Université d'Oran

School on Particle Physics and Cosmology

Oran, Les Andalouses, 02-10 May 2009

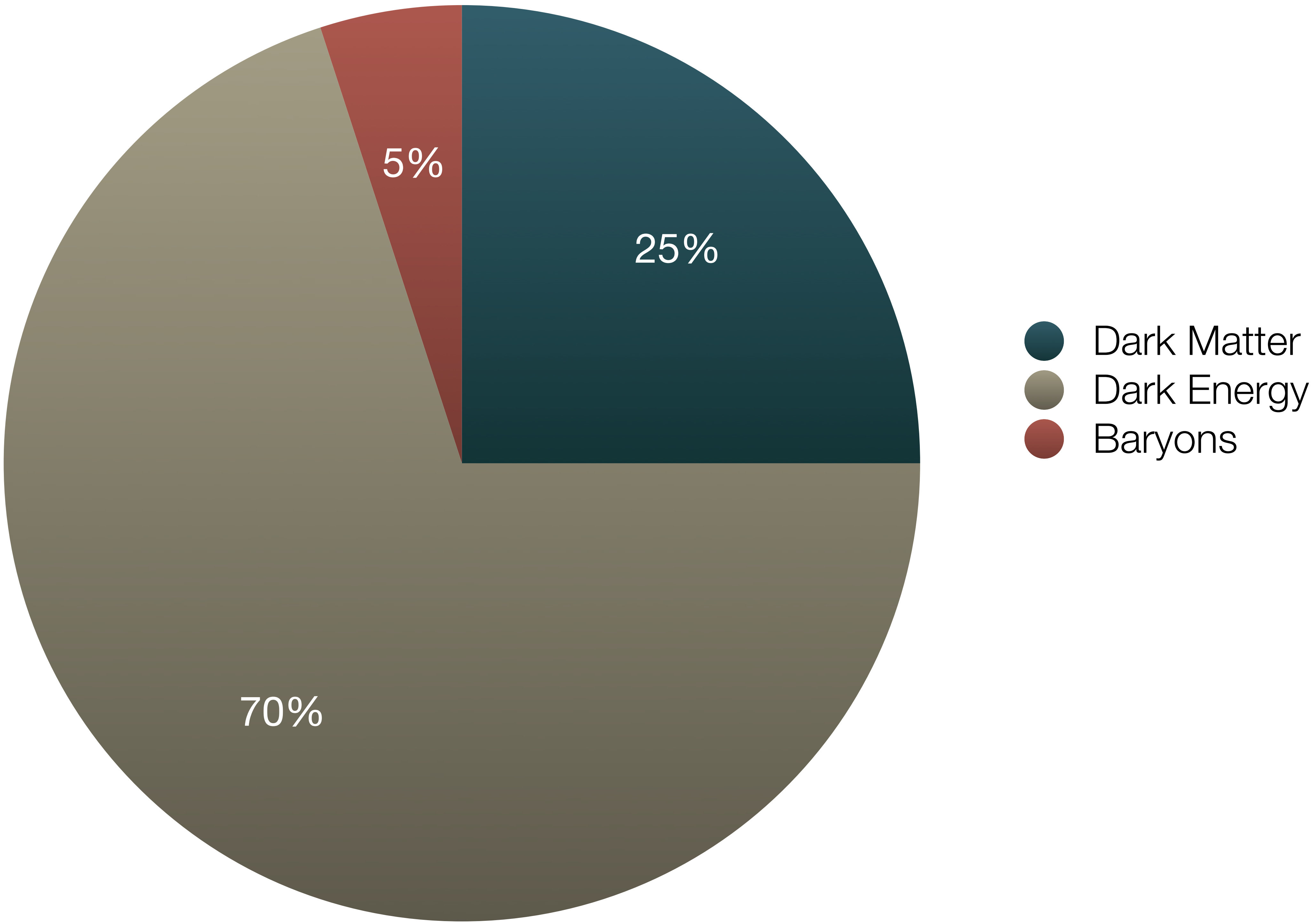
LPTO
Laboratoire de Physique Théorique d'Oran

Dark Matter Searches in the 21st Century

Tarek Saab

Oran School on Particle Physics and Cosmology
May 2009

Matter - Energy Budget



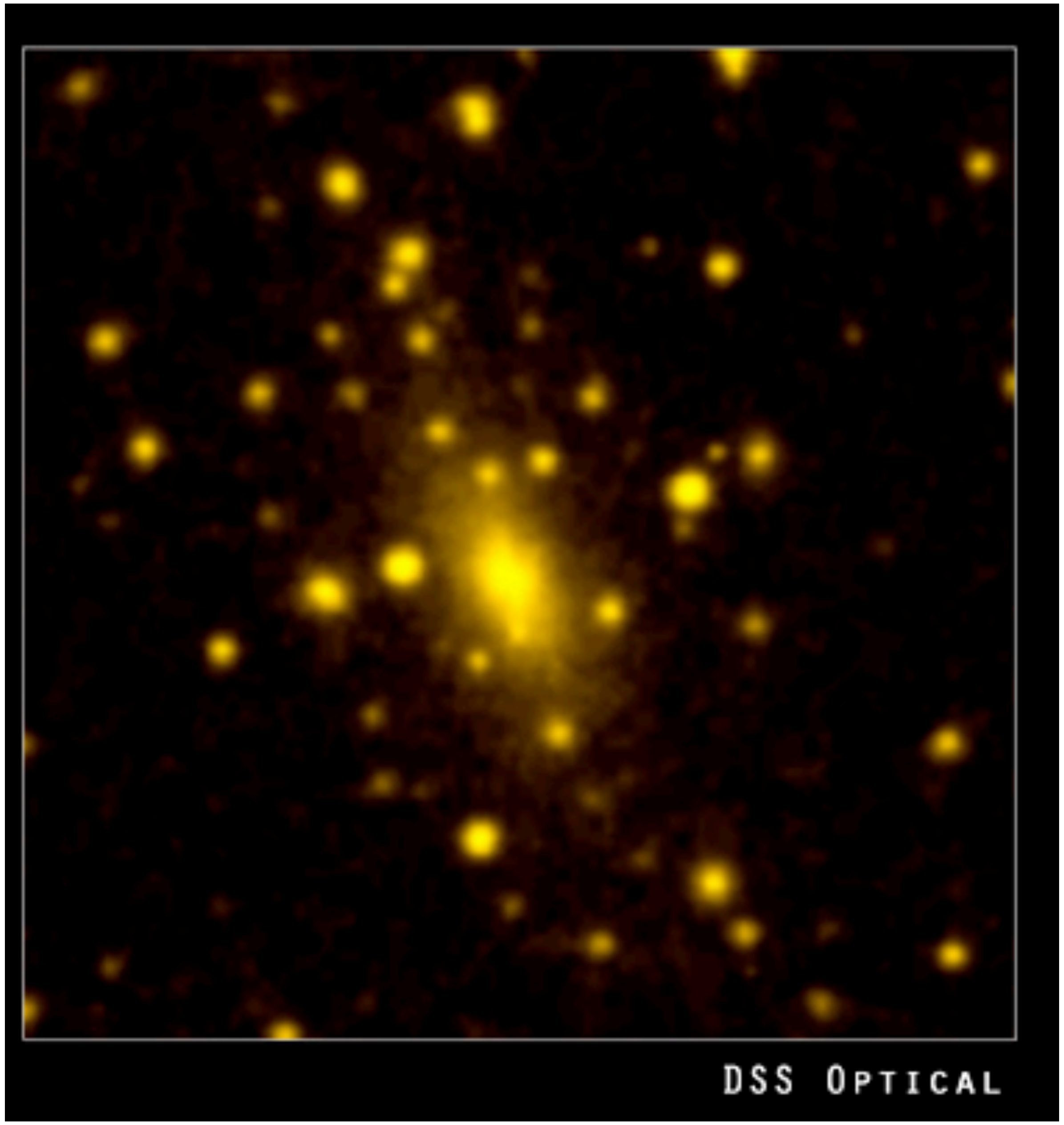
Outline of Talk

- Brief Introduction
    - Cosmology Today
- Principles of Dark Matter Detection
    - Direct Detection
    - Indirect detection
- Experimental Implementations
    - DAMA/Libra
    - CDMS
    - Xenon

      ...
- Current Limits & Looking to the future

The Optical View on the Universe

- Galaxy cluster properties provide a strong handle on cosmology
- Large in the sky :
  can't be confused with anything else
- Can be seen up to large distances (z ~1.5)

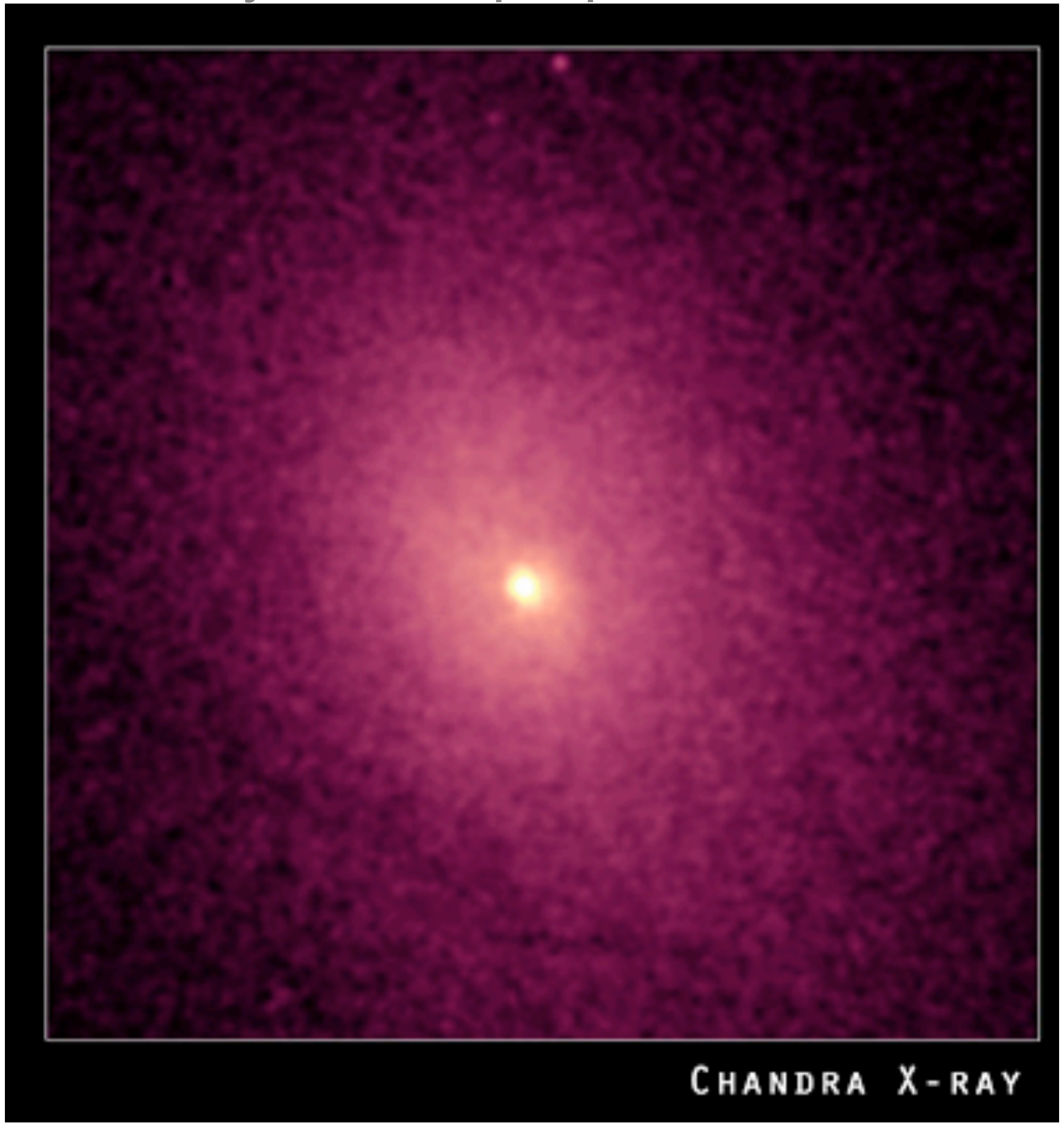


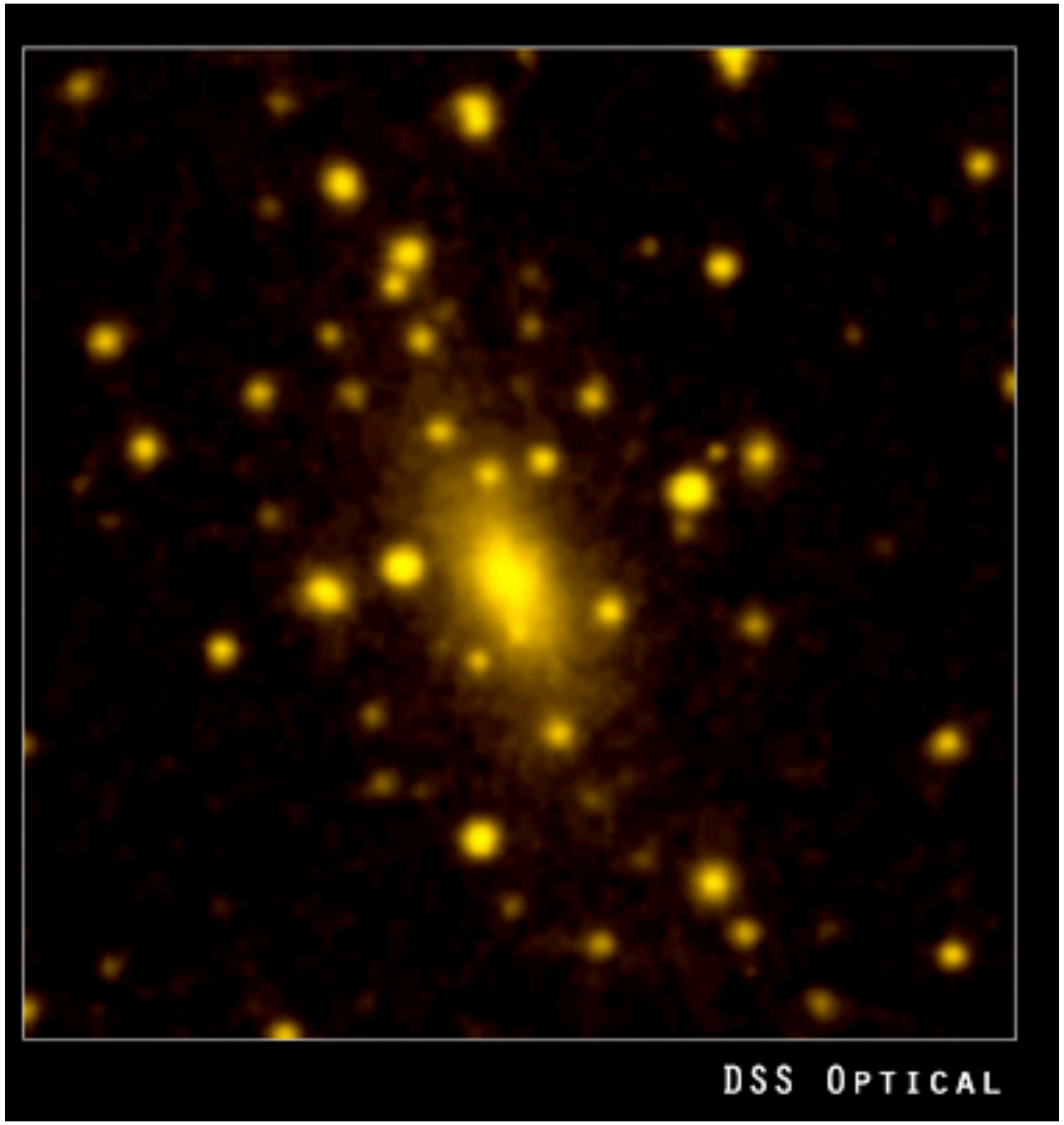
The X-ray View on the Universe

- Galaxy cluster properties provide a strong handle on cosmology
- Large in the sky :
  can't be confused with anything else
- Can be seen up to large distances (z ~1.5)
- Mass determined from temperature of x-ray emitting gas

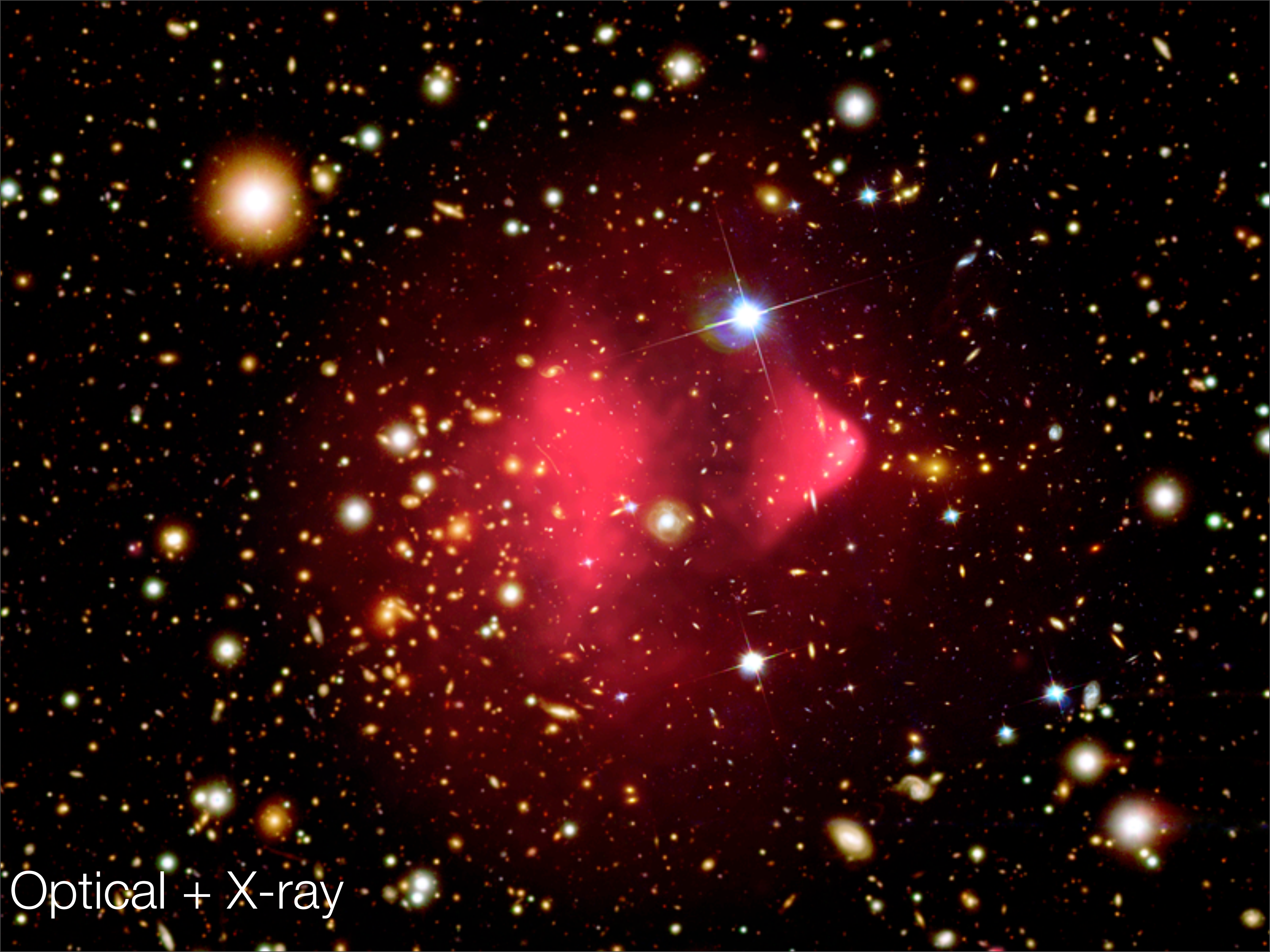
The X-ray View on the Universe

- Galaxy cluster properties

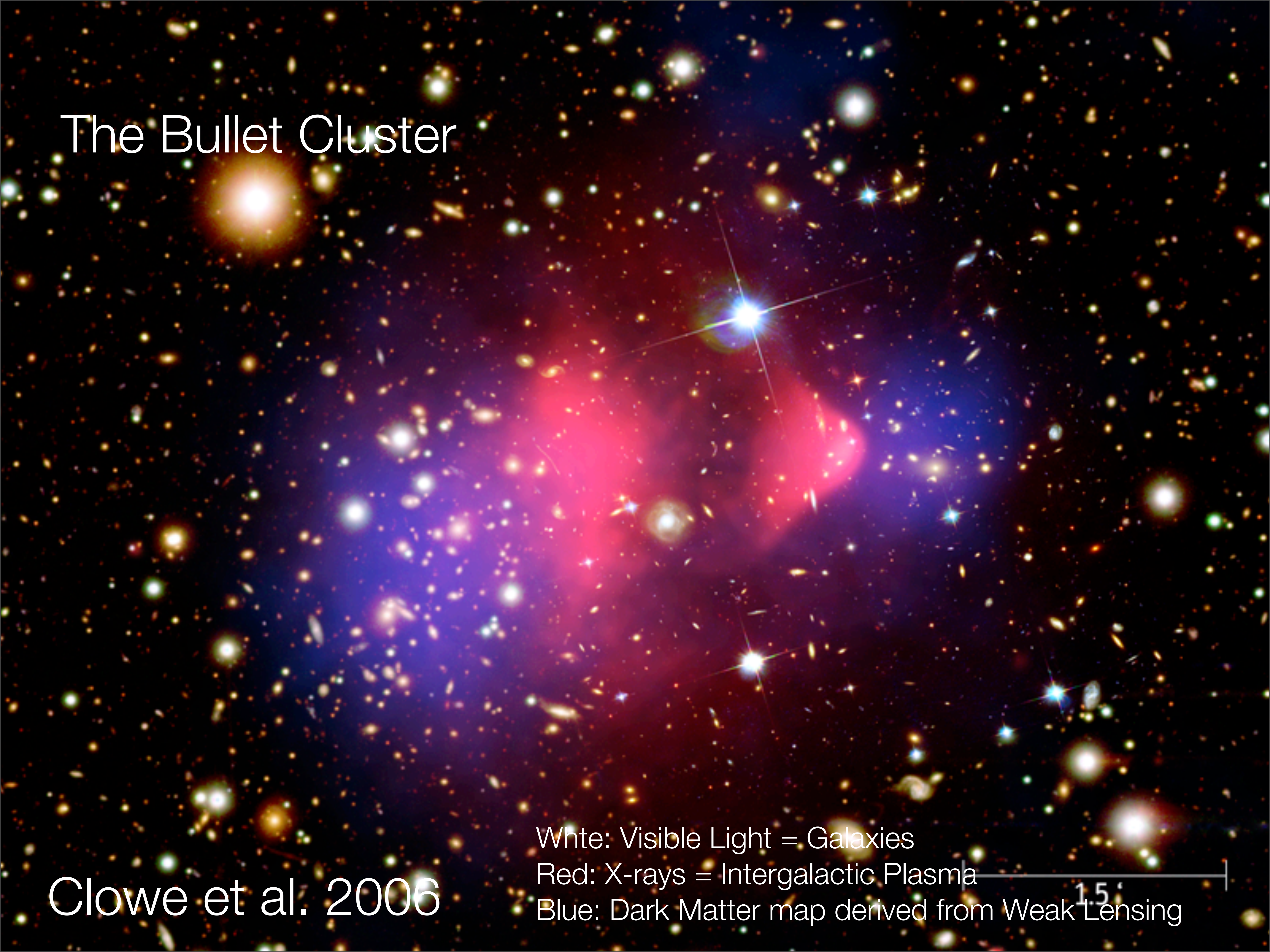




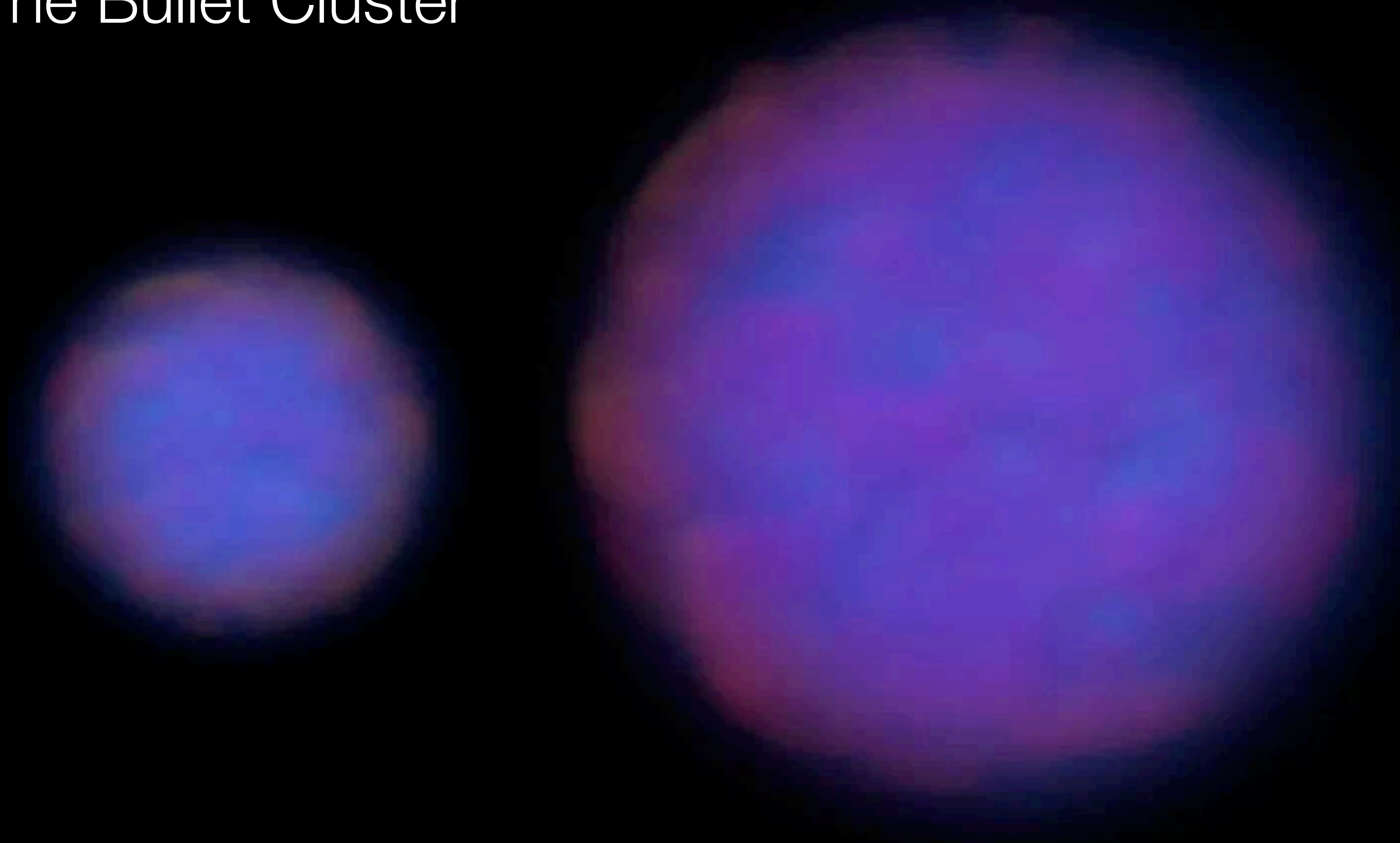

Optical


Optical + X-ray


Optical + weak-lensing


The Bullet Cluster
Clowe et al. 2006
Whte: Visible Light = Galaxies
Red: X-rays = Intergalactic Plasma
Blue: Dark Matter map derived from Weak Lensing
1.5'

The Bullet Cluster



Chasing the WIMP

- We “know” that Dark Matter must
  - Have some mass: (due to its gravitational effect)
  - Has a certain annihilation cross section: (based on the current total matter density of the Universe)
  - Have been non-relativistic early on in cosmological time: (based on the formation of clusters in the early universe)
- There exists “several” theoretical candidates for such a particle
- I will focus on one particular candidate
  - The lightest supersymmetric particle commonly referred to as the neutralino
  - If we have time at the end, I will talk briefly about axions

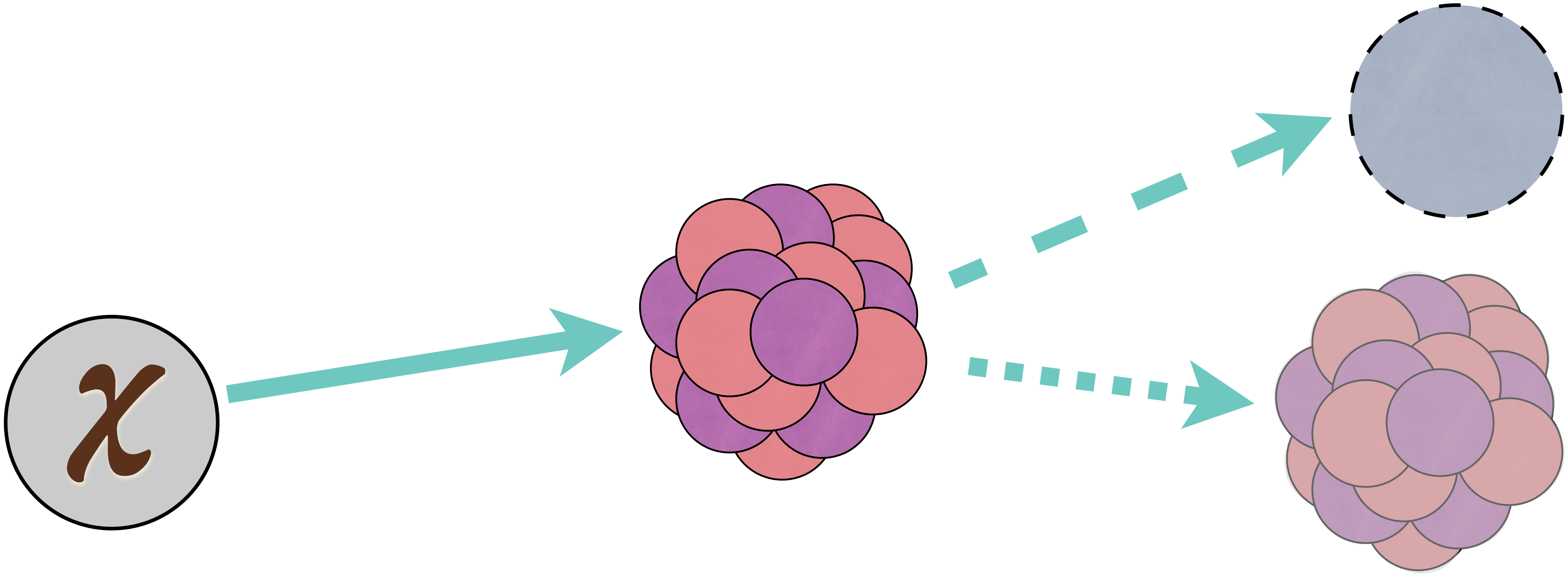
$$\chi$$

Dark Matter Searches:
I - Principles and Design Considerations

Principles of
Direct Detection

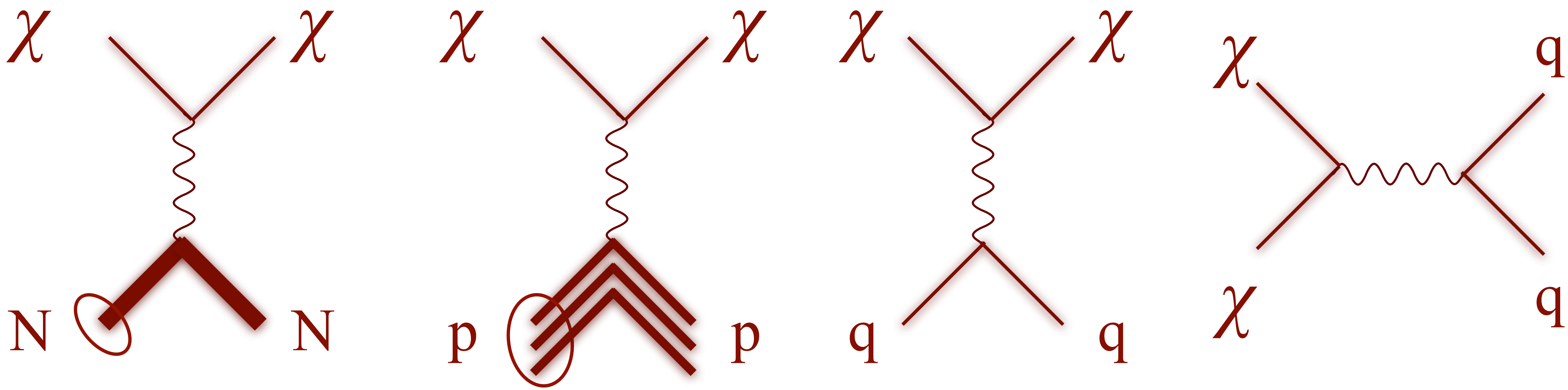
Principles of Direct Detection

- 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.



Principles of Direct Detection

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



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

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

Little Bit more Detail on Cross Section

- WIMP-quark scalar interaction:
  - $\sigma_{0\text{-scalar}}(q \rightarrow 0) = 4m_r^2/\pi\ [Zf_p + (A-Z)f_n]^2$ ~
    we assume $f_p \approx f_n \rightarrow \sigma_{0\text{-scalar}} \propto A^2$

- WIMP-quark spin interaction:
  - $\sigma_{0\text{-spin}}(q \rightarrow 0) = 32/\pi\ G_F^2\ (1/J\ [a_p\langle S_p\rangle + a_n\langle S_n\rangle])^2\ J(J+1)$

Principles of Direct Detection

Input from Particle Physics

$$\sigma_0 = \left(\frac{m_r}{m_{r-p}}\right)^2 A^2 \sigma_{\chi-p}$$

Knowledge of Nuclear Structure

$$F^2(Q) = \left[\frac{3j_1(qR_1)}{qR_1}\right]^2 \exp\left(-(qs)^2\right)$$

$$\boxed{\frac{dR}{dE_R} = \frac{\sigma_0 \rho_0}{\sqrt{\pi} v_0 m_\chi m_r^2} F^2(Q) T(Q)}$$

Choice of Target Nucleus

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

$$m_{r-p} = \frac{m_\chi m_p}{m_\chi + m_p}$$

Input from Astrophysics

$$T(Q) = \exp\left(-v_{min}^2 / v_0^2\right)$$

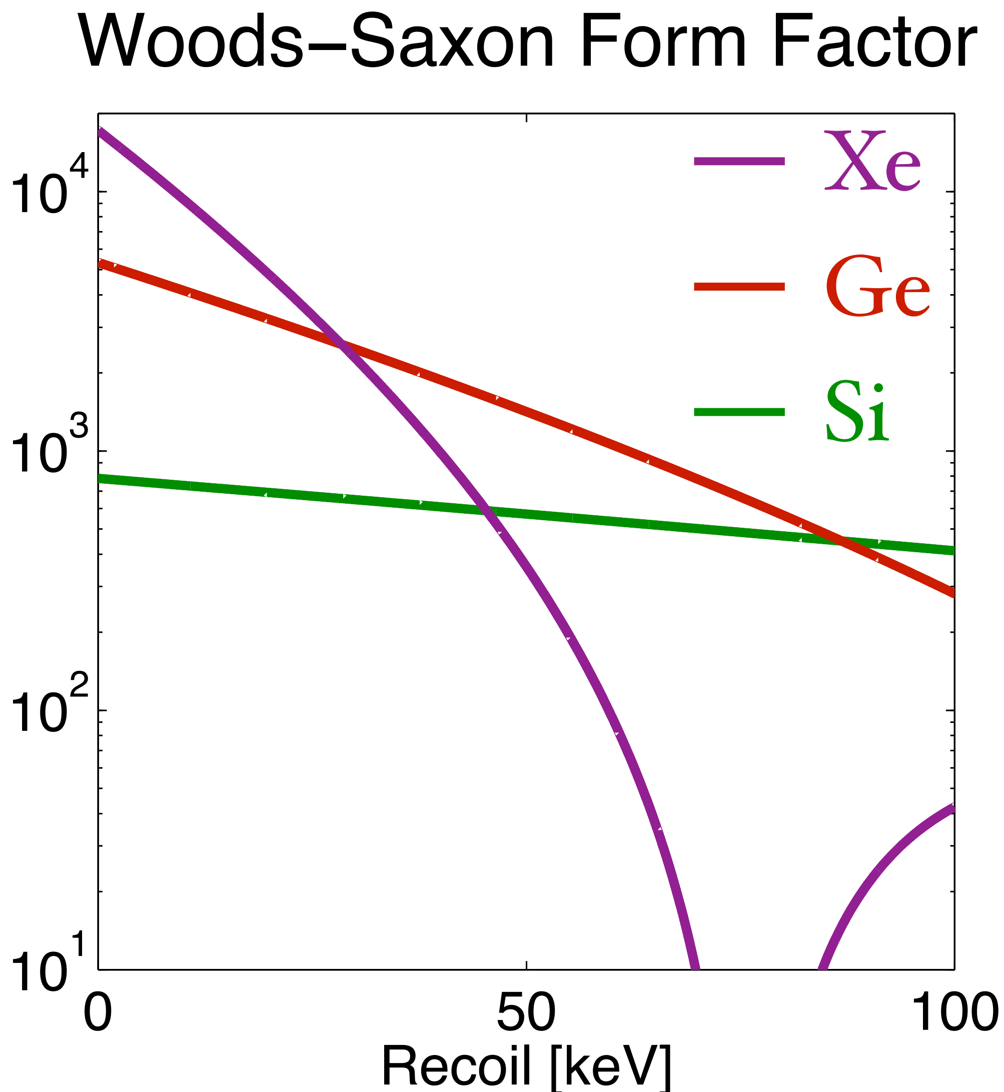
$$v_{min} = \sqrt{\frac{E_R m_N}{2m_r^2}}$$

$$v_0 \approx 220\,\mathrm{km/s}$$

Exercise

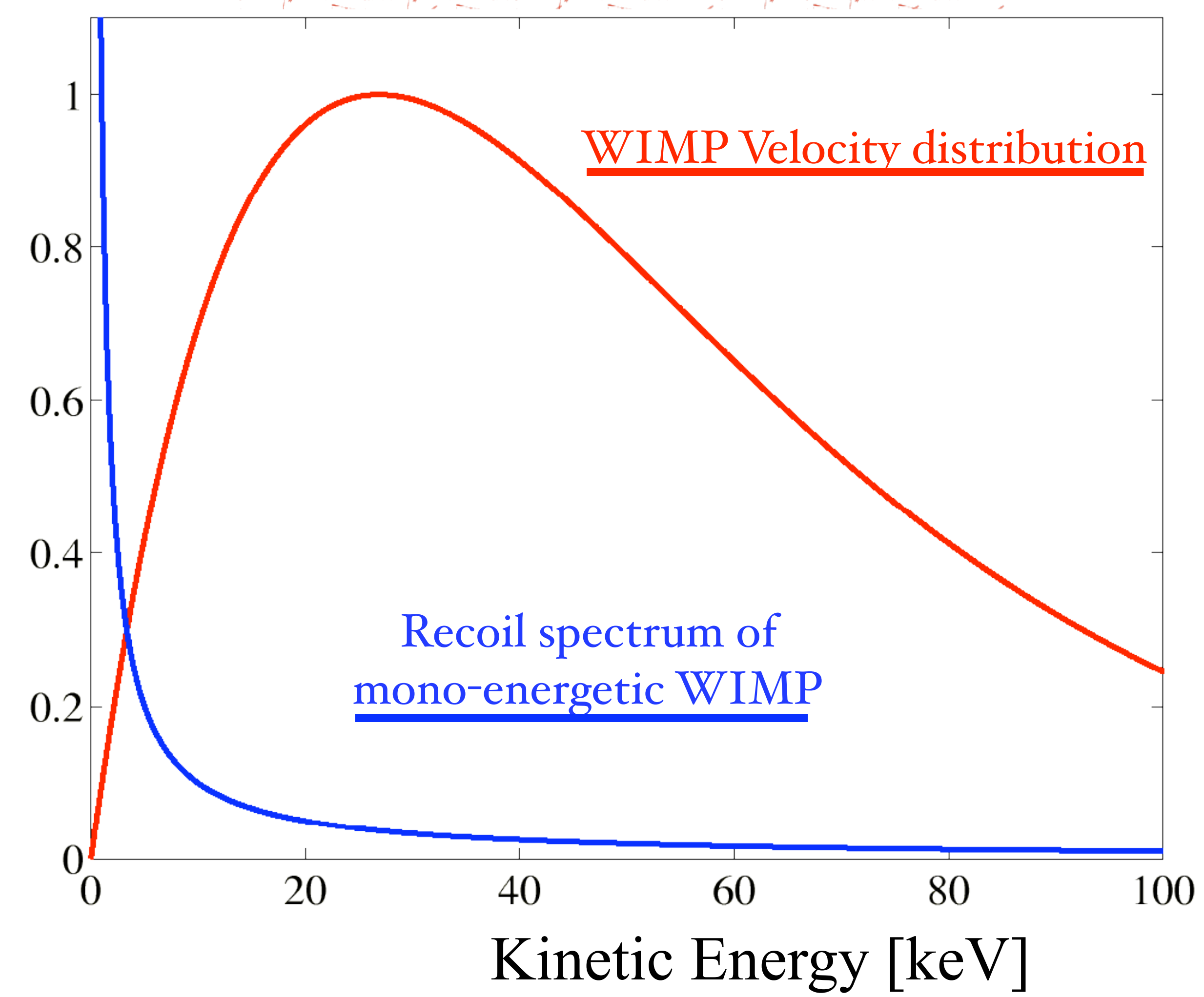
- What is the minimum velocity needed v_{min} for a WIMP with mass m_X to produce a 10 keV recoil in a nucleus of mass m_N ?

- 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 ?



A² x Form Factor F(Q)

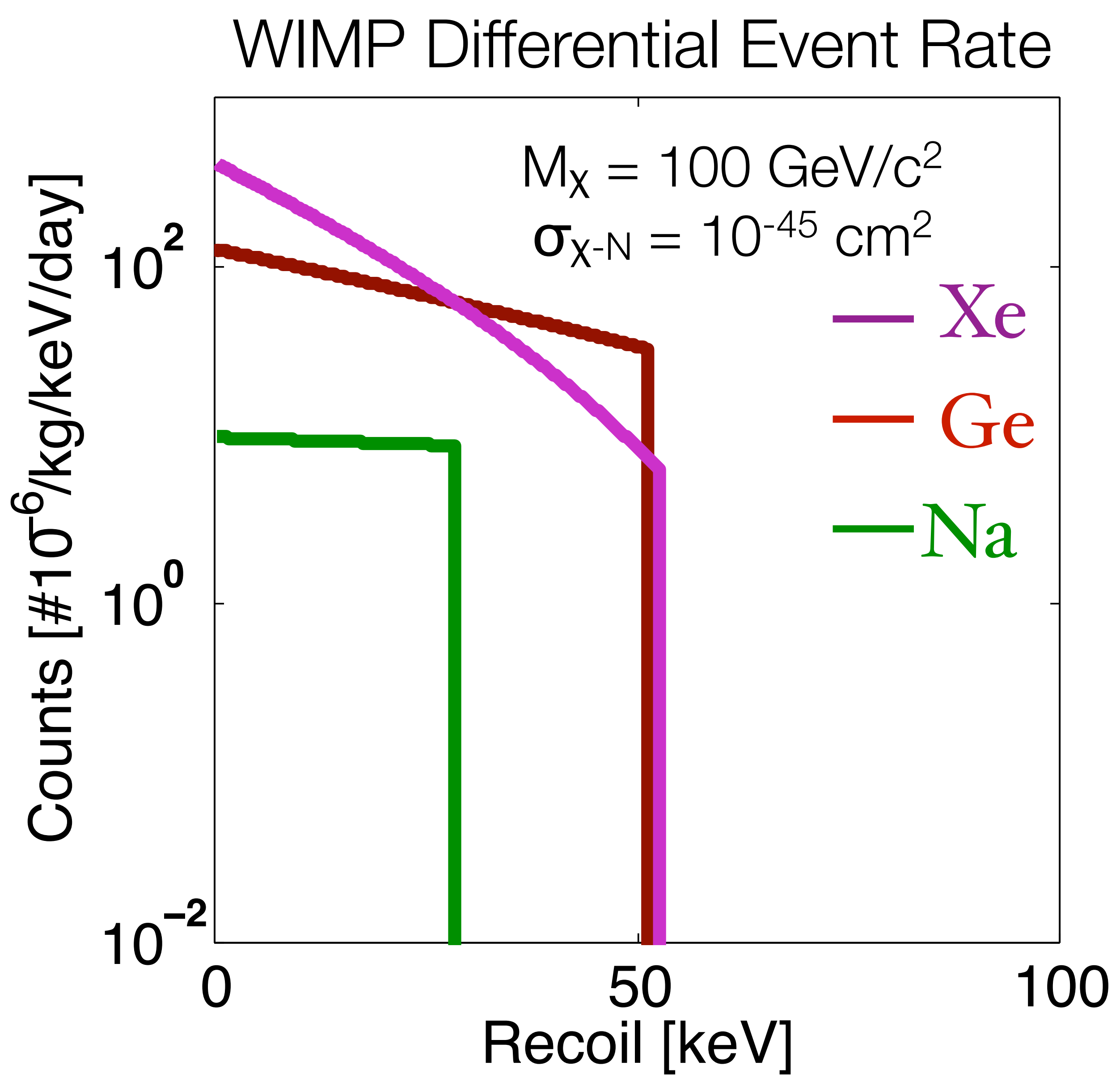
WIMP velocity distribution



Input Functions

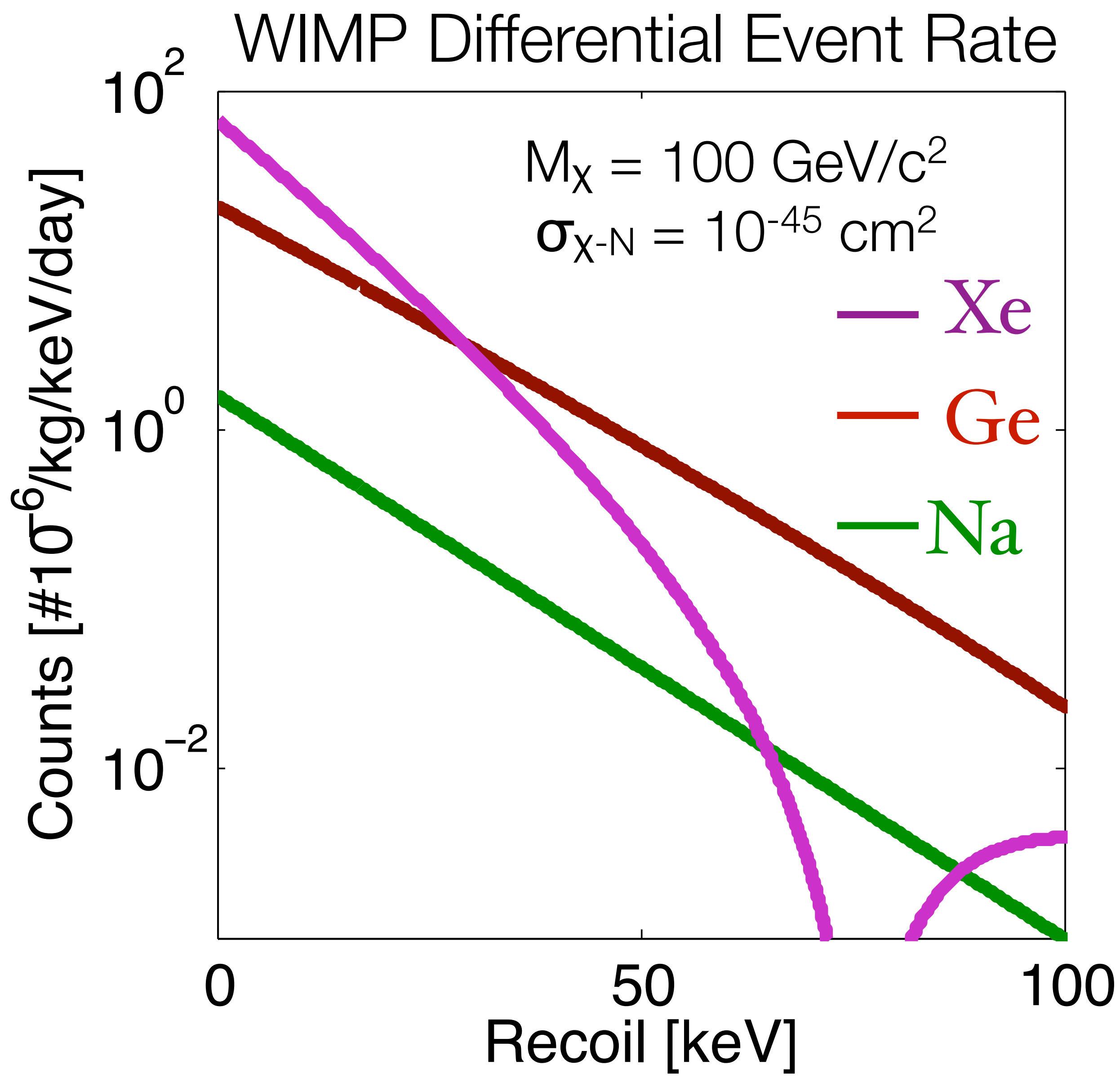
Principles of Direct Detection

- Elastic scattering of a WIMP from a nucleus deposits a small, but detectable amount of energy ~ few x 10 keV
    - For spin-indep. event rate scales as A^2
    - For spin-dep. event rates determined by the spin of the nucleus ~ J



