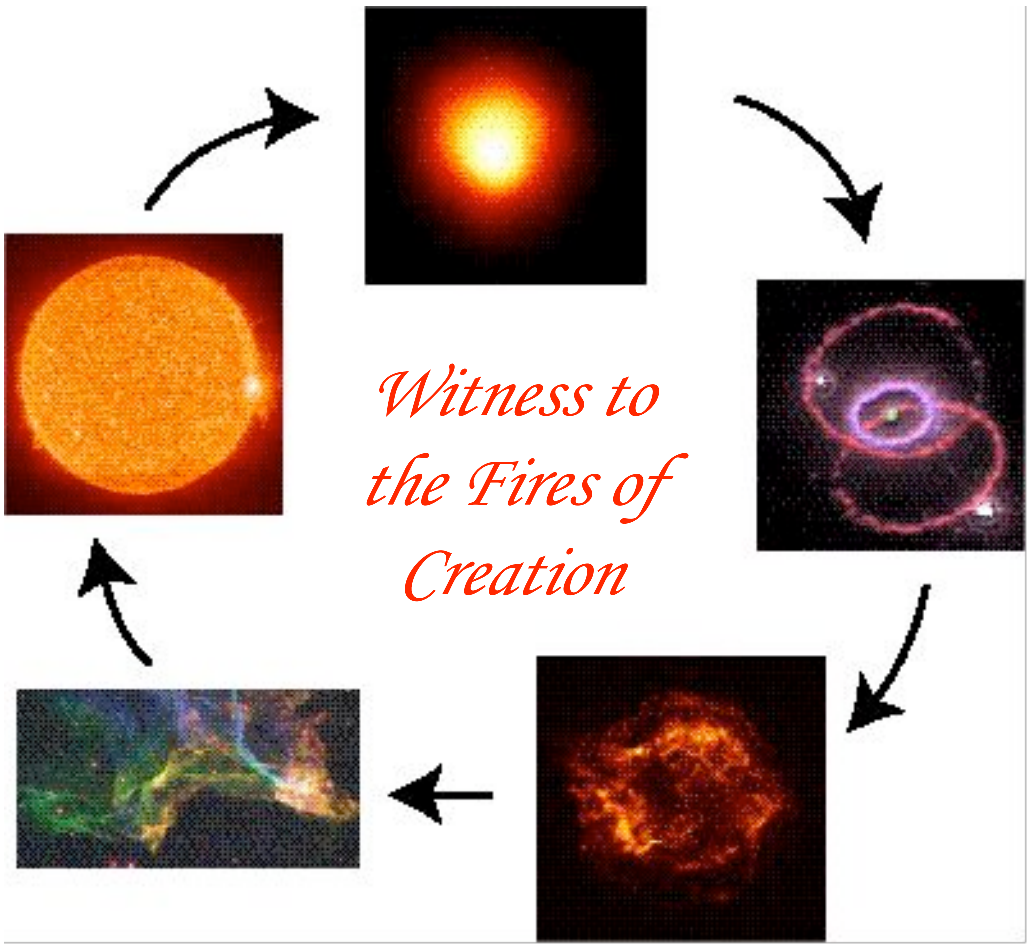
The Advanced Compton Telescope

1. ACT science goals
2. ACT instrument/mission
3. NCT balloon payload

Q: How sensitive?



"to uncover how supernovae and other stellar explosions work to create the elements"
-SEU Roadmap 2003

Steve Boggs
Department of Physics
University of California, Berkeley

KITP/UCSB 3/13/07

Do we wait until >2025?

- What sensitivity threshold is interesting?
- 5-10 SNe Ia, $\Delta M_{56}/M_{56} < 10\%$?
- Narrow FoV, pointed telescope?
- Driven by optical triggers?
- What is distance uncertainty at 20 Mpc?

Questions I am working on this week:

- is M_{56} interesting on its own?
- ΔM_{56} achievable on a small mission
- catalogue of all optical SNe Ia < 50 Mpc in 2005-2006, distances, discovery time
- distance uncertainties to out to Virgo

ACT Overview

Enable high sensitivity γ-ray spectroscopy

Life Cycles of Matter

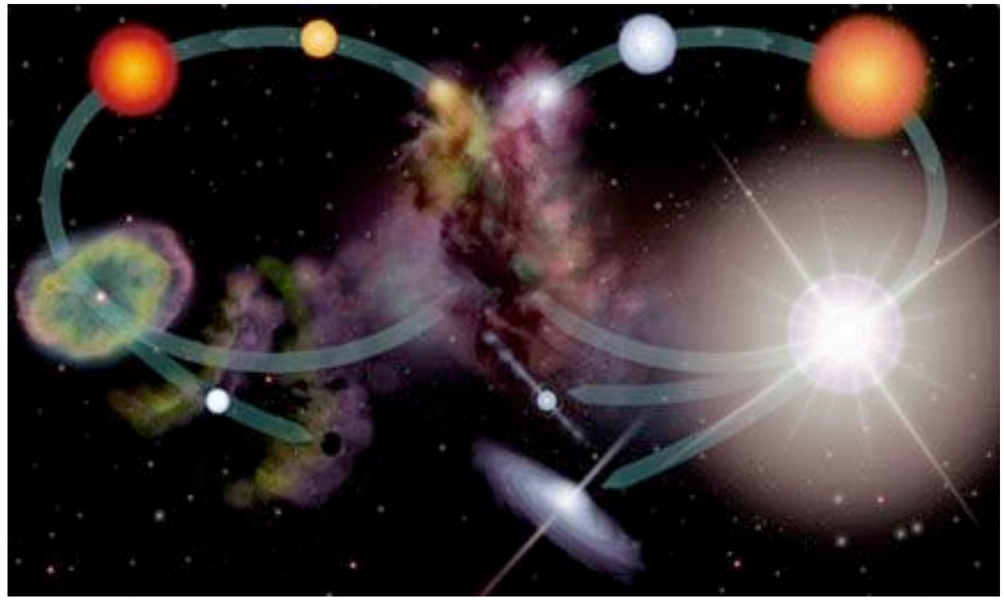
- ✓ Supernovae & nucleosynthesis
- ✓ Supernova remnants & interstellar medium
- ✓ Neutron stars, pulsars, novae

Black Holes

- ✓ Creation & evolution
- ✓ Lepton vs. hadron jets
- ✓ Deeply buried sources

Fundamental Physics & Cosmology

- ✓ Gamma-ray bursts & first stars
- ✓ History of star formation
- ✓ MeV dark matter



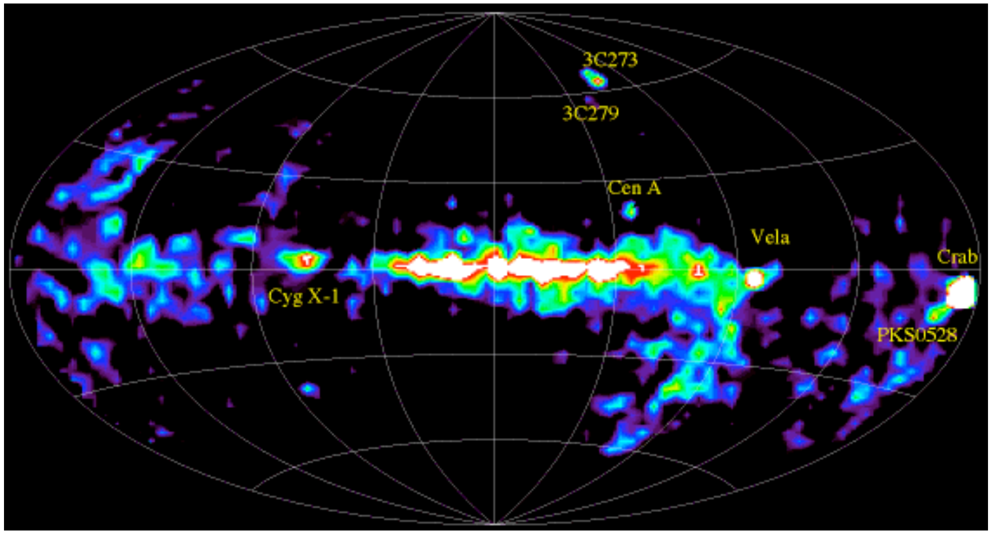
- 100× sensitivity improvement for spectroscopy, imaging & polarization (0.2-10 MeV)
- Advanced 3-D positioning γ-ray spectrometers, 25% sky field-of-view
- LEO equatorial orbit, zenith-pointing survey mode (baseline mission), 80%/orbit

Cosmic High Energy Laboratories

Why MeV gamma-rays?

Unique 0.2-10 MeV Science
- nuclear lines
- e-/e+ mass, annihilation
- peak emission: AGN, BHs, GRBs
- polarization

COMPTEL 1-30 MeV Source Catalog



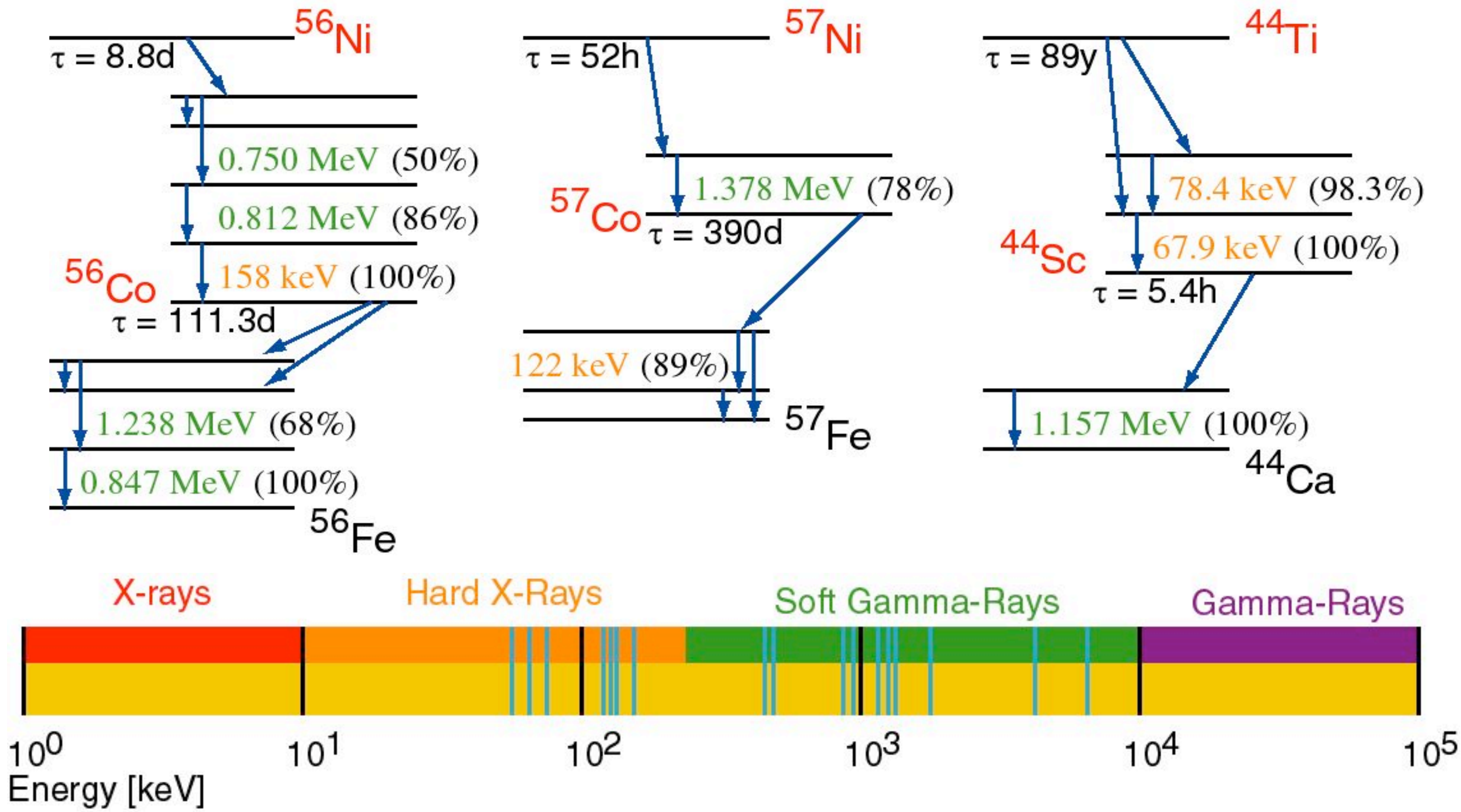
(Schönfelder et al. 2000)

Sources (5 yr)	COMPTEL	ACT
Supernovae	1	100-200
AGN	15	200-500
Galactic	23	300-500
GRBs	31	1000-1500
Novae	0	25-50

"…to explore the profound mysteries of life, space, time and the workings of the universe."

