The Search for Dark Matter in Our Universe: CDMS (Cryogenic Dark Matter Search)

Fermilab Academic Lecture Series
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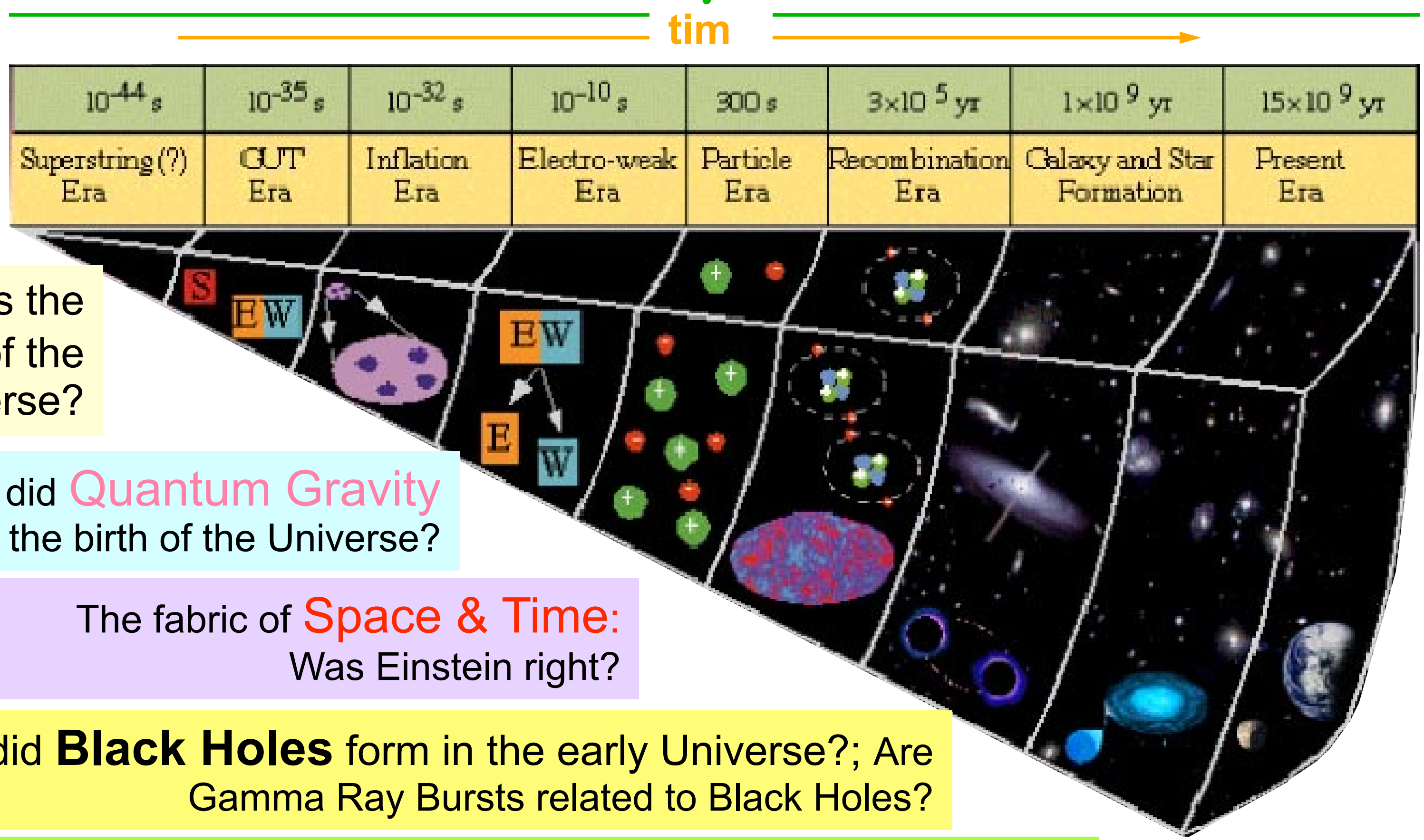
Blas Cabrera
Stanford University

CDMS Collaboration

Dark Matter WIMPs

- The Science
  - Scientific case compelling for dark matter WIMPs both from particle physics side and astrophysics side
- Galaxy formed in dark matter gravitational potential
  - Our solar system rotates through flux of WIMPs $\sim 10^9/m^2/s$
  - These would only interact with nuclei not electrons $\sim (m_N/m_e)^2 \sim 10^{10}$
  - Nearly all backgrounds interact with e's produced by gammas
- Superconducting TES technology for optical, x-ray and dark matter detectors
- Existing CDMS II detectors and program
  - Tower 1 (4 Ge and 2 Si detectors) at SUF (neutron limited)
  - Same Tower 1 & new Tower 2 at Soudan - PRL **96**, 011302 (2006) best x10
  - Towers 1-5 (2006-7) - x20 (then n limited)
- Future SuperCDMS program
  - SuperCDMS 25 kg Ge experiment new proposal
    - initially 2 Towers at Soudan then 7 Towers at deeper SNOLab
  - Can run up to 1000 kg Ge at SNOLab before neutron limited

The BIG questions



?

What is the **Origin** of the Universe?

What role did **Quantum Gravity** play in the birth of the Universe?

The fabric of **Space & Time:** Was Einstein right?

How did **Black Holes** form in the early Universe?; Are Gamma Ray Bursts related to Black Holes?

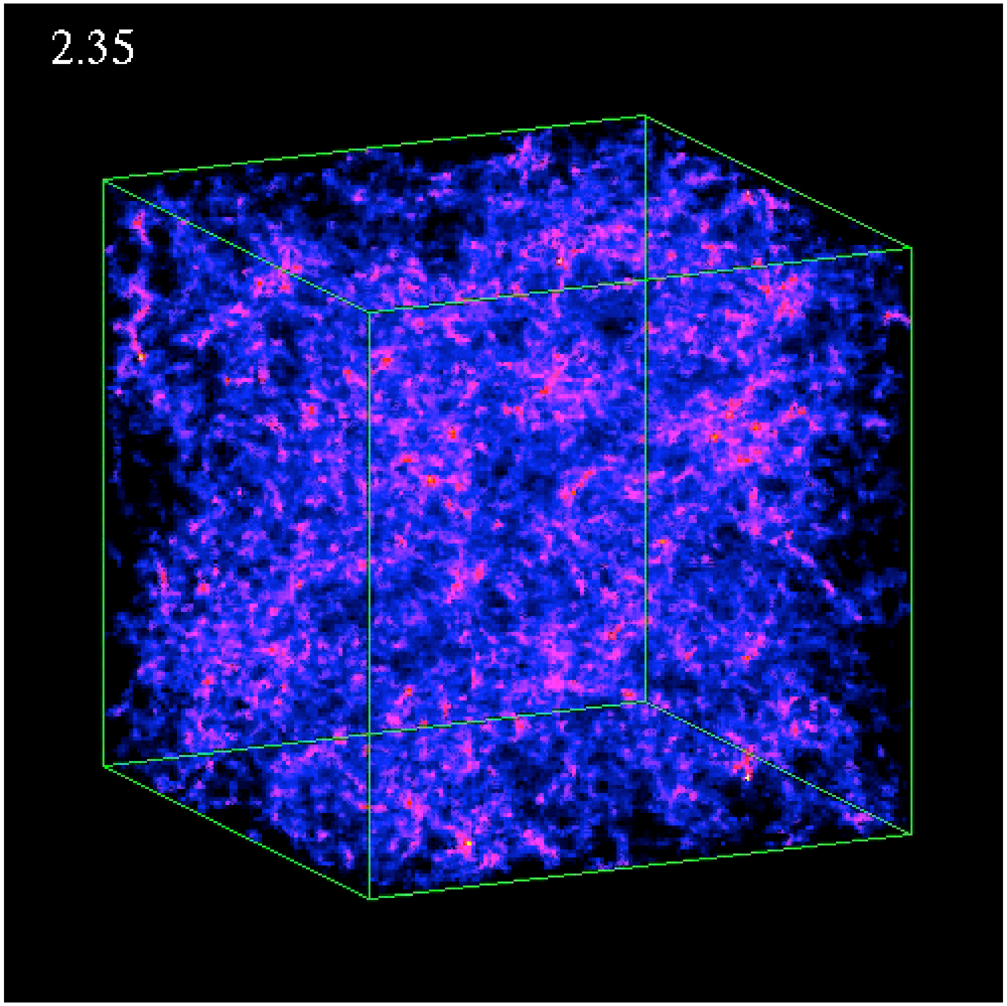
What is **Dark Matter**? Does **Dark Energy** really exist?

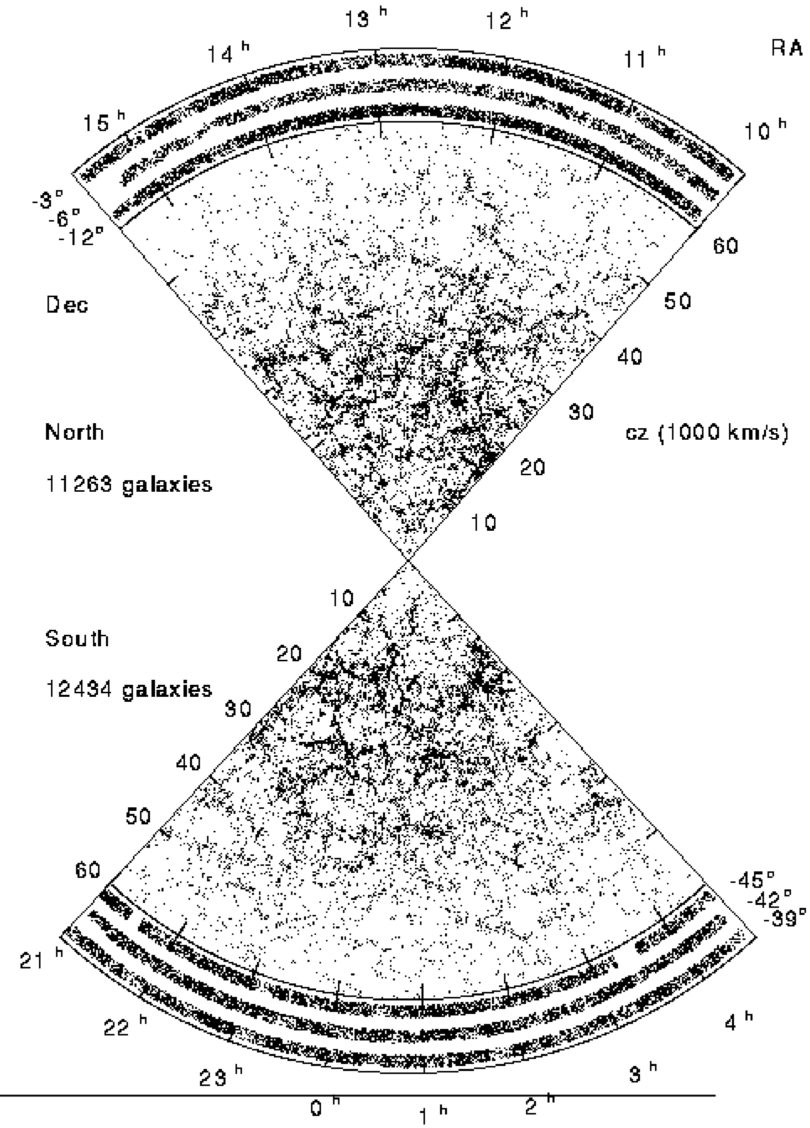
How did **Galaxies** form? Which came first, Black Holes or Galaxies?

How does our star work? Is **Life** in our galaxy unique?

