Results from the CDMS 5-tower Experiment at Soudan Underground Laboratory

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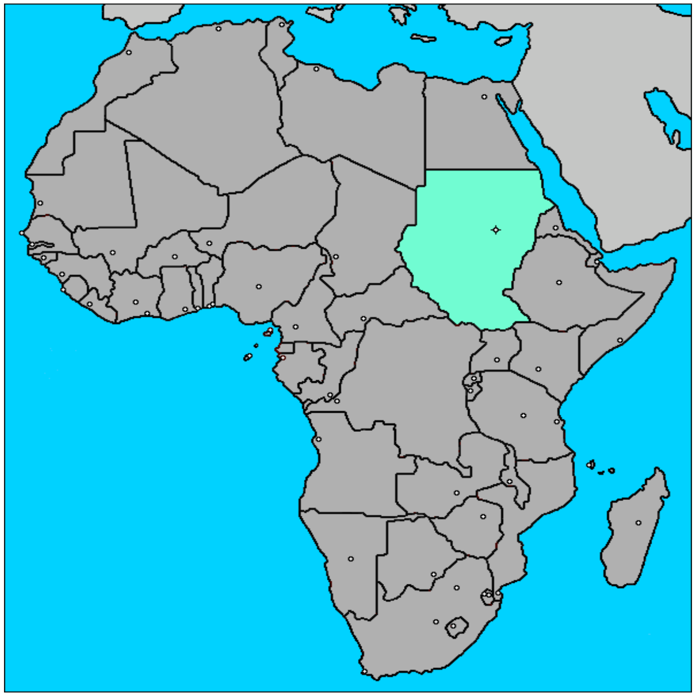
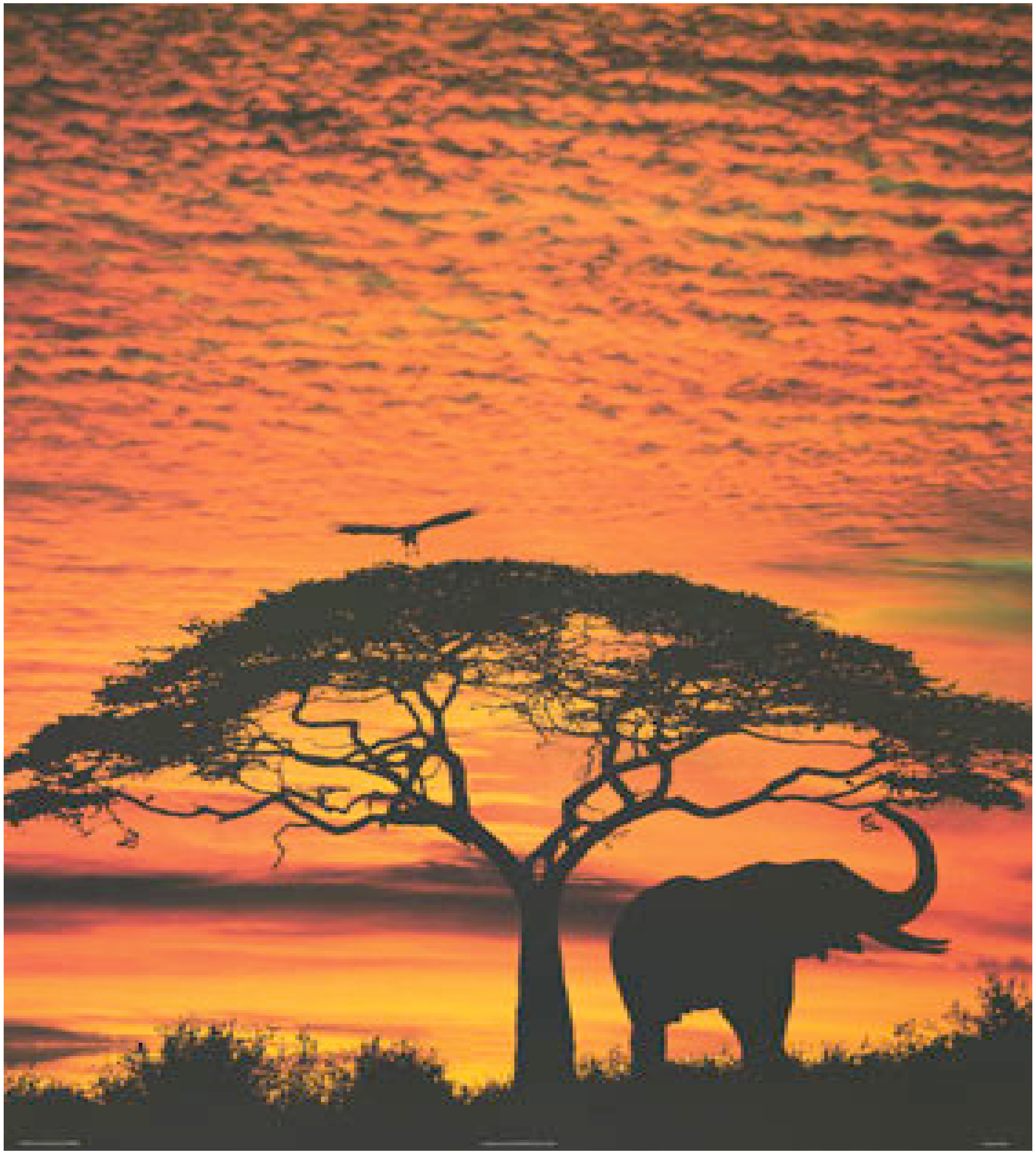
IHEP Beijing China

Outline

- Introduction
- CDMS WIMP Search
- CDMS Axion Search
- Summary

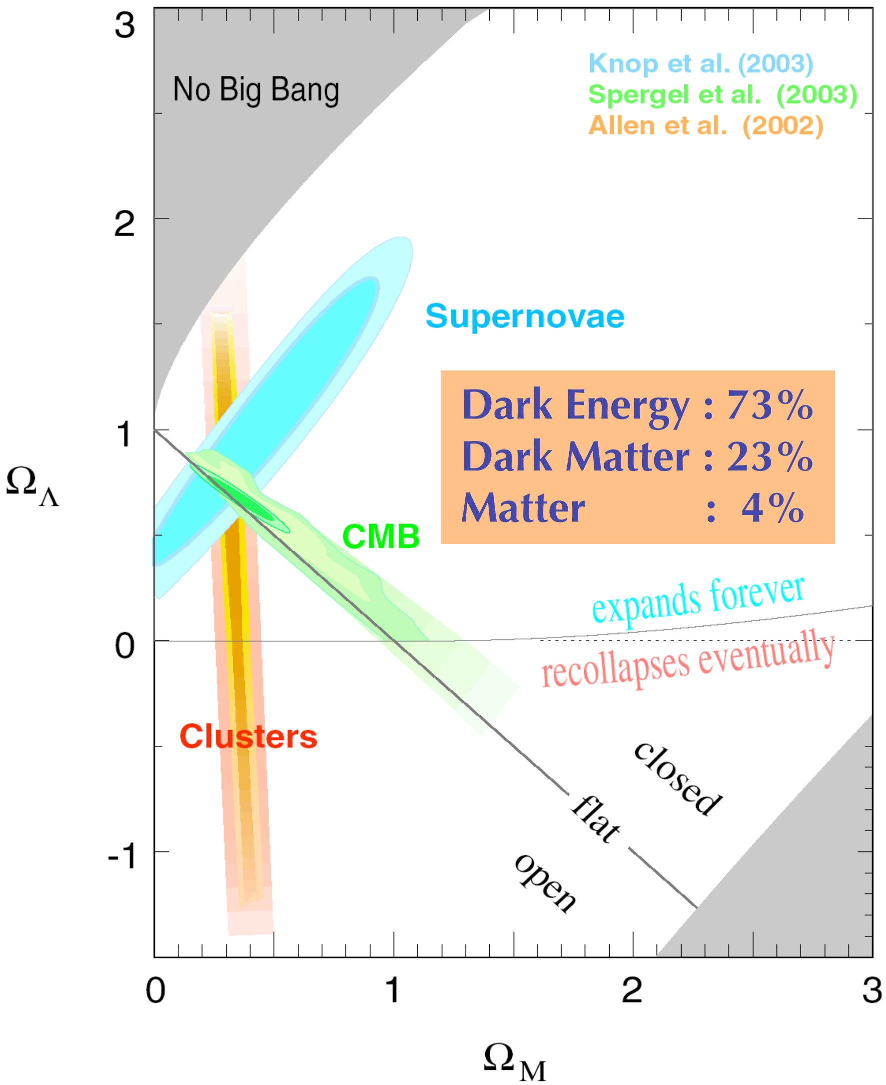
Sudan ?





Soudan

The Missing Components in the Universe



Dark Energy	: 73%
Dark Matter	: 23%
Matter	: 4%

- We know the Dark Matter is
  stable / non-baryonic / non-relativistic /
  interact gravitationally

- We don't know what it actually is
  mass / coupling / spin / composition /
  distribution in the Universe ...

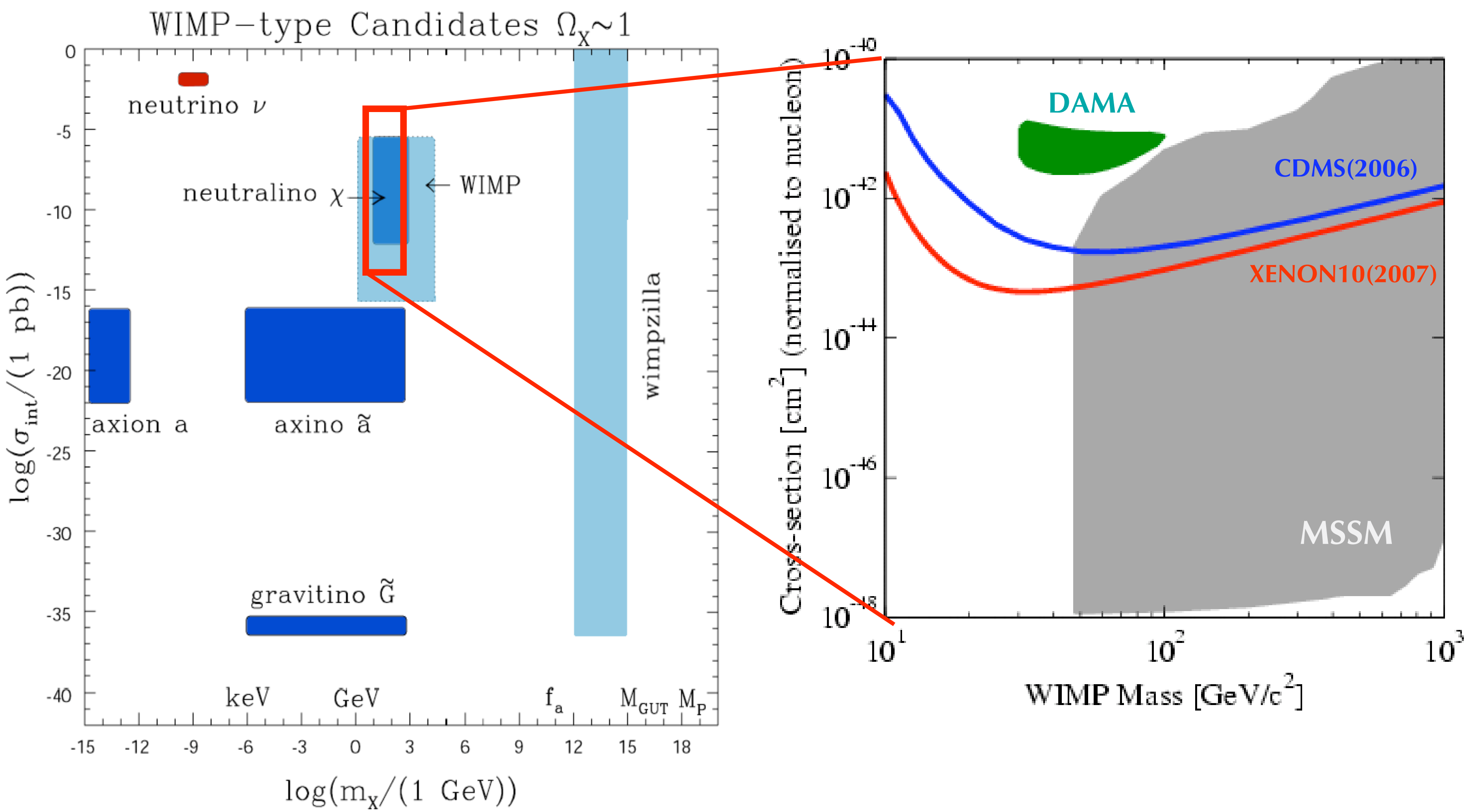
- Cosmology suggests to probe EW scale

$$\Omega_{DM} \sim \langle\sigma_A v\rangle^{-1}$$
$$\sigma_A = \alpha^2/M^2_{EW}$$

- SUSY model provides electroweak scale stable neutral particle : LSP

- However the Dark Matter is not necessarily a SUSY particle.

Map of WIMPs : Where Are We Going ?



L. Roszkowski

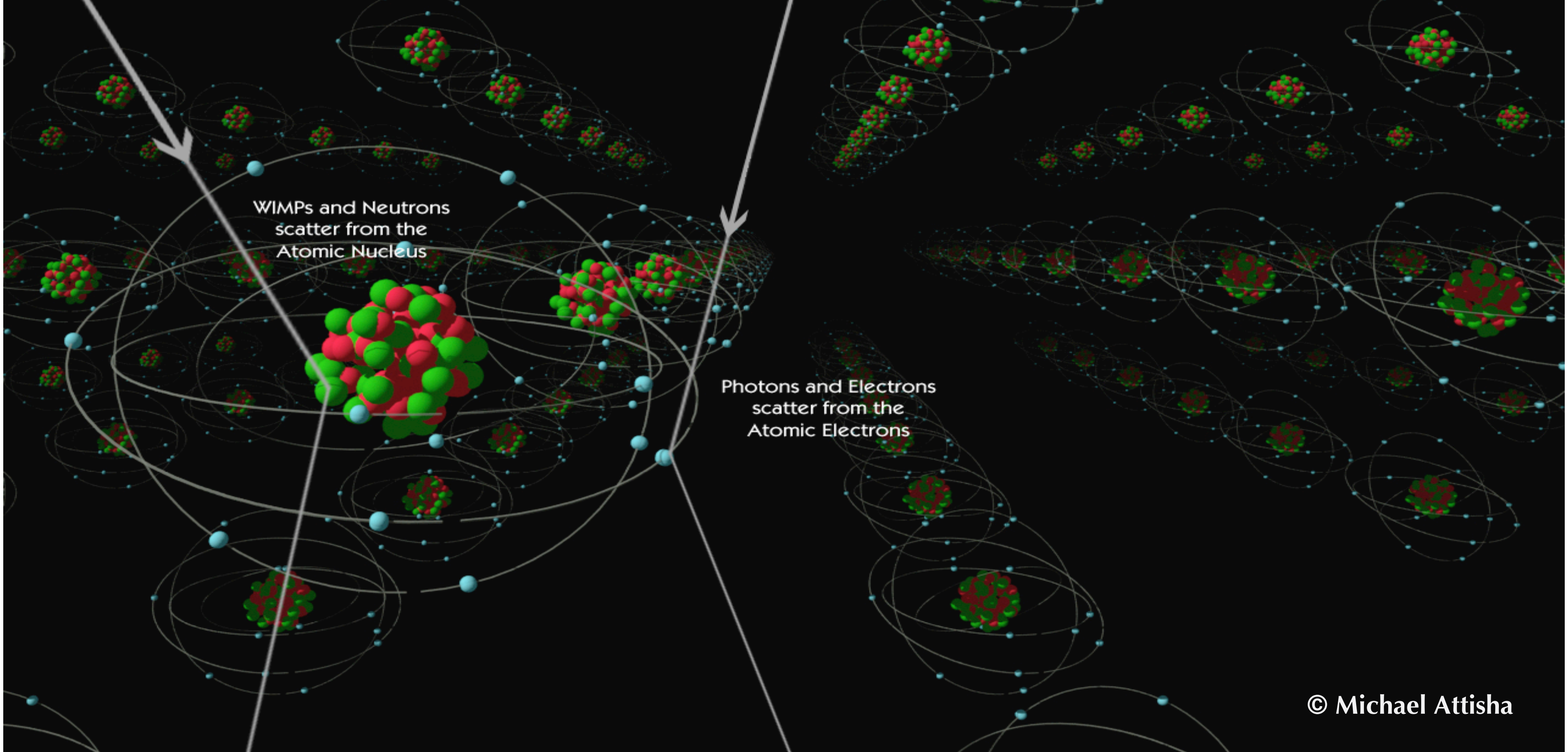
Direct Detection of WIMP

WIMP interaction signature

- nuclear recoil
- single scatter (weak interaction)
- coherent scattering : $\sigma \sim A^2$

