Superconducting Transition Edge Sensors for Particle Astrophysics and Cosmology

International Symposium on the Development of Detectors for Particle, Astro-Particle and Synchrotron Radiation Experiments

SLAC, Stanford University, CA, April 4, 2006

Blas Cabrera - Stanford University & KIPAC

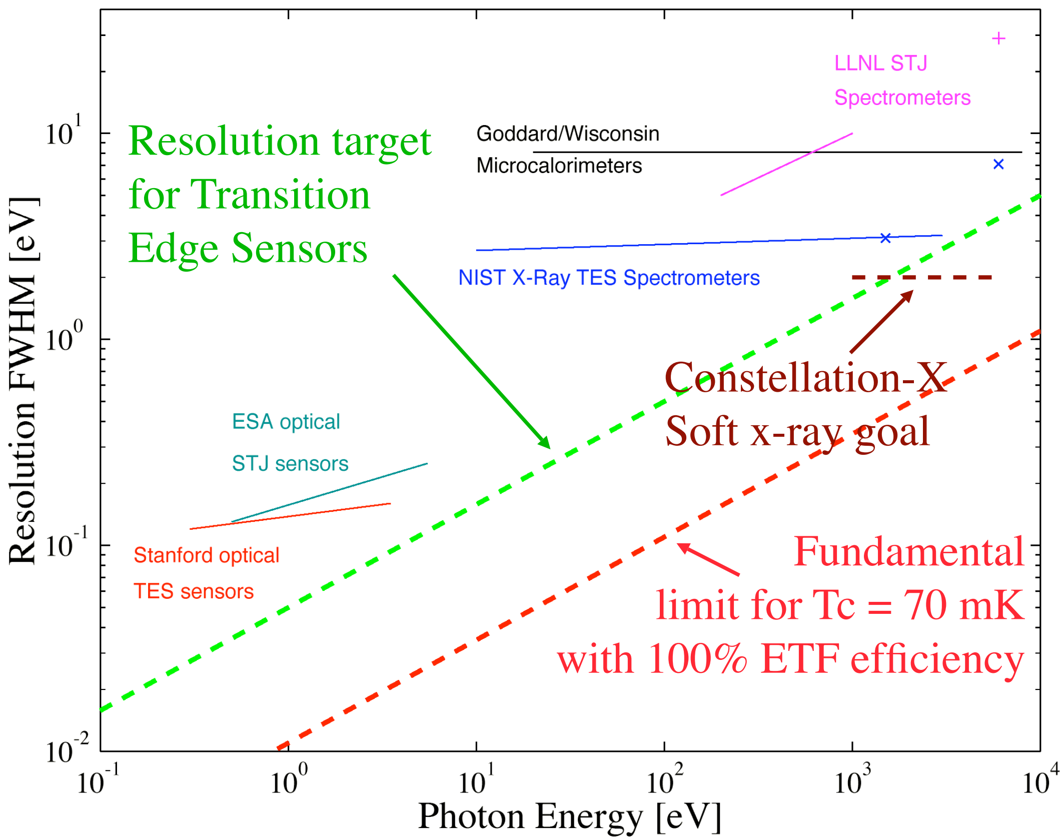
CDMS Detector Fabrication: Paul Brink, Astrid Tomada, Larry Novak, Matt Pyle
(collaborators: NIST, Boulder, Kent Irwin; UCD, Martin Huber)
Optical Detectors: Roger Romani, Jen Burney, TJ Bay, Joelle Barral
(collaborators: NIST, Boulder, Sae Woo Nam, Aaron Miller)
X-Ray Detectors: Steve Kahn, Steve Leman, Bill Craig
(collaborators: Lockheed, Palo Alto, Bob Stern, Steve Deiker, Dennis Martinez)

Overview of TES applications (*this talk)

- CMB with polarization: A. Lee (UCB) and A. Lange (Caltech)
- Sub-mm astronomy: SCUBA 2: more than 10,000 TES pixels
  - NIST delivering TES arrays
- *Near IR/optical/near UV ground & space: Stanford/NIST
  - casualty of NASA downscaling R&D for future instruments
- X-Ray astrophysics: NIST/Goddard; Joel Ullom (next talk)
- *X-Ray macropixel: Stanford/Lockheed/NIST
- Dark matter searches:
  - *CDMS collaboration: TES sensors on Ge and Si crystals
  - *SuperCDMS future; Walter Ogburn (#147/150 poster)
  - CRESST search uses SPT with SQUID readout
  - Large negative ion TCP: Jeff Martoff (#188 poster)

TES Single Photon Detectors

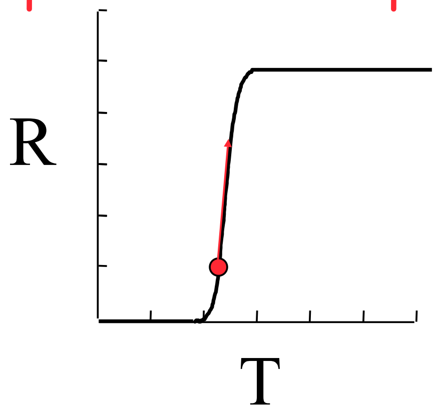
- **Demonstrated Sensitivity with TES**



- NIST Mo/Cu TESs
2.37 eV FWHM @ 6 keV
- Goddard Mo/Au TES
3.7 eV FWHM @ 3.3 keV
- NIST Mo/Cu TES
2.0 eV FWHM @ 1.5 keV
- Stanford W TES
0.12 eV FWHM @ 1.5 eV
- A factor of 2-3 improvement is likely with an additional factor of 4 to the fundamental limit

Superconducting Transition Edge Sensors

- Steep Resistive Supeconducting Transition



- W $T_c \sim 70$ mK
- 10-90% <1 mK

unitless measure
of transition width

$$\alpha = \frac{dR}{dT} \Big/ \frac{R}{T}$$

- Voltage bias is intrinsically stable

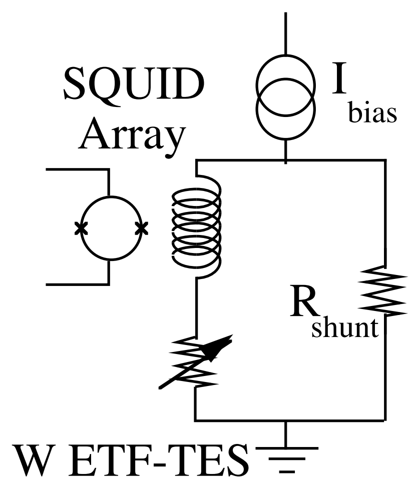
The Joule heating produced by bias

$$P_J = \frac{V_B^2}{R} \quad \Rightarrow \quad P_J \downarrow \text{ when } R \uparrow$$

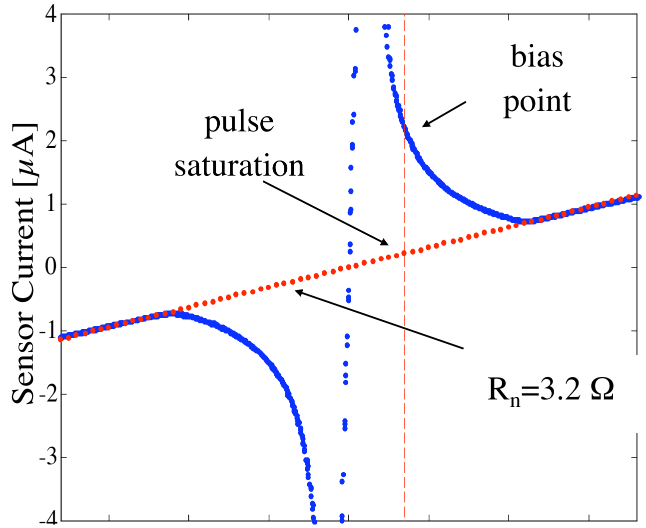
is stable whereas for current bias

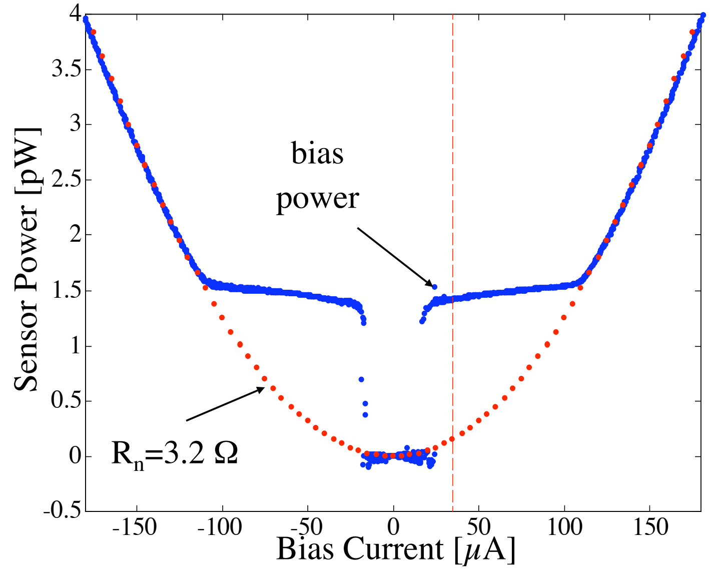
$$P_J = I_B^2 R \quad \Rightarrow \quad P_J \uparrow \text{ when } R \uparrow$$

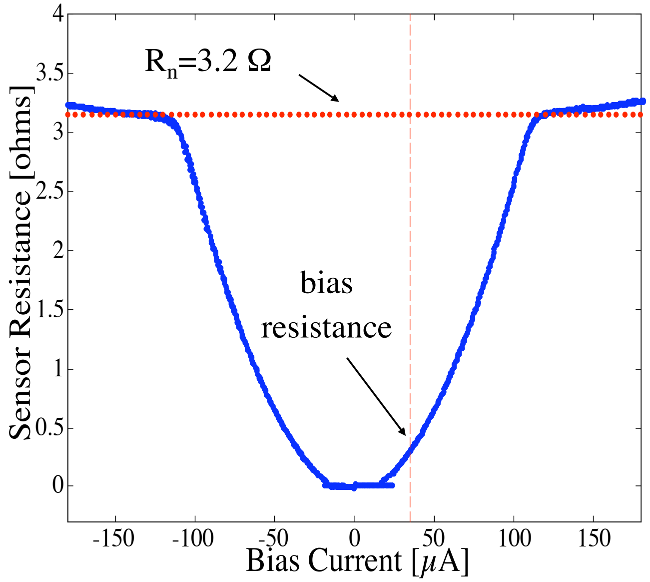
which is intrinsically unstable



Characterize Performance of TES

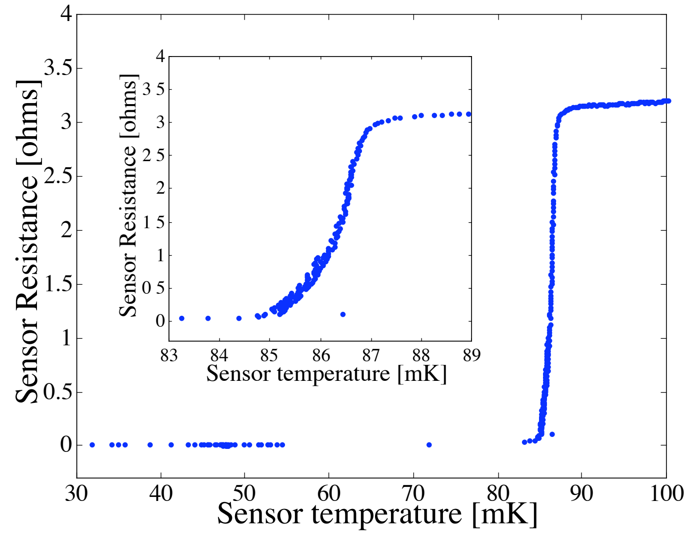






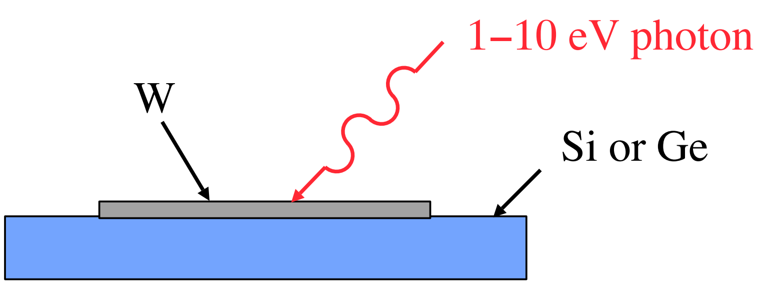
We calculate transition width from power curve using

$$P_J = \Sigma\left(T_e^5 - T_{ph}^5\right)$$

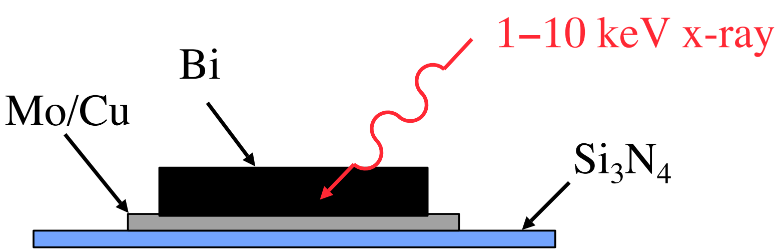


Three Types of Detectors

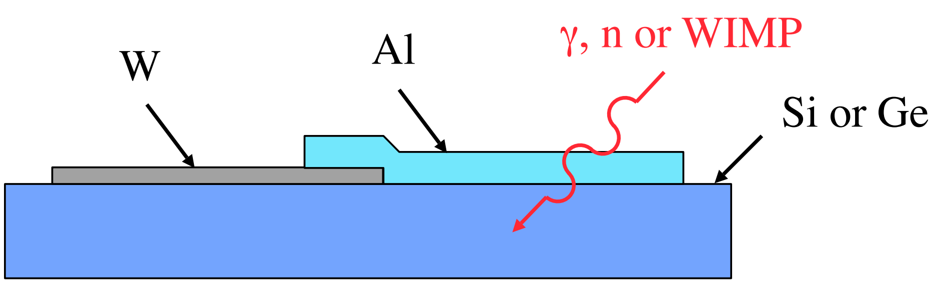
- Direct absorption of photon in TES (e. g., IR-optical-UV photons)



- Photon absorber in electical contact with TES (e. g., x-ray detectors)

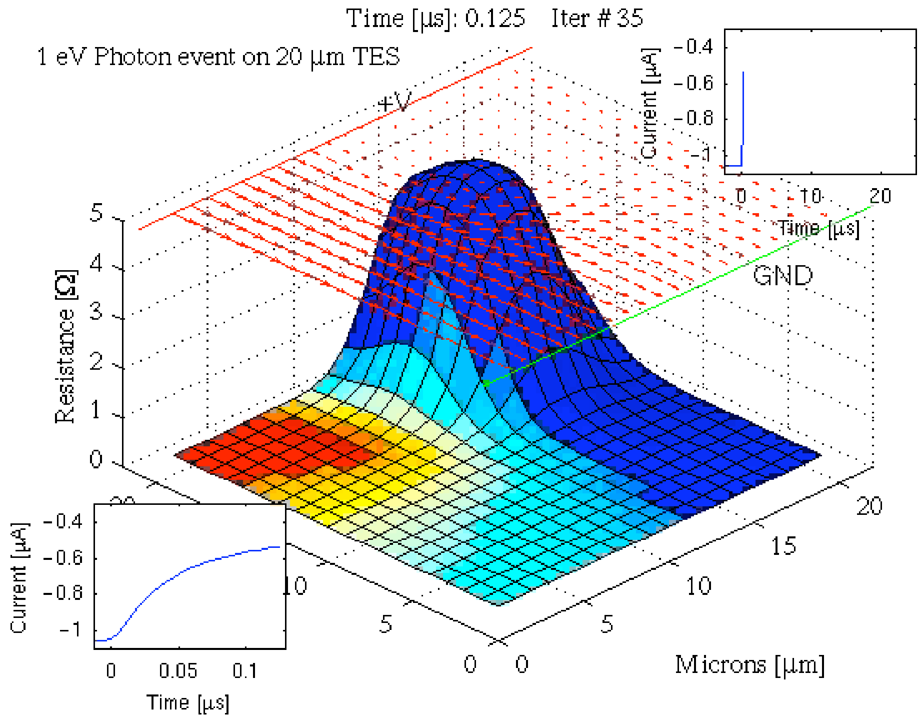


- Large mass absorbers generate phonons which are converted into quasiparticles which diffuse to the TES (e. g., dark matter detectors)



TES Simulation

- Optical photon absorbed in TES (Tali Figueroa)

