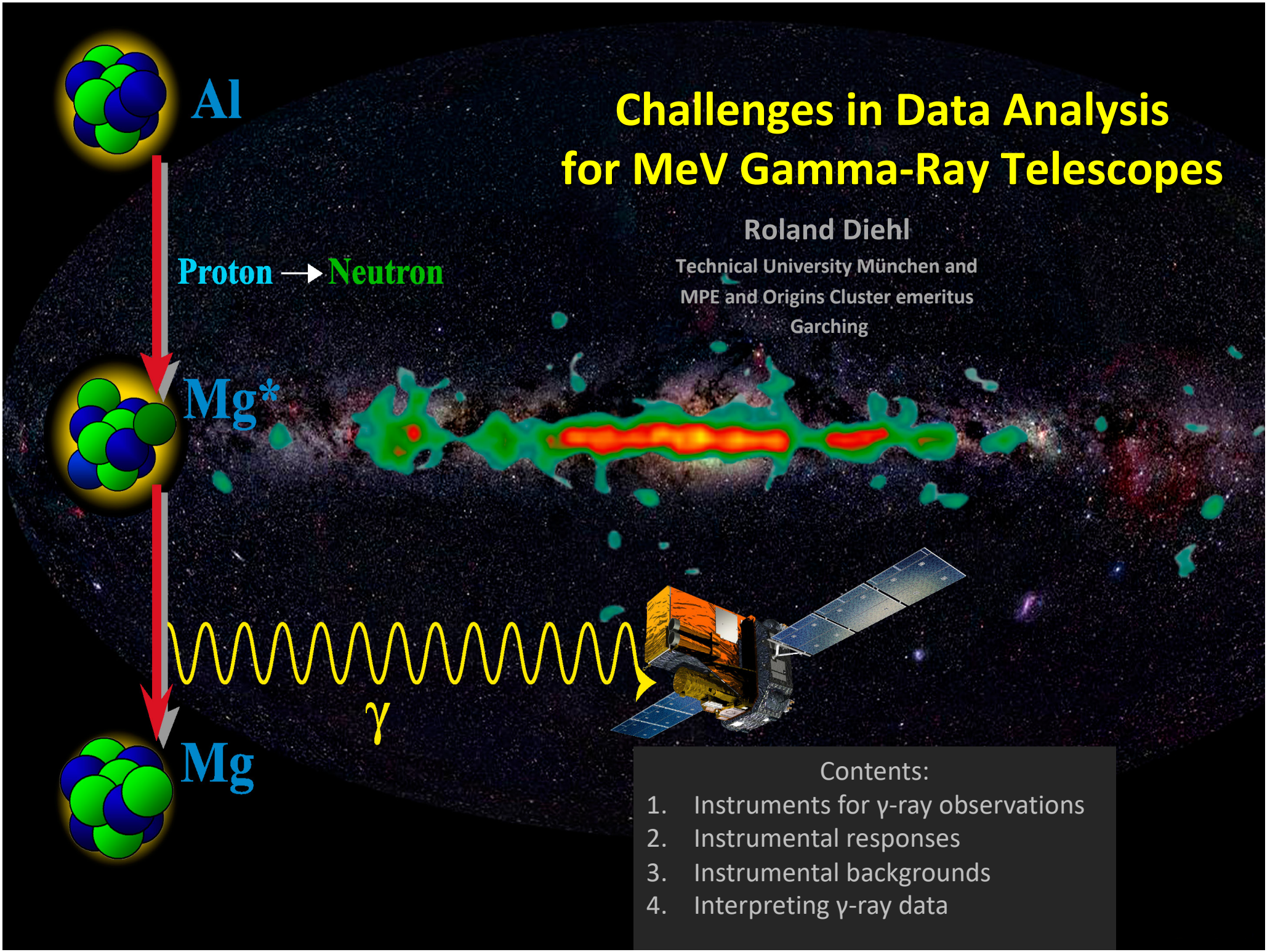


Challenges in Data Analysis for MeV Gamma-Ray Telescopes

Roland Diehl

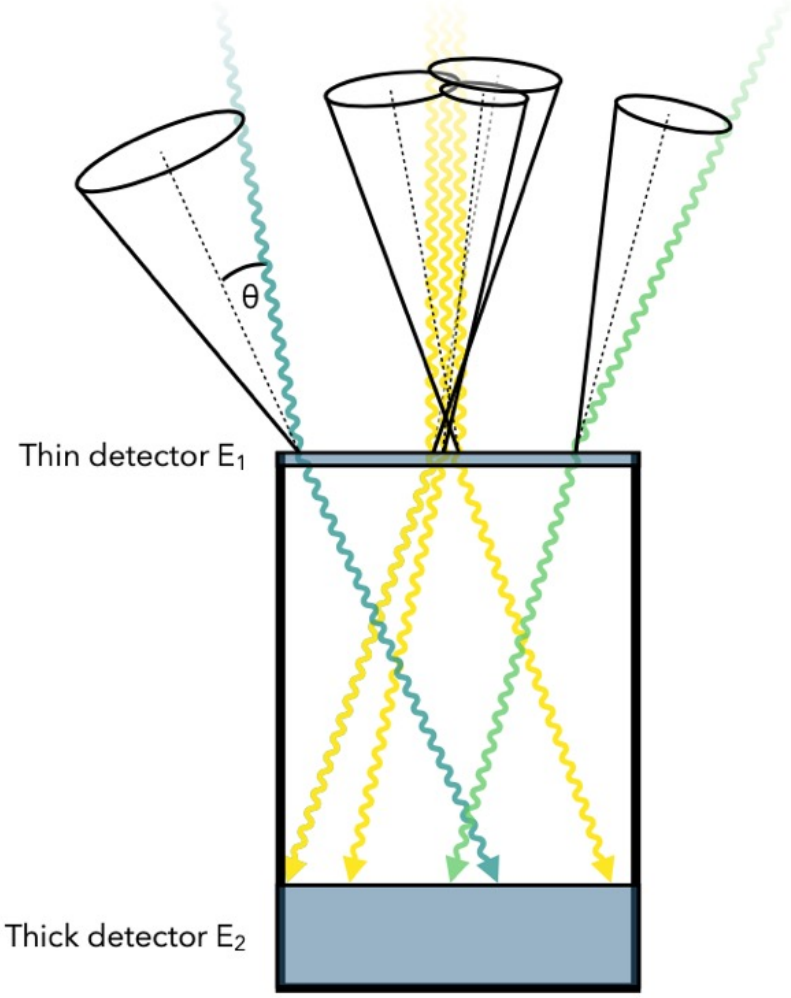
Technical University München and
MPE and Origins Cluster emeritus
Garching

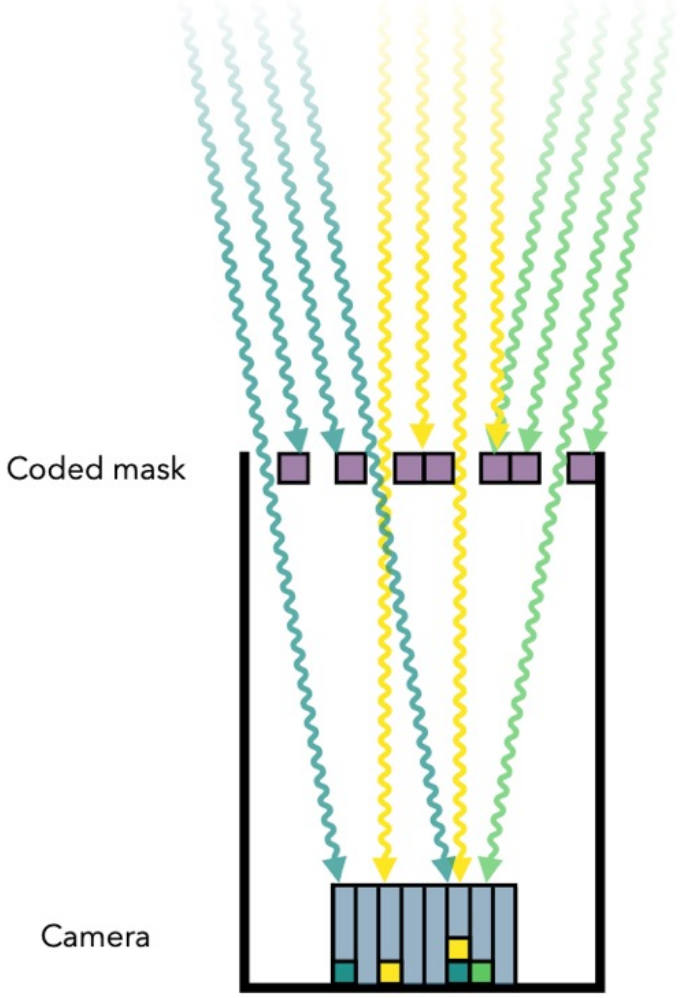
Contents:

