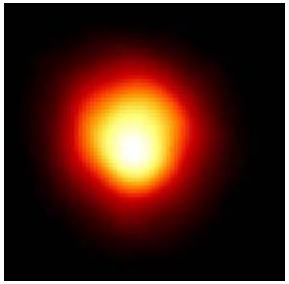
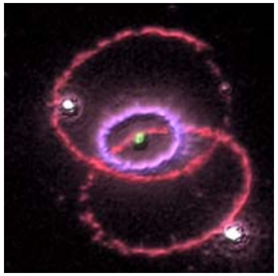
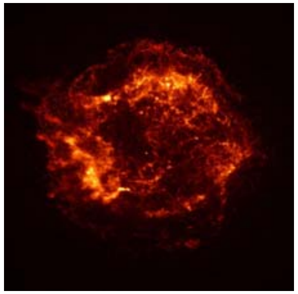
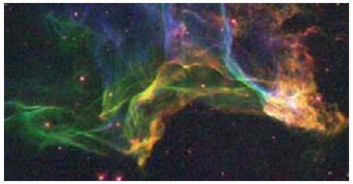
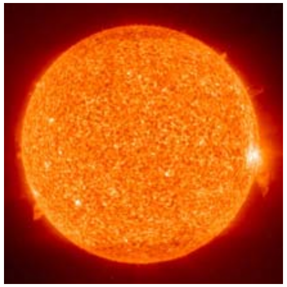
The MeV Sky
through ACT's Eyes –
Nucleosynthesis and Beyond











Witness to the Fires of Creation

Advanced Compton Telescope

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

Cornelia Wunderer
for the ACT Team
University of California, Berkeley

ACT Collaboration

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[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

ACT in NASA's Strategic Plan

✓Nuclear astrophysics was identified by the Gamma-Ray Astrophysics Working Group (GRAPWG) in 1999 as the 'highest-priority science goal', and ACT as the 'highest priority major gamma-ray mission'

✓ACT identified in the 2003 SEU Roadmap under *Cycles of Matter and Energy* ("will be undertaken after Beyond Einstein has begun")

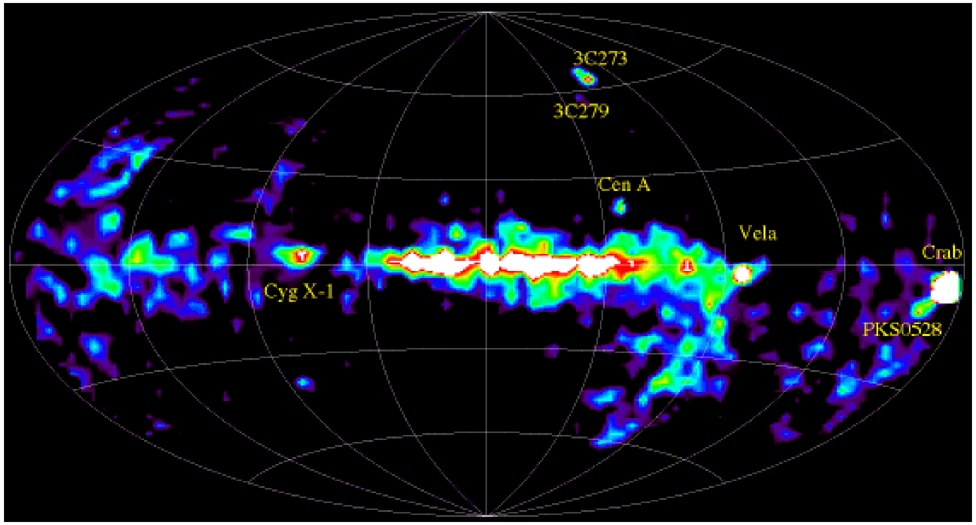
✓Space Science strategic objective 5.12 – understand the development of structure and the cycles of matter and energy in the evolving universe (2003)

✓ Selected in March 2004 for a NASA Vision Mission concept study

✓2005 NASA Universe Strategic Roadmap identifies the *Nuclear Astrophysics Compton Telescope* as a *Pathways to Life Observatory*

Why MeV γ-Rays ?

COMPTEL 1-30 MeV Source Catalog



(Schönfelder et al. 2000)

Unique 0.2-10 MeV Science

- nuclear lines
- e-/e+ annihilation
- peak emission: AGN, BHs, GRBs
- polarization

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

ACT Overview

enable high-sensitivity γ-ray spectroscopy

Life Cycles of Matter

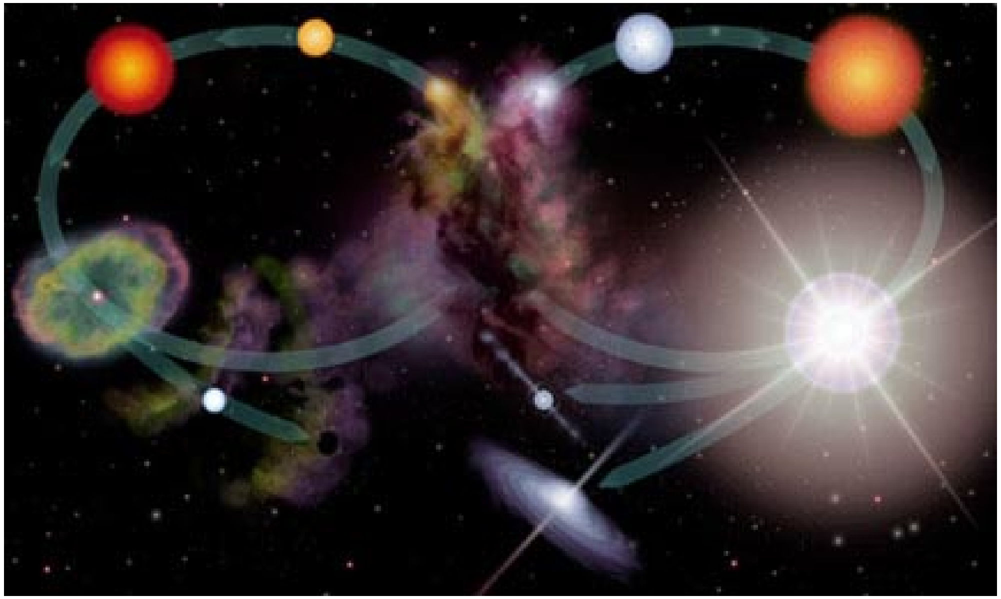
- ✓ Supernovae & nucleosynthesis
- ✓ Supernova remnants & interstellar medium
- ✓ Neutron stars, pulsars, novae