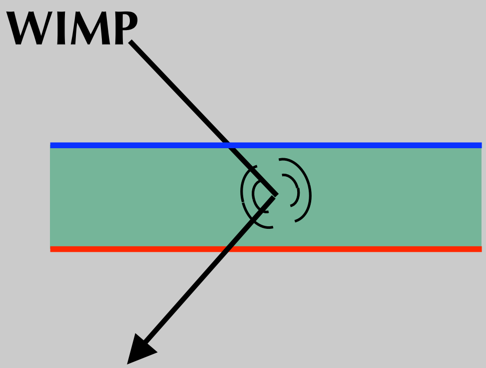
Neutron interaction signature

- nuclear recoil
- multiple scatter
- Ge and Si target have similar cross section

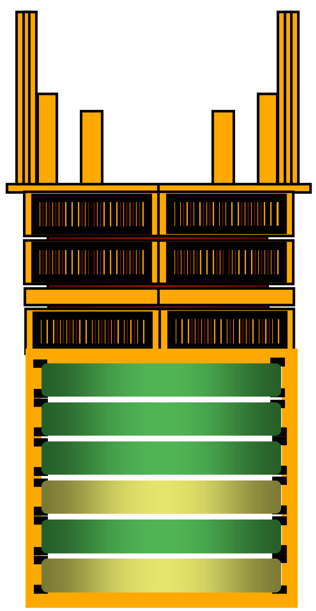


CDMS

WIMP Detection Strategy of CDMS



- Direct detection of WIMP signal
- Nucleus recoil by elastic scattering
- Read out phonons from recoil together with ionization signal



Weakly Interacting

WIMP mean free path in Ge ~ 10^{10}m

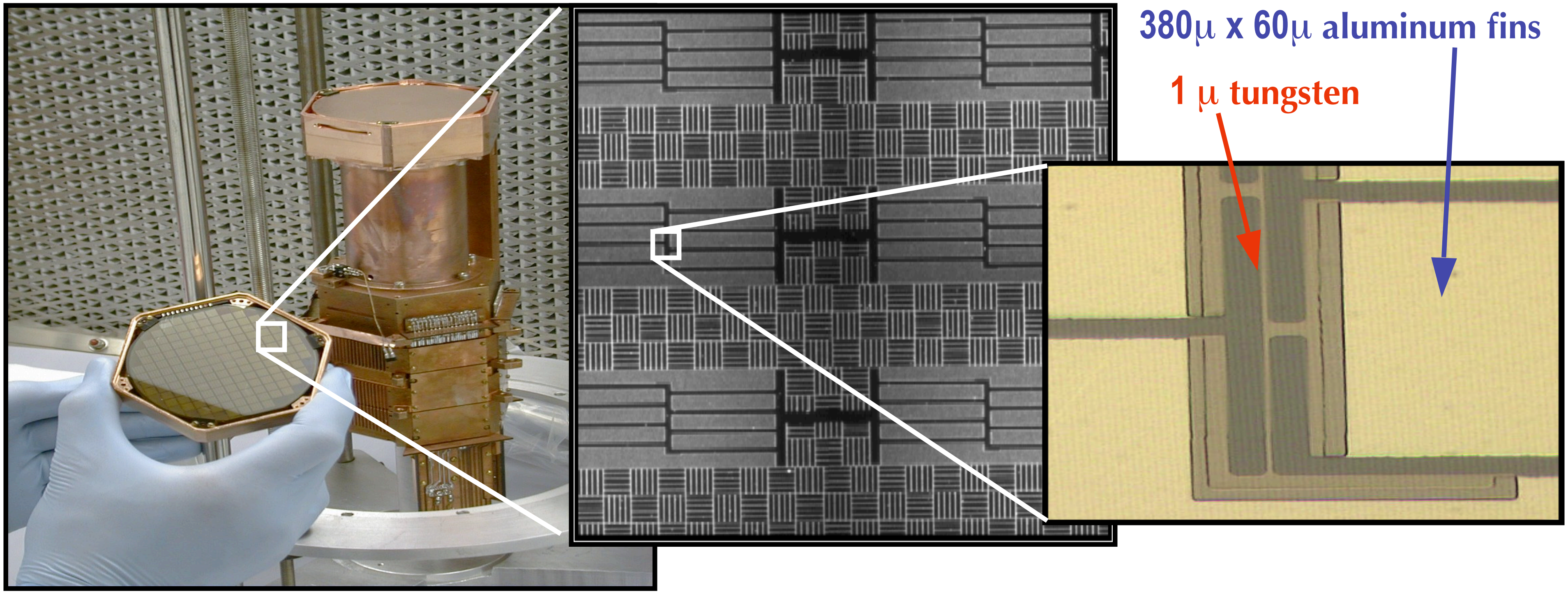
The event will single scatter

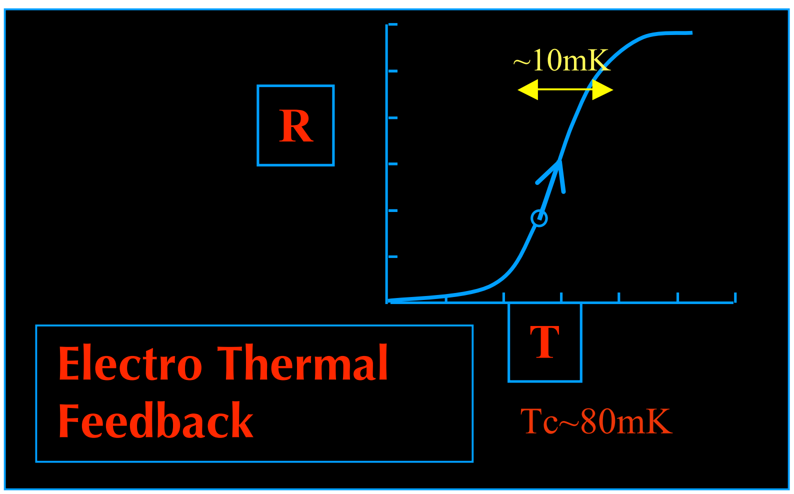
Interaction Rate $\propto A^2$

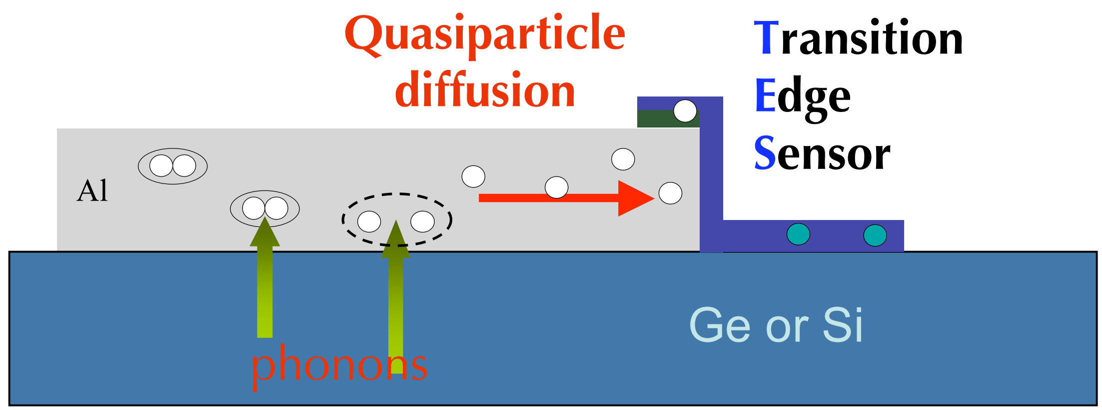
Use both Ge(73) and Si(28) targets

R(Ge/Si) = ~7

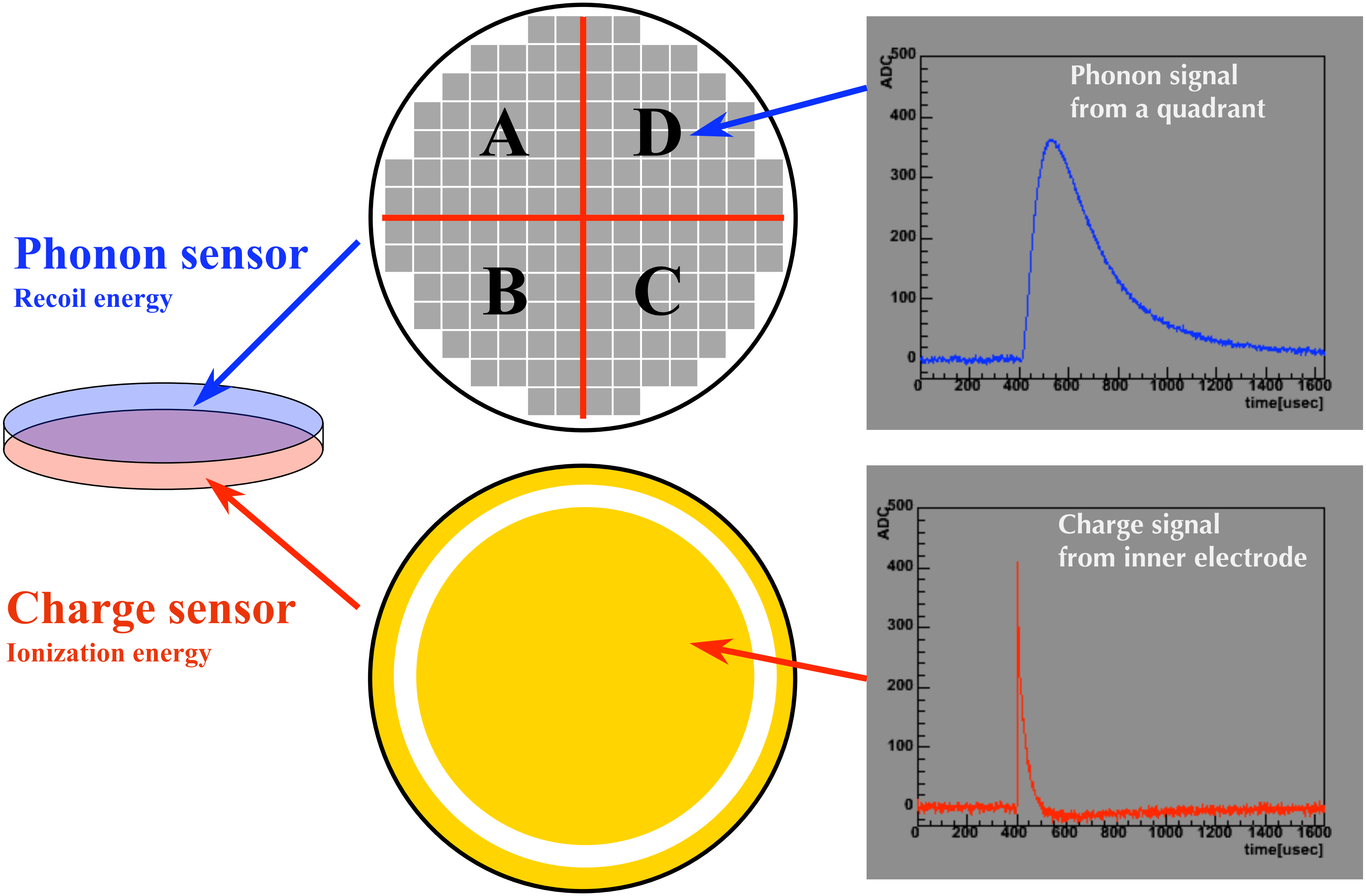
CDMS Detector





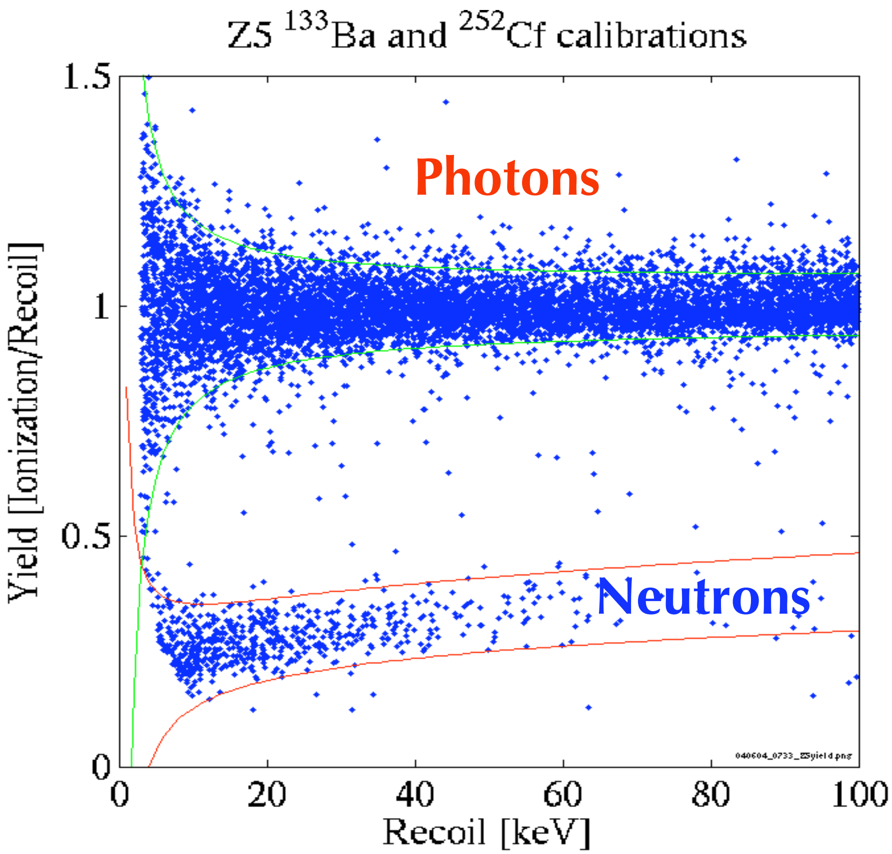


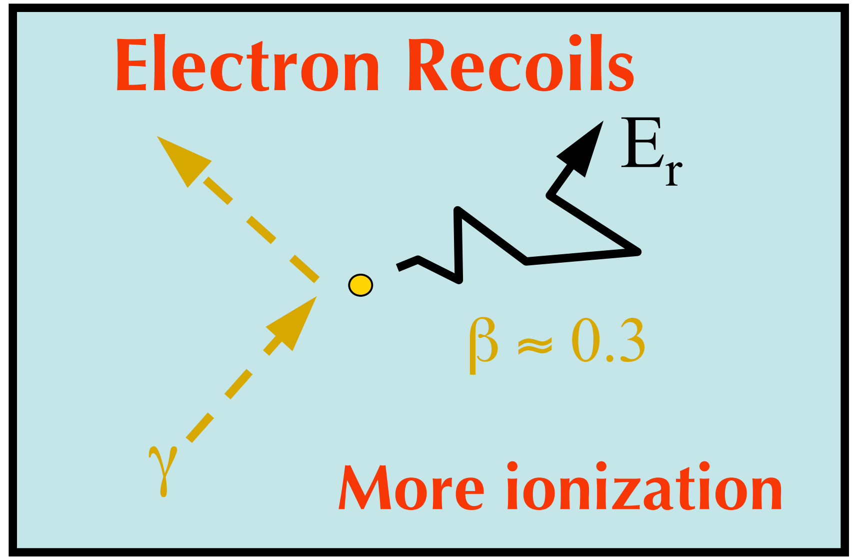
CDMS Detector Readout

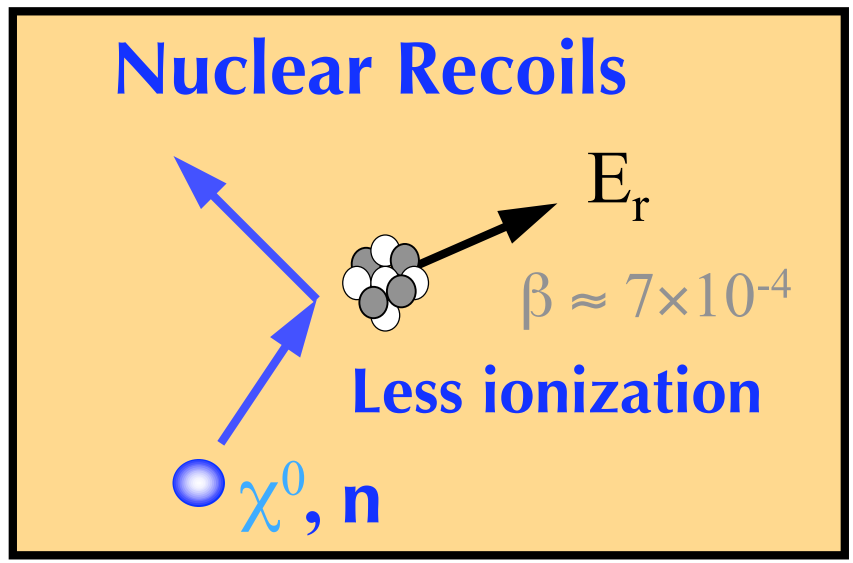


Gamma Background

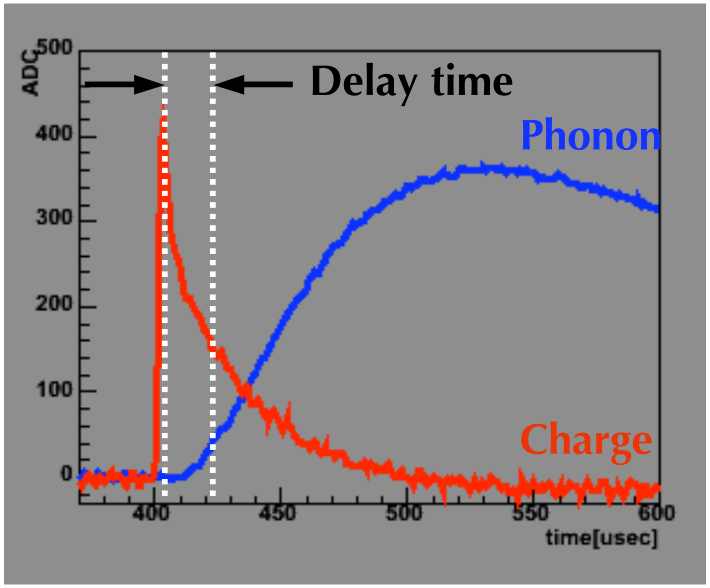
Yield = E(ionization) / E(recoil)

