Direct Dark Matter Detection

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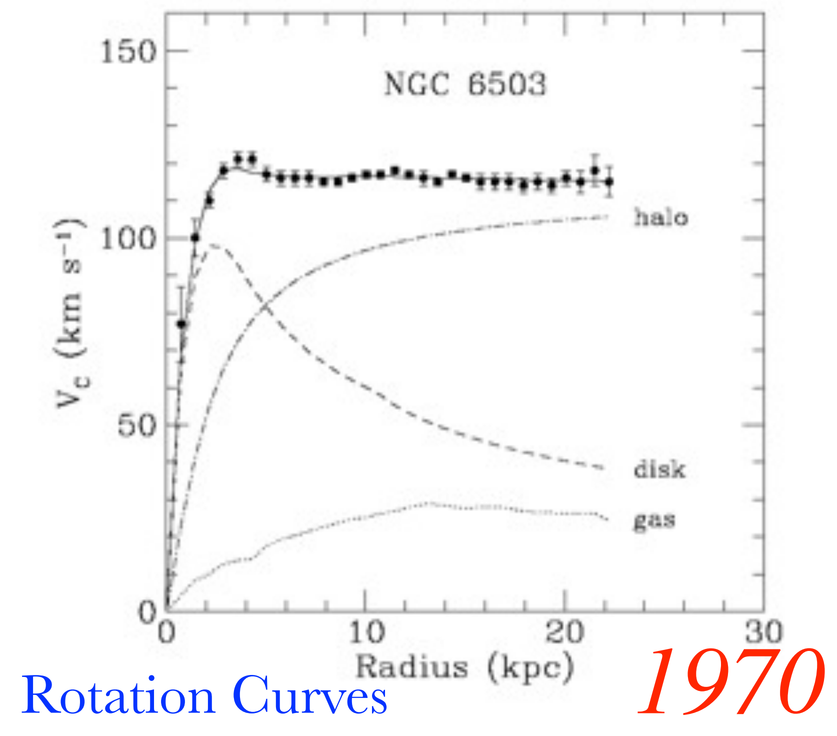
Outline

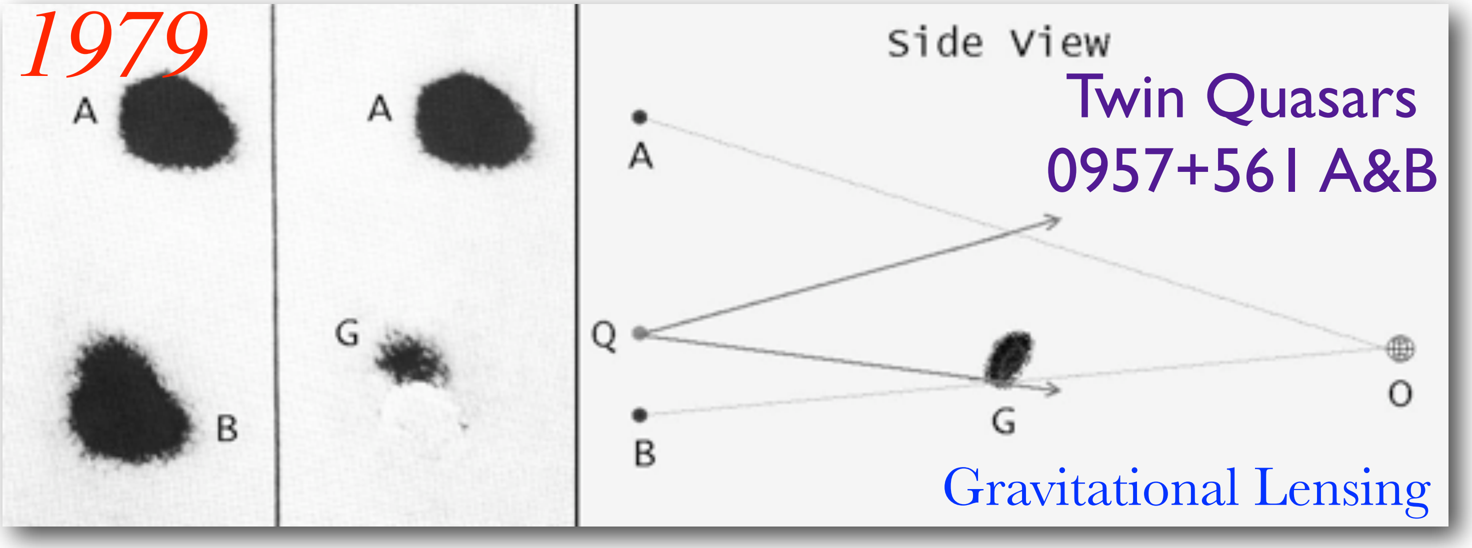
- Part 1: General Principles
    - Rates, backgrounds, signals, etc
- Part 2: Direct Detection Searches
    - Liquid Nobles
    - Cryogenic Detectors
    - Other Novel Technologies

Further Reading

- Classic Papers on specific calculations
  - Lewin, Smith, Astroparticle Physics 6 (1996) 87-112
  - Kurylov and Kamionkowski, Physical Review D 69, 063503 (2004)
  - G. Jungman, M. Kamionkowski, K. Griest, Phys. Rep. 267 (1996) 195-373, arXiv:hep-ph/9506380
- Books/Special Editions that Overview the Topic of Dark Matter
  - Bertone, Particle Dark Matter Observations, Models and Searches, Cambridge University Press, 2010. ISBN 978-0-521-76368-4
  - Physics of the Dark Universe, vol 1, issues 1-2, Nov. 2012 (http://www.journals.elsevier.com/physics-of-the-dark-universe/)

Evidence of Existance



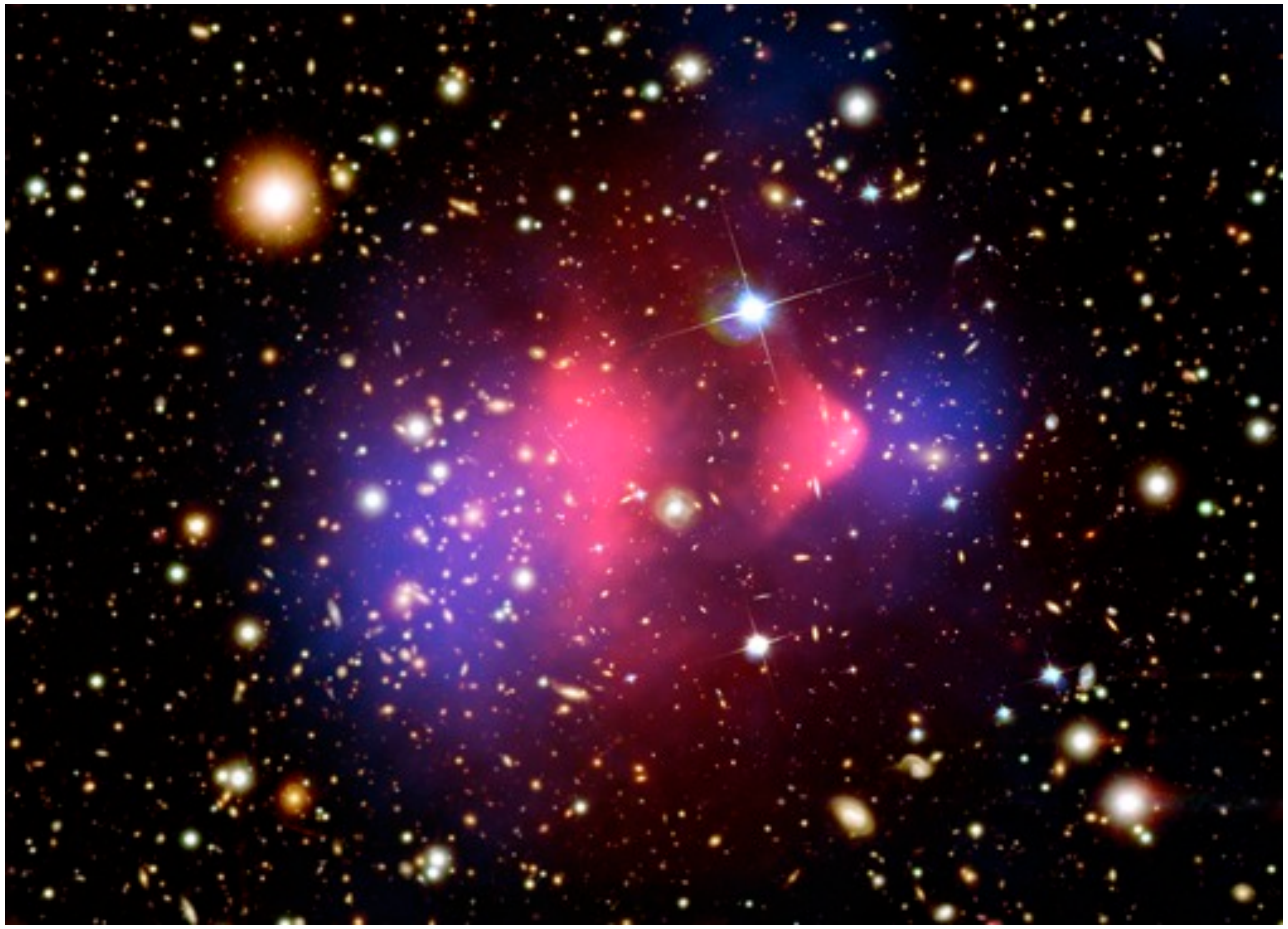


Evidence of the existence of dark matter comes from it's gravitational effects.

Particle Nature

- Observations of the Bullet Cluster in the optical and x-ray fields combined with gravitational lensing provide compelling evidence that the dark matter is particles.

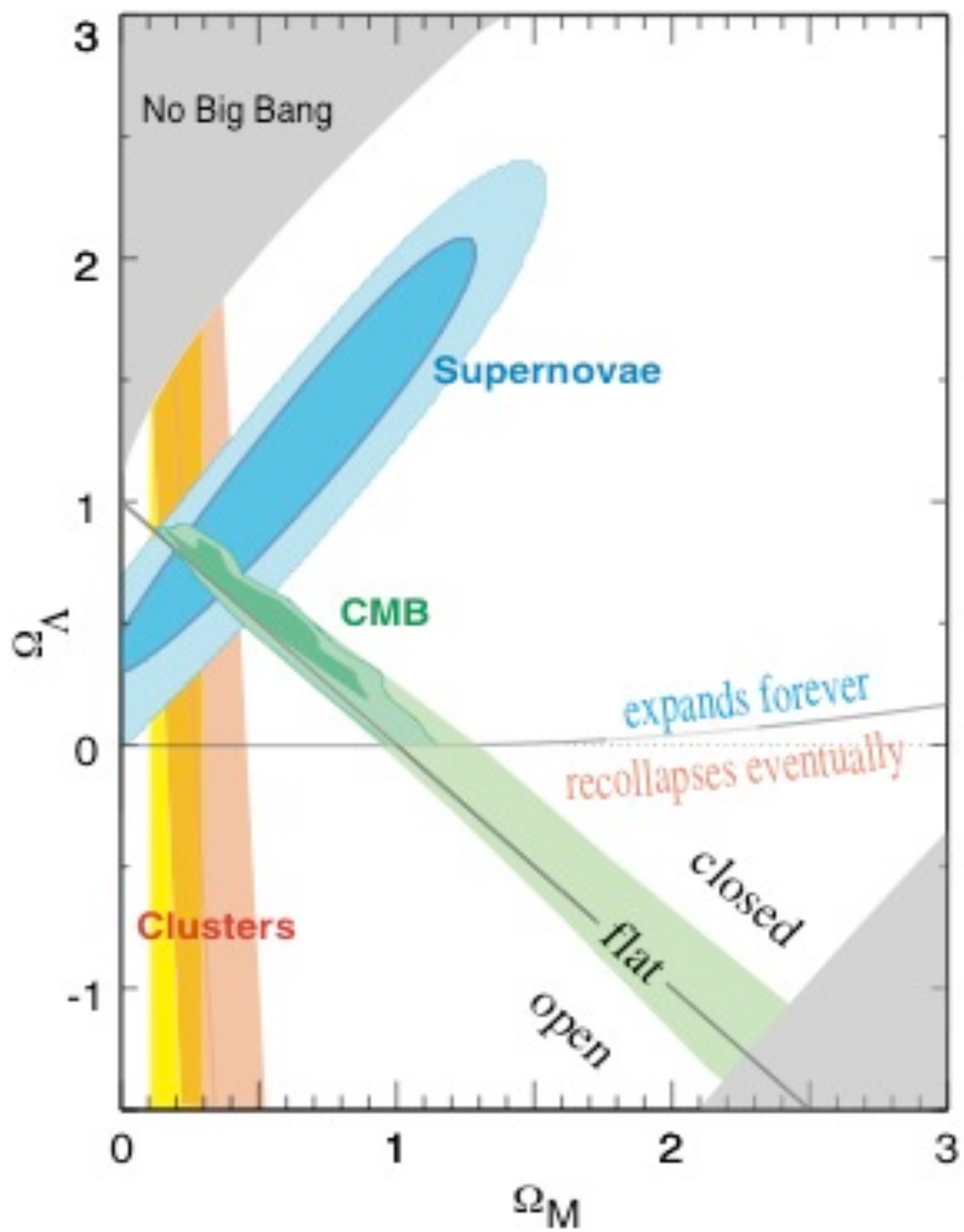
- Gravitational lensing tells us mass location
  - No dark matter = lensing strongest near gas
  - Dark matter = lensing strongest near stars

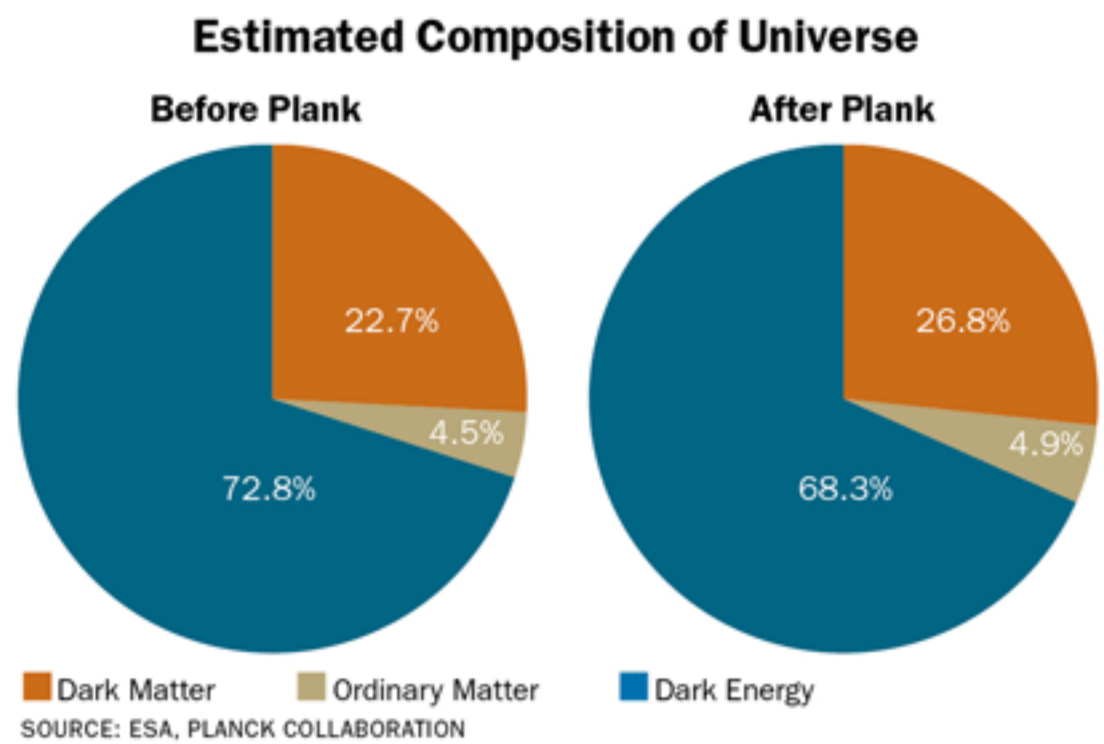


Clowe et al., ApJ, 648, 109

blue = lensing
red = x-rays

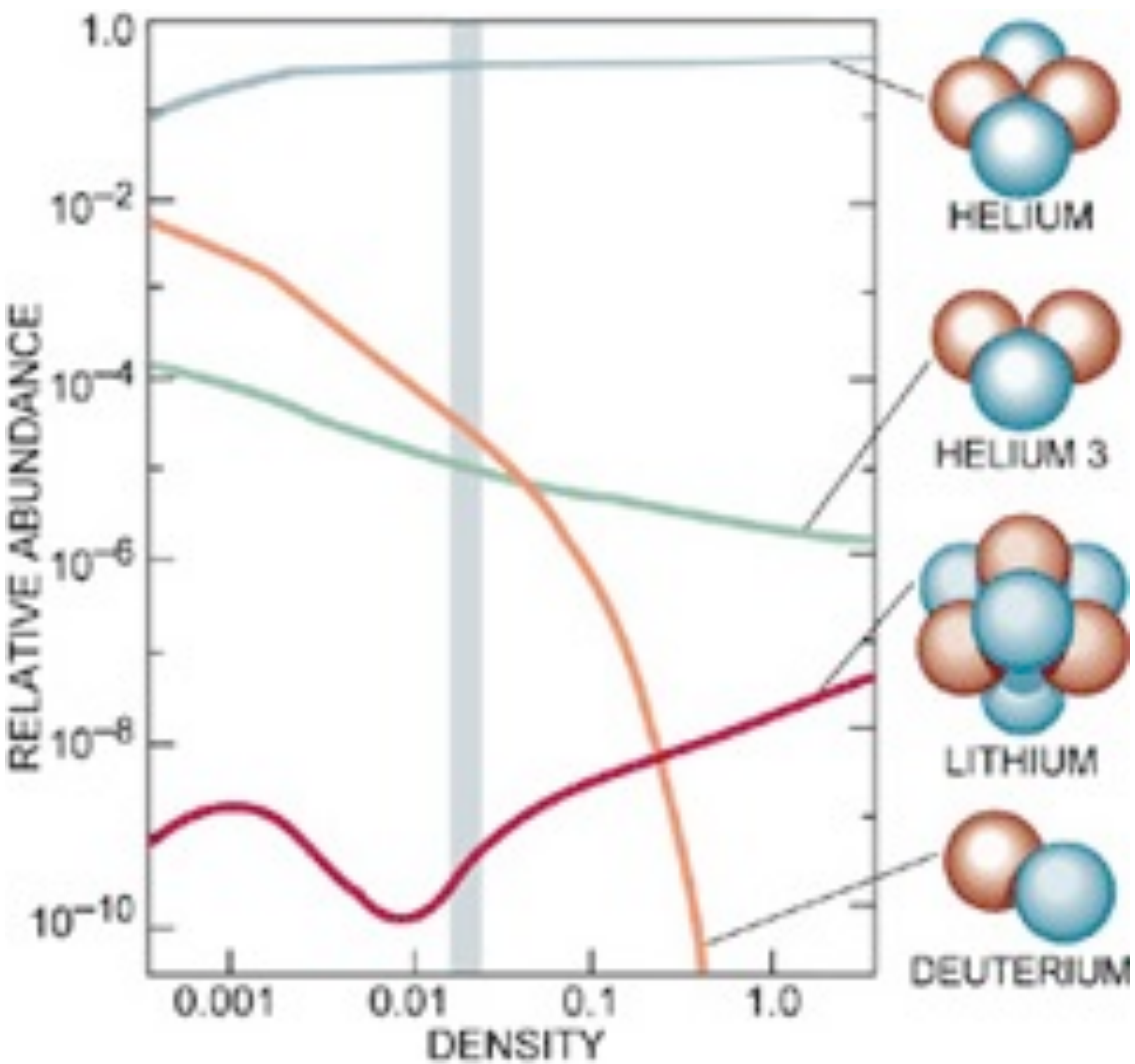
Cosmic Pie





Measurements from CMB + supernovae + LSS indicate that ~ a quarter of our Universe is composed of dark matter.

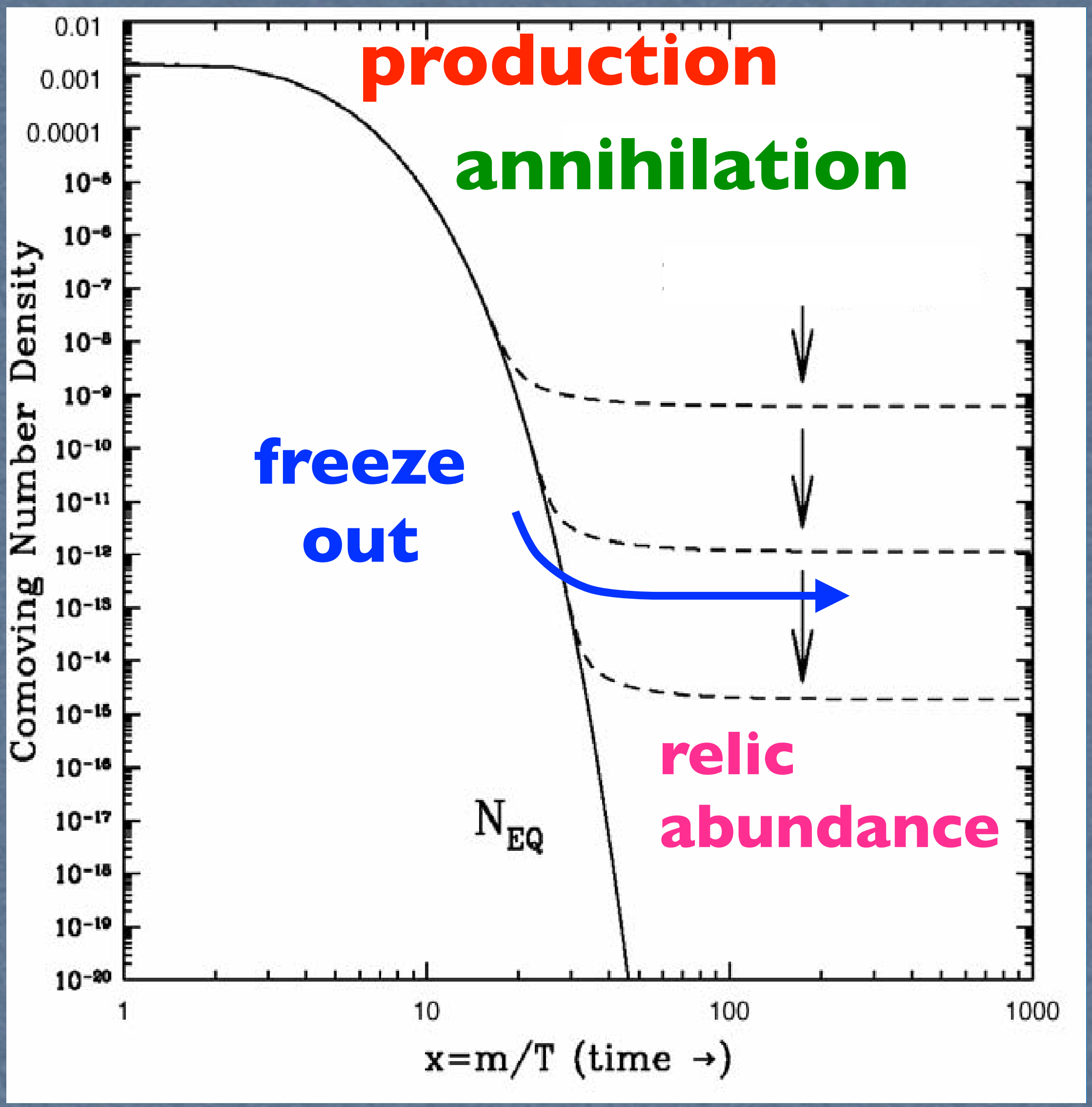
What Could Dark Matter Be?



- Warm or **Cold**?
  - ordinary vs can not make up LSS of universe

- Baryonic or **Non-Baryonic**?
  - to avoid skewing formation of light elements in BBN

Motivated Candidate



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

Weakly **I**nteracting **M**assive **P**articles

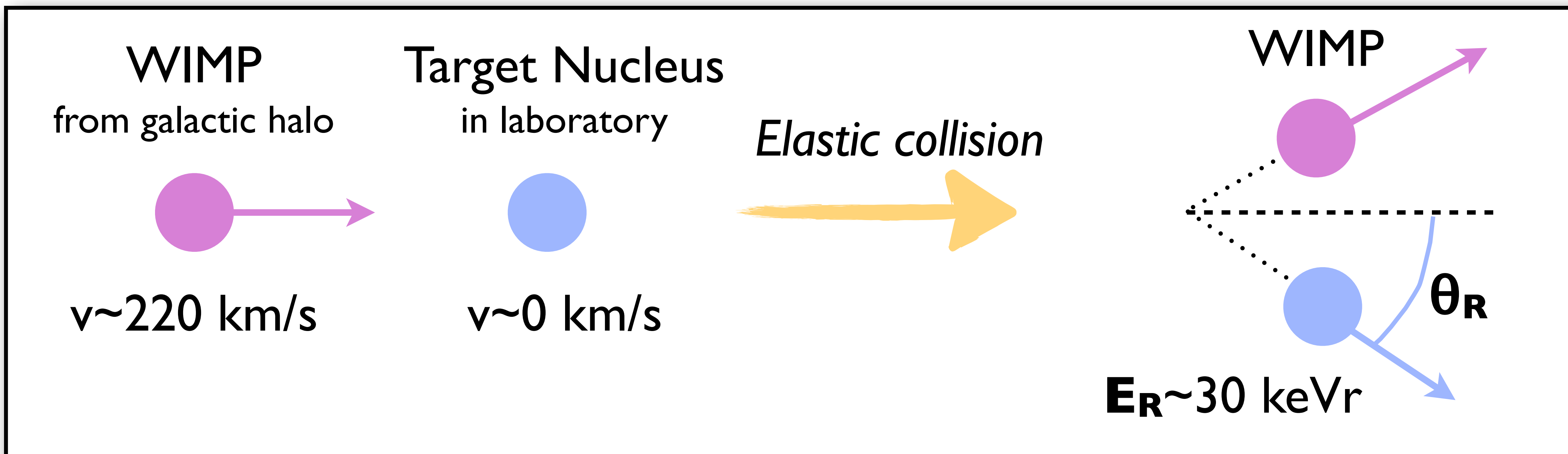
- New stable, **massive** particle produced thermally in early universe
- **Weak-scale** cross-section gives observed relic density

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

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

Direct Detection Rates

Assume that the dark matter is not only gravitationally interacting (WIMP).



- Elastic scatter of a WIMP off a nucleus
  - Imparts a small amount of energy in a recoiling nucleus
  - Can occur via spin-dependent or spin-independent channels
  - Need to distinguish this event from the overwhelming number of background events

Event Rate: Simplified WIMP

The differential event rate for simplified WIMP interaction is given by:

event rate

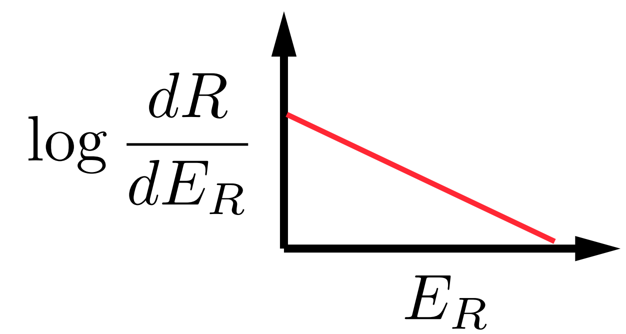
total event rate

$$\frac{dR}{dE_R} = \frac{R_0}{E_0 r} e^{-E_R/E_0 r}$$

recoil energy

most probable incident energy

kinematic factor



$$\boxed{r = \frac{4M_\chi M_N}{(M_\chi + M_N)^2}}$$

If we integrate

$$\int_0^\infty \frac{dR}{dE_R} dE_R = R_0$$

and

$$< E_R >= \int_0^\infty E_R \frac{dR}{dE_R} dE_R = E_0 r$$

Event Rate: Calculation

Let's plug in some numbers and see what we get.

$$M_\chi = M_N = 100 \text{ GeV}/c^2$$

The resulting kinematic factor is

$$r = \frac{4M_\chi M_N}{(M_\chi + M_N)^2} = \frac{4(100)(100)}{(100+100)^2} = 1$$

For a WIMP with velocity 220 km/s

$$\beta = v/c \sim 0.73 \times 10^{-3}$$

Recoil Energy is then given by

$$E_R = E_0 r = \frac{1}{2}M_\chi \beta^2 c^2 = \frac{1}{2}(100\frac{GeV}{c^2})(0.73 \times 10^{-3})^2 c^2$$

$$E_R = 27 \text{ keV}$$

Event Rate

The differential event rate:

[counts kg^{-1} day^{-1}] $\longrightarrow$ (dru = differential rate unit)

need input from astrophysics, particle physics and nuclear physics

local WIMP density

WIMP-nucleon scattering cross section

$$\boxed{\frac{dR}{dE_R} = \frac{\rho_0}{m_N m_\chi}\int_{v_{min}}^{\infty} v f(v)\frac{d\sigma}{dE_R}(v, E_R)dv}$$

nucleus mass

WIMP mass

WIMP speed distribution in detector frame

Minimum WIMP velocity which can cause a recoil of energy E_R.

$$\boxed{v_{min} = \sqrt{\frac{E_R m_N}{2\mu^2}}}$$

Elastic scattering happens in the extreme non-relativistic case in the lab frame

$$\boxed{E_R = \frac{\mu_N^2 v^2 (1 - \cos\theta^*)}{m_N}}$$

where

$$\mu = \frac{m_\chi m_N}{m_\chi + m_N}$$

reduced mass

WIMP-Nucleon Interaction

Event rate is found by integrating over all recoil:

$$\boxed{R = \int_{E_T}^{\infty} dE_R \frac{\rho_0}{m_N m_\chi} \int_{v_{min}}^{\infty} v f(v) \frac{d\sigma}{dE_R}(v, E_R) dv}$$

Minimum WIMP velocity which can cause a recoil of energy E_R.

$$v_{min} = \sqrt{\frac{E_R m_N}{2\mu^2}}$$

The WIMP-nucleon cross section can be separated

$$\frac{d\sigma}{dE_R} = \underbrace{(\frac{d\sigma}{dE_R})_{SI}}_{\text{Spin-independent}} + \underbrace{(\frac{d\sigma}{dE_R})_{SD}}_{\text{Spin-dependent}}$$

SI arise from scalar or vector couplings to quarks.

SD arise from axial vector couplings to quarks.

To calculate add coherently the spin and scalar components:

$$\boxed{\frac{d\sigma}{dE_R} = \frac{m_N}{2\mu^2 v^2}[\underbrace{\sigma_{SI} F_{SI}^2(E_R)}_{\text{Spin-independent term}} + \underbrace{\sigma_{SD} F_{SD}^2(E_R)}_{\text{Spin-dependent term}}]}$$

$F(E_R)$ = Form Factor encodes the dependence on the momentum transfer

WIMP-Nucleon Interaction

WIMP-nucleus cross sections:

$$\sigma_{SI} = \frac{4\mu^2}{\pi}\left[Zf_p + (A-Z)f_n\right]^2 \propto A^2$$

best sensitivity with high A

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

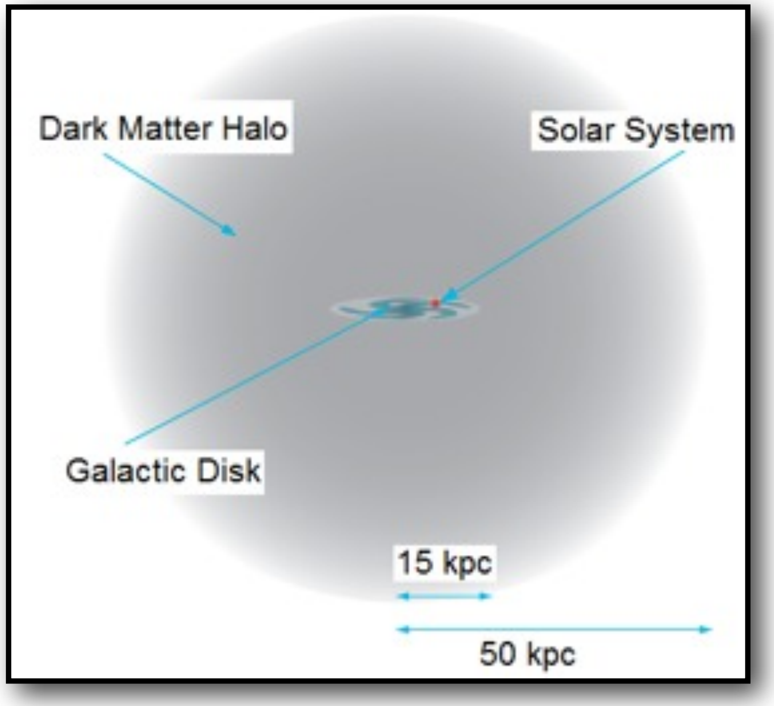
need a nucleus with spin

Nucleus	Z	Odd Nucleon	J	$\langle S_p\rangle$	$\langle S_n\rangle$	C_A^p/C_p	C_A^n/C_n
^{19}F	9	p	1/2	0.477	-0.004	9.10×10^{-1}	6.40×10^{-5}
^{23}Na	11	p	3/2	0.248	0.020	1.37×10^{-1}	8.89×10^{-4}
^{27}Al	13	p	5/2	-0.343	0.030	2.20×10^{-1}	1.68×10^{-3}
^{29}Si	14	n	1/2	-0.002	0.130	1.60×10^{-5}	6.76×10^{-2}
^{35}Cl	17	p	3/2	-0.083	0.004	1.53×10^{-2}	3.56×10^{-5}
^{39}K	19	p	3/2	-0.180	0.050	7.20×10^{-2}	5.56×10^{-3}
^{73}Ge	32	n	9/2	0.030	0.378	1.47×10^{-3}	2.33×10^{-1}
^{93}Nb	41	p	9/2	0.460	0.080	3.45×10^{-1}	1.04×10^{-2}
^{125}Te	52	n	1/2	0.001	0.287	4.00×10^{-6}	3.29×10^{-1}
^{127}I	53	p	5/2	0.309	0.075	1.78×10^{-1}	1.05×10^{-2}
^{129}Xe	54	n	1/2	0.028	0.359	3.14×10^{-3}	5.16×10^{-1}
^{131}Xe	54	n	3/2	-0.009	-0.227	1.80×10^{-4}	1.15×10^{-1}

Tovey et al., PLB488 17 (2000)

Standard Halo Model

- Energy spectrum and rate depend on details of WIMP distribution in the dark matter halo.



- Local Dark Matter Density

$$\rho_0 \equiv \rho(r = R_0) = 0.3 \;\; \mathrm{GeV/cm^3}$$

- Speed Distribution - isotropic, Maxwellian

$$f(\vec{v}) = \frac{1}{\sqrt{2\pi}\sigma} exp(-\frac{|\vec{v}|^2}{2\sigma^2})$$

where

$$\sigma = \sigma_{rms} = \sqrt{\frac{3}{2}} v_0 = 270 \; \mathrm{km/s} \quad \text{and} \quad v_0 = 220 \; \mathrm{km/s}$$

This corresponds to an isothermal sphere with density profile

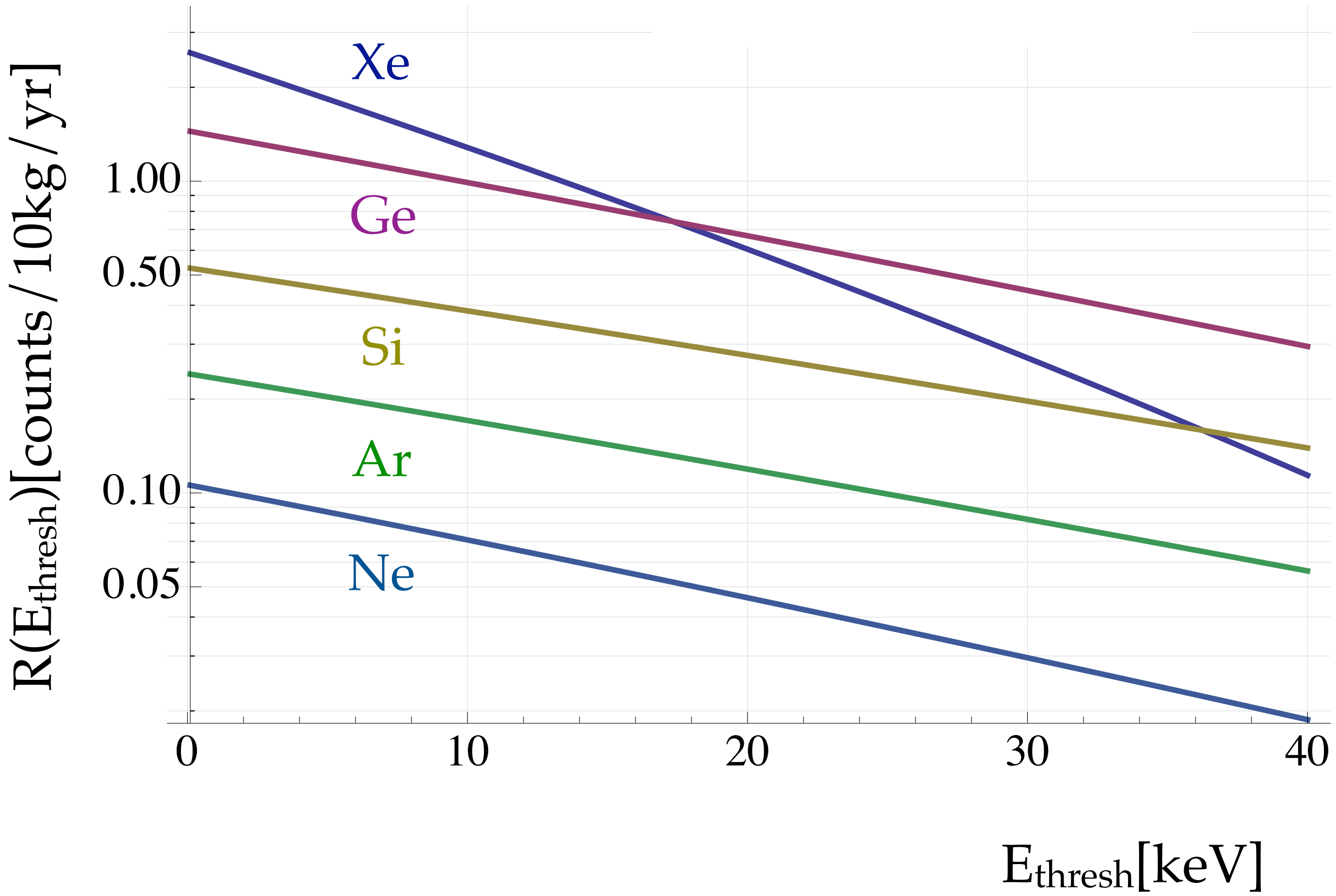
$$\rho \propto r^{-2}$$

- Note Particles with speed greater than the local escape speed are not gravitationally bound. The standard halo extends out to infinite radii and thus the speed distribution in this model must be truncated "by hand". We take v_{esc} = 650 km/s.

Event Rates

- Elastic scattering of WIMP deposits small amounts of energy into a recoiling nucleus (~few 10s of keV)
- Featureless exponential spectrum with no obvious peak, knee, break ...
- Event rate is very, very low.
- Radioactive background of most materials is higher than the event rate.

