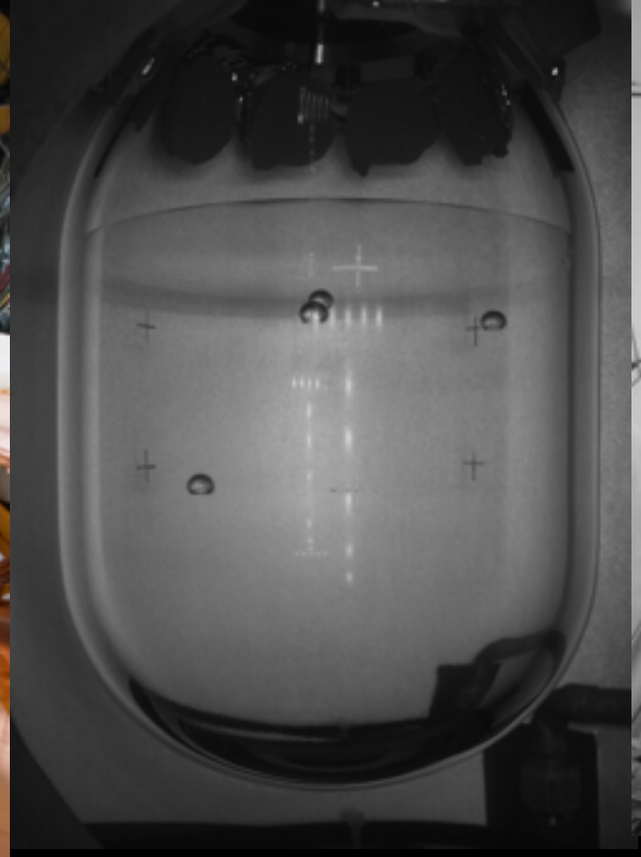
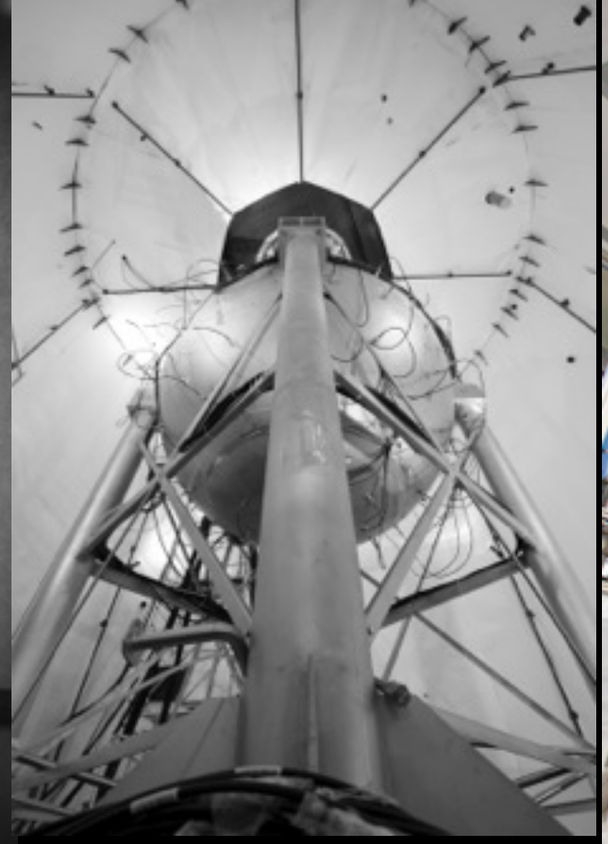




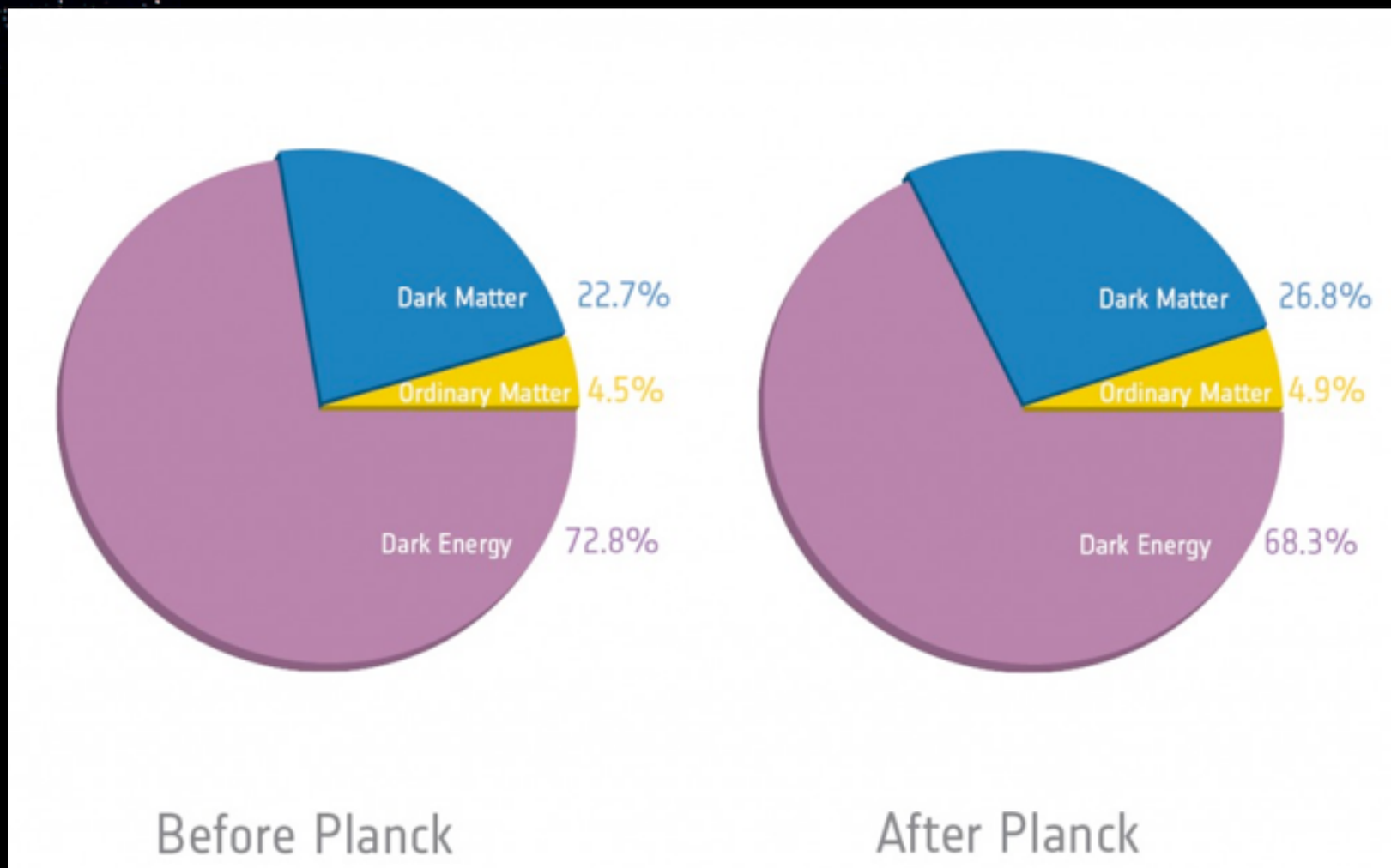

Searching for Dark Matter

Hugh Lippincott
Fermilab Center for Particle Astrophysics

Summer Intern Undergraduate Lecture Series
July 10, 2014

There is pretty strong consensus regarding how much stuff there is in the universe

By that same consensus, we only understand 5% of it



Dark matter - evidence?

- Galaxy rotation curves

Vera Rubin, 1970s

Dark matter - evidence?

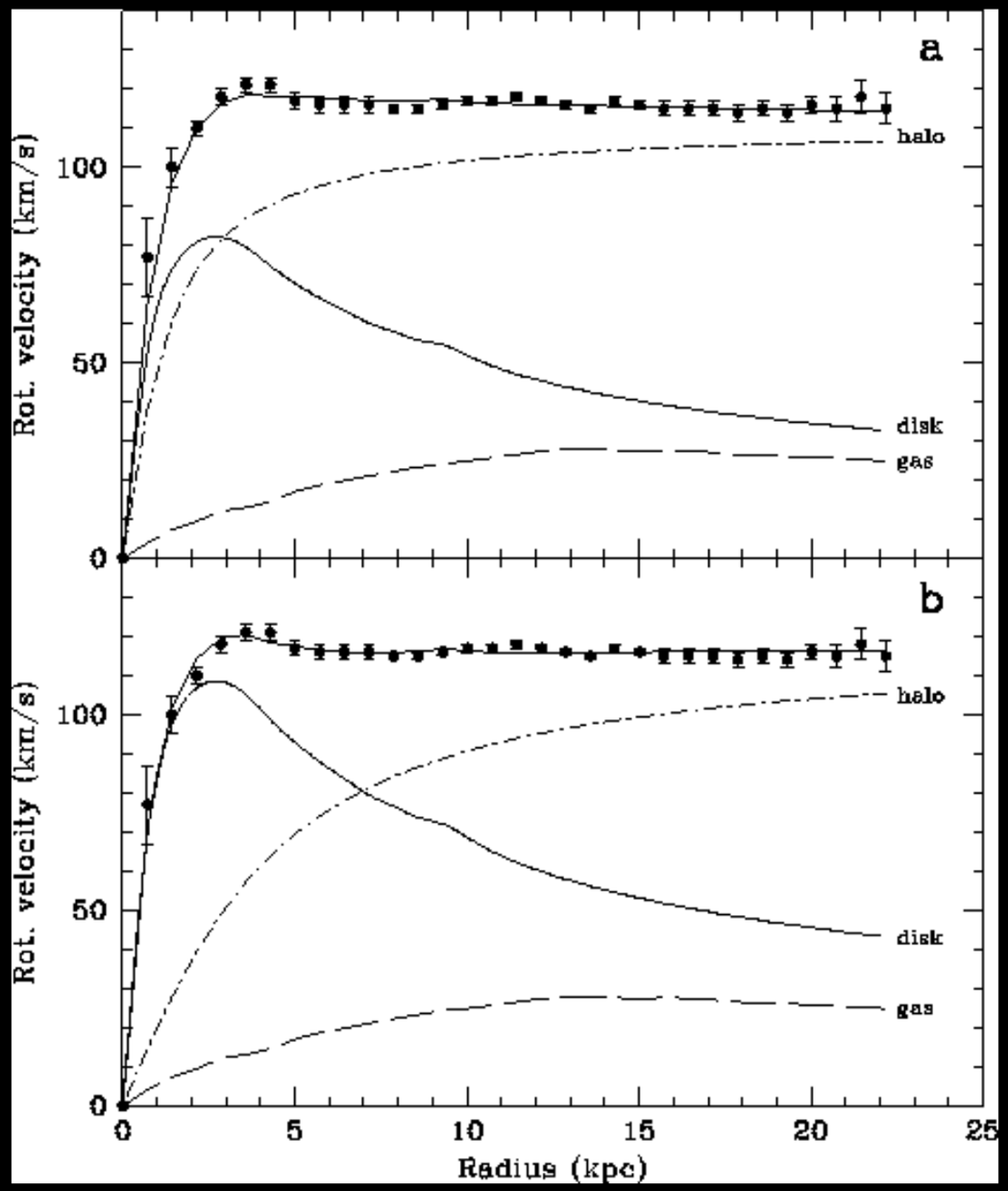
- Galaxy rotation curves

In Newtonian dynamics, the rotational velocity of an object in circular motion is

$$v(r) = \sqrt{\frac{GM(r)}{r}},$$

where M is the mass within the orbit. If r_l is the radial extent of the luminous part, and all mass is in the luminous part of the galaxy, then M is constant for $r > r_l$ and

$$v(r) \propto \frac{1}{\sqrt{r}} \text{ for } r > r_l.$$



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Fritz Zwicky, 1930

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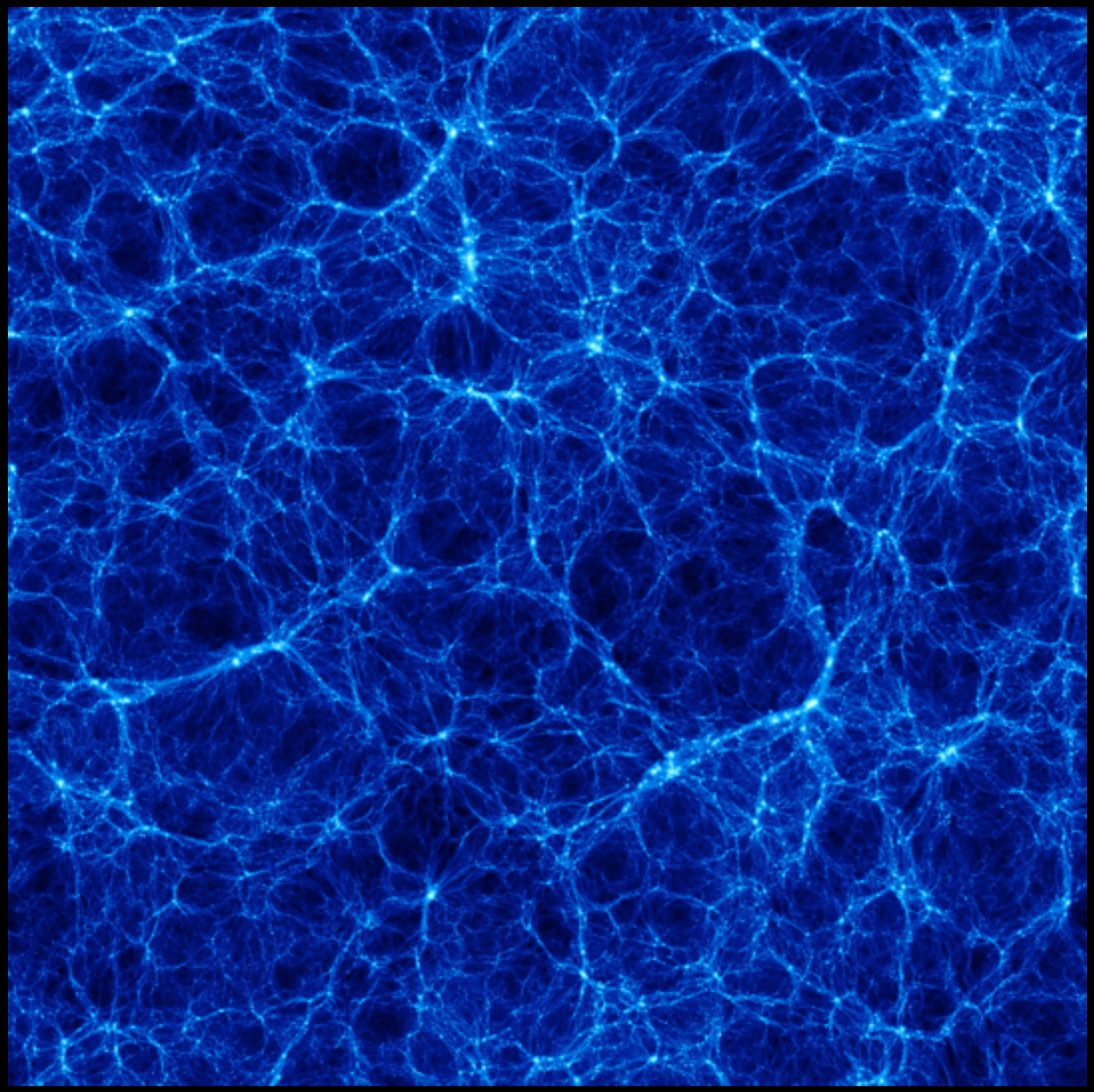

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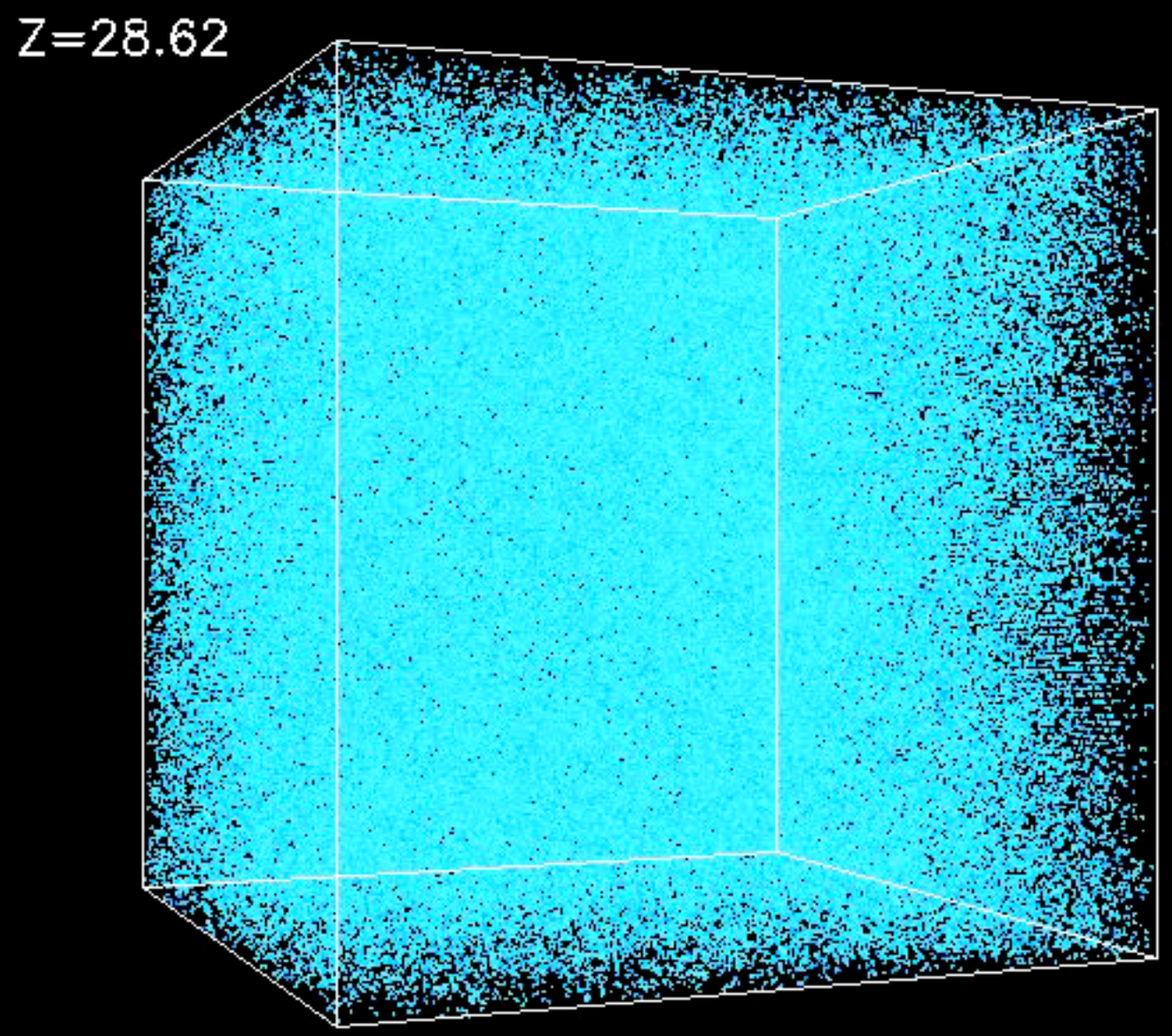
- Galaxy



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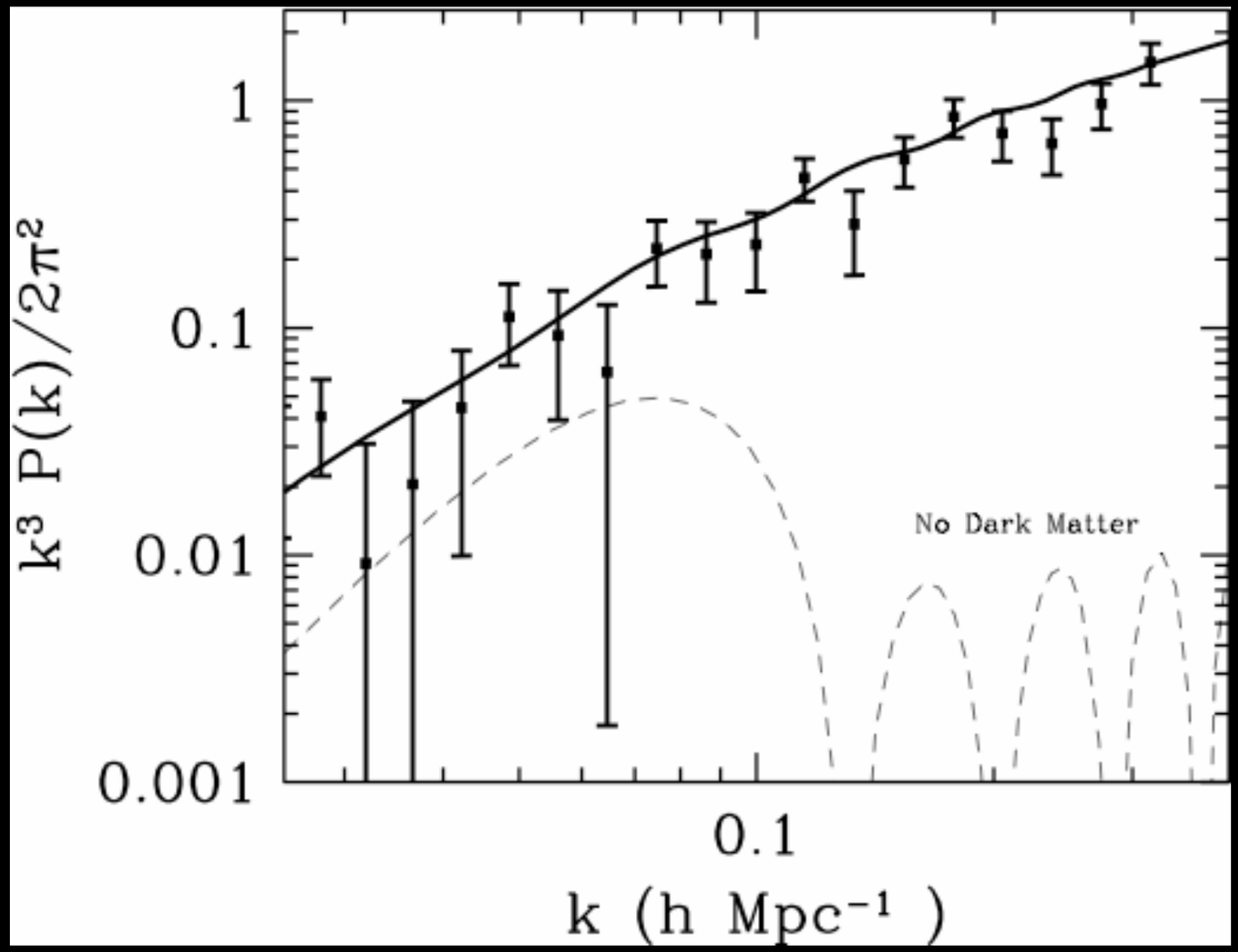

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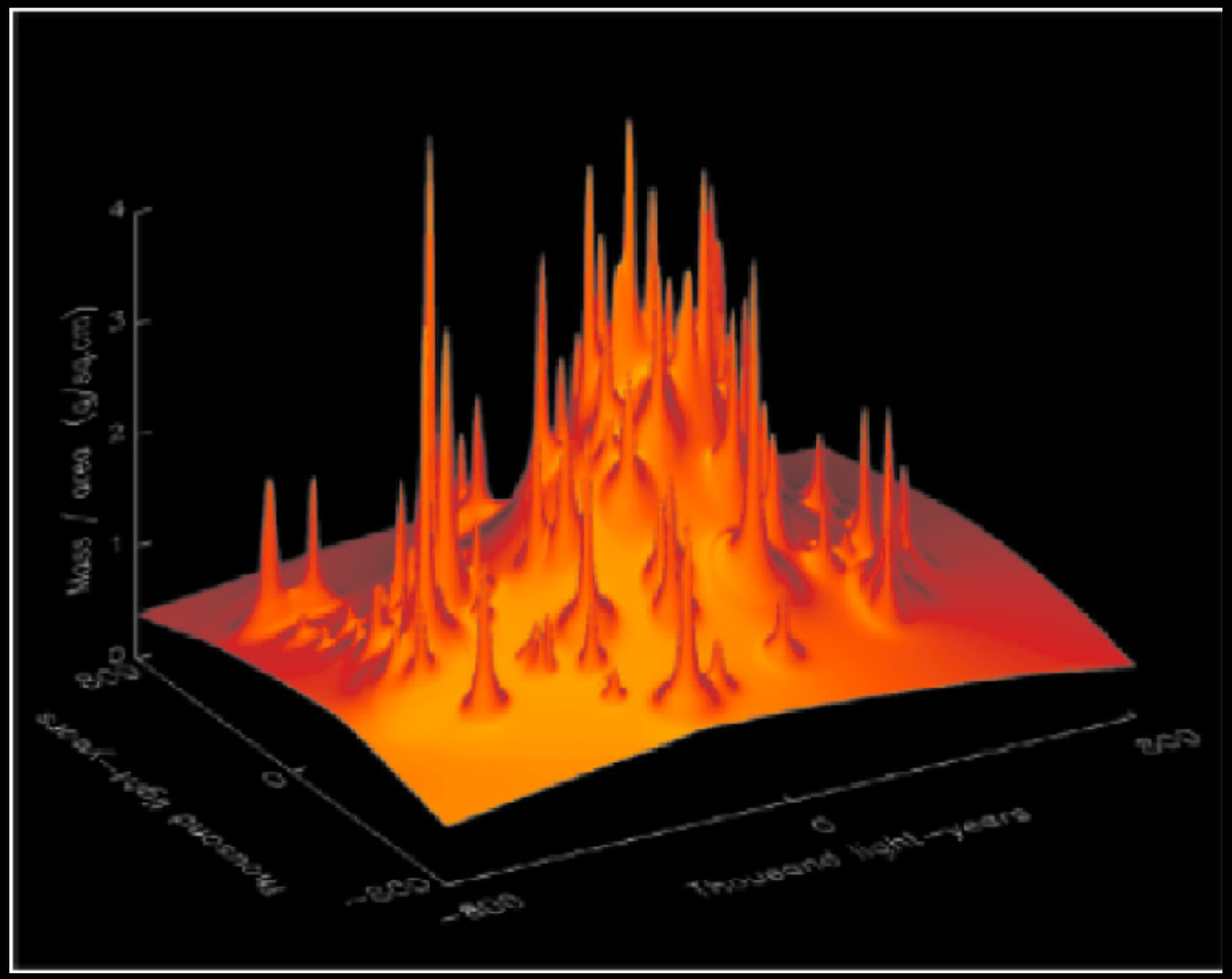

Dark matter - evidence?

