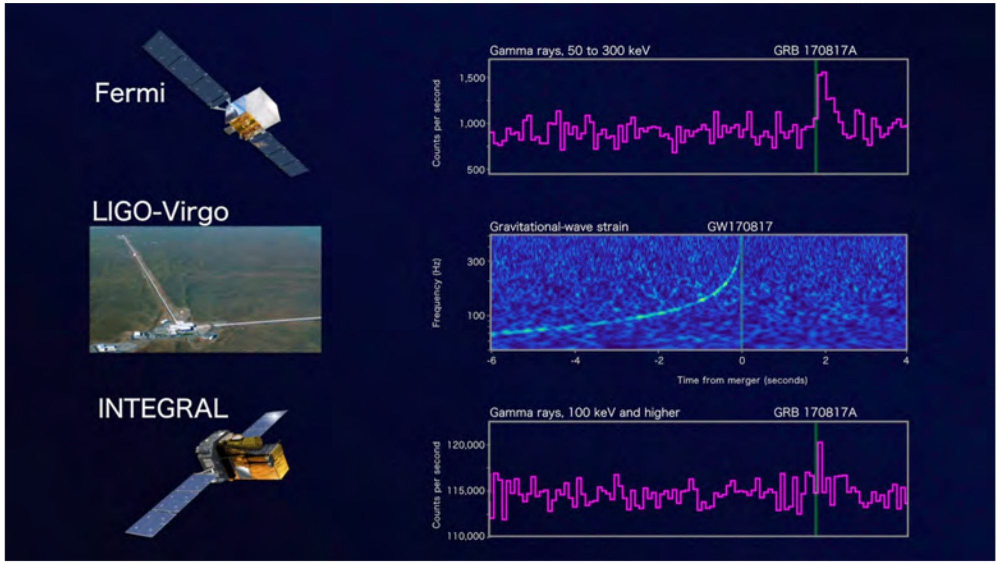
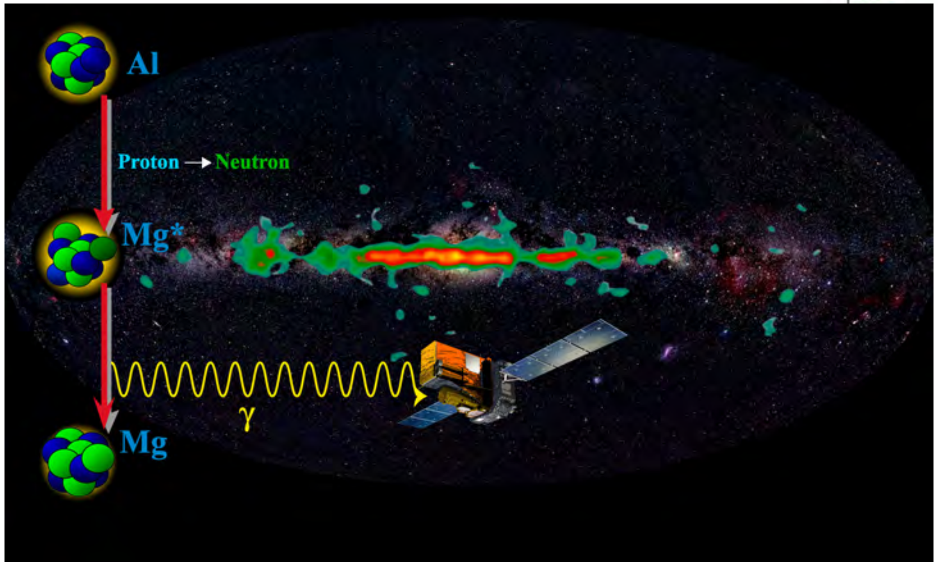
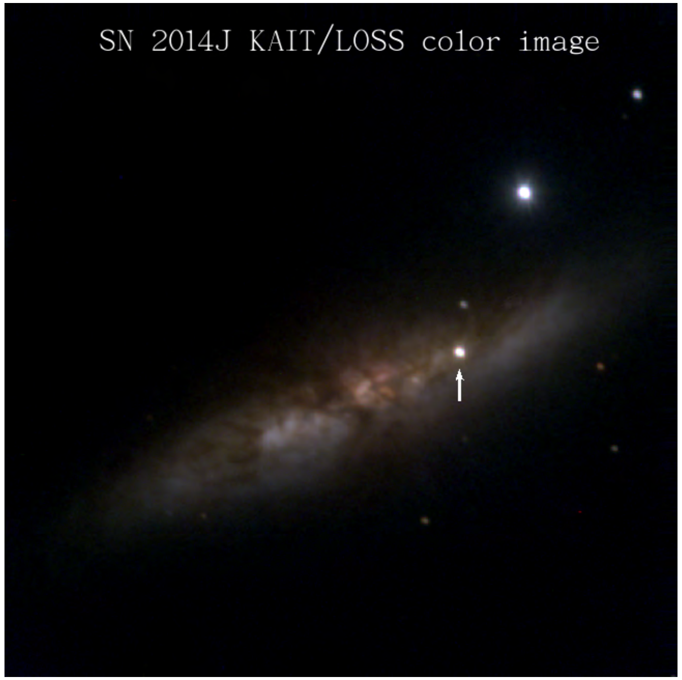
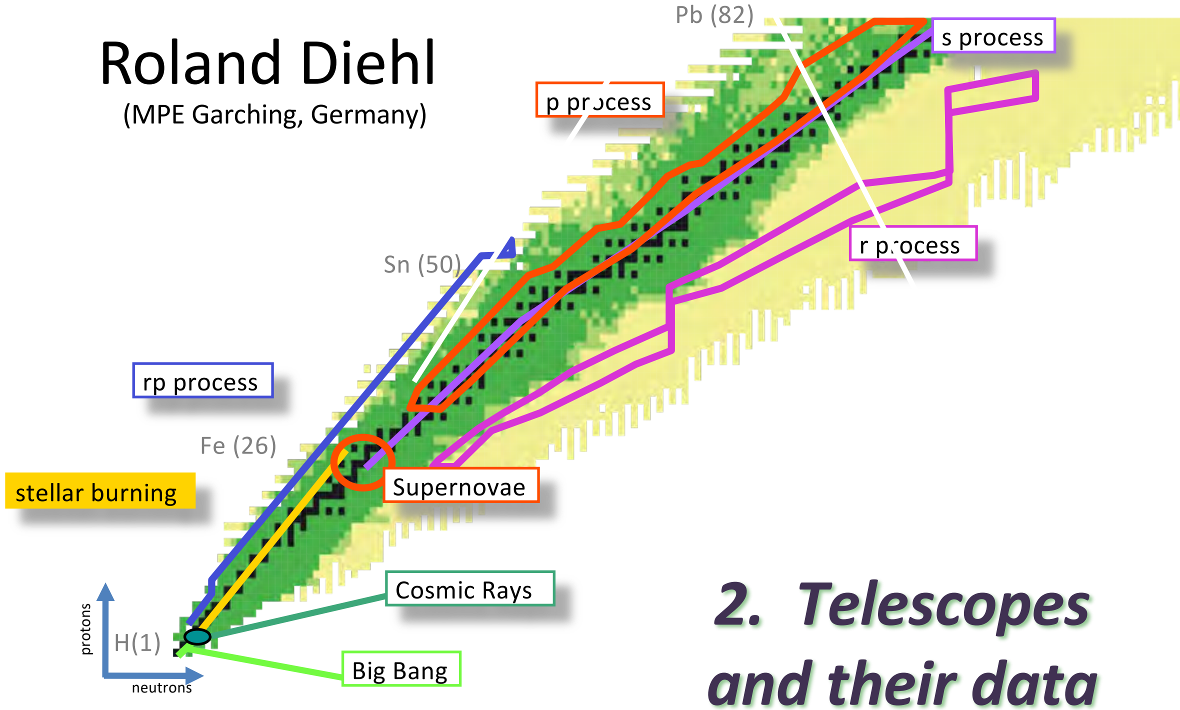
Gamma-ray spectroscopy from cosmic nuclei





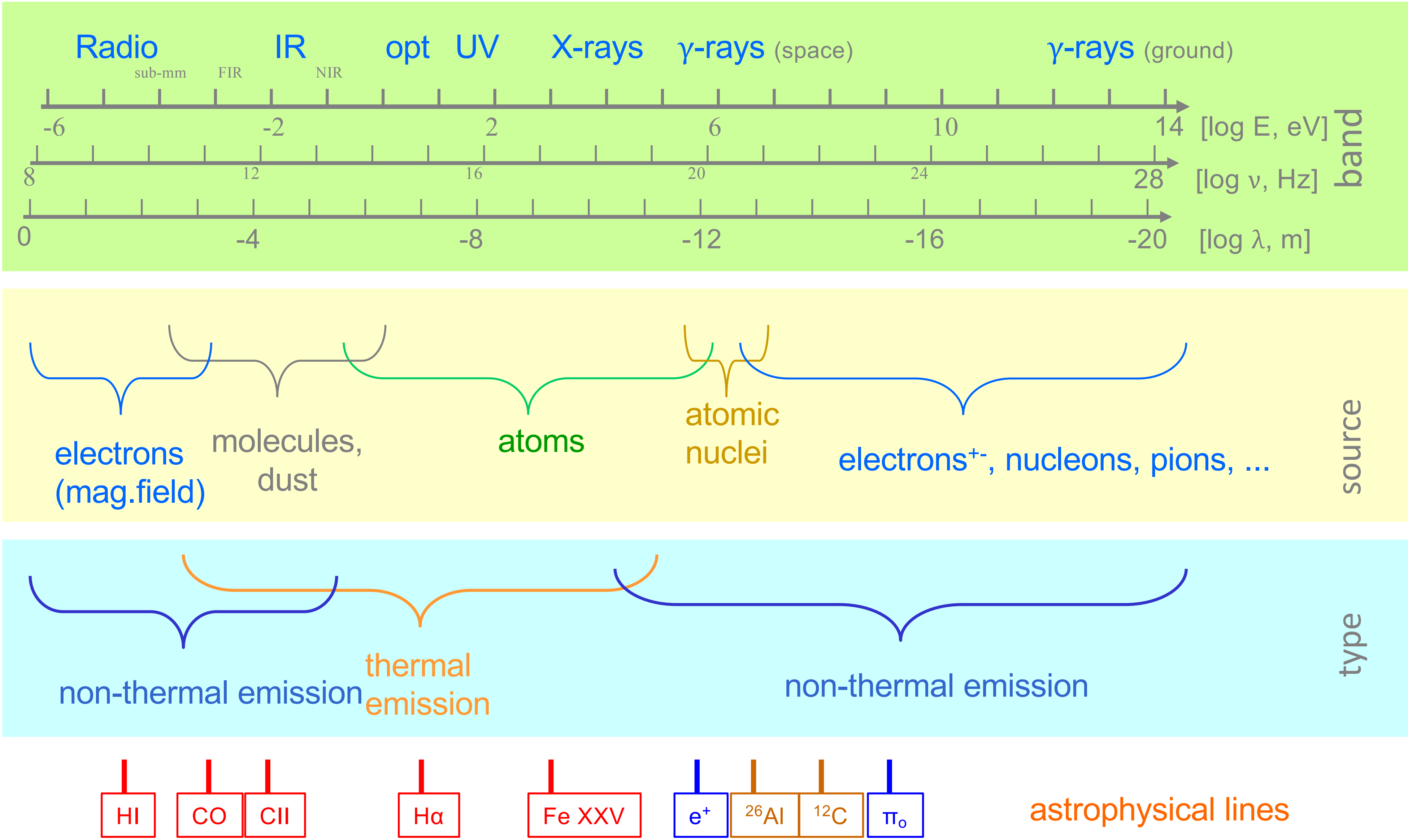


Roland Diehl
(MPE Garching, Germany)

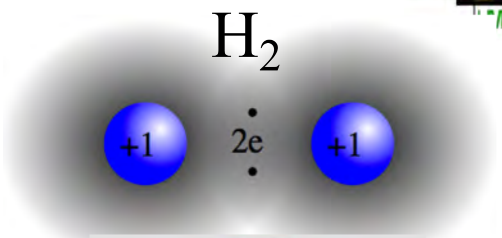


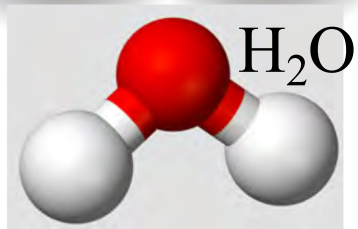
2. Telescopes and their data

Line Spectroscopy across the Electromagnetic Spectrum

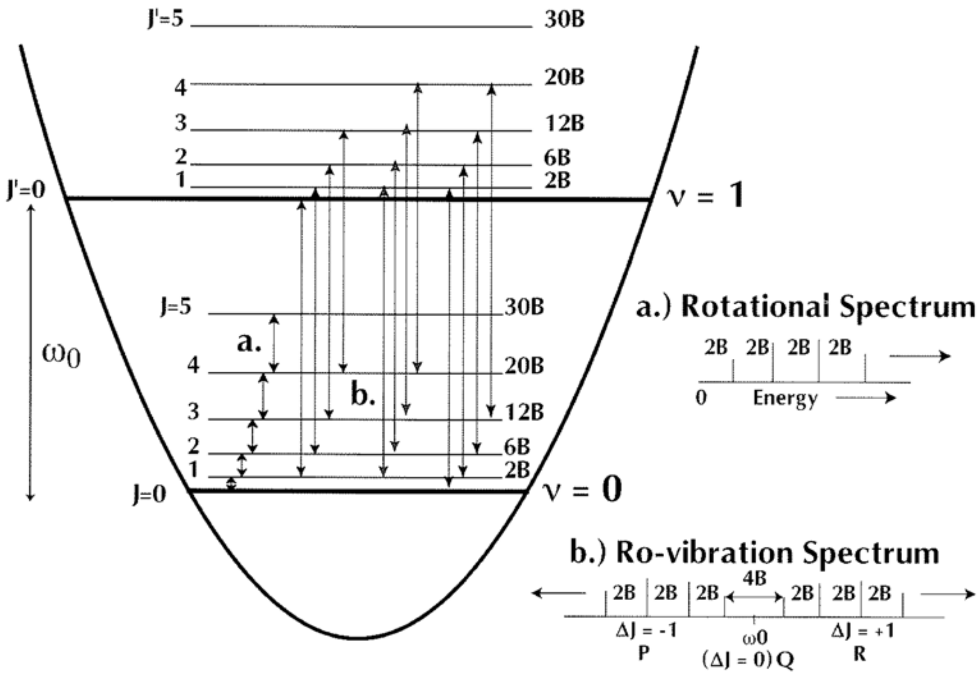


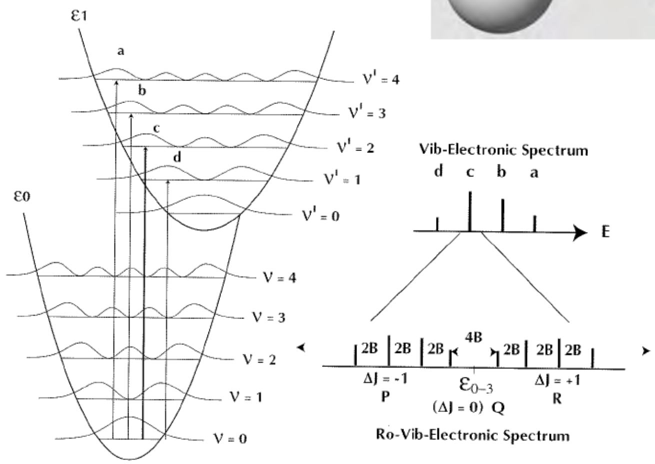
Molecular Lines

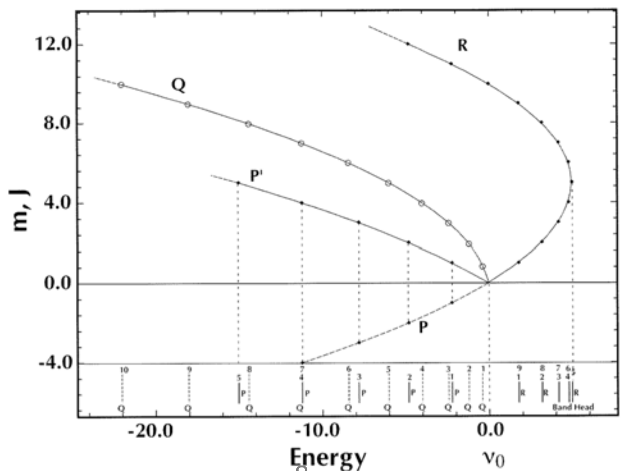




- Electrons 'shared' by several nuclei
- new degrees of freedom: nuclear motion
  - ☆ rotation around main molecular axis
  - ☆ vibration, oscillating nuclear separation
    - ☞ line bands with characteristic structure

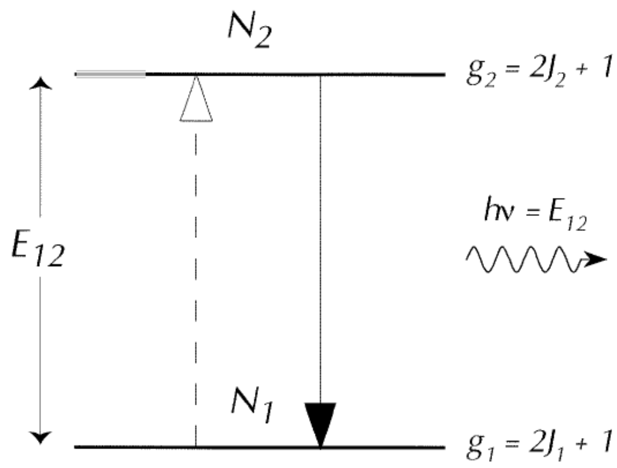


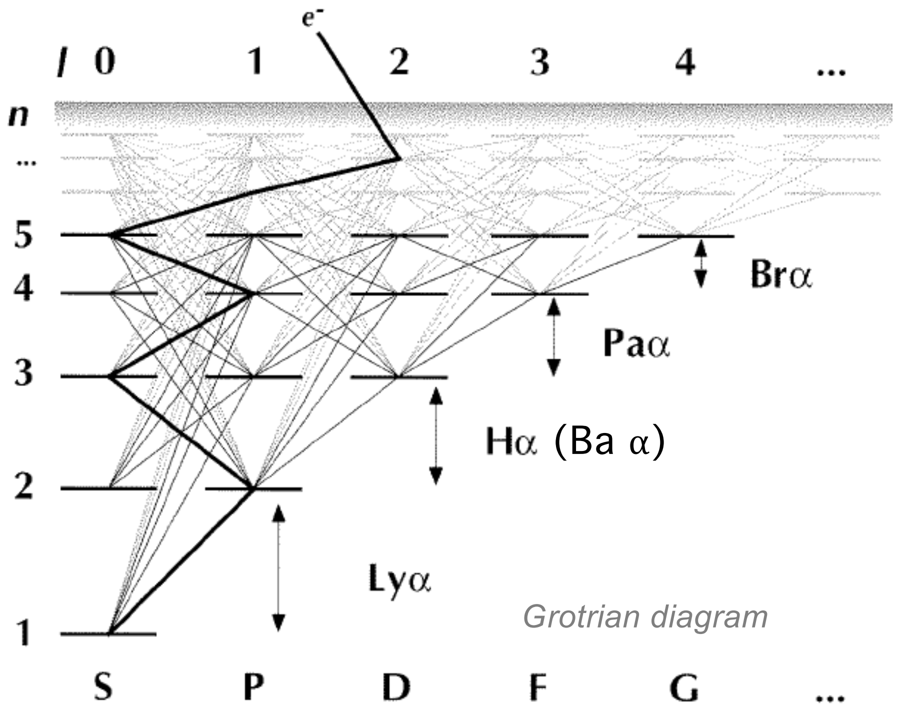




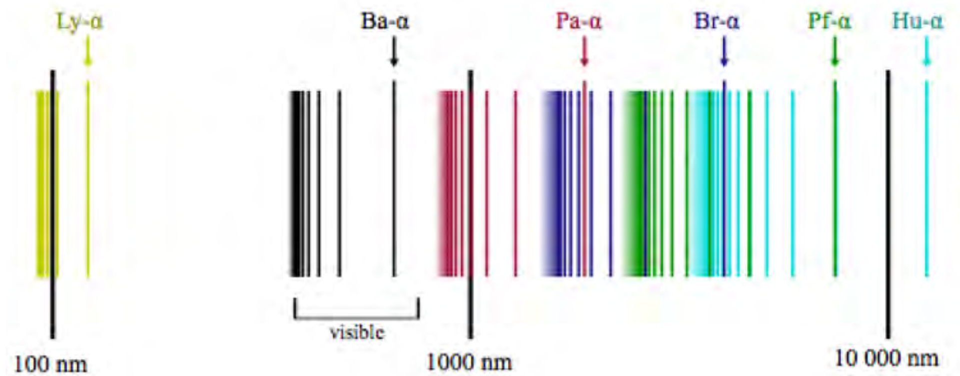
Atomic Energy Levels and Transitions

- Level structure:
  - ☆ electron orbit number
  - ☆ angular momenta of orbit and spin
    - ☞ LS coupling $\langle \vec{L} \cdot \vec{s} \rangle = \frac{\hbar^2}{2}[j(j+1) - l(l+1) - s(s+1)]$
      ...and JJ coupling, and HFS
      - 'allowed' (LS), 'semi-forbidden', 'forbidden' transitions