Black Holes

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

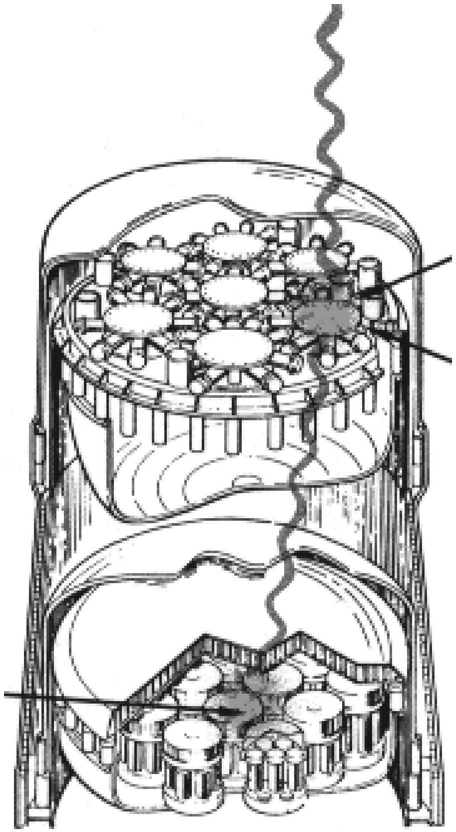
Fundamental Physics & Cosmology

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



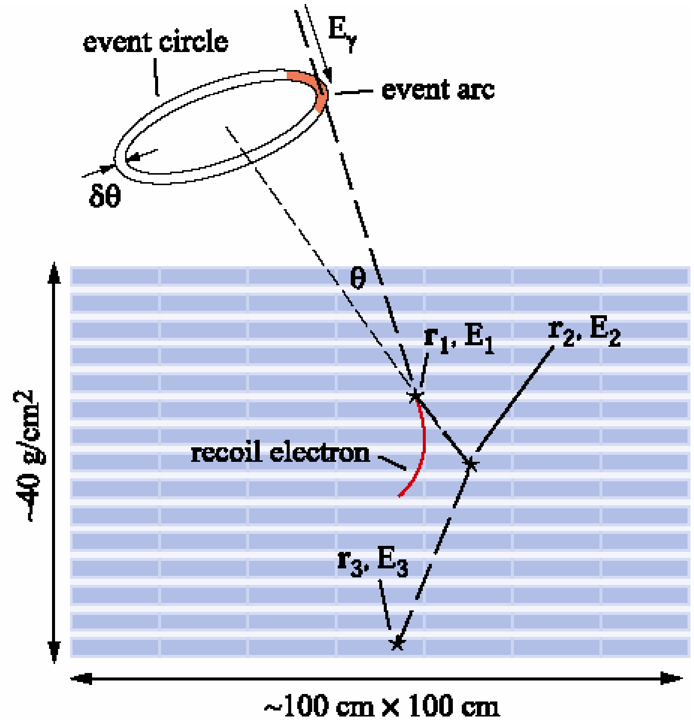
- 100× sensitivity improvement for spectroscopy, imaging & polarization (0.2-10 MeV)
- Advanced 3-D positioning γ-ray spectrometers, 25% sky field-of-view
- LEO equatorial orbit, zenith-pointing survey mode (baseline mission), 80%/orbit

Compton Telescopes – then & now



CGRO/COMPTEL

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



ACT Enabling Detectors

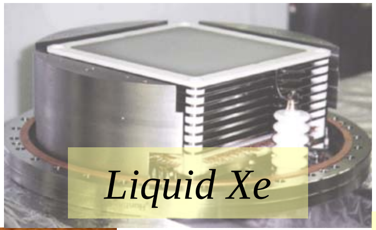
- 1 mm^3 resolution
- $\Delta E/E$ ~ 0.2-1%
- 10-20% efficiency
- background rejection
- polarization
- wide FoV

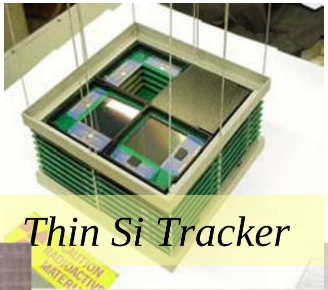
ACT Enabling Technologies

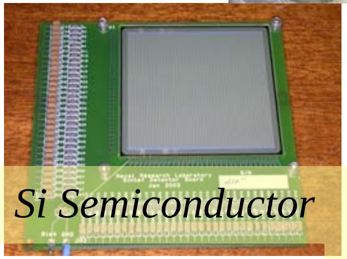
The ACT Vision Mission study identifies the most promising detectors and highest priority technology developments.

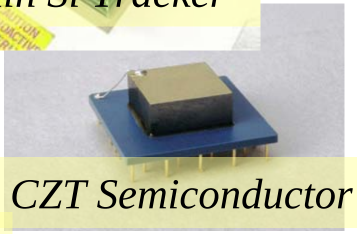
Recommendations:

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









Property	**Si Strip**	**Ge Strip**	**Liquid Xe**	**CZT Strip**	**Xe μWell**
ΔE/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	-30º C	-190º C	-100º C	10º C	20º C

Type Ia Supernovae

Cosmic Cauldrons – and Cosmic Yardsticks

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.

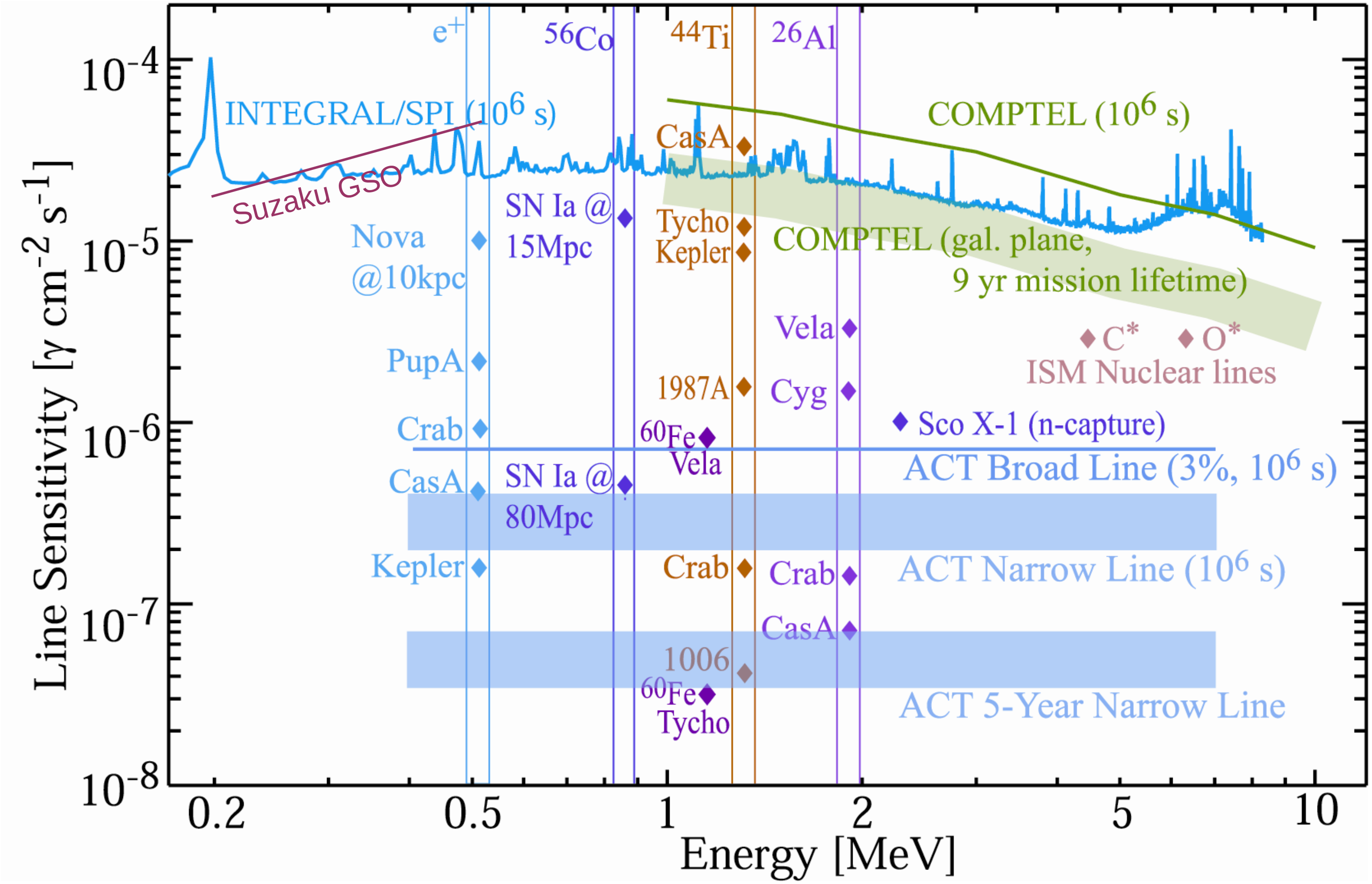
Leading to key instrumental requirements:

- broad (3%) line sensitivity at 847 keV: ~7×10^{-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 Sensitivities

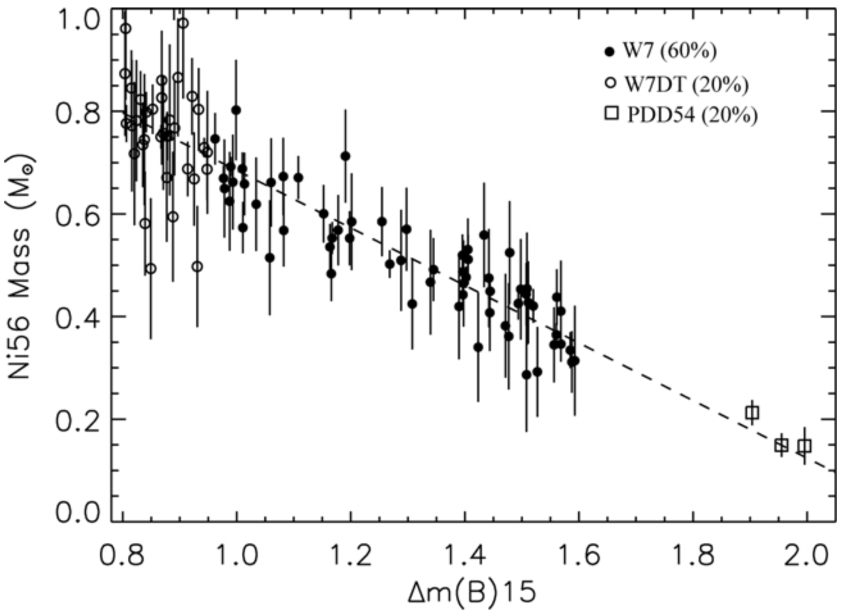
Primary science requirement: systematic study of SNIa spectra & lightcurves to uniquely determine the explosion mechanism, ^{56}Co (0.847 MeV) abundances.