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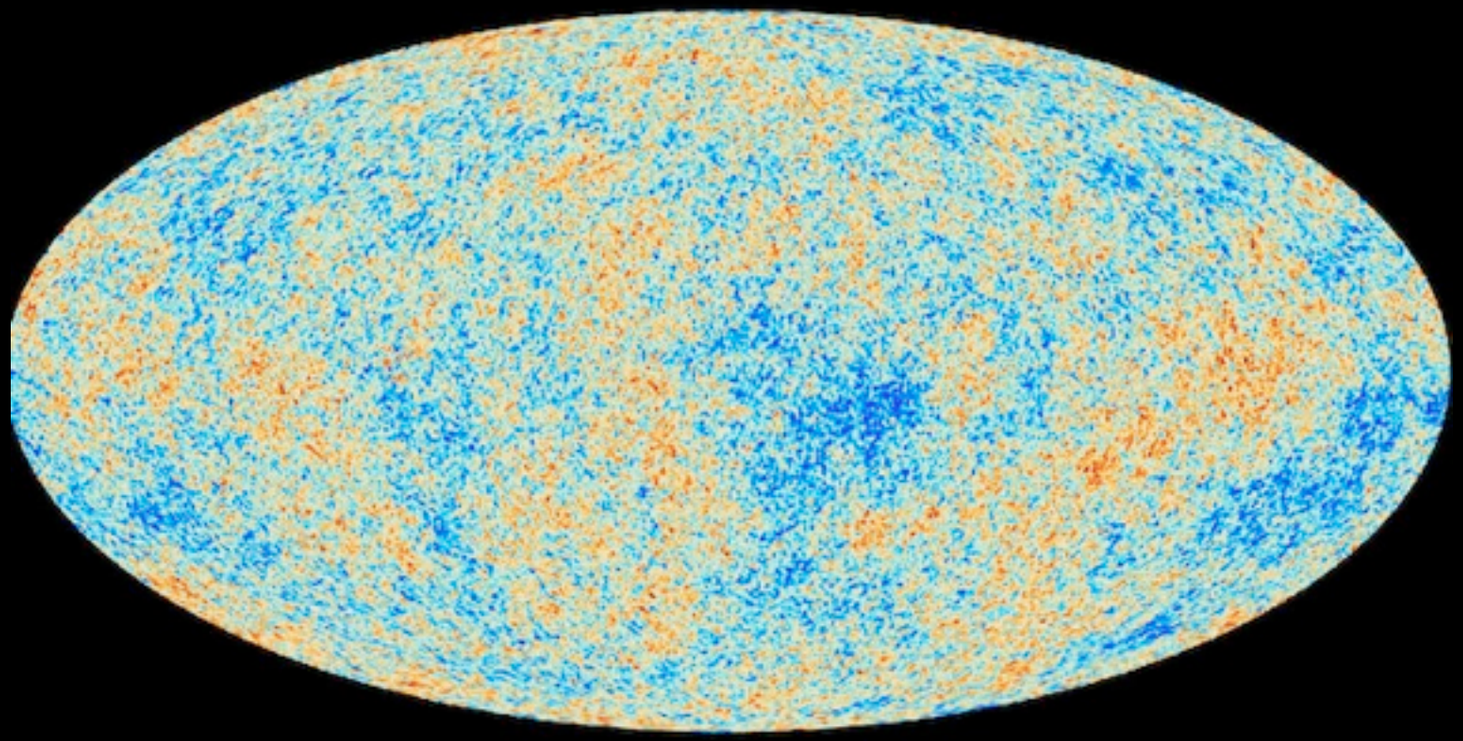
- Cosmic microwave background



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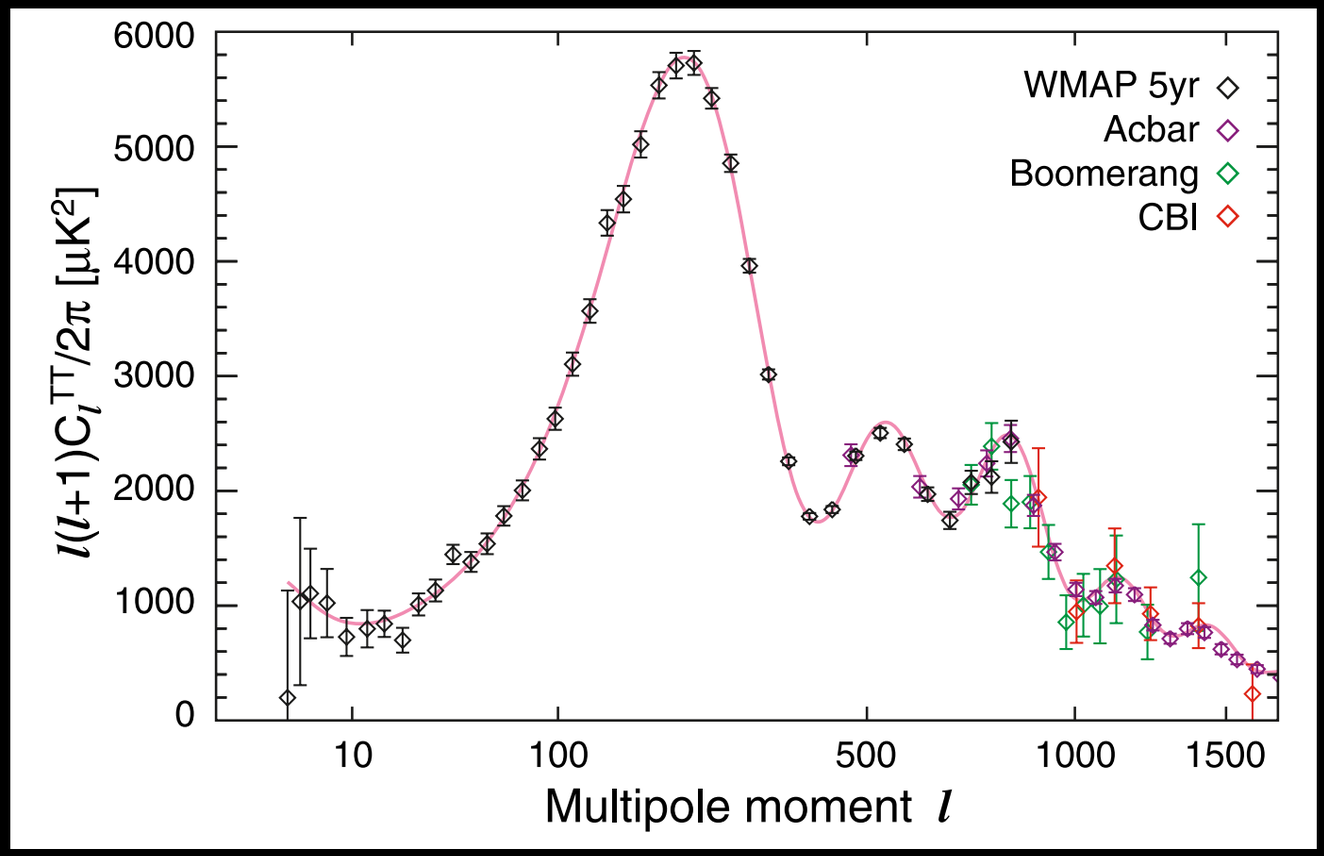

So what is it?

- We know it interacts gravitationally
- It is "dark" - should not interact with light or electromagnetism
- Nearly collisionless
- Slow

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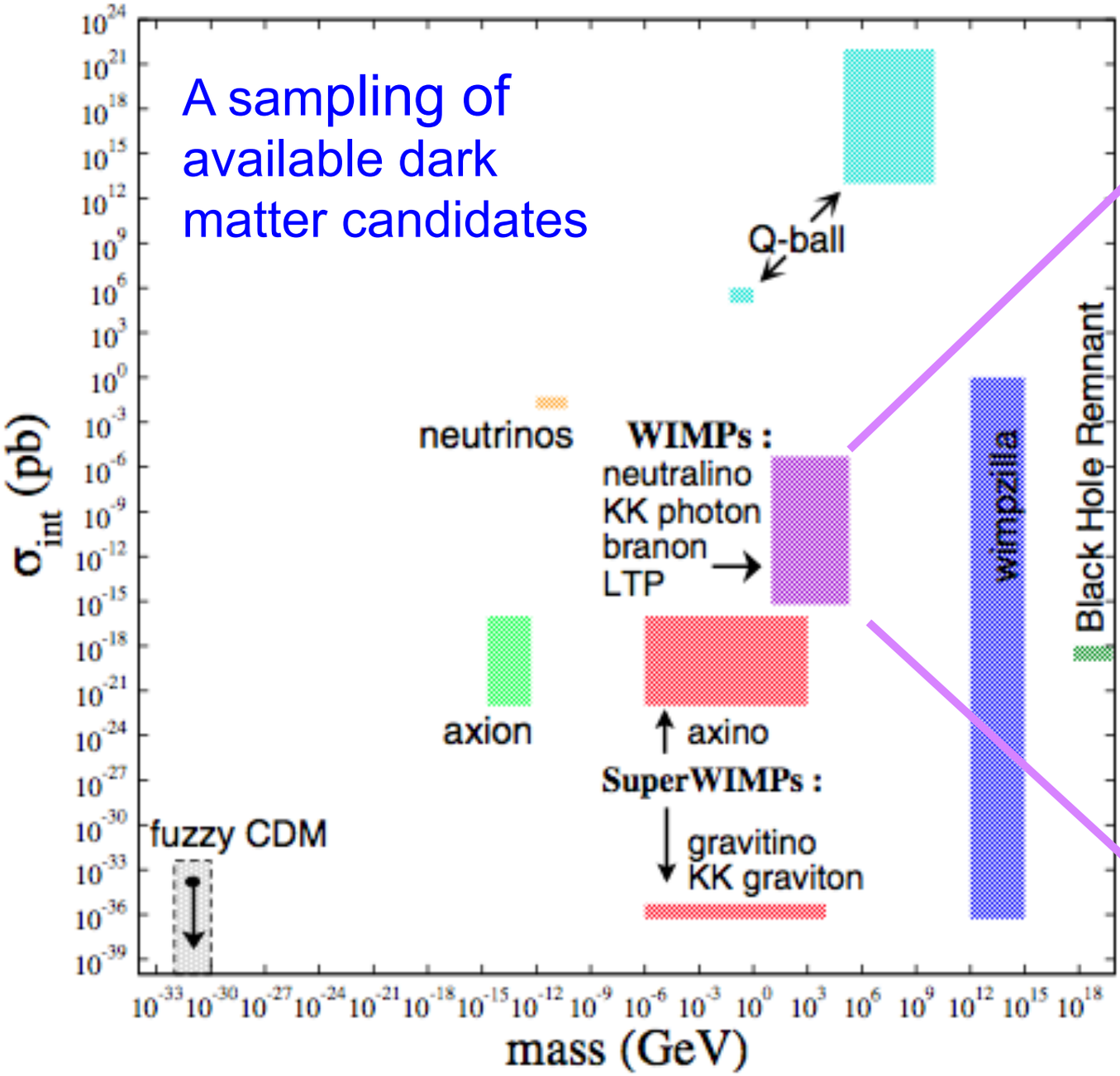
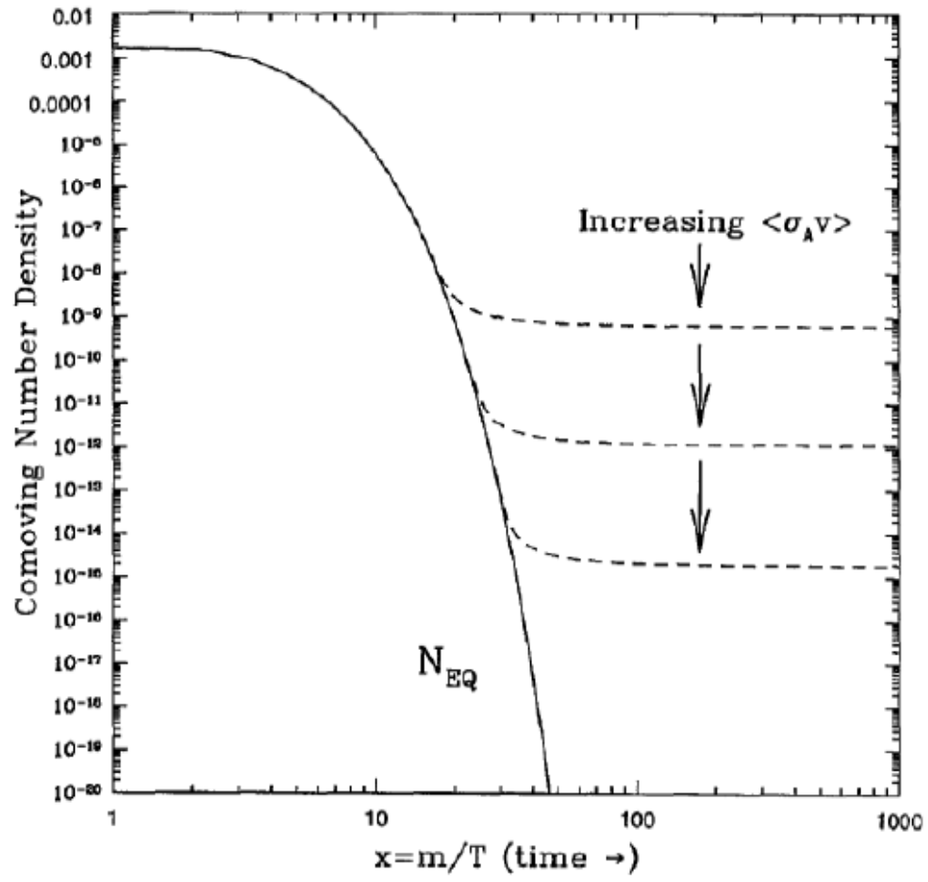
Beyond the Standard Model!

Why Weakly Interacting Massive Particles (WIMPs)?

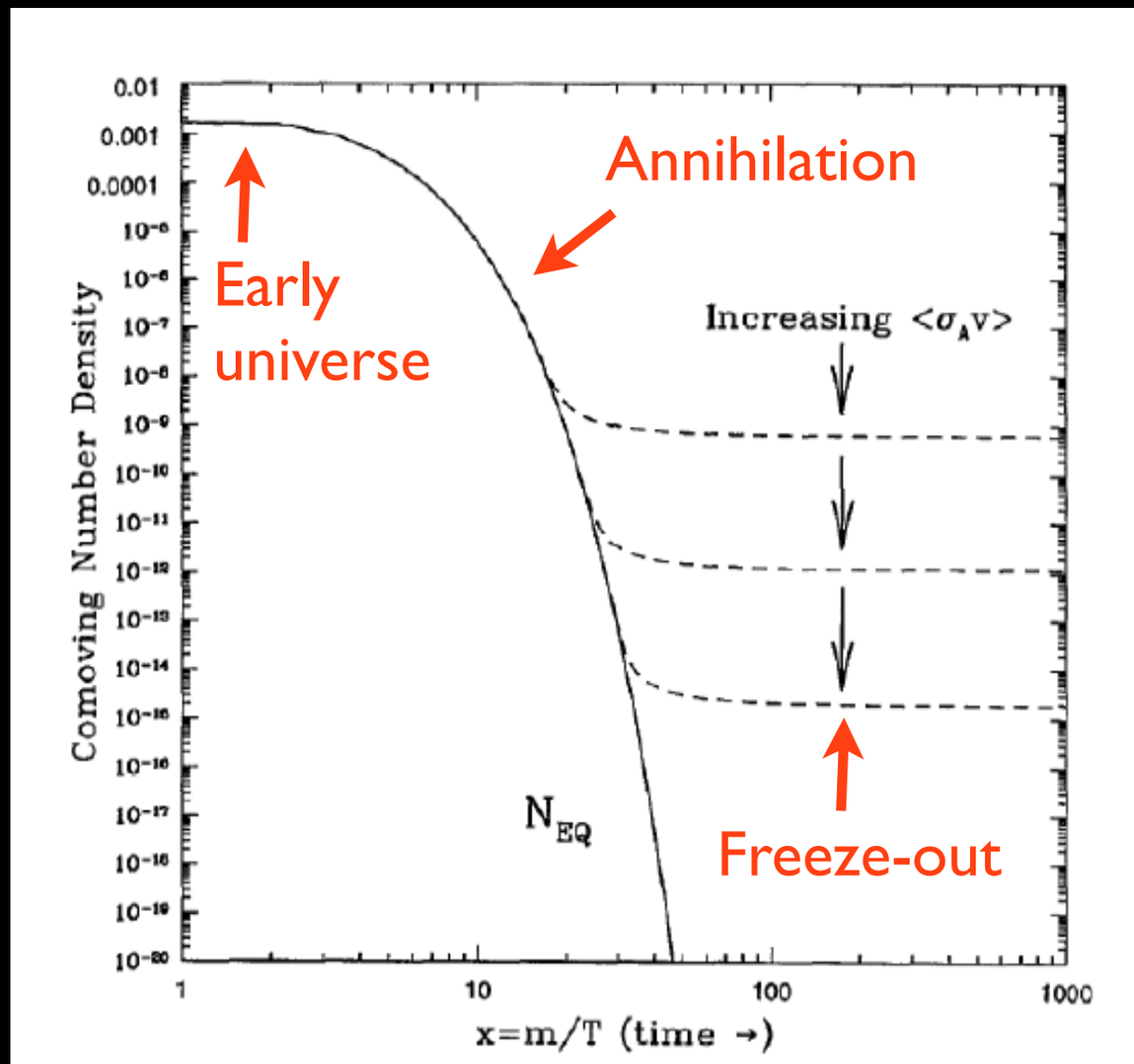


The "WIMP Miracle"



WIMPs

- Produced during big bang
- Decouples from ordinary matter as the universe expands and cools
- From cosmology we can calculate the relic abundance of a non-relativistic species



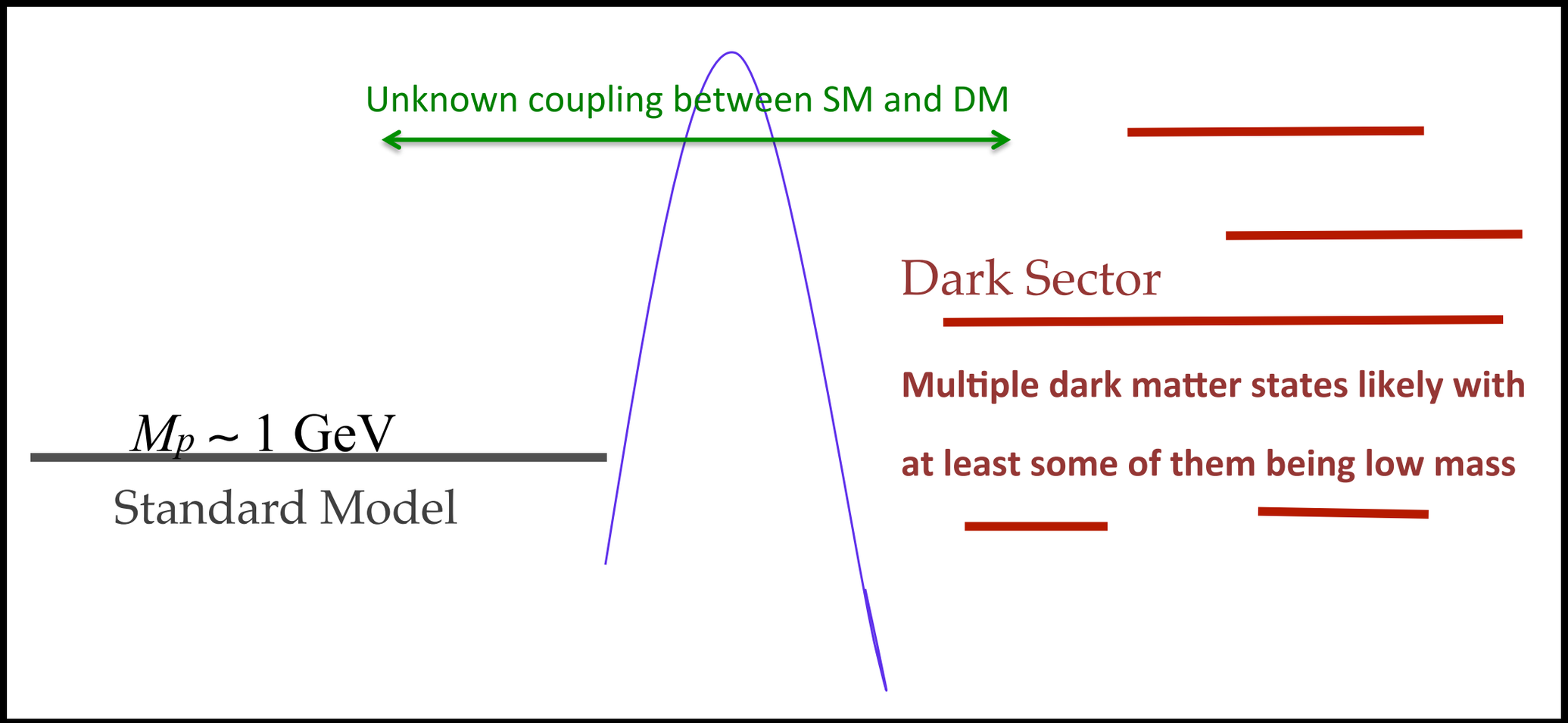
$$\Omega_\chi h^2 = m_\chi n_\chi / \rho_c \approx \frac{3 \times 10^{-27}\ \mathrm{cm^3 s^{-1}}}{< \sigma_A v >}.$$

