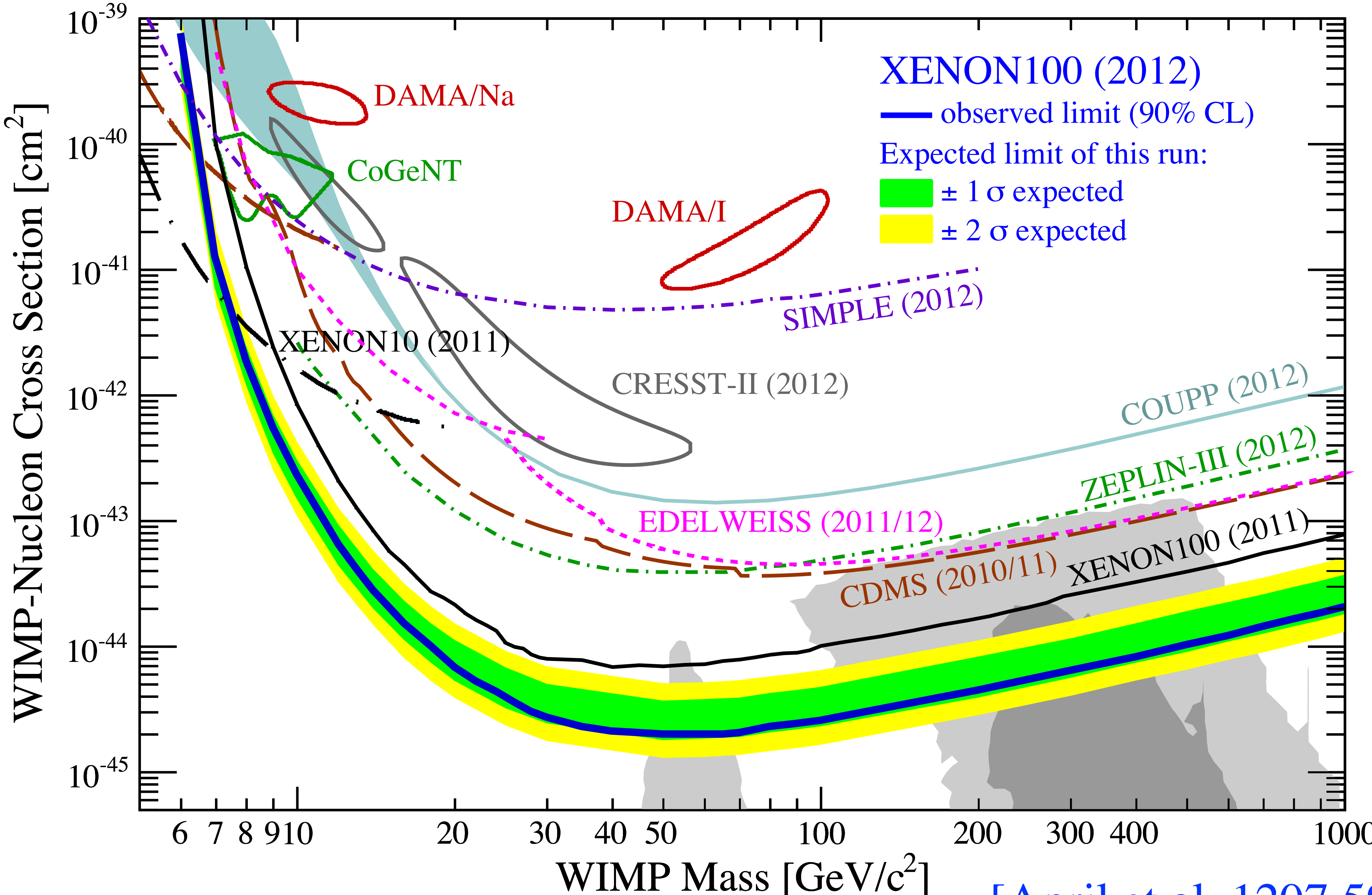
[April et al, 1207.5988]

due to DM number density decreases

XENON100

[2] E. Aprile et al. The XENON100 Dark Matter Experiment. Astropart.Phys., 35:573–590, 2012.
[3] E. Aprile et al. Dark Matter Results from 225 Live Days of XENON100 Data. Phys.Rev.Lett., 109:181301, 2012.

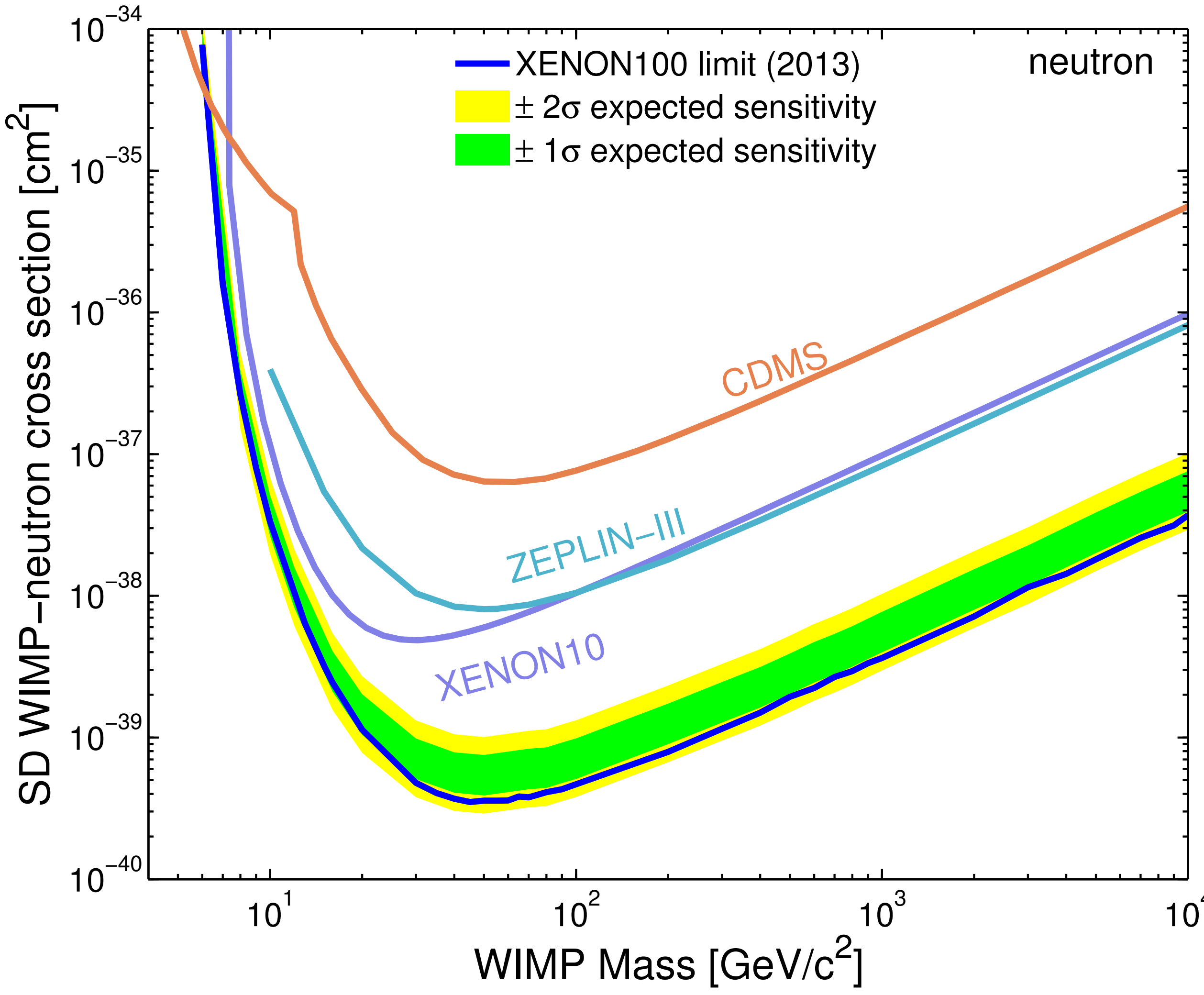
225 live days of XENON 100 data: World best limit on SI cross section
: NO detection of DM signal yet, disfavors DAMA, CoGent and CRESST.

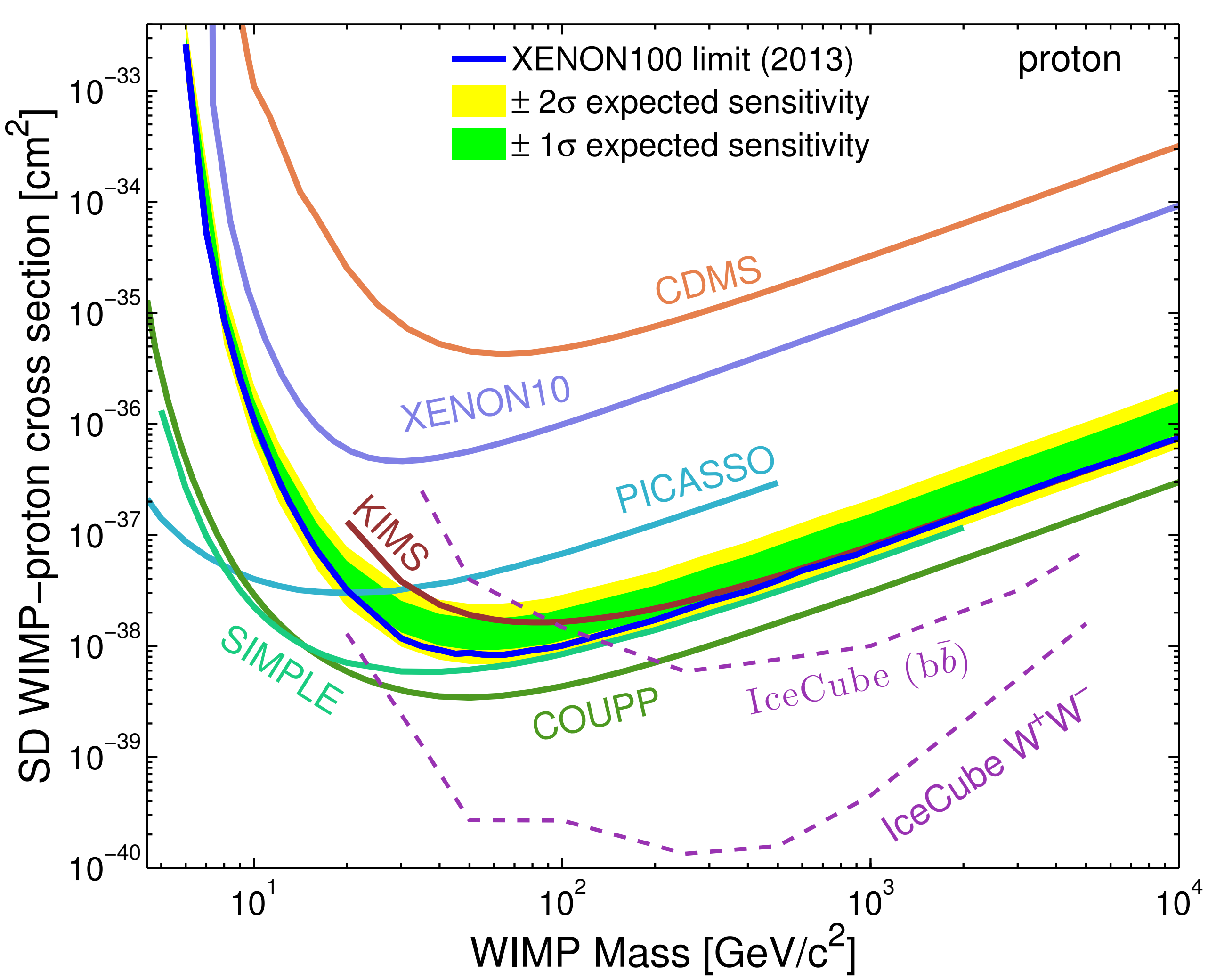


[April et al, 1207.5988]

Spin-Dependent Direct Detection

[April et al, 1301.6620]





- Signals in the direct detection?

Claims for signals reported in the direct detection.

- DAMA/LIBRA : annual modulation (DAMA/NaI 7yrs + DAMA/LIBRA 6yrs)

  8.9 sigma evidence of signal

- CoGent : annual modulation

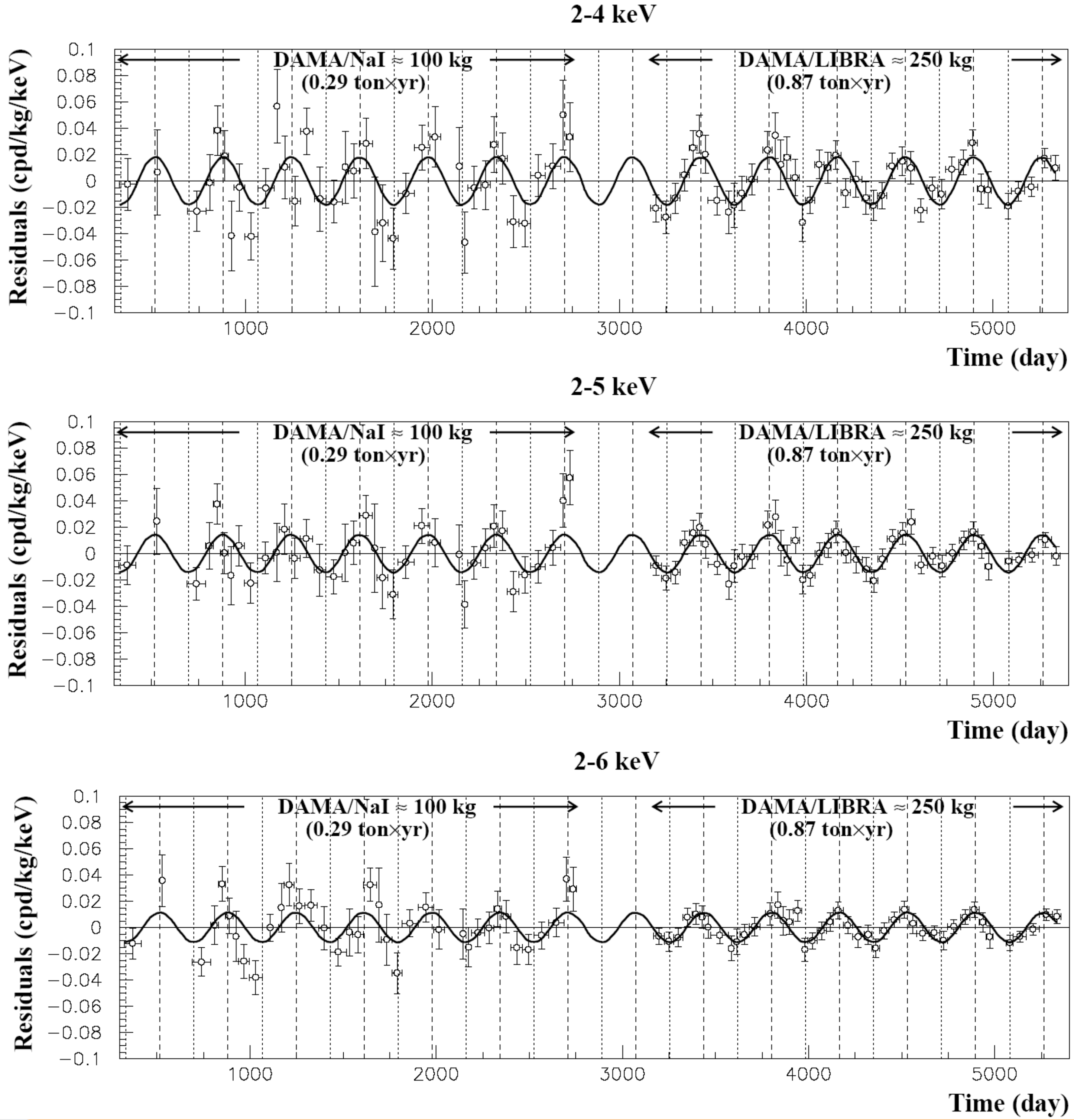
- CRESST II: 67 events, 4 sigma detection of new source, $CaWO_4$ crystals

- CDMS II -Si : Detect 3 signals

Model Independent Annual Modulation Result

DAMA/NaI (7 years) + **DAMA/LIBRA** (6 years) Total exposure: 425428 kg×day = **1.17 ton×yr**

experimental single-hit residuals rate vs time and energy



2-4 keV

A=(0.0183±0.0022) cpd/kg/keV

χ^2/dof = 75.7/79 8.3 σ C.L.

Absence of modulation? No

χ^2/dof=147/80 ⇒ P(A=0) = 7×10^{-6}

2-5 keV

A=(0.0144±0.0016) cpd/kg/keV

χ^2/dof = 56.6/79 9.0 σ C.L.