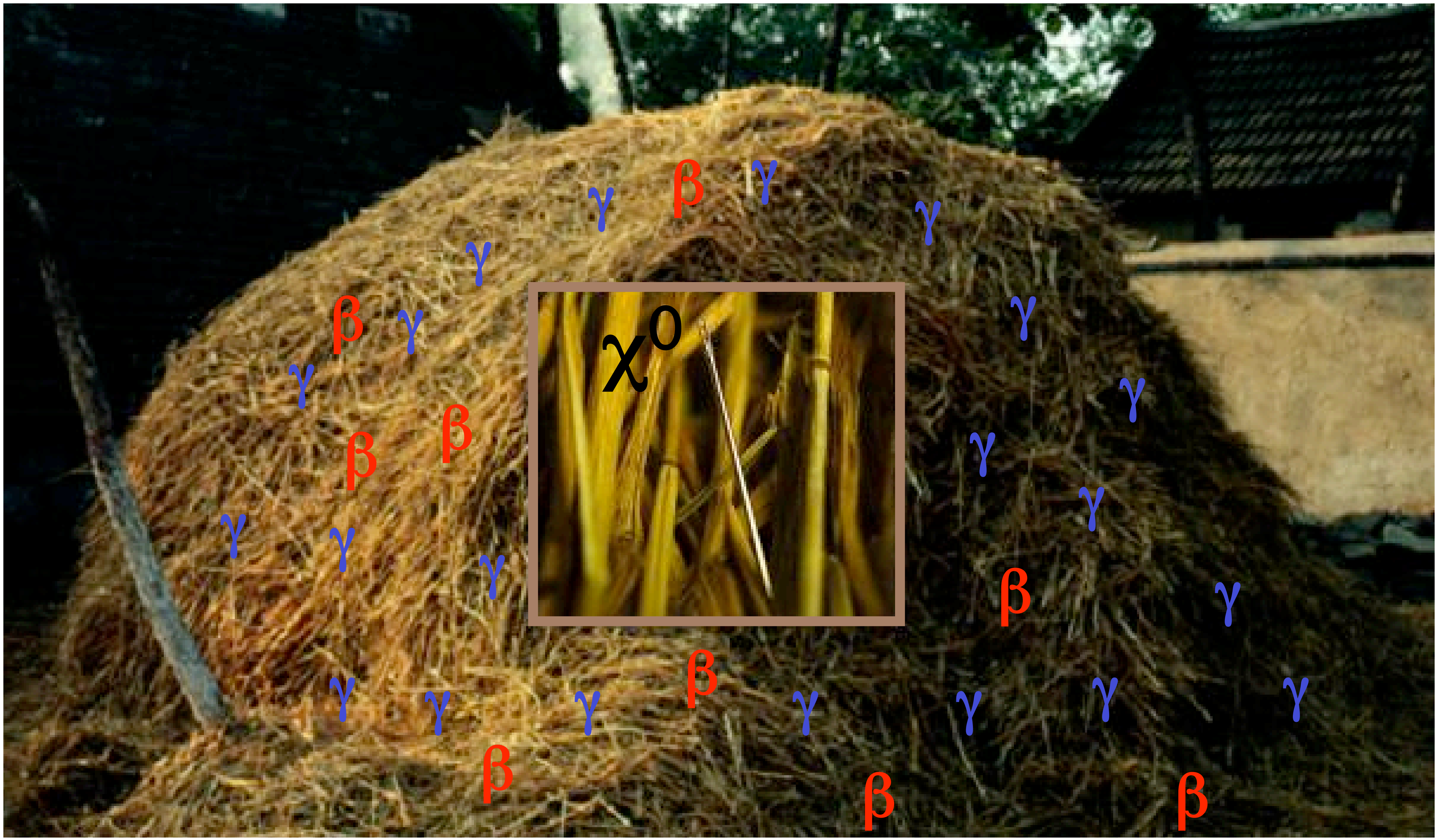
Total Event Rate
(m_χ = 100 GeV/c^2, $\sigma_{\chi\text{-}n} = 10^{-45}$ cm^2)



Detection Principles

- Various experimental methods exist for measuring such an energy deposition
    - Scintillation in crystals/liquids
    - Ionization in crystals/liquids
    - Thermal/athermal heating in crystals
    - Bubble formation in liquids/gels
- Easy in principle, hard in practice
    - Significant uncertainties/unknowns in estimating DM event rates and energy spectrum
    - Background rates overwhelm the most optimistic DM scattering rates.
    - And did I forget to mention - neutrons look just like the DM in our detectors.

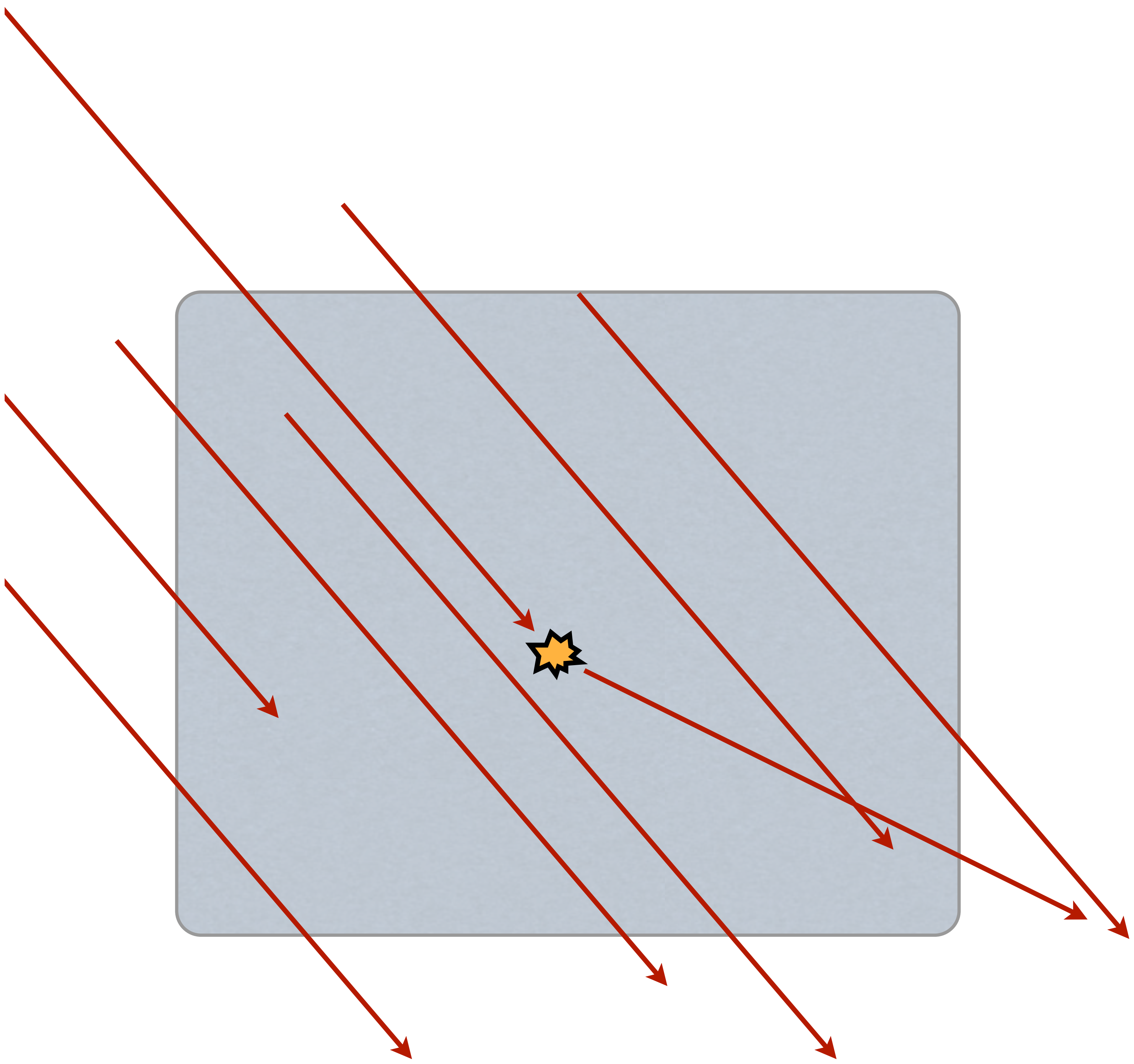
Looking for a Small Needle in a Very Large Haystack



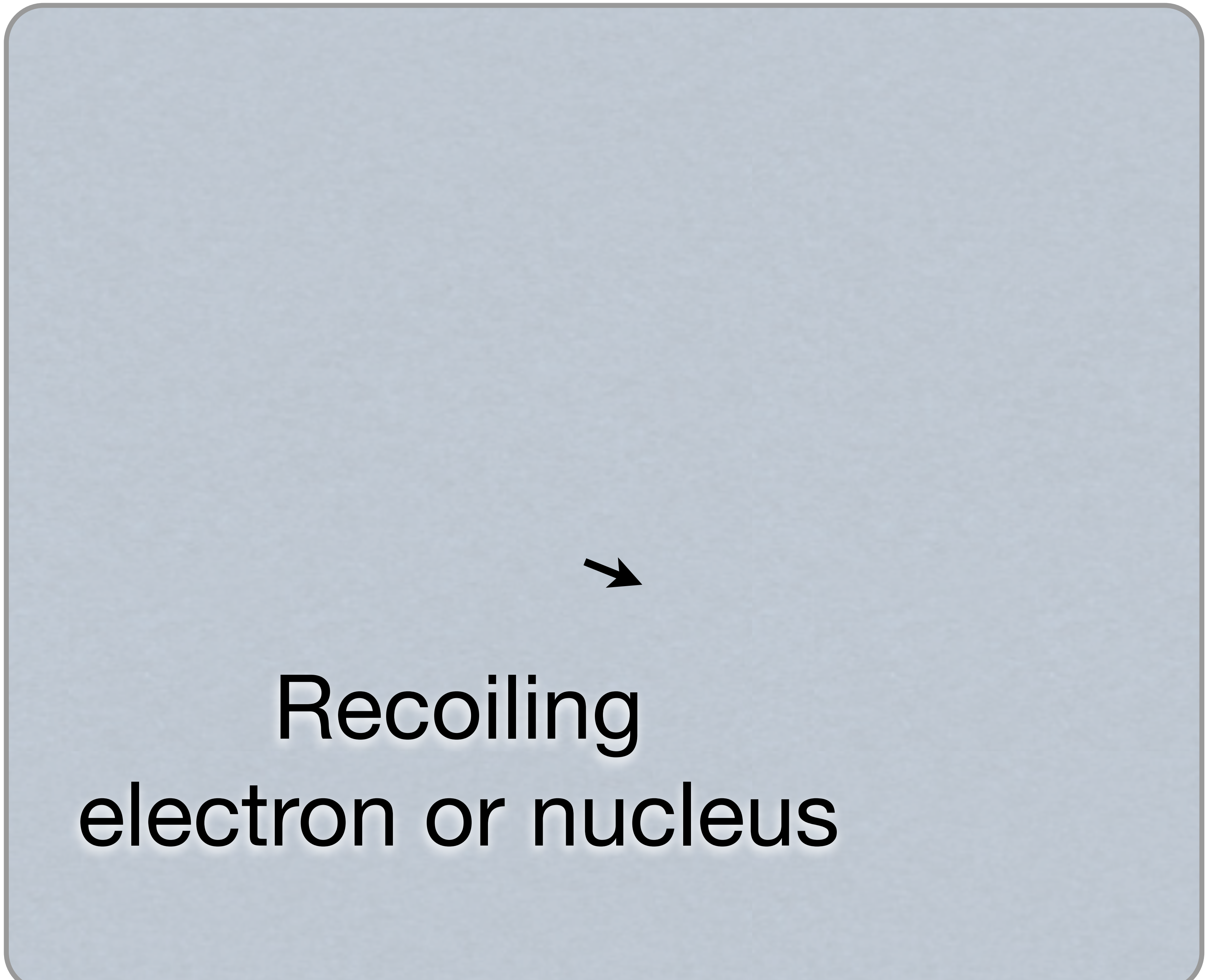
Looking for a Small Needle in a Very Large Haystack

Somewhere in the Midwest!

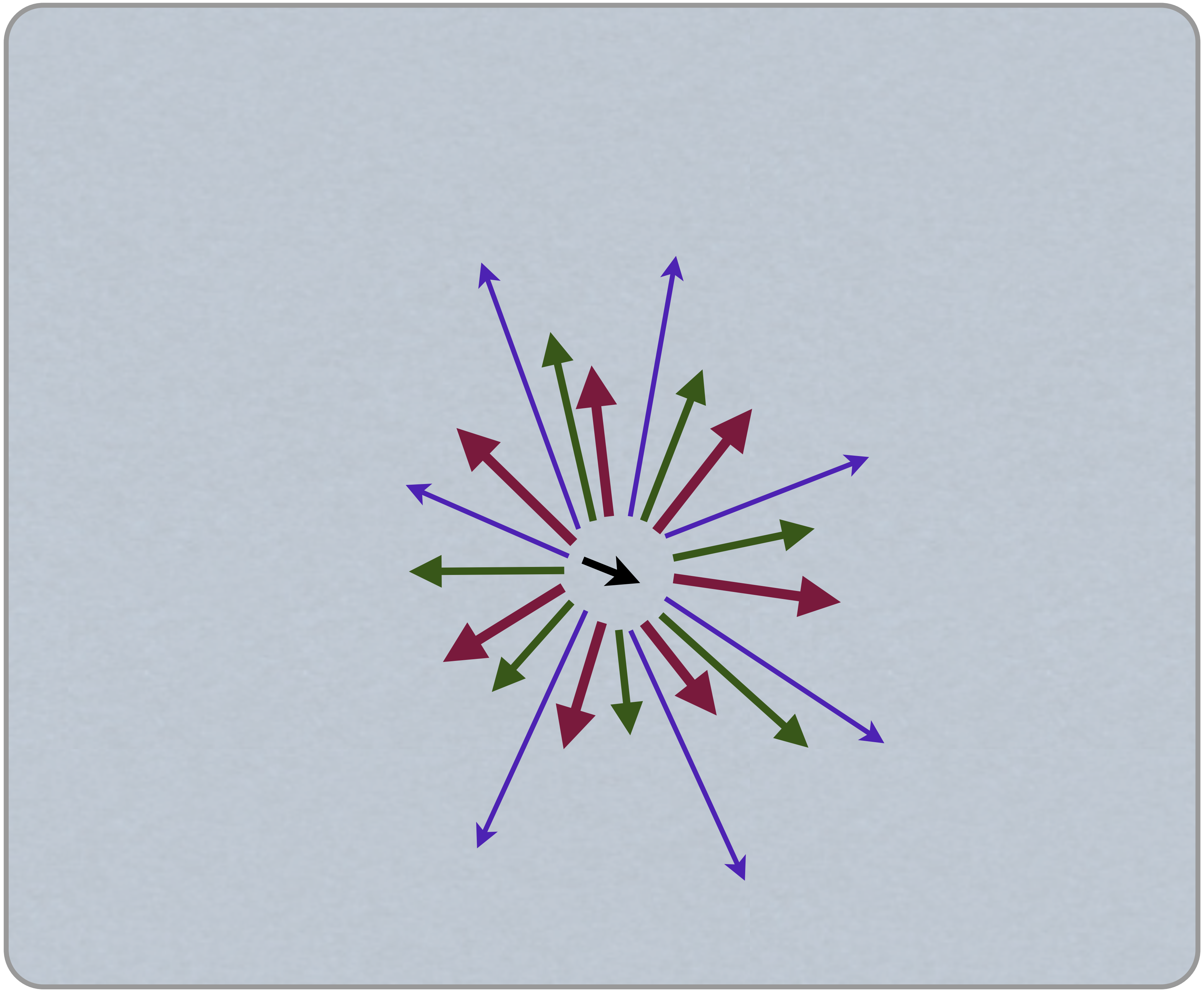
General Detection Principles



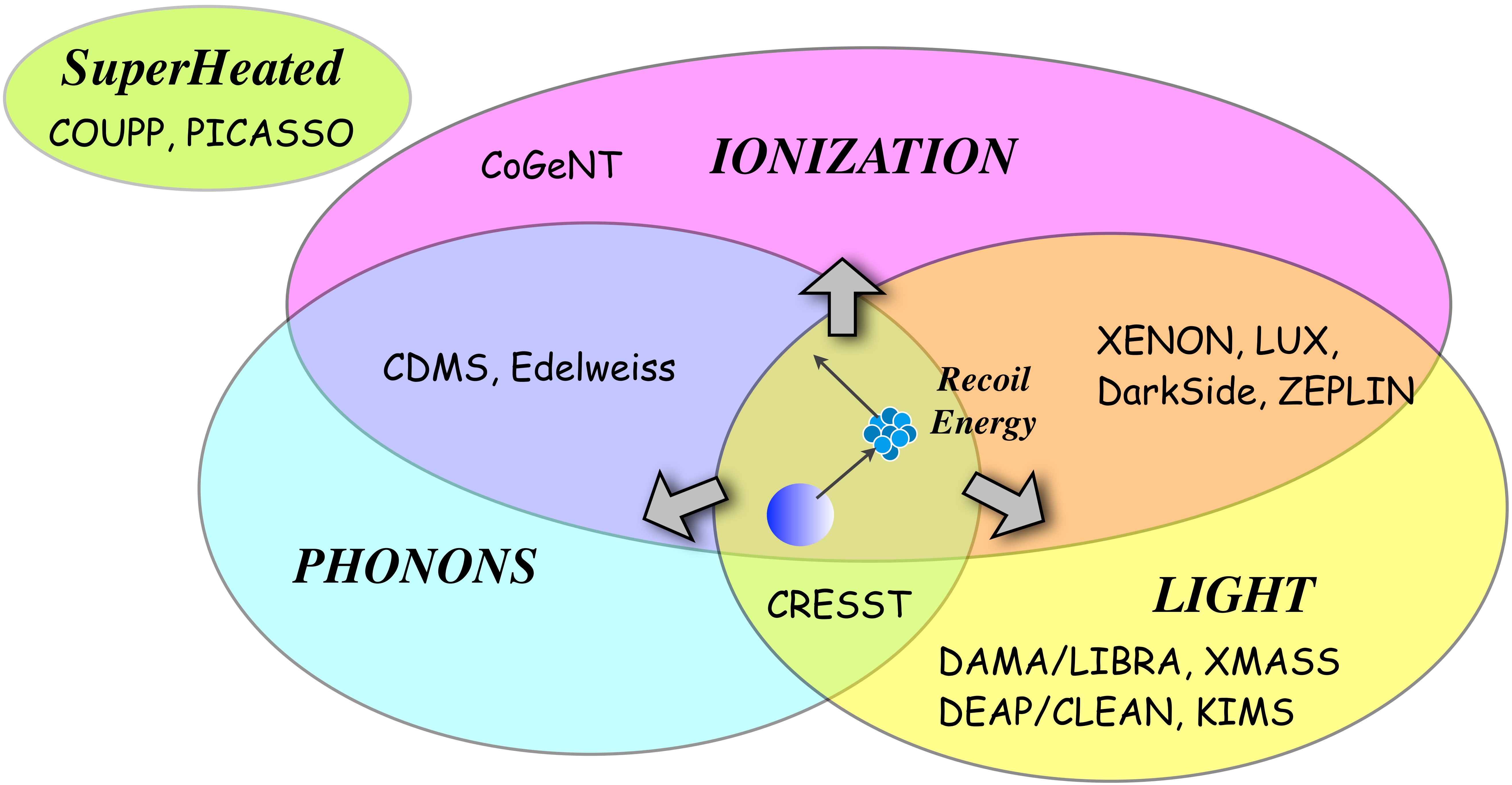
General Detection Principles



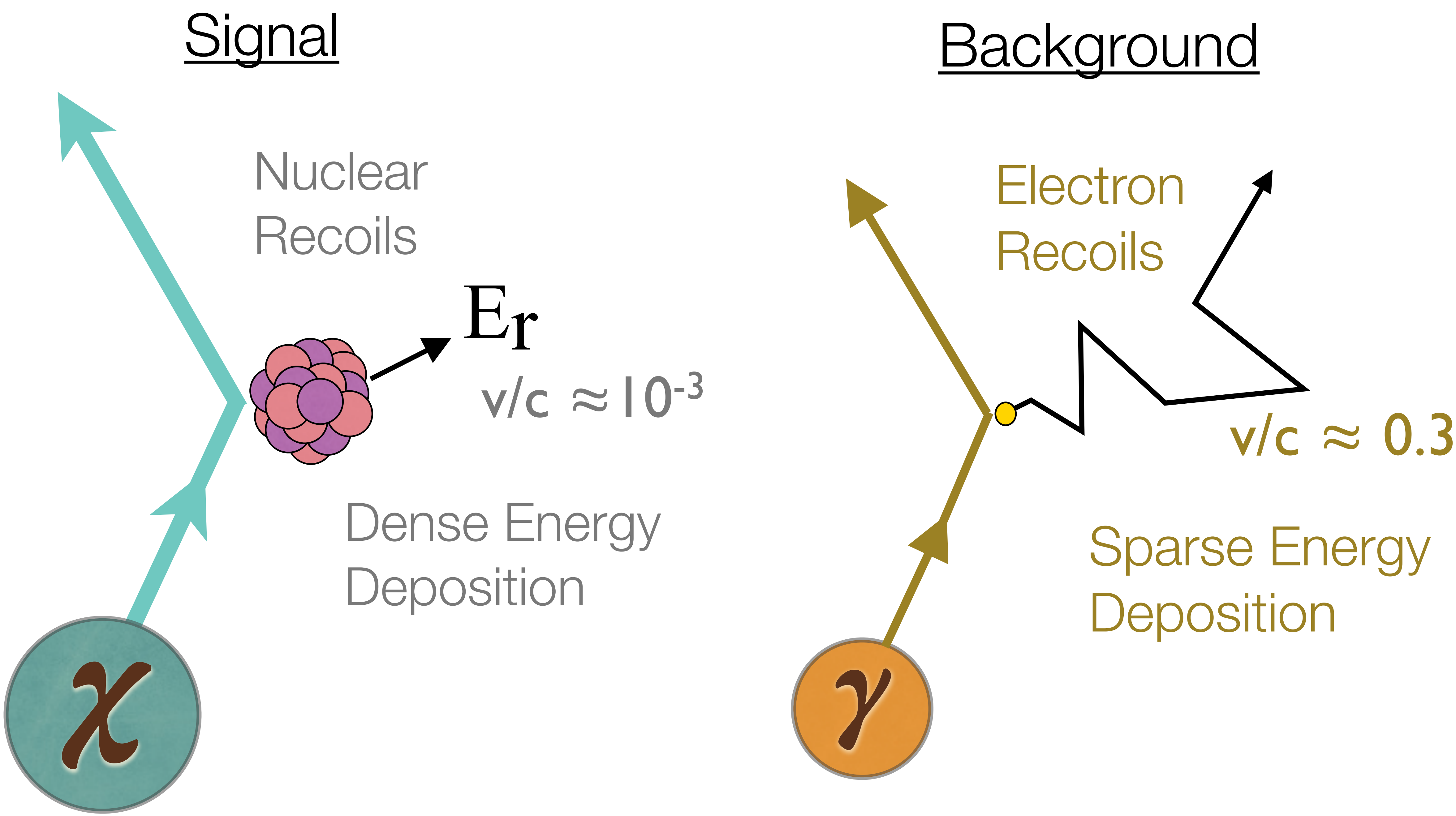
General Detection Principles



Direct Detection Principles



Detection Principles



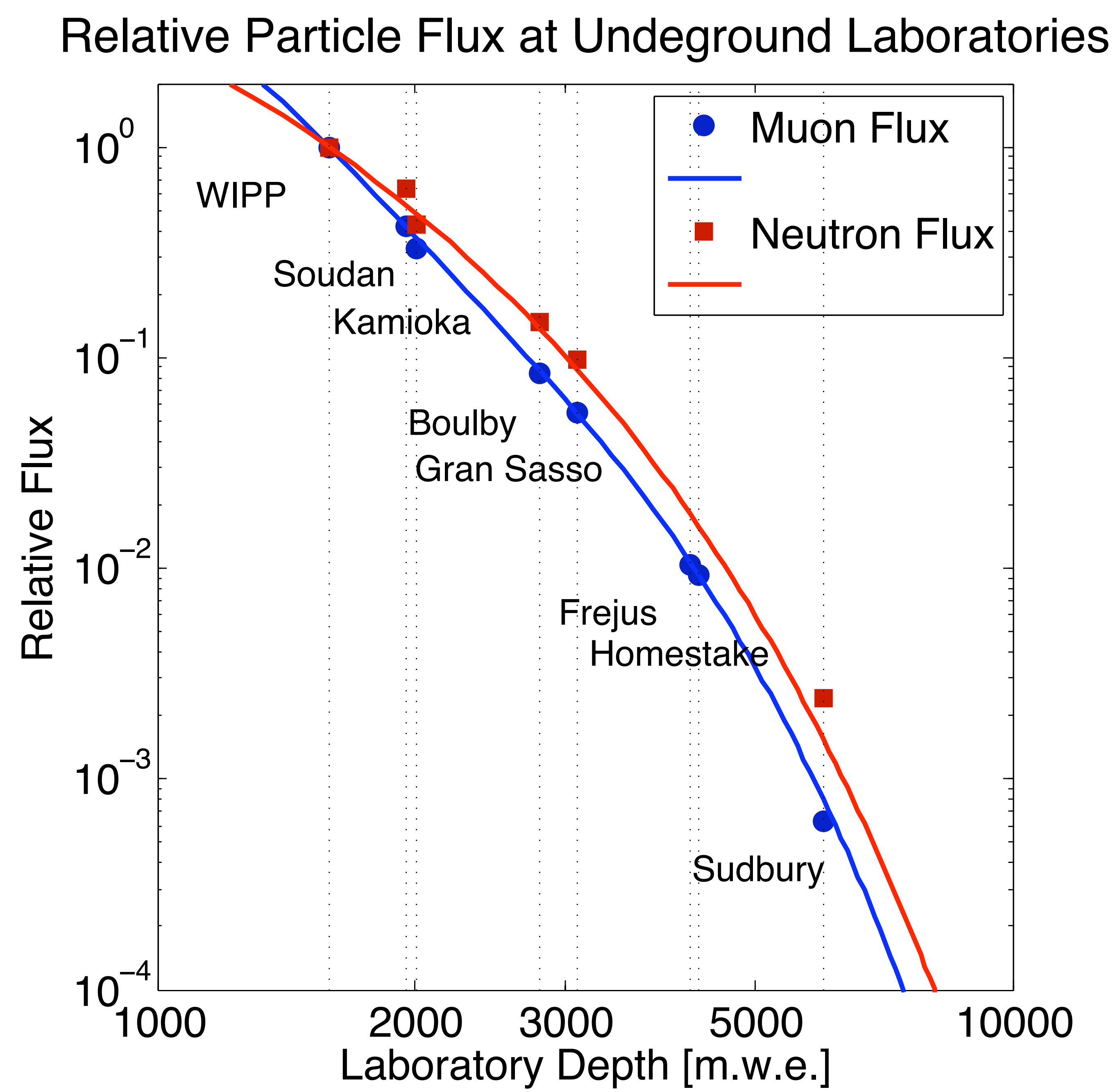
Particle Identification

- Scattering from an atomic nucleus leads to different physical effects than scattering from an electron in most materials.
- Sensitivity to this effect reduces background.
    - Dark Matter is expected to interact with the nucleus and backgrounds interact with electrons*.

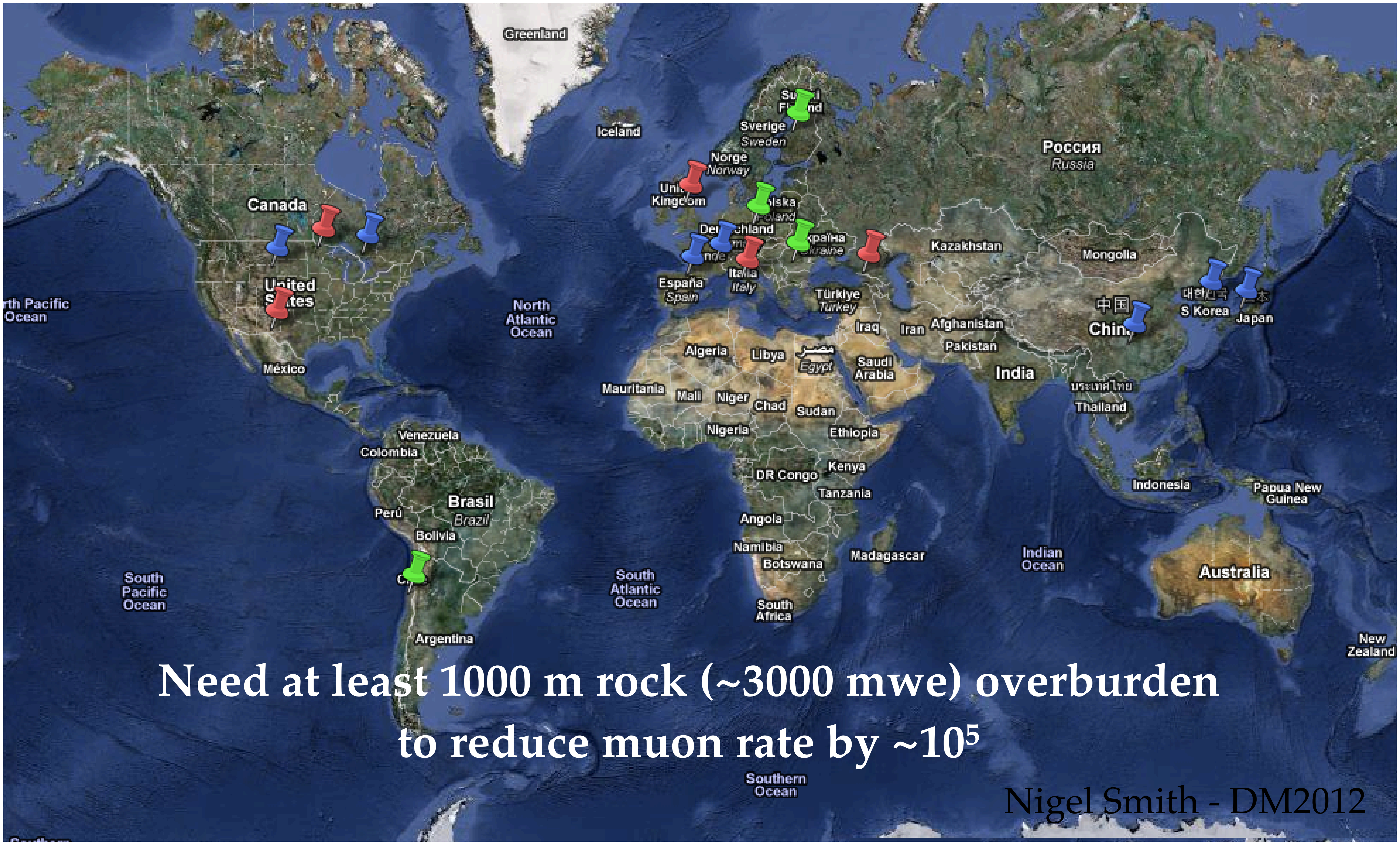
*CAVEAT: Neutrons interact with the nucleus.

Neutrons: Unrejected Background

- Neutrons recoil off atomic nuclei, thus appearing as WIMPs
- Neutrons come from
    - Environmental radioactivity
        - Slow/low energy
        - Can be addressed by shielding
    - Spallation due to cosmic muons
        - Fast/energetic = not shieldable
        - Must go deep underground to avoid



Minimize Backgrounds



Need at least 1000 m rock (~3000 mwe) overburden to reduce muon rate by ~10^5

Site experiments underground.

Minimize Backgrounds

Active Muon Veto:
rejects events from cosmic rays

- Scintillating panels
- Water Shield

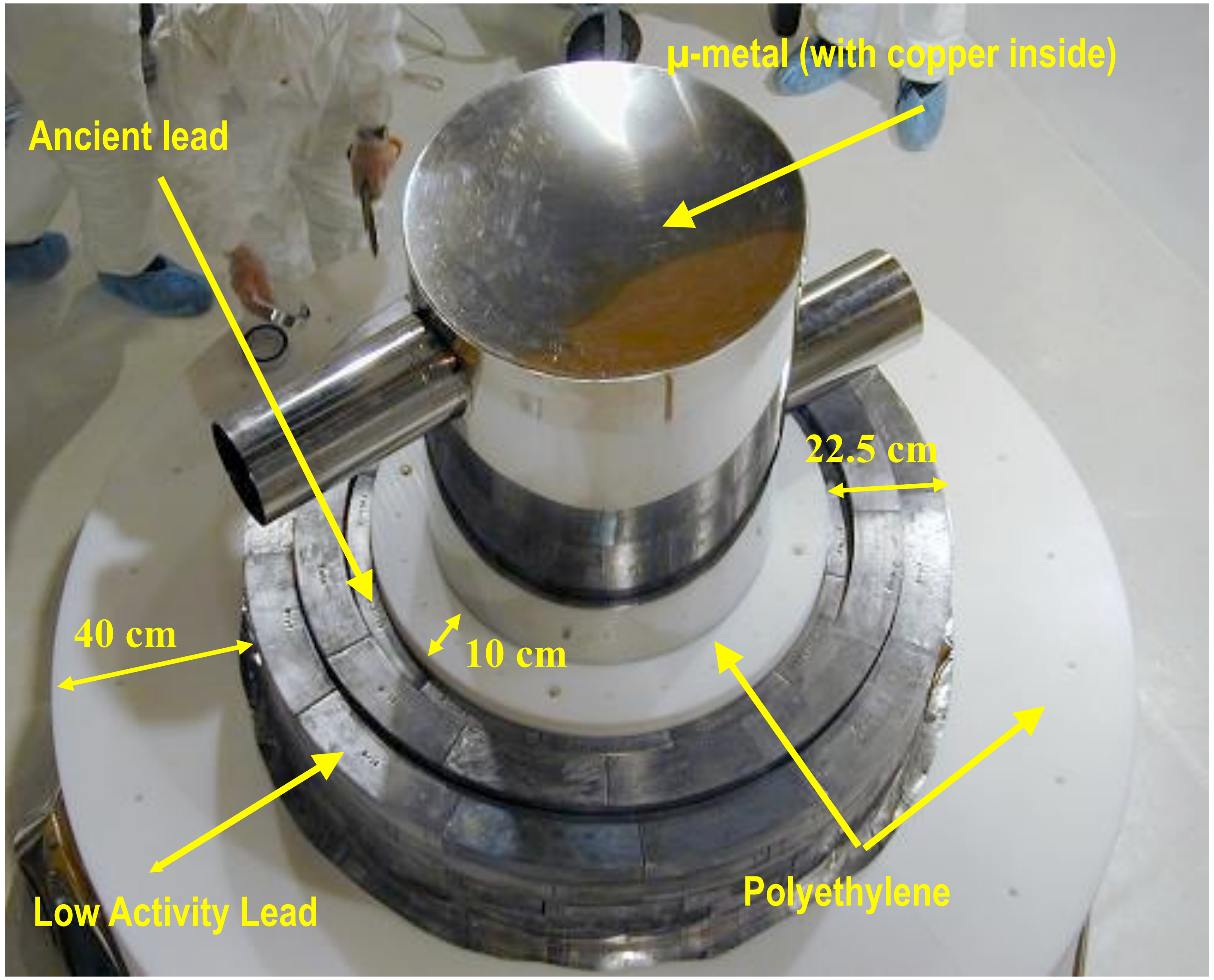
SCDMS active muon veto

LUX water shield

Minimize Backgrounds

Pb: shielding from gammas resulting from radioactivity

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

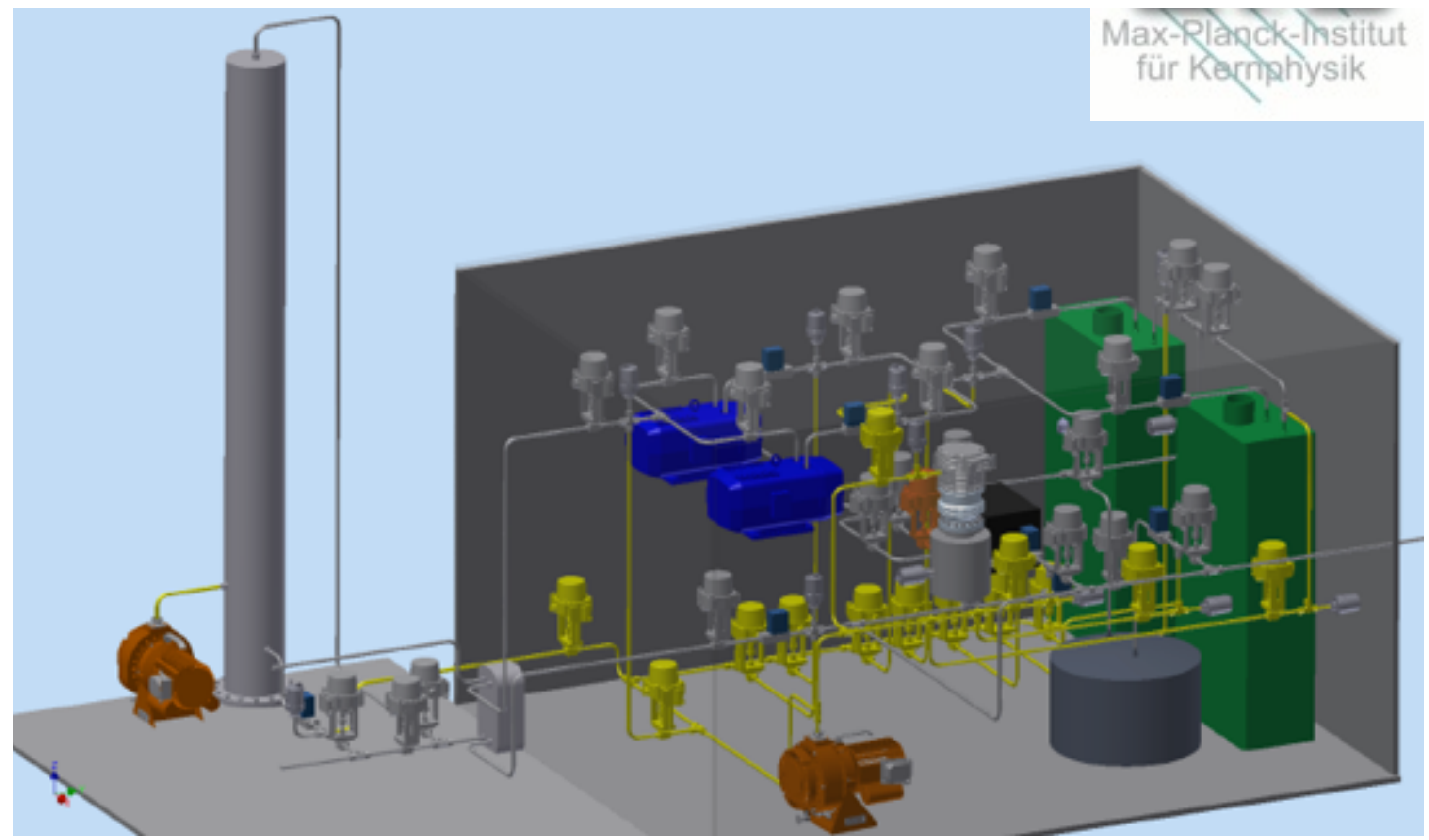


SCDMS - Layers of Polyethylene and Lead

Use Passive Shielding

Minimize Backgrounds

mobile radon extraction unit @ MPIK

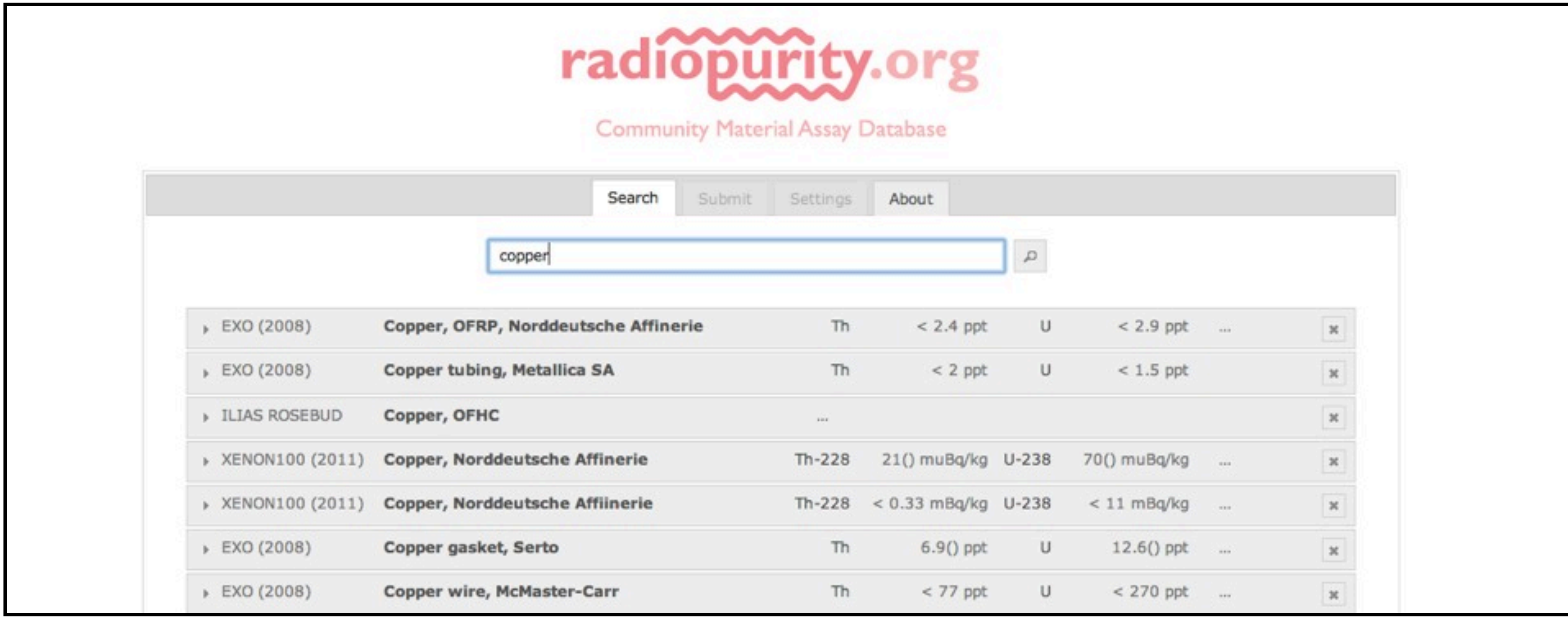


XENON1T purification loop with large charcoal tower.

