Future Gamma-Ray Missions

Cornelia Wunderer & Steve Boggs

Reminder – Challenges of γ-ray Instrumentation

Reminder – Imaging Options at MeV Energies

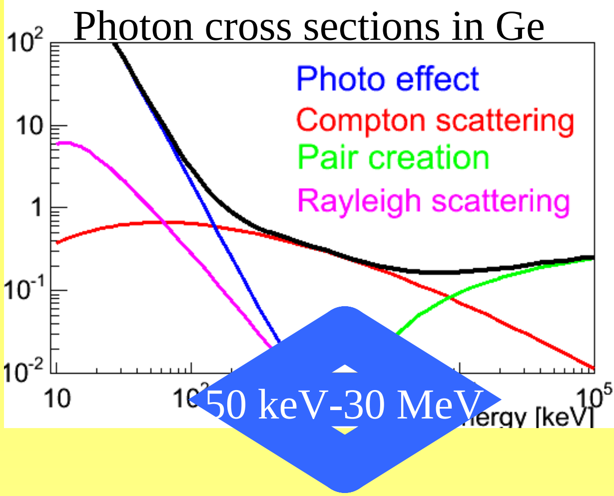
Instruments to look forward to …

Advanced Compton Telescope

Lenses for MeV Photons

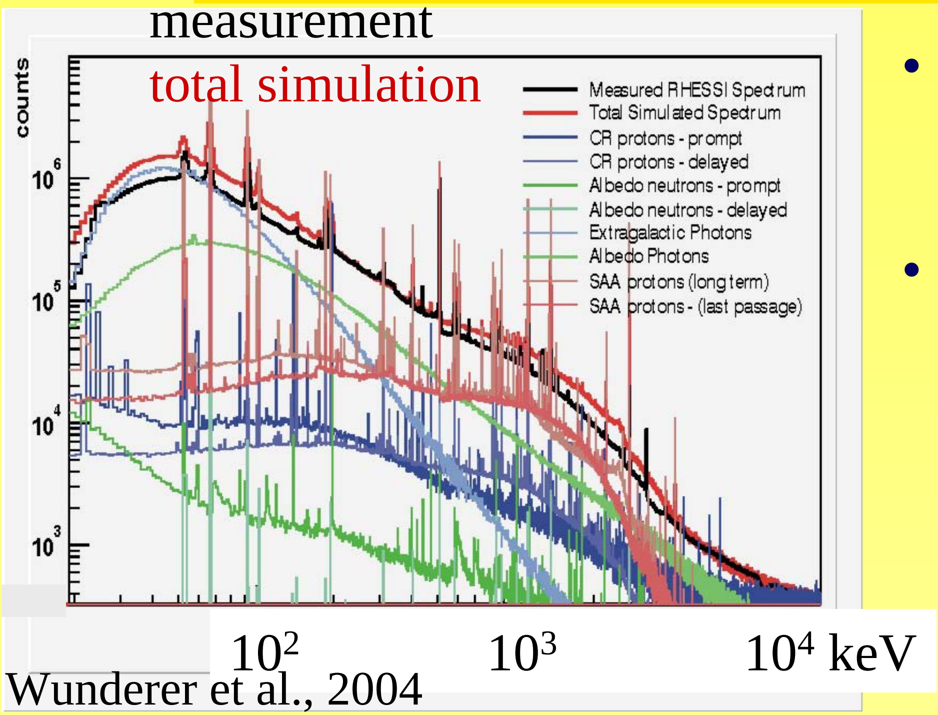
Challenges of MeV Instrumentation

- Materials most transparent at MeV energies
- As a consequence, MeV astronomy
  - requires massive detectors
  - complete shielding of background nearly impossible



- No simple focusing – in traditional MeV astronomy, collection area = detector area
- Huge and complex instrumental backgrounds
  - Induced by space environment
  - Often instrumental lines underlying astrophysical ones
  - ➢ background prediction crucial for instrument development, and hopefully one day accurate enough to advance data analysis …
  - *Directional information reduces applicable instrument backgrounds!*

Background of a Spectrometer in Low-Earth Orbit



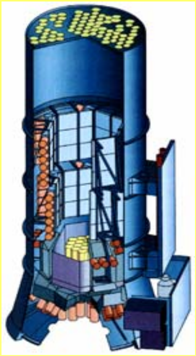
Wunderer et al., 2004

RHESSI spectrometer background simulations (red) compared with measured background (black). Simulations use the GEANT-based MGGPOD suite (Weidenspointner et al., 2004)

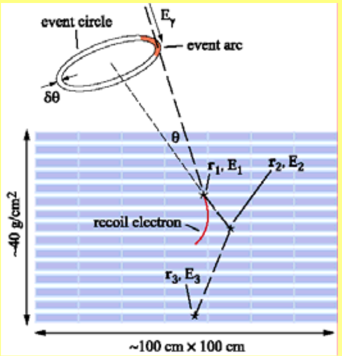
- High background levels at MeV energies lead to S/B levels of ~ 1% or less
- Complex background
  - Cosmic and earth albedo photons
  - Albedo neutrons and cosmic-ray particles induce prompt backgrounds
  - Albedo neutrons and cosmic hadrons generate isomeric-state and radioactive nuclei $\Rightarrow$ delayed background component
- Accurate background prediction / knowledge crucial to MeV instrument design / data analysis

Imaging at Nuclear-Line Energies

- Conventional lenses cannot be used
- Collimators, earth occultation
- Coded aperture imaging (INTEGRAL, SWIFT)