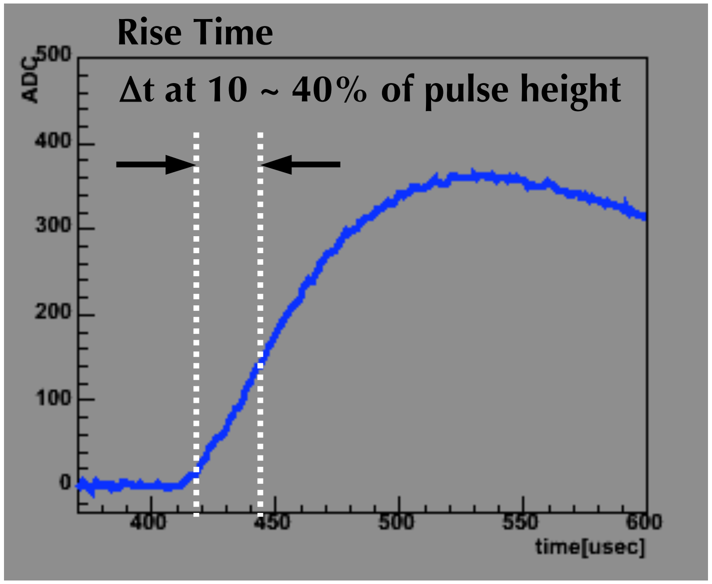


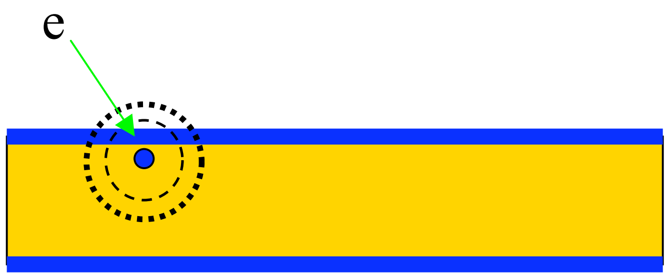


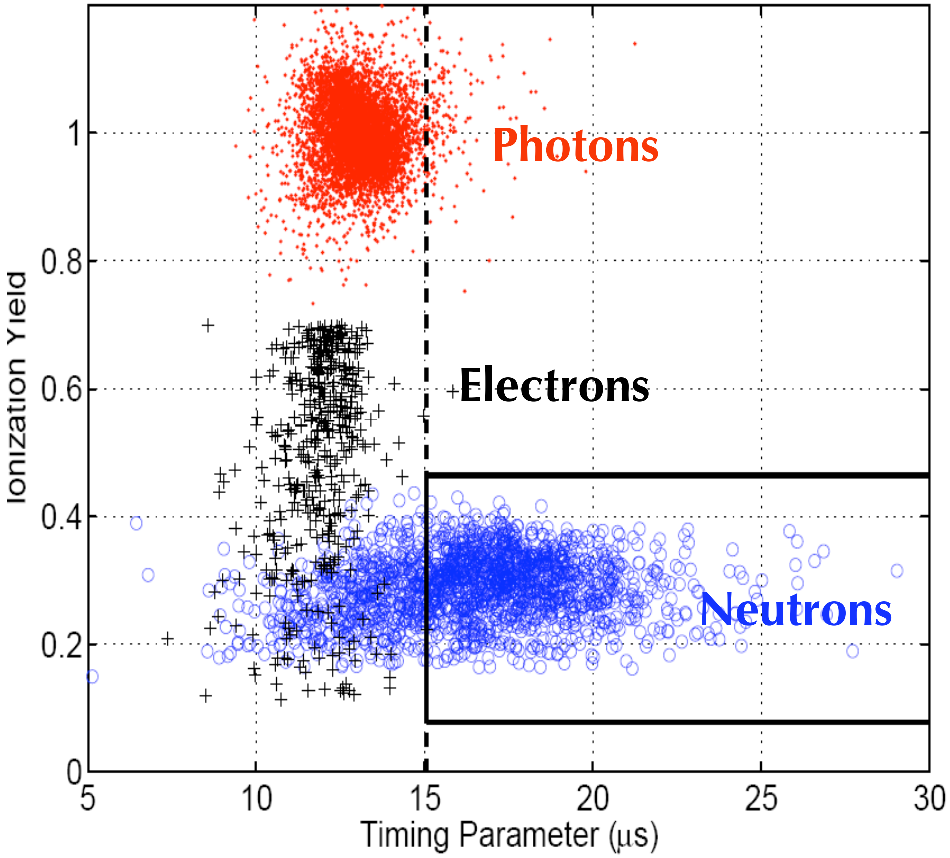


Electron Background





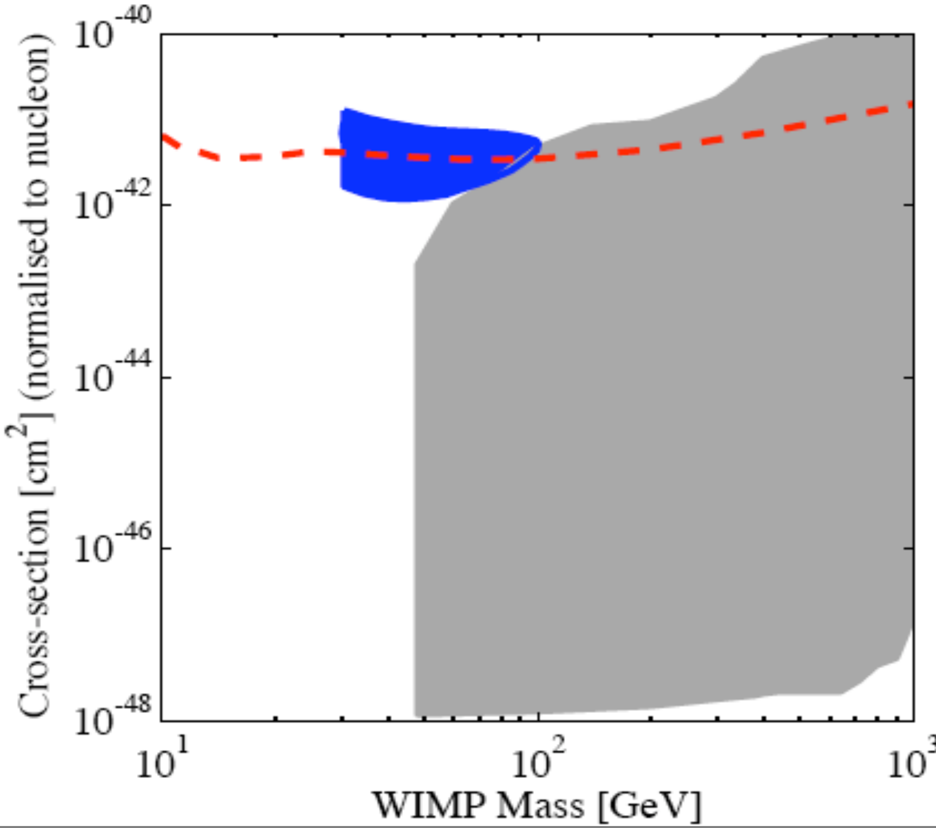




Neutron Background : Cosmogenic

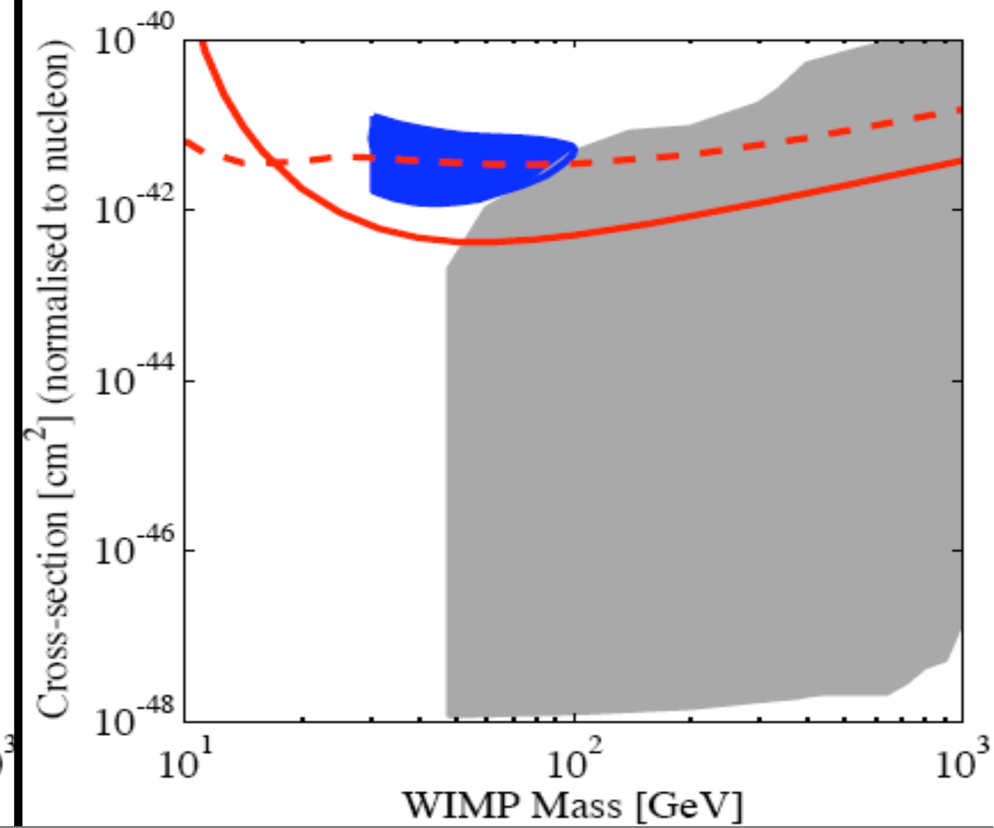
Stanford

- 2001-2002 operation
- 12m underground (50 μ/sec/m²)
- Single Tower (4Ge + 2Si detectors)
- 28 kg-days detector exposure
- 20 nuclear recoil events

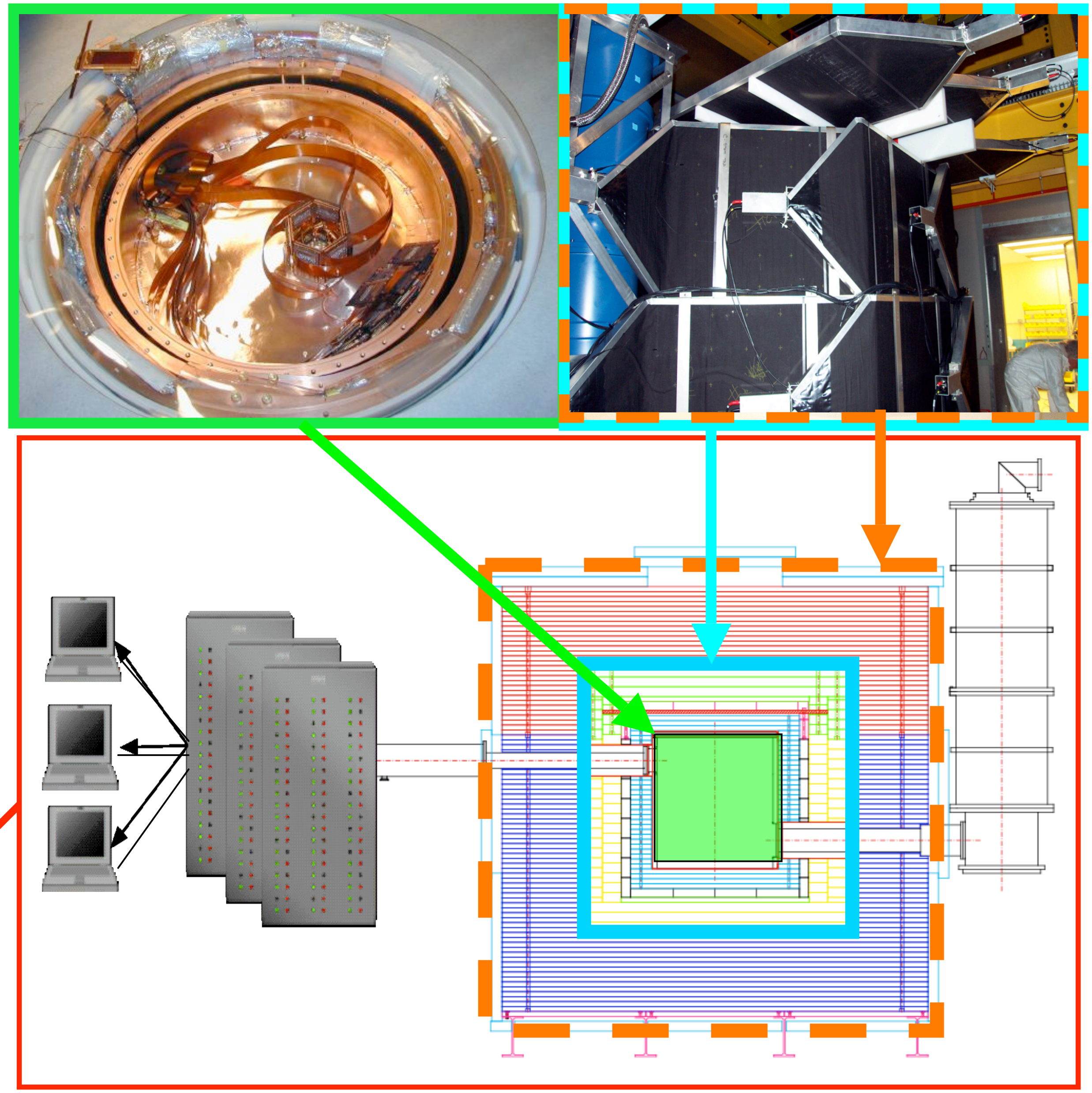


Soudan

- 2003 operation
- 780m underground (0.004 μ/sec/m²)
- Single Tower (4Ge + 2Si detectors)
- 19 kg-days detector exposure
- 1 nuclear recoil events (?)

