Overview of Direct Detection Dark Matter Experiments

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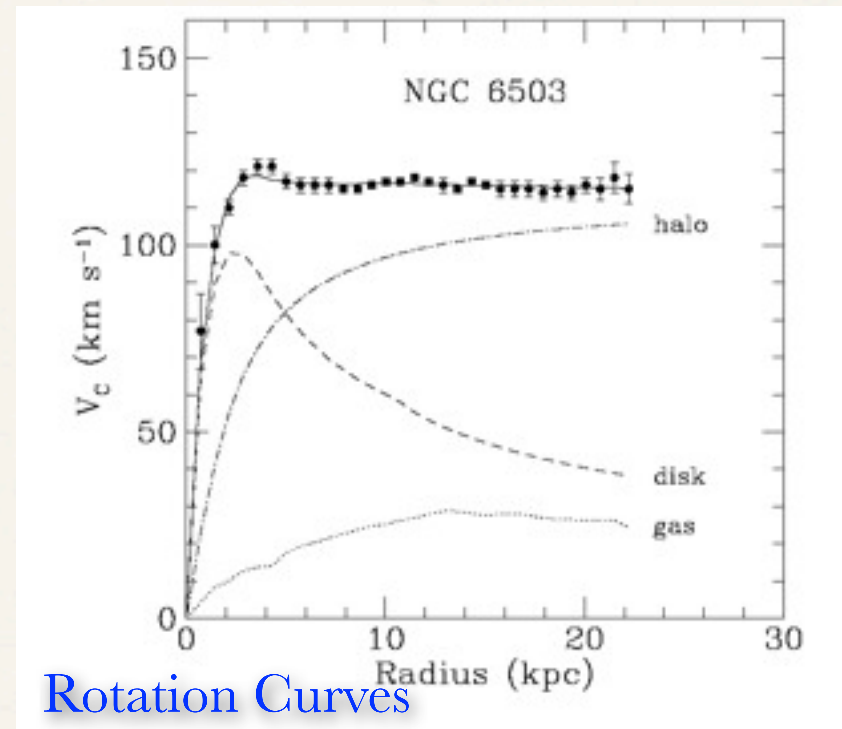
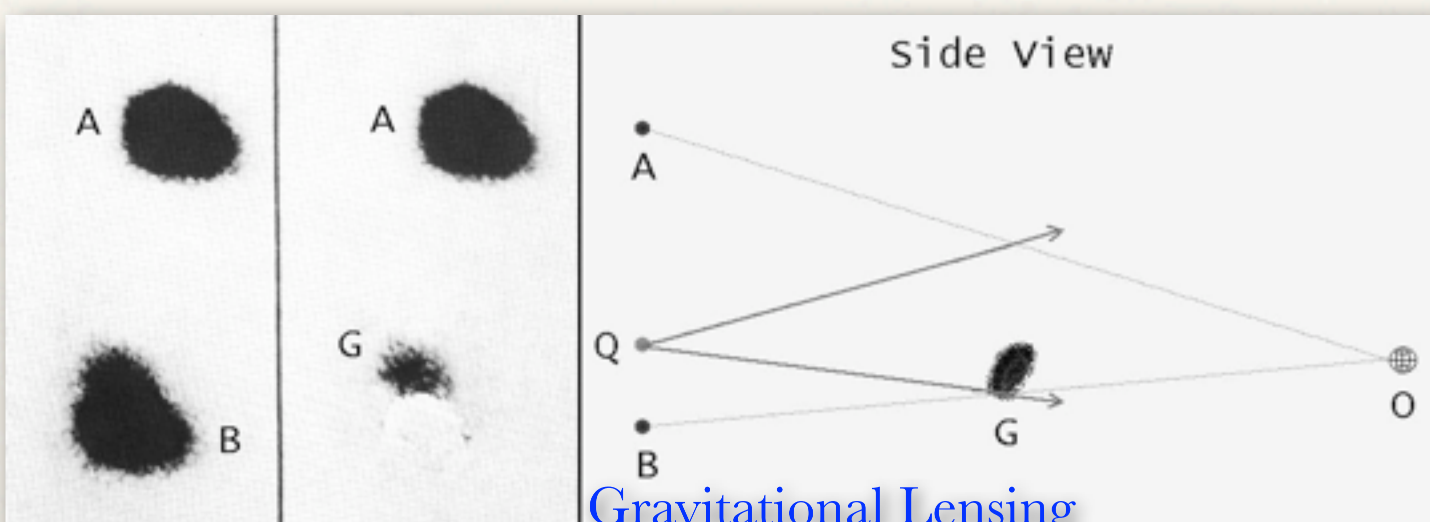
SMU

Outline

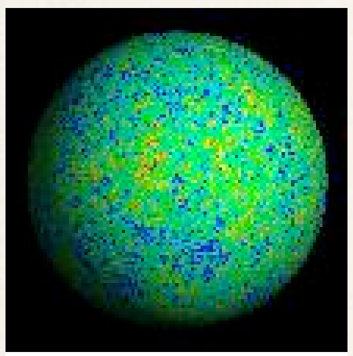
- Motivation and General Principles Shared by Experiments
  - Rates, backgrounds, detection principles
- Experiments
  - Those that see excess events over their predicted backgrounds
  - Those that do not see excess events over their predicted backgrounds
    - Solid state devices
    - Noble liquid detectors
- Concluding Remarks

Evidence from Gravitational Effects

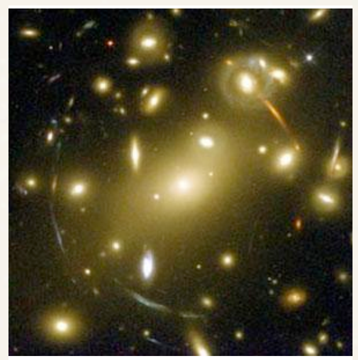




Properties of Dark Matter

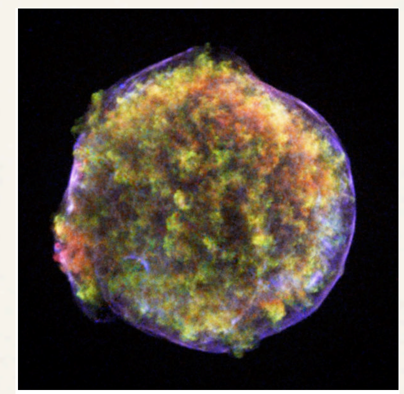


Microwave background

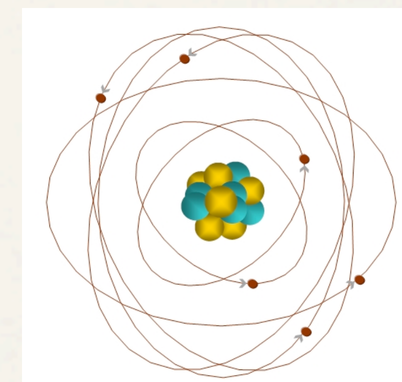


Gravitational lensing

Galaxy clusters



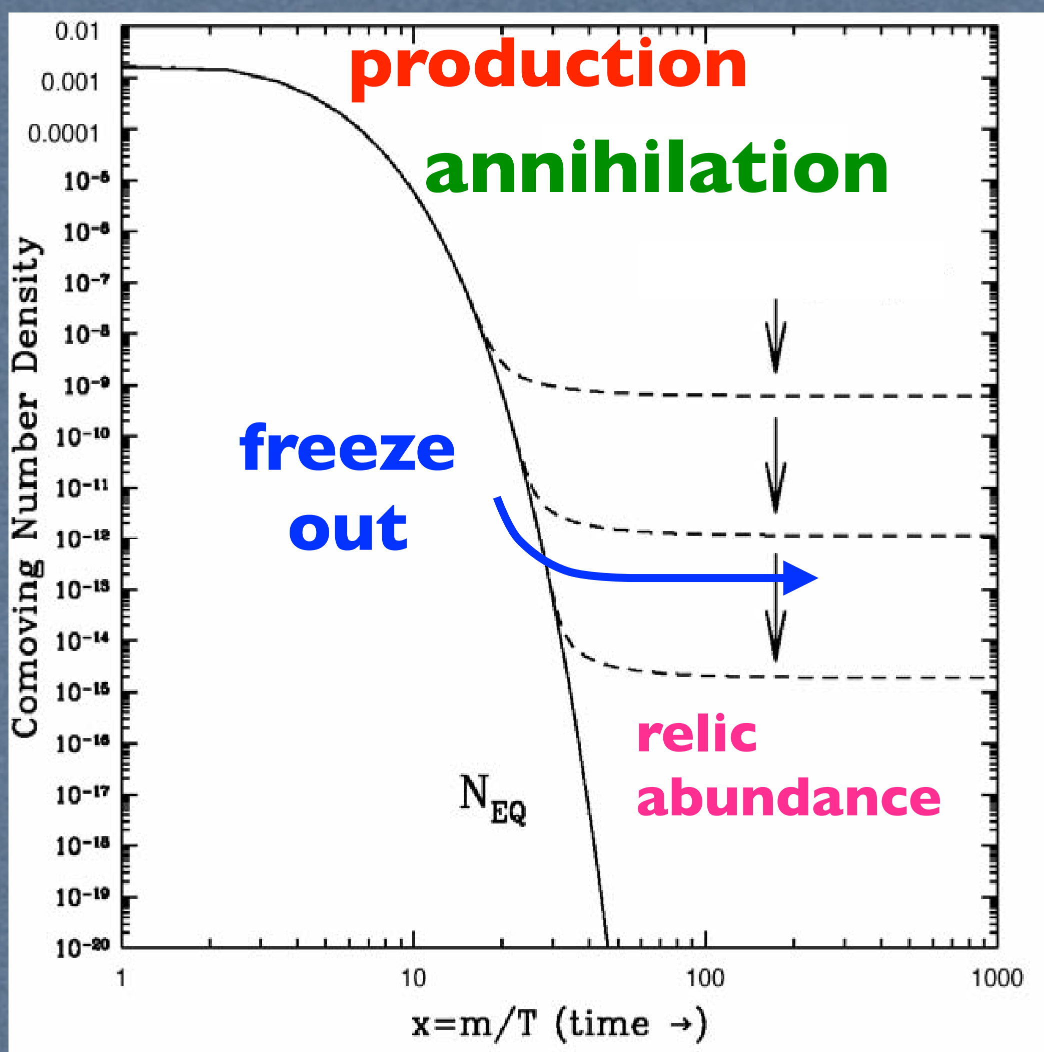
Supernovae Ia



Big Bang nucleosynthesis

~23% of our Universe is composed of non-baryonic, cold dark matter

WIMP Dark Matter



$$\Omega_\chi h^2 \approx \frac{3 \times 10^{-27}}{< \sigma_\chi v >}$$

Weakly Interacting Massive Particle

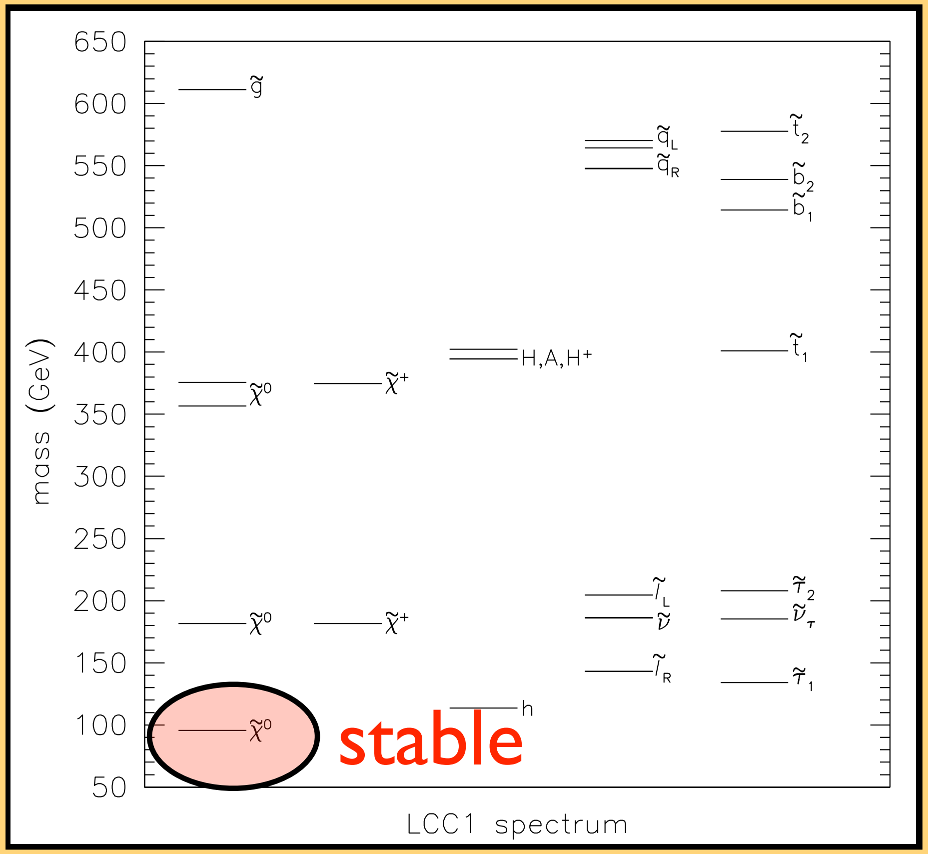
- New stable, **massive** particle produced thermally in early universe
- **Weak-scale** cross-section gives observed relic density

WMAP $0.095 < \Omega h^2 < 0.129$

$$\sigma_\chi \approx 10^{-37} cm^2$$

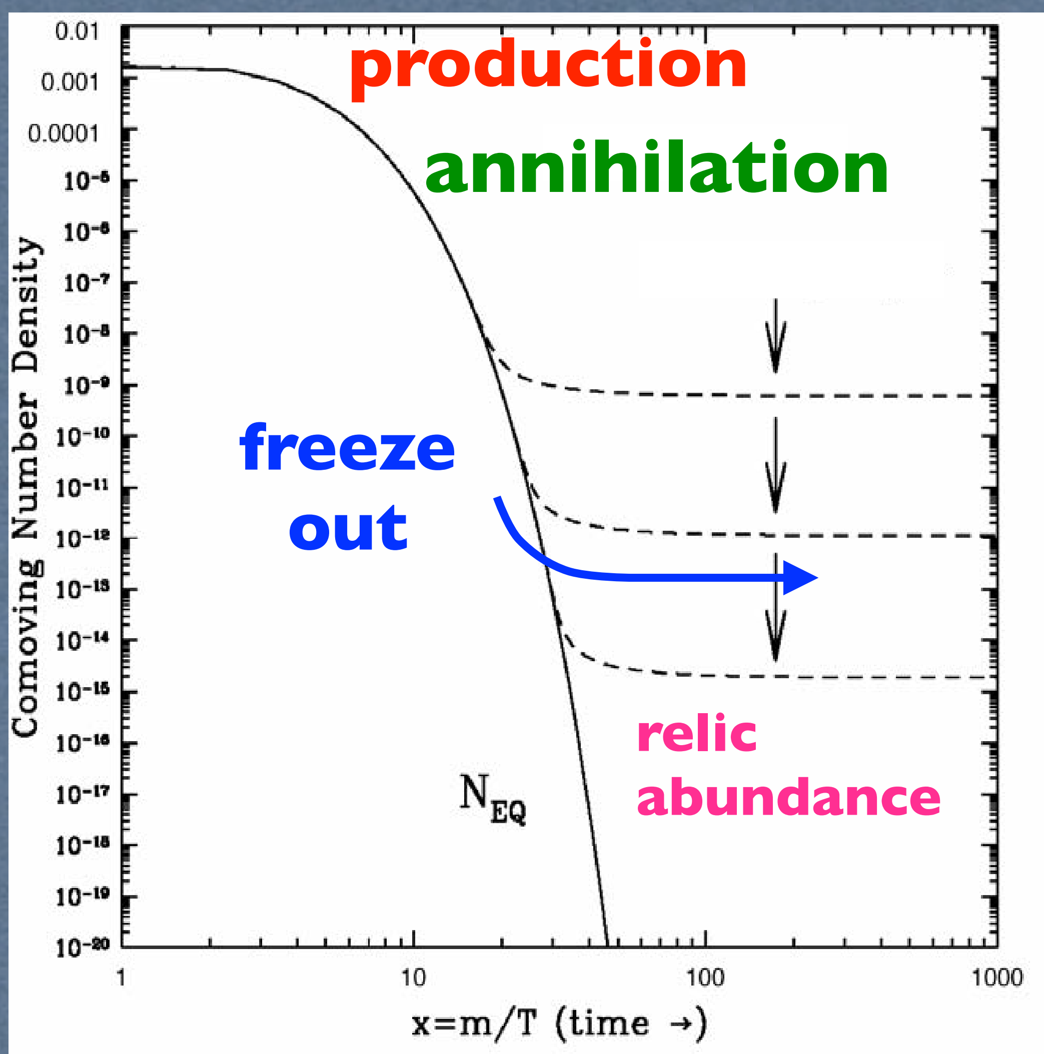
WIMP Dark Matter

- New TeV physics is required to explain radiative stability of weak scale.
  - SuperSymmetry
  - Extra Dimensions
  - ...
- These theories give rise to convenient dark matter candidates.
  - LSP, LKP

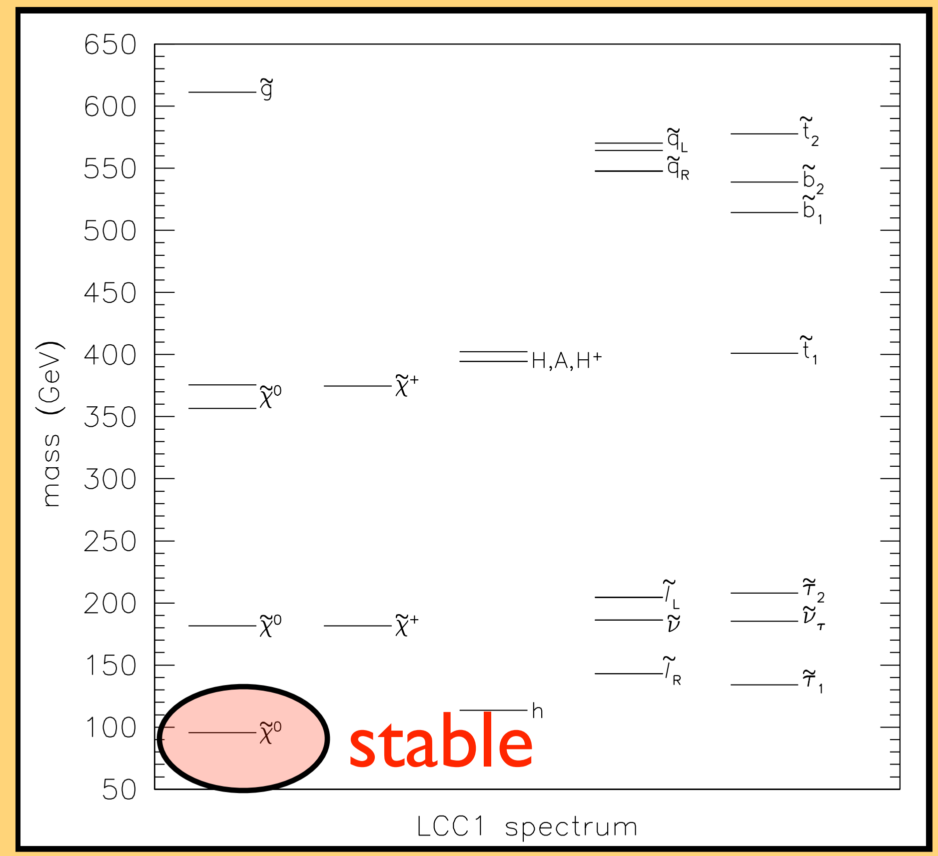


Baltz et al., PRD **74**, 103521 (2006)

Happy Coincidence!



$$\Omega_\chi h^2 \approx \frac{3 \times 10^{-27}}{< \sigma_\chi v >}$$

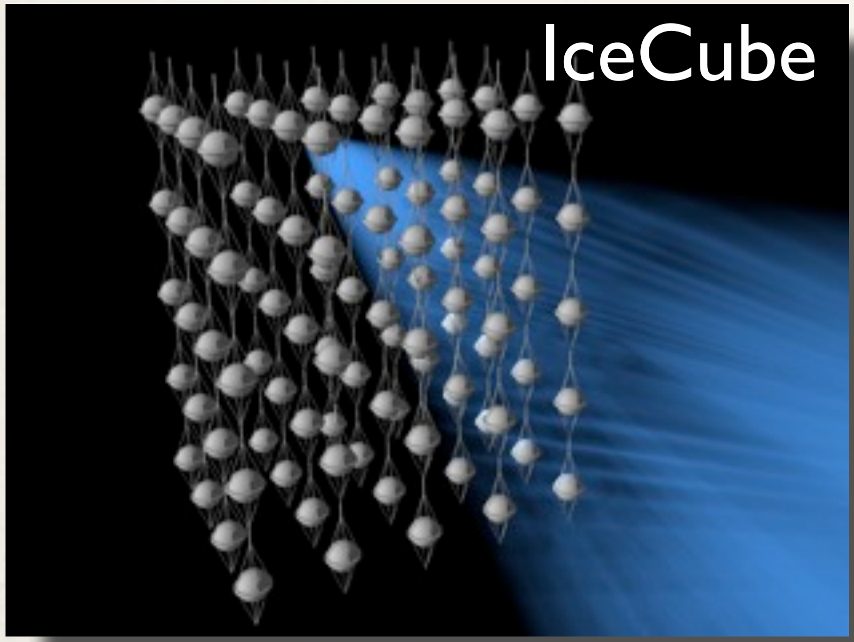


Baltz et al., PRD **74**, 103521 (2006)

How to Detect Dark Matter

← WIMP scattering on Earth

WIMP production on Earth →



← WIMP annihilation in the cosmos

Direct Detection Event Rates

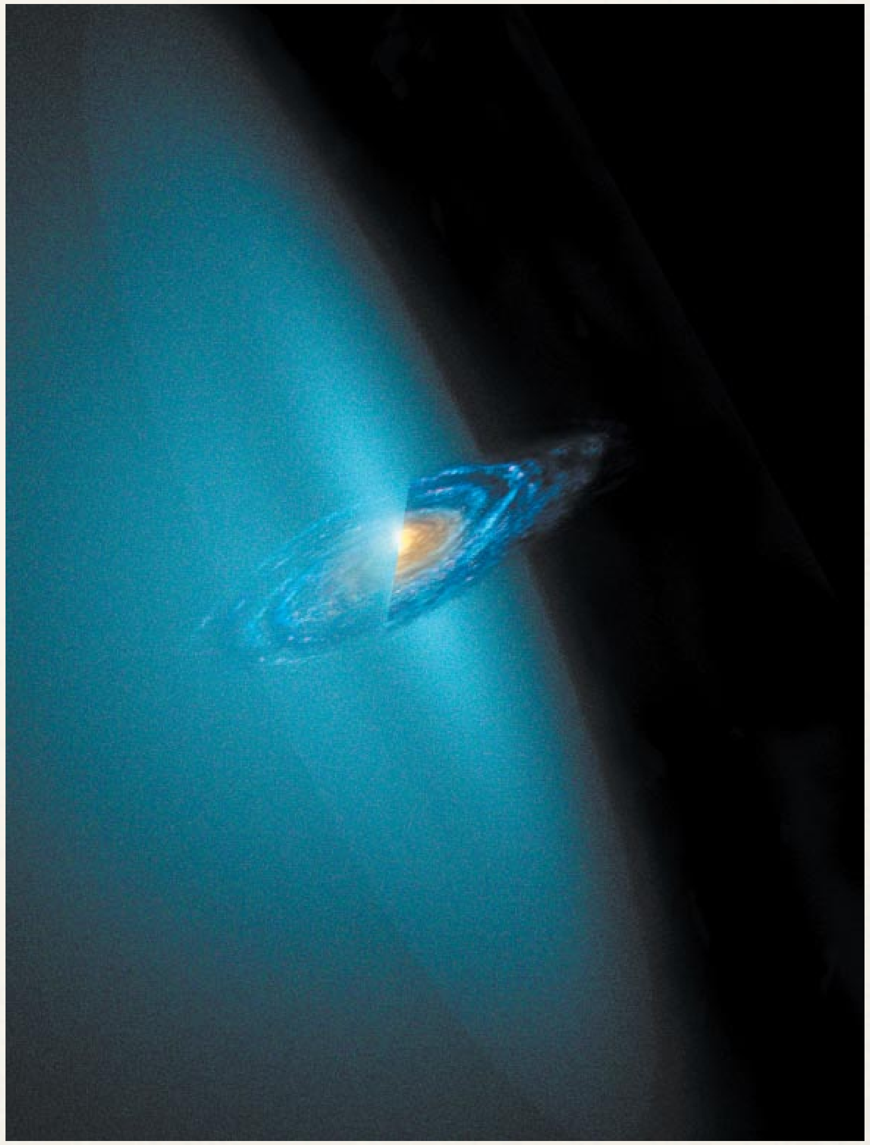
Halo Model

local density (ρ_o) = 0.3 GeV/cm^3,
Maxwellian distribution,
rms velocity (v_o) = 220 km/s,
v_{esc} = 650 km/s

