Direct + indirect detection of Dark Matter

Ranny Budnik

Weizmann Institute of Science

מכון ויצמן למדע
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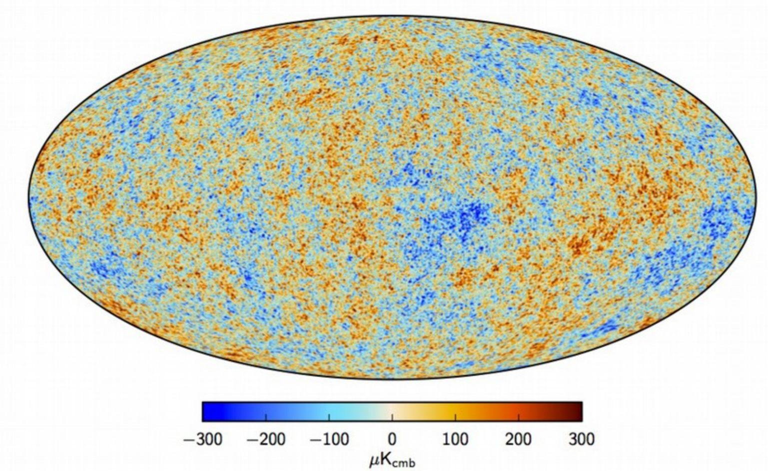
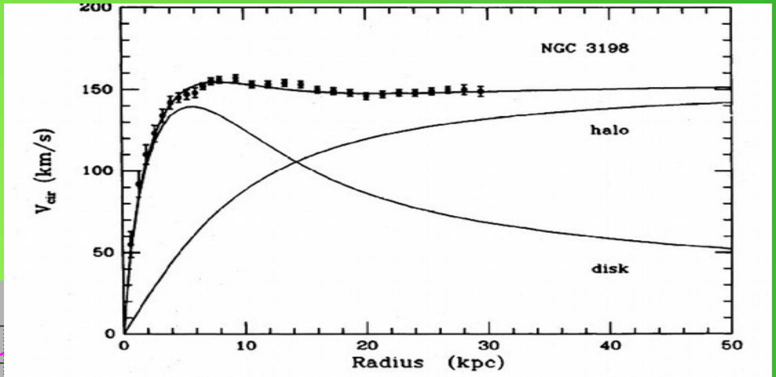
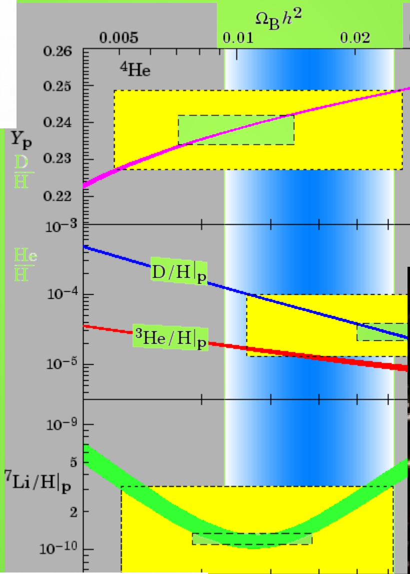
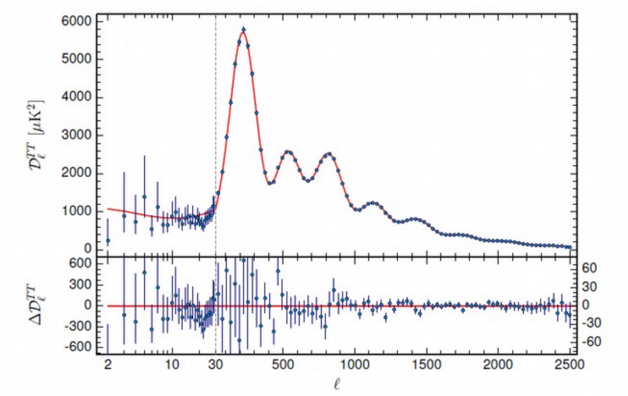
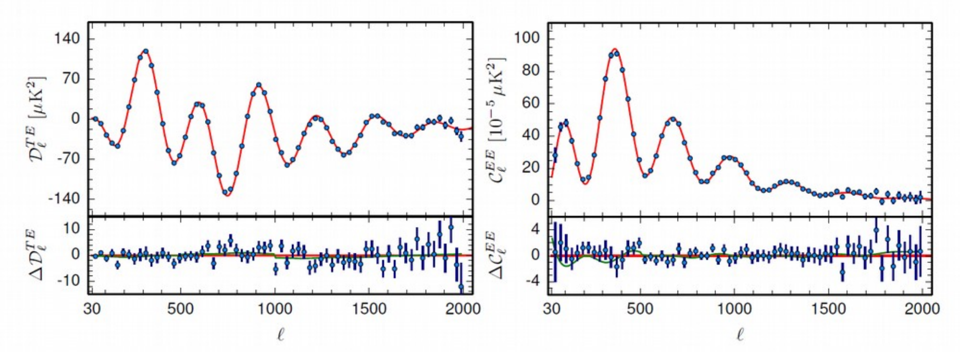
DM evidence in one slide



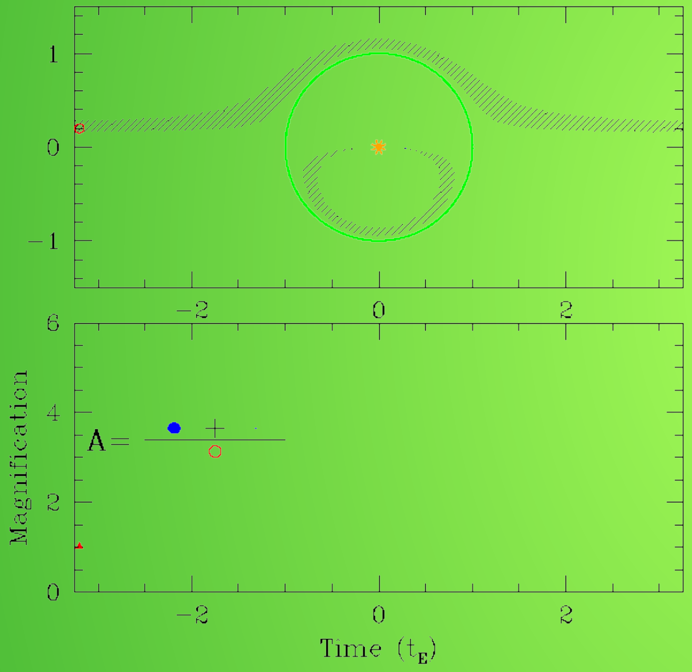








Machos



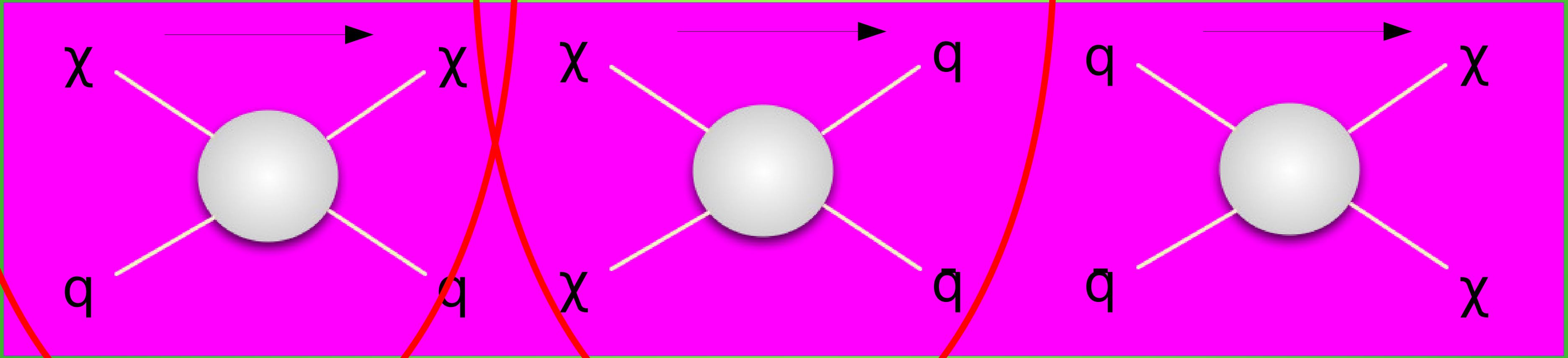
- Massive Compact Halo Objects might be the DM
- They can be seen by microlensing events of background stars
- Campaigns measuring these events have concluded that MACHOs can not account for the DM in our Galaxy

A short reminder, we are looking for WIMPs...

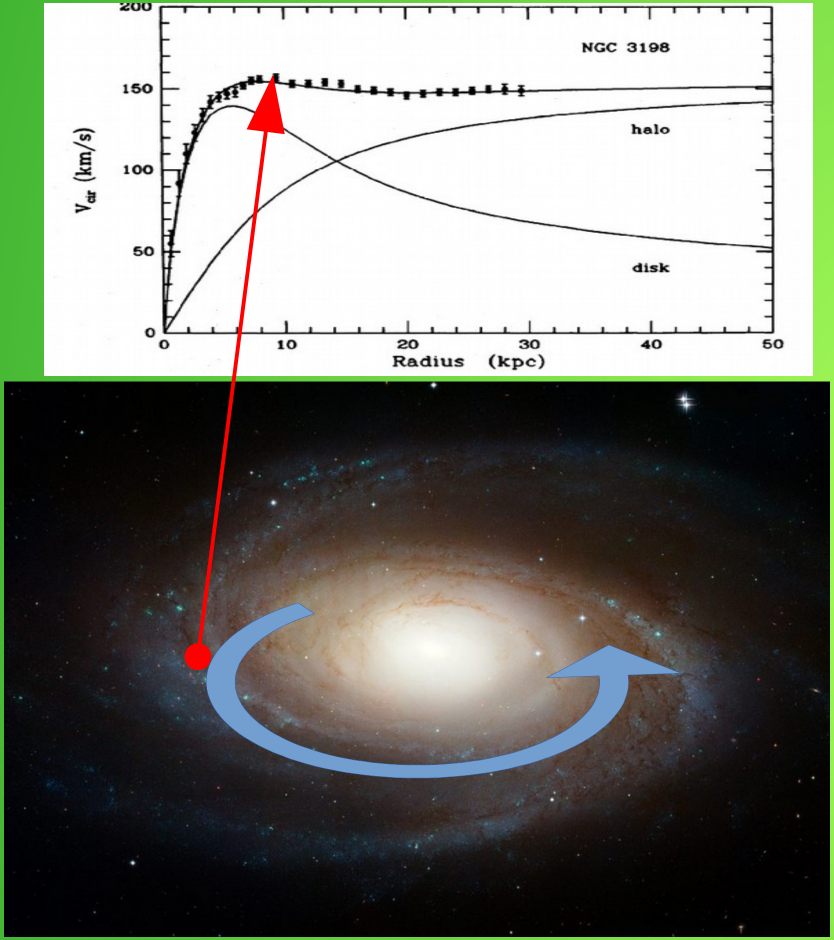
Underground

Above ground

At the LHC



Galactic DM



- Our Galaxy is rotating at ~200 km/s at the Sun's orbit
- DM is “standing still”
- Hence, there is a “constant” flux of DM through Earth!
- Velocities are non-relativistic, $\beta \sim 10^{-3}$
- $\langle v^2_{DM} \rangle = v^2_{SUN}$ (or close to it)

Principles of Direct Detection

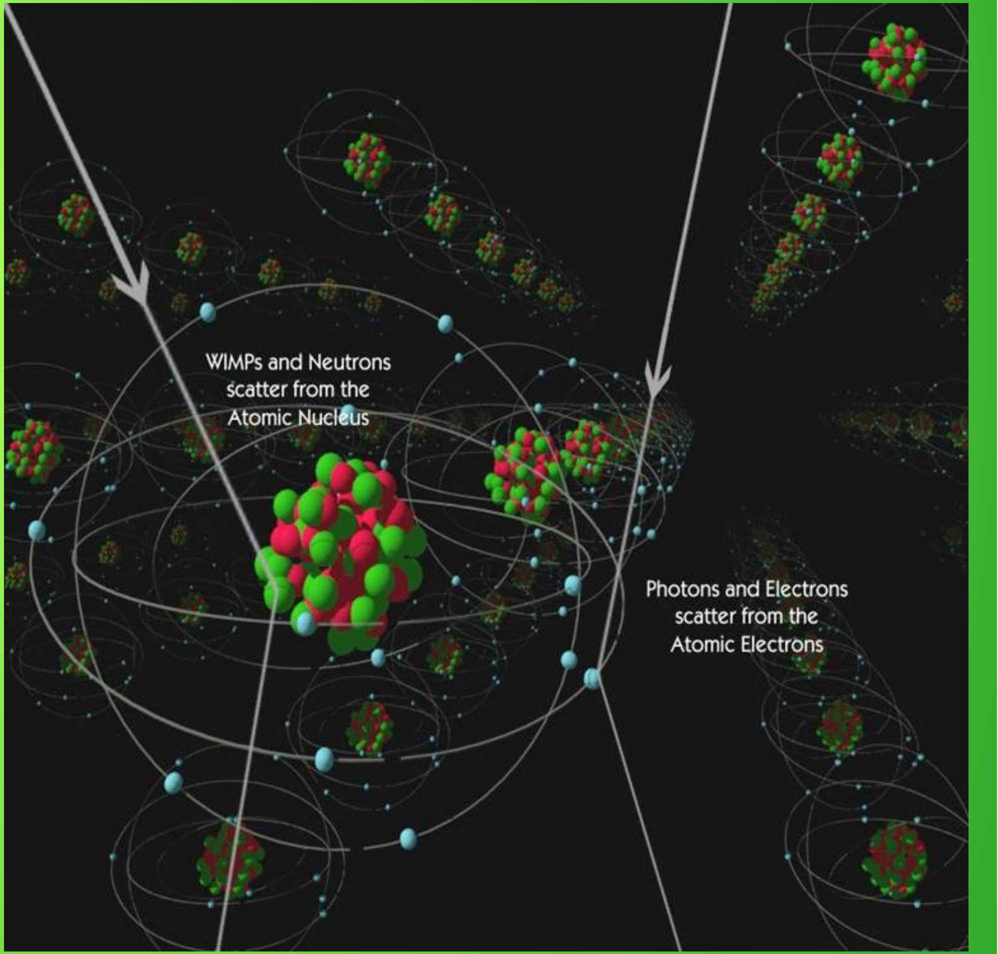
- Movement with respect to the galactic frame imply DM flux,

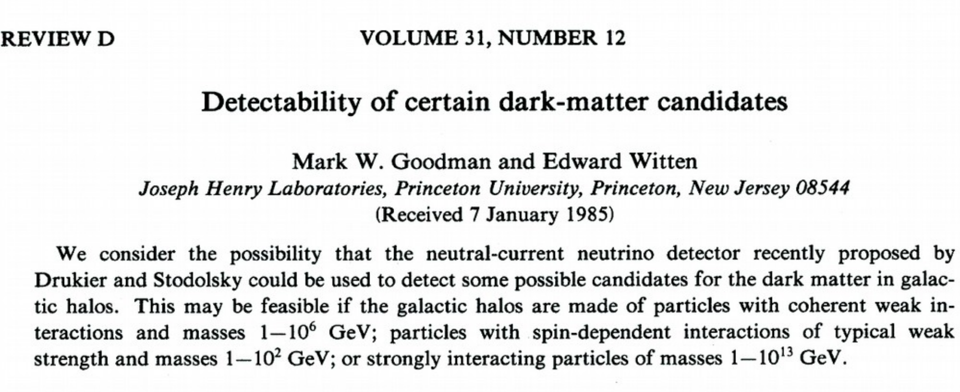
$$\Phi \simeq 7.5 \times 10^4 \text{ particles}/\text{cm}^2/\text{sec}$$

(for ~100 GeV particle)

- DM recoils off a target material, leaving
  some energy in the form of:
  - Ionized electrons.
  - Scintillation light.
  - Heat/phonons.

- Signal is collected and the recoil energy is extracted.




REVIEW D VOLUME 31, NUMBER 12

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses 1–10^6 GeV; particles with spin-dependent interactions of typical weak strength and masses 1–10^2 GeV; or strongly interacting particles of masses 1–10^{13} GeV.

Some thumb rules for the interaction

- Assuming an isothermal halo $\rho_{DM} \approx 0.3\ \mathrm{GeV/cm^3}$
- Velocity of the sun around the Galaxy "rest frame" $v_0 \sim 230\ \mathrm{km/s}$, escape velocity $\sim 550\ \mathrm{km/s}$
- Recoil energy of a nucleus by elastic scattering:

  $$E_{r,\mathrm{max}} = \frac{p_\chi}{2m_N} \sim \frac{(100\mathrm{GeV/c^2} \times 10^{-3}c)^2}{2 \times 100\mathrm{GeV/c^2}} \approx 50\ \mathrm{keV} \Rightarrow \text{Low energy detectors}$$

- Coherent scattering

  $$\frac{\lambda_{\mathrm{DeBroglie}}}{2\pi} = \frac{\hbar}{p} \approx 1\mathrm{fm} \approx r_{\mathrm{nuc}} \Rightarrow \sigma_{SI} \propto A^2$$

- Rate of interactions:

  $$\Gamma = \Phi \sigma_{\chi,N} N_{\mathrm{Detector}} A^2, \text{ for } \sigma_{\chi,N} = 10^{-45}\ \mathrm{cm^2}, m_\chi = 100\ \mathrm{GeV}$$

  $$\Gamma \sim 100\ \text{events/ton/yr}$$

True for elastic recoils only!

Of course, reality is a bit more complicated...

Dark Matter Direct Detection

Goal: Observe WIMP interactions with some target material

Expected interaction rate

Number of targets

WIMP density

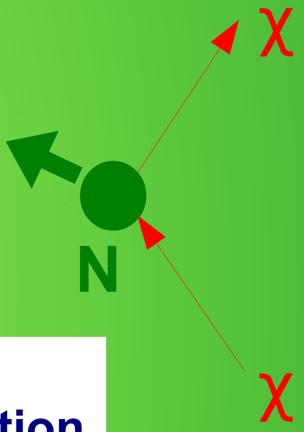
Nuclear Form factor

$$\frac{dR}{dE_{NR}} \propto N \frac{\rho_\chi}{2 m_\chi \mu^2} \sigma_N \left|F^2(E_{NR})\right| \int_{v_{min}}^{v_{esc}} \frac{f(\vec{v})}{v} d^3v$$

WIMP mass

Interaction cross section

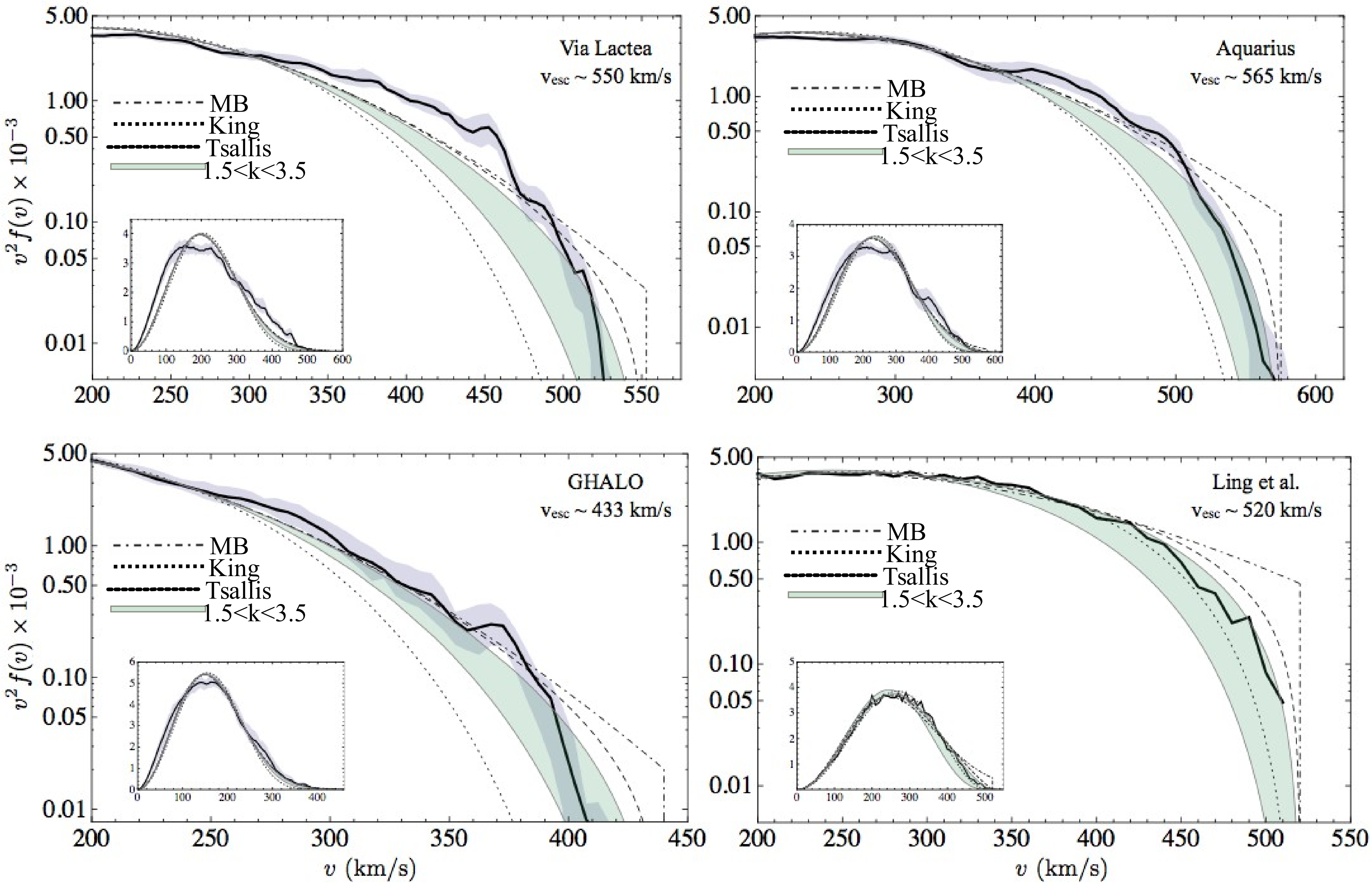
WIMP velocity distribution



$$v_{min} = \sqrt{\frac{m_N E_{nr}}{2\,\mu^2}}$$

- Only those WIMPs with velocity above threshold will contribute to that energy
- For Spin Independent interactions the cross section is enhanced by a factor A^2 (coherent scattering)