1. Instruments for γ-ray observations
2. Instrumental responses
3. Instrumental backgrounds
4. Interpreting γ-ray data

MeV Range Gamma-Ray Telescope Imaging Principles

Compton Telescopes and Coded-Mask Telescopes

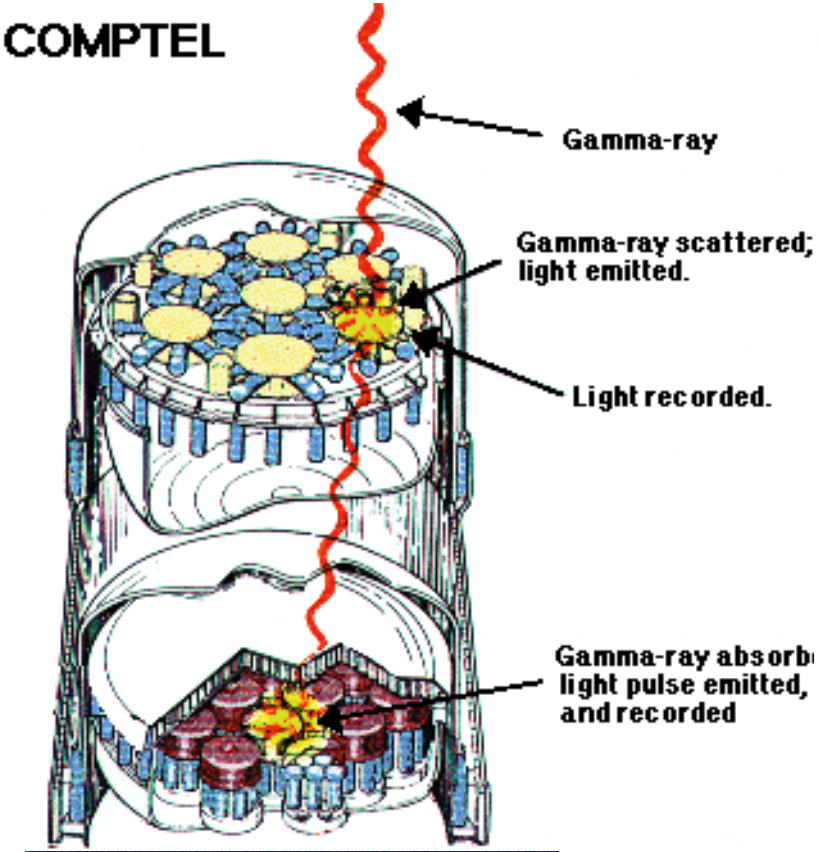


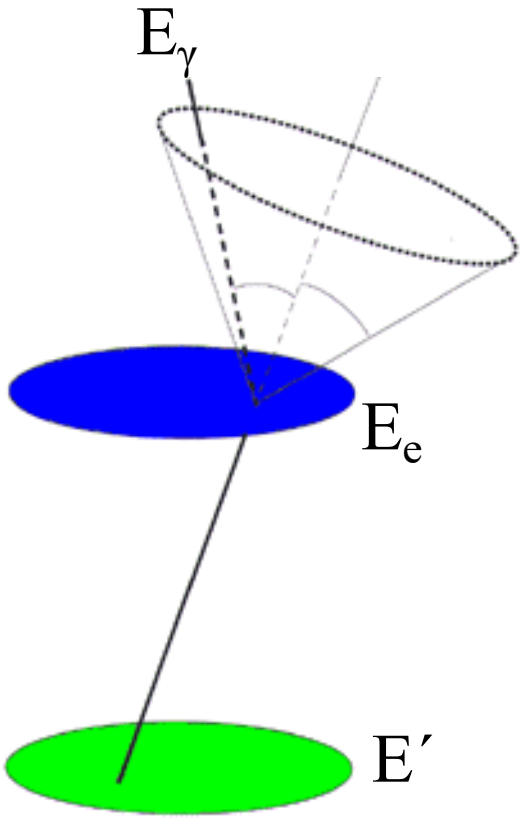


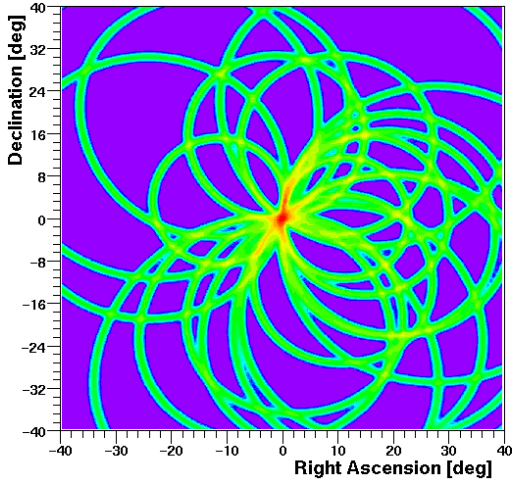
Currently achieved: Sensitivity ~10^{-5} ph cm^{-2} s^{-1} Angular Resolution ≥ deg

The Compton Telescope

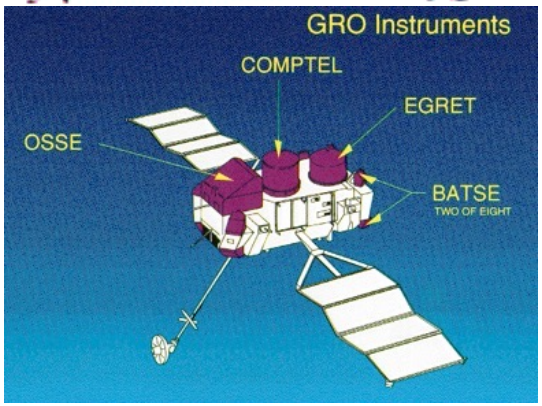
Compton Scattering → Coincidence Instruments





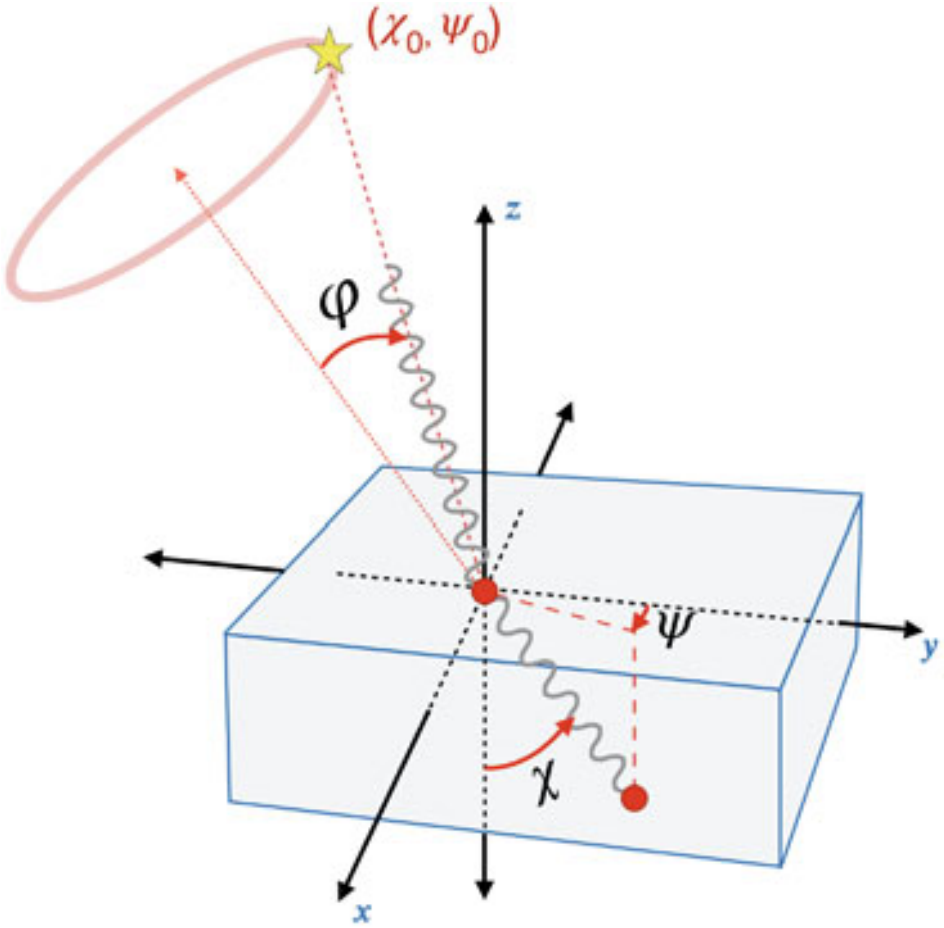


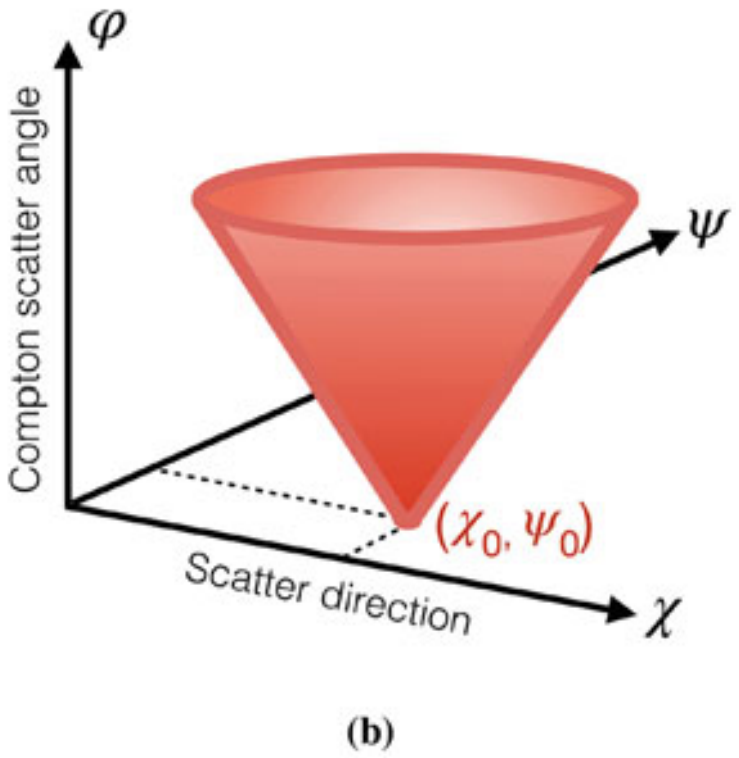
$$E' = \frac{E}{1 + \frac{E}{m_e c^2}(1 - \cos\theta)}$$



$$\varphi_{geometric} = \arccos\left\{1 + m_e c^2 \left(\frac{1}{E_\gamma} - \frac{1}{E_\gamma - \Delta E}\right)\right\}$$