Interaction Details

spin-independent,
coherent scattering

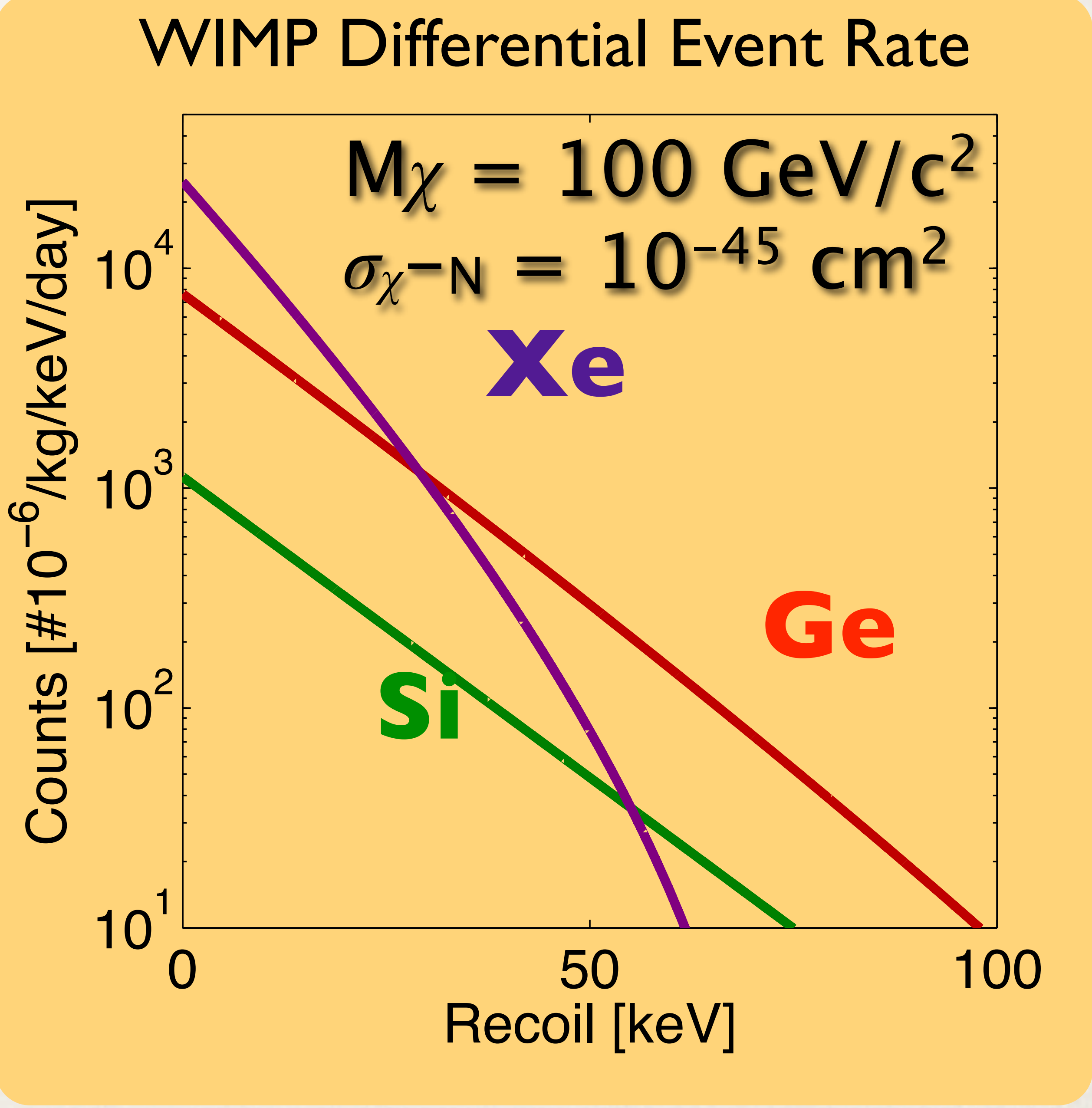
$$\sigma_{\chi-N} \propto A^2$$



D. Cline, *Scientific American* 2003

Direct Detection Event Rates

- **Elastic scattering** of a WIMP deposits small amounts of energy into recoiling nucleus (~ few 10s of keV)
- Featureless **exponential spectrum**
- **Expected rate:**
  < 5 interaction per ton per day
  (3.8×10^{-44} cm^2 for $m_\chi = 70$ GeV)
- Radioactive background of most materials higher than this rate.



Challenges

✓ **Low energy thresholds** (~10 keV)