-NASA Space Science Enterprise Strategy 2003

Nuclear Gamma-Rays



Nuclear Gamma-Rays: ~60 keV - 6 MeV

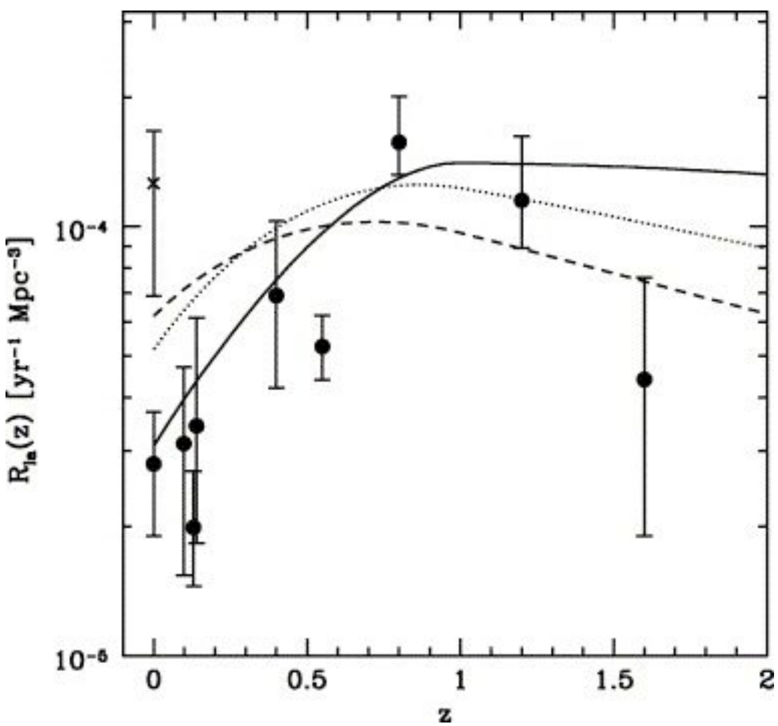
Hard X-rays (Photoabsorption): 10-300 keV

Soft Gamma-Rays (Compton Scattering): 0.3-10 MeV

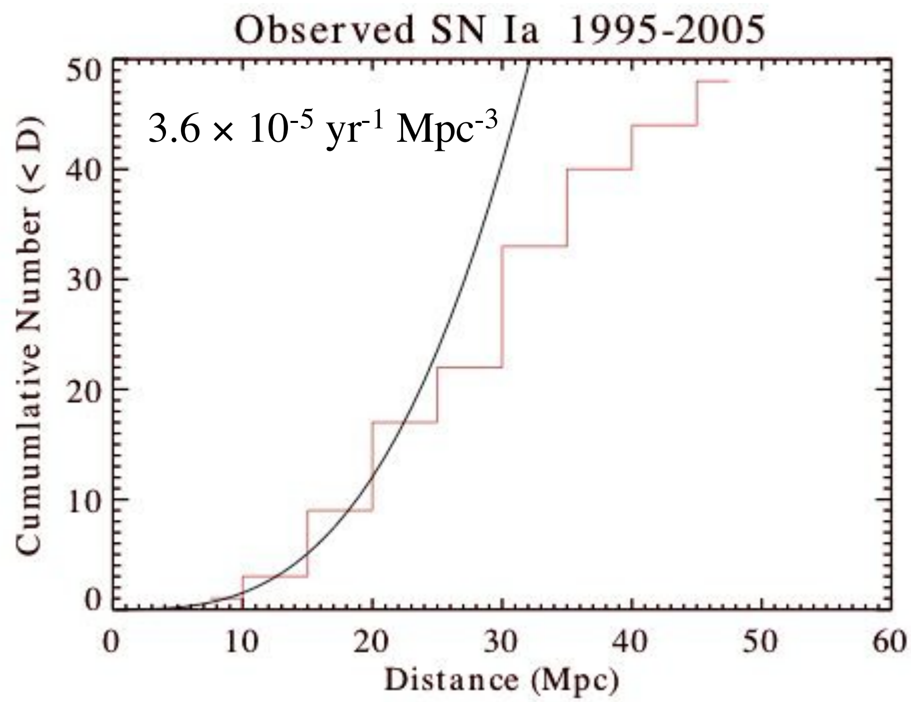
Atmosphere is opaque at these energies.

$^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$ Rough Numbers

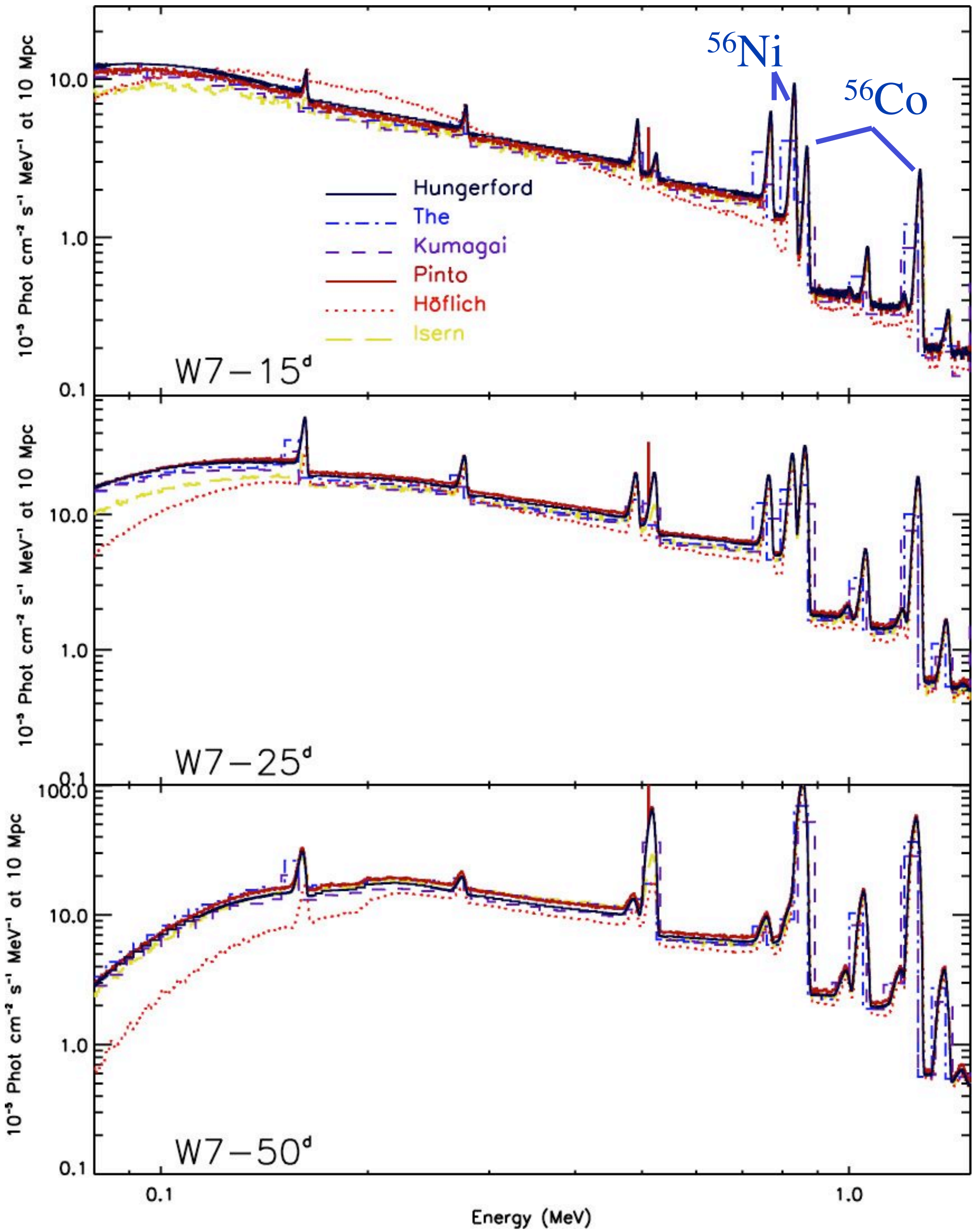
- optically thin: ≤ 100 d
- peak line: 0.847 MeV
- peak flux: $(2\text{-}5)\times10^{-5}$ cm^{-2} s^{-1} $(D/10\ Mpc)^{-2}$
- ΔE/E ~ 3% (~10,000 km/s)
- local SNe Ia rate: ~1.0 yr^{-1} $(D/20\ Mpc)^3$
- @ 1×10^{-6} cm^{-2} s^{-1} , 25-50 detections/yr



(from Strigari 2006, data from Blanc et al. 2004, Dahlen et al. 2004, & Wood-Vasey 2005)

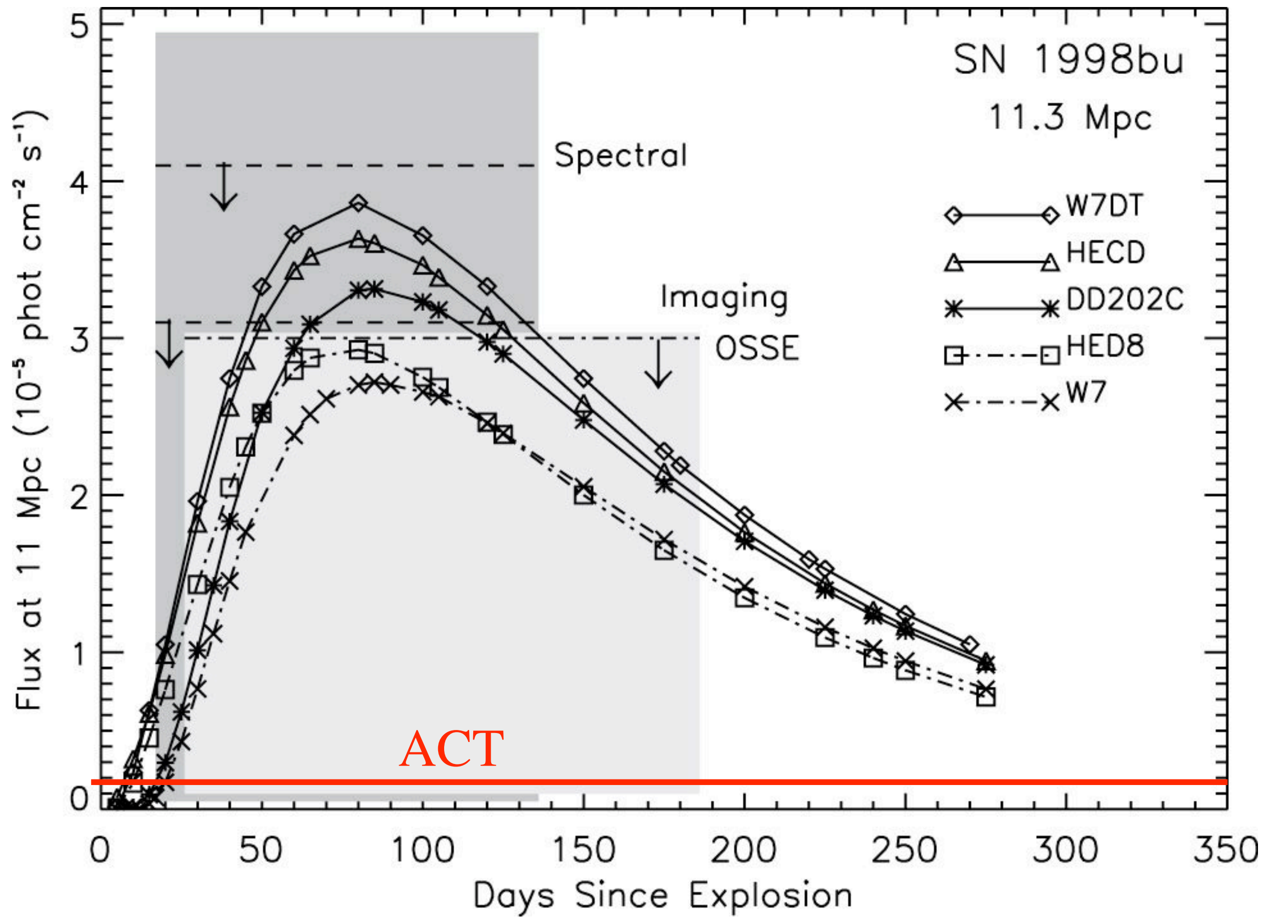


(P. Milne)