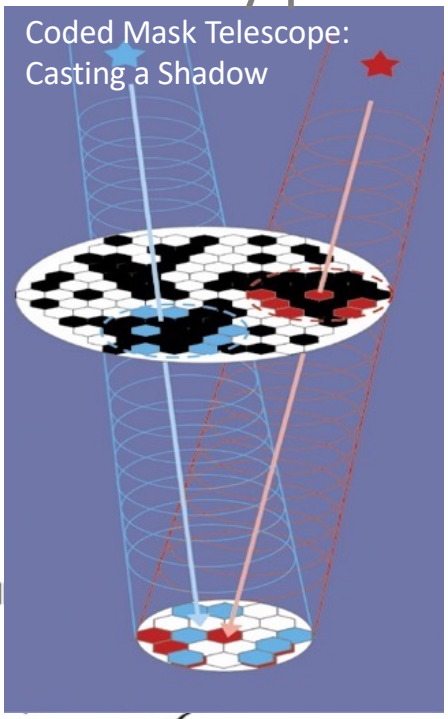
Measurements within a Compton Telescope



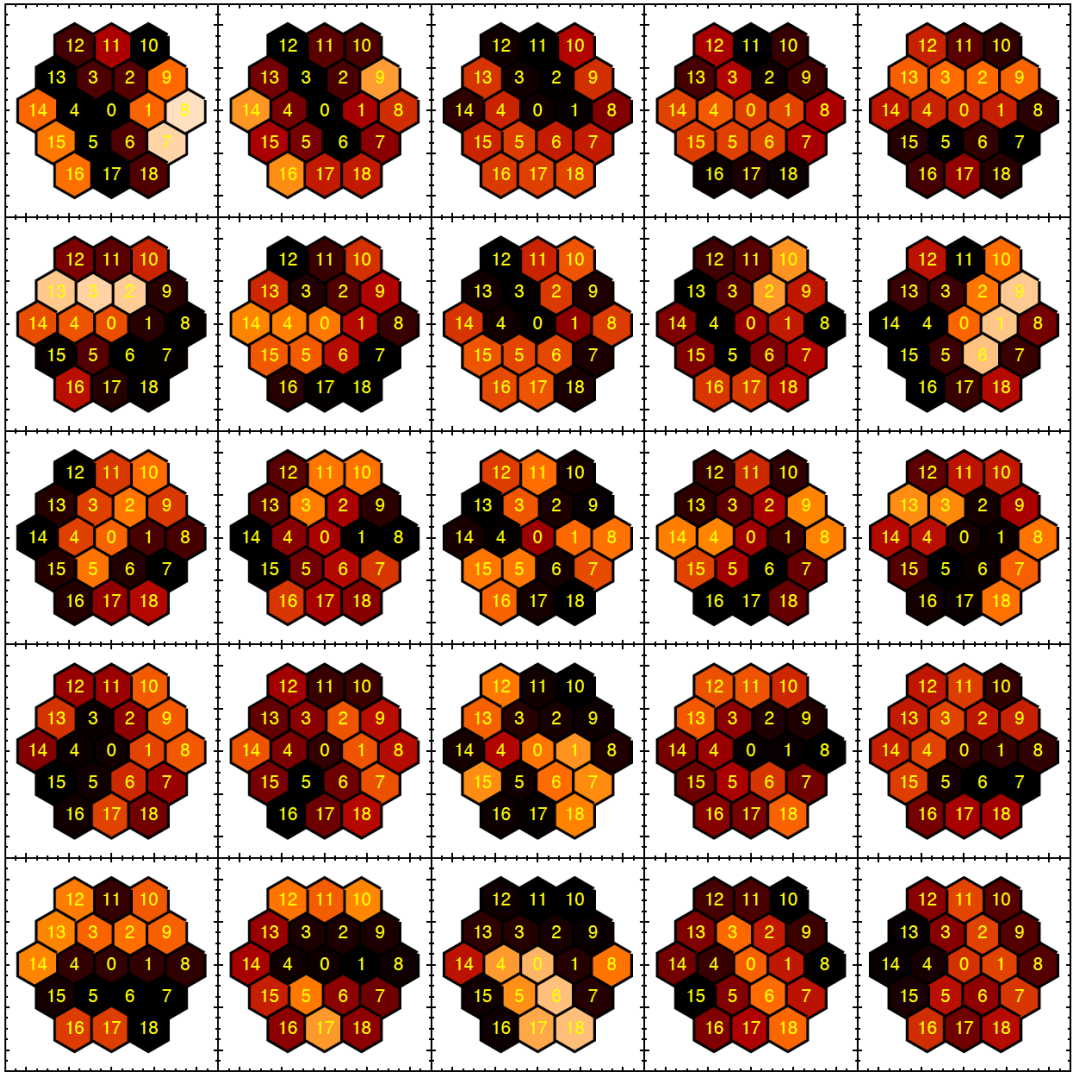


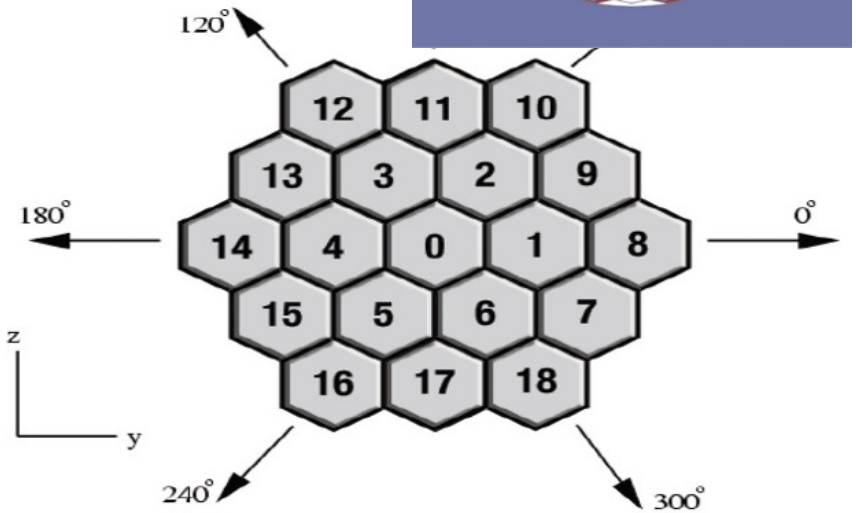
Coded-mask imaging: Ge detector camera and mask

- shadowgram intensity patterns among detectors



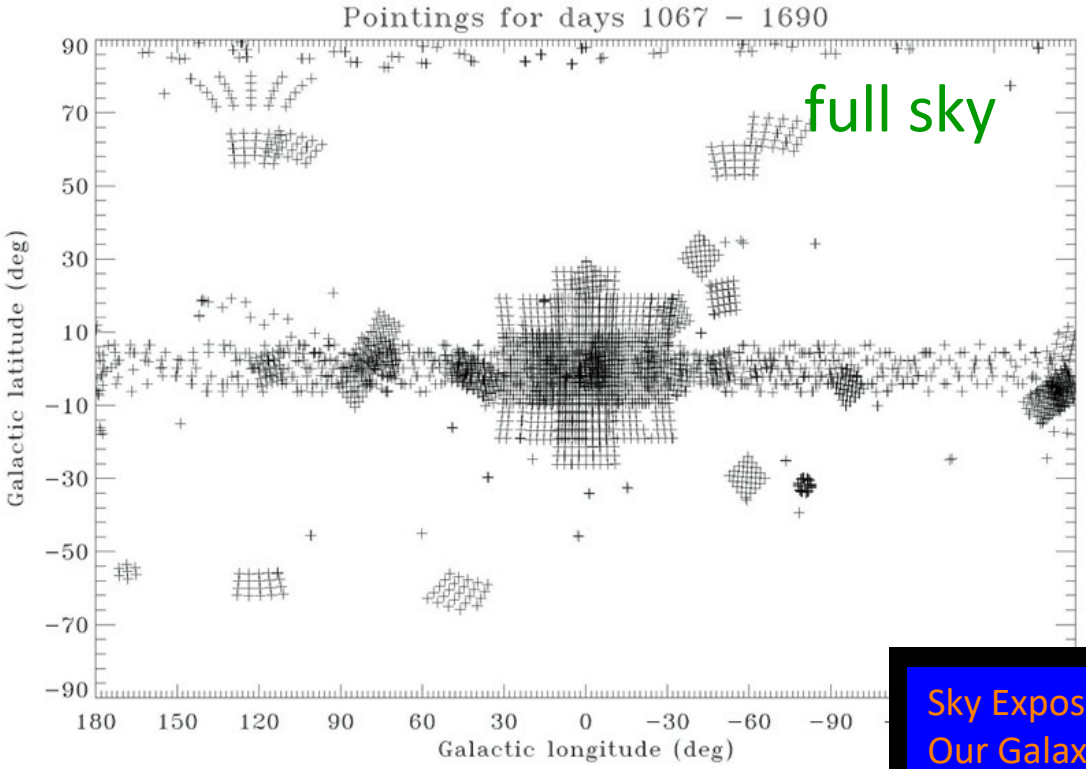
- 'dithering' 5x5 pointing offsets around source for additional 'coding'



