Lecture 18

Other Detectors

Far Infrared detectors

Bolometers, SQIDs

Search for Laboratory dark matter

Types of detectors

An electrical signal can be formed directly by ionization or photo-conversion. Incident radiation quanta impart sufficient energy to individual atomic electrons to form electron-ion pairs (in gases) or electron-hole pairs (in semiconductors and metals).

Other detection mechanisms are:

Excitation of optical states (scintillators)
Excitation of lattice vibrations (phonons)
Breakup of Cooper pairs in superconductors
Formation of superheated droplets in superfluid He

Typical excitation energies:

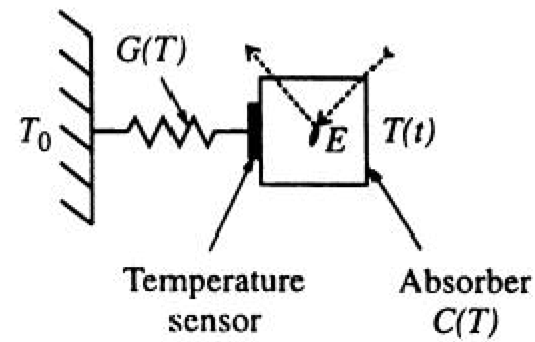
Ionization in gases ~30 eV
Photo-conversion in semiconductors 1 – 5 eV
Scintillation ~10 eV
Phonons meV
Breakup of Cooper Pairs meV

Other types of detectors: bolometers

Assume thermal equilibrium: If all absorbed energy *E* is converted into phonons, the temperature of the sample will increase by

$$\Delta T = \frac{E}{C}$$

where C the heat capacity of the sample (specific heat x mass).



At room temperature the specific heat of Si is 0.7 J/gK, so

E= 1 keV, m= 1 g $\Rightarrow$ ΔT= $2 \cdot 10^{-16}$ K,

which isn't practical.

What can be done?

a) reduce mass

b) lower temperature to reduce heat capacity "freeze out" any electron contribution, so phonon excitation dominates.

Debye model of heat capacity: $C \propto \left(\frac{T}{\Theta}\right)^3$

Example:

m= 15 μg

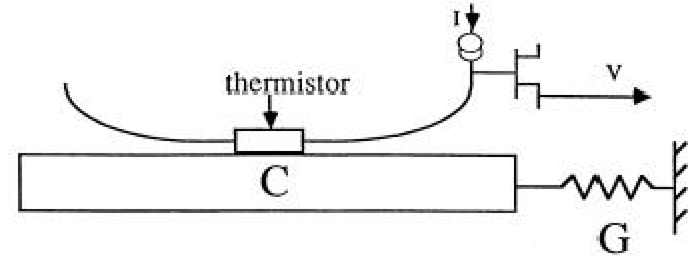
T= 0.1 K

Si $\Rightarrow$ C= $4 \cdot 10^{-15}$ J/K

E= 1 keV $\Rightarrow$ ΔT= 0.04 K

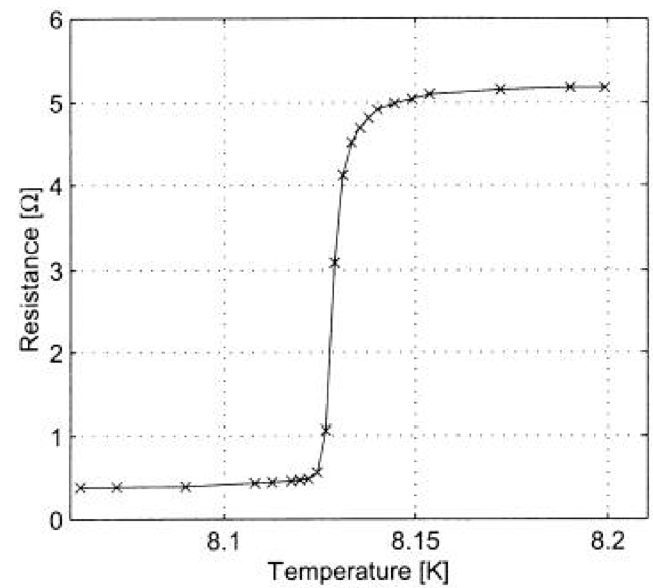
How do we measure the temperature rise?

One idea: couple thermistor to silicon and measure the resistance change:



Thermistors made of very pure semiconductors (Ge, Si) can exhibit responsivities of order 1 V/K, so a 40 mK change in temperature would yield a signal of 40 mV.

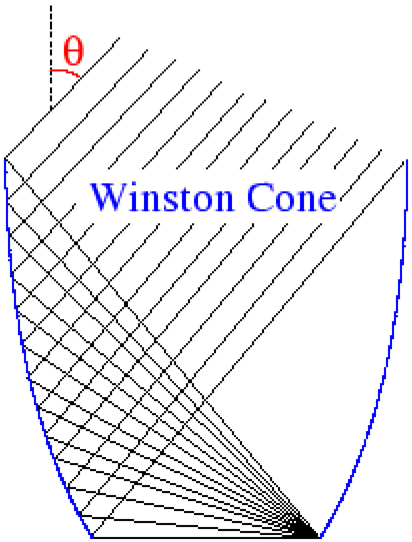
Better idea: Utilize abrupt change in resistance in transition from superconducting to normal state:



At sufficiently low temperatures the electronic contribution to the heat capacity is negligible: $C \propto \exp(-T_c/T)$

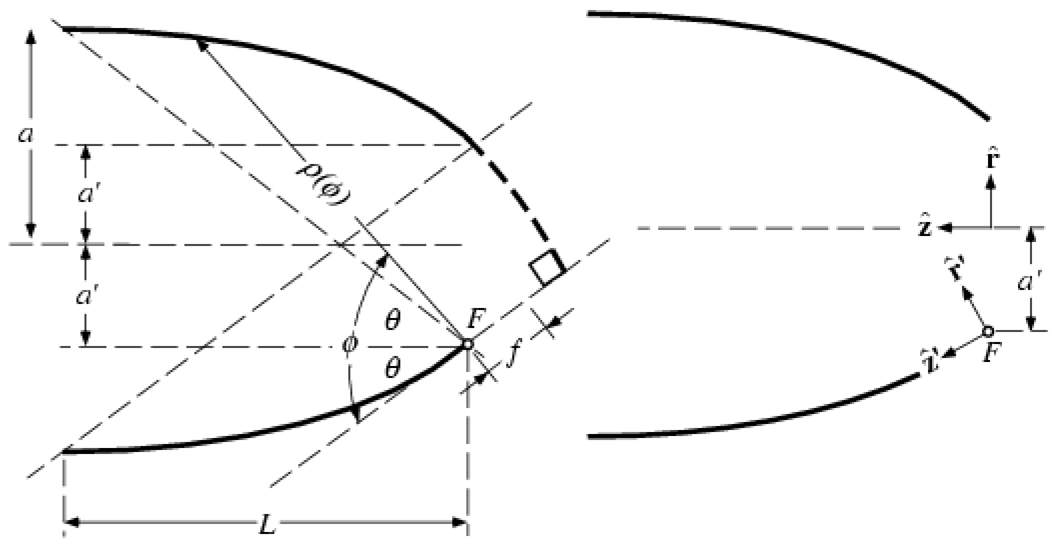
Important constraint:
Since sensor resistance of order 0.1 – 1 Ω, the total external resistance (internal resistance of voltage source and input resistance of current measuring device) must be much smaller to maintain voltage-biased operation, i.e. < 0.01 – 0.1 Ω!
Difficult to achieve at relevant frequencies.

Pseudo-optical systems



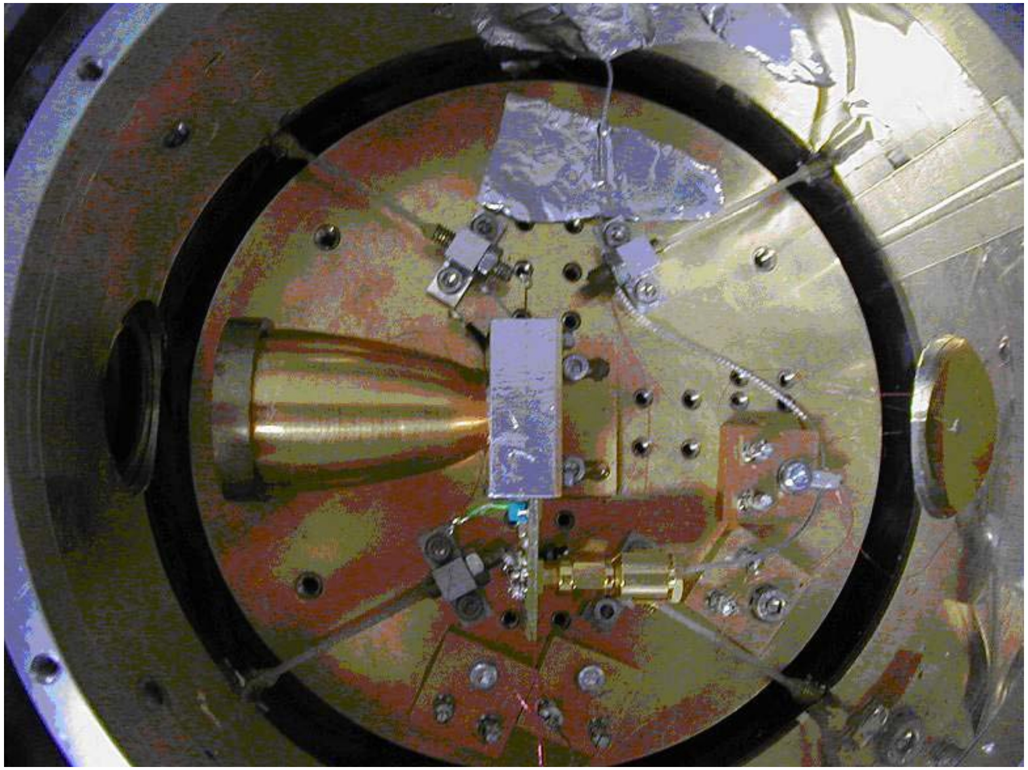
Field of view = 2 $\Theta = 2\tan^{-1}\left(\frac{a}{f'}\right) = 2\tan^{-1}\left(\frac{a}{F'D}\right) \approx \frac{2a}{F'D}$,

F-number = *F'*



Superconducting niobium bolometer system

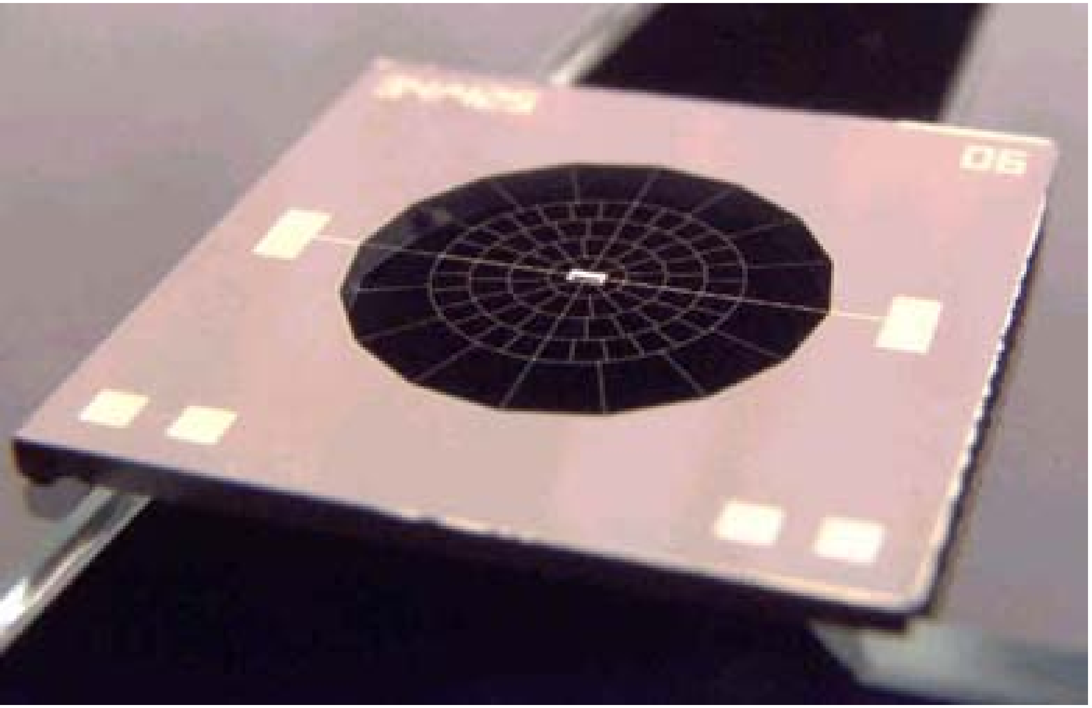
This Nb superconducting hot-electron bolometer is capable of responding to a very broad range of wavelengths. Shown here is a system with a single superconducting Nb hot electron bolometer, with Winston cone coupling optics, control thermometry and bias circuit, quasi-optical filters and a wideband noise-matched preamplifier. This detector has good sensitivity throughout the mm and IR with a one nanosecond response time.



System Optical NEP: < 100 pW.Hz-1/2 measured at 300 GHz (100 kHz modulation.)
Bandwidth: > 200 MHz (τ = 1 x 10-9 second.)
Operating Temperature: 4.2K or below.
Wavelength range: > 150 microns (< 2 THz.)
Coupling Optics: 15 mm diameter at f/3.