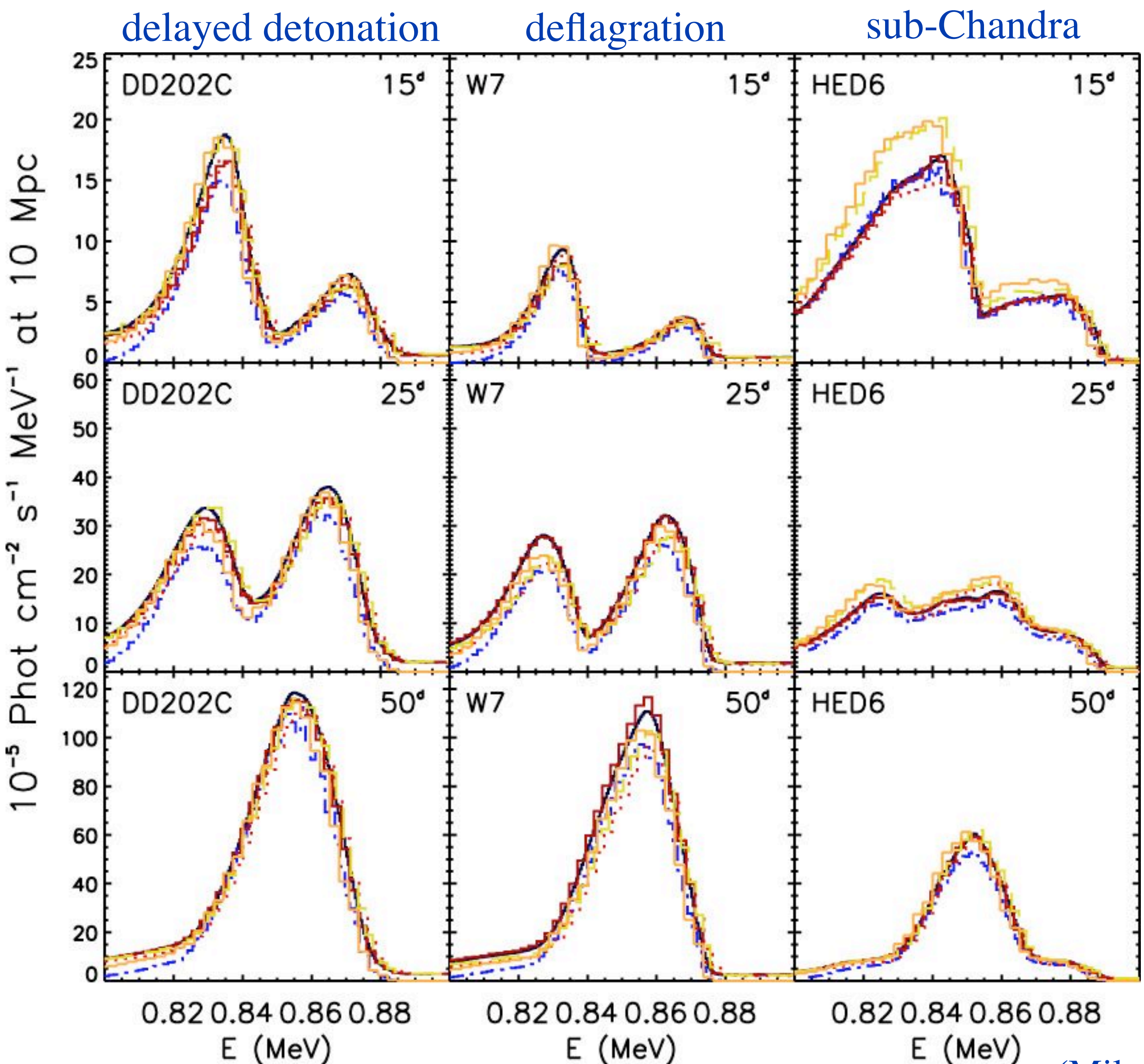


W7: deflagration

(Milne et al. 2004)



(Milne et al. 2004)



(Milne et al. 2004)

Type Ia Supernovae

Cosmic Yardsticks, Alchemists

Goal: study ^{56}Ni & ^{56}Co emission from the core of Type Ia supernovae.

1. **Standard candles** -- characterize the ^{56}Ni production, relation to optical
2. **Explosion physics** -- uniquely distinguish explosion physics
3. **SNe Ia rate, local & cosmic** -- direct rates unbiased by extinction

We define the science requirements in terms of the following objective:

ACT must be able to strongly distinguish typical deflagration models from delayed detonation models, even if the supernovae distances are unknown.

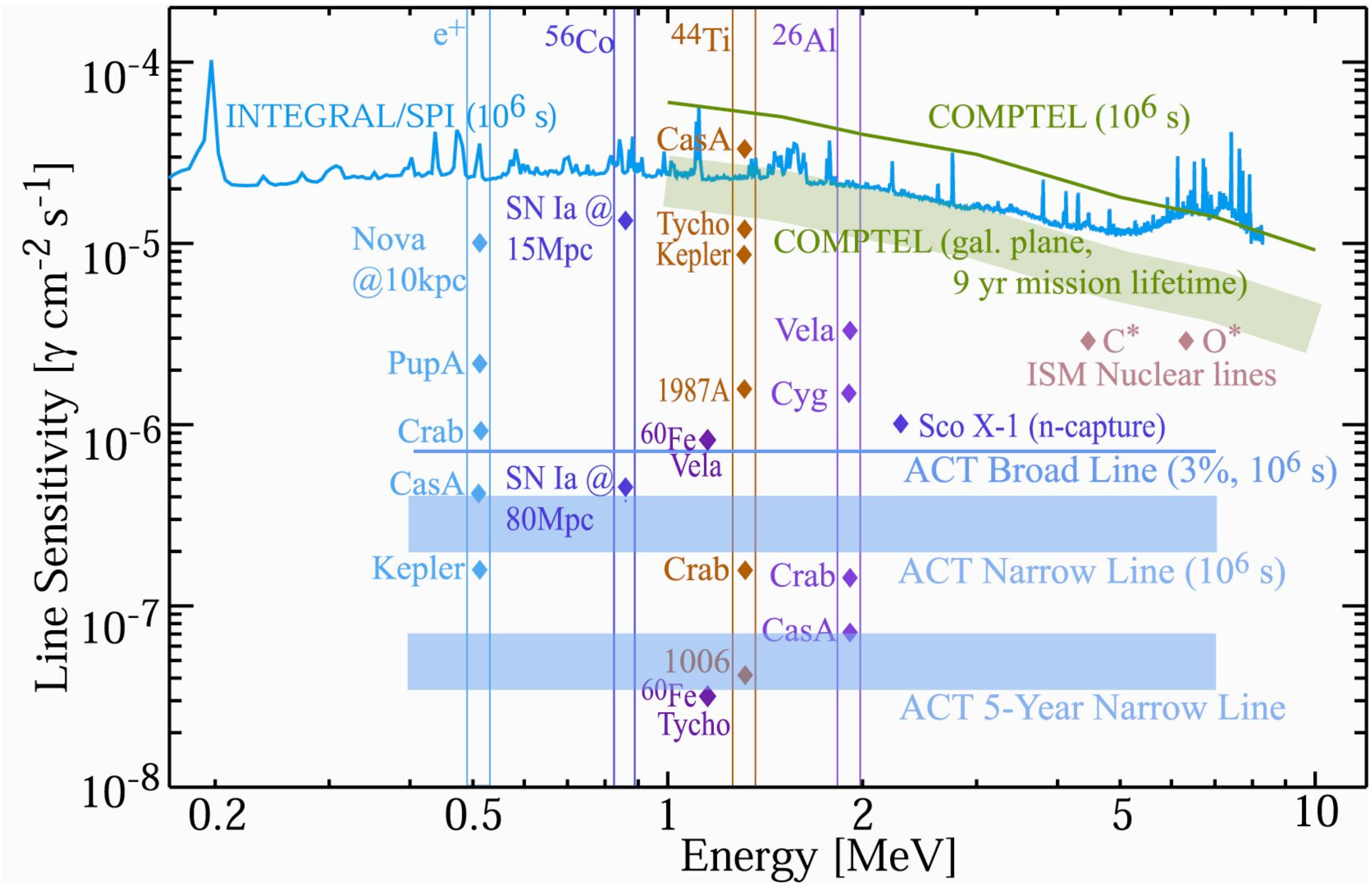
Leading to instrumental requirements:

- broad (3%) line sensitivity at 0.847 MeV: $\sim 7\times10^{-7}$ ph/cm^2/s
- spectral resolution: $\Delta E/E < 1\%$
- wide field of view: 25% sky

….these lead to 40-50 detections/year (5 @ 15σ)!

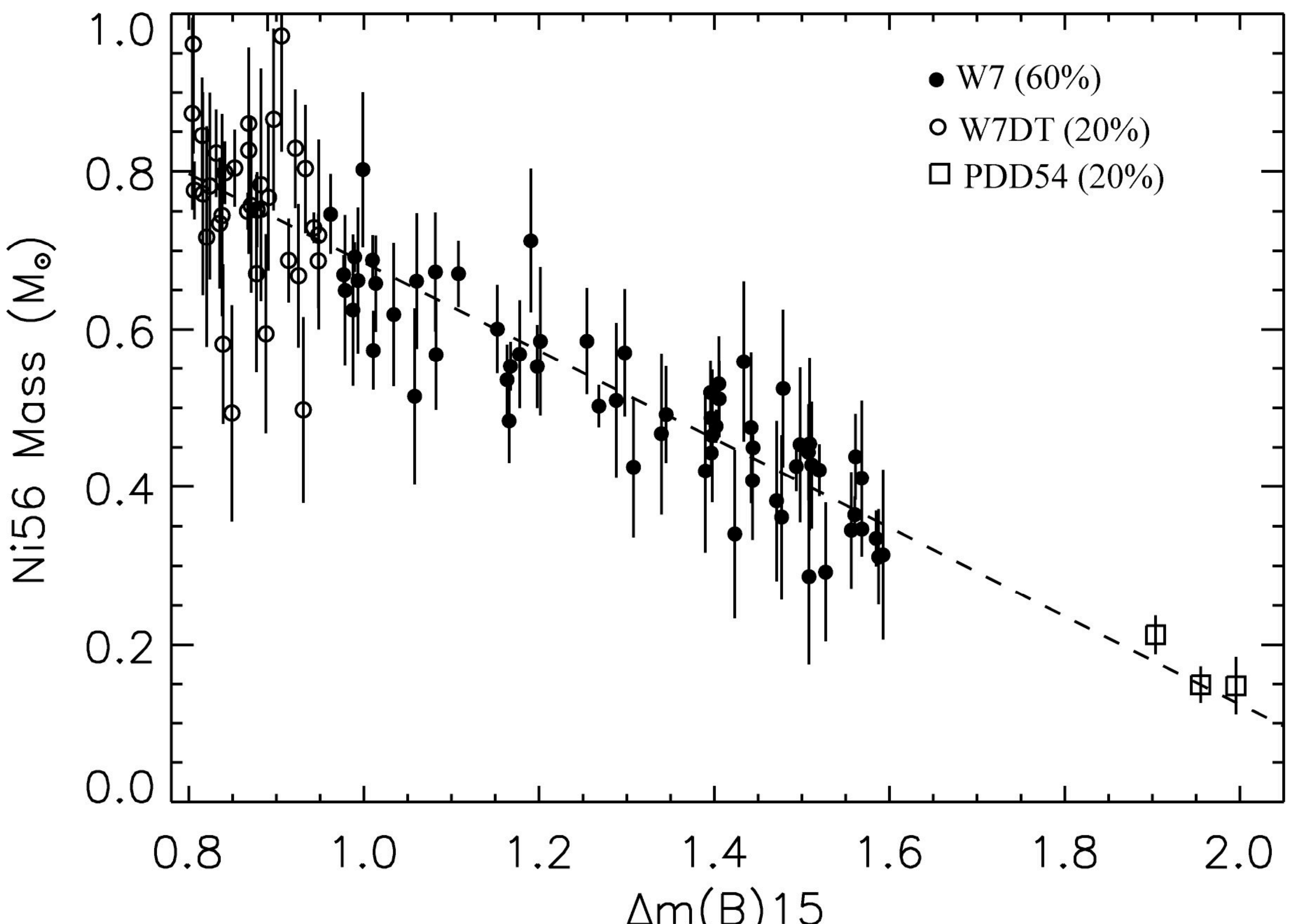
Nuclear Line Sensitivity

Primary science requirement: systematic study of SNIa spectra, lightcurves to uniquely determine the explosion mechanism, ^{56}Co (0.847 MeV) abundances.



