Dark Matter Direct Detection Searches and Techniques

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TASI: The Dark Secrets of the Terascale

University of Colorado, Boulder

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Outline

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

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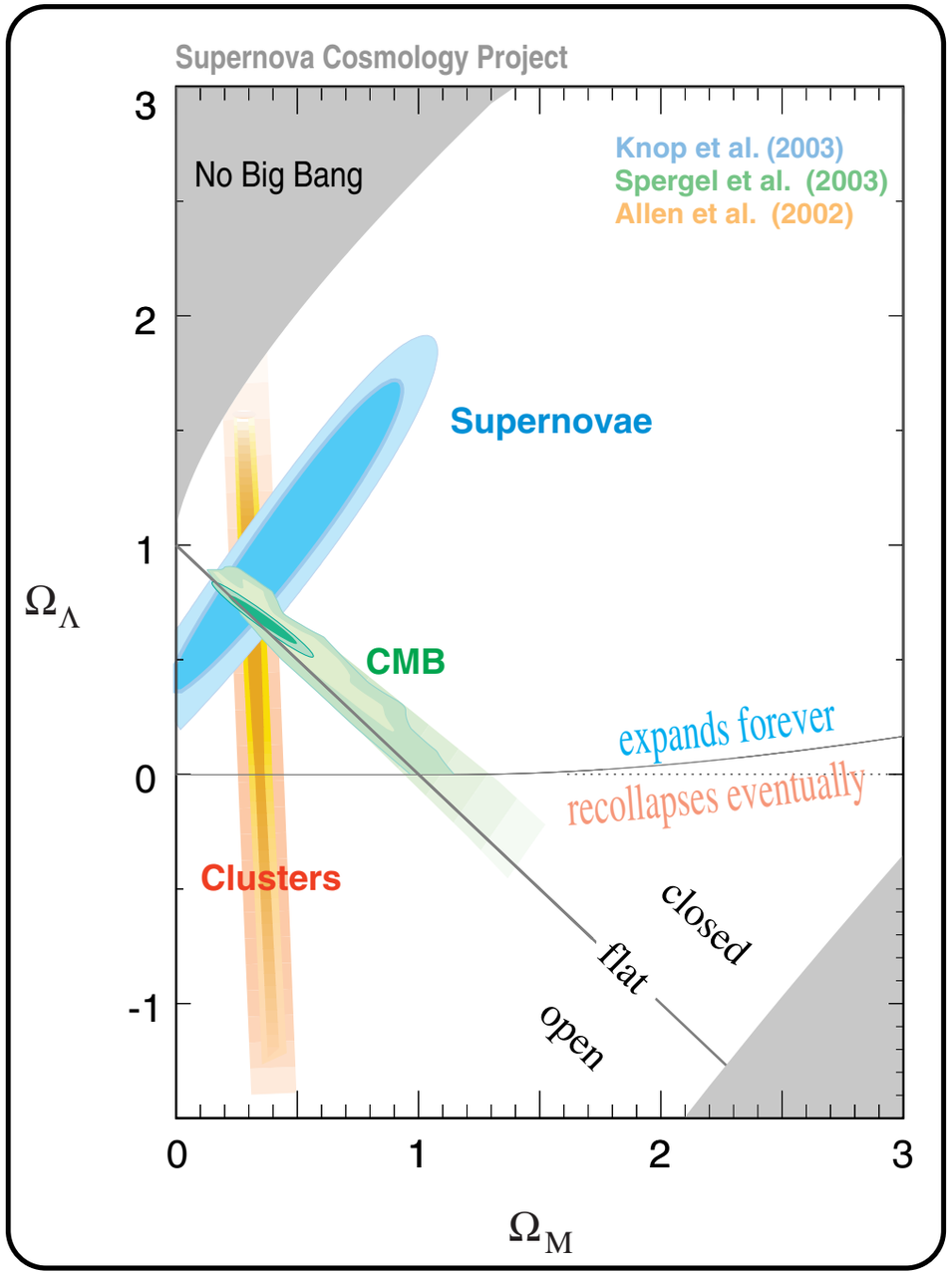
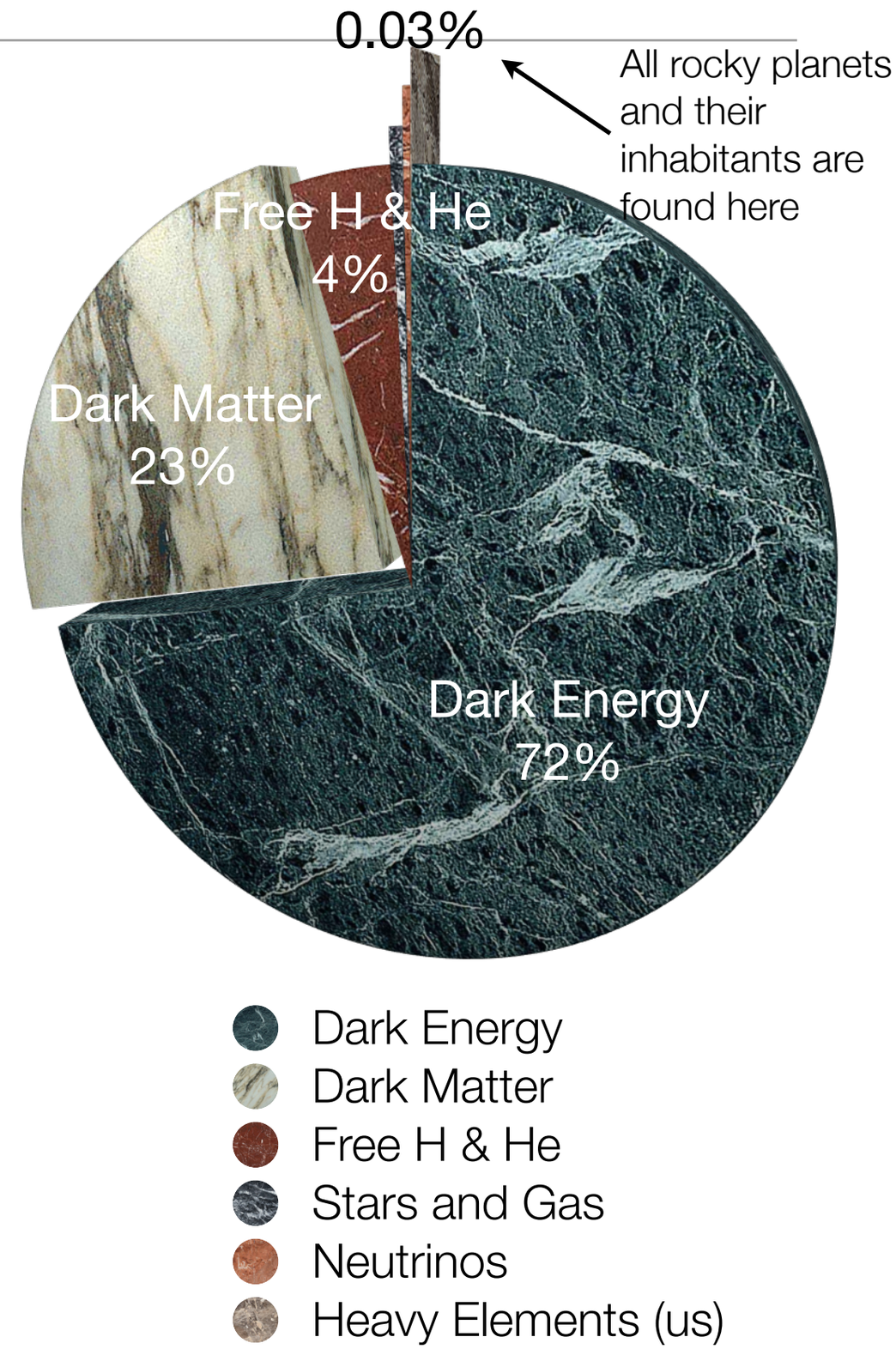
The Concordance Model of Cosmology





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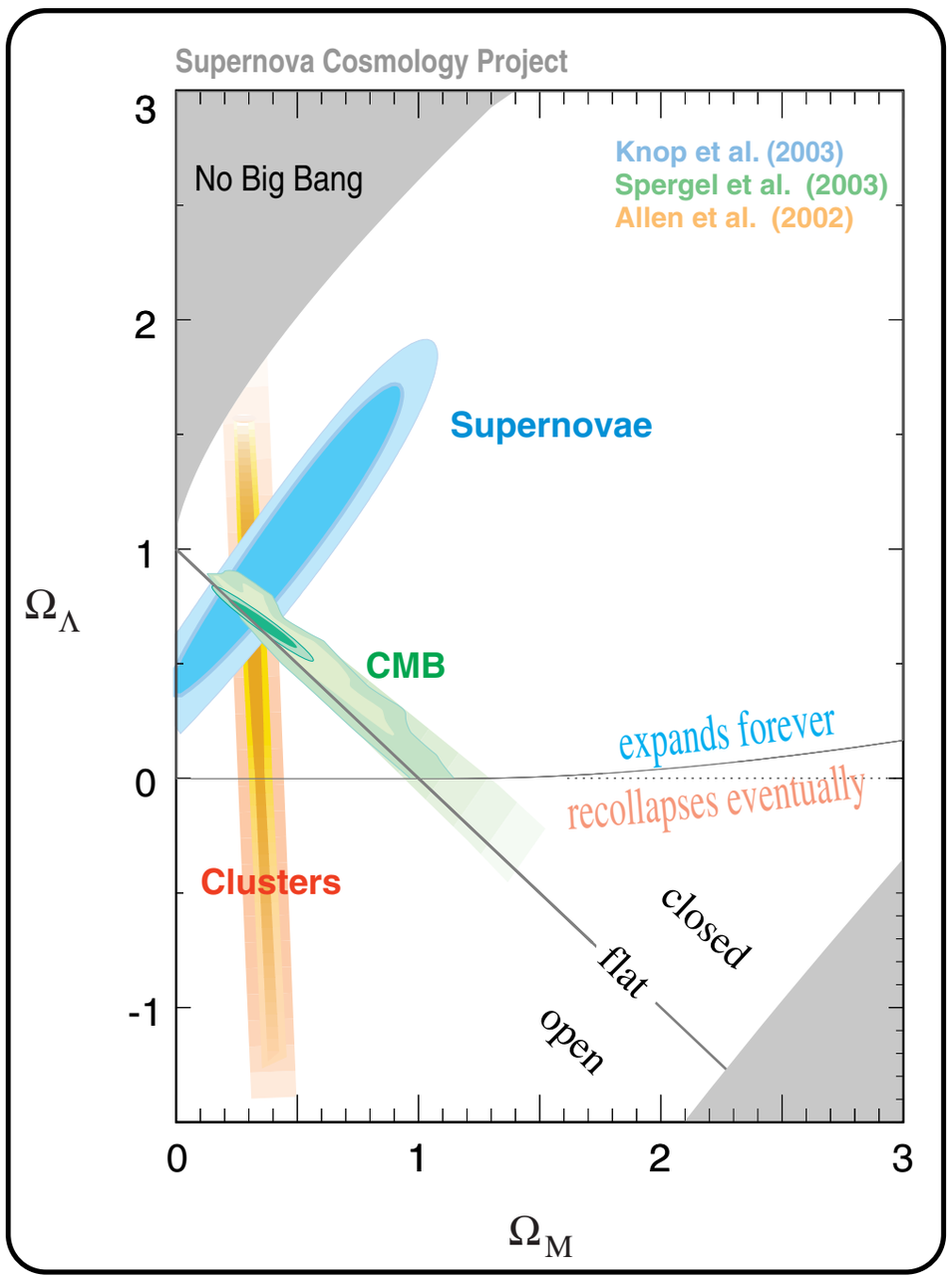
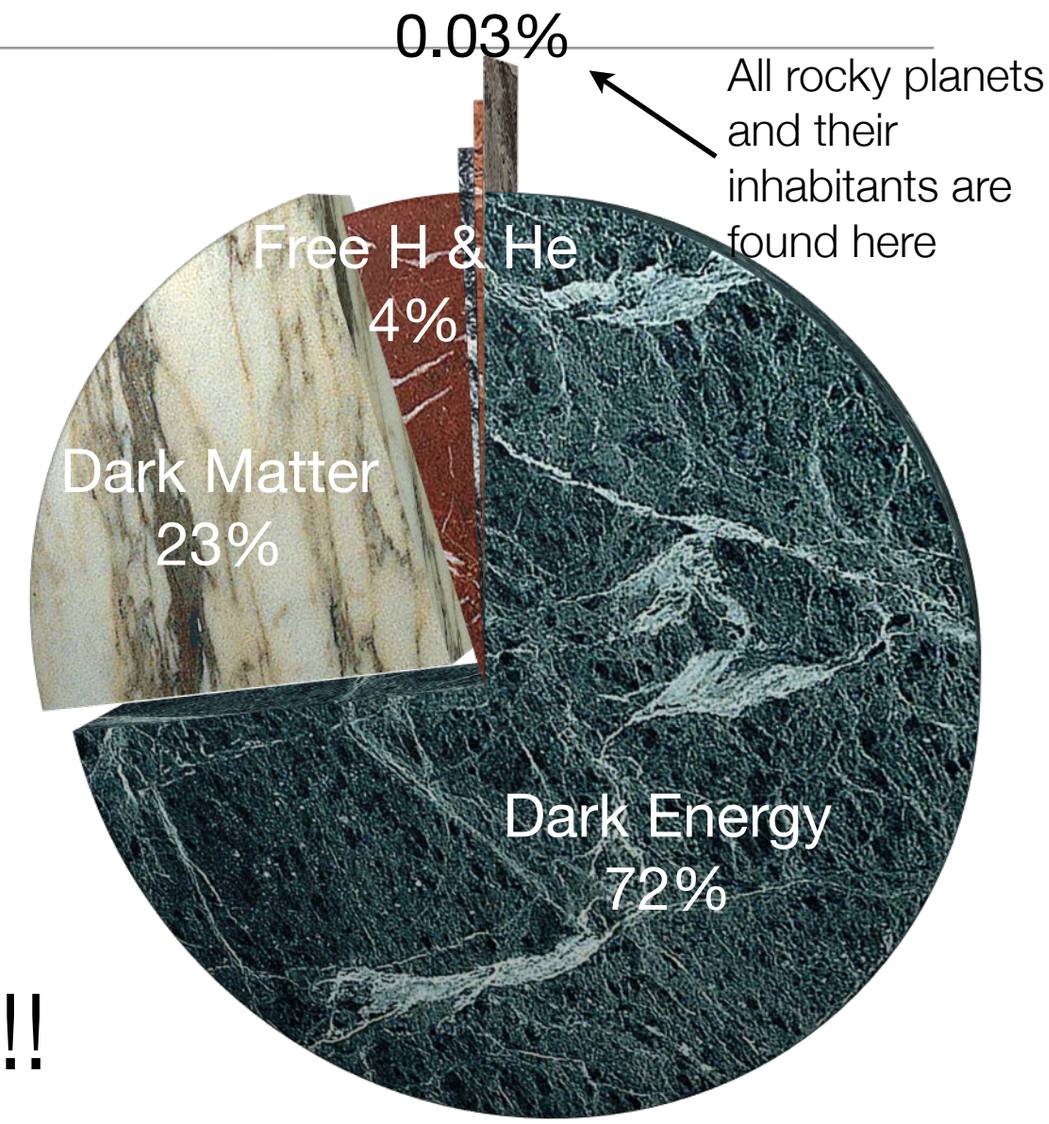


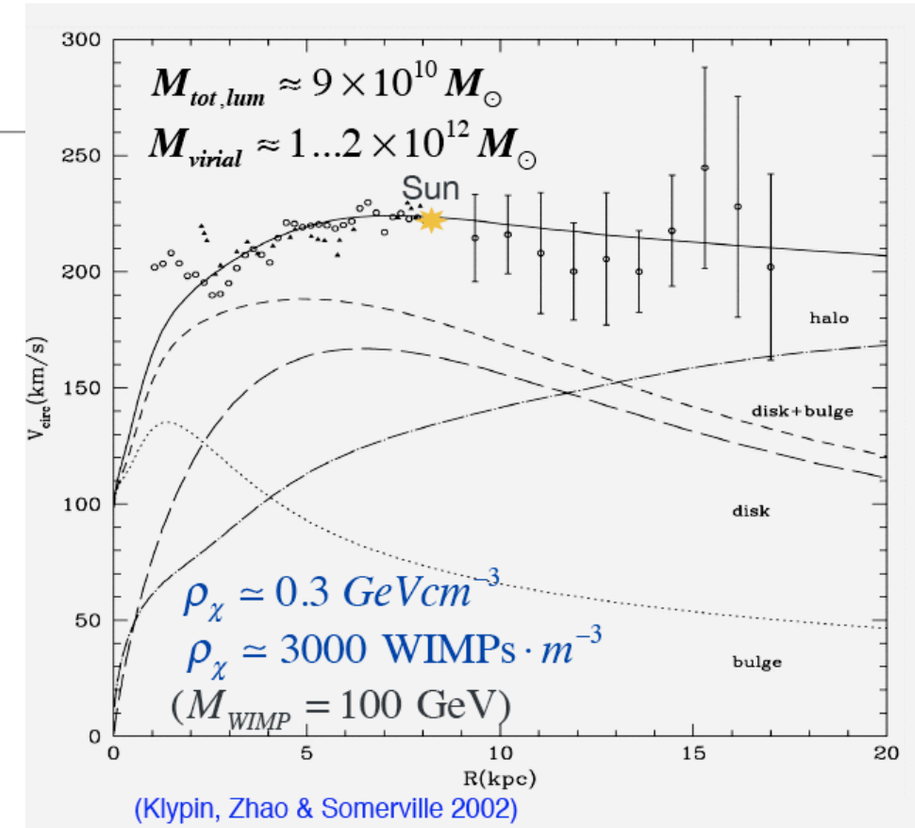
We don't know what 96% of the Universe is made of!!!



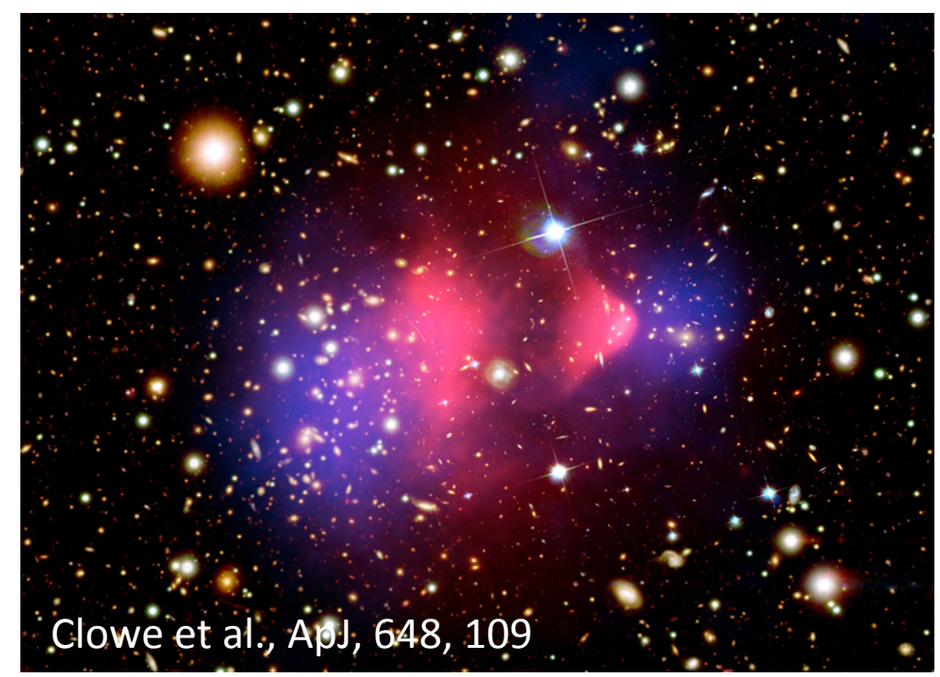
- Dark Energy
- Dark Matter
- Free H & He
- Stars and Gas
- Neutrinos
- Heavy Elements (us)

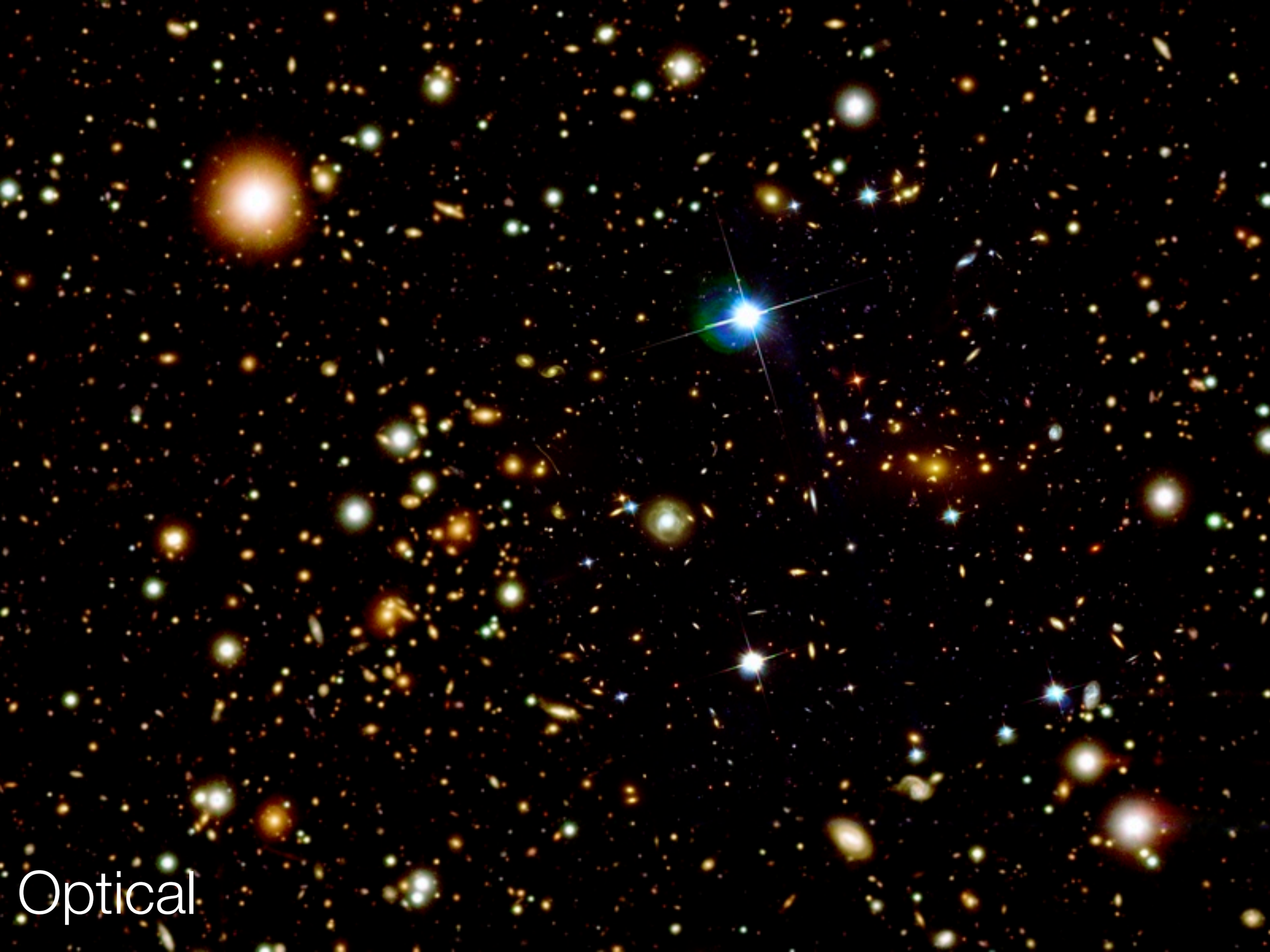
The Nature of Dark Matter

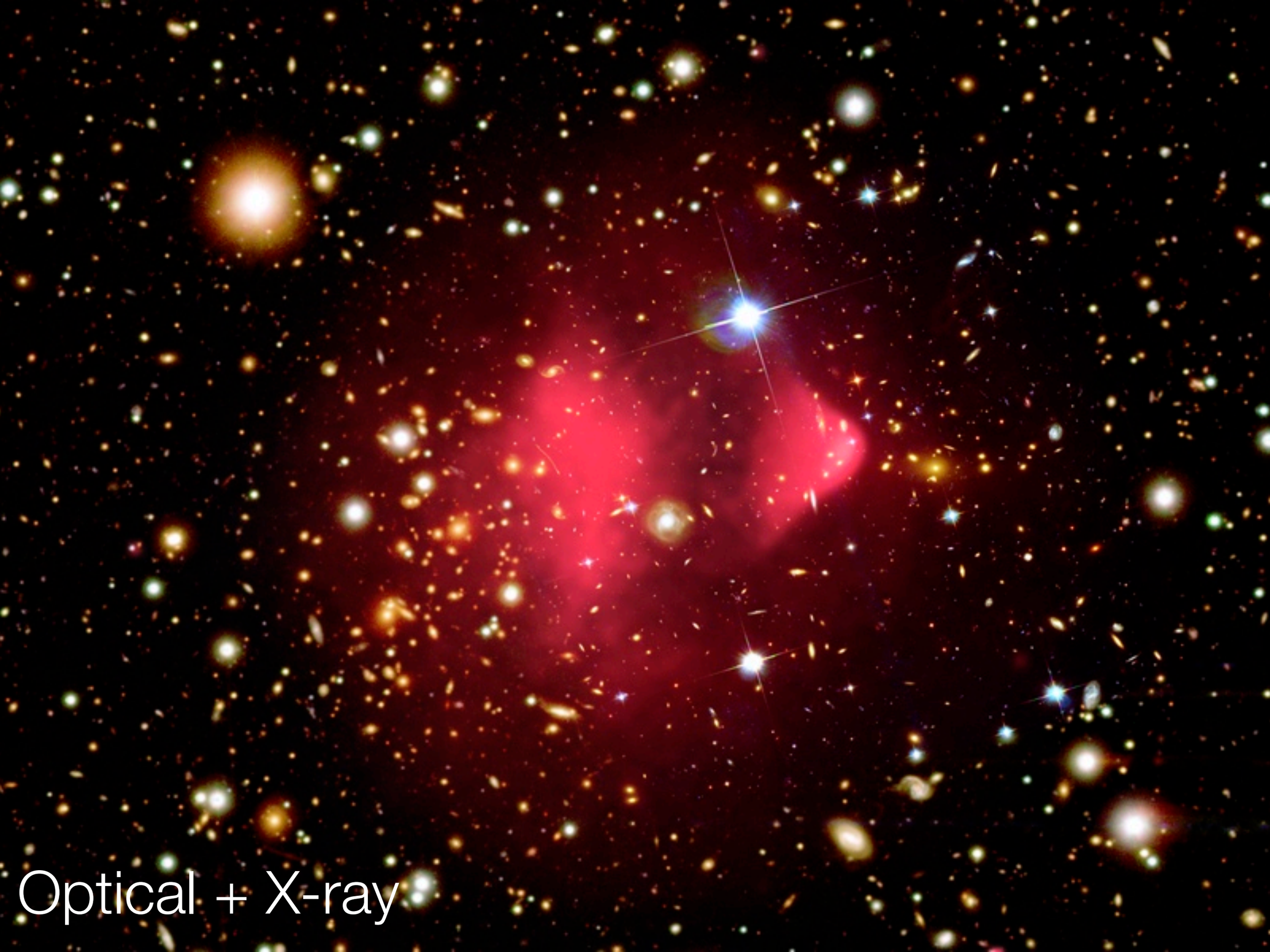
- The Missing Mass Problem:
  - Dynamics of stars, galaxies, and clusters
  - Rotation curves, gas density, gravitational lensing
  - Large Scale Structure formation
- Wealth of evidence for a particle solution
  - MOND has problems with Bullet Cluster
  - Microlensing (MACHOs) mostly ruled out
- Non-baryonic
  - 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

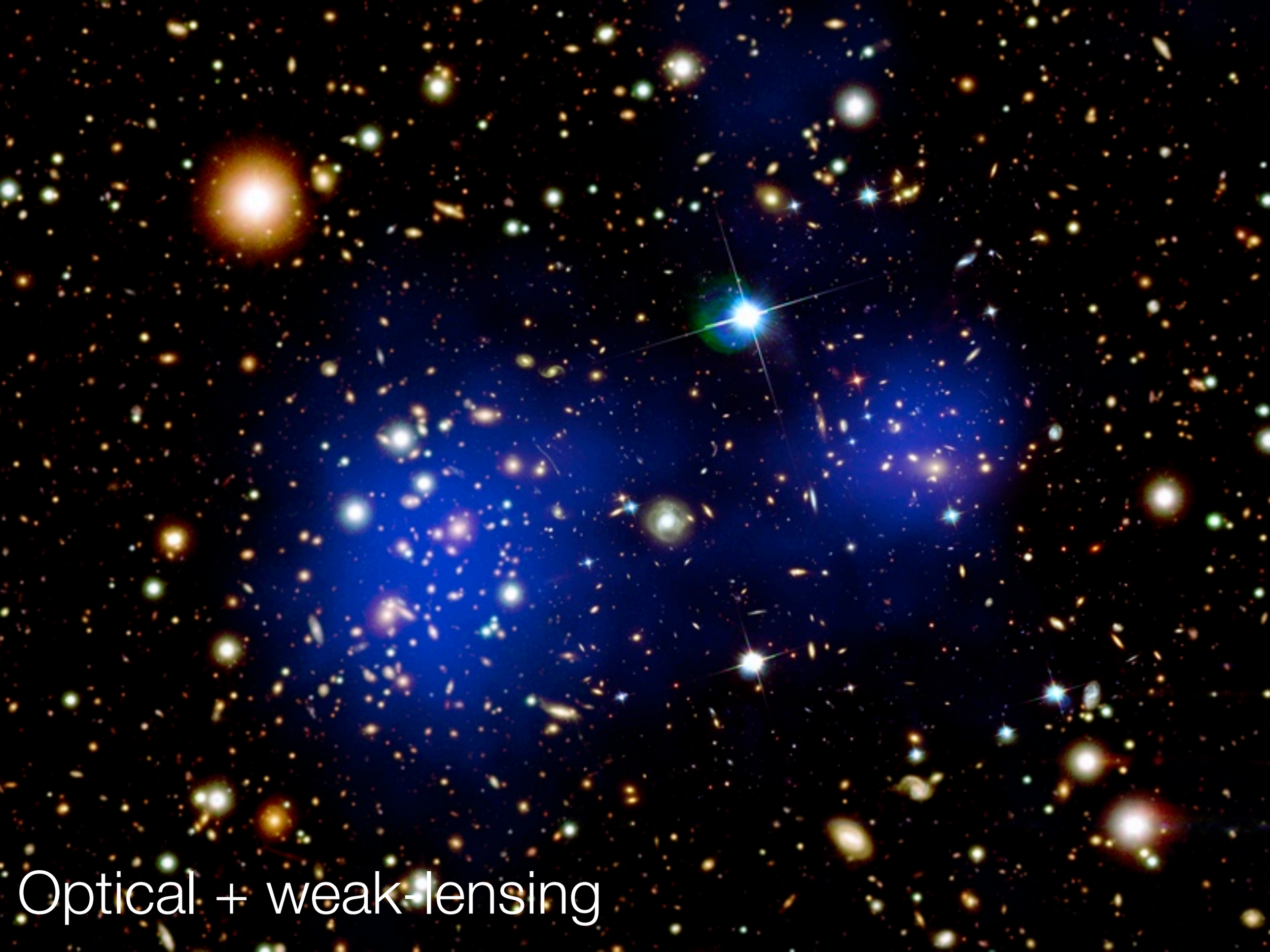


(Klypin, Zhao & Somerville 2002)

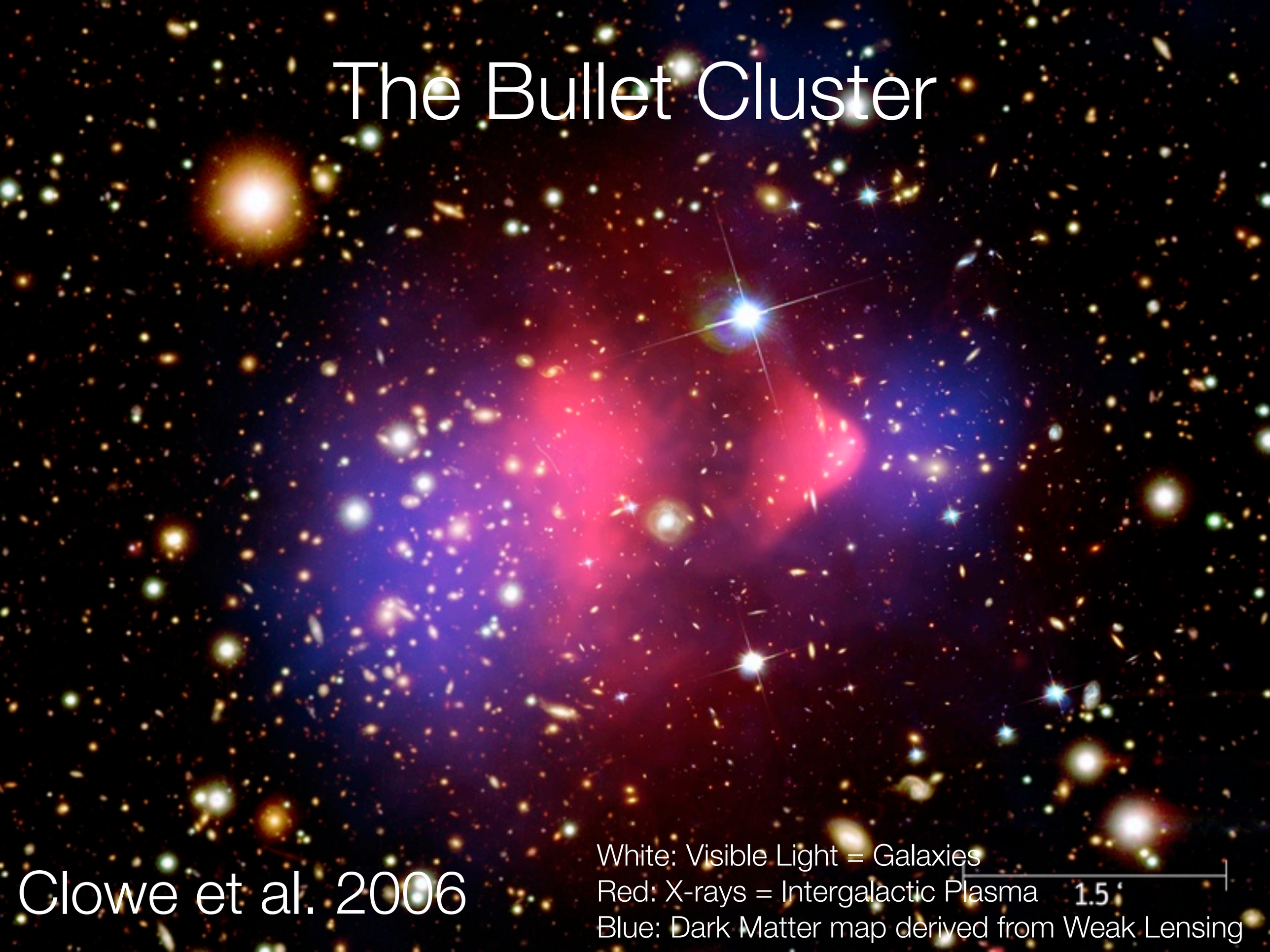

Clowe et al., ApJ, 648, 109


Optical


Optical + X-ray


Optical + weak-lensing

The Bullet Cluster

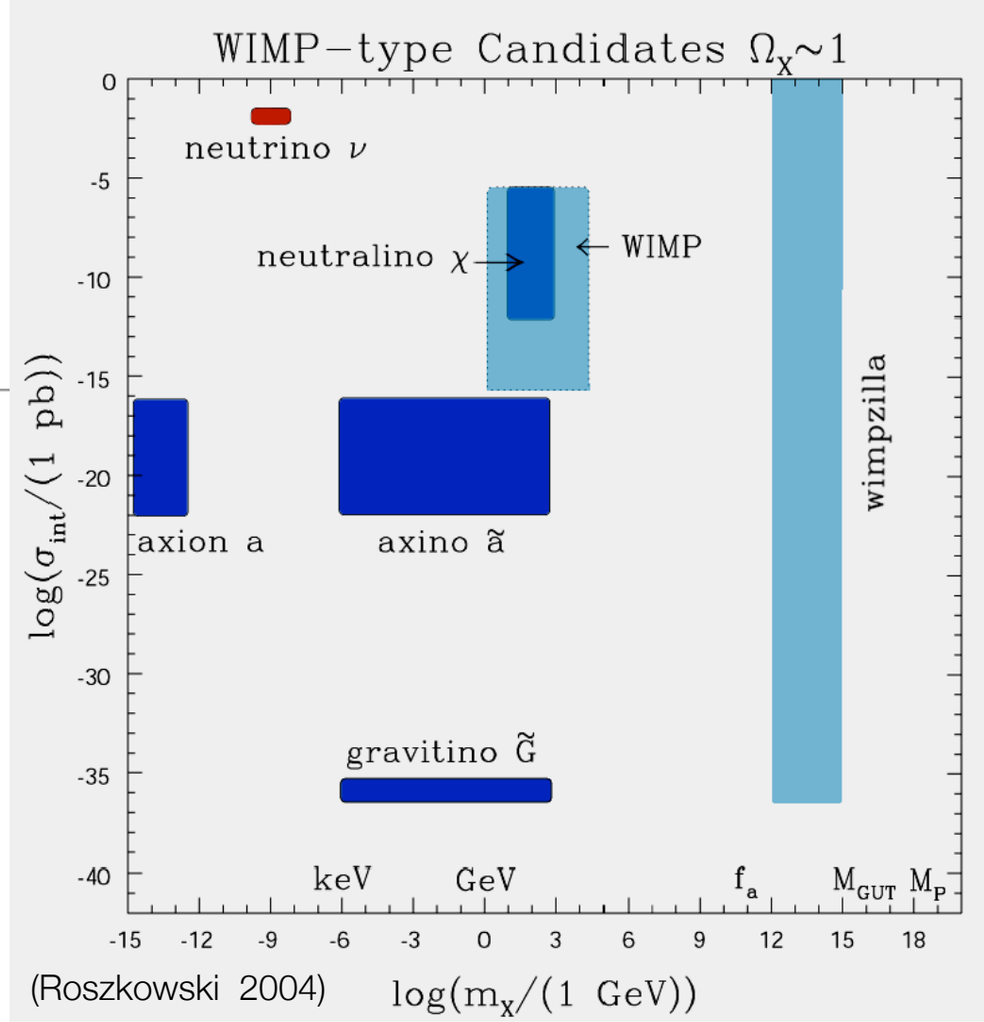


Clowe et al. 2006

White: Visible Light = Galaxies
Red: X-rays = Intergalactic Plasma
Blue: Dark Matter map derived from Weak Lensing

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



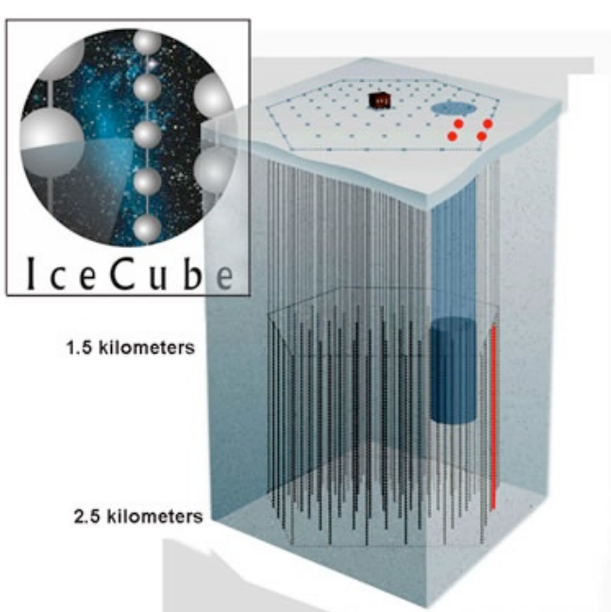
(Roszkowski 2004)

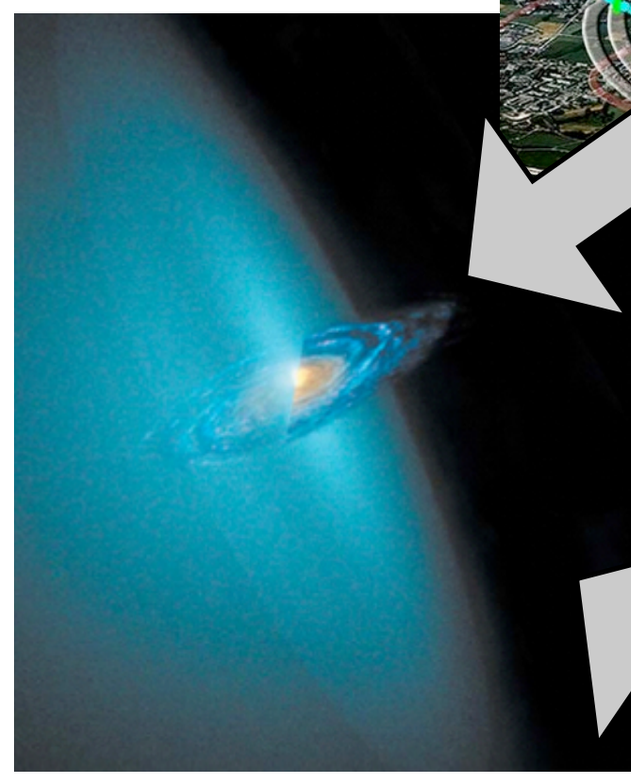
- The Lightest Super Particle (LSP) in many Minimally Supersymmetric Standard Models is a viable candidate. These are called Weakly Interacting Massive Particles: WIMPs

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

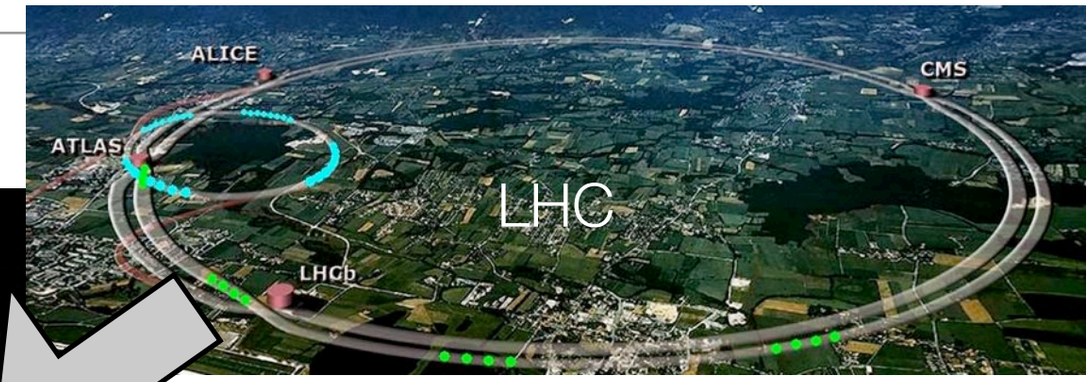
The Hunt for Dark Matter

Annihilation in the Cosmos



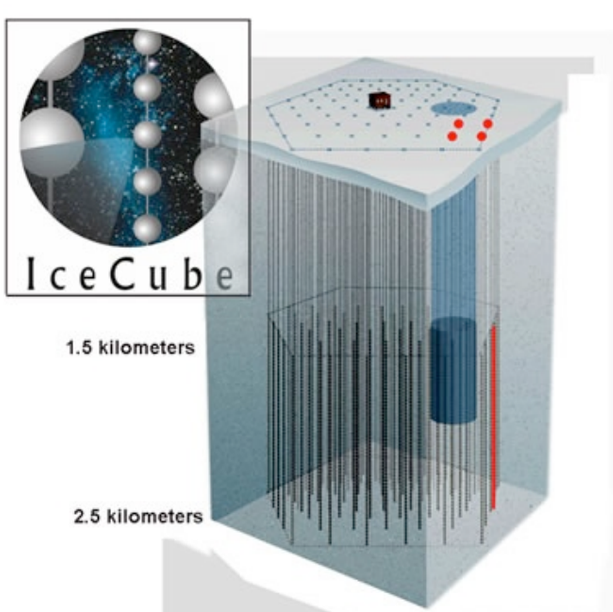


Production in Colliders



Scattering in Terrestrial Detectors

The Hunt for Dark Matter



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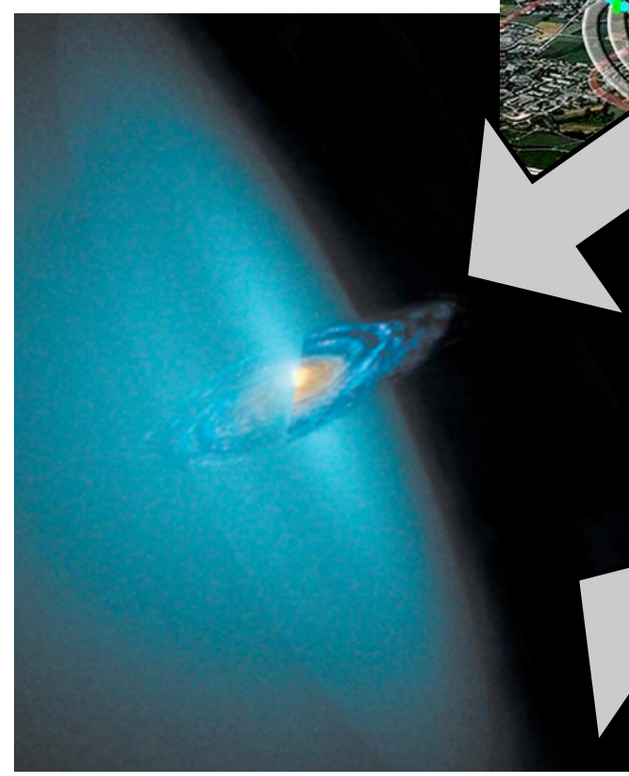

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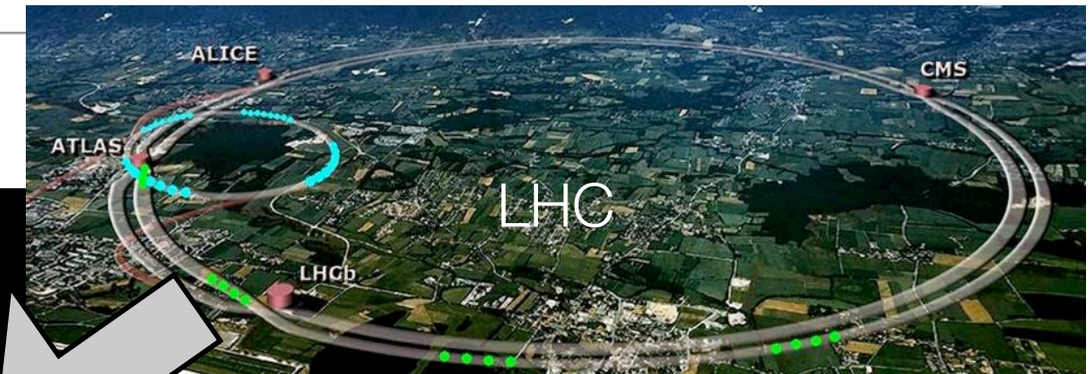

Scattering in Terrestrial Detectors

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  - WIMP-Nucleus Interactions
  - WIMP-Detector Interactions
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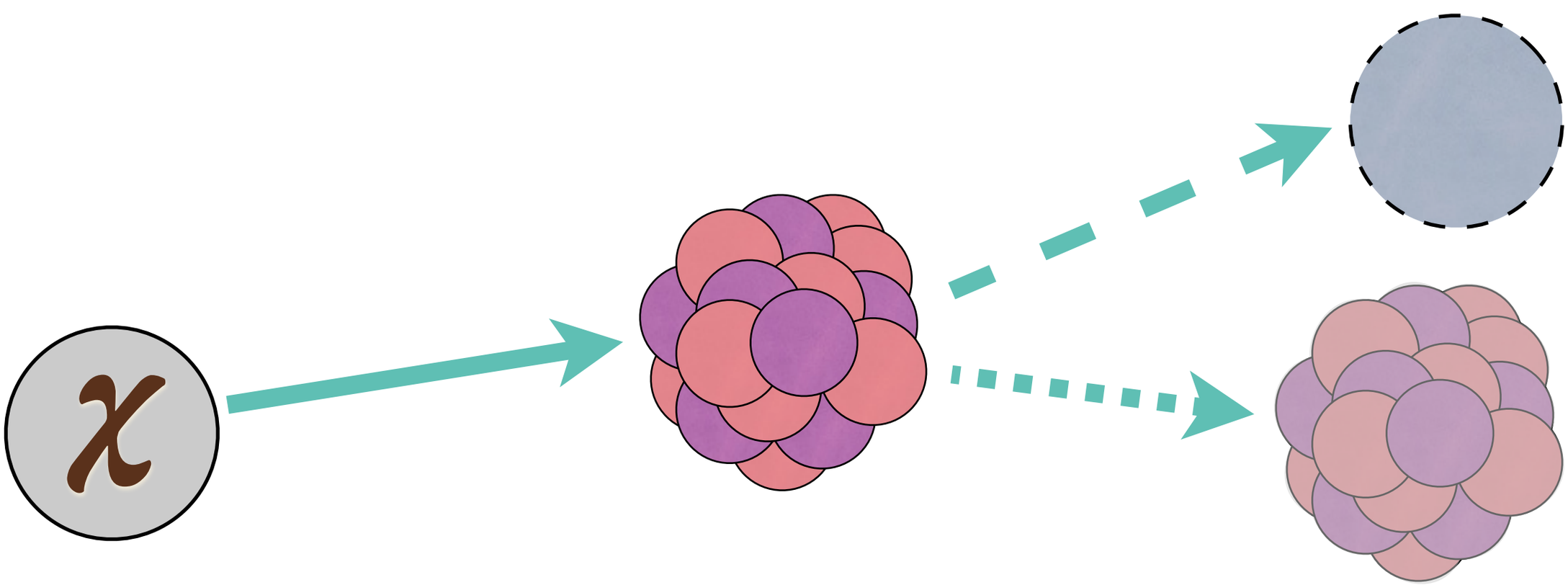
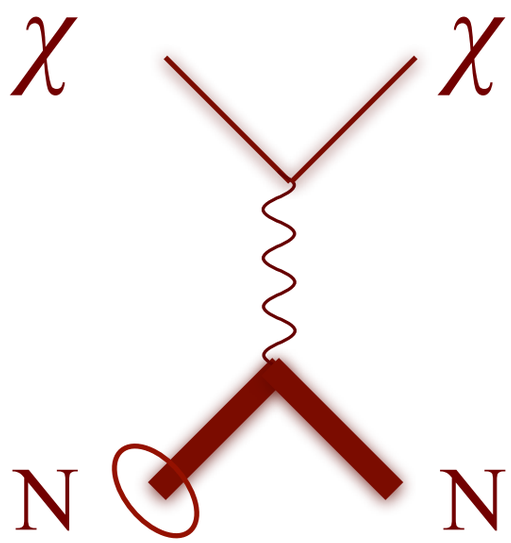
Principles of Direct Detection

- Elastic scattering of the neutralino off of a nucleus :
  - Can occur via spin-dependent/independent channels
  - Must be able to detect the small amount of energy imparted to the recoiling nucleus
  - Distinguish this event from the overwhelming number of background events.



Wimp-nucleus Interaction

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



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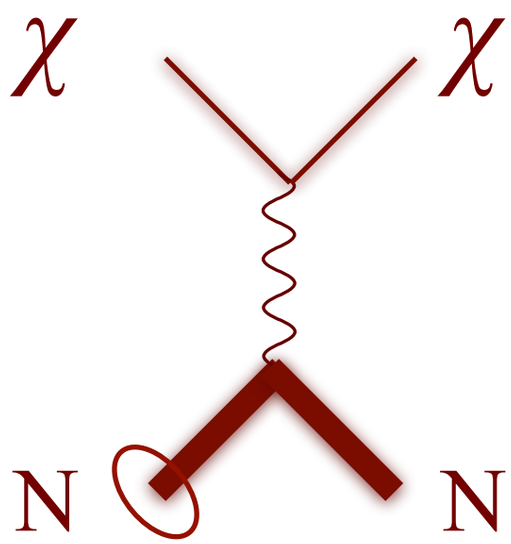

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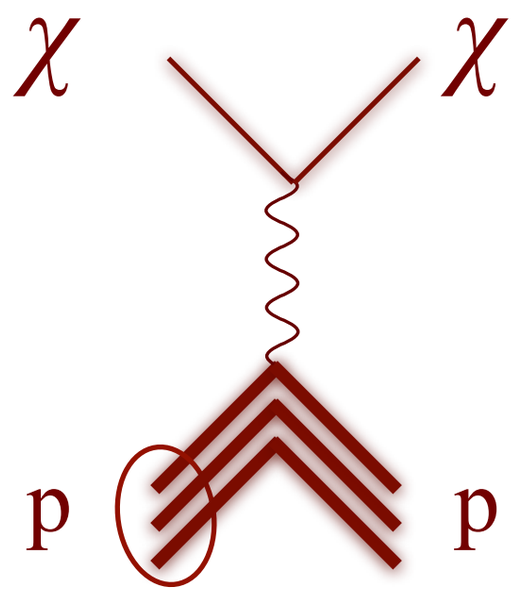

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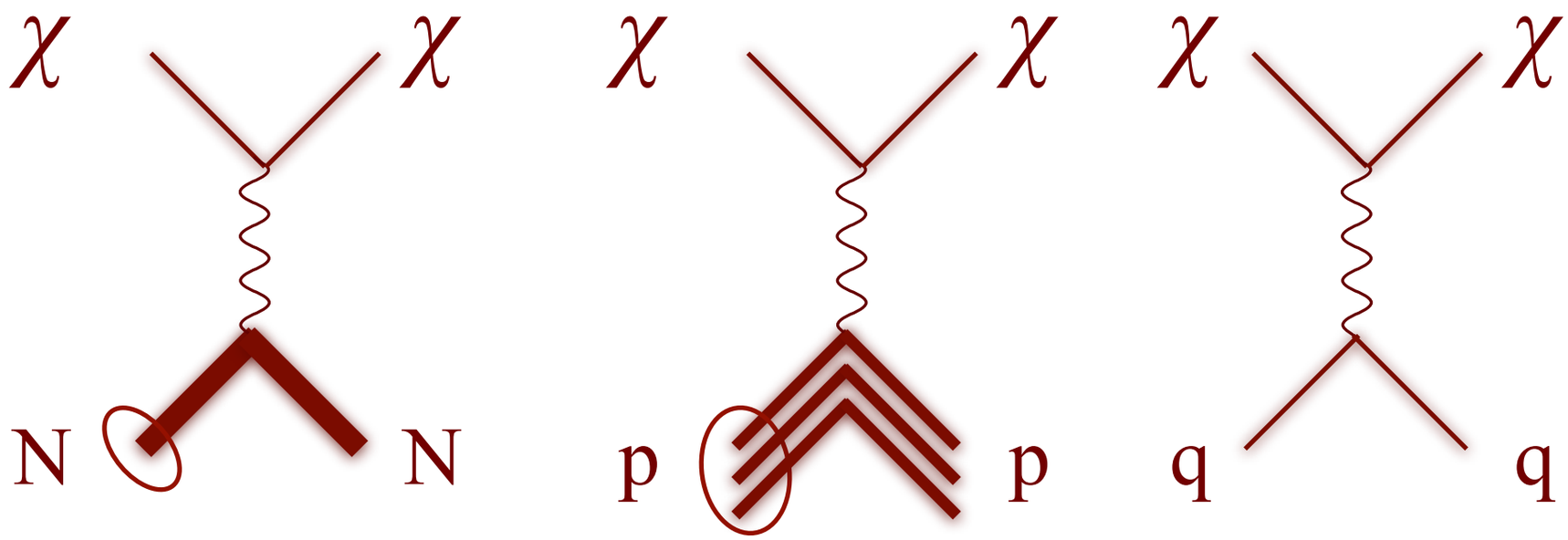

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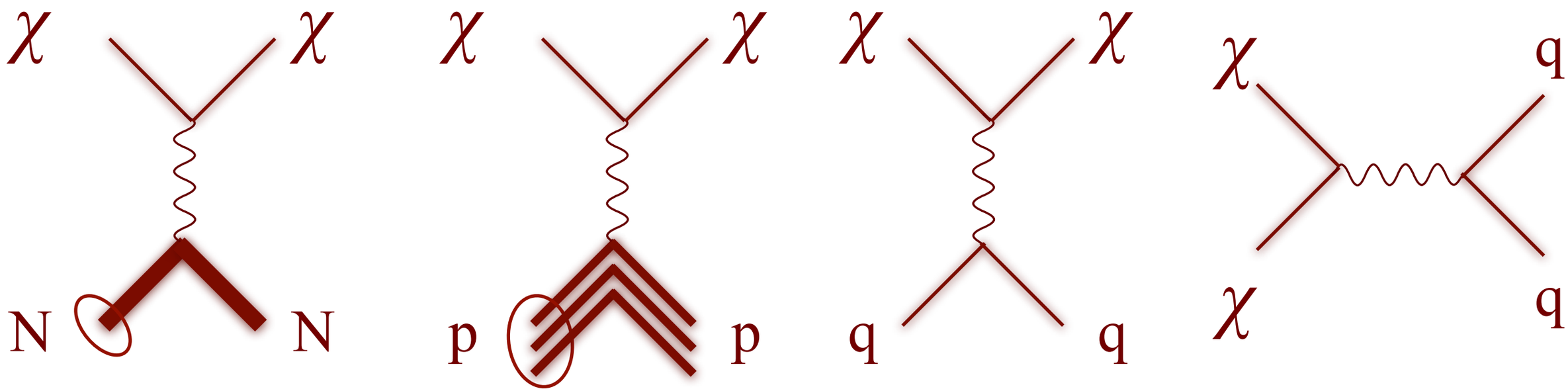

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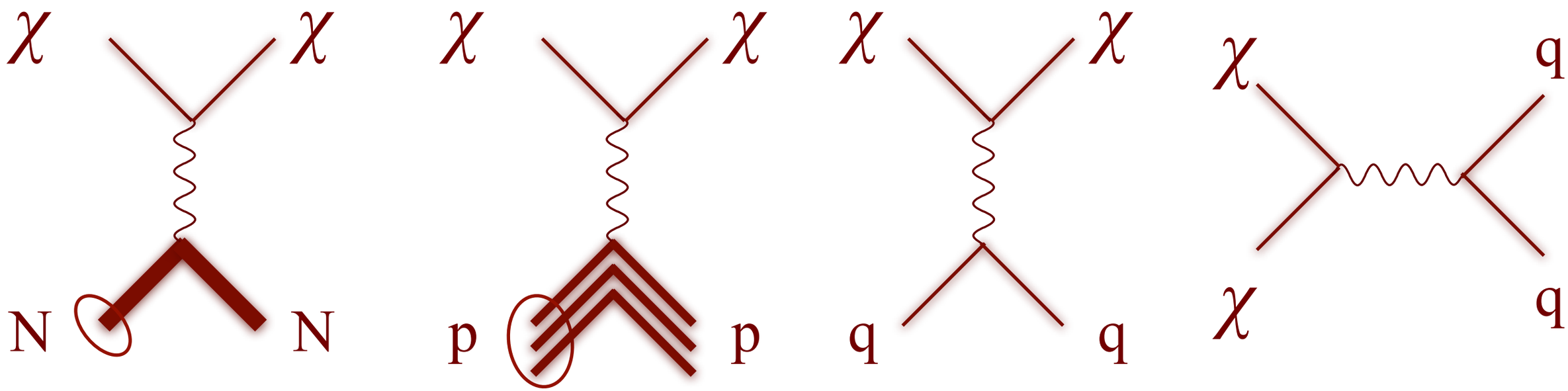

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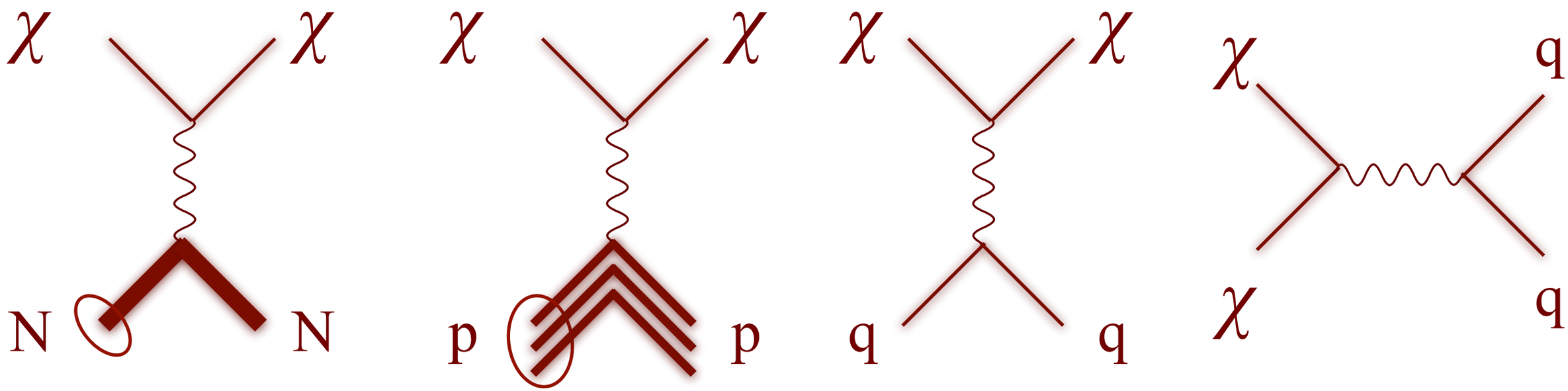

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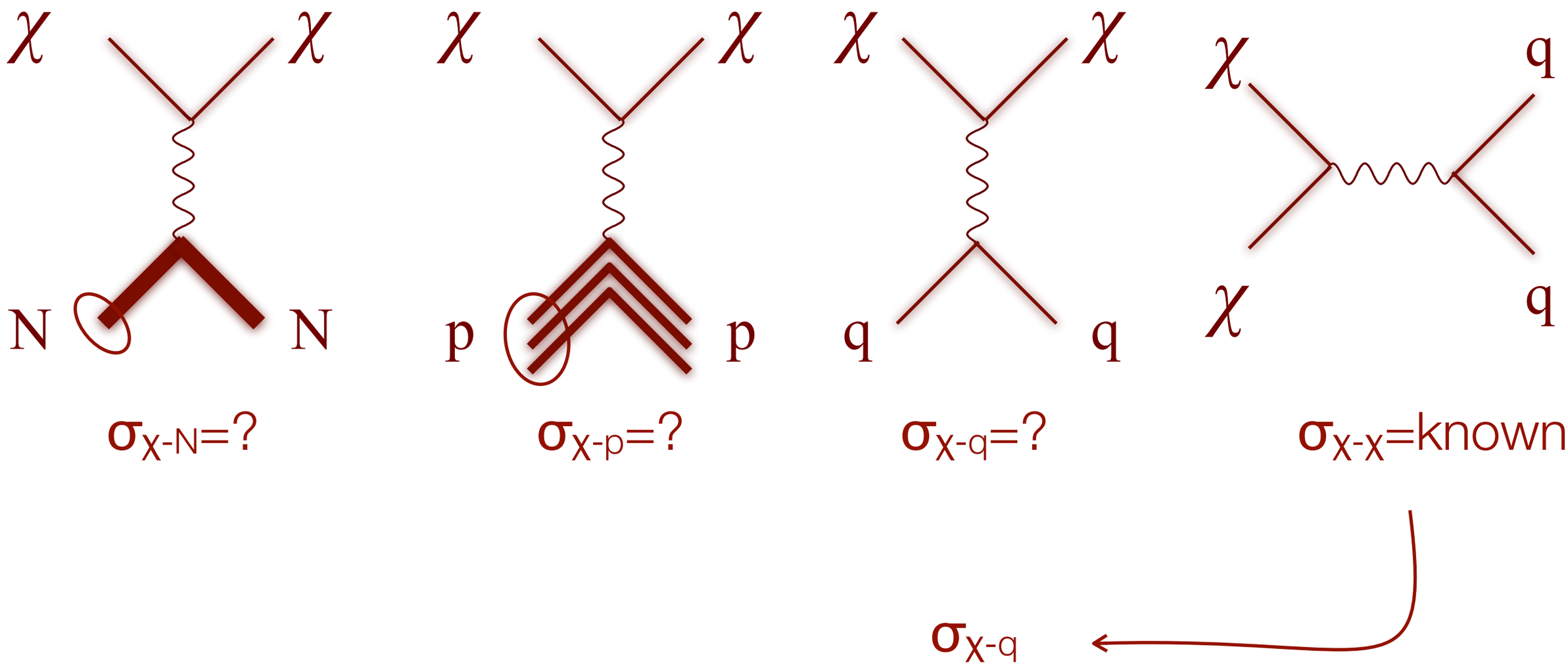

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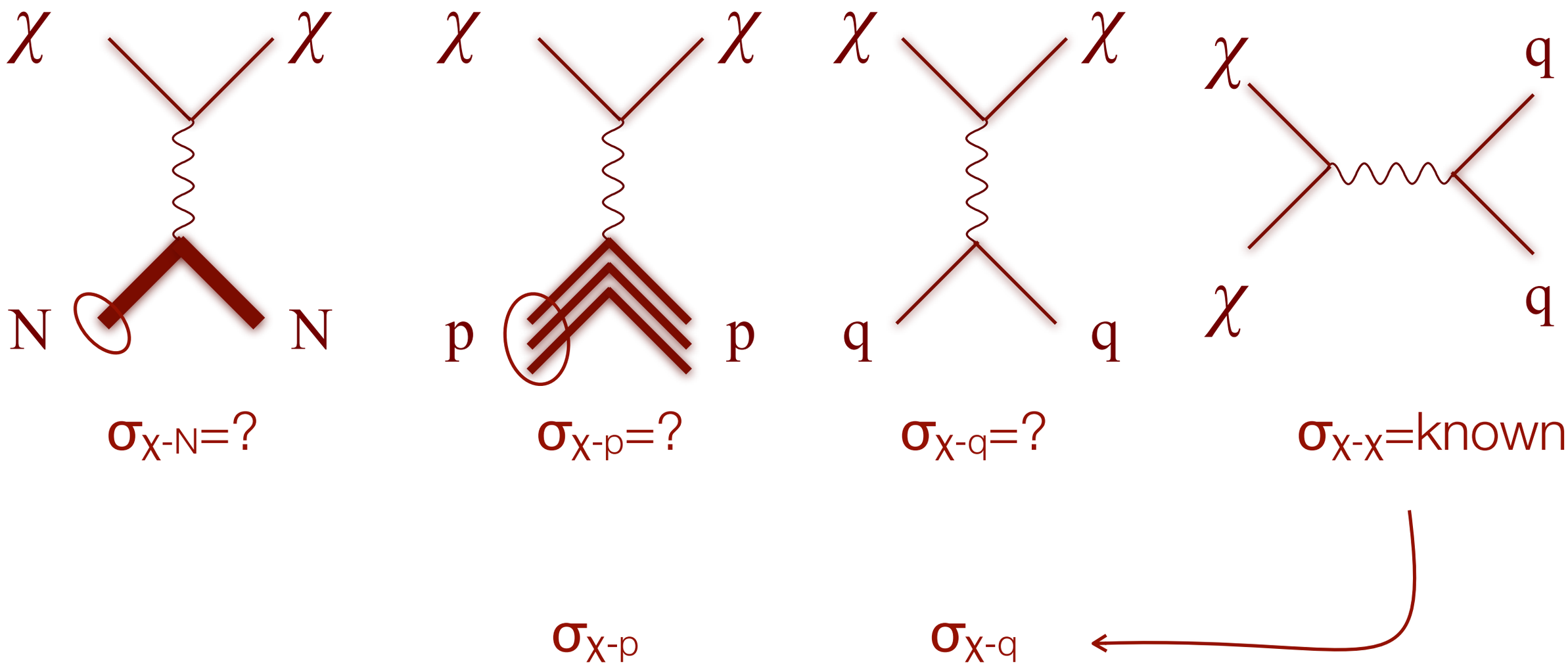

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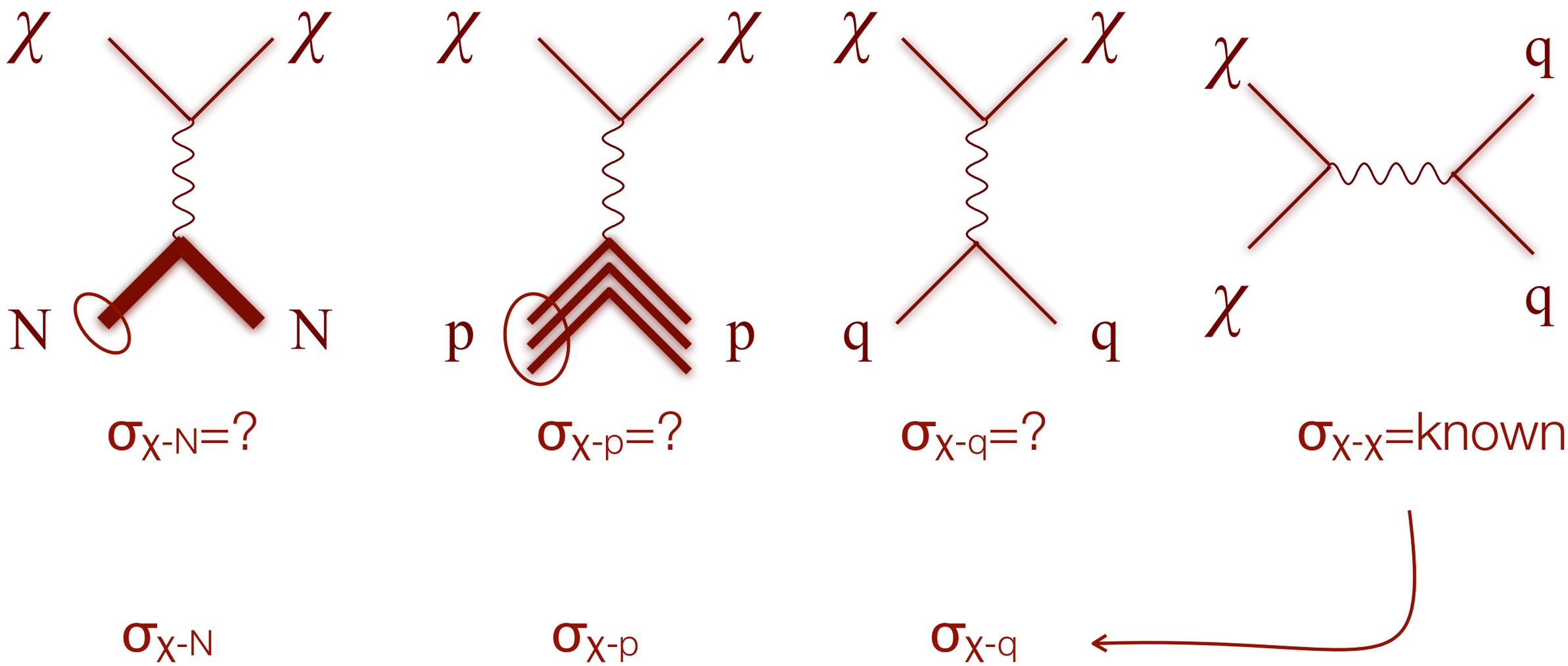

Wimp-nucleus Interaction

- 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

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

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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 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]

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

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

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

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particle theory — $\frac{\sigma_o}{m_\chi}$

nuclear structure — $\frac{F^2(E_R)}{m_r^2}$

local properties of DM halo — $\frac{\rho_o\, T(E_R)}{v_o\, \sqrt{\pi}}$

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

integral over local WIMP velocity distribution

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

Exercise

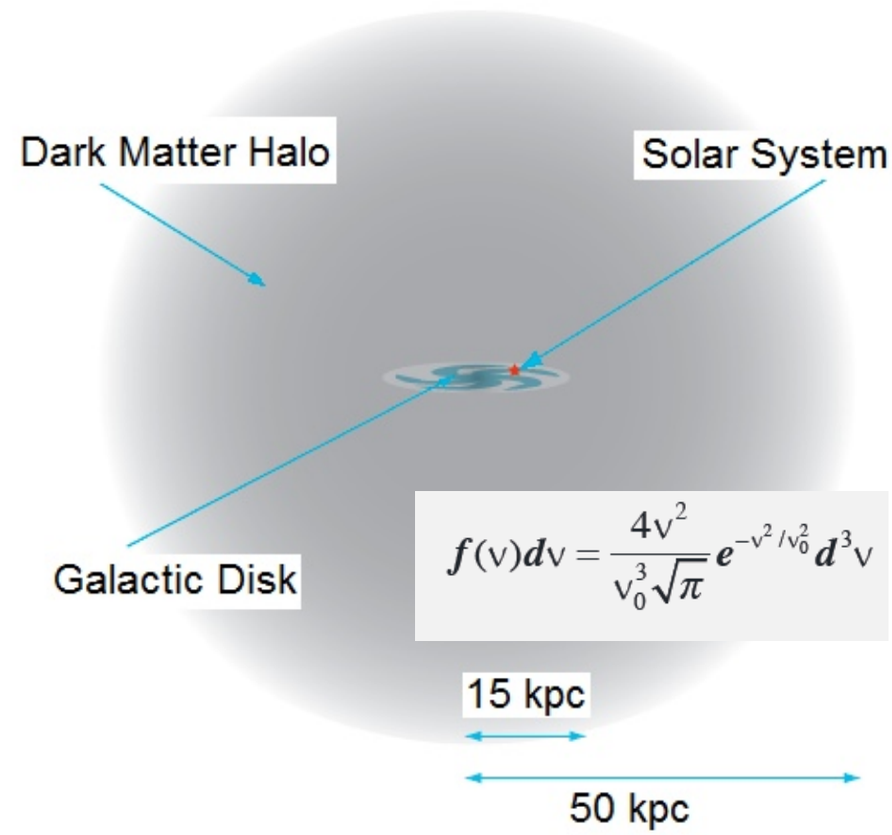
- What is the minimum velocity needed v_{min} for a WIMP with mass m_X to produce a 10 keV recoil in a nucleus of mass m_N ?

- What is the maximum recoil energy E_{max} that a WIMP with mass m_X and velocity v_X can produce in a nucleus of mass m_N ?

