Dark Matter Direct Detection Searches and Techniques

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University of Florida

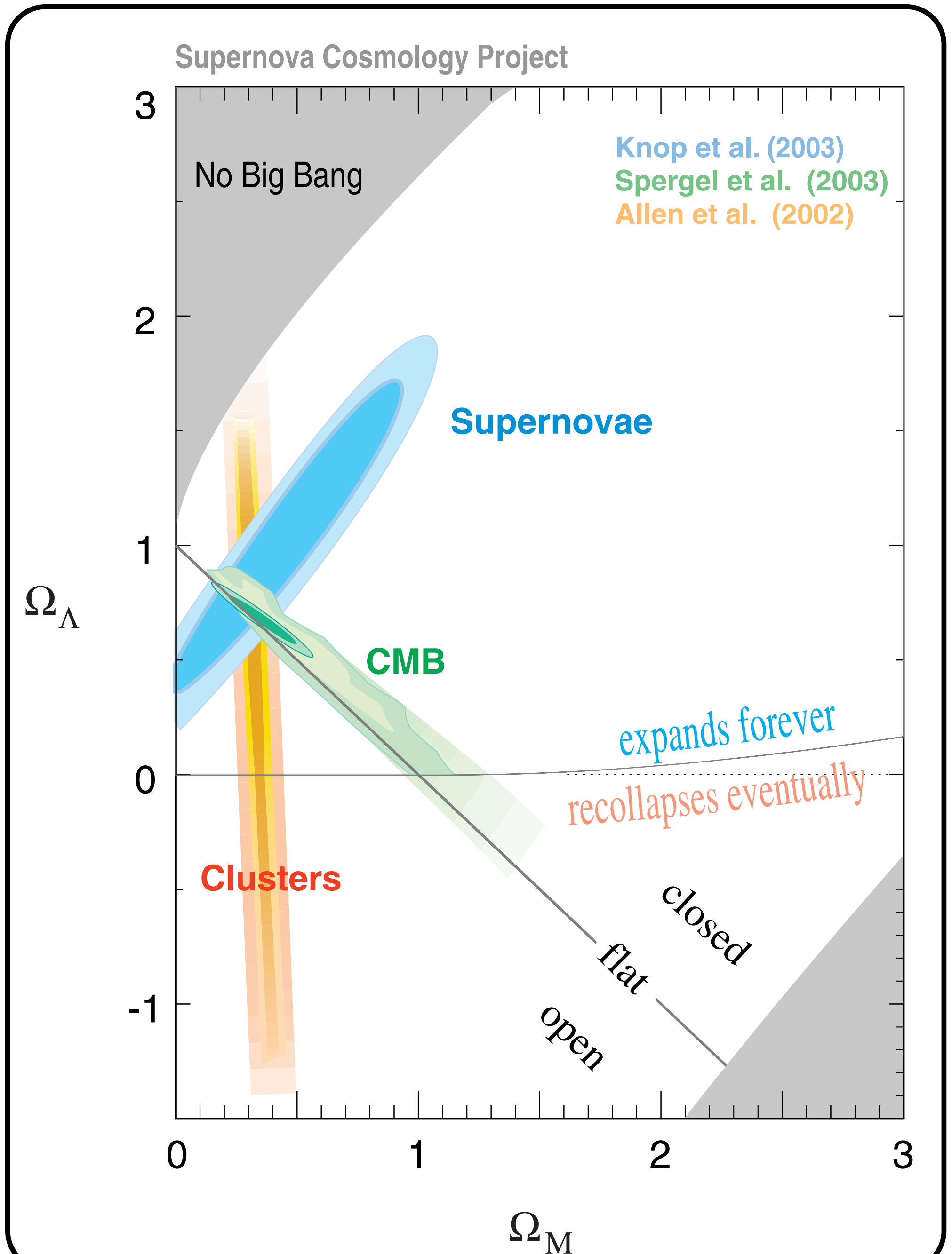
Workshop on Dark Matter in the LHC Era:
Direct and Indirect Searches

Saha Institute of Nuclear Physics
4th - 8th January, 2011

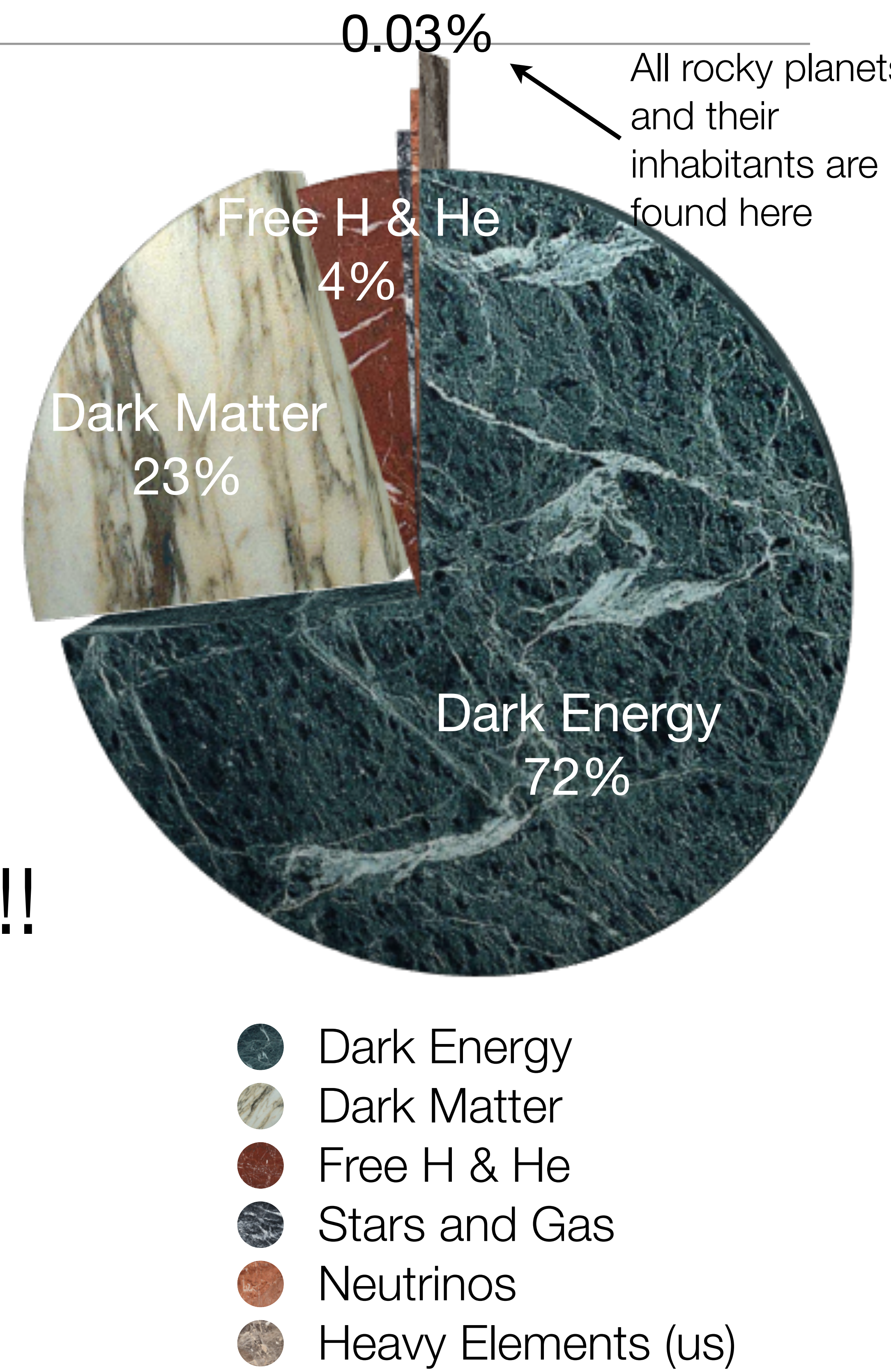
Outline

- Overview of the Dark Matter Problem
- Principles of Direct Detection
- Experimental Searches for WIMPS
    - The CDMS Experiment
- Outlook for the future

The Concordance Model of Cosmology

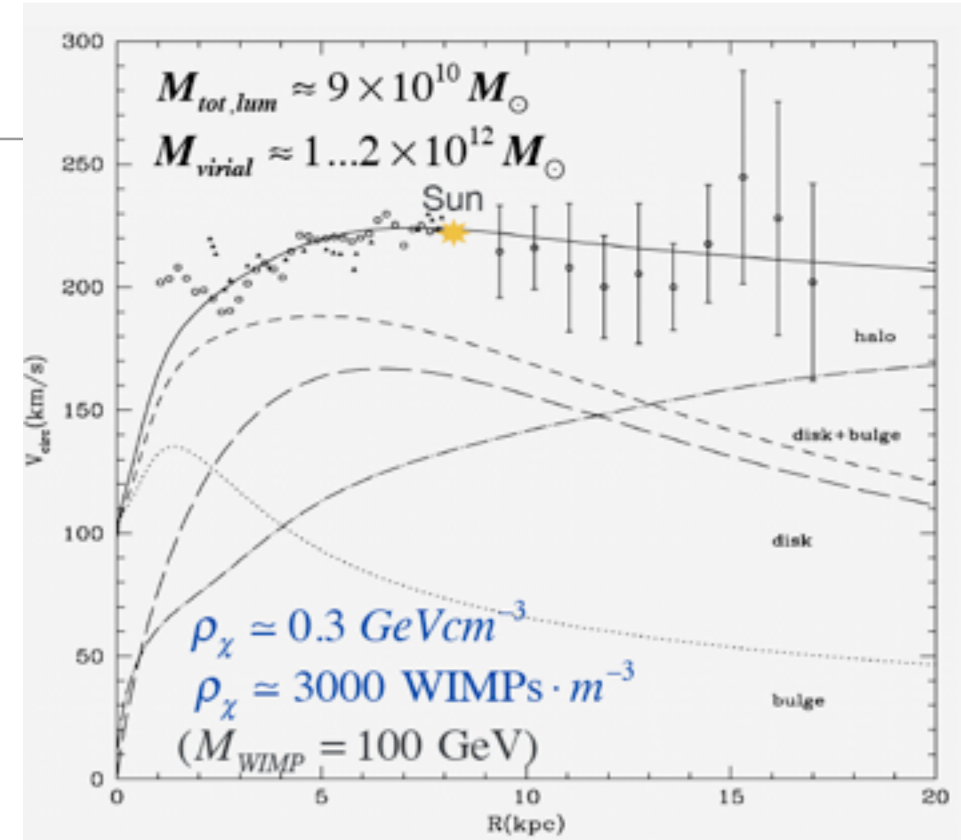


We don't know what 96% of the Universe is made of!!!



The Nature of Dark Matter

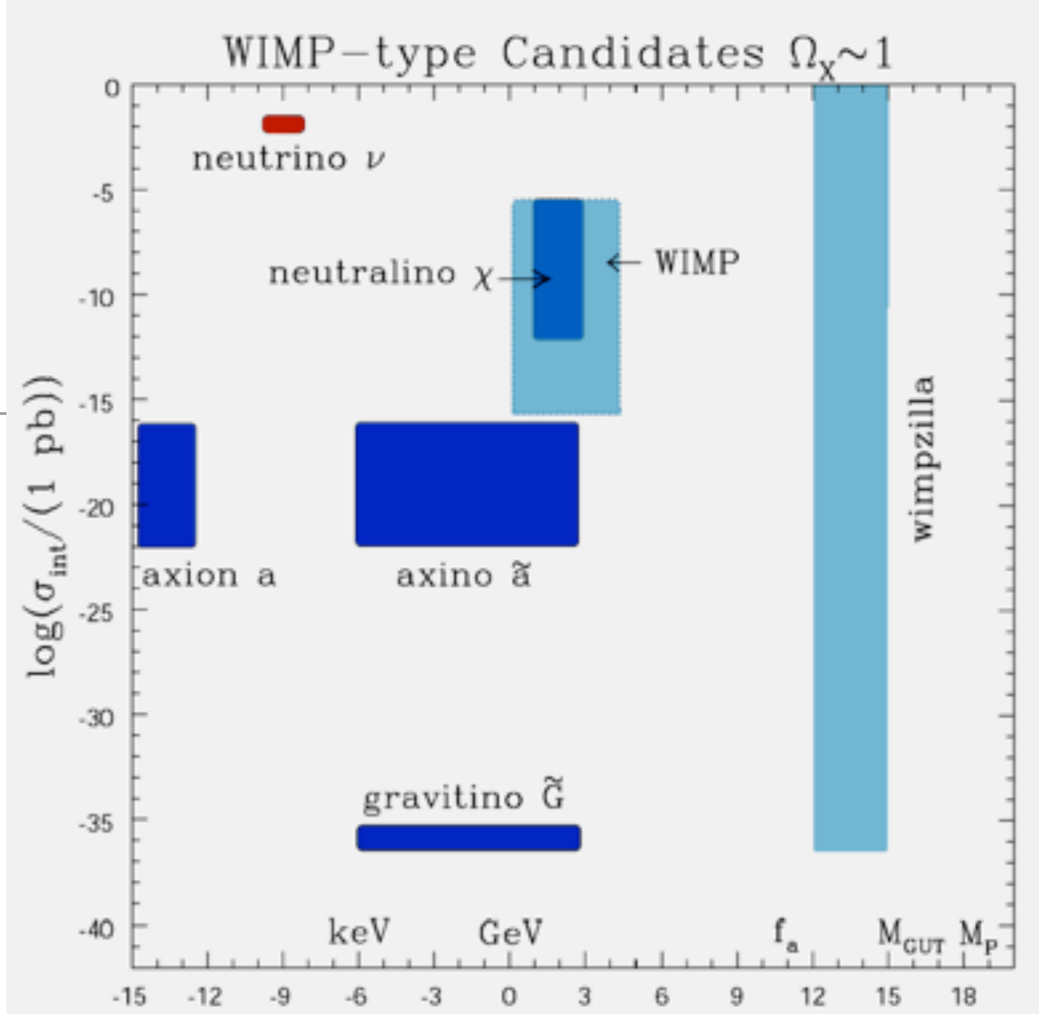
- The Missing Mass Problem:
  - Dynamics of stars, galaxies, and clusters
  - Rotation curves, gas density, gravitational lensing
  - Large Scale Structure formation
- Wealth of evidence for a particle solution
  - MOND has problems with Bullet Cluster
  - Microlensing (MACHOs) mostly ruled out
- Non-baryonic
  - Height of acoustic peaks in the CMB (Ωb)
  - Power spectrum of density fluctuations (Ωm)
  - Primordial Nucleosynthesis
- And STILL HERE!
  - Stable, neutral, non-relativistic
  - Interacts via gravity and/or weak force



(Klypin, Zhao & Somerville 2002)


Clowe et al., ApJ, 648, 109

WIMPs and WISPs



(Roszkowski 2004)

- We "know" that Dark Matter
  - Has mass
  - Is non-baryonic
  - Was non-relativistic early on in cosmological time
  - Has a certain annihilation cross section
  - Should have a non-zero cross section with quarks

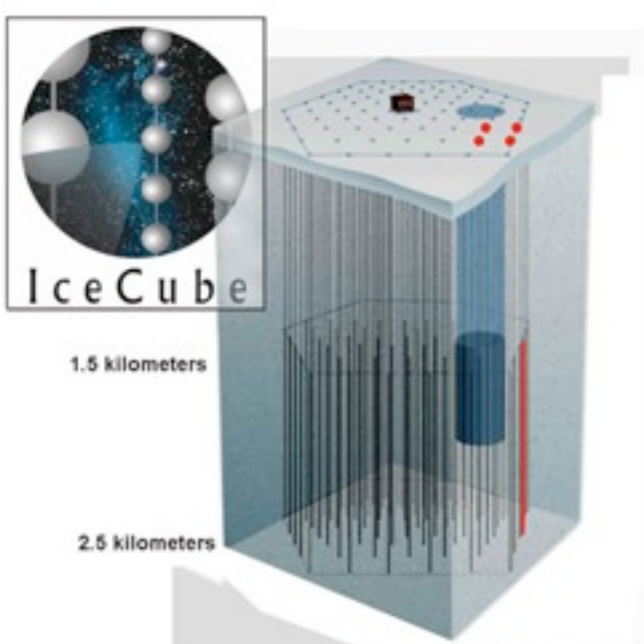
- The Lightest Super Particle (LSP) in many Minimally Supersymmetric Standard Models is a viable candidate. These are called Weakly Interacting Massive Particles: WIMPs

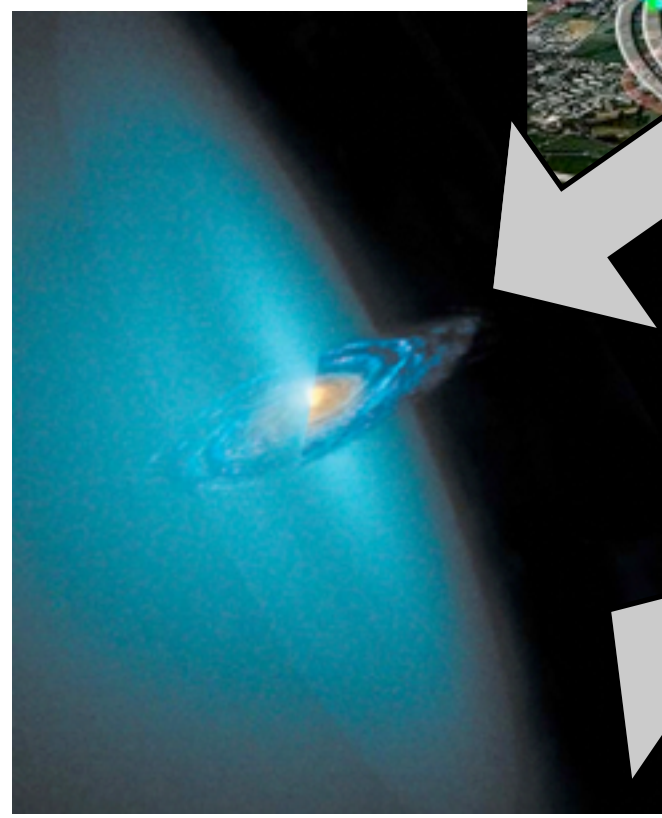
- Another set of candidates are Weakly Interacting Sub-eV Particles: WISPs. This set includes axions and axion-like particles.

The Hunt for Dark Matter

Production in Colliders

Annihilation in the Cosmos





Scattering in Terrestrial Detectors

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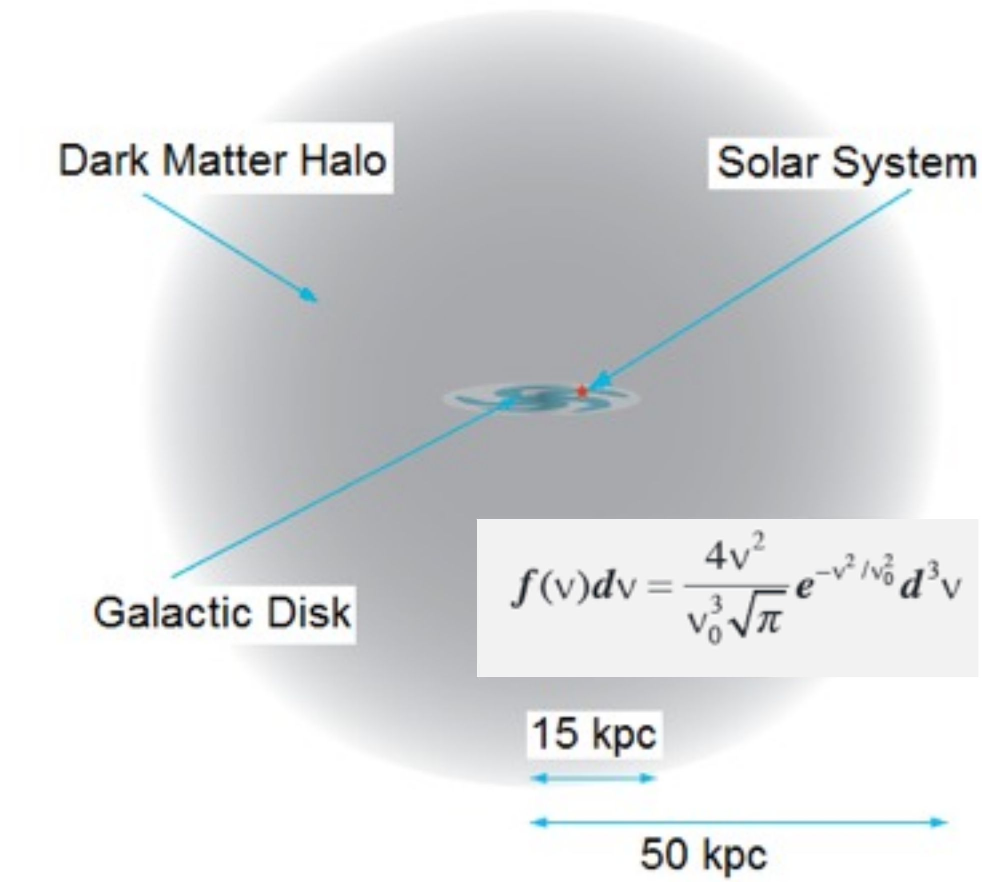
Direct Detection and WIMP Astrophysics

Energy spectrum & rate depend on WIMP distribution in Dark Matter Halo

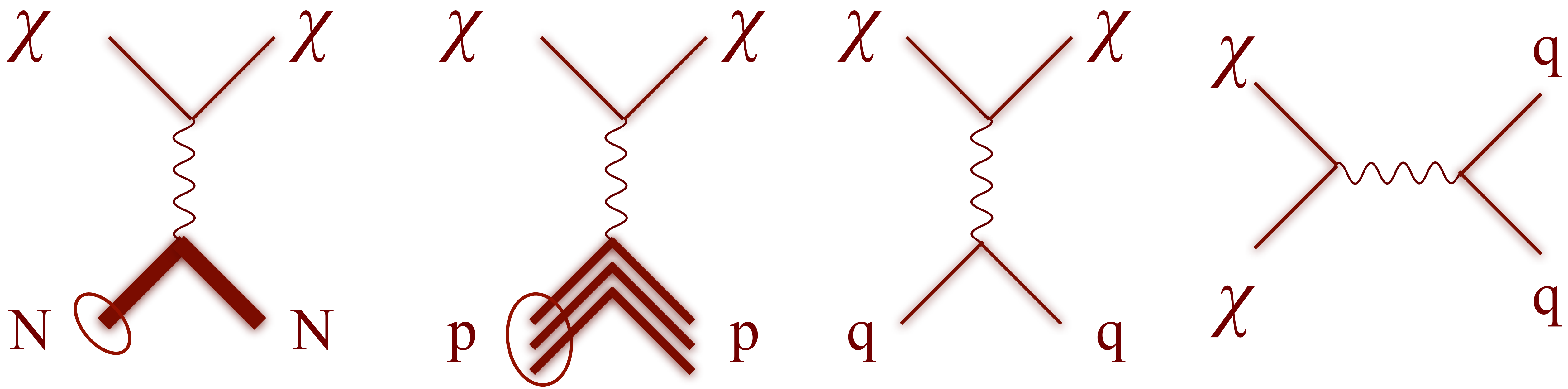
- "Basic" assumptions: isothermal and spherical, with Maxwell-Boltzmann velocity distribution
- v_0 = 220 km/s, v_{rms} = 270 km/s, v_{esc}= 650 km/s
- ρ = 0.3 GeV/cm^3
- Assume mass = 60 GeV/c^2
- Density = 5000 part/m^3



10 WIMPs on average, inside a 2 liter bottle (if mass=60 x proton)

Wimp-nucleus Interaction

- How does a WIMP interact with a nucleus (or how do you calculate its cross section?)



$\sigma_{\chi\text{-}N}$=? $\sigma_{\chi\text{-}p}$=? $\sigma_{\chi\text{-}q}$=? $\sigma_{\chi\text{-}\chi}$=known

$\sigma_{\chi\text{-}N}$ $\sigma_{\chi\text{-}p}$ $\sigma_{\chi\text{-}q}$

Wimp-nucleus Interaction

- Spin-Independent:
  - The scattering amplitudes from individual nucleons interfere.
  - For zero momentum transfer collisions (extremely soft bumps) they add coherently:

$$\sigma_o \simeq \frac{4m_r^2}{\pi} f A^2$$

atomic mass

coupling constant

Enormous enhancement for heavy nuclei target!

$$m_r = \frac{m_\chi m_N}{m_\chi + m_N} = \text{“reduced mass”}$$

Wimp-nucleus Interaction

- Spin-Dependent:
  - Dominated by unpaired nucleons.
  - For spin-less nuclides, SD cross section = 0.
  - For zero momentum transfer collisions (extremely soft bumps) the cross section is approximately:

$$\sigma_o = \frac{32(J+1)}{\pi J} G_F^2 m_r^2 \left(a_p \langle S_p \rangle + a_n \langle S_n \rangle\right)^2$$

nuclear spin Fermi Constant coupling constant

Principles of Direct Detection

Interaction Rate = [counts/keV/kg/day]

	particle theory	nuclear structure	local properties of DM halo

$$\frac{dR}{dE_R} = \frac{\sigma_o}{m_\chi} \frac{F^2(E_R)}{m_r^2} \frac{\rho_o\, T(E_R)}{v_o\,\sqrt{\pi}}$$

$$F(E_R) \simeq \exp\left(-E_R\, m_N\, R_o^2/3\right)$$

"form factor" (quantum mechanics of interaction with nucleus)

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

"reduced mass"

$$T(E_R) \simeq \exp(-v_{\rm min}^2/v_o^2)$$

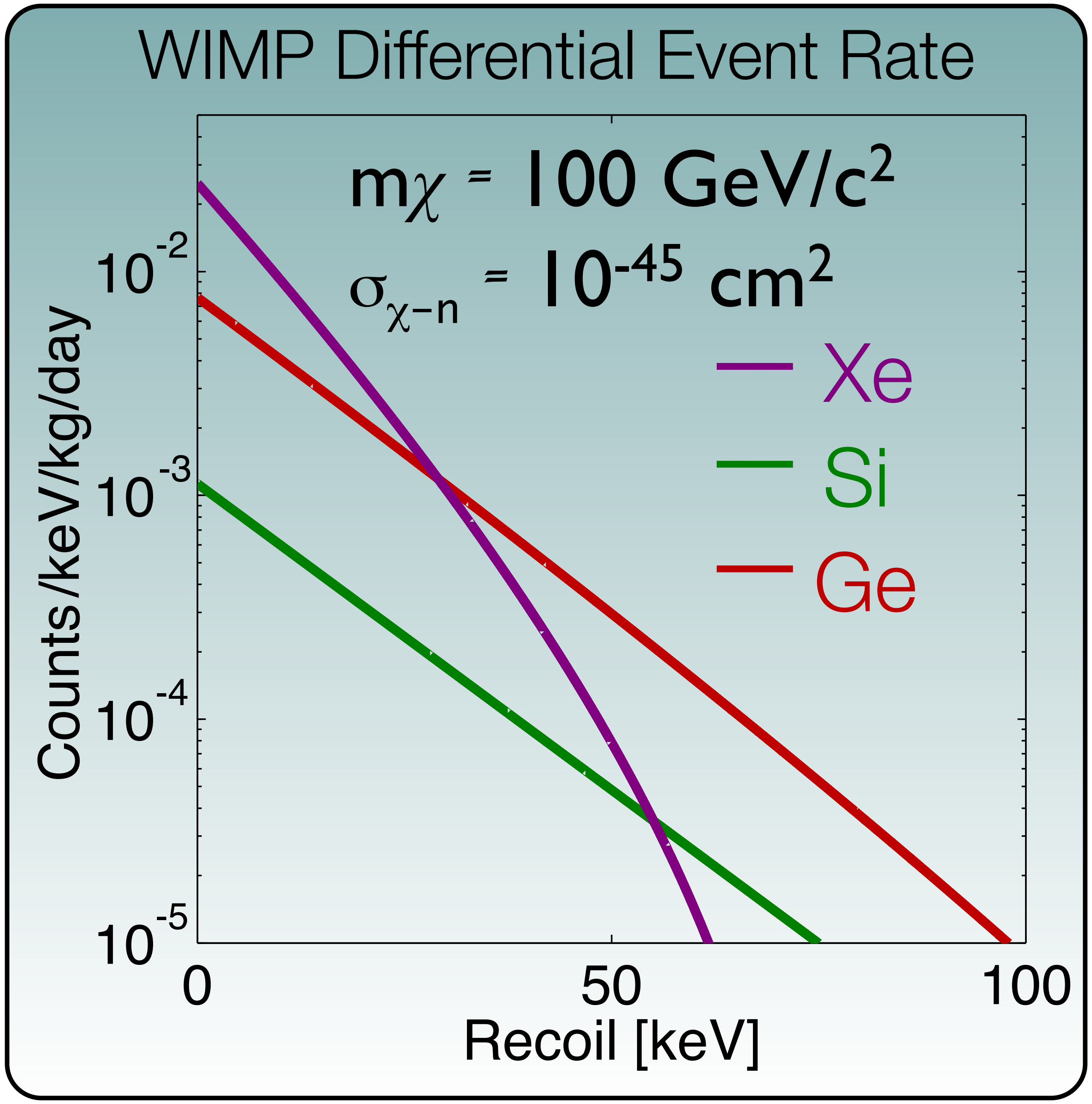
integral over local WIMP velocity distribution

$$v_{\rm min} = \sqrt{E_R\, m_N/(2m_r^2)}$$

minimum WIMP velocity for given E_R

WIMP Hunting

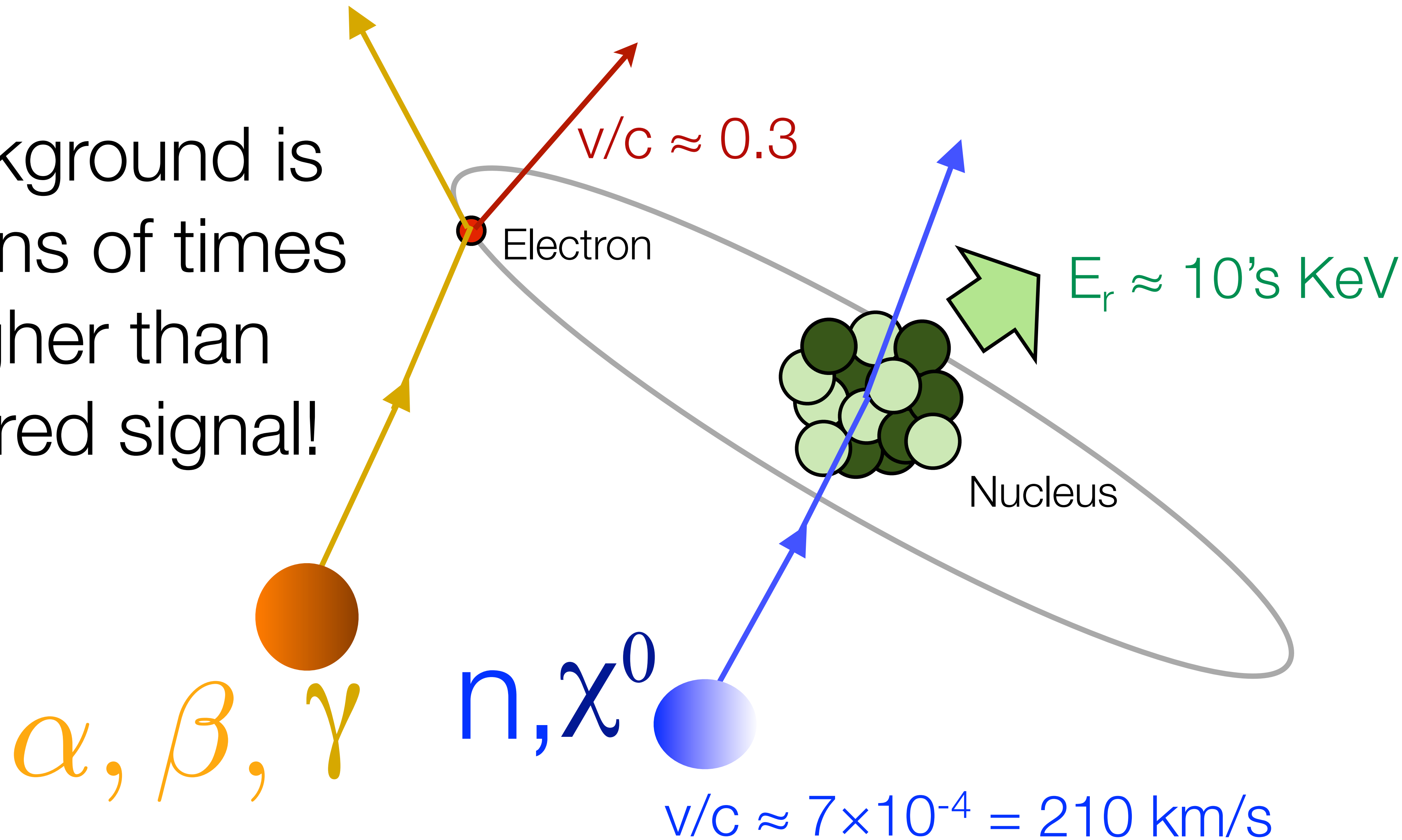
- Elastic scattering of a WIMP from a nucleus deposits a small, but detectable amount of energy ~ few x 10 keV
- Featureless exponential energy spectrum with 〈E〉 ~ 50 keV
- Expected rate < 0.01/kg-day (based on $\sigma_{\chi\text{-}n}$ and ρ)
- Radioactive background a million times higher
- Background Reduction/Rejection is key



Low background (< 1) almost a prerequisite for discovery

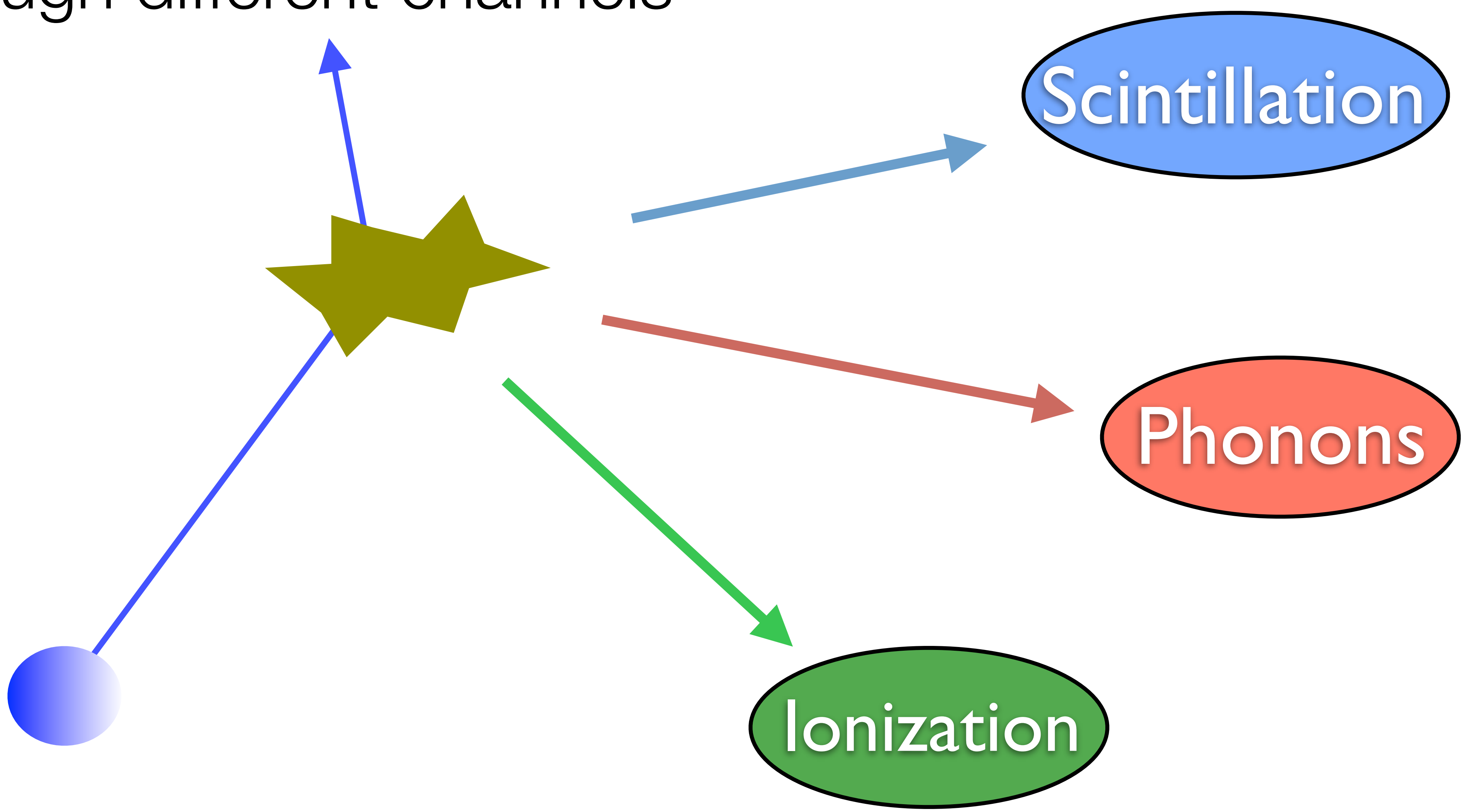
Signal and Backgrounds

Background is
millions of times
higher than
desired signal!