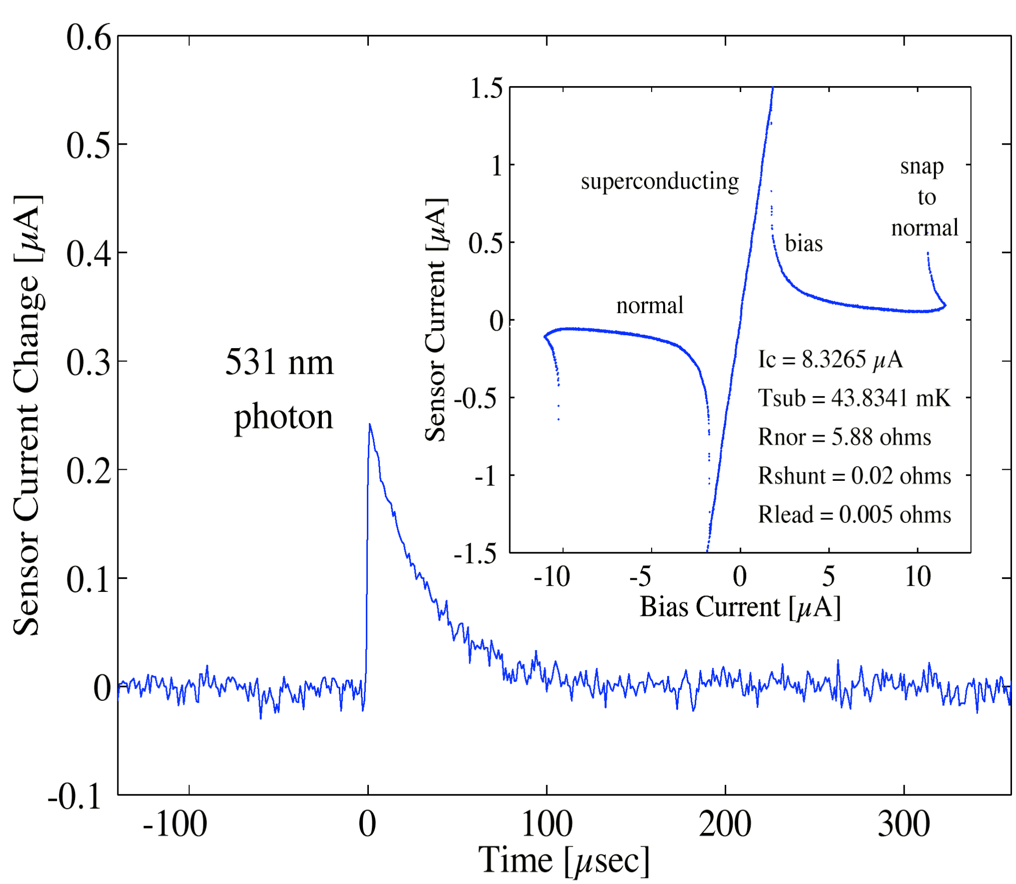


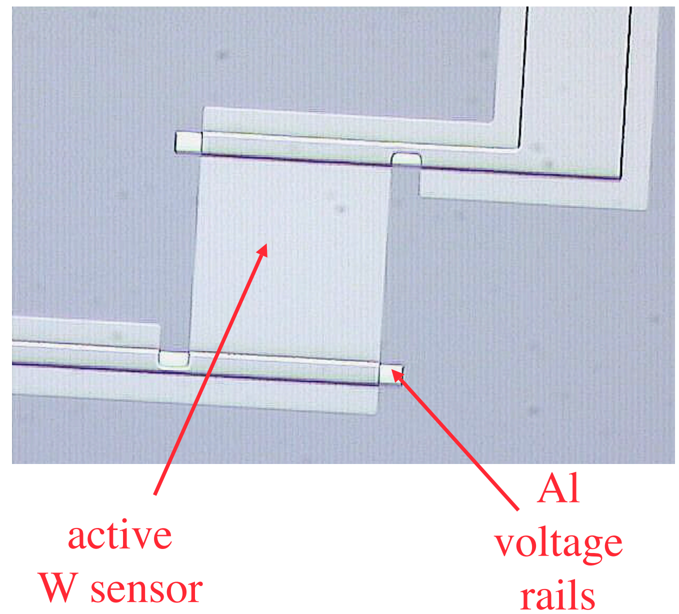
Science Objectives for Optical/UV TESs

- Time variable sources
  - White dwarf binaries, neutron stars, pulsars
  - Black hole binaries, and supernovae
- Distant galaxies
  - Direct redshift measurements for faint galaxies
  - Highest photon efficiency
- Imaging UV spectroscopy
  - R~300 for nearby sources
  - Search for ionized clouds as dark baryonic matter

Optical Photon Detectors

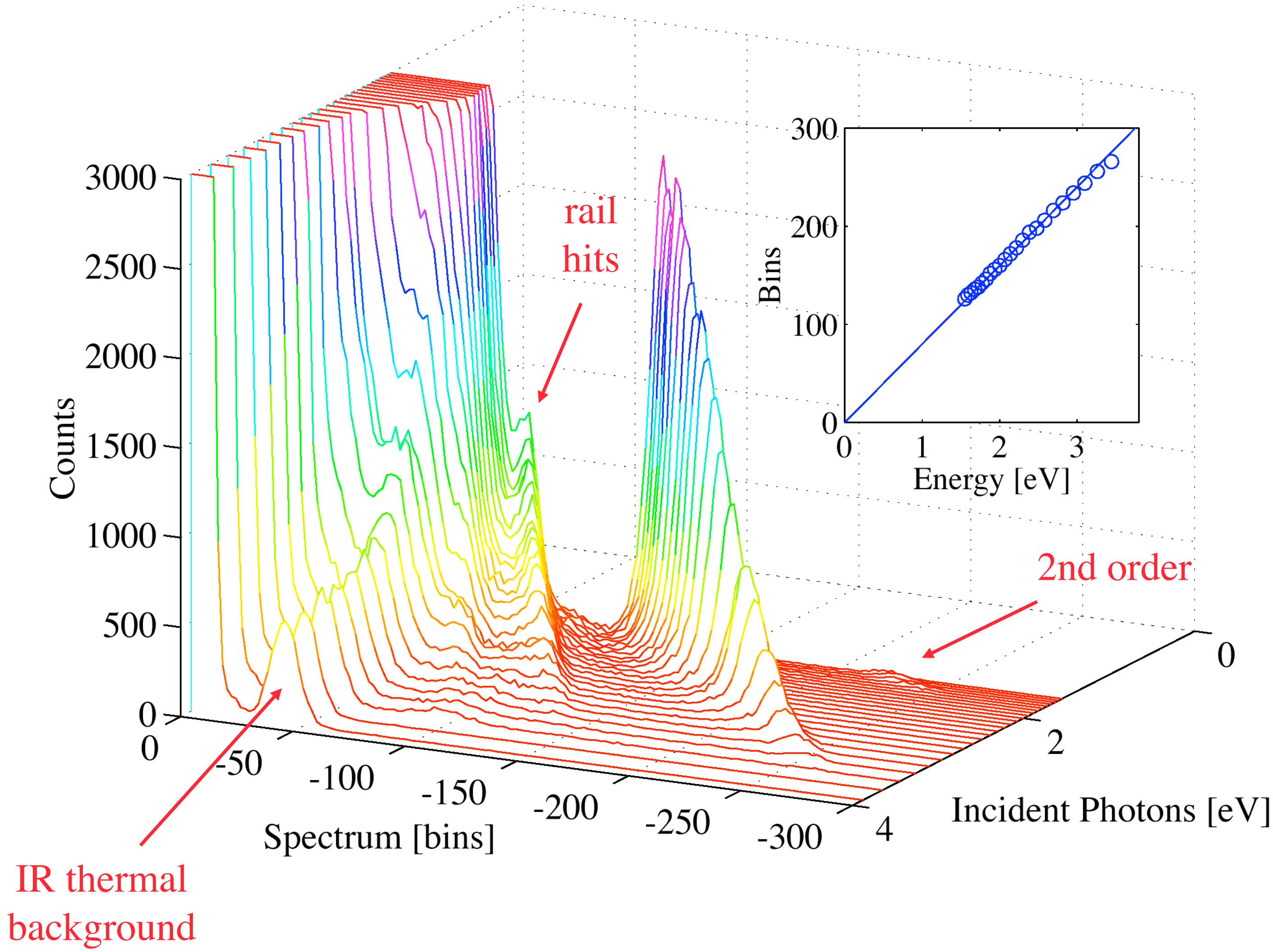
- **Demonstration of W TES sensitivity**



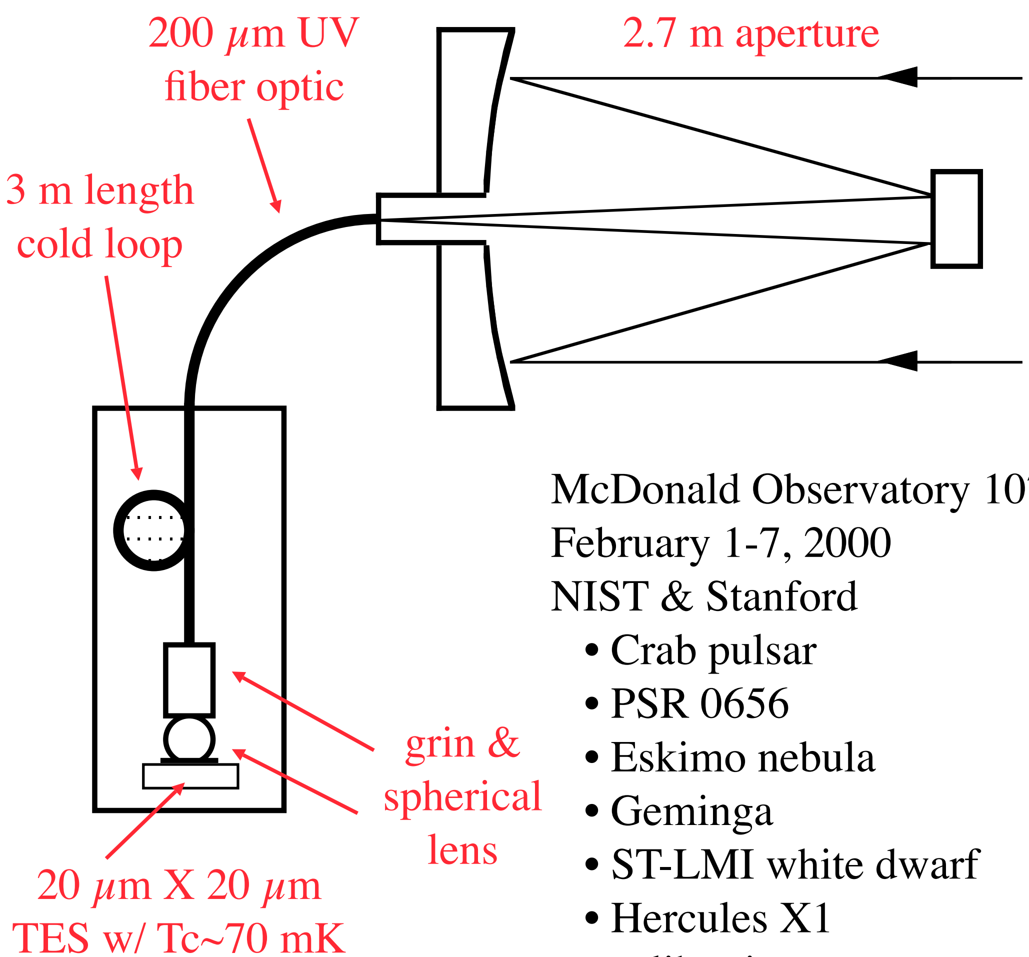


Appl. Phys. Lett. 73, 735 (1998)
B. Cabrera, R. Romani, A. J. Miller
E. Figueroa-Feliciano, S. W. Nam

Monochromator Calibrations



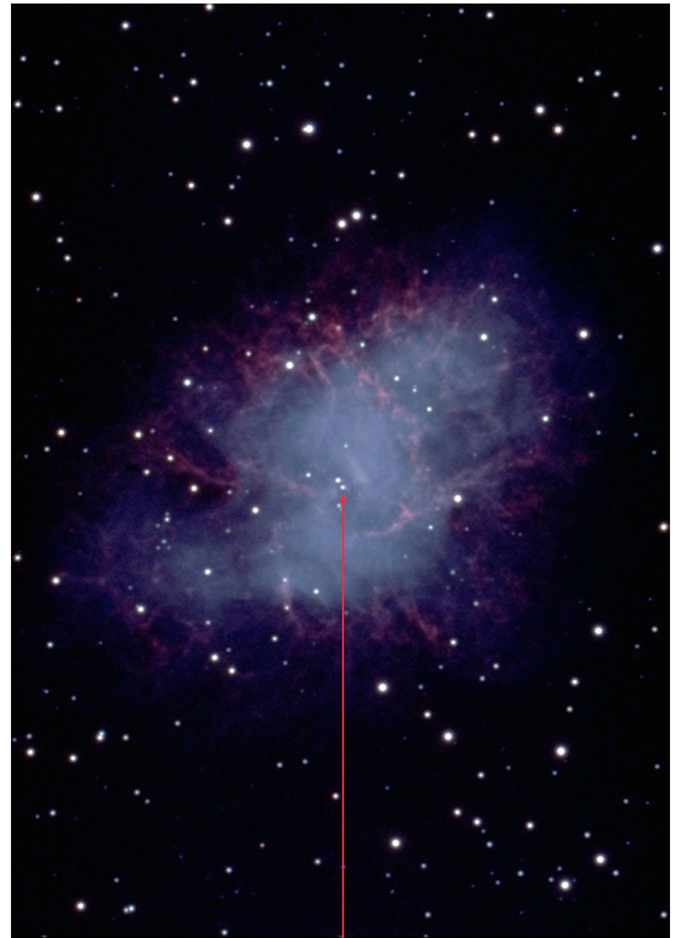
McDonald Observatory 107" Demonstration



Dilution refrigerator
35 mK base

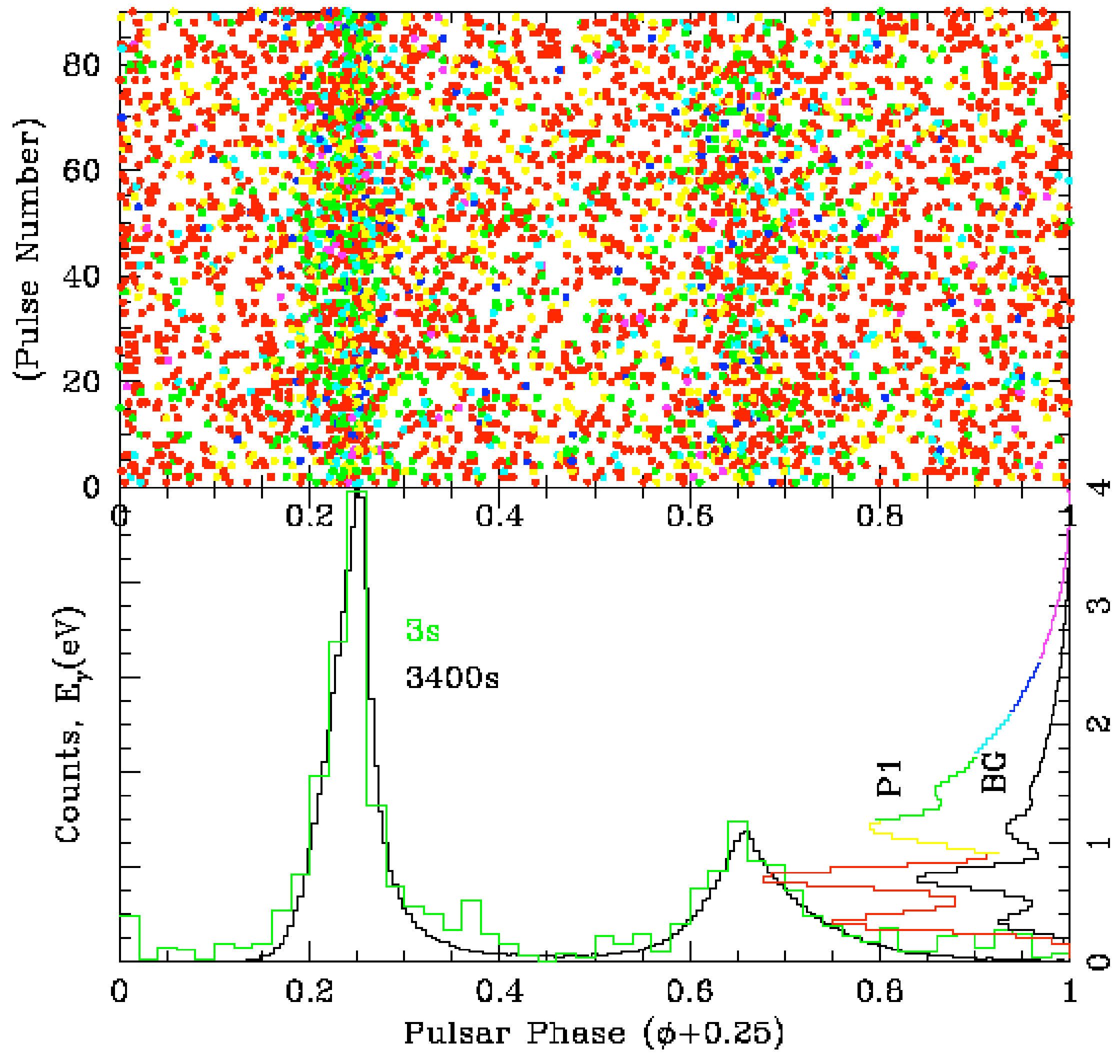
McDonald Observatory 107"
February 1-7, 2000
NIST & Stanford

- Crab pulsar
- PSR 0656
- Eskimo nebula
- Geminga
- ST-LMI white dwarf
- Hercules X1
- calibration stars