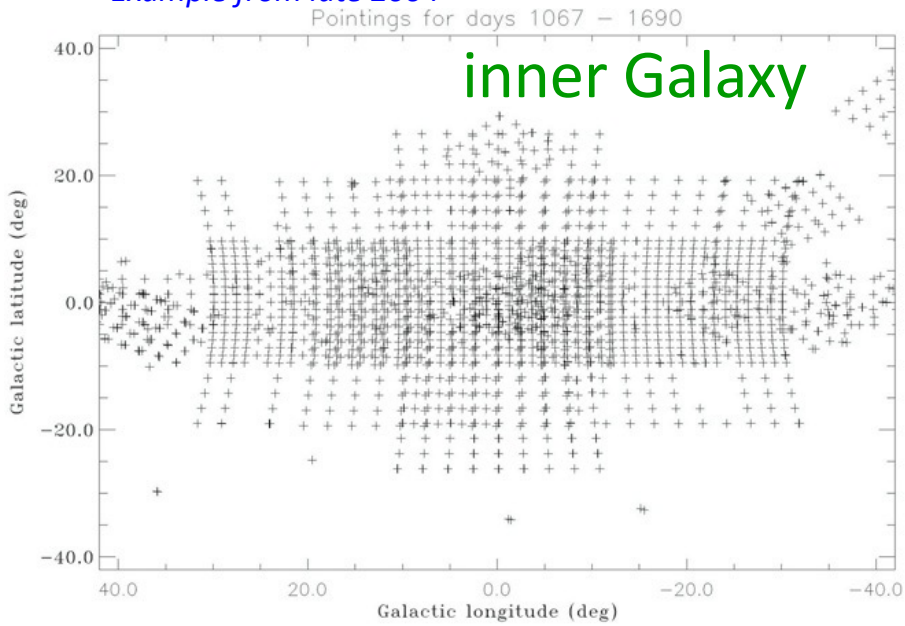


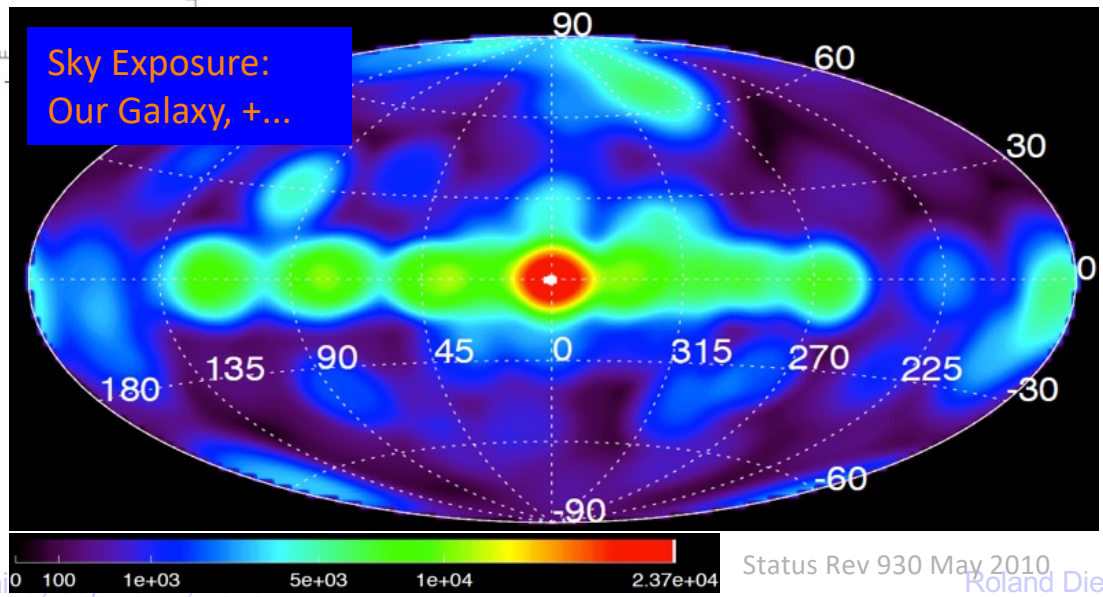
A Sky Survey with INTEGRAL

☆ "Dither Patterns" Scattered over the Sky



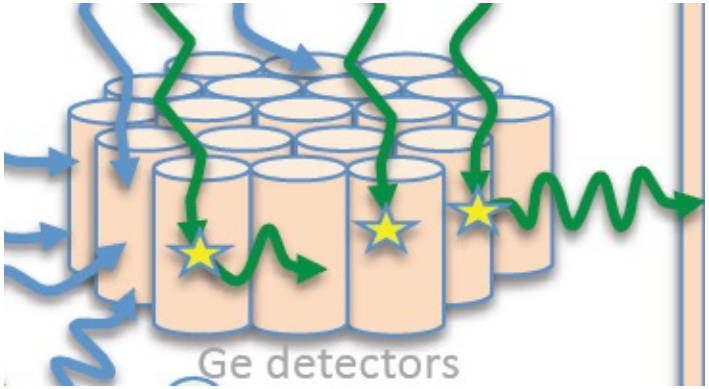
☞ *Example from late 2004*

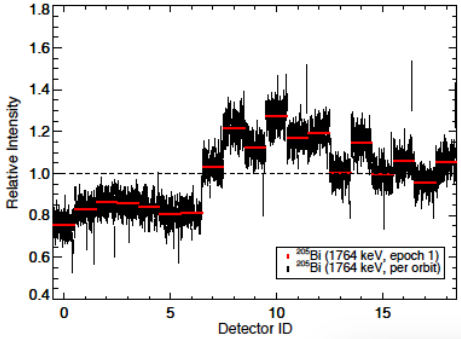


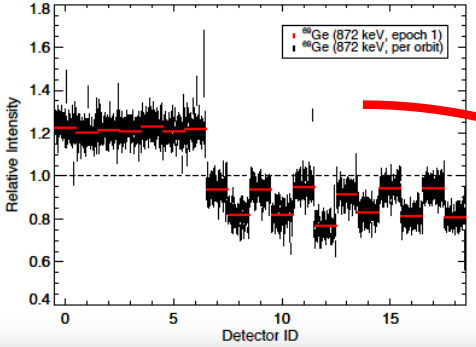


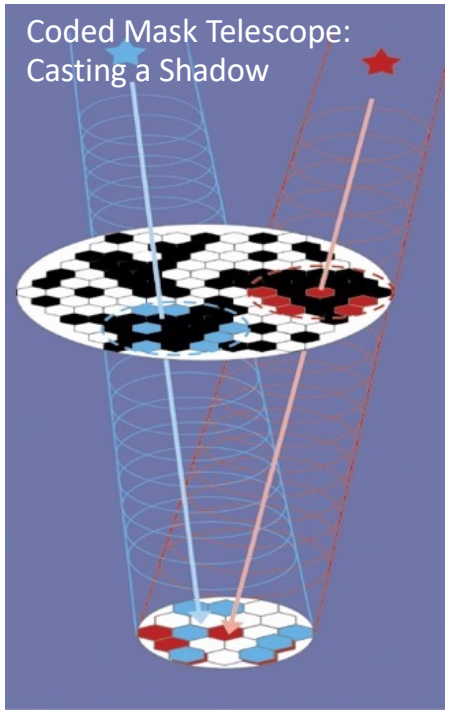
Discriminating Background and Sky Signals in SPI Data

- Tracking the relative count rate ratios among detectors
  - ☞ characteristic signatures from celestial sources withcoded mask, and from background events





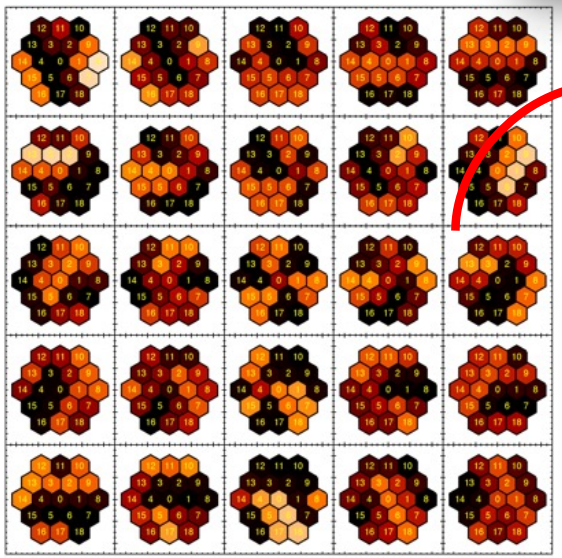


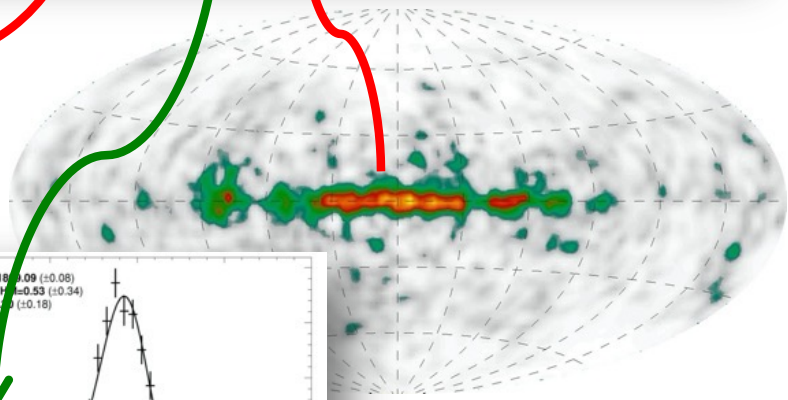


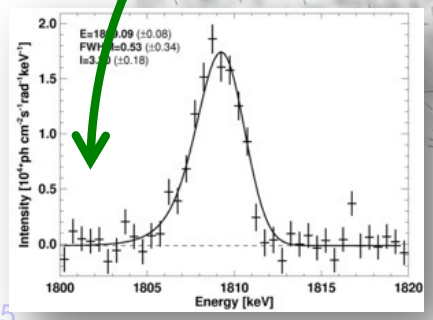
typical: 10^5 spectra

10^4 parameters fitted

$$d_k = \sum_j R_{jk} \sum_{i=1}^{N_I} \theta_i M_{ij} + \sum_t \sum_{i=N_I+1}^{N_I+N_B} \theta_{i,t} B_{ik}$$