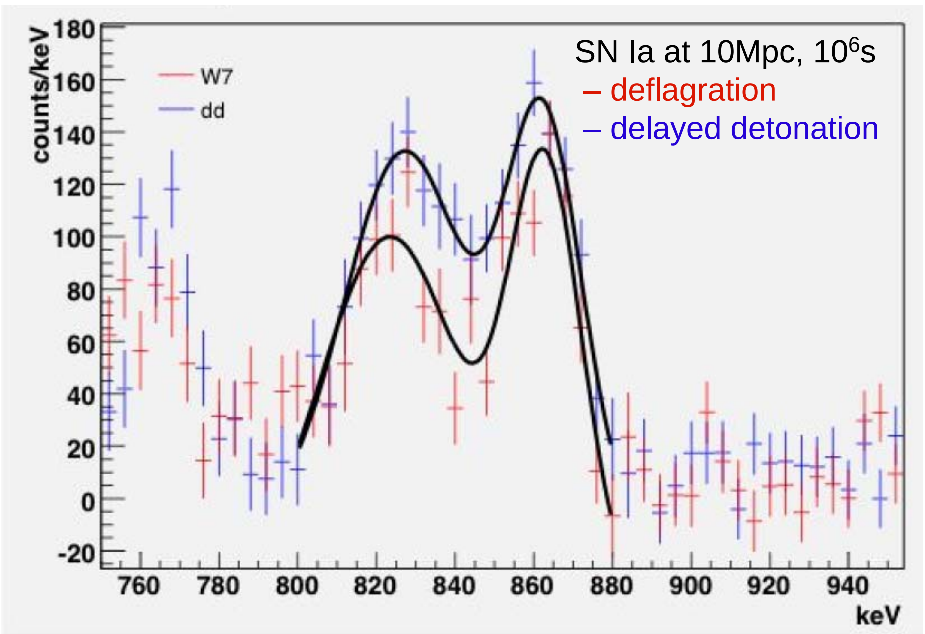


Standard Candle

characterize ^{56}Ni production

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





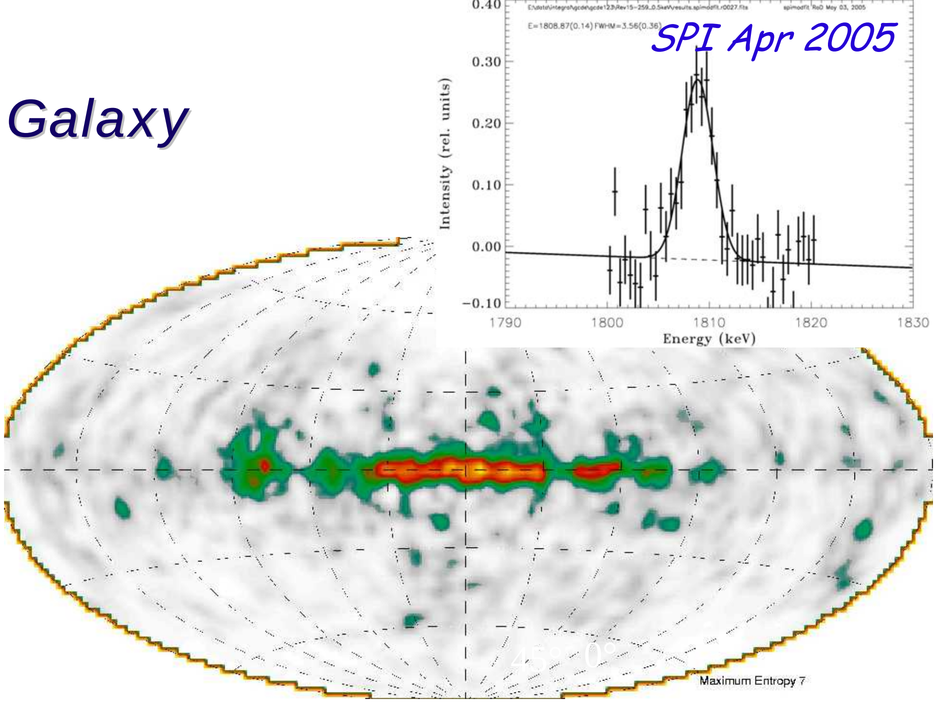
Explosion Physics

flame propagation, dynamics

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

History of nucleosynthesis in our Galaxy

Nuclear Radioactive Emission

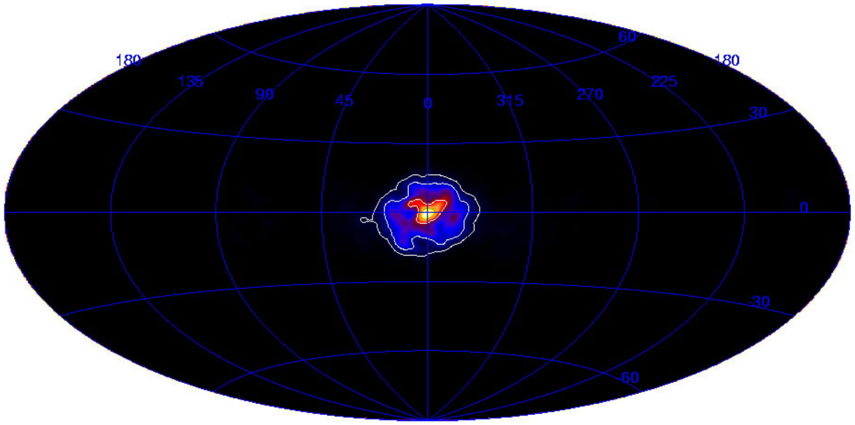


(COMPTEL, Plüschke, 2001)

✓ resolve ^{60}Fe, ^{26}Al, e^+ into hundreds of regions, supernova remnants
✓ identify recent galactic SNe: ^{44}Ti
✓ novae: ^{22}Na, e^+
✓ solar flares and quiescent emission

Exotic physics at our Galaxy's core?

Electron-Positron Annihilation



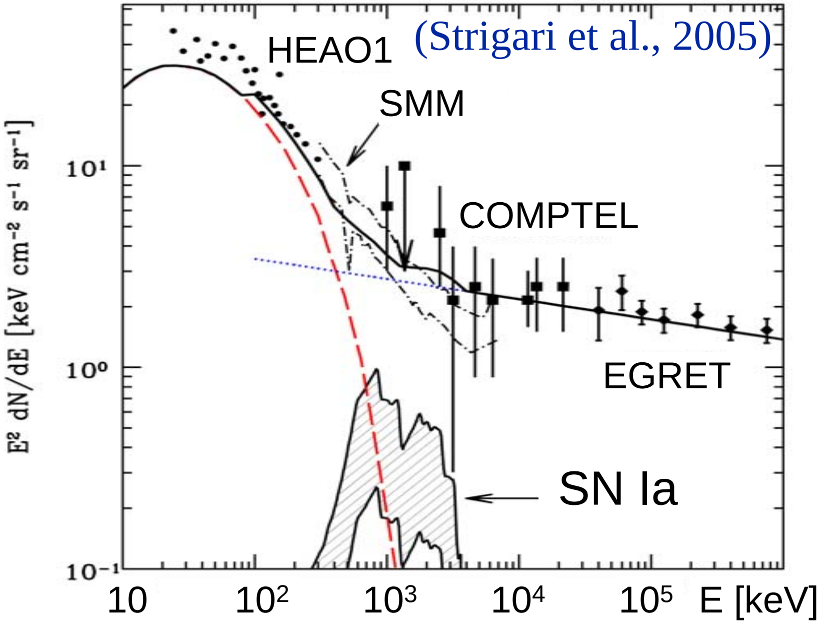
(Knödlseder et al., 2005)

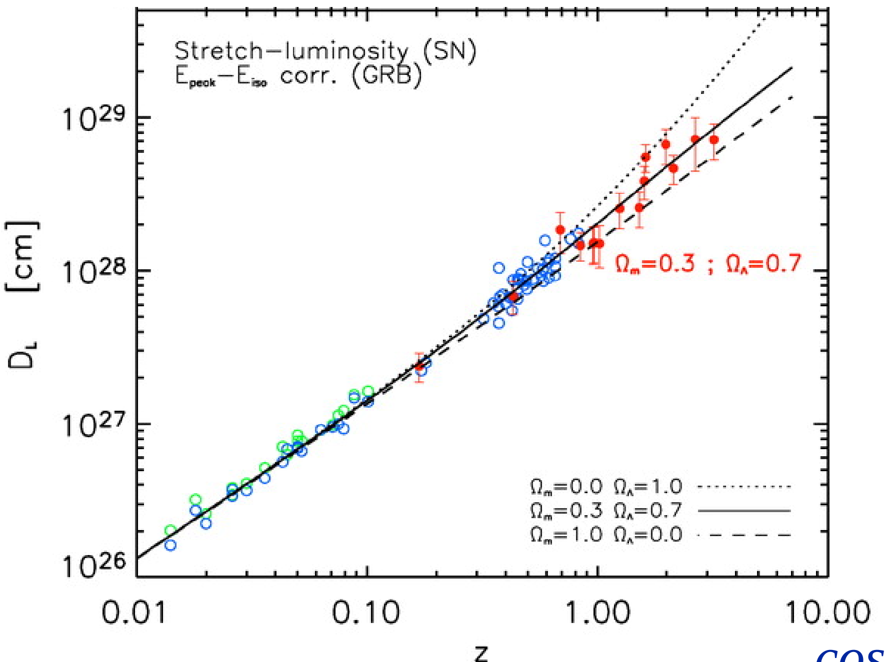
✓ SN Ia, novae, black holes: less likely…
✓ MeV dark matter annihilation/decay?
✓ ACT will provide detailed morphology, spectra of the line & underlying continuum

History of SN Ia & star formation

Cosmic Gamma-Ray Background

- ✓ 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)





(Ghirlanda et al., 2004)

Beacons from the Early Universe

Gamma-Ray Bursts

- ✓ wide FoV, large area, rapid location
- ✓ 10 keV – 30 MeV spectroscopy*
- ✓ polarization

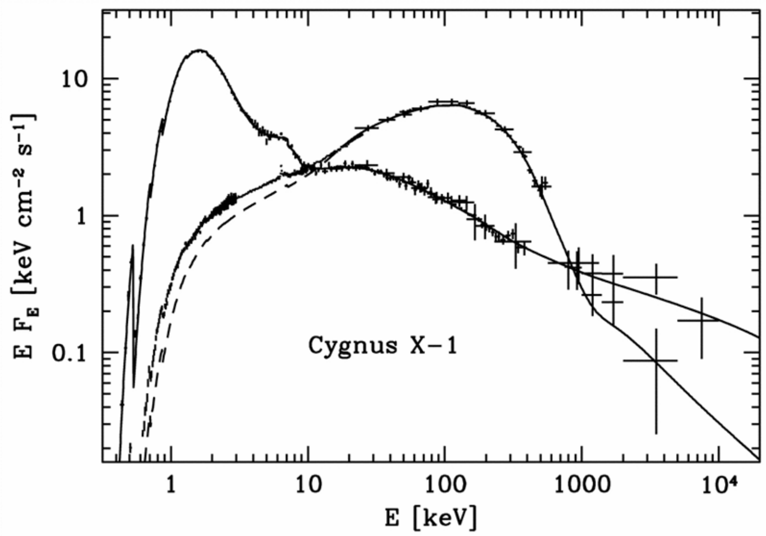
*ACT detector thresholds ~10 keV

Fully enabling the use of GRBs to study cosmology, early universe, fundamental physics.

