Direct Detection Searches for Dark Matter

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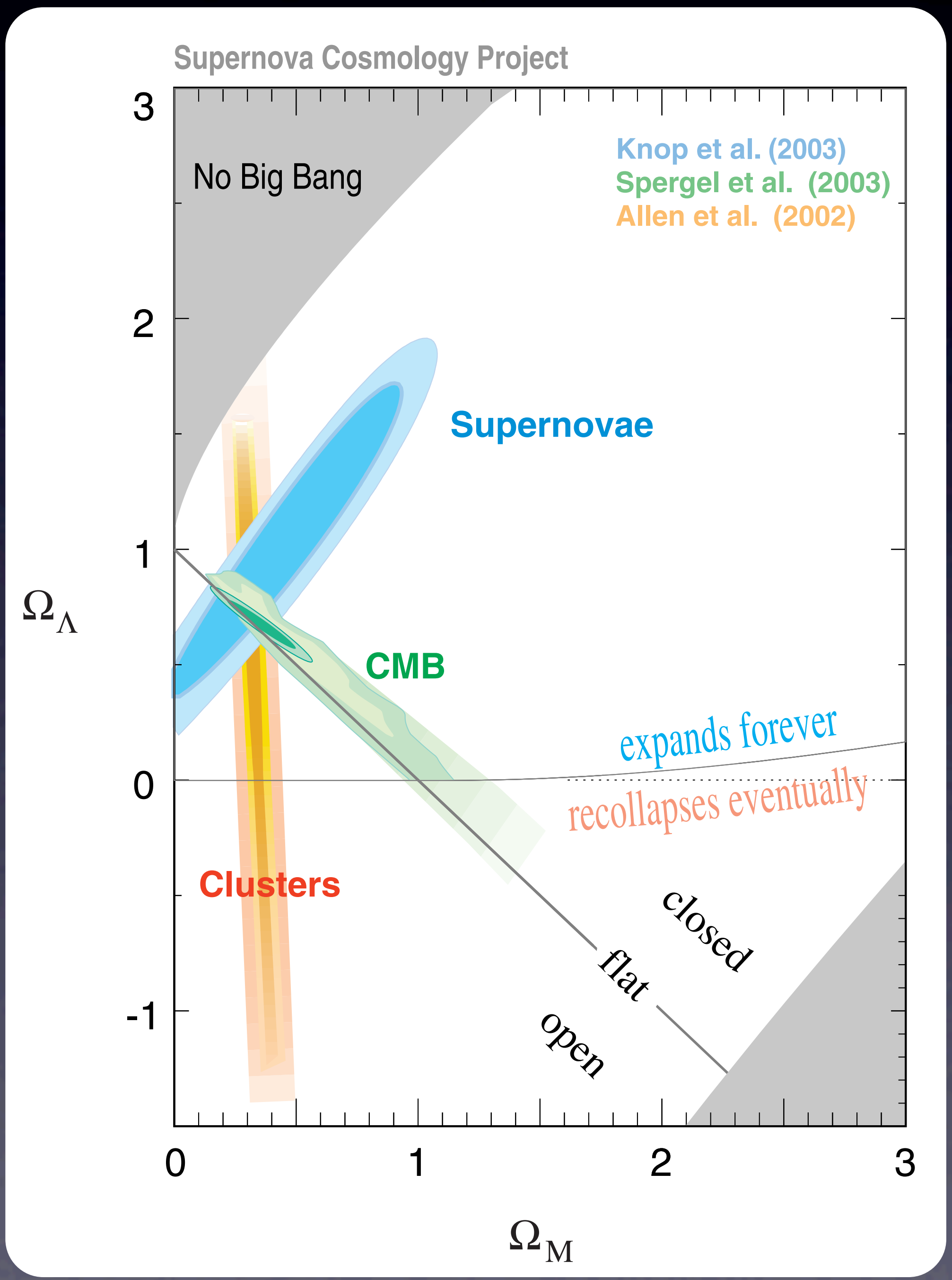
32nd Course: Particle and Nuclear Astrophysics
Erice

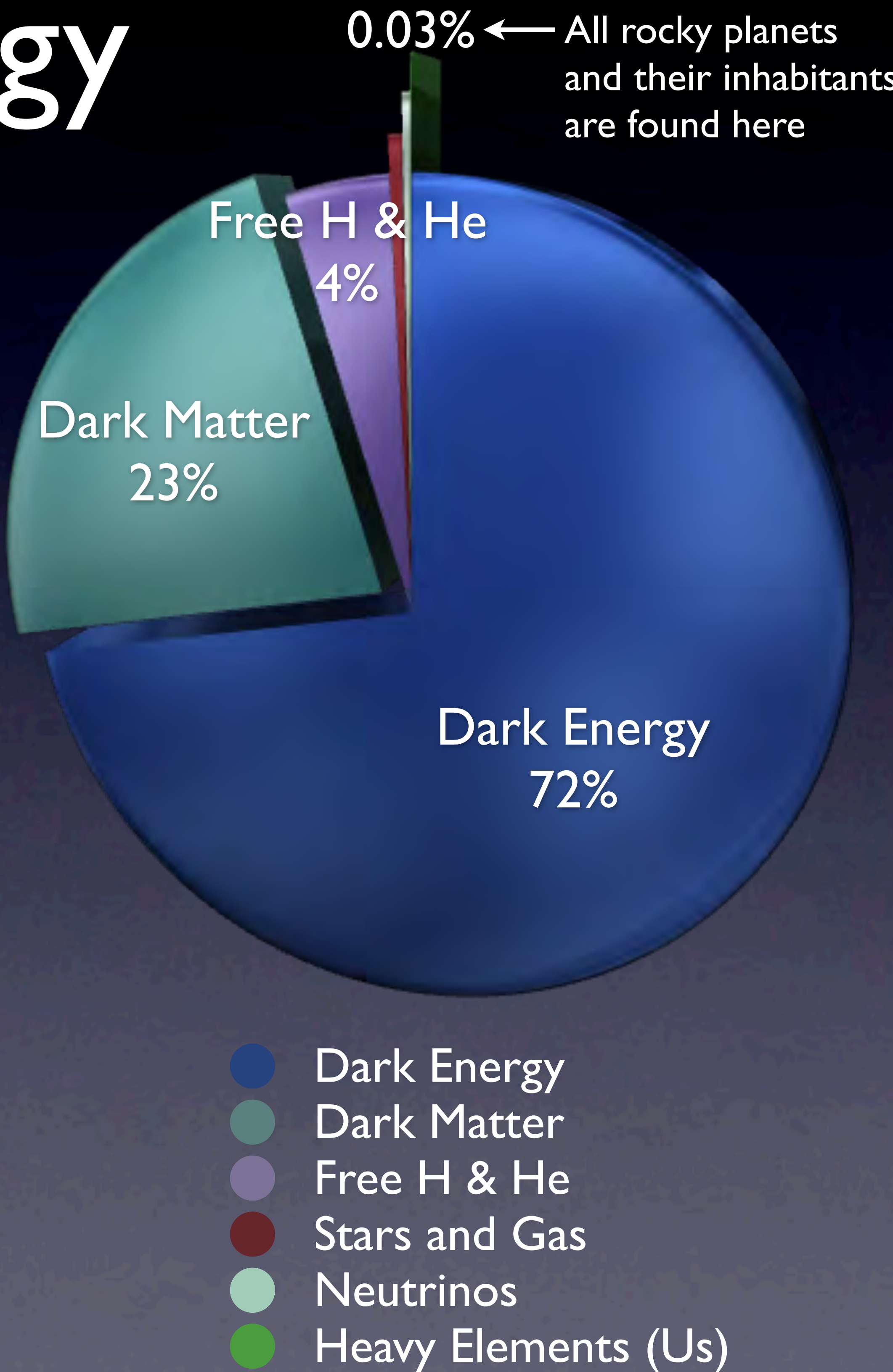
Outline

- 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

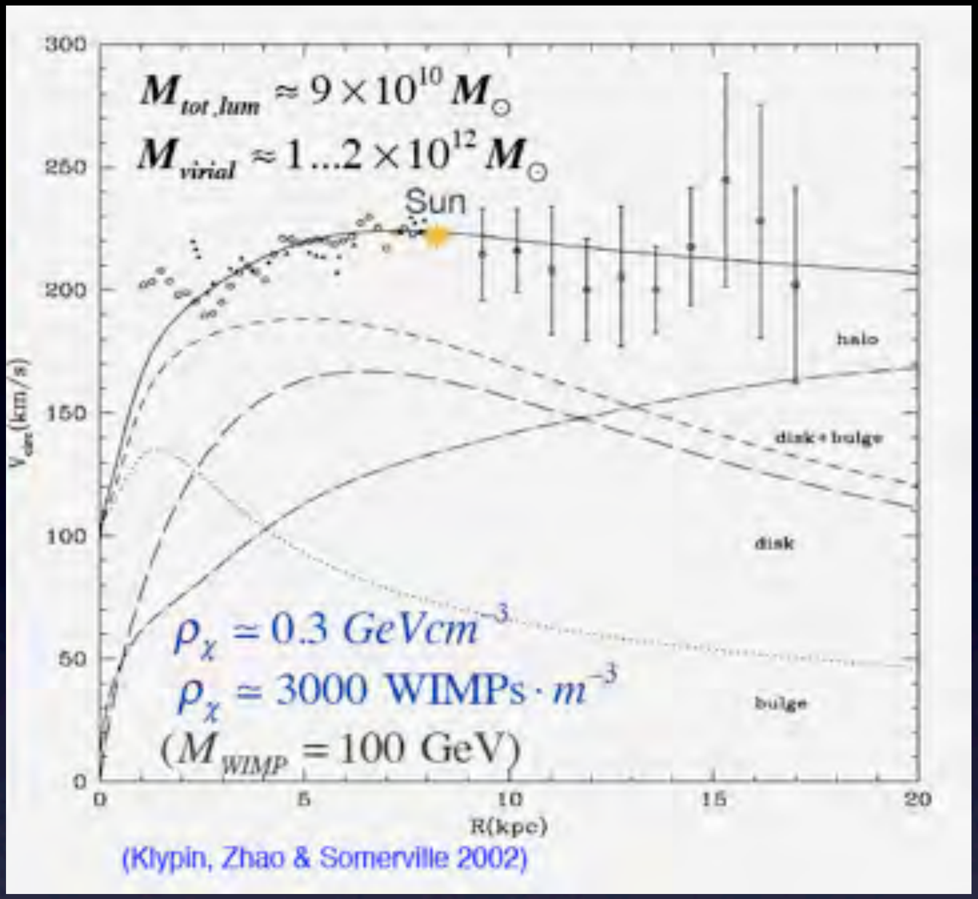


We don't know what 96% of the Universe is made of!!!

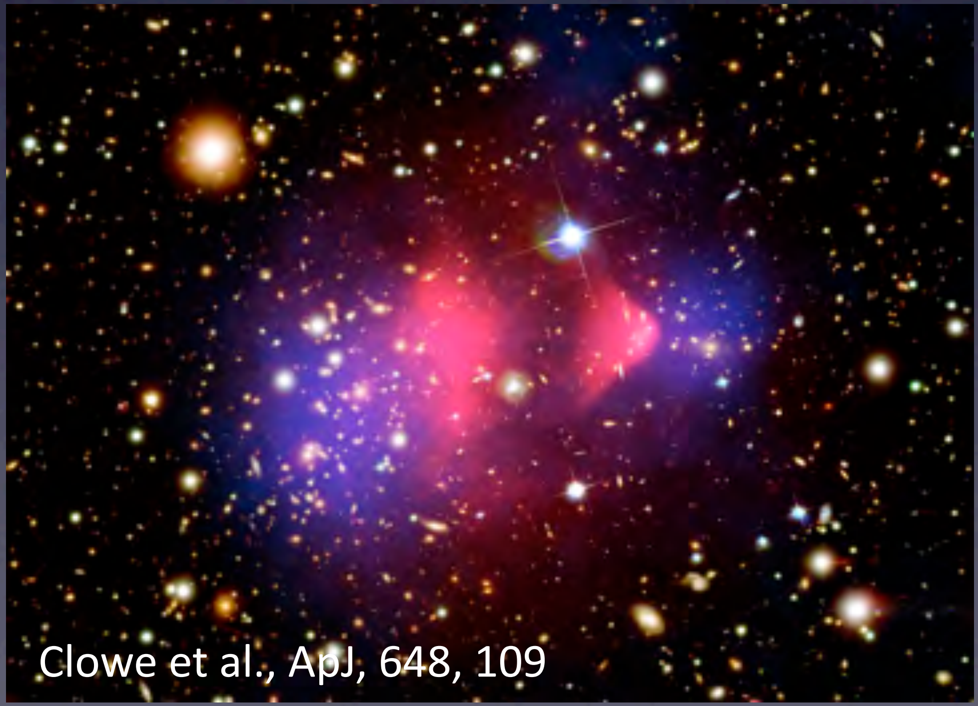


The Nature of Dark Matter

- **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

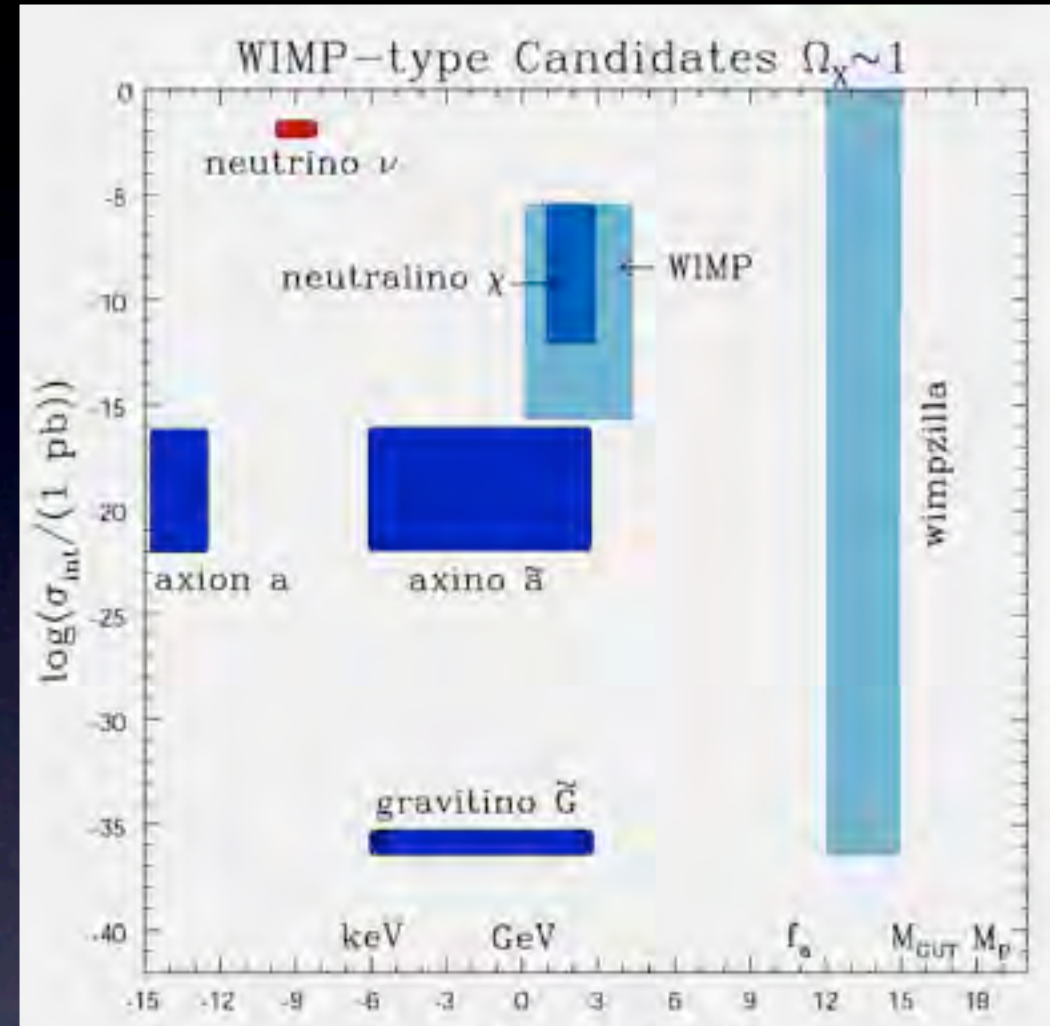


(Klypin, Zhao & Somerville 2002)


Clowe et al., ApJ, 648, 109

WIMPs and WISPs

- 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



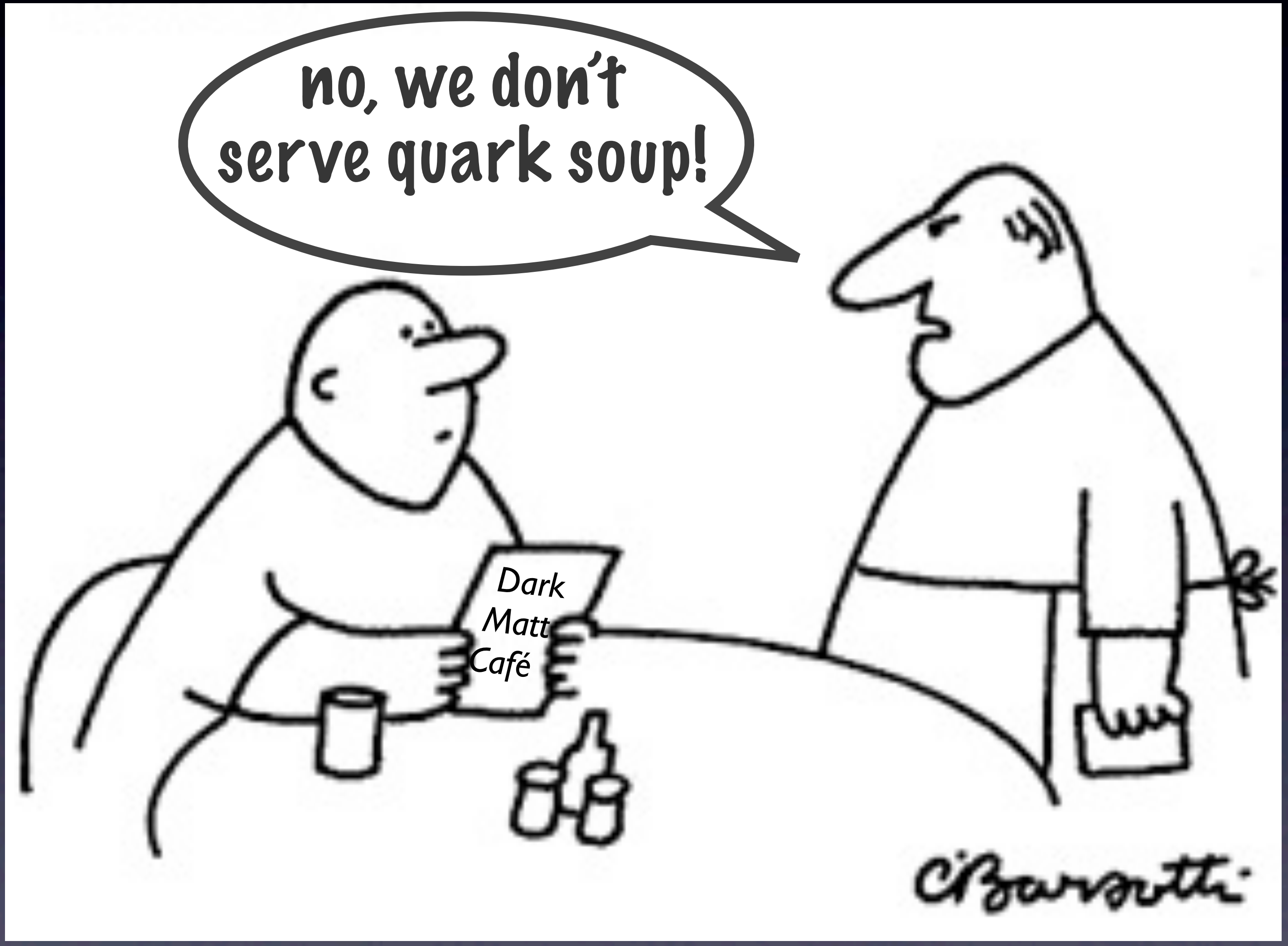
(Roszkowski 2004)

- 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.

Non-baryonic Menu

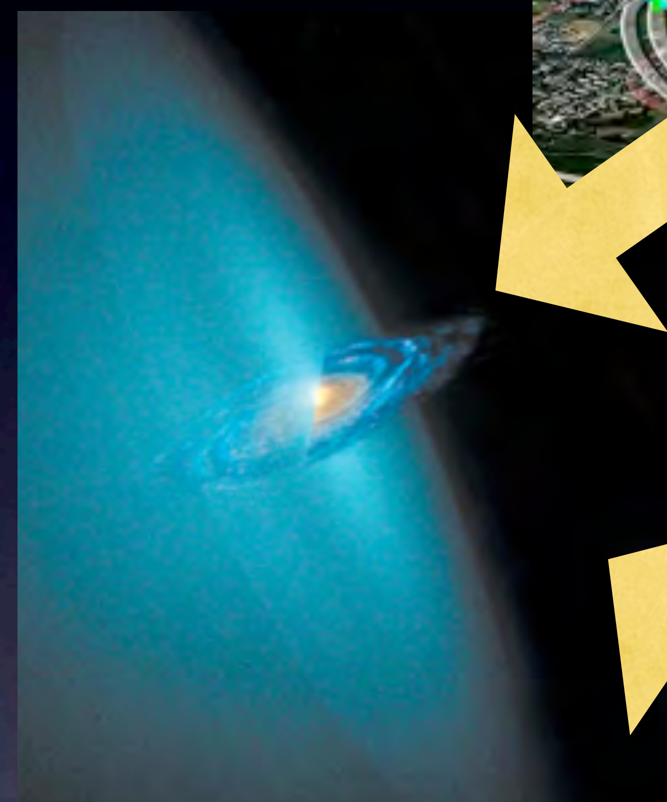
- Axions
- Axino
- Gravitino
- Sterile Neutrinos
- WIMPs
- And many more exotics that can fit the bill...



Talk by Frank Daniel Steffen

The Hunt for Dark Matter

Annihilation in the Cosmos

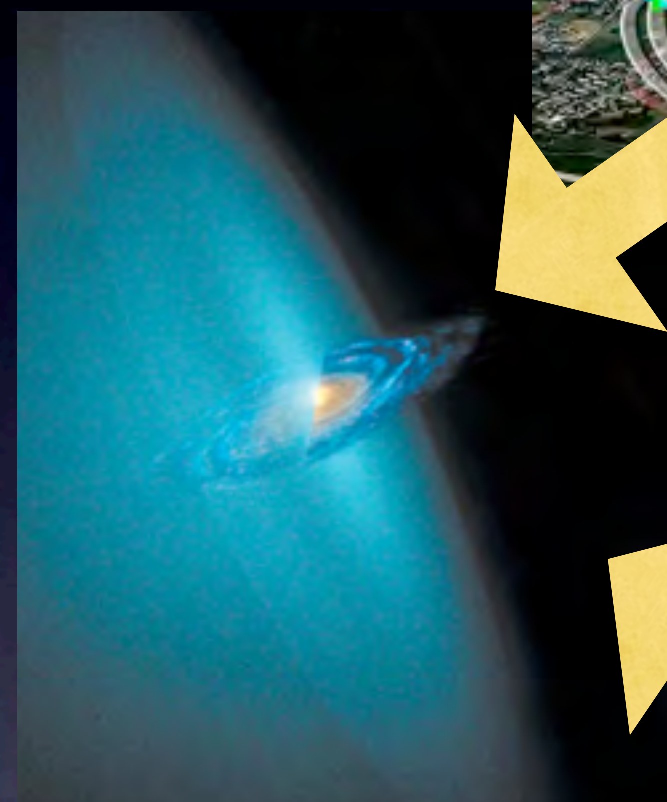


Production in Colliders

Scattering in Terrestrial Detectors

The Hunt for Dark Matter

Annihilation in the Cosmos



Production in Colliders

Scattering in Terrestrial Detectors

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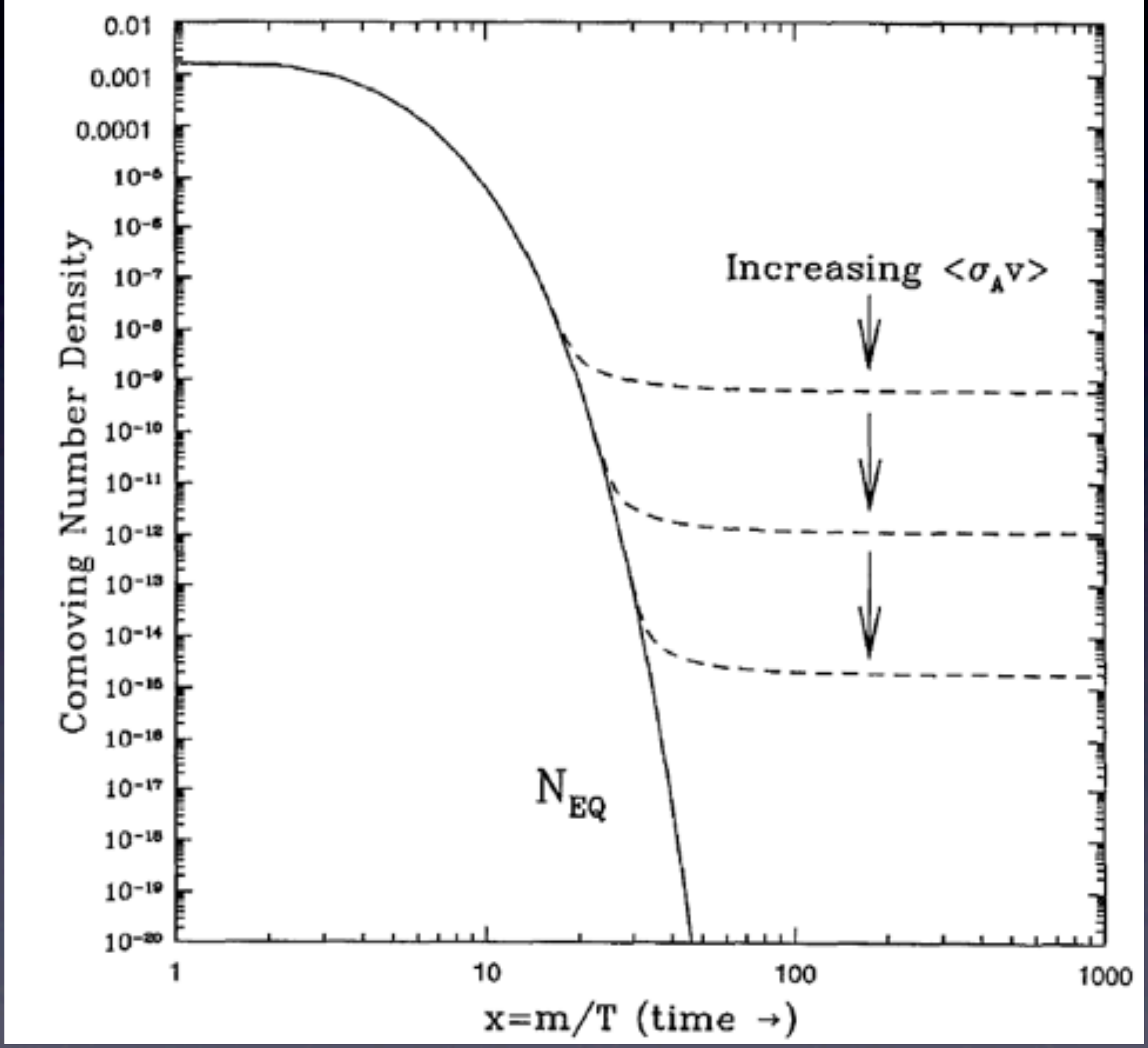
  - The CDMS Experiment
- Outlook for the future

Why WIMPs?

- Supersymmetry (SUSY) appears in many theories for physics beyond the standard model.
- R-parity guarantees that most SUSY theories have a stable LSP.
- From cosmology, the freezeout density requires an interaction cross section in the weak scale (the WIMP miracle)

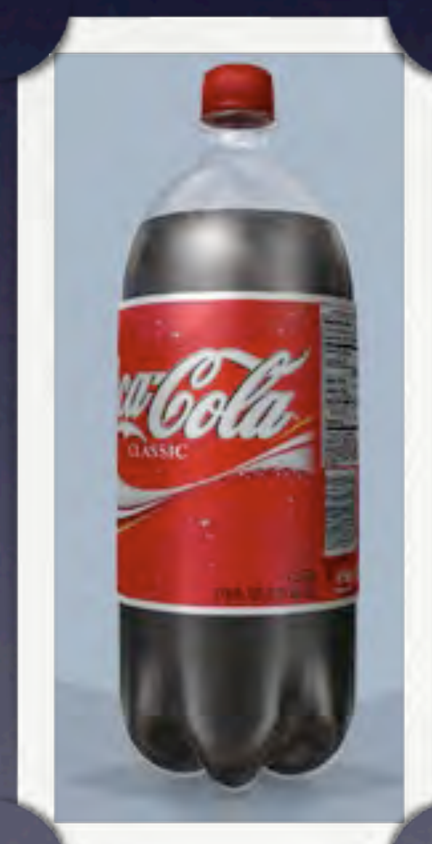


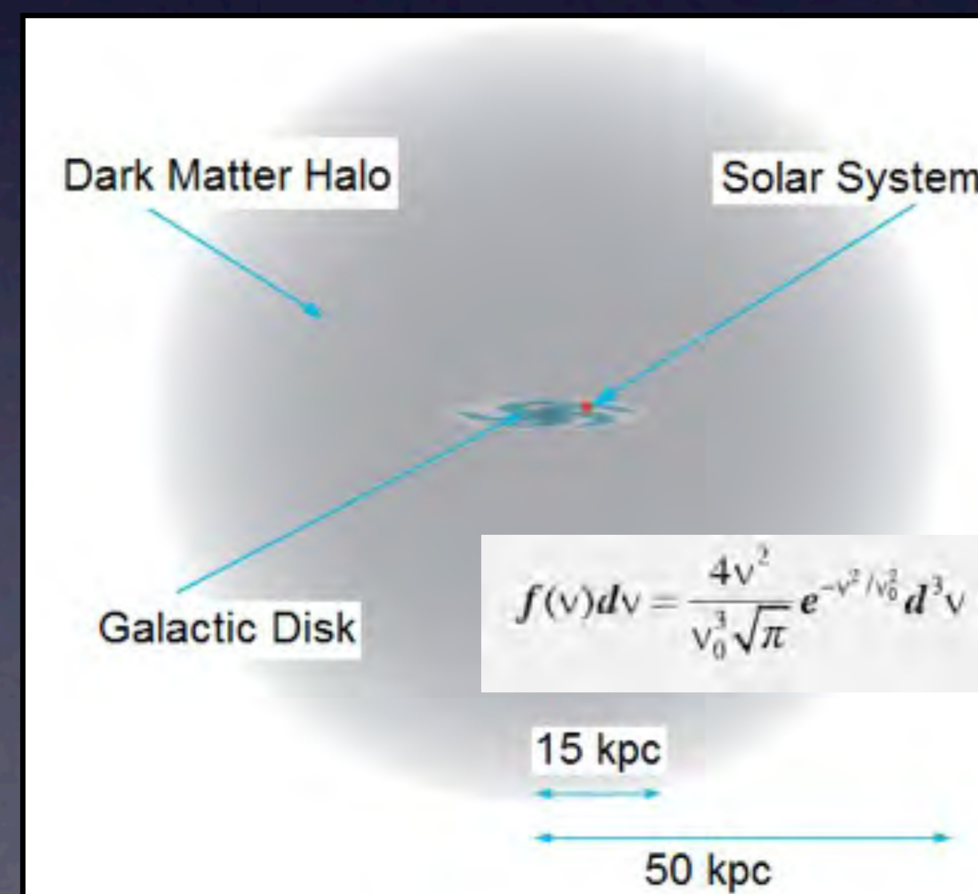
Direct Detection and WIMP Astrophysics

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

- "Spherical-cow" assumptions: isothermal and spherical, with Maxwell-Boltzmann velocity distribution
- v_o = 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)





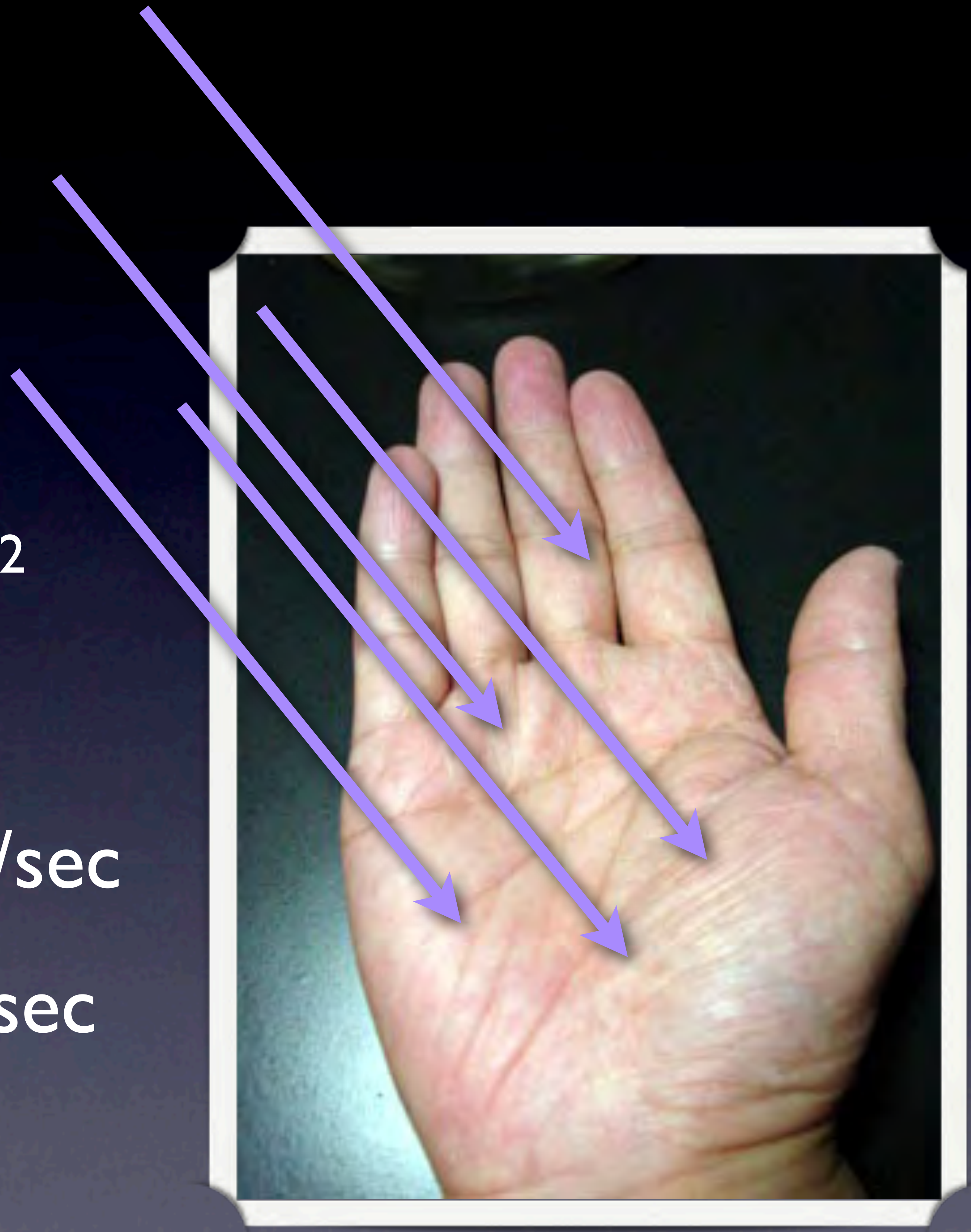
The Dark Matter Wind

apparently “blows”
from Cygnus

Our speed relative to the
halo is ~220 km/s

Flux

- Density: 0.3 GeV/cm^3
- Mass: assume 60 GeV/c^2
- @ ~220 km/s
- ~100,000 $particles/cm^2/sec$
- About 20 million/hand/sec



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!

$$m_r = \frac{m_\chi m_N}{m_\chi + m_N}$$ = "reduced mass"

Wimp-Nucleus Interaction

- Spin-Dependent:
  - Dominated by unpaired nucleons.
  - For spinless 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

Linear with J; spin-independent is usually dominant

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

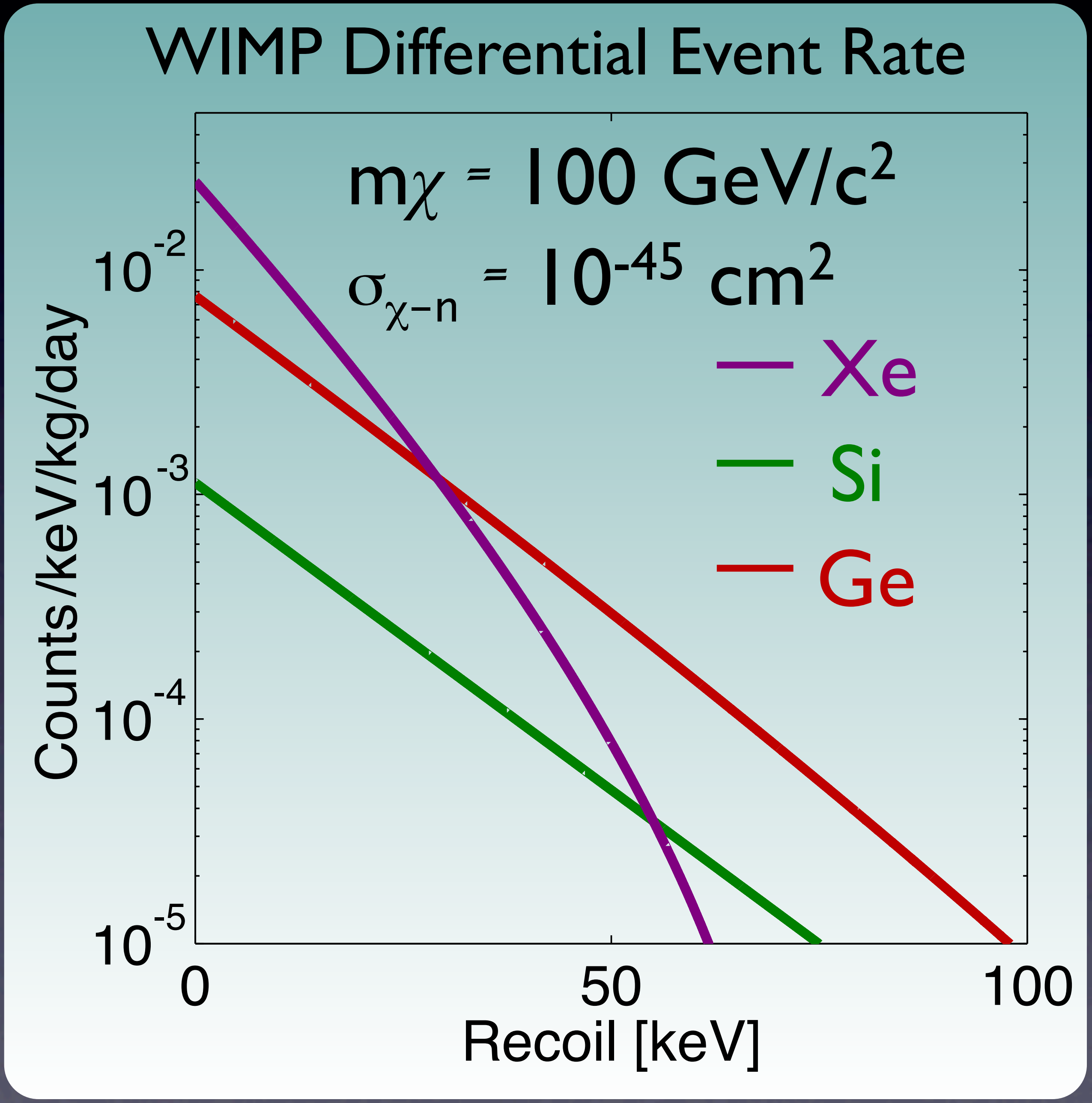
$$v_{\rm min} = \sqrt{E_R\, m_N/(2m_r^2)}$$

minimum WIMP velocity for given E_R

WIMP Hunting

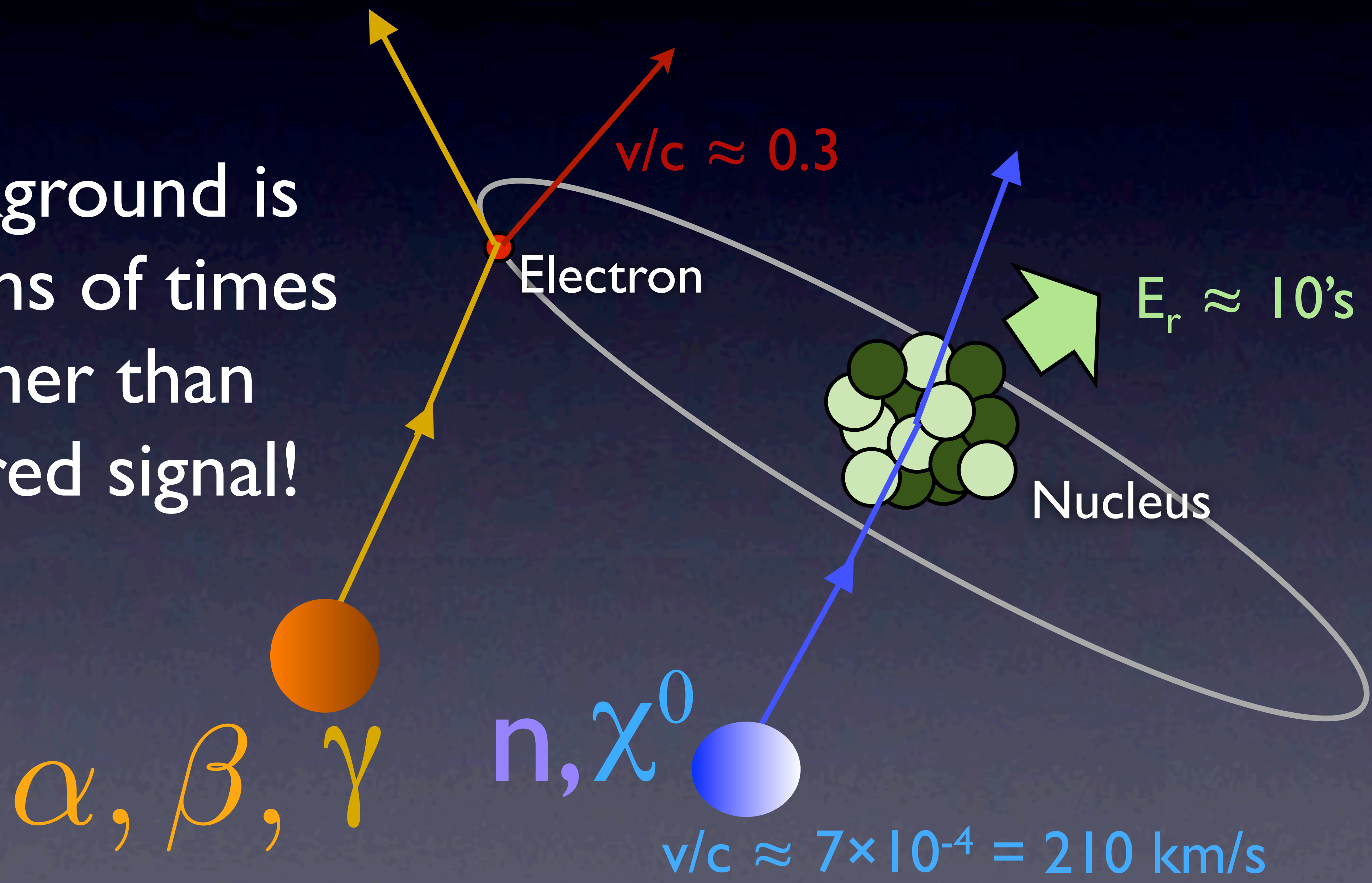
- Elastic scattering of a WIMP from a nucleus deposits a small, but detectable amount of energy ~ few x 10 keV
- Featureless exponential energy spectrum with $\langle E \rangle$ ~ 50 keV
- Expected rate < 0.01/kg-day (based on $\sigma_{\chi-n}$ and ρ)
- Radioactive background a million times higher
-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

Low background (< 1) almost a prerequisite for discovery



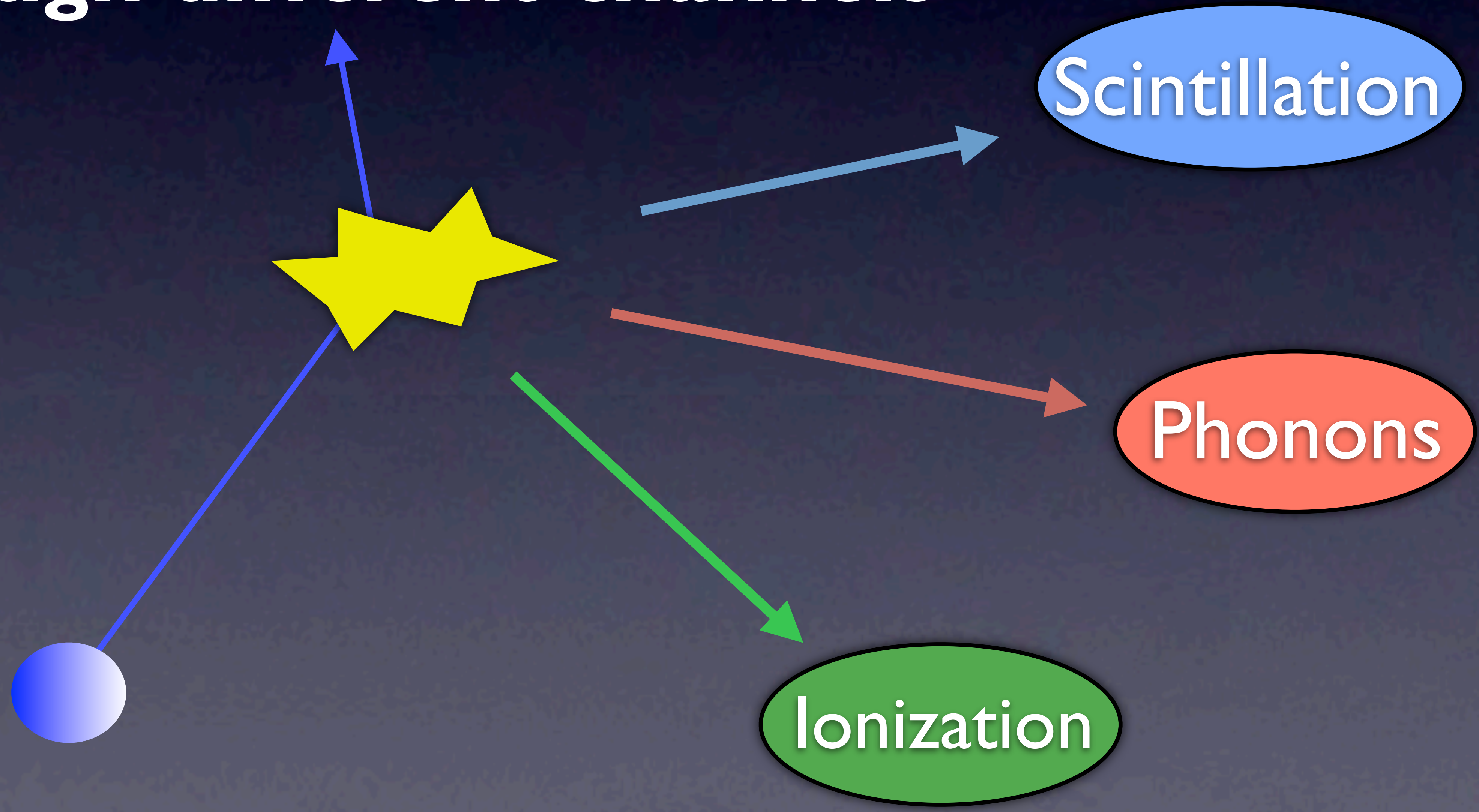
Signal and Backgrounds

Background is millions of times higher than desired signal!