Absence of modulation? No

χ^2/dof=135/80 ⇒ P(A=0) = 1.1×10^{-4}

2-6 keV

A=(0.0114±0.0013) cpd/kg/keV

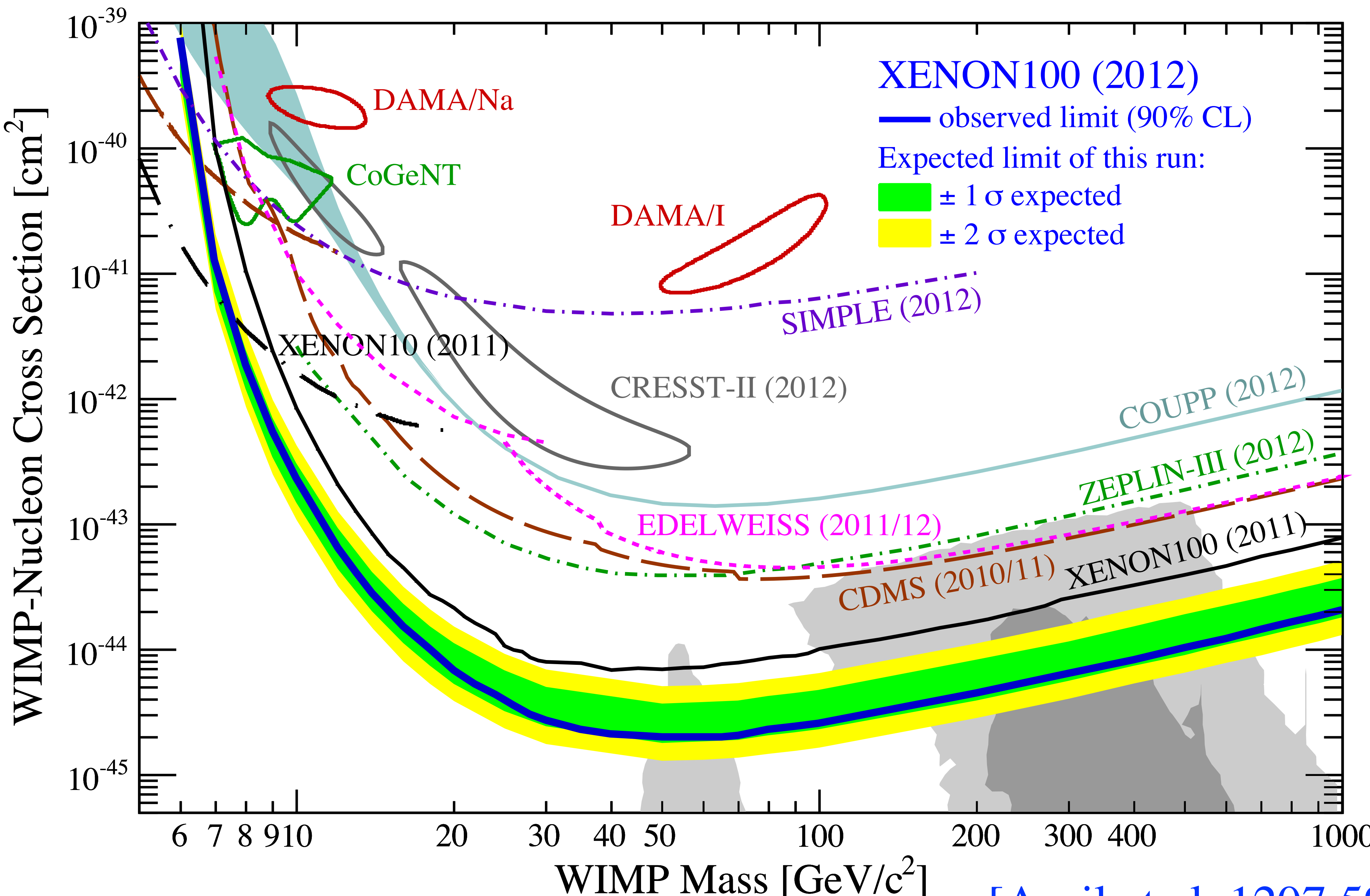
χ^2/dof = 64.7/79 8.8 σ C.L.

Absence of modulation? No

χ^2/dof=140/80 ⇒ P(A=0) = 4.3×10^{-5}

The data favor the presence of a modulated behavior with proper features at 8.8σ C.L.

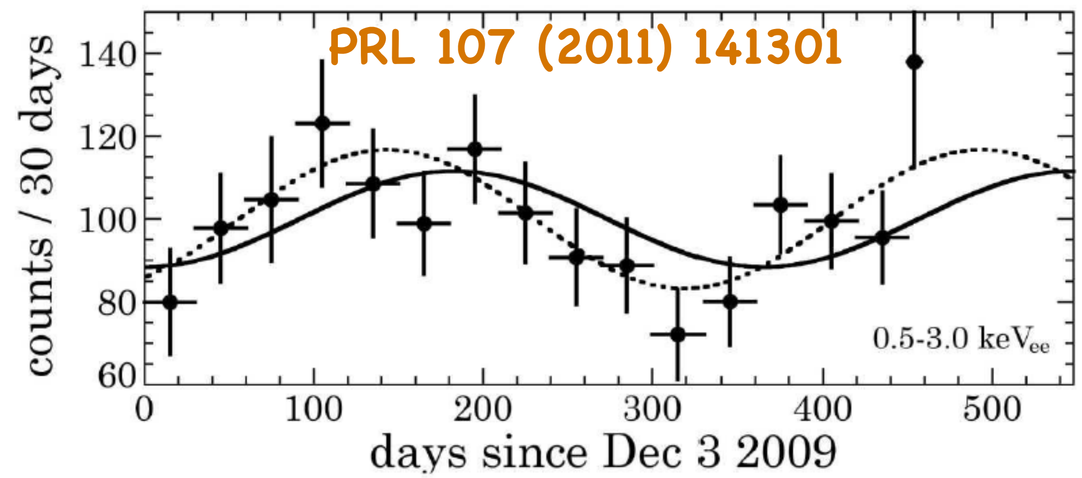
[Cerulli, 2012 IDM talk]

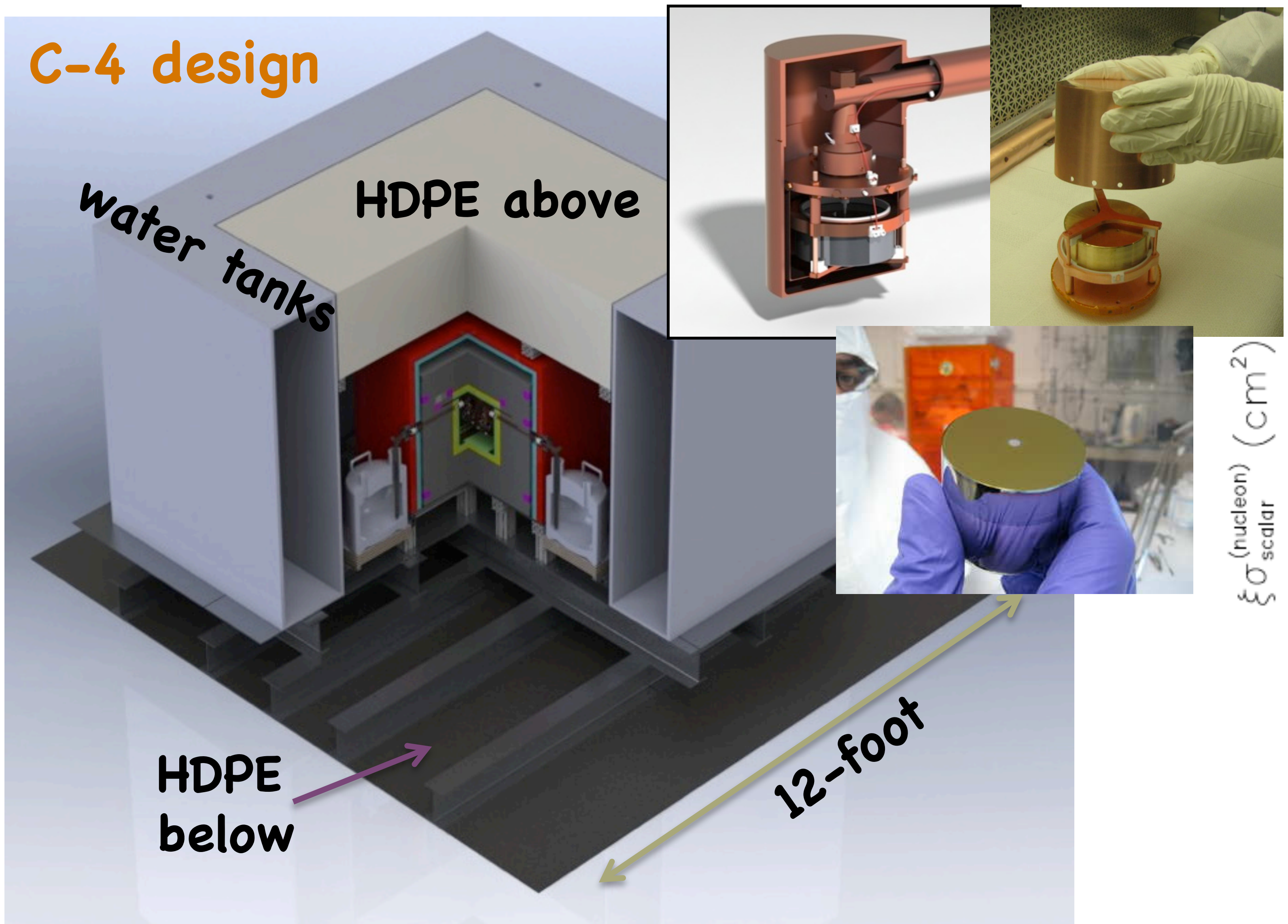


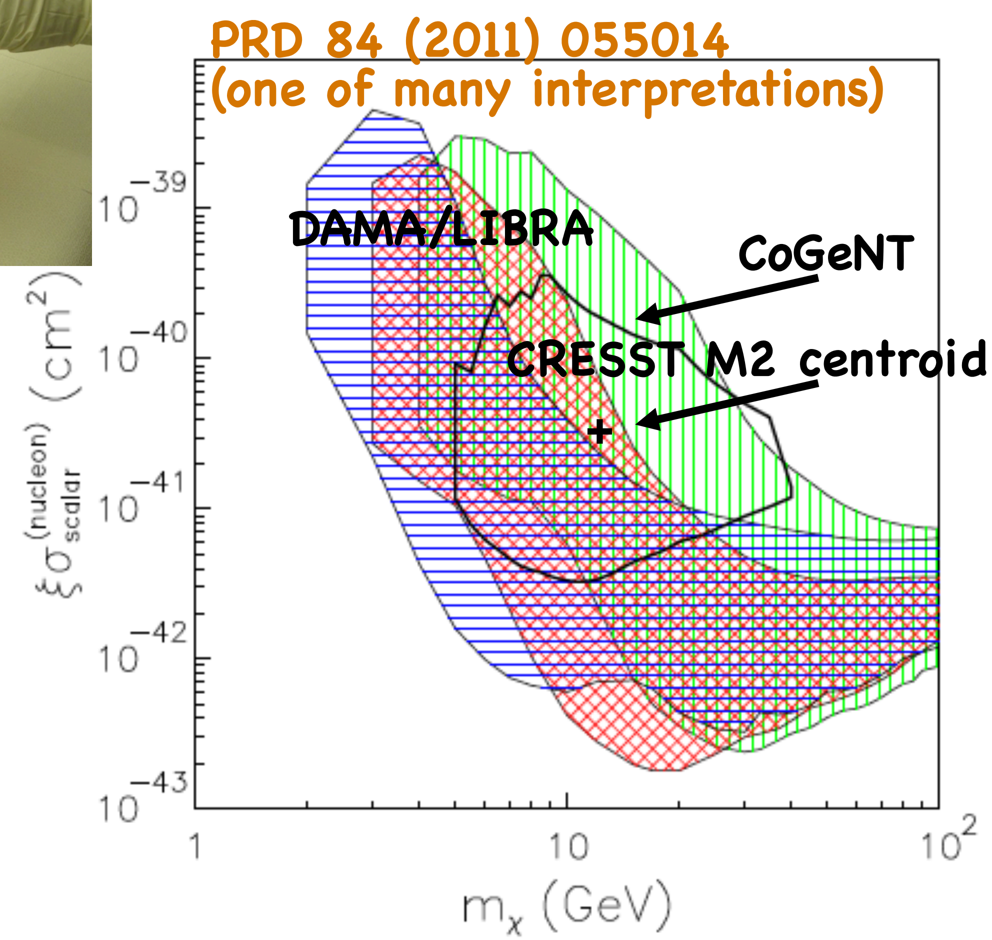
[April et al, 1207.5988]

CoGeNT: a dedicated search for low-mass WIMPs

- An excellent example of synergy with industry: Canberra's PPCs around since early 80's.
- Remarkably simple commercial technology leads to applications in double-beta decay (MAJORANA, GERDA) and astroparticle physics (CoGeNT).
- Searches for an annual modulation require exquisite instrumental stability. <u>But how much is enough?</u>
- PNNL/UC/Canberra C-4 expansion (x10 mass, lower bckgs and threshold) will make it, or break it.







[CoGeNT, 2012 IDM talk]