Grotrian diagram

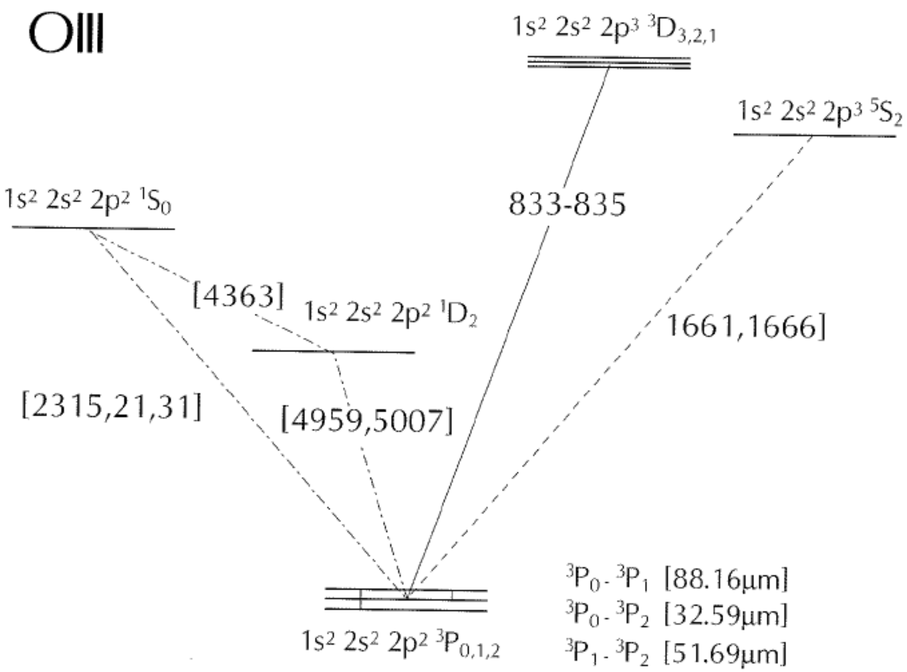


Dopita & Sutherland 2003

Cosmic plasma

- low density → also higher multipolarity transitions occur
  - collision rate low, so collisional de-excitation of levels unimportant;
  - radiative transition probabilities ~ α / ~ α^2 / ~ α^4 - … for E2 / E4 / M2 transitions

☆ *example*: O III lines seen in ISM



Grotrian diagram (excerpt)

Emission from Supernovae / Supernova Remnants

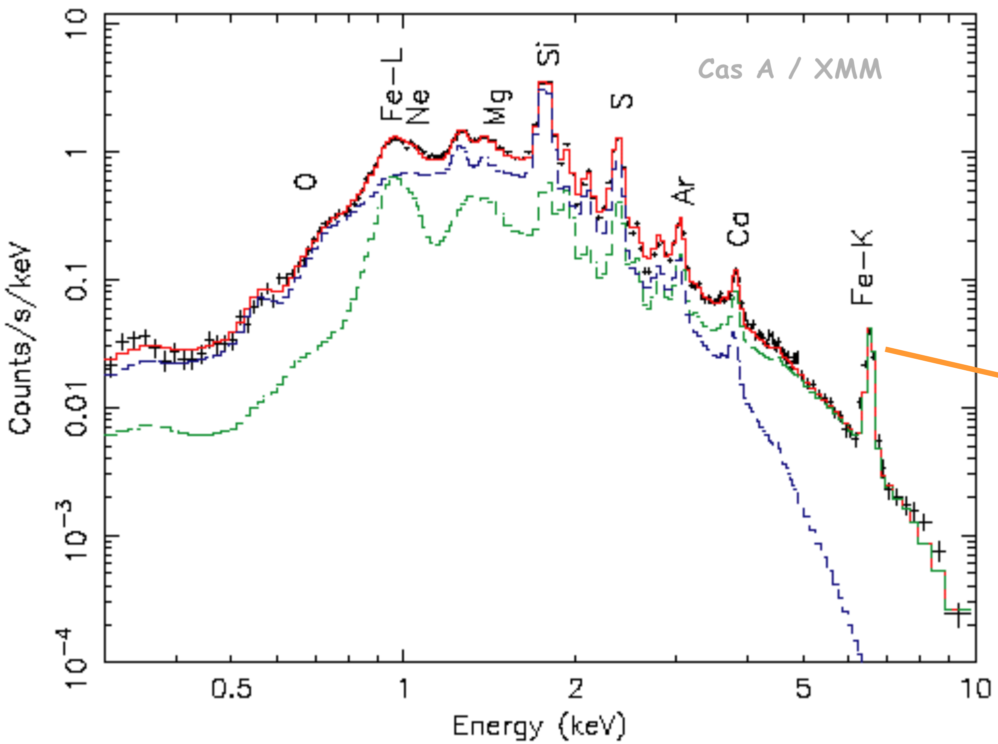


Fig. 2. An example of a spectral fit within a single 20″ × 20″ pixel – cool component in blue, hot component in green and full model in red.

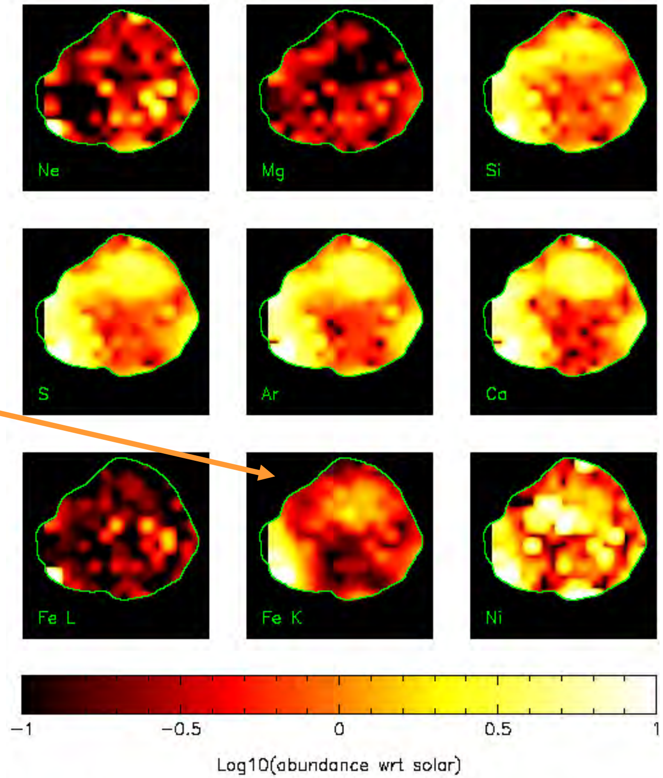
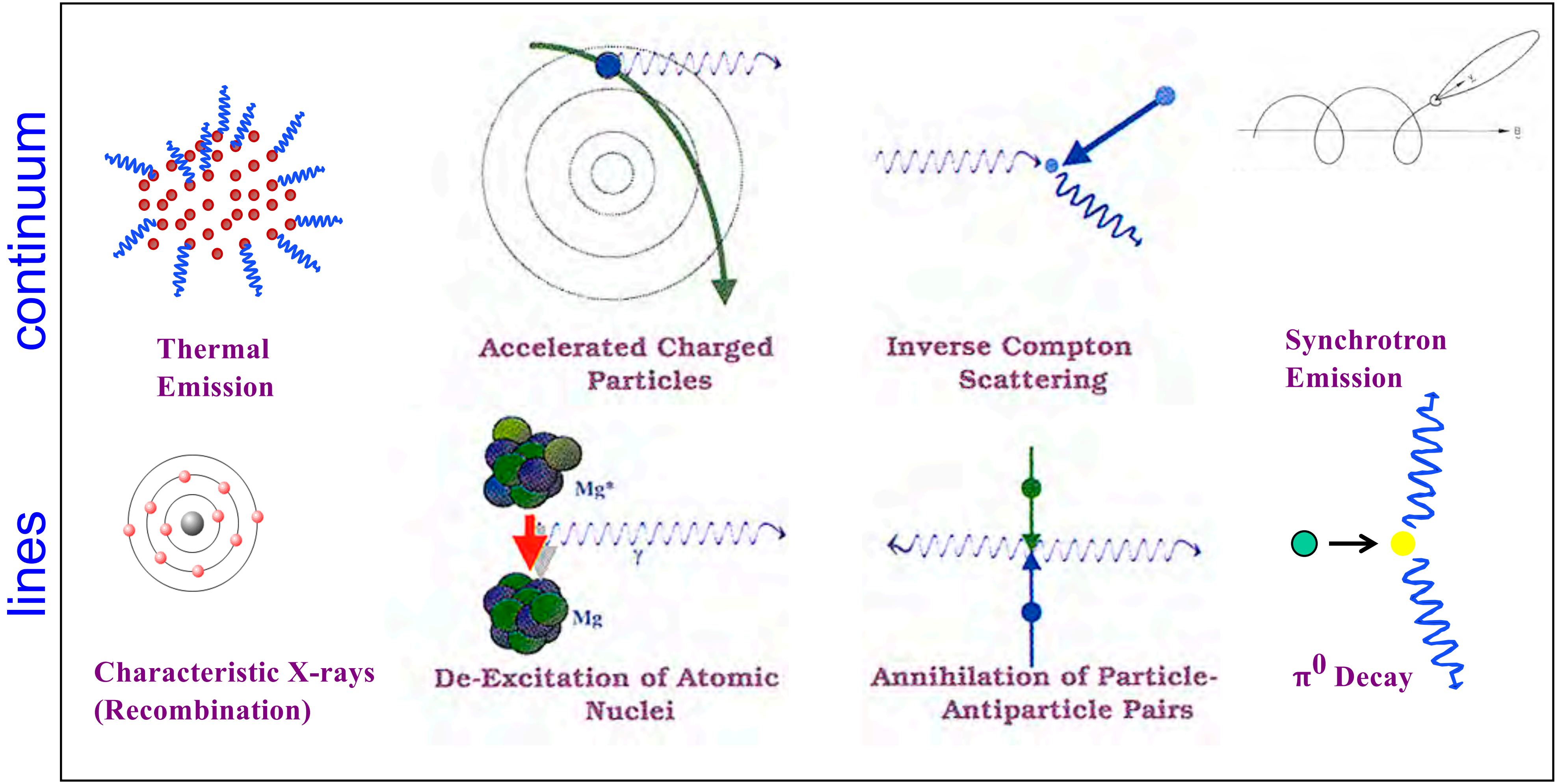


Fig. 5. Abundance maps for the elements included in the spectral fitting. All are plotted on the logarithmic scale indicated by the bar at the bottom.

- SN Material (and Swept-Up Material) Recombination Lines
- + Hot Cavity Thermal Radiation

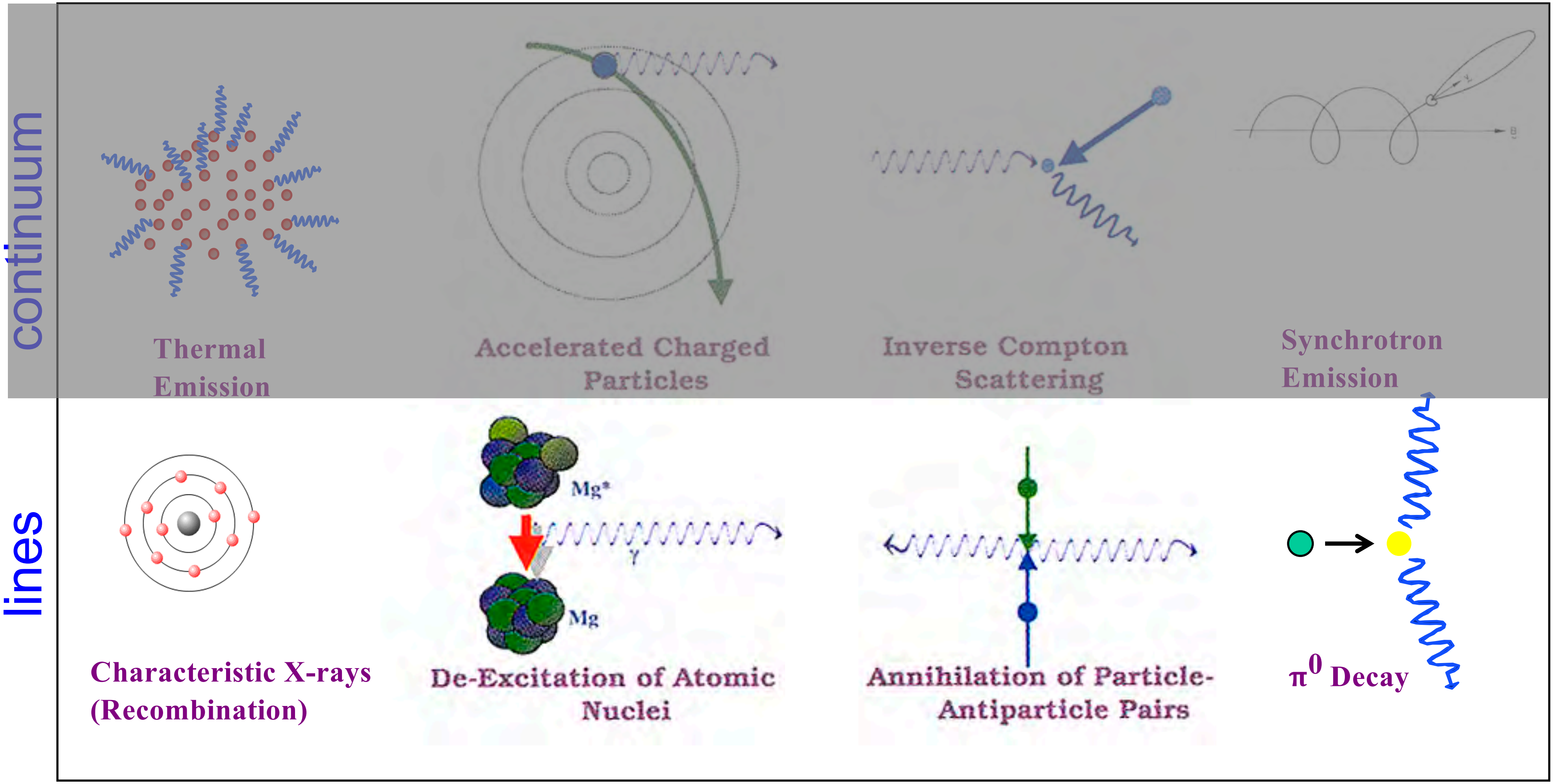
Basic Radiation Mechanisms in HE-Astrophysics



→ apparently, we need to look at

- forms of matter (→ complex systems; intrinsic energies)
- particle and field types, and their interactions and energies

Line Radiation Mechanisms



→ apparently, we need to look at

- forms of matter (→ complex systems; intrinsic energies)
- particle and field types, and their interactions and energies

Nuclear States

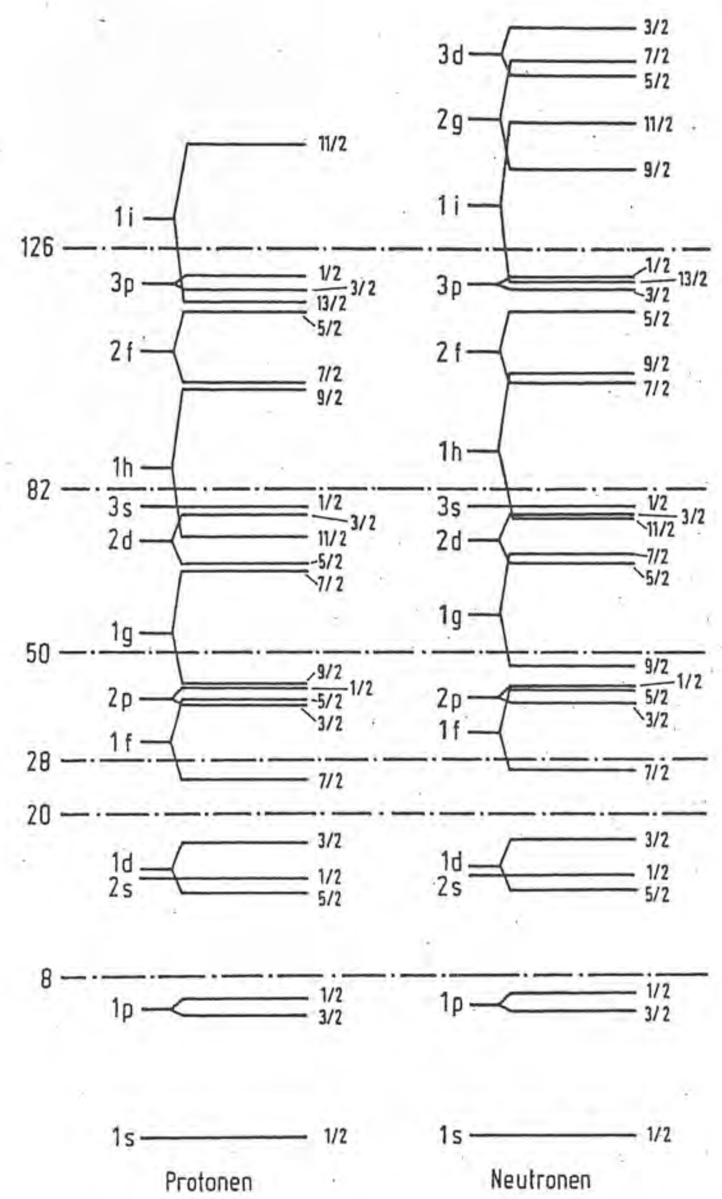
- Shell Model
  - ☆ Orbit and Spin Quantizations
    - ☞ Mean-Field Potential

$$\Psi = R_{n,l}(r) \cdot Y_{l,m}(\theta, \varphi)$$

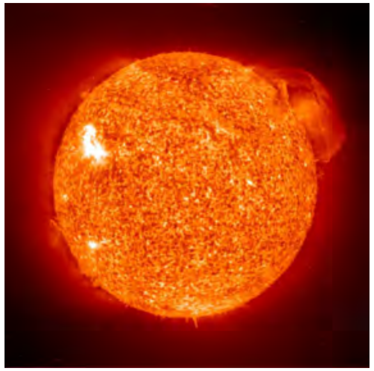
    - ☞ N=2(n-1)+l Energy Levels
  - ☆ Note Difference to Atoms:
    - ☞ Much Stronger Spin/Orbit Coupling

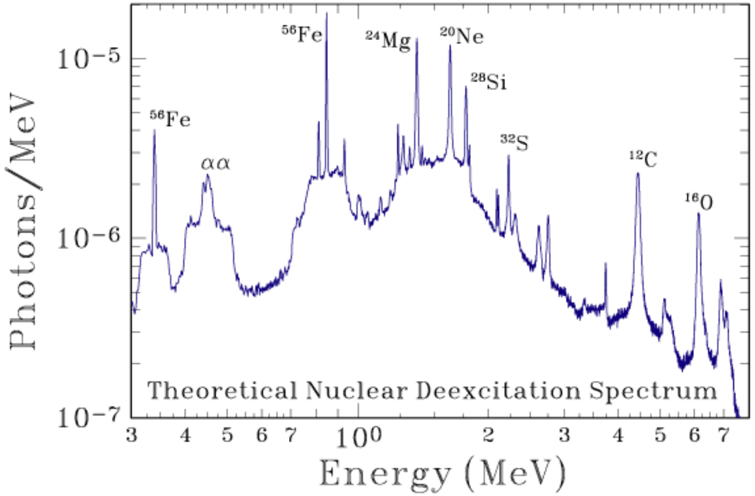
$$\Delta E_{l,s} = -\frac{2l+1}{2} \cdot V_{l,s}(r)$$

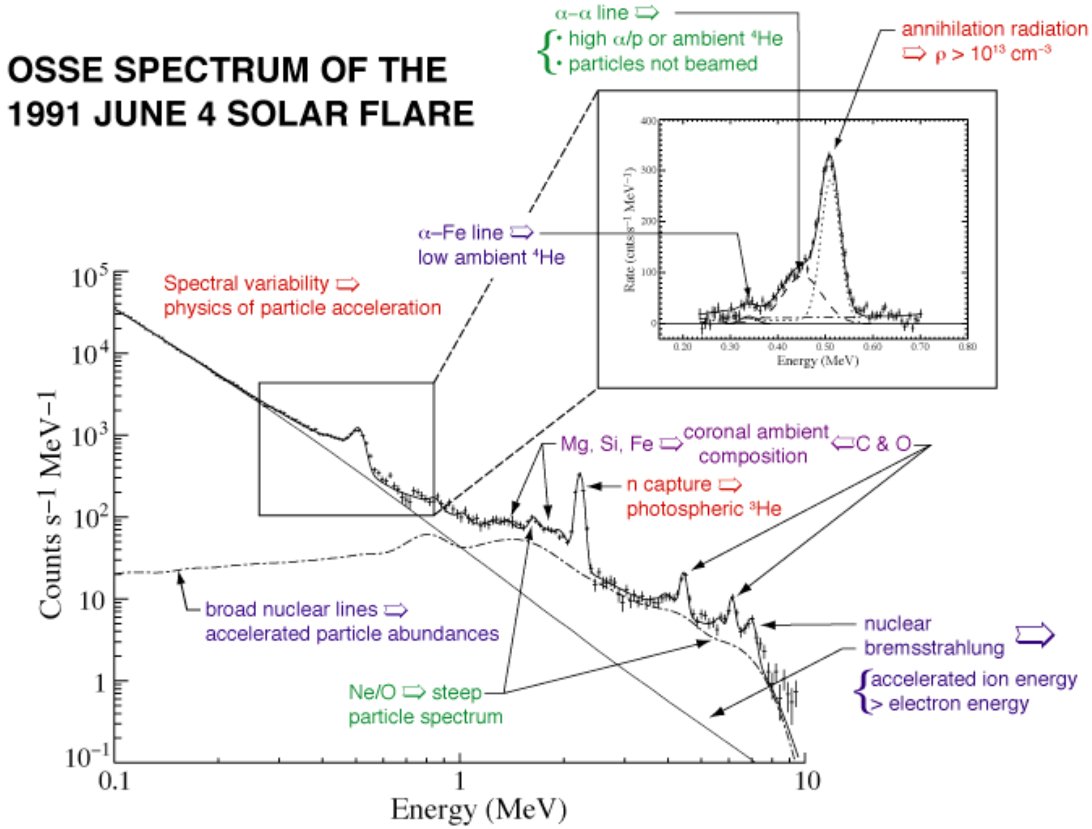
    - ☞ Determined by Strong Force
      (atoms: e.m.force between "magnets")
  - ☆ "Magic Numbers":
    - ☞ Large Energy Gaps between Levels
    - ☞ 2,8,20,28,50,82,126