What is the **ultimate fate** of the Universe?

Expanding universe - simulations and data



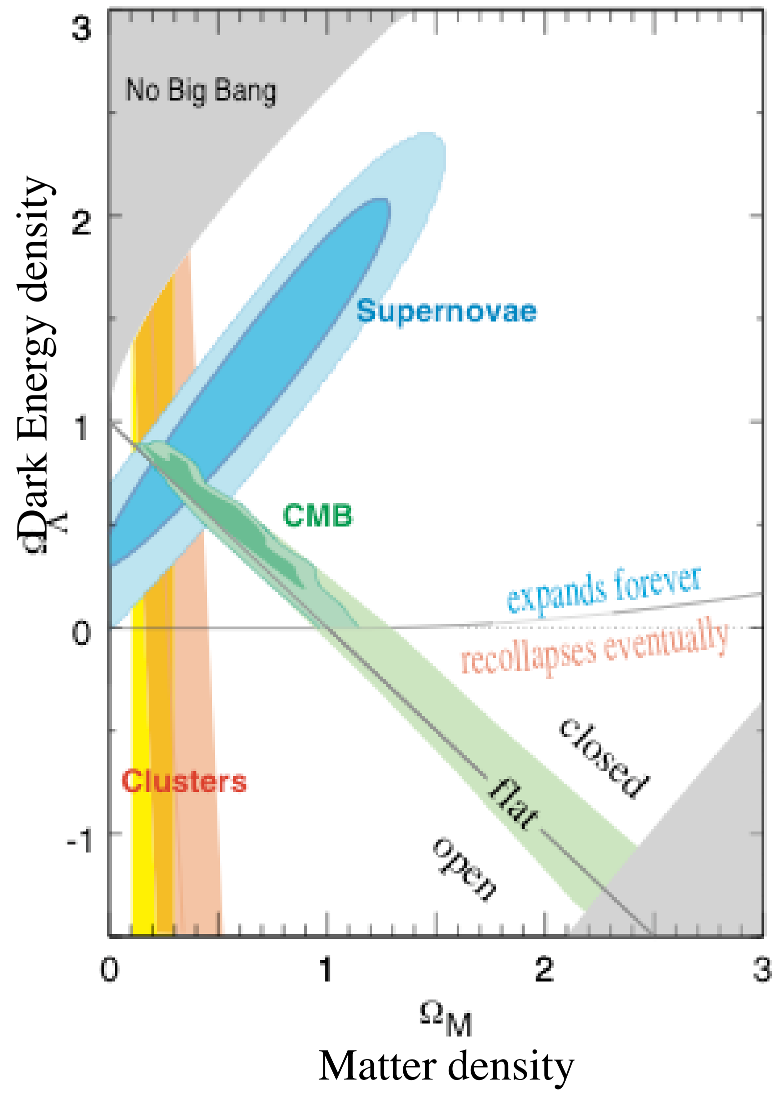


Concordance Model of Cosmology

- Supernovae + Cosmic Microwave Background + Large Scale Structure

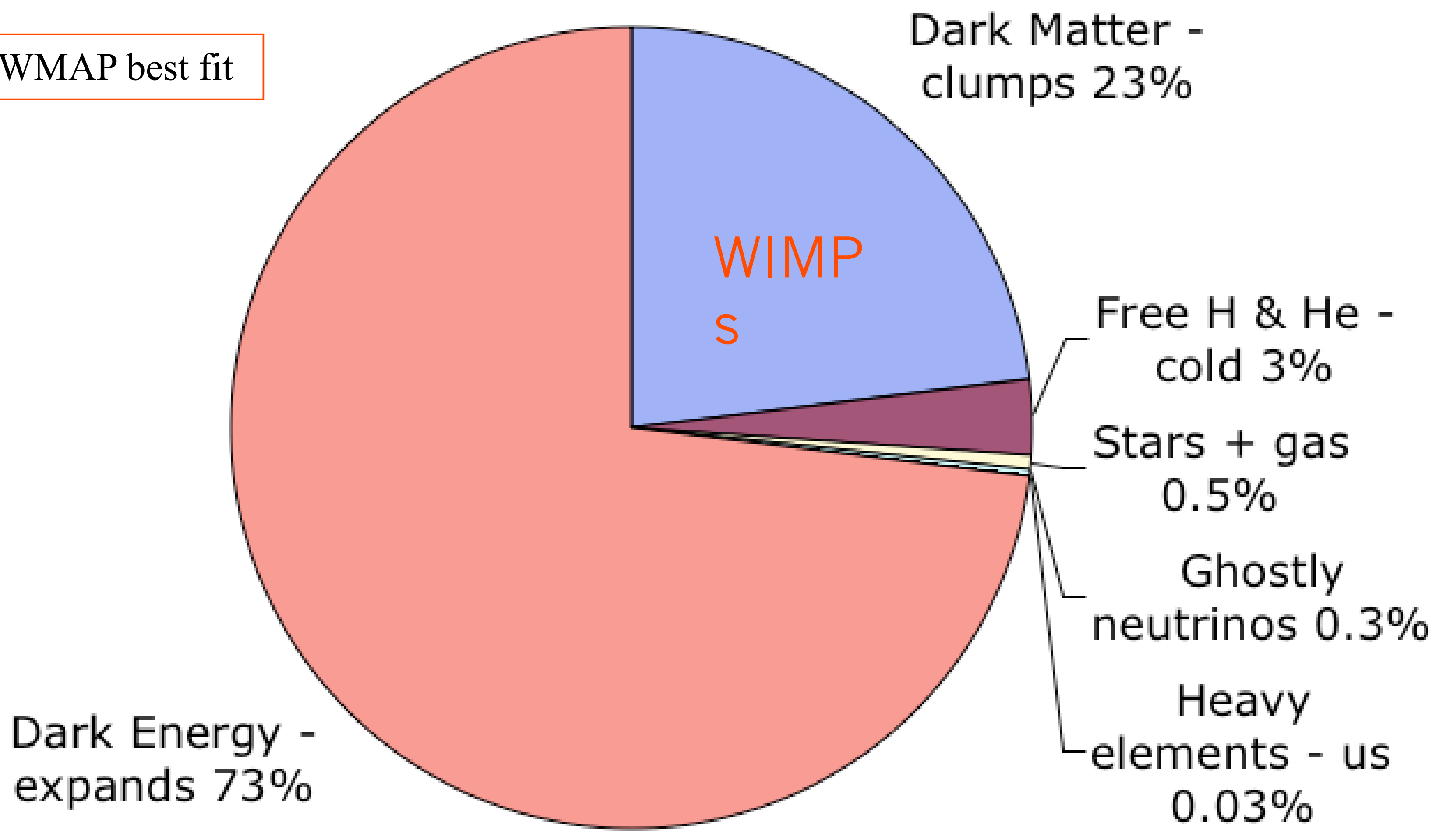
$$\text{WMAP} + \text{flat}:$$
$$\Omega_m = 0.27 \pm 0.04$$
$$\Omega_\Lambda = 0.73 \pm 0.04$$

- Great overall success!
- However raises even more questions about origin of dark energy



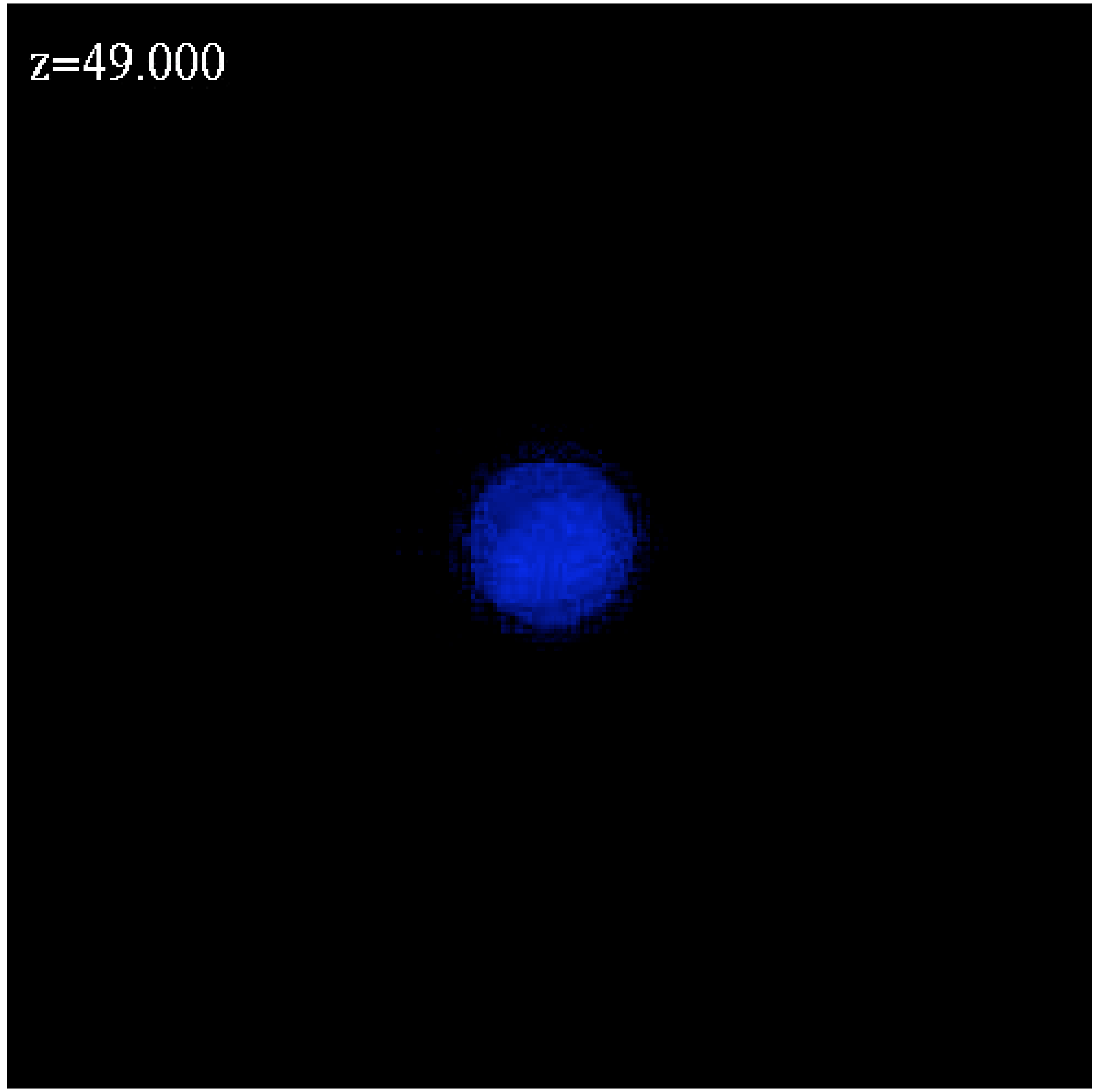
Composition of the Cosmos

WMAP best fit



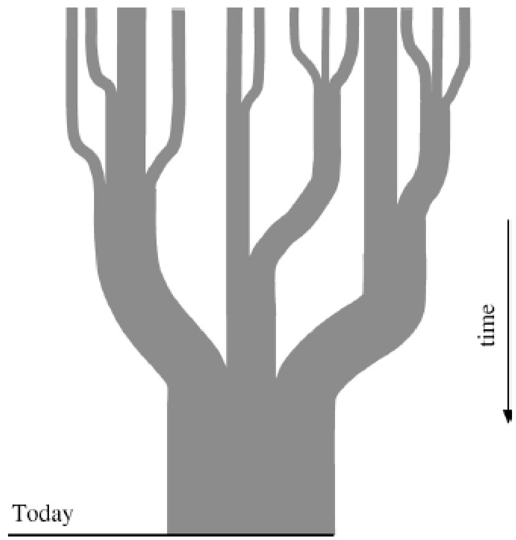
Dark Matter evolution

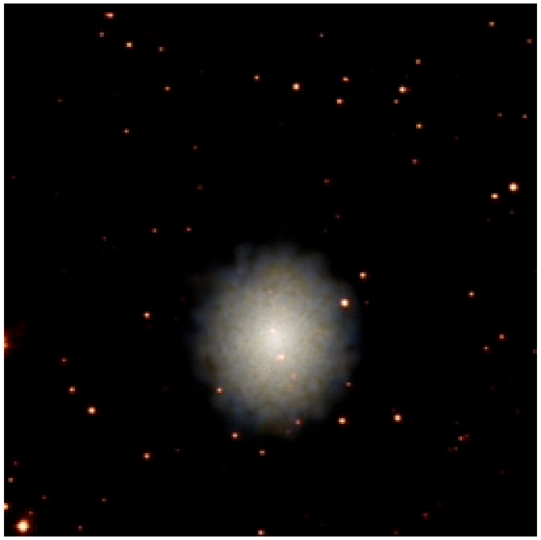
- ΛCDM numerical simulations agree well with observations
- Max Planck Institute Munich (Garching)