Uncertainties in Velocity Distributions



[Lisanti et al., 2010]

Minimum velocity

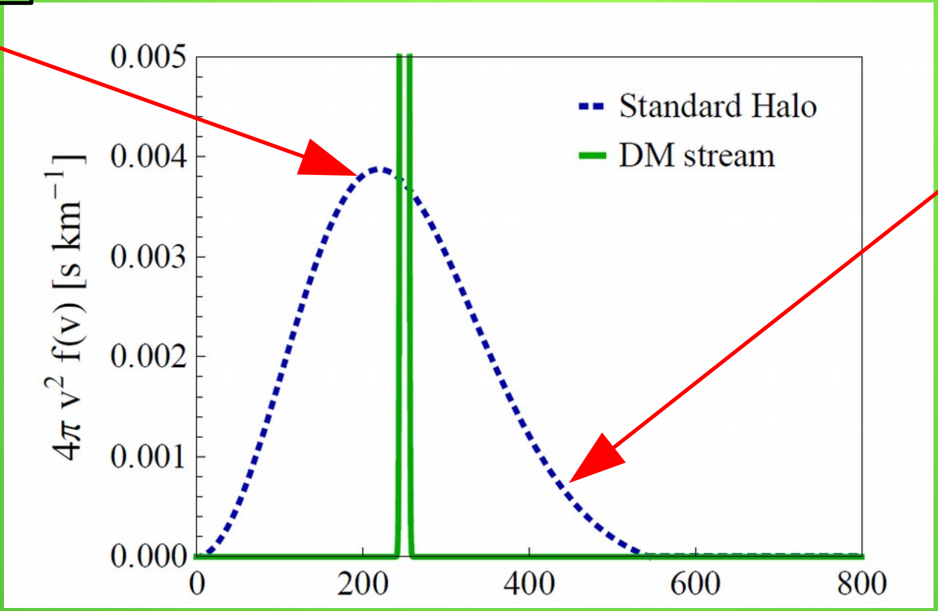
- Each combination of **DM mass**, **target nucleus mass** and detector **threshold** determines v_{min}, under which no recoil can be detected

- As an example,

  For Xe target and threshold of 5 keV:

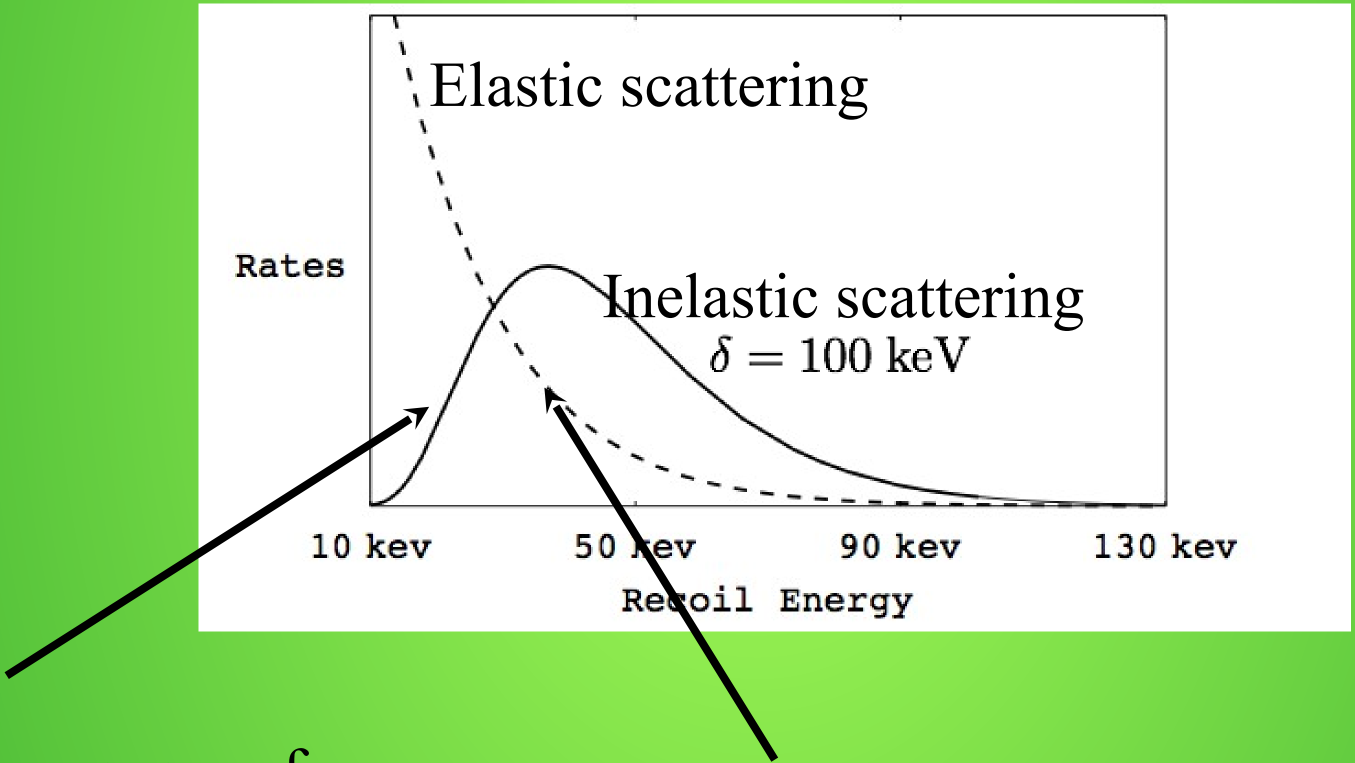
M_{χ} =100 GeV

M_{χ} =10 GeV



Recoil Energy Spectrum

- Exponentially falling for simple scenarios, however there are complications



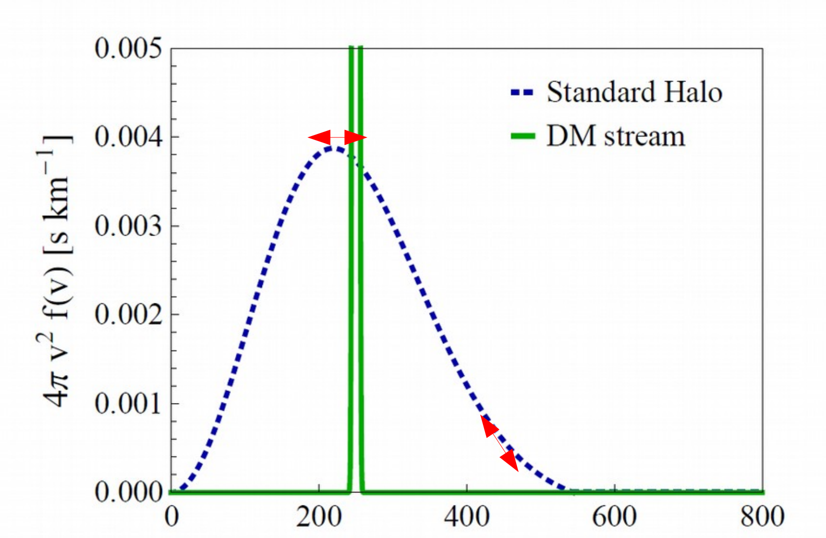
Drop at low energy for inelastic scattering

Exponential fall due to nucleus form-factor and velocity distribution

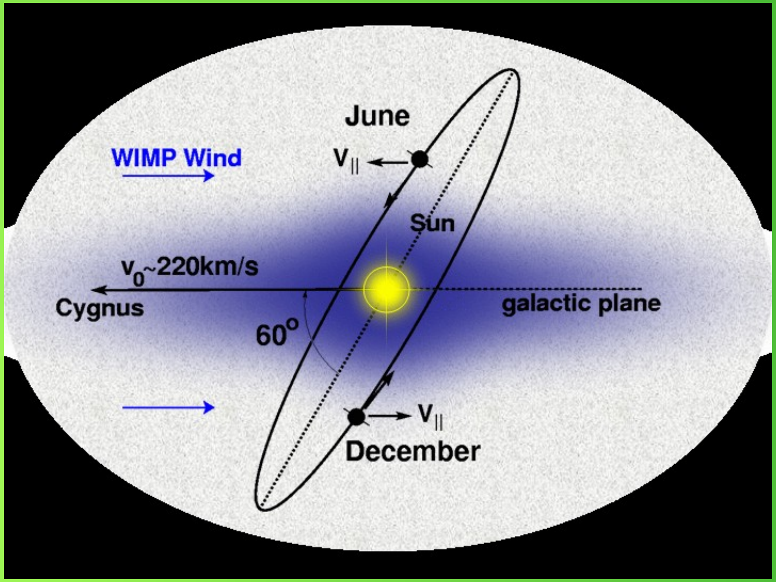
$$v_{\min} = \frac{1}{\sqrt{2 m_N E_R}} \left| \frac{m_N E_R}{\mu} + \delta \right| .$$

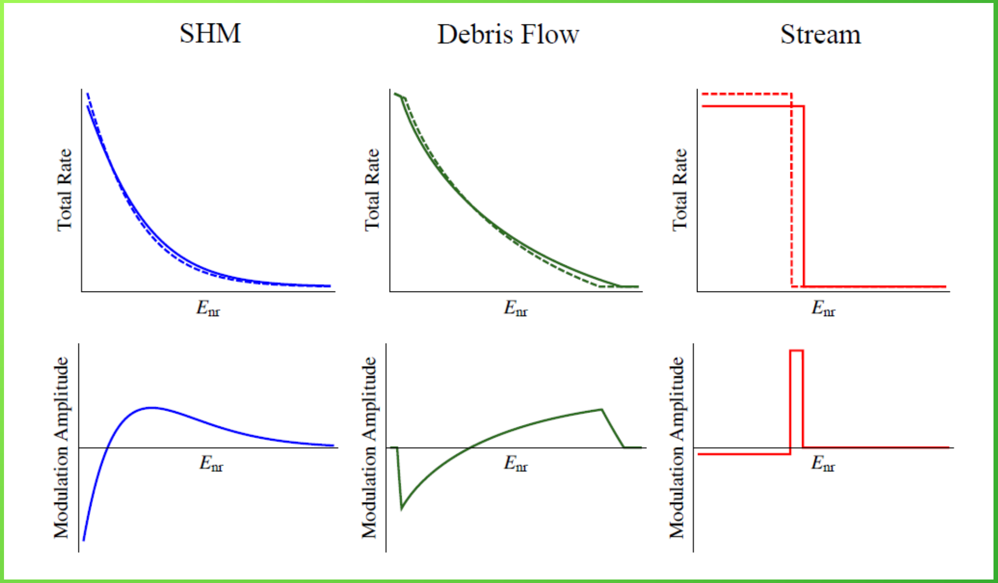
Dark matter and Earth dynamics: Annual modulation

- In general, the higher v_{min}, the stronger the relative modulation, but...



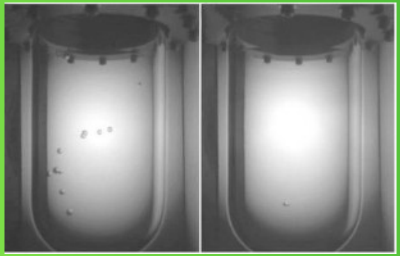
About 7% modulation on <v>, can be much higher in signal





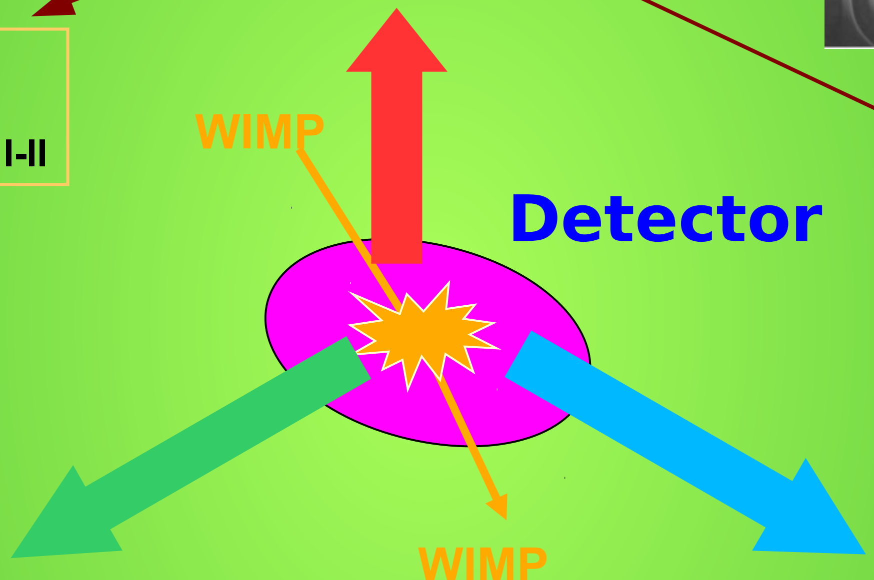
Dark Matter Direct Detection

PICASSO
SIMPLE
COUPP
PICO



HEAT

CDMS I-II
superCDMS
EDELWEISS I-II



WIMP

Detector

WIMP

CRESST -II
ROSEBUD

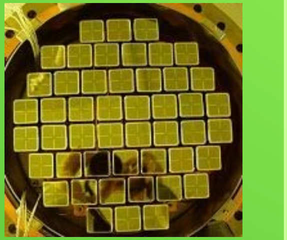
IONIZATION

SCINTILLATION

+time measurement

ZEPLIN I
CLEAN
DEAP
XMASS

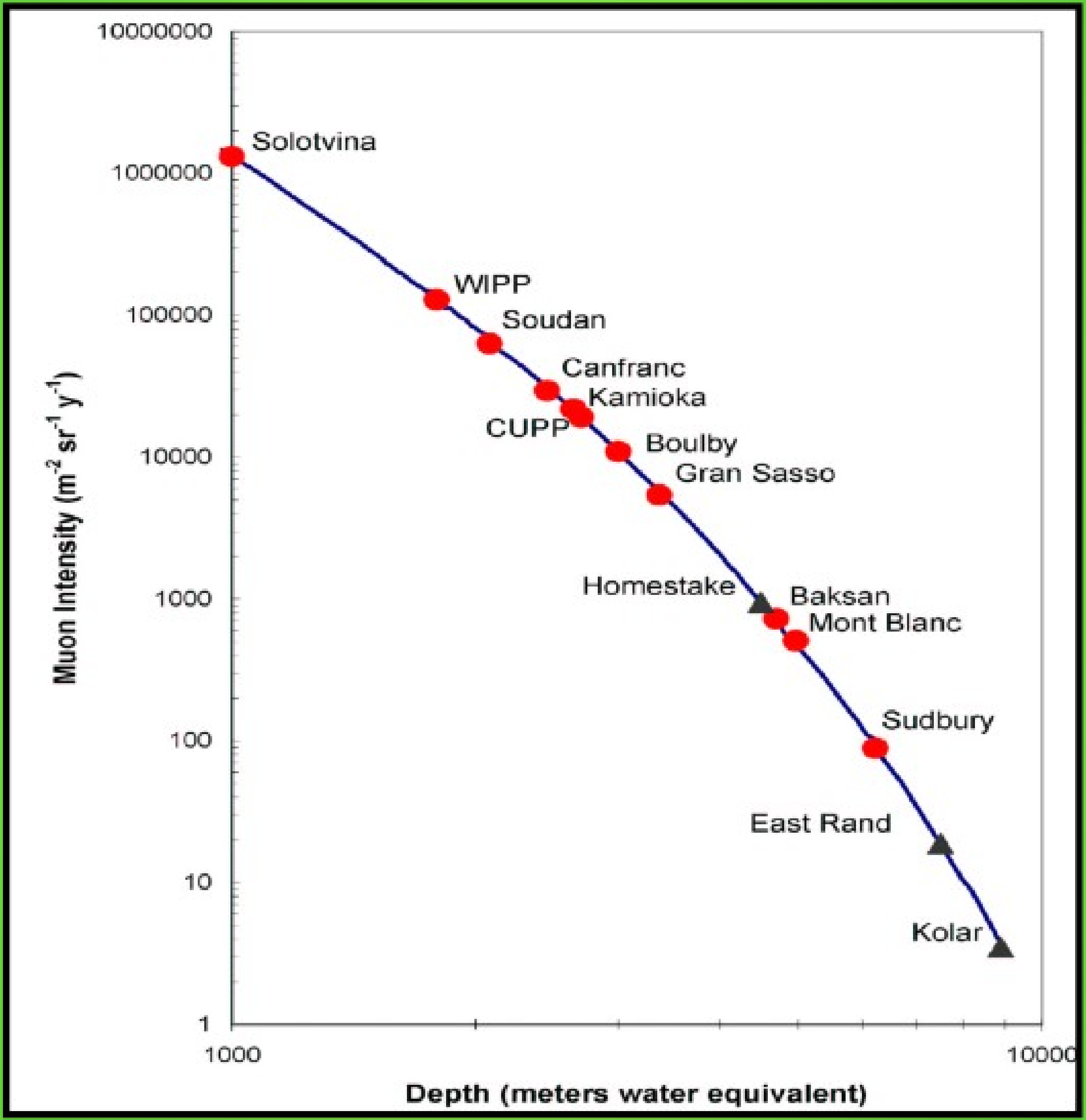
HPGe exp.
IGEX → GEDEON
GERDA
GENIUS
CoGeNT



ZEPLIN II-III
XMASS II
XENON
LUX
WARP,
ArDM
DarkSide

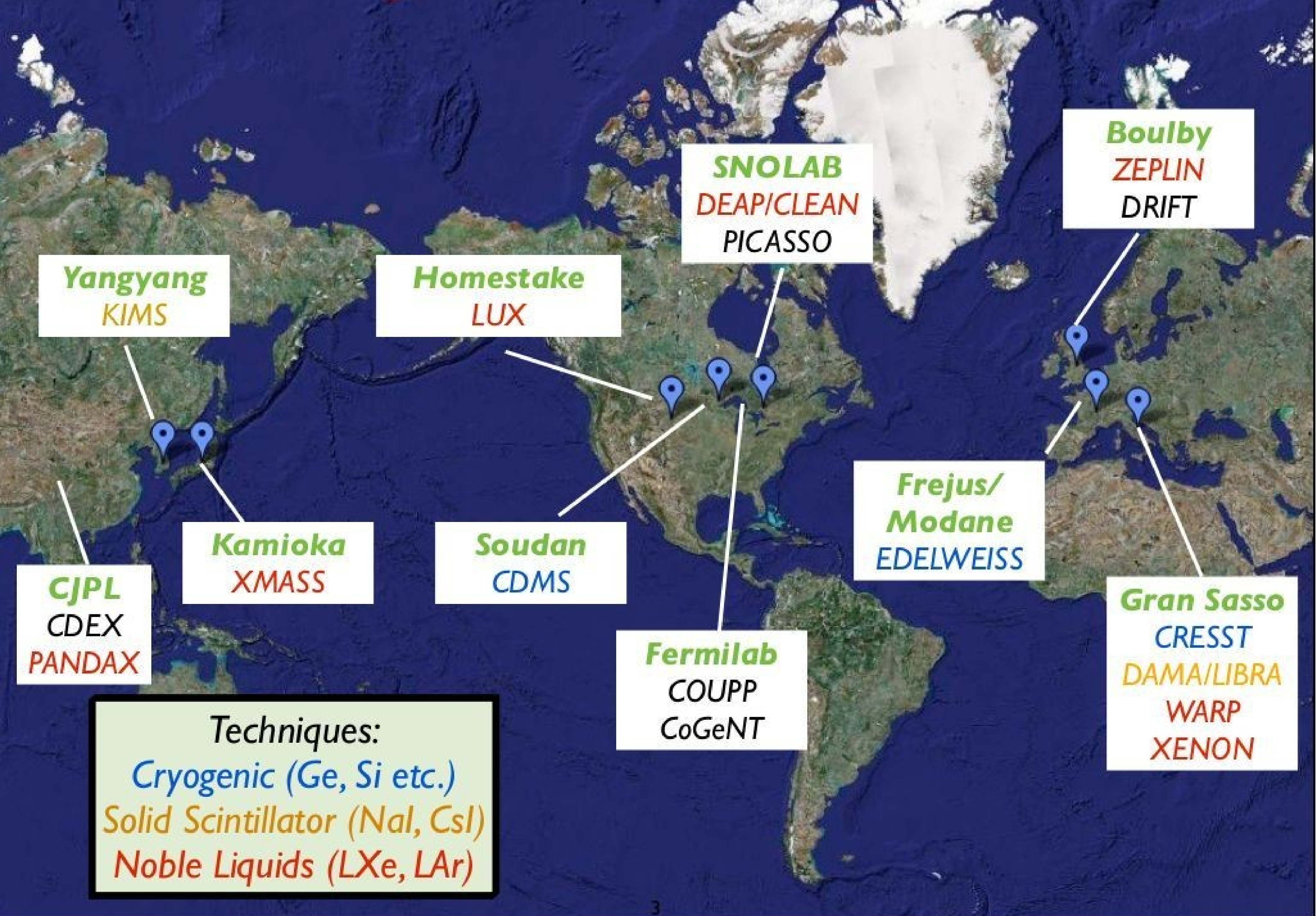
DAMA / LIBRA
KIMS

Direct Detection Muon Background



We must seek shelter underground!