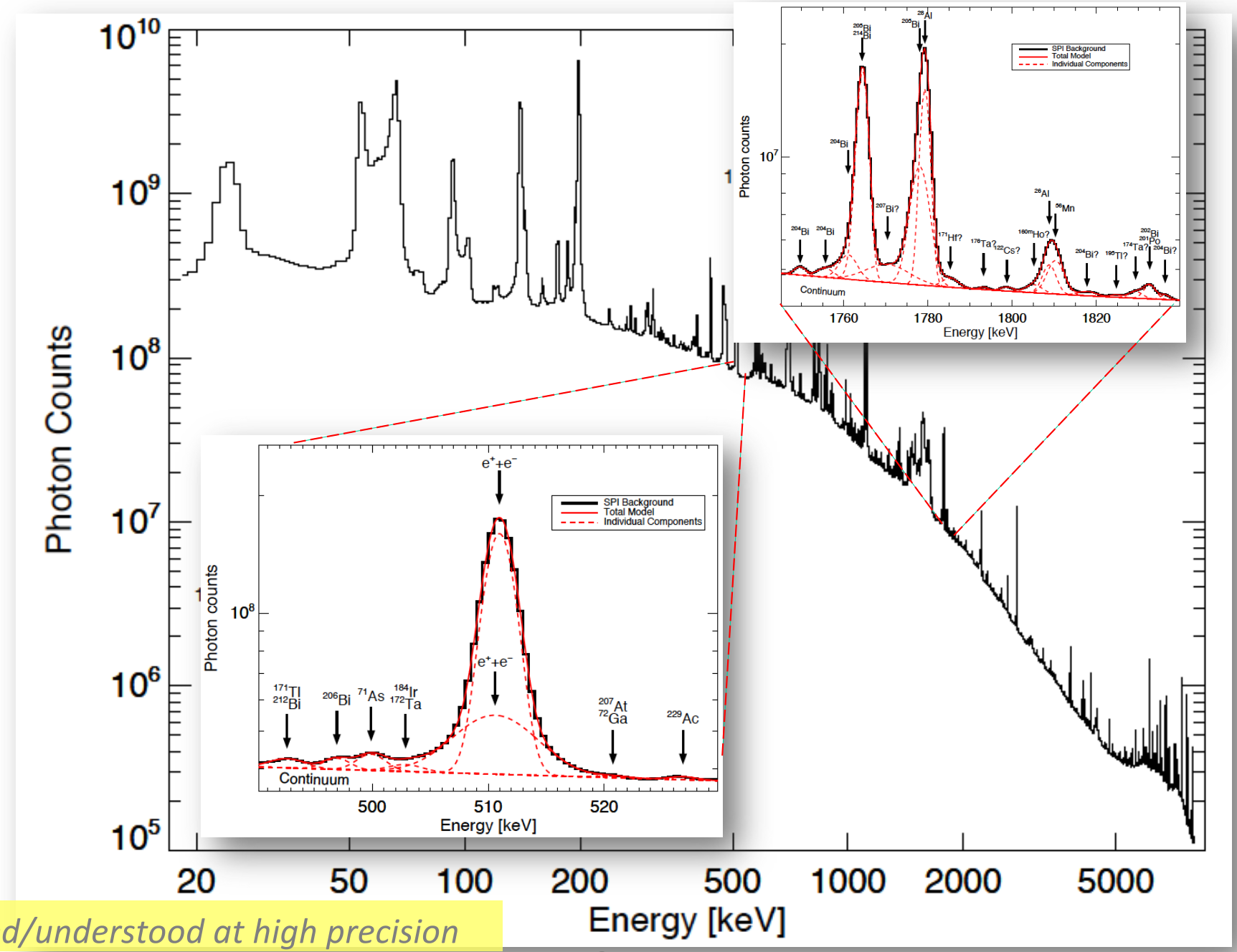






INTEGRAL: Dominance of instrumental background

SPI Ge detector spectra

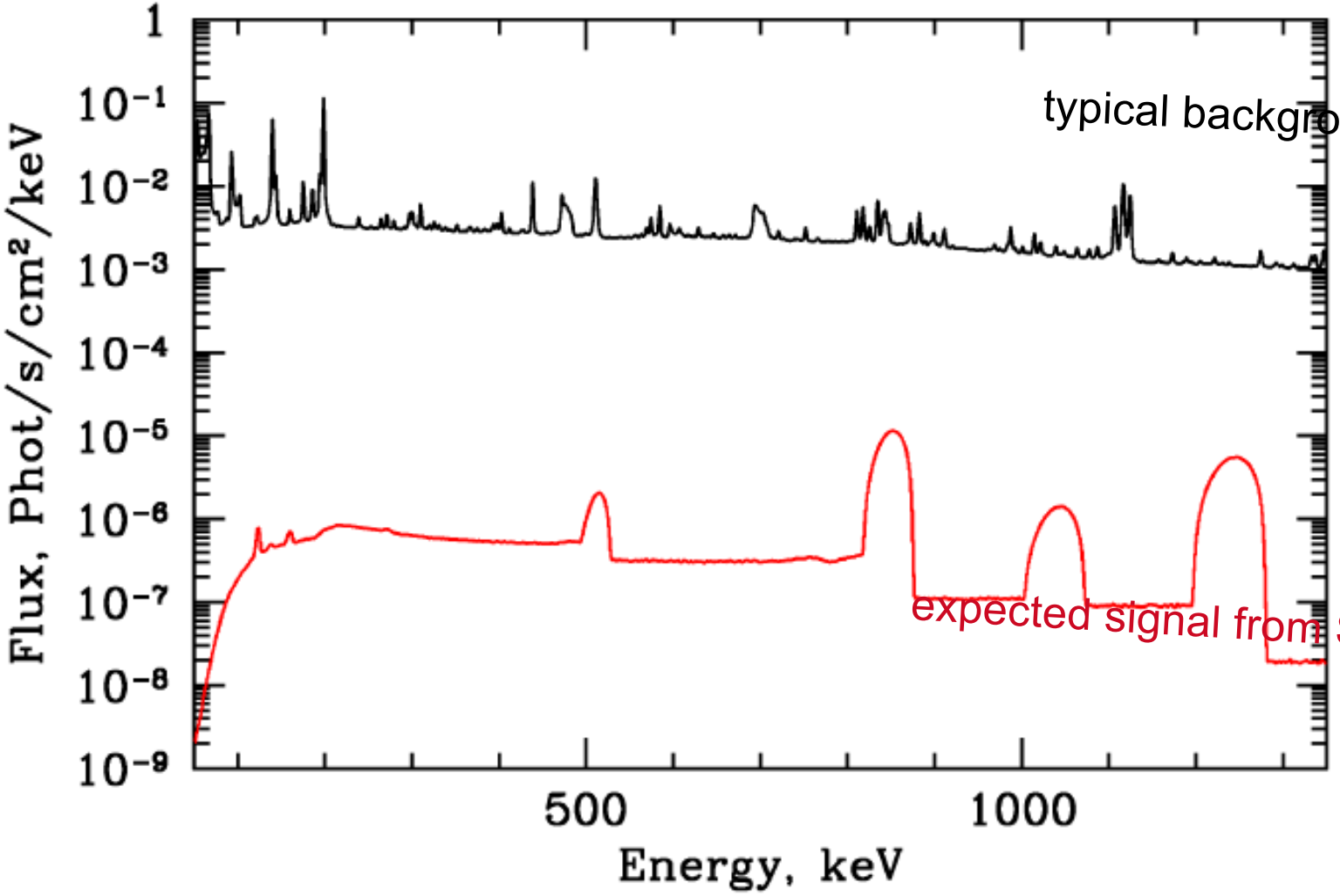


Modelled/understood at high precision

The Challenge of Finding SN2014J Gamma-Rays

☆ Current Gamma-Ray Telescopes
Have Large Intrinsic Background

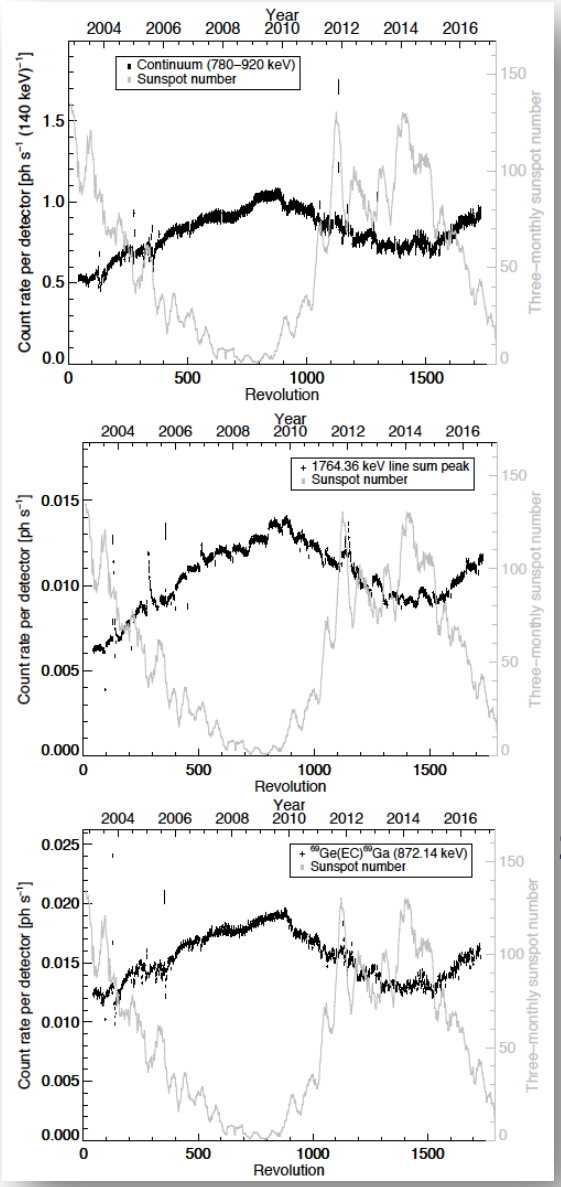
☞ Cosmic Ray Activation of Spacecraft and Instrument



from Churazov et al., 2014

Instrumental background in space orbits

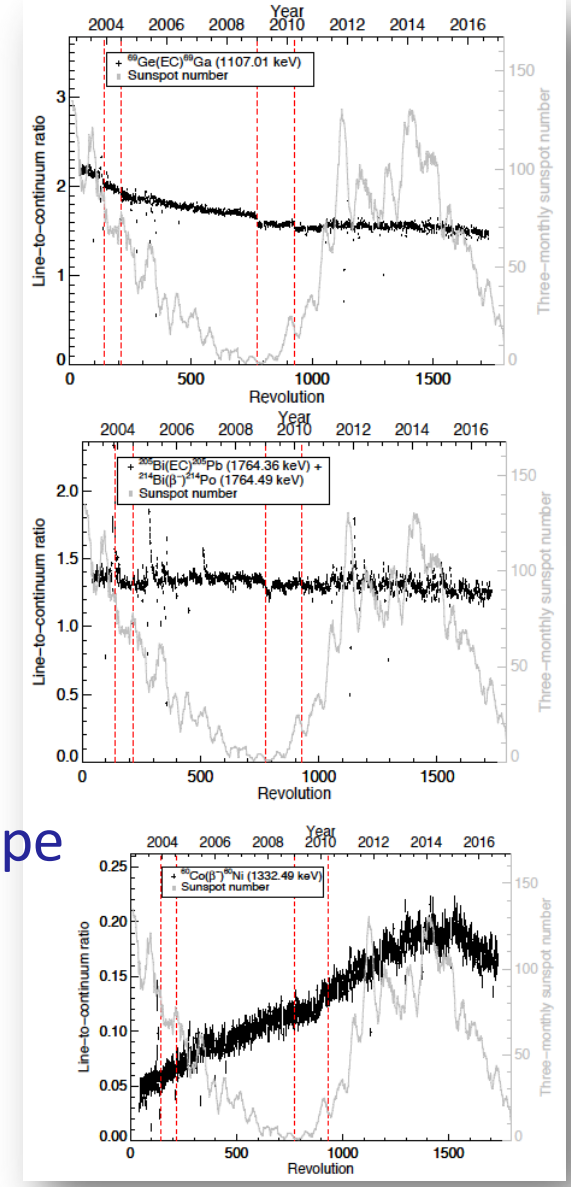
Prompt, delayed, and built-up backgrounds