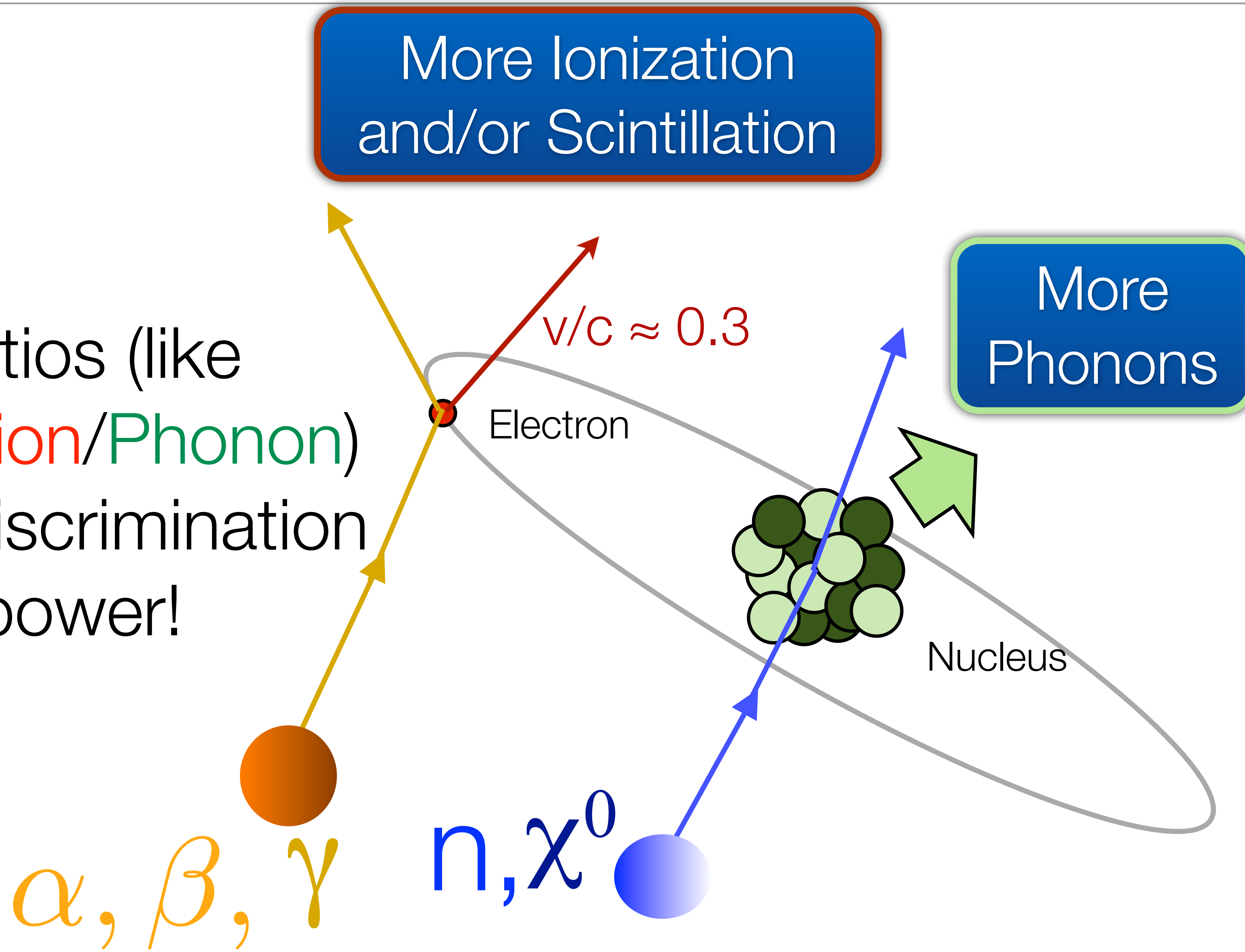
Energy Channels

The energy from scattering events in the atom evolves through different channels



Discrimination Strategies

Ratios (like Ionization/Phonon) have discrimination power!

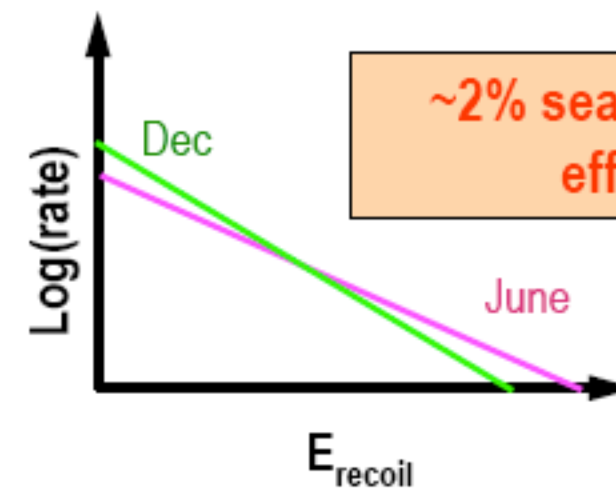


Backgrounds

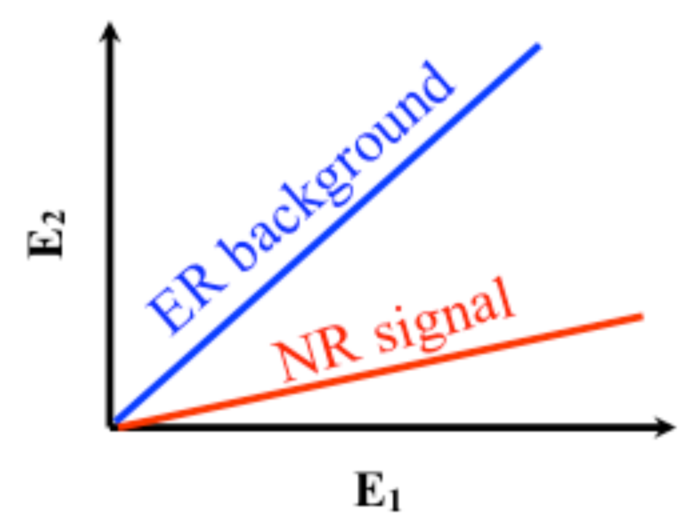
- Backgrounds are much higher than the signal event rate
  - e.g. rate of ^{40}K from a person standing 2m away from Ge detector is 10^4 x expected dark matter signal!
- Gamma-rays and beta decays:
  - Shielding: low activity lead, clean copper, water, noble liquids (active)
  - Select gamma-clean materials
- Neutrons from fission and (alpha,n) interactions from U/Th decays
  - Neutron moderator: polyethylene, paraffin, water, …
- Neutrons from cosmic ray muons:
  - Use muon veto, neutron veto, shielding
  - Go deep underground to reduce muon flux!

Separating Signal from Background?

- Statistical signature of WIMPs
  - Requires significant sample of WIMP recoil events.
  - Annual Modulation in the WIMP recoil spectrum. Earth's velocity through the galactic halo is max in June, min in December (DAMA/LIBRA).
  - Daily modulation of the incident WIMP direction. Measure the direction of the short track produced by nuclear recoil. (DM-TPC)



- Event-by-event discrimination
  - Requires powerful particle identification technique at low energies.
  - Allows to extract good sensitivity from relatively small exposures.



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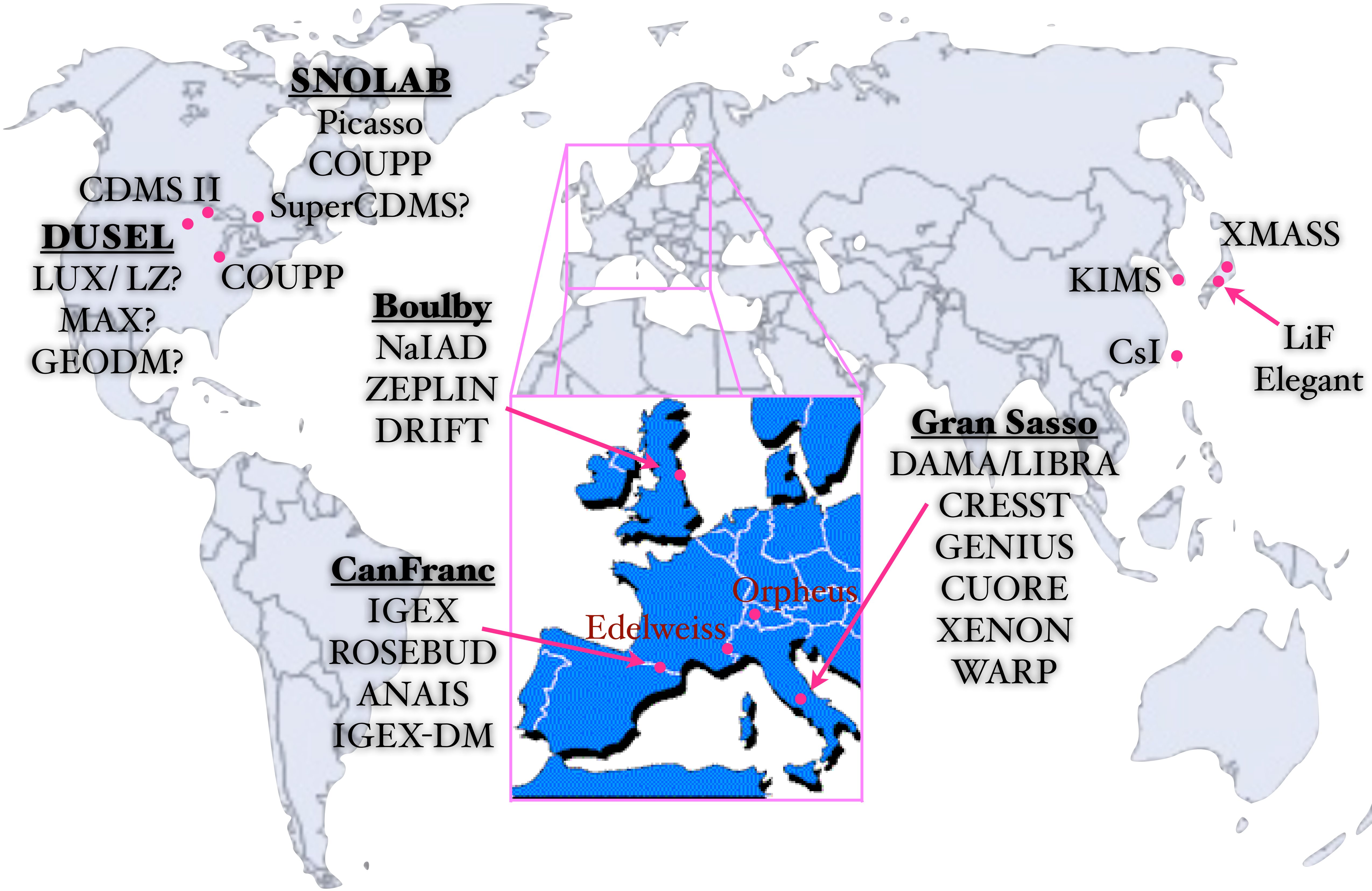
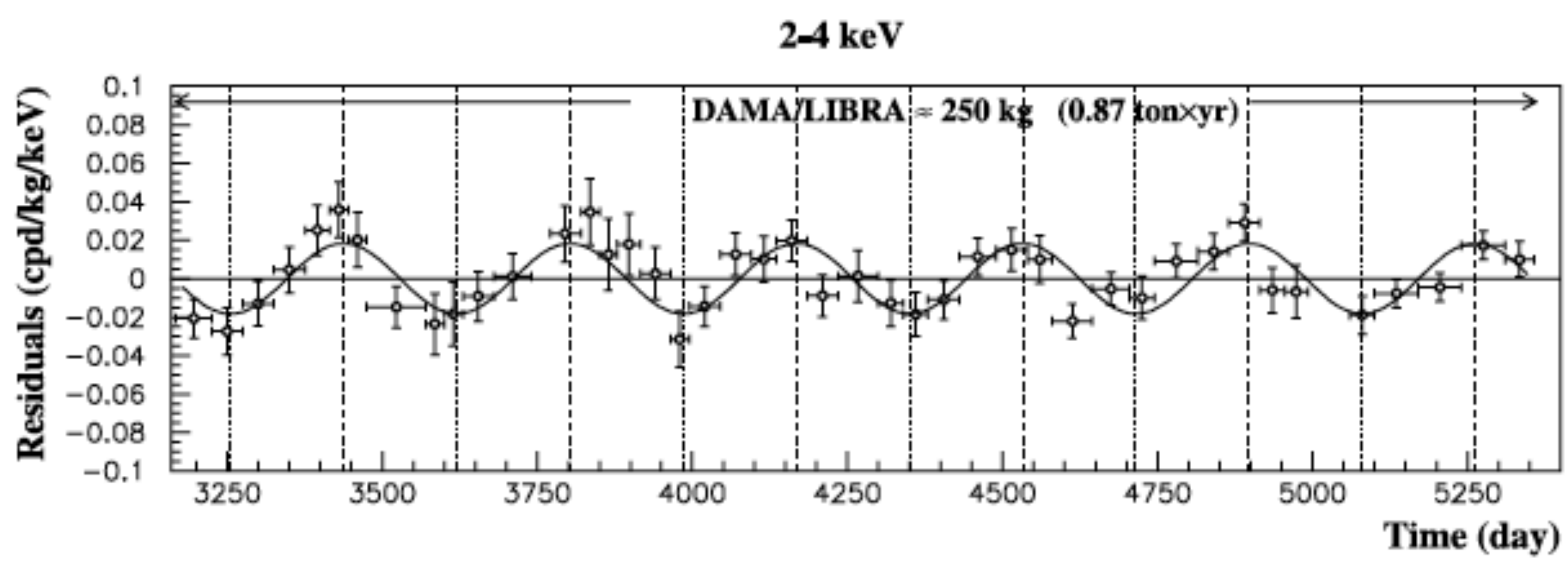


Worldwide Dark Matter Searches

DAMA / LIBRA

- Talk by Fabio Cappella
- Eur. Phys. J. C (2010) 67: 39–49

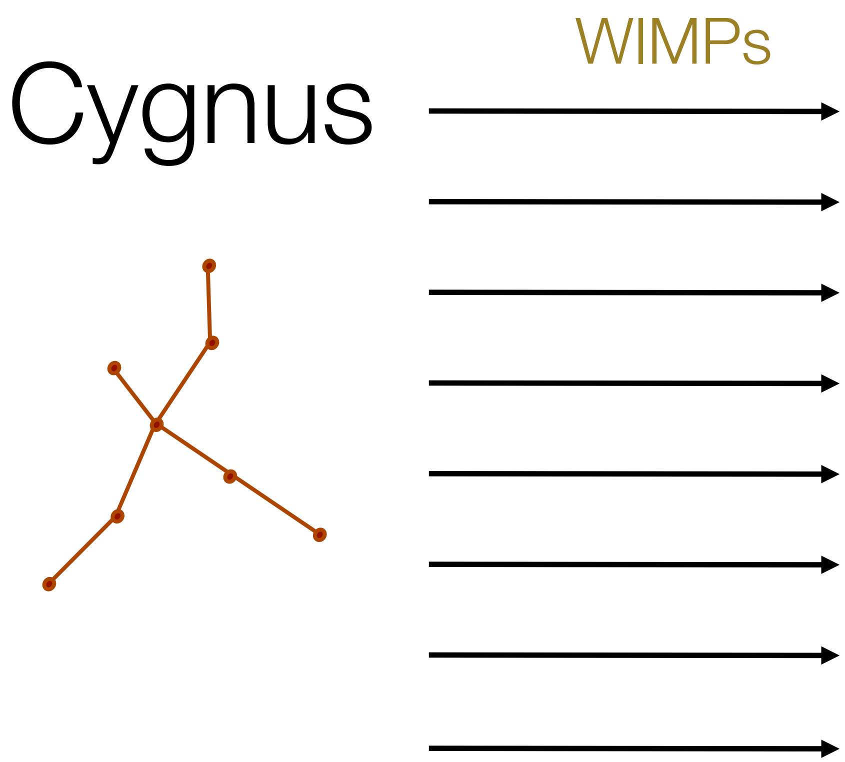
Modulation signal at the level of 0.0116 ± 0.0013) cpd/kg/keV 1.17 ton × yr 13 annual cycles

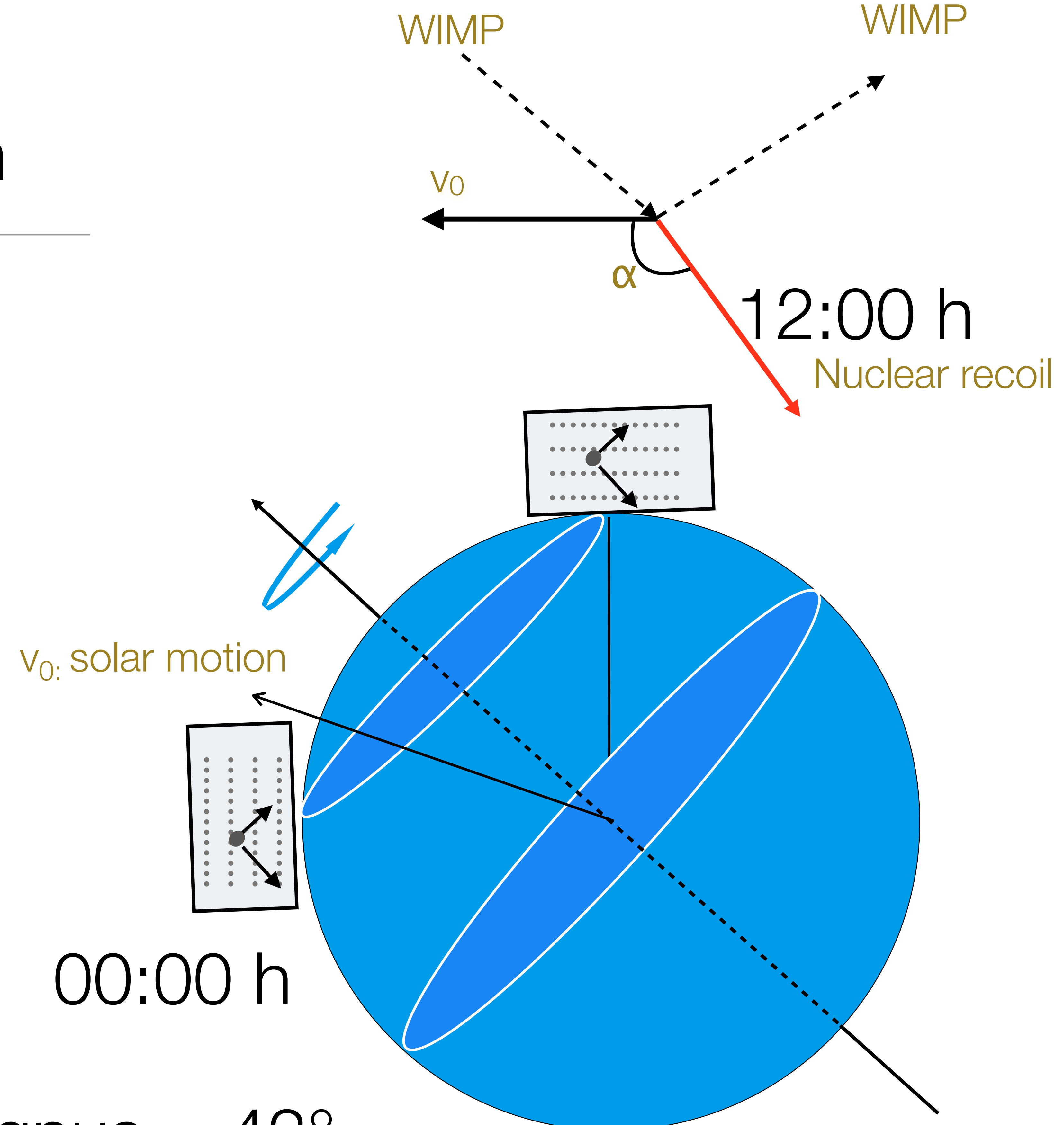


DM-TPC

- A Directional Dark Matter Detector
- Seeks to see the daily modulation of the Dark Matter Signal due to the rotation of the Earth through the prevailing “Dark Matter Wind”

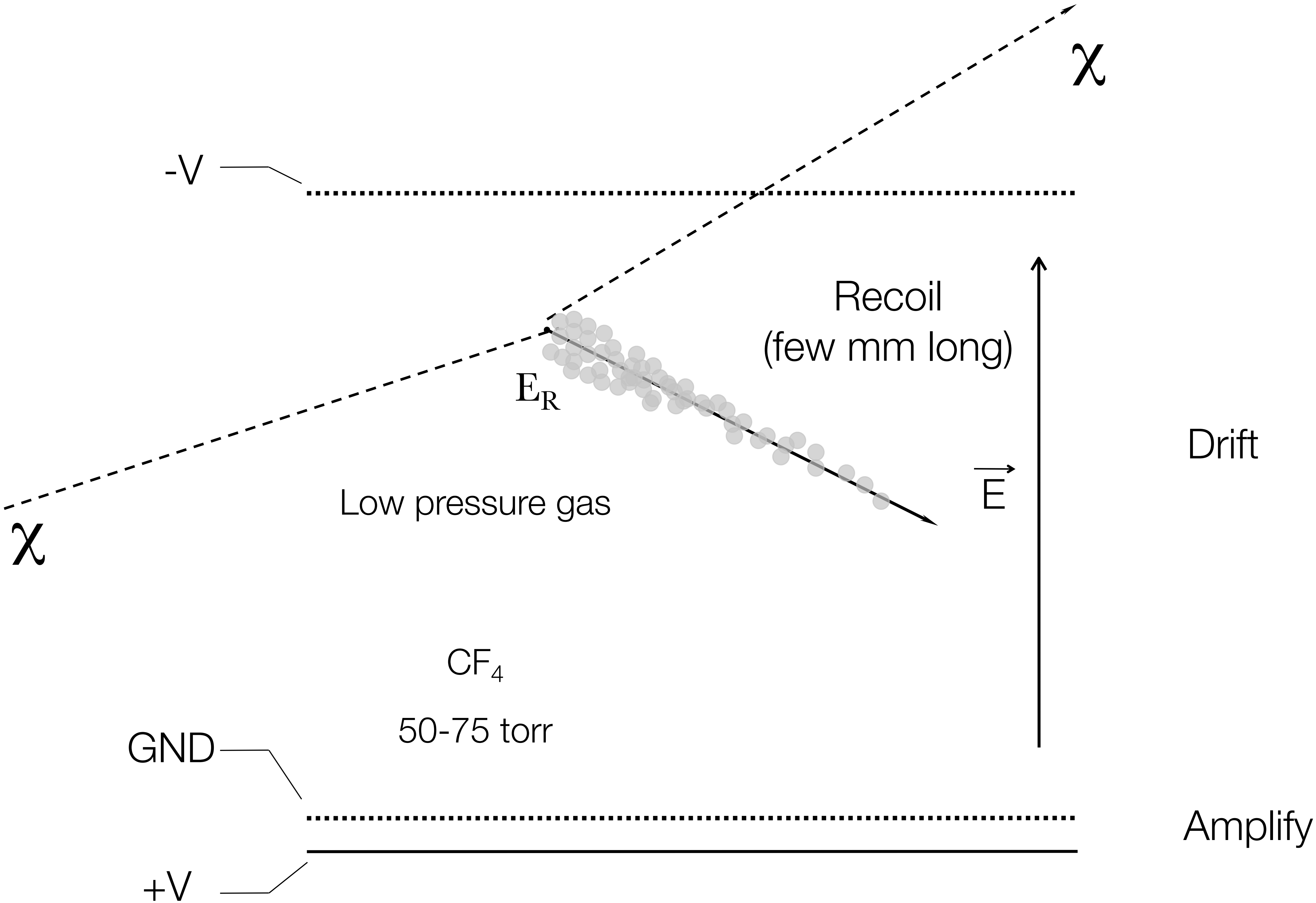
Diurnal modulation

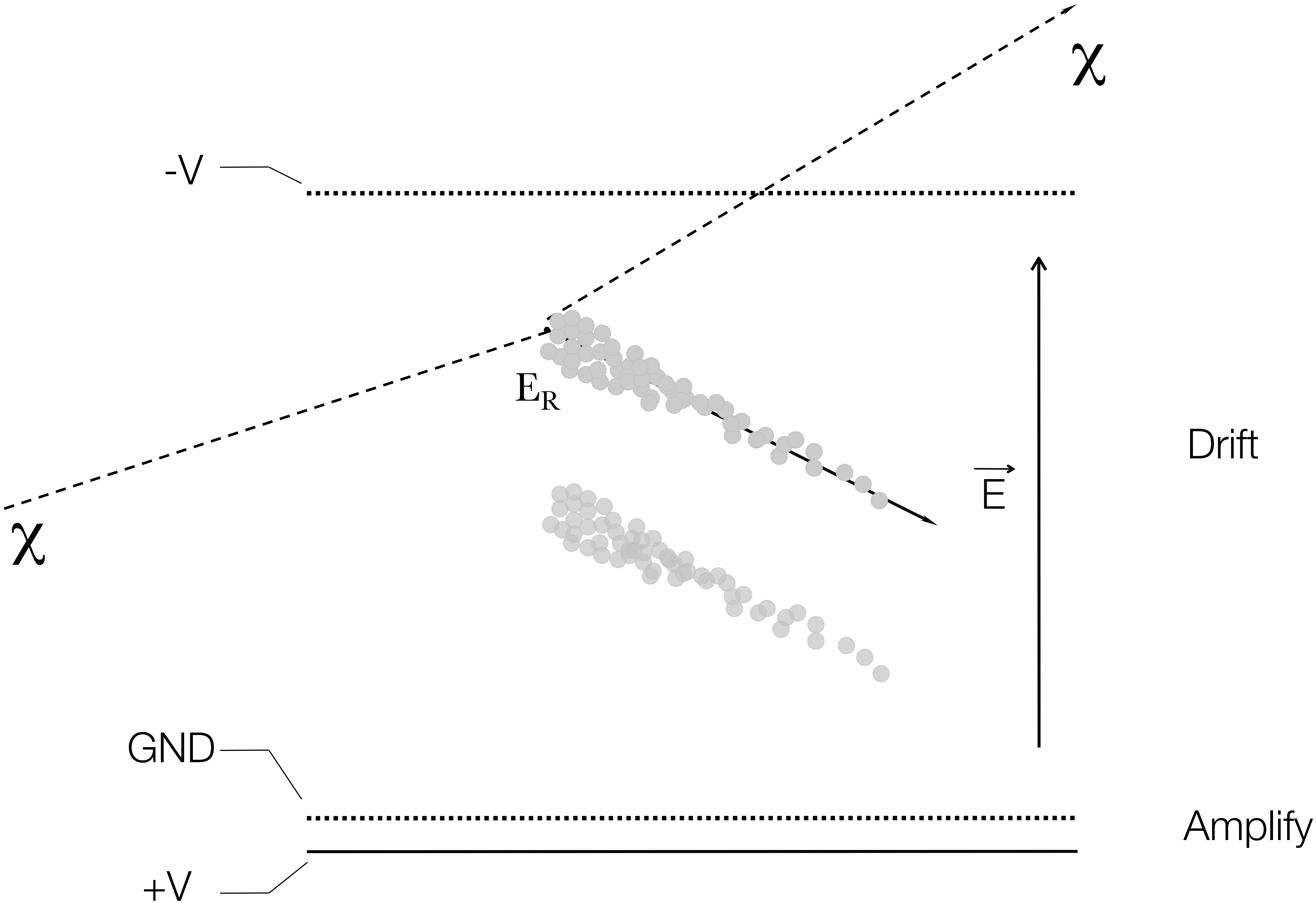




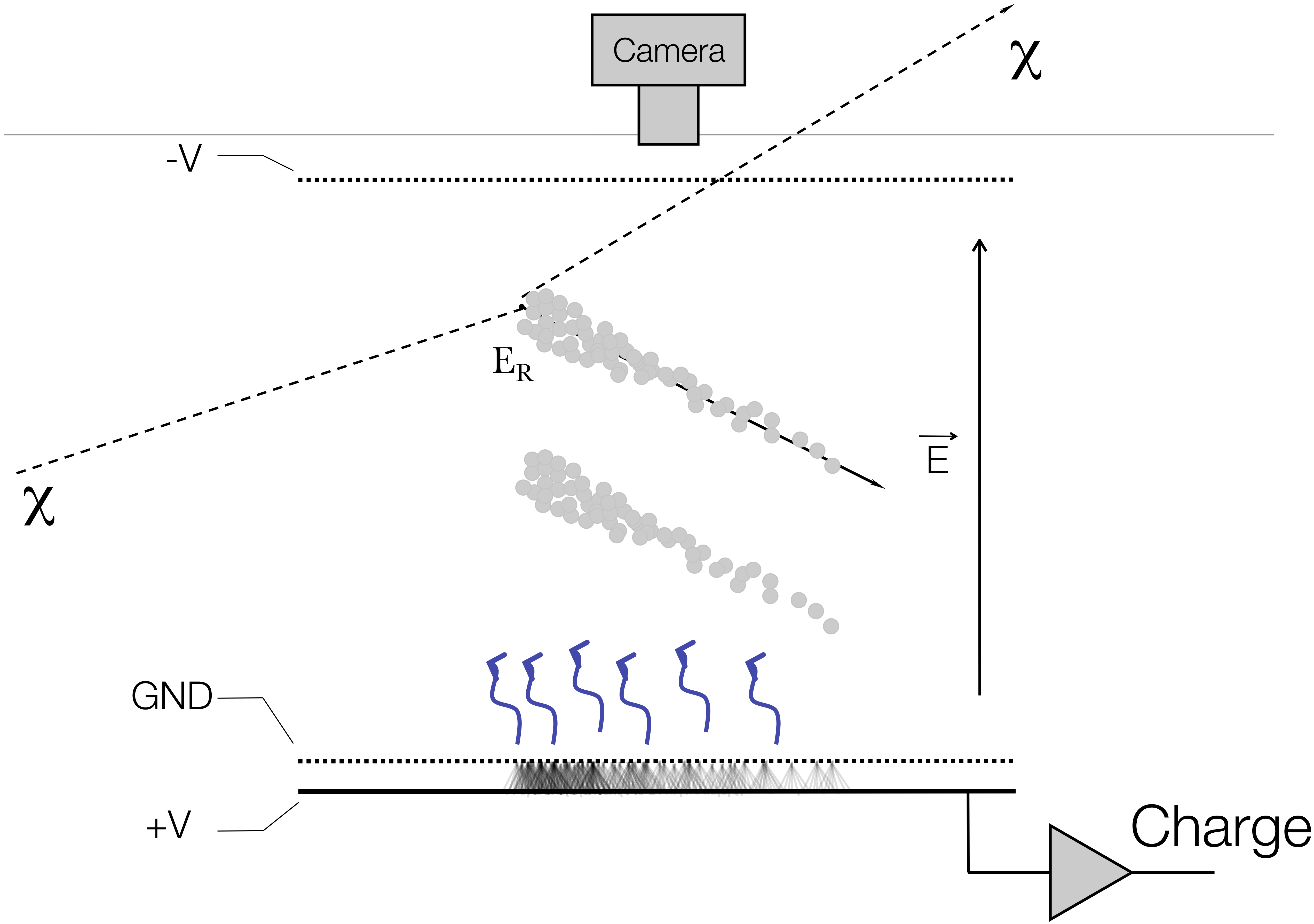
Declination of Cygnus ~42°

Spergel, PRD, 1988


χ
-V
Recoil
(few mm long)
E_R
Drift
$\vec{E}$
Low pressure gas
χ
CF_4
50-75 torr
GND
Amplify
+V