Krypton and Radon Mitigation

Minimize Backgrounds

http://radiopurity.org



EXO (2008)	**Copper, OFRP, Norddeutsche Affinerie**	Th	< 2.4 ppt	U	< 2.9 ppt	...
EXO (2008)	**Copper tubing, Metallica SA**	Th	< 2 ppt	U	< 1.5 ppt	
ILIAS ROSEBUD	**Copper, OFHC**	...				
XENON100 (2011)	**Copper, Norddeutsche Affinerie**	Th-228	21() muBq/kg	U-238	70() muBq/kg	...
XENON100 (2011)	**Copper, Norddeutsche Affiinerie**	Th-228	< 0.33 mBq/kg	U-238	< 11 mBq/kg	...
EXO (2008)	**Copper gasket, Serto**	Th	6.9() ppt	U	12.6() ppt	...
EXO (2008)	**Copper wire, McMaster-Carr**	Th	< 77 ppt	U	< 270 ppt	...

Supported by AARM, LBNL, MAJORANA, SMU, SJTU & others

Use Clean Materials

All Hope is Not Loss

If Our Needle is VERY BIG!

Signals

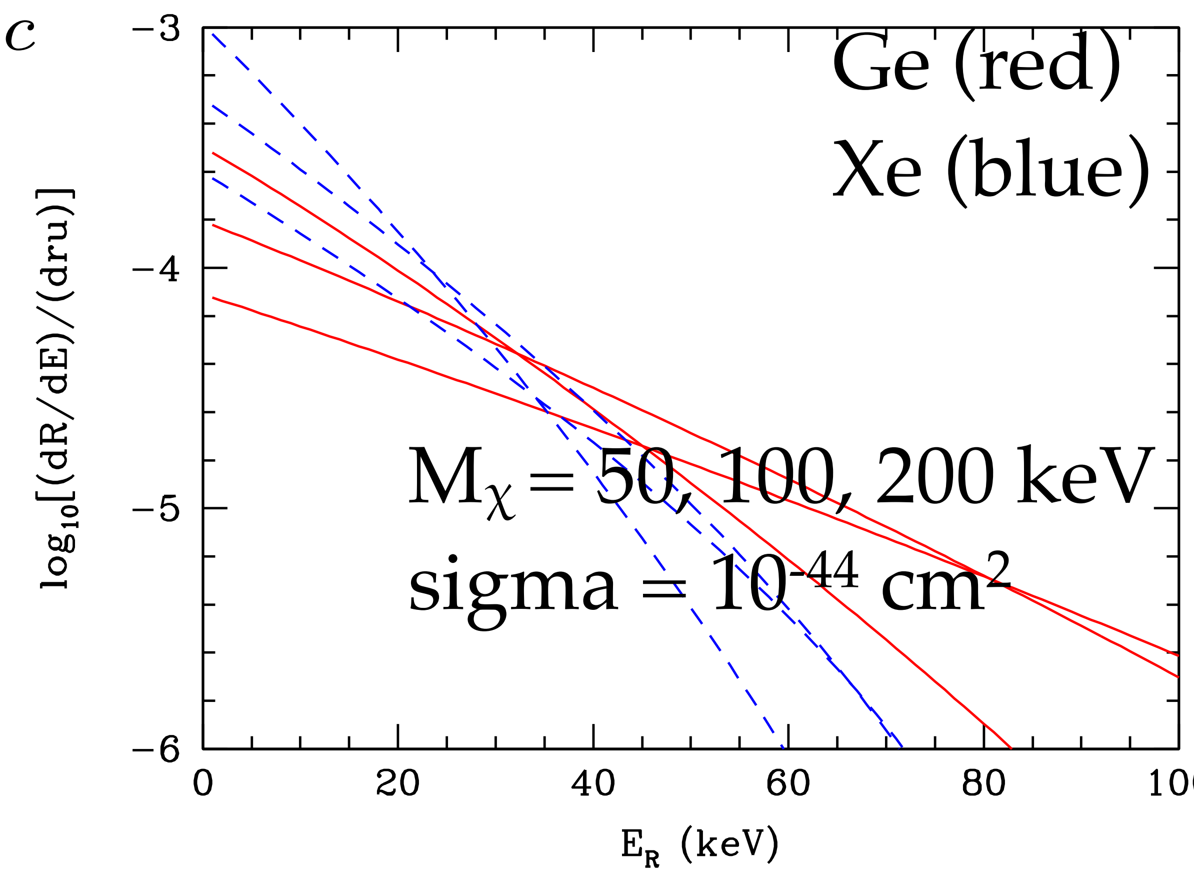
- As we have seen, the recoil rate is energy dependent due to the kinematics of elastic scattering and the WIMP speed distribution.
- In addition, the recoil rate is time- and direction-dependent due to the motion of Earth w.r.t. the galactic rest frame.
- Variations can happen in the
    - Energy spectrum
    - Event rate
    - Recoil direction

Signals: Energy Dependence

For the standard halo model, we can write the differential event rate as:

$$\frac{dR}{dE_R} \approx (\frac{dR}{dE_R})_0 F^2(E_R) exp(\frac{-E_R}{E_c})$$

event rate in
limit E --> 0



Characteristic energy scale given by:

parameter that
depends on target

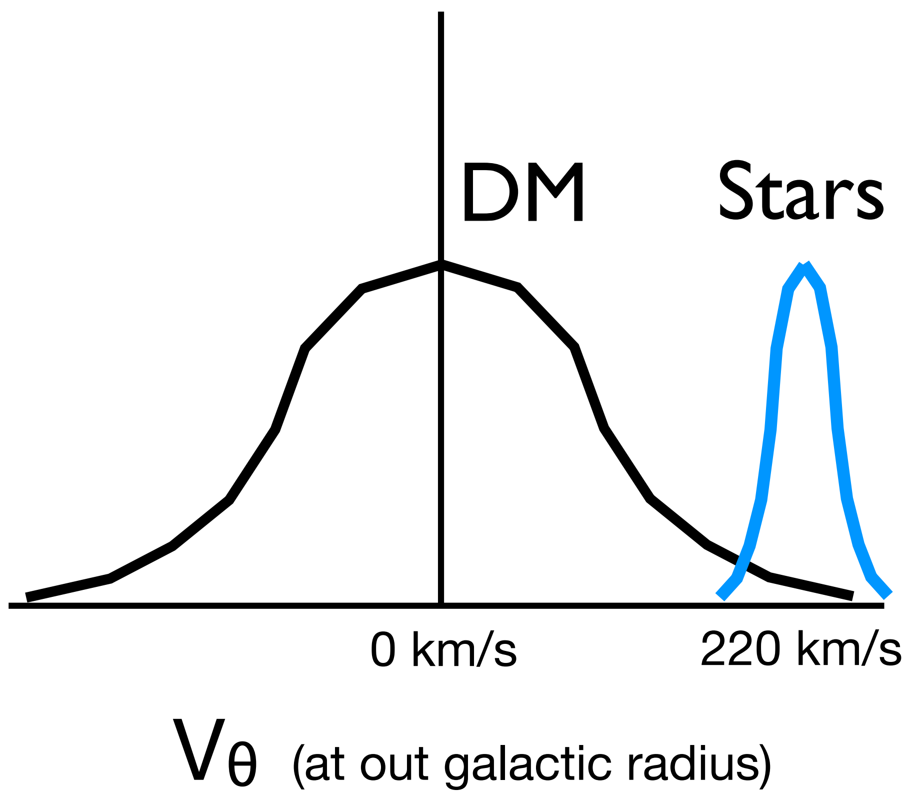
$$E_c = \frac{c_1 2\mu_N^2 v_c^2}{m_N}$$

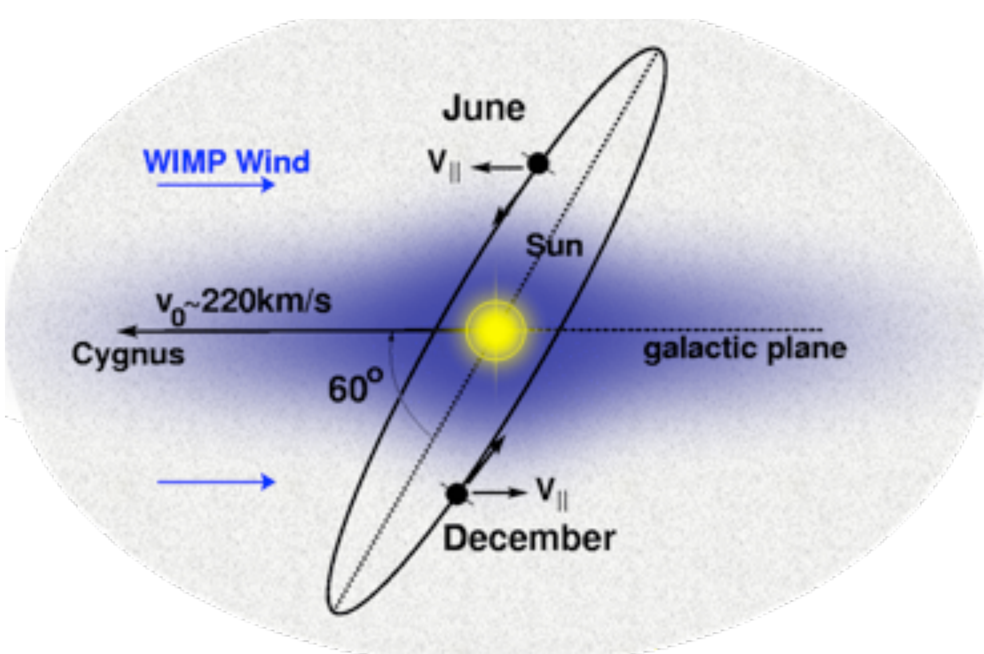
$$m_\chi << m_N \rightarrow E_c \propto \frac{m_\chi^2}{m_N}$$

$$m_\chi >> m_N \rightarrow E_c \propto m_N$$

Total recoil rate is prop to WIMP number density

Signal Modulation



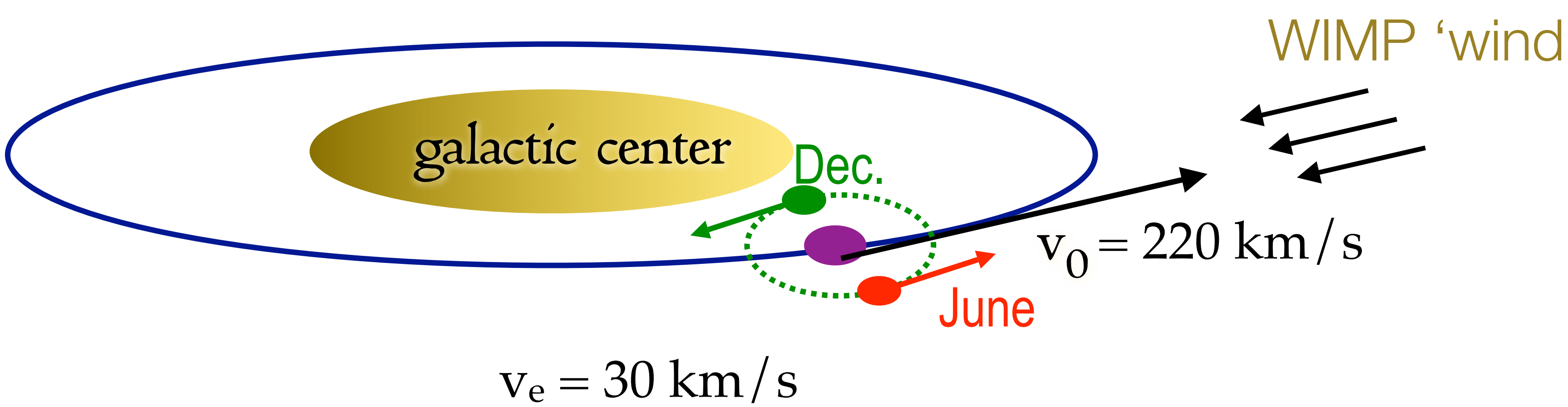


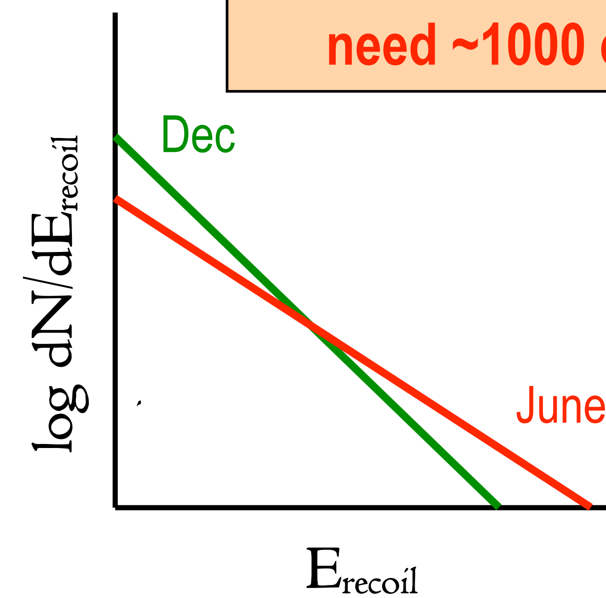
- Baryons travel together in roughly circular orbits with small velocity dispersion
- Dark matter particles travel individually with no circular dependence and large velocity dispersion
- As a result, the flux of WIMPs passing through Earth modulate over the course of a year as Earth rotates around the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

Signal Modulation: Rate

Assume WIMP Isothermal Halo:

~2% seasonal effect - need ~1000 events



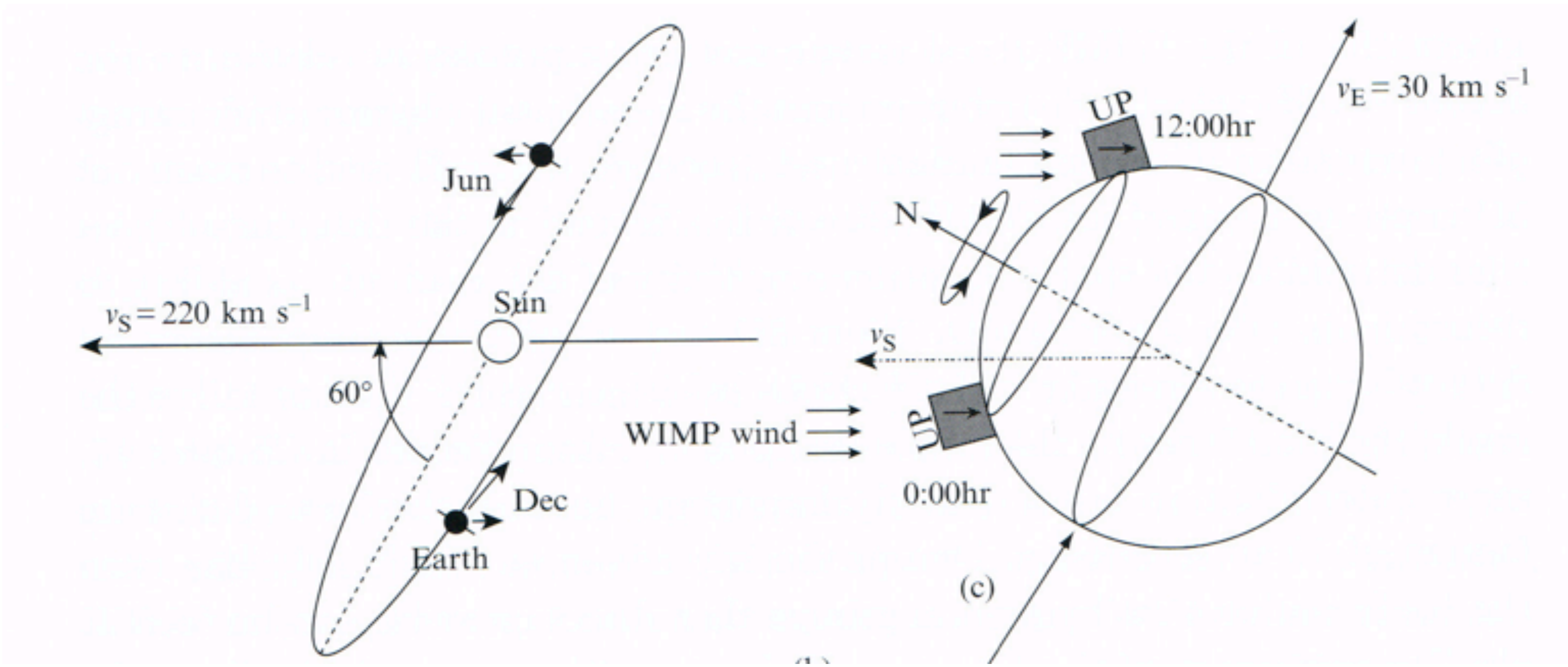


Since Earth's orbital speed around the sun is significantly smaller than the Sun's circular speed, the amplitude of the modulation is small and can be written as a Taylor Series.

$$\frac{dR}{dE_R} \approx \left(\frac{d\bar{R}}{dE_R}\right)[1 + \Delta(E_R)\cos\alpha(t)]$$

where $\alpha(t) = 2\pi(t - t_0)/T$ and T = 1 year, t_0 = 150 days

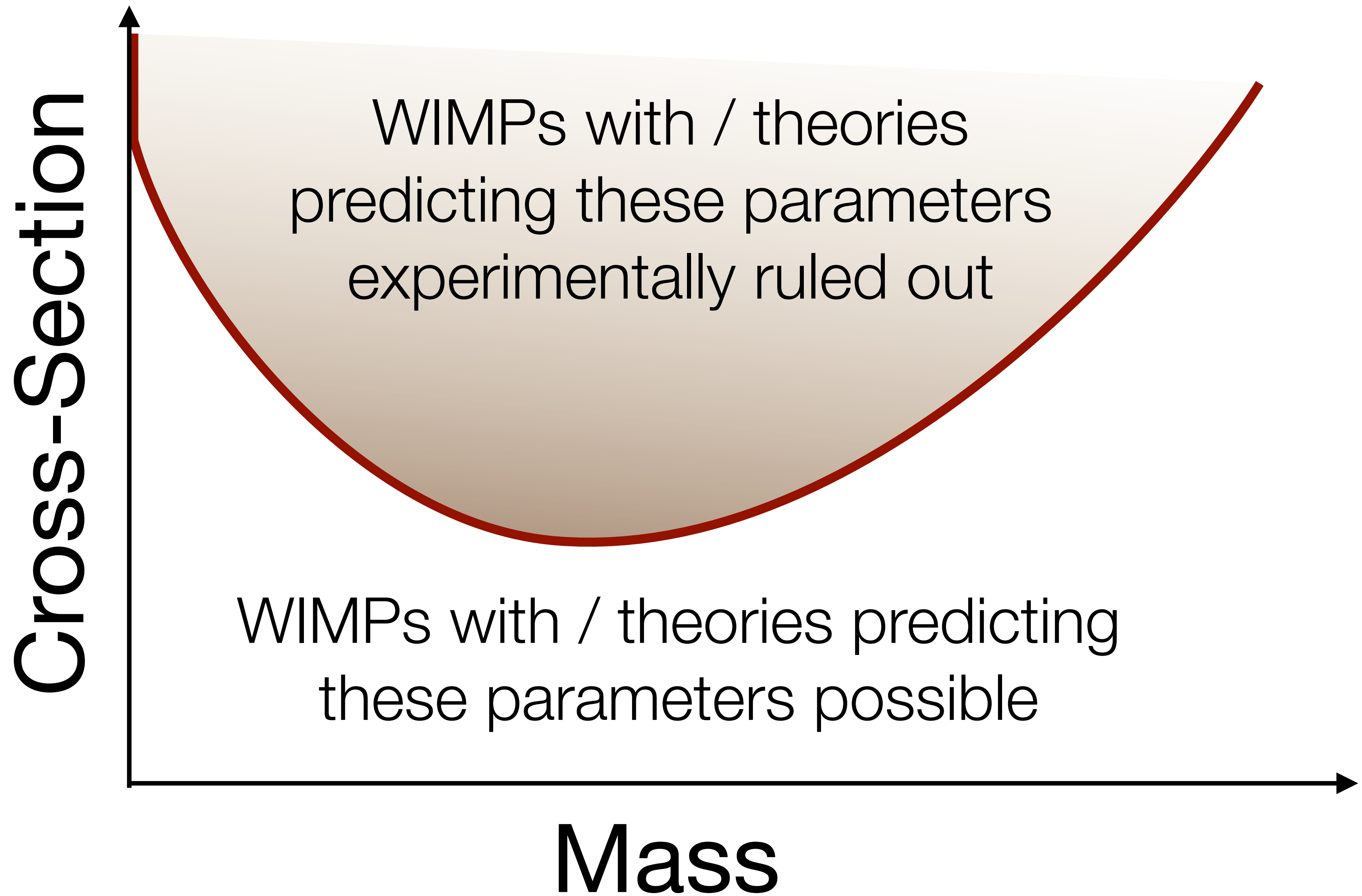
Signal Modulation: Direction



- A detector at 45 degree latitude will see the dark matter wind oscillate in direction over the course of a day.
- This is a sidereal (tied to stars) effect, not diurnal (tied to sun).

WIMP Exclusion Plots

WIMP parameters experimentally determined by direct detection searches: M_χ and $\sigma_{\chi\text{-N}}$.



Direct Detection Searches

Many Experiments

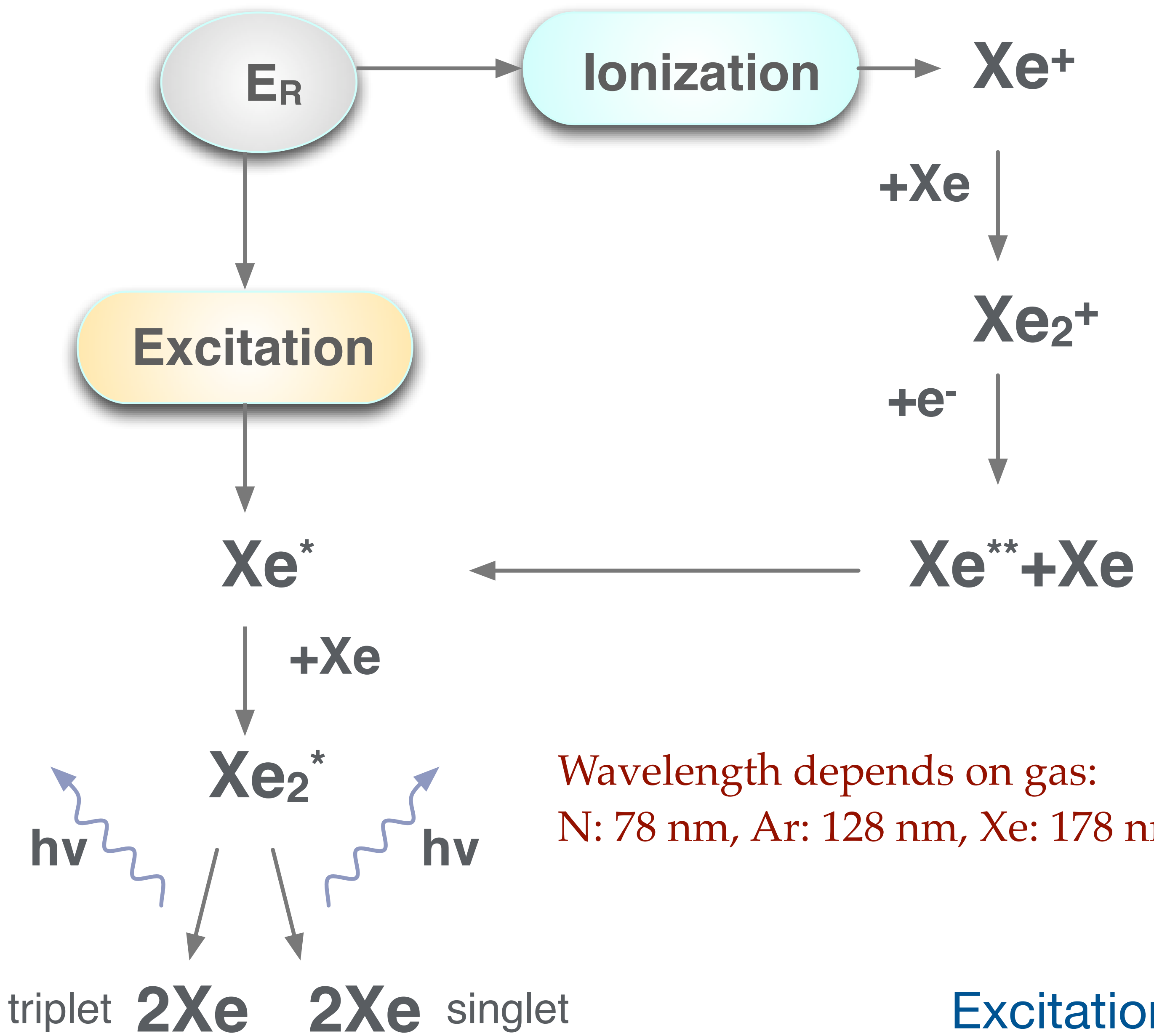
SuperCDMS	XENON	DM-ICE
EDELWEISS	LUX	XMASS
DEAP	ANAIS	KIMS
MiniCLEAN	DarkSide	SIMPLE
DRIFT	DAMA/LIBRA	COUPP
DMTPC	PandaX	EURECA
MIMIC	PICASSO	LZ
NEWAGE	CDEX-TEXANO	MAX

I will only be able to talk in general about techniques they share.

General Detection Principles

- 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.

Liquid Noble Gases: Detection Mechanism



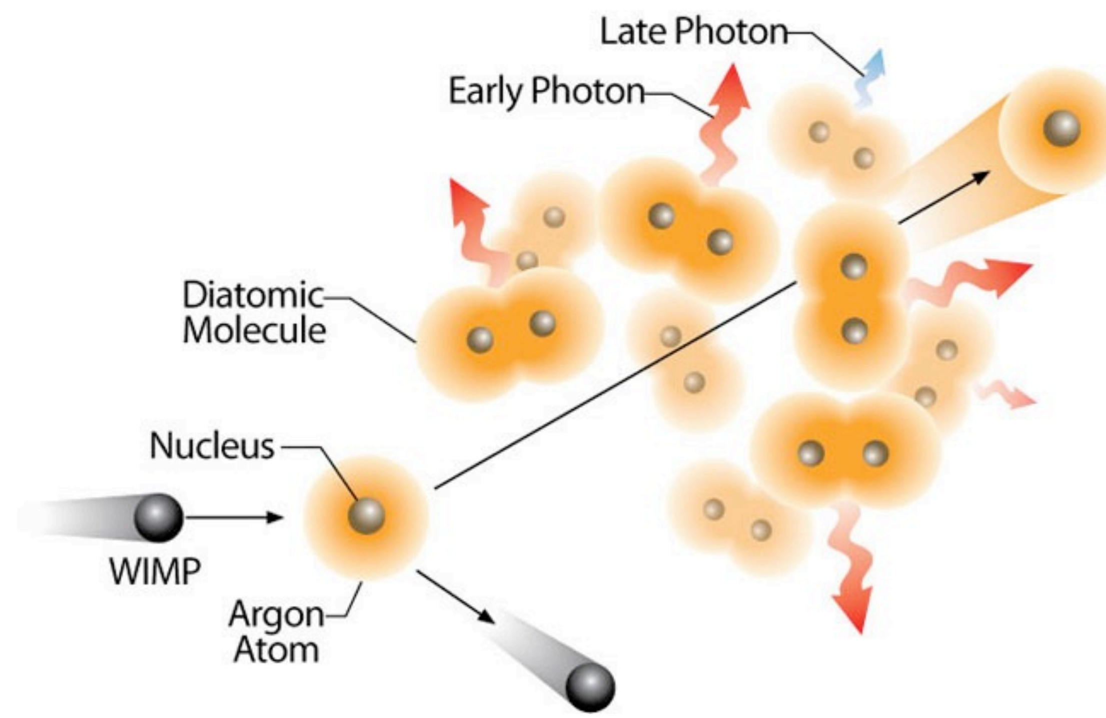
$$\begin{aligned} \mathrm{Xe}^* + \mathrm{Xe} &\rightarrow \mathrm{Xe}_2^* \\ \mathrm{Xe}_2^* &\rightarrow 2\mathrm{Xe} + h\nu \end{aligned}$$

$$\begin{aligned} \mathrm{Xe}^+ + \mathrm{Xe} &\rightarrow \mathrm{Xe}_2^+ \\ \mathrm{Xe}_2^+ + \mathrm{e}^- &\rightarrow \mathrm{Xe}^{**} + \mathrm{Xe} \\ \mathrm{Xe}^{**} &\rightarrow \mathrm{Xe}^* + \mathrm{heat} \\ \mathrm{Xe}^* + \mathrm{Xe} &\rightarrow \mathrm{Xe}_2^* \\ \mathrm{Xe}_2^* &\rightarrow 2\mathrm{Xe} + h\nu \end{aligned}$$

Wavelength depends on gas:
N: 78 nm, Ar: 128 nm, Xe: 178 nm

Time constants depend on gas
(Ne: few ns/15.4μs, Ar: 10ns/1.5μs, Xe: 3/27 ns)

Excitation/Ionization depends on dE/dx!
$\Longrightarrow$ discrimination of signal (WIMPs → NR)
and (most of the) background (gammas → ER)!



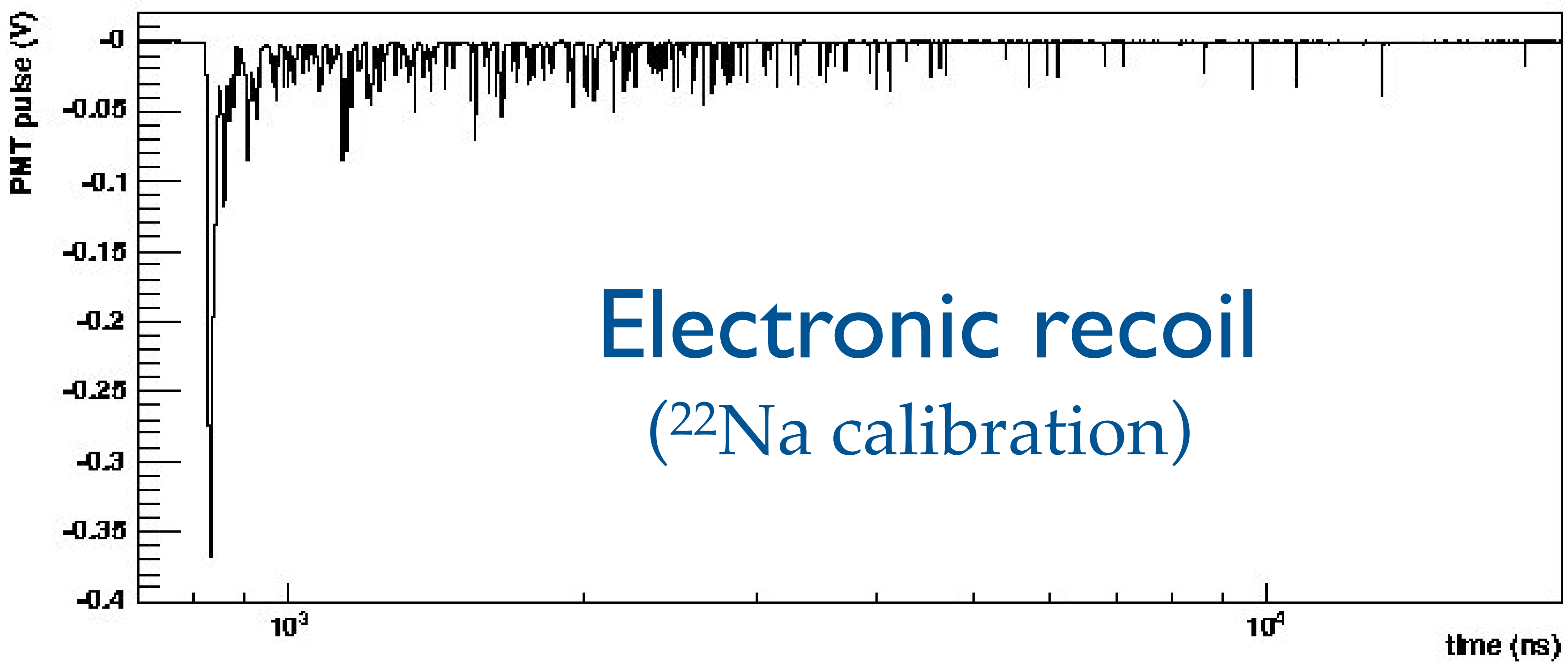
Single Phase Liquid Noble Experiments

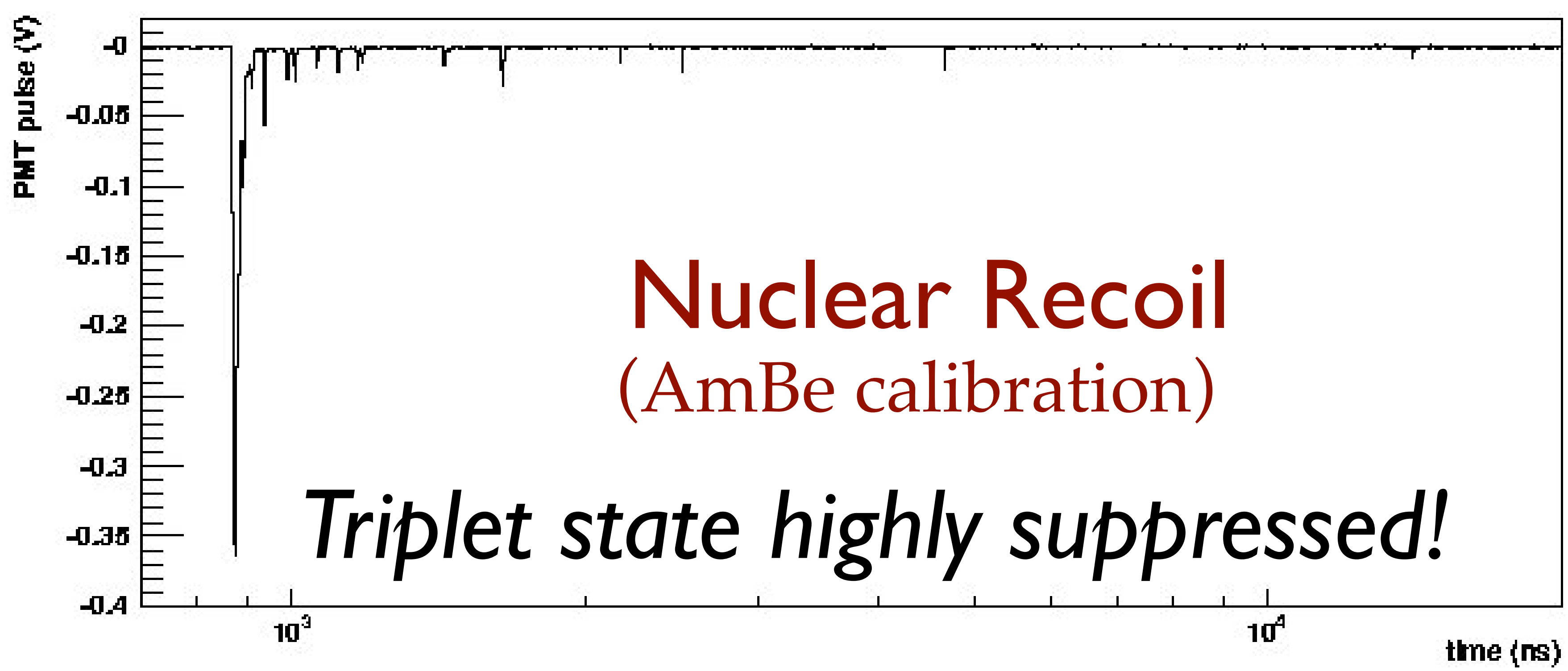
DEAP, XMASS, MiniCLEAN

Pulse Shape Analysis

- Early singlet state and delayed triplet state.
- The triplet state is highly suppressed for nuclear recoils.