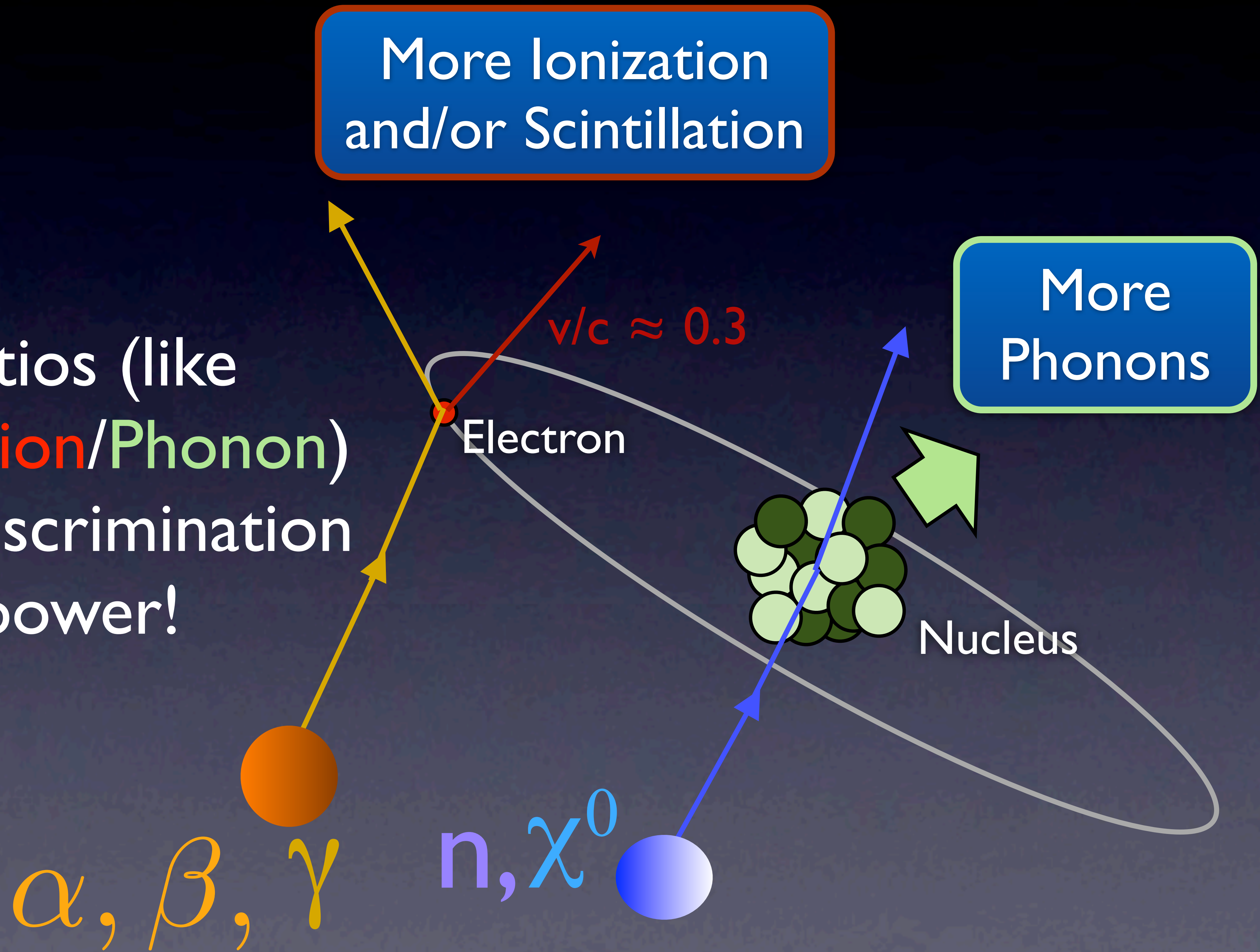


Energy Channels

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

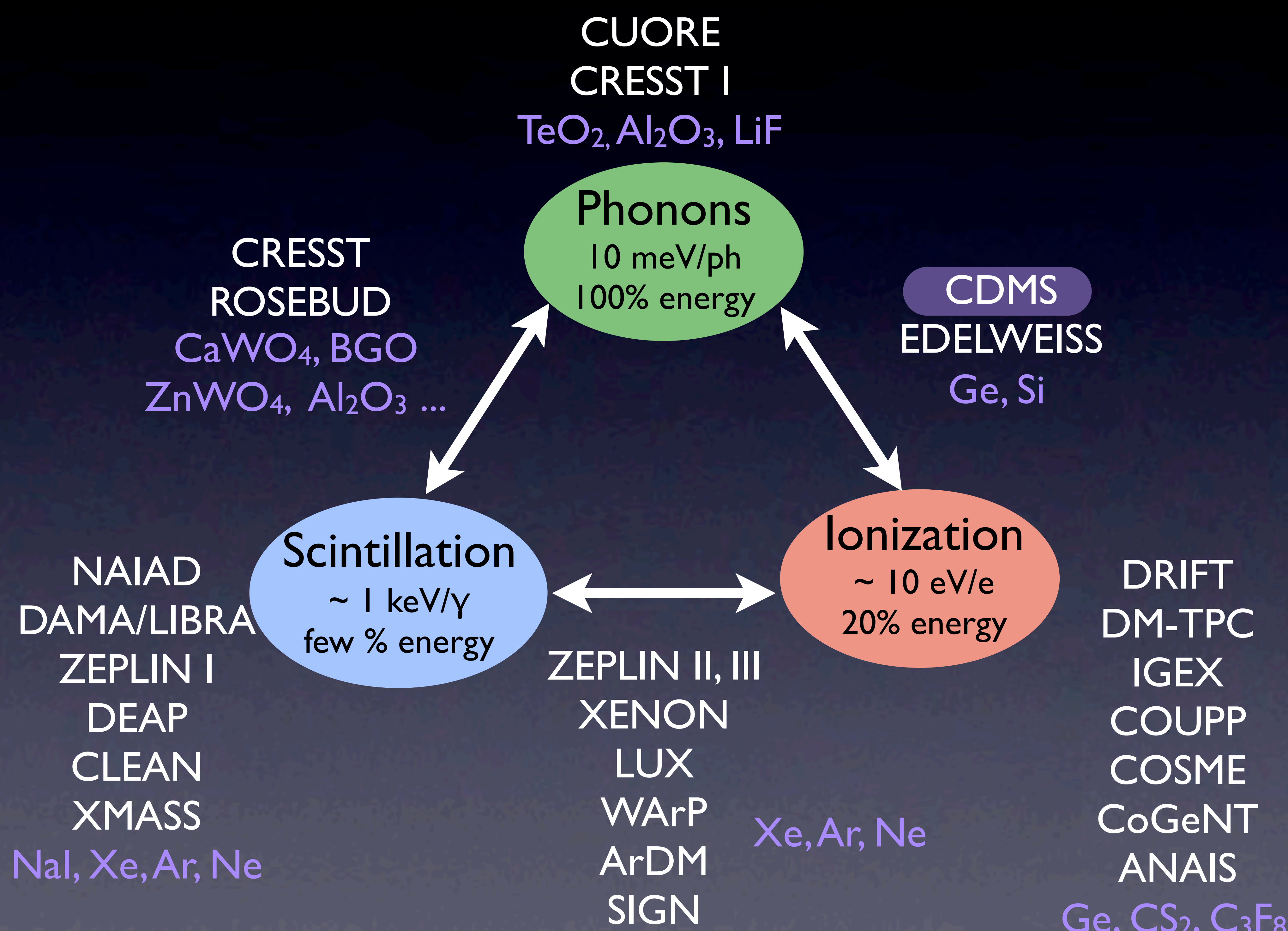


Discrimination Strategies



Ratios (like Ionization/Phonon) have discrimination power!

Discrimination Strategies



Thinking outside the Triangle...

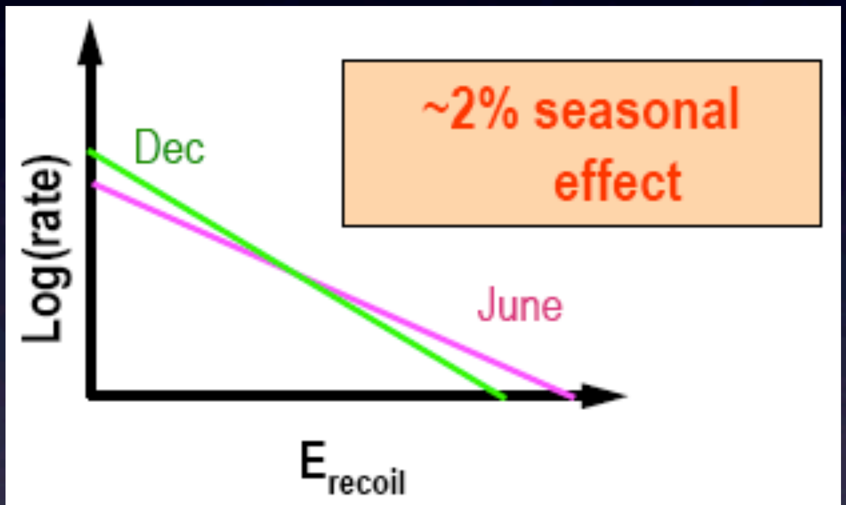
- Scintillation Timing (DEAP/CLEAN)
- Signal Modulation (DAMA/LIBRA, DRIFT, DM-TPC, etc...)
- Nuclear-recoil-only trigger mechanism (a la COUPP...)
- Self-Shielding (XMASS)
- Others...

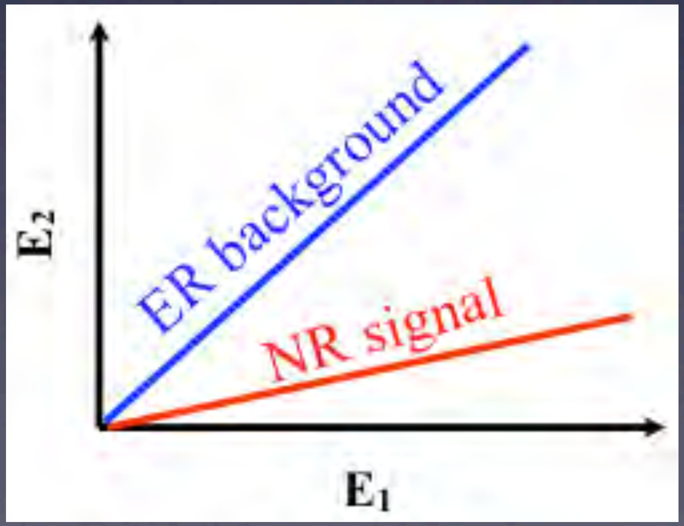
Backgrounds

- Backgrounds are much higher than the signal event rate
  - e.g. rate of ^{40}K from a person standing 2 m 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: polyethelyne, paraffin, water, …
- Neutrons from cosmic ray muons:
  - Use muon veto, neutron veto, shielding
  - Go deep underground to reduce muon flux!

How to Separate 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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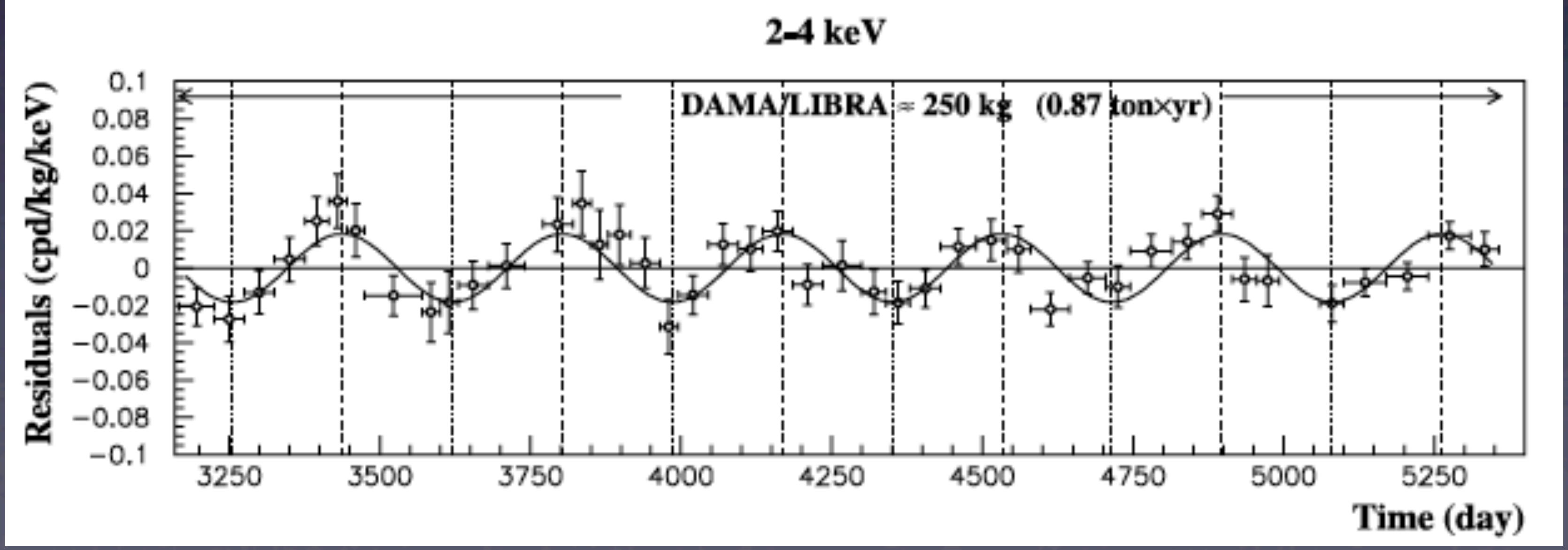
Dark Matter Map

Looking for the needle in the haystack

DAMA / LIBRA

- Talk by Rita Bernabei
- 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 anual cycles

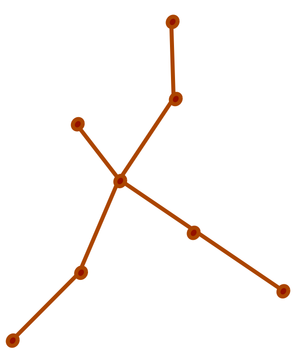


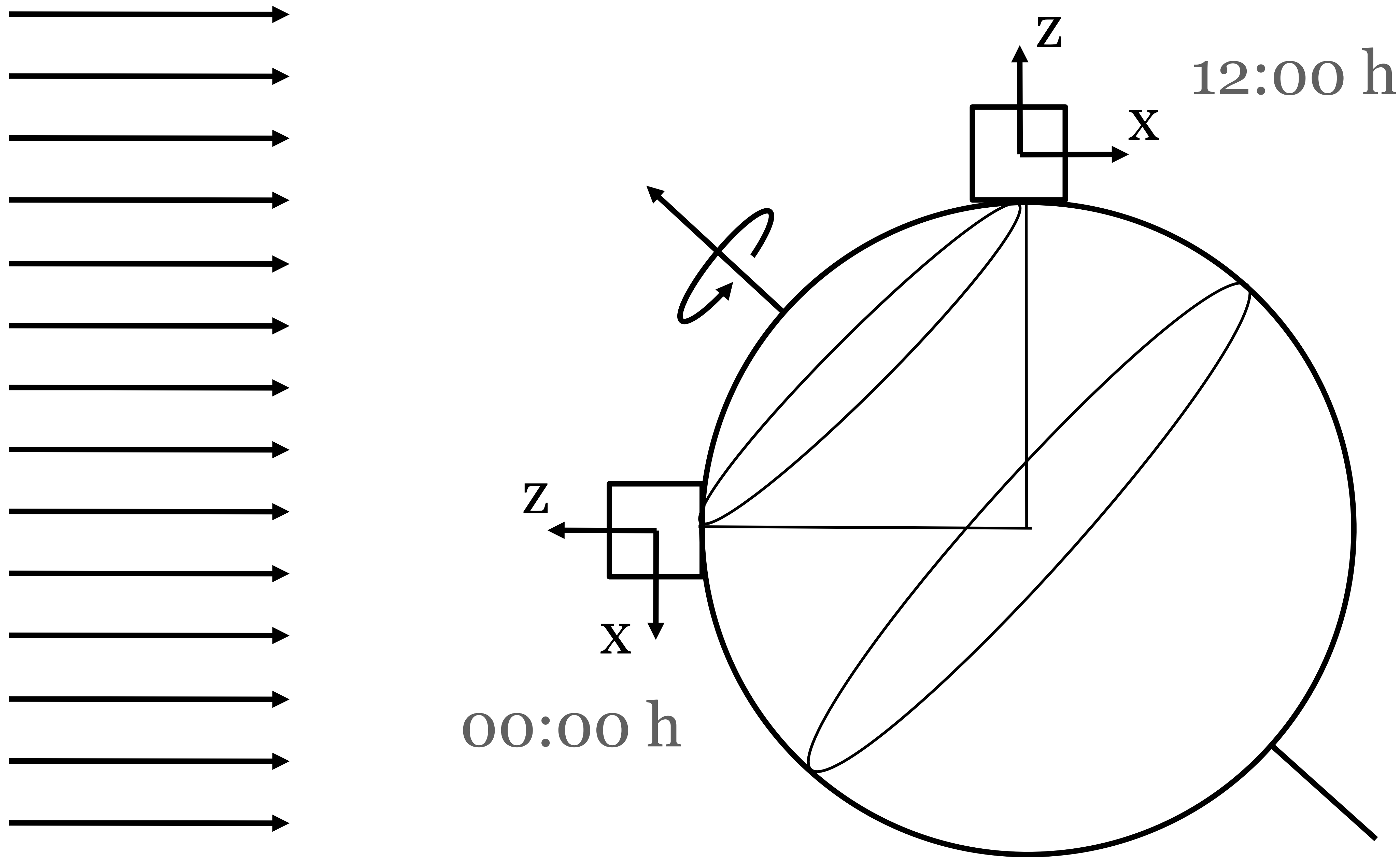
DM-TPC

- 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"

The direction modulation

Cygnus

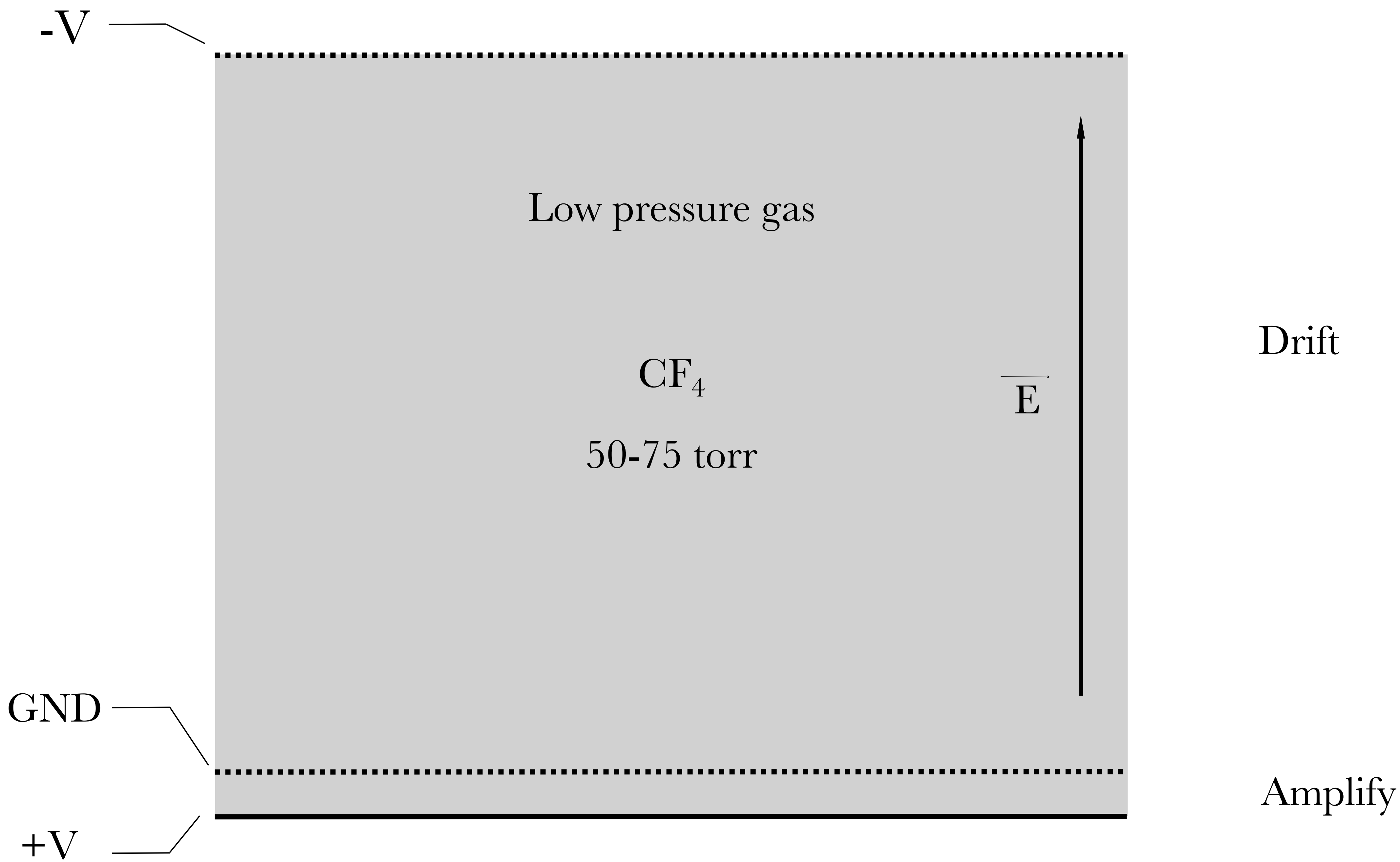




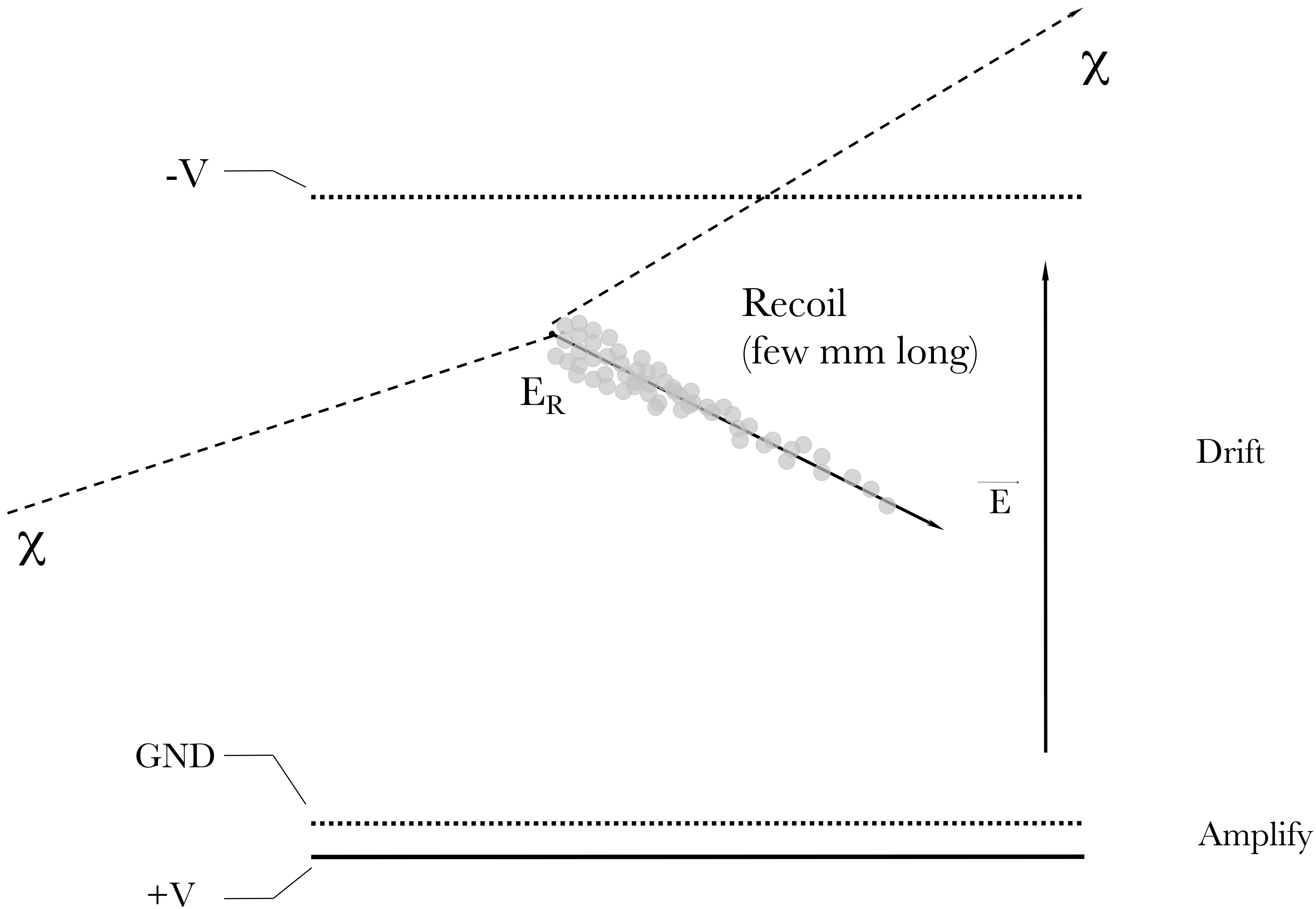
Declination of Cygnus ~42°

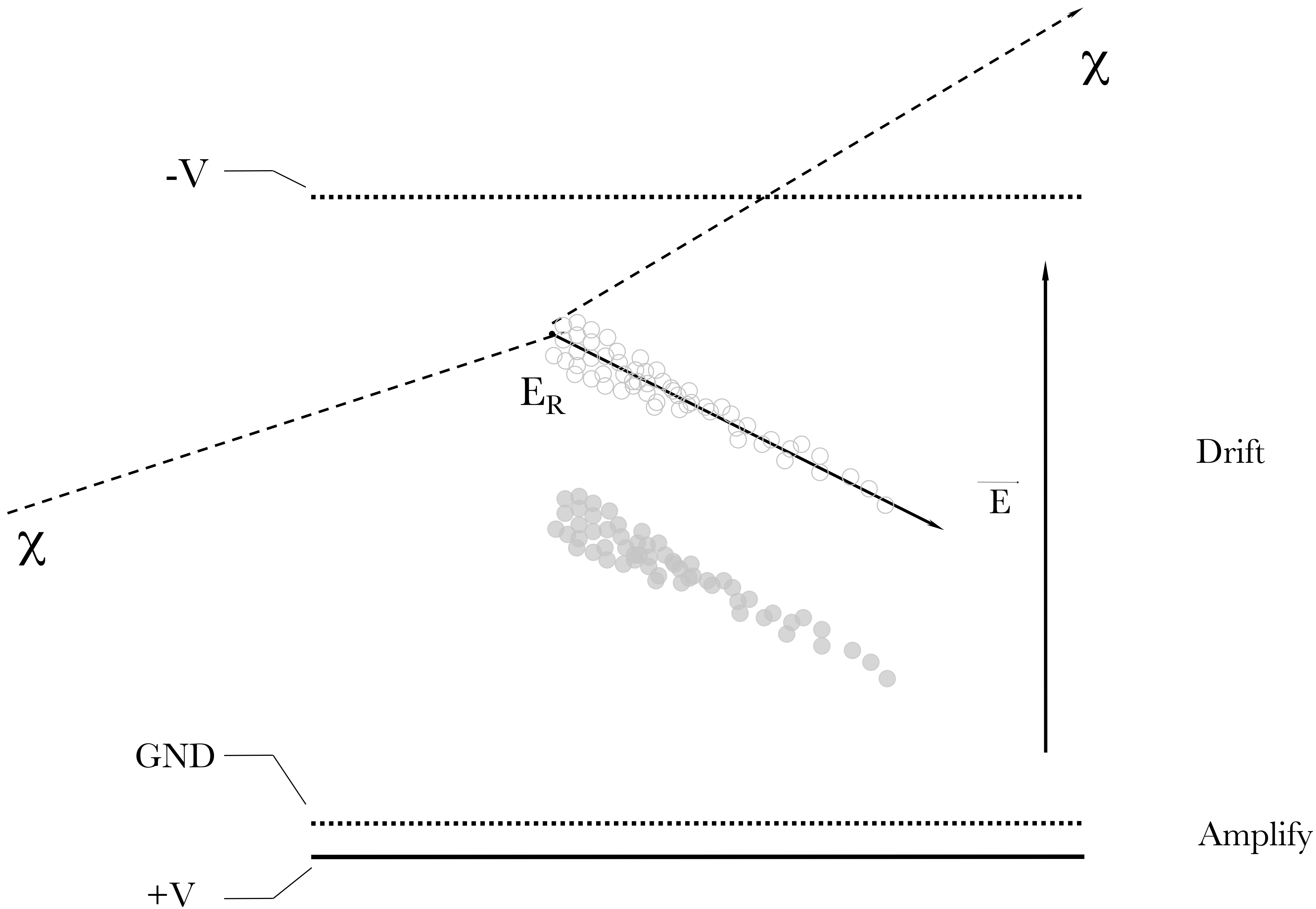
Spergel, PRD, 1988

Time Projection Chamber

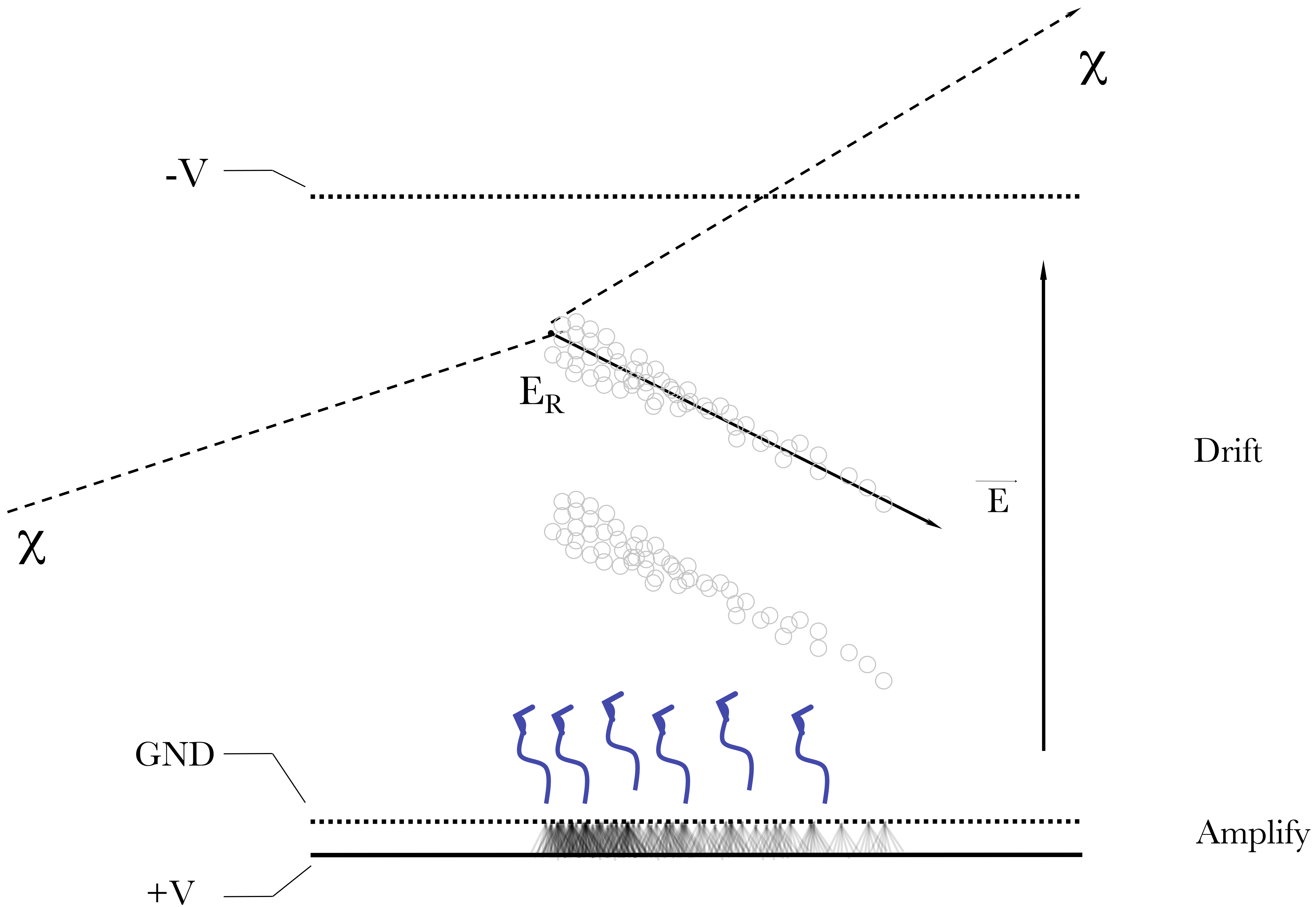


Side view

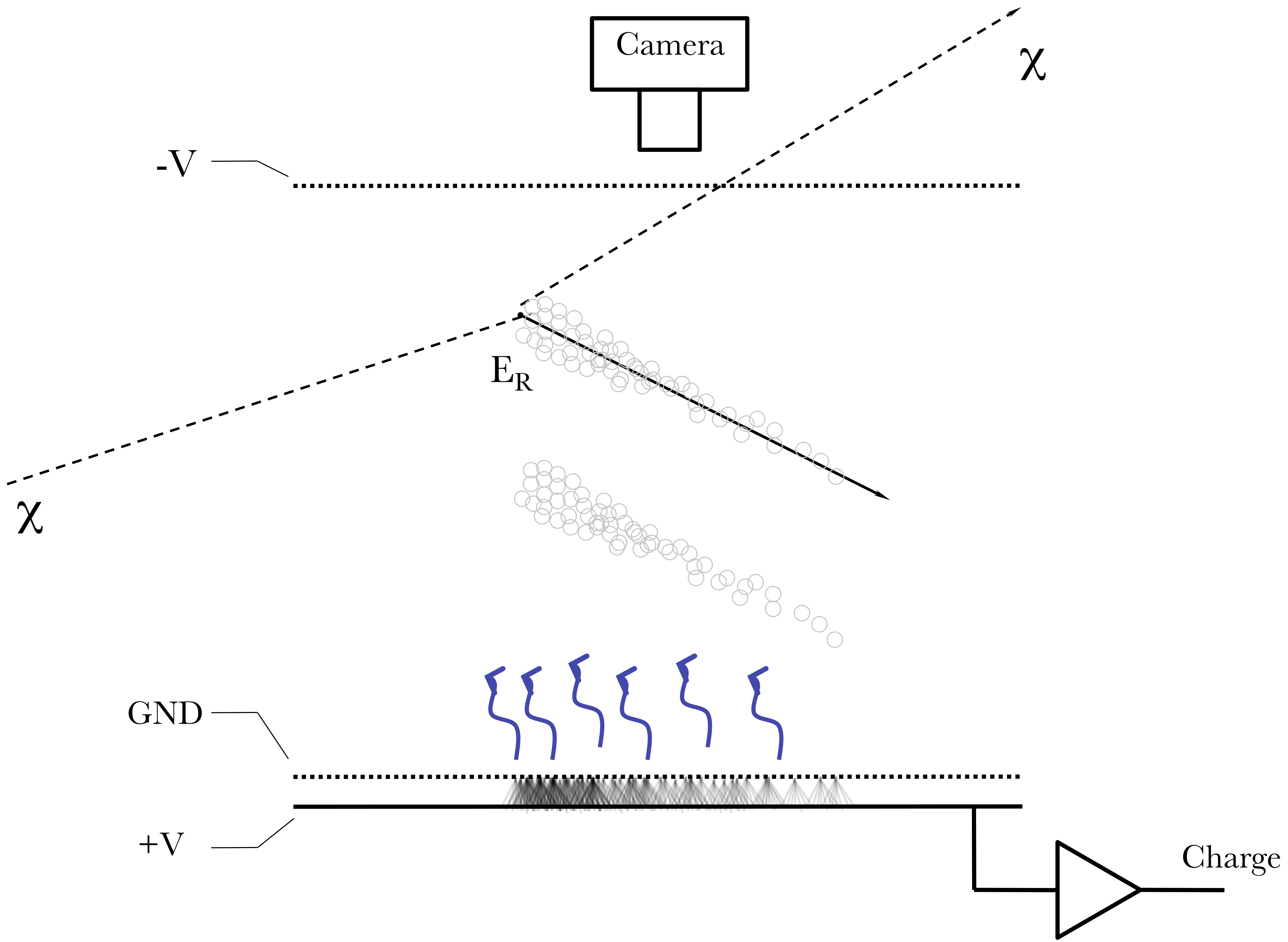

χ
-V
Recoil
(few mm long)
E_R
$\vec{E}$
Drift
χ
GND
Amplify
+V



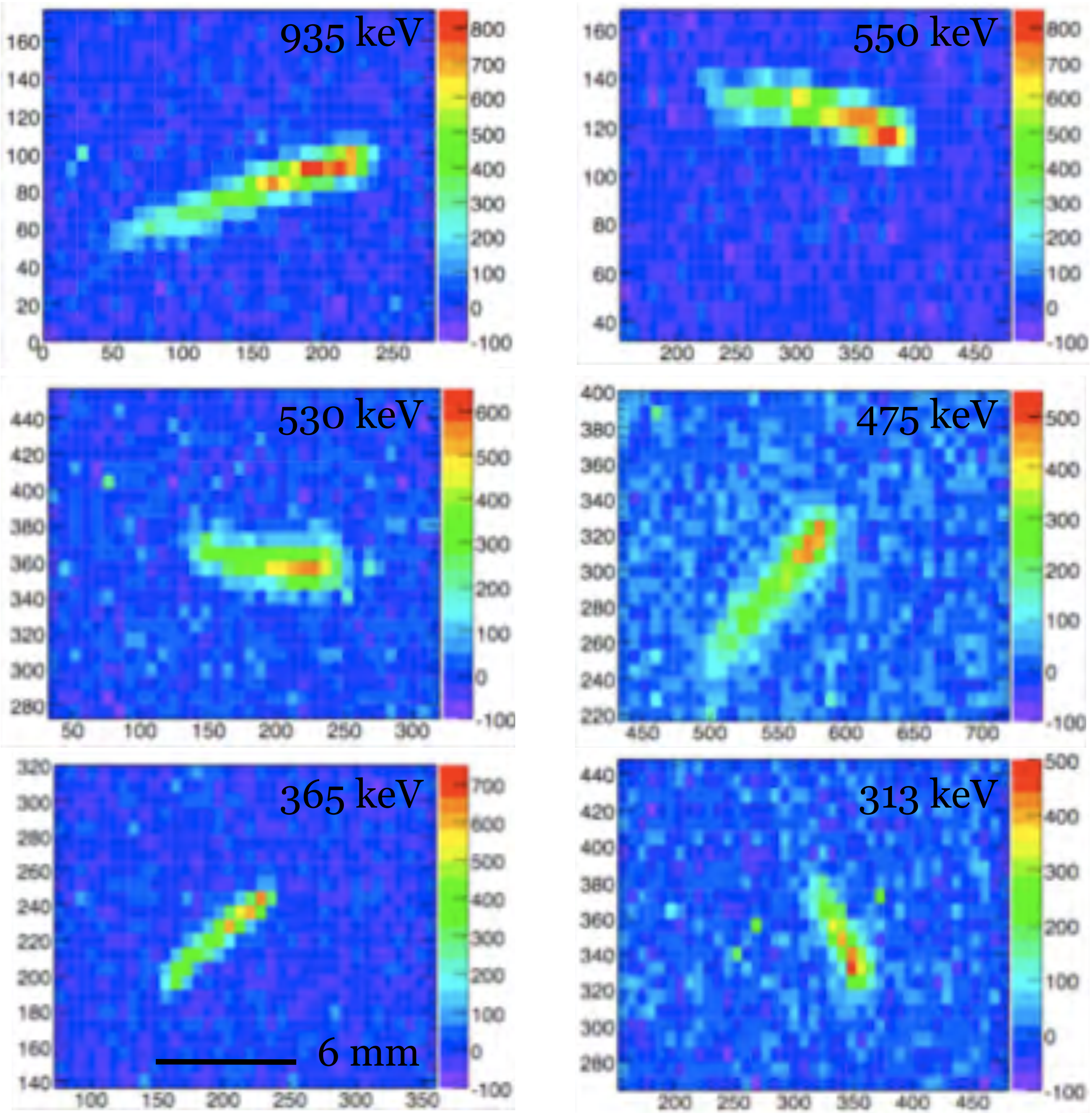
χ
-V
E_R
Drift
$\vec{E}$
χ
GND
Amplify
+V