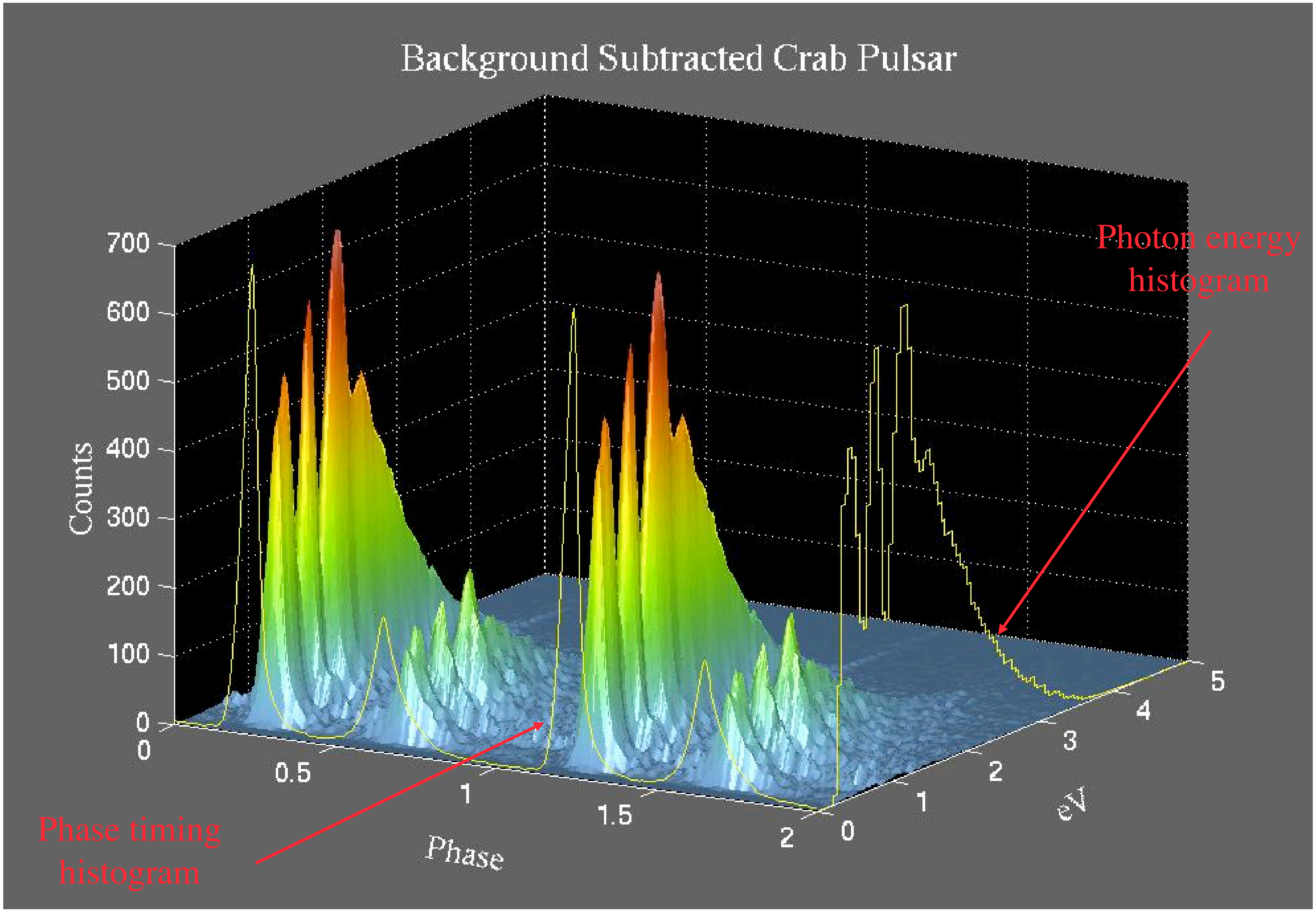


Crab pulsar

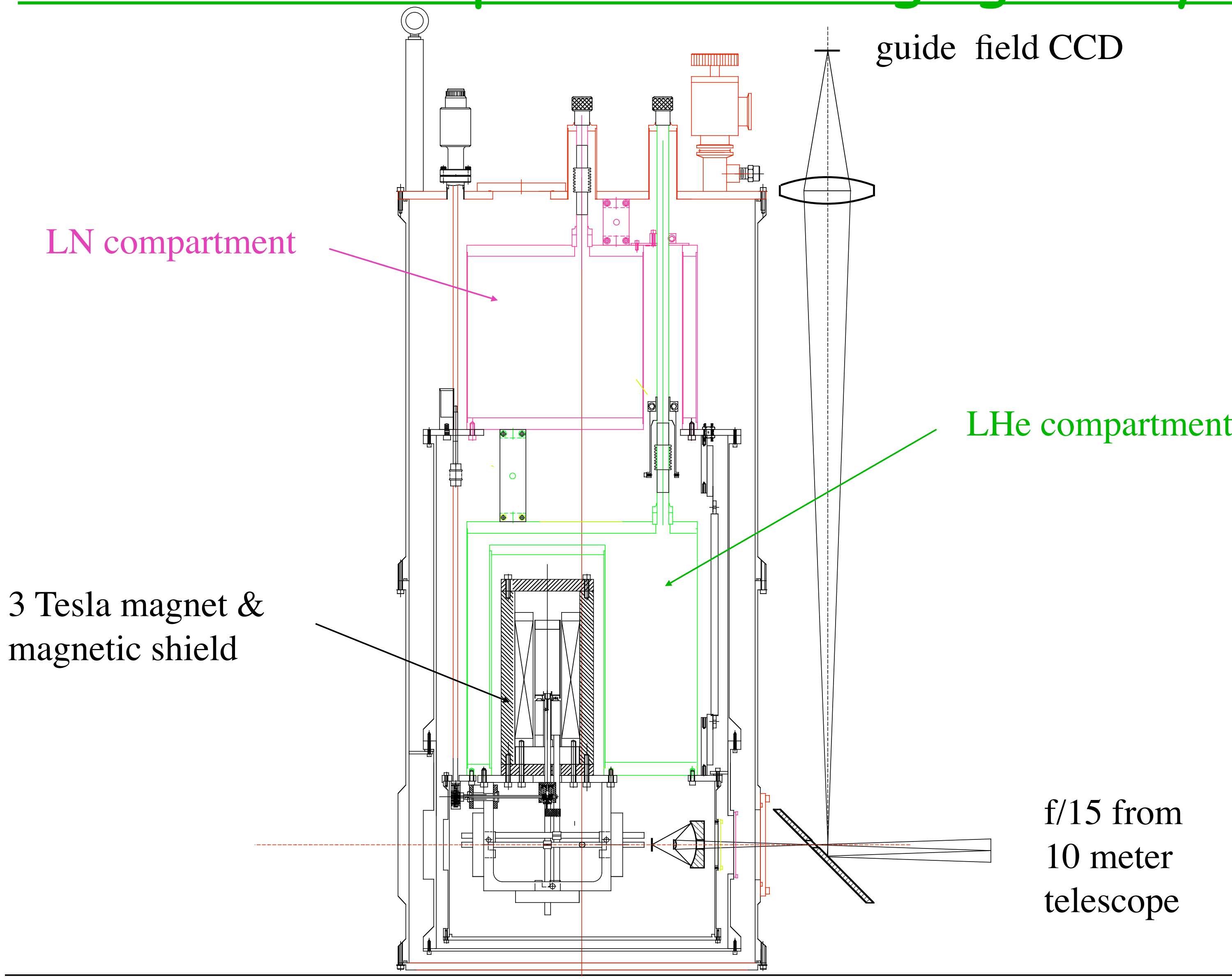
Crab Pulsar Data from McDonald 107"



Background Subtracted Energy vs Phase

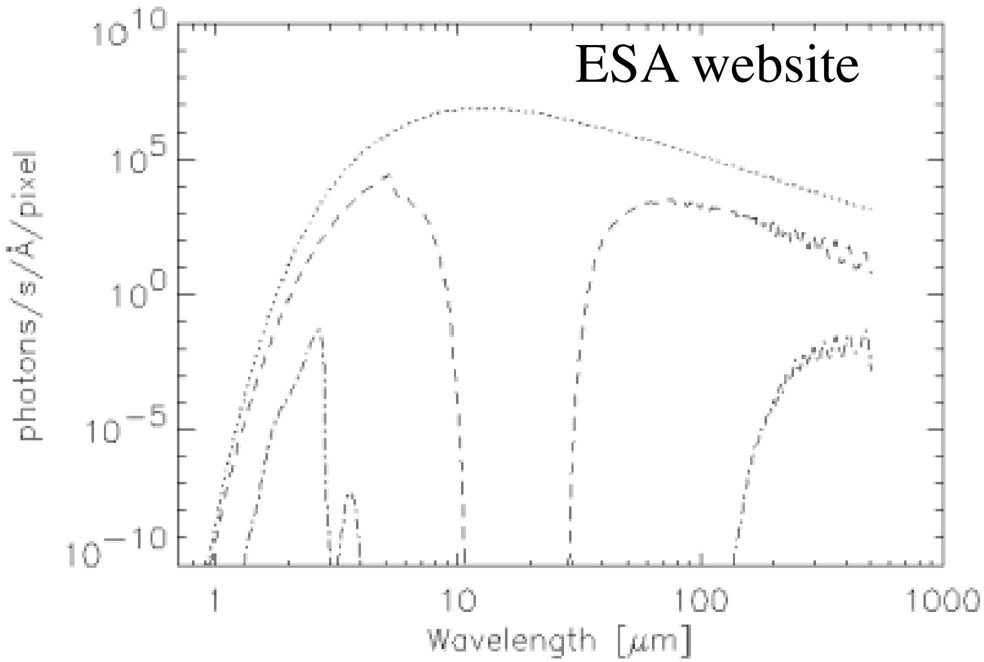


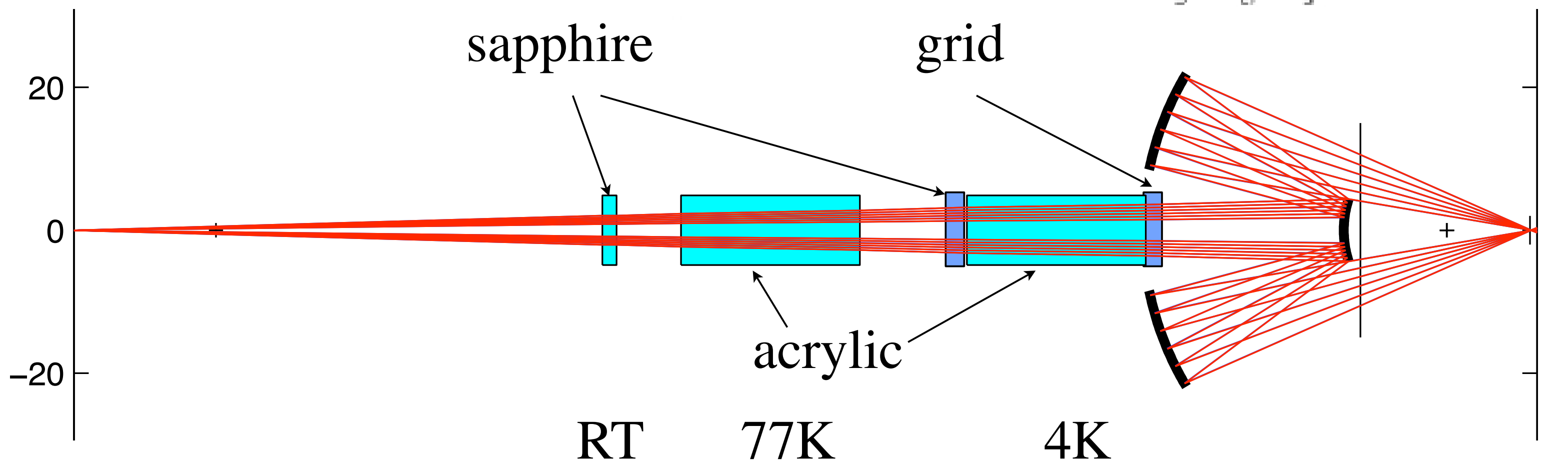
ADR for Optical/UV Imaging Array



Infrared Loading a Challenge

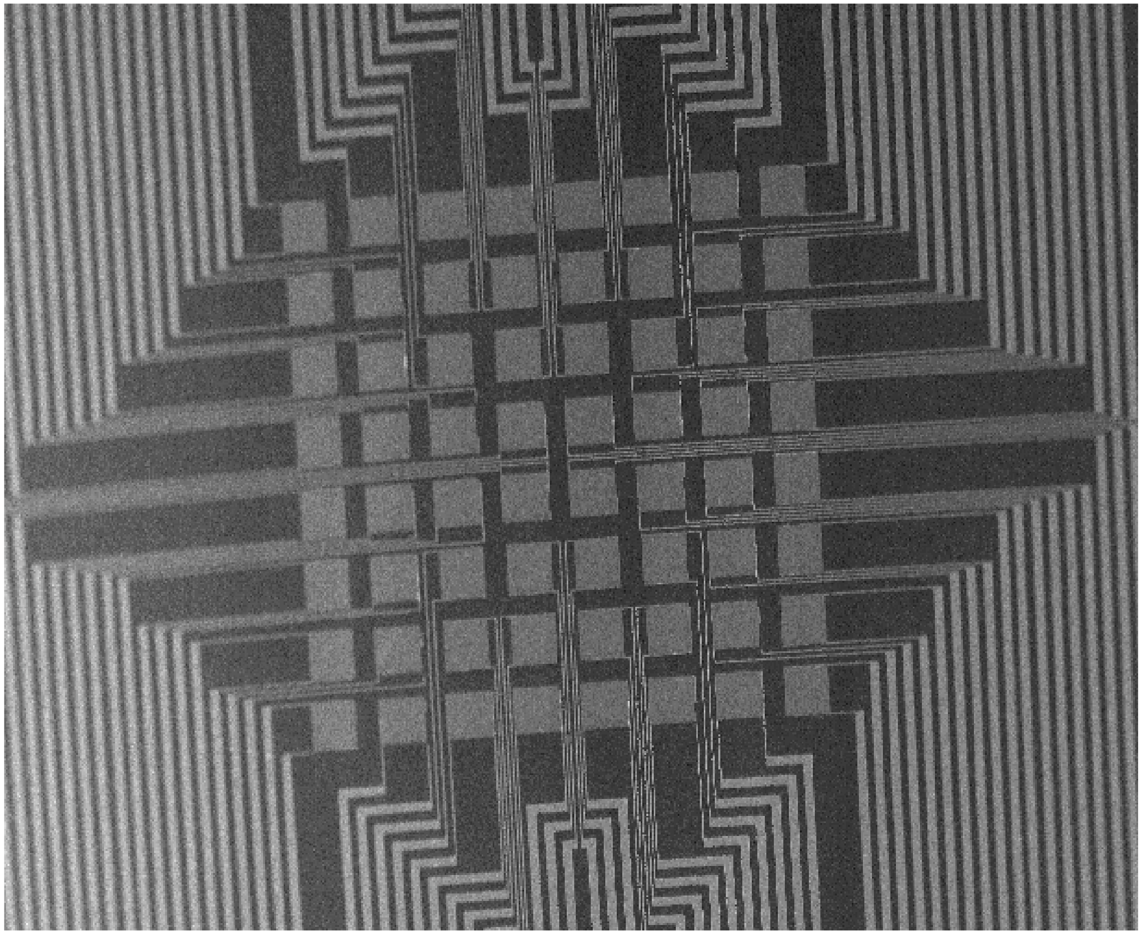
- Block ~2 μm and ~100 μm using sapphire, KG-3, KG-5, acrylic, and grid filters





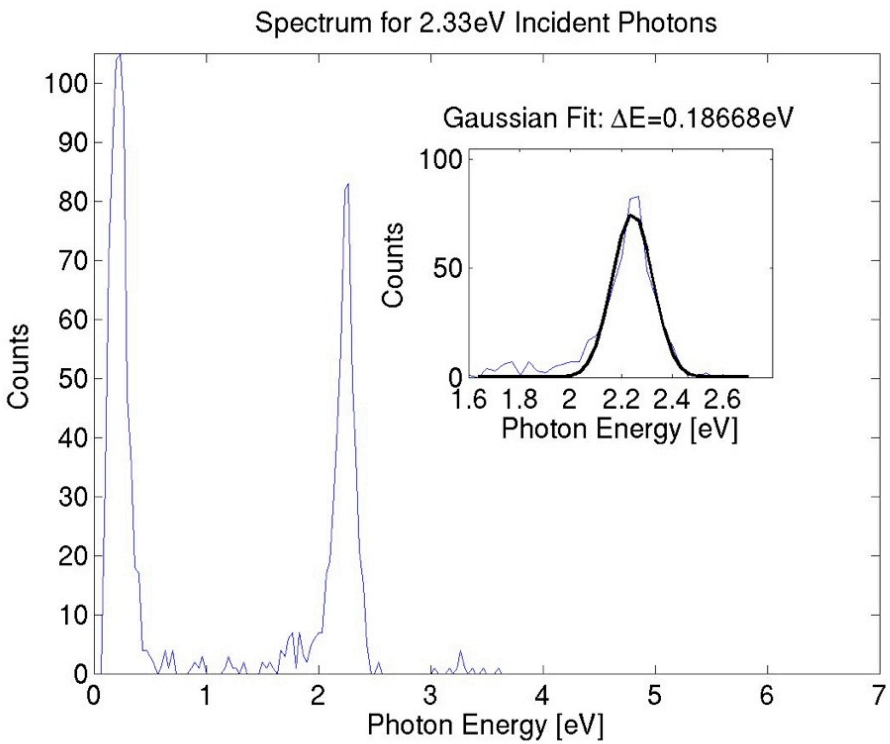
New 8 x 8 array

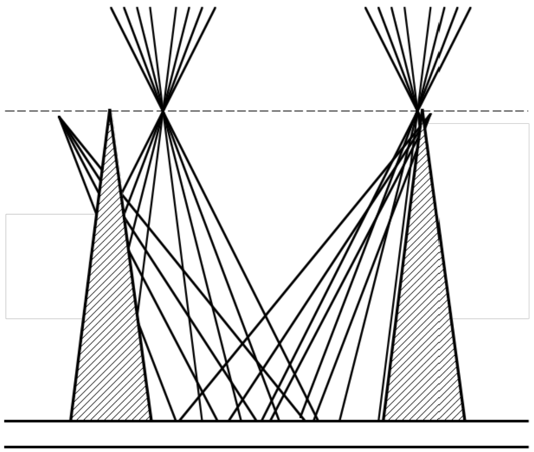
- Array of 24 μm square pixels on 36 μm centers

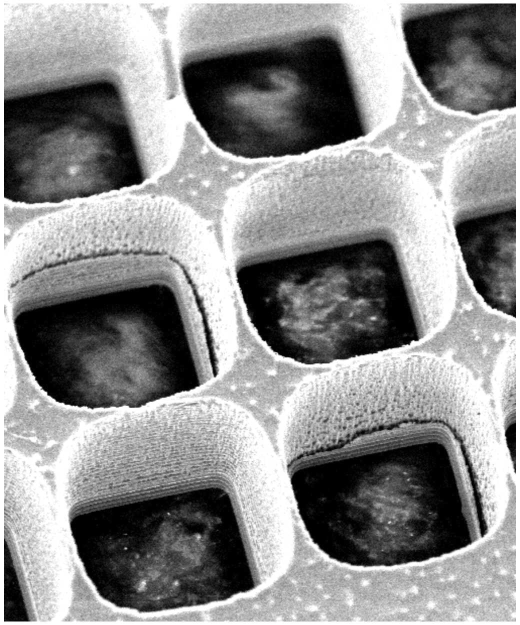


Improve PSF with Reflection Mask

Reflection mask covers rails and reflects photons that would have hit the rails back onto the active pixels.