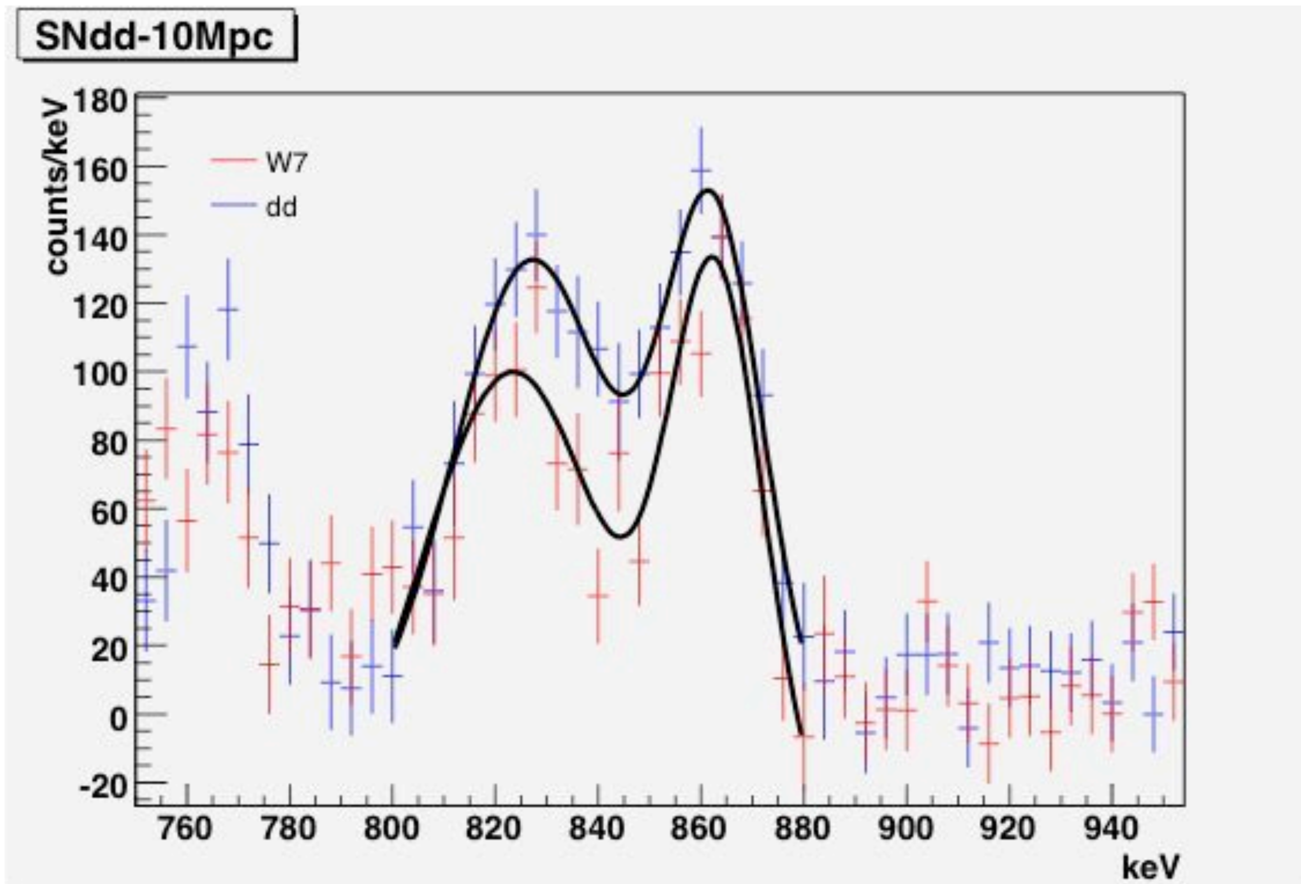
Standard Candle: characterize ^{56}Ni production

Requirements: measurement of ^{56}Ni production in >100 SNe at >5σ levels.



Explosion Physics: flame propagation, dynamics

Requirements: high sensitivity (>15σ) lightcurves and high-resolution spectra (ΔE/E<1%) of several SNe Ia events of each subclass over the primary 5-year survey.

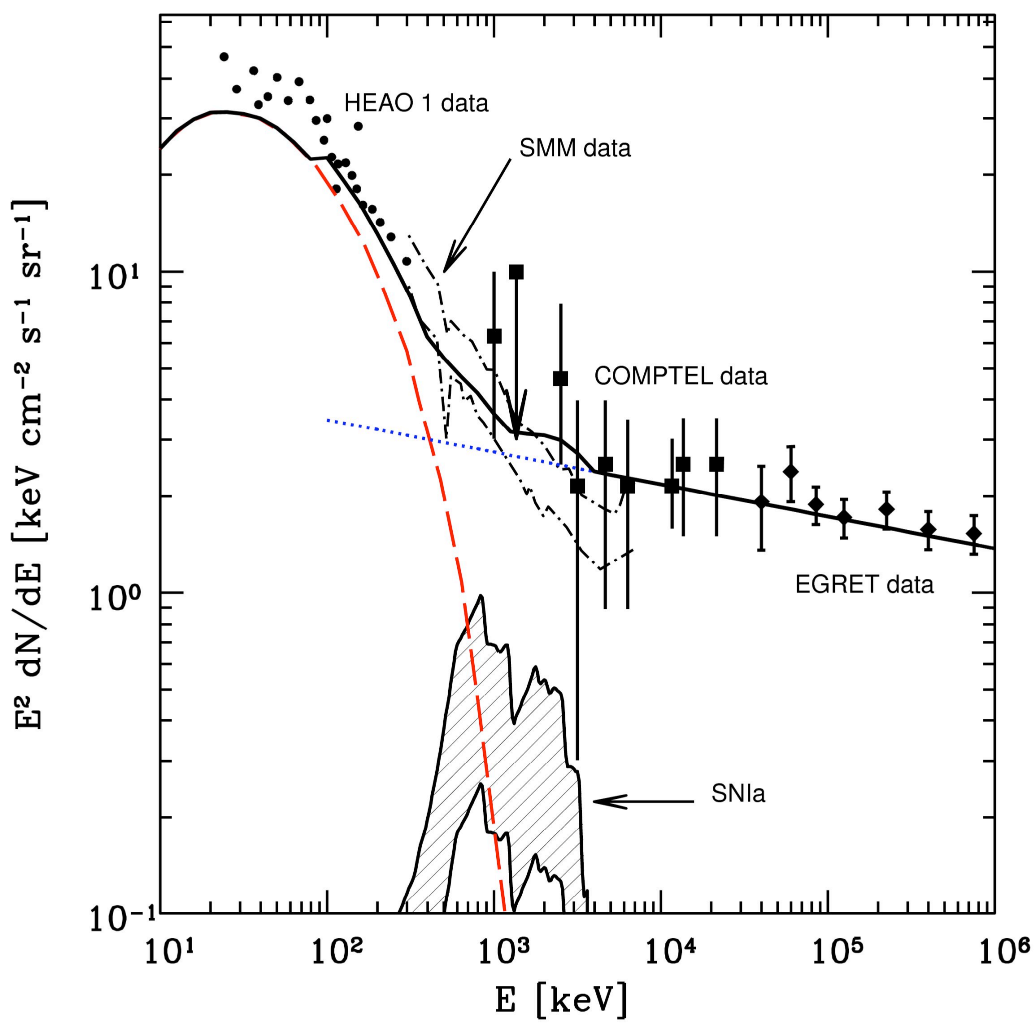


Simulated 10^6 s ACT observation of W7 and DD202c at ~25 d for 10 Mpc distance, distinguished easily by their spectral shape.

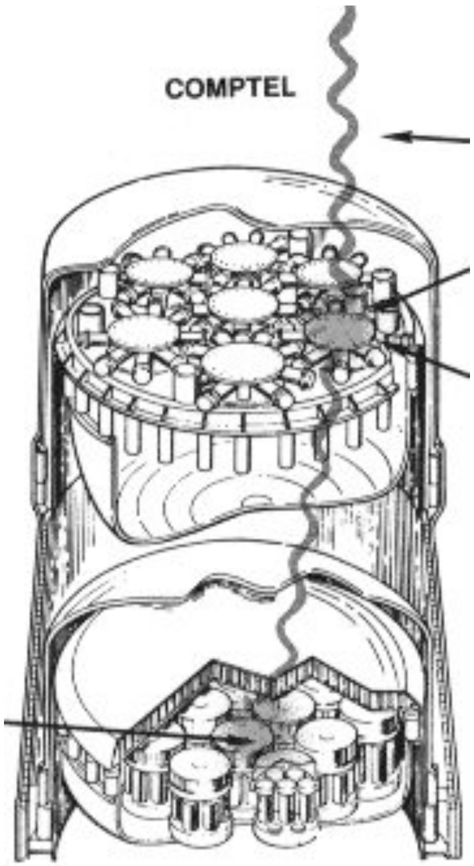
History of SN Ia & star formation: Cosmic γ-Ray Background

(Strigari et al. 2005)

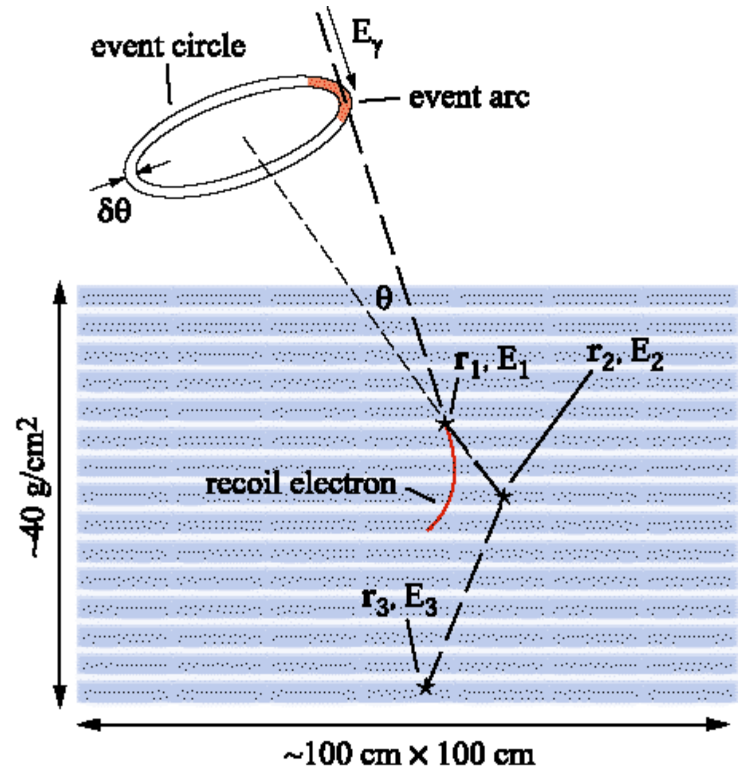
- ✓ first measurement of the MeV CGB
- ✓ bolometric output of SN Ia to z~1-2
- ✓ trace cosmic star formation rate to z ~1-2 (with some delays)
- ✓ angular correlations can reveal SN Ia contribution (Zhang & Beacom 2004)



Compton Telescopes: Then & Now



CGRO/COMPTEL
- ~40 cm^3 resolution
- $\Delta E/E$ ~ 10%
- 0.1% efficiency



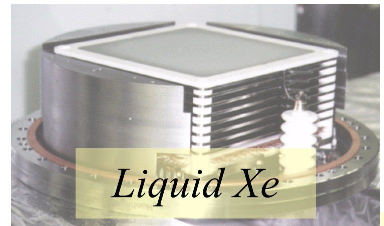
ACT Enabling Detectors
- 1 mm^3 resolution
- $\Delta E/E$ ~ 0.2-1%
- 10-20% efficiency
- background rejection
- polarization, wide FoV

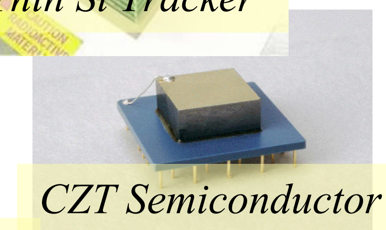
ACT Enabling Technologies

The ACT Vision Mission study identifies the most promising detectors and highest priority technology developments.