Principles of Direct Detection

- Elastic scattering of a WIMP from a nucleus deposits a small, but detectable amount of energy ~ few x 10 keV
  - For spin-indep. event rate scales as A^2
  - For spin-dep. event rates determined by the spin of the nucleus ~ J
  - Featureless exponential energy spectrum
- no obvious peak, knee, break, ... that determines M_χ or v_0
- hard to distinguish from background



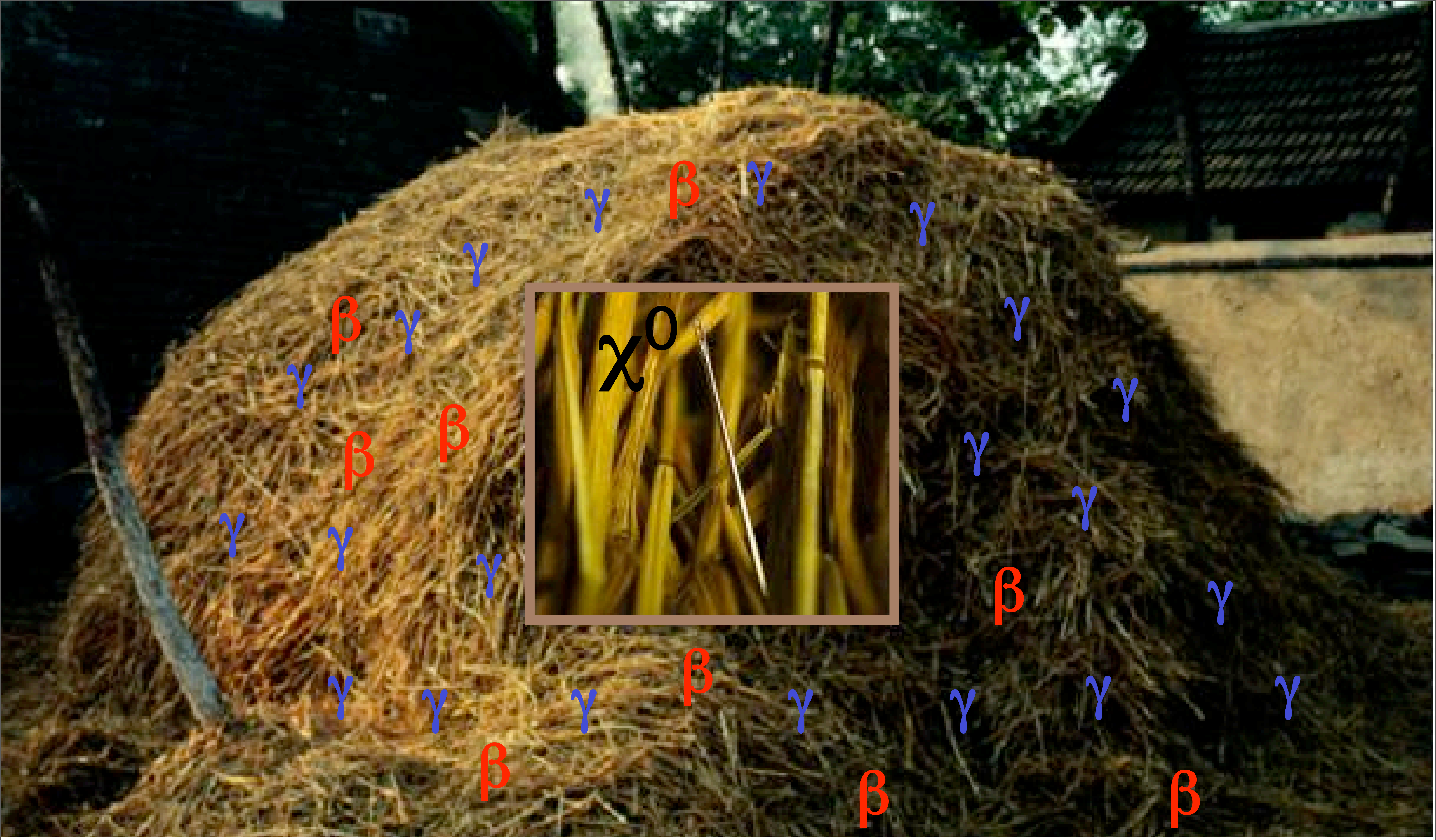
Principles of Direct Detection

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

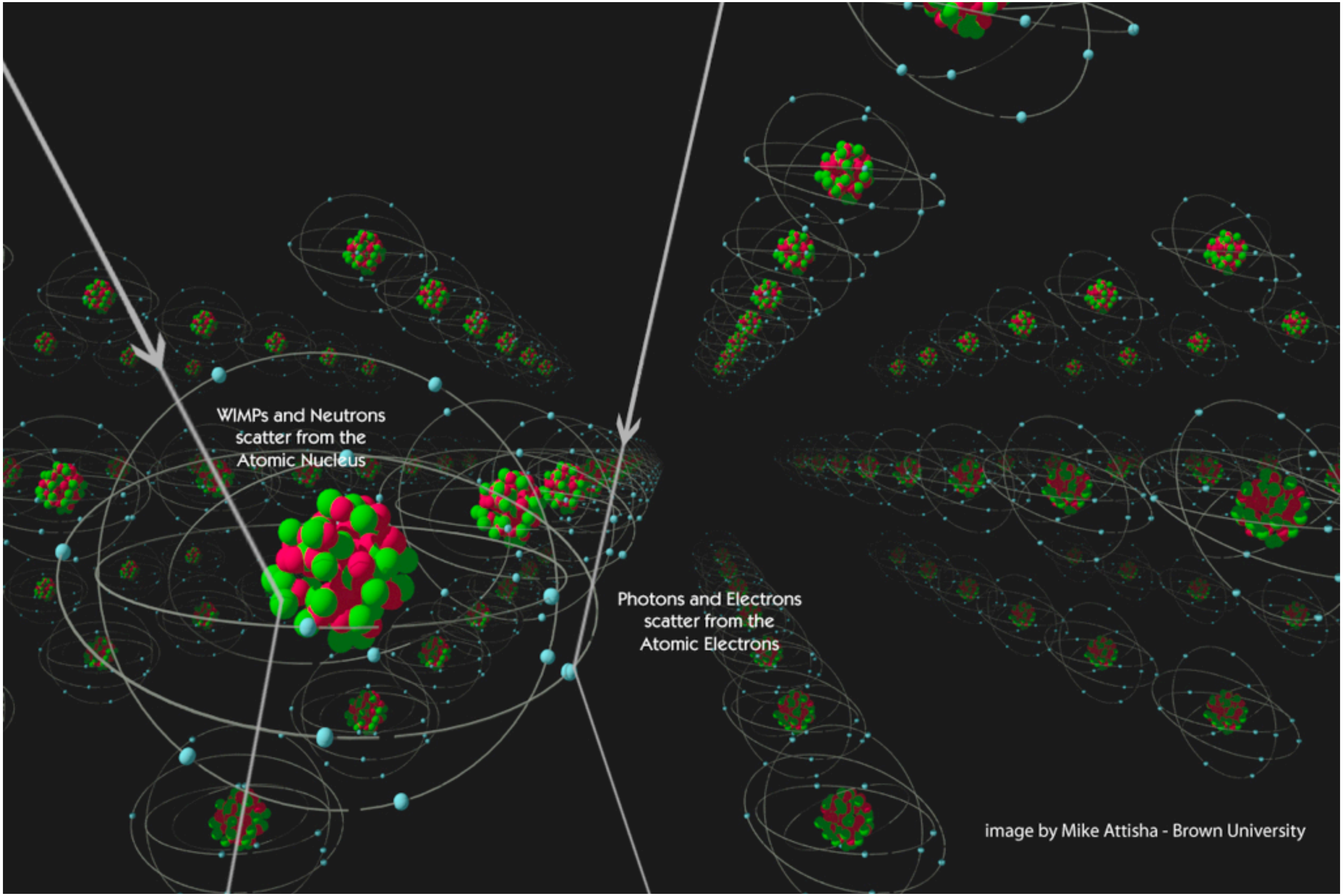
- Equally important considerations :
  - When dealing with 10^{26} nuclei, must consider the physical behavior of the solid/liquid/gas which the nuclei form
  - How can we extract/measure the recoil information in a given medium
  - What are the background issues associated with this material

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 !!

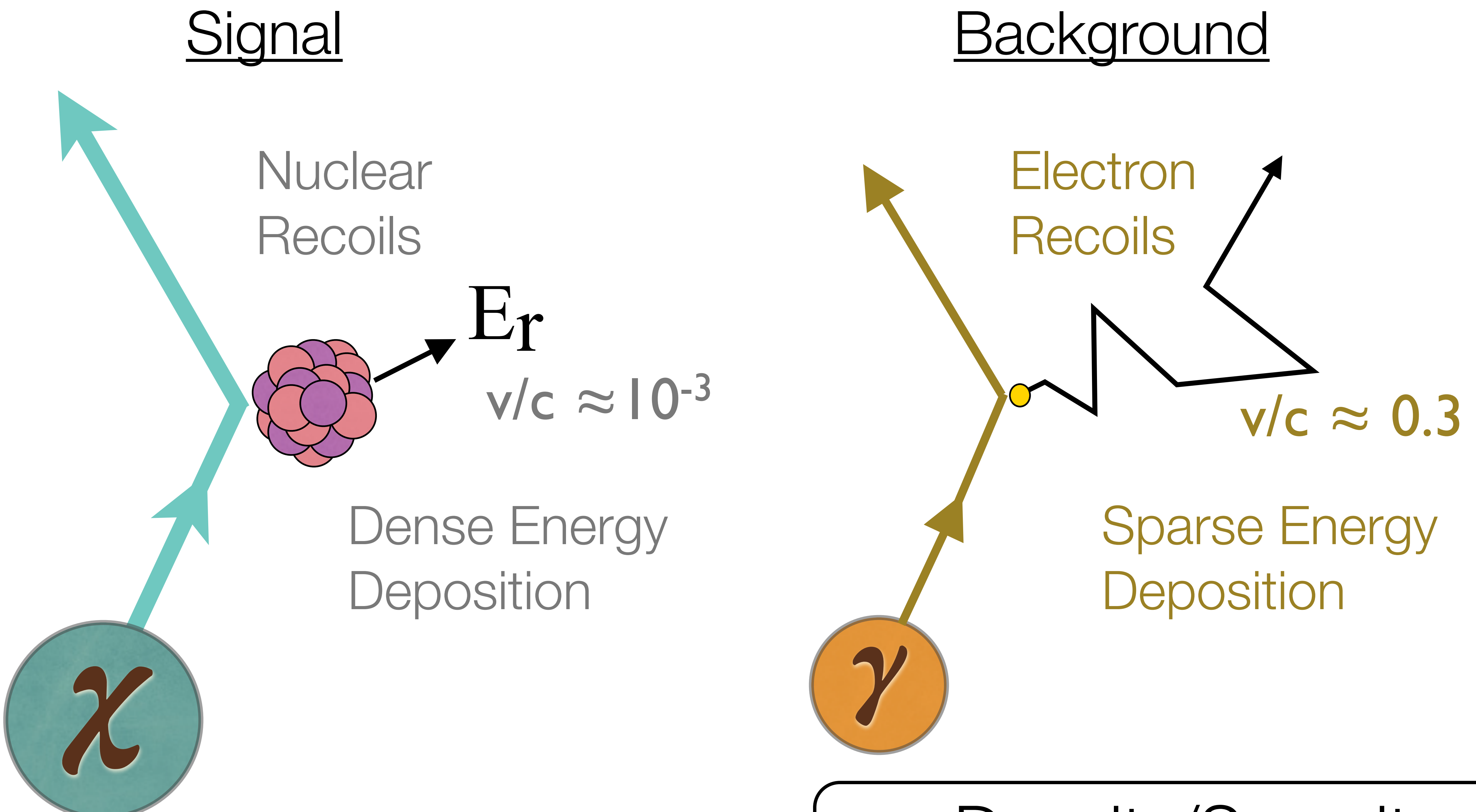


Looking for a very small needle in a big haystack



Detector Physics to the Rescue

Detector Physics to the Rescue



Density/Sparsity:
Basis of Discrimination

Event Discrimination = Particle ID

- Scattering from an atomic nucleus vs an atomic electron leads to different physical effects in most materials

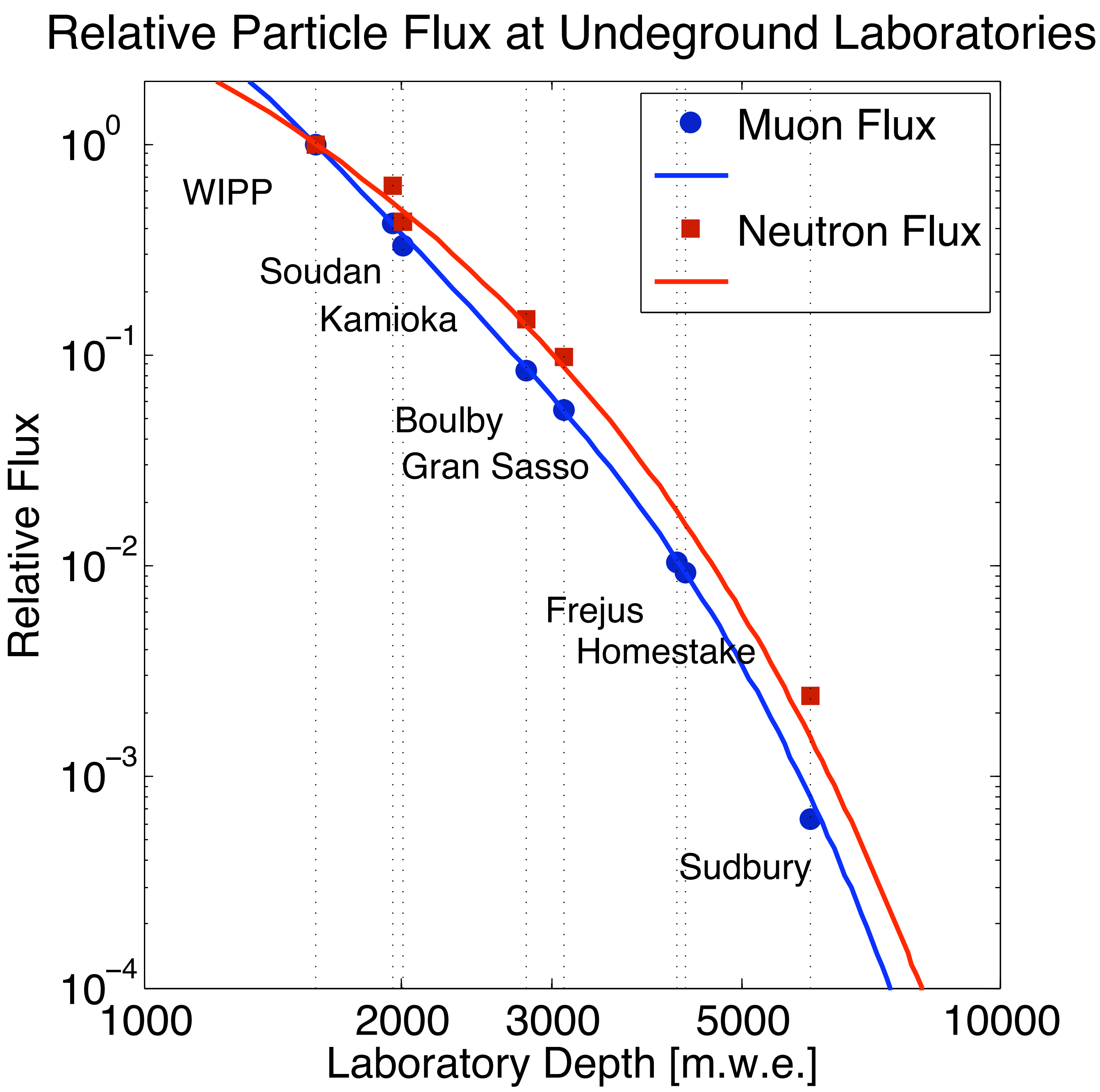
- Sensitivity to this effect effectively reduces background
  - Dark Matter is expected to interact “exclusively” with the nucleus while backgrounds interact predominantly with the electrons

The performance we need from our detectors

Backgrounds can't be eliminated entirely

Neutrons : Unrejected background

- Neutrons recoil off of atomic nuclei, thus appearing as WIMPS
- Neutrons come from
  - Environmental radioactivity
    - Slow / low energy
    - Can be addressed with shielding
  - Spallation due to cosmic muons
    - Fast / energetic = un-shieldable
    - Must go deep underground to avoid

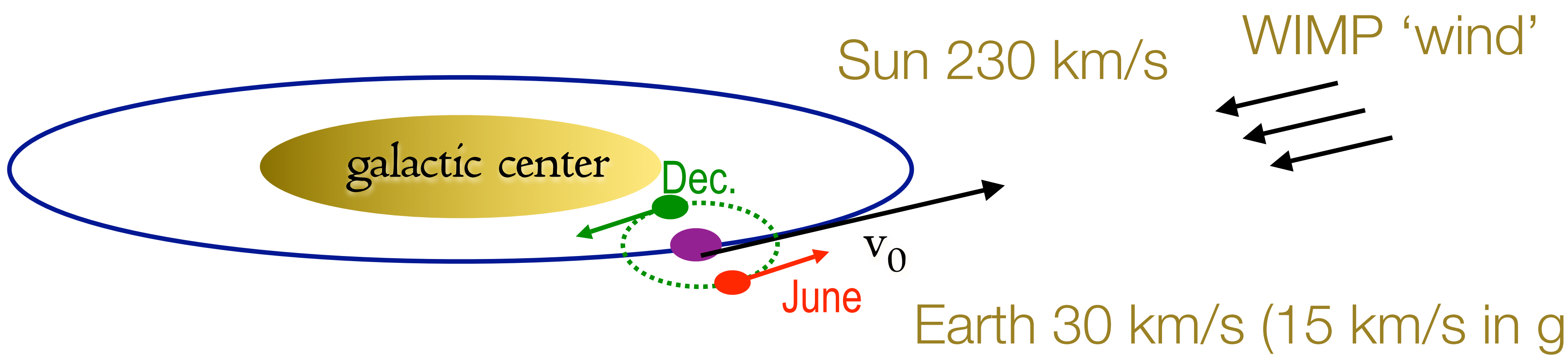


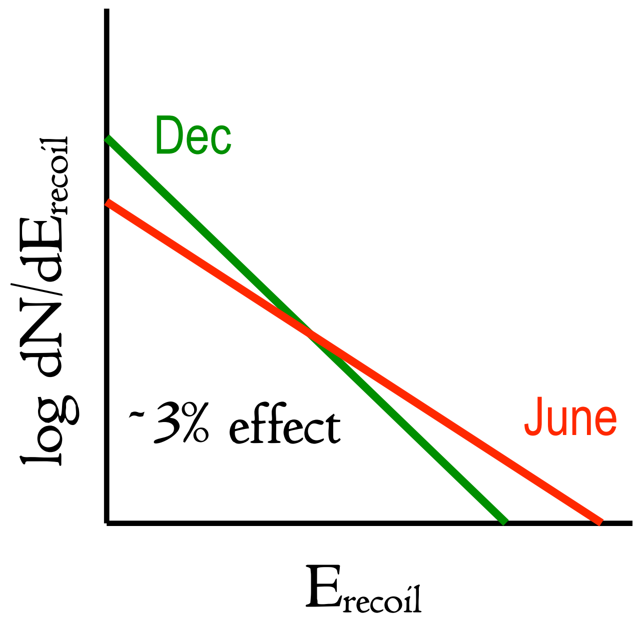
Directional Signal

- 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





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

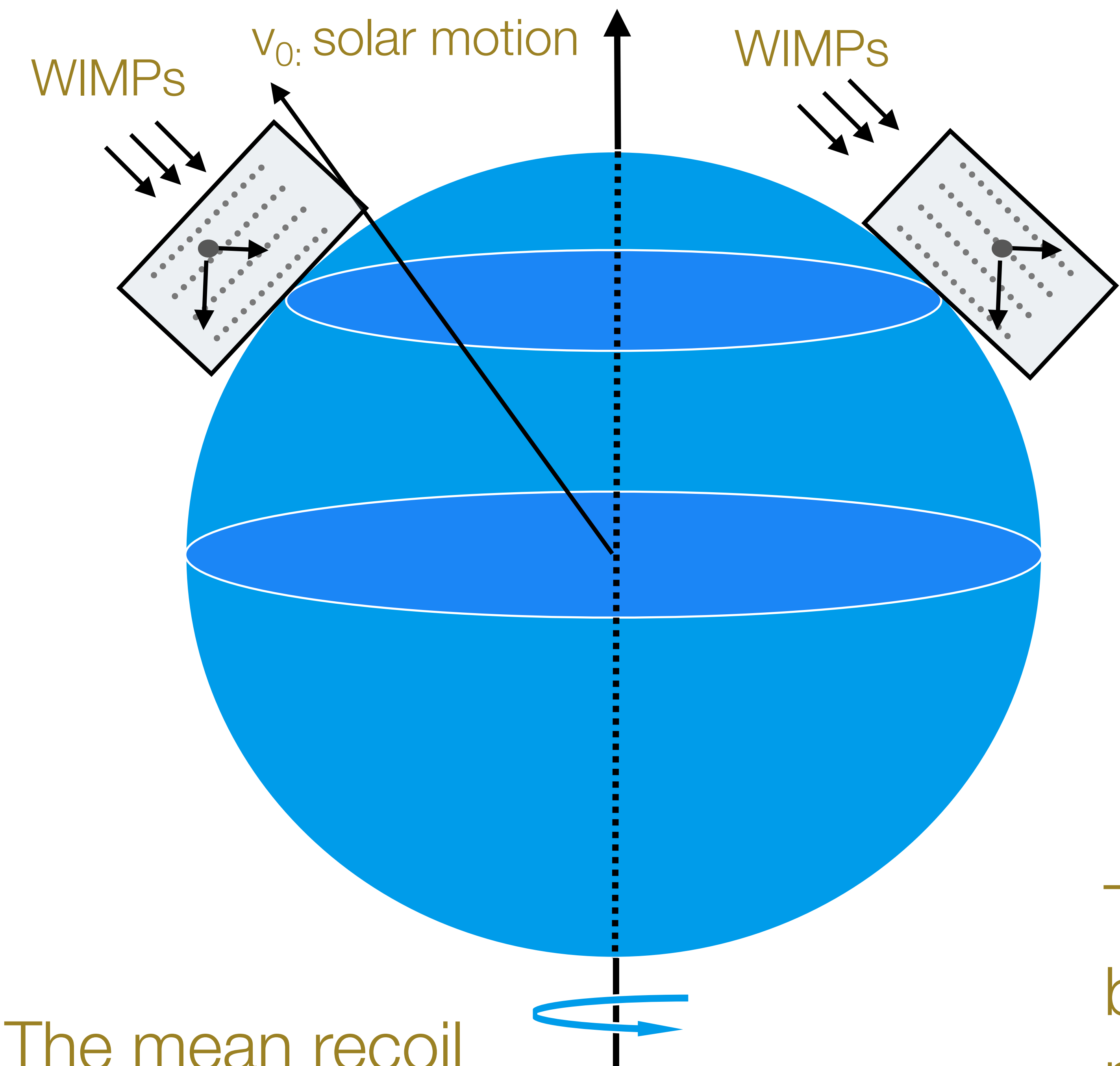
$$f(v)dv = \frac{vdv}{v_e v_o\sqrt{\pi}}\left\{\exp\left[-\frac{(v-v_e)^2}{v_0^2}\right] - \exp\left[-\frac{(v+v_e)^2}{v_0^2}\right]\right\}$$

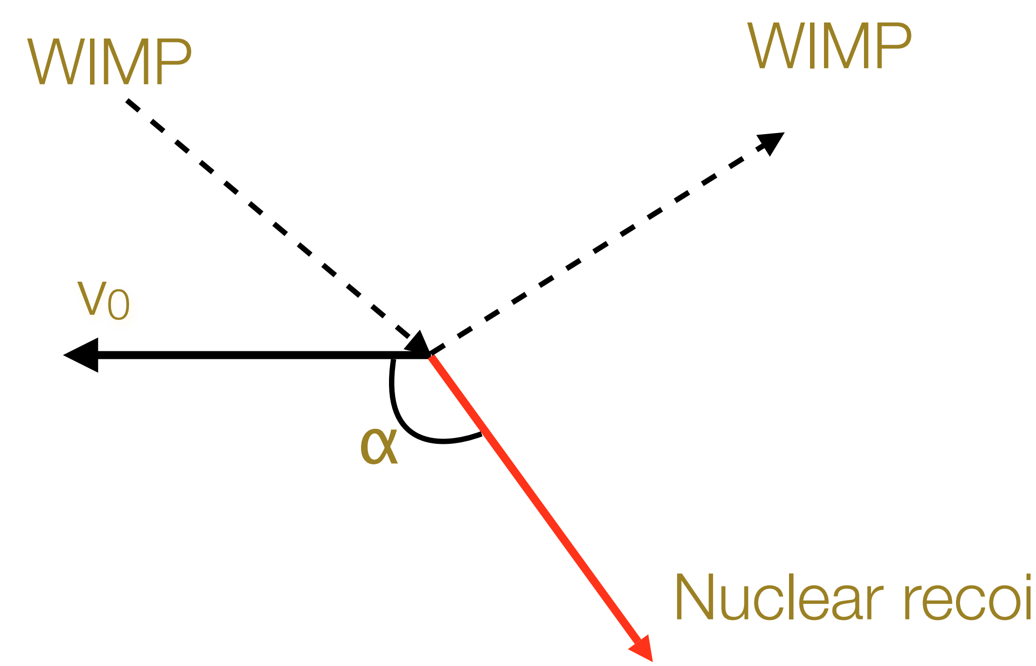
$$T(Q) = \frac{\sqrt{\pi}}{2}v_0\int_{v_{min}}^{\infty}\frac{f(v)dv}{v} = \frac{\sqrt{\pi}v_0}{4v_e}\left[\mathrm{erf}\left(\frac{v_{min}+v_e}{v_0}\right) - \mathrm{erf}\left(\frac{v_{min}-v_e}{v_0}\right)\right]$$

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?

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°

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)

Experimental Reach: Non-Discriminating

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

$$S_{90} \propto \frac{2.3}{\alpha M T}$$

    the sensitivity improves linearly with exposure

  - When some background events (N_{bkg}) are observed, the limits becomes:

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

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

Experimental Reach: Discriminating

- 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:

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

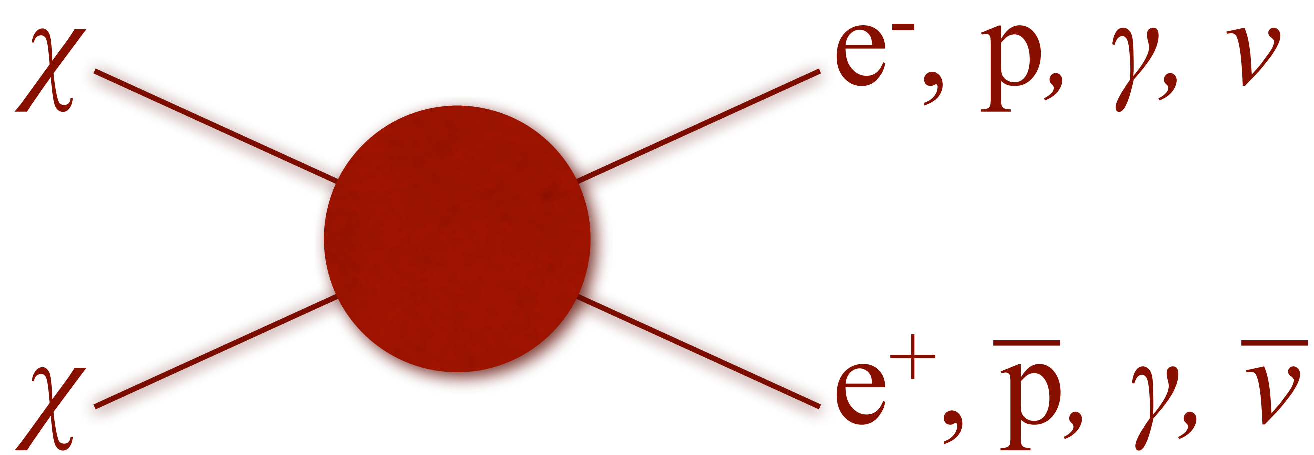
  - Let $Q \equiv \beta(1-\beta)/(\alpha-\beta)^2$, the value of η can be chosen to minimize Q.
  - For discriminating detectors, values of $Q \sim 10^{-3}$ are achievable, leading to a very low sensitivity (this is a good thing)
  - When some background events (N_{bkg}) are observed, the limit continues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

Dark Matter Detection References

- Jungman et al. Supersymmetric dark matter. Physics Reports (1996) vol. 267 pp. 195
- Lewin and Smith. Review of mathematics, numerical factors, and corrections for dark matter experiments based on elastic nuclear recoil. Astroparticle Physics (1996) vol. 6 pp. 87
- Saab. A Survey of Dark Matter Direct Detection Searches and Techniques at the Beginning of the 21ST Century. Modern Physics Letters A (2008) vol. 23 pp. 457
- R. Gaitskell et al. The statistics of background rejection in direct detection experiments for dark matter. Nuclear Physics B, Proceedings Supplements, 51B:279–283, 1996.
- Gaitskell. Direct Detection of Dark Matter. Annual Review of Nuclear and Particle Systems (2004) vol. 54 pp. 315

Principles of Indirect Detection

Principles of Indirect Detection



$$\boxed{\phi = \frac{\langle \sigma_{ann}\, v \rangle\, \rho_\chi^2}{m_\chi^2} g}$$

Input from Particle Physics

σ_{ann} : annihilation cross section

m_χ : WIMP mass

Input From Astrophysics

ρ : WIMP density at source

v : WIMP velocity at source

g : Propagation factor to earth

Annihilation Sources: Where the WIMPS are

- To know where to look for DM annihilation we must ask where is the dark matter to be found:

- A few sources:

  - Towards the center of our galaxy. The WIMP density increases rapidly toward the center of the galaxy leading to ρ^2 enhancement in the signal

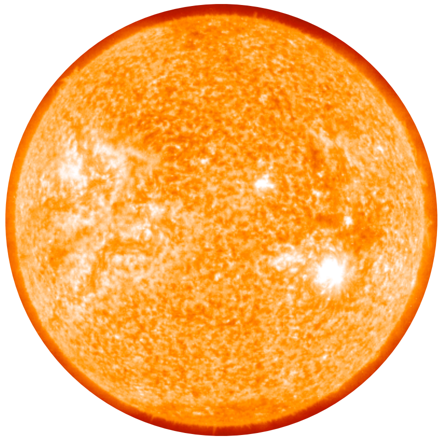
  - From neighboring dwarf/satellite galaxies

    There are the “obvious sources”. Galaxies formed in the gravity well of the dark matter halo

  - From the Sun, Earth, Jupiter?
    This are not so obvious sources. What is Dark Matter doing in the Sun?

Annihilation Sources: Where the WIMPS are

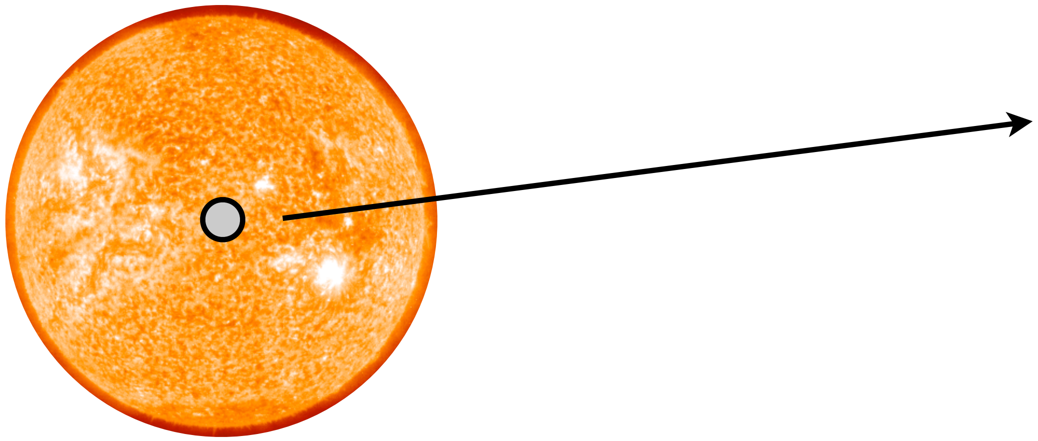
- From the Sun, Earth, Jupiter?
    - Dark Matter accumulates over time in the center of large objects
    - The rate of accumulation helps probe the χ-p scattering cross-section



I: WIMP is away from sun. Has velocity v_∞

Annihilation Sources: Where the WIMPS are

- From the Sun, Earth, Jupiter?
  - Dark Matter accumulates over time in the center of large objects
  - The rate of accumulation helps probe the χ-p scattering cross-section

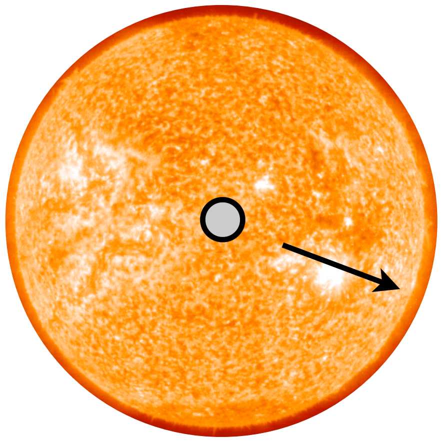


I: WIMP is away from sun. Has velocity v_∞

II: WIMP passes through the sun. Has velocity $v_\infty + v_{esc}$

Annihilation Sources: Where the WIMPS are

- From the Sun, Earth, Jupiter?
  - Dark Matter accumulates over time in the center of large objects
  - The rate of accumulation helps probe the χ-p scattering cross-section



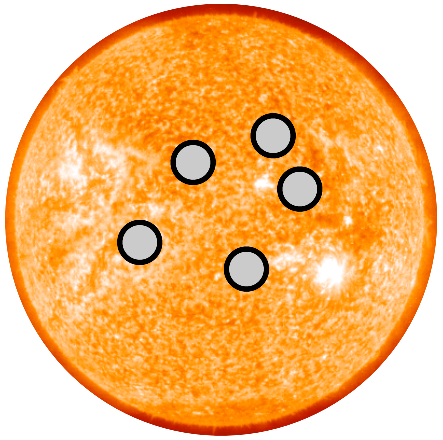
I: WIMP is away from sun. Has velocity v_∞

II: WIMP passes through the sun. Has velocity $v_\infty + v_{esc}$

III: WIMP scatters with an atom in the sun. Has final velocity $v < v_{esc}$

Annihilation Sources: Where the WIMPS are

- From the Sun, Earth, Jupiter?
  - Dark Matter accumulates over time in the center of large objects
  - The rate of accumulation helps probe the χ-p scattering cross-section



I: WIMP is away from sun. Has velocity v_∞

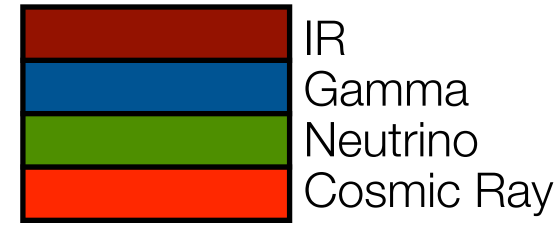
II: WIMP passes through the sun. Has velocity $v_\infty + v_{esc}$

III: WIMP scatters with an atom in the sun. Has final velocity $v < v_{esc}$

IV: WIMP is trapped in the sun. Accumulate over time until $\rho > \rho_c$, annihilation begins

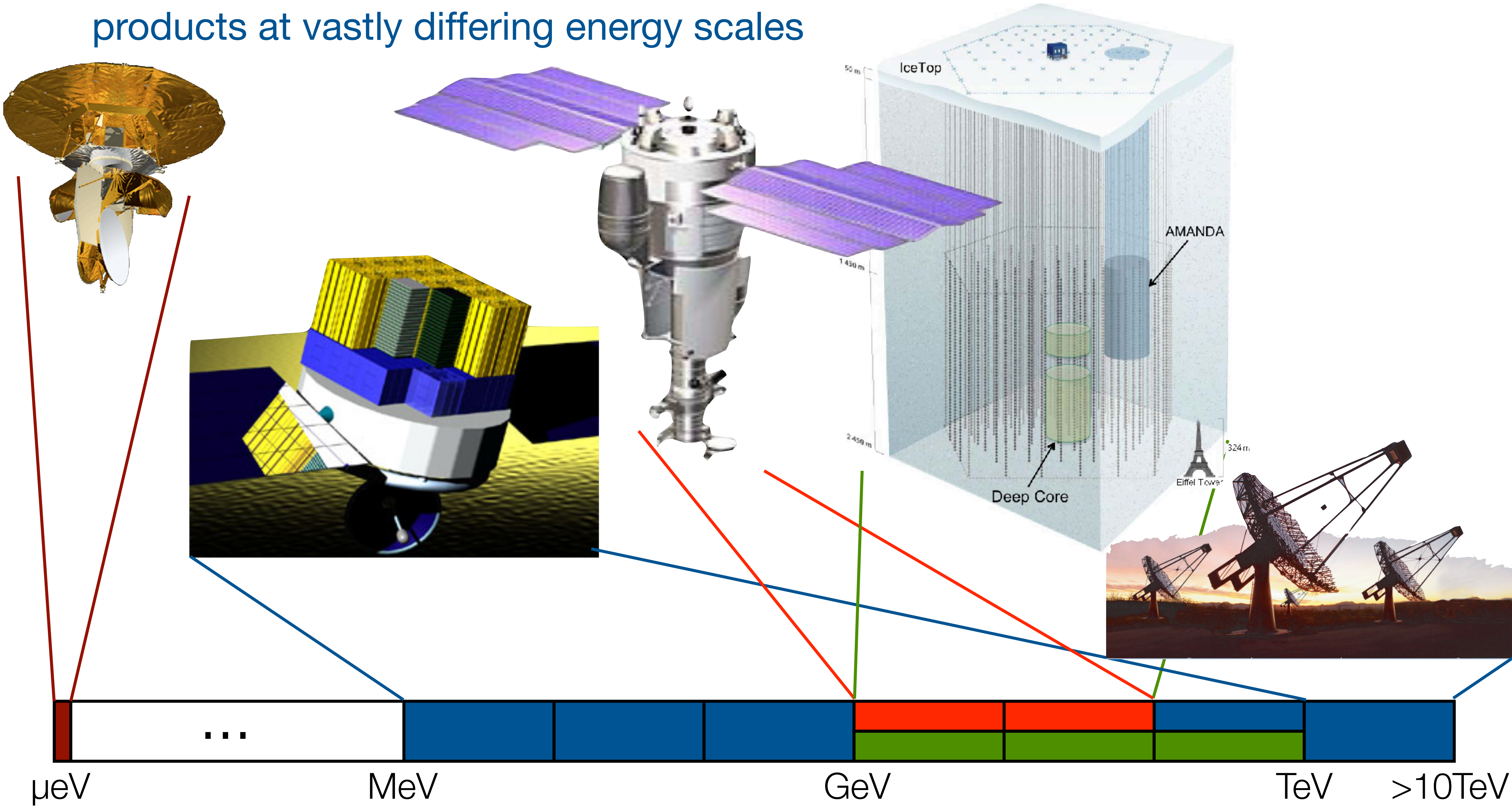
Final Products & Energy Scale

- Various experimental approaches exist to look for the different annihilation products at vastly differing energy scales
  - Sub-mm photons: space based bolometers: e.g. WMAP
  - MeV-GeV photons: space based calorimeters e.g. EGRET, FERMI
  - 1-100 GeV cosmic rays: space base spectrometers: PAMELA, ATIC, HEAT, FERMI
  - 100 GeV-10 TeV photons: ground based atmospheric cherenkov imaging detectors: HESS, VERITAS, MAGIC, CANGAROO
  - GeV-TeV neutrino: water/ice based neutrino detectors: Super-K, ANTARES, IceCube ...

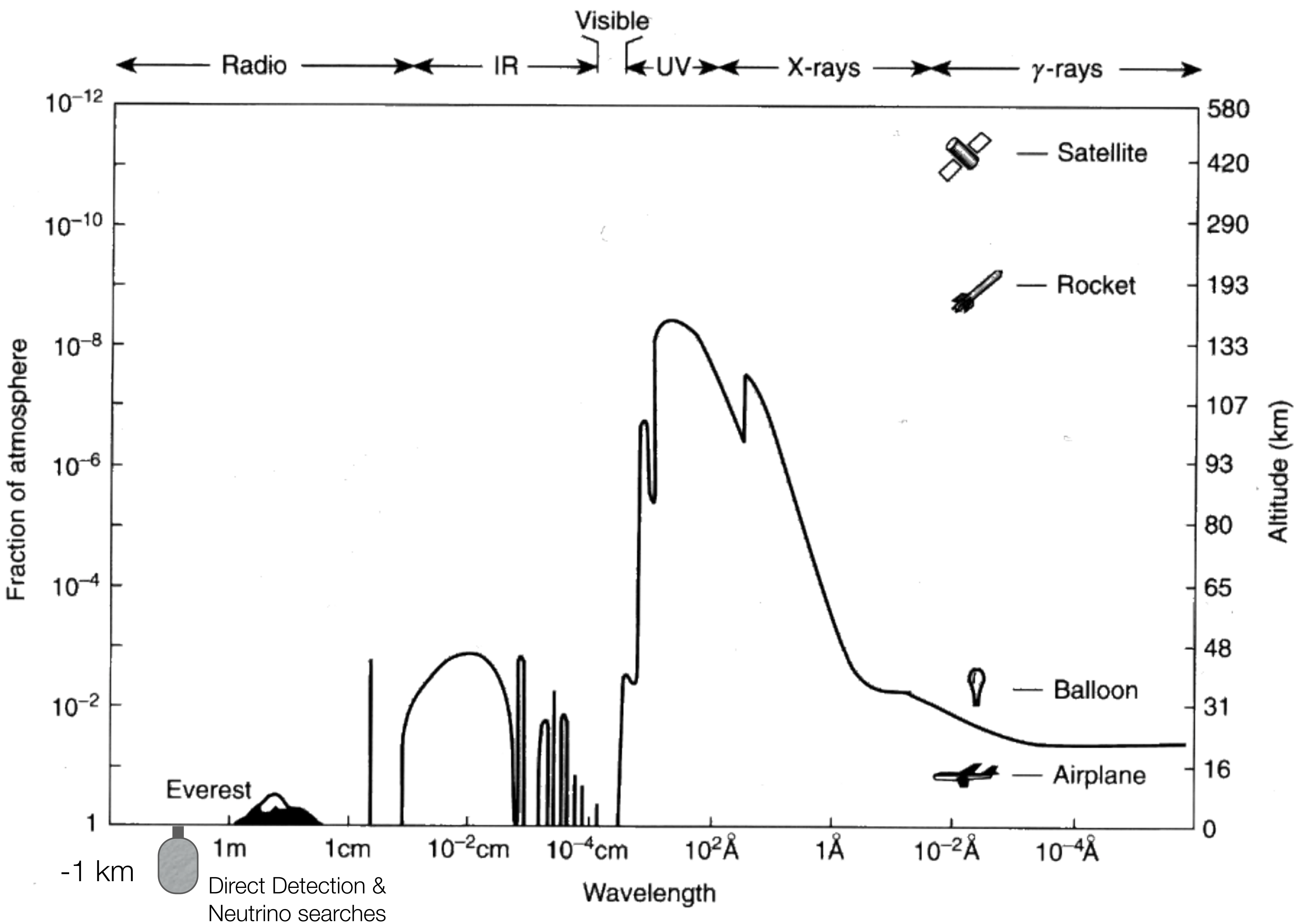


Final Products & Energy Scale

- Various experimental approaches exist to look for the different annihilation products at vastly differing energy scales

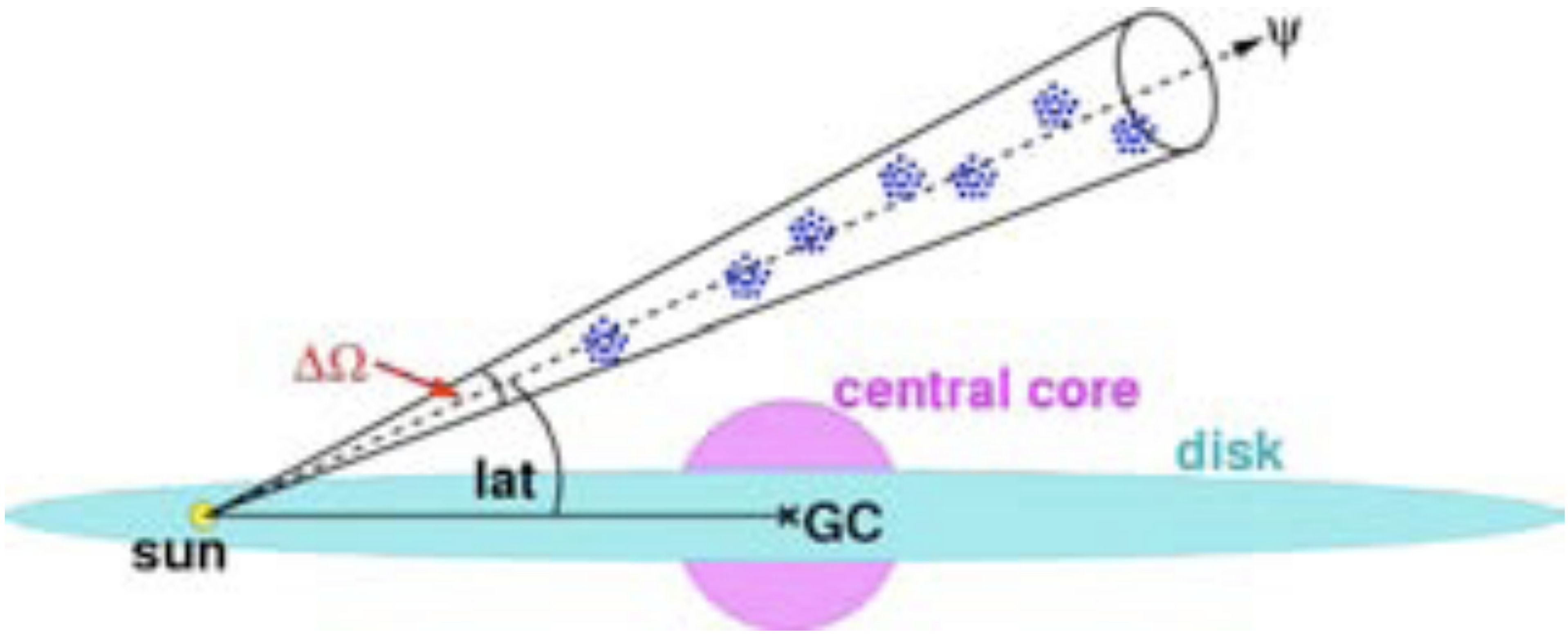


Astrophysics From All Altitudes



The Line of Sight Factor

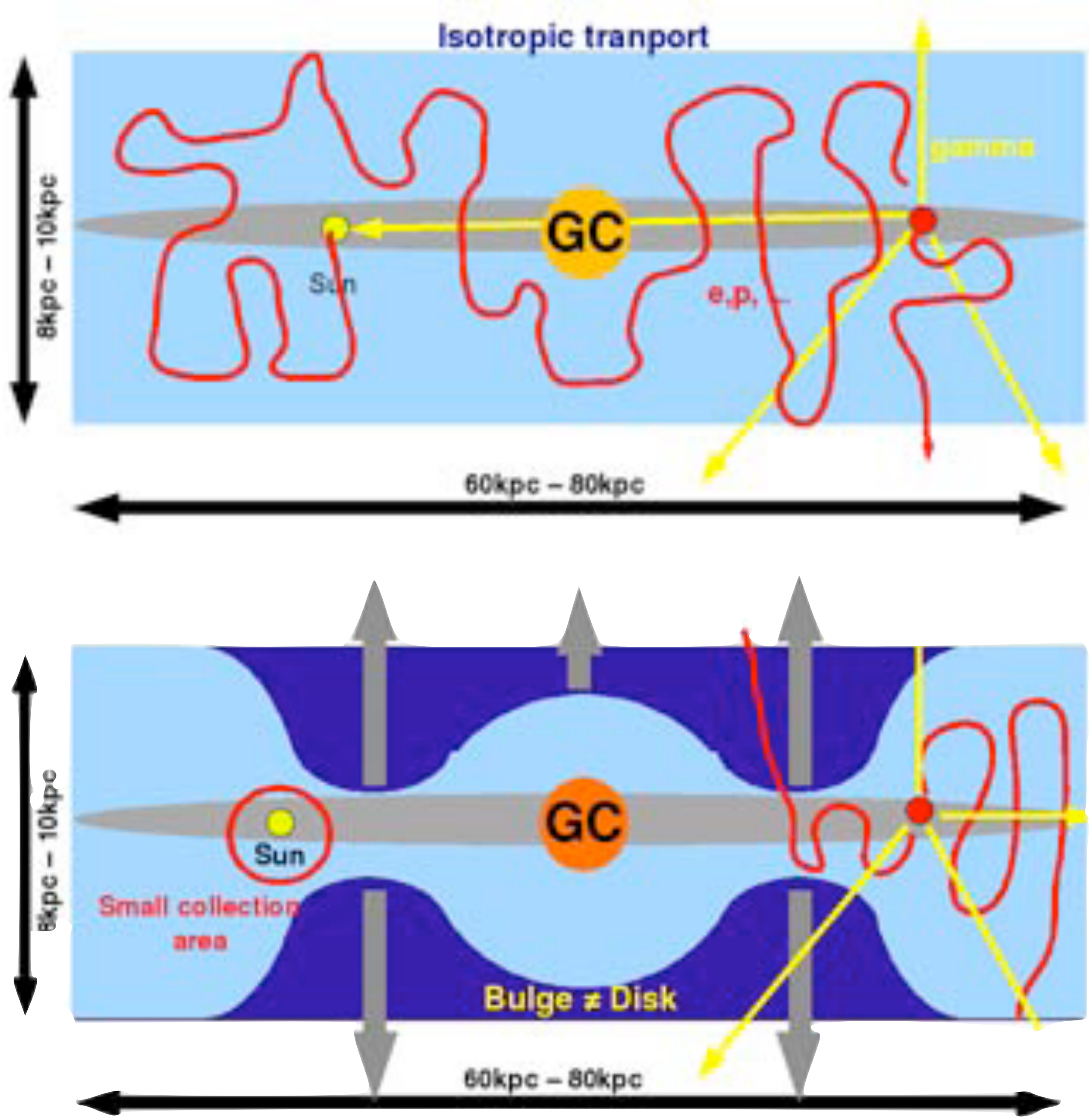
- Indirect detection of Dark Matter decay products (e.g. photons) is sensitive to the annihilation rates along any given line of sight
  - Must integrate over all DM densities in any given line of sight