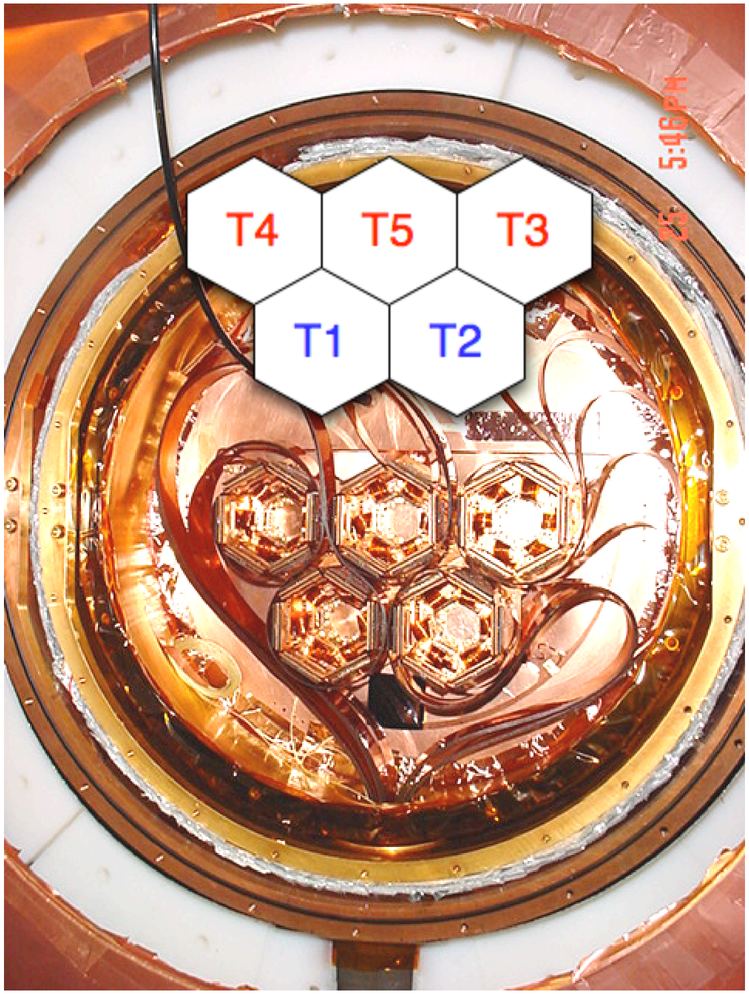


Experimental Setup in the Soudan Mine



Five Tower Runs

30 ZIPs (2 Towers + 3 new)
4.75 kg Ge, 1.1 kg Si



Low Background Towers
- Newer Towers have 2-3X lower BG from Rn

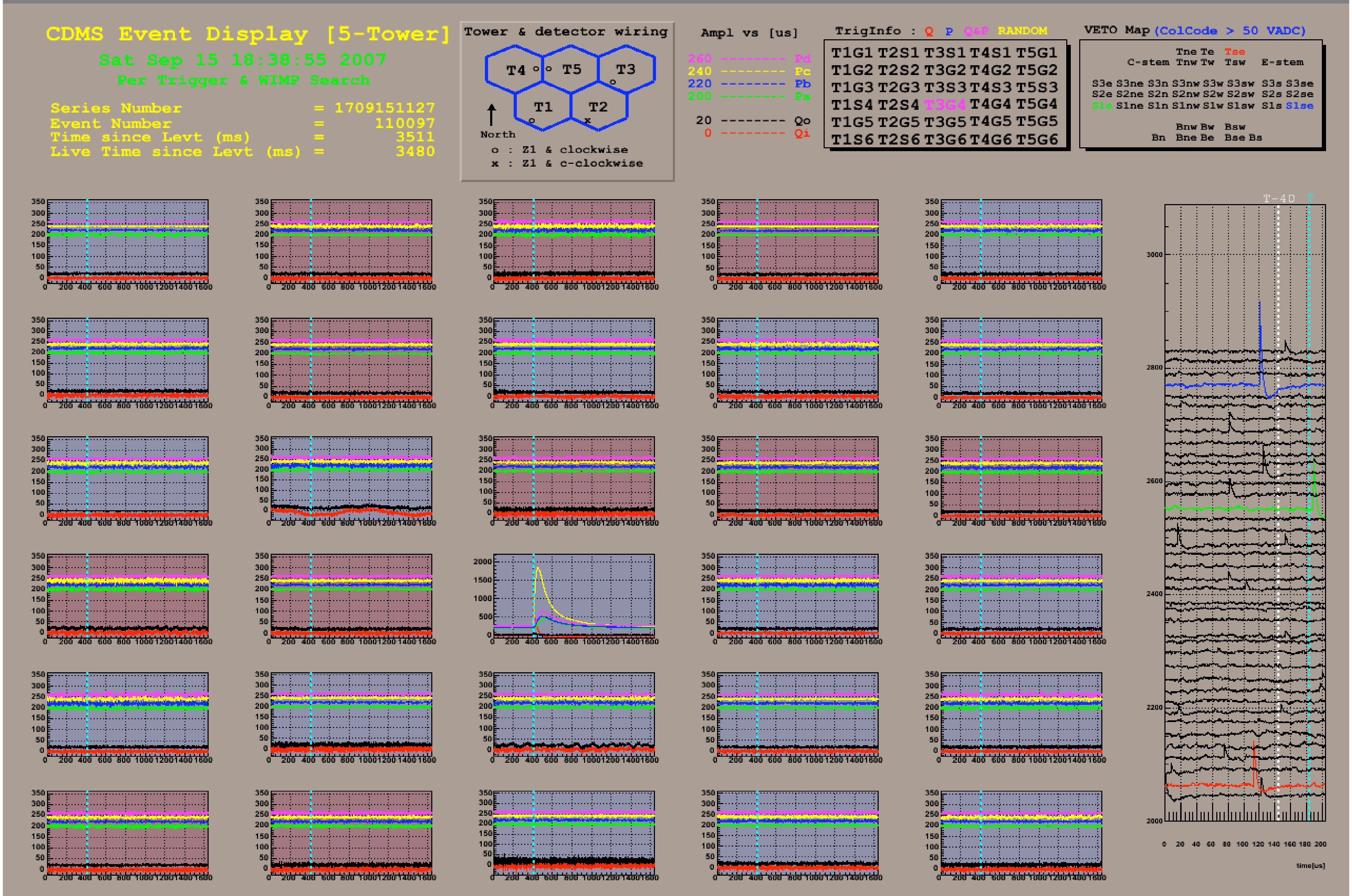
Cryogenics
- ~6 months of stable base temperature
- Outstanding operation management

Improved DAQ
- 10X Faster (100 Hz) calibration speed
- GPS time record for NuMI event veto
- Online & Offline data quality monitoring

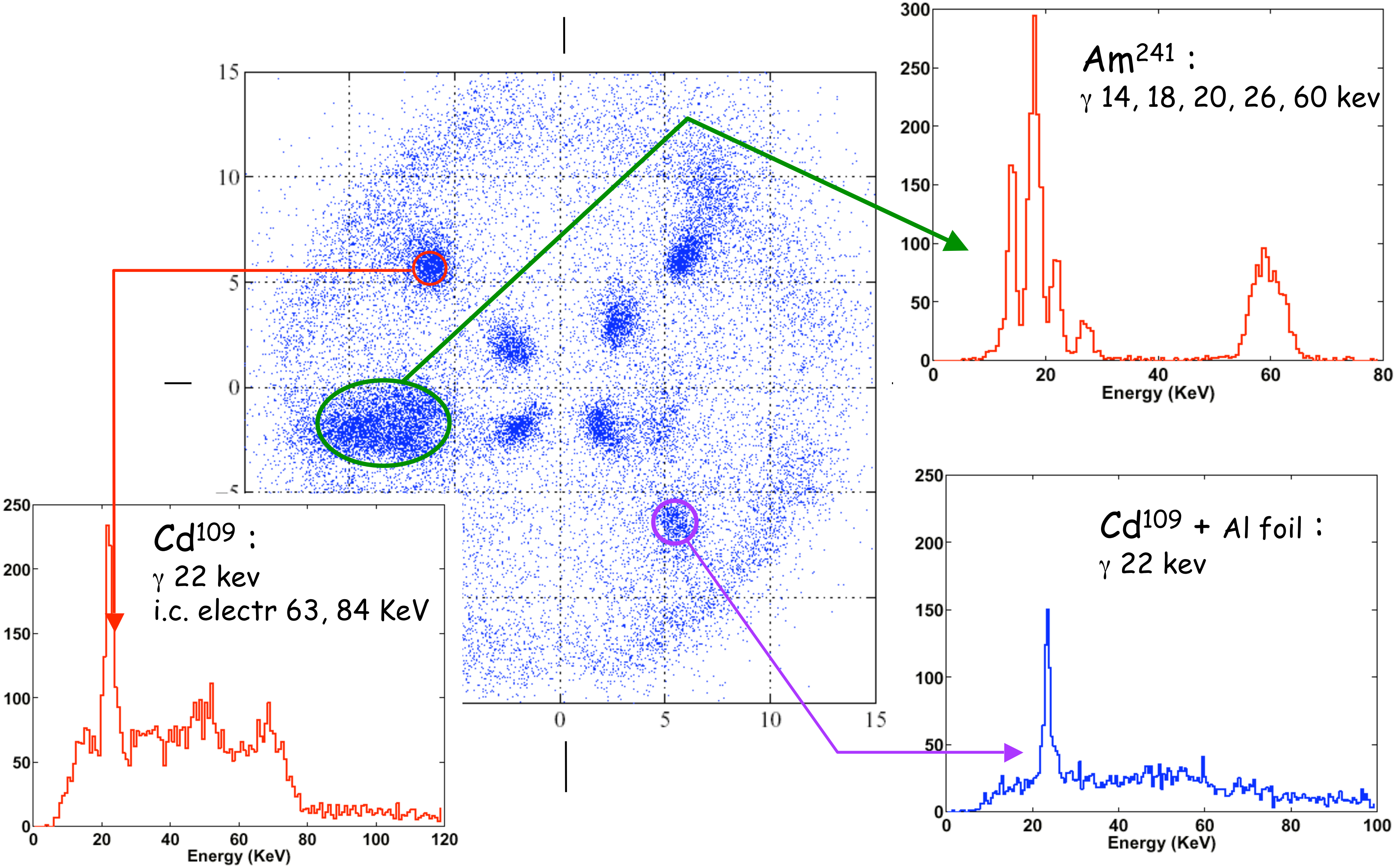
New Analysis Pipeline
- Huge calibration sample (4TB, 60M events)
- Data processing at FermiGrid

Detector Livetime (Ge)
- R123 (2006.10.21~2007.03.21) 430kg-d
- R124 (2007.04.20~2007.07.16) 224kg-d
- R125 (2007.07/21~2008.01.09) 465kg-d
- R126 (2008.01.17~2008.05.02) 271kg-d

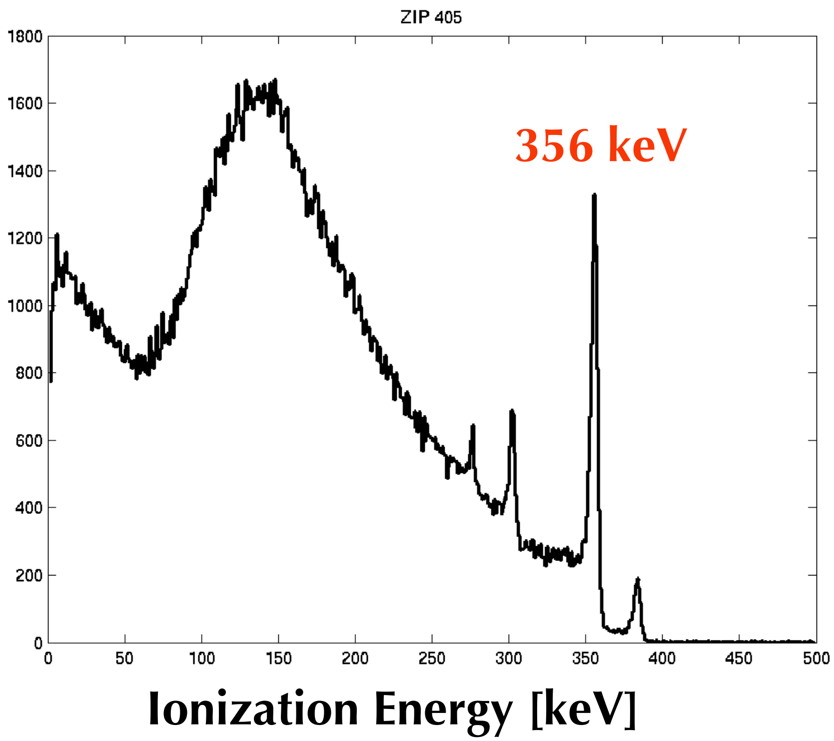
Real Time Event Monitor

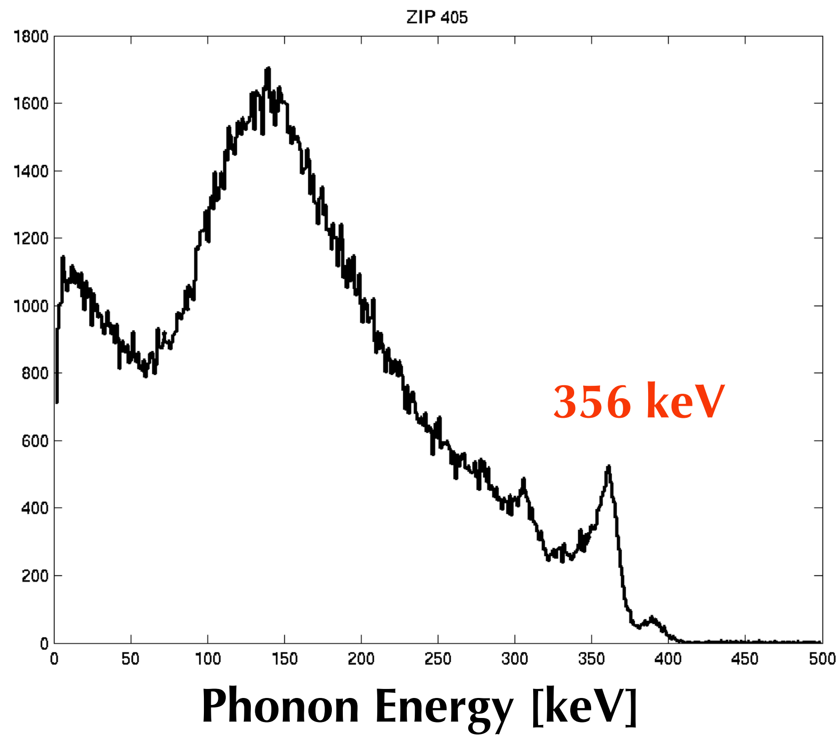


Position Resolution



Photon Calibration with ^{133}Ba

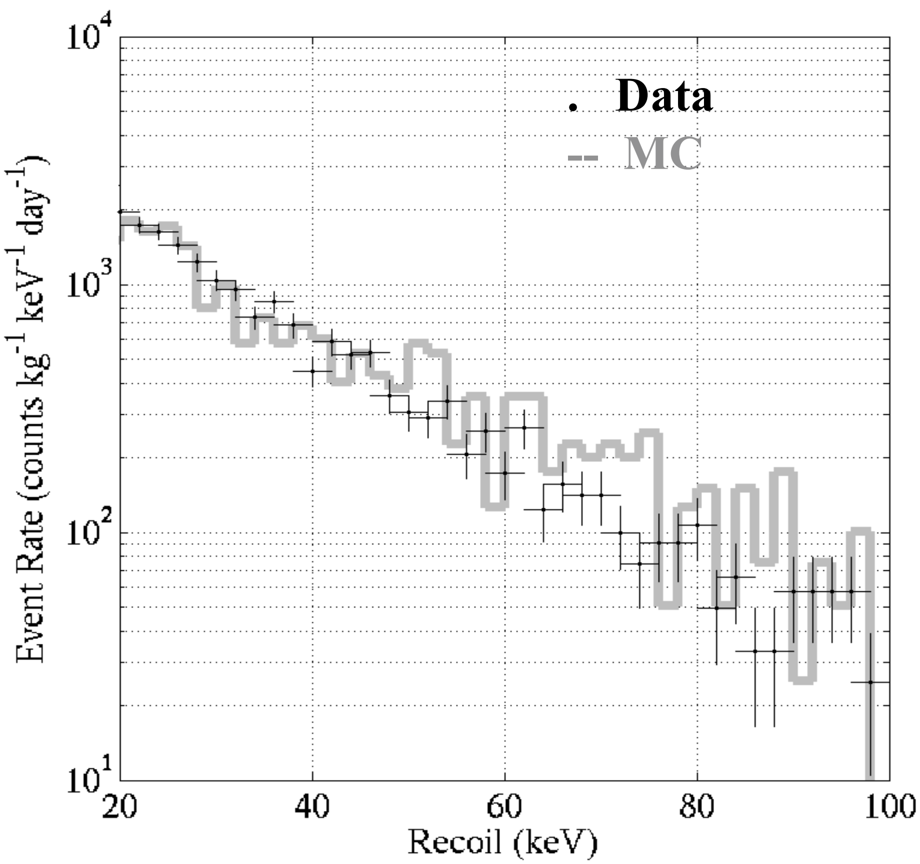




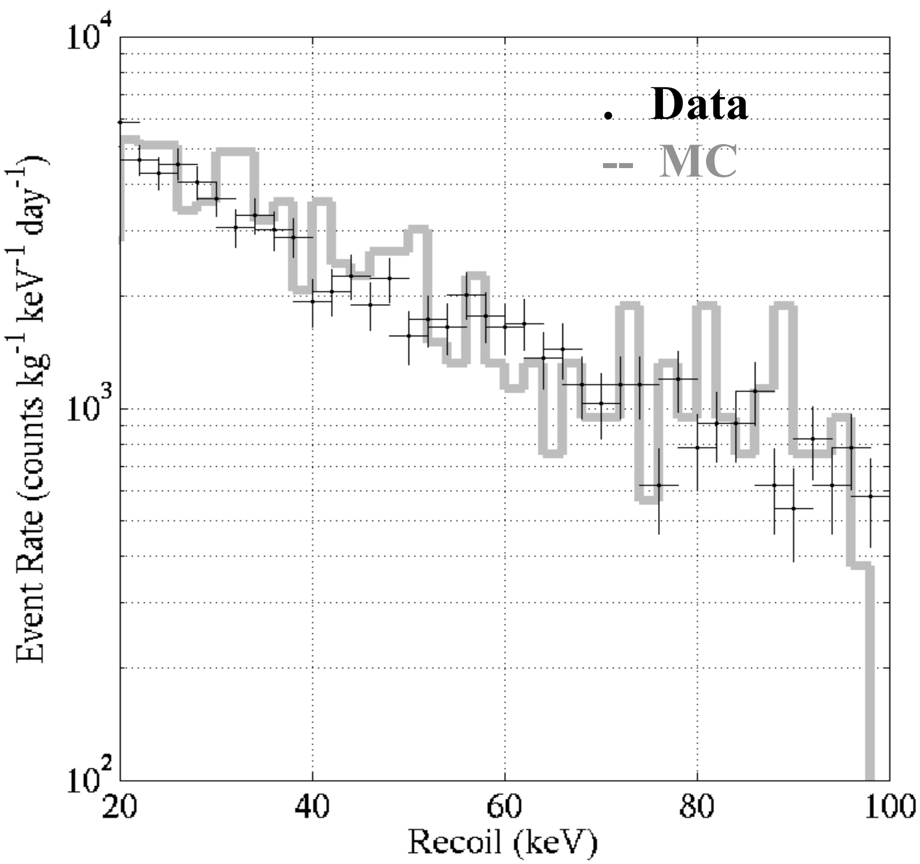
- Ba source (4 uCi), 60M events are collected during the period
- 100Hz detector read out performance
- Ba calibration gamma peak (356 keV) is used for absolute energy calibration