- A particle with weak scale interactions has annihilation cross section

$$< \sigma_A v > \sim \alpha^2 (100\ \mathrm{GeV}^{-2}) \sim 10^{-25}\ \mathrm{cm^3 s^{-1}}.$$

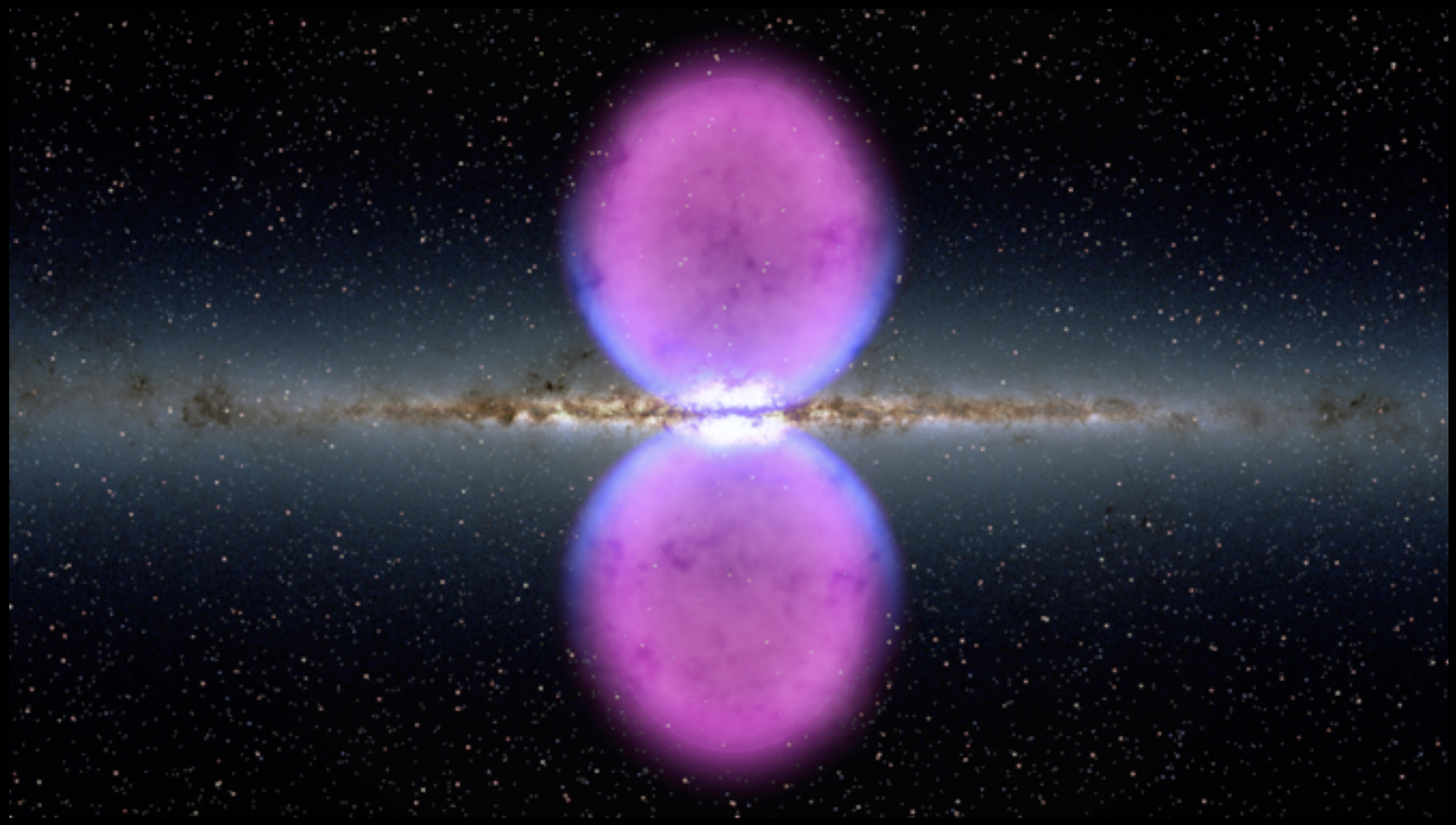
WIMPs not necessarily related to supersymmetry

- Dark sector could be as complicated as standard model
- Searches not limited by expectations from SUSY models



How do we find it?

- Indirect - detect annihilation products from regions of high density like the sun or the center of the galaxy



Fermi bubbles, courtesy of NASA

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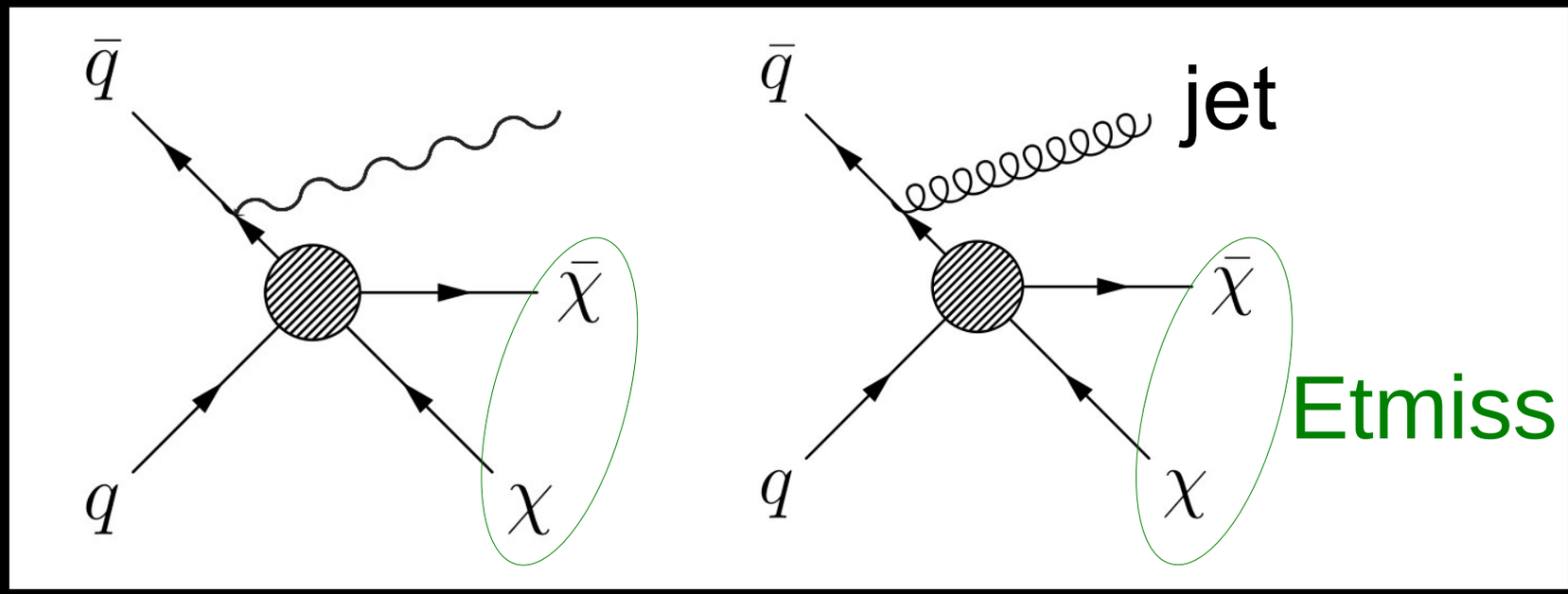
- Accelerators - create a WIMP at the LHC
  - Missing ET and monojet searches



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- Indirect - detect annihilation products from regions of high density like the sun or the center of the galaxy
- Accelerators - create a WIMP at the LHC
  - Missing ET and monojet searches
- Direct detection - WIMPs can scatter elastically with nuclei and the recoil can be detected

Direct Detection

- Can calculate an interaction rate from first principals and some assumptions about the dark matter distribution and interaction

- Two main interactions are considered (other terms tend to be suppressed)

  - Spin independent (SI) - couples to all nucleons

    - In low momentum transfer, this is coherent across the nucleus, providing an enhancement for large nuclei

- Spin dependent (SD) - couples to the spin of the nucleon (requires unpaired spin in the nucleus)

  - Interactions with individual nucleons, no enhancement factor

Rate calculation

- The differential cross section (for spin-independent interactions) in events/kg/keV mass per unit recoil energy is

$$\frac{dR}{dQ} = \frac{\rho_0}{m_\chi} \times \frac{\sigma_0 A^2}{2\mu_p^2} \times F^2(Q) \times \int_{v_m} \frac{f(v)}{v} dv \tag{3}$$

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- The nuclear part, approximately given by $F^2(Q) \propto e^{-Q/Q_0}$ where $Q_0 \sim \frac{80}{A^{5/3}}$ MeV
- The velocity distribution of dark matter in the galaxy - of order 30% uncertainty (not-statistical), and $v_m = \sqrt{Qm_N/2m_r^2}$ (here $m_r = m_N m_\chi/(m_N + m_\chi)$ is the reduced mass of the nucleus)

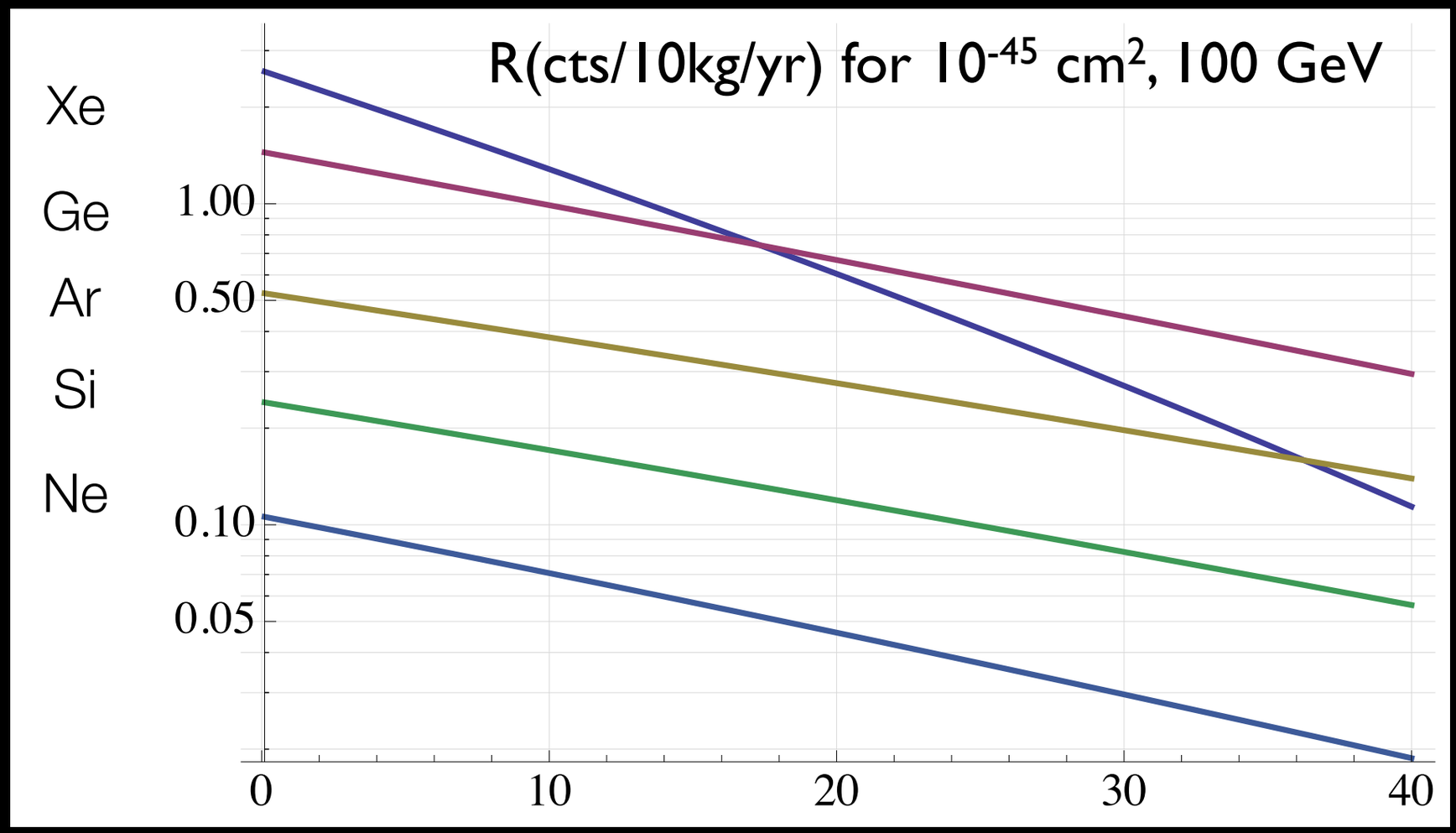
The energy scale

- Energy of recoils is tens of keV
- Entirely driven by kinematics, elastic scattering of things with approximately similar masses (100 GeV) and v ~ 0.001c

$$\frac{1}{2} m_N v_N^2 = \frac{1}{2} \times 100\,\mathrm{GeV} \times 10^{-6} = 50\,\mathrm{keV}$$

How do we find it?

- Very low rate process (~events/year)



- Rate depends crucially on WIMP mass and threshold

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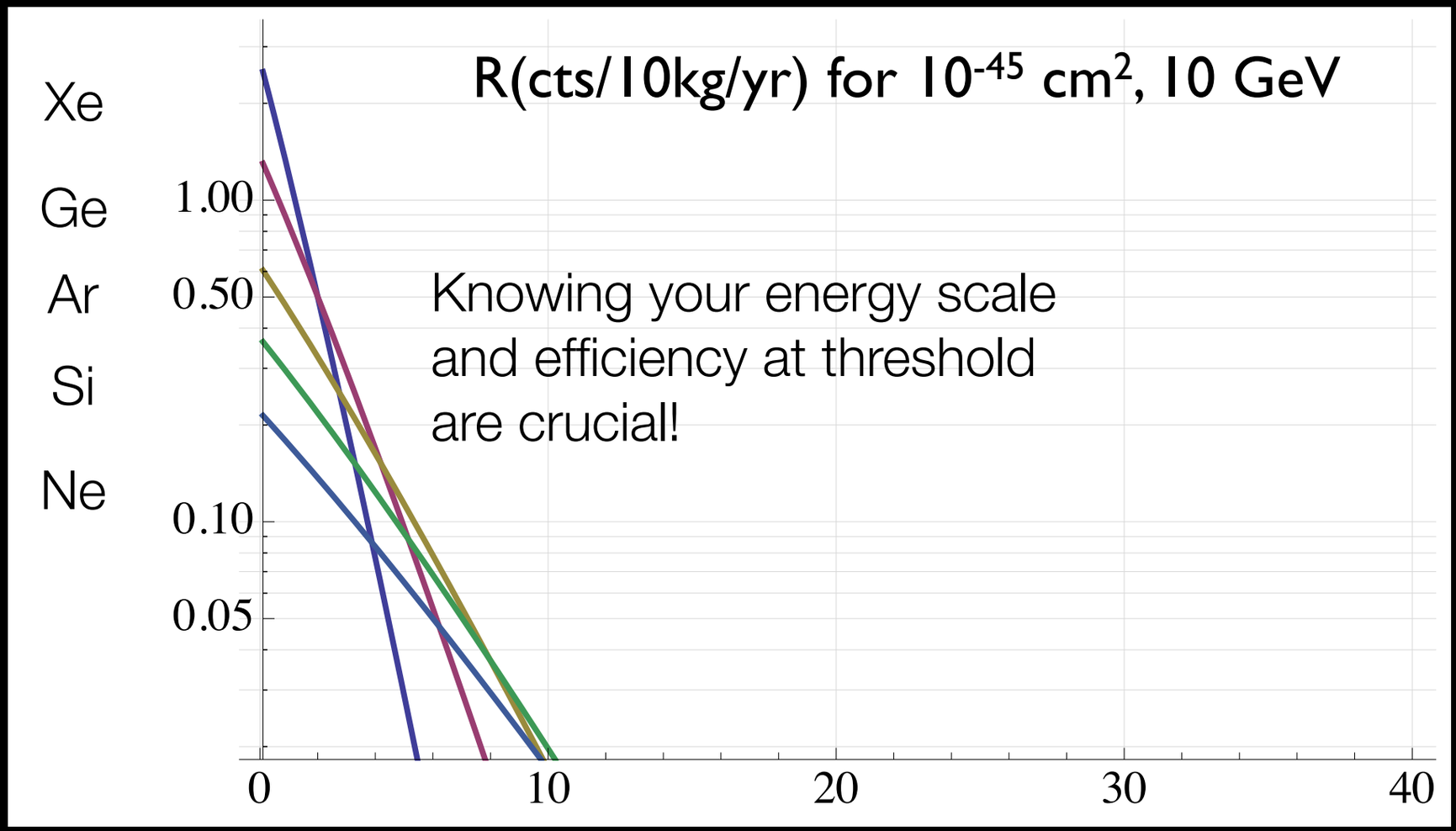
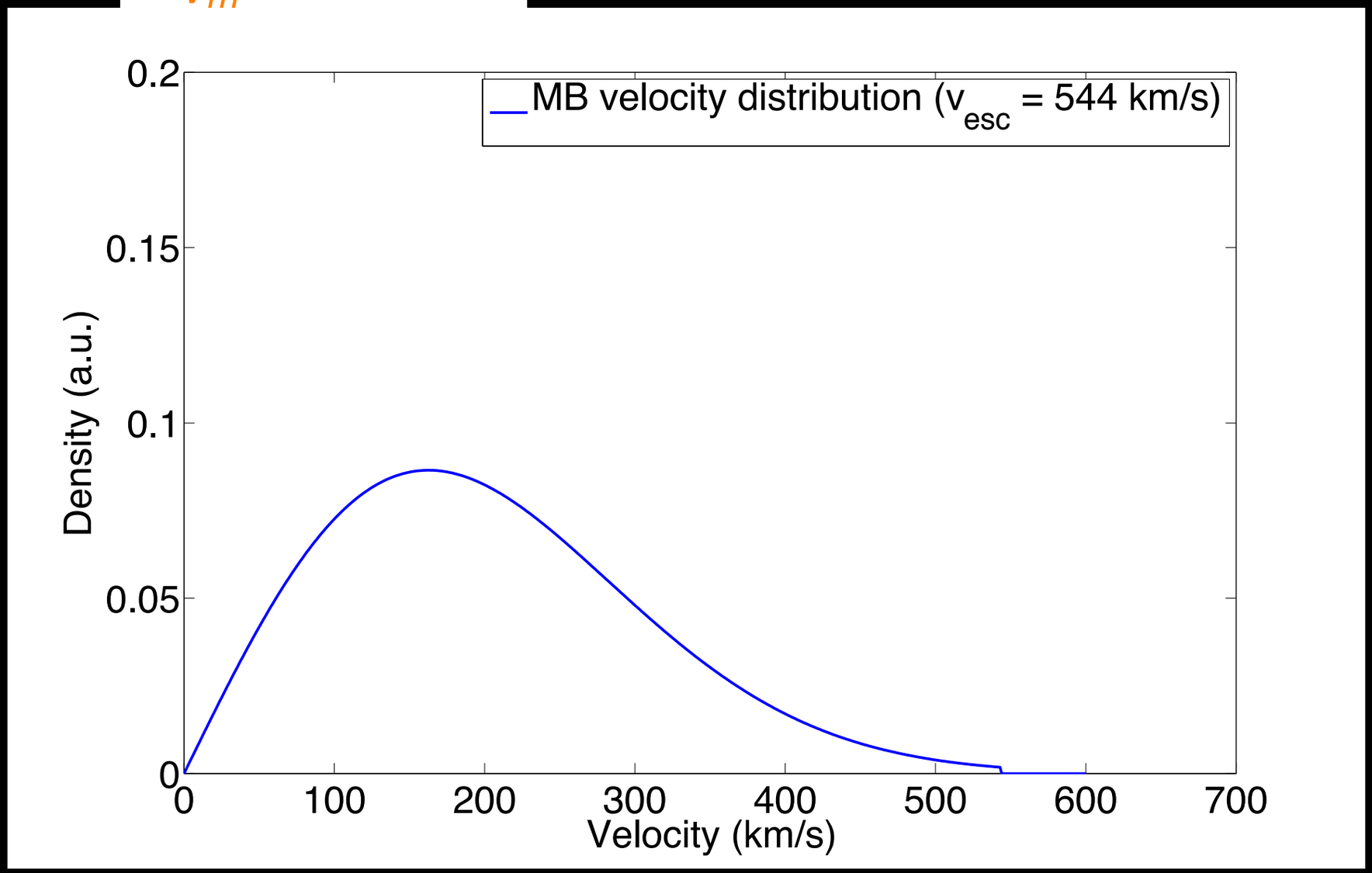


- Rate depends crucially on WIMP mass and threshold

Much of that dependence comes through velocity distribution

$$\int_{v_m} \frac{f(v)}{v} dv$$

$$v_m = \sqrt{Q m_N / 2 m_r^2}$$



- v_{esc} - speed above which WIMPs are no longer bound (currently taken to be 544 km/s)