Looking for Dark Matter at Underground Labs



Yangyang
KIMS

Homestake
LUX

SNOLAB
DEAP/CLEAN
PICASSO

Boulby
ZEPLIN
DRIFT

CJPL
CDEX
PANDAX

Kamioka
XMASS

Soudan
CDMS

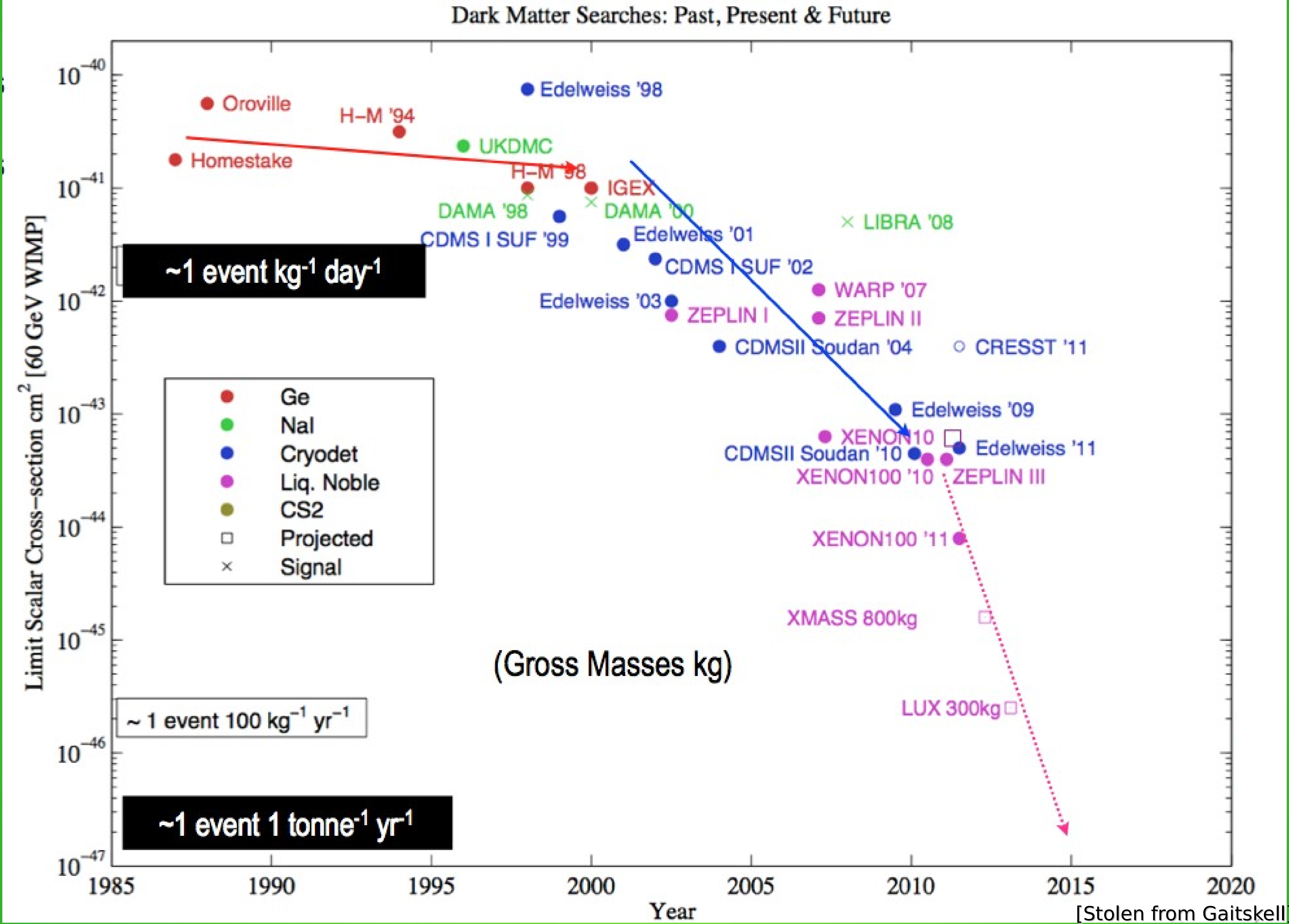
Fermilab
COUPP
CoGeNT

Frejus/ Modane
EDELWEISS

Gran Sasso
CRESST
DAMA/LIBRA
WARP
XENON

Techniques:
Cryogenic (Ge, Si etc.)
Solid Scintillator (NaI, CsI)
Noble Liquids (LXe, LAr)

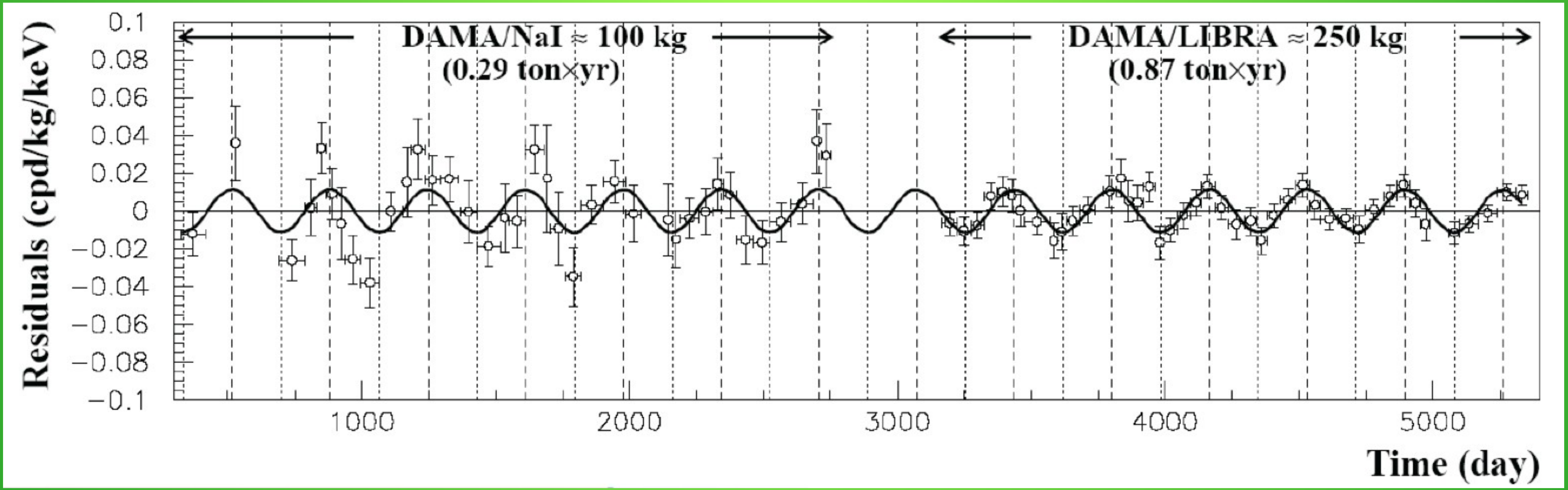
Direct Detection Progress



[Stolen from Gaitskell]

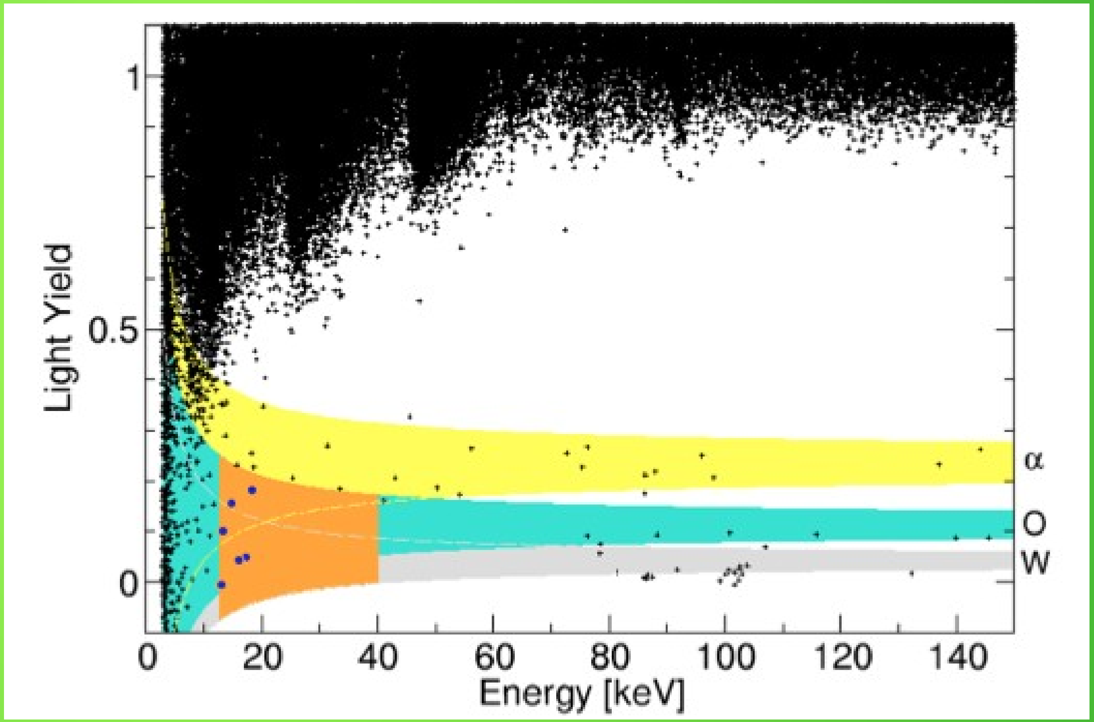
DAMA – claimed detection

- Long standing measurement (first positive result in 1999).
- Uses NaI crystals (250 kg in second DAMA/LIBRA phase).
- No background/signal discrimination. Searches for annual modulation.
- Results in 0.87 ton-year of data, and 8.9σ evidence for modulation (13 cycles)! Phase is correct - peak at June 2 ± week.



CRESST II – detection and confusion

- Cryogenic calorimeter. Collects phonons and scintillation light.
- Target: $CaWO_4$
- First analysis:
    - 730 kg-days
    - Found 67 events
    - 4.2σ-4.7σ
- A new analysis:
    - 572 kg-days
    - Found 52 events.
    - 1.9σ-2.5σ



CoGeNT (Coherent Germanium Neutrino Technology)

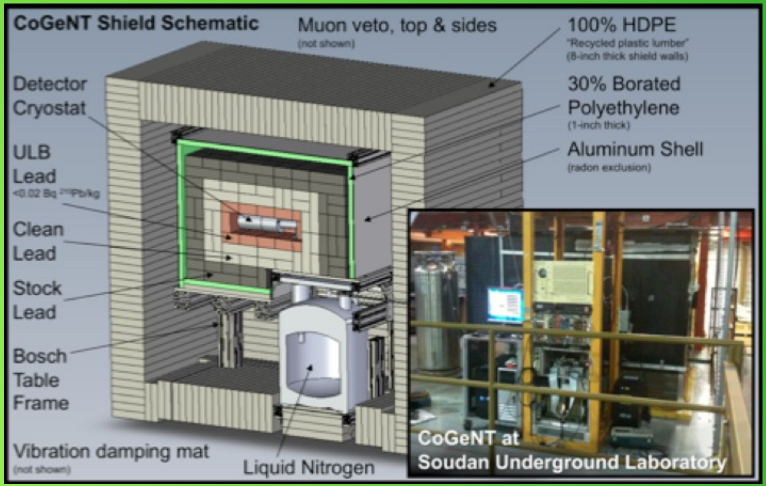
- Germanium detector in Soudan Underground Lab.
  0.5 keV threshold. No signal/background discrimination.

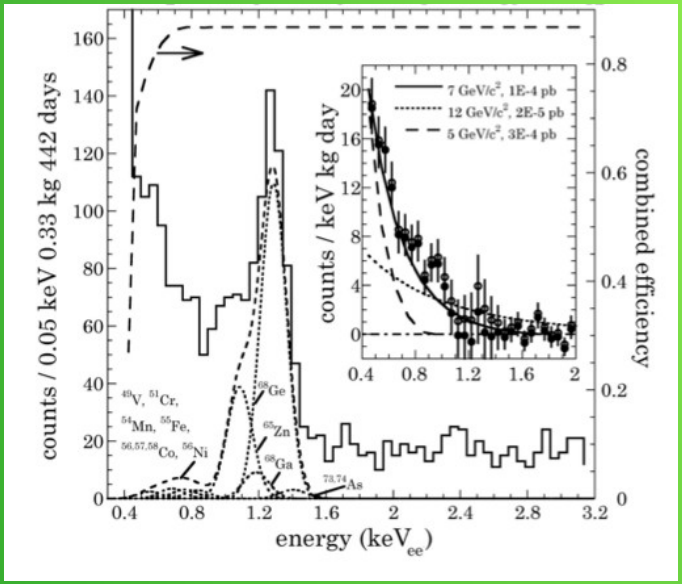
- Started taking data 2009. Fire broke in Mar. 2011.
  Resumed July 2011.

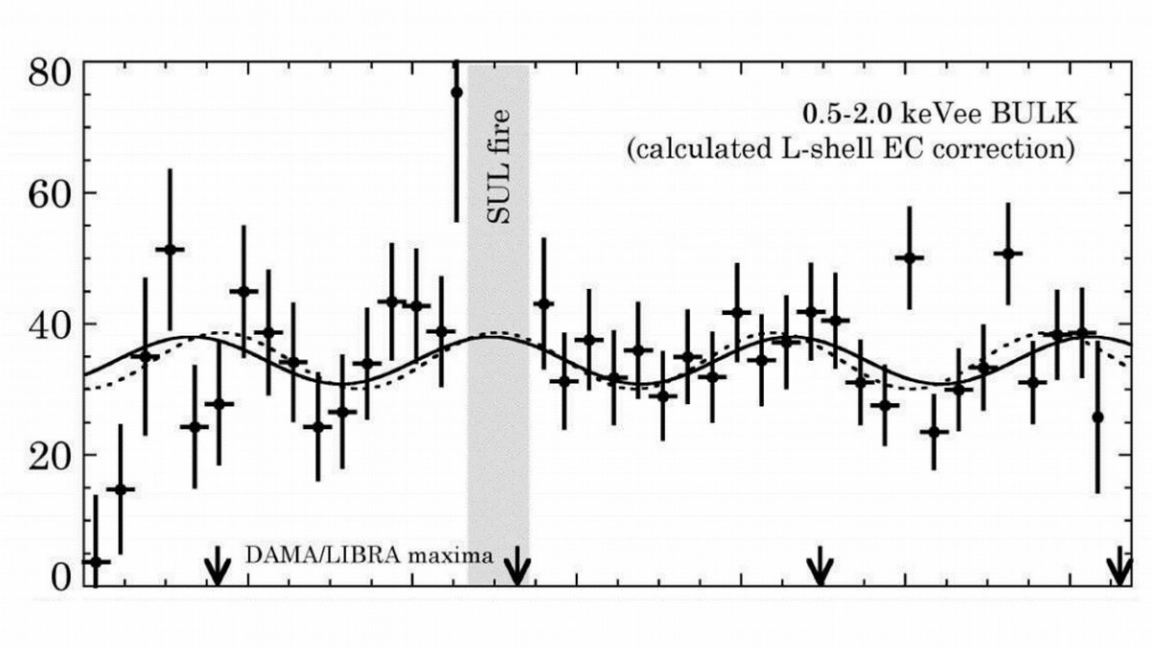
- Reported 442 live days on a 0.33kg Ge detector.

- CoGeNT's first release claimed an exponentially falling set of events, unexplained by background.
  Later an annual modulation was claimed.

- Latest results show decreased significance, but they are not discouraged!