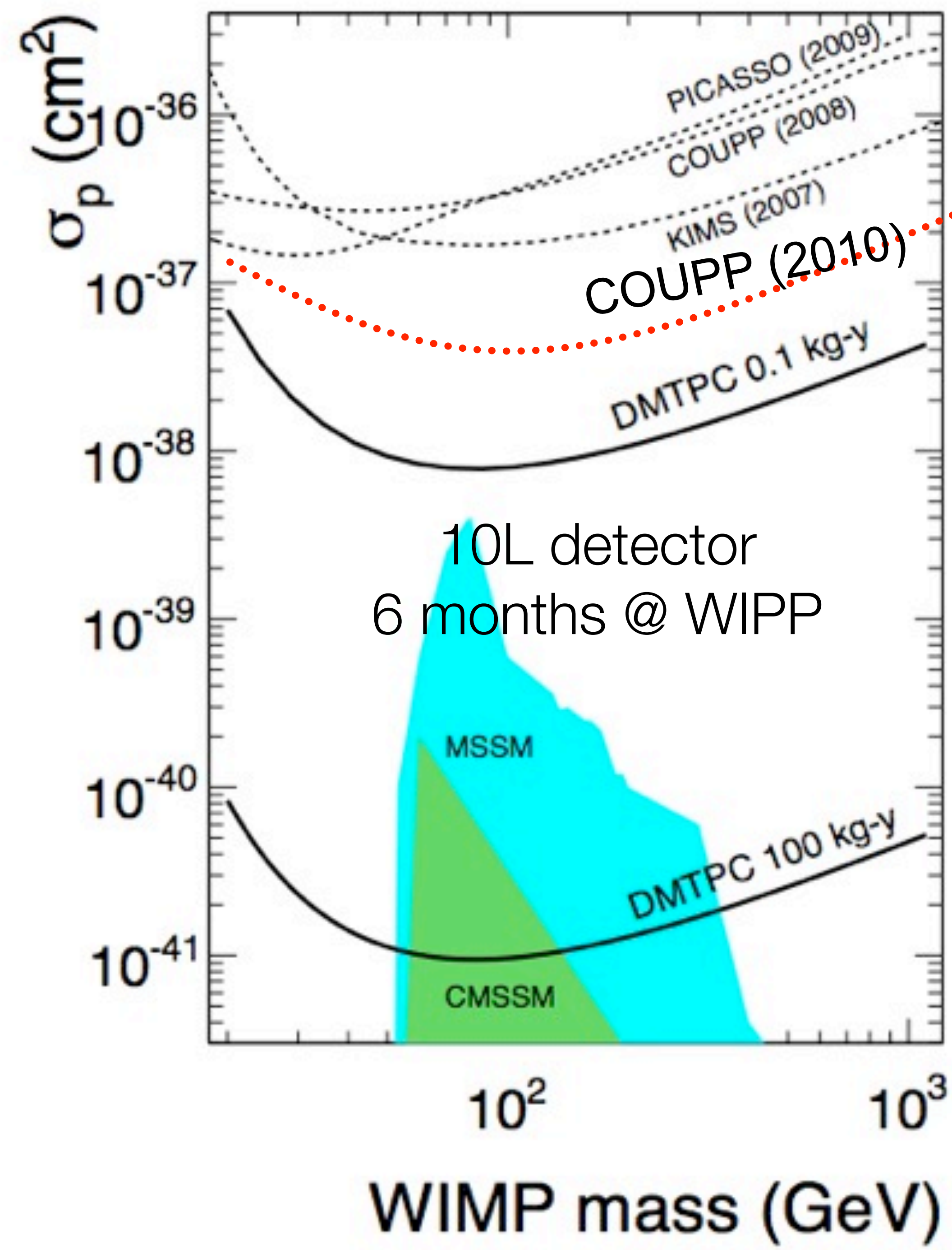


χ
-V
χ
E_R
Drift
$\vec{E}$
GND
Amplify
+V


Camera
χ
-V
E_R
$\vec{E}$
χ
GND
+V
Charge

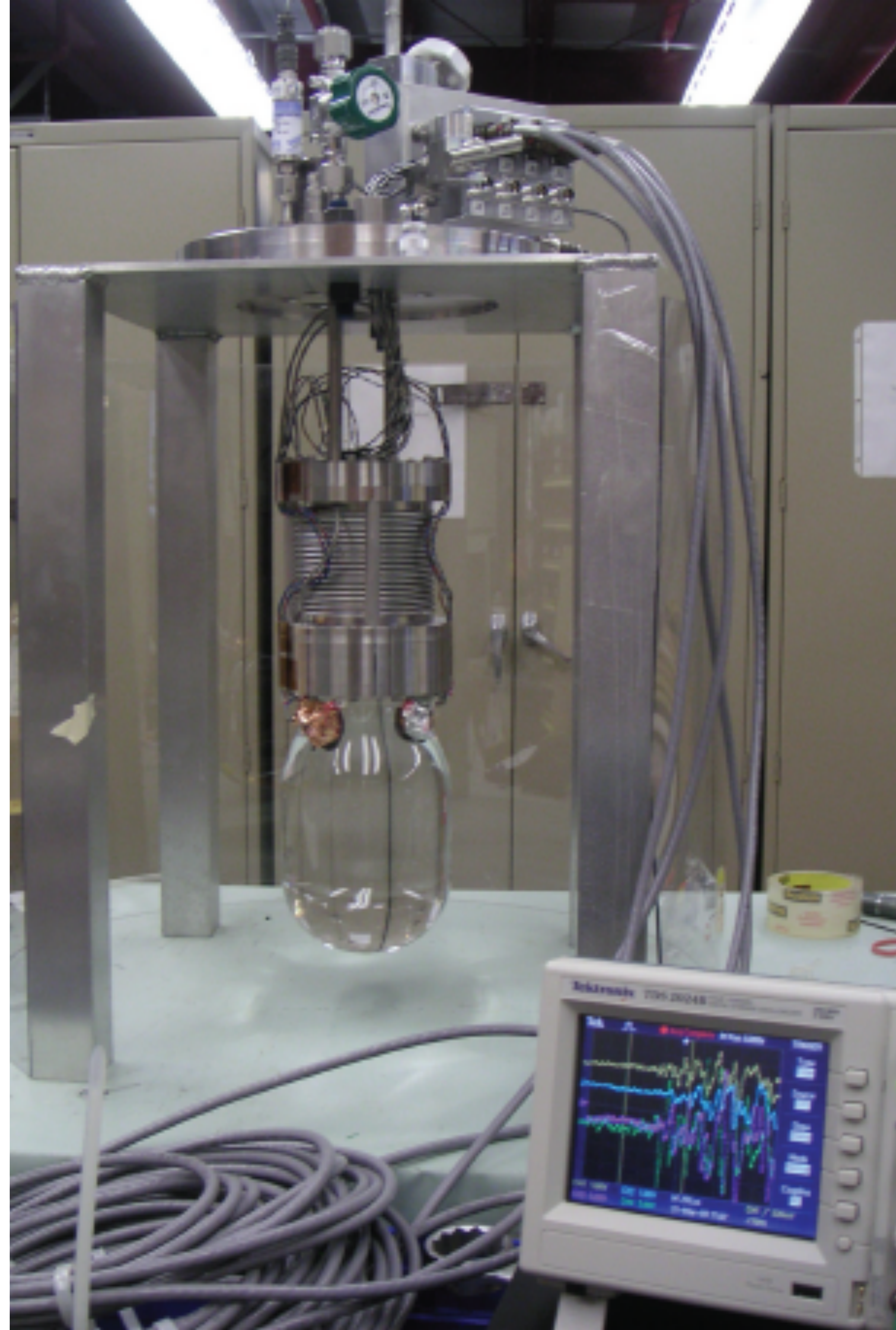
DM-TPC Status

- Installing a 10 liter CF_4 detector underground at WIPP
- Expect competitive sensitivities to Spin-Dependent WIMPs.

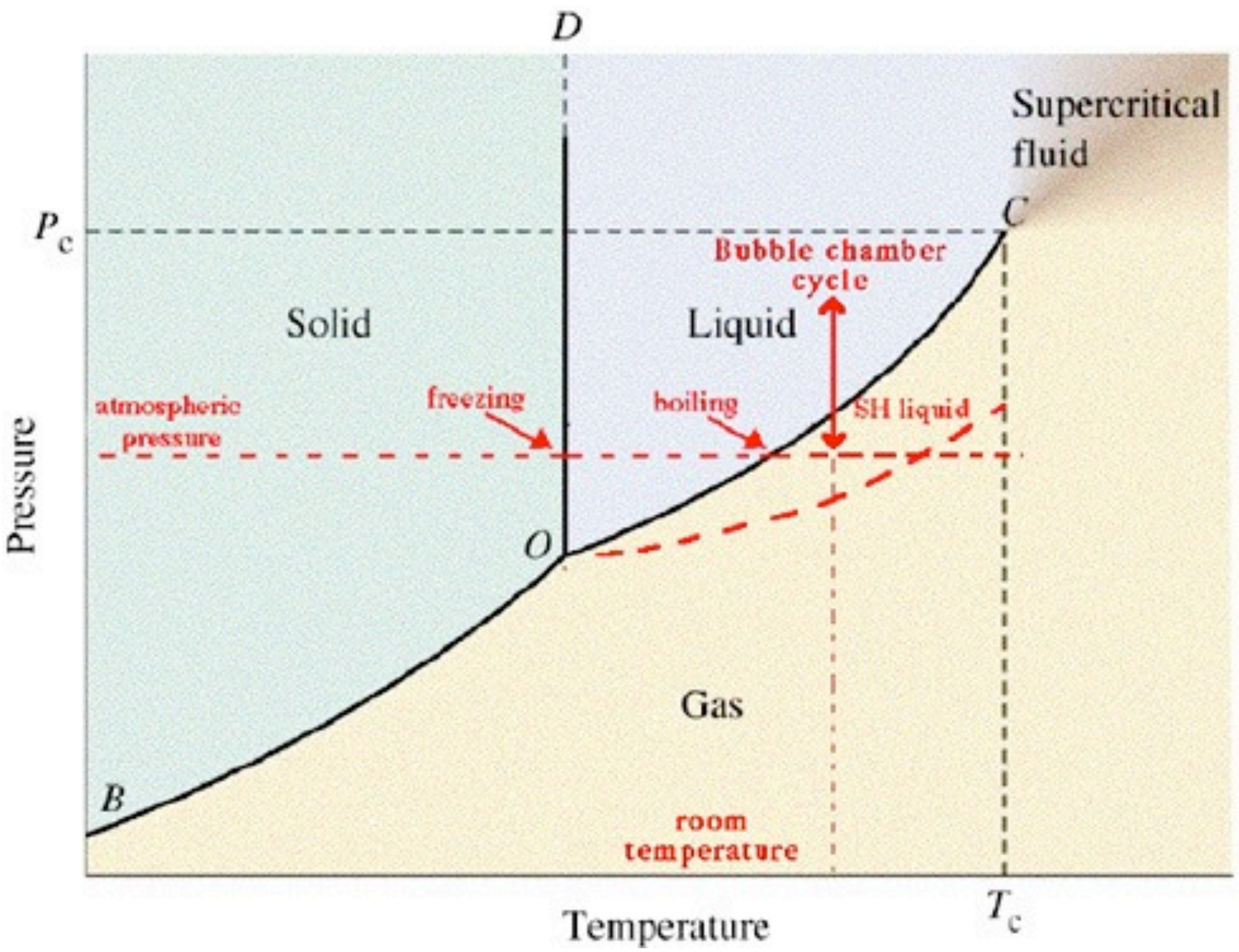


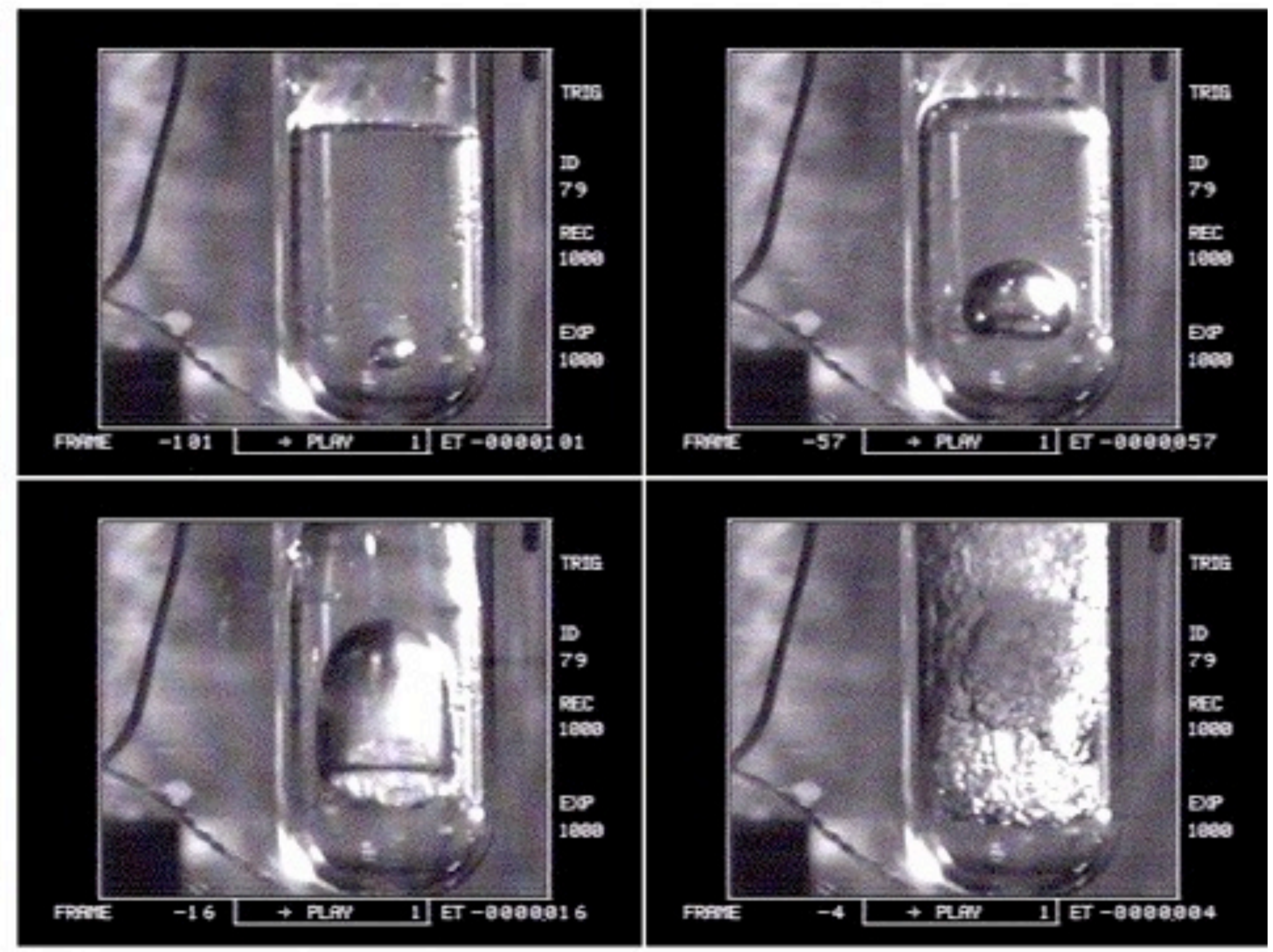
COUPP

- Superheated Bubble Chamber
- Insensitive to photons (but sensitive to alphas)
- Uses superheated CF_3I (sensitive to both spin-dependent and spin-independent interactions)



Bubbles!

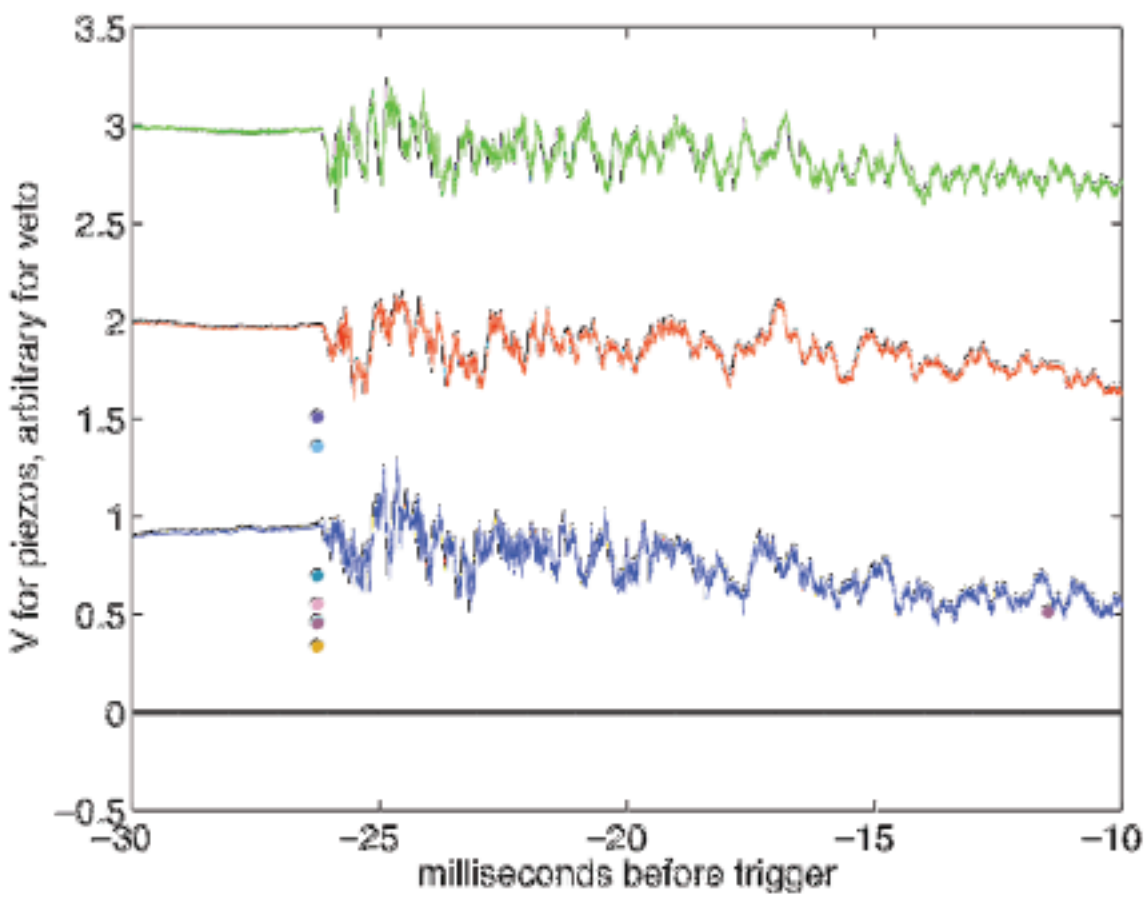




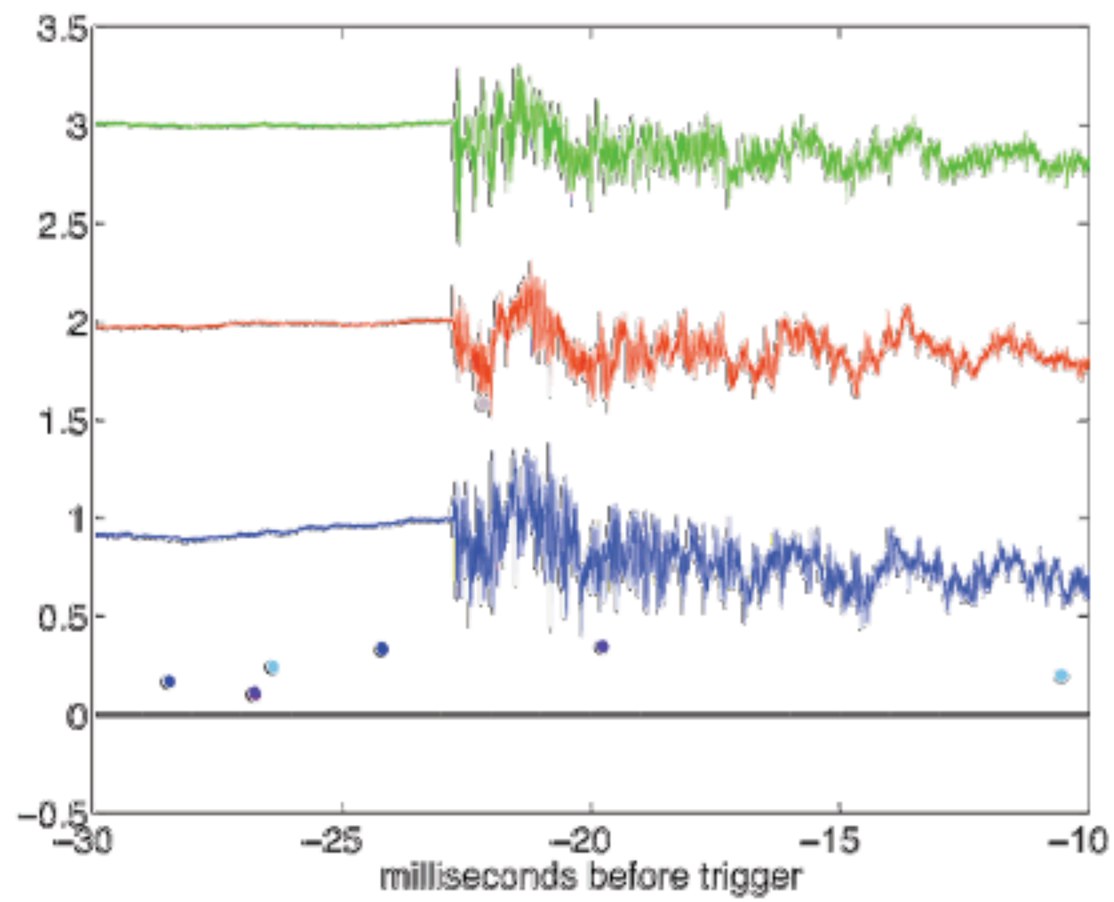
Alpha event

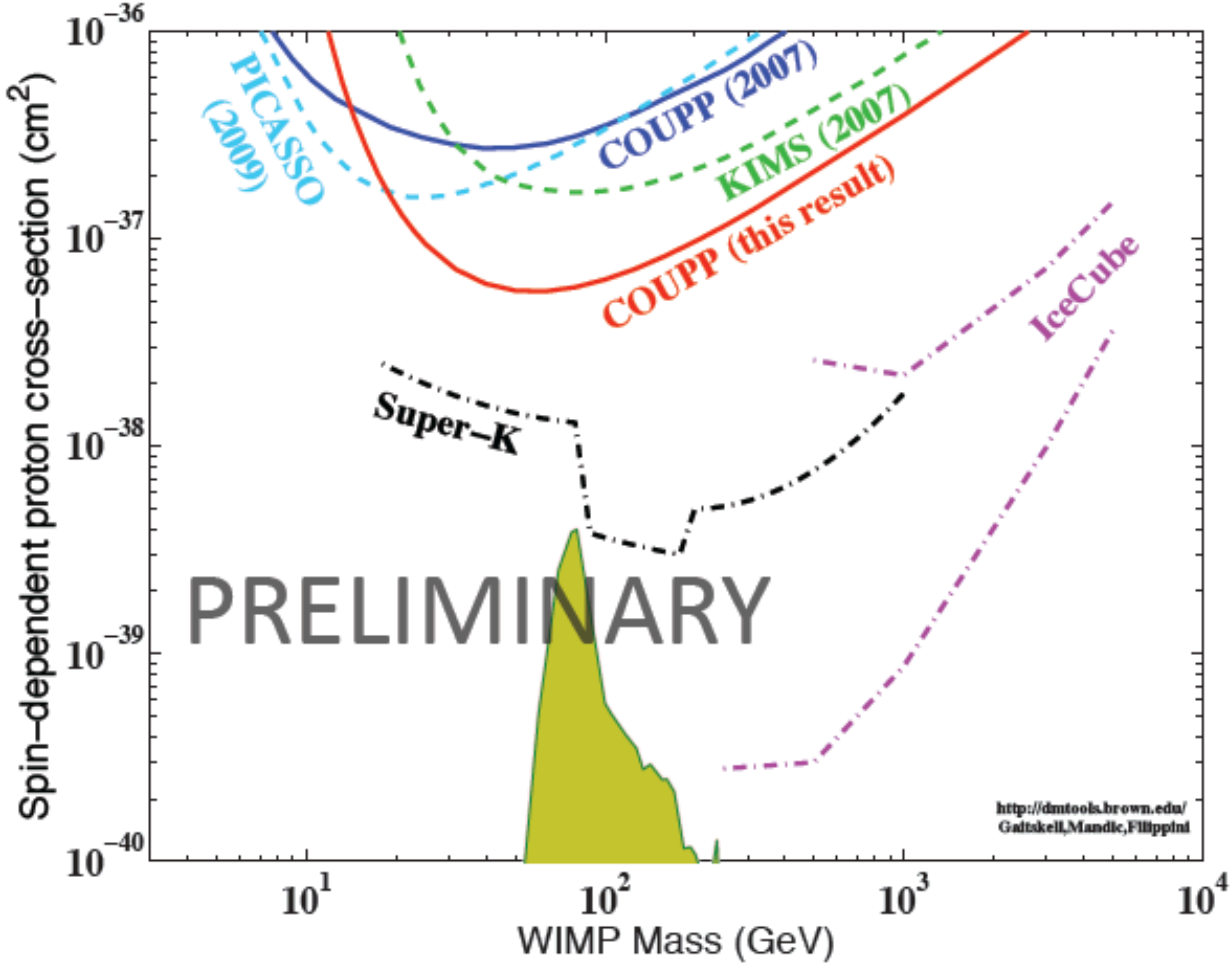
Acoustic Discrimination Between Neutrons and Alphas

Neutron



Alpha Particle





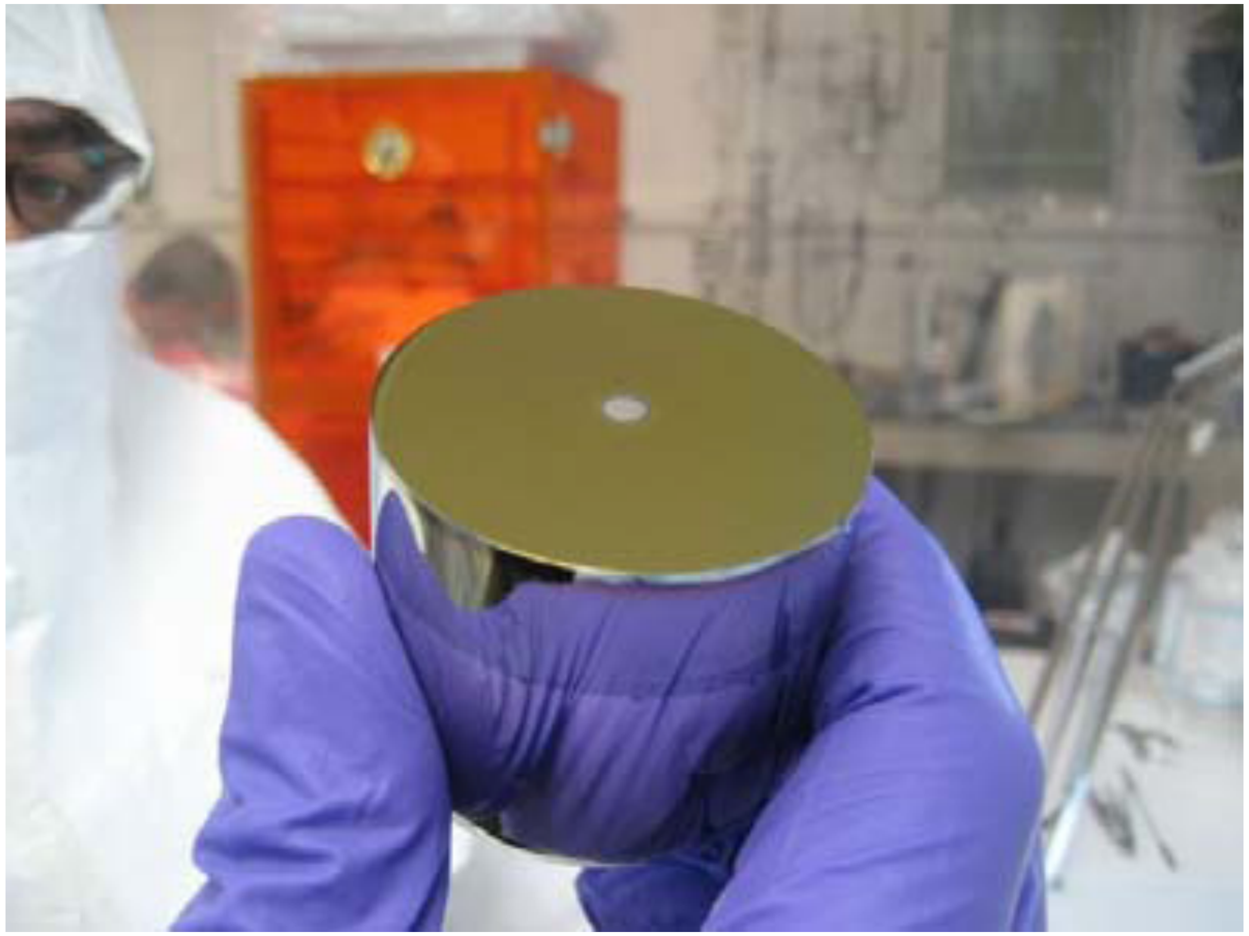
COUPP Spin-Dependent Limit

COUPP 60 kg

- A 60 kg bubble chamber is being tested at Fermilab and will be moved to SNOLab in the near future...

