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Positron science with the Soft Gamma-ray Detector onboard ASTRO-H and future Compton telescope missions

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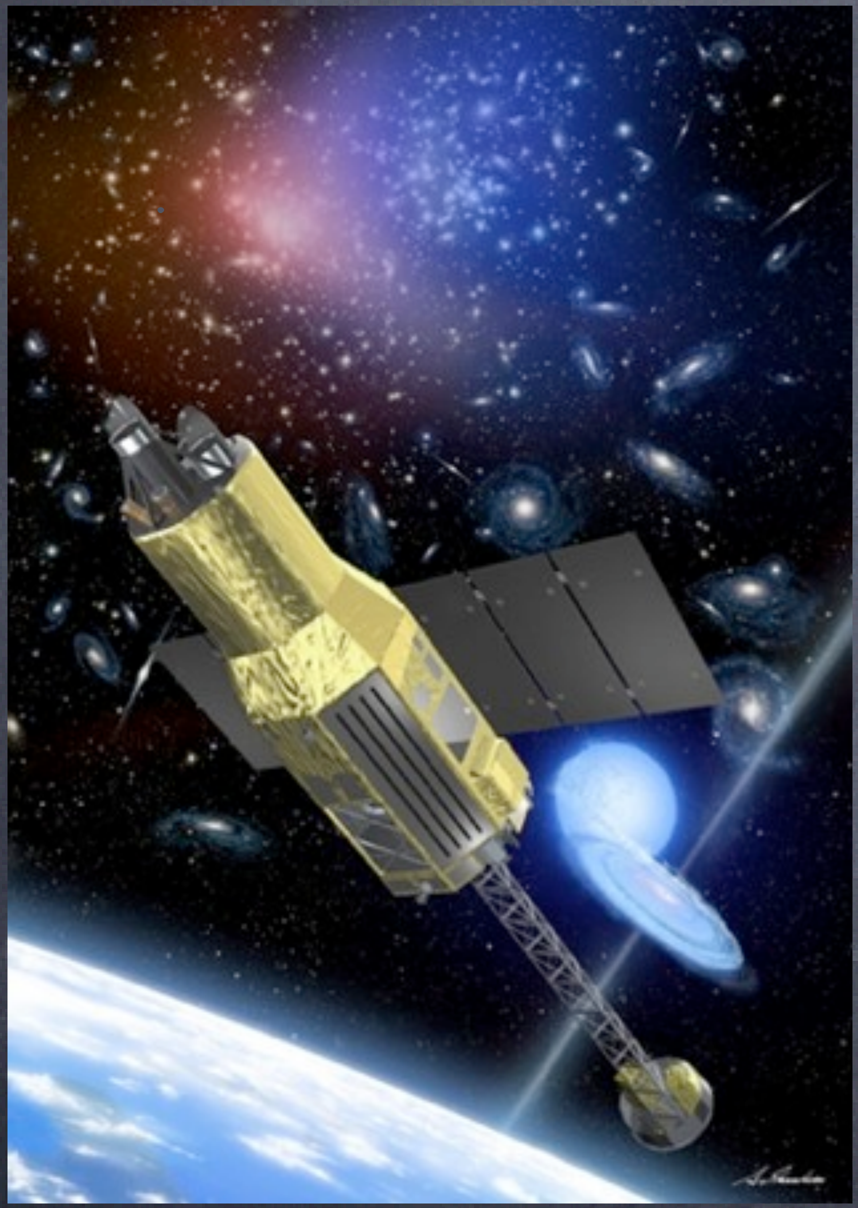
and the HXI/SGD collaboration

The ASTRO-H Mission



ASTRO-H is an international X-ray observatory, which is the 6th Japanese X-ray satellite scheduled for launch in **2014** from Tanegashima Space Center, Kagoshima, Japan.

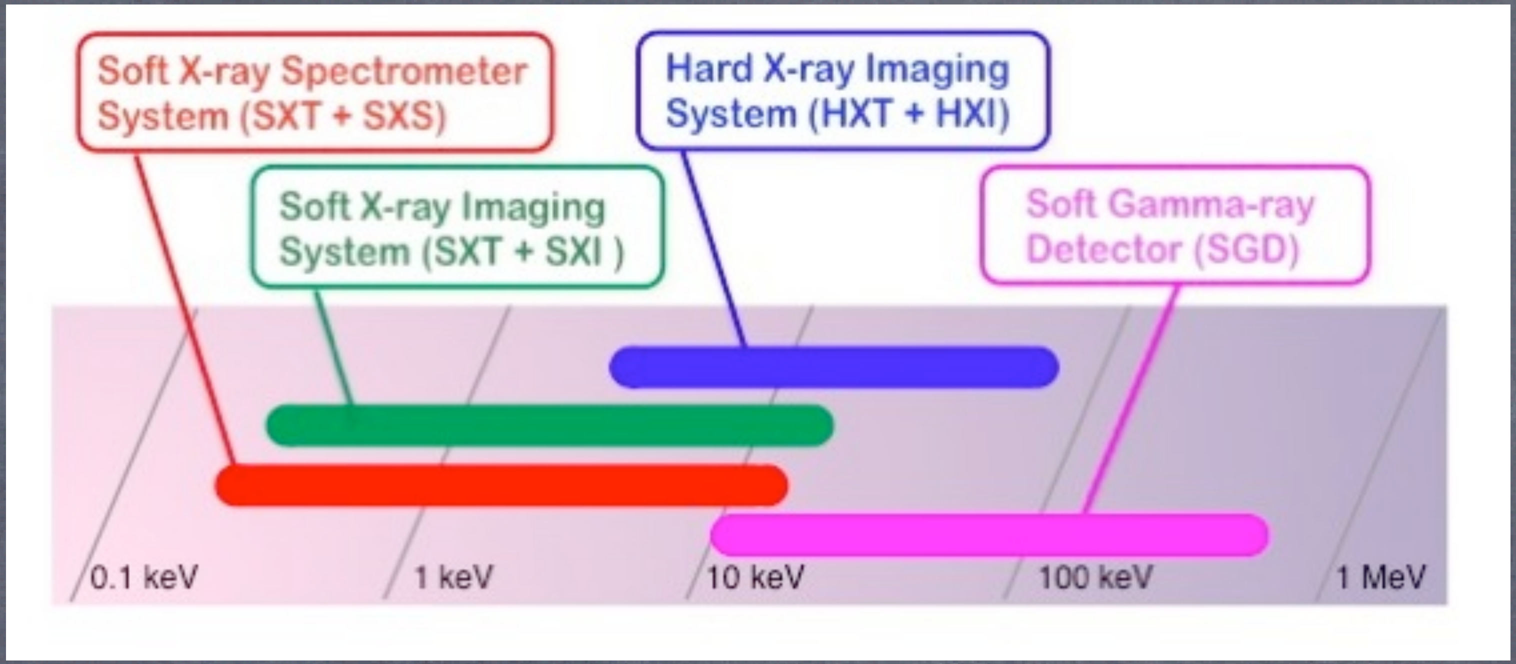
ASTRO-H will explore the energetic universe; for example,

- black holes: strong gravitation
- clusters of galaxies: the largest self-gravity system, evolution of our universe
- supernova remnant: powerful energy source, cosmic-ray accelerator

Takahashi+ SPIE (2010)

Four Instruments on board ASTRO-H

to cover wide energy band: 0.3 - 600 keV



- SXS: micro-calorimeter array operated at 50 mK to achieve excellent energy resolution of 5 eV at 6 keV.
→ detailed line spectroscopy, measurements of plasma dynamics, temperature and density.
- HXI: hard-X-ray super mirror + semiconductor detector stack
→ imaging capability and drastically improved sensitivity (x100) for hard X-ray (or non-thermal energetic) sources.