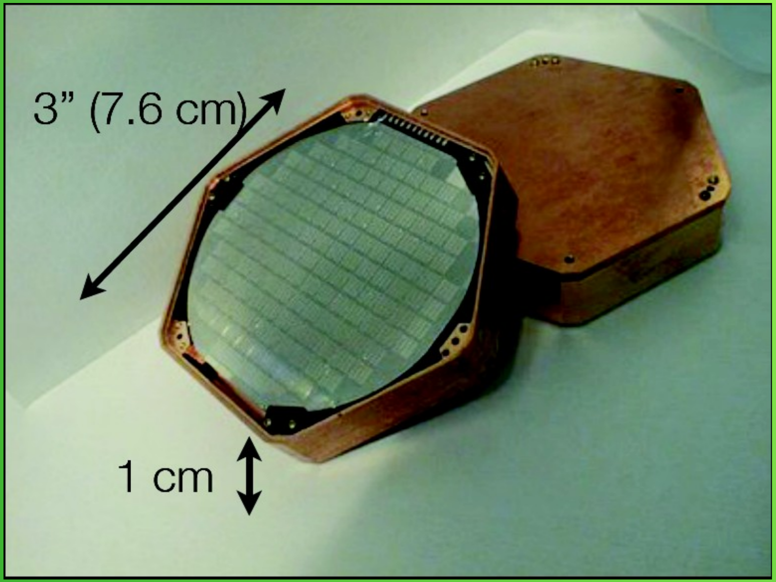


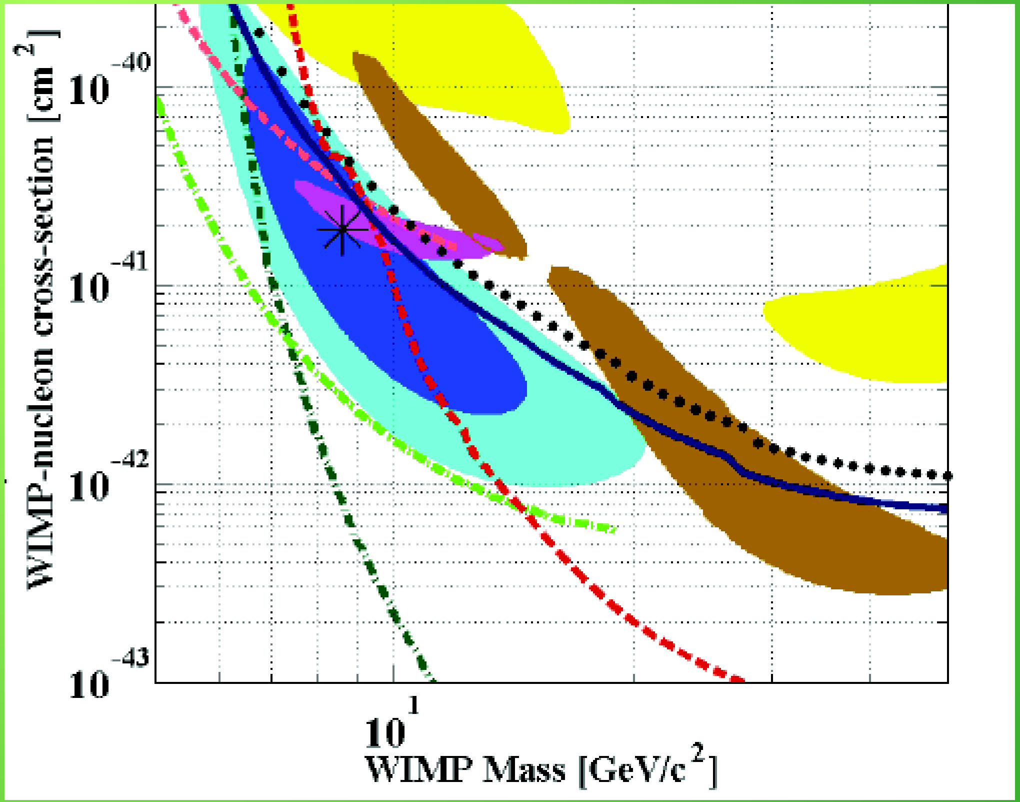




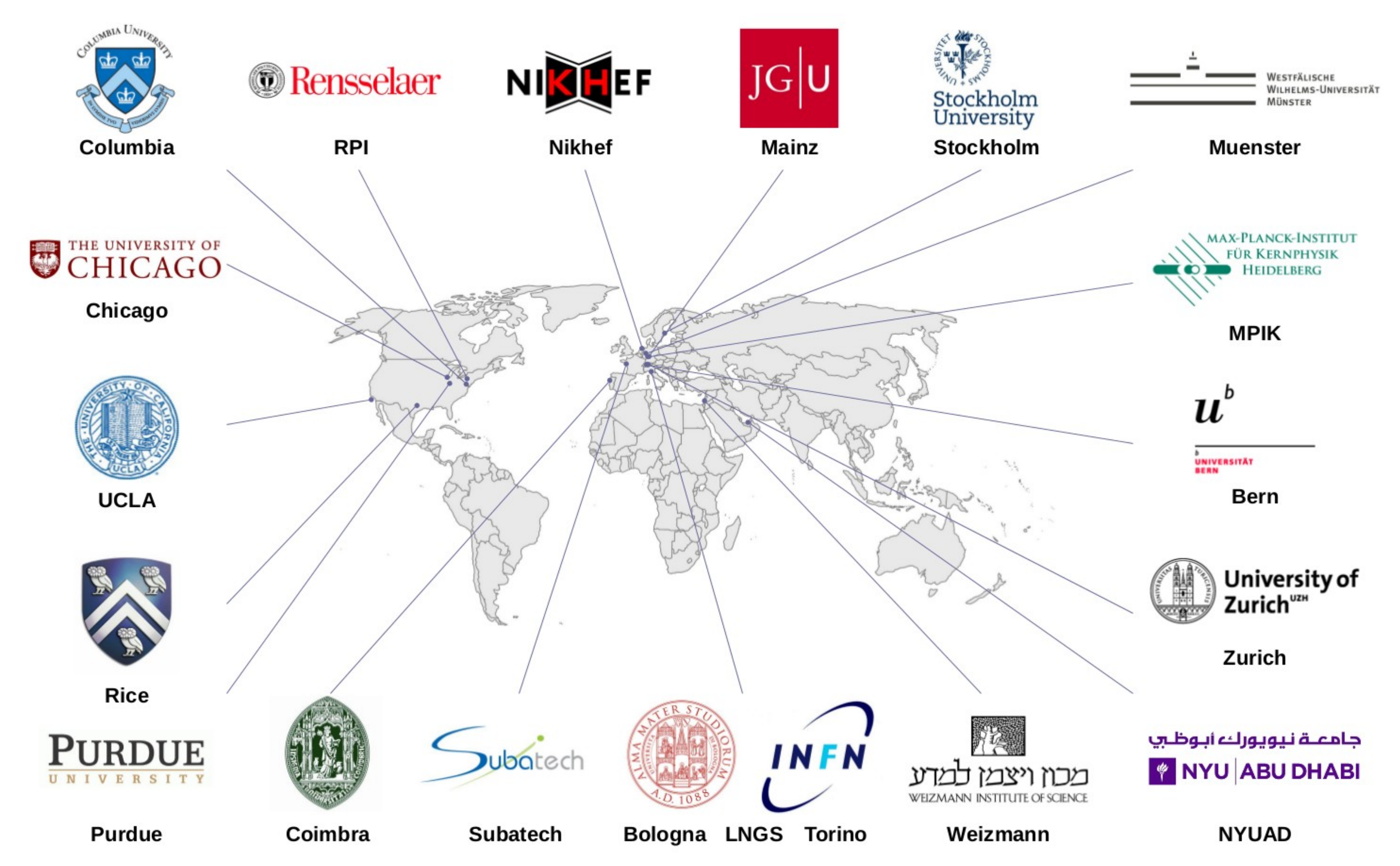
CDMS: Cryogenic DM Search

- Uses Ge and Si detectors with two channels: Ionization and heat (on phase transition)
- Features background rejection, but still not backgroud-free
- Lately analyzed data from 2006 in Si detectors and found 3 events, expecting 0.7
- Is it a claim???





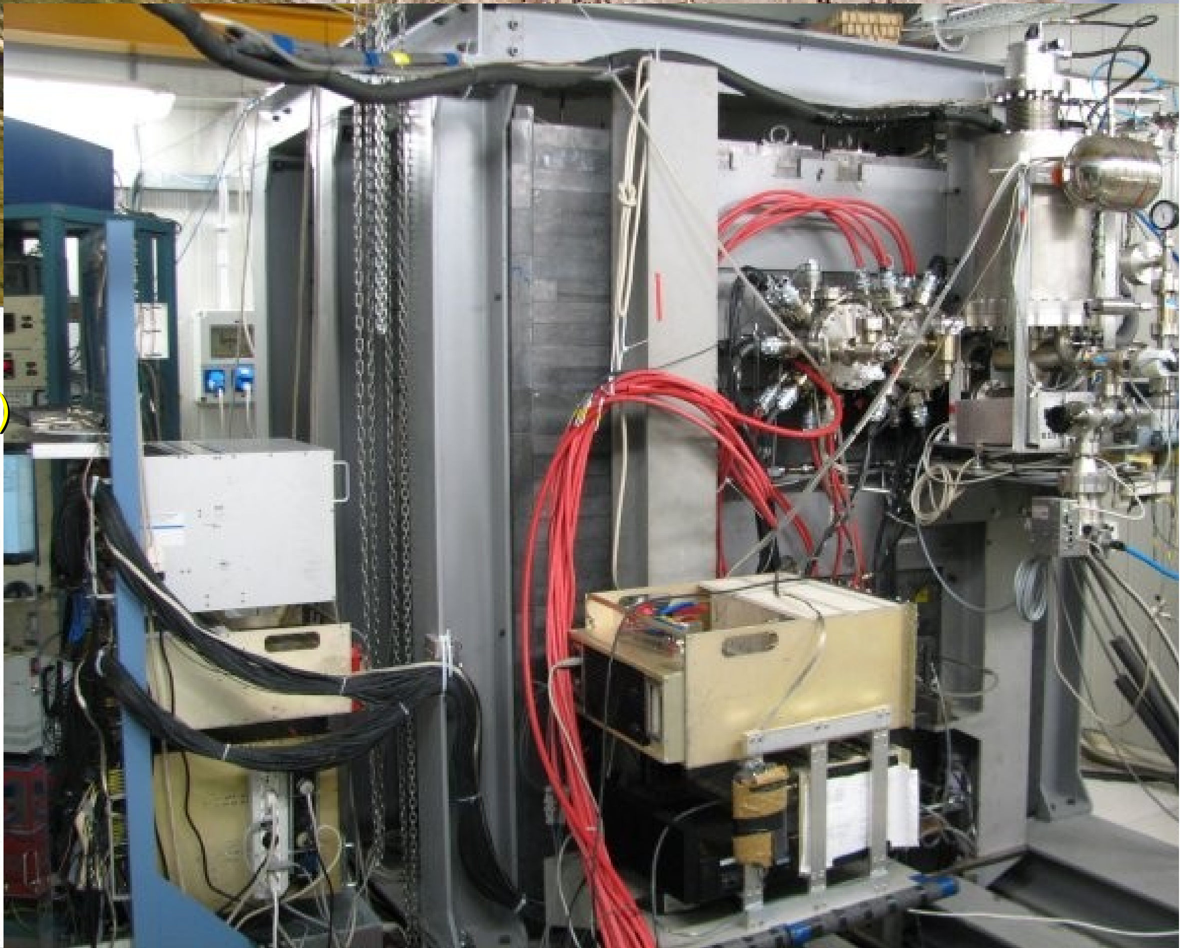
The XENON project as an example



An international collaboration from 2002

Laboratori Nazionali del Gran Sasso (LNGS)

LNGS: 1.4km rock
(3700 mwe)

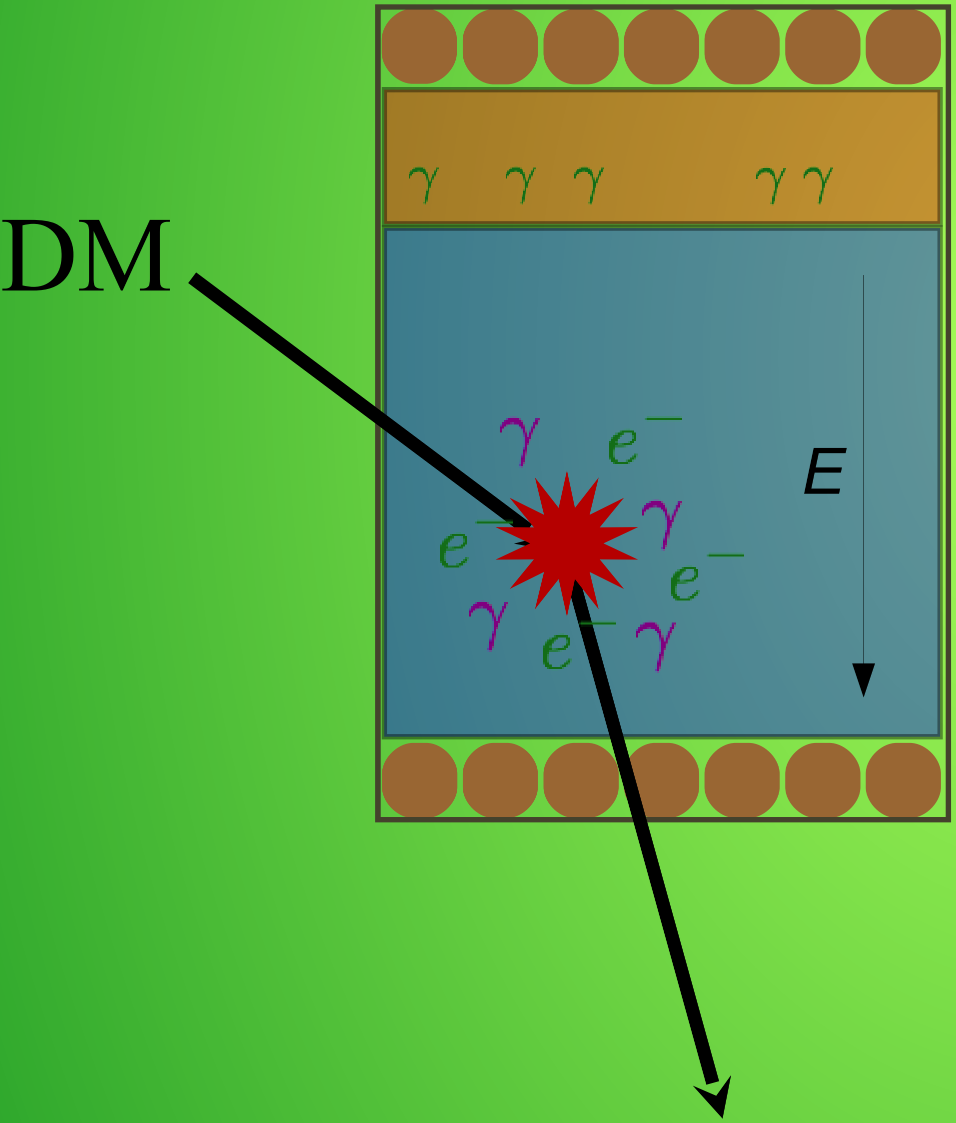


Two-Phase Xenon Detector

Time Projection Chamber = TPC

$$\mathrm{Xe} \rightarrow \mathrm{Xe}^*,\ \mathrm{Xe}^+$$

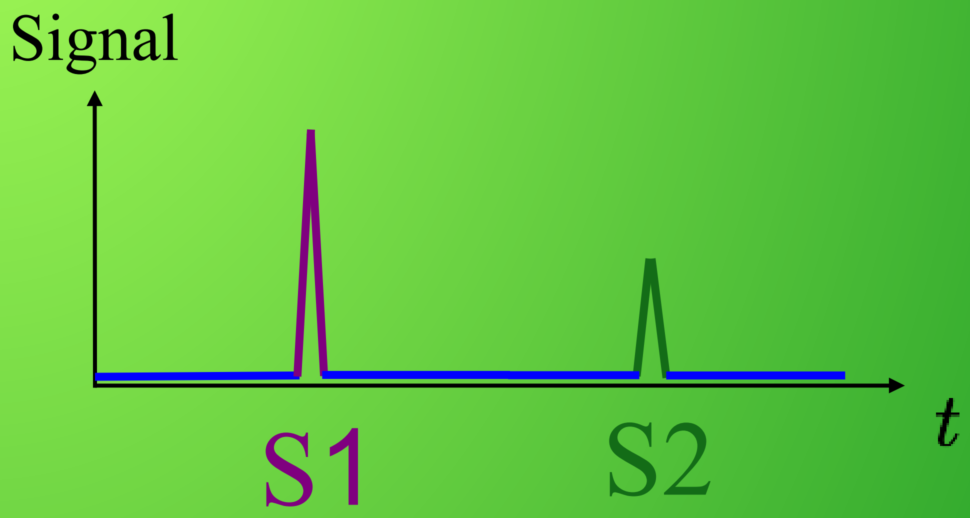
produces photons and electrons



Two types of signal:

S1: prompt scintillation

S2: proportional scintillation (from ionization)



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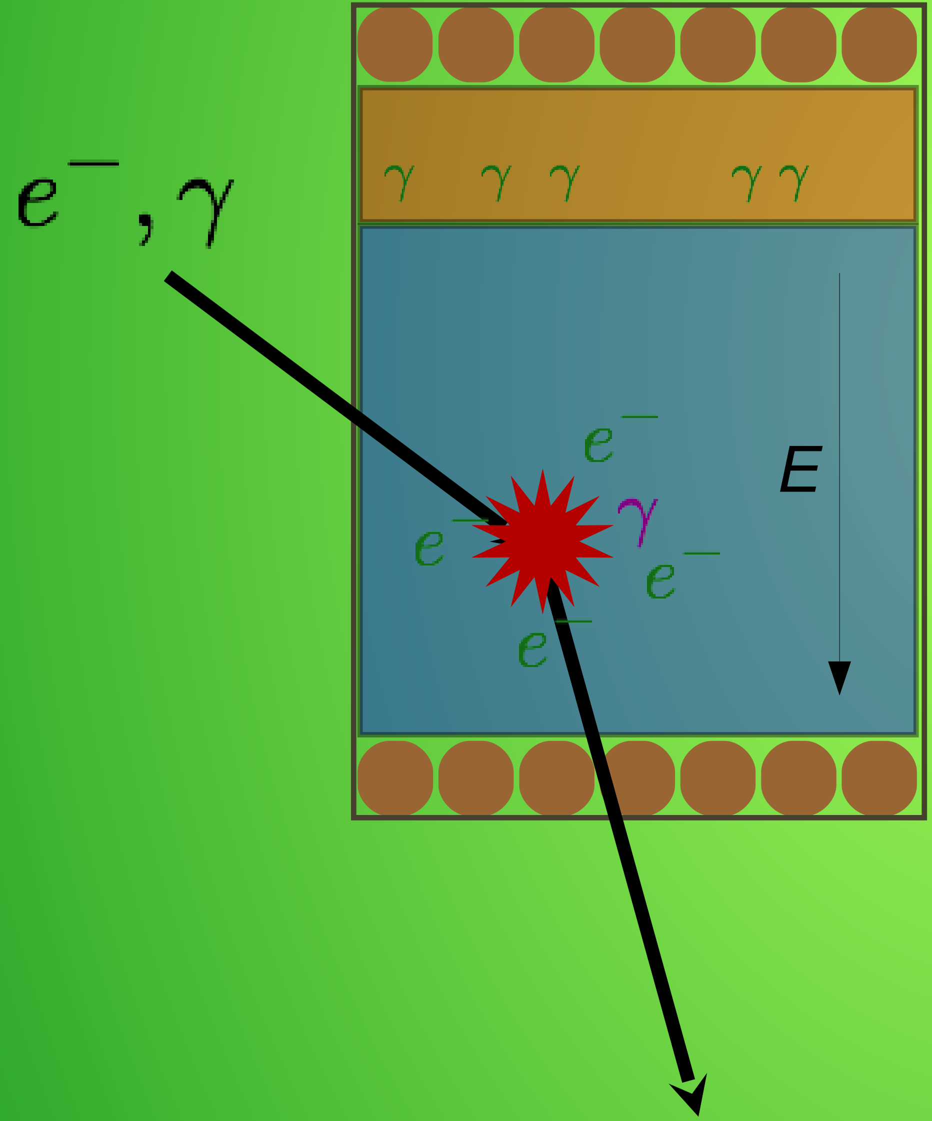

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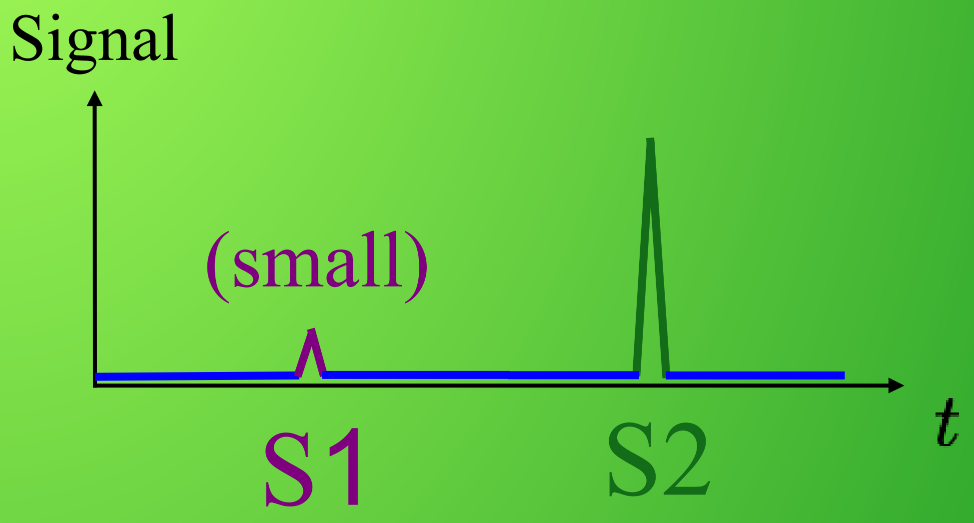
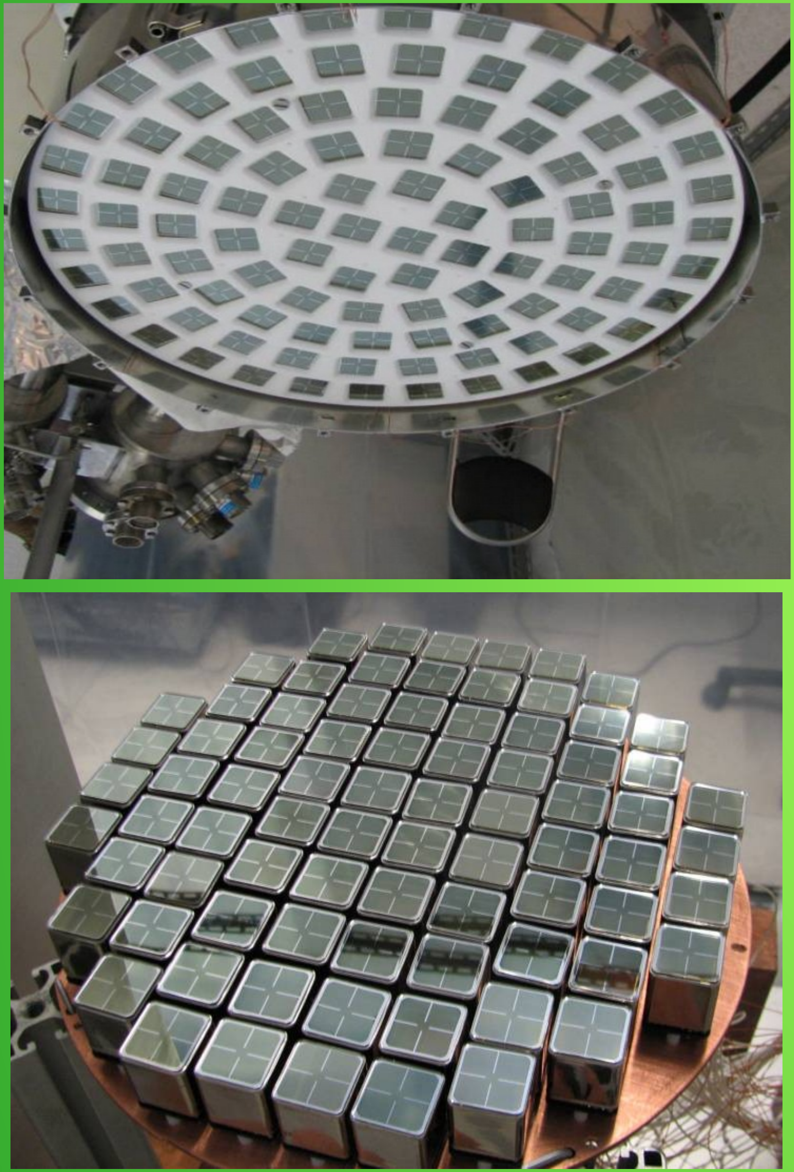