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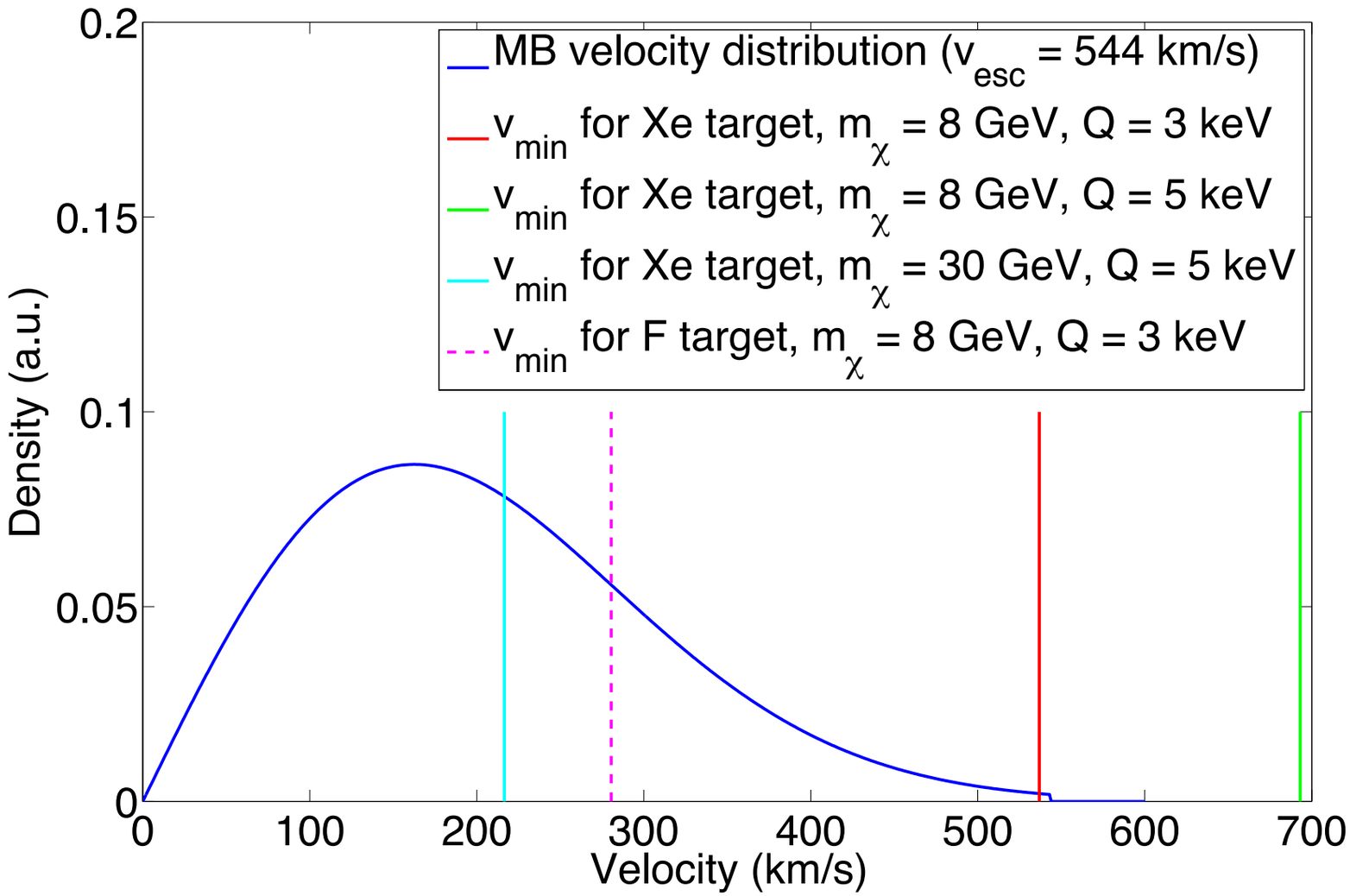
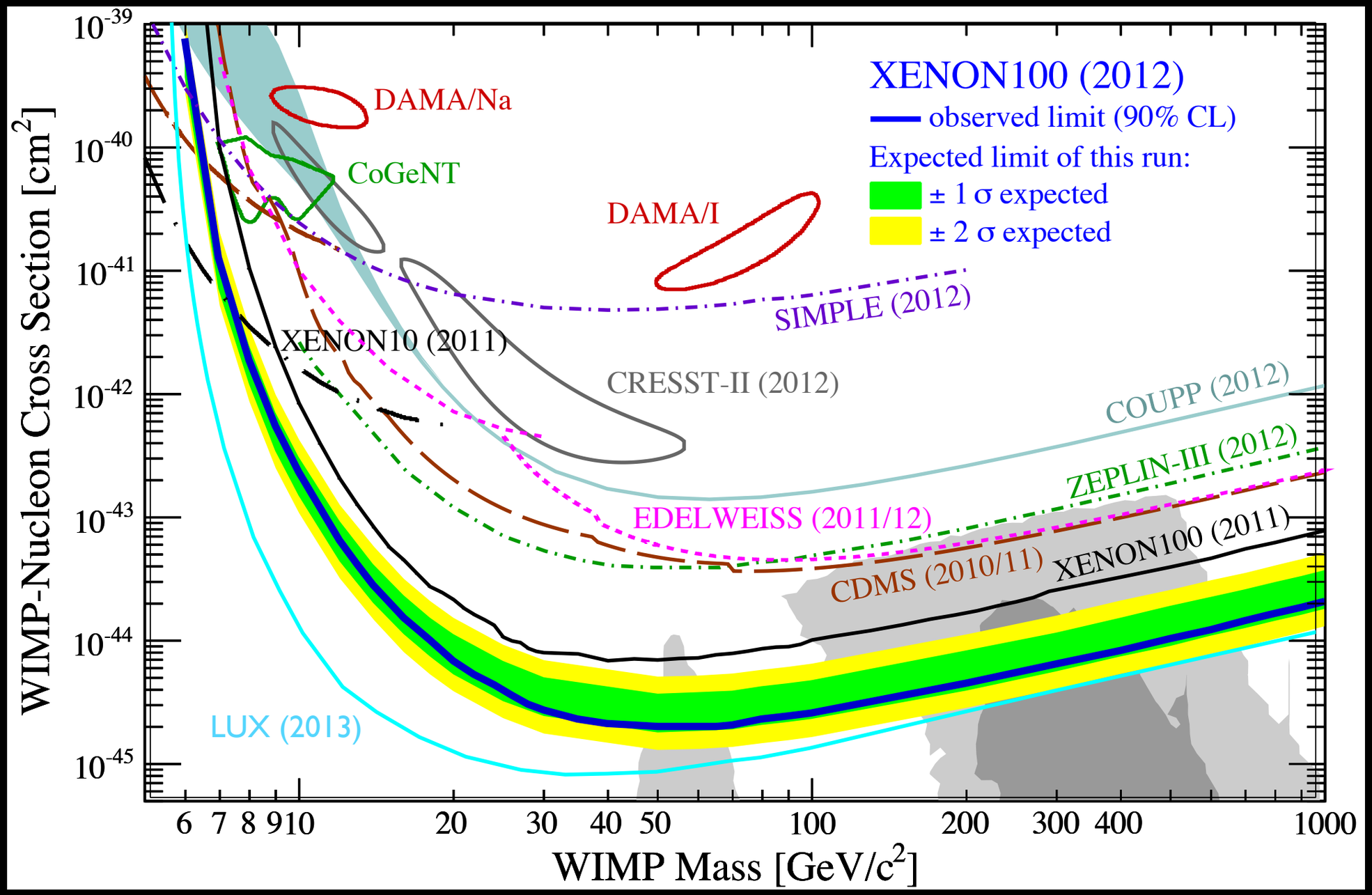
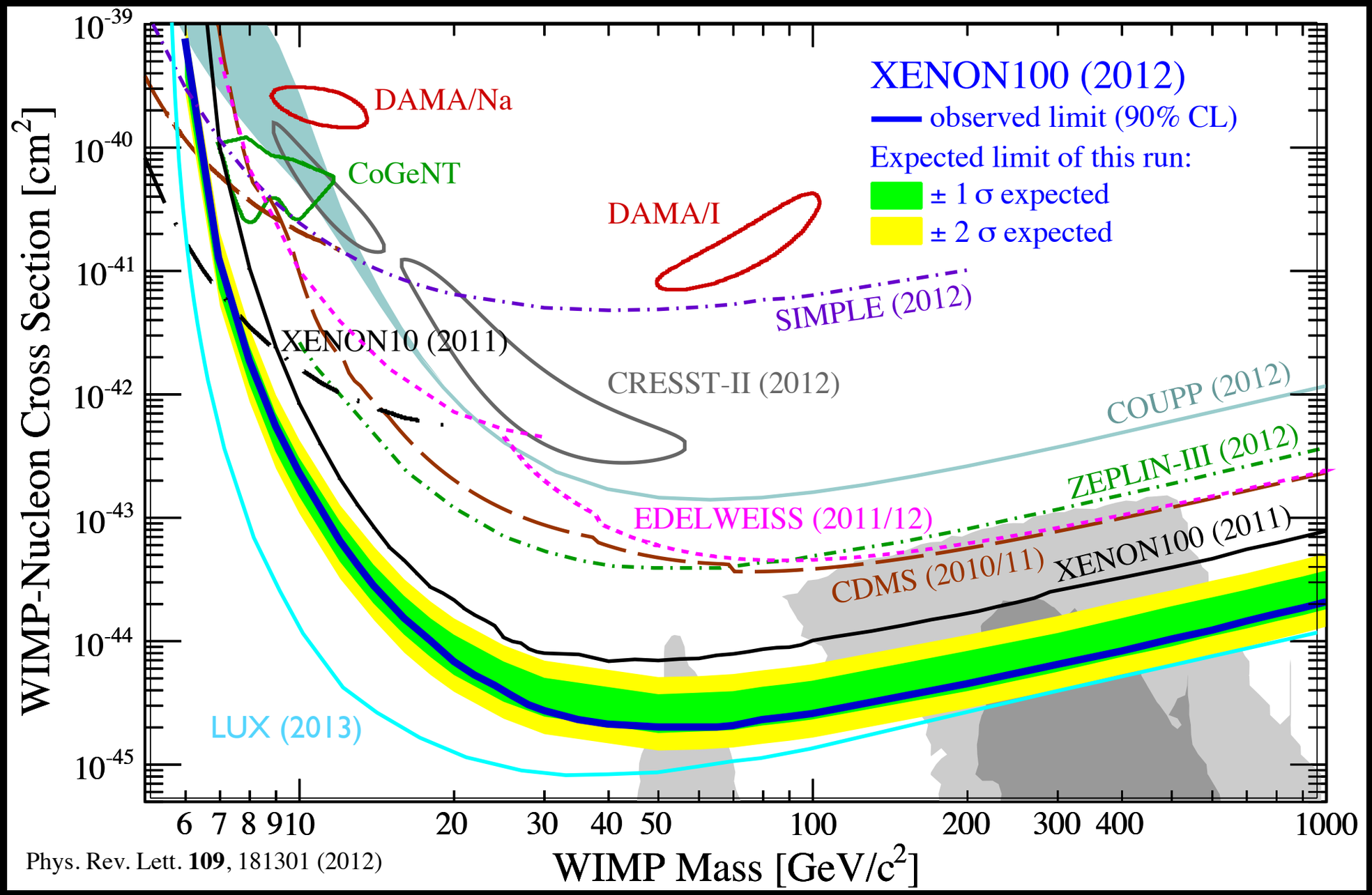


The canonical plot



- Limited at low mass by detector threshold and kinematics
- Limited at high mass by density

The canonical plot



- What happened to "weakly" interacting?
- Mediation via Z was excluded long ago (~10^{-39} cm^2), but only now are we probing Higgs exchange

So we look for WIMPs

- A few hundred just passed through us, and we might expect a handful of counts in a detector per year

So we look for WIMPs

- A few hundred just passed through us, and we might expect a handful of counts in a detector per year
- The problem is that background radioactivity is everywhere!

100 events/second/kg =
3,000,000,000,000 events/year
in a ton-scale experiment

Backgrounds!

Background sources

- Cosmic rays are constantly streaming through
  - All experiments have to go underground to get away from cosmic rays


SNOLAB
Mining for knowledge
Creuser pour trouver... l'excellence

Background sources

- Cosmic rays are constantly streaming through
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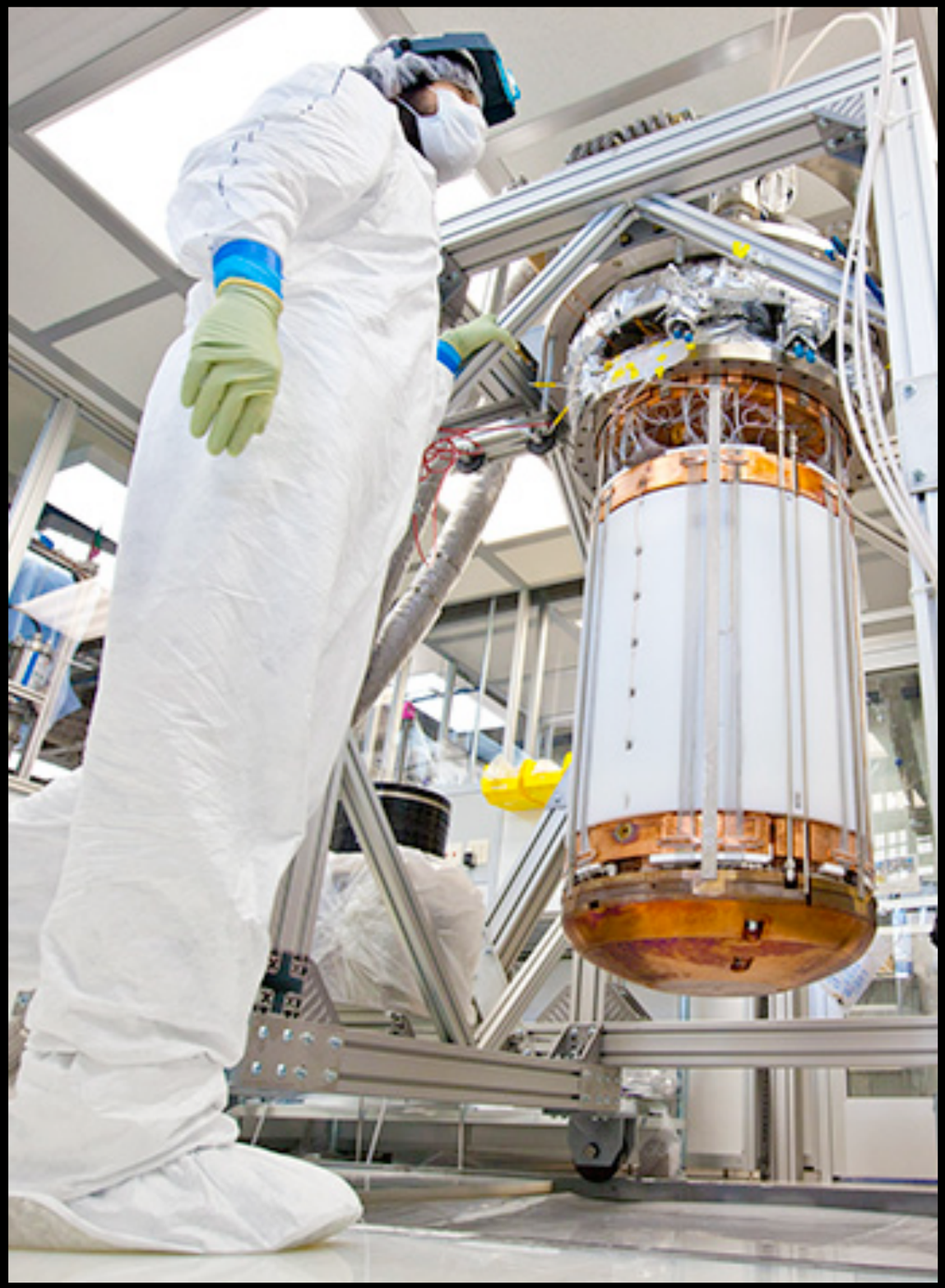
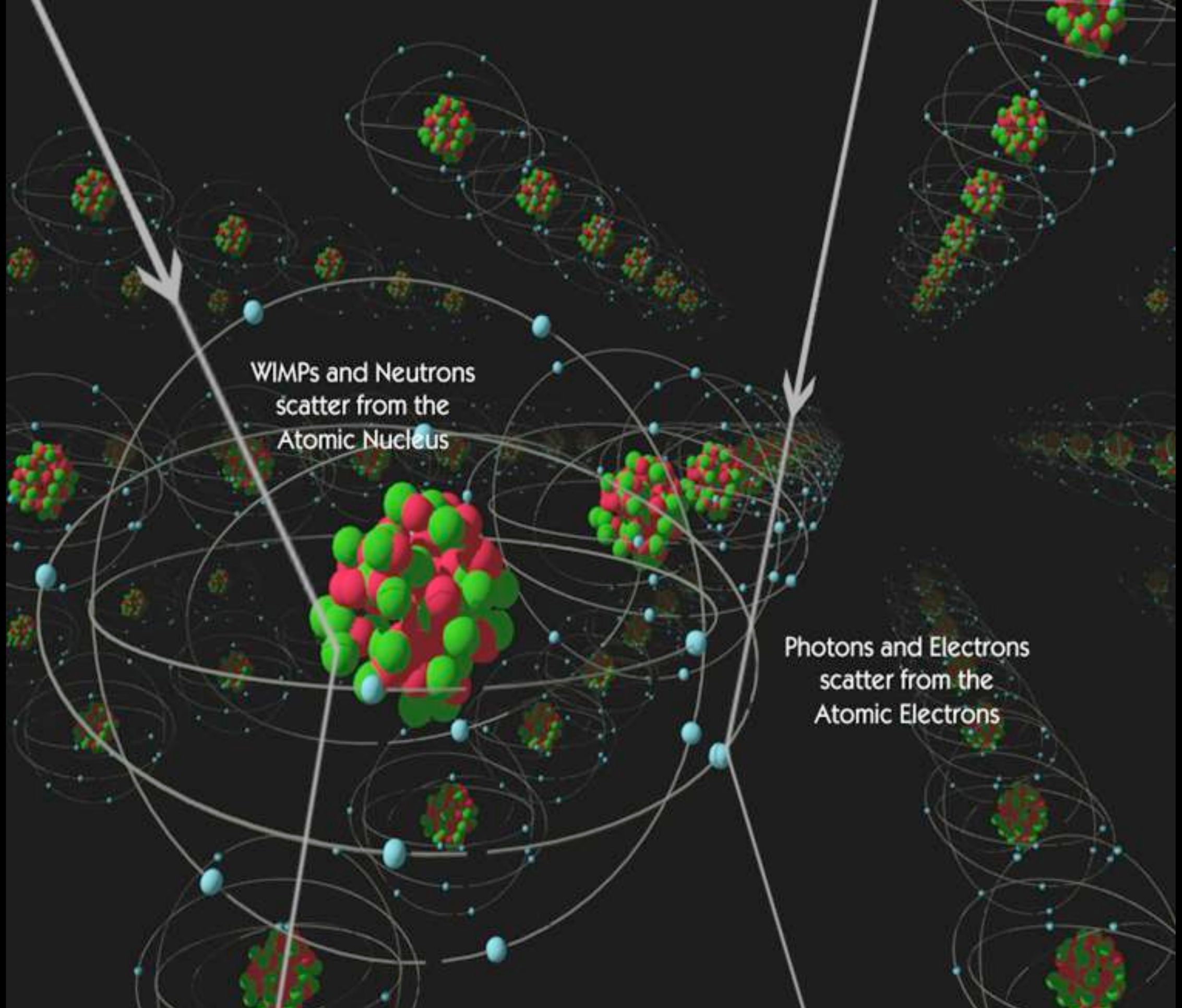
- Radioactive contaminants - rock, radon in air, impurities
  - Emphasis on purification and shielding



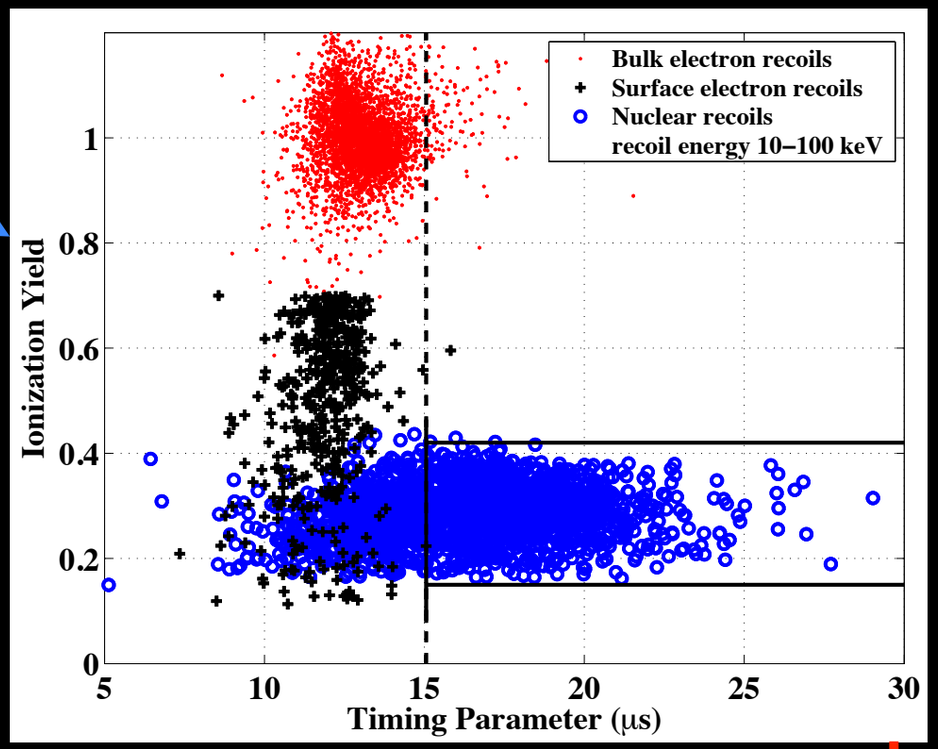
Background sources

- Cosmic rays are constantly streaming through
  - All experiments have to go underground to get away from cosmic rays
- Radioactive contaminants - rock, radon in air, impurities
  - Emphasis on purification and shielding
- The detector itself - steel, glass, detector components
  - Self-shielding to leave a clean inner region
  - Discrimination - can you tell signal from background (gamma rays, alphas, neutrons, etc)?