Probing spacetime on the edge

AGN & Galactic Black Holes

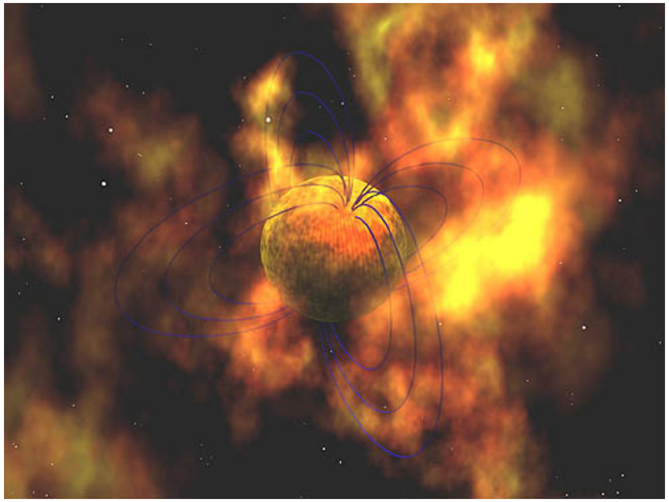
- ✓ all-sky: variability & transients
- ✓ broad spectral band & high resolution
- ✓ fast timing
- ✓ polarization



(McConnell et al. 2002)

Matter in extreme environments

Neutron Stars & Pulsars



(R. Mallozzi)

- ✓ equation of state (neutron-capture line)
- ✓ polarization: outer gap vs. polar cap
- ✓ ACT & GLAST: particle acceleration
- ✓ continuous pulsar timing

ACT Mission Overview

✓ Instrument Synthesis & Analysis Laboratory (ISAL), September 2004

✓ Integrated Mission Design Center (IMDC), November 2004

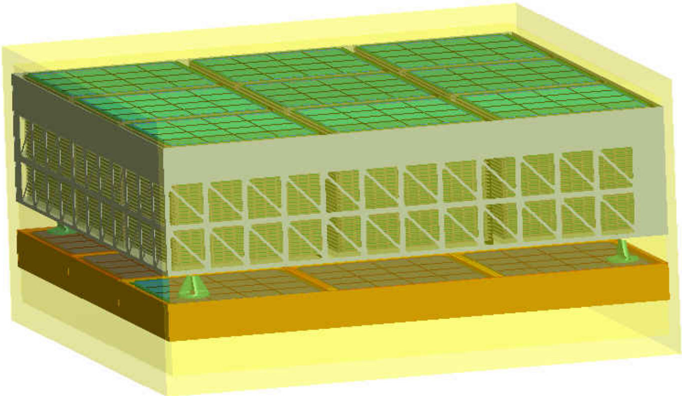
⇨ all mission components (power, telemetry, cooling, data rate) TRL 7 to 9

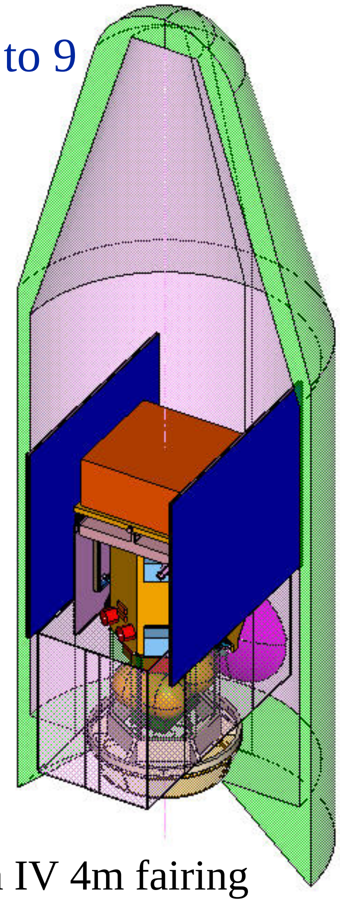
"Baseline ACT" for ISAL & IMDC:

D1: 32 layers SiDs
2-mm thick each

D2: 3 layers, GeDs
16-mm thick each

1.2 m^2 area, 144 detectors/layer





Delta IV 4m fairing

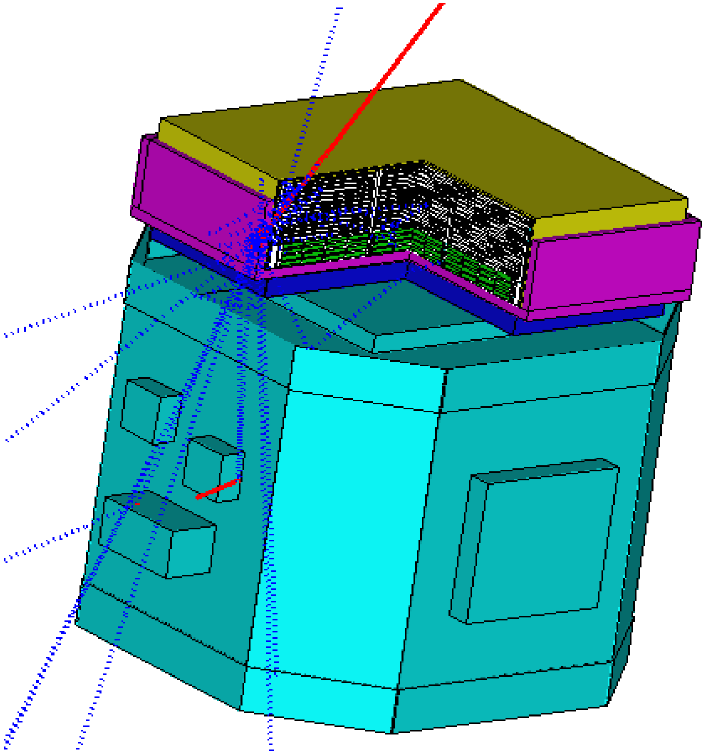
- launch ~2015, 5-10 year lifetime
- 550 km LEO, <10° inclination, Delta IV (4240)
- 1° attitude, 1' aspect, zenith pointer
- instrument 1700 kg, S/C 1425 kg, propellant 462 kg
- 3800 W power, 69 Mbps average telemetry

Modern Detector Technologies

- Strengths
  - ☺ 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, GasXe
  - ☺ Very fast timing (<1 ns, enabling ToF): Xe, LaBr
  - ☺ Room temperature operation: CdZnTe, LaBr

- Hits
  - ☹ Cooling: Ge, LXe, thick Si
  - ☹ Efficiency: GasXe, thin Si
  - ☹ Spectral resolution: LXe, GasXe, LaBr, CdZnTe
  - ☹ Power (readout electr.): thin Si, GasXe