I. Gebauer

The Propagation Factor

- Diffusive transport of charges cosmic rays requires detailed knowledge of galactic structure
  - Galactic winds can remove DM decay products
  - Diffusive transport parameters may be position dependent

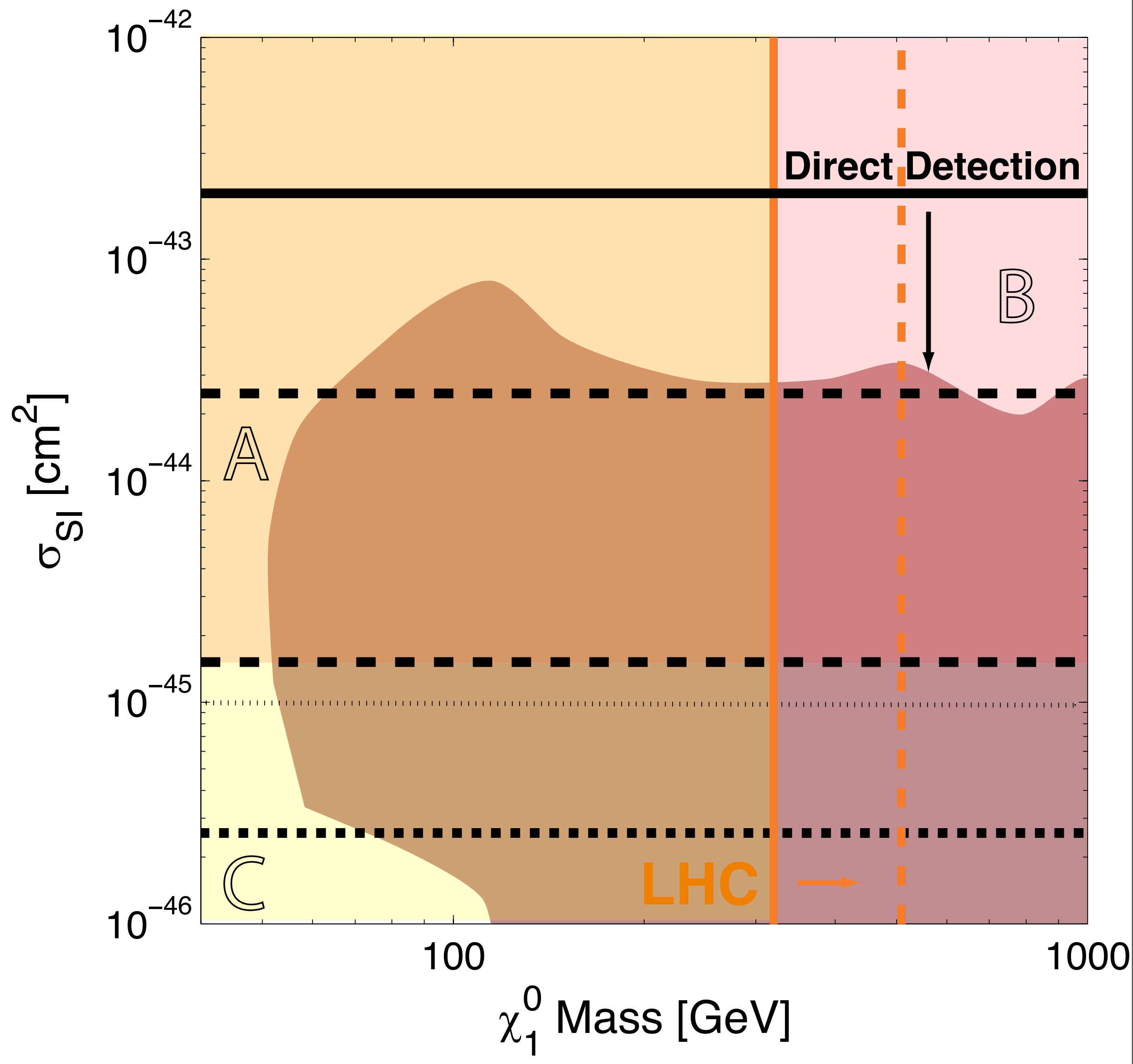


I. Gebauer

Complementarity with Colliders

Direct Detection and the LHC

- For most generic WIMP candidates information from both accelerators and direct detection experiments is required to fully identify and understand the particle
  - e.g. It is hoped / expected that the LHC will be able to produce the Lightest Supersymmetric Particle, however, it will not be able to identify it as the cosmological Dark Matter



Three way Complementarity

Direct Detection

- Discover relic particle
- Constrain m_χ, $\boldsymbol{\rho\sigma}_{dir}$
- With LHC input determine $\boldsymbol{\rho}_{local}$

Indirect Detection

- Discover relic particle
- Constrain m_χ, $\boldsymbol{\sigma}_{in}\int\boldsymbol{\rho}^2$
- With LHC input determine $\boldsymbol{\rho}_{halo}$ (or GC)

Collider Production

- Discover supersymmetric particles
- Determine physics model behind m_χ
- Predict $\boldsymbol{\sigma}_{(in\text{-})direct}$

Dark Matter Searches:
II - Experimental Implementations

Direct Detection Searches

World Wide ~~Web~~ Wimp searches

Over 2 dozen experiments worldwide

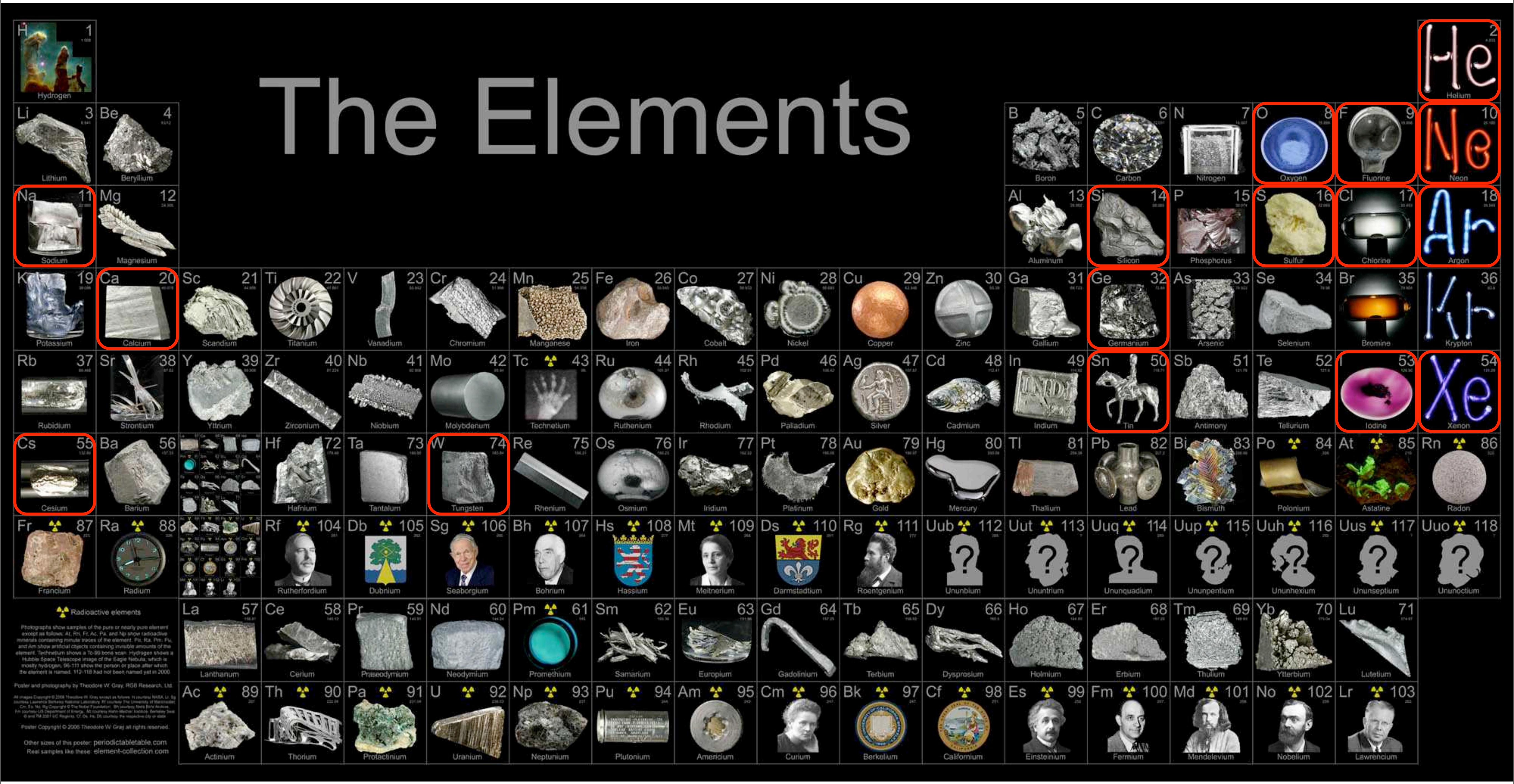
Current DM Searches

From : DIRECT DETECTION OF DARK MATTER,
R. J. Gaitskell, Annu. Rev. Nucl. Part. Sci. 2004. 54:315–59

TABLE 2 Current status of dark matter experiments (by technology)

Collaboration	Location	Readout	Target mass	Search dates
IGEX–DM	Baksan (Russia)	Ionization (77 K)	3 kg Ge	2001–
IGEX–DM	Canfranc (Spain)	Ionization (77 K)	2 kg Ge	2001–
GENIUS TF	Gran Sasso (Italy)	Ionization (77 K)	∼5 kg Ge $\beta\beta$	2002–2005
NAIAD	Boulby (UK)	Scintillator (∼300 K)	∼50 kg NaI array	2001–2005
LIBRA	Gran Sasso (Italy)	Scintillator (∼300 K)	≤250 kg NaI array	2003–
ANAIS	Canfranc (Spain)	Scintillator (∼300 K)	11 kg NaI prototype	2000–2005
Rosebud	Canfranc (Spain)	Therm. phon. (∼20 mK)	≤1 kg Ge, Al_2O_3	1995–
Rosebud	Canfranc (Spain)	Therm. phon. + scint. (∼20 mK)	∼1 kg $CaWO_4$, BGO	2000–
CDMS II	Soudan (USA)	Non-therm. phon. + ioniz. (<50 mK)	0.2–1.5 kg Si, 1–4.2 kg Ge	2001–2006
EDELWEISS II	Fréjus (France)	Therm. phon. + ioniz. (∼30 mK)	1 kg Ge	2000–2004
CRESST II	Gran Sasso (Italy)	Therm. phon. + scint. (∼10 mK)	1 kg $CaWO_4$	2000–2006
CUORICINO	Gran Sasso (Italy)	Therm. phon. (∼20 mK)	40 kg $T2O_2$ $\beta\beta$	2002–
ORPHEUS	Bern (Switzerland)	Superconducting grains (∼4 K)	0.5 kg Sn	2001–
SIMPLE	Rustrel (France)	Superheated droplets (∼300 K)	Freon	1999–
PICASSO	Sudbury (Canada)	Superheated droplets (∼300 K)	∼10 g–1 kg Freon	2001–
ZEPLIN I	Boulby (UK)	Scintillator PSD (∼150 K)	6 kg LXe	2002–2004
Xenon		Scint. + Ioniz	10 kg	2006--
XMASS-DM	Kamioke (Japan)	Scint. + ioniz. (∼150 K)	2 kg LXe	2002–2004
XMASS-DM	Kamioke (Japan)	Scint. + ioniz. (∼150 K)	14 kg LXe	2004–
DRIFT–I	Boulby (UK)	ioniz. NITPC (300 K)	0.167 kg CS_2	2002–2005
Bubble Chamber (Chicago)	Soudan (USA)	Superheated liquid (∼300 K)	1 kg Freons	2004–
(MACHe3)	Grenoble (France)—not underground	Exciton (∼20 mK)	0.02 g He_3	1998–

Dark Matter Search Elements



The Classical Approach

LIBRA

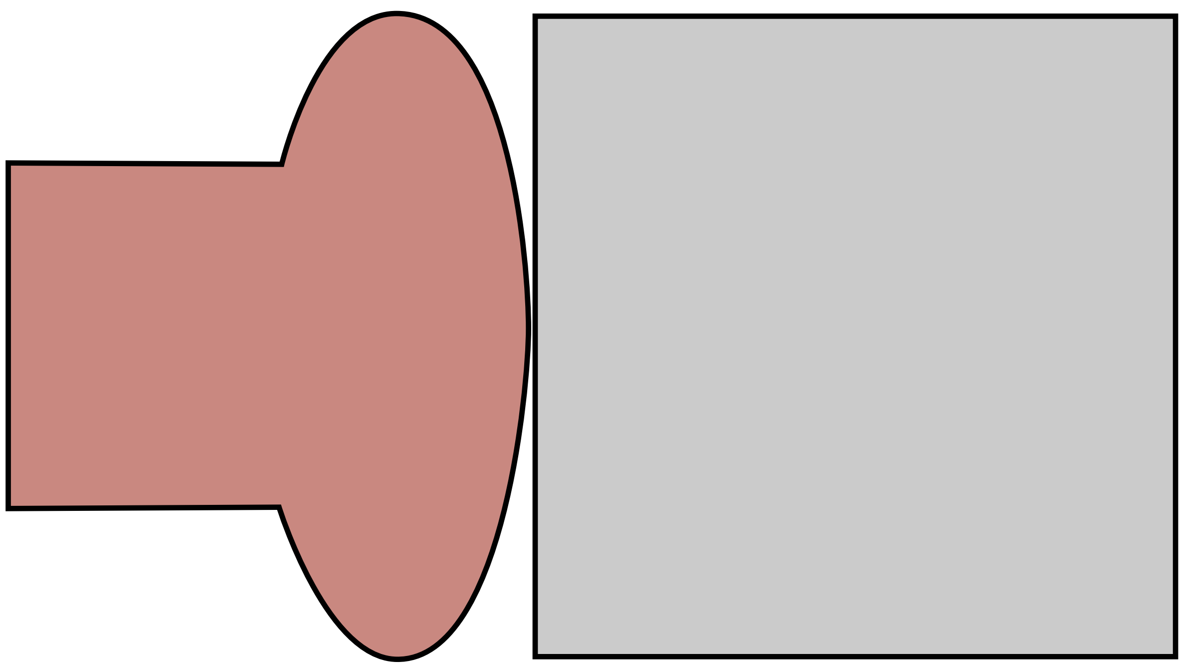
- Large sodium Iodide Bulk for RAre processes
- Target : Room Temp Scintillator
  - NaI crystals
  - Naturally abundant odd-spin isotopes allow for some sensitivity to both spin dependent and spin independent interactions
- Detection Mechanism
  - Photomultiplier tubes detect scintillation photons
  - #scintillation photons proportional to recoil energy (roughly 6 photoelectrons per keV)

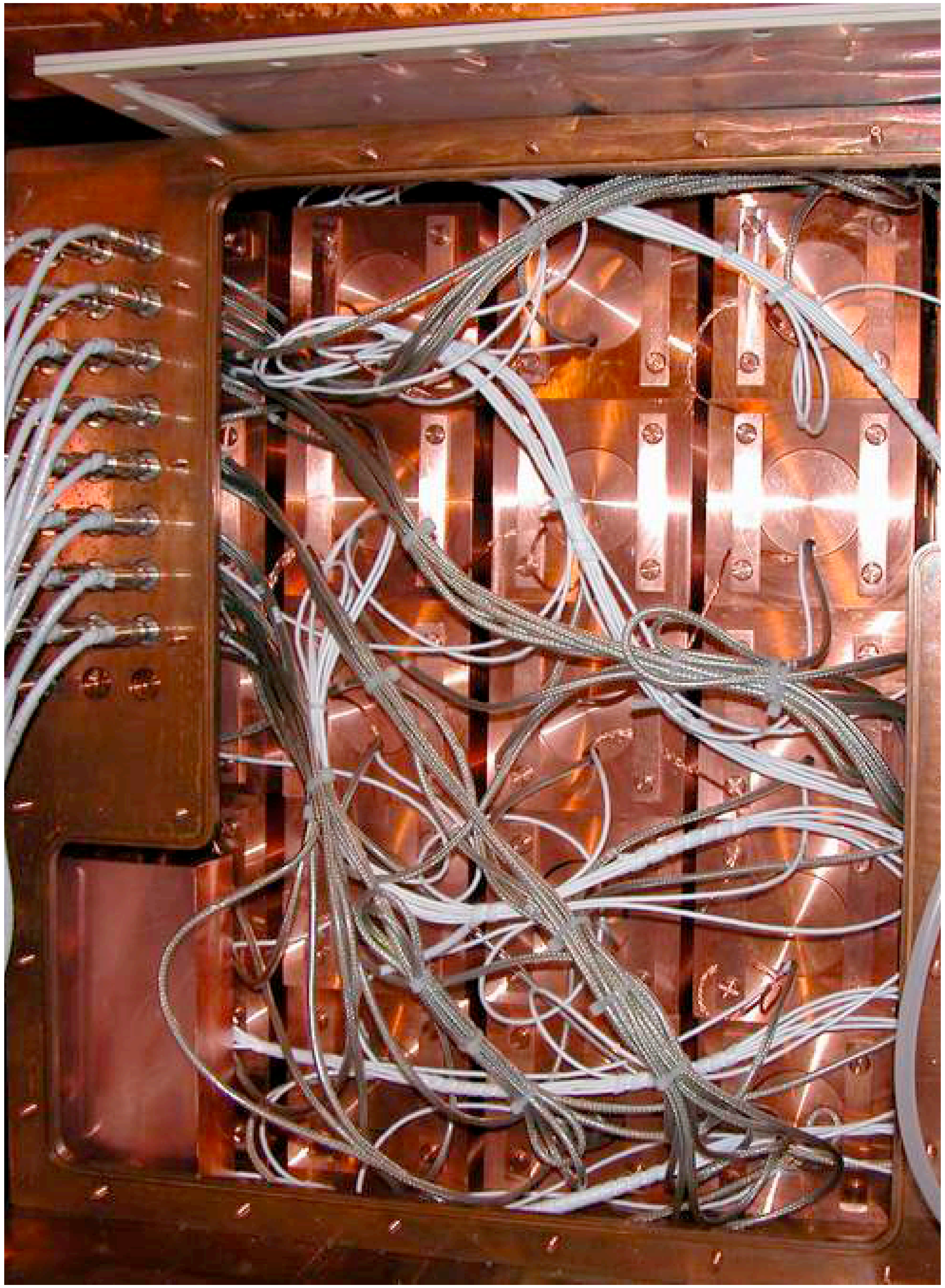
LIBRA

- 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

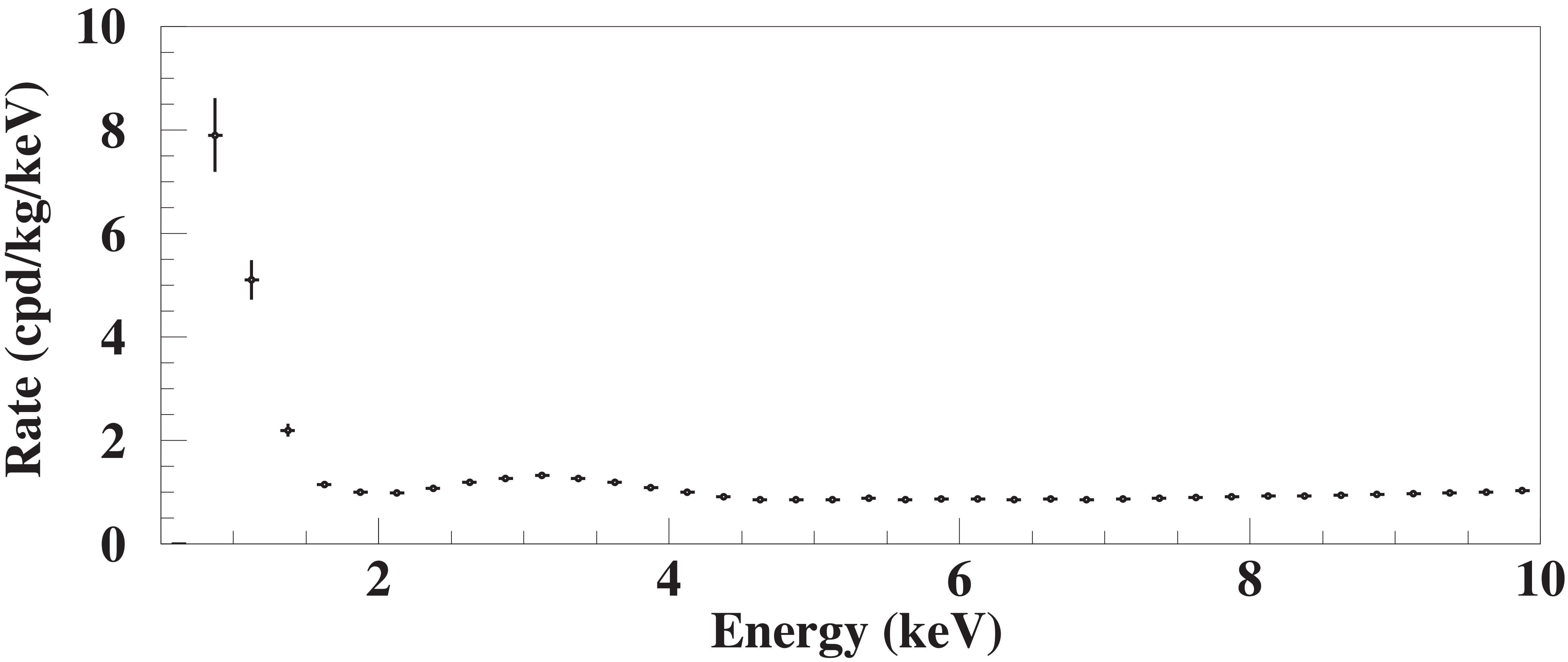




Inside LIBRA

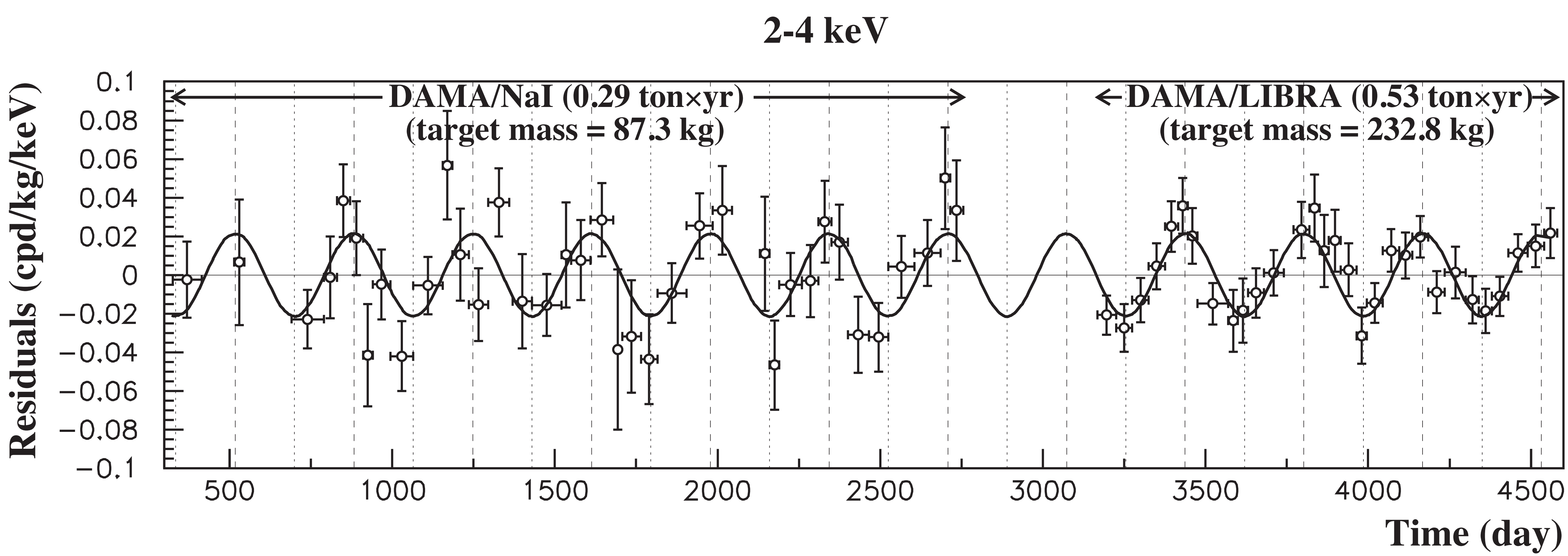
DAMA/LIBRA Collaboration

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



HDMS

- Heidelberg Dark Matter Search
- Target : Ge Crystals (cooled to liquid nitrogen temp.)
  - enriched Ge (A=72)
  - Largely sensitive to spin-independent interactions, although enriched presence ^{73}Ge allows for some spin-dependent sensitivity
- Detection Mechanism
  - Ionization signal : Electrons drifted through the crystal by an electric field result in a signal proportional to the recoil energy
  - #ionization electrons proportional to recoil energy

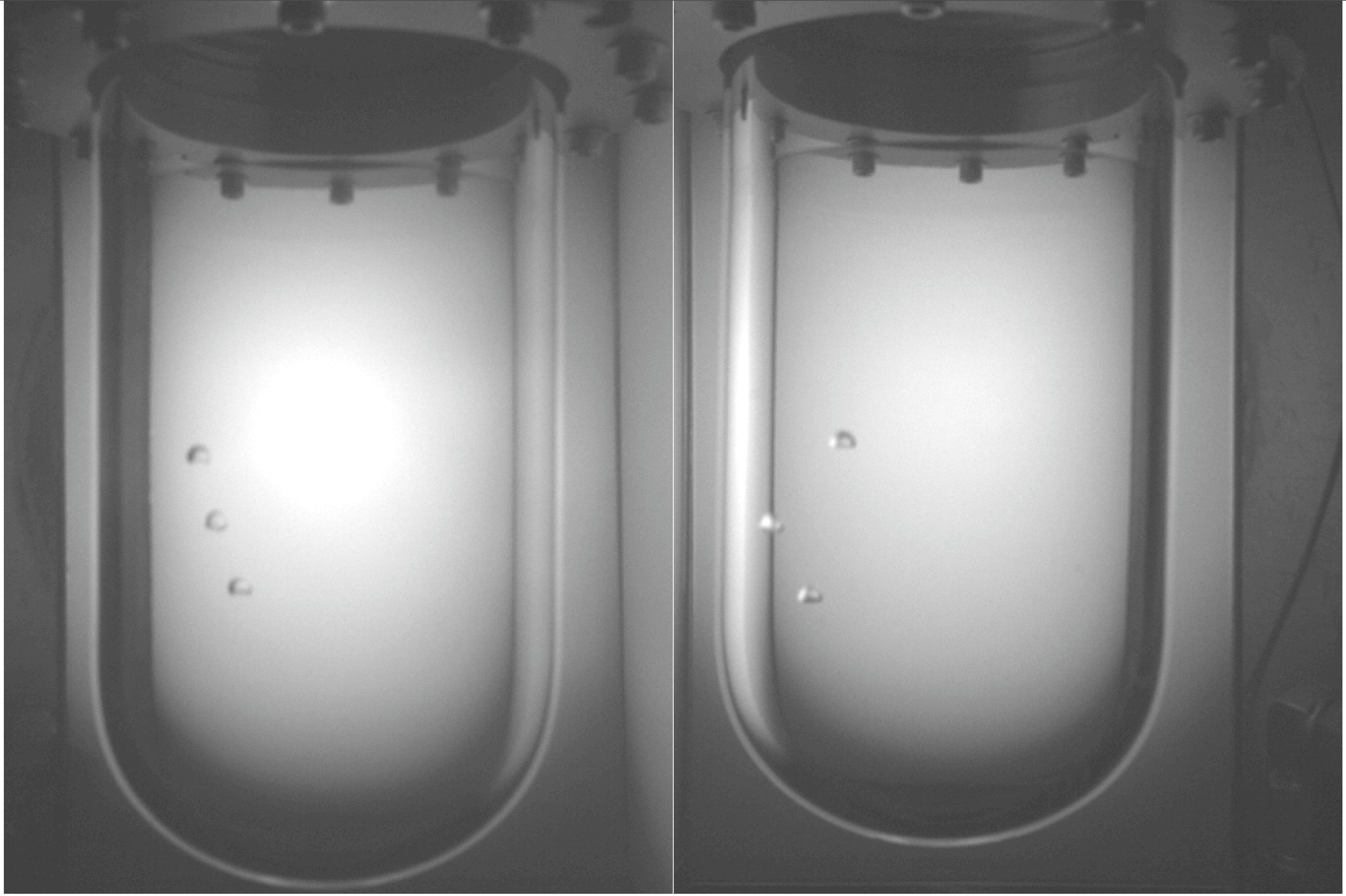
Insensitivity to Backgrounds

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

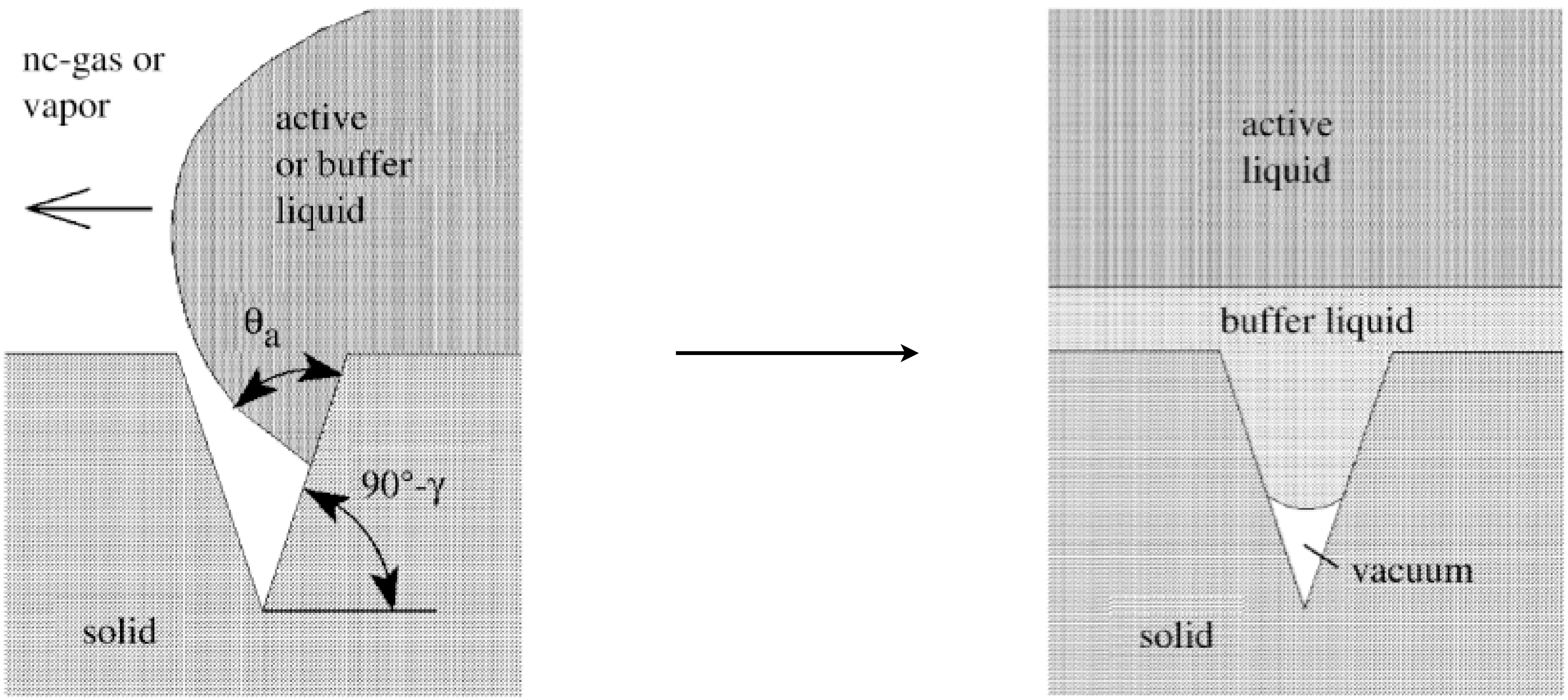
- Background Discrimination :
  - Insensitive to electron recoils (deposited energy density insufficient to create bubble)
  - By selecting operating pressure can reduce fraction of electron recoils resulting in bubble to ~ 10^{-9}
- Mass / Exposure
  - Finished operating 2 kg of detector at Fermilab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


COUPP Collaboration

COUPP in Action

A triple scatter neutron event

Bubble at the interface



جامعة وهران
Université d'Oran

School on
Particle Physics and Cosmology
Oran, Les Andalouses, 02-10 May 2009

LPTO
Laboratoire de Physique Théorique d'Oran

Dark Matter Searches in the 21st Century

Tarek Saab

Oran School on Particle Physics and Cosmology
May 2009

Recap

- So far, we have discussed
  - The kinematics of Dark Matter / Nucleus scattering
  - General behavior of scattering cross-section with nuclear properties
  - Variety of detection techniques available for DM searches
  - Experimental reach (or sensitivity) of an experiment
- Today we will cover:
  - Finish the survey of direct detection experiments
  - Discuss the latest Dark Matter direct exclusion limits
  - Brief survey of indirect detection searches
  - If time allows, ... discussion of axion search experiments

Experimental Sensitivity vs Time

Zero Events

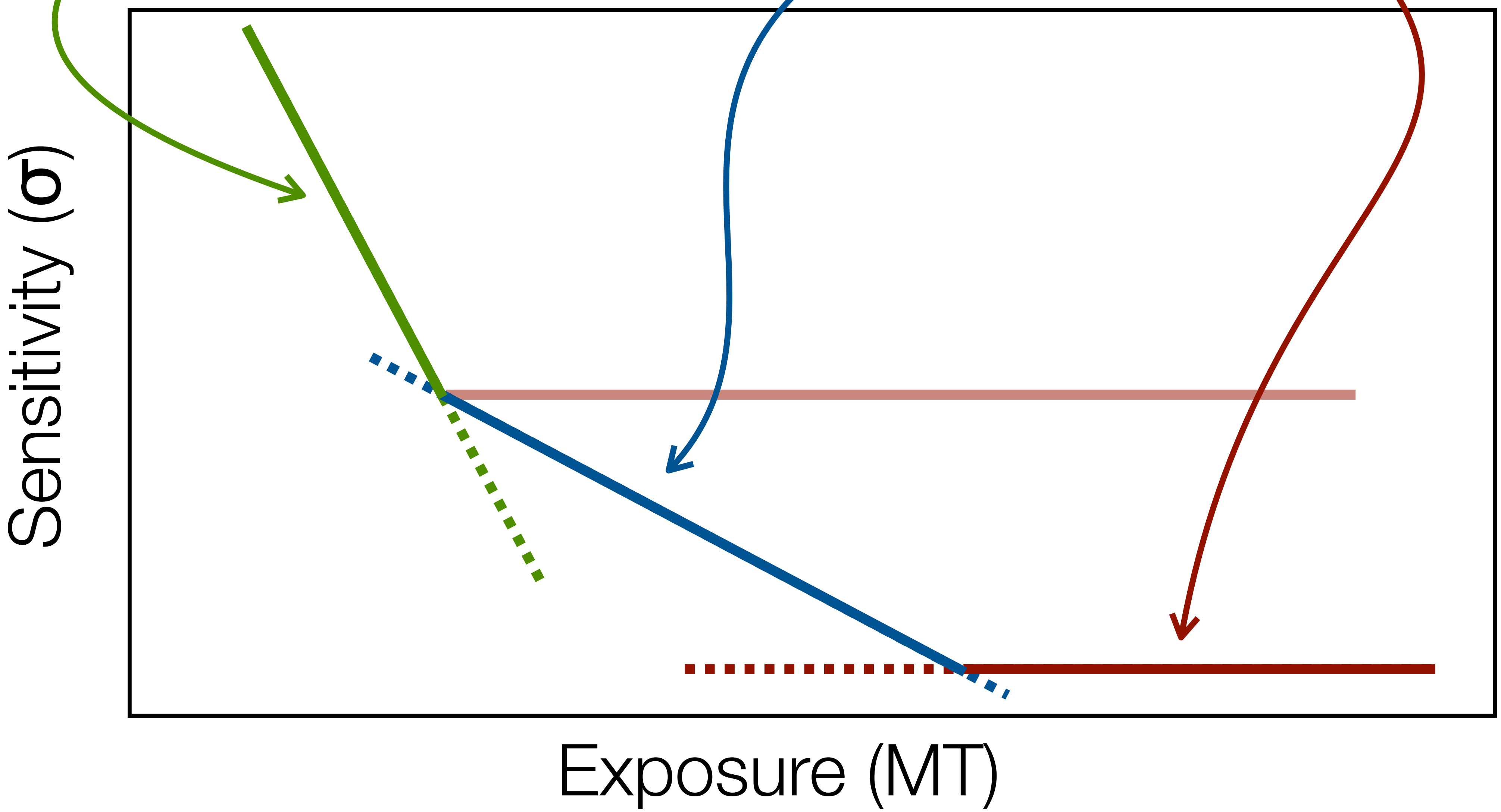
$$S_{90} \propto \frac{2.3}{\alpha M T}$$

Discriminating Detector

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

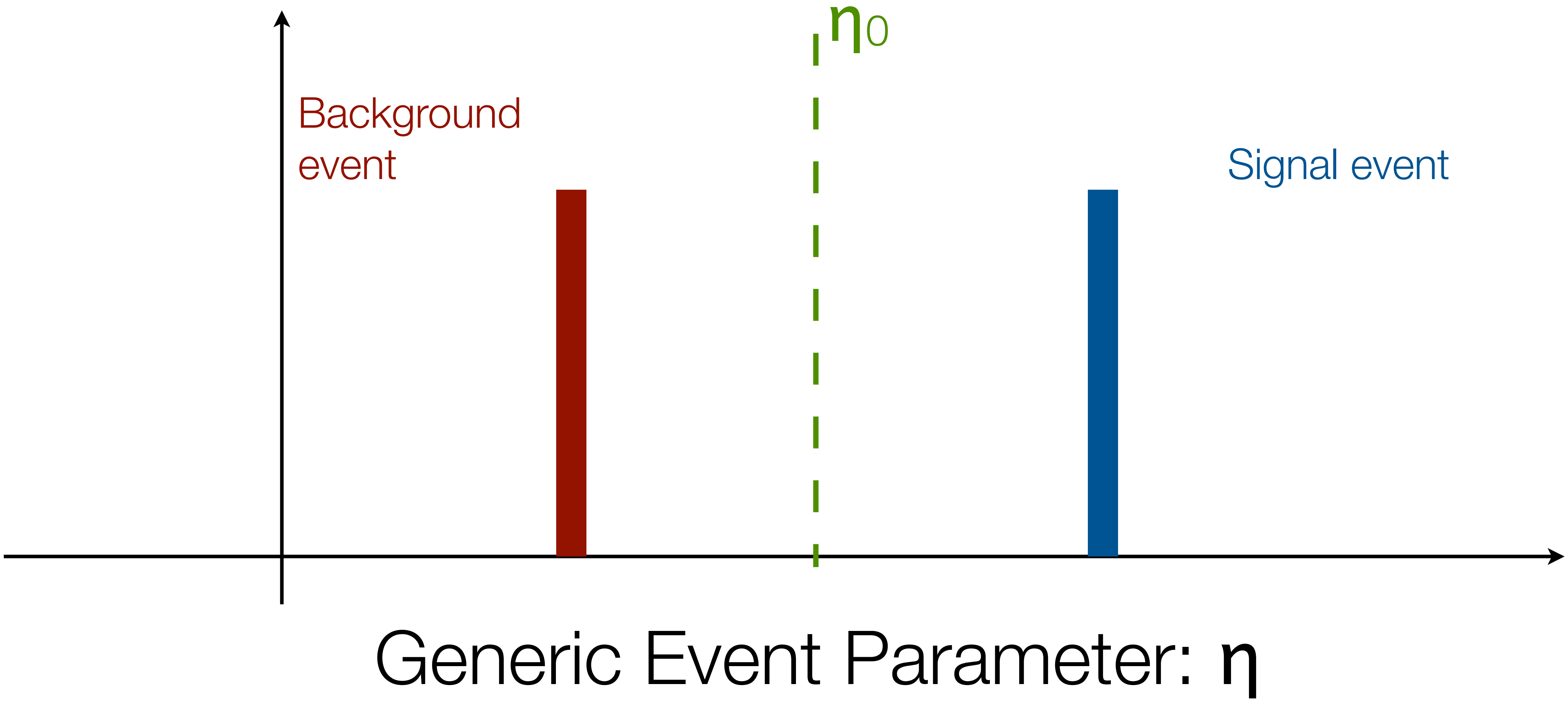
Non-Discriminating

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



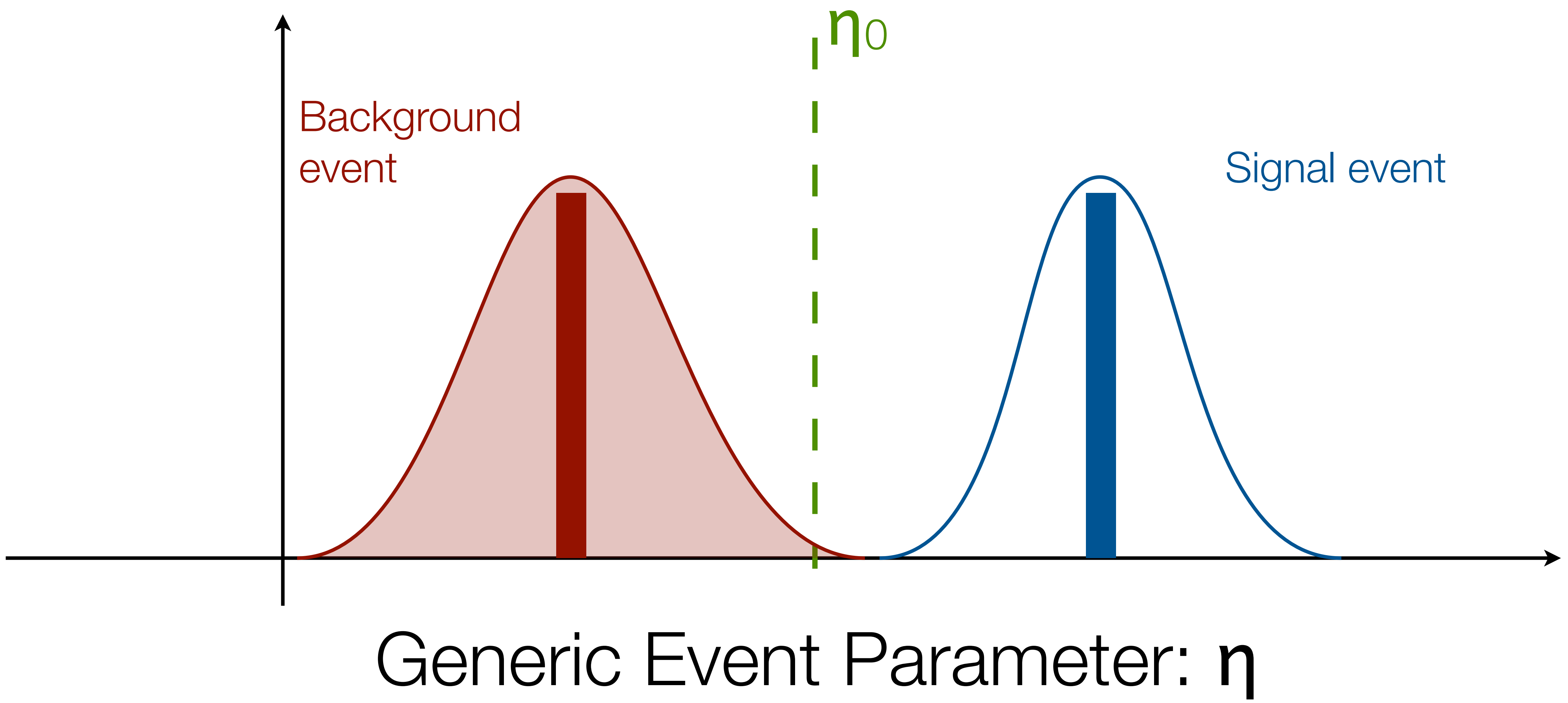
Discriminating Variables

- 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 $\beta\neq0$, $\alpha<1$



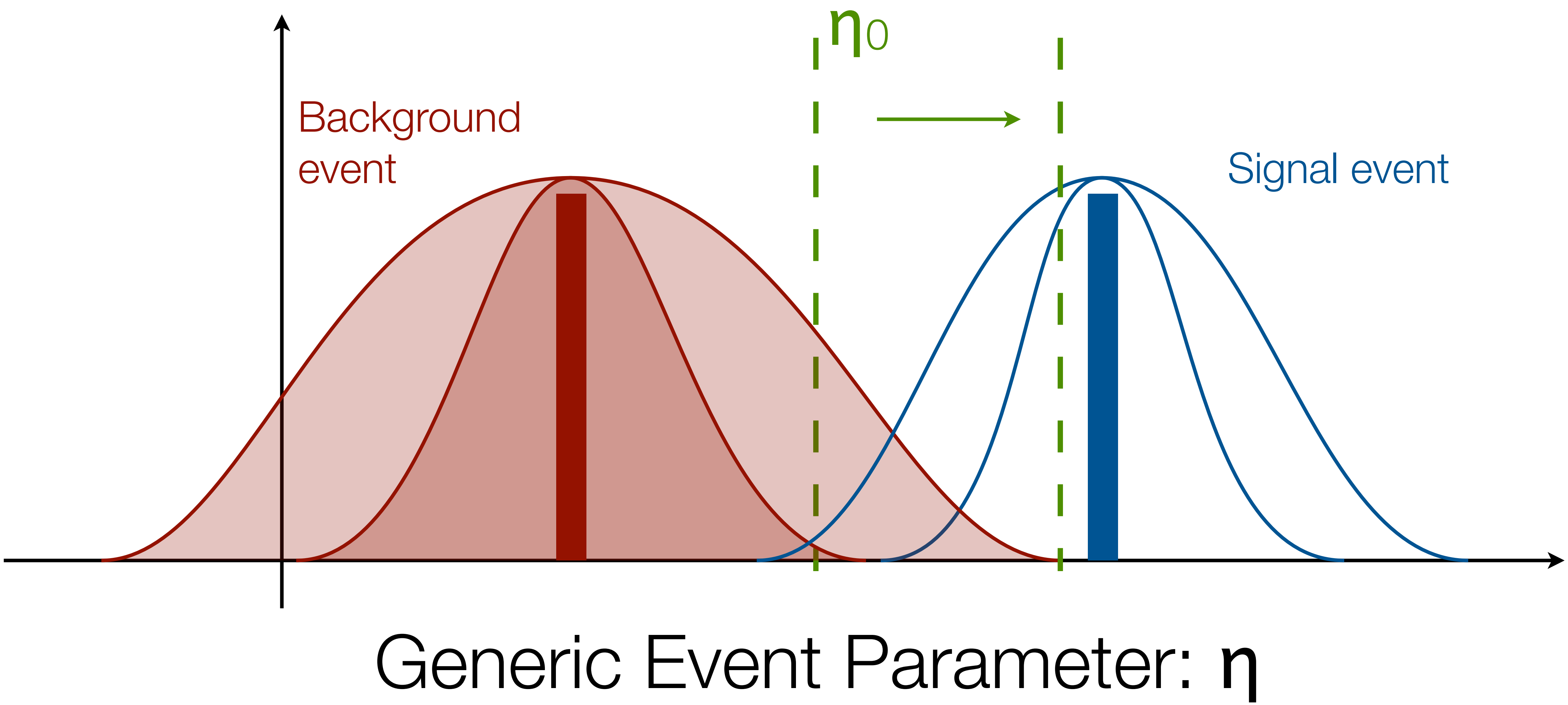
Discriminating Variables

- 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 $\beta\neq0$, $\alpha<1$



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 $\beta\neq0$, $\alpha<1$



Insensitivity to Backgrounds

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

PICASSO

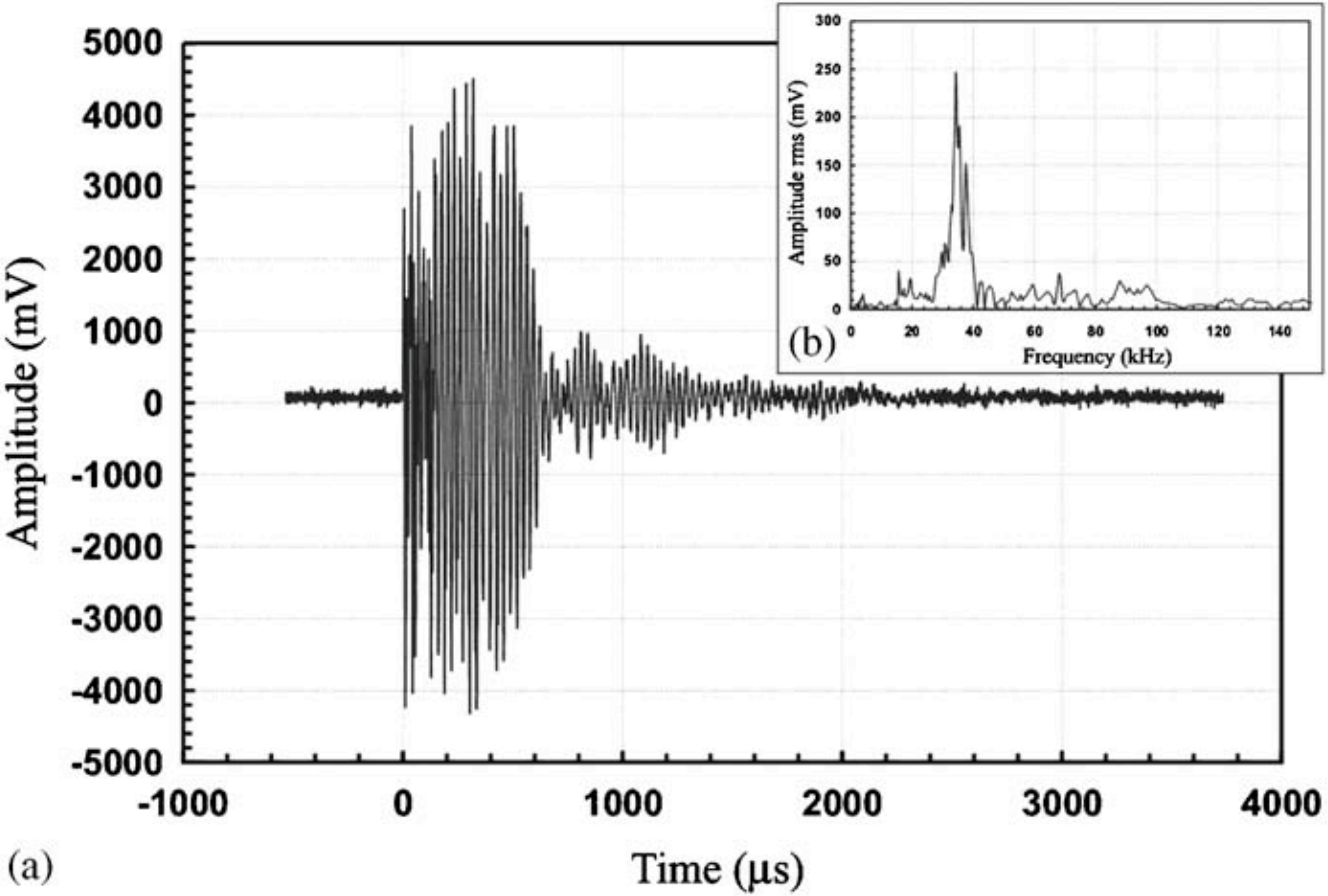
- Project In CAnada to Search for Supersymmetric Objects
- Target : Fluoriunated Halocarbon liquids
  - CF_4
  - Sensitive to spin-dependent interactions
- Detection Mechanism
  - Bubble formation in superheated liquid
  - Acoustic sensors detect formation of bubble
  - Sensitive to events with recoil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