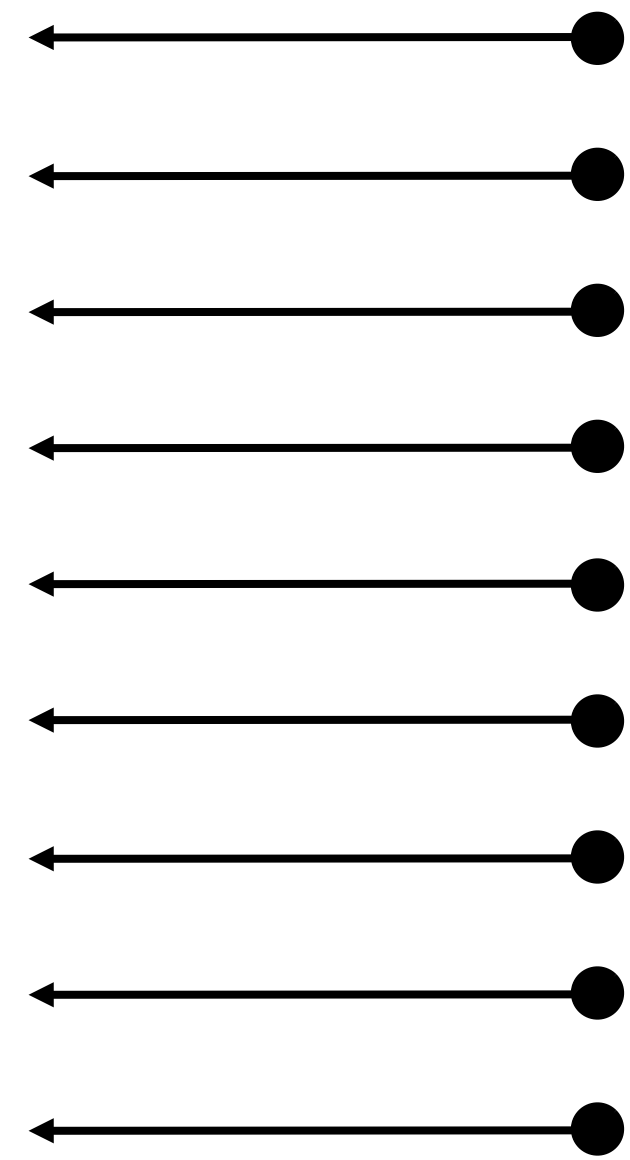
χ
-V
E
Drift
E_R
χ
GND
Amplify
+V


Camera
χ
-V
E_R
χ
GND
+V
Charge

Measurement of head-tail



Cf-252 neutrons



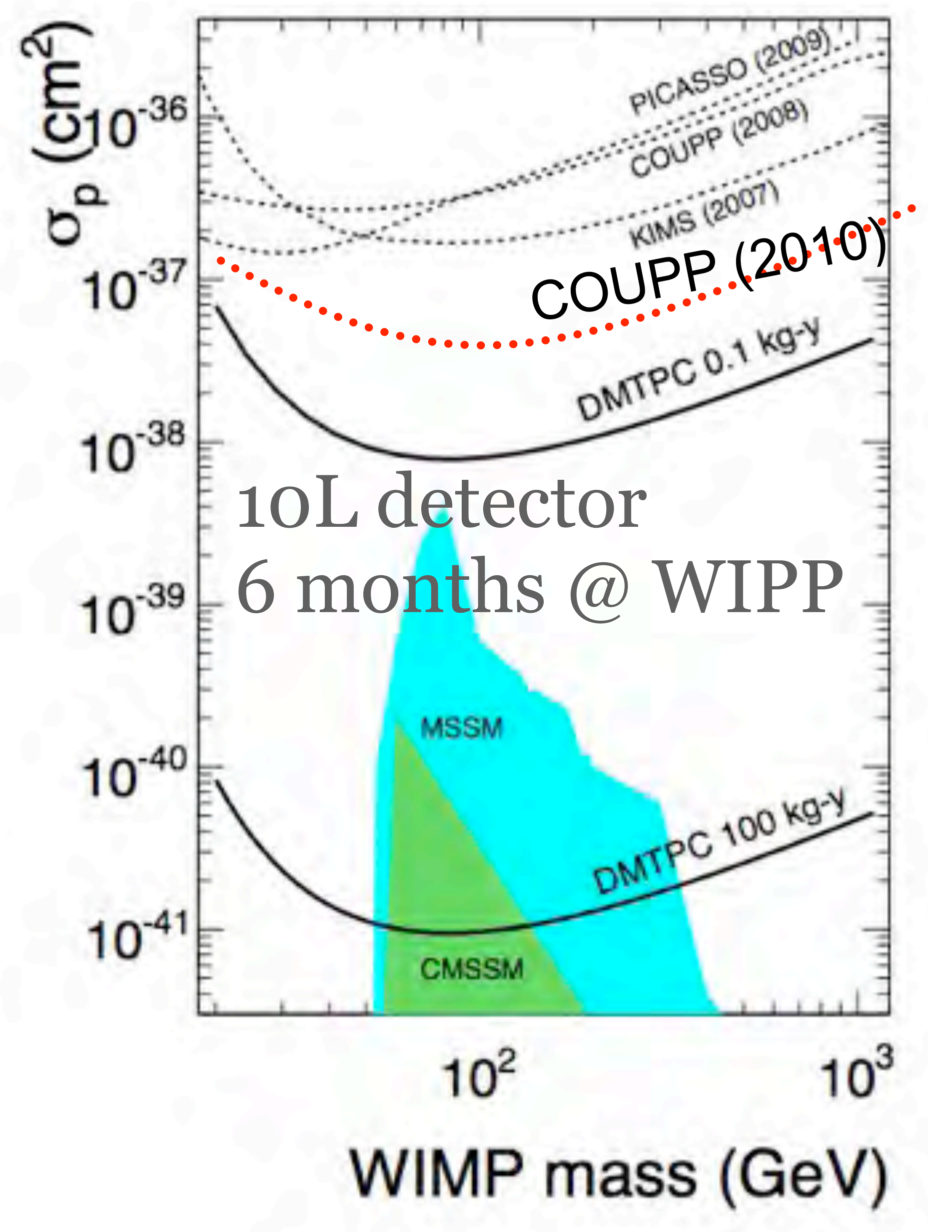
P = 75 torr

100 pixels = 6 mm

Dujmic et al. Astropart. Phys. 30 (2008) arXiv:0804.4827

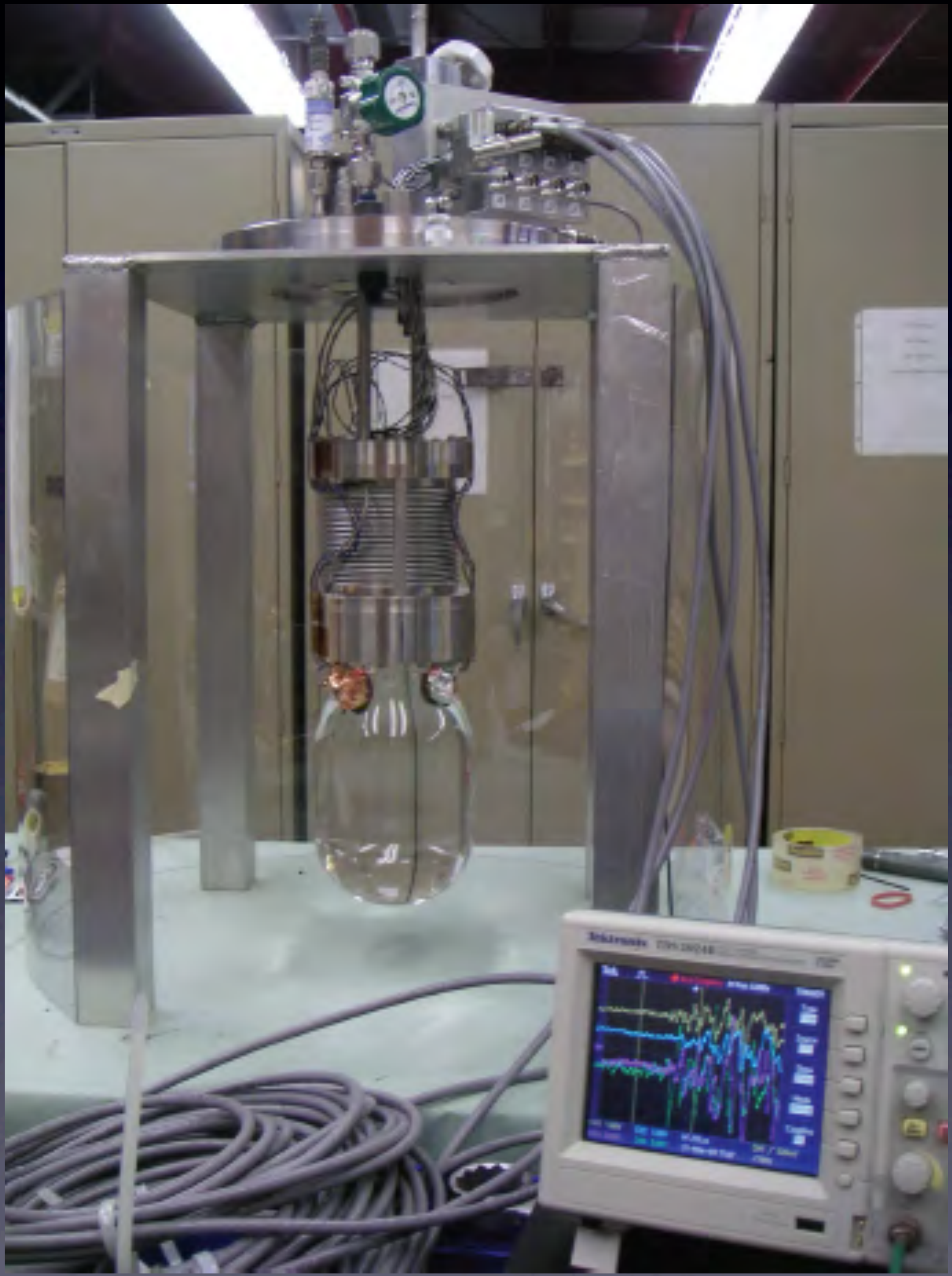
DM-TPC Status

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



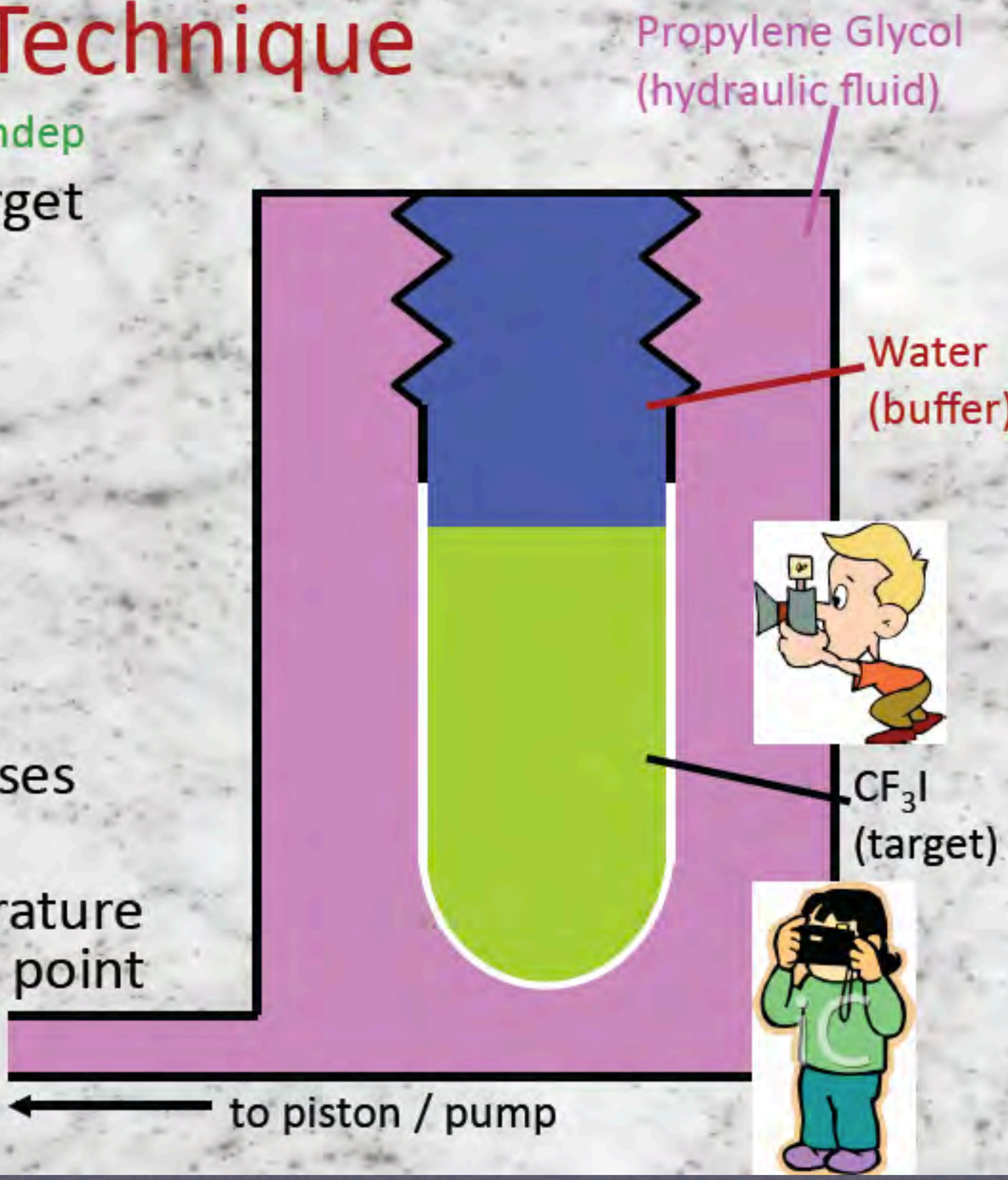
COUPP

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

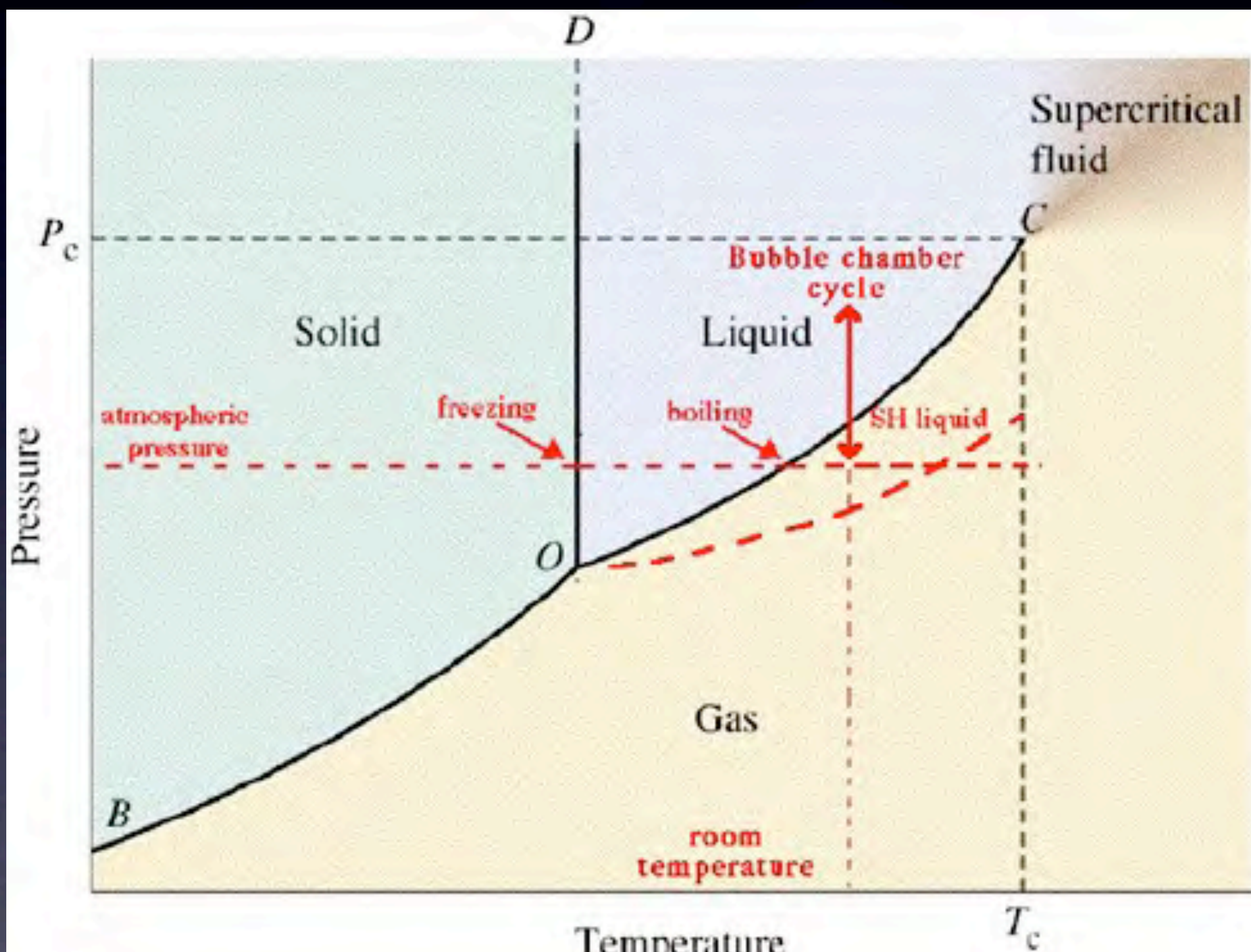


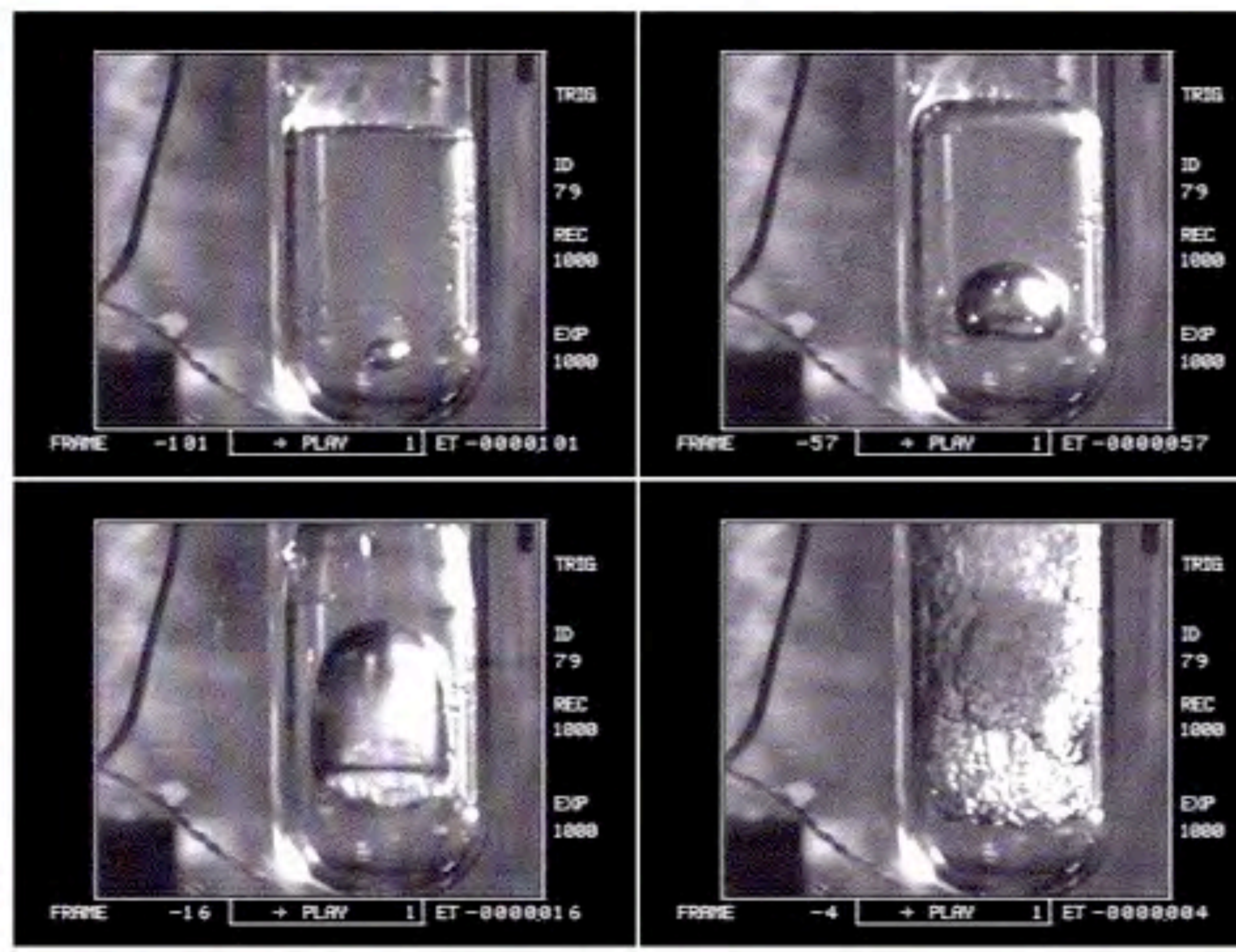
Technique

- Superheated CF_3I target (Spin-indep: I; Spin-dep: F)
- Particle interactions nucleate bubbles
- Cameras capture stereoscopic bubble images
- Chamber recompresses after each event
- Pressure and temperature define the operating point



Bubbles!





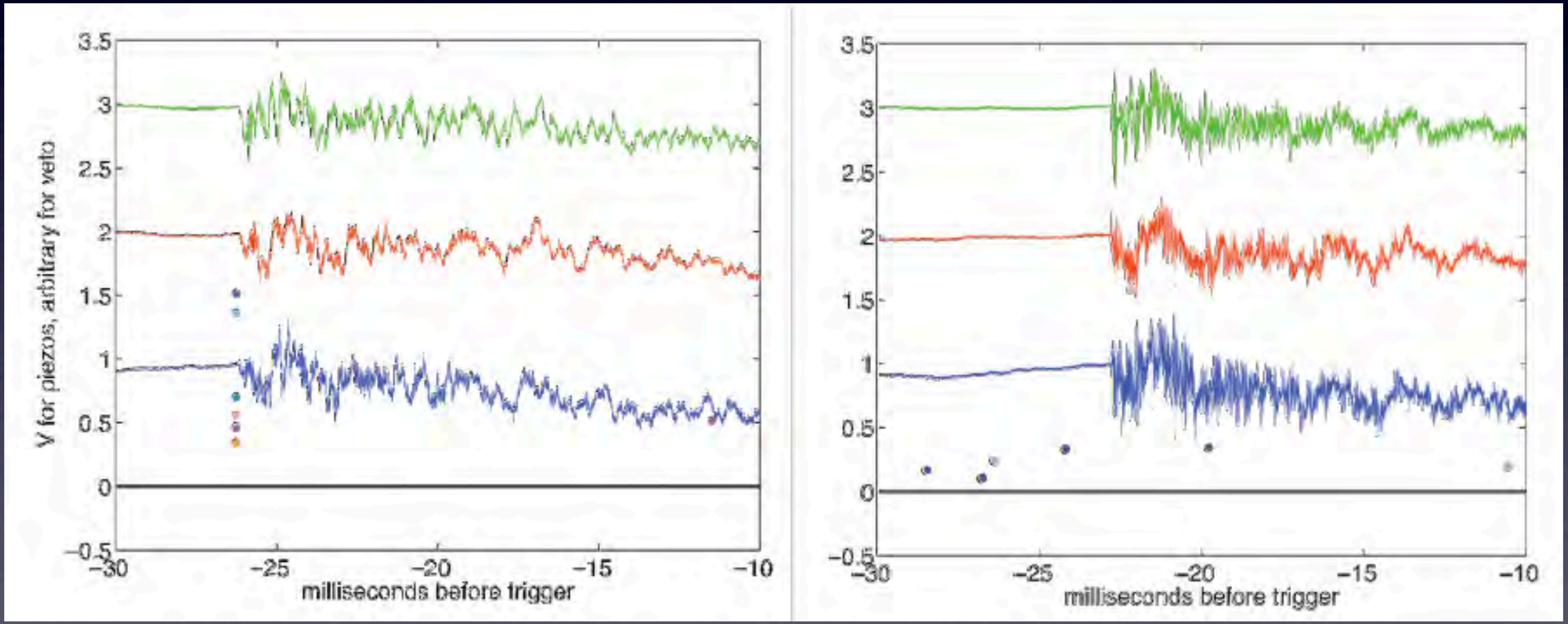
neutrton

alpha

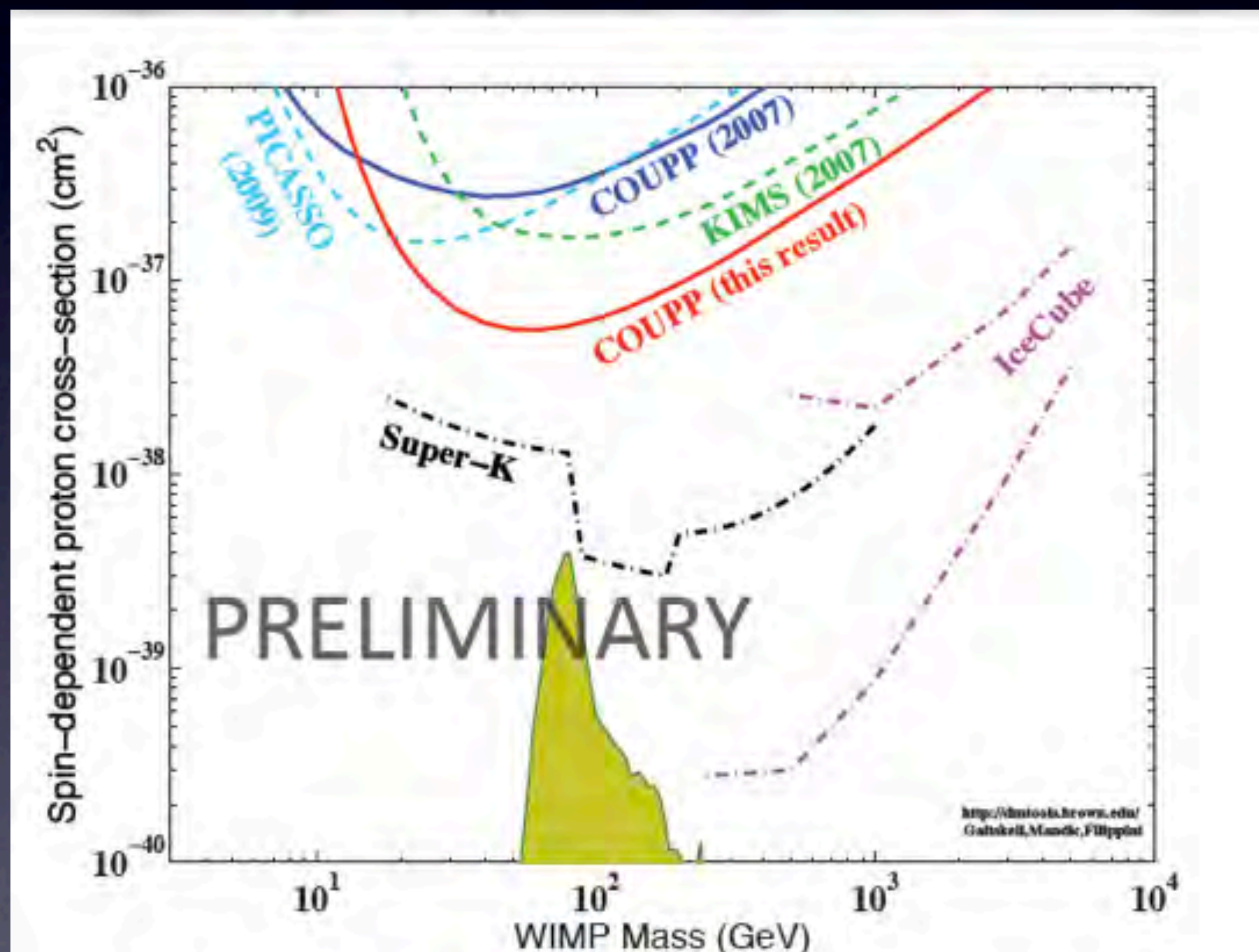
Acoustic Discrimination Between Neturons and Alphas

Neutron

Alpha Particle



COUPP Spin-Dependent Limit

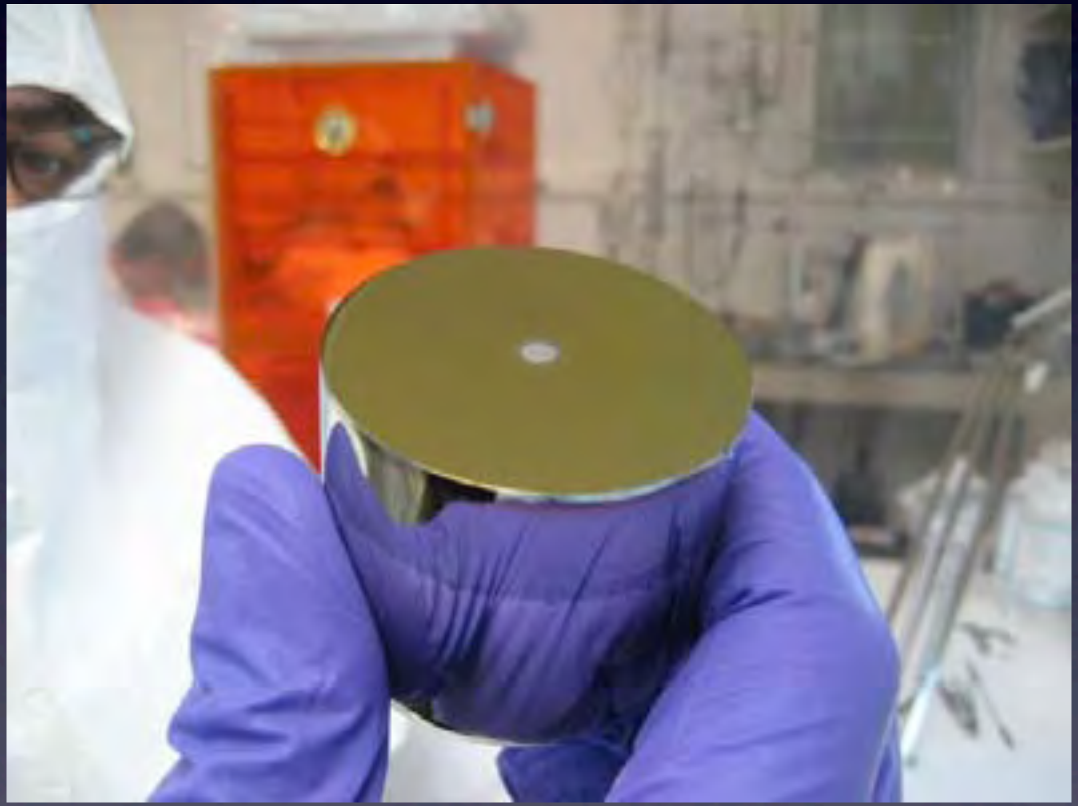


COUPP 60 kg

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

CoGeNT

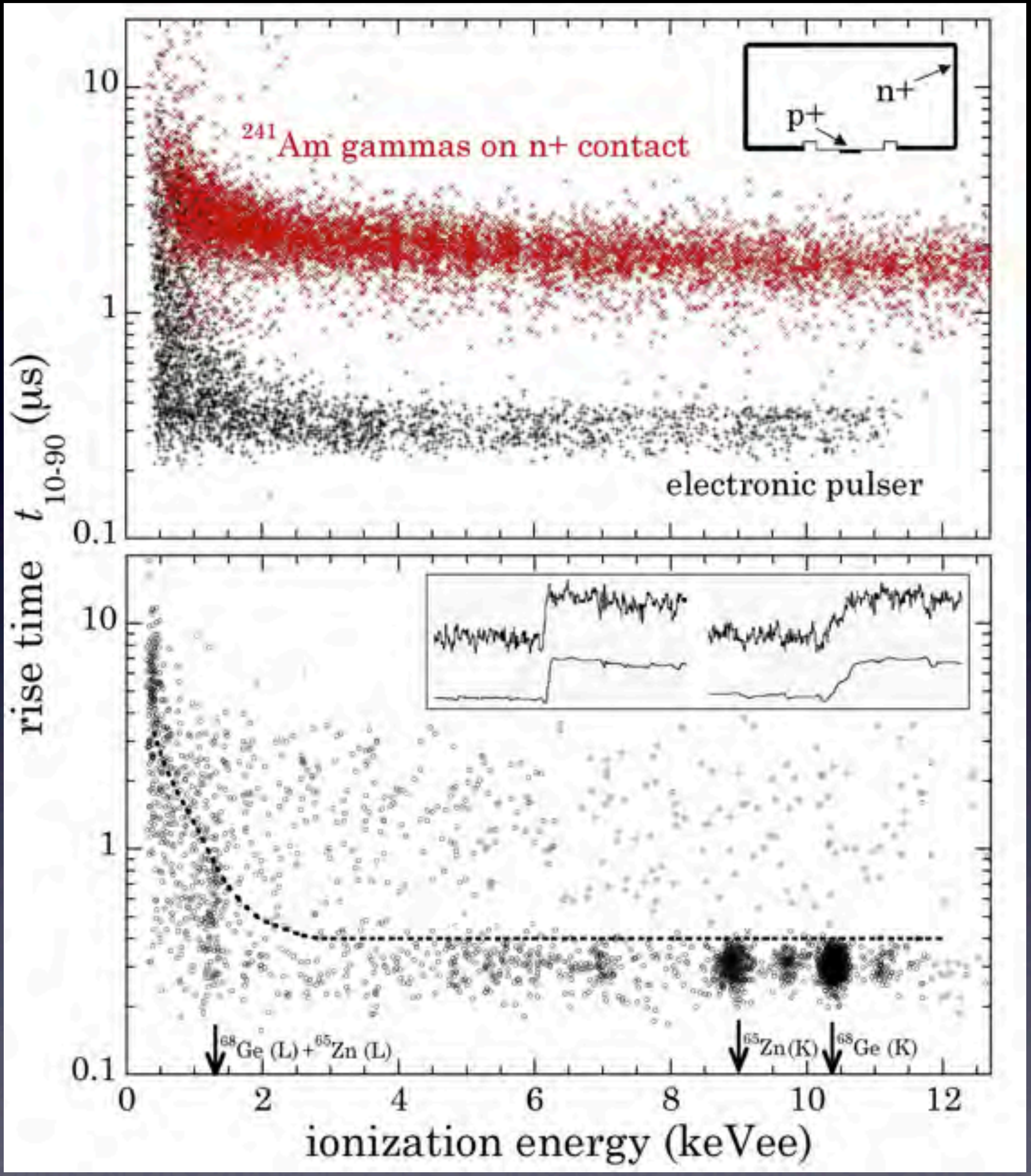
- P-type Point Contact Germanium Detector
- 440 g detector
- Low 0.4 keVee threshold
- Operating in Soudan Mine in Minnesota



arXiv: 1002.4703v2

Surface Event Discrimination

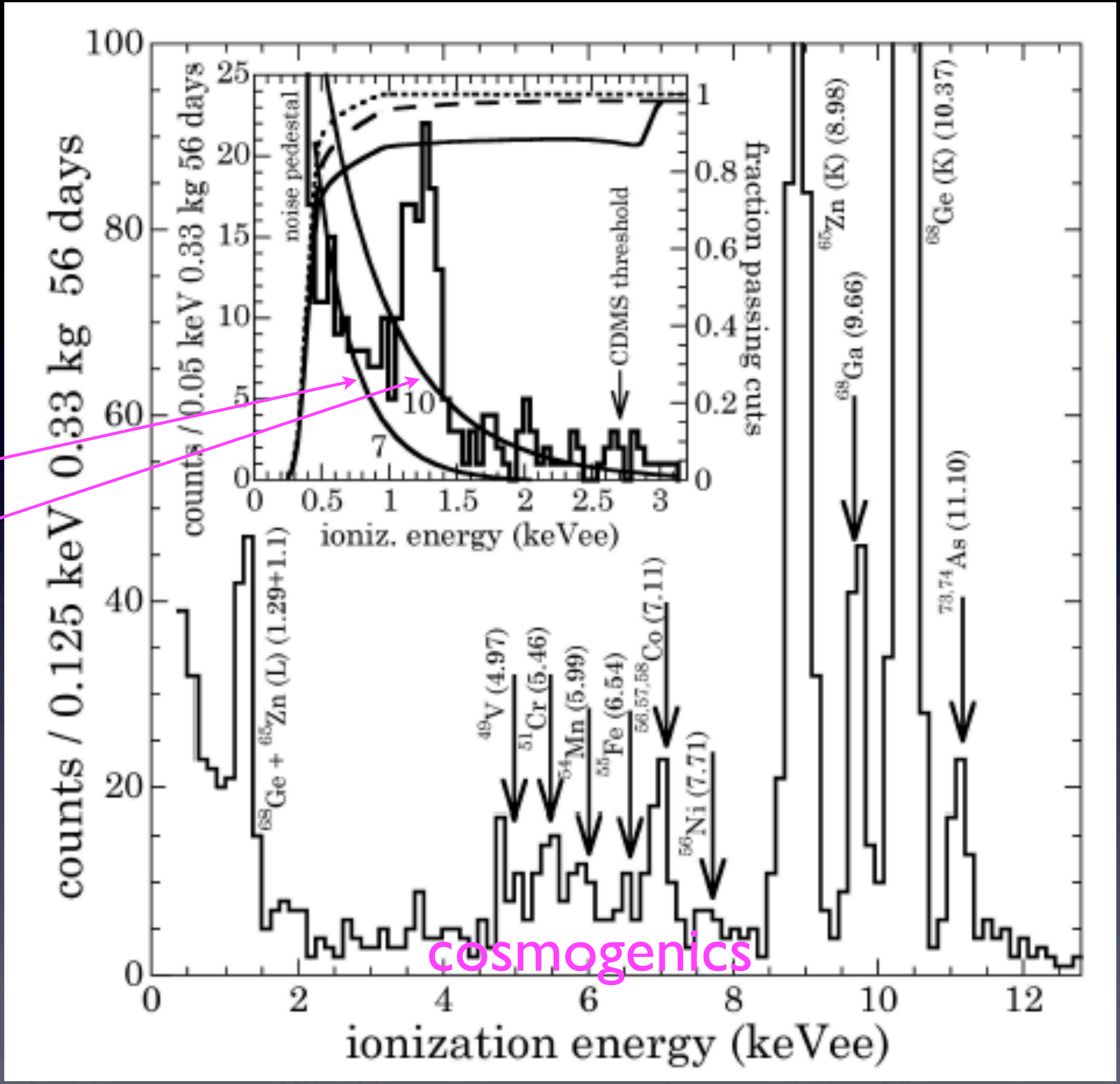
- Slower Risetime of pulses on the n+ surface allows a cut to be placed on DM search data (lower)
- Inset shows fast and slow risetime pulses



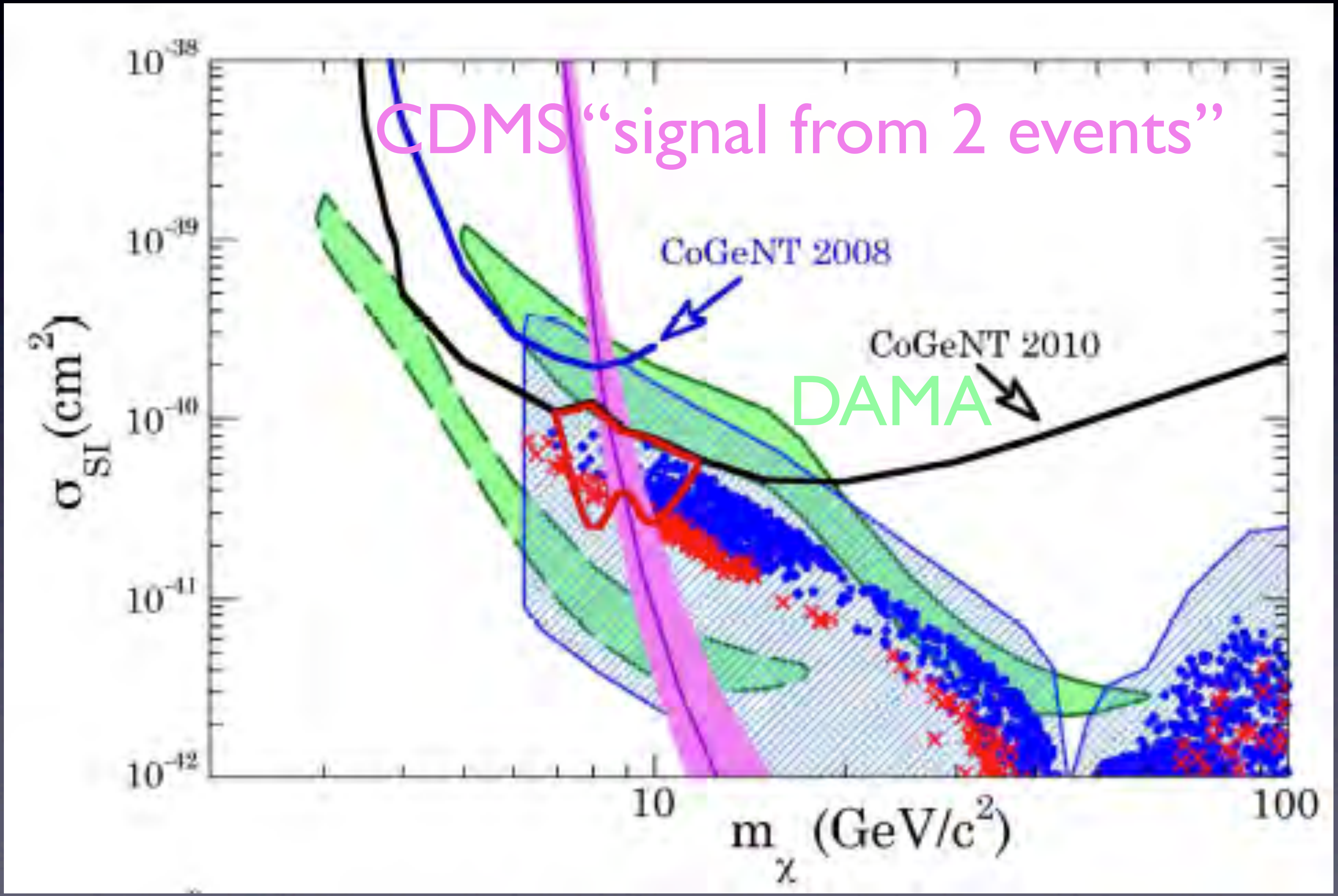
WIMP Signal?