The Soft Gamma-ray Detector

the highest energy instrument

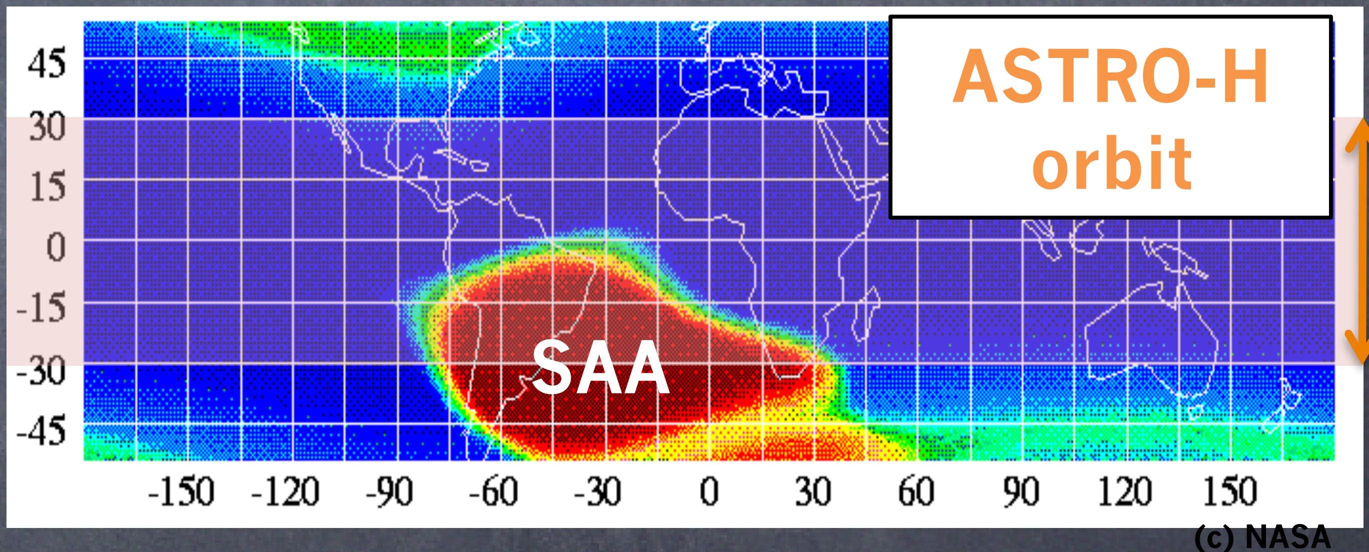
Tajima+ SPIE (2008)

What's Difficult?

Difficulties with the soft-gamma-ray bands (0.1 -10 MeV)

- Low detection efficiency: photoelectric absorption hardly occurs.
- High background level in orbit: cosmic-ray protons/electrons, cosmic X-ray/gamma-ray background, and albedo gamma rays/electrons/ neutrons can fake signals.
  In addition, gamma rays, electrons, or positrons from radio-activated isotopes can generate backgrounds inside the detector.

Altitude	550 km
Inclination	30 degrees

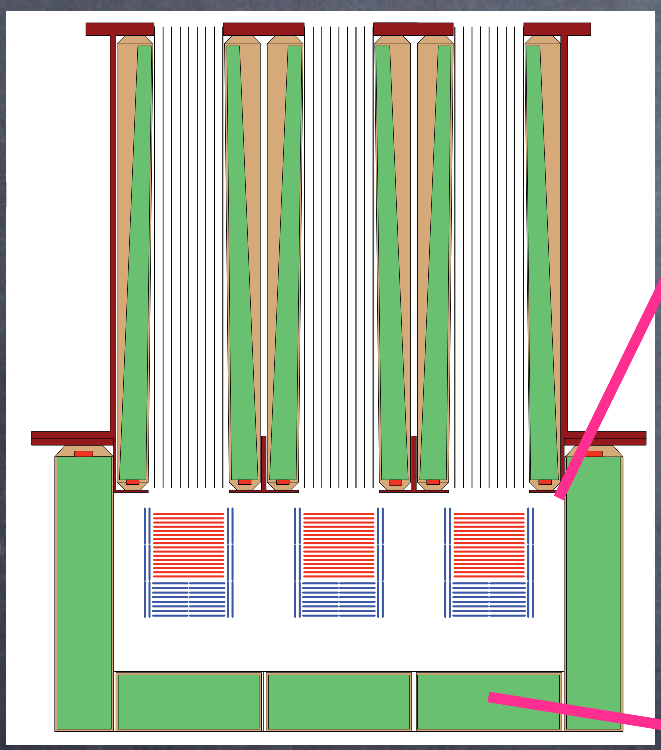


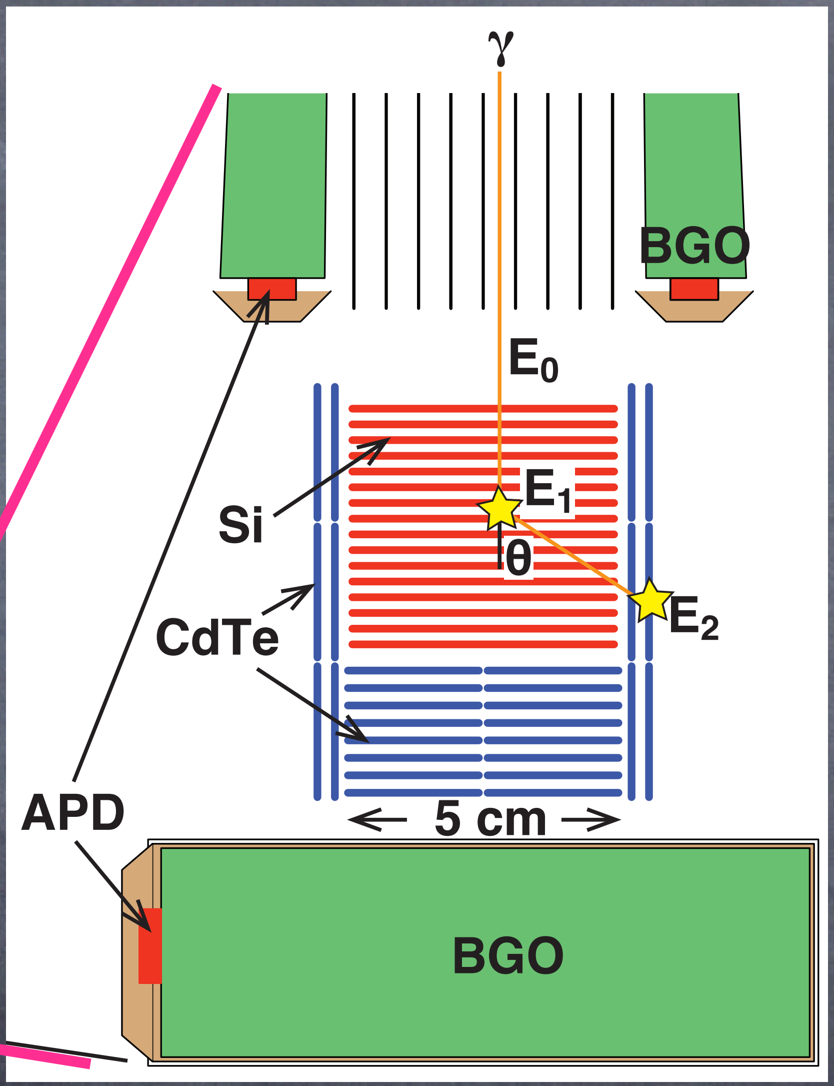
Thanks to the orbital altitude, ASTRO-H will achieve low and stable background levels, except for passages in the South Atlantic anomaly (SAA), in which geo-magnetically trapped protons activate detector materials.