Superconducting Bolometer Array

ACBAR (Caltech)



TES versus STJ Comparison

TES

$$\Delta E_{FWHM} = 2.355\sqrt{4\,k_B\,T_e^2\,C\sqrt{\tfrac{n}{2}}\big/\alpha}$$

$n = 5$ electron - phonon coupling

$T_e \approx T_c$

$E_{sat} \approx T_c\,C/\alpha$

$$\Delta E_{FWHM} = 2.355\sqrt{6.4\,k_B\,T_c\,E_{sat}}$$

$$\boxed{\Delta E_{FWHM} \approx 15\text{ meV}\left(\frac{E_{sat}}{1\text{ eV}}\right)^{1/2}\left(\frac{T_c}{70\text{ mK}}\right)^{1/2}}$$

STJ & L_K

$$\Delta E_{FWHM} \approx 2.355\sqrt{E\,\varepsilon_0\,(F+G)}$$

$\varepsilon_0 \approx 1.7\Delta \approx 1.7(1.76\,k\,T_c) = 3\,k\,T_c$

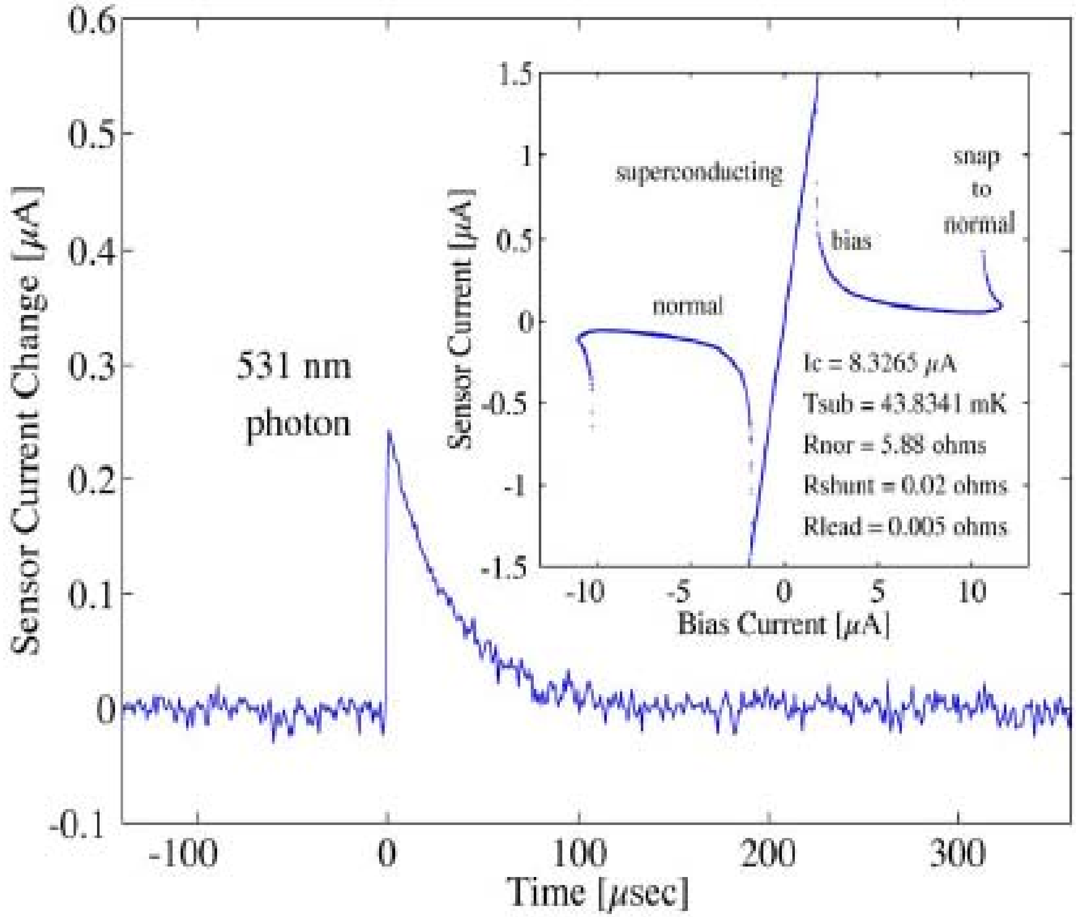
$F \approx 0.2$ is the Fano factor

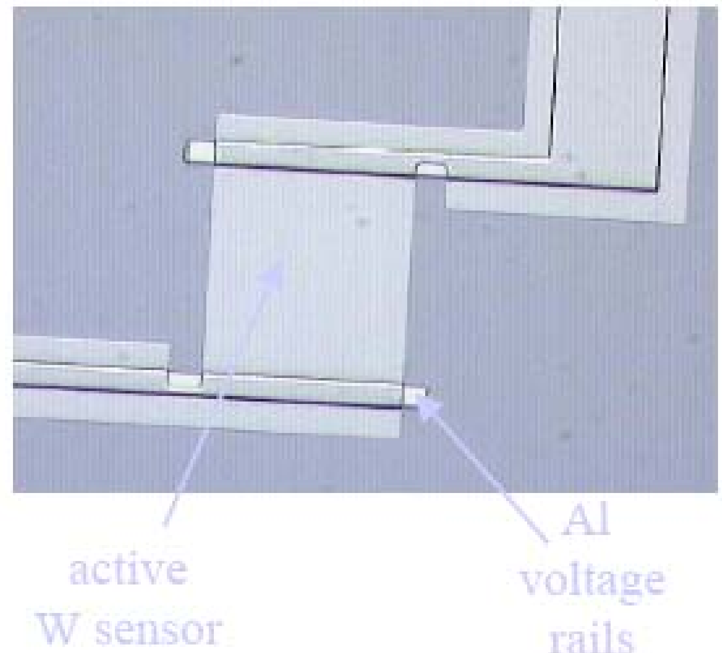
$G \approx 1$ - 2 (tunneling noise)

$$\Delta E_{FWHM} \approx 2.355\sqrt{3.6\,k\,T_c\,E}$$

$$\boxed{\Delta E_{FWHM} \approx 45\text{ meV}\left(\frac{E}{1\text{ eV}}\right)^{1/2}\left(\frac{T_c}{1\text{ K}}\right)^{1/2}}$$

- **Demonstration of W TES sensitivity**

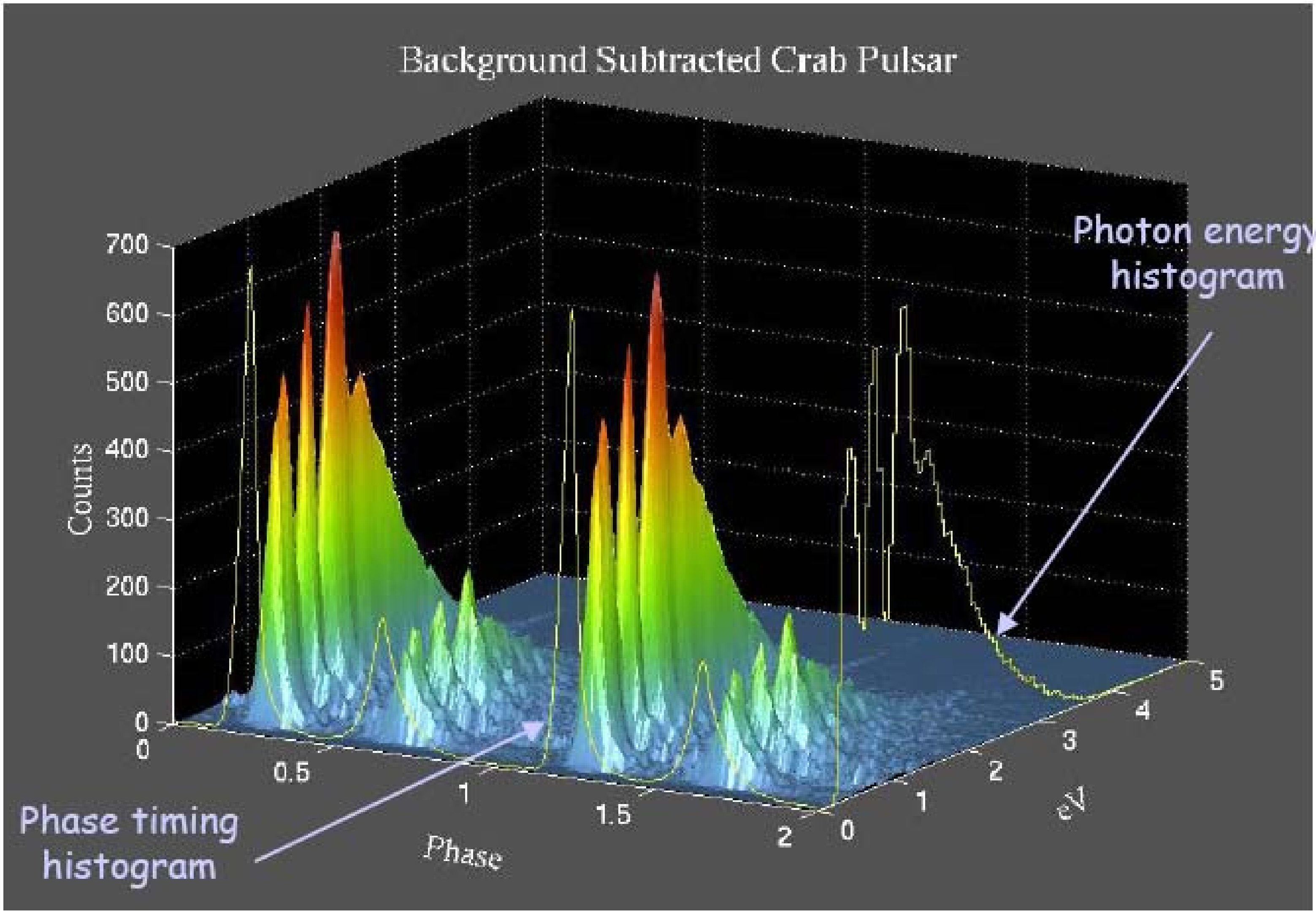




Appl. Phys. Lett. 73, 735 (1998)
B. Cabrera, R. Romani, A. J. Miller
E. Figueroa-Feliciano, S. W. Nam

Application of TES to optical astronomy

Simultaneous photon timing and spectroscopy of Crab pulsar



Cryogenic detectors

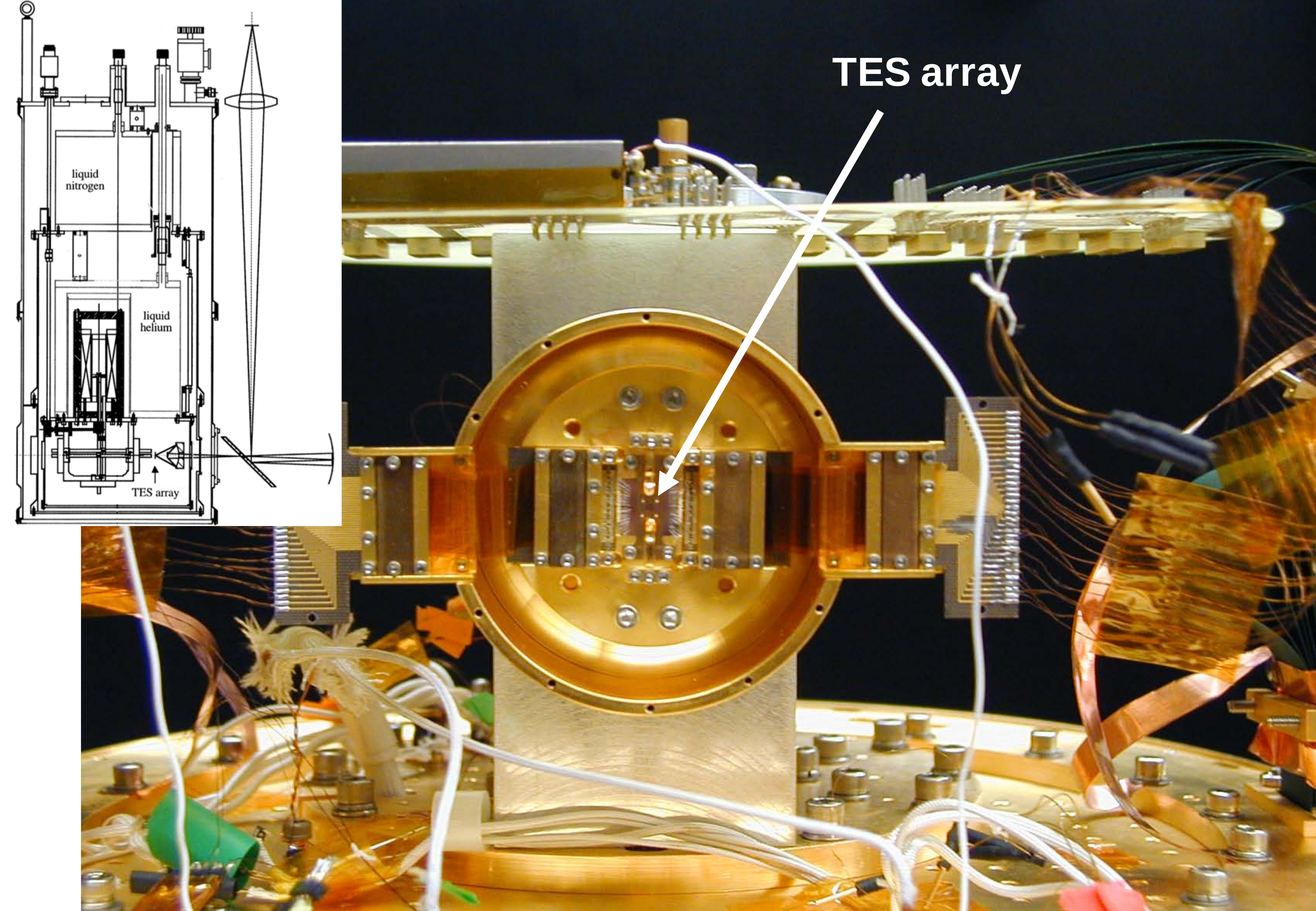
Quantum limited: photon noise in IR background is
$(NEP)^2 = 2P h\nu$, where P = incident power