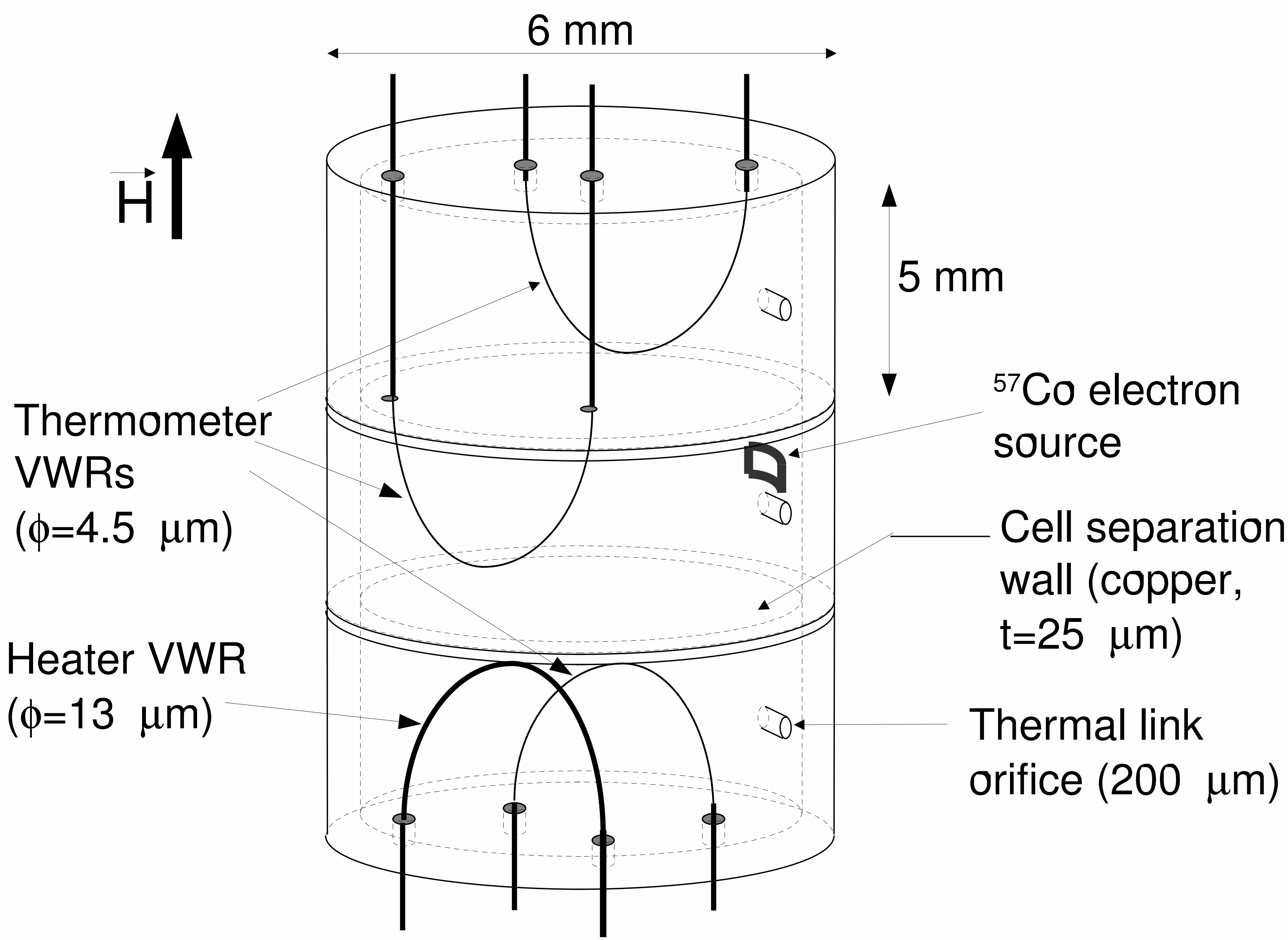
PICASSO in Action

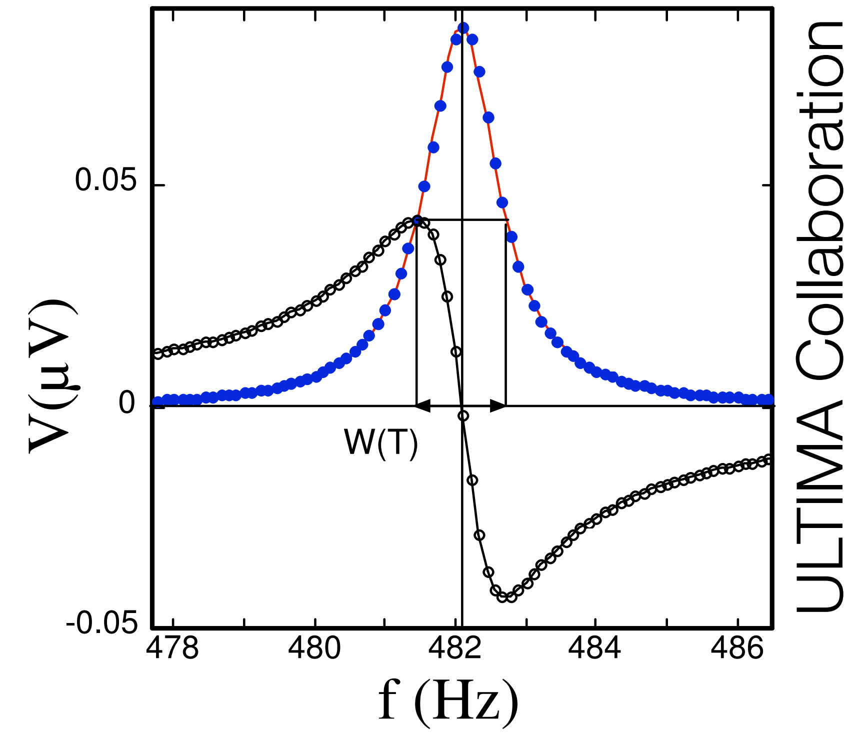


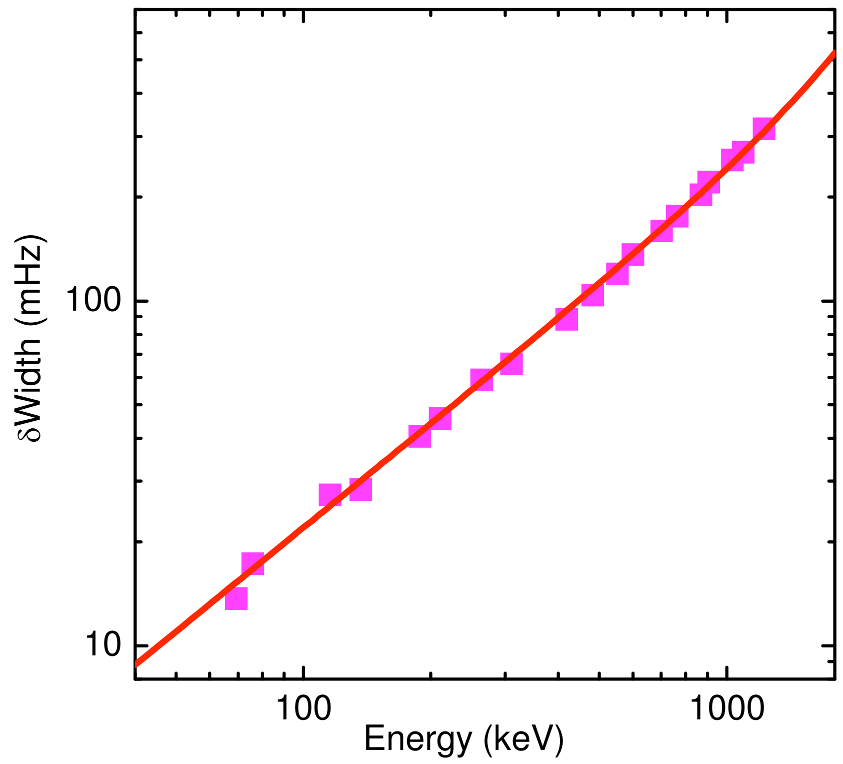
PICASSO in Action

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

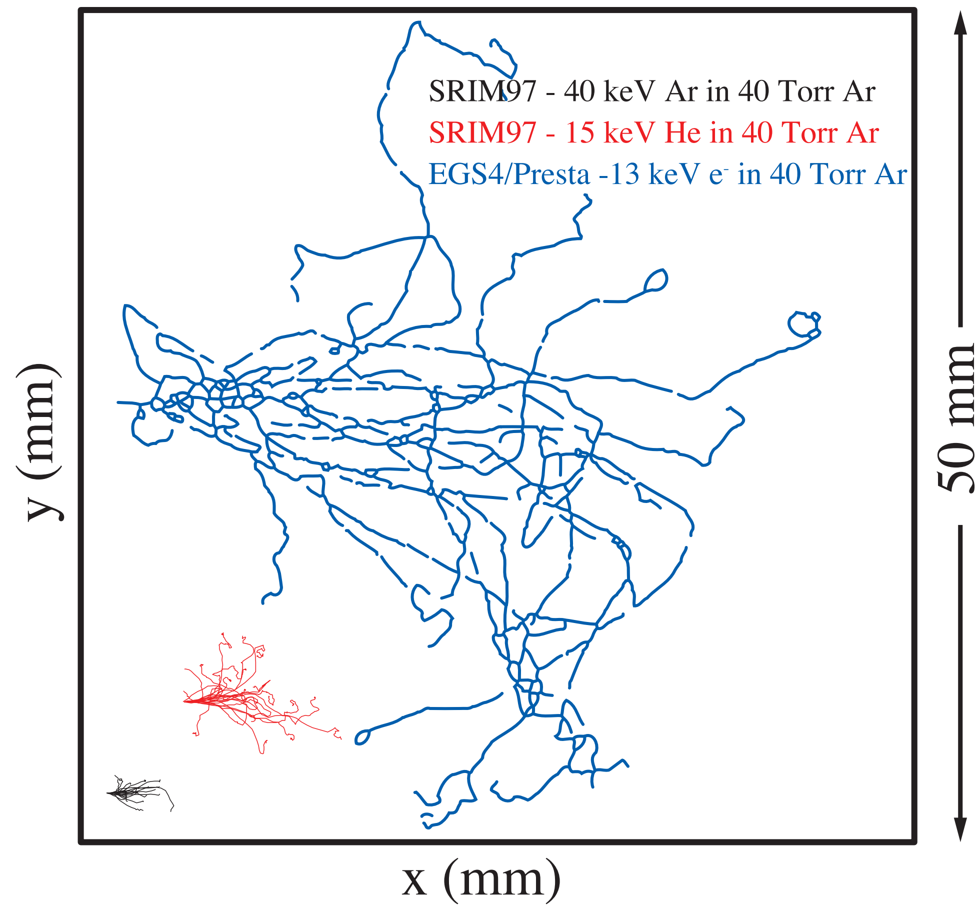
DRIFT

(see also DM-TPC / NEWAGE)

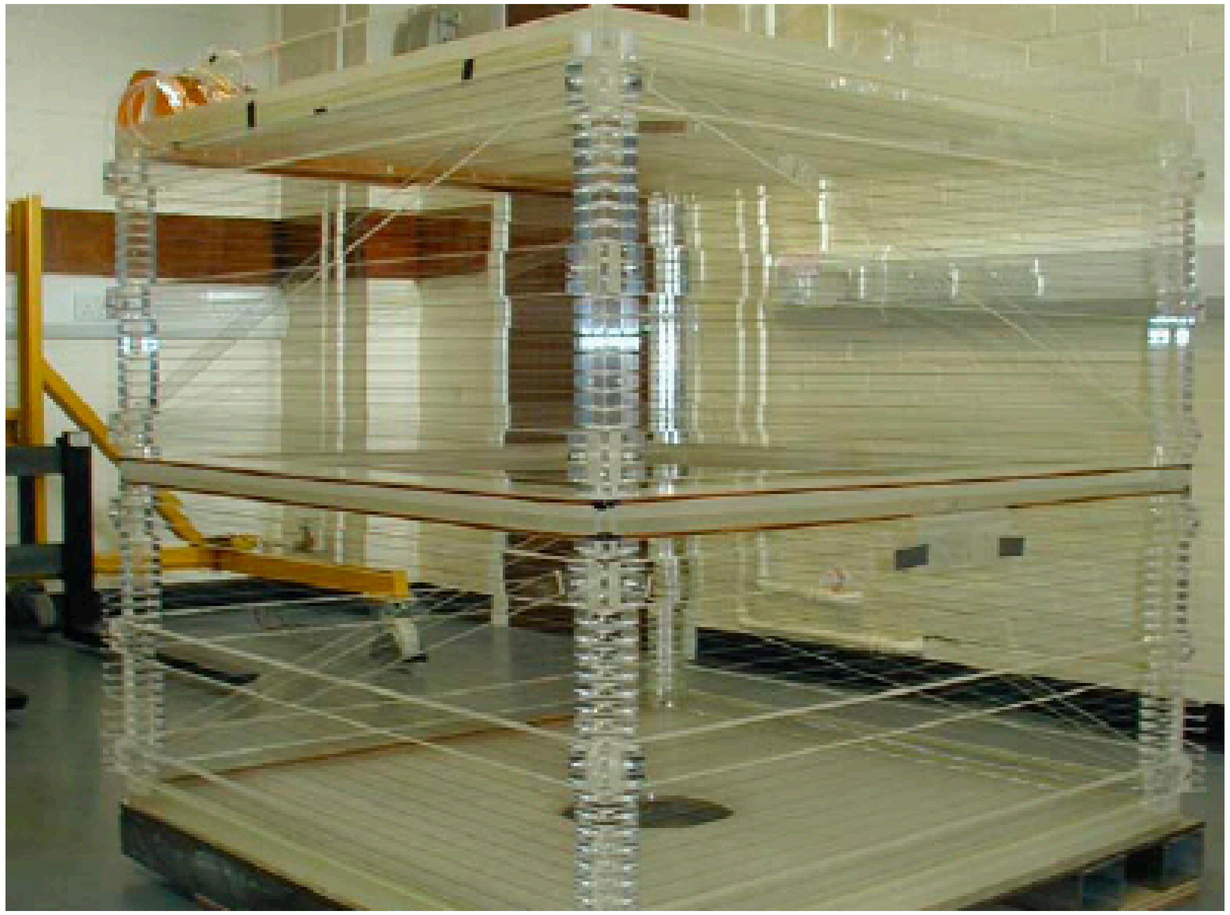
- Directional Recoil Identification From Tracks
- Target :
  - CS_2 gas
  - Sulfur : A=32
  - Sensitivity to spin-independent interactions
- Detection Mechanism
  - Time projection chamber
  - Length/shape of track dependent on energy density of recoiling particle

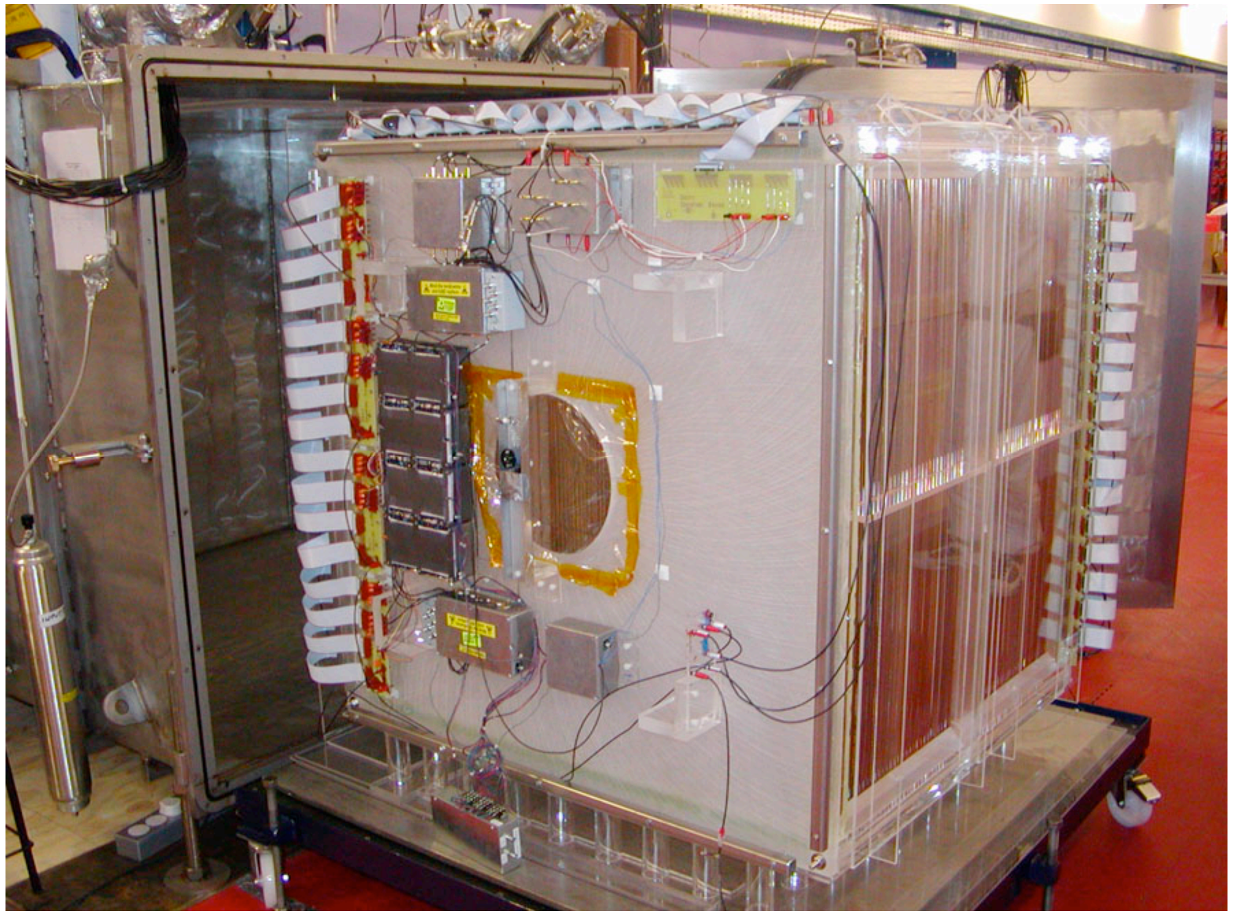
DRIFT

- Background Discrimination :
    - Track shape
    - Recoil directional



- Mass / Exposure
    - DRIFT-II : 10 kg-day data accumulated
    - DRIFT-III : 100 kg target mass





DRIFT Collaboration

Inside DRIFT

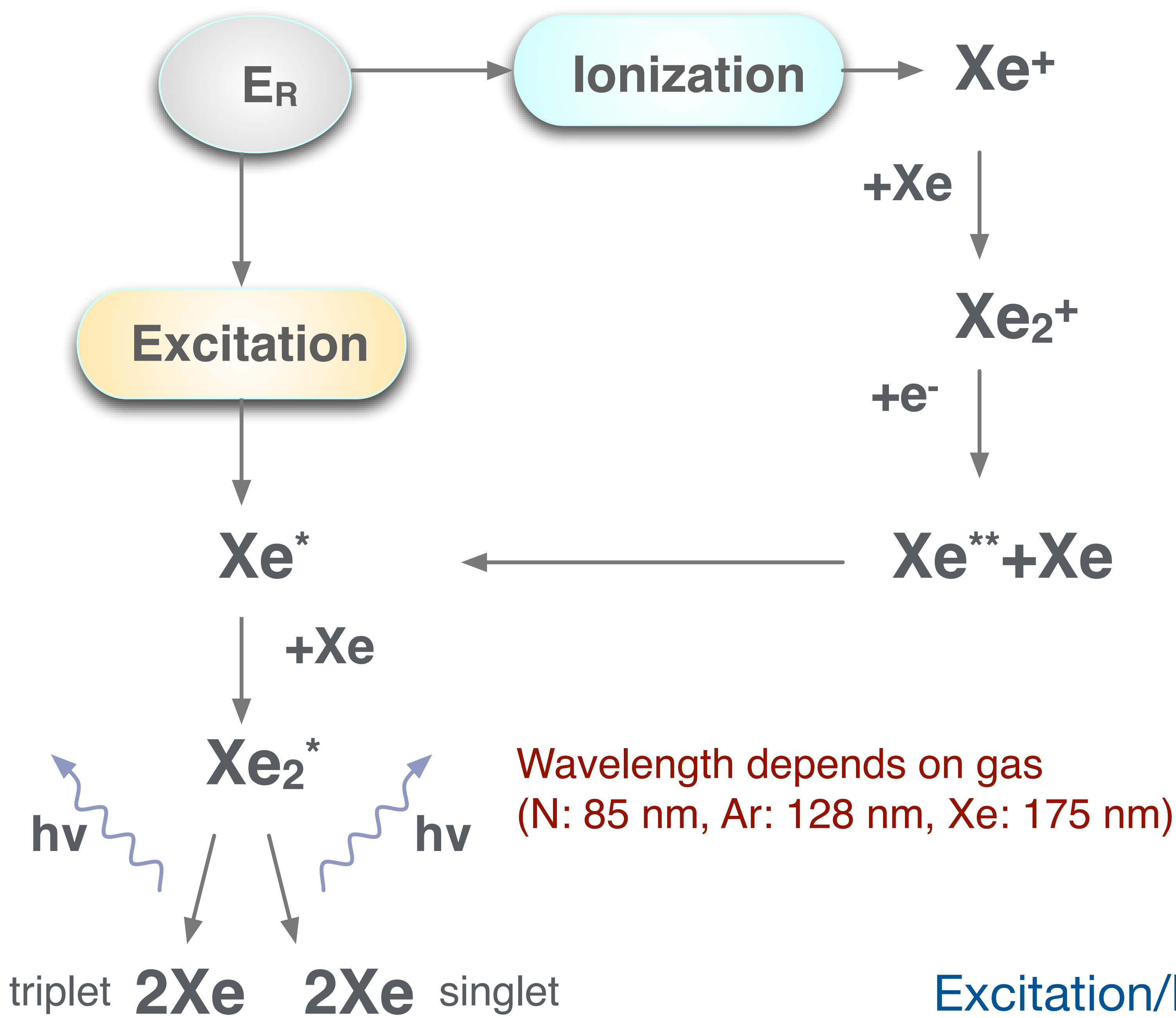
Liquid Nobles

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



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

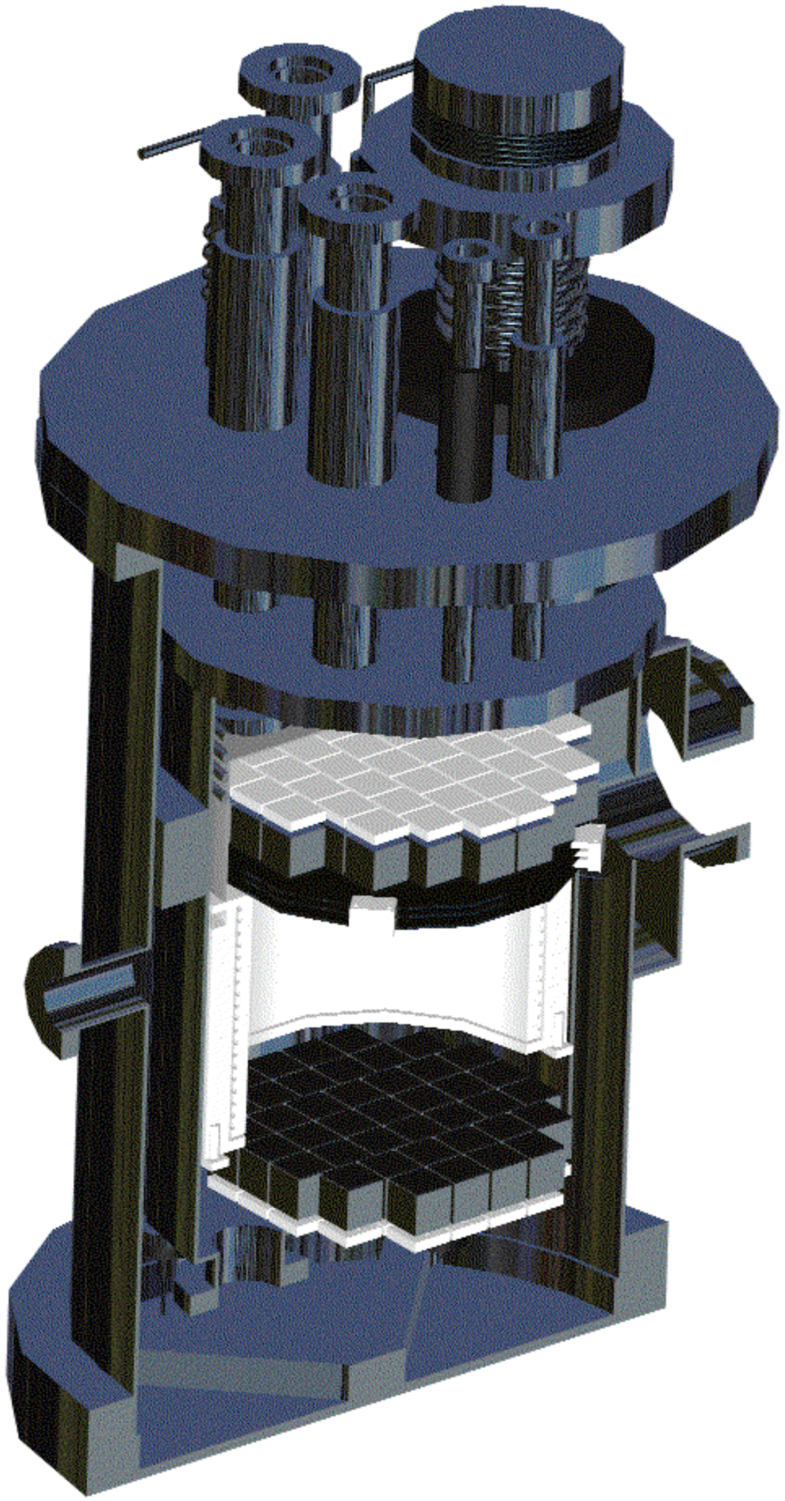
$$
\begin{aligned}
\mathrm{Xe}^+ + \mathrm{Xe} &\rightarrow \mathrm{Xe}_2^+ \\
\mathrm{Xe}_2^+ + \mathrm{e}^- &\rightarrow \mathrm{Xe}^{**} + \mathrm{Xe} \\
\mathrm{Xe}^{**} &\rightarrow \mathrm{Xe}^* + \mathrm{heat} \\
\mathrm{Xe}^* + \mathrm{Xe} &\rightarrow \mathrm{Xe}_2^* \\
\mathrm{Xe}_2^* &\rightarrow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

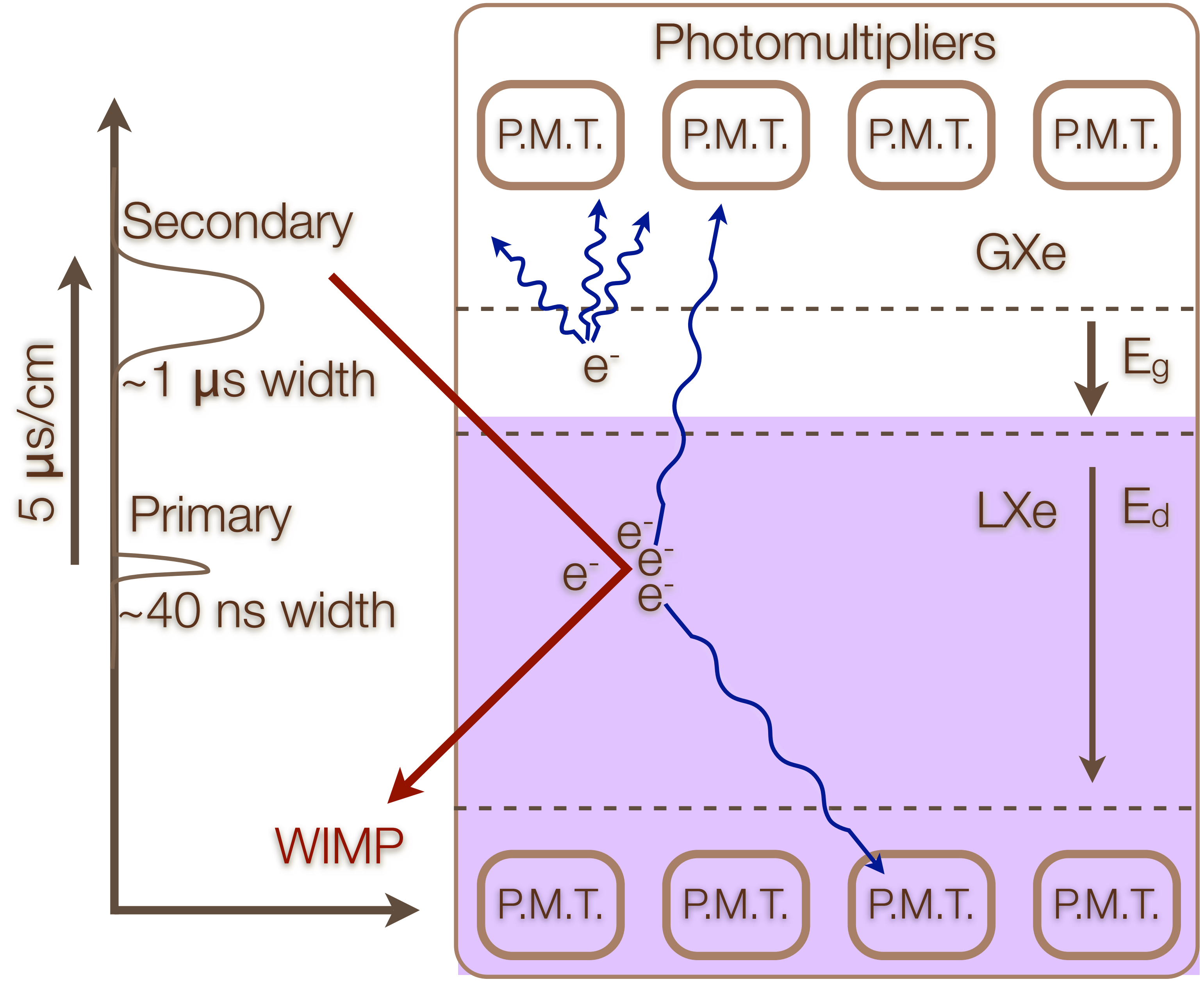
Time constants depend on gas
(Ne: few ns/15.4µs, Ar: 10ns/1.5µs, Xe: 3/27 ns)

Excitation/Ionization depends on dE/dx!
⟹ 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



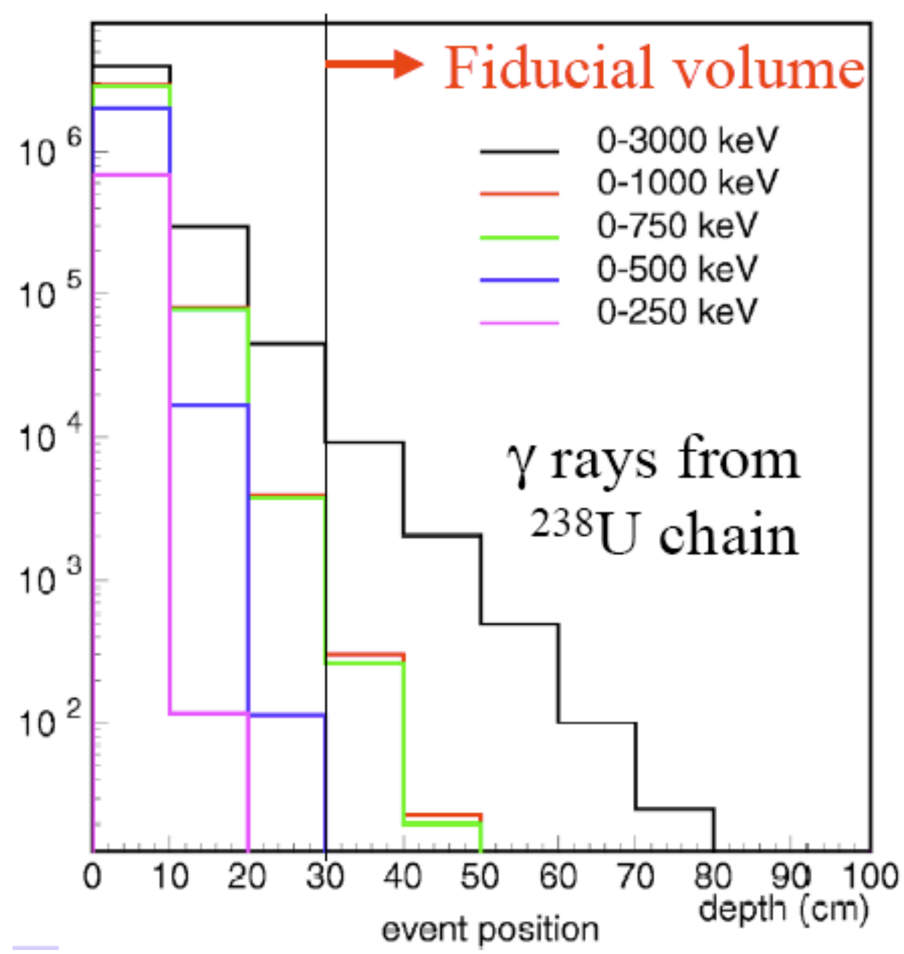


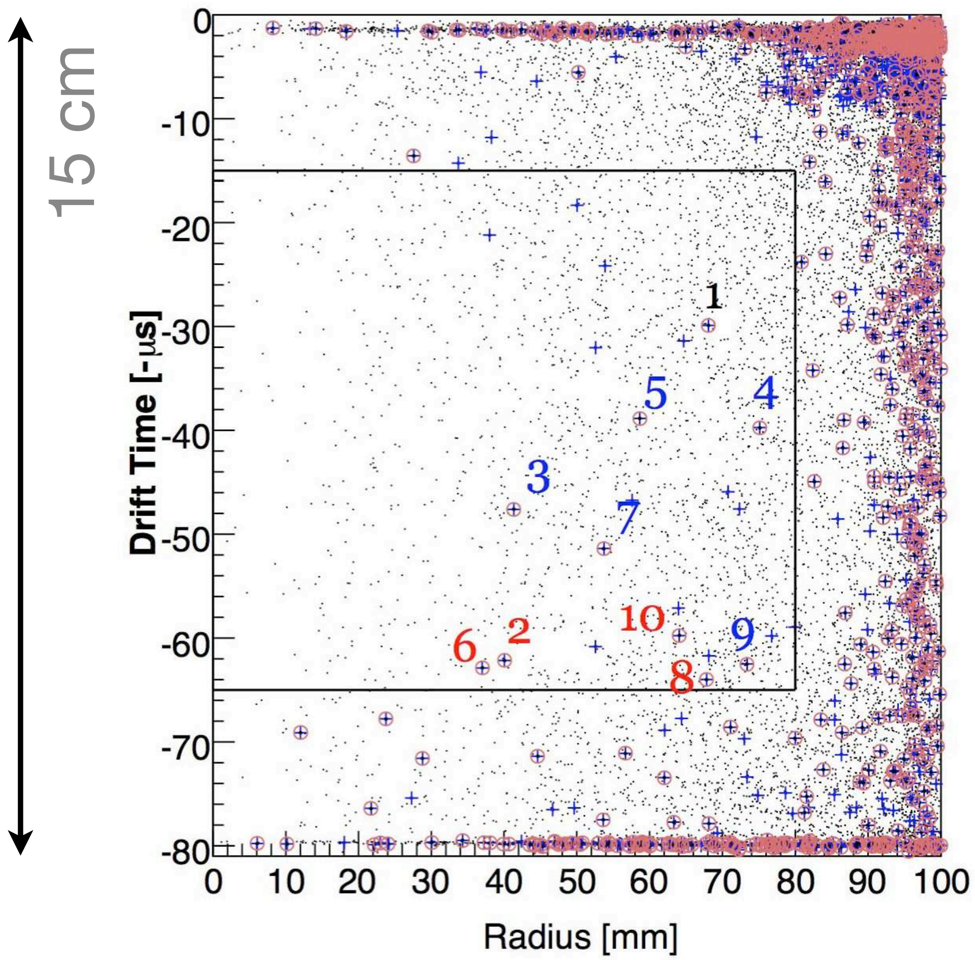
The XENON Design

Self shielding in Liquid Xenon

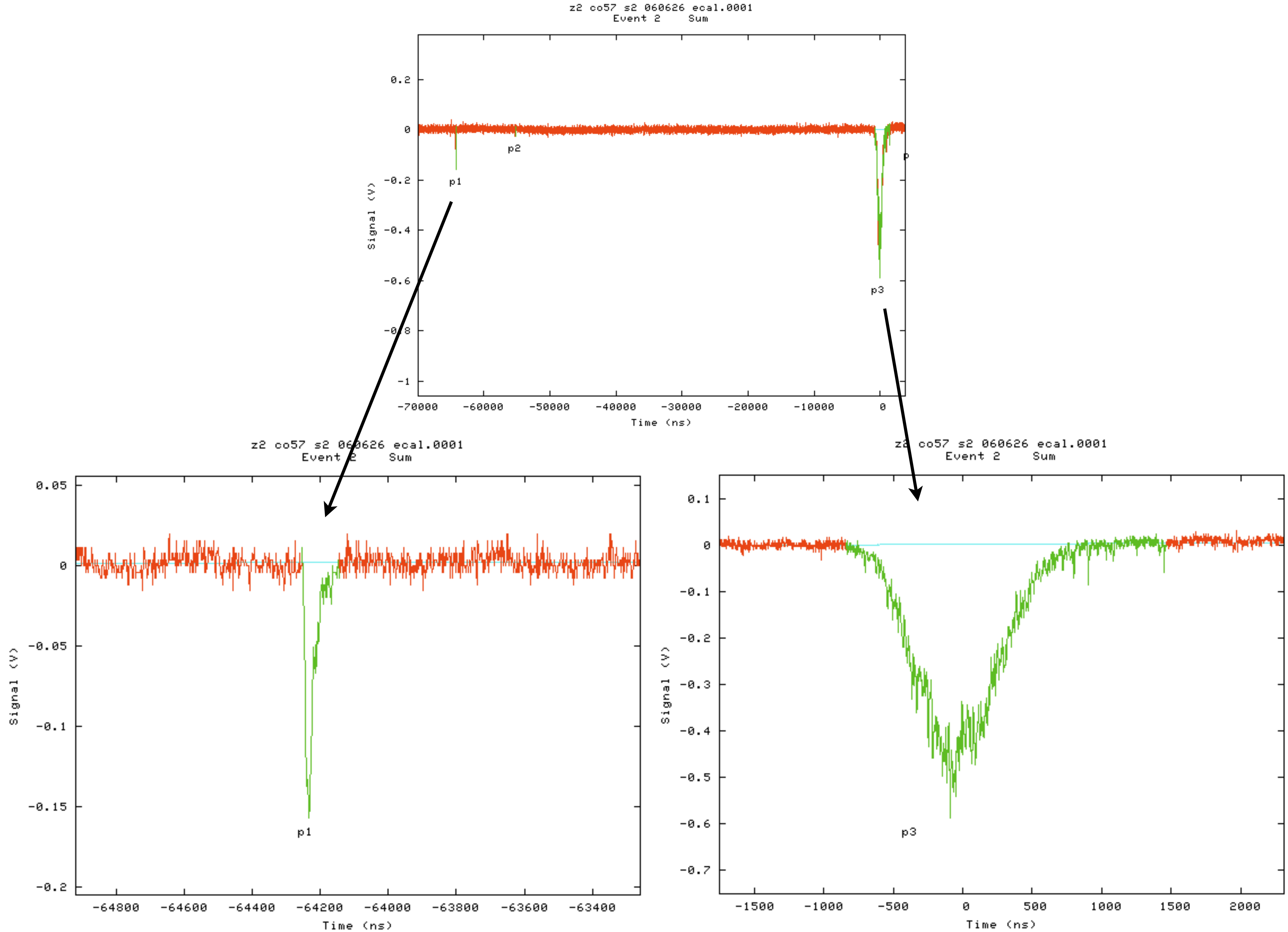
- A big advantage of the liquid xenon detector is its self shielding ability
  - Xenon is a heavy nucleus, and LXe is a dense material --> excellent particle attenuation properties
  - Xenon liquifies at 166K, so most impurities will be frozen out outside the detector