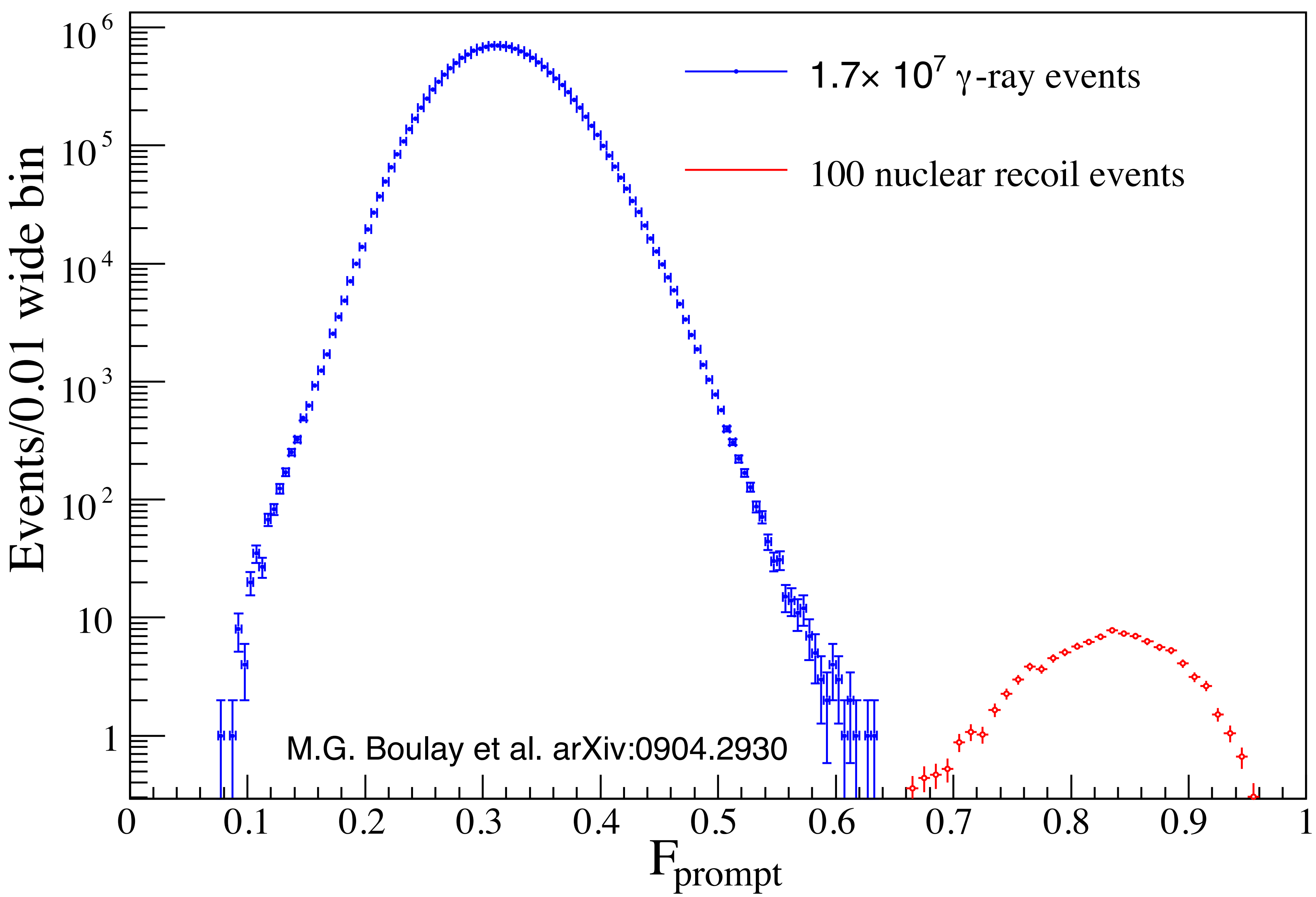
	Singlet	Triplet
Ne	< 18.2 ns	14.9 μs
Ar	7ns	1.6 μs
Xe	4.3 ns	22 μs





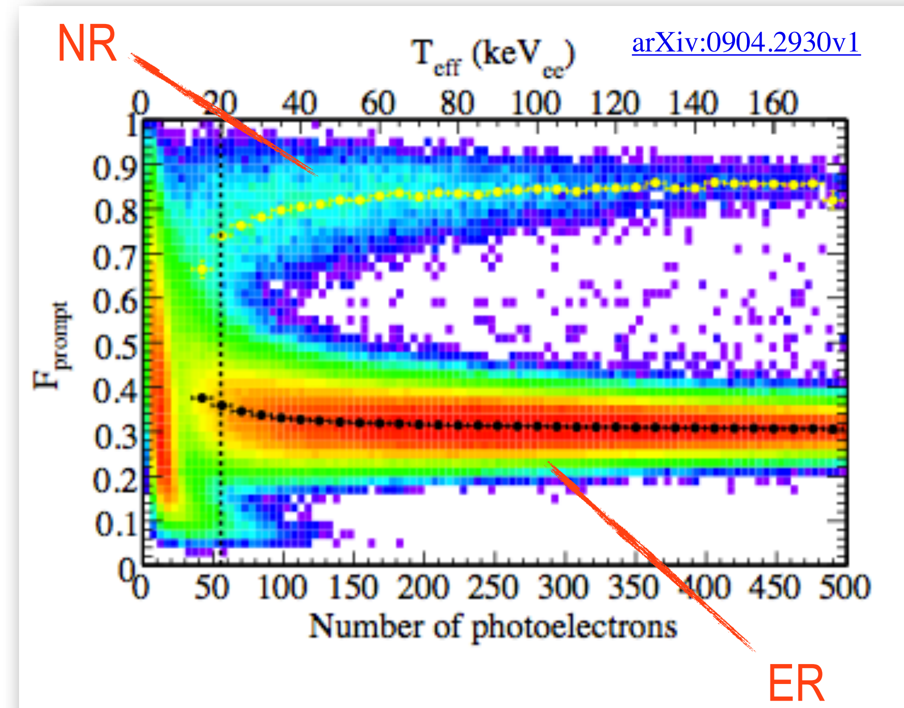
DEAP - Pulse Shape Discrimination

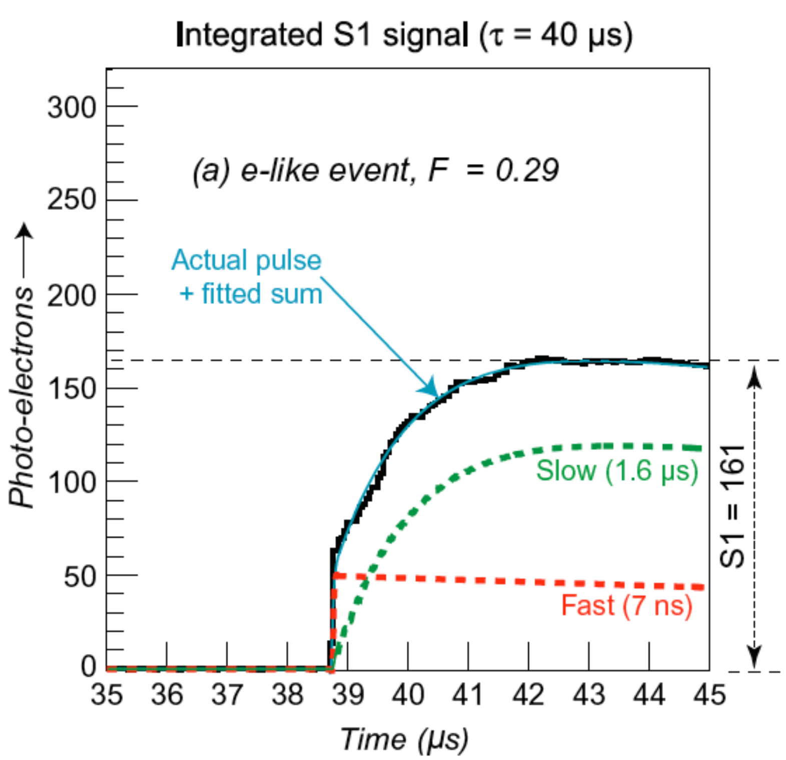
- Discriminate with ratio of prompt light (F_{prompt}) to total light.
- Reject beta and gamma backgrounds with less than 10^{-8} leakage.



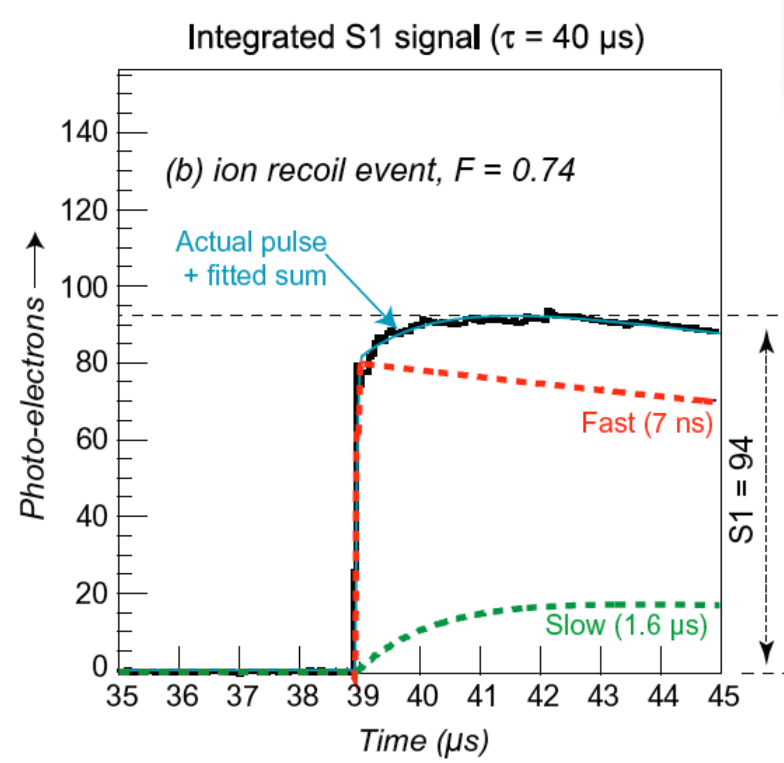
DEAP - Pulse Shape Discrimination

- 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.





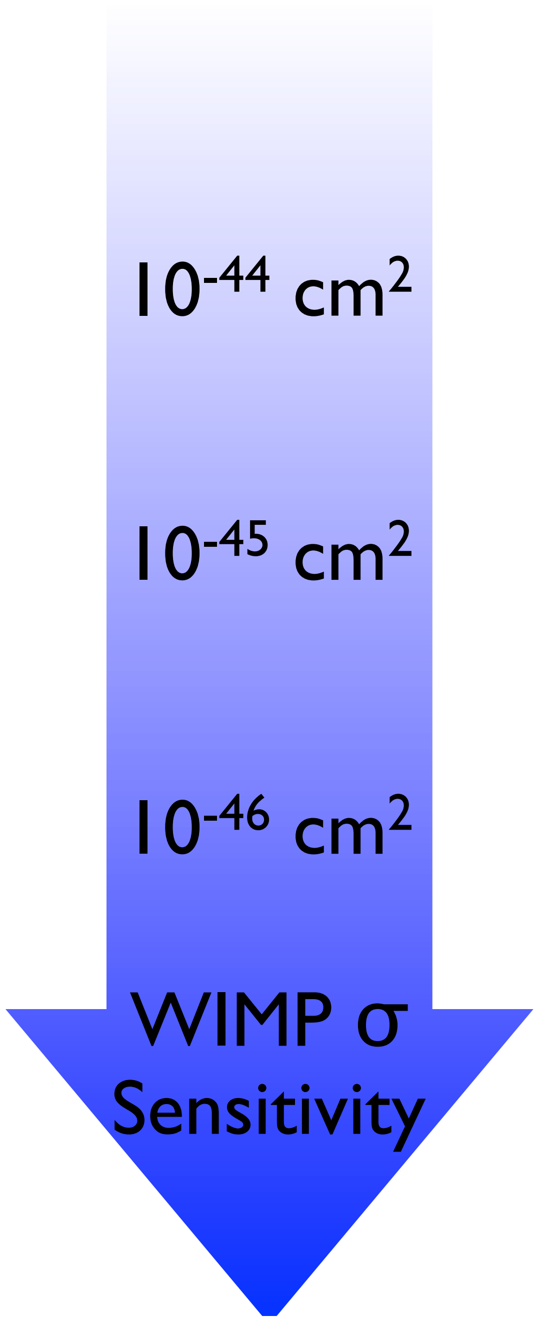
(a)



(b)

- 70% of excimer states created by nuclear recoils are singlets
- 30% of excimer states created by electron recoils are triplets

DEAP/CLEAN Program



DEAP-0:
Initial R&D detector

DEAP-1:
7 kg LAr
2 warm PMTs
At SNOLab since 2008

picoCLEAN:
Initial R&D detector

microCLEAN:
4 kg LAr or LNe
2 cold PMTs
surface tests at Yale

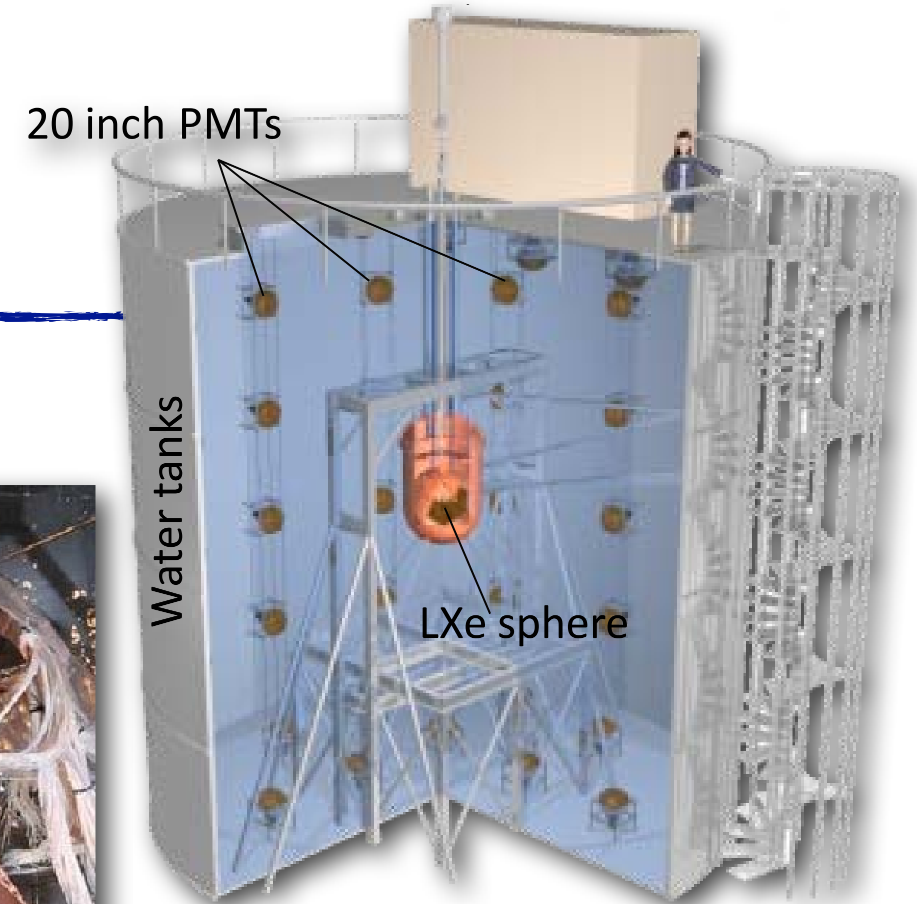
MiniCLEAN:
500 kg LAr or LNe (150 kg fiducial mass)
92 cold PMTs
SNOLAB 2013

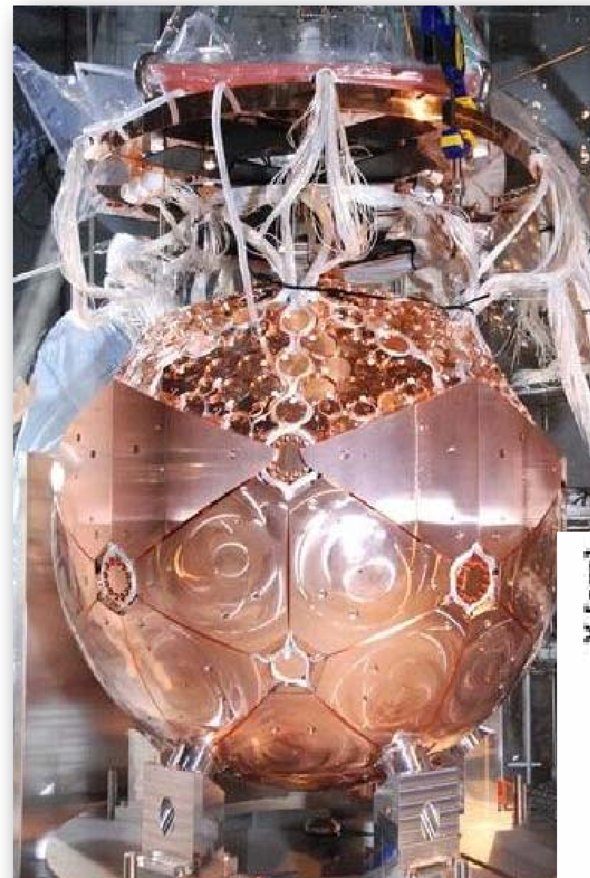
DEAP-3600:
3600 kg LAr (1000 kg fiducial mass)
266 warm PMTs
SNOLAB 2014

40-140 tonne LNe/LAr Detector:
pp-solar ν, supernova ν, dark matter $<10^{-46}$ cm^2
~2018?

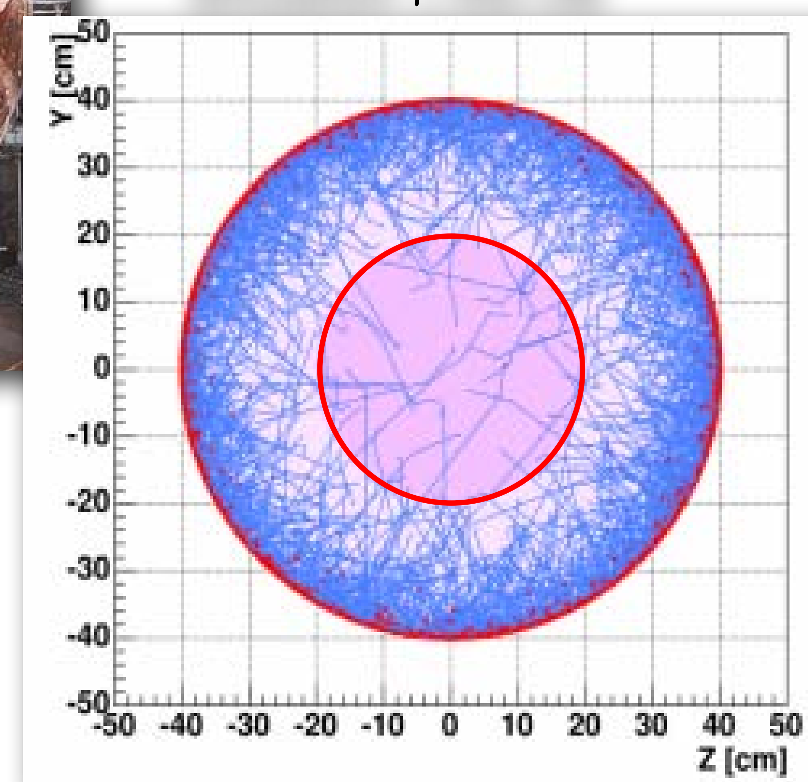
XMASS

- 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 from materials used to support PMTs.





Simulation: γ into LXe

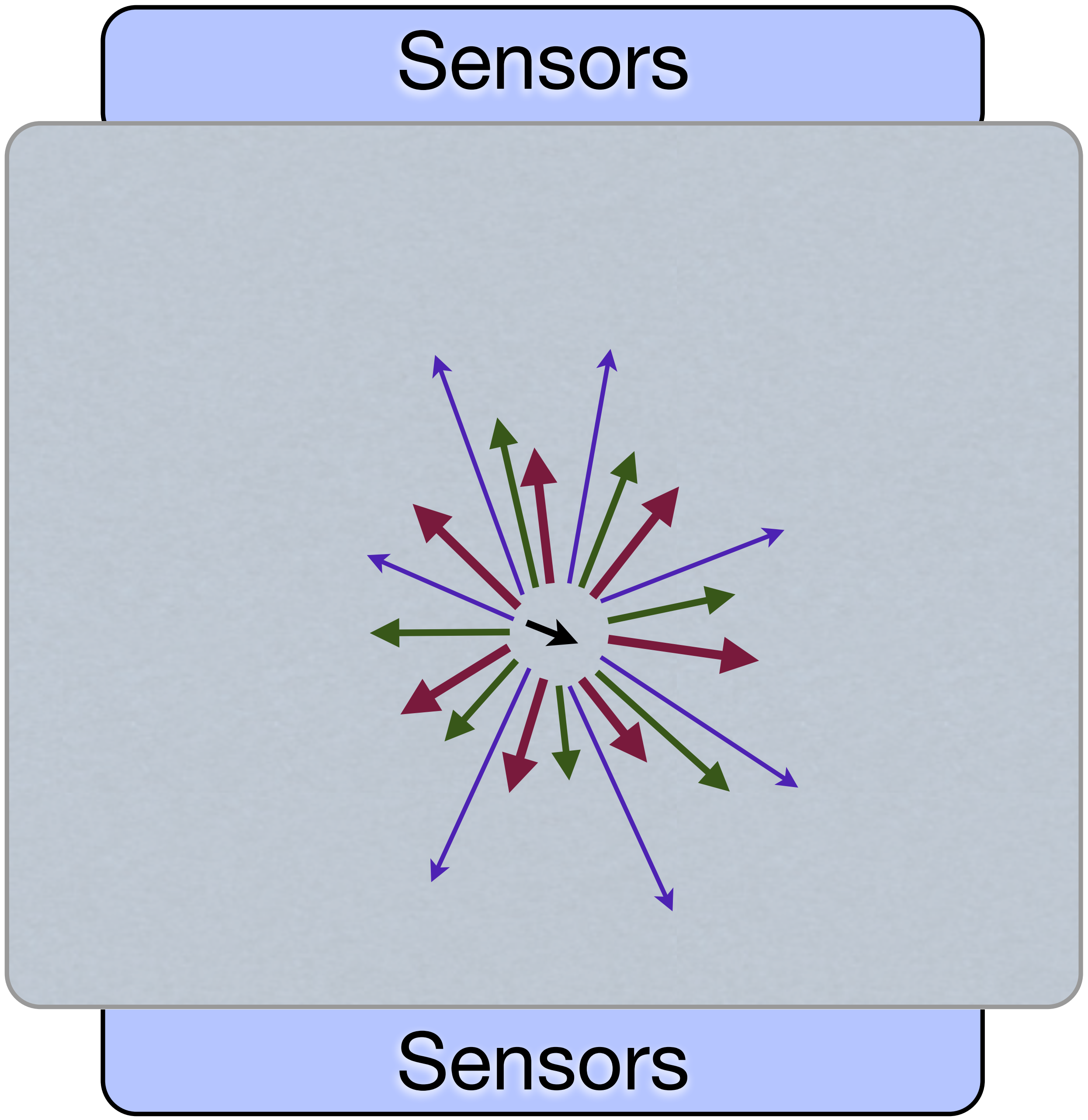


J. Liu TAUP 2011

Two Phase Experiments

CRESST, EDELWEISS, SuperCDMS,
DarkSide, LUX, PandaX, XENON,
and others.

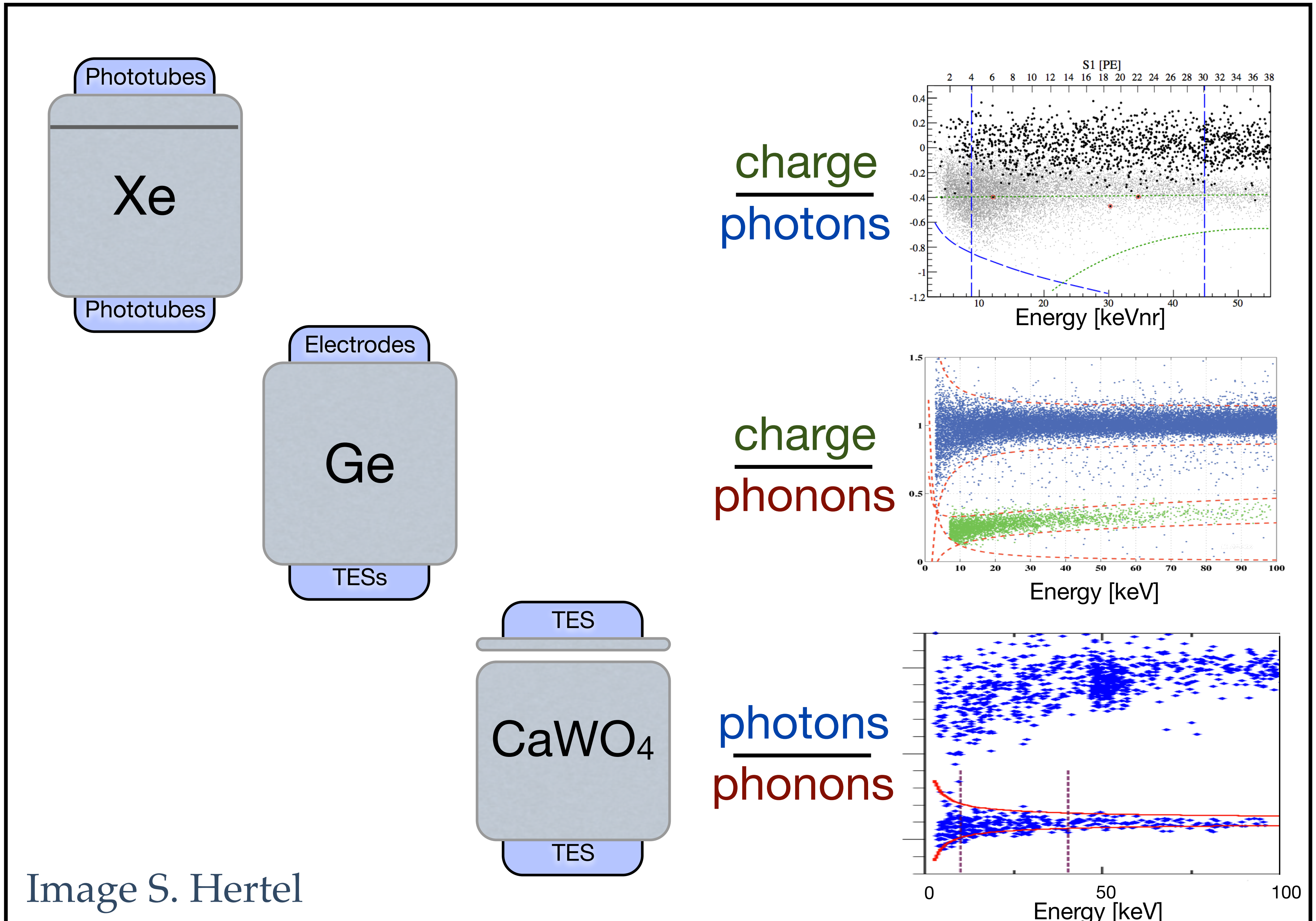
Two Phase Detectors



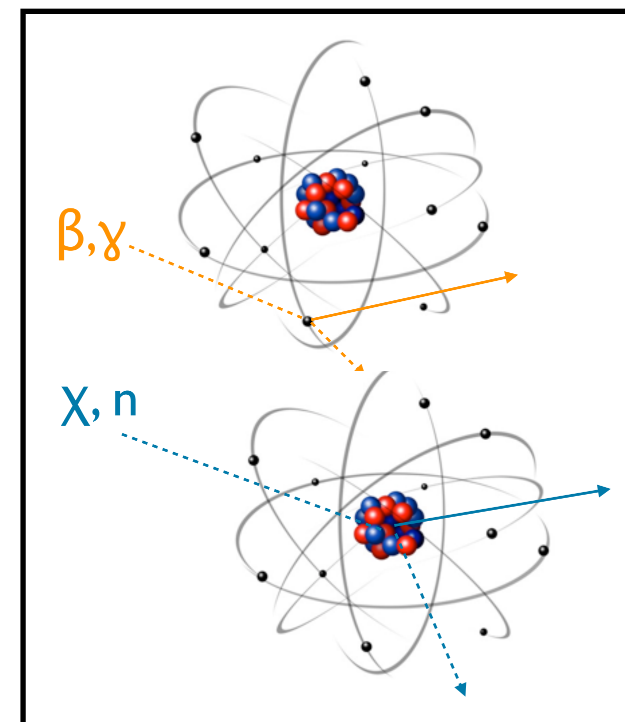
Phonons
Charge Carriers
Photons

Relative fractions depend on dE/dx

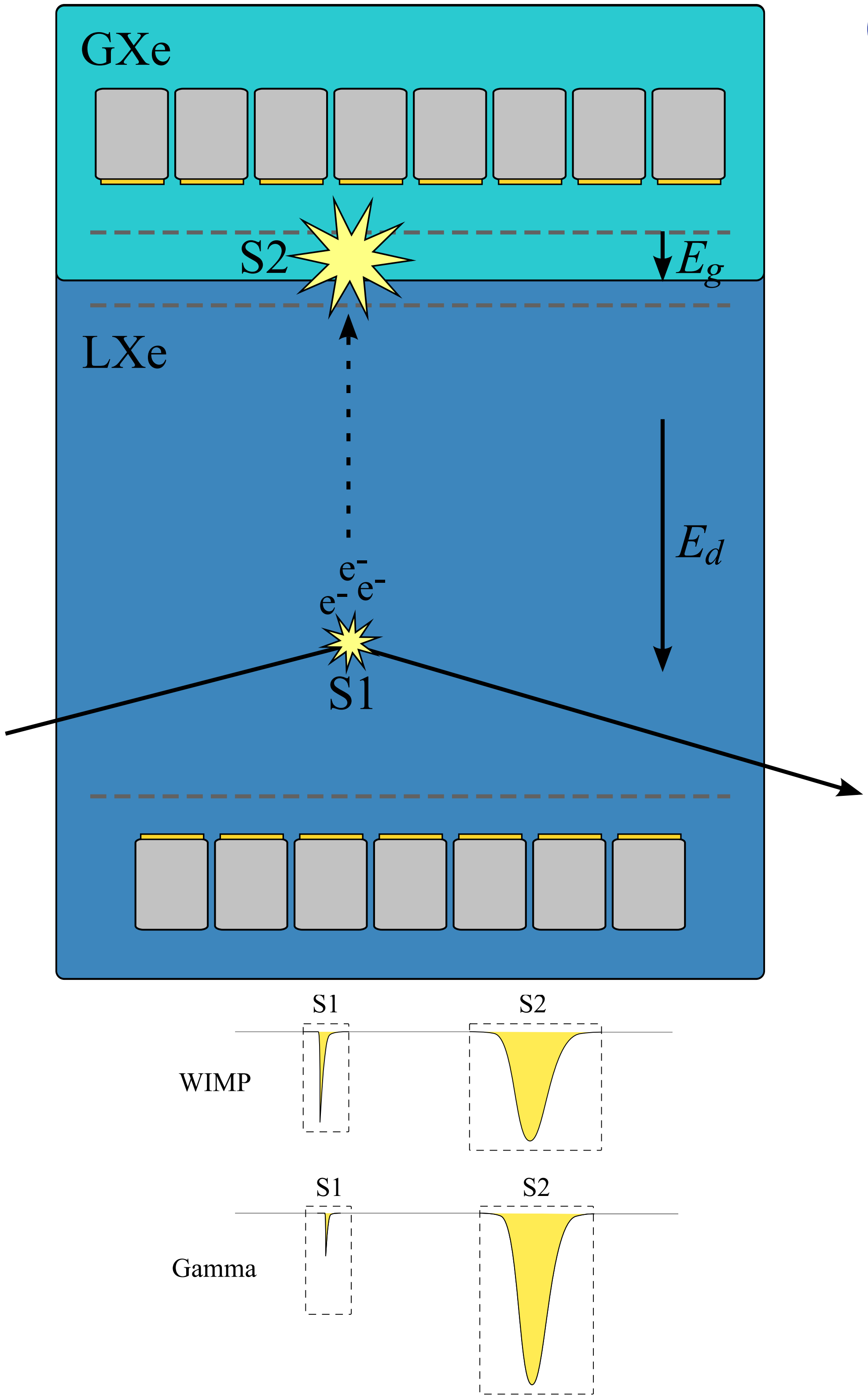
Particle Dependent Response



CRESST, DarkSide, Edelweiss, LUX, SuperCDMS, XENON, etc.



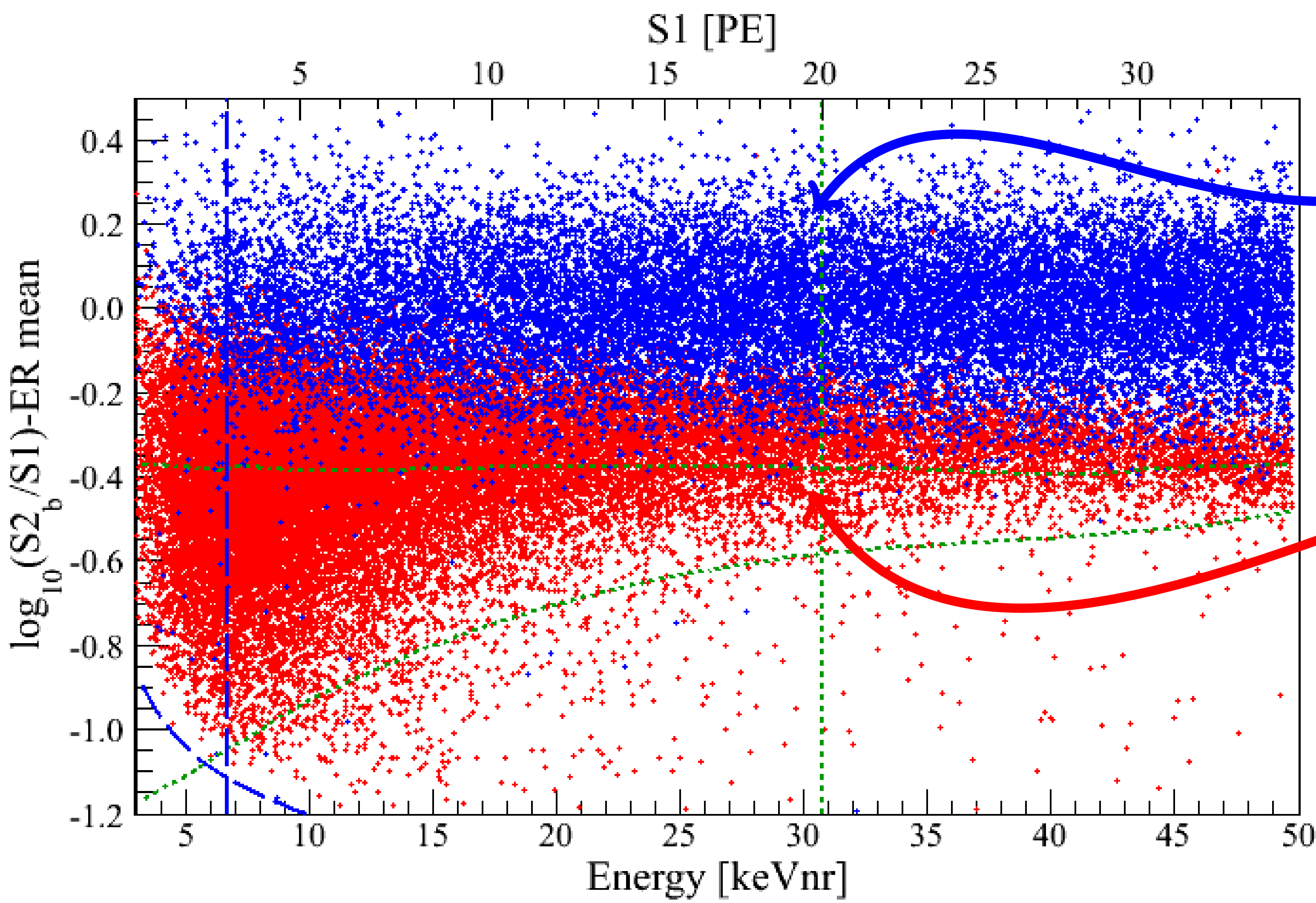
Dual Phase Time Projection Chambers



(XENON, LUX, DarkSide, PandaX and others)

- Interactions in the liquid produce excitation and ionization.
- Excitation leads to scintillation light emission
- Ionization electrons are drifted with an applied electric field into the gas phase (S1).
- In the gas phase, electrons are further accelerated producing proportional scintillation (S2).
- PMTs on the bottom and top of the chamber record scintillation signals.
- Distribution of S2 give xy coordinates, drift time gives z coordinates
- Ratio of S2/S1 discriminates electron and nuclear recoils

XENON Calibration Data



ER calibration data

^{60}Co and new ^{232} Th source

35$\times$ science data

NR calibration data

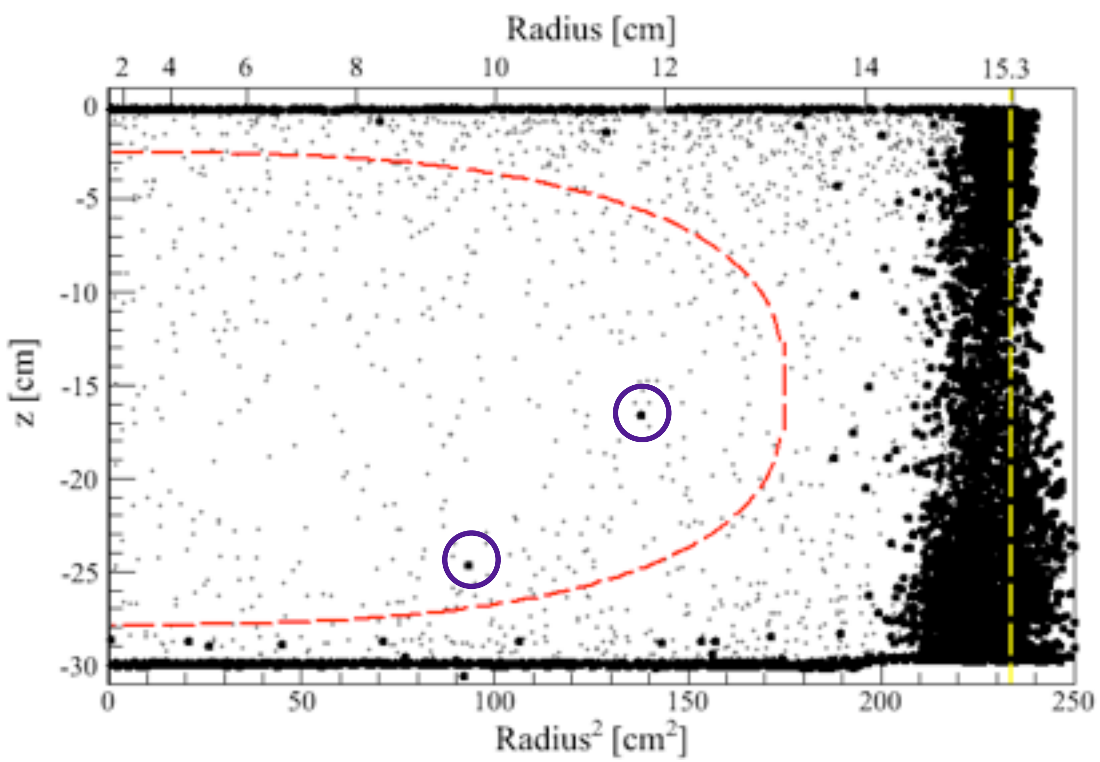
AmBe source

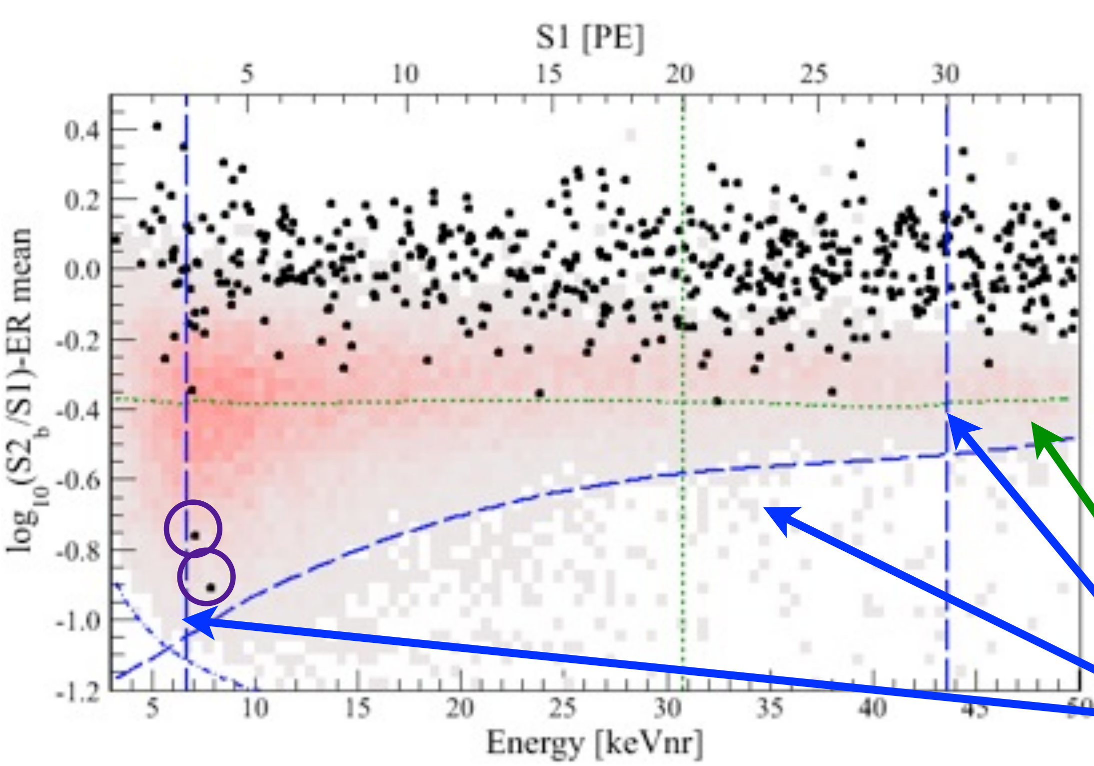
beginning and end of run

2013 Closing in on Dark Matter - E. Pantic

~99.5% ER rejection at 50% NR acceptance.