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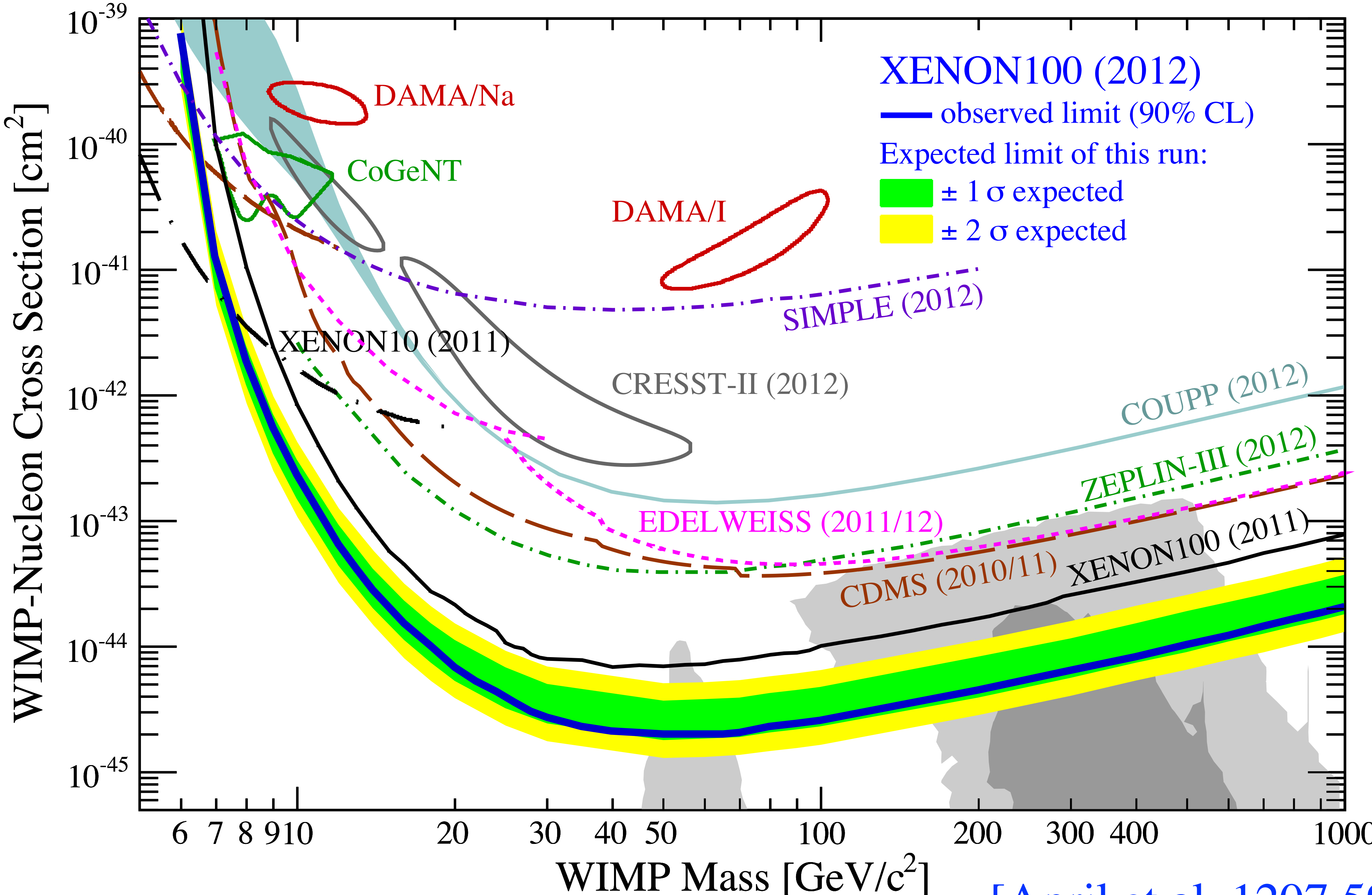
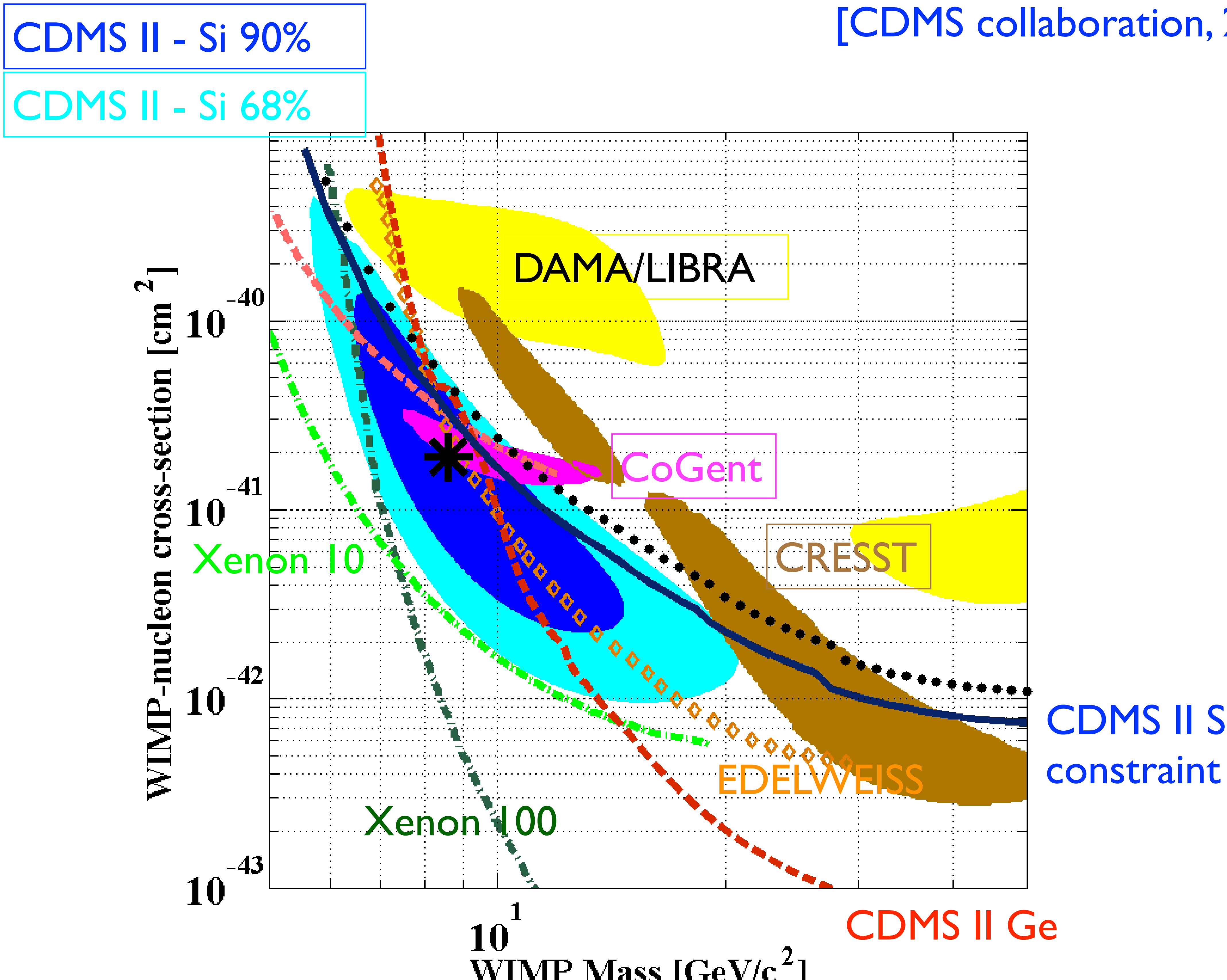


[April et al, 1207.5988]

Dark Matter Search Results Using the Silicon Detectors of CDMS II

[CDMS collaboration, 2013]



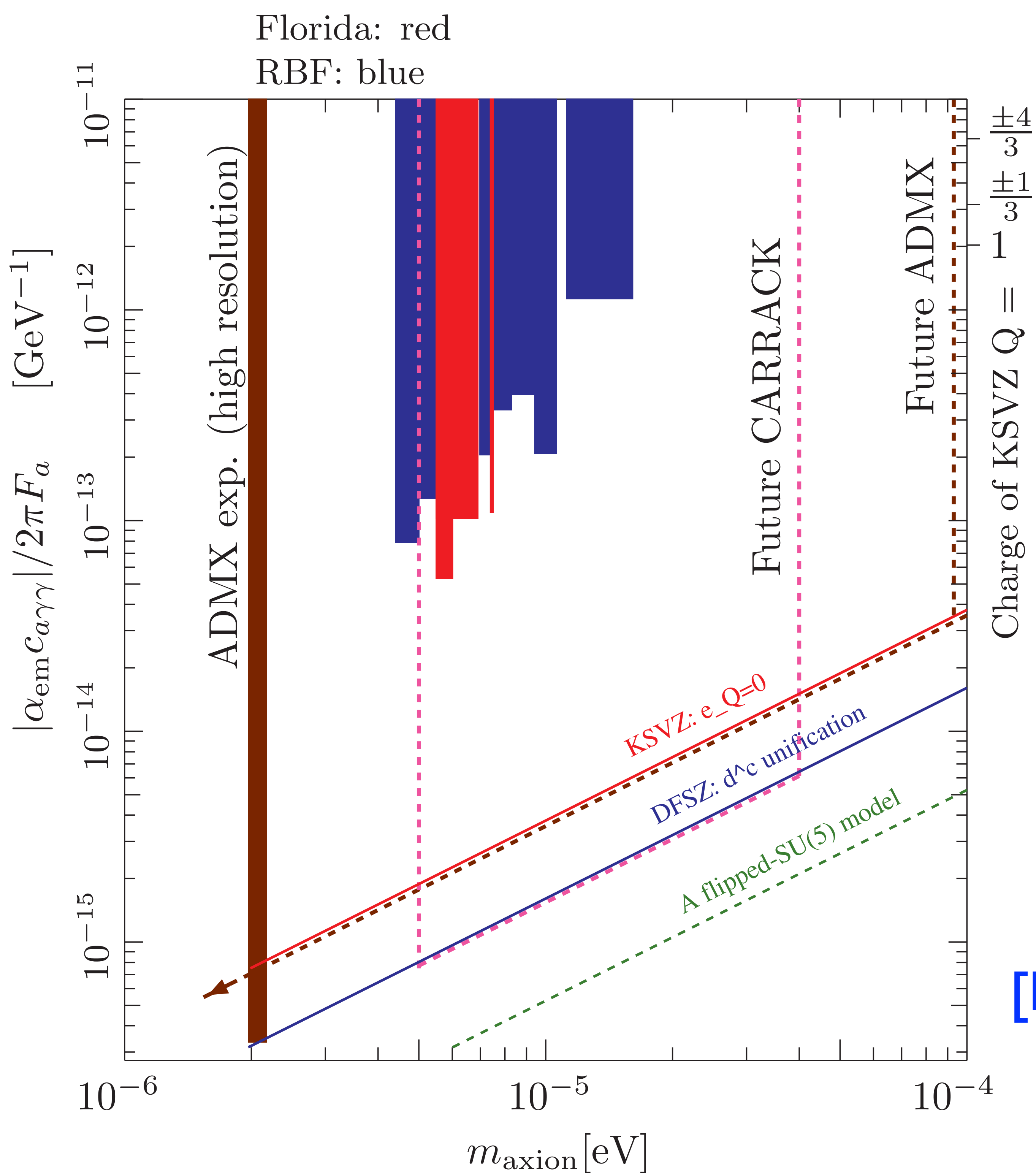
Dark Matter Search in the Direct Detection

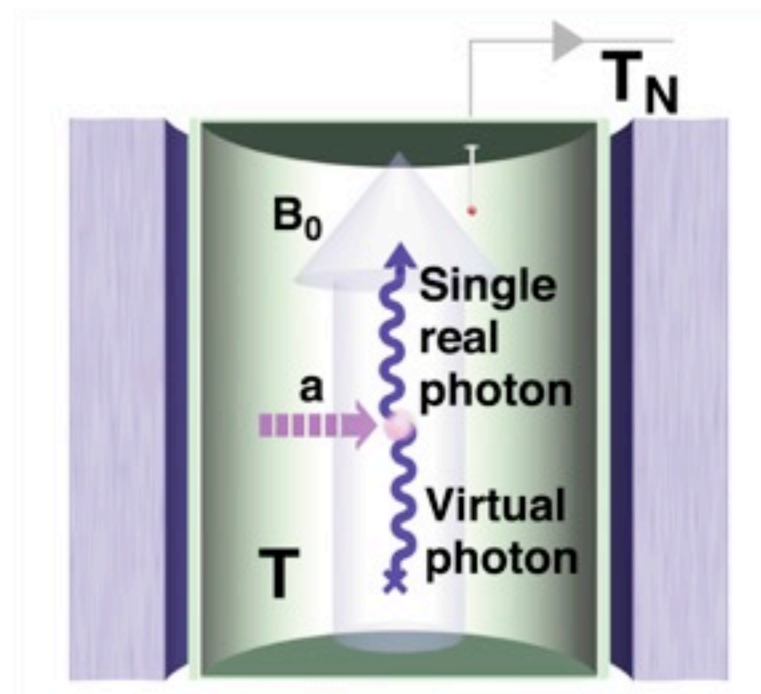
There are some signals which cannot be explained by the known background. Those may the signal of DM?

However they are inconsistent each other and also have tension with limits from other experiments, especially Xenon10 and Xenon100.

Maybe unknown backgrounds? or signal of DM?

Axion dark matter search : ADMX, CARRACK





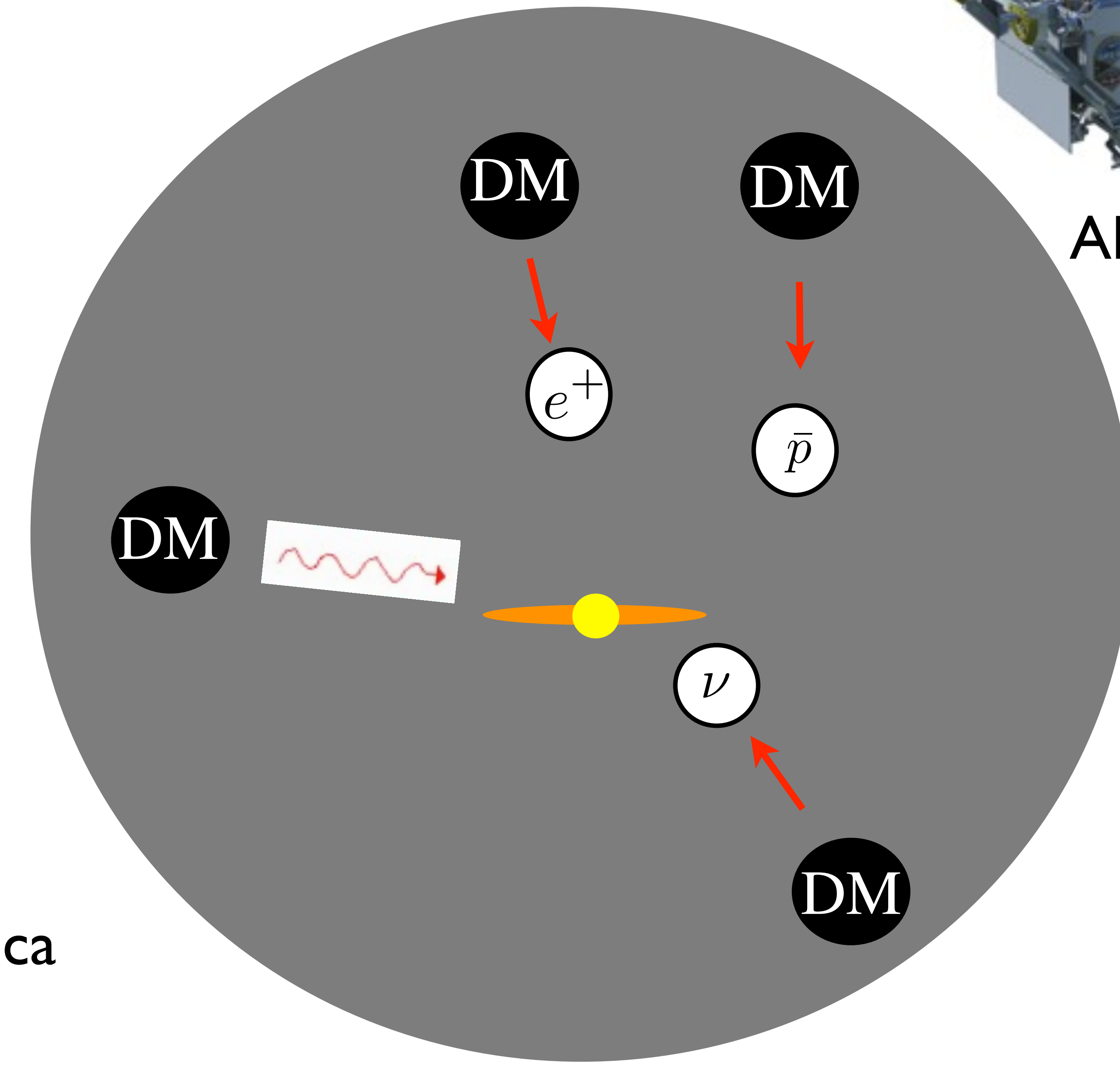
[KIm, Carosi, 2010]