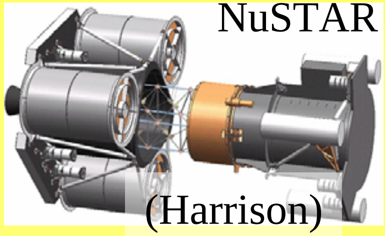
- Imaging through reconstruction of individual photons' interactions
  - Compton-scatter (COMPTEL on CGRO, ACT)
  - Pair events (COS-B, EGRET on CGRO, GLAST)



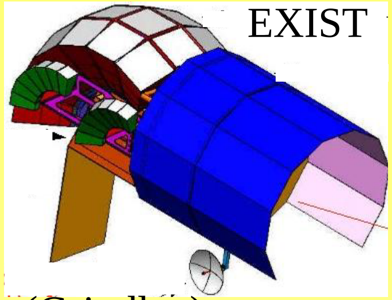
- Multilayer grazing-incidence Wolter optics (up to a few 100 keV)
- Focusing via Laue - Diffraction (CLAIRE/MAX)
- Focusing with Fresnel Phase-shift Lenses (G. Skinner, 2000)

Upcoming & Envisioned Missions Observing at Nuclear-Line Energies

- NuSTAR (multilayer mirror, CZT, 6 keV – 80 keV)

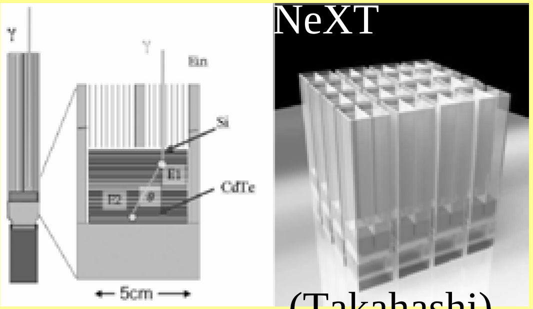


- Black Hole Finder Probe (EXIST/CASTOR) (coded aperture, wide FoV, Si-Strip/CZT or Scintillator, 5 keV – 300/600 keV)



(Grindlay)

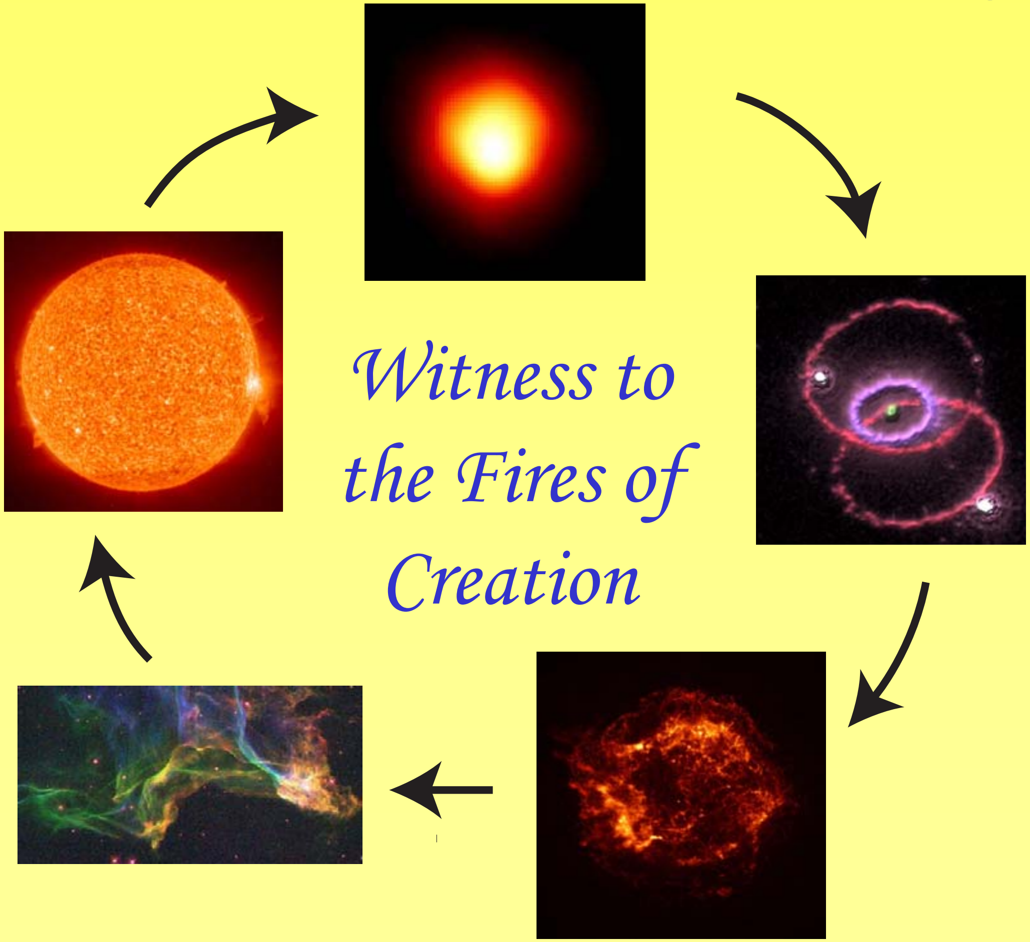
- ACT (Compton Imager - more later)
- MAX (Laue Lens, France - more later)
- NeXT (combined multilayer mirror and deep-well Compton Si/CdTe detector, 0.2keV – 80 keV and 100 keV – 1 MeV, Japan)



(Takahashi)

Advanced Compton Telescope

(Elemental Origins Probe)



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

Requires two orders of magnitude improvement in sensitivity over COMPTEL on the Compton γ-Ray Observatory

ACT Mission Study Collaboration
UC Berkeley, NRL, New Hampshire, GSFC, Columbia, LANL, UC Riverside, Clemson, Rice, U Arizona, CESR, MPE, IEEC, ASU, Sonoma State, Ball Aerospace, UC Santa Cruz, UC San Diego, MSFC, Stanford, SLAC, UAH, LLNL, Chicago, ISAS, IHEP