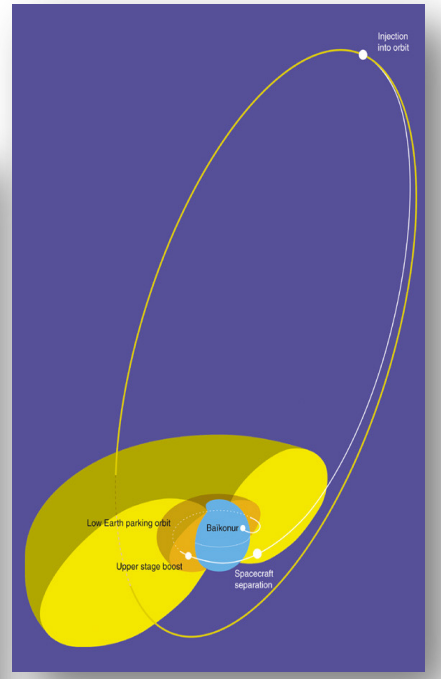


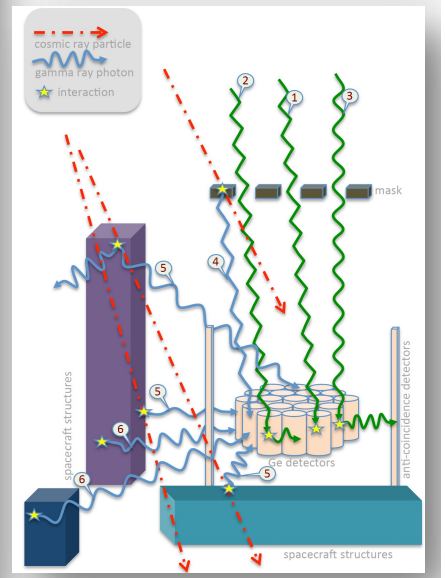
linked to
solar activity

normalise with continuum
→

characteristics
specific per isotope



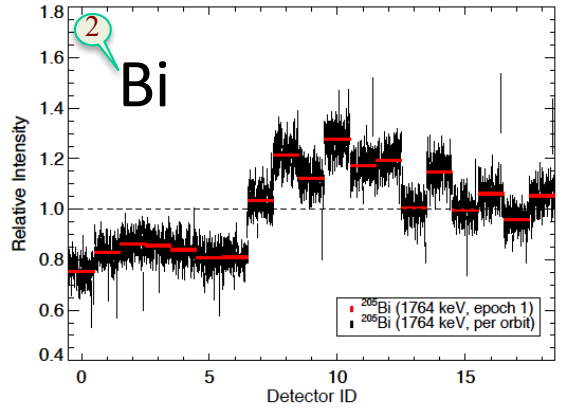


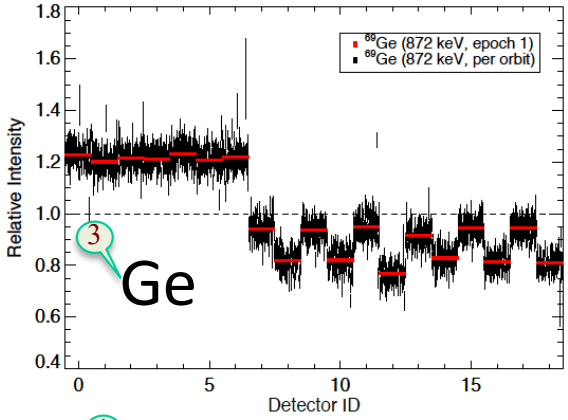


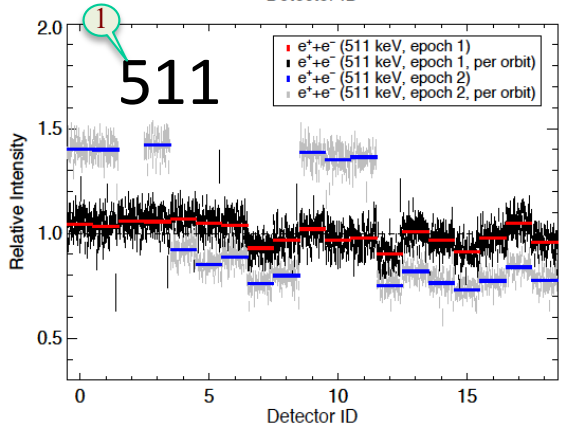
Diehl+, A&A (2018)

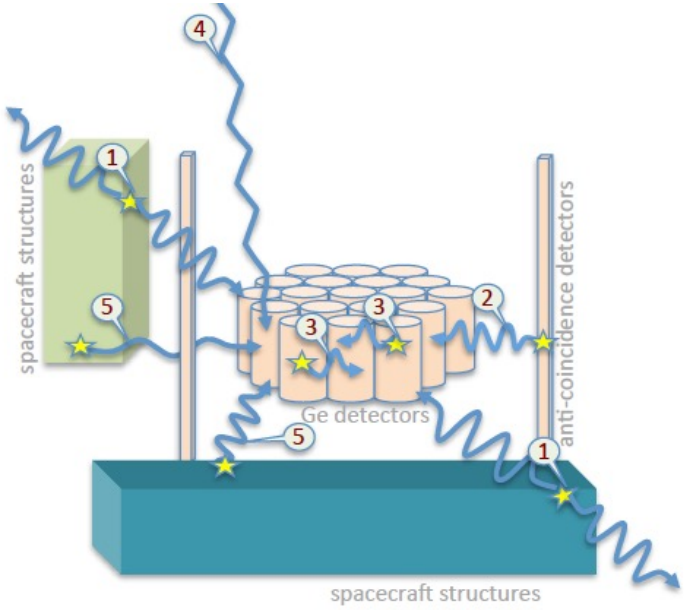
SPI instrumental background lines:

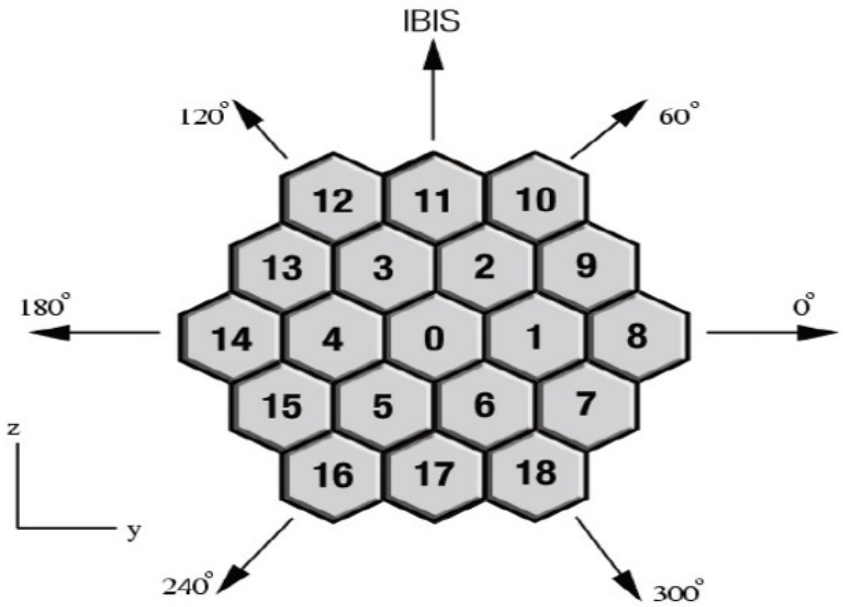
Lines show a characteristic intensity pattern in SPI Ge camera