Direct Detection and WIMP Astrophysics

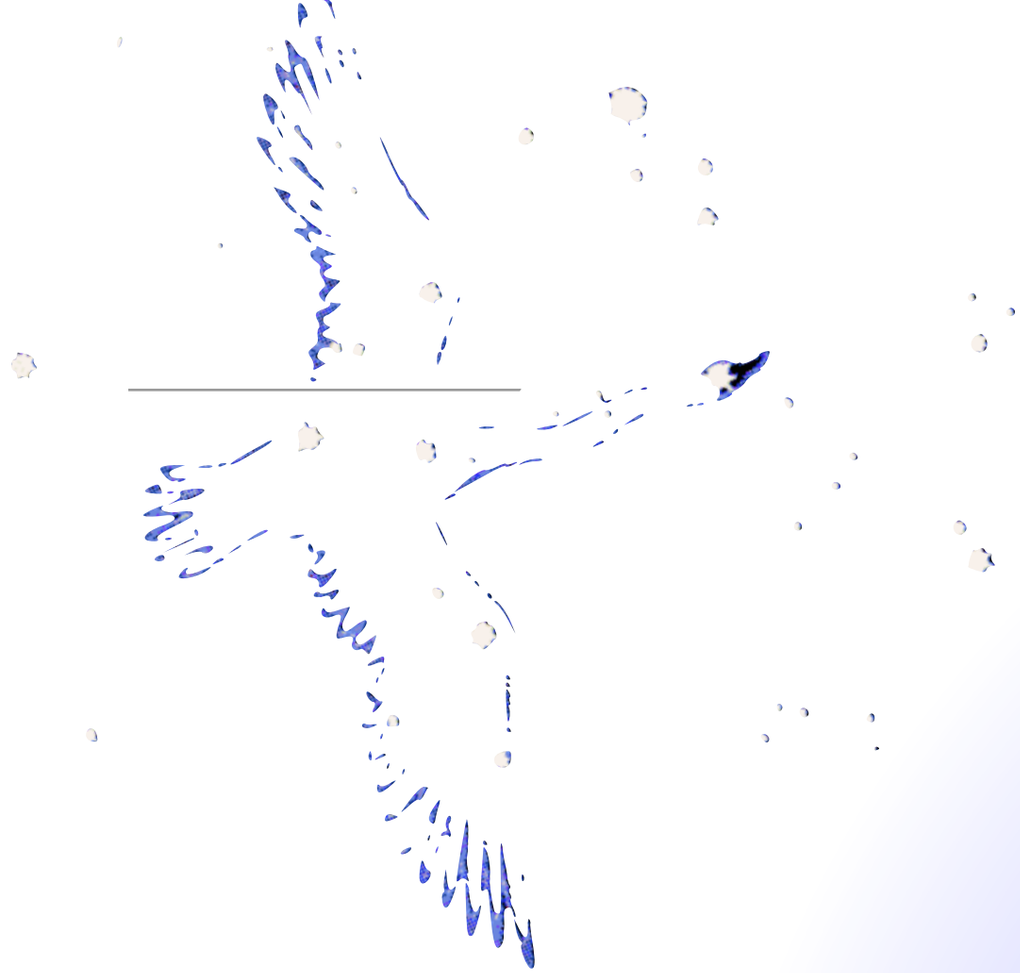
Energy spectrum & rate depend on WIMP distribution in Dark Matter Halo

- “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



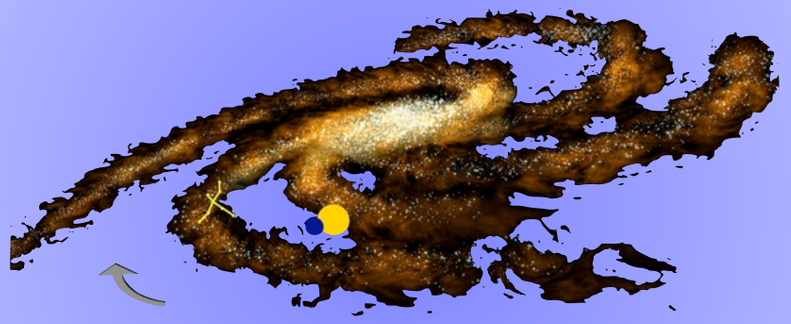
10 WIMPs on average, inside a 2 liter bottle (if mass=60 x proton)

The Dark Matter Wind



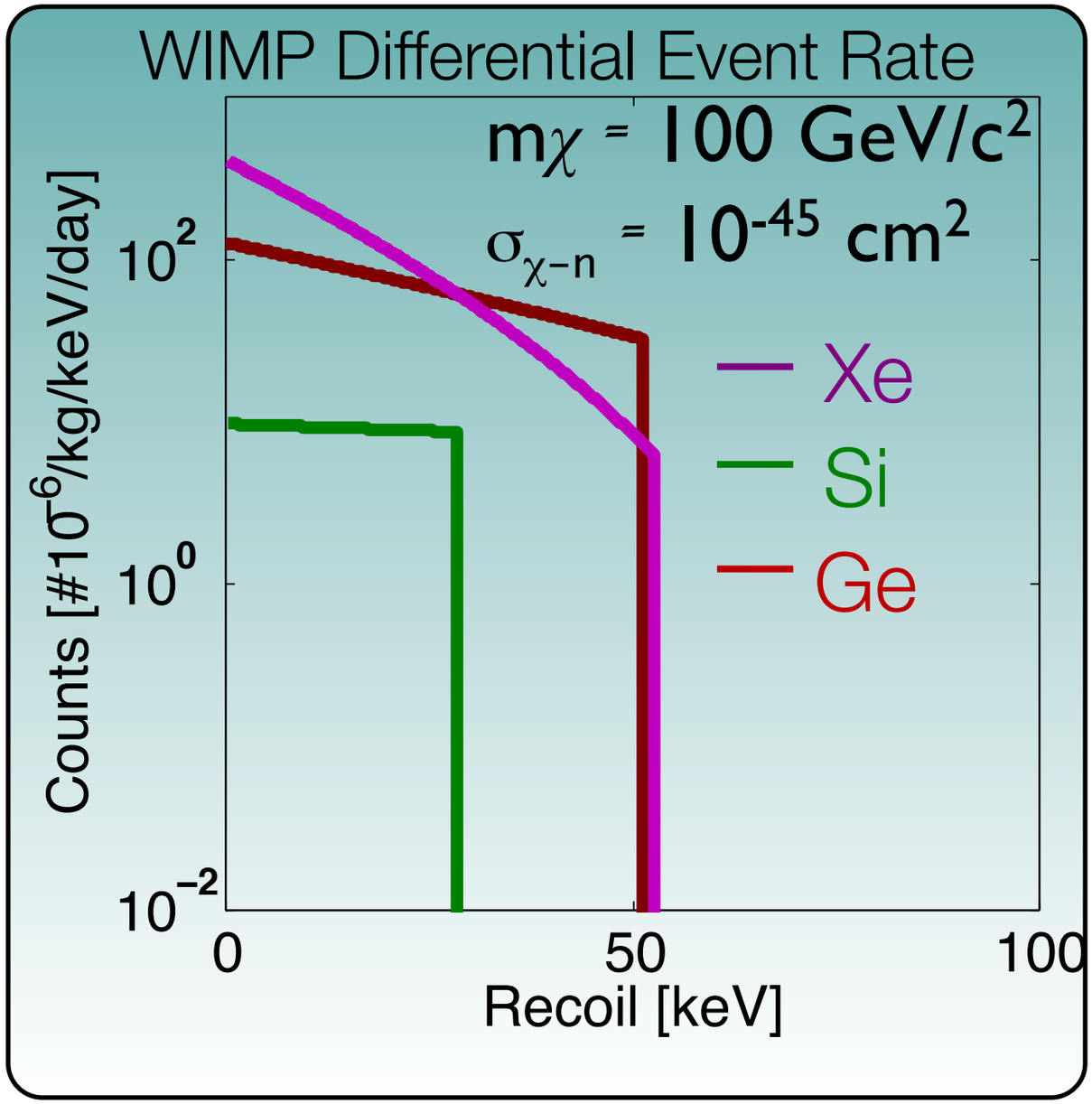
apparently “blows”
from Cygnus

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



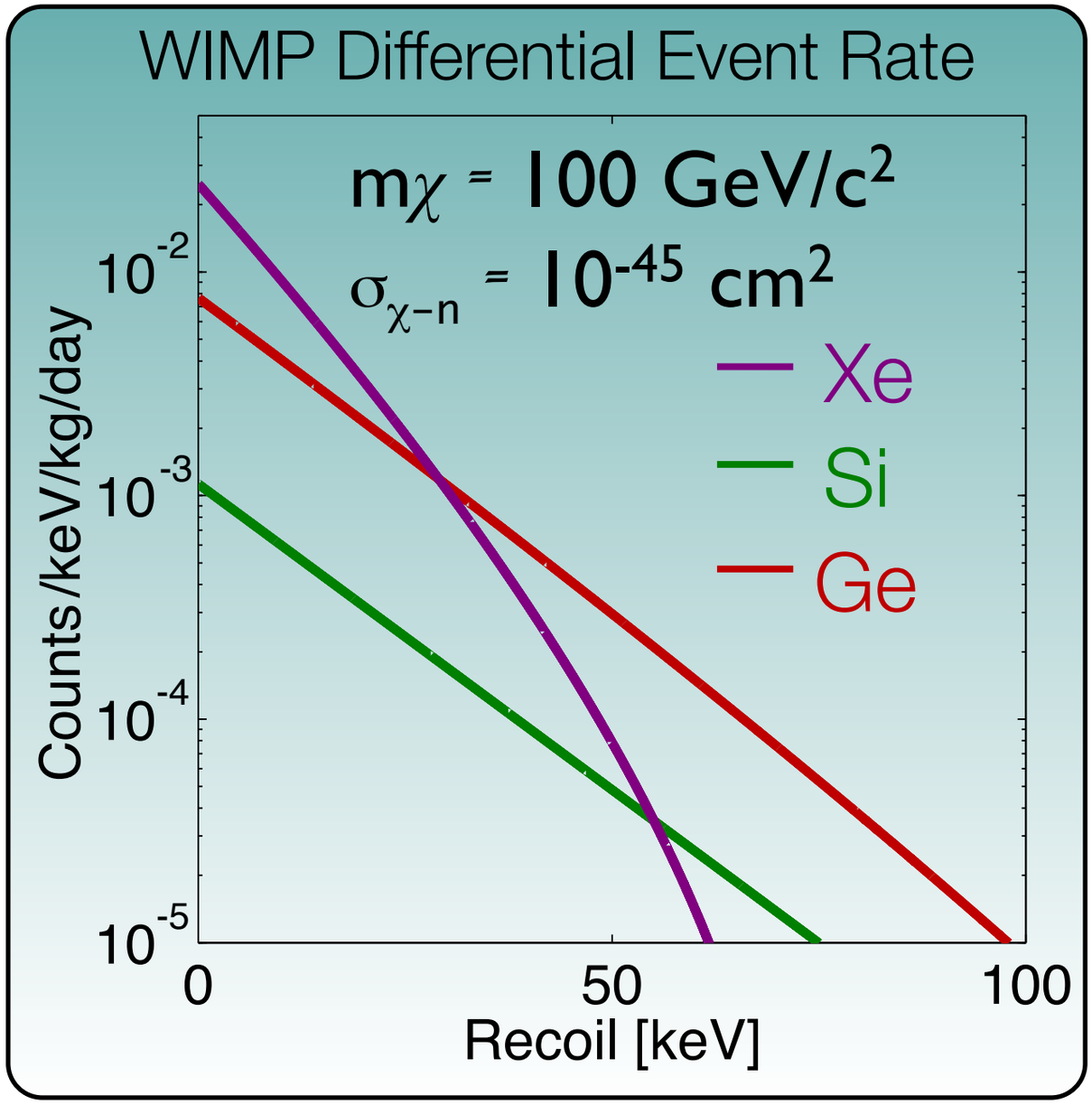
WIMP Recoil Spectrum

- Elastic scattering of a WIMP from a nucleus deposits a small, but detectable amount of energy ~ few x 10 keV
  - If the WIMPs are mono-energetic (or rather have a single velocity)



WIMP Recoil Spectrum

- 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**



Exercise

- Even under the assumption of a standard non-rotating, isotropic halo, the velocity distribution of WIMPS is not truly Maxwellian.
  It has a cutoff at v_{max}, where v_{max} is the escape velocity of the WIMP at the radius of the sun in the galaxy. If v_{max} = 600 km/s what is the total mass M_G of the milkyway contained inside the solar orbit radius?

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Principles of Direct Detection

- The physics discussed so far is required for choosing the “ideal” target nucleus for maximizing the rate of Dark Matter interactions in your experiment

- Equally important considerations :
  - When dealing with 10^{26} nuclei, must consider the physical behavior of the solid/liquid/gas which the nuclei form
  - How can we extract/measure the recoil information in a given medium
  - What are the background issues associated with this material

Principles of Direct Detection

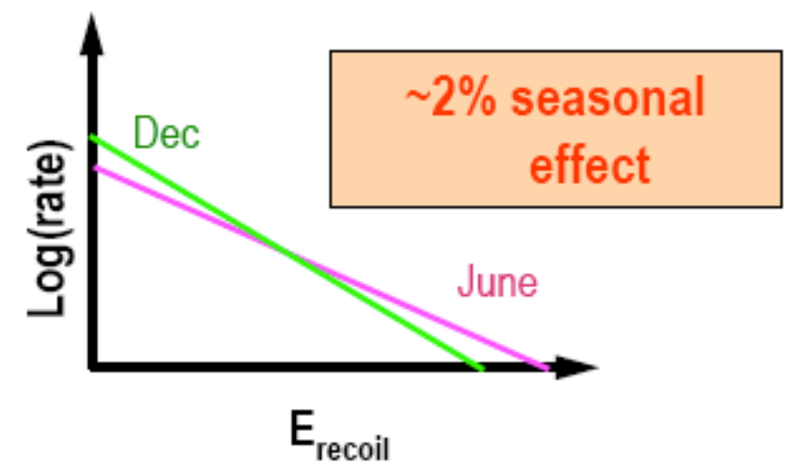
- Various experimental methods exist for measuring such an energy deposition
  - Scintillation in crystals / liquids
  - Ionization in crystals / liquids
  - Thermal / athermal heating in crystals
  - Bubble formation in liquids / gels
- Easy in principle, hard in practice
  - Significant uncertainties/unknowns in estimating DM event rates / energy spectrum
  - Background rates overwhelm the most optimistic DM scattering rates !!

Backgrounds

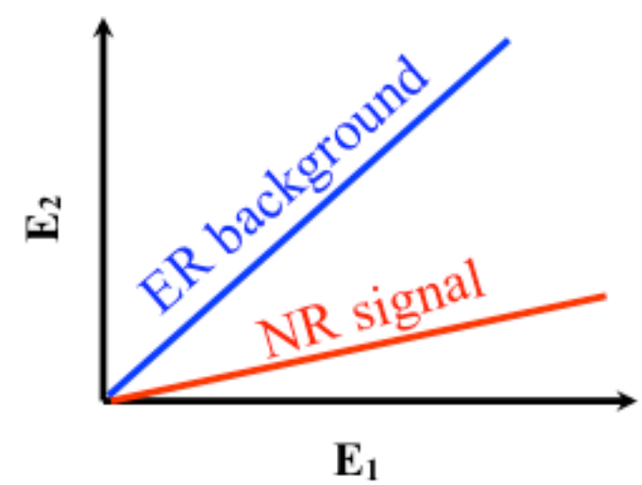
- Backgrounds are much higher than the signal event rate
  - e.g. rate of ^{40}K from a person standing 2m away from Ge detector is 10^4 x expected dark matter signal!
- Gamma-rays and beta decays:
  - Shielding: low activity lead, clean copper, water, noble liquids (active)
  - Select gamma-clean materials
- 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.
  - Requires accurate knowledge of the astrophysical parameters of the WIMP halo
    - 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.



Directional Signal

- Temporal variation of the WIMP signal provides a means to distinguish it from background

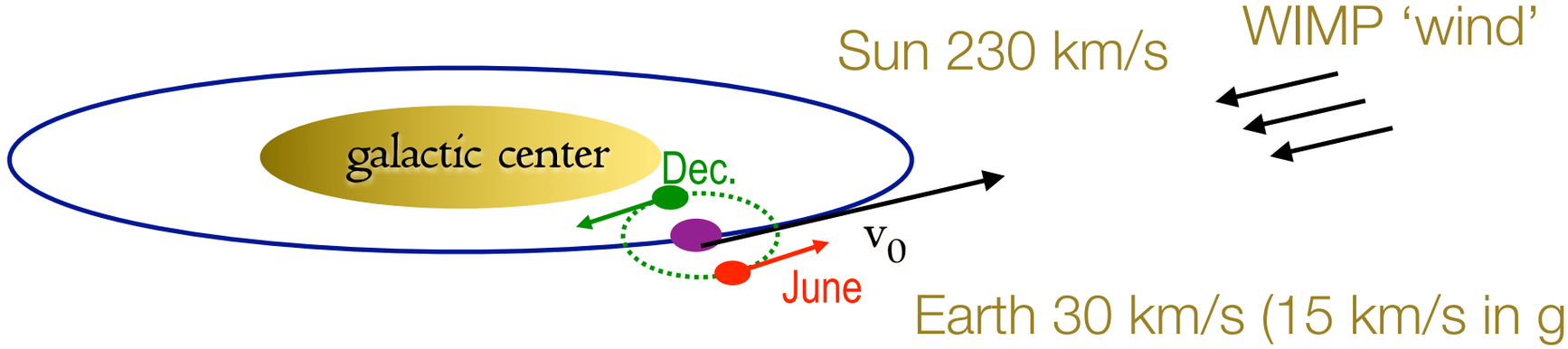
- Variation can happen in the:

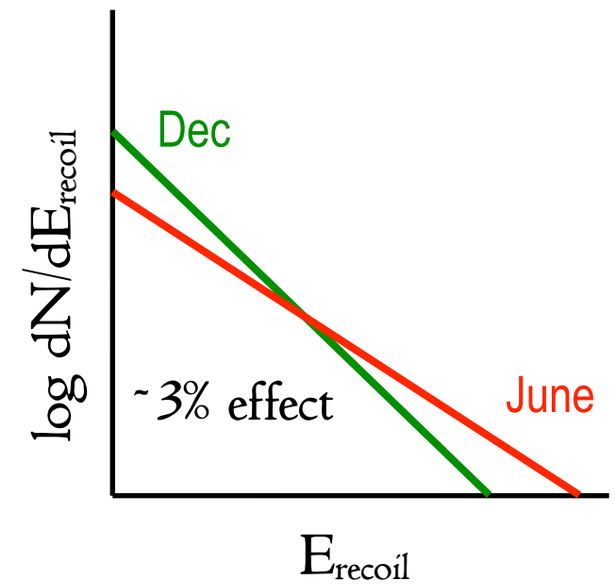
  - Energy spectrum
  - Event rate
  - Recoil direction

- All such variations depend on direction of the earth through the WIMP “wind”

Annual Modulation

WIMP Isothermal Halo (assume no co-rotation) v_0~ 230 km/s



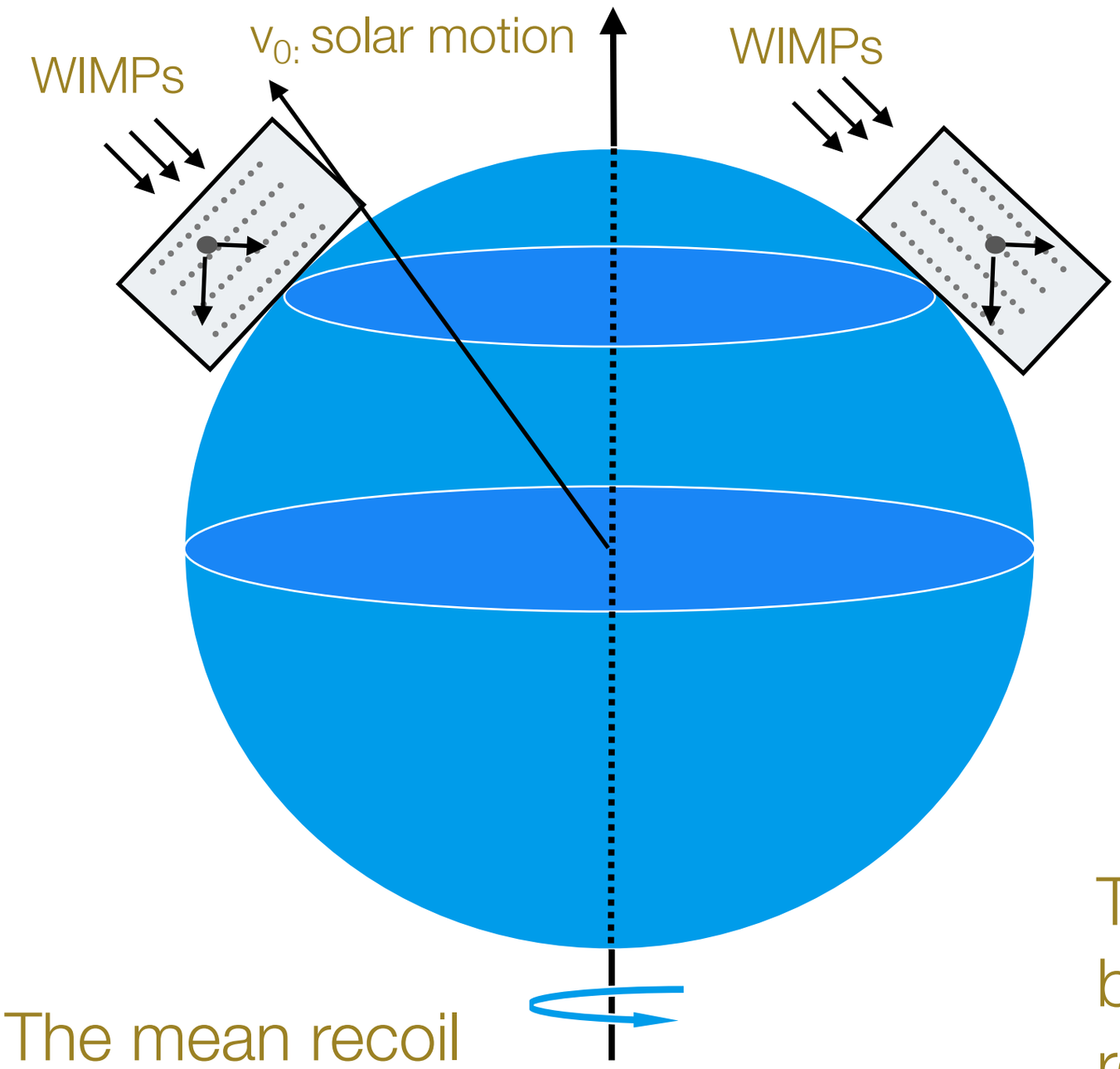


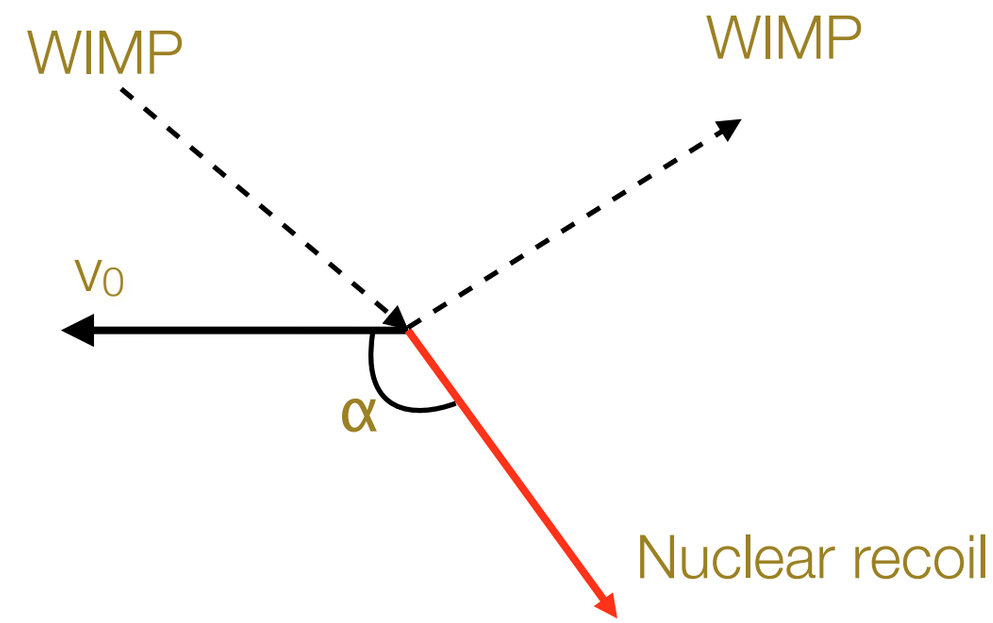
$$v_e = v_0 \left[1.05 + 0.07 \cos\left(\frac{2\pi(t - t_p)}{1\,\mathrm{yr}}\right)\right]$$

$$f(v)dv = \frac{v dv}{v_e v_o \sqrt{\pi}} \left\{ \exp\left[-\frac{(v - v_e)^2}{v_0^2}\right] - \exp\left[-\frac{(v + v_e)^2}{v_0^2}\right] \right\}$$

$$T(Q) = \frac{\sqrt{\pi}}{2} v_0 \int_{v_{min}}^{\infty} \frac{f(v)dv}{v} = \frac{\sqrt{\pi} v_0}{4 v_e} \left[\mathrm{erf}\left(\frac{v_{min} + v_e}{v_0}\right) - \mathrm{erf}\left(\frac{v_{min} - v_e}{v_0}\right)\right]$$

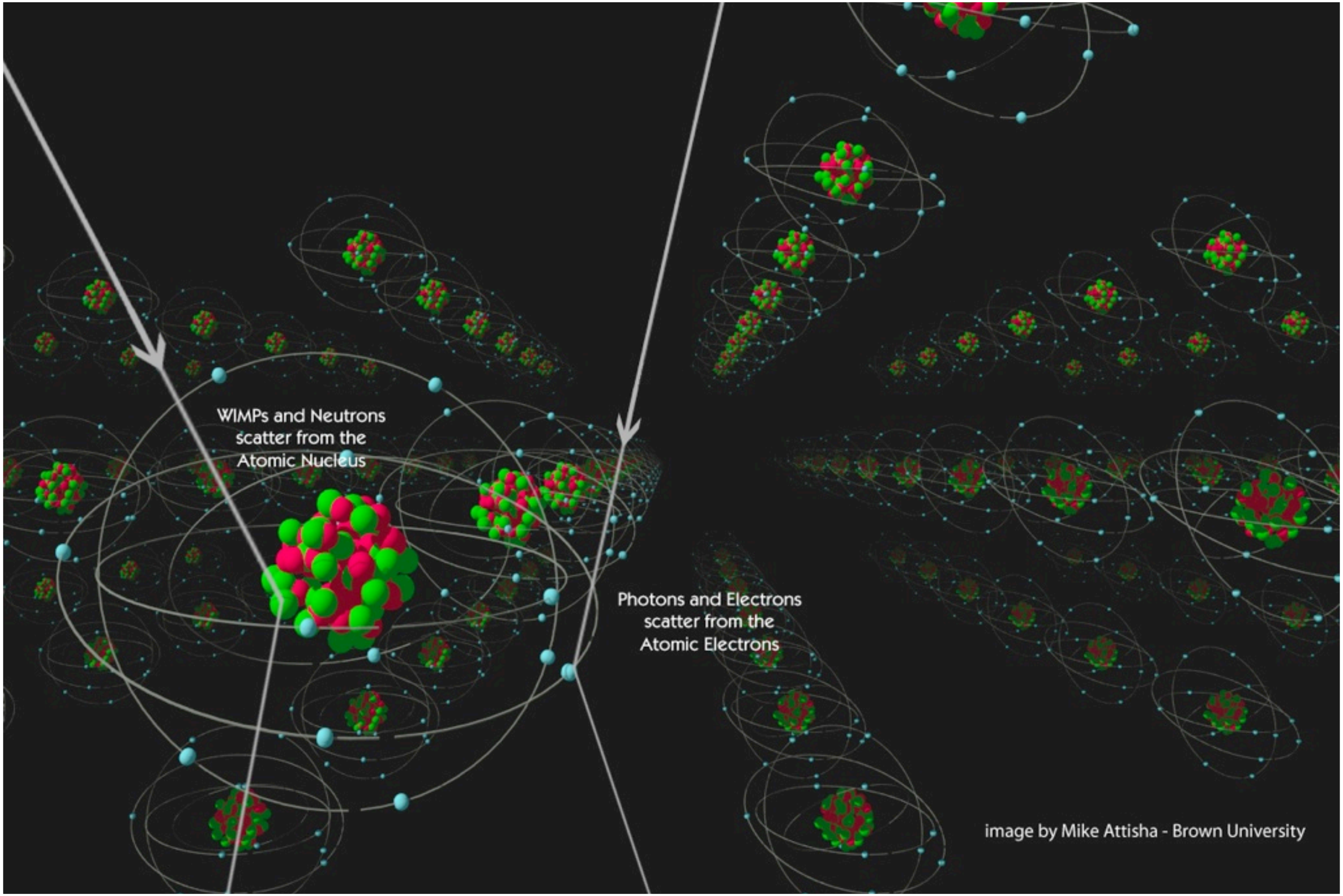
Diurnal Modulation





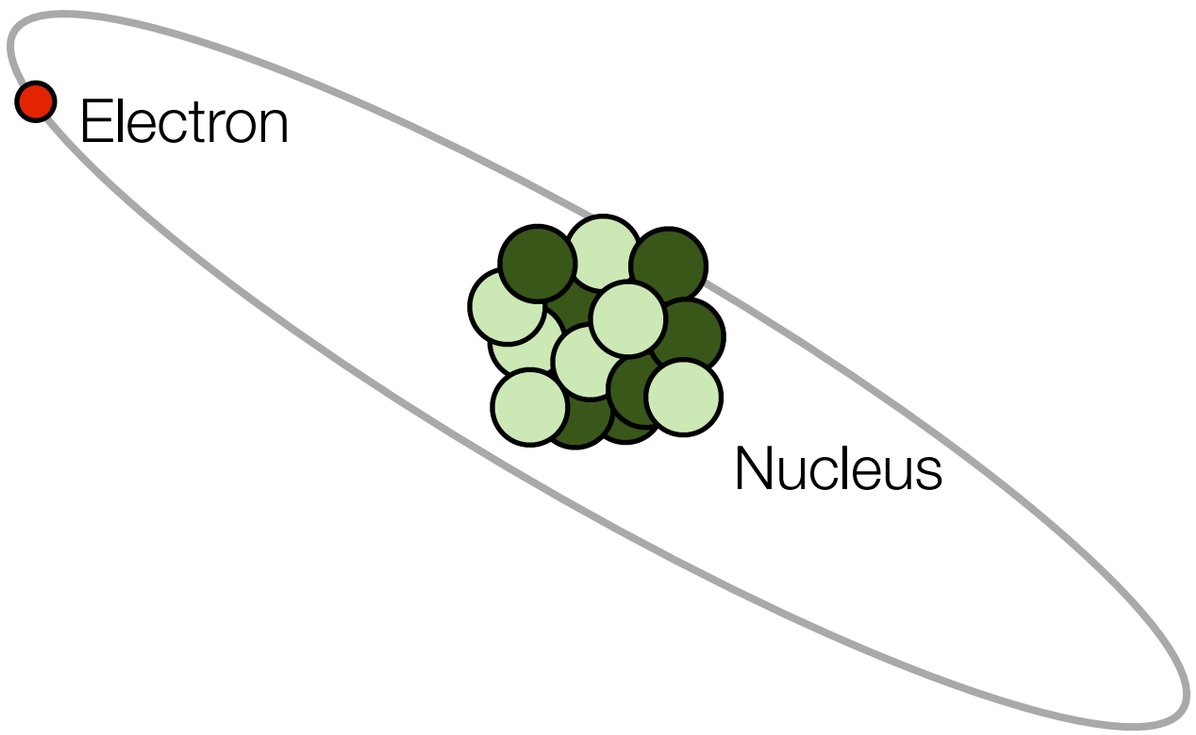
The mean recoil direction rotates over one sidereal day

The distribution of the angle **α** between the solar motion and recoil directions: peaks at **α**=180°

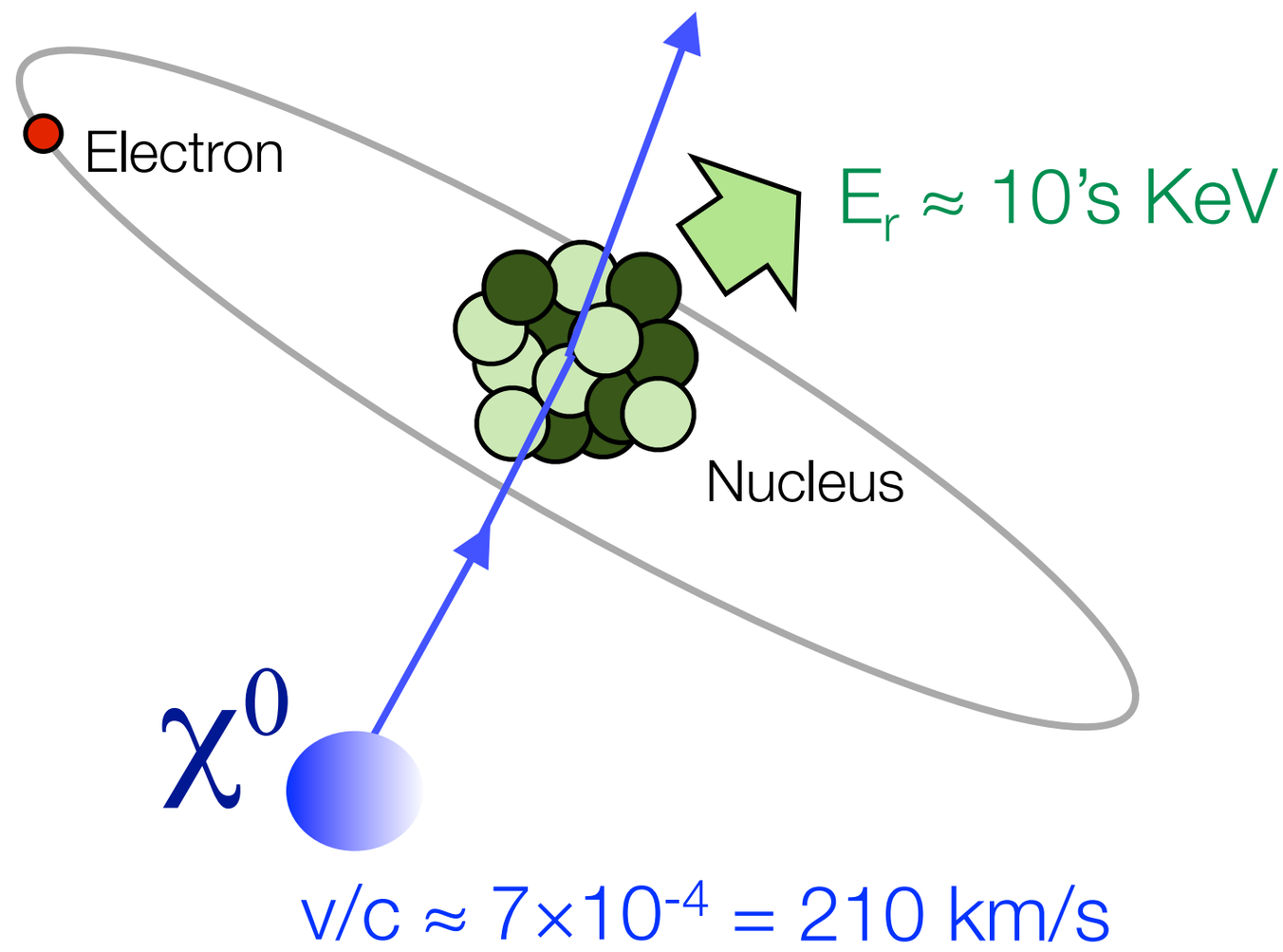


Detector Physics to the Rescue

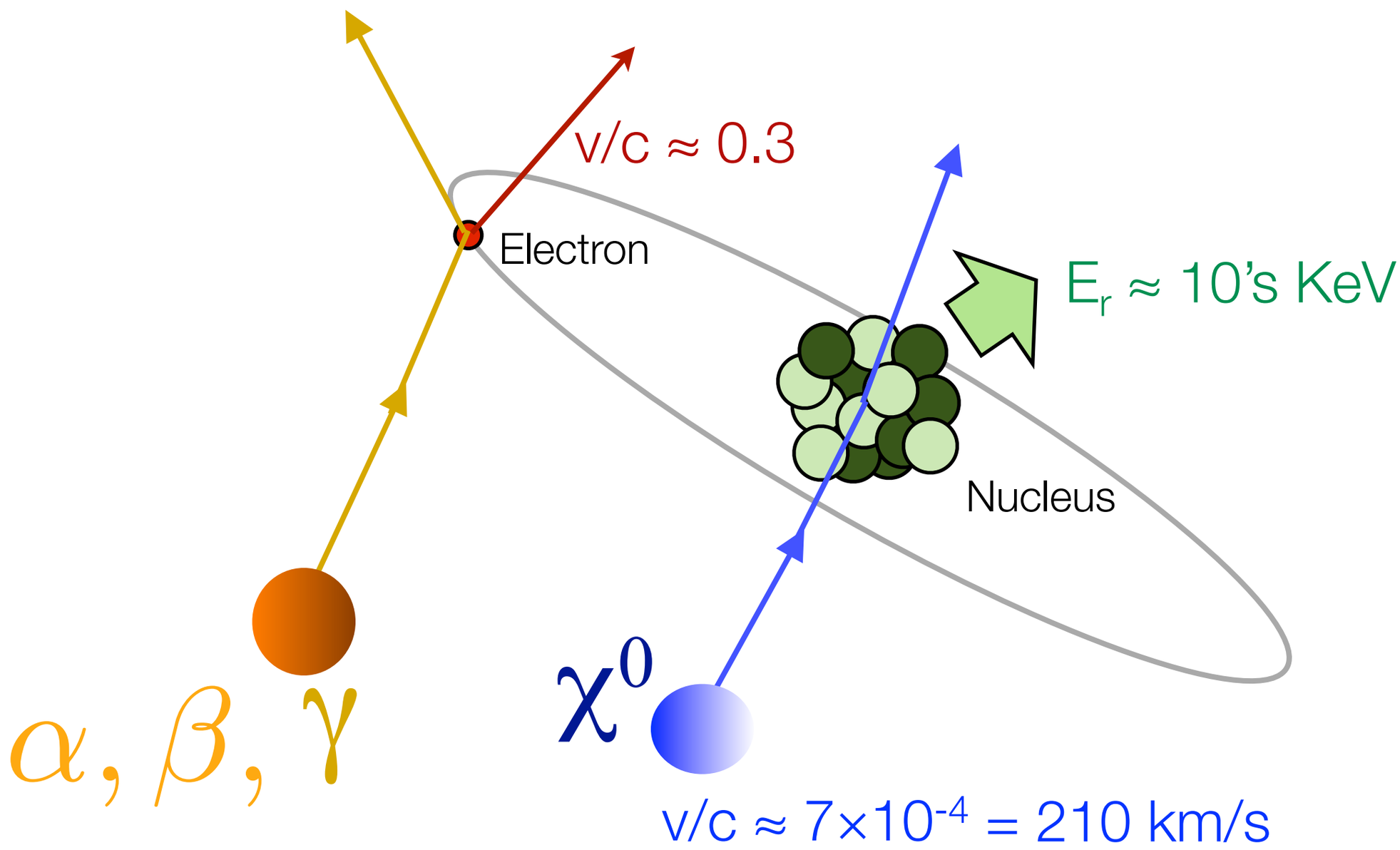
Signal and Backgrounds



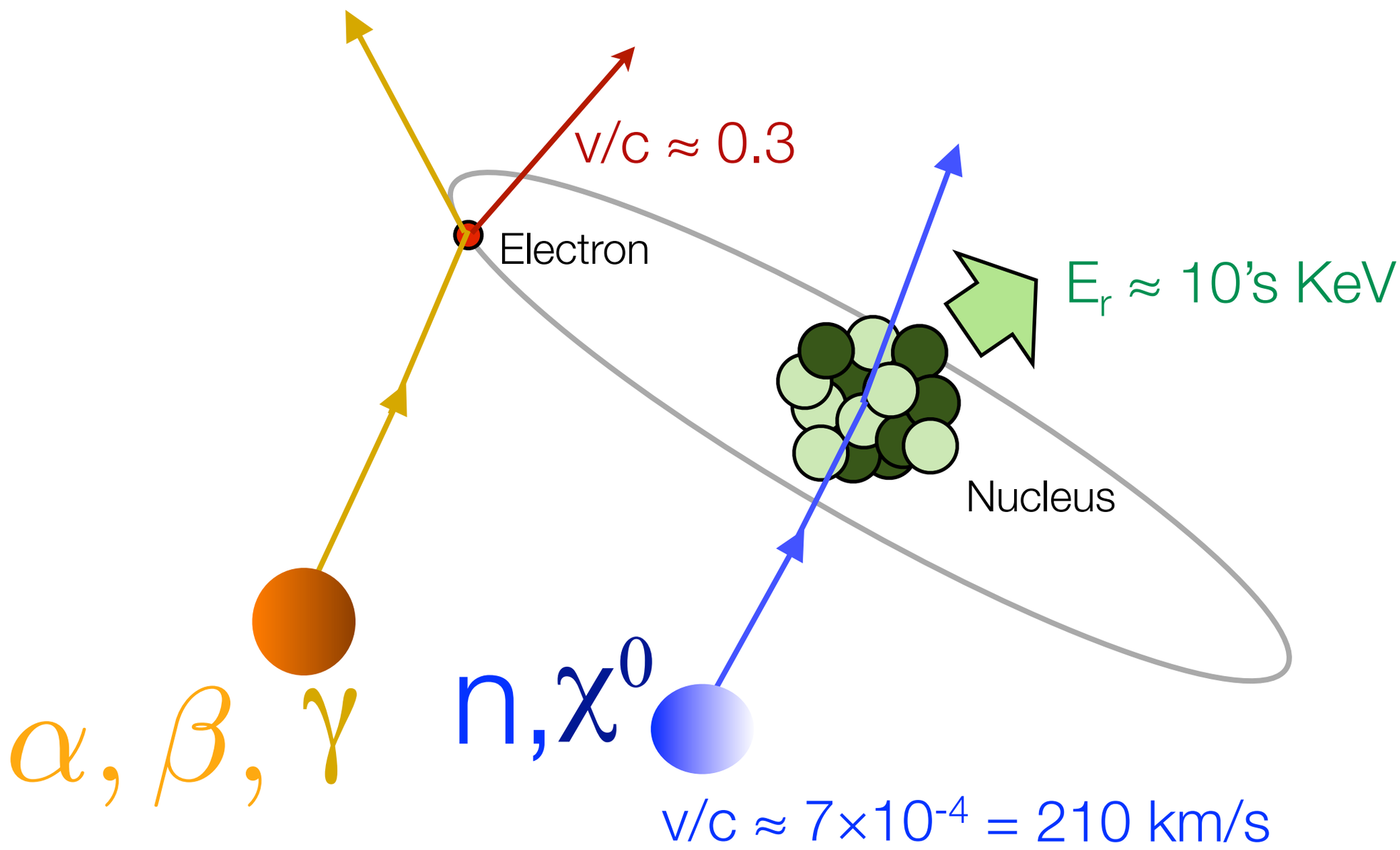
Signal and Backgrounds



Signal and Backgrounds

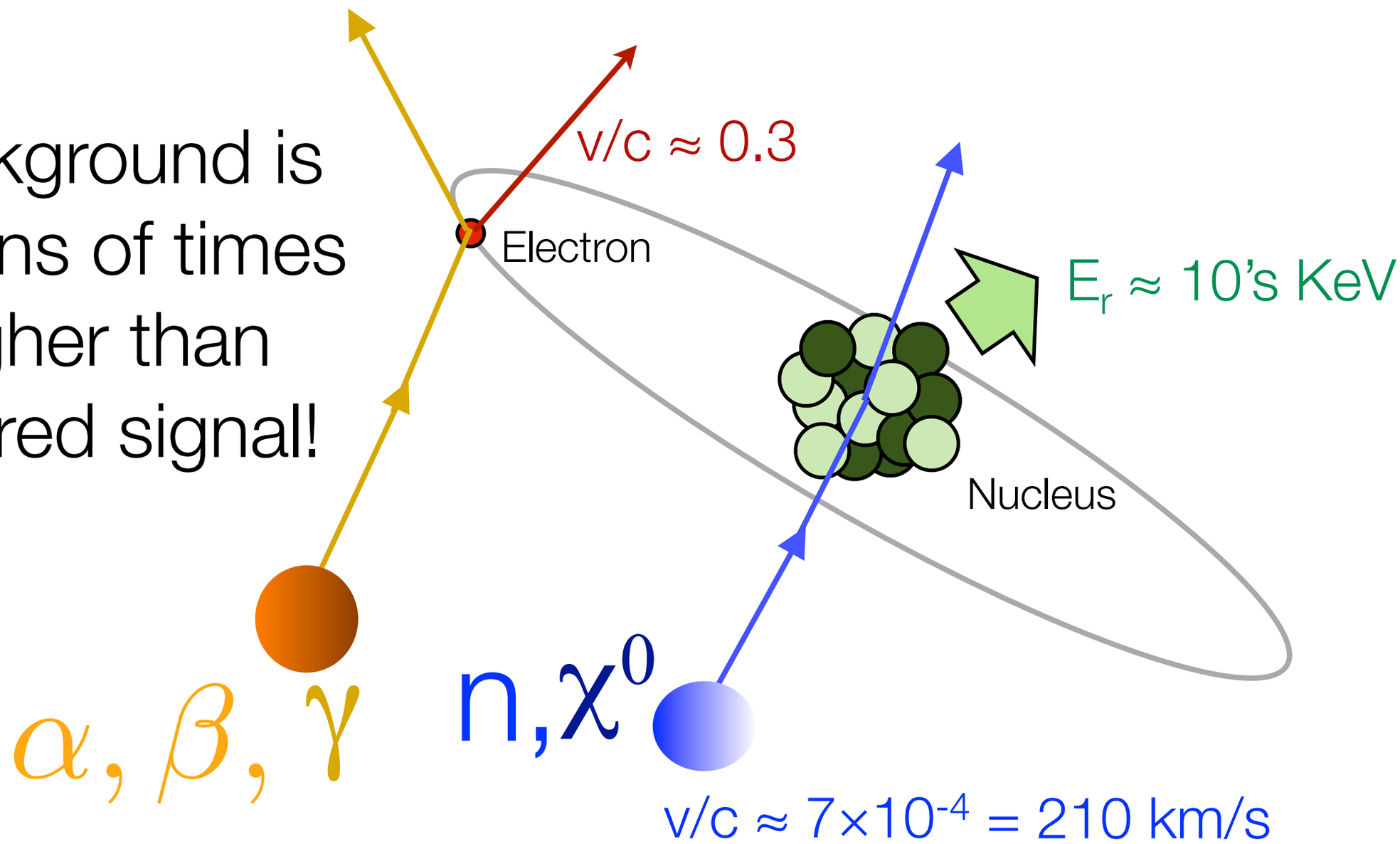


Signal and Backgrounds



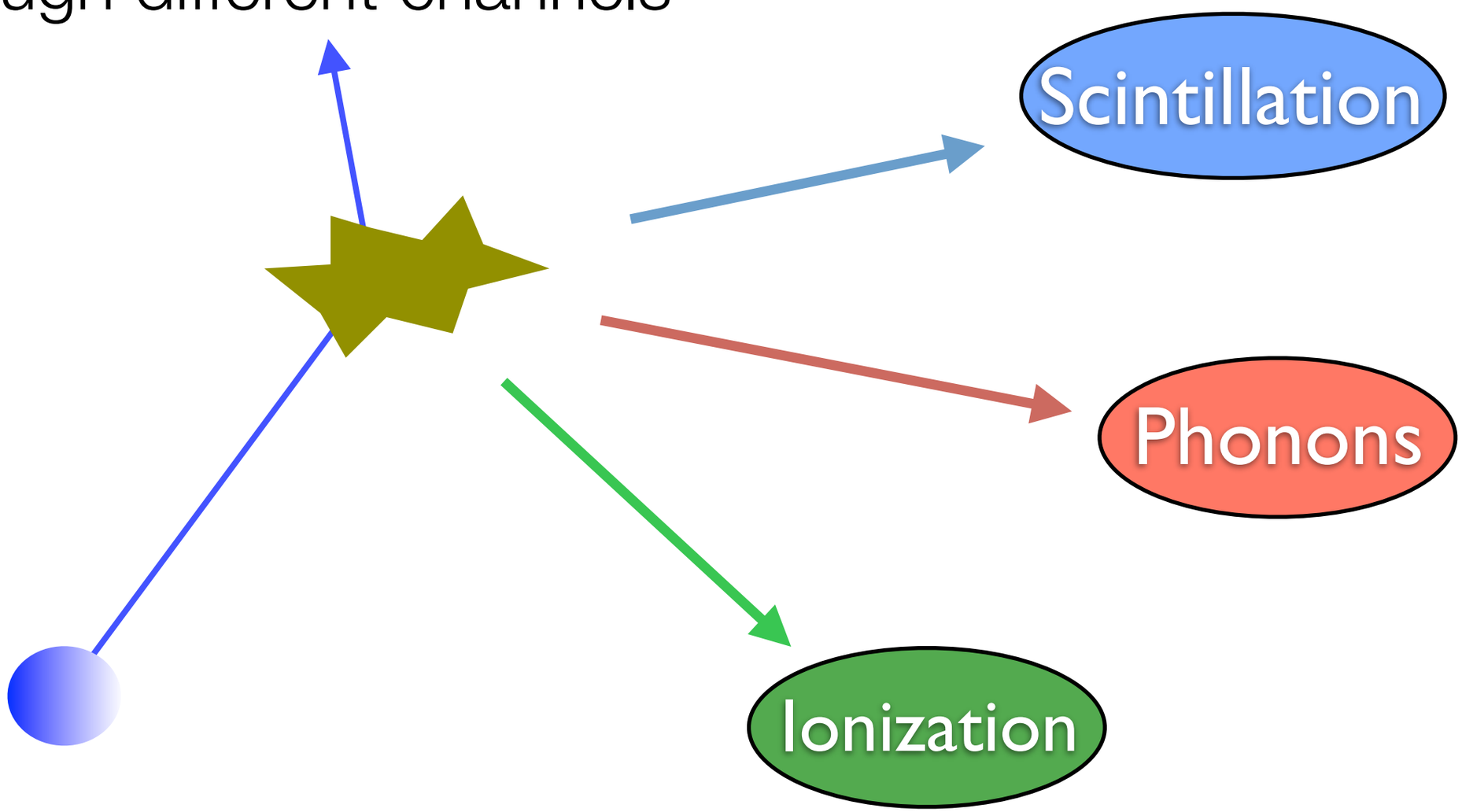
Signal and Backgrounds

Background is millions of times higher than desired signal!

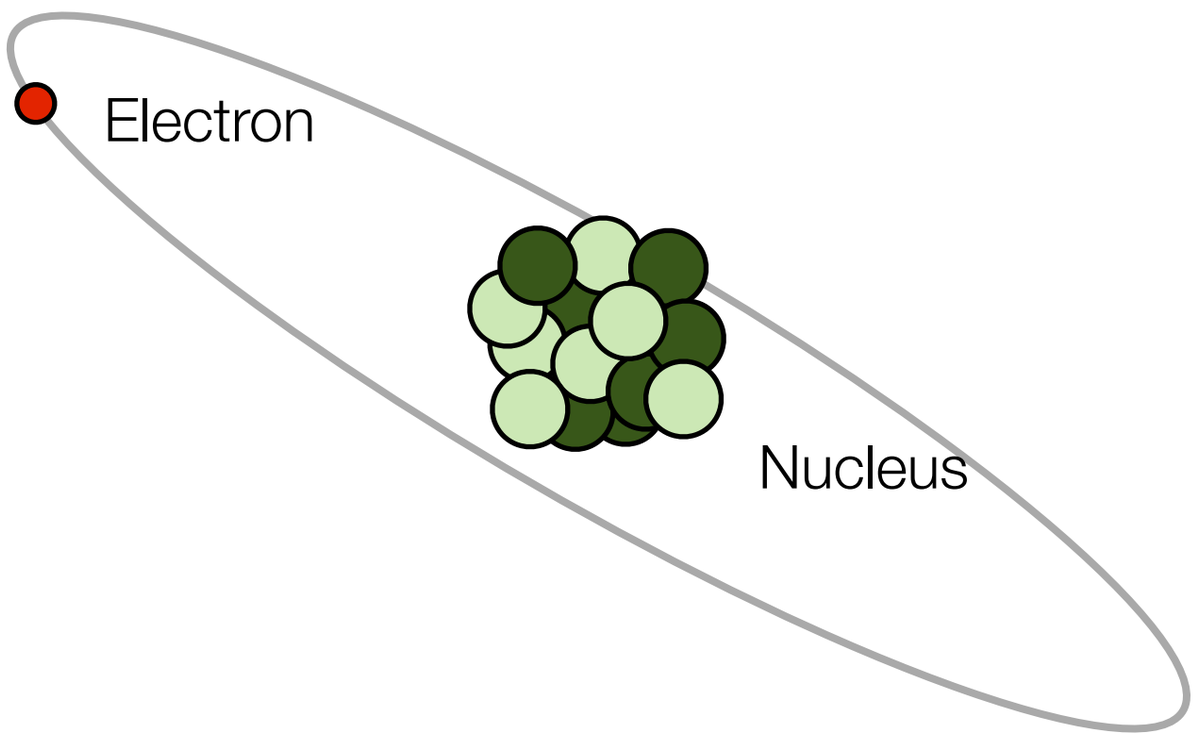


Energy Channels

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



Discrimination Strategies



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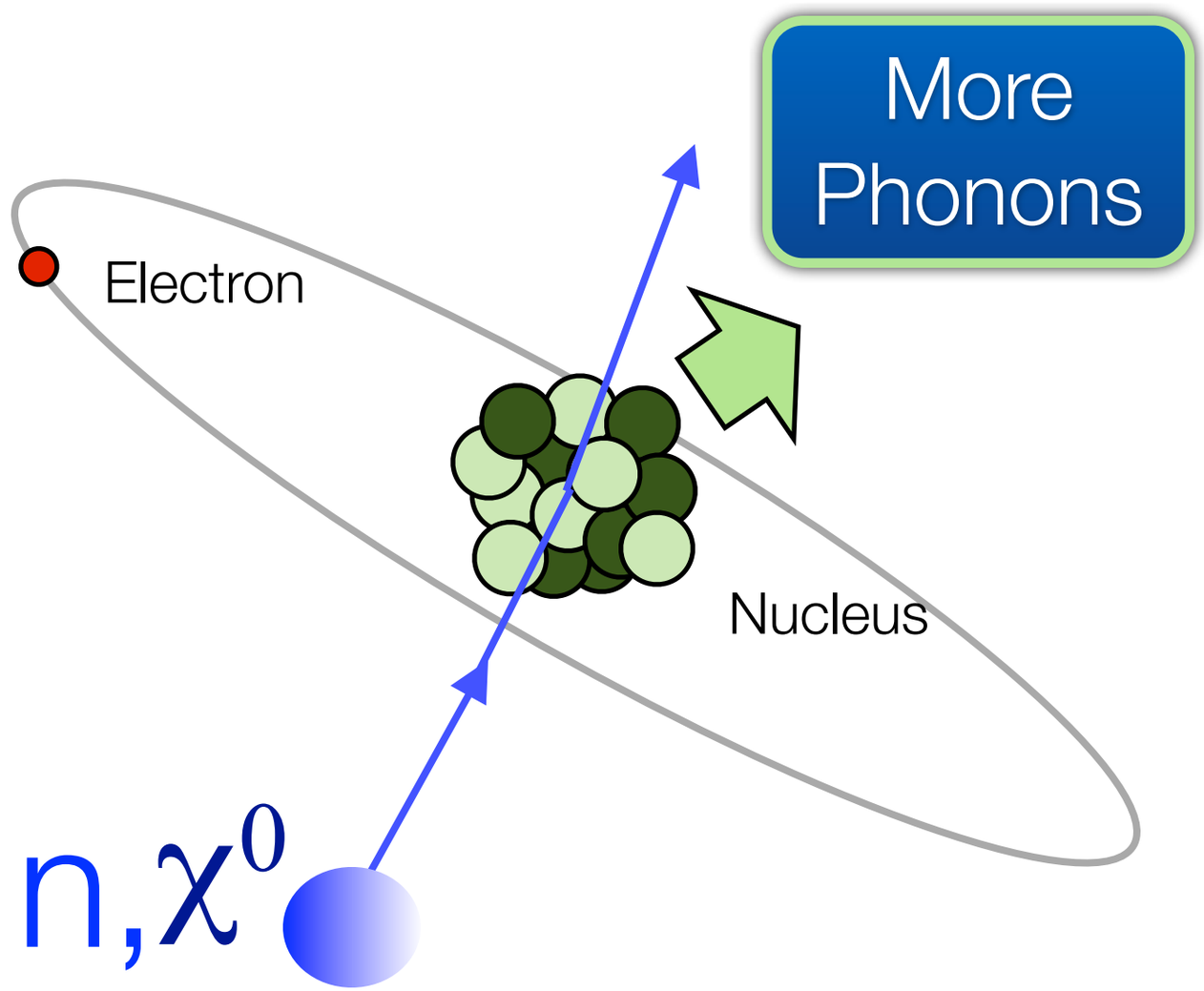

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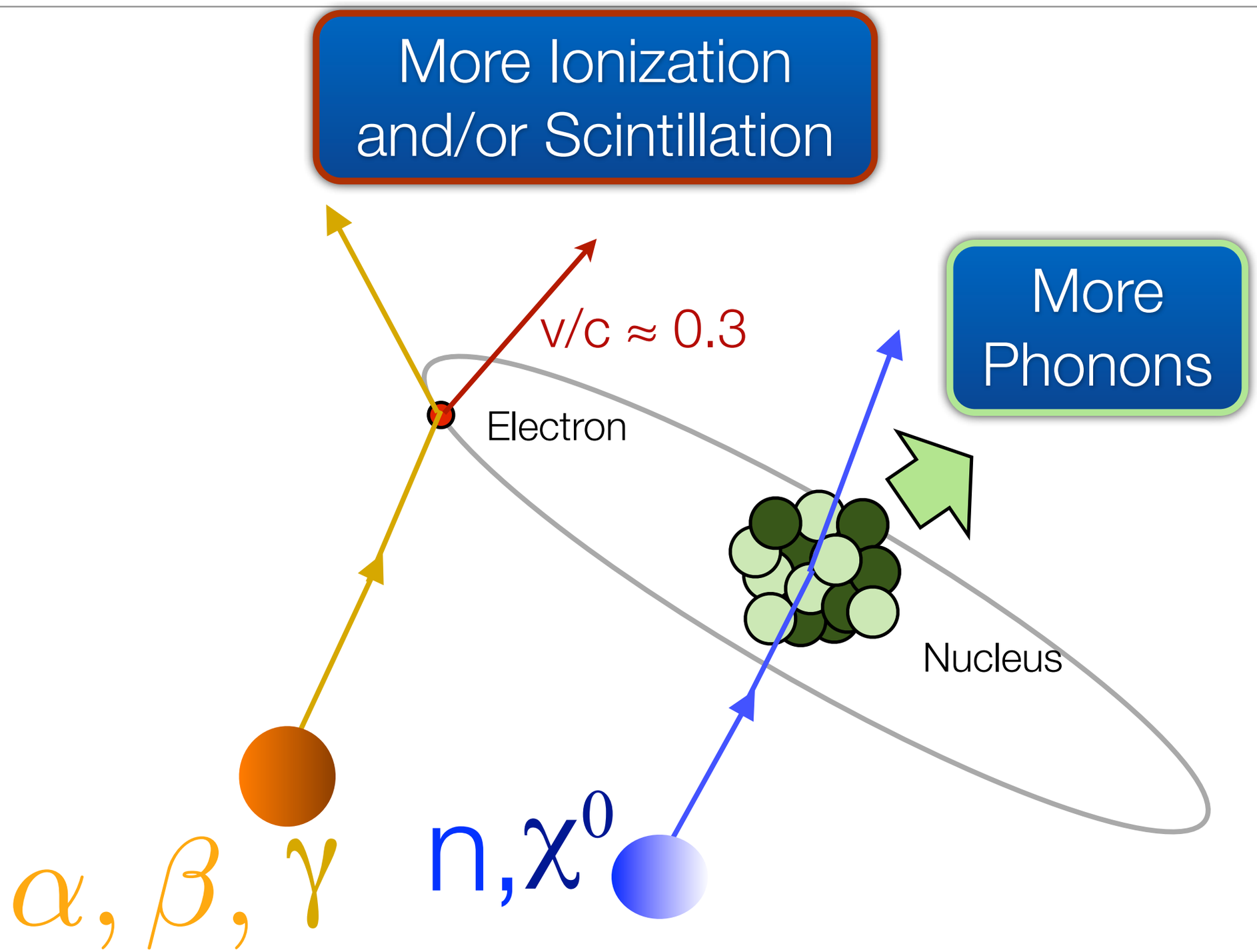
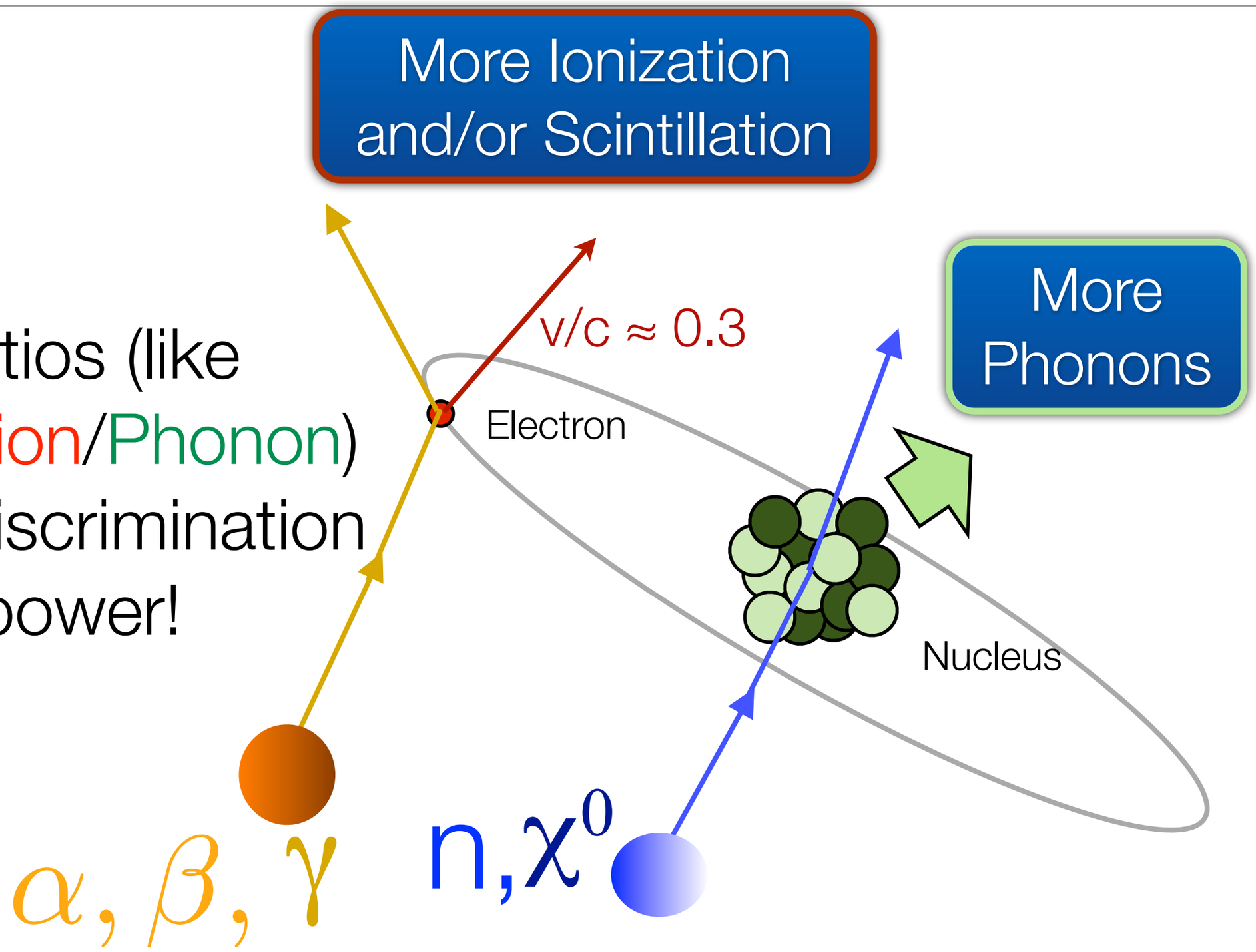
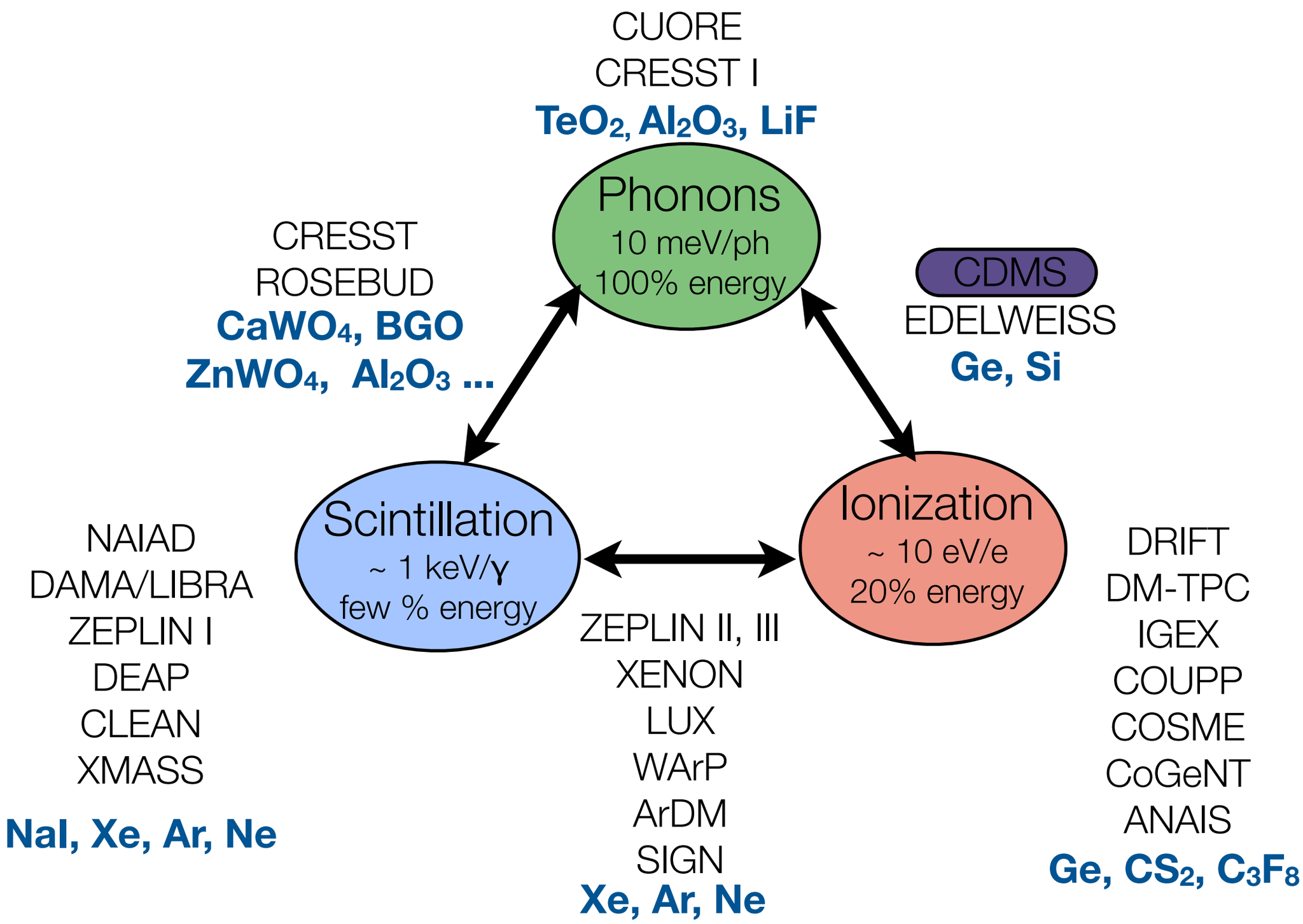


Discrimination Strategies

Ratios (like Ionization/Phonon) have discrimination power!



Discrimination Strategies



The Dark Matter Reach of an Experiment

- The reach, or sensitivity, of an experiment can be quantified as a function of four parameters:
  - The background rate: B
  - The background misidentification fraction: β
  - The signal acceptance fraction: α
  - And the exposure: MT (where M is the mass of the detectors and T is the duration of the experiment)

The Dark Matter Reach of an Experiment

- For experiments which do not distinguish between signal and background:
  - $\beta = 1$, $0<\alpha<1$
  - For the case of zero observed events, the 90% confidence level sensitivity (S_{90}) is:

$$S_{90} \propto \frac{2.3}{\alpha MT}$$

    the sensitivity improves linearly with exposure
  - When some background events (N_{bkg}) are observed, the limits becomes:

$$S_{90} \propto \frac{N_{bkg} + 1.28\sqrt{N_{bkg}}}{\alpha MT} \longrightarrow \frac{B}{\alpha} + \frac{1.28}{\alpha}\sqrt{\frac{\beta B}{MT}}$$

  - So, as soon as background is “accurately” observed, i.e. $\langle N_{bkg} \rangle = BMT$, the sensitivity stops improving

Experimental Reach: The Power of Discrimination

- For experiments which do distinguish between signal and background:
  - Define a continuous parameter η. η is any event parameter on which β and α can depend, i.e. β(η) and α(η)
  - The statistical sensitivity (S_{stat}) is:

$$S_{stat} = \sqrt{\frac{\beta(1-\beta)}{(\alpha-\beta)^2}}\sqrt{\frac{B}{MT}}$$

  - Let $Q \equiv \beta(1-\beta)/(\alpha-\beta)^2$, the value of η can be chosen to minimize Q.
  - For discriminating detectors, values of $Q \sim 10^{-3}$ are achievable, leading to a very low sensitivity (this is a good thing)
  - When some background events (N_{bkg}) are observed, the limit continues to improve with the square root of MT

Experimental Sensitivity vs Time

Zero Events

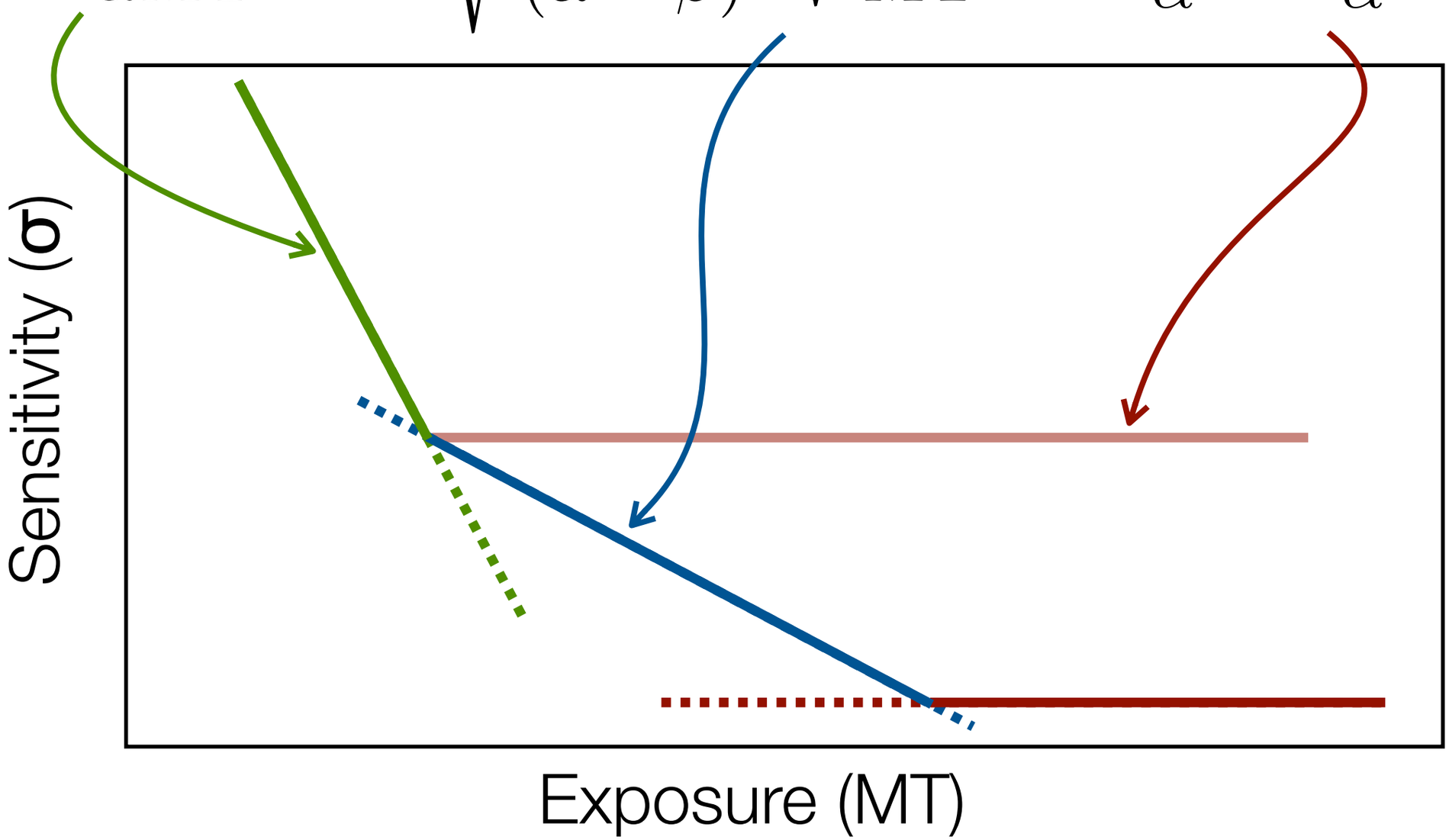
$$S_{90} \propto \frac{2.3}{\alpha MT}$$

Discriminating Detector

$$\sqrt{\frac{\beta(1-\beta)}{(\alpha-\beta)^2}}\sqrt{\frac{B}{MT}}$$

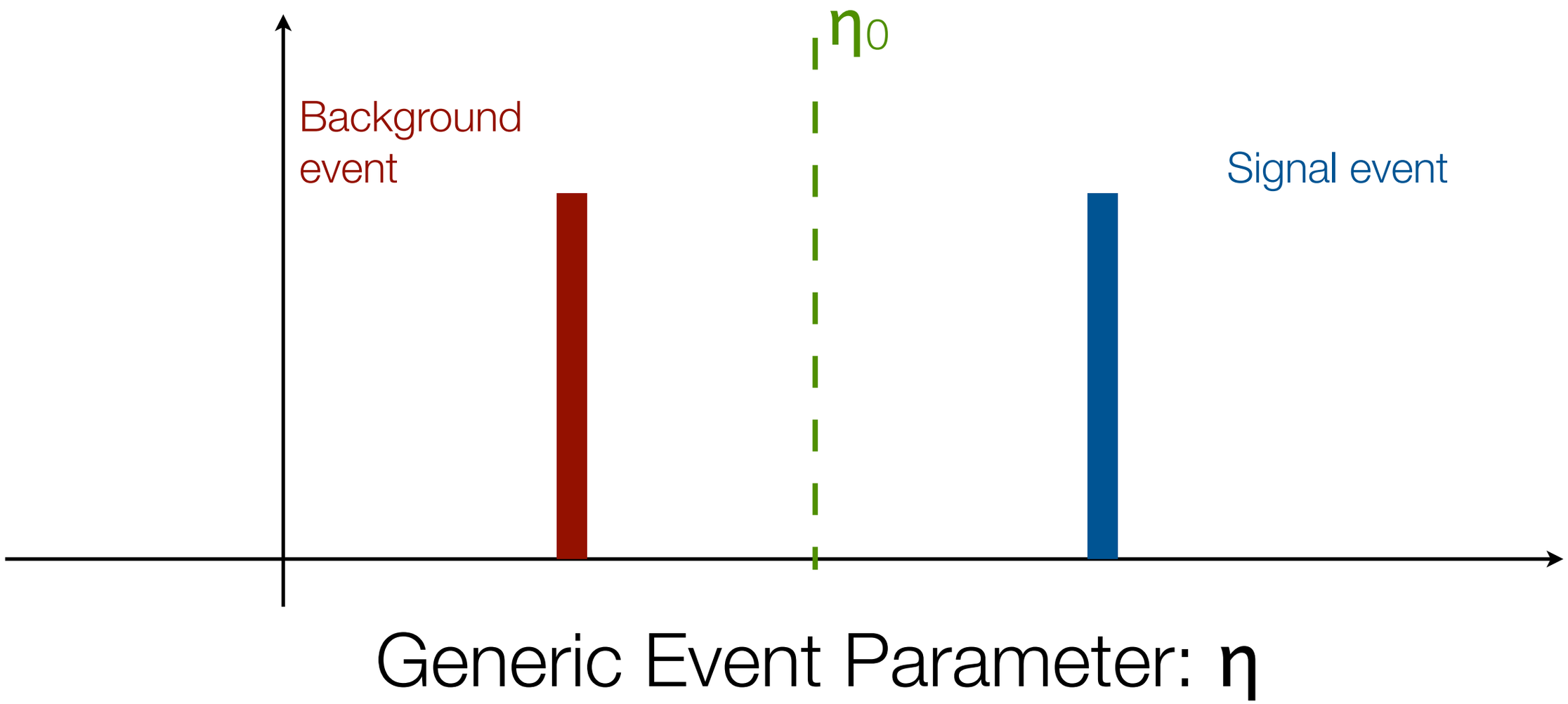
Non-Discriminating

$$\frac{B}{\alpha} + \frac{1.28}{\alpha}\sqrt{\frac{\beta B}{MT}}$$



Discriminating Variables

- Ideal behavior = Perfect discrimination between signal and event.
  - Place a cut at η_0 anywhere: We get the ideal detector behavior, i.e. $\beta=0$, $\alpha=1$
- Real detector resolution: Discrimination ability is somewhat degraded
  - There is now a preferred location for the cut η_0 with $\beta\neq0$, $\alpha<1$



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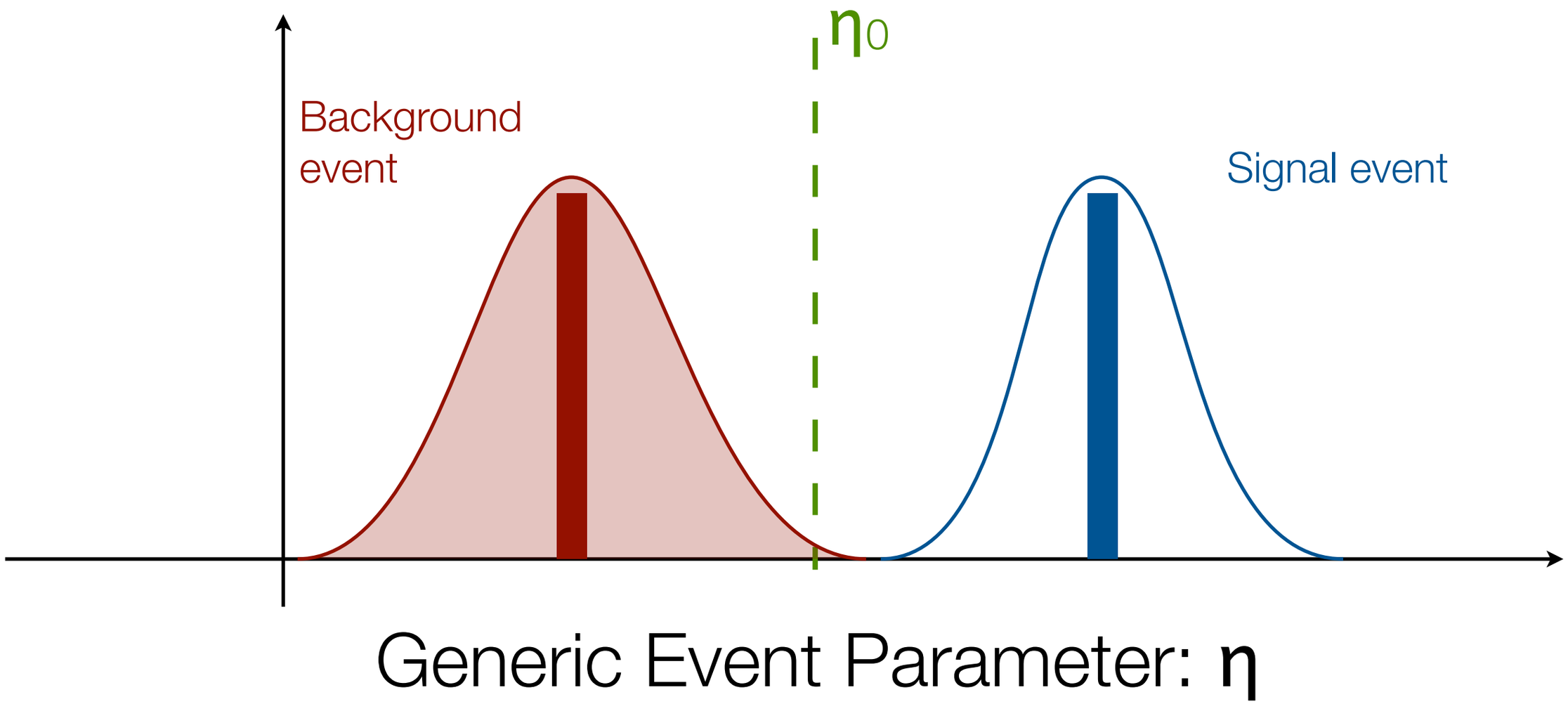