✓ Rigid **background controls**

- ➡ Clean materials
- ➡ shielding
- ➡ discrimination power

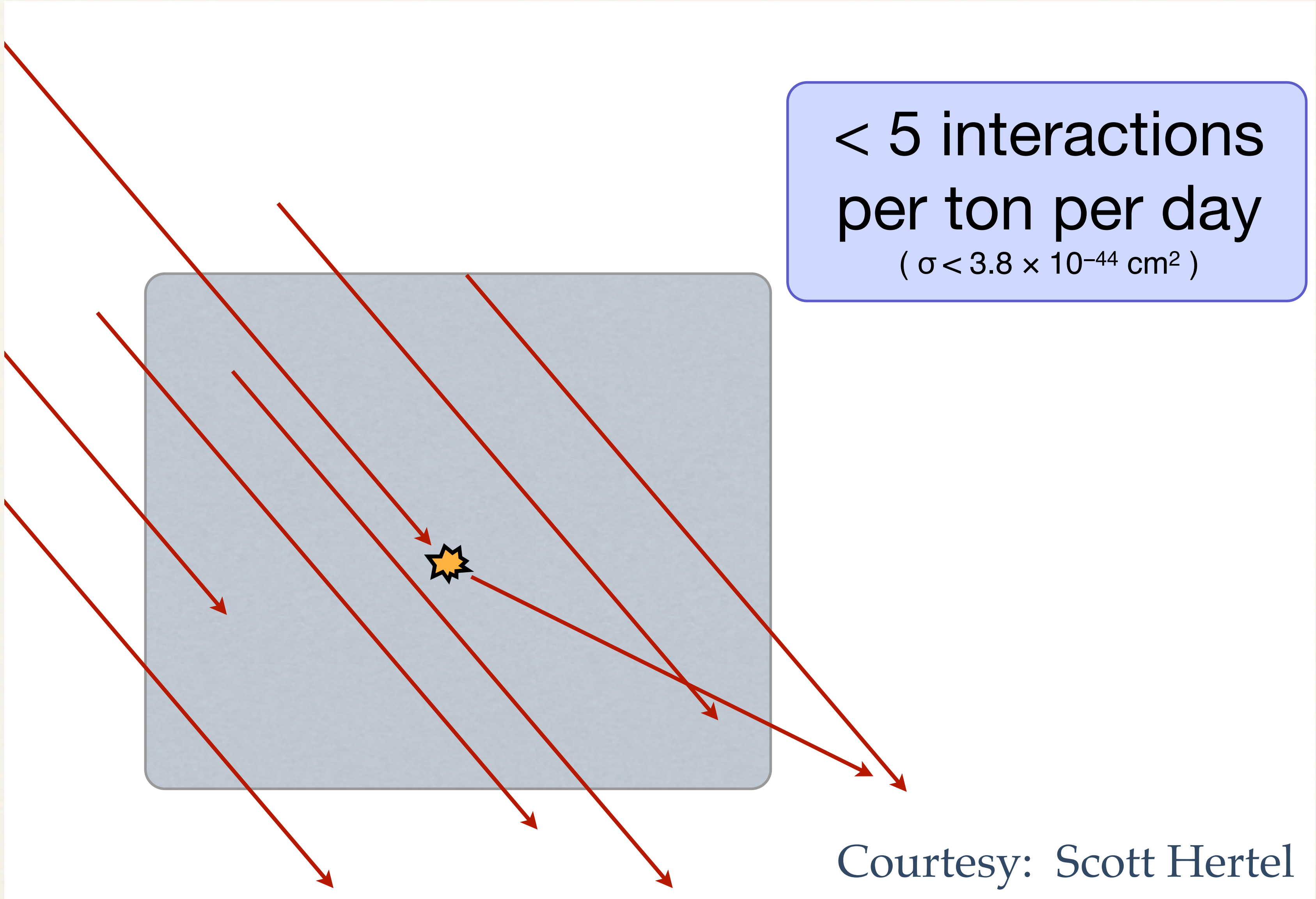
✓ Substantial **Depth**

- ➡ neutrons look like WIMPS

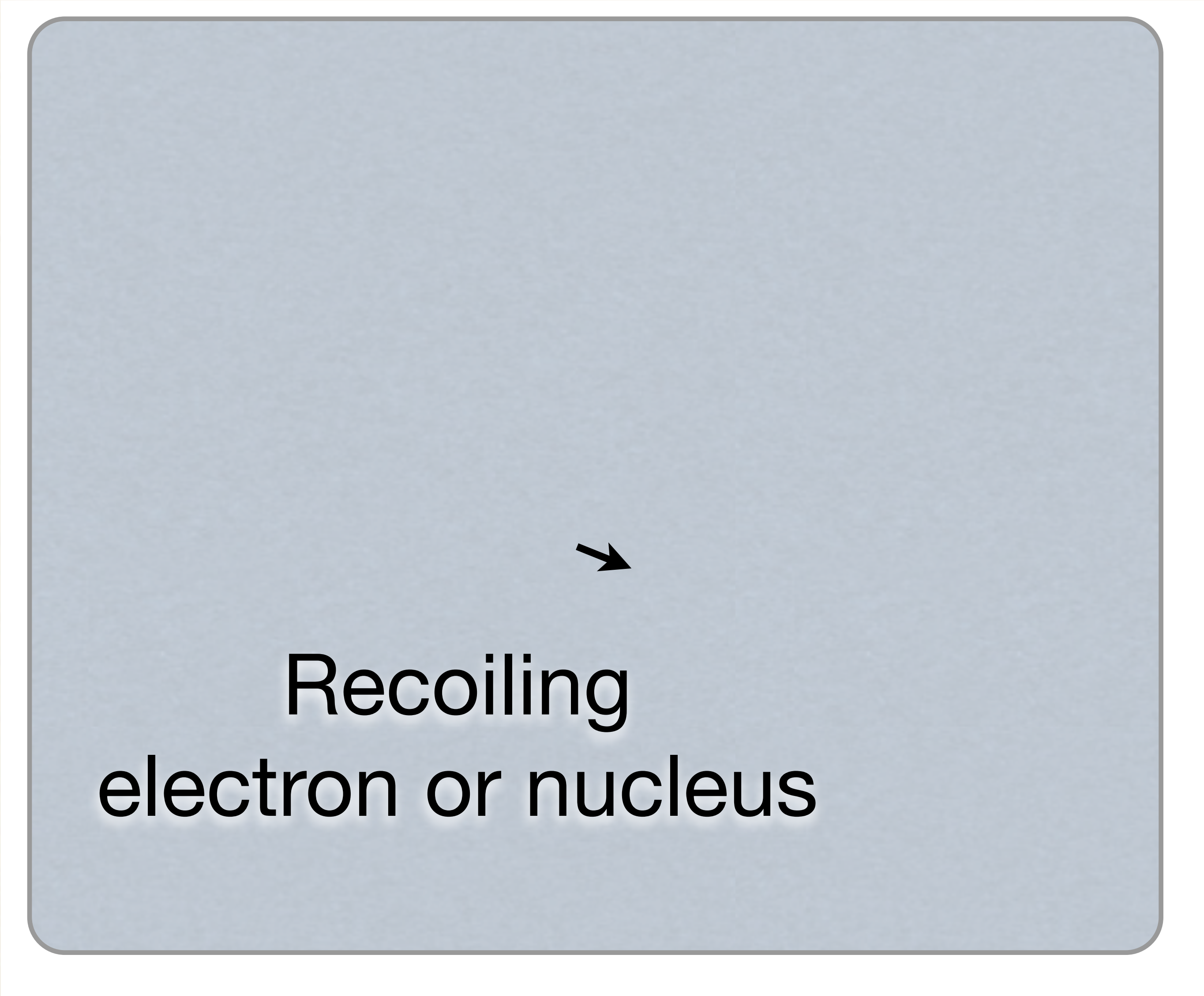
✓ **Long exposures**

- ➡ large masses, long term stablility

General Detection Principles

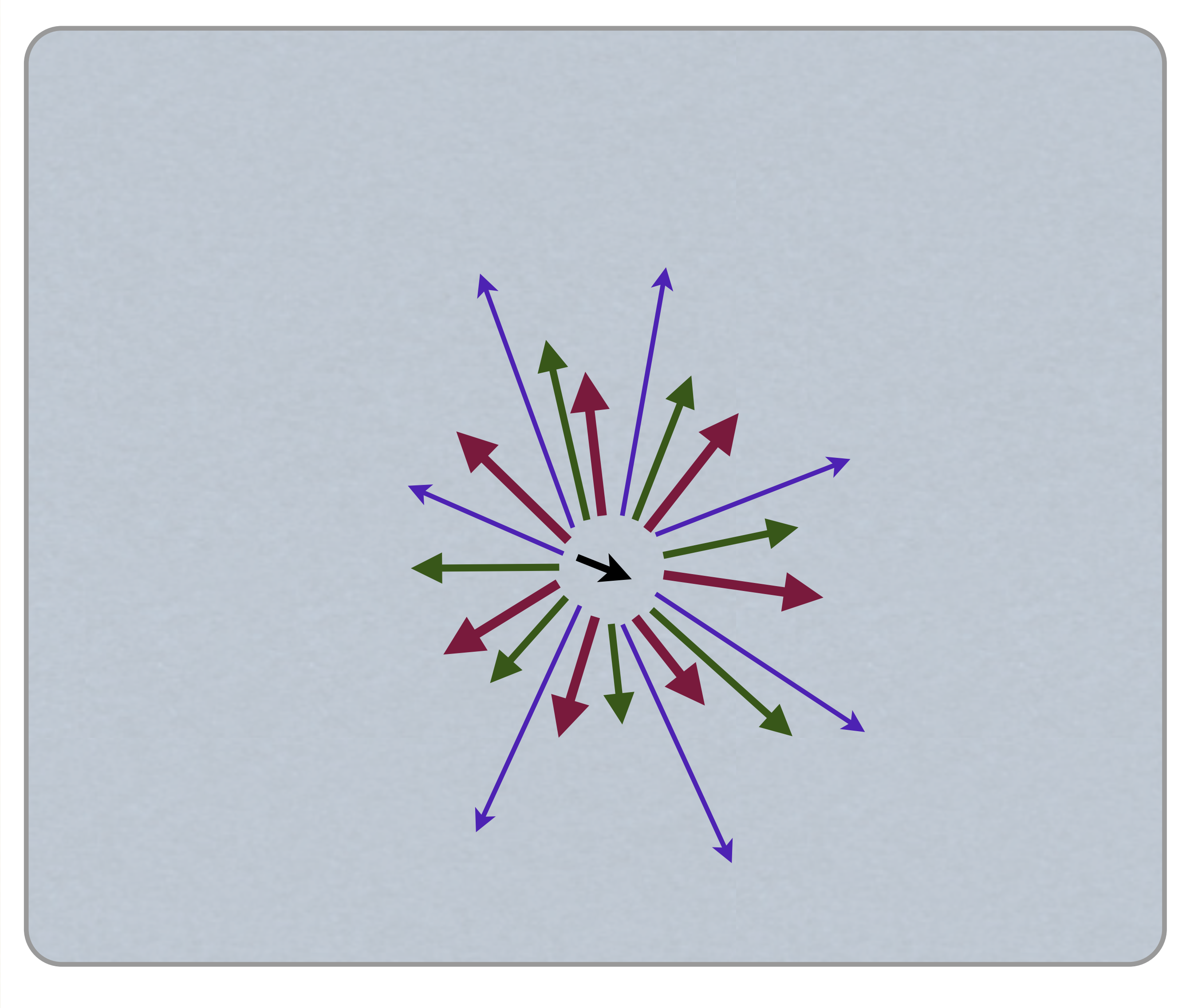


General Detection Principles



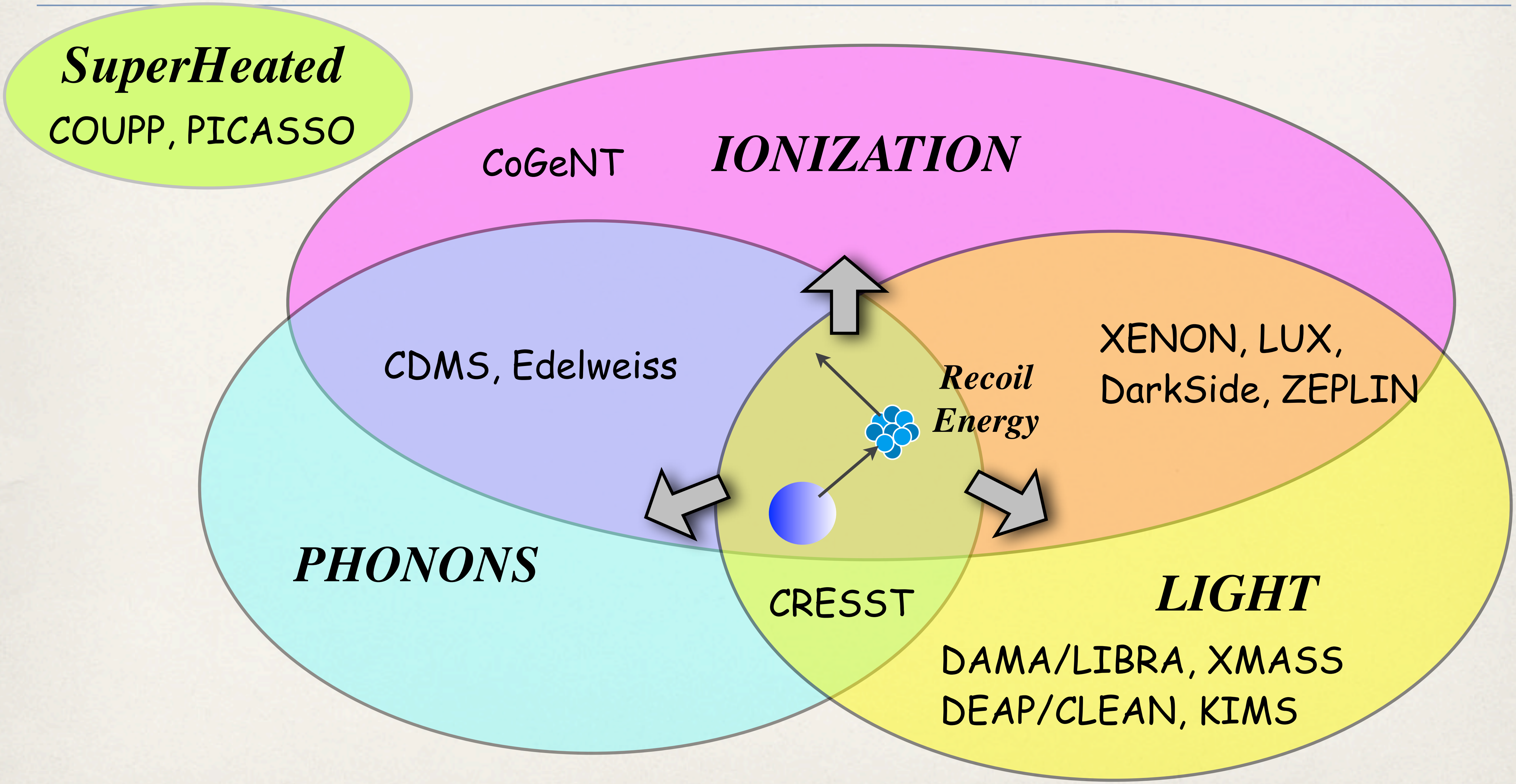
Courtesy: Scott Hertel

General Detection Principles

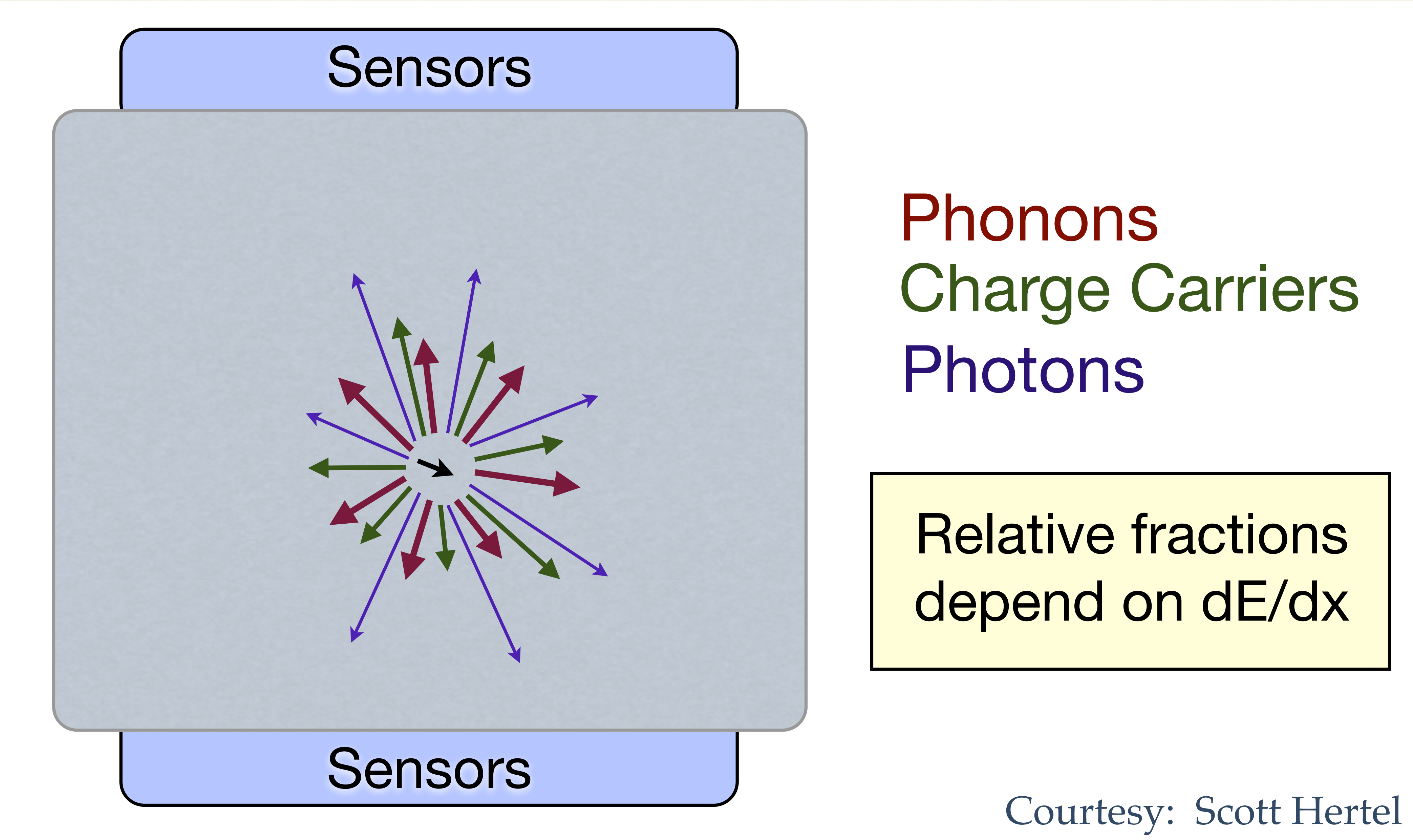


Courtesy: Scott Hertel

Direct Detection Principles

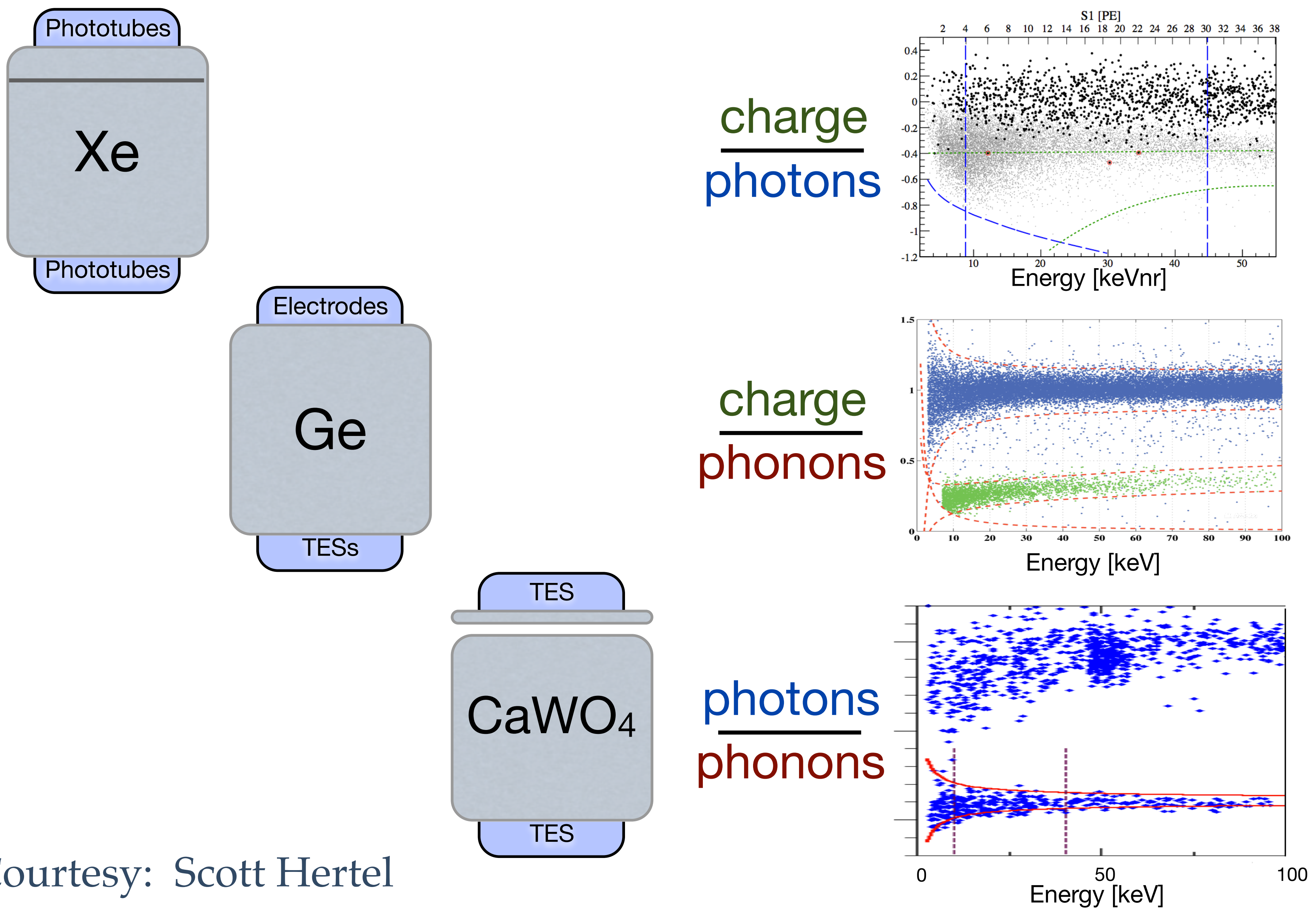


General Detection Principles



Courtesy: Scott Hertel

General Detection Principles



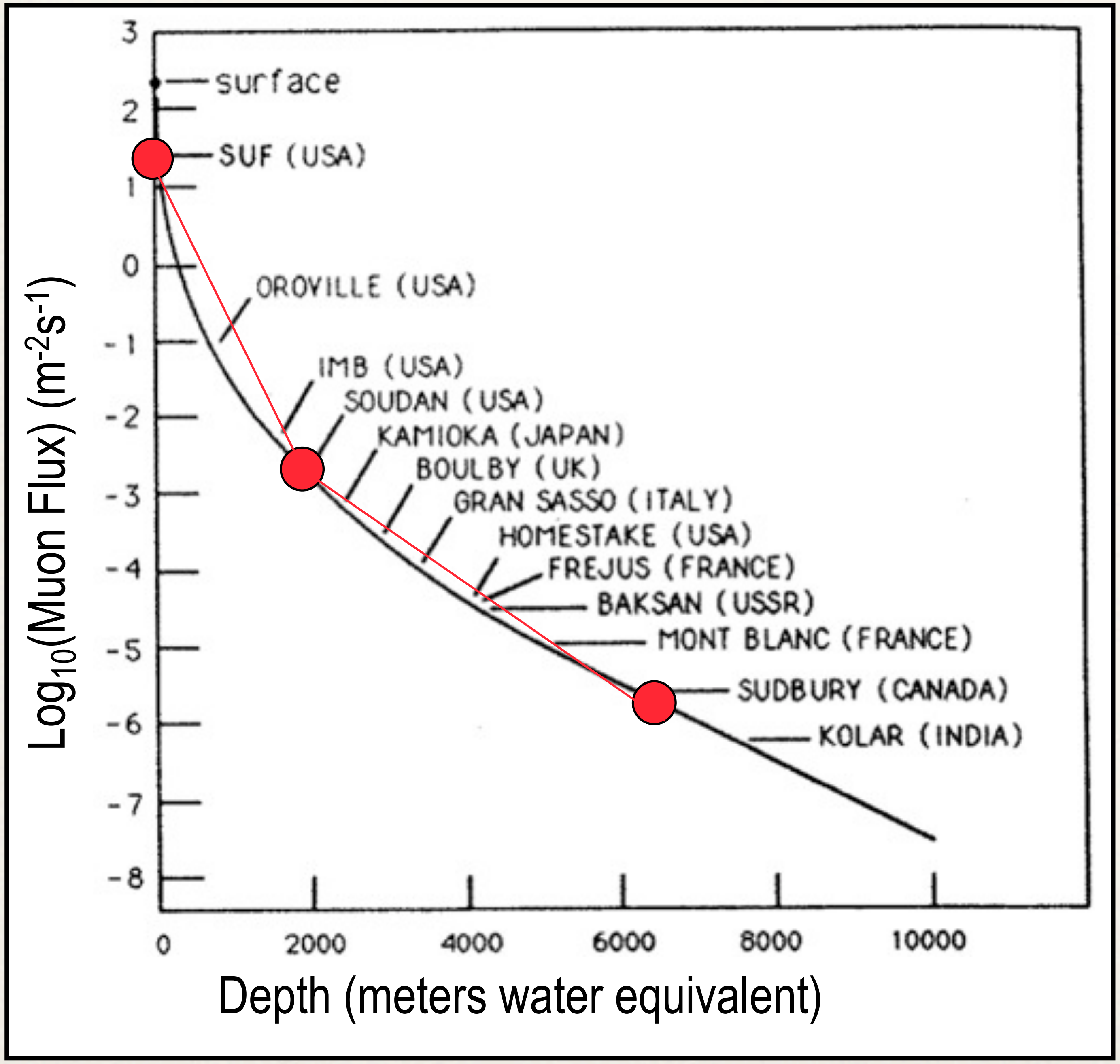
Courtesy: Scott Hertel

General Detection Principle

- Many direct detection experiments have excellent discrimination between electron recoils (ER) and nuclear recoils (NR) from the simultaneous measurement of two types of energy in an event.
- Most backgrounds will produce electron recoils.
- WIMPs and neutrons produce nuclear recoils.
  - Need to keep neutrons away from the detectors.
  - Despite the excellent discrimination capability of these detectors, we still want to keep the backgrounds as small as possible.

Underground Facilities

Depth is Important!



mwe = meters water equivalent

SUF

17 mwe

0.5 n/d/kg

(182.5 n/y/kg)

Soudan

2090 mwe

0.05 n/y/kg

SNOLab

6060 mwe

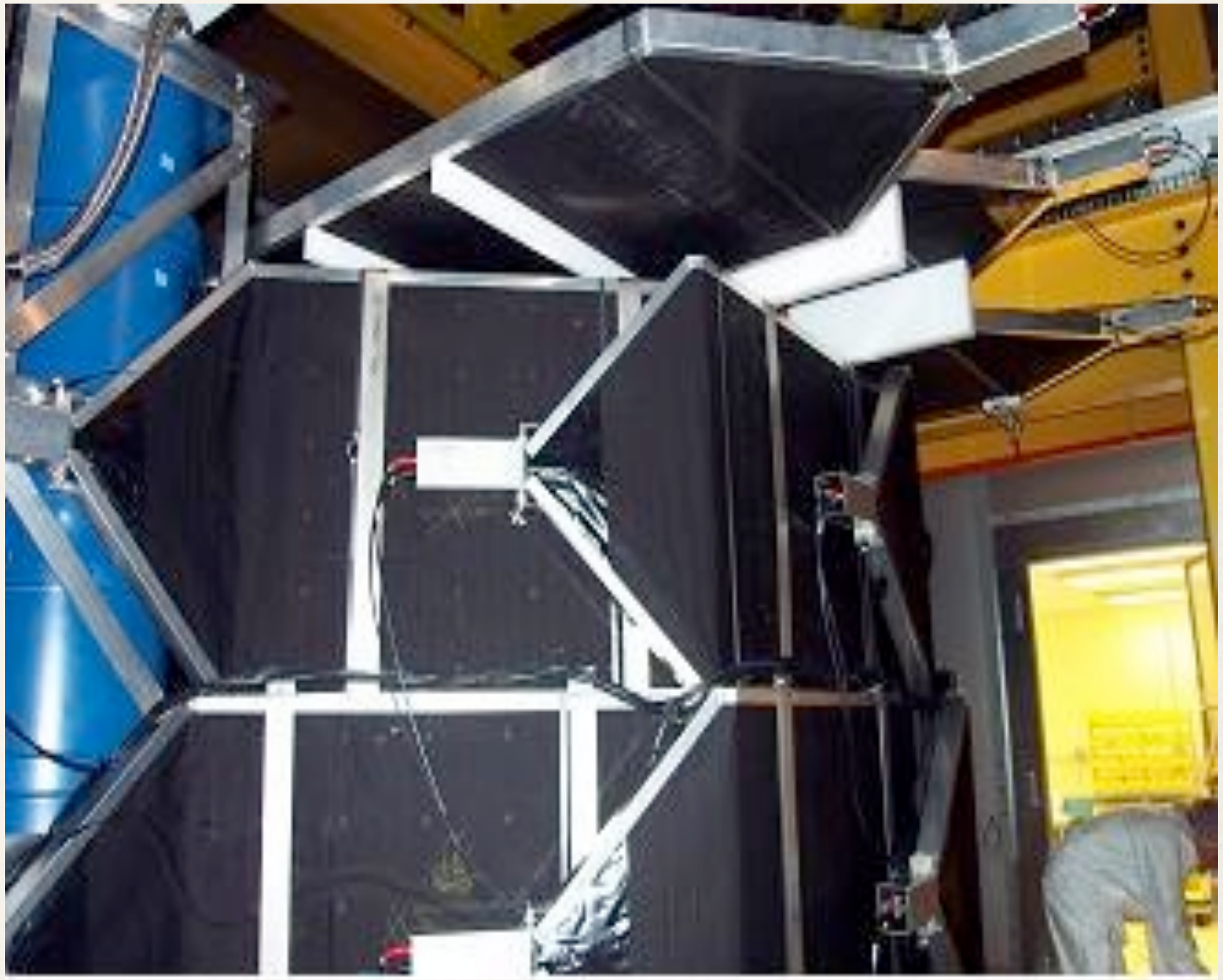
0.2 n/y/ton

(0.0002 n/y/kg)

Shielding

Active Muon Veto:
rejects events from cosmic rays

- Scintillating panels
- Water Shield



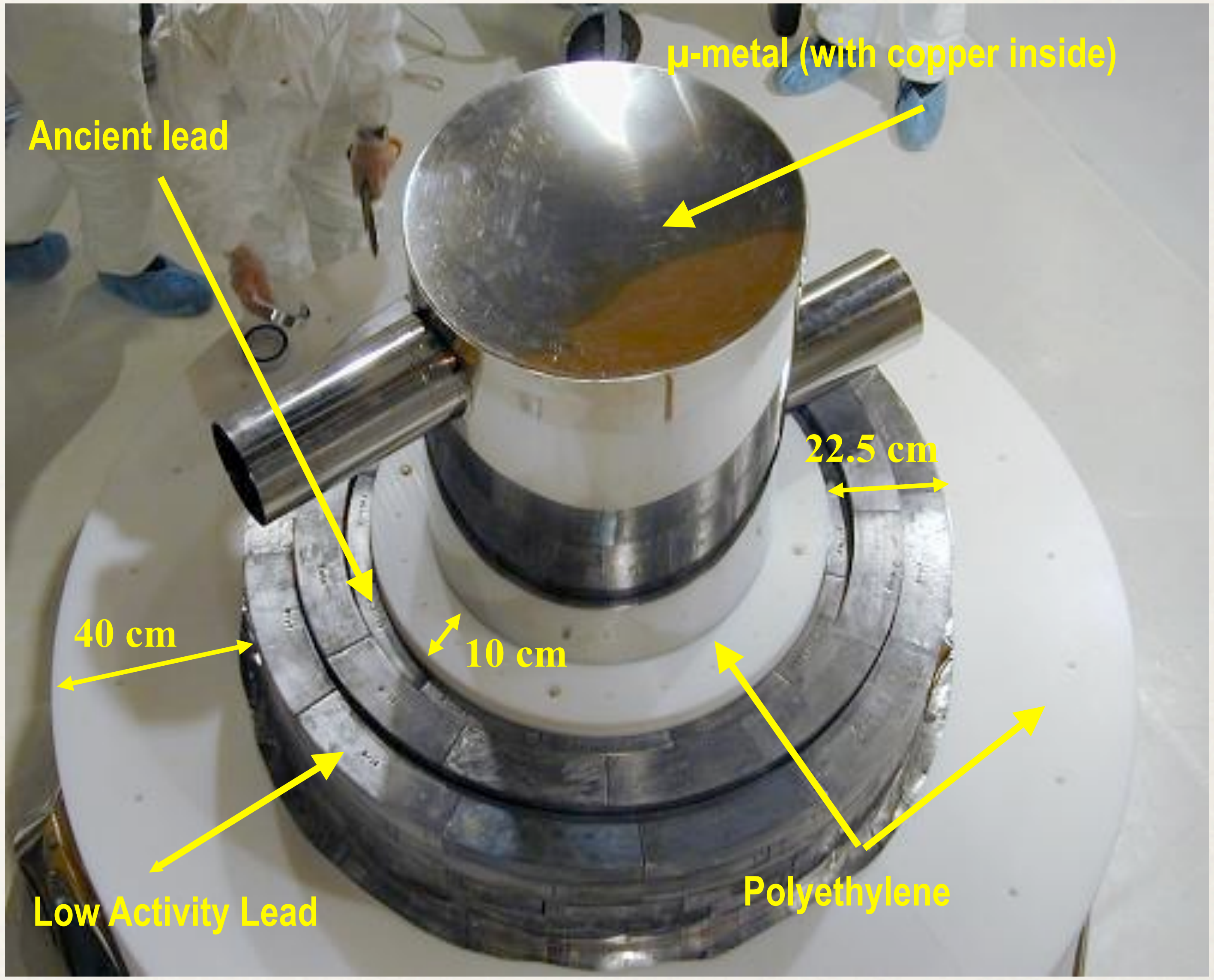
CDMS active muon veto

Shielding - An Example

Active Muon Veto: rejects events from cosmic rays

Pb: shielding from gammas resulting from radioactivity

Polyethyene: moderate neutrons produced from fission decays and from (α,n) interactions resulting from U/Th decays



CDMS - Layers of Polyethylene and Lead

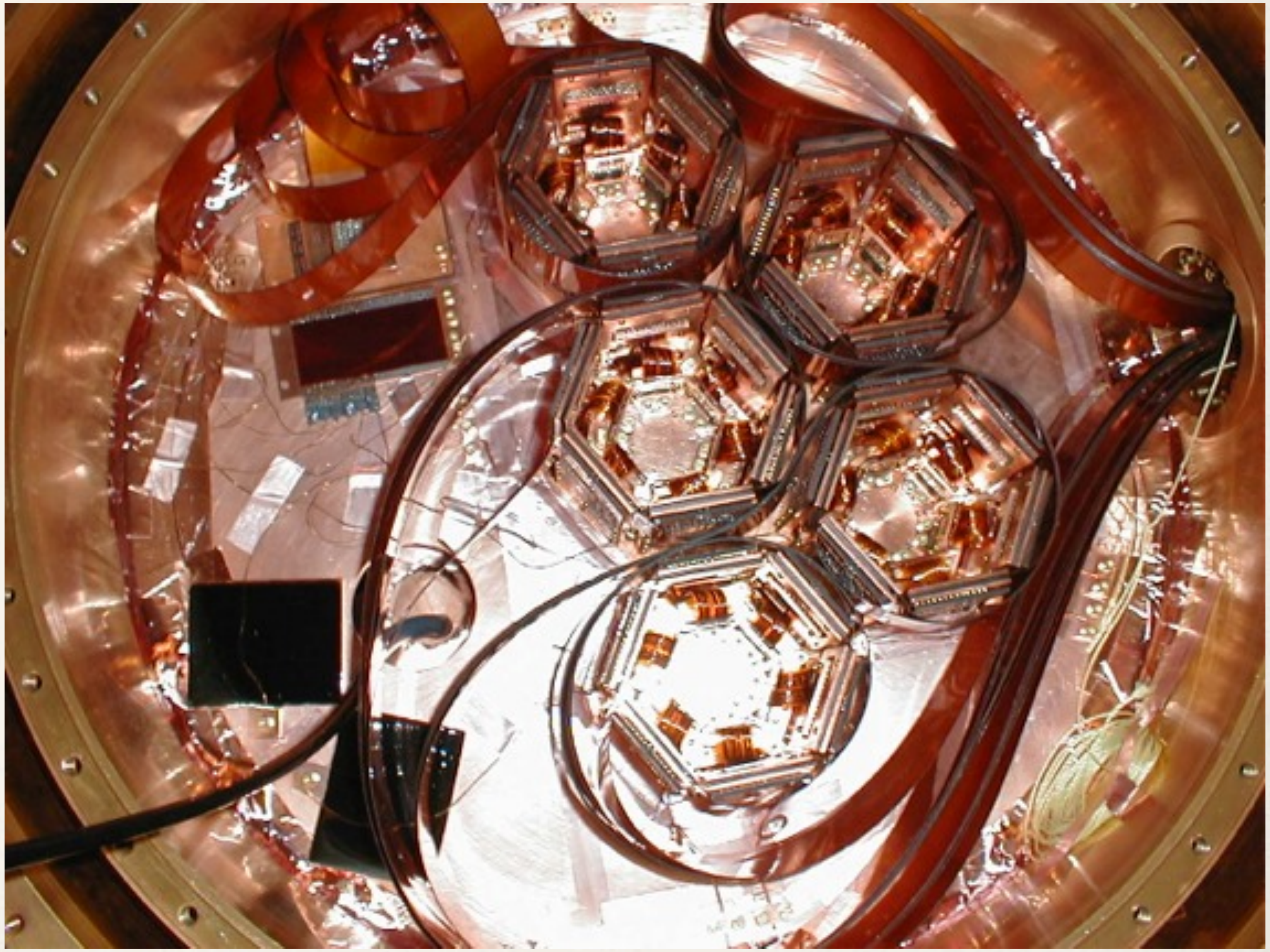
Shielding

Active Muon Veto:
rejects events from cosmic rays

Pb: shielding from gammas resulting from radioactivity

Polyethylene: moderate neutrons produced from fission decays and from (α,n) interactions resulting from U/Th decays

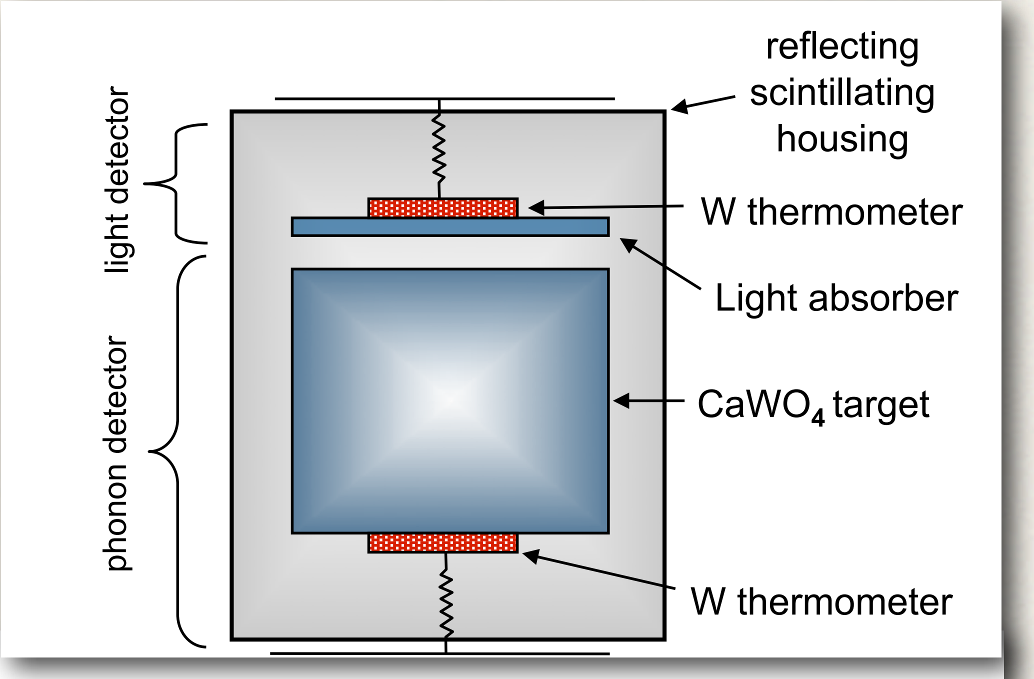
Cu: shielding from gammas

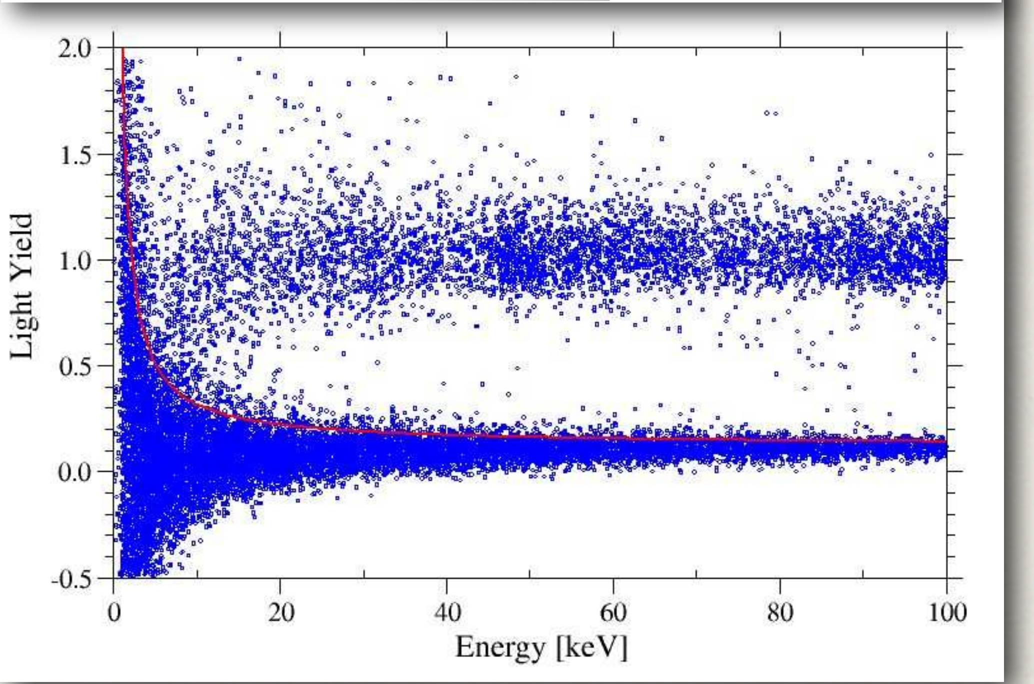


CDMS - Top view of inner most shield layer

CRESST-II

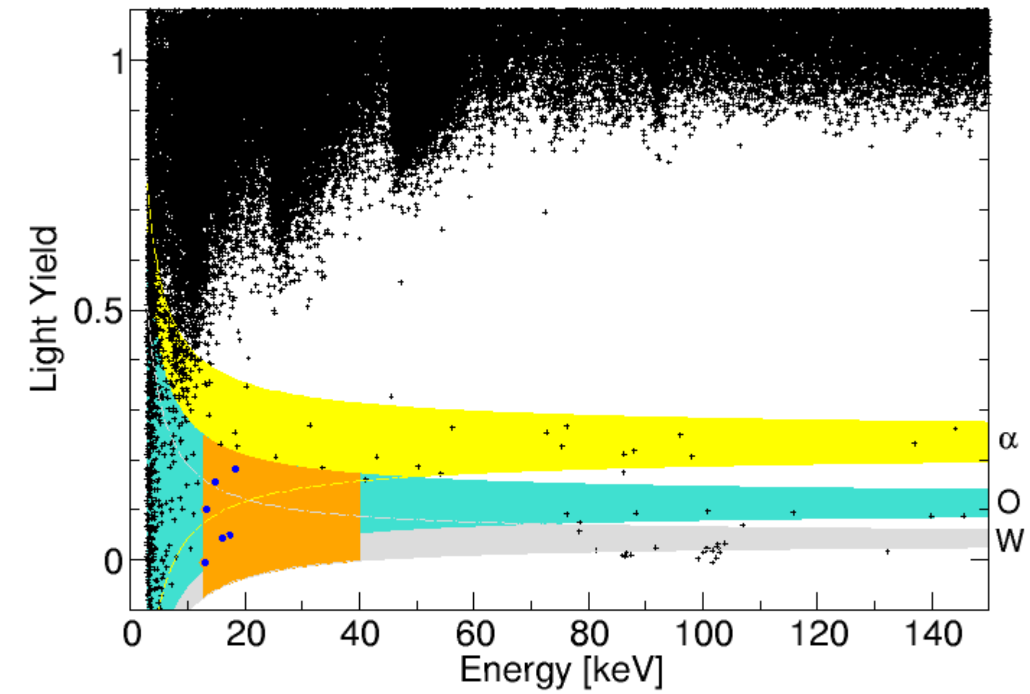
- Cryogenic $CaWO_4$ crystals are instrumented to readout phonon energy and scintillation.
  - operated at ~10 mK
  - each crystal ~ 300 g
- Located in Laboratori Nazionali del Gran Sasso, Italy
- Discrimination between ER and NR events via light yield (light/phonon energy)
  - Signal expected to produce nuclear recoils
  - Dominant background from radioactivity produces electron recoils.