XMASS Collaboration





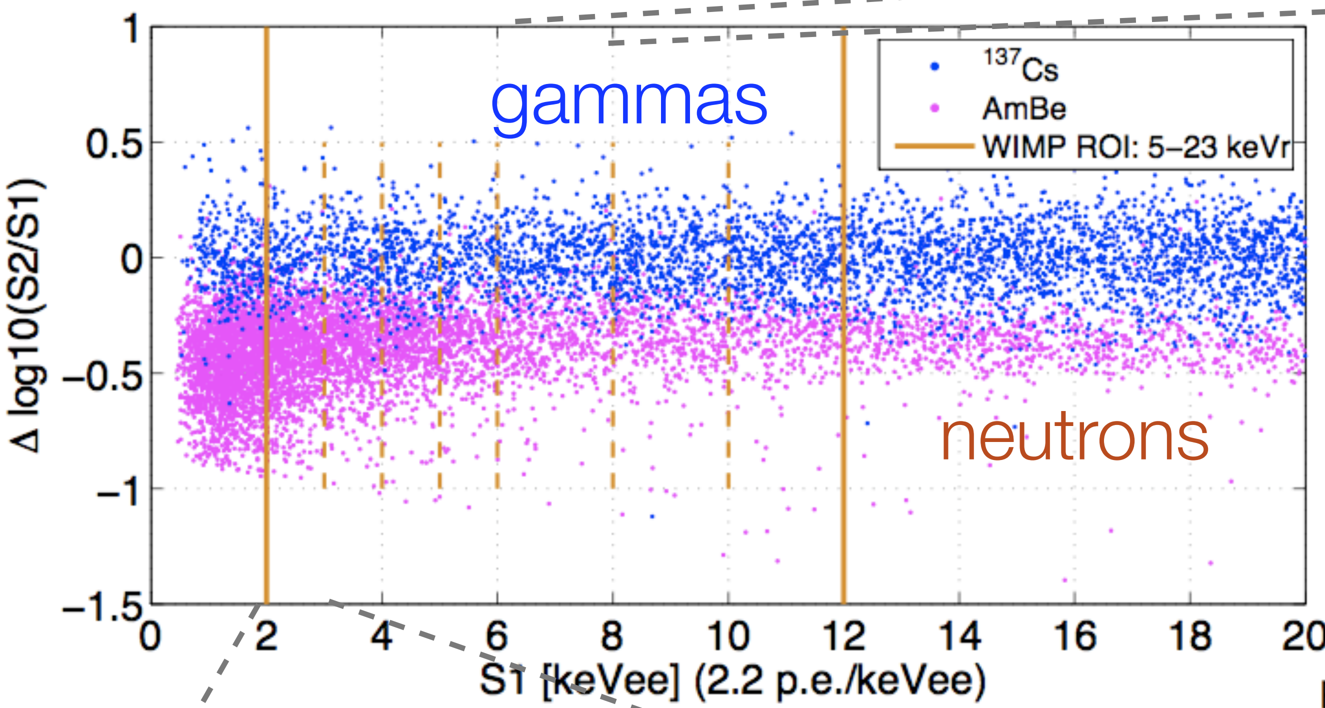
XENON Collaboration

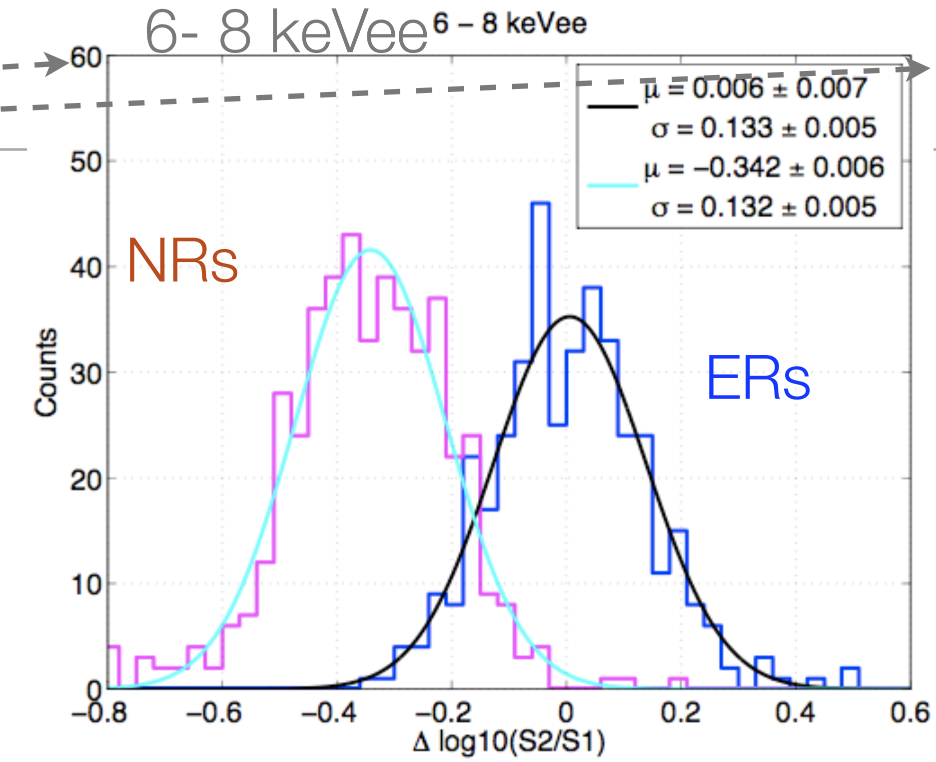


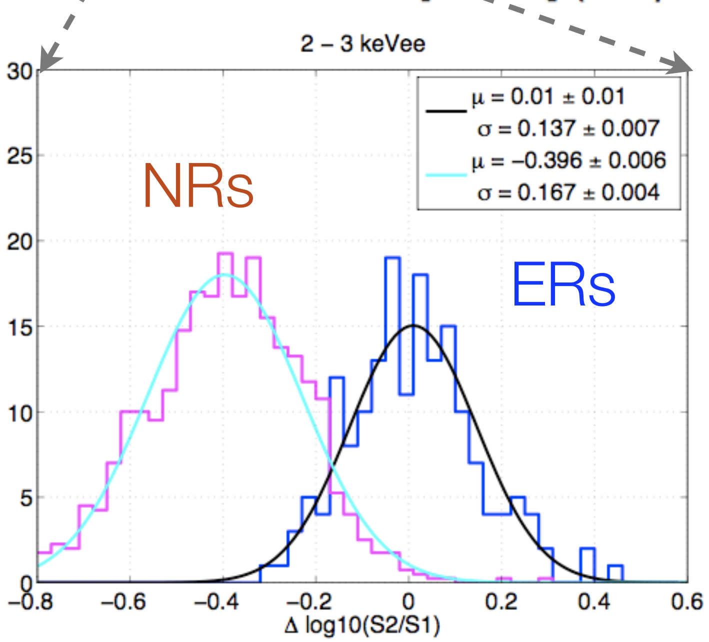
Event Signals in Liquid Xenon

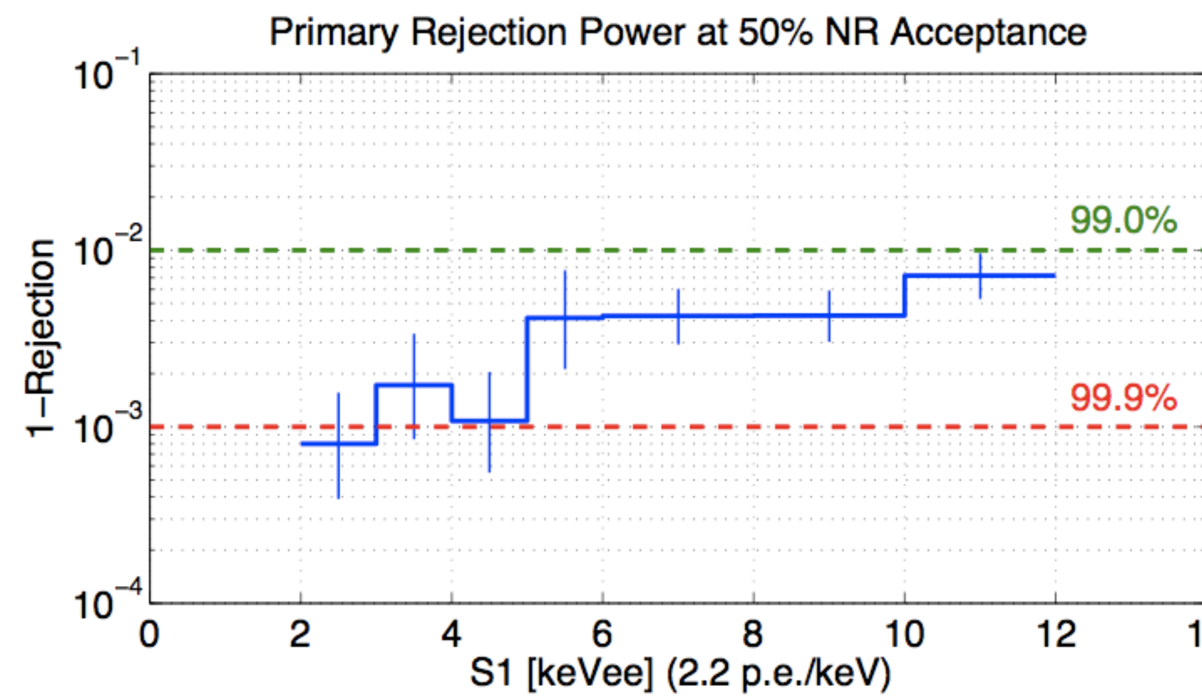
Zooming in on S1 & S2

XENON Discrimination



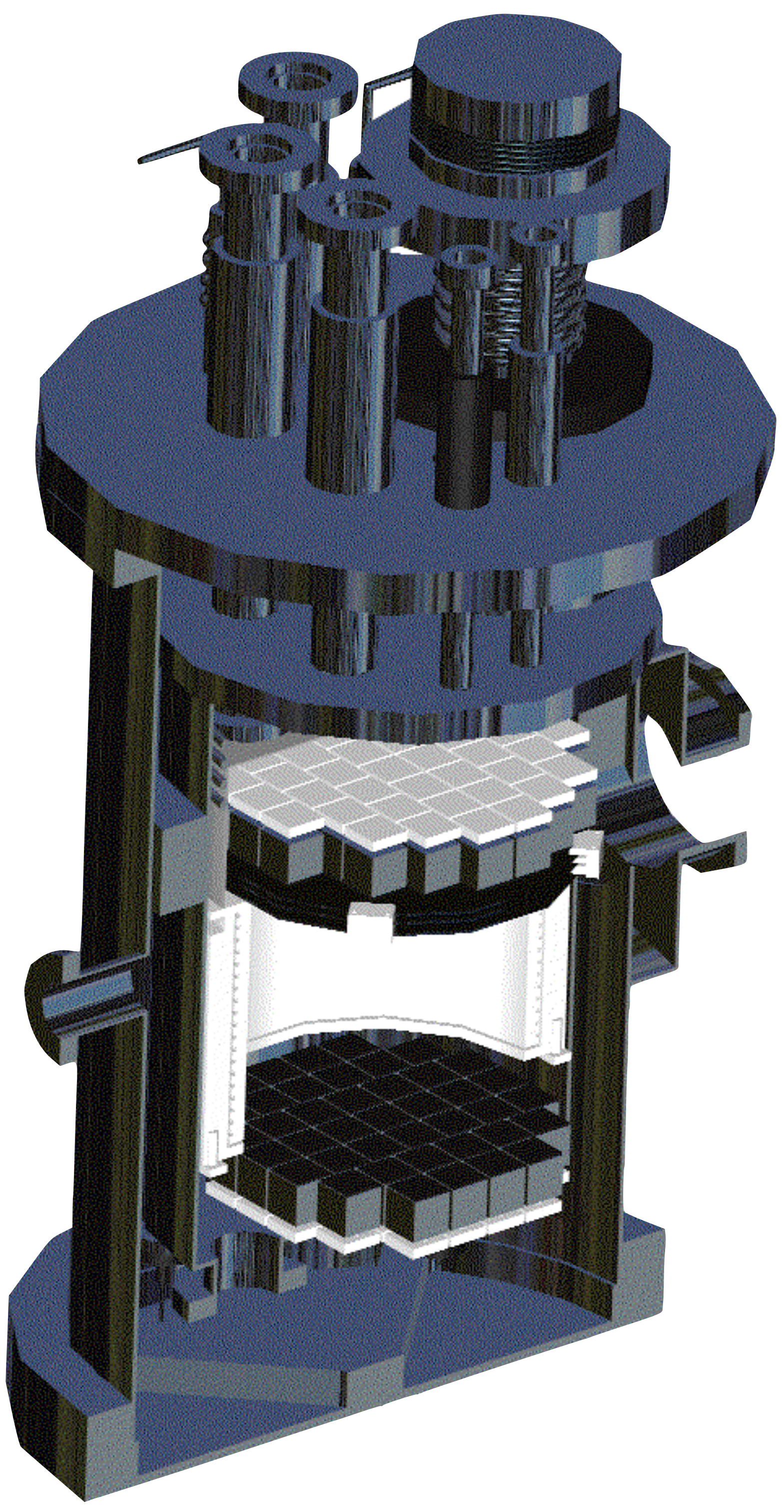


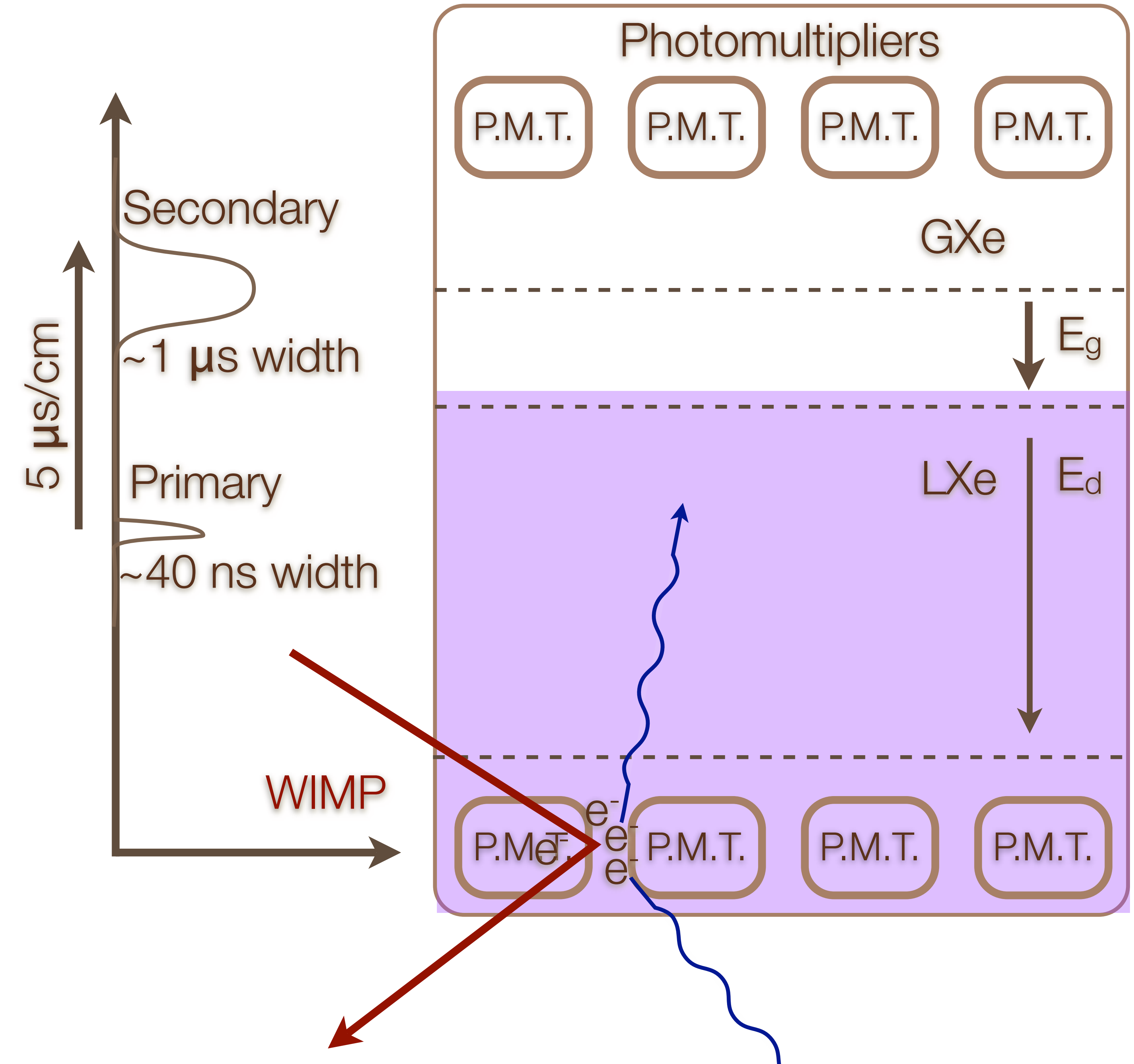




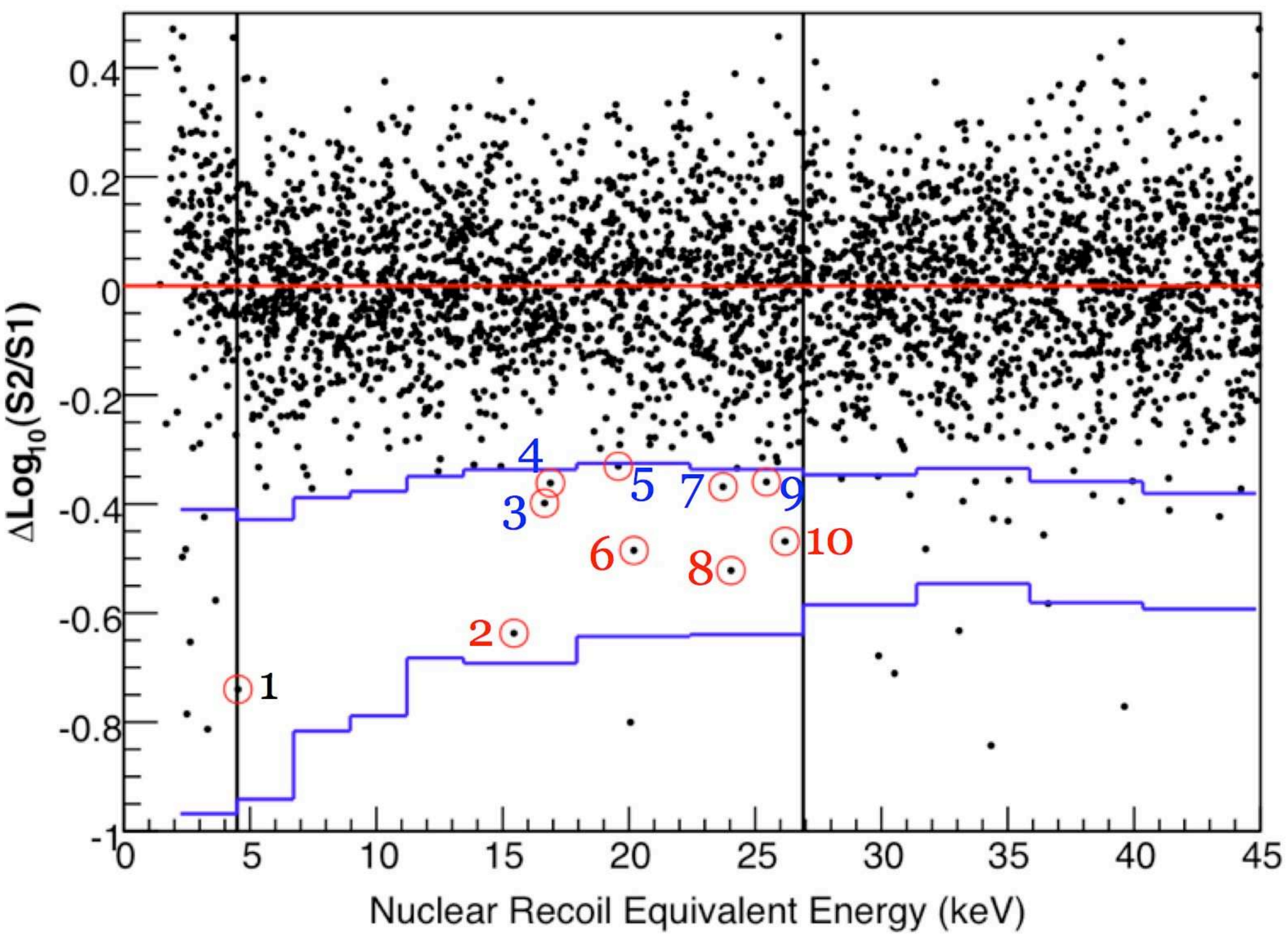
- Rejection is > 99.6% for 50% Nuclear Recoil acceptance
  - Cuts: fiducial volume (remove events at teflon edge where poor charge collection)
  - Multiple scatters (more than one S2 pulse)

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
$\Delta \mathrm{Log}_{10}(S2/S1)$
Nuclear Recoil Equivalent Energy (keV)
1
2
3
4
5
6
7
8
9
10

Cryogenic Experiments

CDMS

(see also CRESST / Edelweiss)

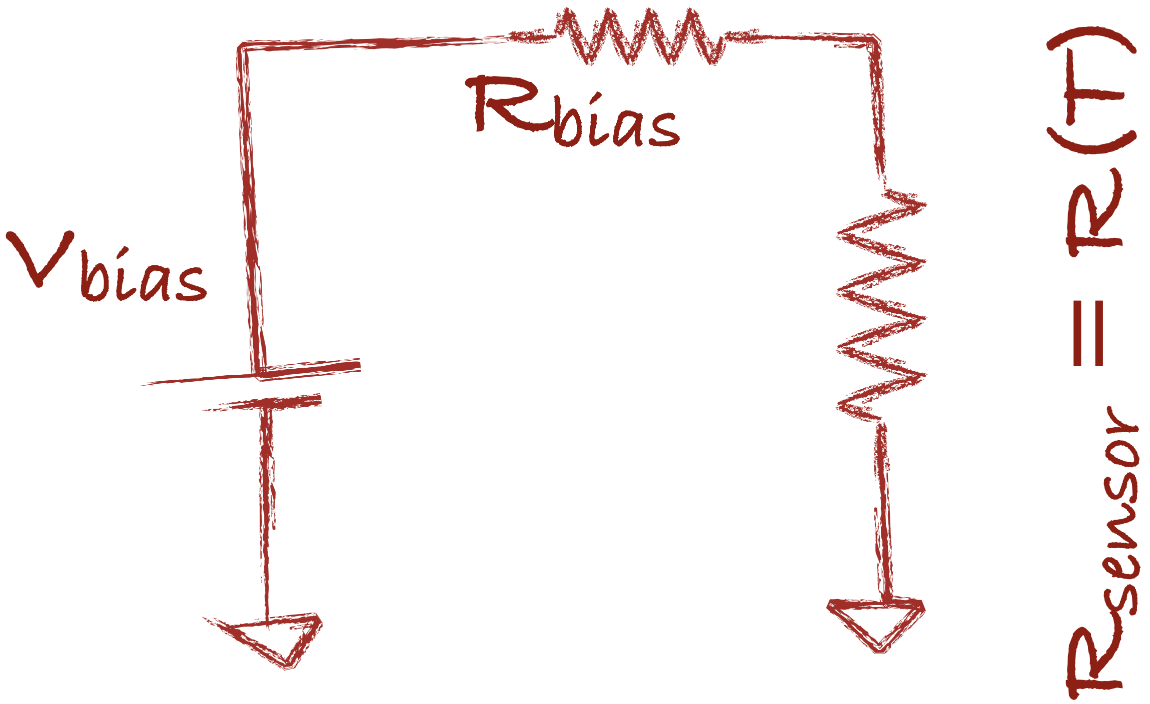
- Cryogenic Dark Matter Search
- Target : Semiconductor crystals
  - Ge (A=72) / Si (A=28)
  - Largely sensitive to spin-independent interactions, although presence of some naturally abundant odd spin isotopes allows for some spin-dependent sensitivity
- Detection Mechanism
  - Athermal phonons in crystal : provide a calorimetric measure of the recoil energy
  - Ionization signal : Electrons drifted through the crystal by an electric field result in a signal proportional to the recoil energy

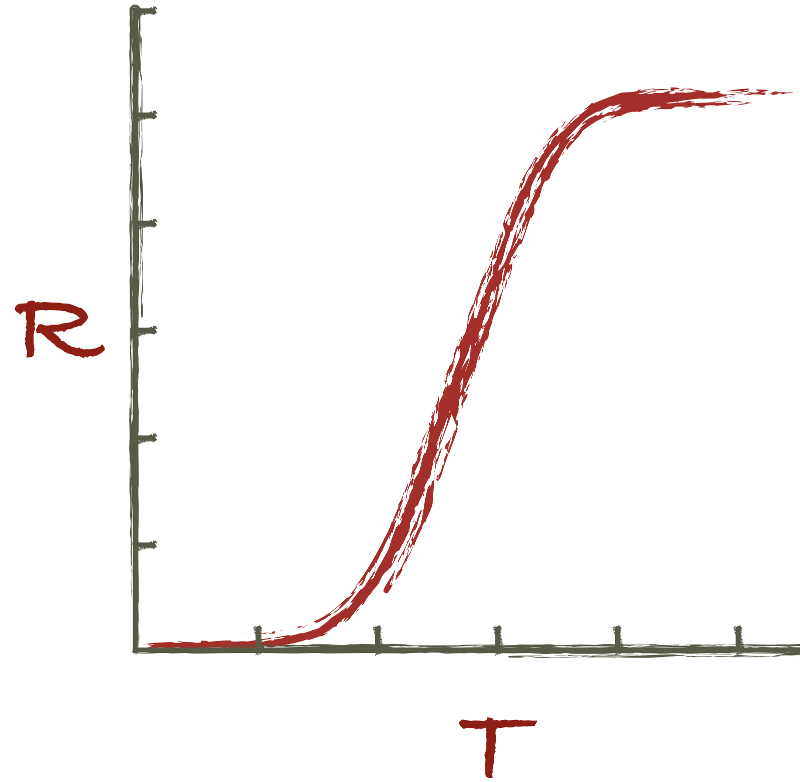
CDMS

- Background Discrimination :
  - Higher ratio of ionization to athermal signals for electron recoils
  - Able to reject bulk electron recoils at the 1 in 10^6 level
- Mass / Exposure
  - Operated 5 kg of detectors at the Soudan underground laboratory (~2000 mwe)
  - Background rate ~ 1 evt/kg/keV/day
  - Planning upgrade in detector mass to 25 kg (SuperCDMS)

CDMS Detectors

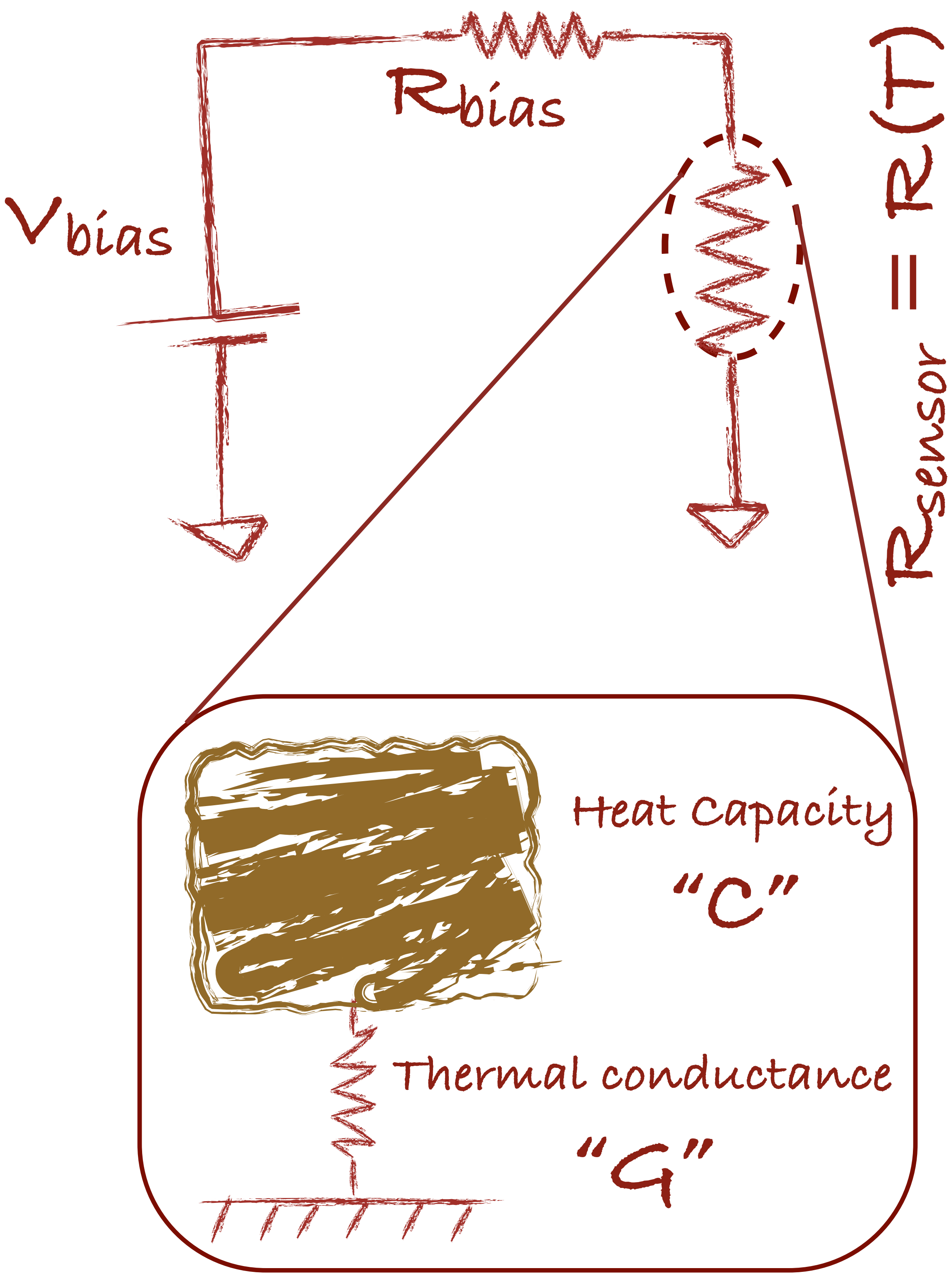
Consider the following electrical/thermal circuit

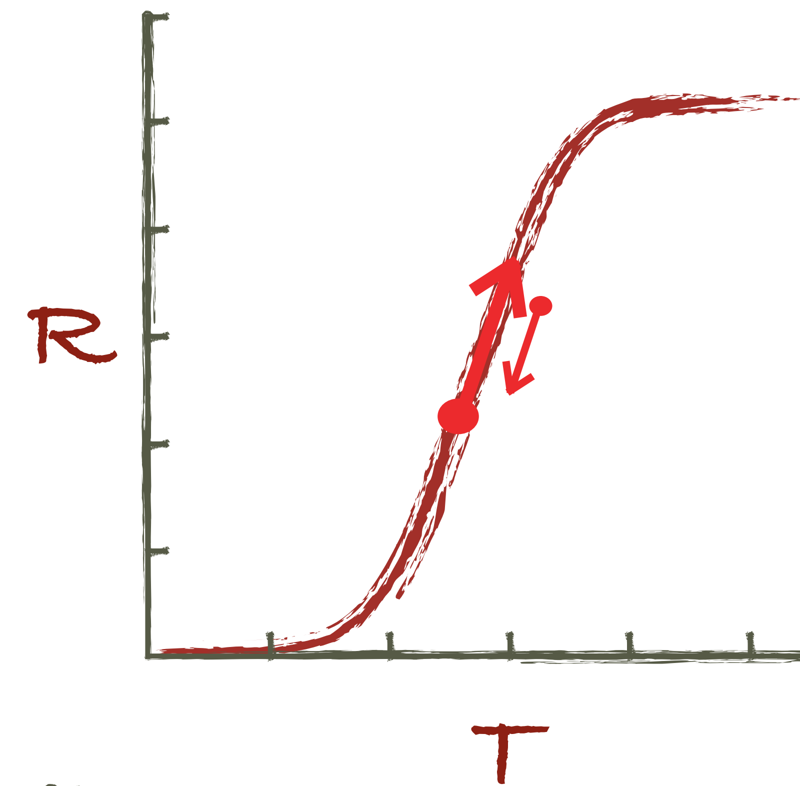


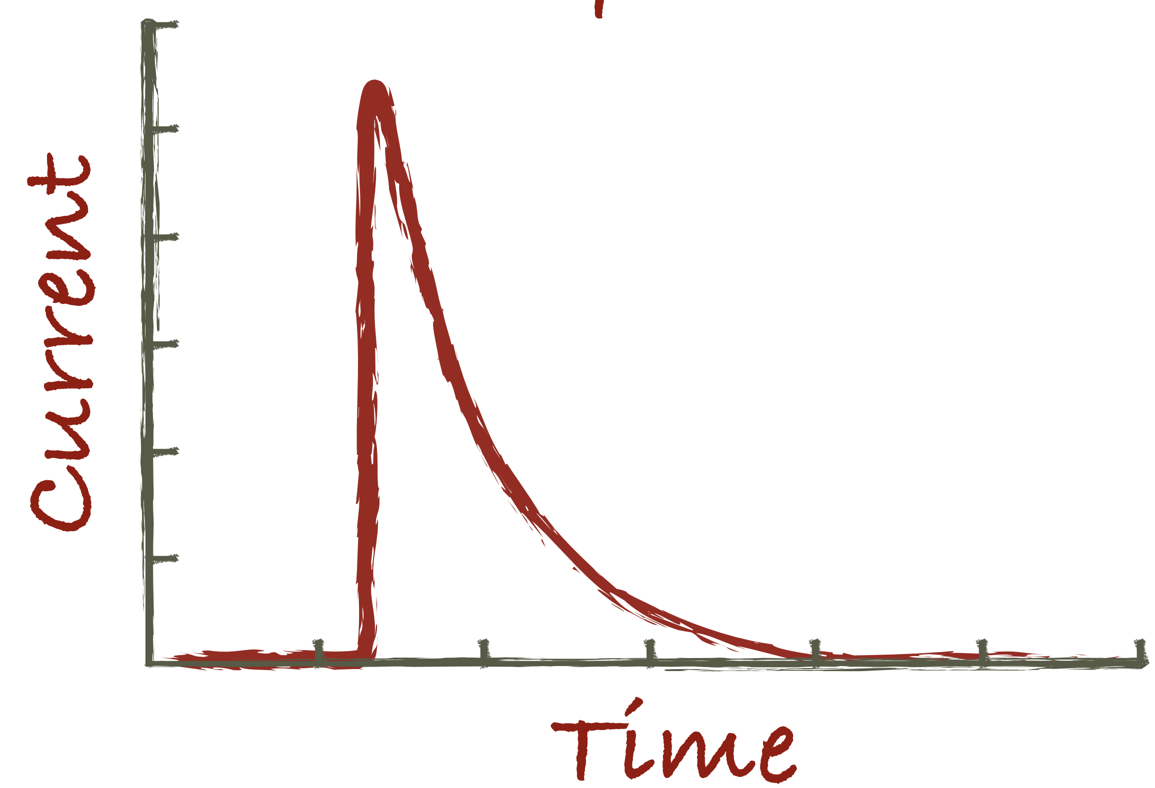


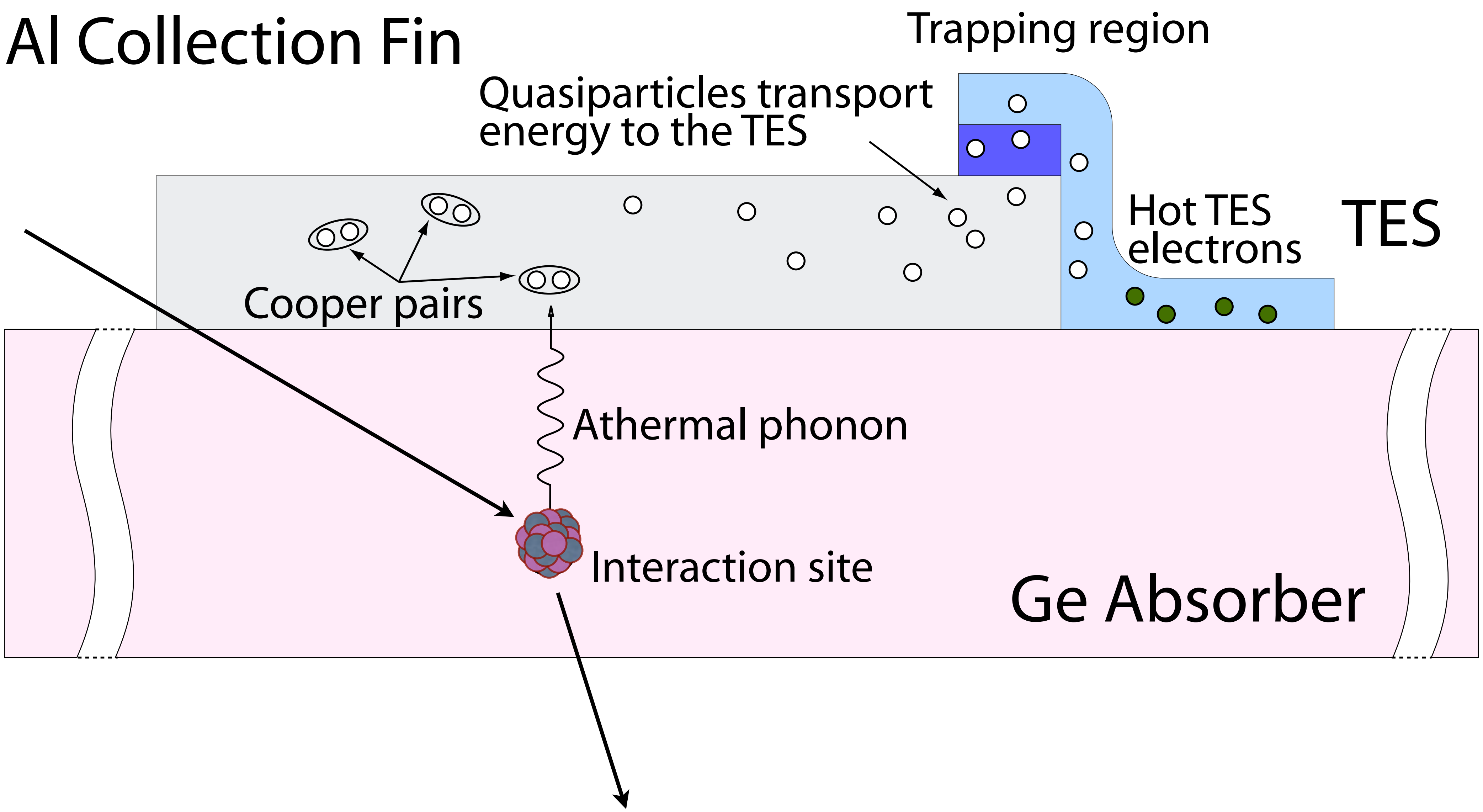
CDMS Detectors

Consider the following electrical/thermal circuit





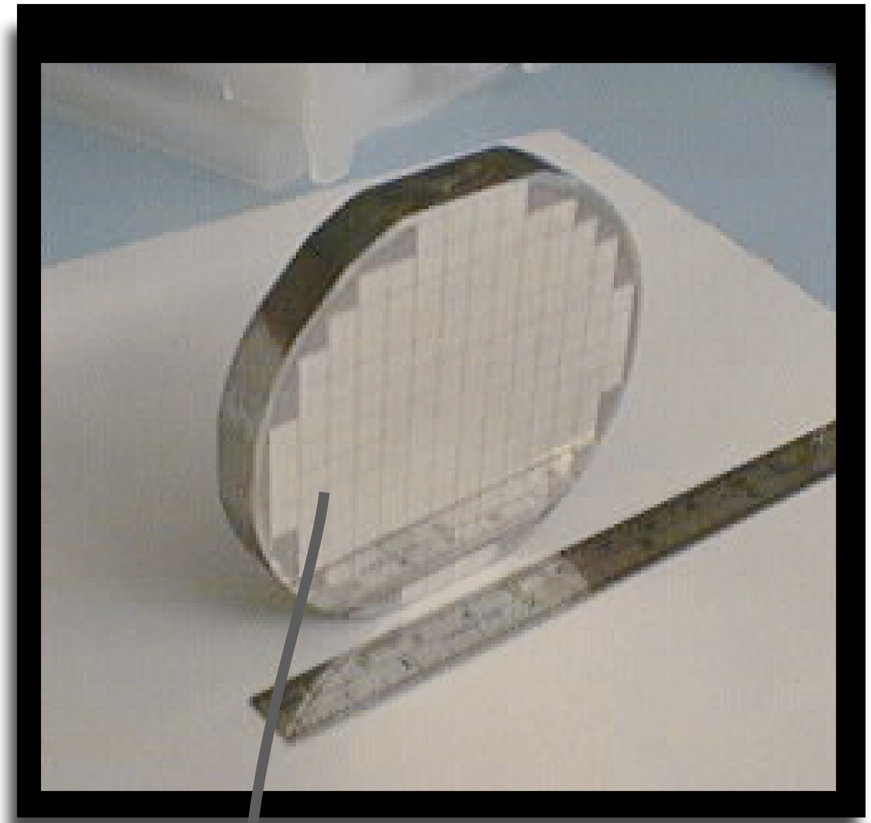


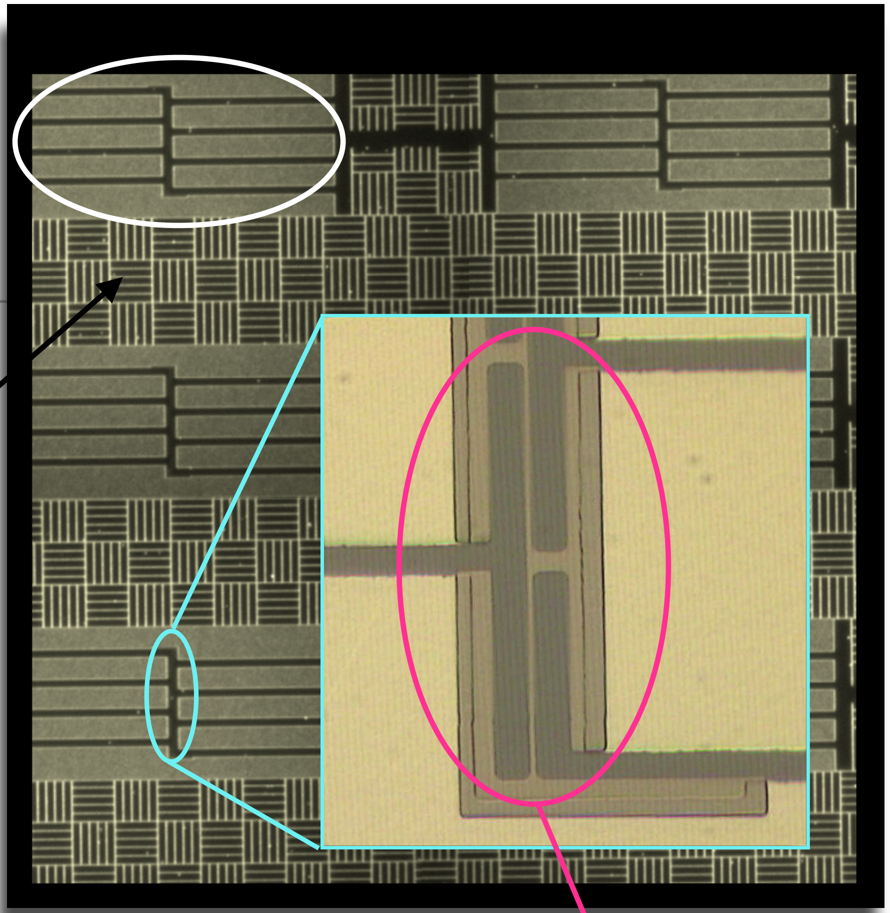


Getting the Energy to the Sensors

Athermal Phonons and Quasiparticles

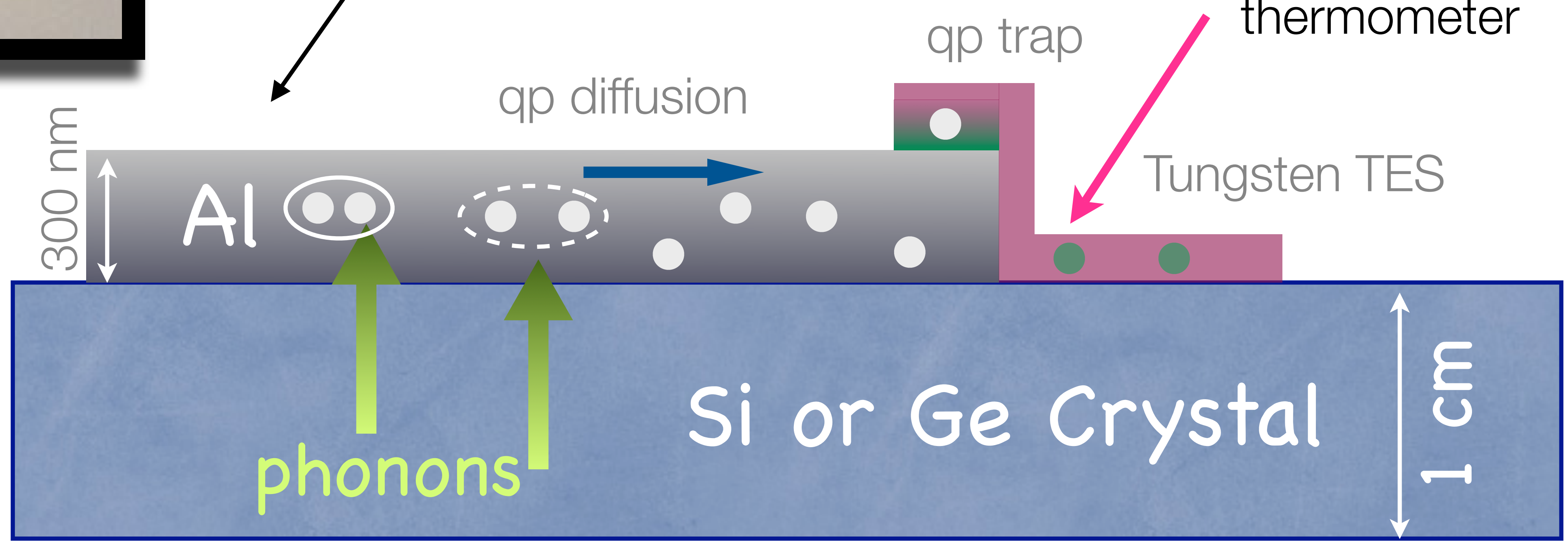
Anatomy of a CDMS Detector



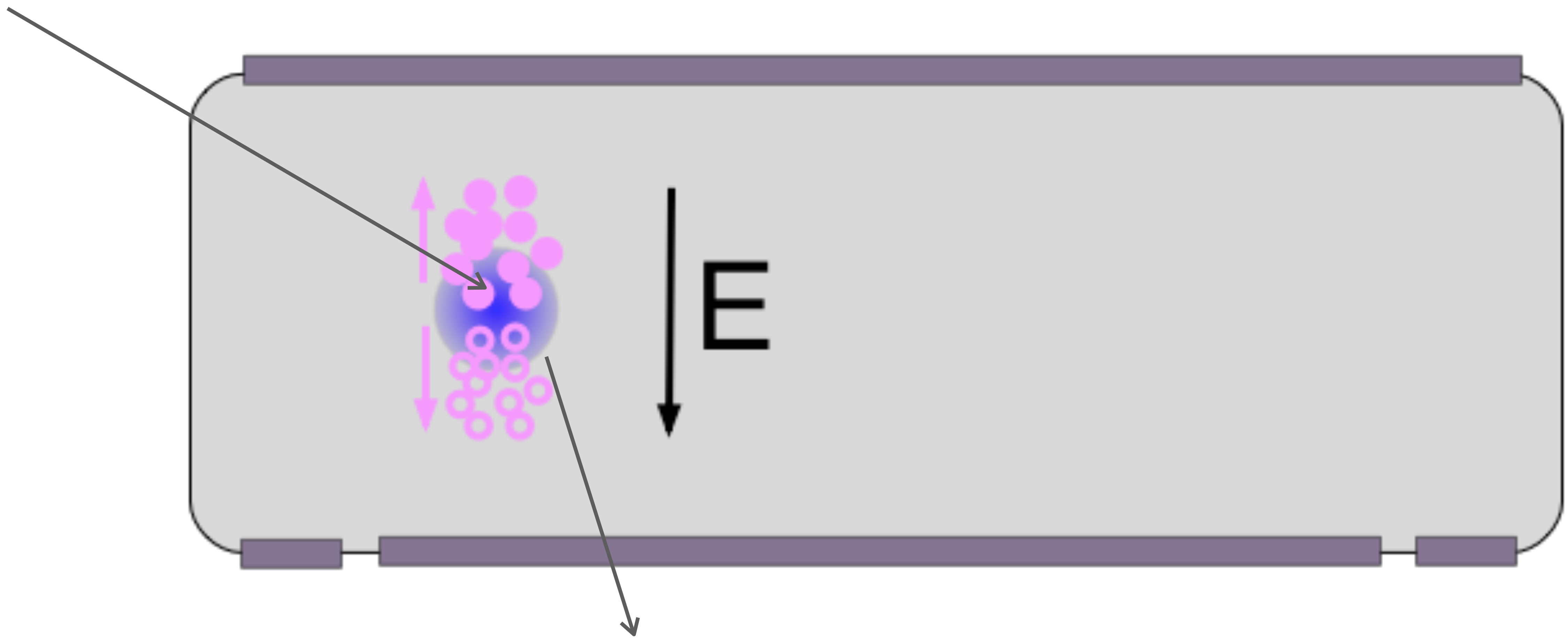


These are the Aluminum collection fins

This is the superconducting thermometer



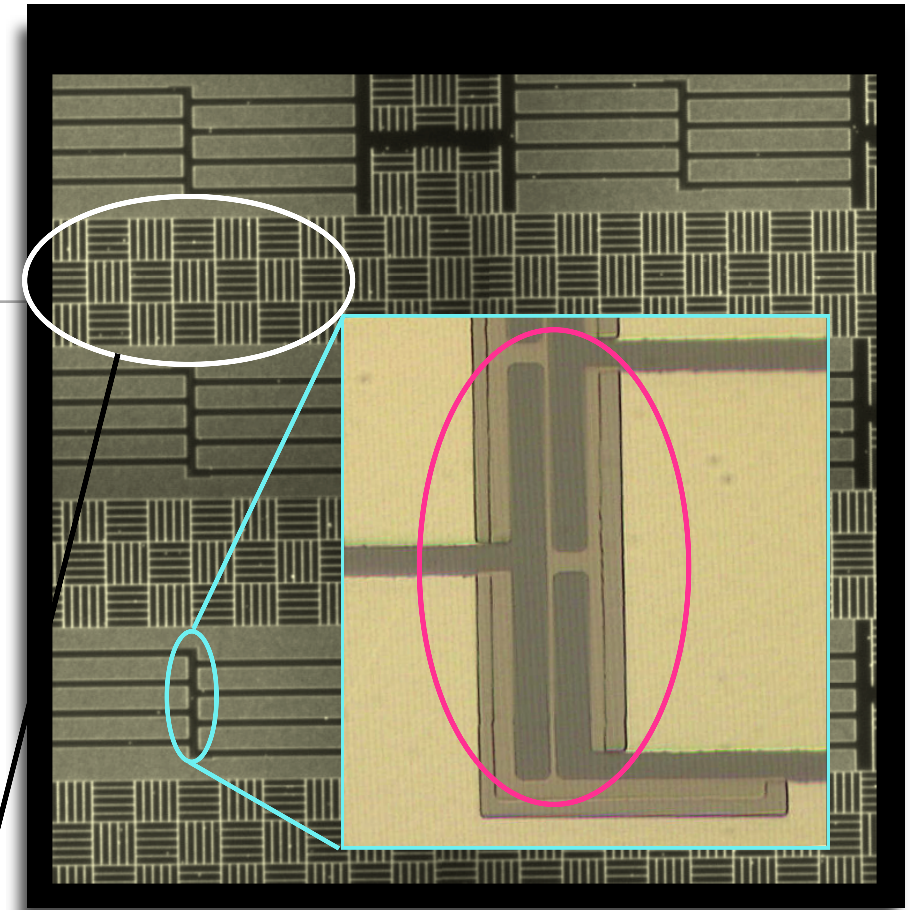
Electrons and holes are drifted across the crystal by an electric field of a few V/cm