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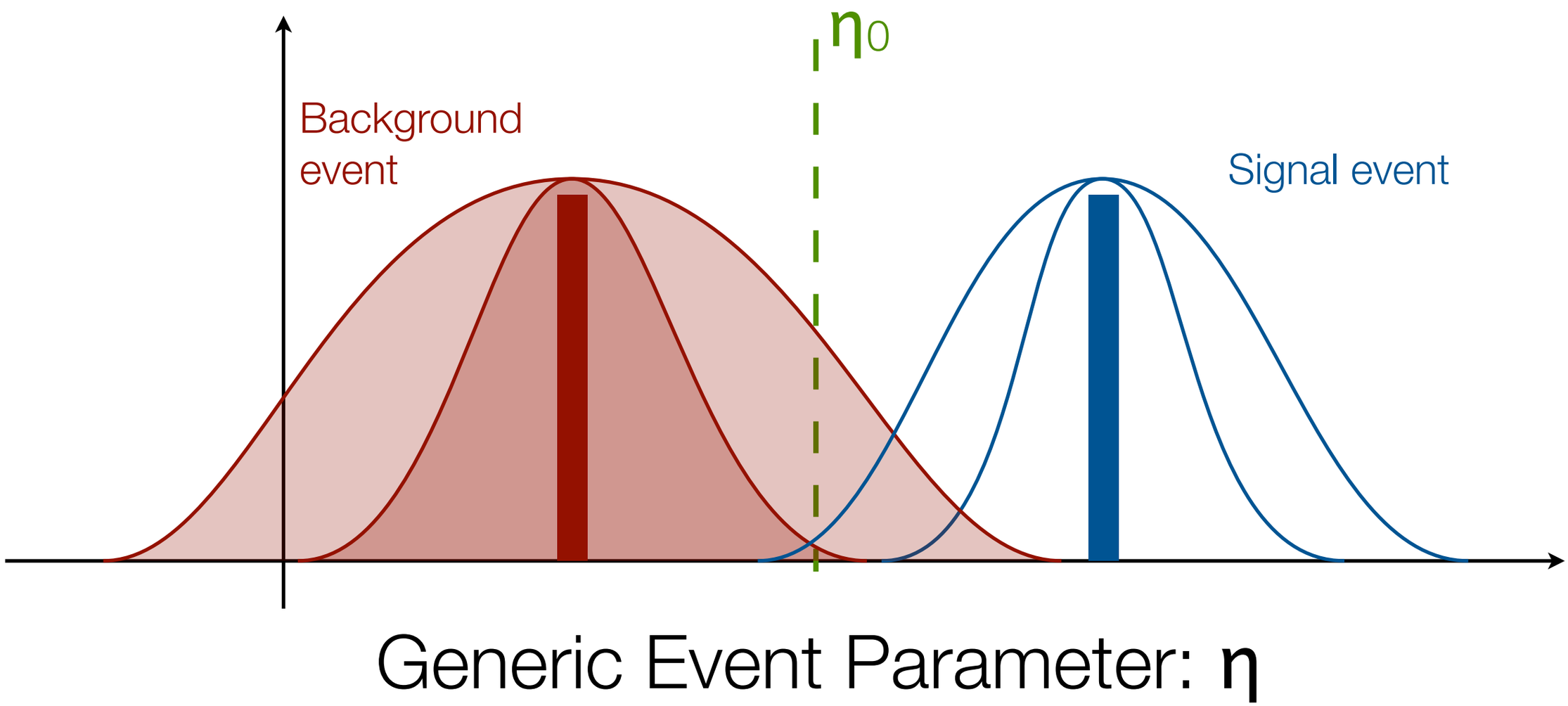

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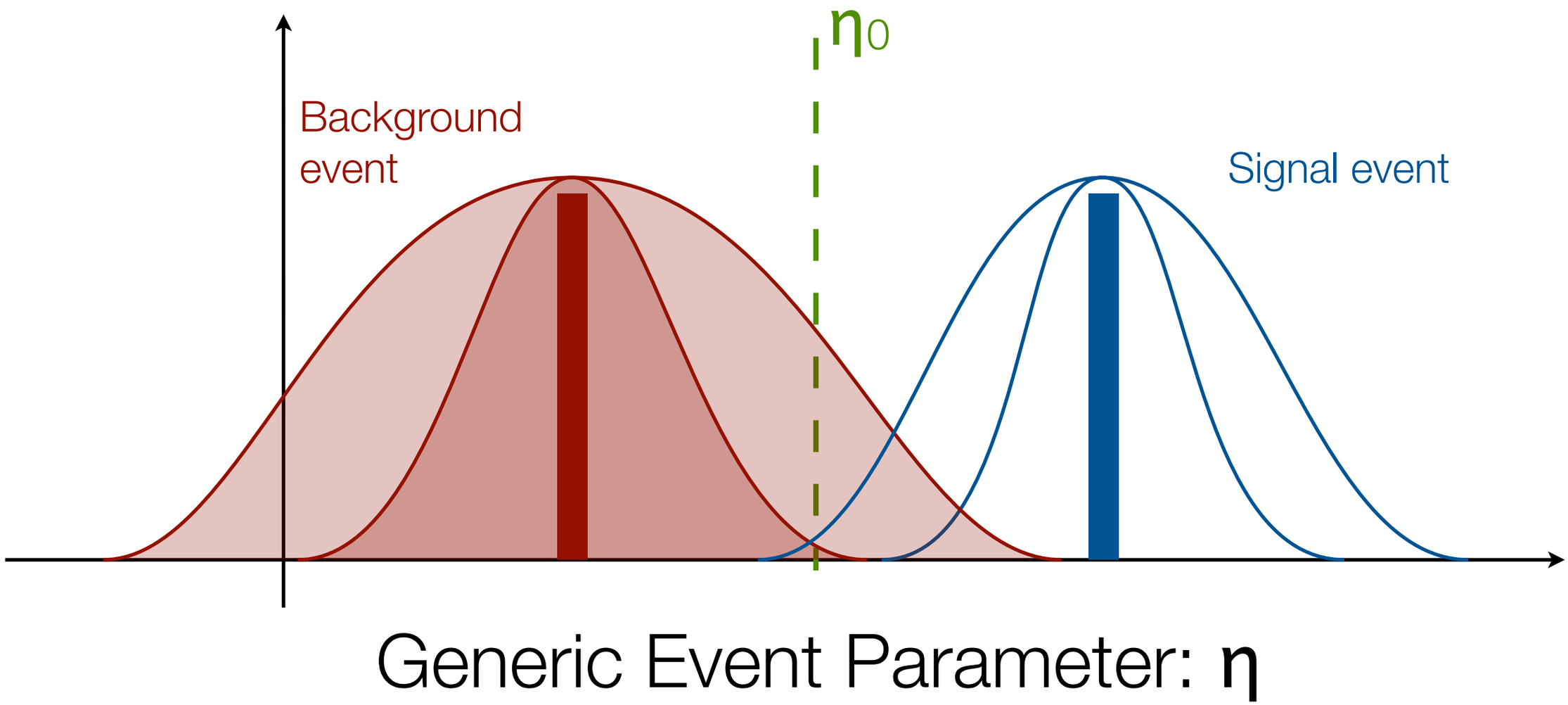

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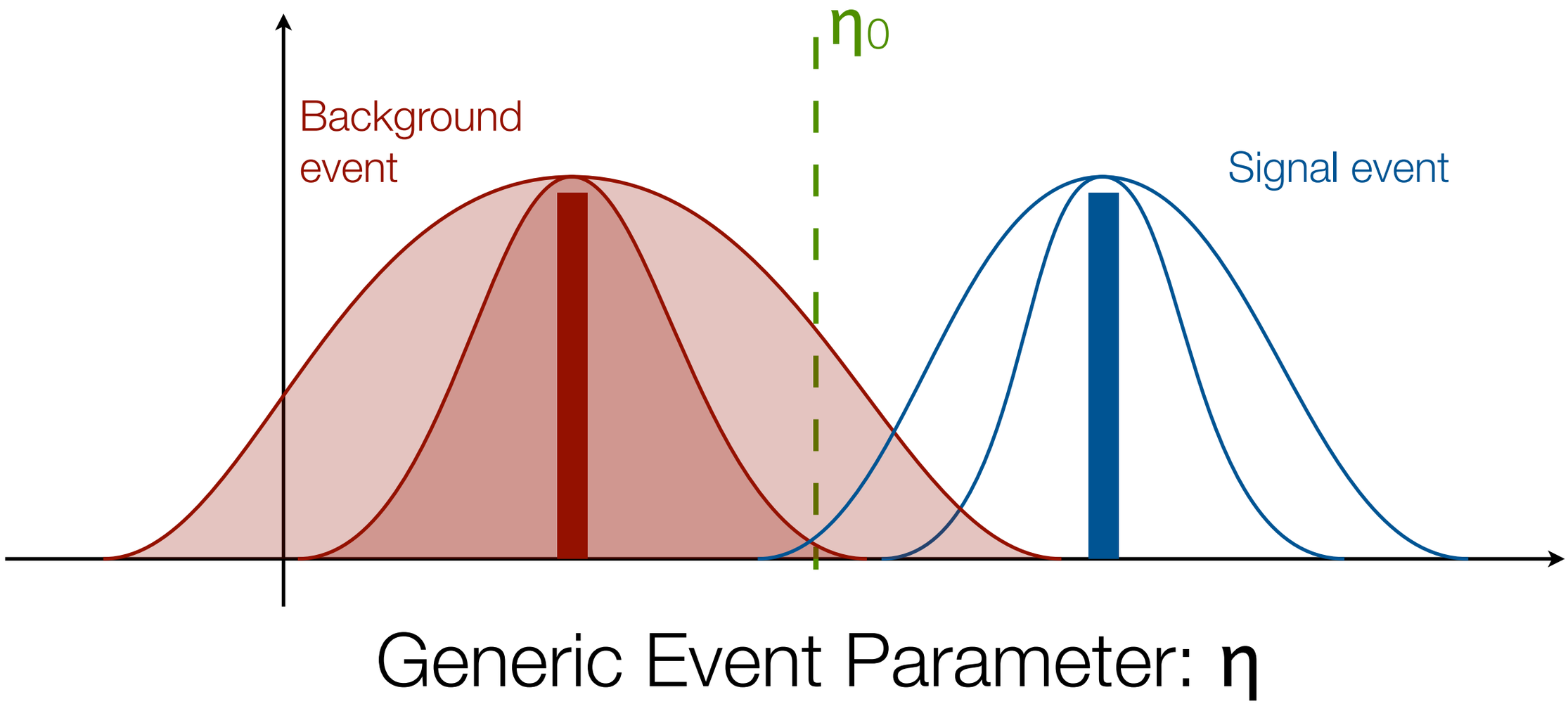

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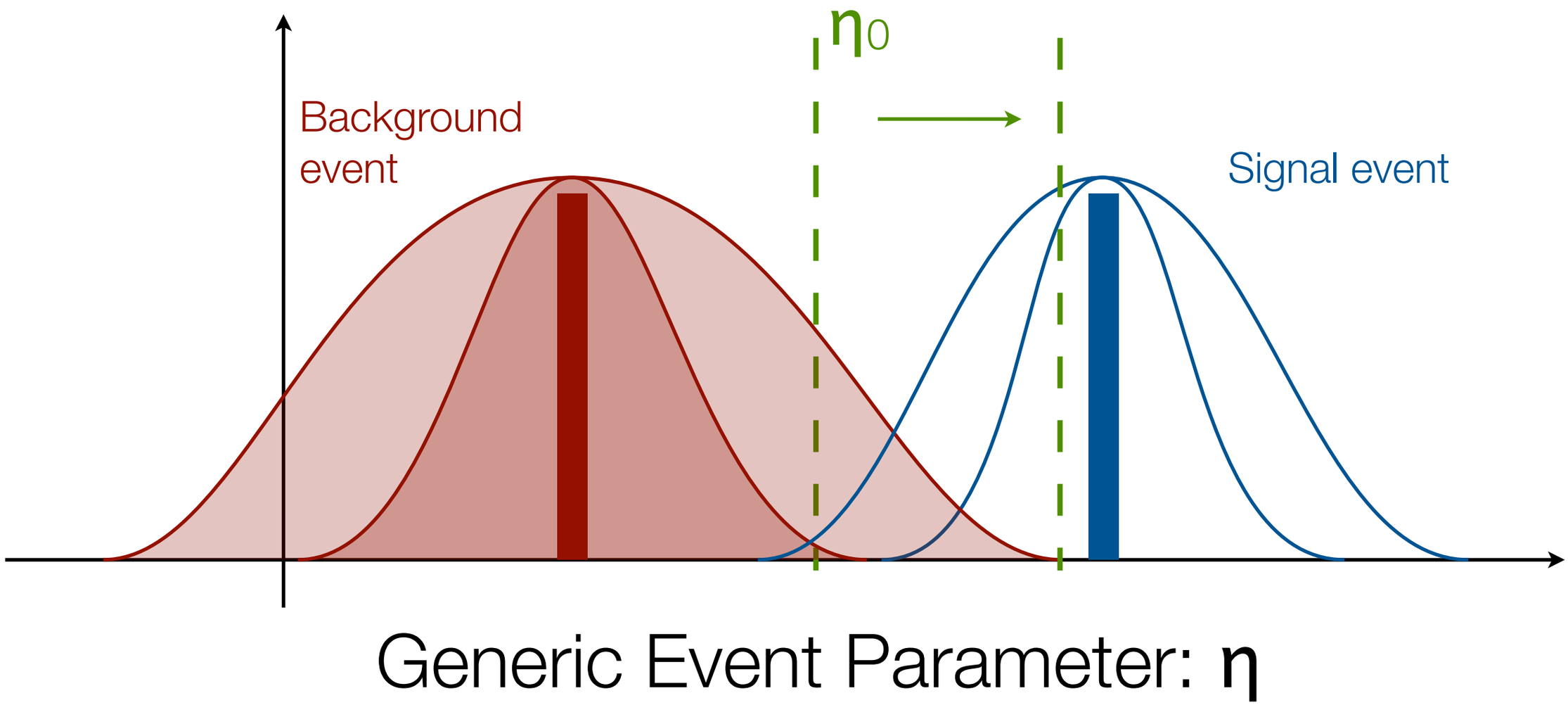

Dark Matter Direct Detection Searches and Techniques

Tarek Saab
University of Florida

TASI: The Dark Secrets of the Terascale

University of Colorado, Boulder

29 - 30th June, 2011

Outline

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

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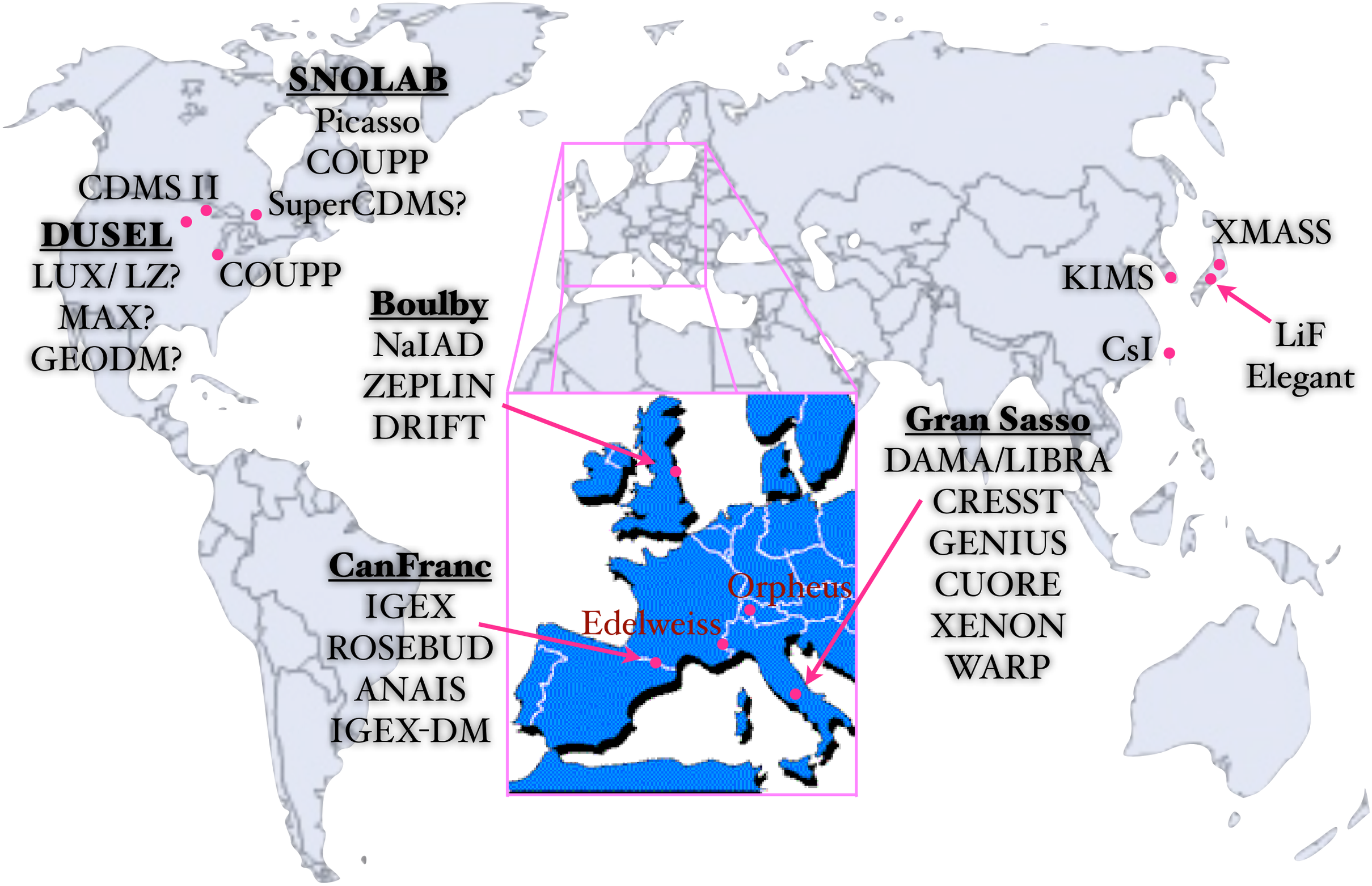
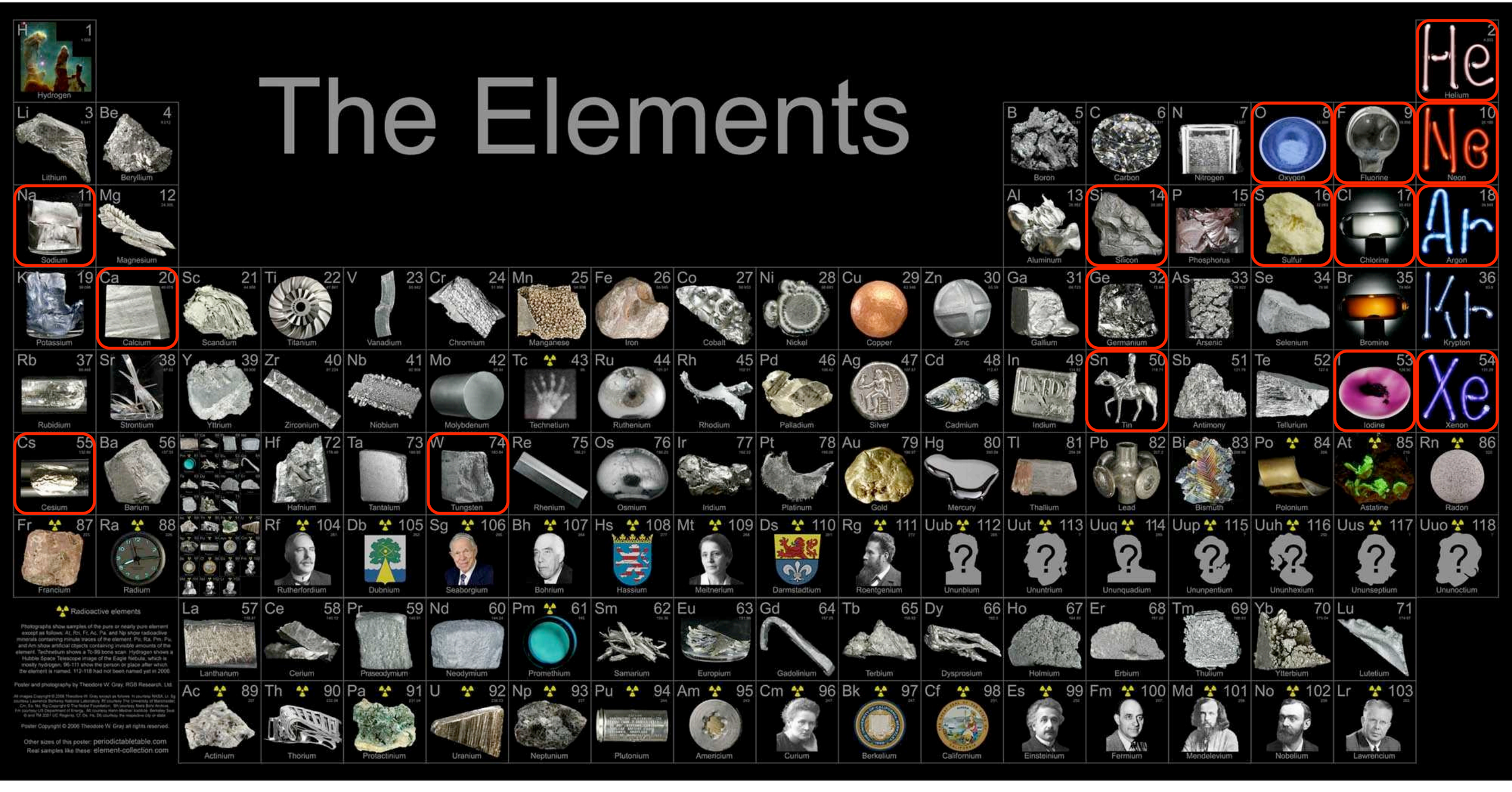


Worldwide Dark Matter Searches

Dark Matter Search Elements

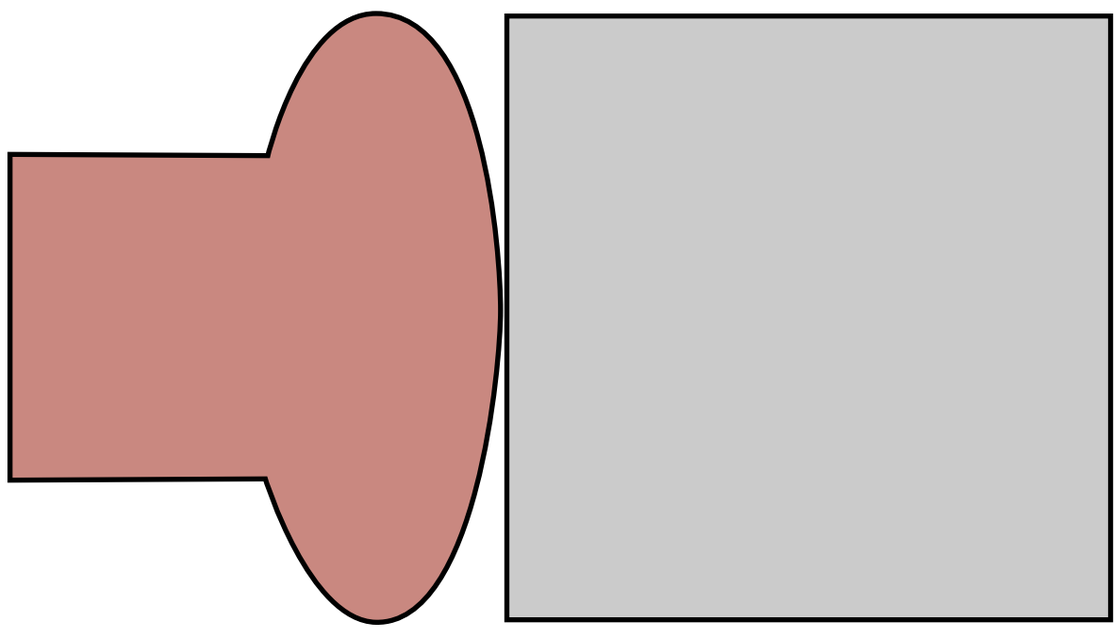


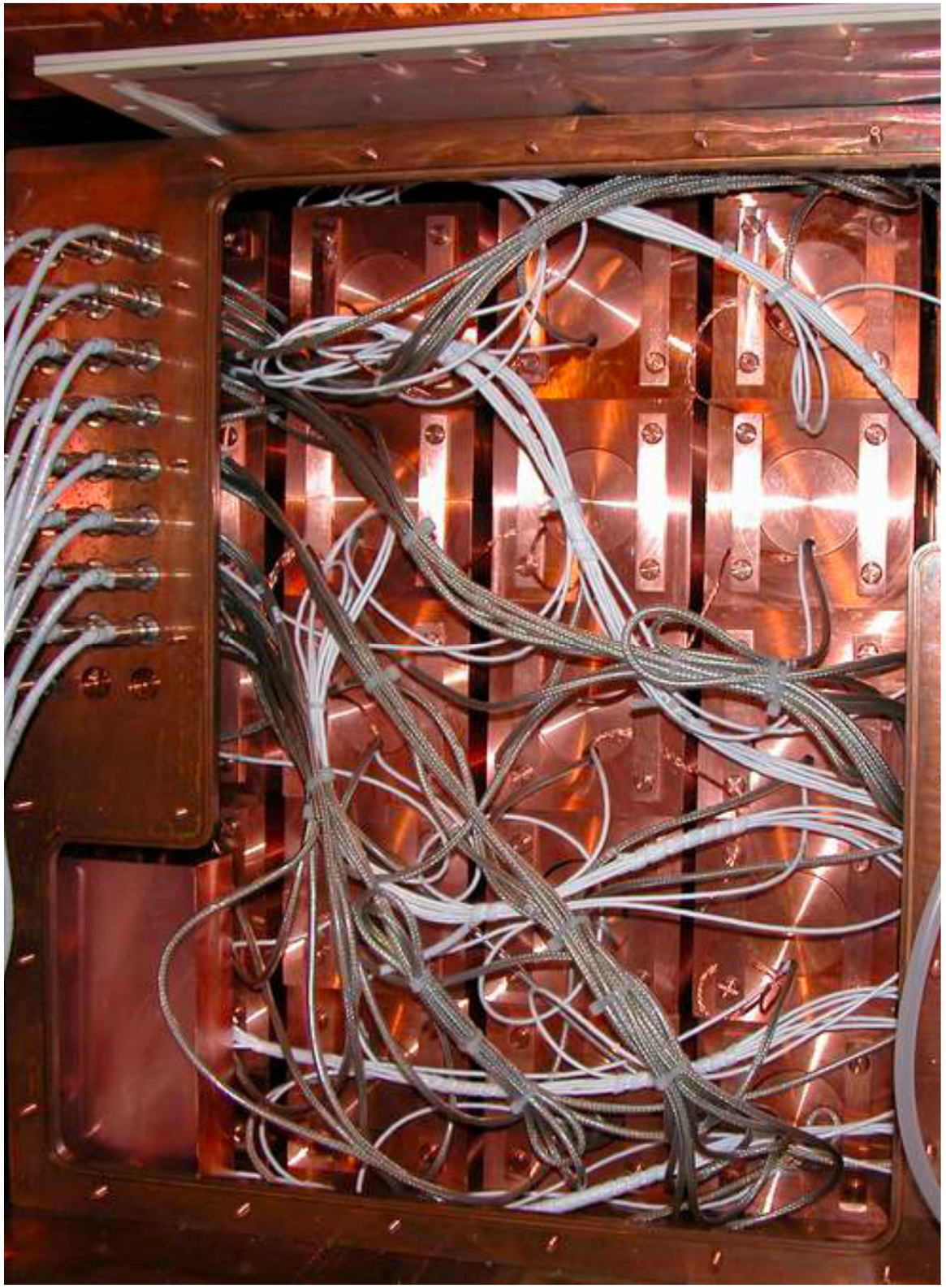
The Classical Approach

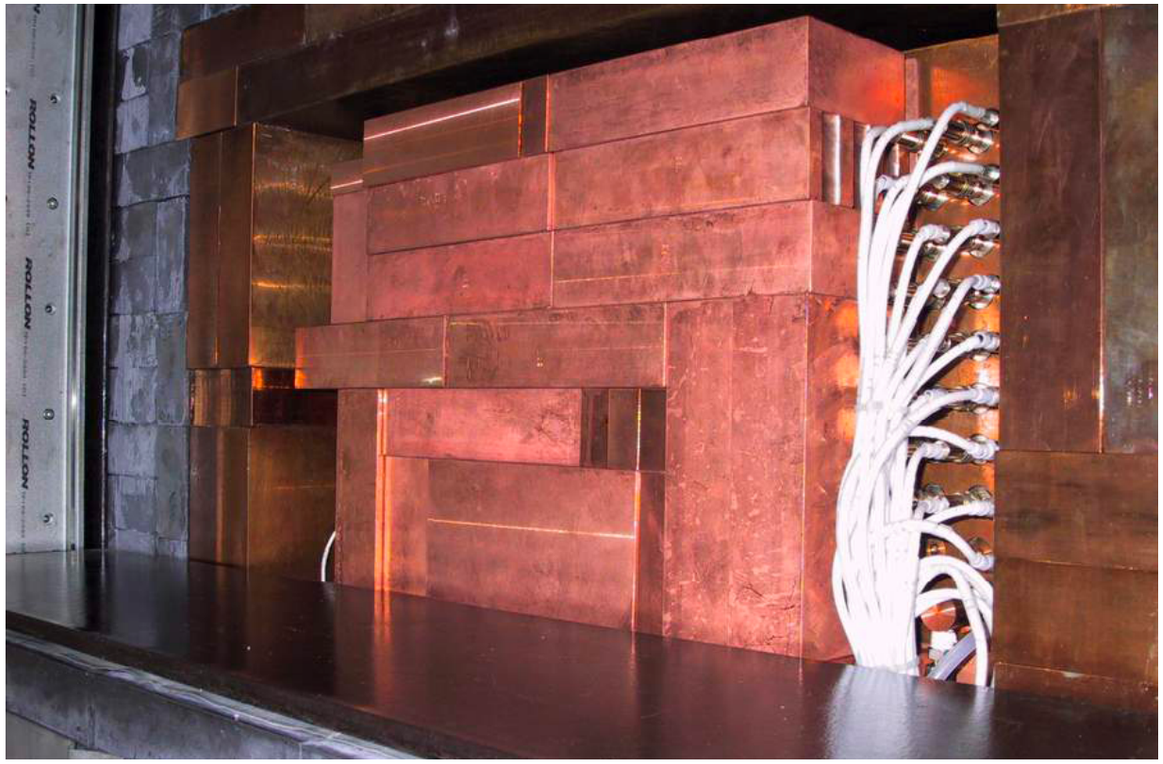
LIBRA

- Background Discrimination :
  - Small difference in pulse shape between electron and nuclear recoils
  - Insufficient for event by event discrimination, but can be used on a statistical basis
- Mass / Exposure
  - Operating 250 kg of detectors at the Gran Sasso underground laboratory (~3000 mwe) since 2003
  - Recently finished operating 100 kg of detectors for 7 years (DAMA)
  - Background rate ~ 1 evt/kg/keV/day

NaI Scintillator



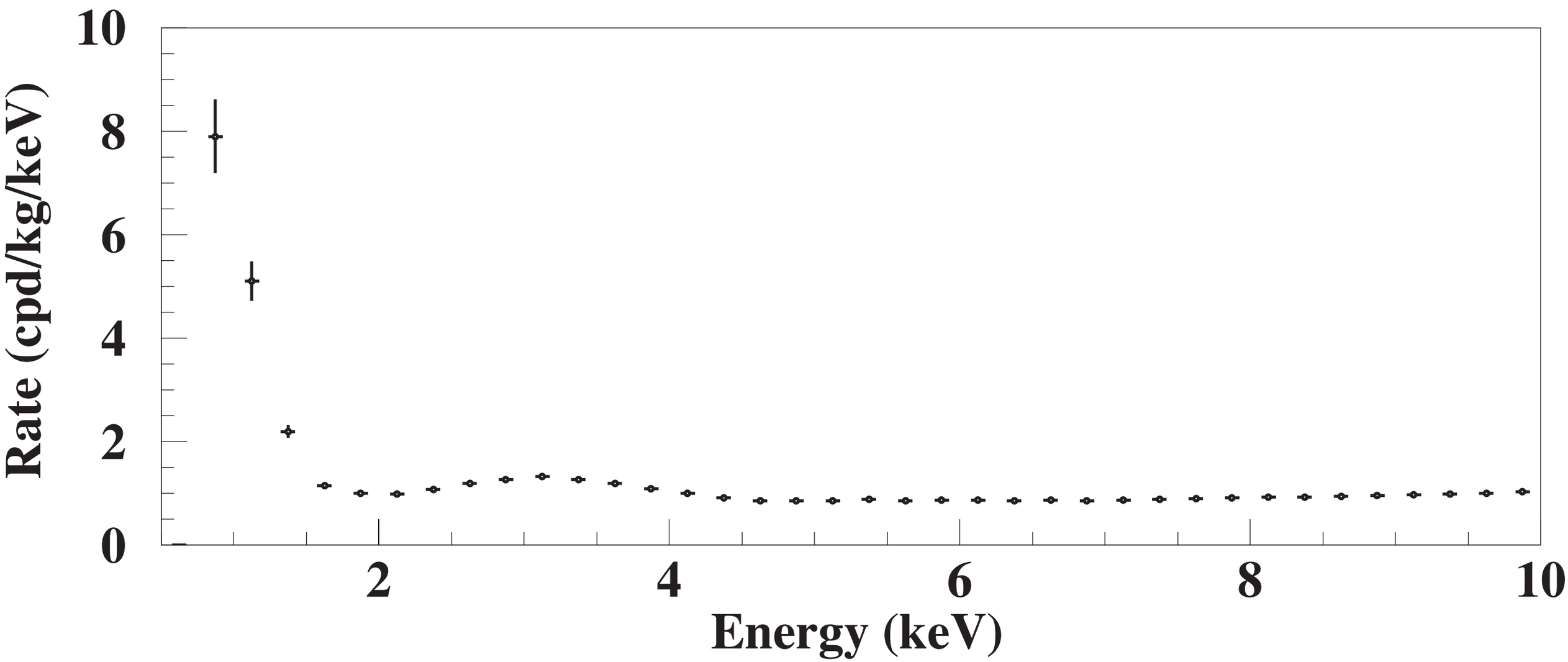




Inside LIBRA

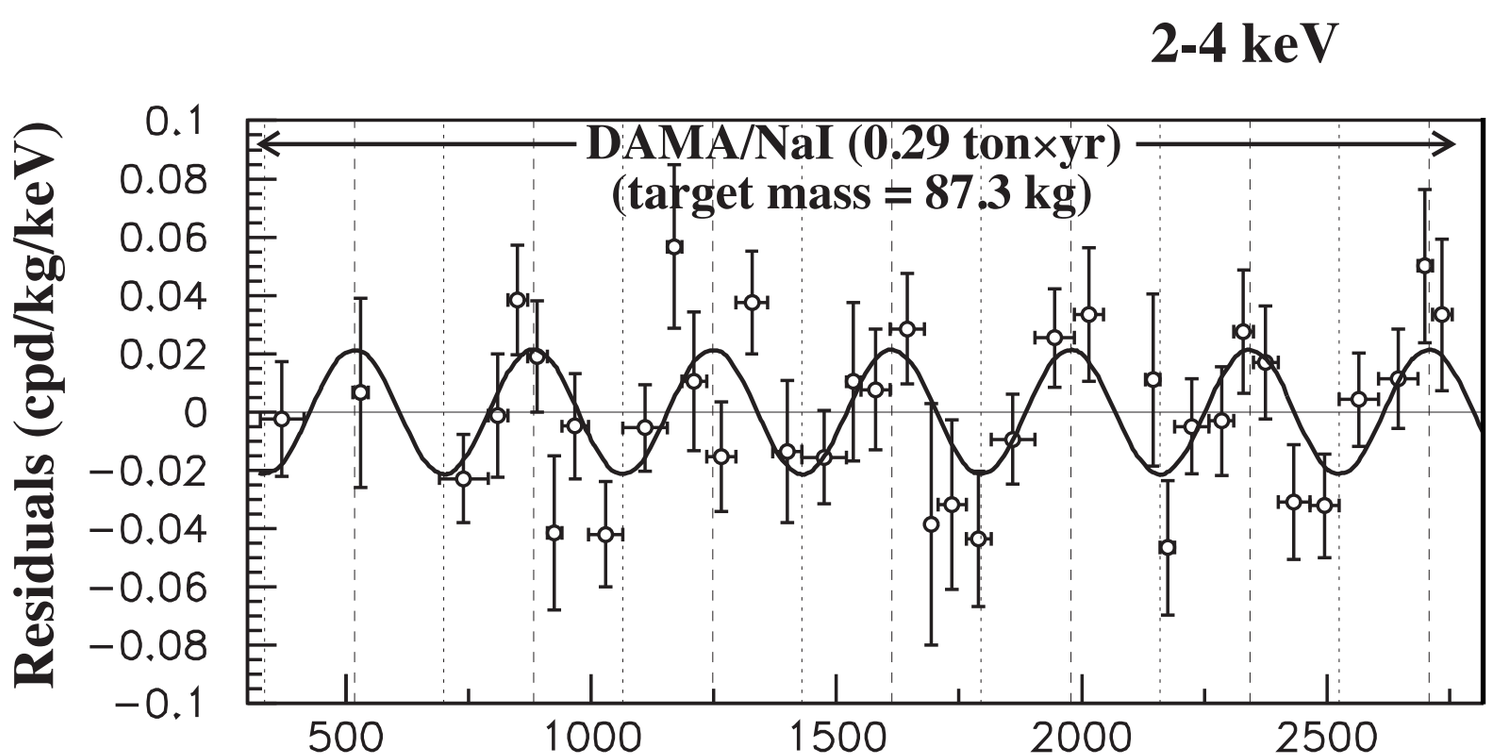
DAMA/LIBRA Collaboration

Libra Spectrum



The Libra/DAMA Signal

- Observed a modulating signal in the lowest energy bins
  - Amplitude and phase of modulation consistent with standard WIMP halo model



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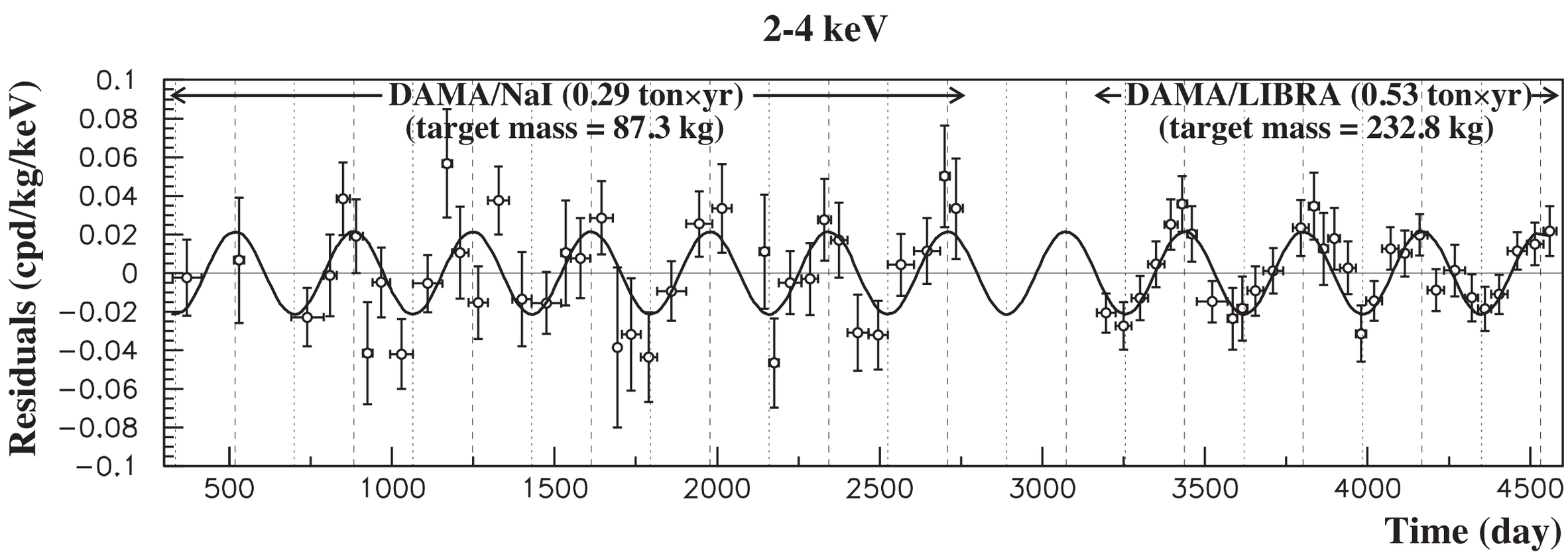
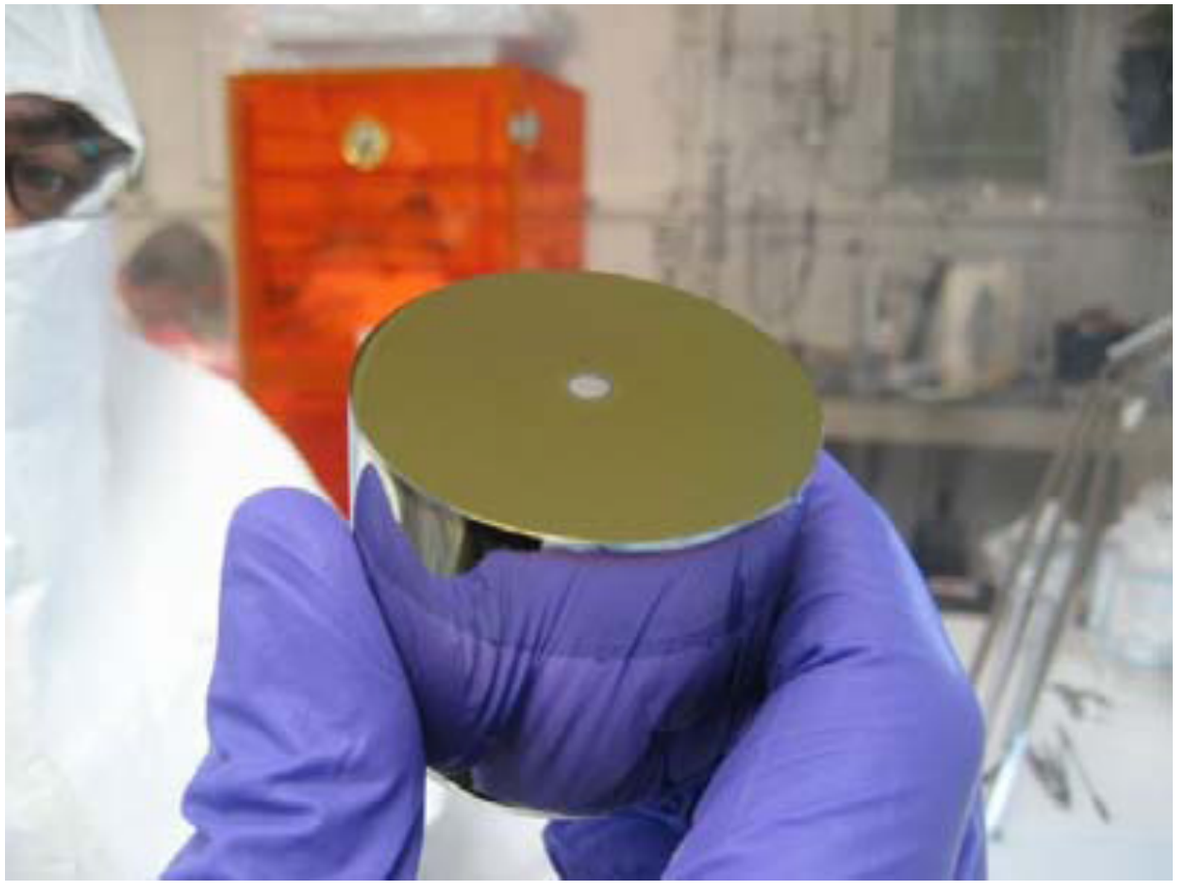


CoGeNT

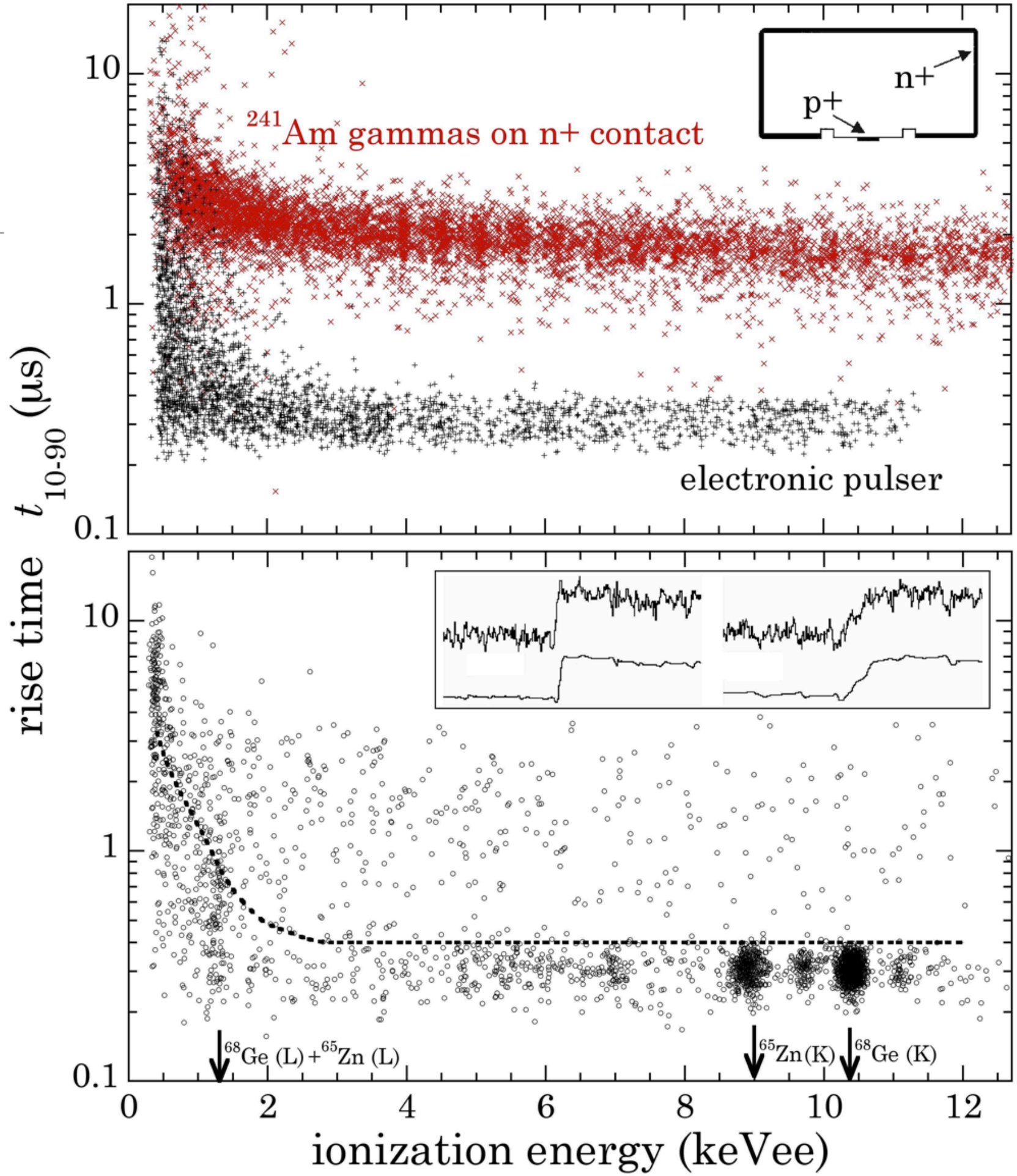
- P-type Point Contact Germanium Detector
- 440g detector
- Low 0.4 keVee threshold
- Operating in the Soudan Mine in Minnesota



arXiv: 1002.4703v2

Surface Event Discrimination

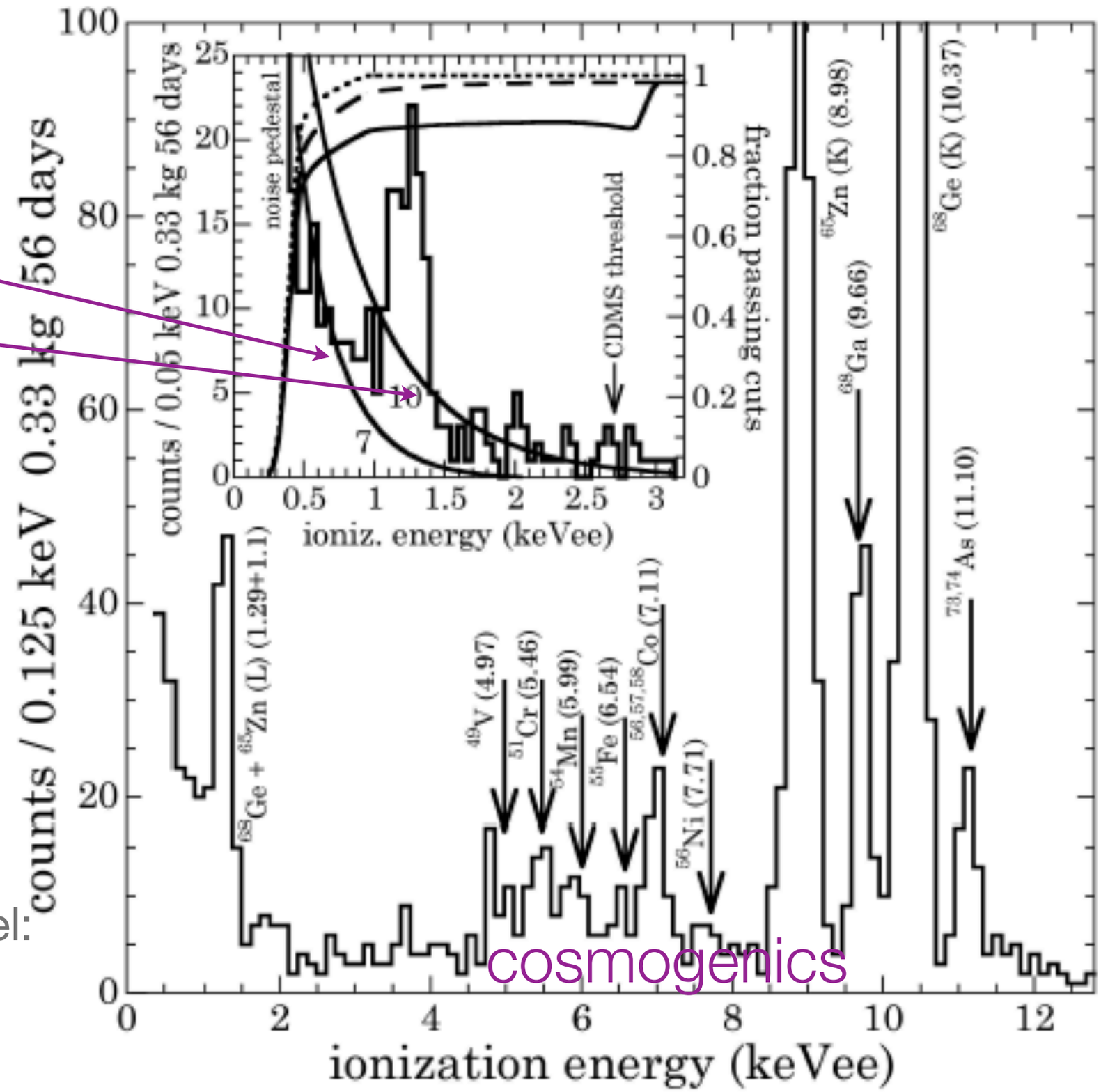
- Slower risetime of pulses on the n+ surface allows a cut to be placed on DM search data (lower)
- Inset shows fast and slow risetime pulses



WIMP Signal?

7 GeV WIMP
10 GeV WIMP

- Fitting the data:
  - Background only model: $\chi^2 = 20.4/20$
  - Background + WIMP model: $\chi^2 = 20.1/18$



WIMP Signal?

7 GeV WIMP

10 G

Science 3 June 2011:
Vol. 332 no. 6034 pp. 1144-1147
DOI: 10.1126/science.332.6034.1144

- NEWS FOCUS

PHYSICS

Possible Sighting of Dark Matter Fires Up Search and Tempers

A second experiment may have spotted hypothetical dark matter particles called WIMPs, but its leader's take-no-prisoners attitude has competitors steaming.

"I have not seen a sloppier job than what XENON is pushing," says Collar, who seems to straddle a youthful rebelliousness and middle-aged curmudgeonliness. "They cannot fool all of the people all of the time." Collar's stinging remarks—one of his slides describes a particular XENON result as "pure, weapons-grade balonium"

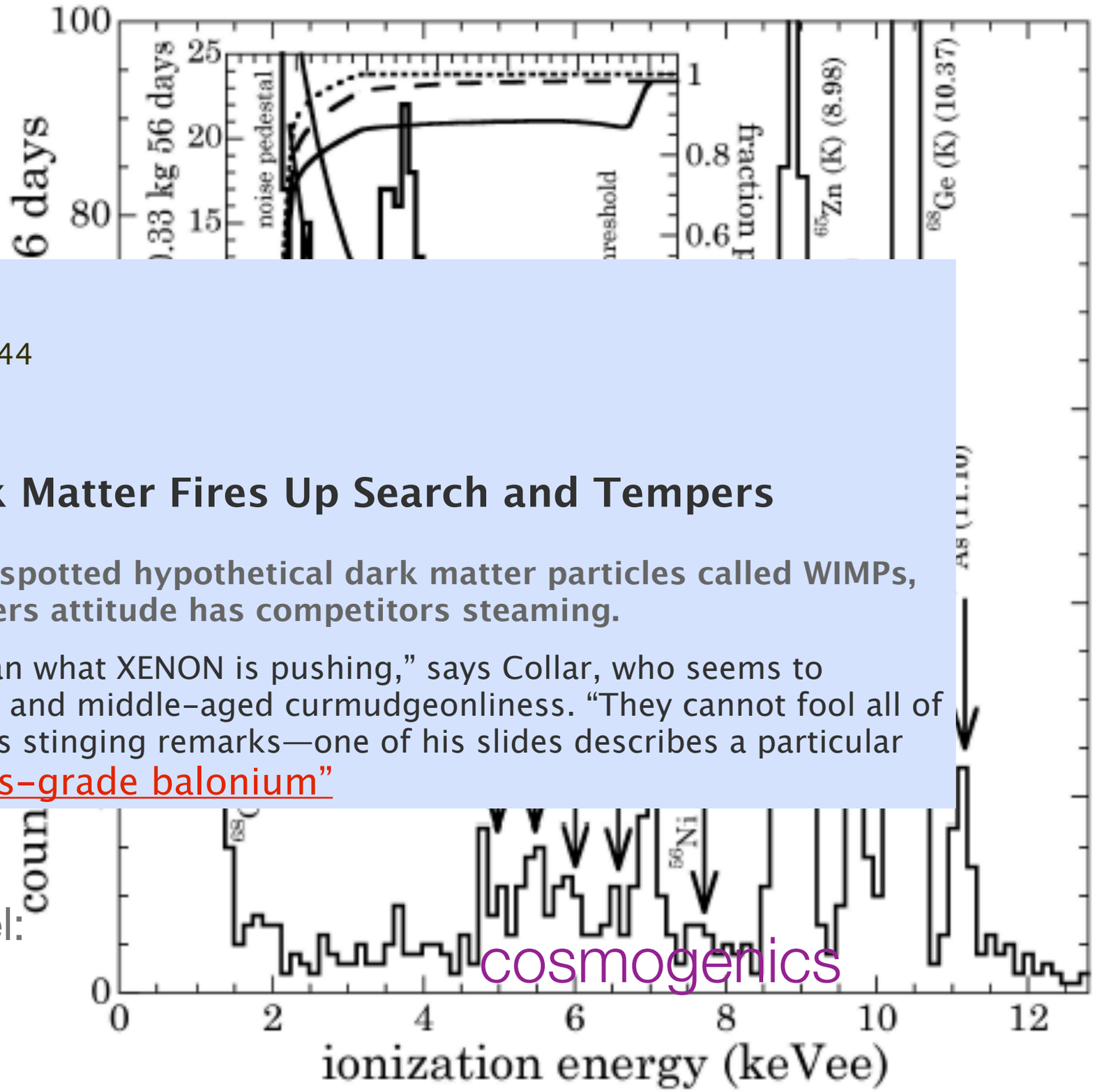
- Fittin

  - B

    χ

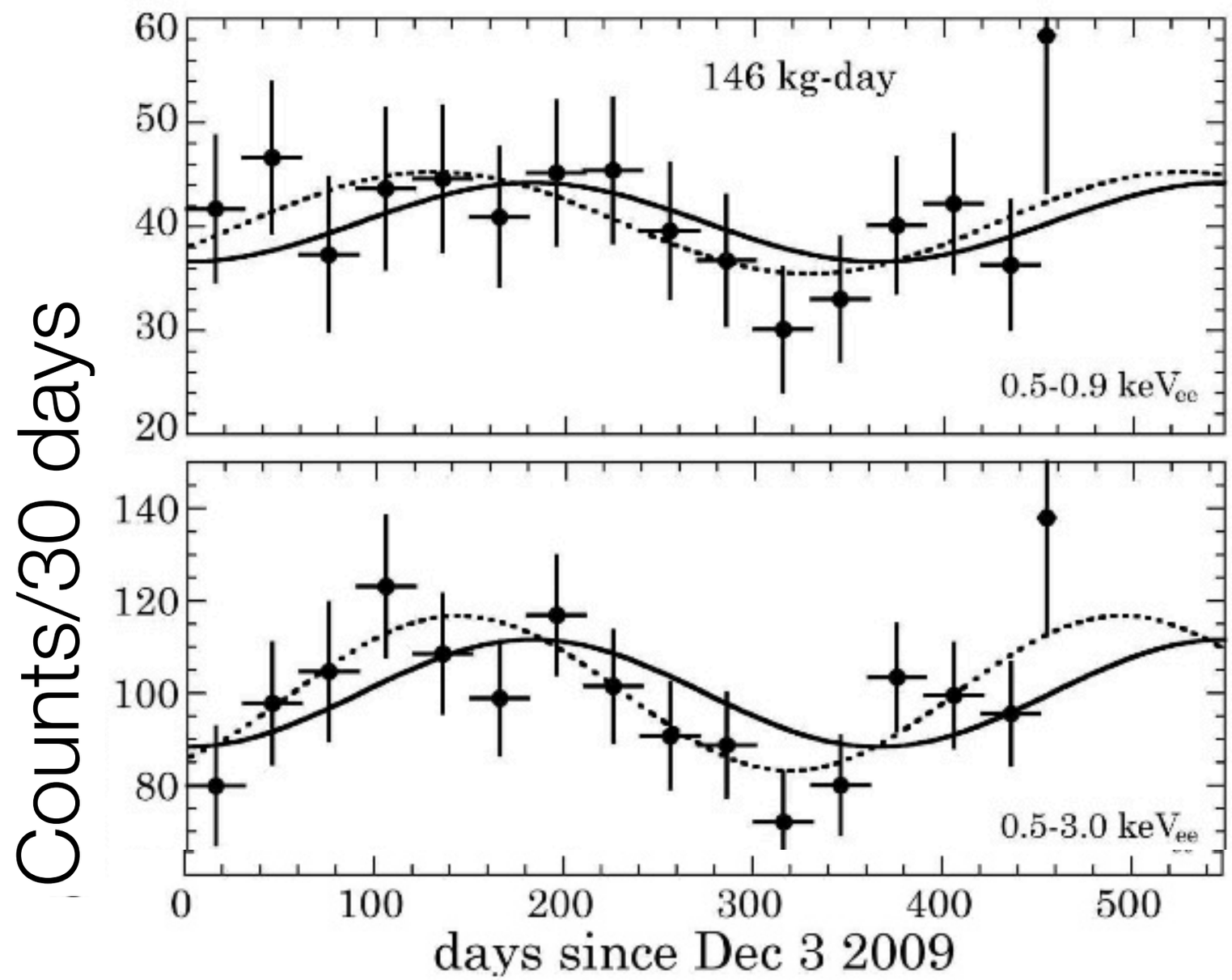
- Background + WIMP model:

  $\chi^2 = 20.1/18$



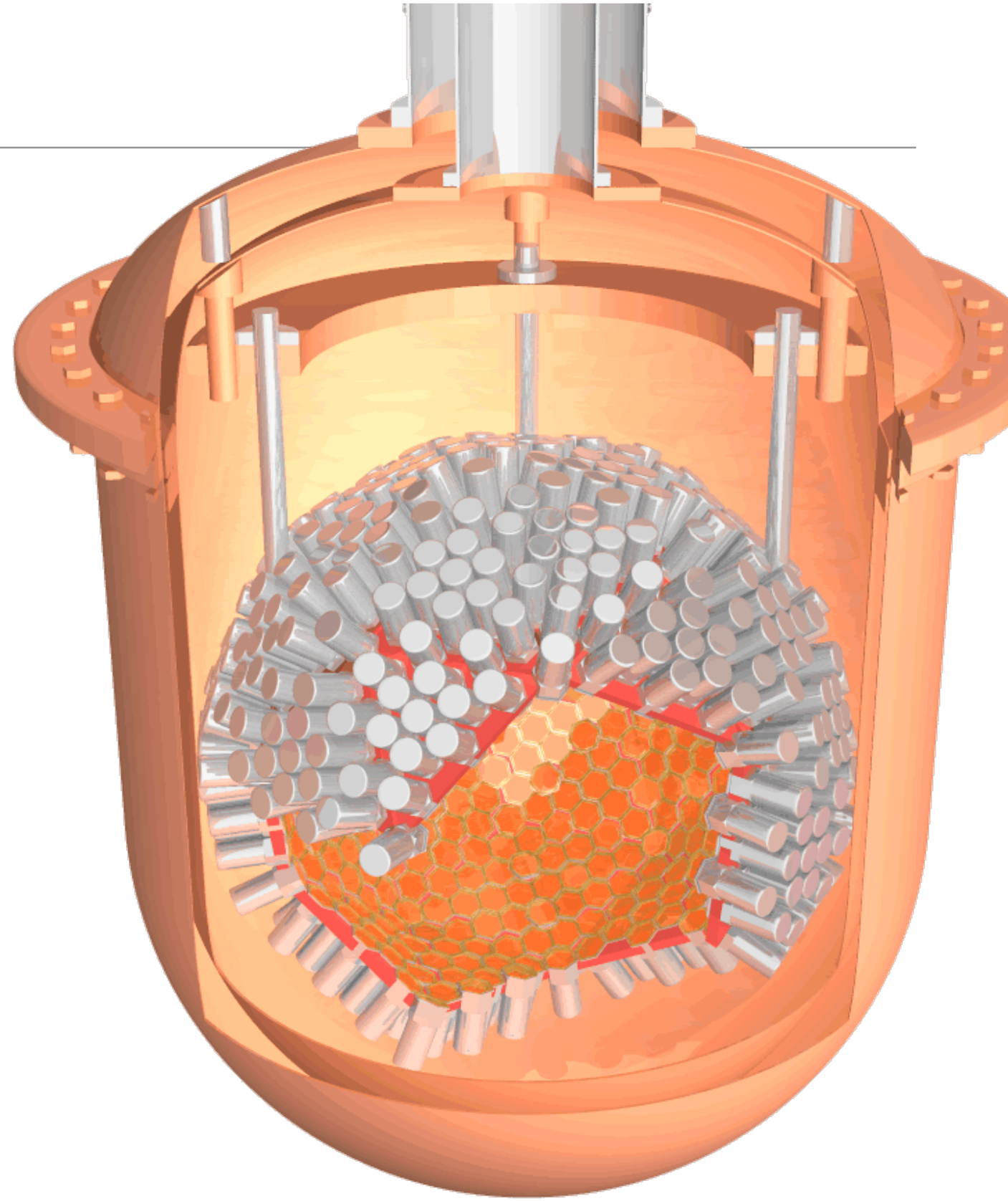
WIMP Modulation Signal?

- Fitting the data:
  - Modulation minimum in October 16
  - DAMA modulation minimum in Dec 2

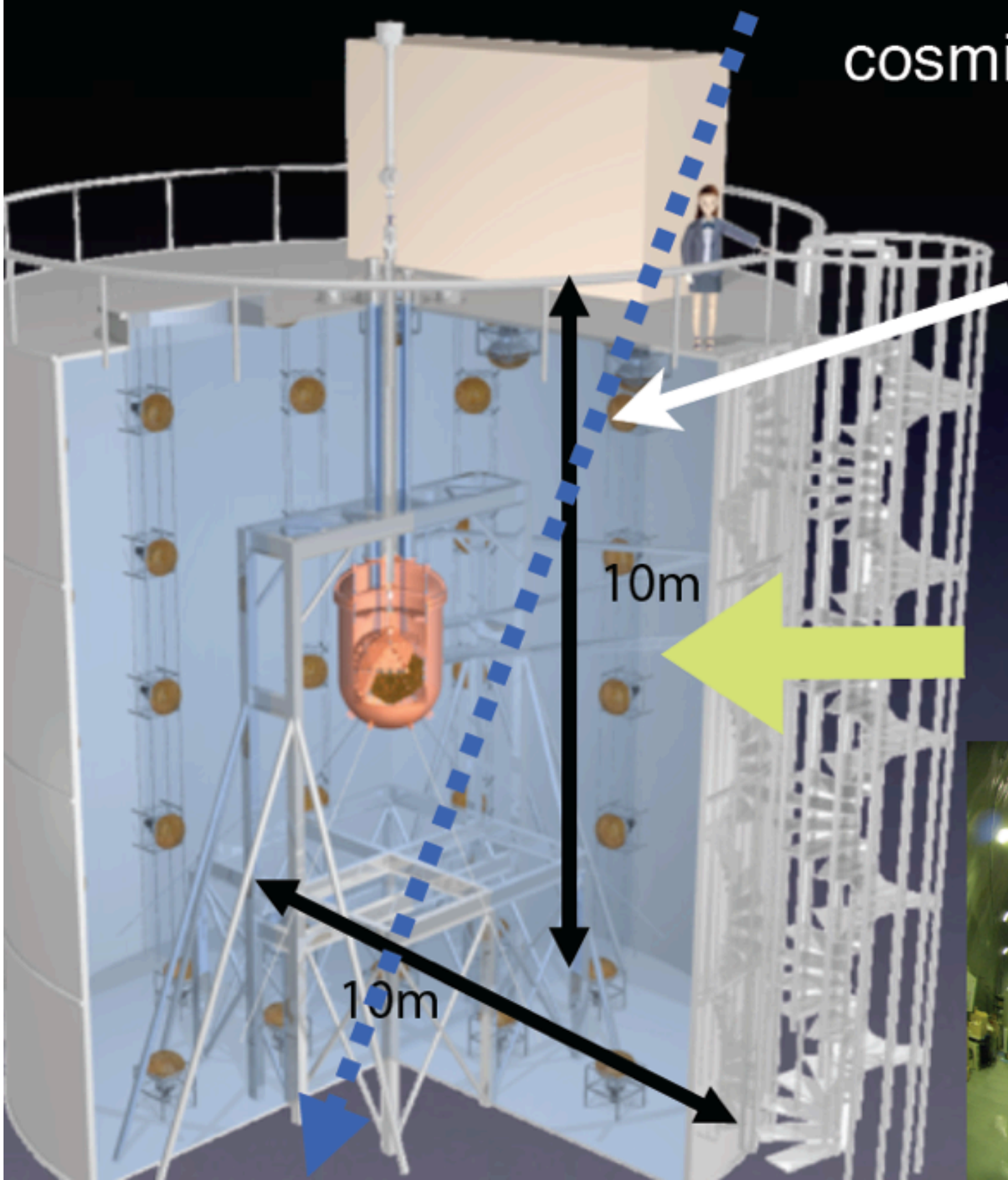


XMASS

- 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



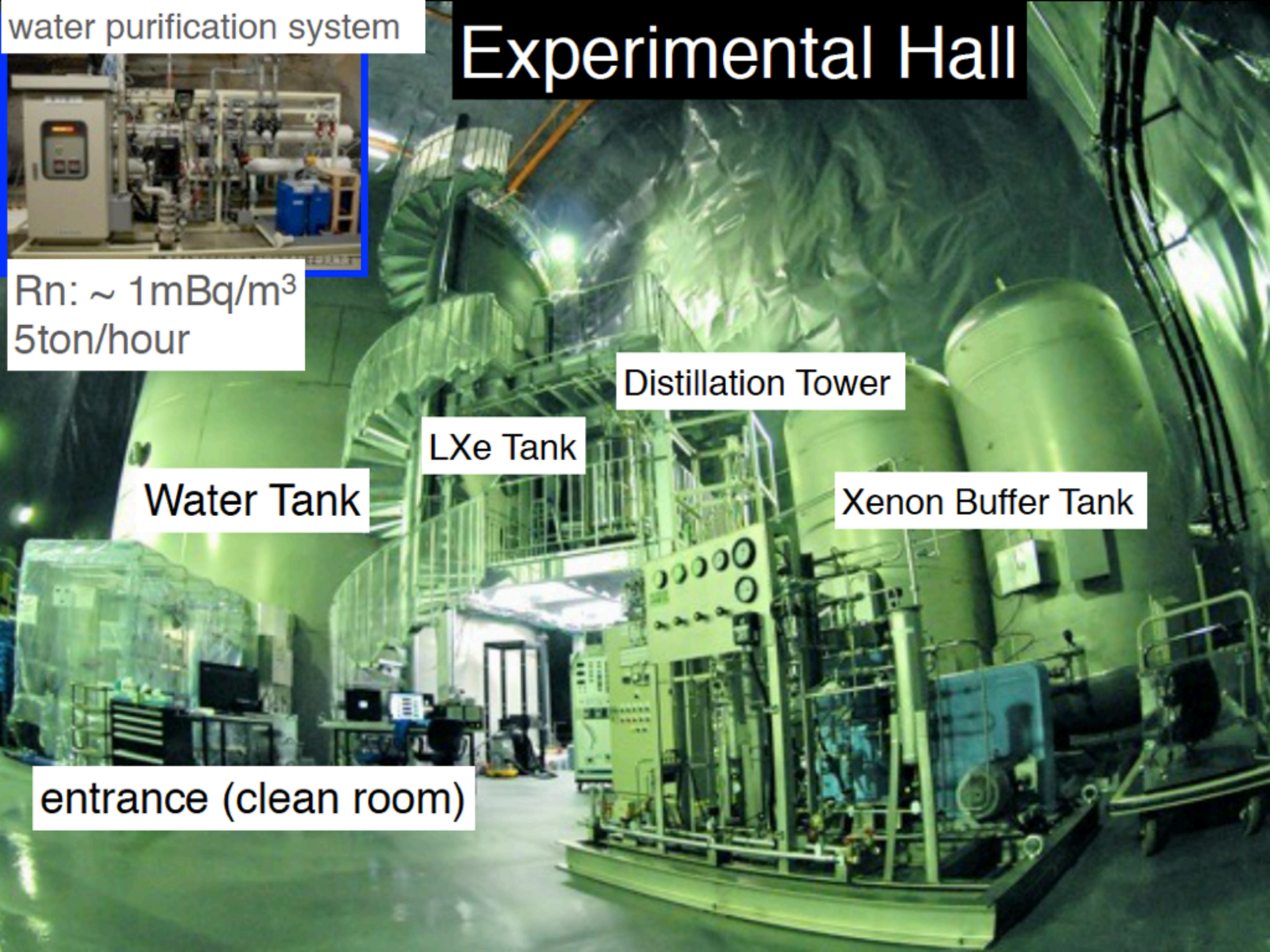
70 PMTs (20 inch) to detect Cerenkov Light (same as SK)

Active shield for muon induced events

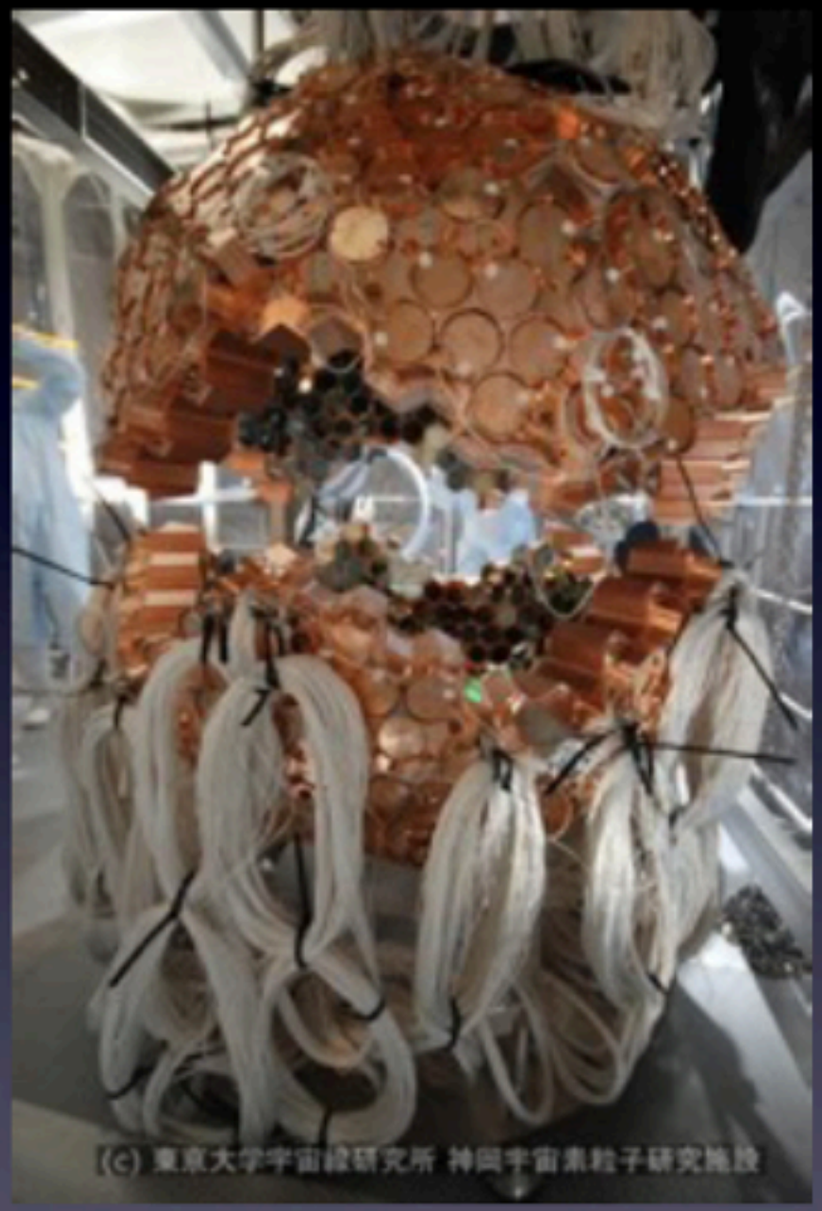
Passive shield for γ and neutron from Rock

mashita

Experimental Hall



PMT Holder



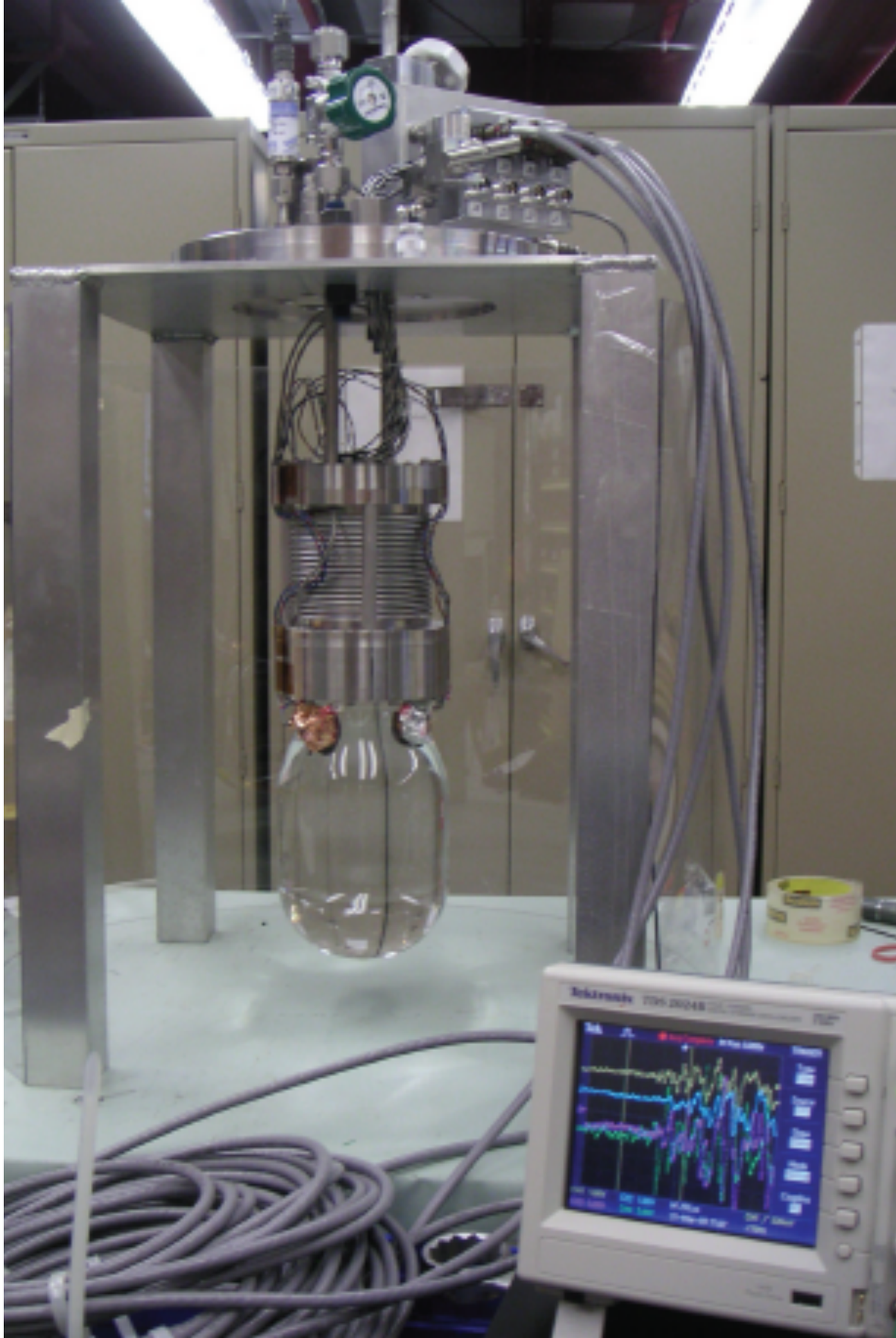
Data Coming Soon!