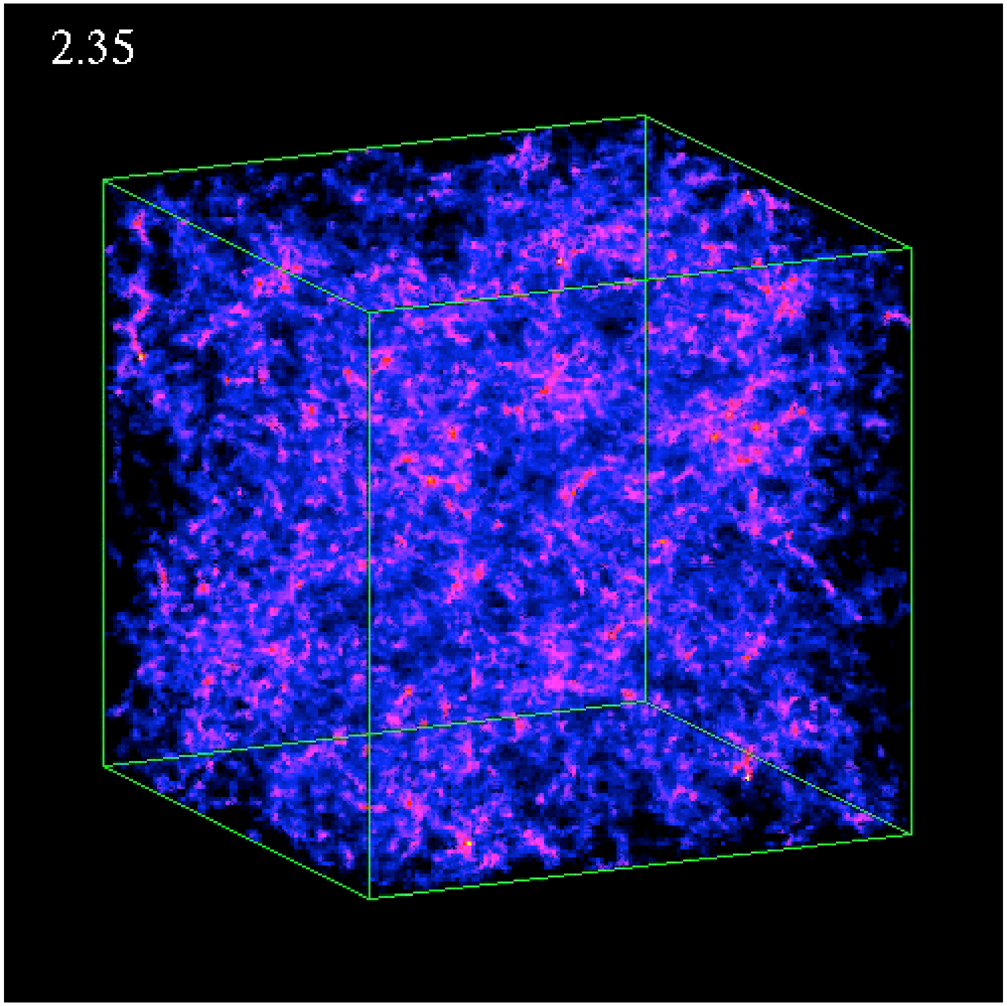


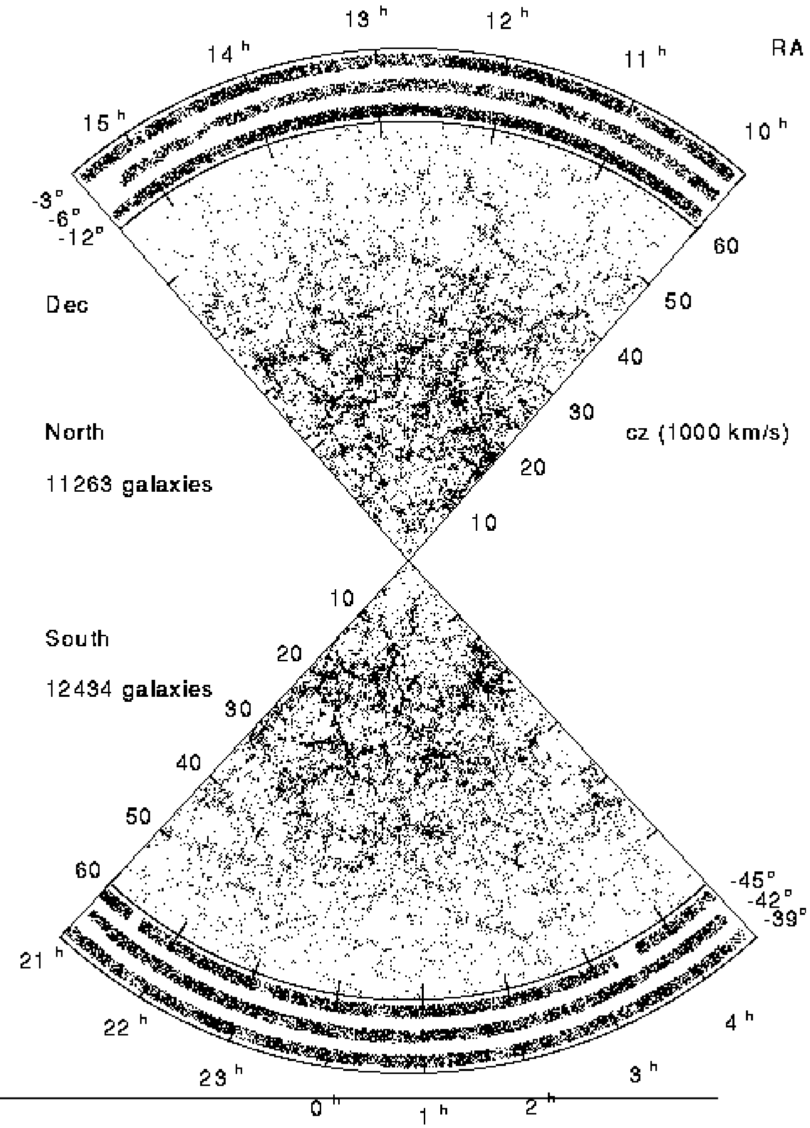


Large Area TES X-Ray Detectors

- Figure of merit is etendue given by: $A\Omega = 0.012\ d^2$ cm^2-sr, where the detector diameter d is in cm.
- Square detecter 25 mm on an edge with 1 mm square pixels and with an energy resolution of 4 eV FWHM would enable:
  - Search for missing baryons in warm-hot interstellar medium (WHIM)
  - Surveys of clusters and groups of galaxies as a probe of the growth of structure
- A number of efforts to multiplex large numbers of single pixels - time domain and frequency domain schemes
- We are developing macropixel to cover large areas

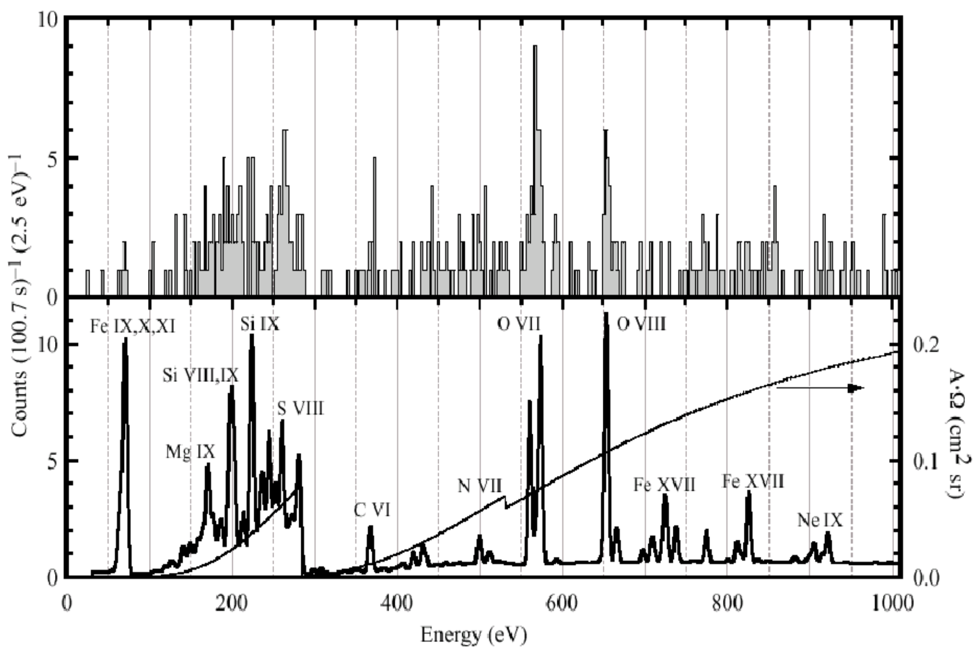
Expanding universe - simulations and data

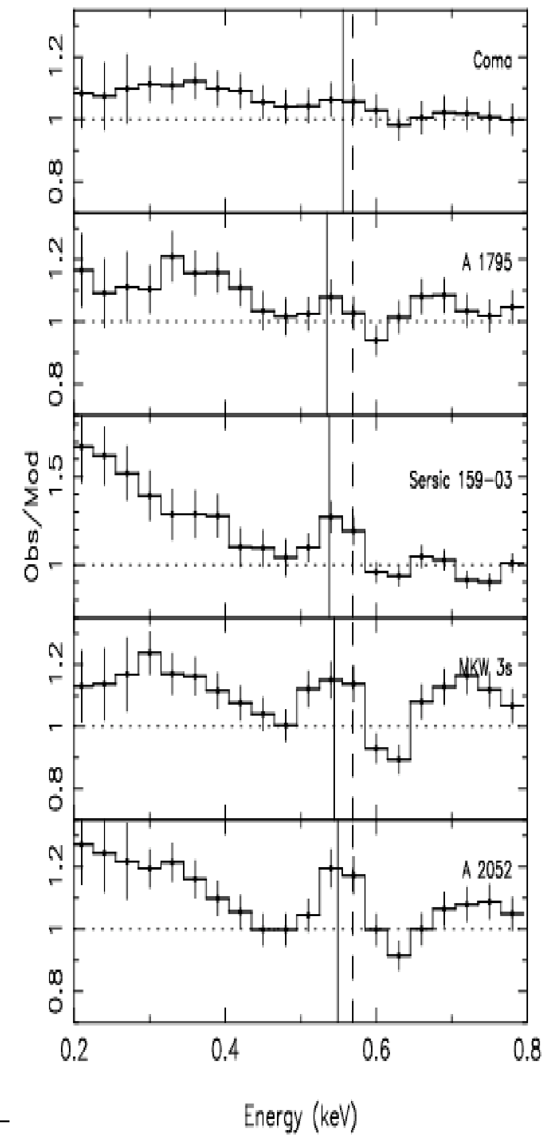




Huge Advances from Imaging TES

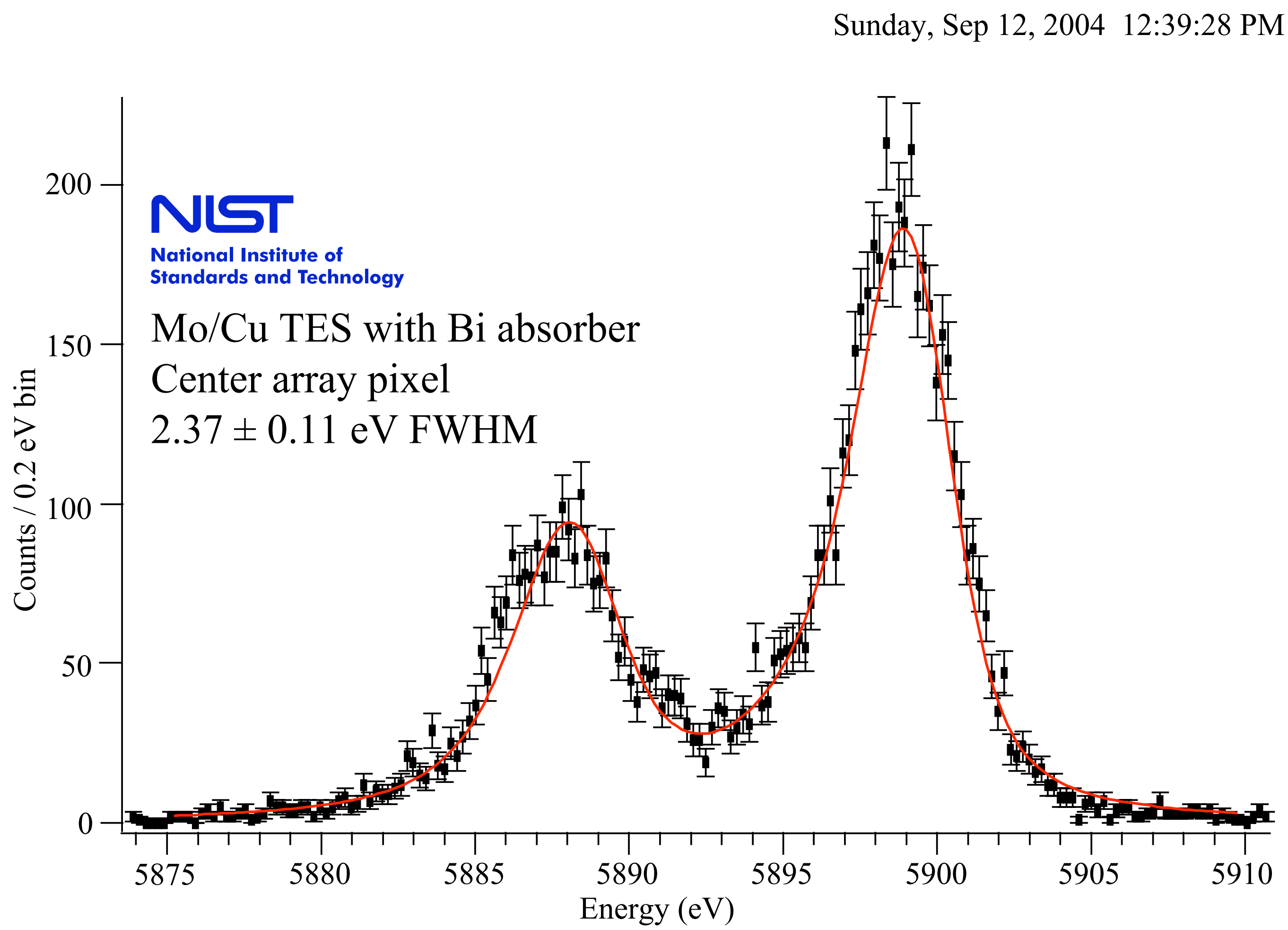
- XRS microcalorimeter diffuse background rocket flight versus state-of-the-art CCD over similar energy
- Astro E2 XRS dewar failure