Indirect Detection

• Indirect Detection

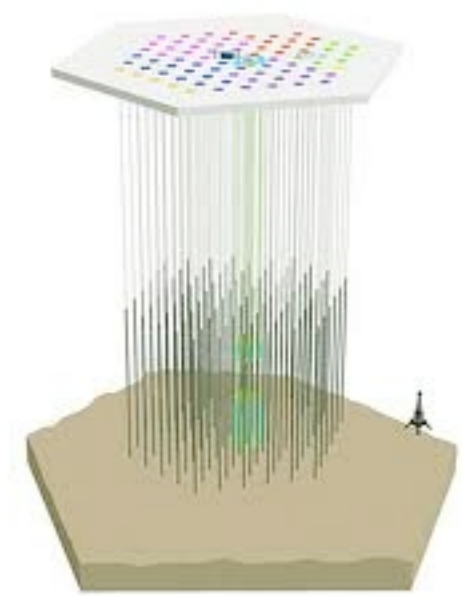
Fermi-LAT, 2008

HESS in Nambia of Africa

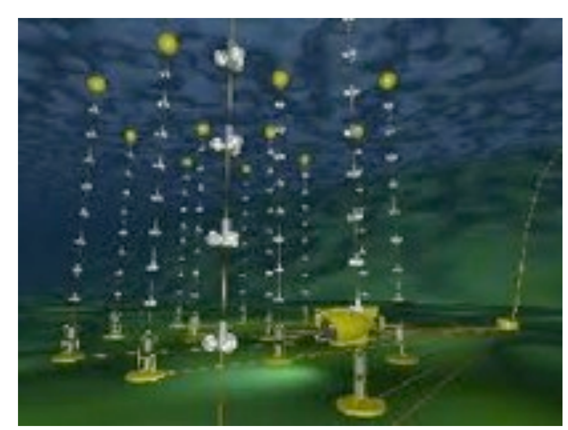


AMS-02

PAMELA, 2006



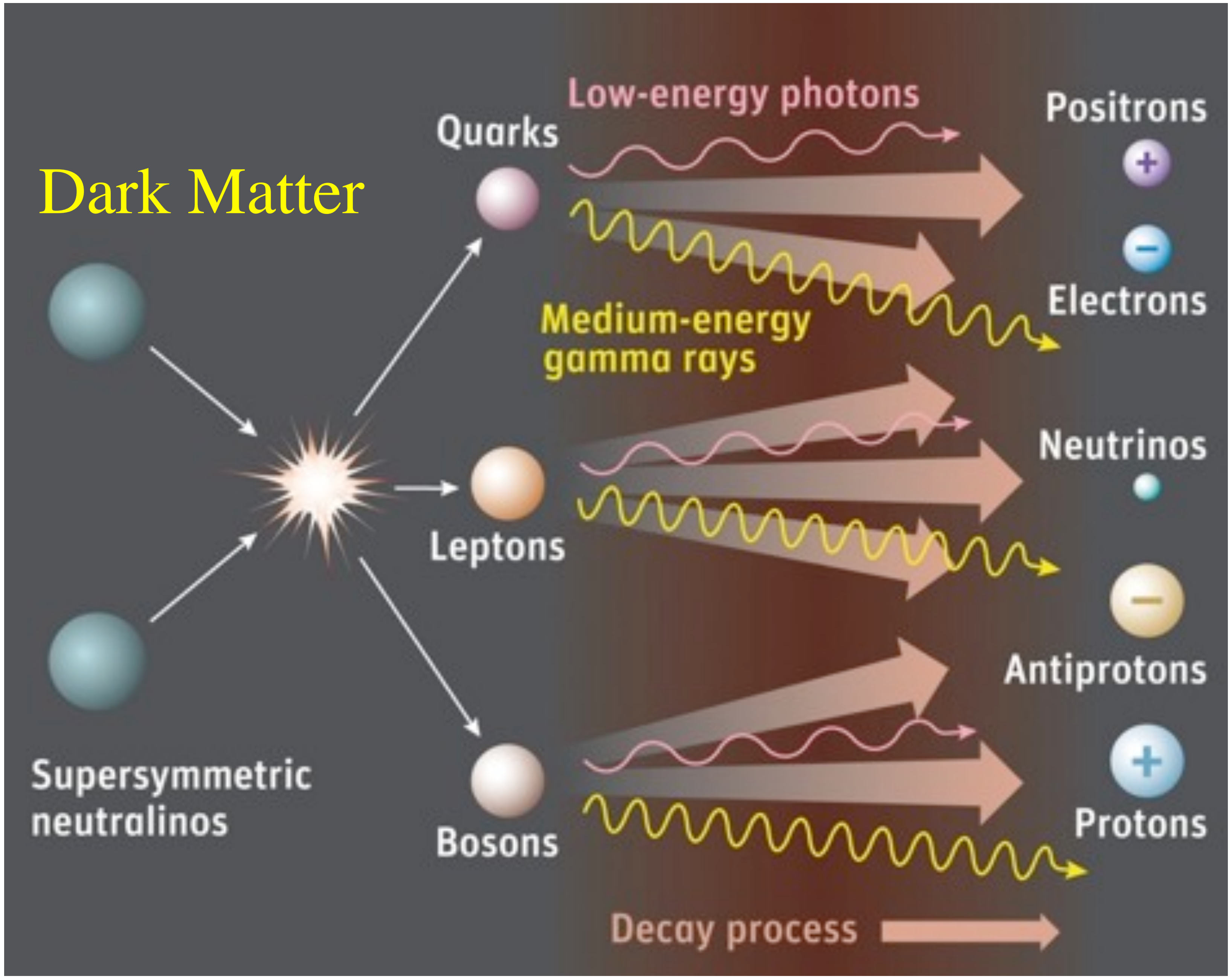
IceCube



Antares

- Indirect Detection

Dark Matter can self annihilate or decay to produce cosmic rays, photons or neutrinos.



Credit: Sky & Telescope / Gregg Dinderman

- Indirect Detection : gamma-ray

They come through directly from the source to the detector around Earth.

Satellite

Fermi-LAT

$$N = \phi_\gamma \cdot A_{\rm eff} \cdot T_{\rm exp}$$

	(Effective Area)	(Exposure time)
satellite	$1\, m^2$	$1\, yr = \pi \times 10^7$ sec
ground-based telescope	$10^5\, m^2$	$100h \simeq 10^5$ sec

Ground-based telescope (air cherenkov telescopes)

HESS

VERITAS

MAGIC

Observed flux from Dark Matter

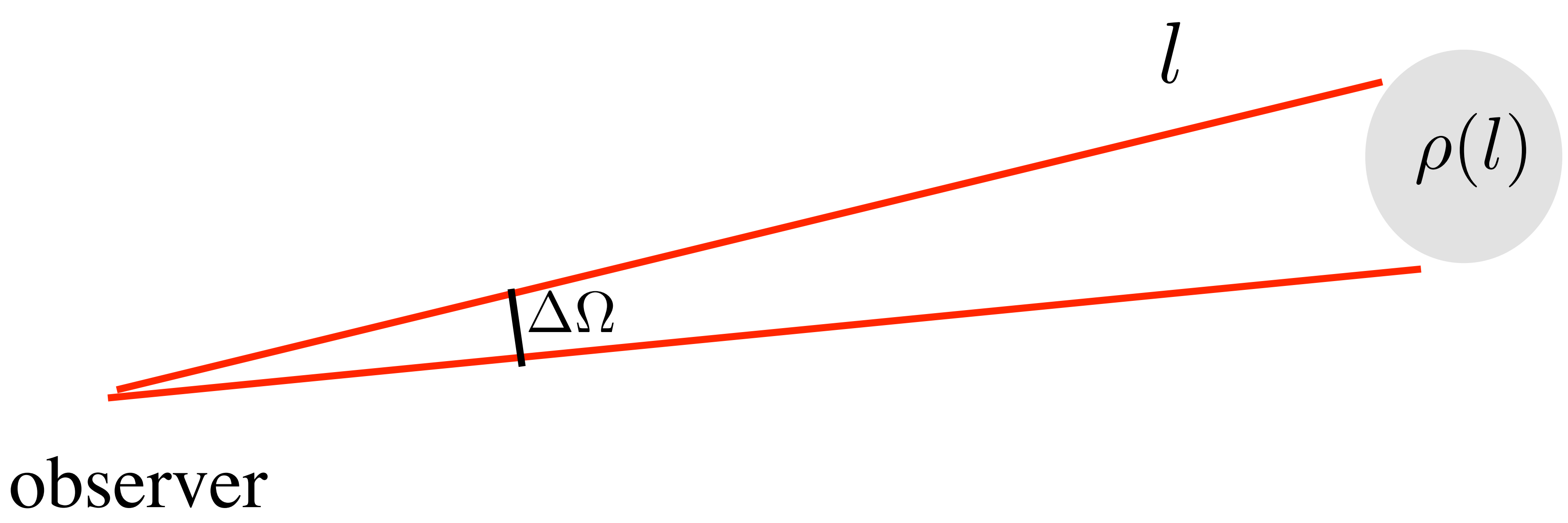
Astrophysics

$J-\text{factor}$

Particle Physics

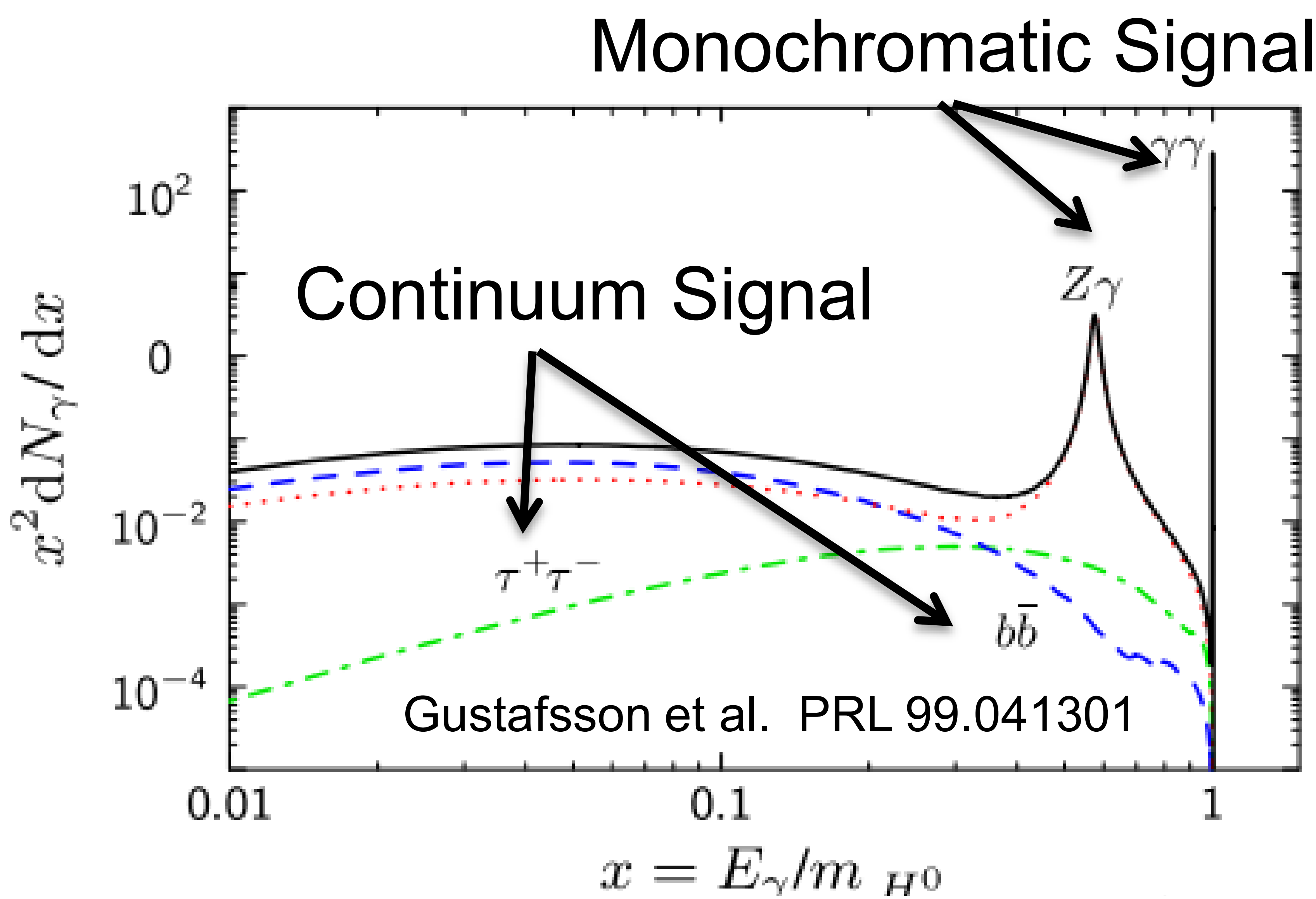
ann. $$\phi_\gamma(E,\Delta\Omega) = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_\chi^2}\sum_f \frac{dN_f}{dE}B_f\Delta\Omega\left\{\frac{1}{\Delta\Omega}\int_{\Delta\Omega}\int_{l.o.s} dl\rho^2(l(\Omega))\right\}$$

decay $$\frac{\Gamma_D}{m_\chi} \qquad \rho(l)$$



Particle Physics

$$\phi_\gamma(E, \Delta\Omega) = \frac{1}{4\pi} \frac{\langle \sigma v \rangle}{2m_\chi^2} \sum_f \frac{dN_f}{dE} B_f \Delta\Omega \left\{ \frac{1}{\Delta\Omega} \int_{\Delta\Omega} \int_{l.o.s} dl \rho^2(l(\Omega)) \right\}$$

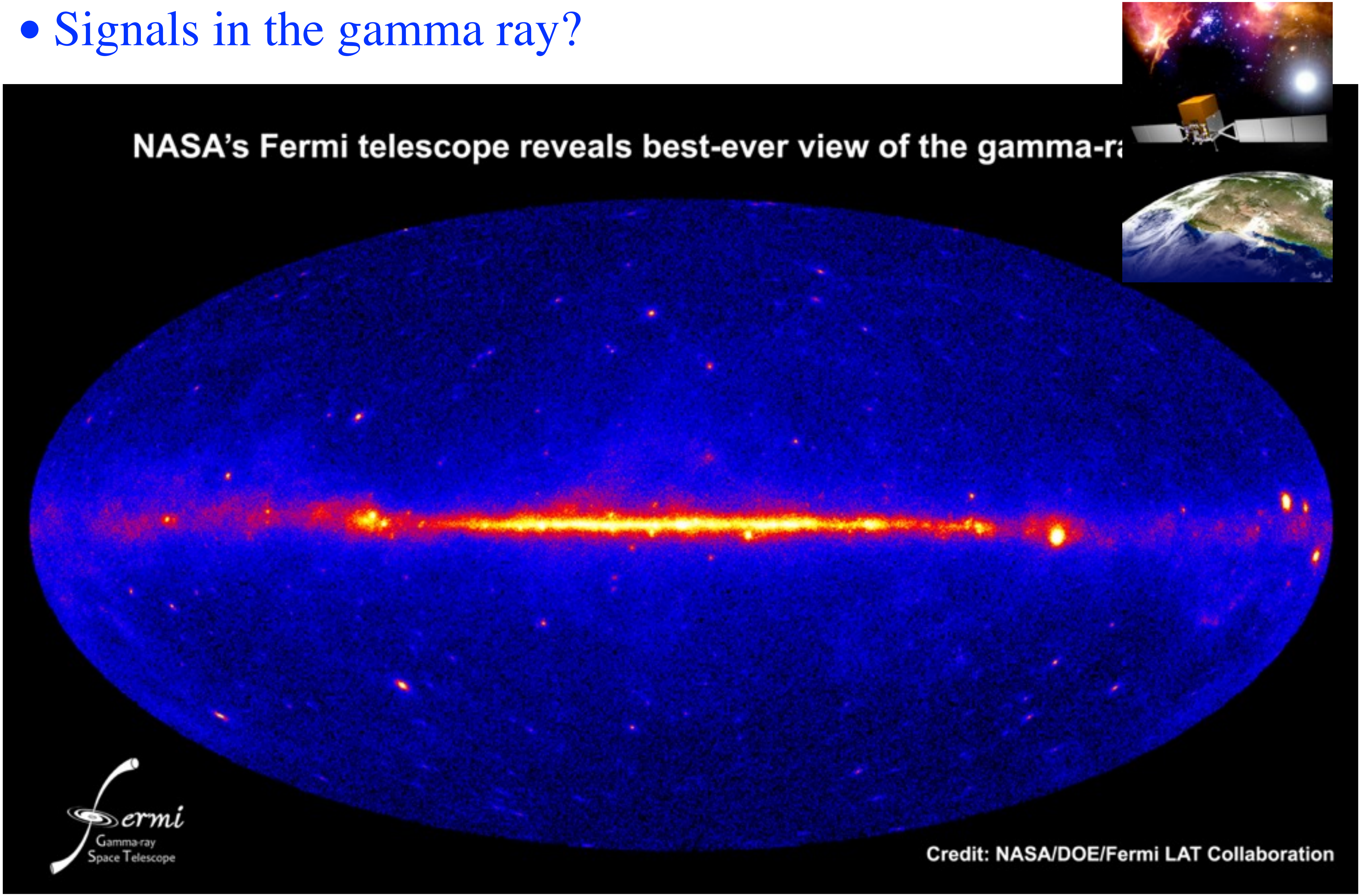


Astrophysics $J-\text{factor}$

$$\phi_\gamma(E,\Delta\Omega) = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_\chi^2}\sum_f \frac{dN_f}{dE}B_f\Delta\Omega\left\{\frac{1}{\Delta\Omega}\int_{\Delta\Omega}\int_{l.o.s} dl\rho^2(l(\Omega))\right\}$$