OFHC Filler

Insensitivity to Backgrounds

COUPP

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



COUPP

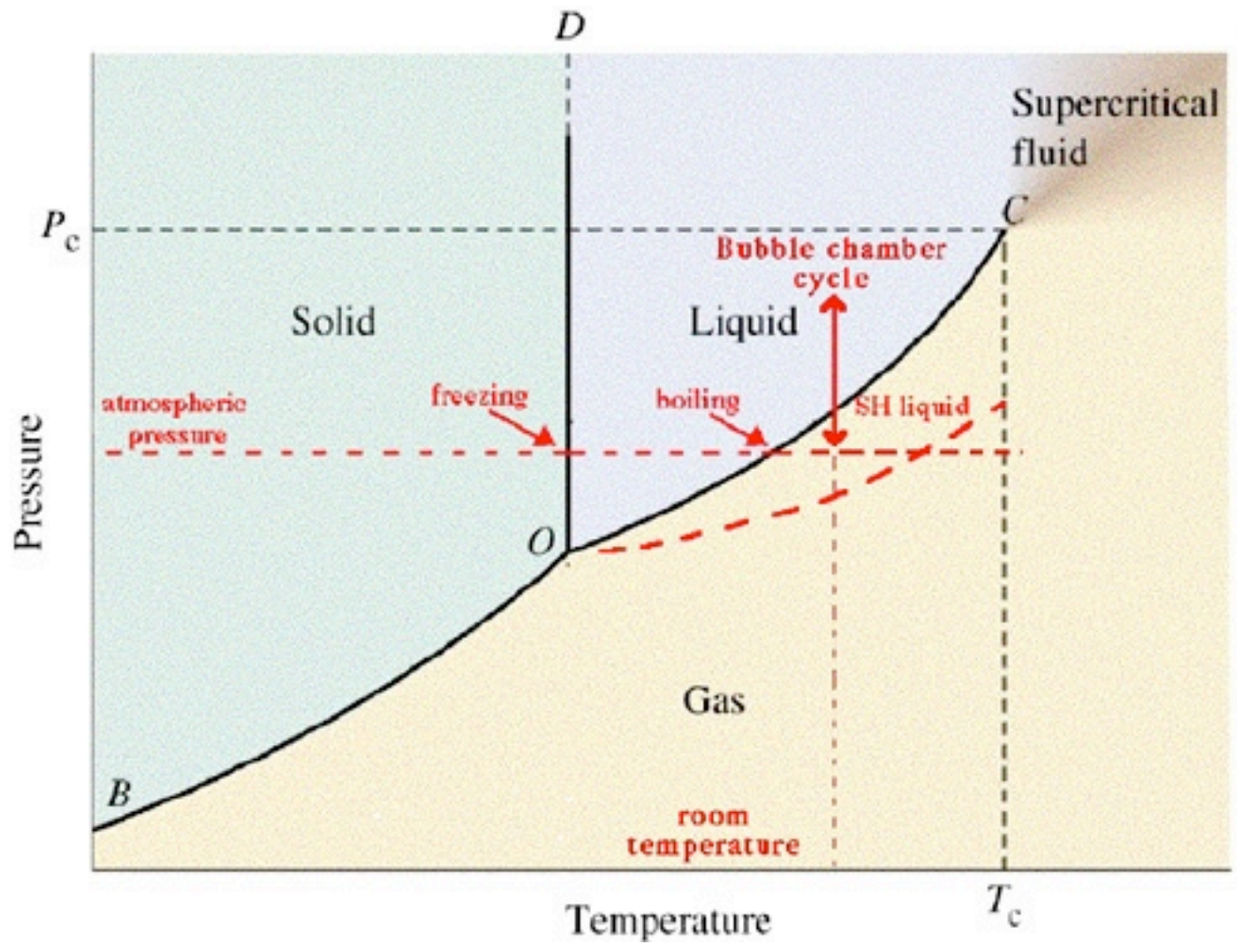
(see also PICASSO / ORPHEUS)

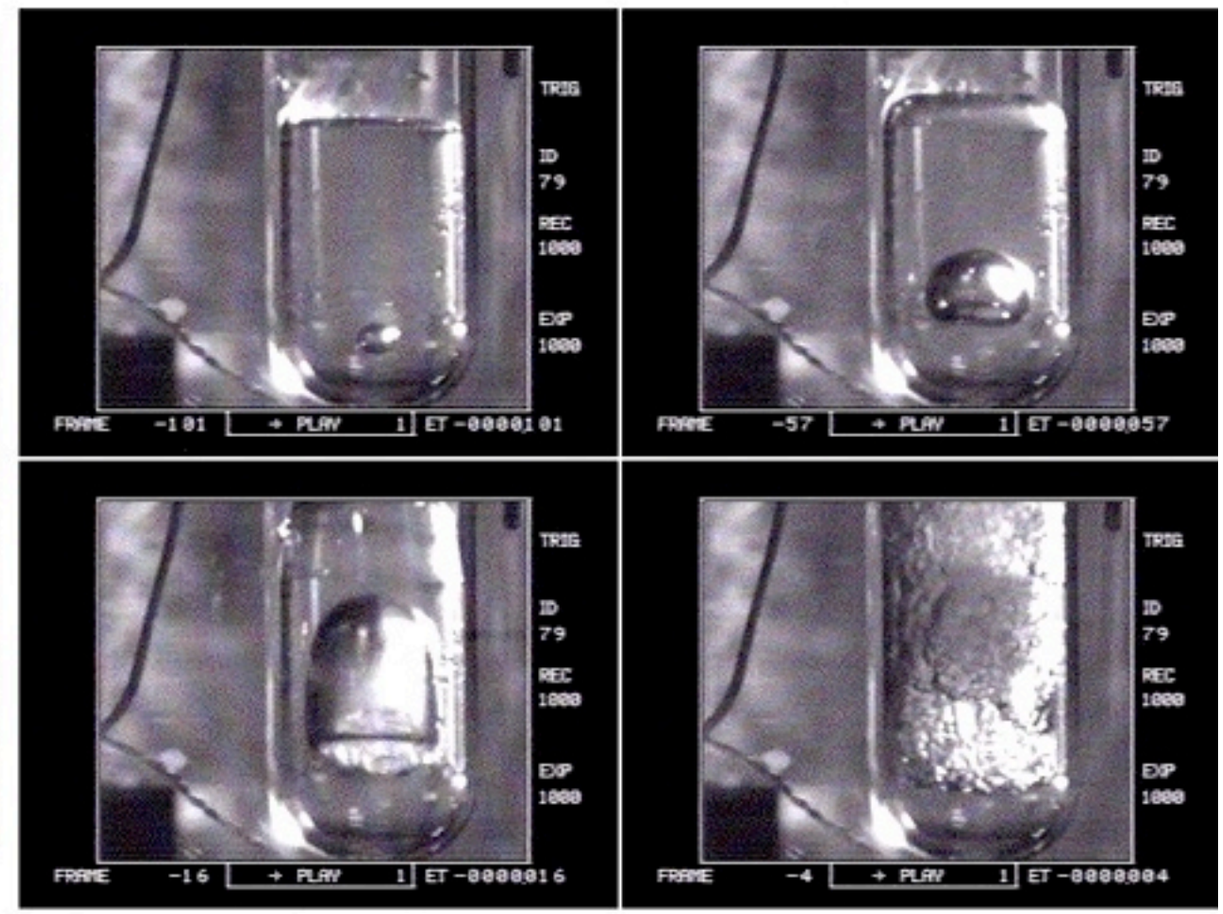
- Chicagoland Observatory for Underground Particle Physics
- Target : Halocarbon liquids
  - CF_3Br, CF_3I, ... (even Xe)
  - Sensitive to both spin-dependent AND spin-independent interactions
- Detection Mechanism
  - Bubble formation in superheated liquid
  - Pressure sensor detects formation of bubble, triggers imaging camera
  - Sensitive to events with recoil energy above a specific tunable threshold

COUPP

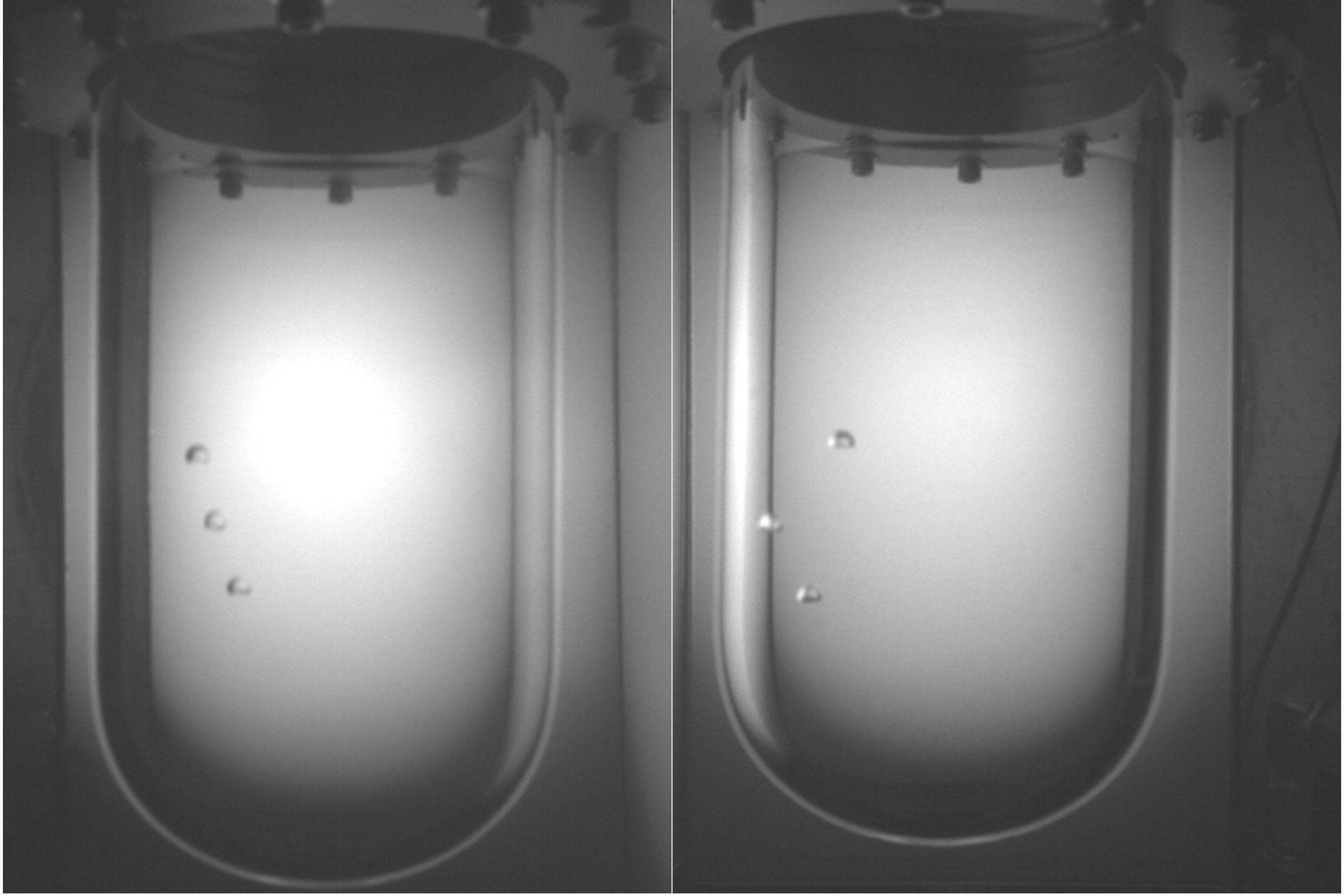
- Background Discrimination :
  - Insensitive to electron recoils (deposited energy density insufficient to create bubble)
  - By selecting operating pressure can reduce fraction of electron recoils resulting in bubble to ~ 10^{-9}
- Mass / Exposure
  - Finished operating 2 kg of detector at Fermilab underground site (~300 mwe)
  - Currently upgrading towards larger mass detectors: ~ 60 kg
  - Expect background rate ~ 10^{-5} evt/kg/keV/day

Bubbles!





Alpha event

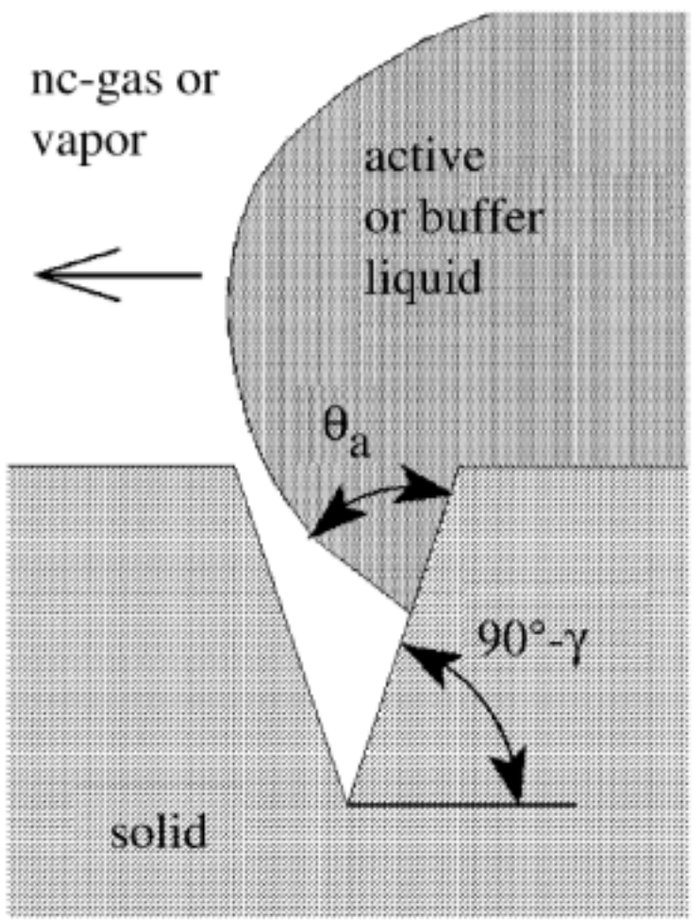


COUPP Collaboration

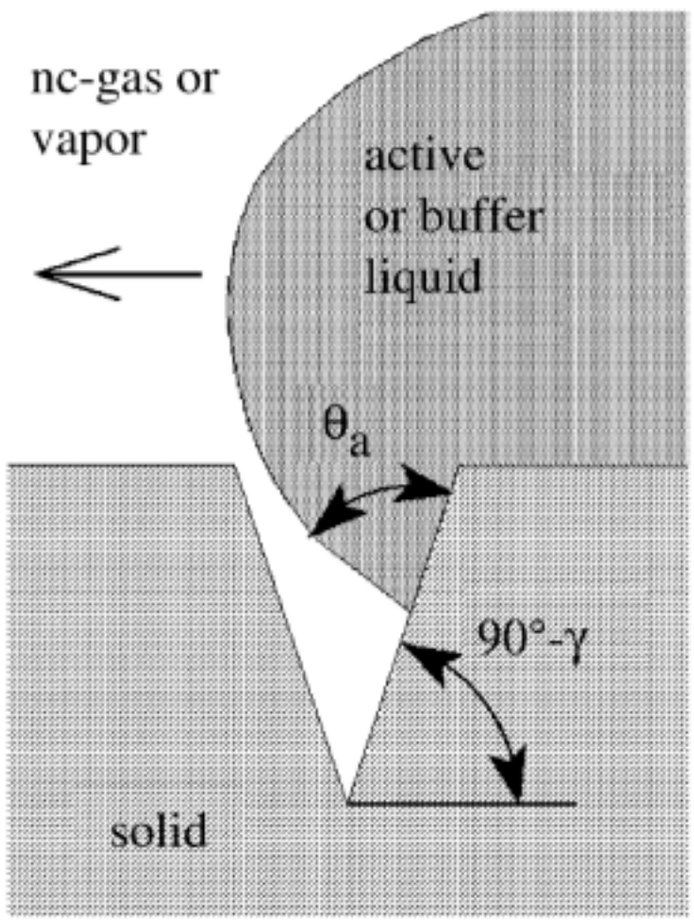
COUPP in Action

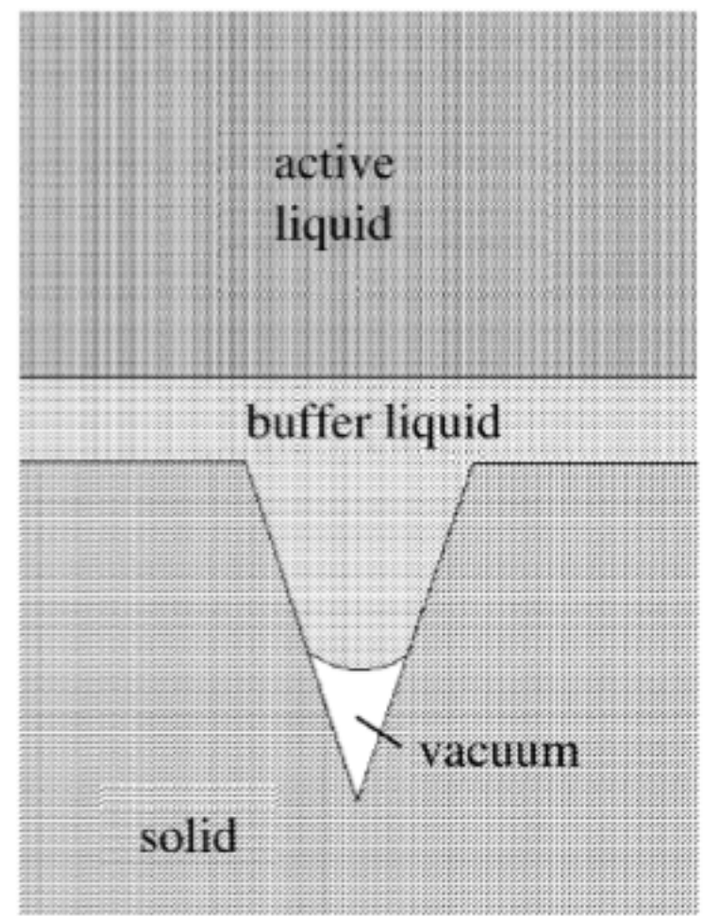
A triple scatter neutron event

Bubble at the interface

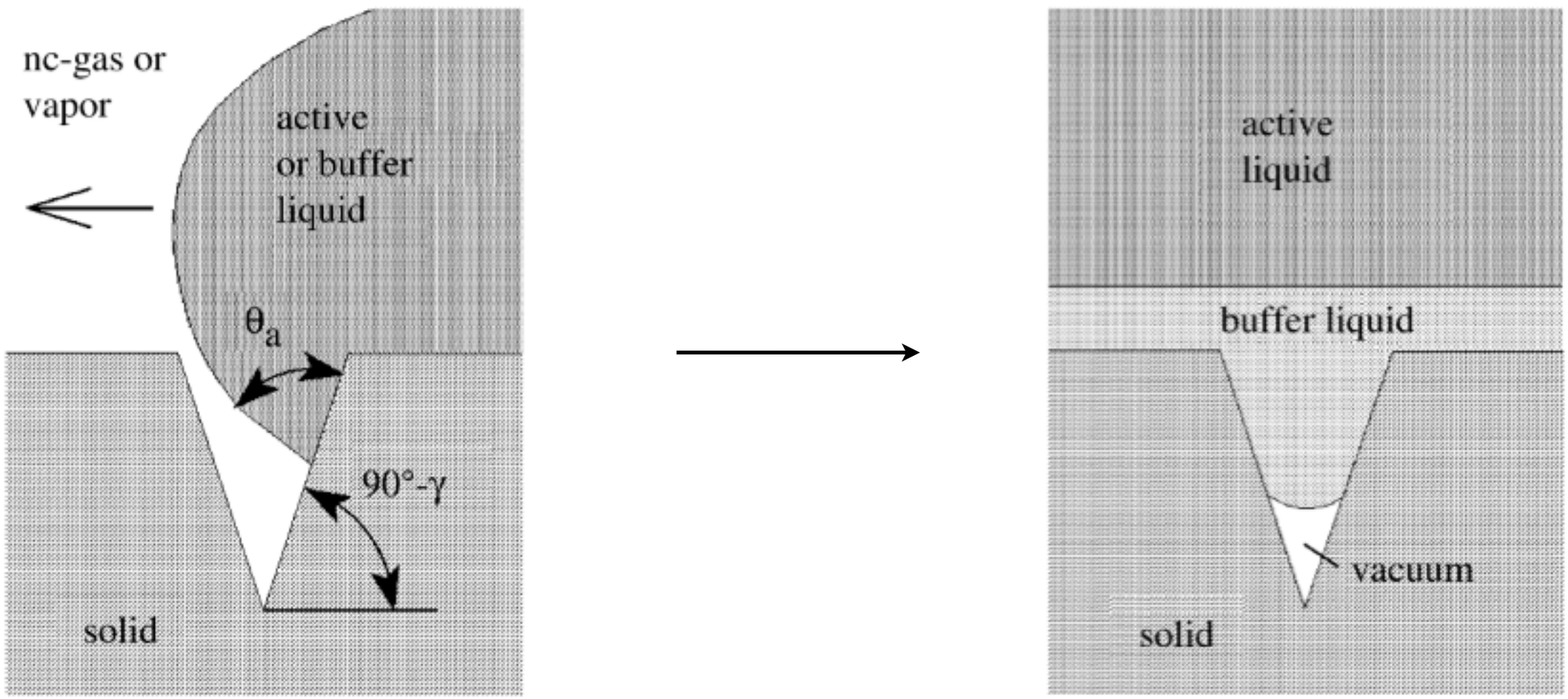


Bubble at the interface



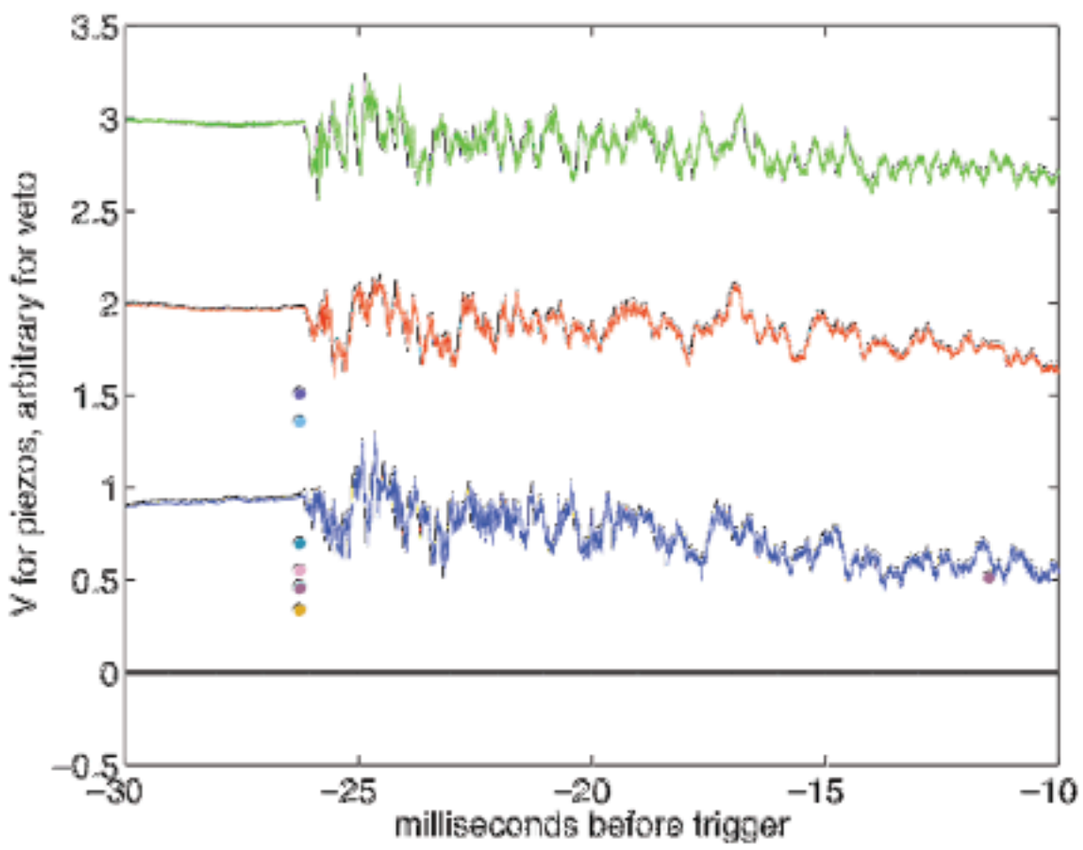


Bubble at the interface

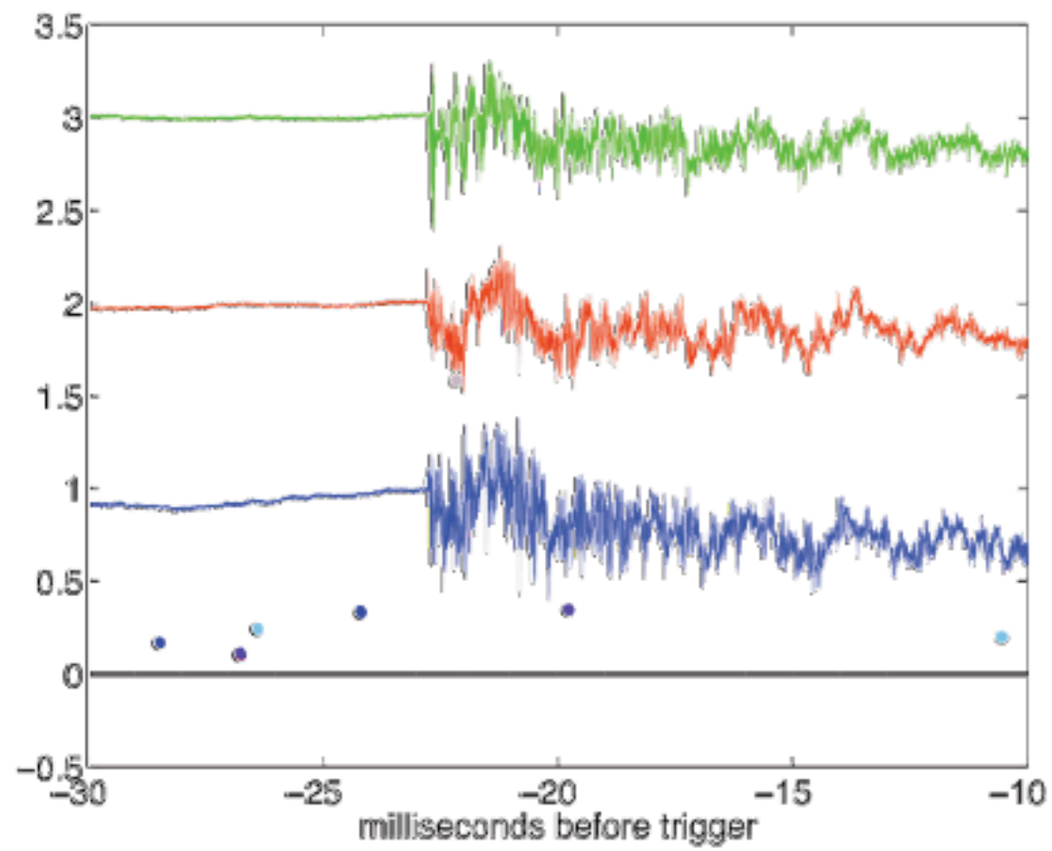


Acoustic Discrimination Between Neutrons and Alphas

Neutron

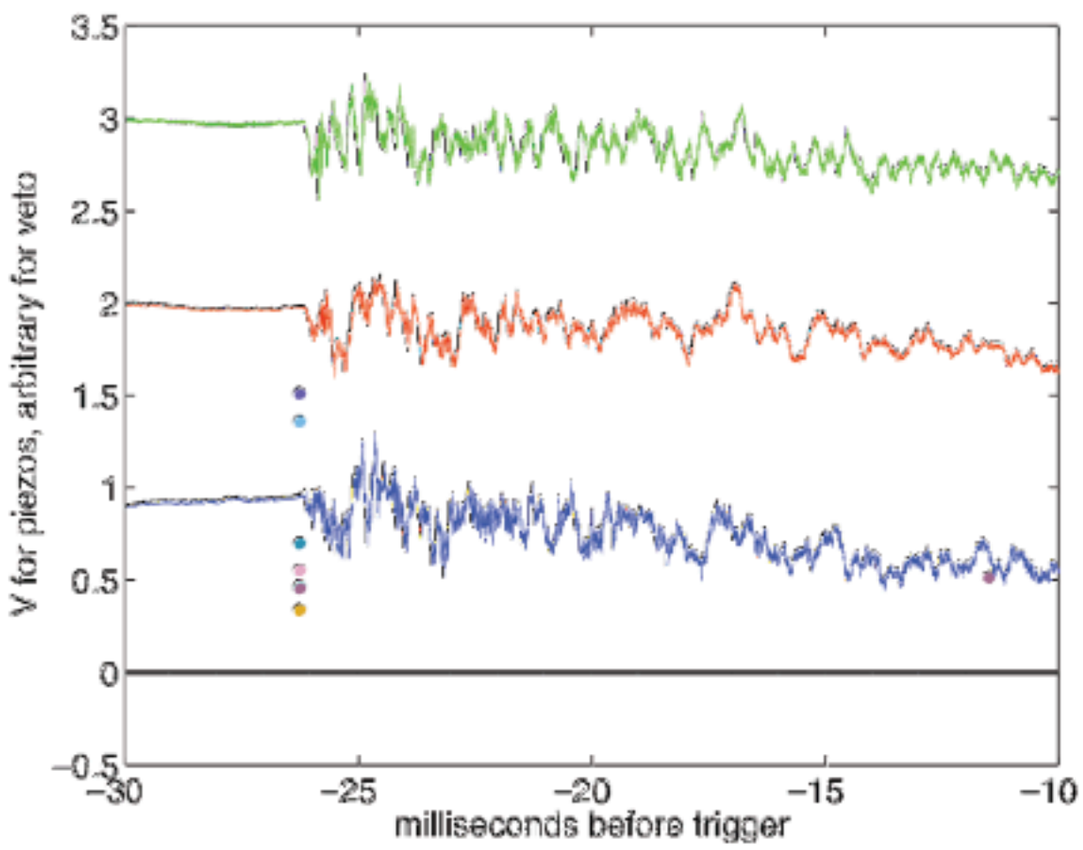


Alpha Particle

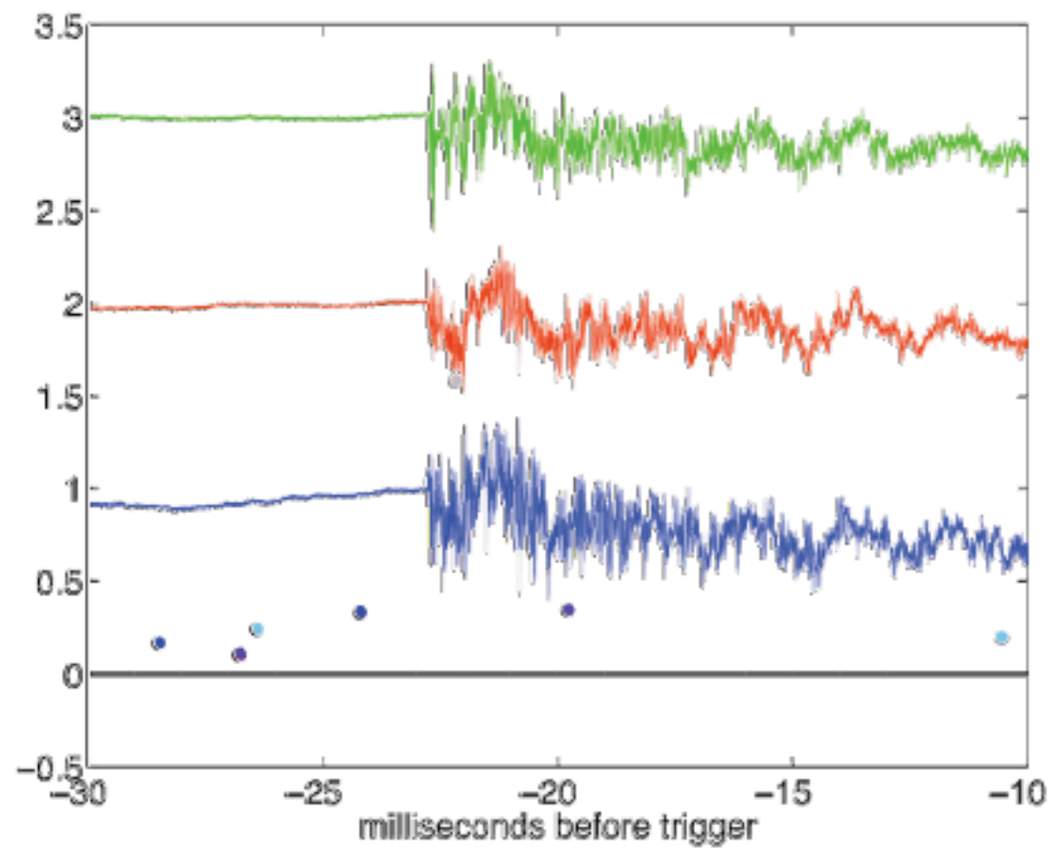


Acoustic Discrimination Between Neutrons and Alphas

Neutron



Alpha Particle



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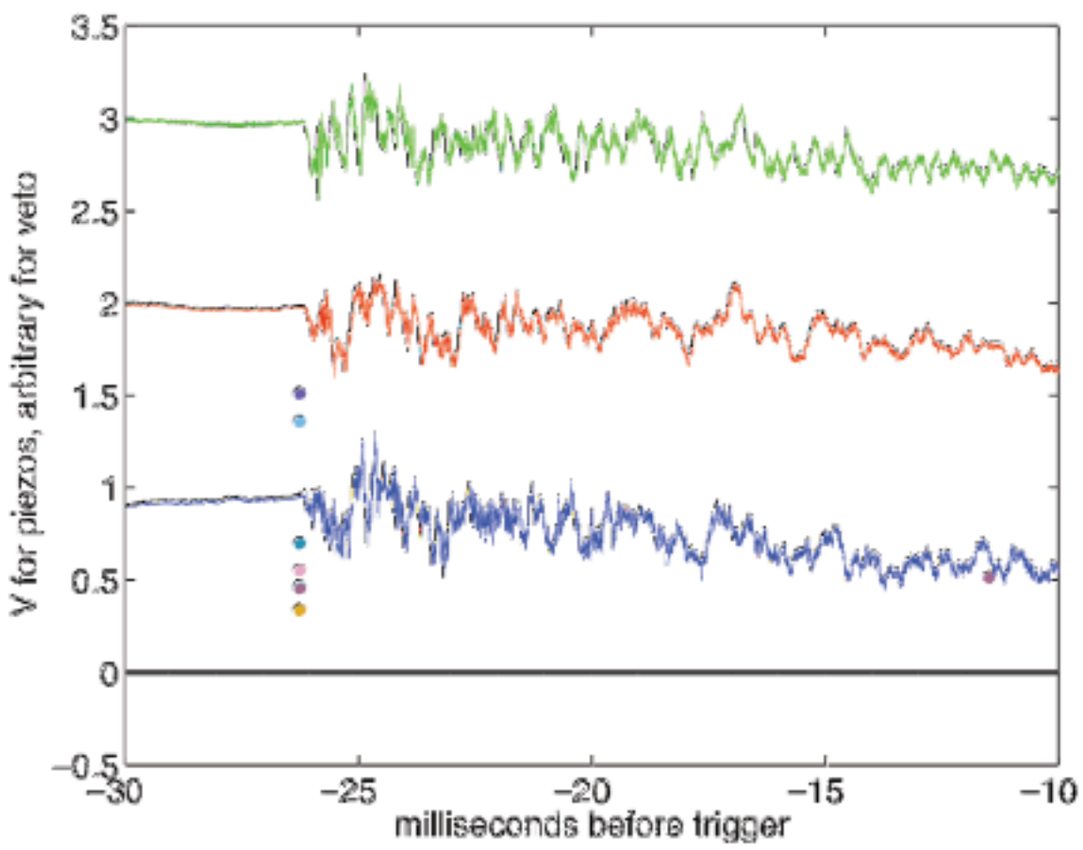

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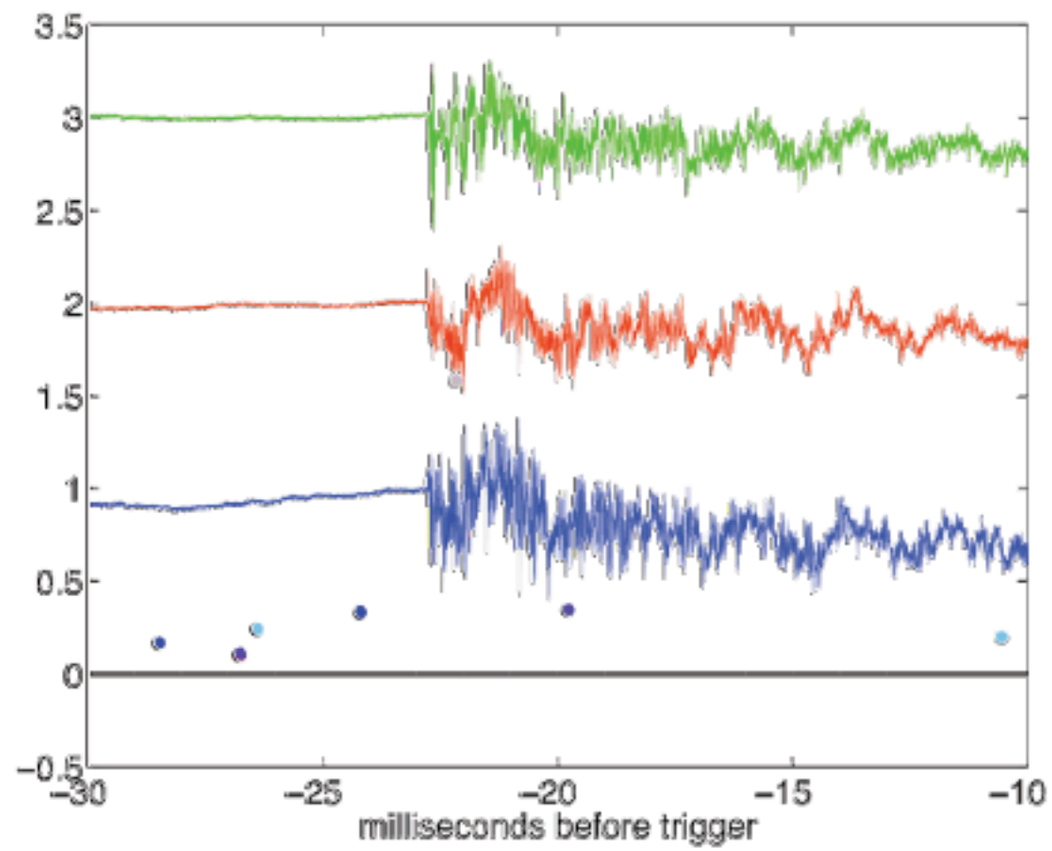


COUPP 60 kg

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

PICASSO

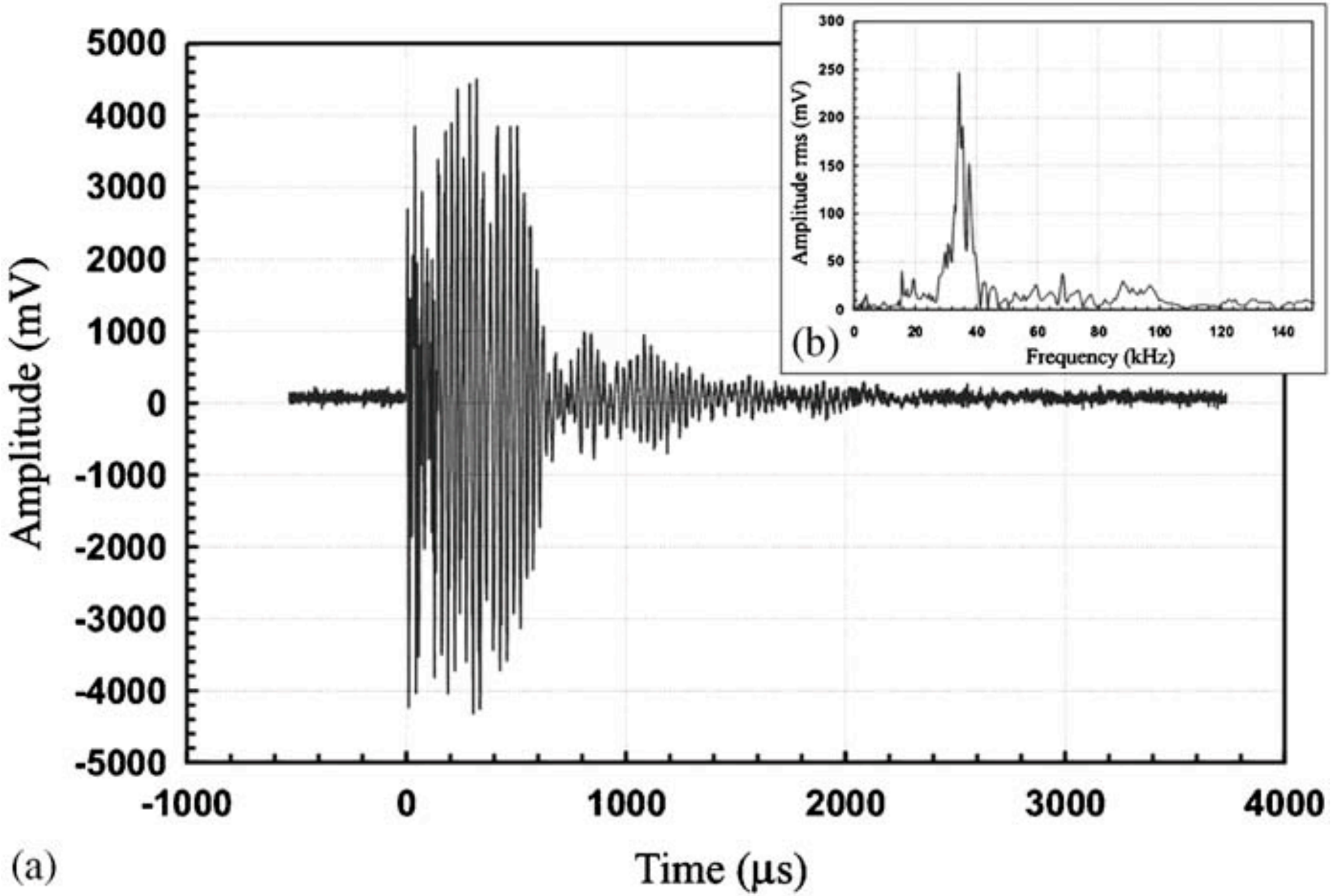
- Project In CAnada to Search for Supersymmetric Objects
- Target : Fluoriunated Halocarbon liquids
  - CF_4
  - Sensitive to spin-dependent interactions
- Detection Mechanism
  - Bubble formation in superheated liquid
  - Acoustic sensors detect formation of bubble
  - Sensitive to events with recoil energy above a specific tunable threshold

PICASSO

- Background Discrimination :
  - Insensitive to electron recoils (deposited energy density insufficient to create bubble)
  - By selecting operating temperature can vary nuclear recoil energy thresholds
  - Sensitive to α interactions in the detectors
- Mass / Exposure
  - Currently operating 3 detectors with an active target mass of 19.4 g at SNOLab (~6060 mwe)
  - 1.98 kg day of exposure accumulated

PICASSO Collaboration

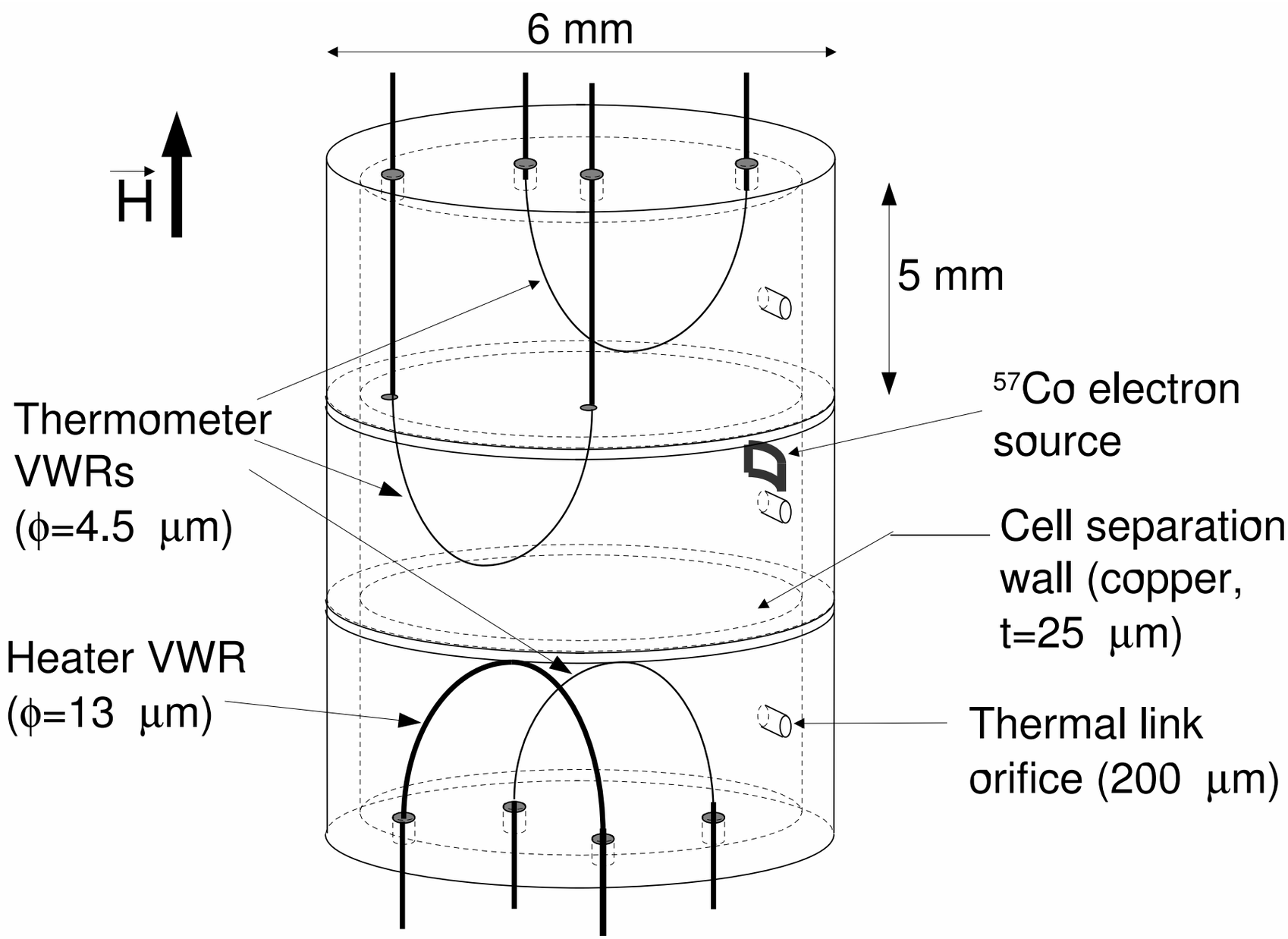
PICASSO in Action

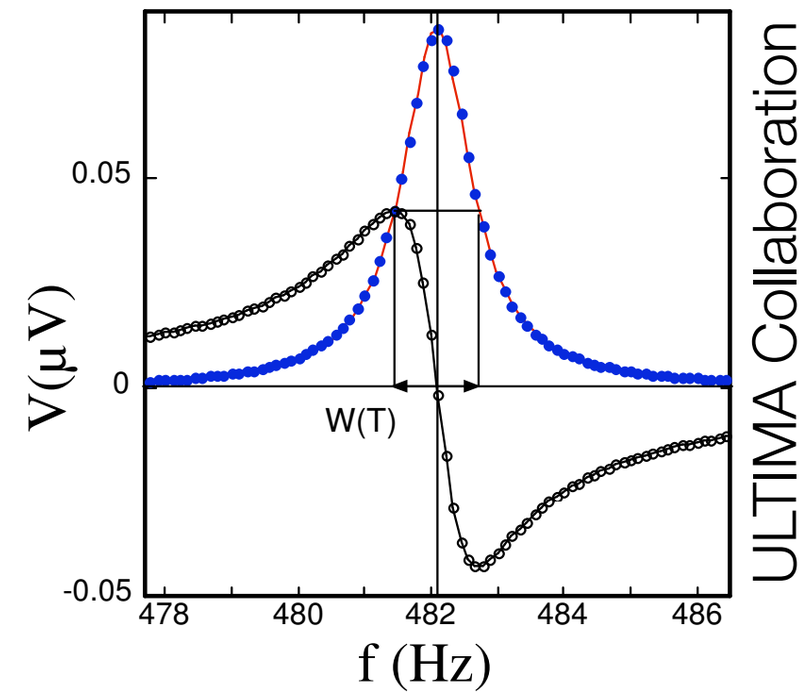


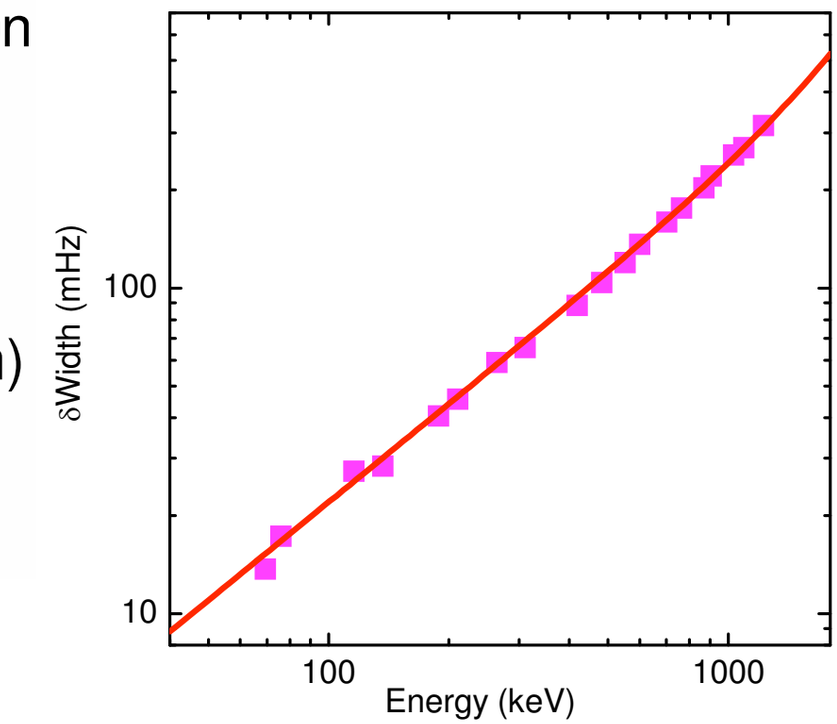
PICASSO in Action

ULTIMA

- Ultra Low Temperature Instrumentation for Measurements in Astrophysics
- Target : ^{3}He Superfluid
  - Sensitive to spin dependent interactions
- Detection Mechanism
  - Recoil energy: Calorimetric measurement via quasiparticle induced damping of a vibrating wire resonator
- Background Performance :
  - Extreme purity of ^{3}He results in an intrinsically low background detector
  - Scintillation photons can be absorbed/measured by a neighboring detector
  - Potential pulse shape based discrimination







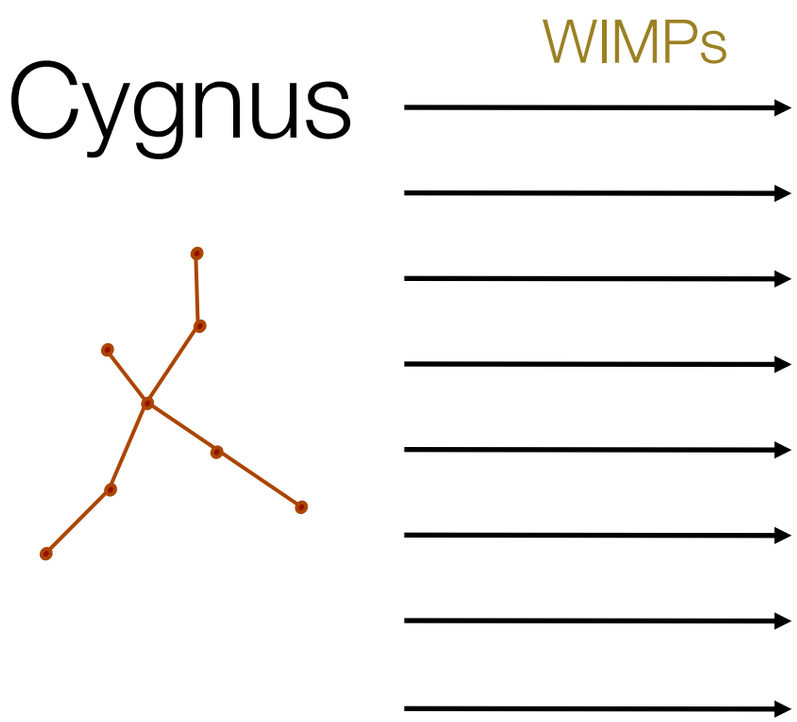
ULTIMA in Action

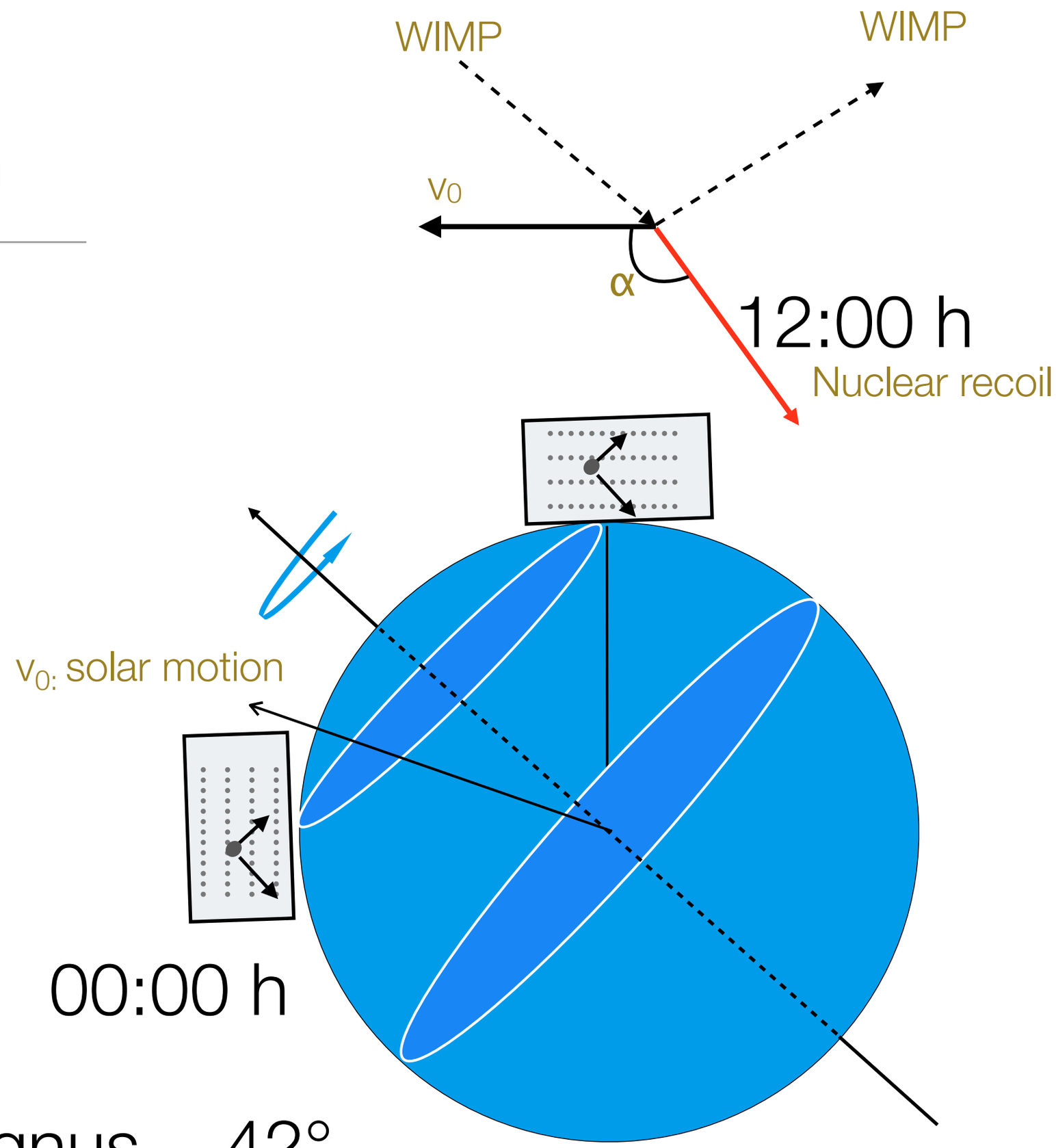
Background Rejection

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

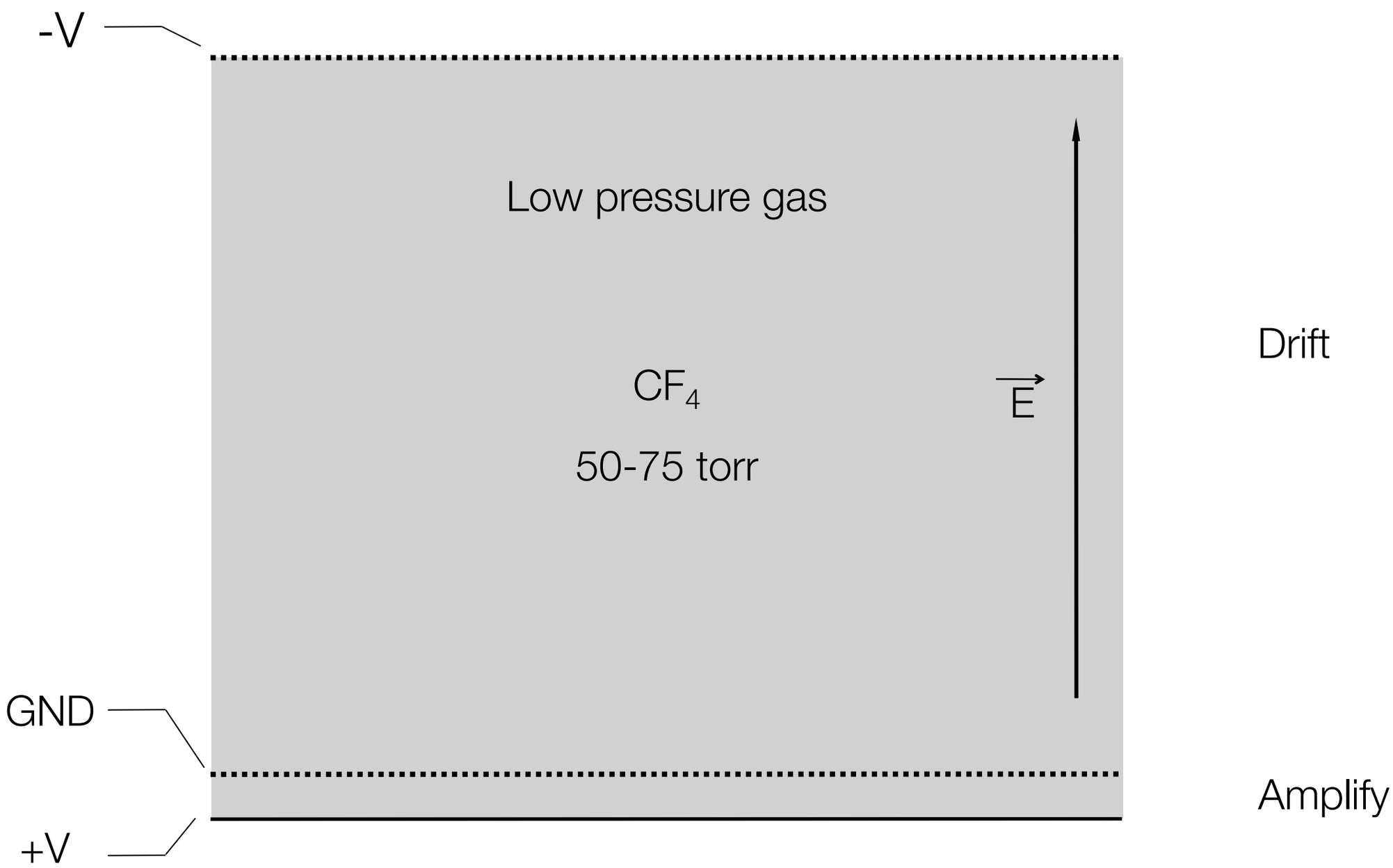




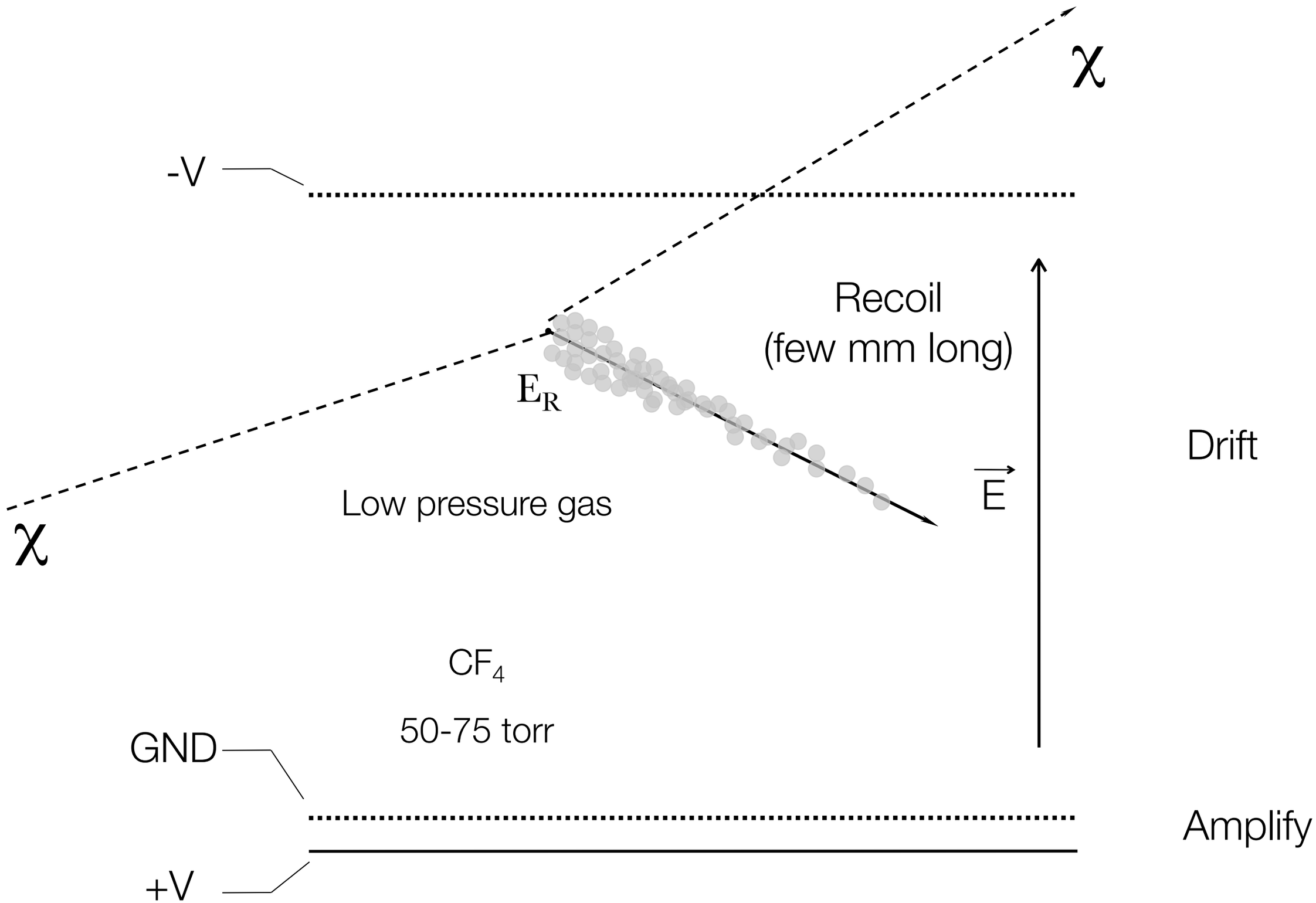
Declination of Cygnus ~42°

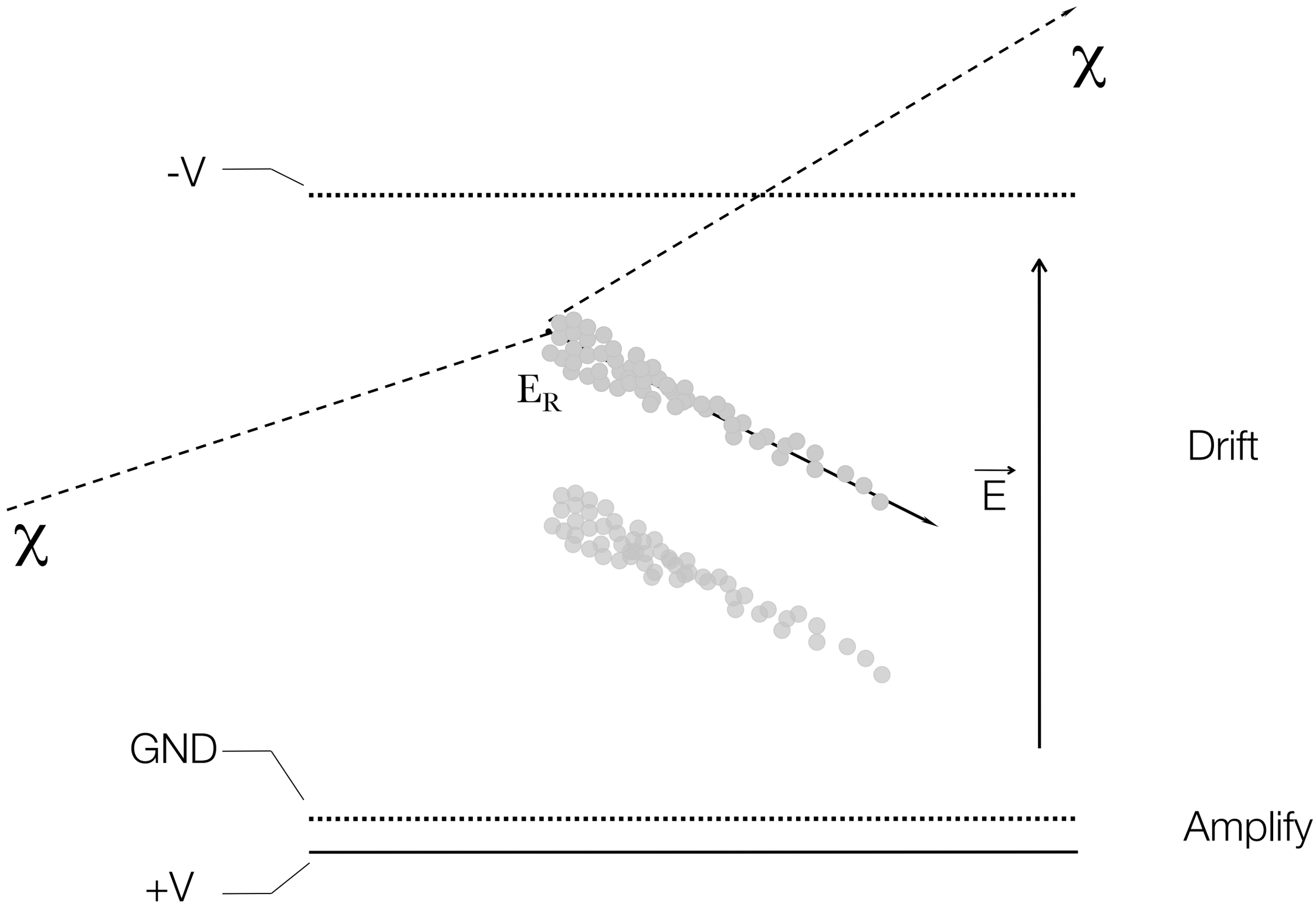
Spergel, PRD, 1988

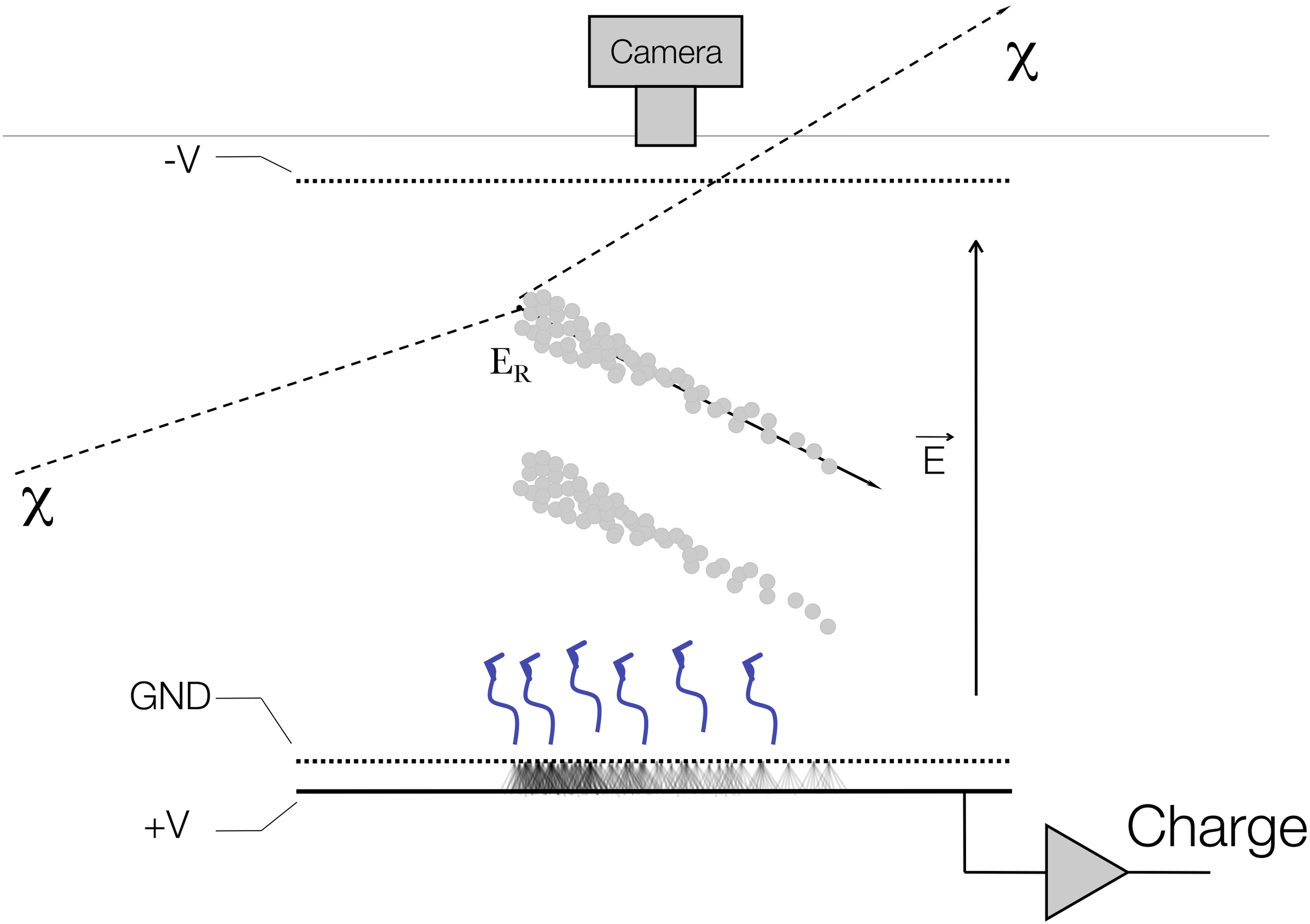
Time Projection Chamber



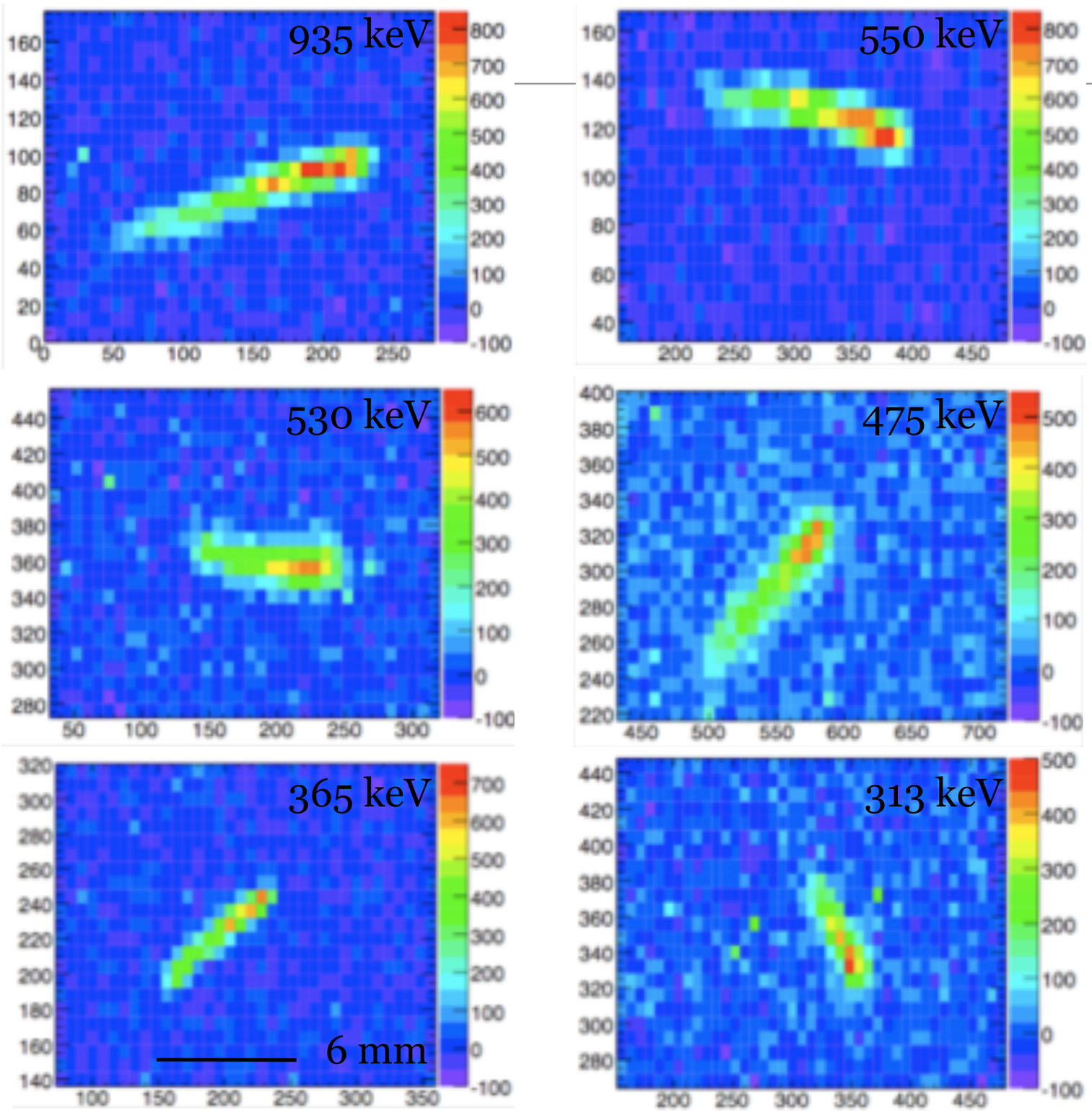
Side view

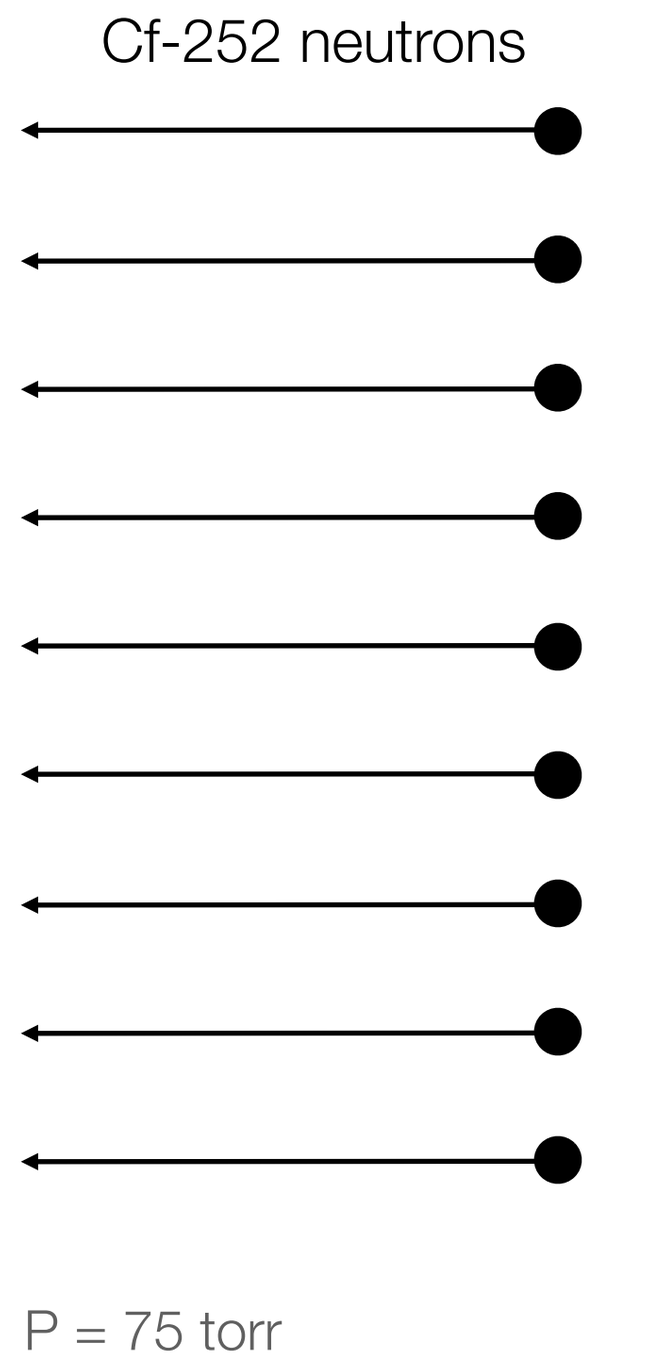

χ
-V
Recoil
(few mm long)
E_R
Drift
$\vec{E}$
Low pressure gas
χ
CF_4
50-75 torr
GND
Amplify
+V


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


Camera
χ
-V
E_R
E
χ
GND
+V
Charge

Measurement of head-tail direction





100 pixels = 6 mm

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

Liquid Nobles

Liquid Noble Detectors

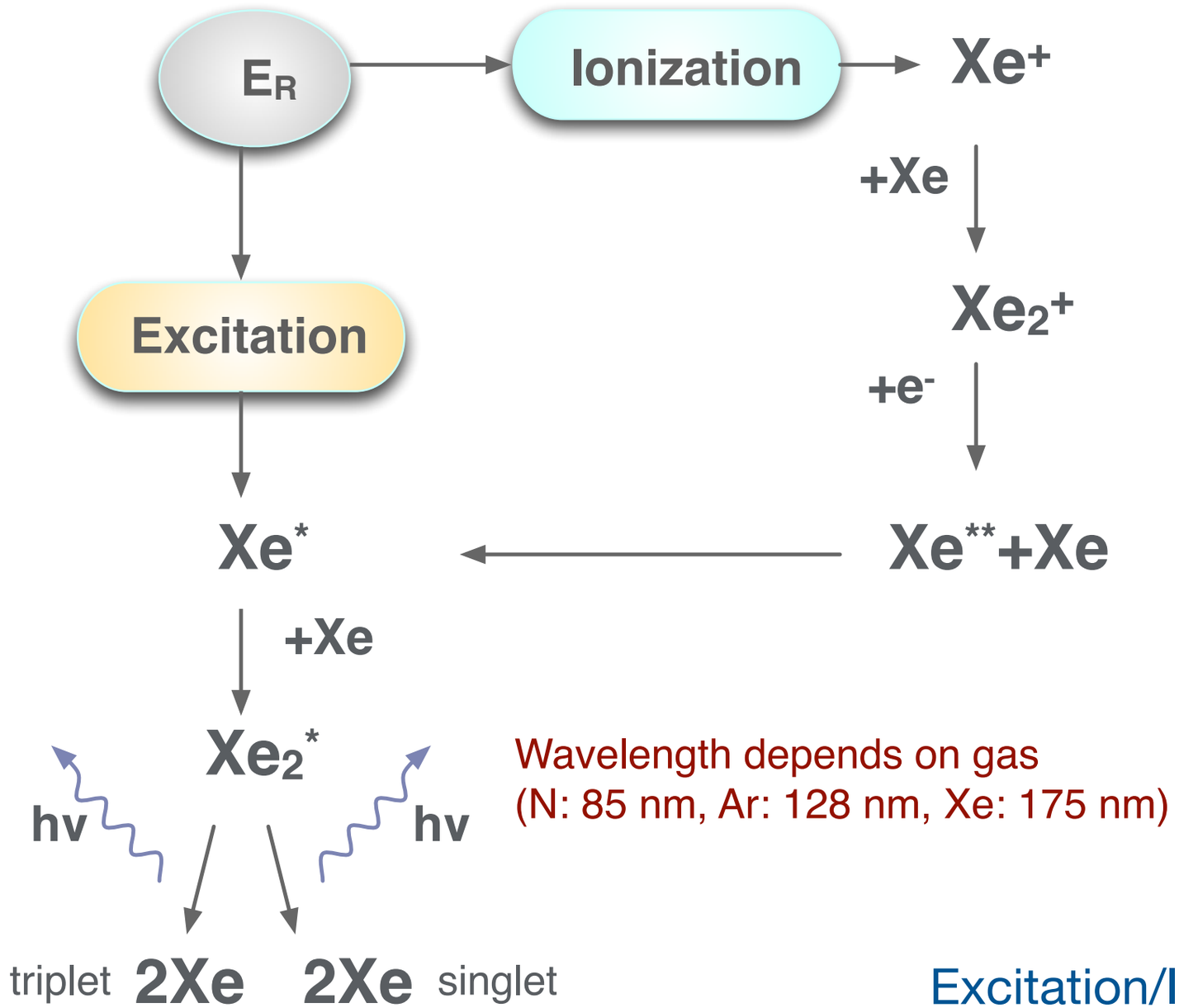
- Time Projection Chambers
  - XENON
  - LUX
  - Zeplin (also a Xe TPC)
  - WArP (uses Argon)
- Single Phase Detectors
  - DEAP / CLEAN (Argon and Neon)
  - XMASS (800 kg under construction!)