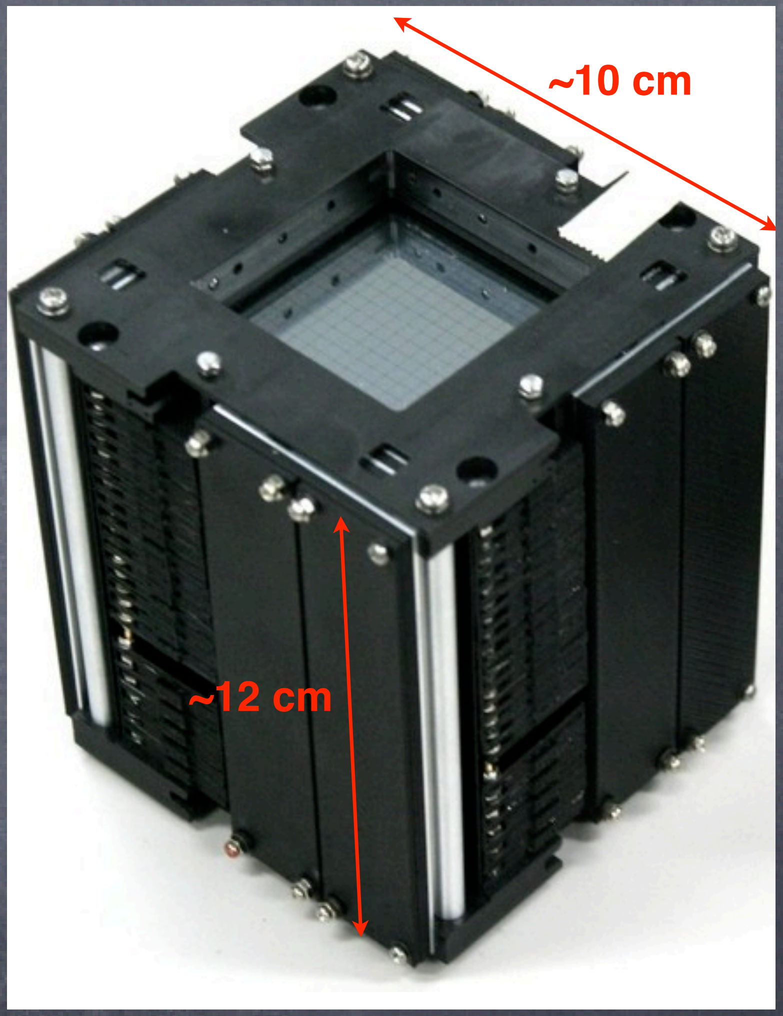
Detector Design

Our answer is a narrow field-of-view (FOV) Compton telescope based on advanced technologies of semiconductor detectors.

BGO active shield







Main detector: Si/CdTe Compton camera

Si pad detector: 0.6 mm thick, 32 layers; energy resolution = 1.1 keV (FWHM)
CdTe pad detector: 0.75 mm thick, 8 layers at bottom, 2 layers at each side; energy resolution = 1% (FWHM) at 511 keV
Readout channels: 13312 channels/CC unit × 6 CC = 79872 channels

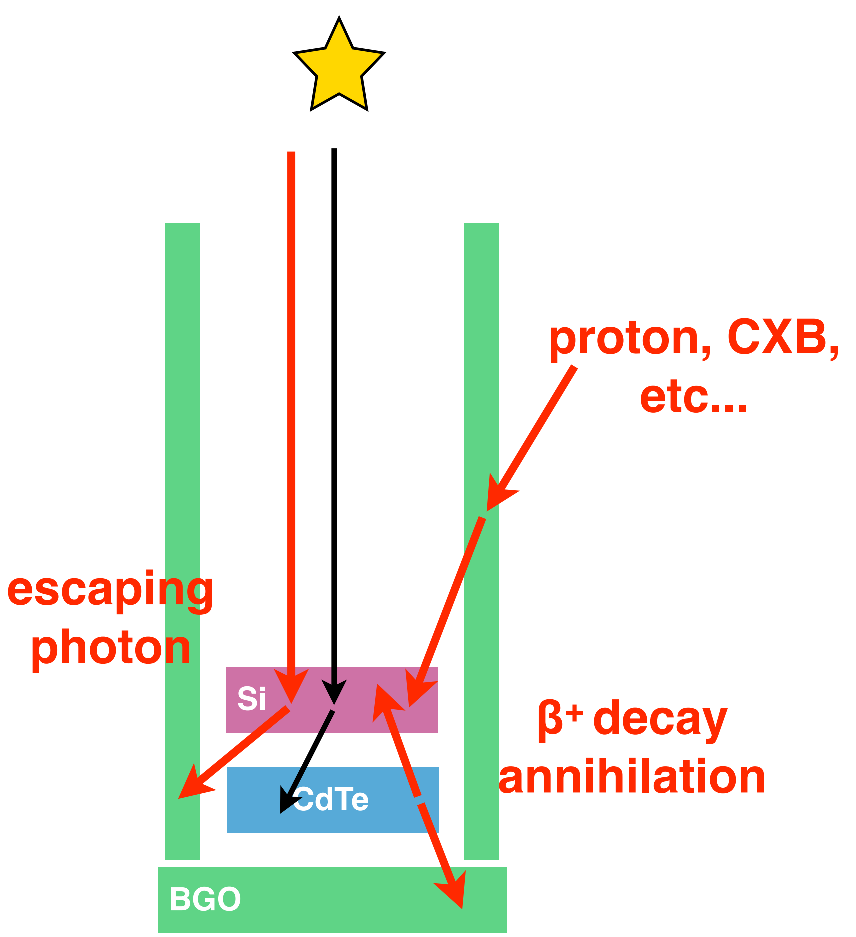
How to Overcome the Problems

Narrow FOV Compton telescopes

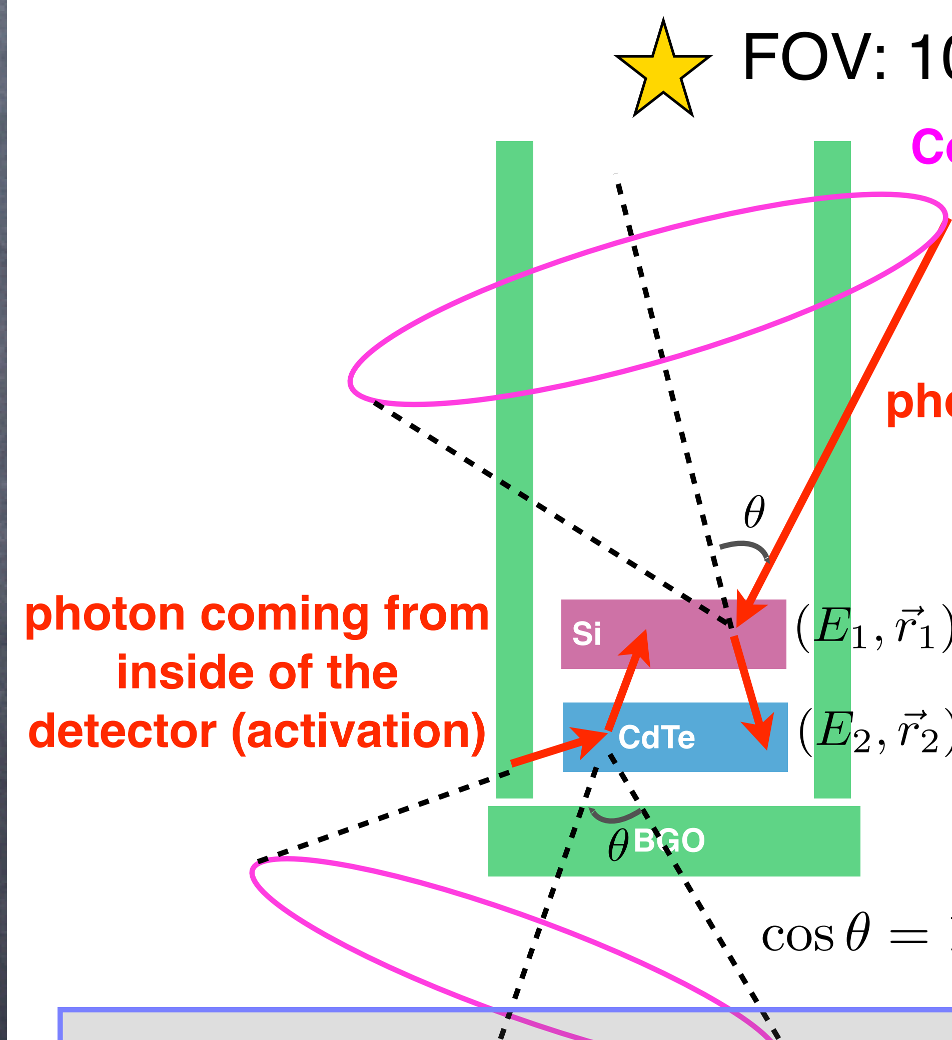
1. Use Compton scattered event -> acceptable detection efficiency
2. Narrow field of view -> reject gamma-ray background (cosmic/albedo)