Solar Flares:
Particle Acceleration → Nuclear Excitation

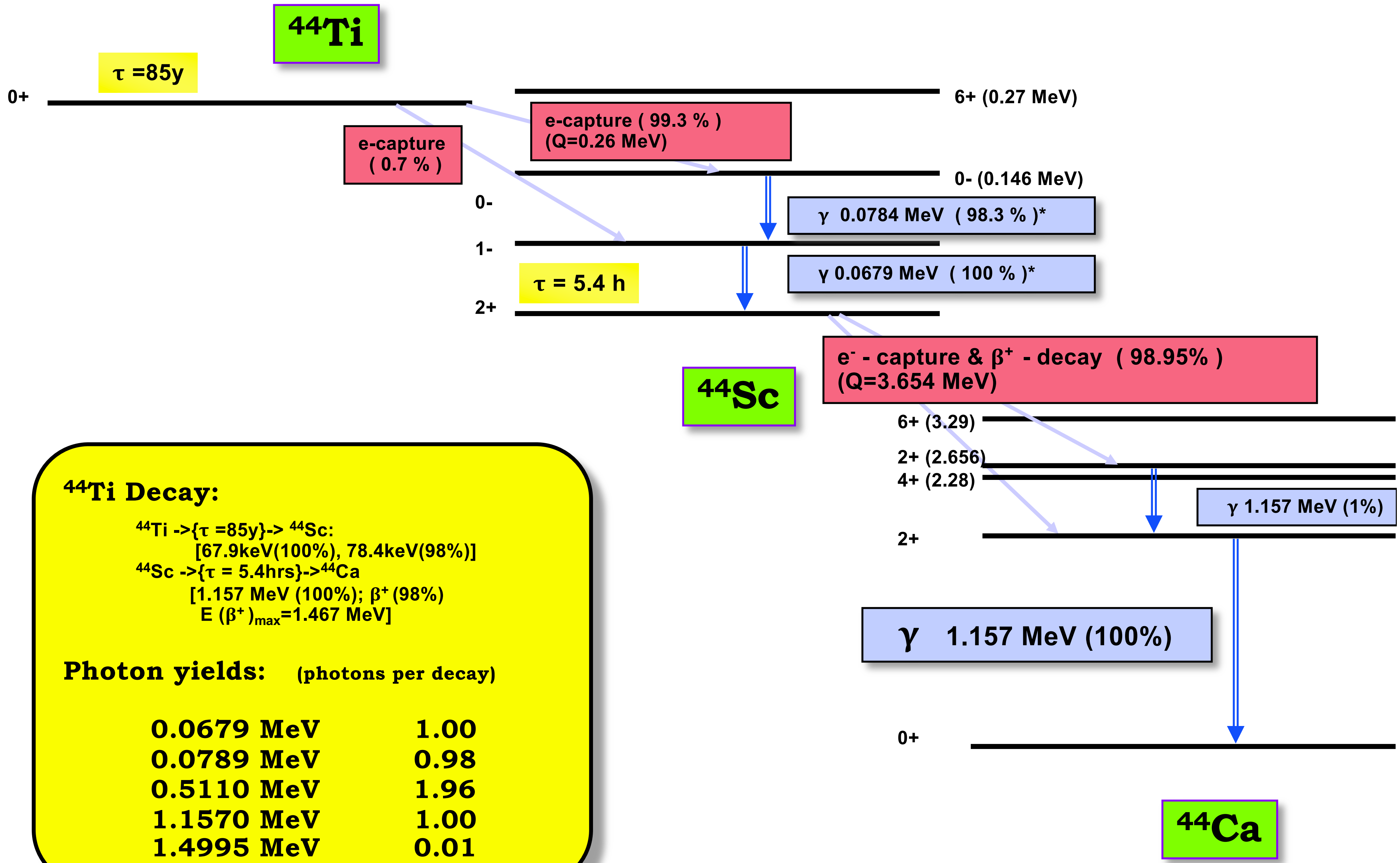






- Particle Acceleration from Magnetic-Field Reconfigurations
- Collisions of Energetic Parcticles with Solar Matter
- Nuclear Excitation, de-excited through gamma-ray emission

^{44}Ti Decay



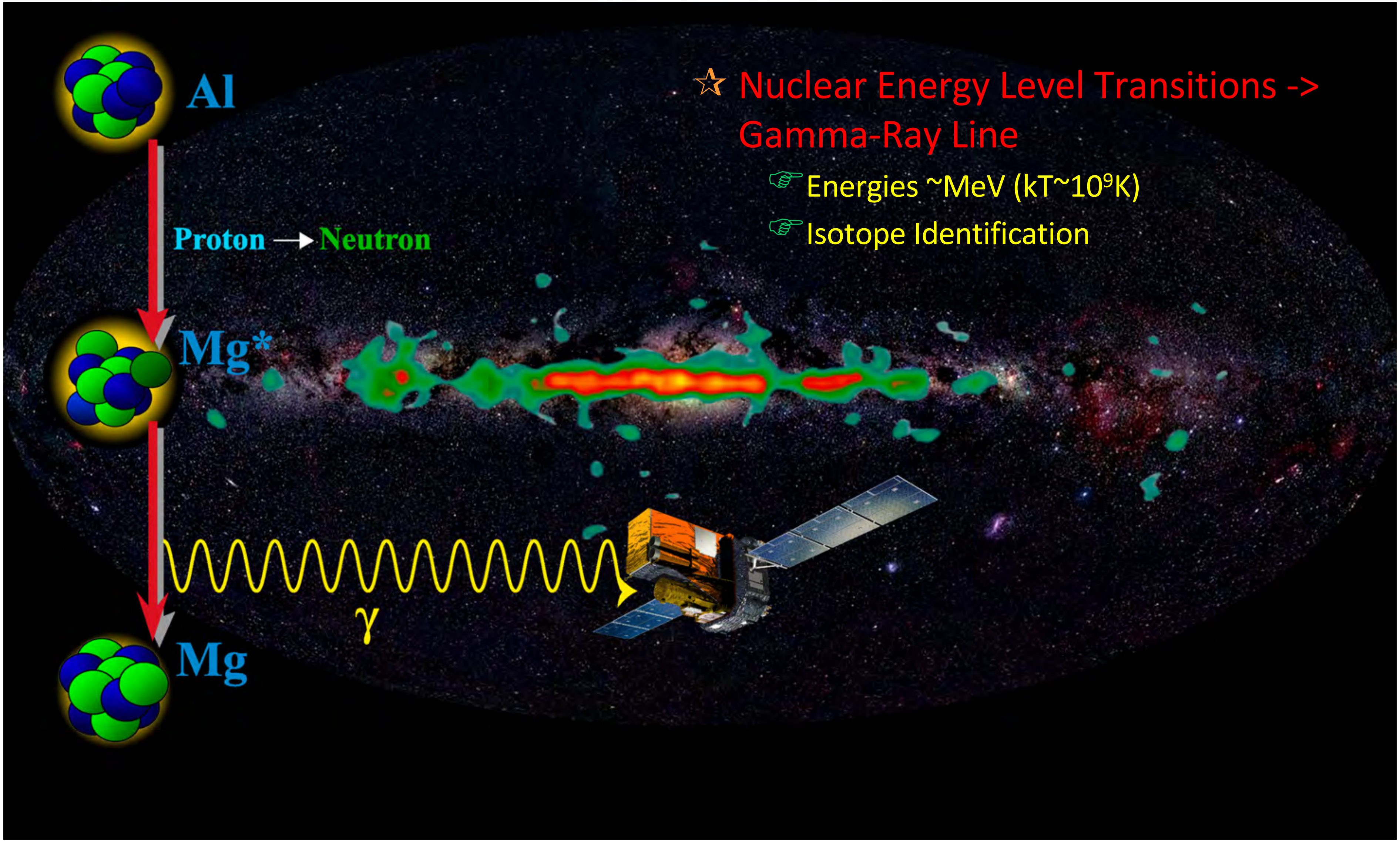
^{44}Ti Decay:

^{44}Ti ->{τ =85y}-> ^{44}Sc:
[67.9keV(100%), 78.4keV(98%)]
^{44}Sc ->{τ = 5.4hrs}->^{44}Ca
[1.157 MeV (100%); β^+ (98%)
E $(\beta^+)_{max}$=1.467 MeV]

Photon yields: (photons per decay)

0.0679 MeV	1.00
0.0789 MeV	0.98
0.5110 MeV	1.96
1.1570 MeV	1.00
1.4995 MeV	0.01

Radioactive Decay Gamma-Rays



Nuclear Gamma-Ray Lines

Isotope	*Mean Lifetime*	*Decay Chain*	*γ-Ray Energy (keV)*
^{7}Be	77 d	$^{7}Be \rightarrow {}^{7}Li^*$	478
^{56}Ni	111 d	$^{56}Ni \rightarrow {}^{56}Co^* \rightarrow {}^{56}Fe^* + e^+$	158, 812; 847, 1238
^{57}Ni	390 d	$^{57}Co \rightarrow {}^{57}Fe^*$	122
^{22}Na	3.8 y	$^{22}Na \rightarrow {}^{22}Ne^* + e^+$	1275
^{44}Ti	85 y	$^{44}Ti \rightarrow {}^{44}Sc^* \rightarrow {}^{44}Ca^* + e^+$	78, 68; 1157
^{26}Al	$1.04\ 10^{6}$y	$^{26}Al \rightarrow {}^{26}Mg^* + e^+$	1809
^{60}Fe	$3.8\ 10^{6}$y	$^{60}Fe \rightarrow {}^{60}Co^* \rightarrow {}^{60}Ni^*$	59, 1173, 1332
e^+	…. 10^{5}y	$e^+ + e^- \rightarrow Ps \rightarrow \gamma\gamma$..	511, <511

individual object/event (^{7}Be to ^{44}Ti)

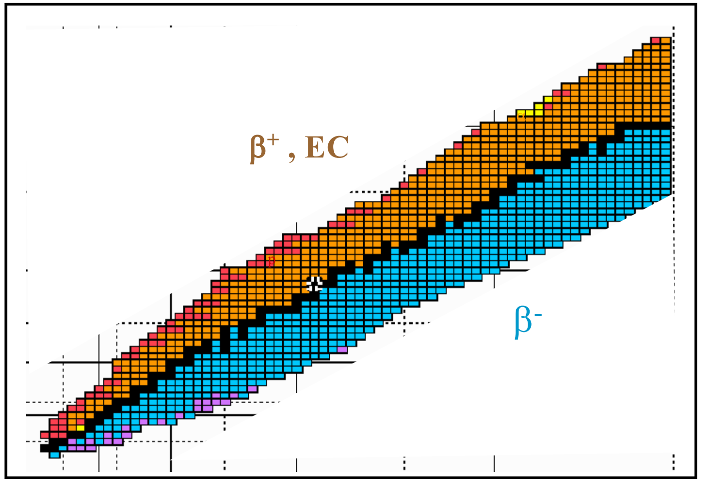
cumulative from many events (^{26}Al, ^{60}Fe, e^+)

Radioactive trace isotopes are by-products of nucleosynthesis

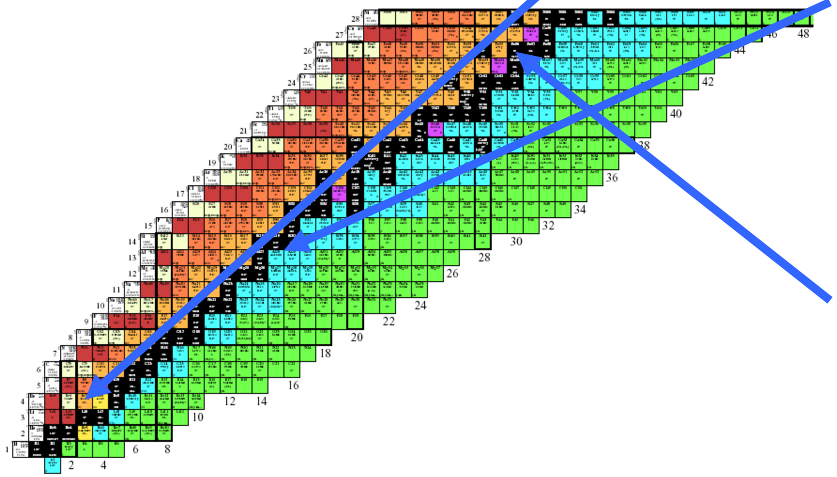
For gamma-ray detections we need:

- ☞ Decay Time > Source Dilution Time (~weeks) (→ no < days lifetimes)
- ☞ Yields > Instrumental Sensitivities (10^{-5} ph cm^{-2} s^{-1}) (→ no elements > Fe)

Gamma-Rays from Radio-Isotopes



- Nucleosynthesis Reactions Produce Isotopes on Proton- and Neutron-Rich Sides of "Valley of Stability"
  - ☞ Radioactive Decays
    - β decay, electron capture
    - β+ decay



- 511 keV, ^{7}Be -> Novae
  → p-Captures, β^+ Decays
  → ^{19}F Production...
- ^{26}Al -> Reaaction Path Details in Stars/SNe, ν-Process
  → Metal/Fe Ratio, Si/Fe
- ^{44}Ti, ^{56}Ni -> Most Stable Isotopes ^{56}Ni/^{4}He, Freeze-Out of NSE
  → Metal/Fe Ratio, Heavies/Fe

The Target Science for low-energy γ-ray astronomy

☆Stellar Interiors

☞Where nuclear reactions act

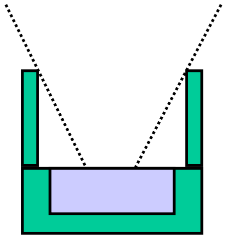
☆Cosmic explosions

☞Where high-temperature reactions and dynamics act

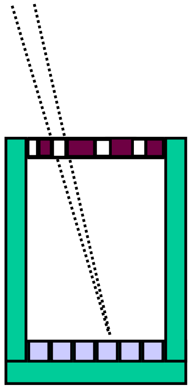
☆The compositional evolution

☞Where new nuclei are fed into the cycle of matter

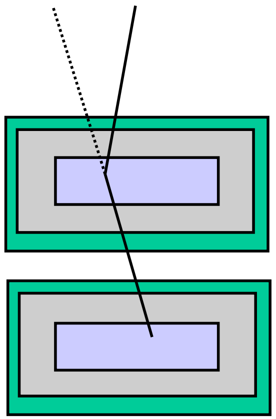
MeV Range Gamma-Ray Telescope Principles



- **Simple Detector (& Collimator)**
  (e.g. HEAO-C, SMM, CGRO-OSSE)
  Spatial Resolution (=Aperture) Defined Through Shield



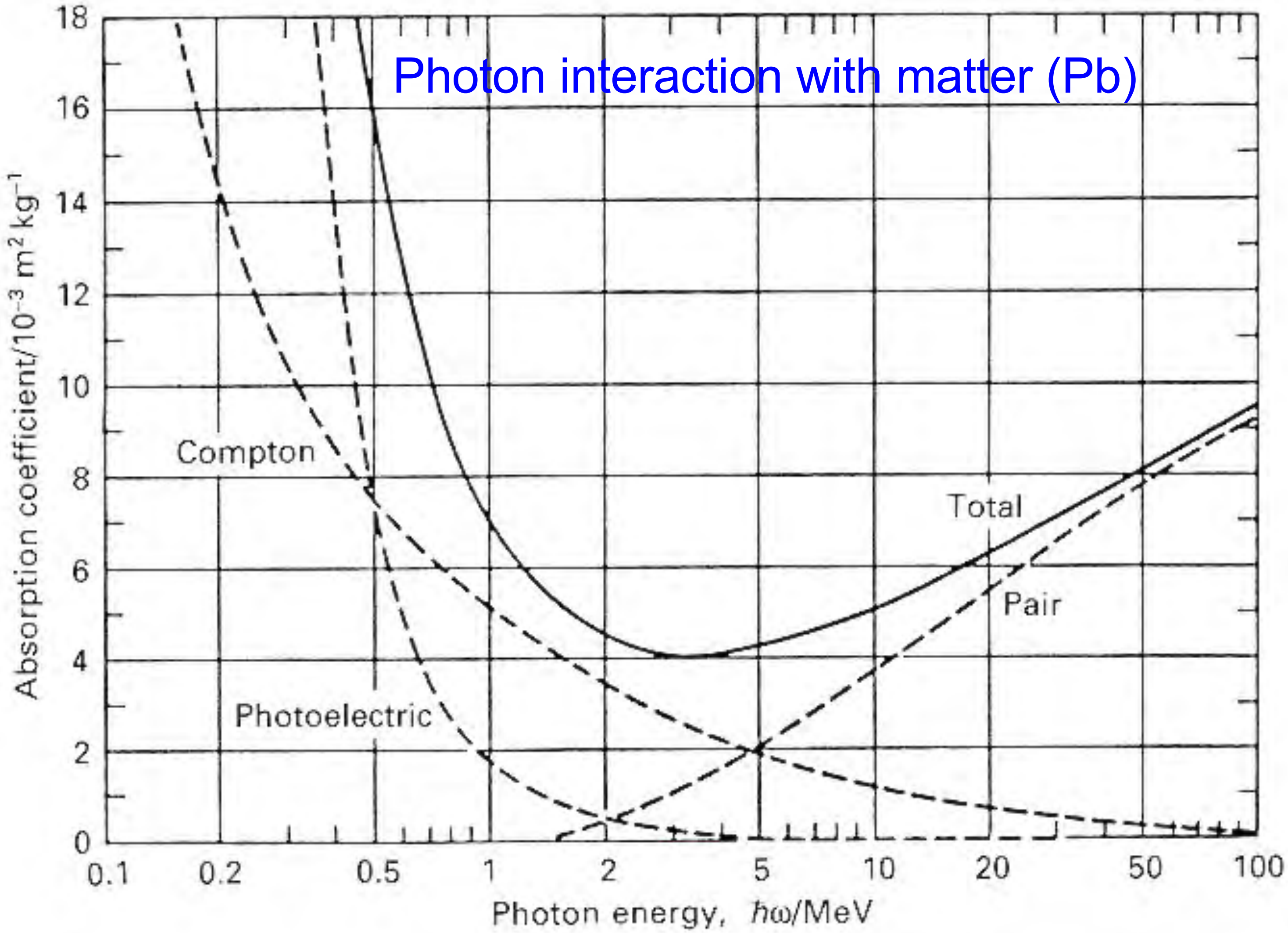
- **Coded Mask & Detector Array**
  (e.g. SIGMA, INTEGRAL, SWIFT)
  Spatial Resolution Defined by Mask & Detector Elements Sizes



- **Compton Telescopes**
  (Coincidence-Setup of Position-Sensitive Detectors)
  (e.g. CGRO-COMPTEL, GRIPS, ACT, ASTROGAM...)
  Spatial Resolution Defined by Detectors' Spatial Resolution

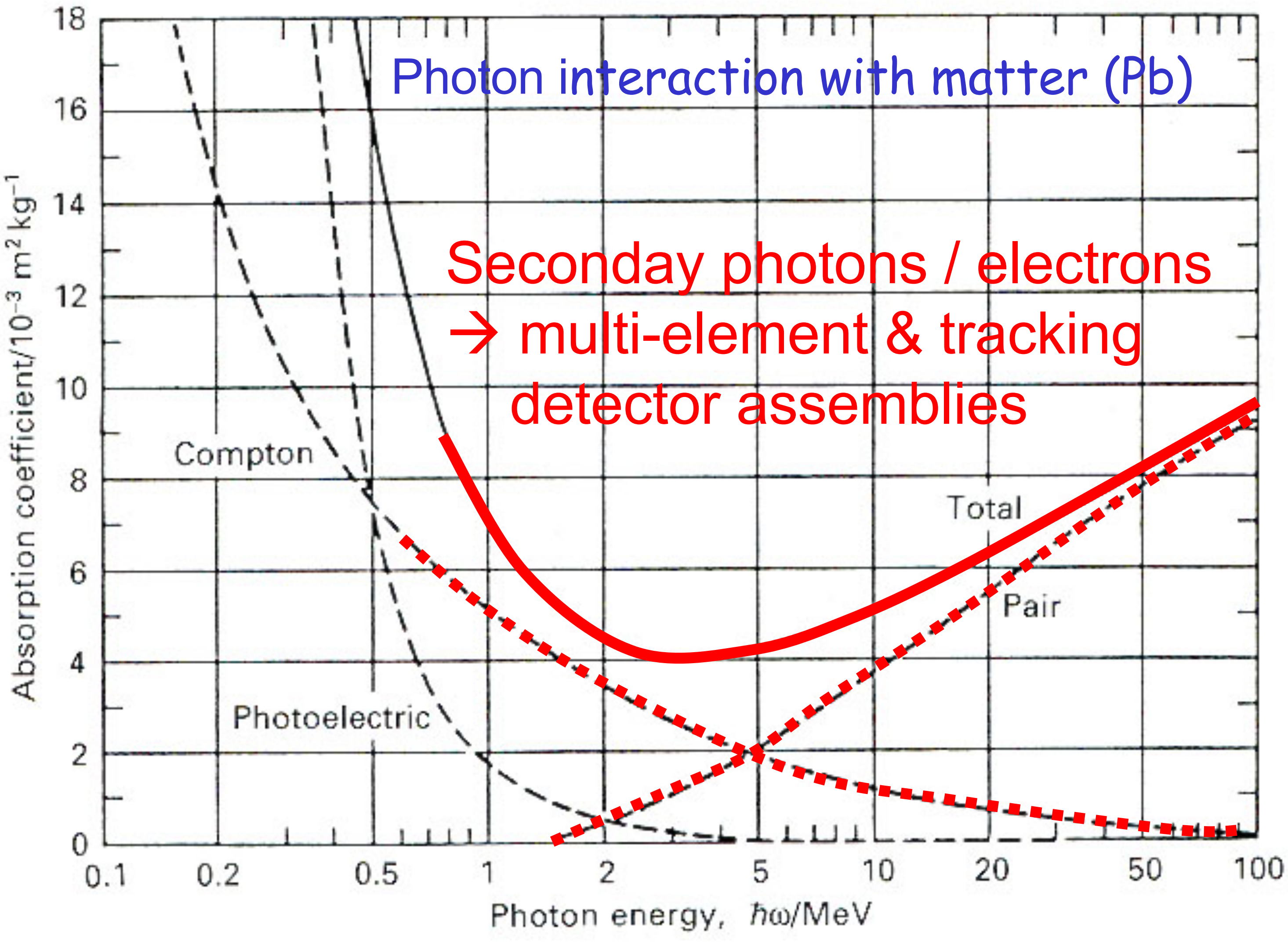
Achievable Sensitivity: ~10^{-5} ph cm^{-2} s^{-1}, Angular Resolution ~ deg