7 GeV WIMP

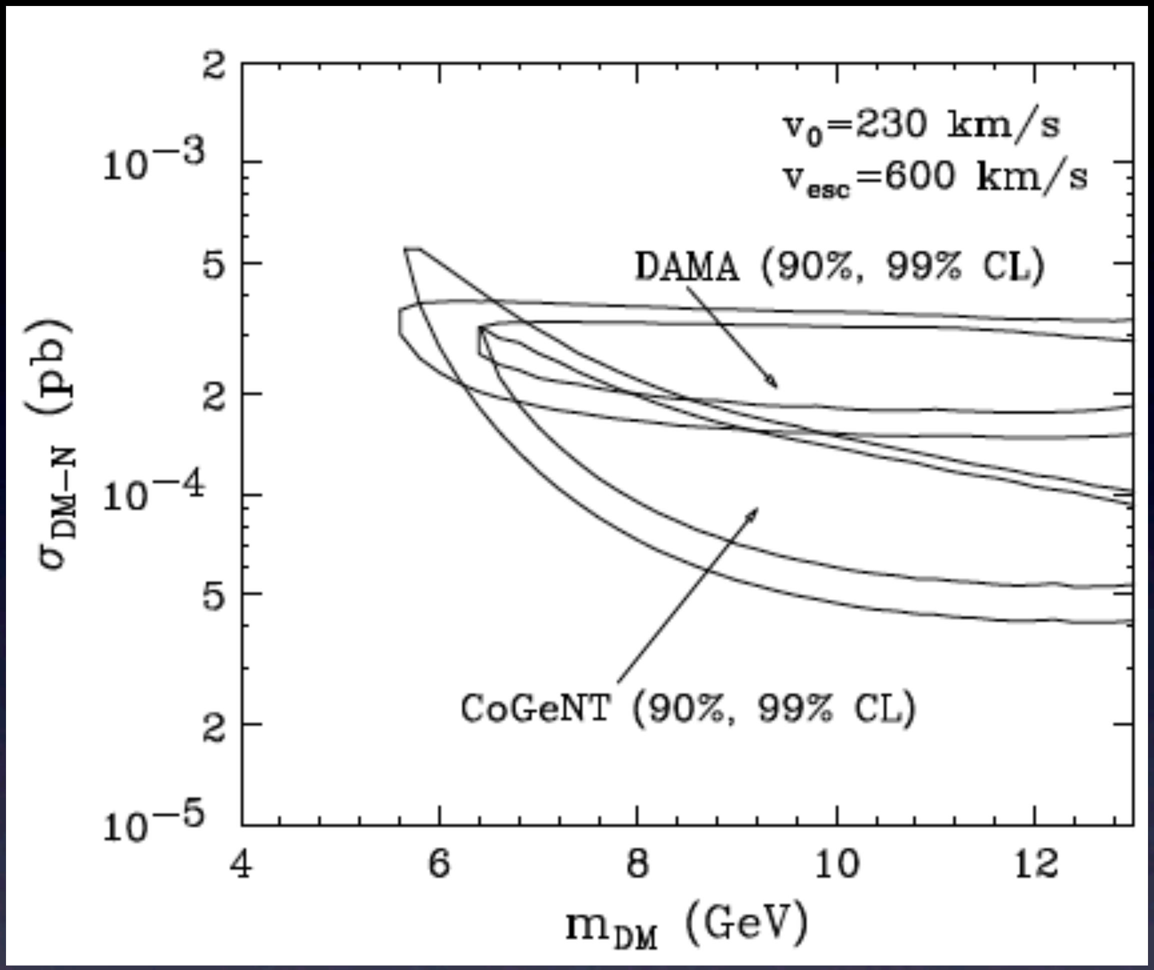
10 GeV WIMP

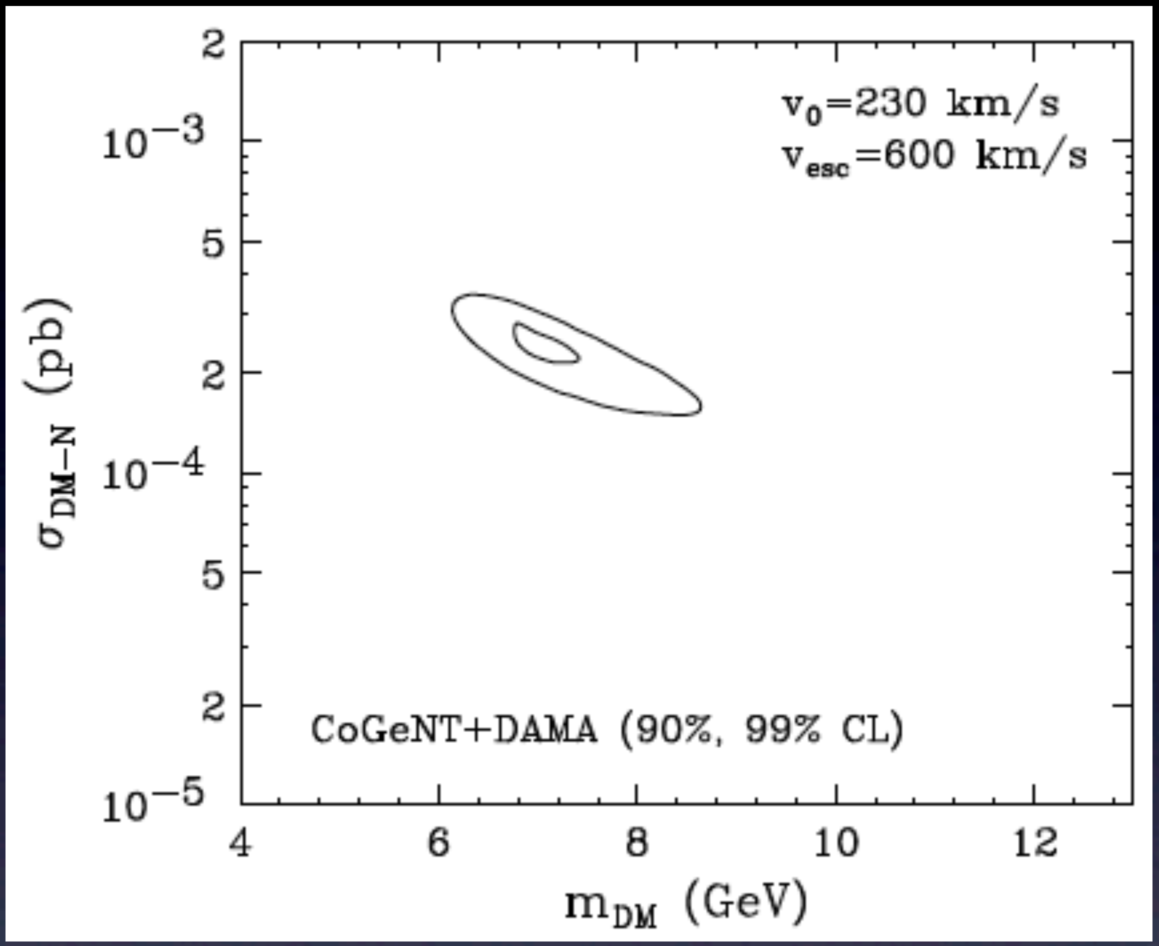


CoGeNT Signal Region



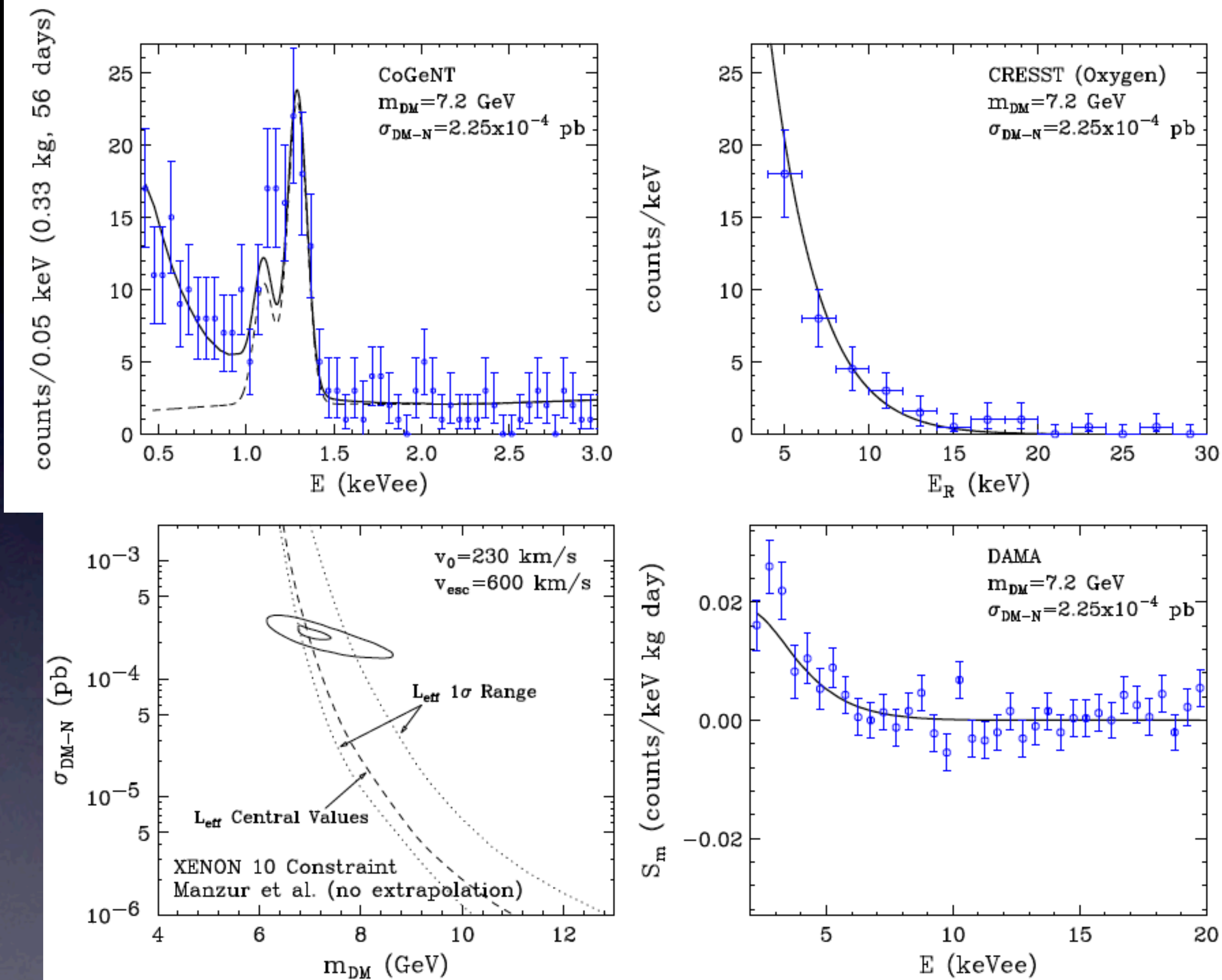
Interpretations...





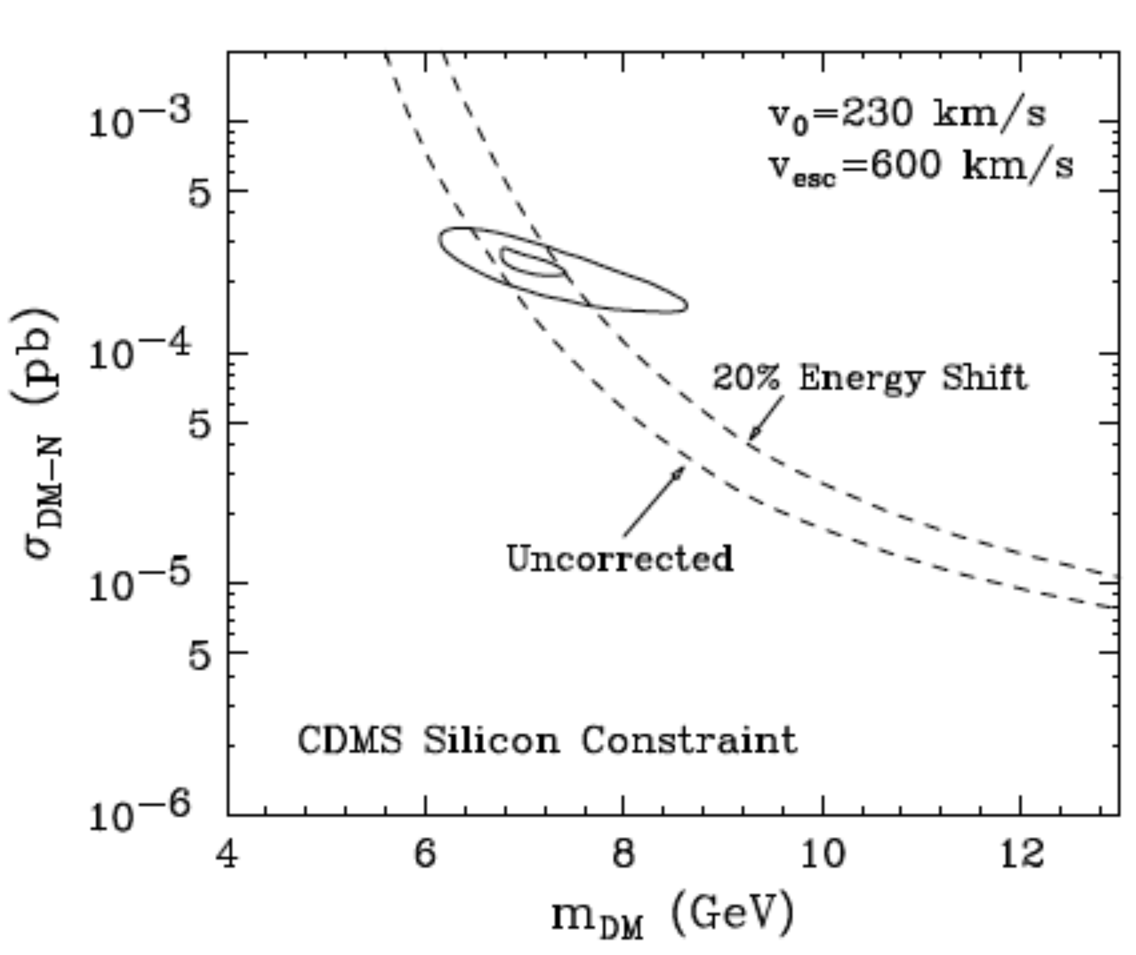
- Hooper et. al give a possible WIMP candidate consistent with CoGeNT, DAMA, CRESST, and the null results by XENON and CDMS.

arXiv:1007.1005v2


CoGeNT
m_{DM}=7.2 GeV
σ_{DM-N}=2.25x10^{-4} pb
counts/0.05 keV (0.33 kg, 56 days)
E (keVee)
CRESST (Oxygen)
m_{DM}=7.2 GeV
σ_{DM-N}=2.25x10^{-4} pb
counts/keV
E_R (keV)
v_0=230 km/s
v_{esc}=600 km/s
L_{eff} 1σ Range
L_{eff} Central Values
XENON 10 Constraint
Manzur et al. (no extrapolation)
σ_{DM-N} (pb)
m_{DM} (GeV)
DAMA
m_{DM}=7.2 GeV
σ_{DM-N}=2.25x10^{-4} pb
S_m (counts/keV kg day)
E (keVee)

Should we uncork the Champagne?

- CDMS will report very soon on new Si low-threshold limits…
- Stay tuned…

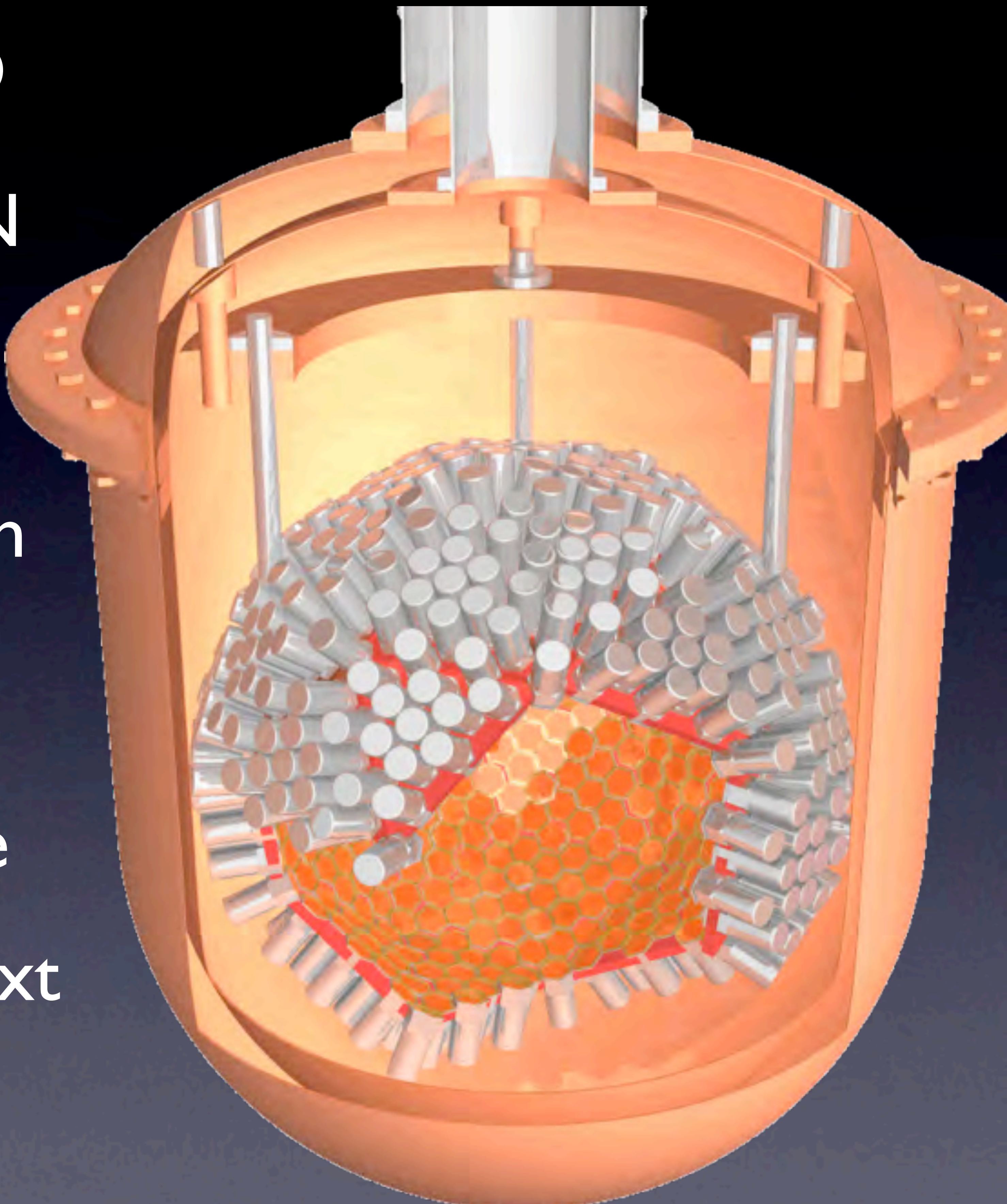


Liquid Noble Detectors

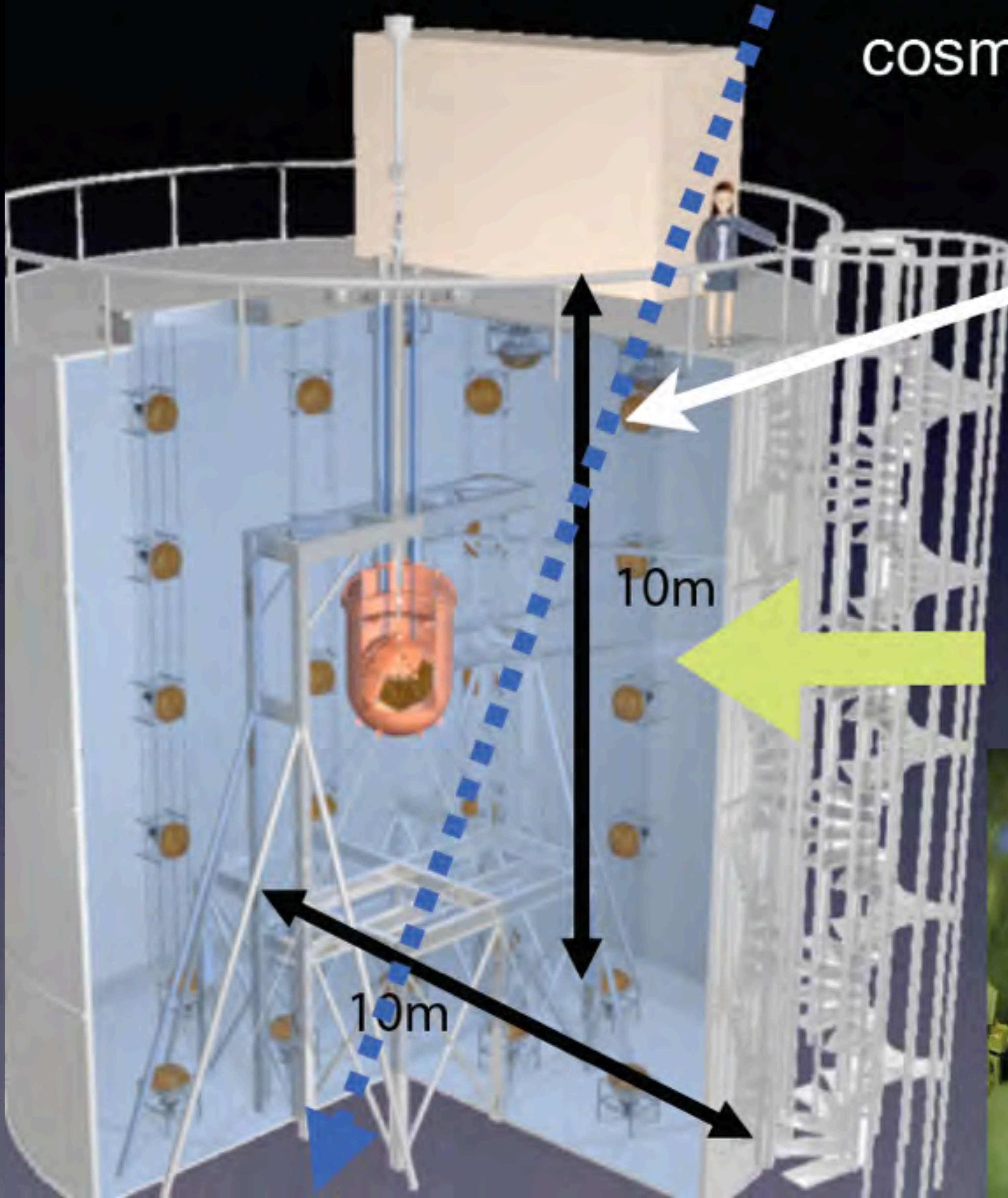
- Time Projection Chambers (already covered)
  - XENON (talk by Christian Weinheimer)
  - LUX (a cousin of XENON)
  - Zeplin (also a Xe TPC)
  - WArP (uses Argon)
- Single Phase Detectors
  - DEAP / CLEAN (Argon and Neon)
  - XMASS (800 kg under construction!)

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

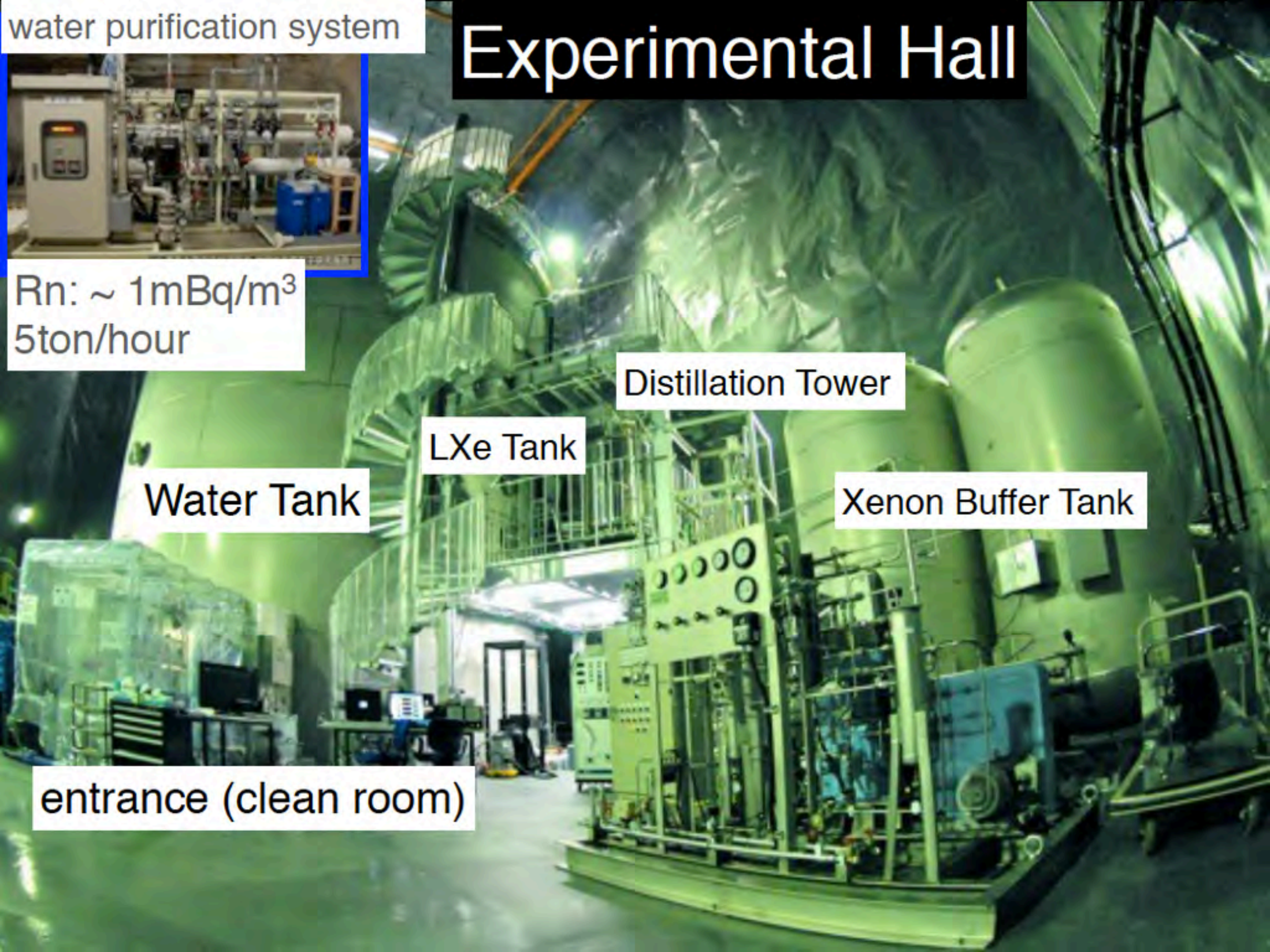


70 PMTs (20 inch) to detect Cerenkov Light (same as SK)

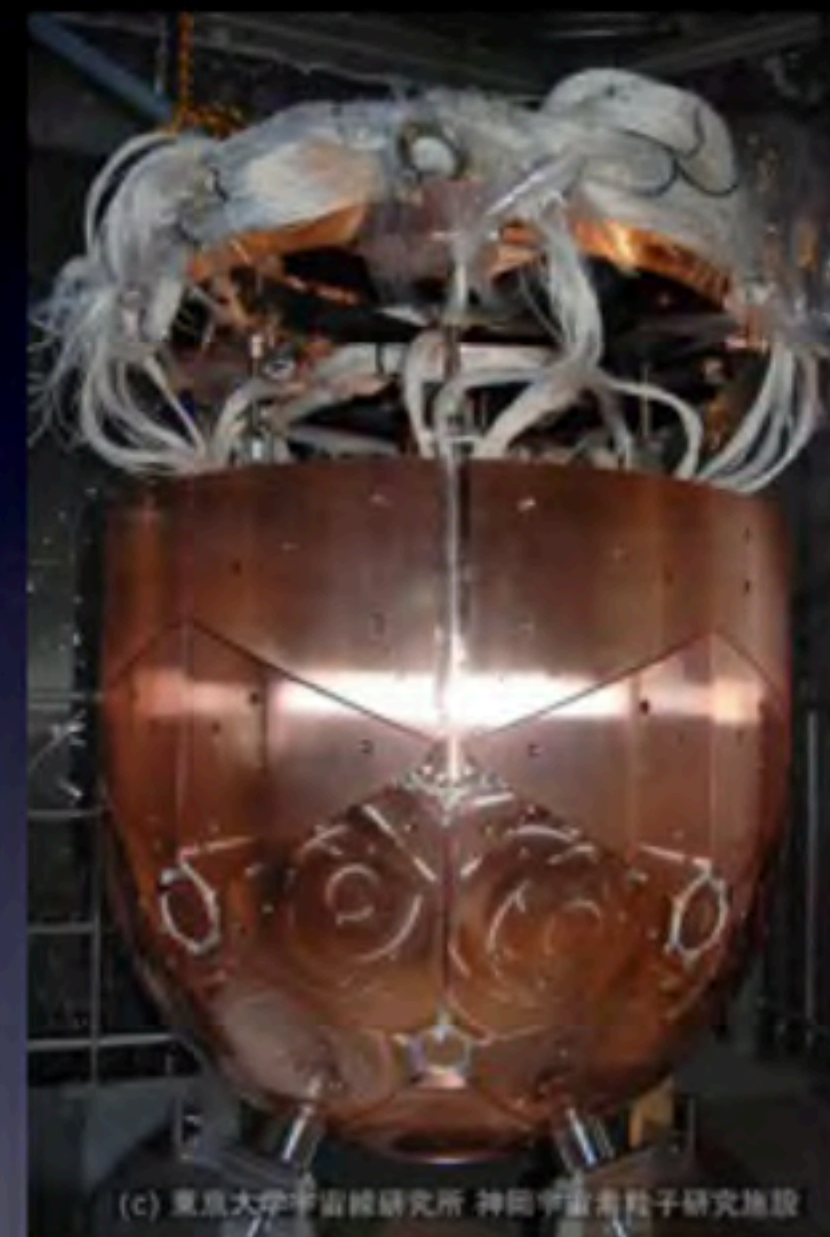
Active shield for muon induced events

Passive shield for γ and neutron from Rock

Experimental Hall



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

- Main Players:
  - CRESST (talk by Josef Jochum)
  - Edelweiss (pictured)
  - CDMS

Outline

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

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

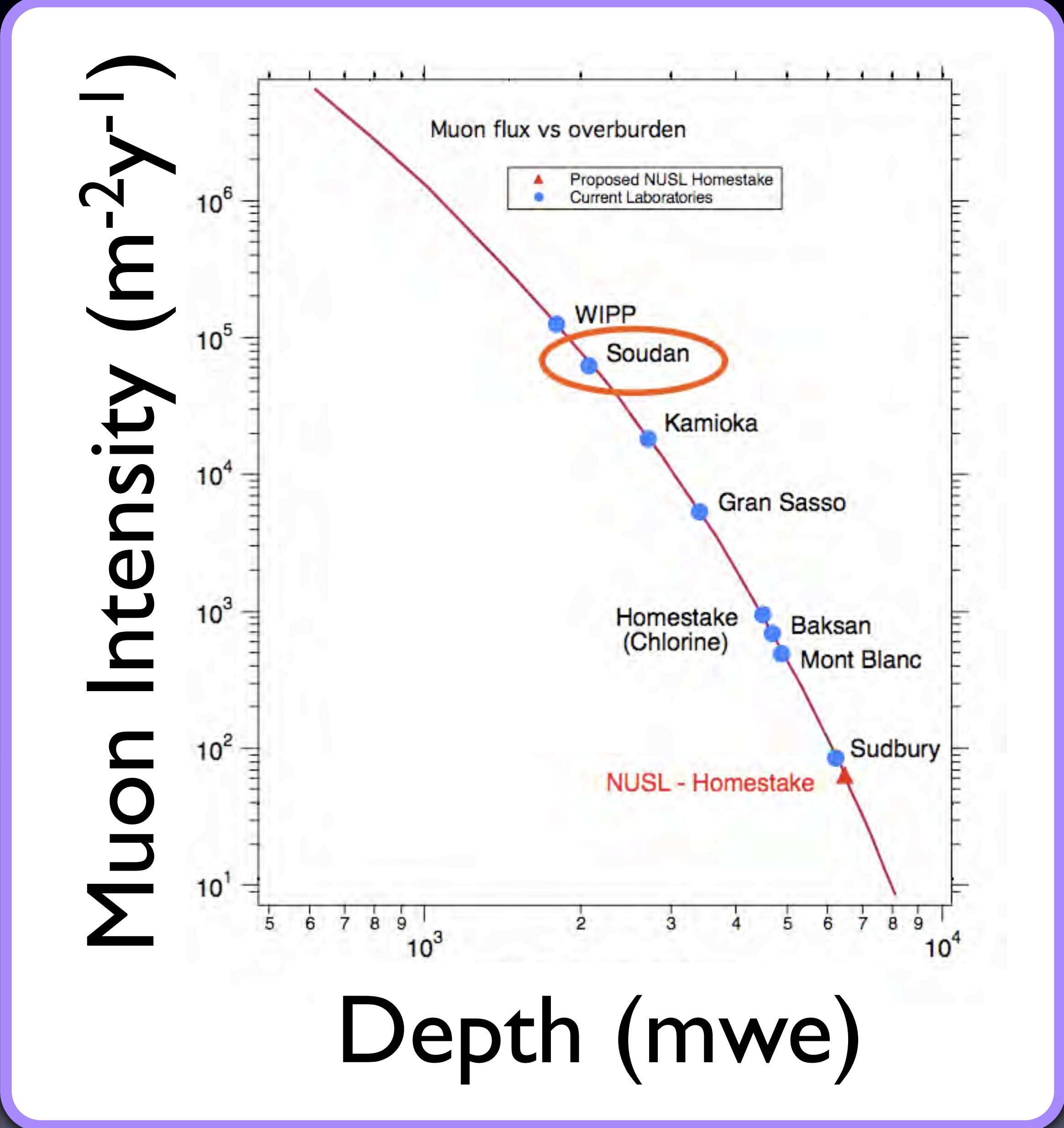
Observation Strategy

1. **Suppress all backgrounds** (factor of millions)
2. **Discriminate between remaining background and desired signal** (make your detector as smart as possible)

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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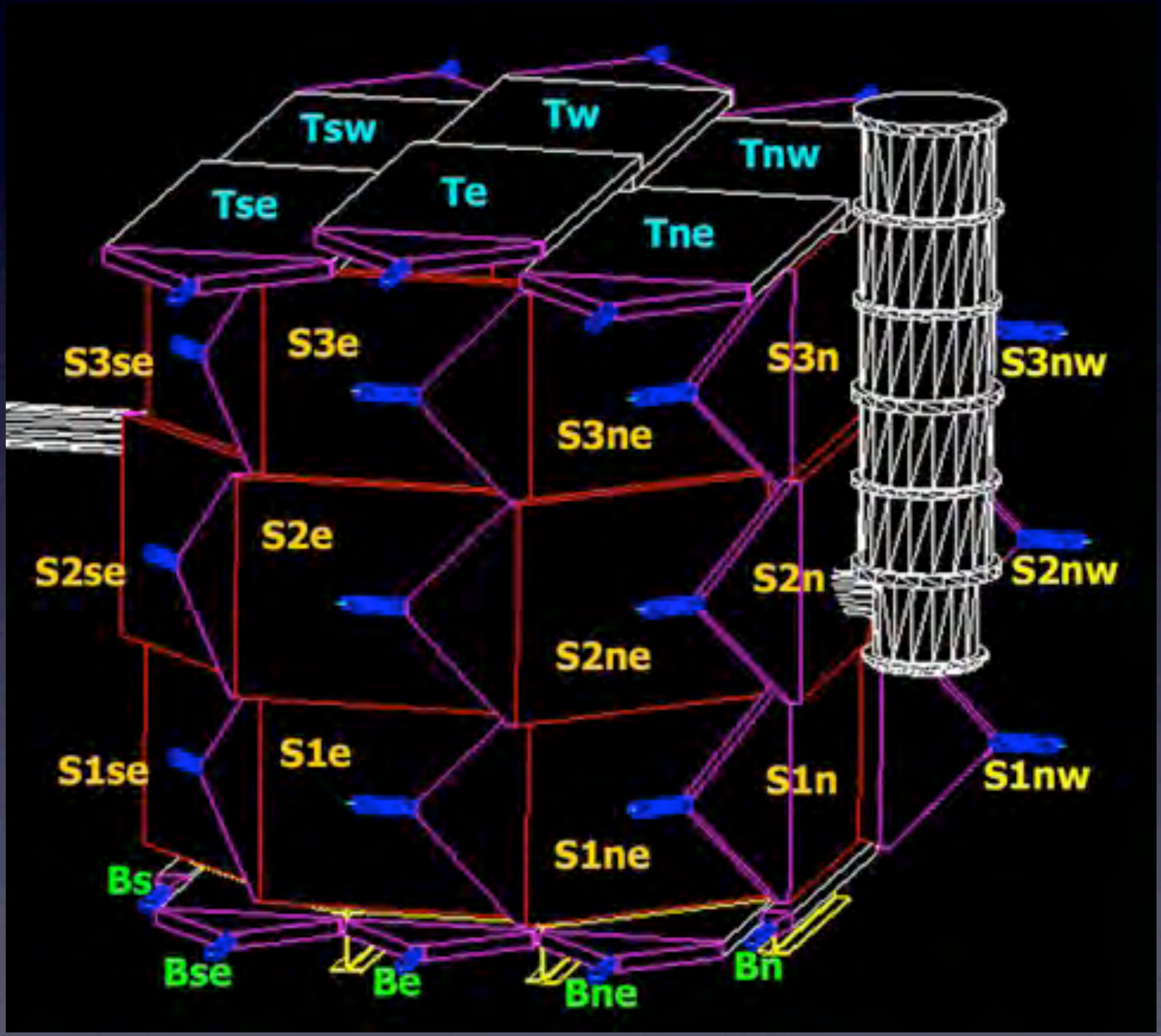

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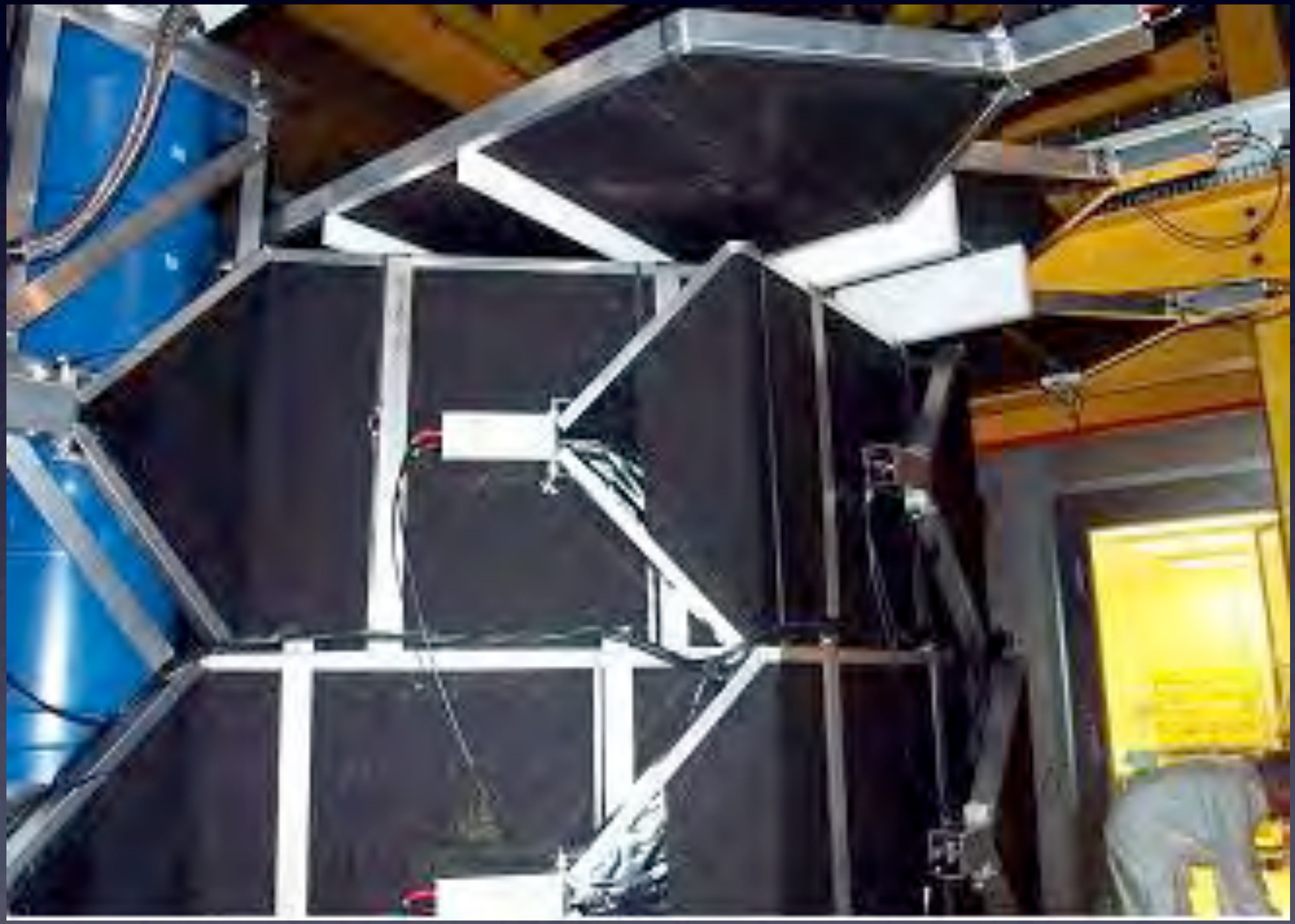

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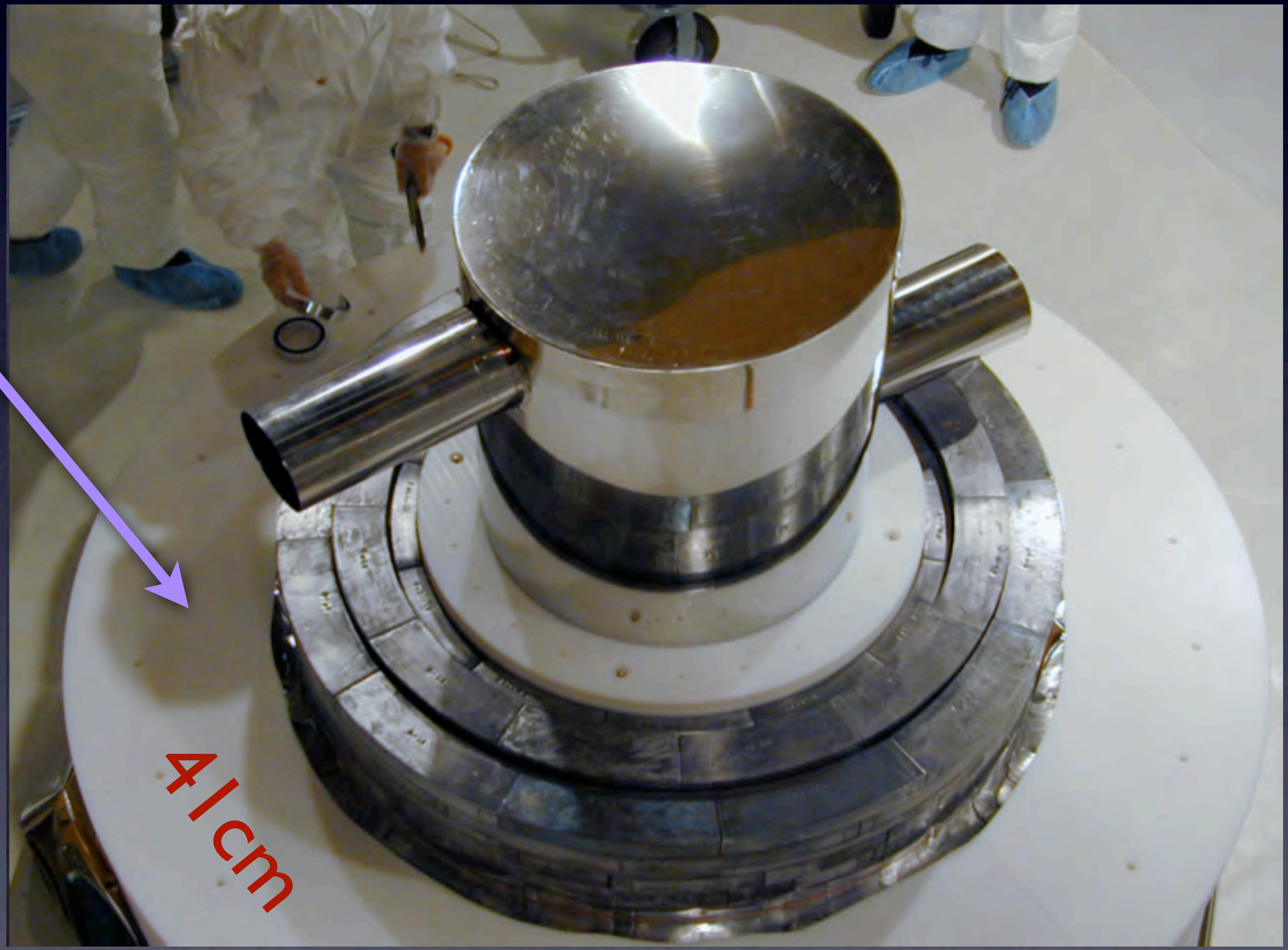

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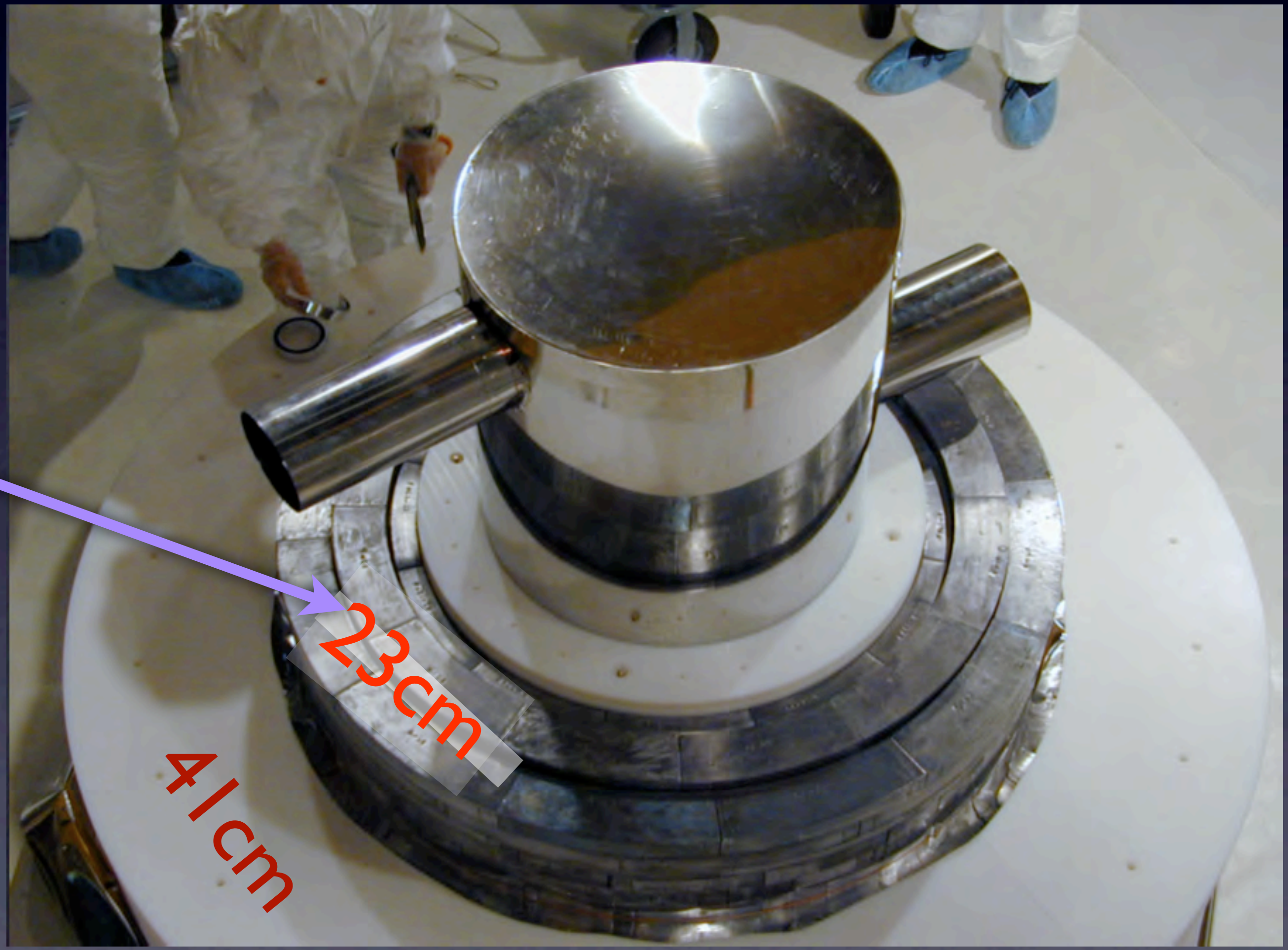