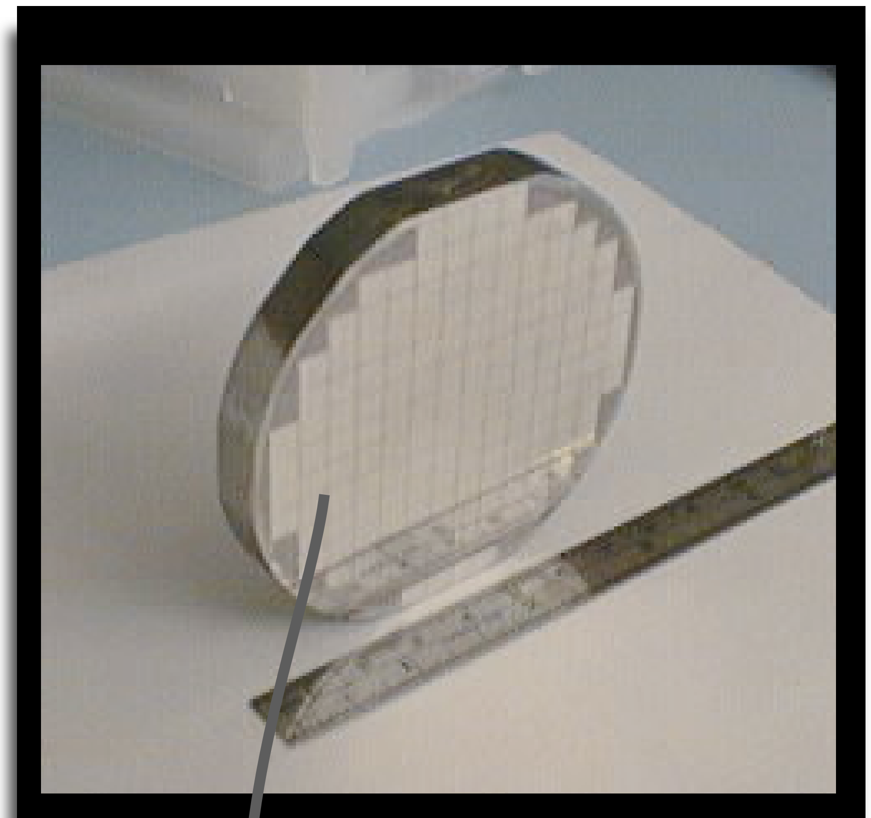


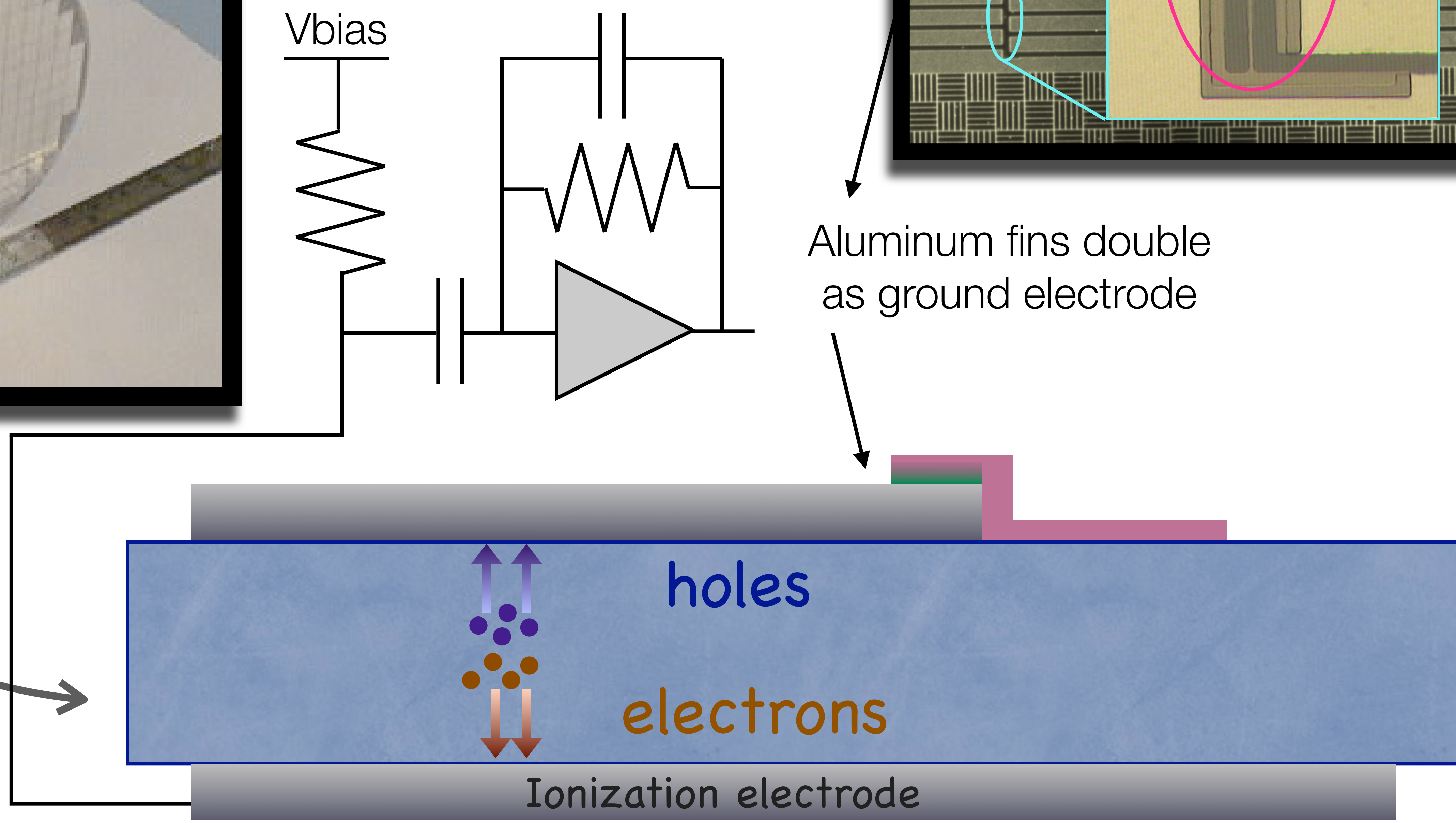
Getting the Energy to the Sensors

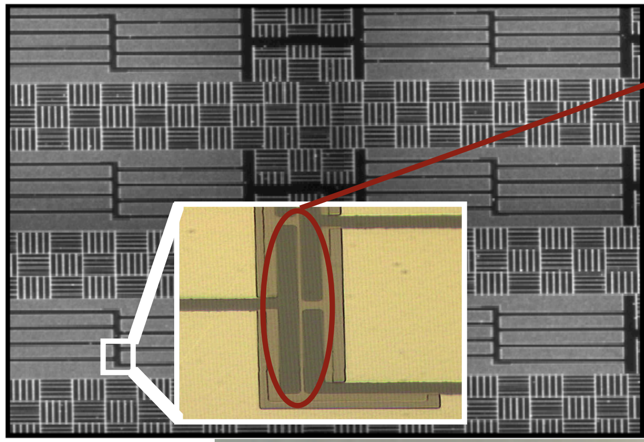
The Ionization Signal

Anatomy of a CDMS Detector

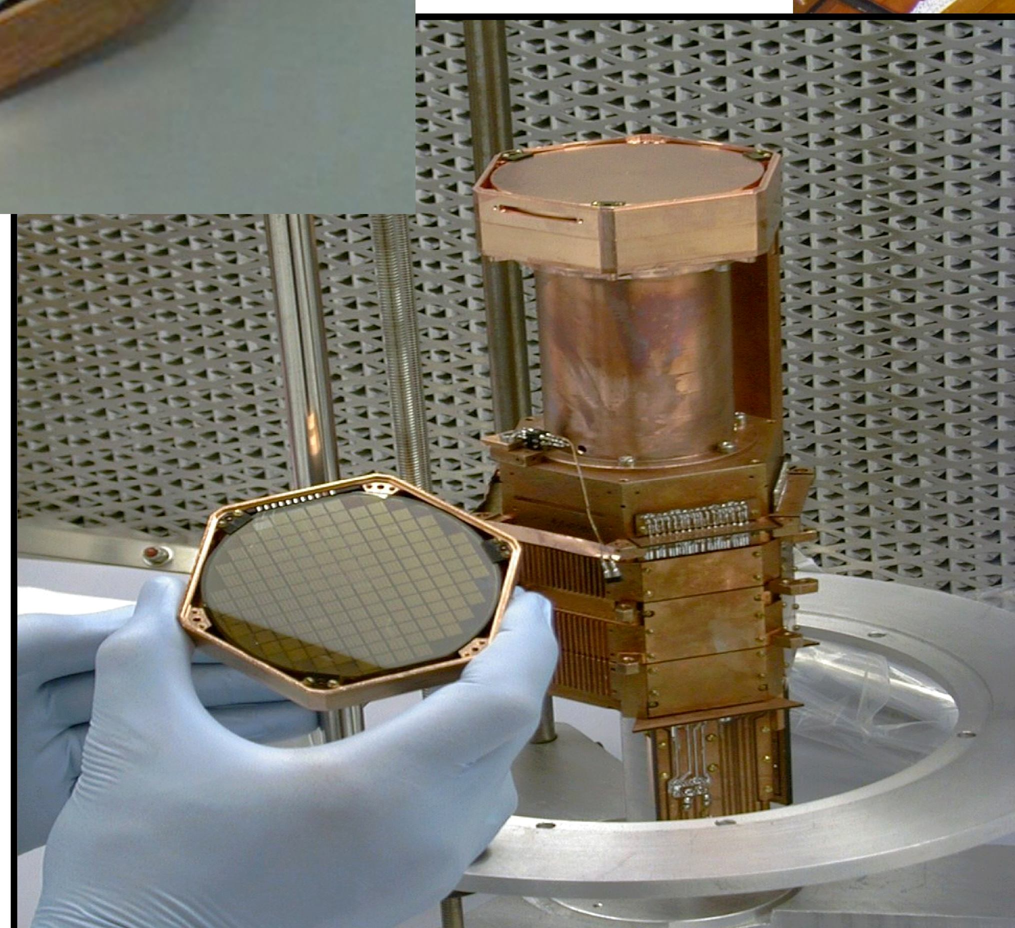


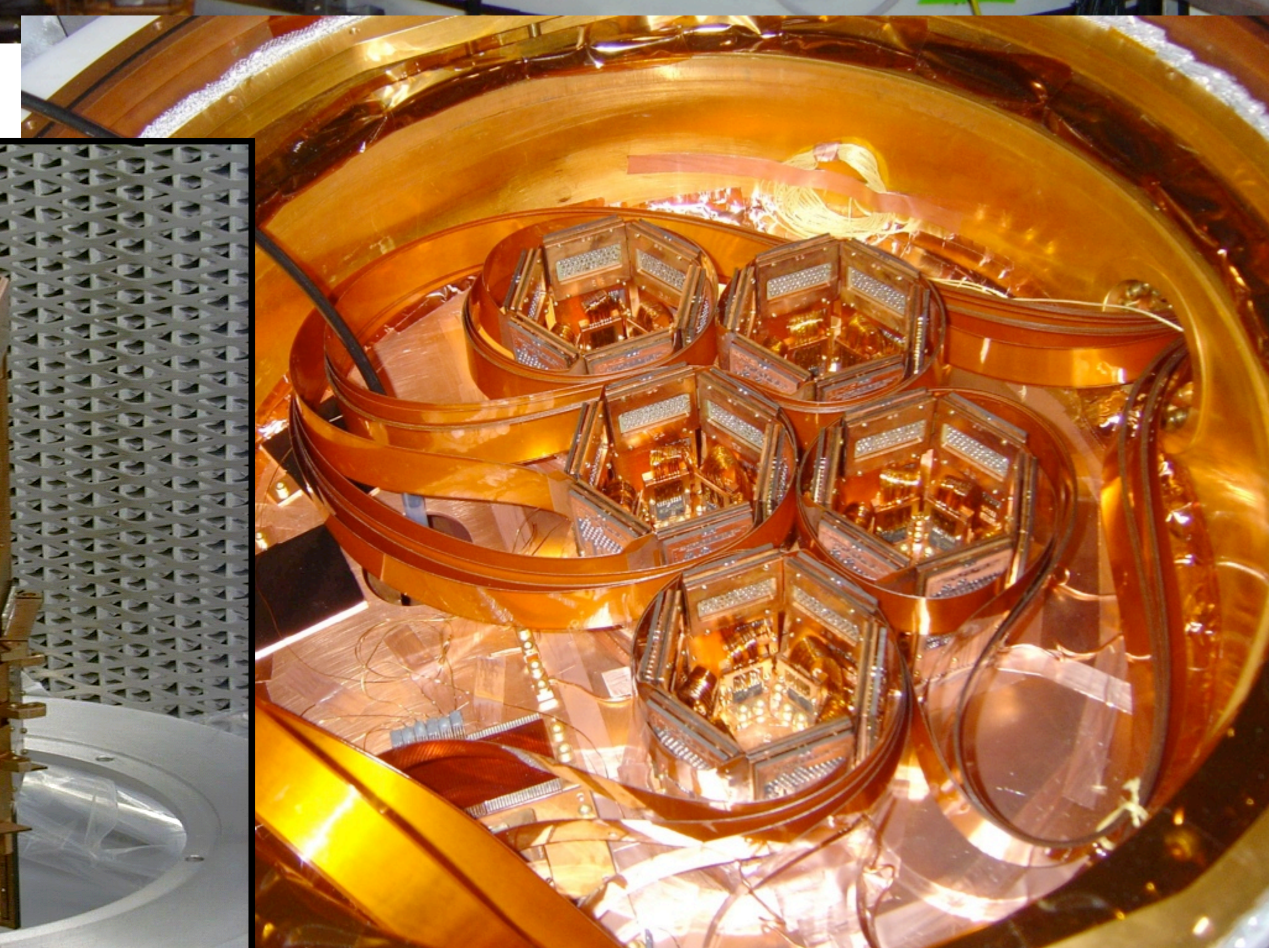






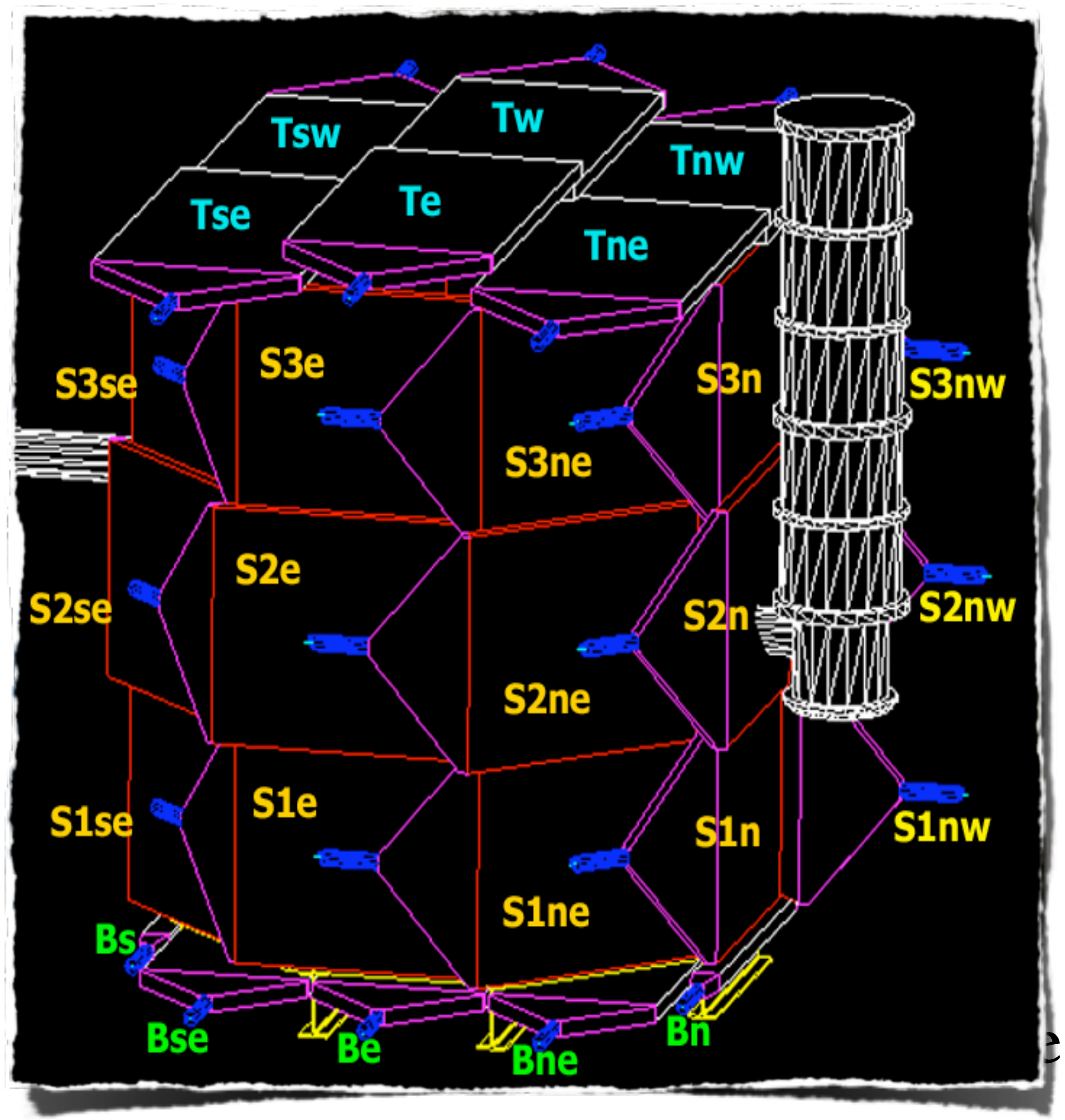
This the superconducting thermometer $1 \times 250\ \mu m$





CDMS Shields Outside-In

- Surround detectors with active muon
- Use passive shielding to reduce gamma/Neutrons
- Overburden reduces muon-induced Neutrons
- Polyethylene for low-energy neutron
- Lead and Copper for photon
- Neutron background small in Soudan, for recent runs

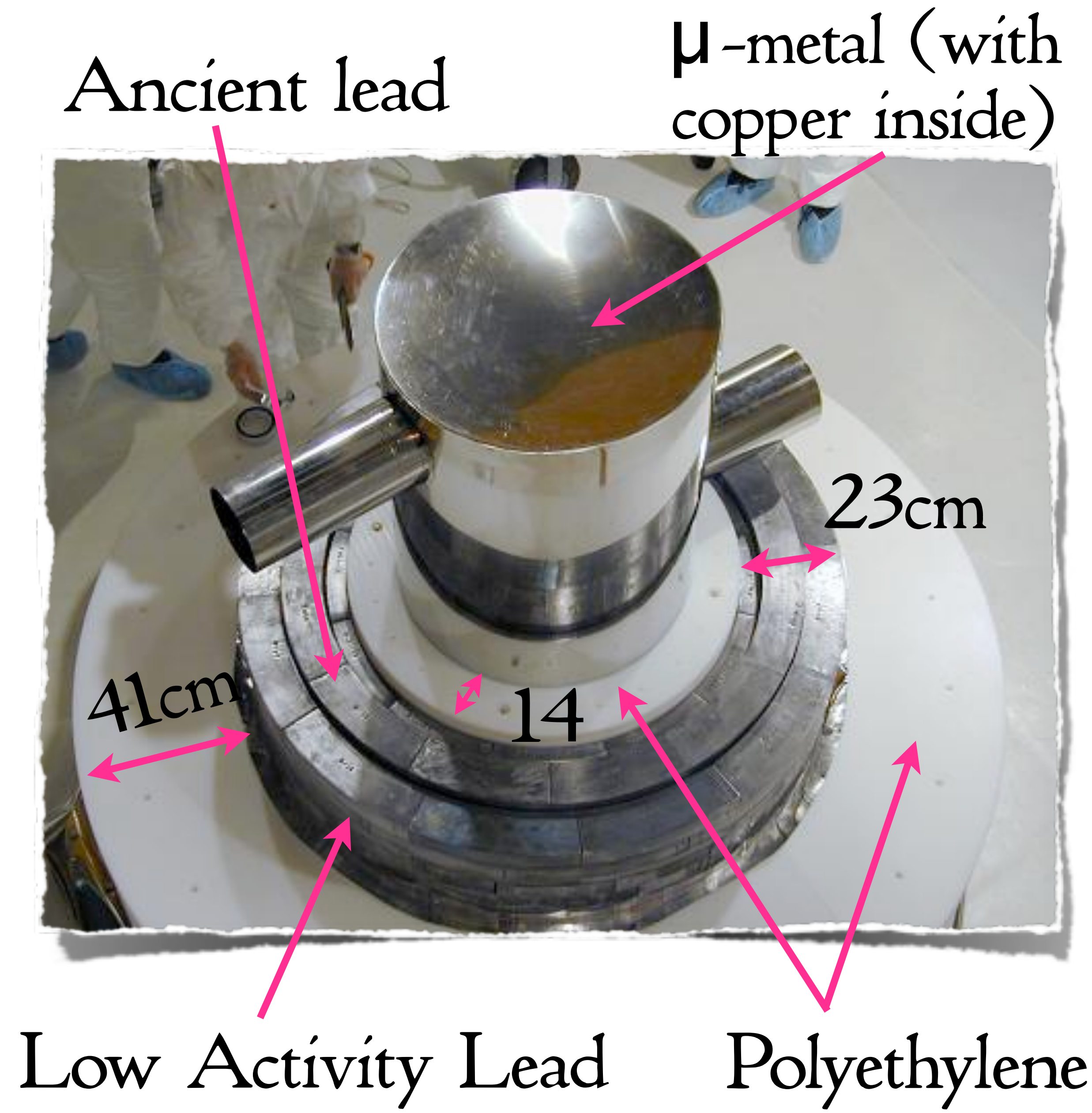


CDMS Shields Outside-In

- Surround detectors with active muon
- Use passive shielding to reduce gamma/Neutrons
- Overburden reduces muon-induced Neutrons
- Polyethylene for low-energy neutron
- Lead and Copper for photon
- Neutron background small in Soudan, for recent runs

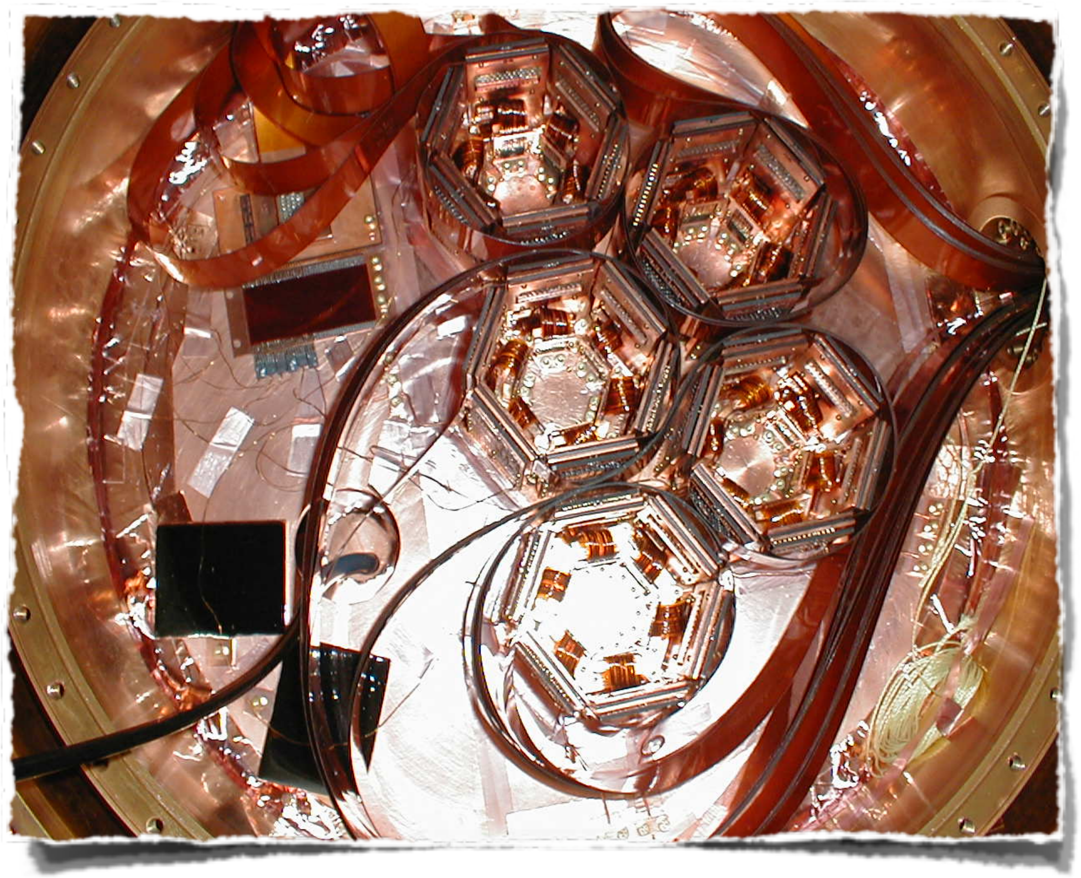
CDMS Shields Outside-In

- Surround detectors with active muon
- Use passive shielding to reduce gamma/Neutrons
- Overburden reduces muon-induced Neutrons
- Polyethylene for low-energy neutron
- Lead and Copper for photon
- Neutron background small in Soudan, for recent runs



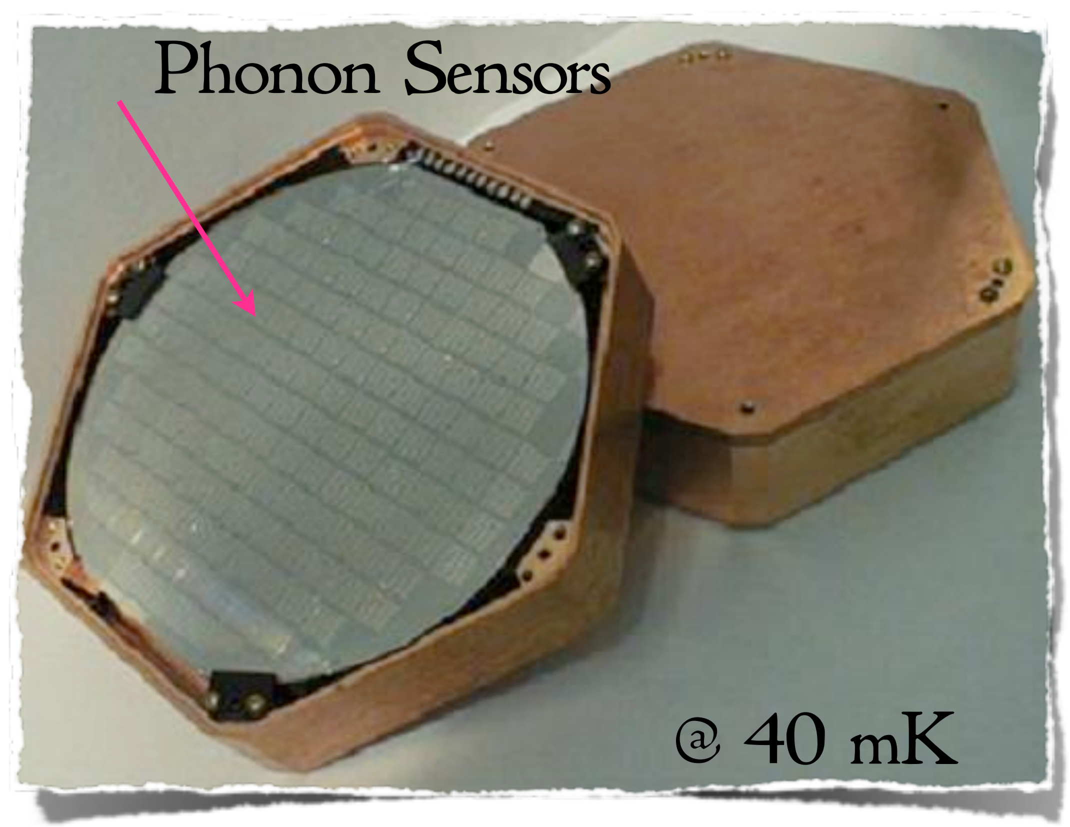
CDMS Shields Outside-In

- Surround detectors with active muon
- Use passive shielding to reduce gamma/Neutrons
- Overburden reduces muon-induced Neutrons
- Polyethylene for low-energy neutron
- Lead and Copper for photon
- Neutron background small in Soudan, for recent runs



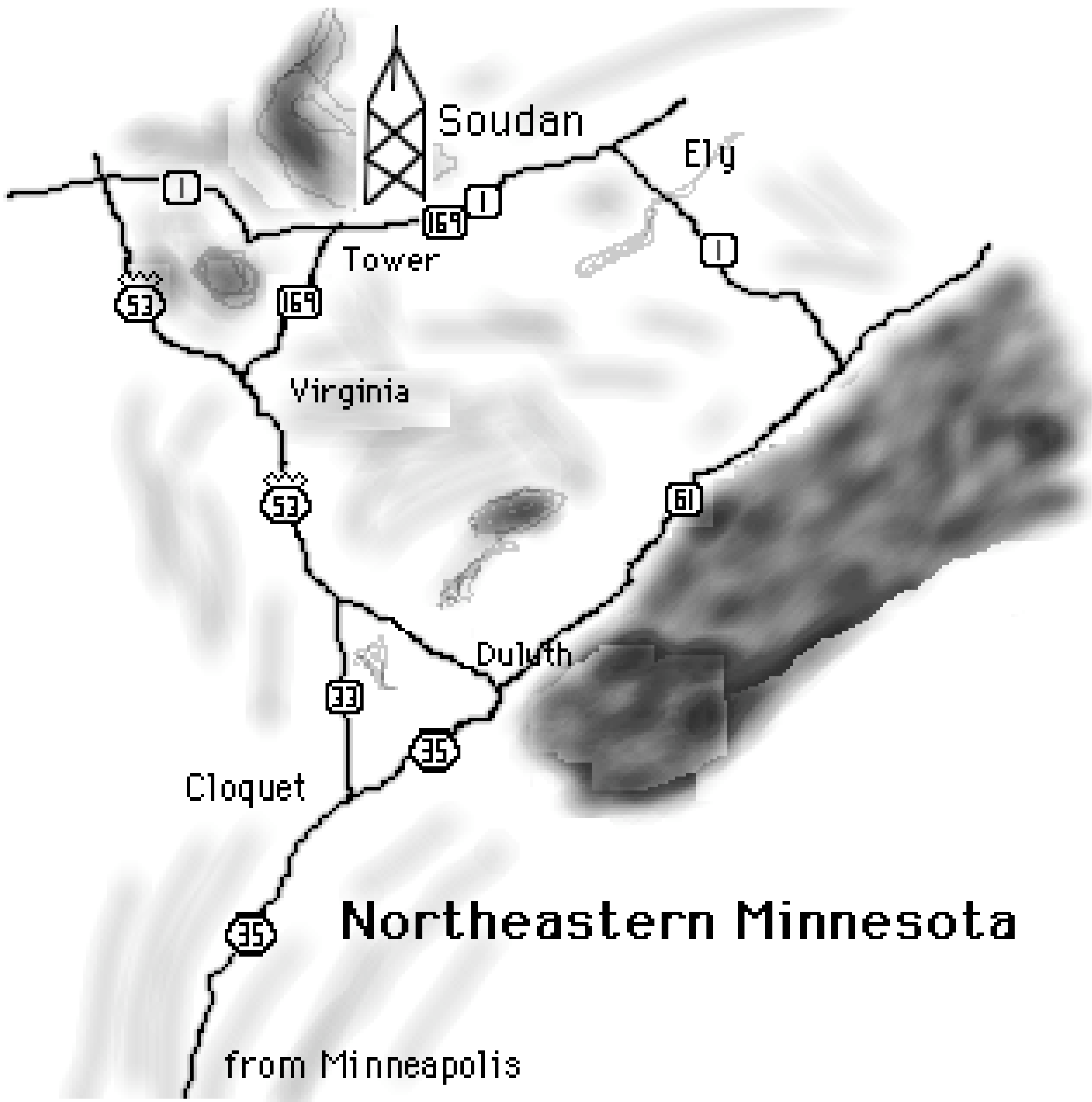
CDMS Shields Outside-In

- Surround detectors with active muon
- Use passive shielding to reduce gamma/Neutrons
- Overburden reduces muon-induced Neutrons
- Polyethylene for low-energy neutron
- Lead and Copper for photon
- Neutron background small in Soudan, for recent runs



Box it all up and go to Northern Minnesota

4 hours drive North
of Minneapolis



CDMS Collaboration

CDMS Institutions

National Laboratory

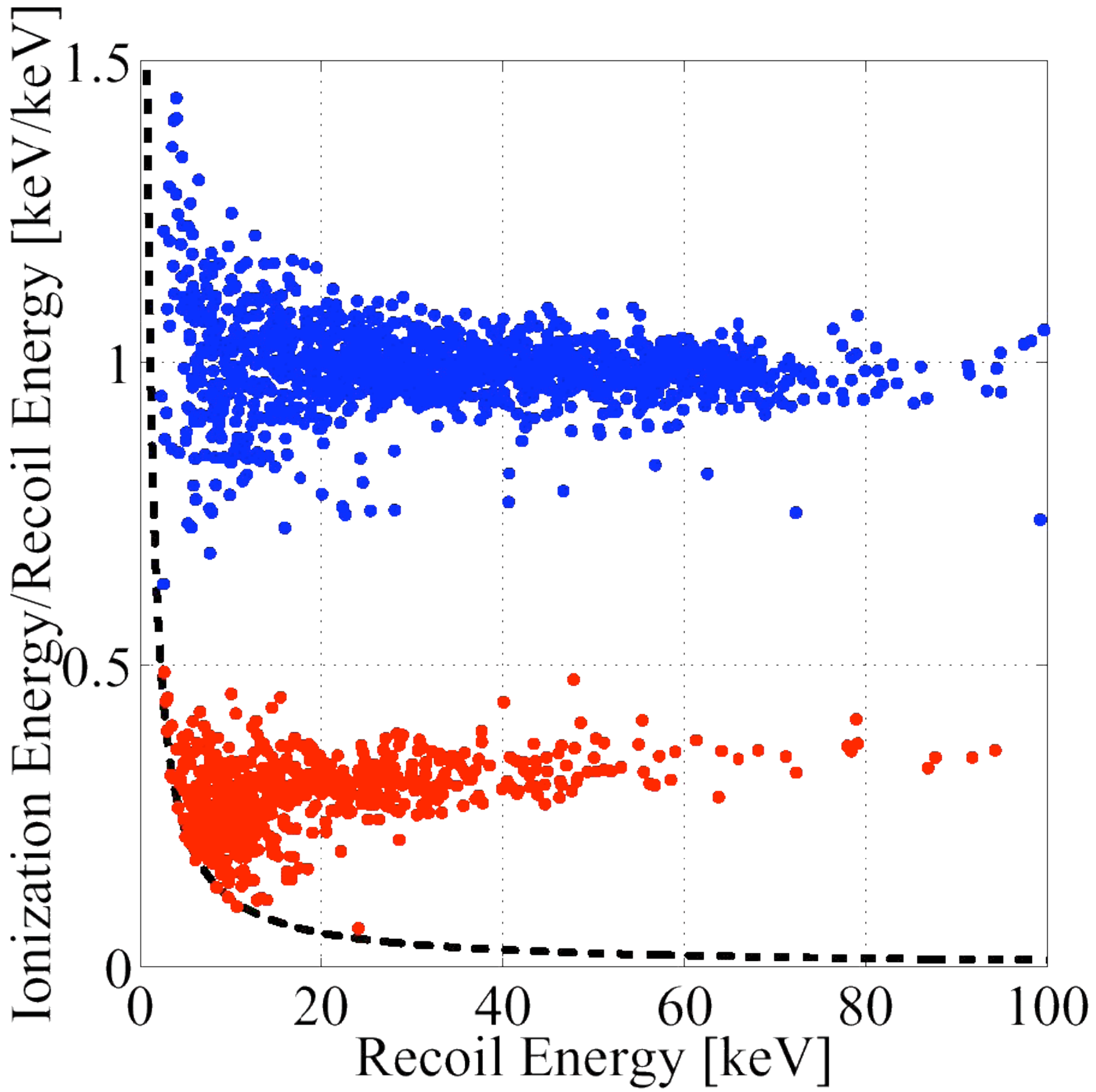
- -Fermilab
- -NIST

University

- CalTech
- Case Western
- Colorado (Denver)
- Florida
- Queen's
- Minnesota
- MIT
- Stanford
- Santa Clara
- Syracuse
- UC Berkeley
- UC Santa Barbara
- Zurich

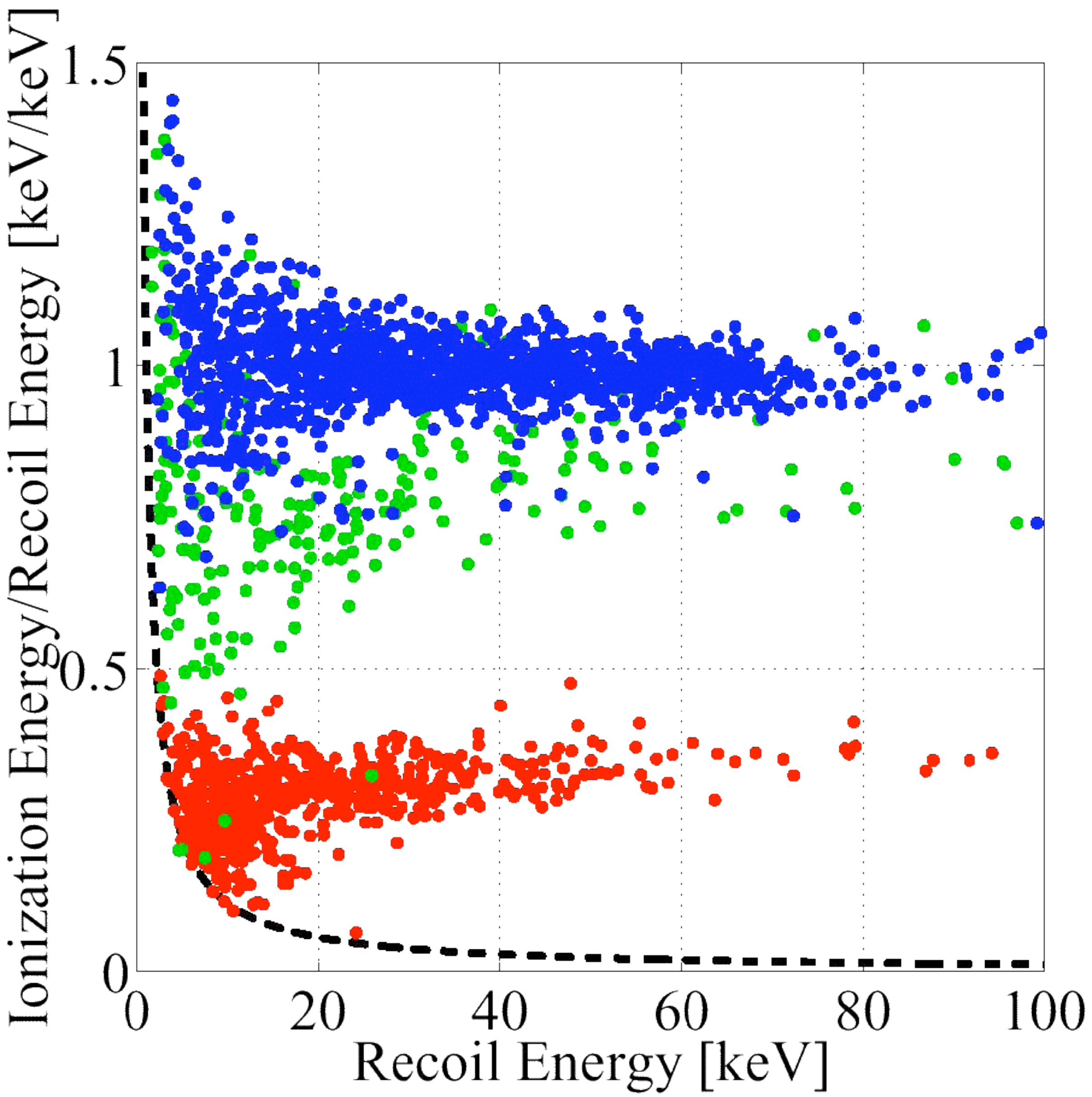
CDMS Background Discrimination in Action

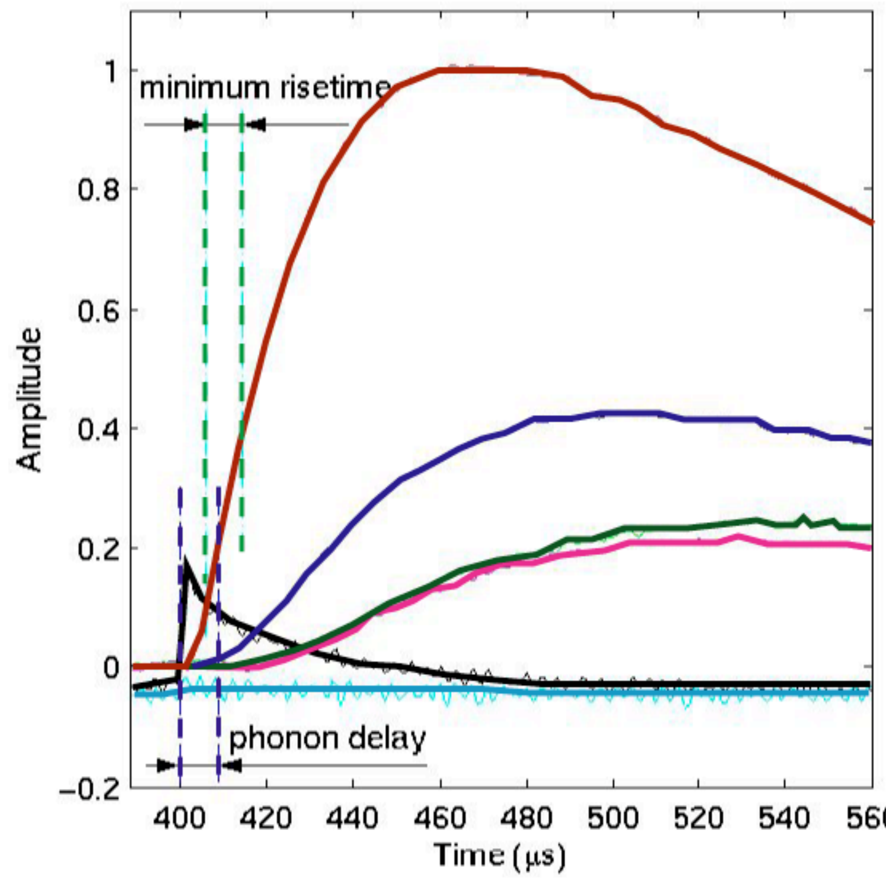
- Calibration with ^{60}Co (γ) source results in the blue (high yield) electron recoils
- Calibration with ^{252}Cf (n) source results in the red (low yield) nuclear recoils
- Can identify/eliminate the electron recoils better than 1 in 10^6
- ... BUT ...



CDMS Background   Achilles' Heel

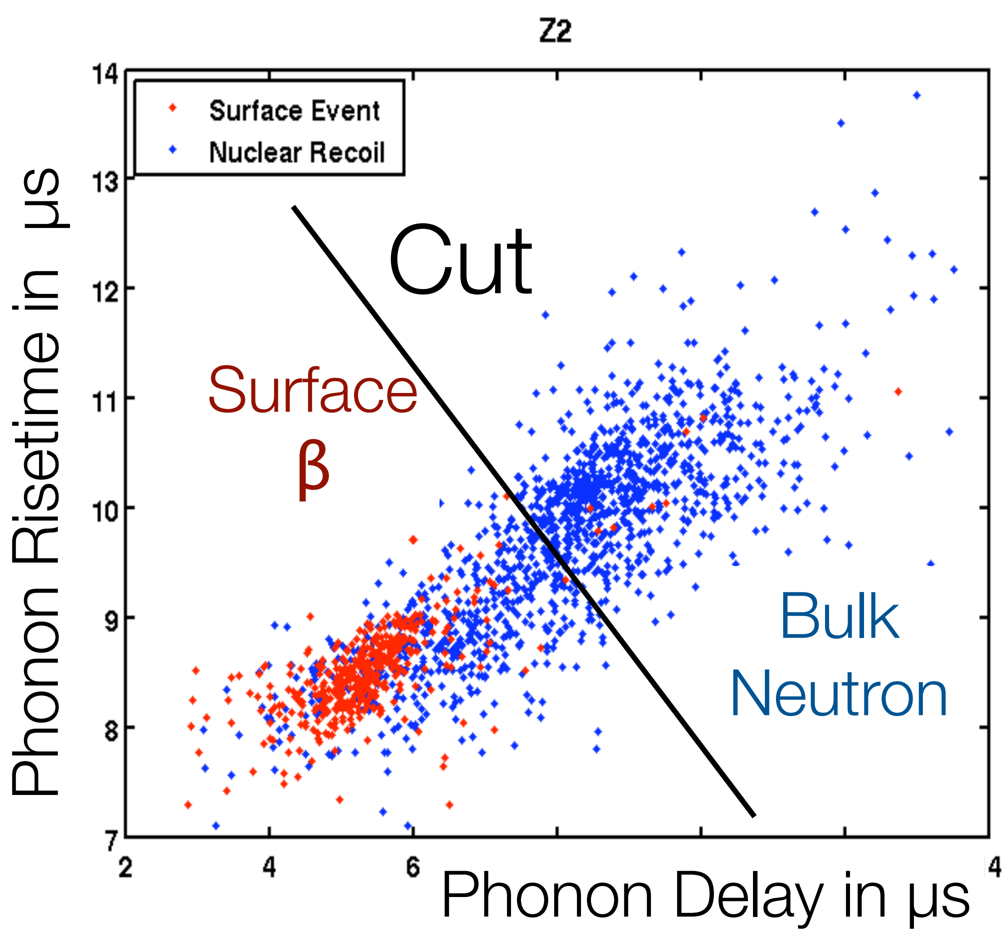
- Calibration with ^{60}Co (γ) source also results in the green (mid yield) electron recoils
- Events are due to electrons that interact near the surface (dead layer) of the detector
- Can be mis-identified as nuclear recoils

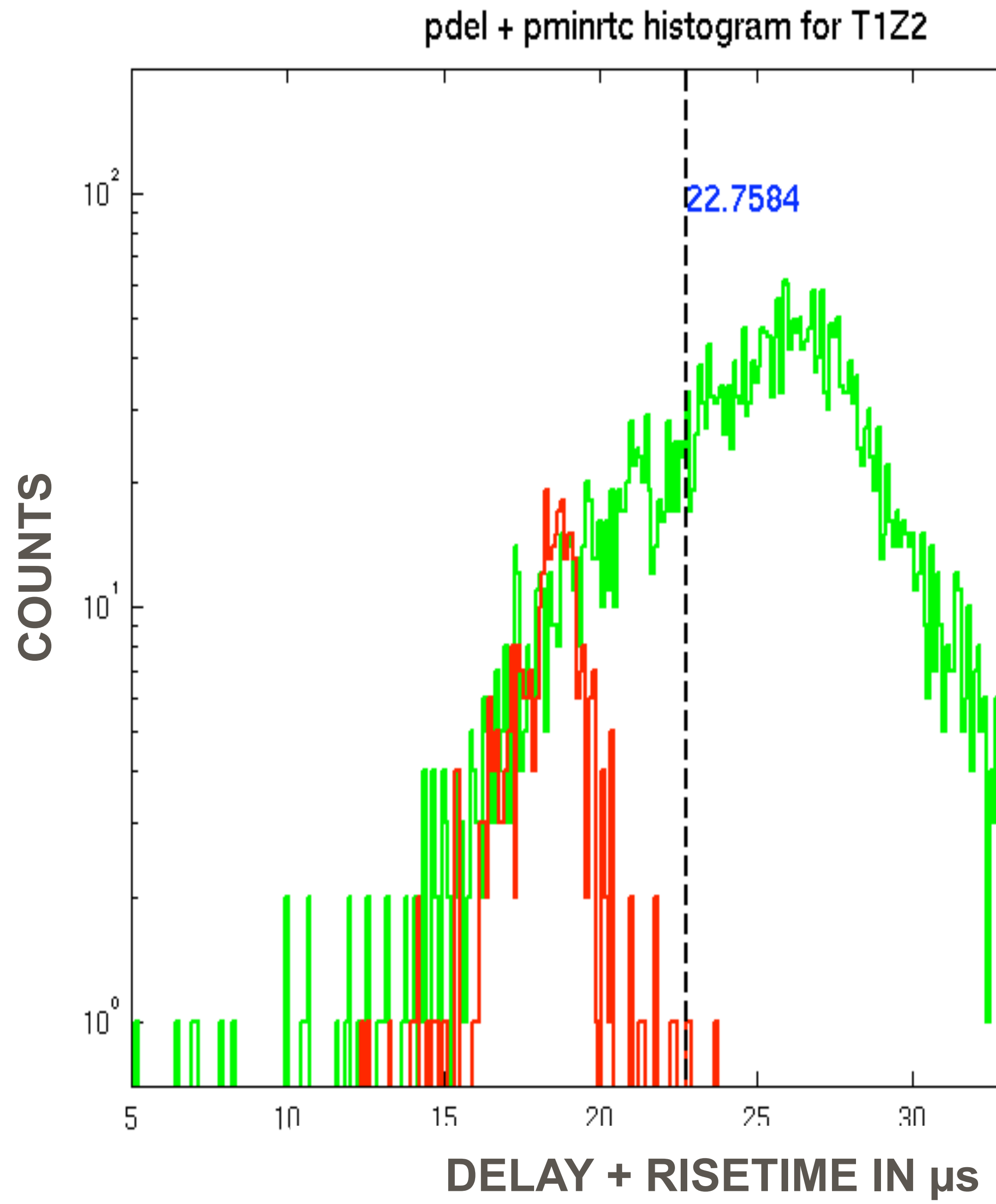


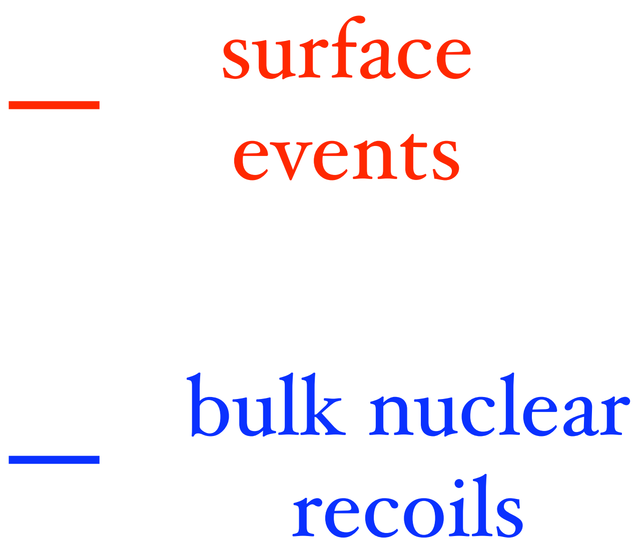


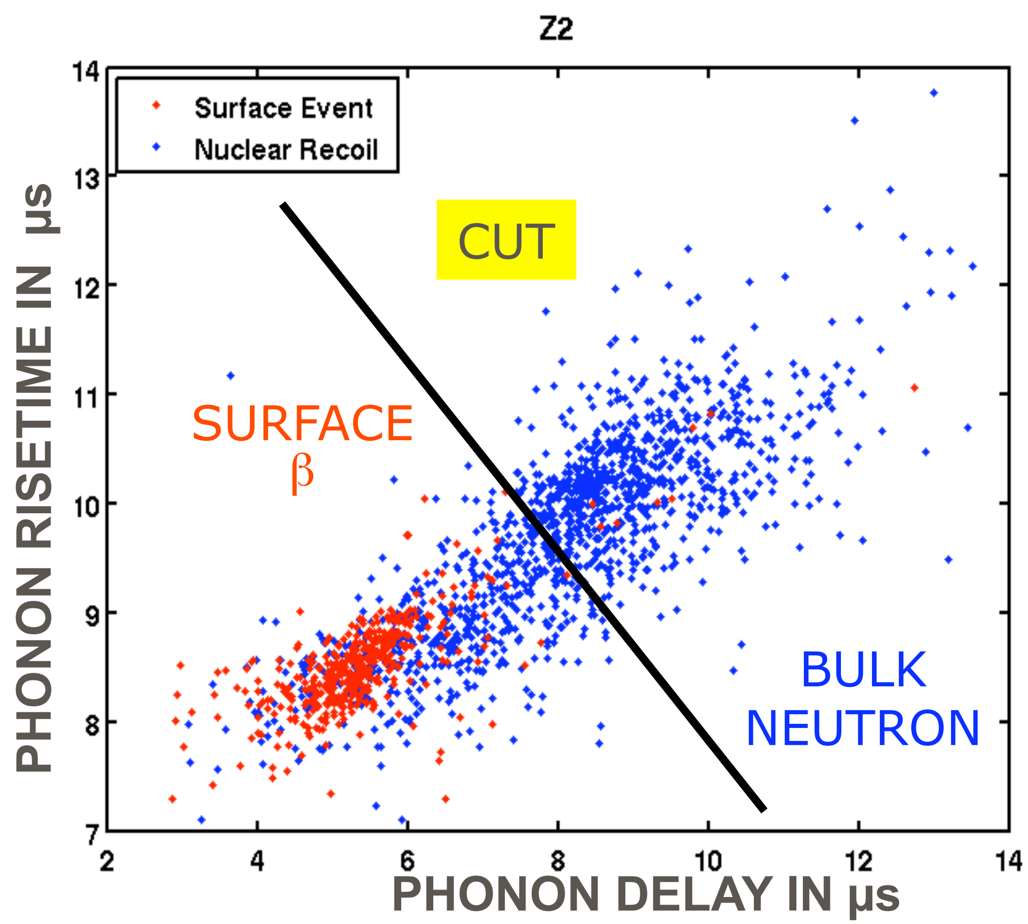
Timing to The Rescue

- Analysis of pulse shapes / timing parameters further separates the event populations