Interaction of high-energy photons with matter



Gamma-Ray Astronomical Telescopes:

Interaction of high-energy photons with matter



→ Secondary Particles … → e.m. cascade

Data from a Gamma-Ray Telescope

- Instrument features multiple detector units
  - ☆ Each photon interaction with instrument detector units → data
    - ☞ General detector event parameters: time, telescope pointing, environment
    - ☞ Detection parameters and measurement: flags for detetcors → selections , energy measurement, directional measurements (?)
  - ☆ An event message is a complex of data

- Data collection occurs over longer times
  - ☆ Instrument pointing and environment varies between photon measurements
    - ☞ Need to ensure proper tracking of instrumental response
    - ☞ Need to collect additional data to track/trace backgrounds and environment

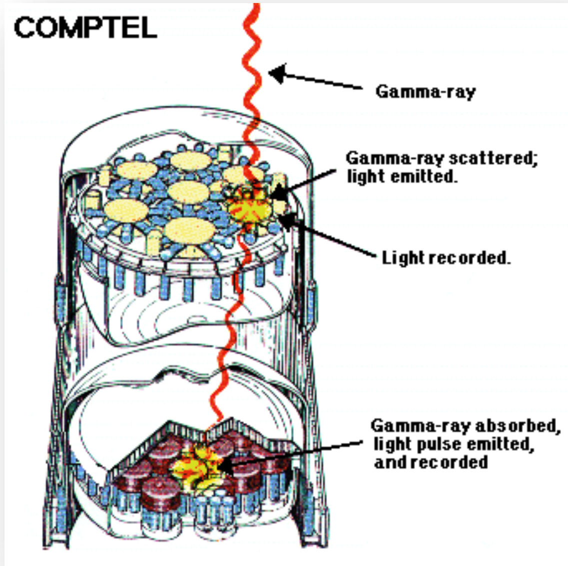
Data from Telescopes

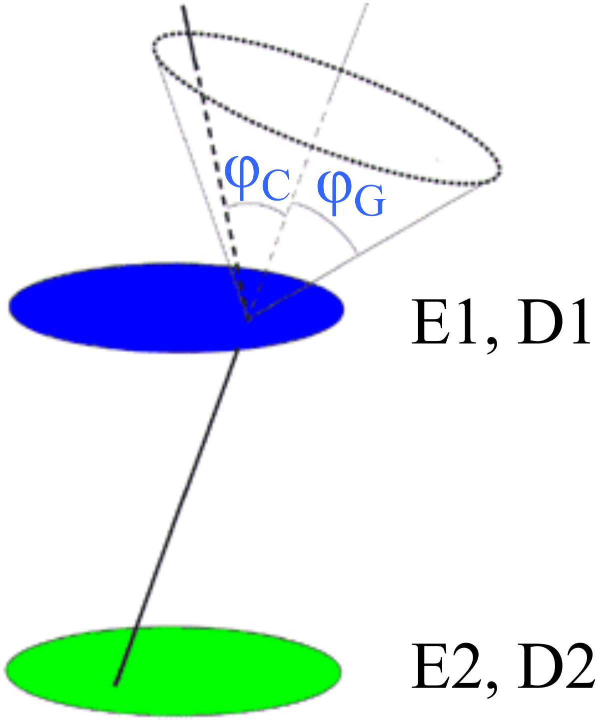
- Gamma-Ray Telescope
  - ☆ Each photon interaction with instrument detector units → data
    - ☞ General detector event parameters: time, telescope pointing, environment
    - ☞ Detection parameters and measurement: flags for detetcors → selections , energy measurement, directional measurements (?)
- Conventional Telescope
  - ☆ Instrument provides an image of a field of view
    - ☞ Image parameters: flux per sky direction
    - ☞ Spectral information: typically per direction in the sky

→ The analysis/decovolution/computing algorithm is part of a gamma-ray telescope's data generation

Data Example: COMPTEL on CGRO

- Event Message Components
  - ☆ Event trigger time
  - ☆ Detector IDs for D1, D2
  - ☆ Energy measurements in D1, D2
  - ☆ Pulse shape measurement in D1
  - ☆ Time of Flight measurement D1→ D2





Compton Formula

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

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

Evaluate Compton formula for

- Measured energy deposits ϕ_C
- Geometry of triggered detectors φ_G

→ Derived measurement of A.R.M..= φ_C - φ_G

Analysing COMPTEL Data

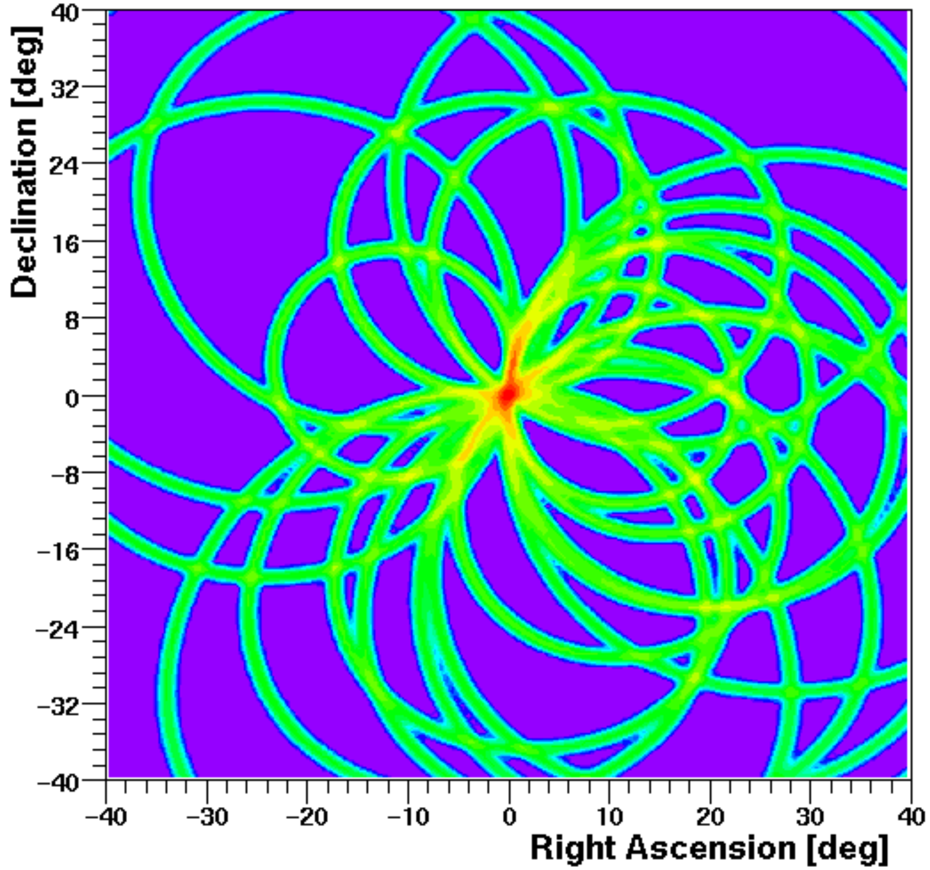
☆ Event parameters E_{total}, χ,Φ_G,ϕ_c

- $E_{total} = E_1 + E_2$
- Direction of scattered photon from interaction locations χ,Φ_G
- Compton scatter angle estimate from measured energy deposits ϕ_c

☆ 'Event Circle' Method:

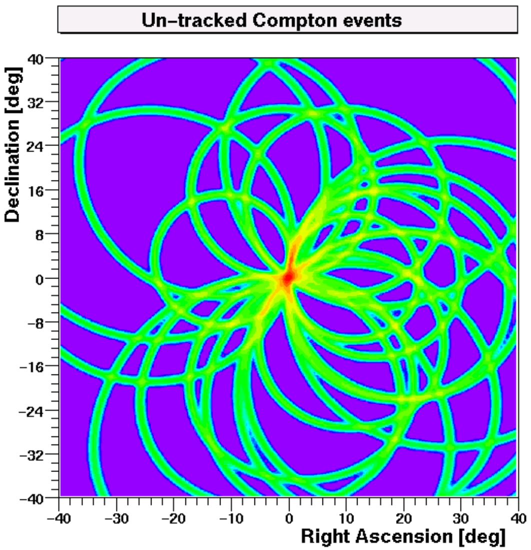
☞ Project idealised possible arrival directions onto the sky

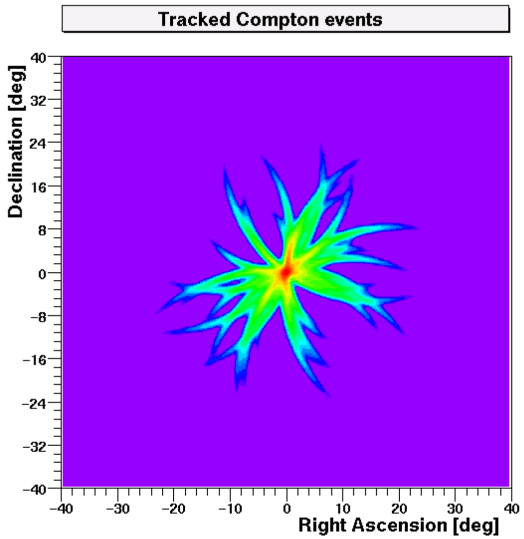
☞ Accumulate candidate arrival directions
→ sky map of events' origins

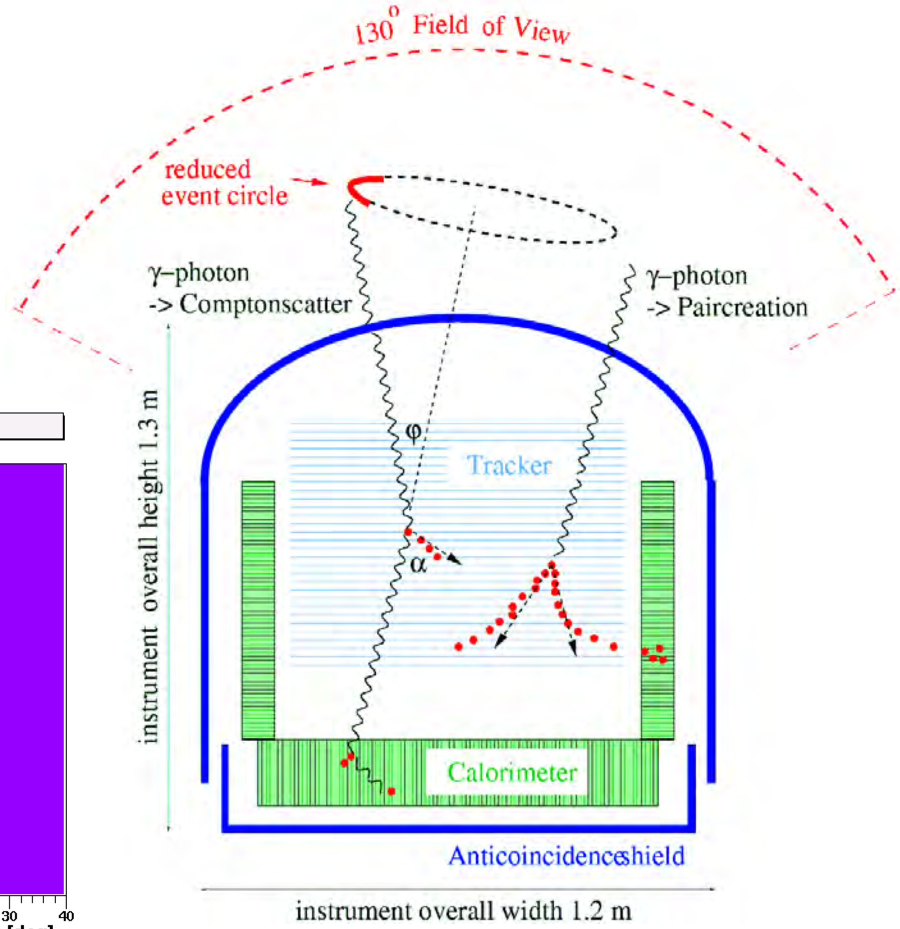


Analysing COMPTEL Data

- Interpret Set of Measurements in terms of Expected Response
  - ☆ ‘Event Circle’ Method:
    - ☞ Improvement as Direction (momentum) of secondary electron is measured in a tracker

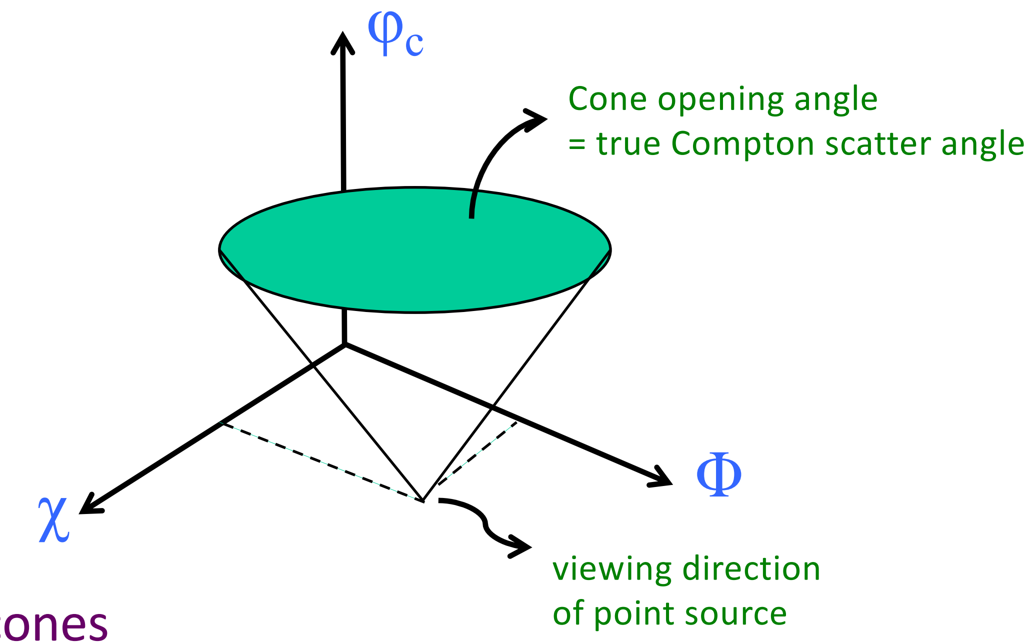






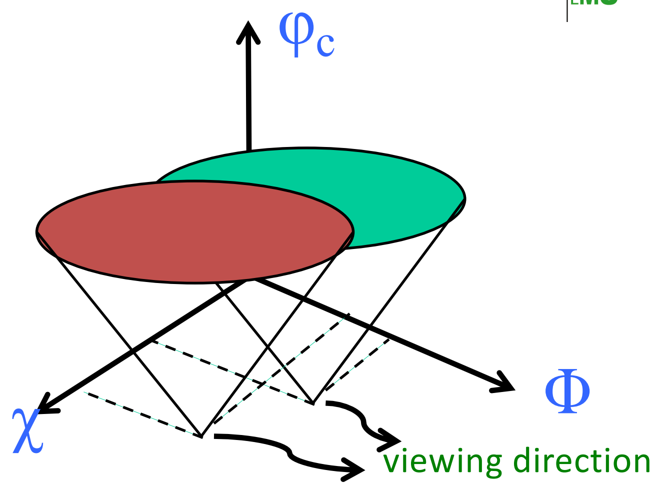
Analysing COMPTEL Data *('properly')*

- Interpret Set of Measurements in terms of Expected Response
  - ☆ 'Event Cone' Method:
    - ☞ Use event messages as measured, i.e. E_{total}, χ, Φ, ϕ_c
    - ☞ Calculate probabilities to measure such events, given the detector configuration and its properties resolutions) in interaction energies and locations
    - ☞ For a point source, ideally the measured events are found at the mantle of a cone
    - ☞ Method: Fit possible sources in data space as superimposed cones



Analysing COMPTEL Data

- Poissonian Statistics of Event Measurements
  - ☆ Incorporate expected statistical fluctuations
- Ambiguities for any E1, E2, X1, X2 set: different photon origins
  - ☆ Incorporate degeneracy of instrumental response



→ Iterative methods of improving a forward-folded model for data

- Statistical de-convolution, or model fitting:
  - ☆ Likelihood of observing measured data, given a model
  - ☆ Discrepancy with real measurement used to improve model parameters
  - ☆ Improve model until "best fit" achieved / select best-fitting model

- Deconvolution results depend on model and fit/convergence method
  - ☆ Maximum Likelihood
  - ☆ Maximum Entropy
  - ☆ ...

Spectroscopy with COMPTEL

- Modest Energy Resolution of ~10% (FWHM)
  - ☆ Analysis results compared for different energy bands

C. Dupraz et al.: COMPTEL search for galactic ^{44}Ti emission 685

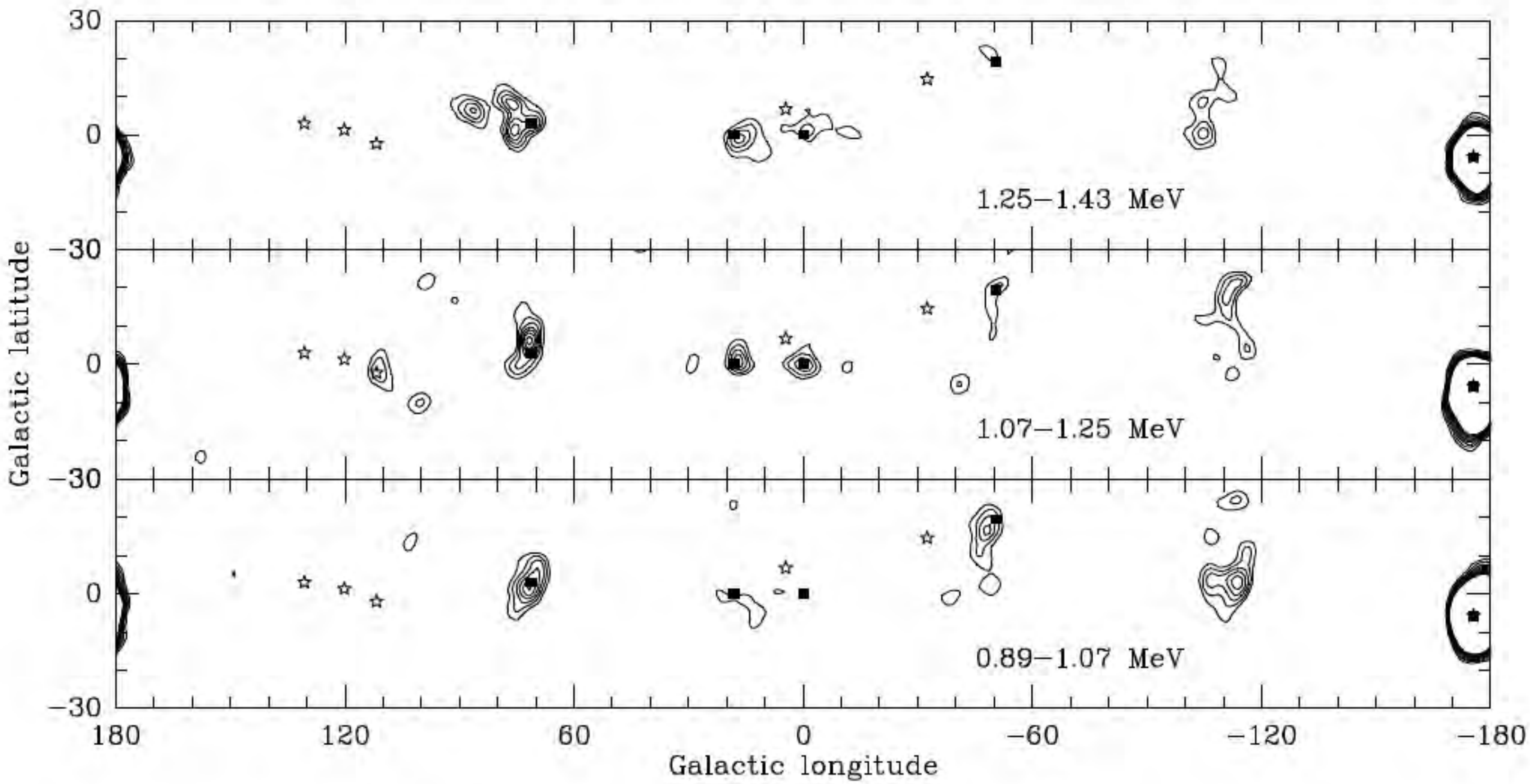
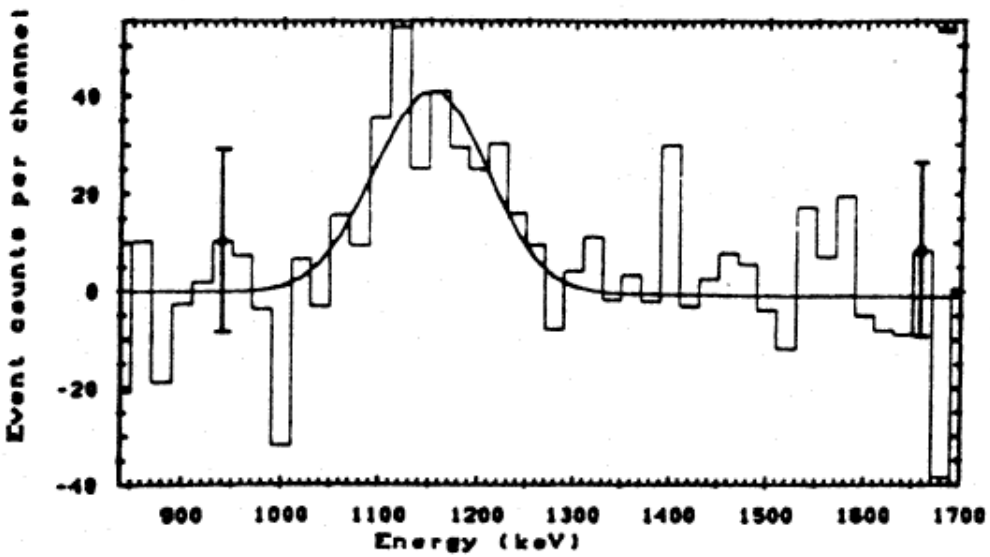


Fig. 1. Maximum-likelihood maps of the Galactic plane in three energy bands: 0.89–1.07 MeV (*bottom*), 1.07–1.25 MeV (*middle*), 1.25–1.43 MeV (*top*). The contours start at $-2 \ln \lambda = 6$ with steps of 3. The central map includes ^{44}Ti line emission at 1.157 MeV. Continuum sources are indicated by filled squares (Table 1). Stars show historical SNR s from the last millenium (Table 2).