XENON 100 RESULTS





Phys. Rev. Lett. 109, 181391 (2012)

- 224.6 live days acquired from Feb. 2011 to Mar. 2012 in fiducial mass 34 kg liquid Xe.
- 2 events observed on a predicted background of 1.0 ± 0.2 background events (NR and ER 0.79 ± 0.16)
- Red shading (below) indicate nuclear recoil region measured by neutrons from ^{241}AmBe source.
- Grey dots (above) are events above the 99.75% ER rejection line.
- WIMP search region is restricted to 3 - 20 PE in S1.

99.75% ER Rejection Line
Profile Likelihood Analysis Threshold

Energy

Nuclear recoils are measured through a combination of scintillation light and ionization. The nuclear recoil energy is related to S1 by

observed
scintillation [PE]

[keV$_{nr}$]

$$E_{nr} = \frac{S1}{L_y L_{eff}} \times \frac{S_e}{S_r}$$

suppression of scintillation signal from electric field for ER and NR events

light yield
[PE/keVee]

scintillation efficiency
of NR in LXe

L_{eff} accounts for the quenching of the scintillation signal for a nuclear recoil.

$$L_{eff} \equiv \frac{S1(E_{nr})/E_{nr}}{S1(122keV_{ee})/122keV_{ee}}$$

122 γ line from
^{57}Co source

Energy - Continued

The nuclear recoil energy is related to S2 by

observed
scintillation [PE]

$$E = \frac{S2}{Y} \frac{1}{Q_y(E)}$$

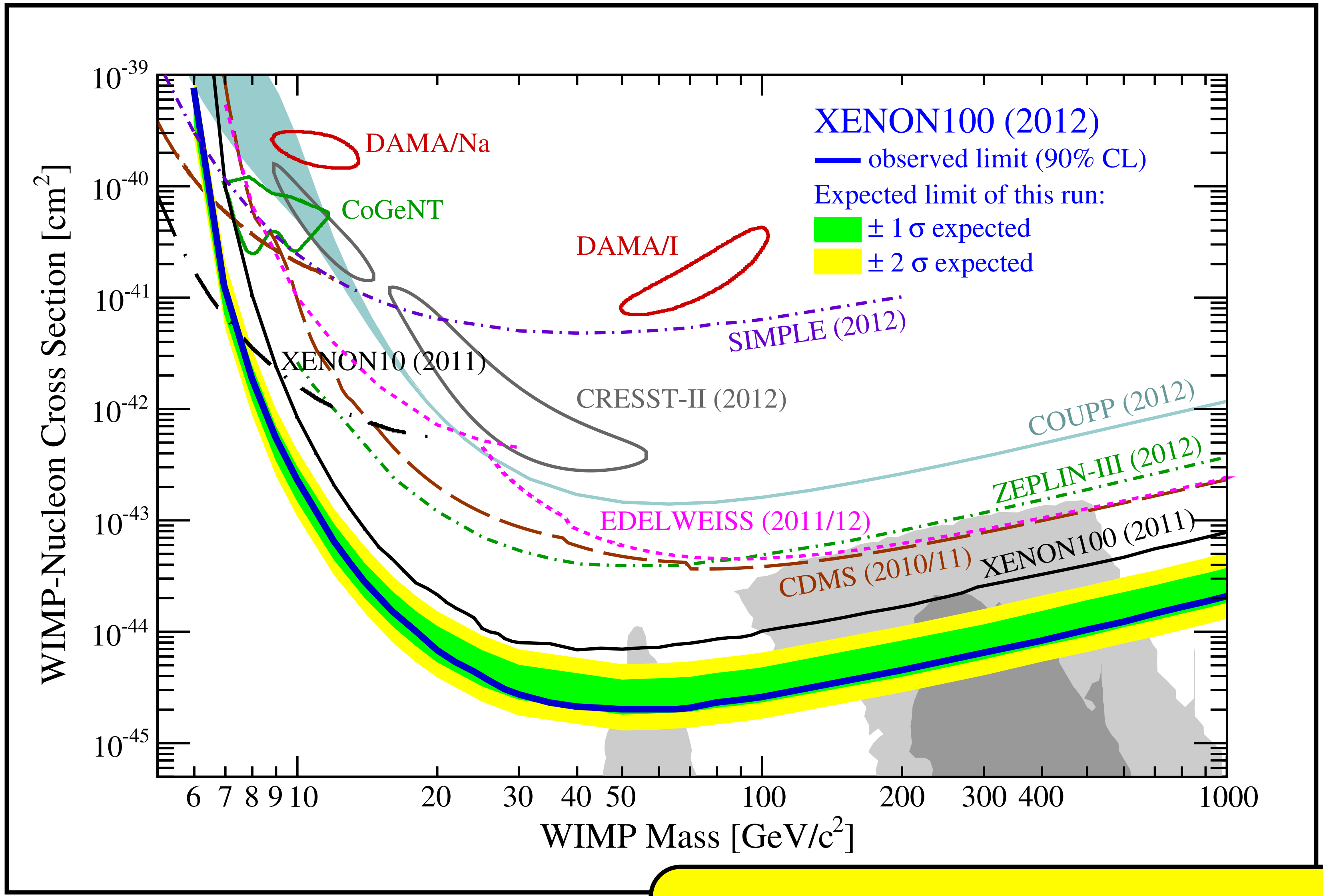
[keV_{nr}]

secondary
amplification factor
[pe/e^-]

number of free electrons
per unit energy

XENON100 Results

- Upper limit at 90% C.L. on the WIMP-nucleon cross section is 2.0 x 10-45 cm² for WIMPs of mass 55 GeV / c².
- XENON100 continues to acquire data!



Phys. Rev. Lett. 109, 181391 (2012)

Phonon and Heat Signals

(CRESST, EDELWEISS, SuperCDMS, ROSEBUD)

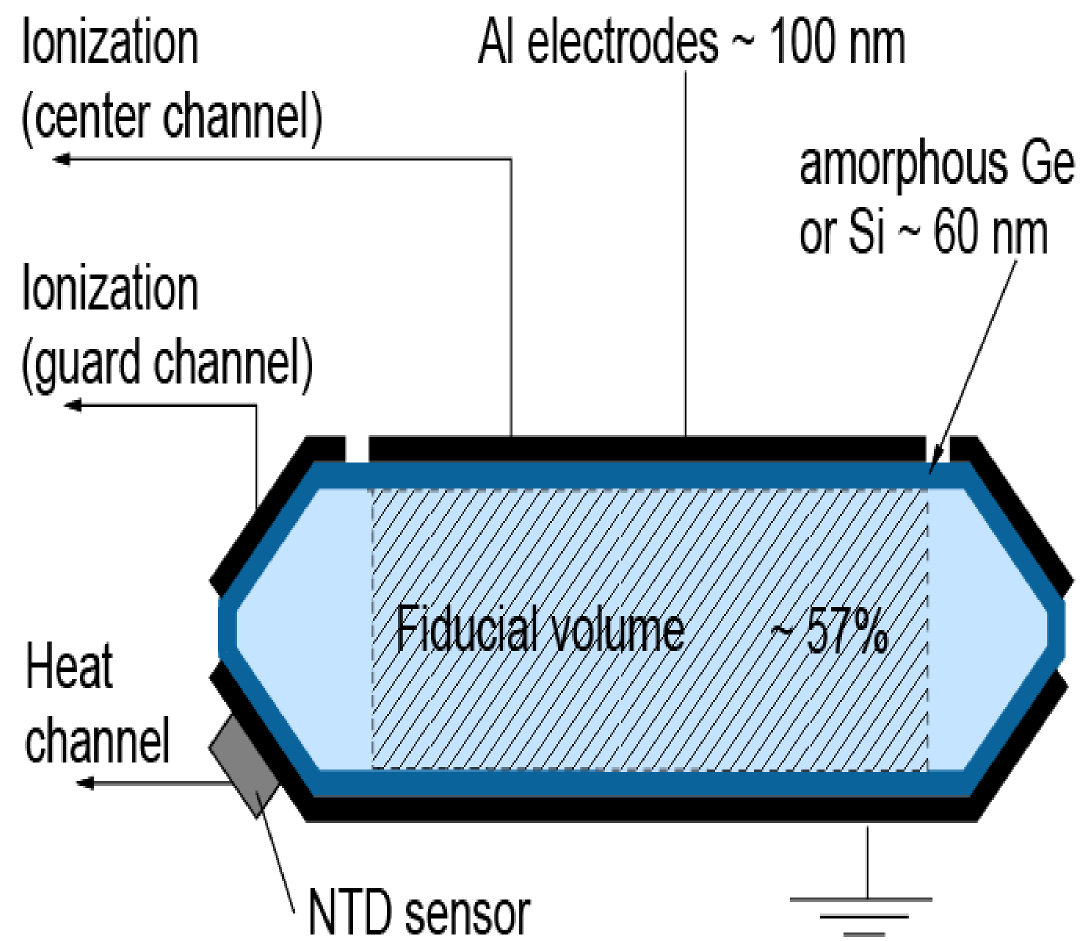
- Two families of sensors for phonon signal, themal and athermal
  - Thermal sensors - wait for the full thermalization of the phonons within the bulk of the detector and the sensor itself
  - Temperature increase is equal to the deposited energy over the heat capacity of the system.
- Two most widely used technologies to measure these signals are neutron doped germanium sensors (NTD) and transition edge sensors (TES)

NTDs

- NTDs are small Ge semiconductor crystals that have been exposed to a neutron flux to make a large, controlled density of impurity.
- NTD measures small temperature variations relative to T_0 which is set to be on the transition from superconducting and resistance regime with dependence of the resistance with temperature T

$$\exp\left(-\sqrt{\frac{T}{T_0}}\right)$$

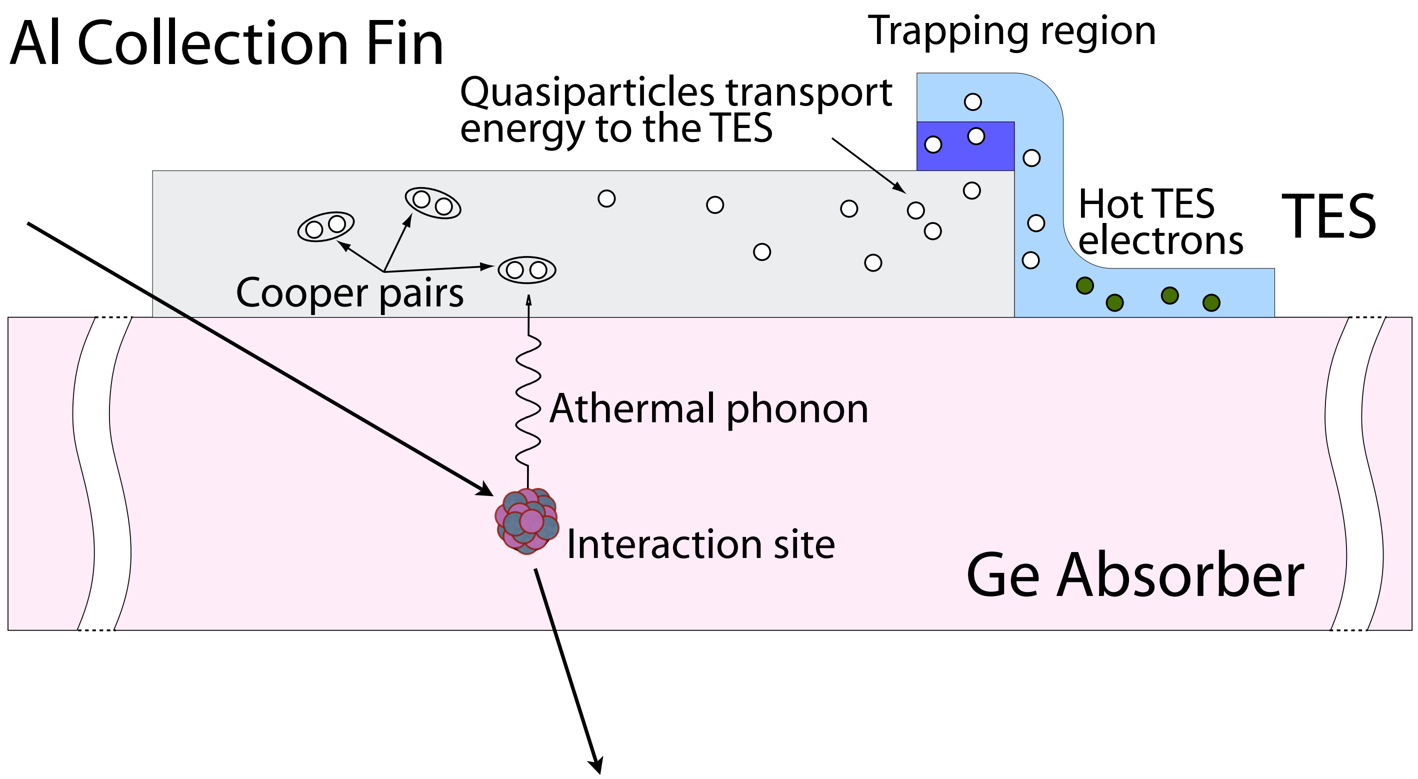
- Resistance is continuously measured by flowing current through it and measuring the resulting voltage.
- Sensors are glued onto detector.

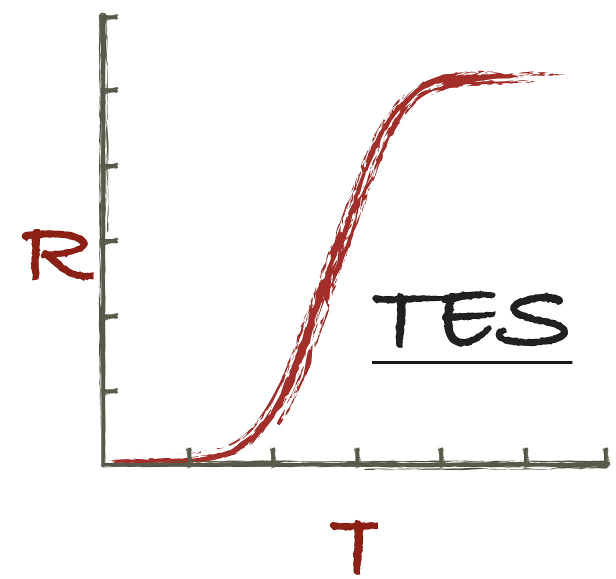


Schematic “Ge-NTD” EDELWEISS-II detector

TESs

ZIP detector schematic from CDMS II





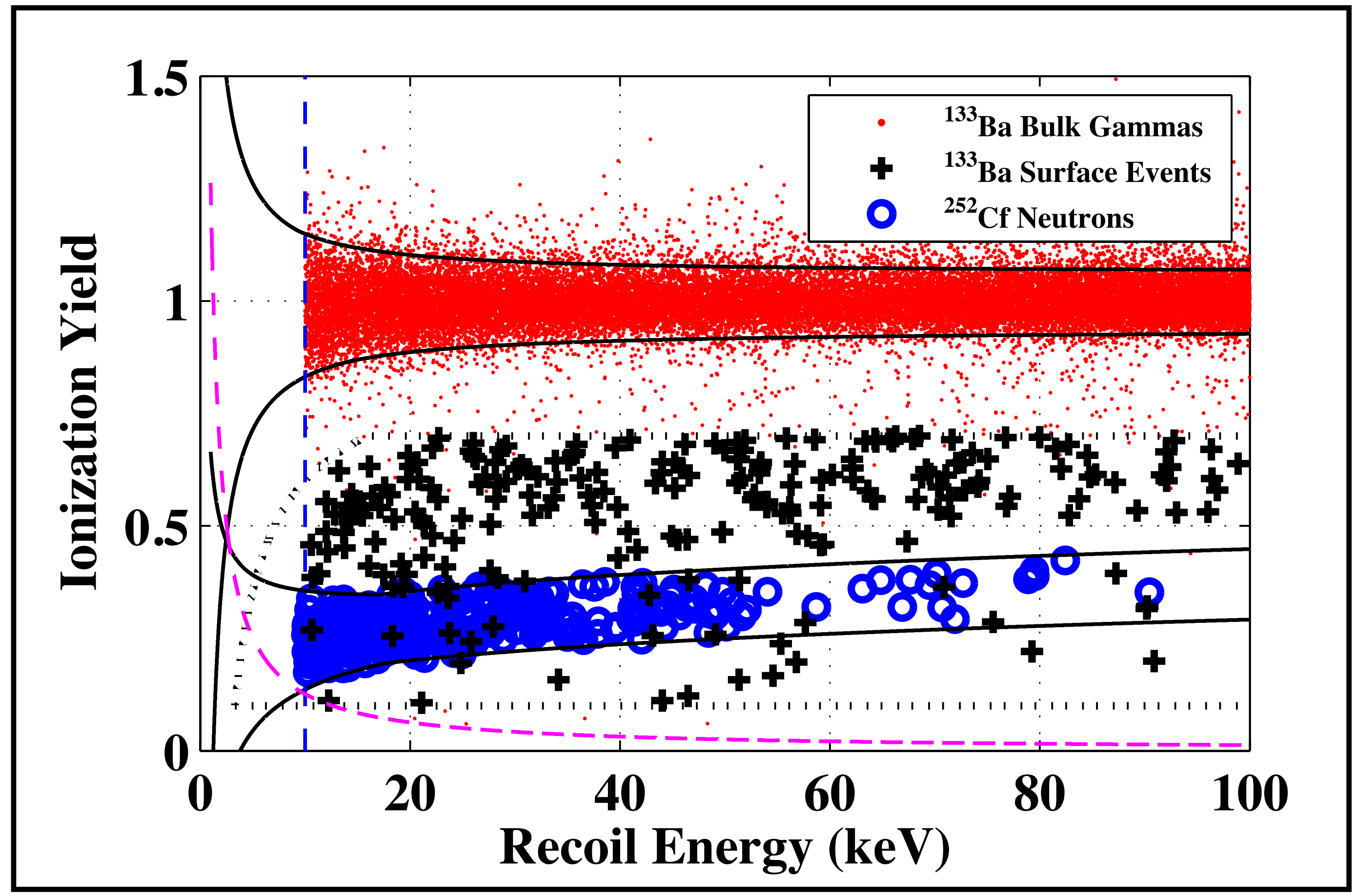
- TES is a thin superconducting film operated near its T_c.
- A heater with an electothermal feedback system maintains temperature at superconducting edge.
- Temperature changes are detected by a change in the feedback current, collected by a SQUID.

CDMS II

- Ionization yield (ionization energy per unit phonon energy) depends strongly on particle type.

- Most backgrounds produce electron recoils

- WIMPs and neutrons produce nuclear recoils



- Excellent yield-based discrimination for electron recoils: $< 10^{-4}$ mis-id probability

- Surface events suffer reduced ionization yield

Energy

The total energy (phonon) is given by

recoil energy
[keV_{nr}]

$$E_{tot} = E_r + \underline{eV_b N_Q}$$

total energy

Neganov-Luke
Phonons

"Luke" phonons are created when charge carriers are drifted across the crystal.

where V_b = bias Voltage (= 3.0 V for CDMS Ge detectors)

and the average number of electron hole pairs produced by an interaction

$$N_Q = \frac{E_R}{\epsilon}$$

epsilon = average energy
to create an e^-/hole pair
(3.0 V in Ge)

Energy - Electron Recoil

Assuming that an event is an ER, the recoil energy in [keVee] can be expresses as --

$$E_r(p_t) = p_t - eV_bN_Q = p_t - \frac{eV_b}{\epsilon}E_Q = p_t - E_Q$$

total phonon energy - Luke energy

$\epsilon_{Ge} = 3.0$ eV

Recall, that ionization yield is defined as

$$y = \frac{E_i}{E_r}$$

($E_i = E_r$ for ER events)

Thus, we can write

$$E_r = p_t - E_r \quad \Longrightarrow \quad \boxed{E_r = \frac{p_t}{2}}$$

recoil energy [keVee]

*A good reference is David Moore's thesis, Chapters 3 and 4 http://thesis.library.caltech.edu/7043/

Energy - Nuclear Recoil

Assuming that an event is a NR, a smaller correction for the Luke phonons is applied.

The mean ionization energy for nuclear recoils ($\mu_{Q,NR}(p_t)$) is determined using calibration data from a ^{252}Cf source.

$$E_r(p_t) = p_t - \mu_{Q,NR}(p_t)$$

[keV$_{nr}$] total phonon energy - Luke energy

where

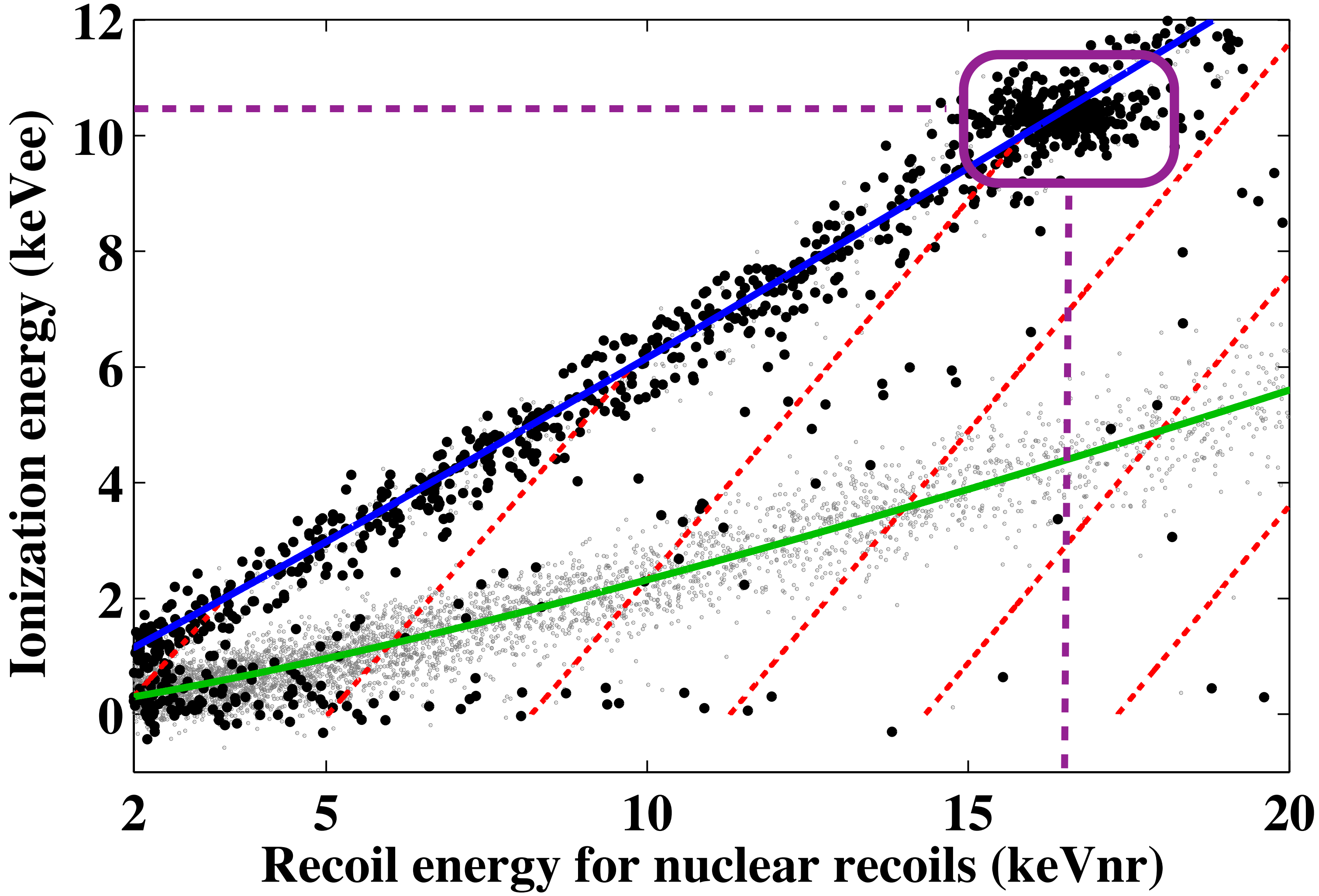
$$\mu_{Q,NR} = AE_r^B$$

Note: Due to the low ionization yield for low energy NR (~15% of total energy), any error due to uncertainties in the measurement of ionization yield is reduced by the same factor.

*A good reference is David Moore's thesis, Chapters 3 and 4 http://thesis.library.caltech.edu/7043/

keVee vs keVnr

Ionization energy vs recoil energy assuming NR scale consistent with Luke phonon contributions for NR.



constant "true" energy
mean NR (^{252}Cf)
mean of ER (^{133}Ba)

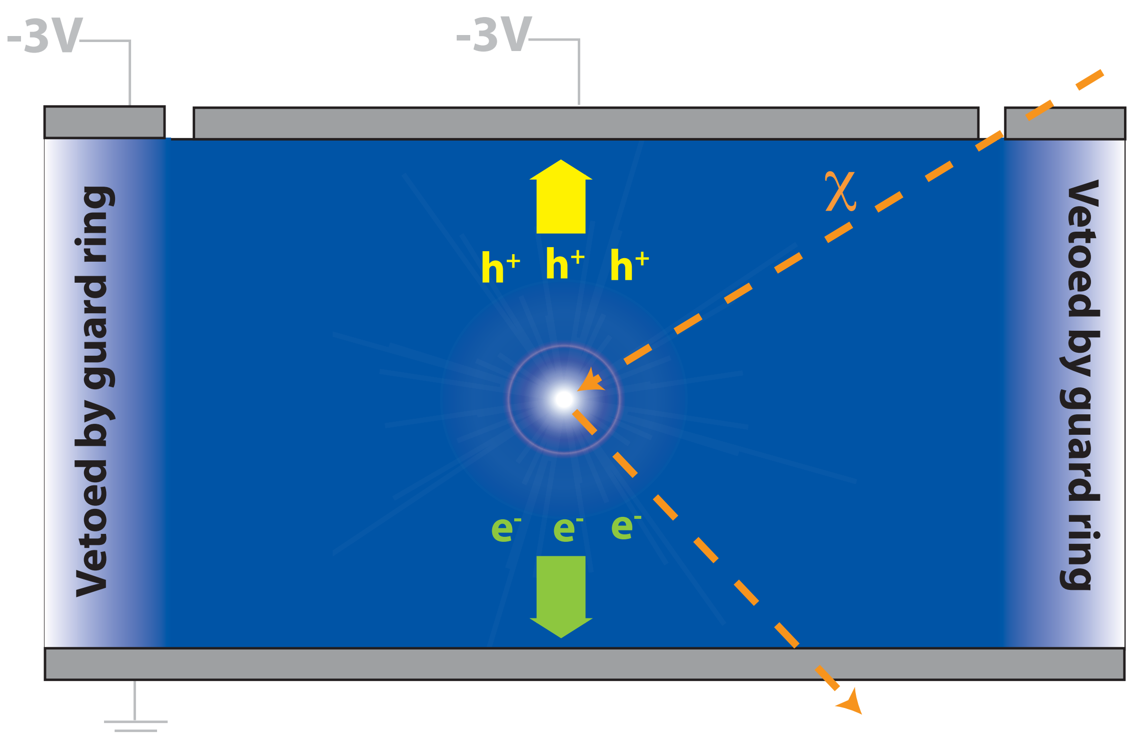
$$y = \frac{E_i}{E_r}$$

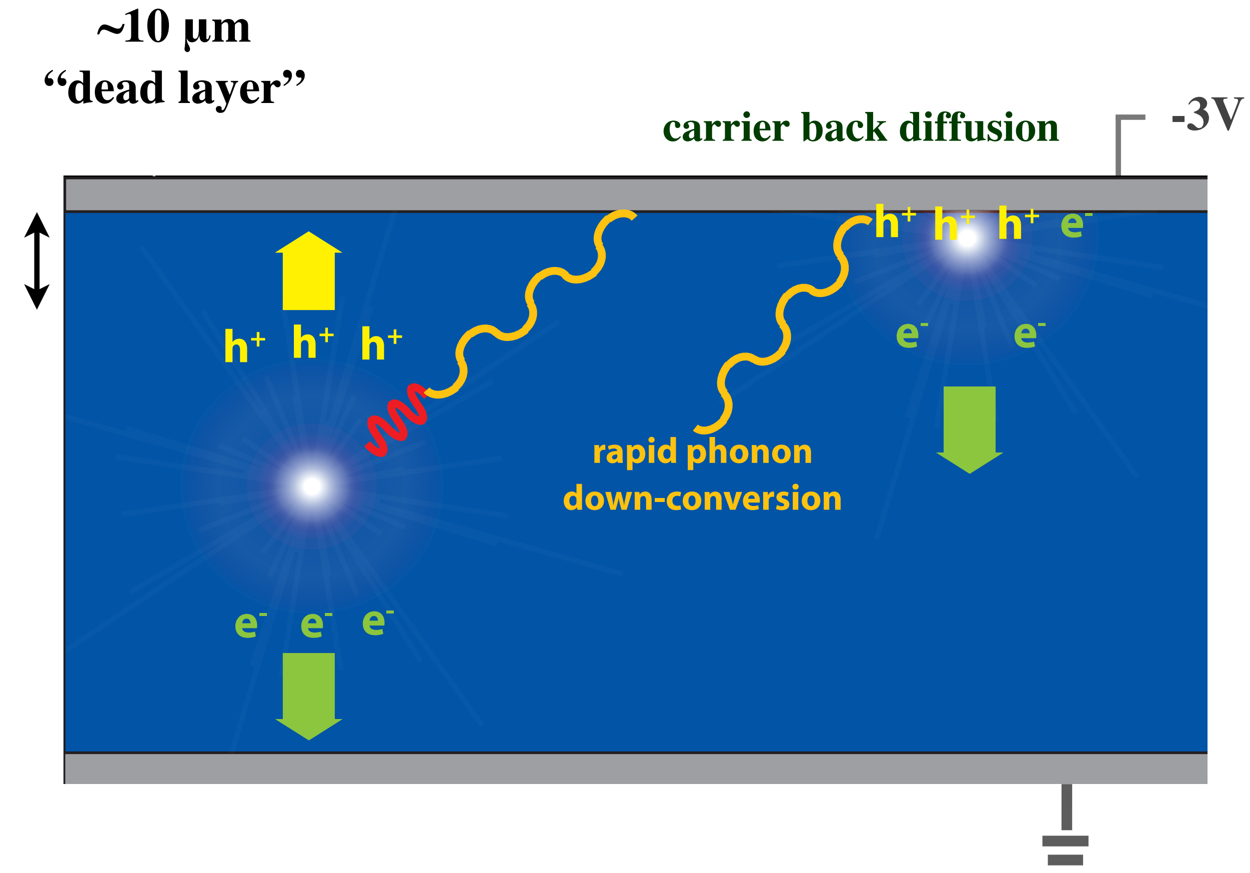
- ER recoils are pushed to higher energies using the NR scale.
  - Example - 10.4 keV_{ee} ER line appears at ~16 keV_{nr}

Summary

- The Luke correction for ER is larger than for NR.
- This effect results the ionization yield difference between ER and NR events.
- The ionization yield of a 50 keV nuclear recoil will lower than that of a 50 keV electron recoil by a factor of ~3.
- The energy dependence of ionization yield is described well by the Lindhard theory for stopping power of ions in matter.

Charge Carrier Back Diffusion

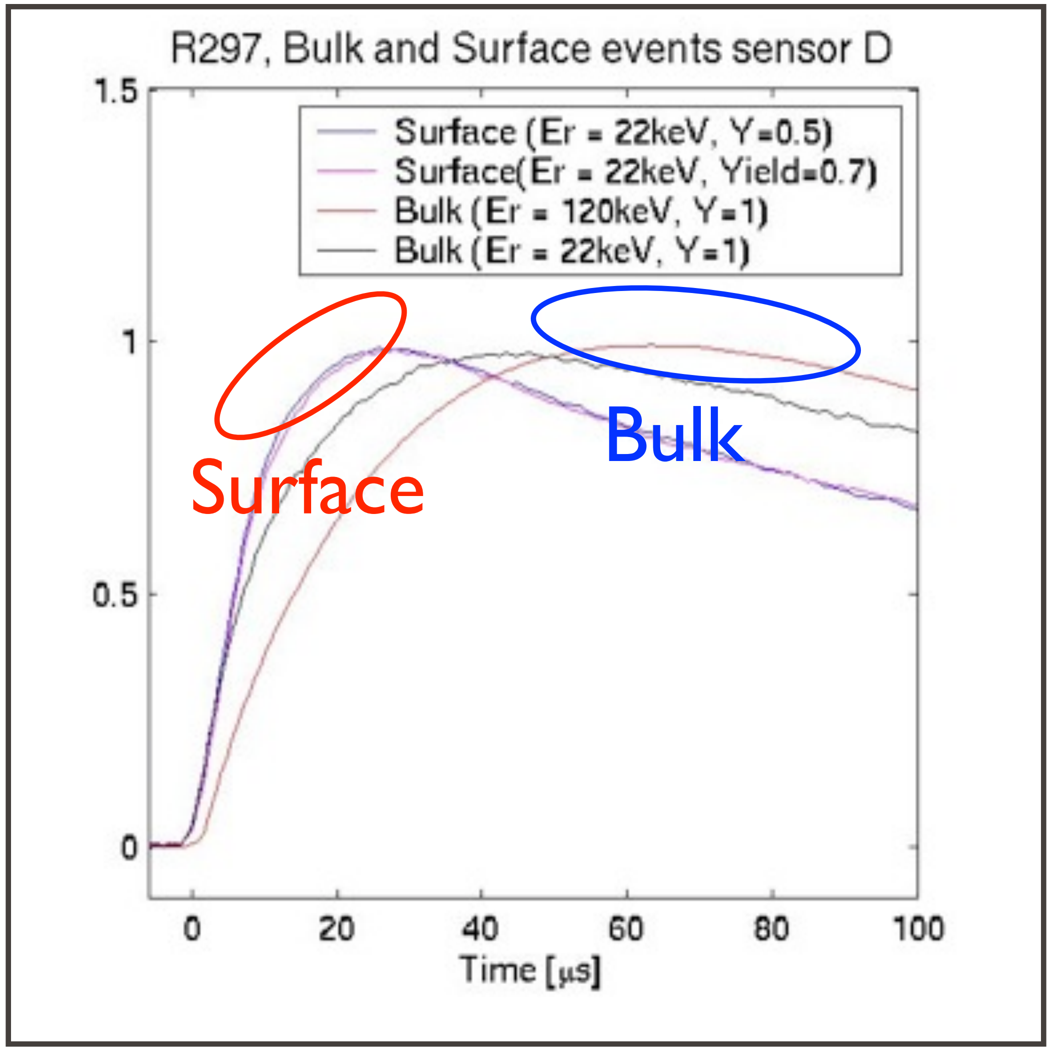


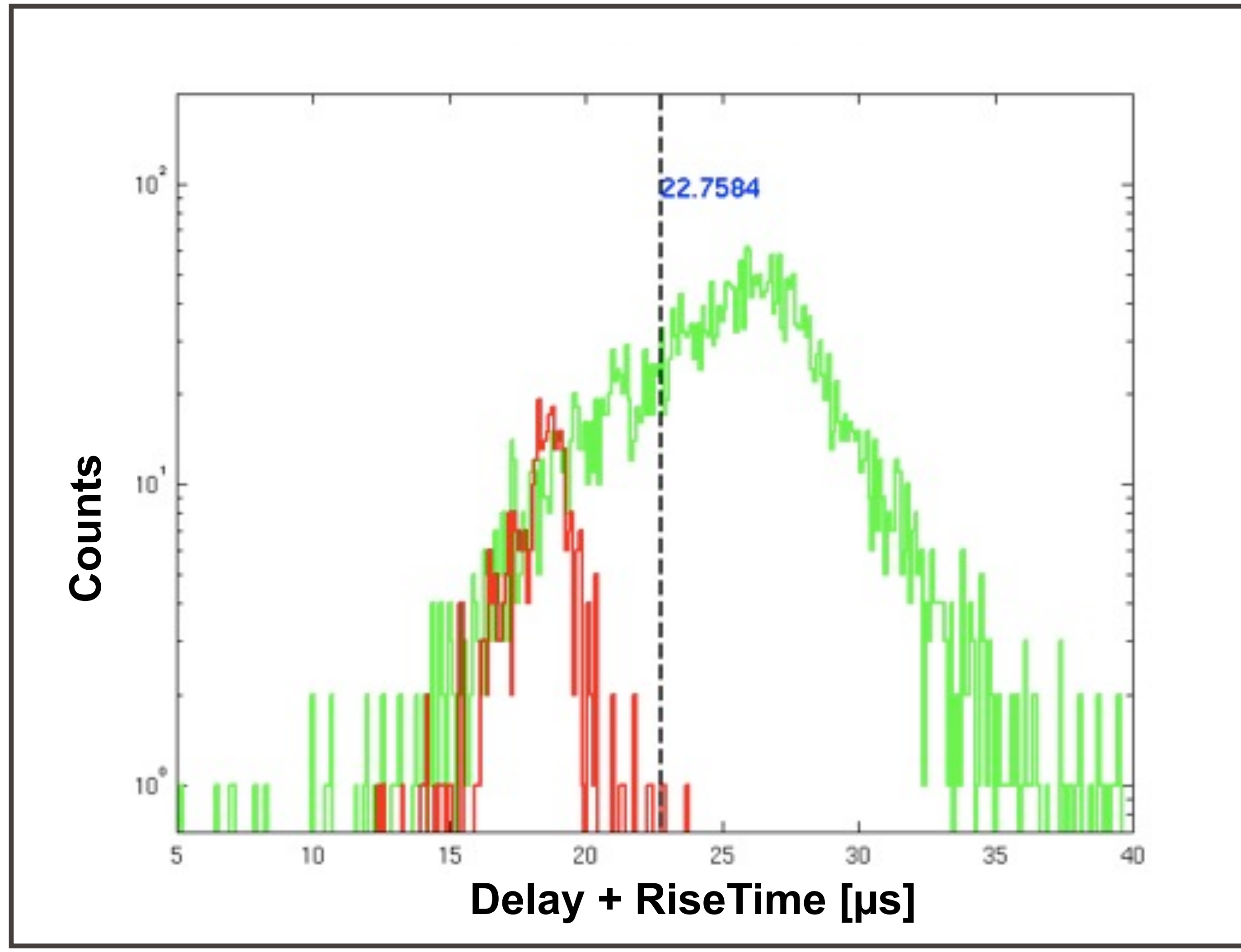


- Reduced charge yield is due to carrier back diffusion in surface events.
- "Dead layer" is within ~10µm of the surface.