- Sensitivity approaching quantum level at mm wavelengths
  - Voltage-biased superconducting transition edge sensors

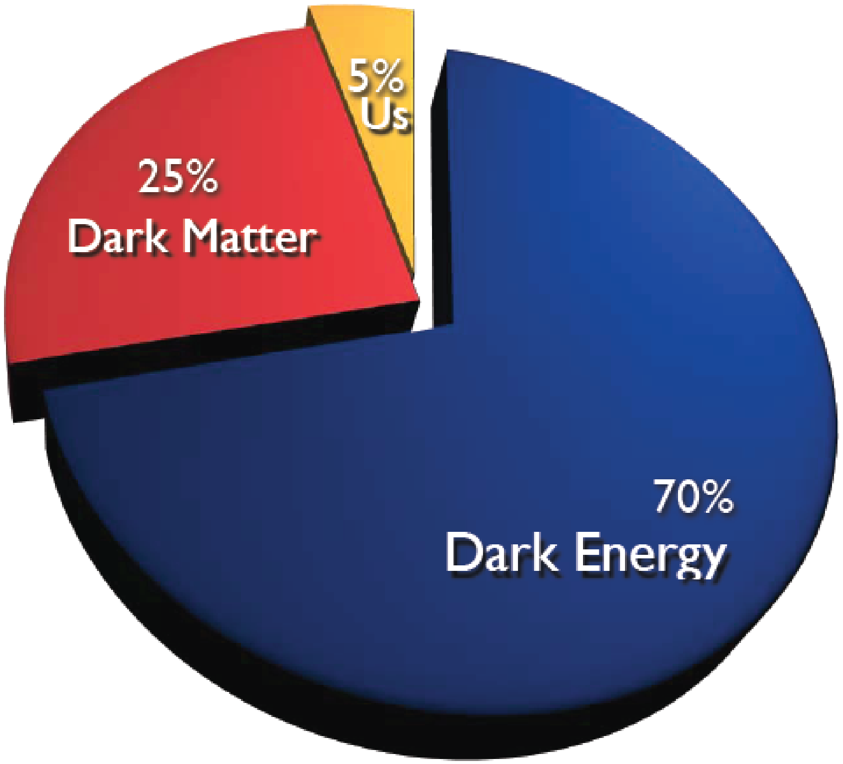
  Stable operation + predictable response

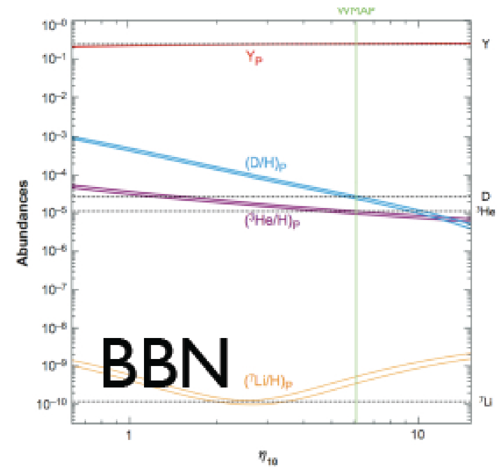
  - Sensors can be fabricated using monolithic technology developed for Si integrated circuits, micro-mechanics (MEMS)
    Economical fabrication of large sensor arrays
  - Open question: Readout (multiplexing of many channels)
    Appears feasible, but much work to do

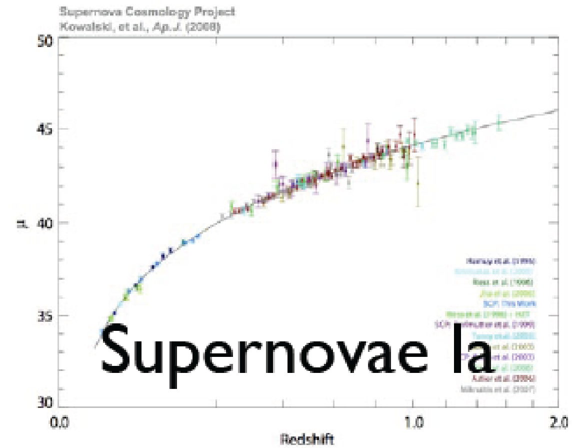
Critical for CMB Polarization SZ Cluster Search Next Generation WIMP detectors

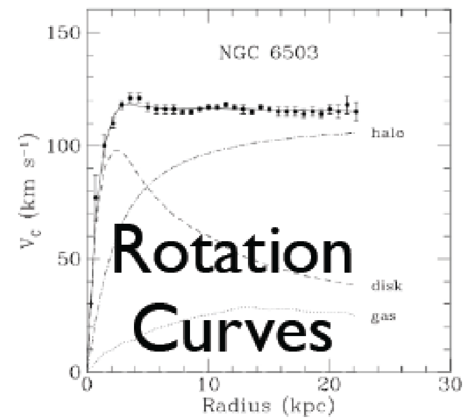

liquid
nitrogen
liquid
helium
TES array
TES array

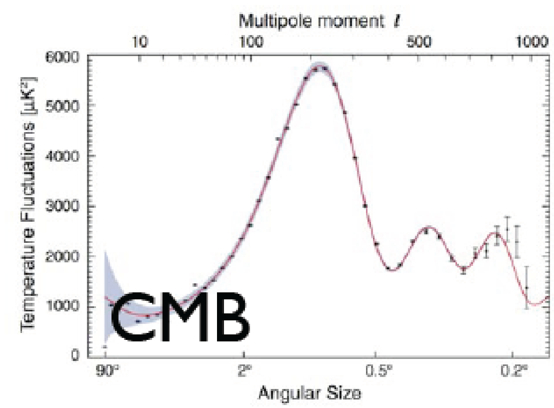
DARK MATTER











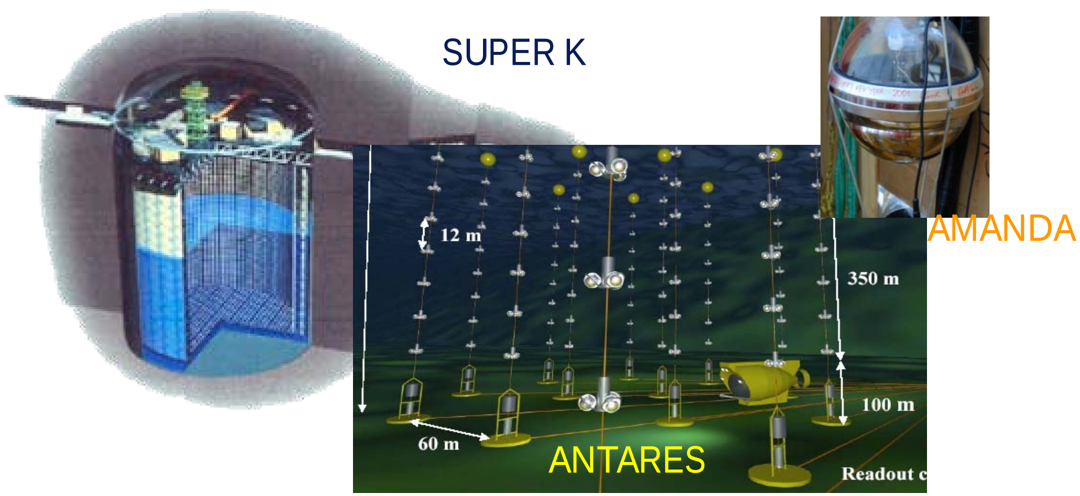
Dark Matter as Weakly Interacting Massive Particles (WIMPs)

- Cross-sections of order of weak scale give good estimate of current relic density
- Independently, SUSY predicts a massive, weakly interacting particle

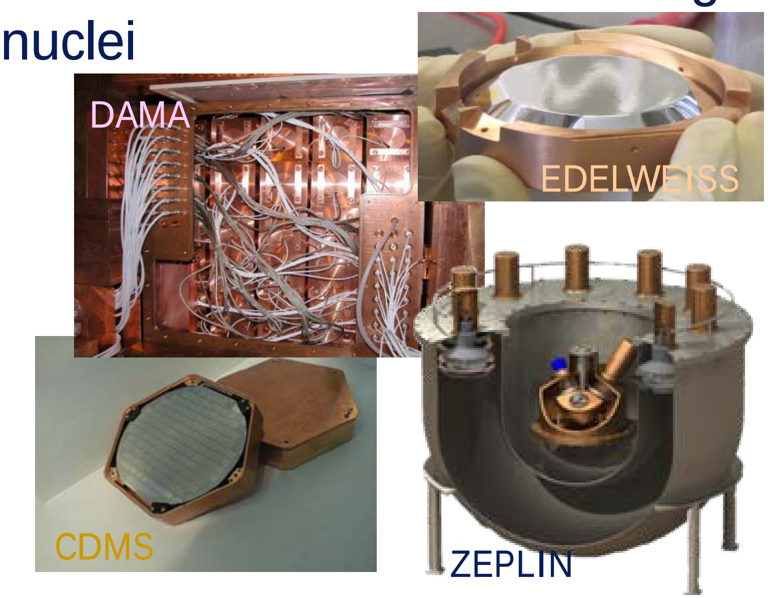
Natural WIMP candidate

- Neutralino definition in the SUSY field
- Stable particle if R-parity conserved (LSP)

- Indirect detection :
  - Detection of WIMPs annihilation products

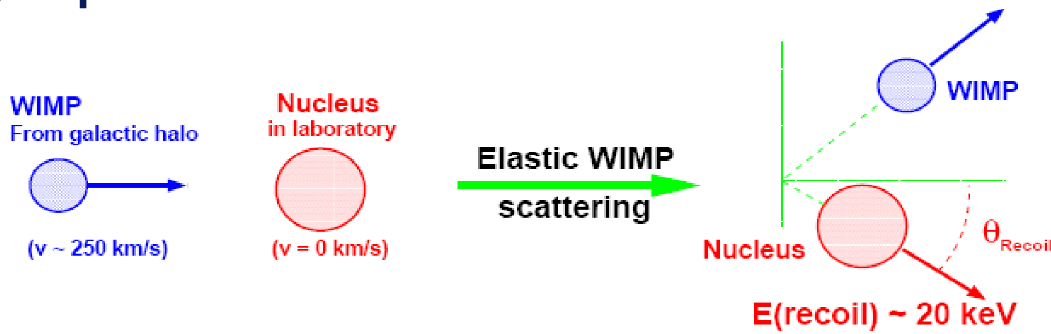


- Direct detection :
  - Detection of WIMPs scattering off nuclei



Direct Search Principle

- Detection of the energy deposit due to elastic scattering on nuclei of detector in laboratory experiment

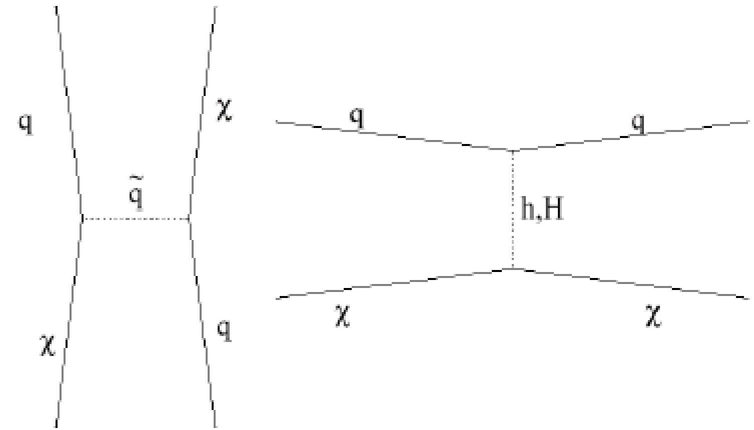


- Optimum sensitivity for $M_{WIMP} \sim M_{RECOIL}$
- Rate < 1 evt/day/kg of detector
  - Need low background
    - » Deep underground sites
    - » Radio-purity of components
    - » Active/passive shielding
  - Need large detector mass (kg -> ton)
- Recoil energy ~ 20 keV
  - Need low recoil energy threshold

WIMPS

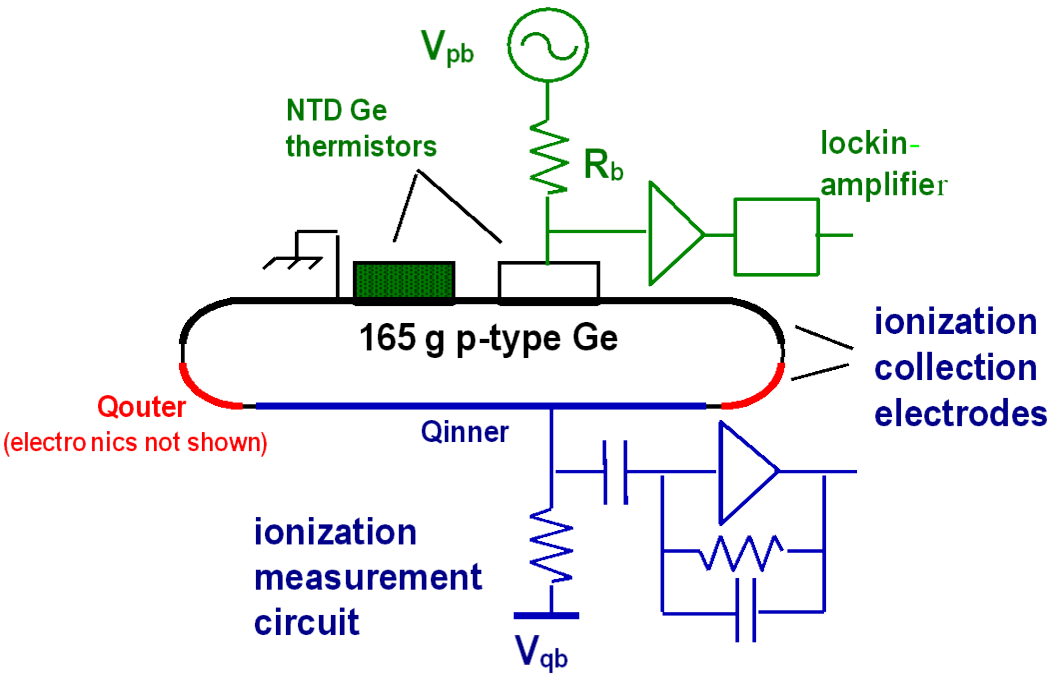
- Sufficiently massive that they could account for the missing mass.
- Rarely interacting with ordinary matter (which is why they have not been observed yet).
- Supersymmetry offers a natural WIMP candidate:
  - For every particle, there is a super-partner particle with spin different by ½.
  - The lightest super-partner (LSP) stable and weakly interacting with ordinary matter ⇒ **natural WIMP candidate!**
  - In most cases, the LSP is a neutralino - a superposition of superpartners of B, W, and two neutral, parity even Higgs fields.