CoGeNT

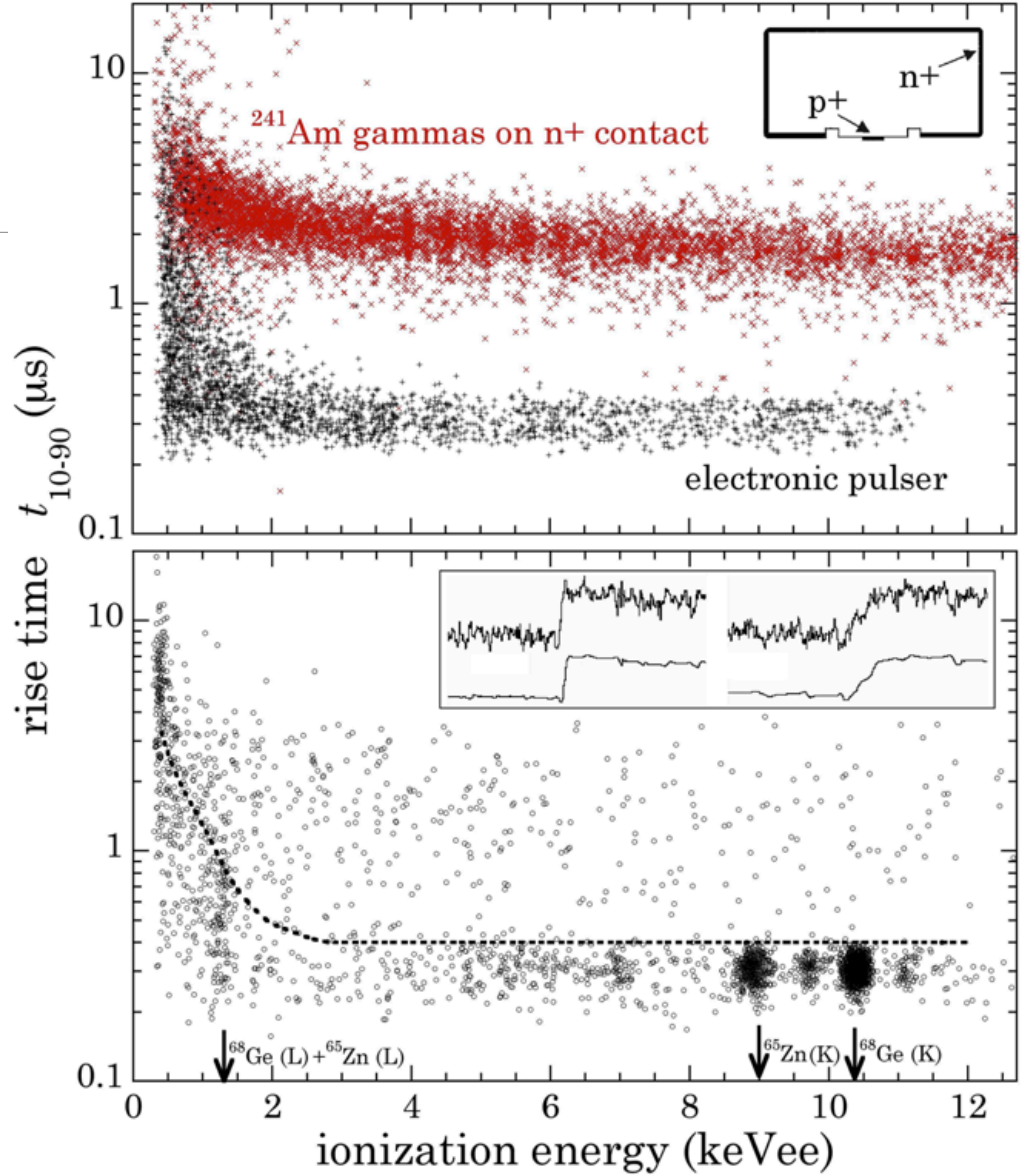
- P-type Point Contact Germanium Detector
- 440g detector
- Low 0.4 keVee threshold
- Operating in the Soudan Mine in Minnesota



arXiv: 1002.4703v2

Surface Event Discrimination

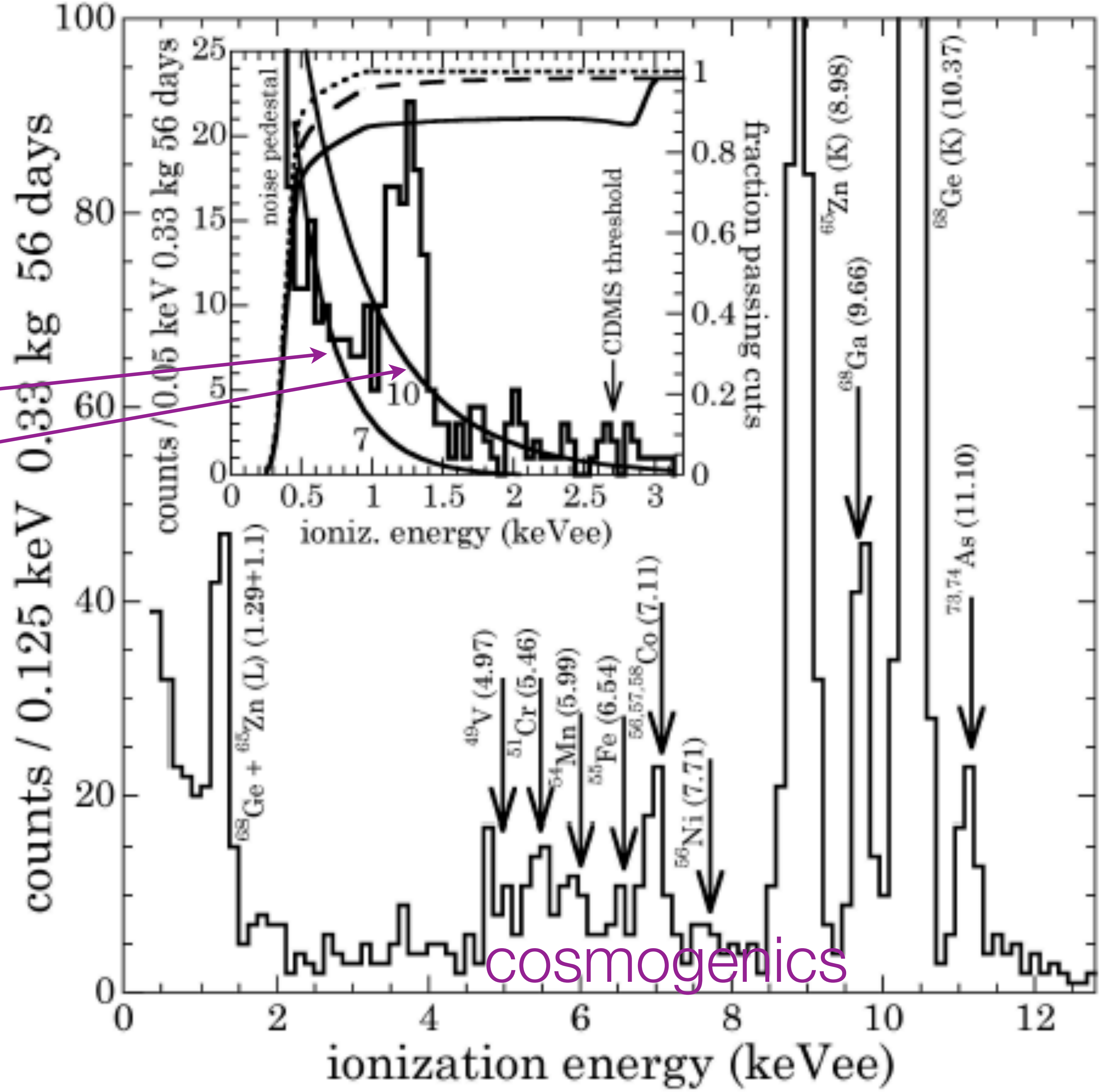
- Slower risetime of pulses on the n+ surface allows a cut to be placed on DM search data (lower)
- Inset shows fast and slow risetime pulses



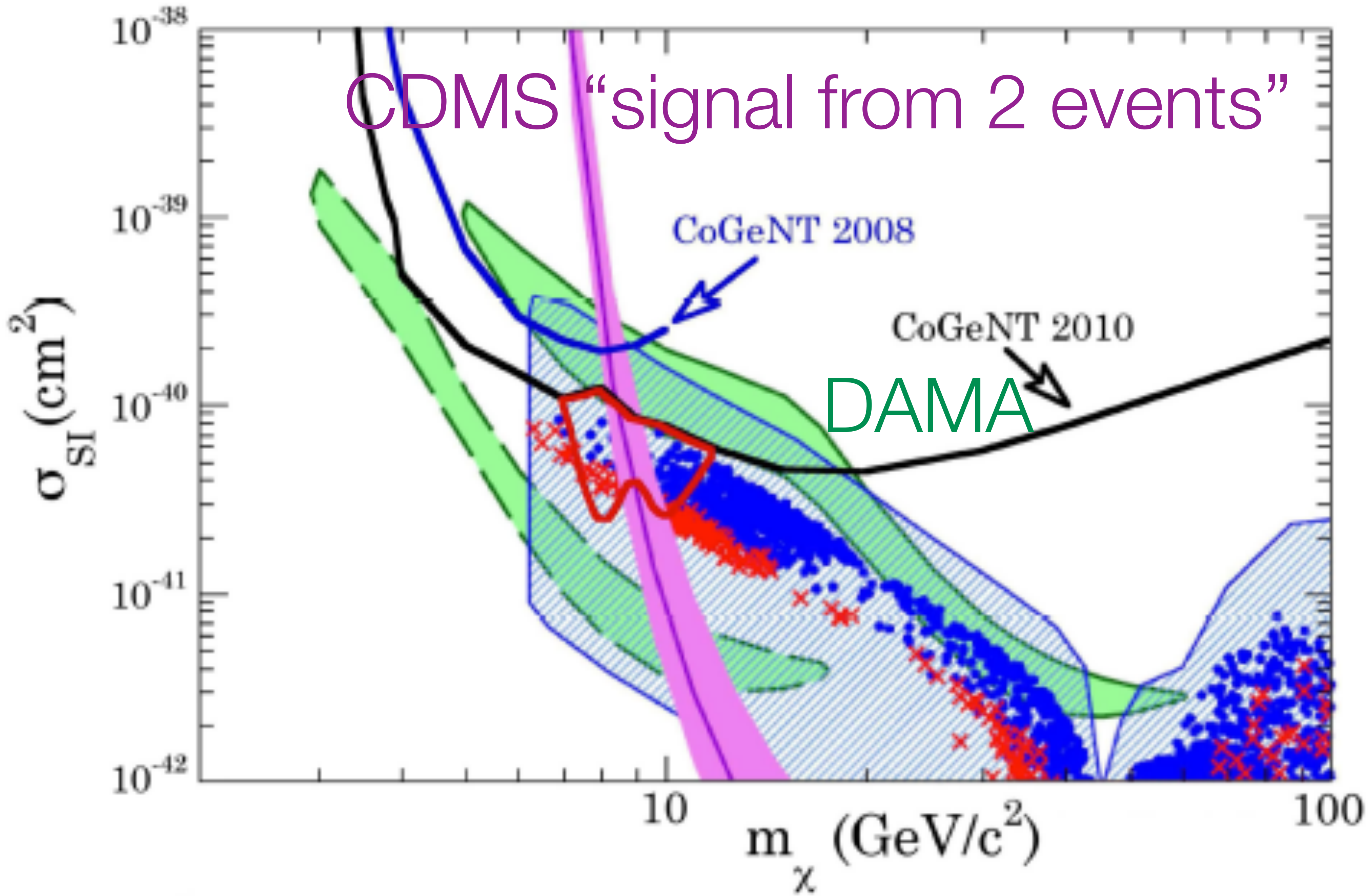
WIMP Signal?

7 GeV WIMP

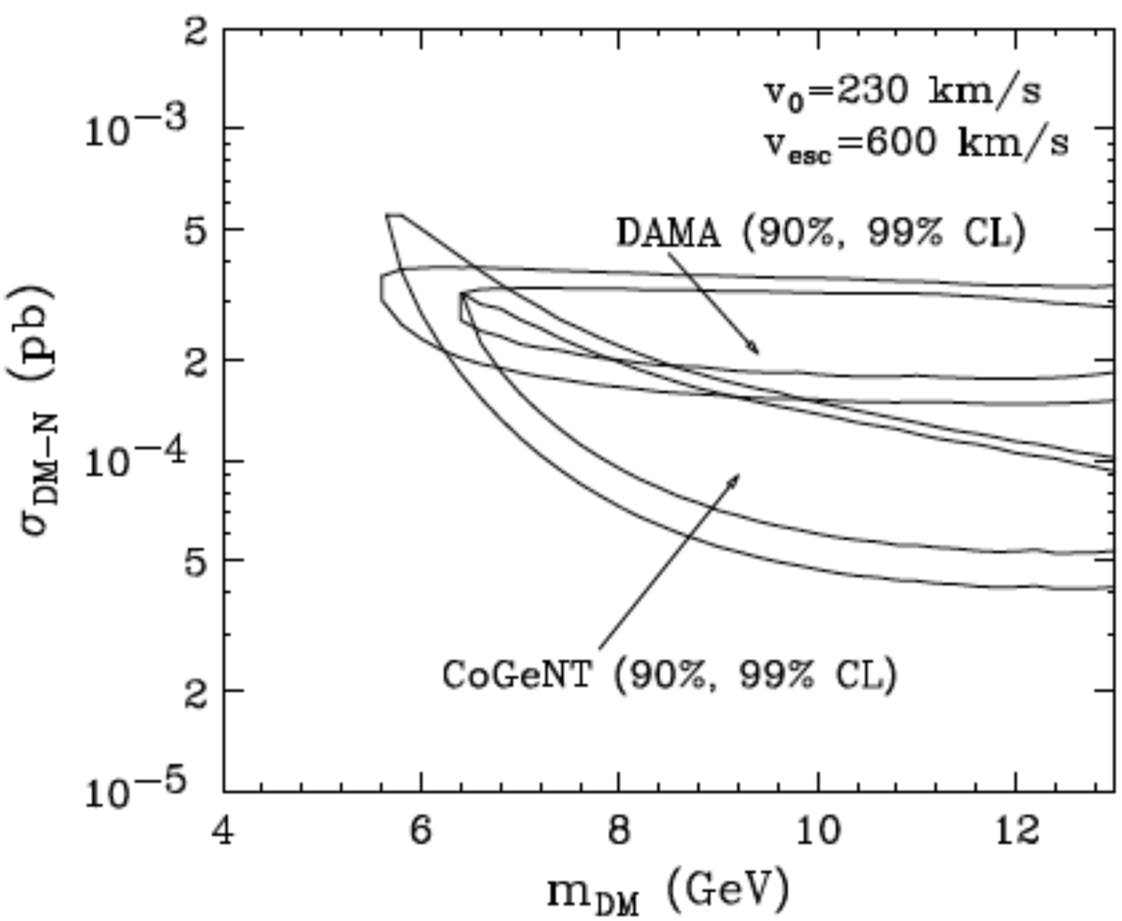
10 GeV WIMP

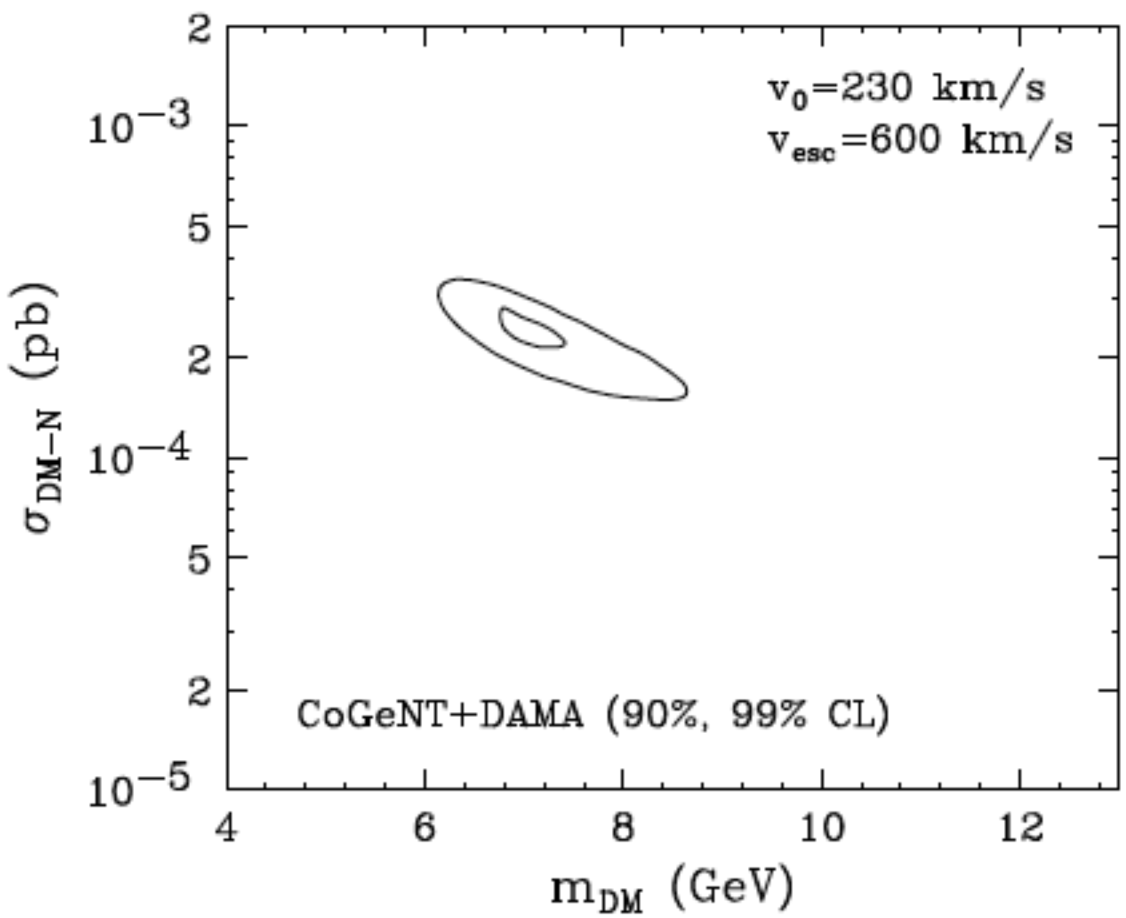


CoGeNT Signal Region



Interpretations...





- Hooper et. al give a possible WIMP candidate consistent with CoGeNT, DAMA, CRESST, and the null results by XENON and CDMS.

- Ritoban Basu Thakur will report on the latest CDMS results on a low mass WIMP candidate

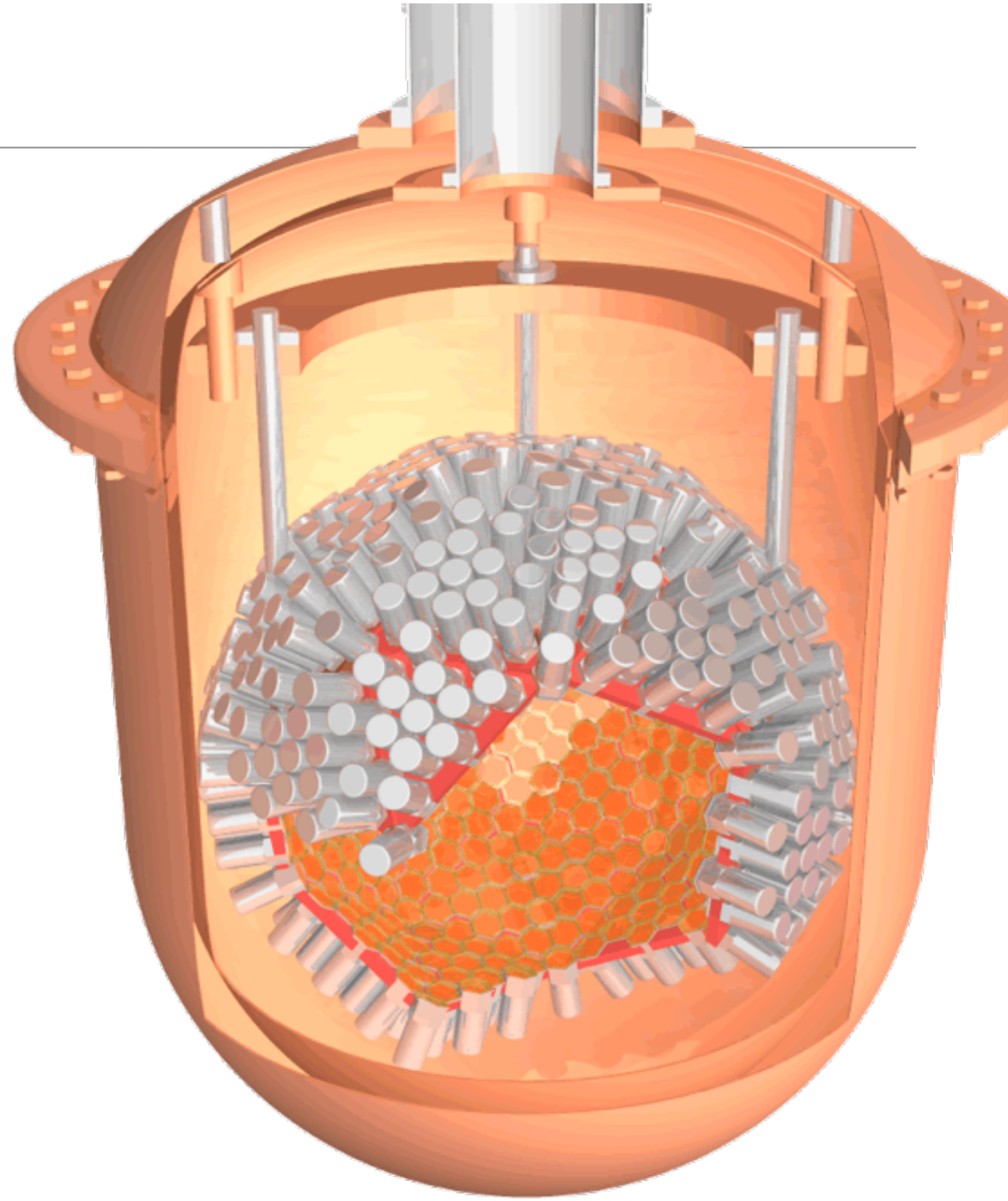
arXiv:1007.1005v2

Liquid Noble Detectors

- Time Projection Chambers
  - XENON
  - LUX
  - Zeplin (also a Xe TPC)
  - WArP (uses Argon)
- Single Phase Detectors
  - DEAP / CLEAN (Argon and Neon)
  - XMASS (800 kg under construction!)

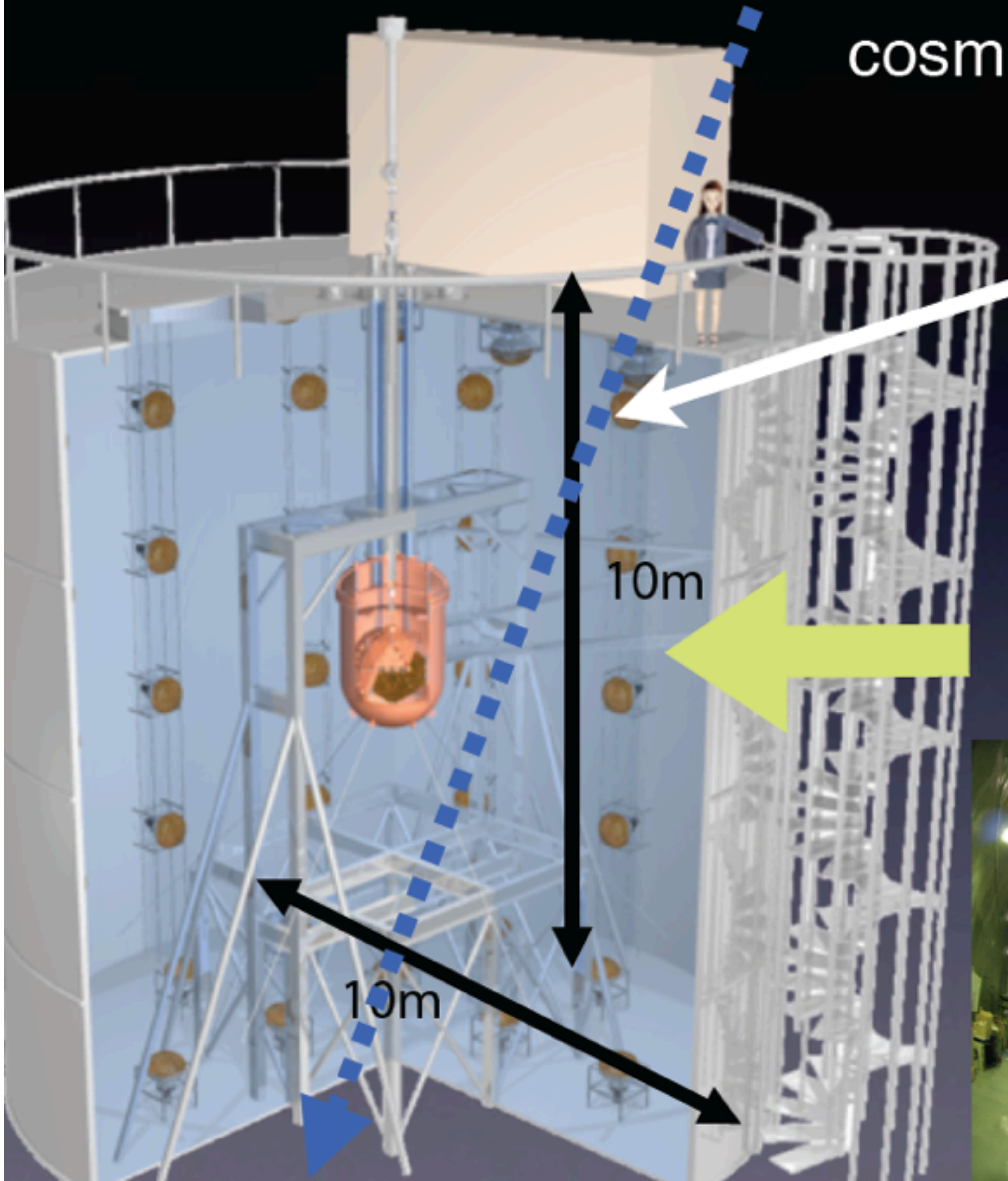
XMASS

- 800 kg Liquid XENON in Kamioka
- Self-Shielding gives a low-background region in the middle of the detector.
- 100 kg Fiducial Volume
- WIMP search early next year.



Water Tank

cosmic ray



70 PMTs (20 inch) to detect Cerenkov Light (same as SK)

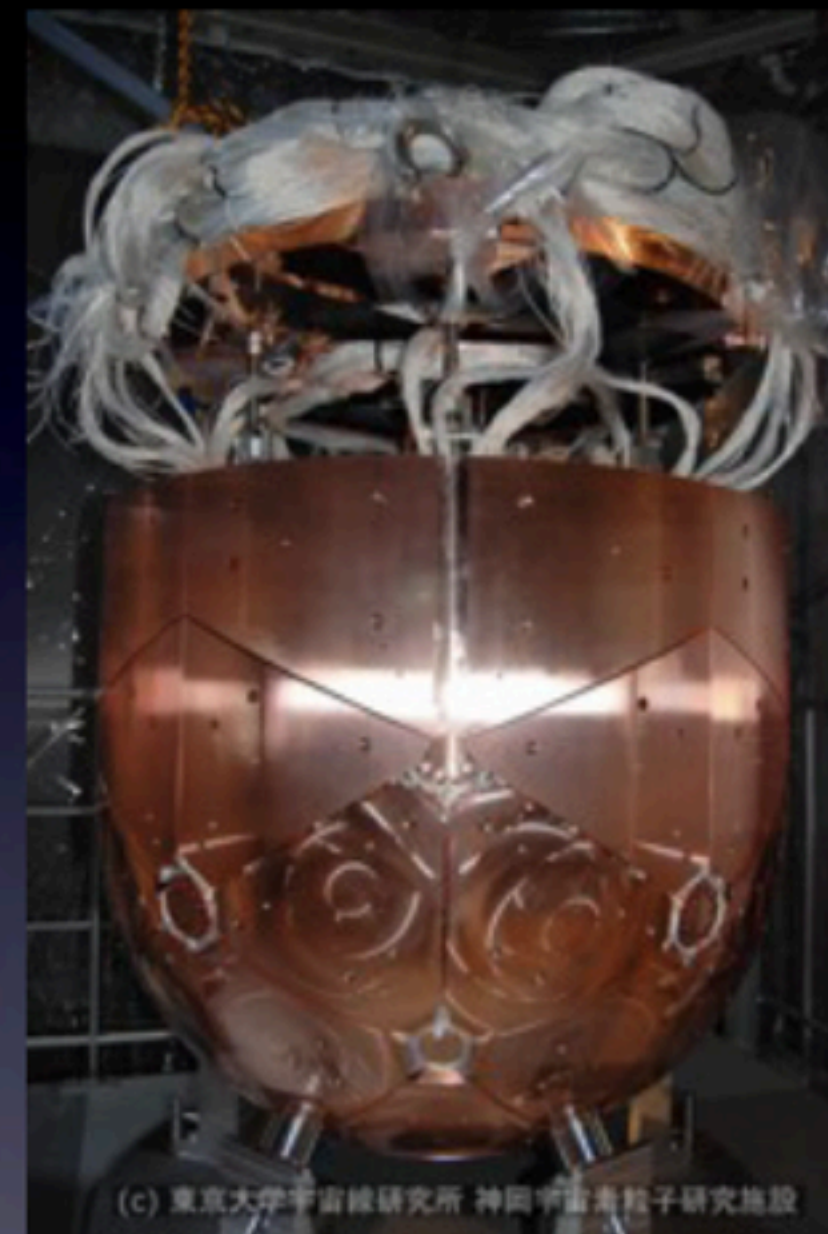
Active shield for muon induced events

Passive shield for γ and neutron from Rock

mashita

PMT Holder

Data Coming Soon!



OFHC Filler

Cryogenic Solid State Detectors

- Array of Smaller Detectors
- Potential for extreme background discrimination
- Aim to operate in “zero” background mode
- Examples:
  - CRESST
  - Edelweiss (pictured)
  - CDMS

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CDMS: The Big Picture

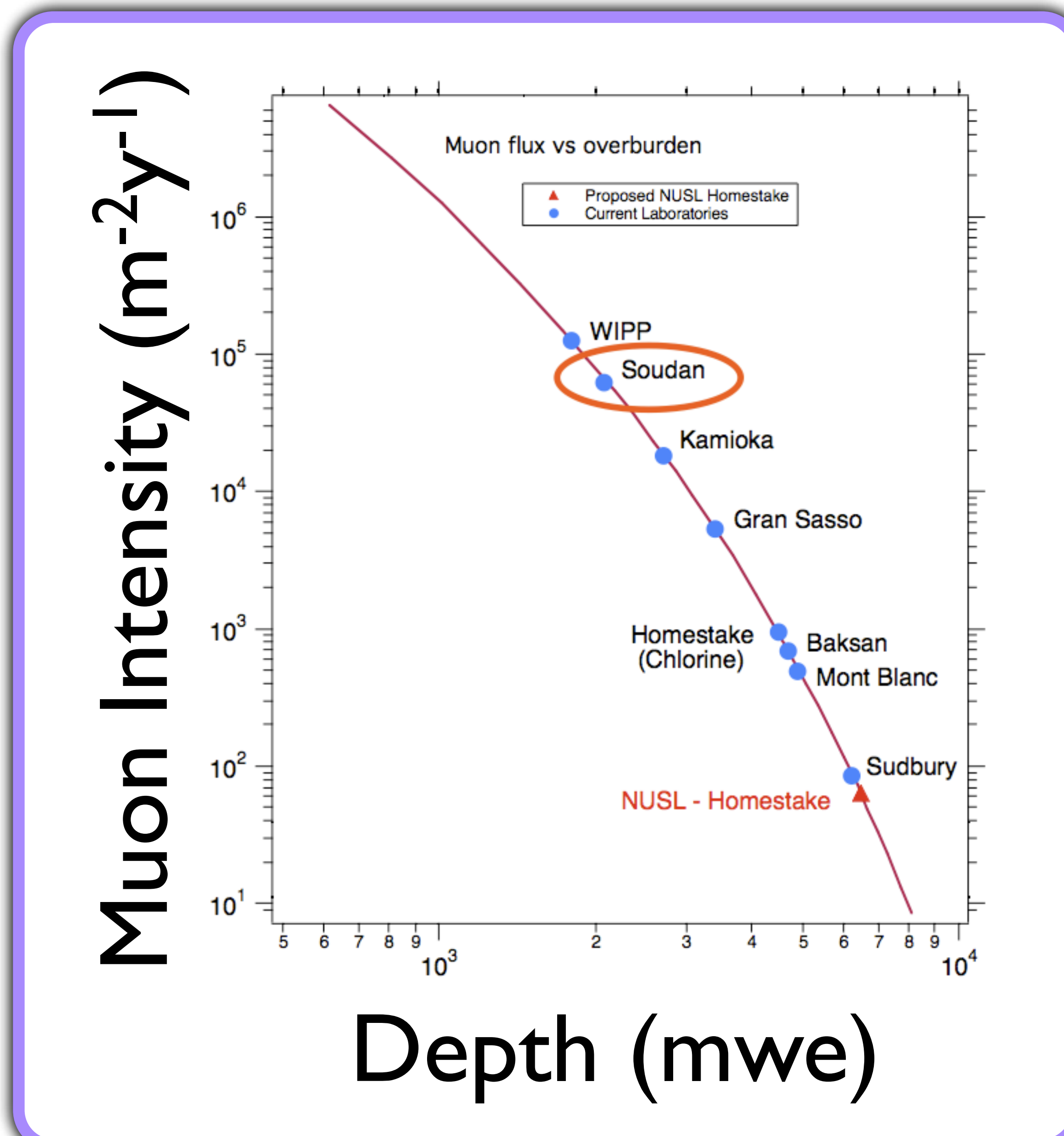
Use discrimination and shielding to maintain a Nearly Background Free experiment with cryogenic semiconductor detectors

- Shielding
  - Passive (Mine Depth, Pb, Poly)
  - Active (muon veto shield)
- Energy Measurement
  - Phonon (True recoil energy)
  - Charge (Reduced for Nuclear)
- Position measurement (x,y,z)
  - From phonon pulse timing

Observation Strategy

1. Suppress all backgrounds

780 m rock	(2090 m water equiv.)
Active veto	muon scintillator
Polyethylene	neutron moderation
Lead	shields gammas
Ancient Lead	shields ^{210}Pb betas
Polyethylene	shields ancient lead
Radiopure Copper inner can	
Radiopure Ge "target"	