The XENON100 experiment



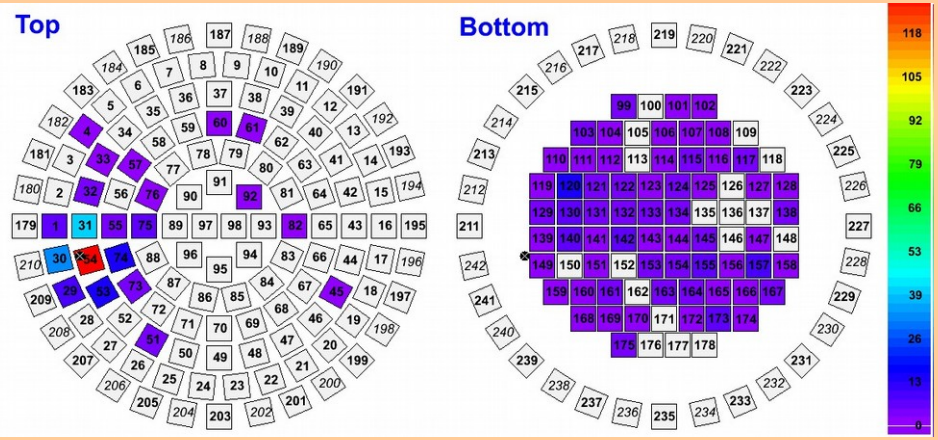
PMT arrays

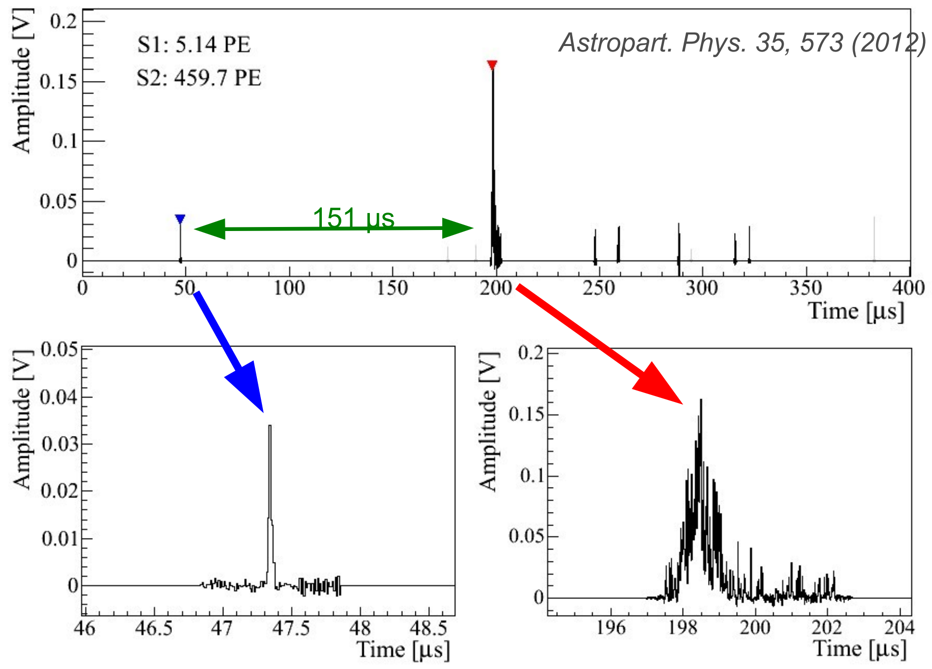
Full TPC

Radiation shield

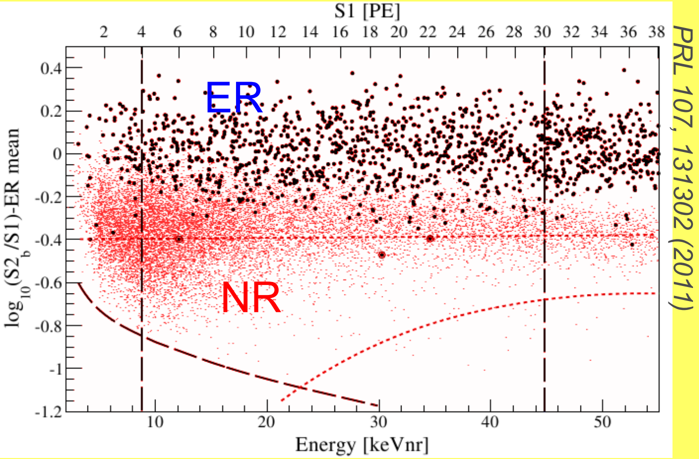
Dual Phase TPC

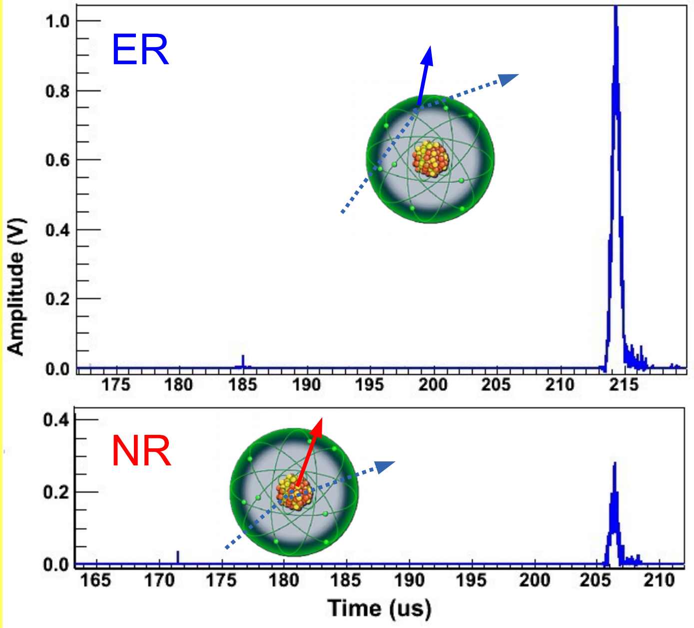
3d Vertex Reconstruction




Astropart. Phys. 35, 573 (2012)

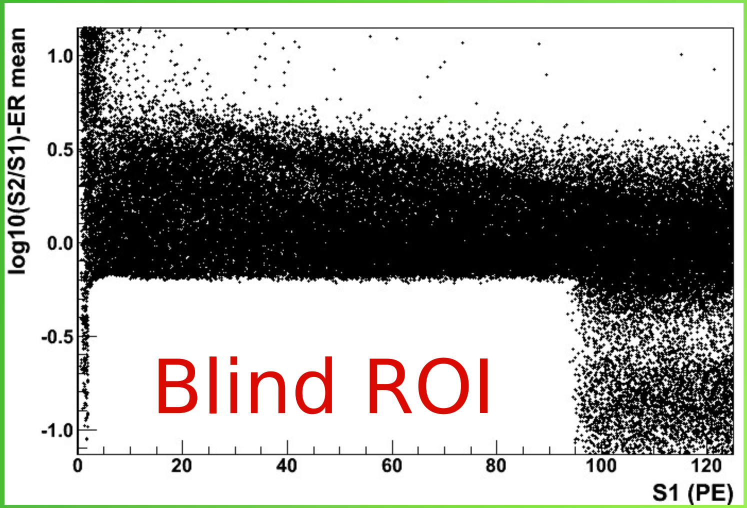
Signal/Background Discrimination


PRL 107, 131302 (2011)

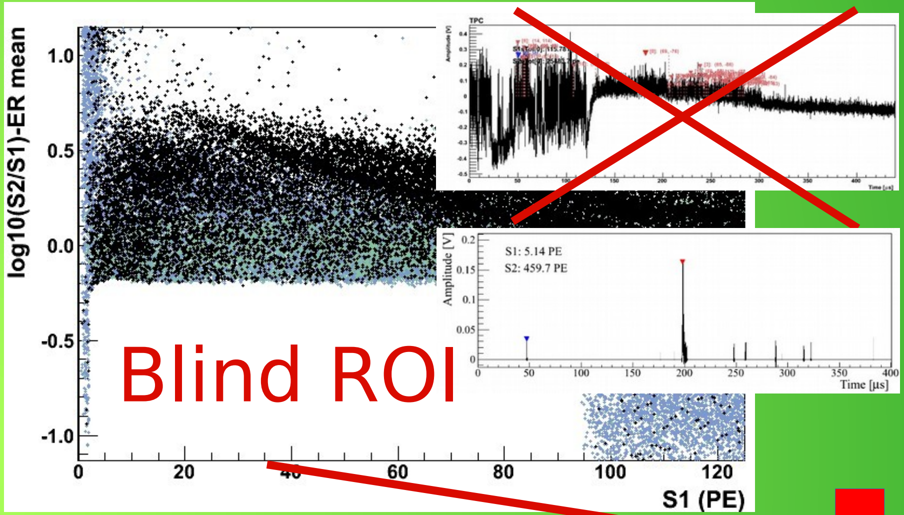


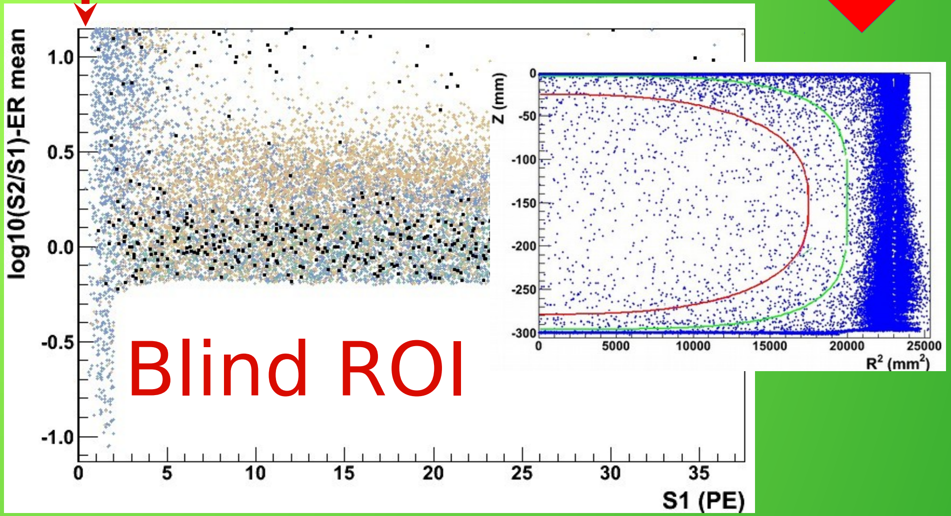
Analysis Sequence

1) Start from all non-blind data

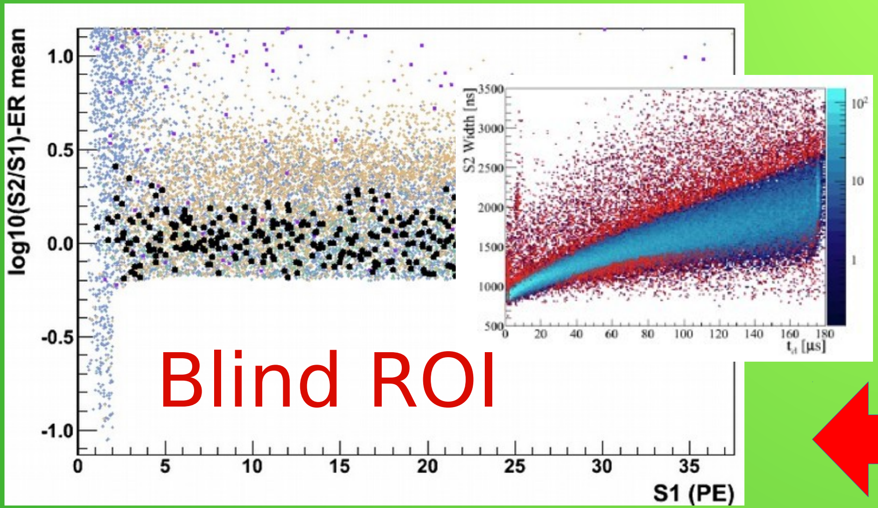


2) Basic quality and single scatter cuts



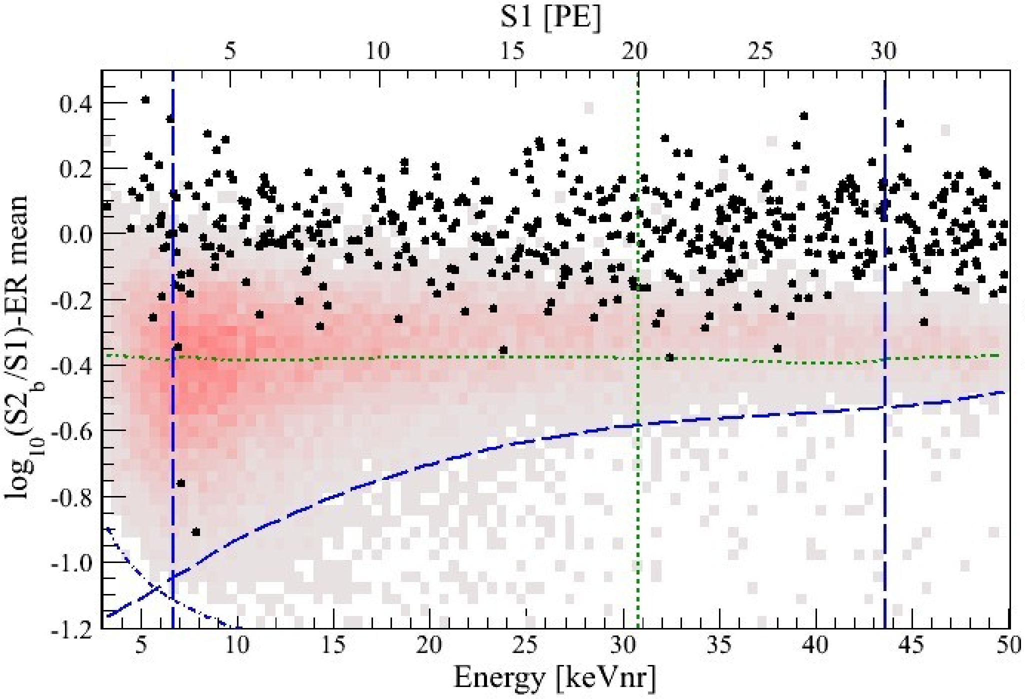


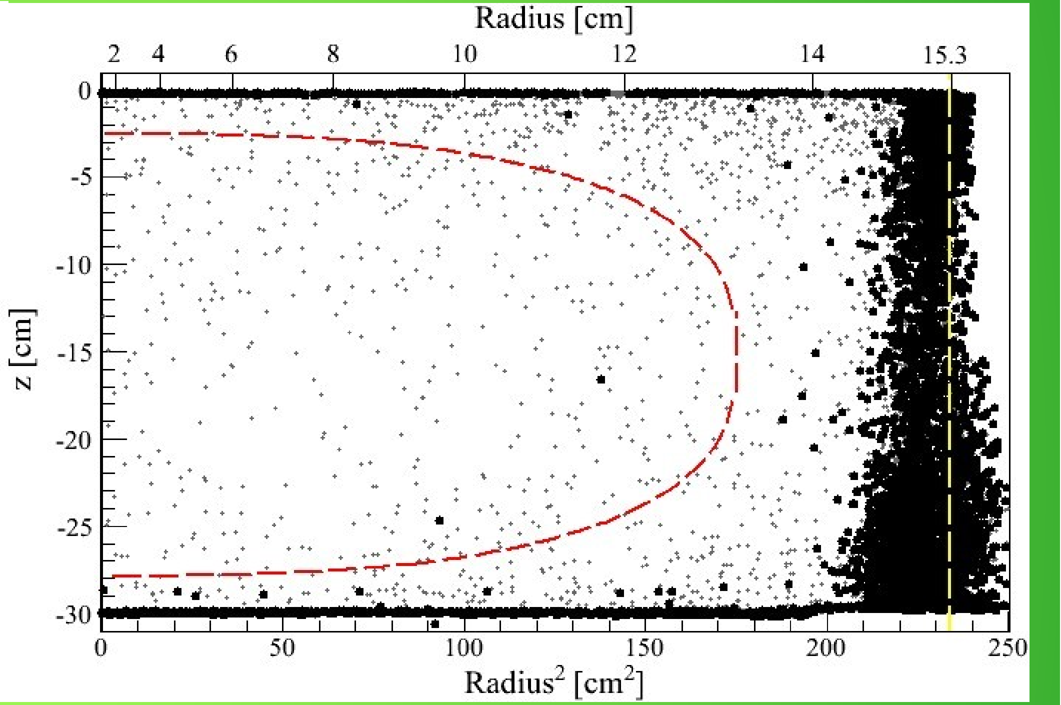
3) Energy threshold and FV cuts



4) Consistency cuts

Unblinding





(1.0 ± 0.2) events expected

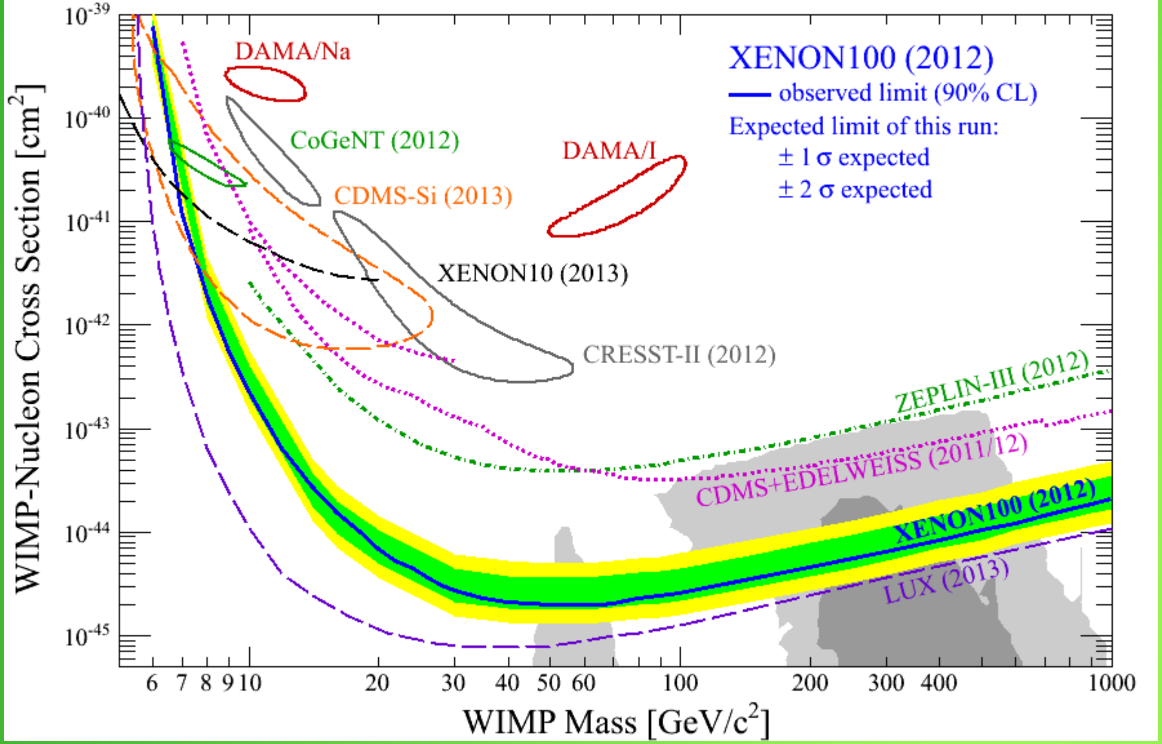
2 events observed

→ 26.4% probability that background fluctuated to 2 events

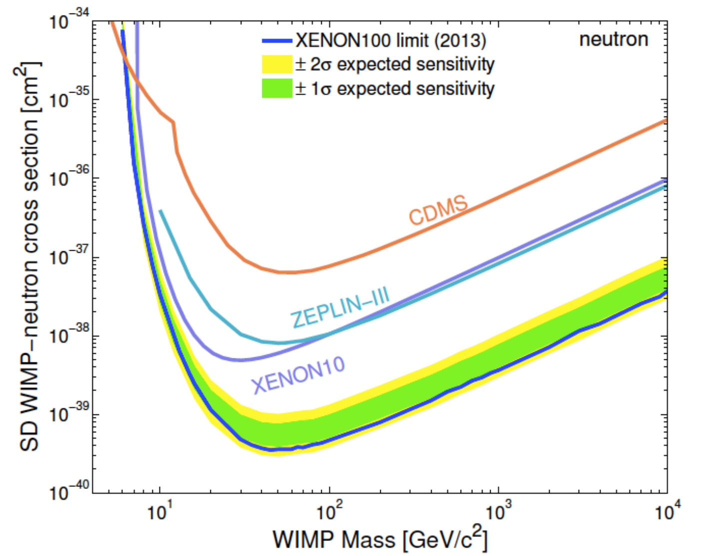
→ PL analysis cannot reject the background only hypothesis

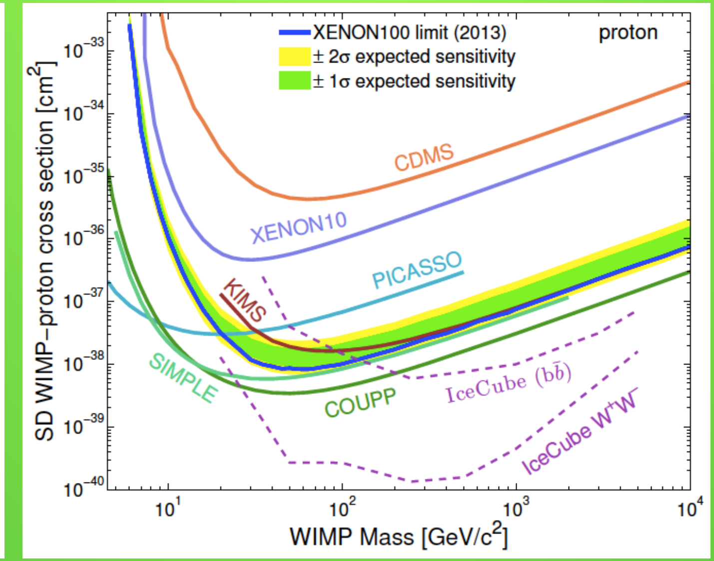
No significant excess due to a signal seen in XENON100 data.