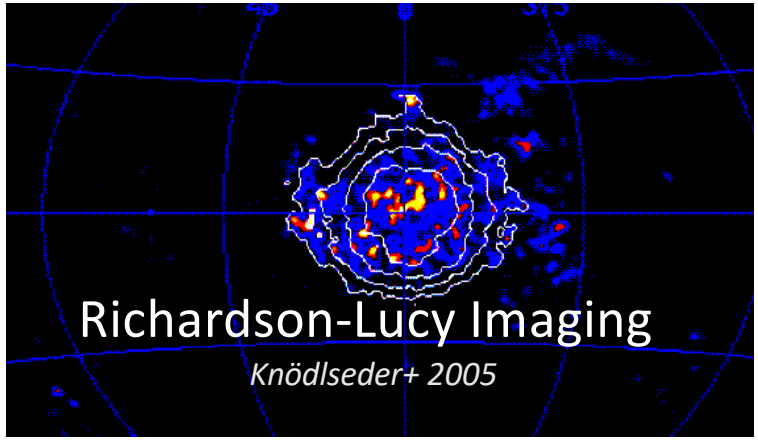


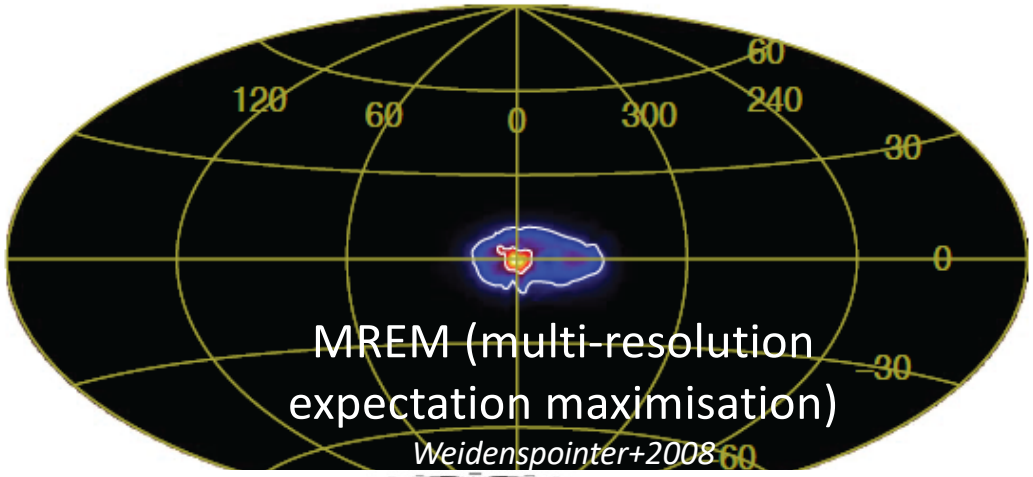


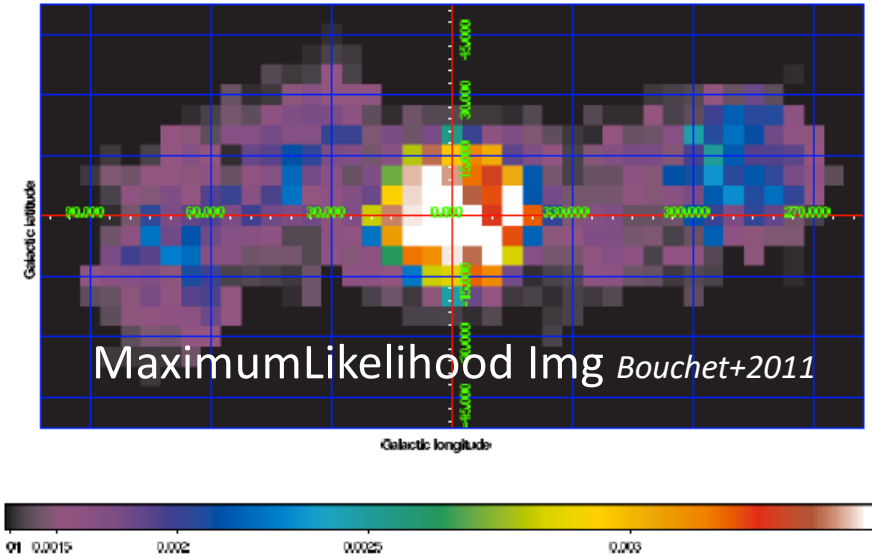
Imaging Approaches with SPI

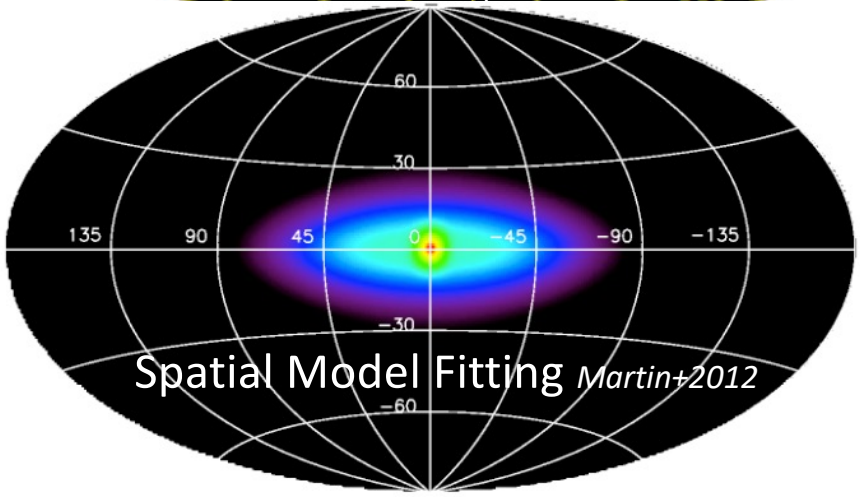
☆ No direct imaging (i.e. locating the original directions of detected photons)

- ☞ Imaging deconvolutions of different types
  - Maximum Likelihood, RL, ME, MREM, ...
- ☞ Model fitting









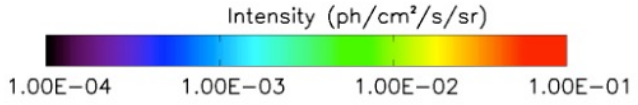
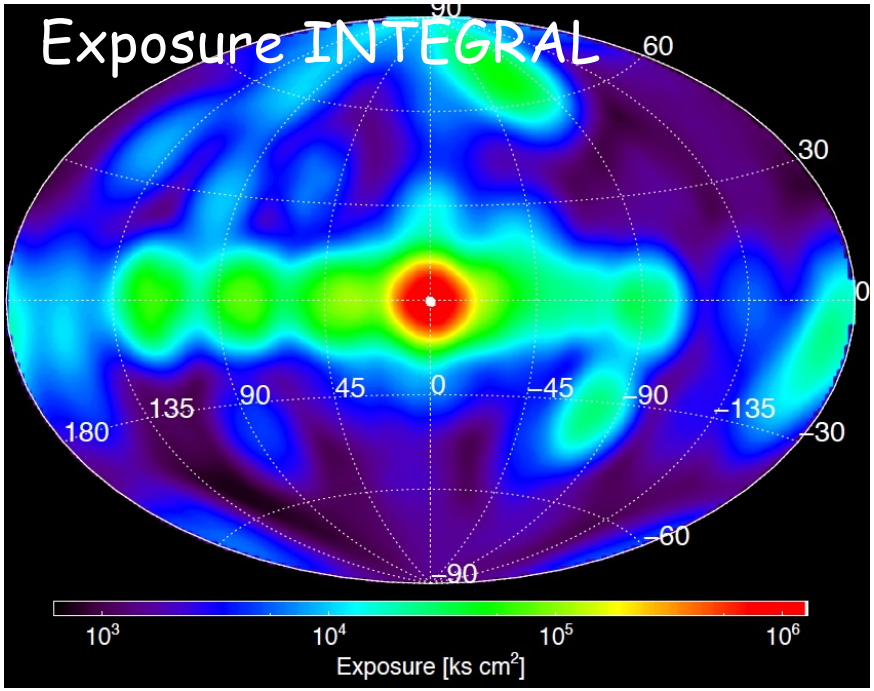
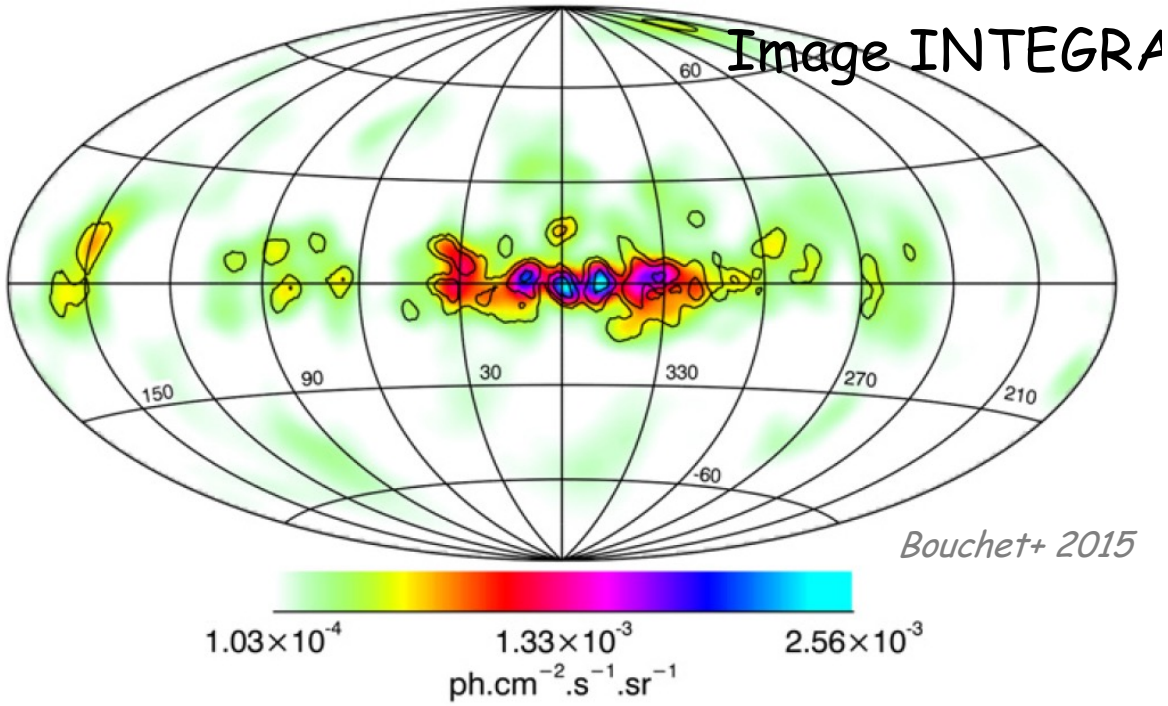


Figure 7. 508.25–513.75 keV *INTEGRAL* SPI smoothed (top hat of 2 pixels) intensity map in photons $cm^{-2} s^{-1}$. Pixel size is 5° × 5°.

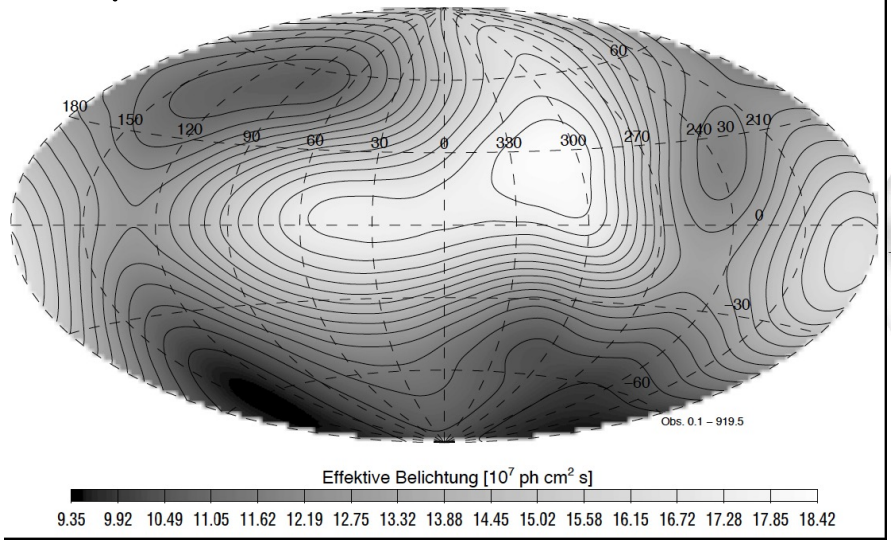
Imaging Galactic ^{26}Al with COMPTEL & SPI