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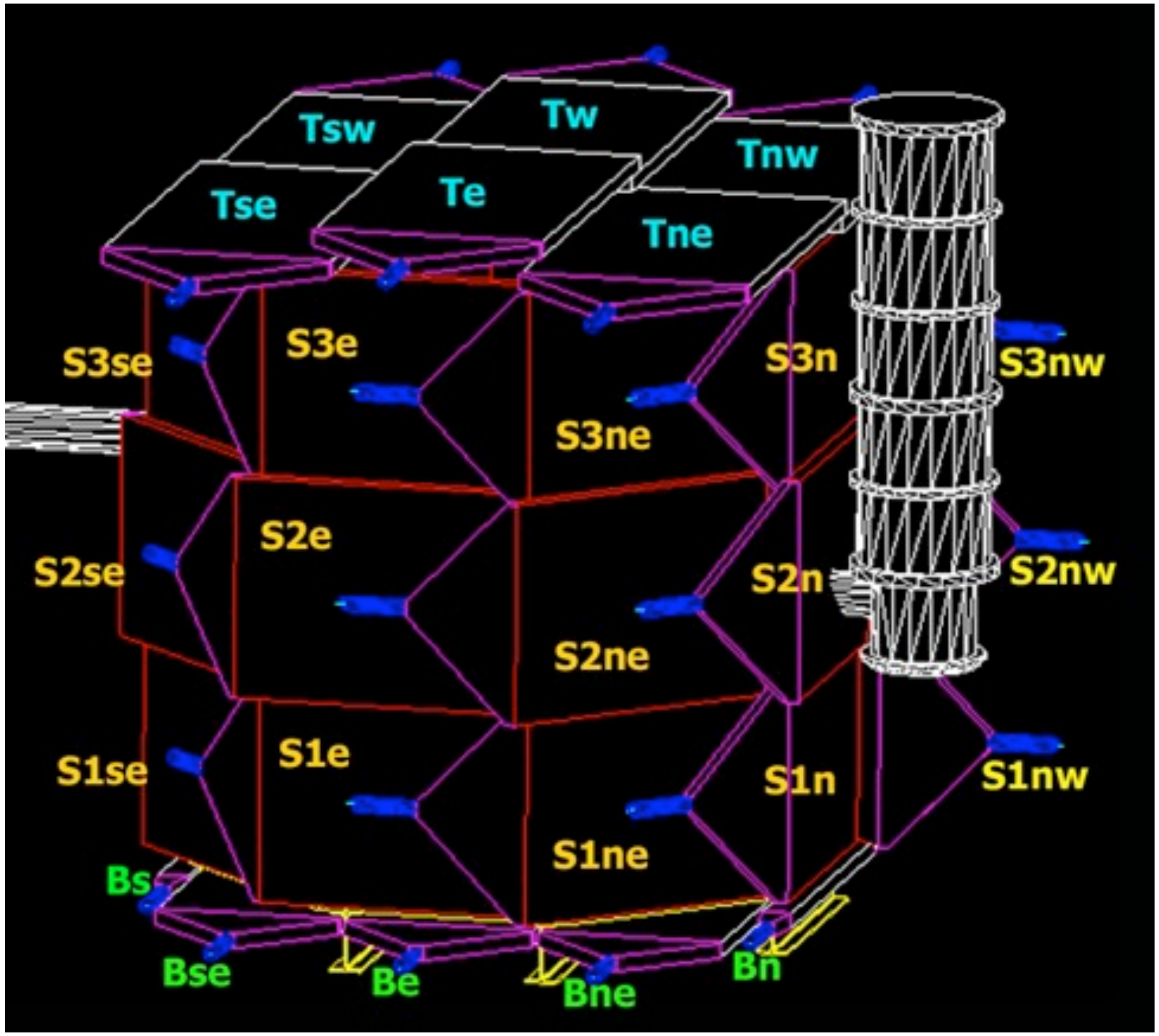

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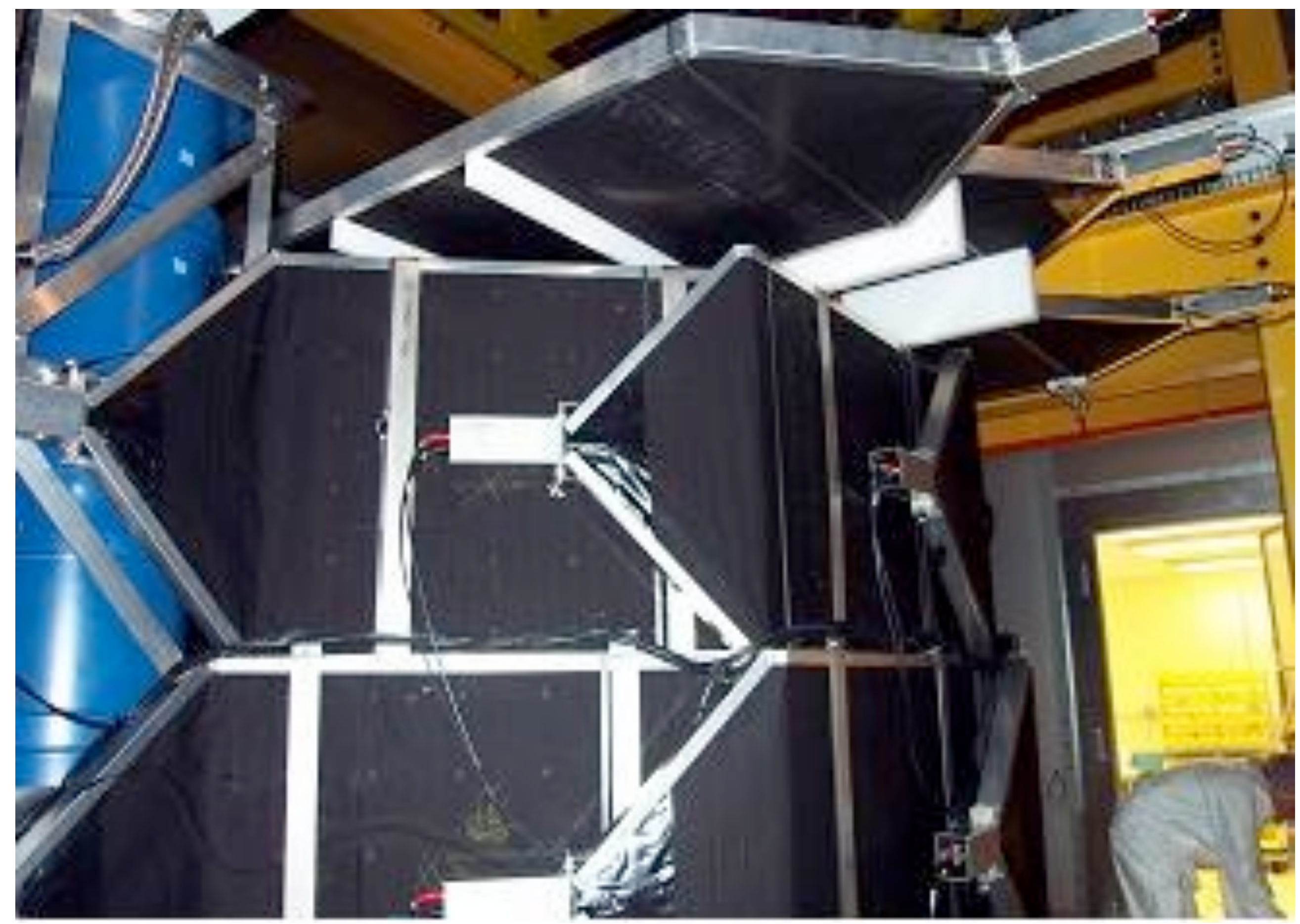

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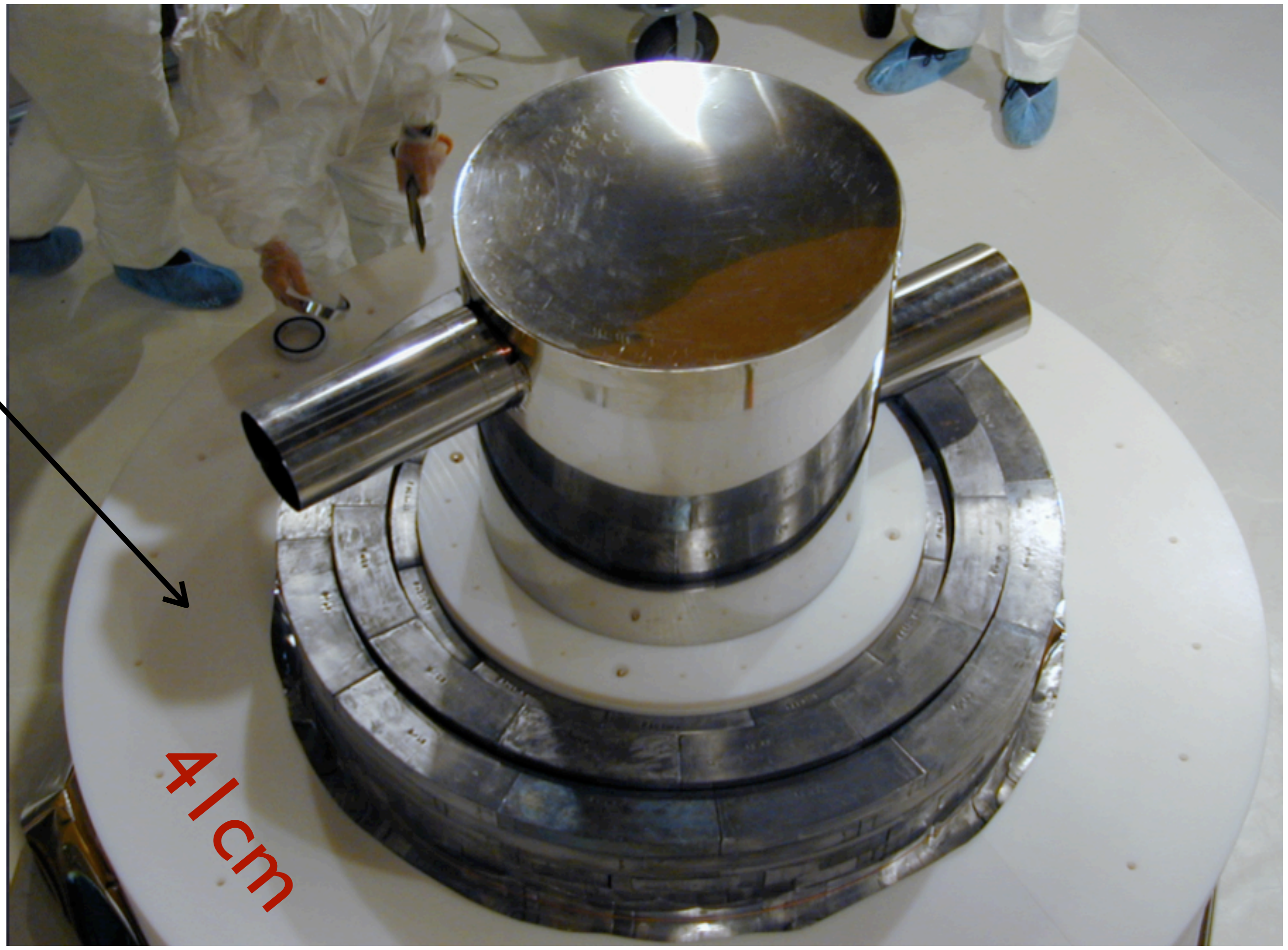

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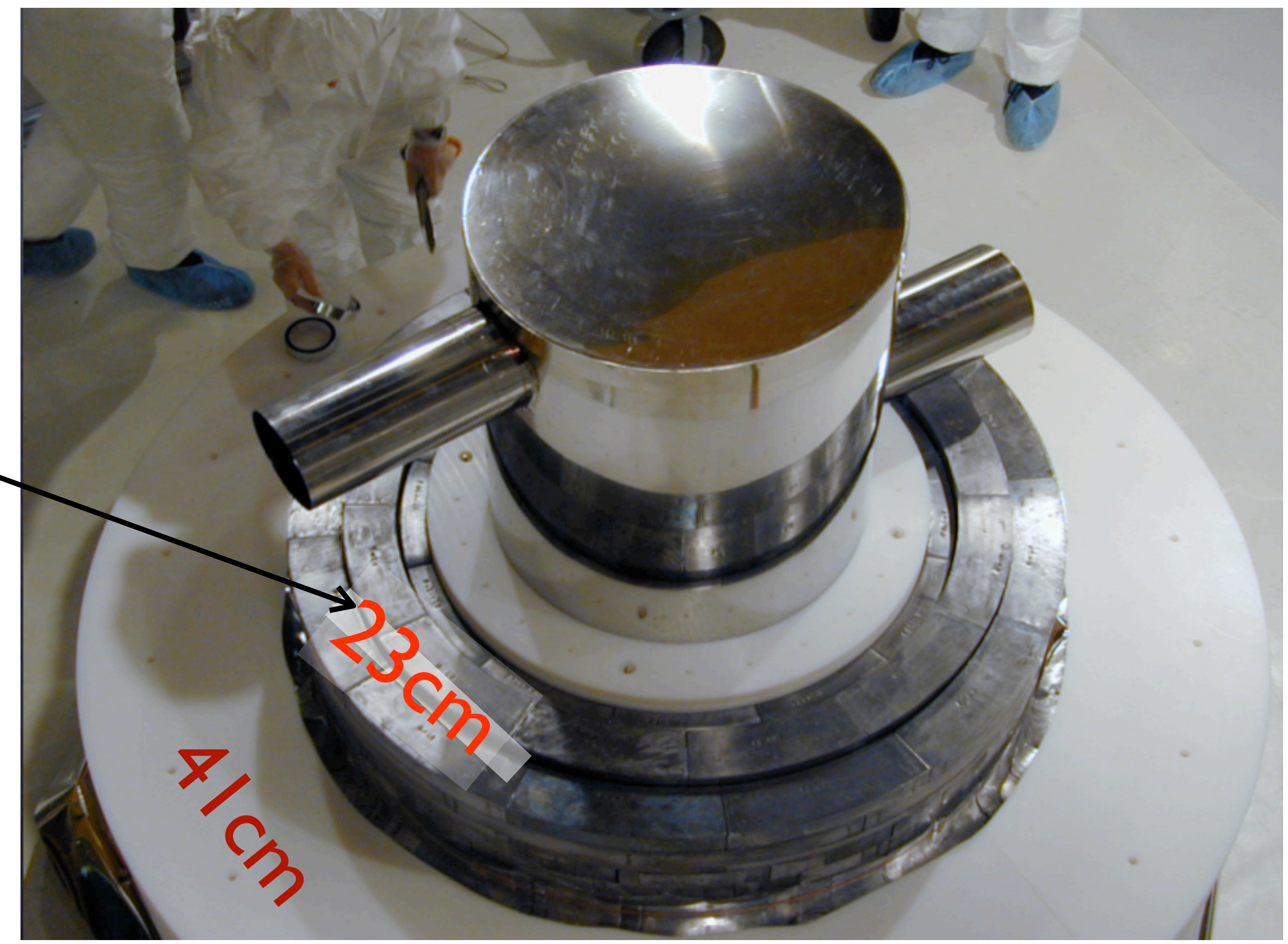

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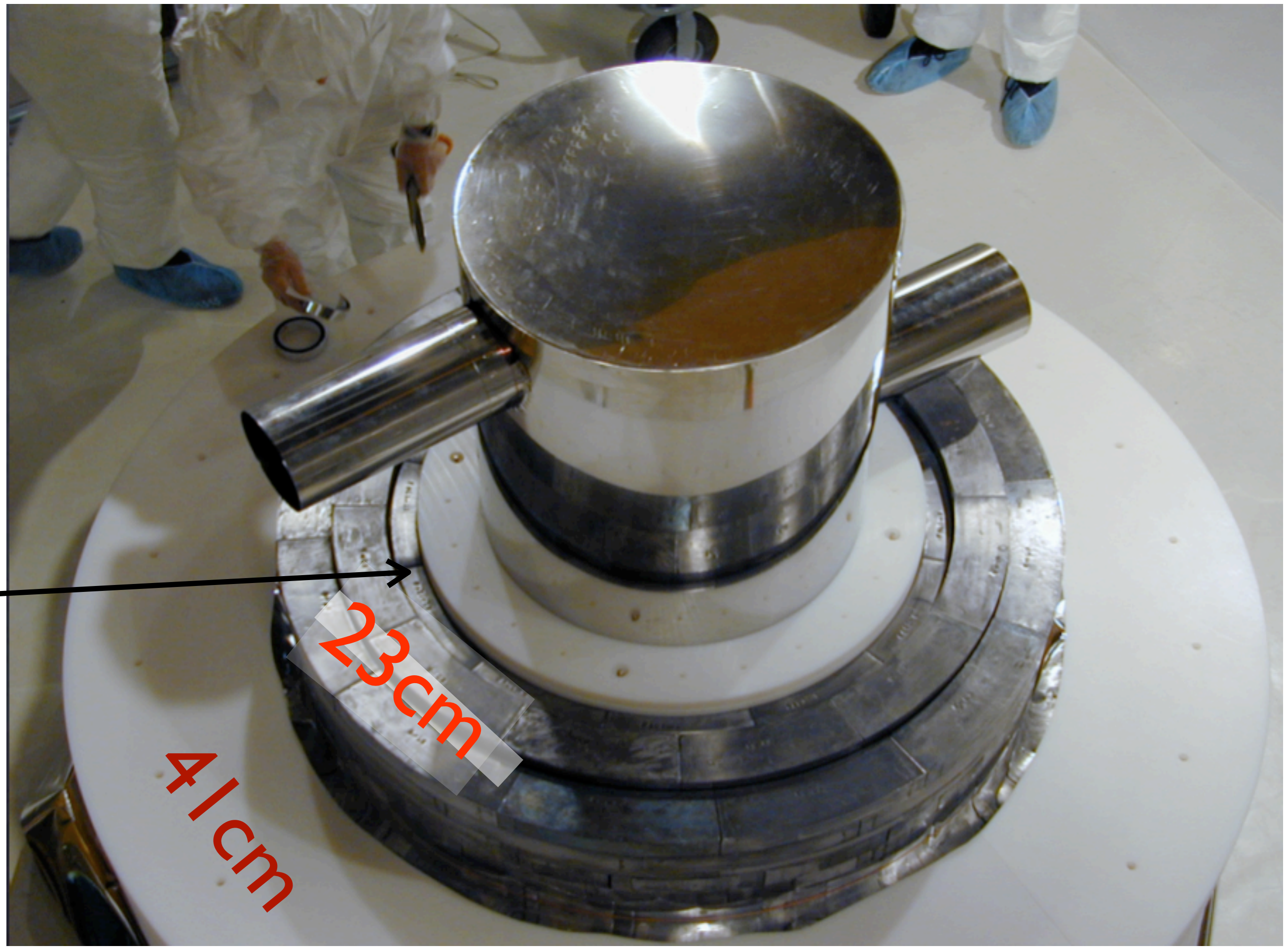

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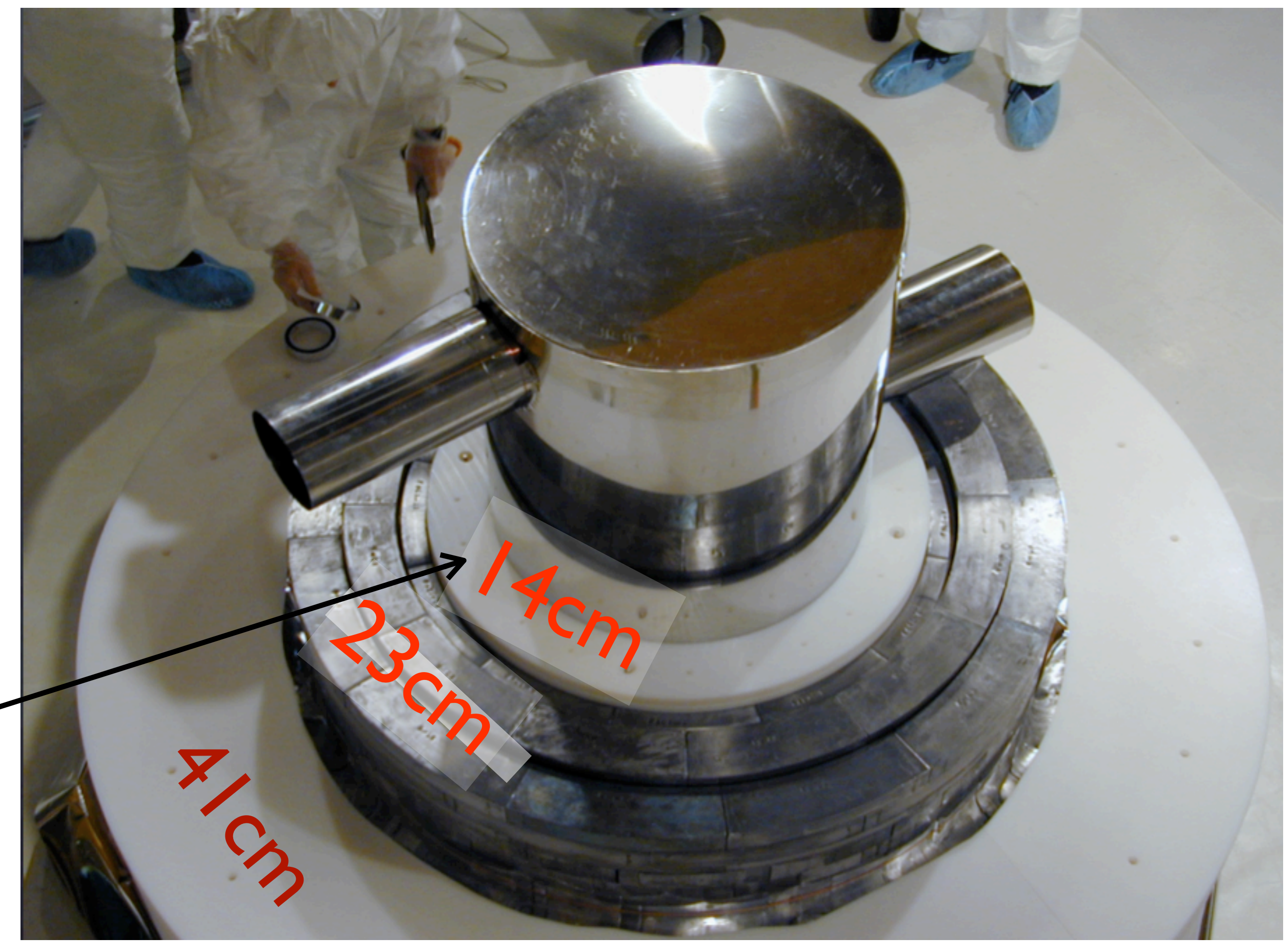

Observation Strategy

1. Suppress all backgrounds

780 m rock	(2090 m water equiv.)
Active veto	muon scintillator
Polyethylene	neutron moderation
Lead	shields gammas
Ancient Lead	shields ^{210}Pb betas
Polyethylene	shields ancient lead
Radiopure Copper inner can	
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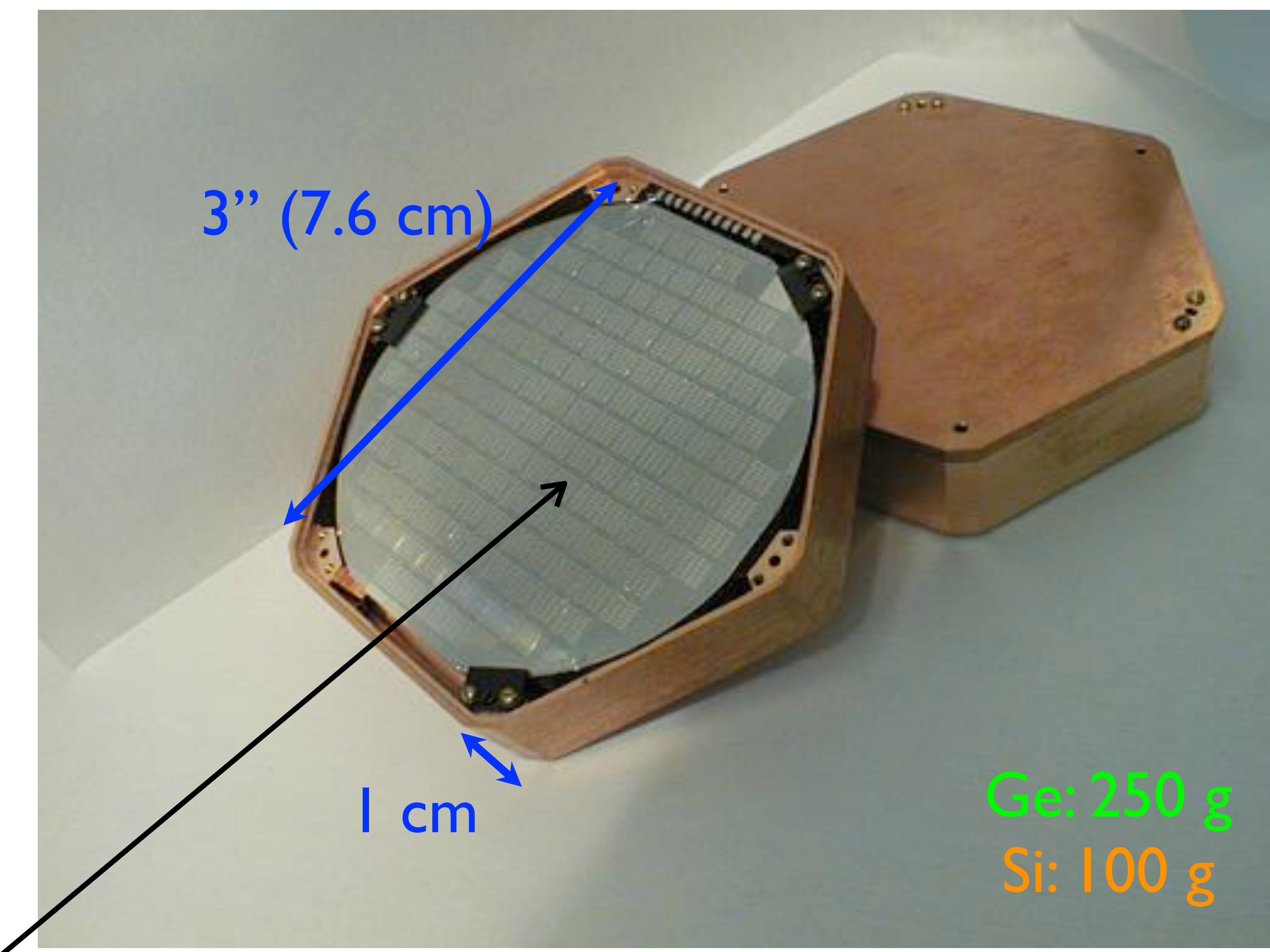
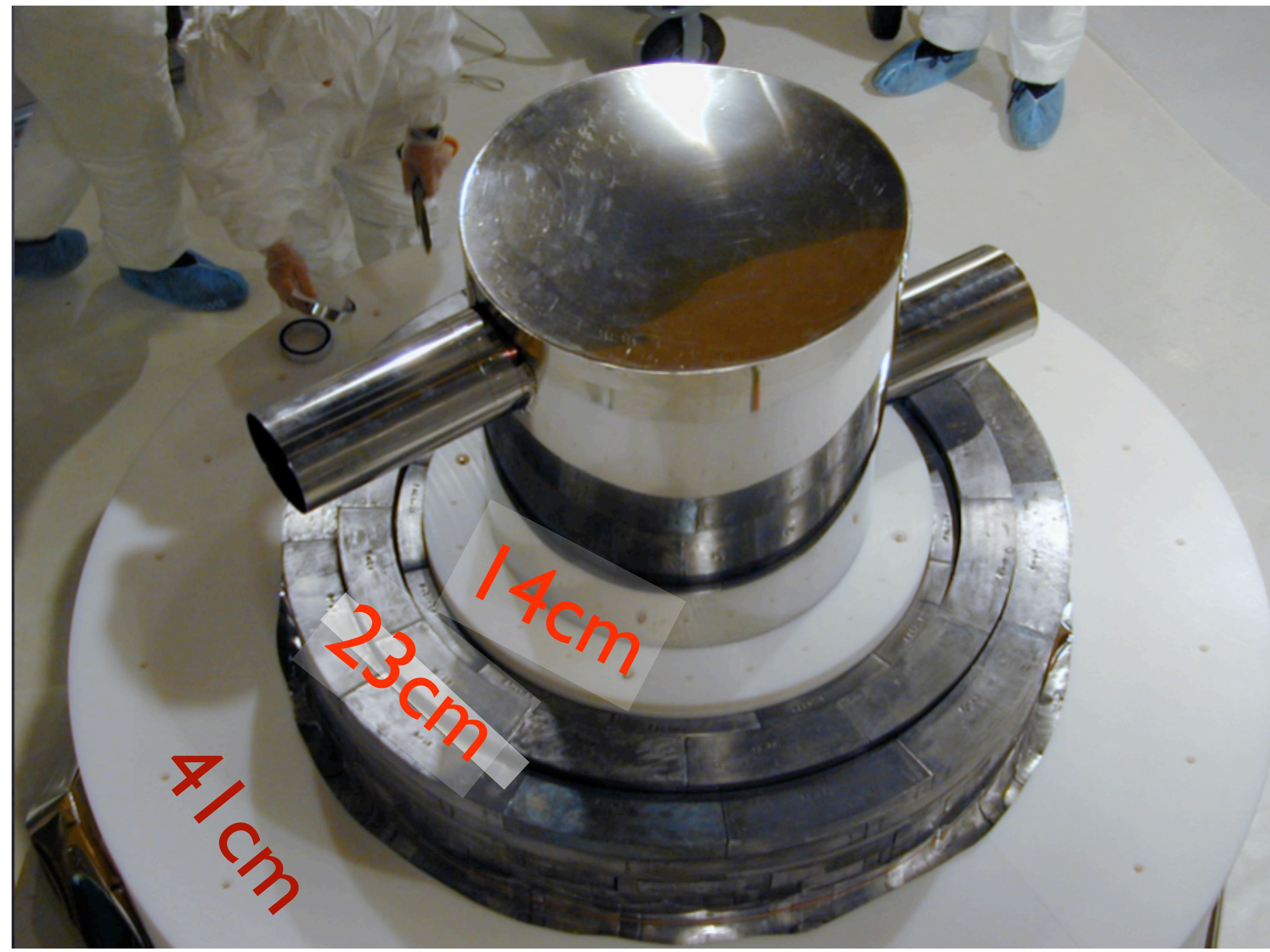


CDMS Detector Array

- 30-40 mK base temperature stage holds an array of Towers

- Each Tower holds up to 6 detectors



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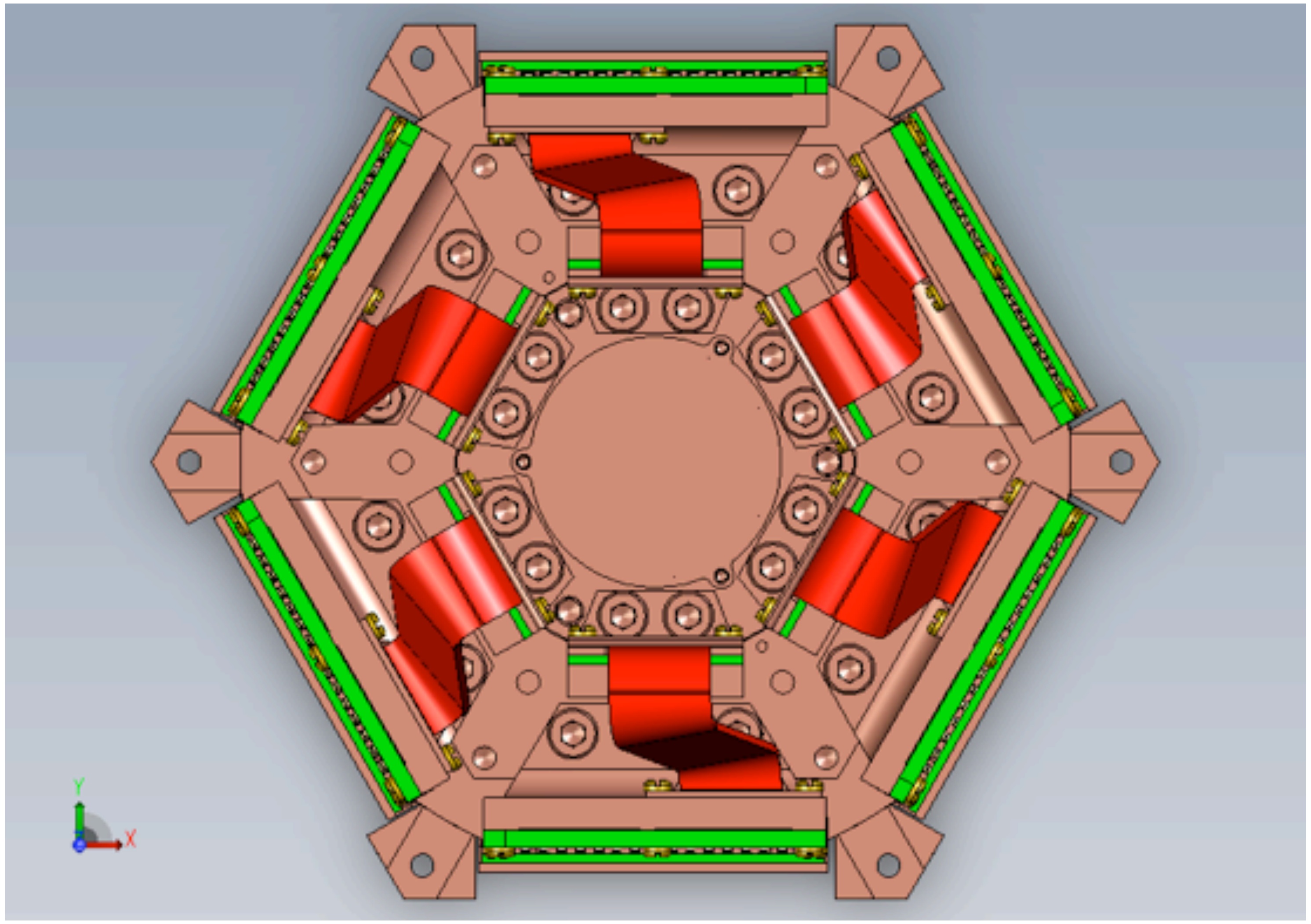