$$\chi_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W}_3 + N_{13}\tilde{H}_1^0 + N_{14}\tilde{H}_2^0$$

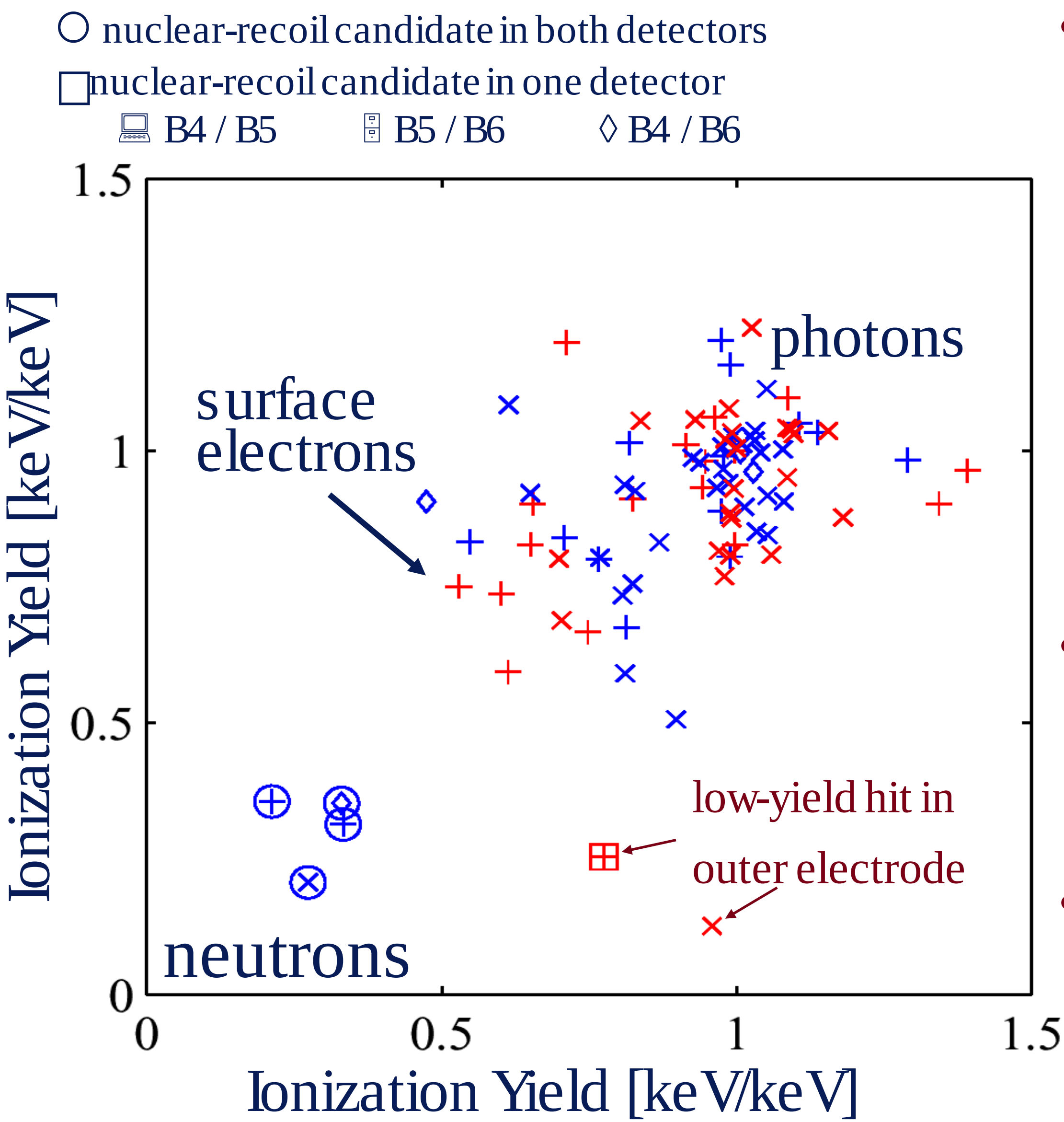


Search for dark matter particles

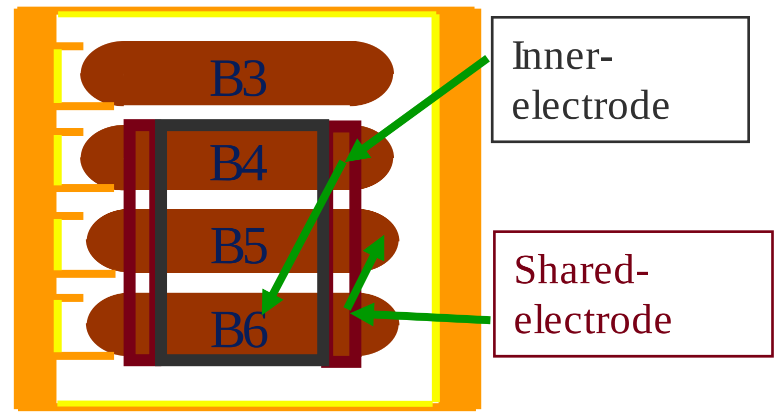
Berkeley Large Ionization-
and Phonon-mediated Detectors



- Four 165 g Ge detectors, for total mass of 0.66 kg during 1999 Run
- Calorimetric measurement of total energy
- Energy resolution: sub-keV FWHM in phonons and ionization

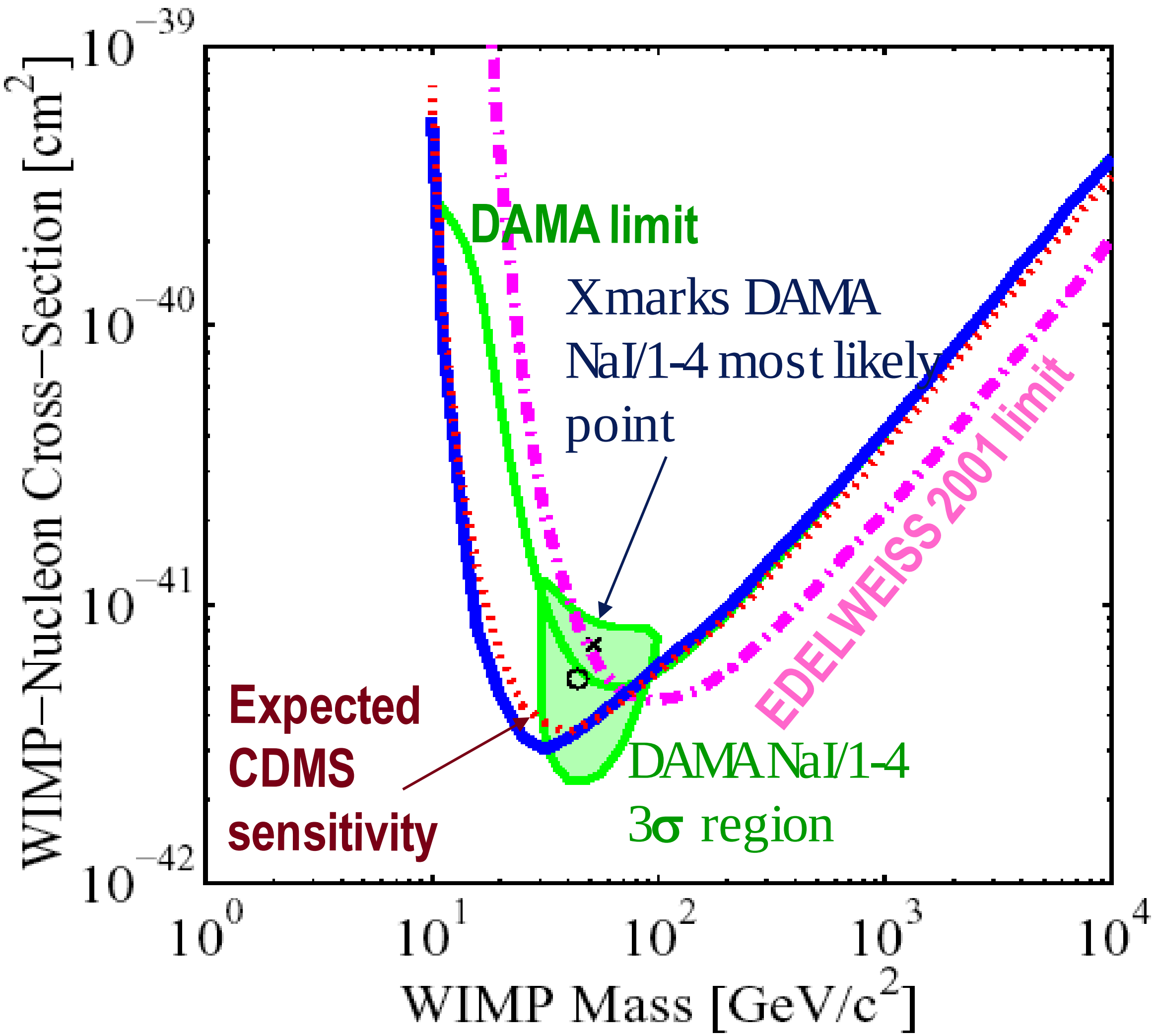


- **Require that at least one hit be in fiducial volume**



- **Observe 4 neutron multiple scatters in 10-100 keV multiple events**
- **Calibration indicates negligible contamination by electron multiples**

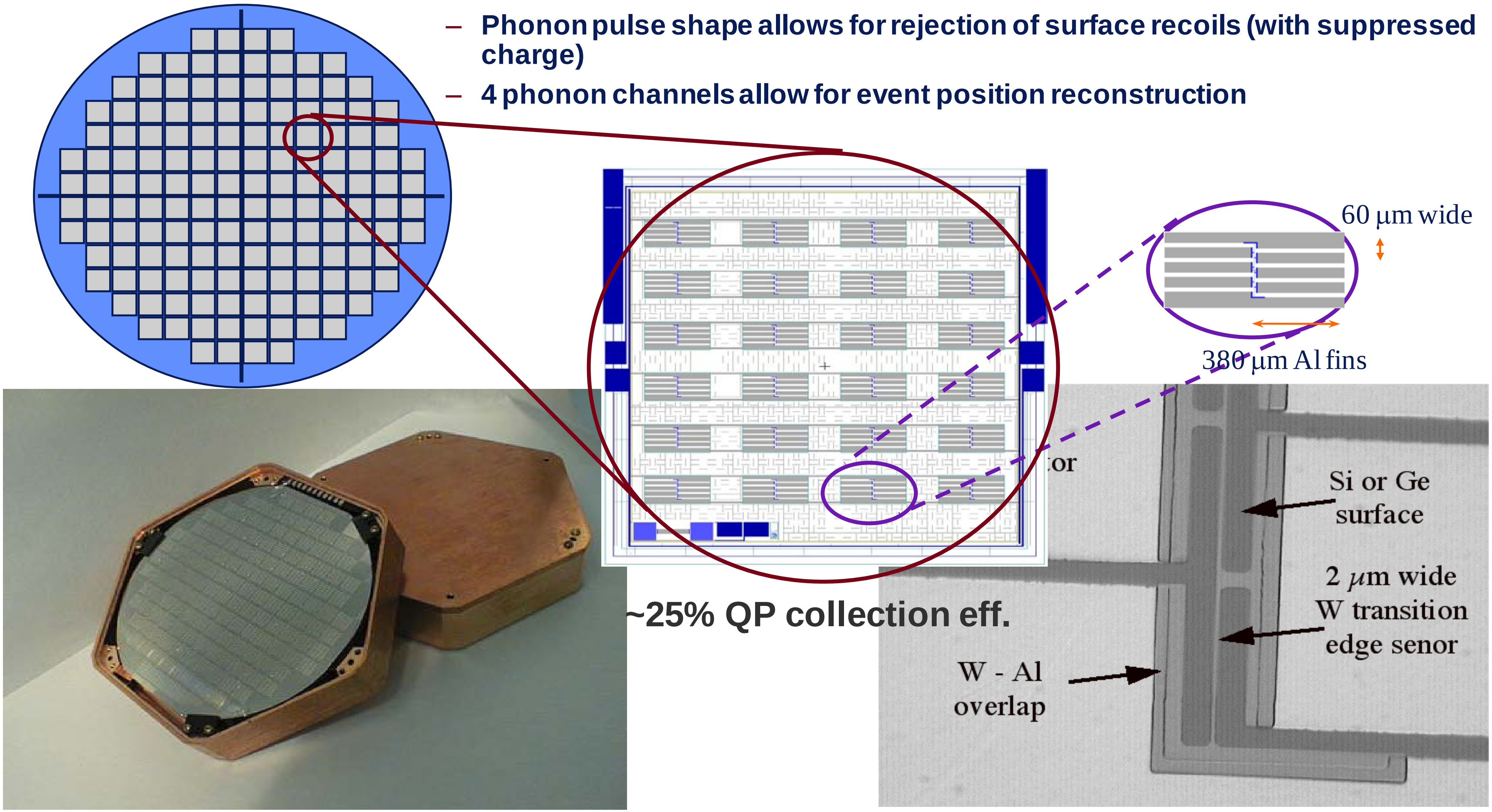
90% CL upper limits assuming standard halo, A^2 scaling