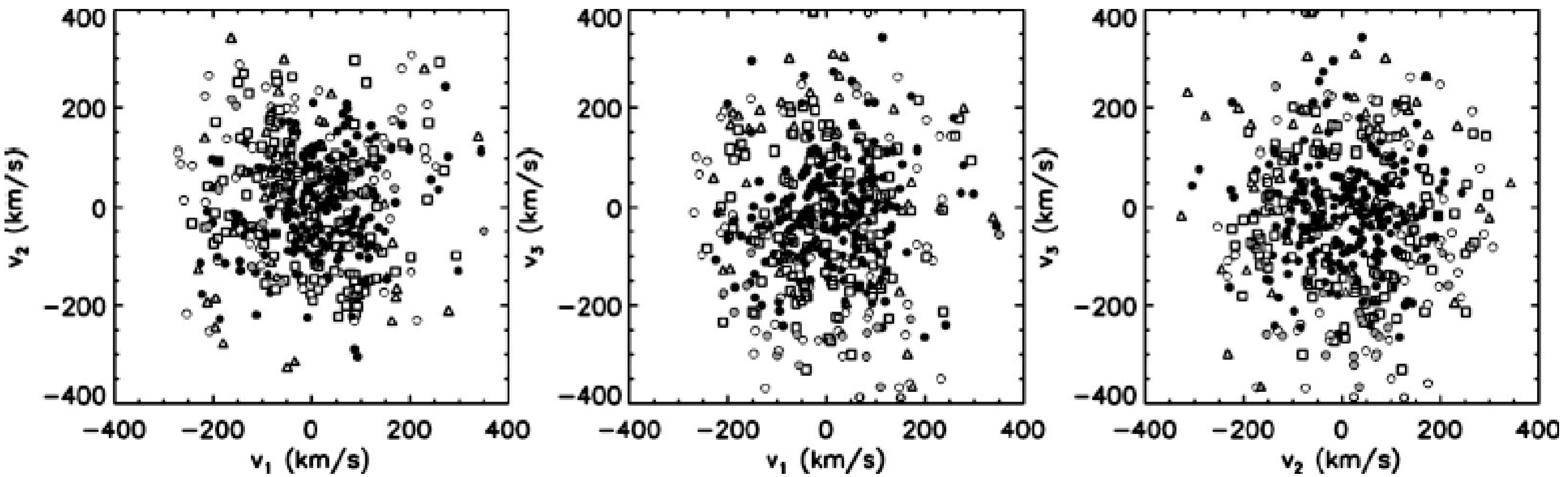


Numerical simulations

- The phase-space structure of a dark-matter halo: Implications for dark-matter direct detection experiments,
  A. Helmi, S. White, and V. Springel
  PRD 66, 063502 (2002)
- Solar system moves with respect to zero mean velocity halo at 220 km/s

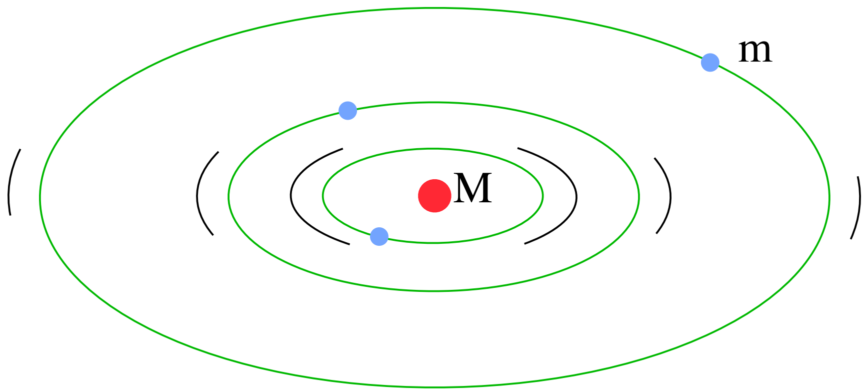






Rotation Curves and Galactic Dark Matter

- Solar System obeys Kepler laws

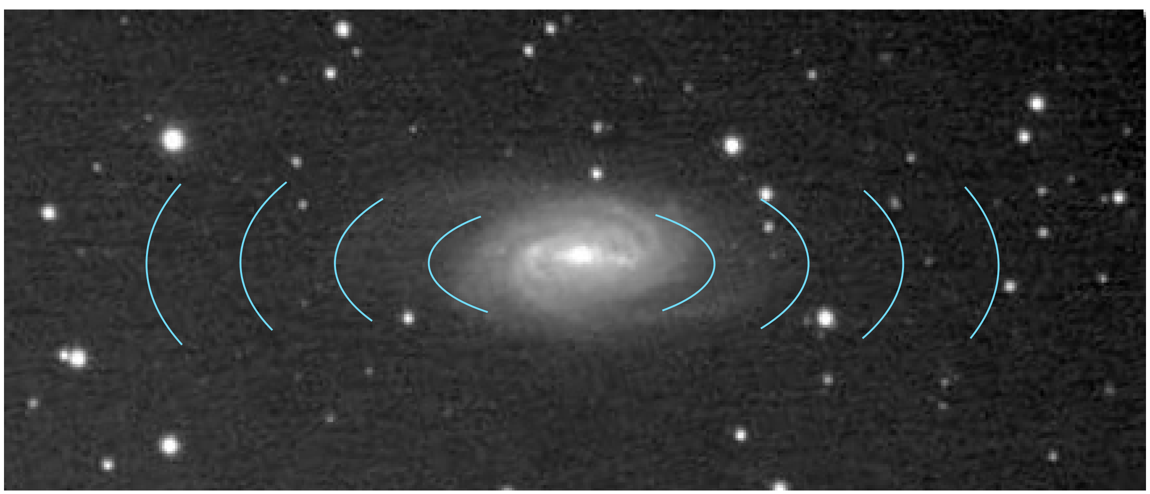


$$\vec{F} = -\frac{G M m}{r^2}\hat{r}$$

$$= -m\frac{v^2}{r}\hat{r}$$

$$v = \sqrt{\frac{G M}{r}}$$

- Galaxies have constant rotation curves



For :

$v \approx \text{constant}$

then :

$M(r) \propto r$

$M_{dark} \geq 10 M_{lum}$

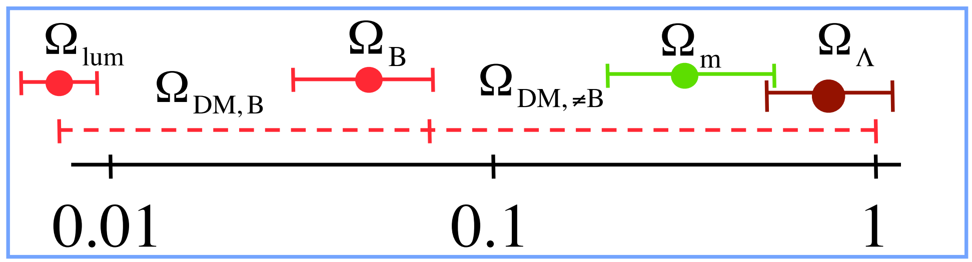
Strong motivation

- Cosmology
  - Theory: $\rho/\rho_{\text{crit}} = \Omega_{\text{m}}; \;\; \Omega_{\text{m}} + \Omega_{\Lambda} = 1; \;\; \Omega_{\Lambda} \neq 0$ still ugly!
  - Observation: $0.25 \leq \Omega_m < 0.30$

But favored by supernova data

- Nuclear Physics: baryons - p, n, e
  - Theory of formation of H, D, He, Li
  - Observations:

$$0.03 < \Omega_B < 0.05$$



- Astronomy: luminous matter
  - Stars & gas $\Omega_{lum} \approx 0.005$
- Baryonic dark matter is necessary: MACHOs at most 20% of halo mass
- Non-baryonic dark matter dominates universe

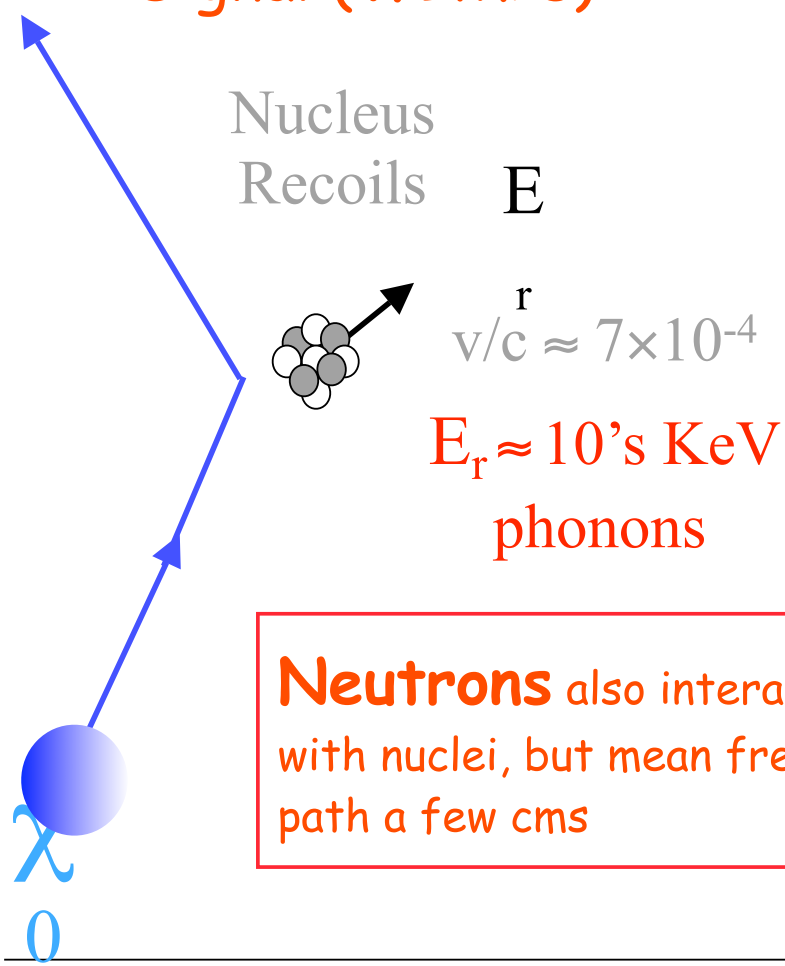
	hot	cold	Ω~1
axions		√	√
neutrinos	X		?
monopoles		√	X
WIMPs		√	√ √

best DM candidates (axions, WIMPs)