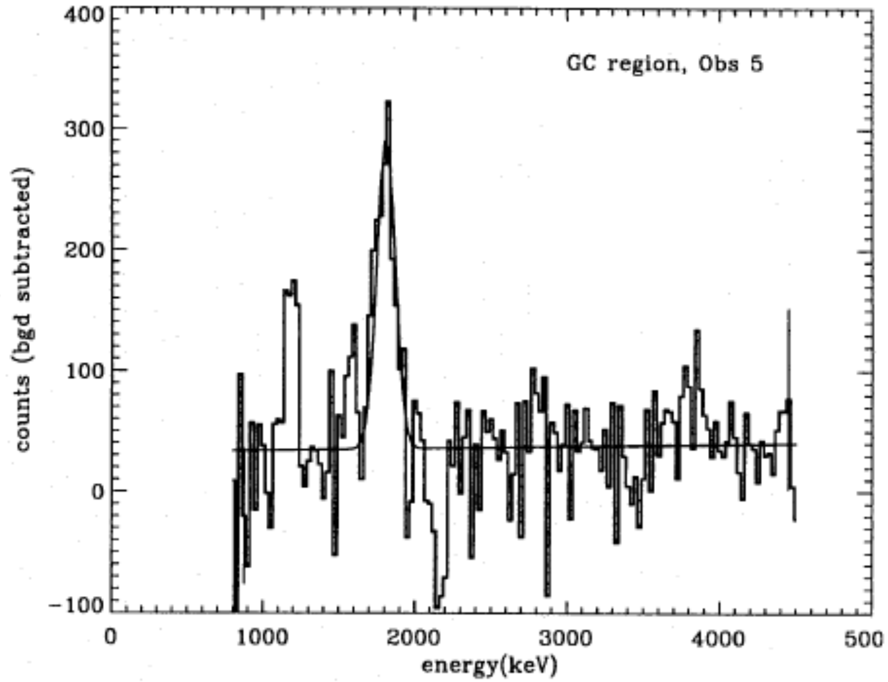
Spectroscopy with COMPTEL

- Modest Energy Resolution of ~10% (FWHM)
  - ☆ Spectra for different energy bands near lines of interest:

☞ 44Ti line at 1157 keV



26Al line at 1809 keV

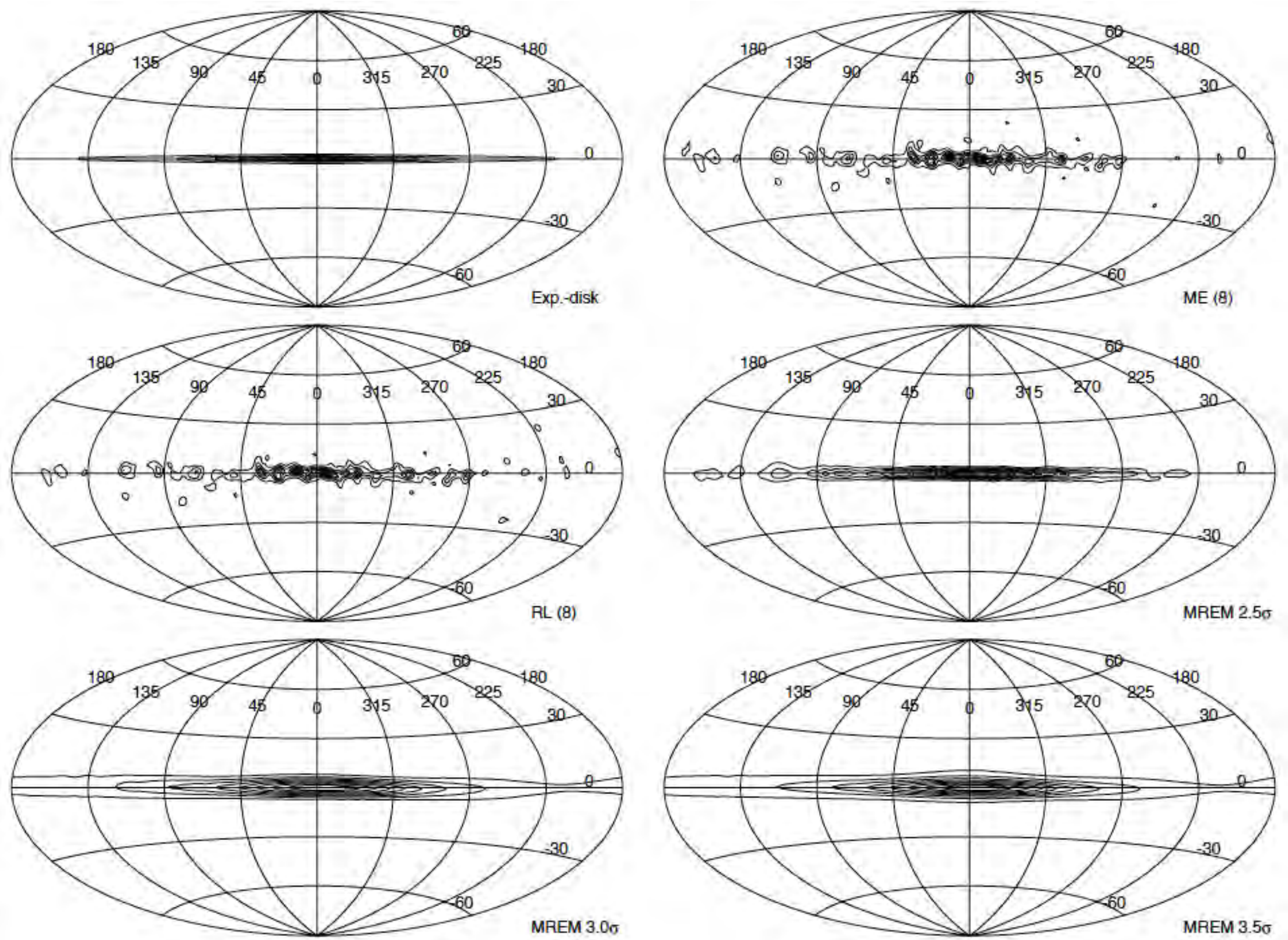


☞Spectra for specific pointings of ~1 month duration, background “subtracted”

COMPTEL Image Variabiities

- Explorations, assuming a disk emission, and an ideal background and response, just including Poisson statistical variations

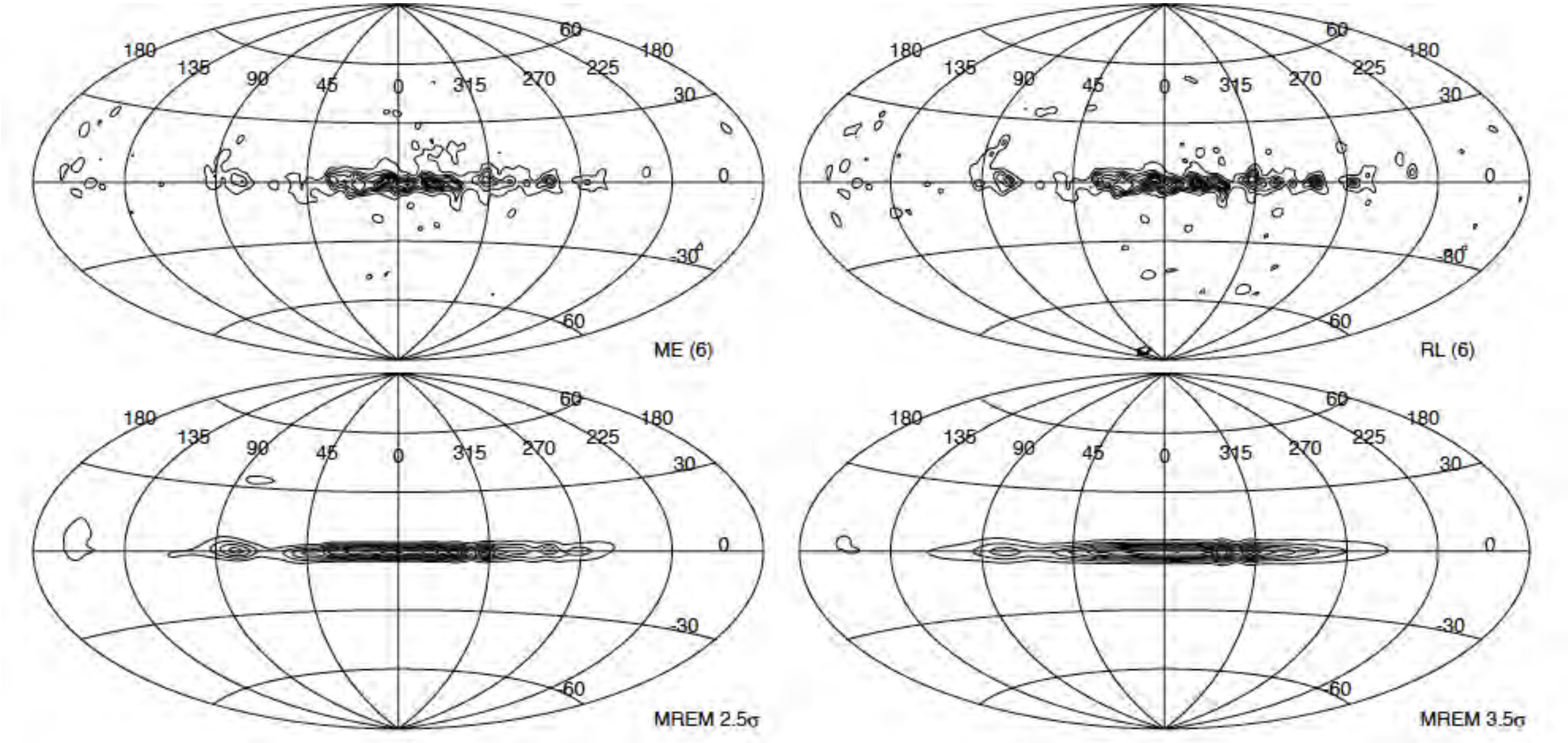
Knödlseder et al. 1999



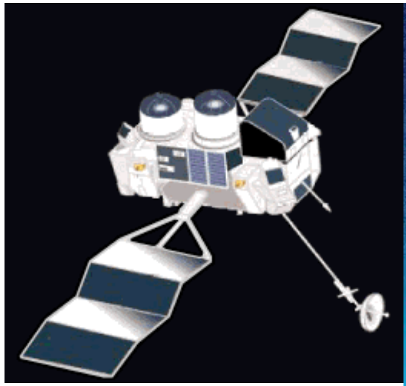
COMPTEL Image Variabiities

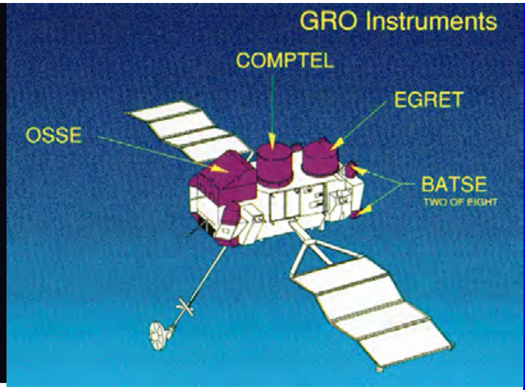
- Explorations of different appearances of 1.8 MeV image

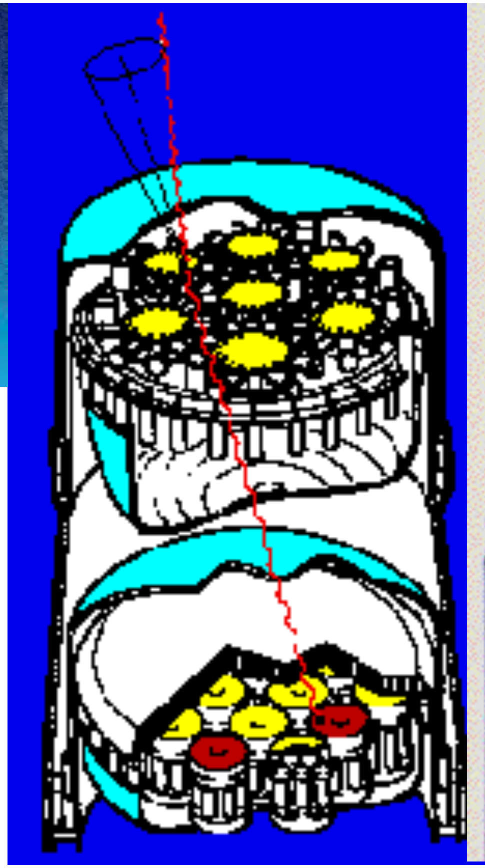
Knödlseder et al. 1999

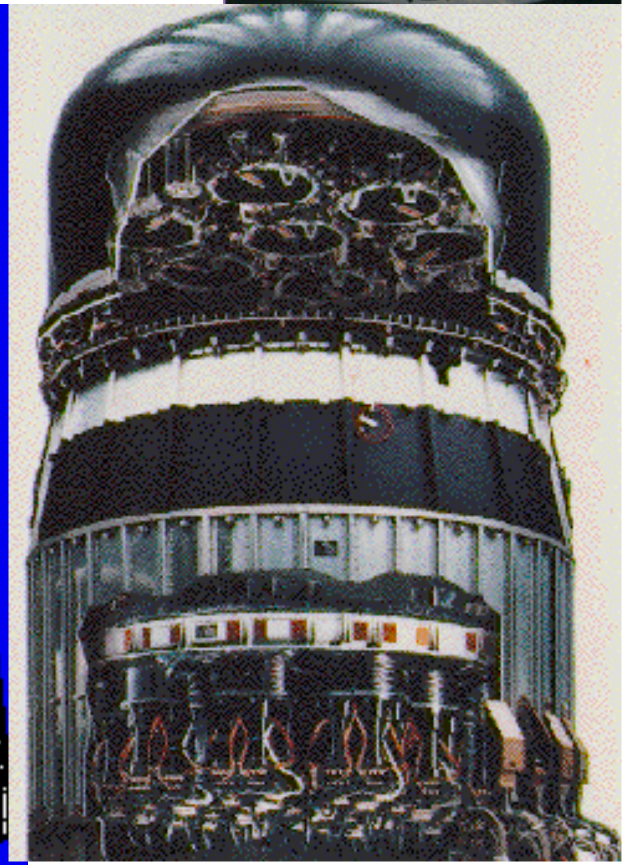


Compton Telescope in Space on CGRO (1991-2000

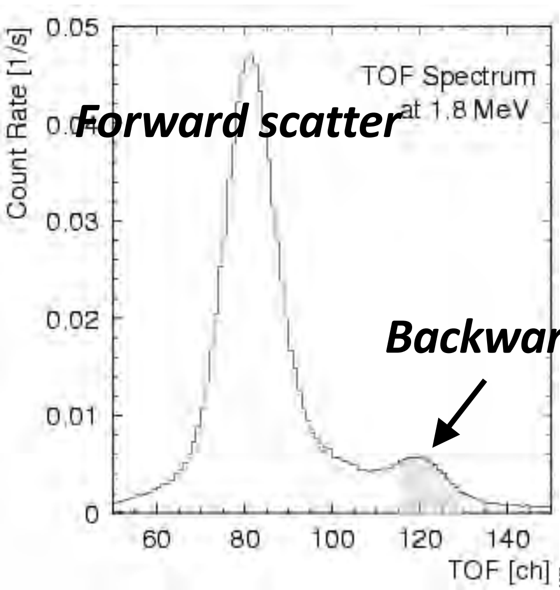








Interaction sequence obtained by time-of-flight (TOF) measurement.

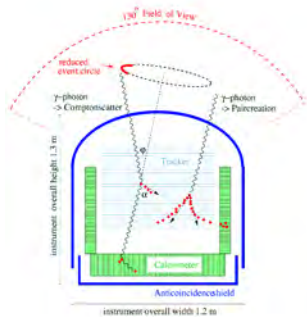


Irradiation in Space by Cosmic Rays Leads to Instrumental-Background Events

Suppression:

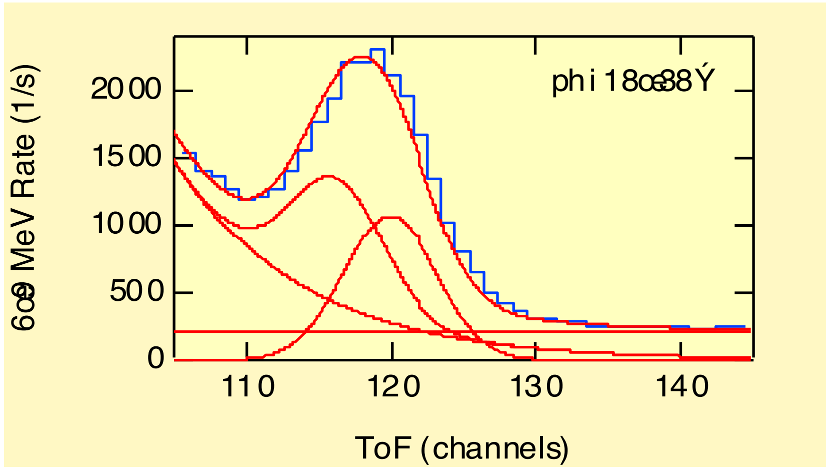
Measure additional Parameters → ToF

Challenges for better Compton Telescopes



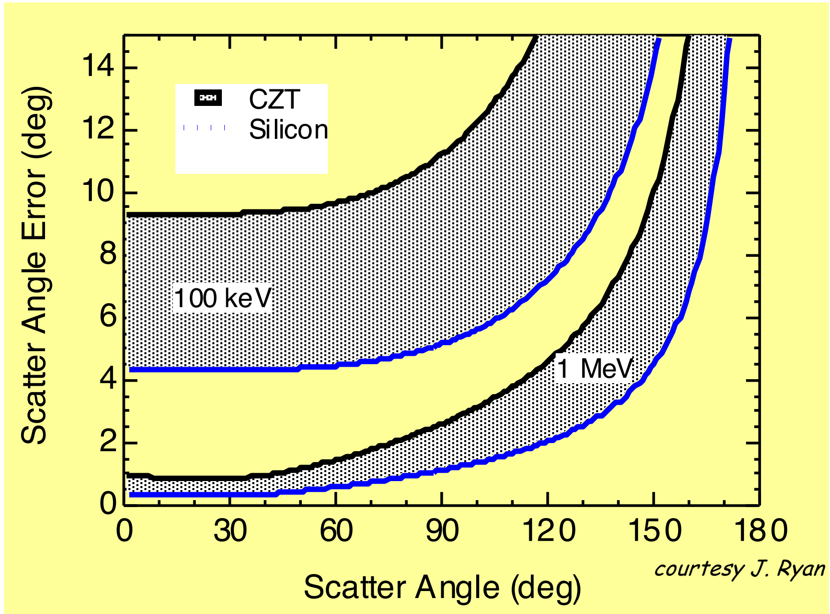
Background Issues:

1. Event ambiguity:
   - Forward vs. backward
   - Neutron vs. γ
2. Accidental coincidences with high count rate from large area
3. Multiple photon-& neutron-induced background
4. Activation of passive material
5. Doppler broadening effect