Recommendations:

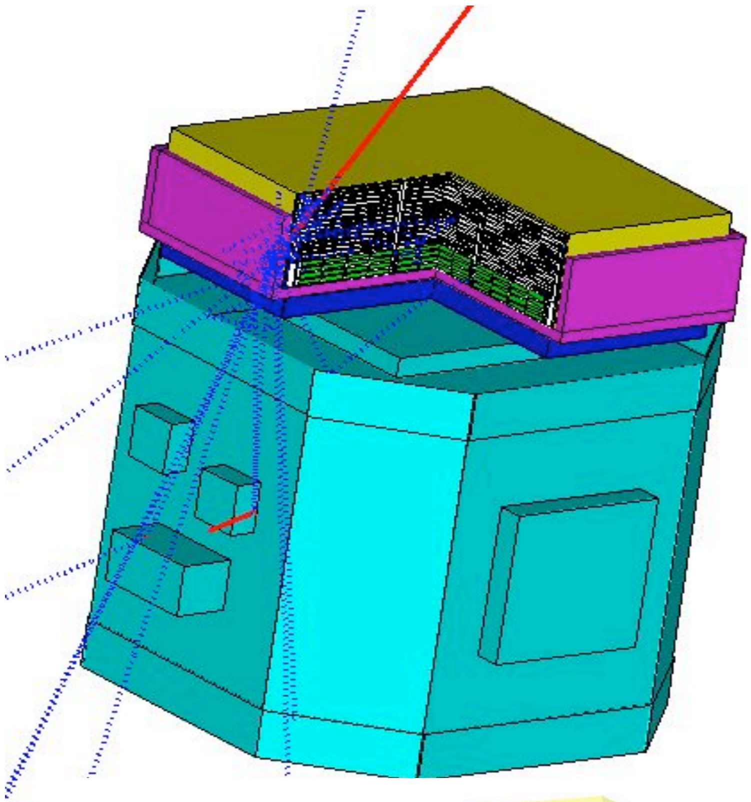
- Ge, thick Si, (LXe)
- low-power readouts
- cryogenics, materials, sims

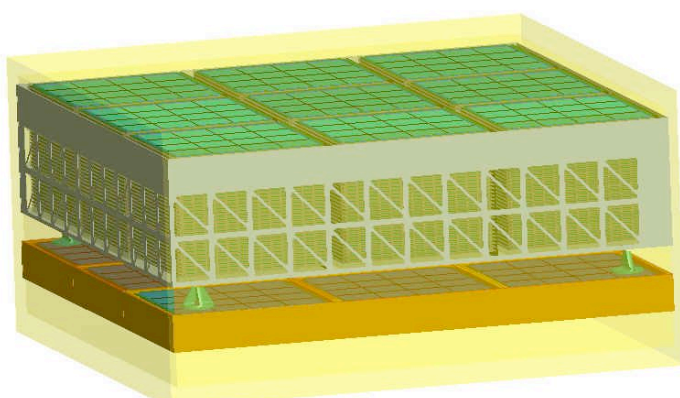




Property	Si Strip	Ge Strip	Liquid Xe	CZT Strip	Xe μWell
$\Delta E/E$ (1 MeV)	0.2-1%	0.2%	3%	1%	1.7%
Spatial Resol.	<1-mm^3	<1-mm^3	<1-mm^3	<1-mm^3	0.2-mm^3
Z density	14 2.3 g/cm^3	32 5.3 g/cm^3	54 3.0 g/cm^3	48 8.3 g/cm^3	54 (3 atm) 0.02 g/cm^3
Volume (achvd.)	60 cm^3	130 cm^3	3000 cm^3	4 cm^3	50 cm^3
Operating T	-30° C	-190° C	-100° C	10° C	20° C

Baseline ACT Instrument





D1: 27 layers 2-mm thick Si
- 10x10 cm2, 64x64 strips
- 3888 det., 248,832 chns
- -30° C, Stirling cycle cooler

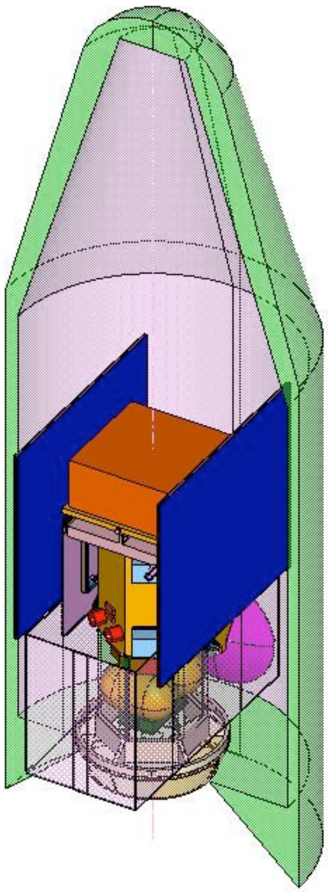
D2: 4 layers, 16-mm thick Ge
- 9.2x9.2 cm2, 90x90 strips
- 576 det., 103,680 chns
- 80 K, Turbo-Brayton cooler

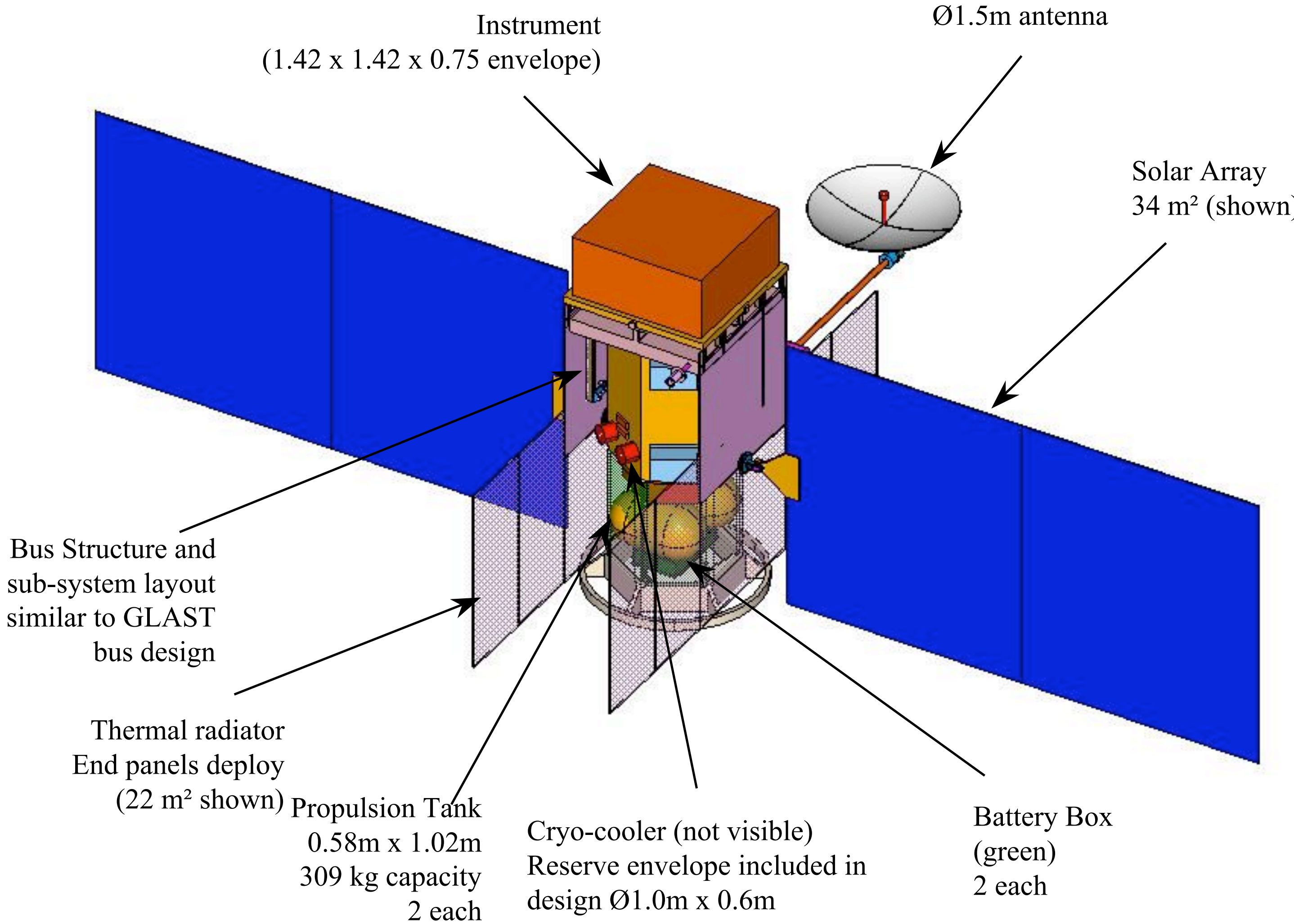
BGO: 4-cm thick shield

ACD: plastic scintillator

ACT Apples/Oranges Envelope:
- 1850-kg instrument (w/o margin)
- 2000 W instrument (w/o margin)
- Delta IV shroud (~4m dia.)

ACT Mission Configuration





ACT Baseline Science Instrument Performance

Energy range	0.2-10 MeV
*Spectral resolution	0.2-1%
*Field of View	25% sky (zenith pointer)
Sky coverage	80% per orbit
Angular resolution	~1°
Point source localization	5’
Detector area, depth	~12,000 cm^2, 47 g/cm^2
Effective area	~1000 cm^2
*3% broad line sensitivity (10^6s)	1.2×10^{-6} $ph/cm^2/s$
Narrow line sensitivity	5×10^{-7} $ph/cm^2/s$
Continuum sensitivity	$(1/E)\times10^{-5}$ $ph/cm^2/s/MeV$
GRB fluence sensitivity	3×10^{-8} erg/cm^2
Data mode	Every photon to ground

**Primary science requirement driven by Type Ia supernovae.*

Modern Detector Technologies

✓Excellent spectral resolution ($\Delta E/E < 1\%$) → *Ge, thick Si*
✓Fine spatial resolution (<1 mm^3) → (nearly) *all*
✓Low-energy electron tracking (<500 keV) → *thin Si, GXe*
✓Very fast timing (<1 ns) → *LXe, LaBr, Gxe*
✓Room-temperature → *CdZnTe, LaBr*

Hits

➢Cooling → *Ge, thick Si, LXe*
➢Efficiency → *GXe, thin Si*
➢Spectral resolution → *LXe, GXe, LaBr, CdZnTe*
➢Power → *thin Si, GXe*

Alternate ACT Designs

Tracking Si/CdZnTe calorimeter (UCR) →e^- tracking, room T
limit: *power (#strips)*

Ge/BGO shield (UCB) → high spectral resolution
limit: *power (cooling), mass (BGO)*