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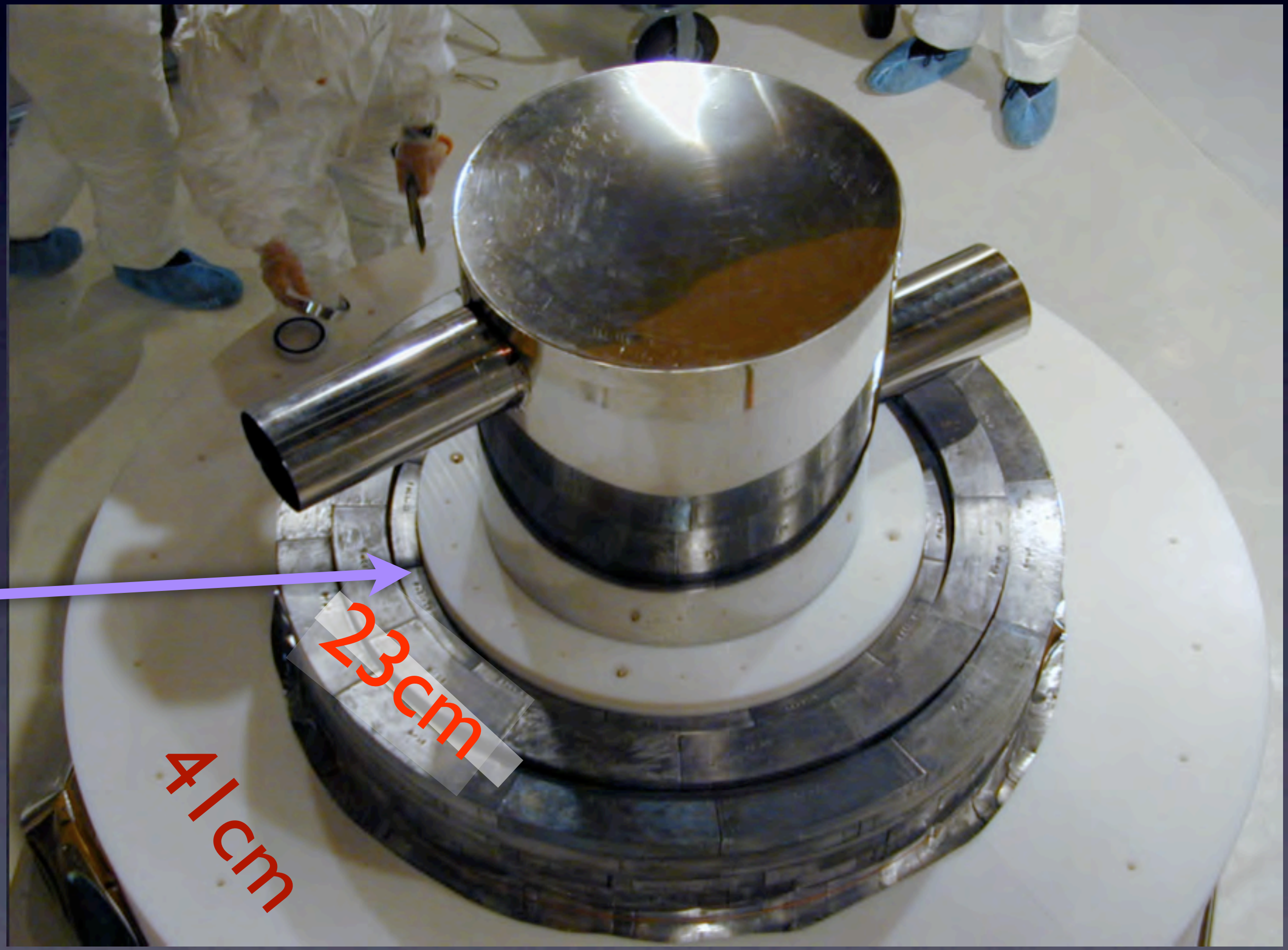

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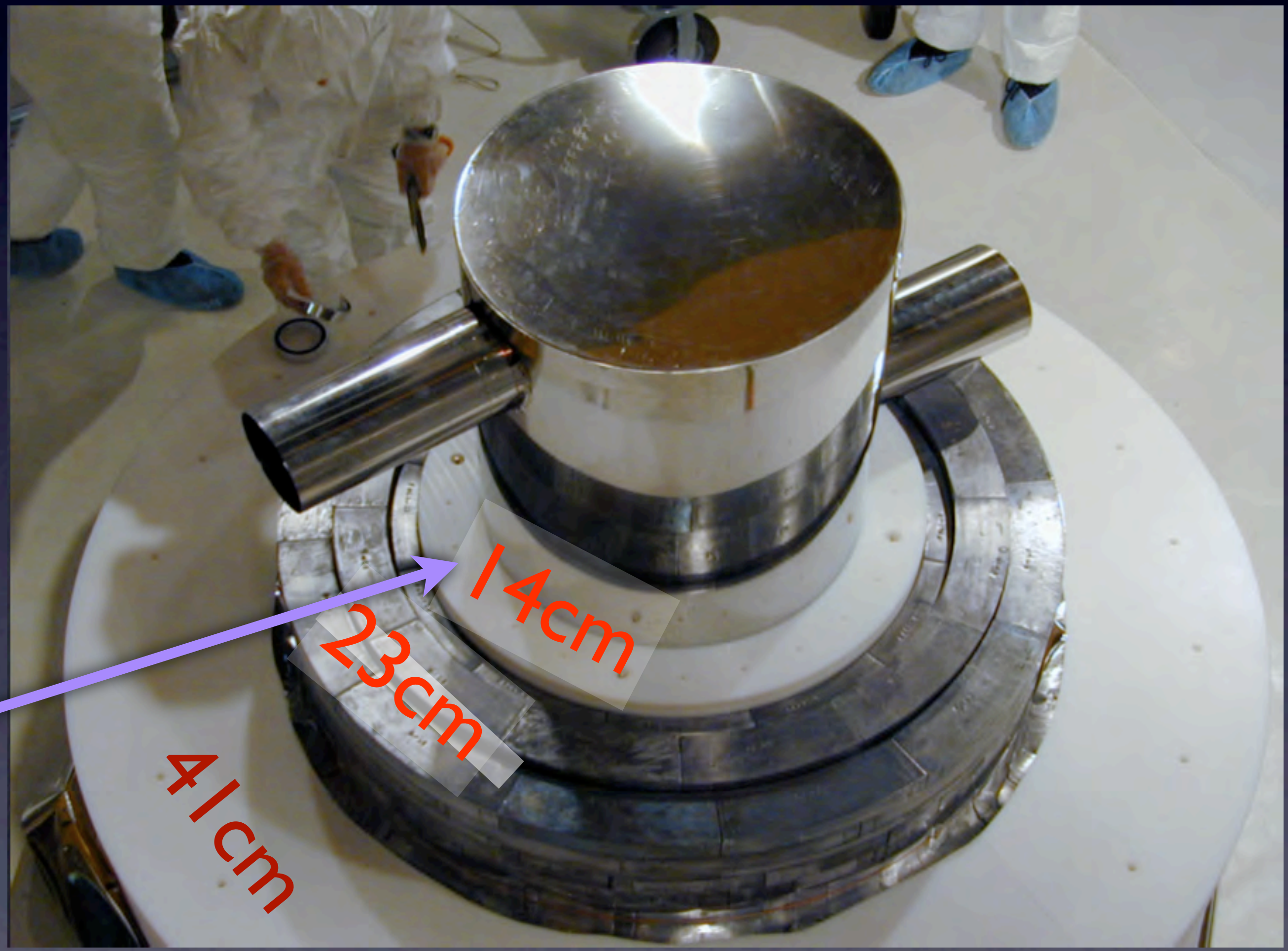

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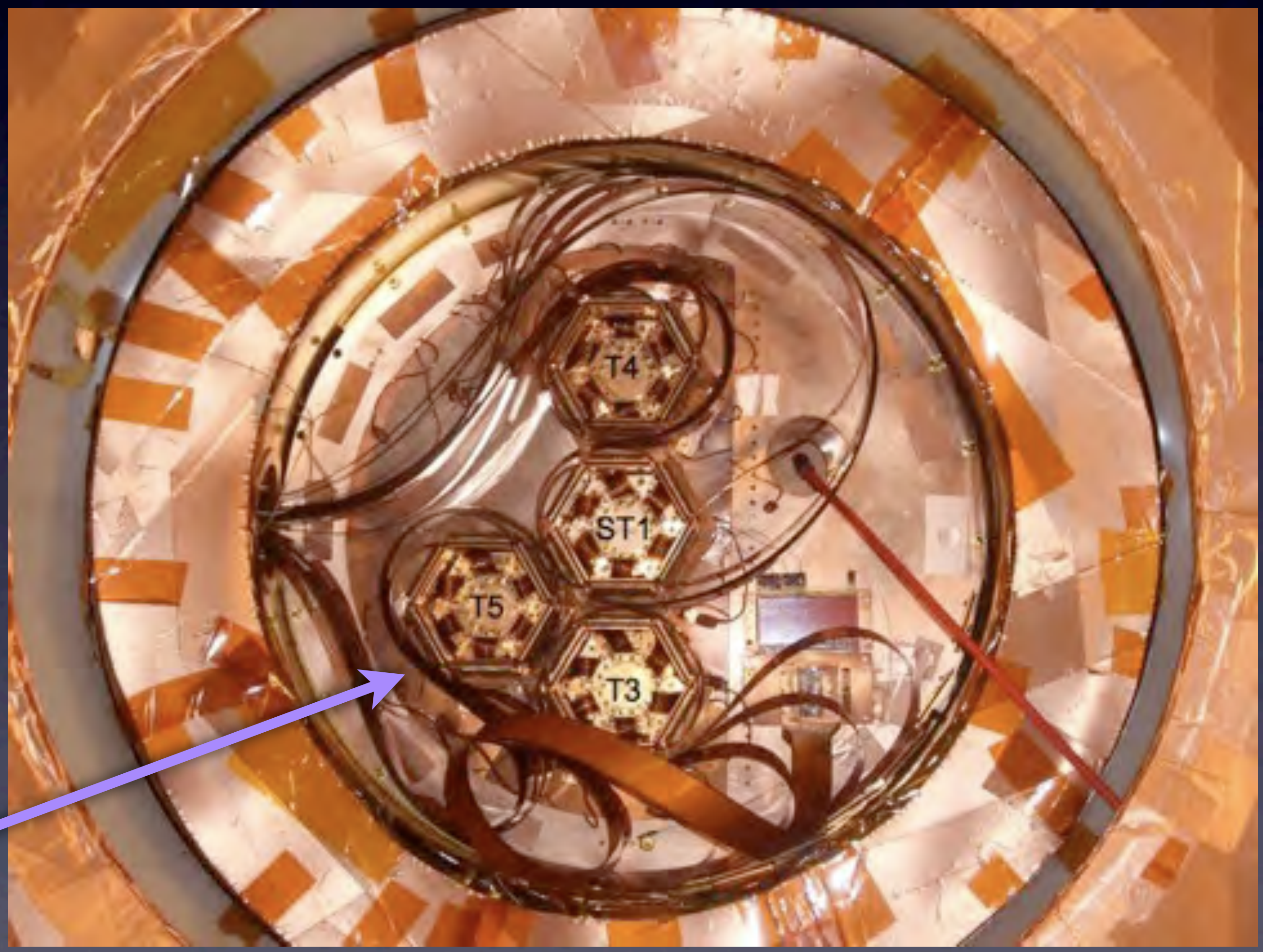

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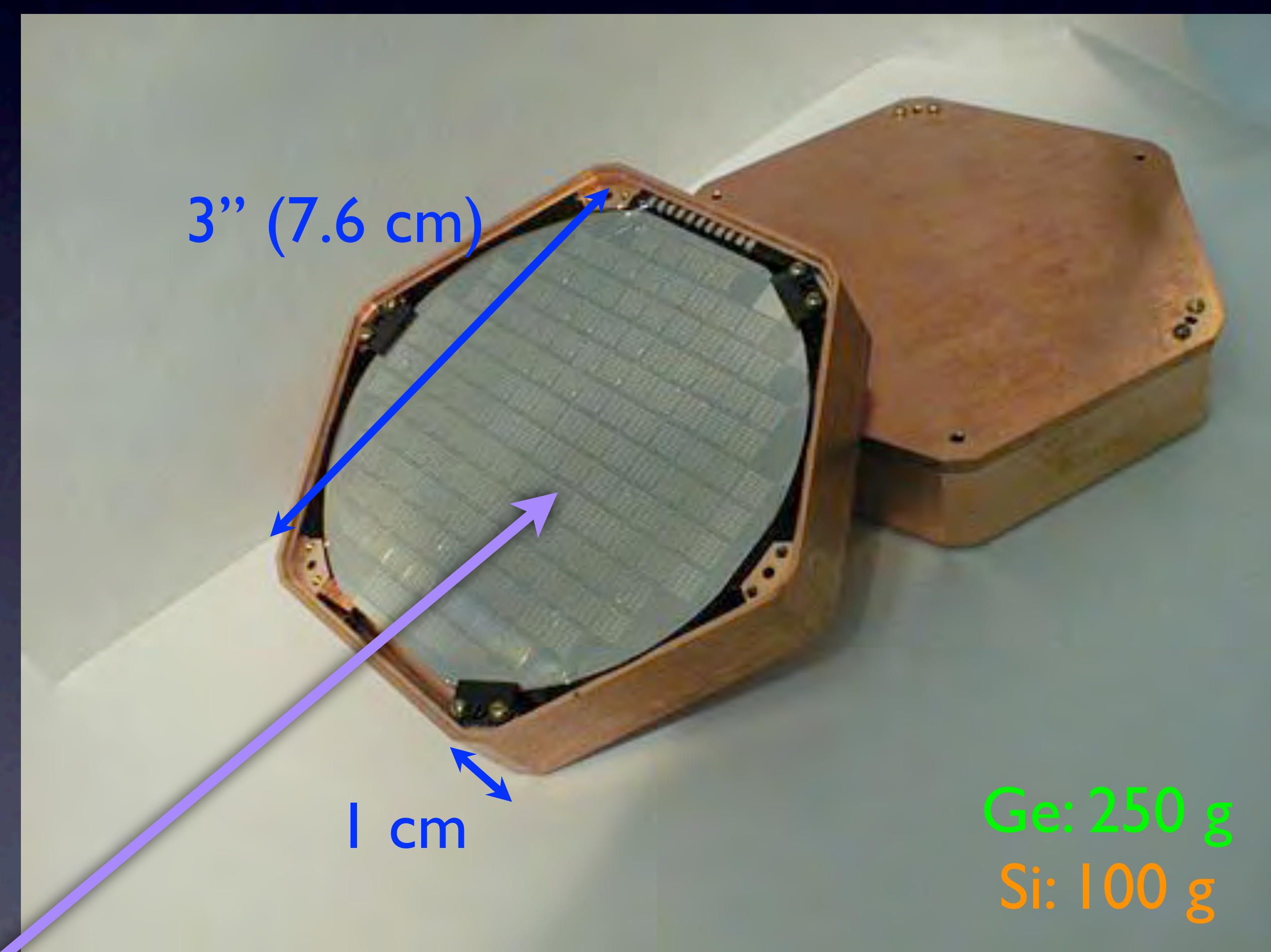

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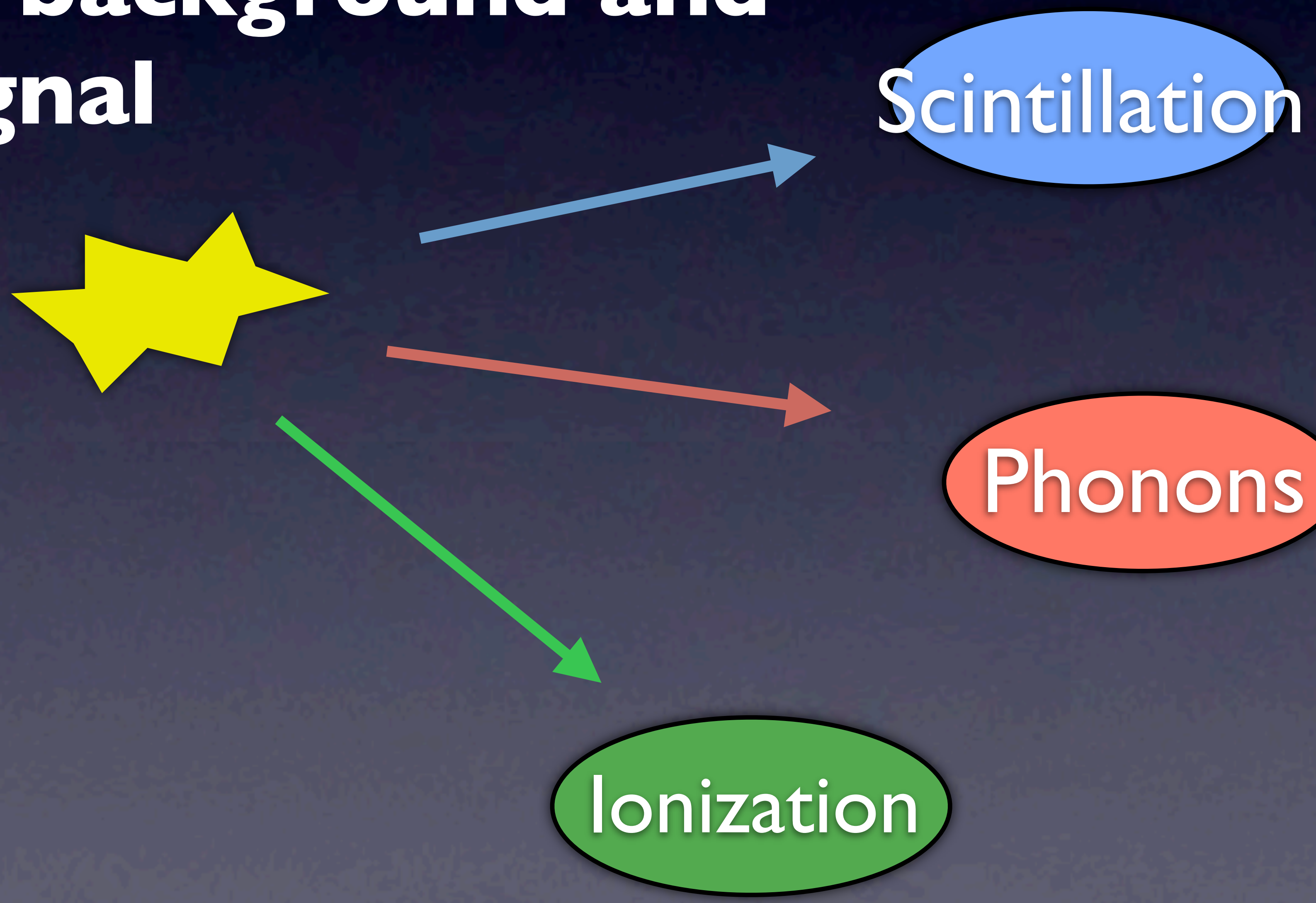
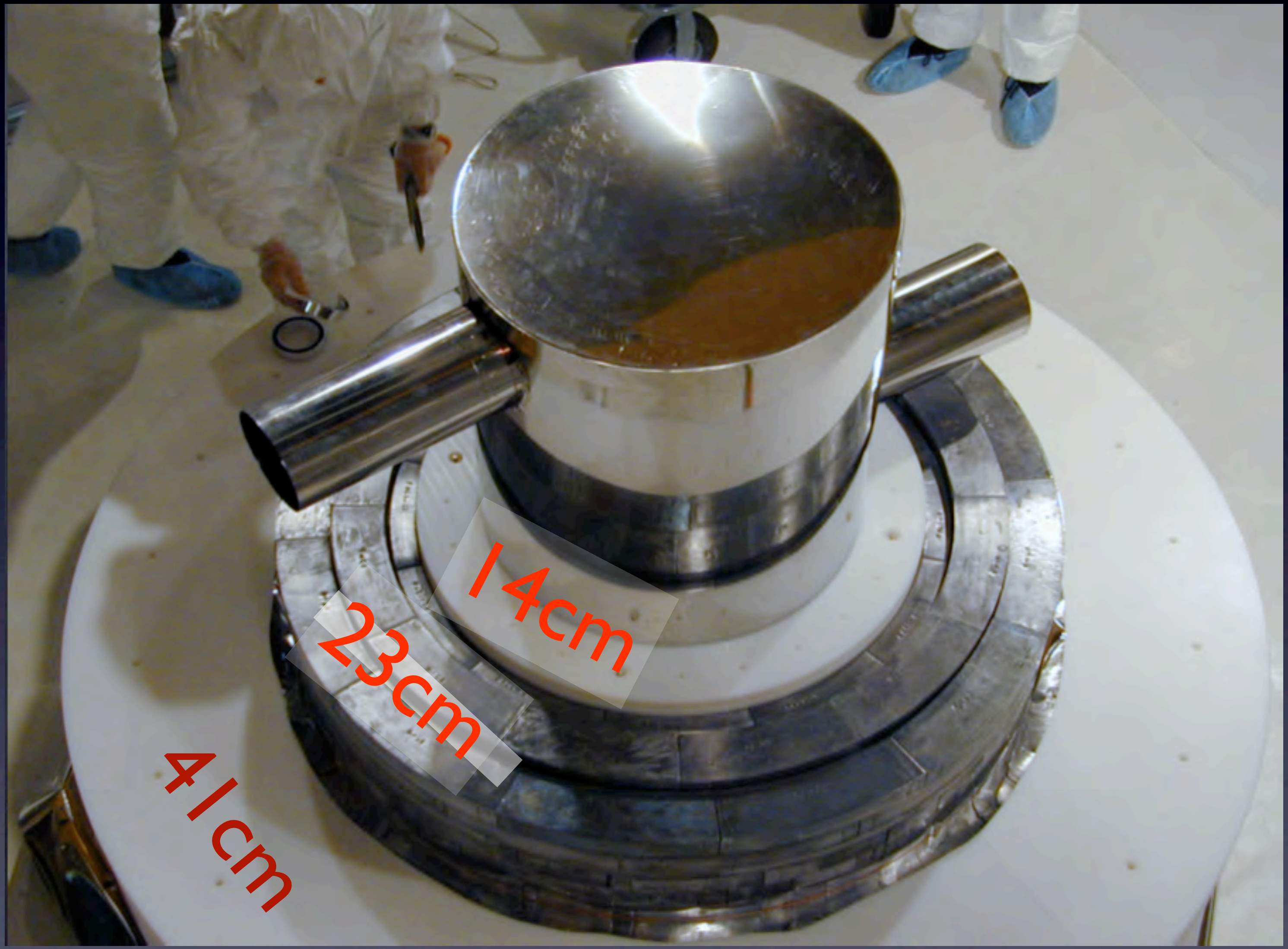


CDMS Detector Array

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

Each Tower holds up to 6 detectors



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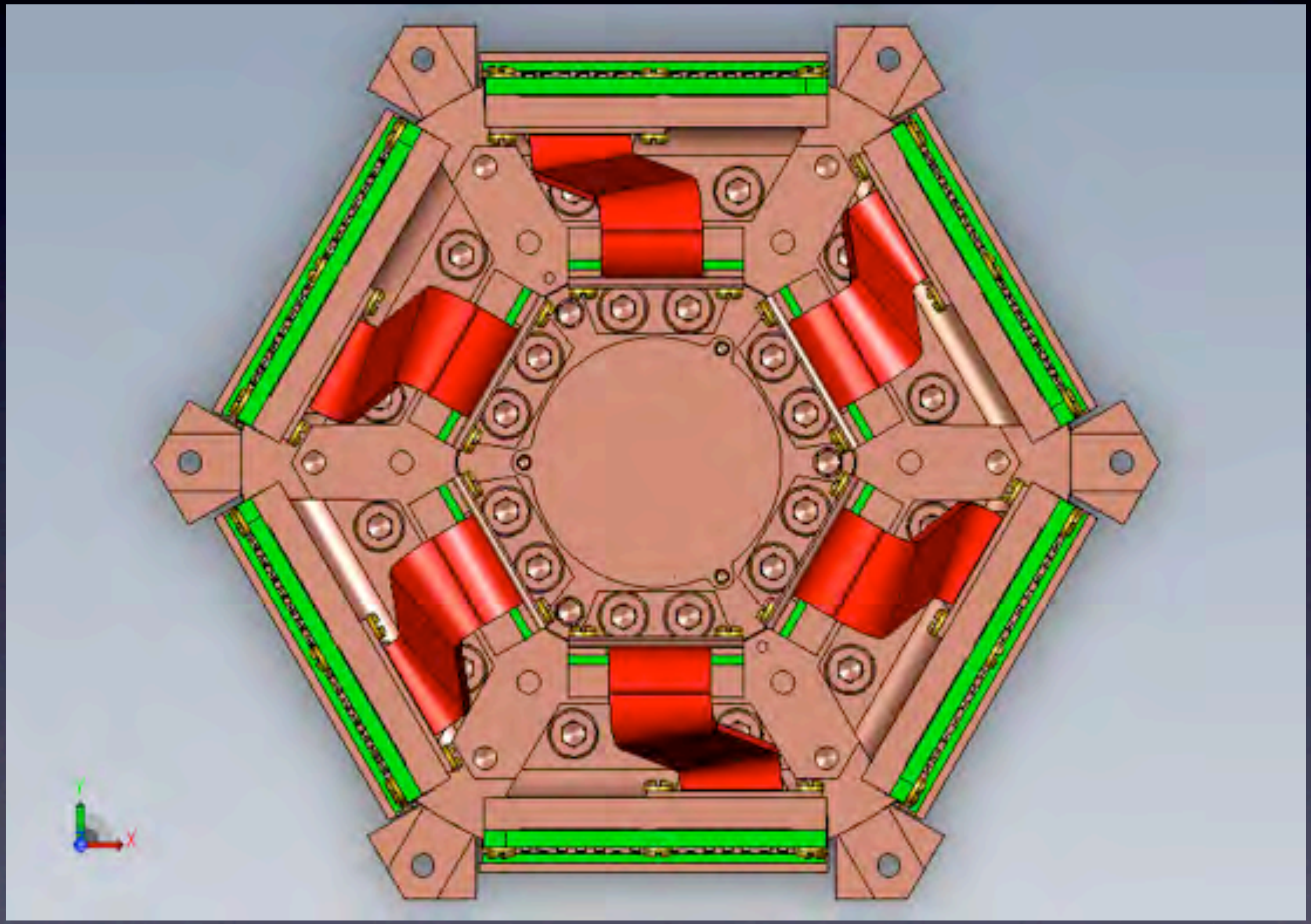

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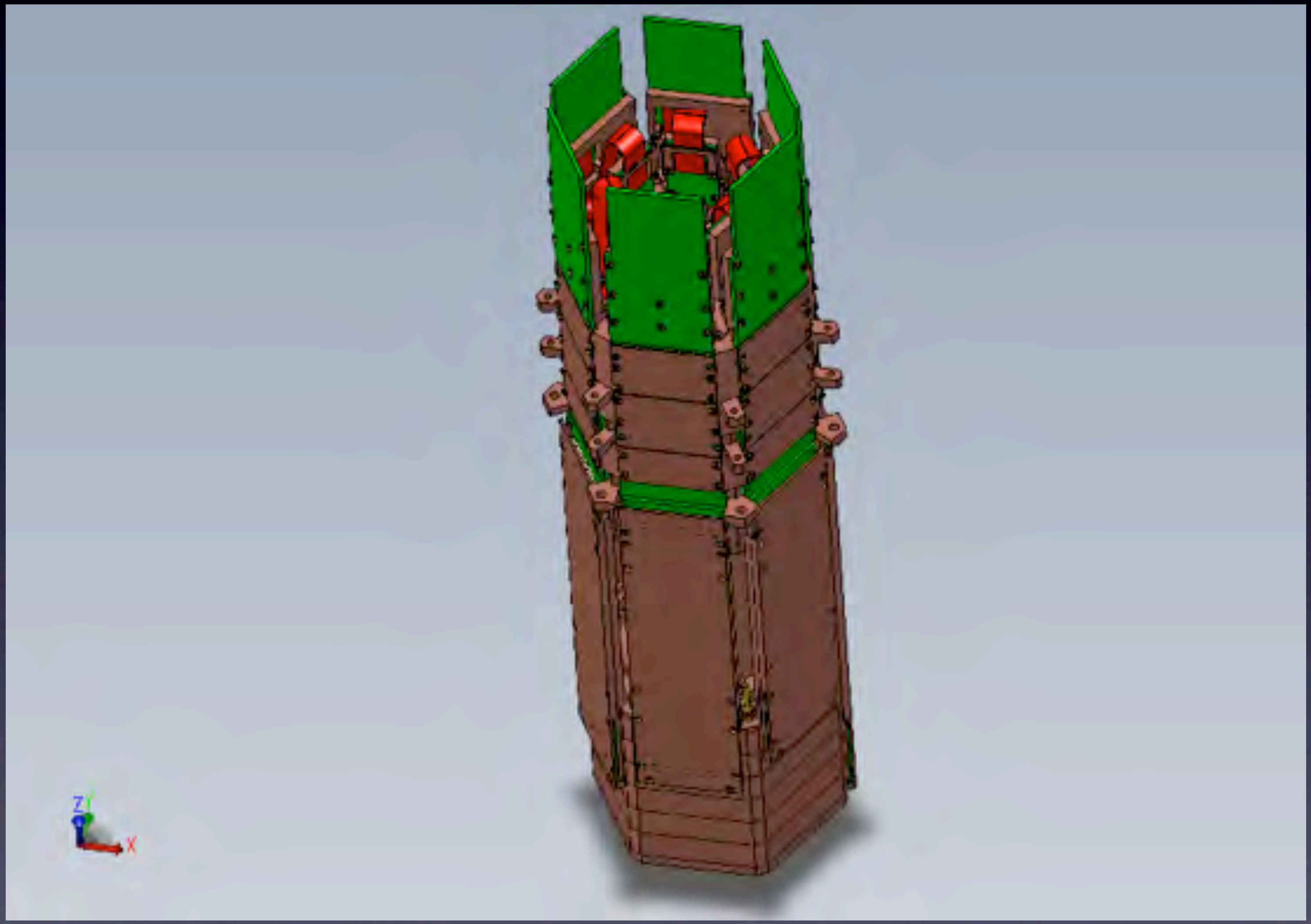

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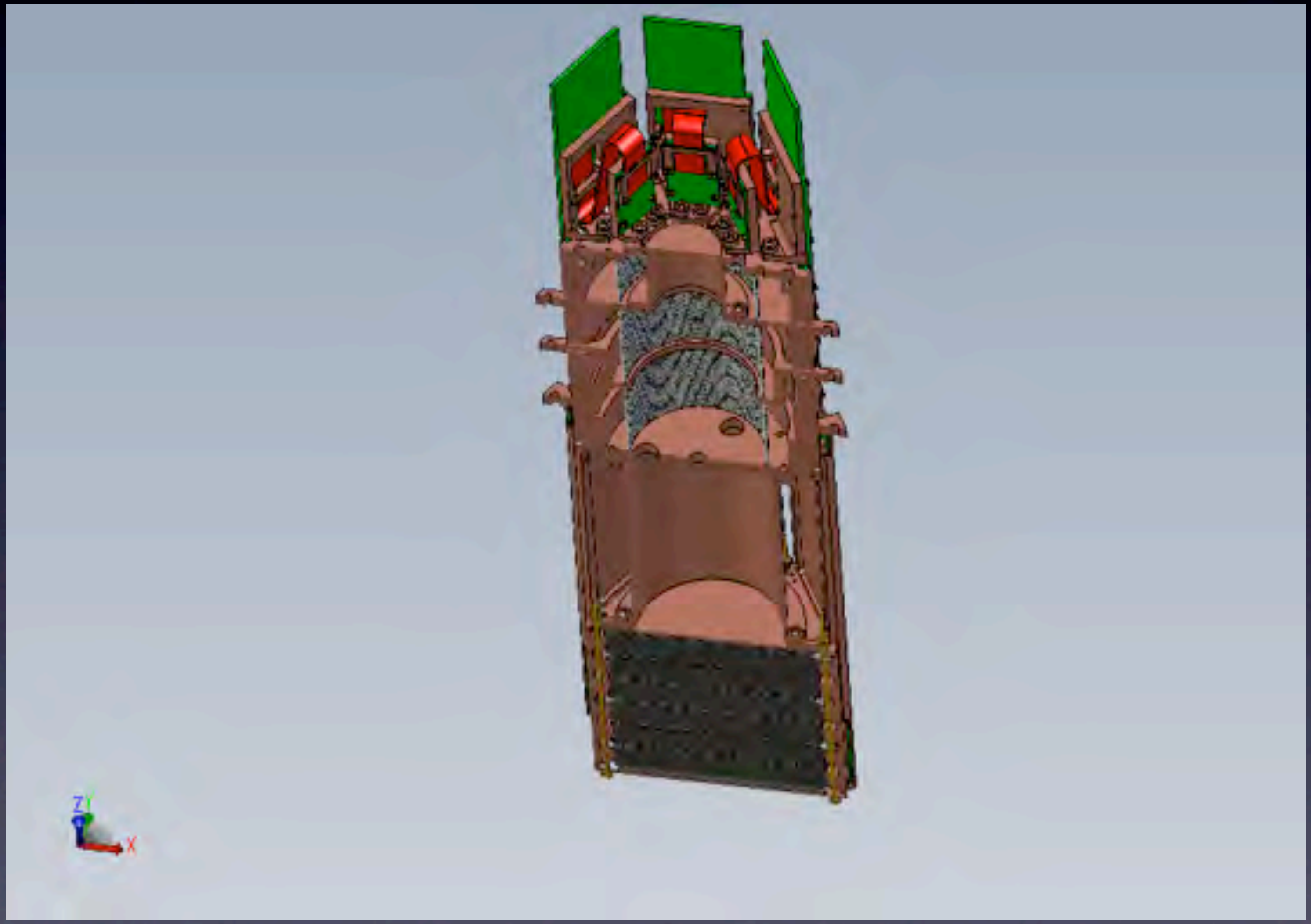

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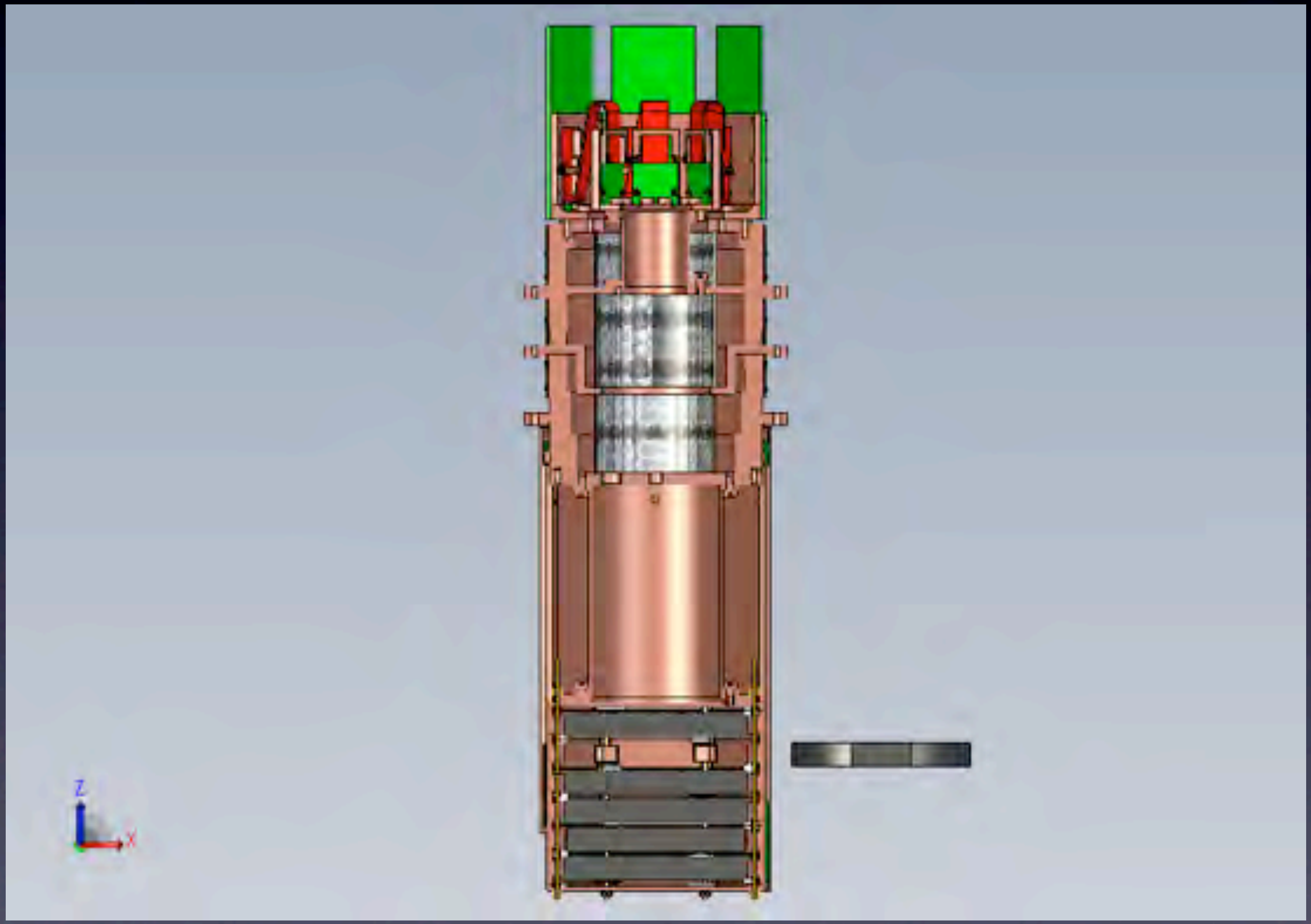

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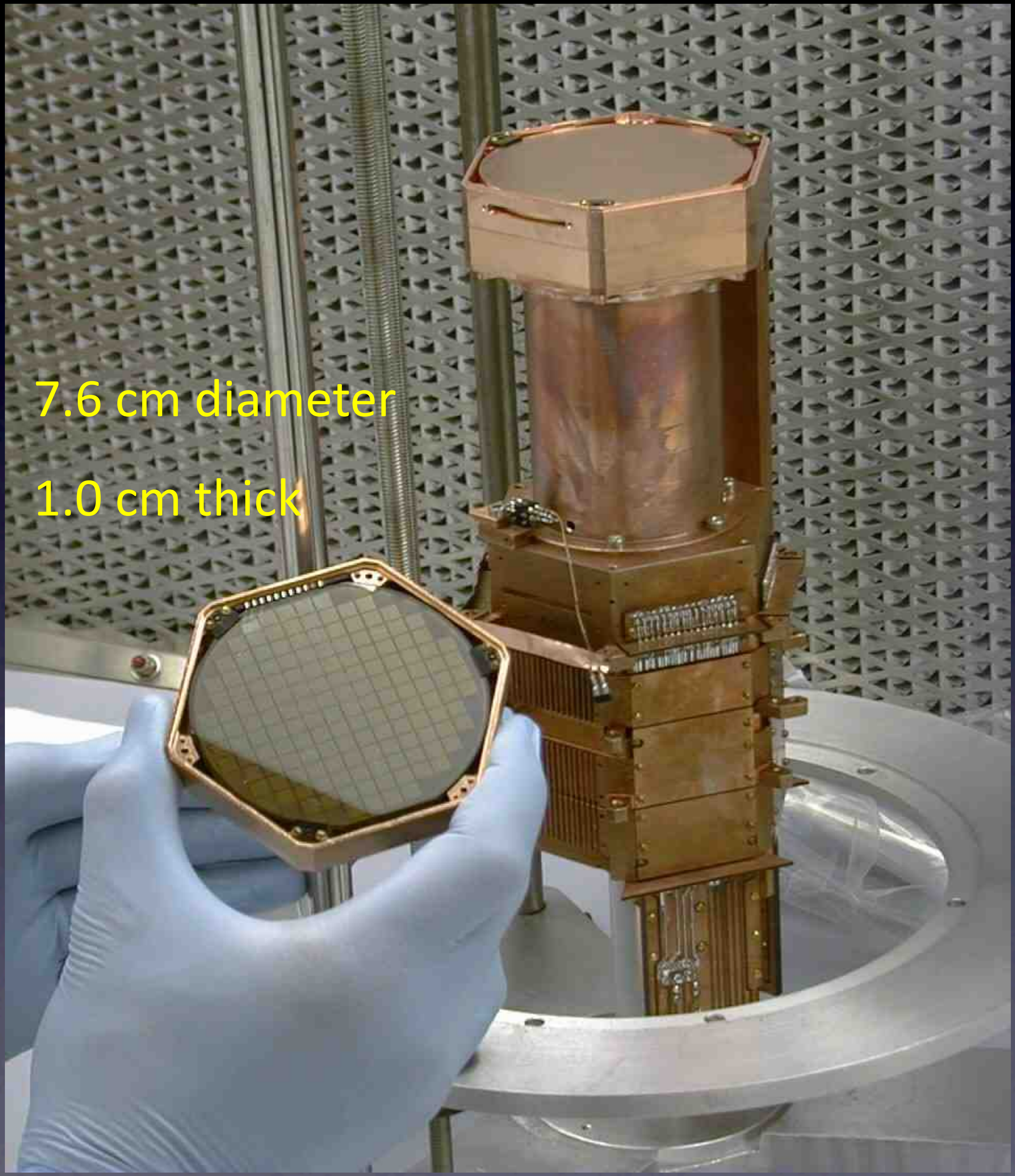
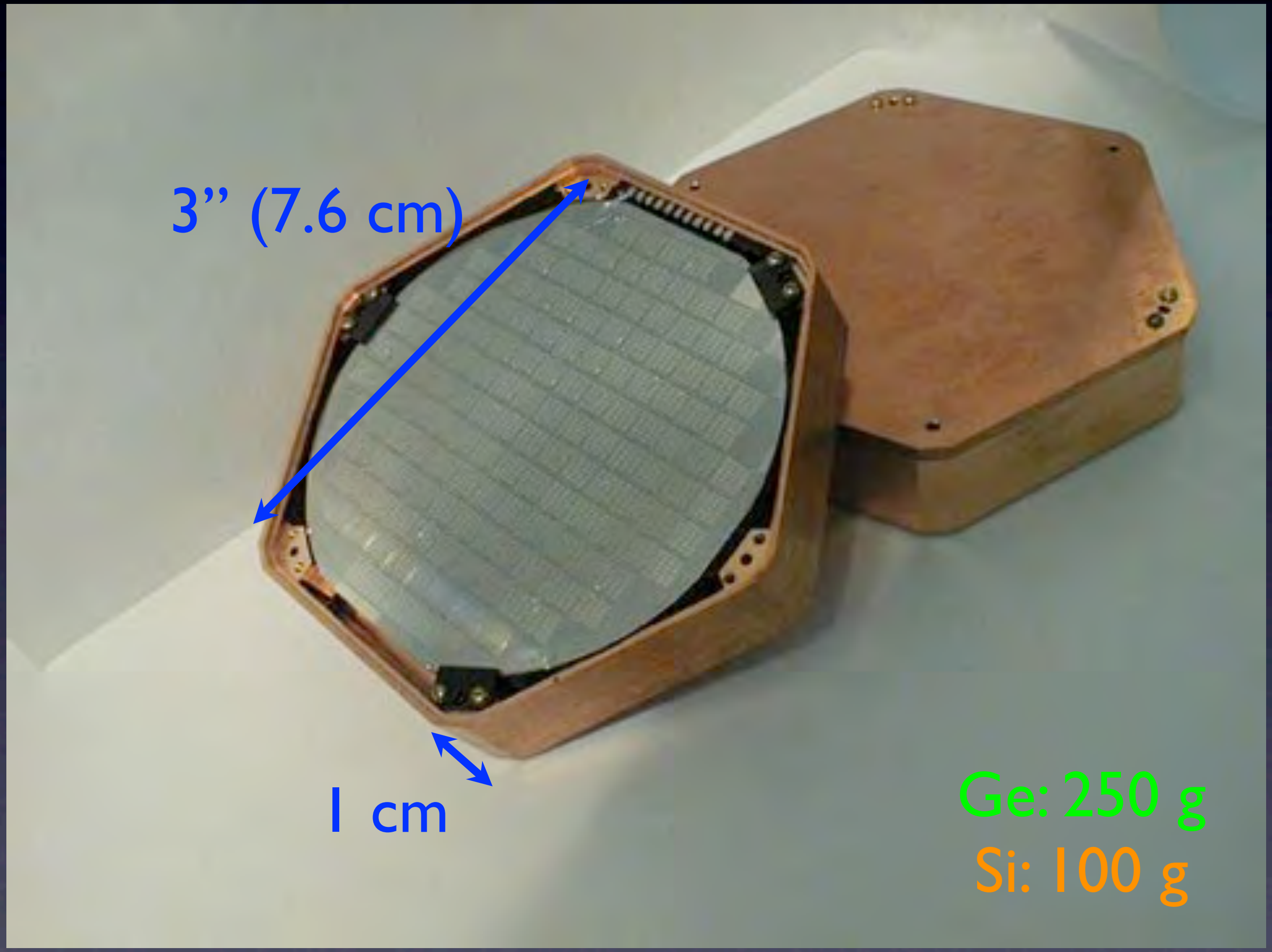


CDMS II Detectors



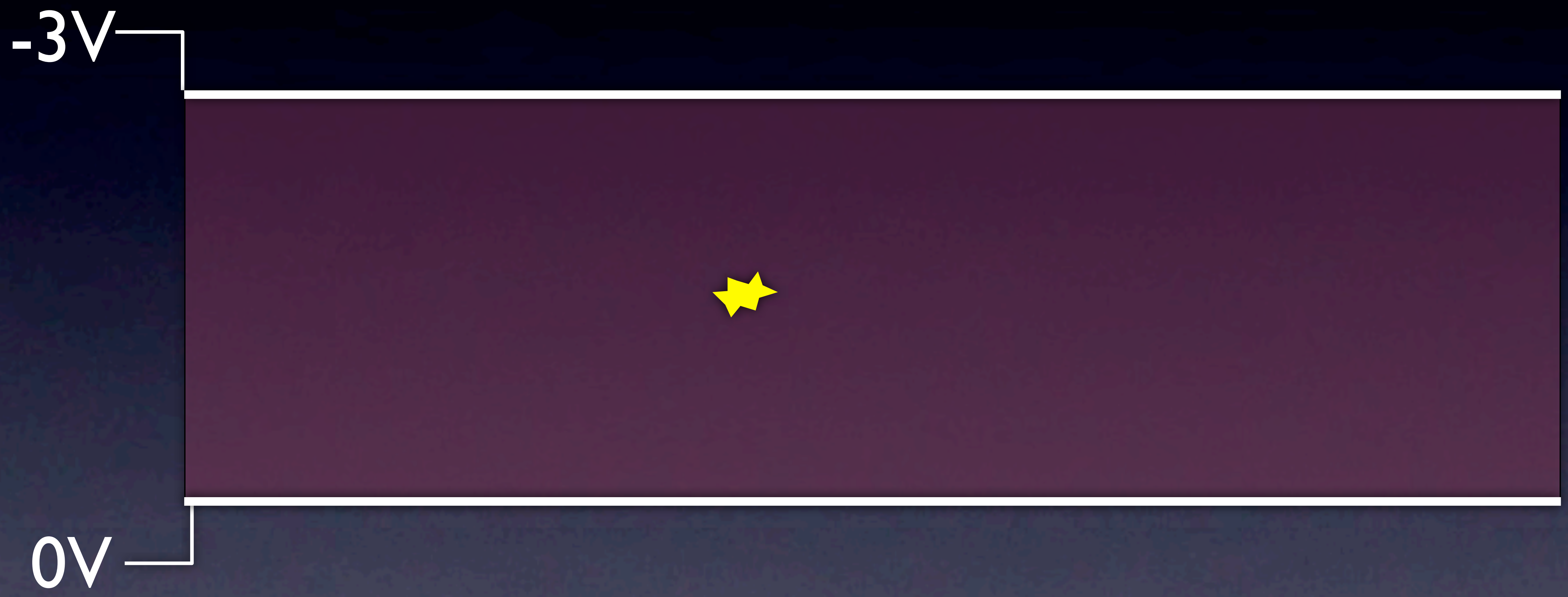
Phonon side: 4 quadrants of athermal phonon sensors
Energy & Position (Timing)