ACT Overview

Enabling high sensitivity γ-ray spectroscopy

Life Cycles of Matter

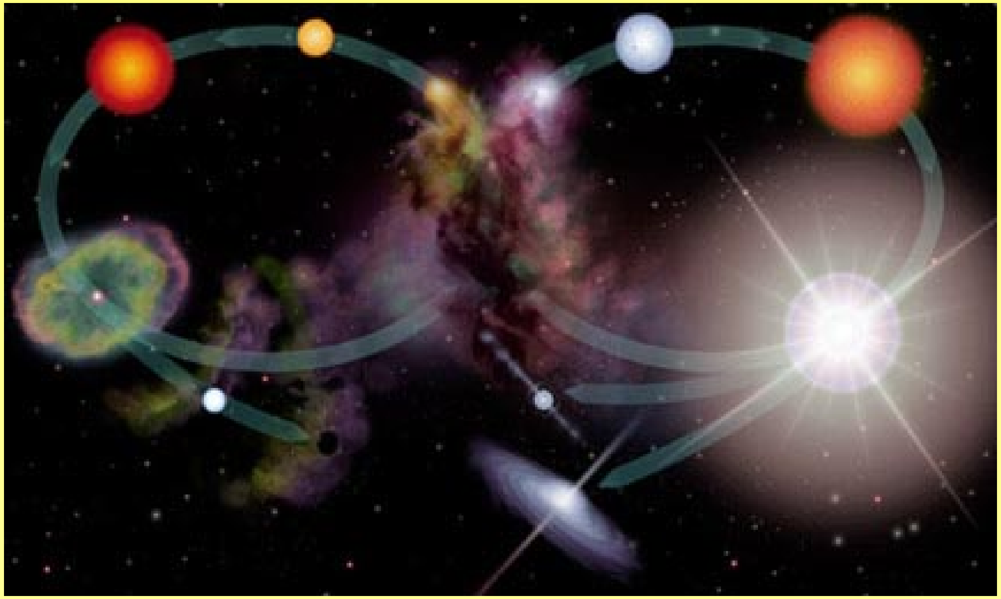
- ✓ Supernovae & nucleosynthesis
- ✓ Supernova remnants & interstellar medium
- ✓ Neutron stars, pulsars, novae

Black Holes

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

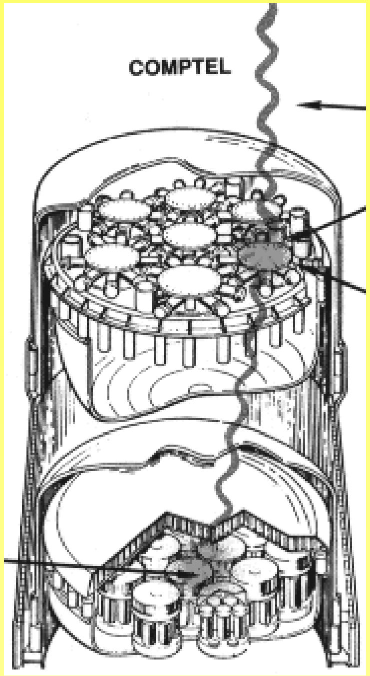
Fundamental Physics & Cosmology

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

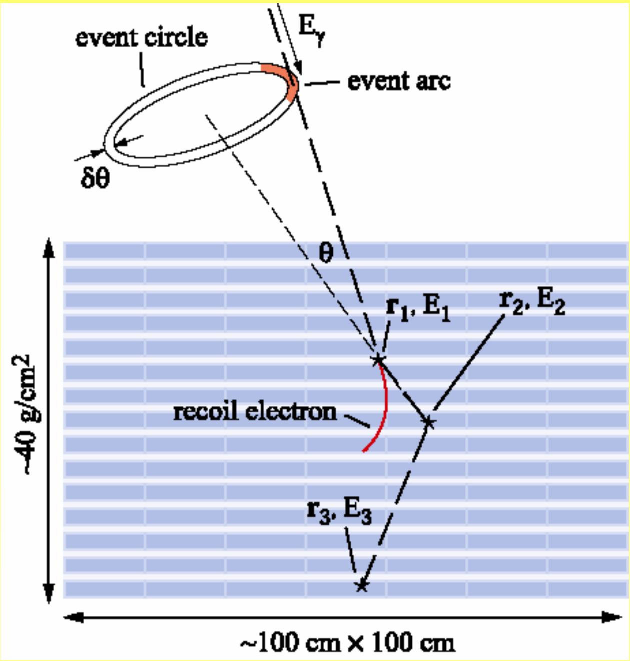


Compton Telescopes: then & now

NASA has invested over 2 decades in advancing γ-ray detector technologies beyond those on CGRO



CGRO/COMPTEL
- ~40,000 mm^3 resolution
- ΔE/E ~ 10%
- 0.1% efficiency



ACT Enabling Detectors
- 1 mm^3 resolution
- ΔE/E ~ 0.2-1%
- 10-20% efficiency
- background rejection
- polarization

Sensor Technologies:
- Ge cross-strip
- Si cross-strip
- Si trackers
- Liquid Xe
- Gaseous Xe
- CZT cross-strip