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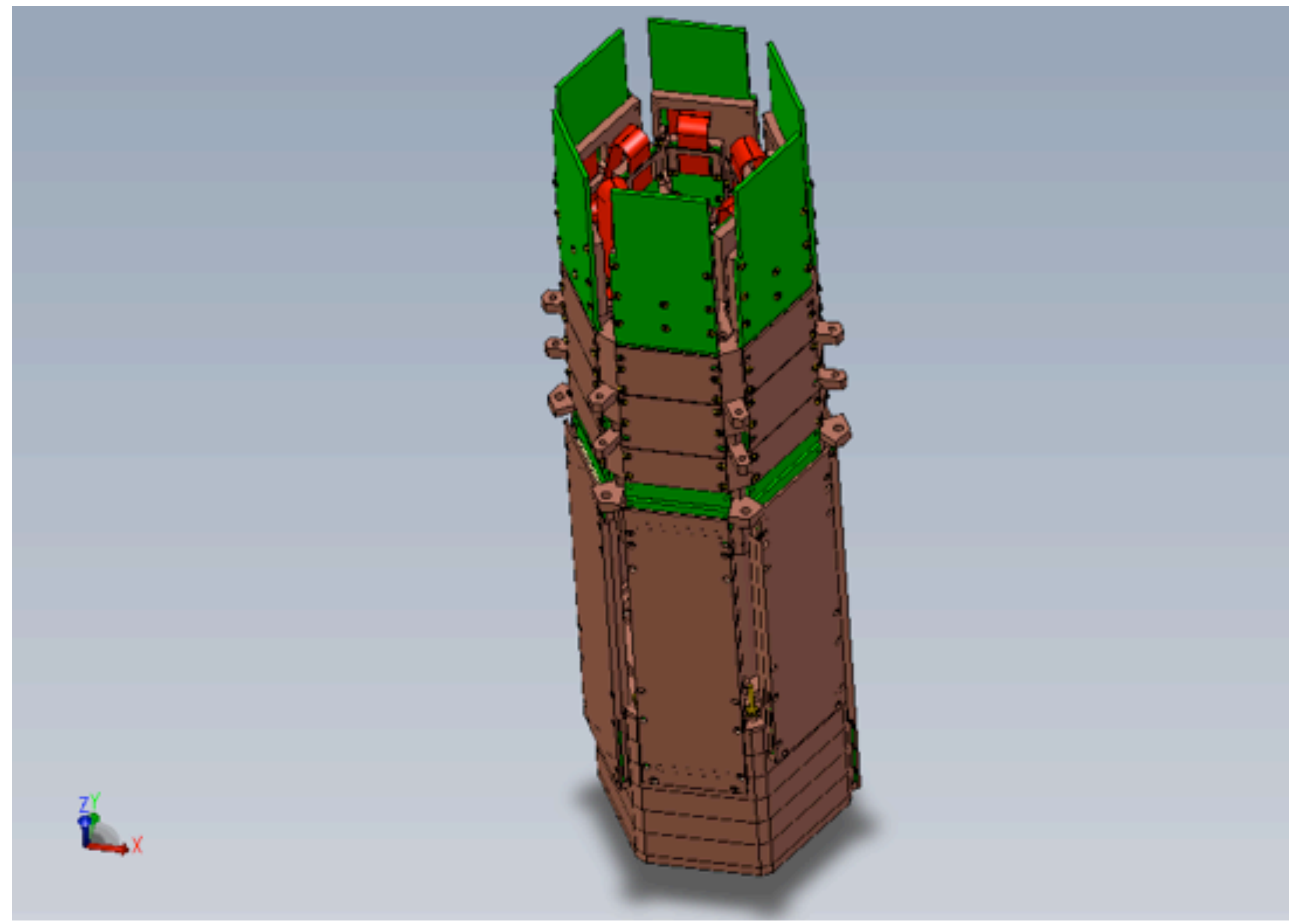

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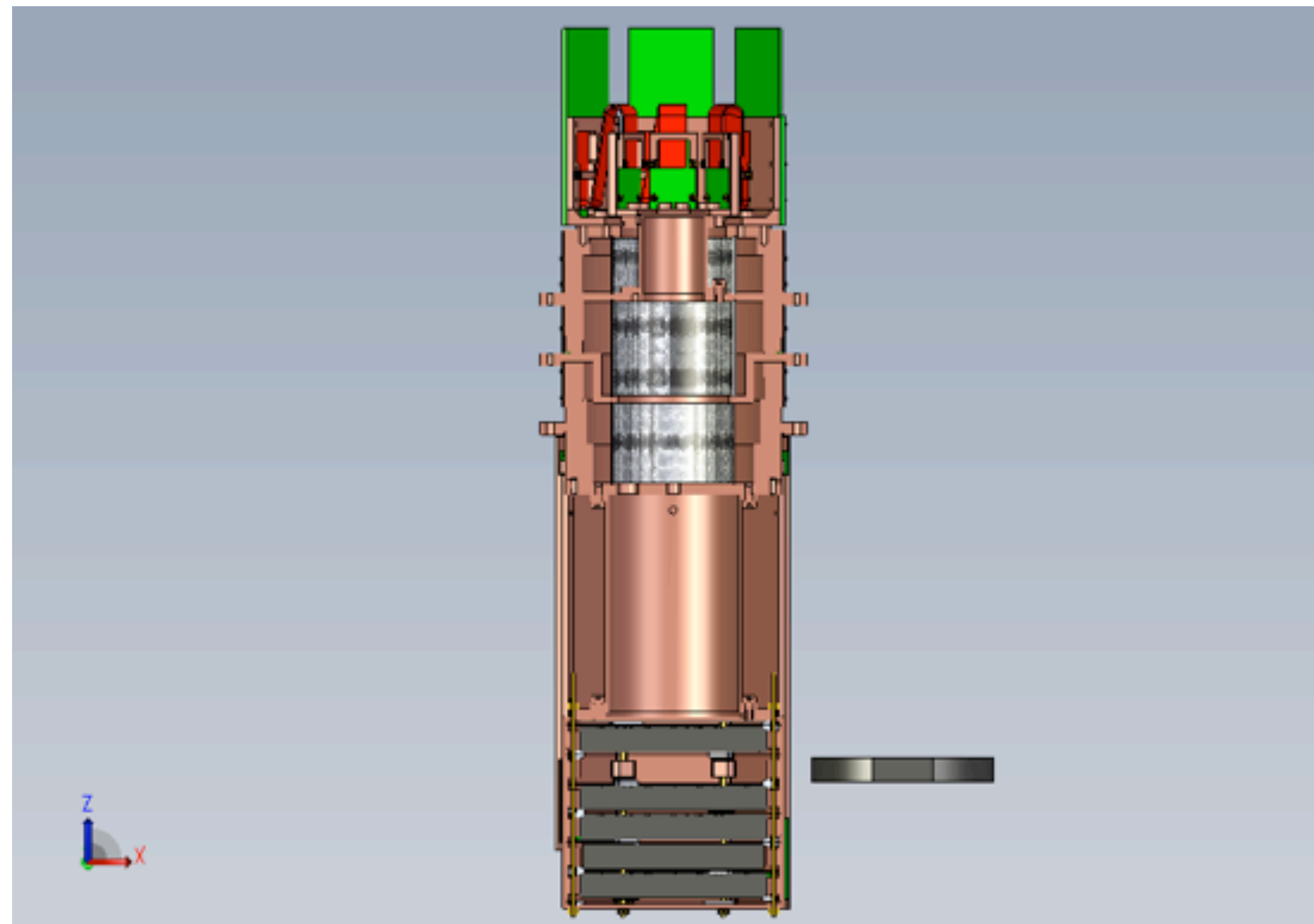

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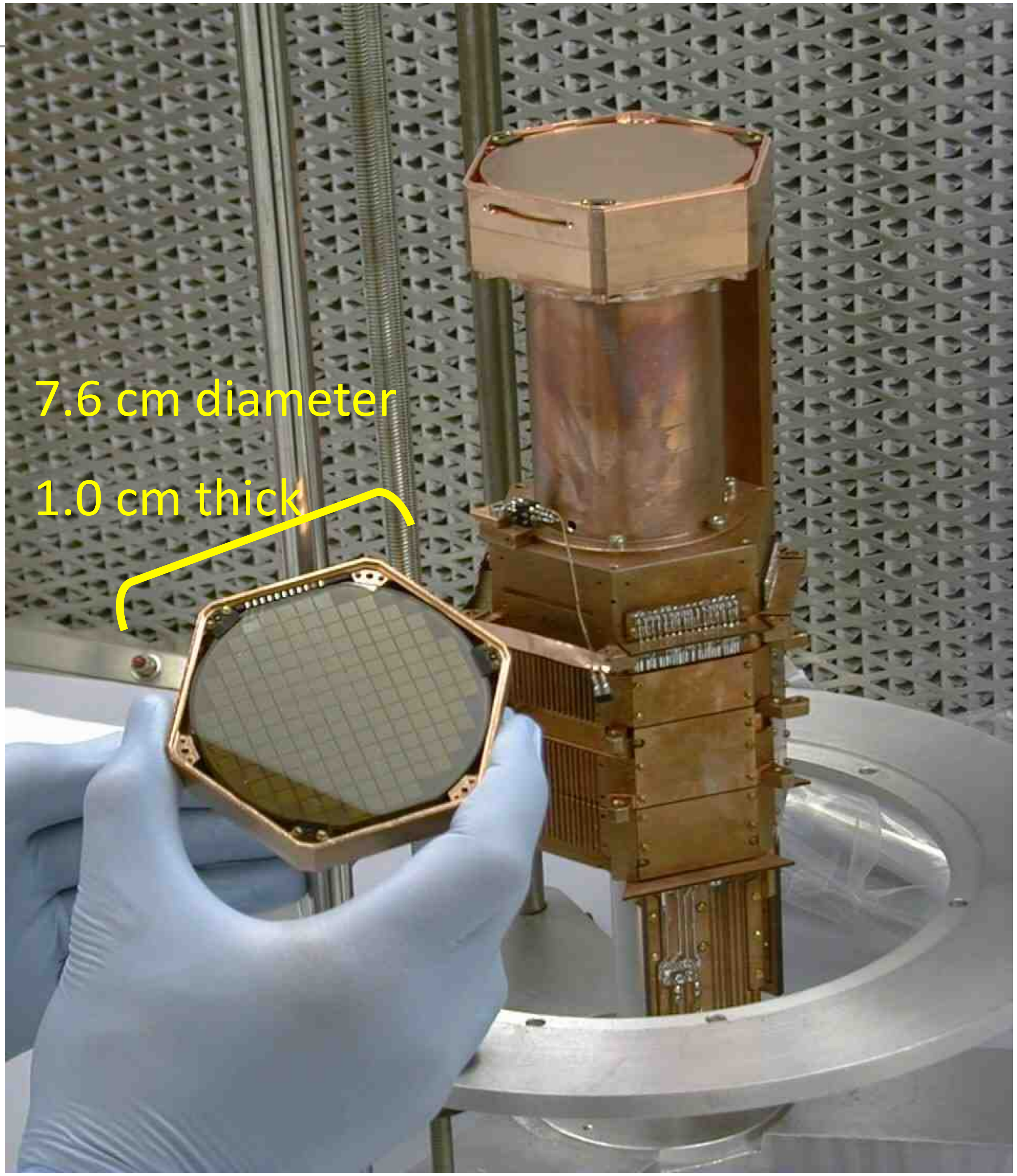
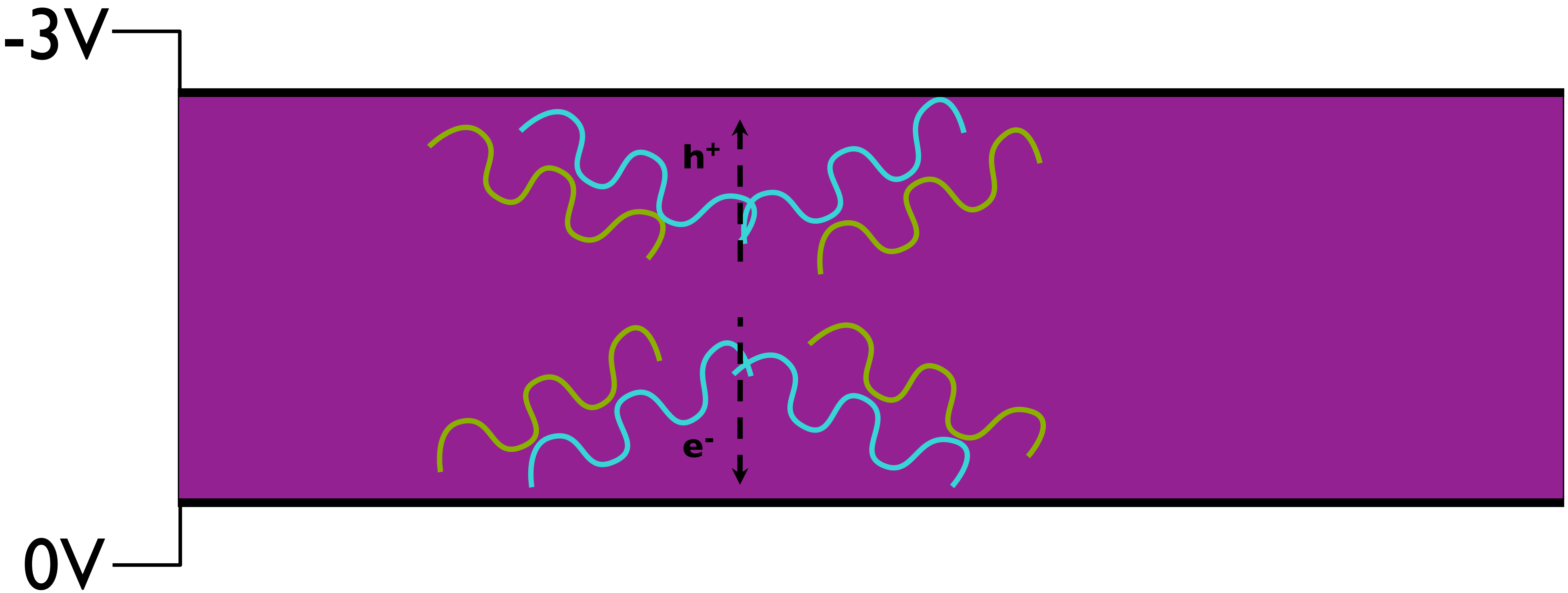


CDMS II Detectors



Hot charge carriers (3eV/pair)

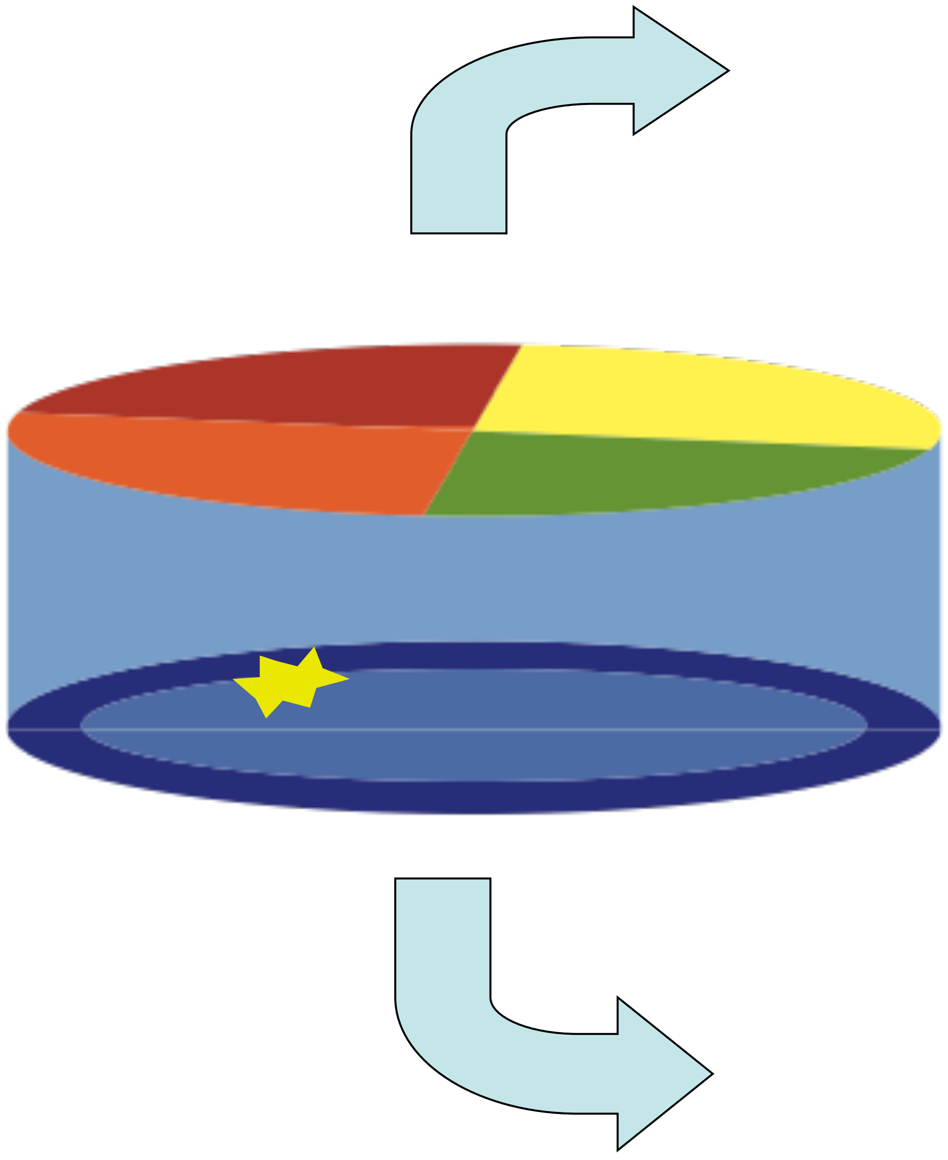
Quasi-diffusive THz phonons

→ Ballistic low-frequency phonons

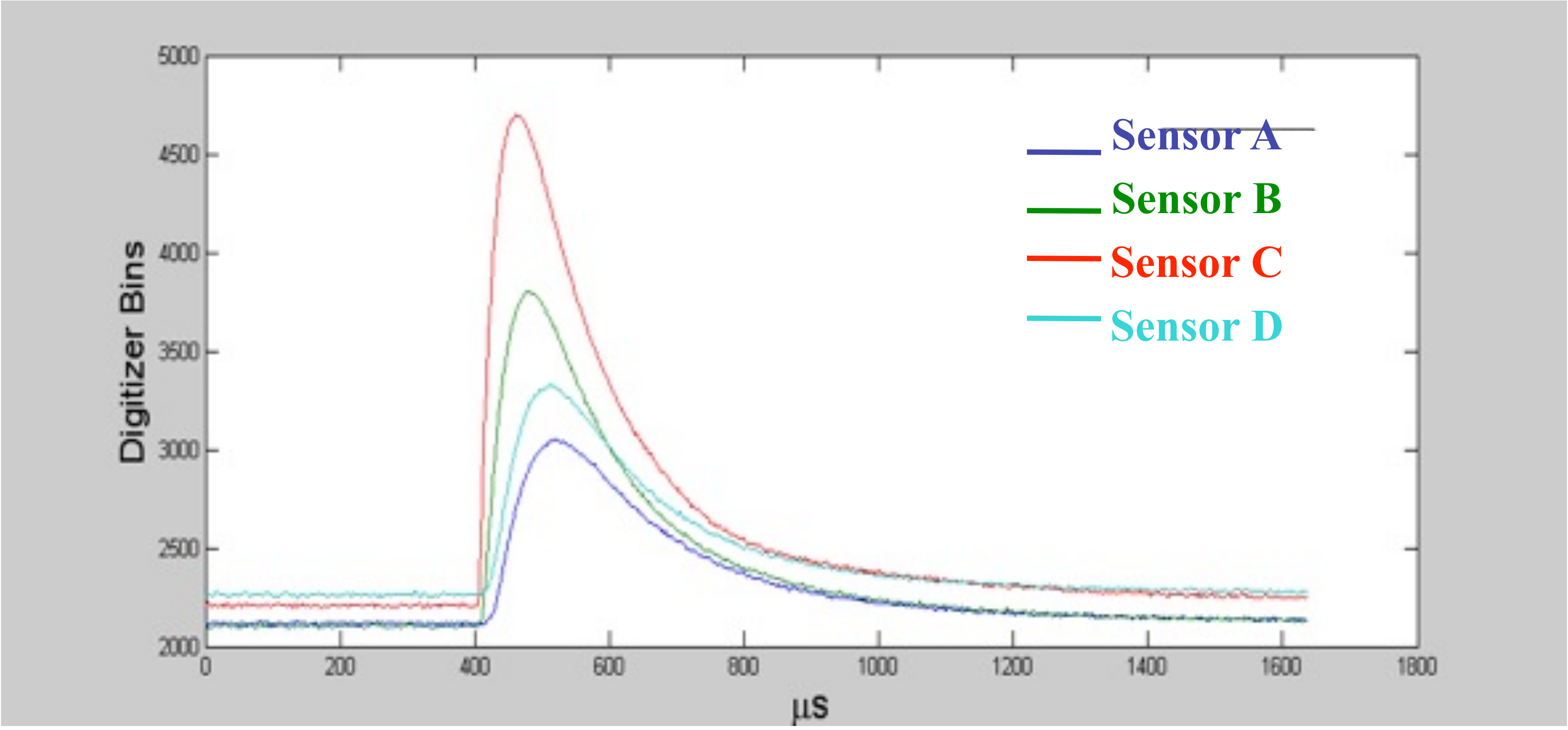
Ballistic Neganov-Luke phonons

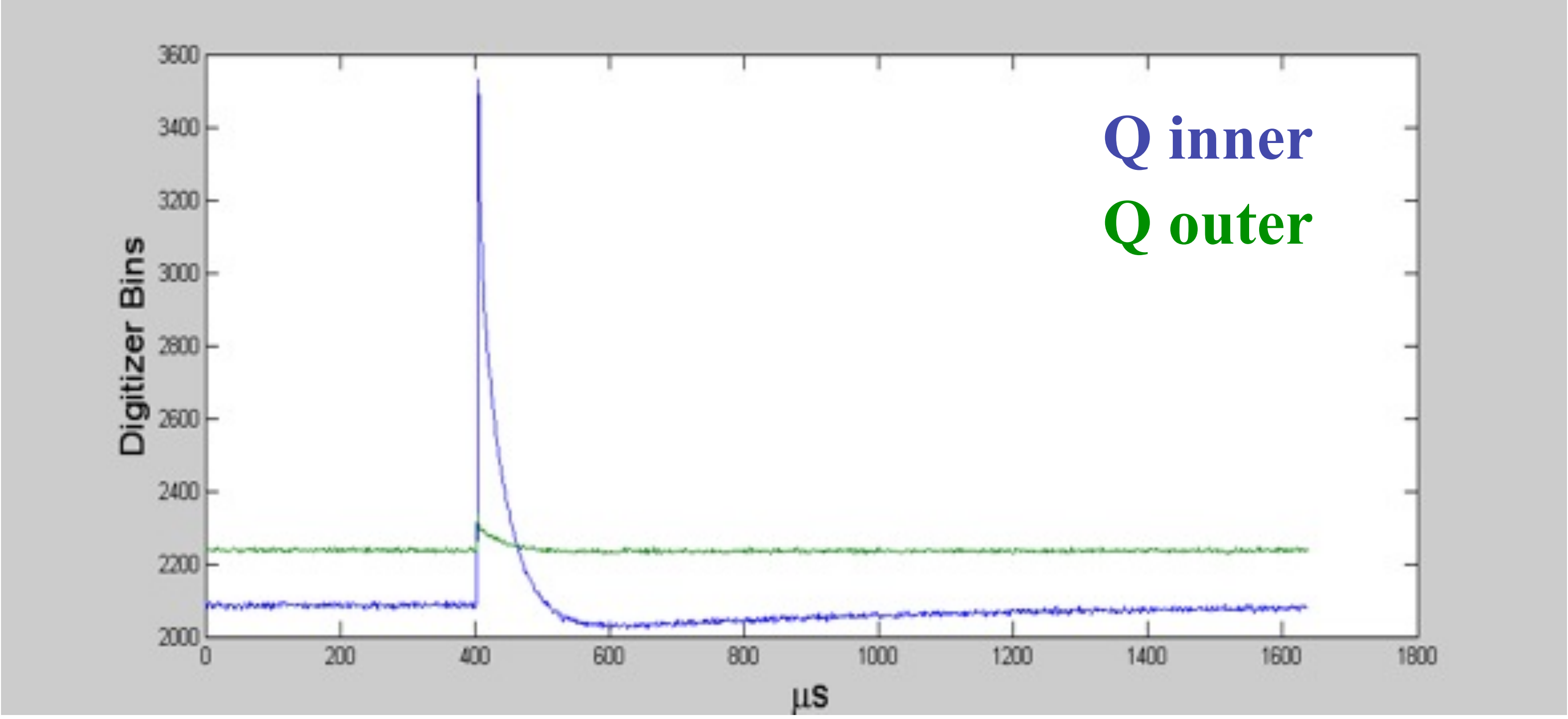
CDMS II Detectors

Phonon Side

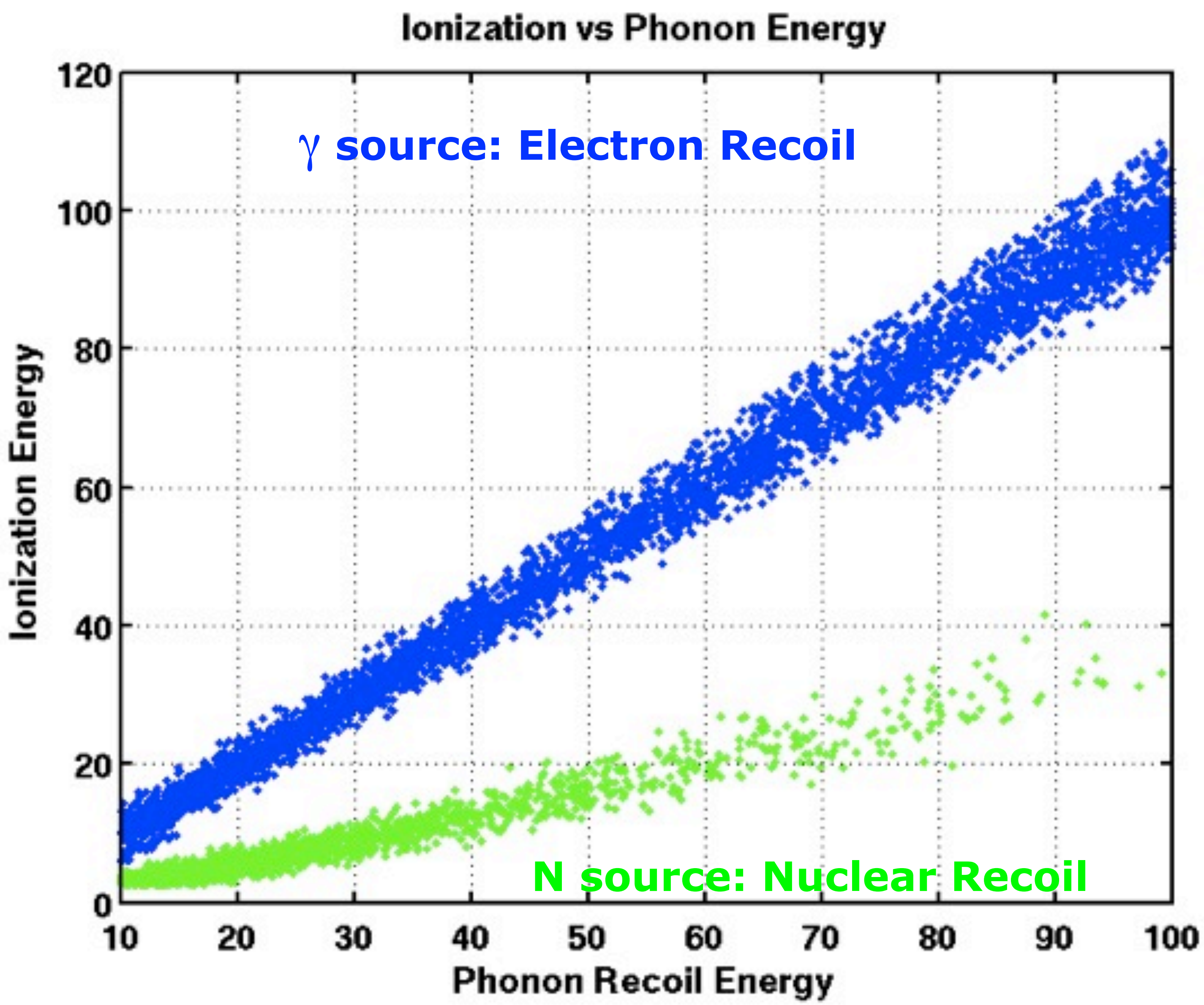


Charge Side





Excellent Primary (γ) Background Rejection



Radioactive source data defines the signal (NR) and background (ER)

>10^4 Rejection of γ

Yield = Ionization/Phonon

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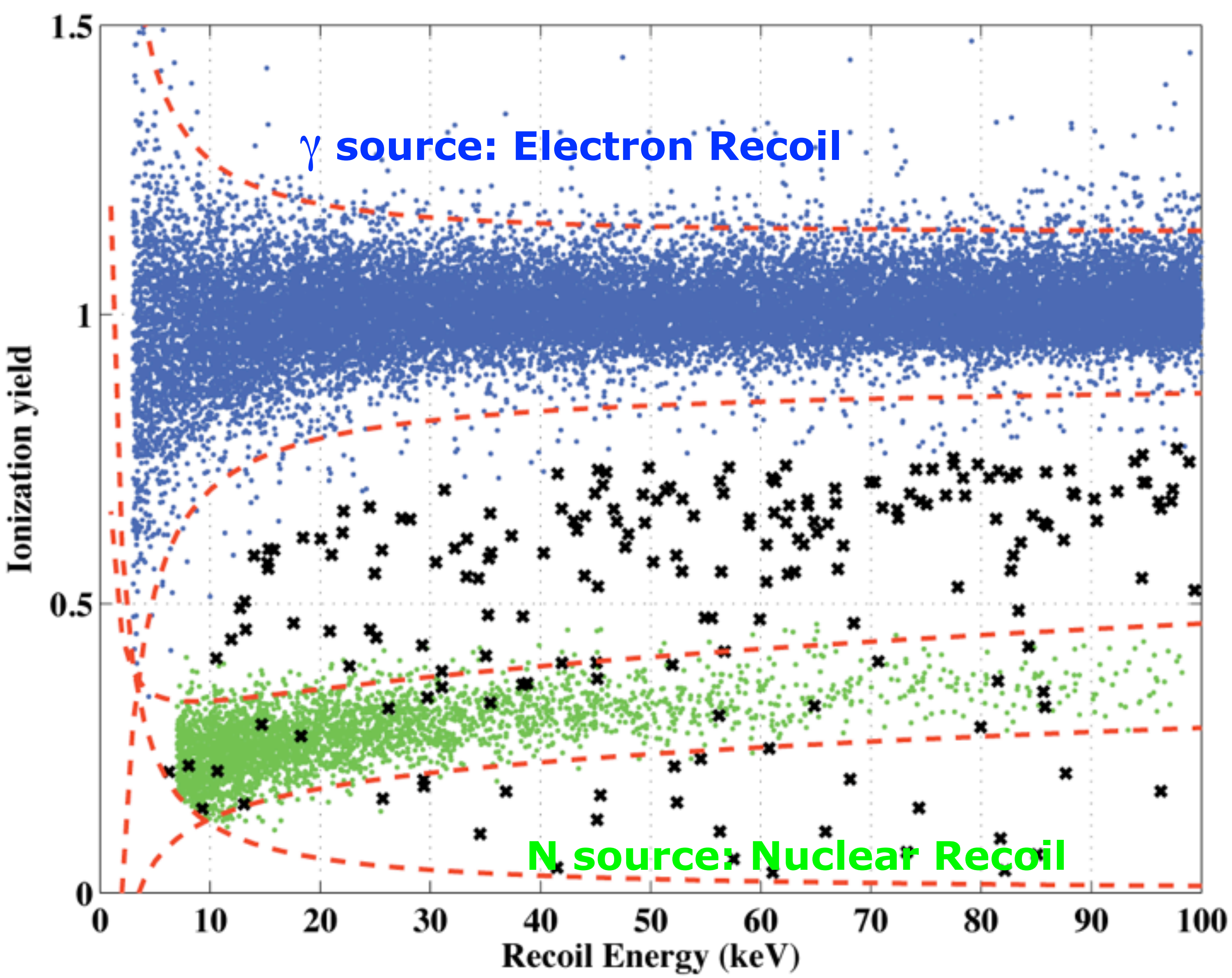


Radioactive source data defines the signal (NR) and background (ER)