Transition Edge Sensors (TES)
Operated at ~40 mK for good phonon signal-to-noise

Charge side: 2 concentric electrodes (Inner & Outer)
Energy (& Veto)

CDMS II Detectors

CDMS II Detectors



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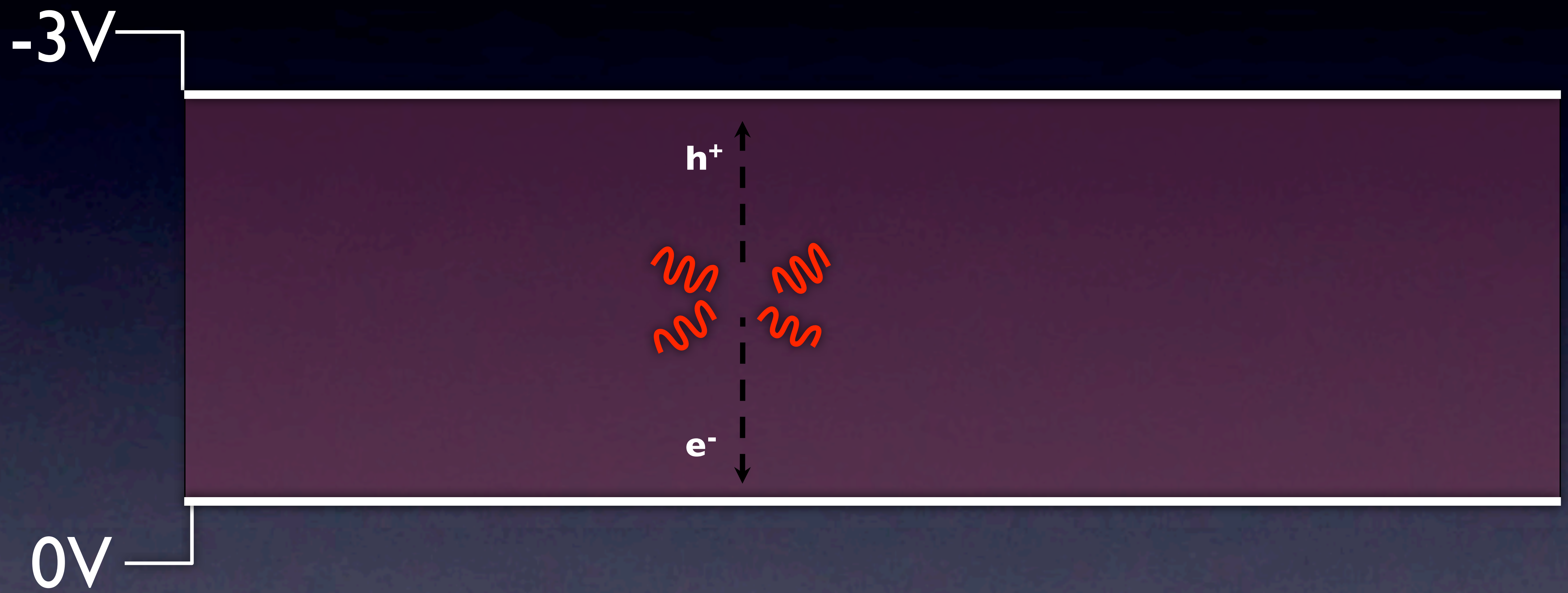

Hot charge carriers (3eV/pair)

Quasi-diffusive THz phonons

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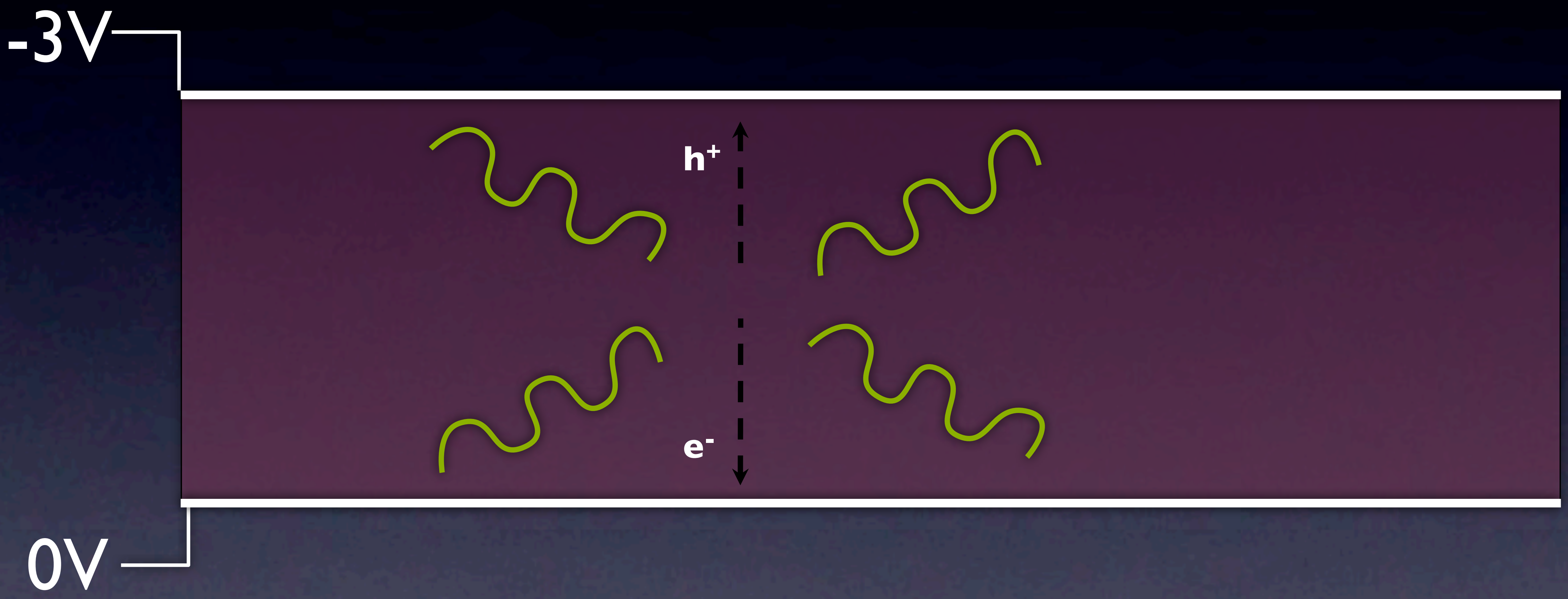

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Quasi-diffusive THz phonons

→ Ballistic low-frequency phonons

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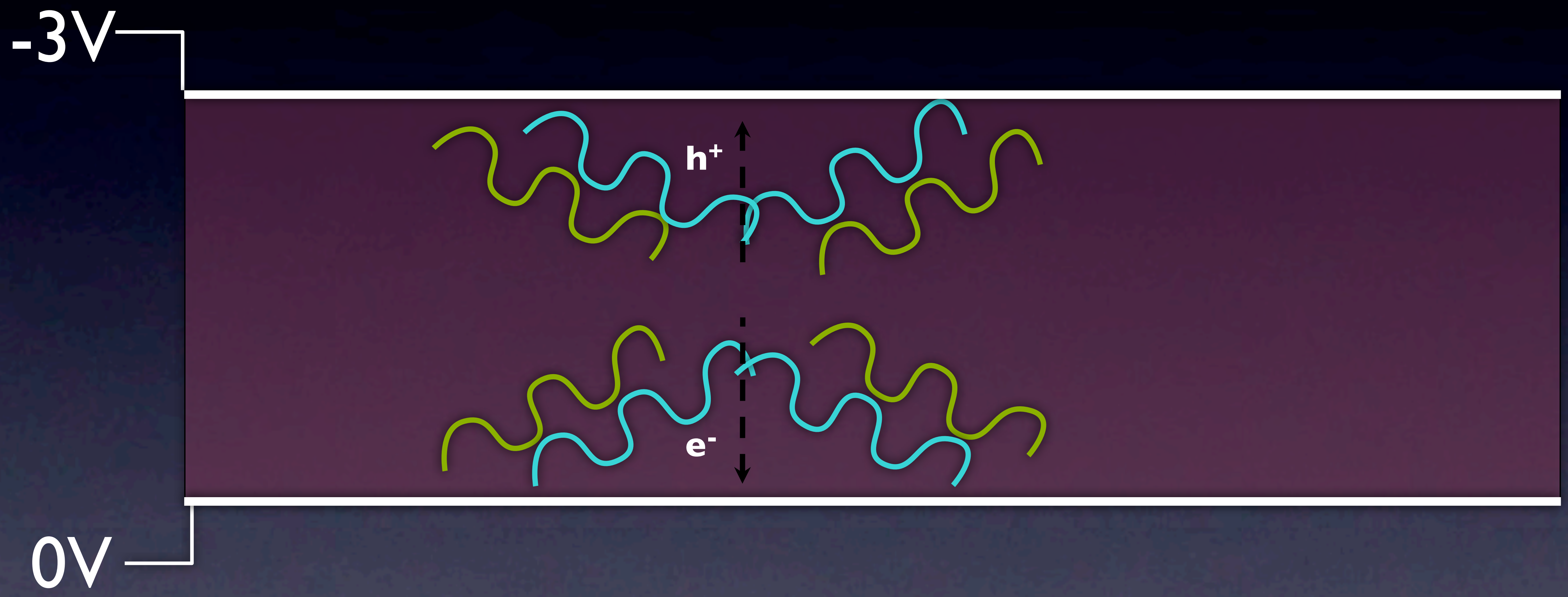


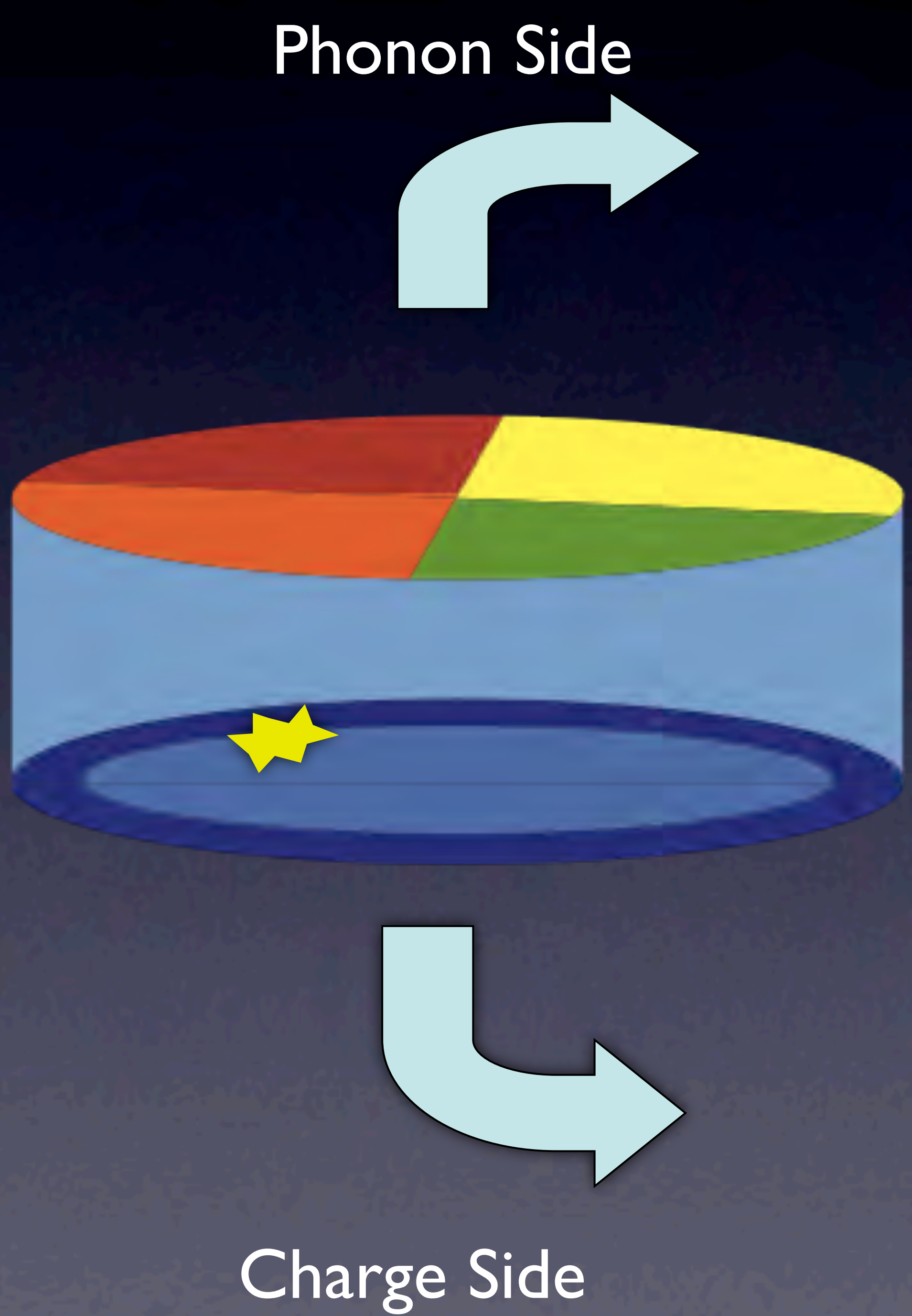
Hot charge carriers (3eV/pair)

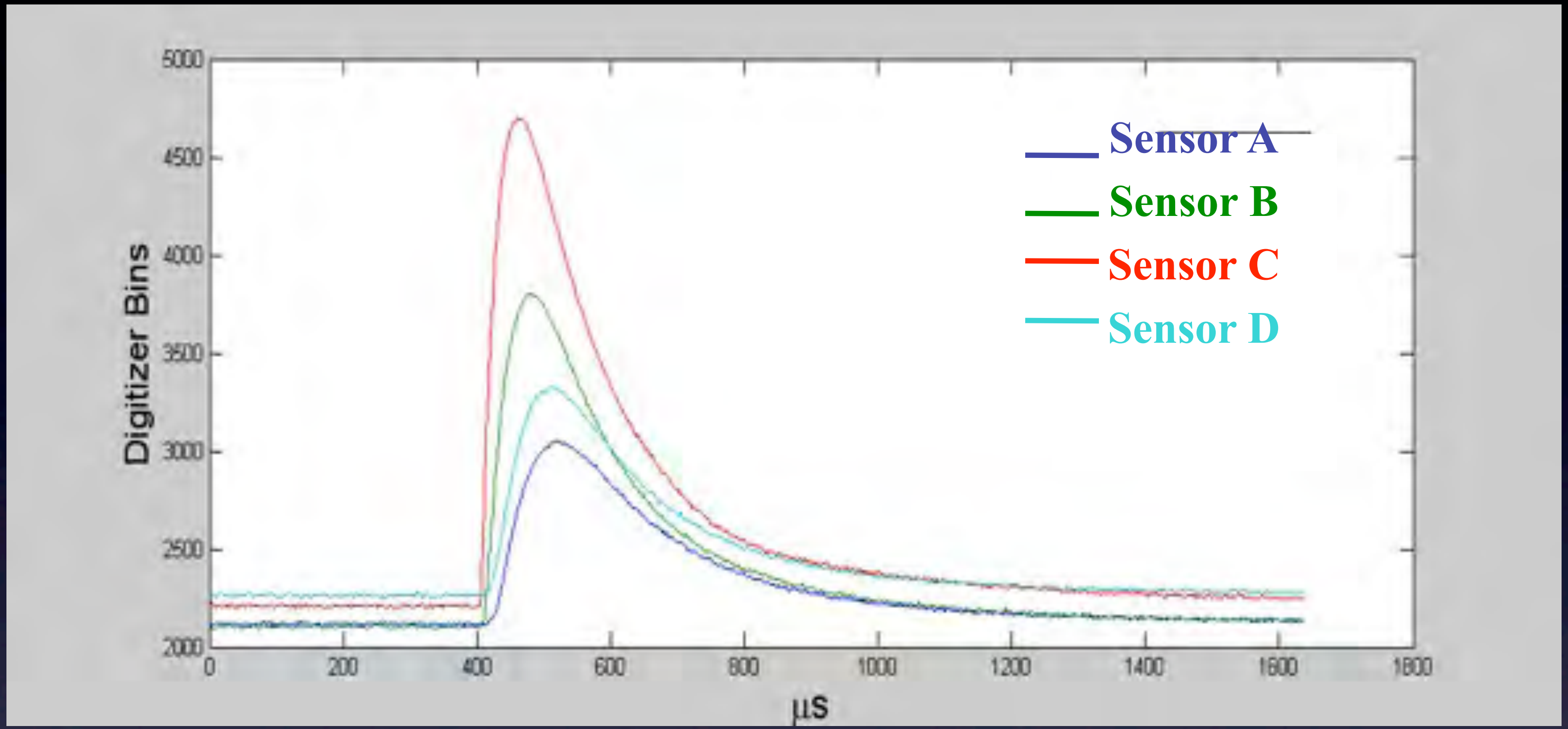
Quasi-diffusive THz phonons

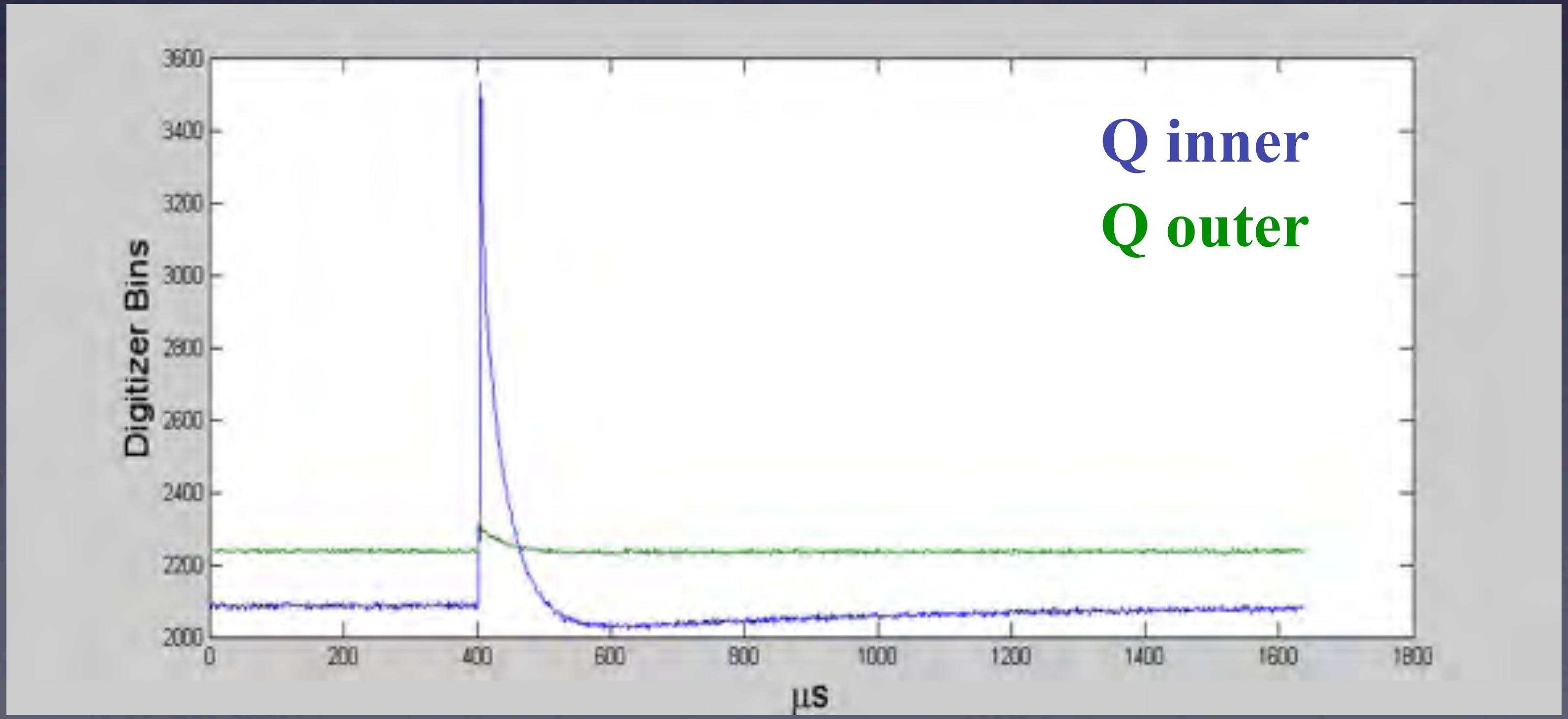
→ Ballistic low-frequency phonons

Ballistic Neganov-Luke phonons

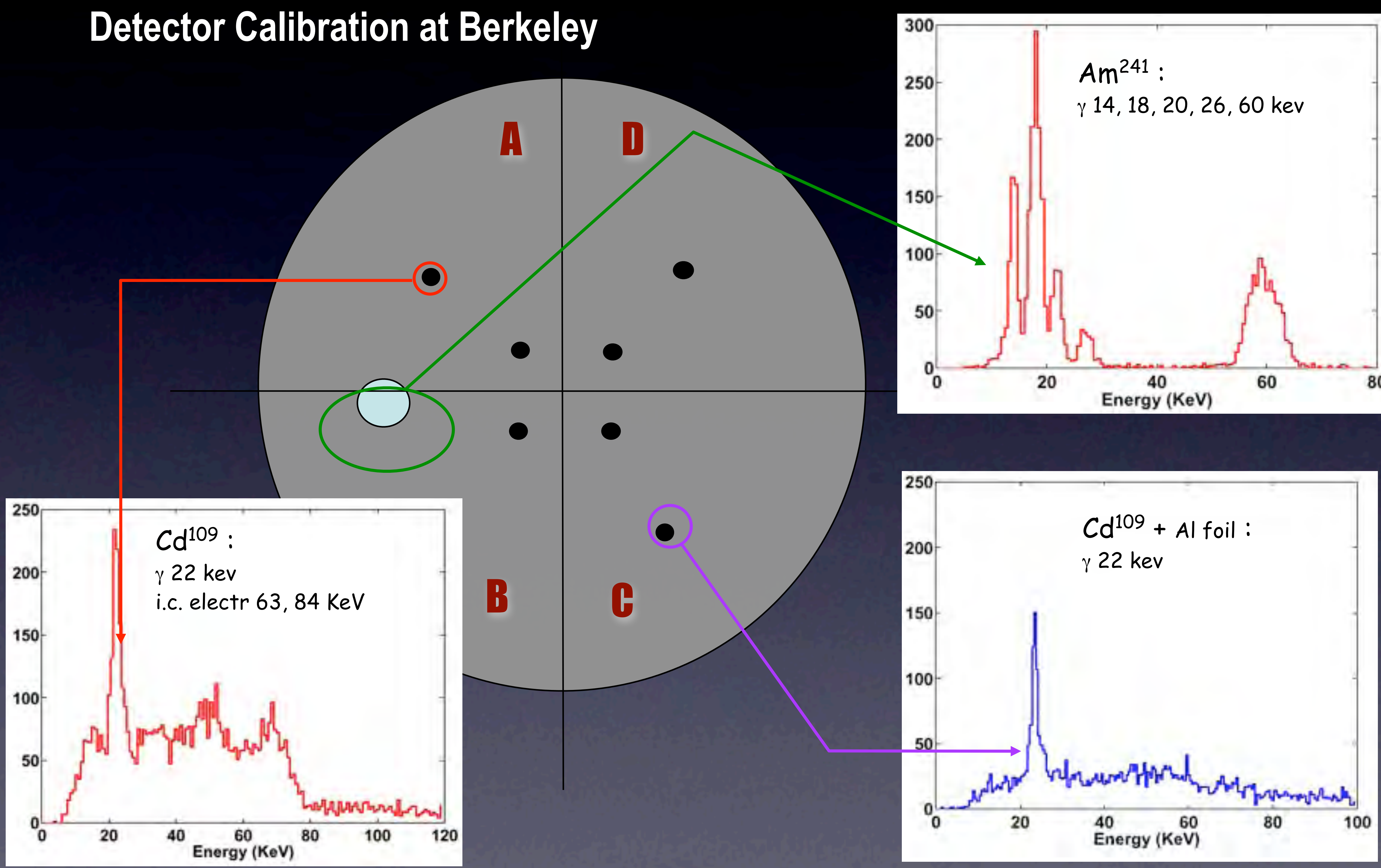
CDMS II Detectors







Excellent Energy and Position Resolution



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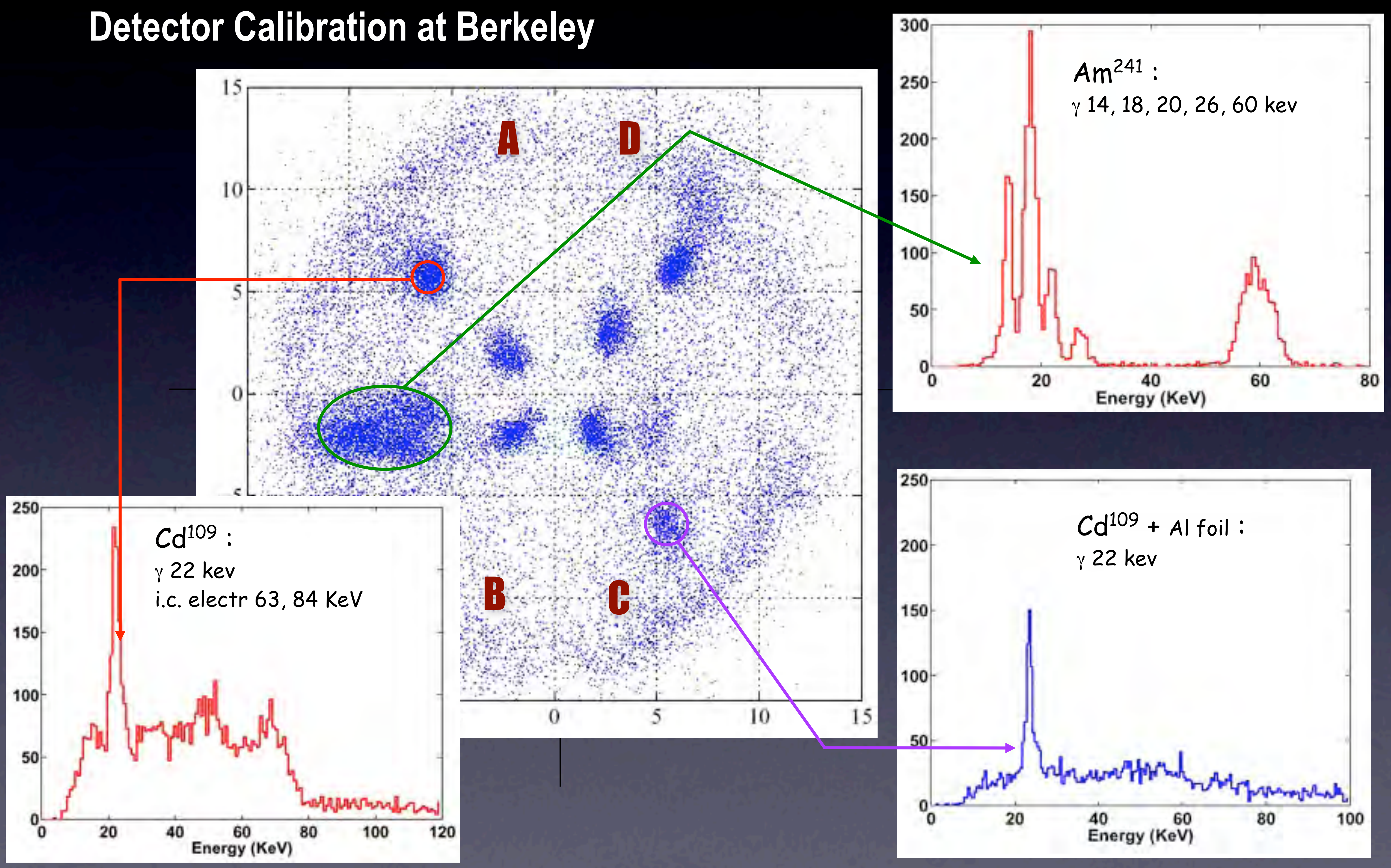
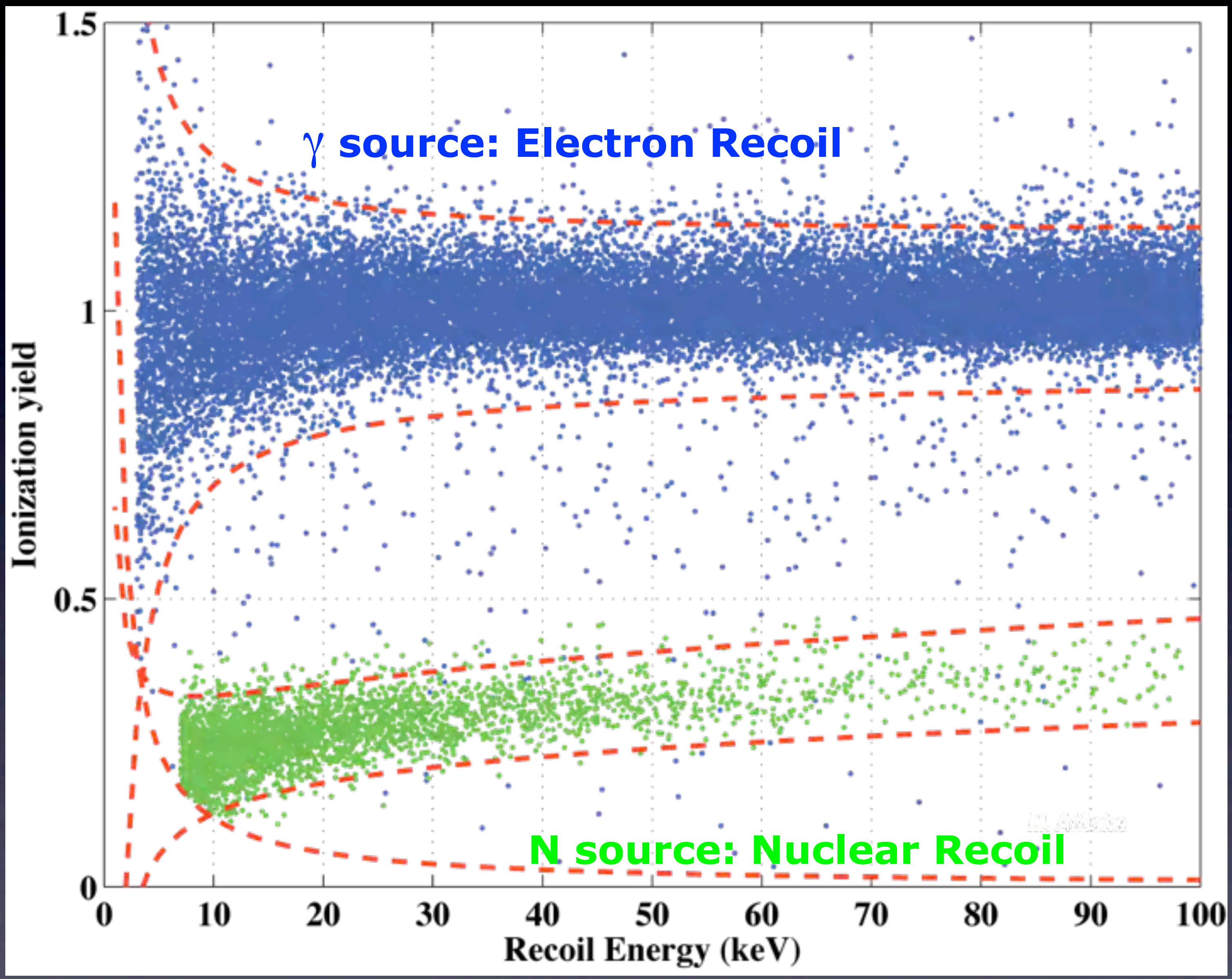


Excellent Primary (γ) Background Rejection



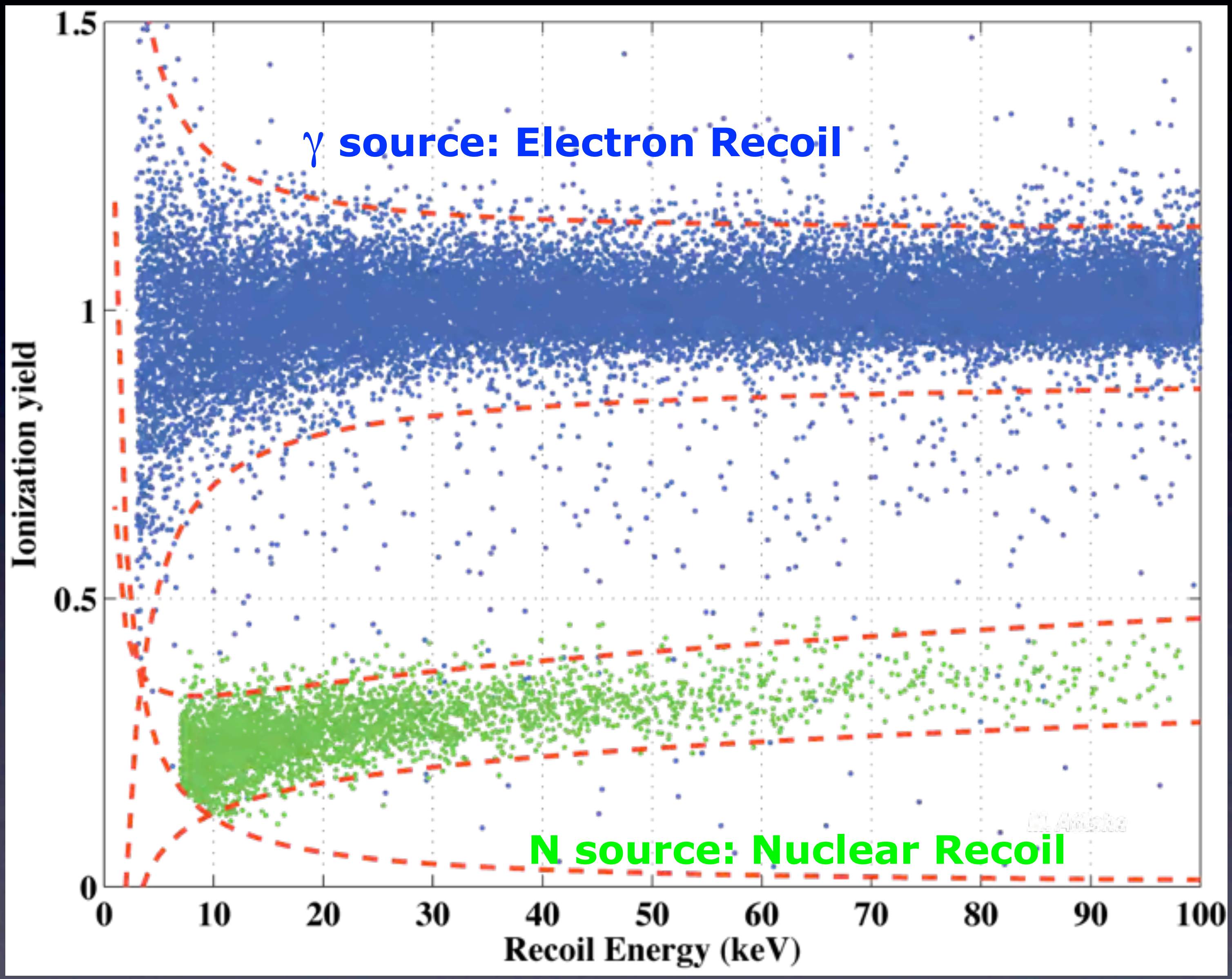
Radioactive source data defines the signal (NR) and background (ER)

>10^4 Rejection of γ

Yield = Ionization/Phonon

Very effective Particle ID

Excellent Primary (γ) Background Rejection



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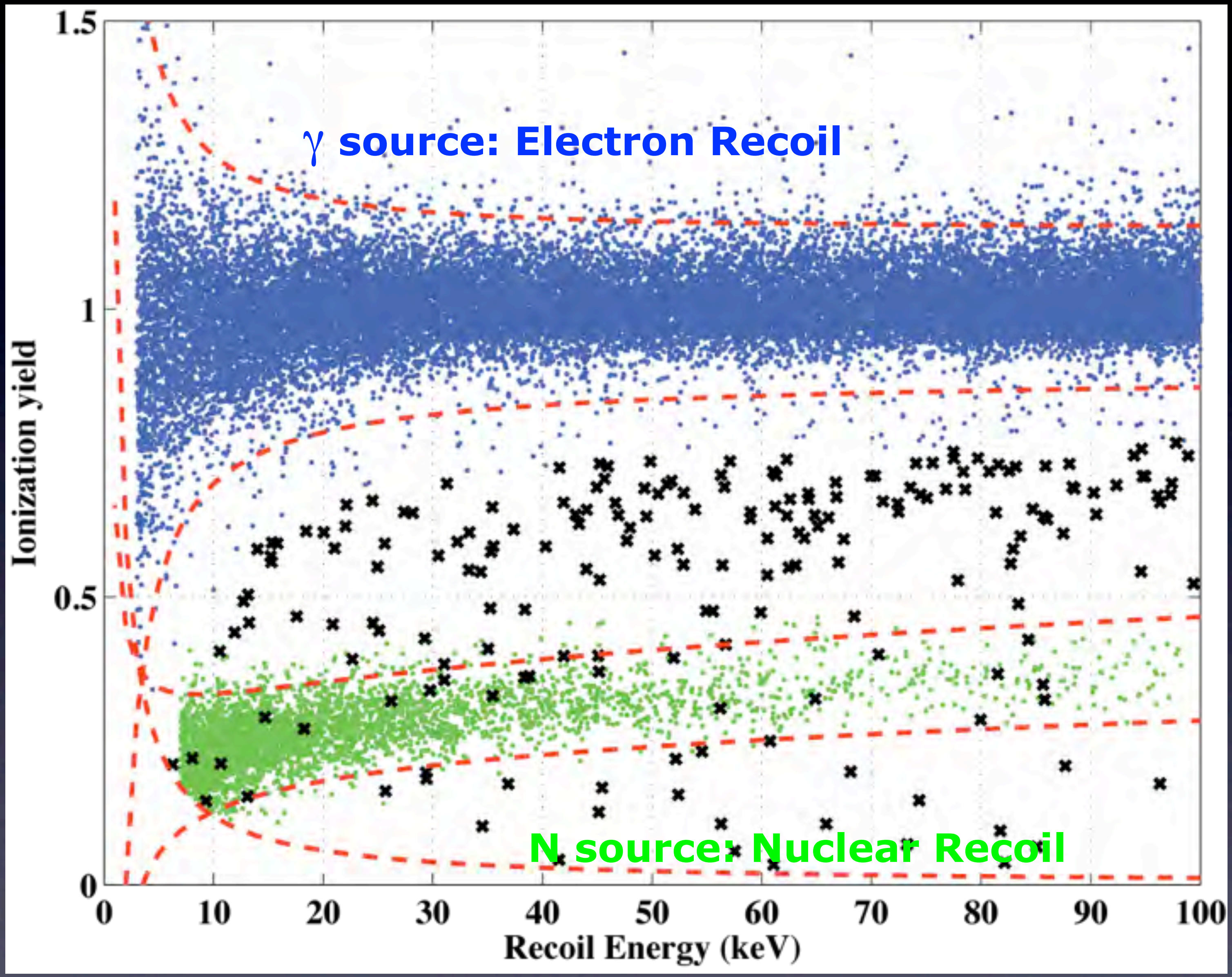
What are these drooping-yield events?

Excellent Primary (γ) Background Rejection



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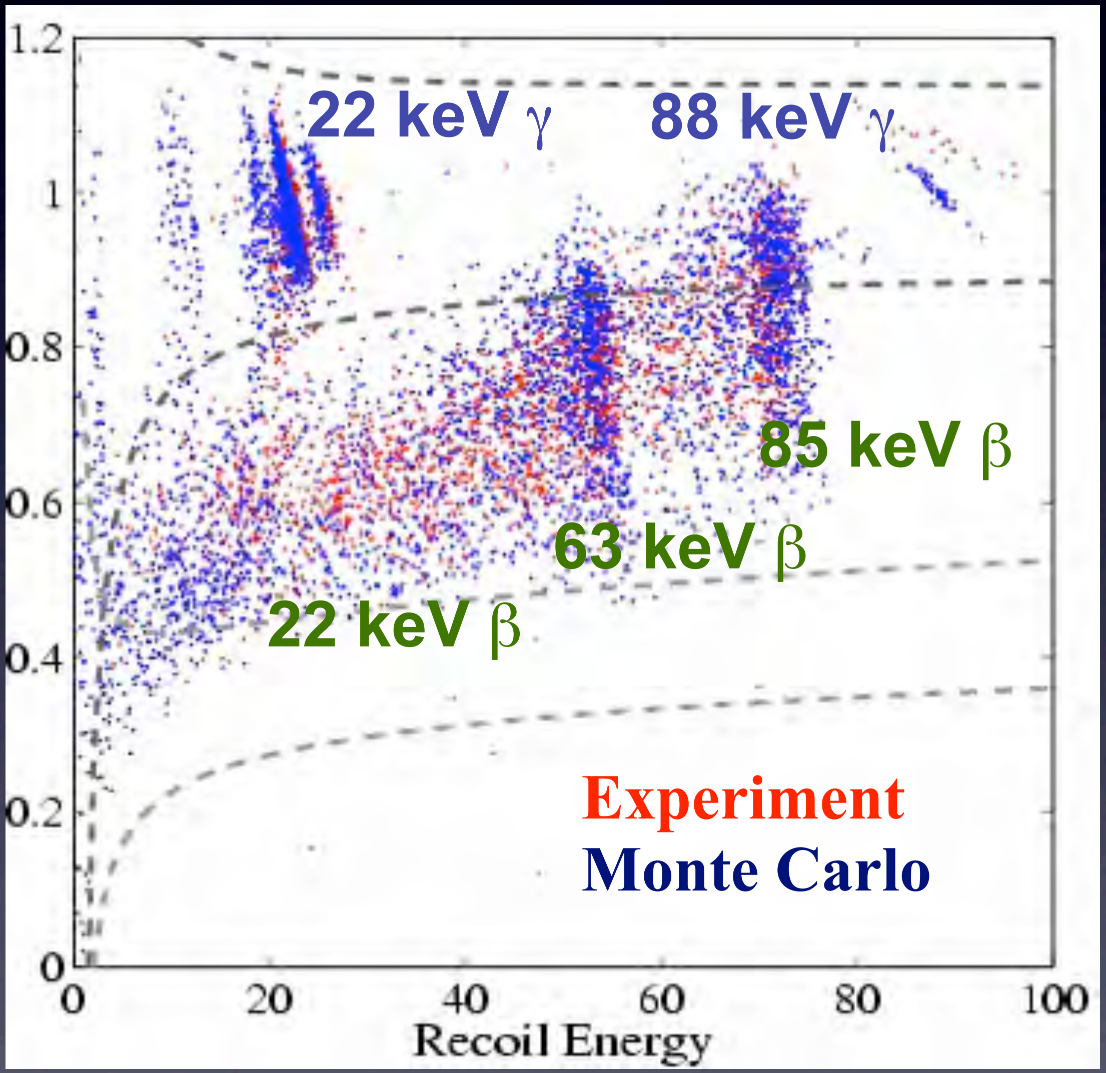
What are these drooping-yield events?