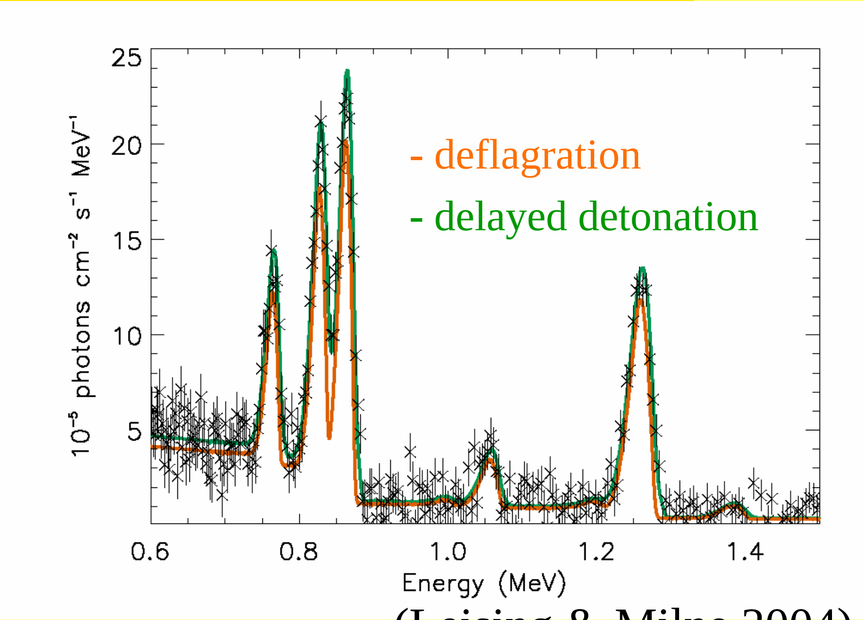
…shake down and recommendations will be part of the ACT concept study report (2005).

Type Ia SN Spectra & Light Curves

Revealing the heart of our cosmic probes

We define the primary science requirements for ACT in terms of the following **objective**:

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



(Leising & Milne 2004)

Leading to primary **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 SN Ia detections/year (5 @ 15σ)!