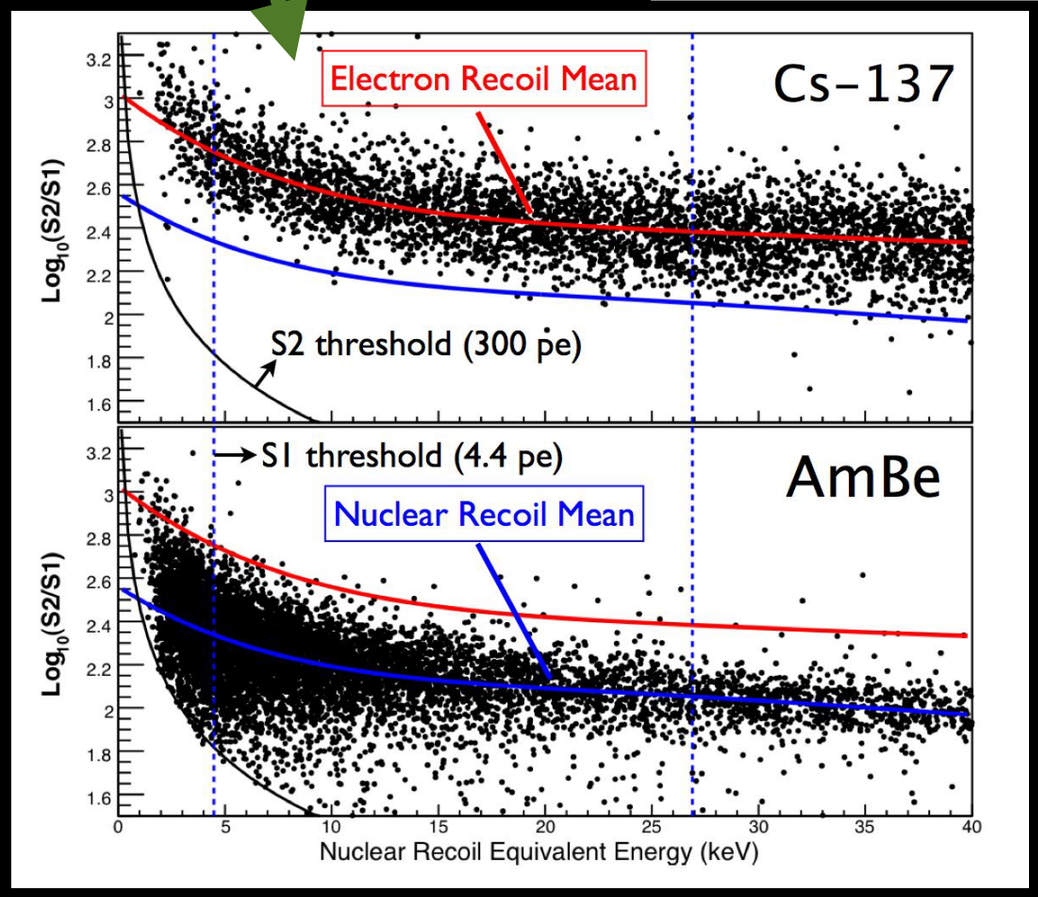

WIMPs and Neutrons
scatter from the
Atomic Nucleus
Photons and Electrons
scatter from the
Atomic Electrons

Electronic recoils (gammas) vs. nuclear recoils (WIMPs)

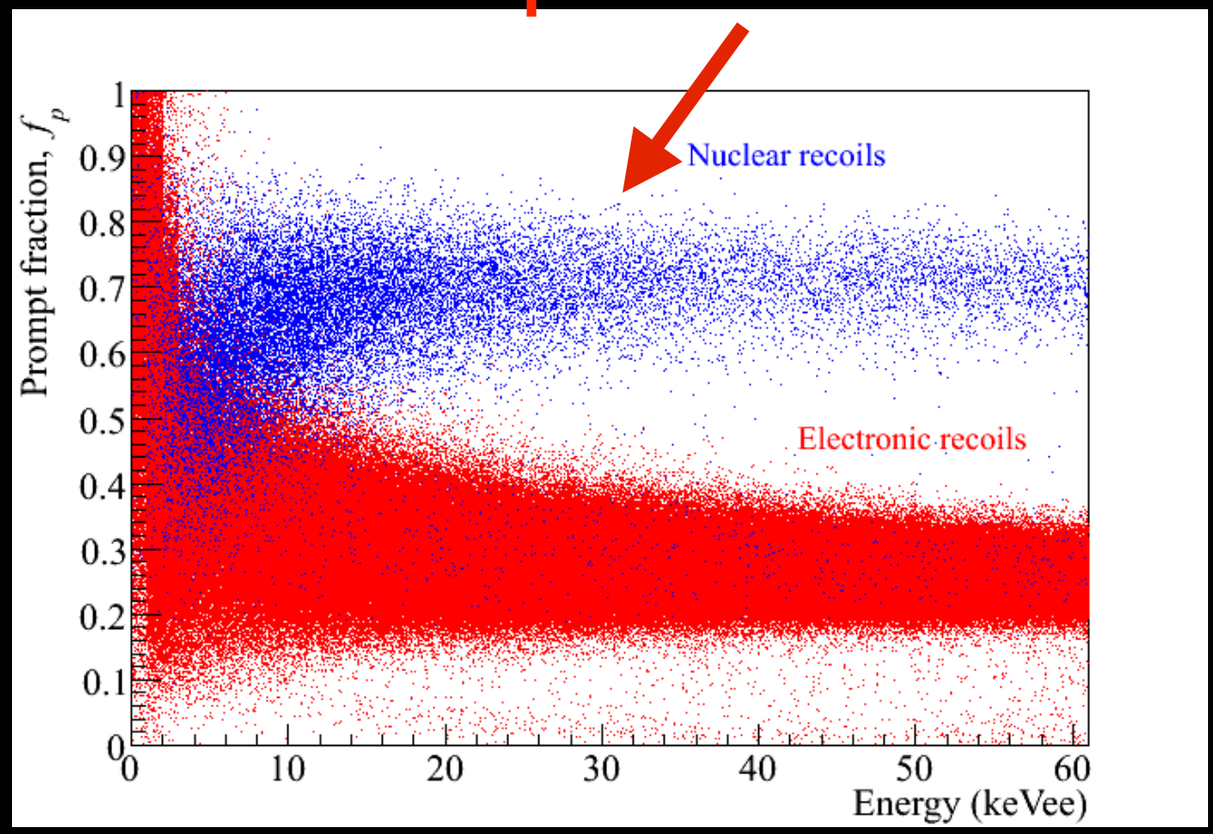
CDMS - Charge to heat



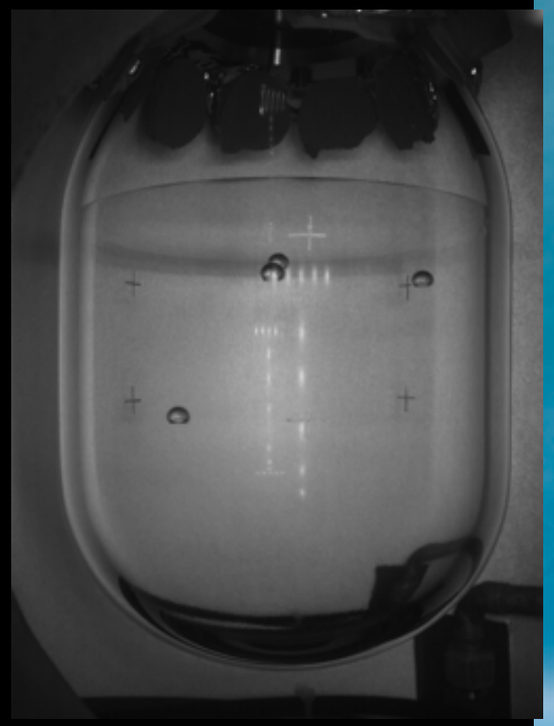
Xenon TPCs - Charge to light



Argon - Pulse shape discrimination

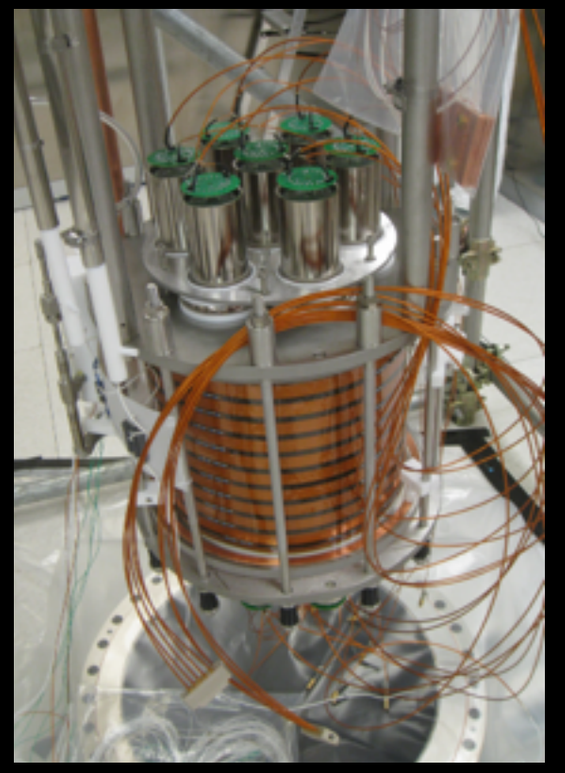


Direct searches (non exhaustive)



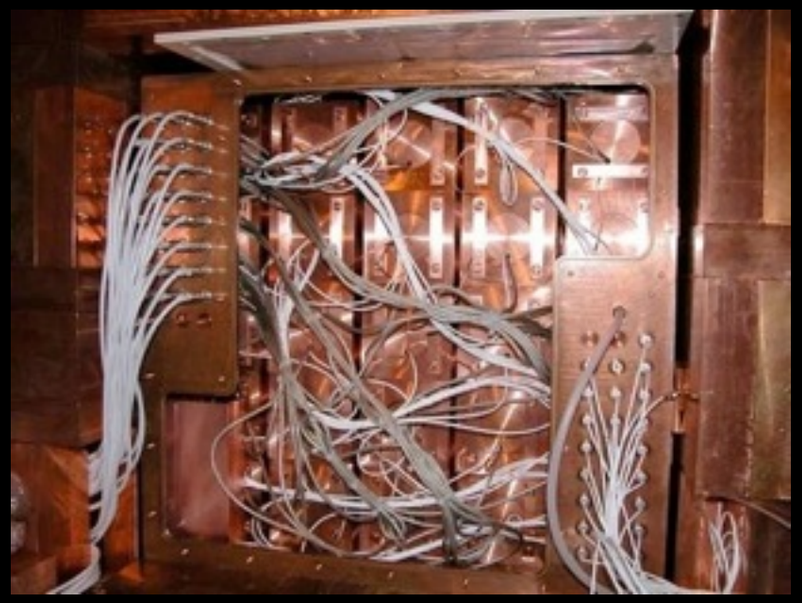
COUPP/PICO
Bubble chambers

LUX/Xenon
Xenon TPC

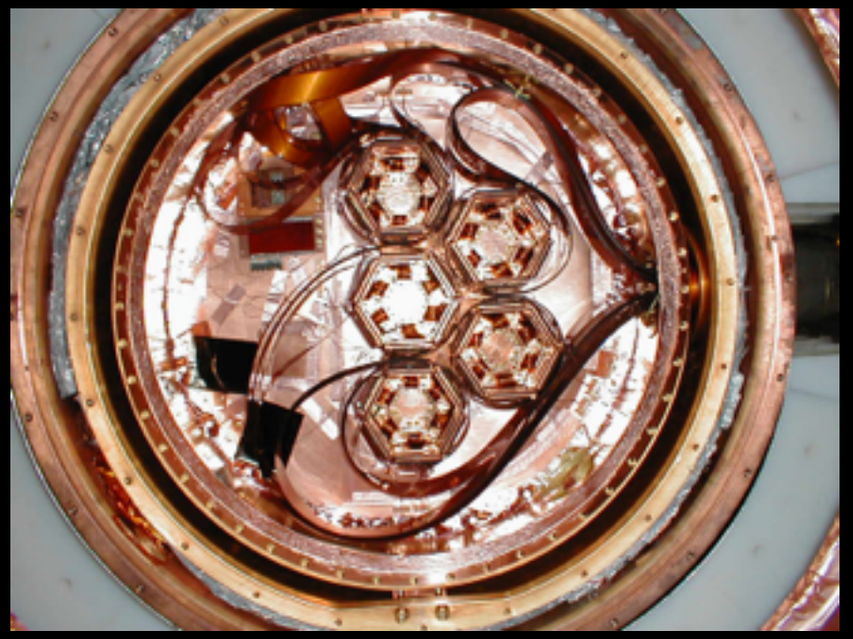


DarkSide
Argon TPC

DAMIC
CCDs (from DECam)



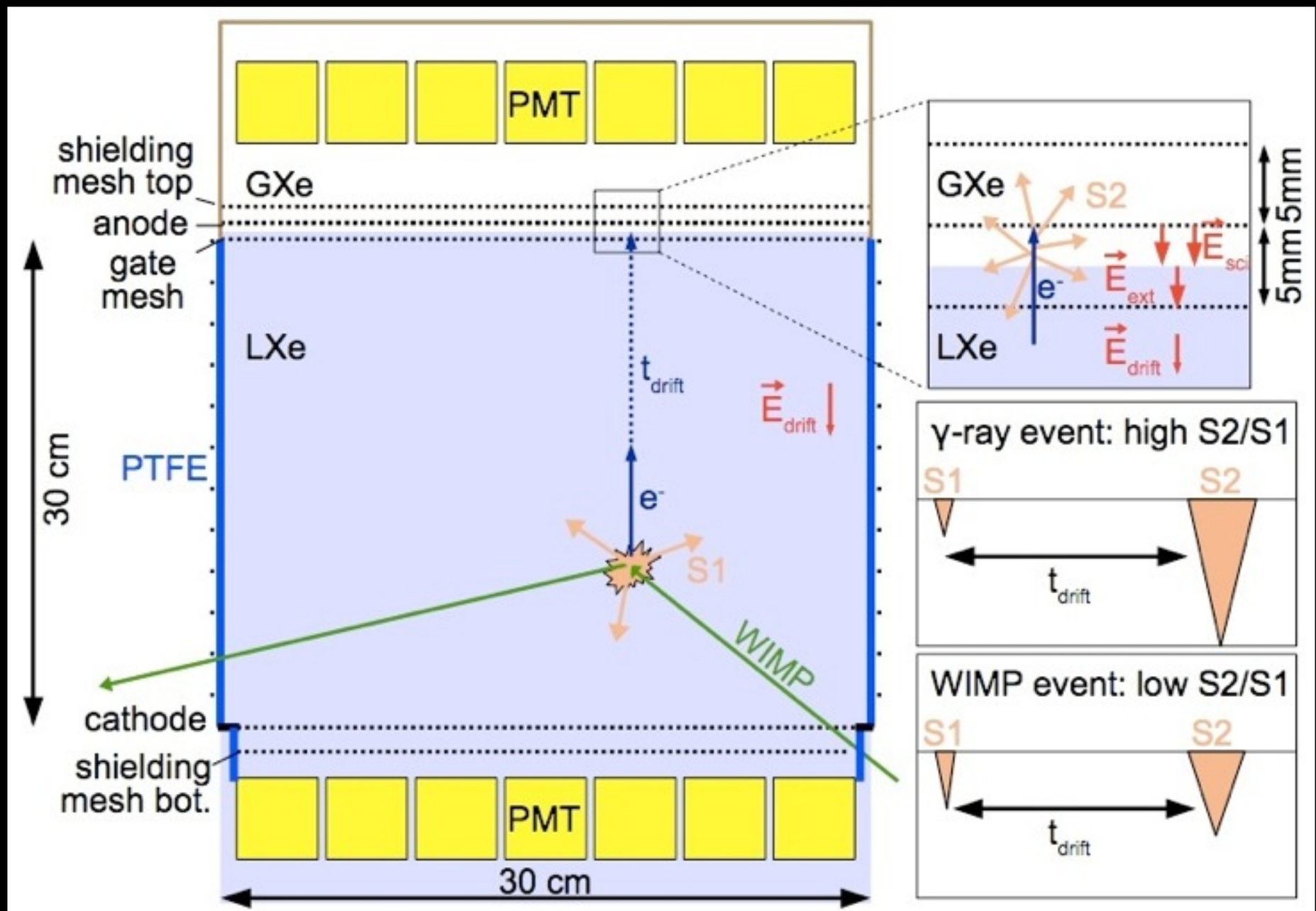
DAMA NaI



CDMS and CoGeNT
Cryogenic Germanium

Xenon and LUX/LZ

- Liquid xenon TPCs - collect light and scintillation light released by energy deposition in the liquid
  - Fragments of Xenon10 - Xenon100/1T in Italy, LUX/LZ in South Dakota



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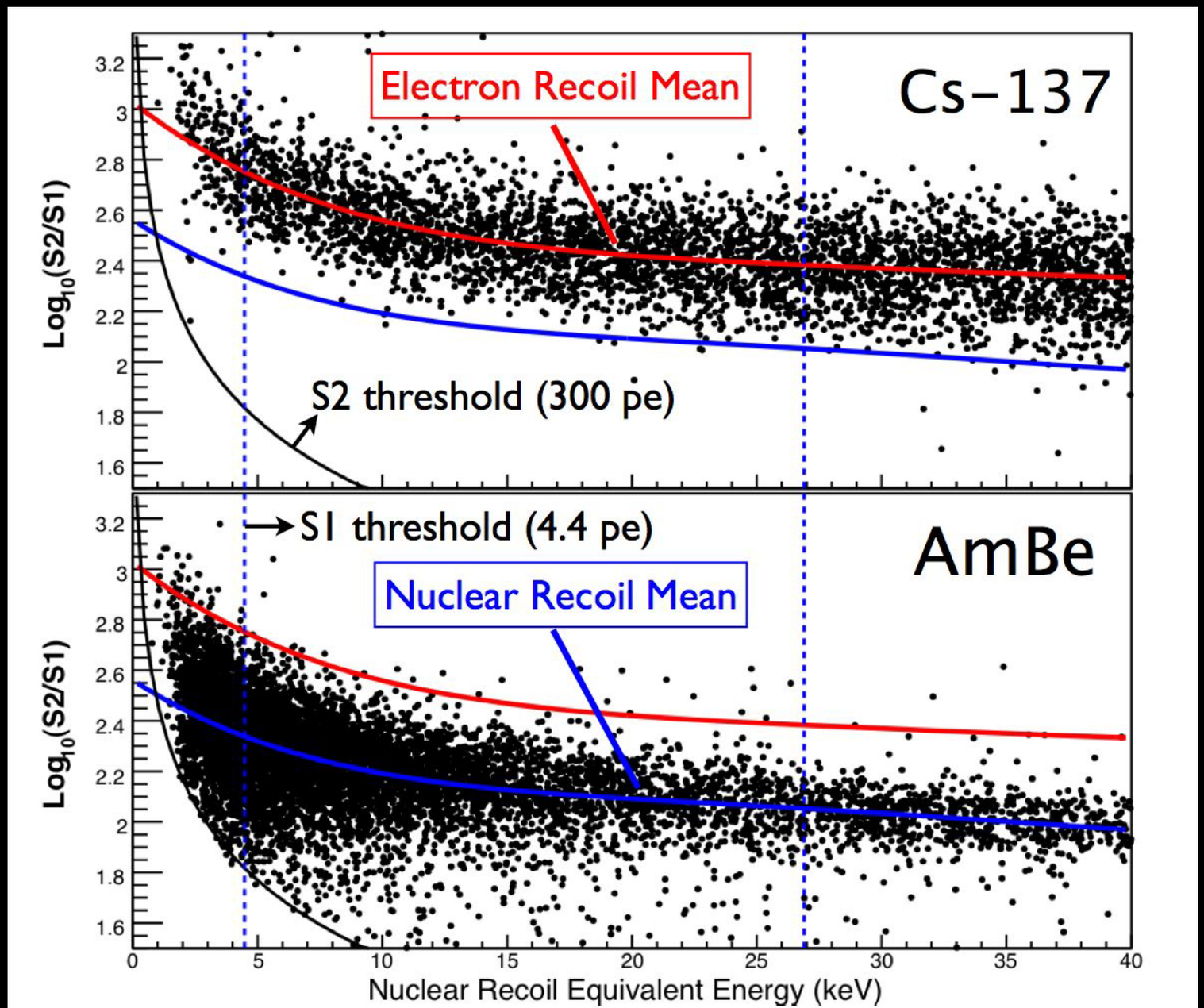
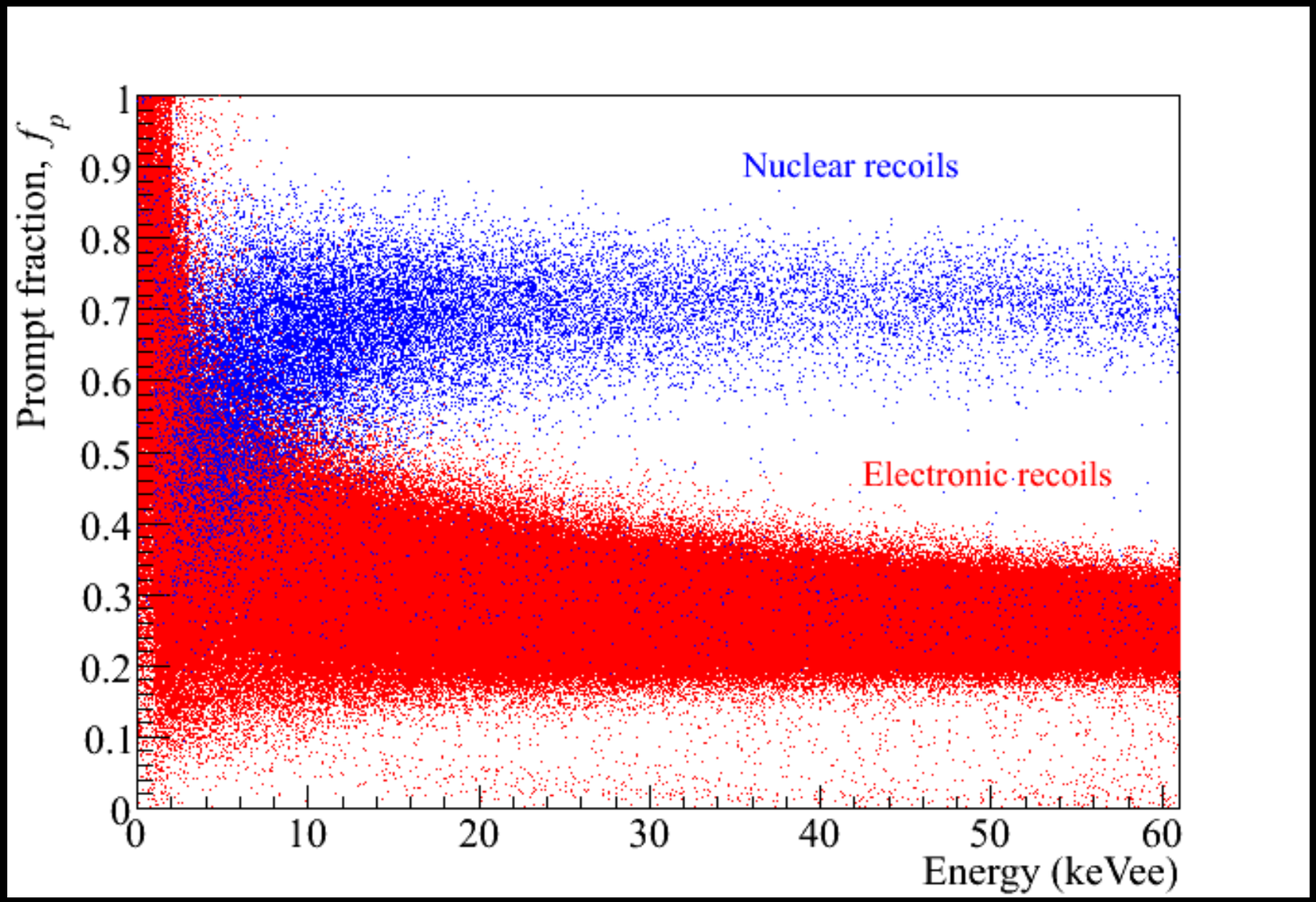


Argon detectors

- DarkSide, the dominant liquid argon experiment in the US - same idea as Xenon TPCs

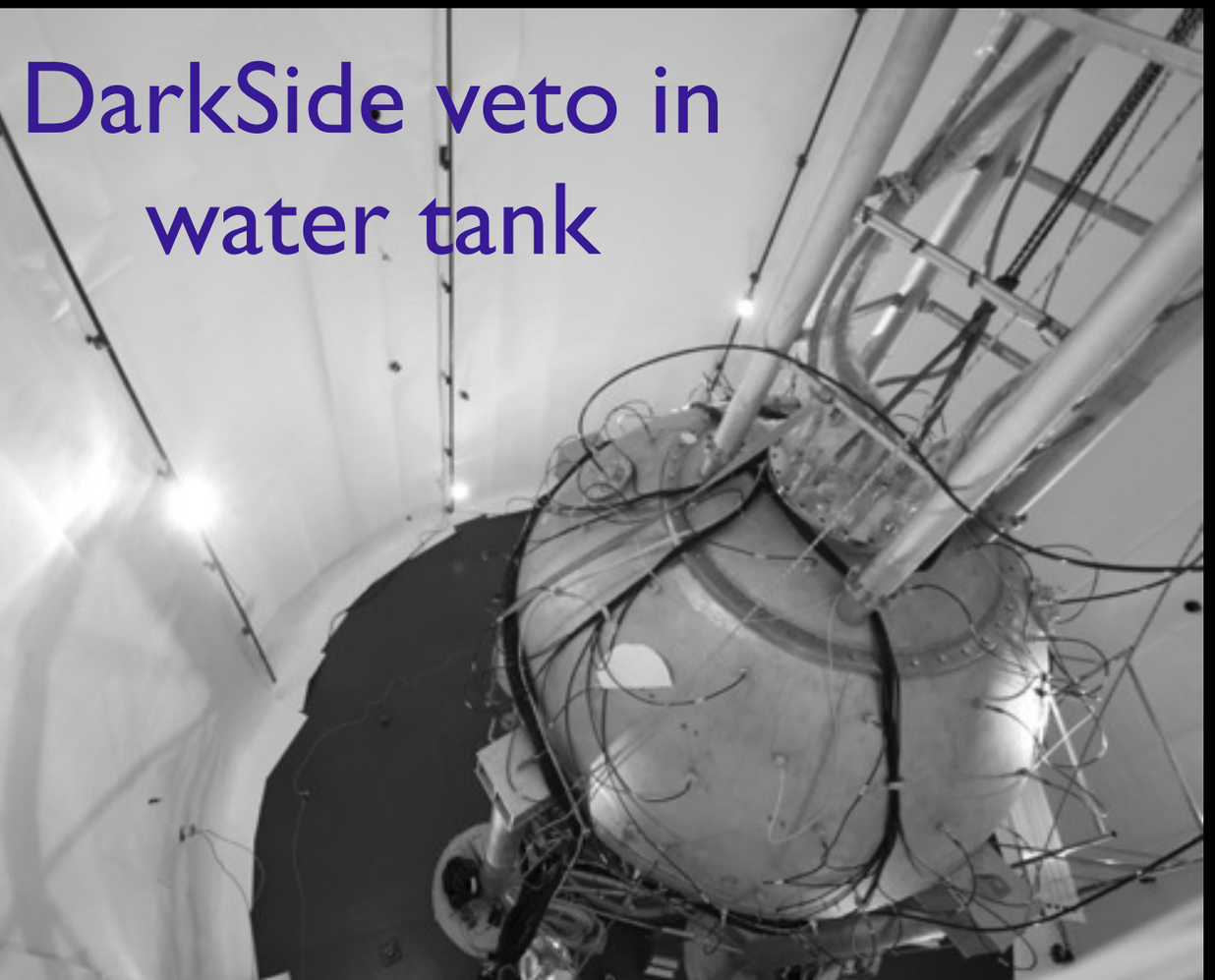
- DEAP/CLEAN (DEAP3600, MiniCLEAN) - Single phase - just collect the light - American and Canadian versions in the same room at SNOLAB