3. Anti-coincidence

[BGO active shield]



4. Compton reconstruction



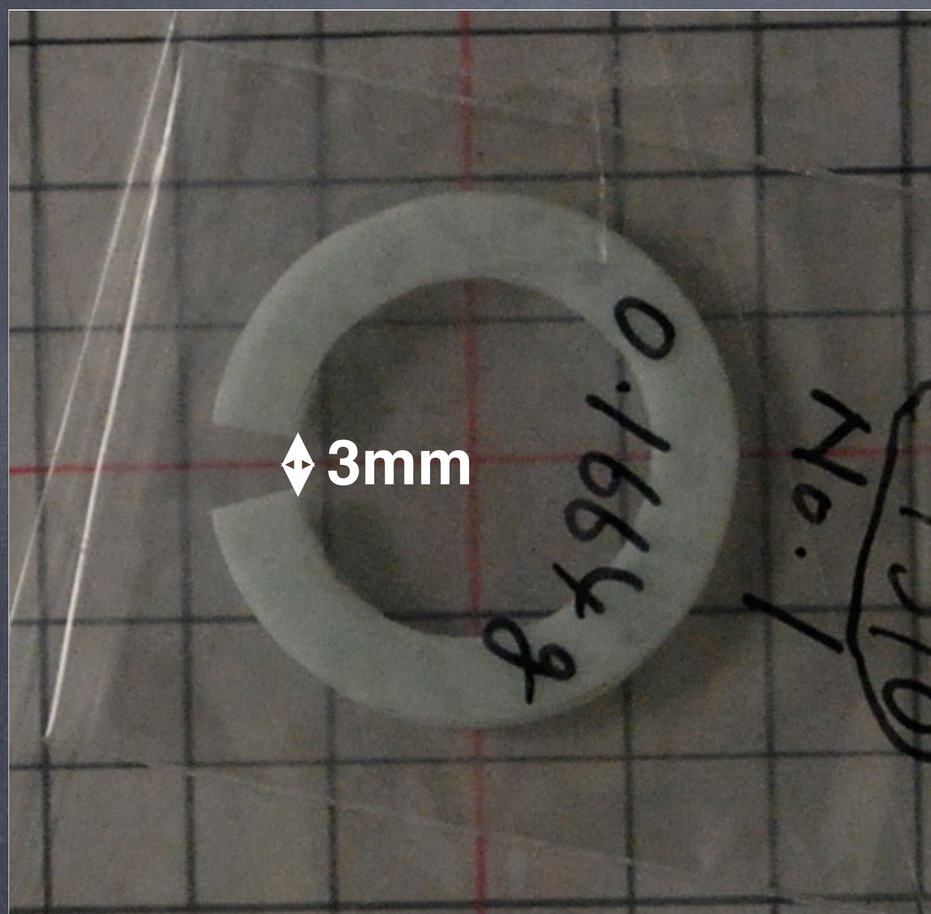
The scattering angle can be calculated by measured energies and positions.

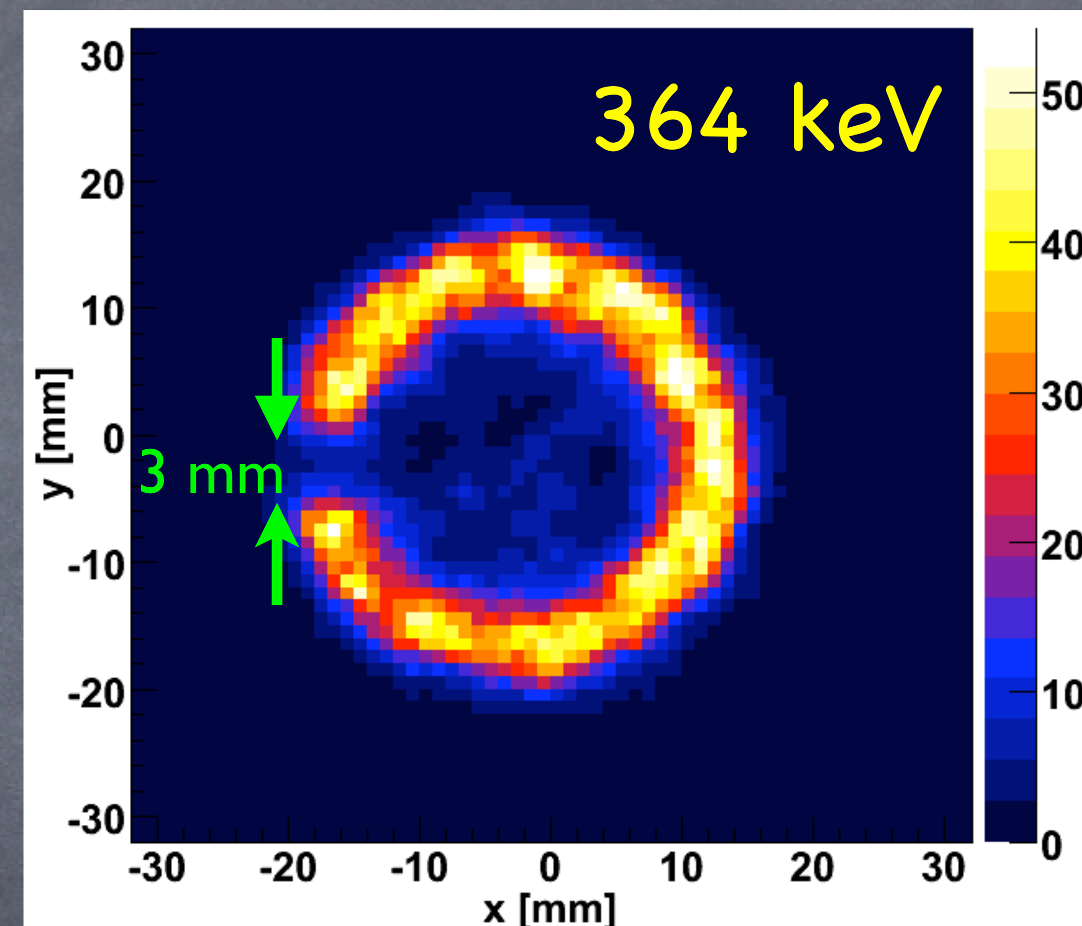
$$\cos\theta = 1 - m_e c^2 \left(\frac{1}{E_2} - \frac{1}{E_1 + E_2} \right)$$

Events inconsistent with Compton scattering are rejected.