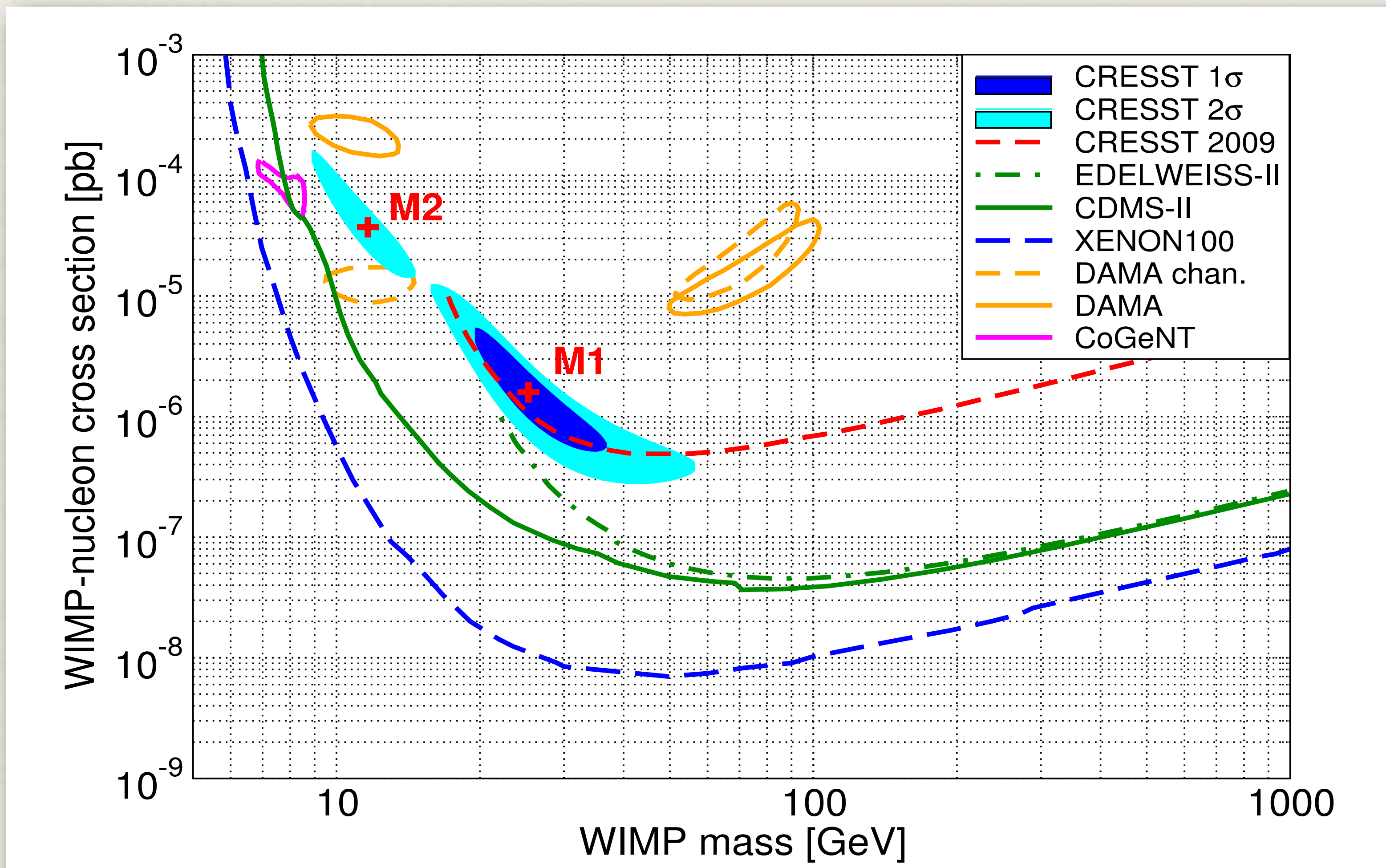
CRESST-II Data Analysis

- Net exposure: 730 kg-day (July 2009 - March 2011) from 8 detector modules.
    - Observed 67 events in acceptance region (orange).
- Analysis used a maximum likelihood in which 2 regions favored a WIMP signal in addition to predict background.
    - M1 is global best fit (4.7 σ)
    - M2 slightly disfavored (4.2 σ)
- Excess events can not be explained by known backgrounds
- Large background contribution



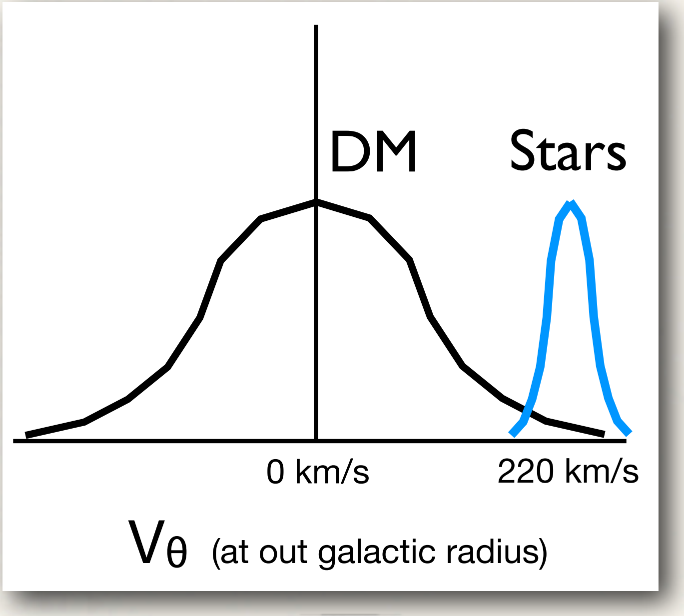
	M1	M2
e/γ events	8.00 ± 0.05	8.00 ± 0.05
α events	$11.5^{+2.6}_{-2.3}$	$11.2^{+2.5}_{-2.3}$
neutron events	$7.5^{+6.3}_{-5.5}$	$9.7^{+6.1}_{-5.1}$
Pb recoils	$15.0^{+5.2}_{-5.1}$	$18.7^{+4.9}_{-4.7}$
signal events	$29.4^{+8.6}_{-7.7}$	$24.2^{+8.1}_{-7.2}$
m_χ [GeV]	25.3	11.6
σ_{WN} [pb]	$1.6 \cdot 10^{-6}$	$3.7 \cdot 10^{-5}$

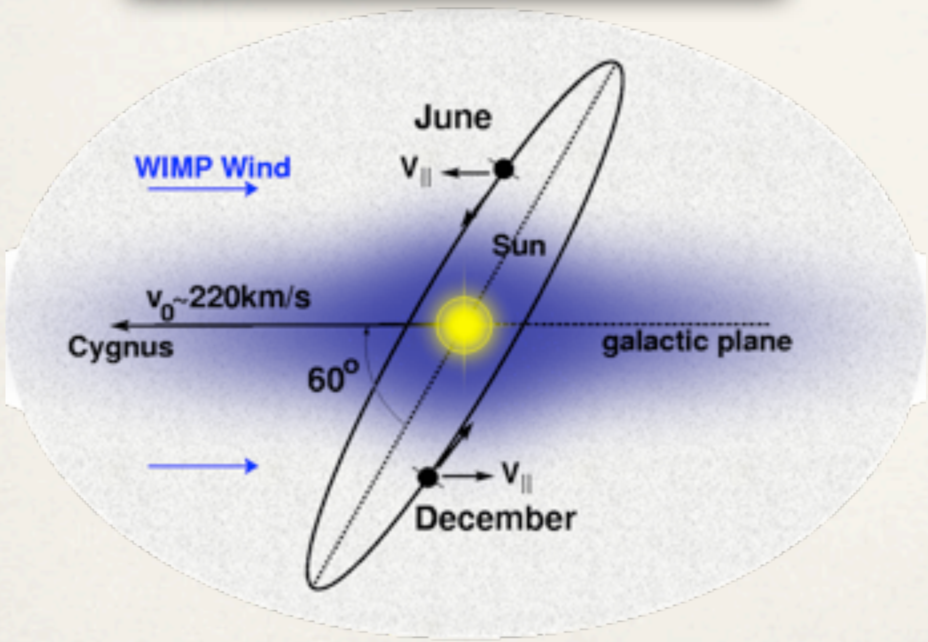
CRESST-II



- Next data run (2012) aims to reduce background, increase detector mass.
    - Alphas - new clamping design
    - Add additional shielding to reduce neutron background

DAMA/LIBRA - Modulation



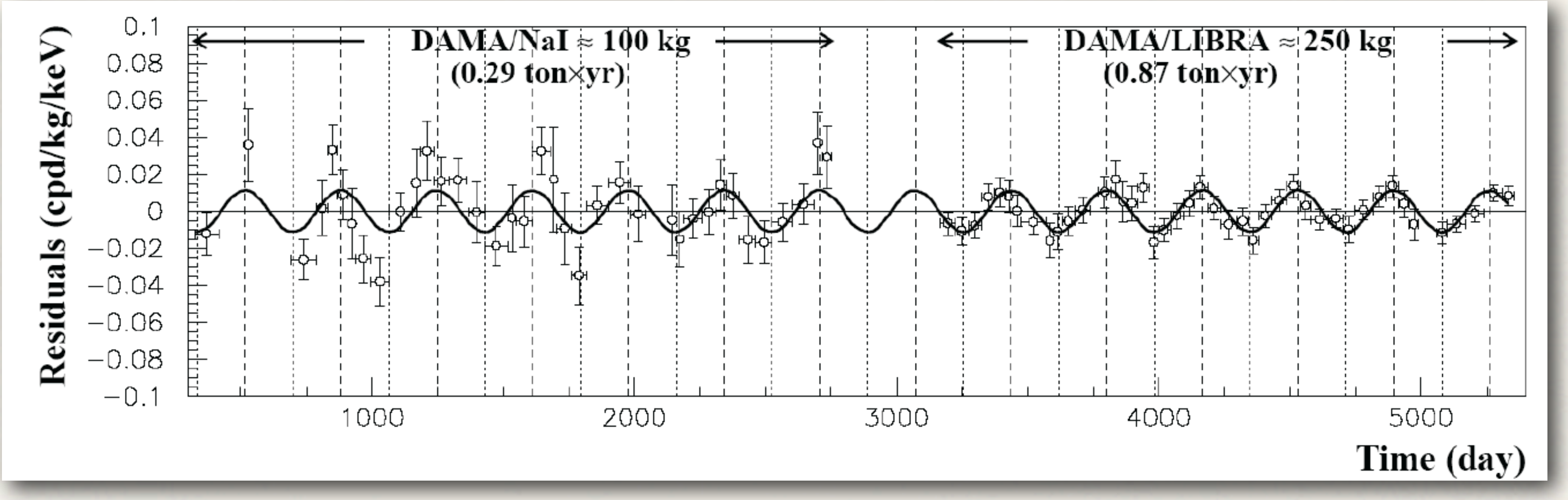


- Baryons travel together in roughly circular orbits with small velocity dispersion
- Dark matter particles travel individually with no circular dependence and large velocity dispersion
- As a result, the flux of WIMPs passing through Earth modulate over the course of a year as Earth rotates around the sun.

DAMA/LIBRA

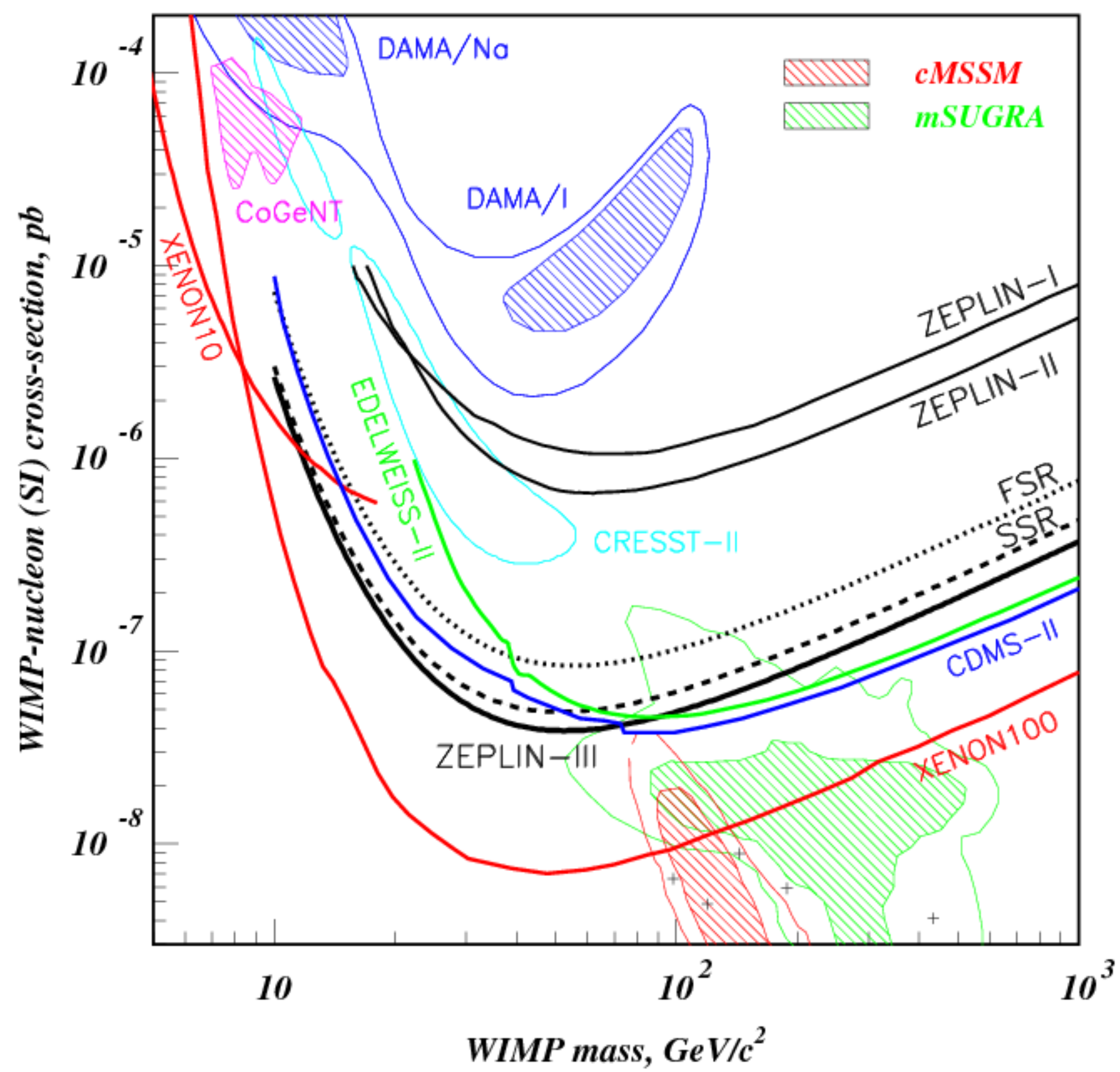
- DAMA
  - 100 kg NaI array operated from 1996 - 2002 in Laboratori Nazionali del Gran Sasso.
  - Measures scintillation from particle interactions in detectors.
    - No discrimination between nuclear and electron recoils
    - Positive results reported in 1998.
- LIBRA
  - 250 kg array operating since 2003 with first results in 2008.

DAMA/LIBRA Modulation Result



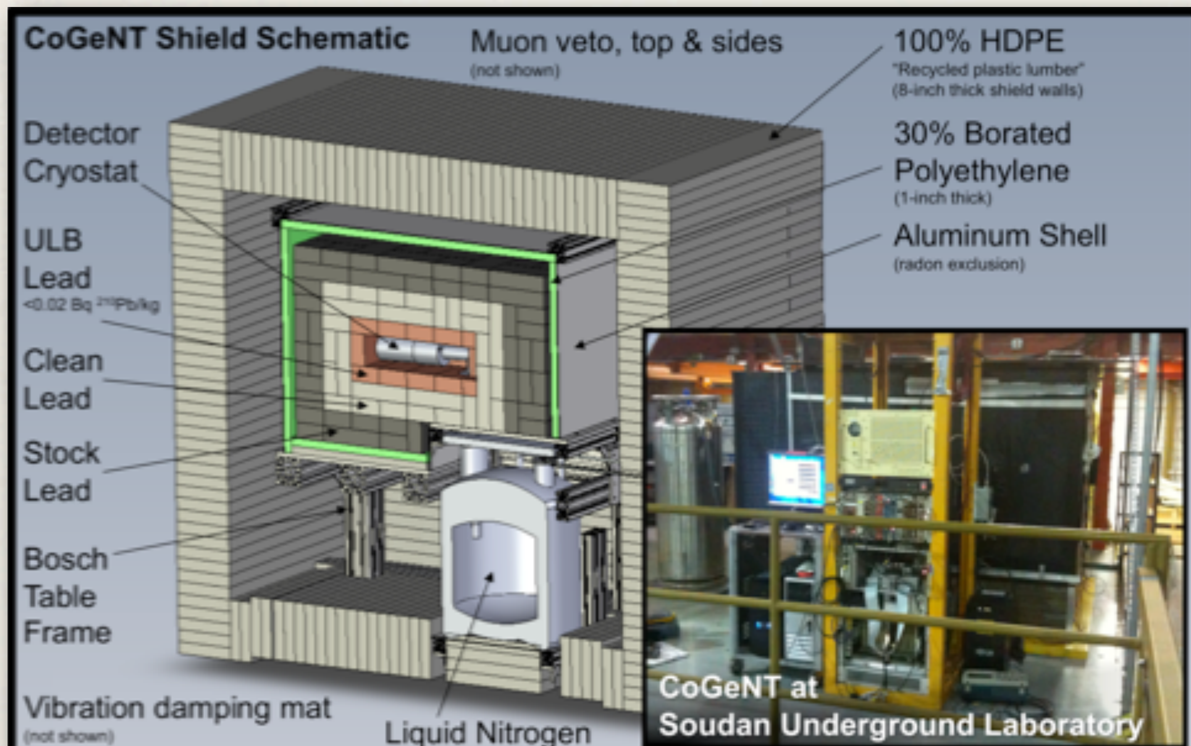
- Modulation has been observed over 13 cycles.
- Significance is 8.9σ.
- Signal is observed only in lowest energy bin.

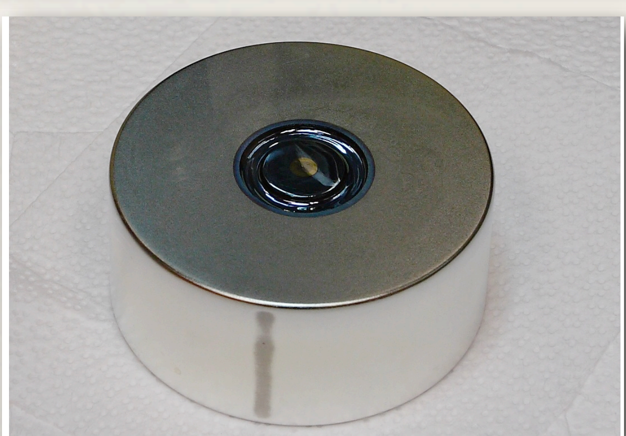
DAMA/LIBRA



From ZIII Araujo
2008 results - no channeling

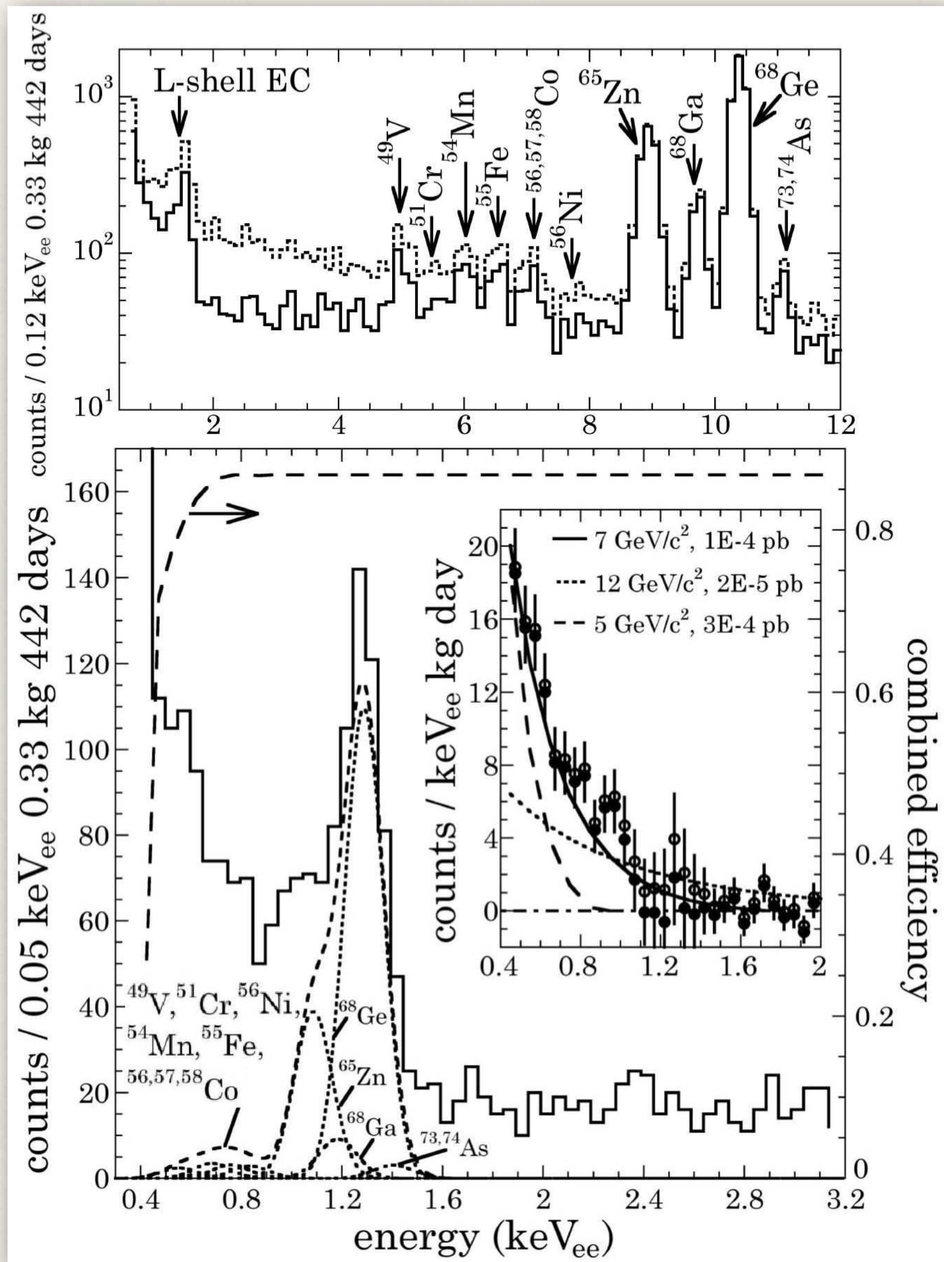
CoGeNT





- Location: Soudan Underground Laboratory, Minnesota, USA
- 440 g HPGe ionization spectrometer
- Data collection from Dec. 4, 2009 - Mar. 6, 2011 (442 live days)
  - Data collection interrupted due to fire.
- Data collection resumed July 2011.