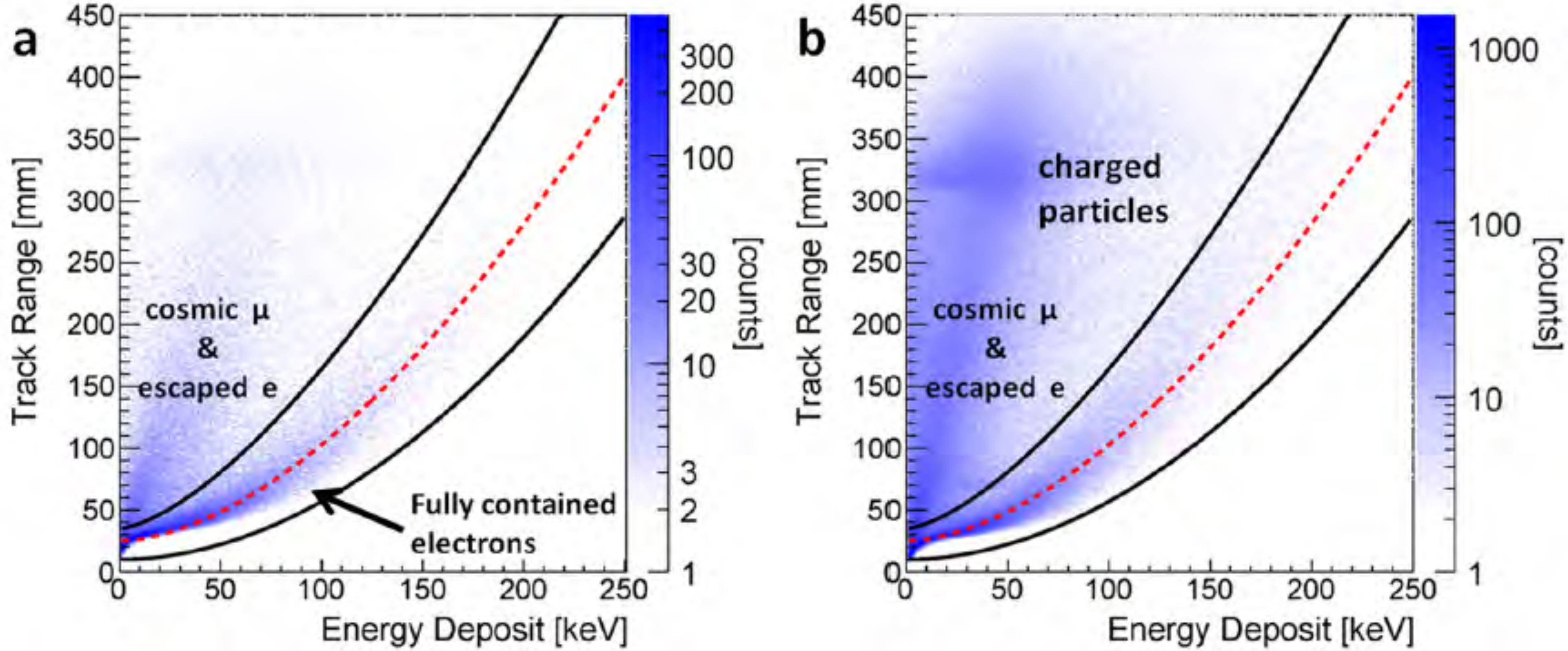
Imaging Resolution:

1. Geometry
   - Large Solid Angle for Scattered Photons
   - Low Energy of Photons Scattered at Large Angles
2. Energy Resolution of Detectors



Challenges for Tracking Chambers (e.g. ETCC)

- Muons and cosmic ray particles constitute a major background
- Compton-electron tracks need to be clearly separated



☆ Ground calibrations with ETCC *(Tanimori+2015)*

INTEGRAL Cosmic Photon Measurements: The SPI Ge γ-Spectrometer

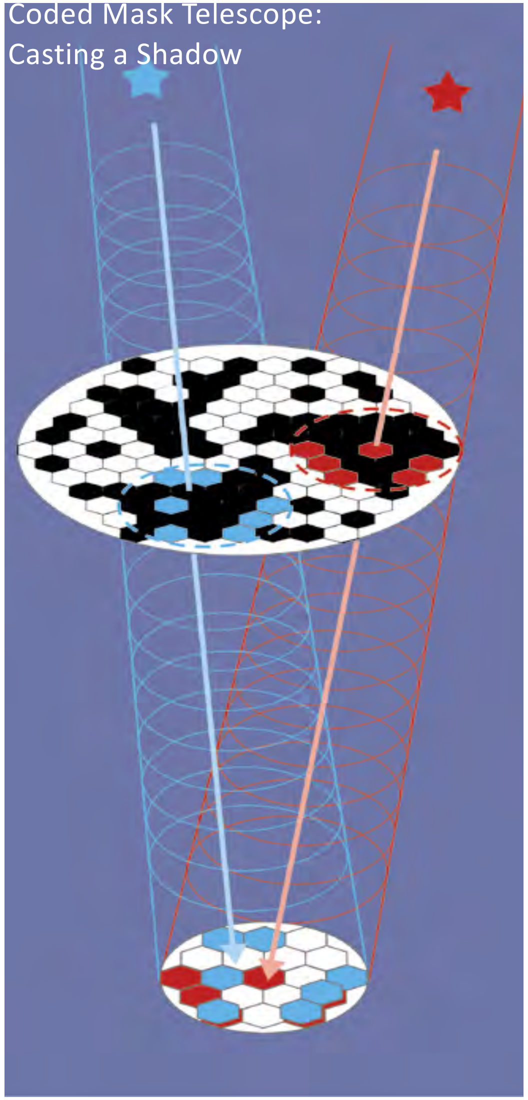
Coded-Mask Telescope

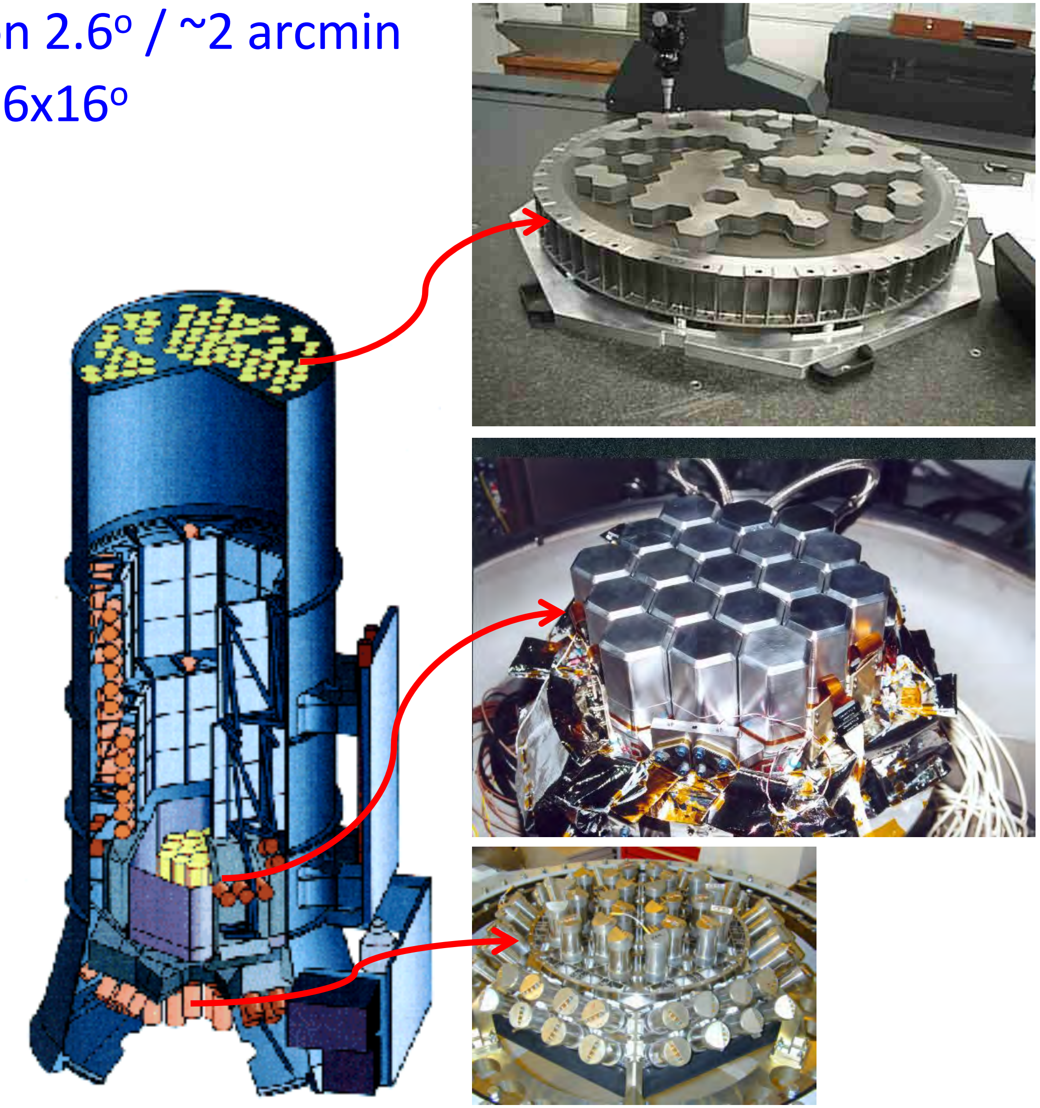
Energy Range 15-8000 keV

Energy Resolution ~2.2 keV @ 662 keV

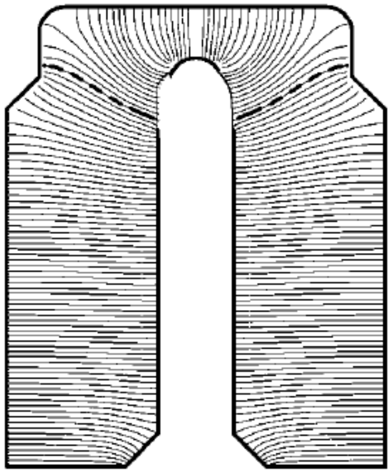
Spatial Precision 2.6° / ~2 arcmin

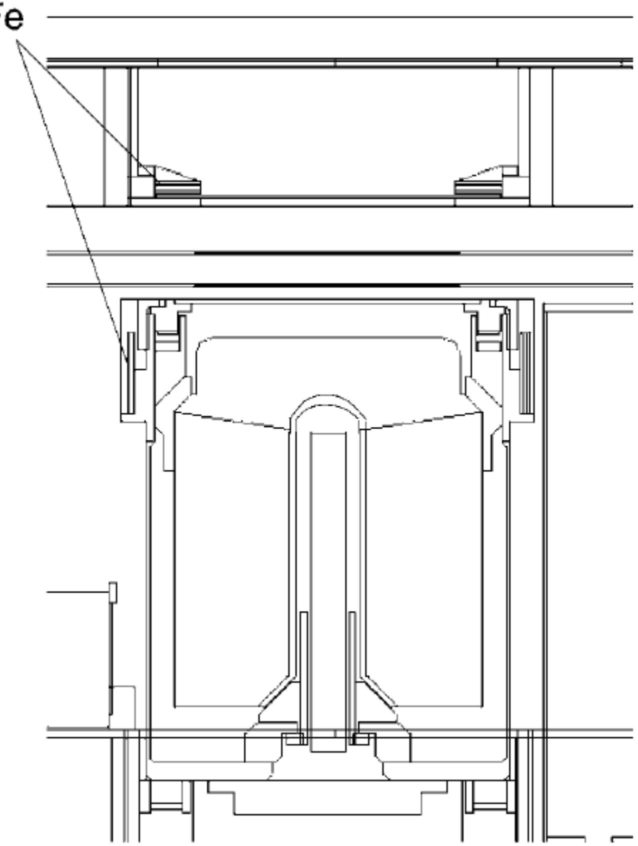
Field-of-View 16x16°





Ge Detectors in Space Telescopes

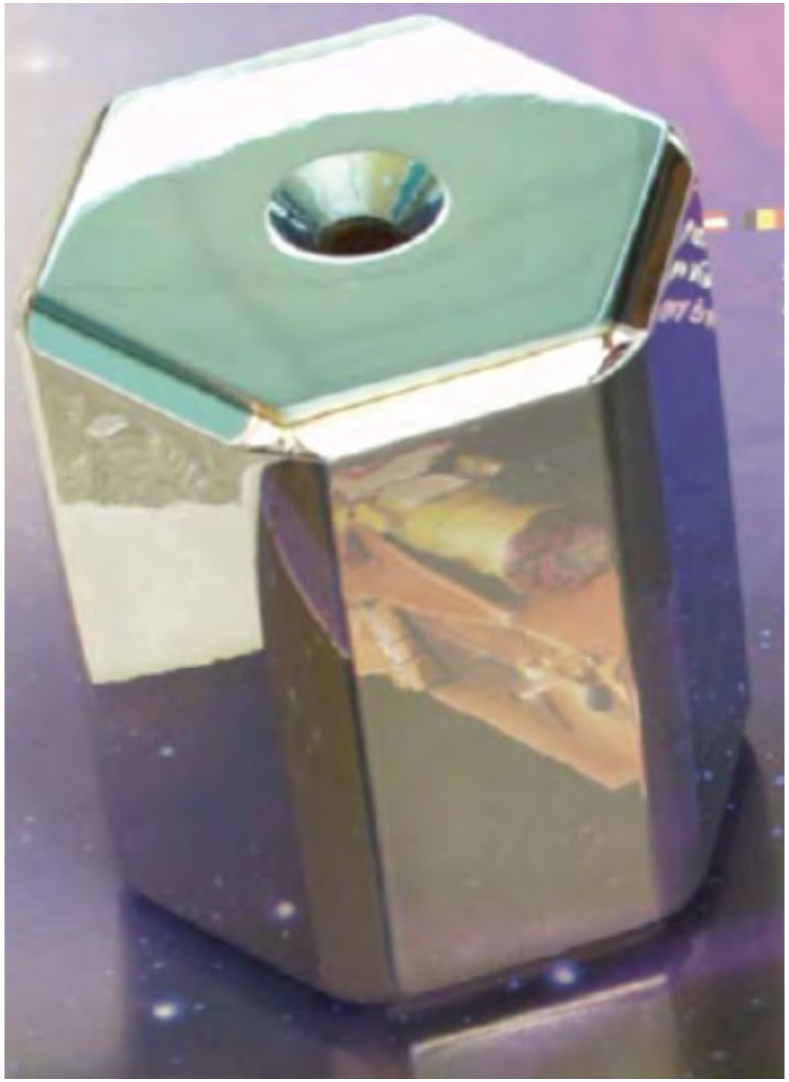




Detector Cross Section

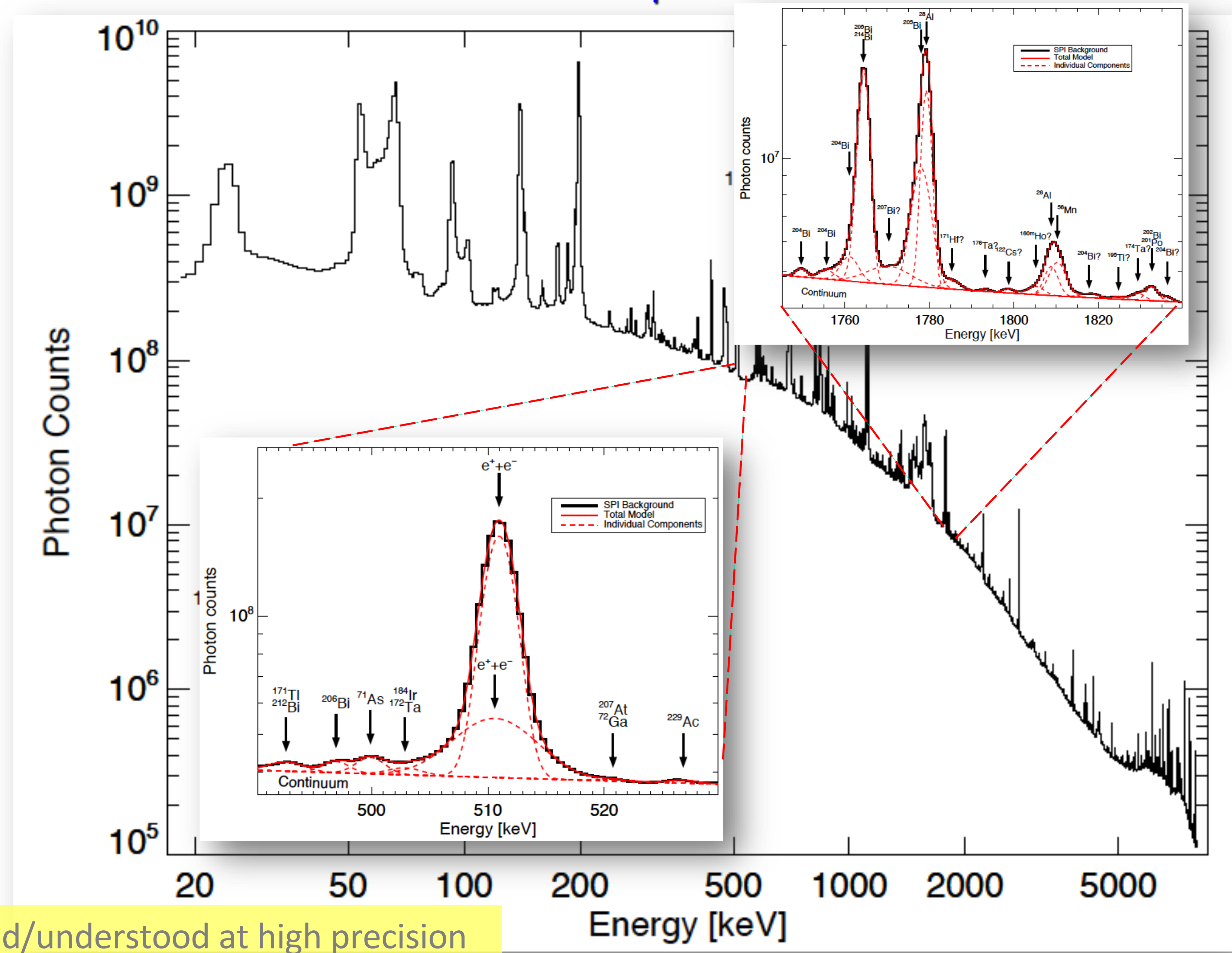
- Electric potential
- Mechanics
- (RHESSI)

Detector of SPI/INTEGRAL



Dominance of instrumental background

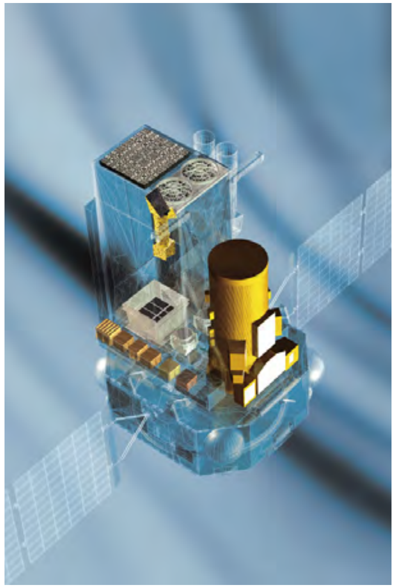
SPI Ge detector spectra

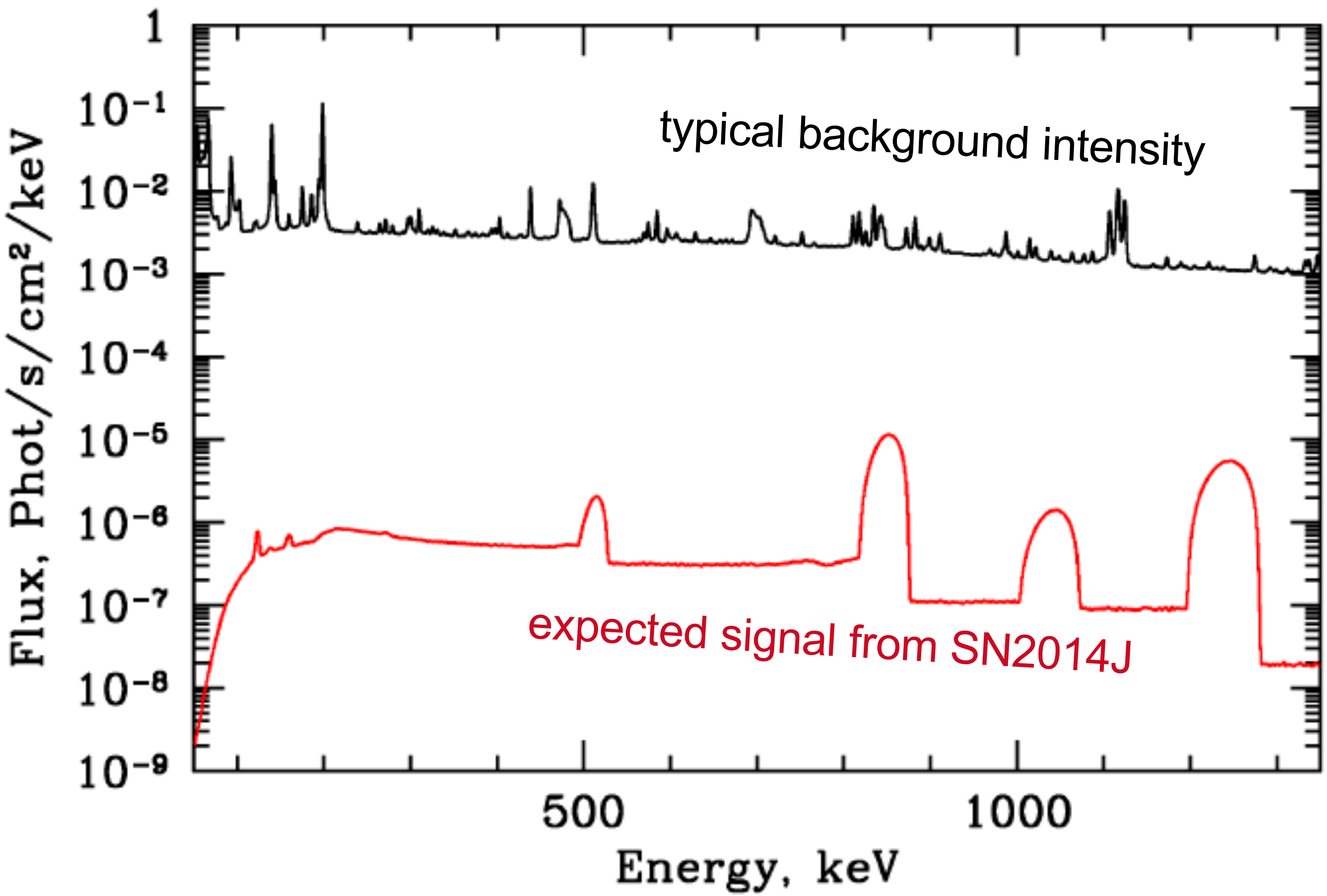


Modelled/understood at high precision

The Challenge of Finding SN2014J Gamma-Rays

- Current Gamma-Ray Telescopes Have Large Intrinsic Background
  - Cosmic Ray Activation of Spacecraft and Instrument