ACT "Baseline" Instrument



D1: 27 layers 2-mm thick Si

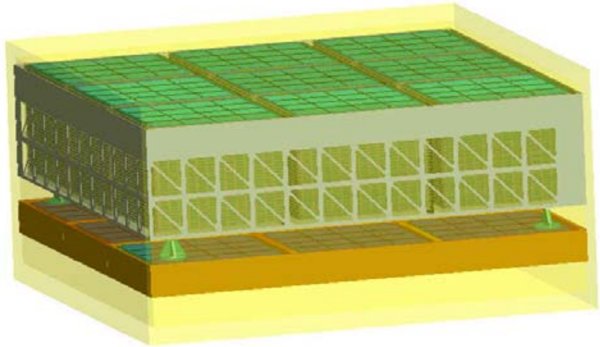
- 10x10 cm2, 64x64 strips
- 3888 det., 248,832 chns
- -30° C, Stirling cycle cooler

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:

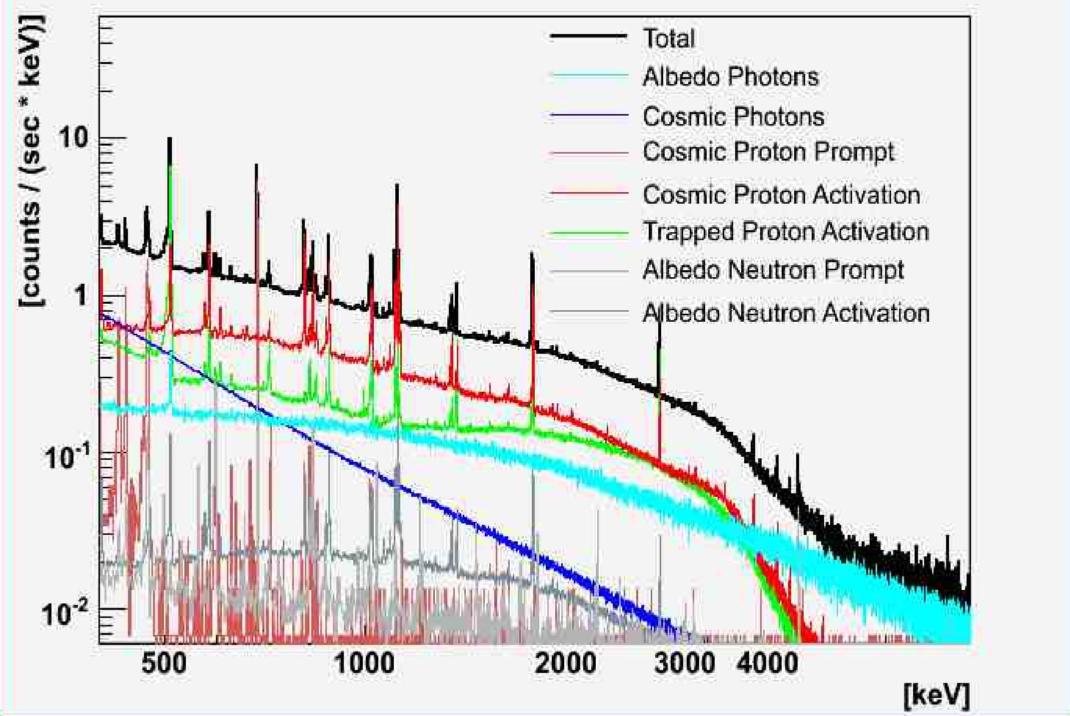
- 1850 kg instrument (w/o margin)
- 2000 W instrument (w/o margin)
- Delta IV shroud (~ 4 m dia.)

End-to-End Simulations Package

- ***Space Environment Model***
- ***Flexible Instrument Model***
  - includes common spacecraft
- ***Reliable Background Predictions*** (MGGPOD)
  - verified with TGRS, INTEGRAL/SPI, and RHESSI
  - includes activation

  (Weidenspointner et al. 2005)

ACT baseline instr. backgr. before event selections

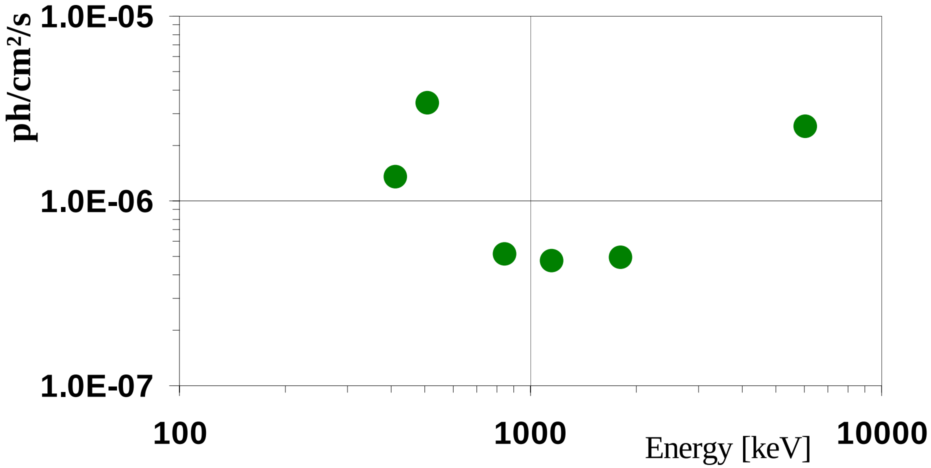


- ***Compton Event Reconstruction & Selection*** (MEGAlib)
  - accurate detector representation for all detector types (positioning accuracy, …)
  - state-of-the-art event reconstruction for all concepts (ToF, e^--tracking, …)
  - background rejection tools

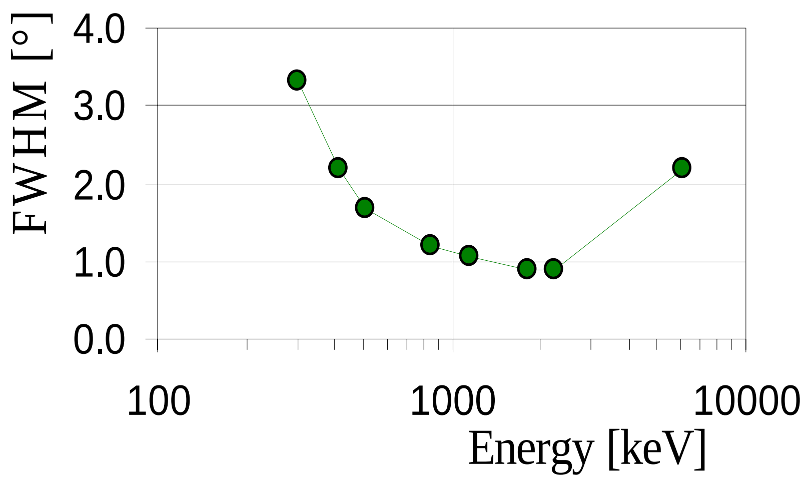
  (Zoglauer et al. 2006)