CoGeNT Data Analysis

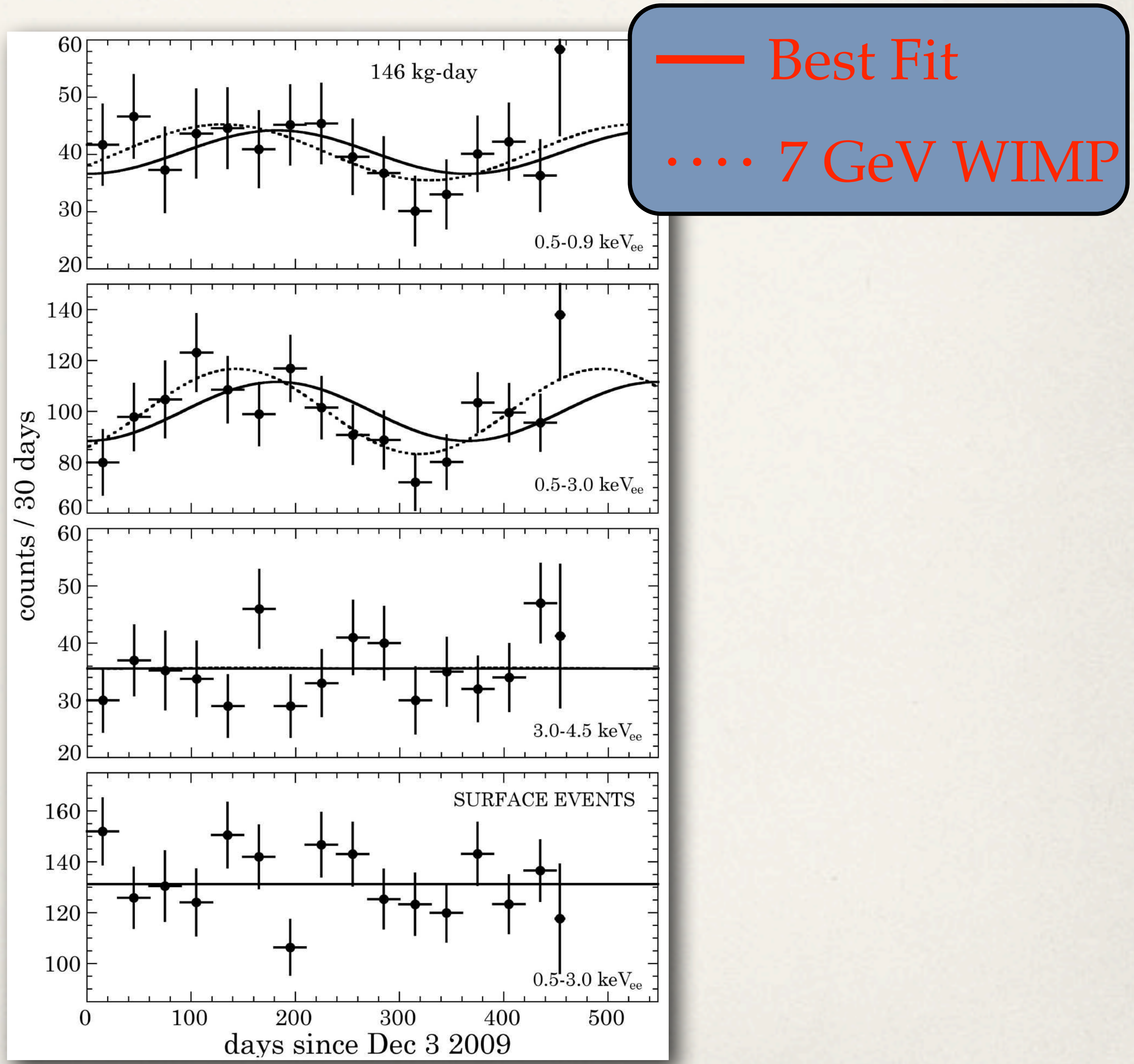


arXiv: 1106.0650v3

- Reject surface events using risetime cut.
- Peaks due to cosmogenic activation of Ge
- After subtraction of known background, an exponential excess of events remains
- Fits to a variety of light-WIMP masses and couplings shown in inset of lower figure.

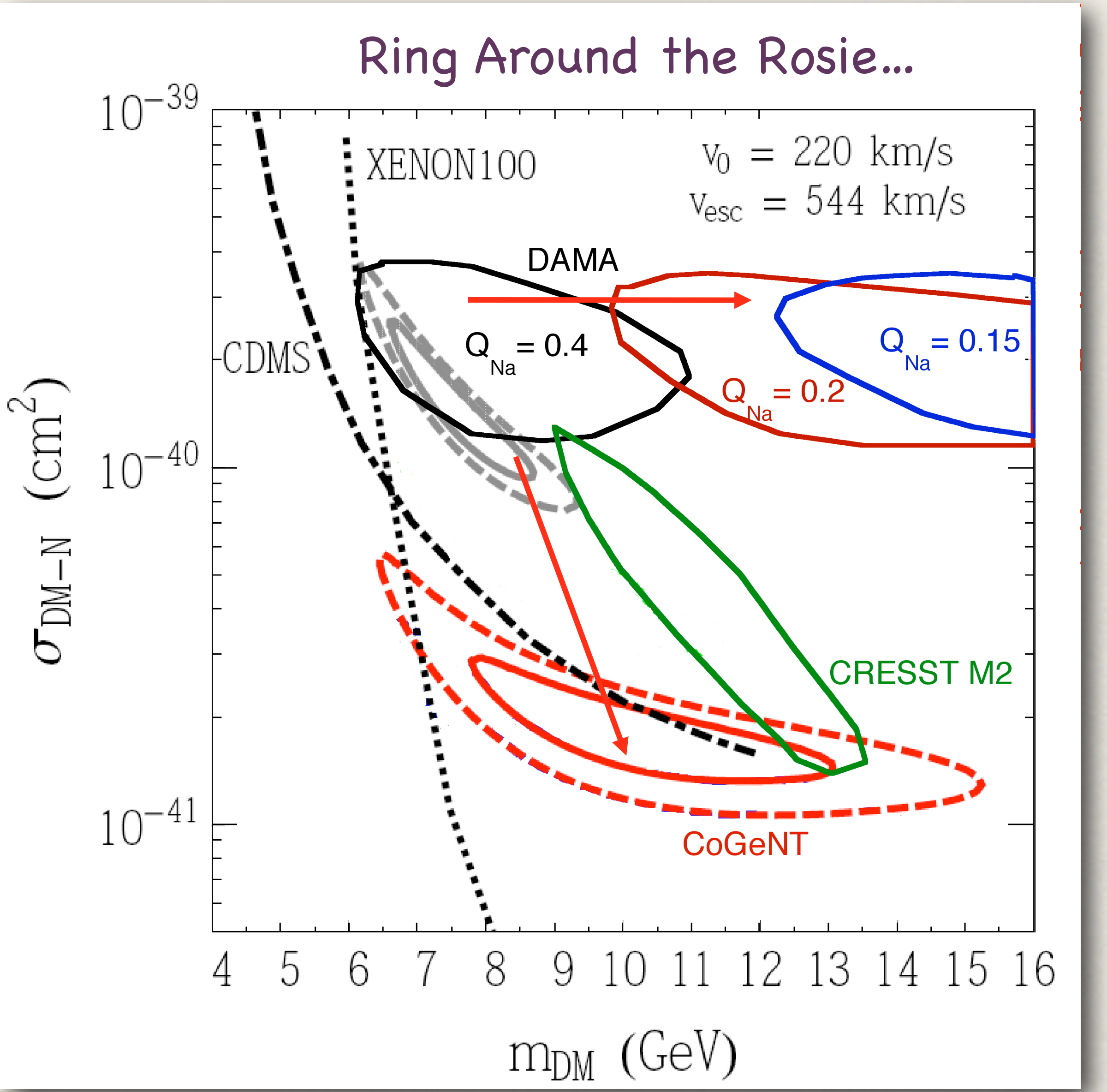
CoGeNT Modulation Analysis

- Energy Range of fit: 0.5 - 3.0 keV_{ee}
  - Period: 347 ± 29 d
  - Modulation Amplitude: 16.6 ± 3.8%
  - Minimum: Oct. 16 ± 12 d
  - Modulation preferred over null at 2.8σ
  - 16% consistent with null hypothesis



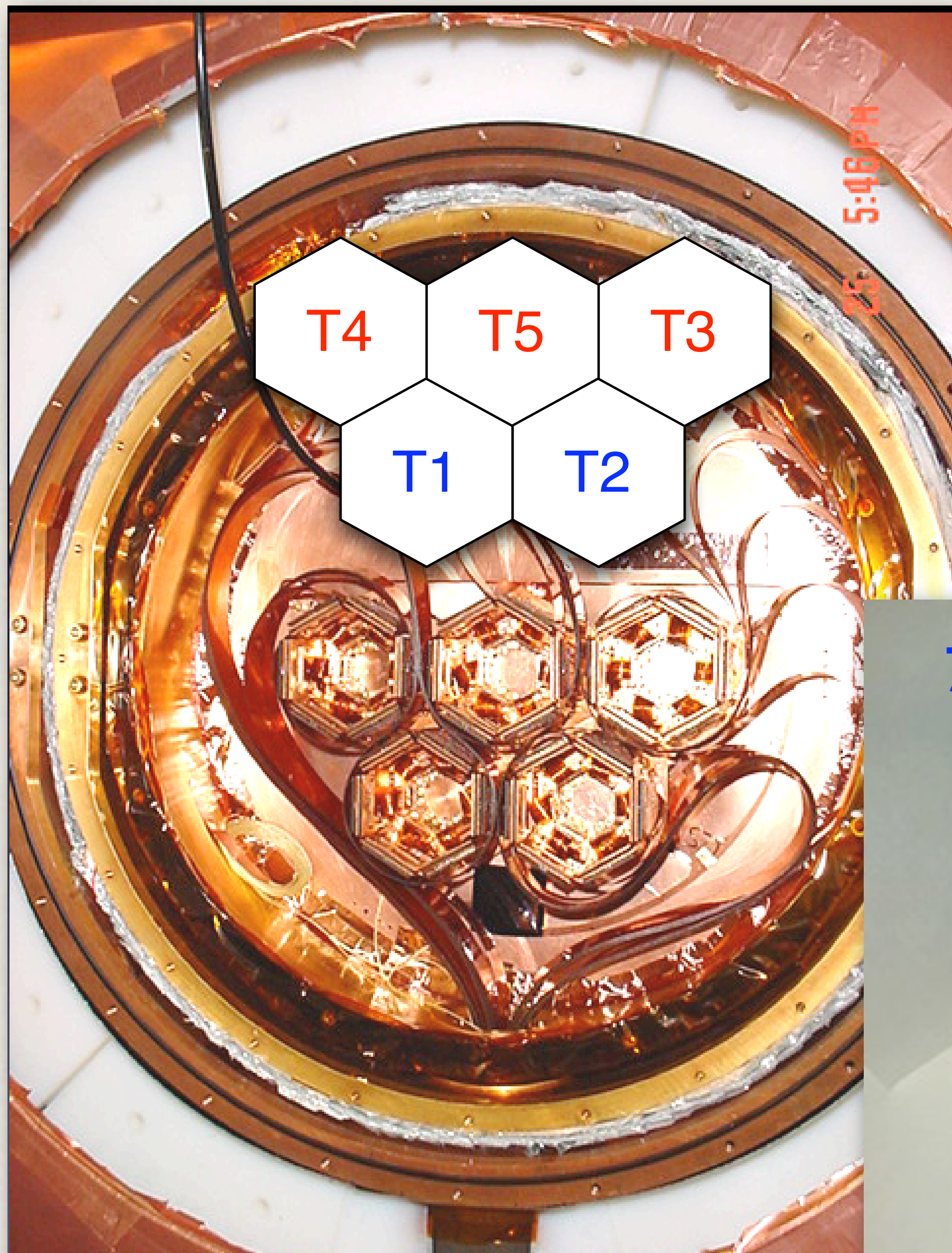
Agreement?

- After application of surface event cut brings the CoGeNT spectral and modulation analyses into agreement.
- $Q_{Na} = 0.4$ is unlikely (arXiv 1007.1005)
- Modulation in CoGeNT would need to be an order of magnitude larger than expected from vanilla Maxwellian halo.

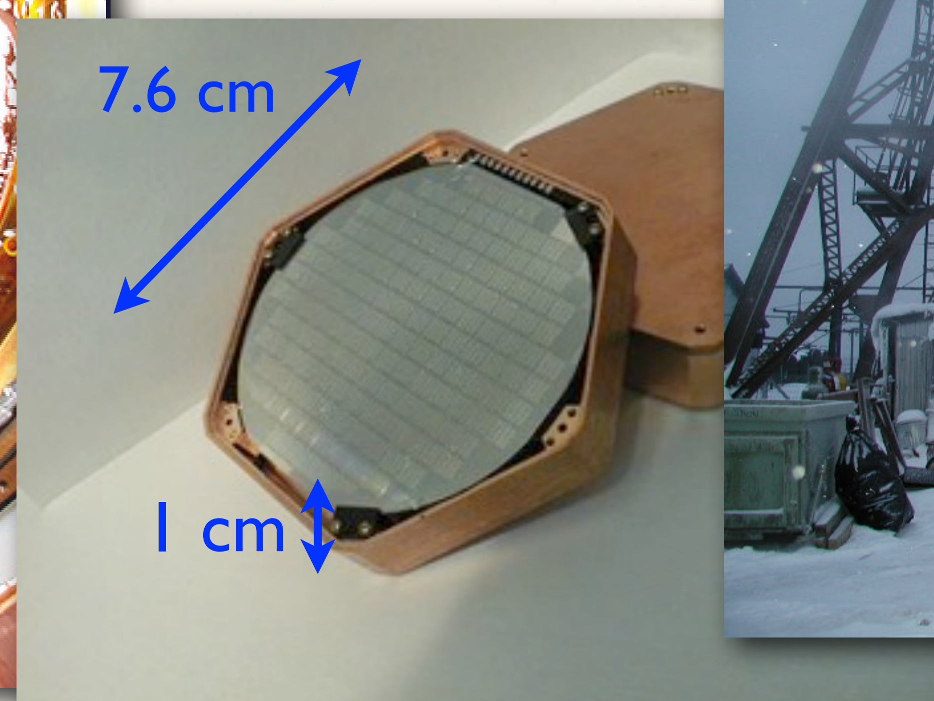


J. Collar DM2012

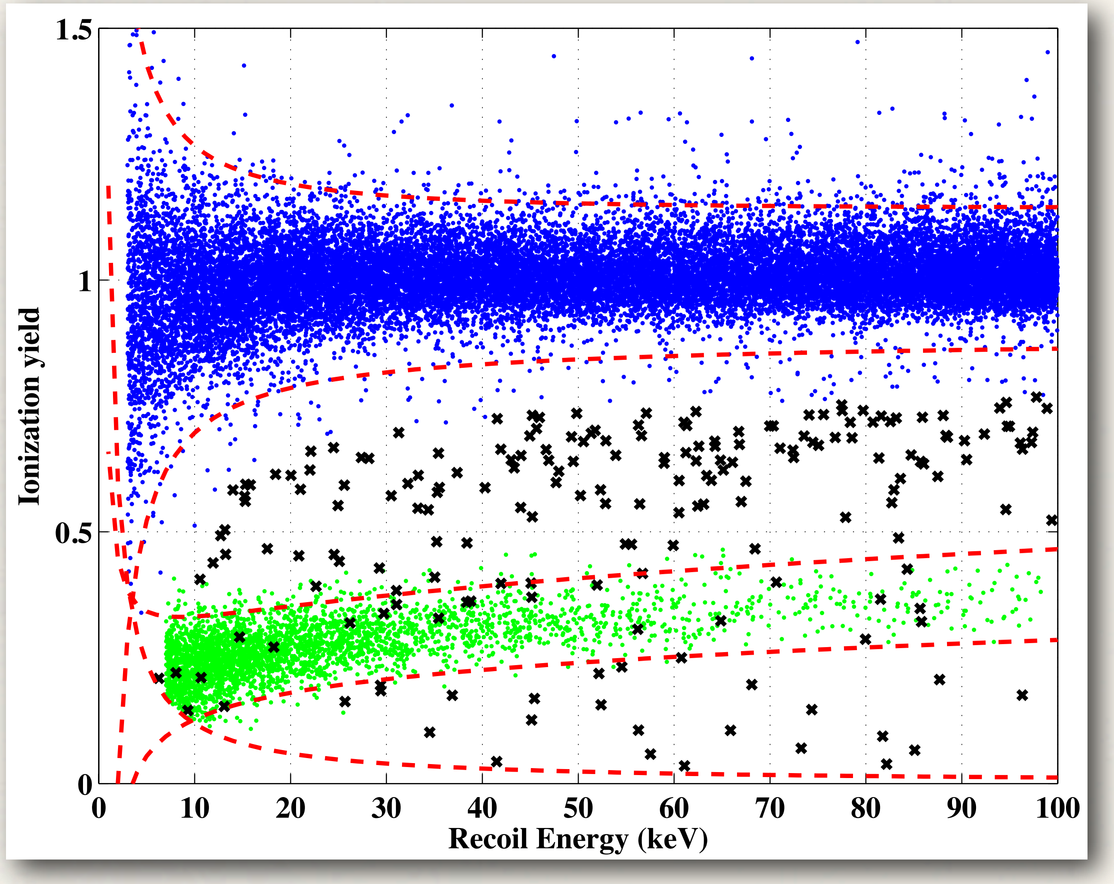
CDMS II and SuperCDMS

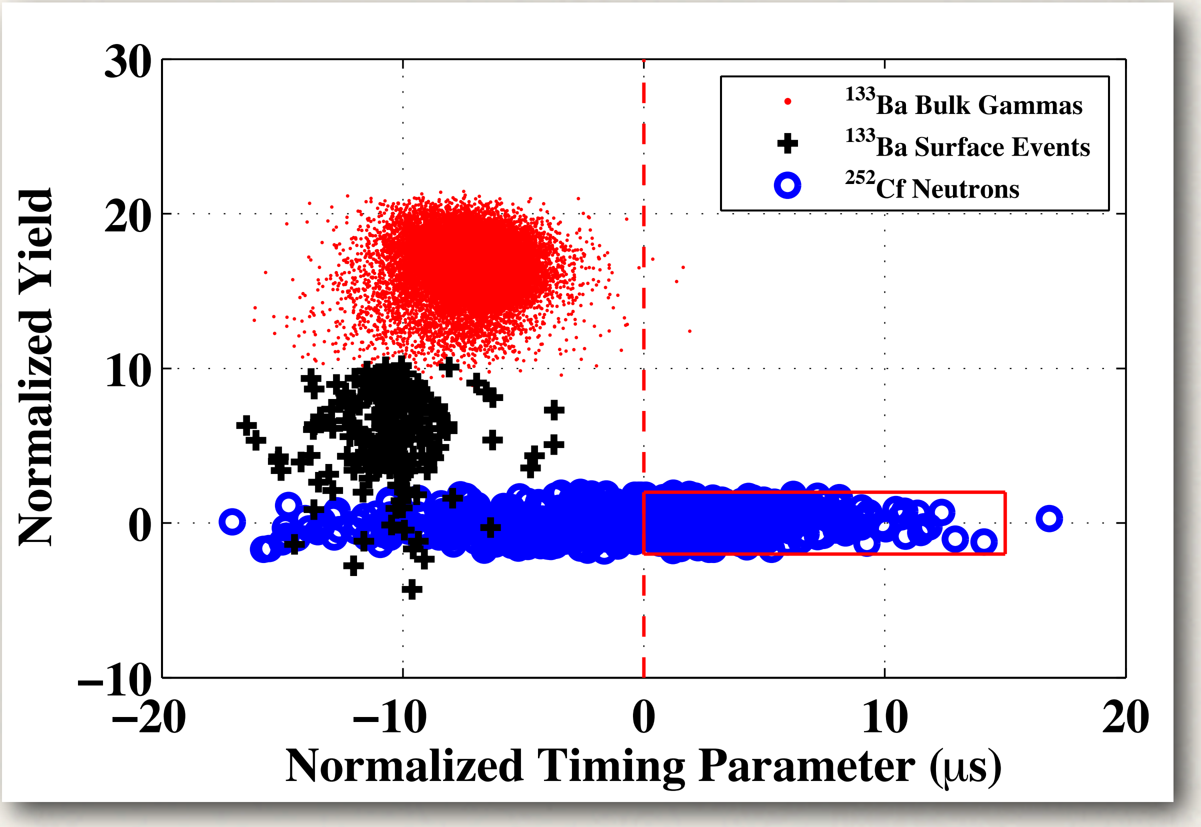


- **CDMS II:** 30 detectors (19 Ge, 11 Si) installed and operated in the Soudan Underground Laboratory, MN, USA from Jun. 06 - Mar. 09.
- Measures ionization and phonons (read out by TES)



CDMS II and SuperCDMS

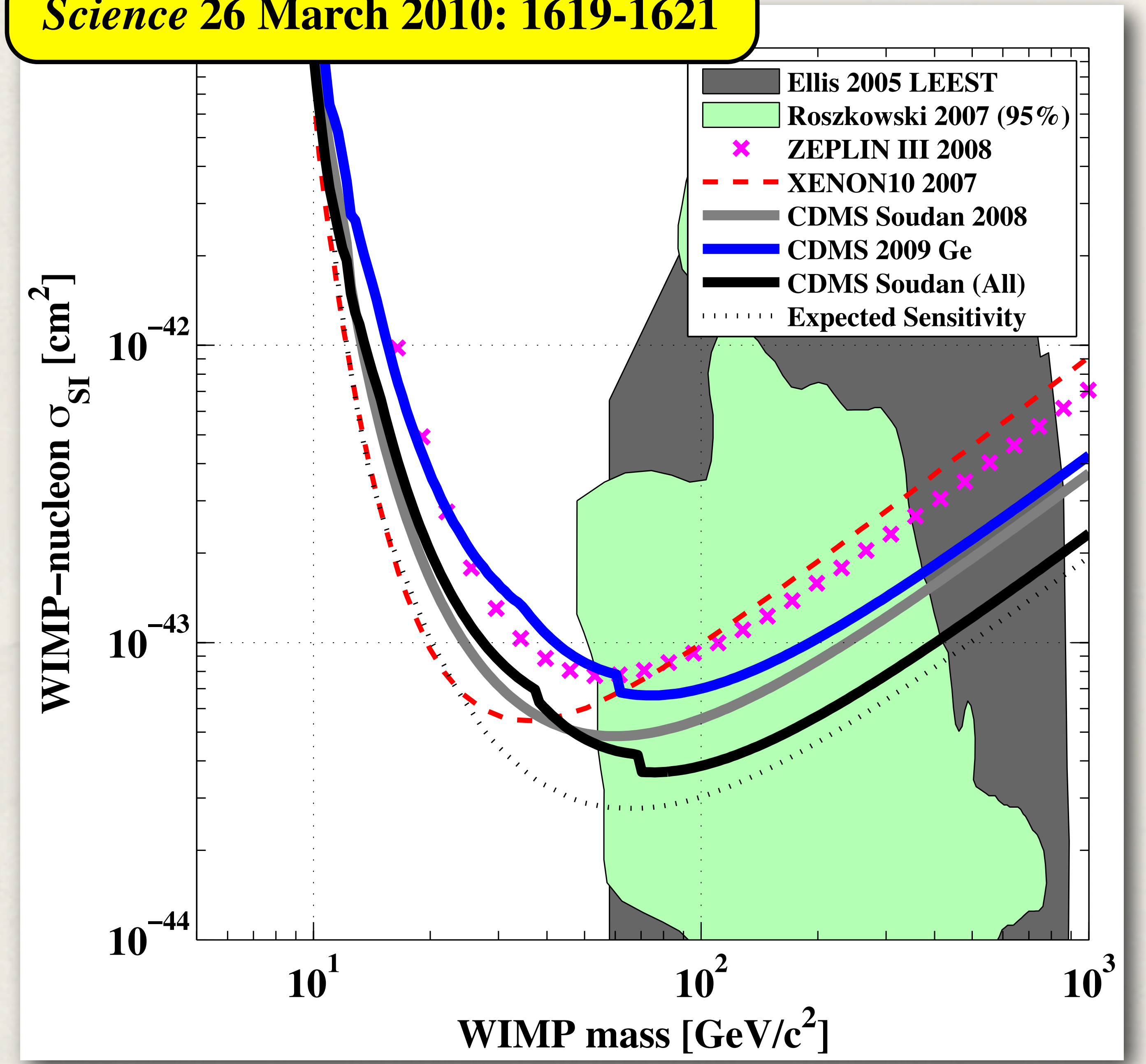




- Most backgrounds produce electron recoils and have yield ~1.
- WIMPs and neutrons produce nuclear recoils and have yield ~0.3.
- Surface events can be identified using timing properties of the phonon and charge pulses.