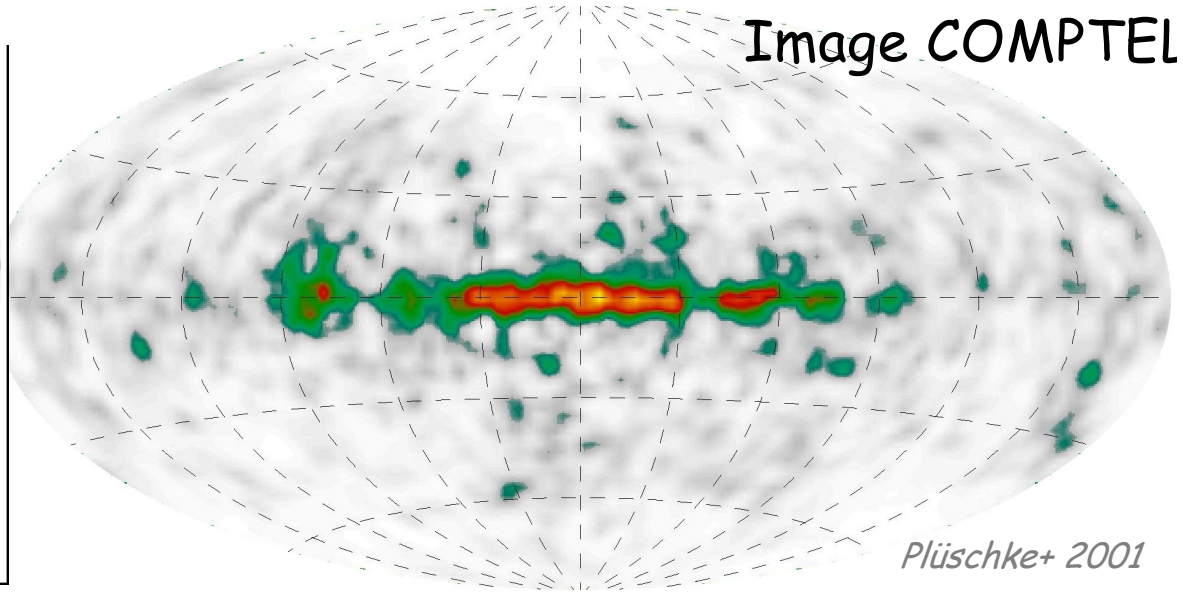




Bouchet+ 2015

Exposure COMPTEL



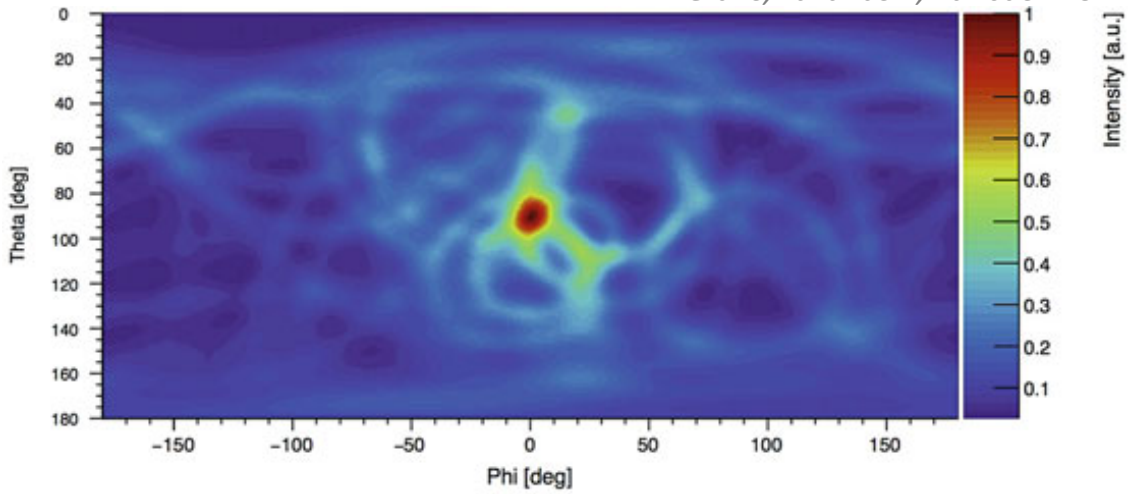


Plüschke+ 2001

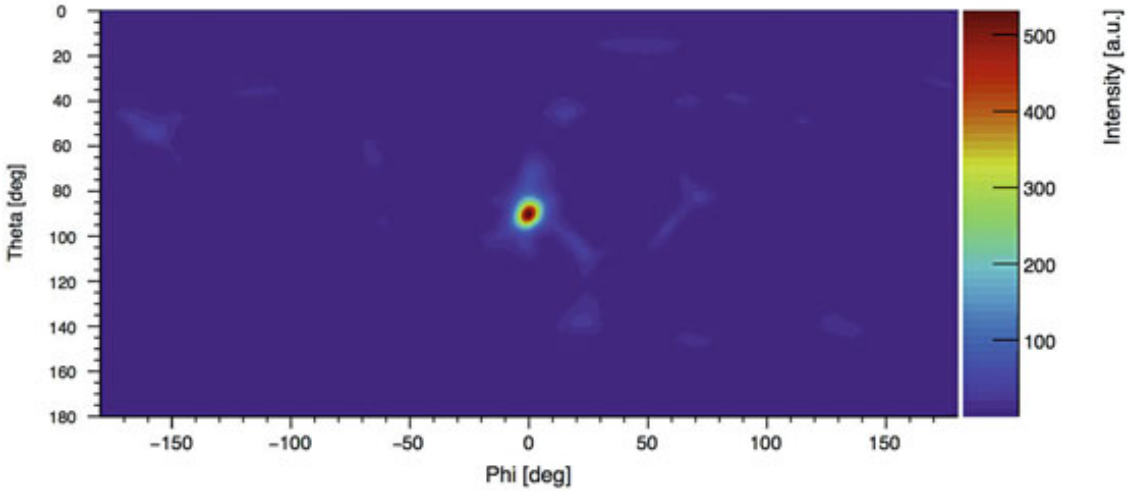
Image Generation with Compton Telescope events

example: point source, 500 keV, 200 events

Kierans, Takahashi, Kanbach 2022



(a) Back-projection of a point source simulation with 200 events.



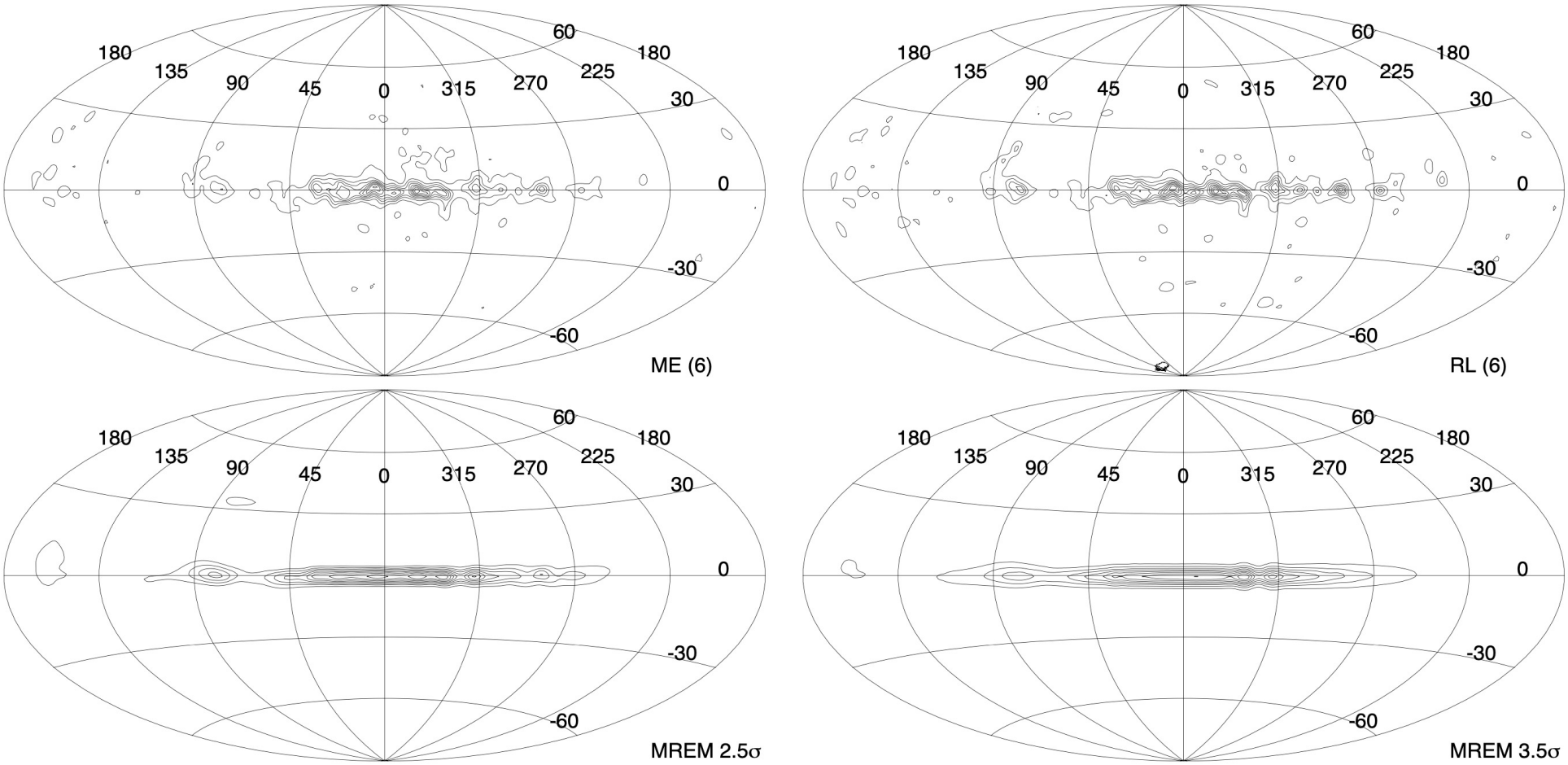
(b) Image obtained after 5 iterations of the LM-ML-EM algorithm.

Image Generation with Compton Telescope events

example: COMPTEL analysis of Galactic ^{26}Al

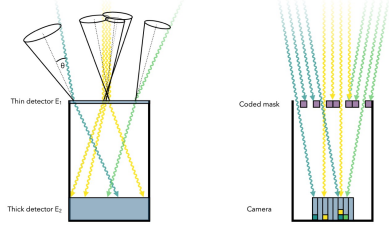
☆comparing different imaging algorithms

Knödlseder+ 1999

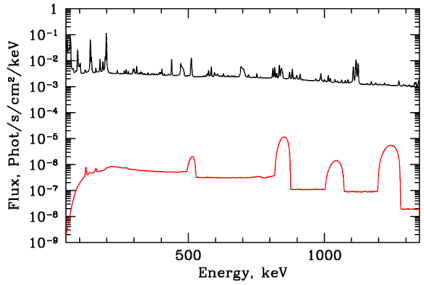


Analysis Challenges for Gamma-Ray Telescopes - Summary

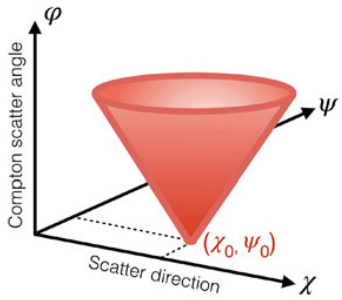
- ☆ Gamma-ray instruments do not produce images:
  photon events are measured within a large field-of-view



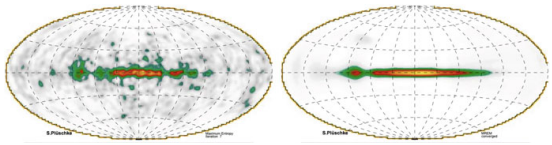
- ☆ Instrumental backgrounds are larger than the celestial signal;
  no 'subtraction' of background possible



- ☆ Multi-parameter pattern recognition is key to data analysis
  (response, and background)
- ☆ Signals from many sources (& bgd) are superimposed:
  all-sky analysis required even for point sources



- ☆ Forward-folding analysis is required: Estimate event data
  for a parametrised model of the astrophysical result
  plus parametrised instrumental response and background



- ☆ Regularisation can be complex:
  many instrumental (response & background) parameters