Supersymmetry LSP (WIMPs) $\chi = N_{10}^{*}\tilde{B} + N_{20}^{*}\tilde{W}^{3} + N_{30}^{*}\tilde{H}_{1}^{0} + N_{40}^{*}\tilde{H}_{2}^{0}$

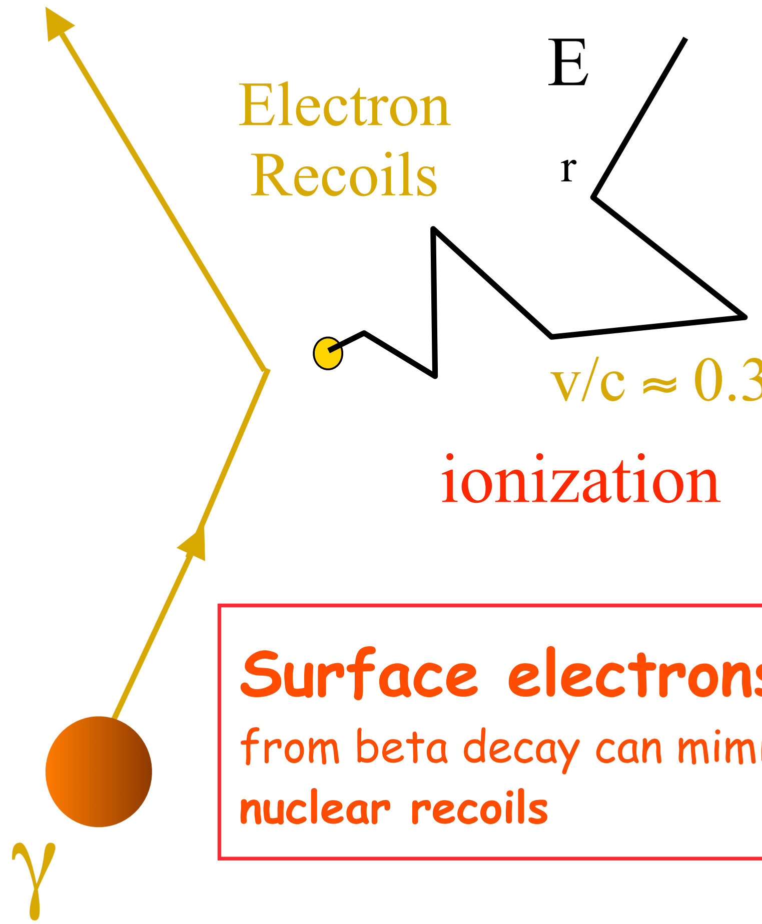
The Signal and Backgrounds

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**

Direct Detection of Neutralinos

- [e. g., Lewin & Smith; and Jungman, Kamionkowski & Griest]
- The observed differential rate of events is given by

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

R in evts/kg-d, typically $\sigma_{0,scalar} >> \sigma_{0,spin}$; ρ_0 WIMP (χ) at earth, ~ 0.3 GeV/cm^3

v_0 velocity of sun around galaxy, ~ 220 km/s

m_χ, m_N mass of neutralino & nucleus, $m_r = \dfrac{m_\chi m_N}{m_\chi + m_N}$; recoil energy $Q = \dfrac{m_r^2 v^2}{m_N}\left(1 - \cos\theta^*\right)$

- For a Maxwell distribution of incident velocities

$$T(Q) = \exp\left[-\left(v_{\min}/v_0\right)^2\right] \text{ where } v_{\min} = \sqrt{Q m_N / m_r}$$

$\eta(Q)$ is the detector efficiency as a function of Q

Spin independent scalar cross section

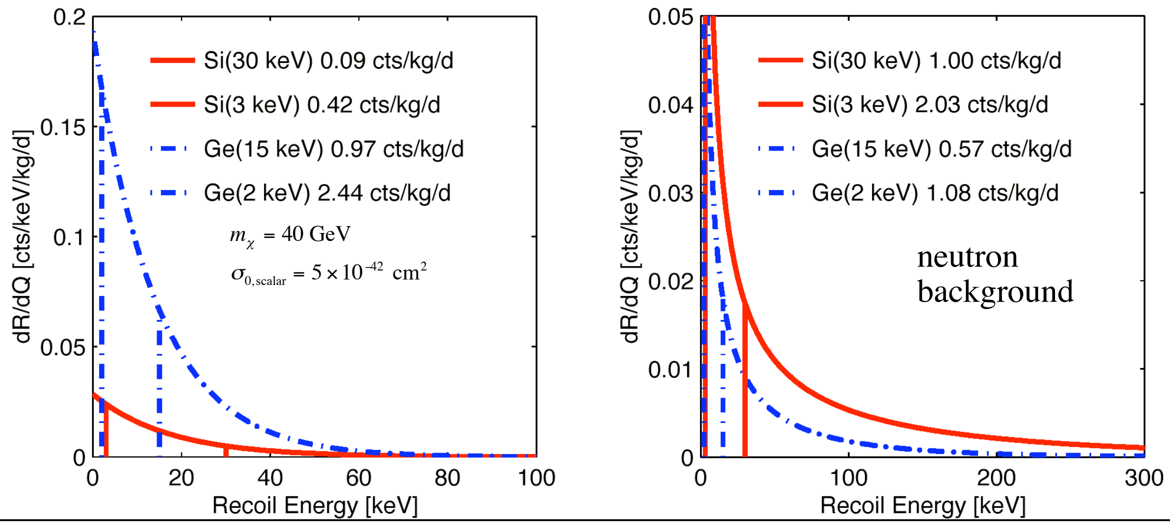
- To compare the coherent rates of different materials

$$\sigma_{0\,scalar} = \frac{4 m_\chi^2 m_N^4}{\pi \left(m_\chi + m_N\right)^2} \left(\frac{f_n}{m_n}\right)^2, \text{ where } f_n \cong f_p \text{ is the WIMP - nucleon coupling}$$

- We define the fundamental WIMP-nucleon cross section

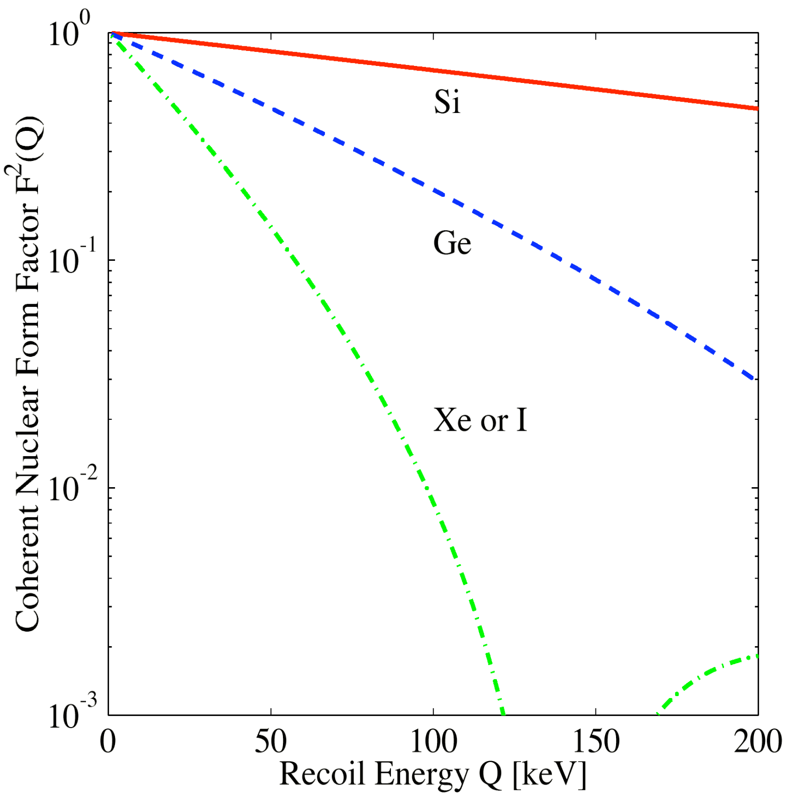
$$\frac{\sigma_{0\,Wn}}{m_{r\chi n}^2} = \frac{4}{\pi} f_n^2 = \frac{\sigma_{0\,scalar}}{A^2 m_{r\chi N}^2}, \text{ which gives } \sigma_{0\,Wn} \text{ in terms of } \sigma_{0\,scalar} \text{ with } A \cong m_N / m_n$$

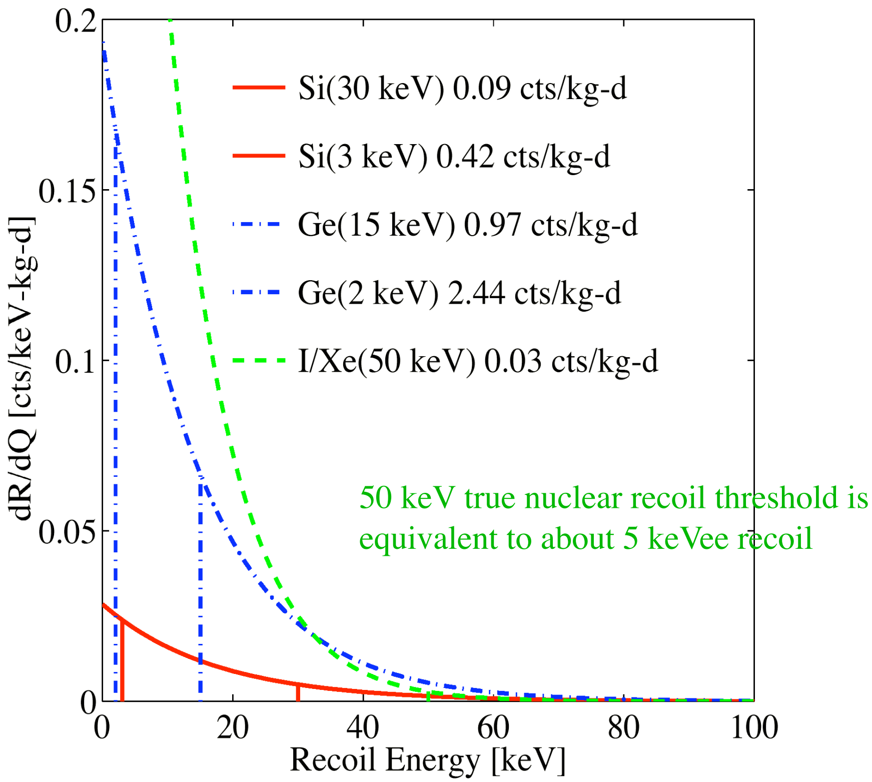
- Two target materials such as Si and Ge very powerful



Nuclear form factor suppression

- For spin-independent or coherent interactions the form factor $F^2(Q)$ suppression is shown below and results in suppressed rates for heavy nuclei