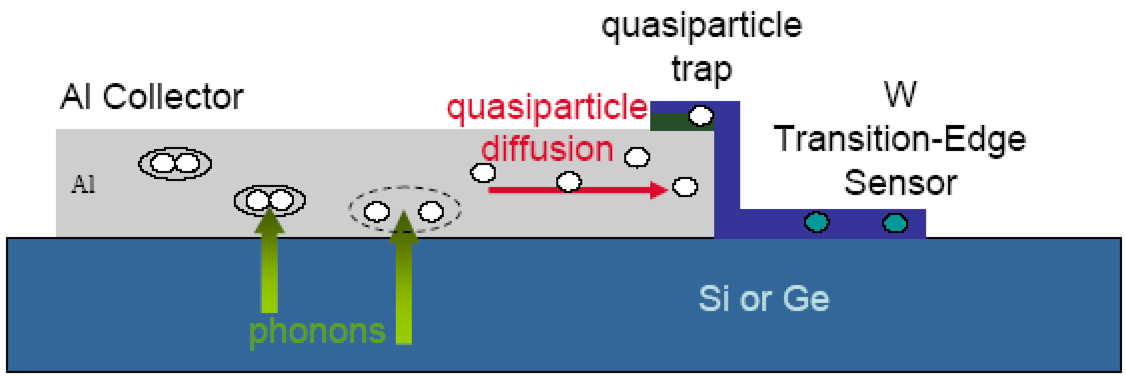
- **CDMS results consistent with all observed 'WIMP' events being neutrons.**
- **CDMS provided the most constraining upper limit of any experiment for WIMPs with 10-70 GeV mass in 2001.**
- **Expected sensitivity is for the expected case of 27 neutron events in Ge, and a background in Si of 7.2 electrons and 4.6 neutrons.**

Better: transition edge detectors

- TES's patterned on the surface measure the full recoil energy of the interaction
- Phonon pulse shape allows for rejection of surface recoils (with suppressed charge)
- 4 phonon channels allow for event position reconstruction

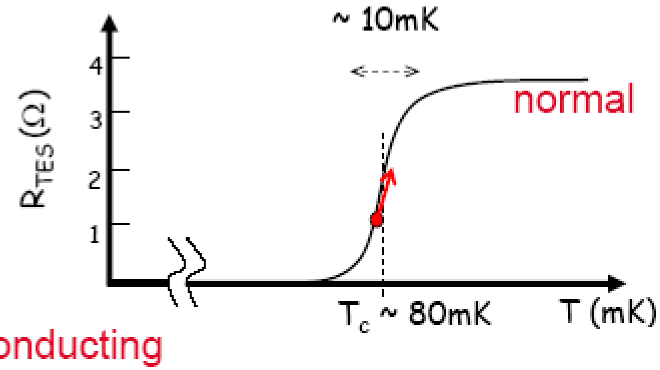


~25% QP collection eff.



W Transition-Edge Sensor:
a really good thermometer

- Measurement of athermal phonon signals maximizes information
- Fast pulse, excellent energy and timing resolution



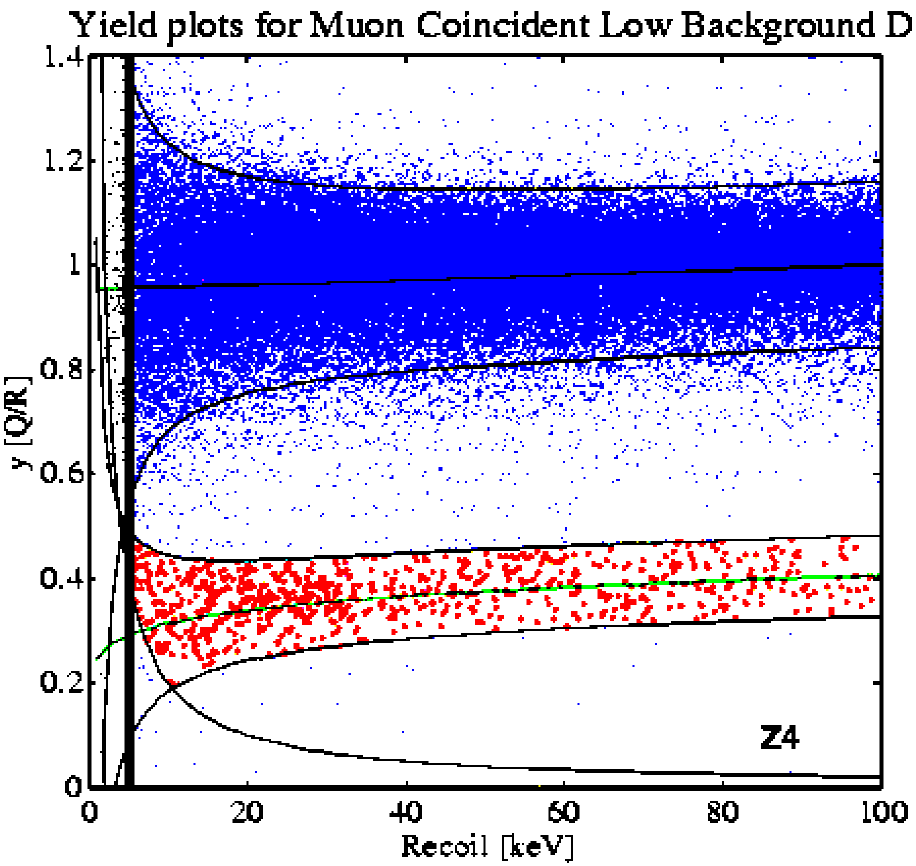
Yield plots for background data

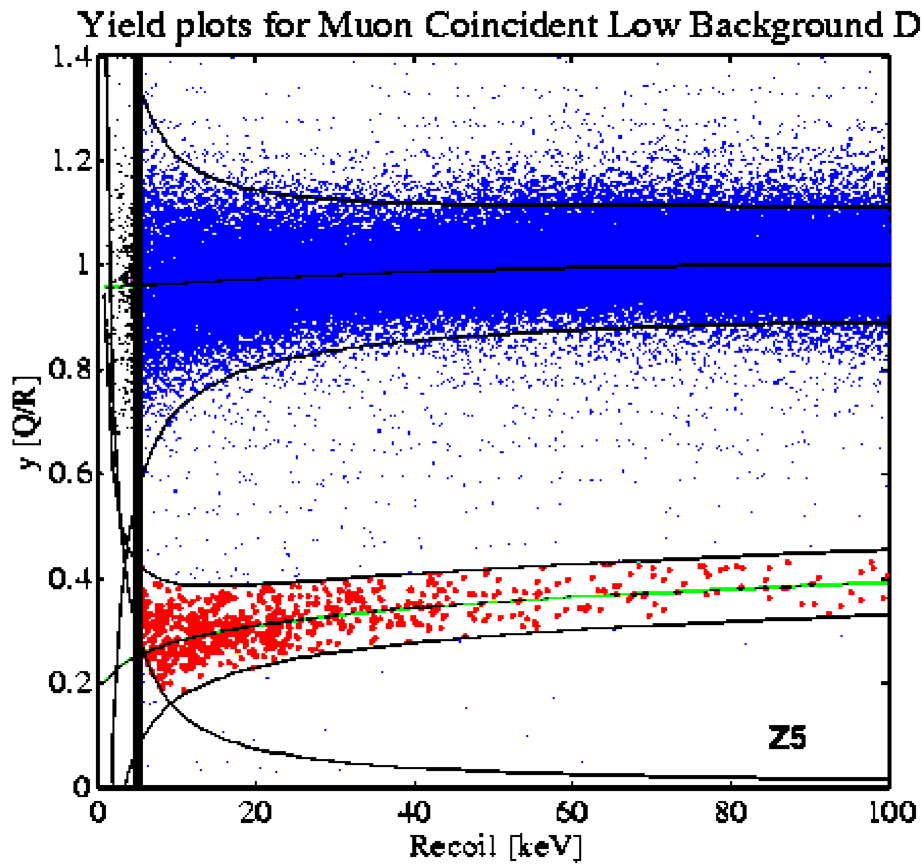
–Muon Coincident Data

–Gamma background band is the dominant feature

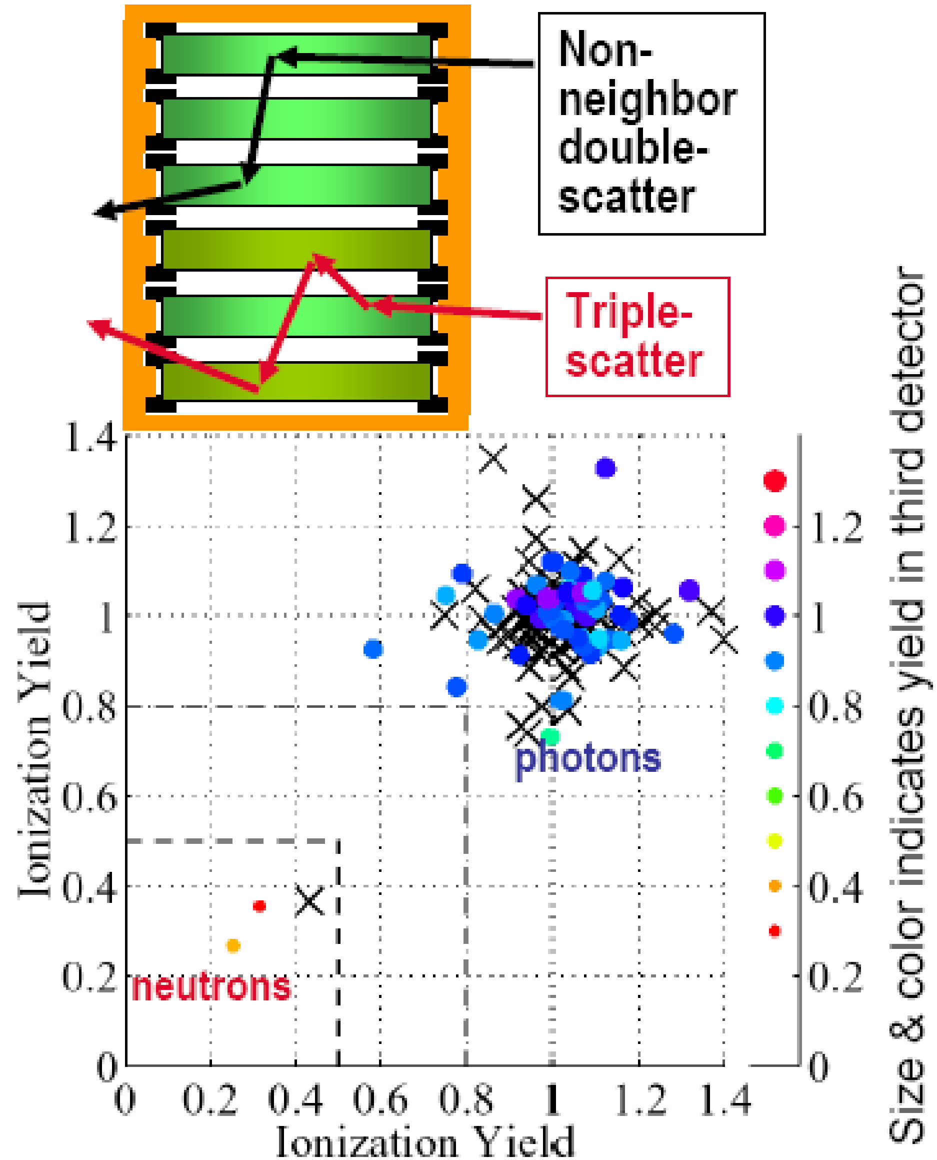
–Muon coincident neutrons populate the nuclear recoil band