CDMS II Results

Science 26 March 2010: 1619-1621

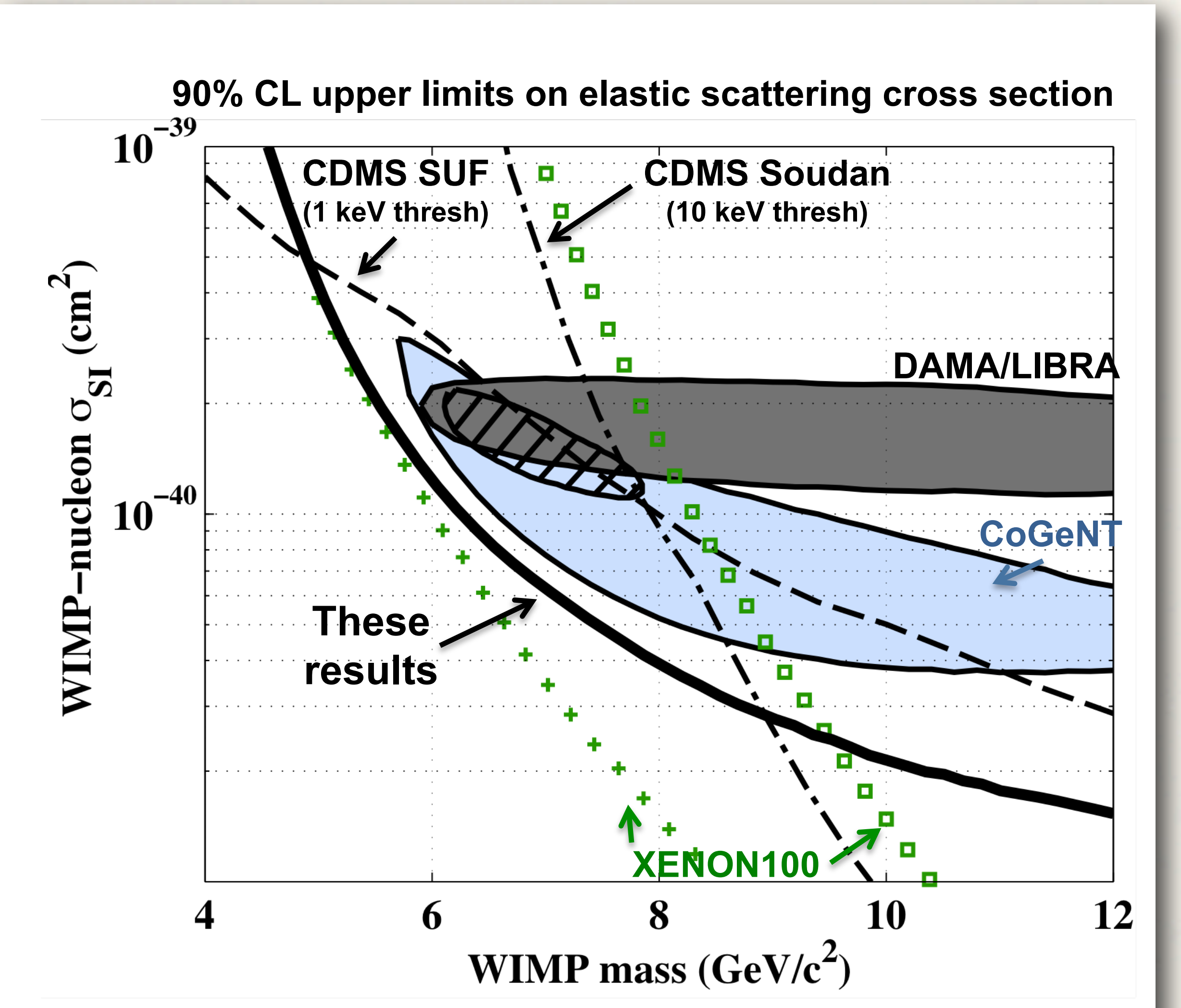


- First results from the final data taken at Soudan.
- Upper limit at 90% C.L. on the WIMP-nucleon cross section is 3.9 x 10^{-44} cm^2 for WIMPs of mass 70 GeV / c^2.

CDMS II Low Mass Analysis

- Reanalysis of CDMS II data
- Lower threshold (2 keV), increases sensitivity to WIMPs with mass below ~10 GeV/c2
- Used 8 Ge detectors with the lowest trigger thresholds (1.5 - 2.5 keV)
- Data taken from Oct. 2006 - Sept. 2008
  241 kg days "raw" exposure)
- No phonon timing cut was used as it is ineffective below ~5 keV

CDMS II Low Mass Results



Phys. Rev. Lett. 106:131302, 2011 (arXiv:1011.2482)

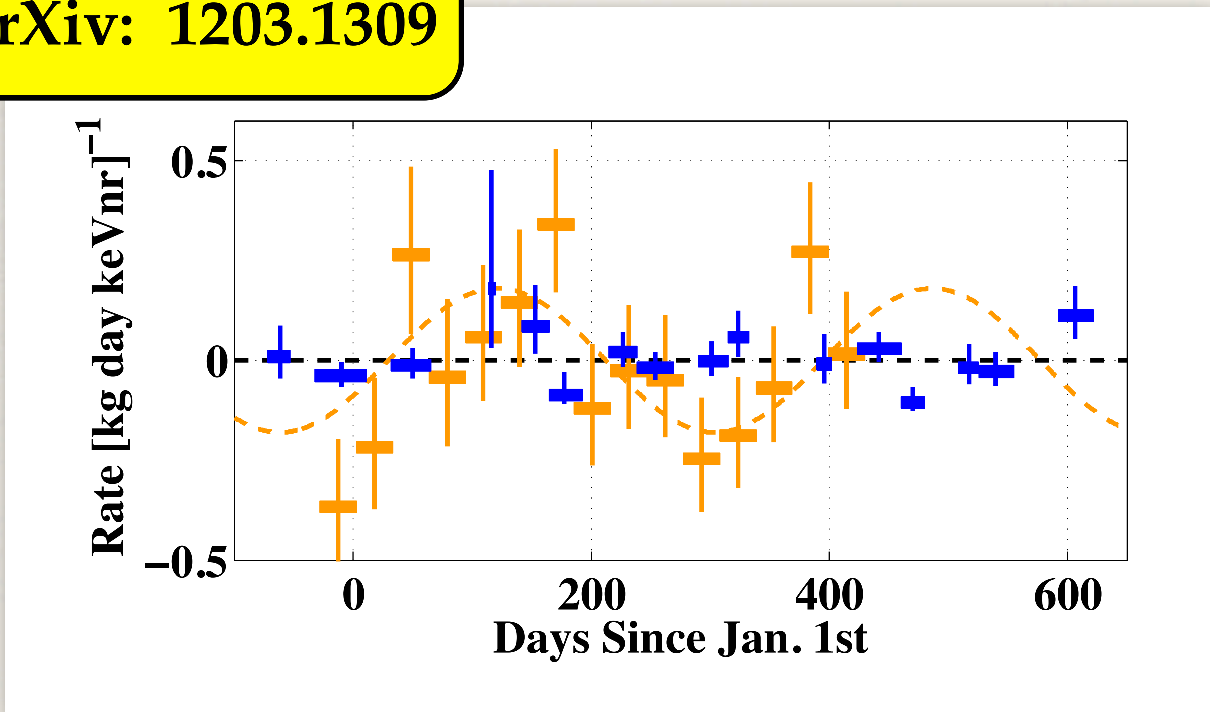
- Assumed that all events could be WIMPs (no background subtraction).
- Limits set using the Yellin Optimum Interval Method.

S. Yellin, PRD, 66, 032005 (2002); arXiv:0709.2701v1 (2007)

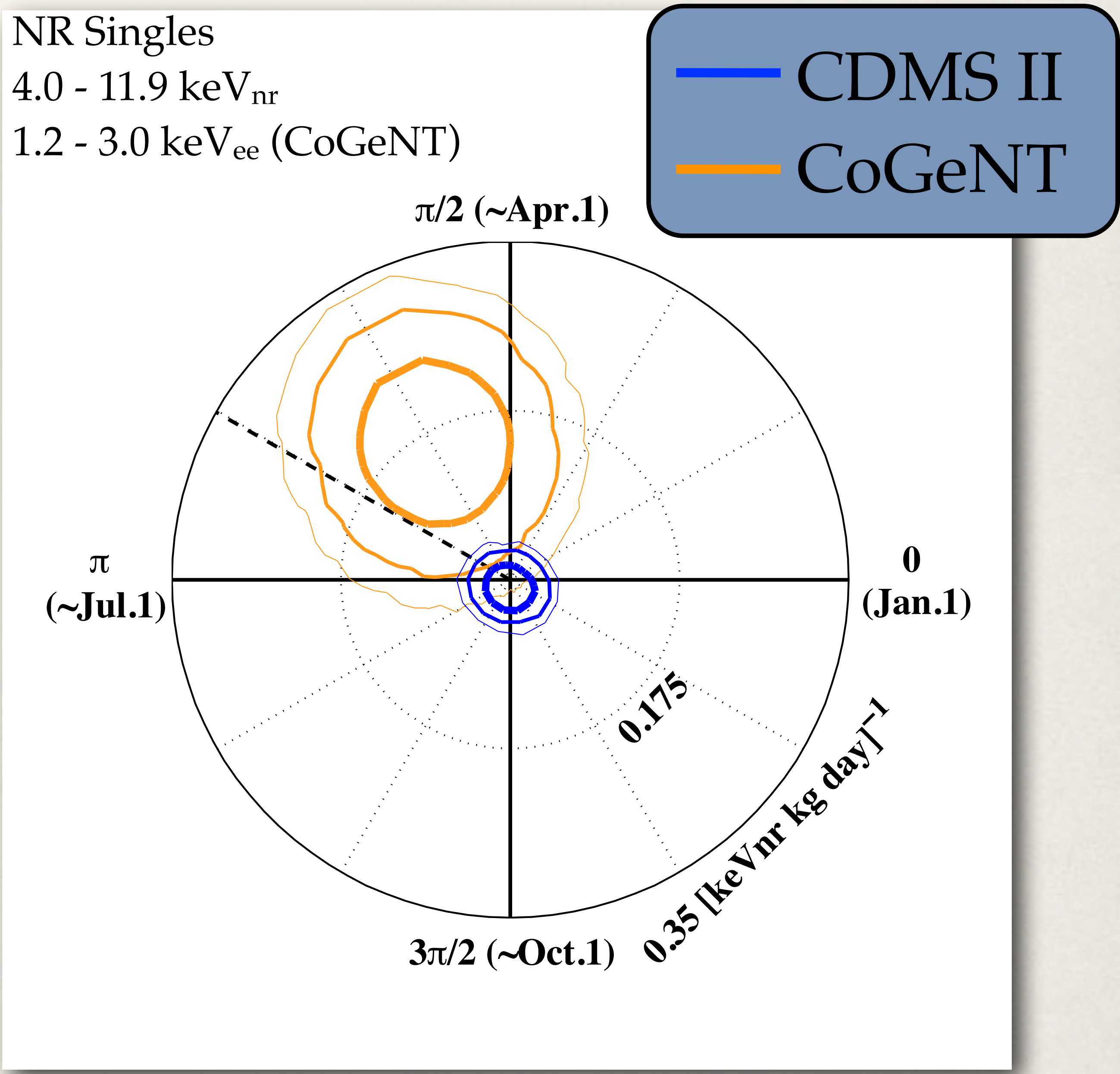
- 90% CL limits are incompatible with DAMA/LIBRA and CoGeNT for spin-independent elastic scattering.

CDMS II Modulation Results

arXiv: 1203.1309



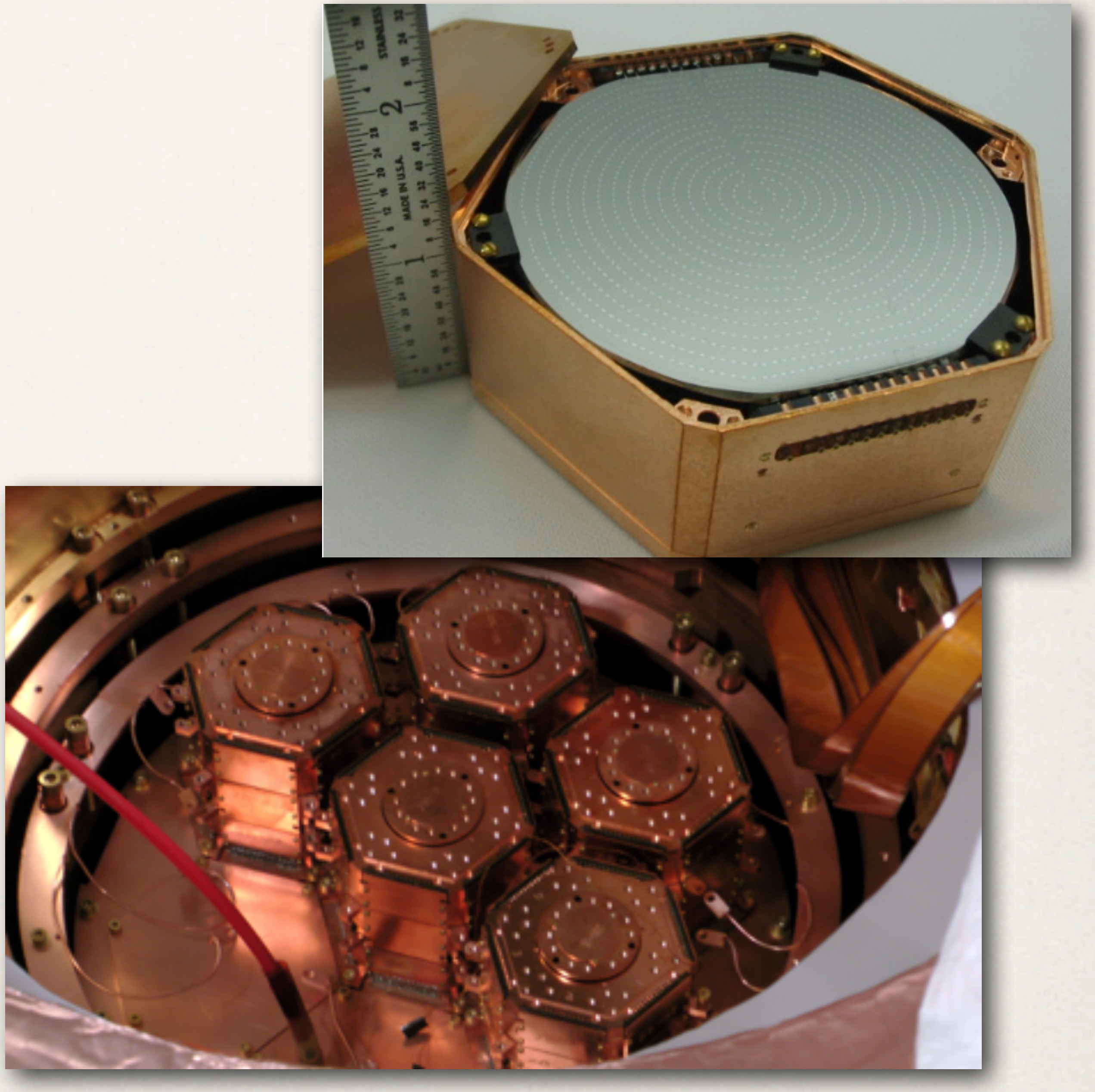
- 5.0 - 11.9 keV_{nr} region considered.
- Rule out modulated rates with amplitude greater than 0.07 [keV_{nr} kg day]$^{-1}$.



See Brink's talk later today!

SuperCDMS at Soudan

- Currently operating 5 towers of of advanced iZIP detectors (~10 kg Ge) in the existing cryostat at the Soudan Underground Laboratory.
- After 2 years of operation, expected to improve sensitivity to spin-independent WIMP-nucleon interactions by a factor of 4 over existing CDMS II results.



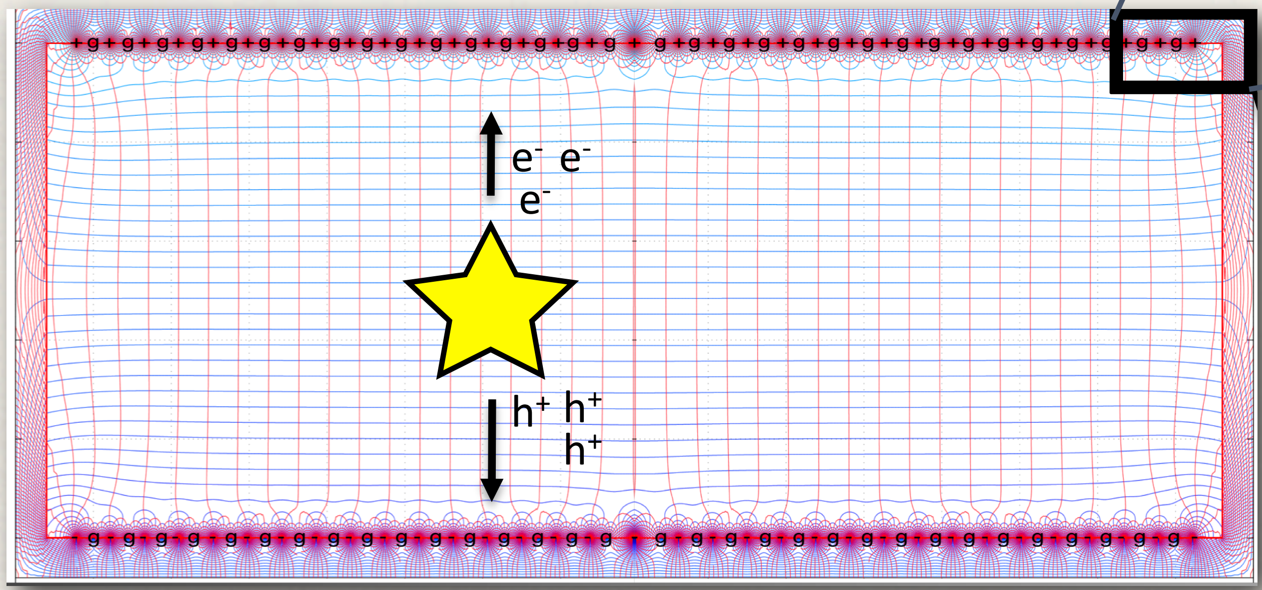
SuperCDMS iZIPs

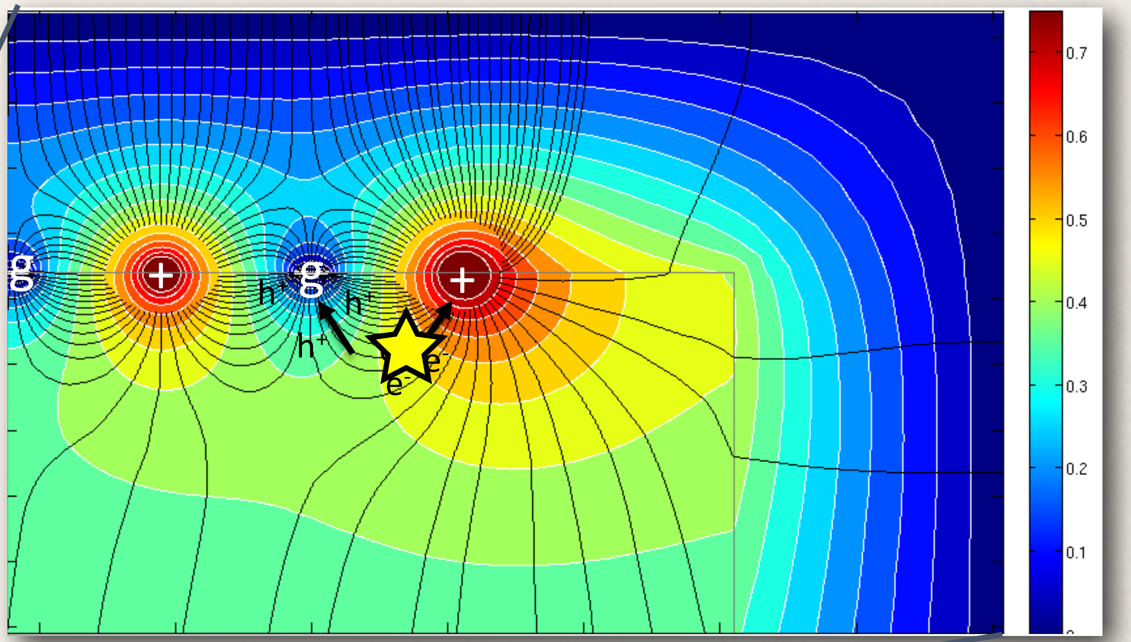
Bulk Events:

Equal but opposite ionization signal appears on both detectors sides (symmetric)

Surface Events:

Ionization signal appears on one detector side (asymmetric)

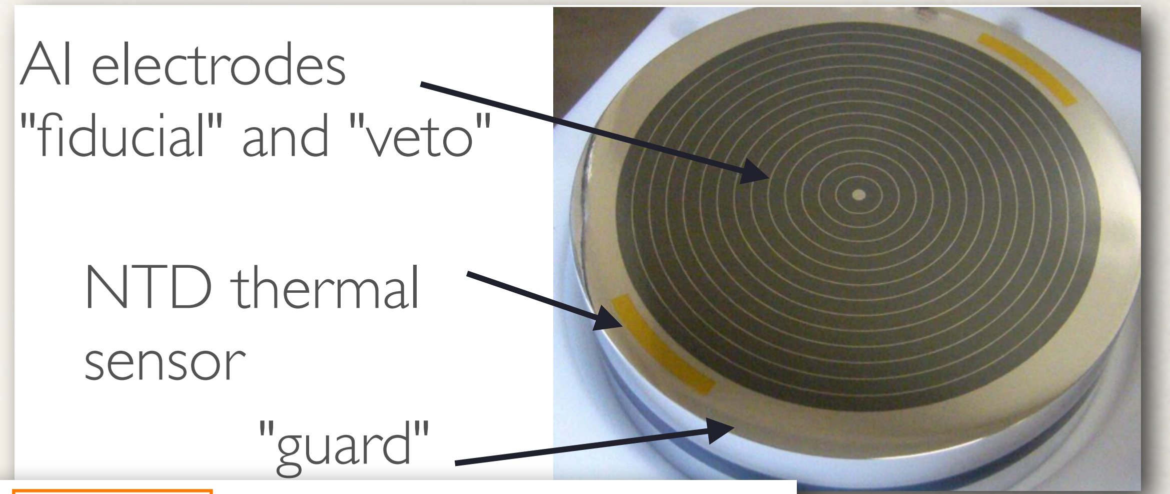


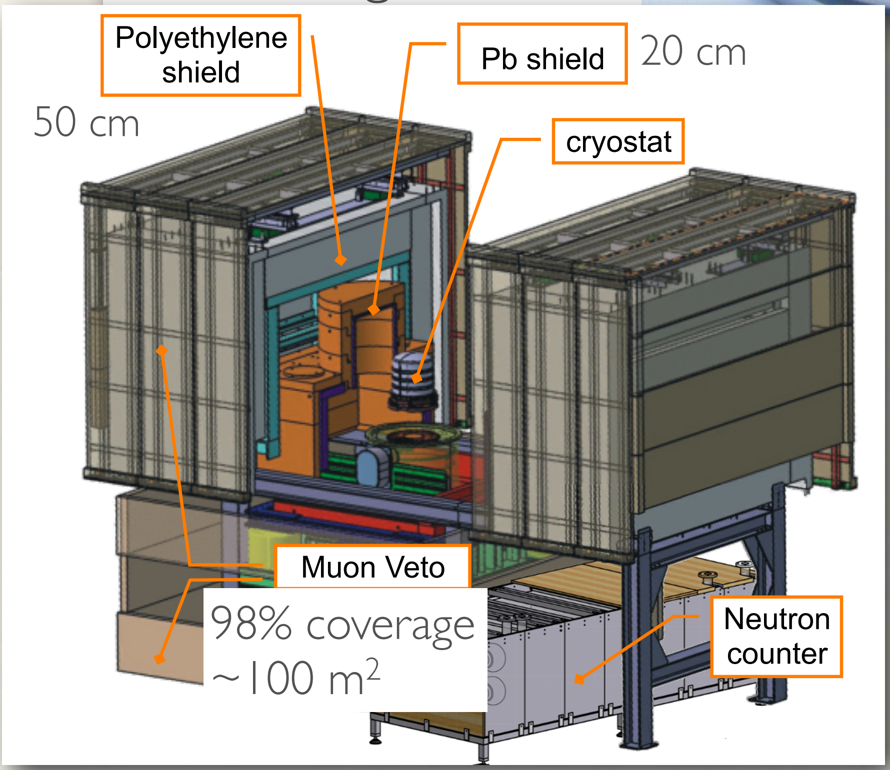


phonon timing pulse information still possible

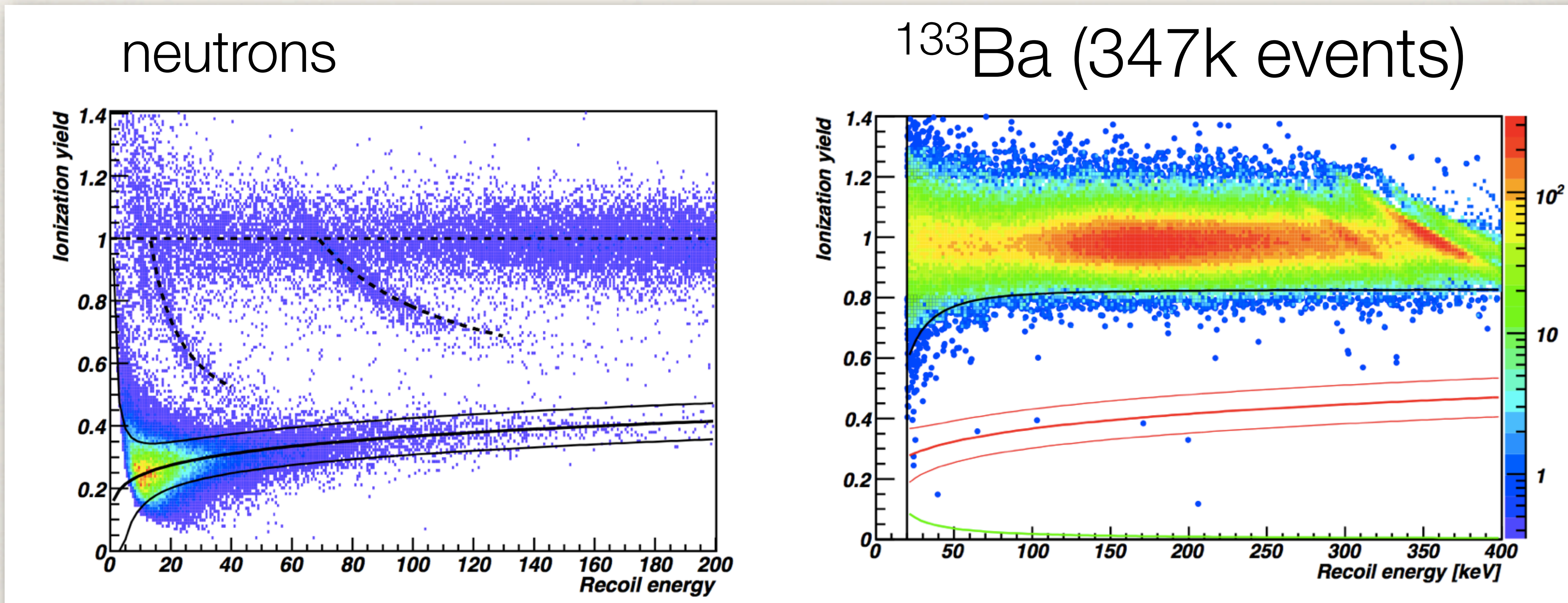
EDELWEISS II

- Located in the Laboratoire Souterrain de Modane (LSM) between Italy and France.
- Similar to CDMS II, except phonon signal is measured by an NTD thermal sensor.
- 10 x 400 g Ge detectors operated from 2008 - 2010