DarkSide TPC in neutron veto

MiniCLEAN inner vessel

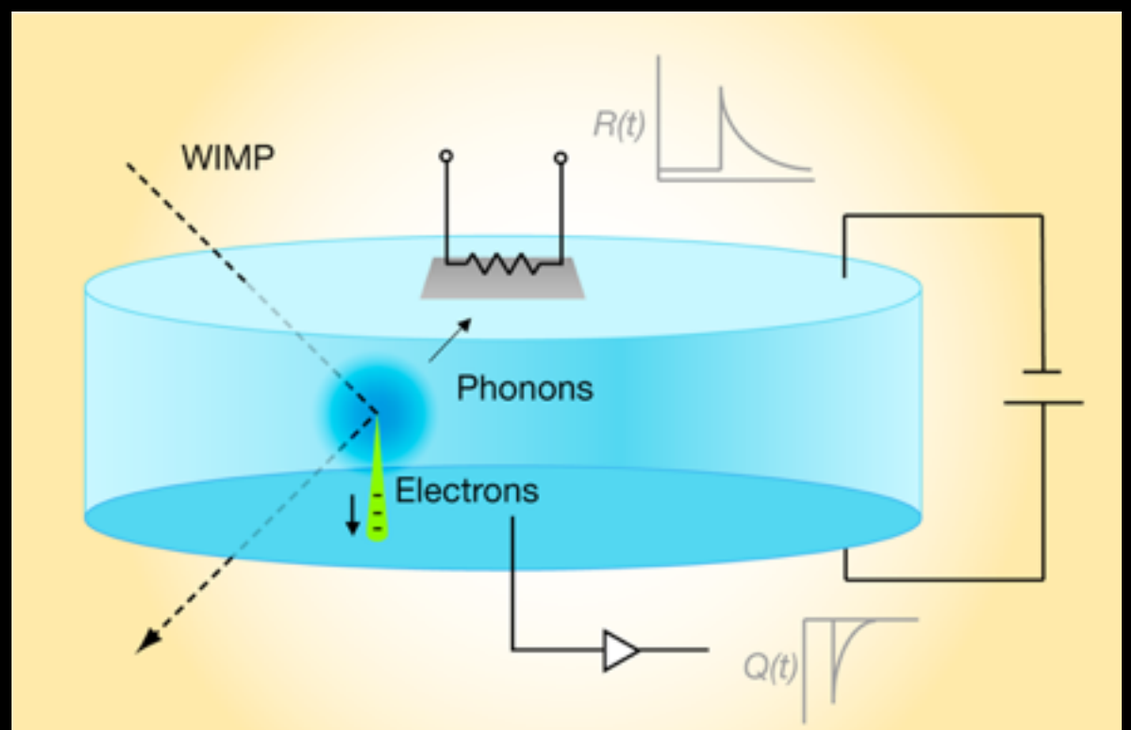
DarkSide veto in water tank

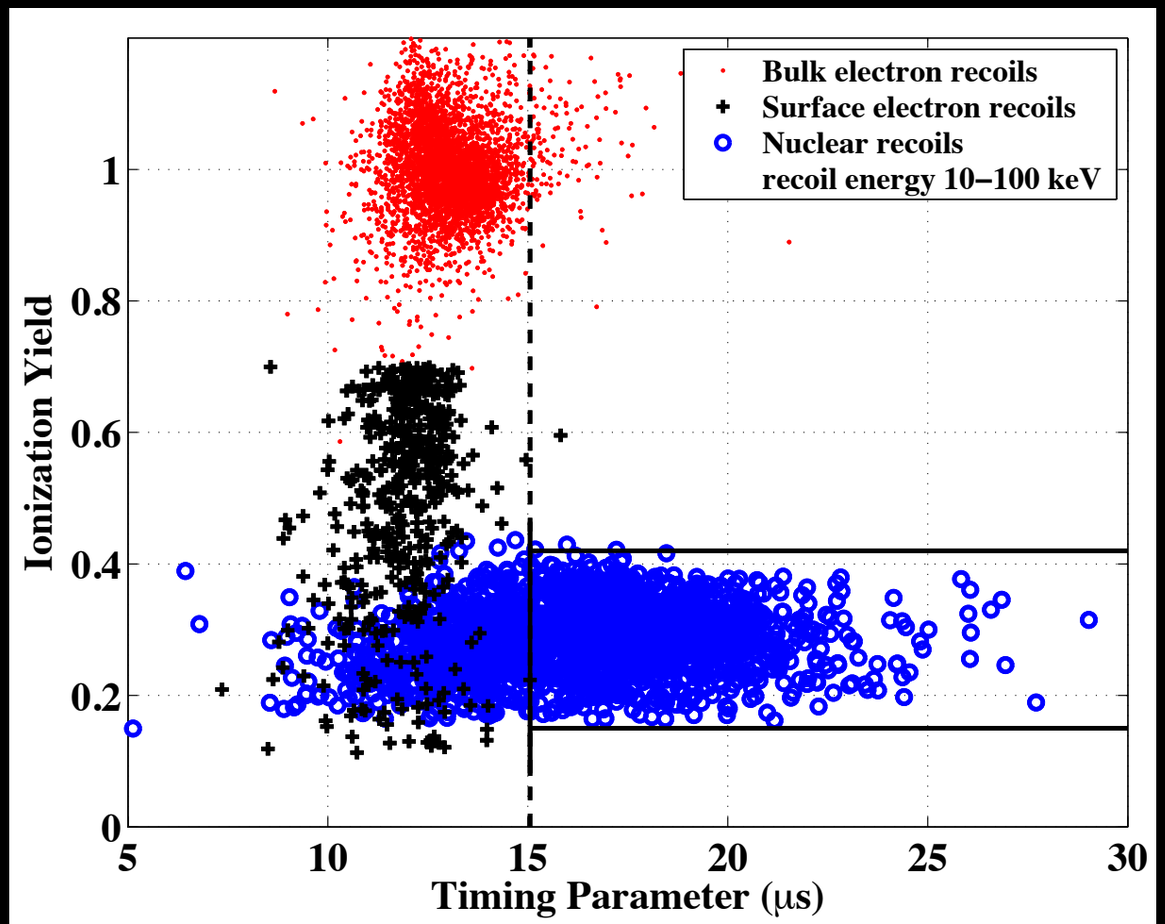


DEAP3600 acrylic vessel

CDMS/SuperCDMS

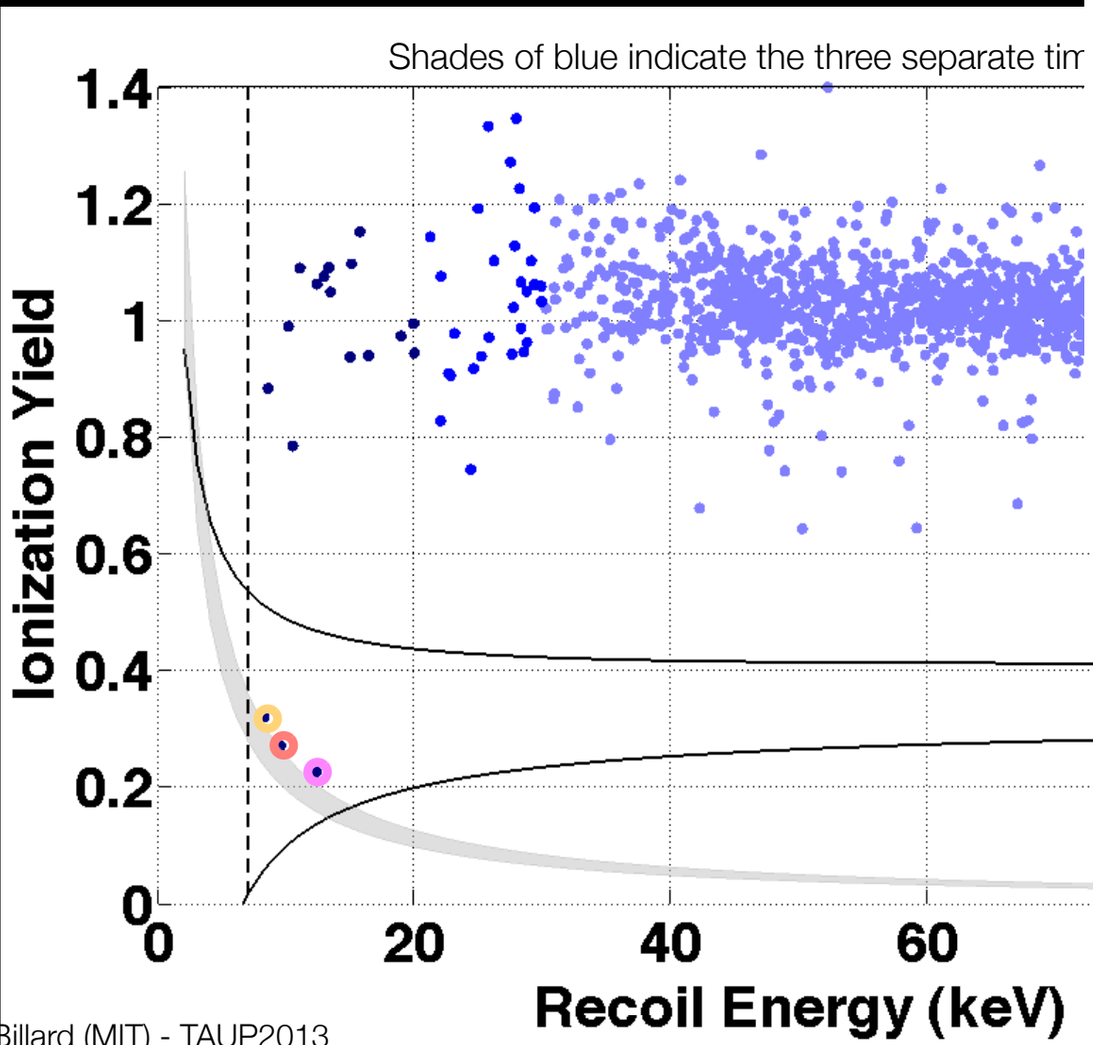
- Collect charge and heat induced by recoils
- Good intrinsic background rejection made better by detector design (iZip)
- SuperCDMS
  - 9 kg currently operating at Soudan mine
  - 200 kg planned for SNOLAB

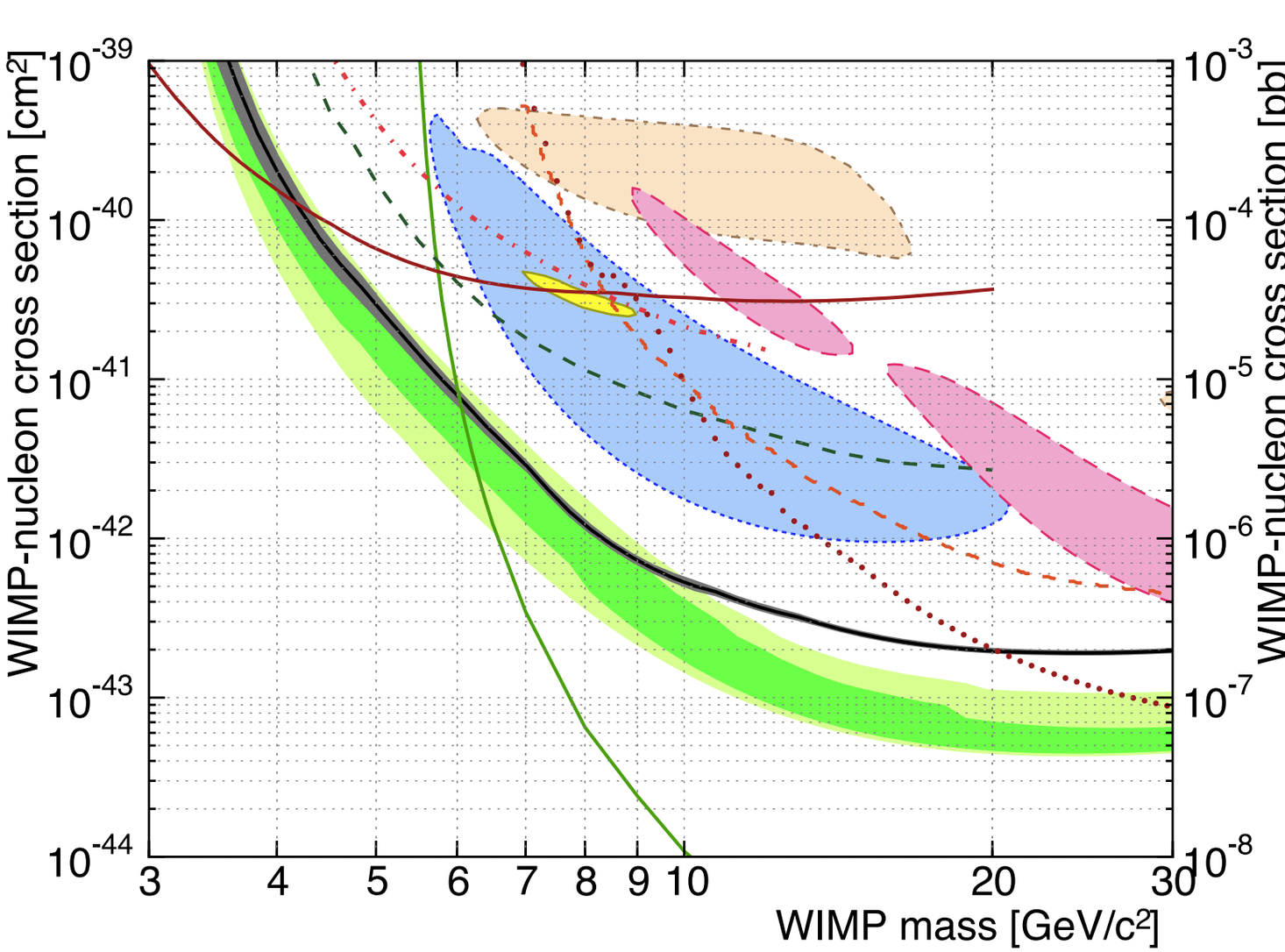




CDMS/SuperCDMS

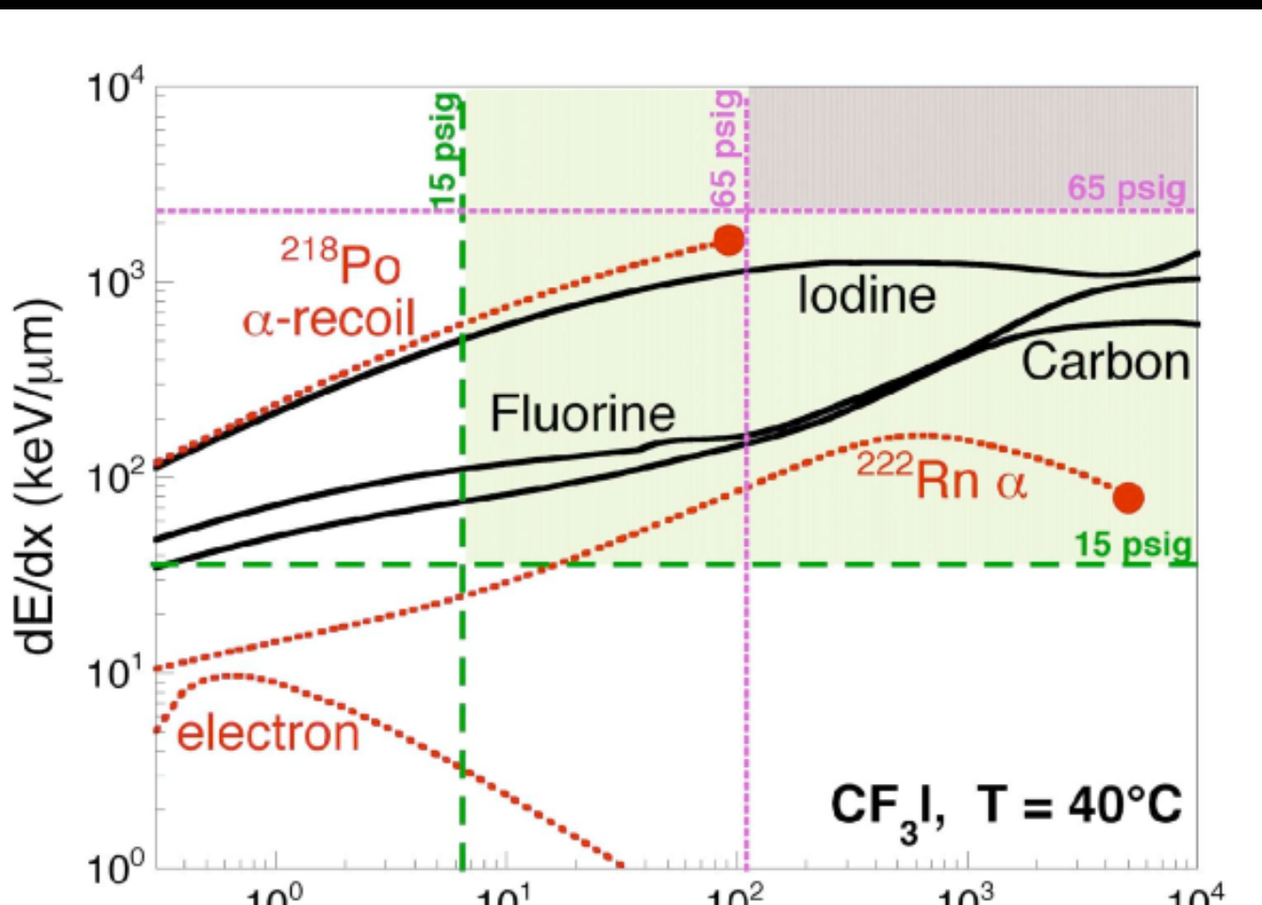
- In April of last year, they observed 3 candidate events
- In conflict with results from February

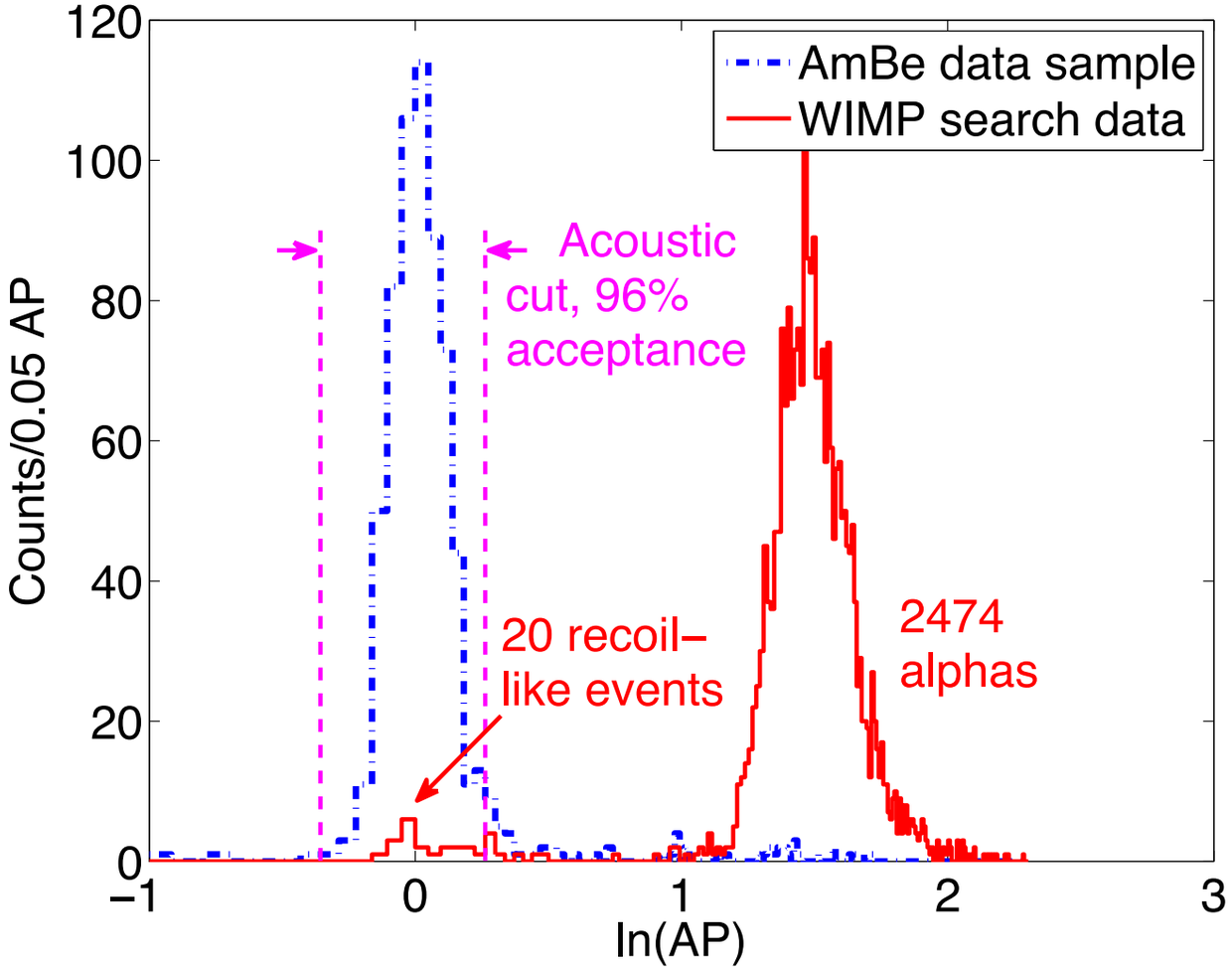




COUPP/PICO

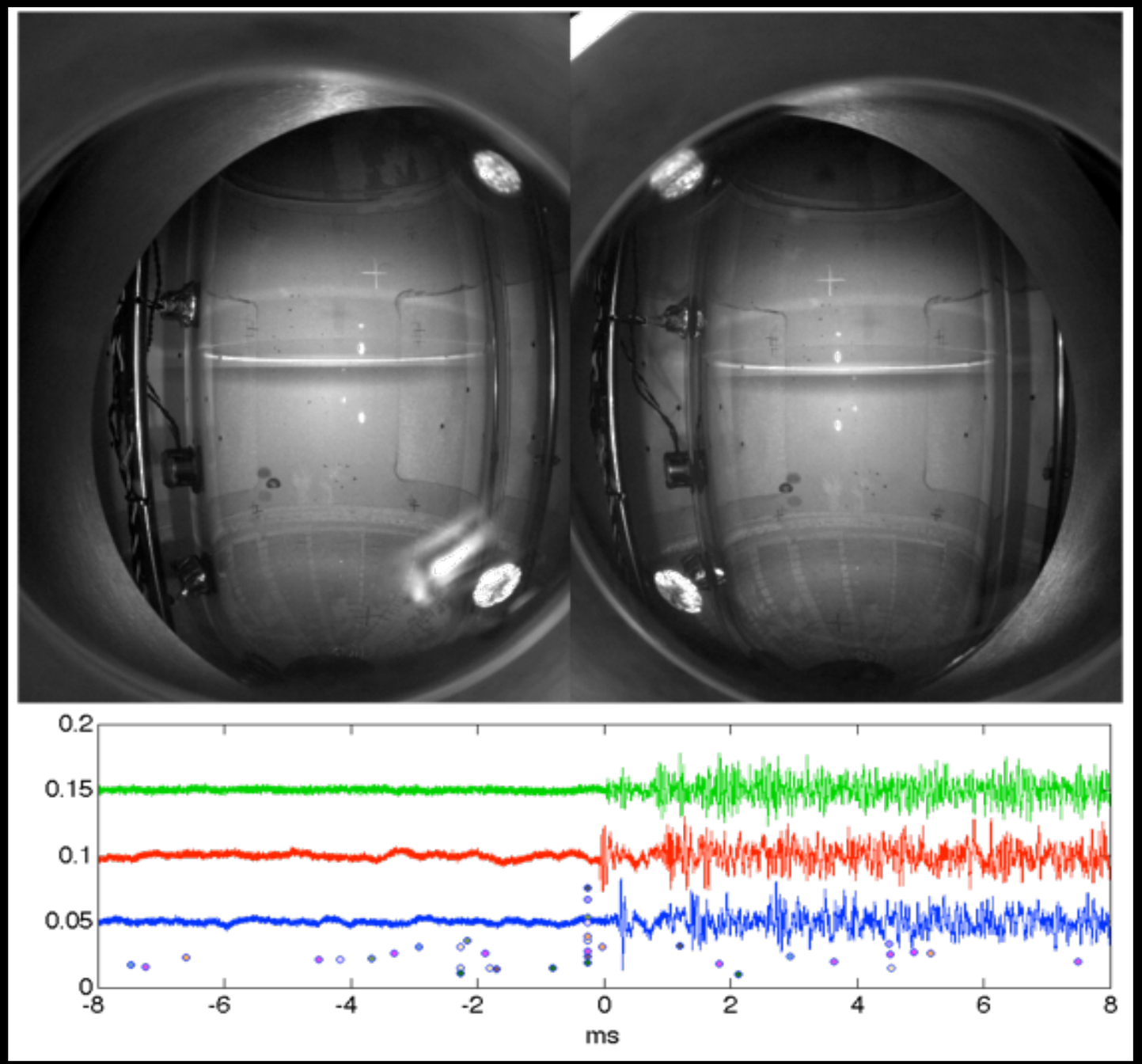
- Bubble chamber
- Electrons and gammas don't make bubbles