Surface Events

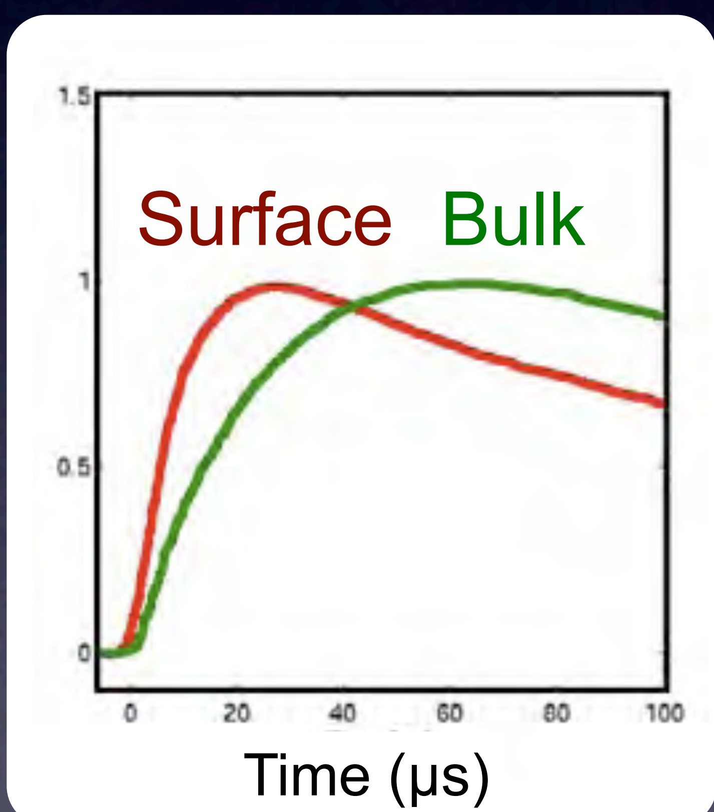


βs and low-energy γs don't penetrate the detector. These surface events can pollute the signal region and are the dominant background for CDMS.

Single scatter surface event rate ~0.4 / kg / day

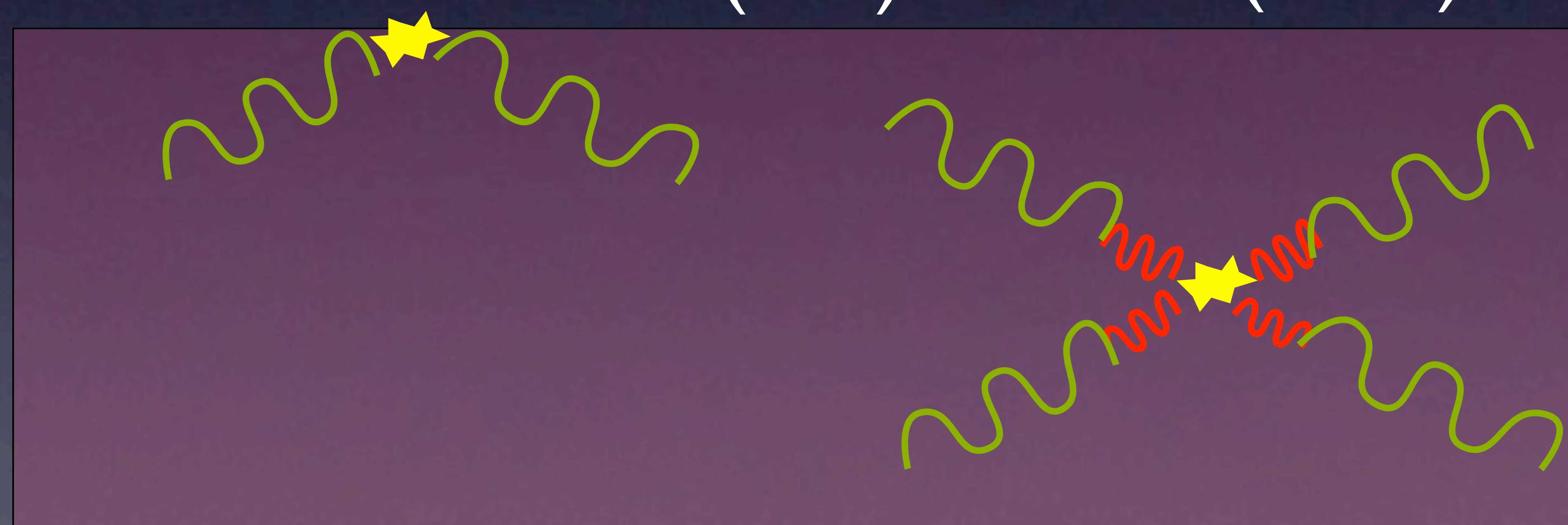
Surface β Rejection

Secondary Discrimination: Phonon Timing



Surface
initial phonons become ballistic at surface (fast)

Bulk
initial phonons diffuse (slow)



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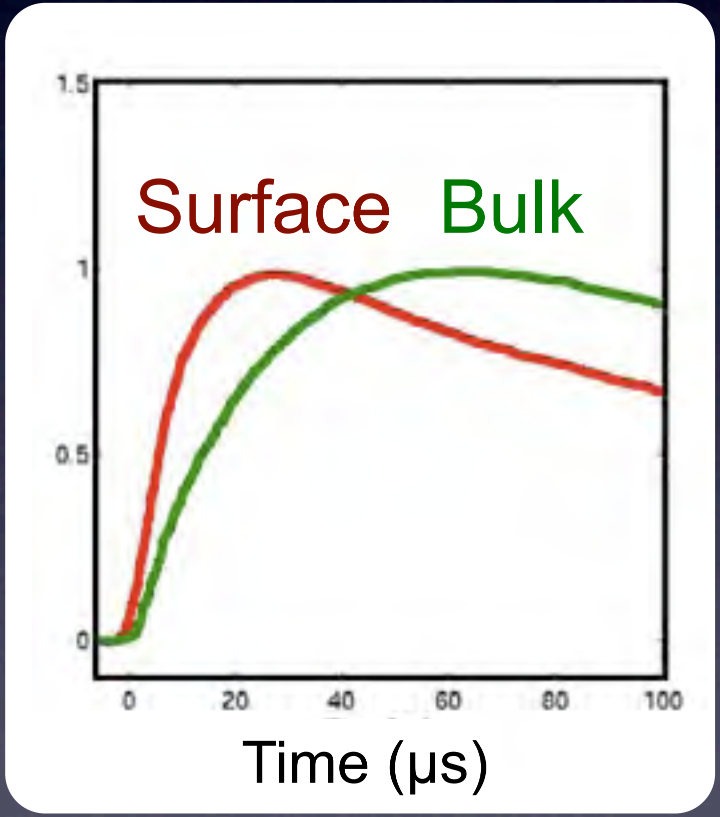

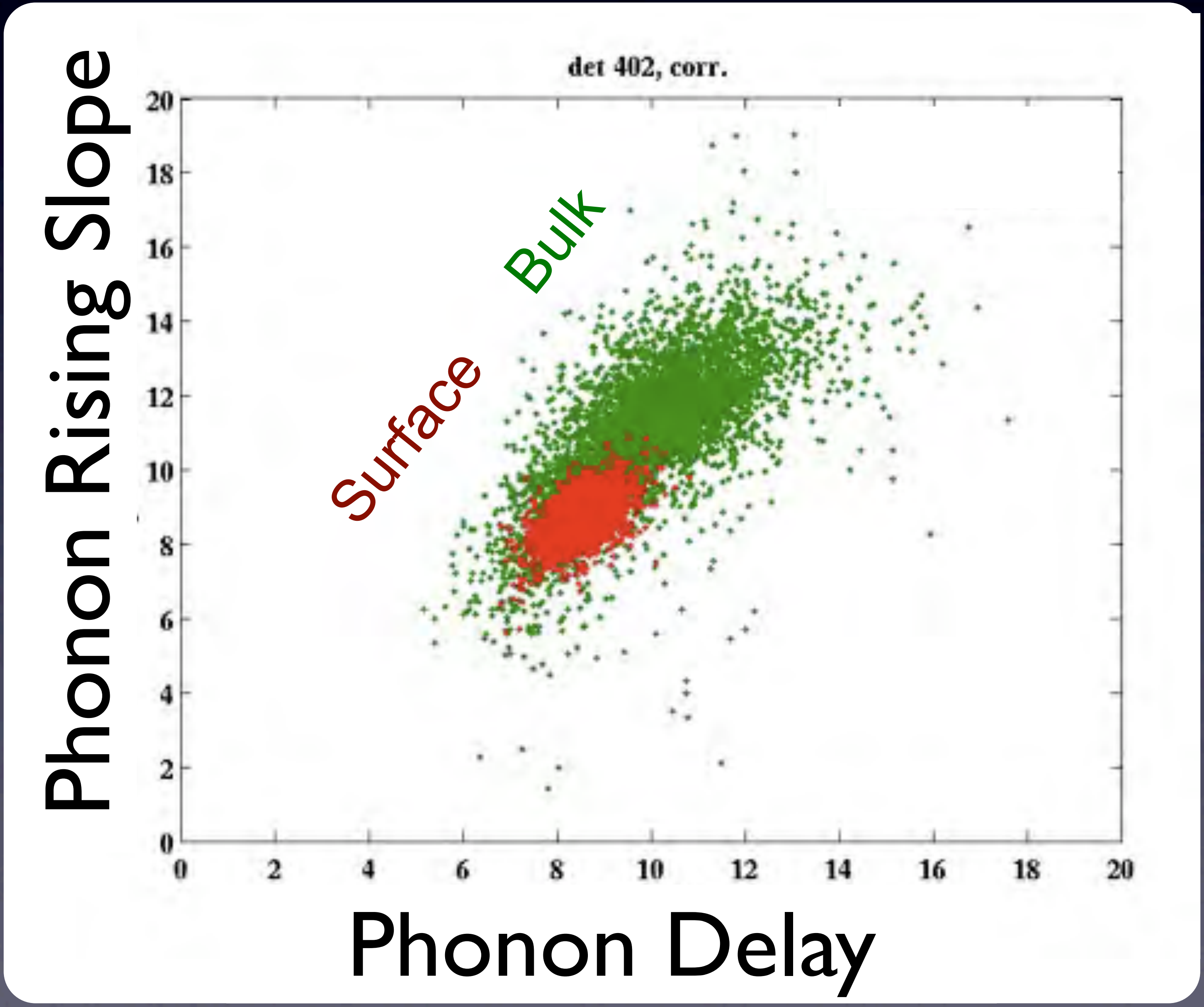

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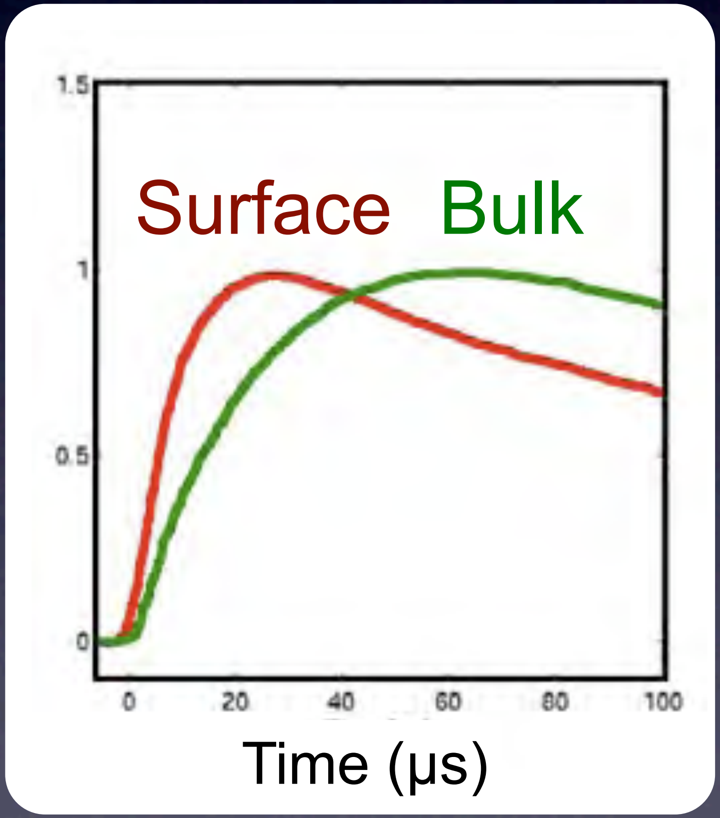

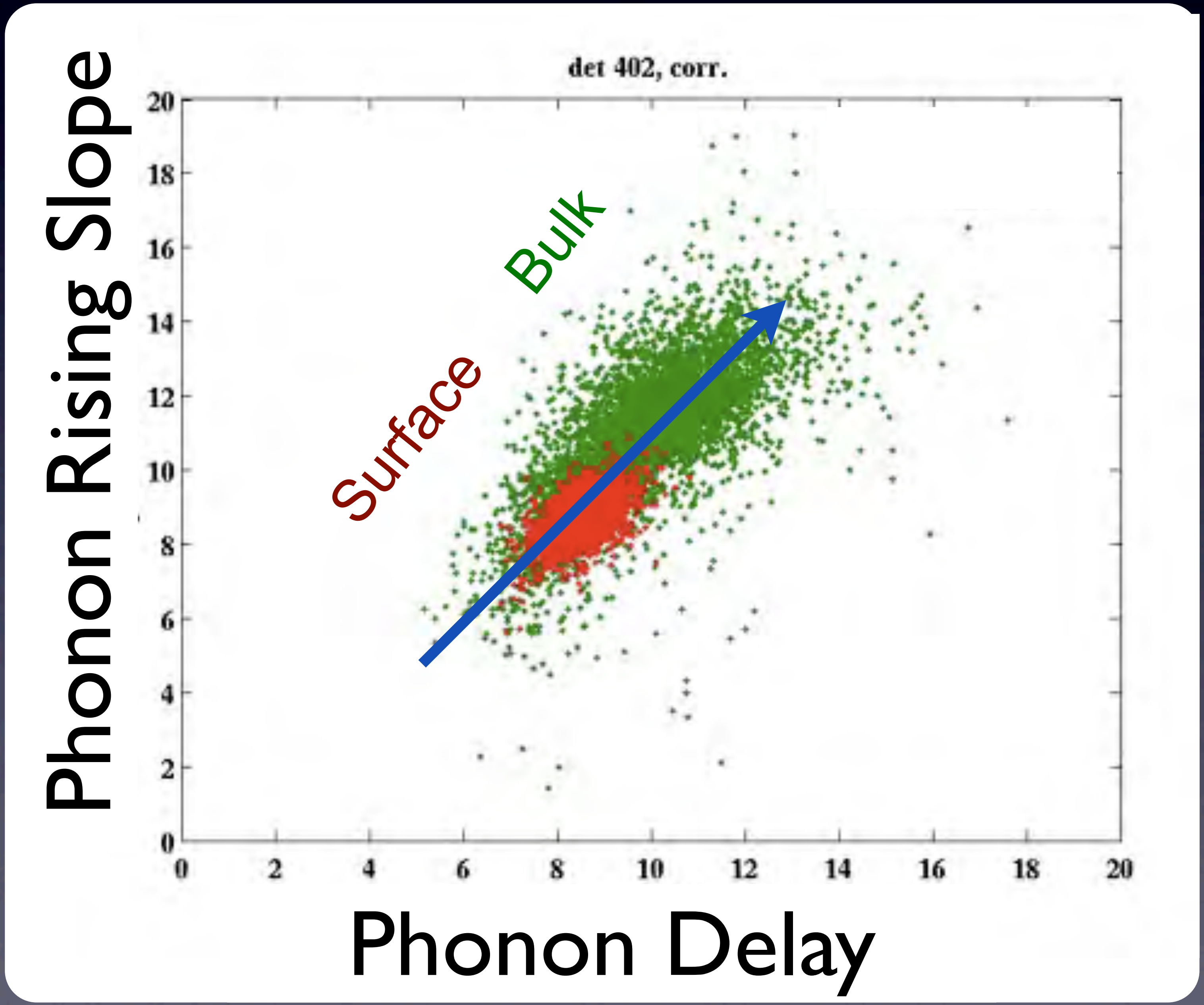

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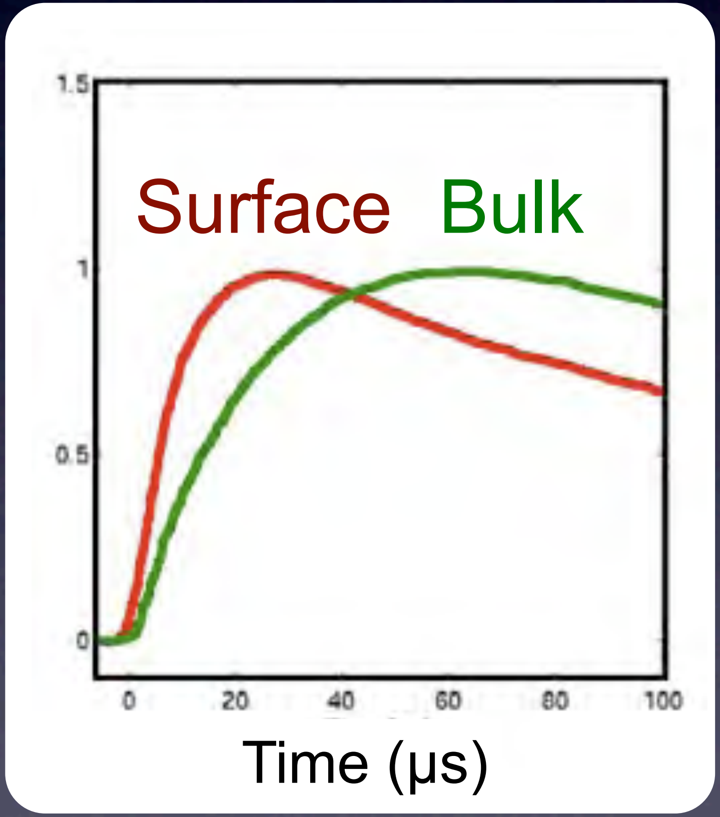
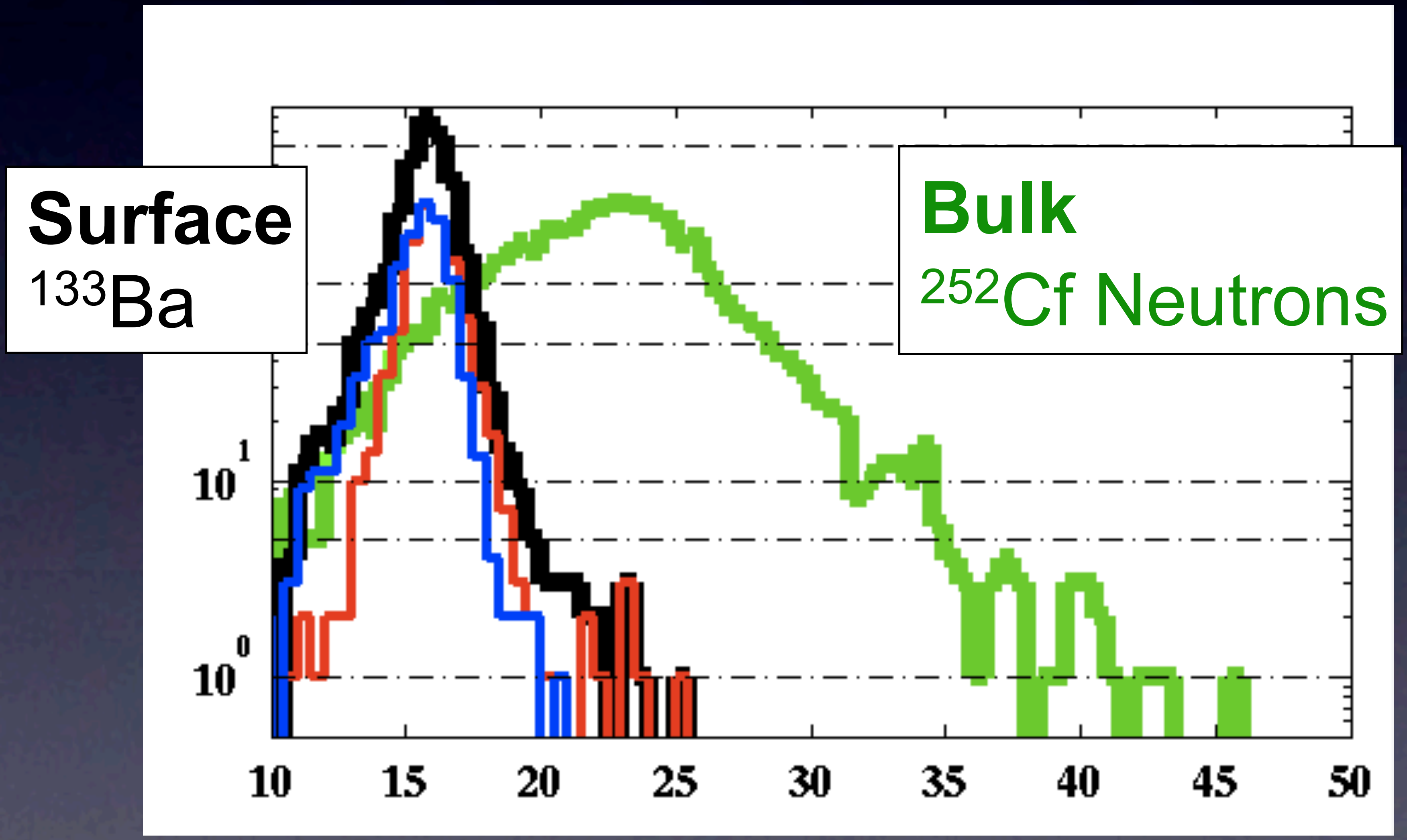
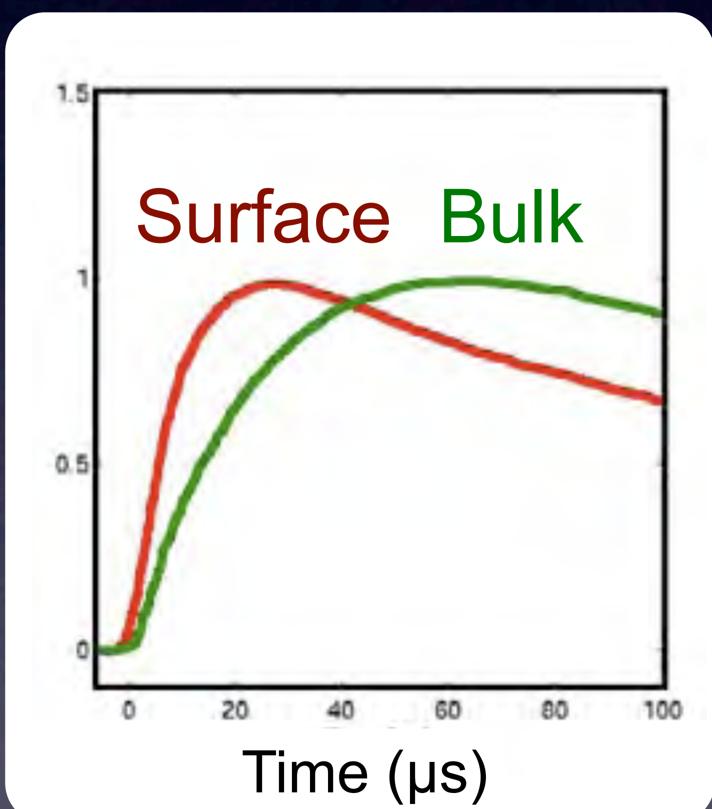


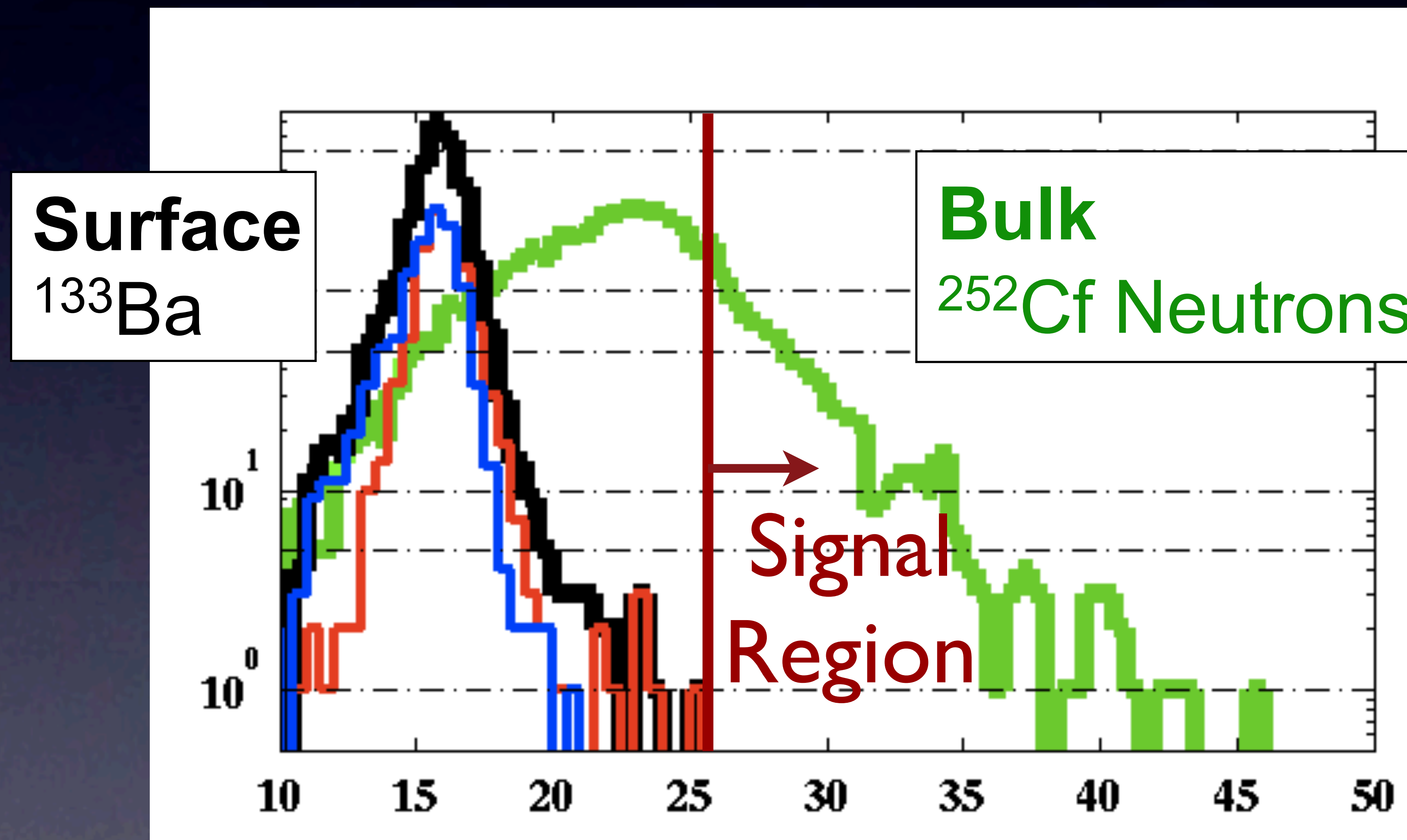


timing parameter
(delay & rising slope)

Surface β Rejection

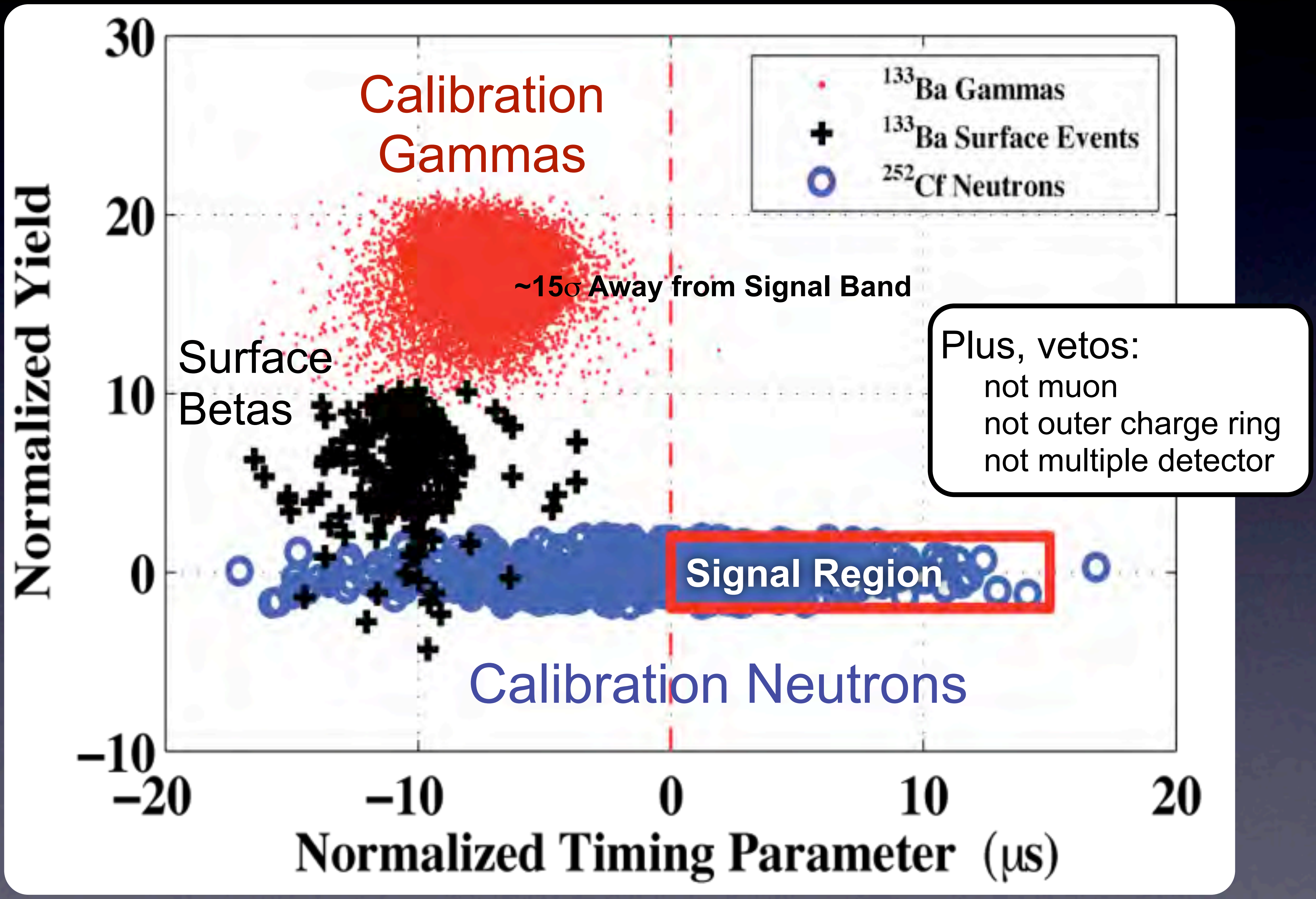
Secondary Discrimination: Phonon Timing



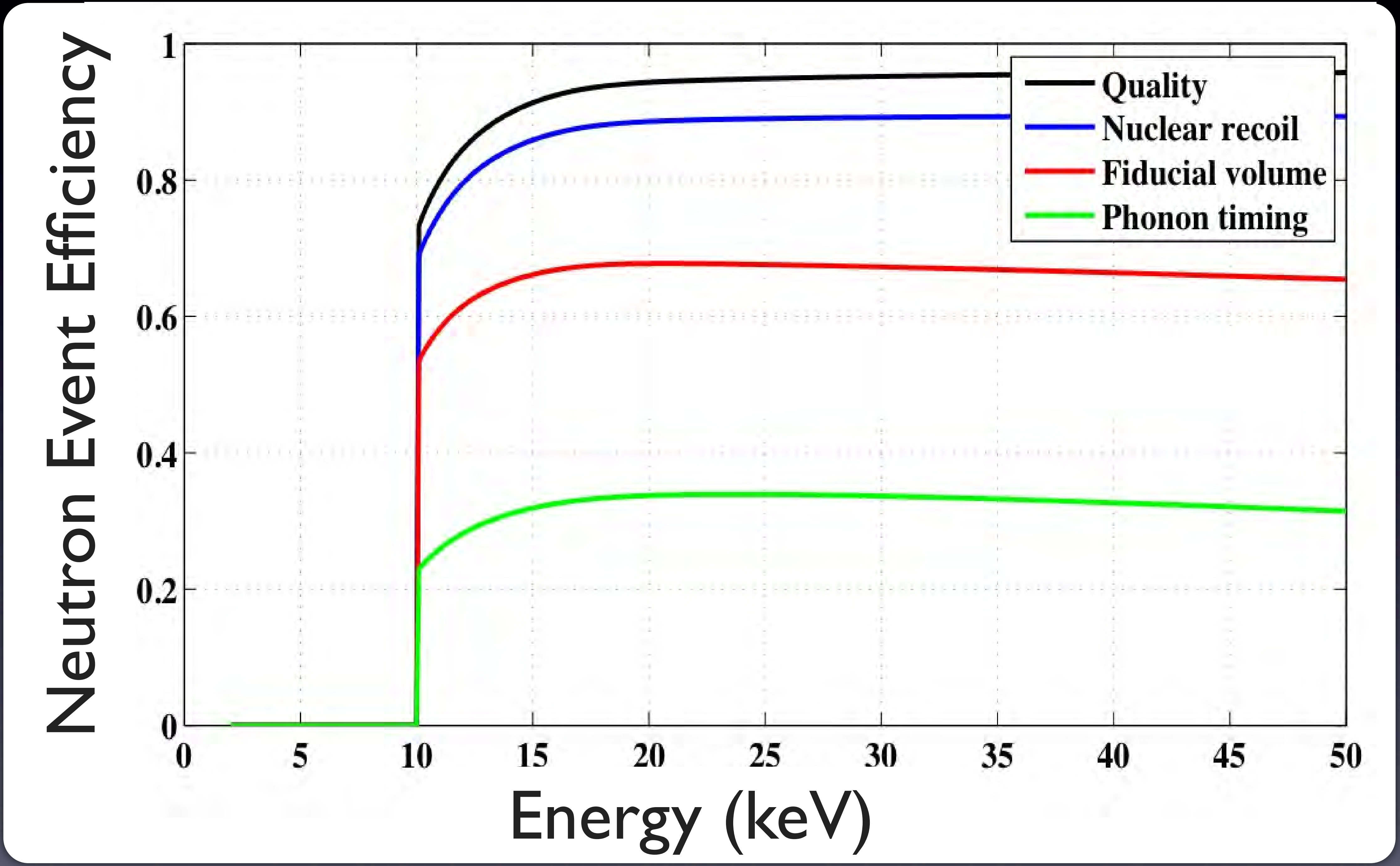


timing parameter
(delay & rising slope)

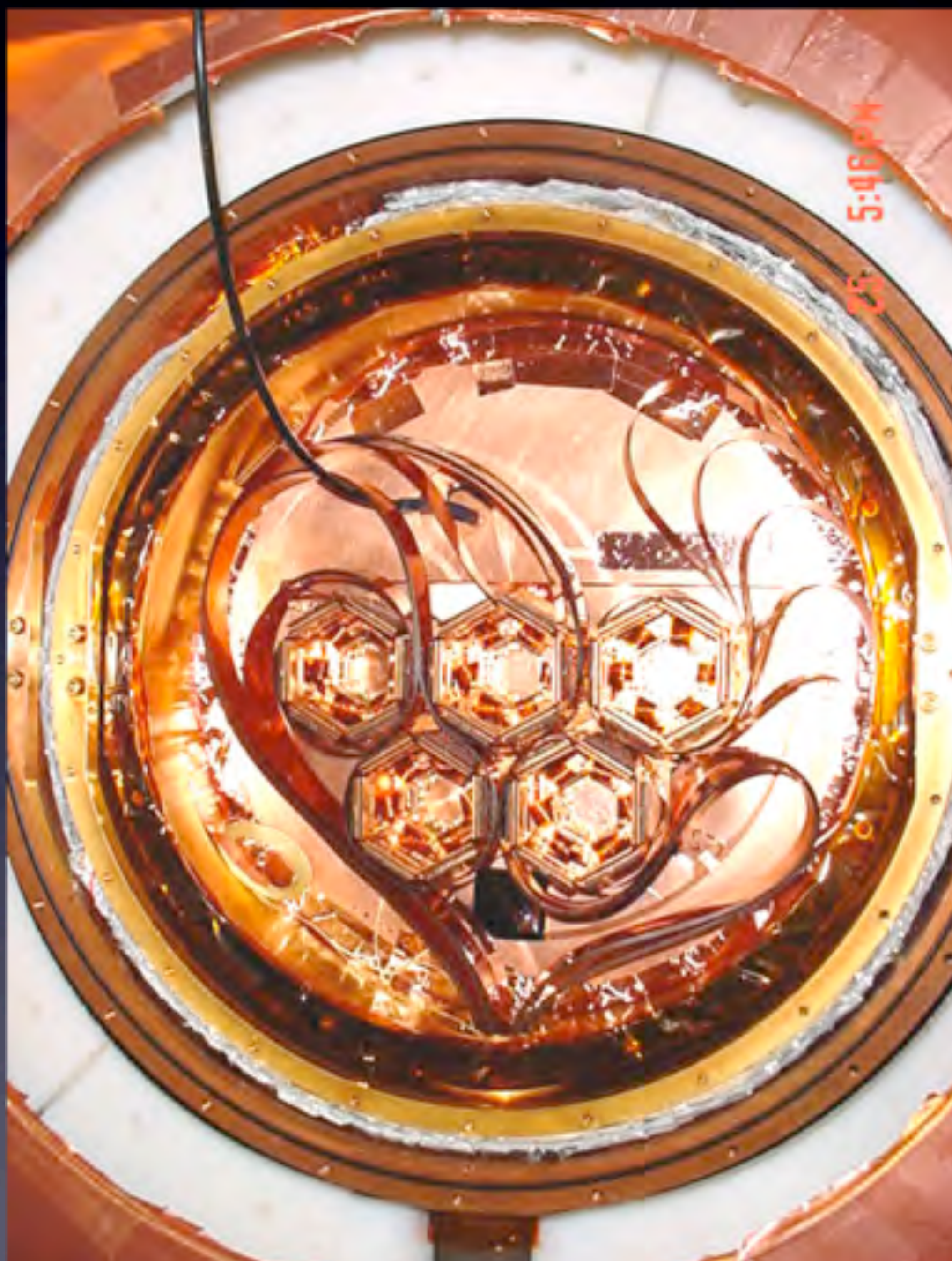
Setting the Signal Region



Average Signal Efficiency: 0.32



CDMS II (2006-2008)



30 detectors (5 Towers) installed in Soudan icebox:

4.4 kg Ge, 1.1 kg Si

	T1	T2	T3	T4	T5
Z1	G6	S14	S17	S12	G7
Z2	G11	S28	G25	G37	G36
Z3	G8	G13	S30	S10	S29
Z4	S3	S25	G33	G35	G26
Z5	G9	G31	G32	G34	G39
Z6	S1	S26	G29	G38	G24

Side View

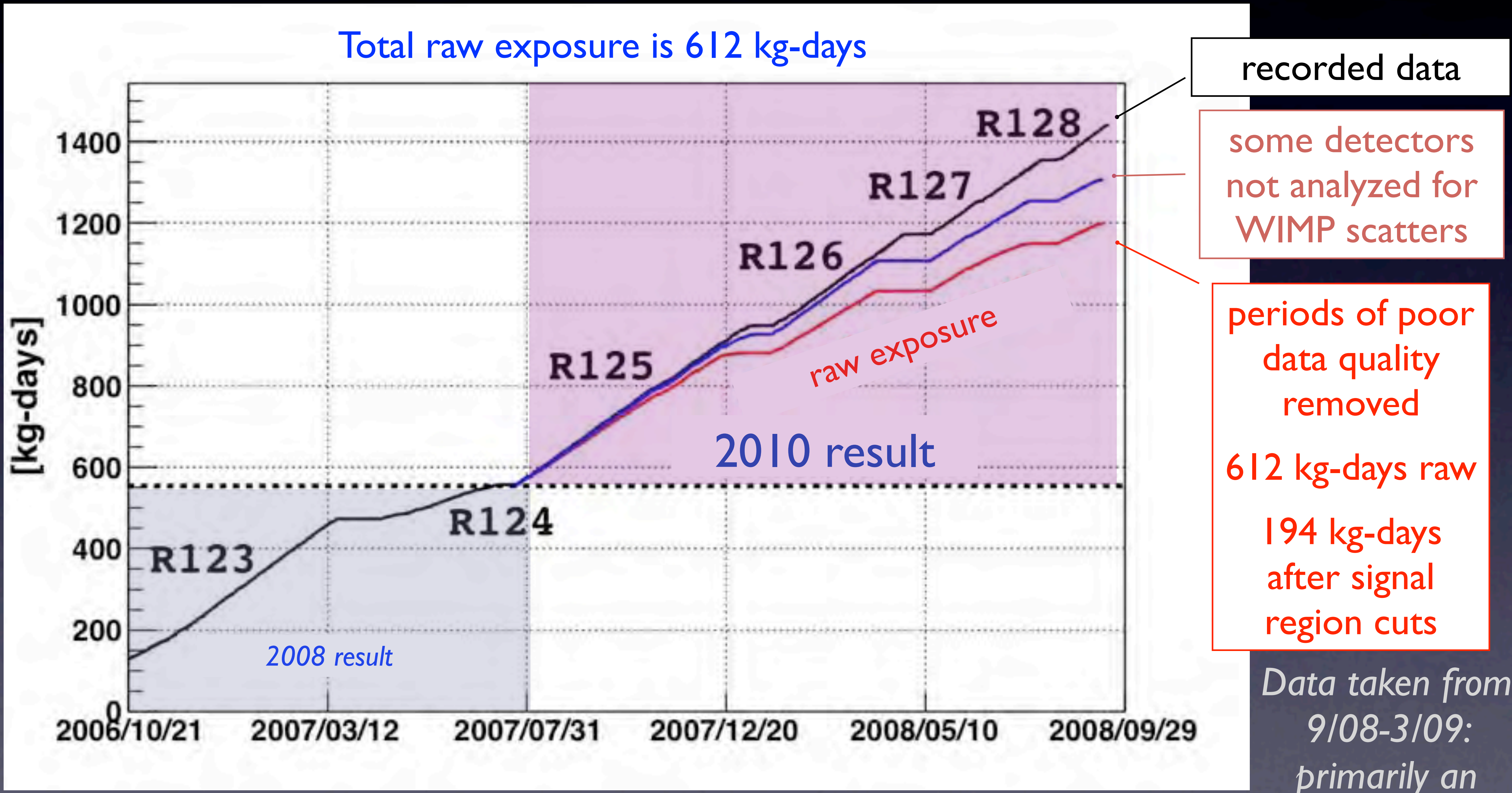
Combination of Ge and Si Detectors

- 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



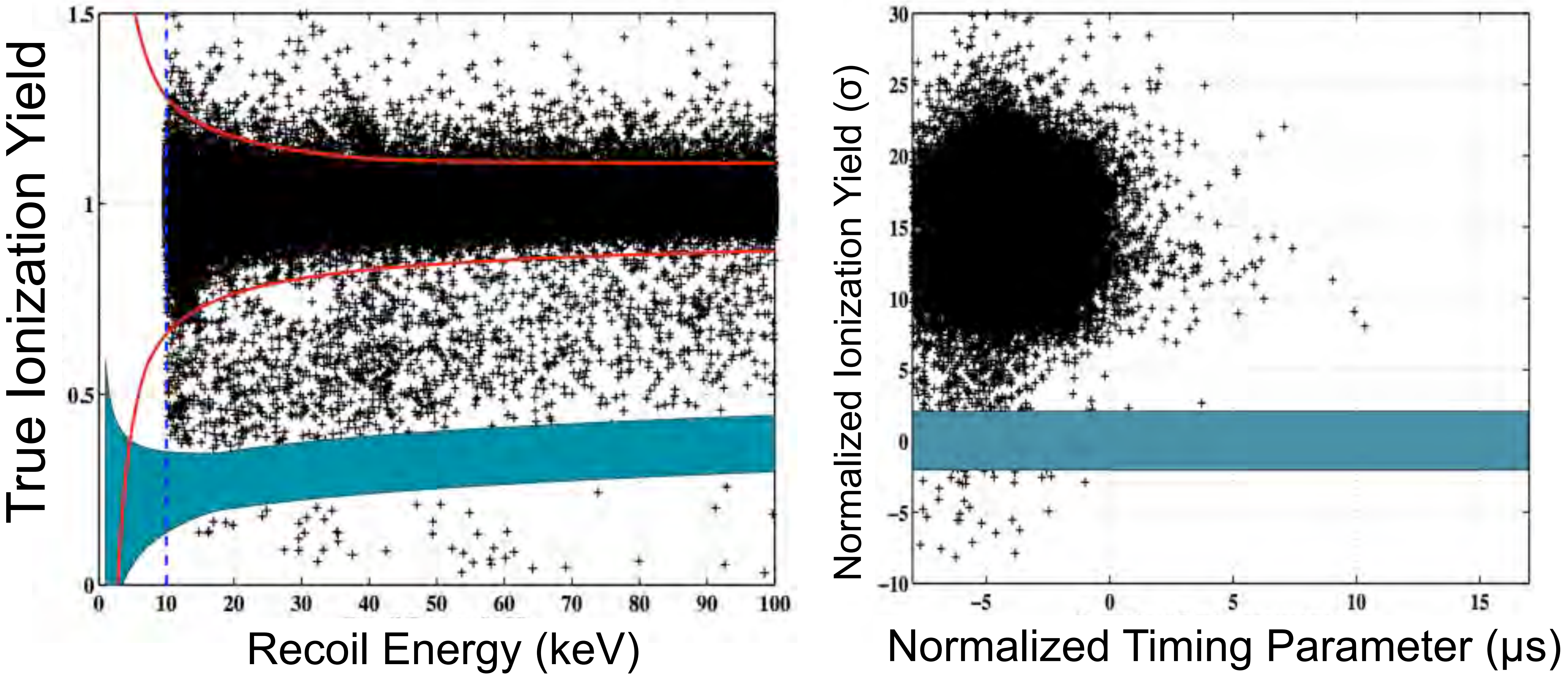
Data taken from 9/08-3/09: primarily an engineering run