Experimental Results from Prototypes

Near-distance Compton imaging





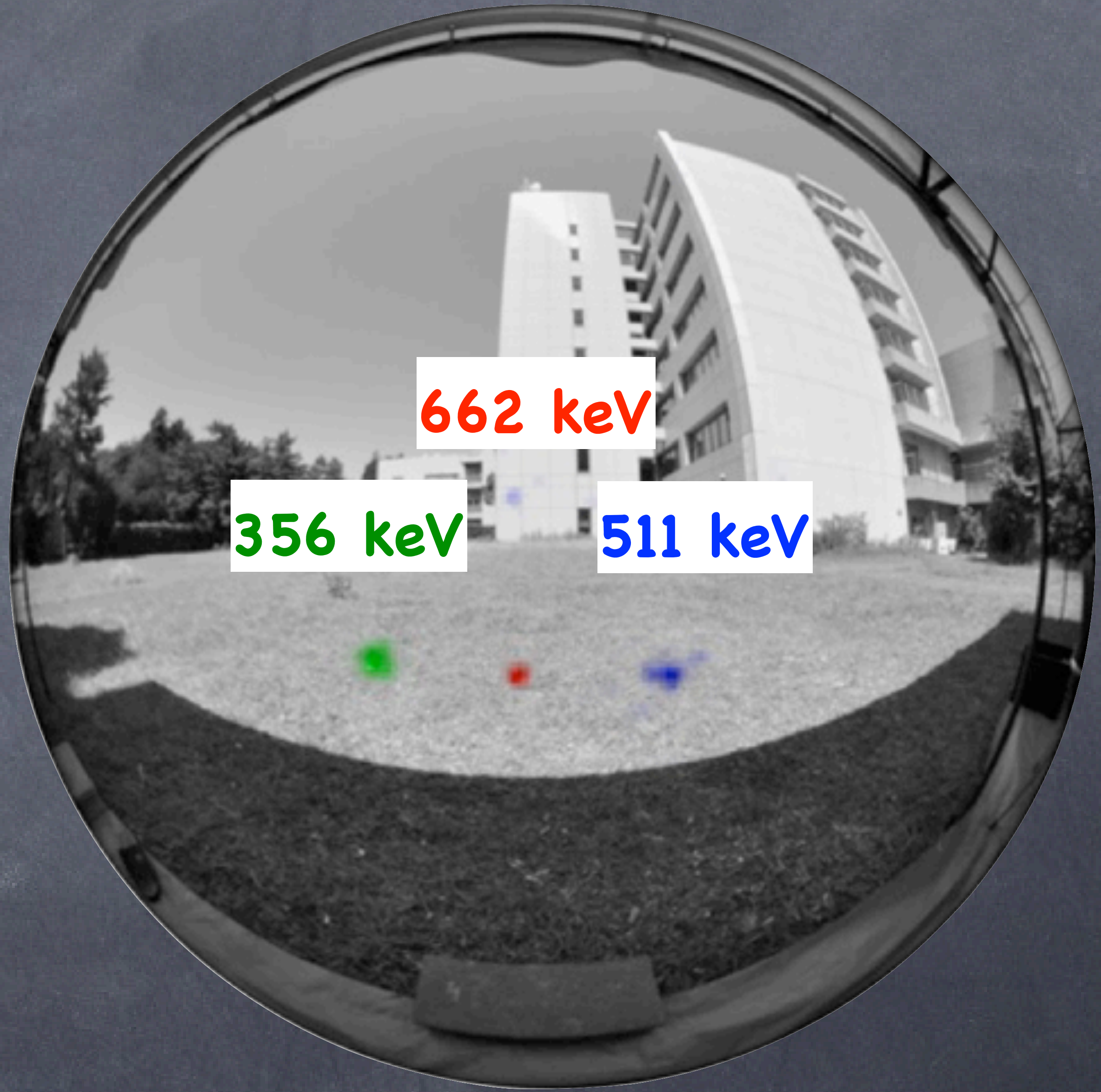
- Liquid ^{131}I source (364 keV)
- reverse "C" shape
- Distance of 30 mm from the top

- Imaging of diffuse emission is well performed as well as point sources.
- Spatial resolution is better than 3 mm. (distance: 30 mm)

Takeda+ (2009) collaboration with Gunma Univ. medical group

Experimental Results from Prototypes

Middle-distance Compton imaging



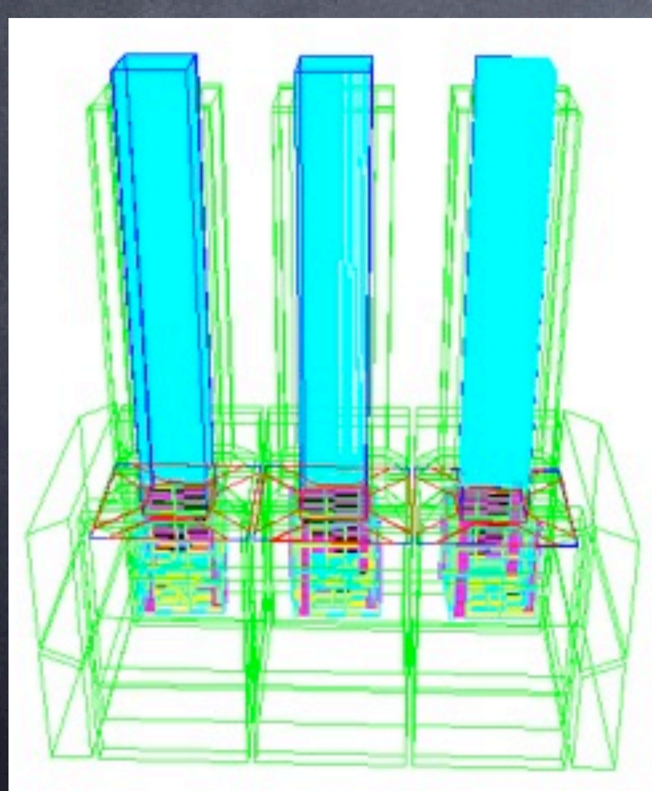
We successfully obtained multi-energy Compton image at a distance of several meters.

Takeda+ (2012)
Odaka+ (2012)