XENON

(see also WARP / CLEAN)

- Target : Liquid Xenon
  - A = 131
  - Large sensitivity to spin-independent interactions
  - Sensitive to spin-dependent interaction through ^{129}Xe, ^{131}Xe isotopes
- Detection Mechanism
  - Scintillation in LXe : detected by photomultiplier tubes above the liquid (prompt signal)
  - Ionization in LXe : Electrons drifted through the liquid by an electric field. Result in scintillation in Xe vapor above the liquid (delayed signal ~ 150 μs)
  - #scintillation photons / ionization electrons proportional to recoil energy (roughly 200 photons for a 16 keV recoil)

XENON: Detection Mechanism



Wavelength depends on gas
(N: 85 nm, Ar: 128 nm, Xe: 175 nm)

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

$$\mathrm{Xe}^* + \mathrm{Xe} \rightarrow \mathrm{Xe}_2^*$$

$$\mathrm{Xe}_2^* \rightarrow 2\mathrm{Xe} + \mathrm{h}\nu$$

$$\mathrm{Xe}^+ + \mathrm{Xe} \rightarrow \mathrm{Xe}_2^+$$

$$\mathrm{Xe}_2^+ + \mathrm{e}^- \rightarrow \mathrm{Xe}^{**} + \mathrm{Xe}$$

$$\mathrm{Xe}^{**} \rightarrow \mathrm{Xe}^* + \mathrm{heat}$$

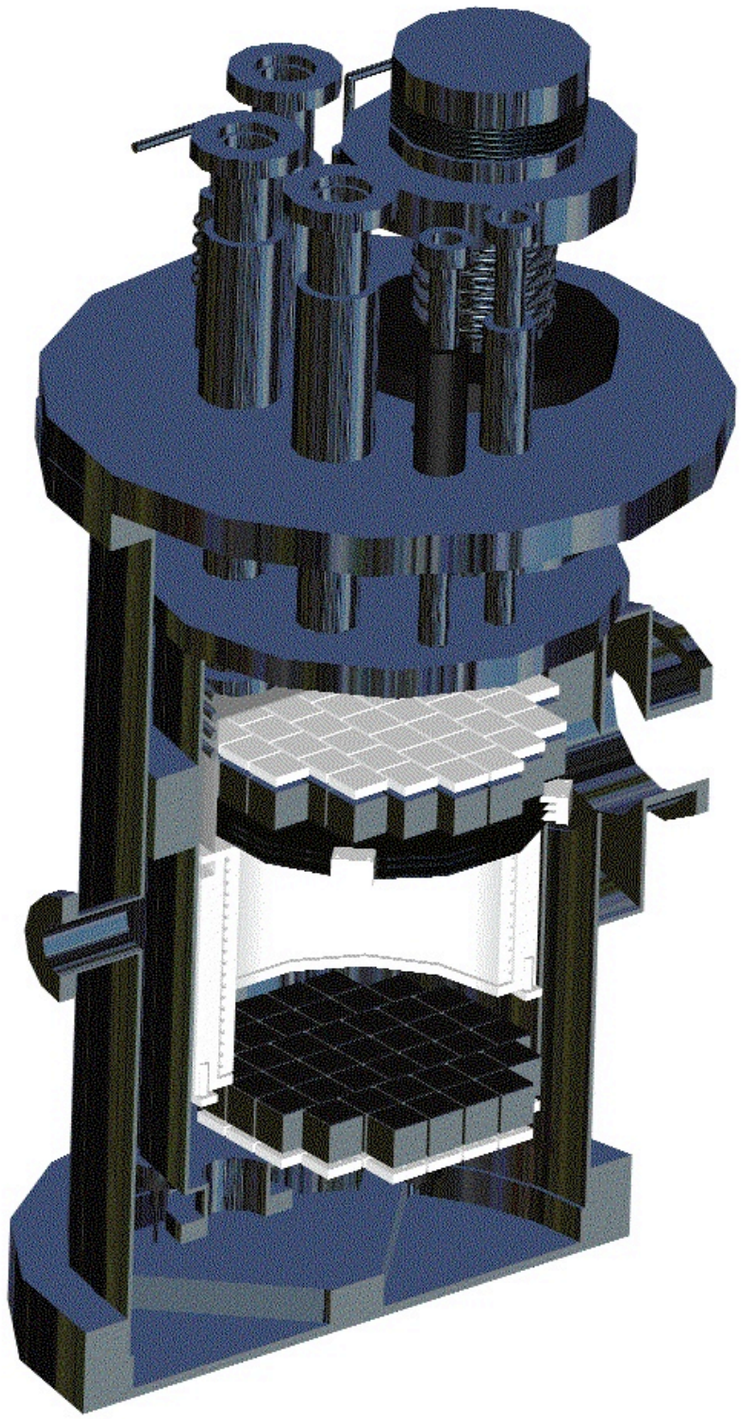
$$\mathrm{Xe}^* + \mathrm{Xe} \rightarrow \mathrm{Xe}_2^*$$

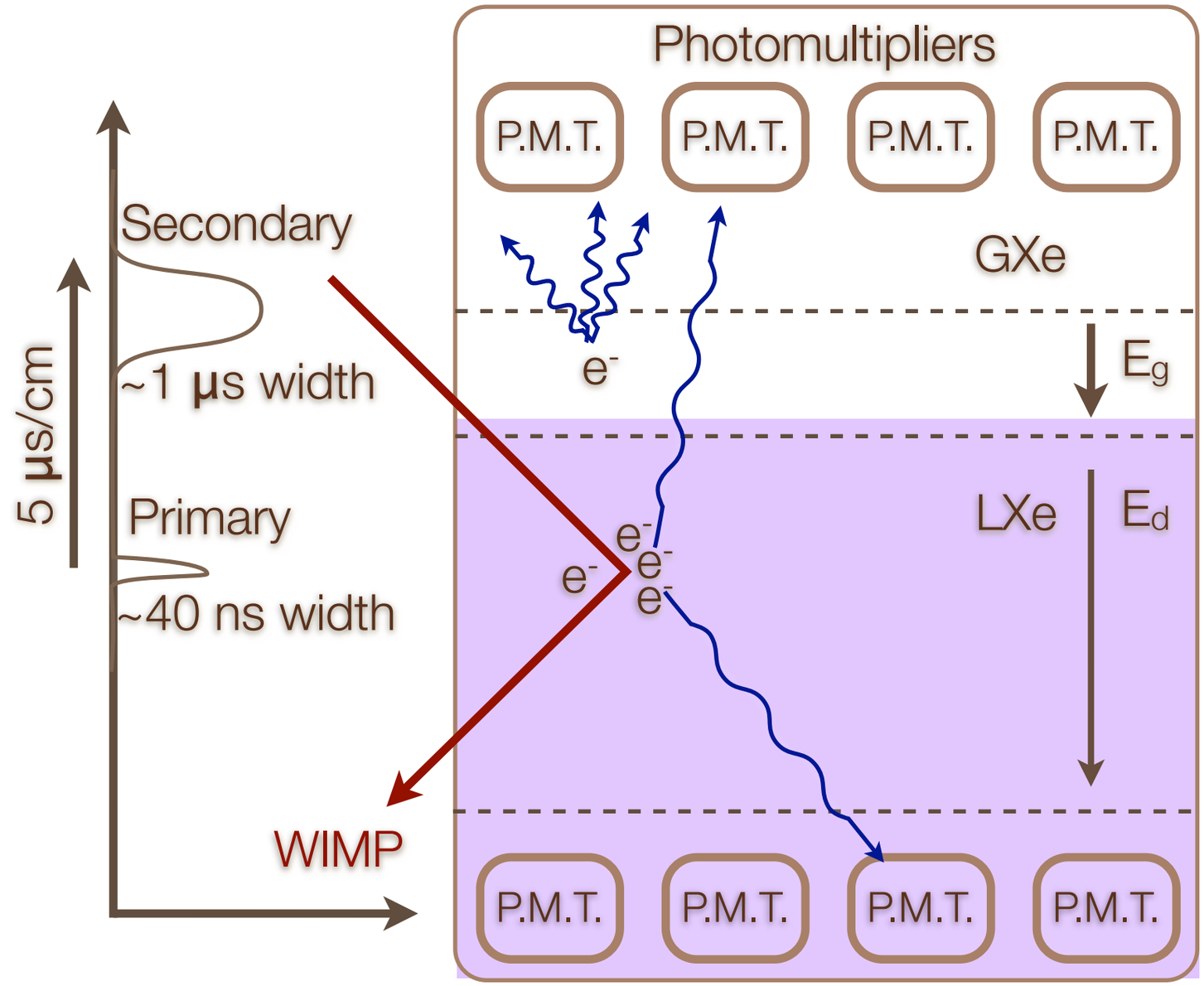
$$\mathrm{Xe}_2^* \rightarrow 2\mathrm{Xe} + \mathrm{h}\nu$$

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

XENON

- Background Discrimination :
  - Higher ratio of scintillation to ionization signal for nuclear recoils compared to electron recoils
  - Able to achieve event be event discrimination at 99%
- Mass / Exposure
  - Operated a 10 kg of detector at the Gran Sasso underground laboratory (~3000 mwe)
  - Exposure of 136 kg-day
  - Currently operating a 100 kg detector



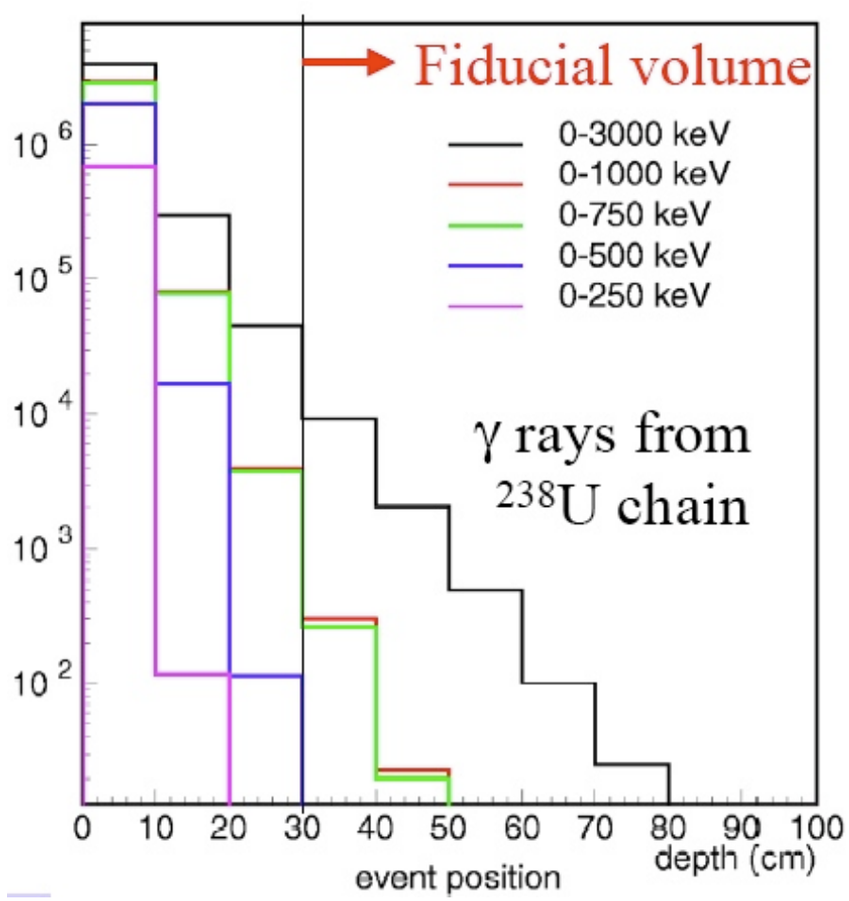


The XENON Design

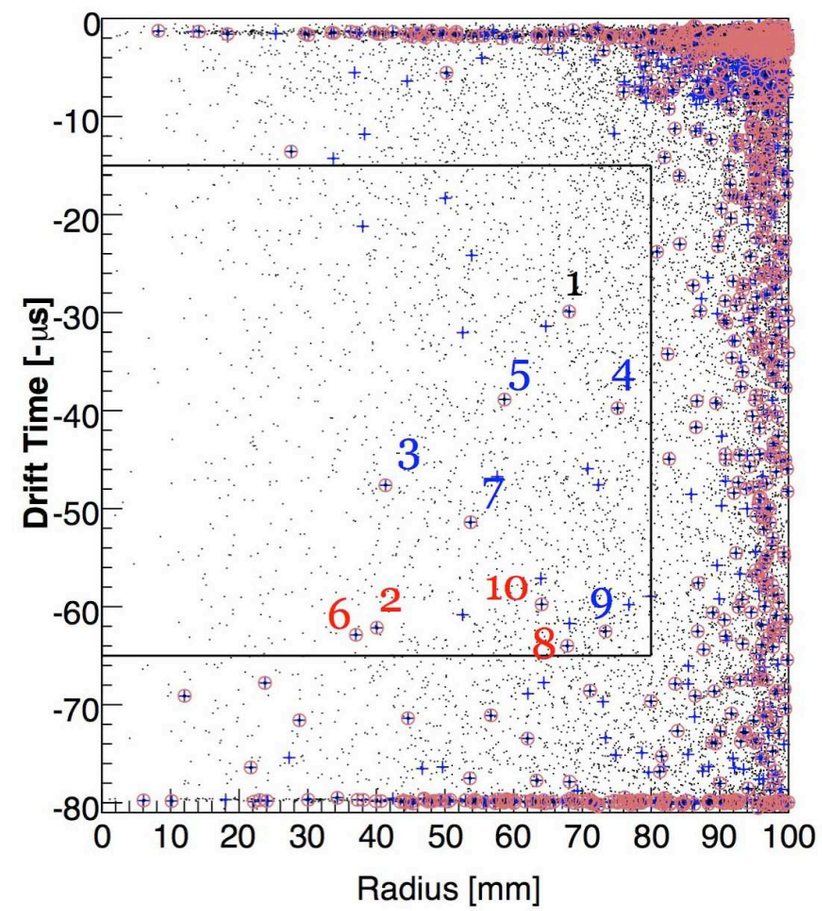
Self shielding in Liquid Xenon

- A big advantage of the liquid xenon detector is its self shielding ability
  - Xenon is a heavy nucleus, and LXe is a dense material --> excellent particle attenuation properties
  - Xenon liquifies at 166K, so most impurities will be frozen out outside the detector

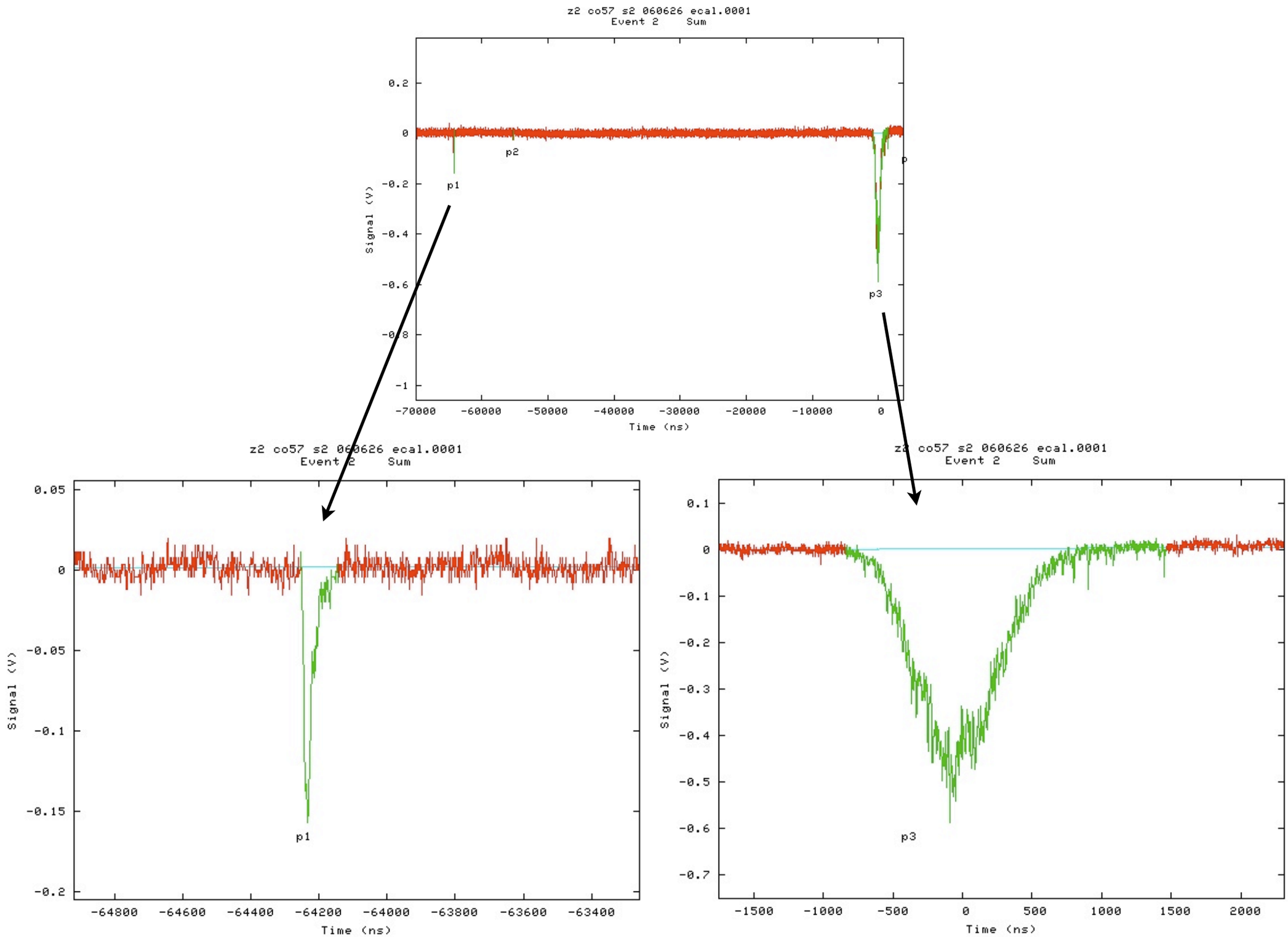
XMASS Collaboration



15 cm



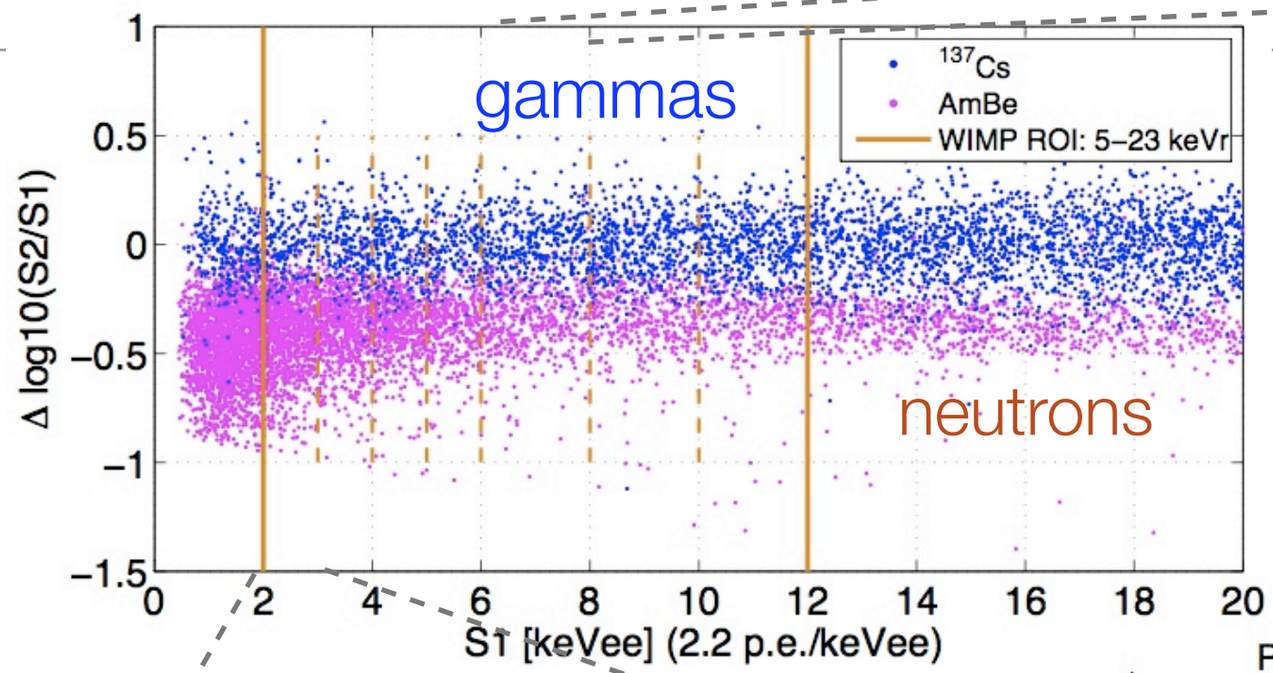
XENON Collaboration



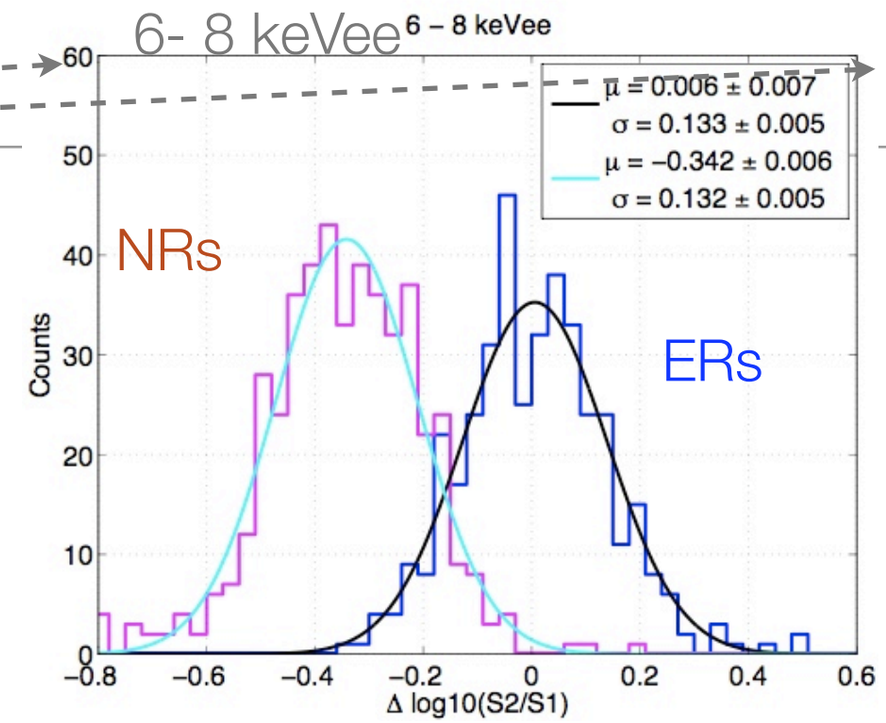
Event Signals in Liquid Xenon

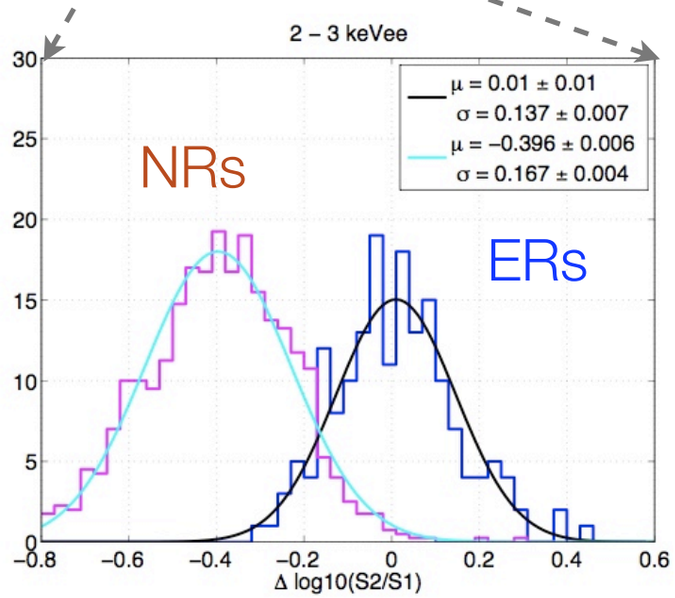
Zooming in on S1 & S2

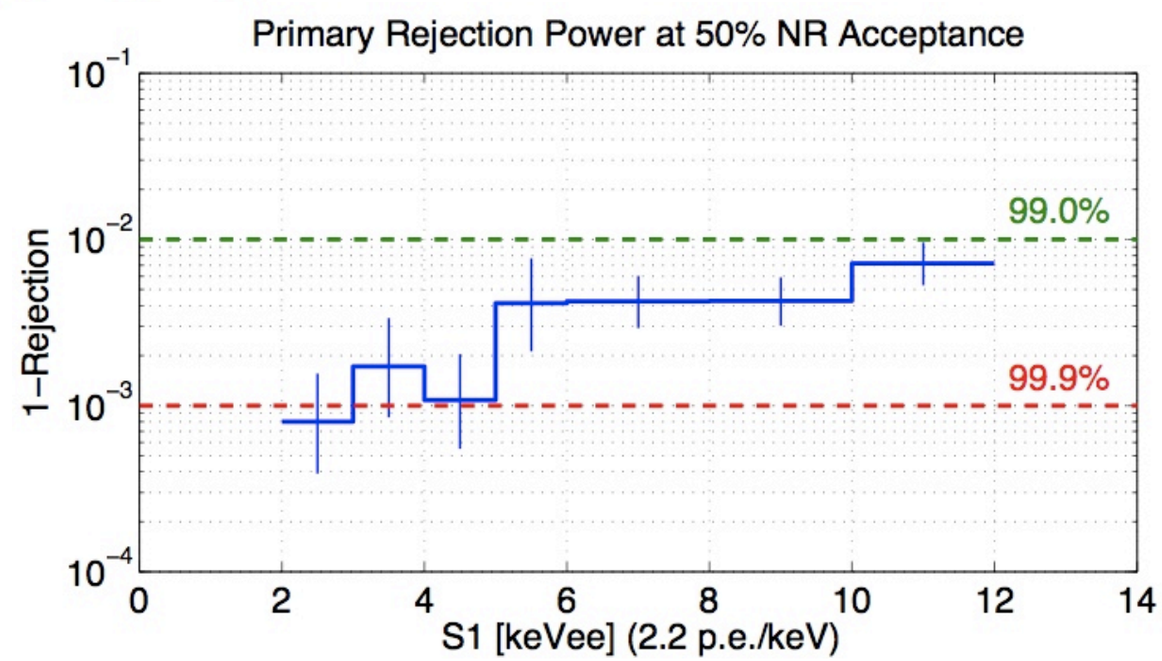
XENON Discrimination



6- 8 keVee

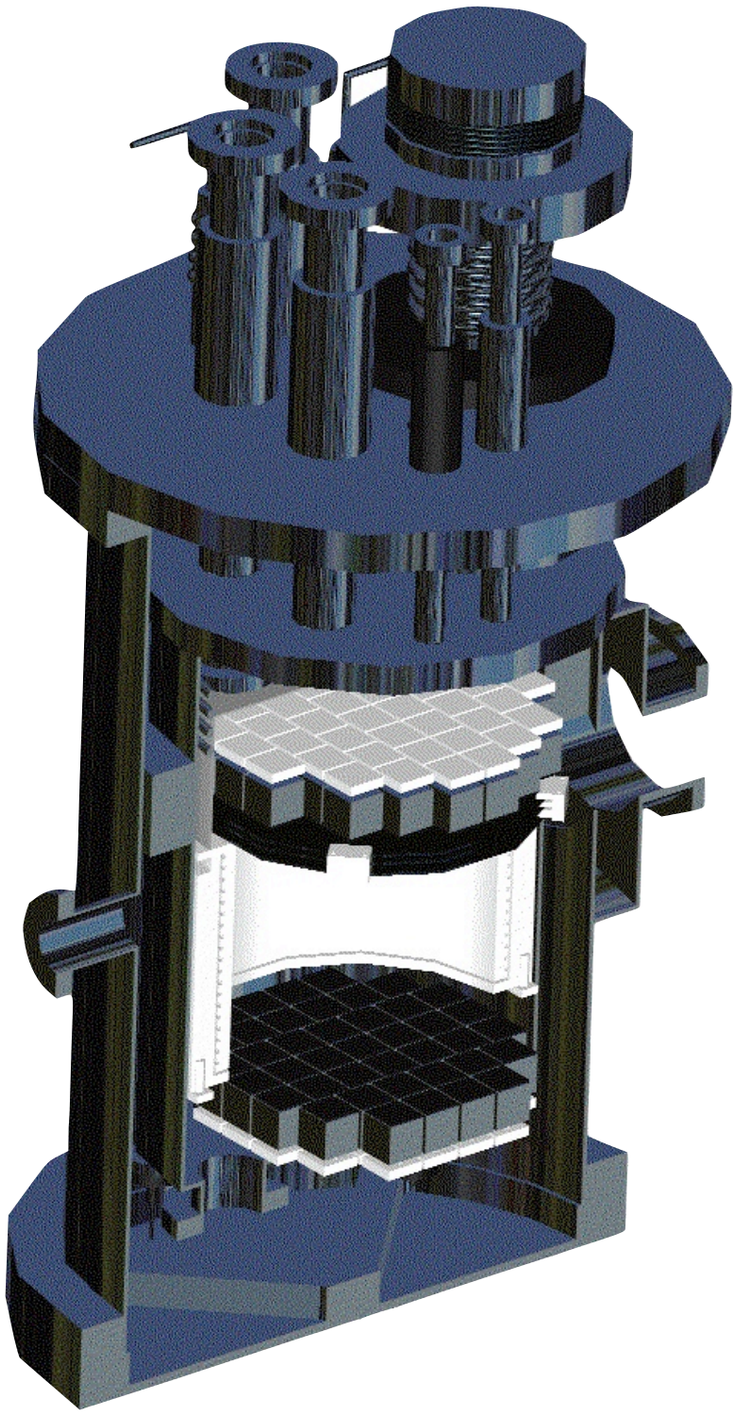


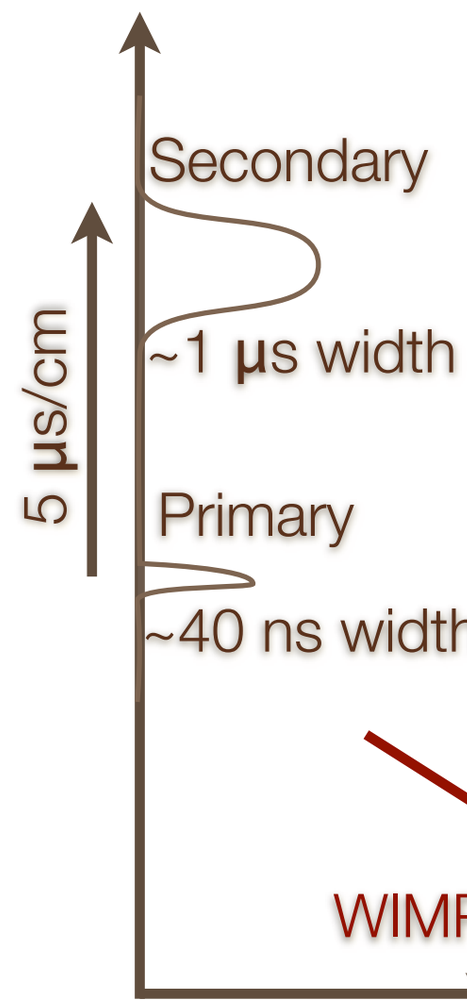


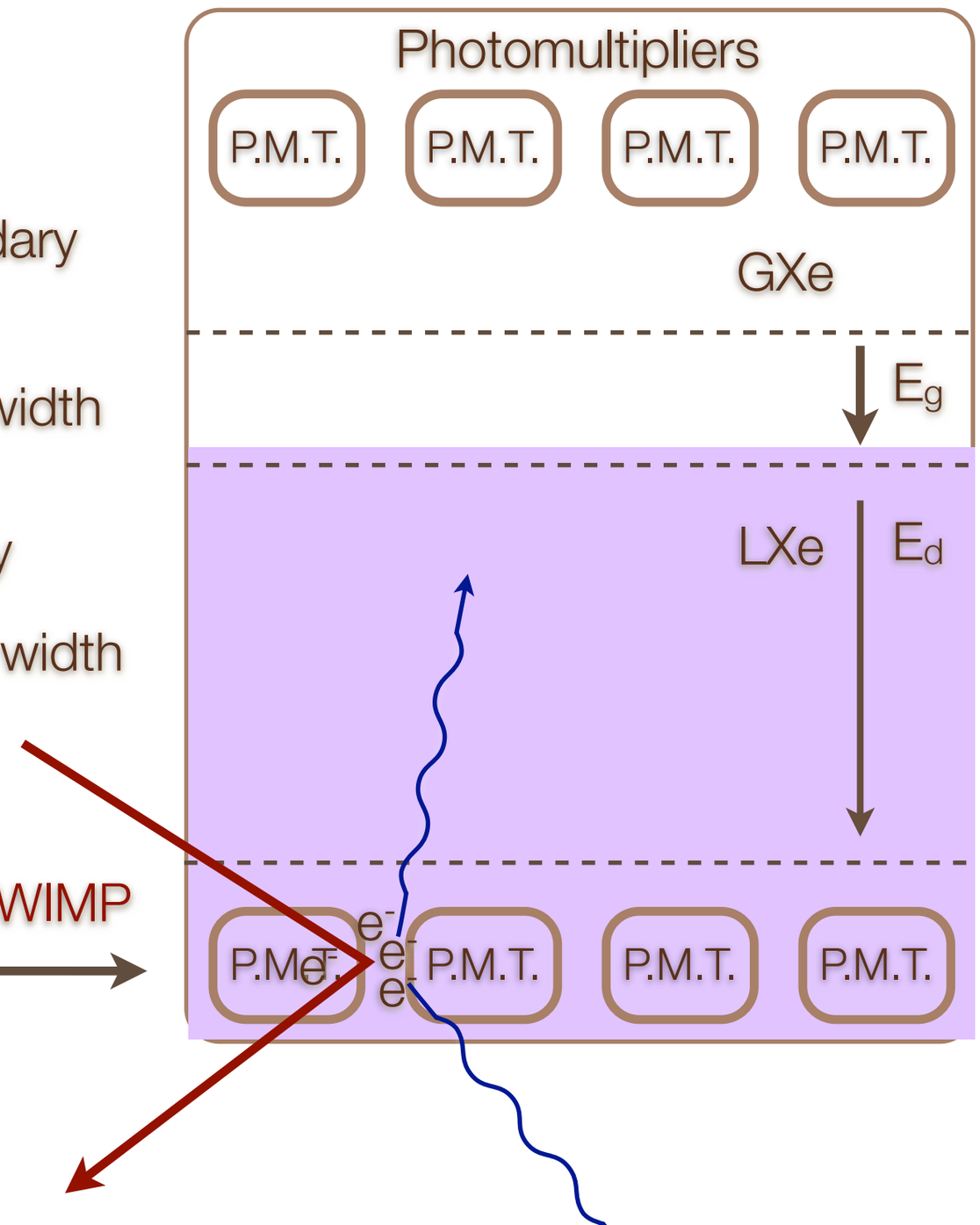


- Rejection is > 99.6% for 50% Nuclear Recoil acceptance
  - Cuts: fiducial volume (remove events at teflon edge where poor charge collection)
  - Multiple scatters (more than one S2 pulse)

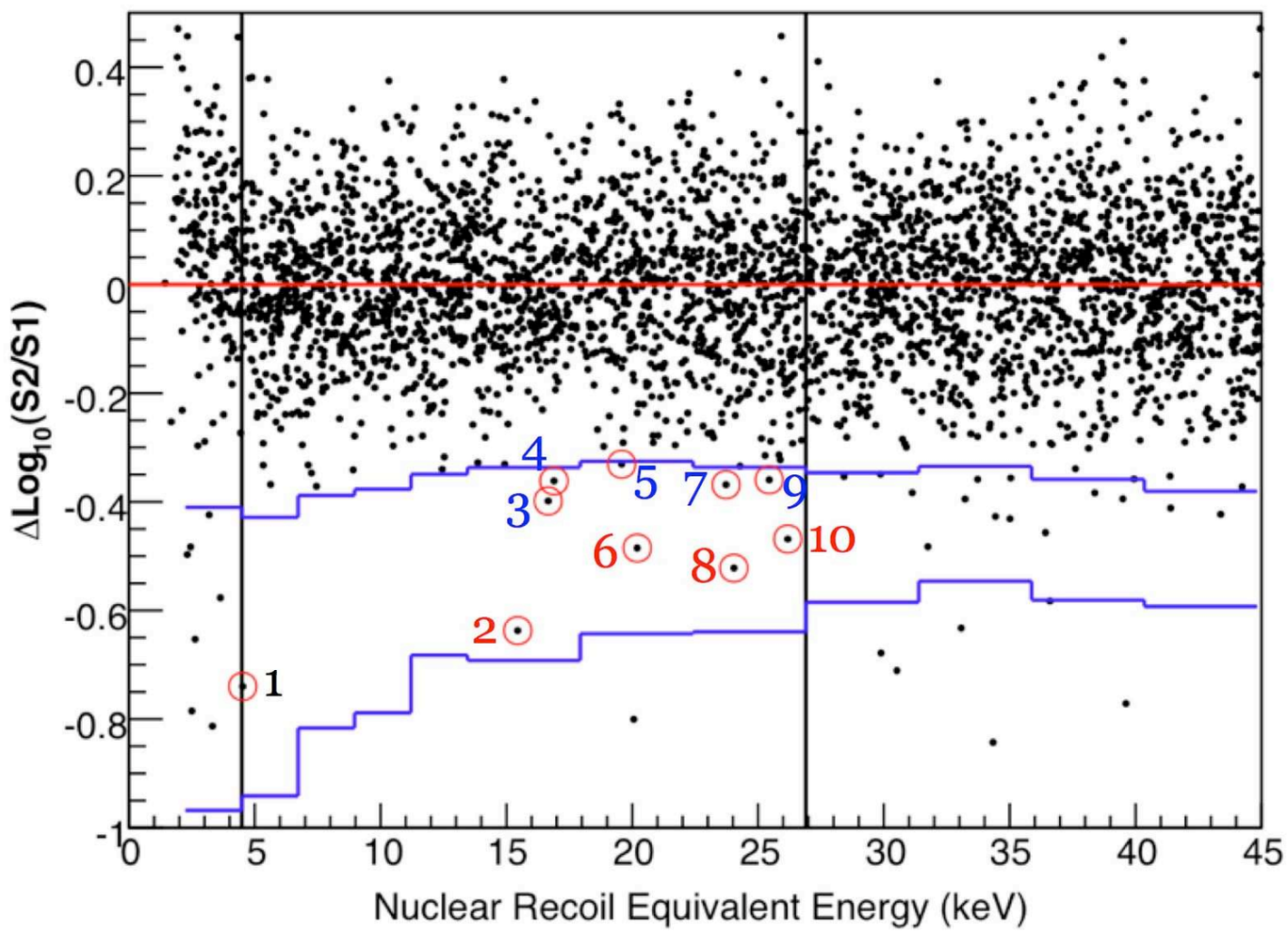
Signal Loss in Liquid Detectors







XENON Data


0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
0
5
10
15
20
25
30
35
40
45
ΔLog10(S2/S1)
Nuclear Recoil Equivalent Energy (keV)
1
2
3
4
5
6
7
8
9
10

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

Outline

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

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- Overview of the Dark Matter Problem
- Principles of Direct Detection
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  - The CDMS Experiment
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CDMS: The Big Picture

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

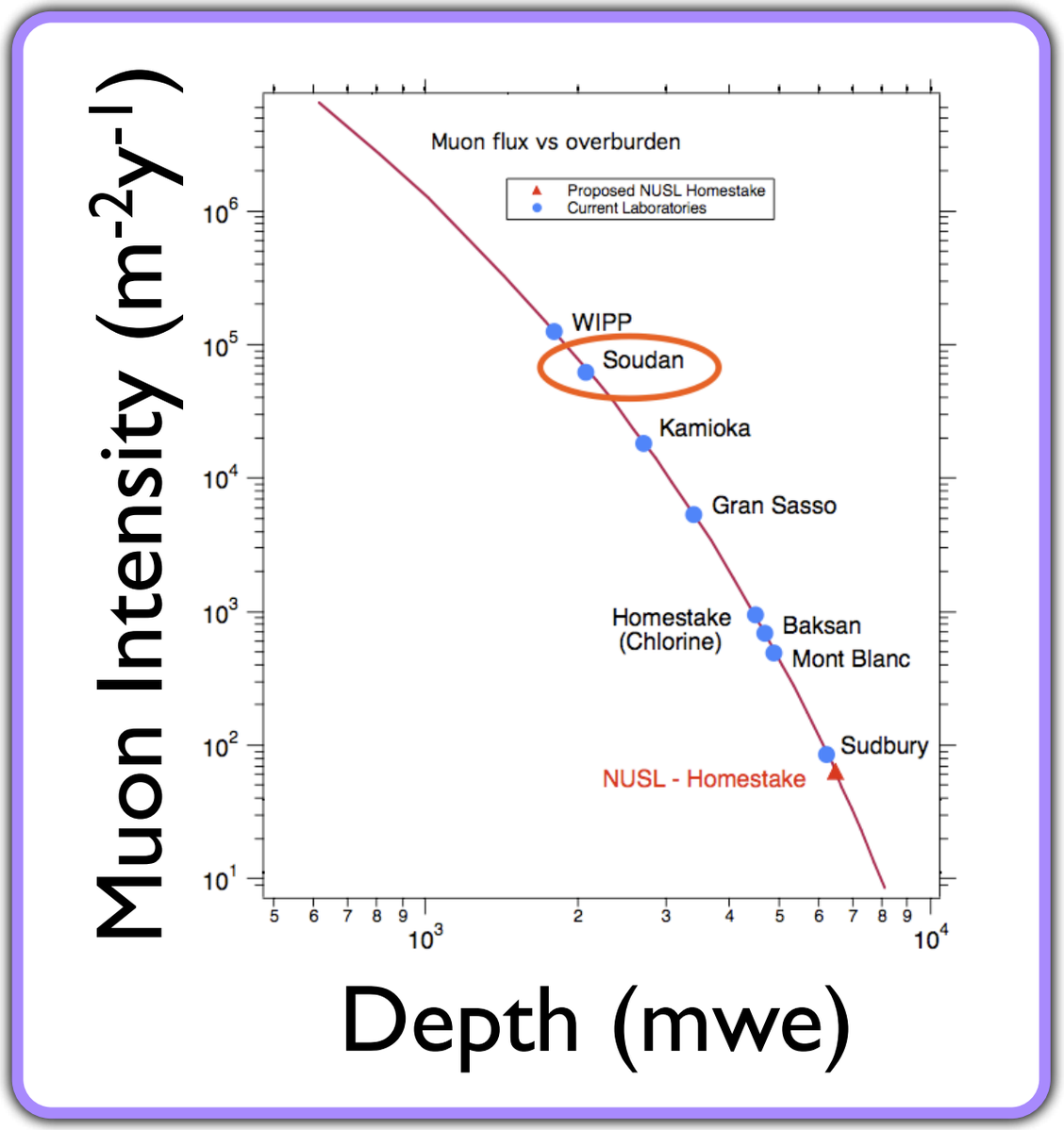
- Shielding
  - Passive (Mine Depth, Pb, Poly)
  - Active (muon veto shield)
- Energy Measurement
  - Phonon (True recoil energy)
  - Charge (Reduced for Nuclear)
- Position measurement (x,y,z)
  - From phonon pulse timing

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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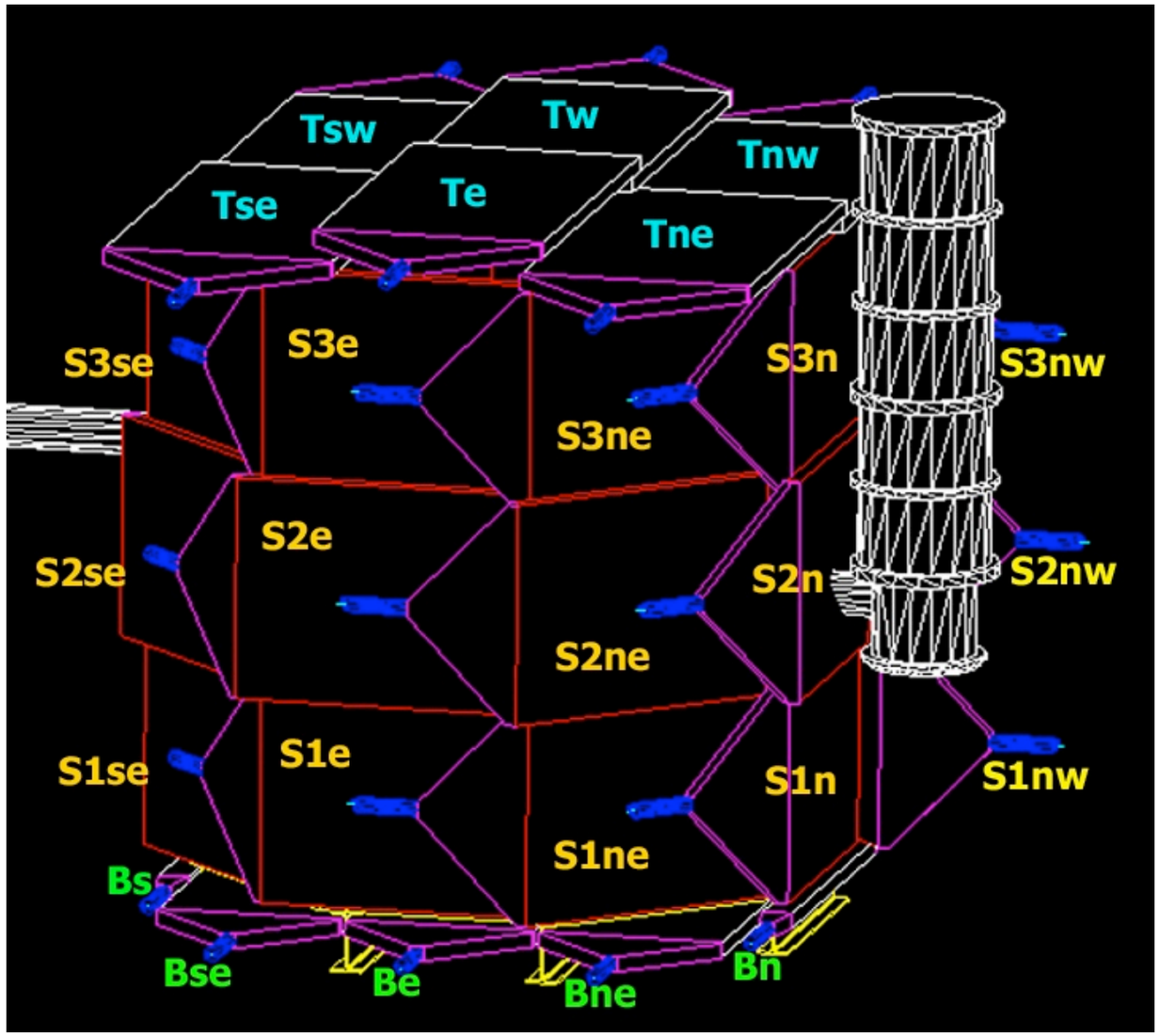
Radiopure Copper inner can

Radiopure Ge “target”



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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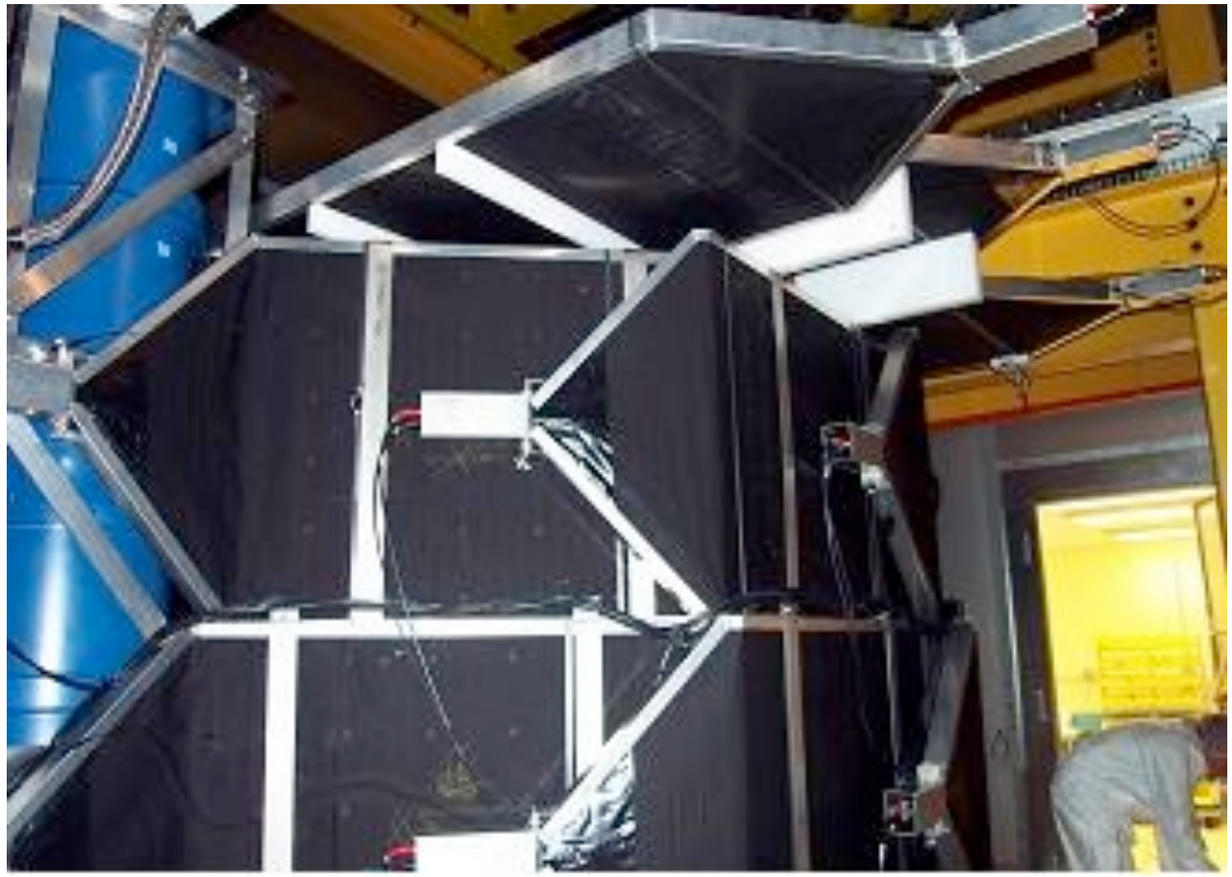

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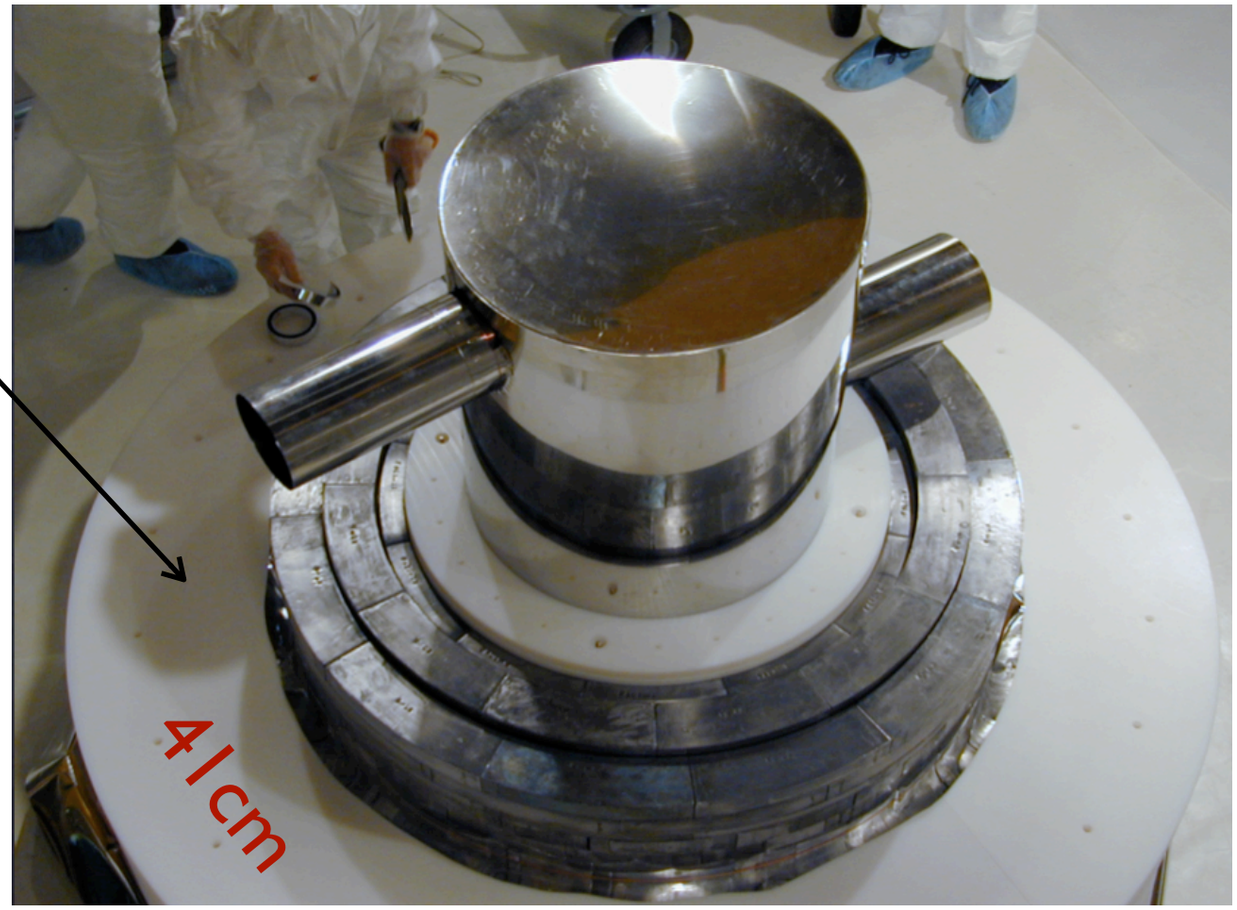

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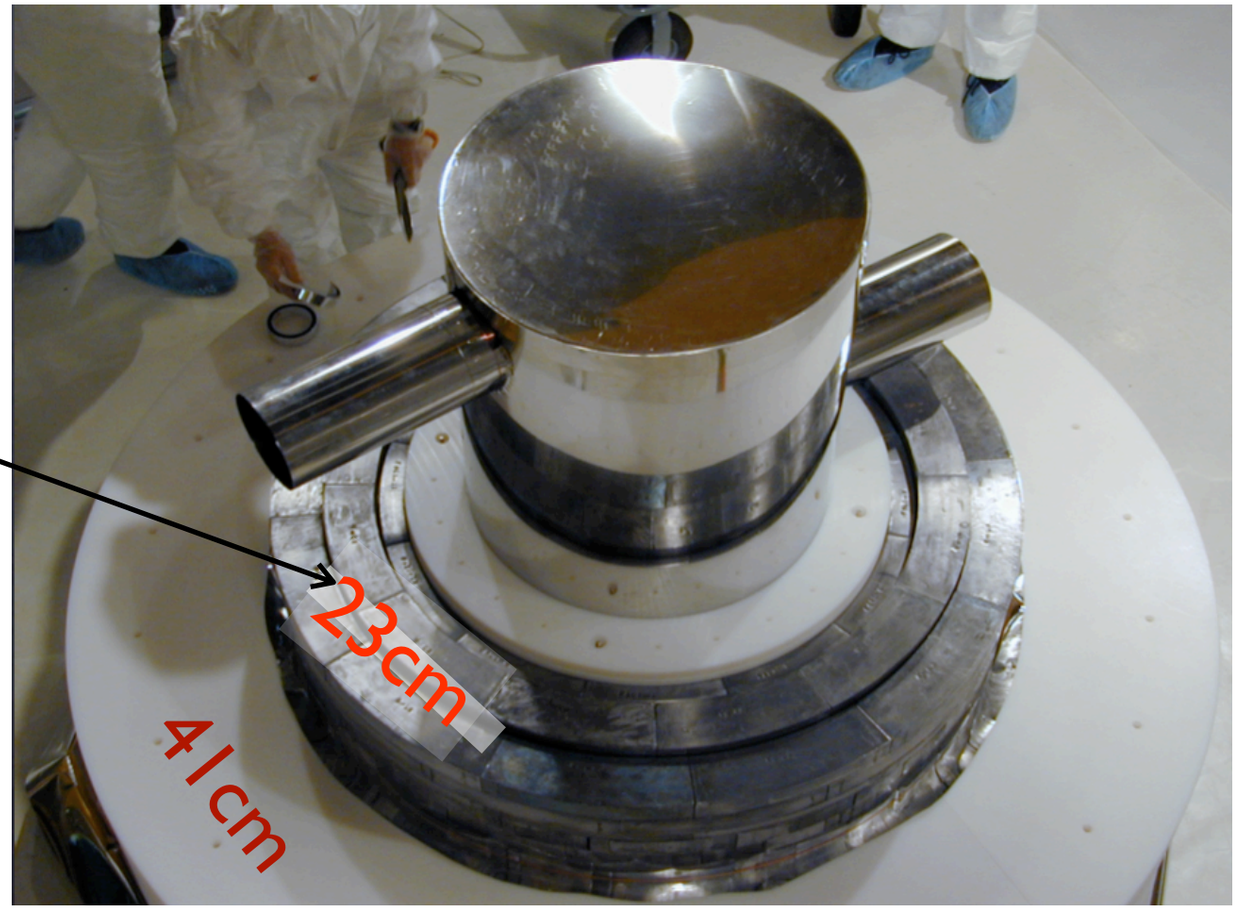

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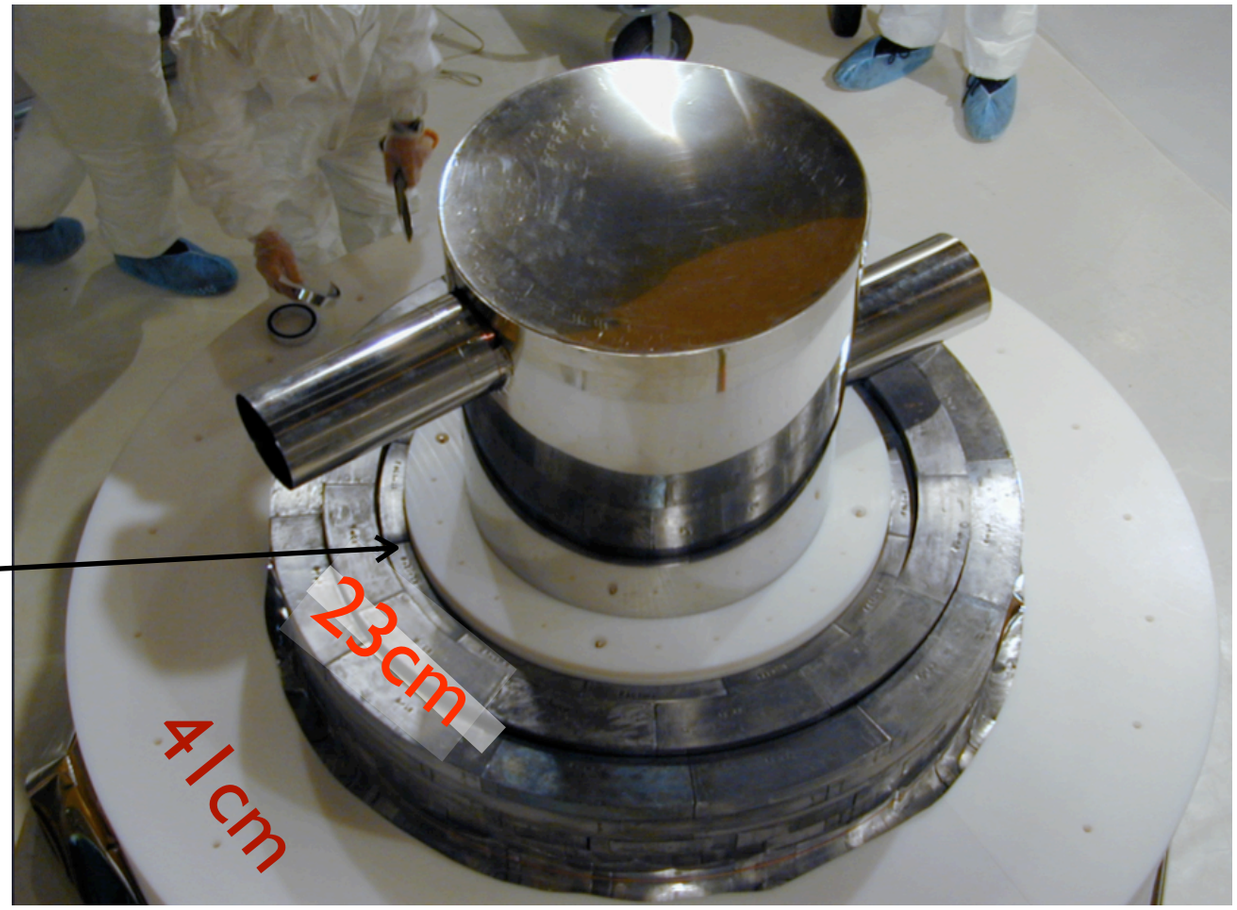

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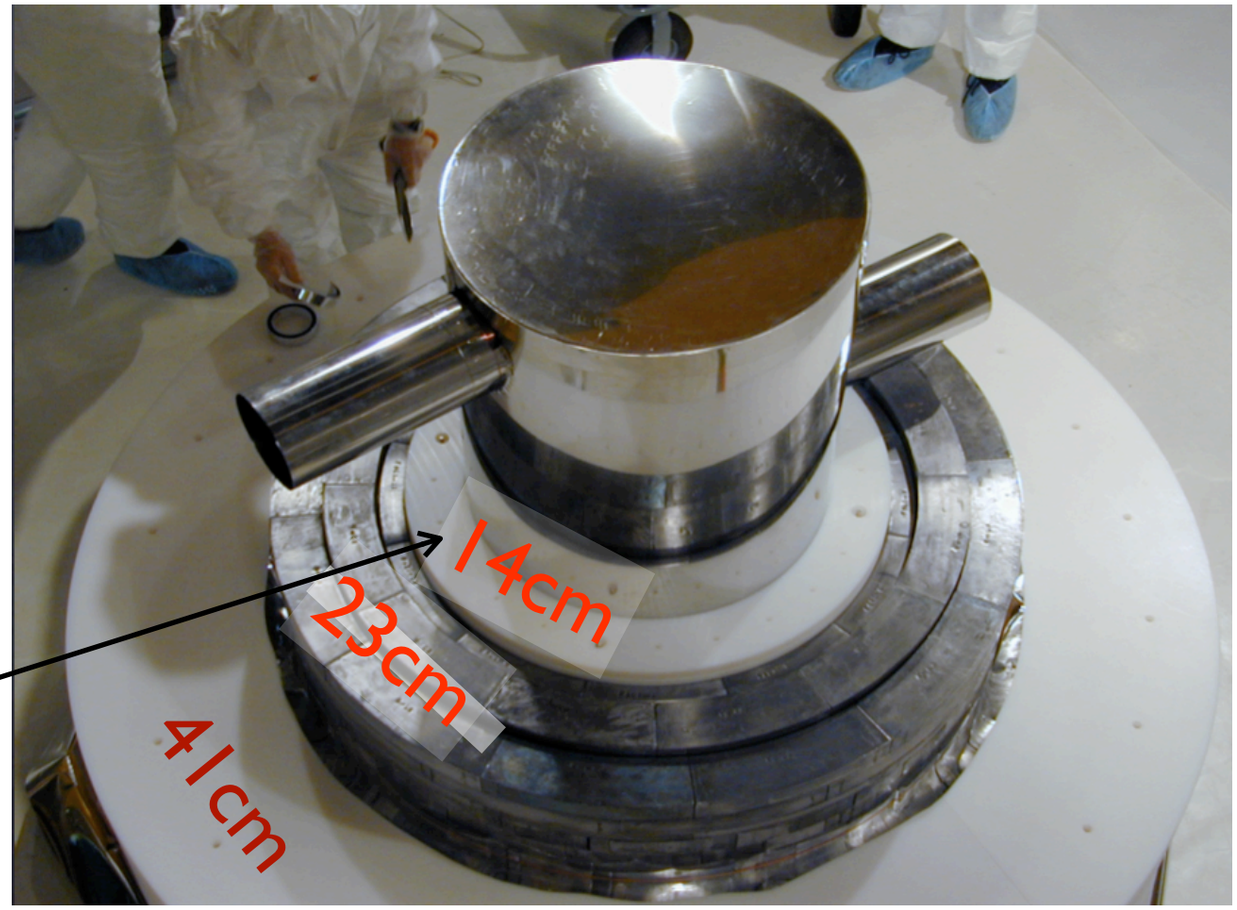

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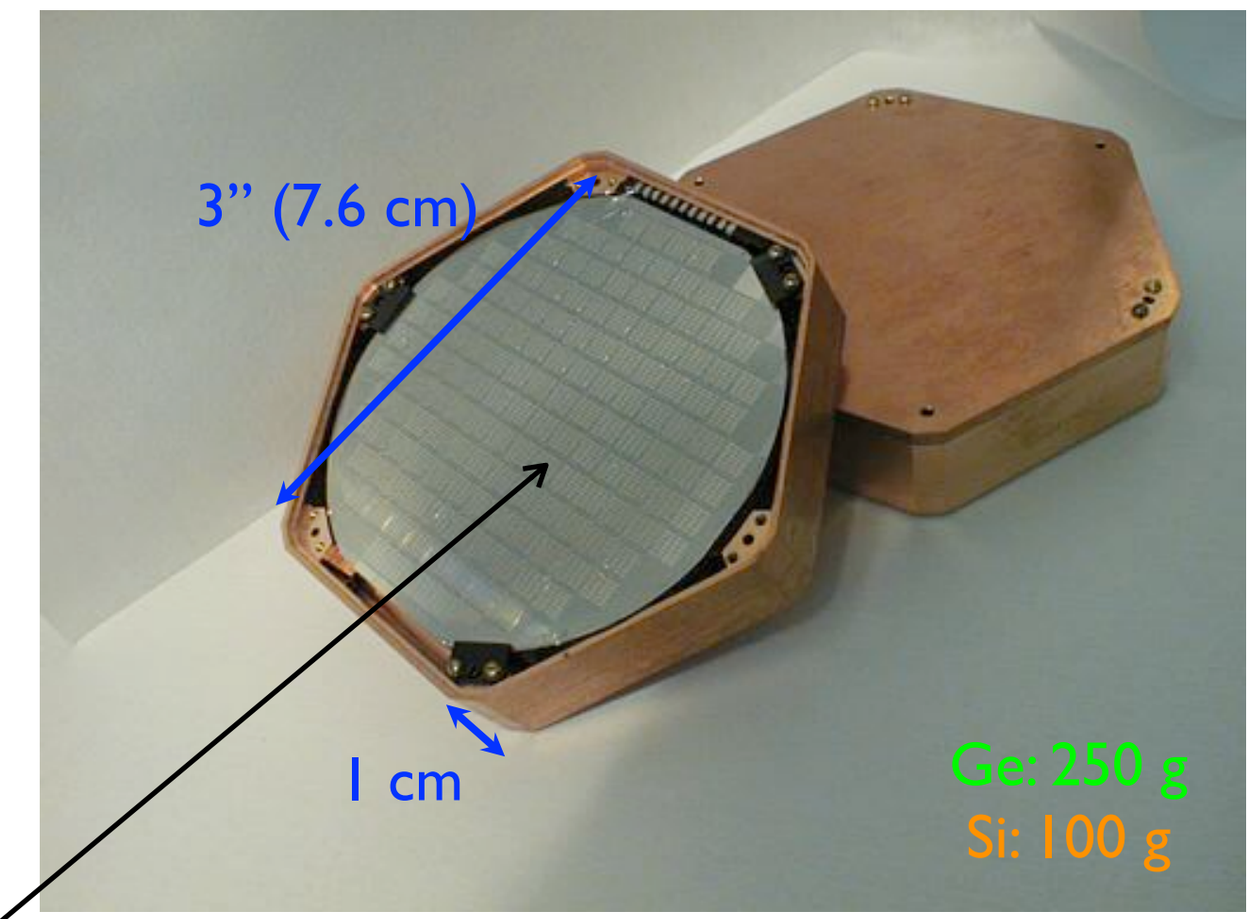
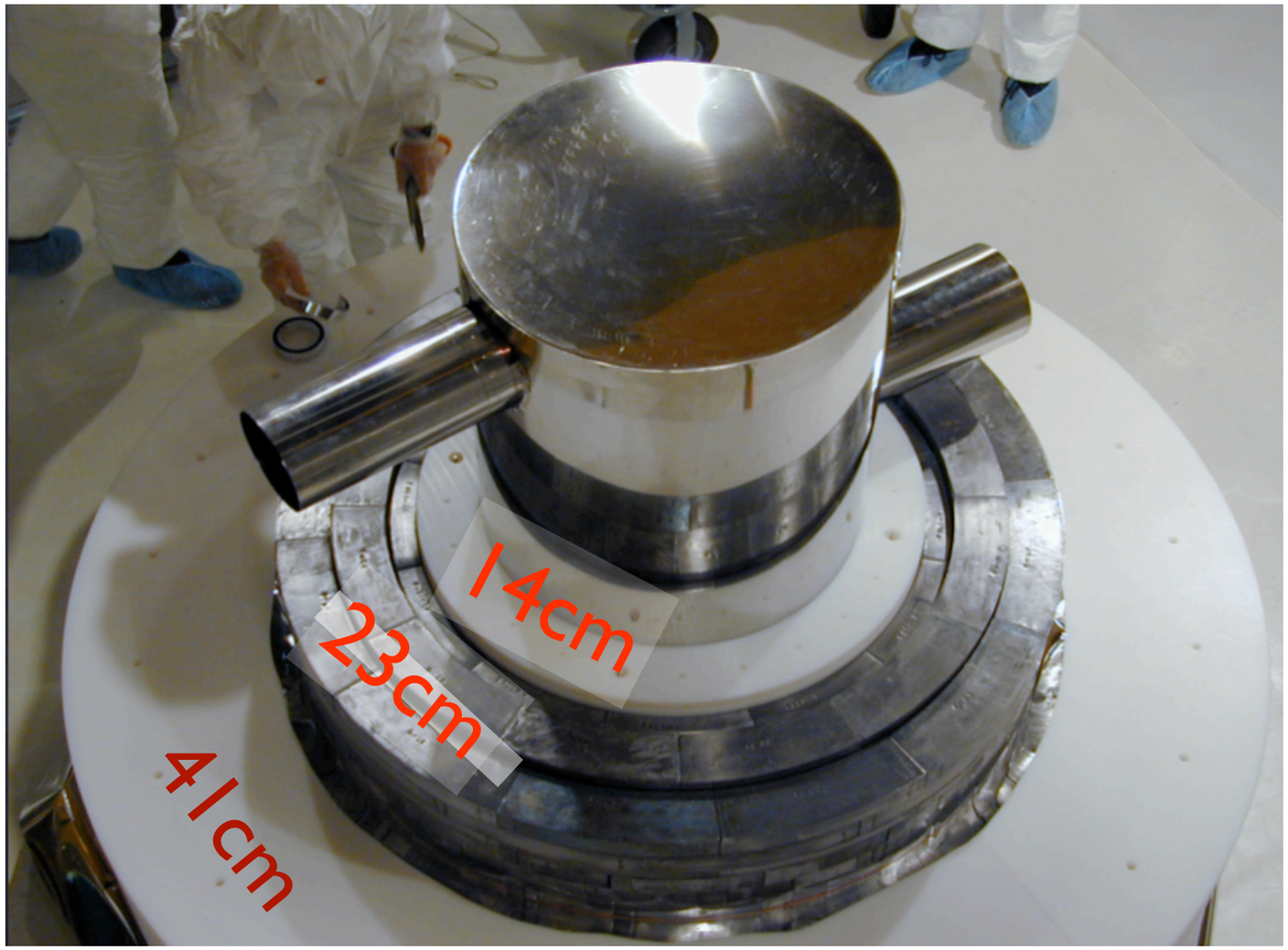