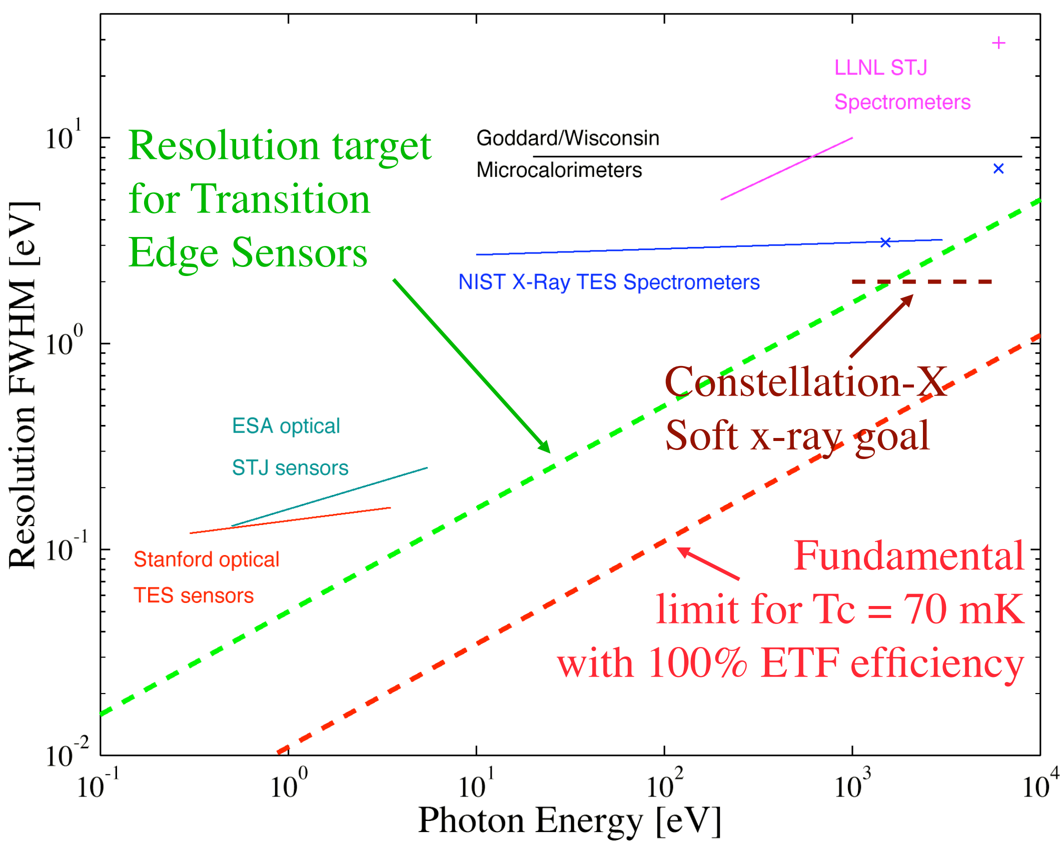
$$F(Q) = 3\frac{j_1(Q r_n/\hbar c)}{Q r_n/\hbar c} exp\left[-(Q s/\hbar c)^2/2\right], \text{ where } r_n \approx \left(0.89\,A^{1/3} + 0.3\right) \text{ fm and } s \sim 1 \text{ fm}$$

Superconducting 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;
- *X-Ray macropixel: Stanford/Lockheed/NIST
- Dark matter searches:
  - *CDMS collaboration: TES sensors on Ge and Si crystals
  - *SuperCDMS 25 kg experiment and then towards 1000 kg;
  - CRESST search uses SPT with SQUID readout (slower related technology)

TES Single Photon Detectors

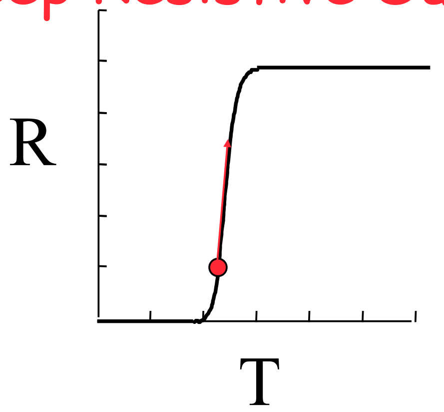
- **Demonstrated Sensitivity with TES**



- 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

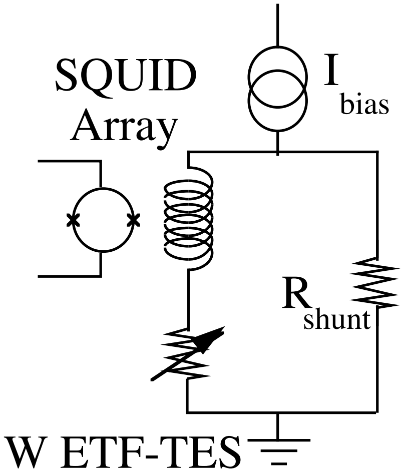
The Joule heating produced by bias

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

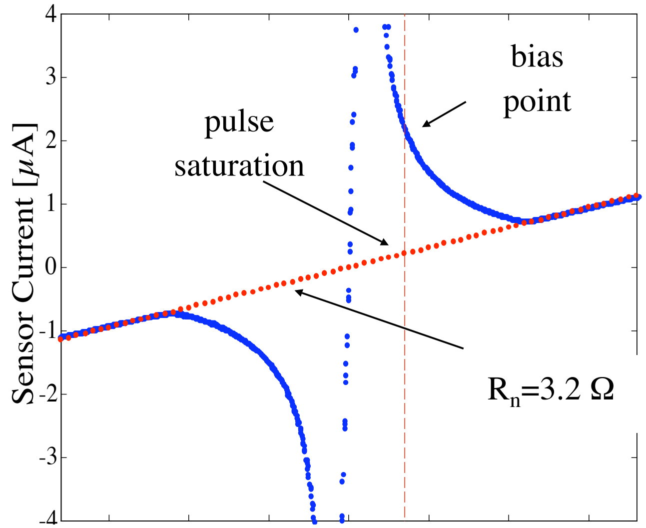
is stable whereas for current bias

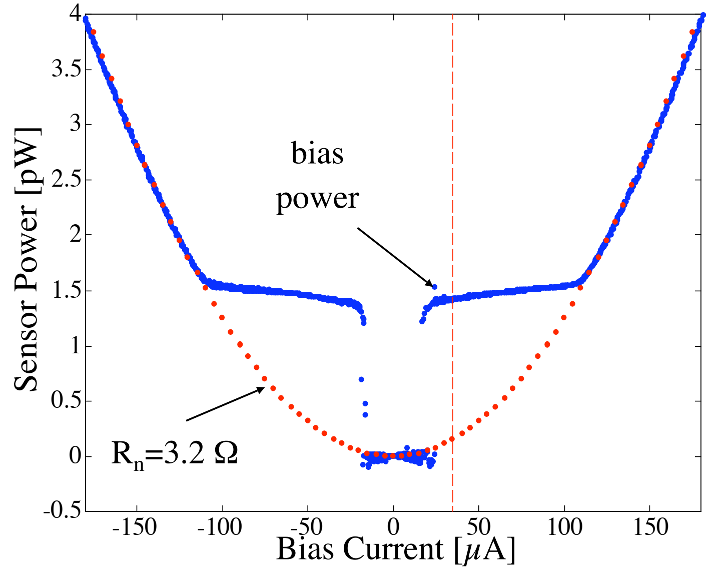
$$P_J = I_B^2 R \quad \Rightarrow \quad P_J \uparrow \text{ when } R \uparrow$$

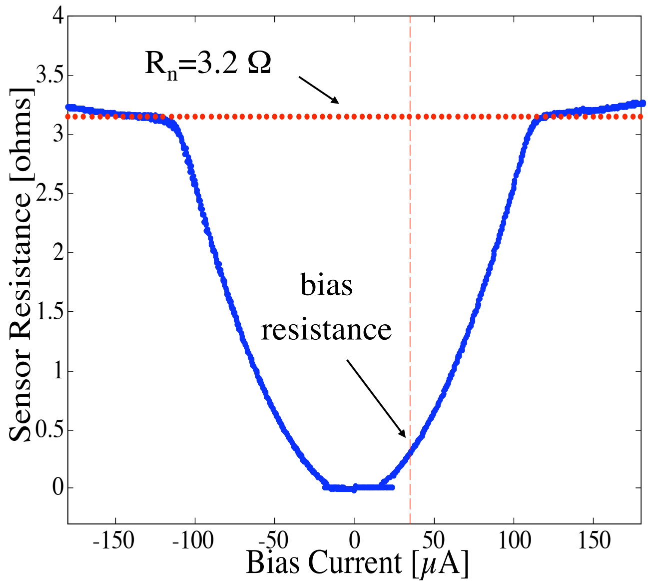
which is intrinsically unstable



Characterize Performance of TES

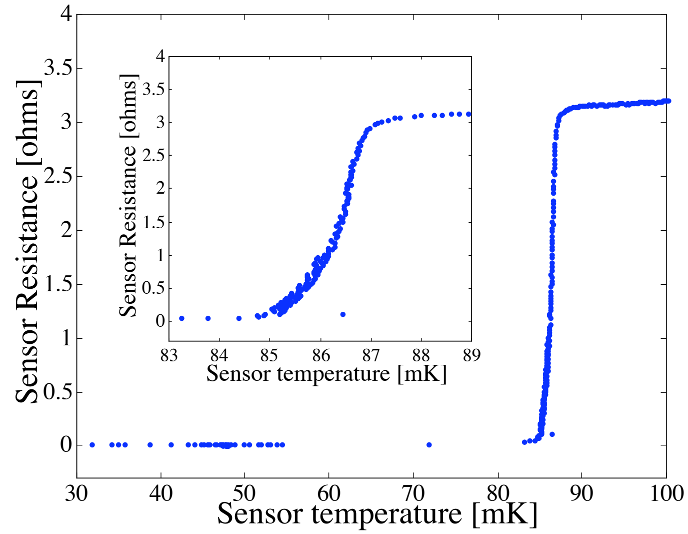






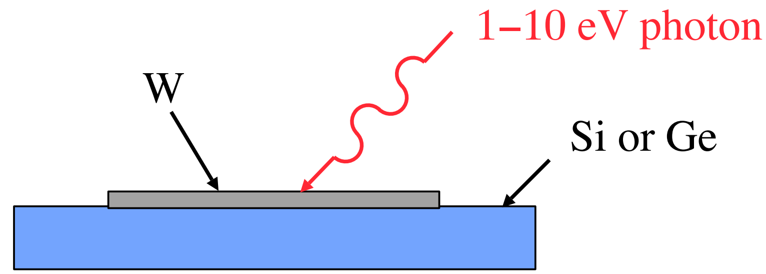
We calculate transition width from power curve using

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

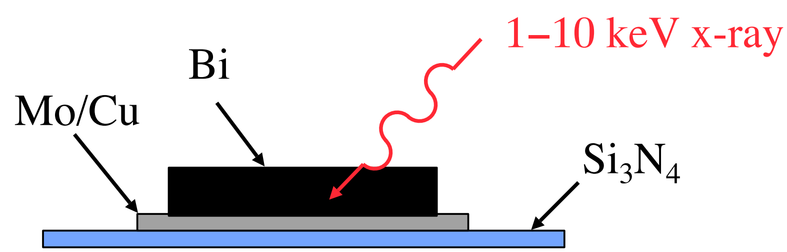


Three Types of Detectors

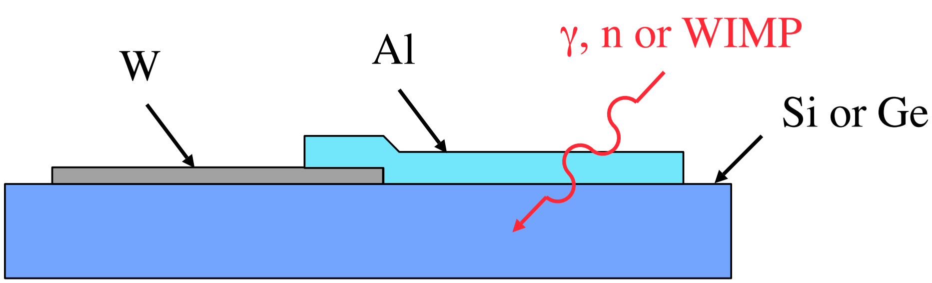
- Direct absorption of photon in TES (e. g., IR-optical-UV photons)