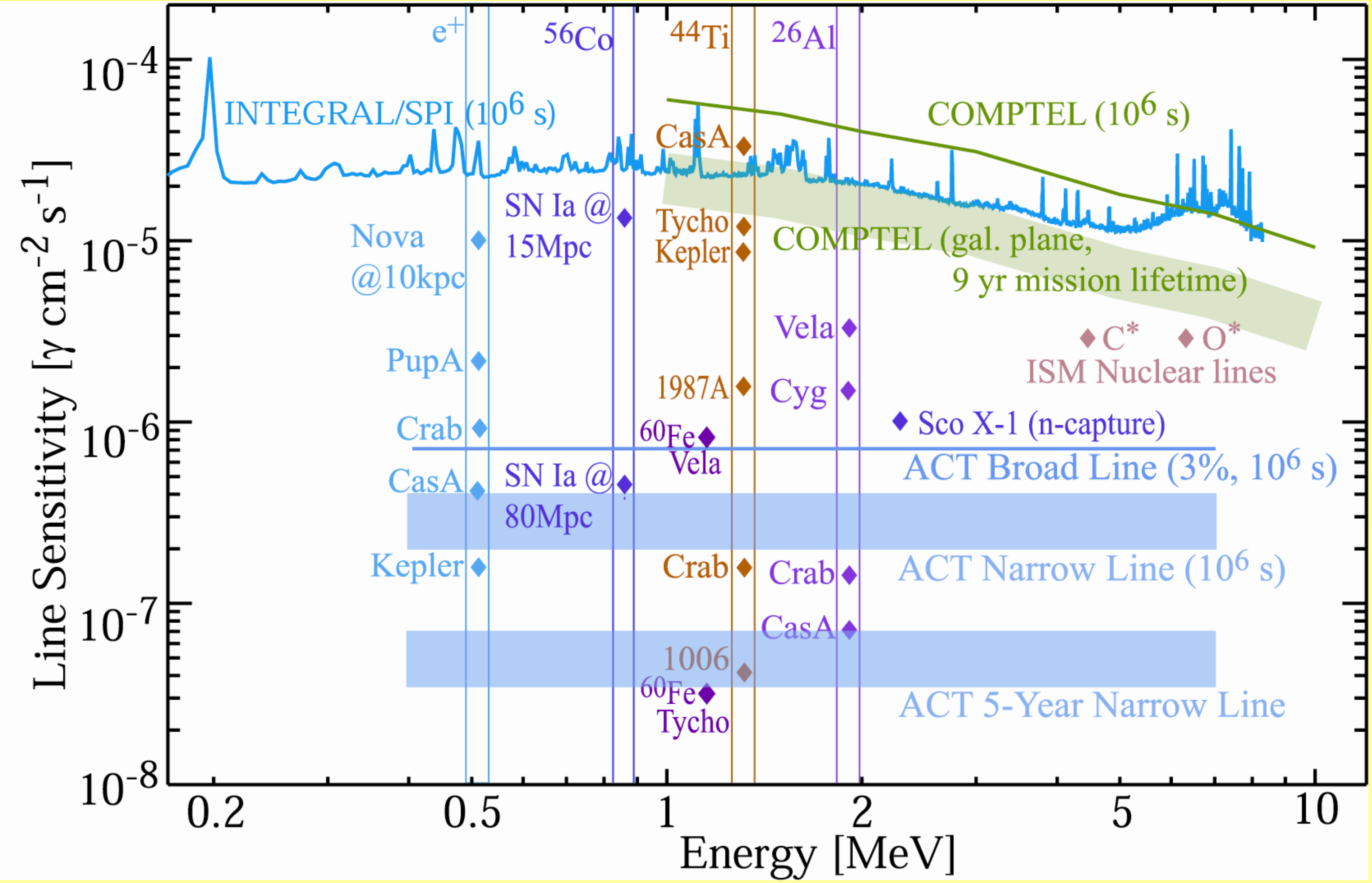
ACT Science Instrument

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

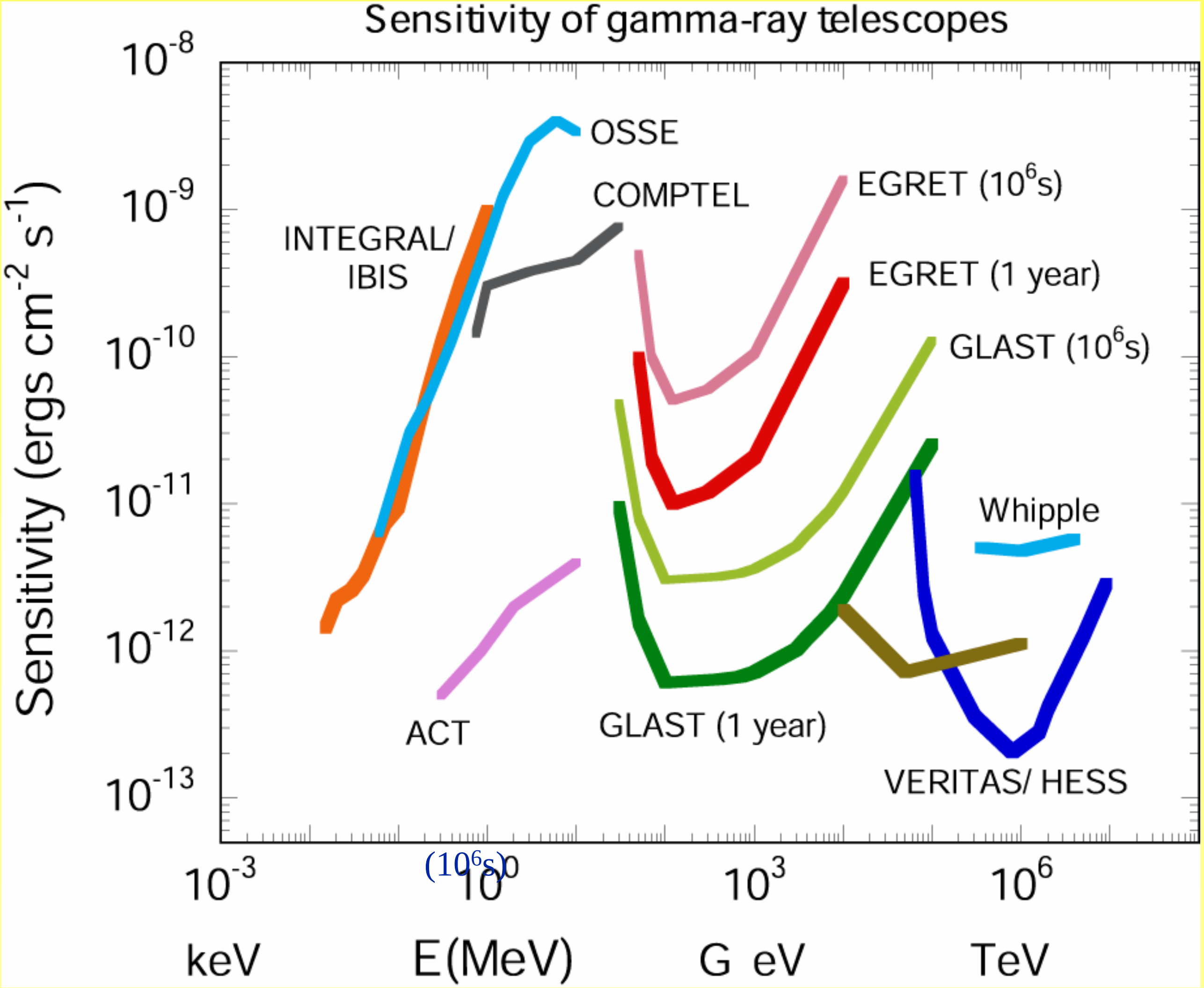
Energy range	0.2-10 MeV
*Spectral resolution	0.2-1%
*Field of View	25% sky (zenith pointer)
Sky coverage	80% per orbit
Angular resolution	1°
Point source localization	5’
Detector area, depth	~10,000 cm^2, 40 g/cm^2
Effective area	~1000-2000 cm^2
*3% broad line sensitivity (10^6s)	7×10^{-7} $ph/cm^2/s$
Narrow line sensitivity	$(2\text{-}4)\times10^{-7}$ $ph/cm^2/s$
Continuum sensitivity	$(5/E)\times10^{-6}$ $ph/cm^2/s/MeV$
Polarization sensitivity (10%)	$(1/E)\times10^{-4}$ $ph/cm^2/s/MeV$
Data mode	Every photon to ground

ACT Nuclear Line Sensitivity

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

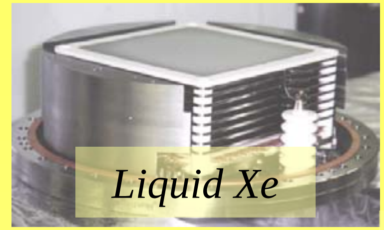


ACT Continuum Sensitivity



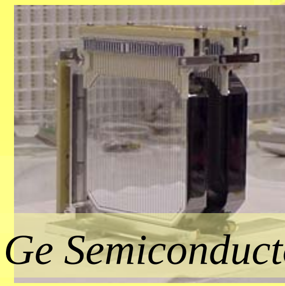
ACT – Enabling Technologies

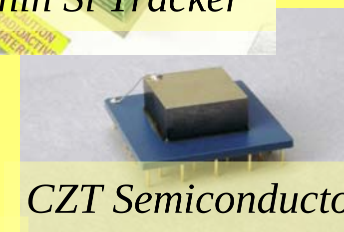
The ACT Vision Mission study will identify the most promising detectors and highest priority technology developments.