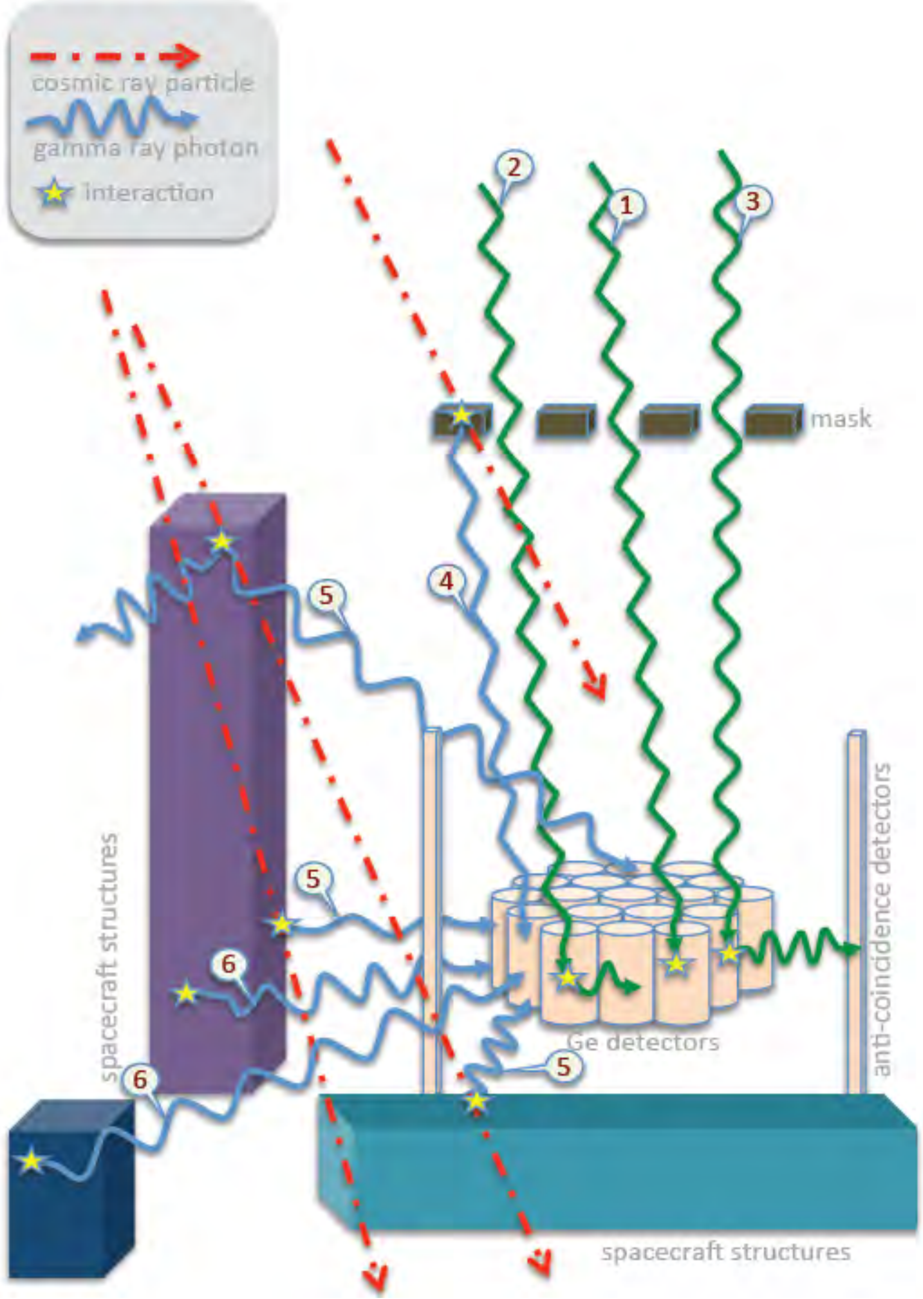




from Churazov et al., 2014

Origins of background in SPI

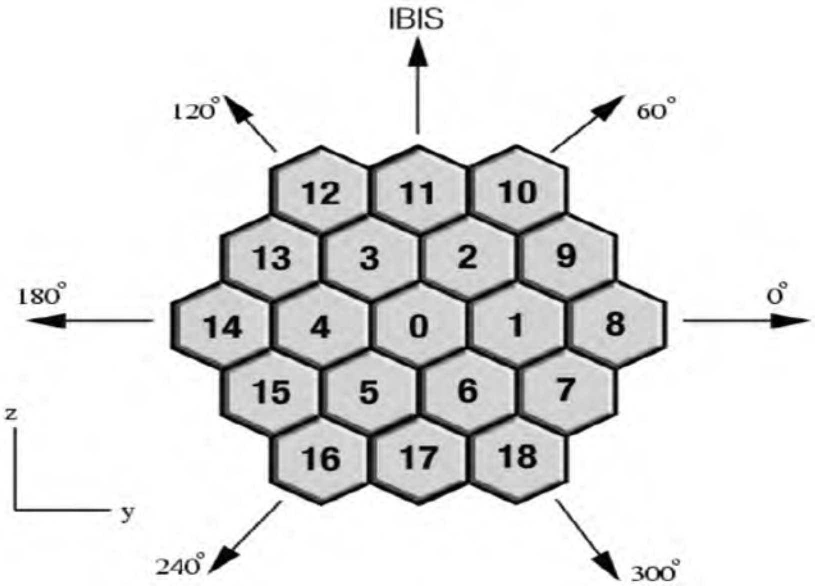
Incident cosmic rays collide with instrument material nuclei and atoms to generate a cascade of secondaries (including gamma-rays), and to make some materials radioactive

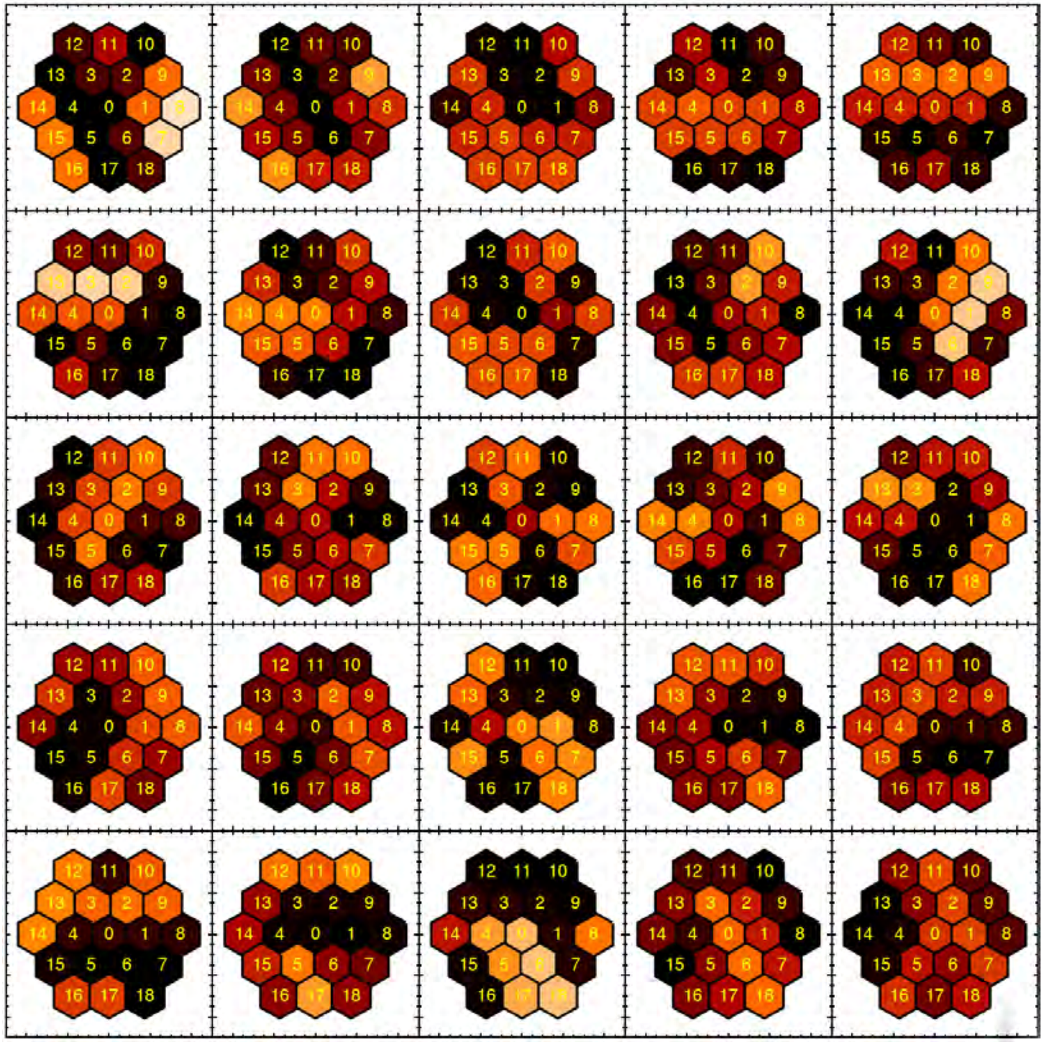


The SPI Ge detector camera and mask

Coded-mask imaging:

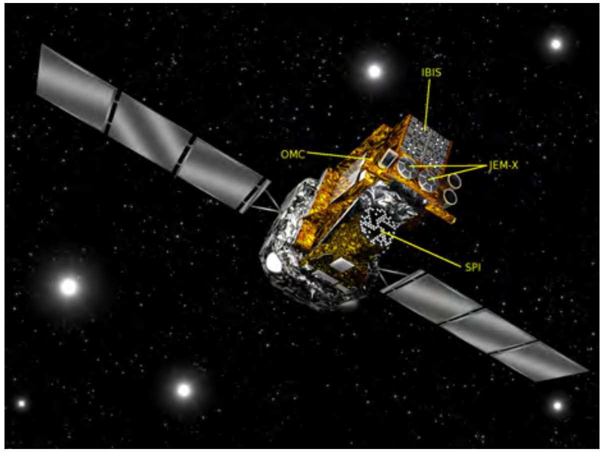
- shadowgram intensity patterns among detectors
- 'dithering' 5x5 pointing offsets around source for additional 'coding'

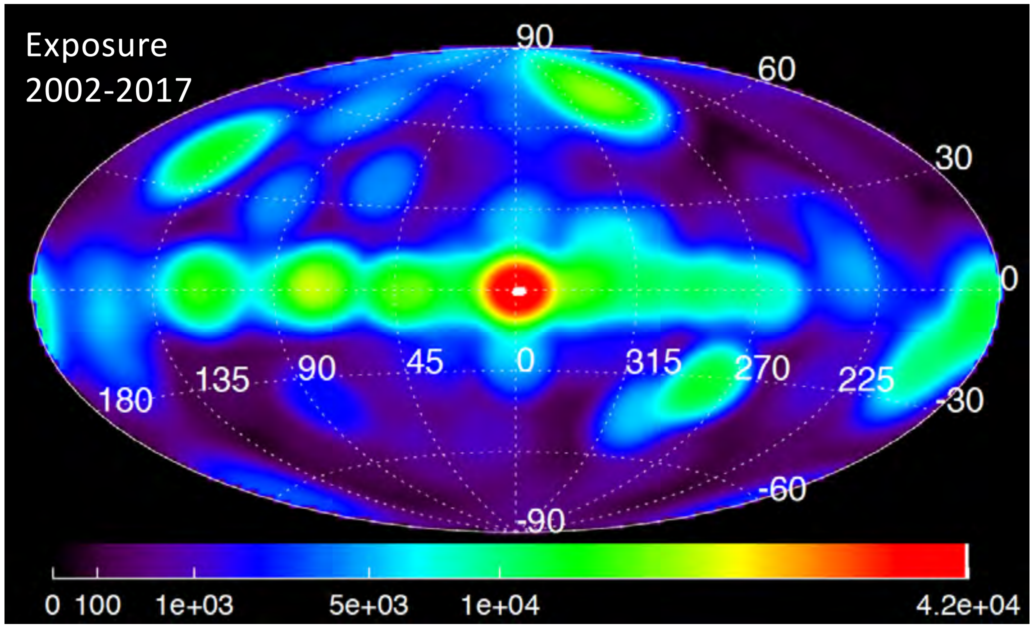


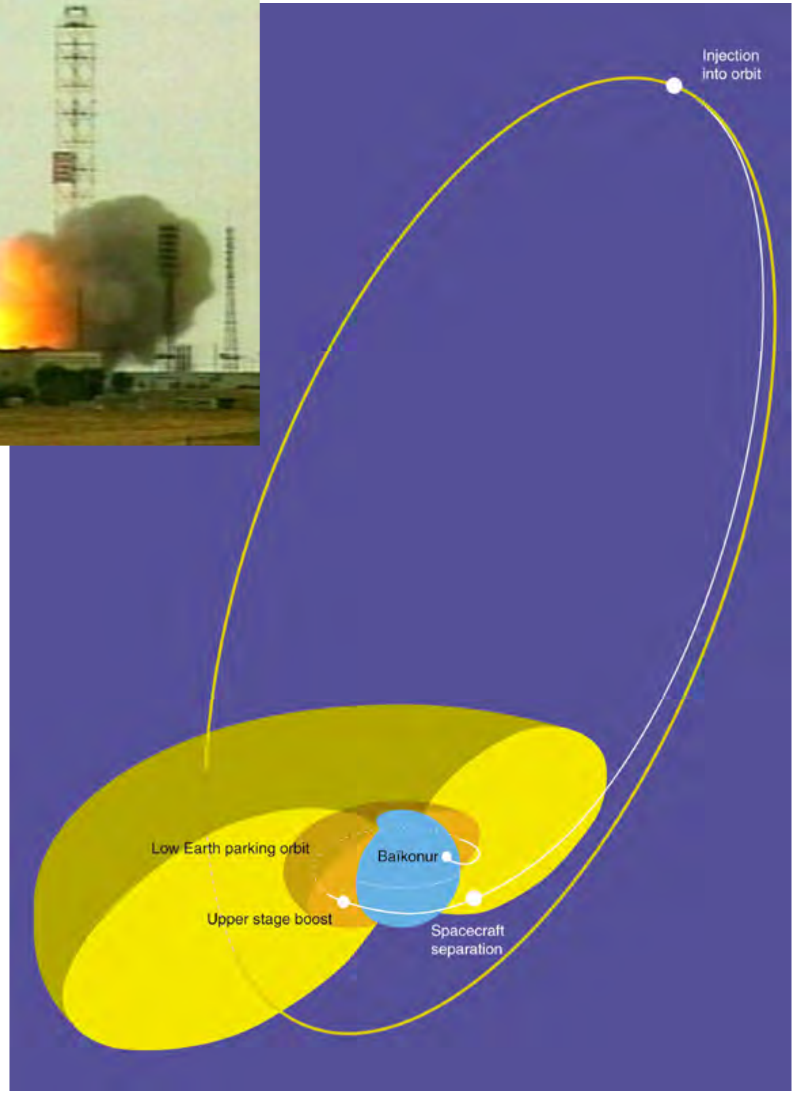


INTEGRAL Mission

- Launch 2002 for 3+2 years; de-orbit in 2029
  - ☞ Extended mission after ESA bi-annual reviews; currently 2018