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

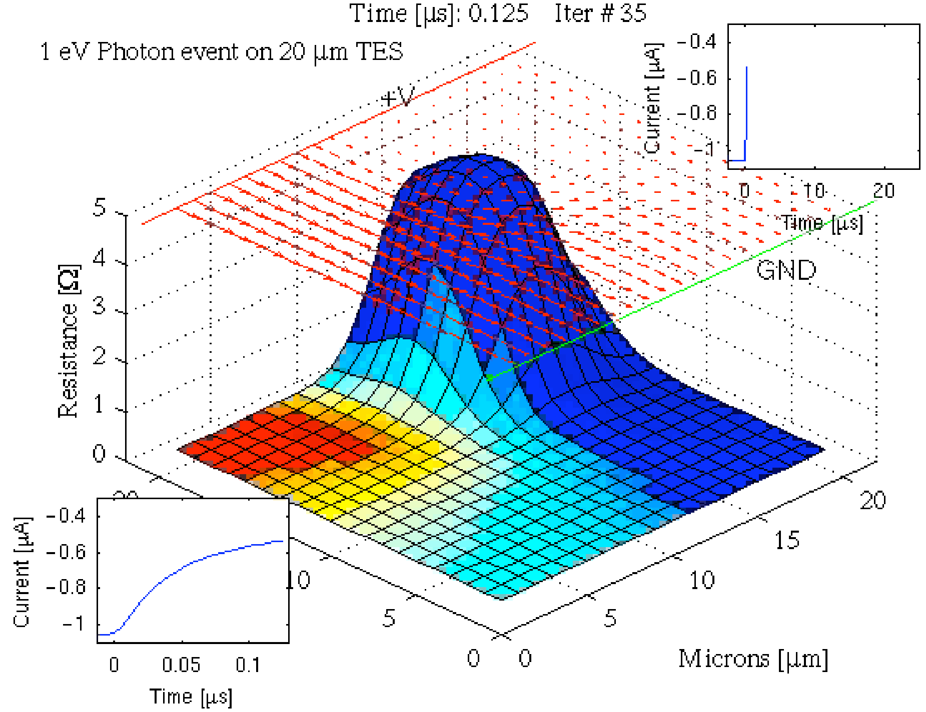


- Large mass absorbers generate phonons which are converted into quasiparticles which diffuse to the TES



TES Simulation

- Optical photon absorbed in TES (Tali Figueroa)