Likely recommendations:

- low-power readouts
- low-energy electron tracking
- fast timing (time of flight)





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

ACT Mission

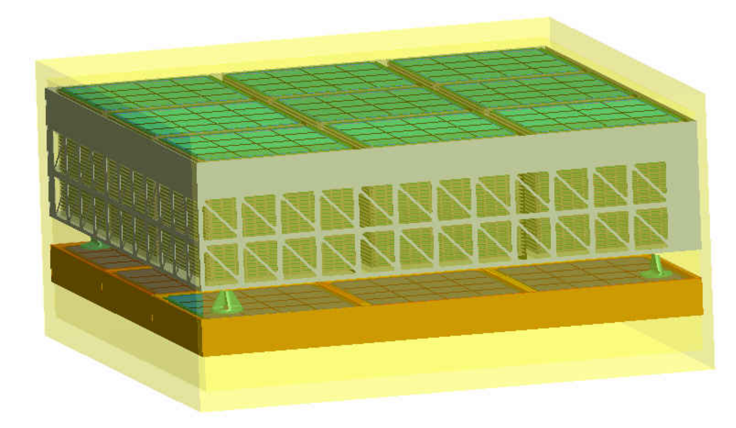
- ✓ Instrument Synthesis & Analysis Laboratory (ISAL), September 2004
- ✓ Integrated Mission Design Center (IMDC), November 2004

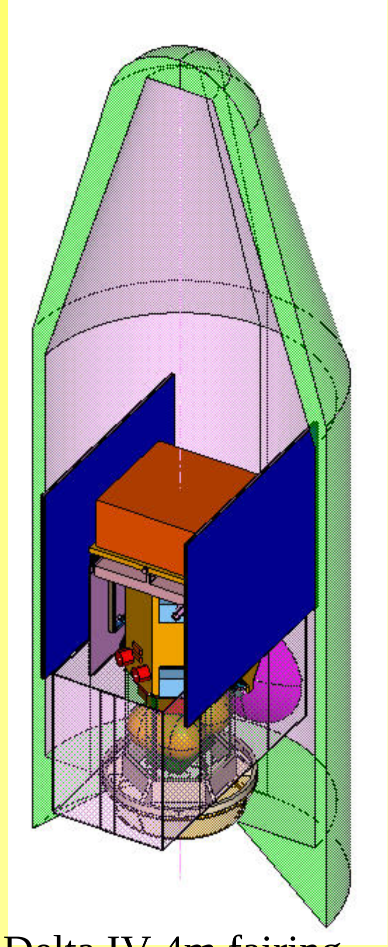
"Baseline ACT" for ISAL & IMDC:

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

Where INTEGRAL and ACT can't take us …

- γ-ray line spectroscopy of individual knots in SN remnants
- Approaching source- (rather than background-) dominated observations at MeV energies

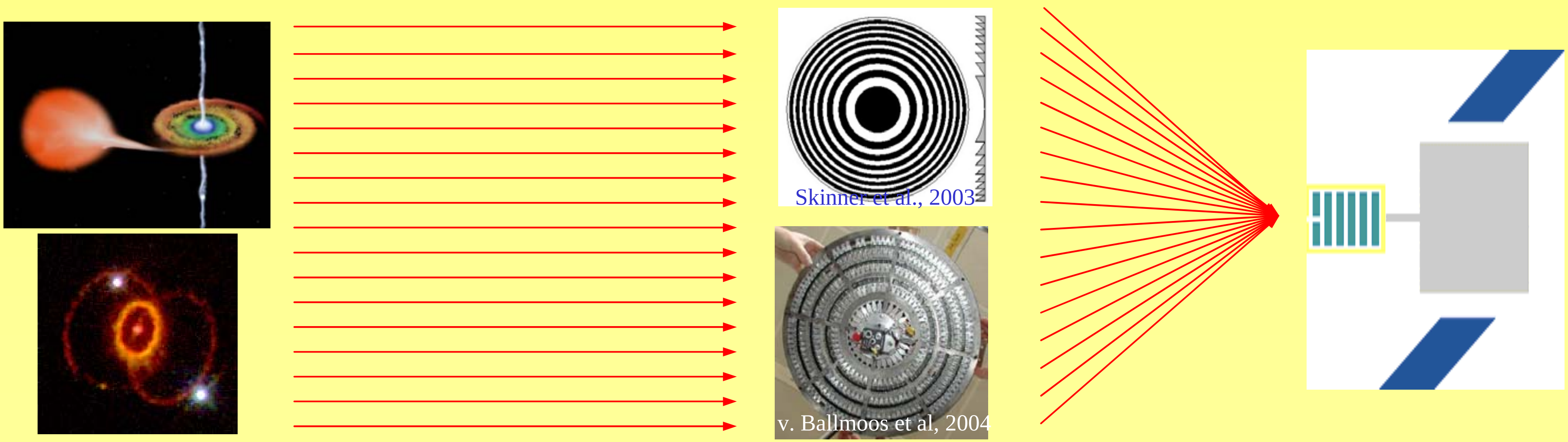
… and beyond:

- Diffraction-limited imaging at MeV energies
- Sensitivities on the order of 10^{-9} ph/(cm^{2}s)