Neutron Calibration with ^{252}Cf

Nuclear recoils in Ge detector

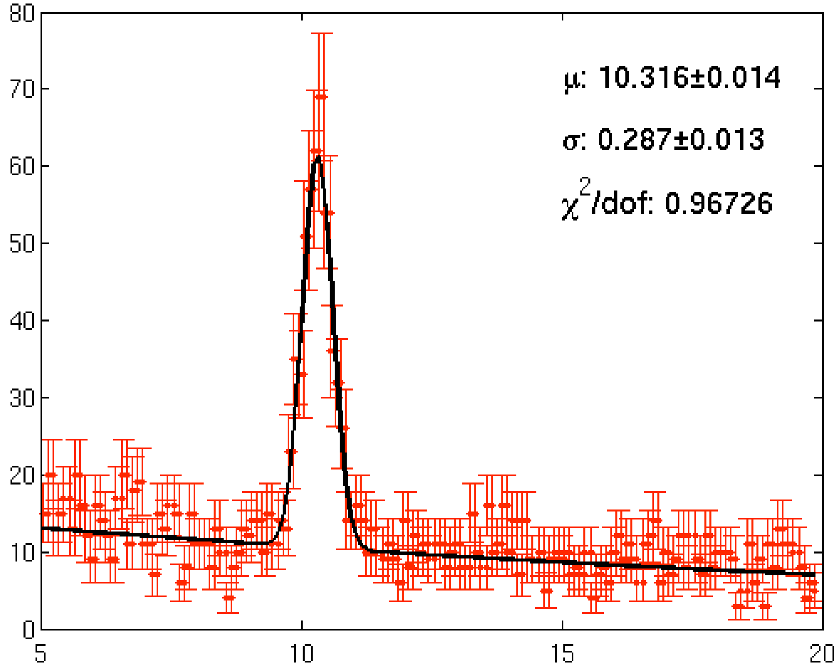


Nuclear recoils in Si detector

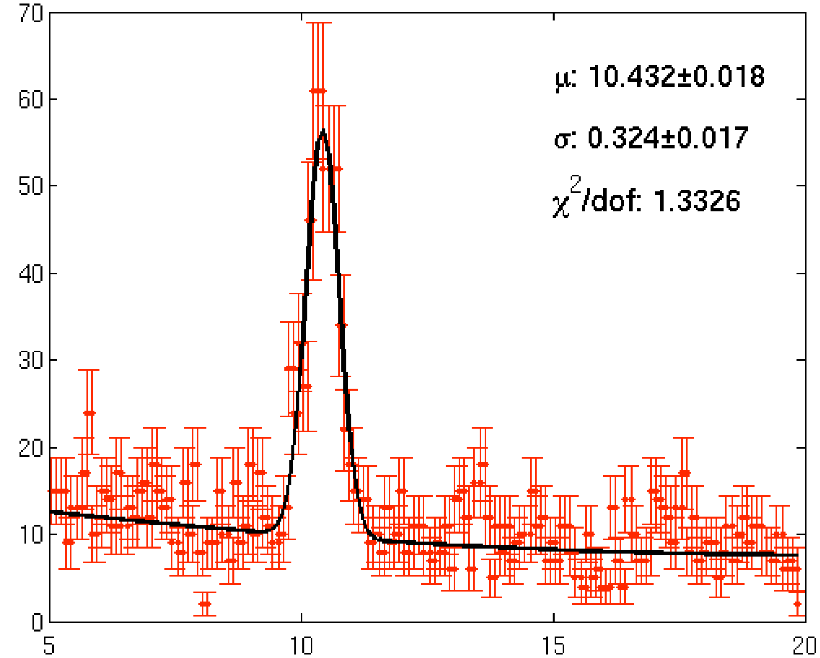


Excellent agreement between data and Monte Carlo
100K of neutron events are used to evaluate WIMP acceptance

10.4 keV Gamma



Ionization Energy [keV]



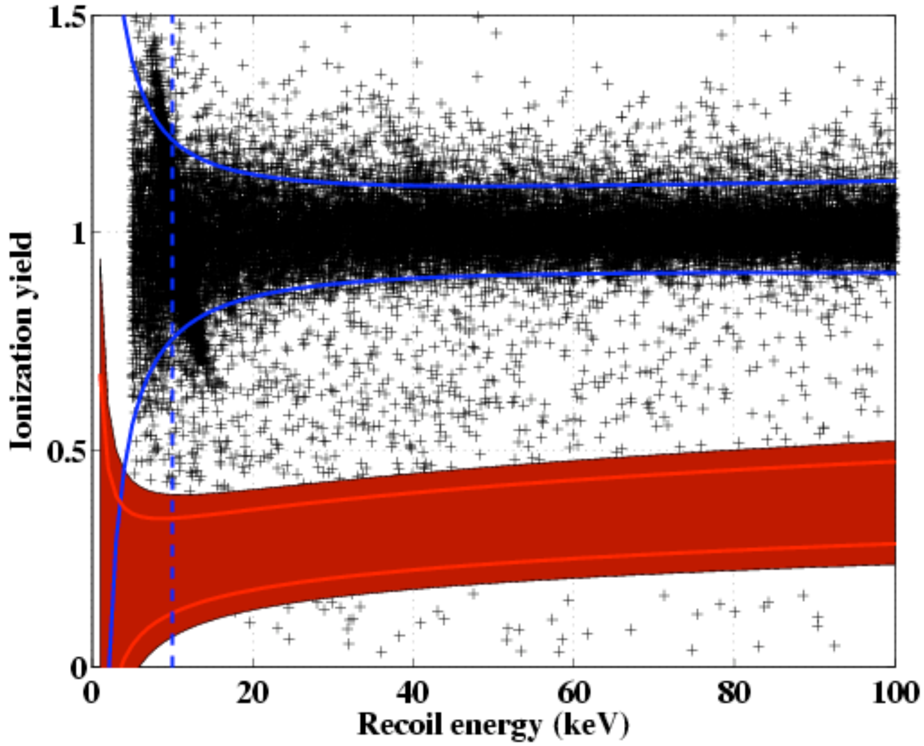
Phonon Energy [keV]

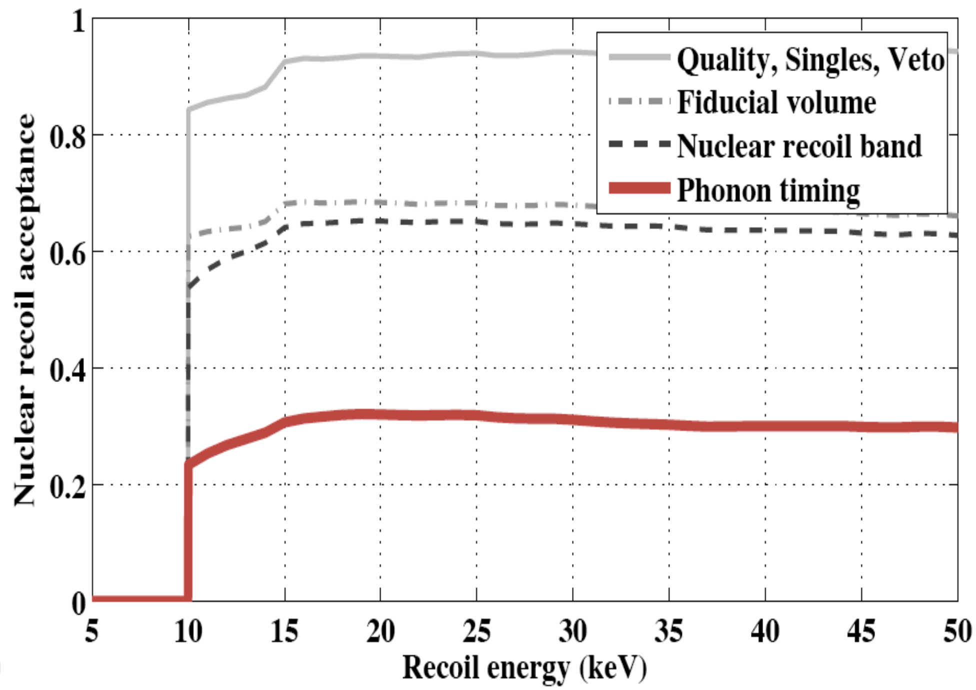
Neutron capture into ^{70}Ge during the Cf calibration
Excited ^{71}Ge emits gammas : 10.4 keV ($t_{1/2}$=11.4 days)

Very useful bulk gamma calibration source in the detector

Demonstrate ~ 5% of energy resolution in the region of interest : 10~100 [keV]

Blind Analysis

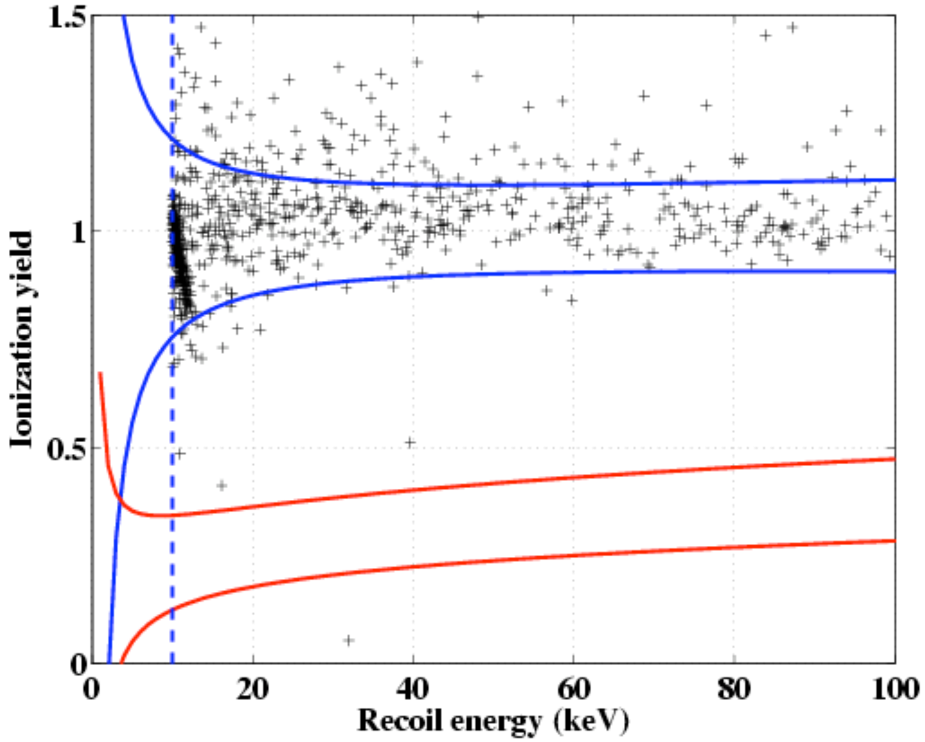


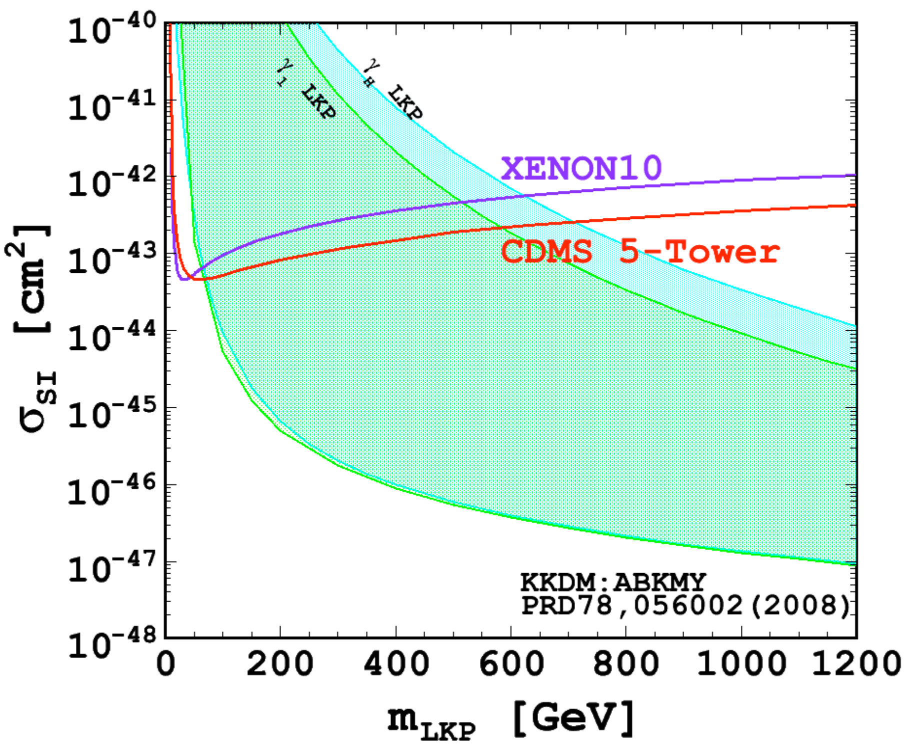


All Cuts set frozen before looking at the signal region

- Data Reconstruction Quality Cuts
- Data Quality Cuts
- Vetos : Muon veto, NuMI beam
- Event Selection
  - Charge energy threshold
  - Fiducial Volume (~30%)
  - Nuclear Recoil Selection
  - Surface Beta Rejection (~30%)

CDMS Dark Matter Search Result





- Gamma BG > 10^6 rejection power
- Neutron BG less than 0.2 event
- Electron BG less than 0.6 event
- Zero-Background
- Null Observation
- Effective Exposure : 121.3 kg-day

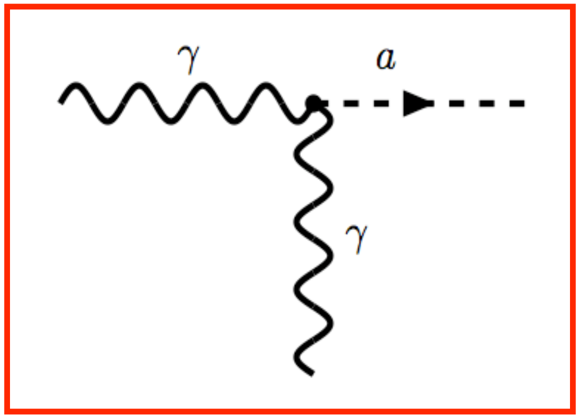
CDMS Combined (@60GeV)
$\sigma = 4.6 \times 10^{-44} cm^2$ (90%CL)

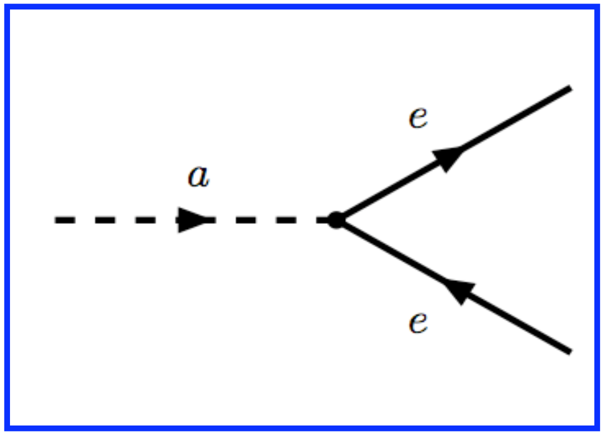
Axion Search

Axions

- Strong CP problem in QCD : null-observation of the neutron dipole moment
- Peccei-Quinn U(1) Symmetry breaking : Pseudo-Goldstone boson
- Invisible Axion Model : J.E.Kim

$$\boxed{L_{\text{int}} = g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} + i g_{aee} a \bar{\Psi}_e \gamma^5 \Psi_e + \ldots}$$