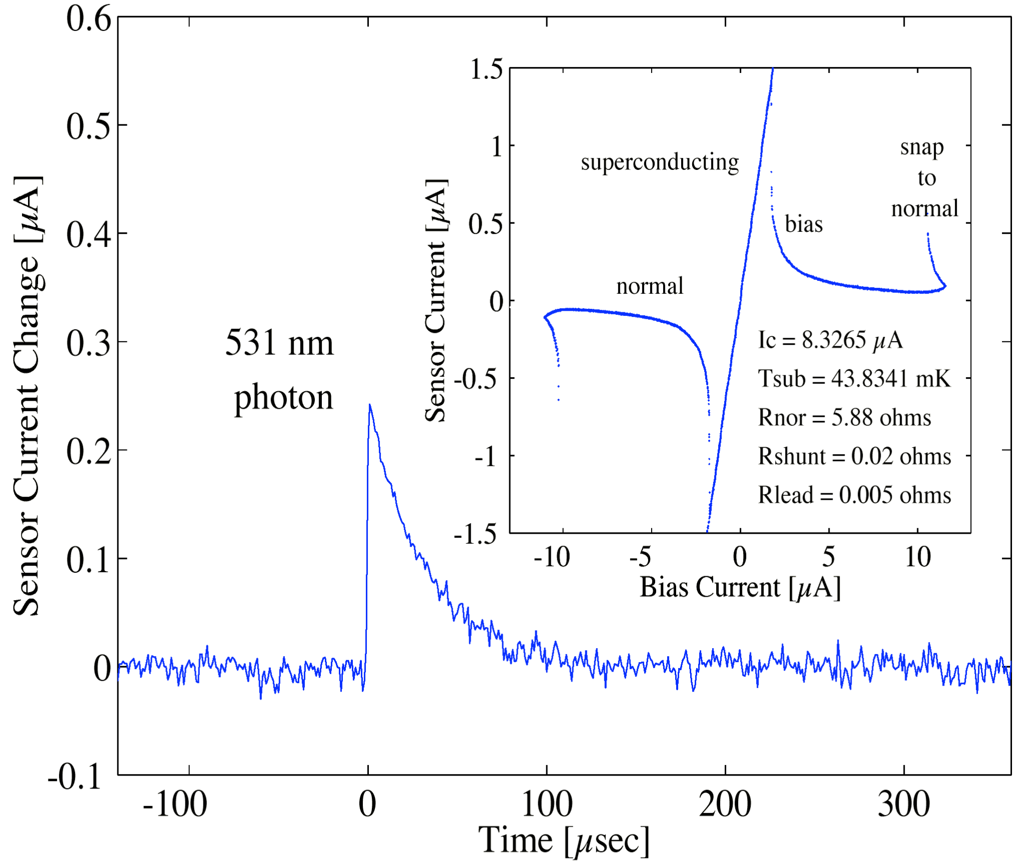


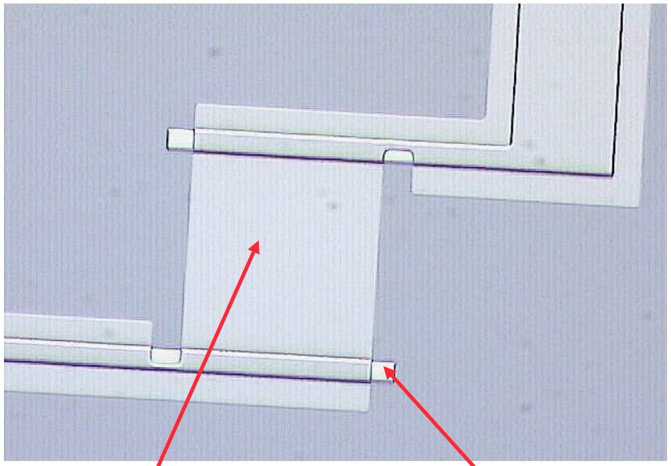
Science Objectives for Optical/UV TESs

- 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**



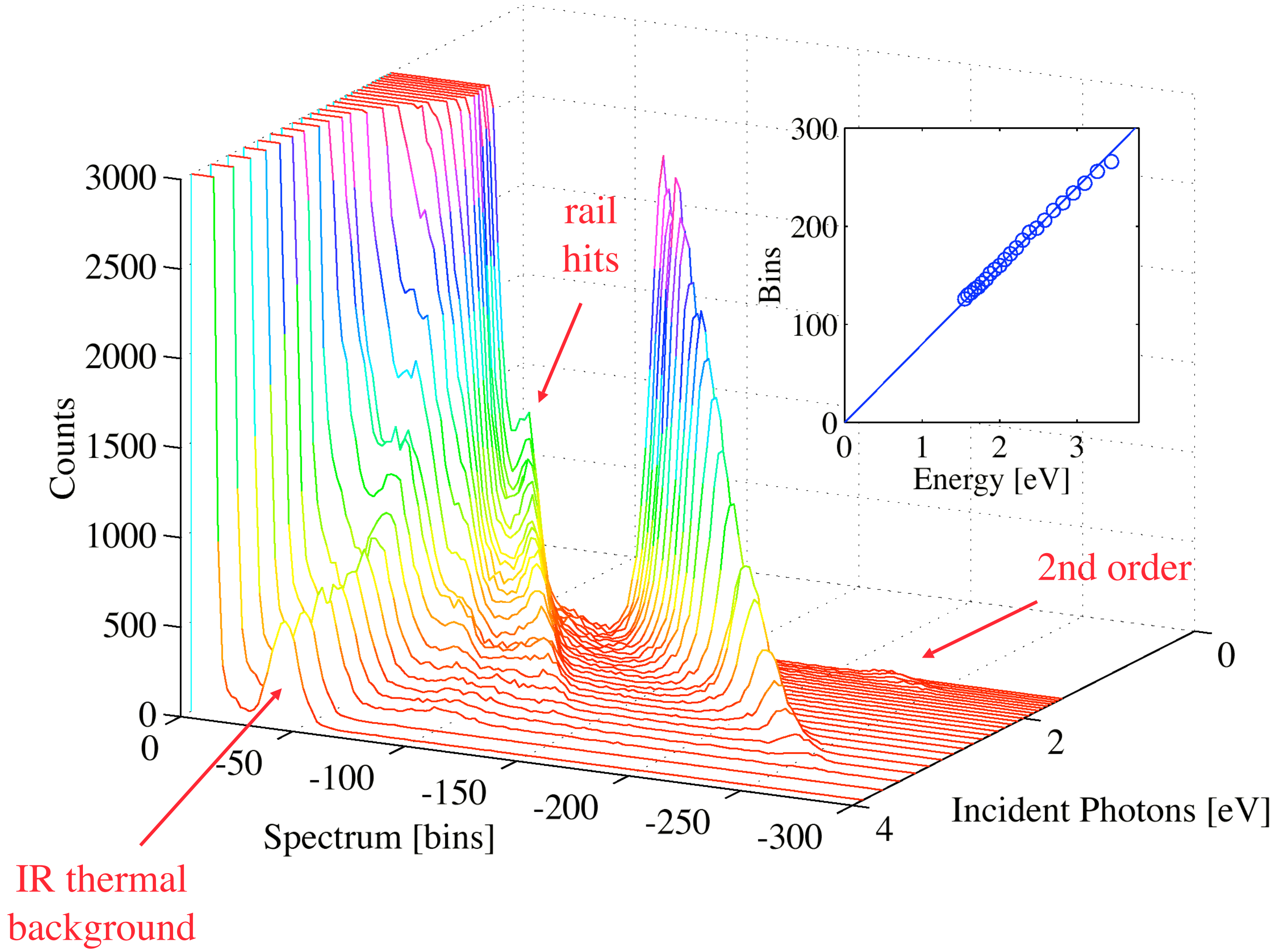


active W sensor

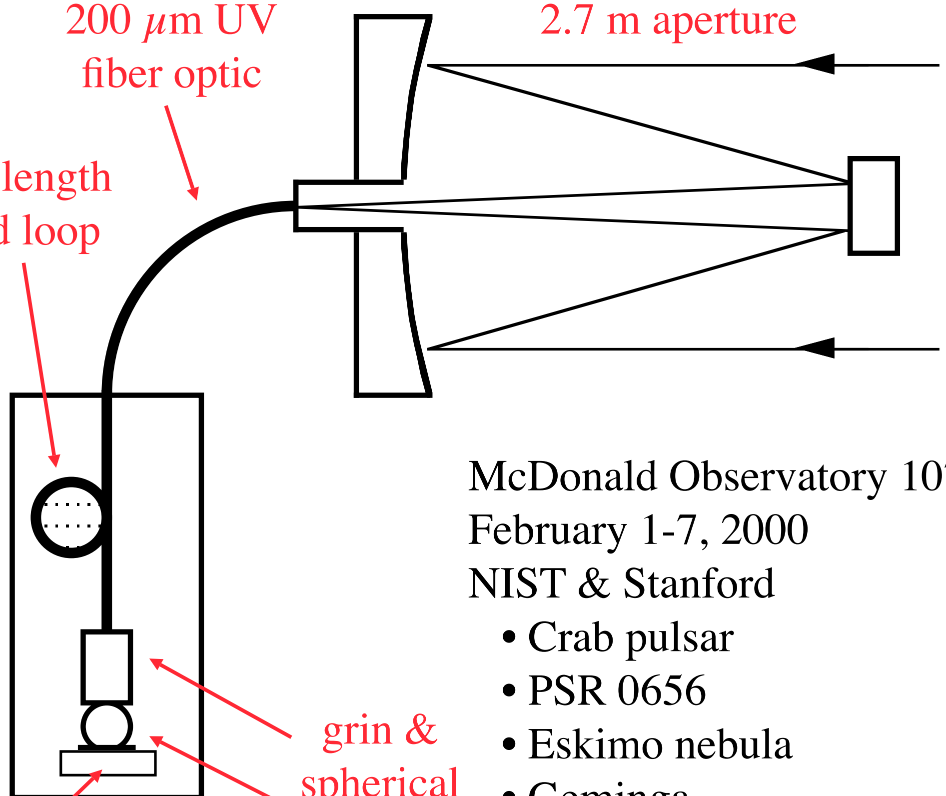
Al voltage rails

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

Monochromator Calibrations

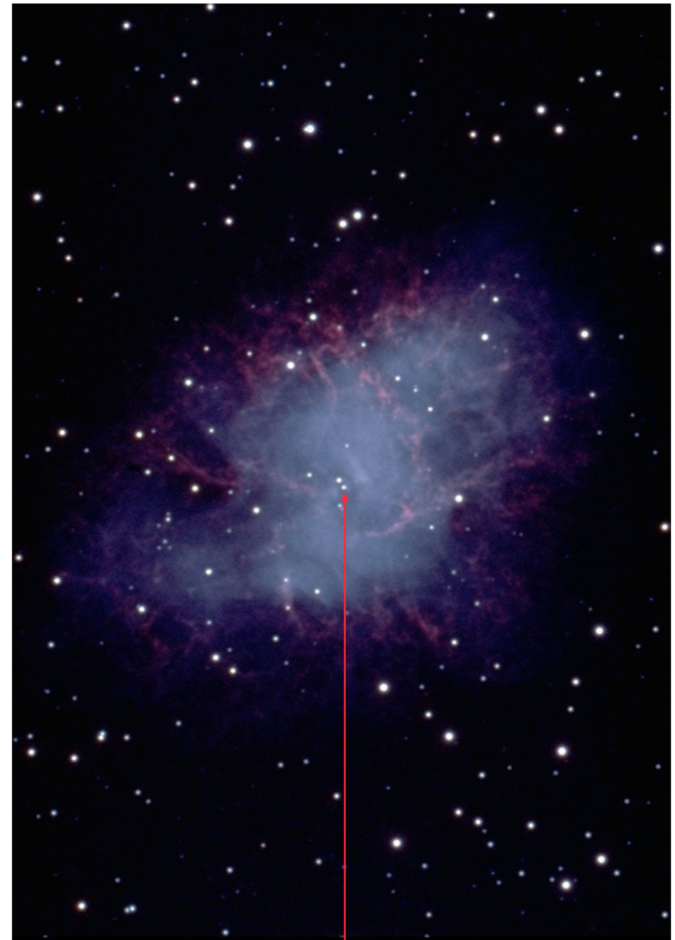


McDonald Observatory 107"

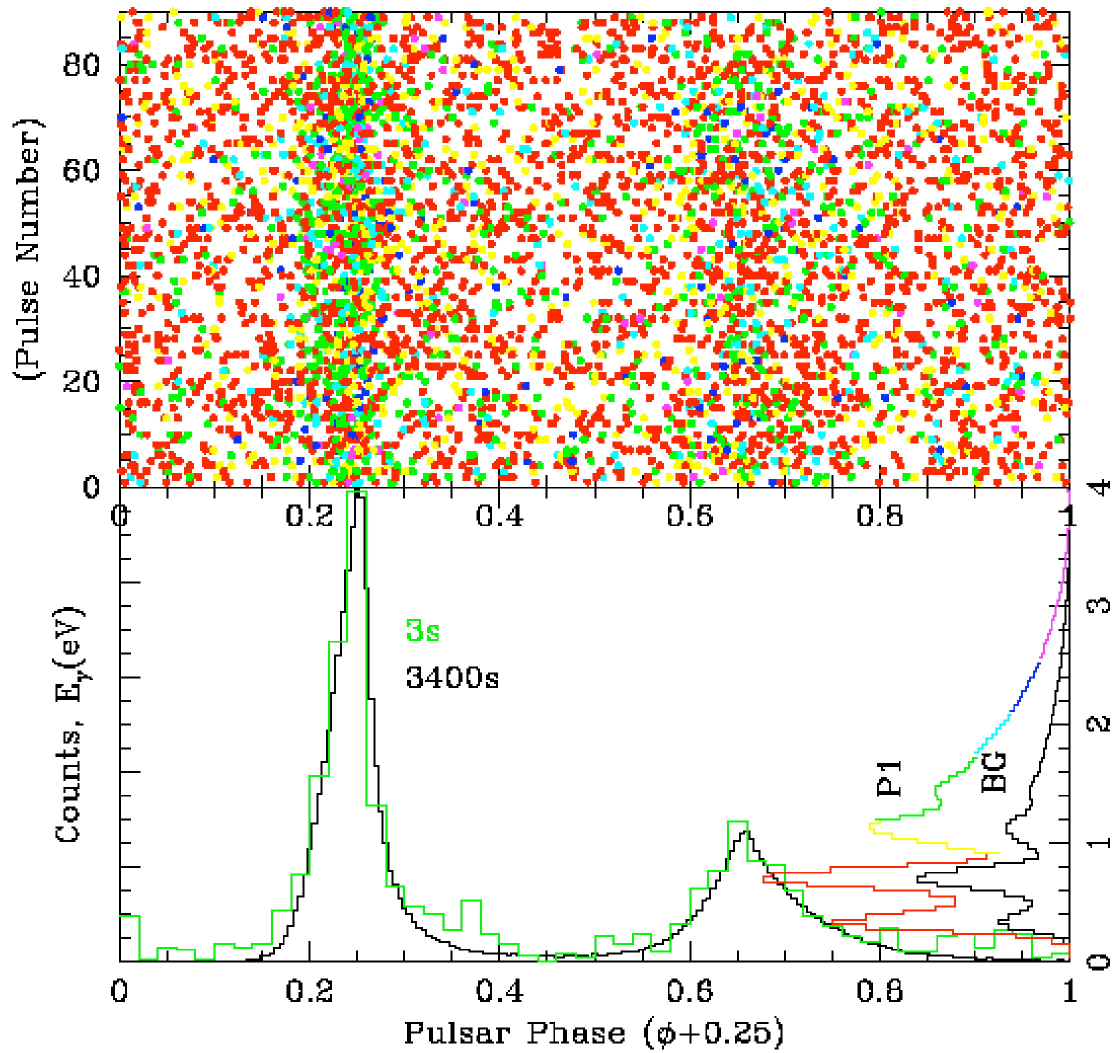


McDonald Observatory 107"
February 1-7, 2000
NIST & Stanford

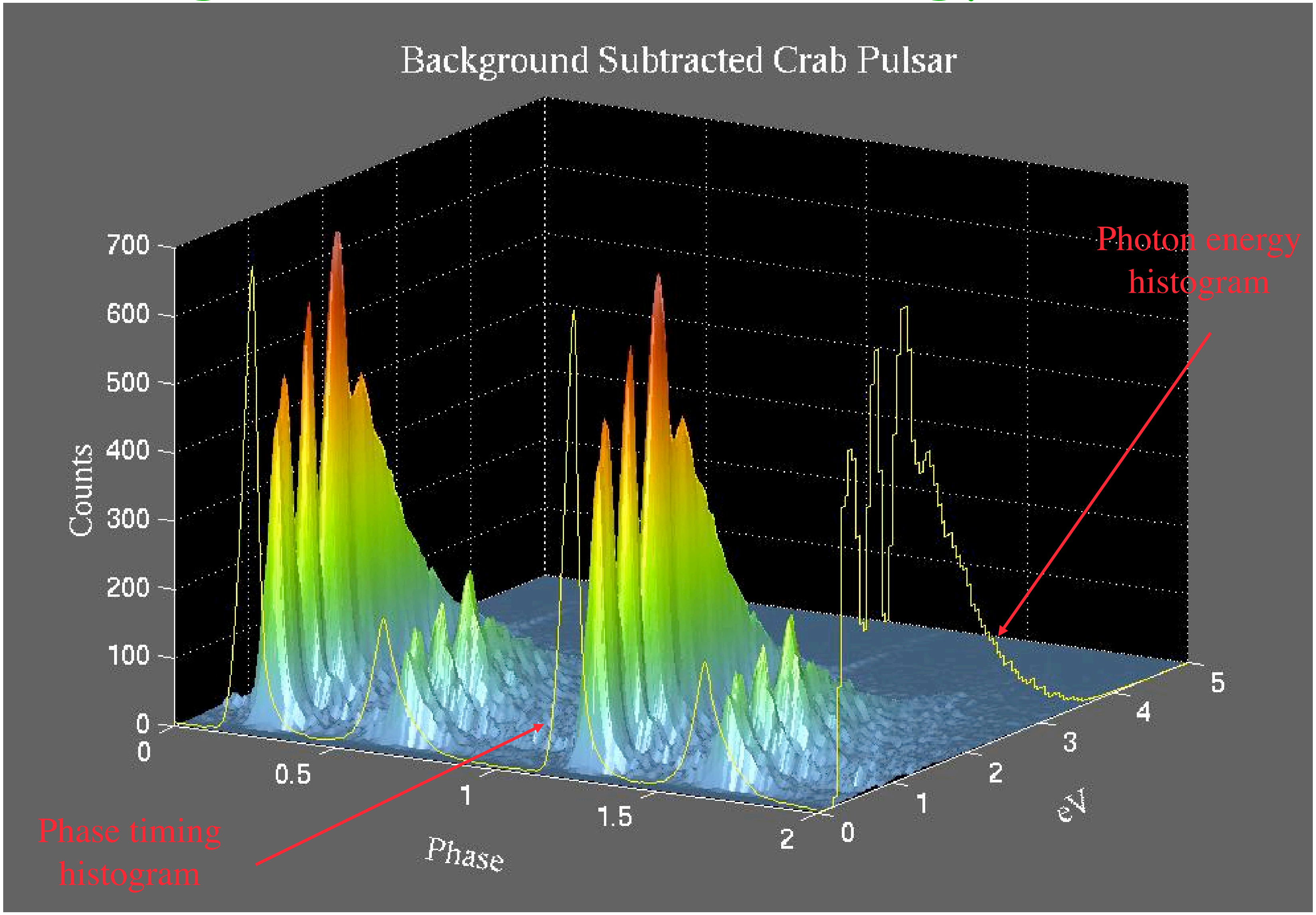
- Crab pulsar
- PSR 0656
- Eskimo nebula
- Geminga
- ST-LMI white dwarf
- Hercules X1
- calibration stars