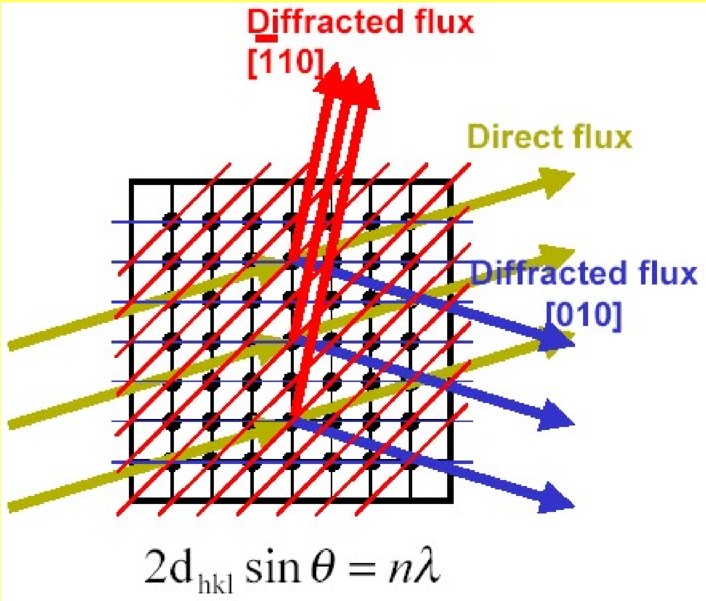
Looking Deeper – Lenses @ MeV Energies

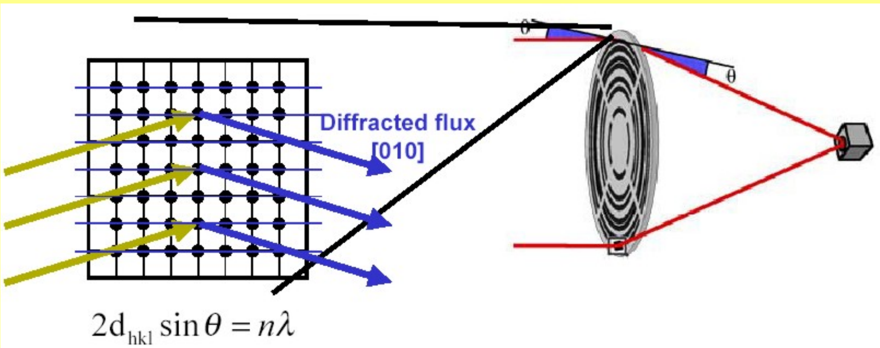
- **Decoupling instrument effective area and detector volume** is the only way to increase point-source sensitivity much beyond ACT

- Contrary to conventional MeV astronomy wisdom, concentrating MeV photons IS possible …
  - Laue Lenses
  - Fresnel Phase-Shift Lenses



Principle of Laue Lenses



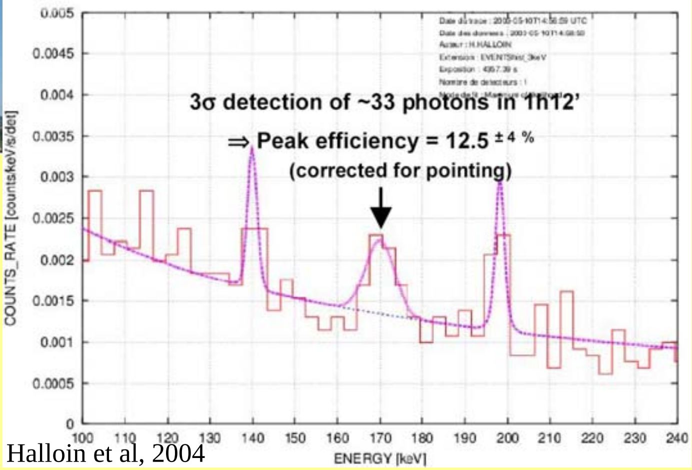


(diagrams curtesy of P.v.Ballmoos)

- Photon diffraction on crystal planes in the volume of a crystal
- Diffraction angle determined by crystal plane spacing and photon energy
- Angles of ~ 1° feasible at 1 MeV
- Mosaic crystals allow bandpasses of several keV per crystal with diffraction efficiencies up to ~ 30%
- crystals can be combined to achieve bandpasses of ~ 100 keV for a 1arcmin FoV

Laue Lenses Work

- Ge mosaic crystal lens tested on a balloon at CESR, France (Halloin, 2003)
- 576 crystals concentrated 170 keV photons onto monolithic Ge detector array
- Crab detection in a short technology-demonstration flight



Halloin et al, 2004

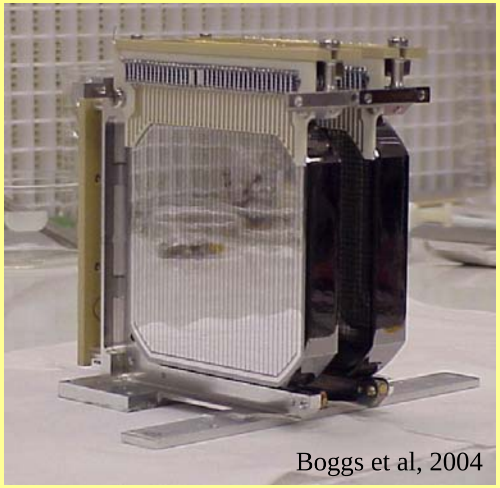

v. Ballmoos et al, 2004

Focal Plane Instrumentation

- Ge offers best energy resolution available at ~ 2-3 keV FWHM,
  $\Rightarrow$ detectors of choice for MeV spectroscopy