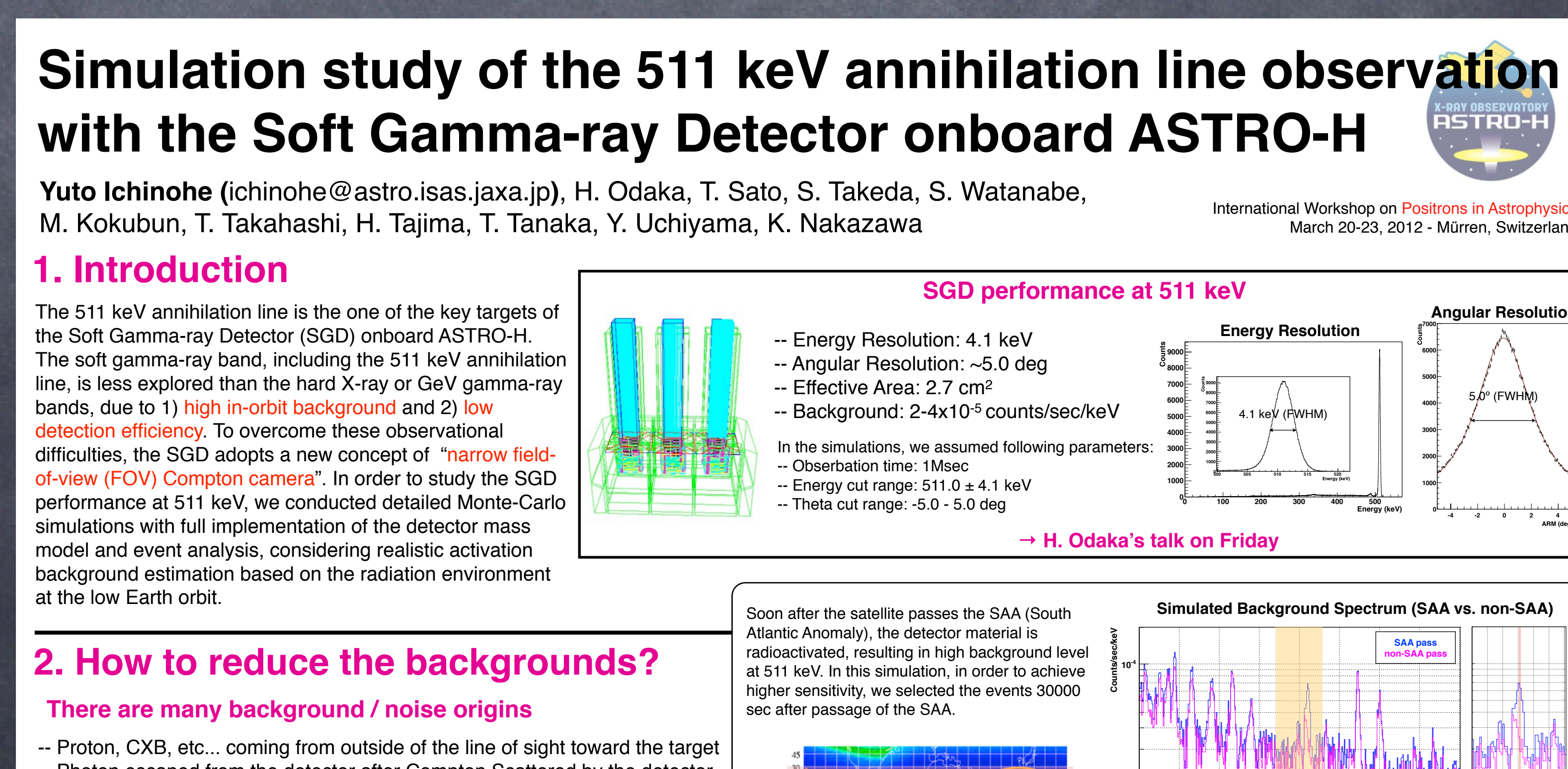
Simulation Study

In order to expect the SGD performance at 511 keV, we conducted detailed Monte-Carlo simulations with full implementation of the detector mass model and event analysis, considering realistic activation background estimation based on the radiation environment at the low Earth orbit.

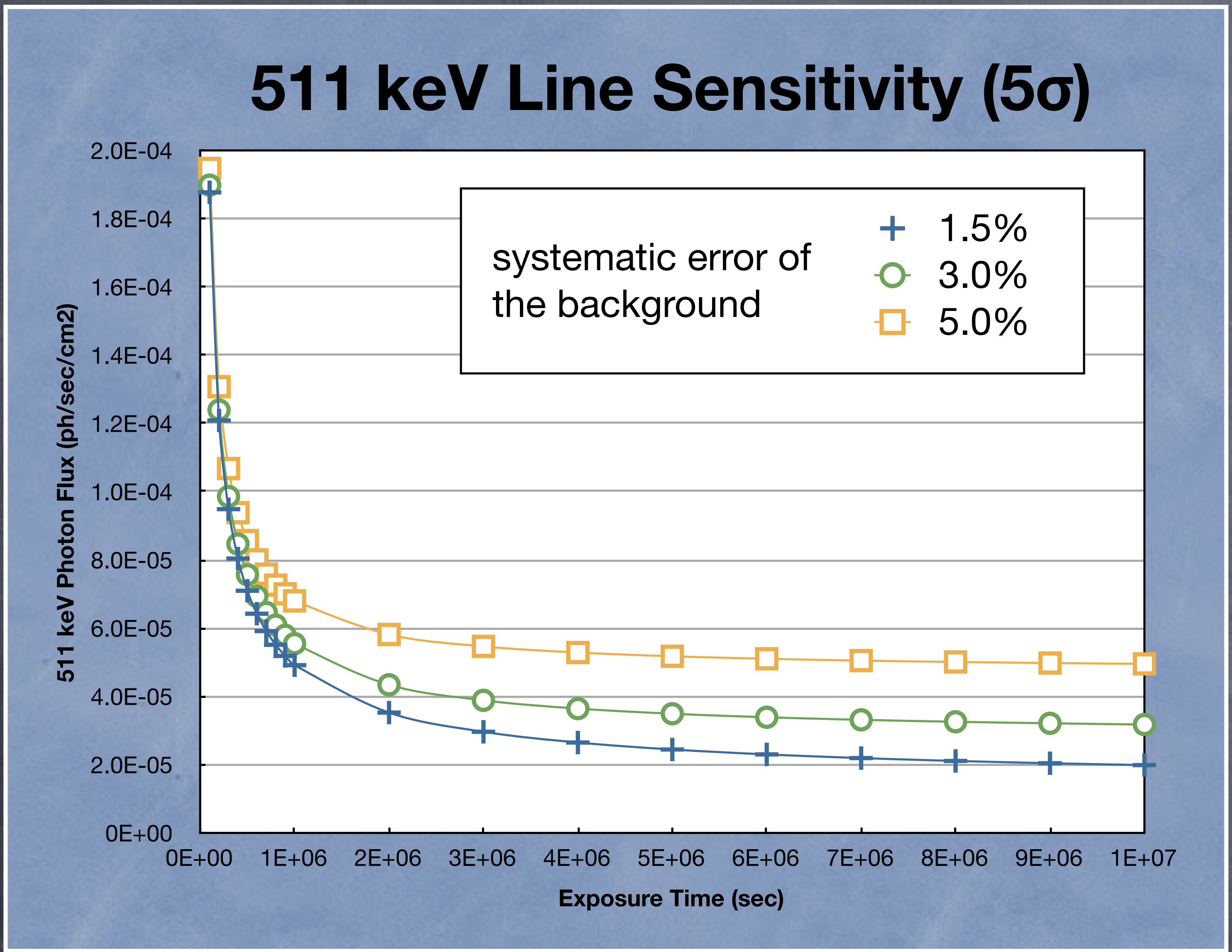
Since simulation parameters are optimized using the recent experimental data, results of this simulation give us the best estimate of the SGD performance in orbit.