Results of direct detection – limits for now



Spin independent





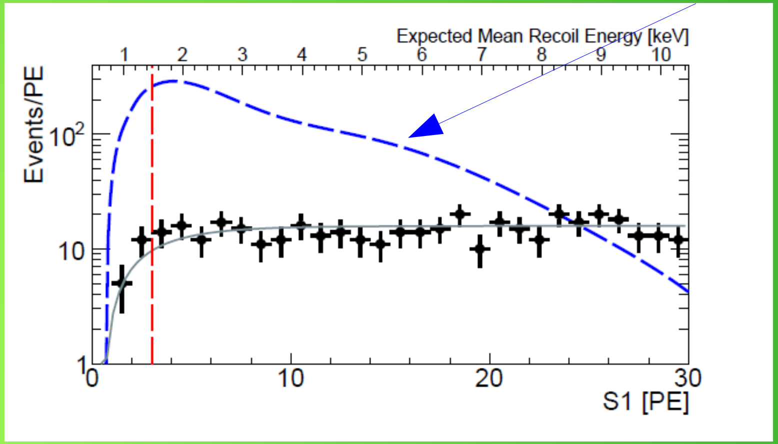
Spin dependent

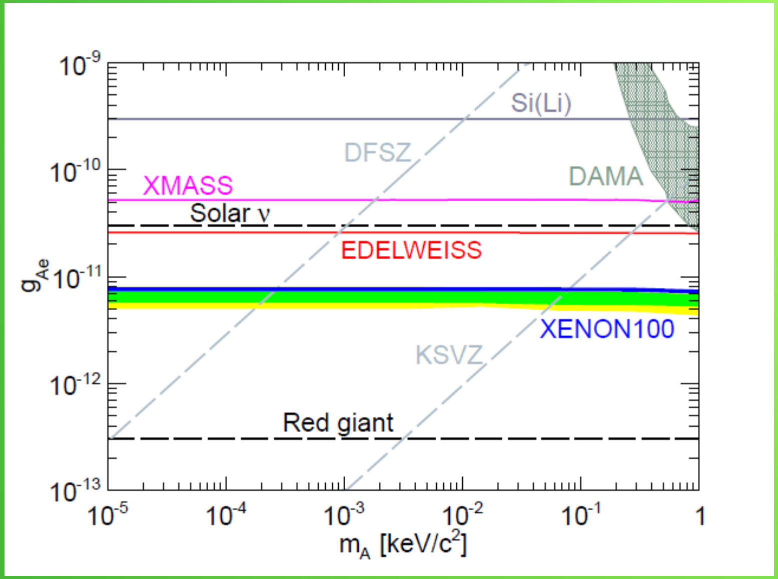
Other NP searches as well

- Look for axion-electron interaction:

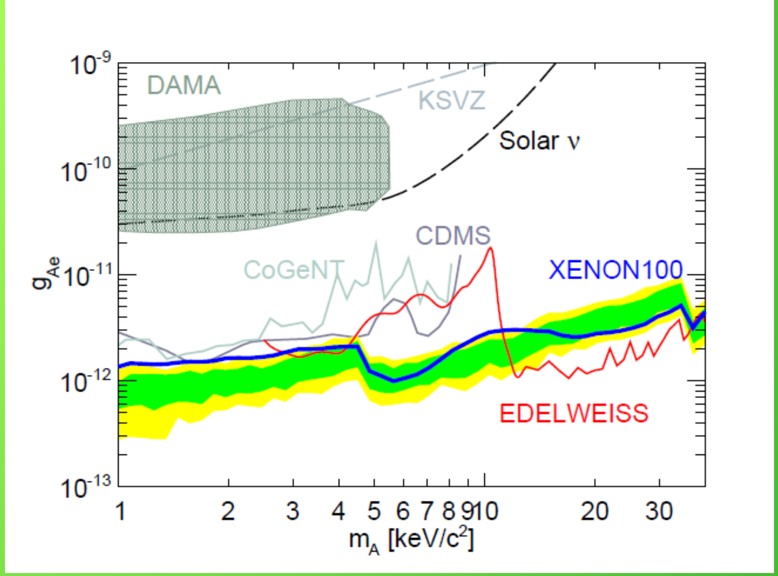
$$\sigma_{Ae} = \sigma_{pe}(E_A)\frac{{g_{Ae}}^2}{\beta_A}\frac{3{E_A}^2}{16\pi\,\alpha_{em}\,{m_e}^2}\left(1-\frac{\beta_A^{2/3}}{3}\right)$$

EDELWEISS best limit



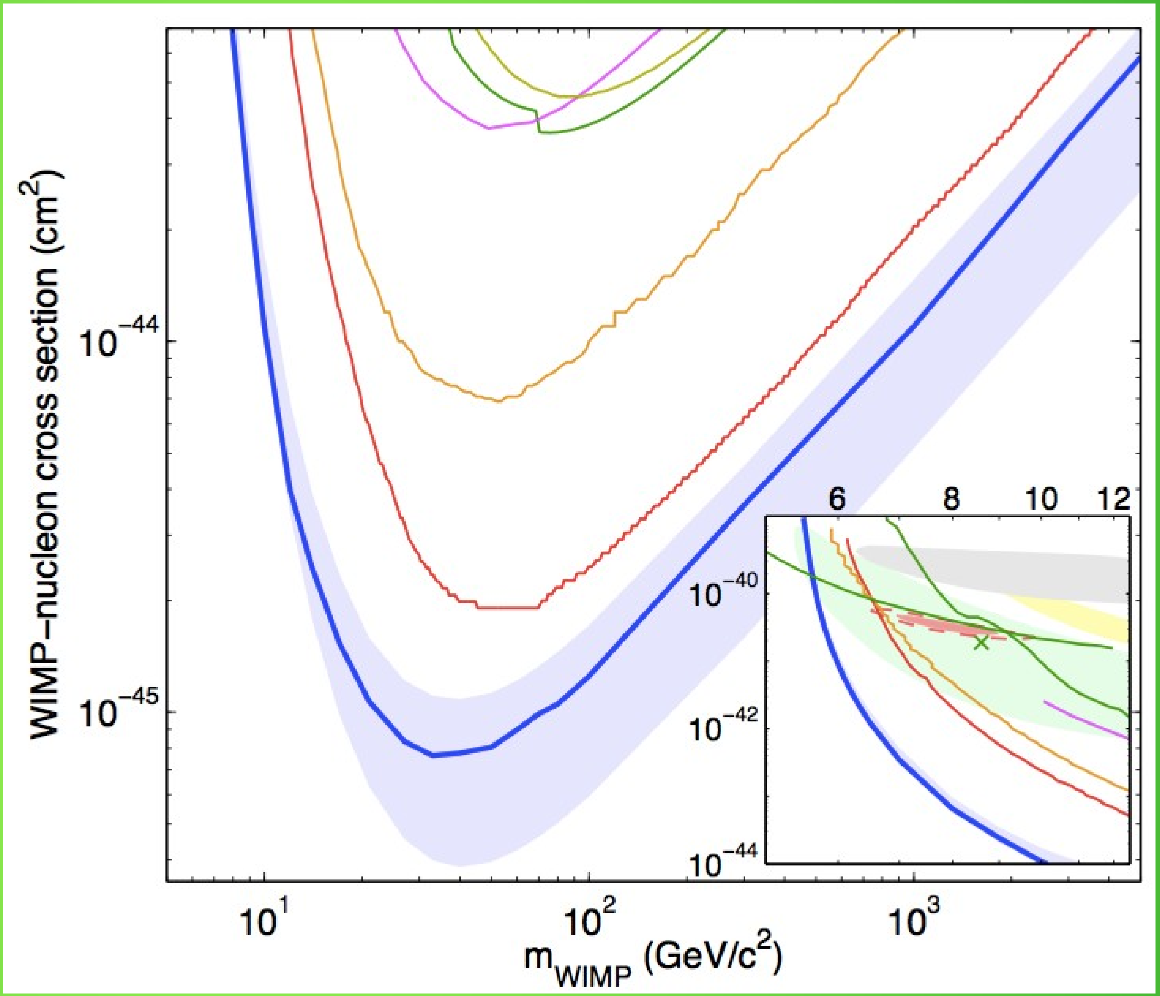


Solar axions



Galactic axions and ALPs

LUX and others – today's frontier

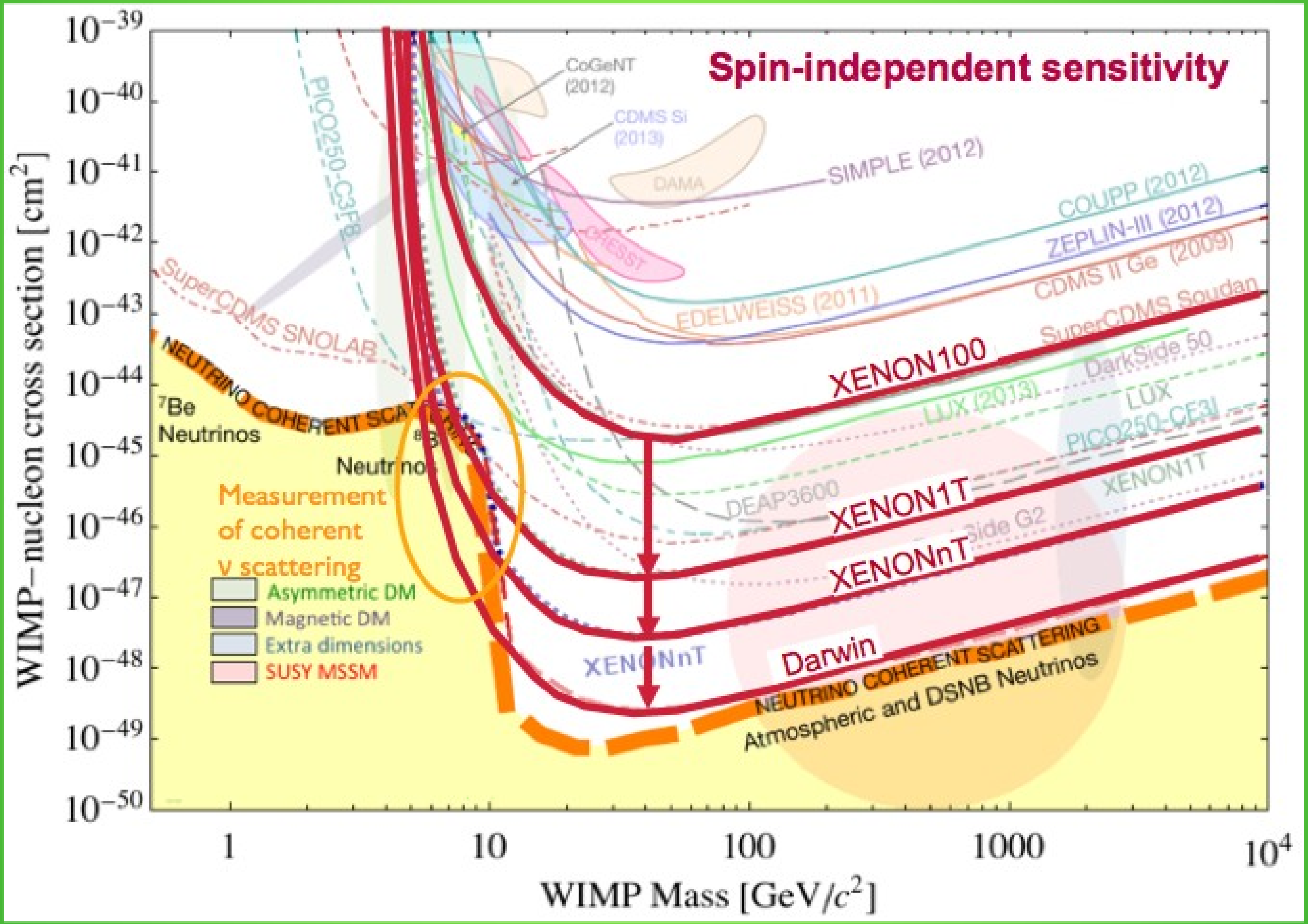


370/250/118 kg, first results of 85 days

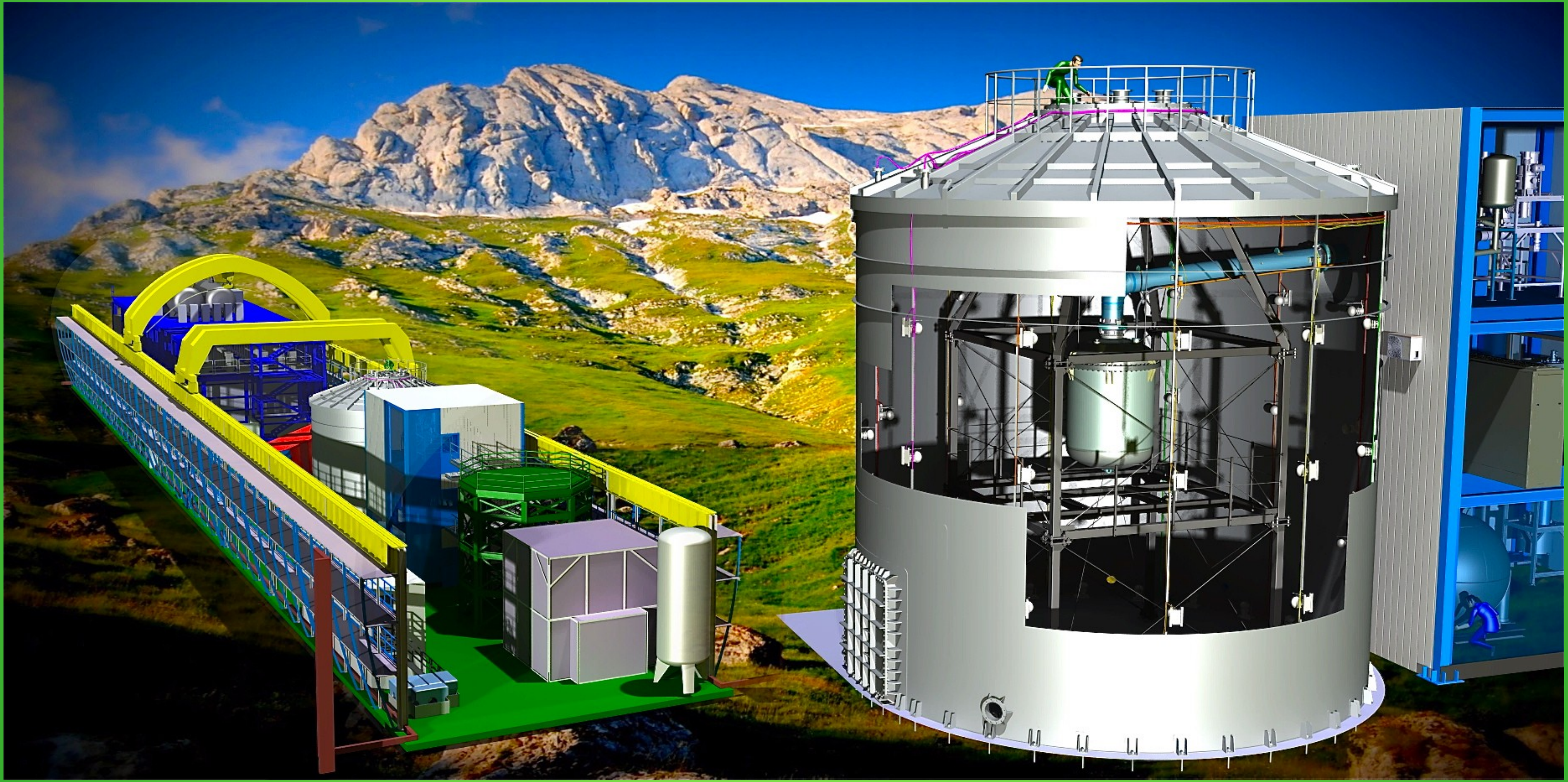
Expected improvement of almost X10!

Akerib et al PRL 112, 2013

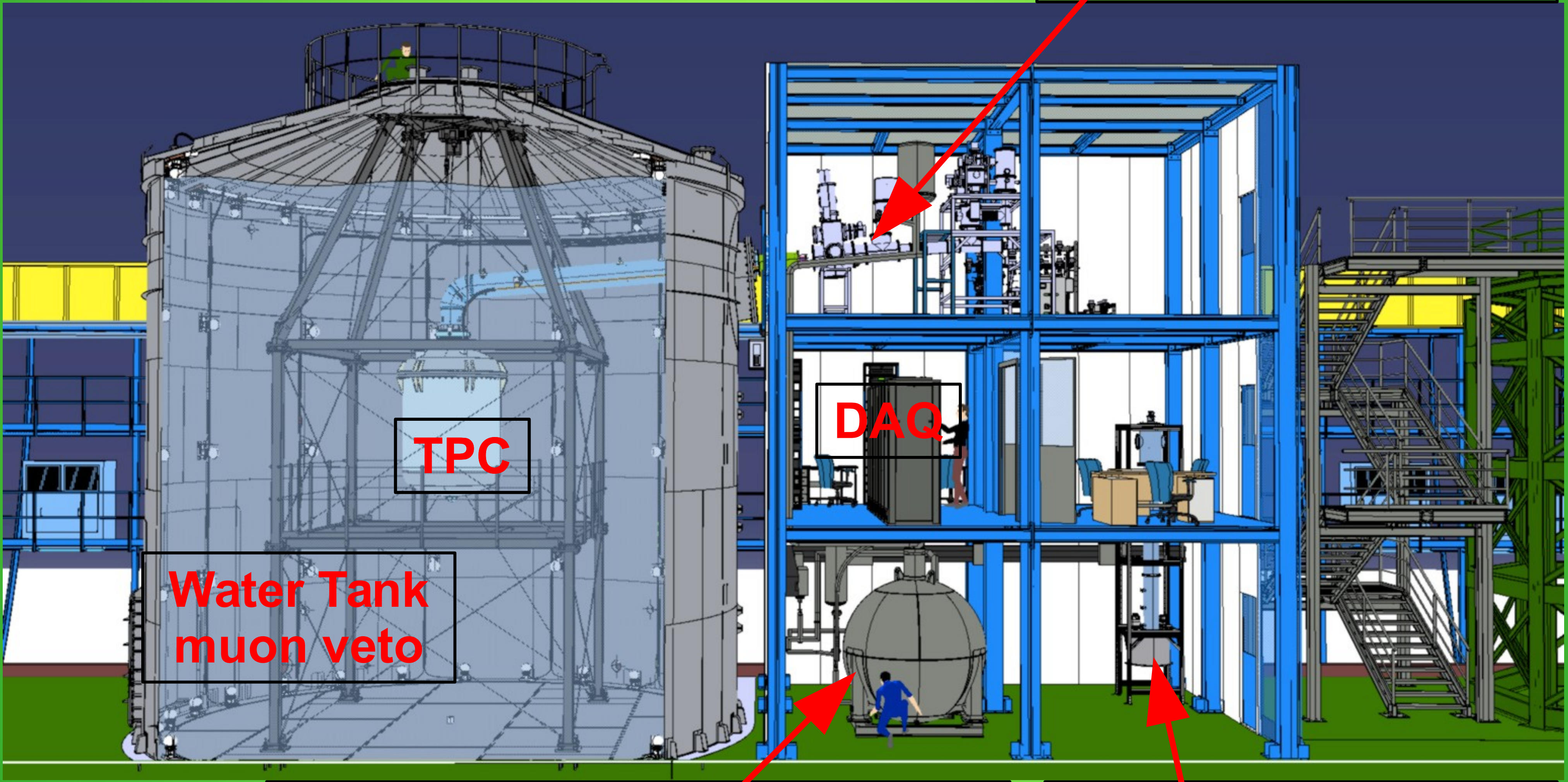
The future: Aiming for size (?)