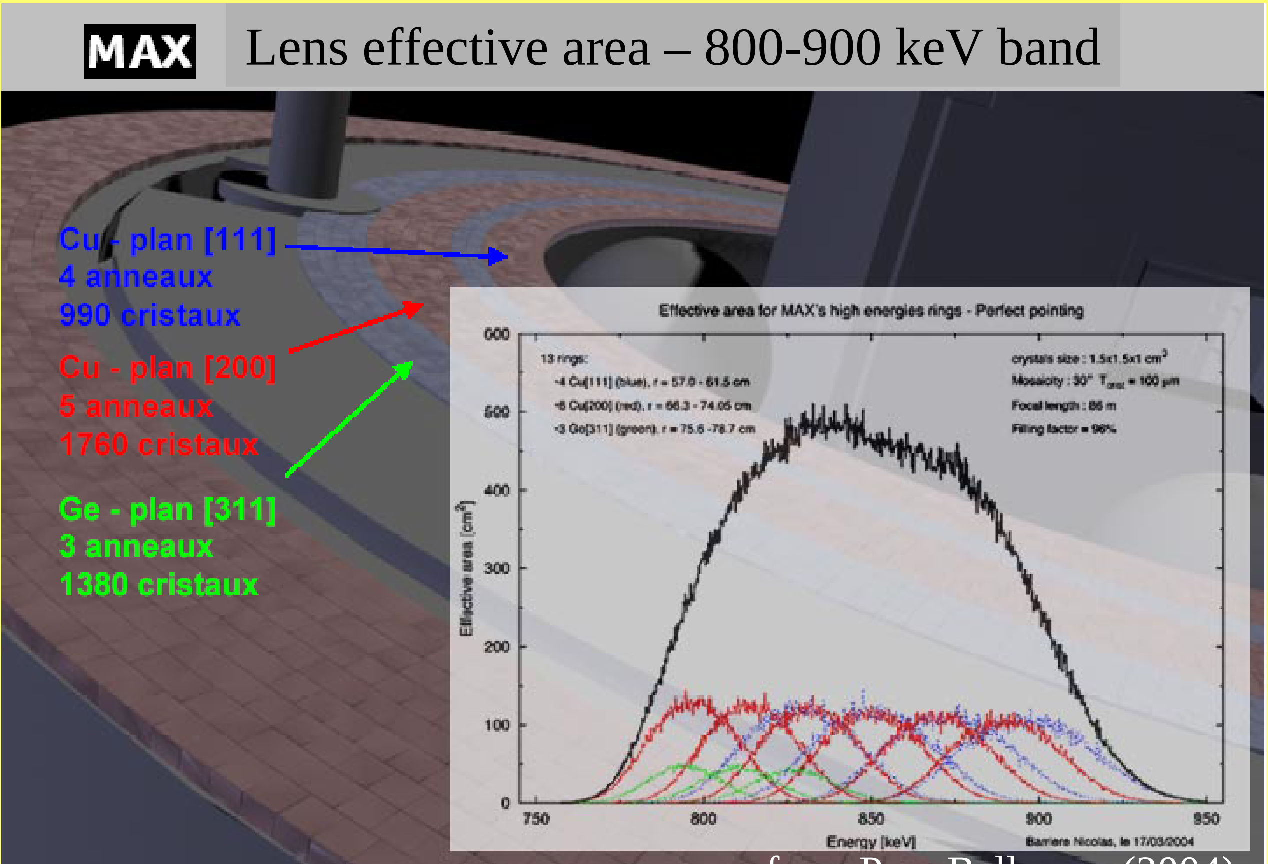
- Compton detector focal plane: advantages over monolithic detector(s)
  - Better capability for background rejection
  - Inherently finely pixellated detector naturally allows selection of events according to focal spot size and position
  - Inherently sensitive to γ-ray polarization

- Ge-strip Compton detectors
  - tested in the laboratory
  - Currently in Ft Sumner, NM, for a balloon test flight this spring (Boggs et al., 2004)



Boggs et al, 2004

MAX mission proposal



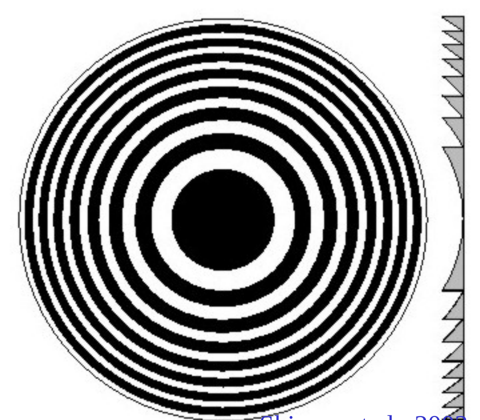
from P. v. Ballmoos (2004)

3 crystal ring groups form 800 – 900 keV band

- two energy bands around 511 keV and 847 keV
- Focal length ~ 100m
- Baseline focal plane detector is a Ge-strip Compton stack
- Sensitivity @ 511 keV on the order of 10^{-6} ph/cm^{2}s
- Formation flying at L2
- Decision from CNES in 2005

Gamma-Ray Imaging at the Diffraction Limit – the (far) Future

- Fresnel phase-shift lenses exploit small deviation of index of refraction from 1 at MeV energies



Skinner et al., 2003

- Potential lens efficiency near 100%
- μarcsec resolution
- Negligible absorption
- Sensitivities on the order of 10^{-9} ph/cm^2/s

- Very small field of view
- Fairly narrow energy band(s)
- So far at gamma-ray energies on paper only
- Focal lengths of Mkm and sub-μarcsec pointing needed!

Summary

- Current satellite instrumentation has too-low γ-ray line sensitivities for a systematic study of individual SNIa and Nova nucleosynthesis

- ACT will provide high-resolution spectra and light curves for SNIa out to ~ 80Mpc
- Wide field-of-view and scanning mode allow ACT to find its own targets (obscured SNae)

- Increasing sensitivities beyond what ACT can provide will require decoupling of collection and detection areas (Lenses)
- Laue Lenses with Compton detector focal plane tested & 'ready'
- Fresnel lenses offer the potential of 10^{-9} ph/cm^{2}s line sensitivities, but require novel mission technologies (pointing)