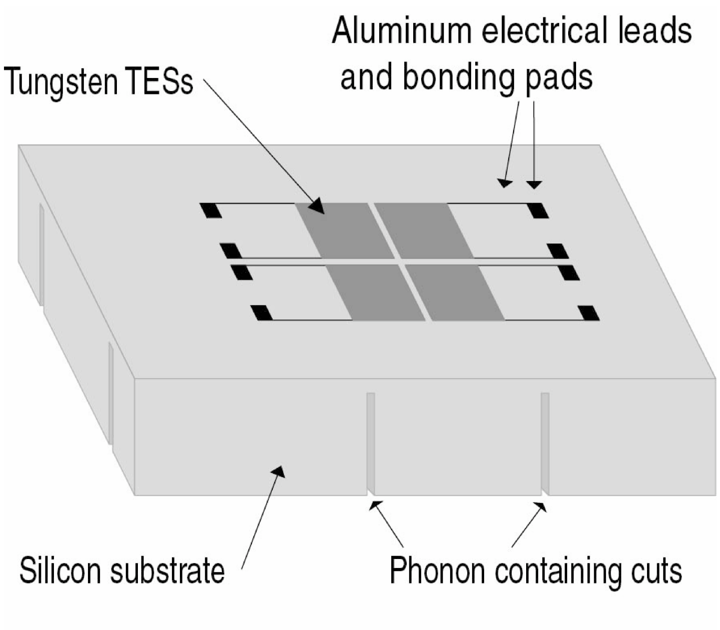
Best Single Pixel X-Ray Resolution

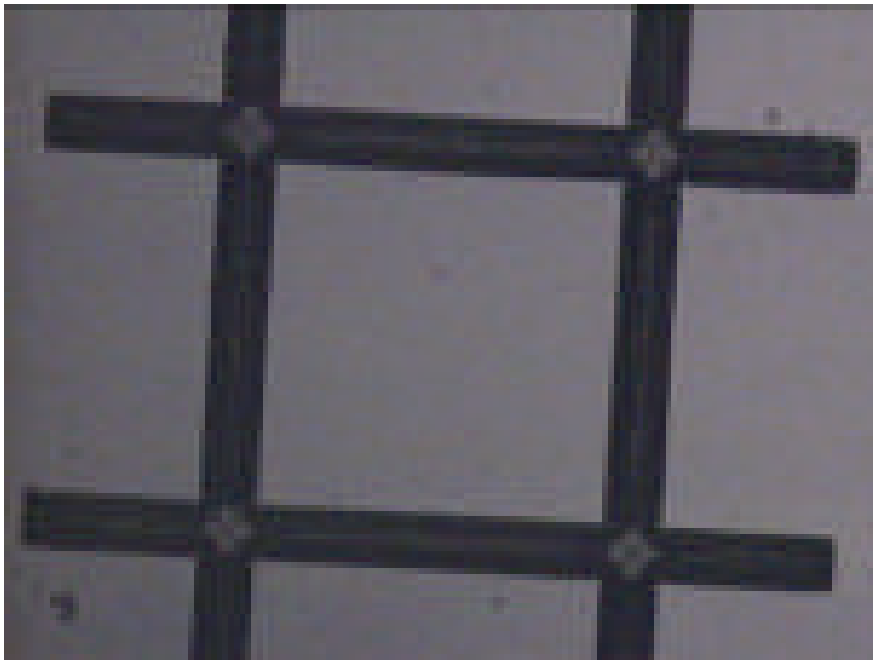
- $R = E/\Delta E = 2{,}490$



Macropixel Concept

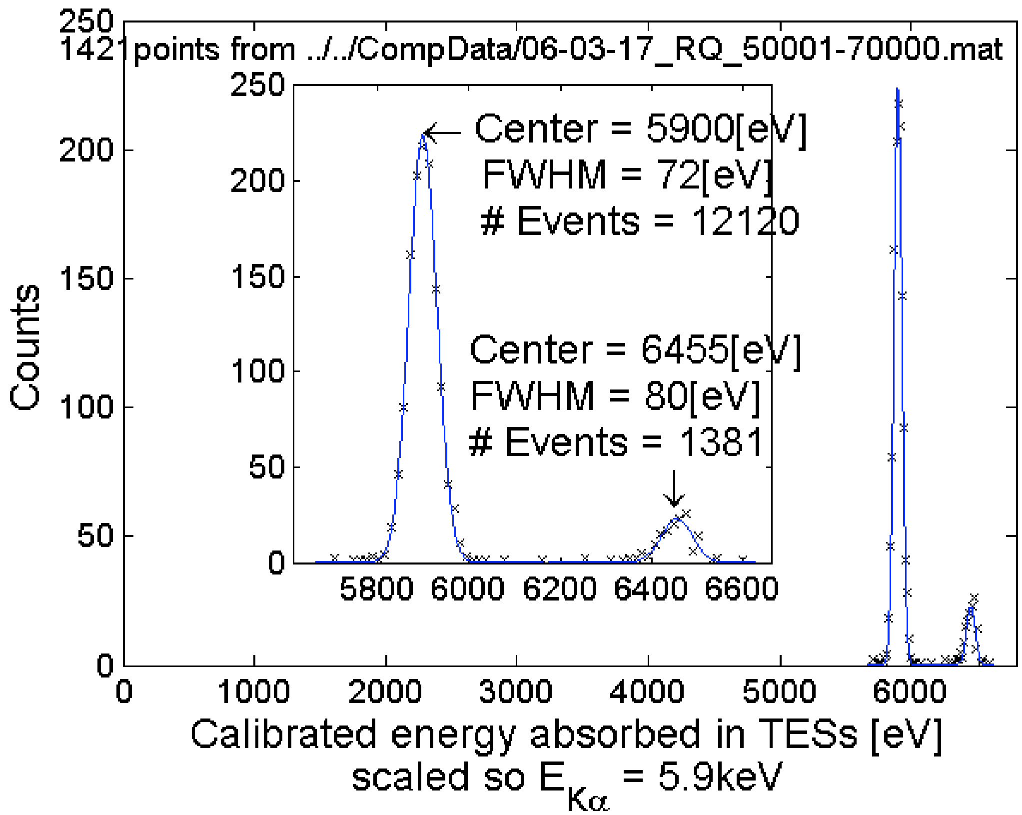
- Demonstration with 300 μm thick Si wafer
- X-rays incident on backside converting to phonons
- Phonon absorbed by TES sensors on front side





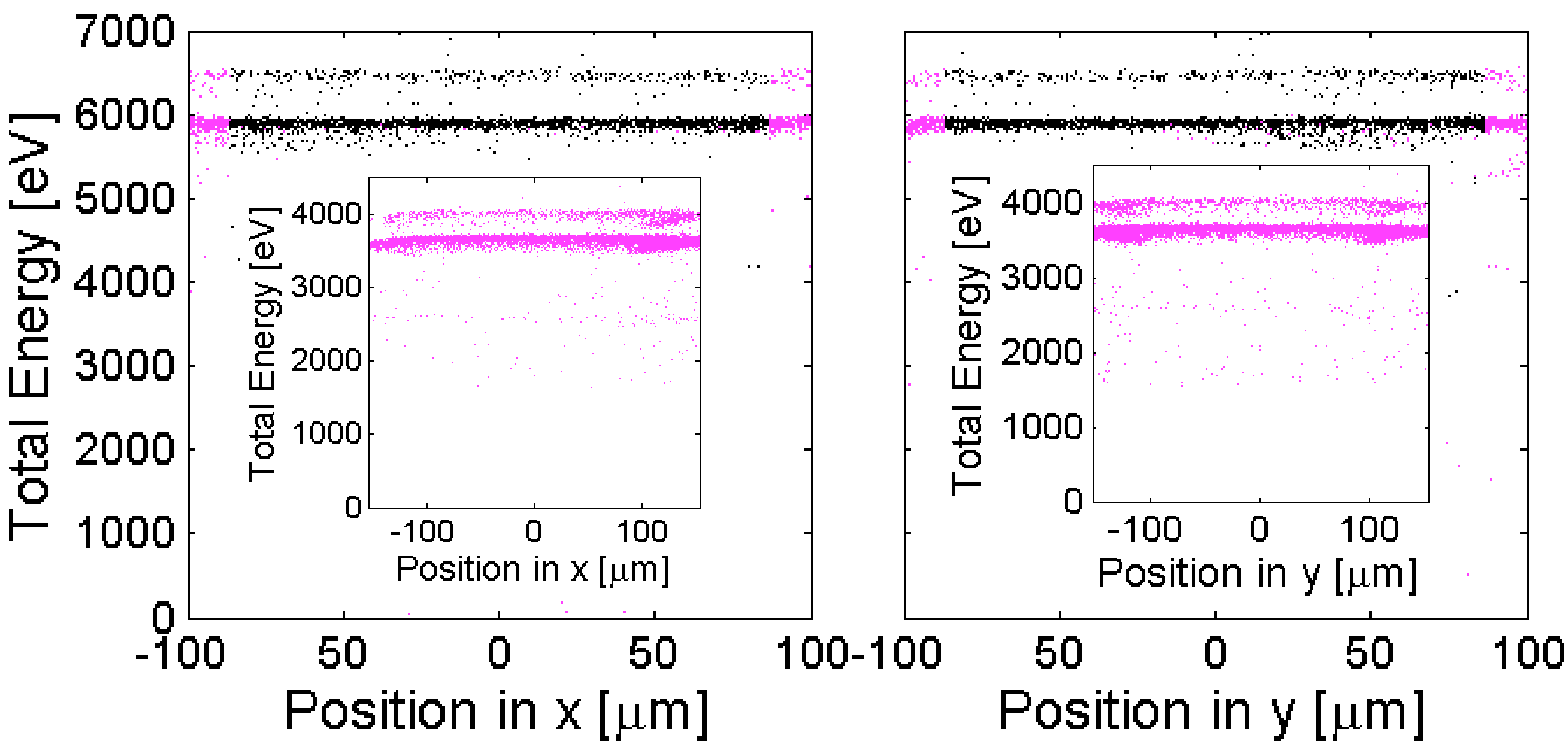
Macropixel Sensitivity

- Response from ^{55}Fe x-rays across macropixel
- Will improve using intrinsic Ge



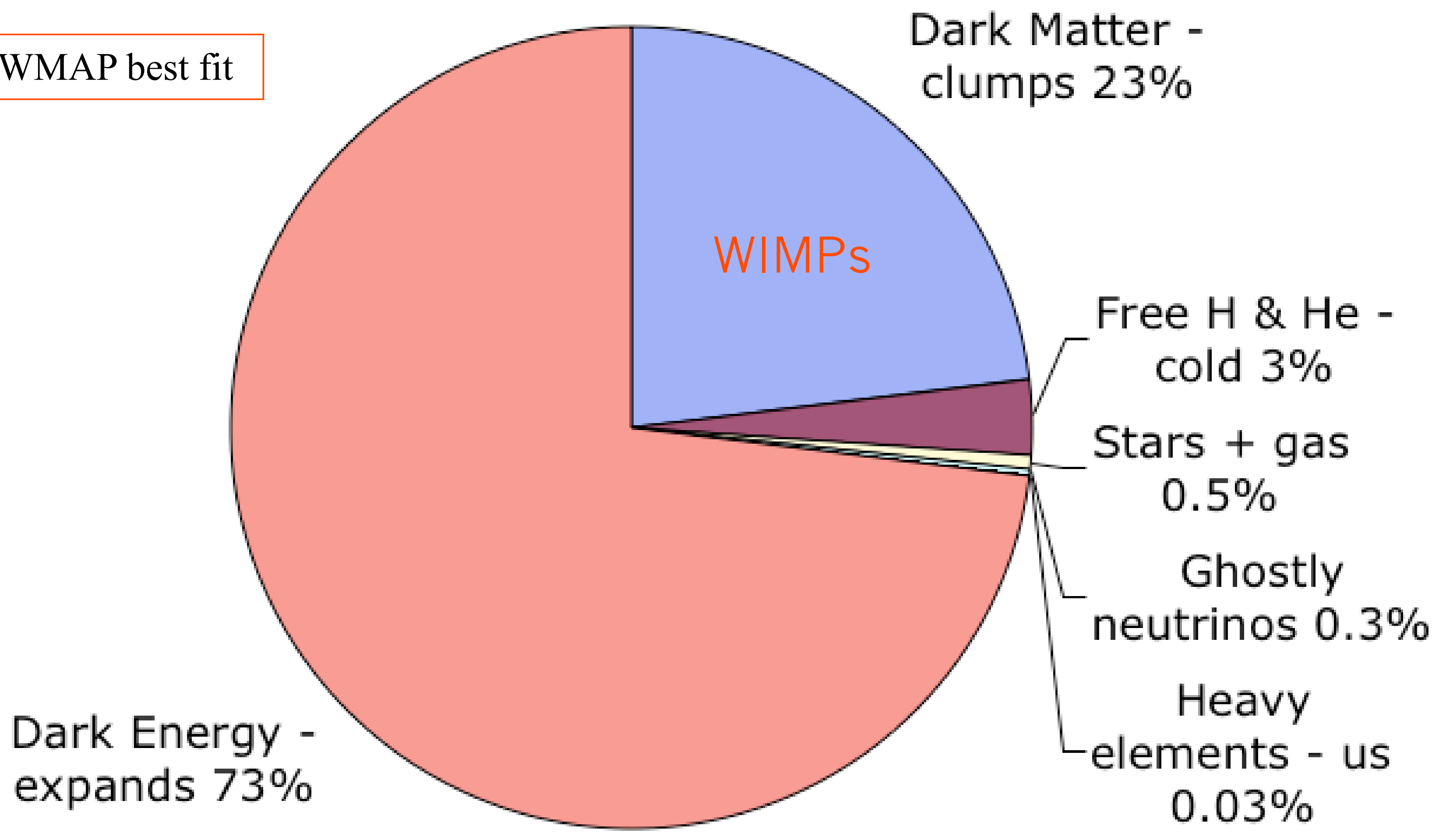
Macropixel Concept

- Simultaneous energy and position resolution
- Inset is raw data and plot after position correction