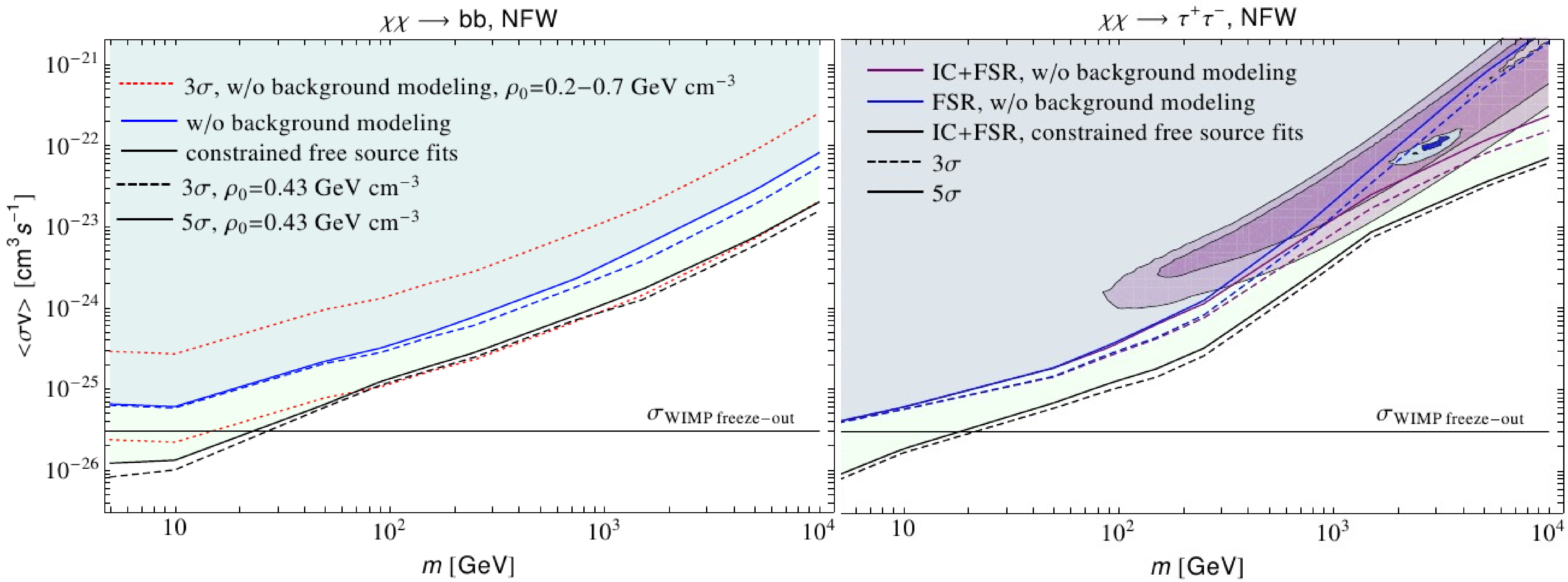
1. Dwarf Spheroidal Galaxies
   - Draco, $J\sim 10^{19}\ \mathrm{GeV^2/cm^5}$, $\pm$ a factor 1.5;
   - Ursa Minor, $J\sim 10^{19}\ \mathrm{GeV^2/cm^5}$, $\pm$ a factor 1.5;
   - Segue, $J\sim 10^{20}\ \mathrm{GeV^2/cm^5}$, $\pm$ a factor 3
2. Local Milky-Way-like galaxies
   - M31, $J\sim 10^{20}\ \mathrm{GeV^2/cm^5}$
3. Local clusters of galaxies
   - Fornax, $J\sim 10^{18}\ \mathrm{GeV^2/cm^5}$
   - Coma, $J\sim 10^{17}\ \mathrm{GeV^2/cm^5}$
   - Bullet, $J\sim 10^{14}\ \mathrm{GeV^2/cm^5}$
4. Galactic center
   - 0.1°: $J\sim 10^{22}\ldots\ 10^{25}\ \mathrm{GeV^2/cm^5}$
   - 1°: $J\sim 10^{22}\ldots\ 10^{24}\ \mathrm{GeV^2/cm^5}$ [Profumo, 1301.0952]

- Signals in the gamma ray?

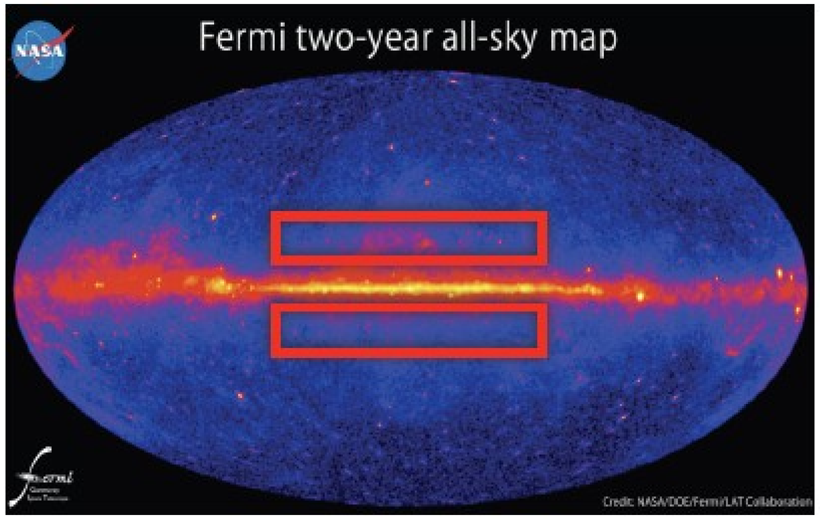


MW Halo Results- $\tau^+ \tau^-$

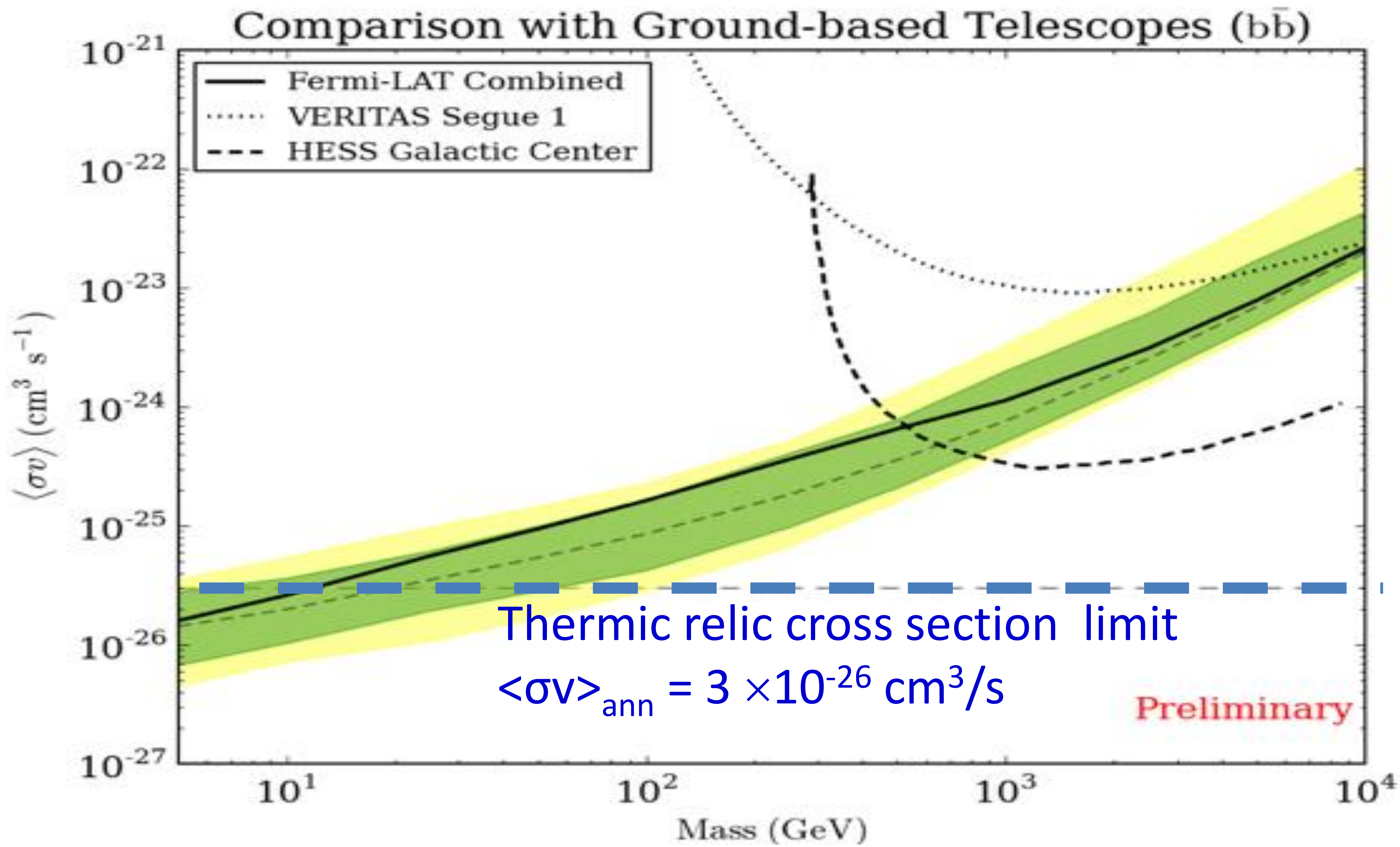
Annihilation (cases for decay are given in the paper)



M. Ackermann et al (Fermi LAT Collaboration)
Accepted for publication in ApJ (arXiv:1205.6474)



Constraints from dwarf spheroidal galaxies

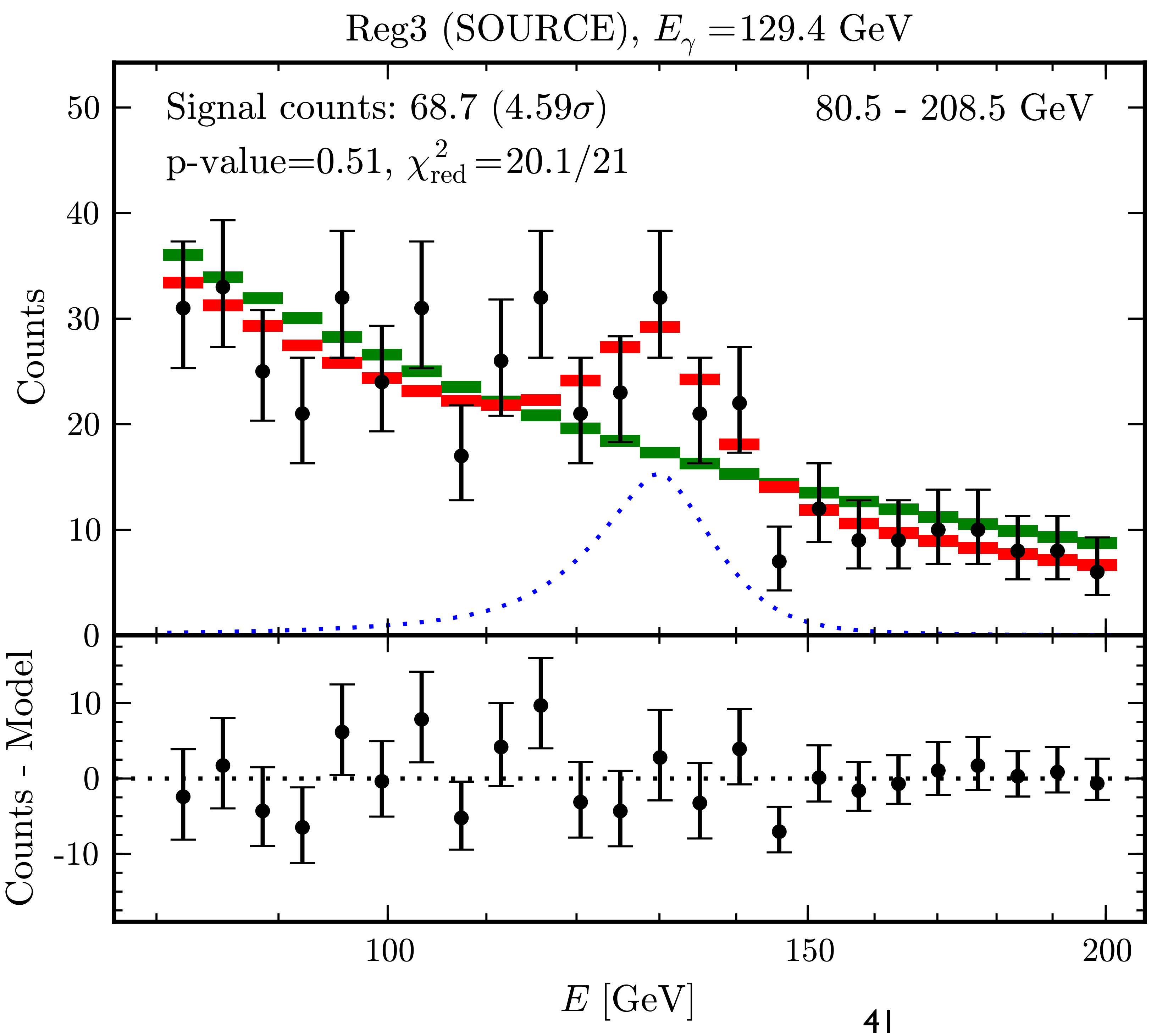


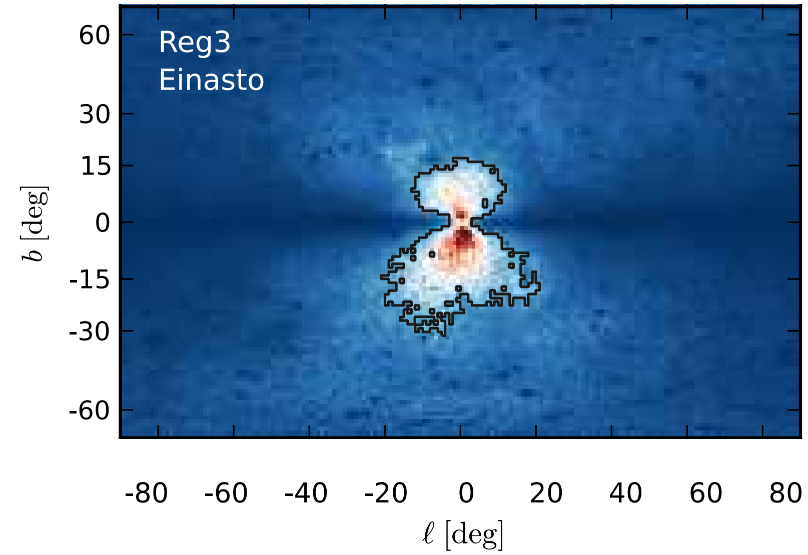
[Taken from Nicola M., - Lepton Photon 2013]

Signals in the gamma ray?

130 GeV gamma-line signal from public Fermi-LAT data

[Bringman et al, 2012, Weniger 2012]





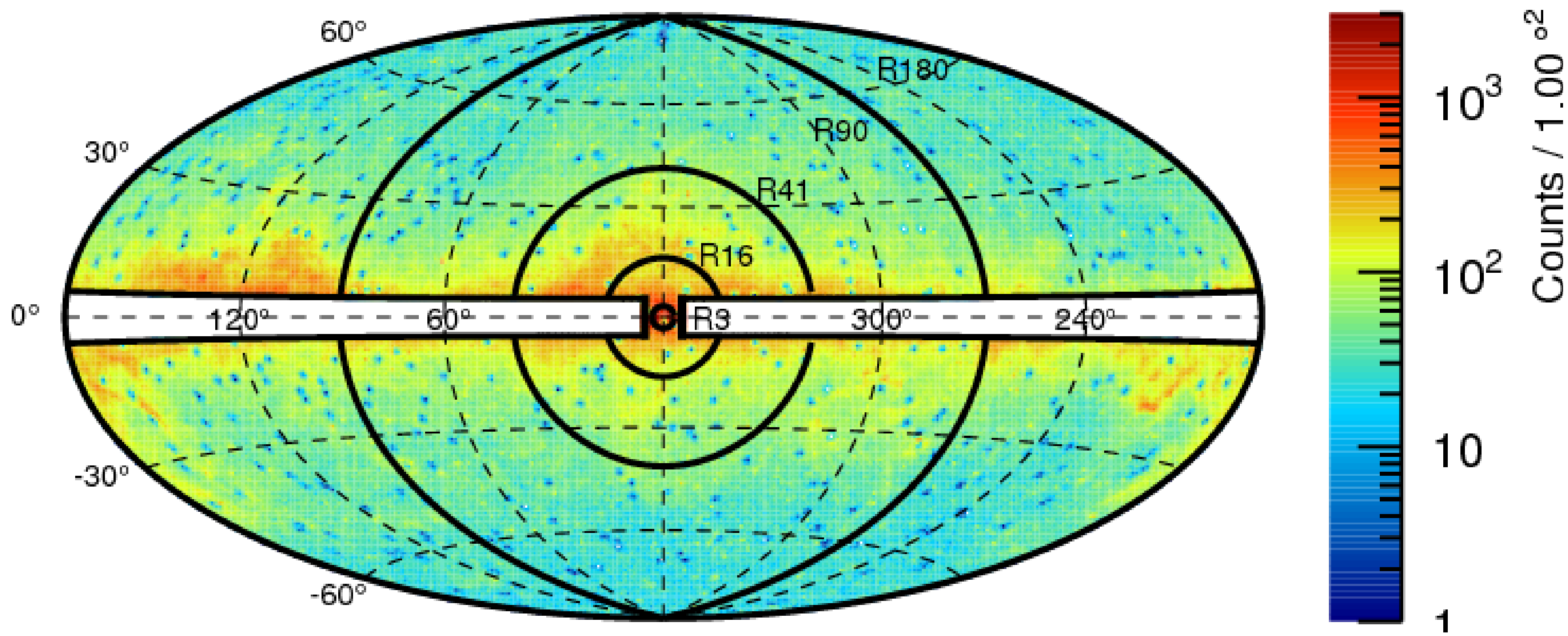
DM annihilation

$$\langle \sigma v \rangle_{\gamma\gamma} \simeq 10^{-27}\ \mathrm{cm}^3/\mathrm{s}$$