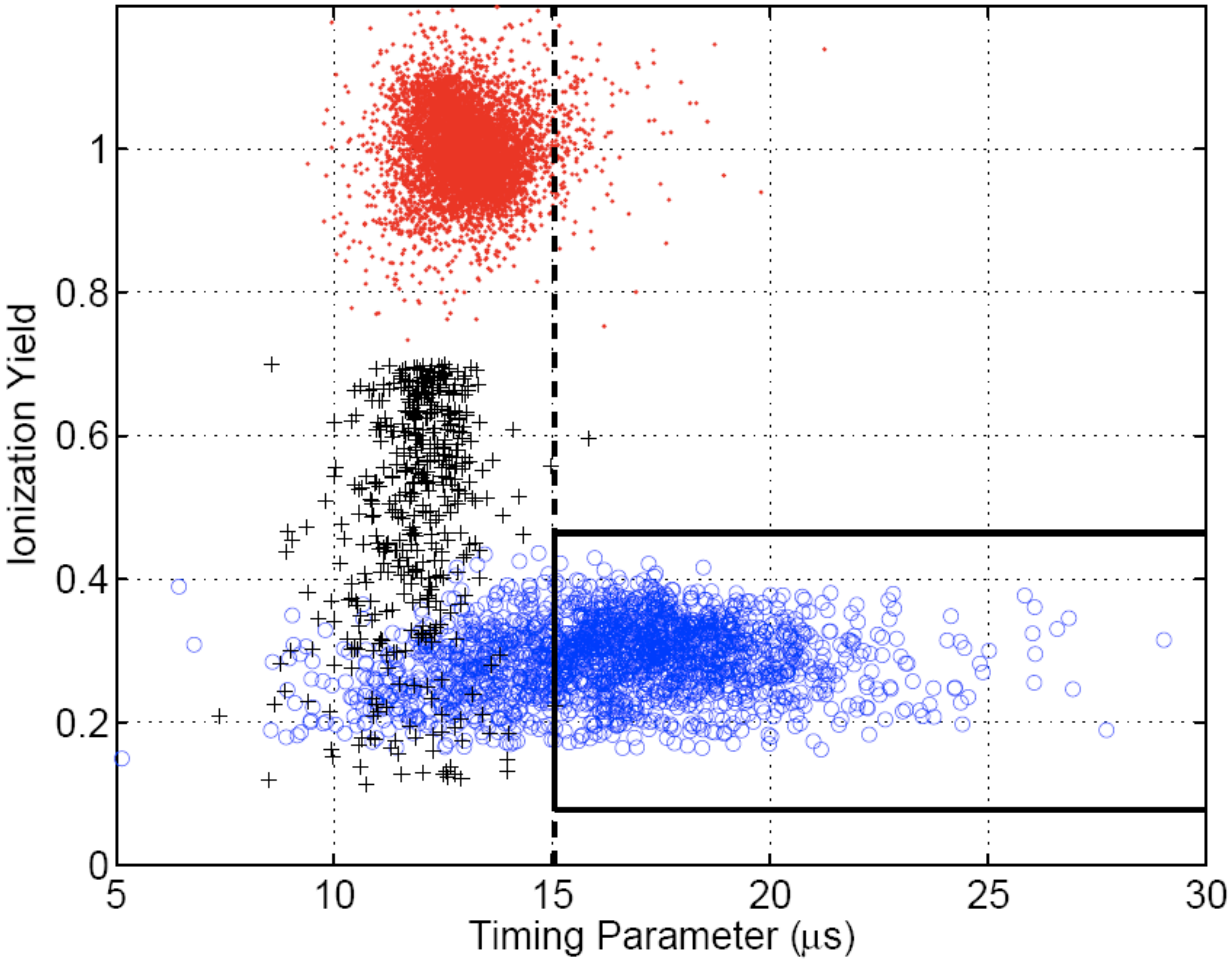








Applying the Timing Cut



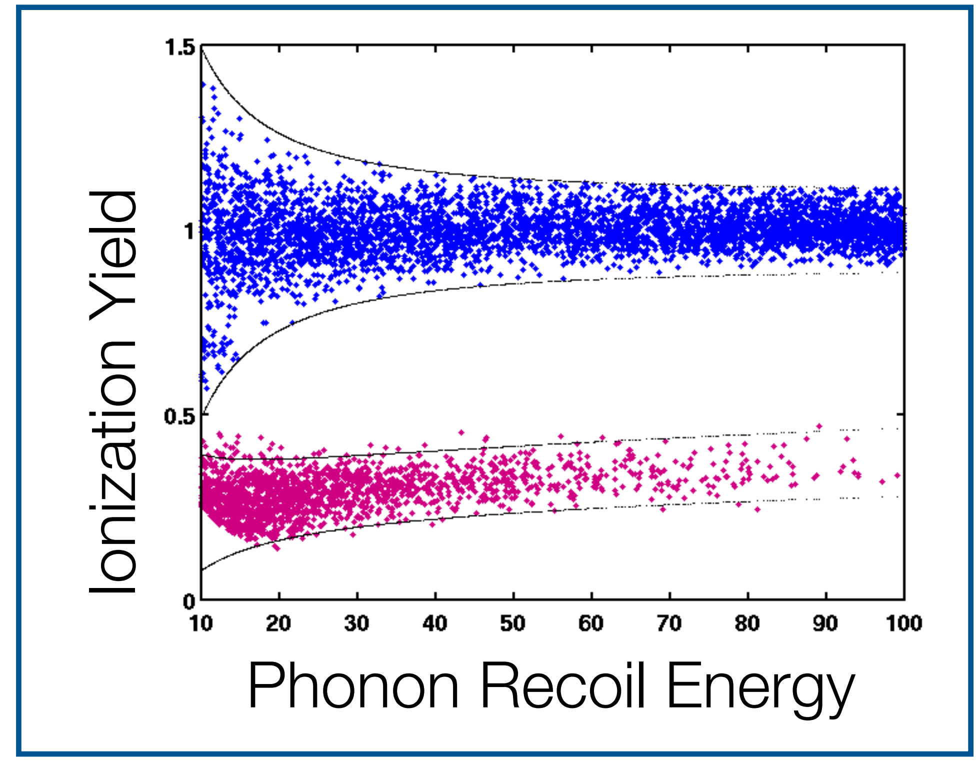
Net CDMS Rejection

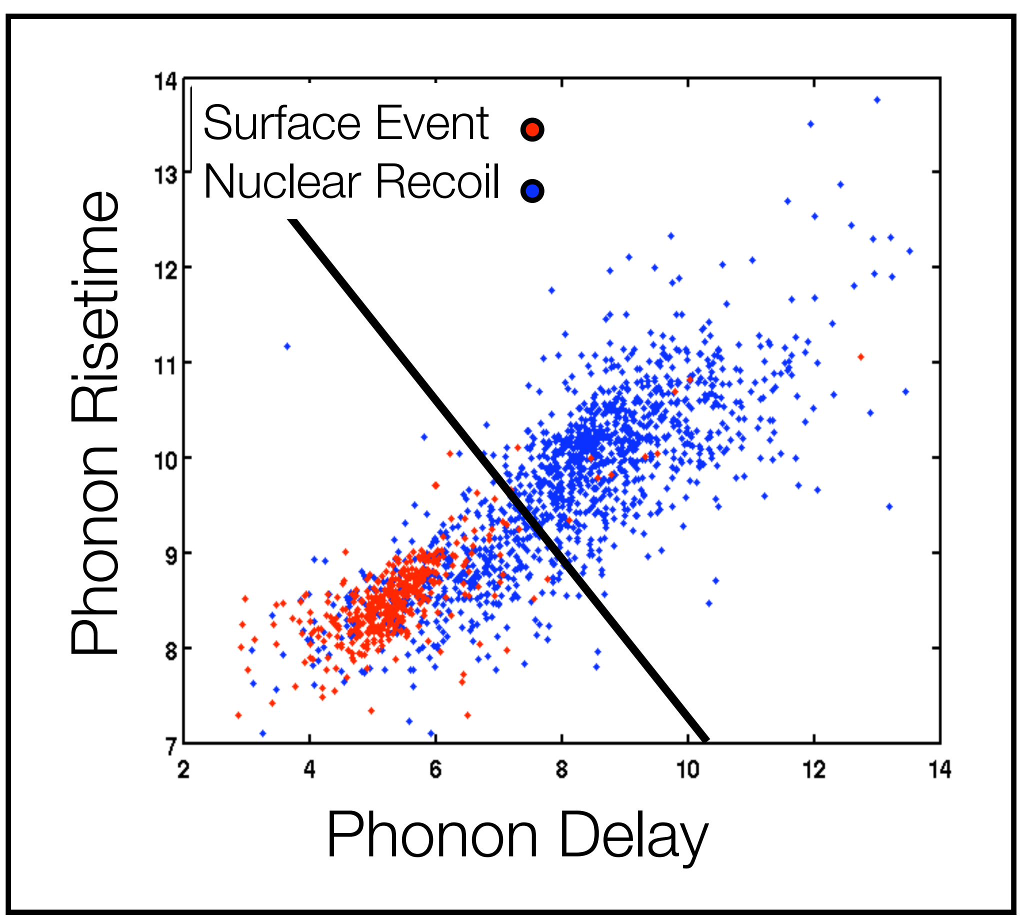
Yield + Timing Provide Excellent ($>10^6$:1) rejection of EM Backgrounds

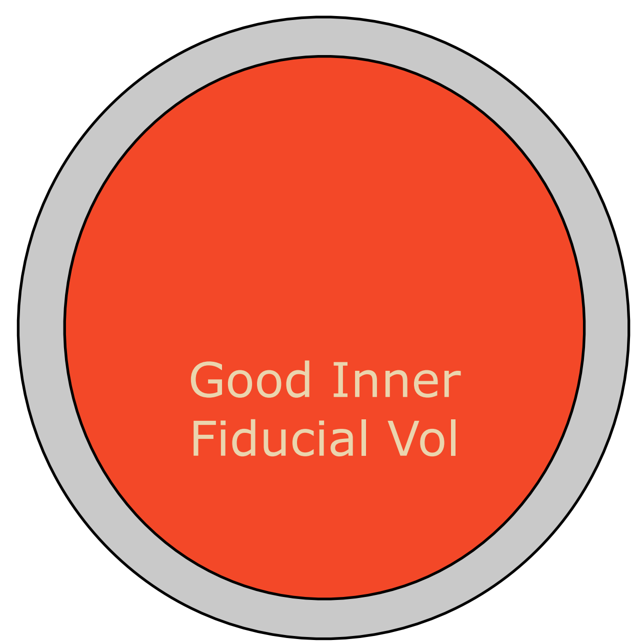
WIMP Candidate: Blind Analysis

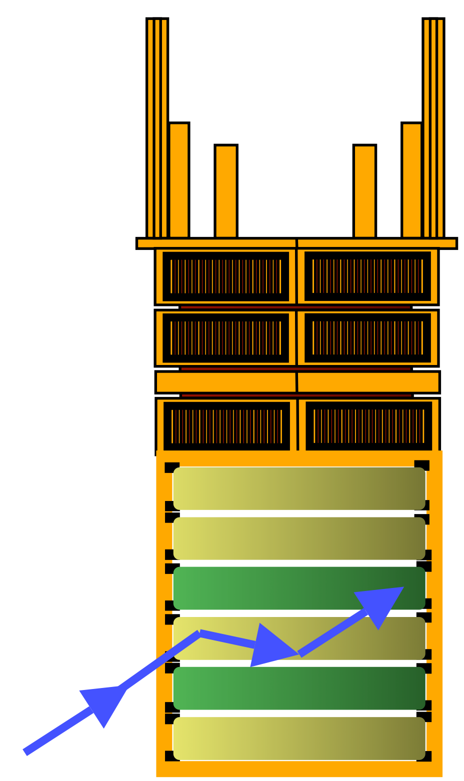
All cuts set blind, without looking at the signal.
i.e. we do not look at events which are:

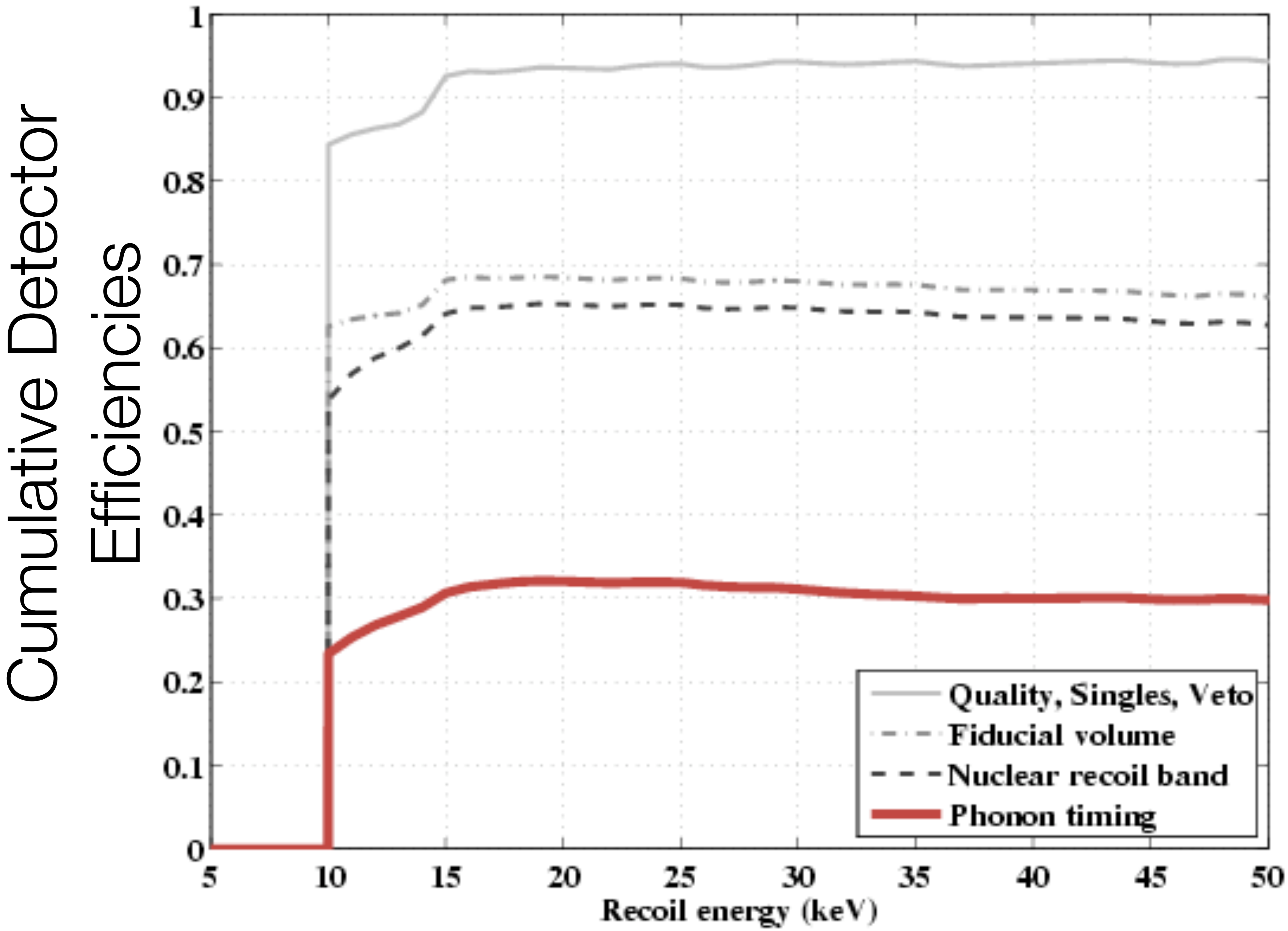
- ☑ Inside the good fiducial volume
- ☑ In the Nuclear Recoil Band
- ☑ Single Scatter
- ☑ Not a surface event: phonon timing cut











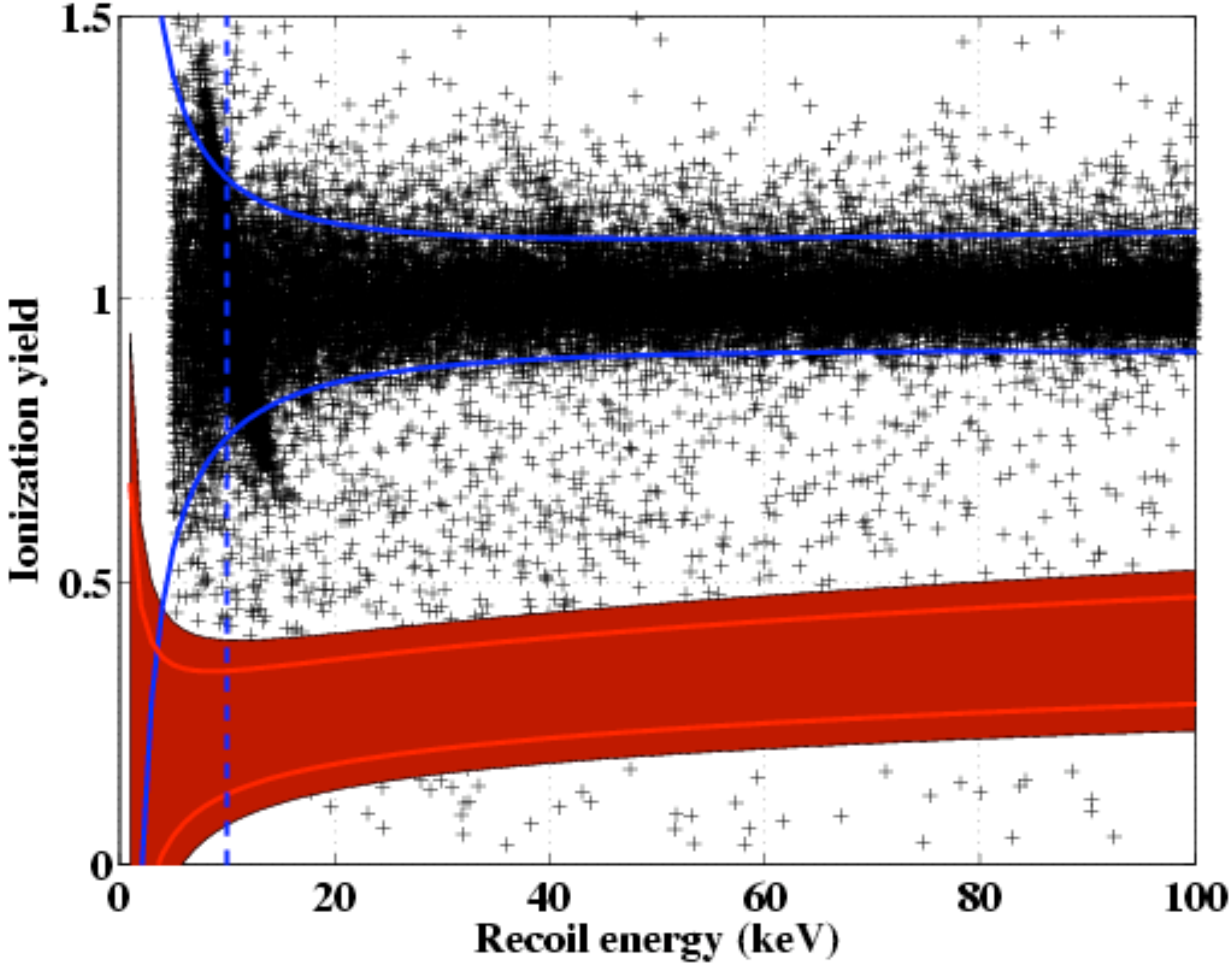
Efficiencies

Total Efficiency with Respect to Full Detector Mass

CDMS Dark Matter Data

- A complete blind analysis was performed

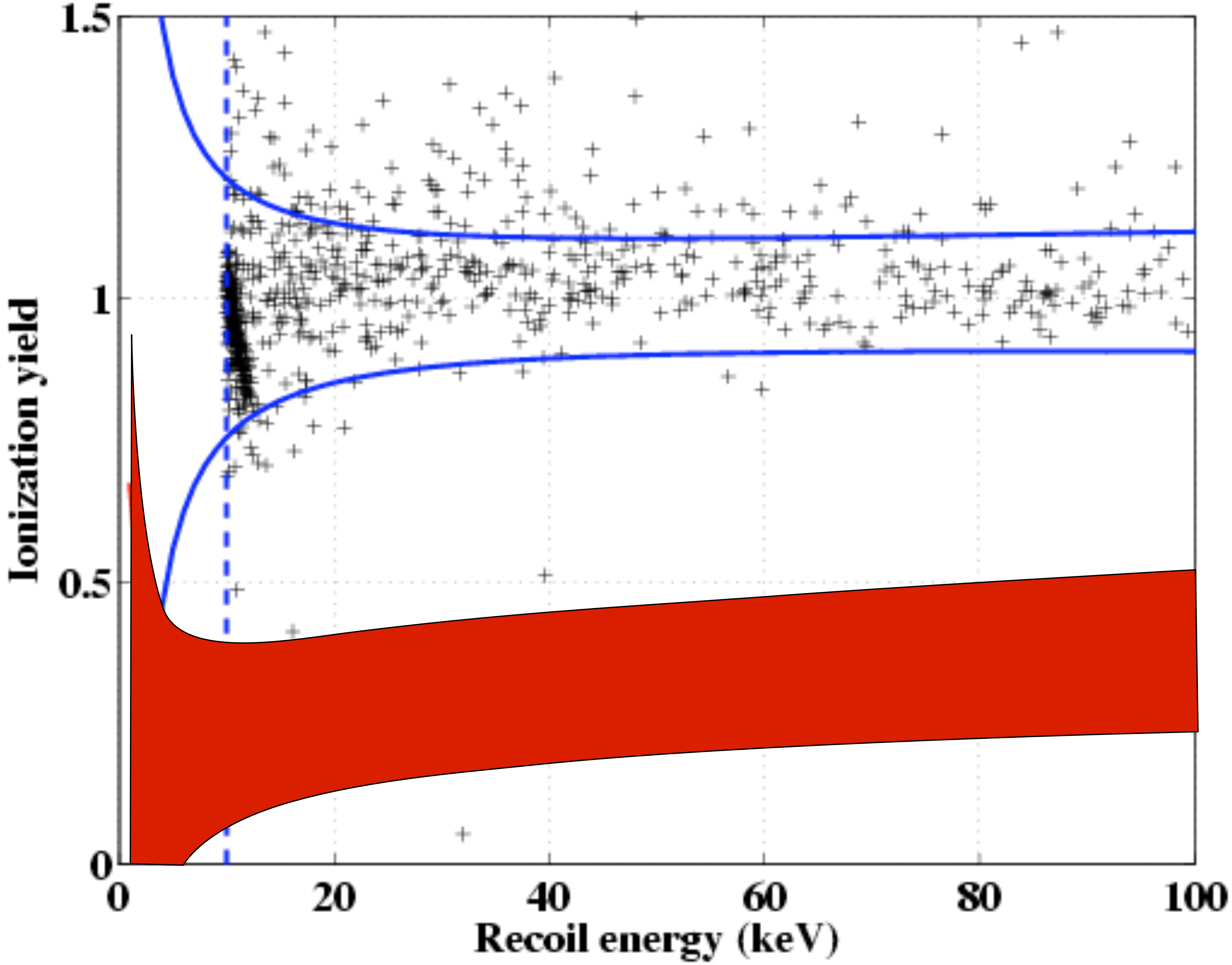
- No events passing the background rejection cuts!!



CDMS Dark Matter Data

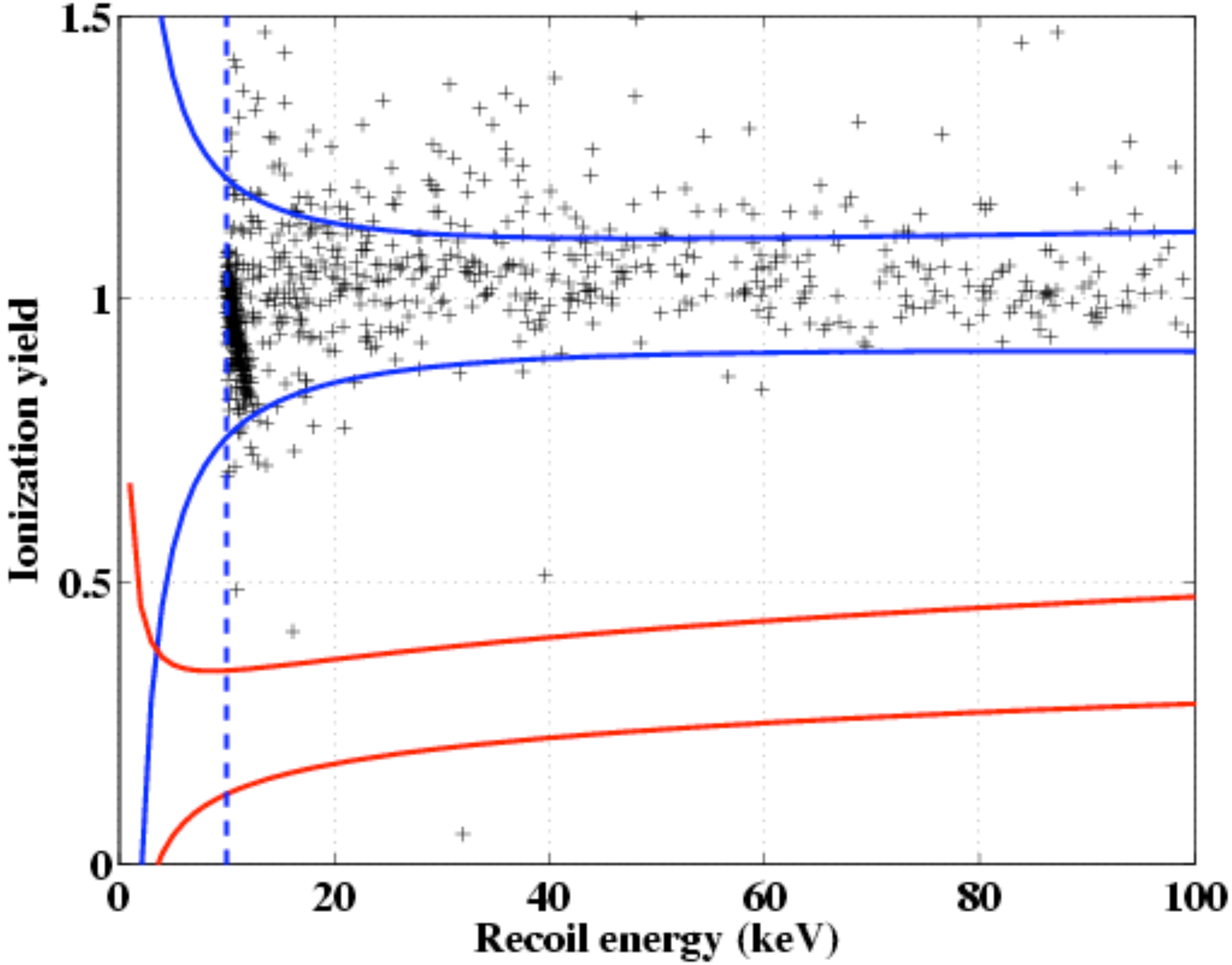
- A complete blind analysis was performed

- No events passing the background rejection cuts!!



CDMS Dark Matter Data

- A complete blind analysis was performed
- No events passing the background rejection cuts!!



CRESST

- Cryogenic Rare Event Search using Superconducting Thermometer

- Target : Scintillating crystals
  - $CaWO_4$: W has A = 184, Ca has A = 40
  - Largely sensitive to spin-independent interactions

- Detection Mechanism
  - Superconducting phase thermometer provides calorimetric measurement of the recoil energy
  - Scintillation photons absorbed/measured by neighboring detector

CRESST

- Background Discrimination :
  - Higher ratio of scintillation to thermal signals for electron recoils
  - Able to reject bulk electron recoils better than 99%
- Mass / Exposure
  - Ran 2 0.3 kg detectors at the Gran Sasso laboratory (~2000 mwe) for 20.5 kg-days
  - Background rate ~ 6 evt/kg/keV/day
  - Planning upgrade in detector mass to 10 kg in 2005