–A number of '*in between*' events

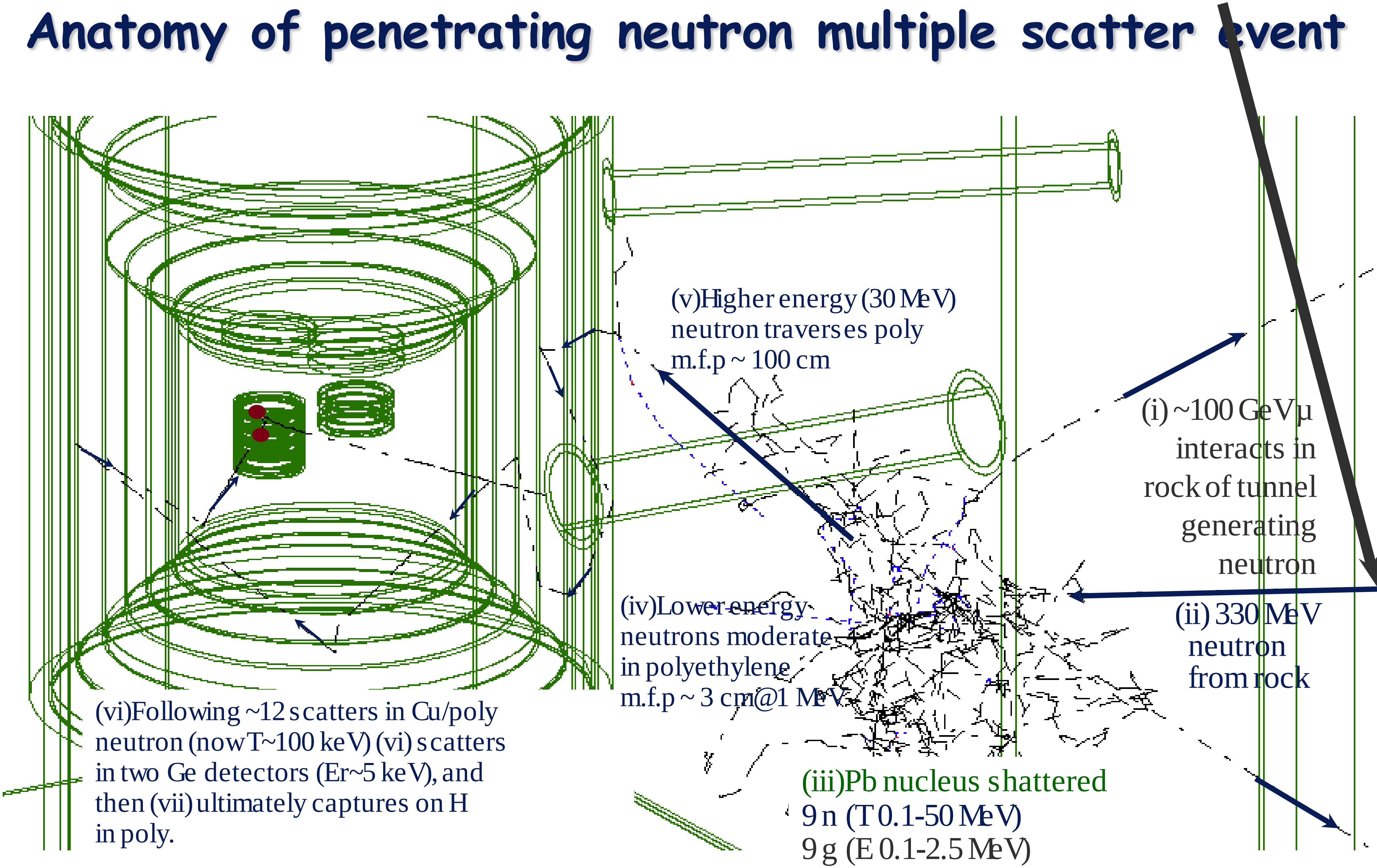




Background: Multiple neutron scatters



Anatomy of penetrating neutron multiple scatter event

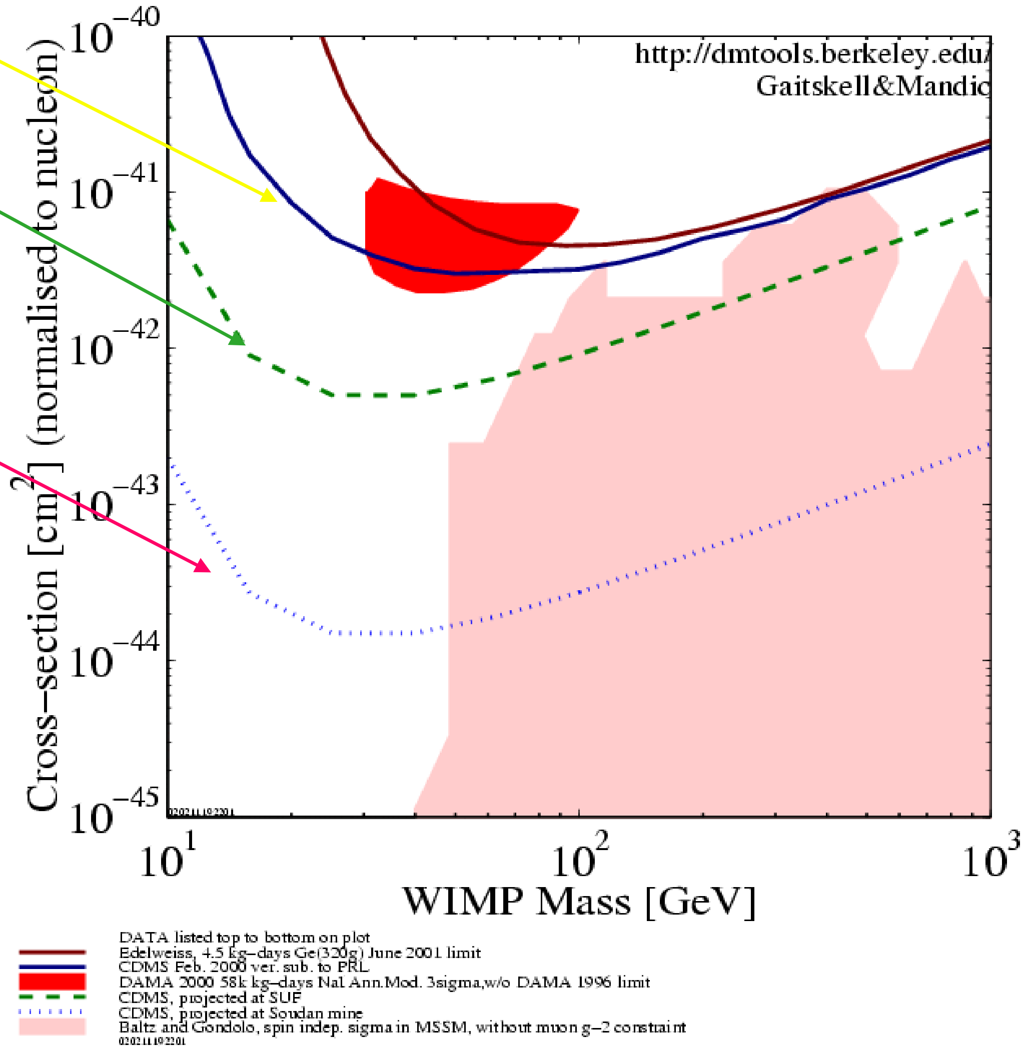


Current and Projected CDMS Limits

Current CDMS SUF R19 Limit

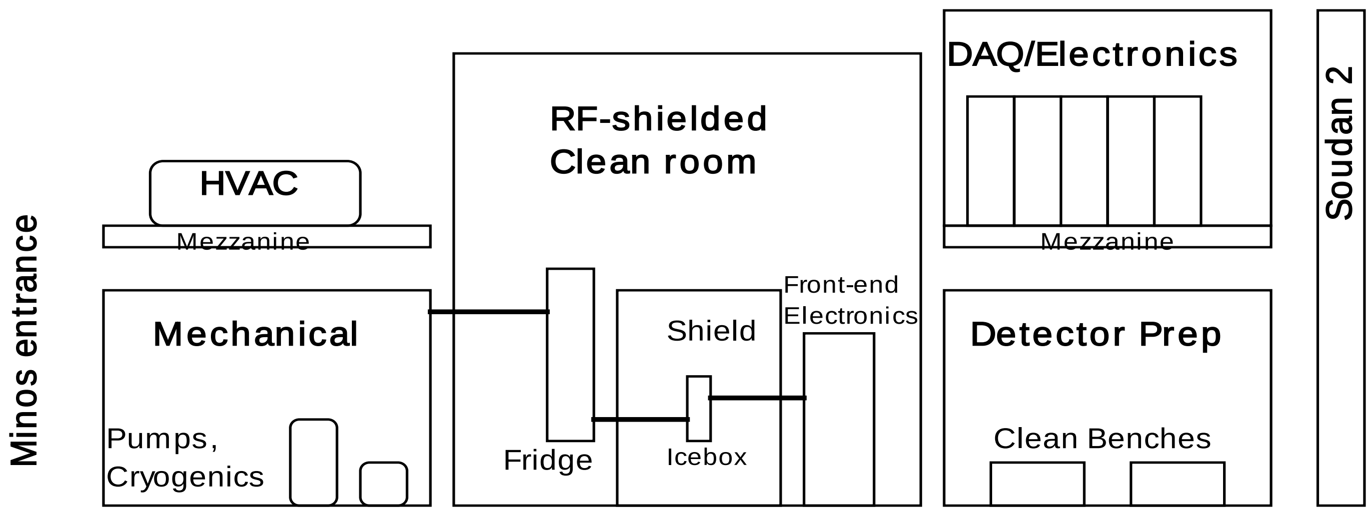
Projected CDMS SUF Limit

Projected CDMS Soudan Limit:
x 100 than present limit at SUF
(0.01 events/kg/keV/day).



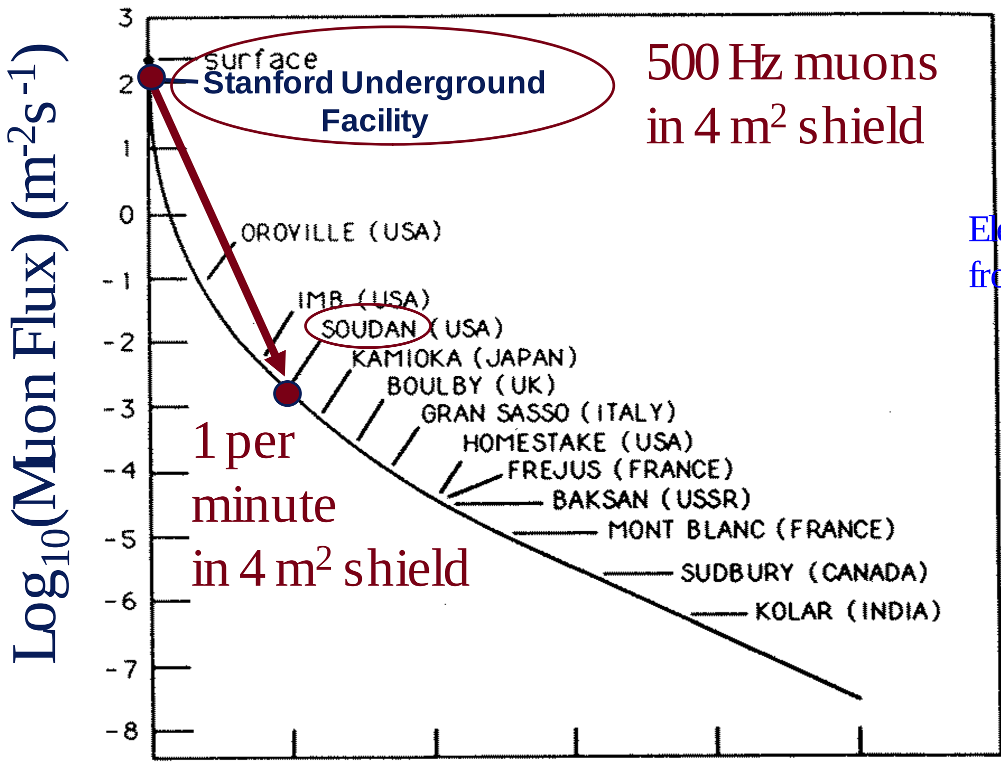
- Increase detector mass by 10.
- Go deep, Cosmics down by 1000.
- Gamma leakage down by 2. (o.k.)
- Beta contamination down by 20. (?)

CDMS II Experimental Enclosure

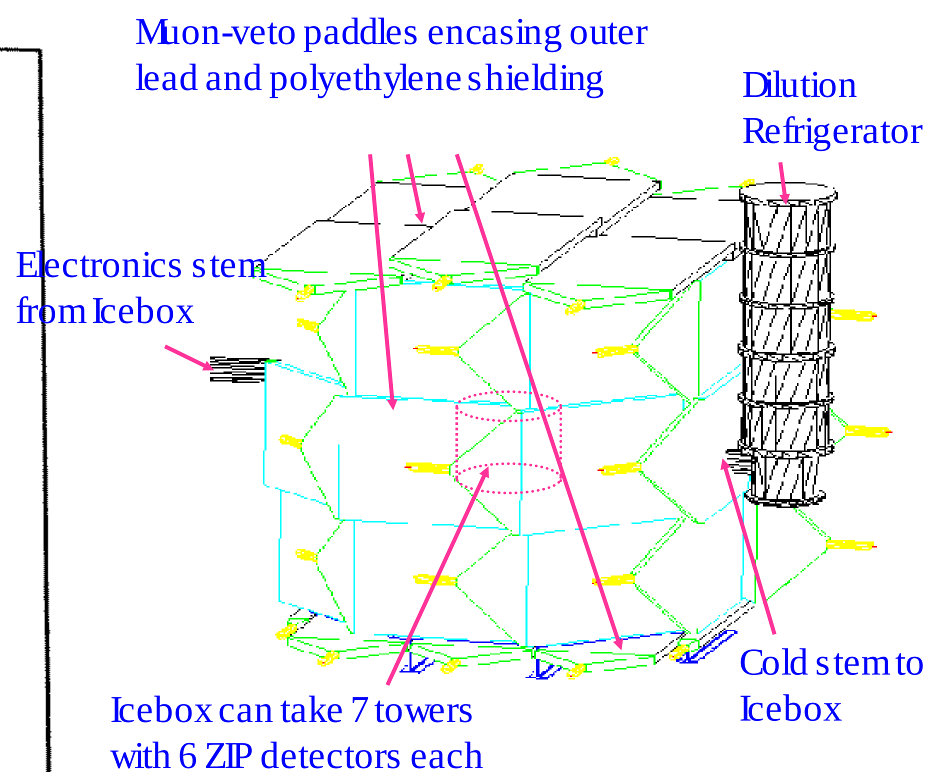


CDMS II at Soudan mine

Depth of 2000 mwe reduces neutron background from ~1 / kg / day to ~1 / kg / year