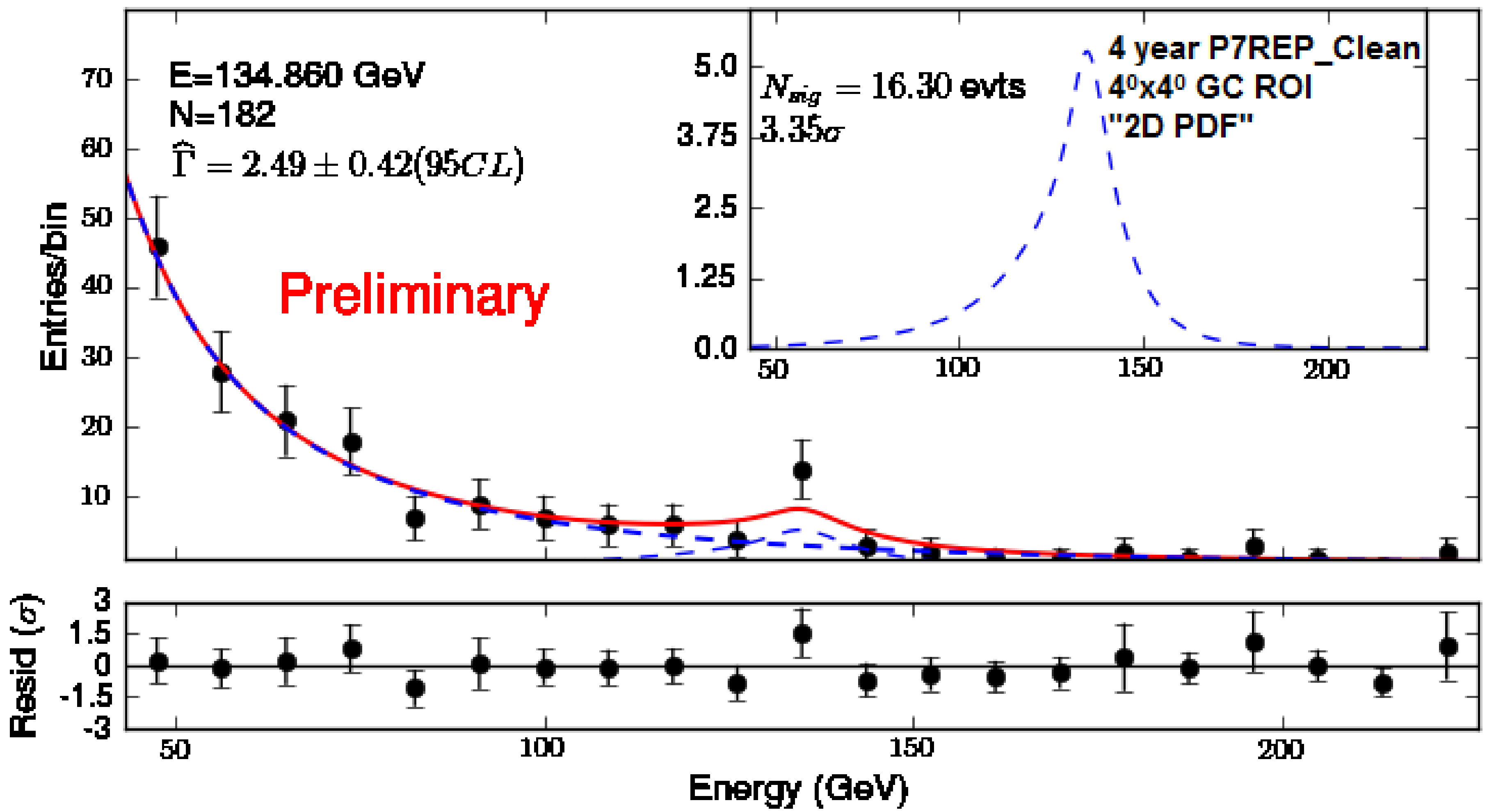
Search for Gamma-ray Spectral Lines with the *Fermi* Large Area Telescope and Dark Matter Implications

[Fermi collaboration, 1305.5597]

Weakly Interacting Massive Particles (WIMPs) are a theoretical class of particles that are excellent dark matter candidates. WIMP annihilation or decay may produce essentially monochromatic γ rays detectable by the *Fermi* Large Area Telescope (LAT) against the astrophysical γ-ray emission of the Galaxy. We have searched for spectral lines in the energy range 5–300 GeV using 3.7 years of data, reprocessed with updated instrument calibrations and an improved energy dispersion model compared to the previous *Fermi*-LAT Collaboration line searches. We searched in five regions selected to optimize sensitivity to different theoretically-motivated dark matter density distributions. We did not find any globally significant lines in our *a priori* search regions and present 95% confidence limits for WIMP annihilation cross sections and decay lifetimes. Our most significant fit occurred at 133 GeV in our smallest search region and had a local significance of 3.3σ, which translates to a global significance of 1.6σ. We discuss potential systematic effects in this search and why the significance of the line-like feature near 130 GeV is less than reported in other works.



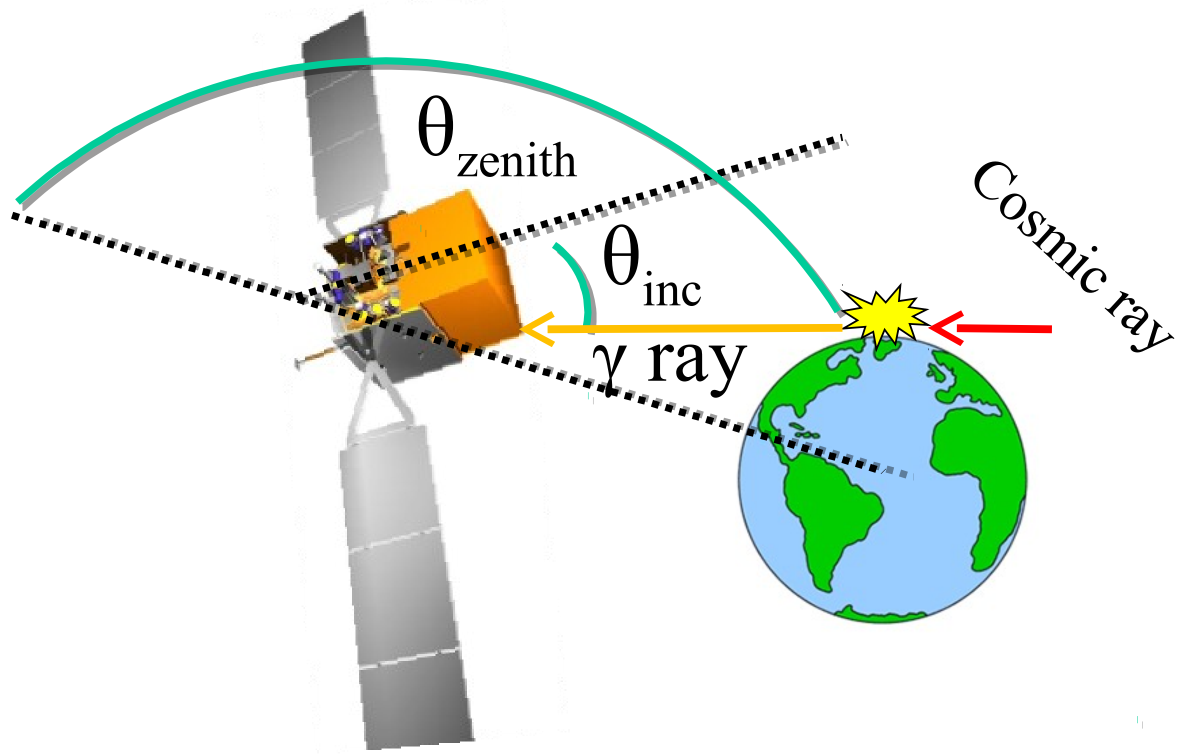
Fermi-LAT Team Line Search at 135 GeV

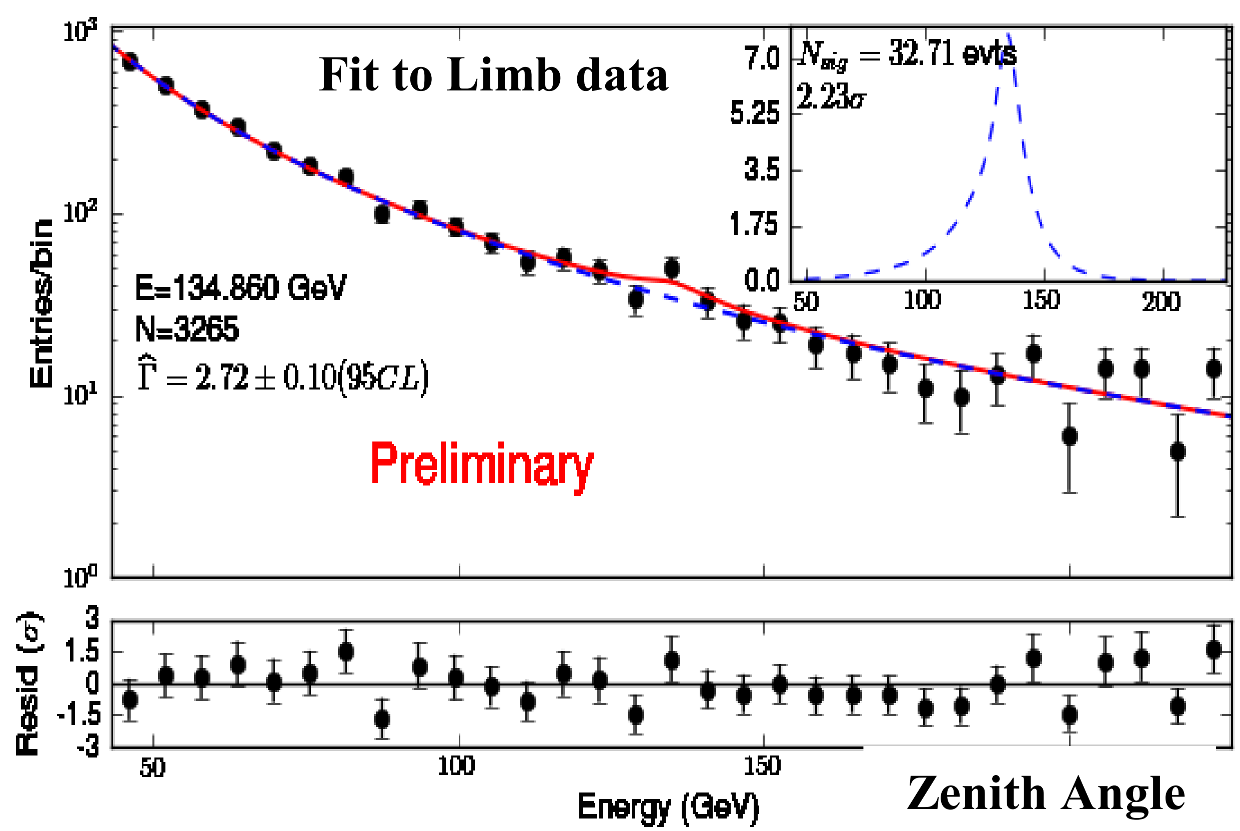


- 4.01σ (local) 1D fit at 130 GeV with 3.7 year unreprocessed data
  - Look in 4°x4°GC ROI, Use 1D PDF (no use of P_E)
- 3.73σ (local) 1D fit at 135 GeV with 3.7 year reprocessed data
  - Look in 4°x4°GC ROI, Use 1D PDF (no use of P_E)
- **3.35σ (local) 2D fit at 135 GeV with 3.7 year reprocessed data**
  - **Look in 4°x4°GC ROI, Use 2D PDF (P_E in data)**
  - **<2σ global significance after trials factor**

135 GeV in the Earth Limb spectrum (1)

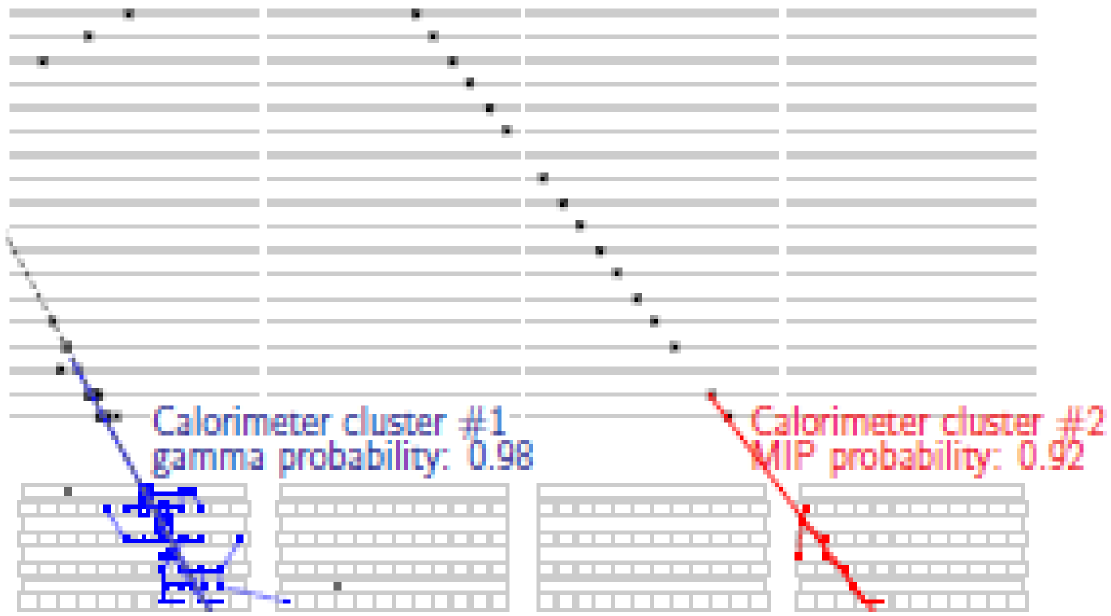
- Earth Limb is a bright, well understood source
  - γ rays from CR interactions in the atmosphere (smooth PWL)
  - Can be used to study instrumental effects
- Need to cut on times when the LAT was pointing at the limb
- Have made changes to increase our Limb dataset
  - Pole-pointed observations each week
  - Extended "targets of opportunity" (Tracing Limb while target is occulted)
- "Signal" is seen! Though not at level of the GC (S/N_{limb} ~15%, while S/N_{GC} ~30% - 66%)



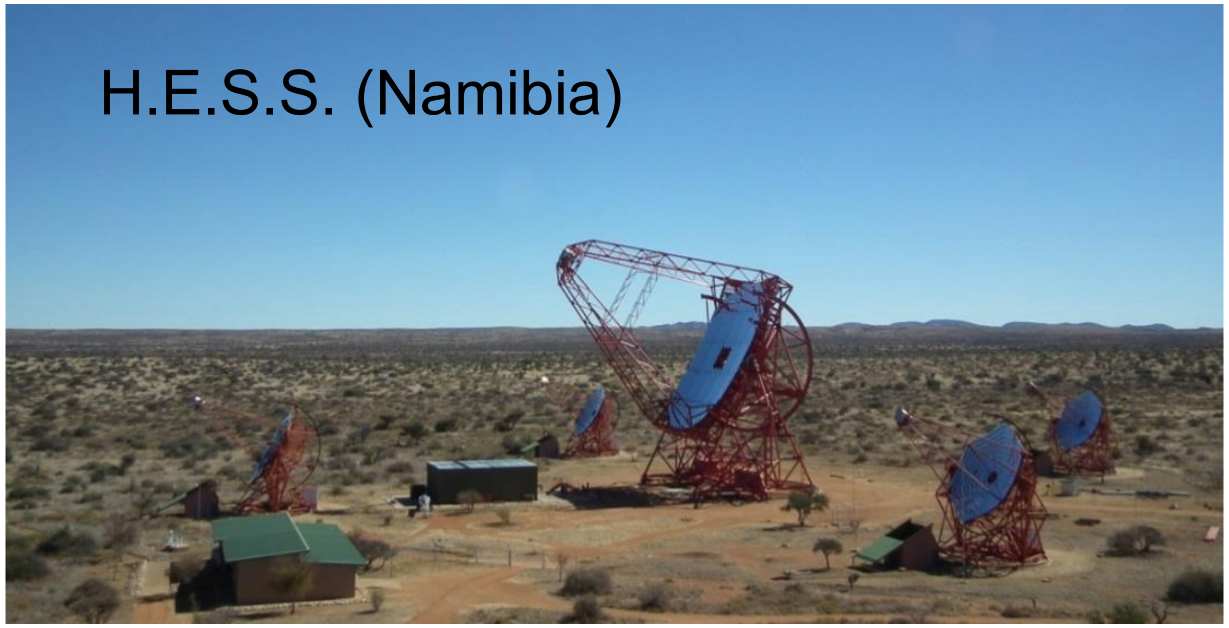


Spectral line search: near terms prospect

- Fermi LAT: improved event analysis (Pass8) and weekly limb observations
  - Call for white papers on possible modifications to the observing strategy
- H.E.S.S. Cerenkov telescope: 50 hours of GC observation could be enough to rule out signature or confirm it at 5 sigma