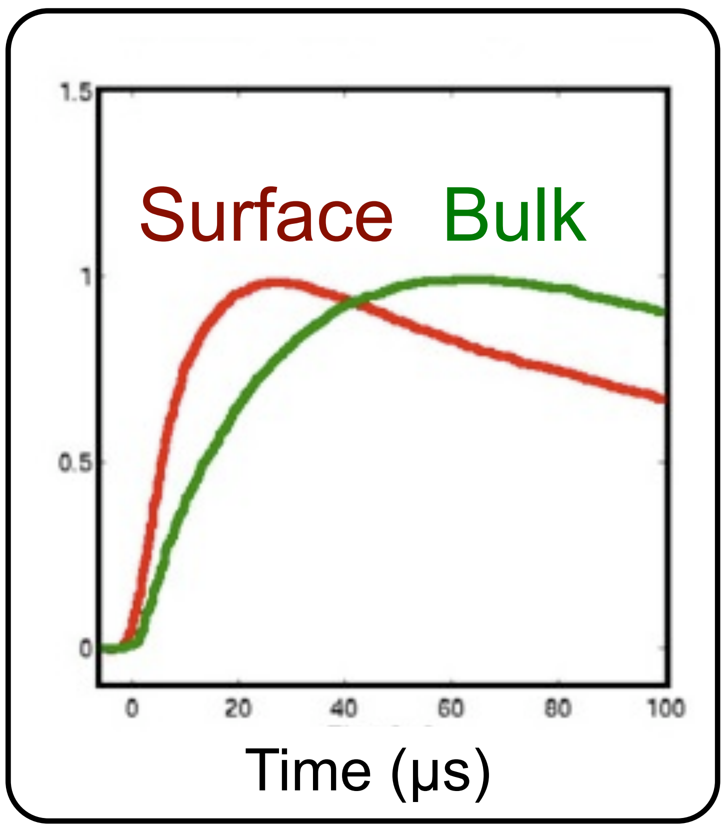
>10^4 Rejection of γ

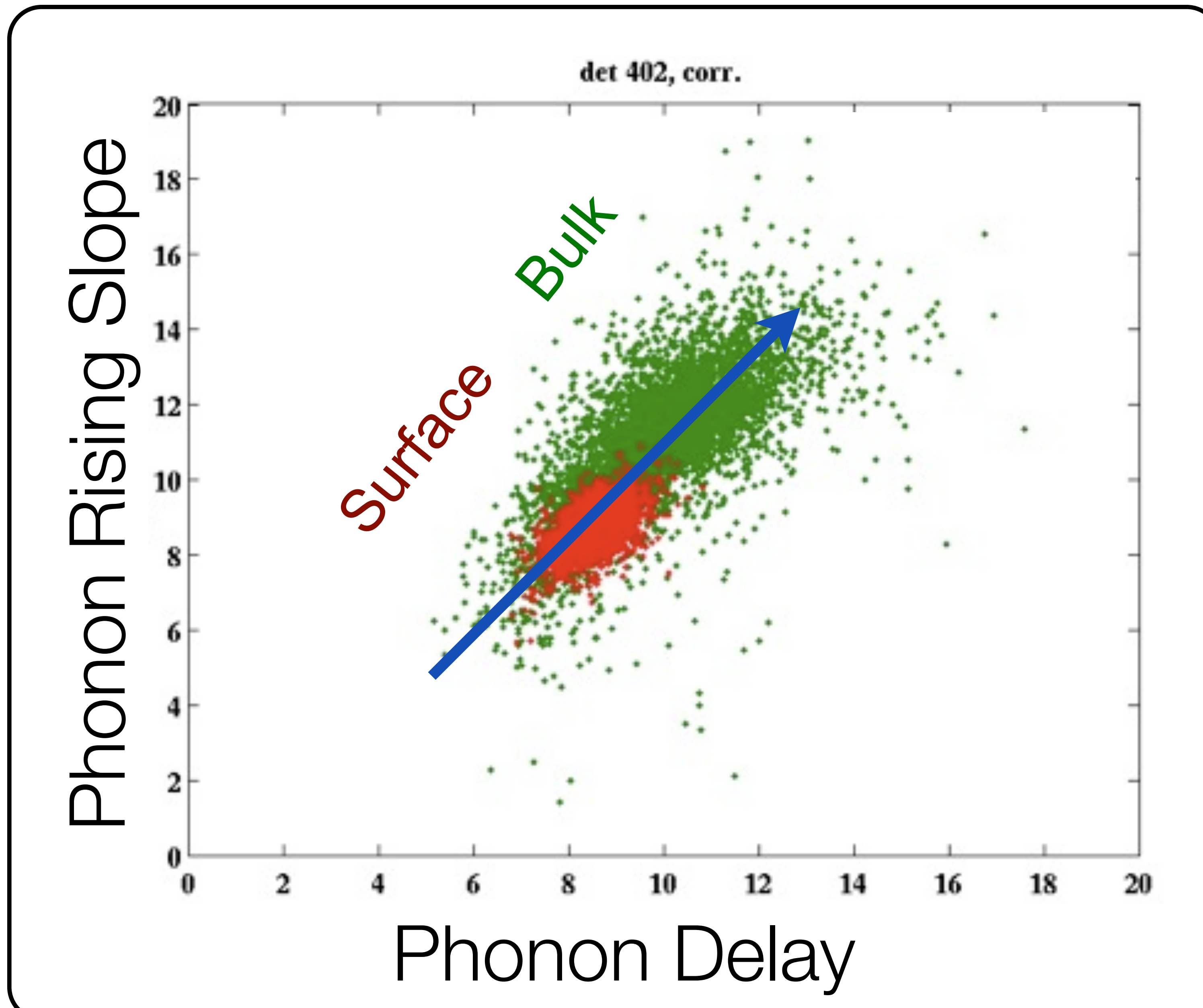
Yield = Ionization/Phonon

Events with low yield can be misidentified as nuclear recoils

Surface β Rejection

Secondary Discrimination: Phonon Timing





Surface β Rejection

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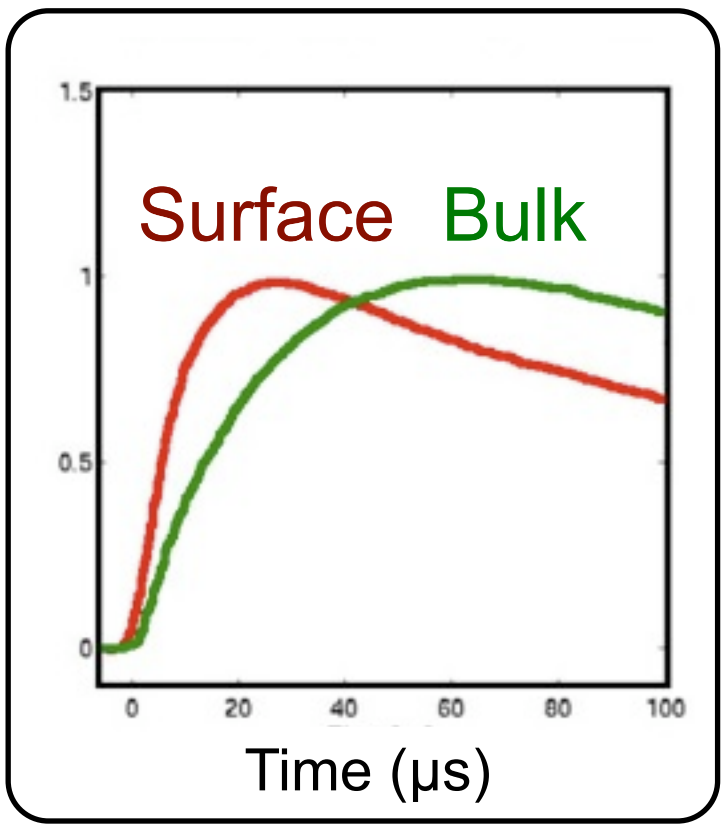
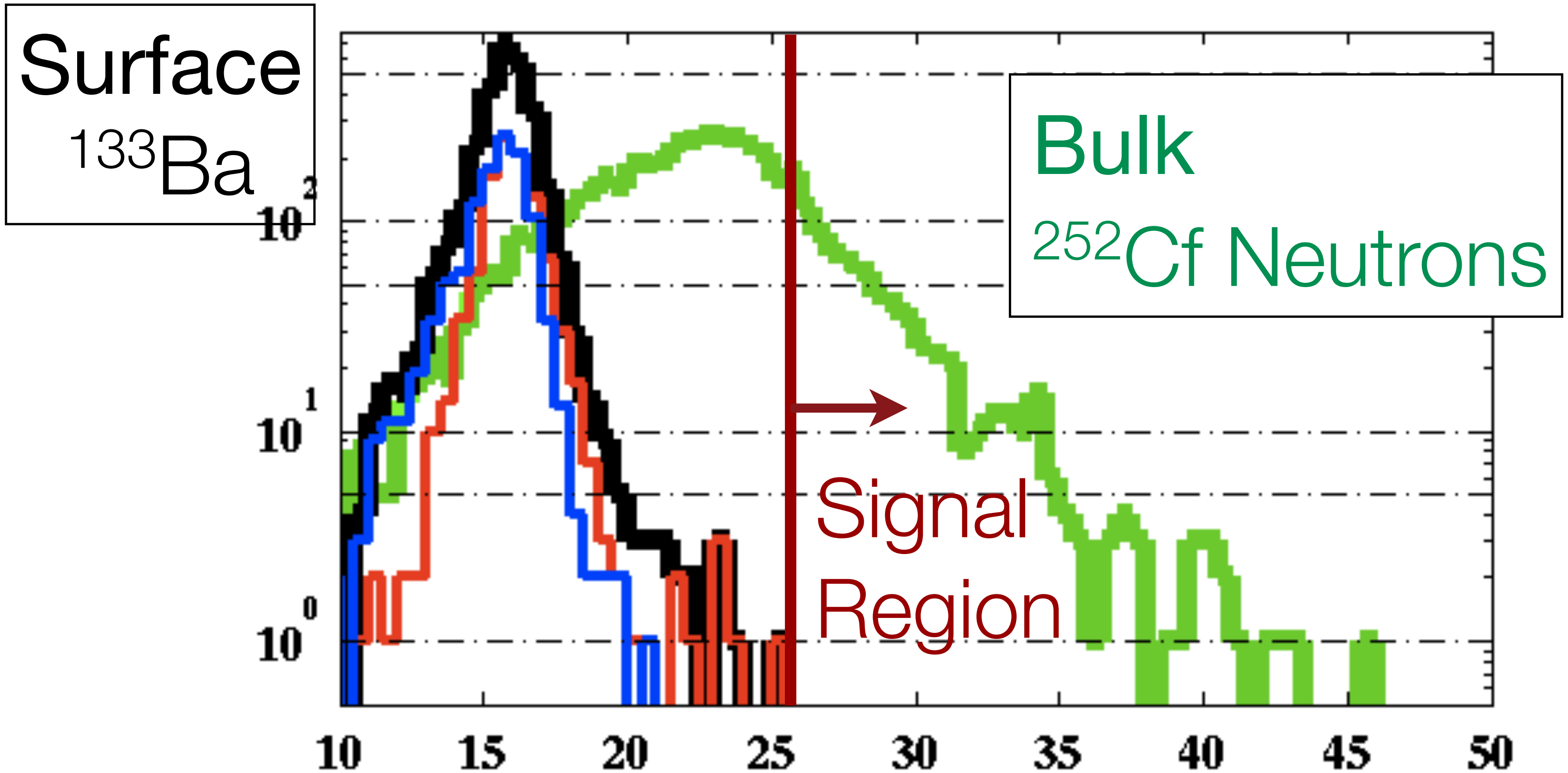
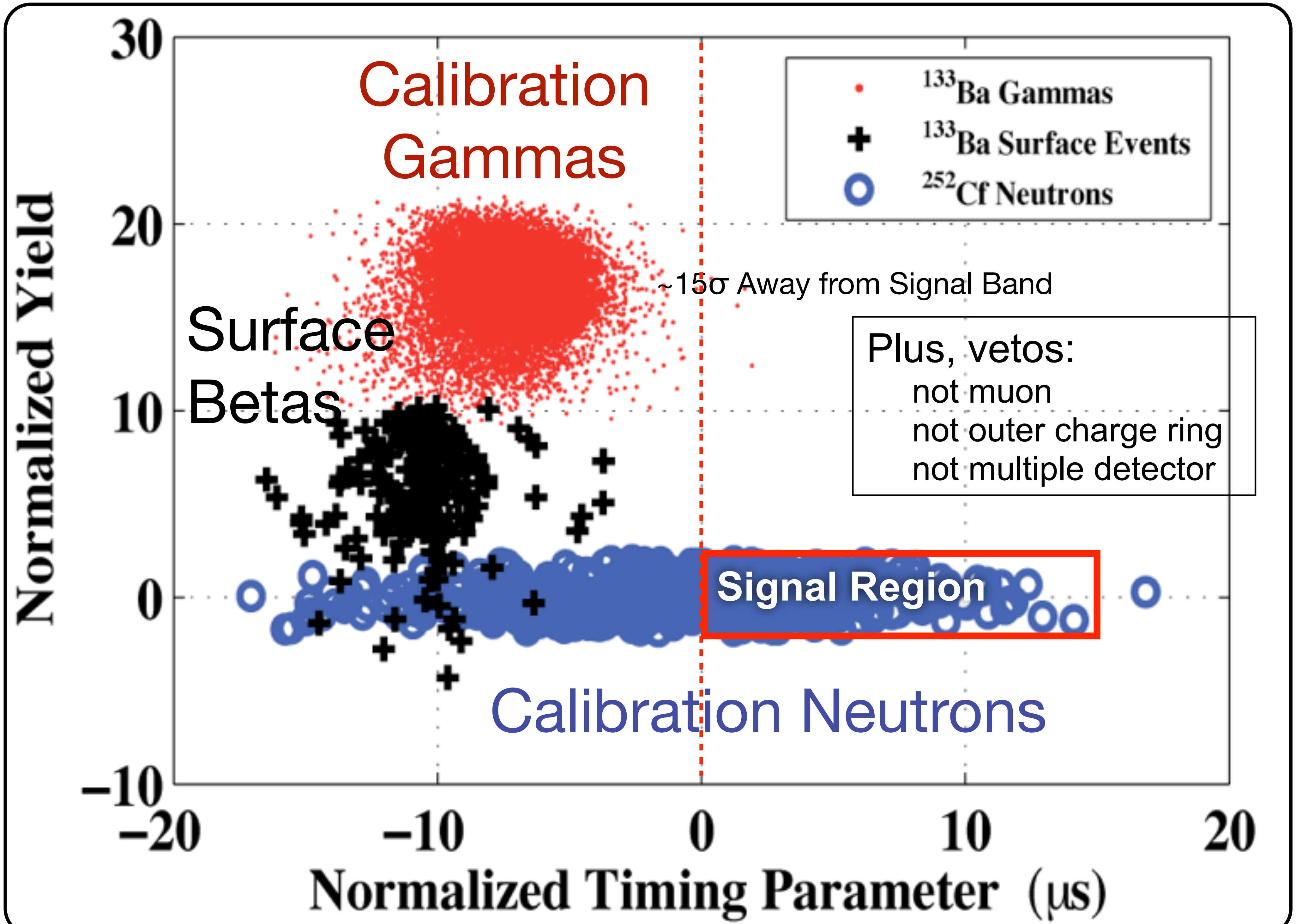
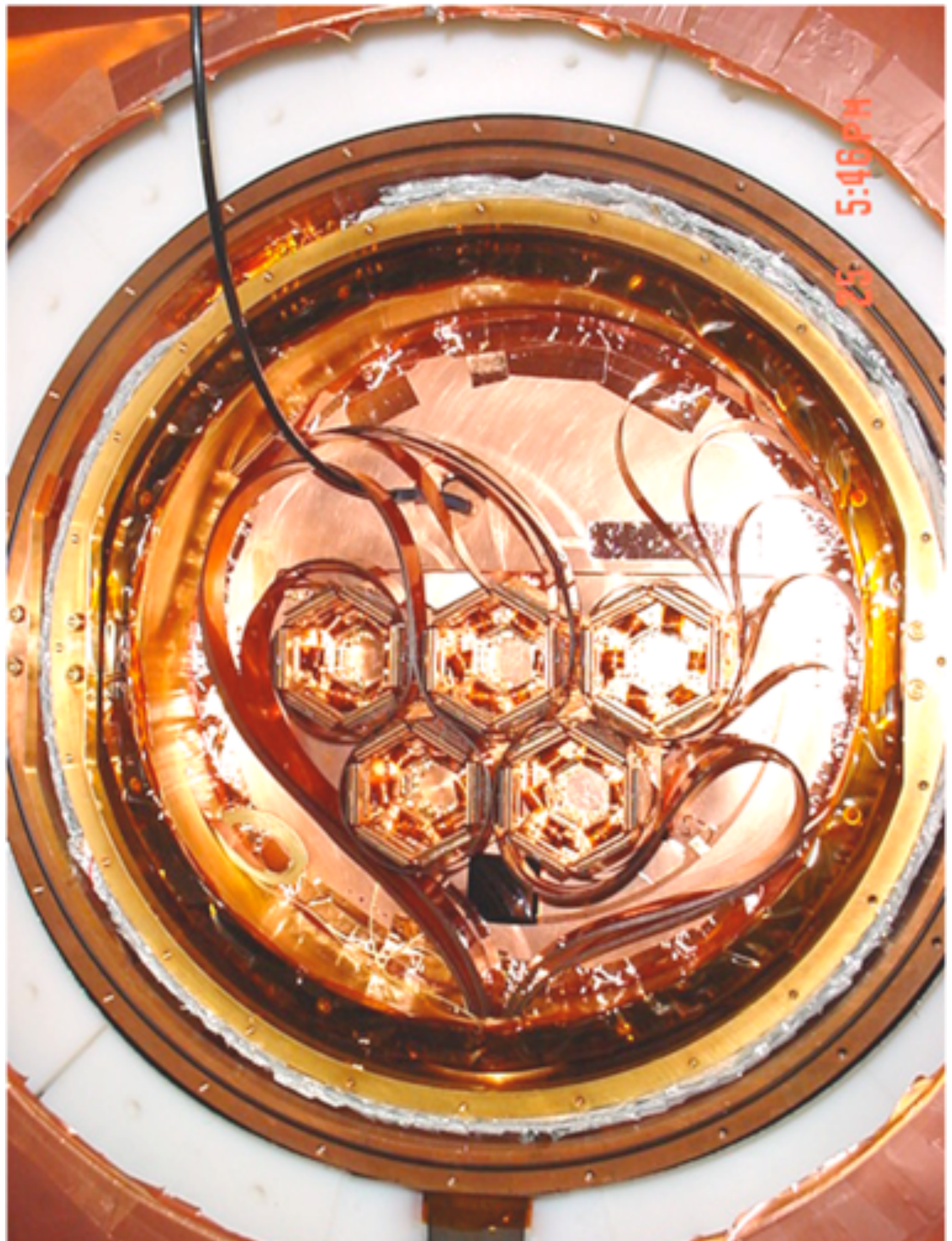




Setting the Signal Region

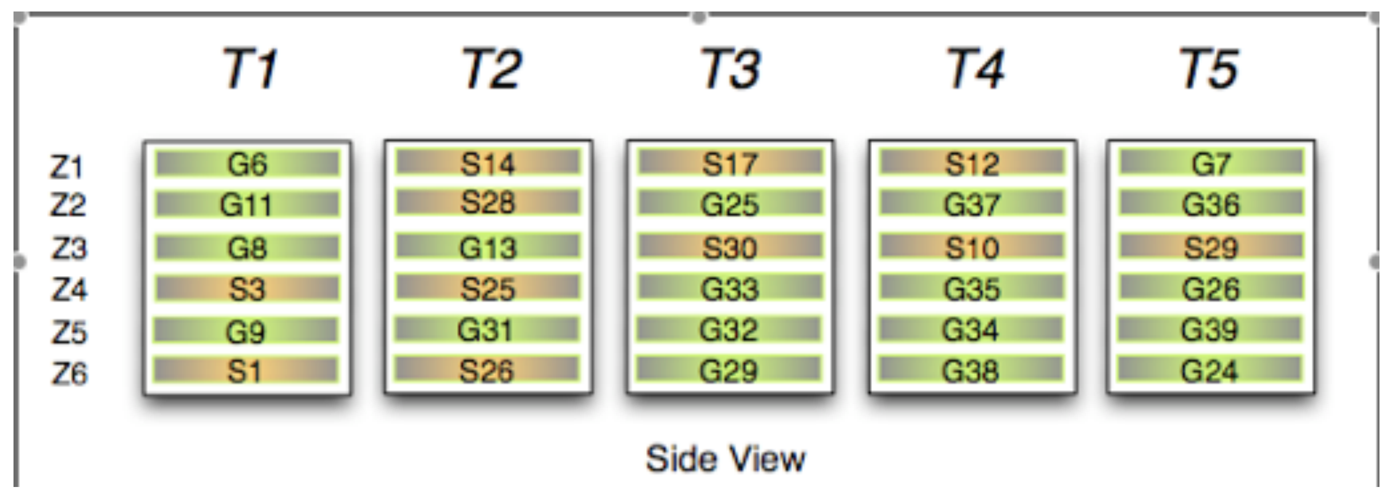


CDMS II (2006-2008)



30 detectors (5 Towers) installed in Soudan icebox:

4.4 kg Ge, 1.1 kg Si



Combination of Ge and Si Detectors

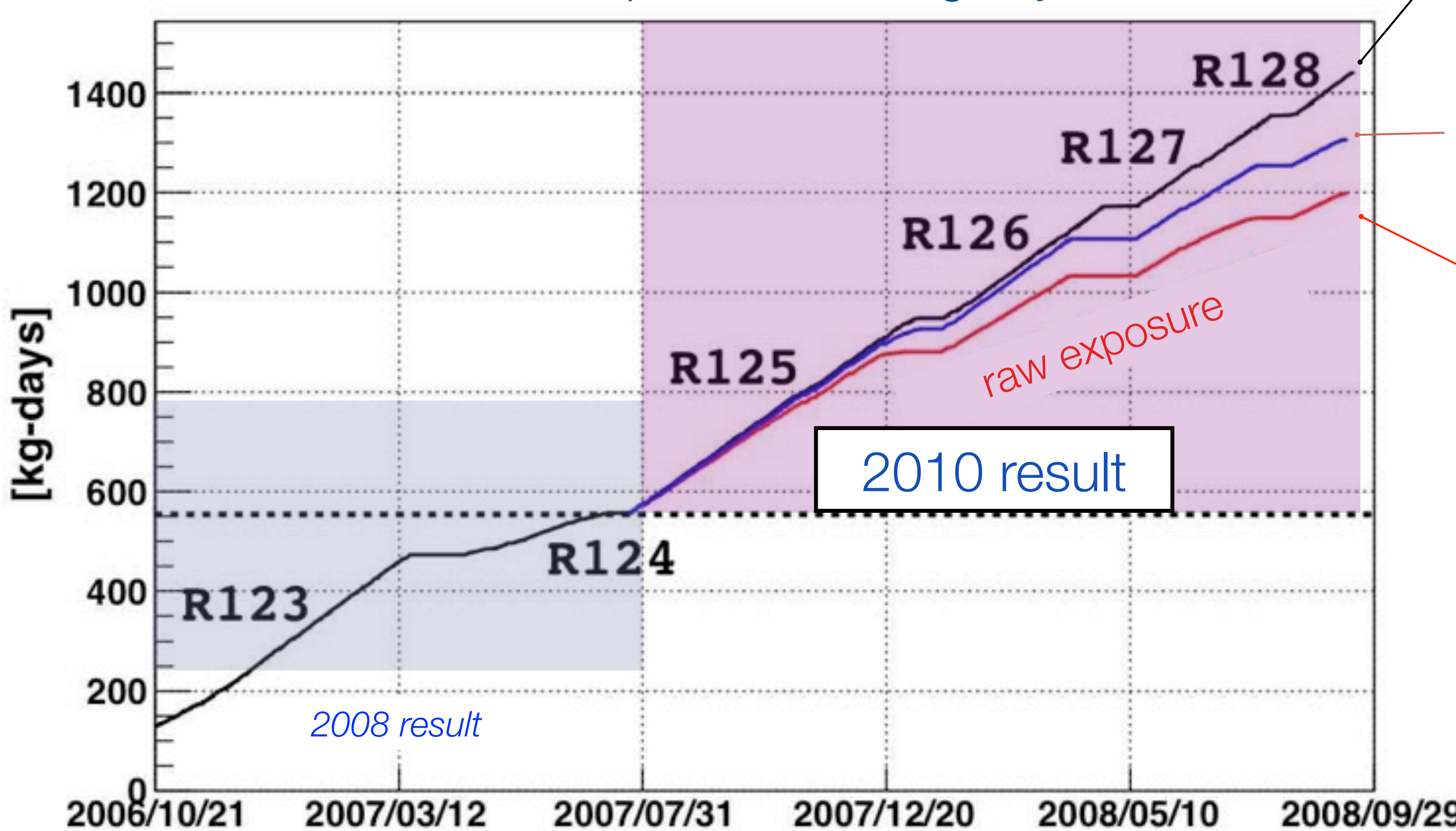
- Neutron background measurement
- WIMP Mass Measurement
- Ge more sensitive to higher mass WIMPs, Si to lower mass WIMPs

WIMP Search Exposure

4 runs separated by partial warmups of cryostat

Dates of data taking: 7/2007 - 9/2008

Total raw exposure is 612 kg-days



recorded data

some detectors not analyzed for WIMP scatters

periods of poor data quality removed

612 kg-days raw

194 kg-days after signal region cuts

Data taken from 9/08-3/09: primarily an engineering run

Background Estimate

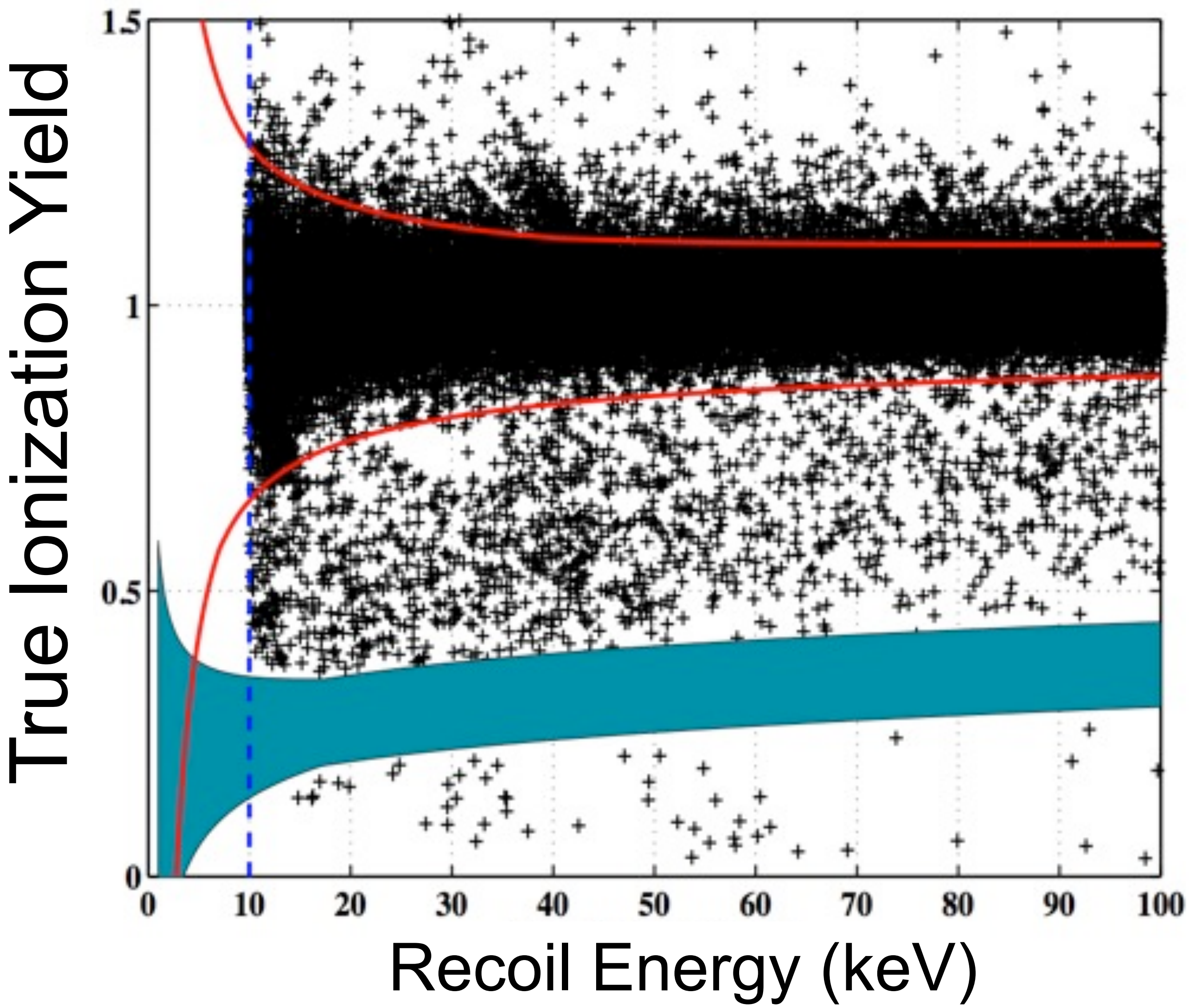
Surface Events: **0.6**±0.1 Data (we *chose* this)

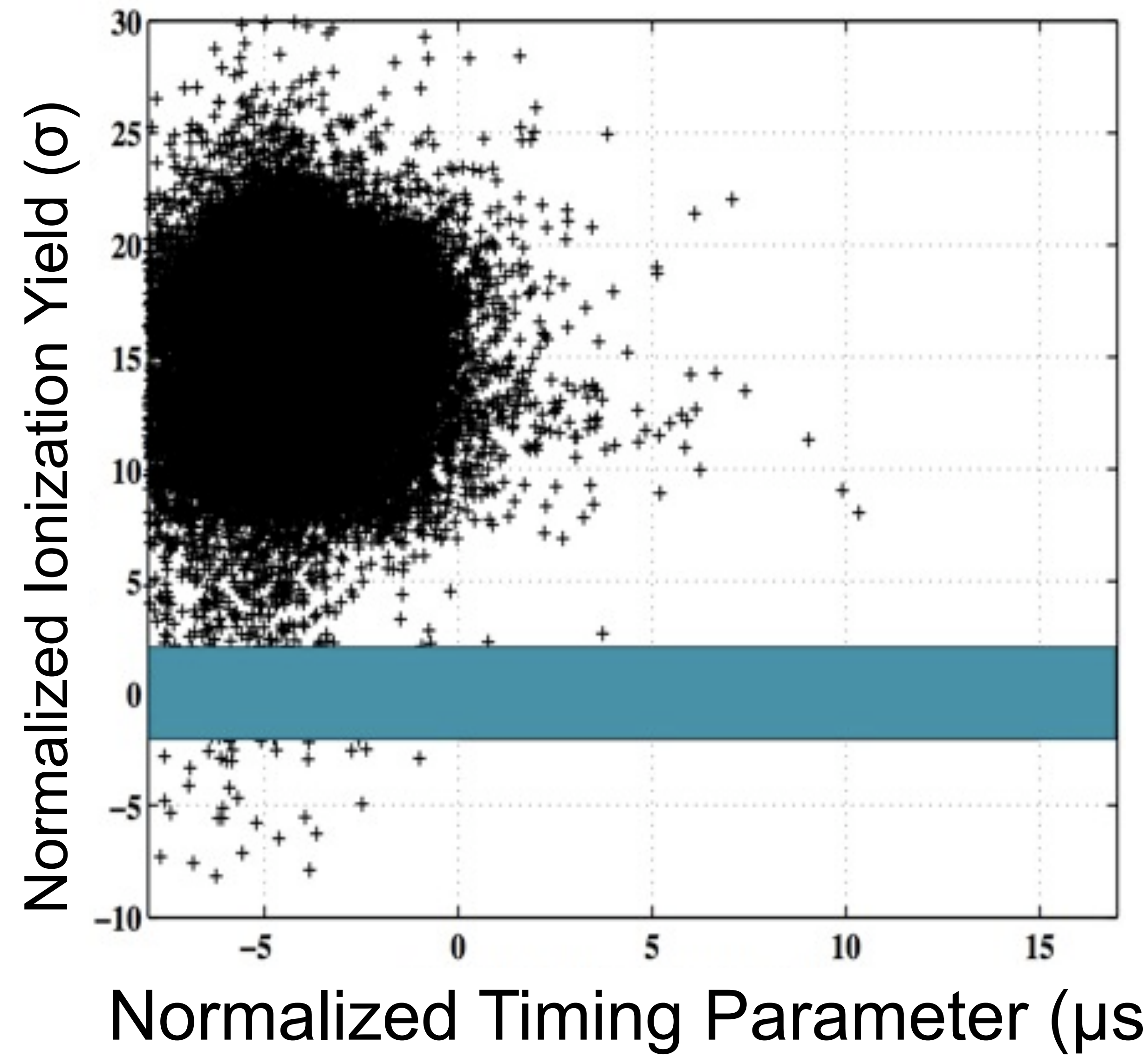
Cosmogenic Neutrons: $\mathbf{0.04}^{+0.04}_{-0.03}$ vetoed Data x $\left(\frac{\text{unvetoed}}{\text{vetoed}}\right)$ Monte Carlo

Radiogenic Neutrons: $\mathbf{0.057}^{+0.0035}_{-0.02}$ Materials Testing & Monte Carlo