ACT Si-Ge Baseline Performance

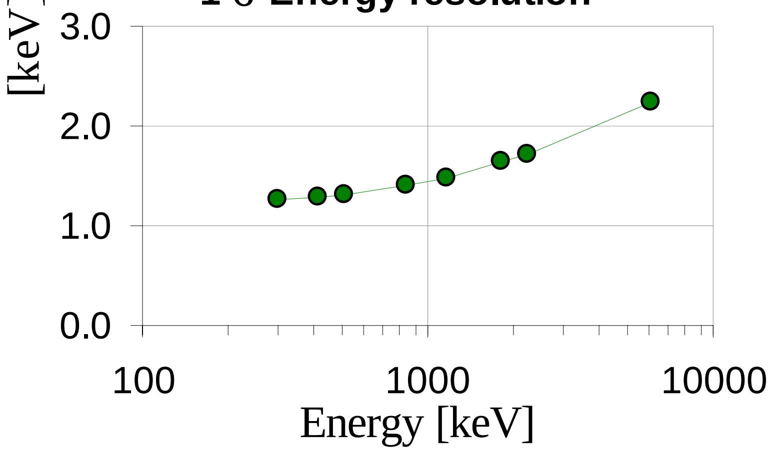
Narrow line sensitivities (3σ, 10^6s)



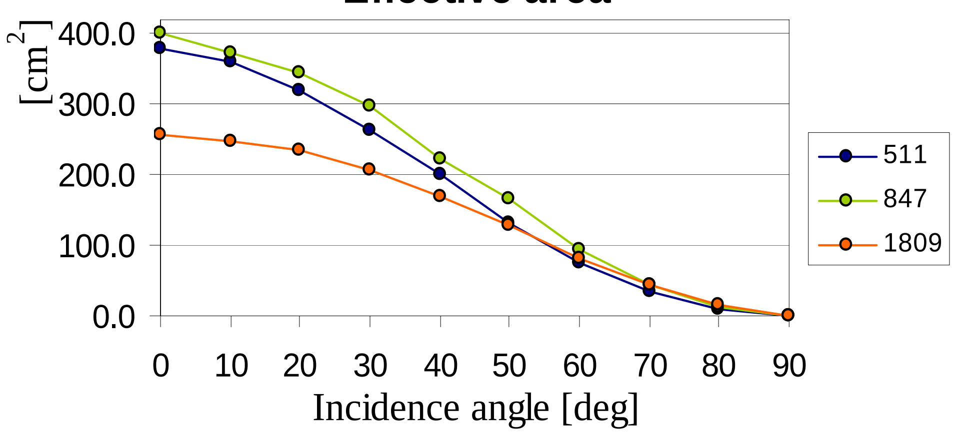
Angular Resolution Measure



1-σ Energy resolution



Effective area



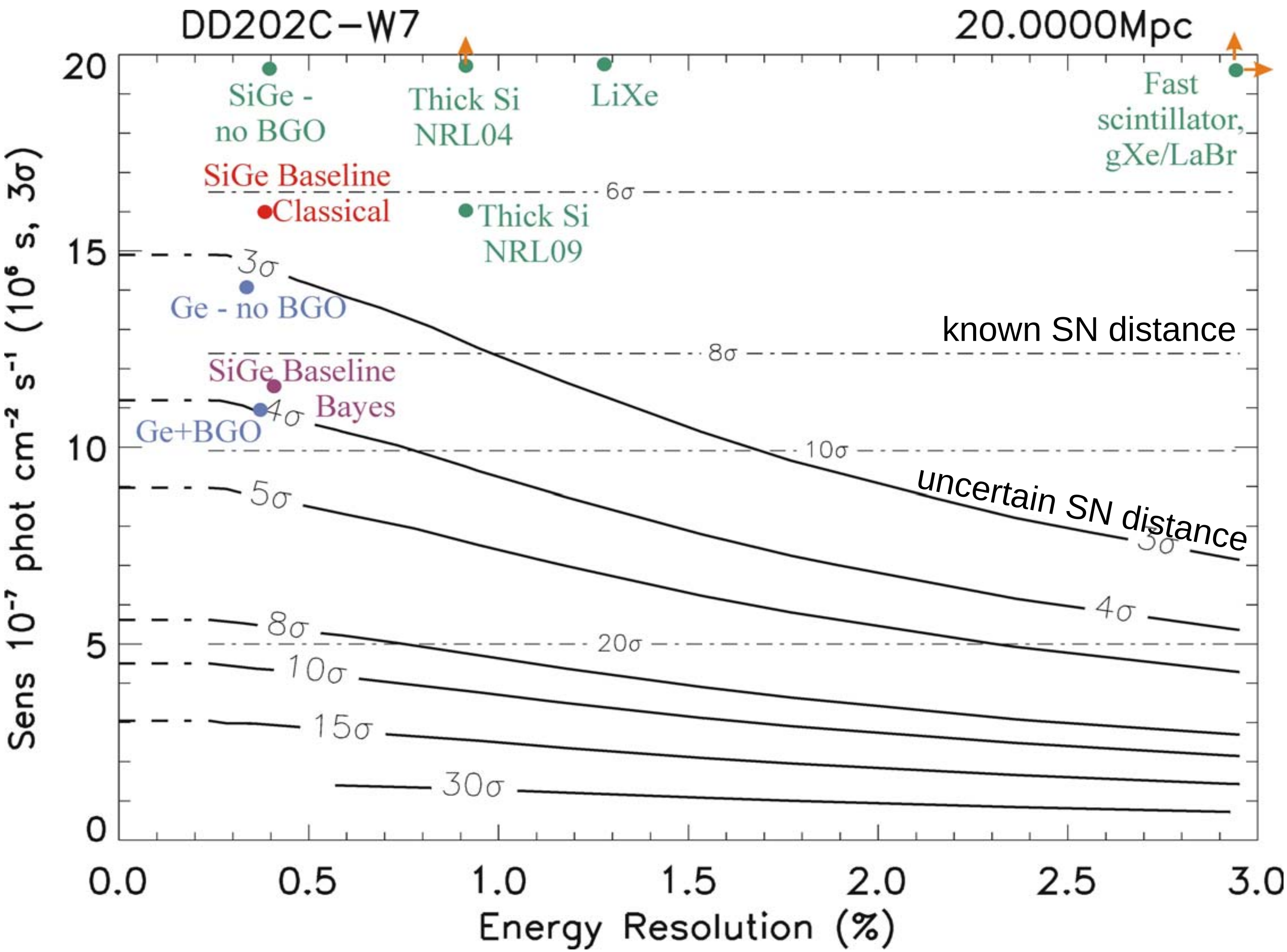
Alternate ACT Designs

compared within a common mass & power envelope

- **Tracking Si/CZT calorimeter** (UCR) ⇒ e^--tracking, room temperature
  limit: *power (# of strips)*
- **Ge/BGO shield** (UCB) ⇒ high spectral resolution
  limit: *power (cooling), mass (BGO)*
- **Thick Si** (NRL) ⇒ reduce Doppler broadening, minimal cooling
  limit: *power (# of channels), mass (detector)*
- **Liquid Xe** (Rice, Columbia) ⇒ fast timing, good stopping power
  limit: *mass (detector)*
- **Gas Xe / $LaBr_3$ calorimeter** (GSFC/UNH) ⇒ high-resolution e^--tracking
  limit: *mass ($LaBr_3$), power (# of channels)*
- **Low-Z-scintillator / $LaBr_3$** (UNH) ⇒ fast timing (modern COMPTEL)
  limit: *mass ($LaBr_3$)*

Technology Comparison

benchmark: distinguish SNIa models



Why the large differences?