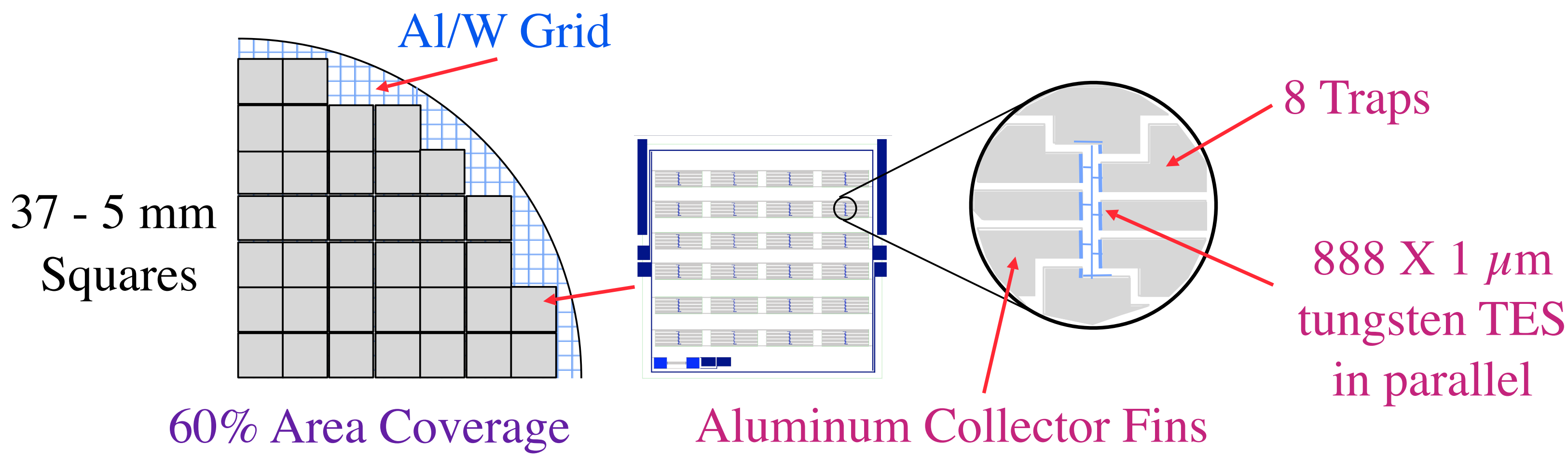


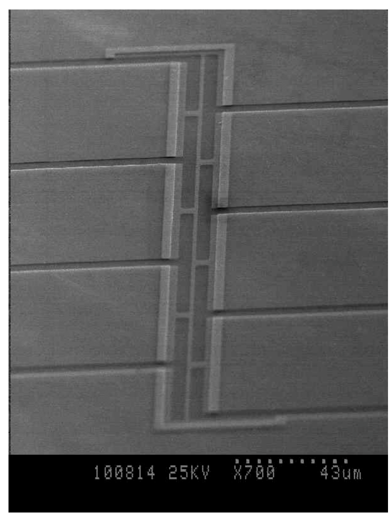
Composition of the Cosmos

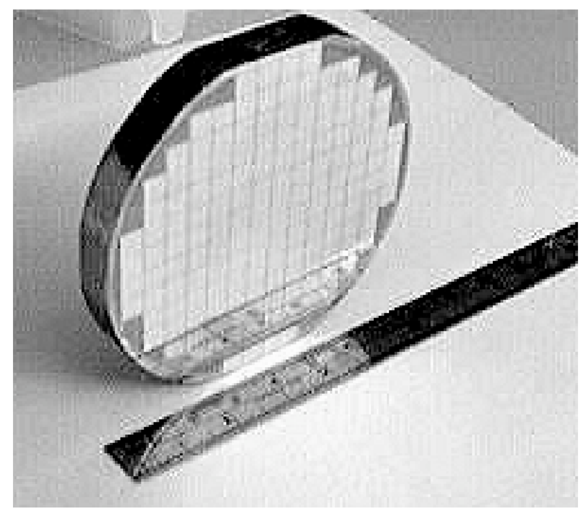
WMAP best fit



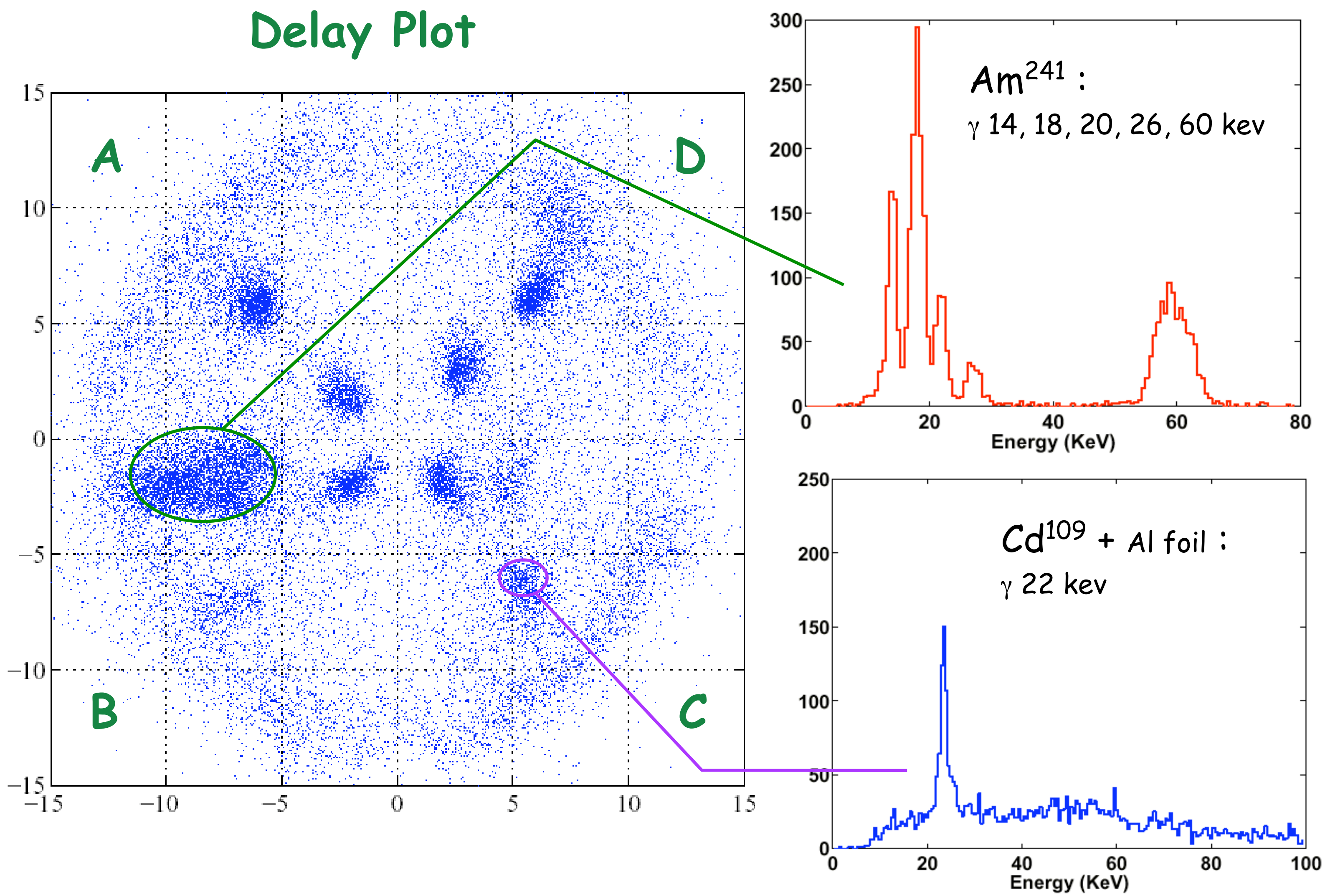
CDMS Ge & Si ZIP Detectors





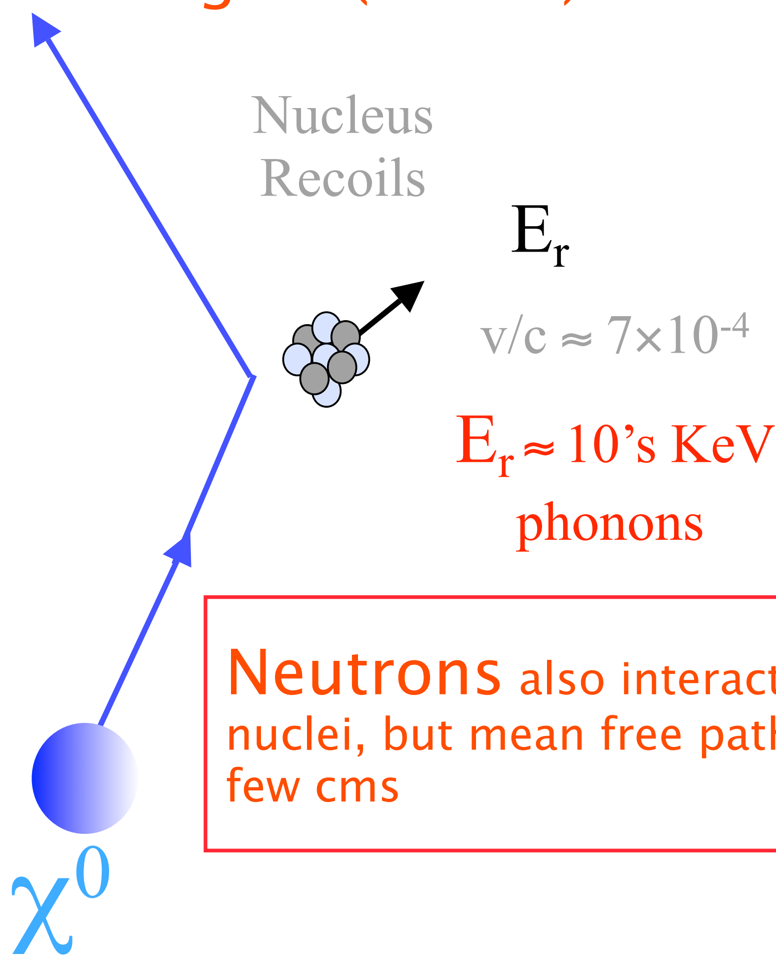


ZIP Phonon Position Sensitivity



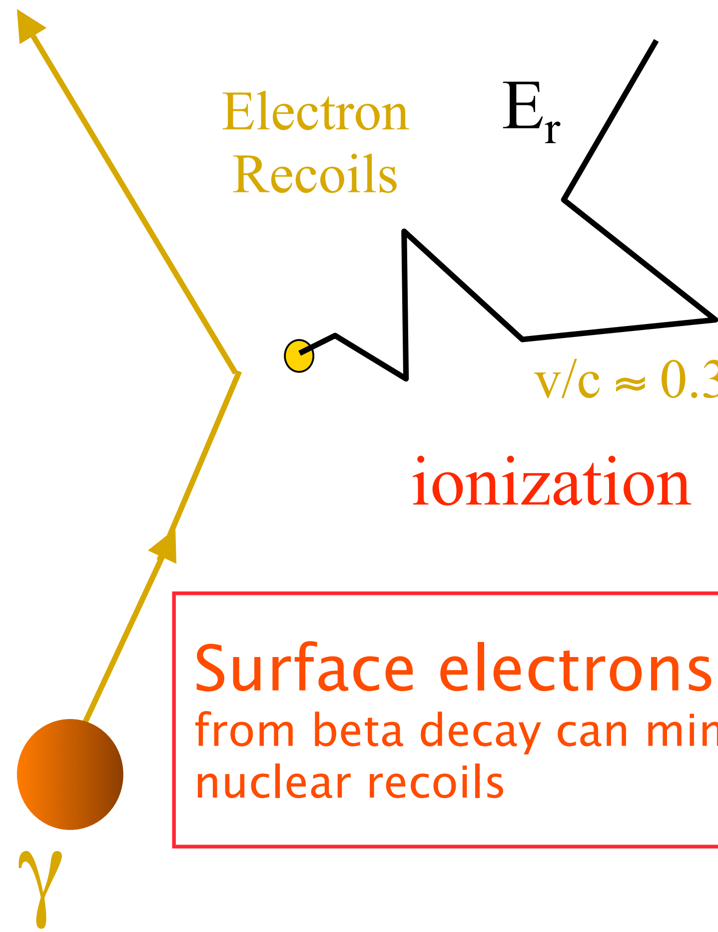
The Signal and Backgrounds

Signal (WIMPs)



Neutrons also interact with nuclei, but mean free path a few cms

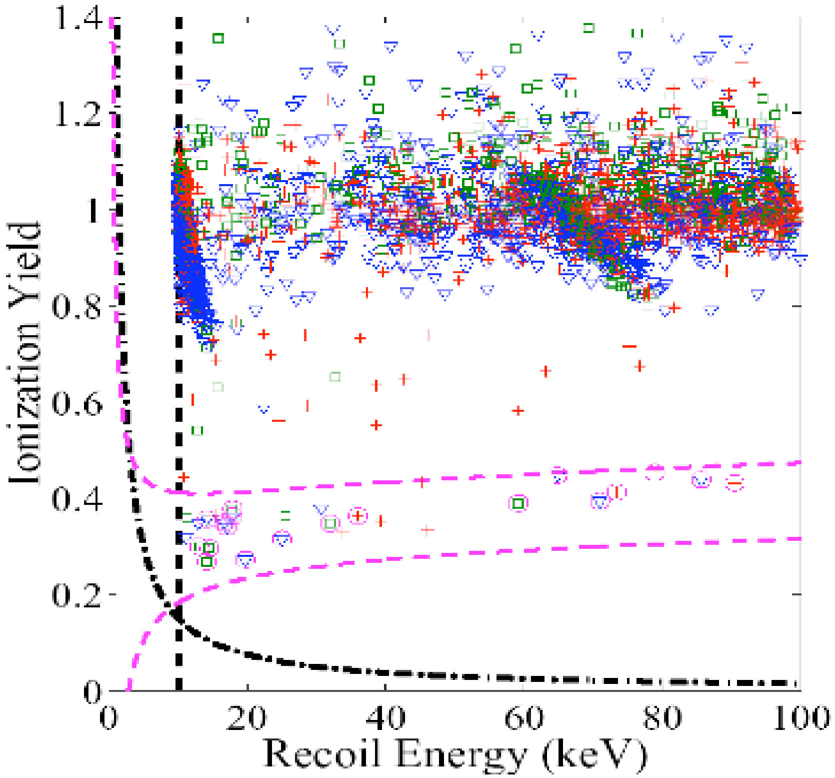
Background (gammas)



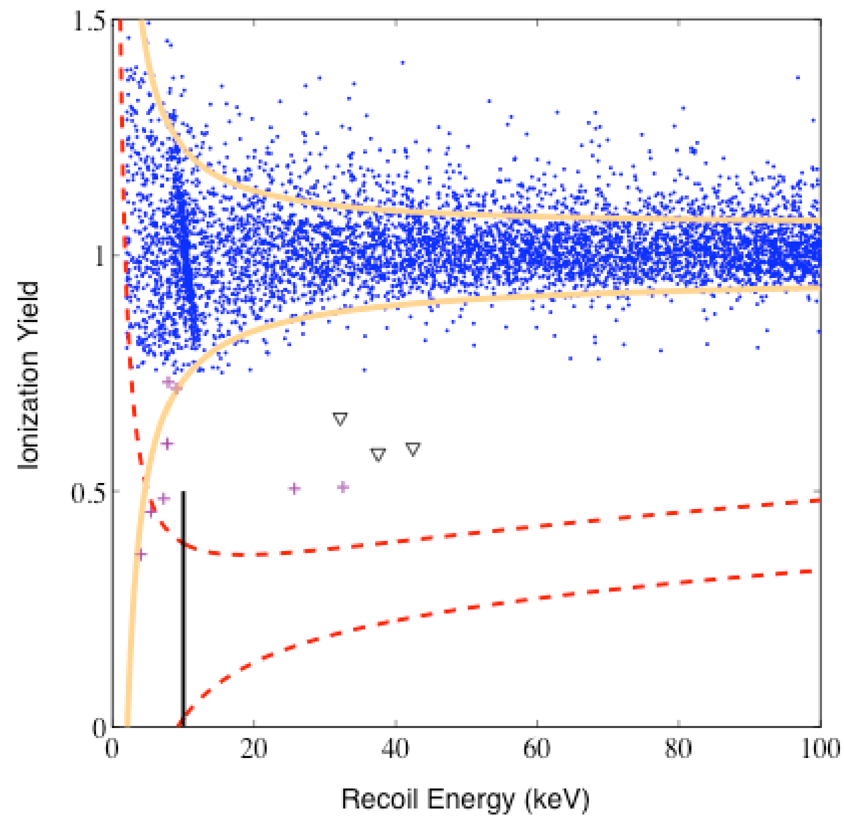
Surface electrons from beta decay can mimic nuclear recoils

ST1&2 Soudan -> SNOLab like Tower 1 SUF -> Soudan

- Tower 1 (4 Ge & 2 Si) at SUF then at Soudan



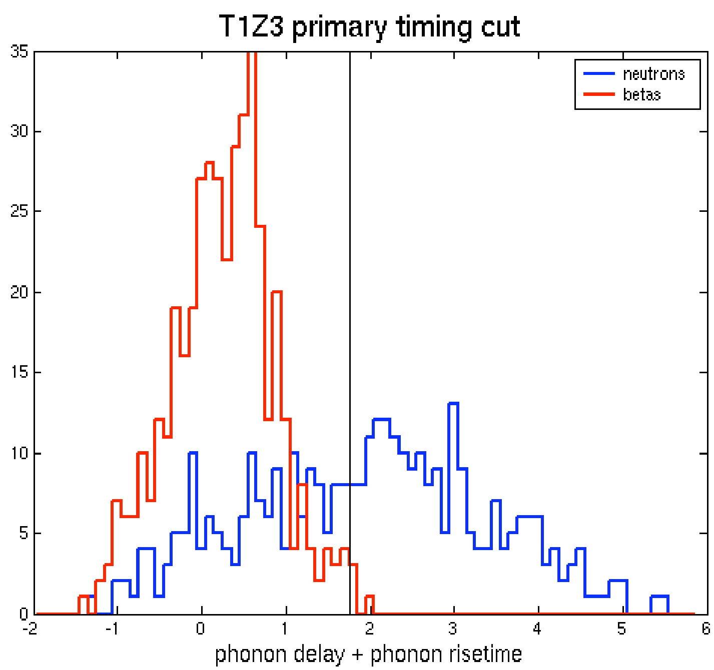
19 neutron events at SUF

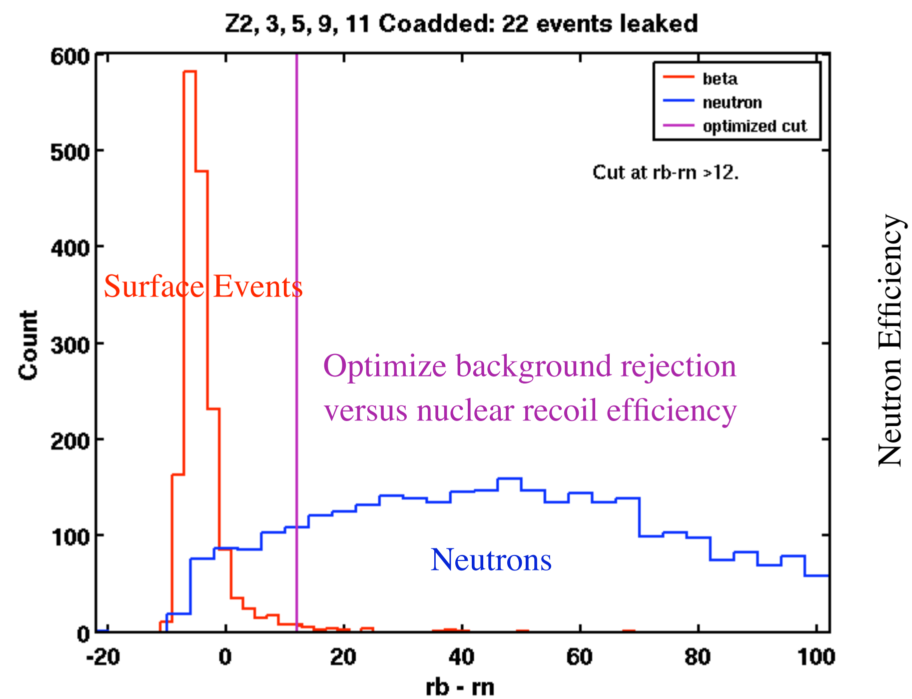


0 events at Soudan

Improvements in Surface Event Rejection

- Significant improvements in our analysis of phonon timing information
  - Surface event rejection improved by x3; kept pace with exposure increase!
  - Cuts are set from calibration data (blind analysis)
- We still have more discrimination power available as needed
  - Can continue to keep backgrounds < 1 event as more data accumulates
  - This is the real strength of CDMS detectors!