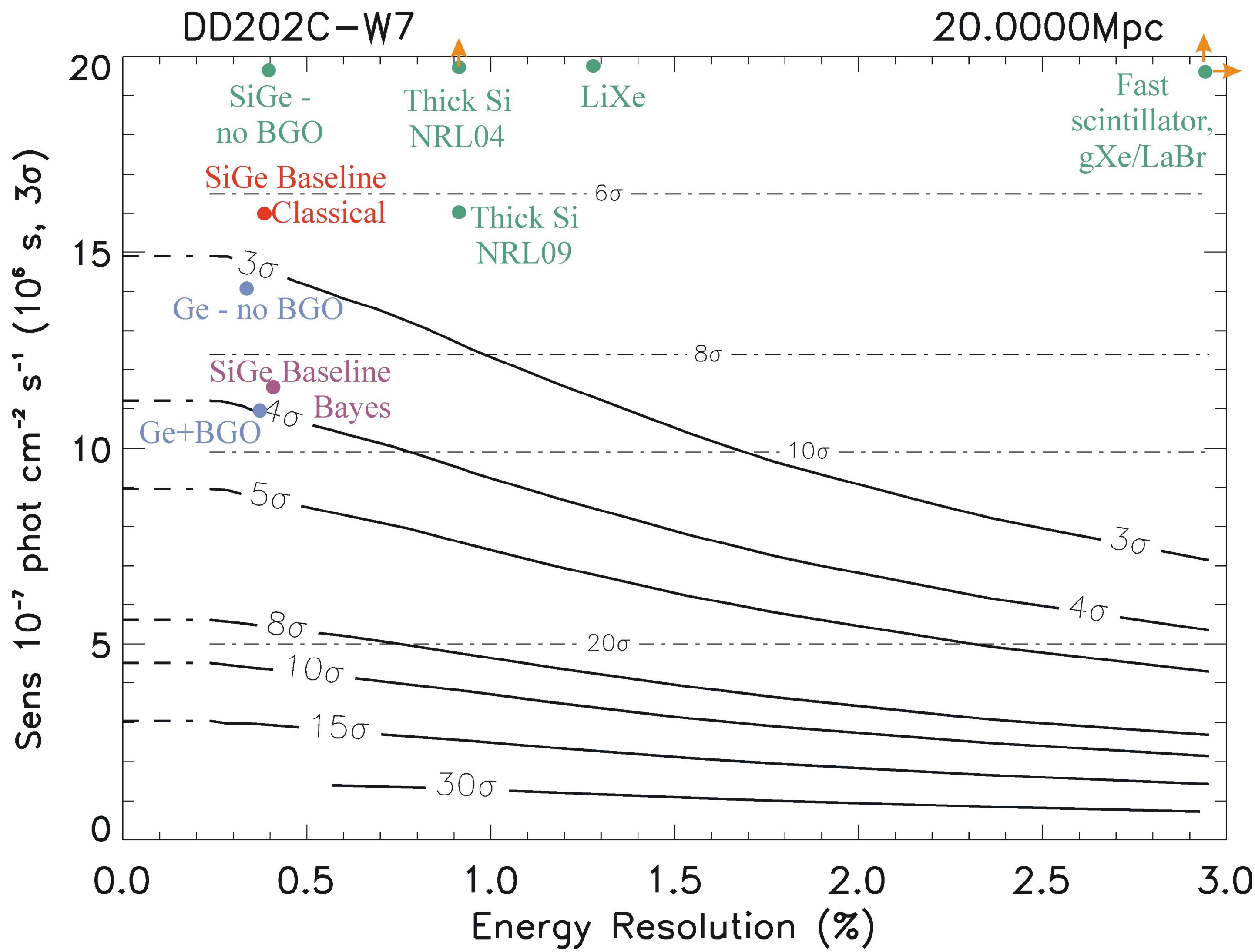
Thick Si (NRL) → reduce Doppler broadening, minimal cooling

LXe (Rice, Columbia) → fast timing, good stopping power
limit: *mass (detector)*

Gaseous Xe/$LaBr_3$ (GSFC/UNH) → e^- tracking
limit: *mass, power (#chns?)*

$LaBr_3$ (UNH) → fast timing (modern COMPTEL)
limit: *mass ($LaBr_3$)*

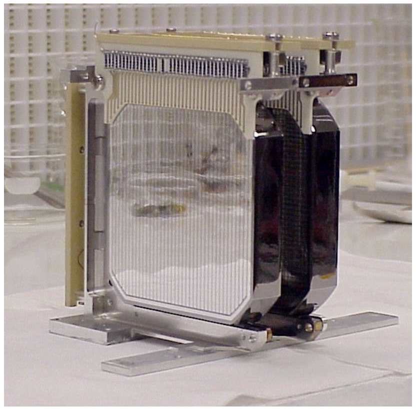
ACT Technology Comparisons



What is the real distance uncertainty at 20 Mpc?

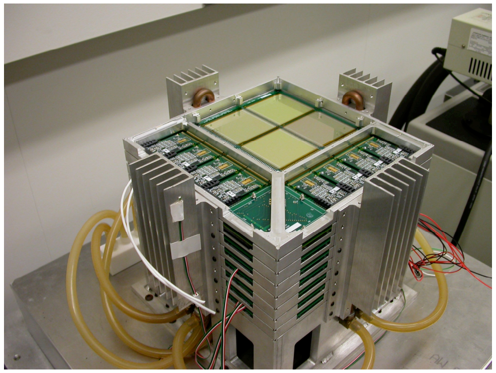
ACT Technology Recommendations

1. Germanium detectors: enabling technology development
- electrode optimization
- environmental testing
- mfg large numbers



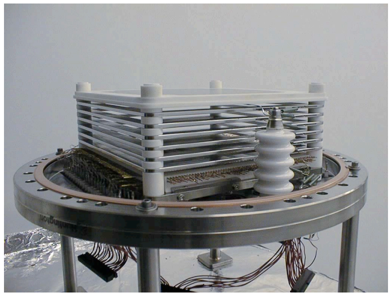
(NCT/UCB)

2. Thick Si detectors: enabling technology development
- basic development for thicker detectors
- mfg large numbers



(NRL)

3. LXe detectors: laboratory demonstration
- optimized spectral performance



(LXeGRIT/Columbia/Rice)

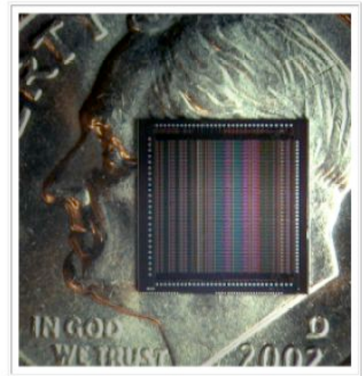
ACT Technology Recommendations (Cont.)

4. Readout electronics: basic development
• ~1 mW/chn readout
• 0.1 mW preamps

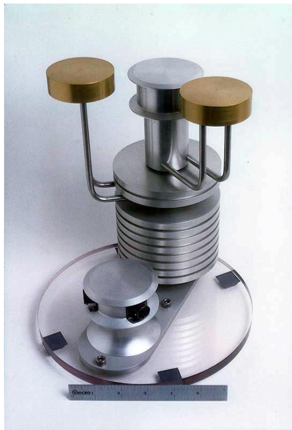
5. Cryogenics: study and development
• detailed technical study
• enabling development of scaling

6. Passive materials: study and development
• low-Z structure
• minimal cryostats

7. Simulation toolset: basic development
• integrated simulation package
• tested environmental inputs
• data and imaging analysis software

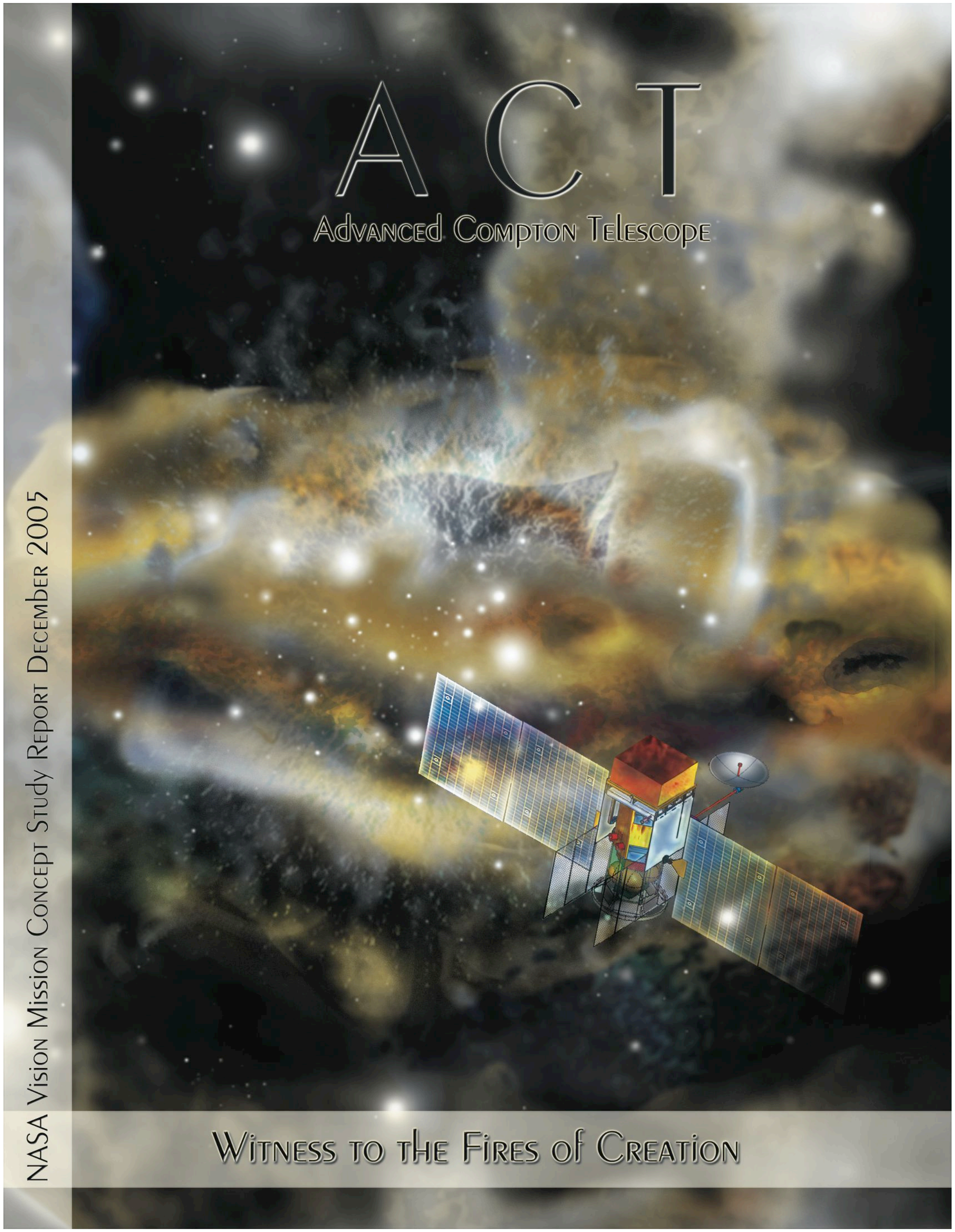


(RENA-2/Nova R&D)



(NICMOS/HST)

→ Plus, balloon demonstrations of all ACT technologies.



astro-ph/0608532

- full science goals
- detailed performance
- mission design & readiness
- technology recommedations

ACT Collaboration

Steven Boggs[a], James Kurfess[b], James Ryan[c], Elena Aprile[d], Neil Gehrels[e], Marc Kippen[f], Mark Leising[g], Uwe Oberlack[h], Cornelia Wunderer[a], Allen Zych[i], Peter Bloser[c], Michael Harris[j], Andrew Hoover[f], Alexei Klimenk[f], Dan Kocevski[h], Mark McConnell[3], Peter Milne[k], Elena I. Novikova[b], Bernard Phlips[b], Mark Polsen[i], Steven Sturner[e], Derek Tournear[f], Georg Weidenspointner[j], Eric Wulf[b], Andreas Zoglauer[a], Matthew Baring[h], John Beacom[l], Lars Bildsten[m], Charles Dermer[b], Dieter Hartmann[g], Margarita Hernanz[n], David Smith[o], Sumner Starrfield[p], for the larger ACT collaboration