Yuto Ichinohe's poster



Sensitivity



Effective area: 2.7 cm^2

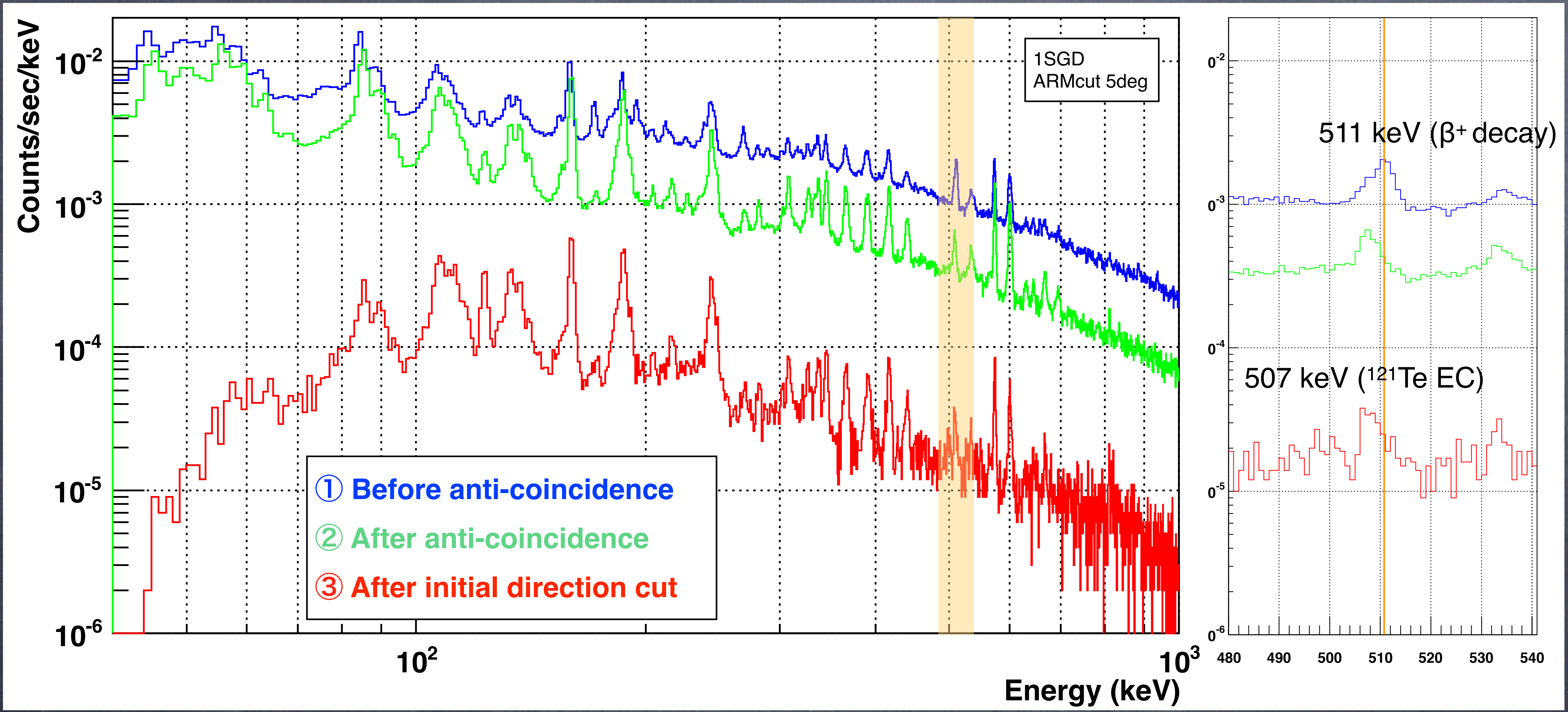
Detection efficiency: 1.7%

candidate sources

Source	511 keV Flux [10^{-5} ph s^{-1} cm^{-2}]
GC, bulge	100
GC, disk	47
LMXB	~1
BH Binary	40 (Cyg X-1)
Nova	10

The sensitivity for the 511 keV annihilation line will reach to about 5×10^{-5} ph s^{-1} cm^{-2} with an exposure time of 1 Ms (depending on the systematic error of the background estimation).

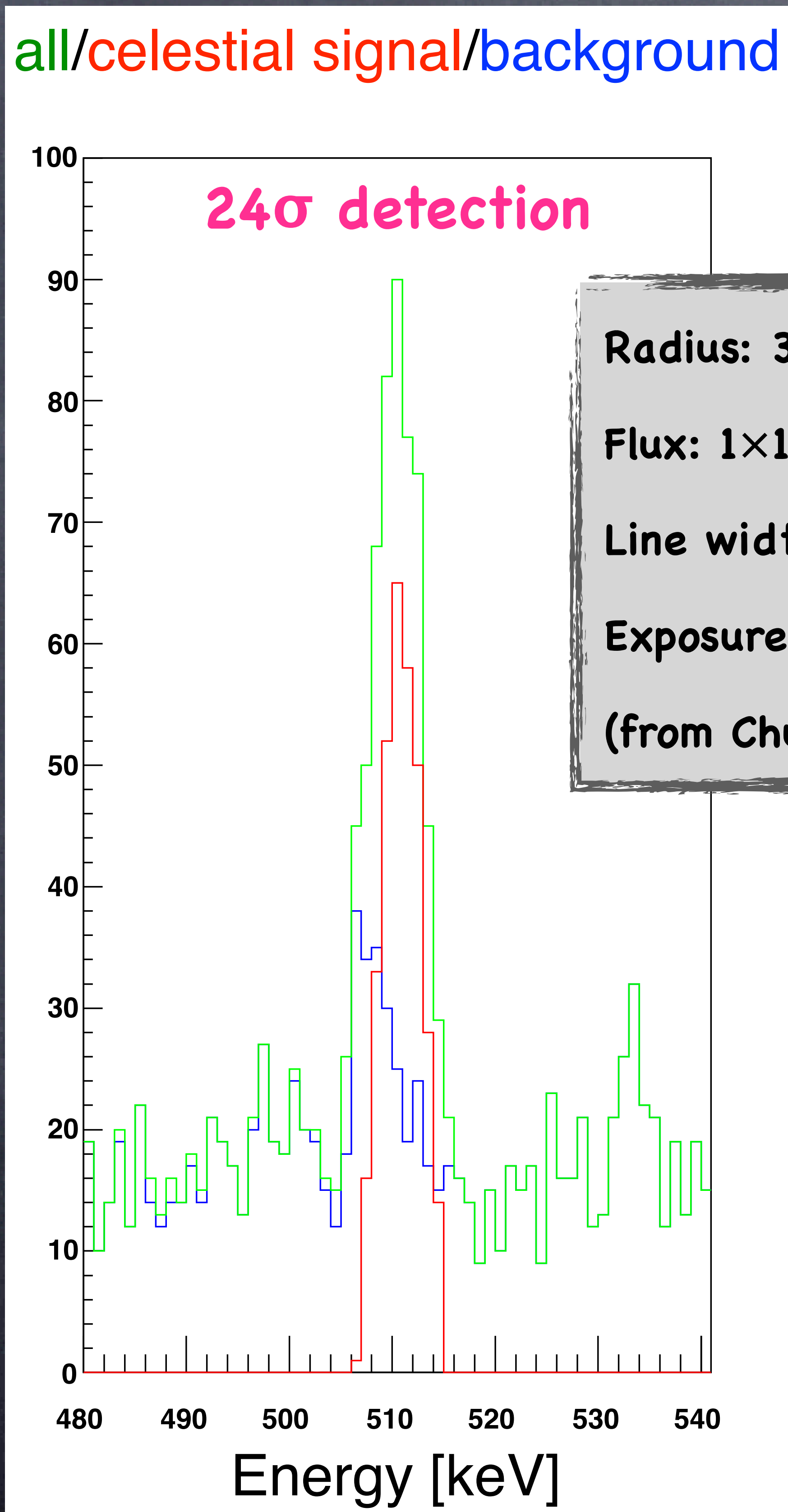
Background Rejection



Note: the events are extracted from orbital passes which do not contain SAA passage.

Background is suppressed by two orders of magnitude with the combination of anti-coincidence and Compton direction reconstruction.