CDMS Detector Array

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

- Each Tower holds up to 6 detectors



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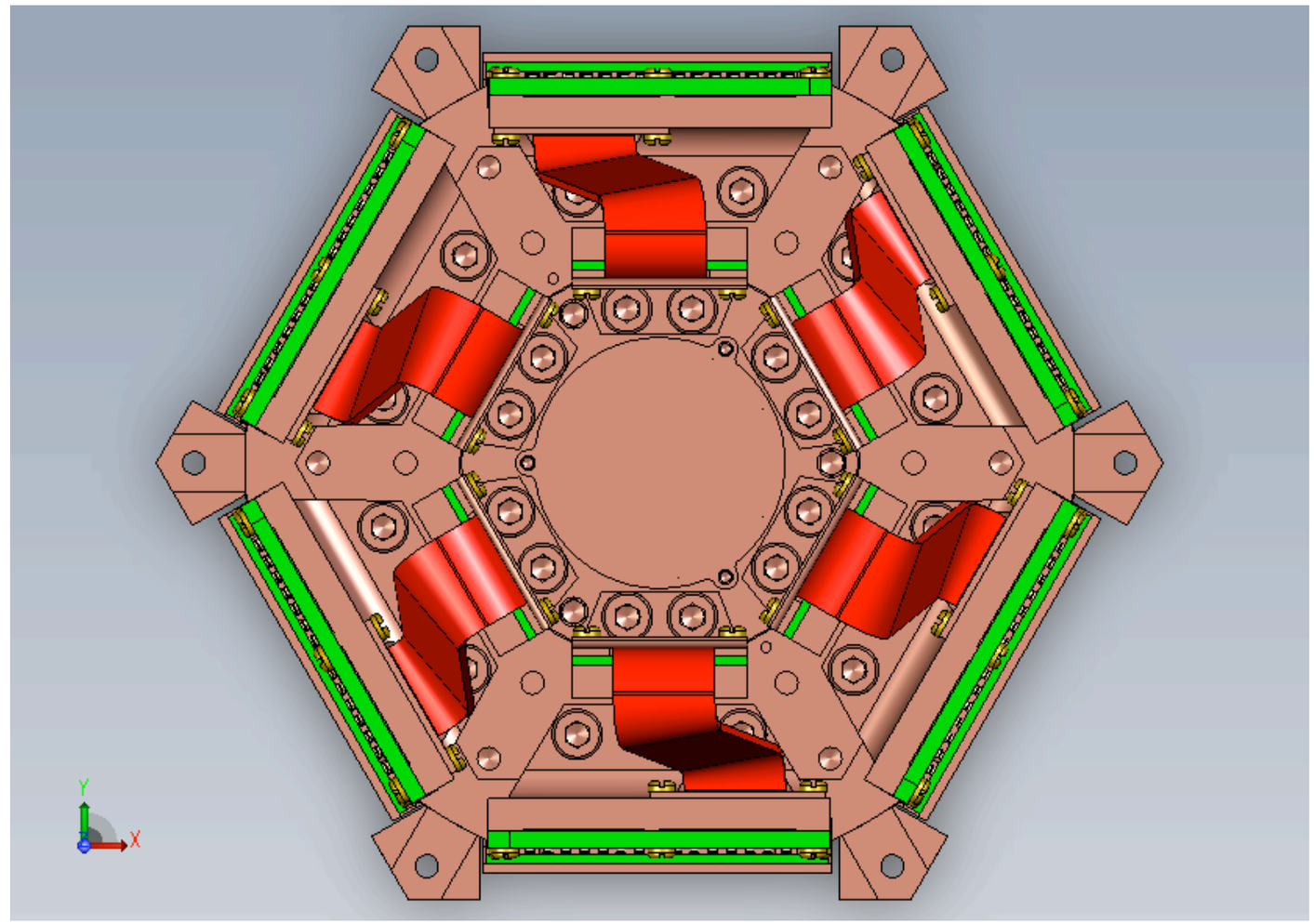

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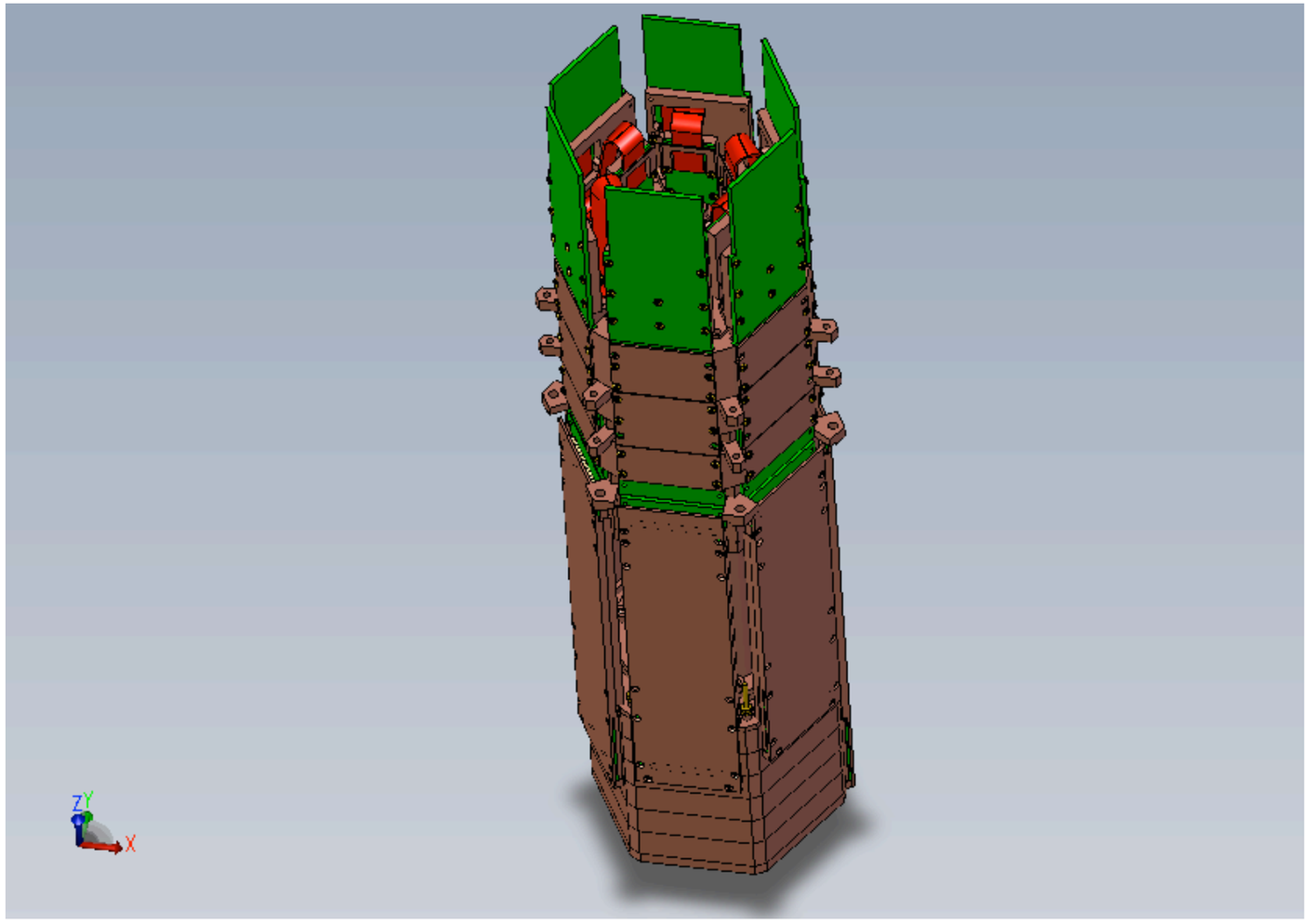

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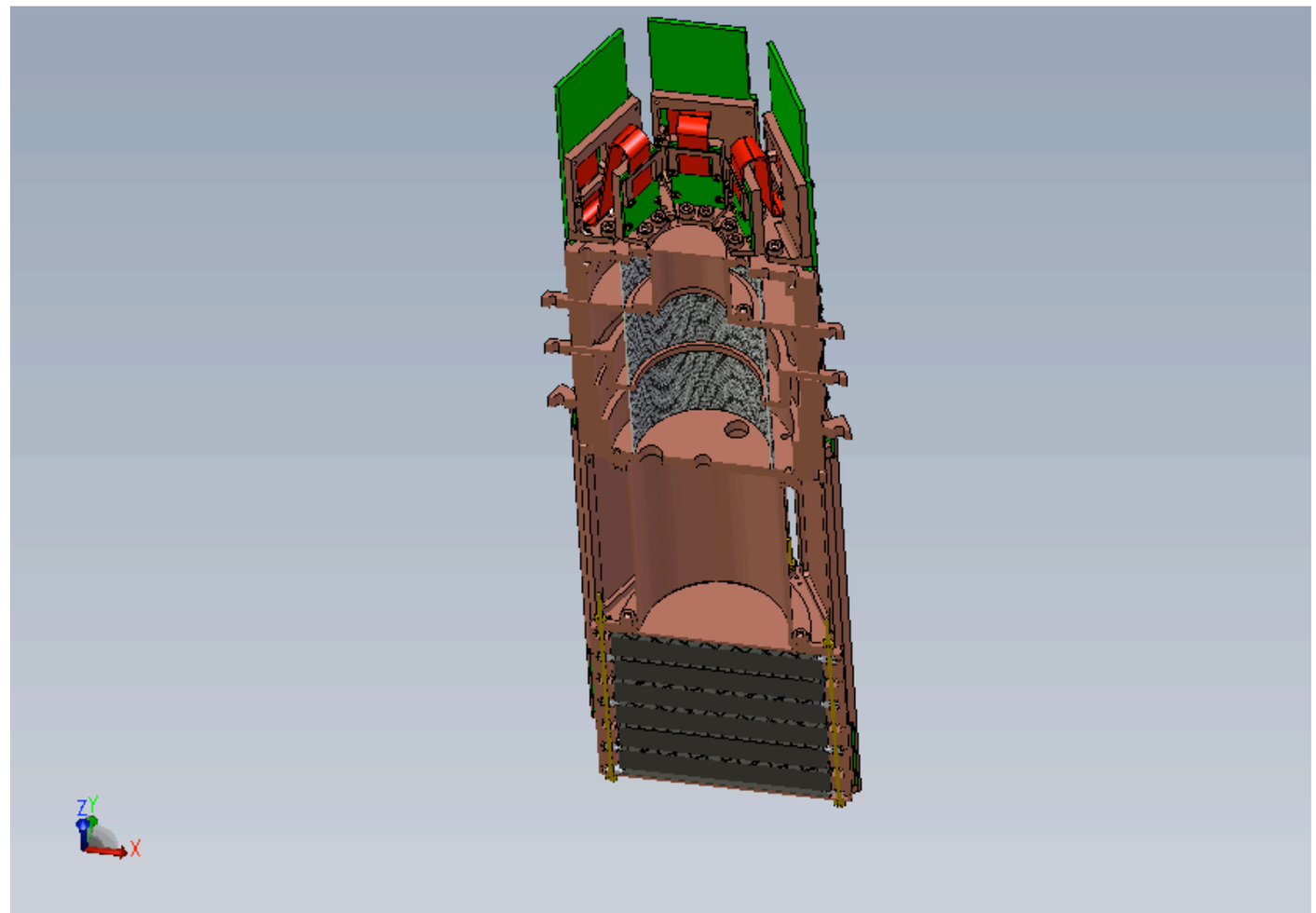

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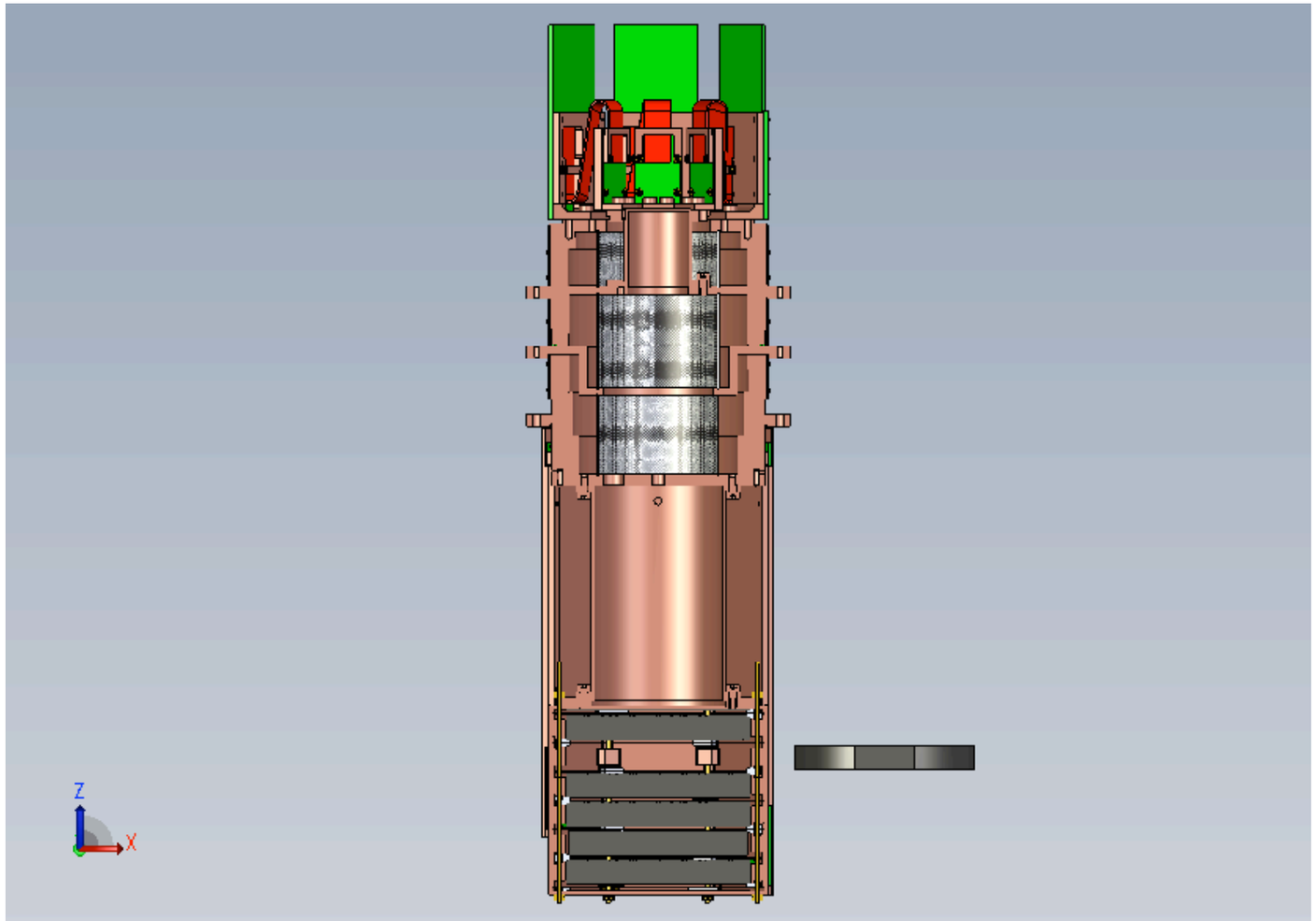

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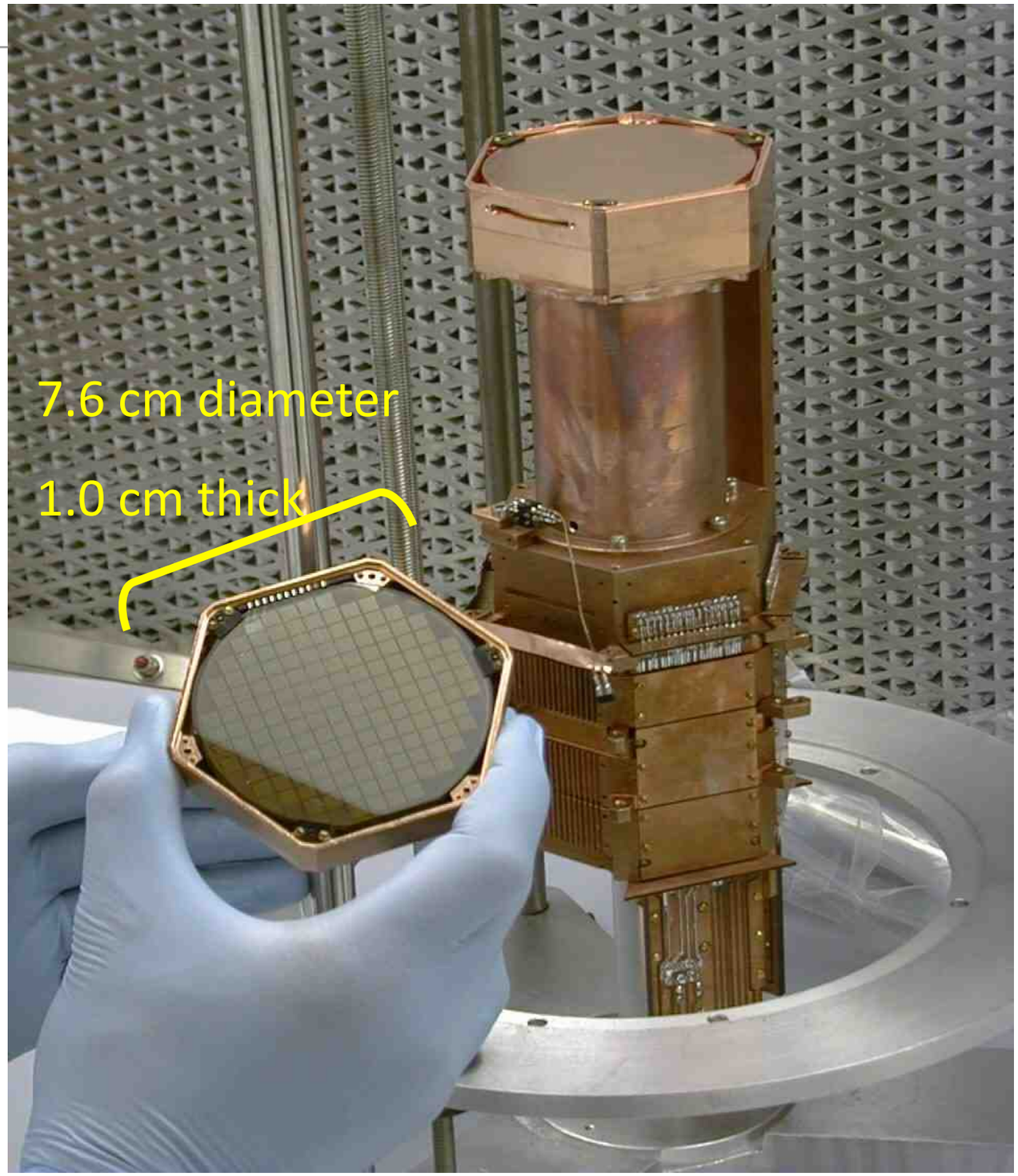
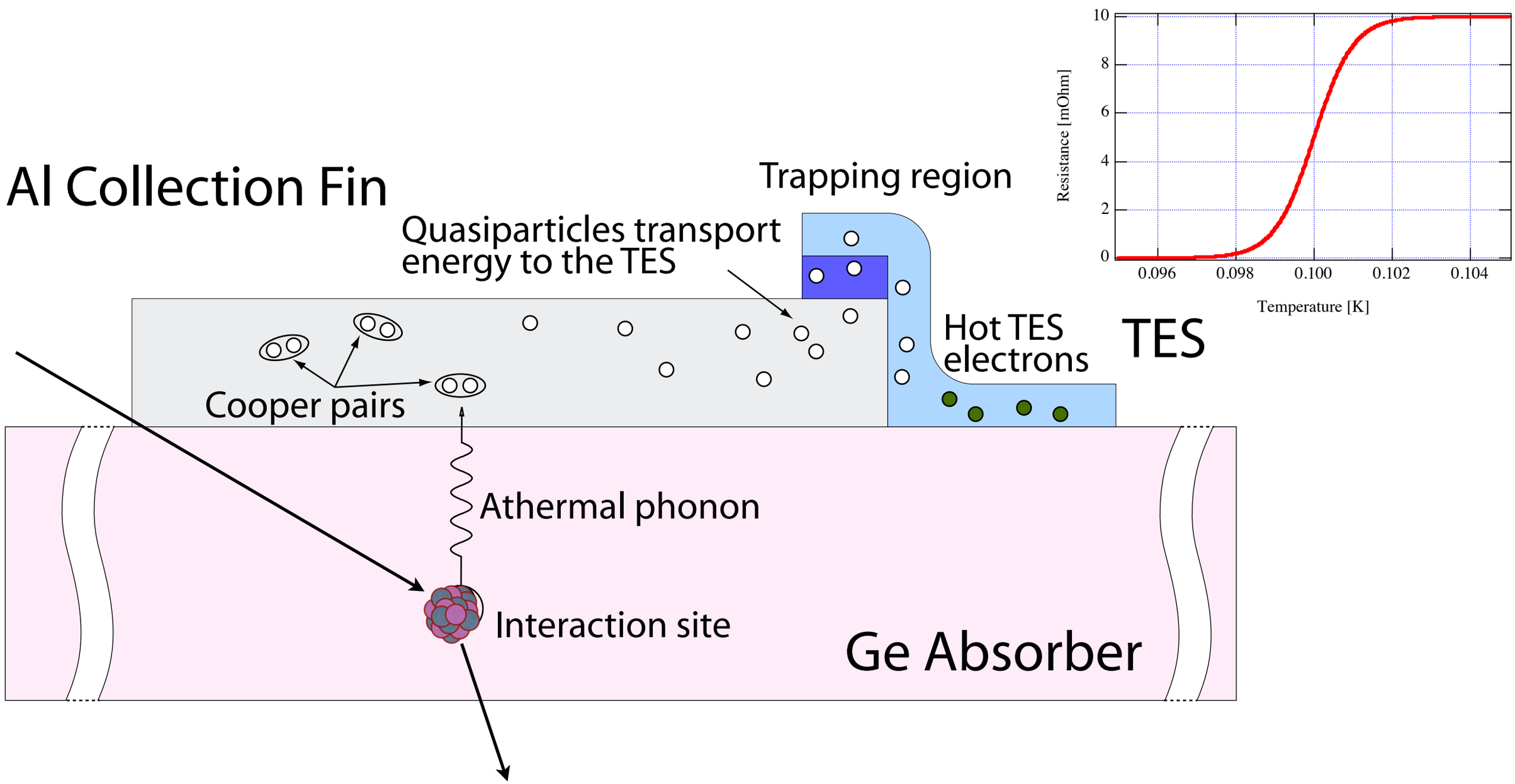
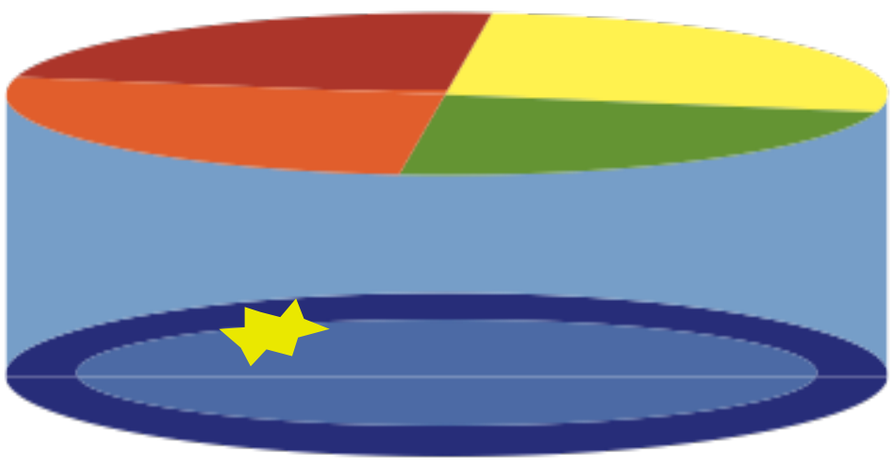


Getting the Energy to the Phonon Sensors



CDMS II Detectors



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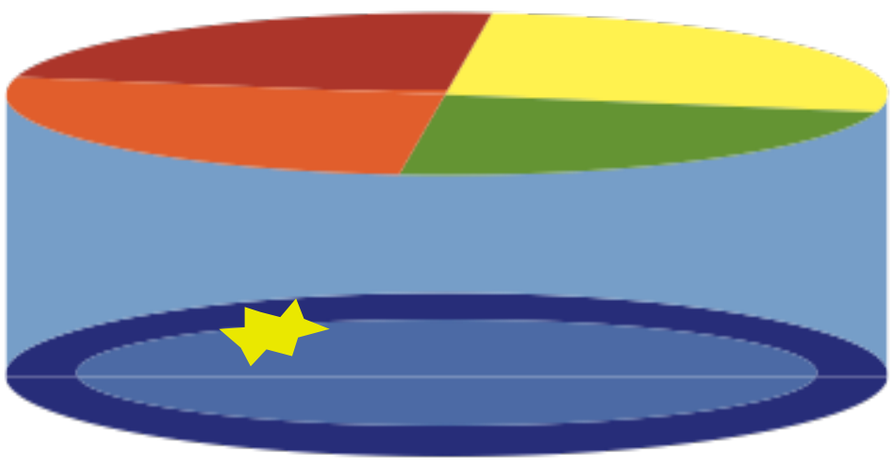
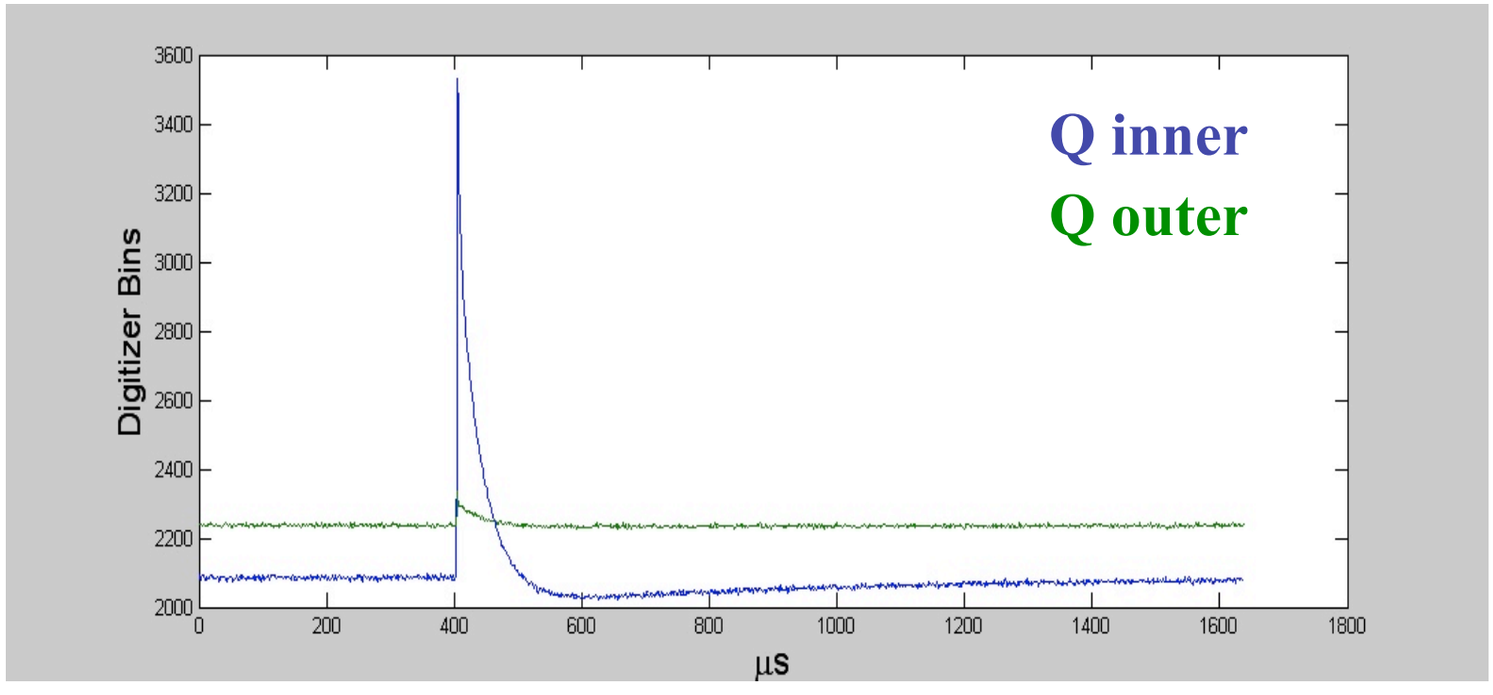


Charge Side



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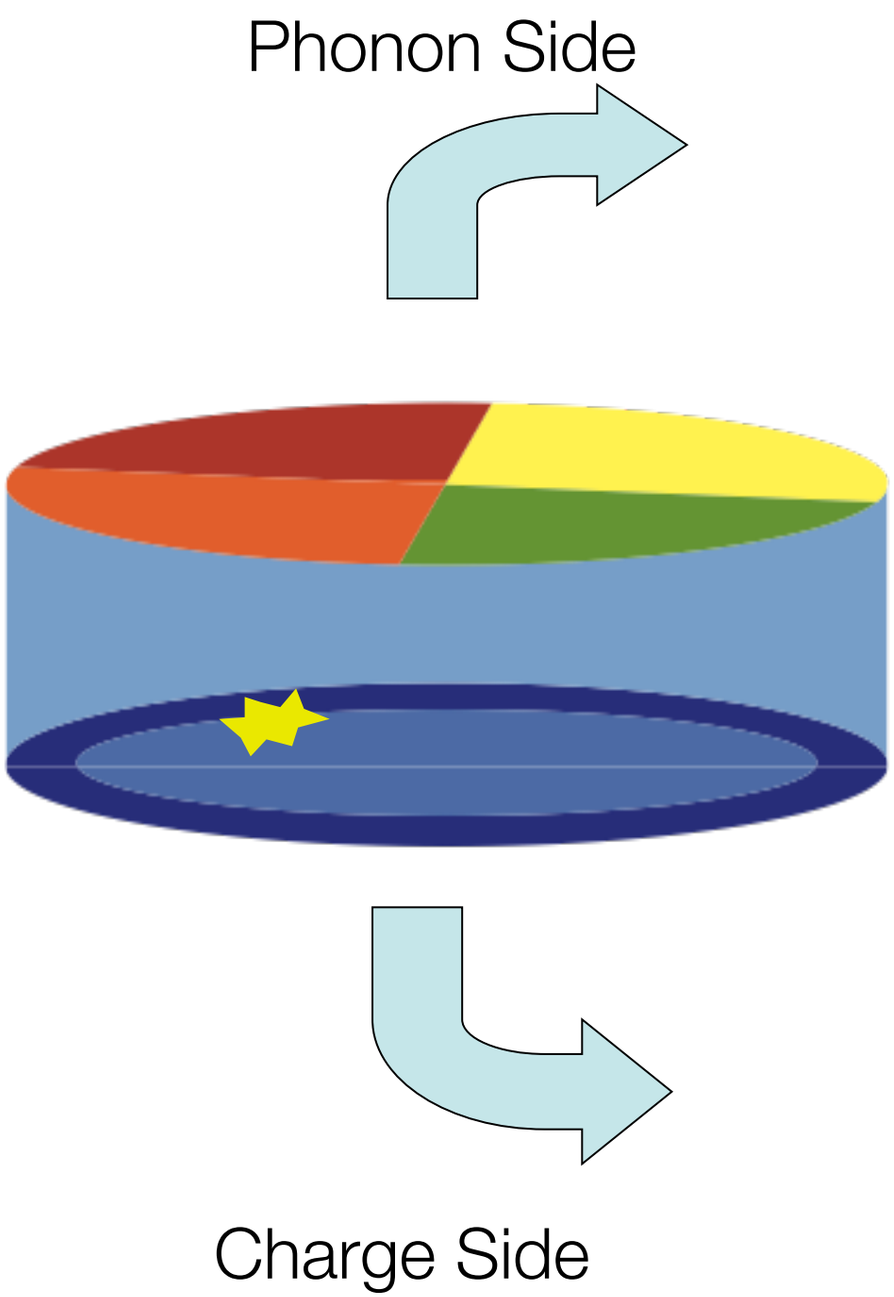
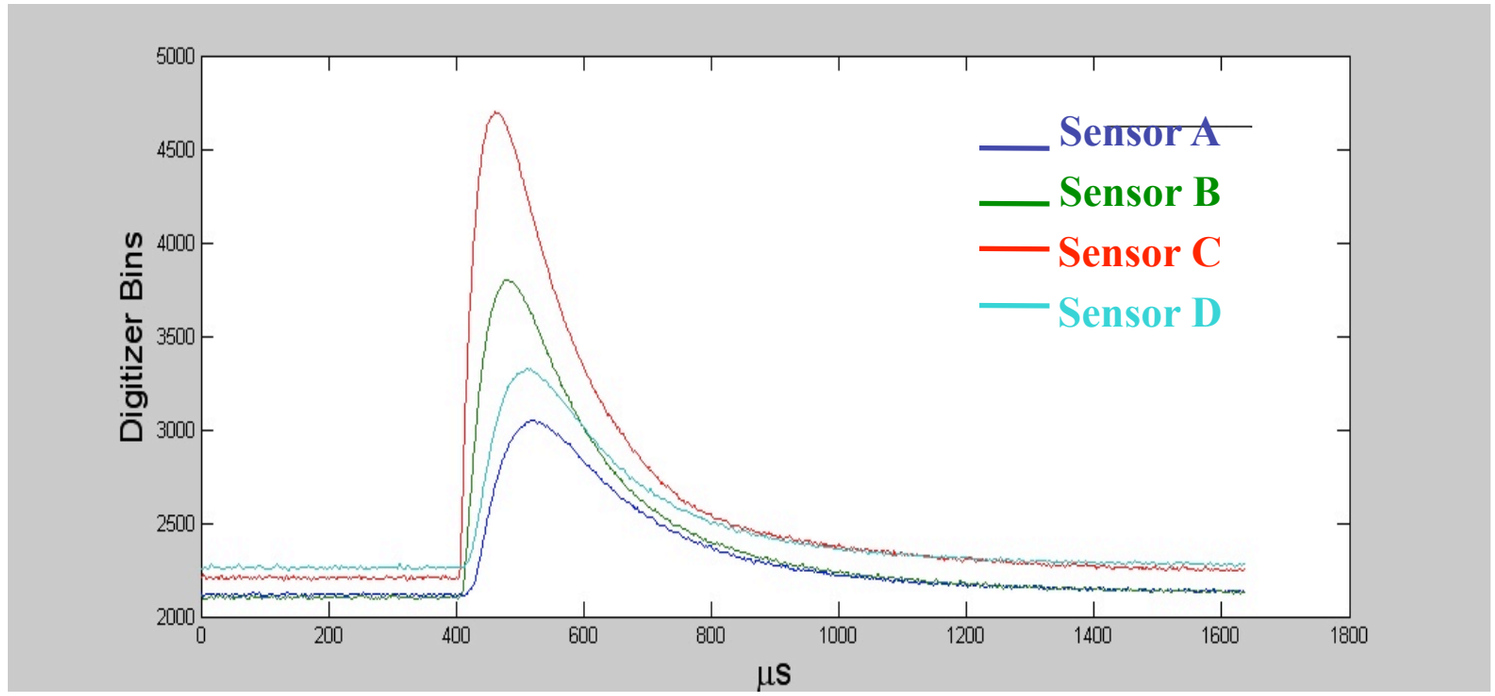
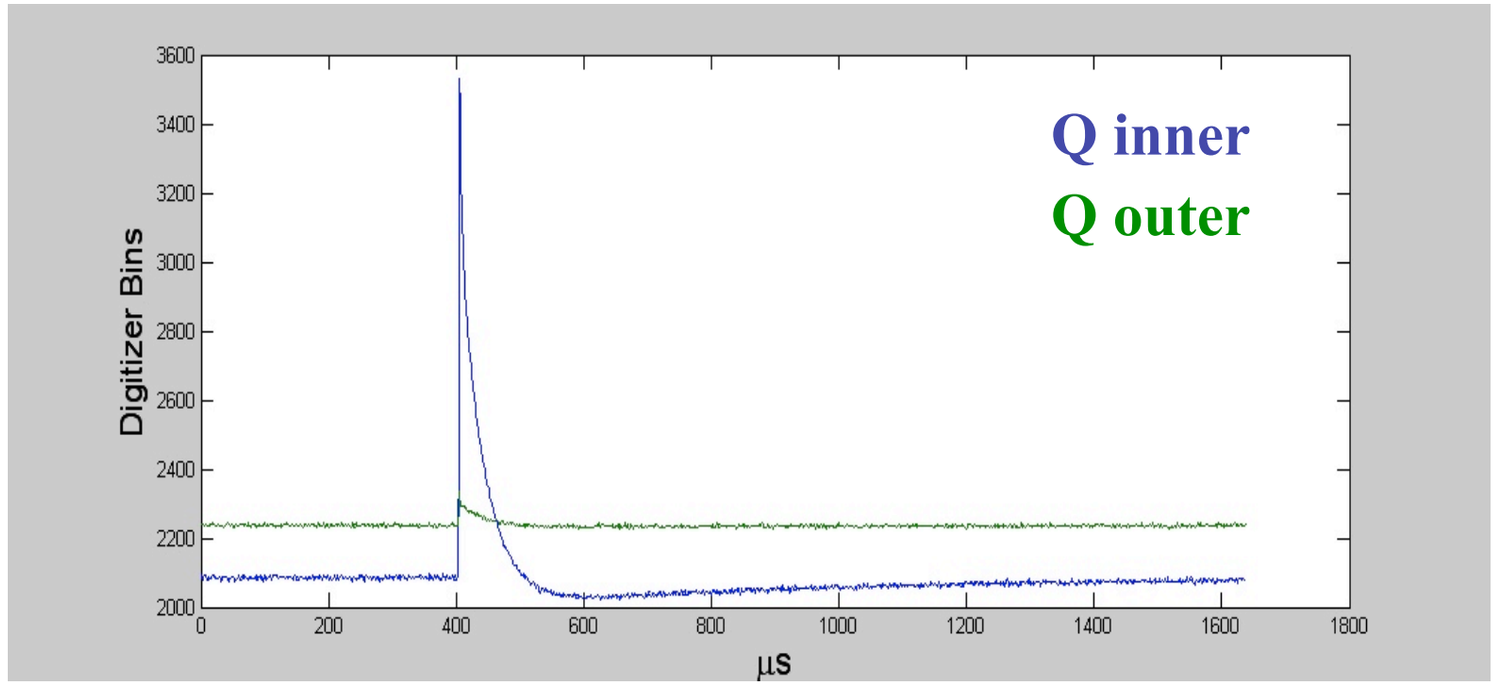
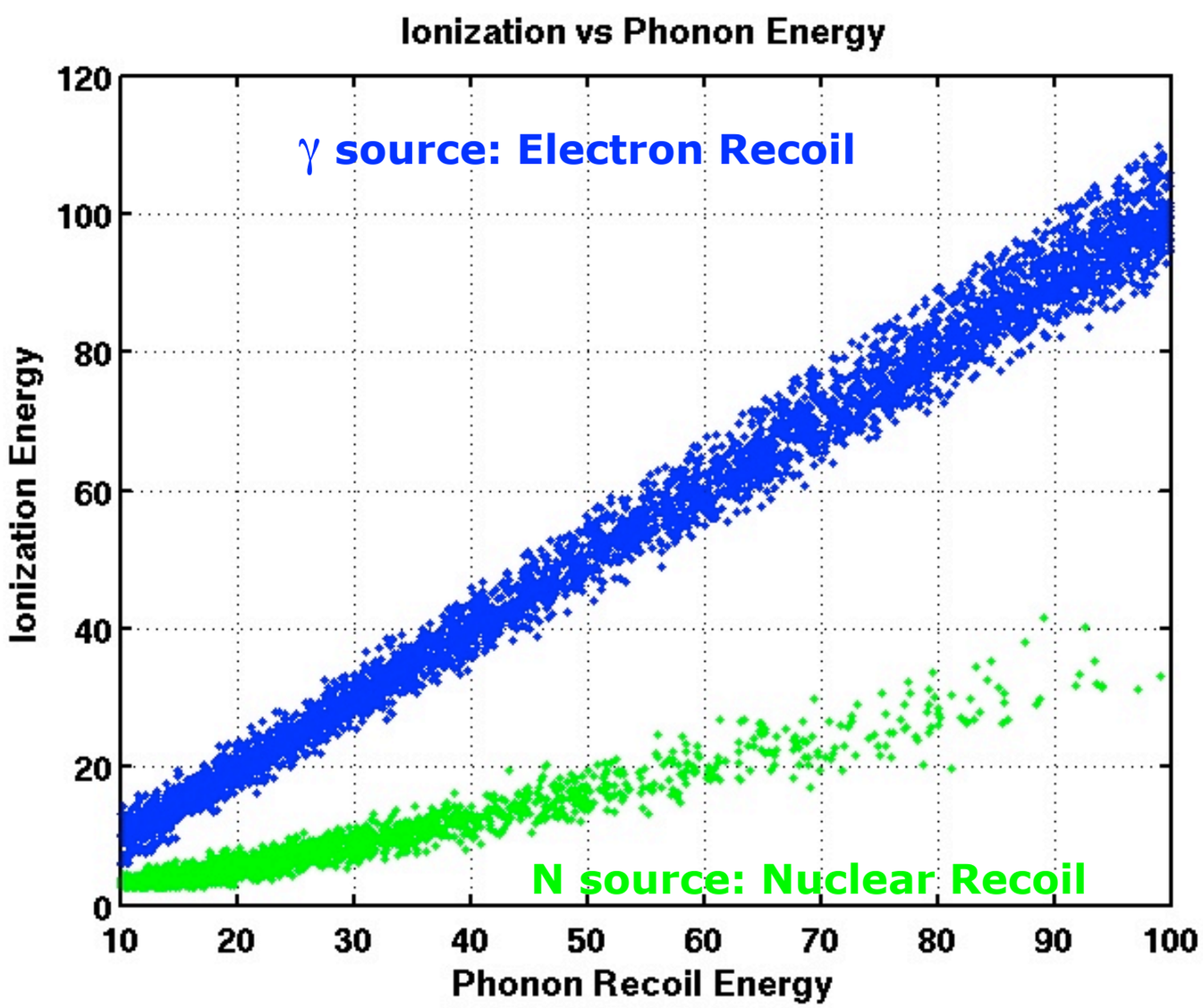






Excellent Primary (γ) Background Rejection



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

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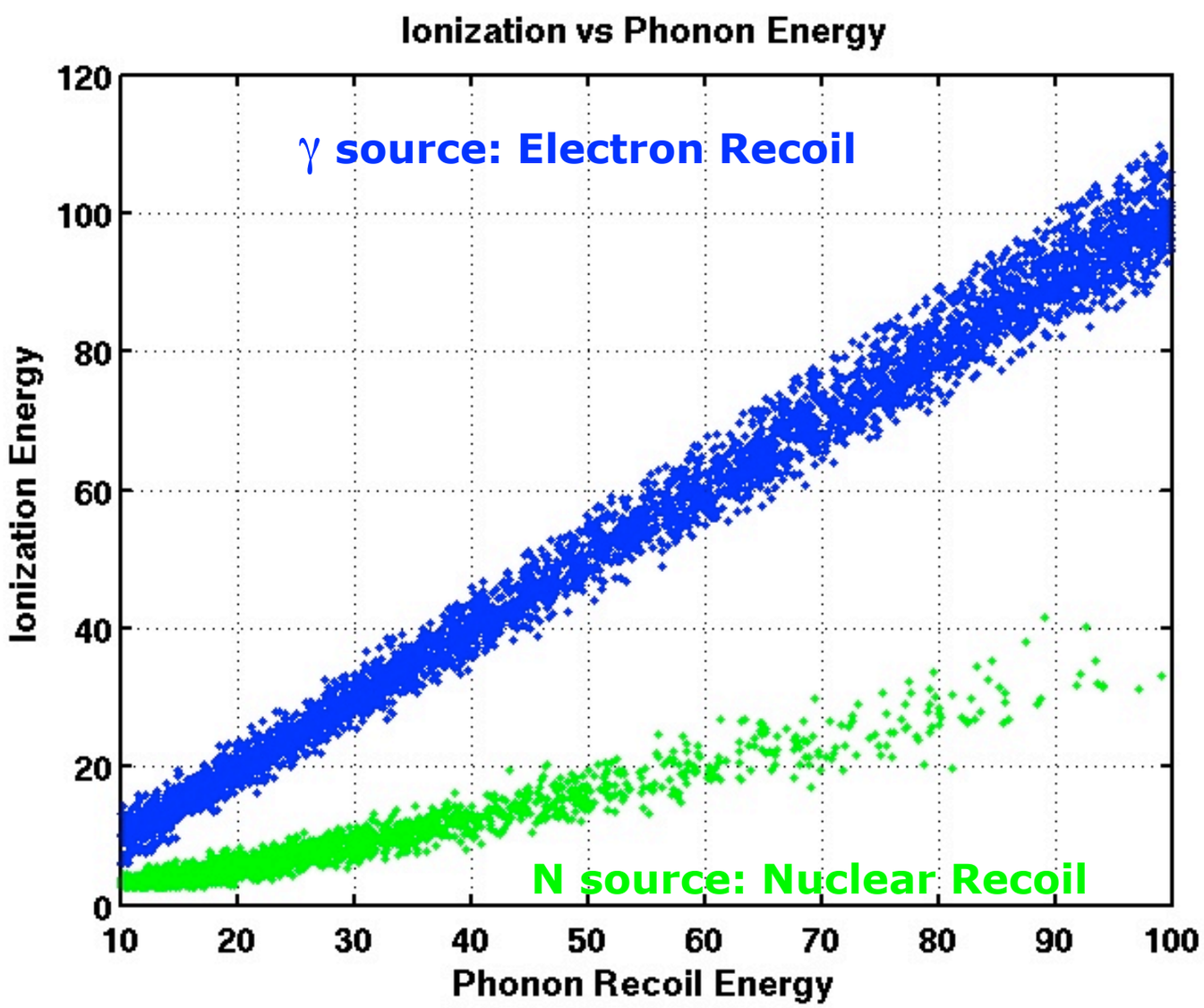

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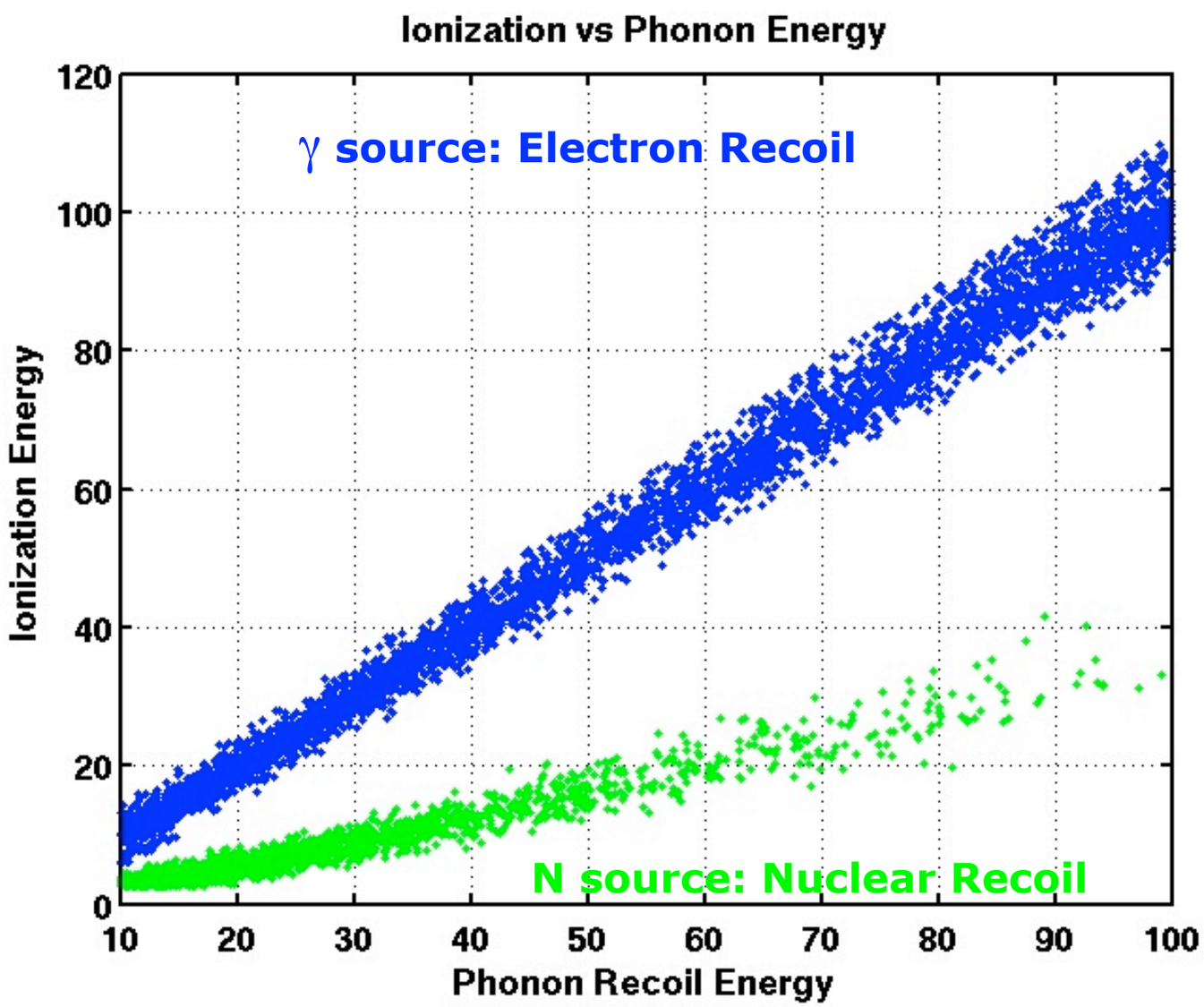

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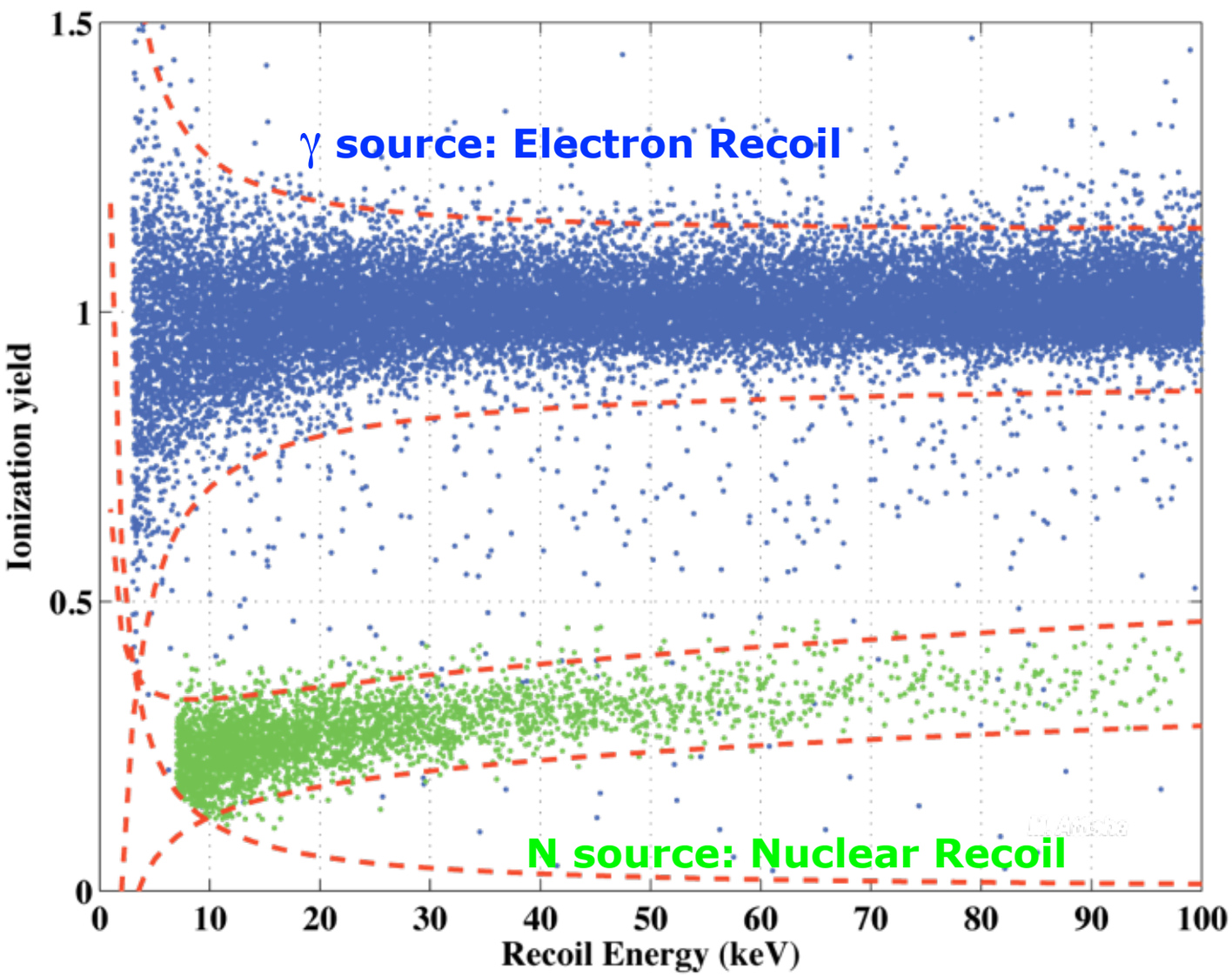

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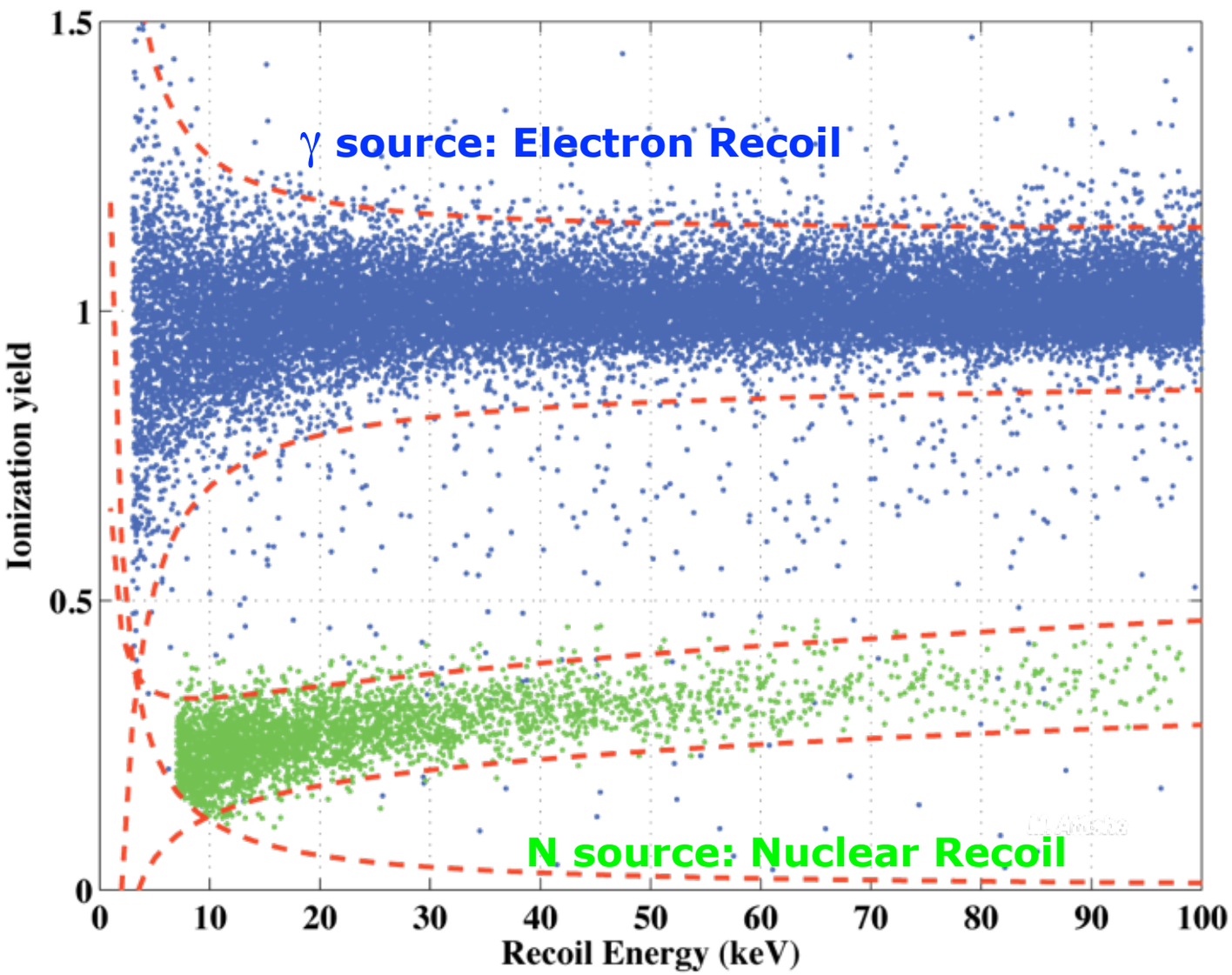

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Events with low yield can be misidentified as nuclear recoils

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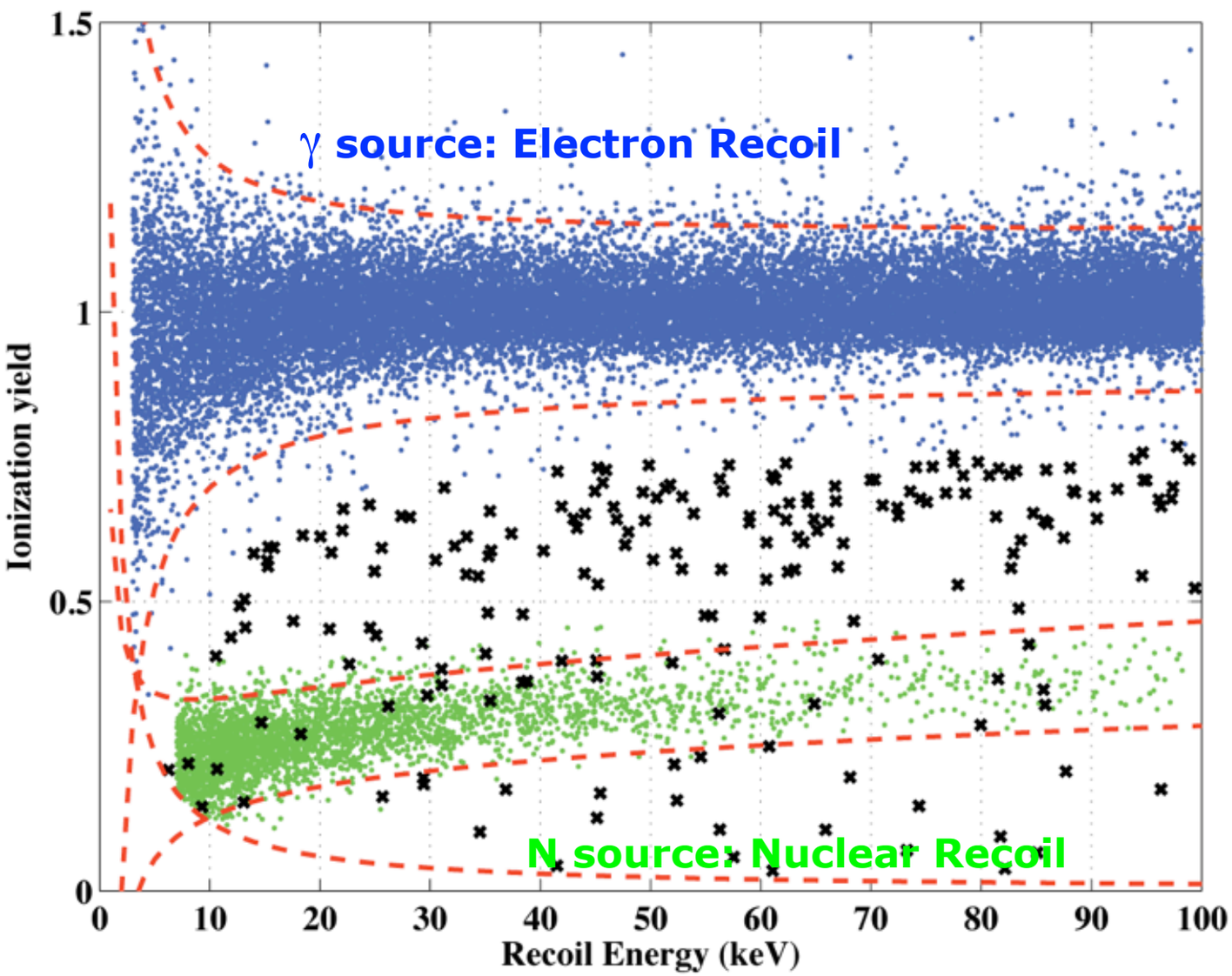

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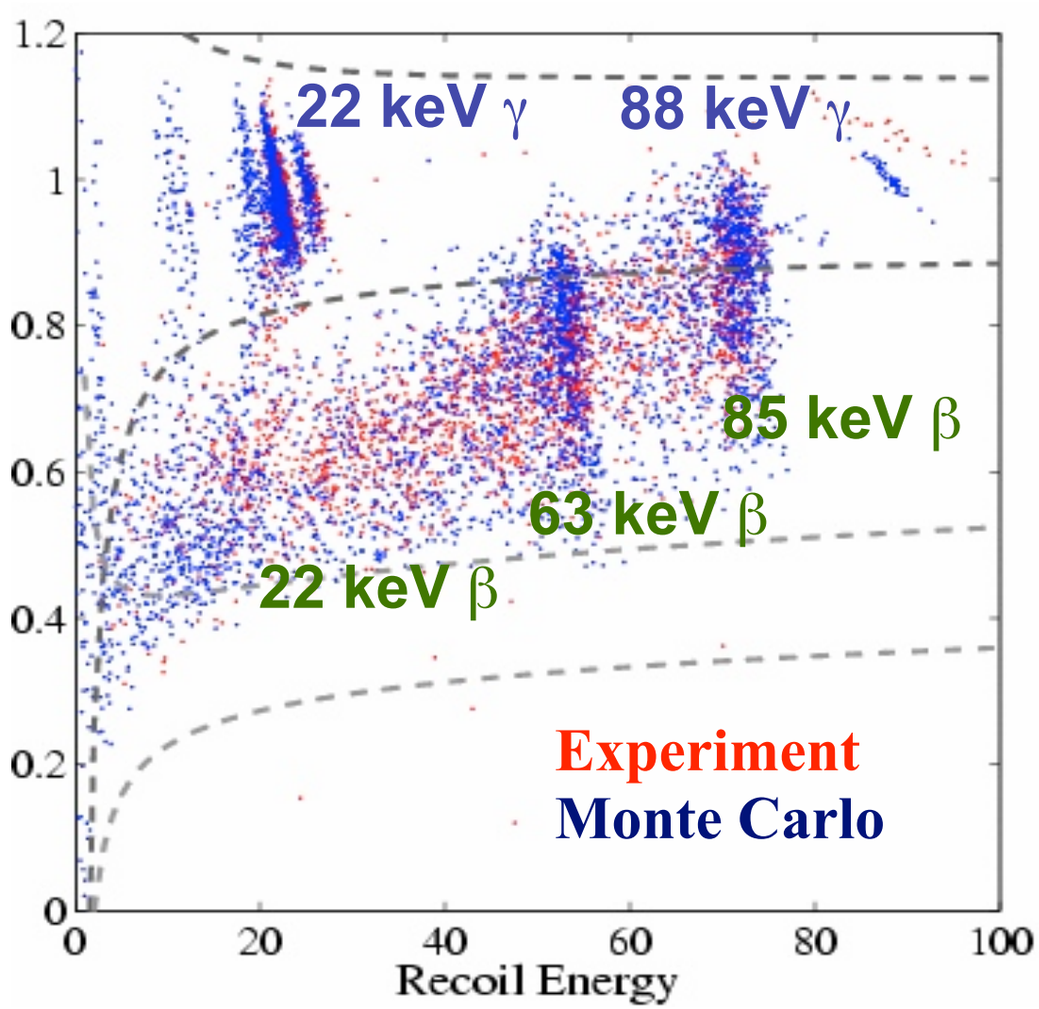
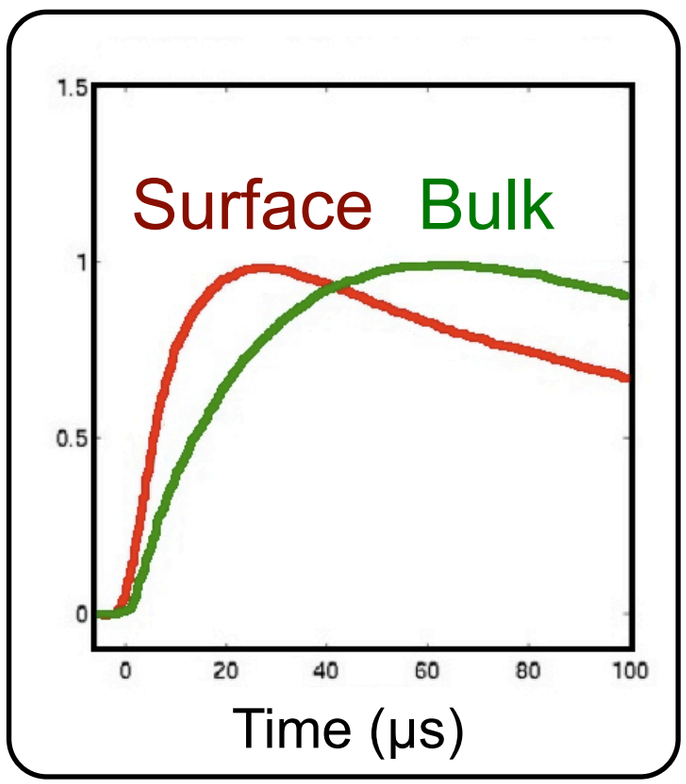
Surface Events

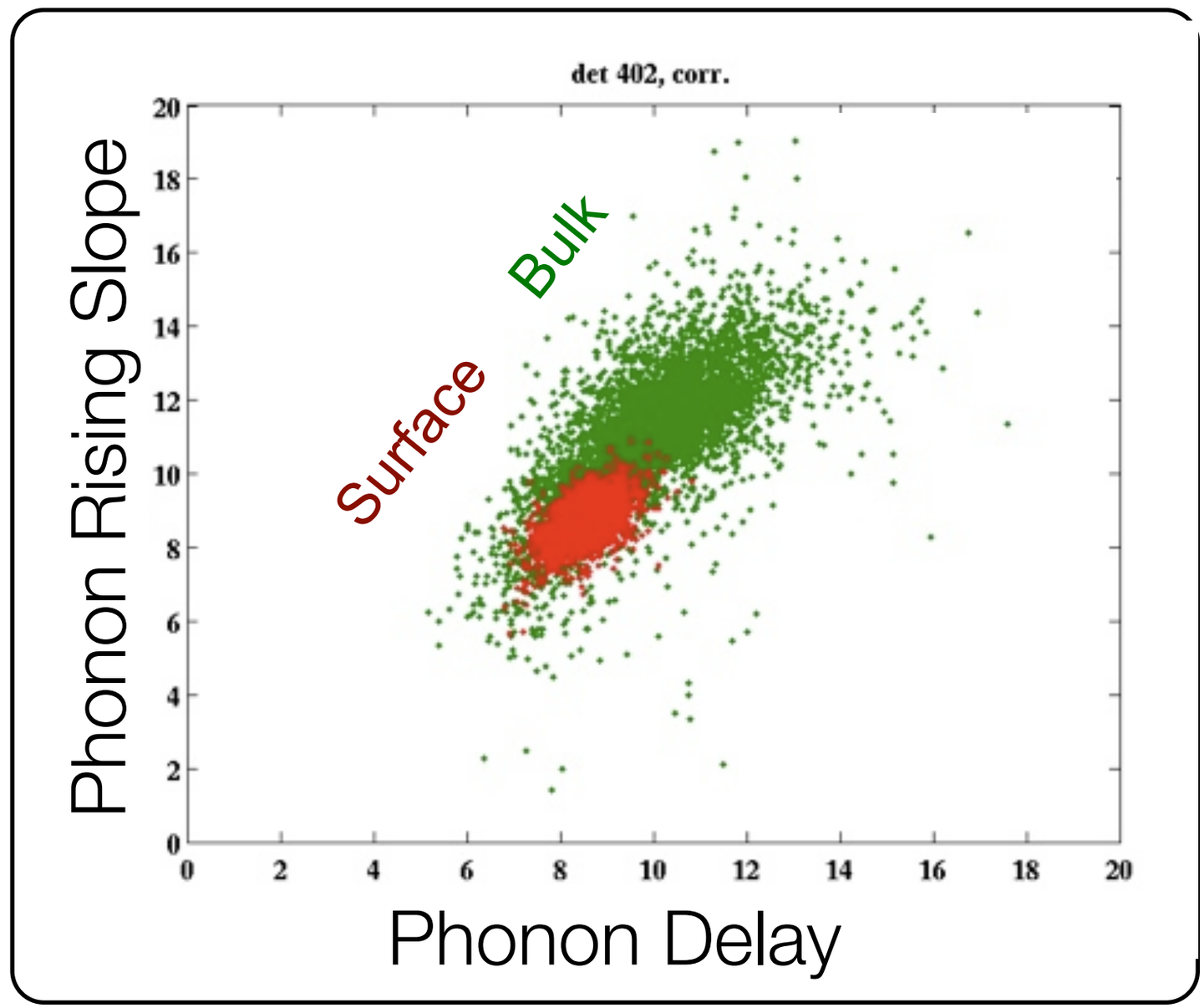


βs and low-energy γs don't penetrate the detector. These surface events can pollute the signal region and are the dominant background for CDMS.