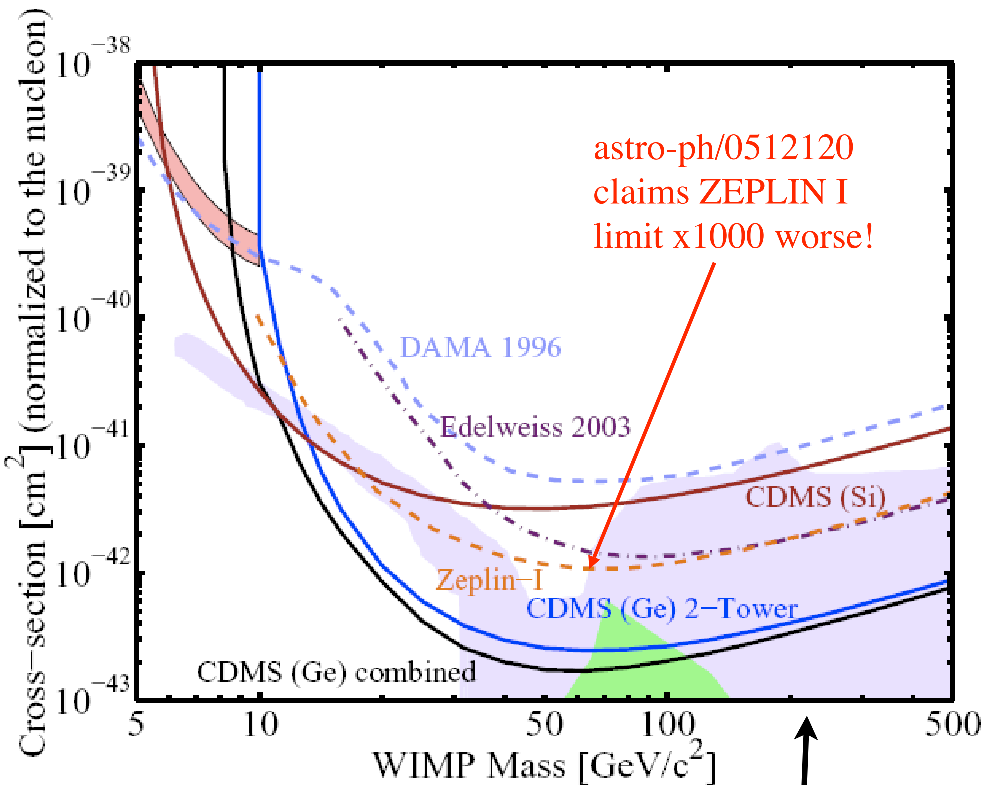


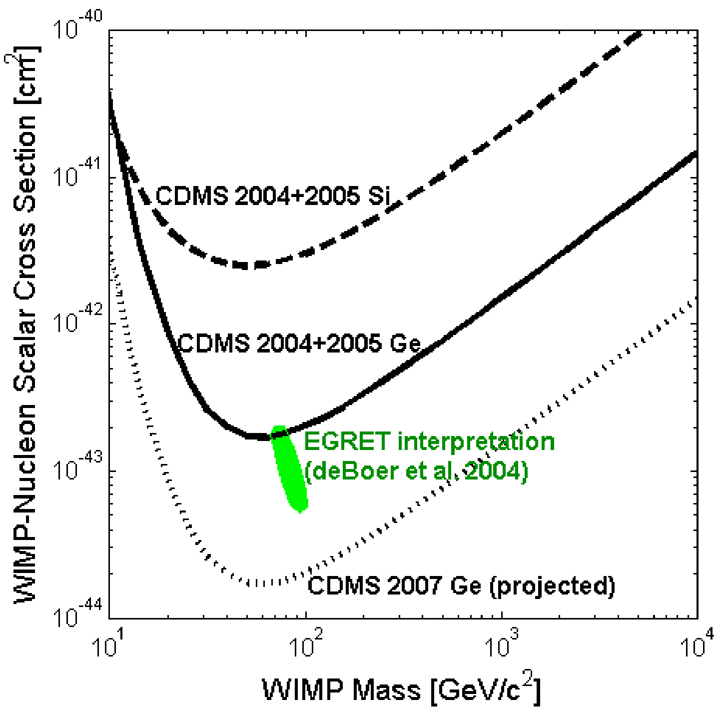
Chi-square (background pulse shape) - Chi-squared (neutron pulse shape)

CDMS-II SI Results & Reach with five Towers

Experimental Motivations

DAMA/NaI
Bernabei et al., astro-ph/0307403





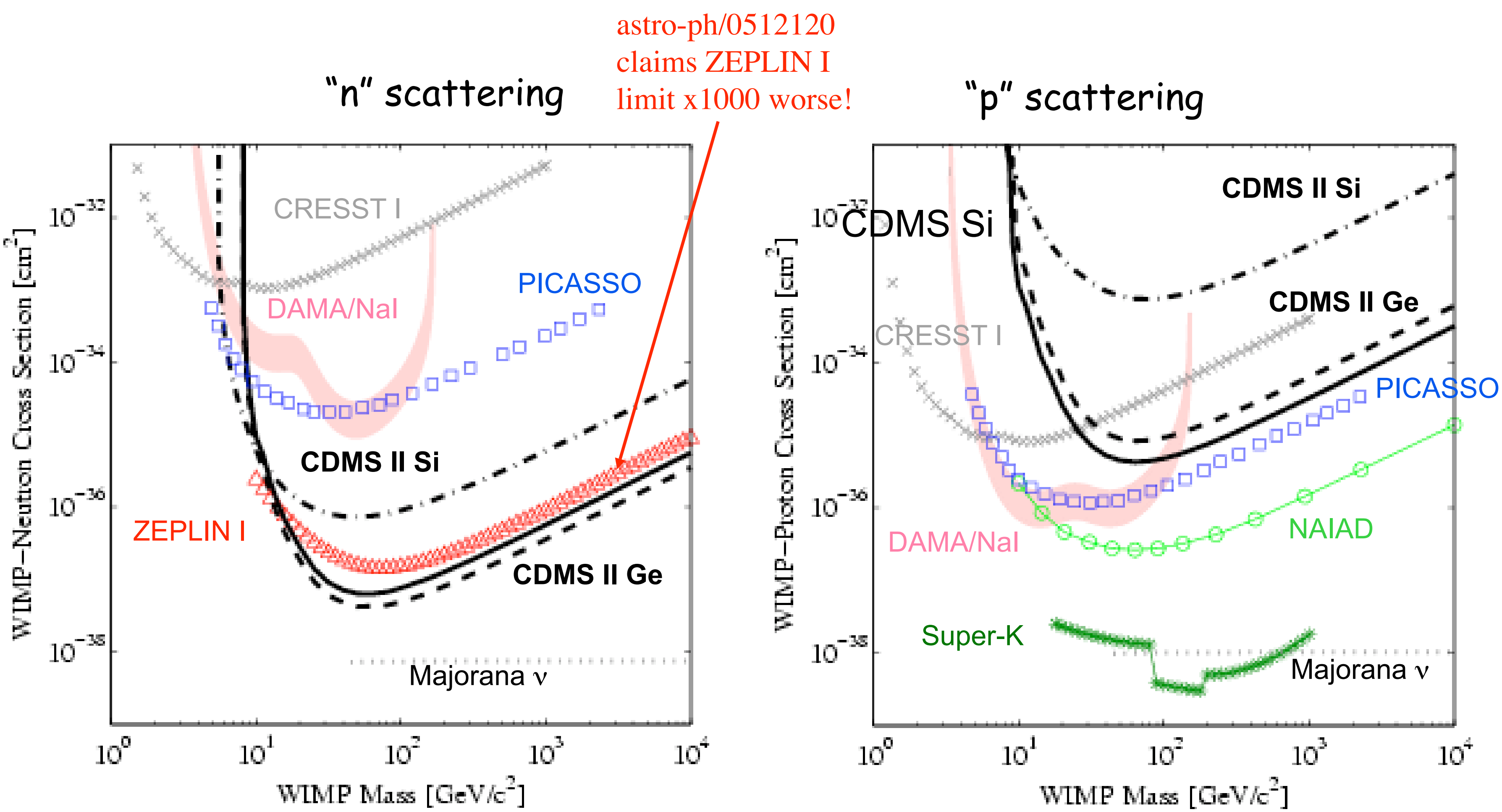
EGRET
de Boer et al., astro-ph/0412620

- Interpret EGRET gamma ray excess as DM annihilation

For further details see PRL 96, 011302 (2006)

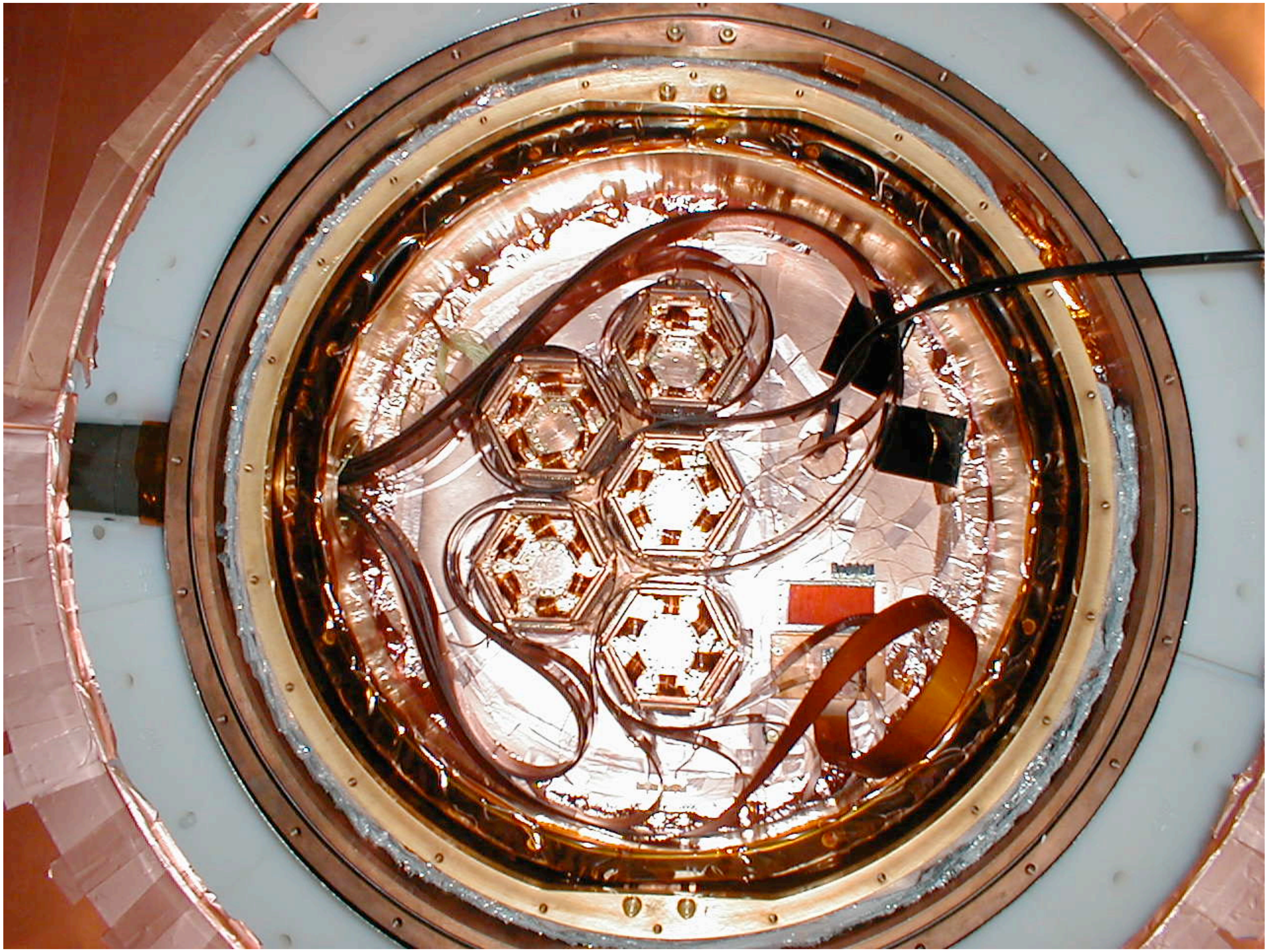
Spin Dependent WIMP limits

Spin-sensitivity from ^{73}**Ge** (J=9/2, 7.7%) and ^{29}**Si** (J=1/2, 4.7%)



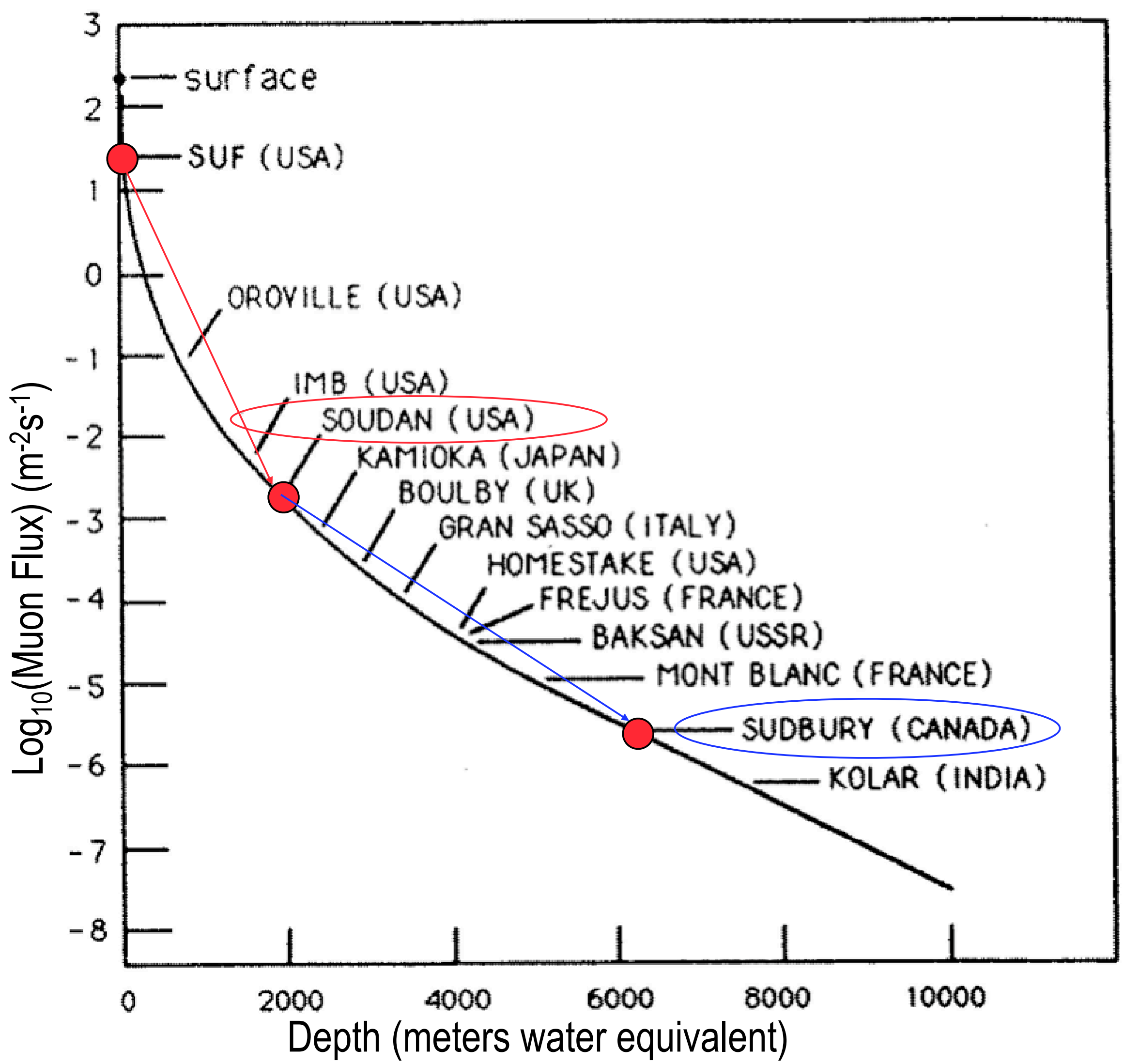
For further details see PRD D73, 011102 (2006)

About to Operate Five Towers in Soudan



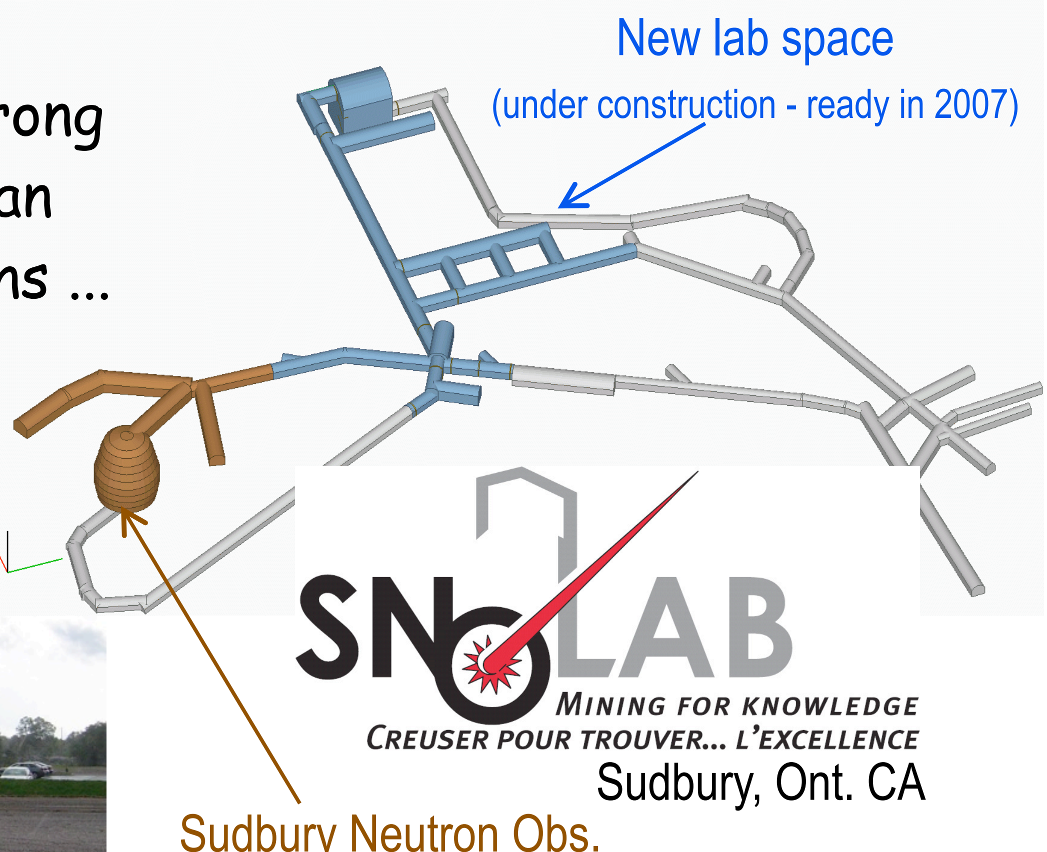
SUF (17 mwe), Soudan (2090 mwe), & SNOLab (6060 mwe)

- At SUF
  - 17 mwe
  - 0.5 n/d/kg
- At Soudan
  - 2090 mwe
  - 0.8 n/y/kg
- At SNOLab
  - 6060 mwe
  - 1 n/y/ton



SuperCDMS at SNOLab

- ★ SuperCDMS is approved to be sited at SNOLab
  - ★ We have received strong interest from Canadian collaborators - Queens ...