Scientific Prospects - the Galactic Center



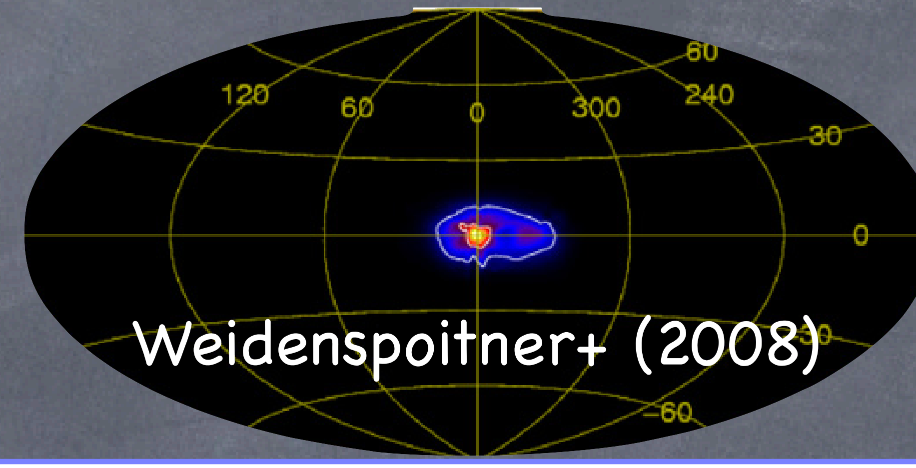
Radius: 3 degree

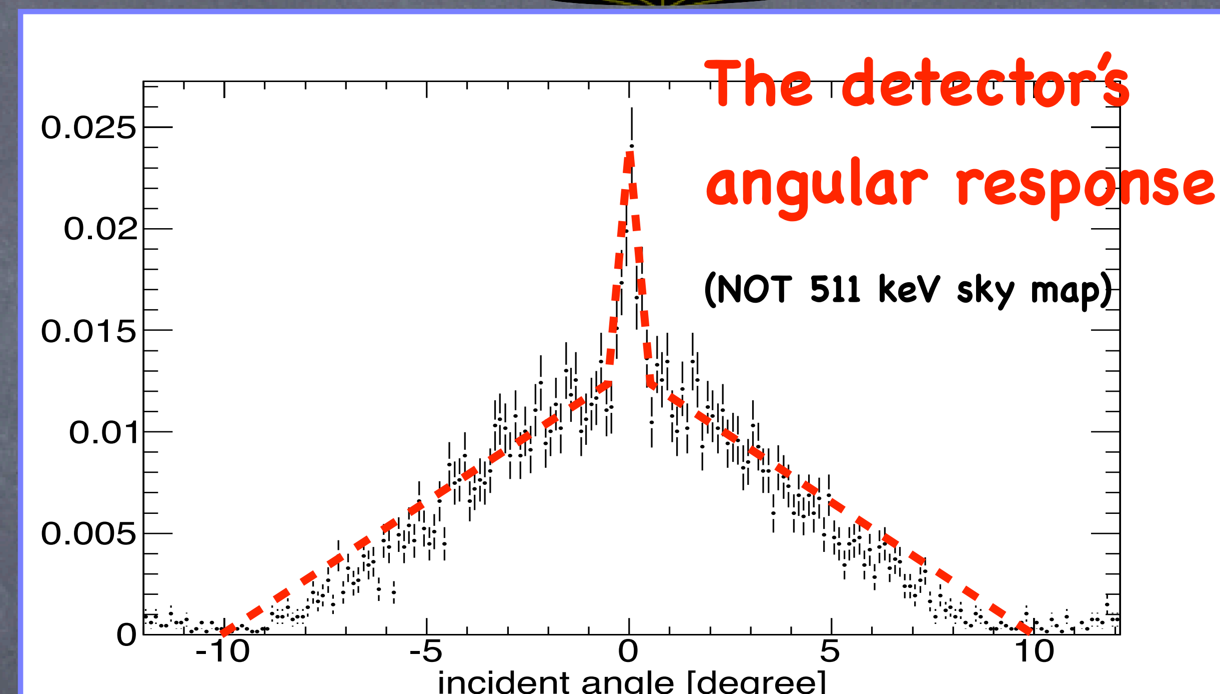
Flux: 1×10^{-3} photons s^{-1} cm^{-2}

Line width: 2.4 keV (FWHM)

Exposure: 1 M second

(from Churazov et al. 2011)





What can be achieved?

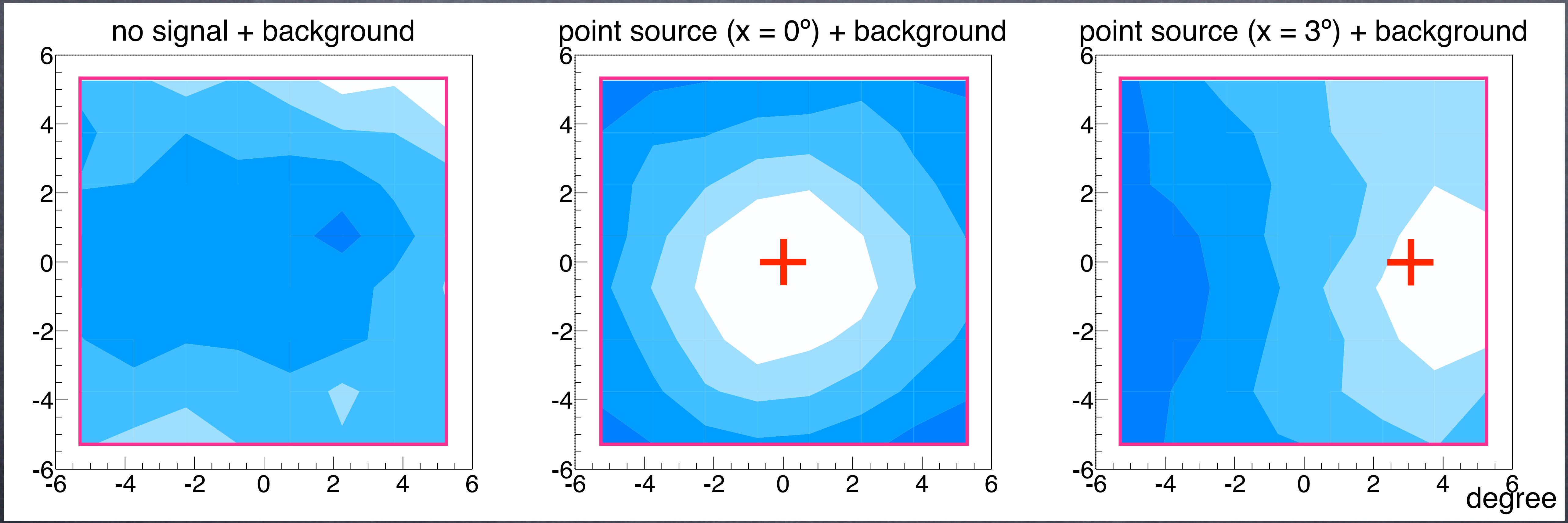
- measure absolute flux of the GC bulge emissions with good precision.

- reconstruct spatial distribution from scan observation data, thanks to the simple angular response.

Scientific Prospects - Identified Sources

Detection of annihilation signals from identified sources is important for understanding physics & astrophysics of production, propagation, and annihilation of positrons.

The black hole binaries (e.g. Cyg X-1) and novae are the best candidates.



Compton imaging is useful to check presence of the celestial signals. More dependable imaging methods are under development.

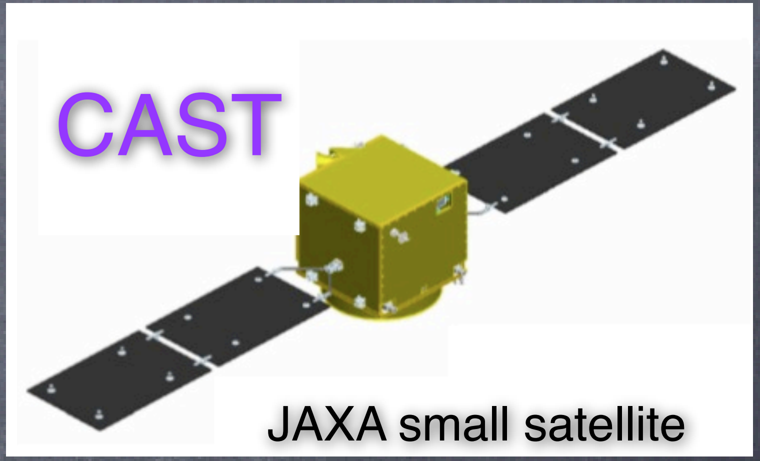
Flux: 4×10^{-4} photons s^{-1} cm^{-2}

Exposure: 1 M second

Future Mission: CAST

The Compton All-Sky Telescope (CAST) is the successor to the SGD. The CAST is a small satellite mission that carries larger effective area and wide FOV Compton telescopes based on our semiconductor detector technologies, planned for launch in late 2010s.

	SGD	CAST
observation	pointing	all sky
FOV	10°	~180°
exposure	~Ms (week-month)	~year
energy range	40-600 keV	0.1-2 MeV
energy resolution	1%	1%
angular resolution	5°	1°
aperture	fine collimator	coded mask (?)
orbit	LEO, i=30°	LEO, equatorial?



The CAST will obtain fine all-sky map of positron annihilation emissions, nuclear gamma-ray lines, and non-thermal continuum.

Concluding Remarks

- The Soft Gamma-ray Detector (ASTRO-H) will be launched in 2014.
  - ✓ We will measure the absolute flux of the GC bulge emissions with good significance. The spatial distribution can be reconstructed by scanning observation. (longer exposure is required.)
  - ✓ The sensitivity will be about 5×10^{-5} photons s^{-1} cm^{-2} for only 1 Ms observation. The SGD will probably be able to detect 511 keV lines from identified sources such as X-ray binaries or novae.
  - ✓ More reliable analysis methods are under development.
  - ✓ Effective observation plans are required.
- The CAST mission will obtain all-sky map of positron signals.