Surface β Rejection

Secondary Discrimination: Phonon Timing





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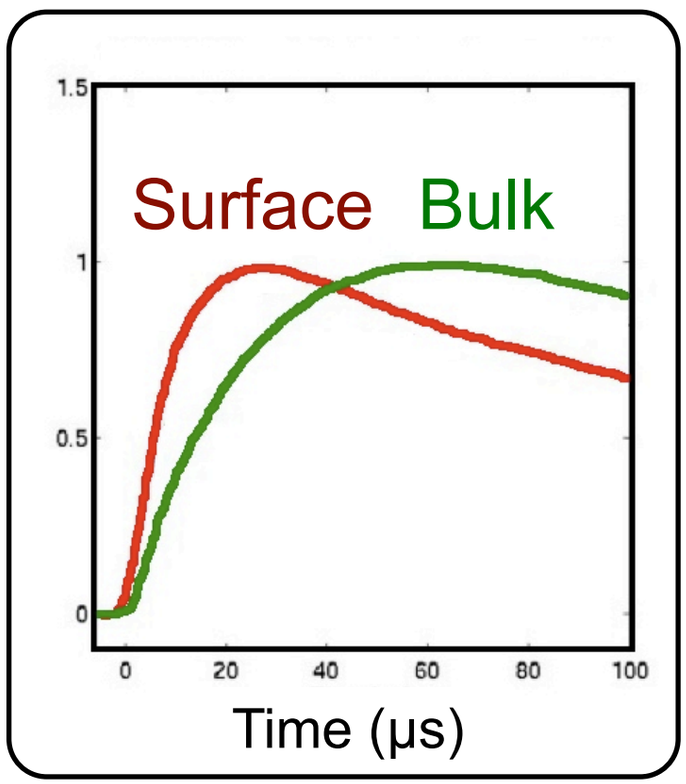

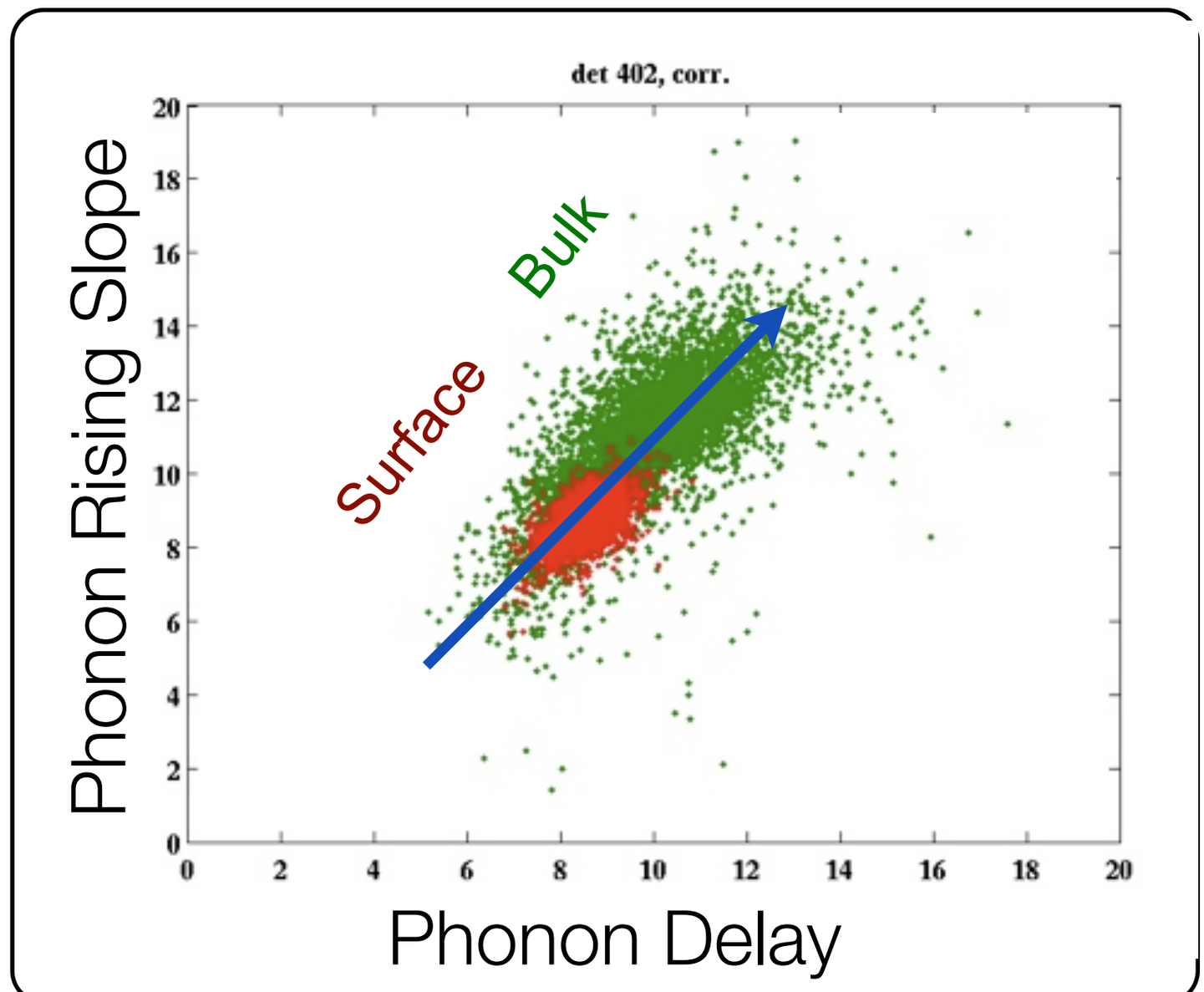

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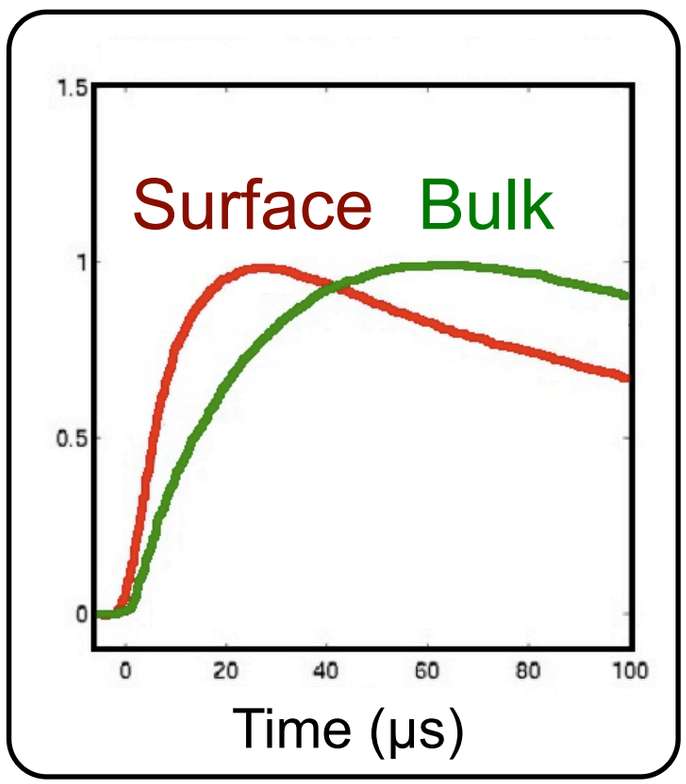

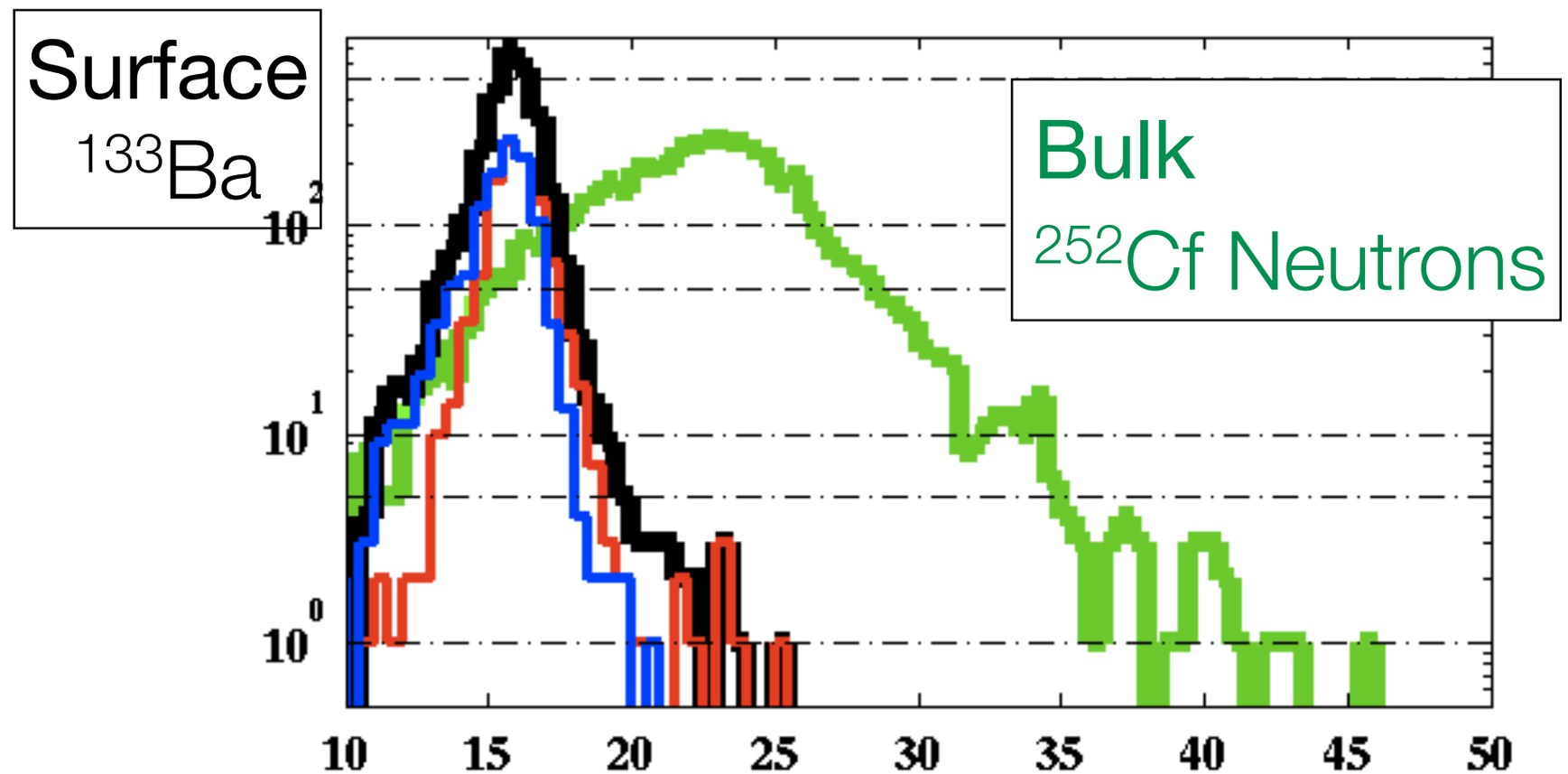

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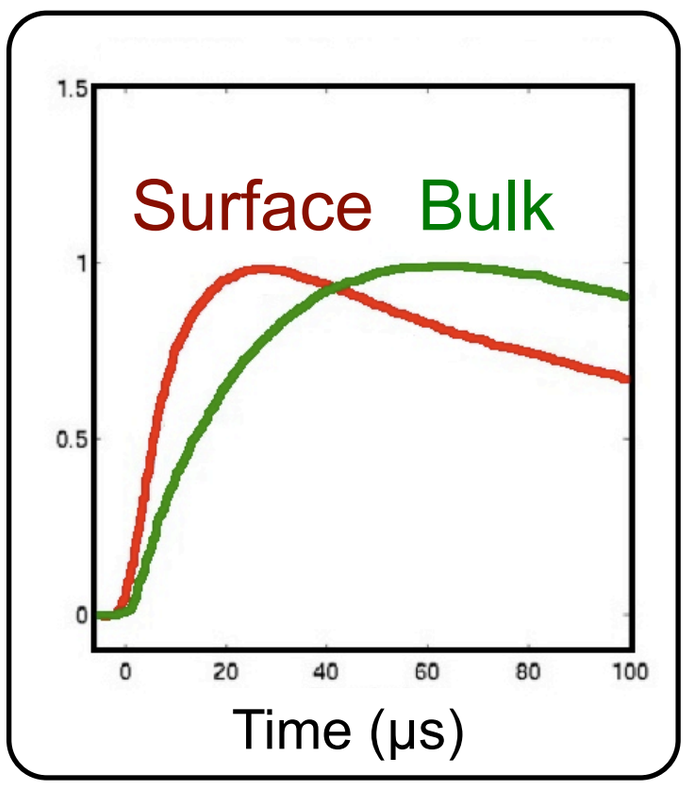
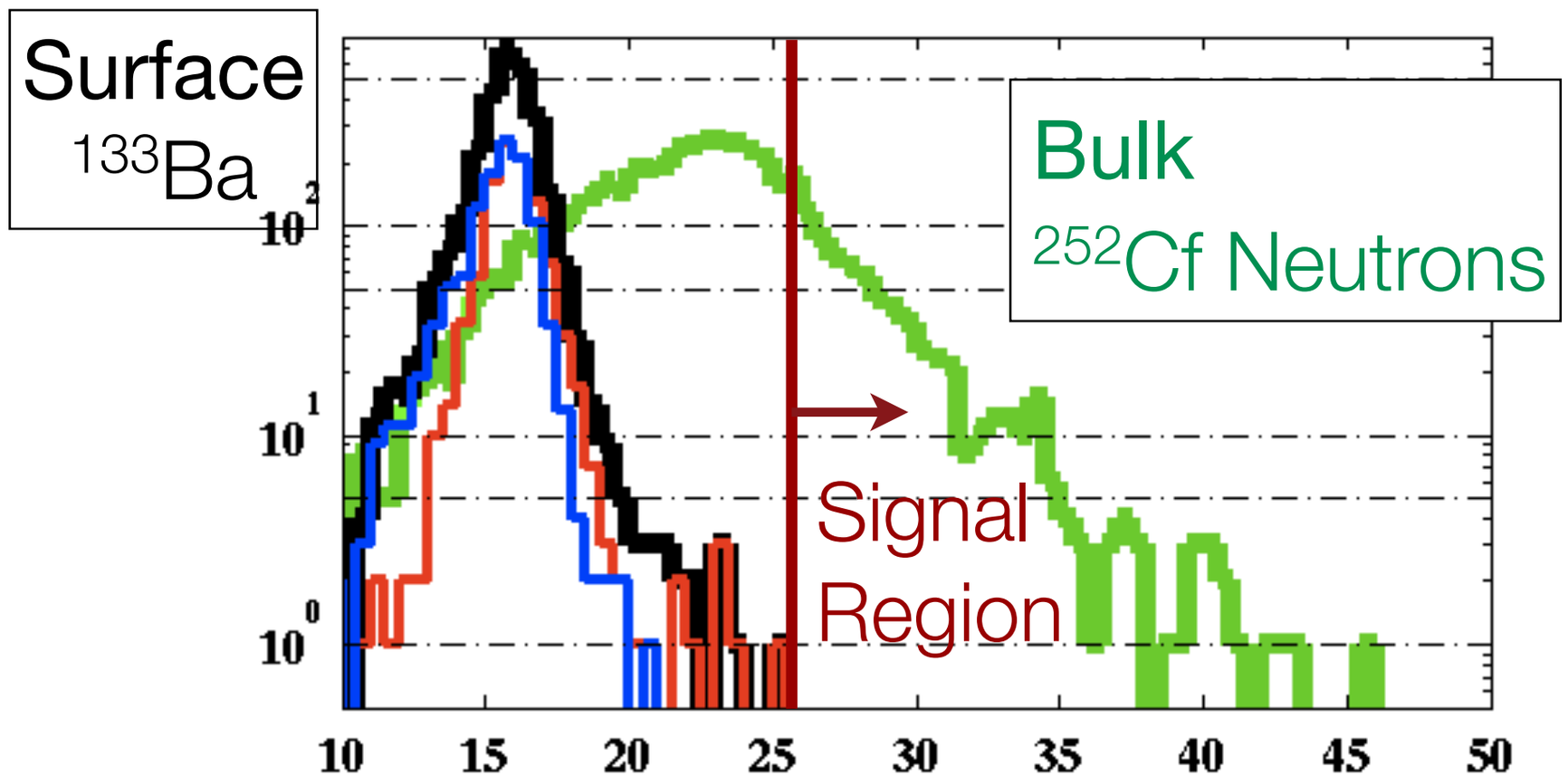
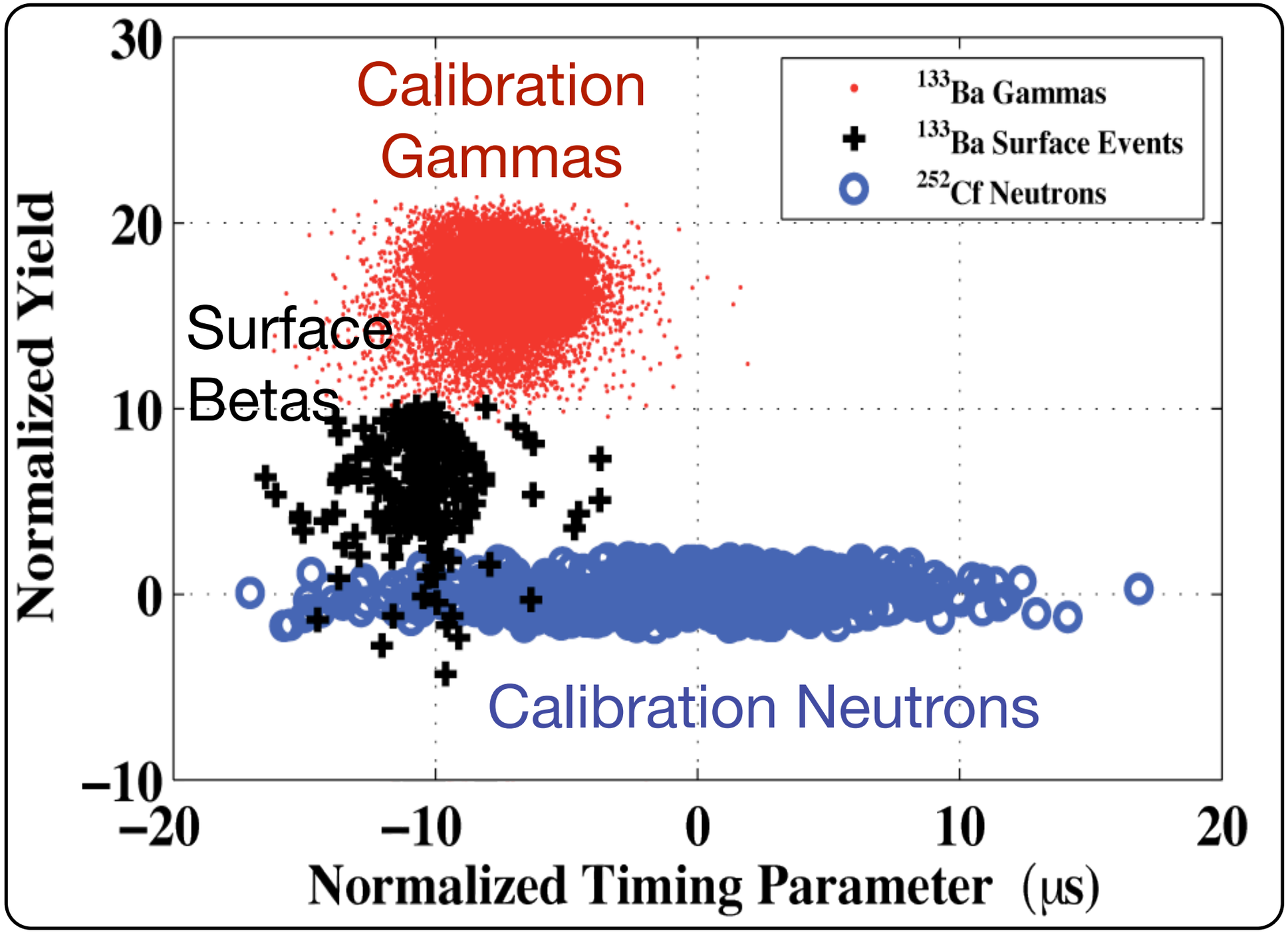




Setting the Signal Region



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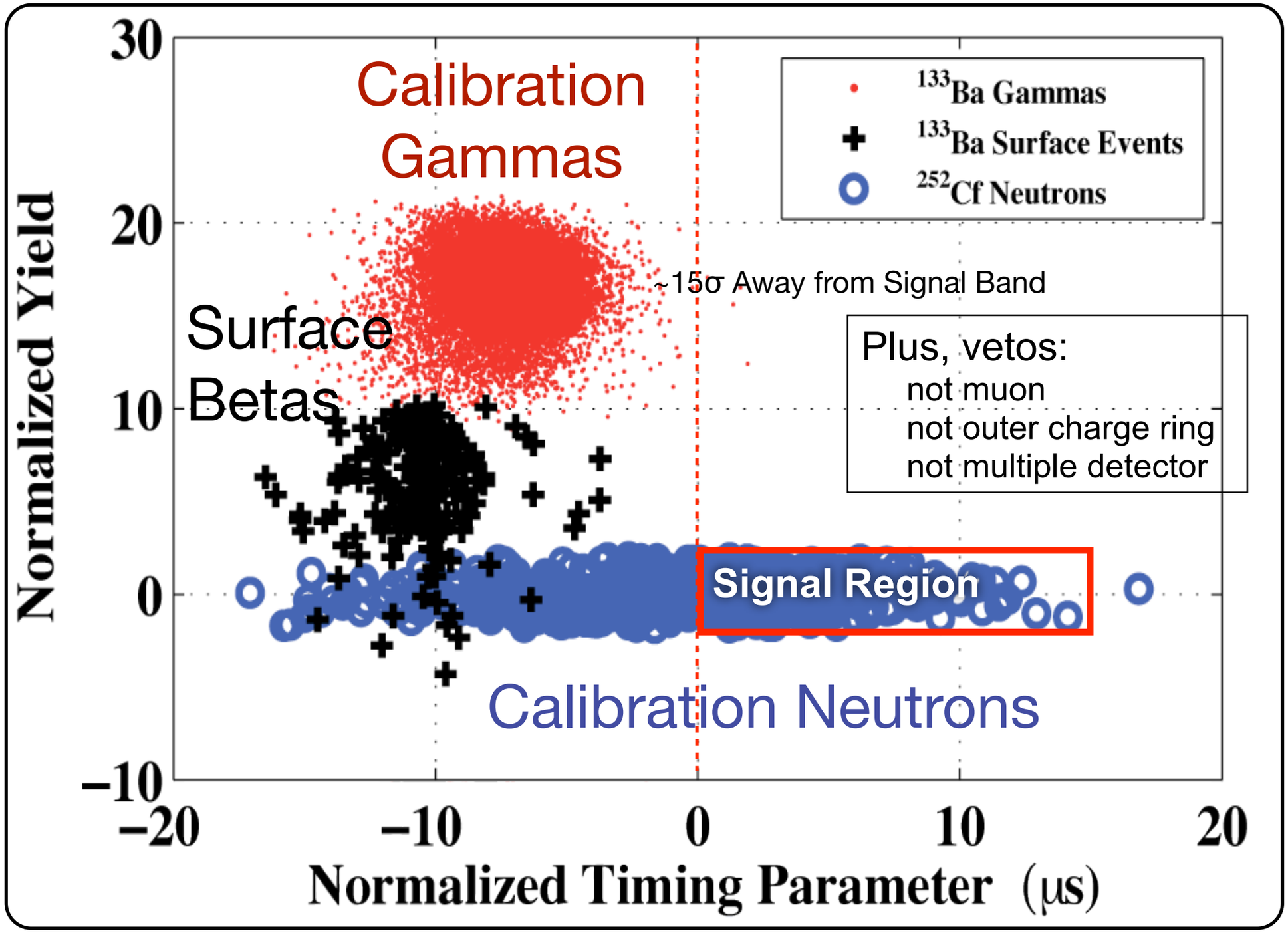
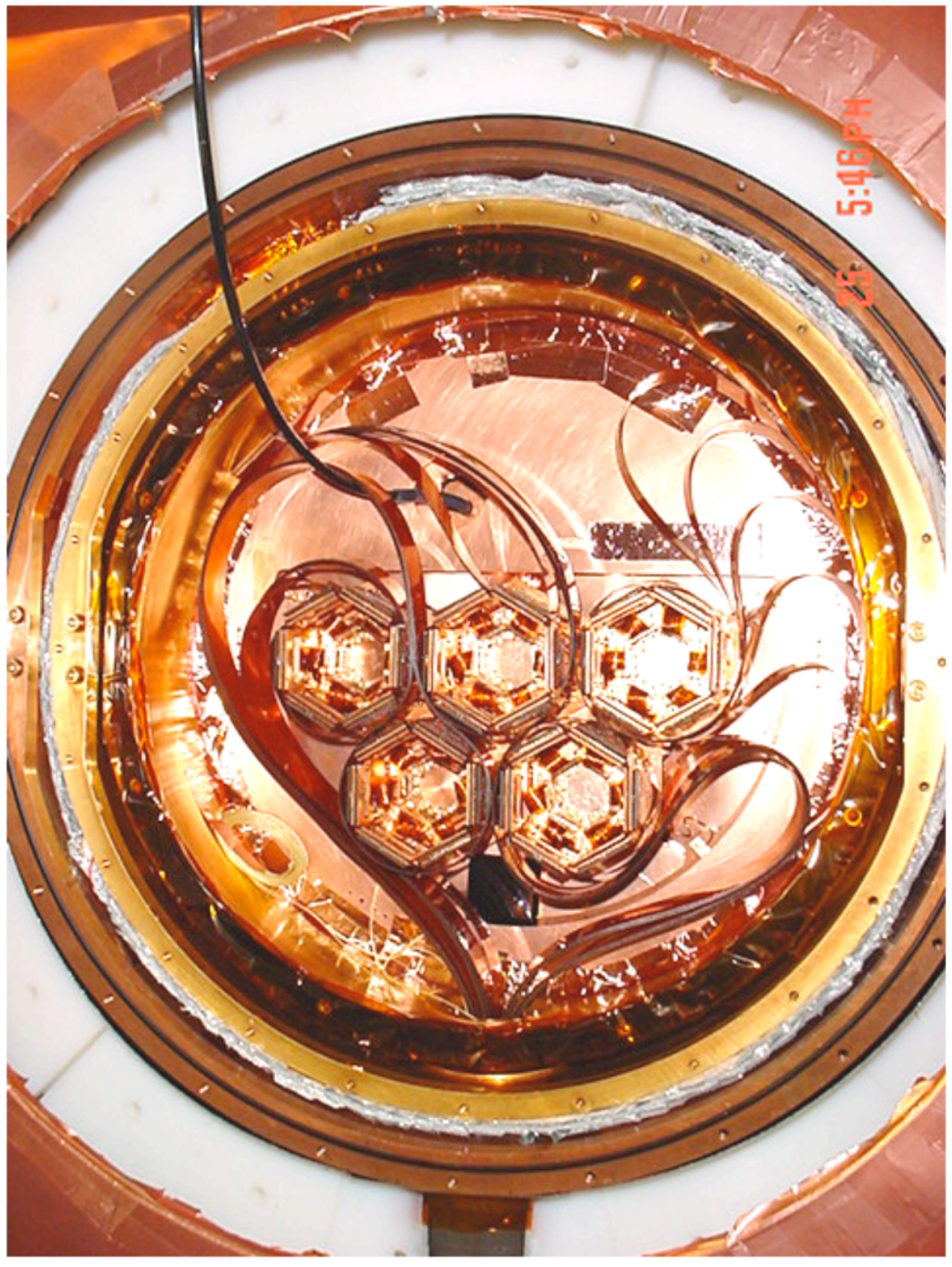
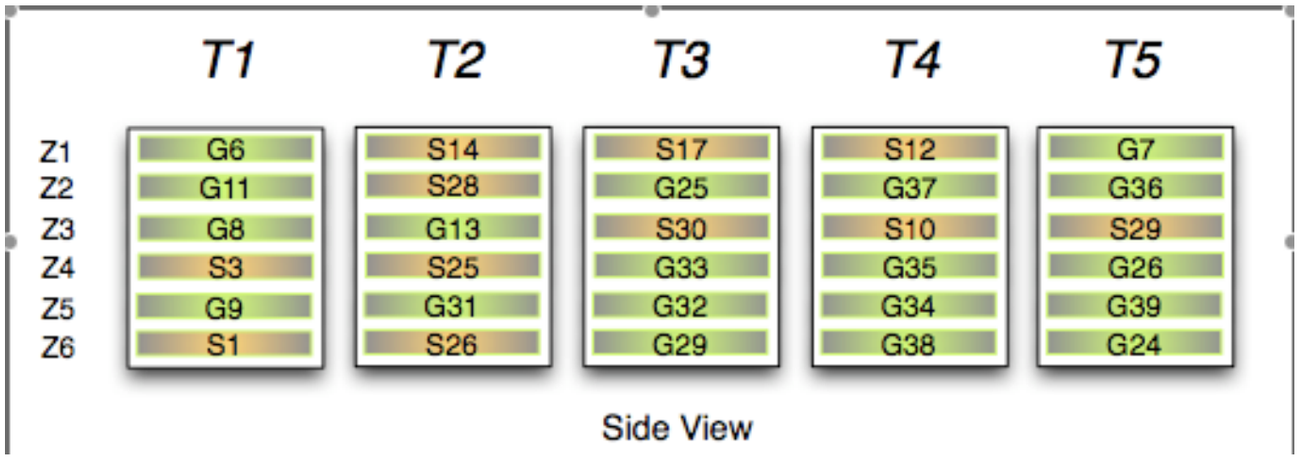


CDMS II (2006-2008)



30 detectors (5 Towers) installed in Soudan icebox:
4.4 kg Ge, 1.1 kg Si



Combination of Ge and Si Detectors

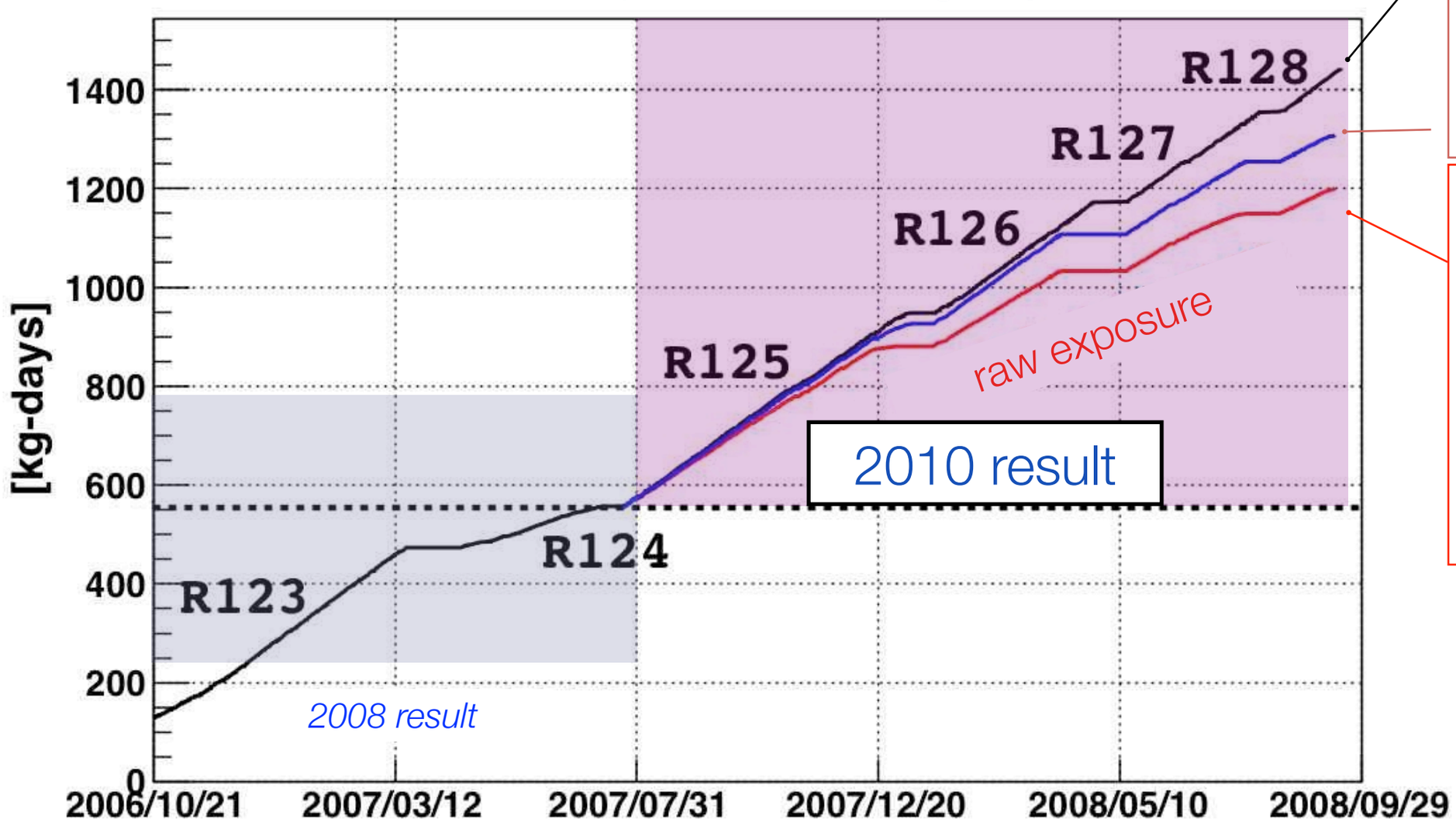
- Neutron background measurement
- WIMP Mass Measurement
- Ge more sensitive to higher mass WIMPs, Si to lower mass WIMPs

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

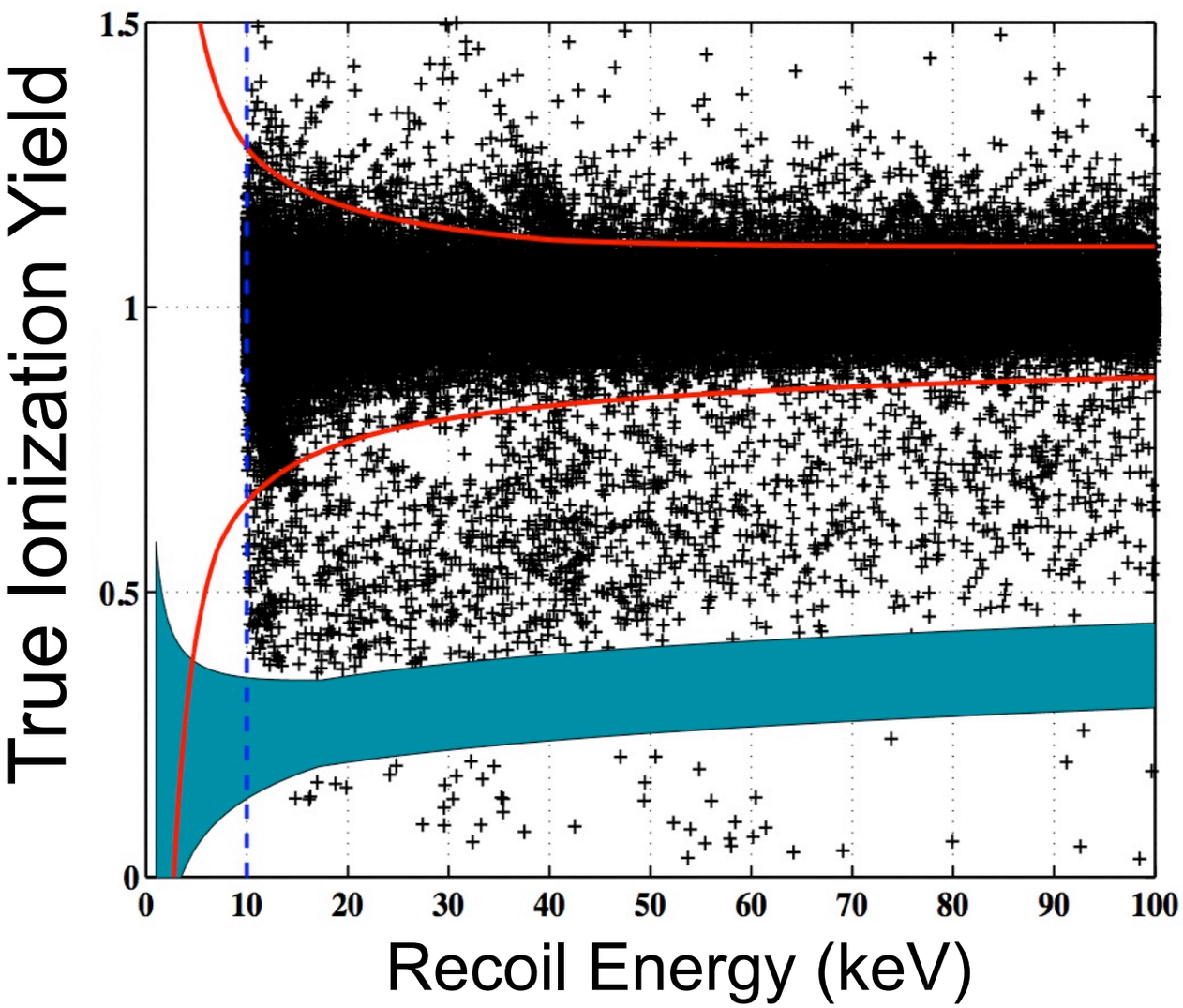
Data taken from 9/08-3/09: primarily an engineering run

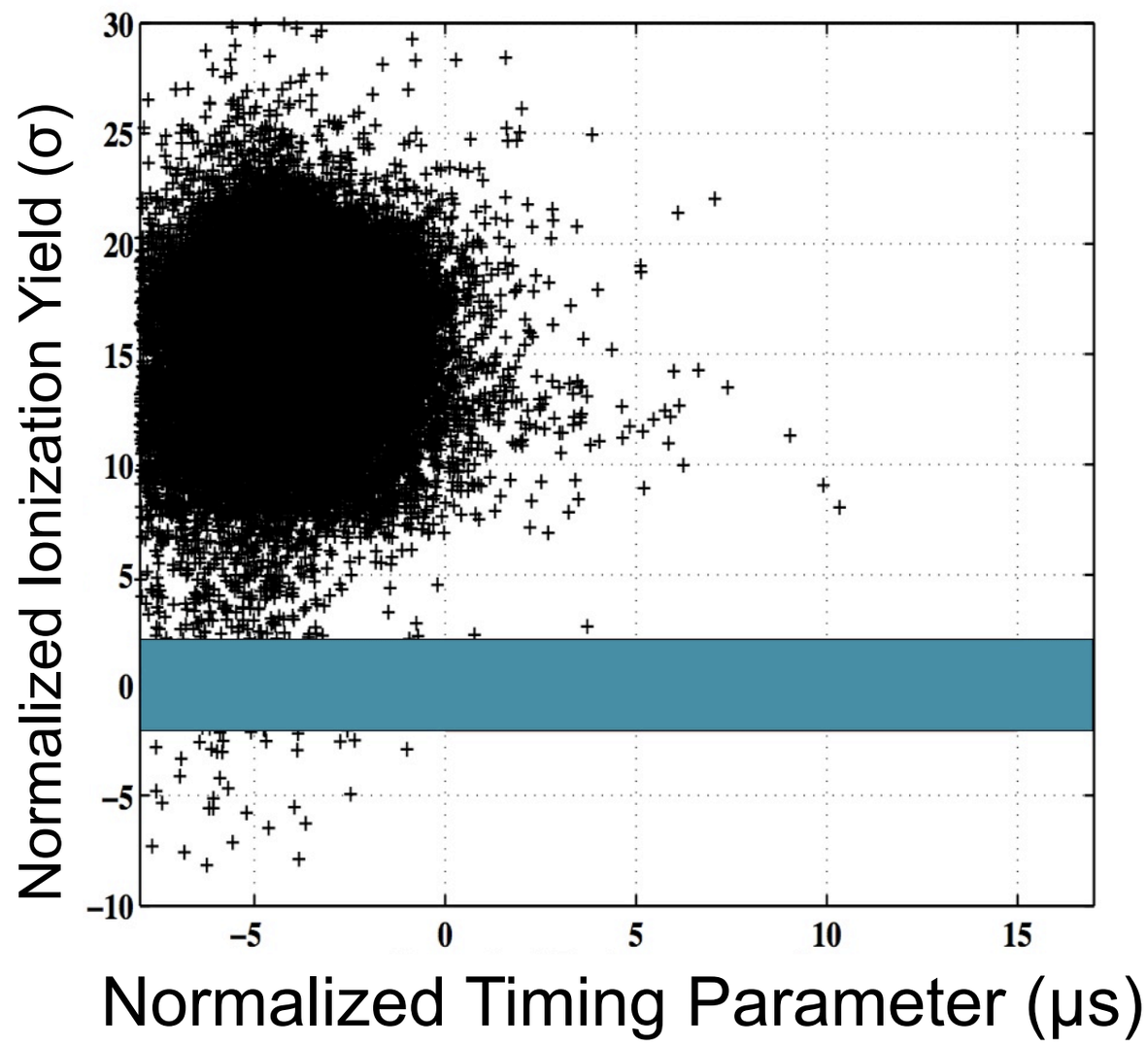
Background Estimate

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

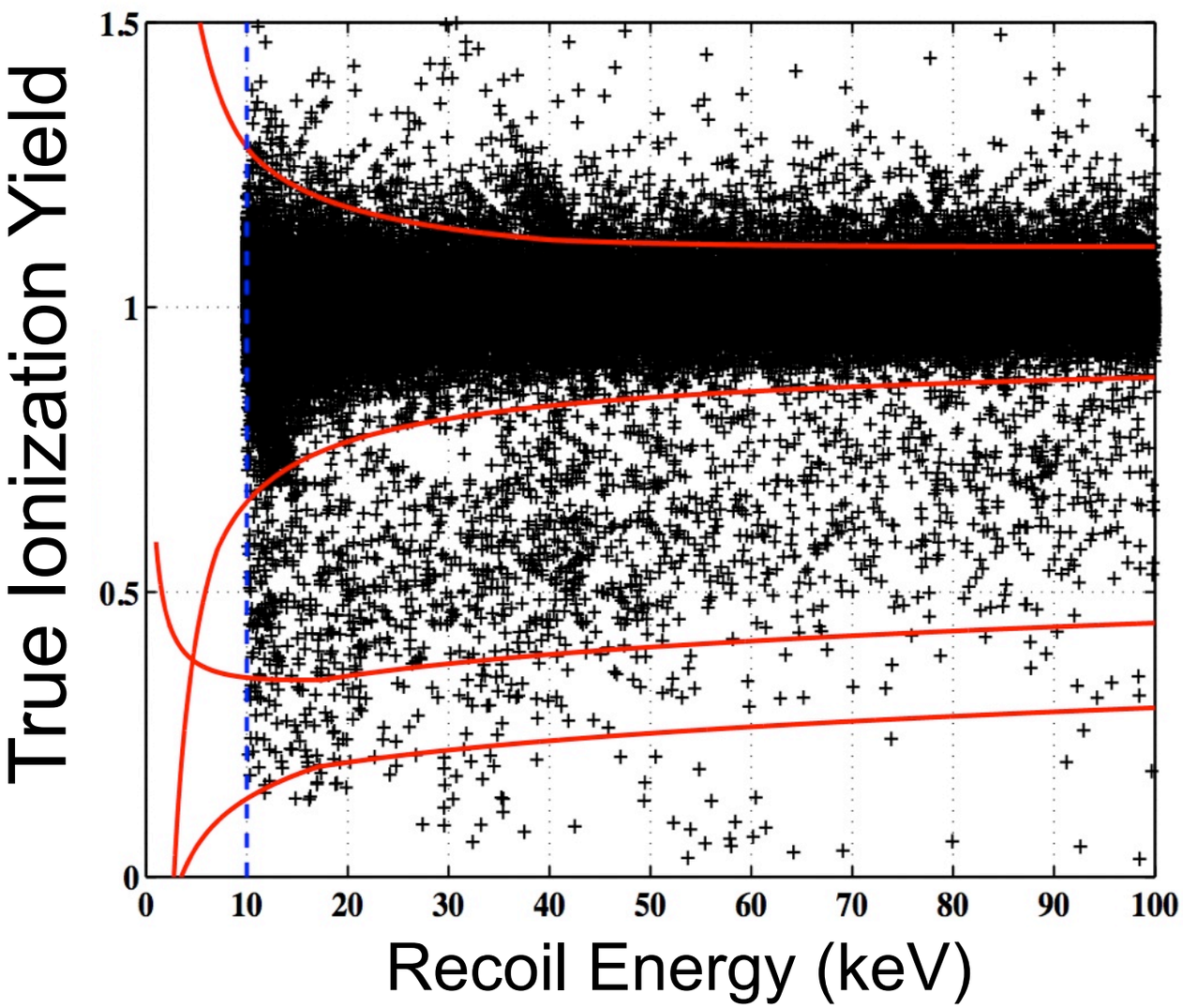
BLINDED:

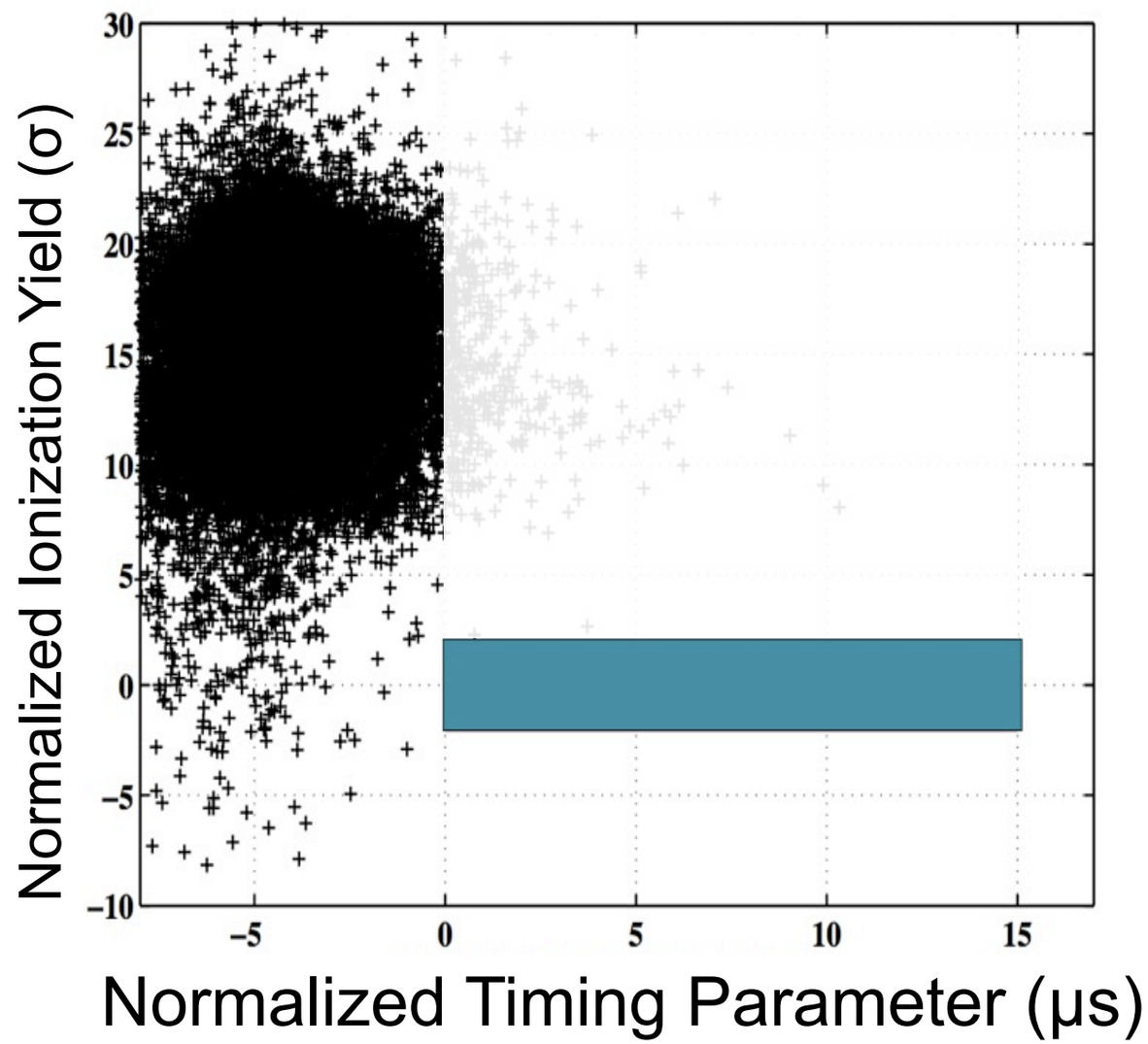




Opening the Box

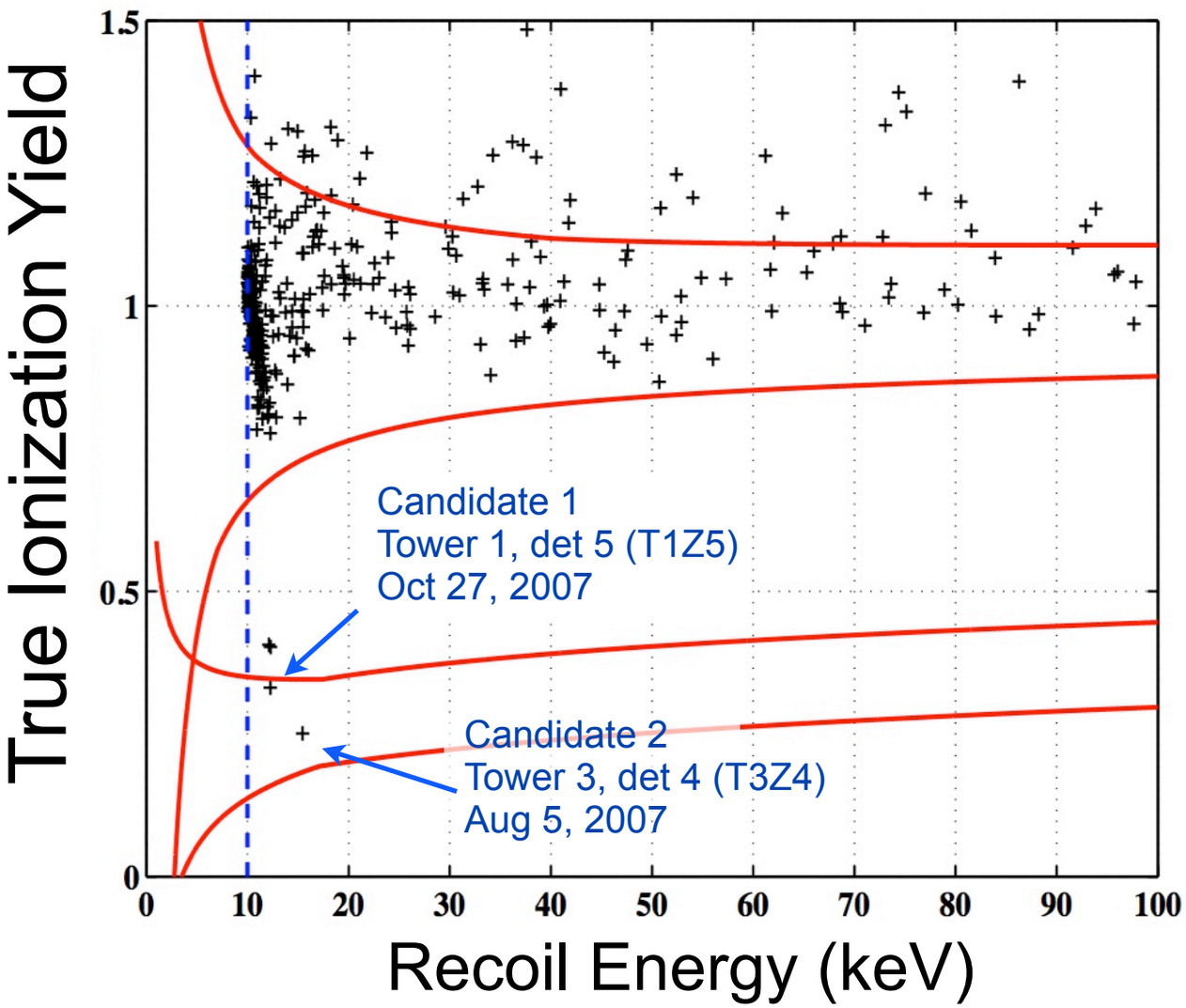
FAIL TIMING CUT:



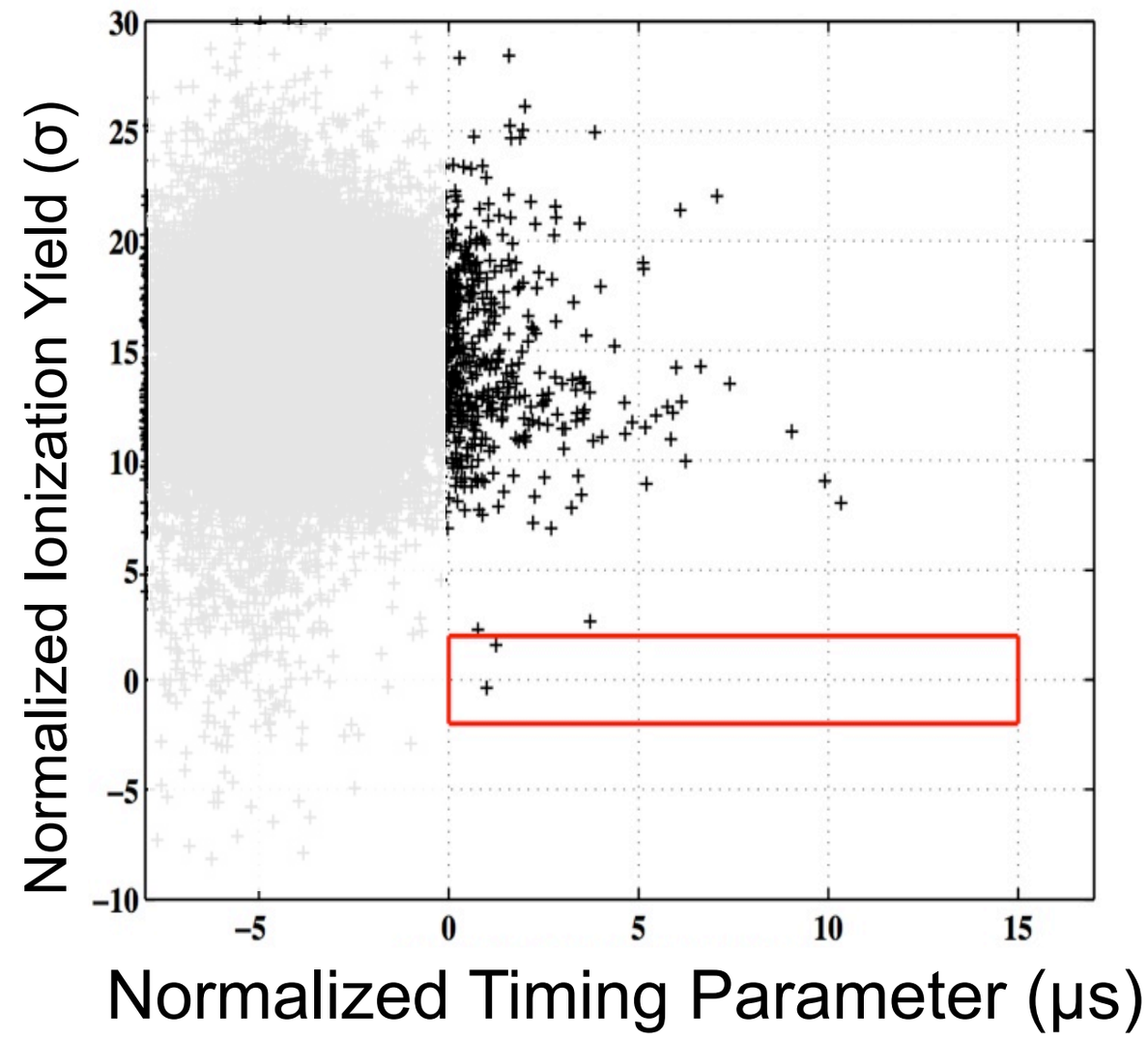


150 events in the NR band fail the timing cut, consistency checks deemed ok

Opening the Box



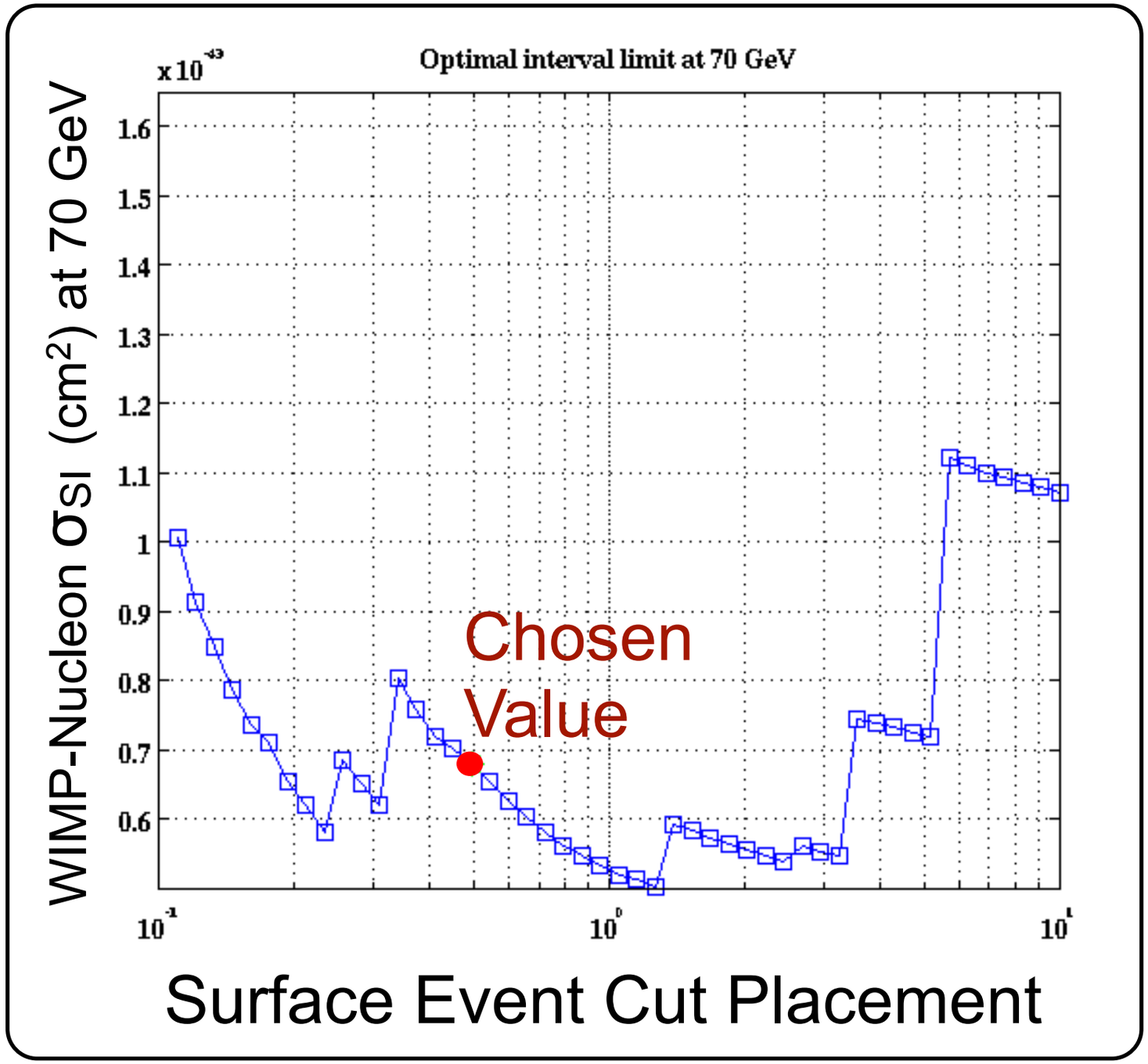
Two Events!



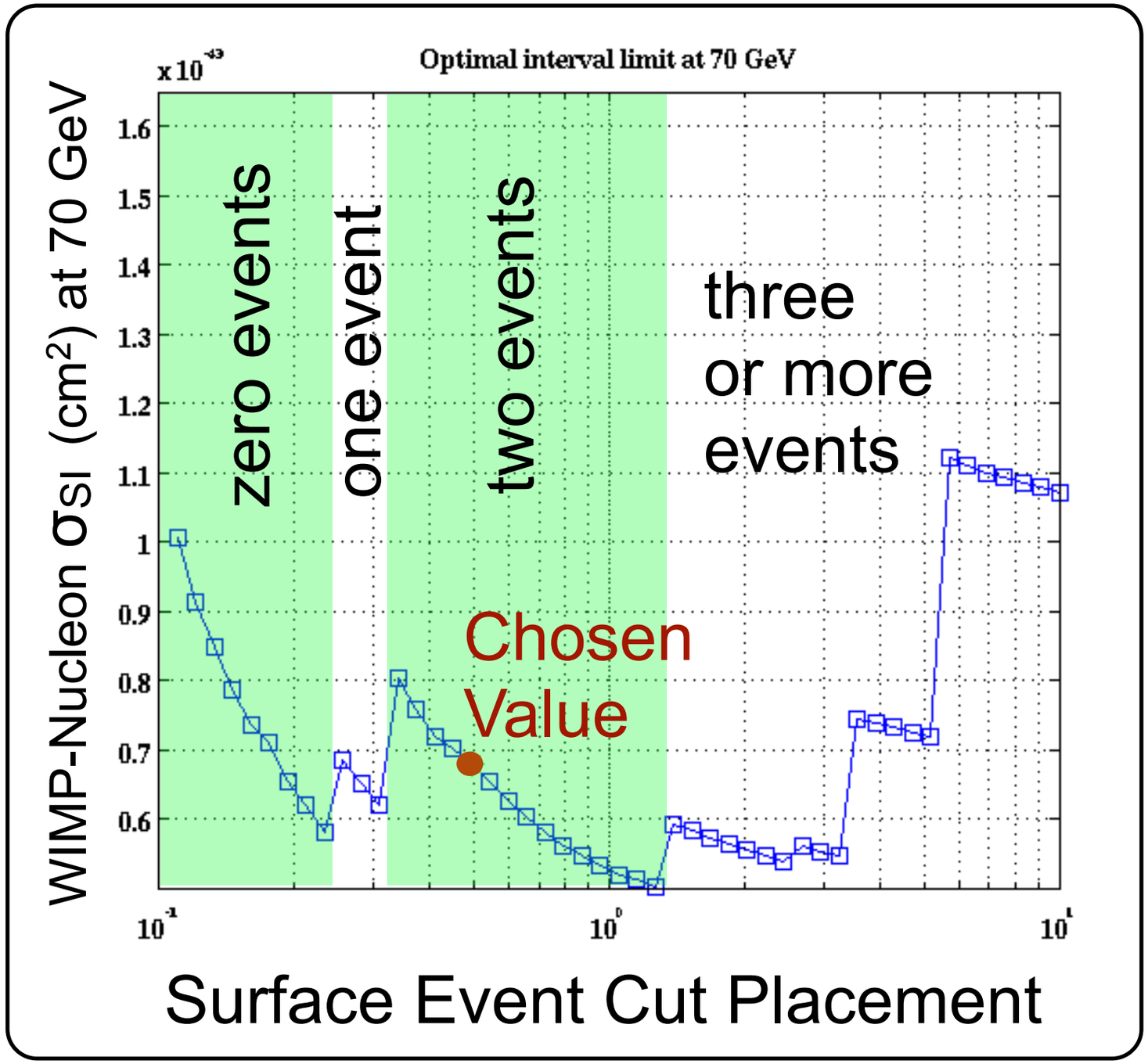
Movie Time

Post-Unblinding Analysis

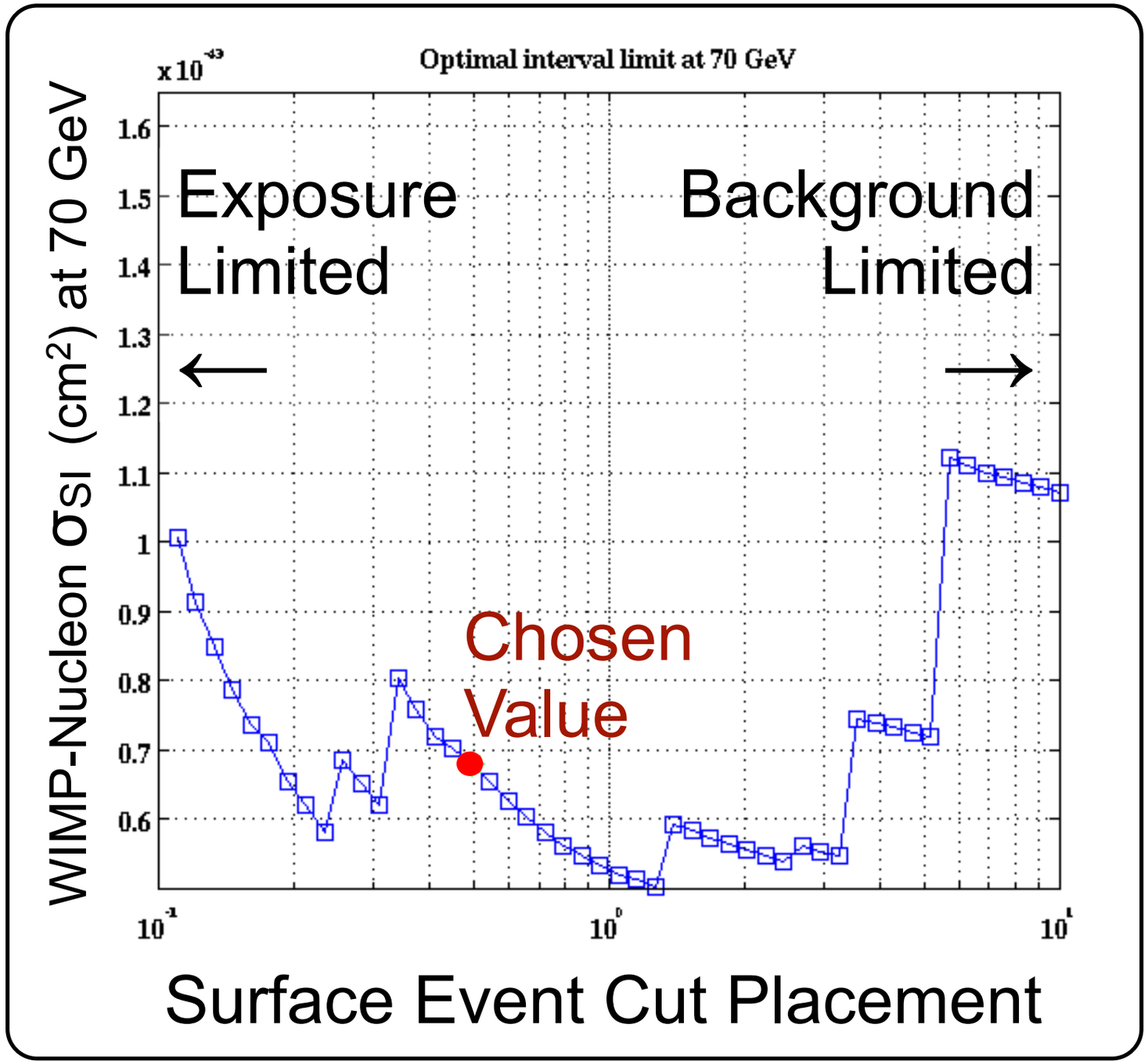
Post-Unblinding Analysis



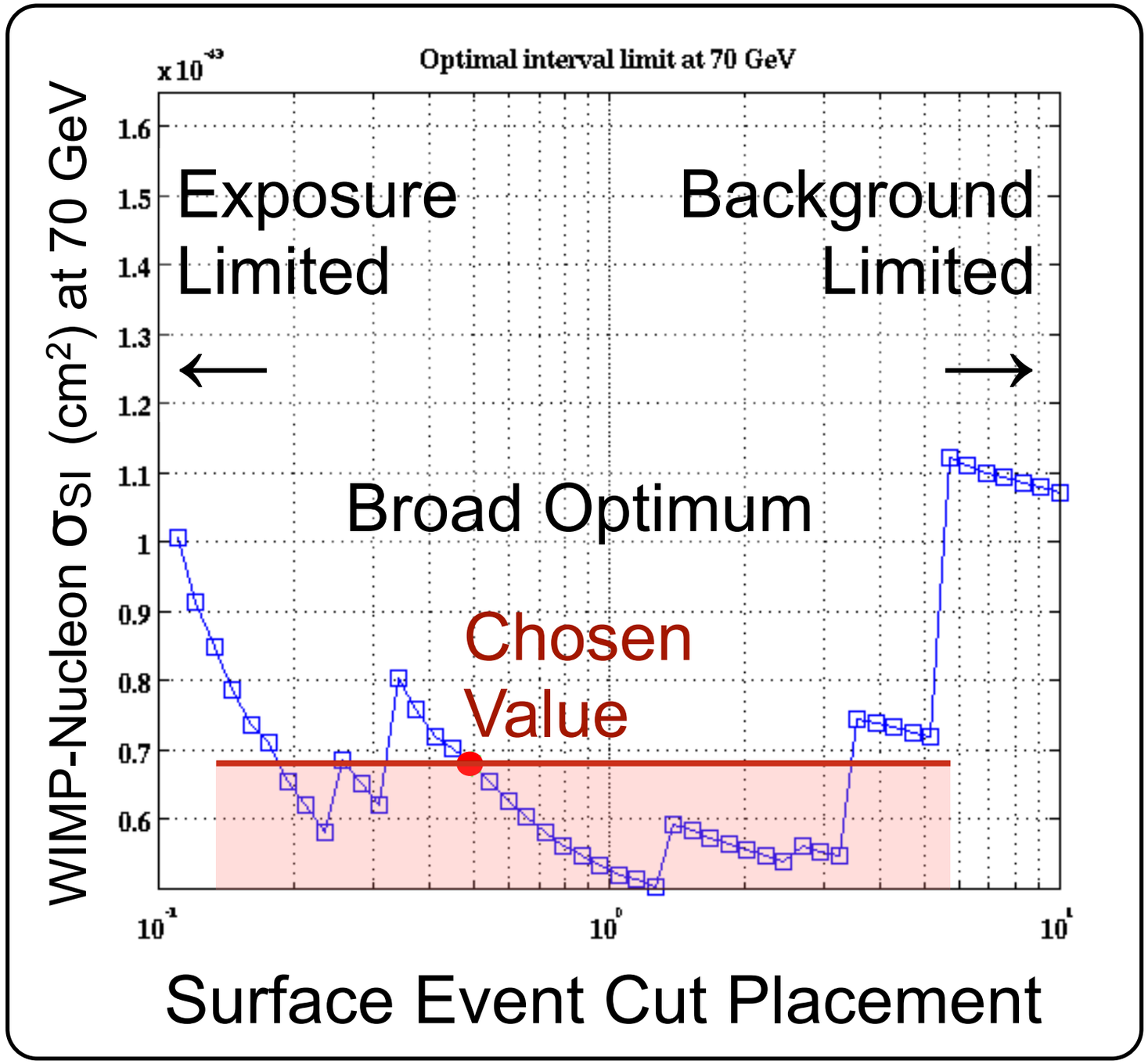
Post-Unblinding Analysis



Post-Unblinding Analysis



Post-Unblinding Analysis



SuperCDMS phases - Moore's Law if zero bkgd

No background subtraction
Background subtraction
No background

WIMP mass = 60 GeV/c^2

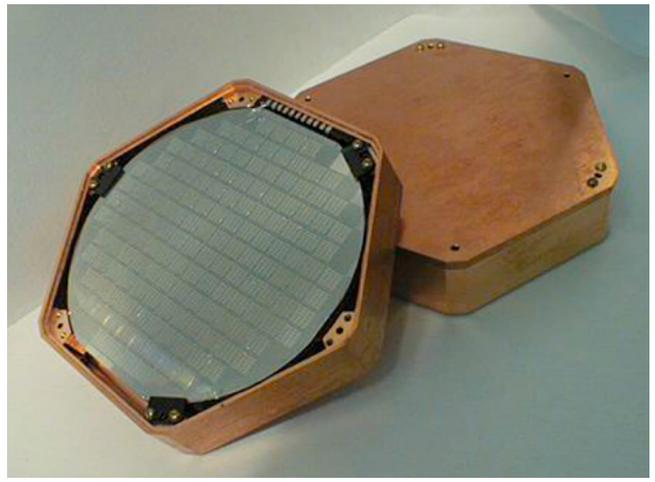
← Tower 1
← Tower 1–2
← CDMSII Feb 2008
← CDMSII Dec 2009

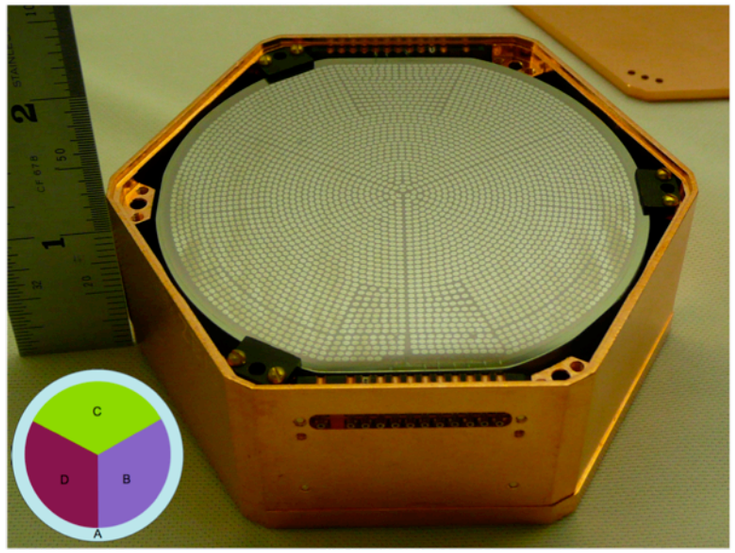
4 kg
CDMS II
15 kg
SuperCDMS Soudan
150 kg
SuperCDMS SNOLAB

Cross section on nucleon (cm^2) 90% CL

Number of events/kg/day

Raw Exposure MT kg days





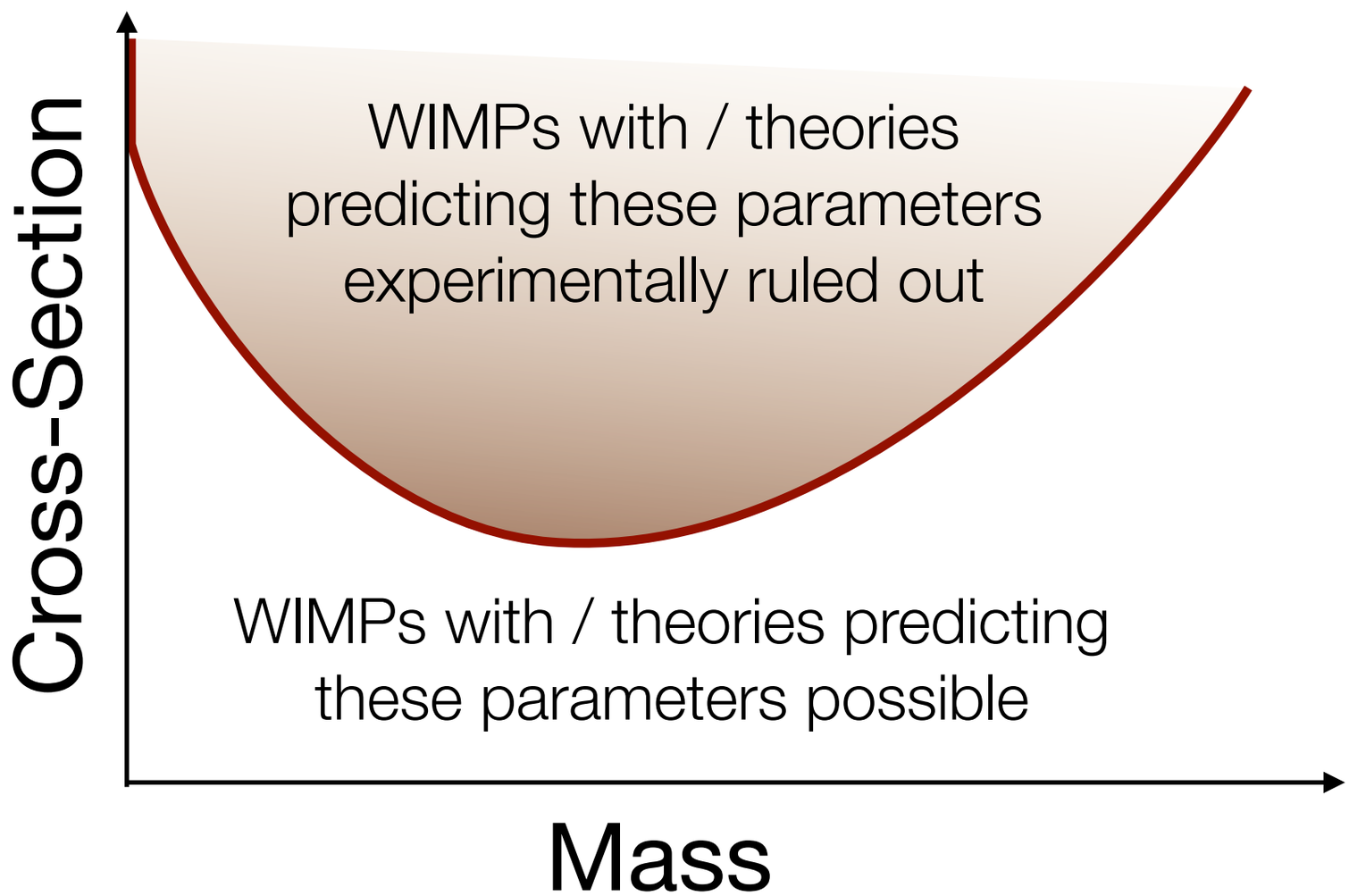
See e.g. 'Background Penalty Factor', Scott Dodelson arXiv 0812.0787v2

GEODM

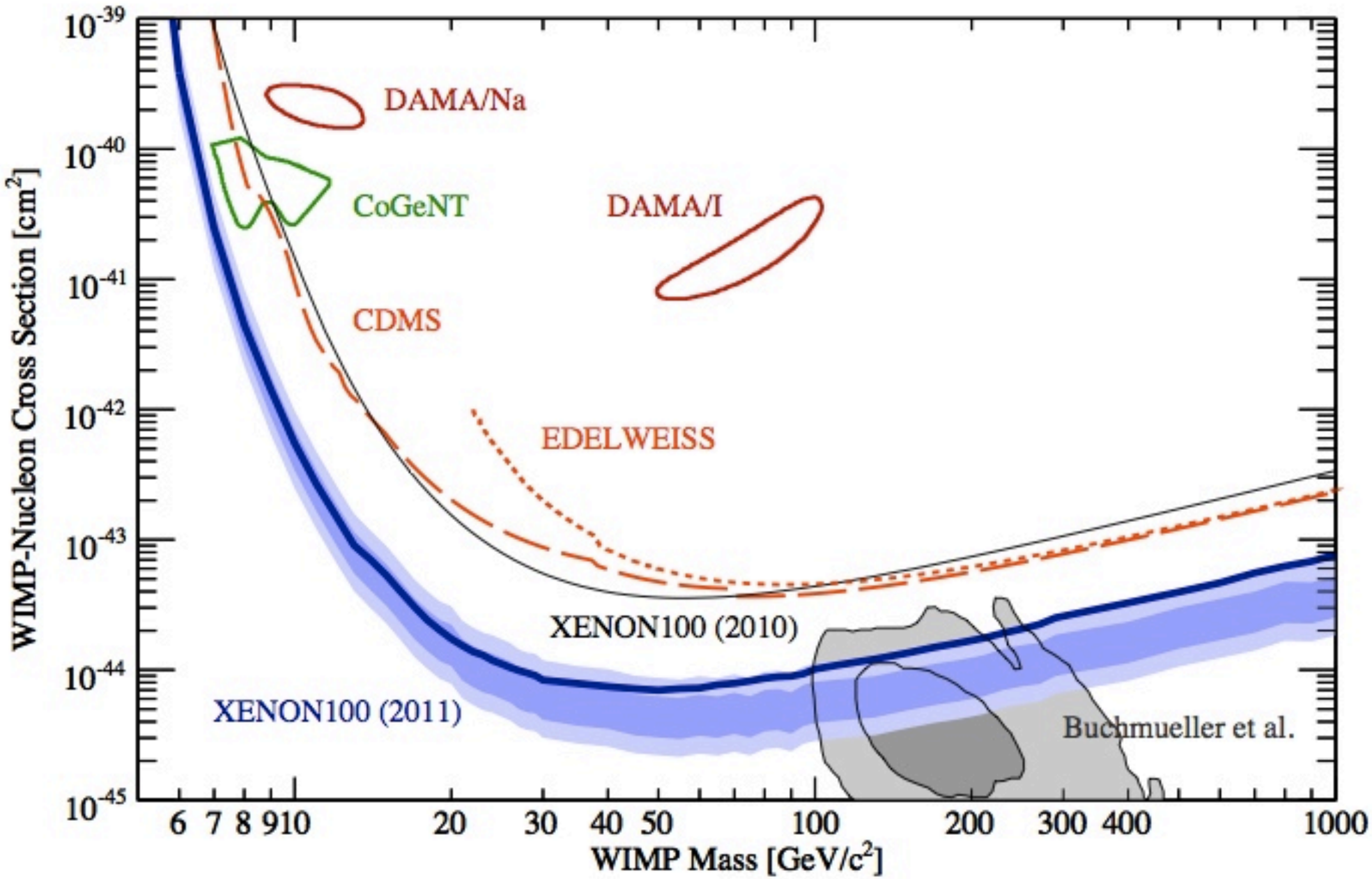
Experimental Limits

WIMP exclusion plots

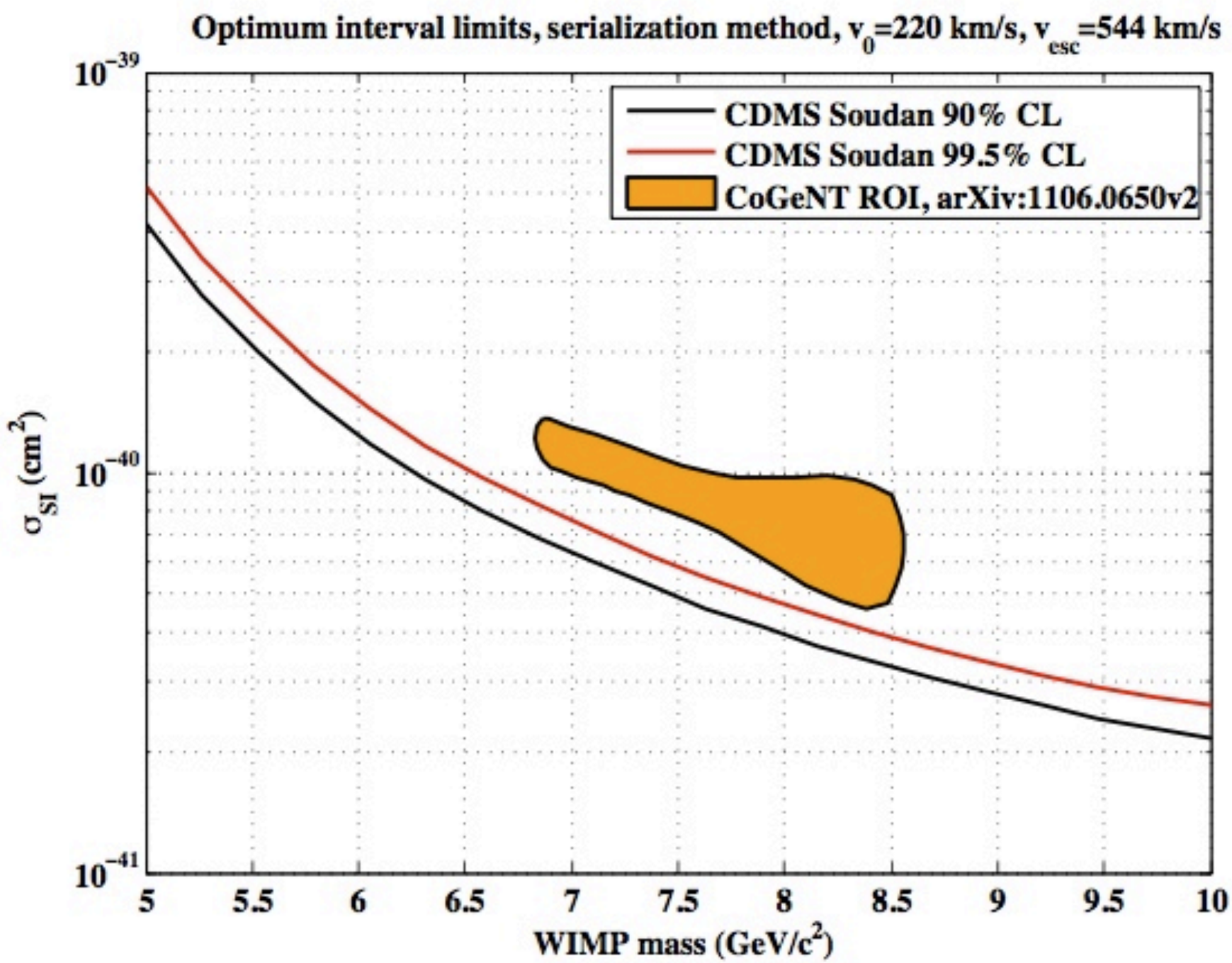
- Two WIMP parameters experimentally determined by direct detection searches : M_χ, $\sigma_{\chi\text{-}N}$