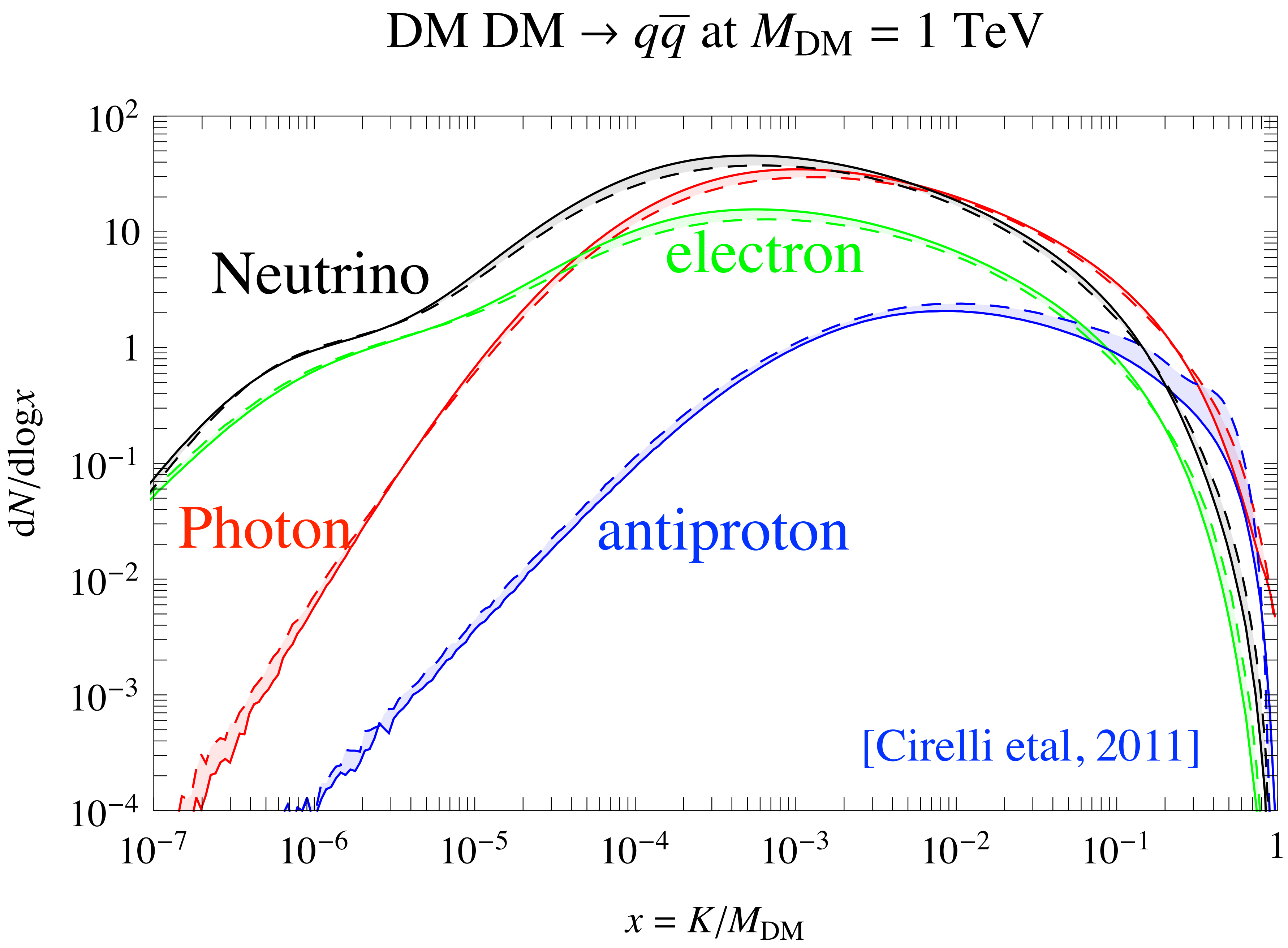


Fermi-LAT Upcoming Developments Pass 8



- Indirect Detection : cosmic rays

Dark Matter annihilation or decay can produce charged particles.



$$\langle \sigma v \rangle \sim 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s},$$

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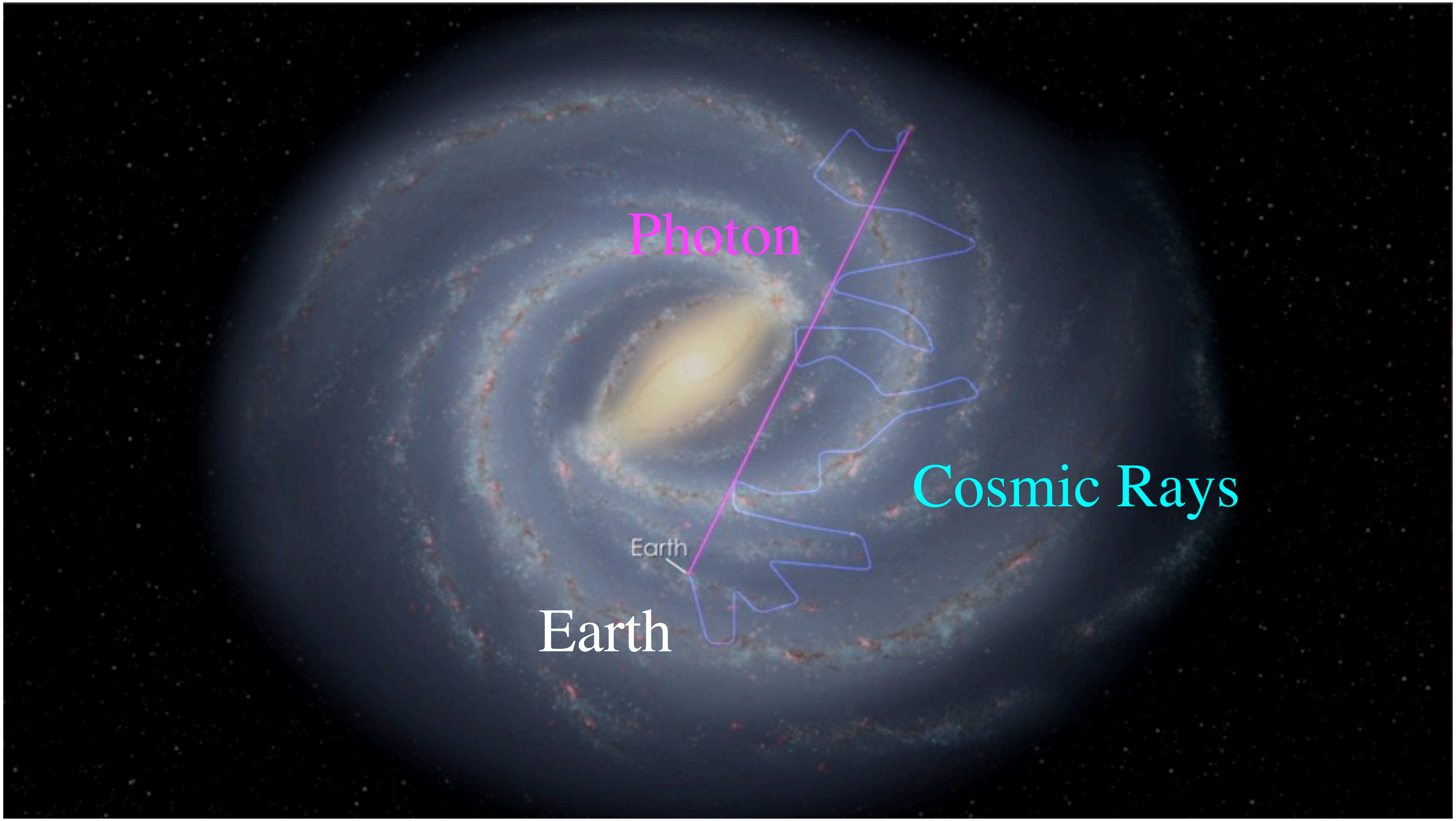
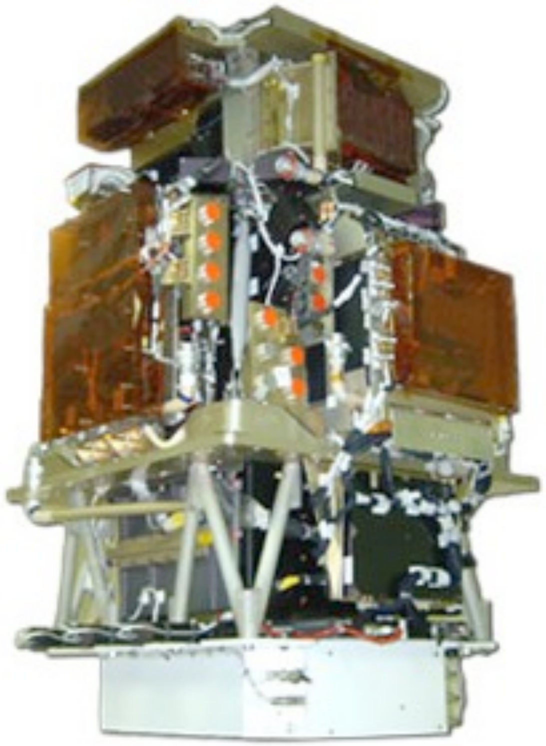
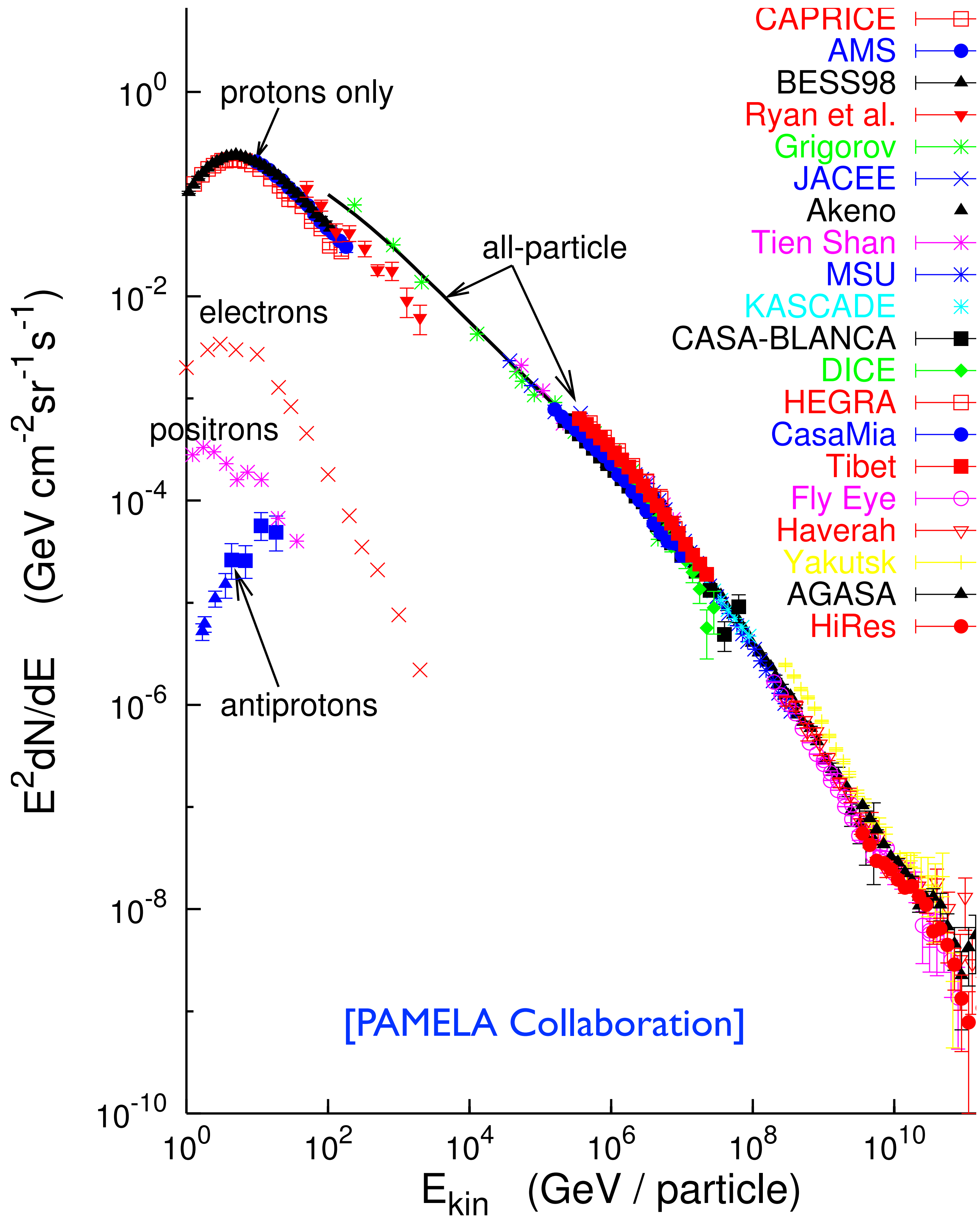
The charged particles scatters in the magnetic field in the Galaxy.





PAMELA

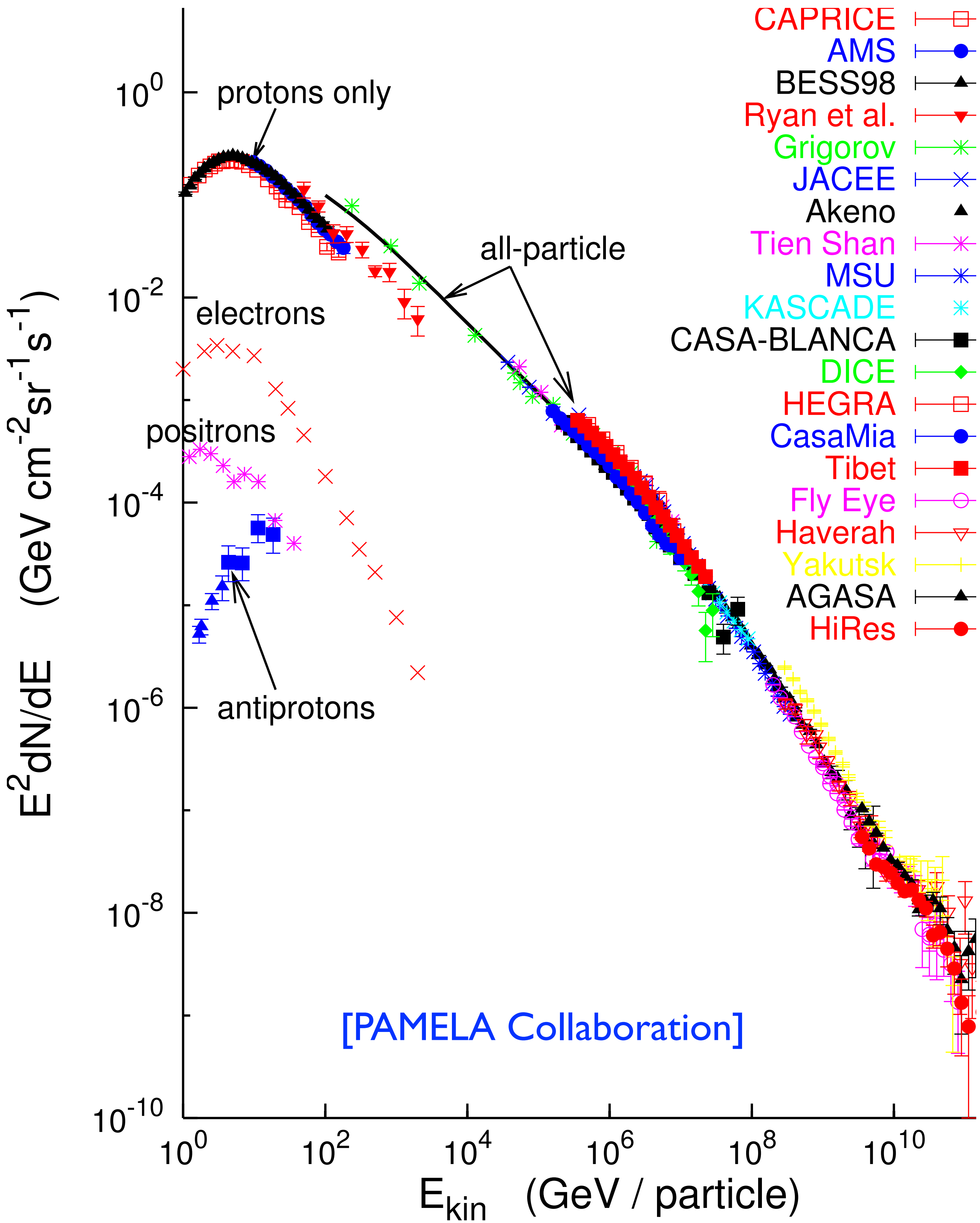
AMS-02



Compare with the DM flux

for $m_W = 100\,\mathrm{GeV}$

$$\phi_0 \simeq 6.6\times 10^4\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$$