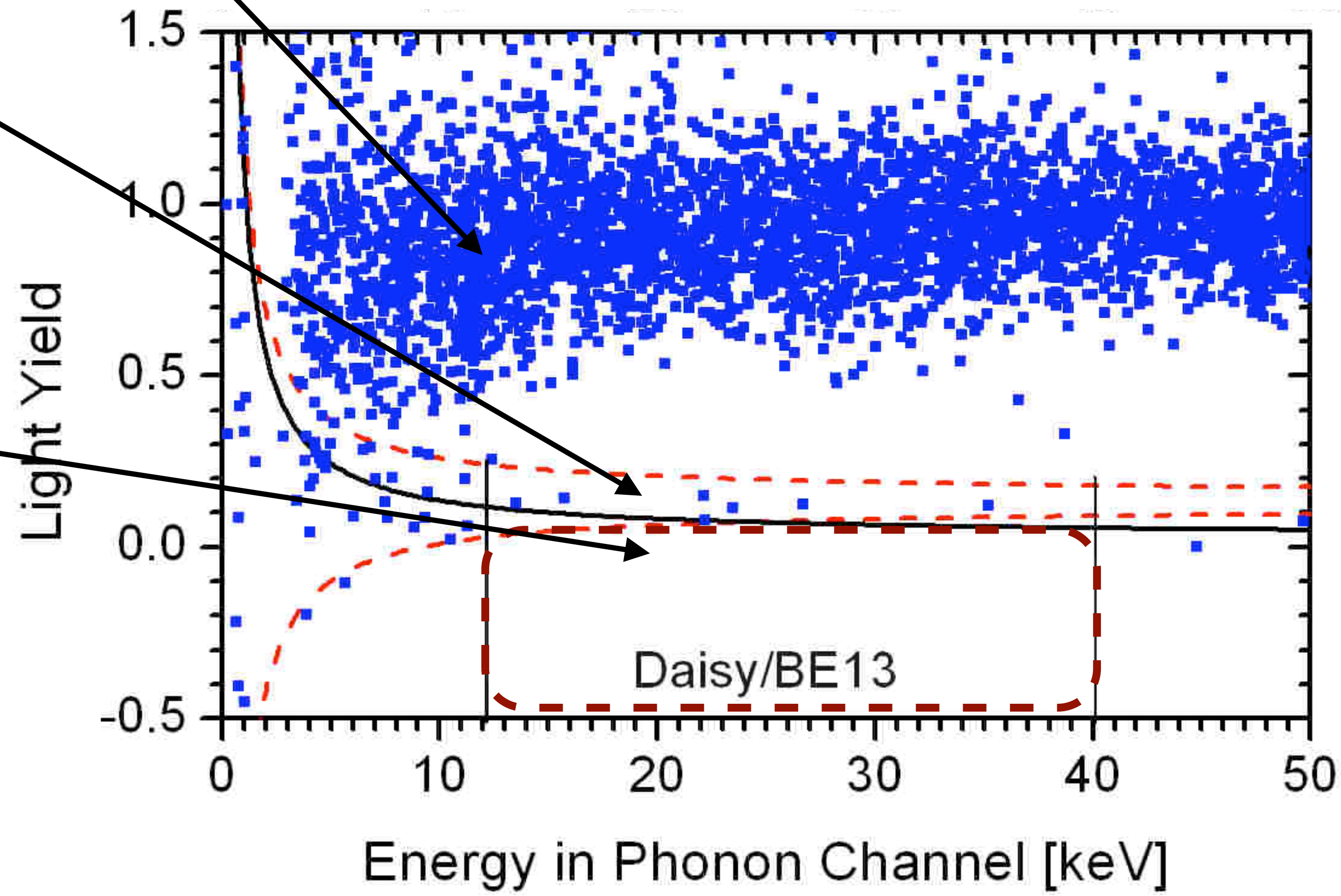
Electron Recoil Band

Dark Matter data

- No events seen that are consistent with W nuclear recoils

Nuclear Recoil Band from Oxygen

Nuclear Recoil Band from Tungsten

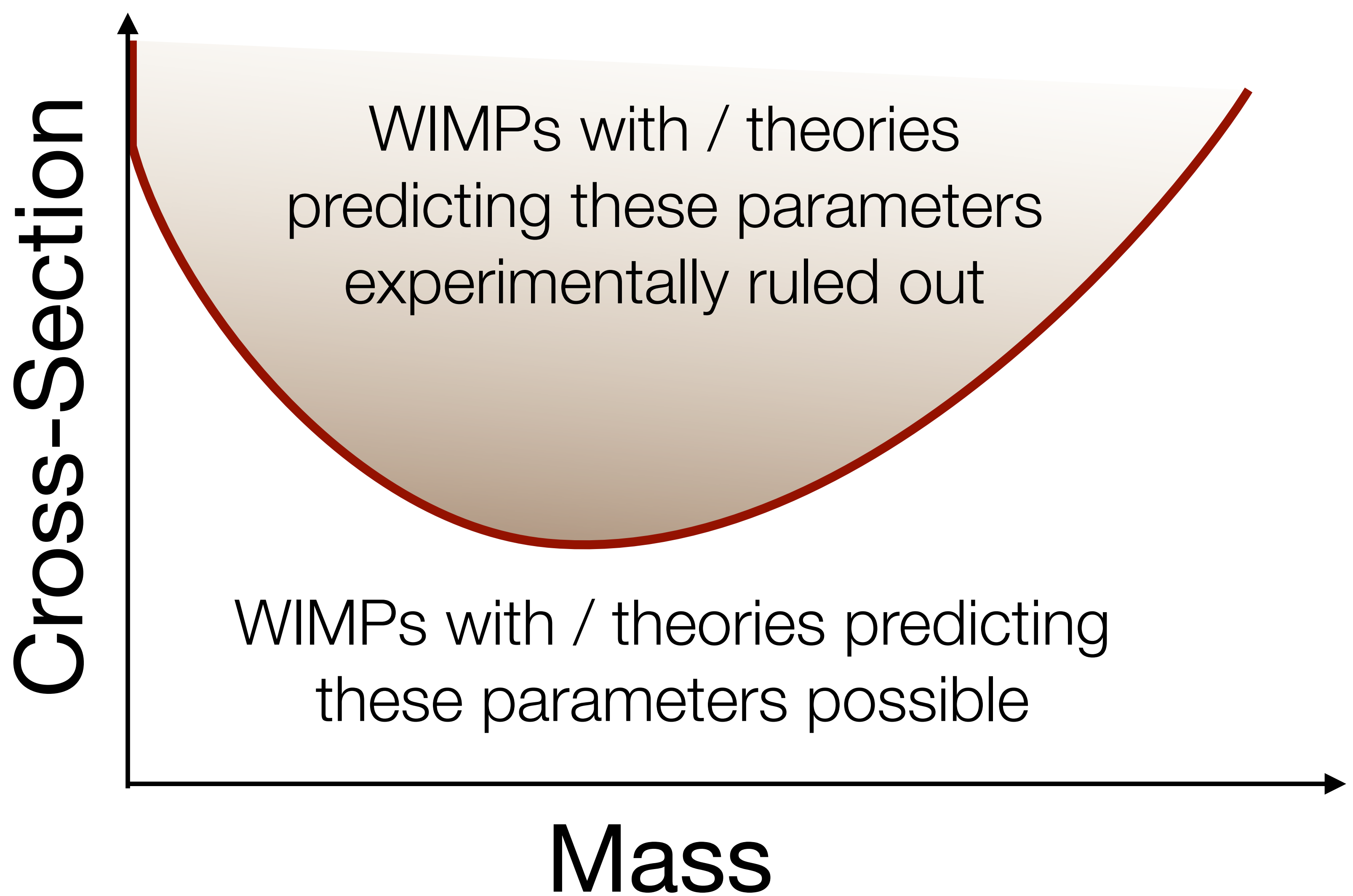


CRESST in Action

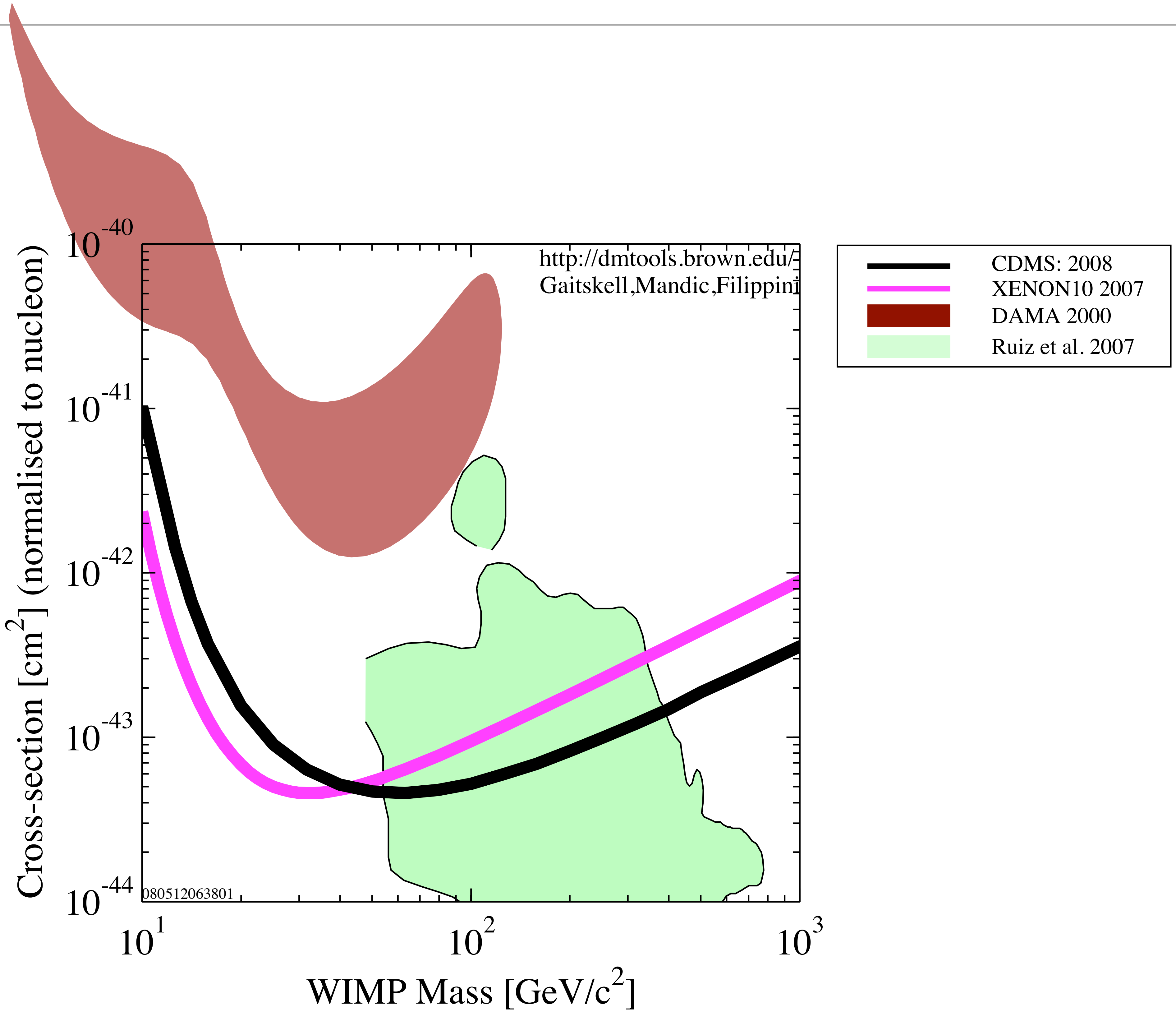
Experimental Limits

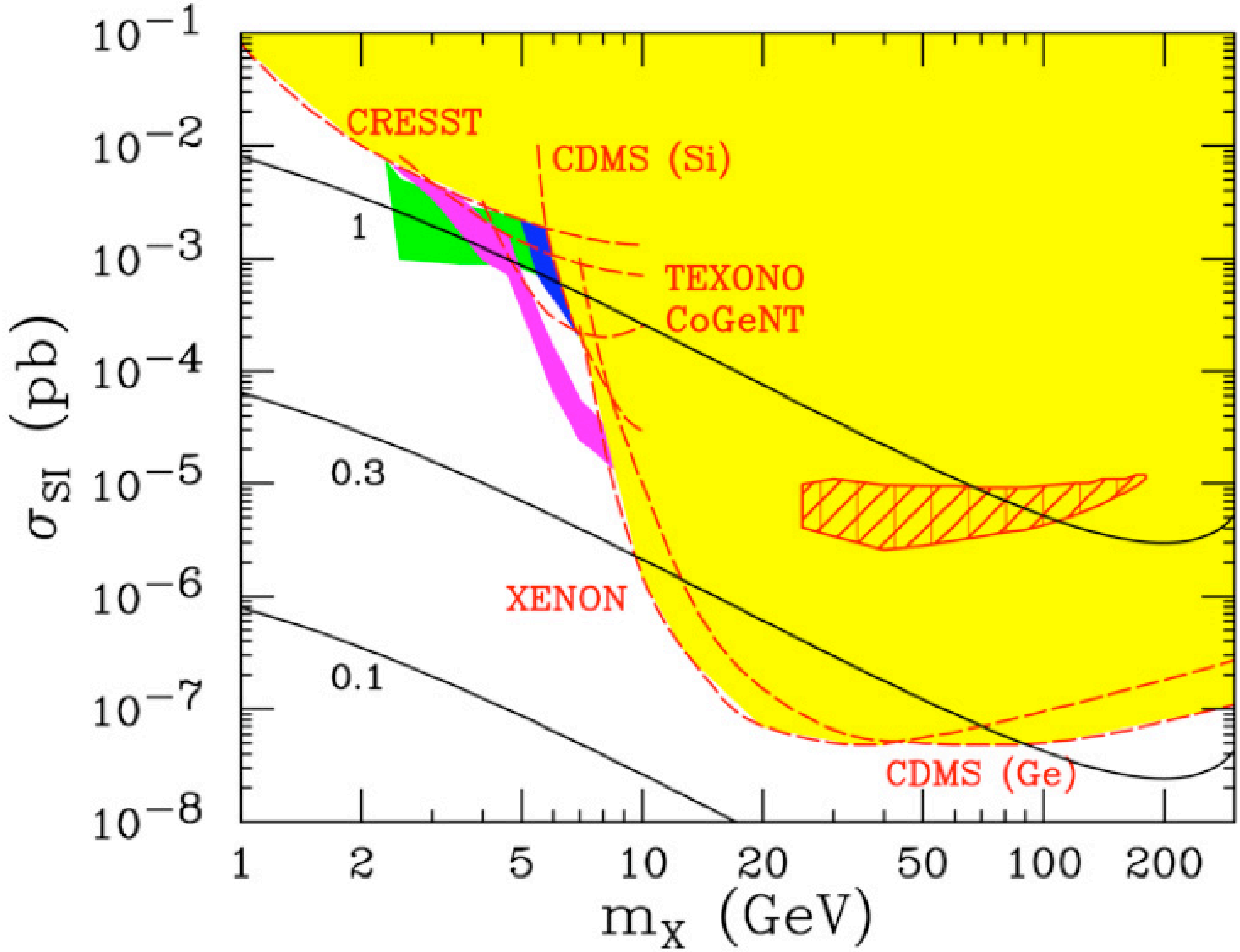
WIMP exclusion plots

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



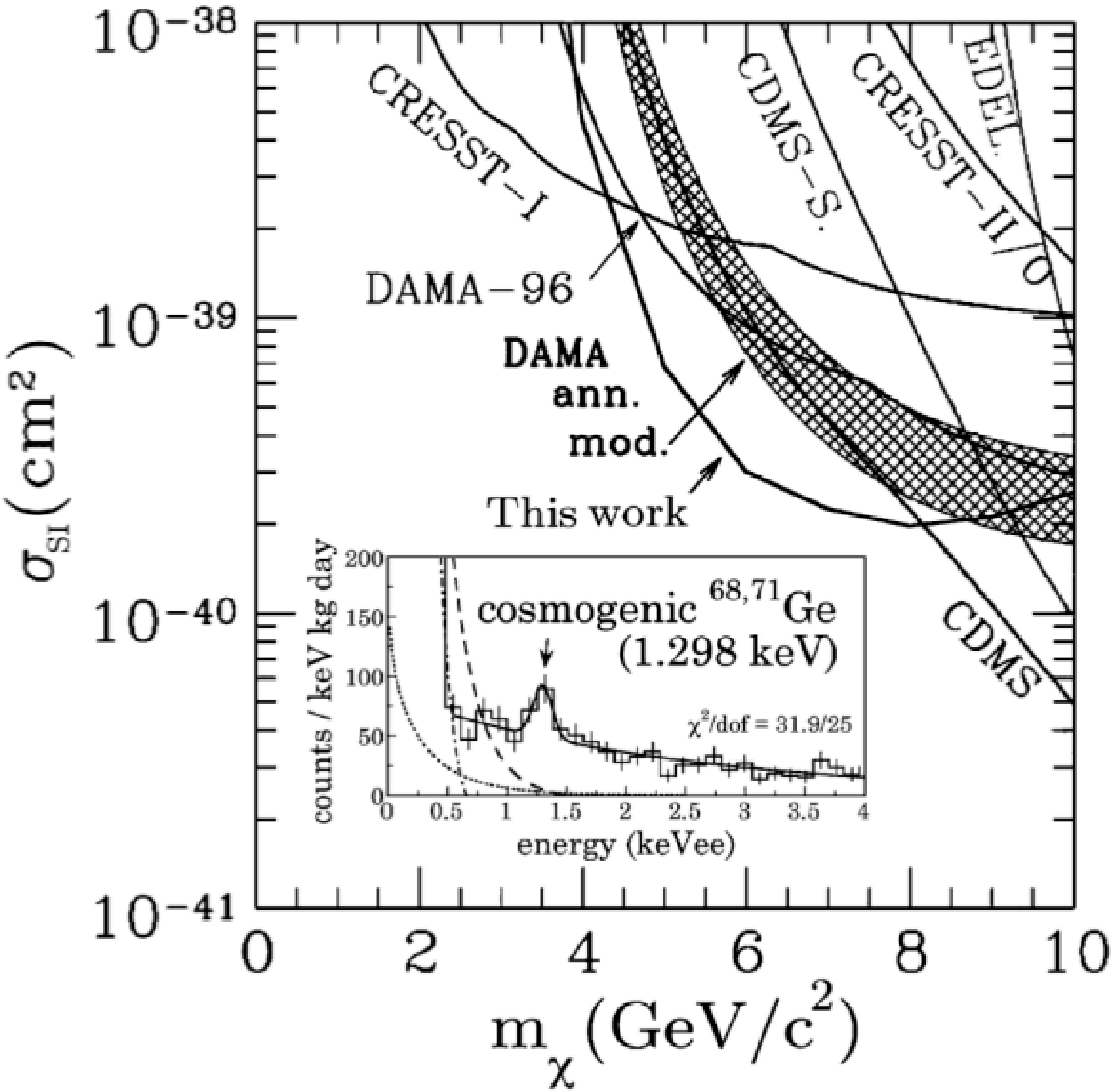
Spin-Independent Limits





Spin Indep Limits at low mass

DAMA is getting squeezed out



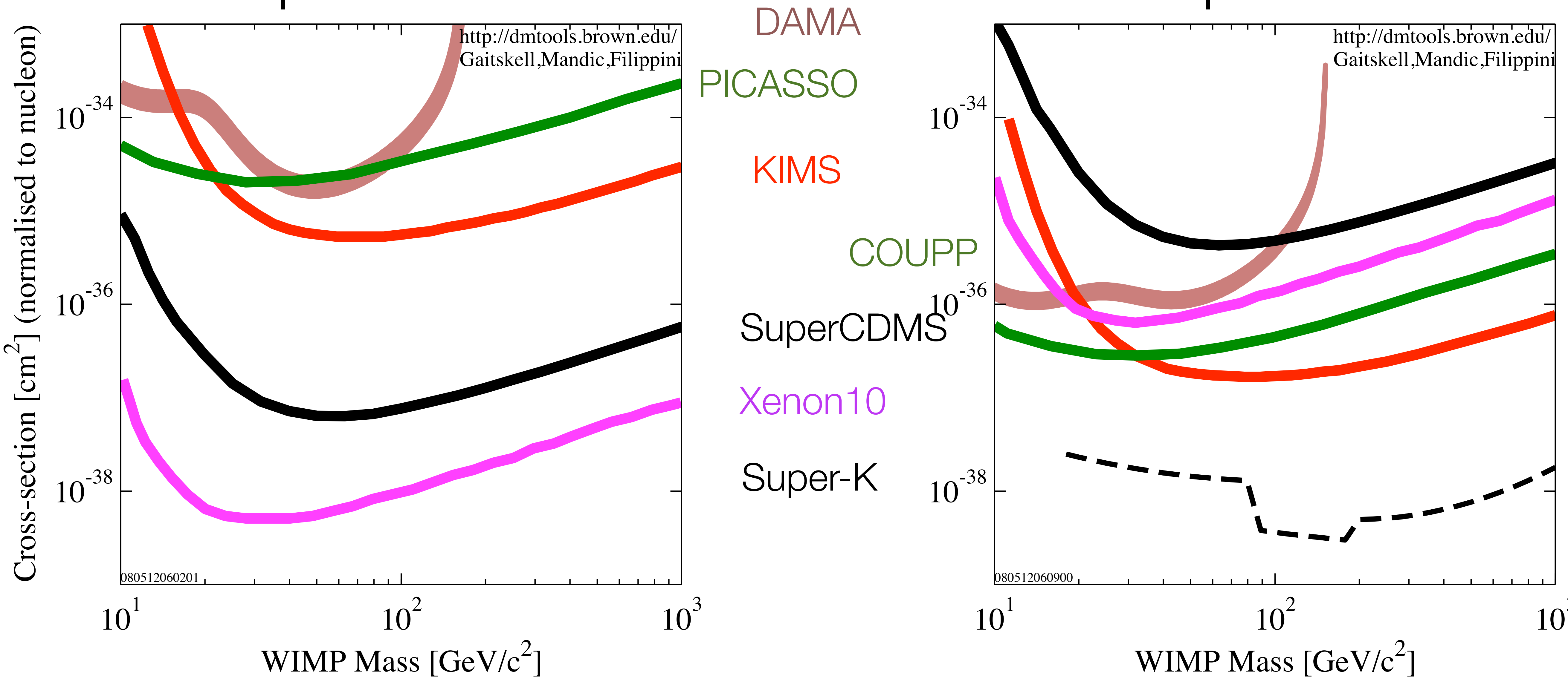
Spin Indep Limits at low mass

DAMA is getting squeezed out

Spin-Dependent Limits

Wimp-Neutron σ

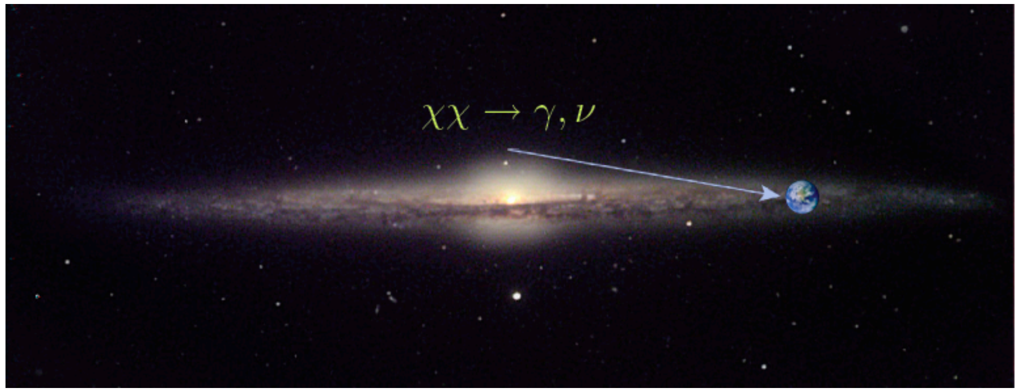
Wimp-Proton σ

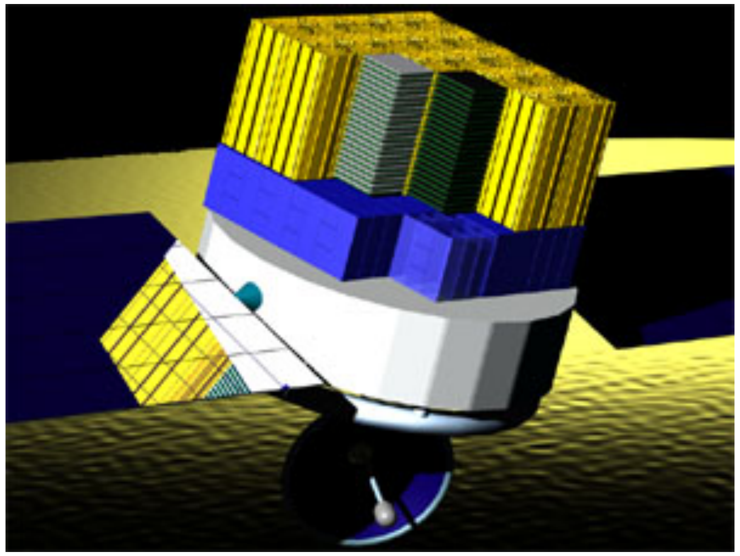


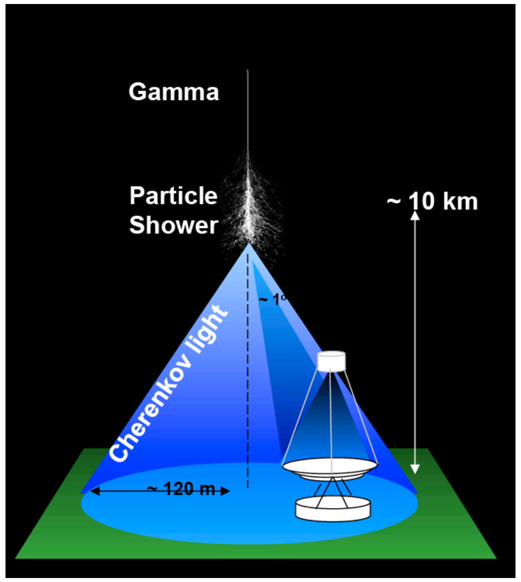
Indirect Detection Searches

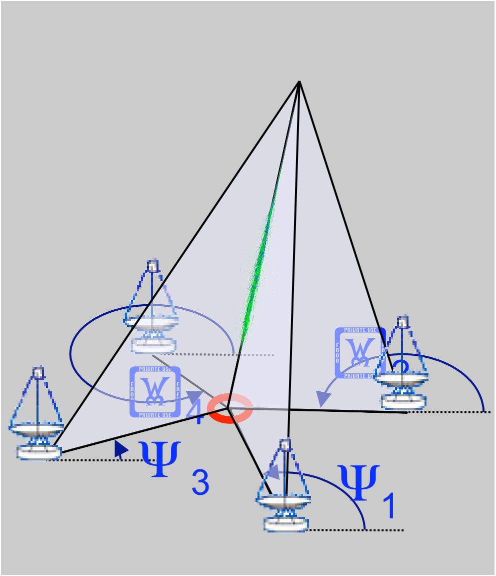
A couple of places to look: Photons

- Galactic and extra-galactic x-rays, gammas
  - EGRET, GLAST, Imaging Atmospheric Cherenkov Counters
- Advantages/Disadvantages:
  - Direct line of travel from source
  - Many "background" astrophysical continuum sources



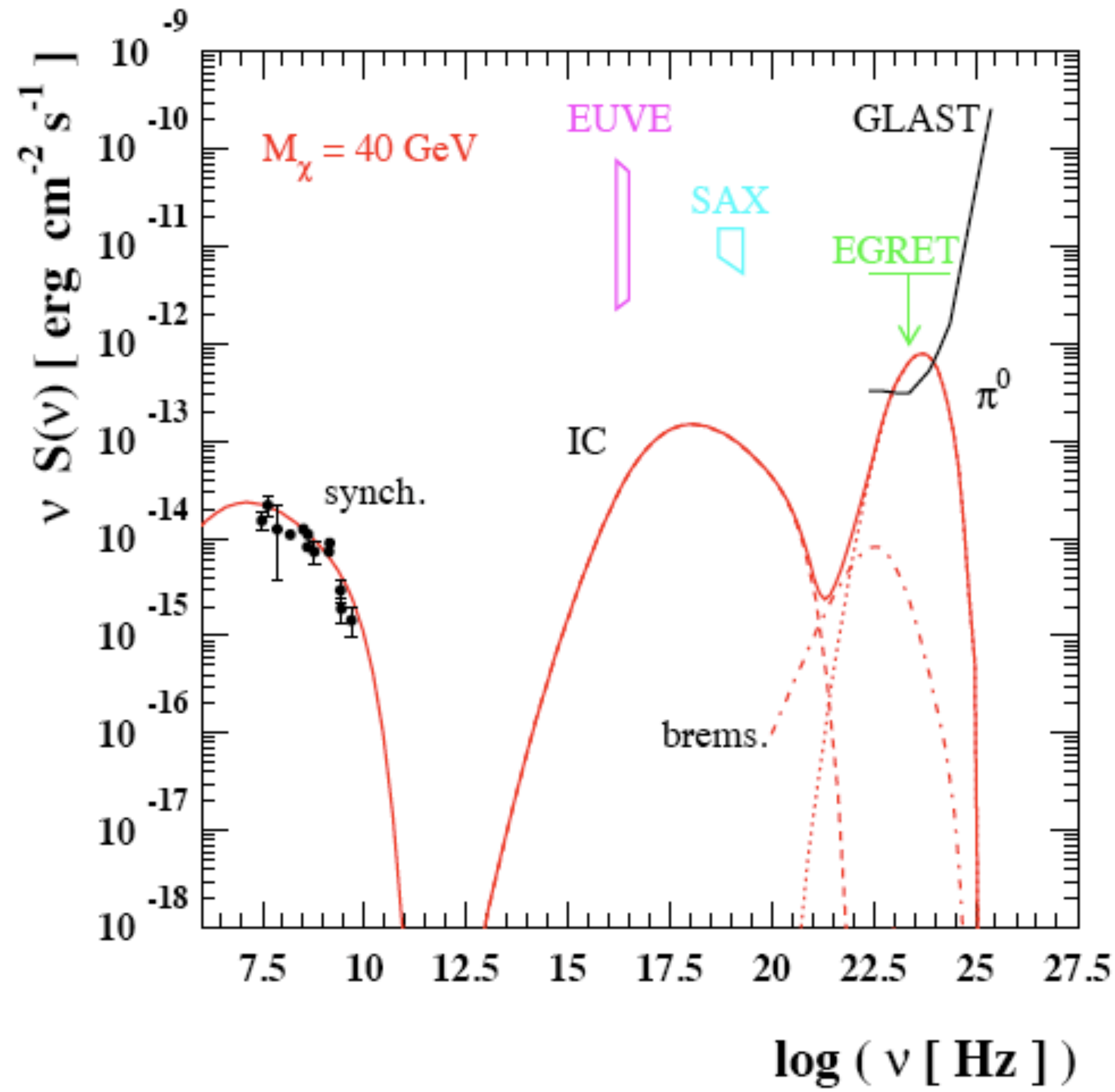






A couple of places to look: Photons

- A closer look at the energy scale of the photon final states
  - All the range is readily covered with modern instrumentation
  - “Mundane” galactic backgrounds dominate in most wavelengths

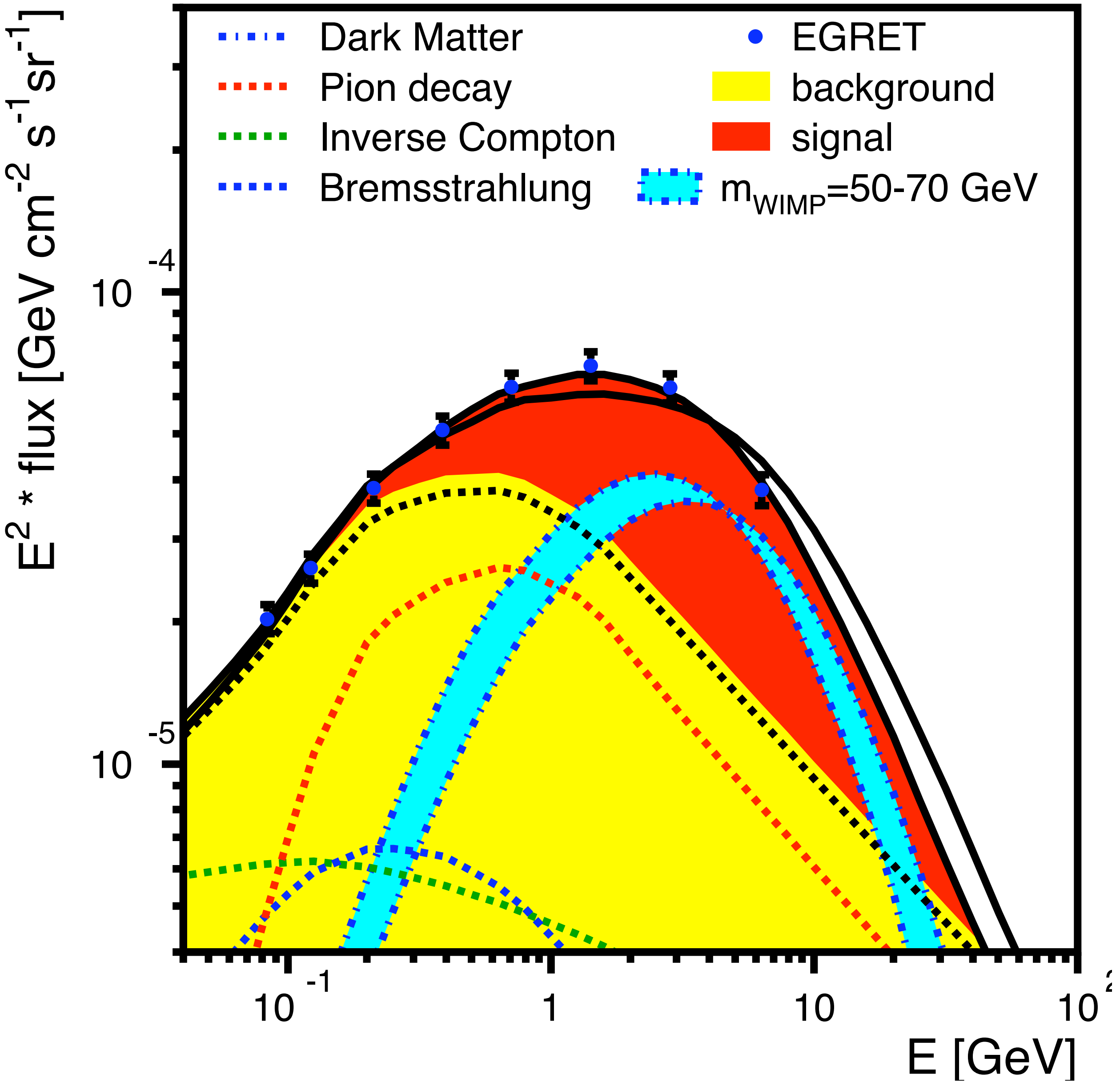


EGRET:
Diffuse Galactic Gammas

- Diffuse galactic gamma component ~ 2x larger than the expected background

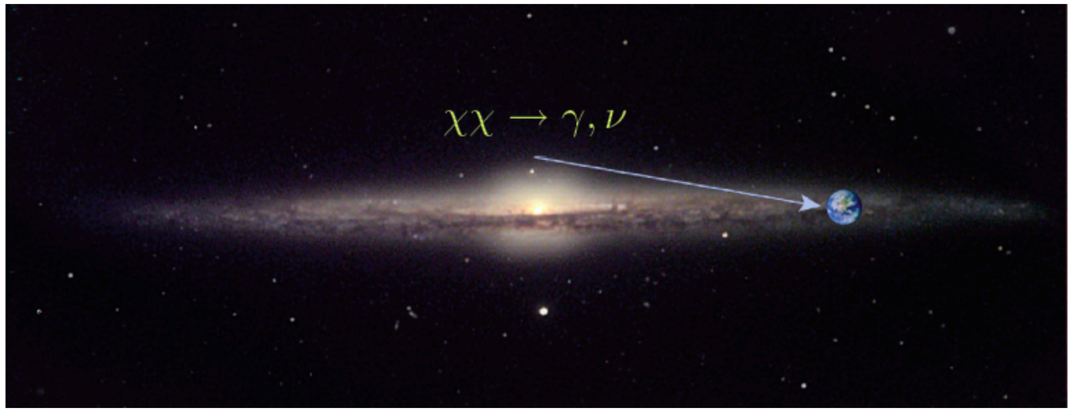
- Can be interpreted as arising from Dark Matter annihilation in the halo with m_χ~60 GeV/c^2

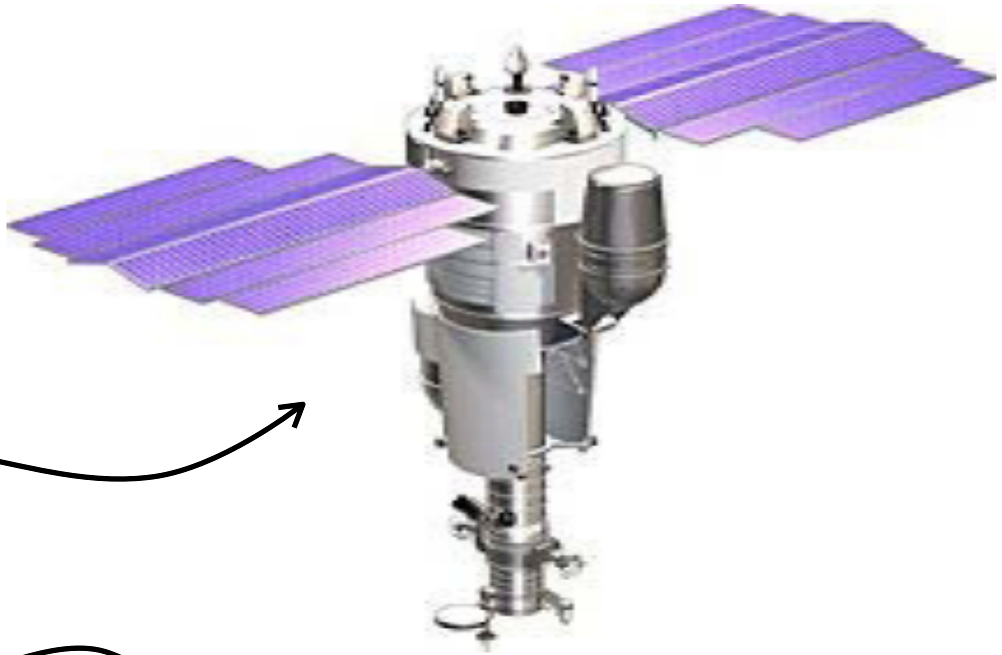
  - W. de Boer et al. astro-ph/0506447 & astro-ph/0508617



A couple of places to look: Charged Cosmic Rays

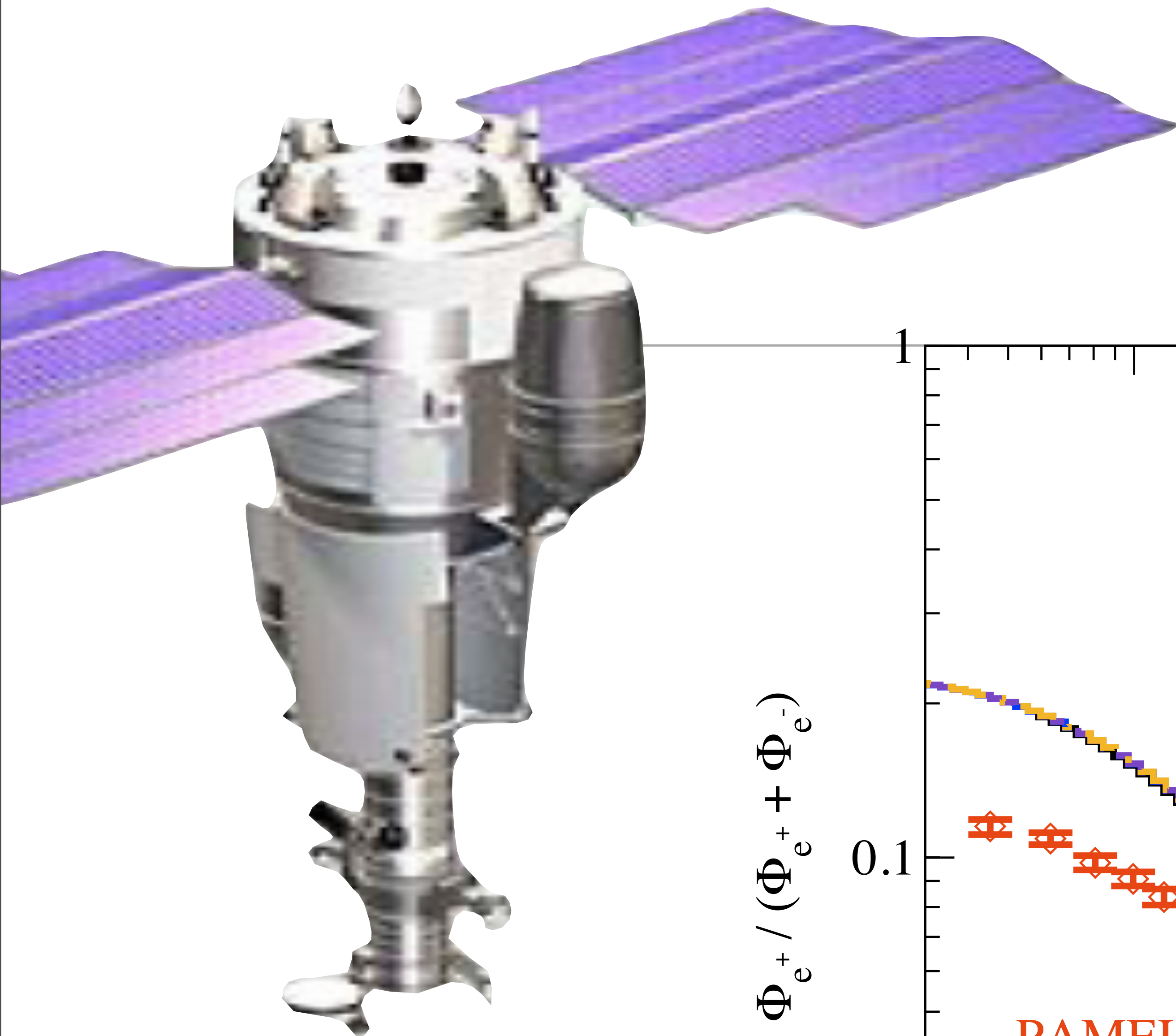
- Galactic and extra-galactic charged particles (positrons/anti-protons)
  - PAMELA, ATIC, HEAT

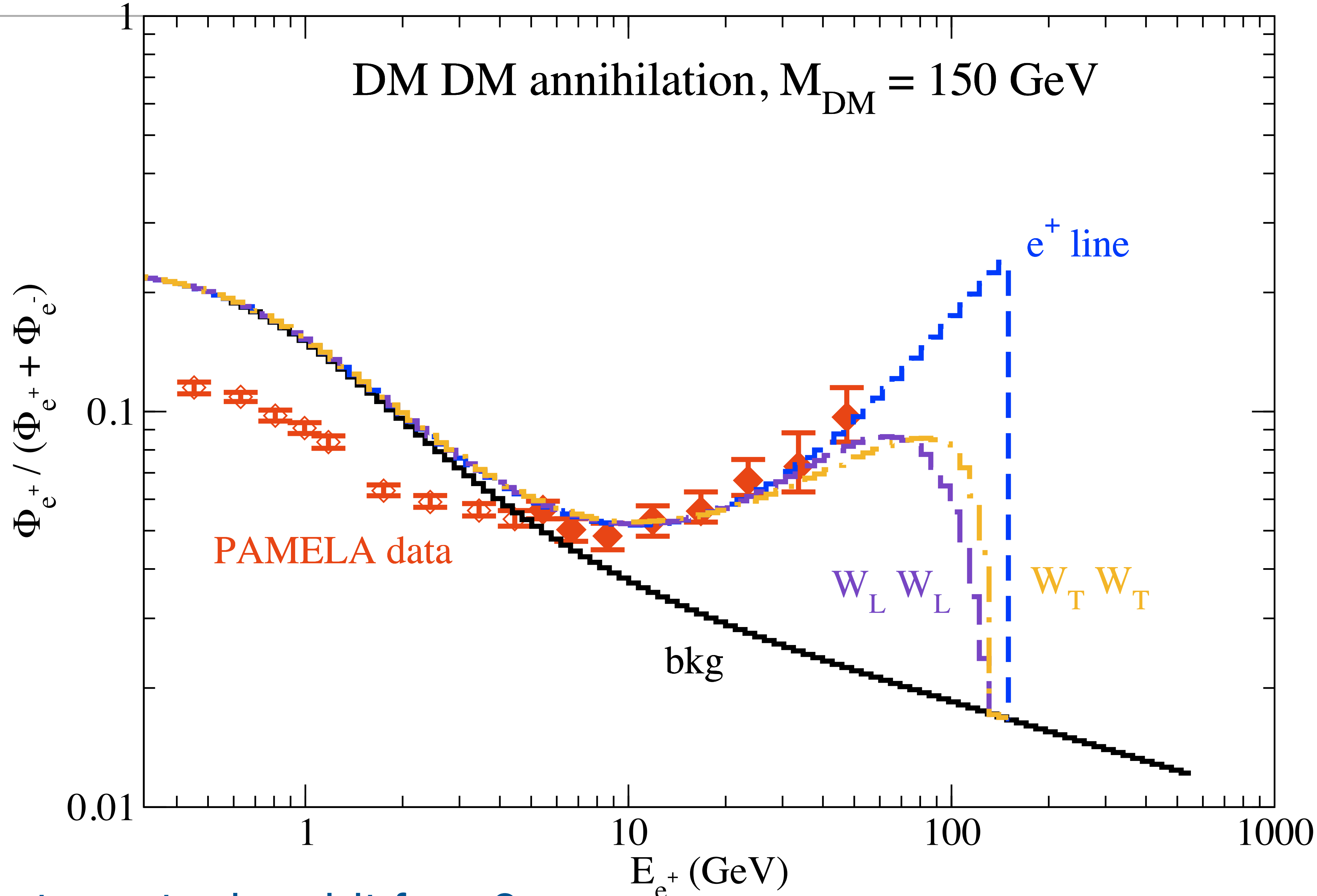




- Advantages/Disadvantages:
  - Slightly fewer "background" astrophysical sources
  - Diffusive travel from source
    - does not point back to origin

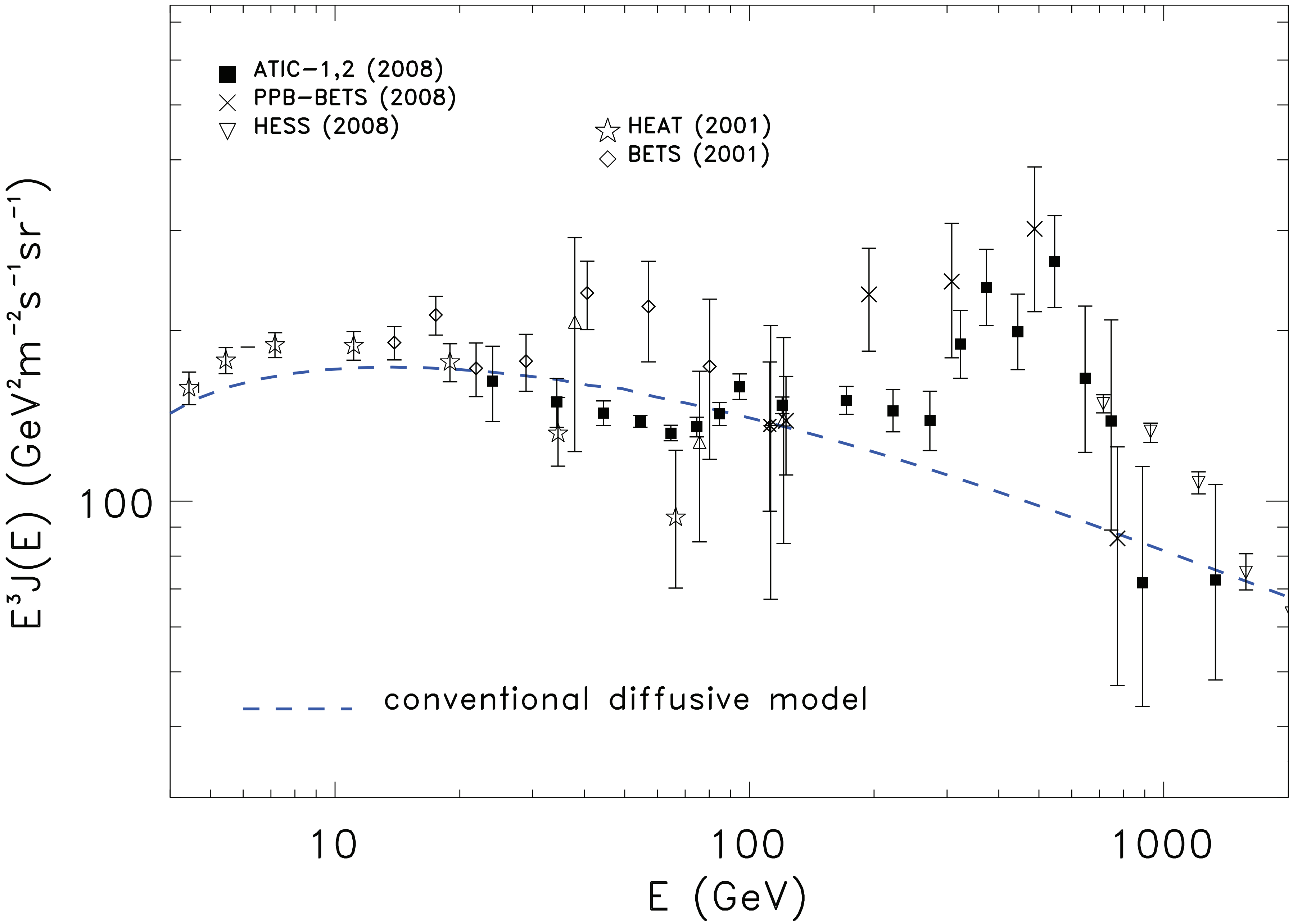
The Pamela Teaser





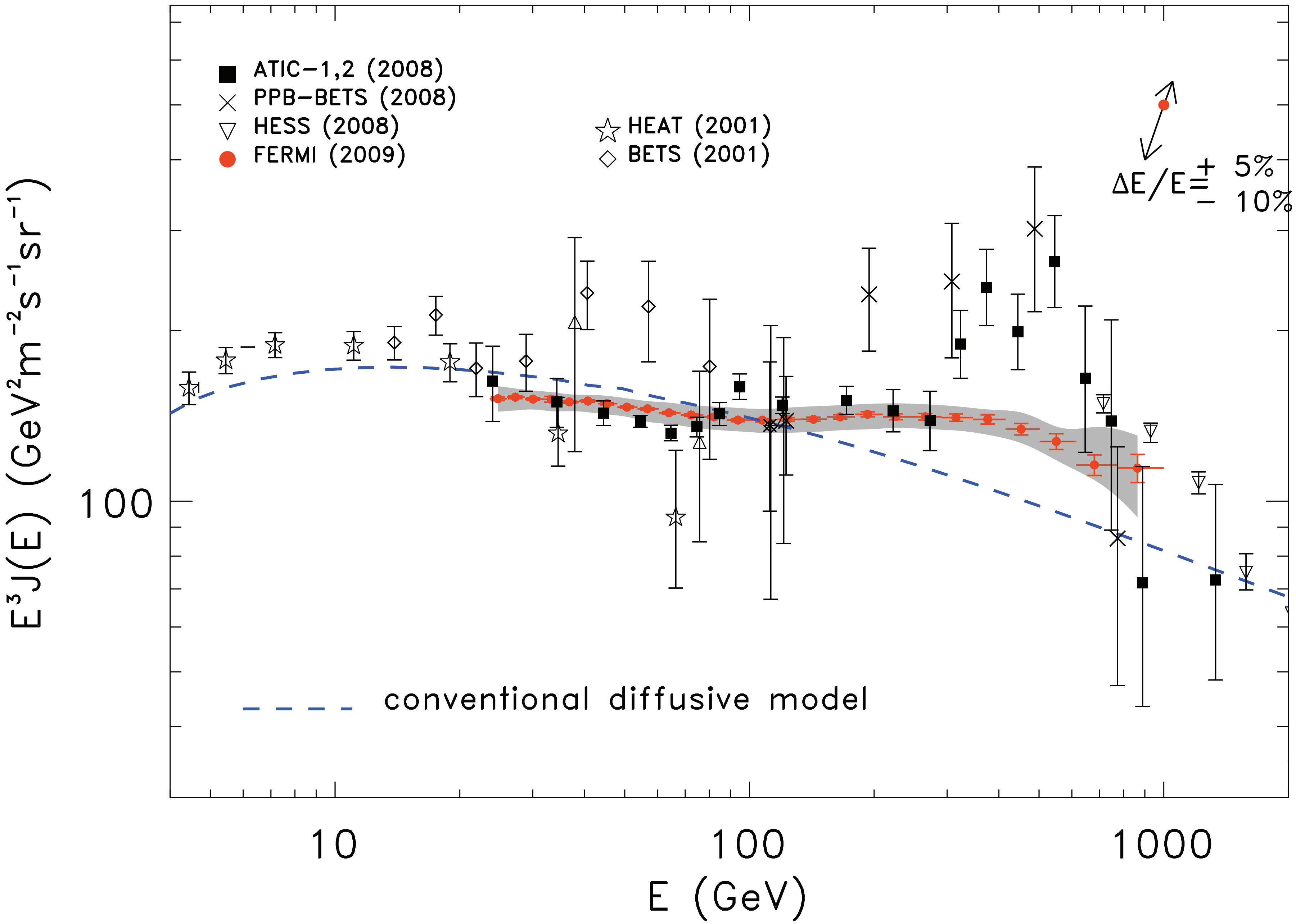
- Electron / proton spectrometer in orbit for >2 yrs
  - Detects an excess of positrons above 10 GeV
  - Possibly from DM with m_X~150 eV, but require very large densities

Hot of the Presses



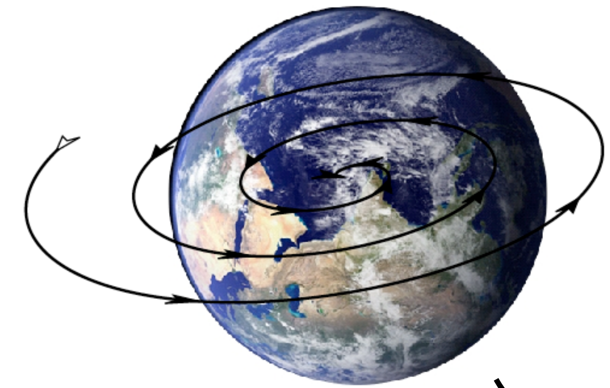
Hot of the Presses

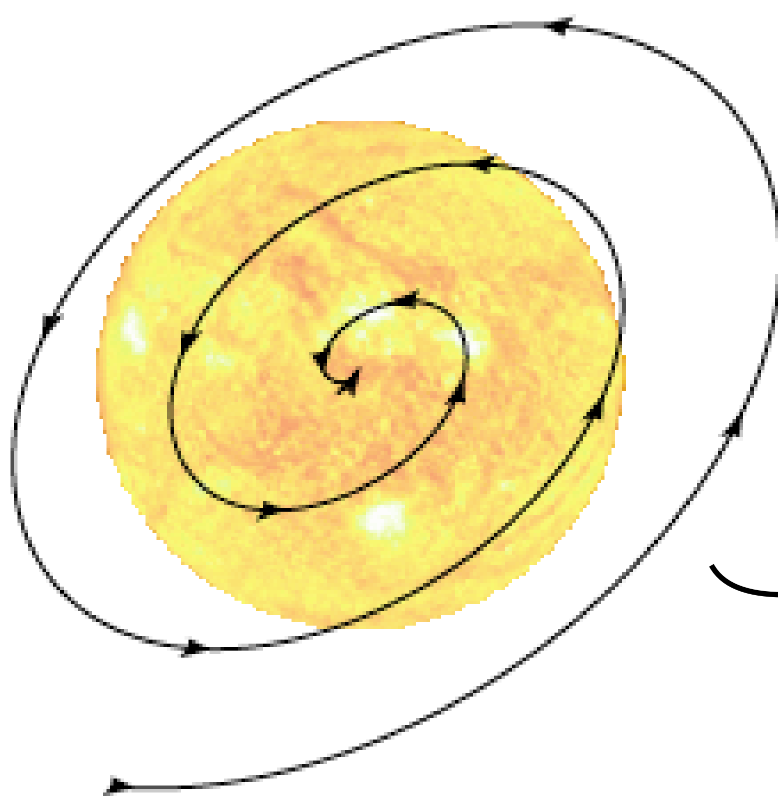
- Recent FERMI data inconsistent with ATIC electron peak

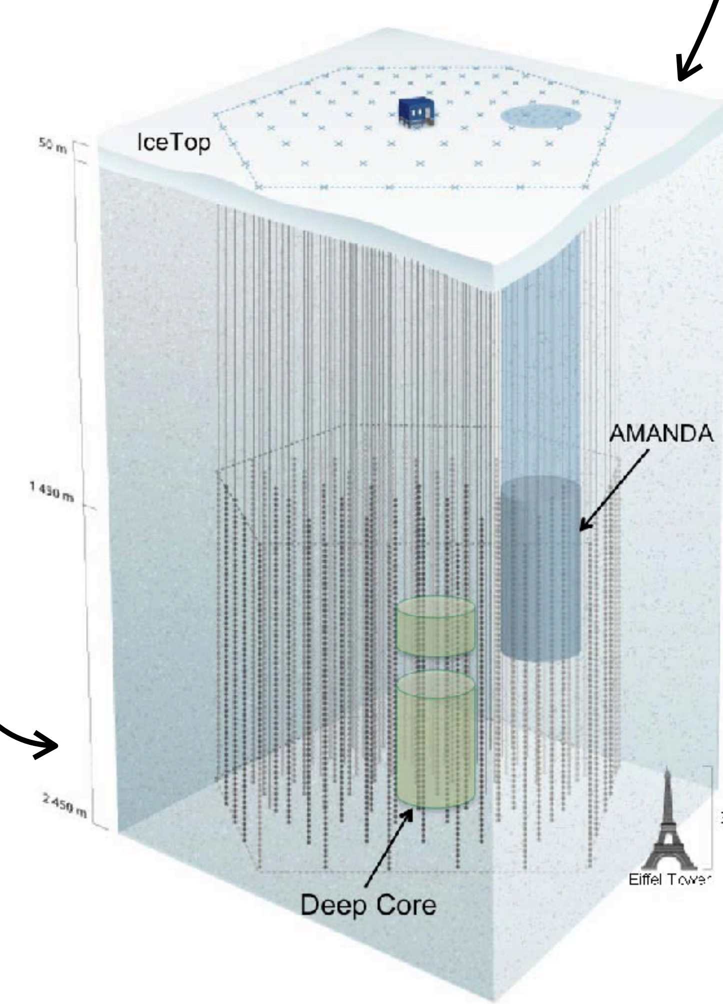


A couple of places to look: Neutrinos

- Neutrinos from the Earth's & Sun's center
  - Super-K, Antares
  - AMANDA, IceCube :
    - Looking for WIMPs in Antarctica







S.H. Seo

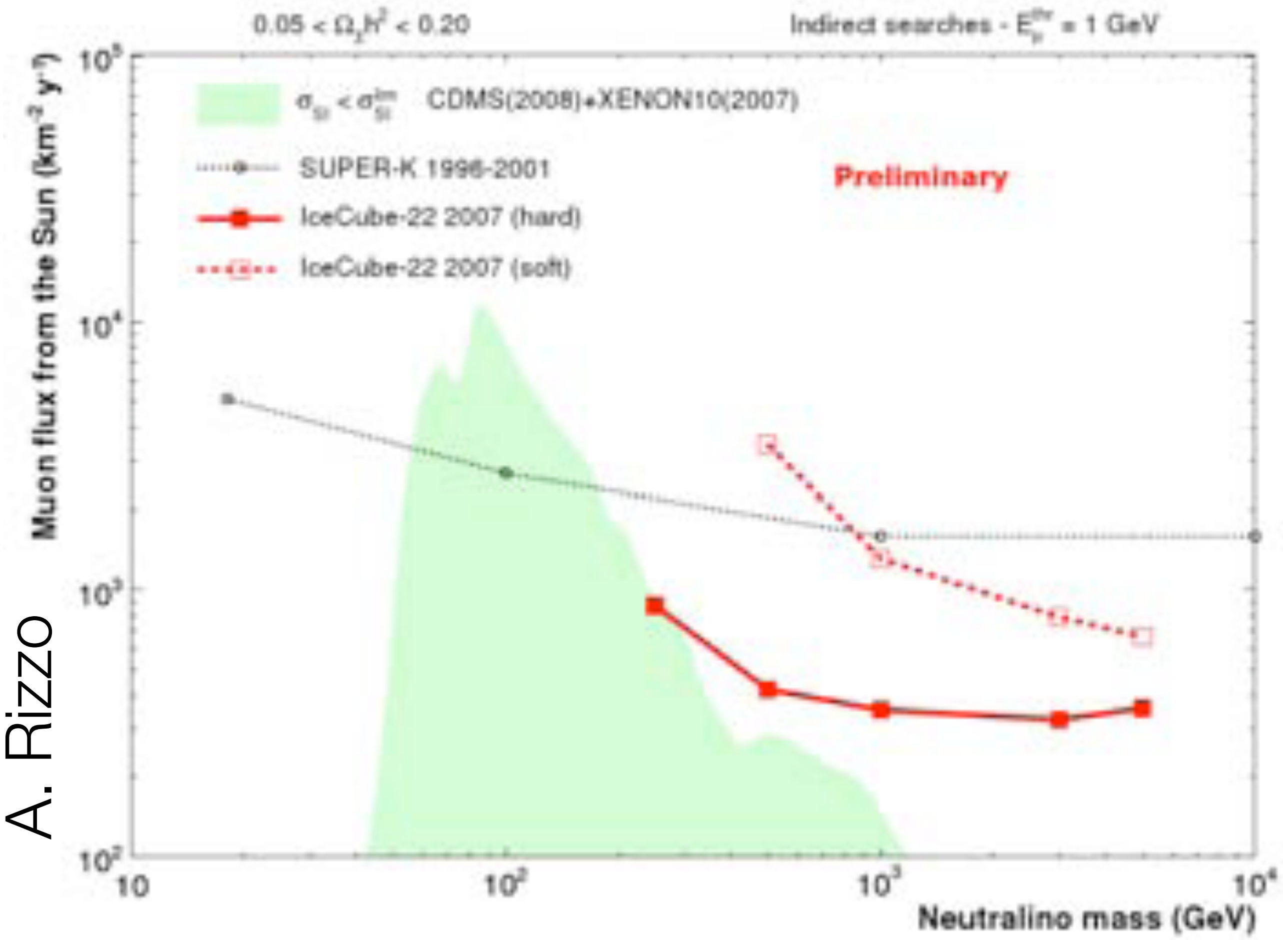
WIMP Annihilation into Neutrinos

- Looking for excess μ's from the Sun's direction, above atmospheric background

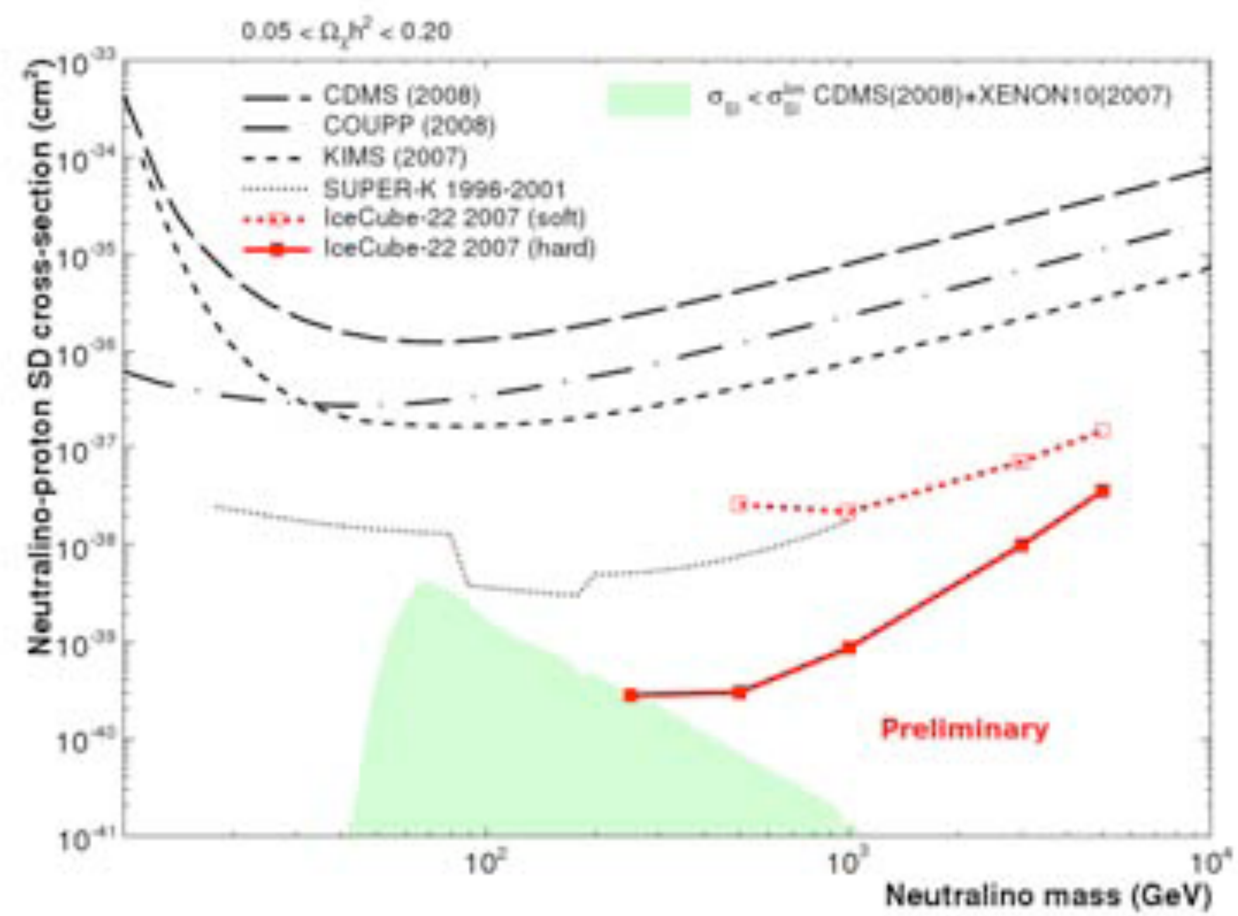
- Upper limit on μ flux translates into WIMP-proton cross section

  - Amanda Astropart. Phys. 24 2006

  - Super-K Phys. Rev D70 2004



A. Rizzo



Final Words

- What if there aren't WIMPs or Axions?
  - 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

Université d'Oran

School on Particle Physics and Cosmology

Oran, Les Andalouses, 02-10 May 2009

LPTO
Laboratoire de Physique Théorique d'Oran

Dark Matter Searches in the 21st Century

Tarek Saab

Oran School on Particle Physics and Cosmology
May 2009