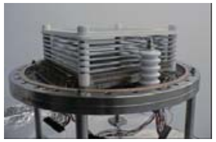
- **Gaseous Xe / $LaBr_3$**:
  - needs a large gasXe volume
  - Thus needs large calorimeter area (mass limit!)
  - Calorimeter mass limit prohibits sufficient gasXe effective area
- **Thin Si / CZT**:
  - Thin-Si tracker needs many channels
  - Thin-Si tracker has comparatively large fraction of passive mass
  - Hard to get sufficient Si effective area
  - Hard to avoid events being partially absorbed in passive material
- **Fast scintillator** ("modern COMPTEL"):
  - Not very compact (2 layers, reduces allowed scatter angles)
  - Energy resolution also influences angular resolution (and thus BG)
- **Thick Si**:
  - Must use a design that allows sufficiently thick Si stack
  - Incompletely absorbed multi-interaction (4+) events can be reconstructed, but with significant loss of energy resolution

Technology Recommendations

1. **Germanium Det.**: *enabling technology development*
2. **Thick Silicon Det.**: *enabling technology development*
3. **Liquid Xenon Det.**: *lab demonstration*
   – Spectroscopy performance
4. **Readout Electronics**: *basic development*
   – ~1 mW/channel readout
   – 0.1 mW preamps
5. **Cryogenics**: *study and development*
6. **Passive Materials**: *study and development*
   – Minimal cryostats, low-Z materials
7. **Simulation Toolset**: *basic development*
   – Integrated simulation package
   – Tested environmental inputs
   – Data and imaging analysis software

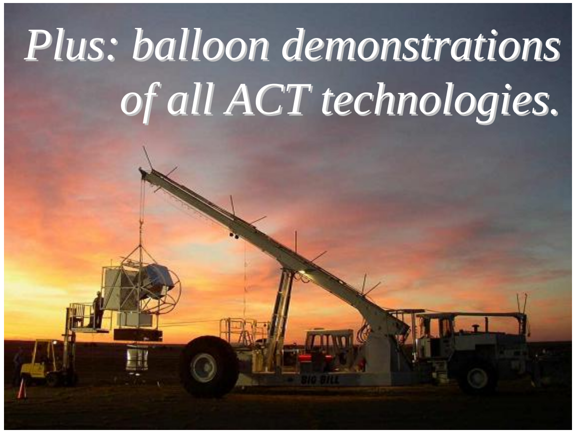

(NRL)

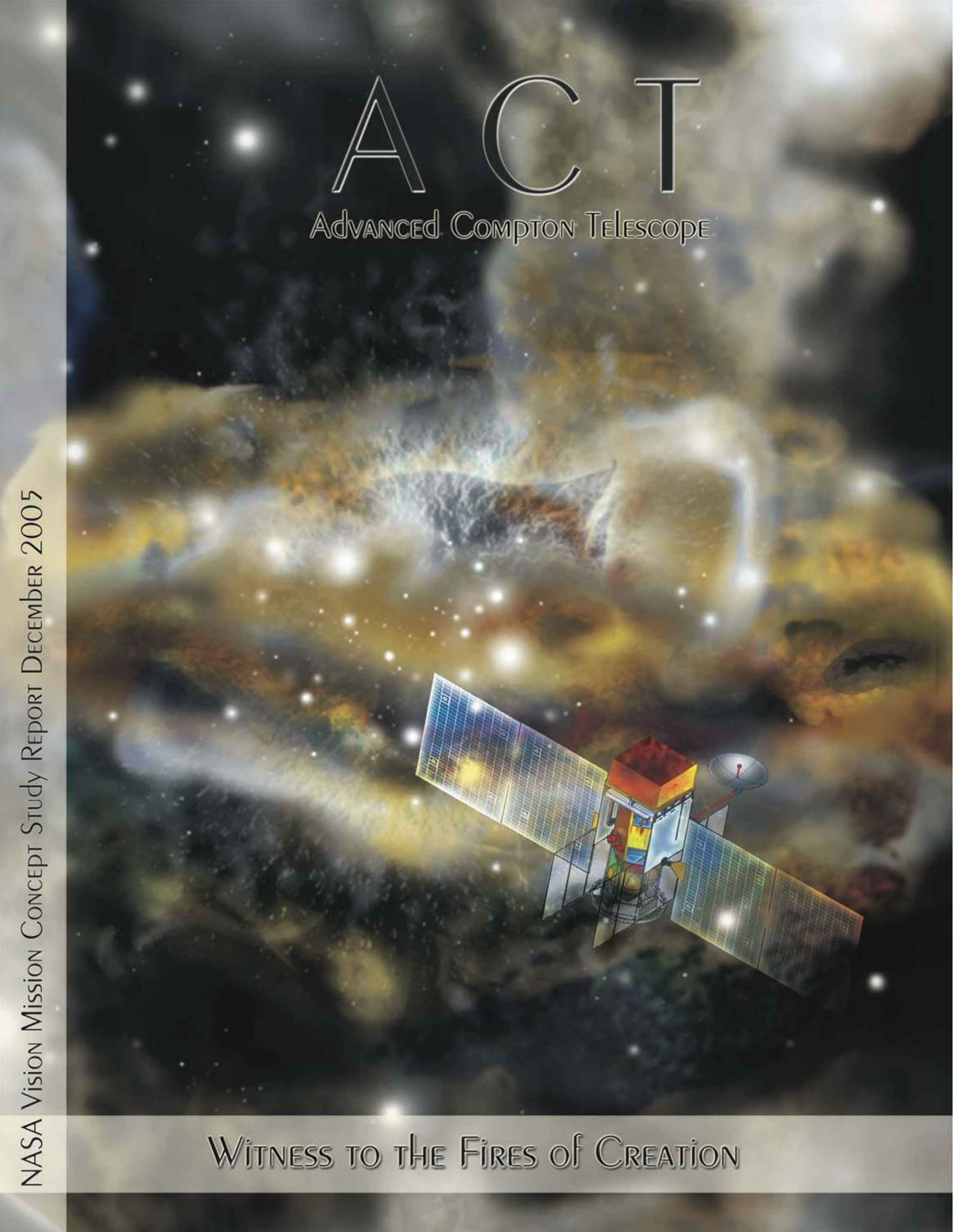

(NCT/UCB)


(LXeGRIT/ Columbia/Rice)


(RENA-2/ Nova R&D)


(NICMOS/HST)





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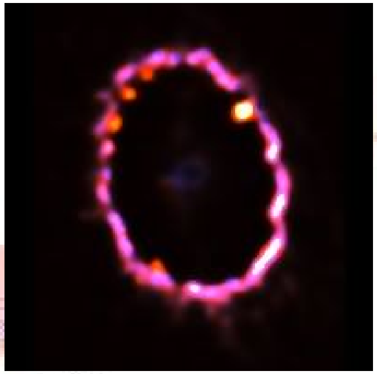
ACT Science Overview

Where do the chemical building blocks of life, planets, stars originate?

How do the chemical elements evolve?

What powers supernovae explosions?

Resolved spectroscopy and flux of nuclear lines from the heart of supernovae



(J. Wilms)

What is the physics at the edge of a black hole?

How do matter & antimatter behave in extreme environments?

Spectroscopy, polarization, and timing of photons from black holes, neutron stars, and novae

When did the first stars form?

Can gamma-ray bursts measure the geometry of the Universe?

Gamma-ray burst localization, spectroscopy, polarization and timing