EDELWEISS II

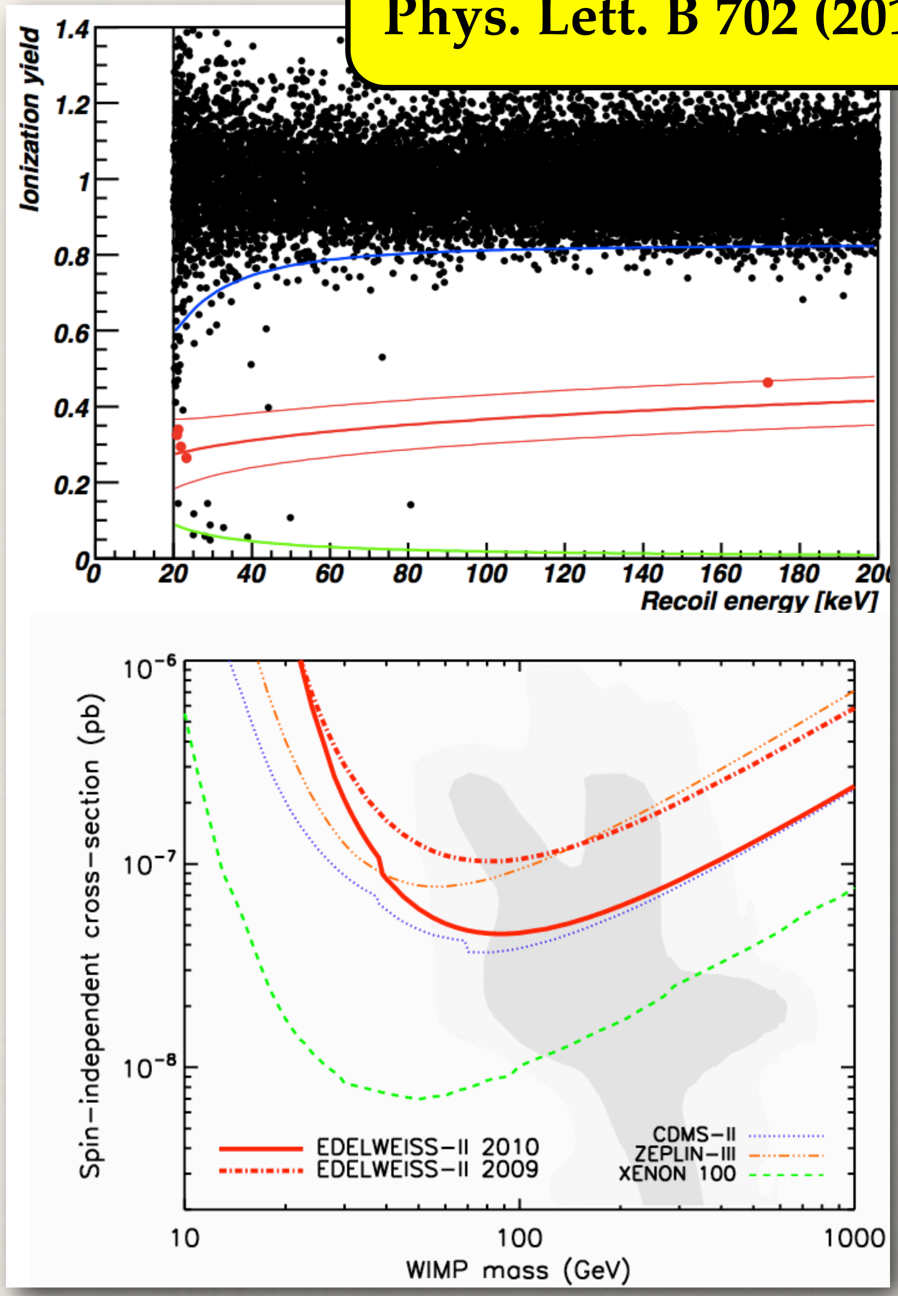


- Discrimination between nuclear recoils (signal) and electron recoils (background) by simultaneous measurement of charge and phonons.

EDELWEISS II Results

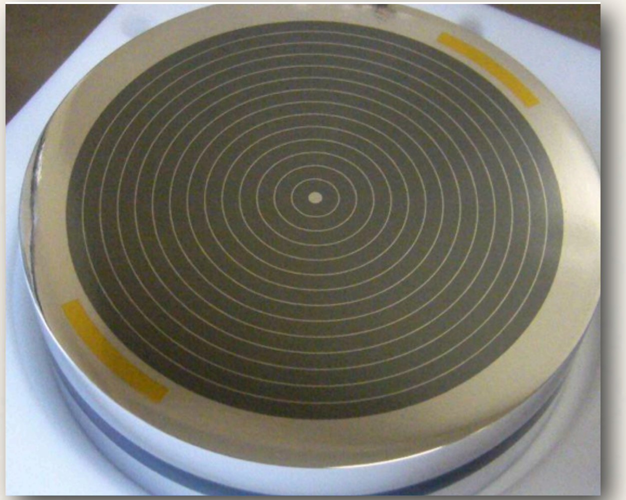
- Final results from 427 kg days.
- 5 events observed in the nuclear recoil band, expected background 3 events
- Upper limit at 90% C.L. on the WIMP-nucleon cross section is 4.4 x 10^{-8} pb (4.4 x 10^{-44} cm^2) for WIMPs of mass 85 GeV/c^2.
- Assumes standard WIMP Halo model and spin independent interactions.

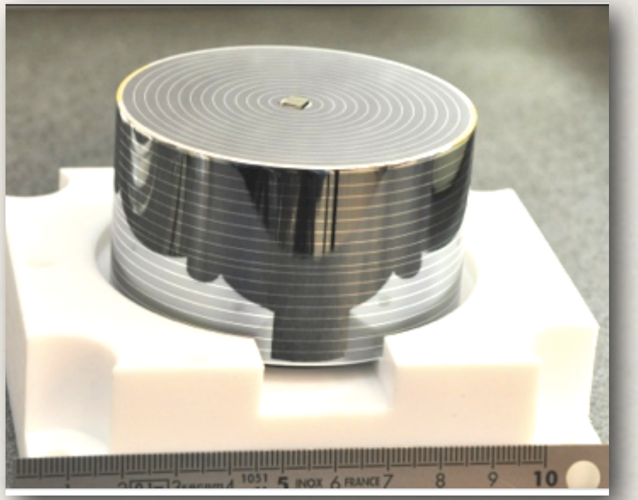
Phys. Lett. B 702 (2011) 335-329

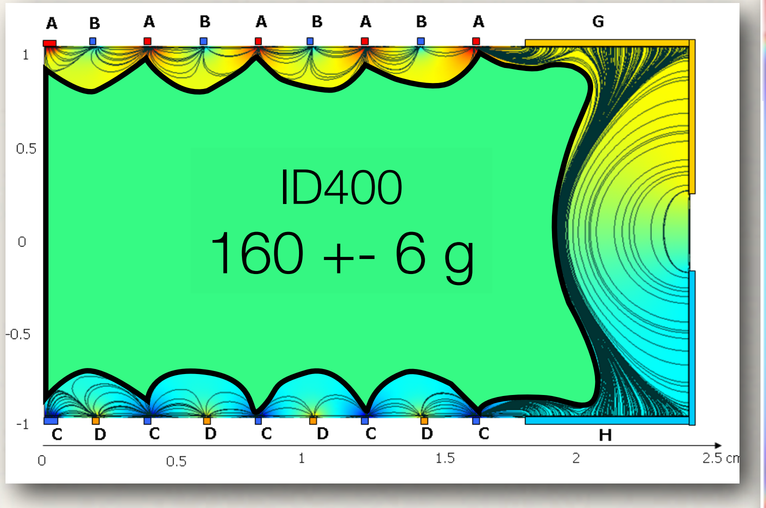


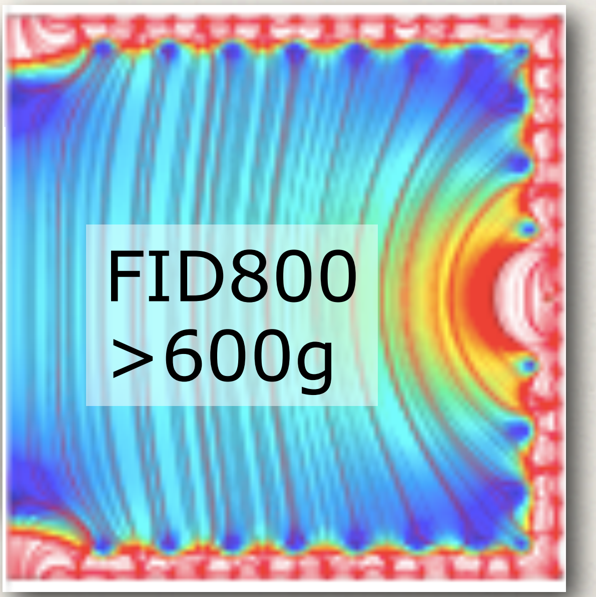
EDELWEISS III

- Goal to obtain 3000 kg-days of exposure.
  - New interdigitized ZIPs
  - Increased detector mass (400 - 800 g)
- Explore low mass region
- Reduce background by factor of 10
  - Shielding, material selection
  - better surface rejection



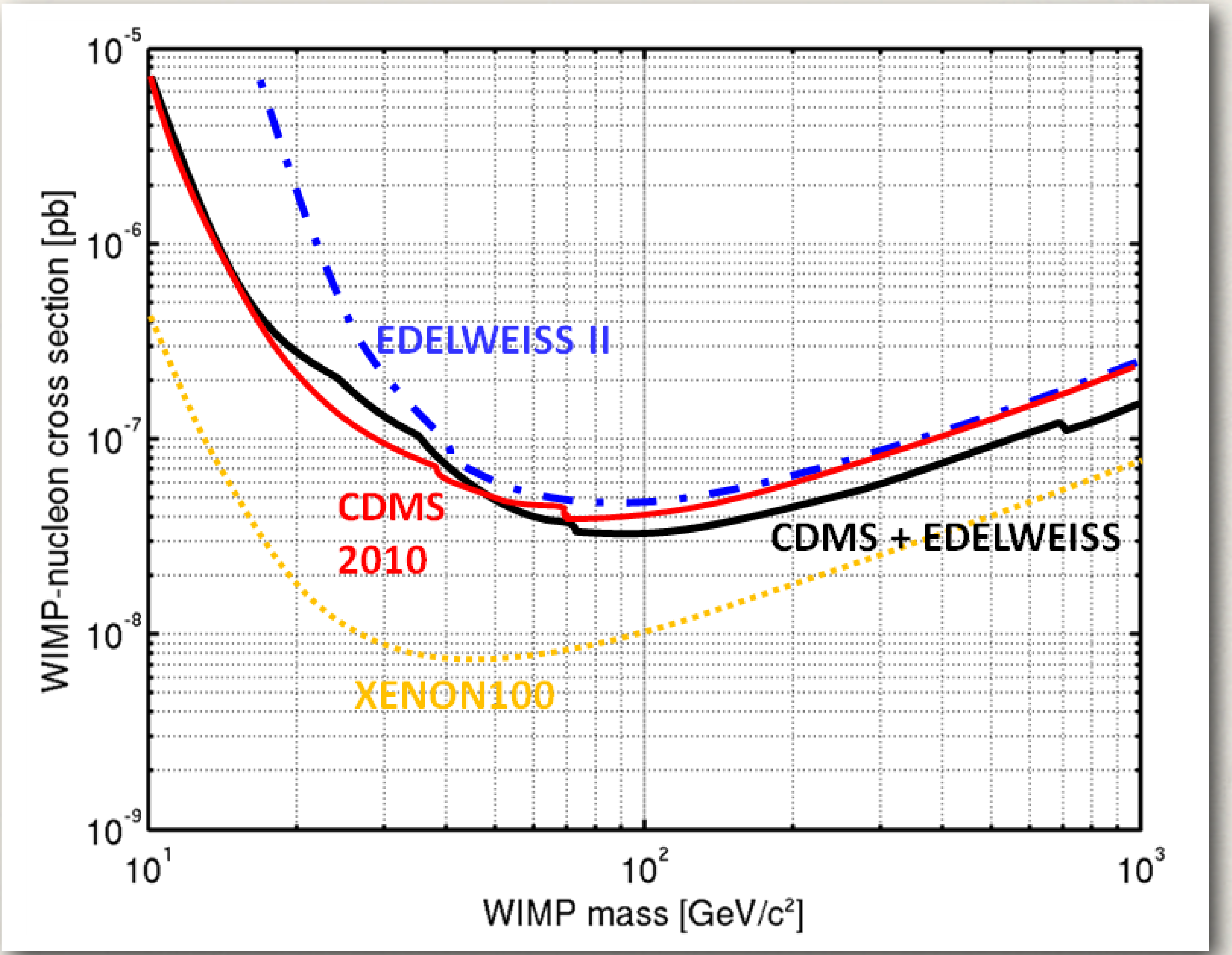




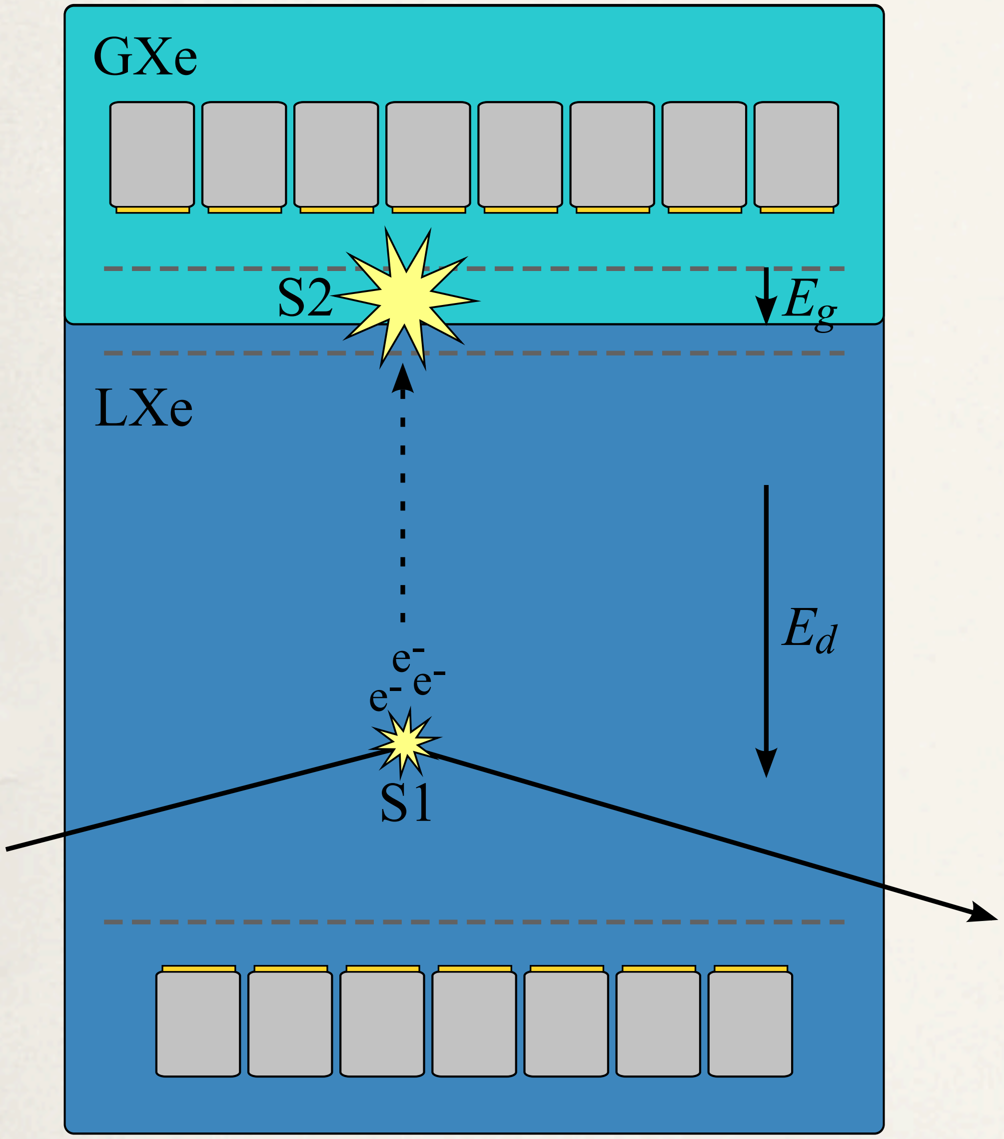


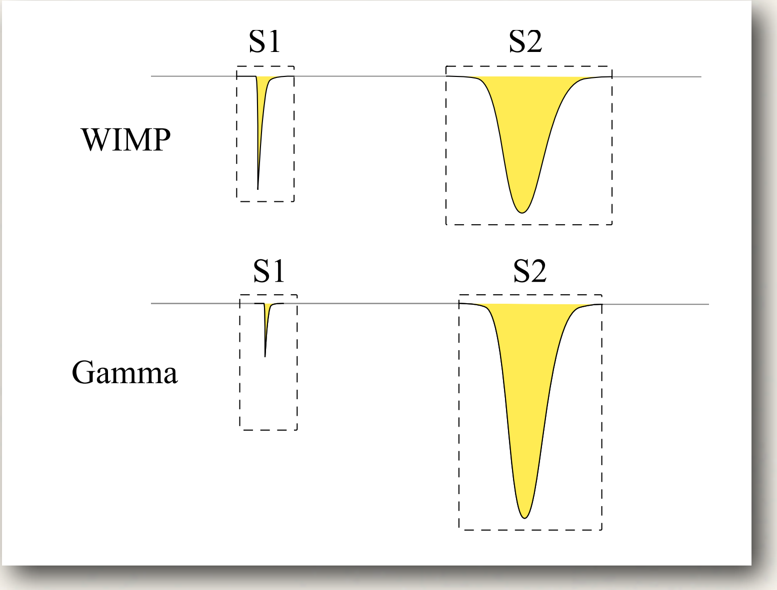
CDMS II - EDELWEISS Joint Analysis

- Edelweiss and CDMS use similar detector technologies.
- Prior to combining the analyses, it was decided to add the candidate lists and exposures together.



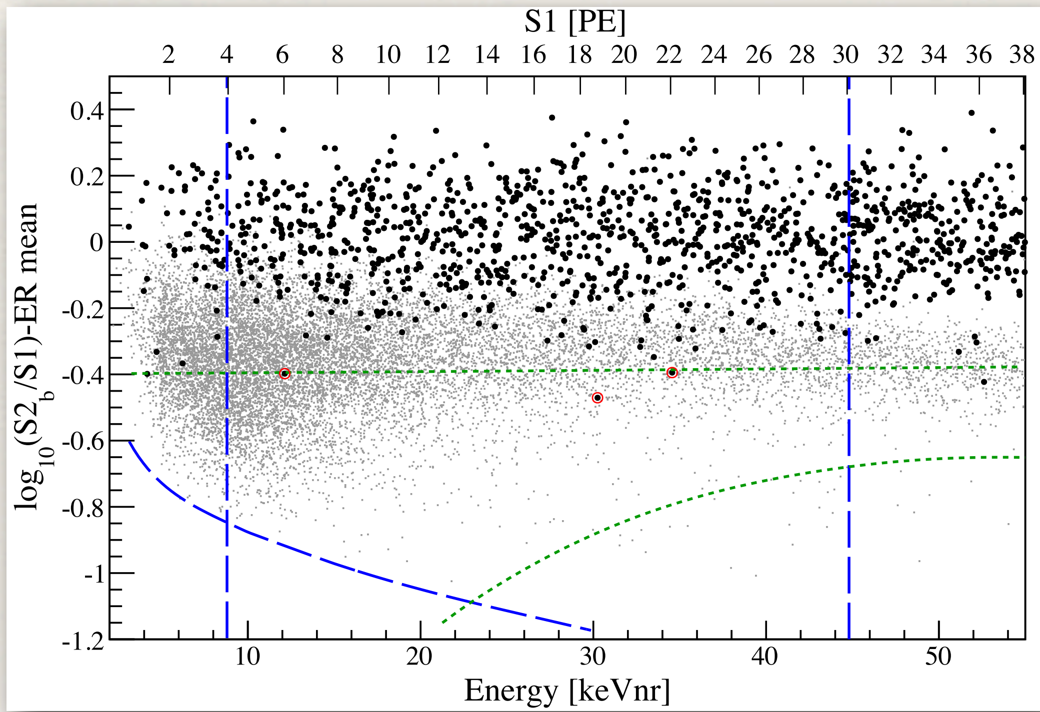
XENON - Detection Principle

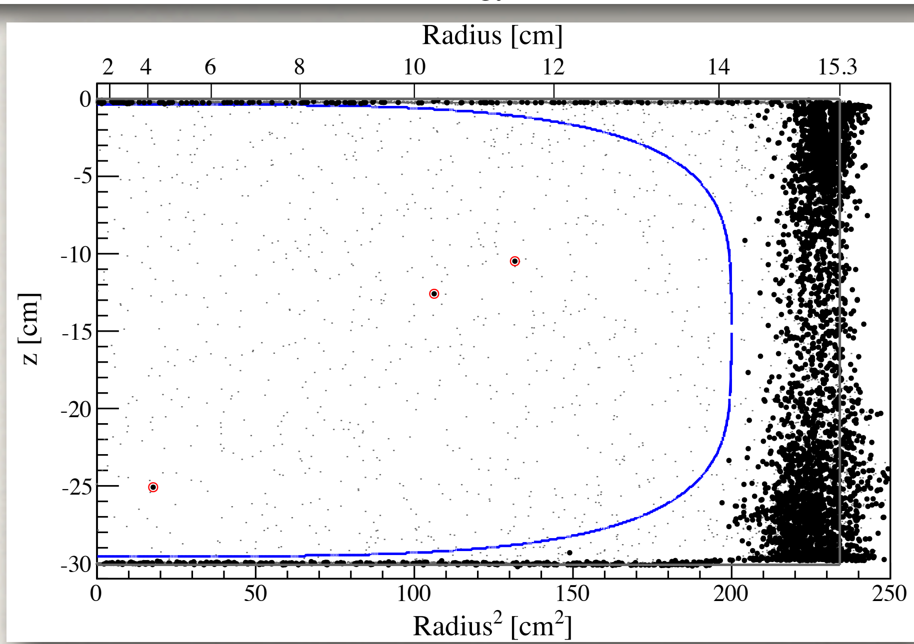




- Two phase TPC detector - bottom PMTs immersed in LXe, detect S1
- Top PMTs in GXe detect S2
- Distribution of S2 give xy coordinates, drift time gives z coordinates
- Ratio of S2/S1 discriminates electron and nuclear recoils