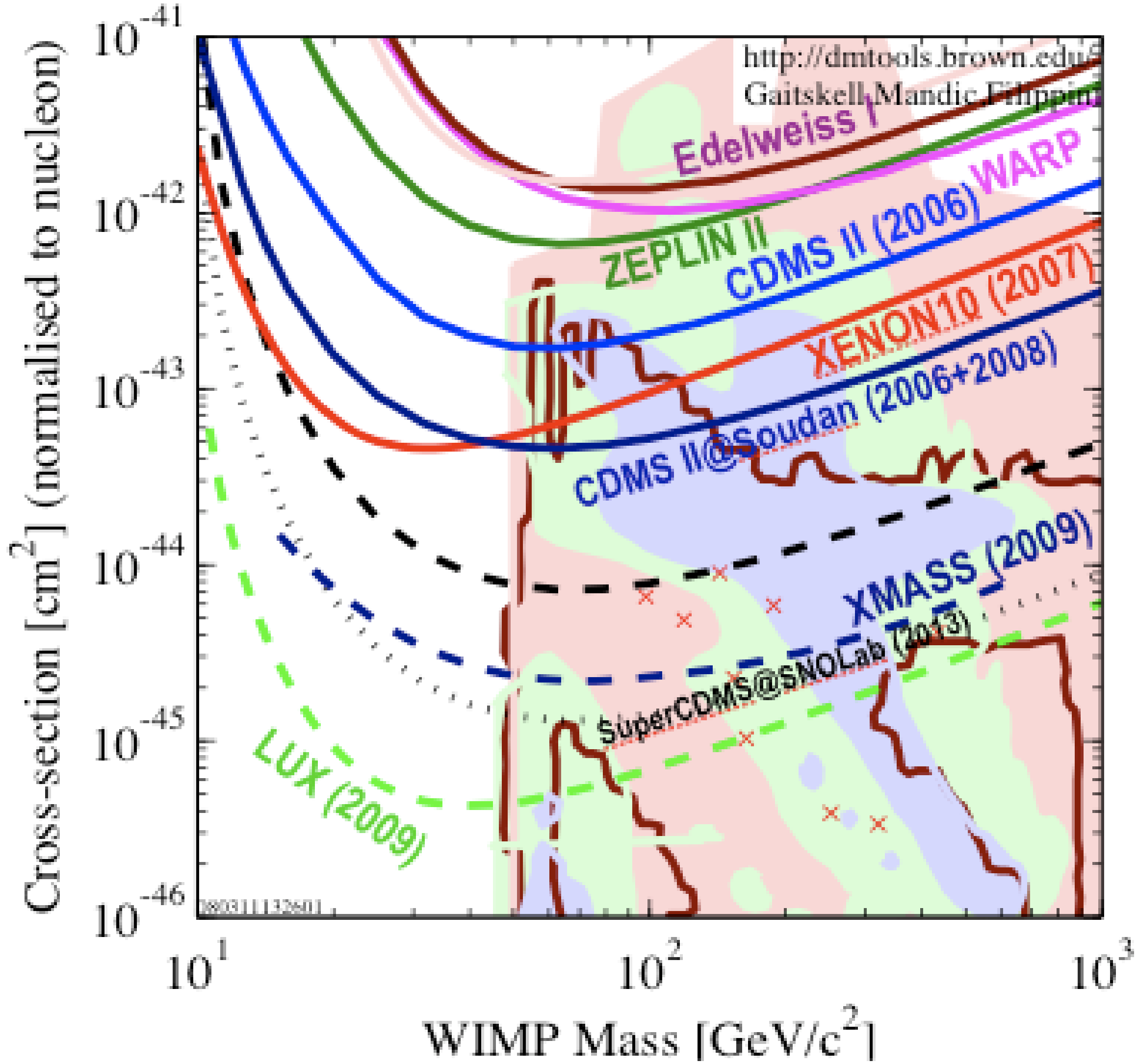


Depth (mwe)

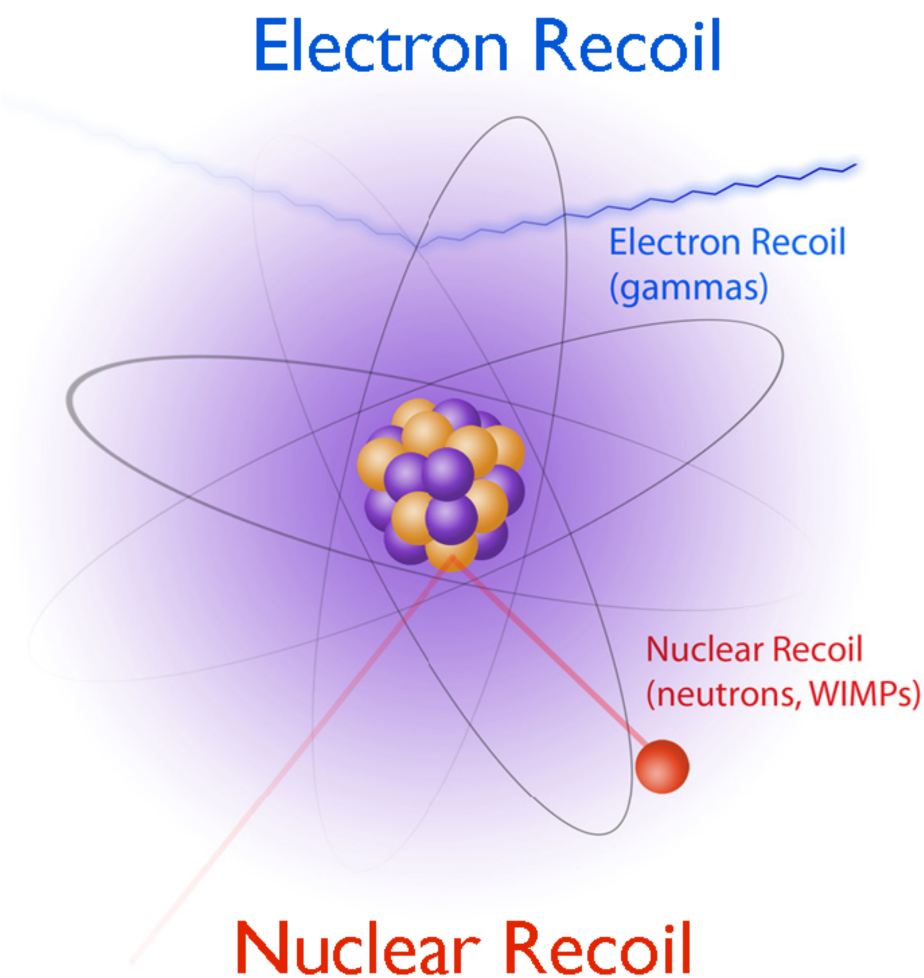


Experimental apparatus

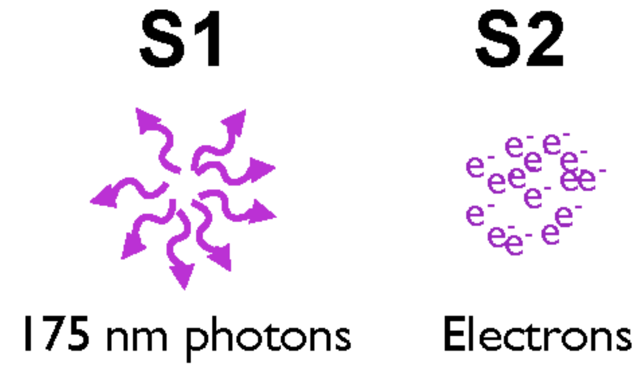
Today’s Dark Matter Landscape

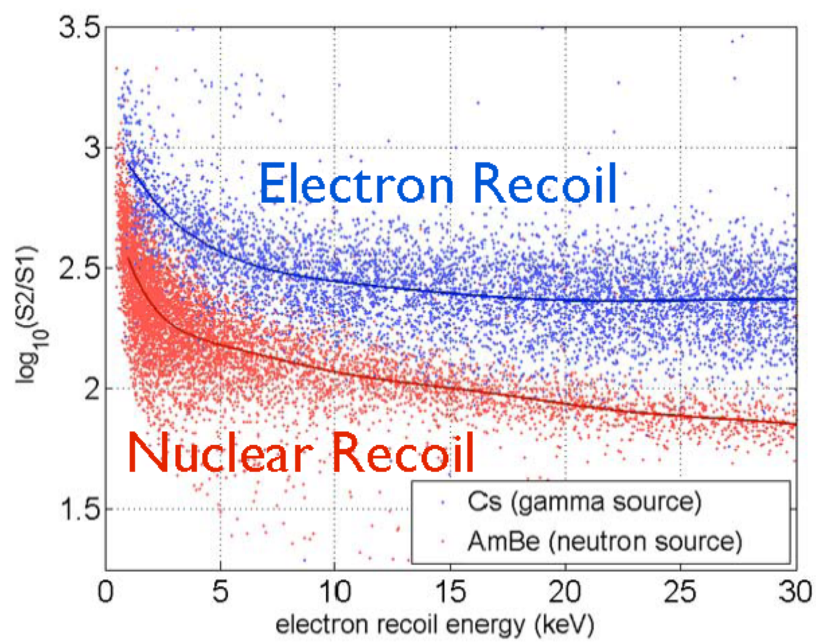


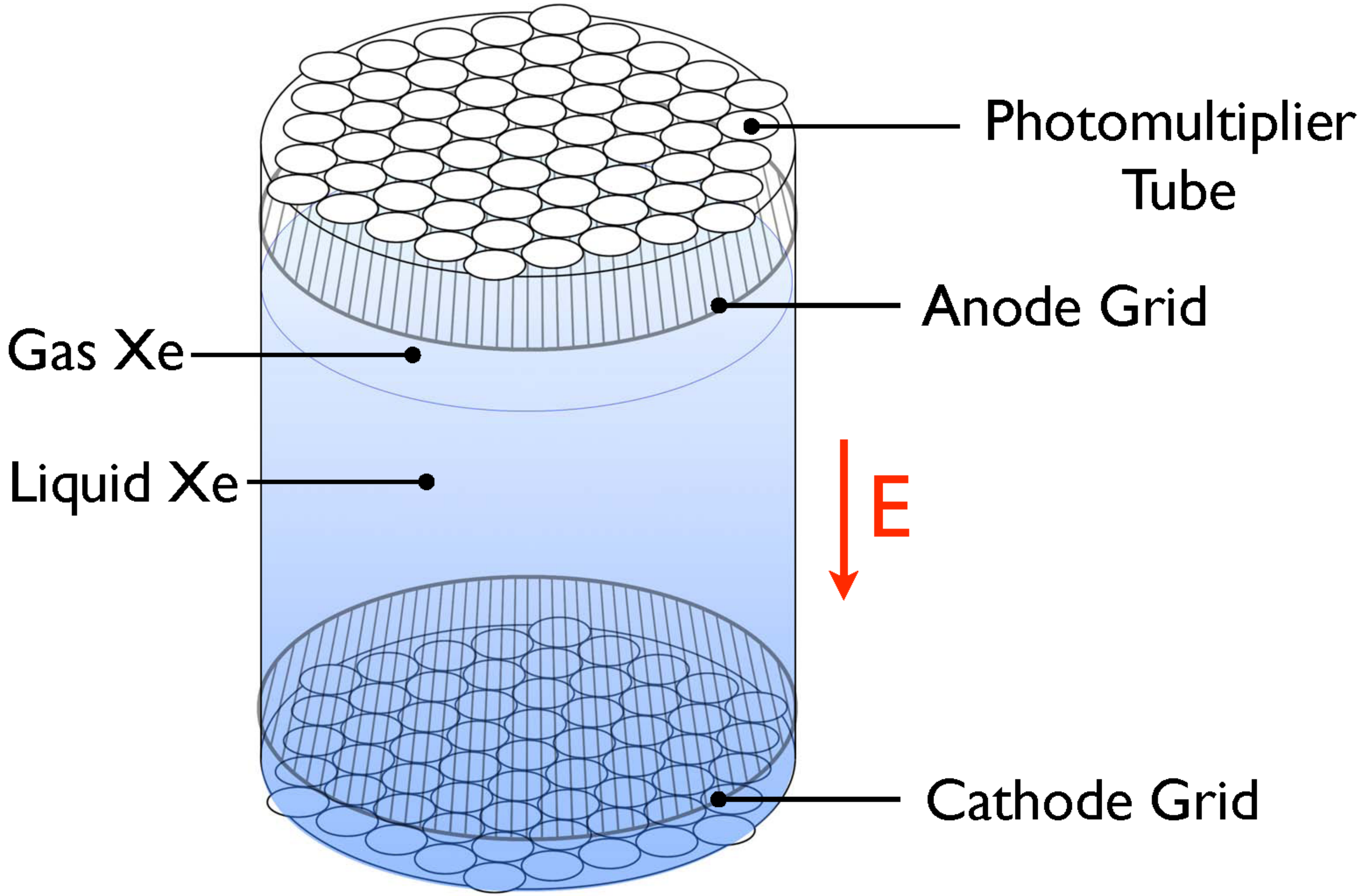
Xenon Signal



Two signals:

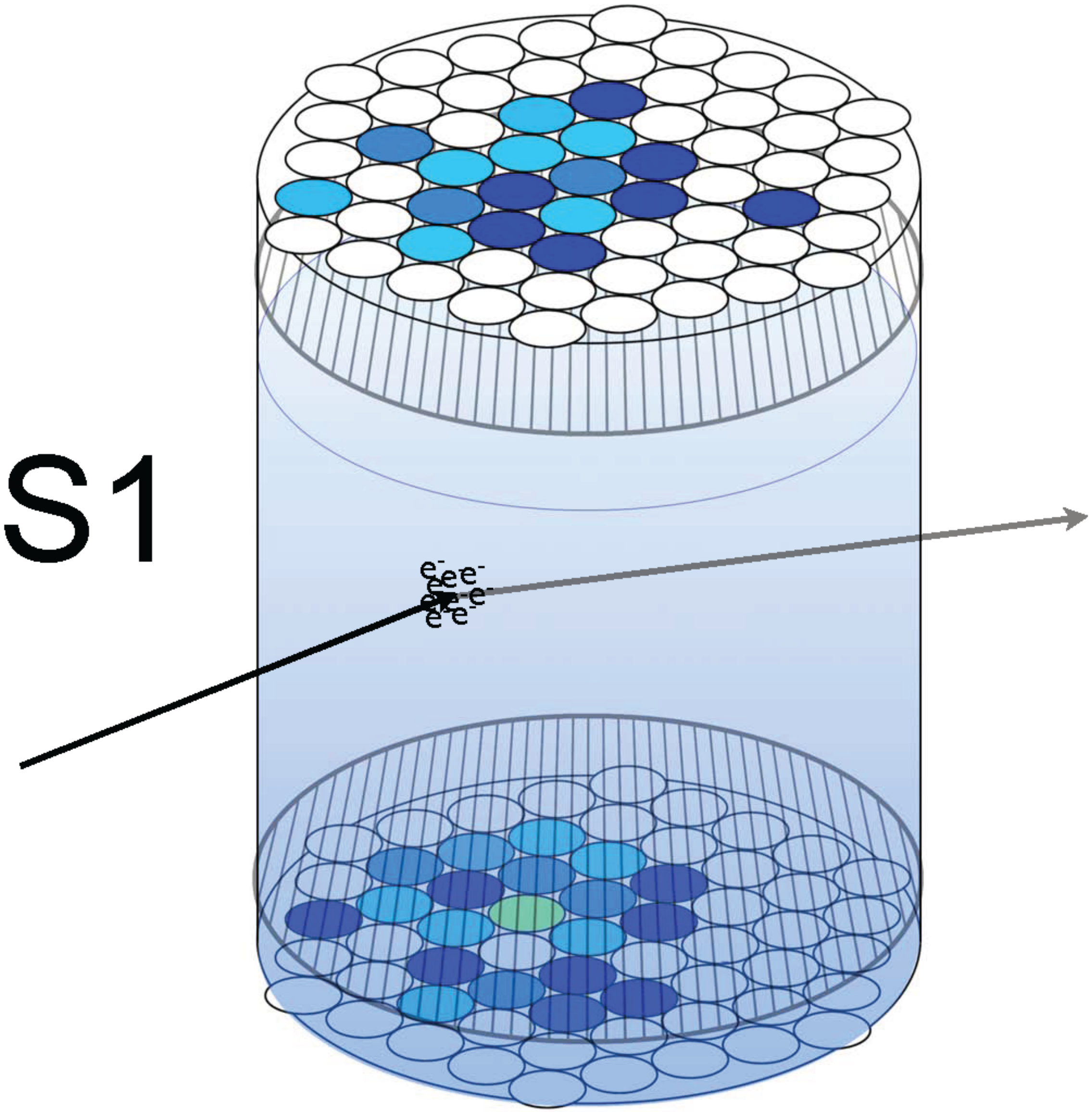


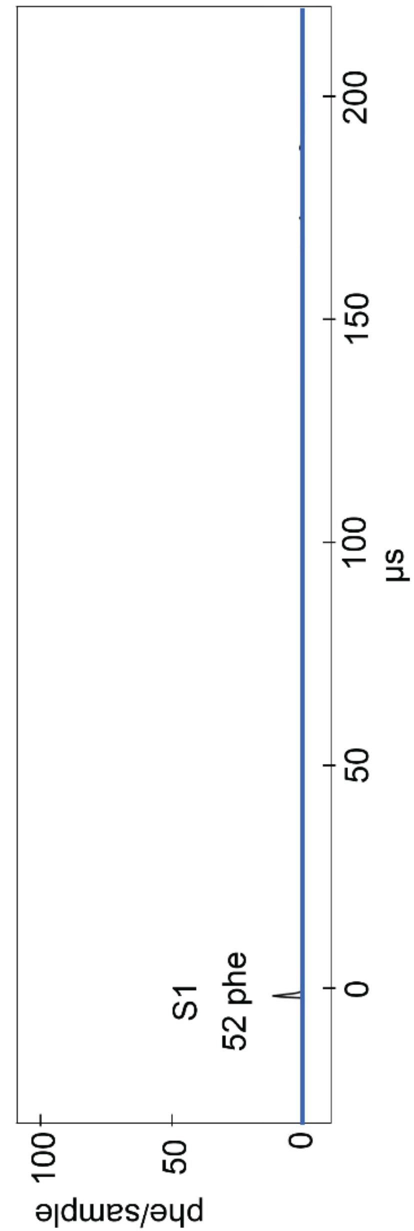




Photomultiplier Tube
Anode Grid
Gas Xe
Liquid Xe
E
Cathode Grid

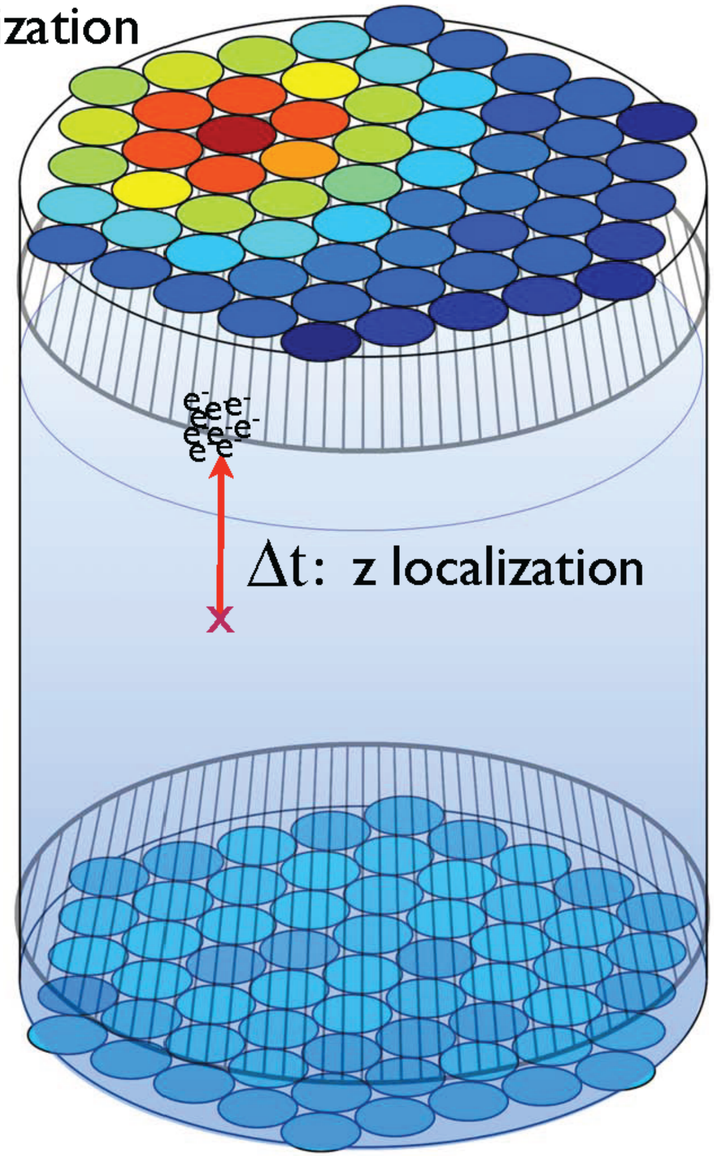
S1

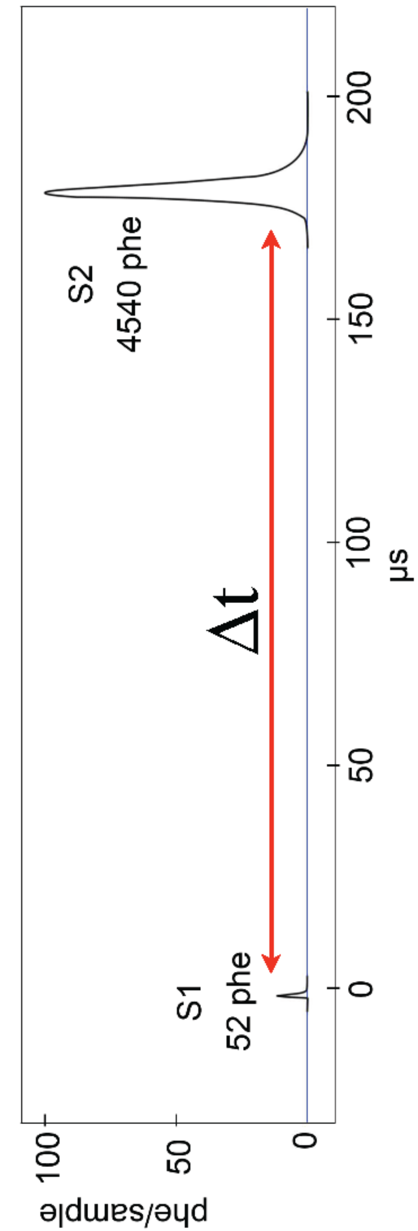




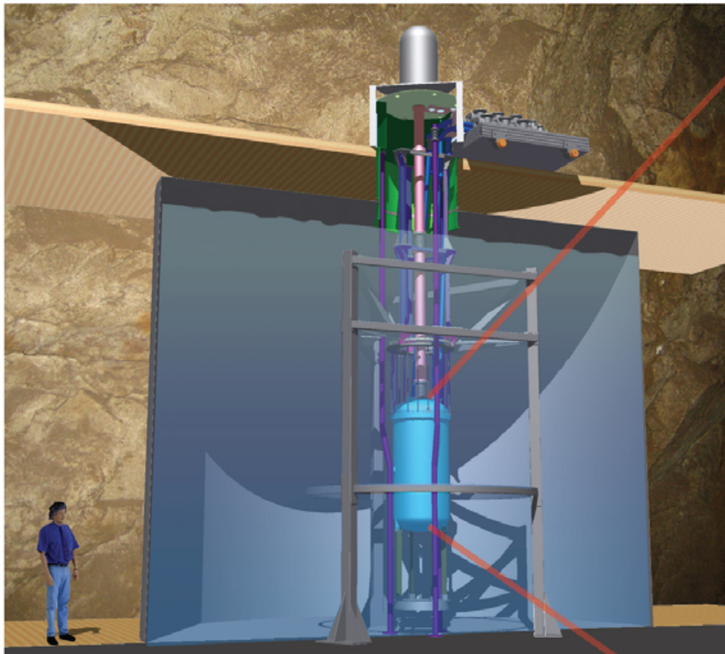
top hit pattern:
x-y localization

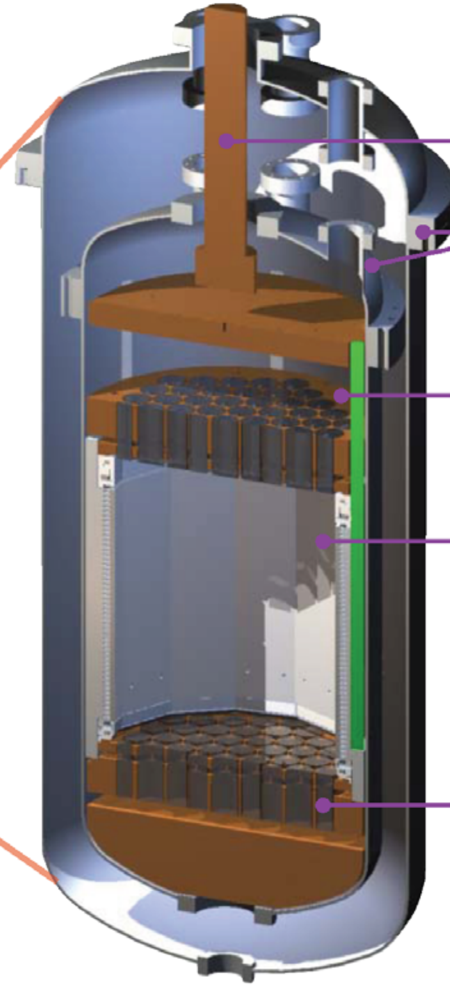
S2



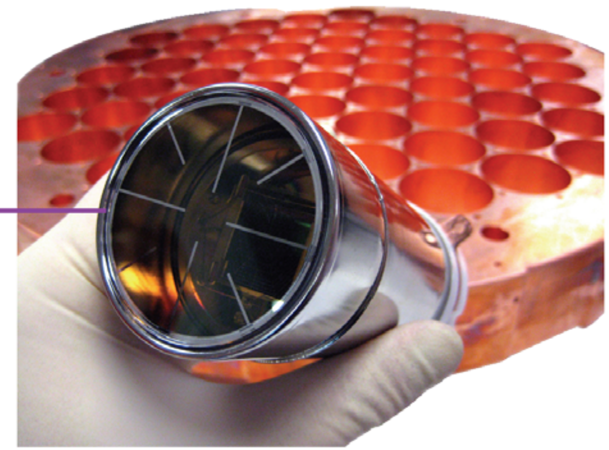


The LUX Experiment





- 350 kg LXe detector
- 122 PMTs (2" round)
- Low-background Ti cryostat
- PTFE reflector cage
- Thermosyphon used for cooling (>1 kW)



2" Hamamatsu R8778
Photomultiplier Tubes (PMTs)