Background Discrimination: Pulse Shape

☑ **Surface events rejected based on pulse shape**

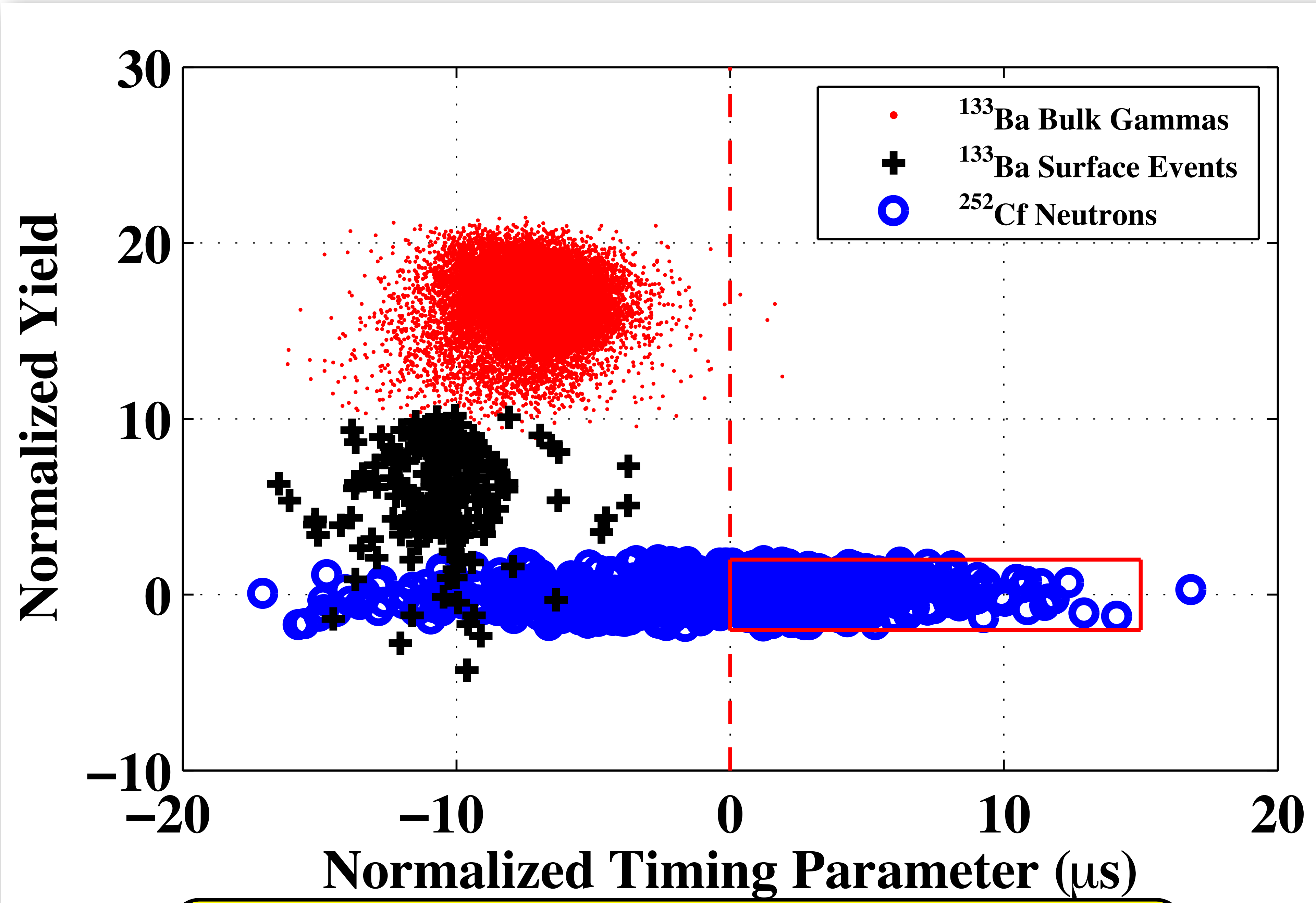




Phonons near surface travel faster, resulting in shorter risetimes of phonon pulse.

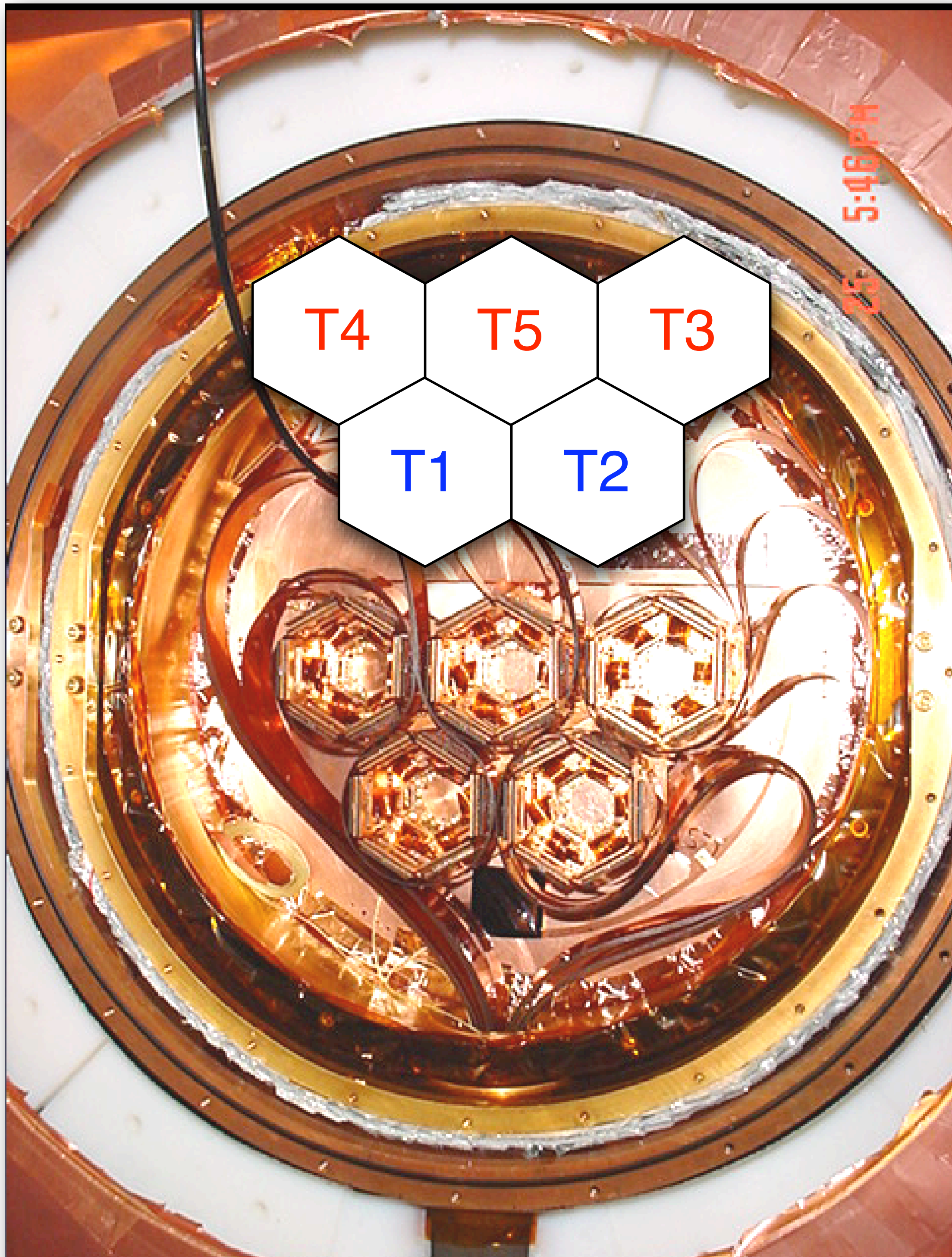
Selection criteria set to accept ~0.5 background events.

CDMS II

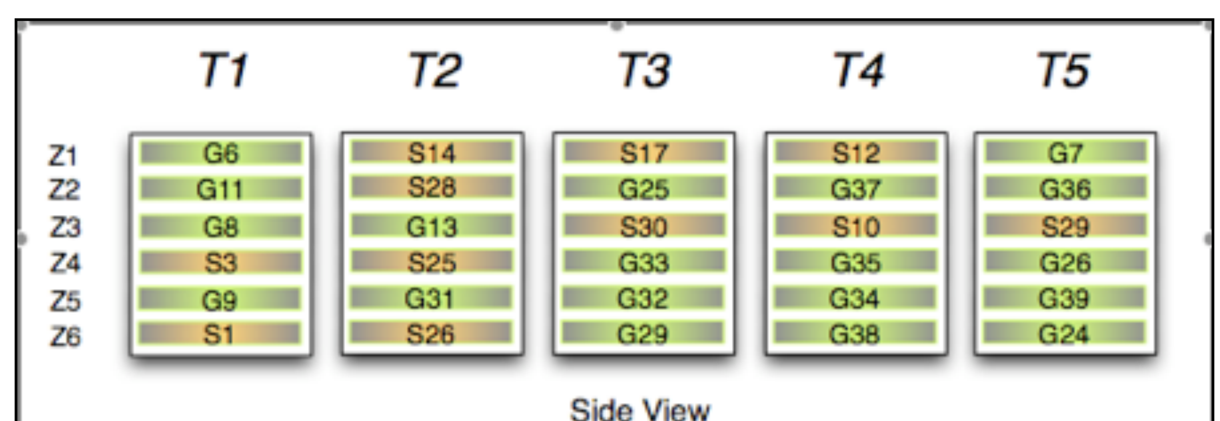


COMBINED ELECTRON RECOIL MIS-ID PROBABILITY: $< 10^{-6}$

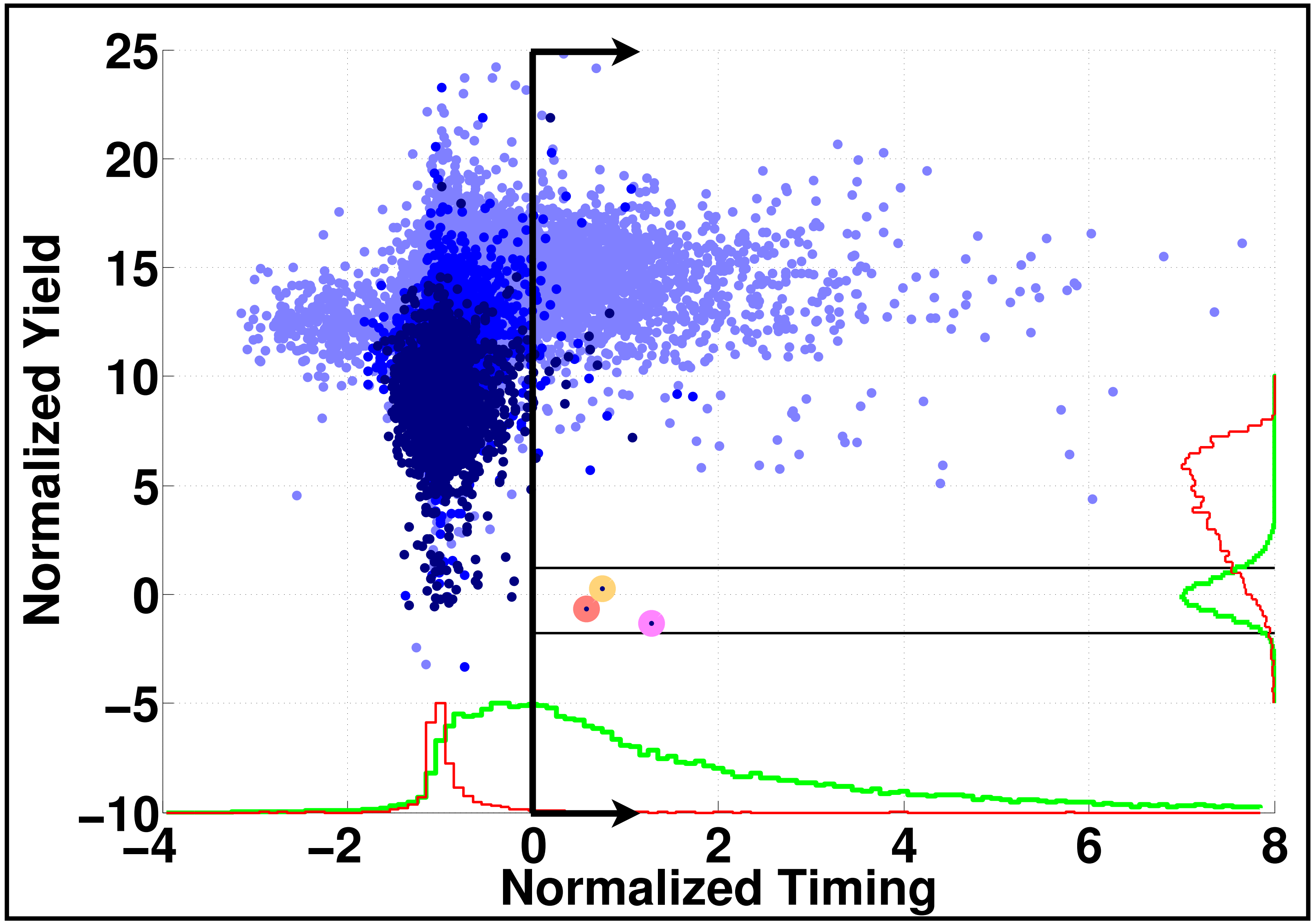
CDMS II - Recent Analysis



- 30 detectors installed and operated in Soudan from June 2006 - March 2009.
    - ~4.75 kg Ge, ~1.1 kg Si
- Seven Total Data Runs
    - R123- R124 (Oct. 2006 - July 2007)
        - 55.9 kg-days in 6 Si detectors
    - **R125 - R128 (July 2007 - Sep. 2008)**
        - **140.23 kg-days in 8 Si detectors**
    - R129 (Nov. 2008 - Mar. 2009)



Results: CDMS II Silicon Detectors



Observed 3 events.

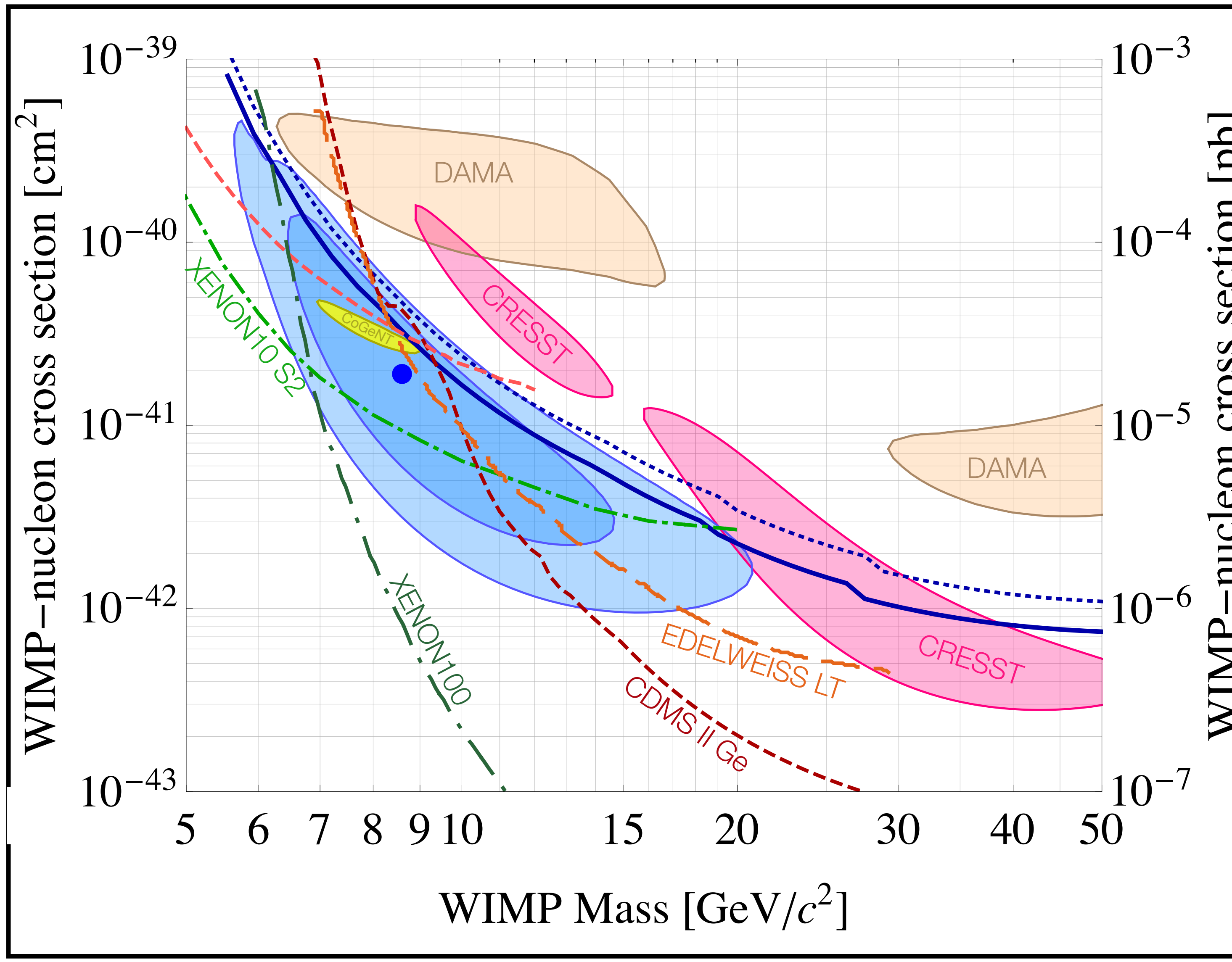
- Shades of blue indicate three separate timing cut energy ranges.
  - 7- 20 keV
  - 20 - 30 keV
  - 30 - 100 keV
- Background Estimate
  - < 0.13 neutrons from Cosmogenics & Radiogenics
  - $0.41^{+0.20}_{-0.08}(stat.)^{+0.28}_{-0.24}(syst.)$
  - < 0.08 ^{206}Pb recoils from ^{210}Pb decays

CDMS II Results

- A profile likelihood analysis favors a WIMP+background hypothesis over the known background estimate as the source of our signal at the 99.81% C.L. (~3σ, p-value: 0.19%)
- Does not rise to level of discovery, but does call for further investigation.

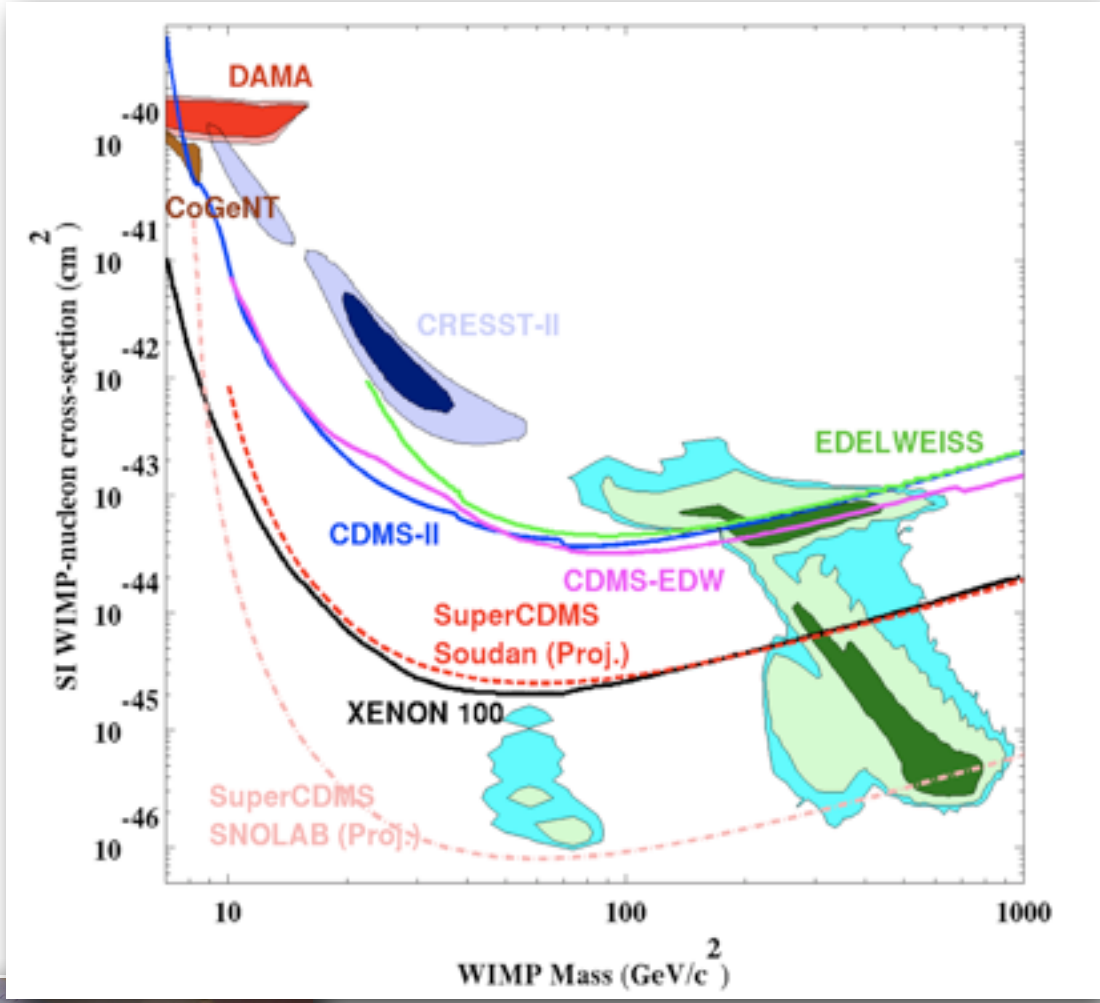
- The maximum likelihood occurs at a WIMP mass of 8.6 GeV / c² and WIMP-nucleon cross section of 1.9 x 10^{-41}.

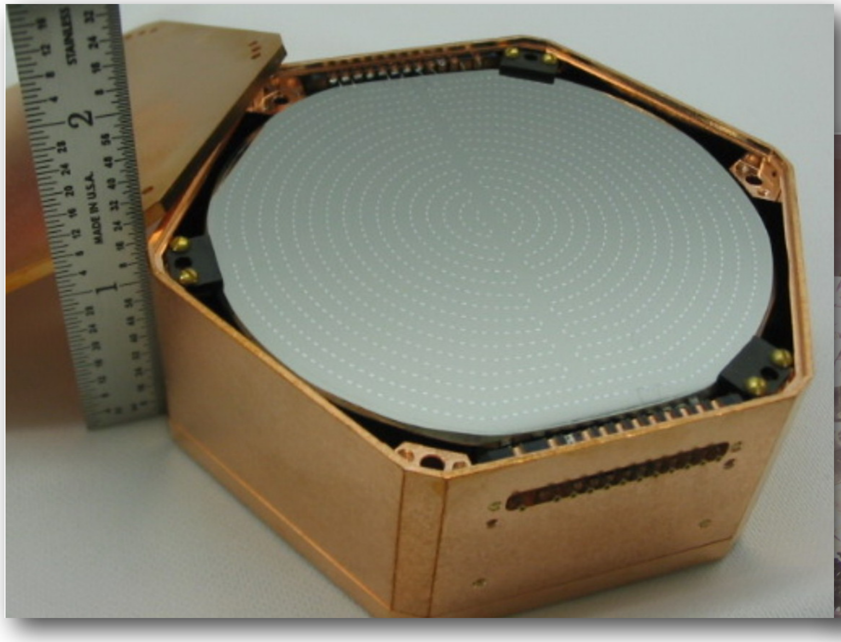
CoGeNT (2013)
CRESST−II (2012)
DAMA/LIBRA (2008)
XENON100 (2012)
XENON10 S2 (2013)
EDELWEISS Low−threshold (2012)
CDMS II Ge (2010)
CDMS II Ge Low−threshold (2011)
90% Upper Limit
90% Upper Limit CDMS II Si Combined
Best fit,
68% C.L.,
90% C.L.,

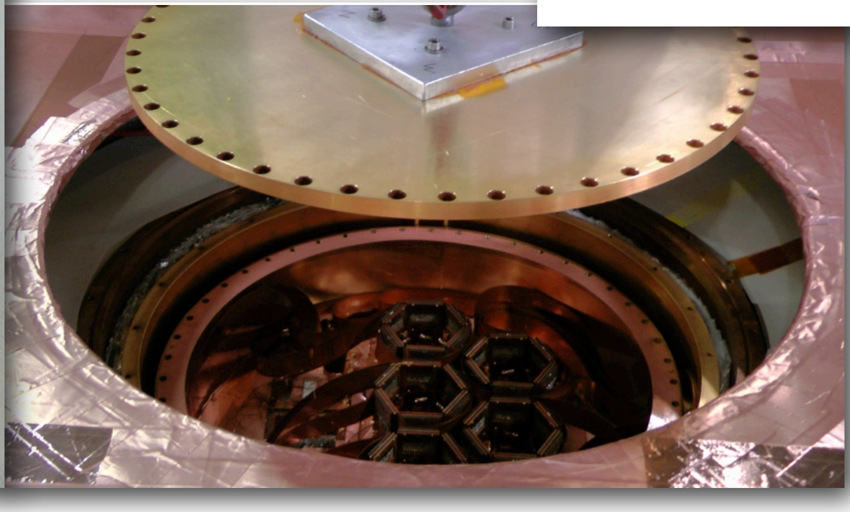


SuperCDMS at Soudan

- Currently operating 5 towers of of advanced iZIP detectors (~9 kg Ge) in the existing cryostat at the Soudan Underground Laboratory.
- After 3 years of operation, expected to improve sensitivity to spin-independent WIMP-nucleon interactions by a factor of ~10 over existing CDMS II results.





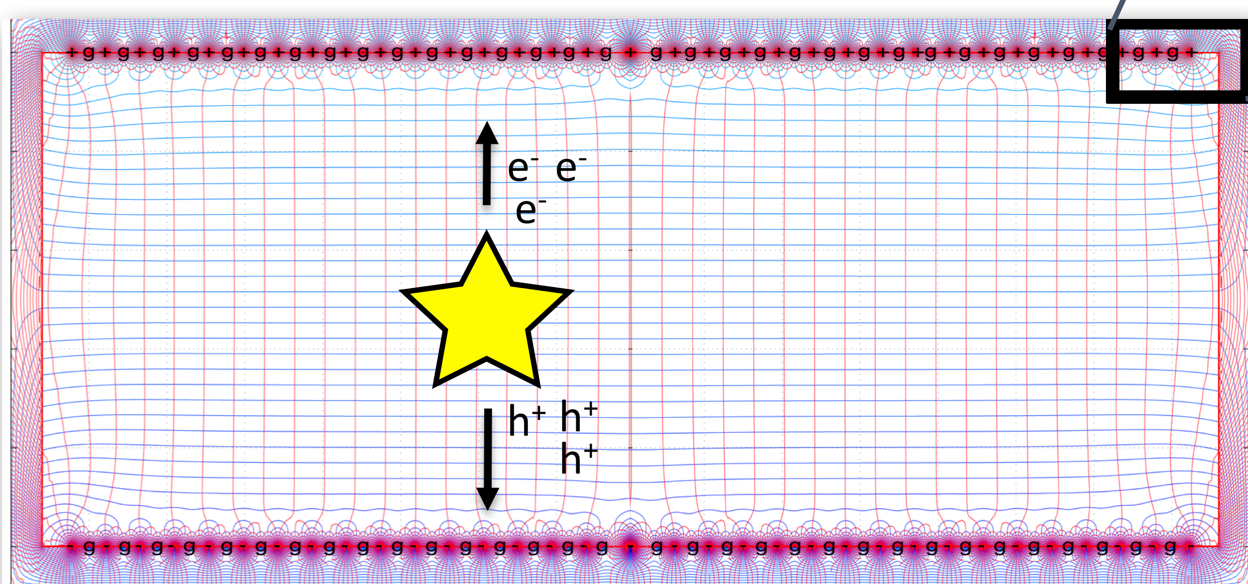


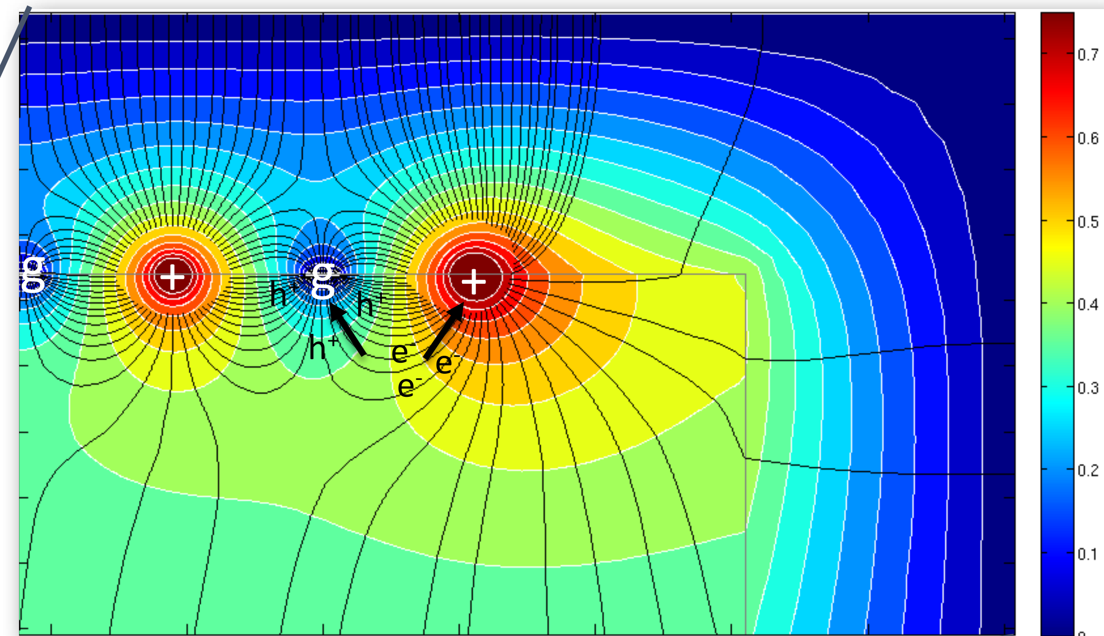
Installation complete Nov. 8, 2011. Operating with final detector settings since Mar. 2012.

SCDMS iZIPs: Charge Signal

Bulk Events:
Equal but opposite ionization signal appears on both sides of detector (symmetric)

Surface Events:
Ionization signal appears on one detector side (asymmetric)





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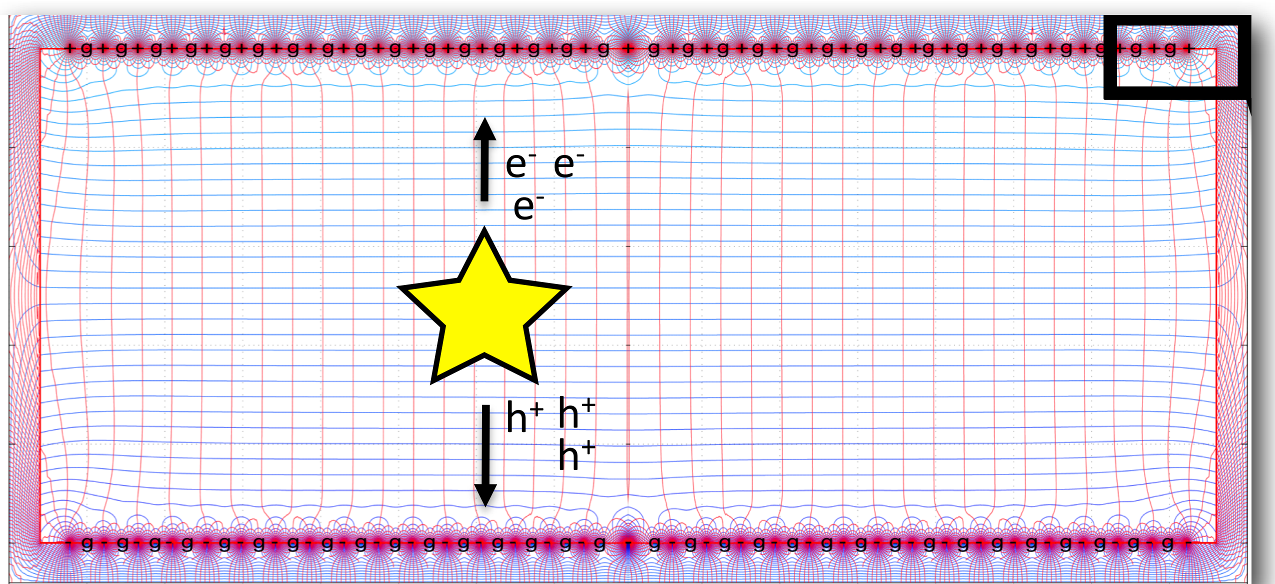
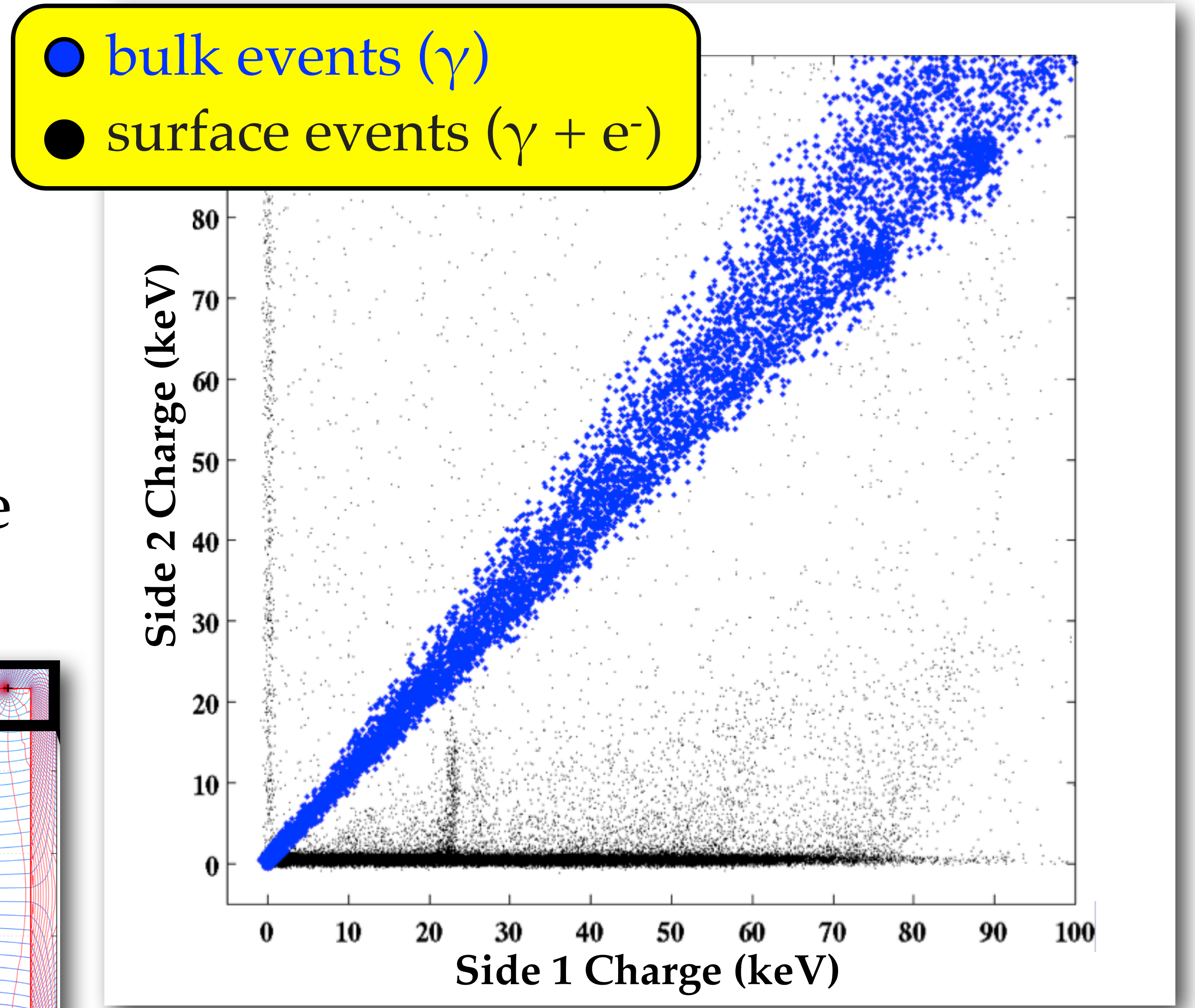
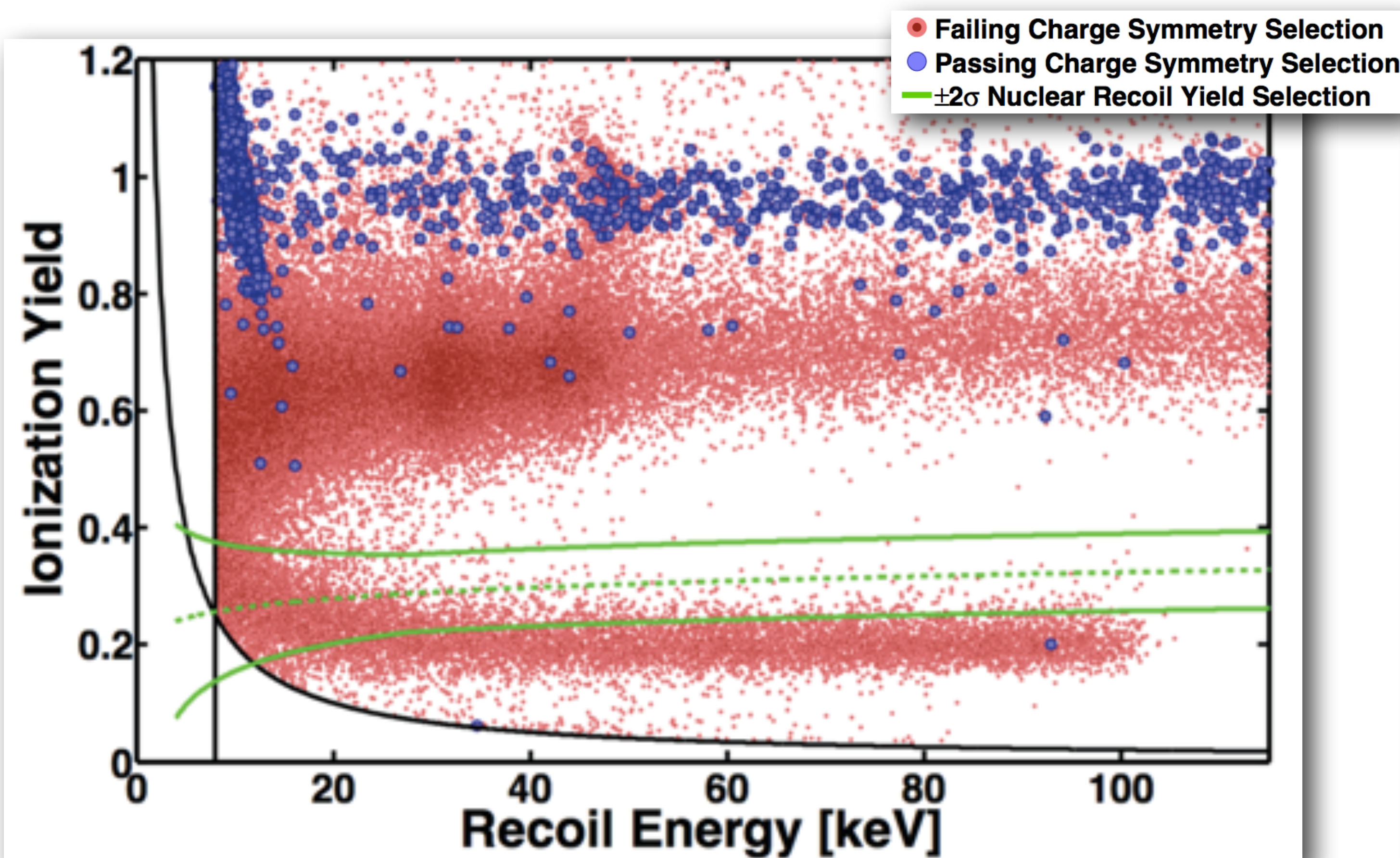
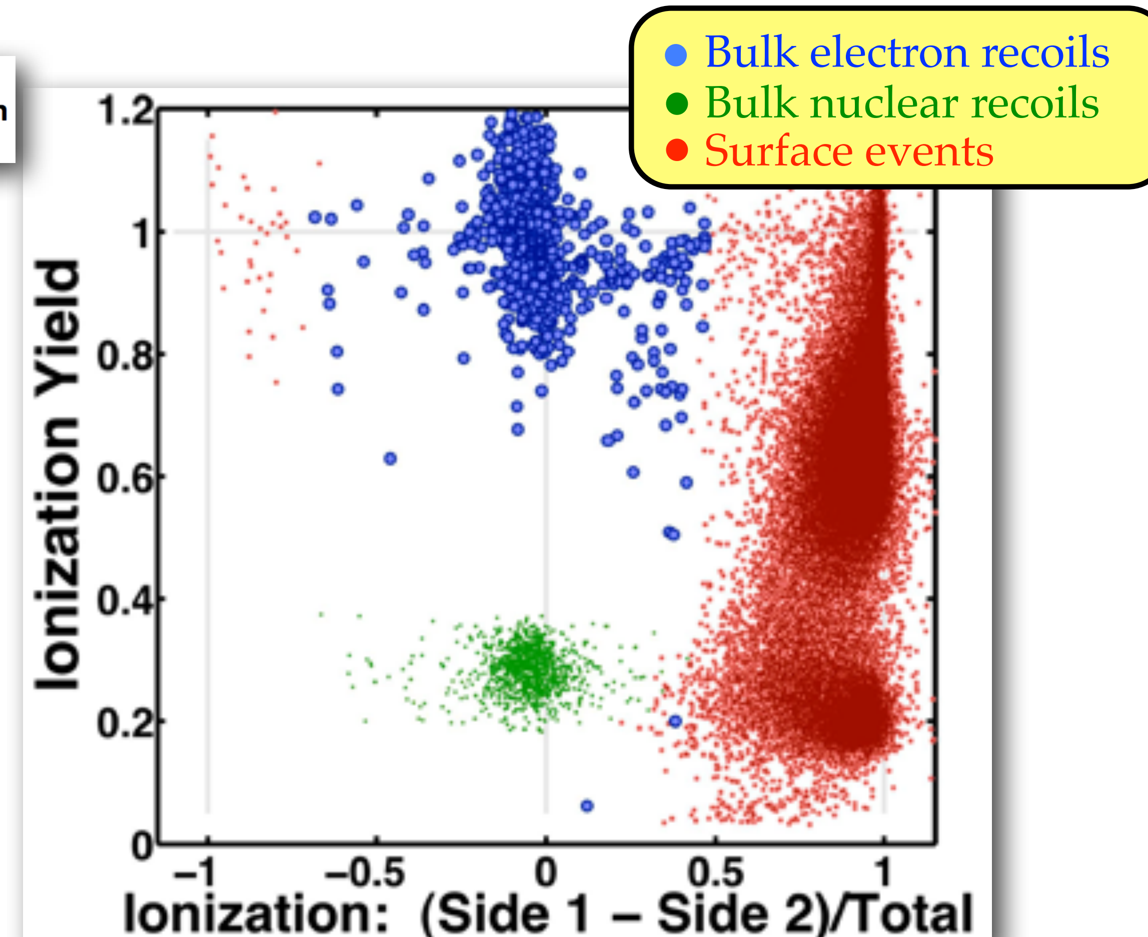




SuperCDMS: ^{210}Pb Test

Two ^{210}Pb sources were deployed with the detectors to test surface rejection capabilities of the new iZIP detectors.