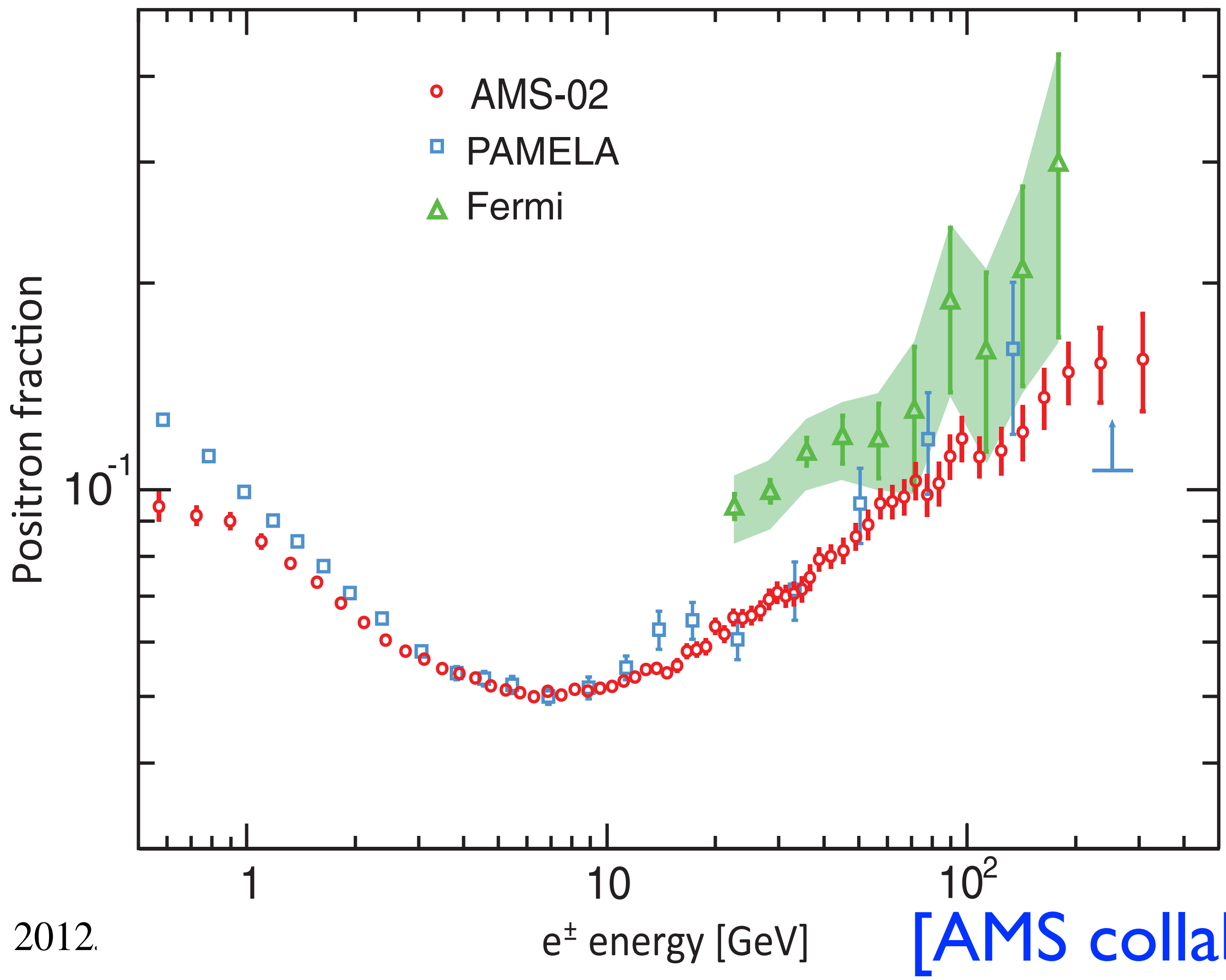


A precision measurement by the Alpha Magnetic Spectrometer on the International Space Station of the positron fraction in primary cosmic rays in the energy range from 0.5 to 350 GeV based on 6.8×10^6 positron and electron events is presented. The very accurate data show that the positron fraction is steadily increasing from 10 to ~250 GeV, but, from 20 to 250 GeV, the slope decreases by an order of magnitude. The positron fraction spectrum shows no fine structure, and the positron to electron ratio shows no observable anisotropy. Together, these features show the existence of new physical phenomena.

Below 10 GeV:

Secondary production of cosmic rays

by collision with intestellar medium



18 months data
from 19 May 2011 to 10 December 2012

[AMS collaboration, PRL 2013]

FIG. 5 (color). The positron fraction compared with the most recent measurements from PAMELA [22] and Fermi-LAT [23].

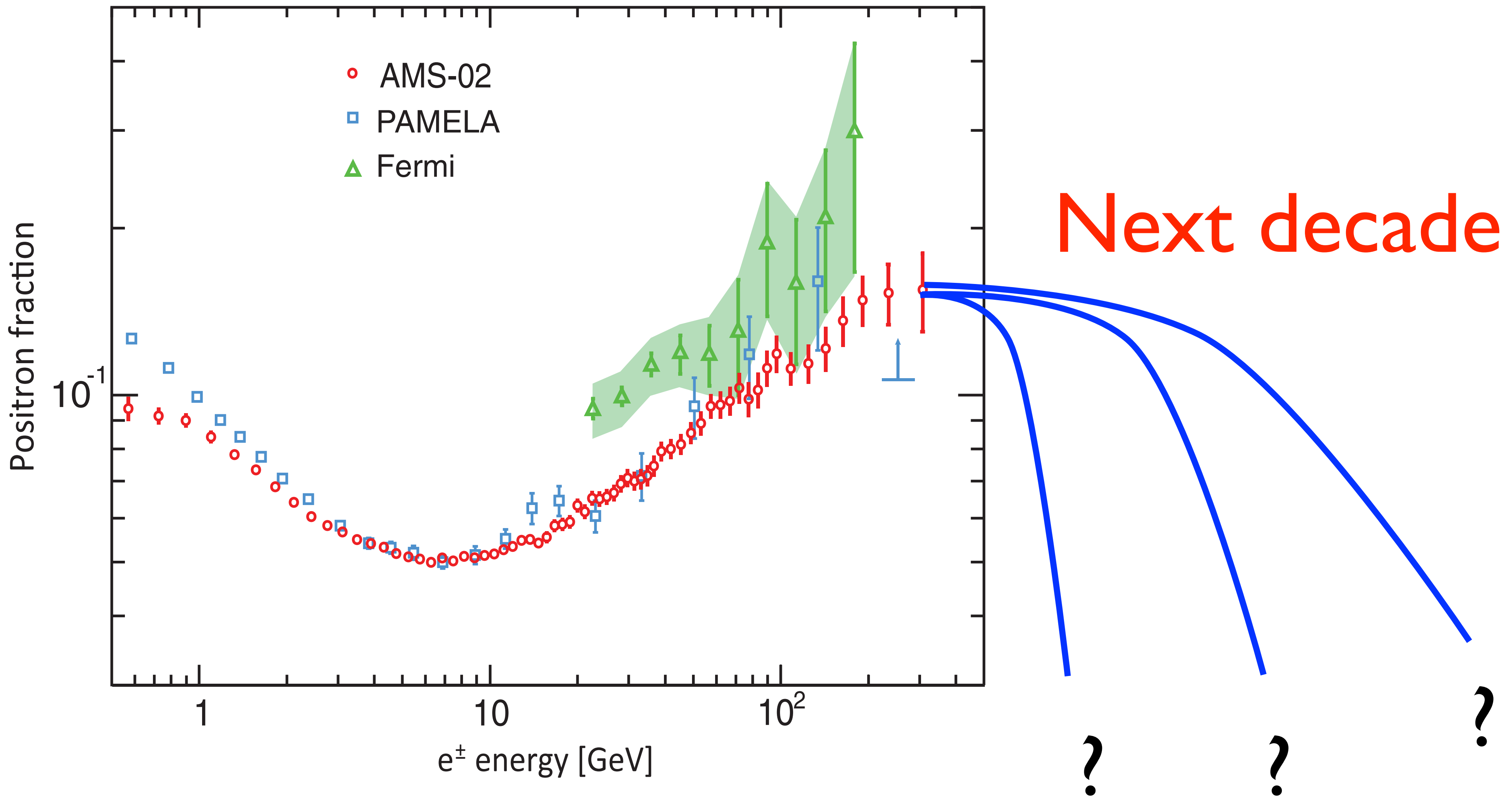


FIG. 5 (color). The positron fraction compared with the most recent measurements from PAMELA [22] and Fermi-LAT [23].

AMS-02 (Alpha Magnetic spectrometer)

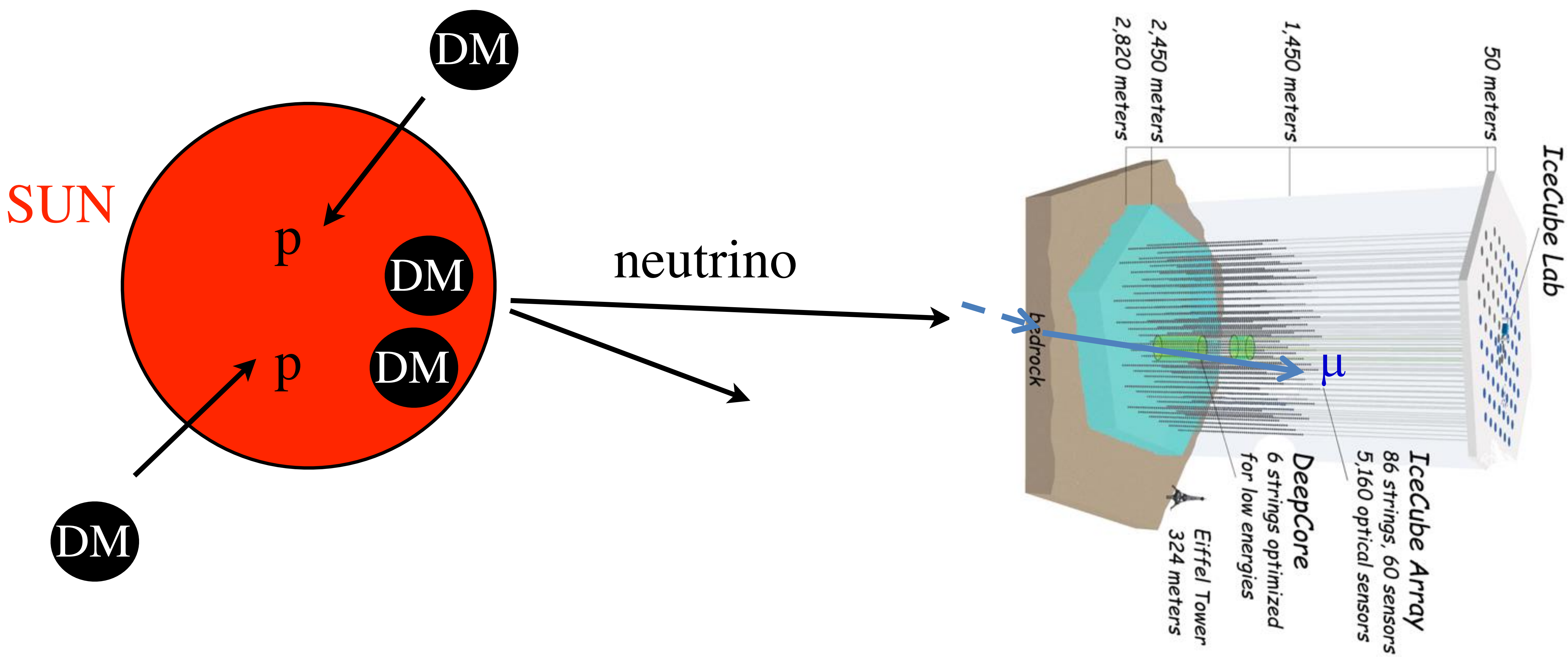
The $2 billion machine was installed on the International Space Station on 19 May 2011, and so far, it has detected 25 billion particle events, including about 8 billion electrons and positrons. It continues for 10 years at ISS.

• Indirect Detection : neutrino

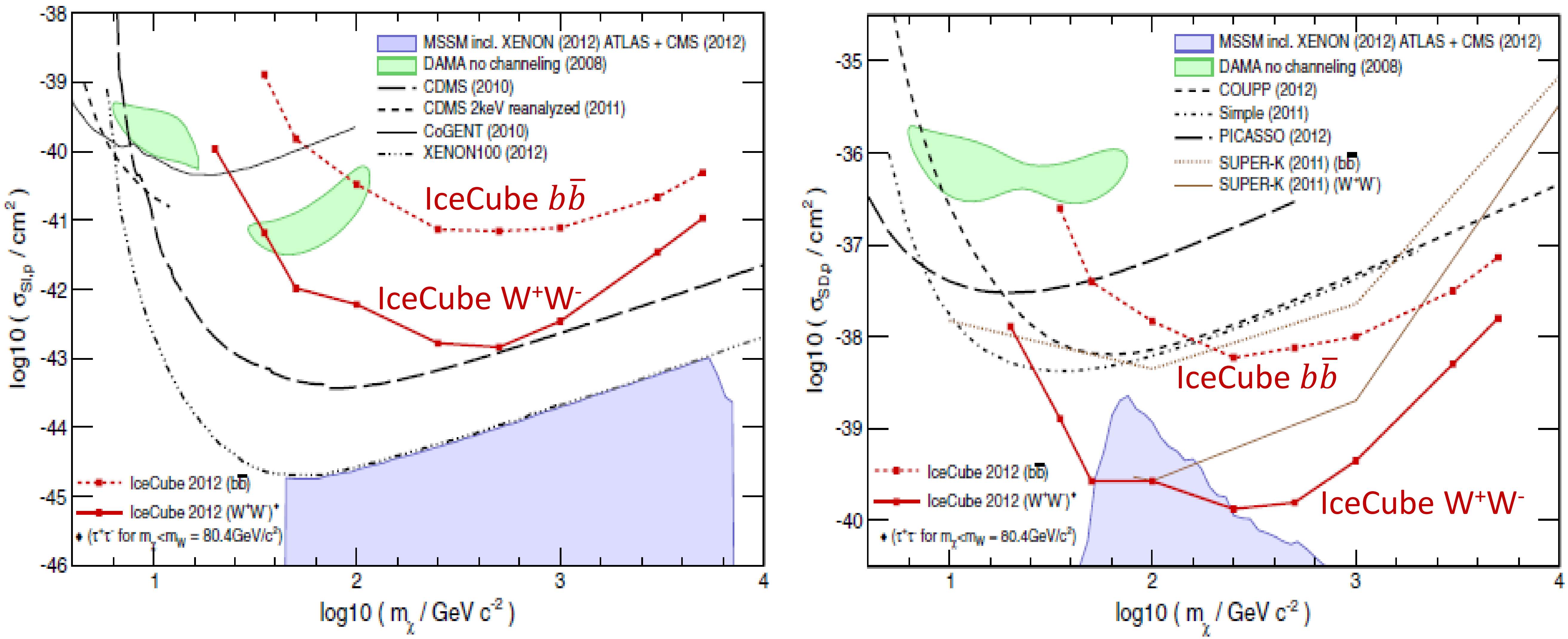
They come through directly from the source to the detector around Earth.

The signal is very weak but also the background is very small.

WIMPs are captured in the Sun by SI or SD scattering and their annihilation produce cosmic neutrinos.



Neutrinos from the Sun $\sigma_{SI,p}$ $\sigma_{SD,p}$ [Aartsen etal, 2013]



95% upper limits on the Spin-Independent (Left) and Spin-Dependent (right) scattering cross section of DM and proton.

Summary

- We need Dark Matter to explain the cosmological and astrophysical observations. All of these are based on the gravitational interaction.

- There are many experiments to see the non-gravitational signals of dark matter. However no conclusive result yet.

- There are some anomalous observations in the direct detection and indirection. However we need more efforts to identify the signatures as dark matter evidence.