XENON 100 Results

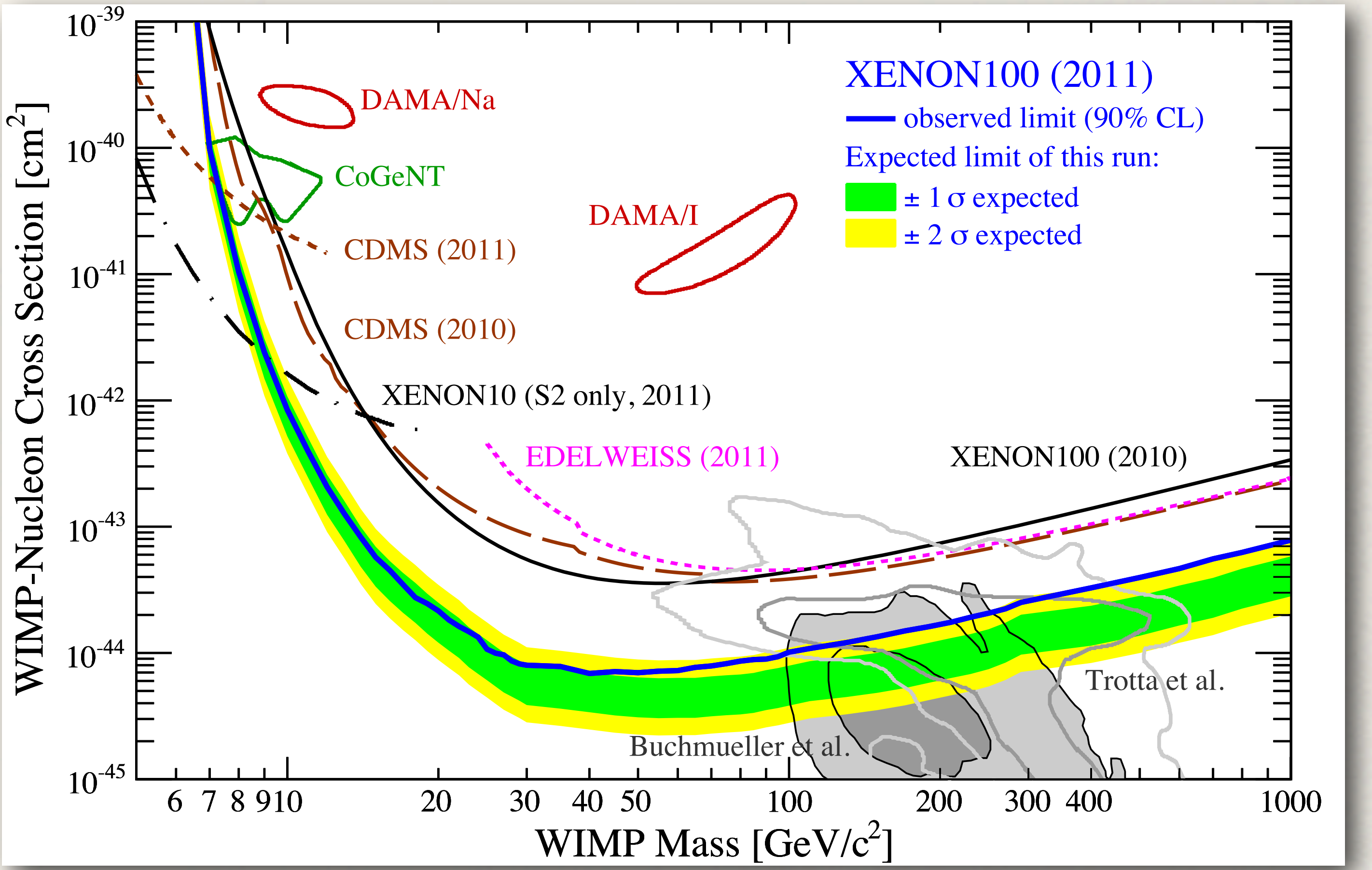




- 100.9 live days acquired from Jan - June 2010.
- Fiducial mass 48 kg liquid Xe
- 3 events observed with a predicted background of 1.8 ± 0.6 gamma events and 0.1 ± 0.08 ± 0.04 neutron event
- Grey dots indicate nuclear recoil region measured by neutrons from ^{241}AmBe source

XENON100

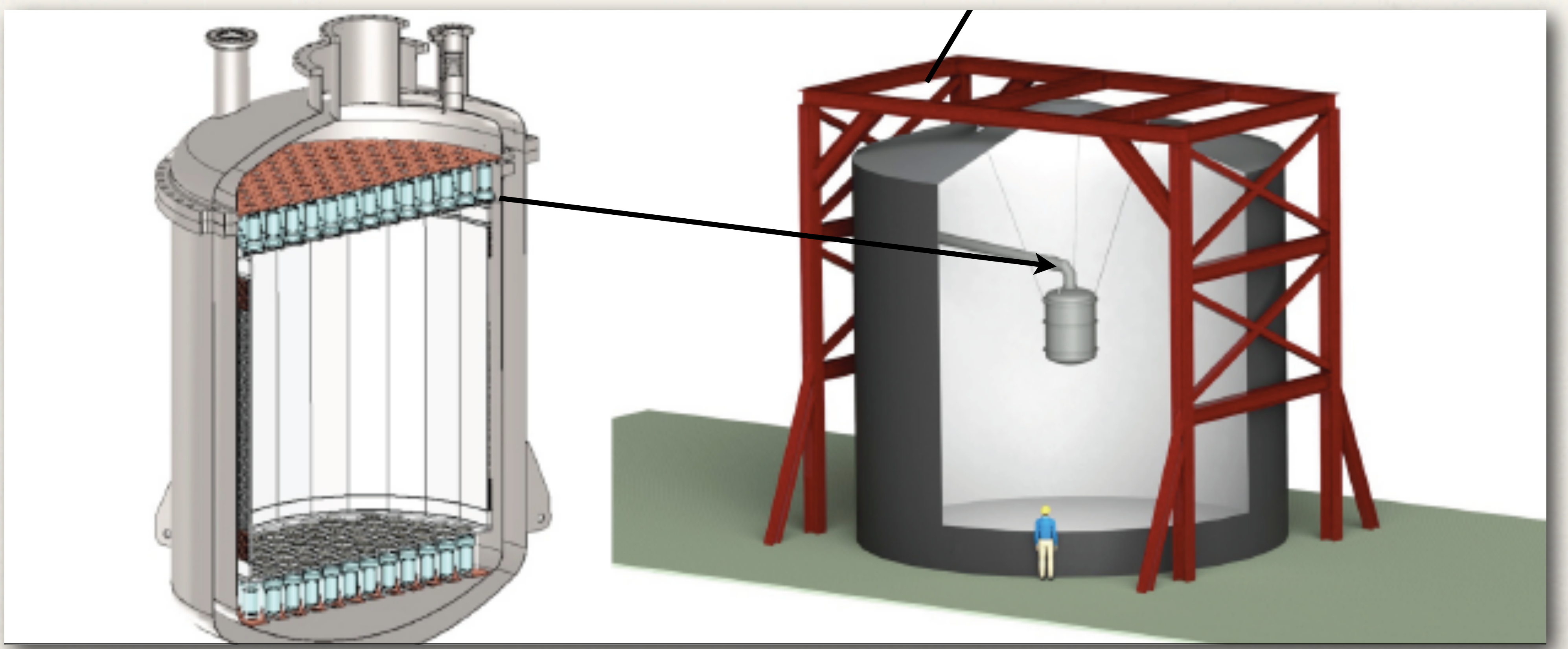
- Upper limit at 90% C.L. on the WIMP-nucleon cross section is 7.0×10^{-45} cm^2 for WIMPs of mass 50 GeV/c^2.
- XENON100 continues to acquire data!



More details: Talk by Alfonsi later today!

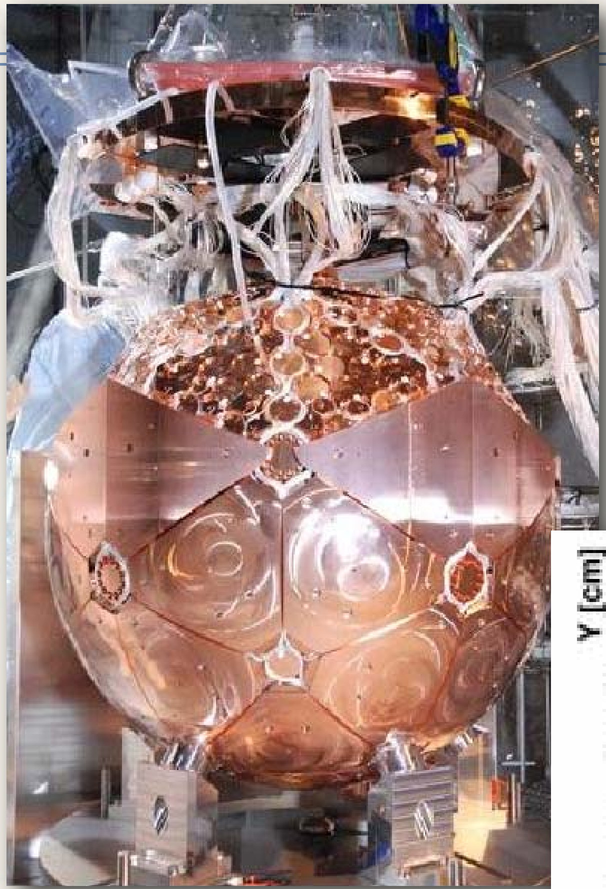
XENON 1T

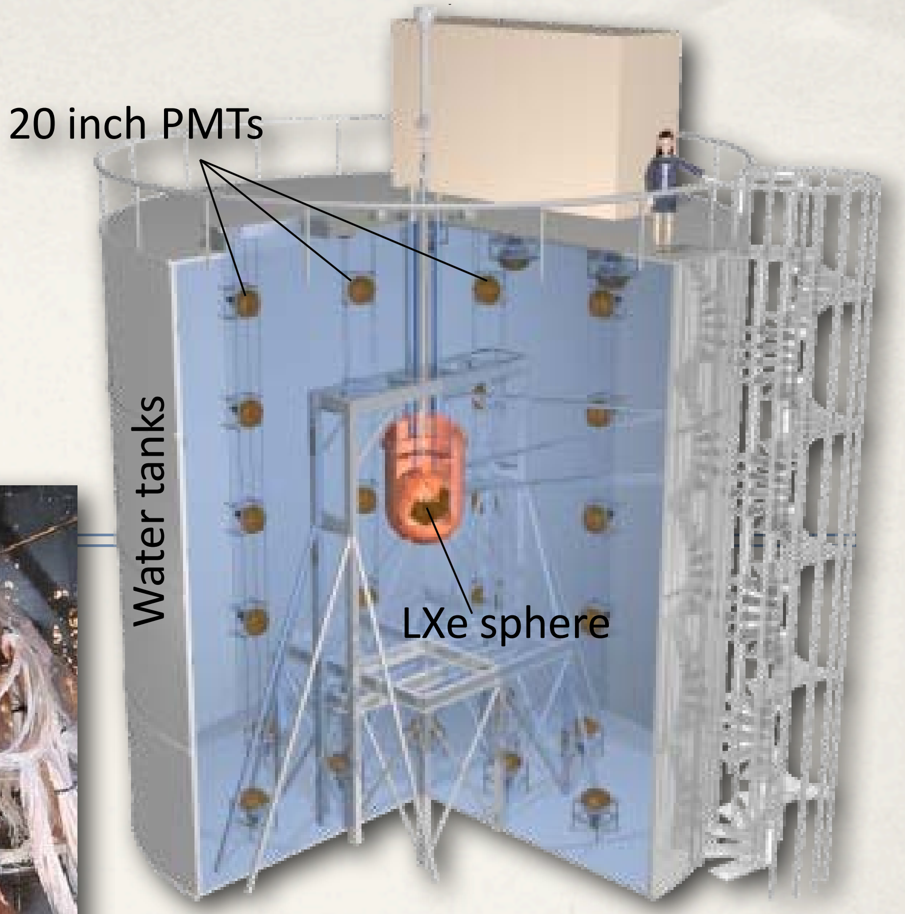
- 2.2 ton LXe TPC with 1 ton fiducial mass.
- 10 m water shield (muon veto)
- Approved by INFN for installation at LNGS
- Majority of funding secured.
- Construction start 2012
- Science data projected to start in 2015.
- Projected sensitivity 2 x 10^{-47} cm^2 after 2 years



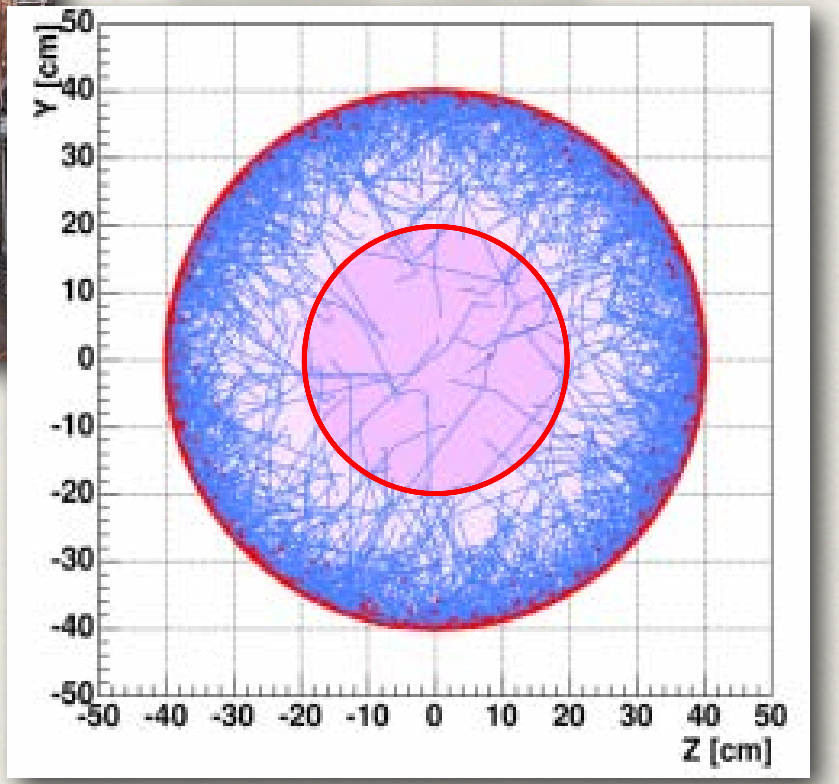
XMASS

- Single phase LXe detector located in the Kamioka Underground Observatory, Japan. Construction finished in late 2010.
- Water tank acts as an active muon veto.
- Key concept to background discrimination is “self-shielding”. Gamma particles are absorbed in the outer region of the liquid xenon.
- WIMPs and neutrons are evenly distributed thoughout volume.
- Recent science run revealed unexpected alpha background





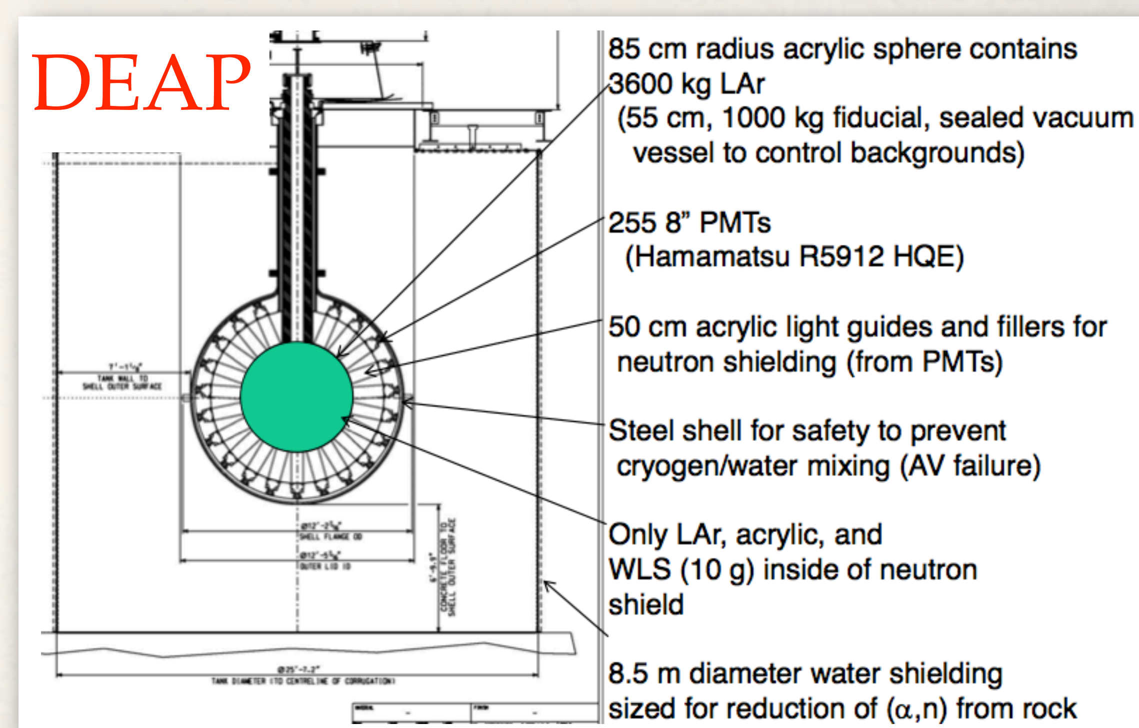
Simulation: γ into LXe



J. Liu TAUP 2011

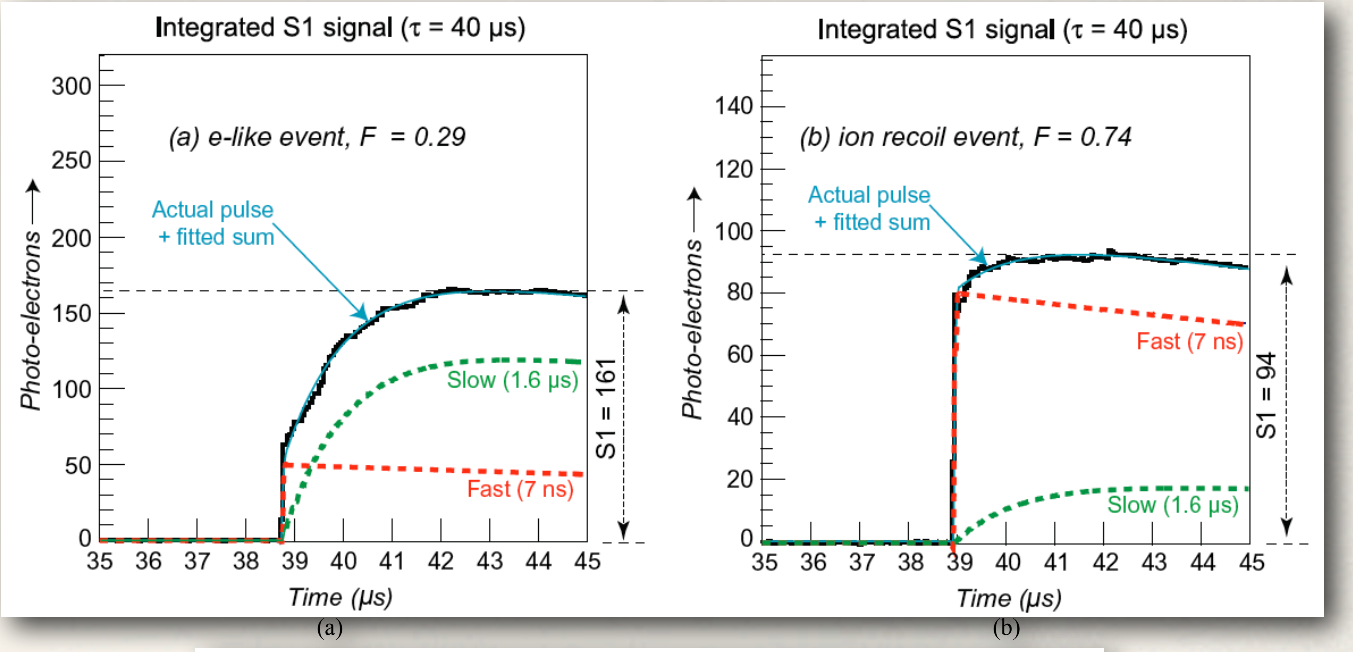
DEAP/CLEAN

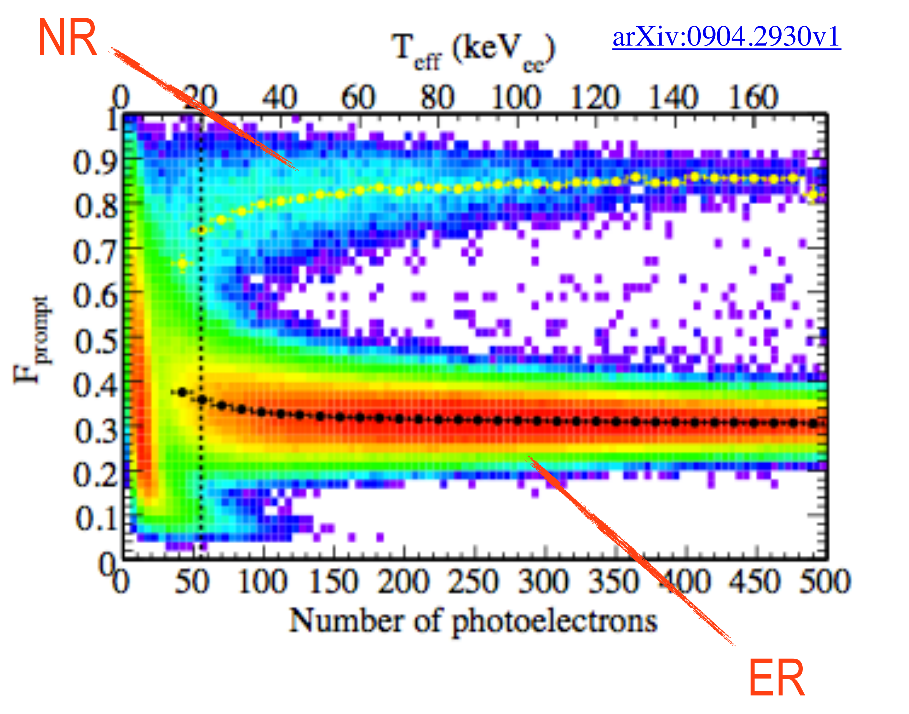
- Single phase LAr detector.
- MiniCLEAN (150 kg fiducial)
  - Construction (2012 - 2012)
  - Science run (2012 - 2014)
  - Sensitivity ~ 2 x 10^{-45} cm^2
- DEAP 3600 (1 tonne fiducial).
  - Construction (2010 - 2013)
  - Science run 2013 - 2017
  - Sensitivity ~ 1 x 10^{-46} cm^2
- DEAP/CLEAN (10 tonne fiducial)
  - Sensitivity ~ 1 x 10^{-47} cm^2



DEAP/CLEAN

- Discrimination between background and signal comes from pulse shape.
  - Excited atoms decay to ground state through formation of single or triplet excimer states which have different decay times.
  - 70% of excimer states created by nuclear recoils are singlets
  - 30% of excimer states created by electron recoils are triplets





Many Experiments -- Little Time

PANDA X

A LXe Dark Matter Experiment at the Jinping Underground Laboratory

PICASSO

LUX

SIMPLE

DMTPC

ZEPLIN-III

COUPP

The Chicagoland Observatory for Underground Particle Physics

DM-Ice

DarkSide

KIMS

ANAIS

CDEX-TEXONO

Future: Very Large ~~Detectors~~ Observatories

DARWIN

SuperCDMS SNOLAB

GEODM

MAX
Multi-Ton Argon & Xenon

LZ

EURECA

Summary and Outlook

- Dark matter experimentalists have come up with clever techniques to suppress backgrounds in an attempt to extract a dark matter signal.
- Three experiments have seen excess events. If these events are interpreted as dark matter it is difficult to reconcile their results.
- Several experiments have excluded the dark matter interpretation under standard assumptions of the excess seen by these experiments at the 90% C.L. or better.
- It is necessary to have several technologies in different locations.
- There are many experiments using different techniques currently running world wide. The techniques employed include solid-state devices, two-phase and single-phase noble liquid detectors, superheated detectors.
- There are many planned upgrades and extensions to existing experiments to achieve greater sensitivity.
- It is an exciting time to be working in this field!