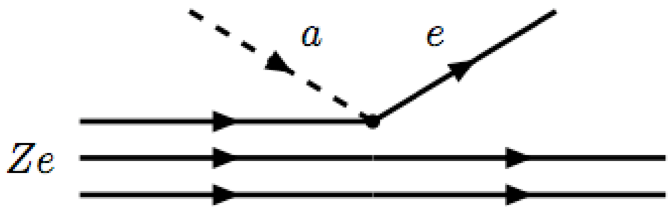


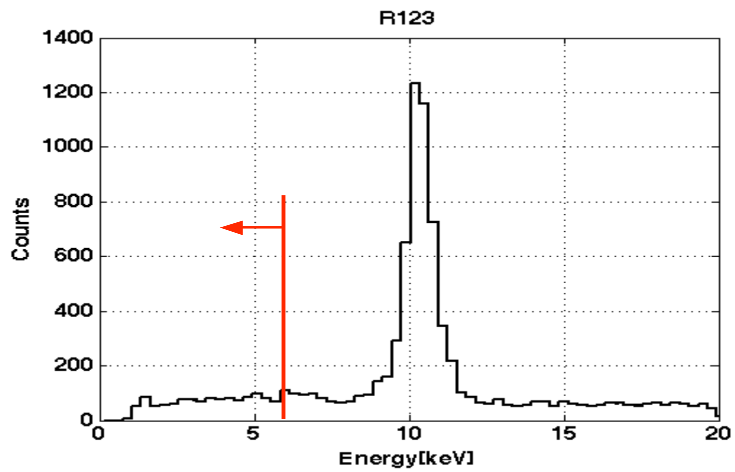
<u>Axion Models</u>

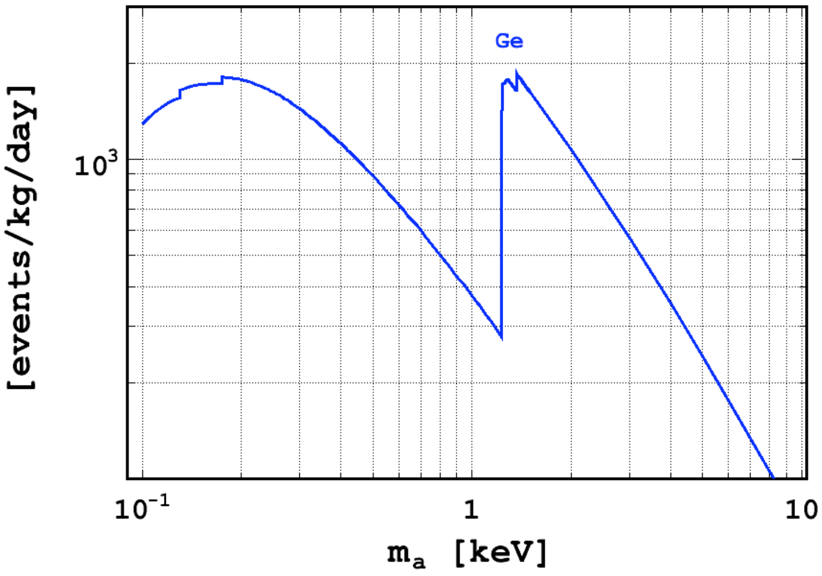
$$g_{a\gamma\gamma} = \frac{\alpha}{2\pi}\left(\frac{E}{N} - \frac{2}{3}\frac{4+z}{1+z}\right)\frac{1+z}{z^{1/2}}\frac{m_a}{m_\pi f_\pi}, \quad z = m_u / m_d = 0.56$$

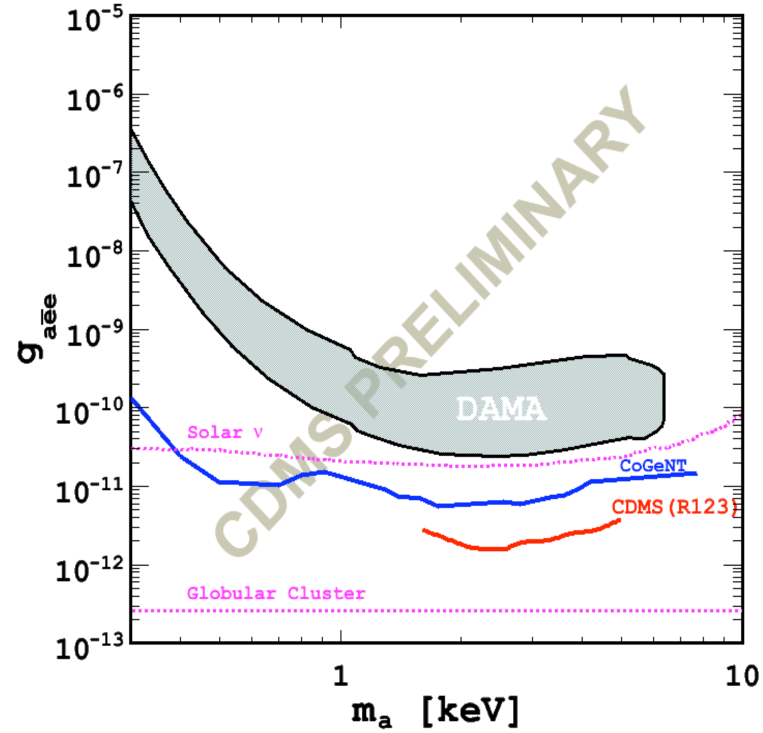
Axio-electric coupling : g_{aee}

- Relic Axions (?)
- Probe DAMA allowed parameter space

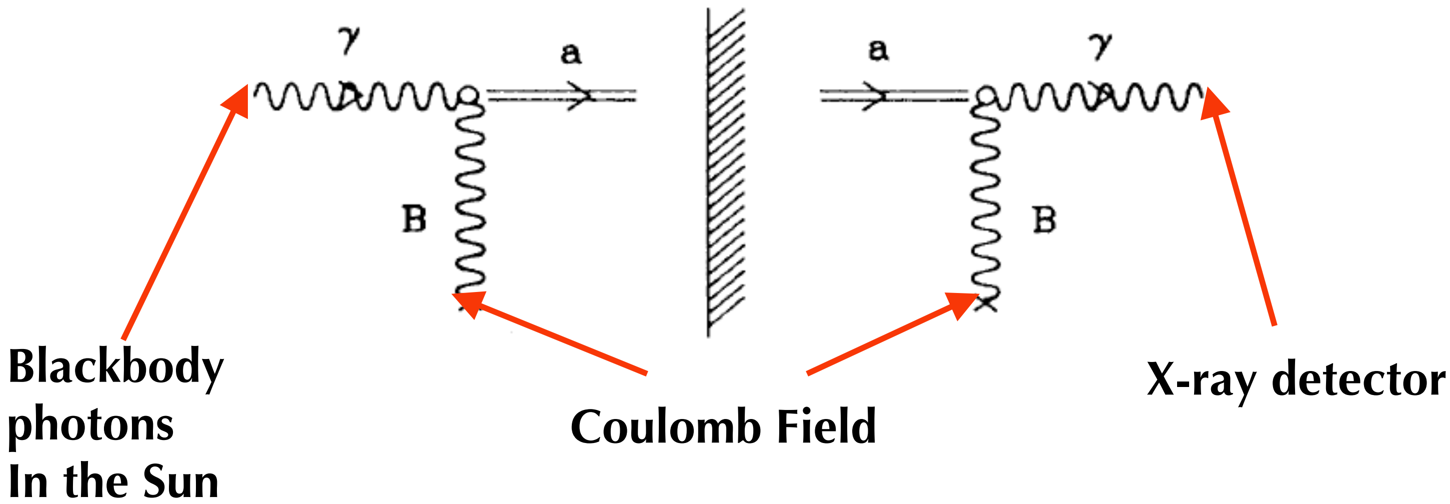


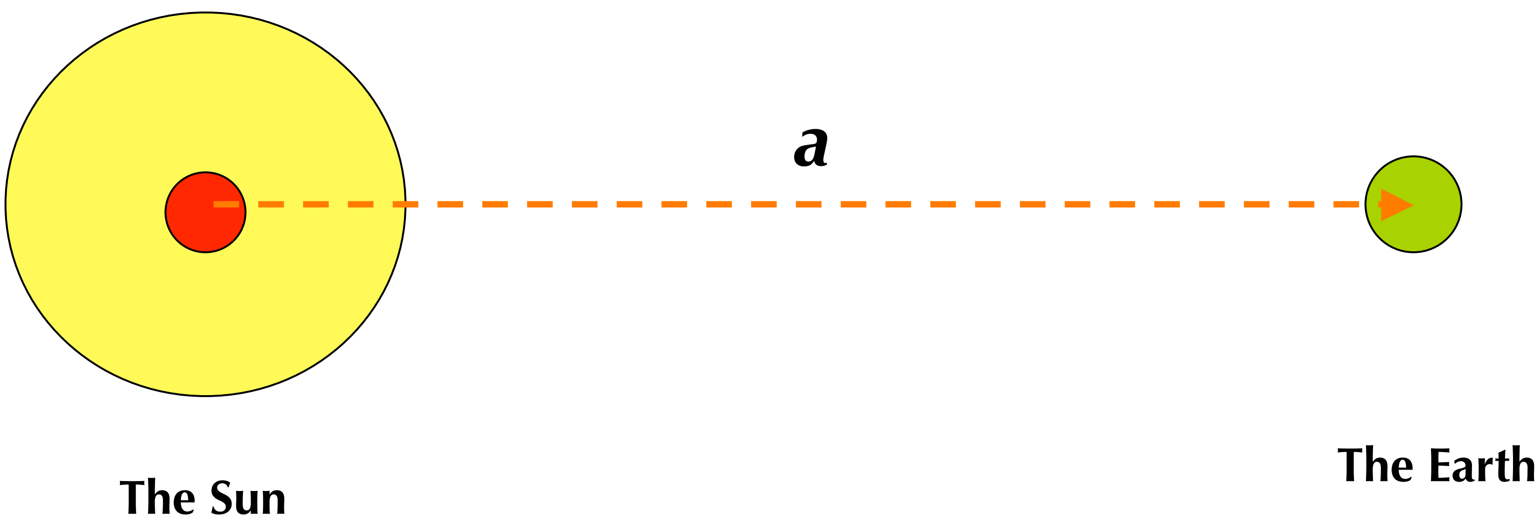




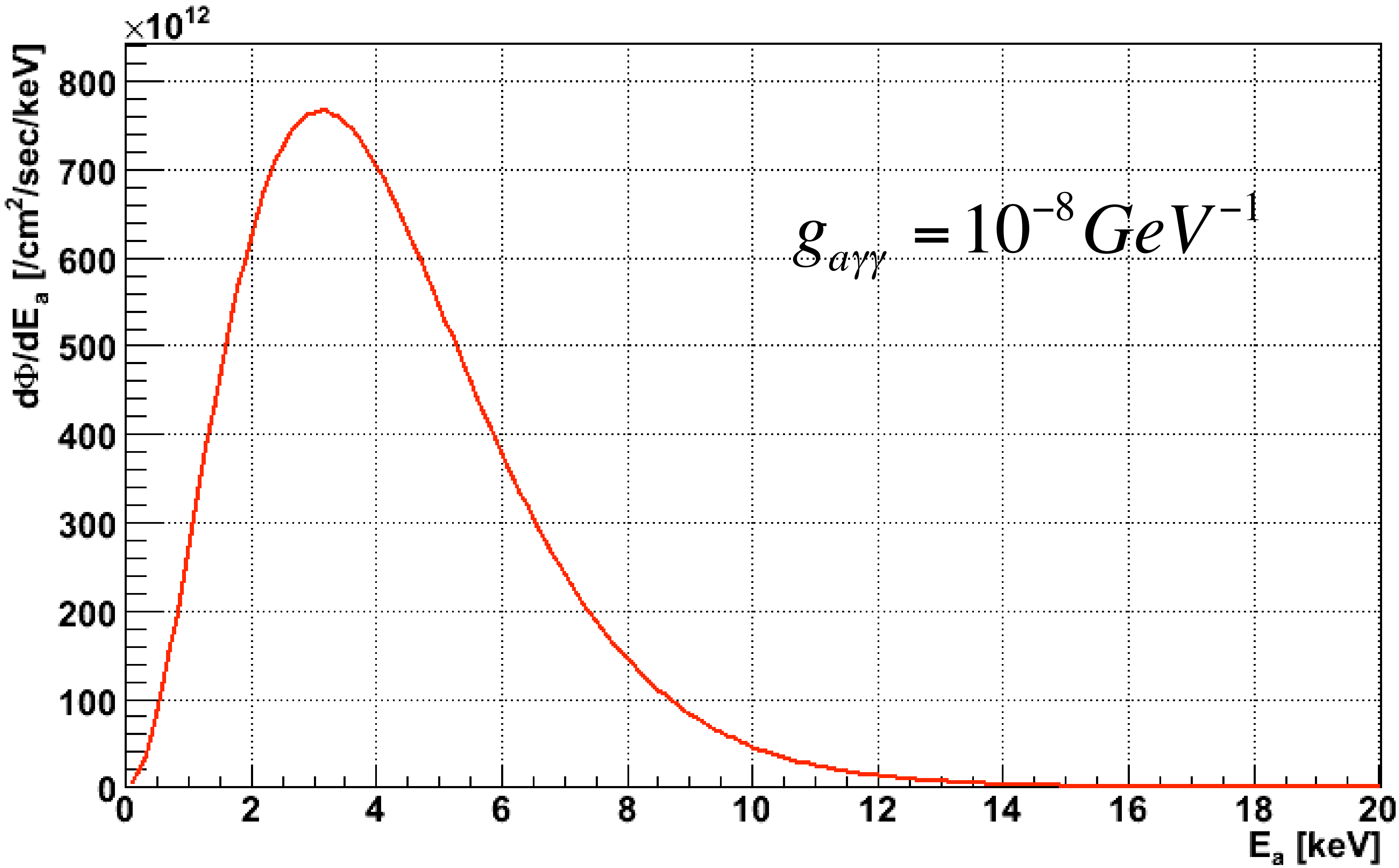


Axion Detection Principle

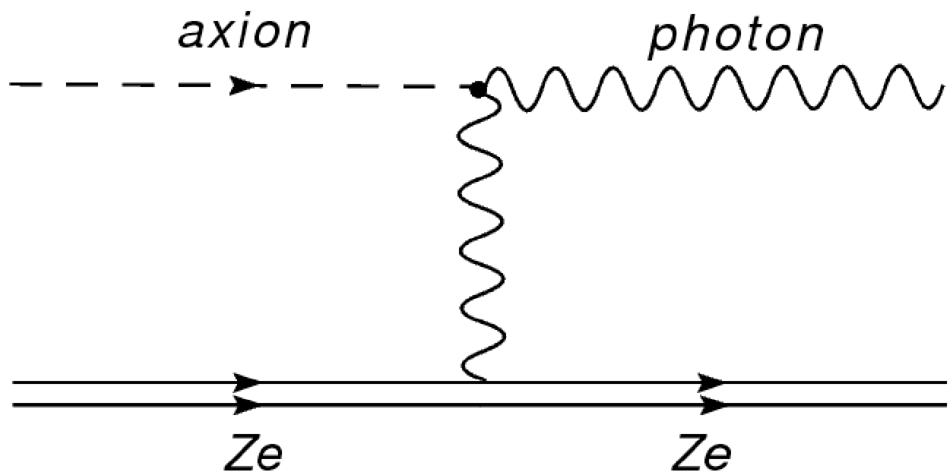




Solar Axion : $g_{a\gamma\gamma}$ coupling



Axion-photon conversion : Primakoff effect



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

$$g_{a\gamma\gamma} = 10^{-8}\,GeV^{-1},\ k \approx keV,\ q \approx keV,\ Z \approx 100$$

$$\sigma \approx 10^{-43}\,cm^2 \ !!$$

Crystal and Bragg Scattering

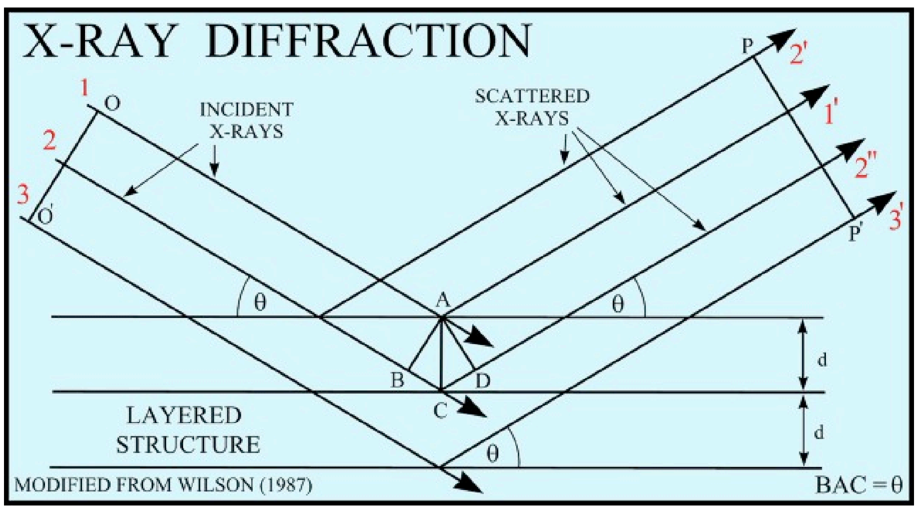
Coherent scattering of an axion in a crystal