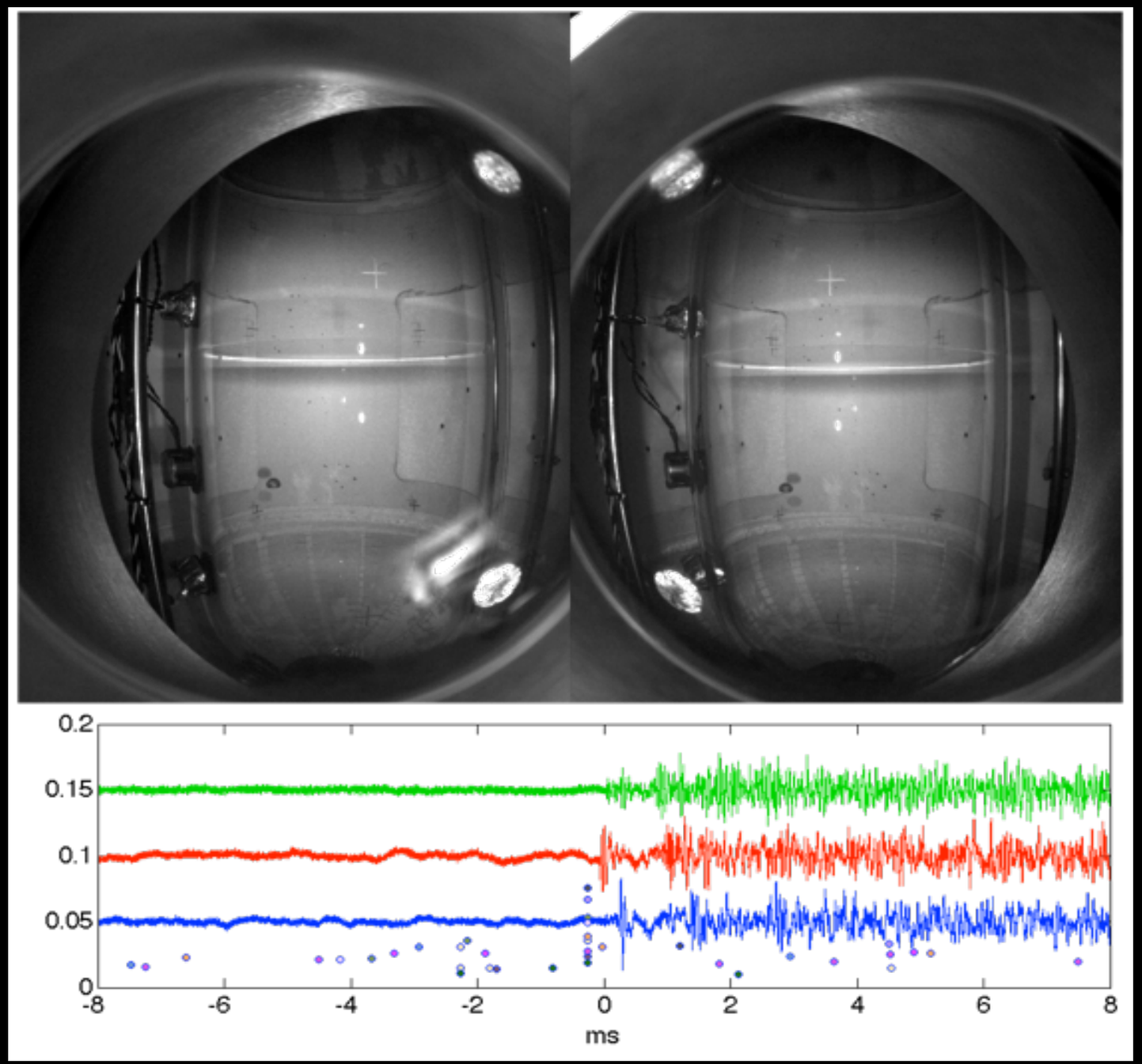


- Alphas are loud!

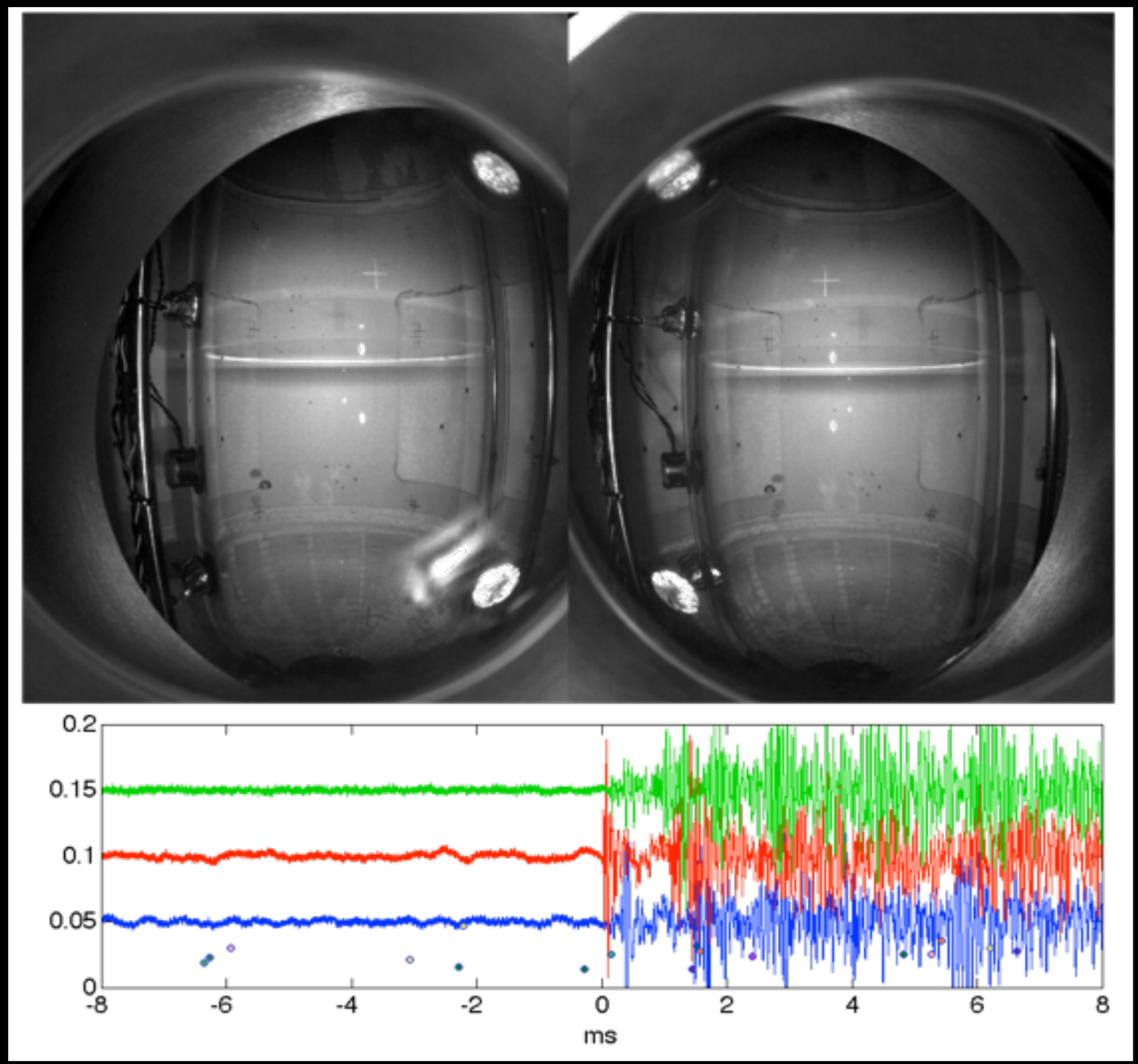
This is what dark matter would sound like



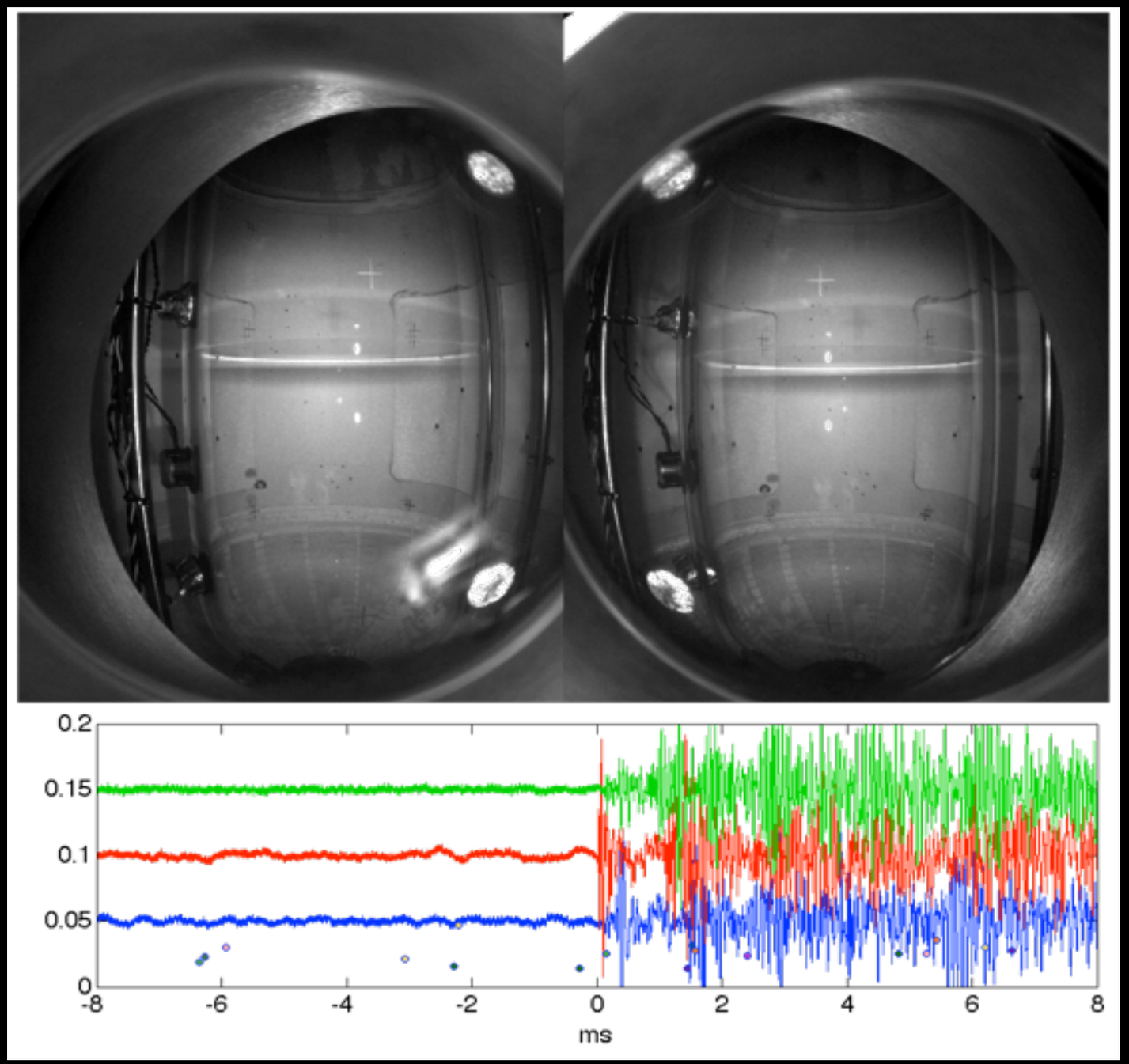
This is what dark matter would sound like



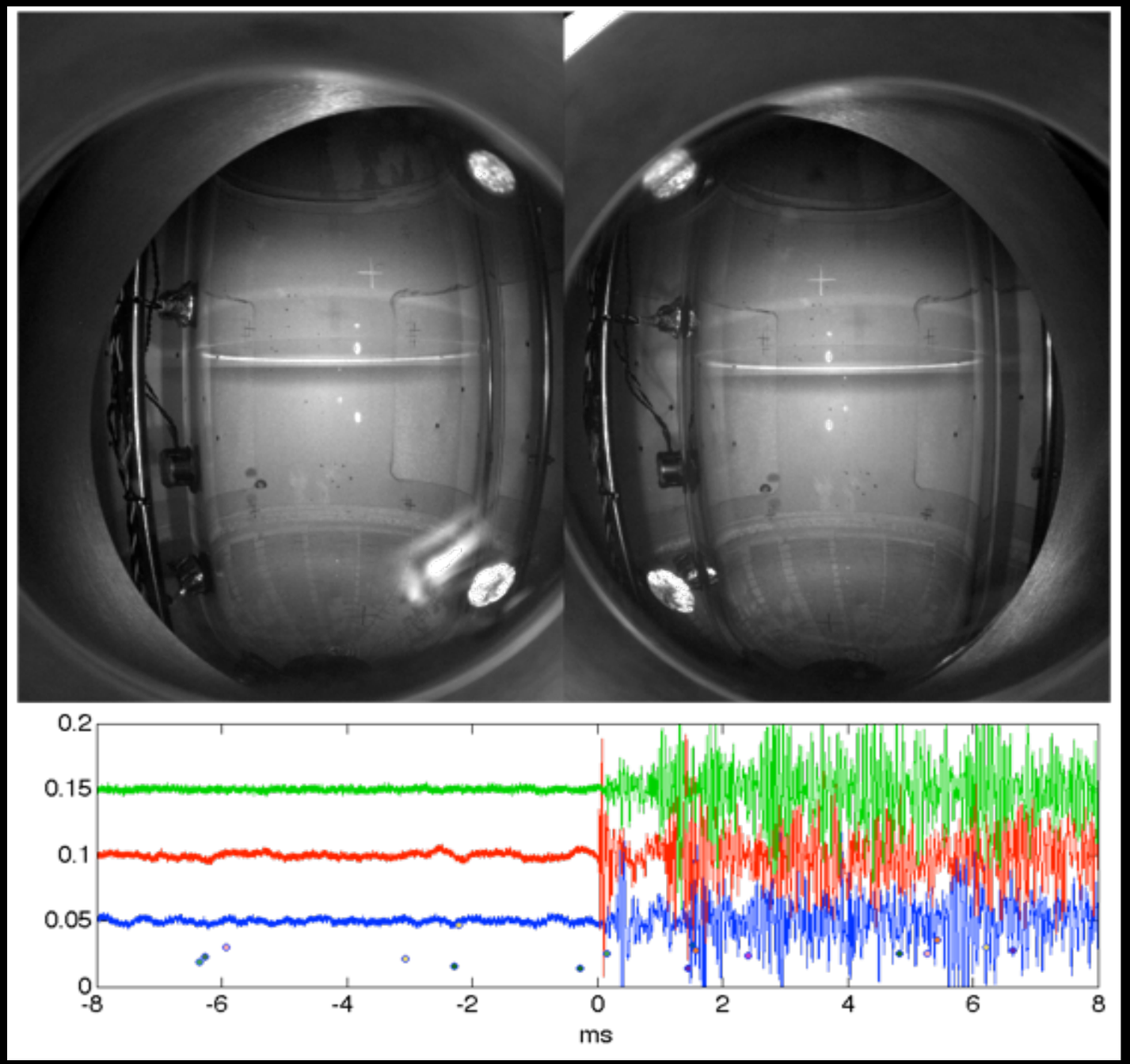
This is what background events (alpha radiation) sound like



This is what background events (alpha radiation) sound like



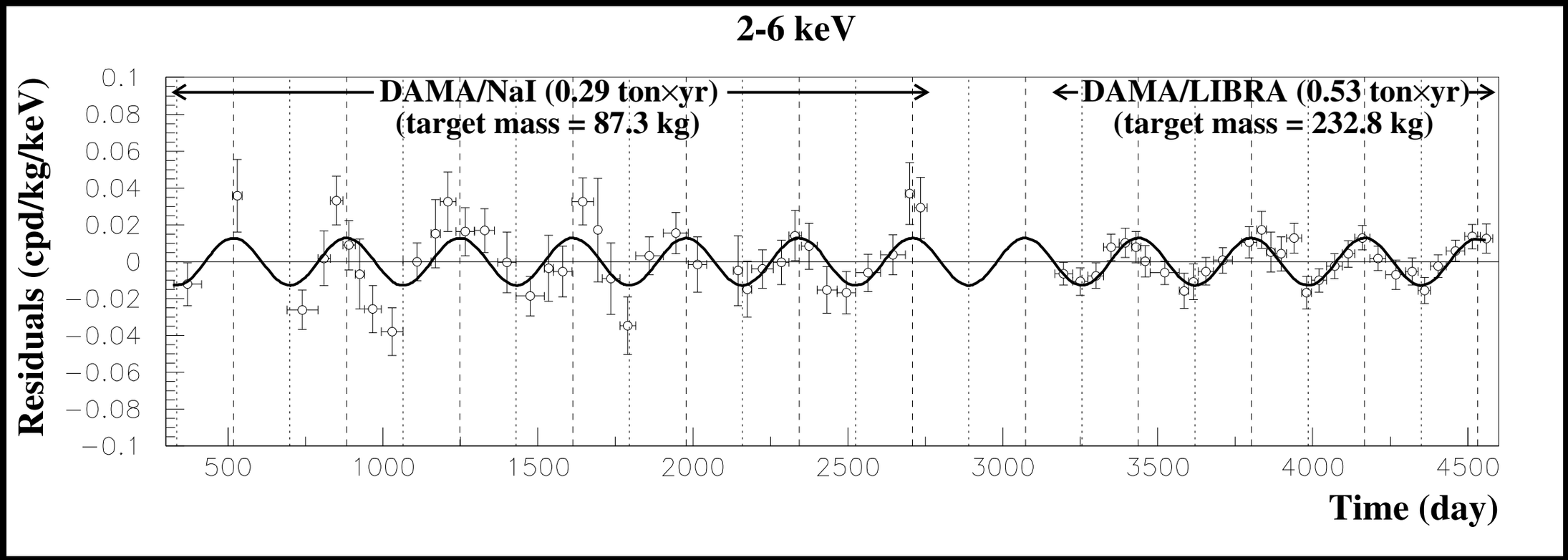
Both together, just to hear the difference




CYLINDER
EMPTY
IN USE

DArk MAtter (DAMA)

- Very radio-pure NaI (not replicated by anyone in 10 years)
  - No discrimination
- Observed an annual modulation for a decade

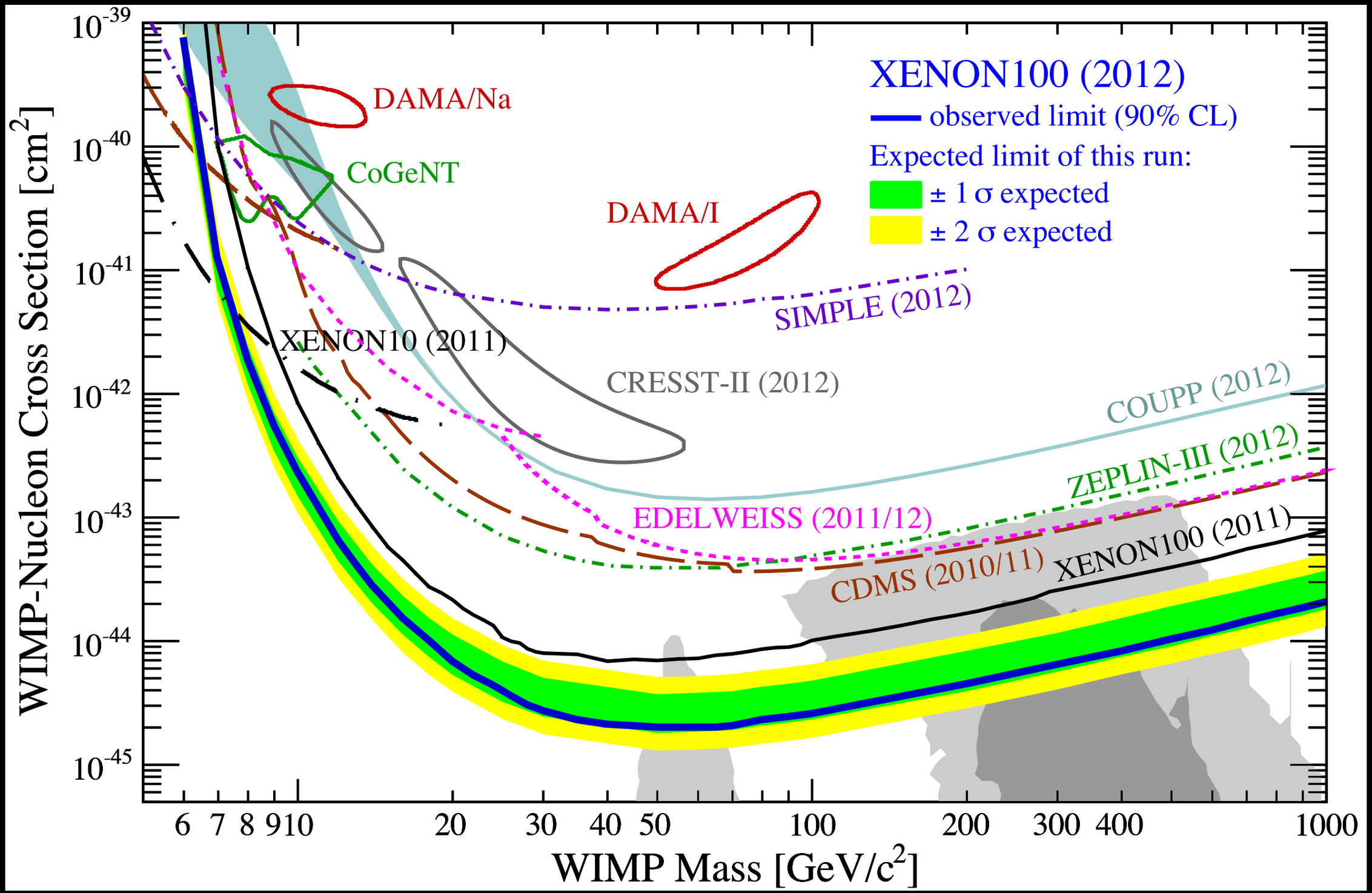


Where are we?