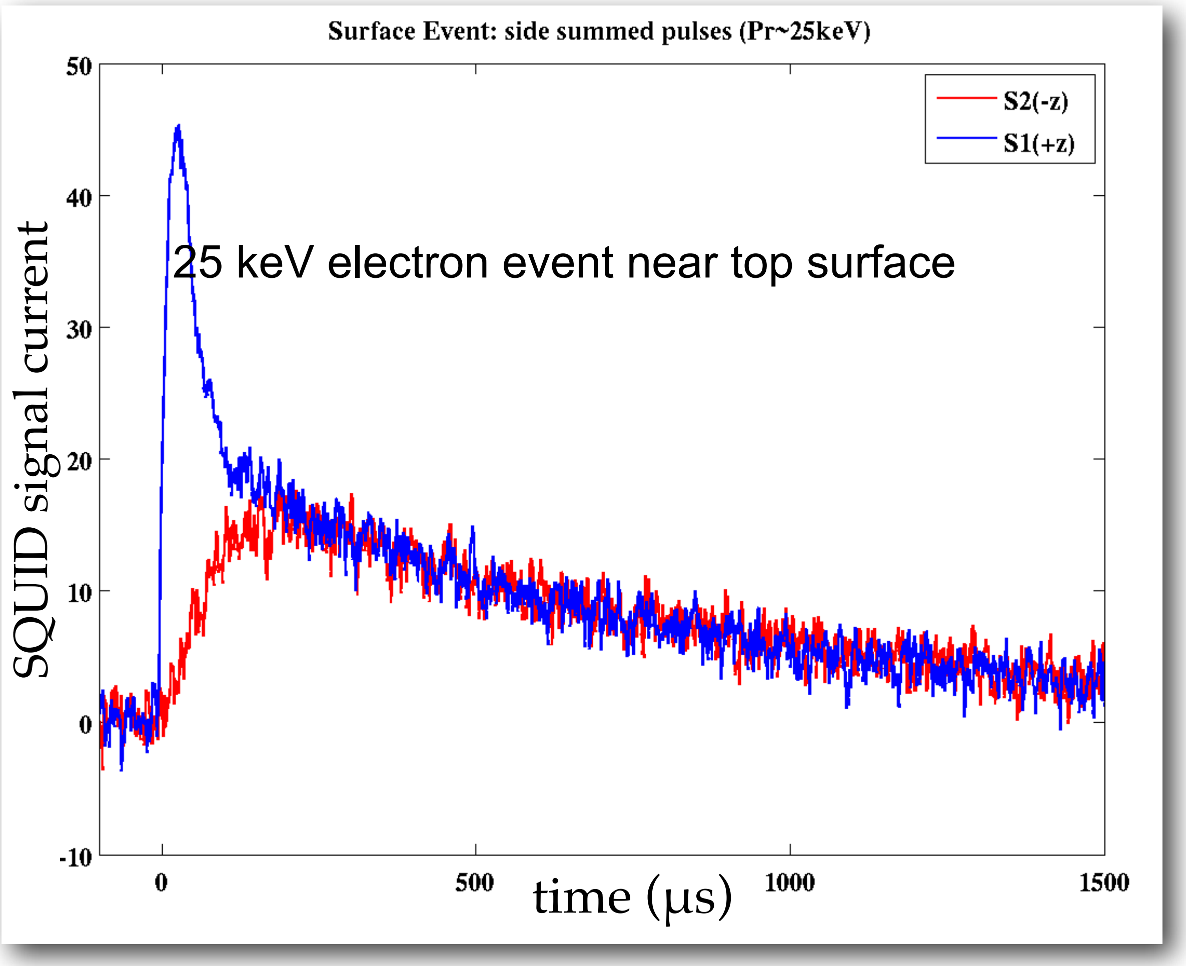


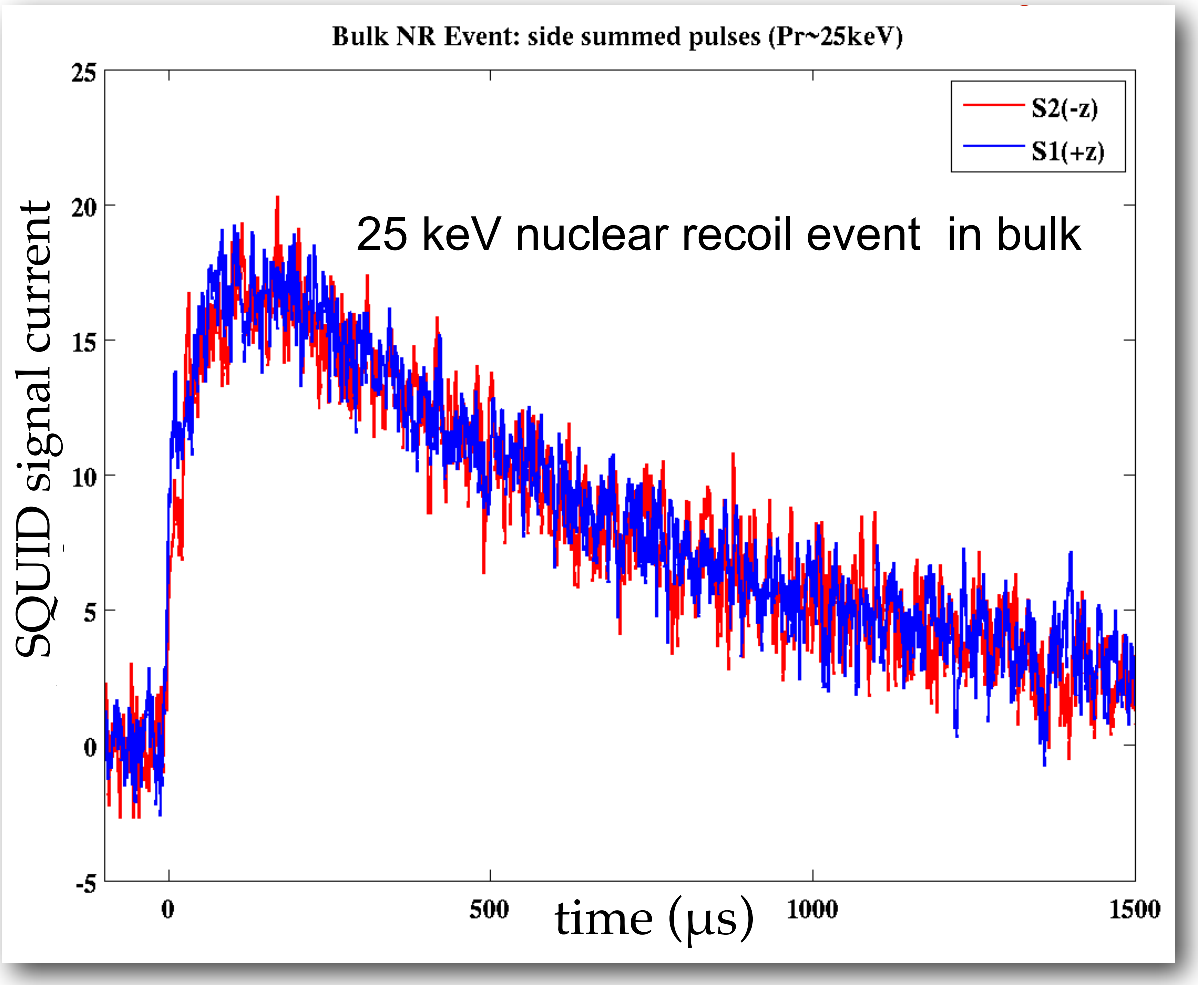


- 71,525 (38,178) electrons and 16,258 (7,007) ^{206}Pb recoil surface event collected from ^{210}Pb source in 905.5 (683.8) live hours
- In ~800 live hours 0 events leaking into the signal region (< 1.7×10^{-5} @90% C.L. misID)

- ~50% fiducial volume (8-115 keVr)
- <0.6 events in 0.3 ton-years
- Good enough for a 200 kg experiment run for 4 years at SNOLAB!

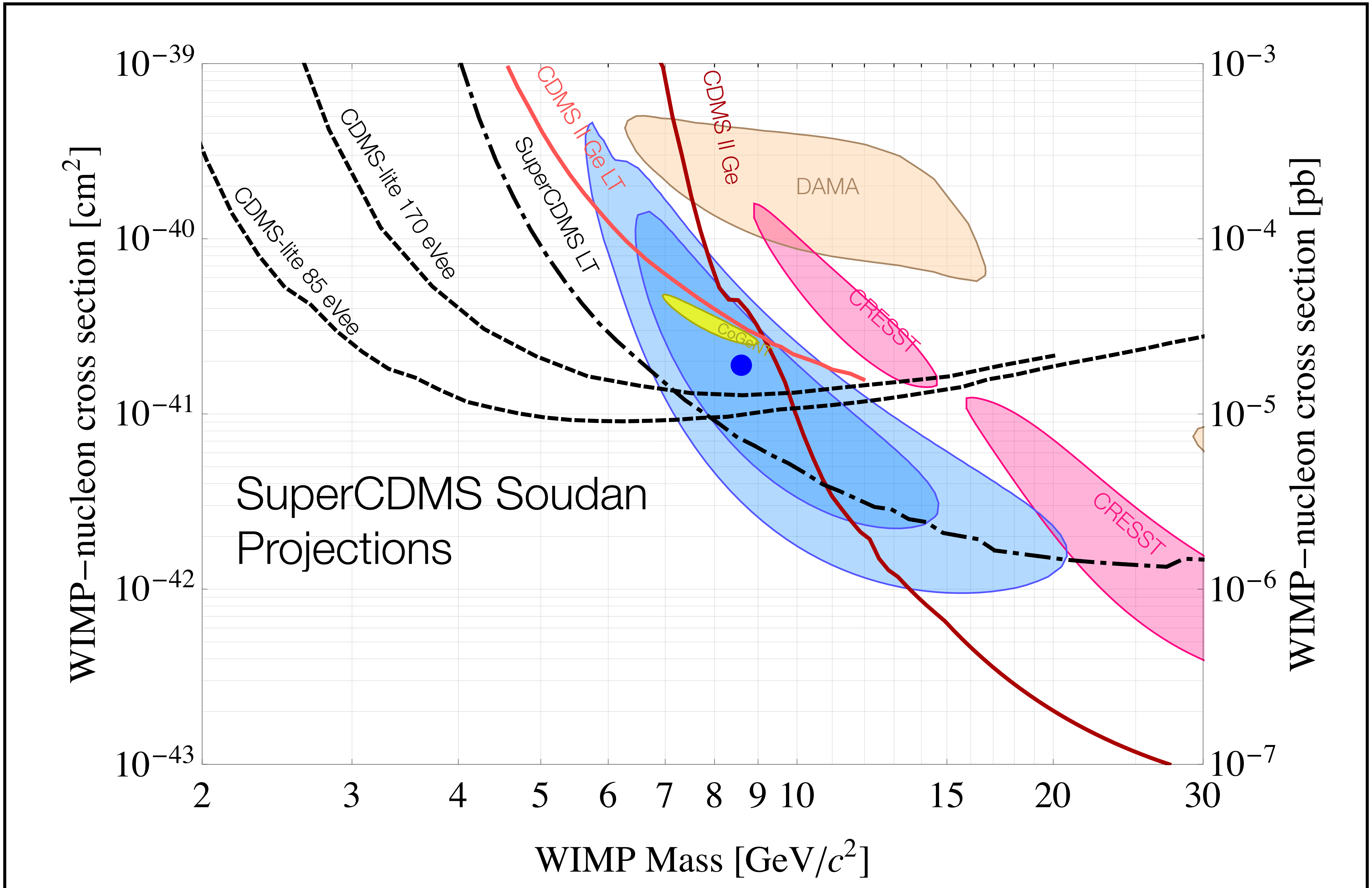
SuperCDMS: Phonon Signal



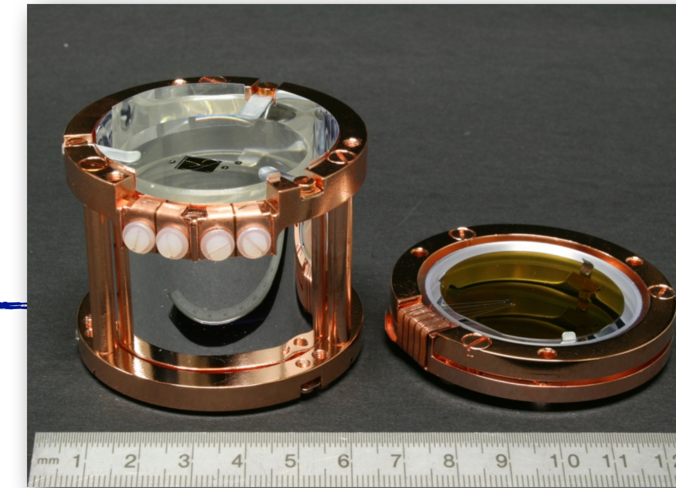


- Phonon timing pulse information still possible.
    - Surface electron vs bulk nuclear recoil event discrimination
- PULSE SHAPE HAS NOT YET BEEN USED! (It's not needed.)

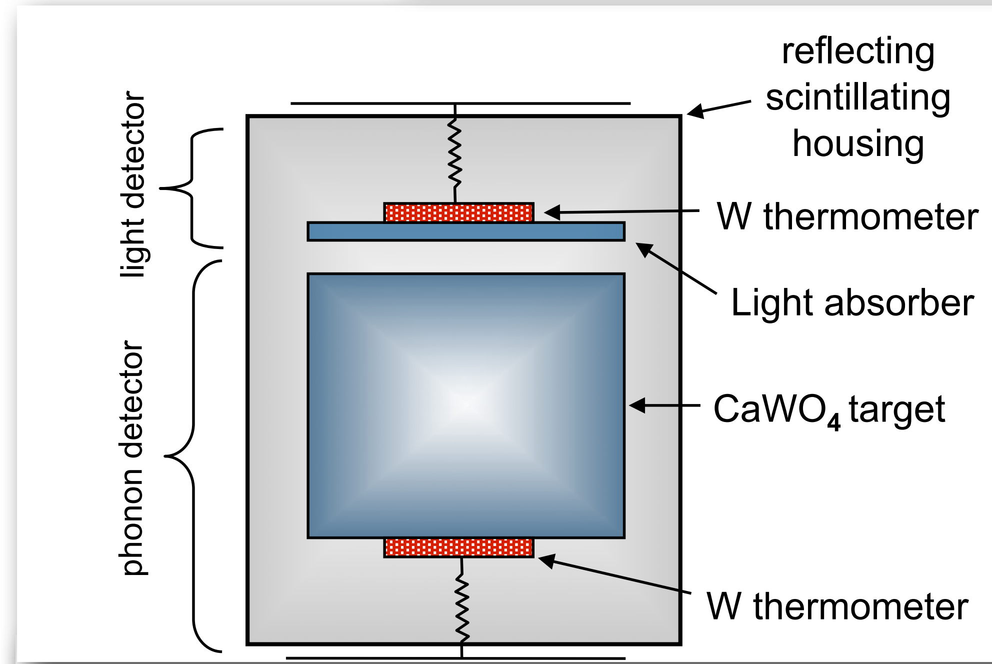
SuperCDMS @ Soudan: Low Mass Projections

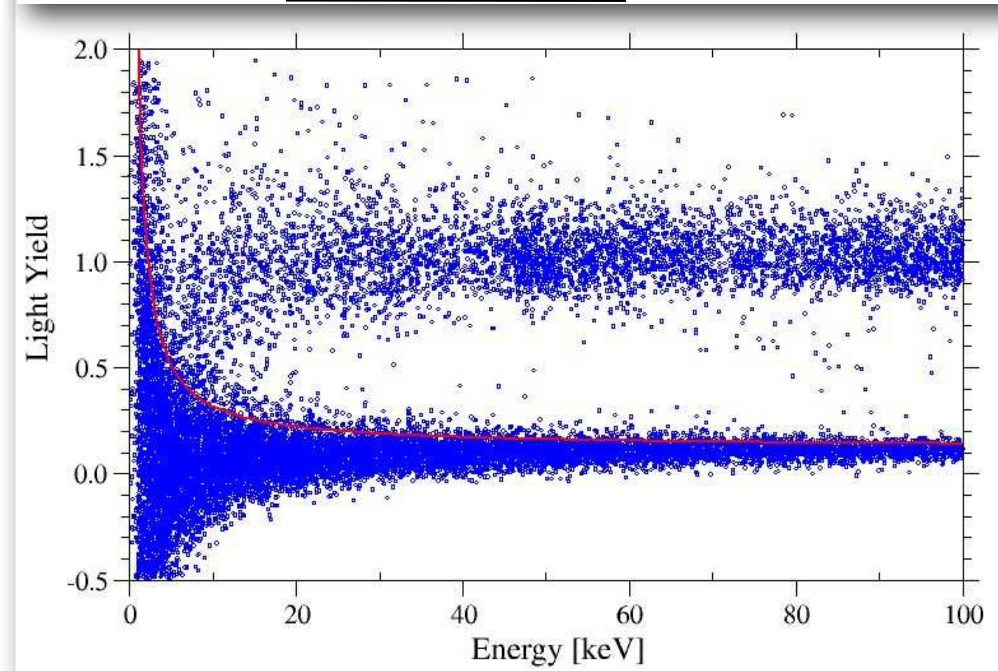


CRESST



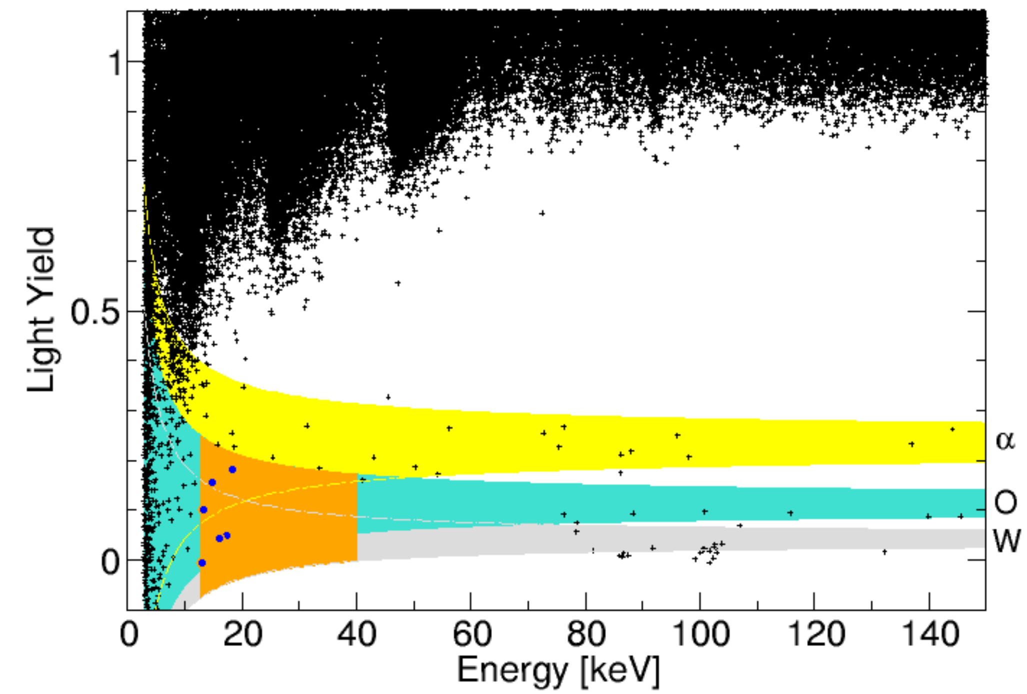
- Cryogenic $CaWO_4$ crystals are instrumented to readout phonon energy and scintillation.
  - operated at ~10 mK
  - each crystal ~ 300 g
- Located in Laboratori Nazionali del Gran Sasso, Italy
- Discrimination between ER and NR events via light yield (light/phonon energy)
- Signal expected to produce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





CRESST-II Data Analysis

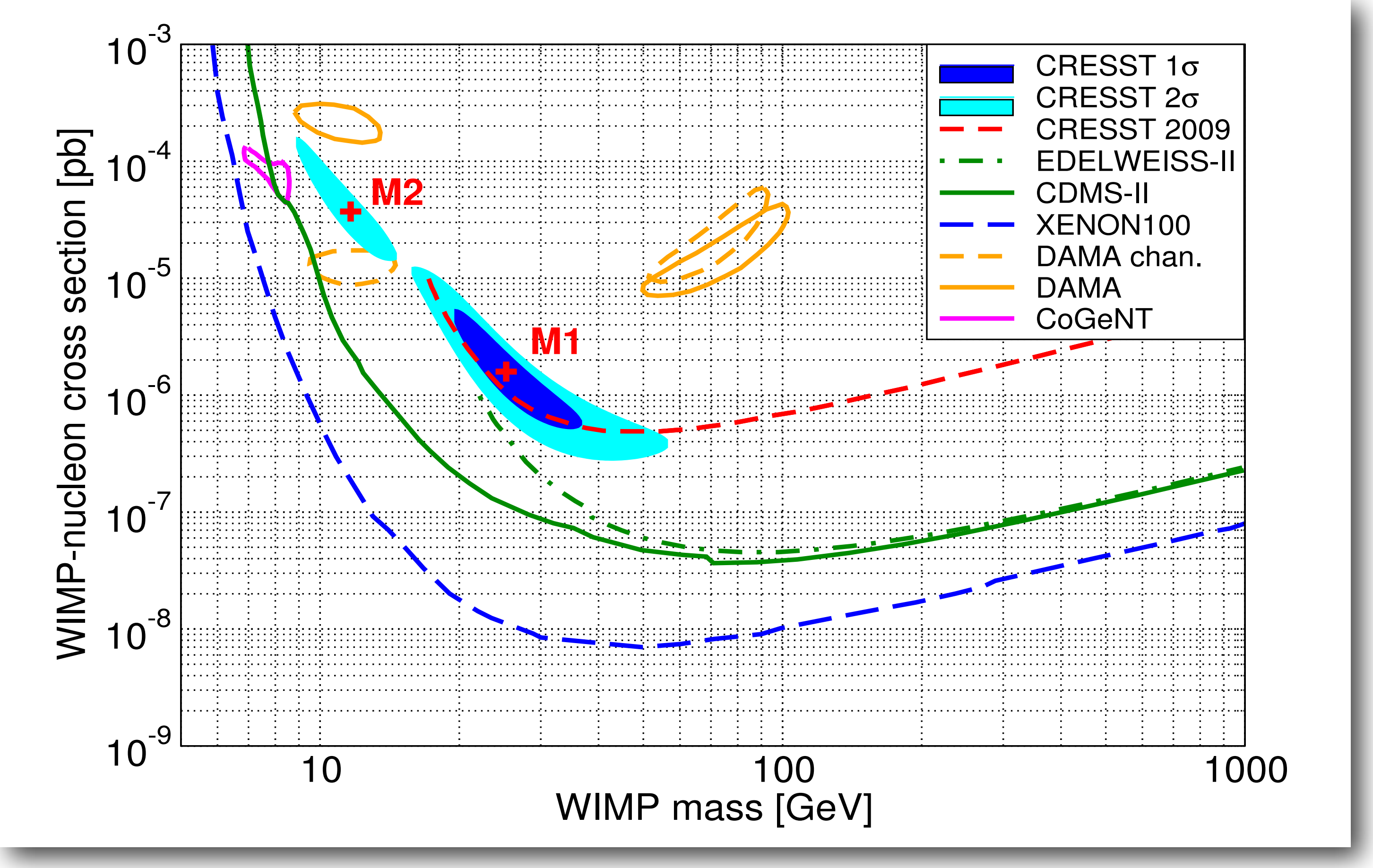
- Net exposure: 730 kg-day (July 2009 - March 2011) from 8 detector modules.
- Observed 67 events in acceptance region (orange).
- Analysis used a maximum likelihood in which 2 regions favored a WIMP signal in addition to predict background.
    - M1 is global best fit (4.7 σ)
    - M2 slightly disfavored (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 Plans

- Next data run (2012) aims to reduce background, increase detector mass.
  - Alphas - new clamping design and material
  - Detector assembly in a radon free environment
  - New detector design to discriminate ^{206}Po recoils
  - Add additional shielding to reduce neutron background

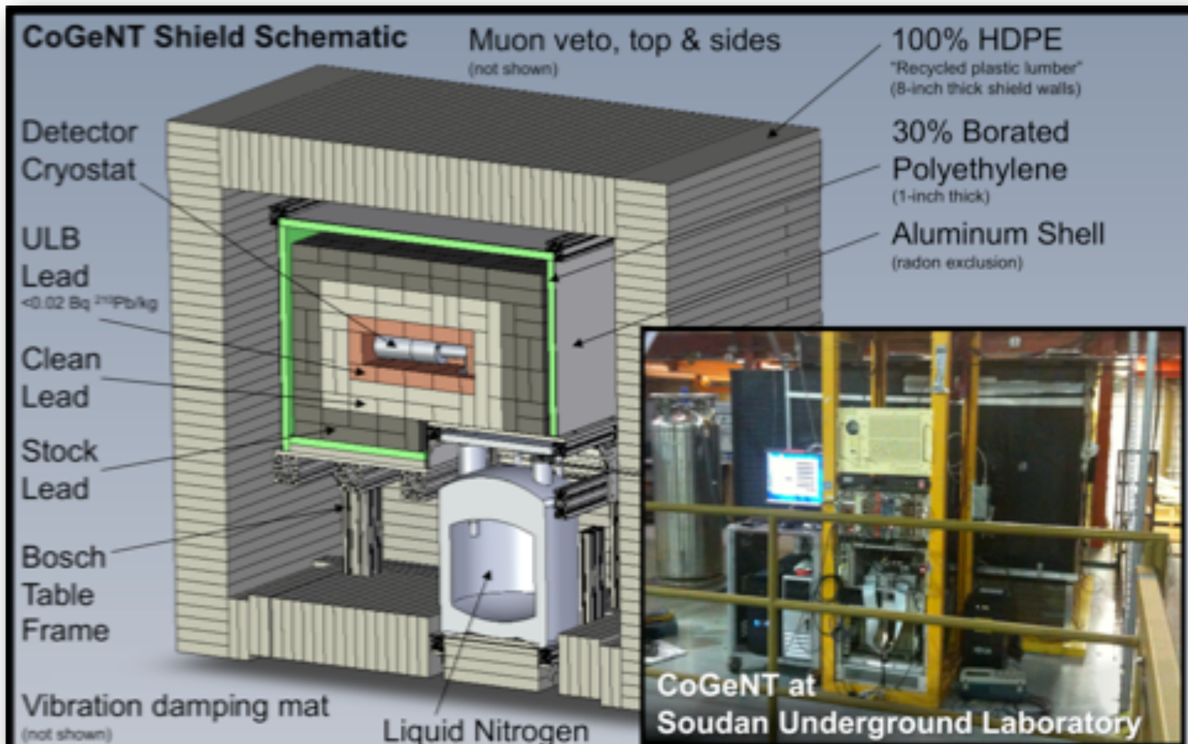


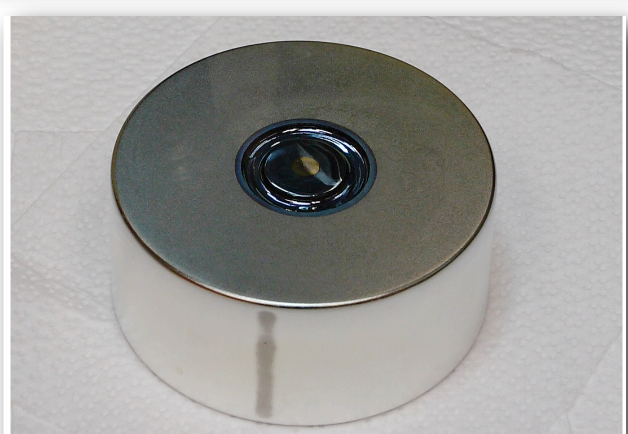
- Currently cooling the cryostat which contains 18 detector modules!

Ionization Only Experiments

CoGeNT, TEXANO, IGEX and others

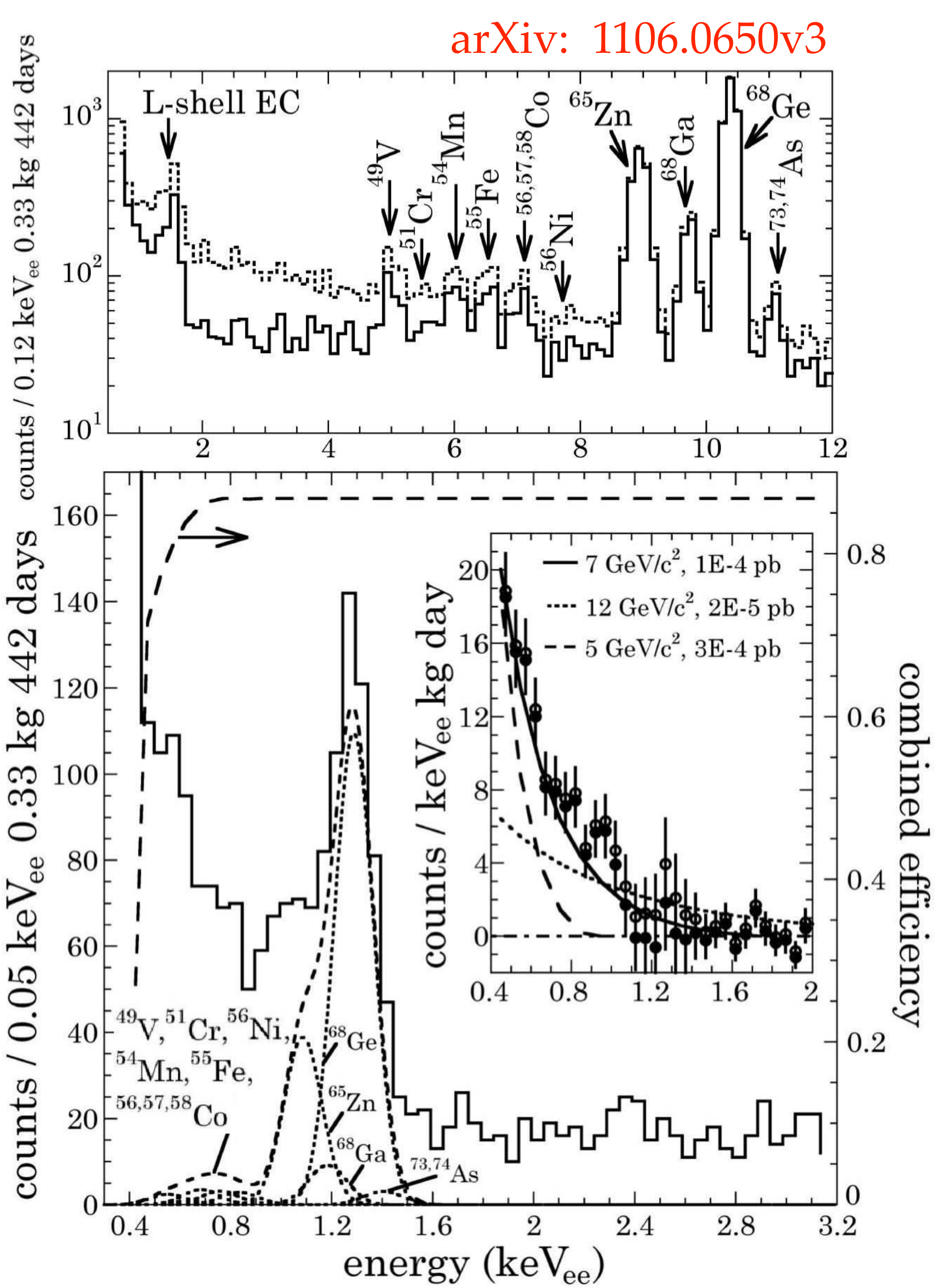
CoGeNT





- 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

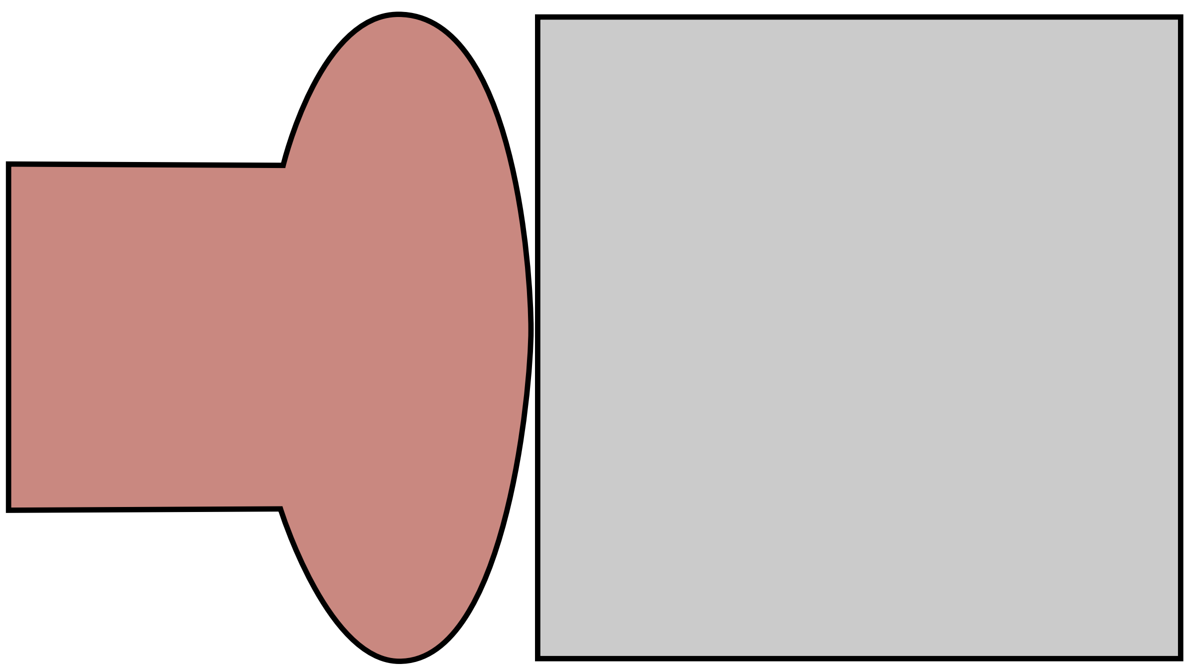


- First claim of excess in 2010.
- Reject surface events using risetime cut (2011).
- Peaks due to cosmogenic activation of Ge
- After subtraction of known background, an exponential excess of events remains
- Fits to a variety of light-WIMP masses and couplings shown in inset of lower figure.

Annual Modulation Experiments

DAMA, KIMS, DM-ICE
and others (CoGeNT, CDMS II, etc.)

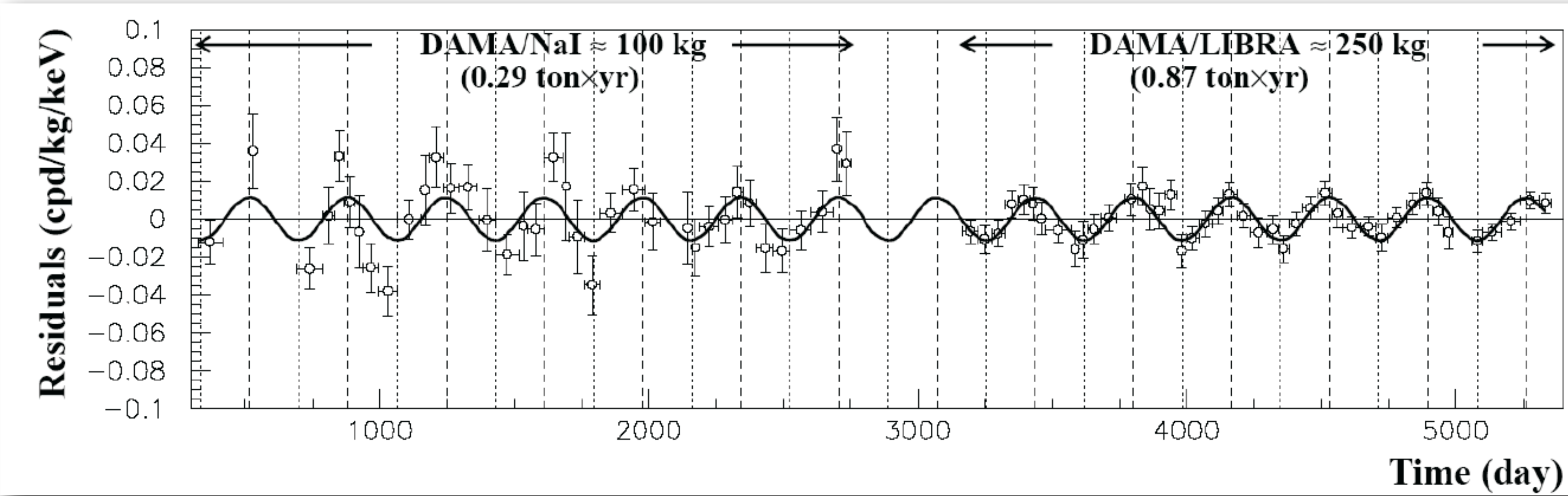
NaI and CsI Scintillator



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.