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

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

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

Bragg condition



BRAGG LAW

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

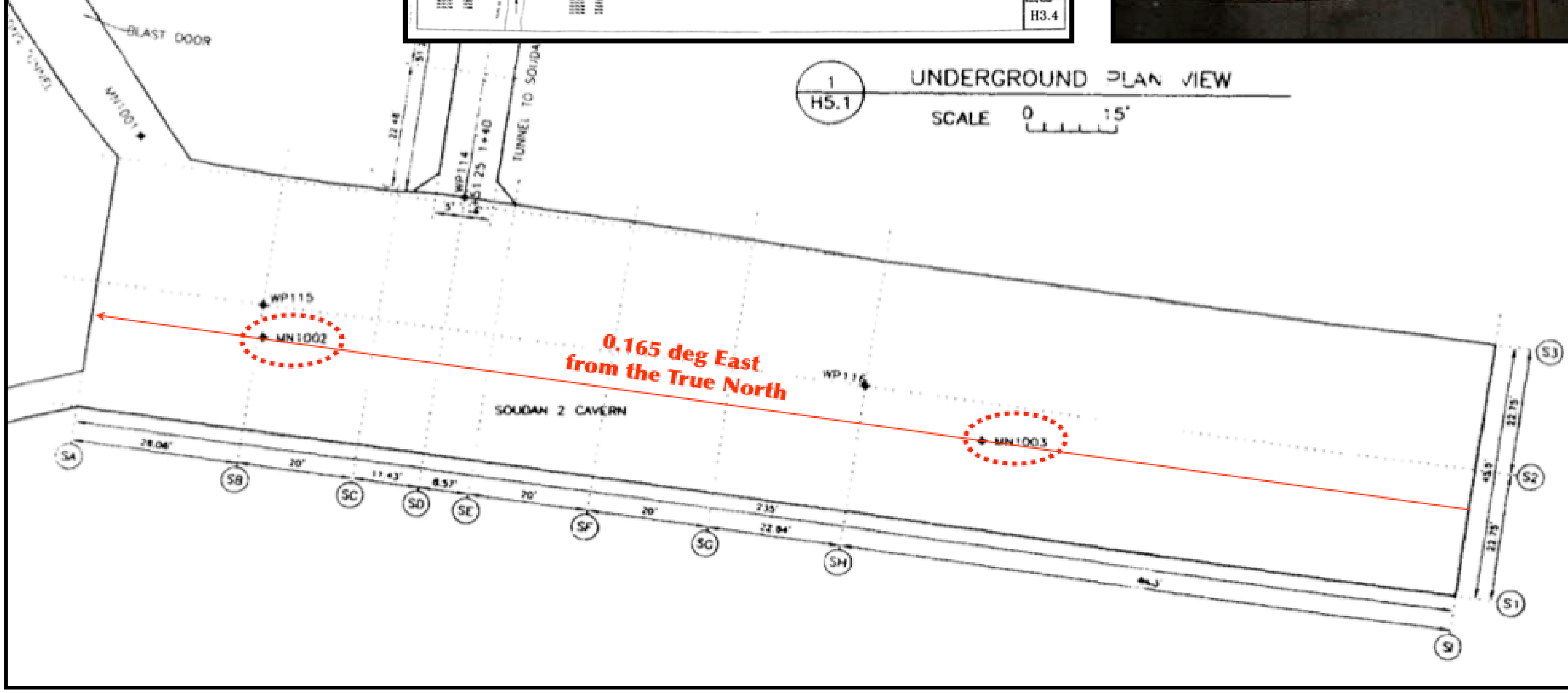
where:
- d = lattice interplanar spacing of the crystal
- θ = x-ray incidence angle (Bragg angle)
- λ = wavelength of the characteristic x-rays

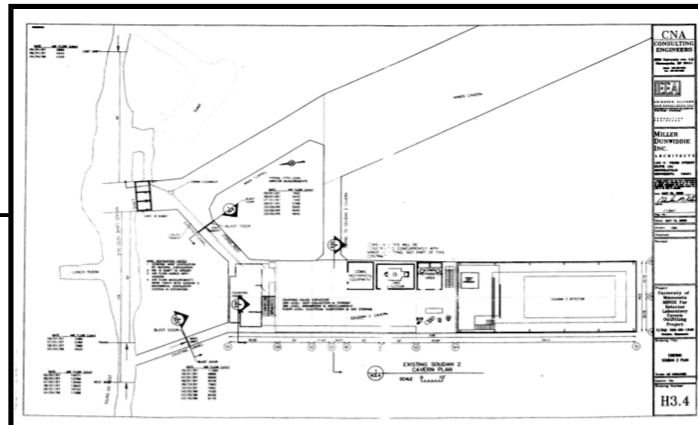
$$E_a = \hbar c \frac{|\vec{G}|^2}{2\hat{u}\cdot\vec{G}}$$

Direction of the CDMS Cavern

- Amazing collaboration among the CDMS, NuMI/MINOS and old mine crews

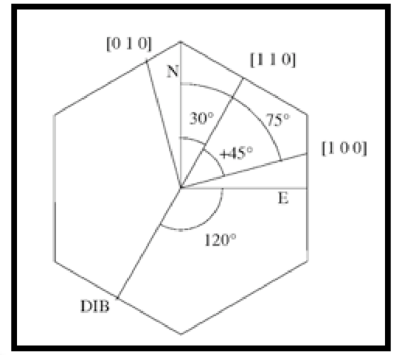
Latitude : 47.815N
Longitude : -92.237E
Altitude : -210m

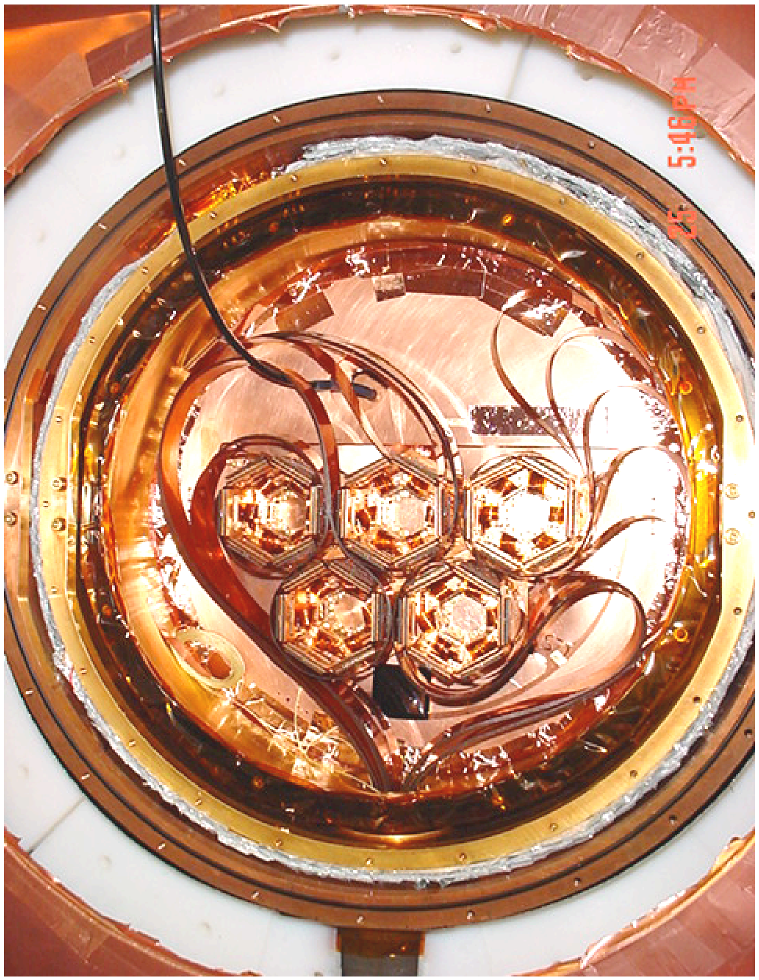


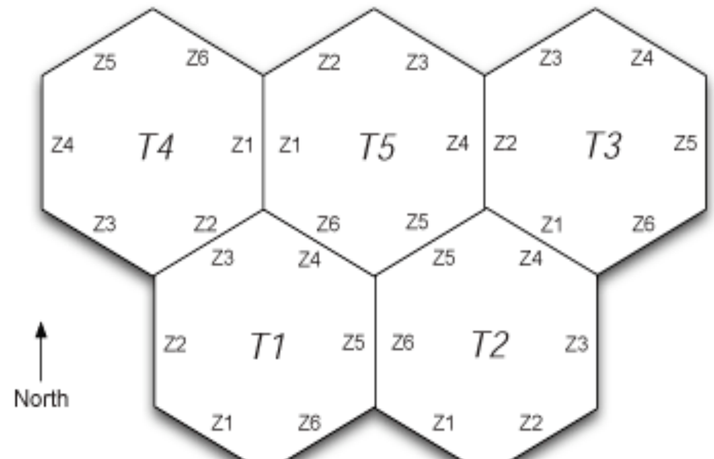


Direction of the crystal plane

- Germanium crystal structure : Face-Centered-Cubic (*fcc*)
- Overall error in the direction measurement : 3 degree

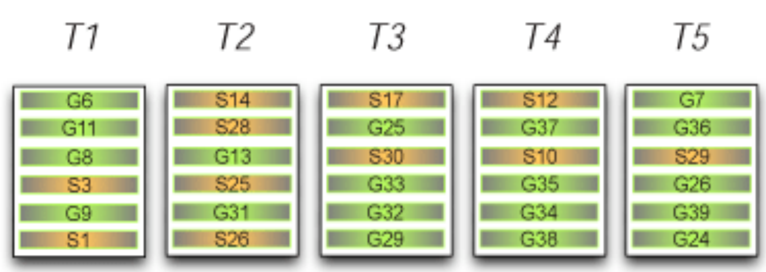






Top View

The following shows detector stack placement:



Side View

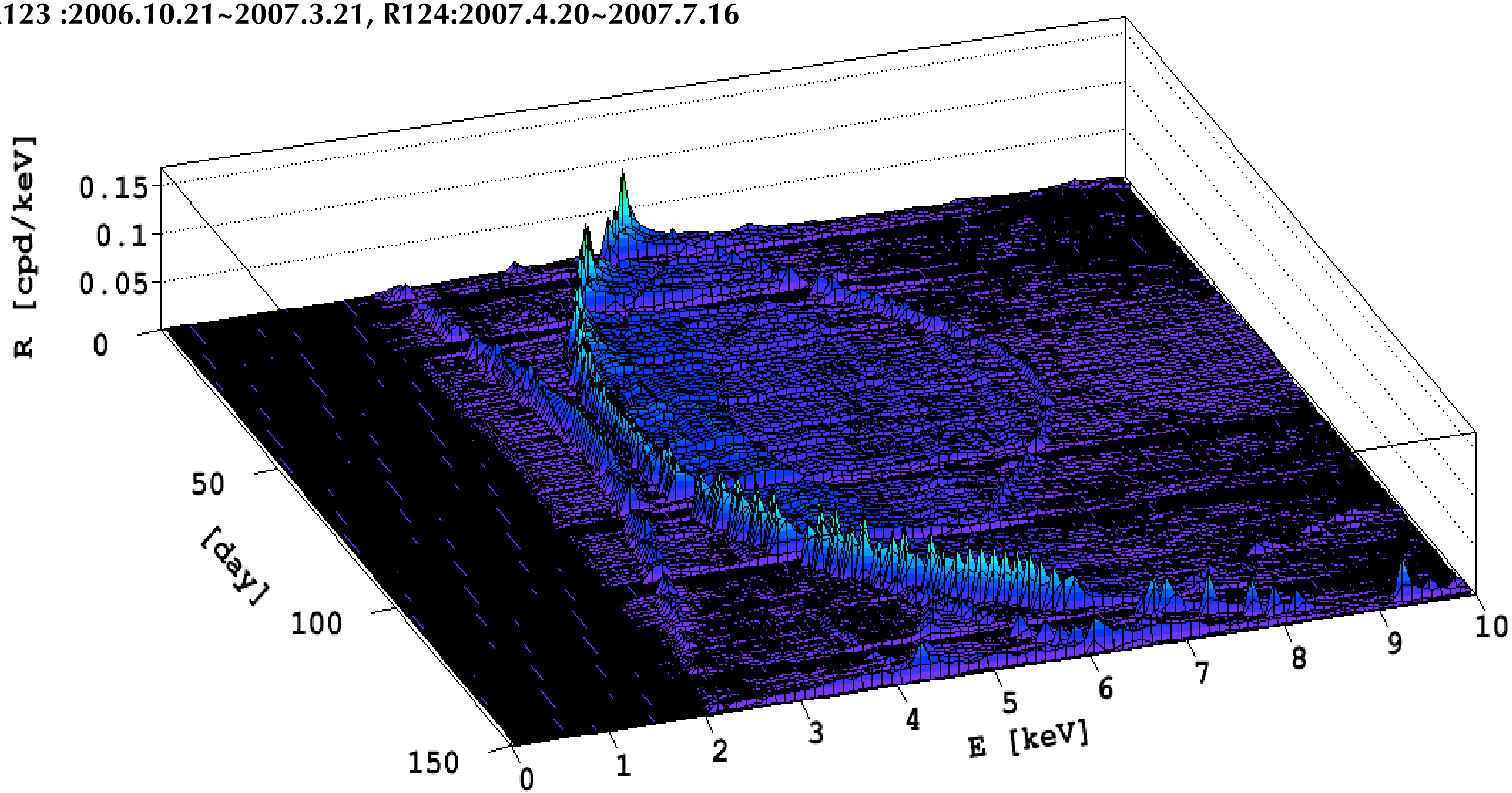
Expected Solar Axion Event Rate

Very detailed calculations are involved

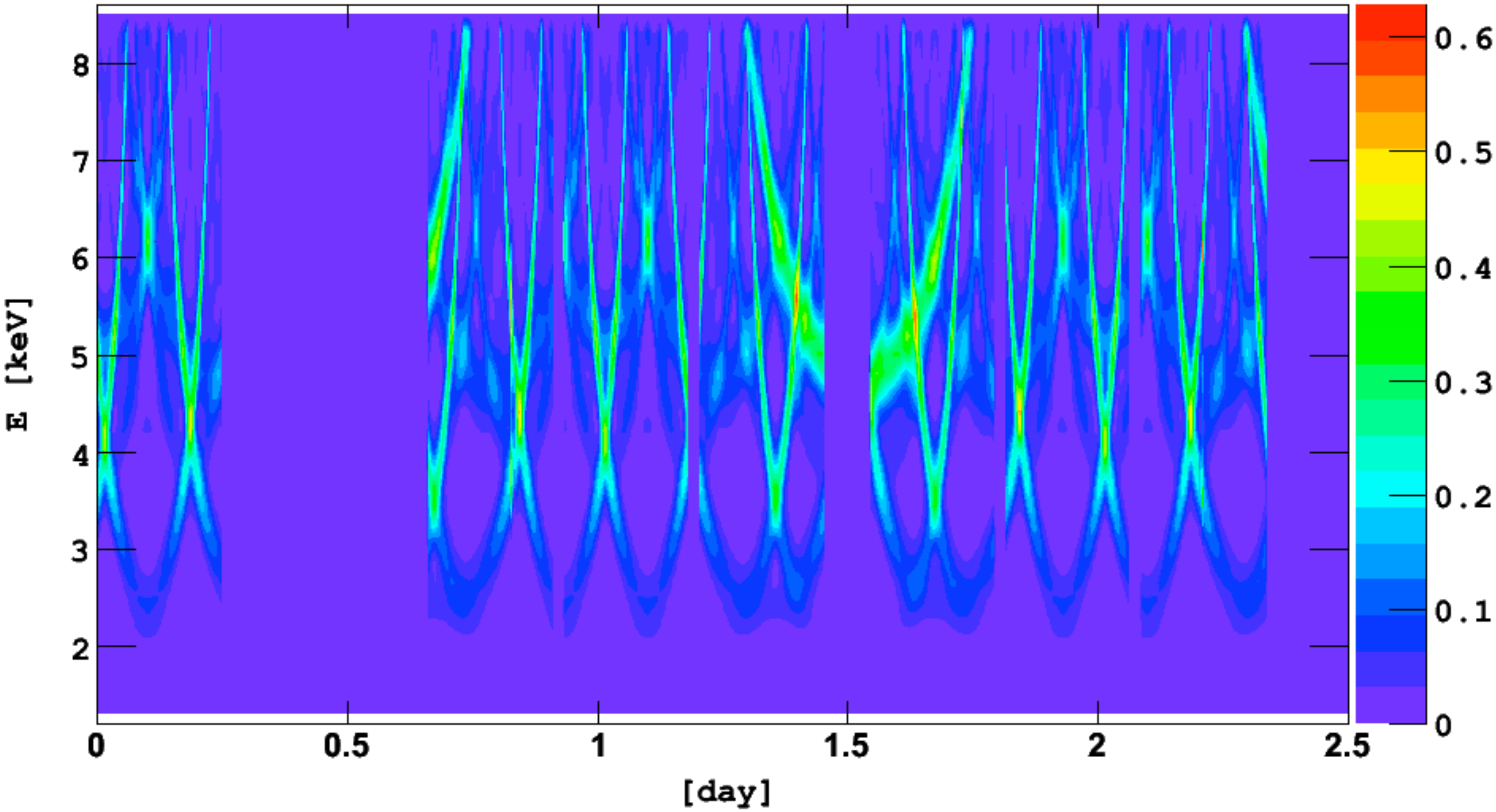
- Seasonal variation of the solar flux
- The height of the Sun changes in seasons
- Detector energy resolutions
- Systematic uncertainty of the detector direction
- Detector livetime information