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

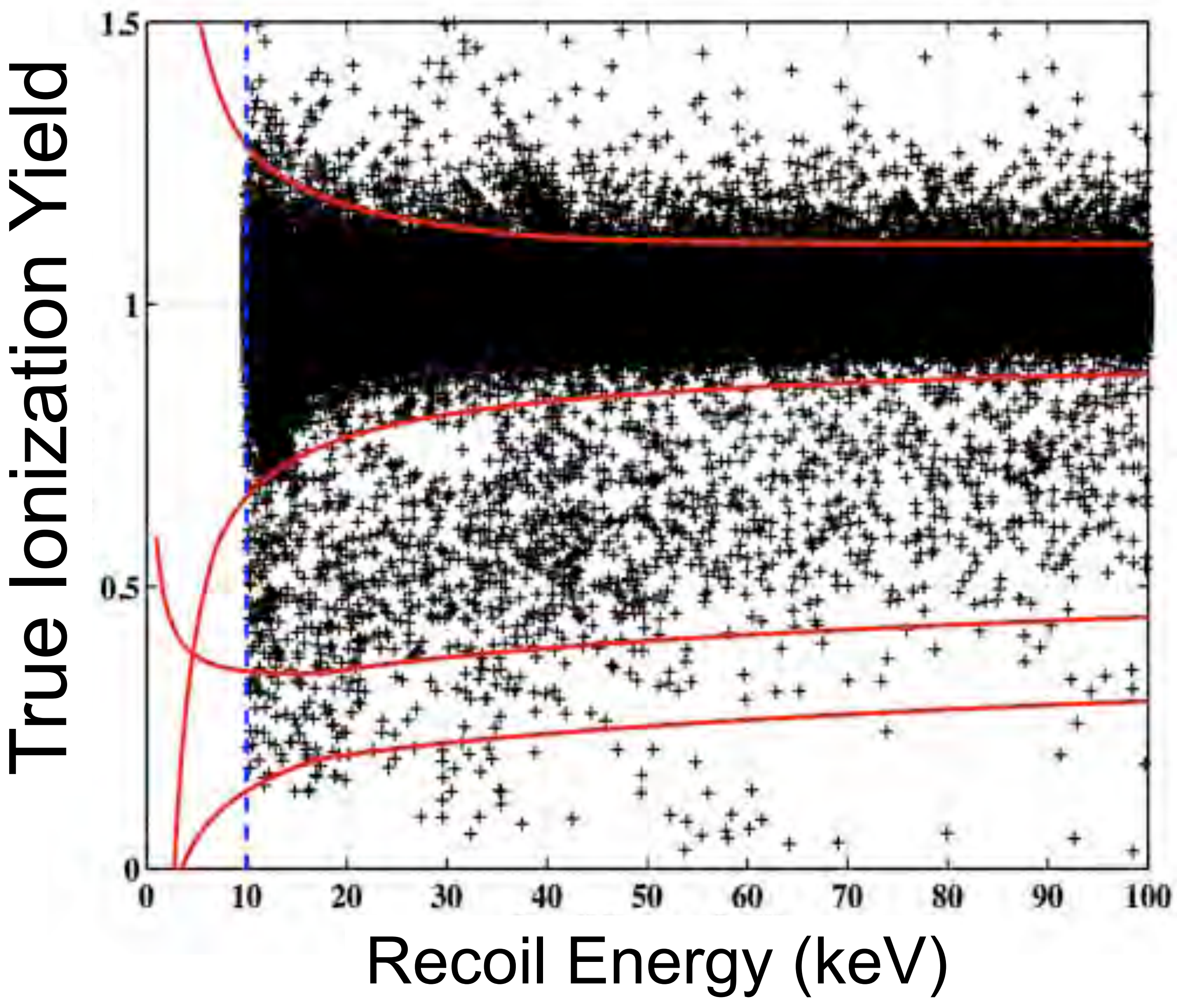
Opening the Box

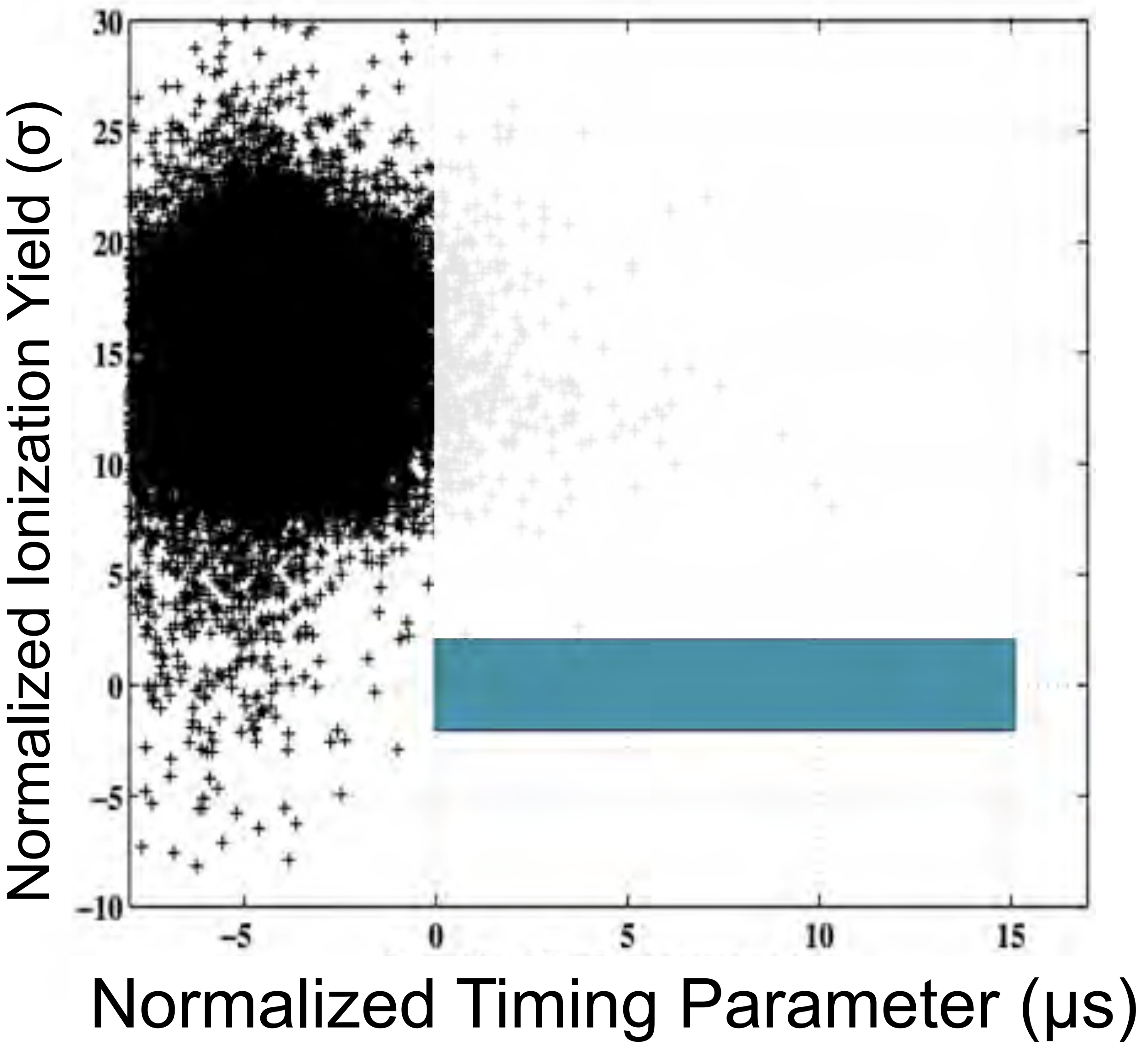
BLINDED:



Opening the Box

FAIL TIMING CUT:

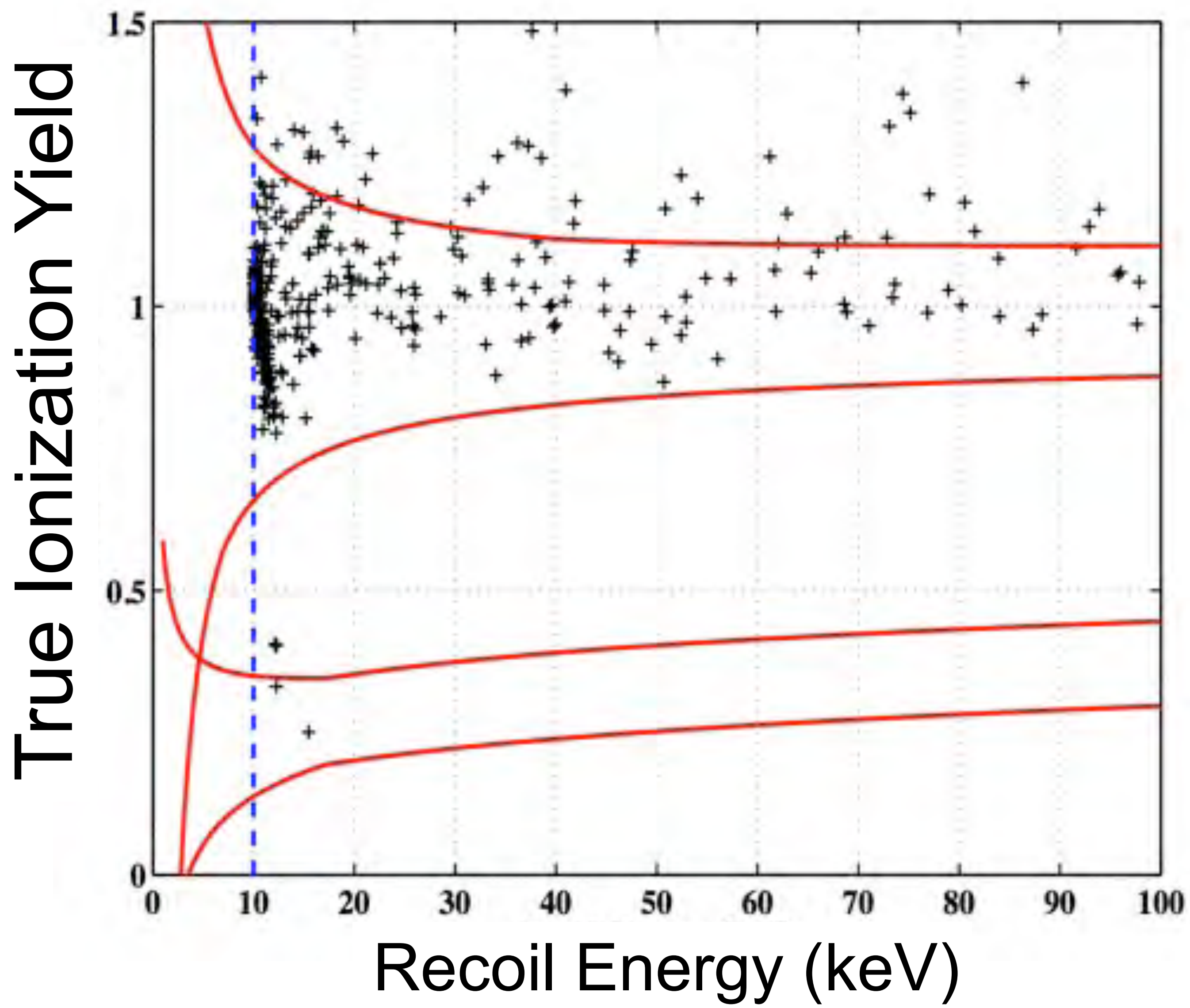


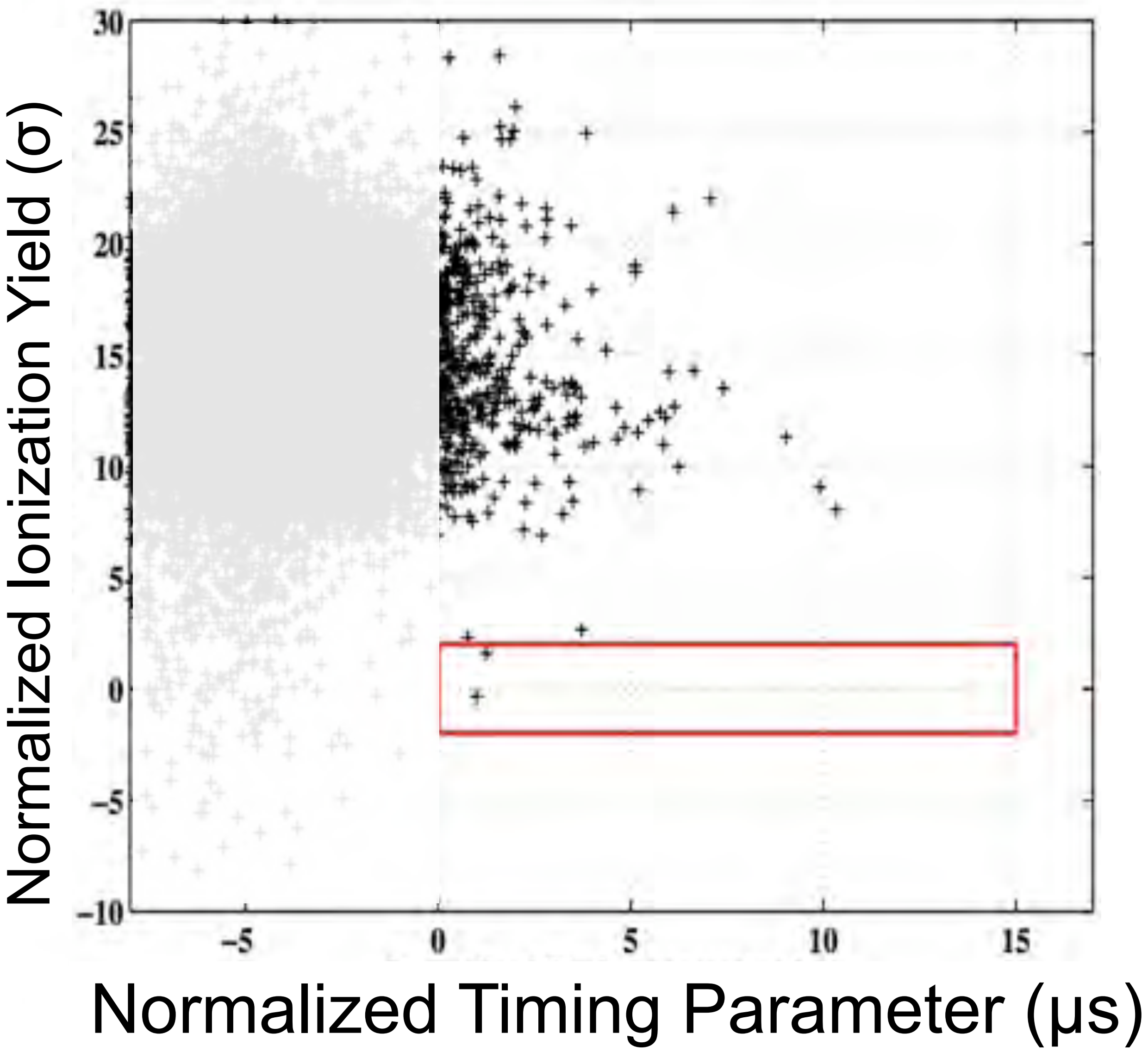


150 events in the NR band <u>fail</u> the timing cut, consistency checks deemed ok

Opening the Box

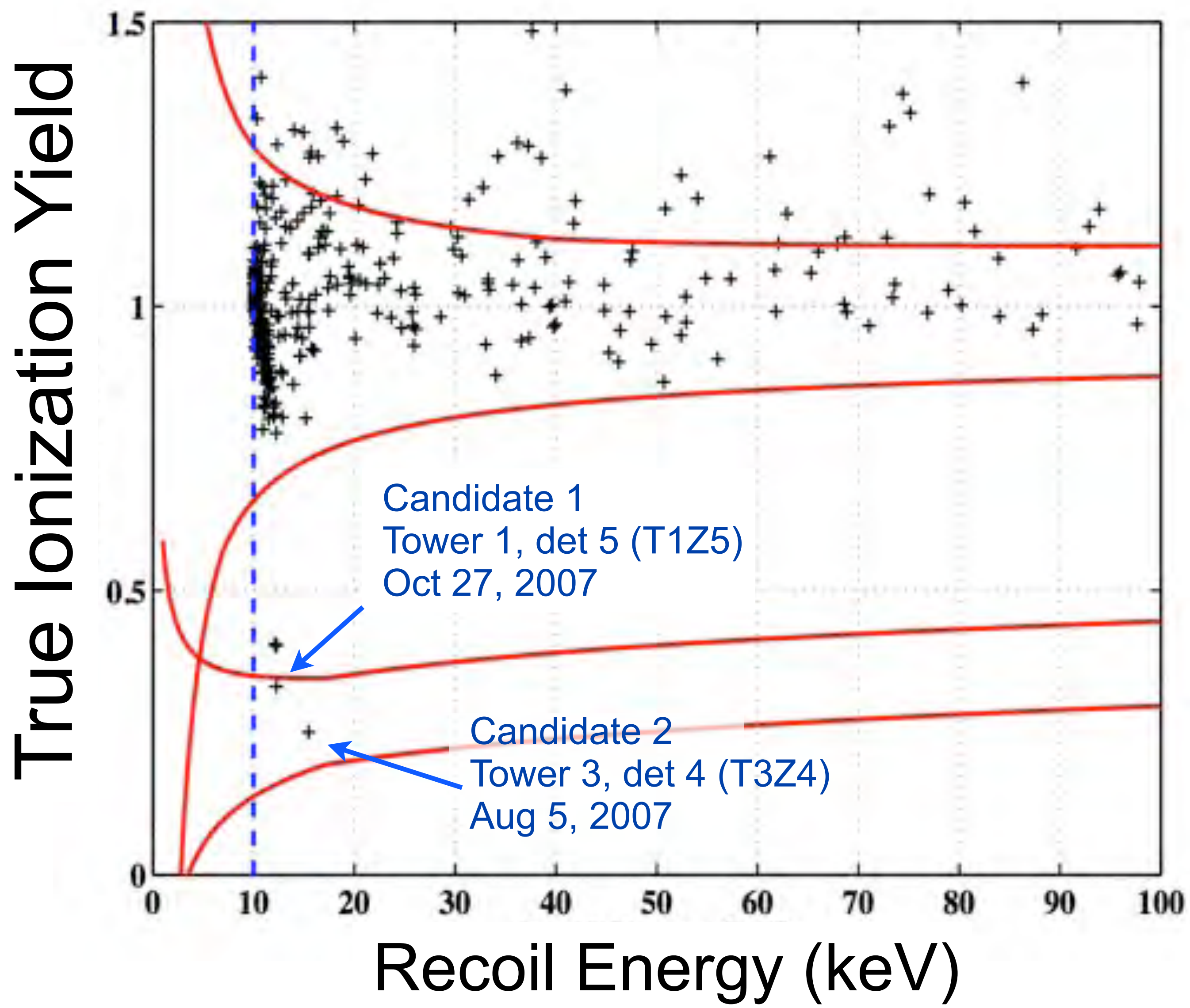
PASS TIMING CUT:

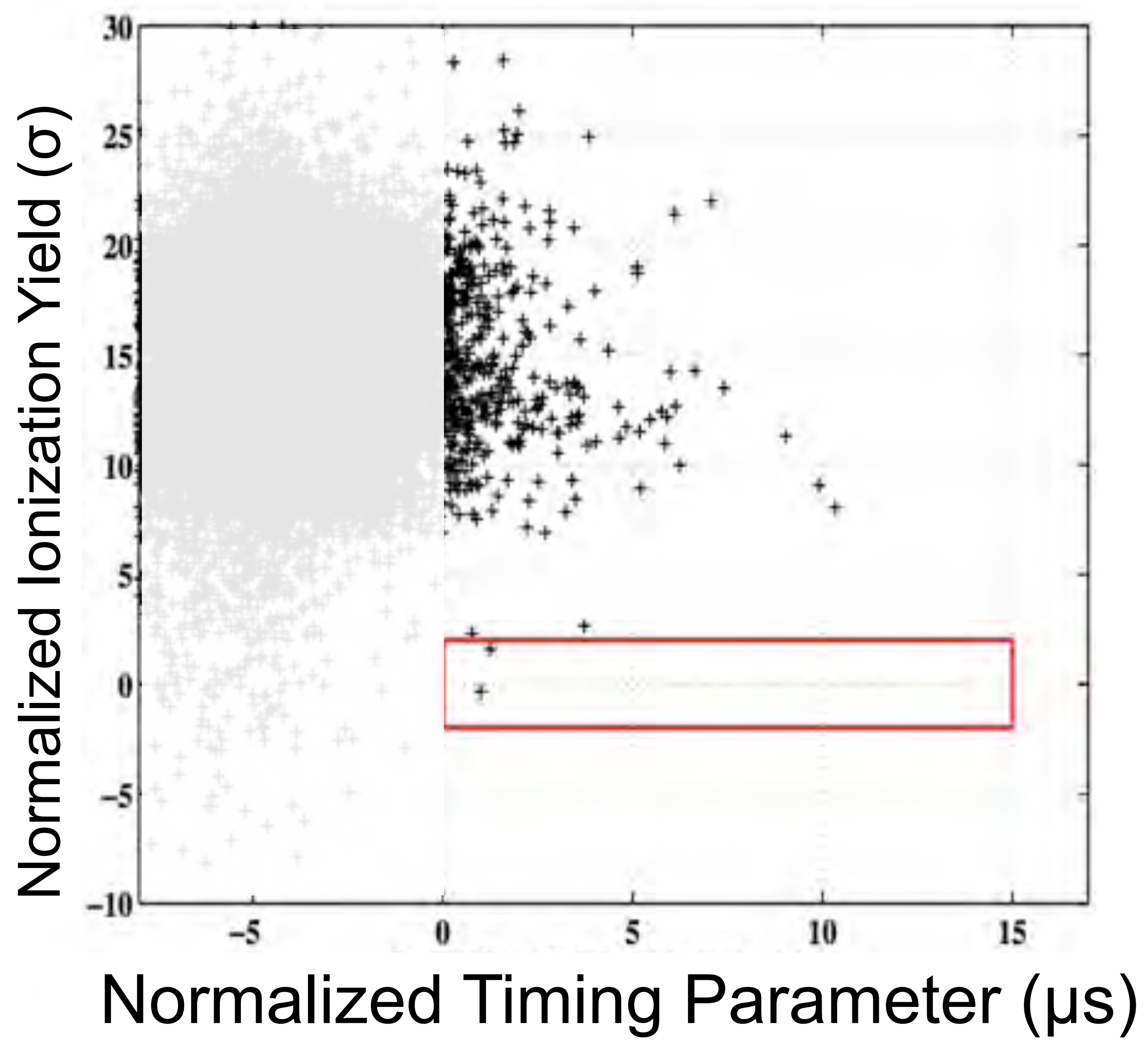




Opening the Box

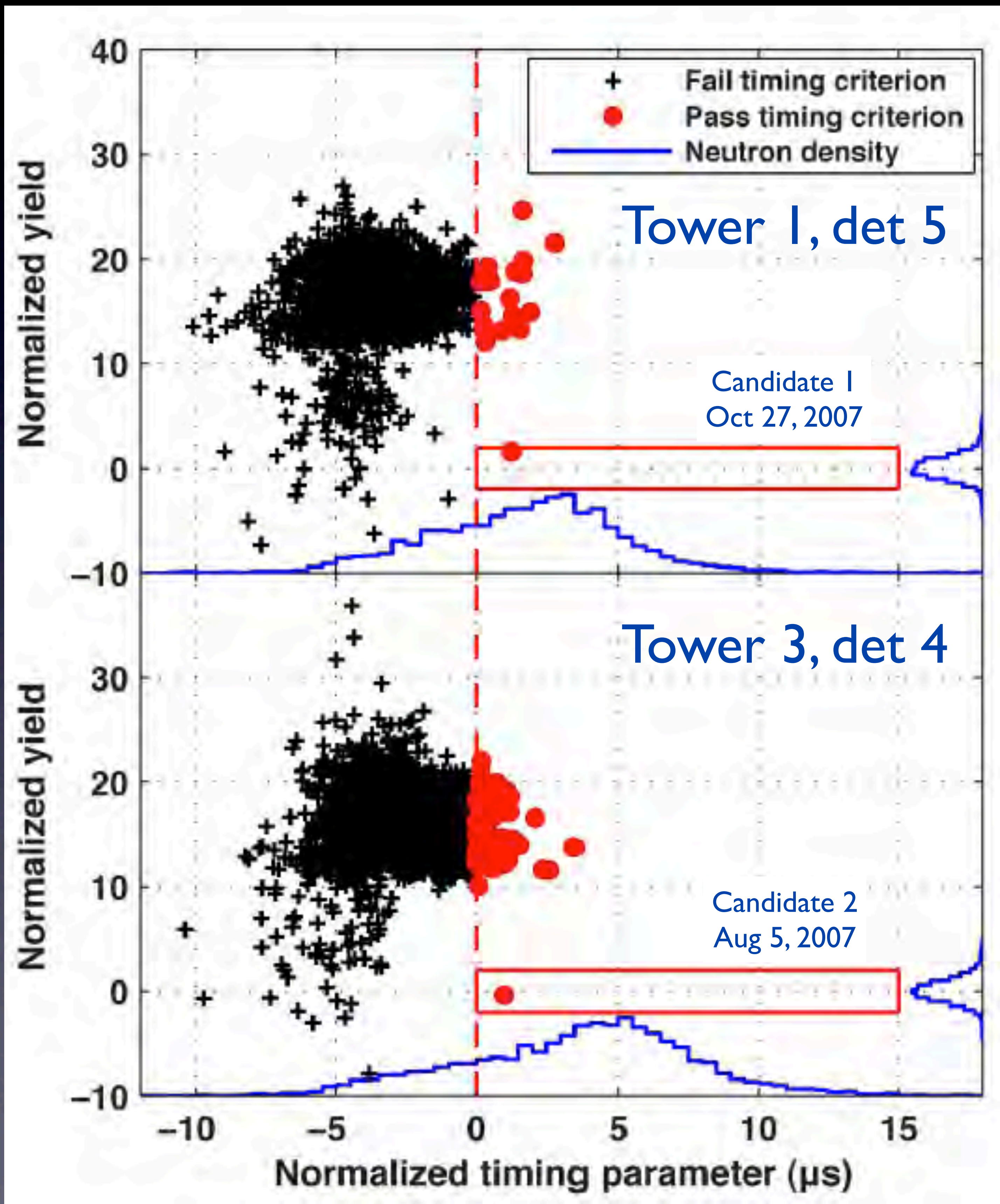
Two Events!





Post-Unblinding Analysis

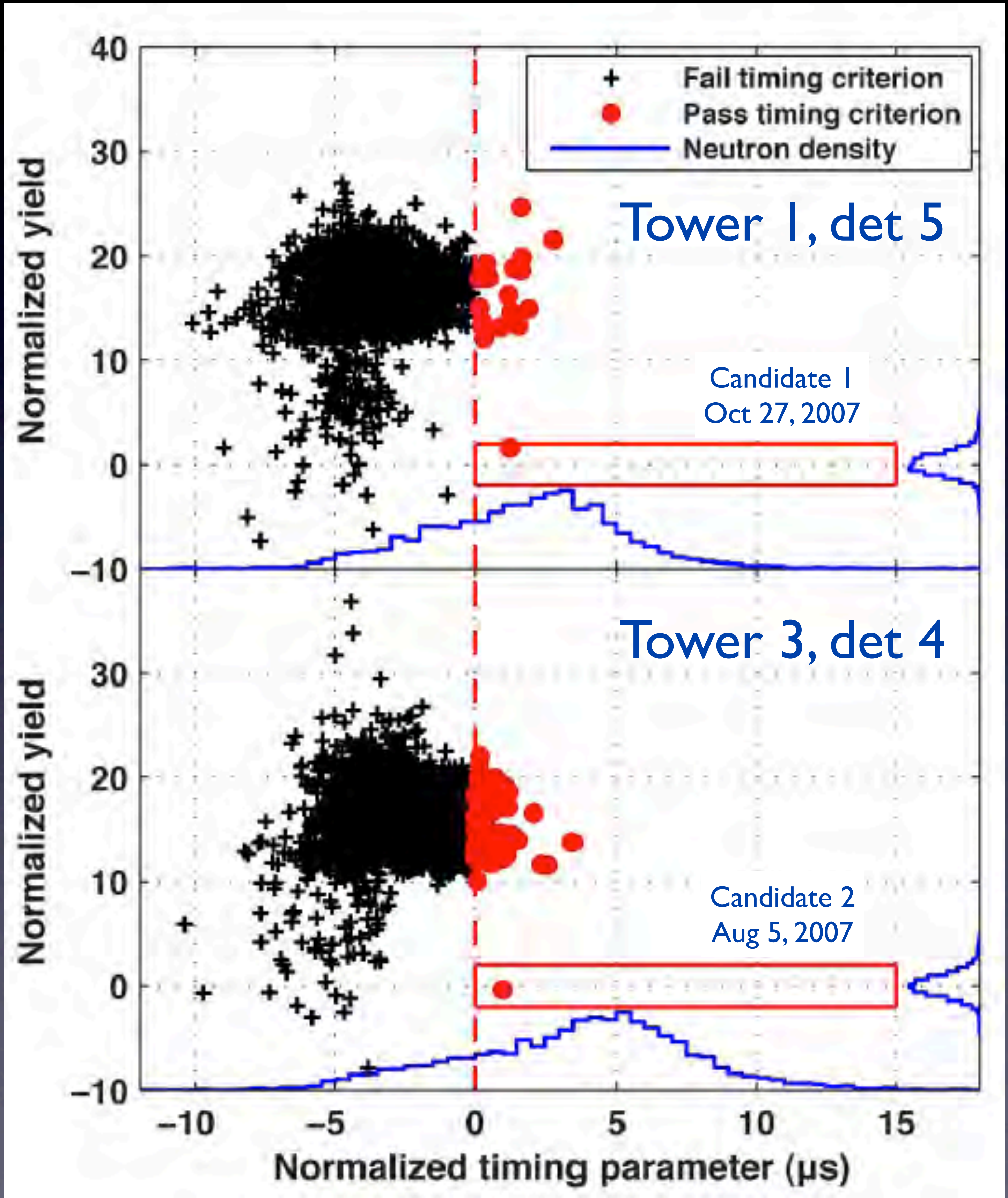
Post-Unblinding Analysis



What can we say post-unblinding?

- separated by several months
- two different detectors
- both *inner* detectors (surface leakage uncertainties low)

Post-Unblinding Analysis



What can we say post-unblinding?

check *everything*:

muon veto performance	good
charge trapping rates	normal
KS tests of distributions	good
noise levels	normal
pre-pulse baselines	normal
electron recoil rates	normal
surface event rates	normal
radial position	well-contained
single-scatter identification	good
special running conditions	no
operator recorded issues	no

Adjusted Background Estimate

Unnoticed systematic at low energies.

Surface Events:	~~0.6±0.1~~	Data (we *chose* this)
Cosmogenic Neutrons:	$0.04^{+0.04}_{-0.03}$	vetoed Data x $\left(\frac{\text{unvetoed}}{\text{vetoed}}\right)$ Monte Carlo
Radiogenic Neutrons:	$0.057^{+0.0035}_{-0.02}$	Materials Testing & Monte Carlo

Adjusted Background Estimate

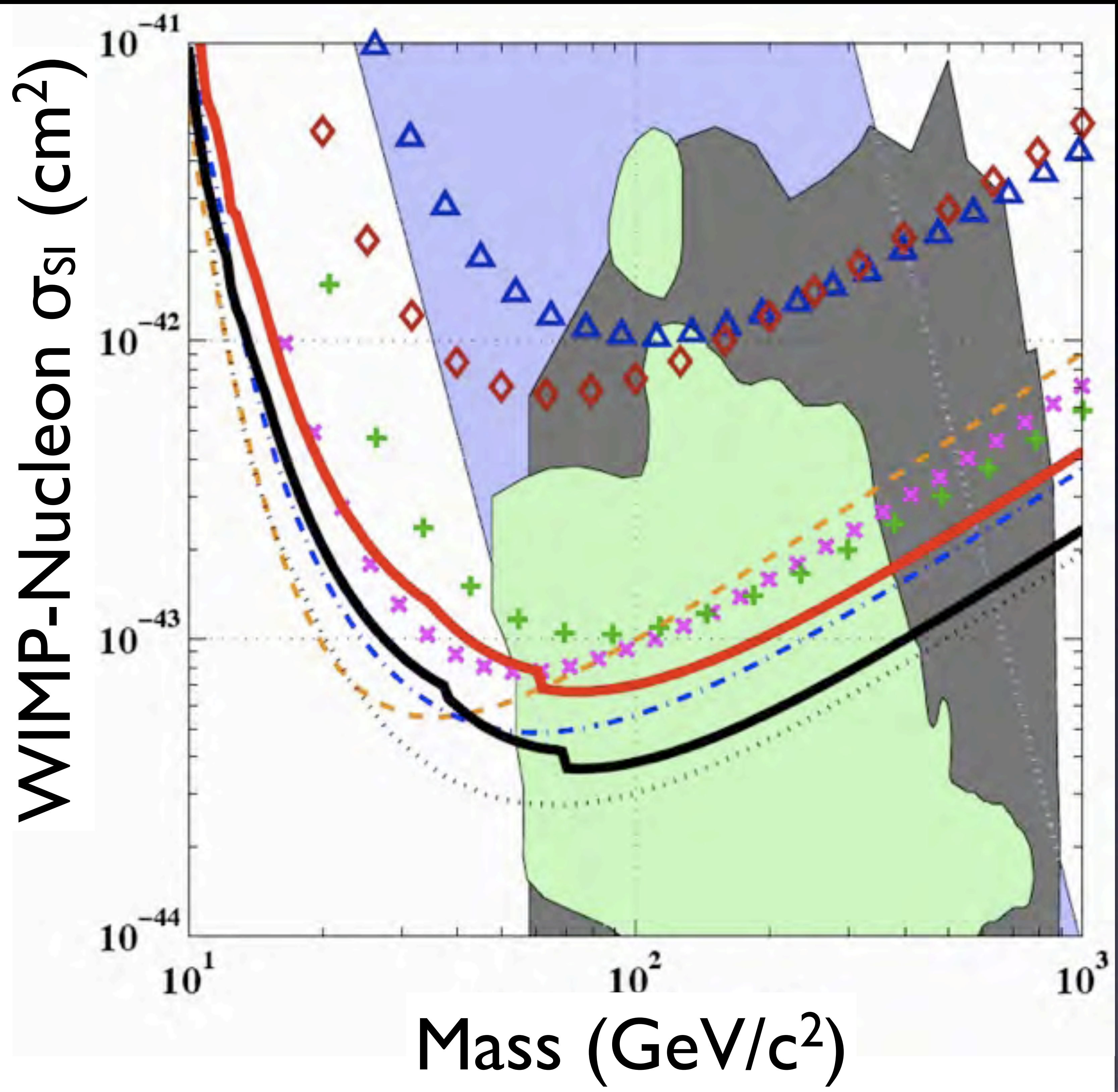
Surface Events: **0.82** $^{+0.12}_{-0.10}$ (stat) $^{+0.20}_{-0.19}$ (syst) — Data (we *ended* with this)

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

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

Probability of 2 or more leakage events : ~23%

New σ_{SI} Upper Limit

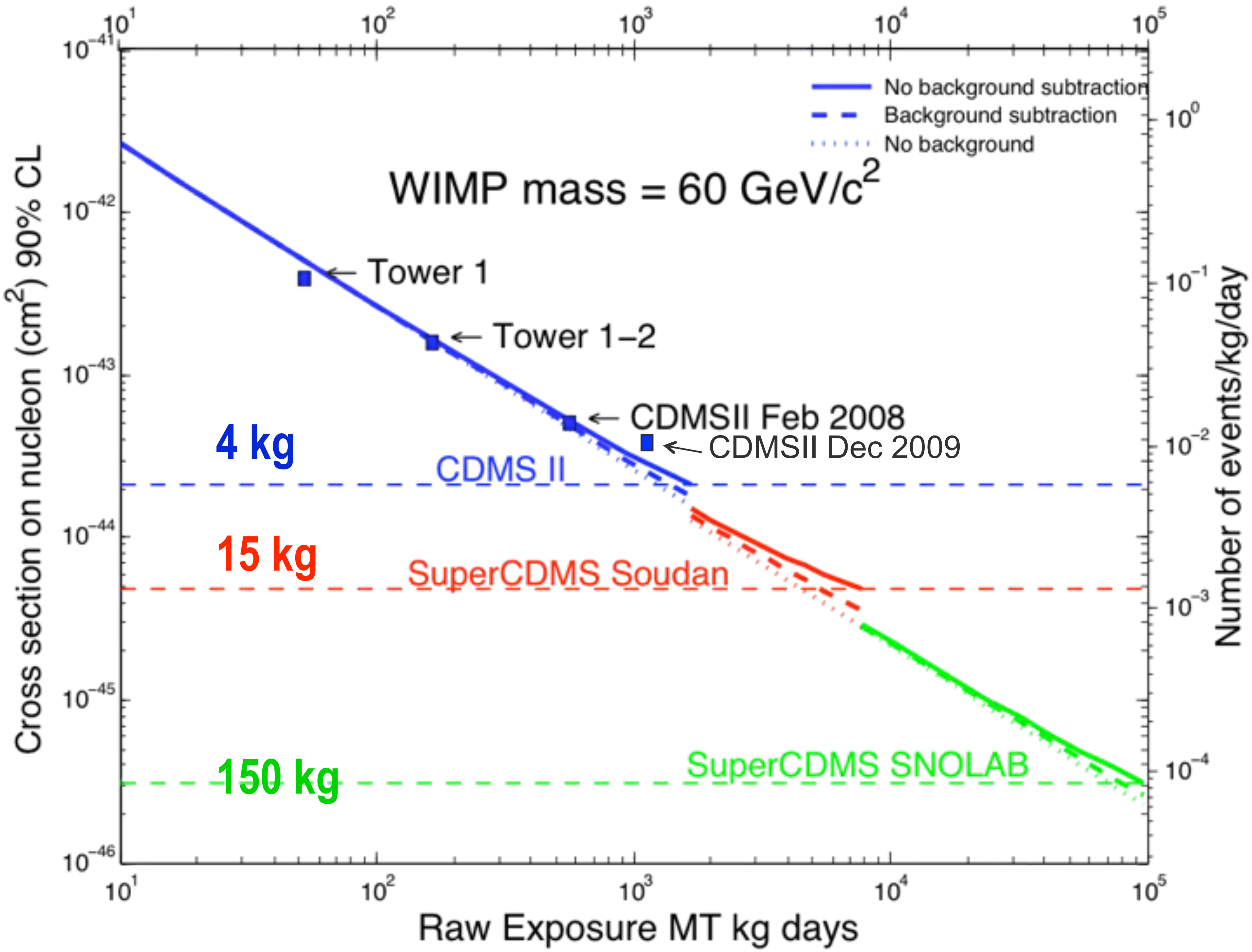


2008 Result
at 70 GeV: **7.0 x 10^{-44} cm^2**

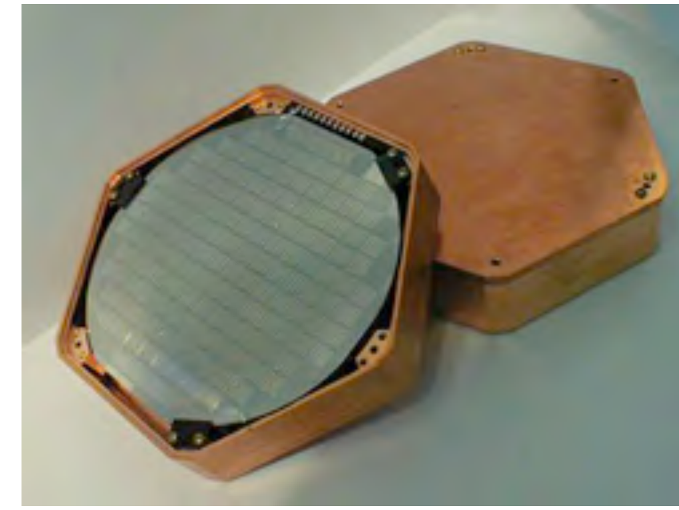
2010 Result
at 70 GeV: **3.8 x 10^{-44} cm^2**

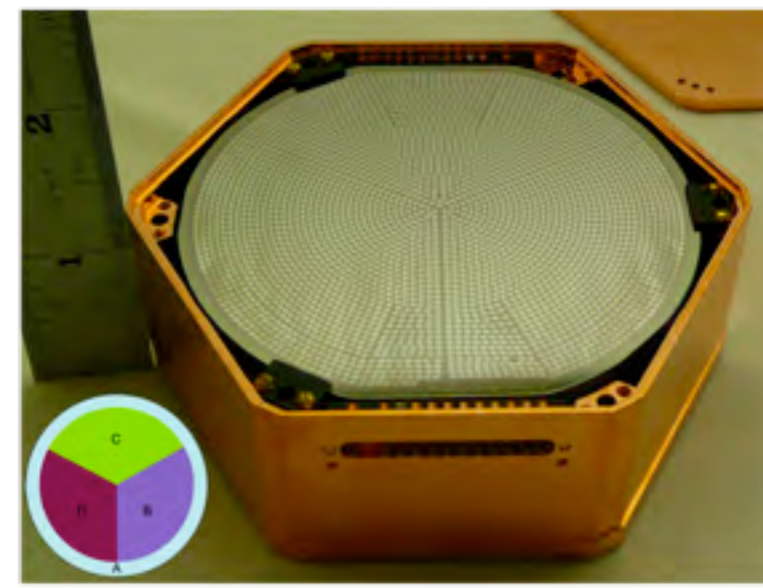
DOI: 10.1126/science.1186112

SuperCDMS phases - Moore's Law if zero bkgd



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





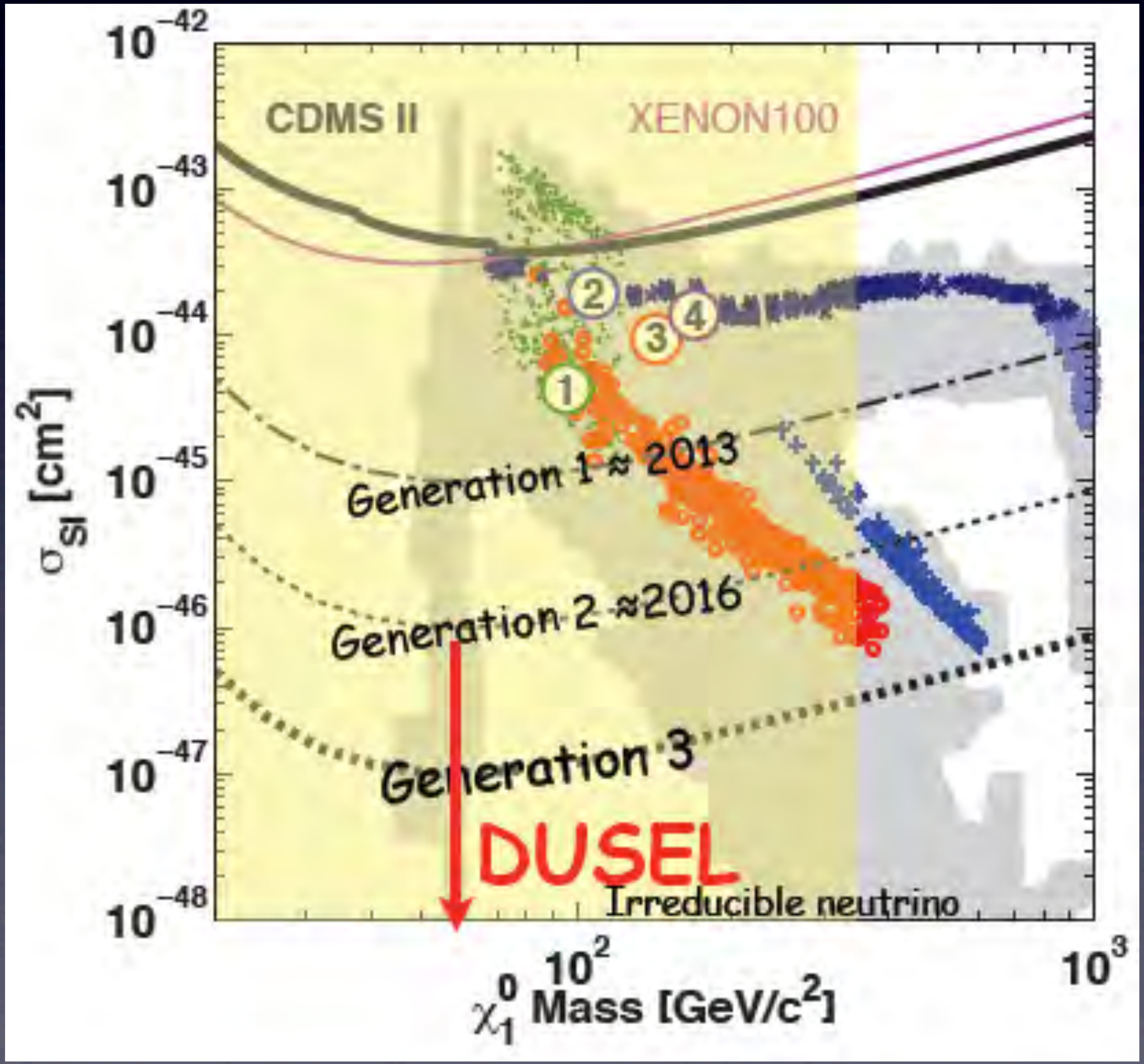
GEODM

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 Nobels, Bubble Chambers, Scintillators, and Cryogenic Detectors.



The Future

- 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.

Exciting Times Ahead!