XENON1T/nT – our future



XENON1T at a glance



Cryogenics and purification

DAQ

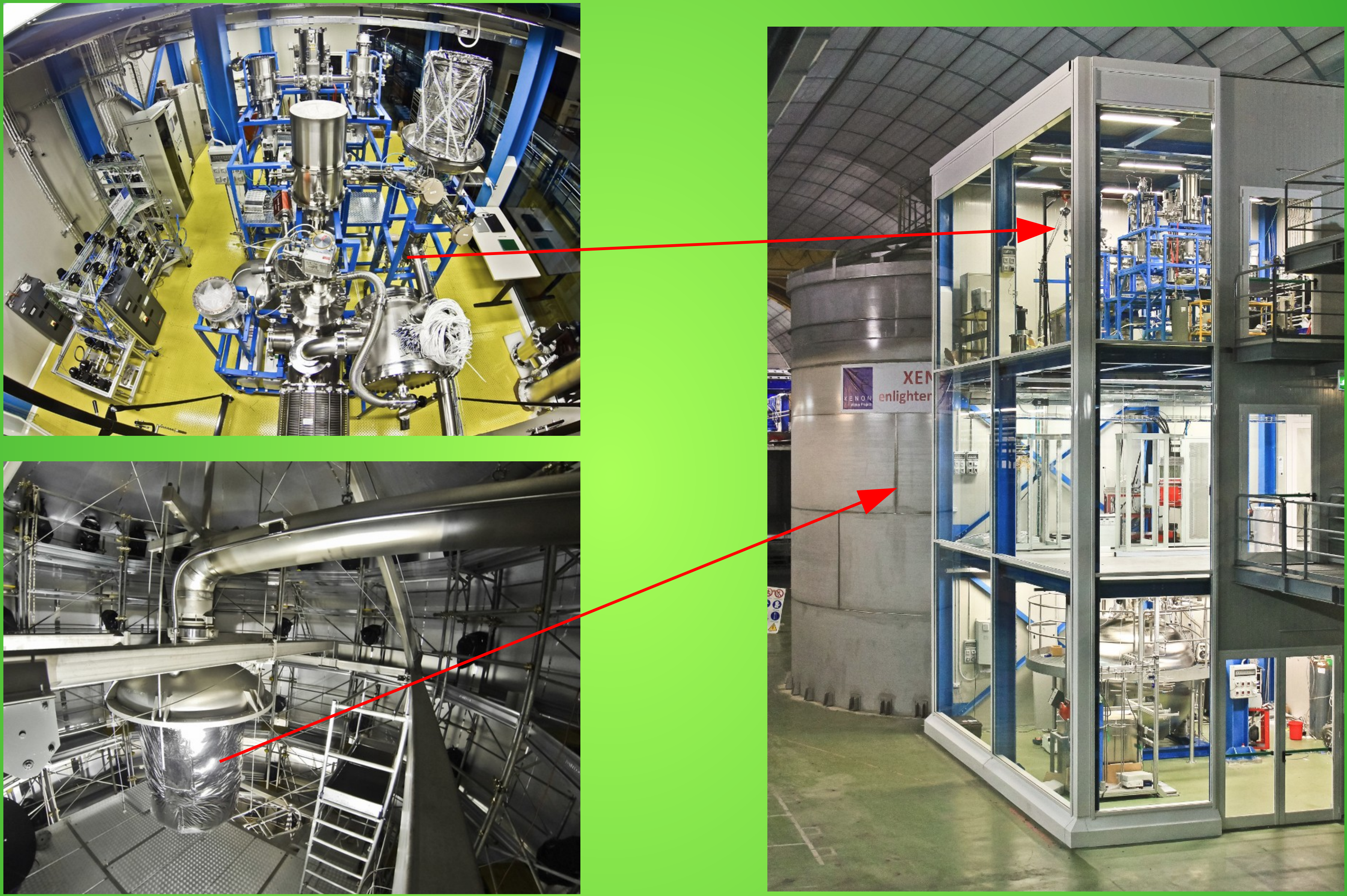
TPC

Water Tank muon veto

Storage and safety recovery

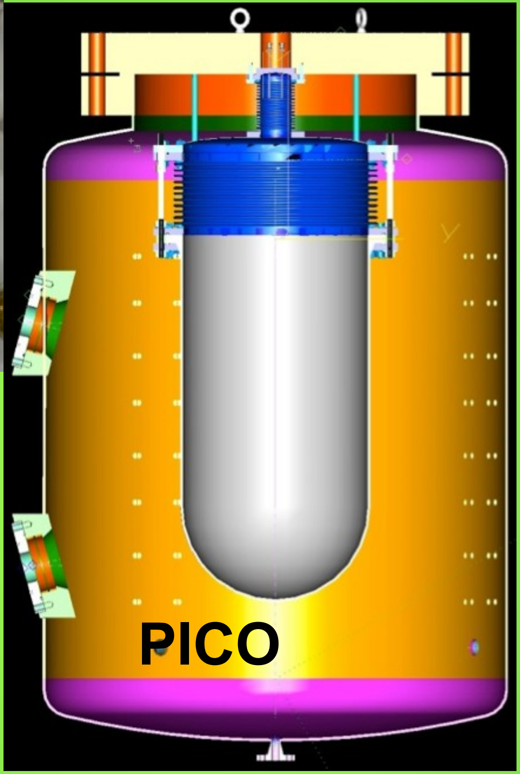
Rn and Kr treatment

XENON1T/nT



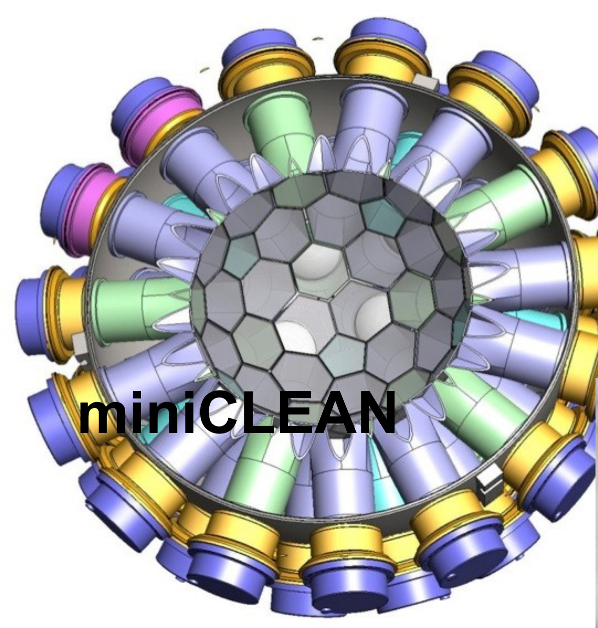
Expected to start running in 2015!

Plenty other experiments



Dark Matter Search

XMASS



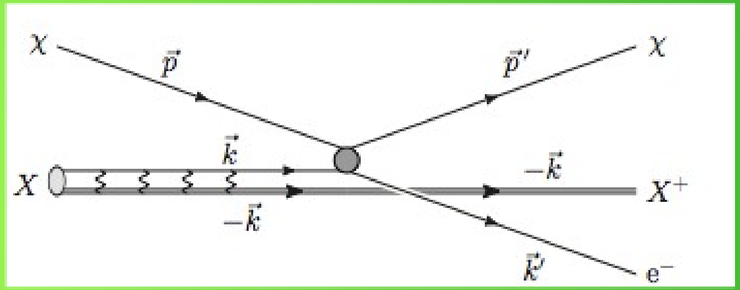
Ways to Detect Light DM

- The available energy is sufficient to induce inelastic atomic processes that would lead to visible signals.

- Three possibilities:

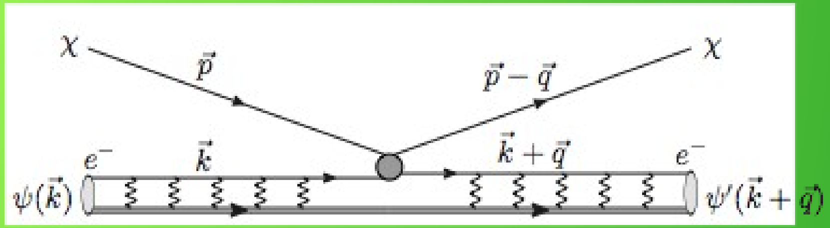
Electron ionization

Threshold: eV - 100’s eV
DM-electron scattering



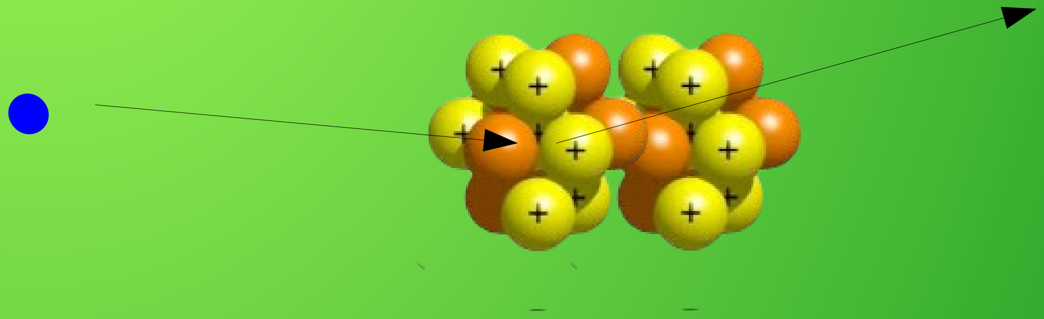
Electronic excitation

Threshold: eV - 100’s eV
DM-electron scattering



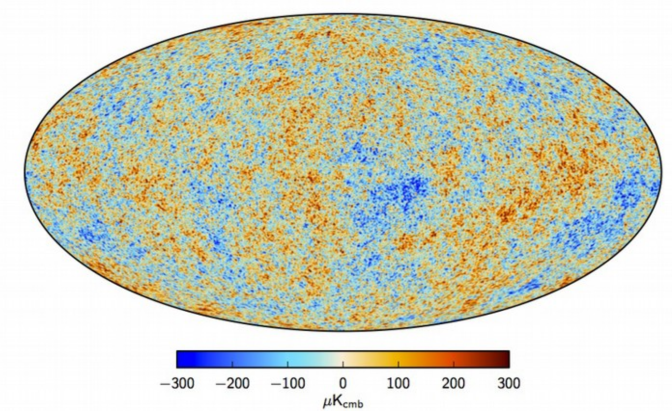
Molecular dissociation

Threshold: ≳ few eV
DM-nucleon scattering



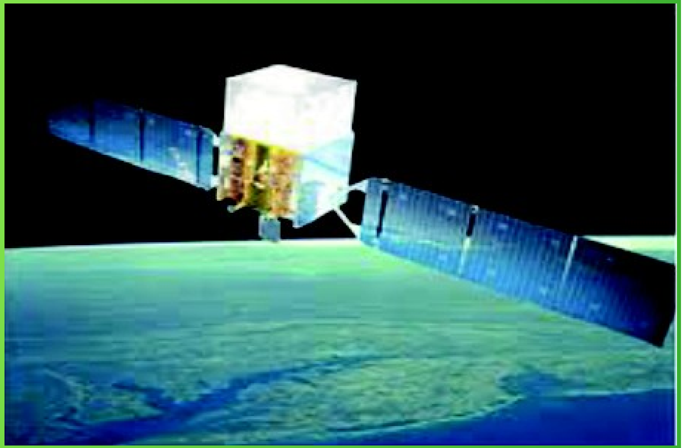
Indirect detection

- There are many different methods to search indirectly for DM
- I will show a few, hopefully representative ones



CMB- Planck

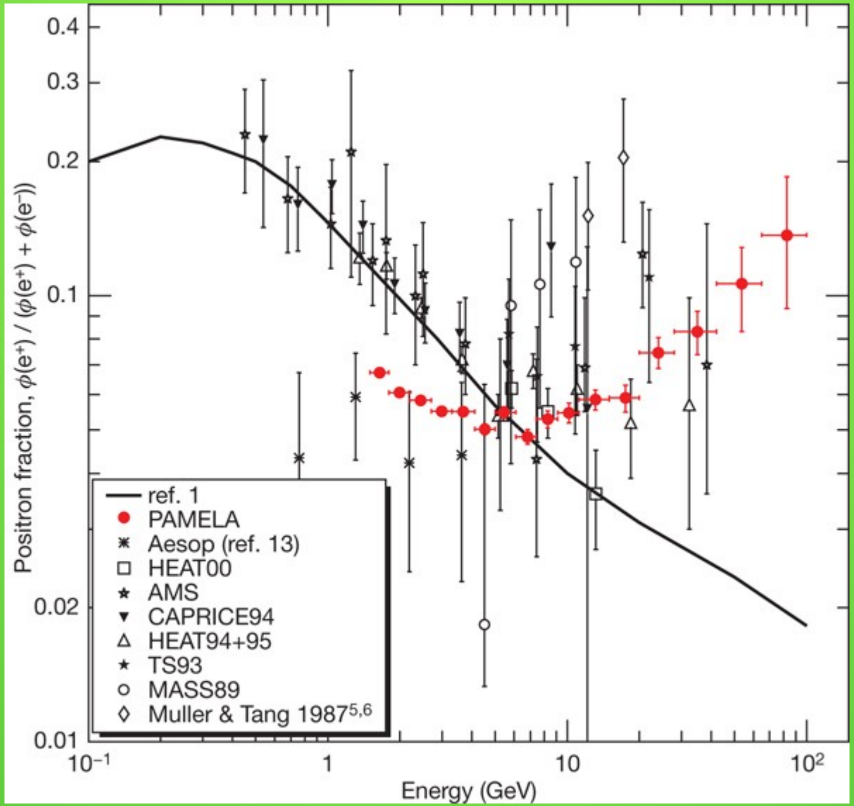
AMS02



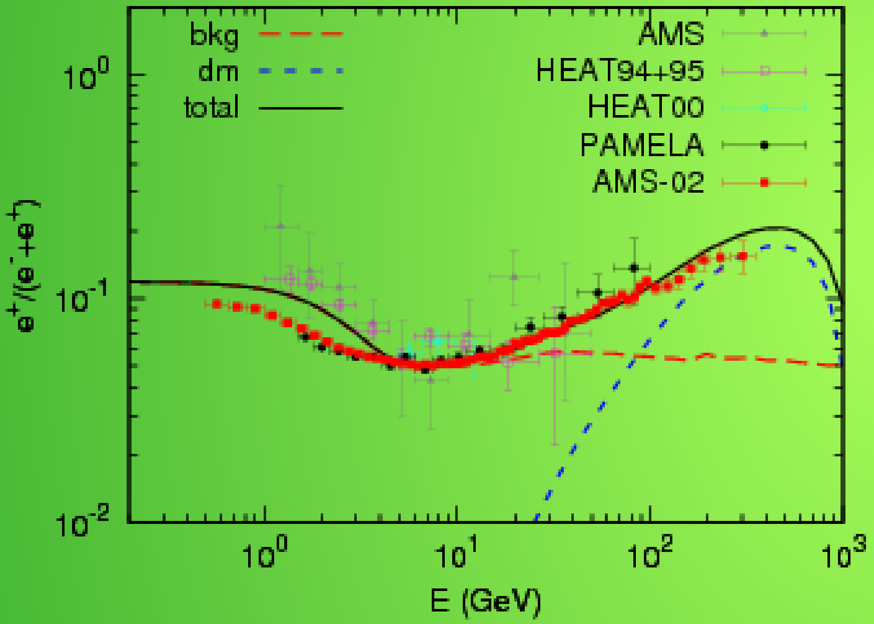
Fermi

Charged antimatter

- “Anomalous” amount or spectrum of antimatter can indicate decay or annihilation of DM
- In the past 6 years many efforts were given to positron production and propagation, following PAMELA:



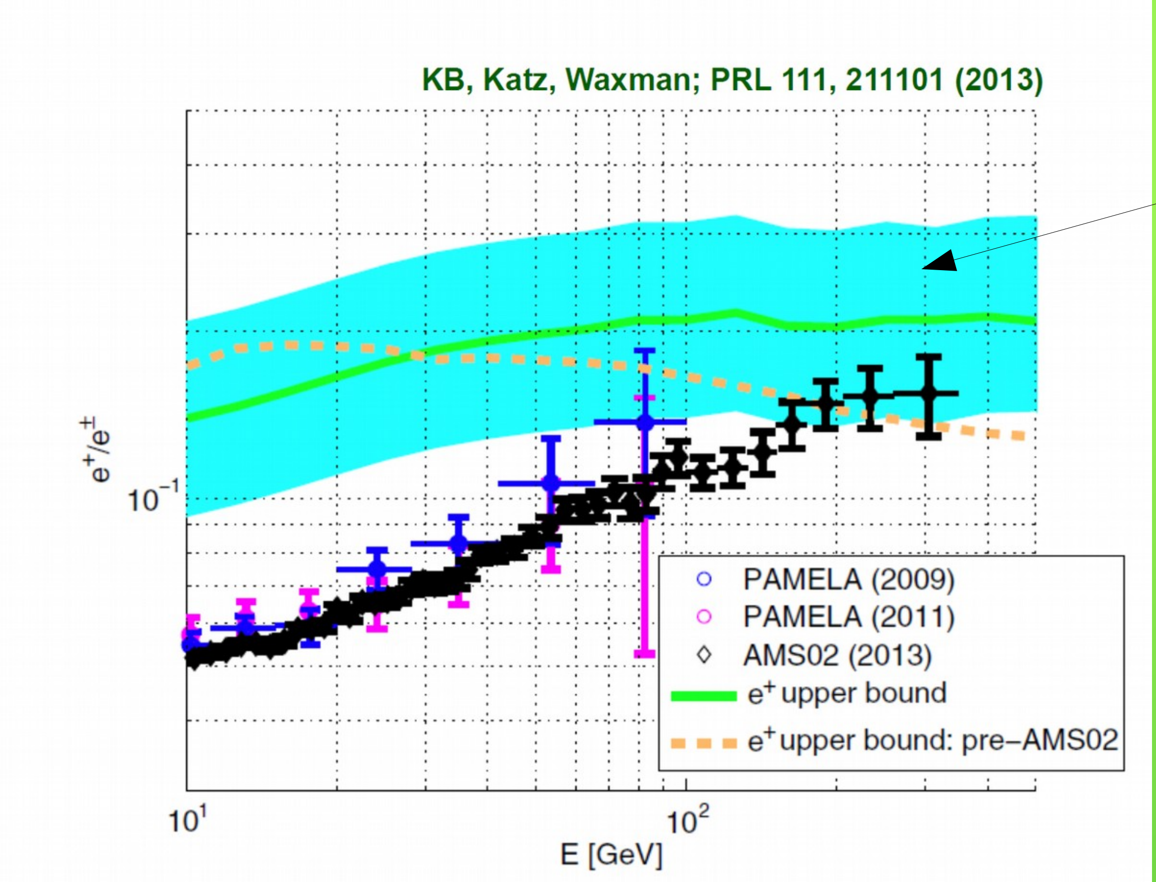
AMS confirms and enhances



- It seems like there is a “bump” above the expected background
- Works naturally with heavy DM decay or annihilation

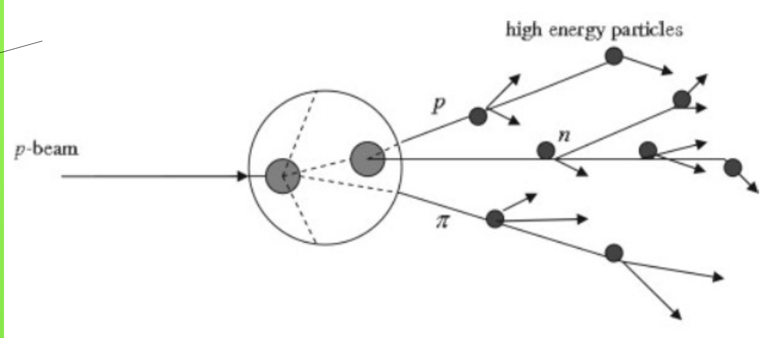
However...