- DAMA - A positive claim for 10 years that successfully does the following:
  - Low energy events (e.g. right spectrum)
  - Modulation with correct period and phase
    - Single hits (multiple hits associated with neutrons)
- No one accepts it

Where are we?

- For a long time no one else saw anything



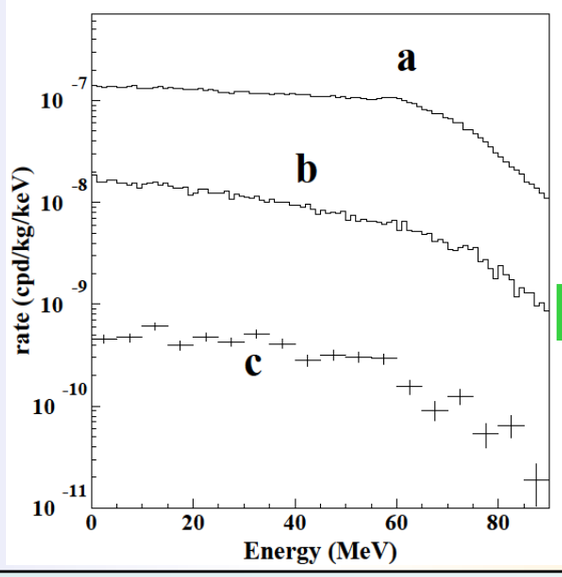
Where are we?

- For a long time no one else saw anything
- Also sociological
    - Proprietary agreement with NaI maker, so no one could replicate crystals
    - Defensive and dismissive of alternative explanations (e.g. response to DM-Ice)
    - Plan is to go bigger instead of change things up (no one doubts the significance of the modulation)
    - Their talks are terrible:

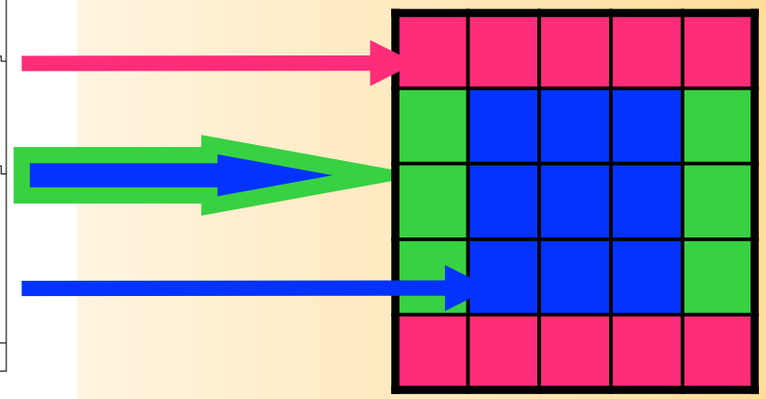
The μ case

MonteCarlo simulation
- muon intensity distribution
- Gran Sasso rock overburden map

events where just one detector fires



DAMA/LIBRA surface ≈ 0.15 m²
μ flux @ DAMA/LIBRA ≈ 2.5 μ/day



1.

Case of fast neutrons produced by μ

Φ_μ @ LNGS ≈ 20 μ $m^{-2}d^{-1}$ (±2% modulated)
Measured neutron Yield @ LNGS: $Y=1\div7\ 10^{-4}$ n/μ/(g/cm²)
R_n = (fast n by μ)/(time unit) = Φ_μ Y M_{eff}

Annual modulation amplitude at low energy due to μ modulation:

$$S_m^{(\mu)} = R_n\ g\ \varepsilon\ f_{\Delta E}\ f_{single}\ 2\% /(M_{setup}\ \Delta E)$$

g = geometrical factor; ε = detection effic. by elastic scattering
$f_{\Delta E}$ = energy window (E>2keV) effic.; f_{single} = single hit effic.

Hyp.: M_{eff} = 15 tons; $g \approx \varepsilon \approx f_{\Delta E} \approx f_{single} \approx 0.5$ (cautiously)
Knowing that: $M_{setup} \approx 250$ kg and ΔE=4keV

→ **$S_m^{(\mu)} < (0.4\div3) \times 10^{-5}$ cpd/kg/keV**

Moreover, this modulation also induces a variation in other parts of the energy spectrum and in the *multi-hits* events
It cannot mimic the signature: already excluded also by R_{90}, by *multi-hits* analysis + different phase, etc.

Can (whatever) hypothetical cosmogenic products be considered as side effects, assuming that they might produce:
- only events at low energy,
- only *single-hit* events,
- no sizable effect in the *multiple-hit* counting rate
- pulses with time structure as scintillation light

?

But, its phase should be (much) larger than μ phase, t_μ :
- if $\tau \ll T/2\pi$: $t_{side} = t_\mu + \tau$
- if $\tau \gg T/2\pi$: $t_{side} = t_\mu + T/4$

It cannot mimic the signature: different phase

The phase of the muon flux at LNGS is roughly around middle of July and largely variable from year to year. Last meas. by LVD and BOREXINO partially overlapped with DAMA/NaI and fully with DAMA/LIBRA: 1.5% modulation and phase
LVD = July 5th ± 15 d, BOREXINO = July 6th ± 6 d

→ DAMA/NaI + DAMA/LIBRA measured a stable phase: May, 26th ± 7 days

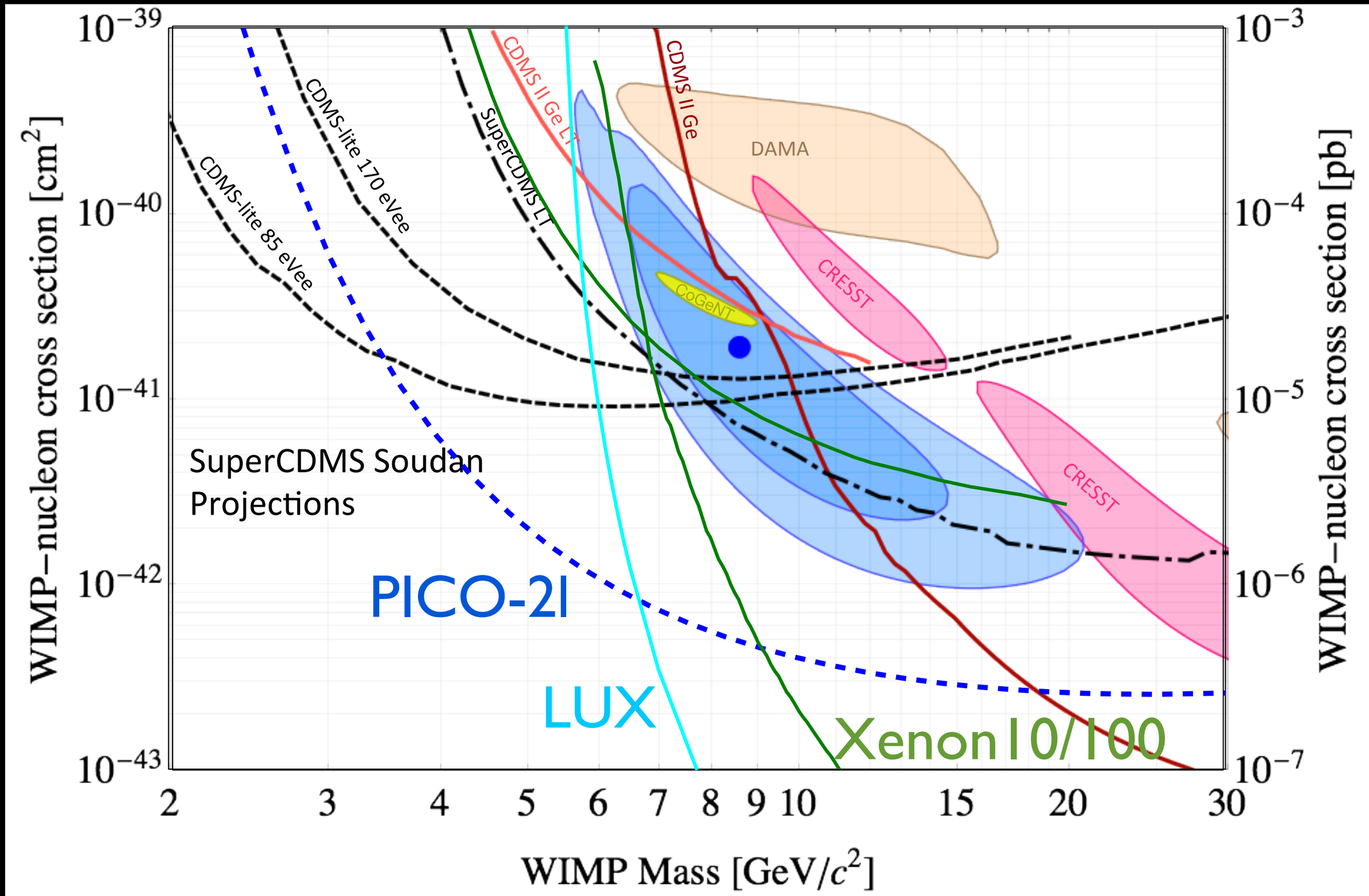
This phase is 7.1 σ far from July 15th and is 5.7 σ far from July 6th

R_{90}, multi-hits, phase, and other analyses → **NO**

Other signals

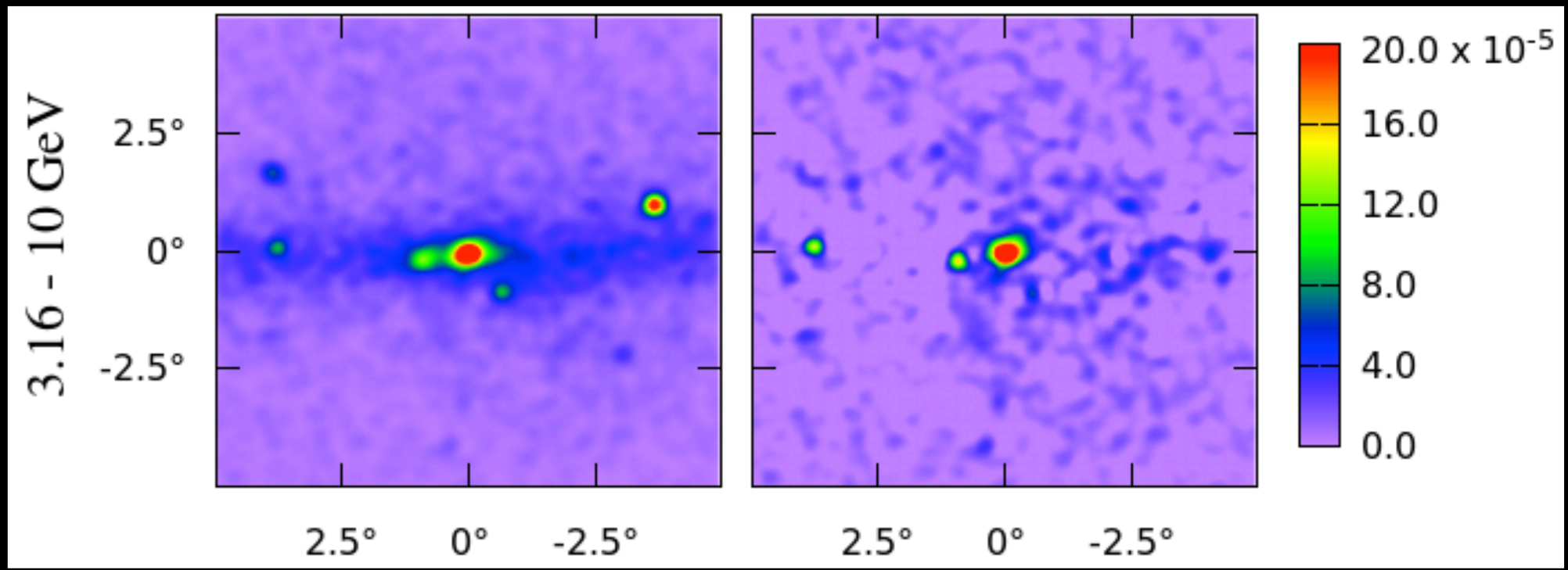
- Many hints in past few years (CoGeNT, Cresst, CDMS)
- Most are going away but DAMA remains
- All signals are in conflict with limits from xenon detectors

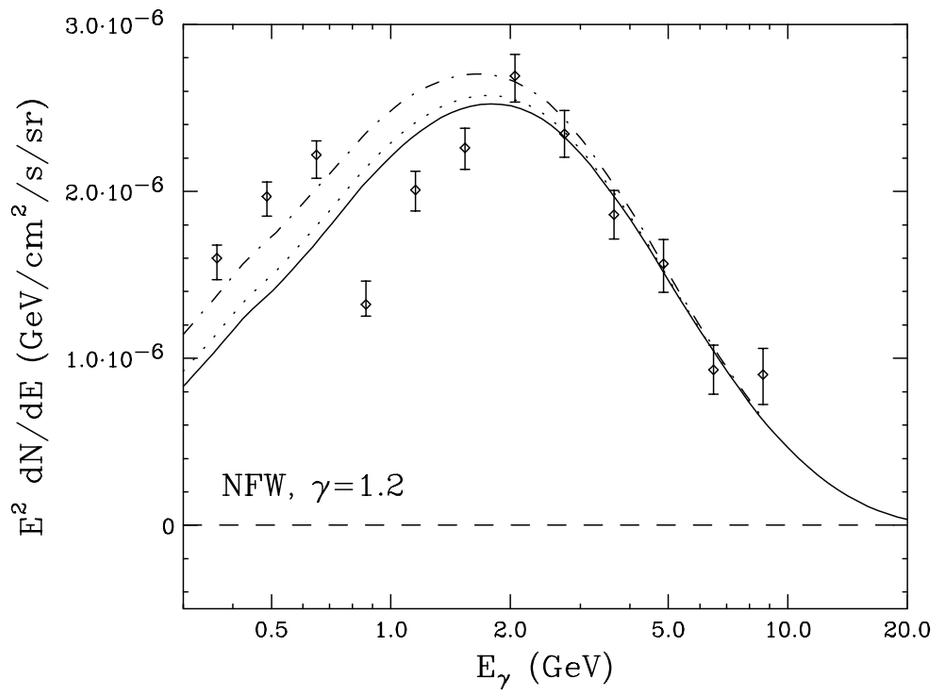
All signals are in conflict with limits from xenon detectors

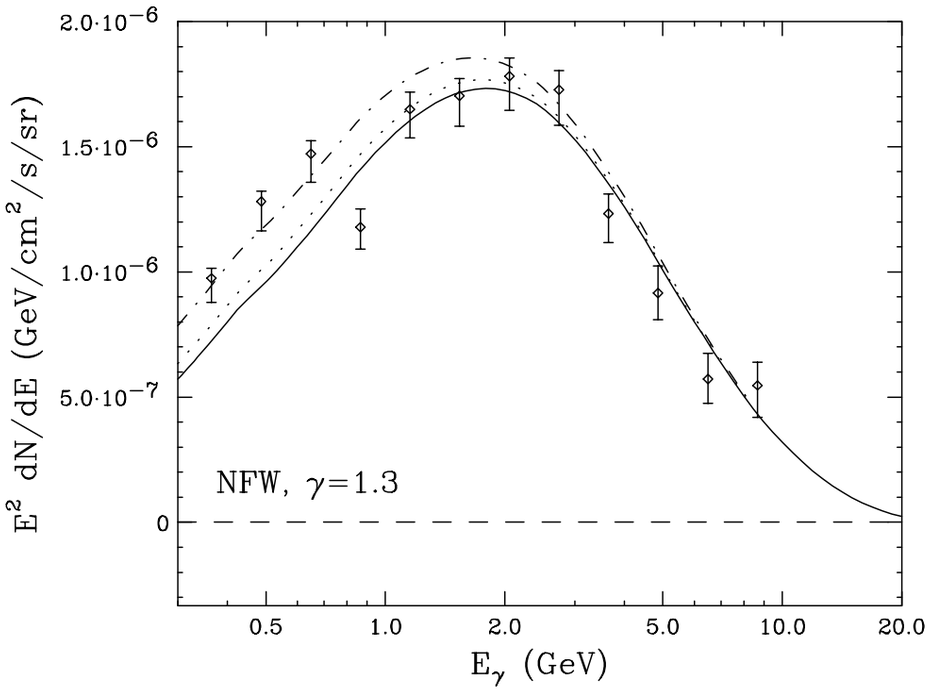


Other signals

- Analysis of Fermi-LAT data ("indirect detection") show an excess in the galactic center







Money and politics

SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
PICO250-C3F8
CDMSlite (2013)
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
CRESST
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
Xenon100 (2012)
SuperCDMS Soudan
LUX (2013)
DarkSide 50
LUX 300-day
SuperCDMS SNOLAB
PICO250-CF3I
DEAP3600
Xenon1T
DarkSide G2
LZ
SuperCDMS SNOLAB
NEUTRINO COHERENT SCATTERING
^{7}Be Neutrinos
^{8}B Neutrinos
NEUTRINO COHERENT SCATTERING
Atmospheric and DSNB Neutrinos

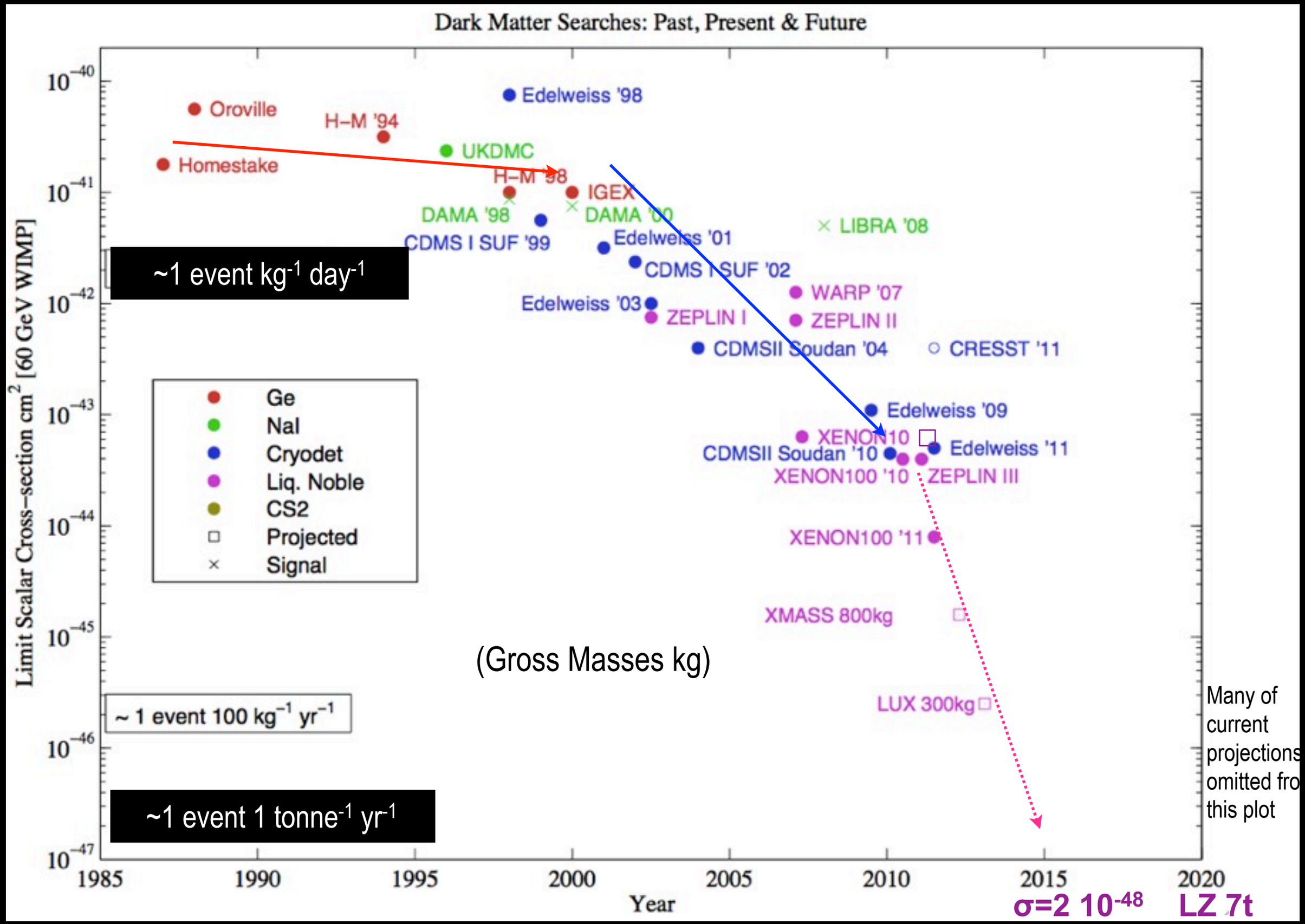
WIMP–nucleon cross section [cm^2]

10^{-39} 10^{-40} 10^{-41} 10^{-42} 10^{-43} 10^{-44} 10^{-45} 10^{-46} 10^{-47} 10^{-48} 10^{-49} 10^{-50}

10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12} 10^{-13} 10^{-14}

1 10 100 1000 10^{4}

WIMP Mass [GeV/c^2]


Dark Matter Searches: Past, Present & Future
Limit Scalar Cross−section cm^2 [60 GeV WIMP]
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
1985
1990
1995
2000
2005
2010
2015
2020
Year
Oroville
H–M '94
Homestake
Edelweiss '98
UKDMC
H–M '98
IGEX
DAMA '98
DAMA '00
CDMS I SUF '99
Edelweiss '01
LIBRA '08
CDMS I SUF '02
WARP '07
Edelweiss '03
ZEPLIN I
ZEPLIN II
CDMSII Soudan '04
CRESST '11
Edelweiss '09
XENON10
CDMSII Soudan '10
Edelweiss '11
XENON100 '10
ZEPLIN III
XENON100 '11
XMASS 800kg
LUX 300kg
~1 event kg^{-1} day^{-1}
Ge
NaI
Cryodet
Liq. Noble
CS2
Projected
Signal
(Gross Masses kg)
~ 1 event 100 kg^{-1} yr^{-1}
~1 event 1 tonne^{-1} yr^{-1}
Many of current projections omitted fro this plot
σ=2 10^{-48}
LZ 7t