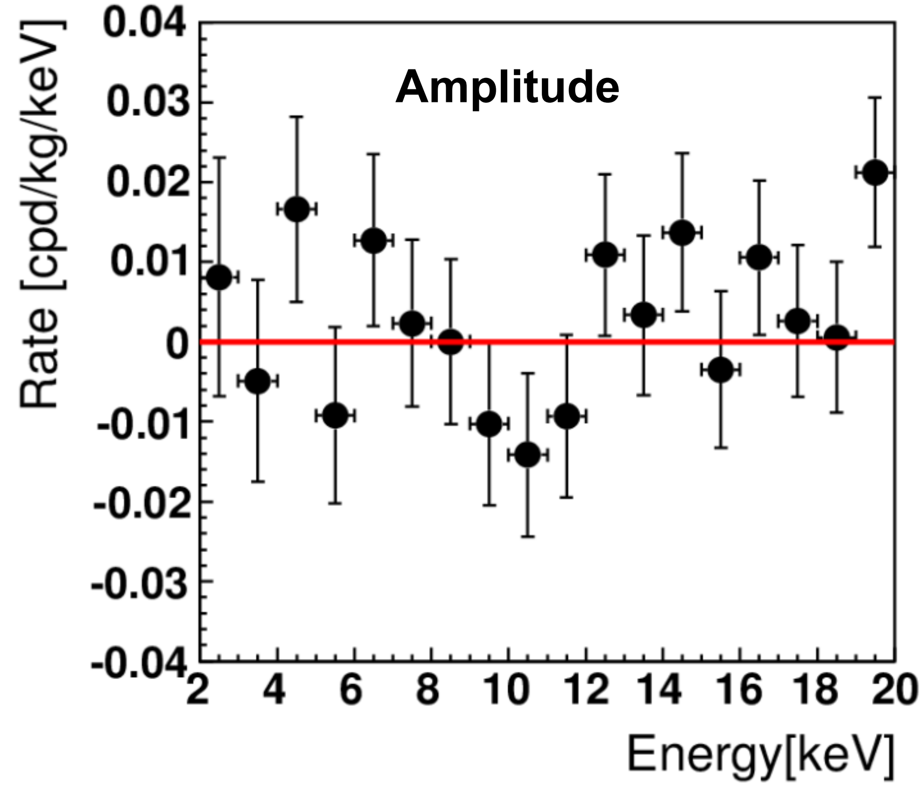
DAMA/LIBRA

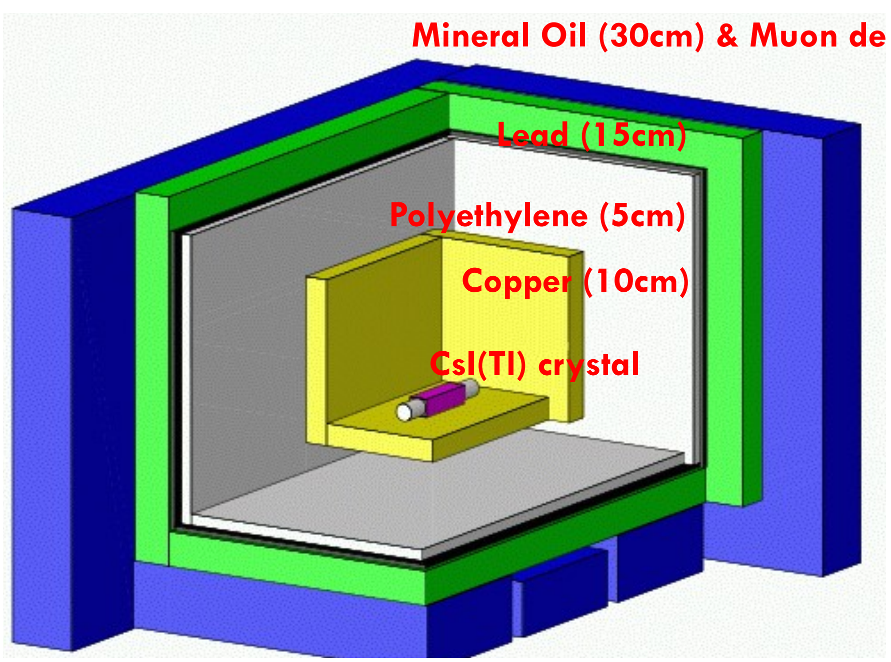


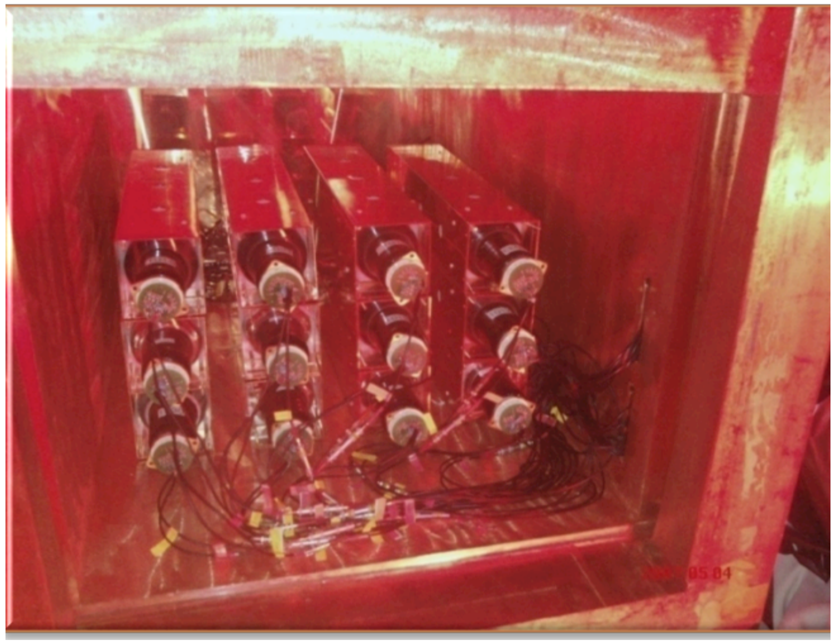
- Modulation has been observed over 13 cycles.
- Significance is 8.9σ.
- Signal is observed only in lowest energy bin.

KIMS

- Direct comparison to DAMA annual modulation signal using CsI(Tl) crystals
    - Pulse shape discrimination also possible
- 12 crystals (104.4 kg) installed
- Data taking from Sept 2009 - Feb. 2012
- Pulse shape discrimination excludes DAMA/LIBRA - PRL 108, 181301 (2012)
- No annual modulation is observed.





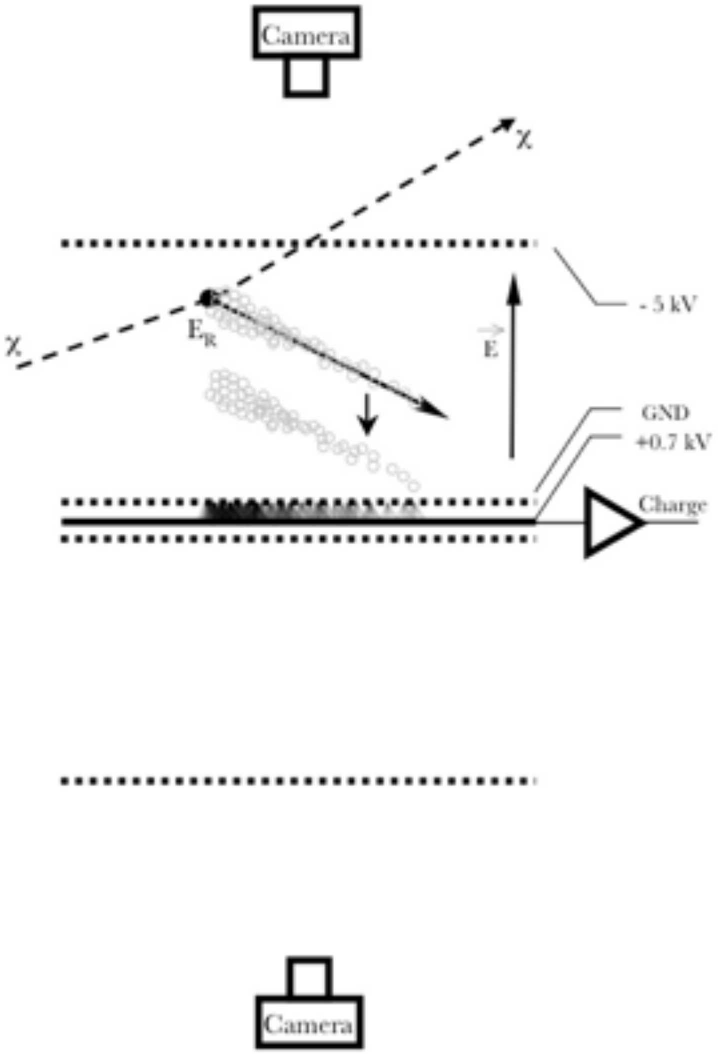


Directional Experiments

DMTPC, DRIFT, MIMAC, NEWAGE,
and others

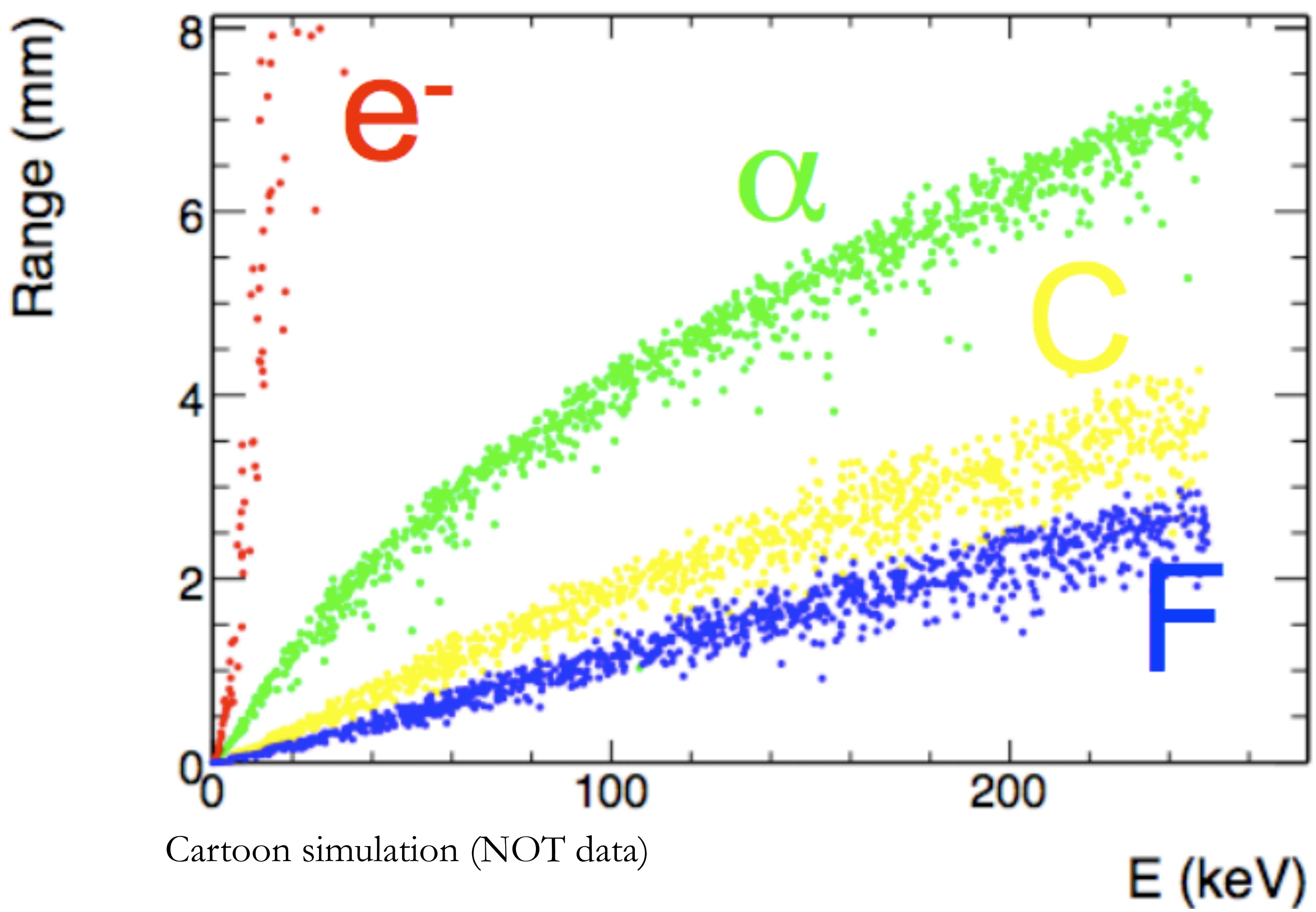
DMTPC

- 10 L prototype underground at WIPP in Carlsbad, NM, USA
- Filled with CF_4 gas to probe the WIMP-^{19}F spin-dependent cross-section
- Dark matter is identified by directional signal.
- In additional, electron recoils can be identified by their low ionization density (i.e. stopping power).



DM-TPC

PID with Range vs. Energy



Cartoon simulation (NOT data)

DMTPC

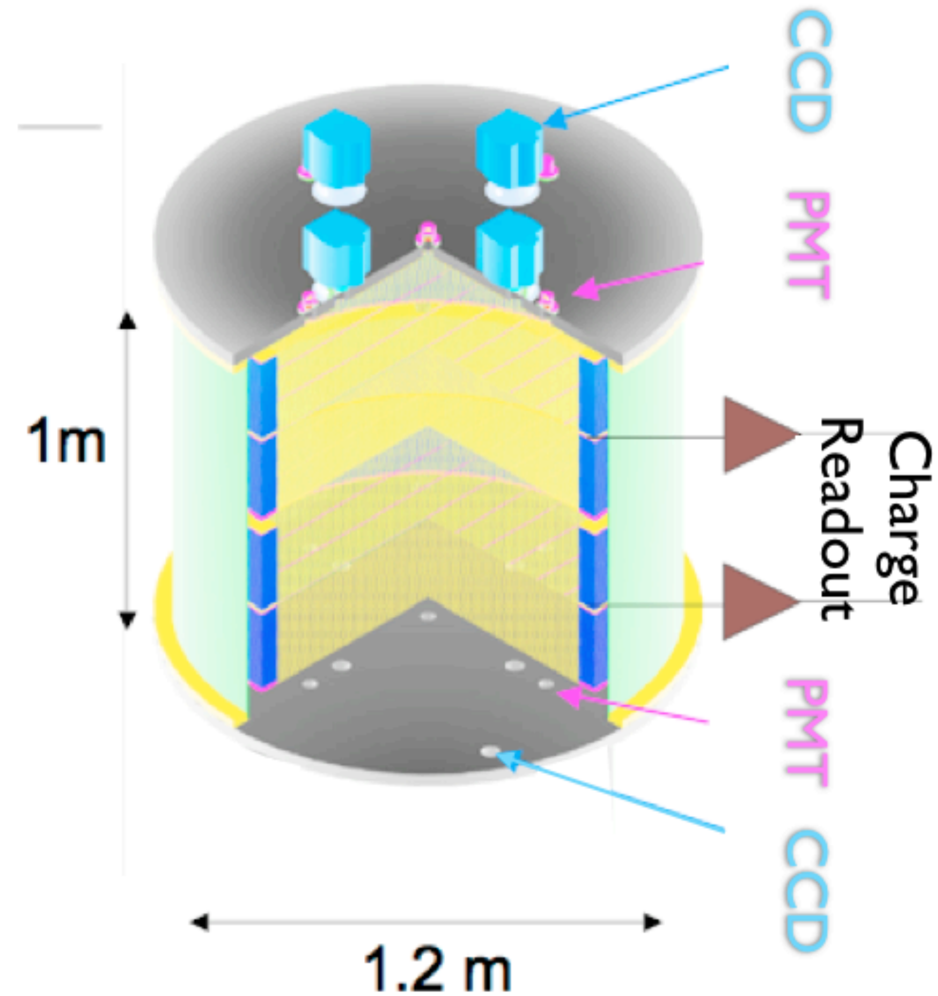
10L

Underground
at WIPP

4Shooter (20L)

At MIT

DMTPCino (1 m^3)



Funded by
NSF+DoE

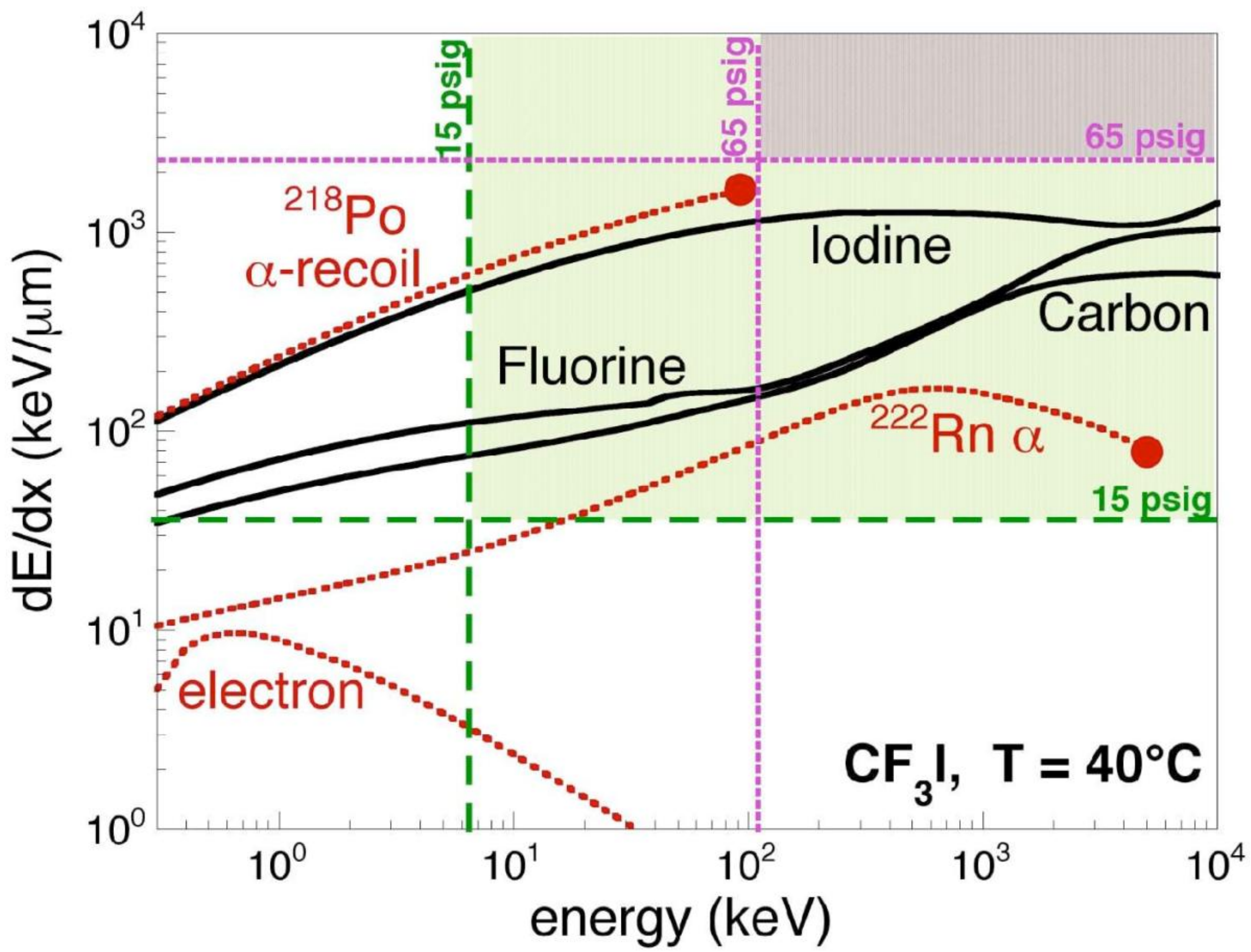
James Battat   Bryn Mawr College

SuperHeated Gas/Gel Experiments

COUPP, PICASSO, SIMPLE and others

Particle Detection in Bubble Chambers

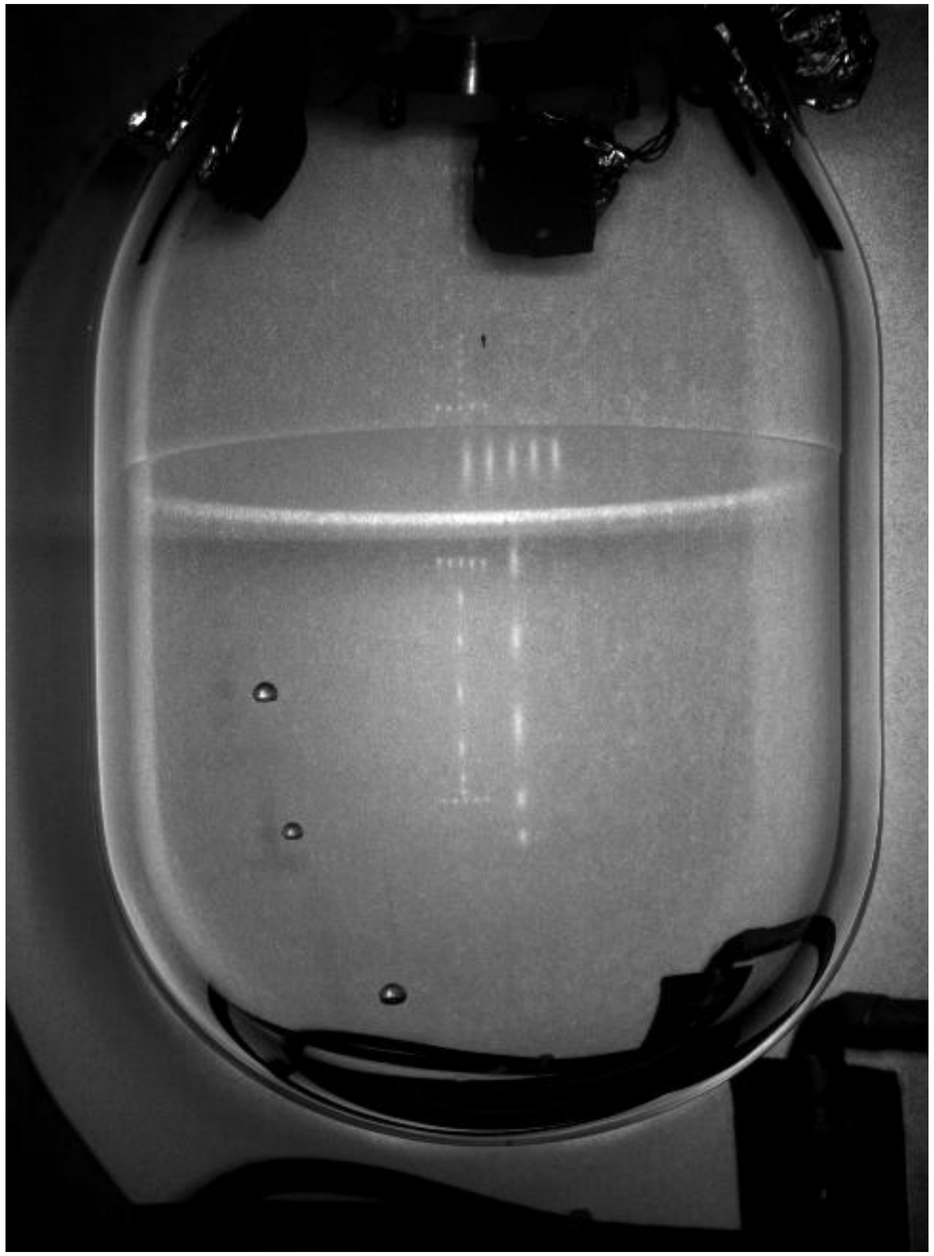
- A bubble chamber is filled with a superheated fluid in a metastable state.
- A particle interaction with energy deposition greater than E_{th} in a radius $< r_c$ results in an expanding bubble.
- A smaller or more diffuse energy deposition will result in a bubble that immediately collapses.



- You can "tune" the chamber to make bubbles for nuclear recoils and not for electron interactions.

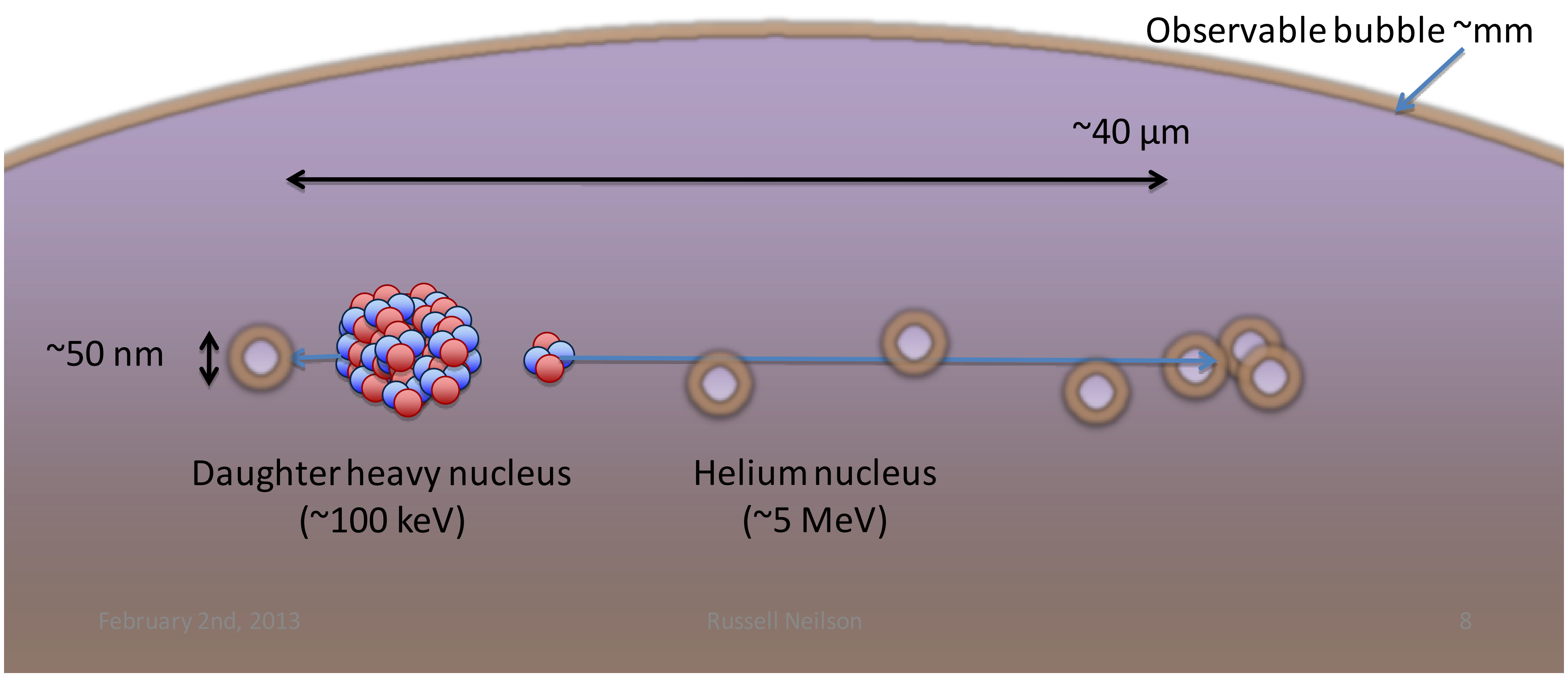
COUPP

- Superheated fluid CF_3I
  - F for spin-dependent interactions
  - I for spin-independent interactions
  - Target can be swapped out
- Bubbles are observed by two cameras and piezo-acoustic sensors
- Better than 10^{-10} rejection of electron recoils
- Alphas can be a concern. However, they can be rejected by acoustic discrimination.

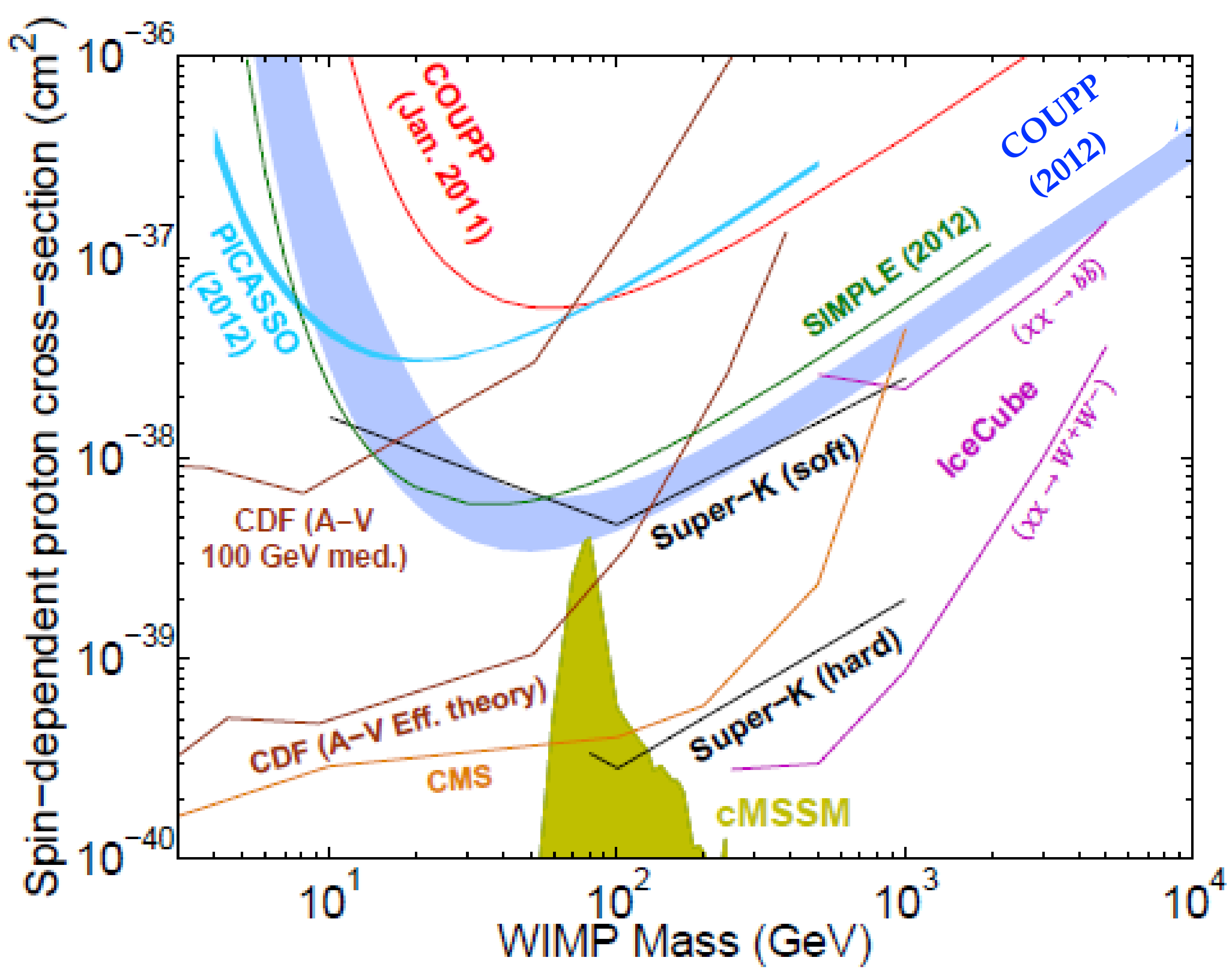


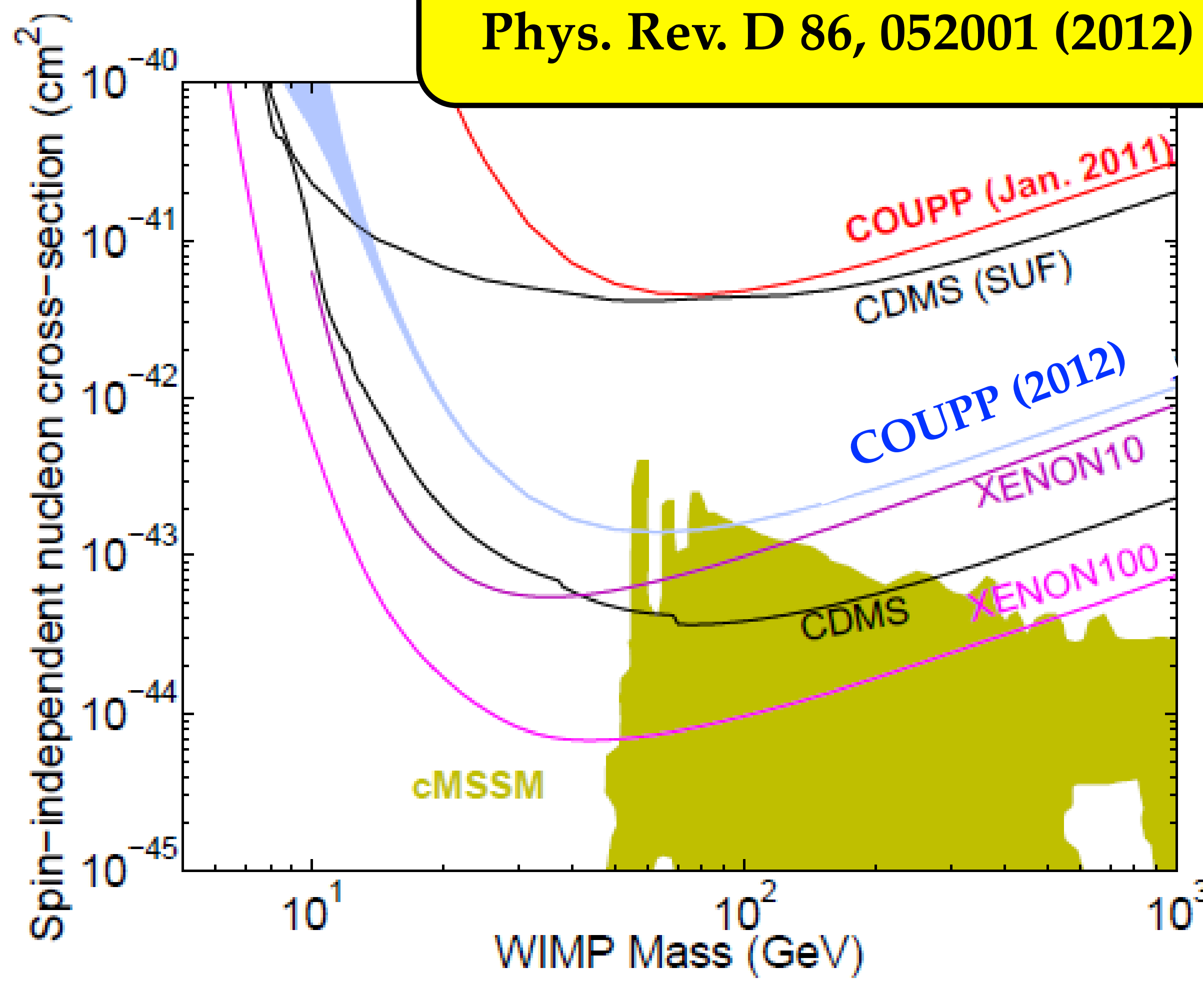
COUPP

- Alphas deposit their energy over 10s of microns.
- Nuclear recoils deposit their energy over 10s of millimeters
- Alpha particles are louder than nuclear recoils. This can be measured by piezoelectric sensors.



COUPP Results

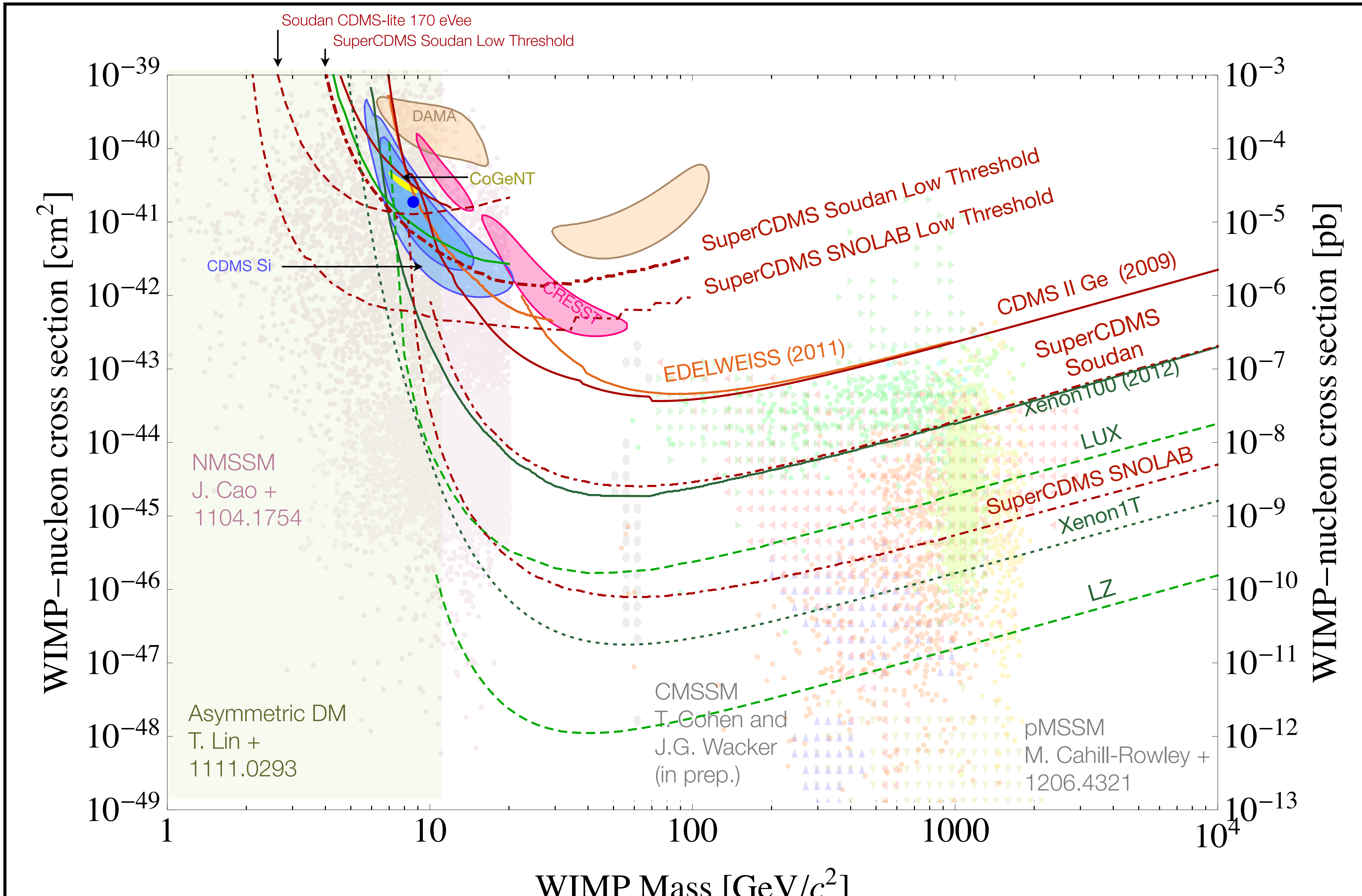




Phys. Rev. D 86, 052001 (2012)

Where are we going?

Where Are We Going?



Further Reading

- Classic Papers on specific calculations
  - Lewin, Smith, Astroparticle Physics 6 (1996) 87-112
  - Kurylov and Kamionkowski, Physical Review D 69, 063503 (2004)
  - G. Jungman, M. Kamionkowski, K. Griest, Phys. Rep. 267 (1996) 195-373, arXiv:hep-ph/9506380
- Books/Special Editions that Overview the Topic of Dark Matter
  - Bertone, Particle Dark Matter Observations, Models and Searches, Cambridge University Press, 2010. ISBN 978-0-521-76368-4
  - Physics of the Dark Universe, vol 1, issues 1-2, Nov. 2012 (http://www.journals.elsevier.com/physics-of-the-dark-universe/)