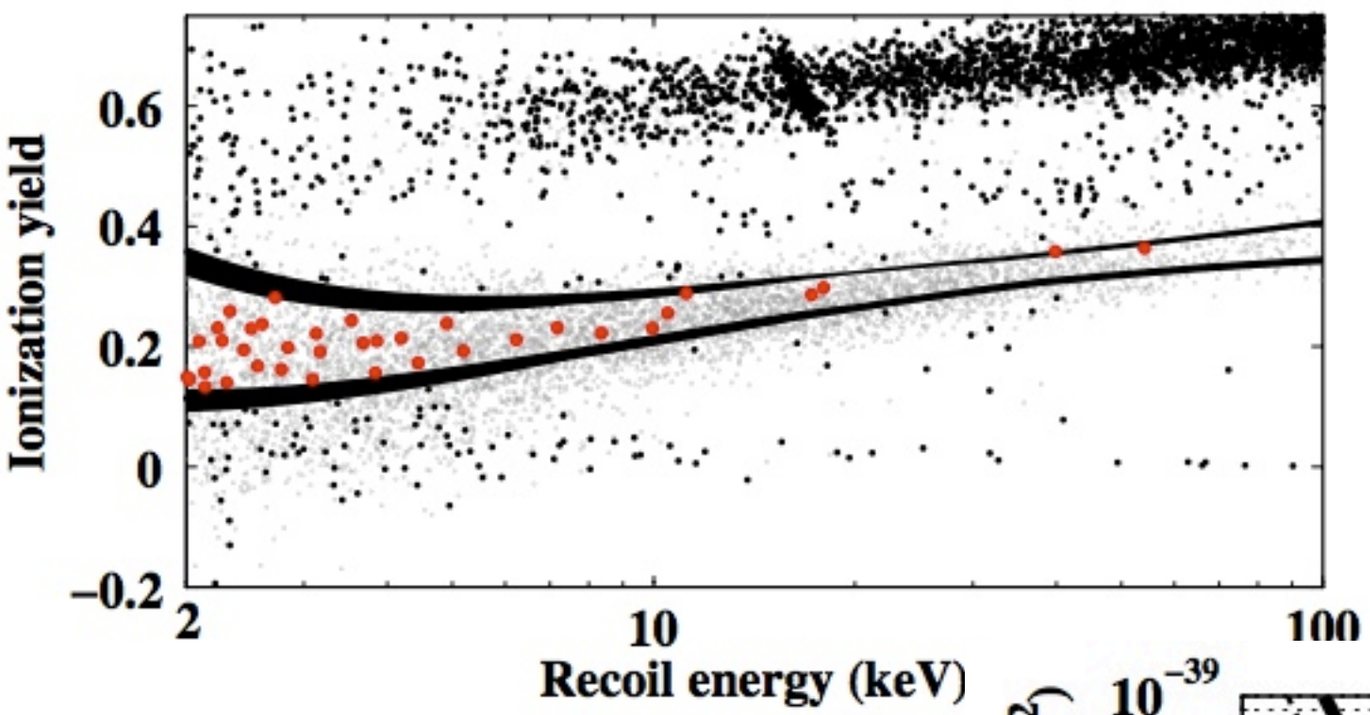
Spin-Independent Limits

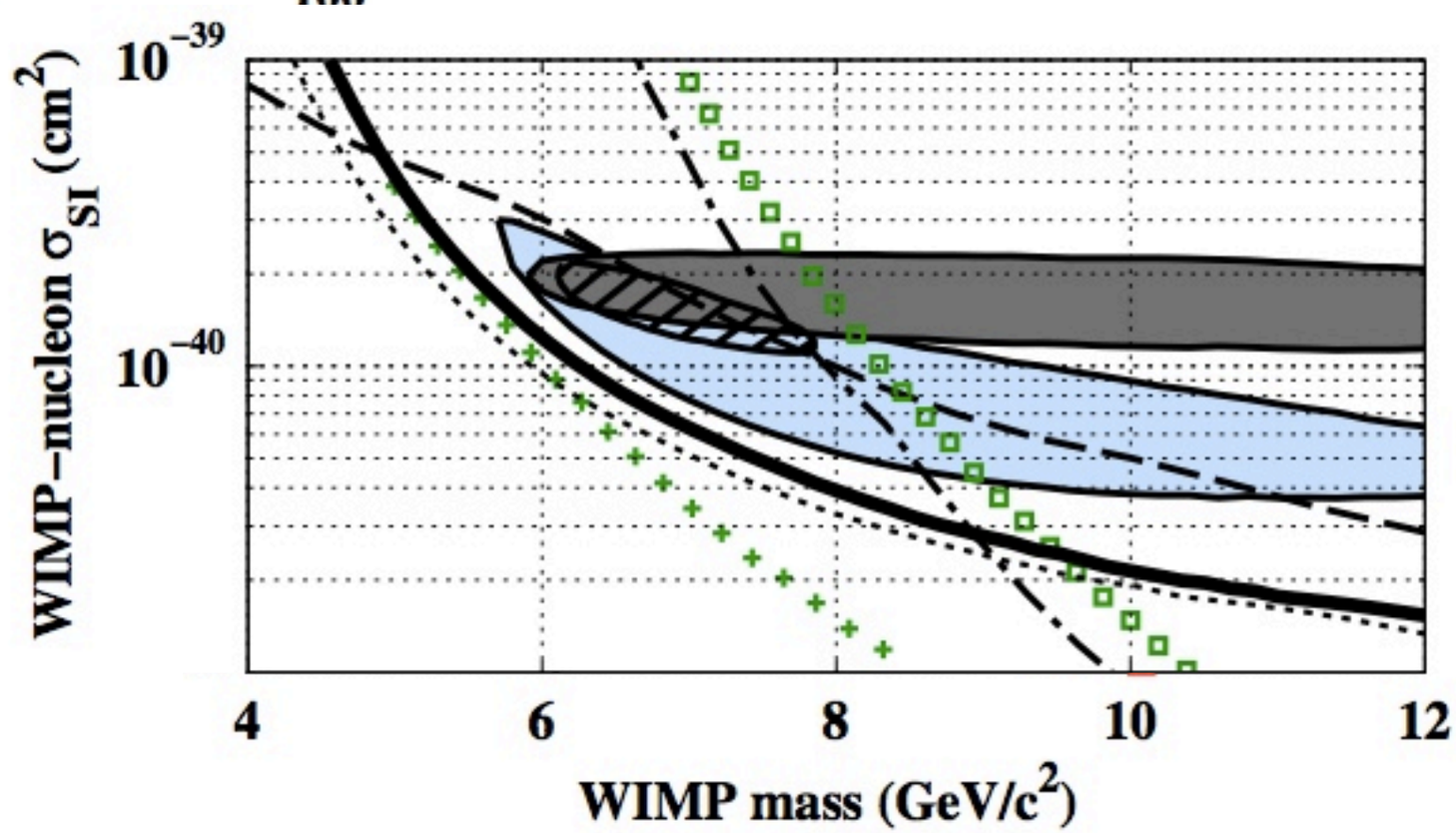


Spin-Independent Limits



Spin-Independent Limits: Low Energy Analysis

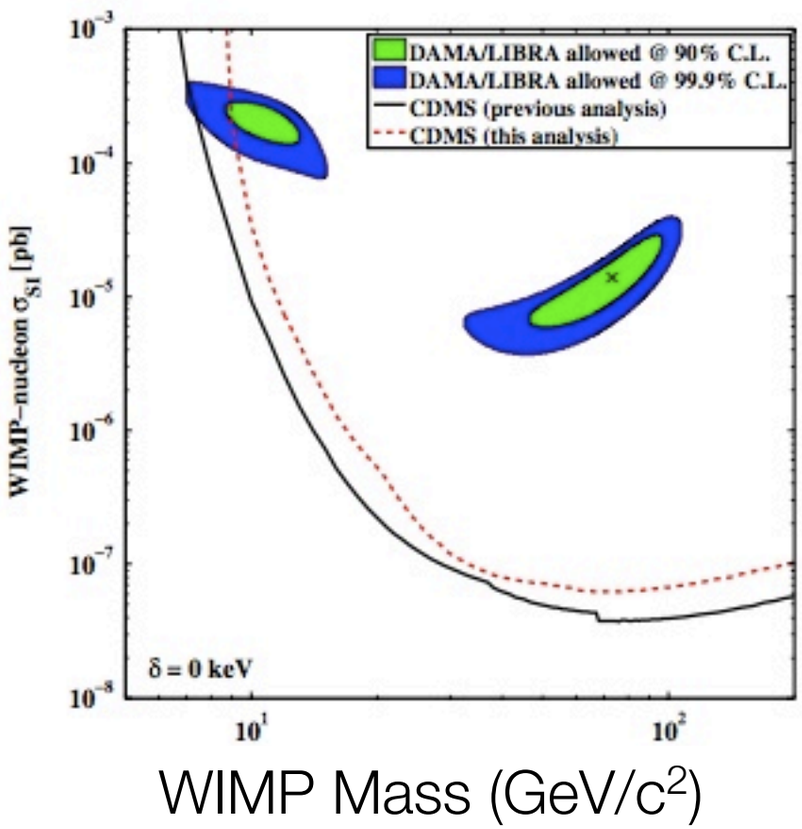




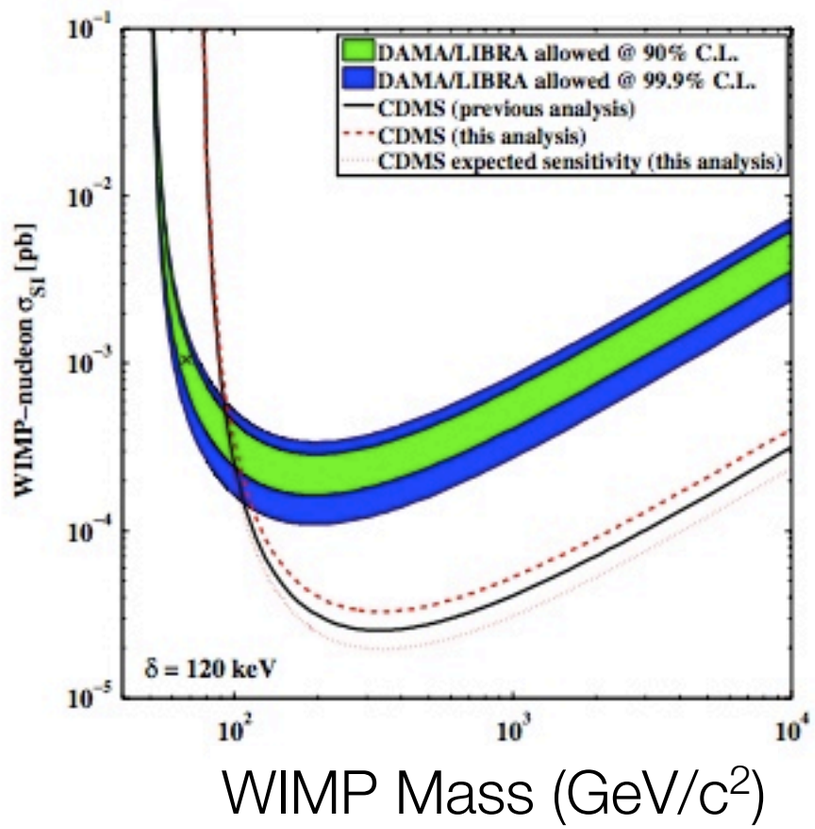
Inelastic Scattering Limits

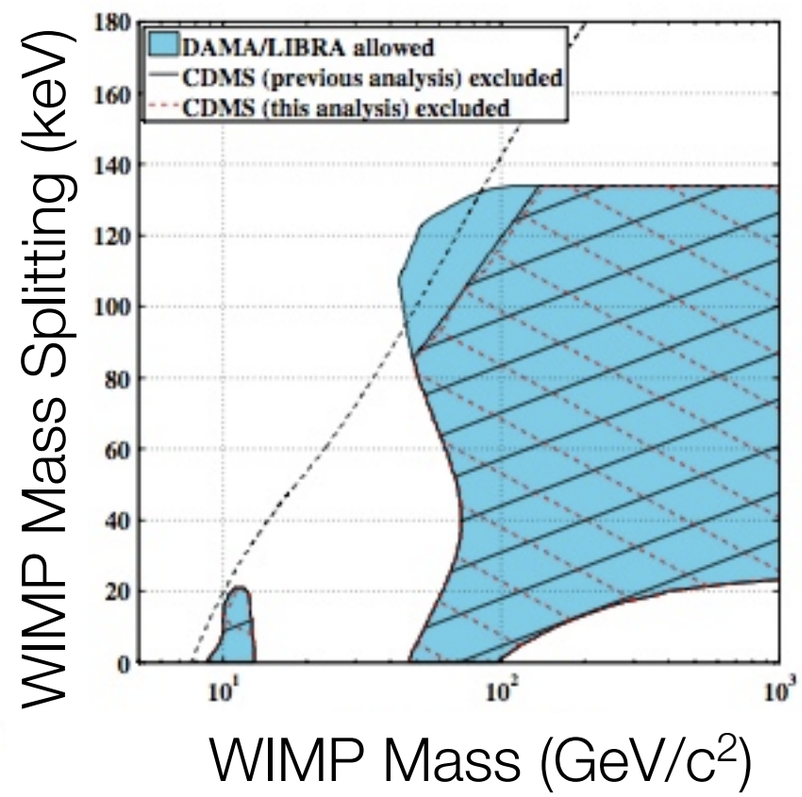
Wimp Mass Splitting:

0 keV = elastic scattering



120 keV





Outline

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

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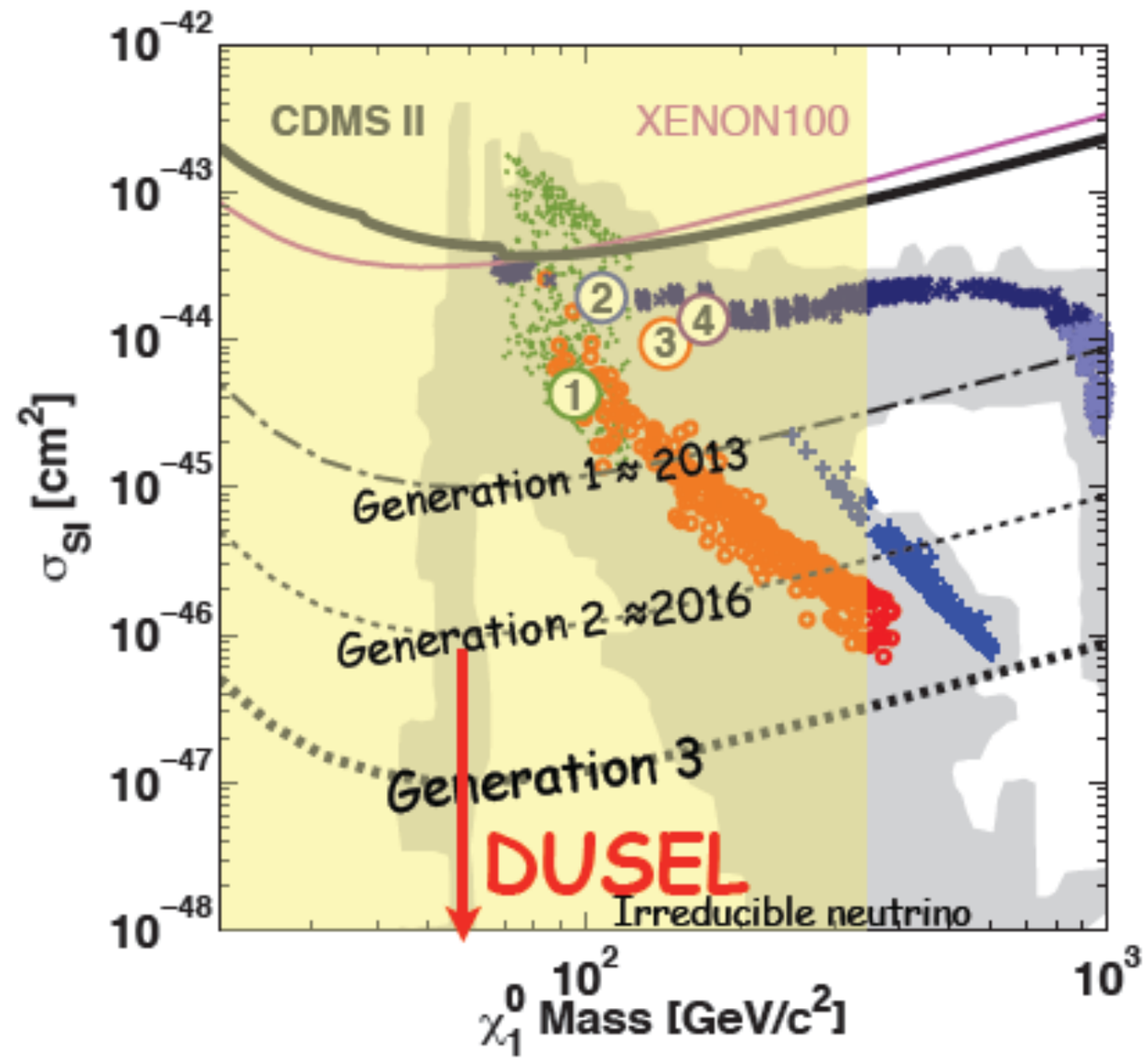
The Future

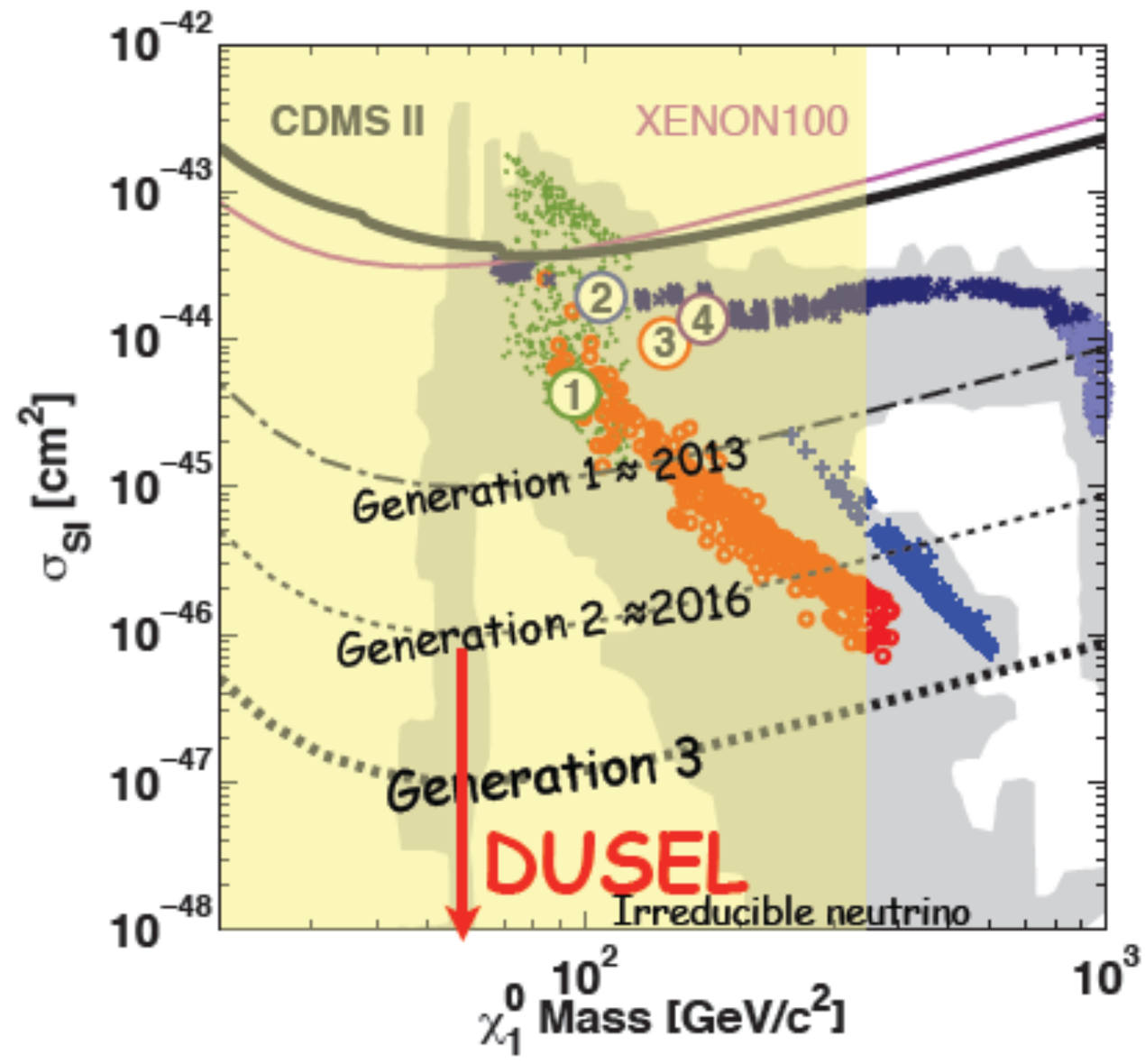
- Next few years will have several experiments probing significant new parameter space.

- 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.



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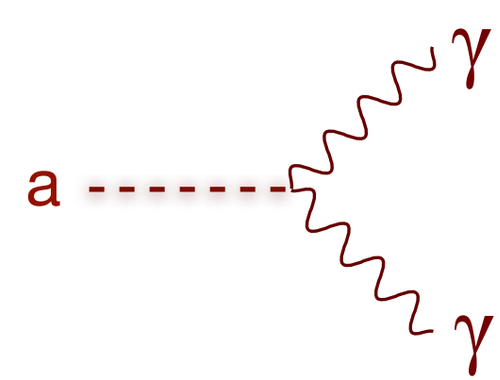
Axions

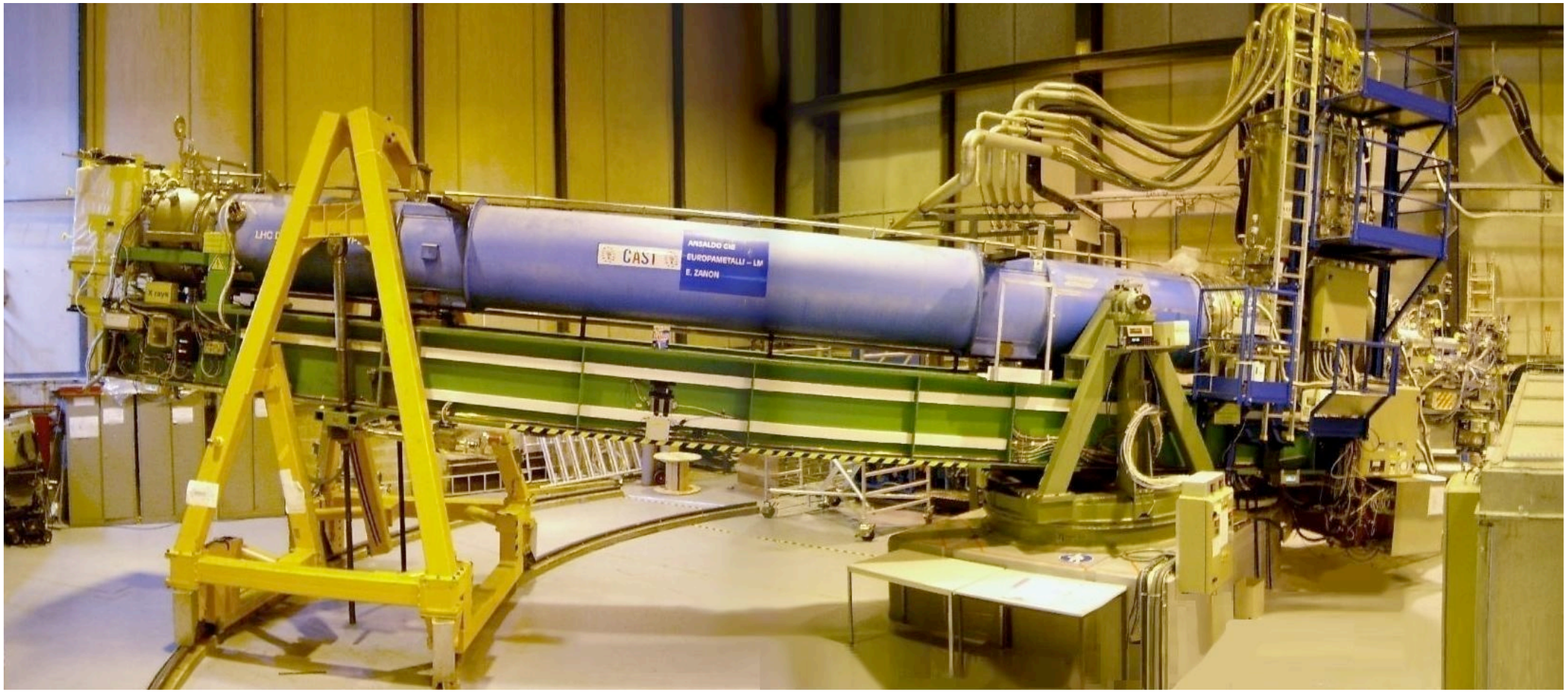
- Other potential type of cold dark matter
  - Recall: the only requirements on Dark Matter is that
    - It is non-baryonic
    - It has mass
    - It was non-relativistic soon after the Big Bang
  - Axions were originally postulated to explain why the strong interactions are invariant under the discrete symmetries P and CP in spite of the fact that the Standard Model as a whole violates those symmetries.
  - Axions can be cold dark matter if their mass is in the μeV-meV range.
  - Can interact via coupling with two photons



Axion Search with Solar Heleoscopes

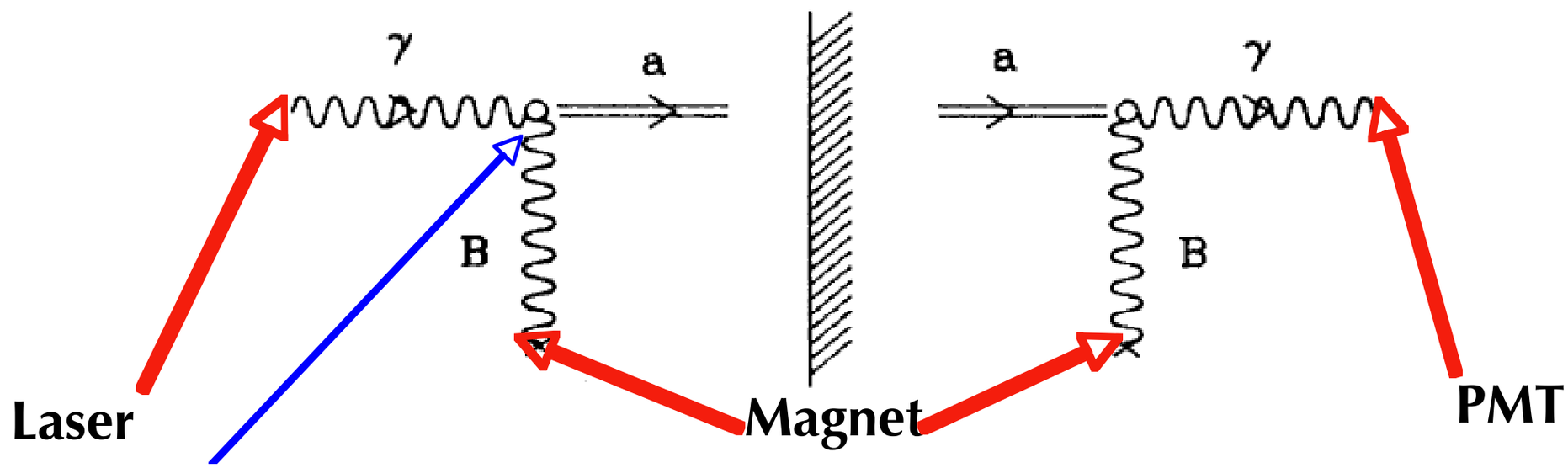
CAST (Cern Axion Solar Telescope)

- New uses for old accelerator parts
  - Uses a decommissioned LHC dipole magnet (8 Tesla) to convert solar axions into detectable x-ray photons
  - Can measures signal / background by pointing at / away from the sun



Shining Light Through Walls

- So far, axion searches have been limited to detecting existing relic axions or thermally produced solar axions
  - What if we can make and detect our own axions?



$$\mathcal{L}_{\rm int} = -\frac{1}{4}\frac{\phi}{M}F_{\mu\nu}\widetilde{F}^{\mu\nu} = \frac{\phi}{M}(\vec{E}\cdot\vec{B})$$

  - Effect is suppressed by $g^2_{a\gamma\gamma}$ but, rate can be enhanced by placing system in a resonant cavity.

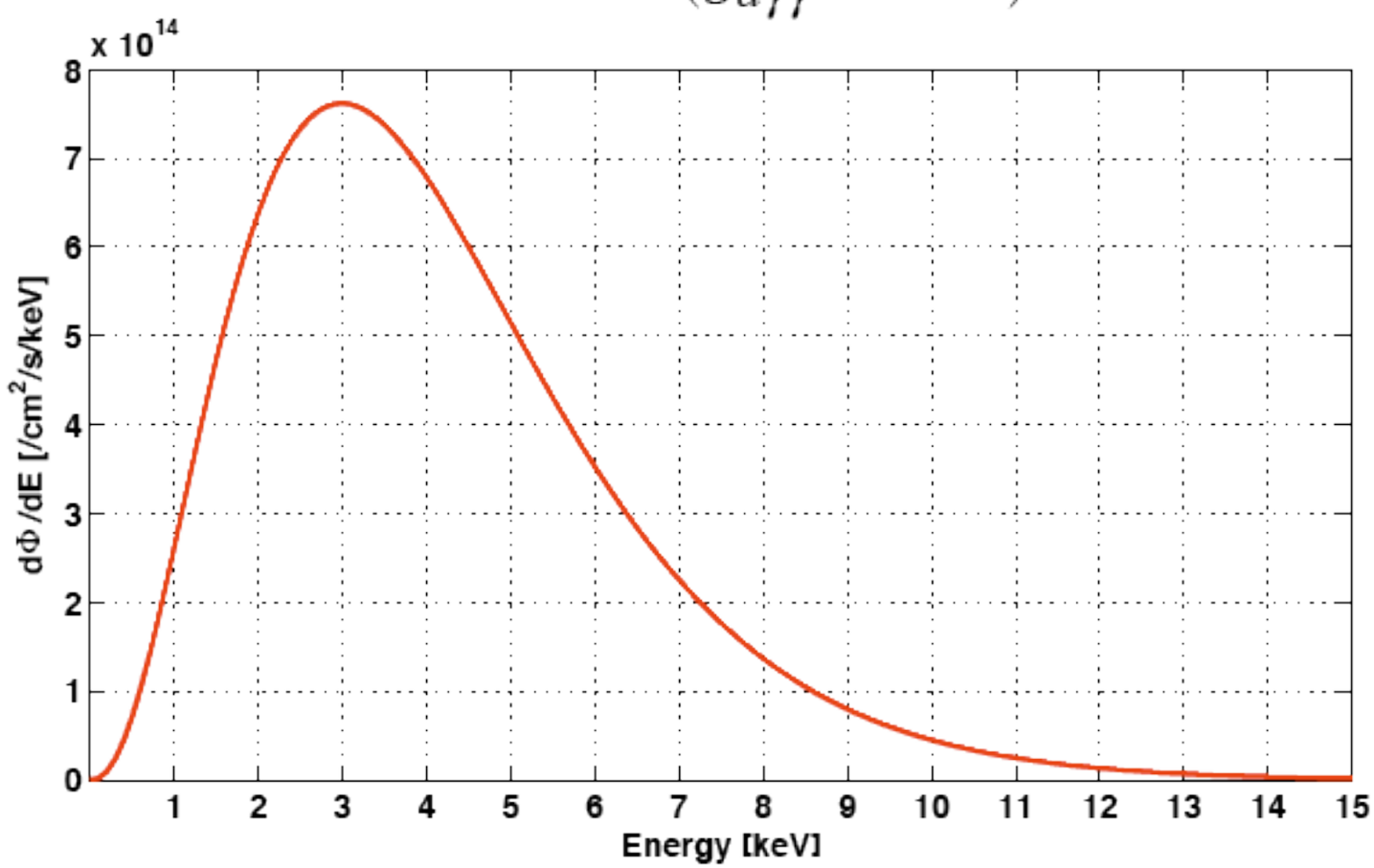
Axion Search with Crystals

Axion Source

- Black body photons convert into axions in the presence of the intense electromagnetic field inside the Sun.
  - The keV scale energy range of the solar interior creates an axion flux on earth given by

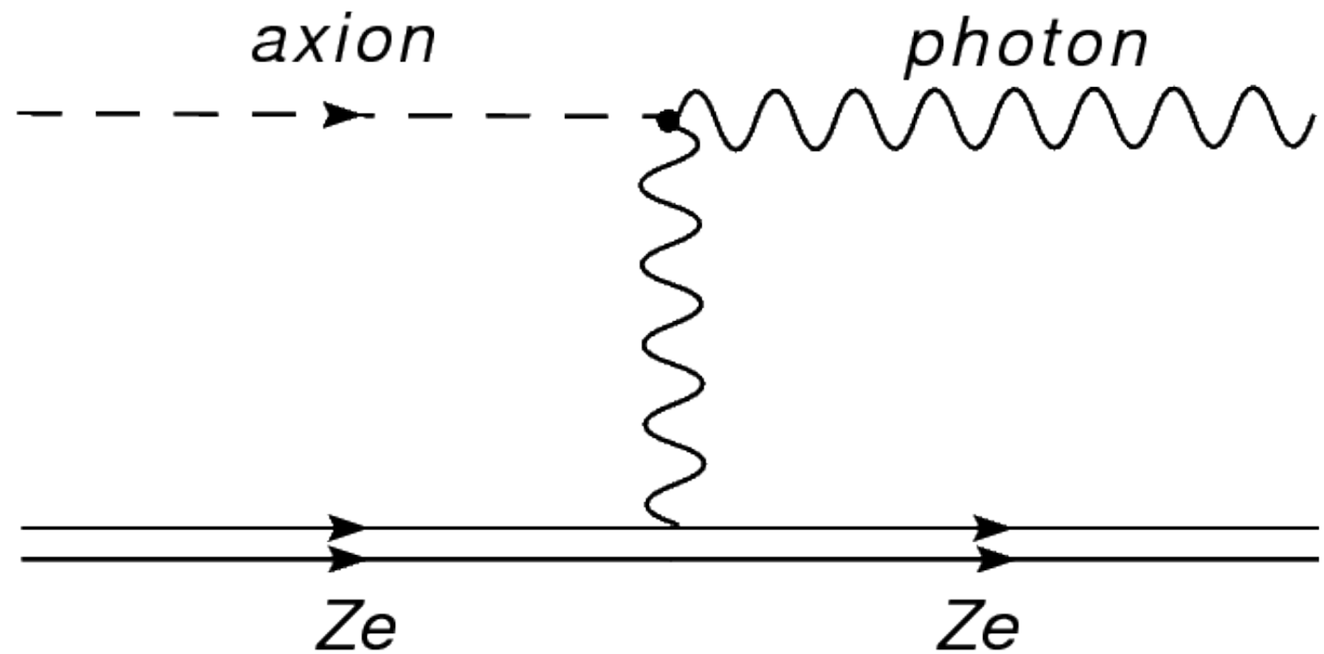
*These are not the relic DM particles, but are the same type of particle being thermally produced

$$\frac{d\Phi}{dE} = 6.02 \times 10^{14} cm^{-2} s^{-1} keV^{-1} (g_{a\gamma\gamma}^2 GeV^{-2}) E^{2.481} e^{-E/1.205}$$



Axion Detection

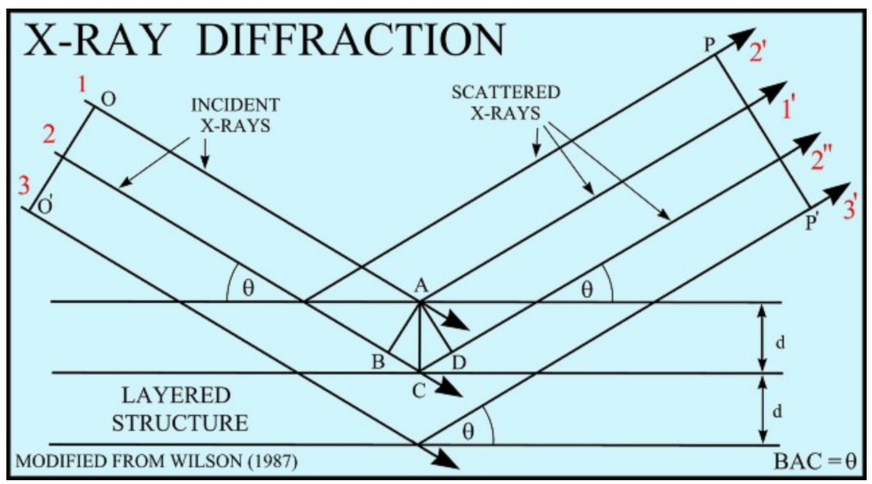
- Conversion of axion into x-rays via the Primakoff effect
  - The axion interacts with a virtual photon from the strong electric field near a nucleus and converts into a real photon
  - The photon will have the energy/momentum of the incoming axion



$$\sigma = \frac{g_{a\gamma\gamma}^2 (Ze)^2}{64\pi^2} \frac{k^4}{(r_0^{-2} + q^2)^2}$$

Axion Detection

- X-ray event rate in a crystal is enhanced when Bragg condition is met
  - Coherent interference of x-rays when wavelength is an integer multiple of the crystal spacing



$$R(E) = \int 2c\frac{d^3q}{q^2} \cdot \frac{d\Phi}{dE} \cdot [\frac{g_{a\gamma\gamma}^2}{16\pi^2}|F(\vec{q})|^2 \sin^2(2\theta)]$$

$$F(\vec{q}) = k^2 \int d^3x\ \phi(\vec{x})e^{i\vec{q}\cdot\vec{x}}$$

$$\phi(\vec{x}) = \sum_i \phi_i(\vec{x}) = \sum_i \frac{Ze}{4\pi|\vec{x}-\vec{x}_i|}e^{-\frac{|\vec{x}-\vec{x}_i|}{r}} = \sum_G n_G e^{i\vec{G}\cdot\vec{x}}$$

BRAGG LAW

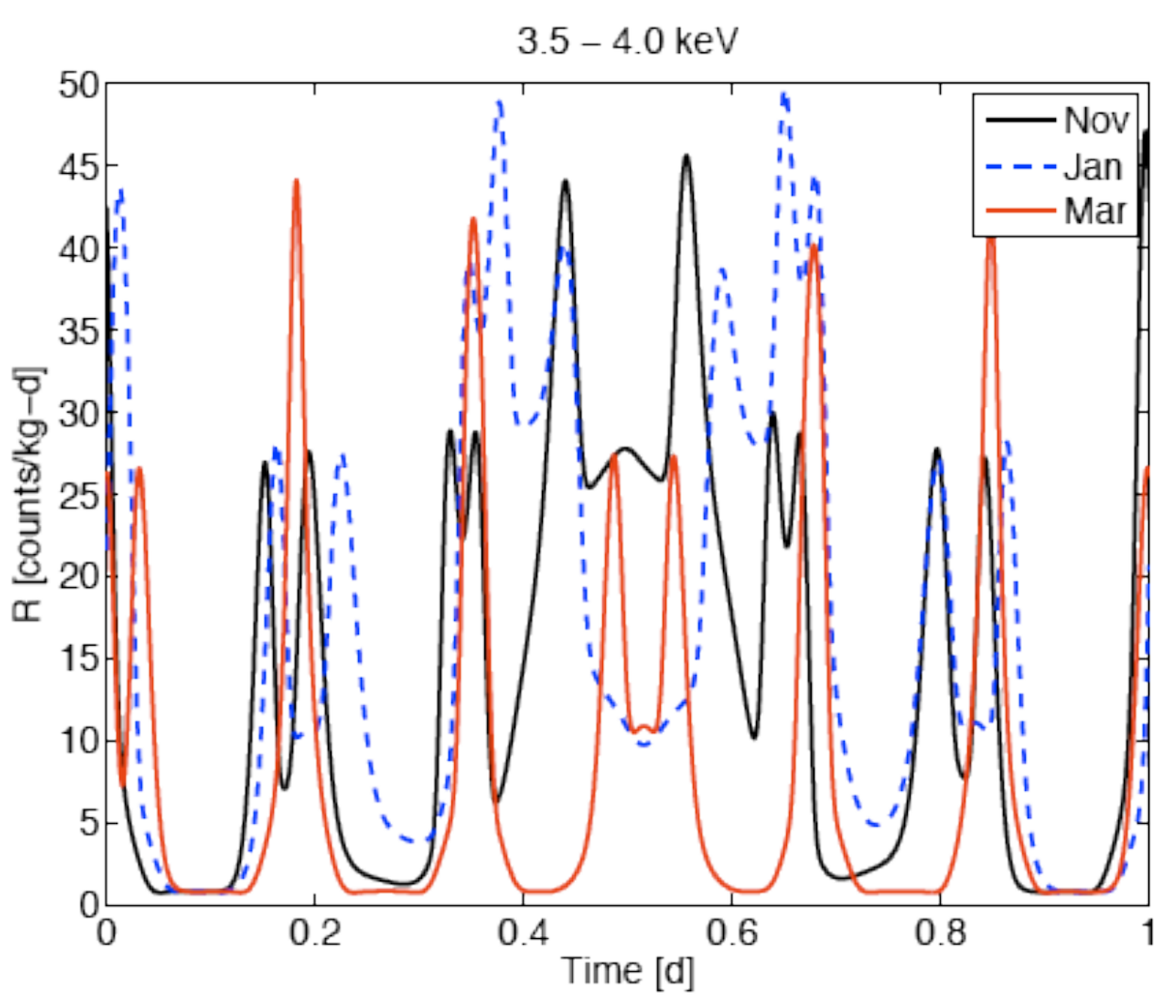
$$2d(\sin\theta) = \lambda_o$$

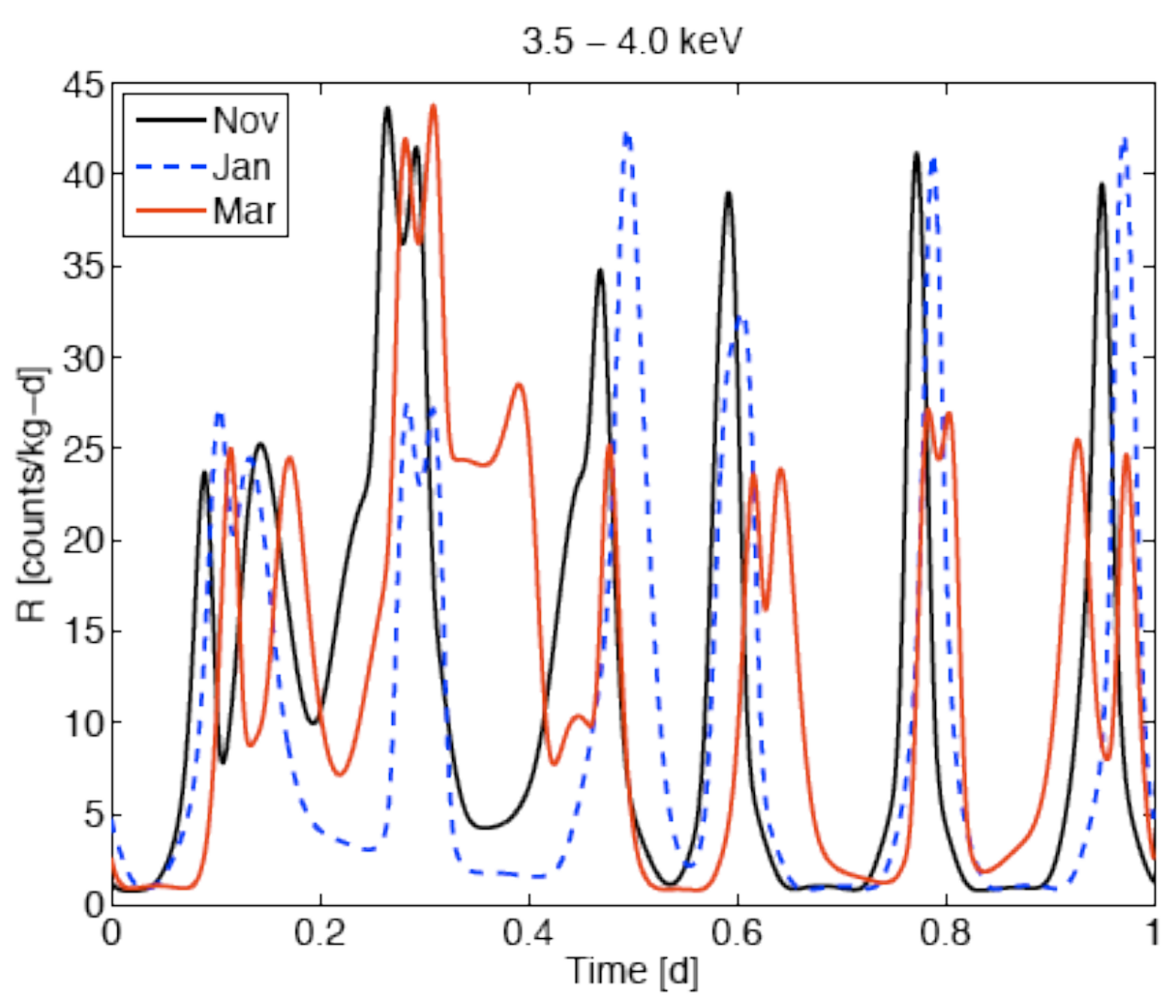
where:
d = lattice interplanar spacing of the crystal
θ = x-ray incidence angle (Bragg angle)
λ = wavelength of the characteristic x-rays

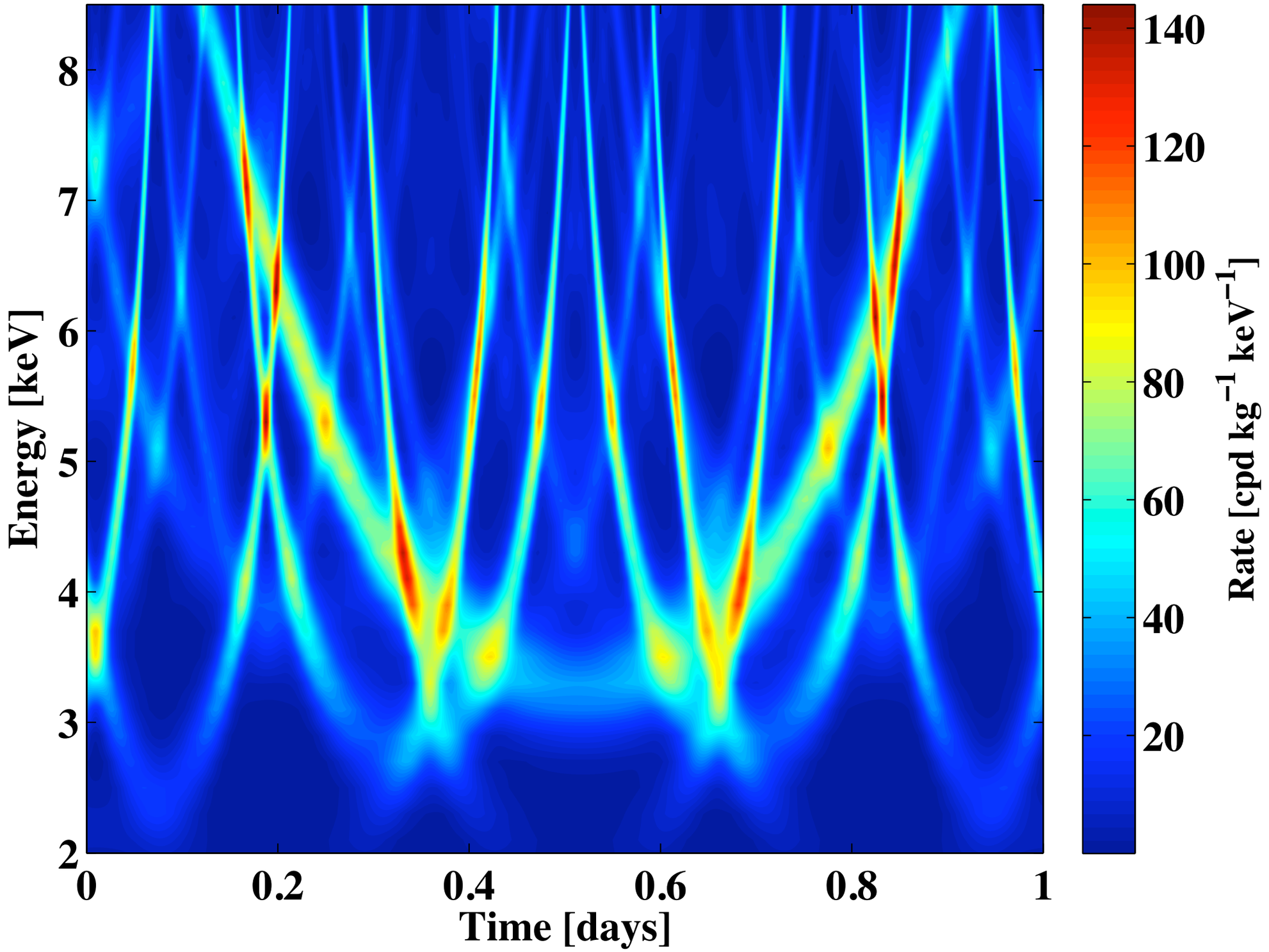
$$E_a = \hbar c\frac{|\vec{G}|^2}{2\hat{u}\cdot\vec{G}}$$

Axion Detection

- Event rate is a function of time of date and detector orientation
  - The figures show events rates for two different crystal orientations

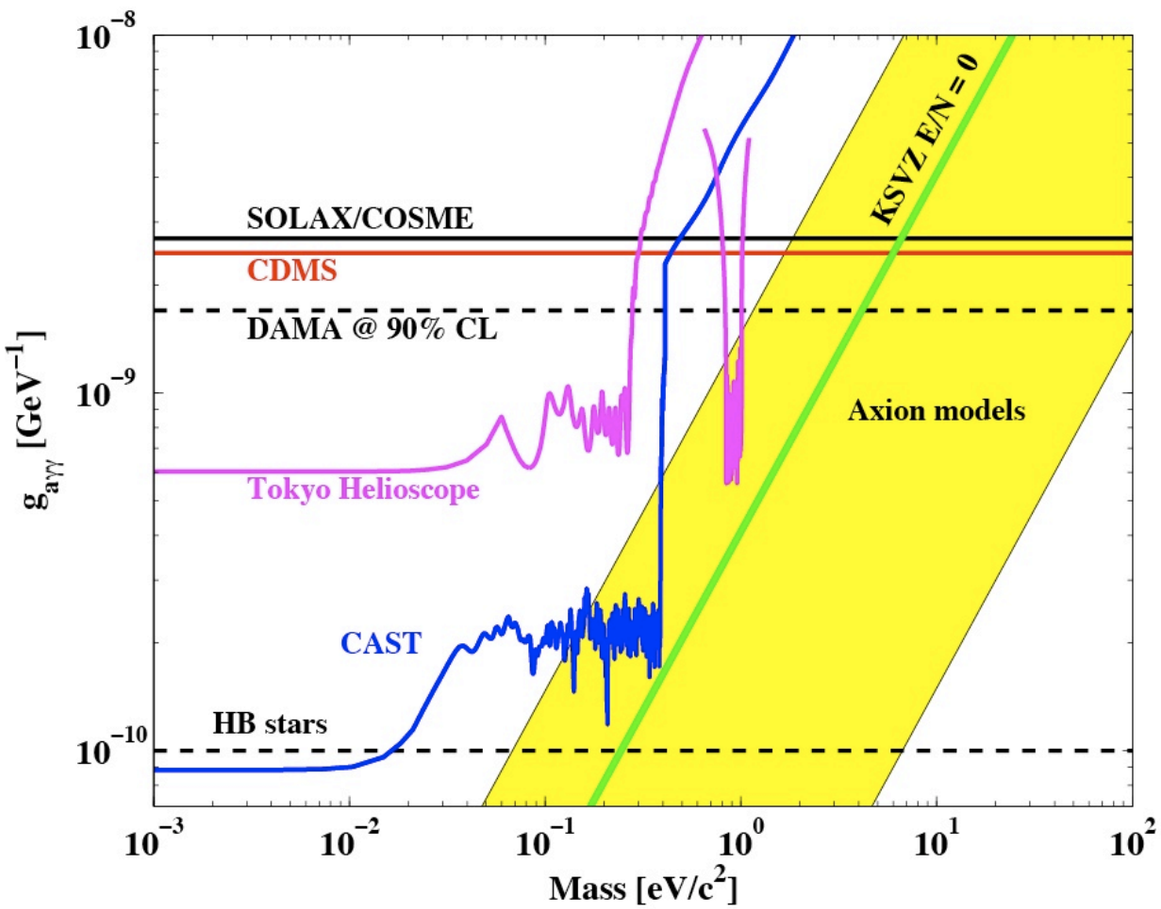


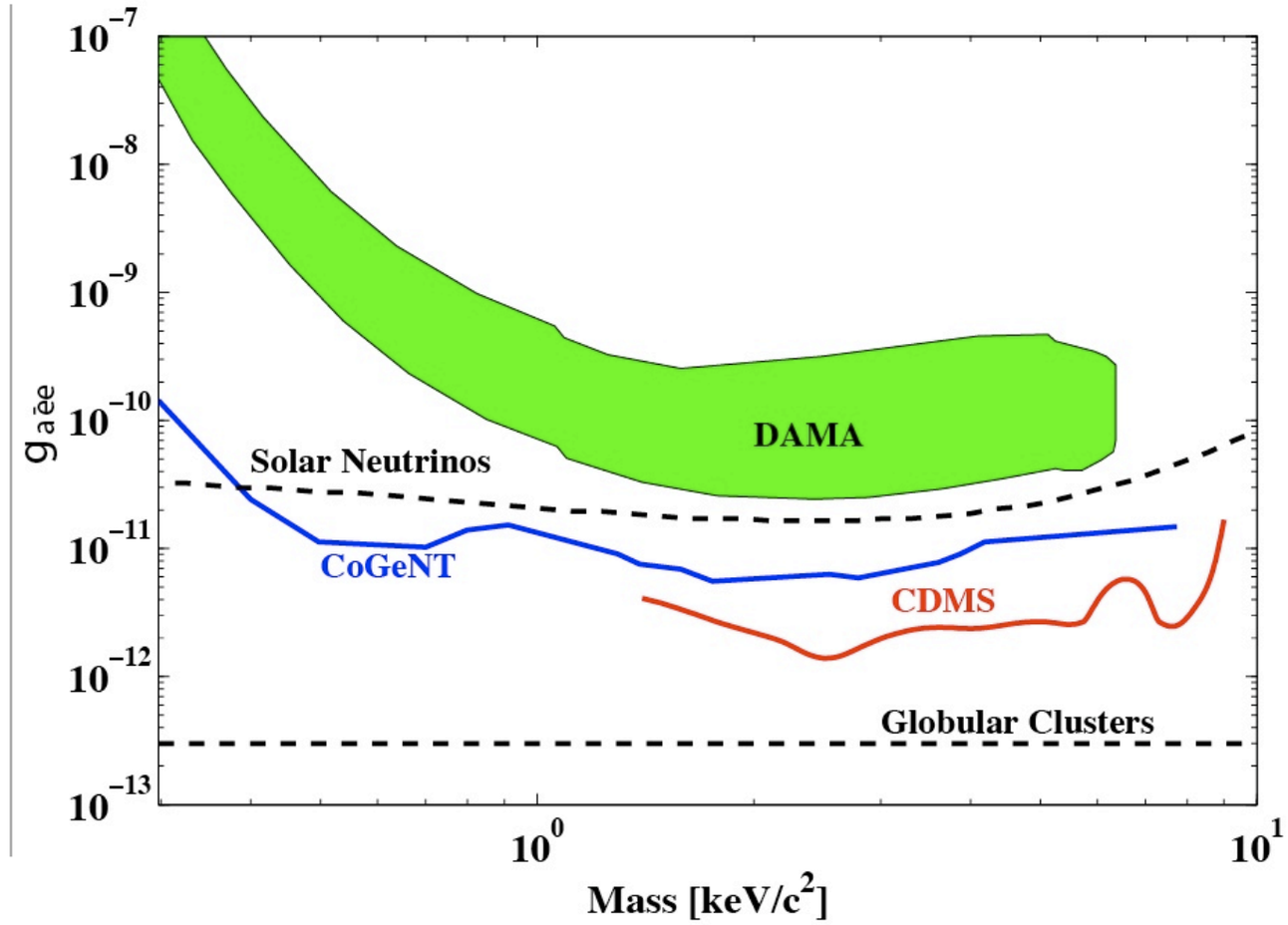




Time and energy dependence of axion conversion rate

Ge crystal: $g_{a\gamma\gamma}$ 10^{-8} GeV^{-1}

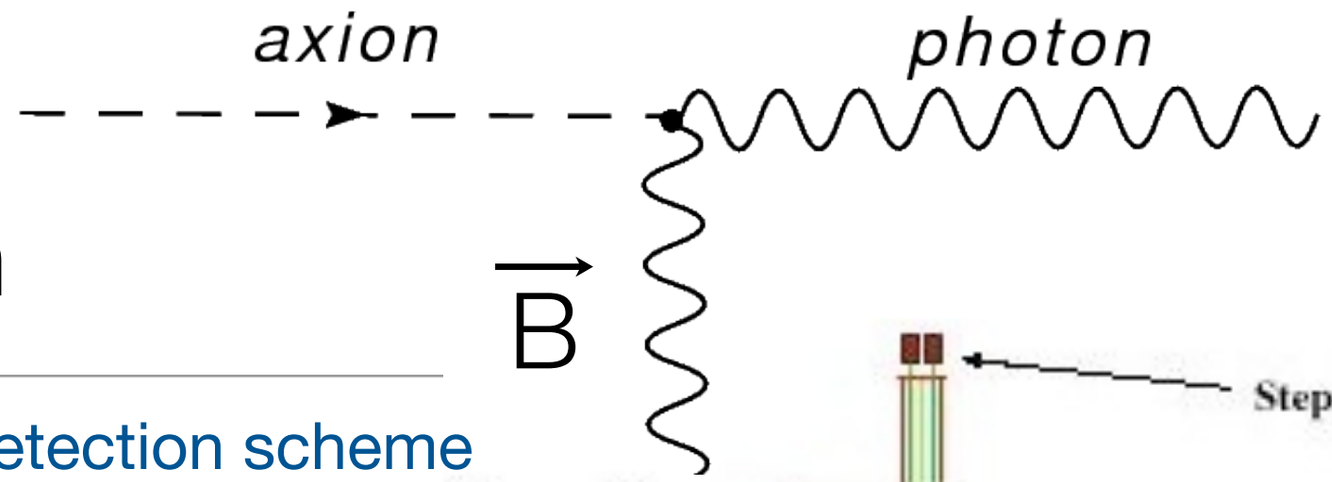




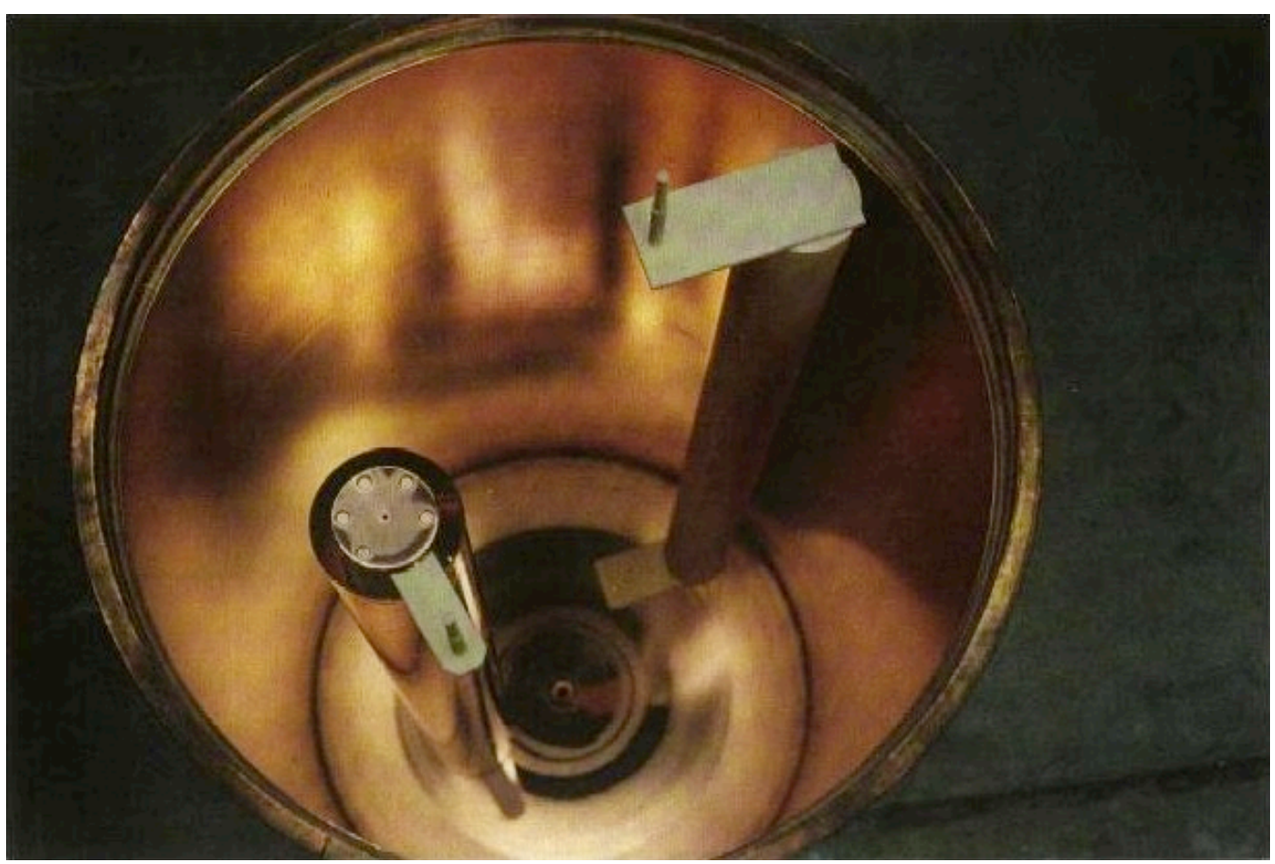
Massive Axion Limits

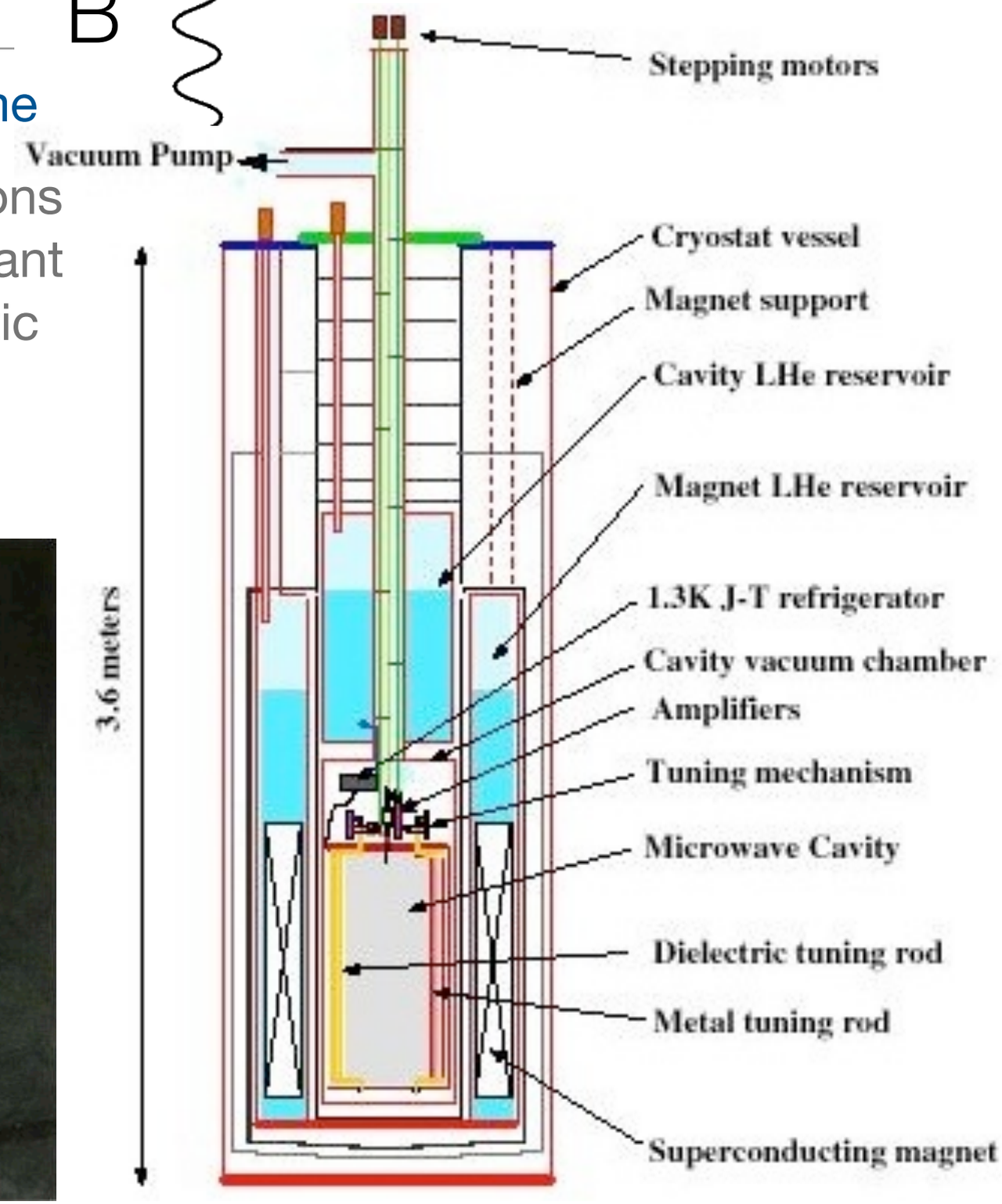
Axion Search with Microwave Resonators

Axion Detection



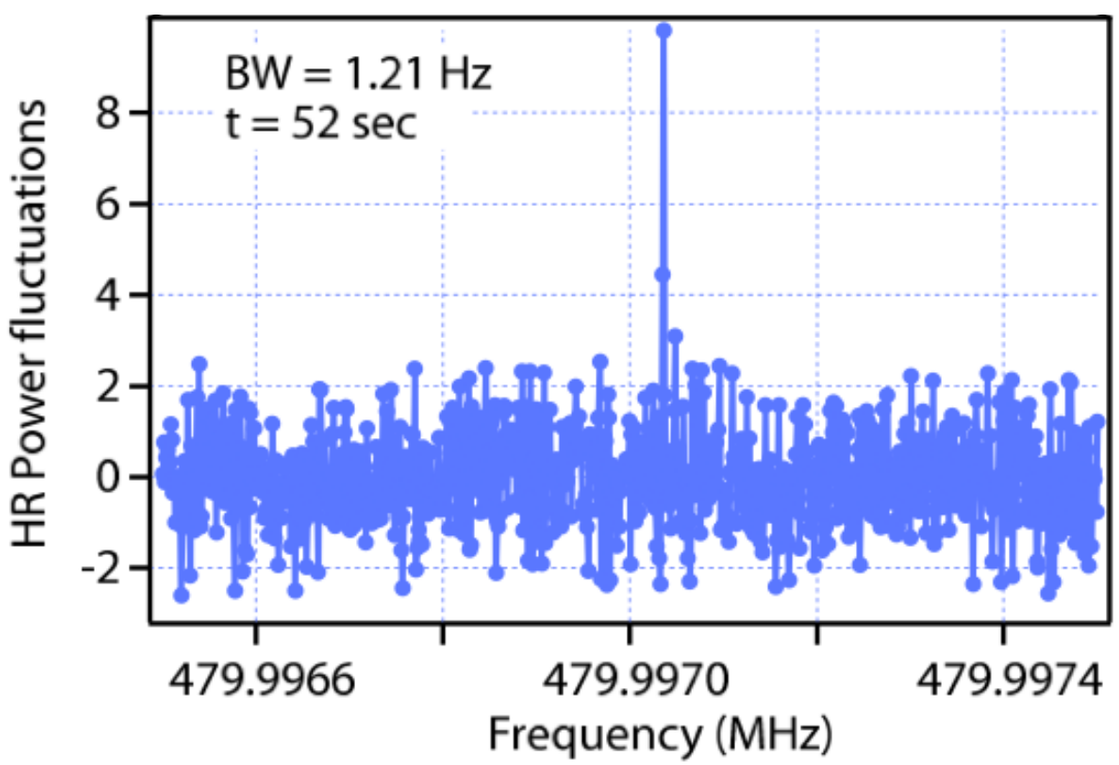
- The " original" axion detection scheme
  - Stimulated conversion of relic axions into microwave photons via resonant interaction with a (8 Tesla) magnetic field
  - Axion energy $E_a \rightarrow h\nu$: ~ 500 MHz

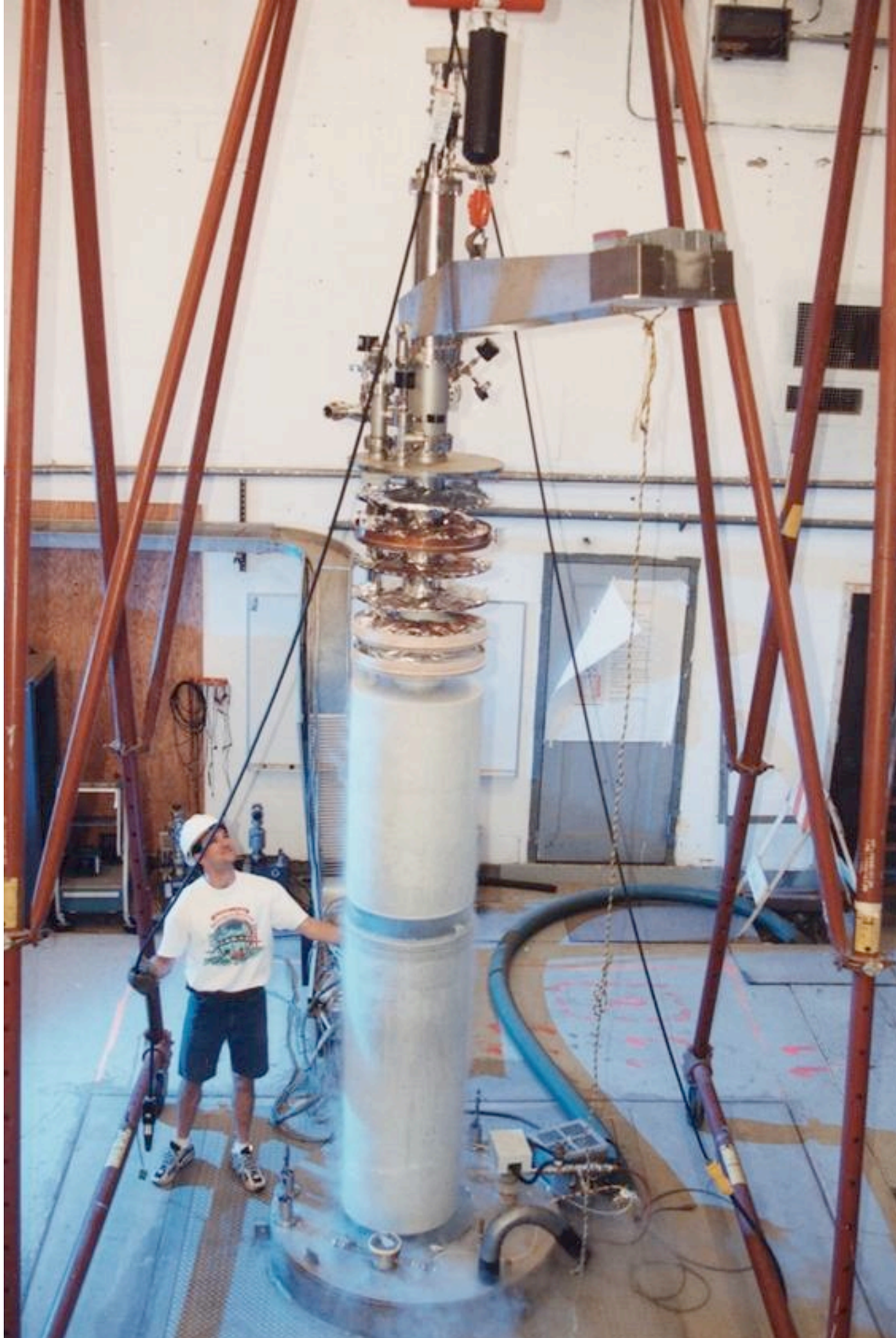


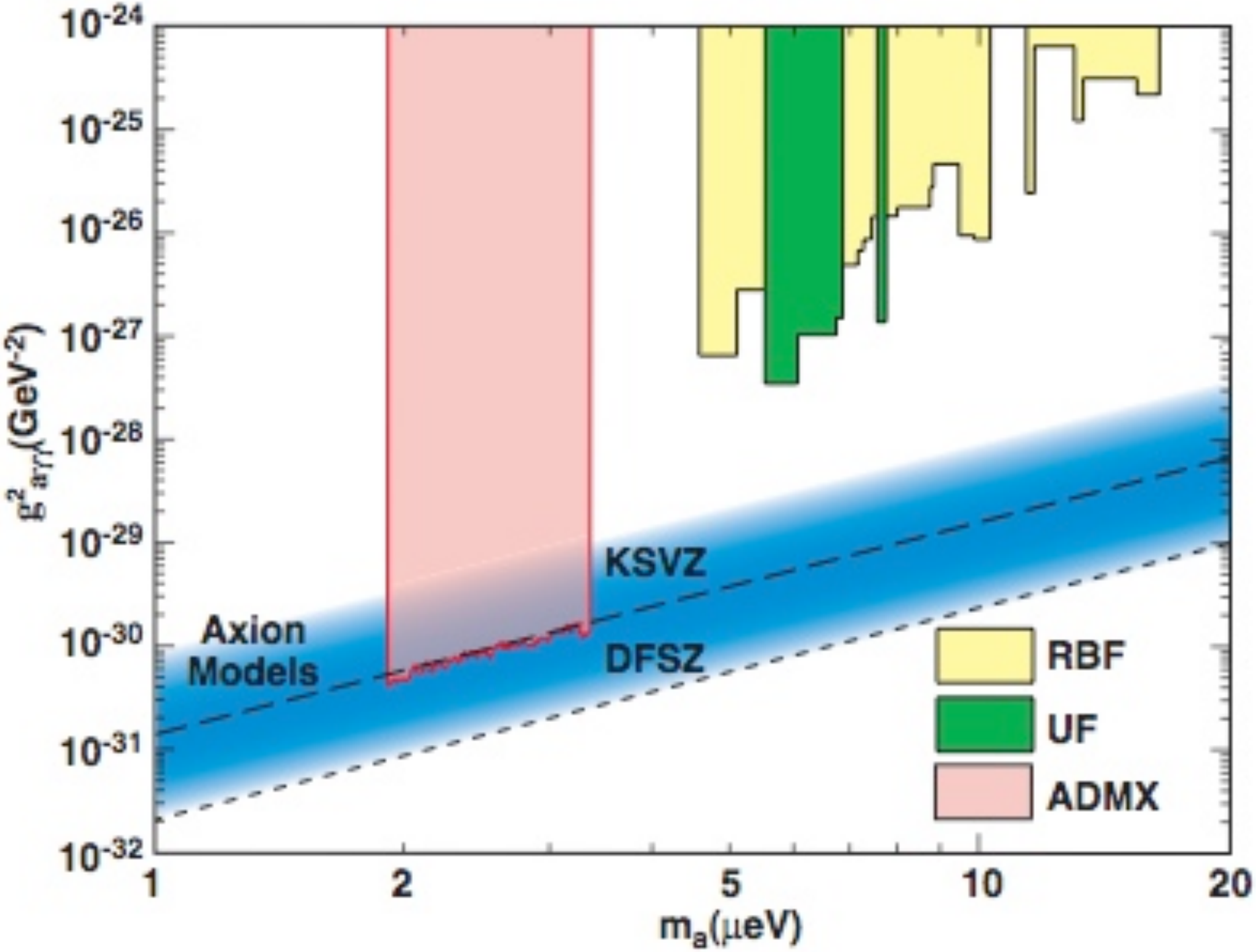


ADMX

- Signal appears as an increase in detected power at a given frequency
- Phase II of the experiment to be cooled to <100 mK to minimize thermal noise







ADMX Limits

Phase II to explore DFSZ model

Final Words

- What if there aren't any WIMPs?
  - The techniques presented here describe the detection of ANY particles that couples with either a photon, electron, or nucleus (our three favorite, and most manipulable tools)
  - As the couplings get weaker, or the densities smaller, we have to keep up by reducing the backgrounds

The truth

is

- If it is out there, ... we will see it

Fox Mulder, X-Files