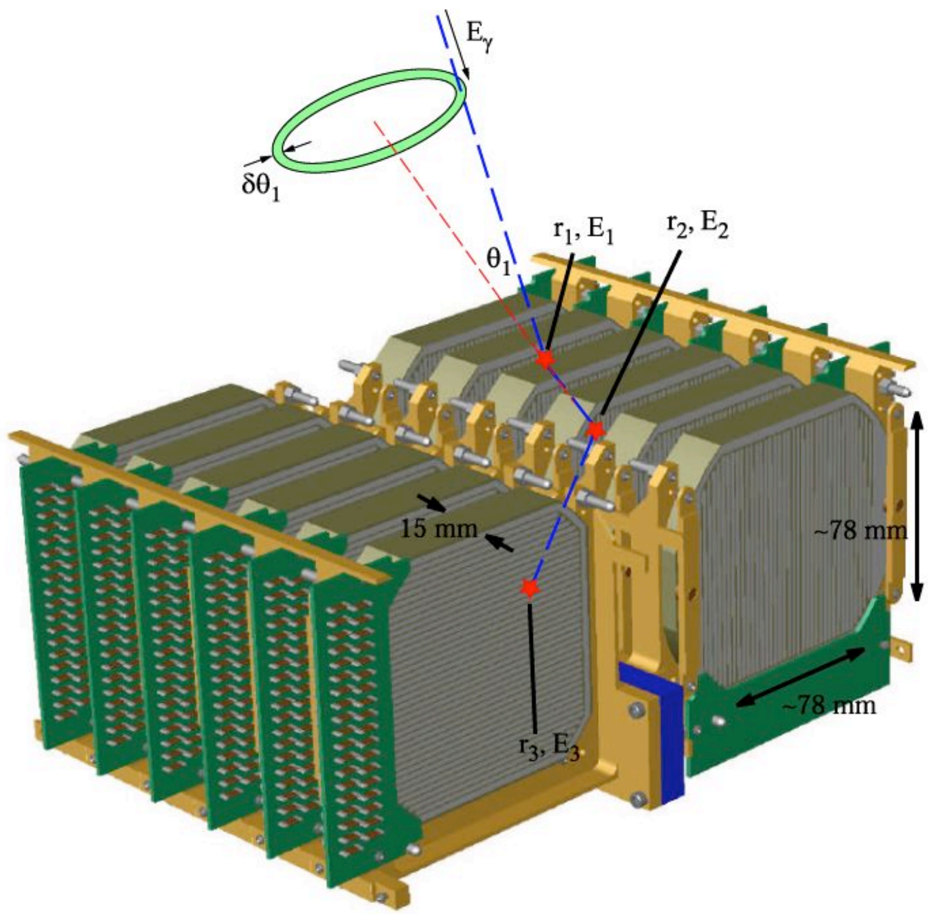
[a]University of California, Berkeley; [b]Naval Research Laboratory; [c]University of New Hampshire; [d]Columbia University; [e]Goddard Space Flight Center; [f]Los Alamos National Laboratory; [g]Clemson University; [h]Rice University, [i]University of California, Riverside; [j]CESR, France; [k]Arizona State University; [l]Ohio State University; [m]University of California, Santa Barbara; [n]IEEC-CSIC, Spain; [o]University of California, Santa Cruz; [p]University of Arizona, Tucson

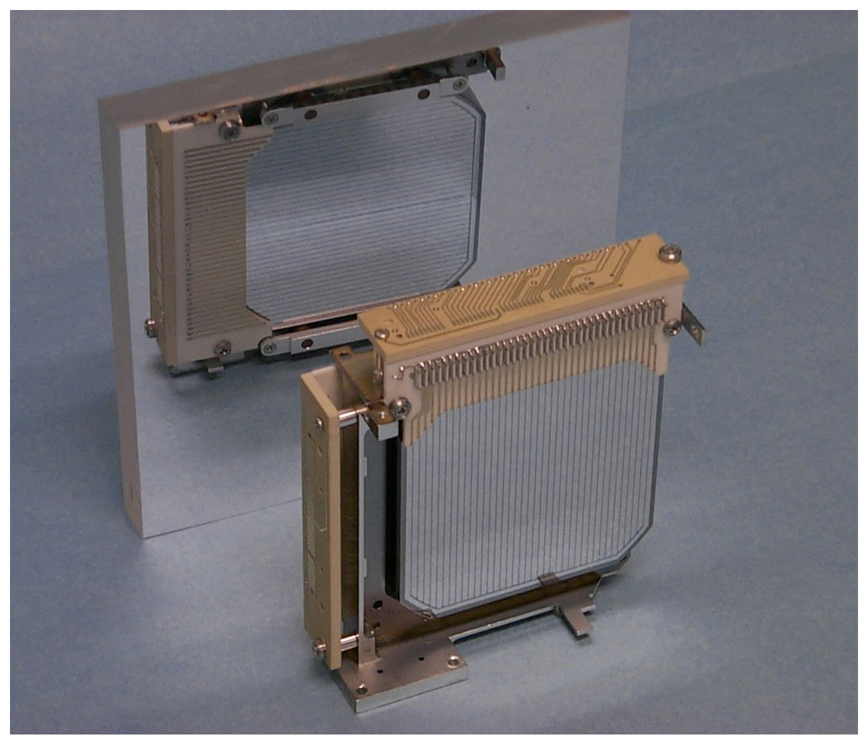
Nuclear Compton Telescope
balloon payload

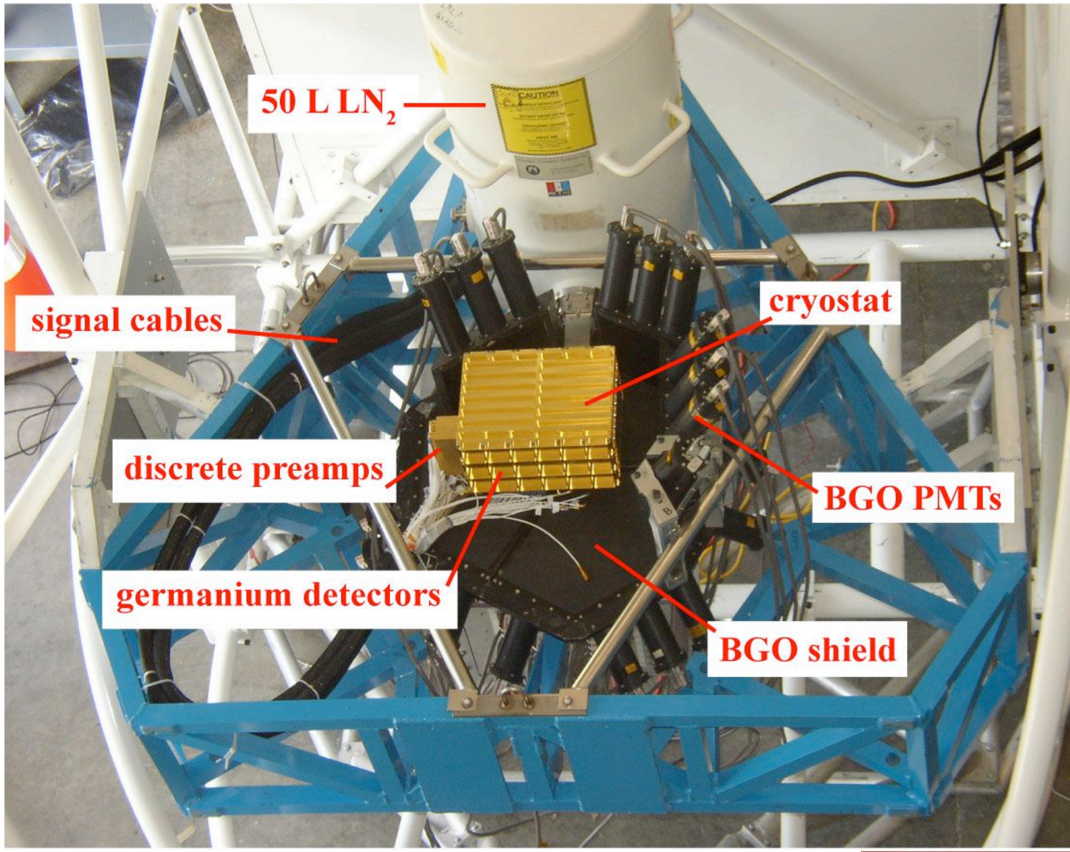
Berkeley, LBNL, NTHU, NCU, NSPO, CESR

Heart of NCT: Cross Strip 3-D GeDs

- 37x37 strips
- 2-mm pitch
- 15-mm thickness
- 81000 mm^3 volume
- 1.6 mm^3 localization
- ~2.1-keV noise resolution