- What do we understand about the astrophysics part?
- The models predicting the fluxes suffer serious systematic errors



KB, Katz, Waxman; PRL 111, 211101 (2013)

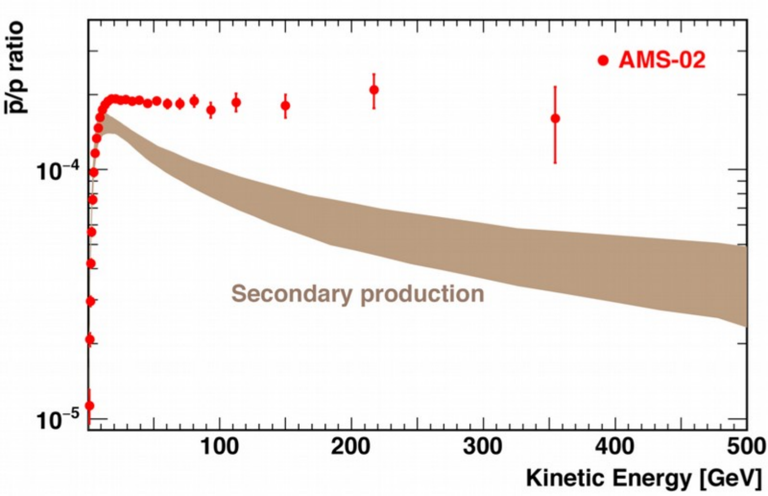
$$pp \rightarrow pn\pi^+ \rightarrow ppe^-e^+\nu_e\bar{\nu}_e\nu_\mu\bar{\nu}_\mu$$



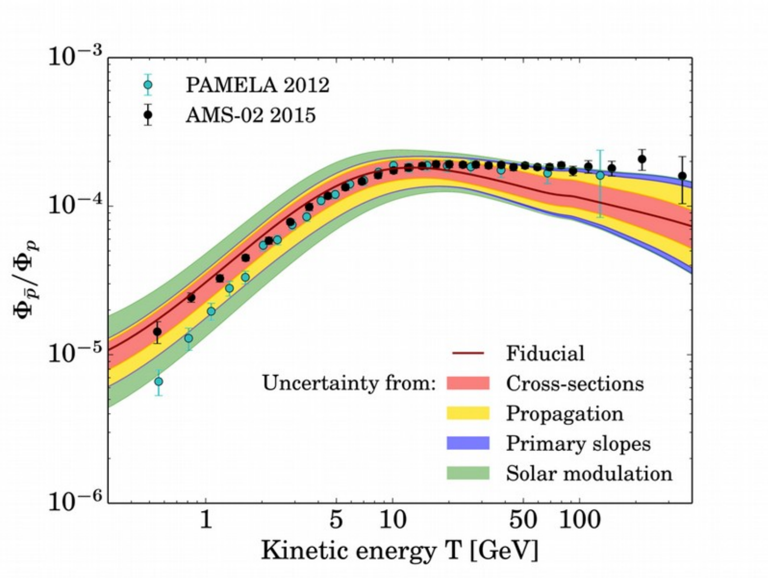
It seems that still, the positron flux is consistent with what we know about “normal” astrophysics

But there's still more

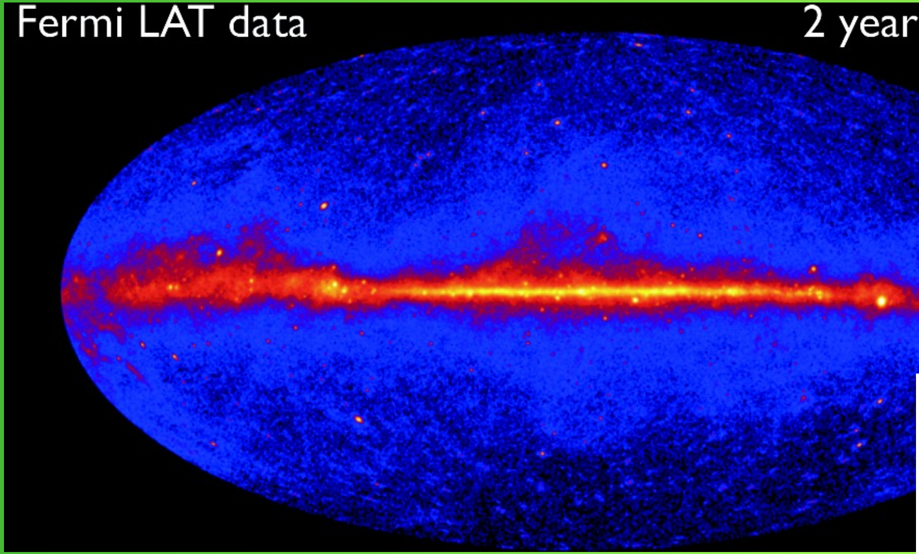
- AMS claim that antiproton flux is overabundant



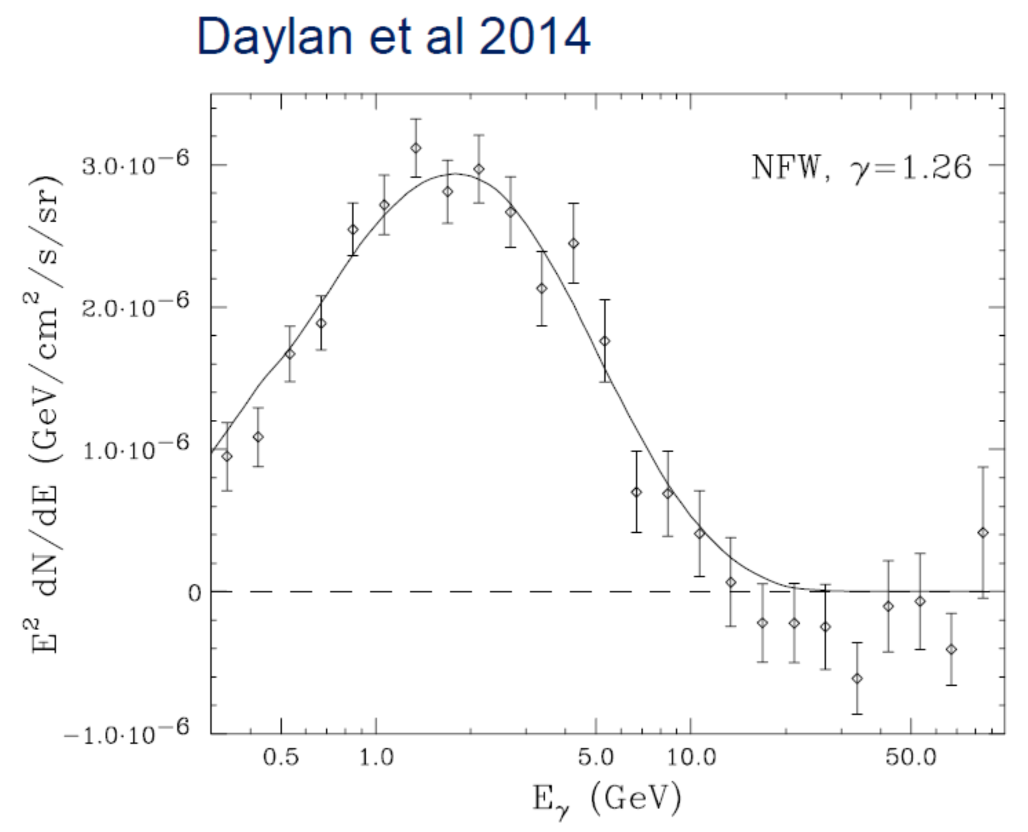
- But including some account of astrophysical + experimental uncertainties....



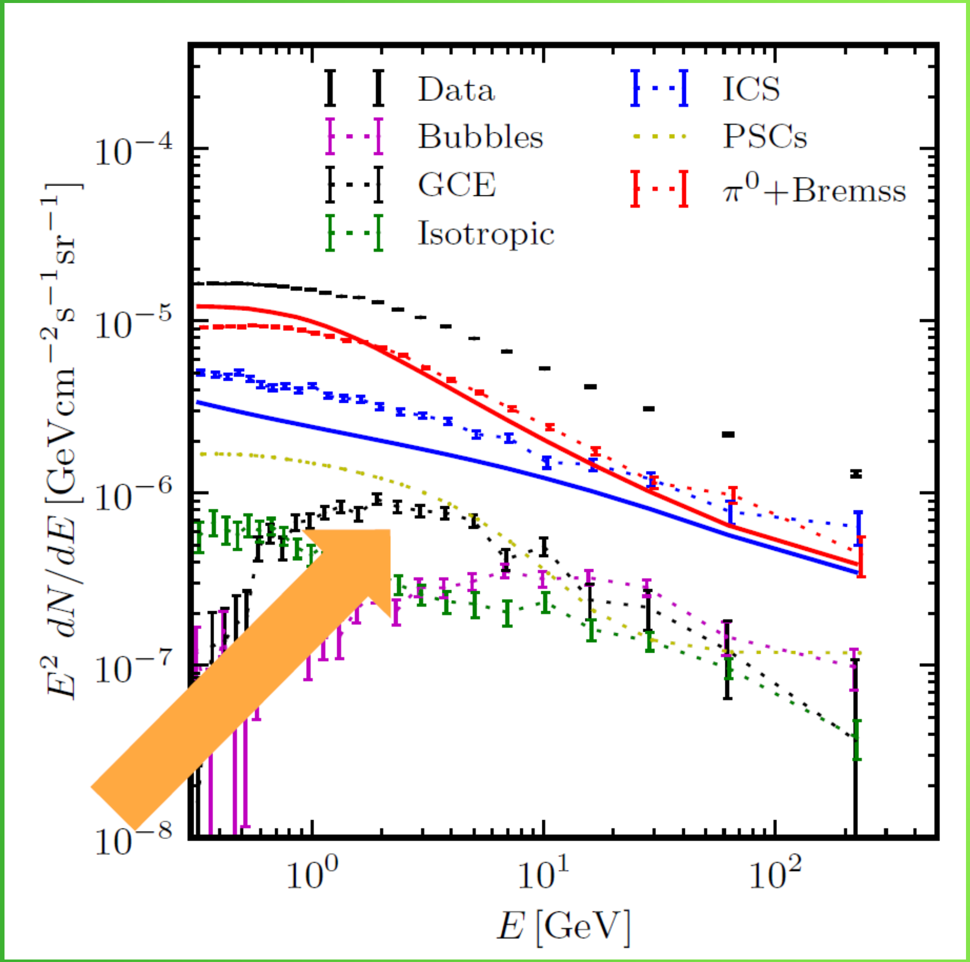
Fermi looking at the galaxy



- Seems that there is an excess at a few GeV
- Astrophysics sources should not show this kind of spectrum


Daylan et al 2014

However, take a closer look

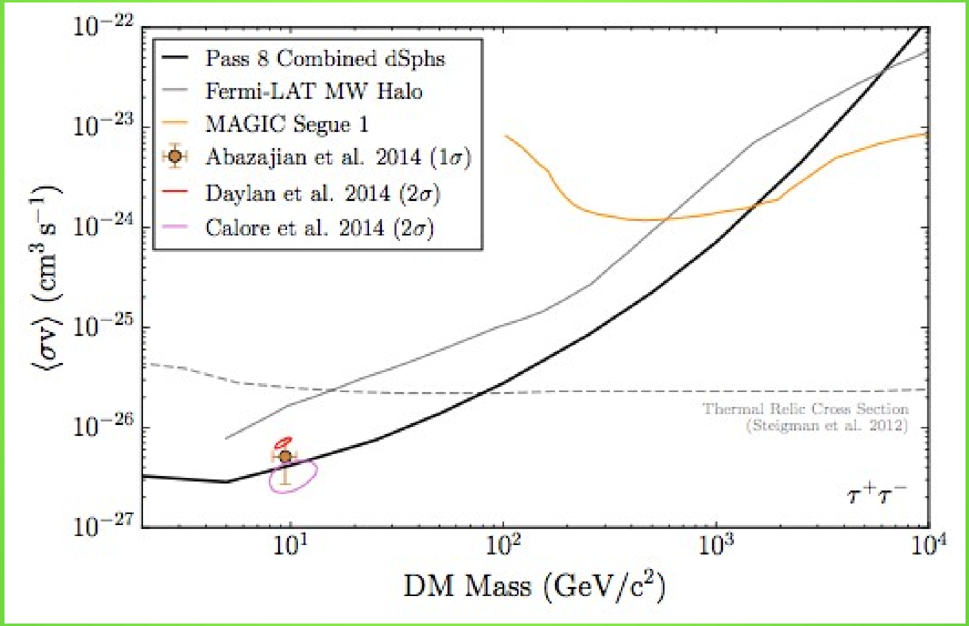


- The “bump” only appears after subtraction of backgrounds that are assumed to be known
- Some of the backgrounds are taken from “templates”, which assume the galaxy has similarities away from the disc
- Some works show that the significance is actually very low

Calore, Cholis, Weniger 2014

Looking for annihilation

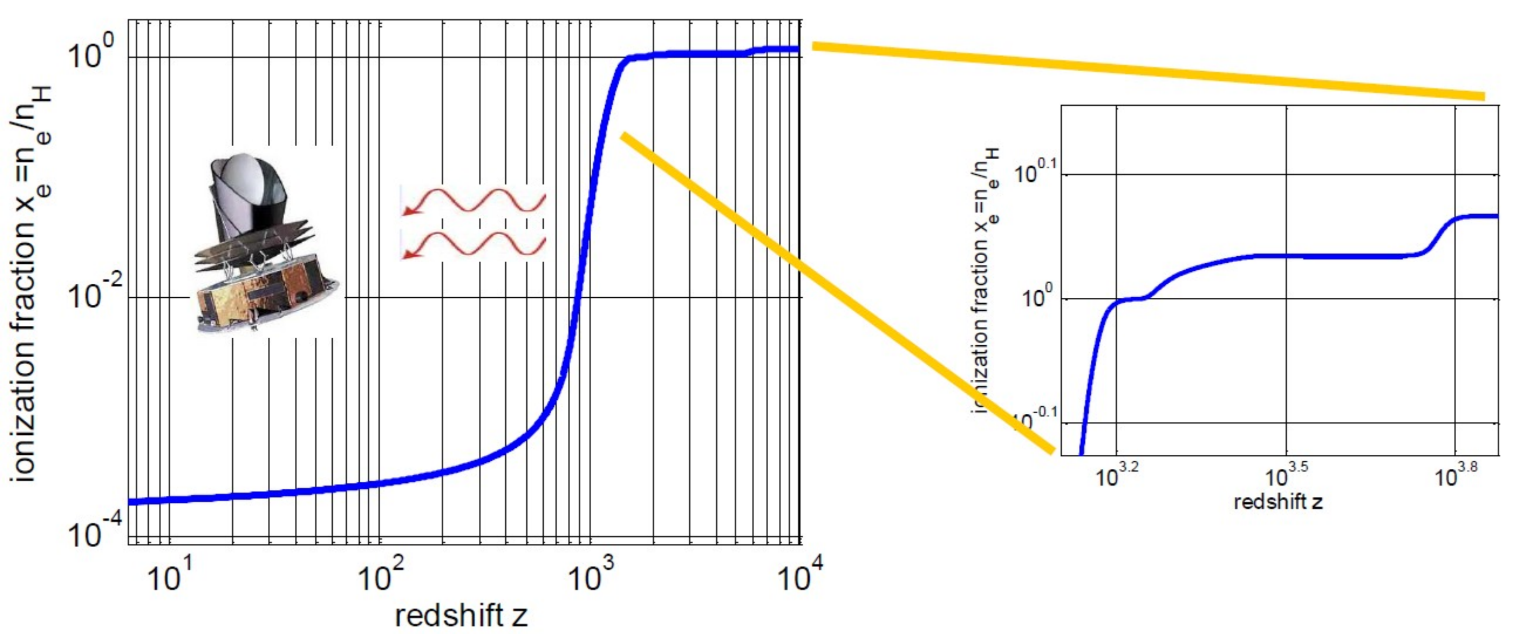
- Fermi limits from dwarf galaxies through annihilation to tau



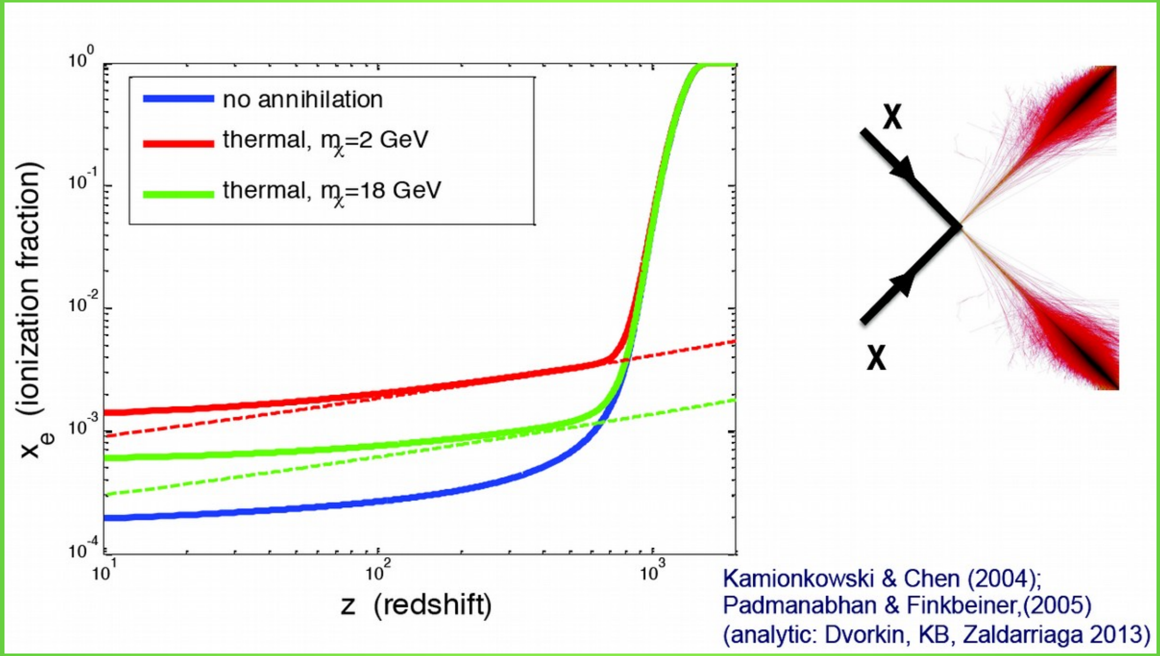
Looking at the CMB

- There is more to the CMB, than running the stress-energy constituents in the Einstein equations.

- Thomson opacity determines where the photons we see last scattered



- Dark matter annihilation would inject energetic particles into the plasma with an efficiency prefactor f
- Ionize hydrogen → excess Thomson scattering

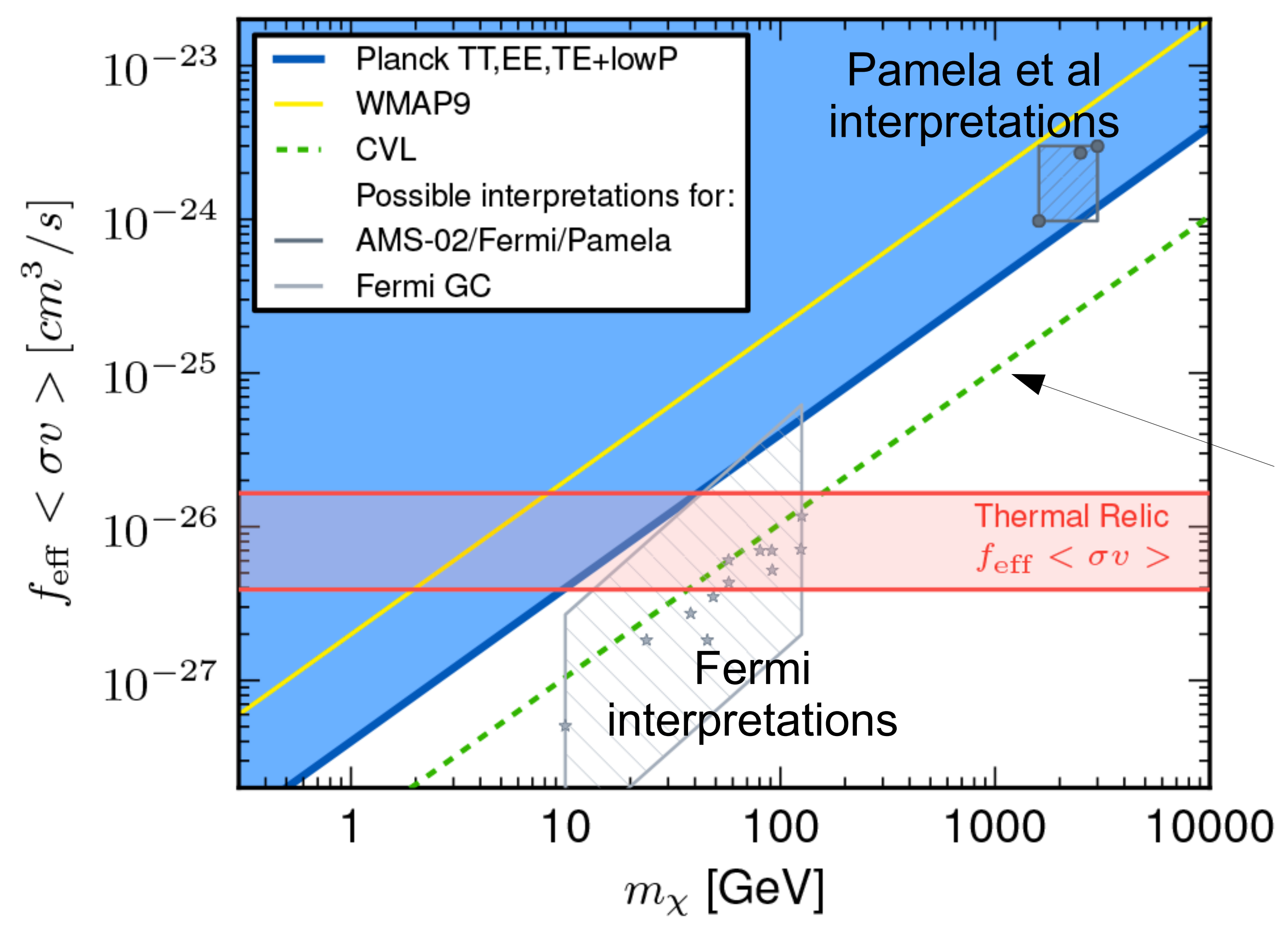


Kamionkowski & Chen (2004);
Padmanabhan & Finkbeiner,(2005)
(analytic: Dvorkin, KB, Zaldarriaga 2013)

From Kfir Blum

Direct result from CMB

- Planck rules out s-wave thermal relic <10 Gev



Pamela et al interpretations

Fermi interpretations

Best possible limit from CMB

Other indirect paths

- Distortions in DM positioning → DM self interaction
- Effects on stellar structure from capture of DM
- Decay/annihilation in the Sun after capture (e.g. neutrinos)
- Other sources of gamma rays (dwarf galaxies, clusters)
- HE neutrinos
- Anomalies in ultra high energy cosmic rays
- Anomalies in precision measurements of time, gravity, dipole moment, isotopes...
- And more!

Summary

- Direct detection is proceeding fast, with each 6-12 month bringing a new leader. Current battle is over size – the bigger, the better

- “Anomalies” still surface, somehow don't yet stick

- Many indirect searches going on, anomalies appear and disappear

- The hope is that one of these will stick around!