SNOLAB
MINING FOR KNOWLEDGE
CREUSER POUR TROUVER... L'EXCELLENCE
Sudbury, Ont. CA

Baseline detector for SuperCDMS

CDMS-II ZIPs:

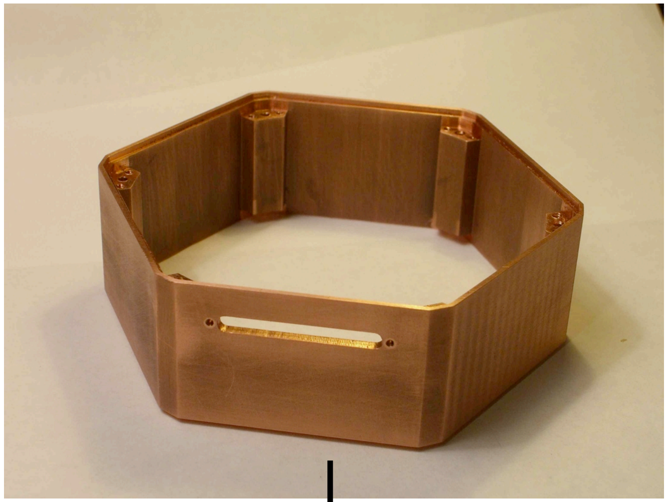
3″ dia x 1 cm => 0.25 kg of Ge

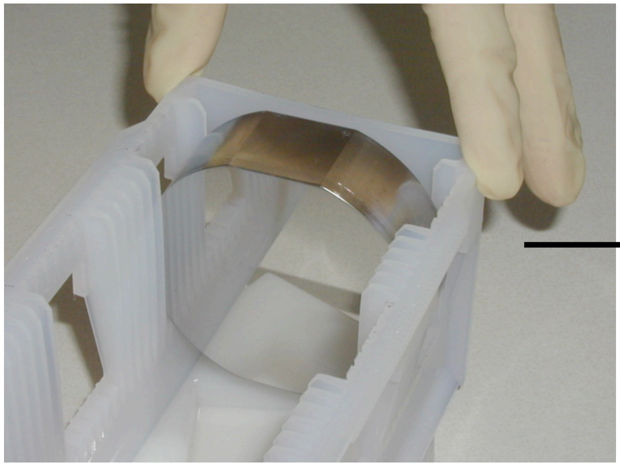
Existing ZIPs

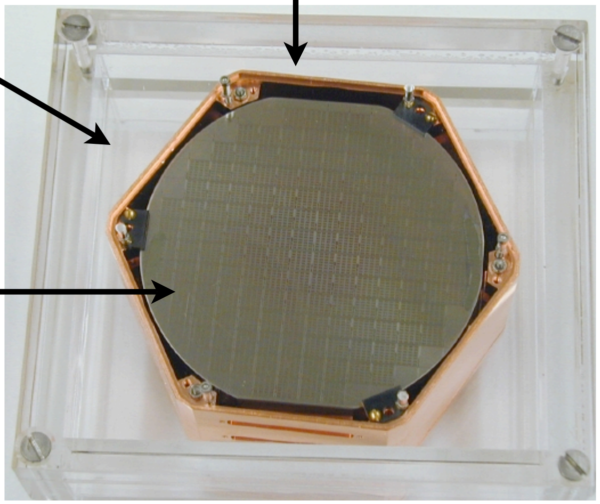
SuperCDMS ZIPs:

3″ dia x 1″ => 0.64 kg of Ge

ZIPs for SuperCDMS



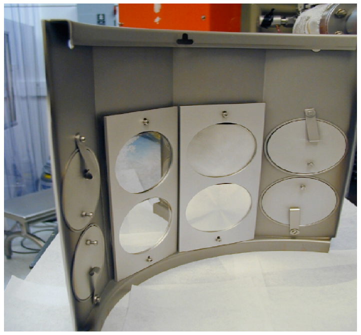


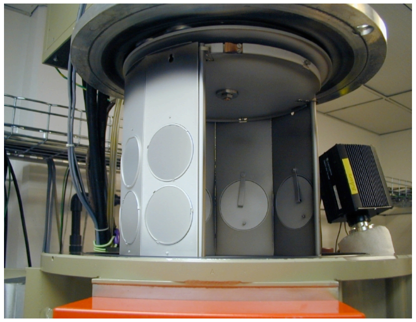


Photolithography test with 1″ Ti

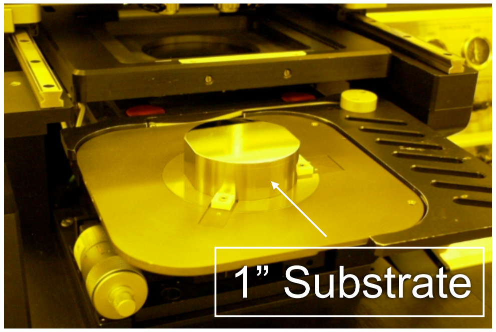
Modifications for 1" processing

sputtering
(design complete
parts in shop)





spinner
(ready)



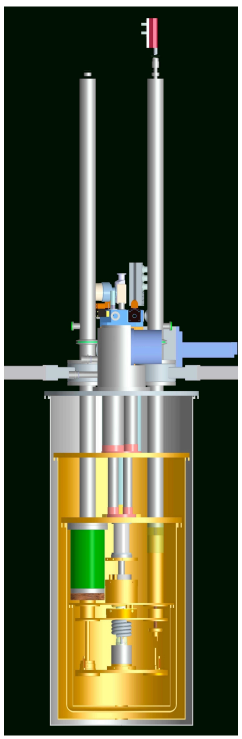
aligner (ready)

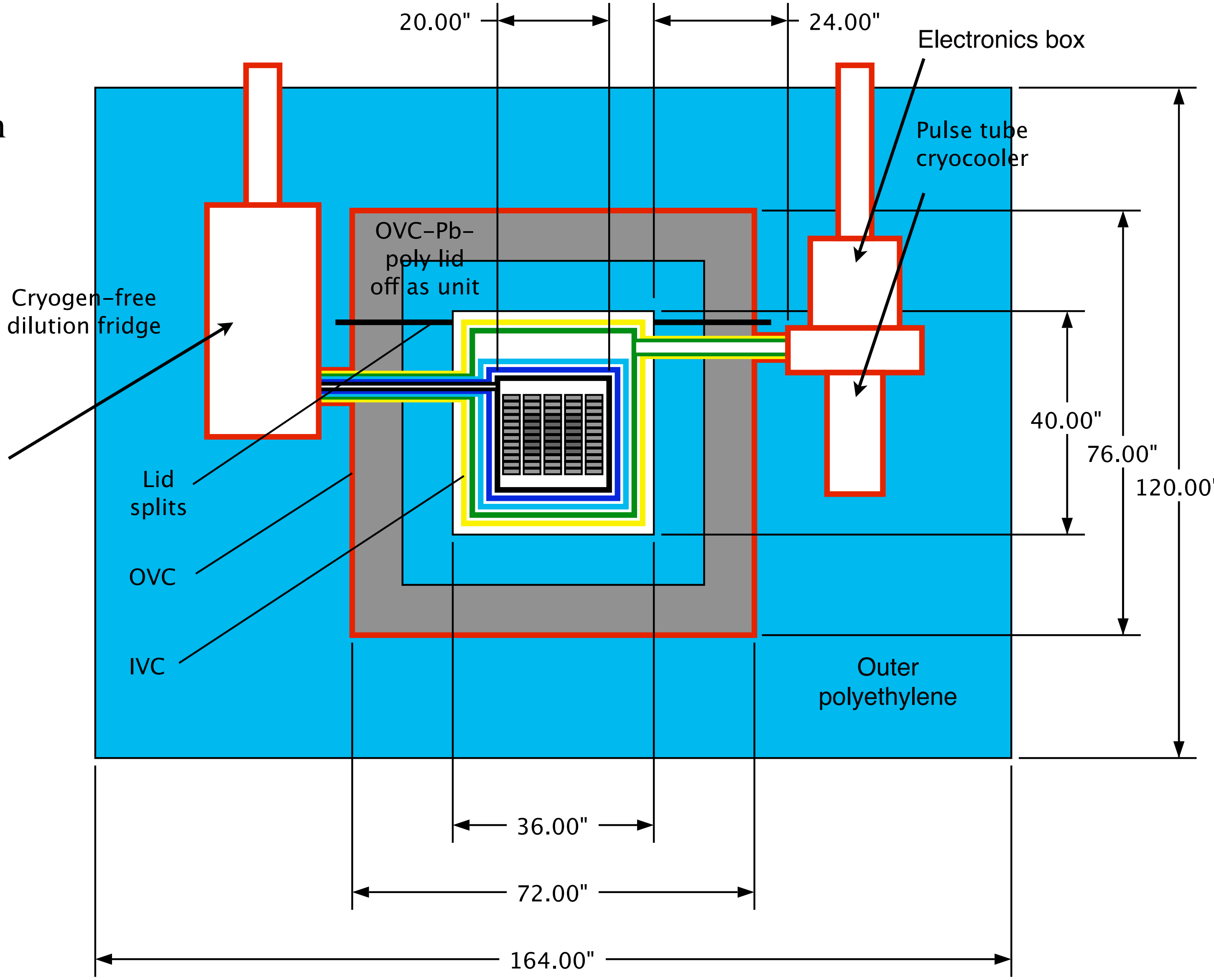
**start first Ge
1" thick
fabrication
in Jan 06**

dry etch
(design
complete)

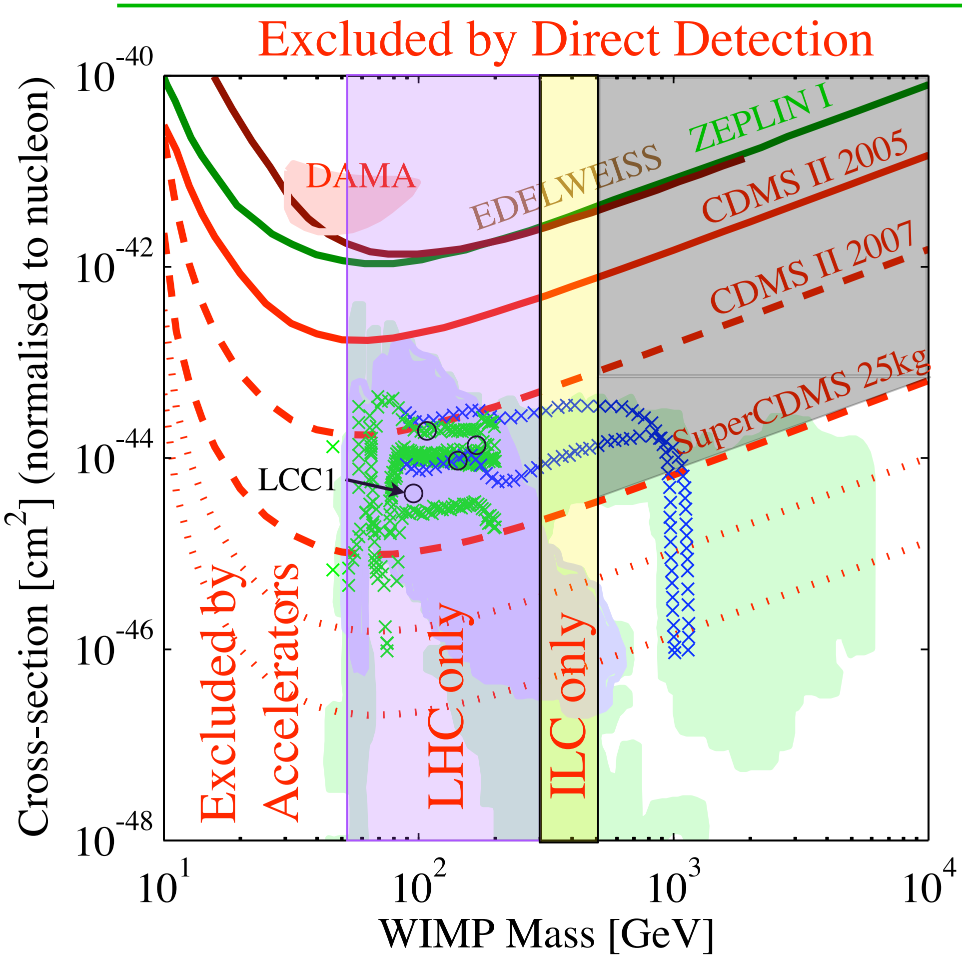
Schematic of new 'SNObox'

Exploring cryocooler system with little or no cryogen servicing



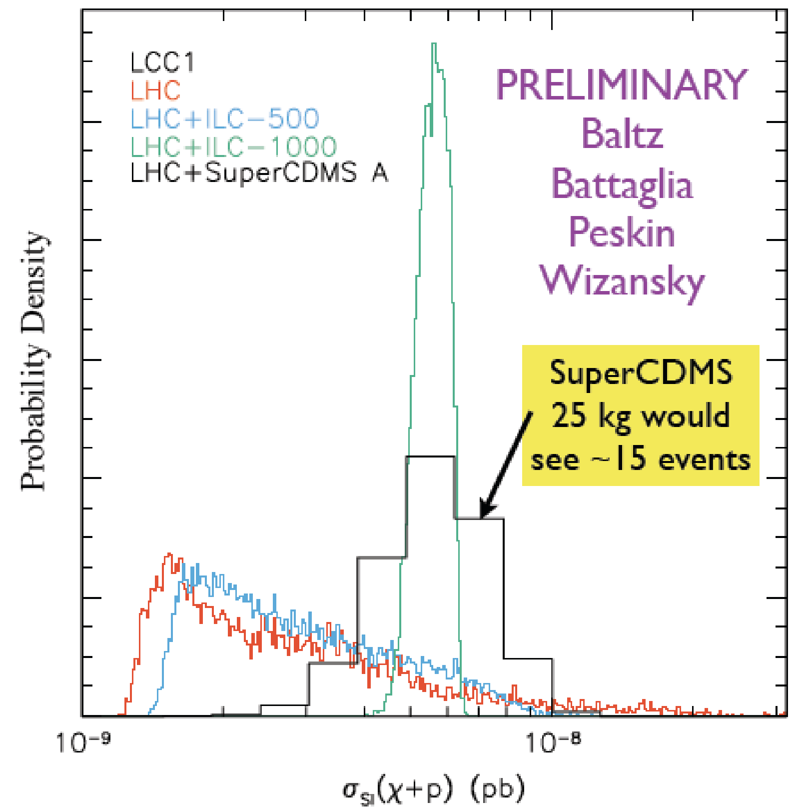


Does the LHC supplant Direct Detection?



Accelerators are *mass-limited*

⇒ spectral info, but often can't see LSP or deduce its relic density



CDMS is *cross section-limited*

⇒ TeV WIMPs detectable, direct connection to cosmology

Summary

- TES detectors are now a well established technology and are at the forefront of sensitivity for all energy scales including optical, x-ray and dark matter searches.
- IR-optical-UV detectors have 0.15 eV FWHM with counting rates up to 10 kHz for single pixels, for a 6 X 6 array. Exciting technology for ground based, long duration balloon instruments from near IR well into UV and satellite missions from 10 μm to 100 nm.
- Large area macropixel x-ray arrays open new science fronts to search for missing baryons as WHIM and study large scale structure with galaxy cluster surveys.
- Dark matter search (CDMS) leads field by factor of ten and is exploring very interesting region of supersymmetry. Another factor of ten with 5 Towers then SuperCDMS.