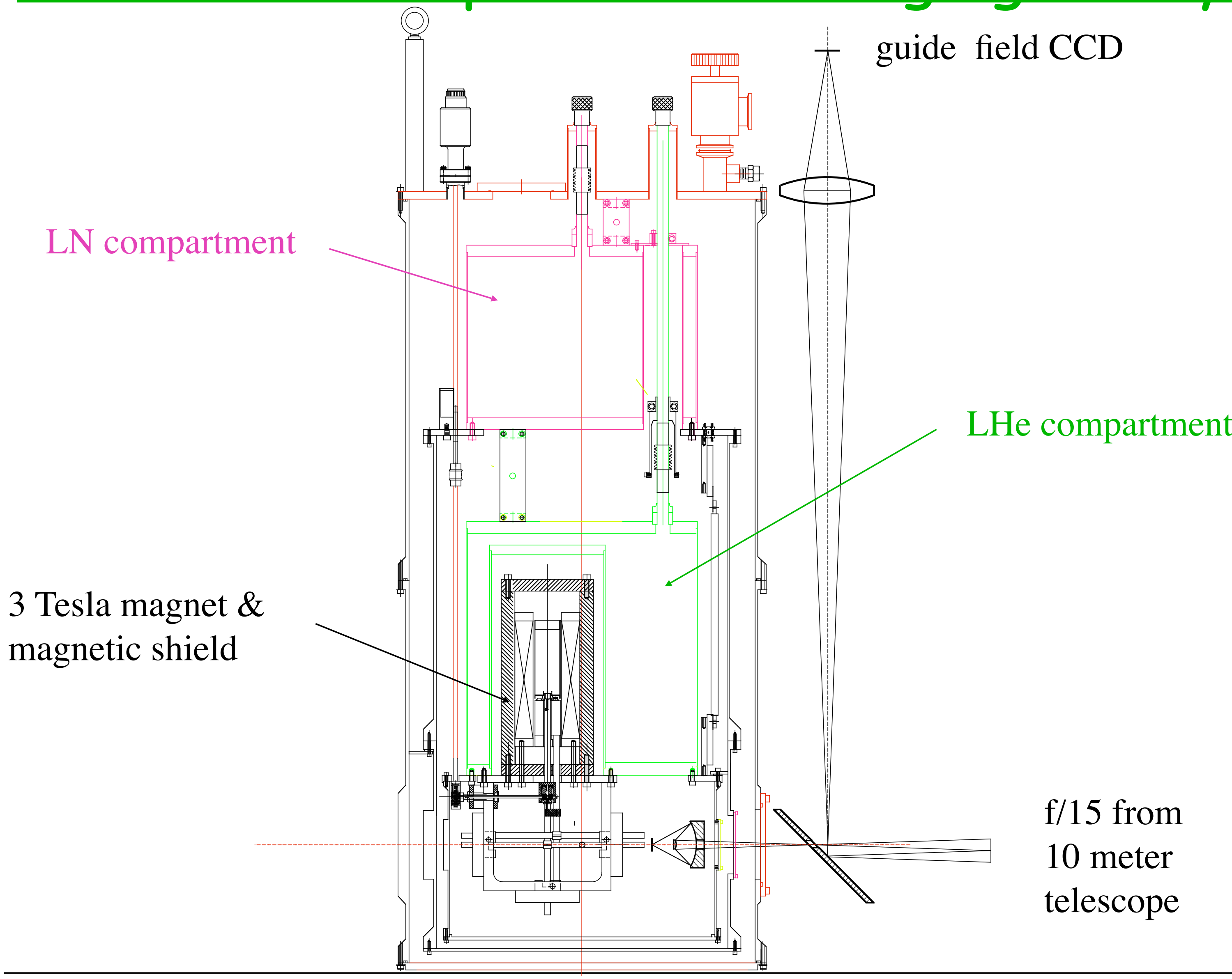
Crab Pulsar Data from McDonald 107"



Background Subtracted Energy vs Phase

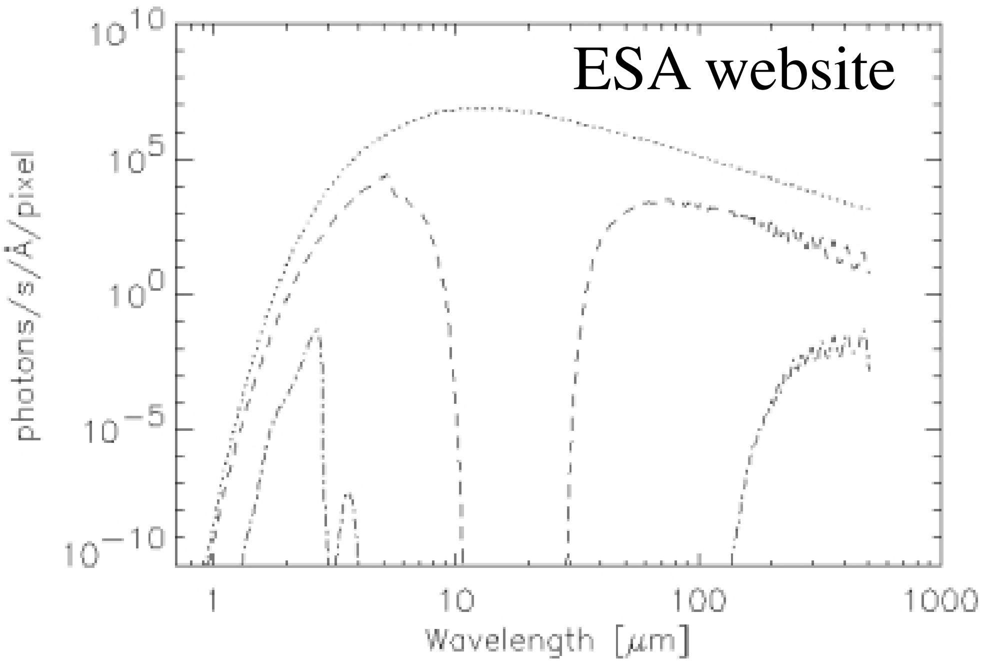


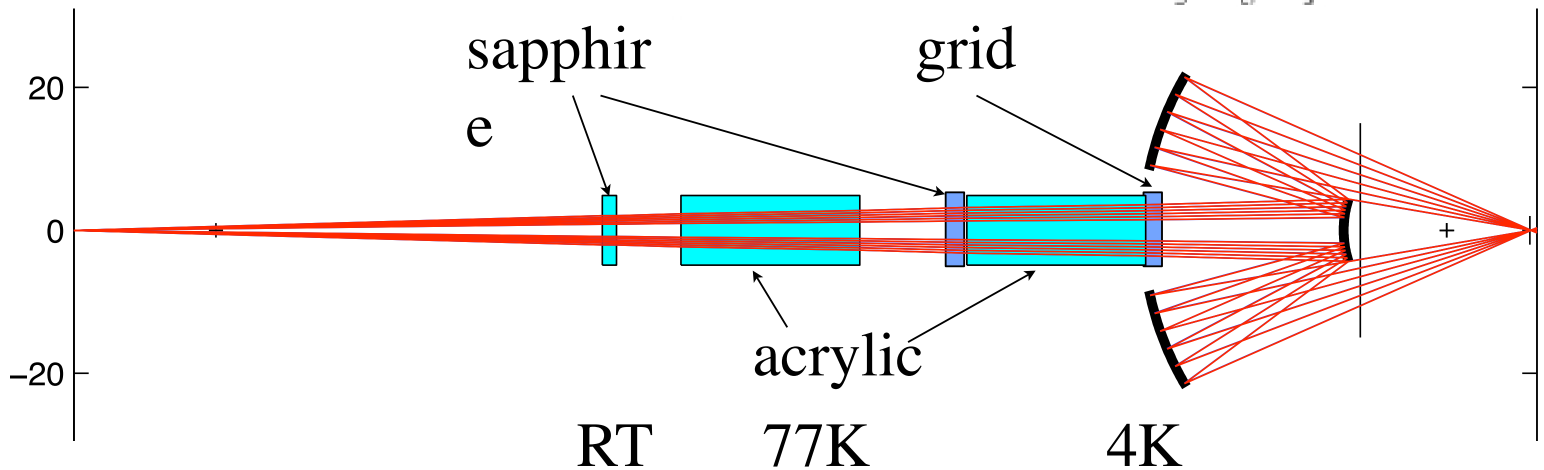
ADR for Optical/UV Imaging Array



Infrared Loading a Challenge

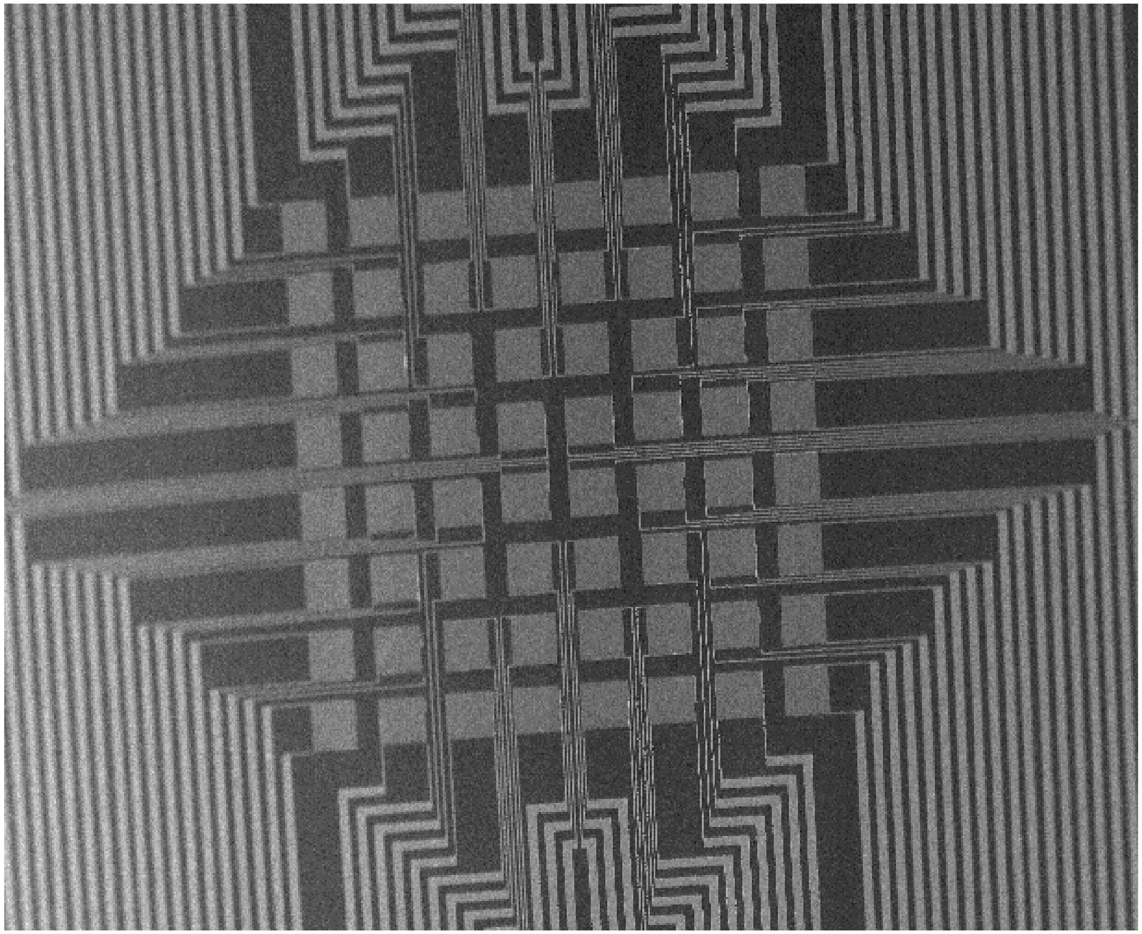
- Block ~2 μm and ~100 μm using sapphire, KG-3, KG-5, acrylic, and grid filters





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.