Opening the Box

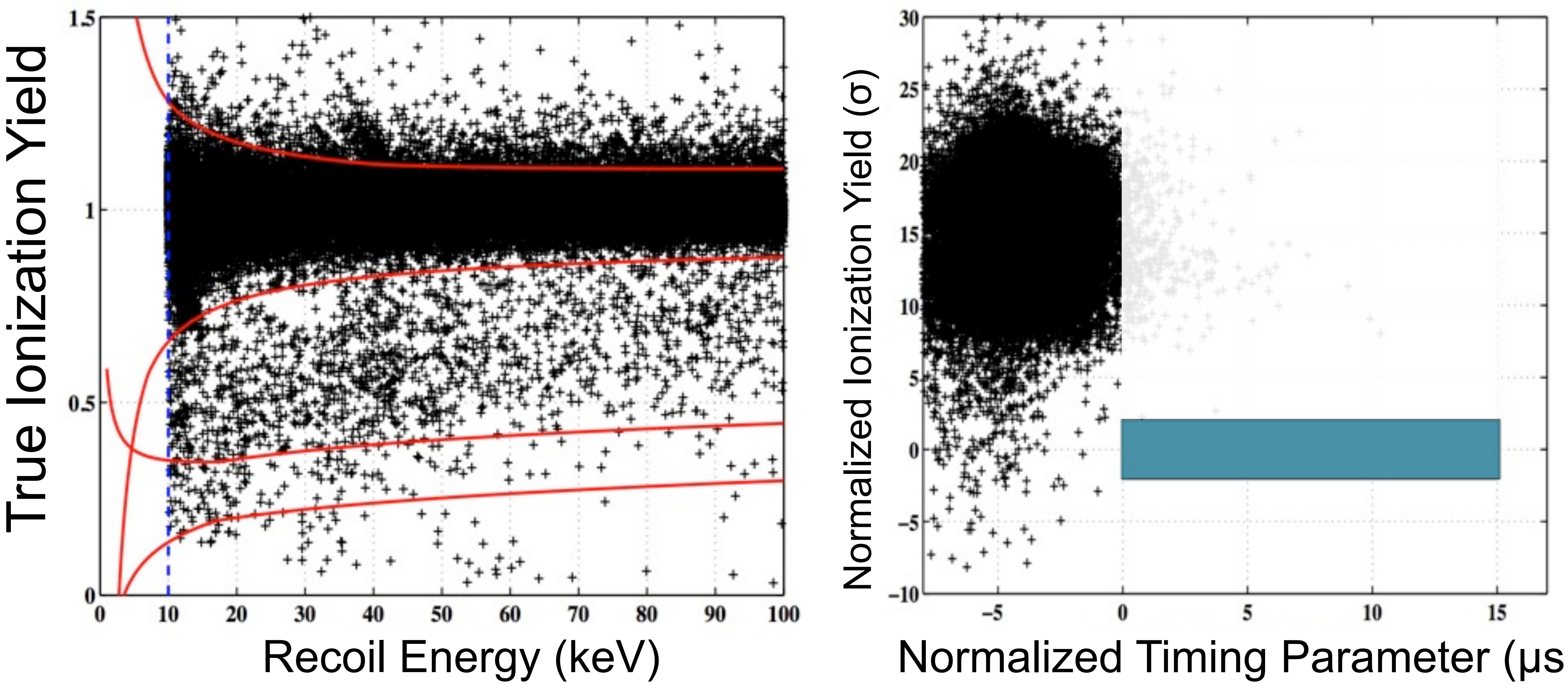
BLINDED:





Opening the Box

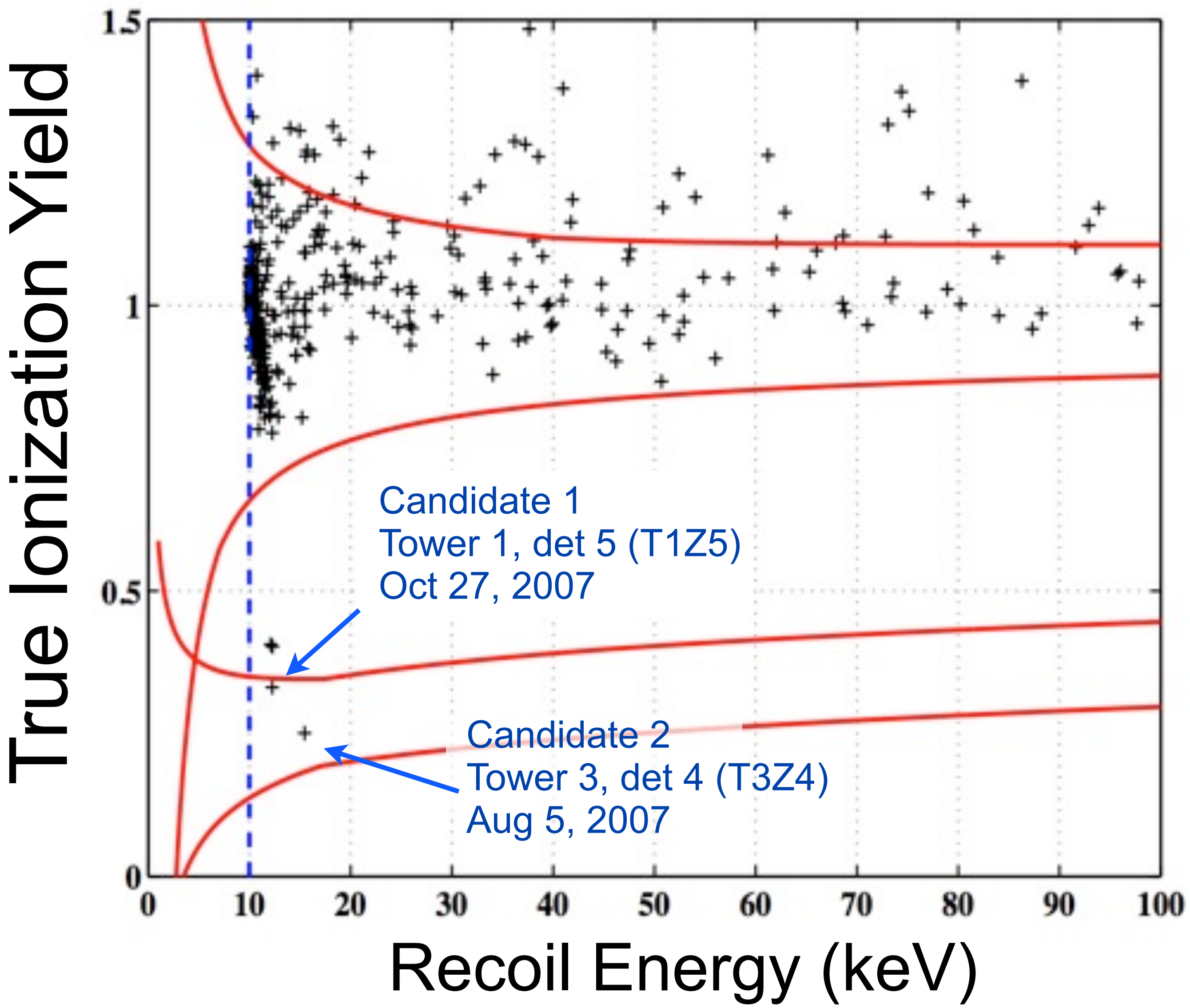
FAIL TIMING CUT:

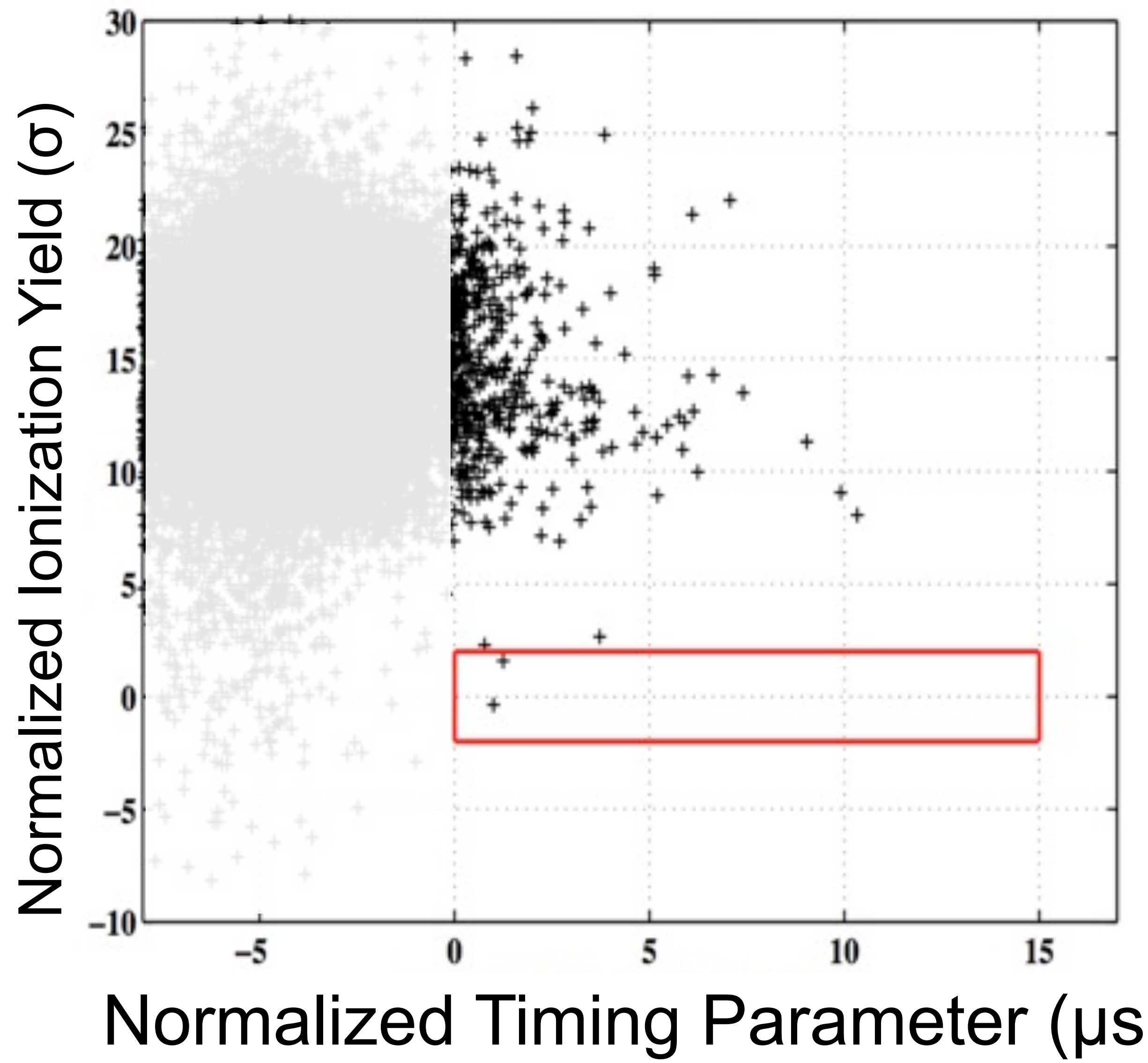


150 events in the NR band fail the timing cut, consistency checks deemed ok

Opening the Box

Two Events!





Post-Unblinding Analysis

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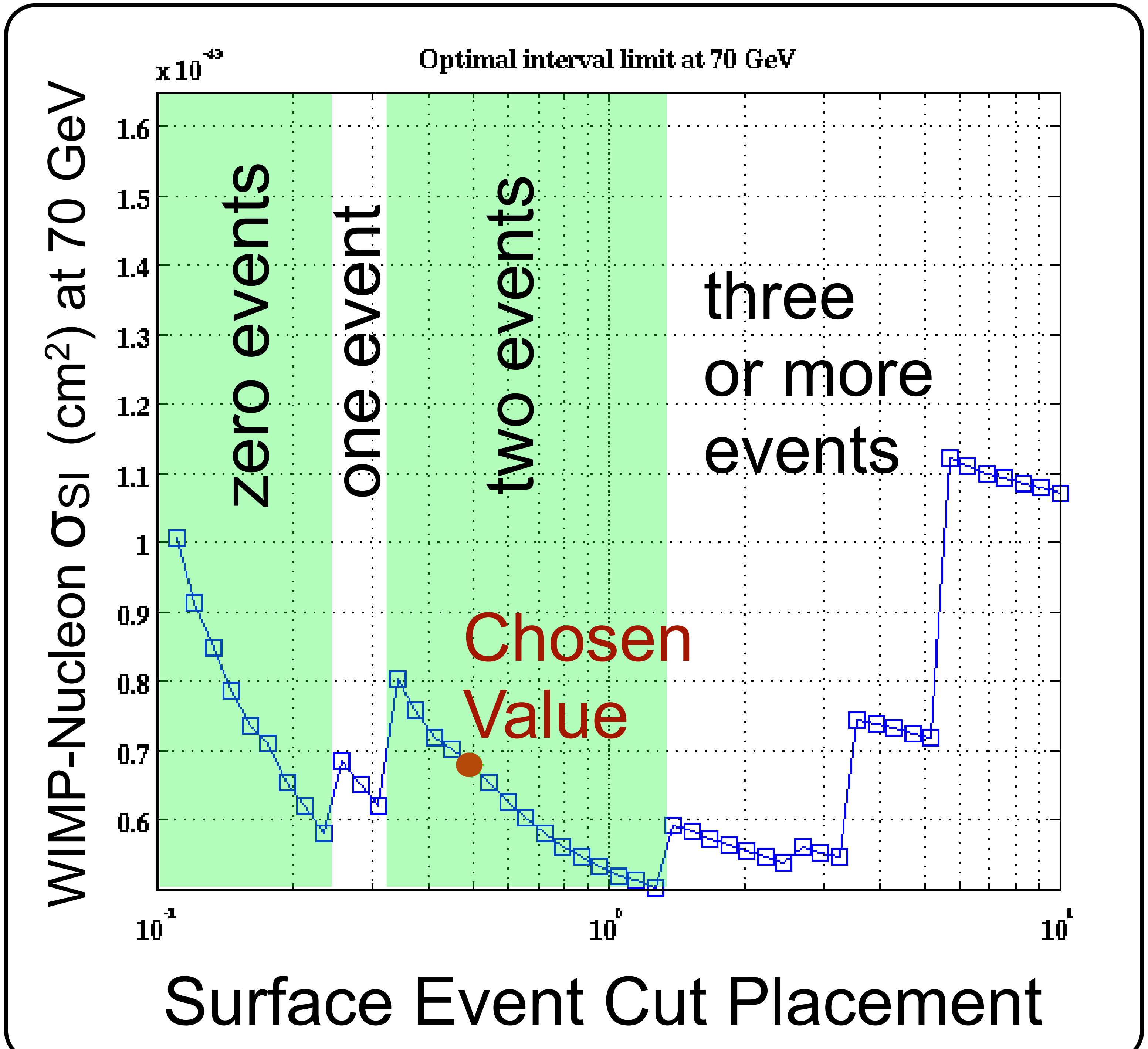

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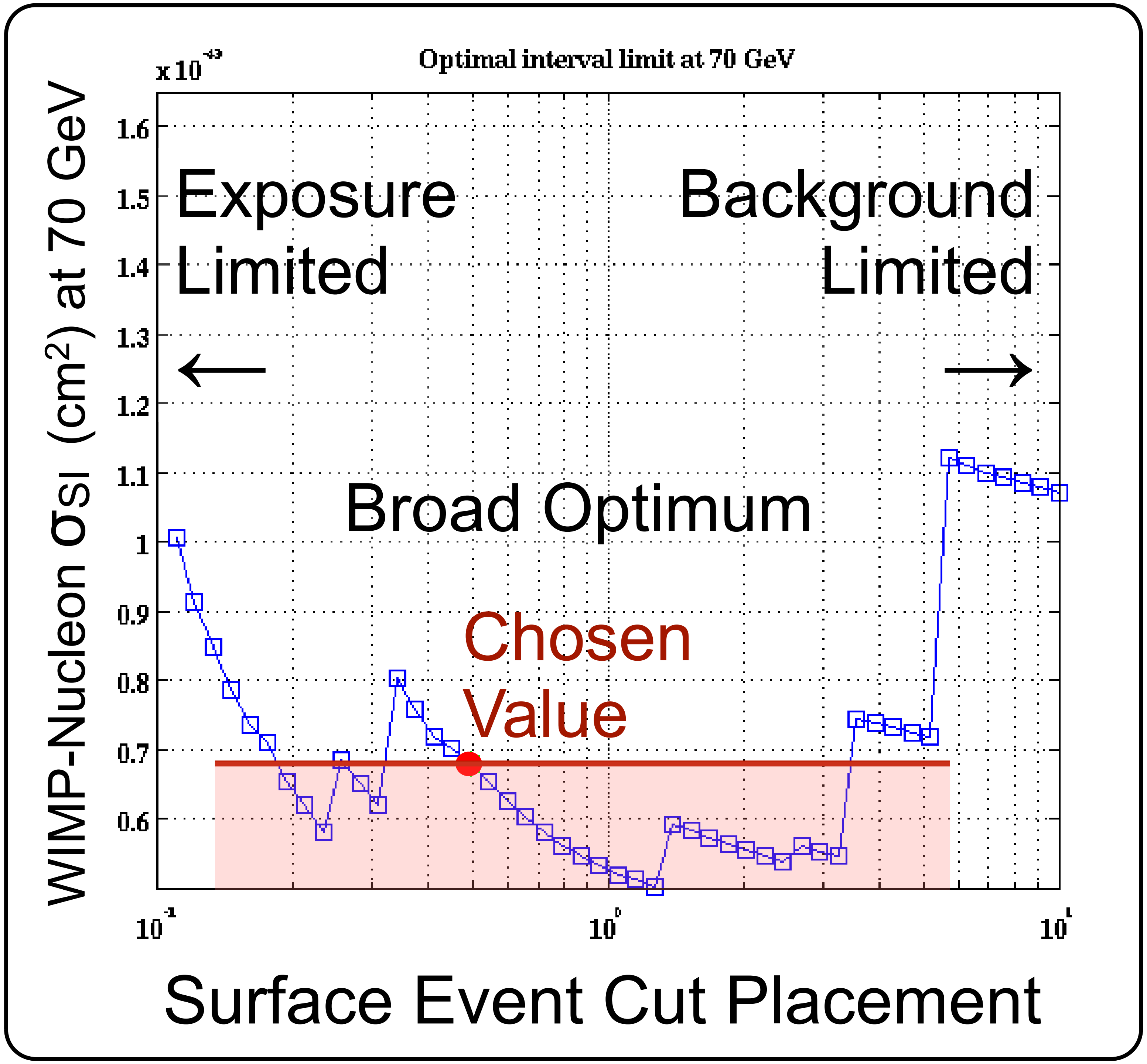
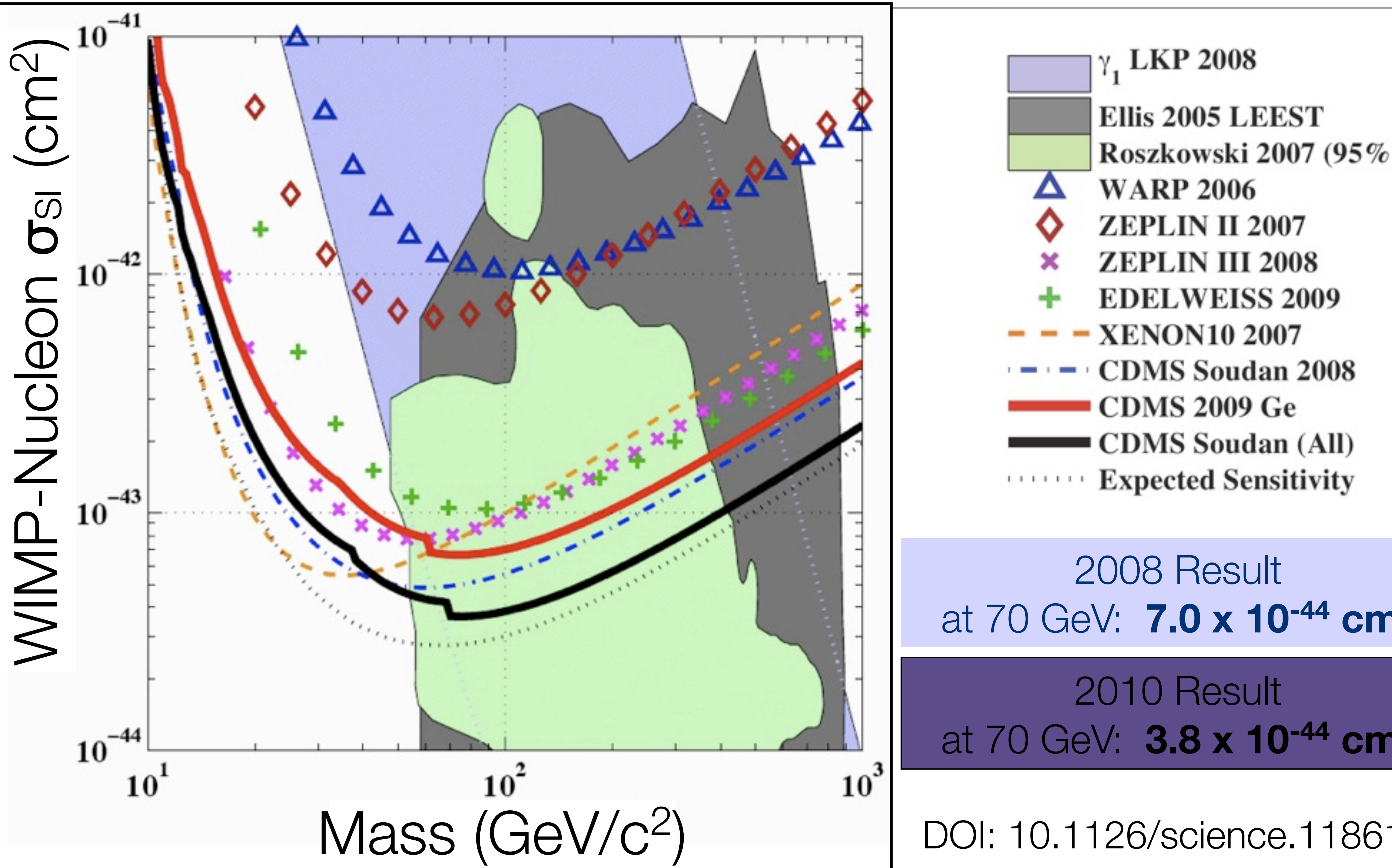


New σ_{SI} Upper Limit

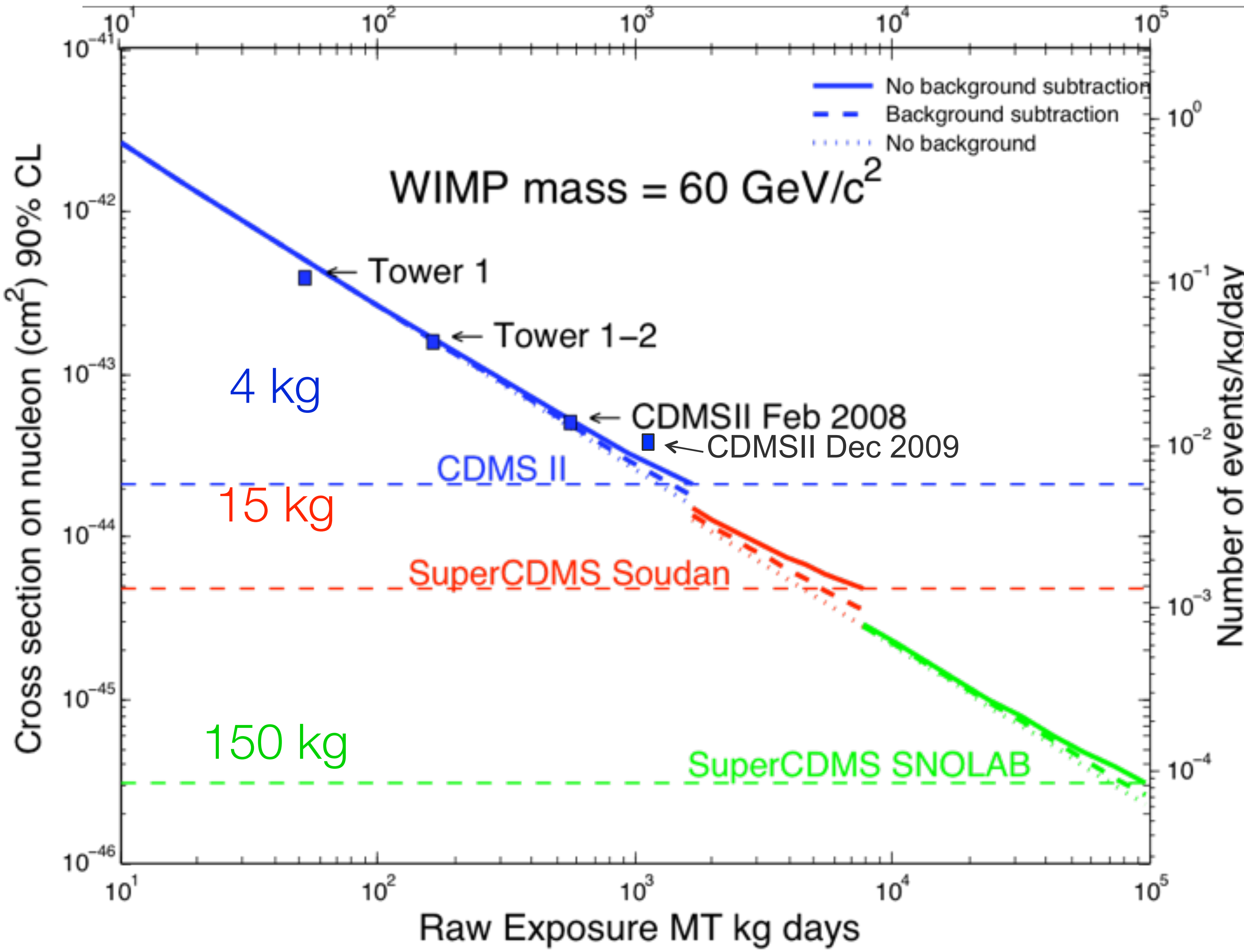


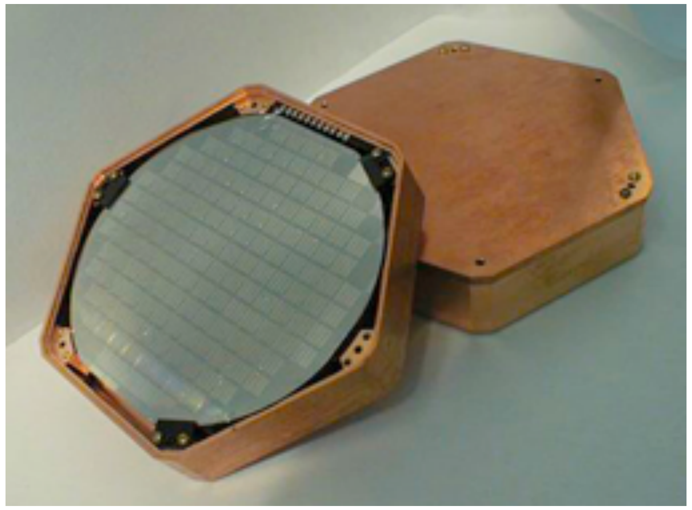
2008 Result
at 70 GeV: **7.0 x 10^{-44} cm^2**

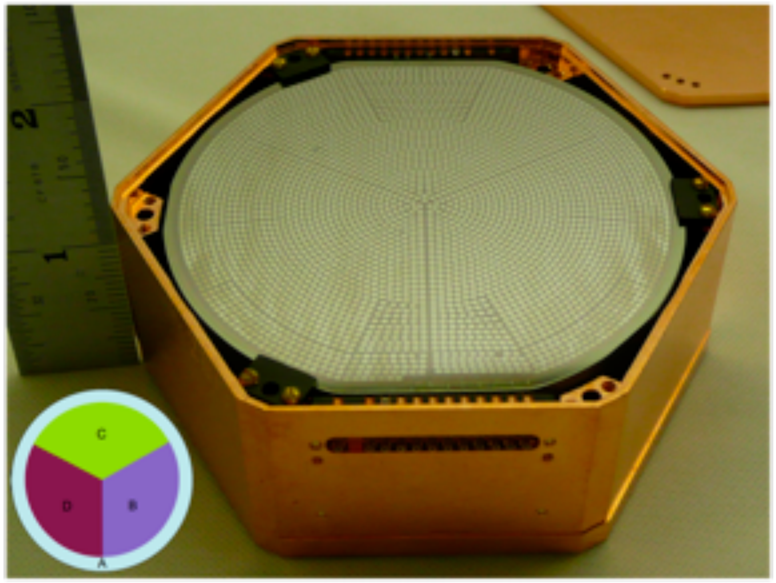
2010 Result
at 70 GeV: **3.8 x 10^{-44} cm^2**

DOI: 10.1126/science.1186112

SuperCDMS phases - Moore's Law if zero bkgd







GEODM

See e.g. 'Background Penalty Factor', Scott Dodelson arXiv 0812.0787v2

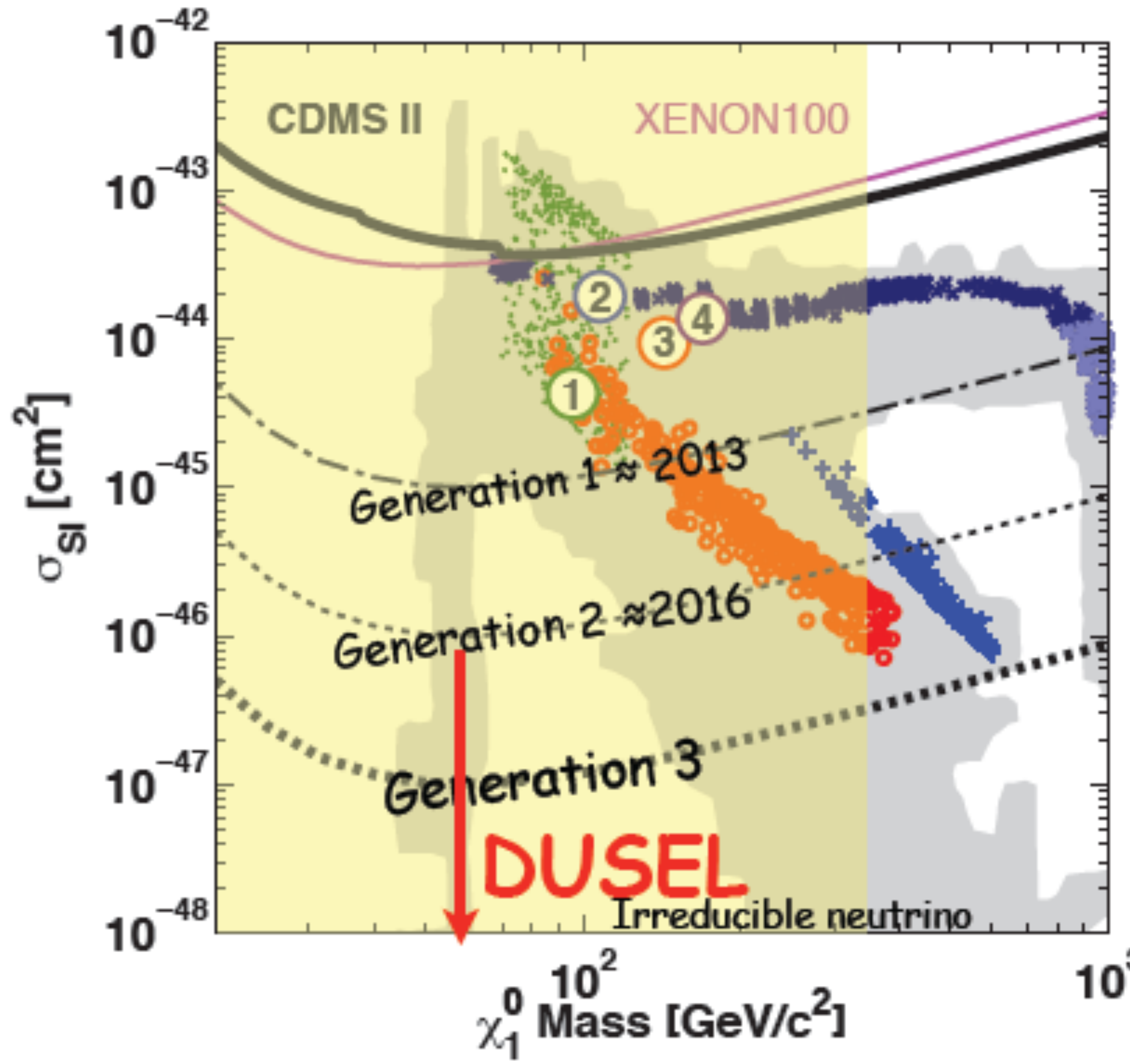
Outline

- Overview of the Dark Matter Problem
- Principles of Direct Detection
- Experimental Searches for WIMPS
  - The CDMS Experiment
- Outlook for the future

The Future

- Next few years will have several experiments probing significant new parameter space.

- Look for new results from Liquid Nobles, Bubble Chambers, Scintillators, and Cryogenic Detectors (see talk by Rupak Mahapatra on the GEODM project).



The Future: Exciting Times Ahead!

- We need several targets to check potential signal's dependence on A and spin.

- We need several technologies with different systematics for cross checks and insurance against unexpected backgrounds in any one experiment.