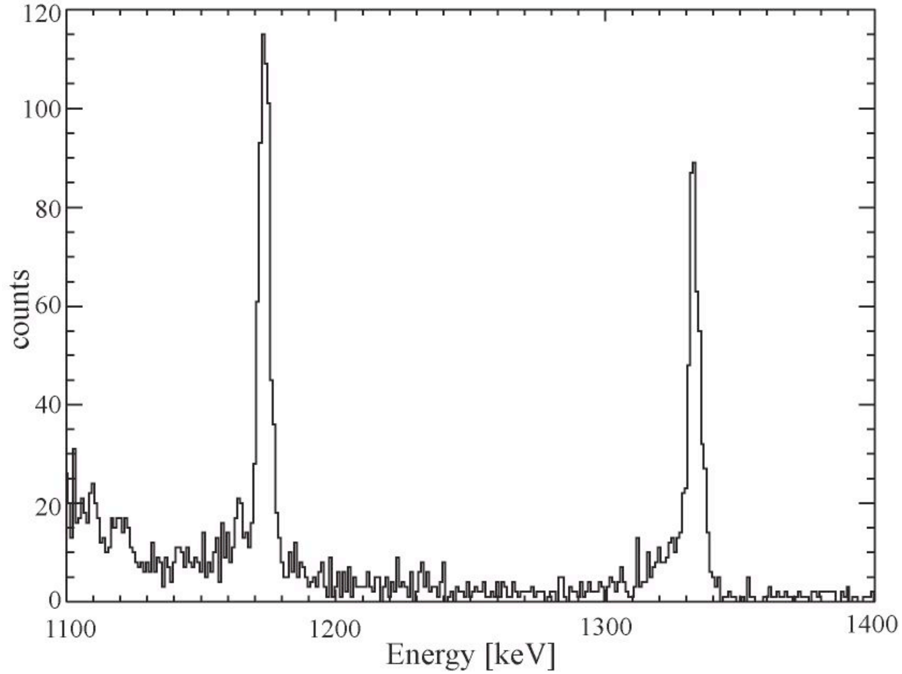




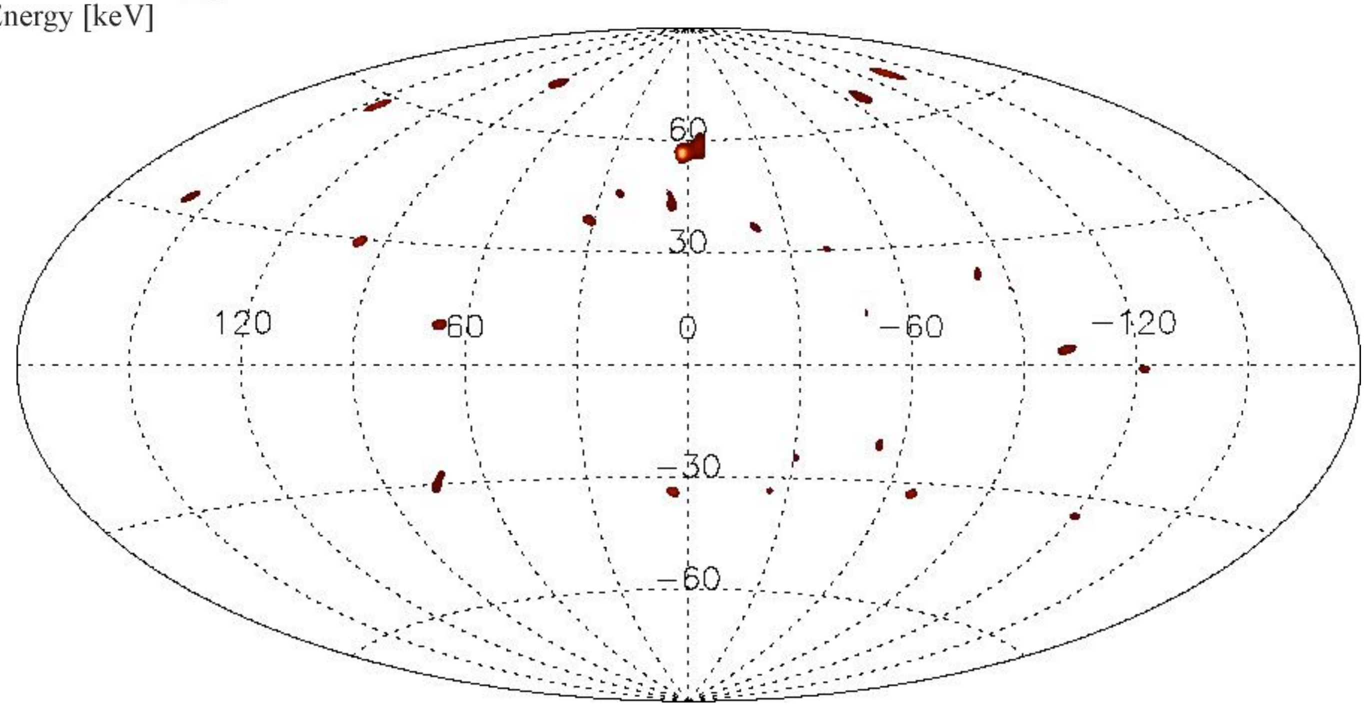

50 L LN2
signal cables
cryostat
discrete preamps
BGO PMTs
germanium detectors
BGO shield

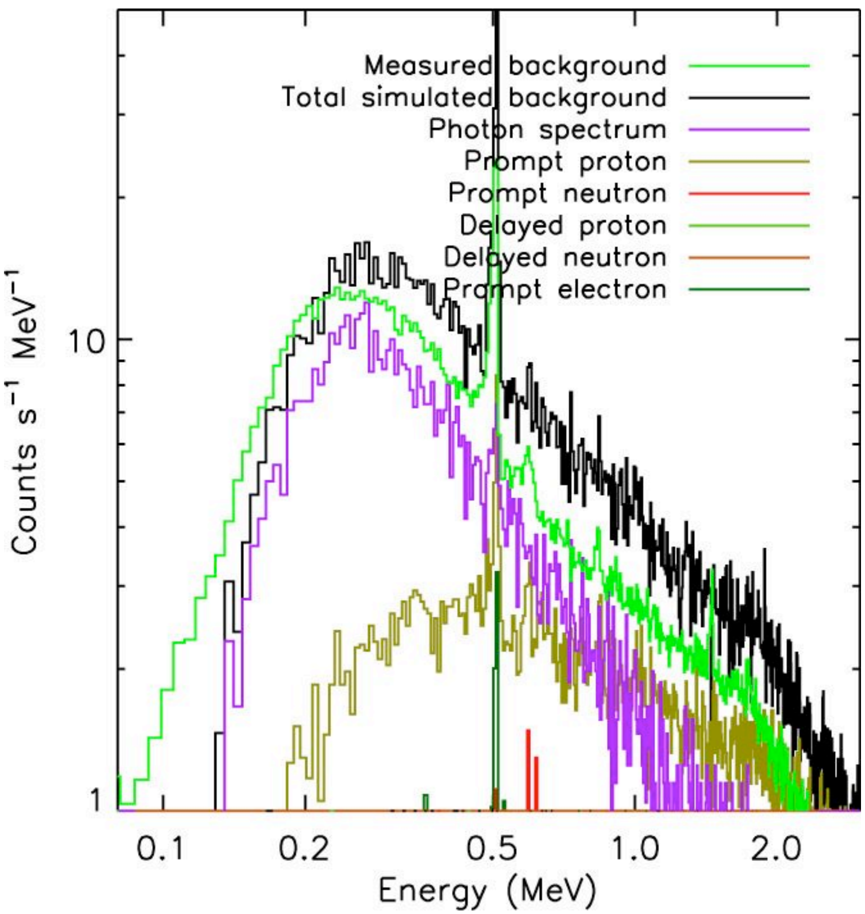

BIG BILL

^{60}Co Laboratory Tests
1.173, 1.333 MeV

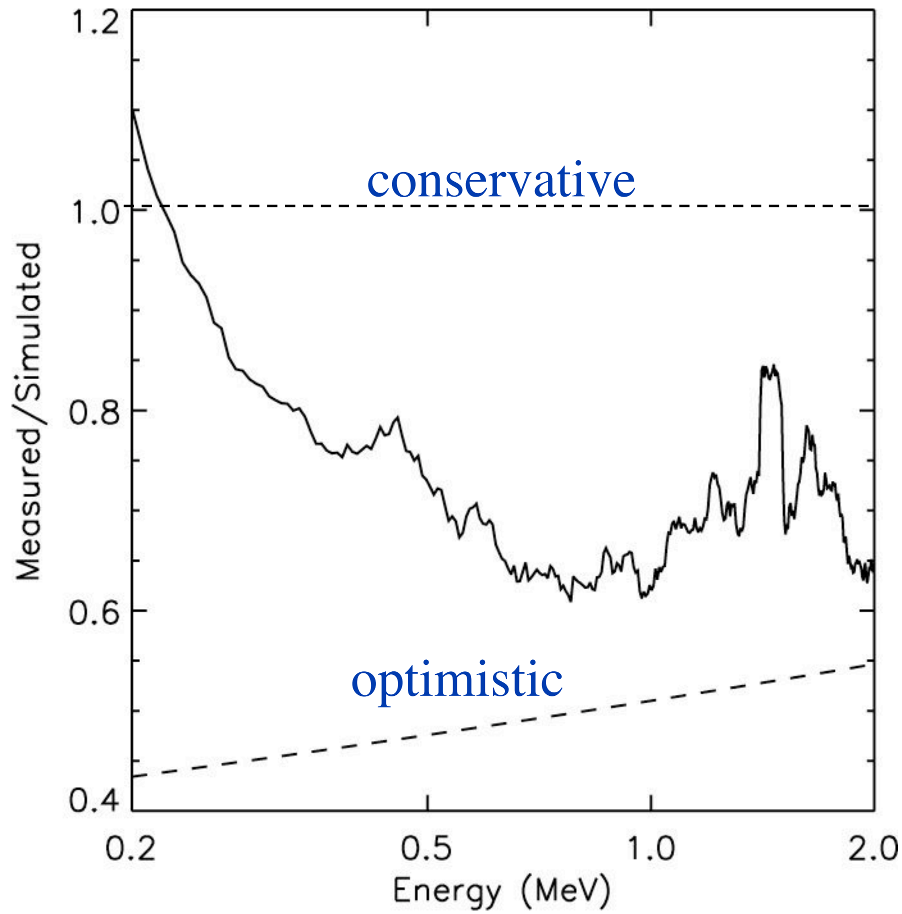


1.173 MeV processed image

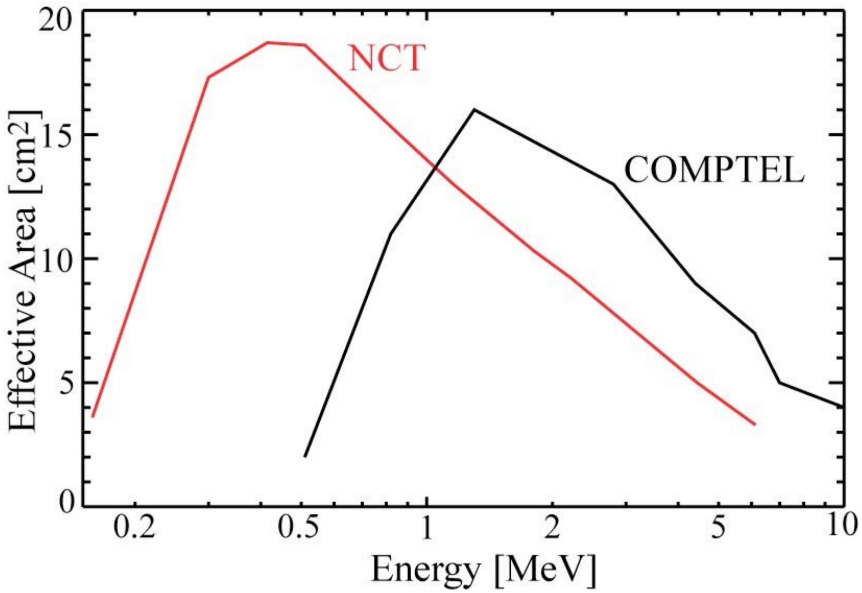




prototype flight, June 2005

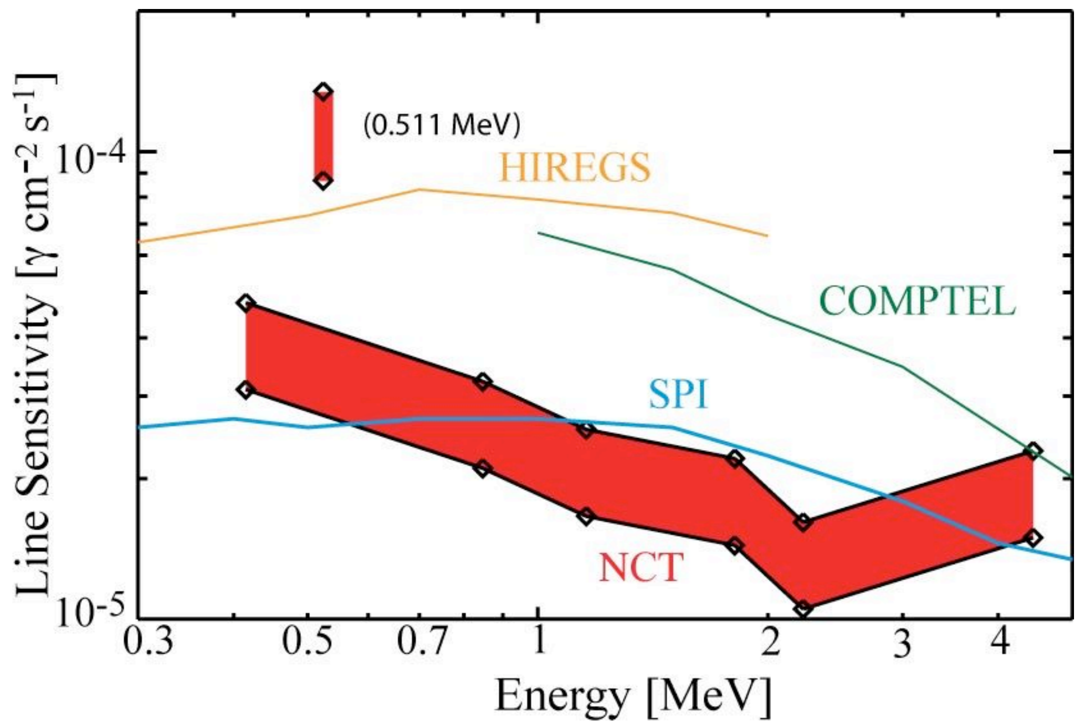


(Gehrels 1985, Dean et al 1991)



Source	Decay	Energy	Goal
SNe Ia (?)	e^+e^-	0.511	36σ map
SNe II/Ib	^{26}Al	1.809 MeV	36σ map
	^{60}Fe	1.173, 1.333	5σ detect
SNe	^{44}Ti	1.157	resolved line
BHs	e^+e^-	≤0.511	discovery

full flight, December 2008



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- What sensitivity threshold is interesting?
- 5-10 SNe Ia, $\Delta M_{56}/M_{56} < 10\%$?
- Narrow FoV, pointed telescope?
- Driven by optical triggers?
- What is distance uncertainty at 20 Mpc?

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- ΔM_{56} achievable on a small mission
- catalogue of all optical SNe Ia < 50 Mpc in 2005-2006, distances, discovery time
- distance uncertainties to out to Virgo