R123 :2006.10.21~2007.3.21, R124:2007.4.20~2007.7.16

200 CPUs x 2 weeks
@FermiGrid

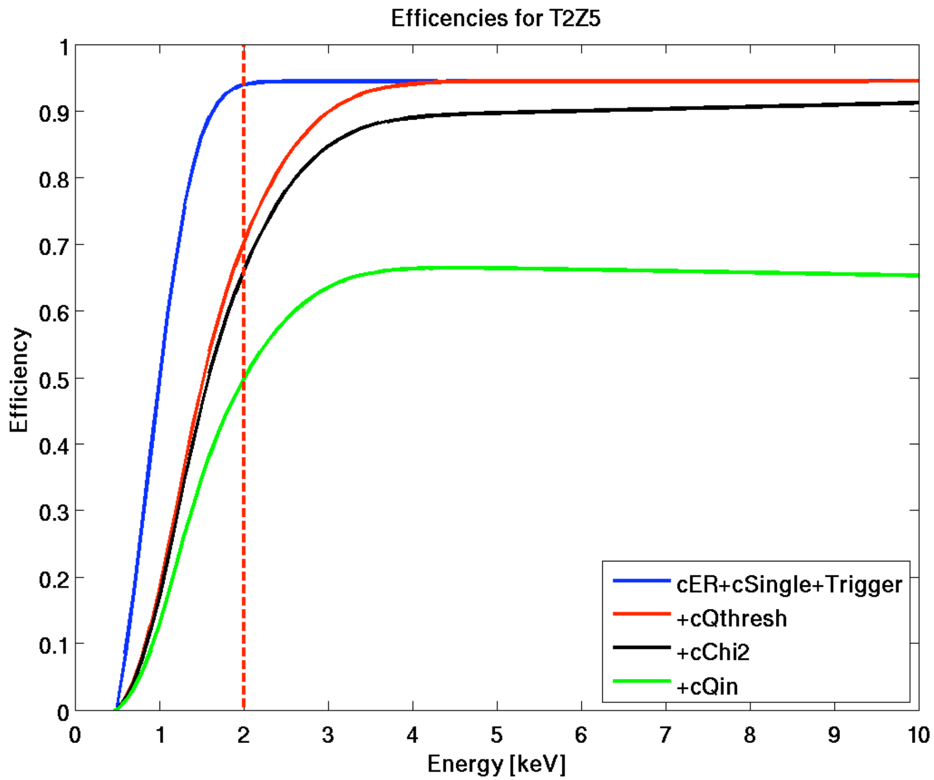


Expected Solar Axion Event Rate

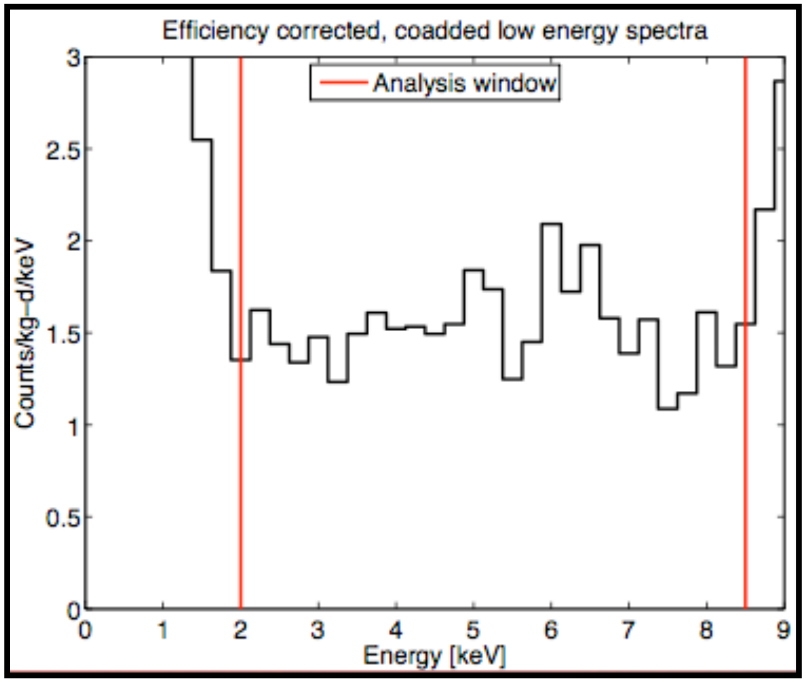


Background Rate and Efficiencies

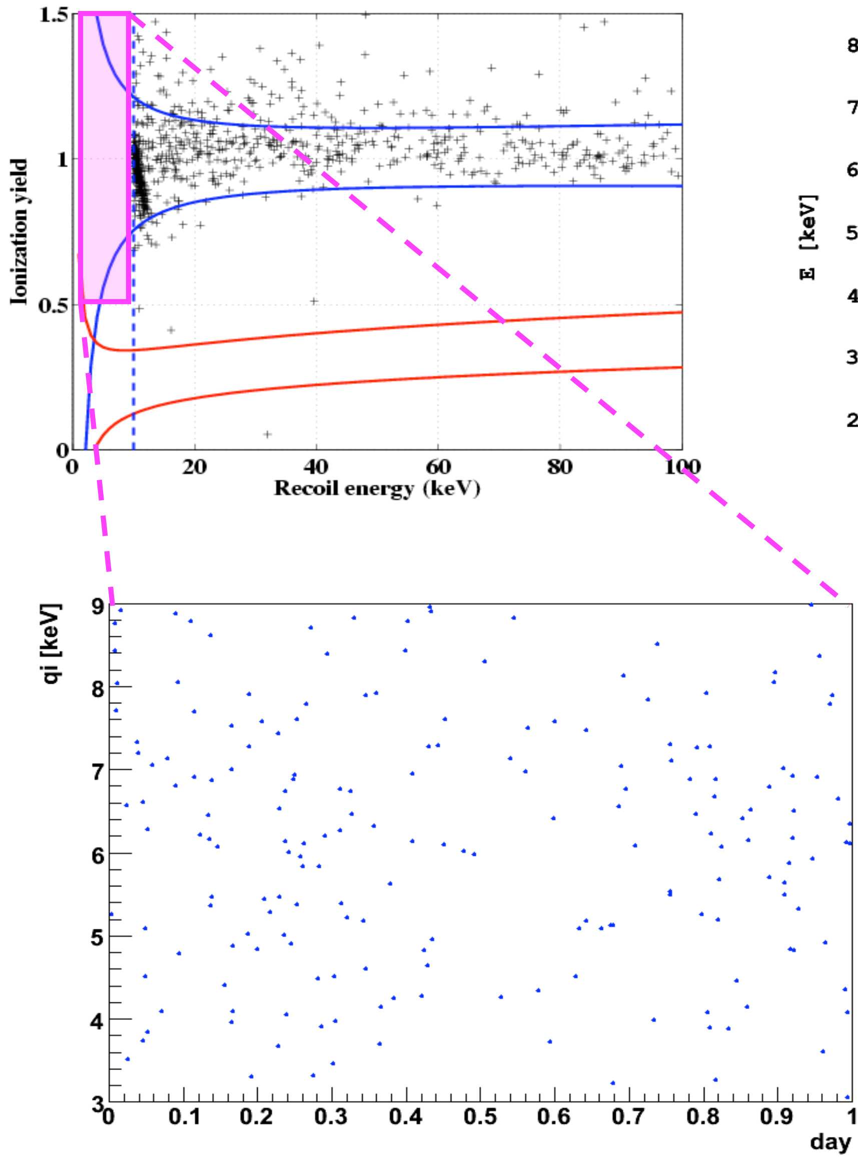
- Electron recoil events
- Within fiducial volume
- Single scatter events
- Detection efficiency : 30%~70%(detector dependent)

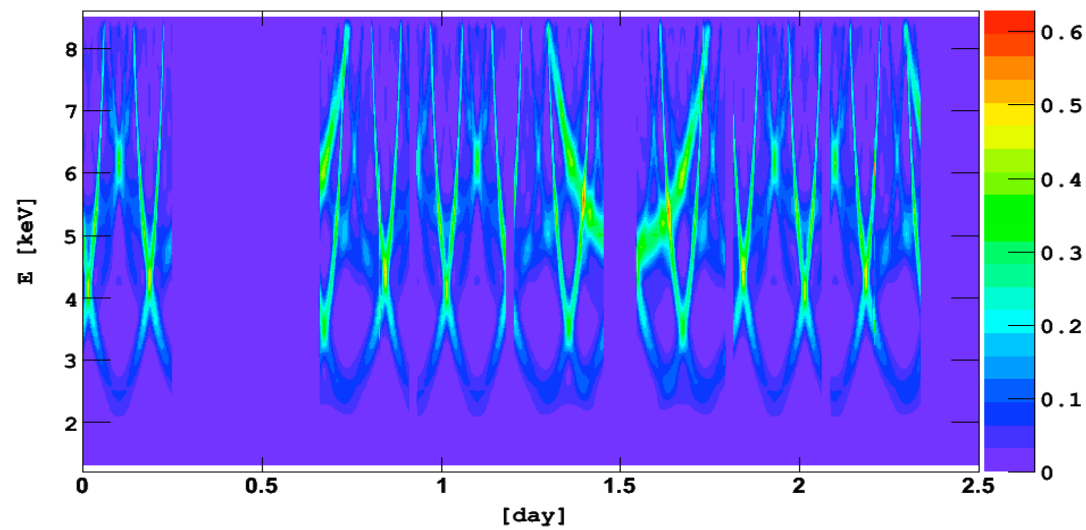


- Total 443.2 kg-days (after quality cuts)



CDMS Low Energy Gammas





Unbinned Likelihood Fit

$$R(E,t,d) = \lambda A(E,t,d) + B(E,d),$$

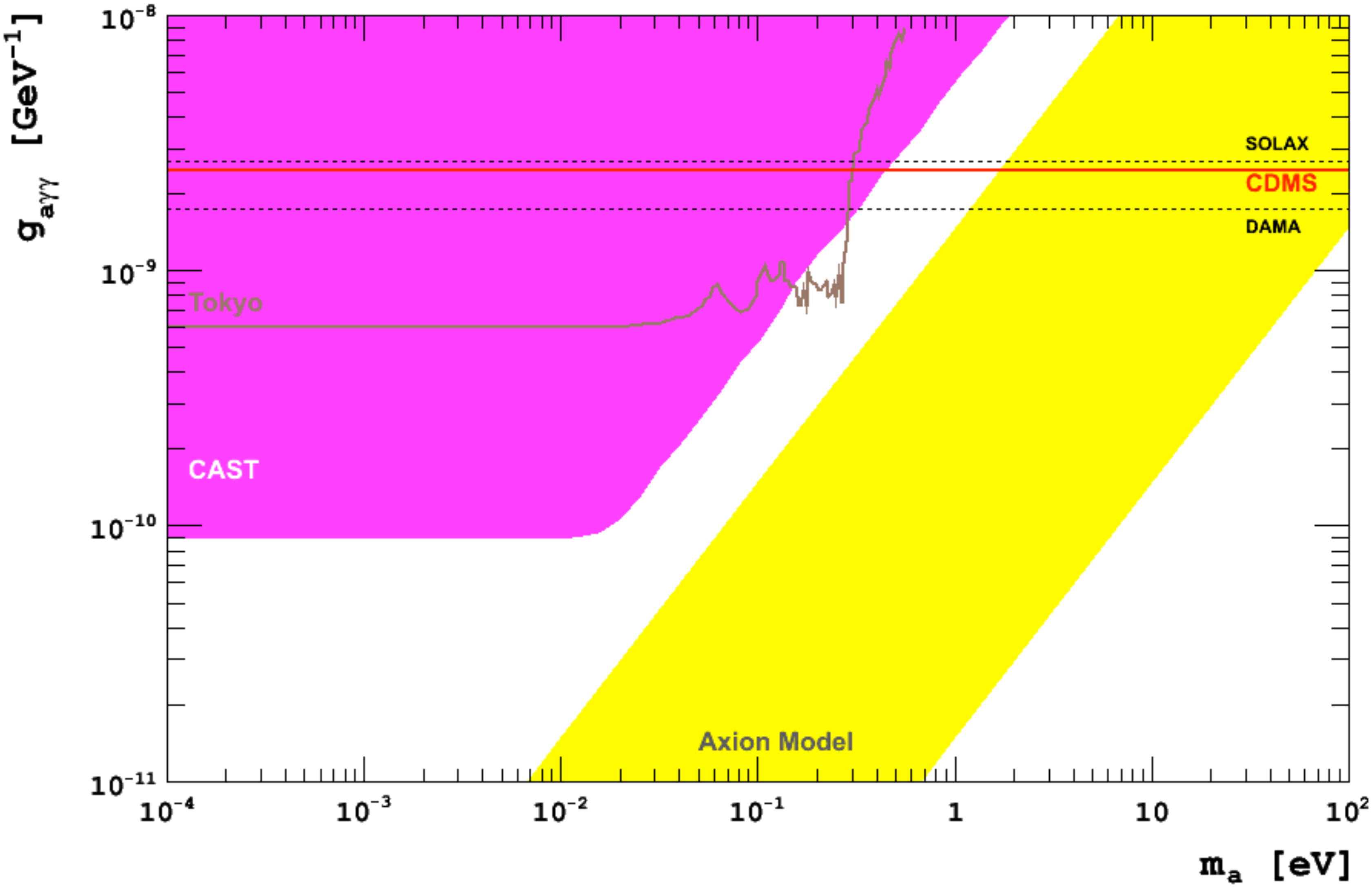
$$\lambda = [g_{a\gamma\gamma}/(10^{-8}\,\mathrm{GeV}^{-1})]^2$$

$$B(E,d) = \varepsilon(E,d)[\alpha(d) + \beta(d)E + \gamma(d)/E]$$

$$R_T = \sum_d \int dE\,dt\,R(E,t,d;\lambda,\alpha(d),\beta(d),\gamma(d))$$

$$\log(L) = -R_T + \sum_i \log(R(E_i,t_i,d_i))$$

The First Solar Axion Limit from CDMS



Summary

- We still have zero background experiment for WIMP search
  It is the only direct detection experiment with less than 1 background

- There are no WIMPs above $\sigma(SI) = 4.6 \times 10^{-44} cm^2$ (90%CL@60GeV)
  It is the world best upper bound above 42 GeV

- A preliminary CDMS limit of axio-electric coupling is presented
  ➔ Best direct experimental limit above 2 keV of axion mass (g_{aee} < 2e-12)
  ➔ Systematic uncertainty and background checks are underway

- A preliminary CDMS solar axion search limit is presented
  ➔ First precise measure of absolute direction of the crystal in the mine
  ➔ Most precise limit above 0.5 eV of axion mass ($g_{a\gamma\gamma}$ < 2.4e-9 GeV^{-1})
  ➔ Systematic uncertainty check is underway

For review of other crystal style detectors : see Talk by Johannes Blumer (Session5)

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