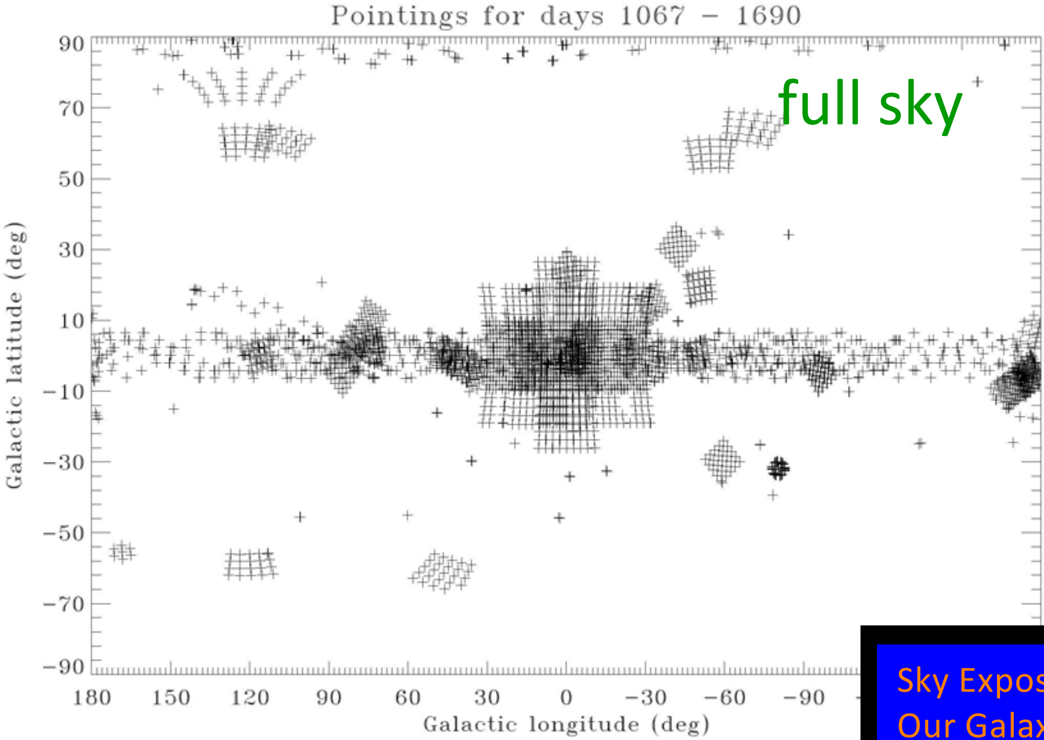




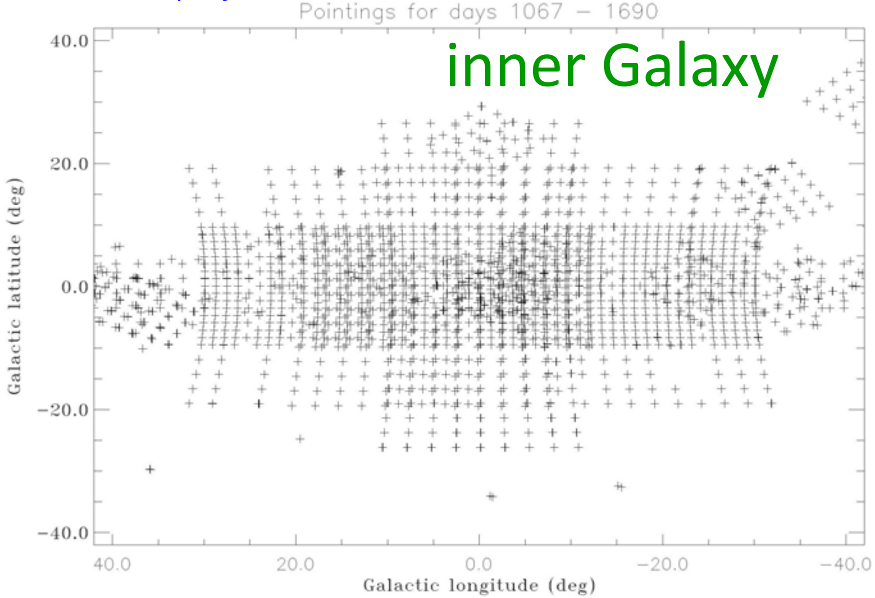


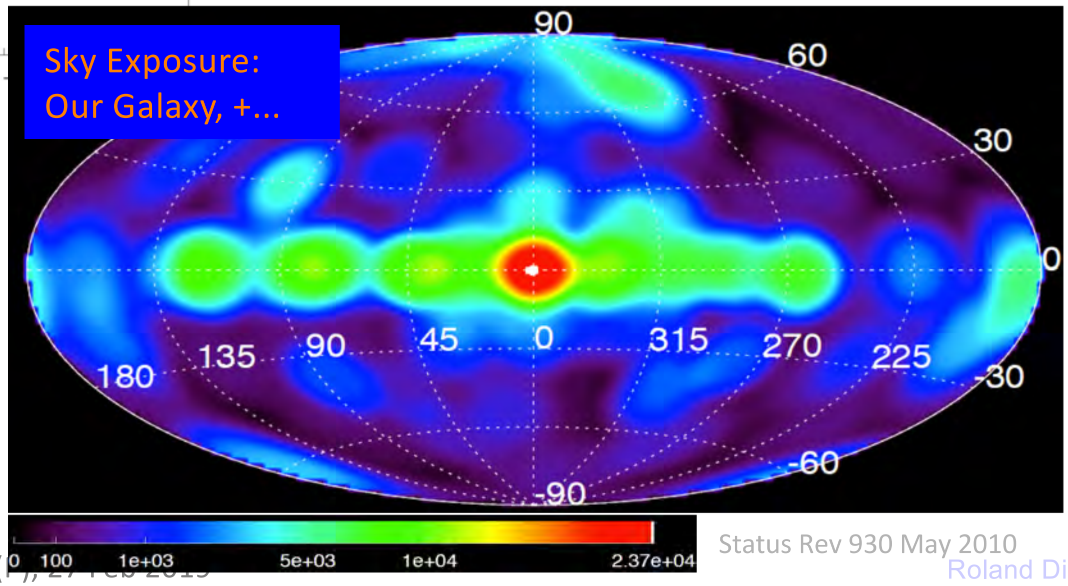
A Sky Survey with INTEGRAL

☆ “Dither Patterns” Scattered over the Sky



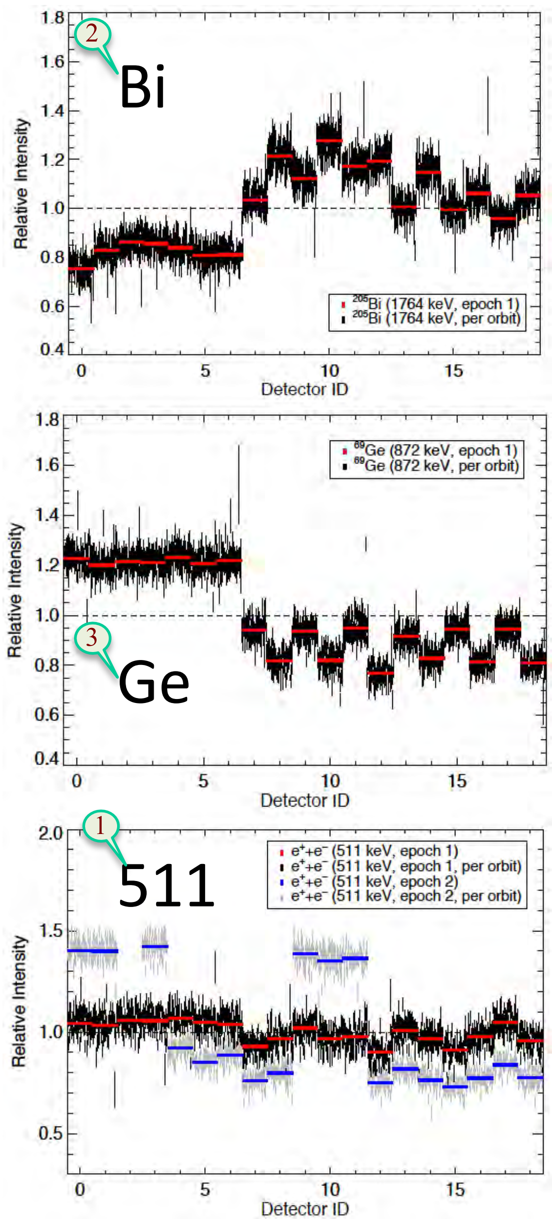
☞ *Example from late 2004*

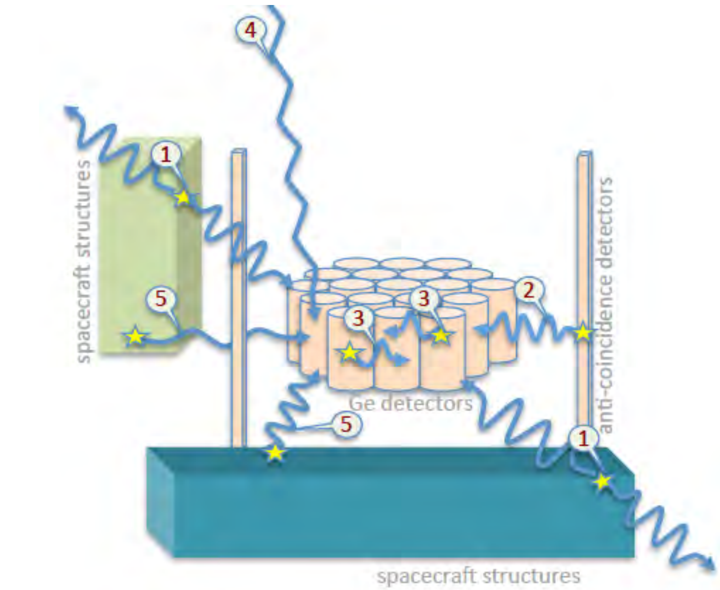


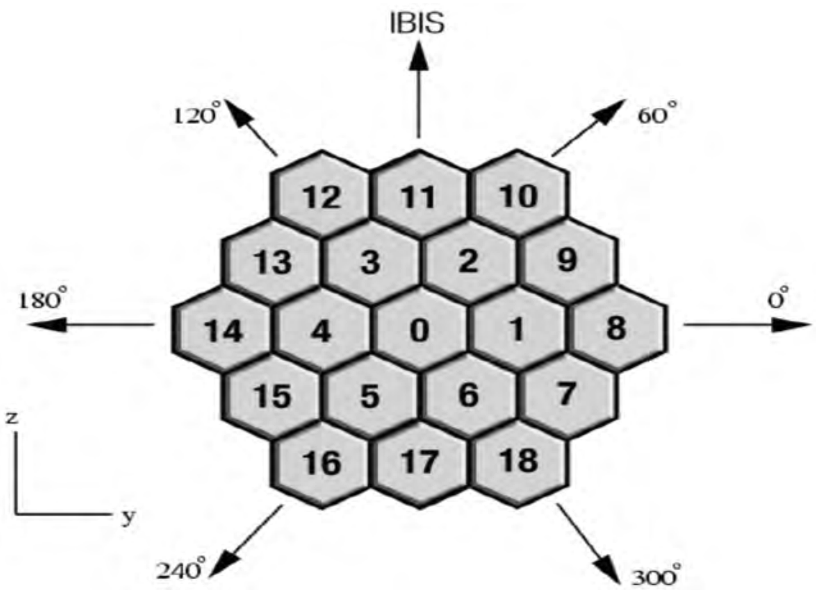


SPI instrumental background lines:

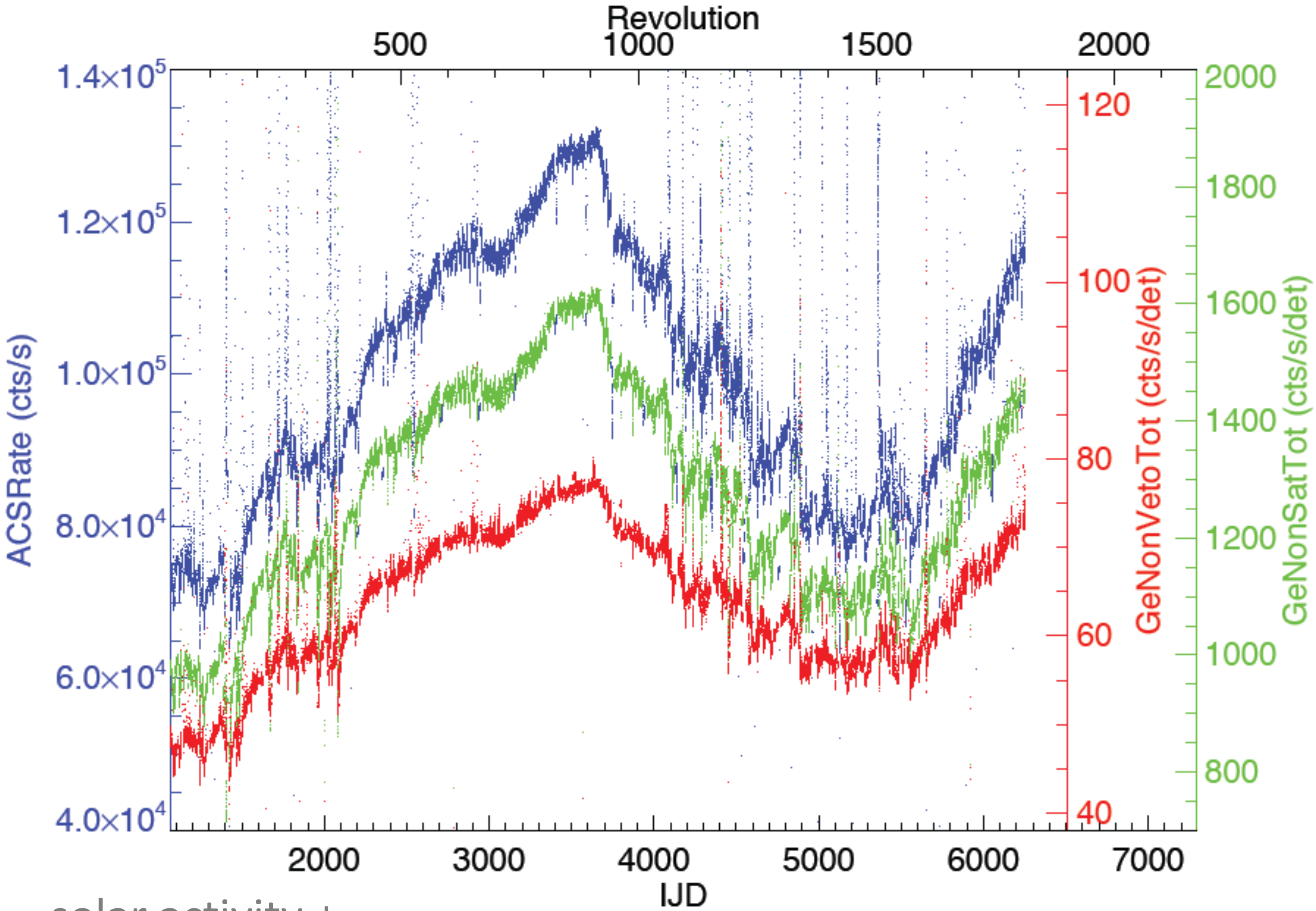
Lines show a characteristic intensity pattern in SPI Ge camera







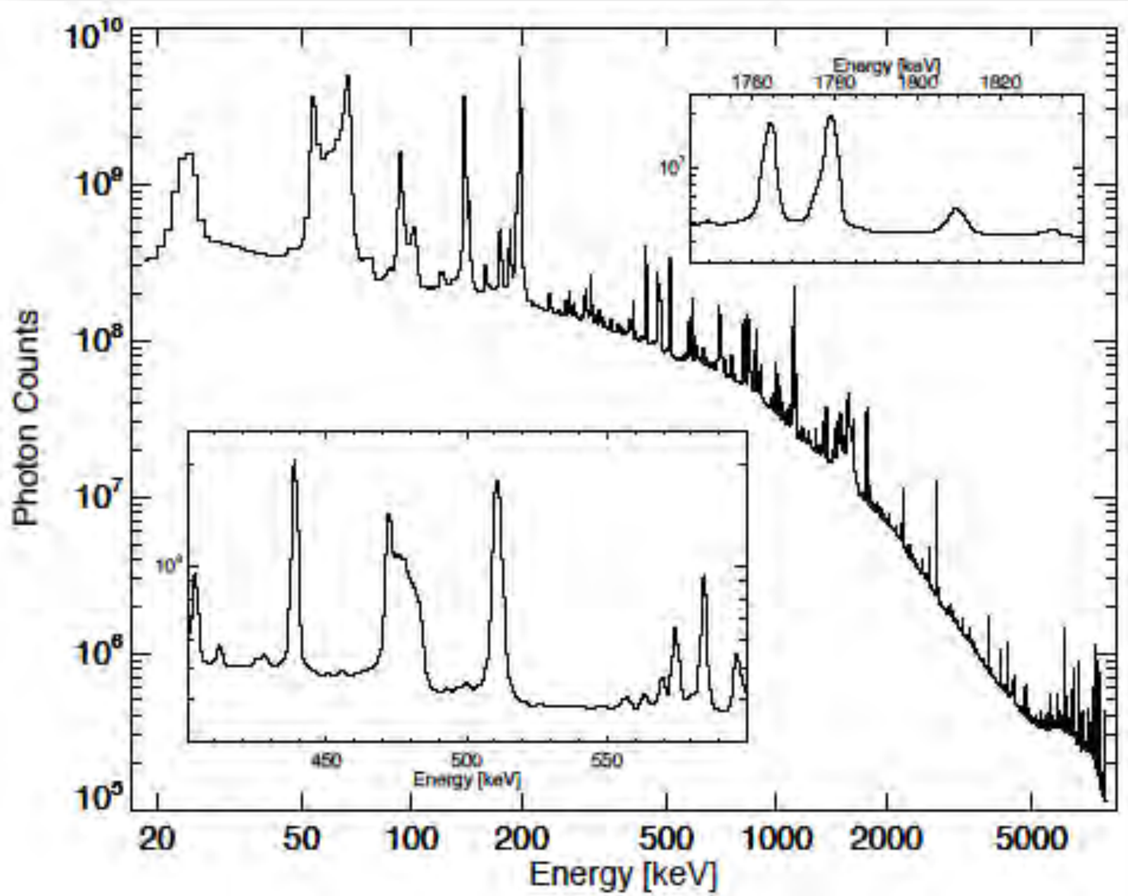
Background history: INTEGRAL/SPI over ~15 years

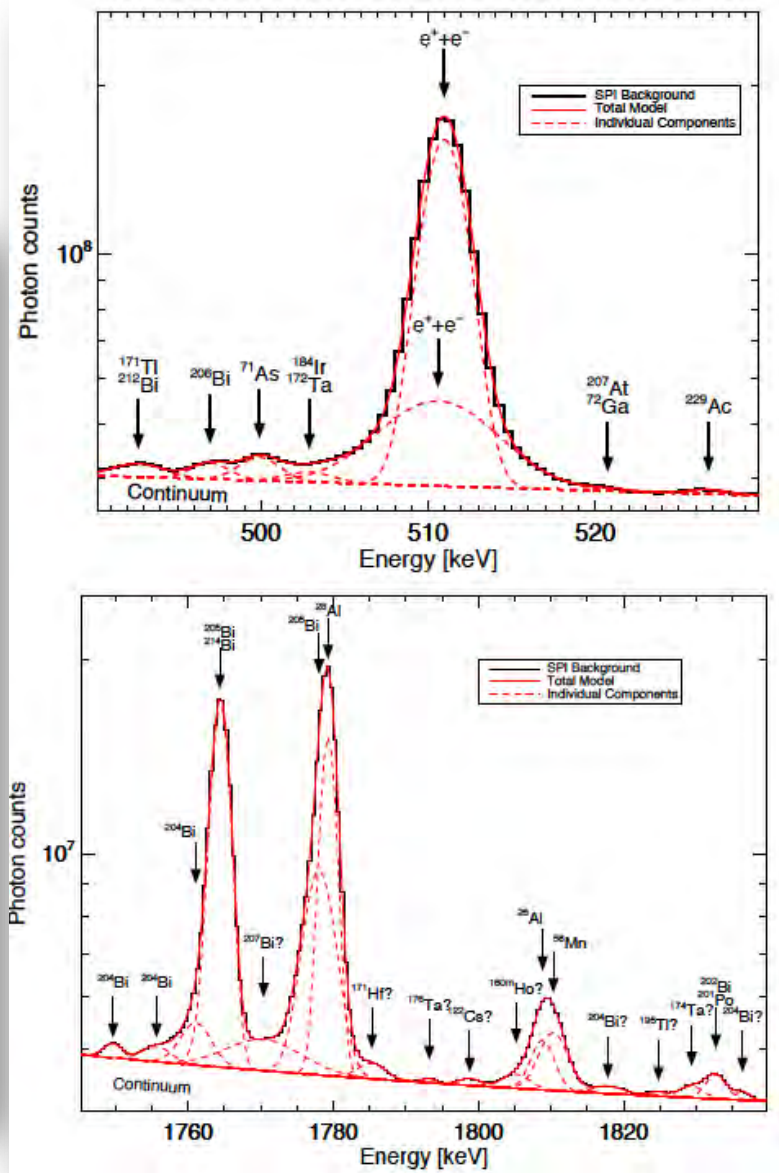


solar activity + …

Spectral Fitting

- Routine decomposition of SPI detector spectra
  - ☆ spectral performance
  - ☆ background situation

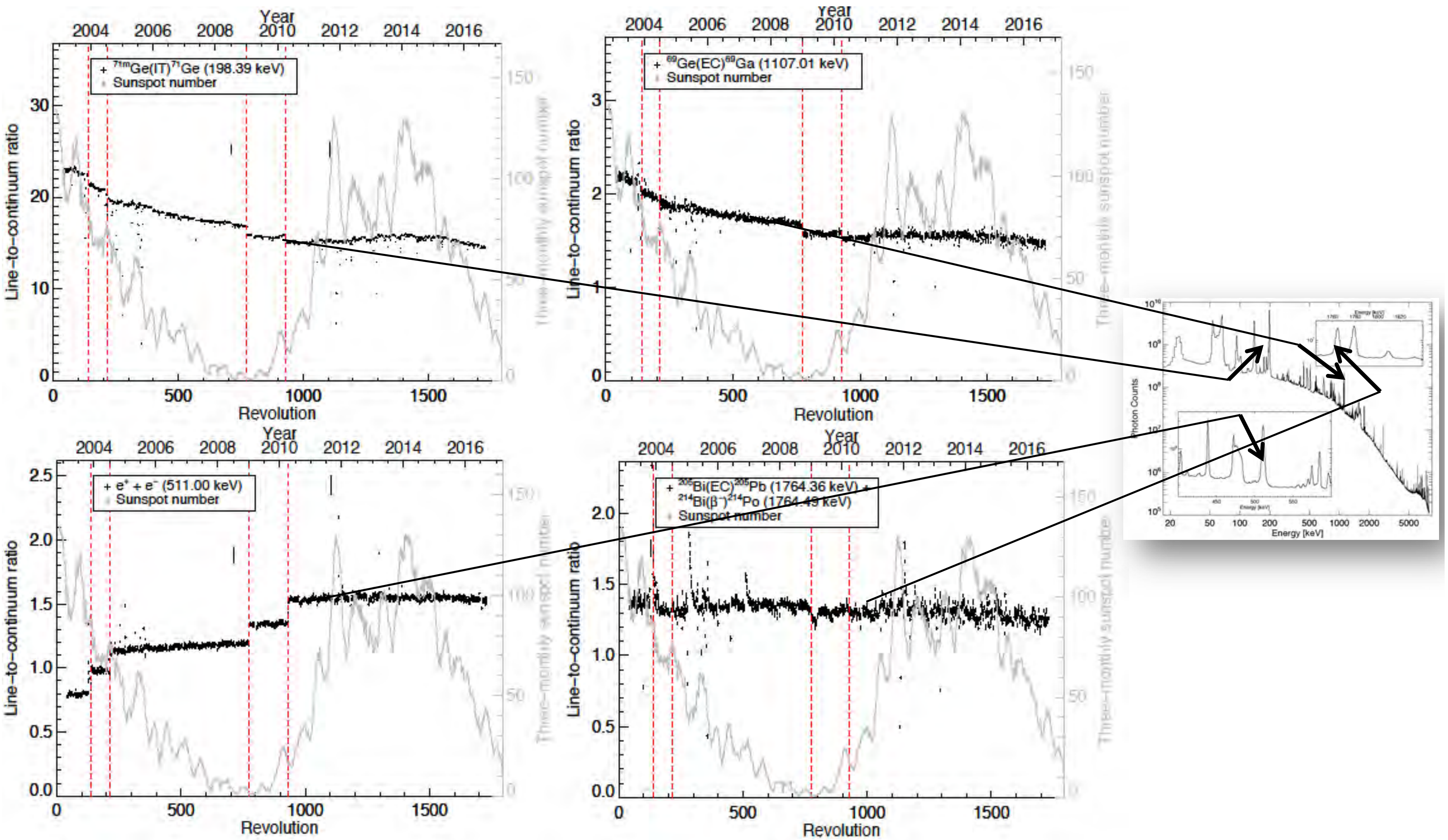




Background Variations

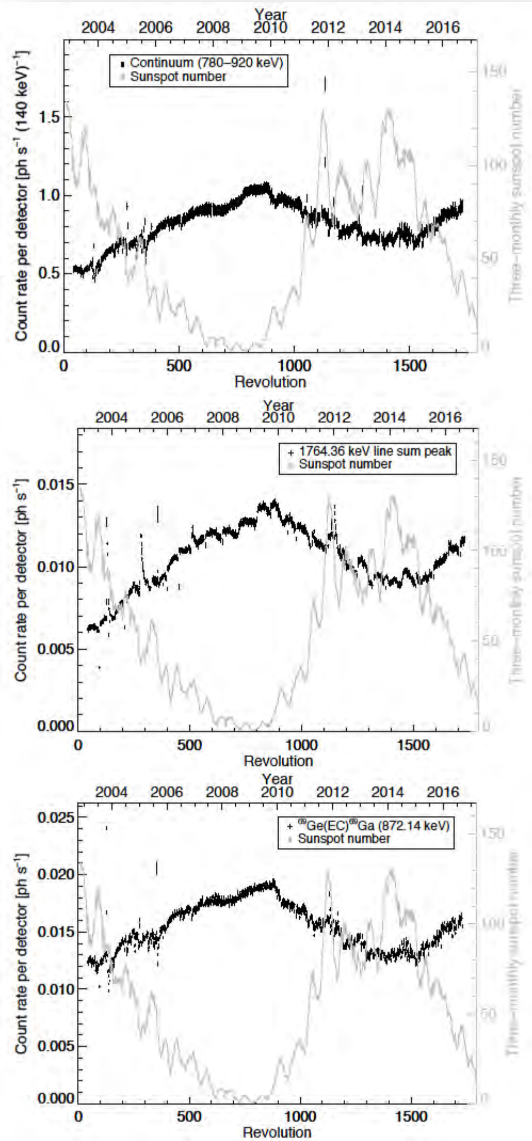
Specific lines have characteristic variations, different to continuum

☞ Illustrated when normalised to continnum to eliminate first-order variations:



Instrumental background in space orbits

Prompt, delayed, and built-up backgrounds

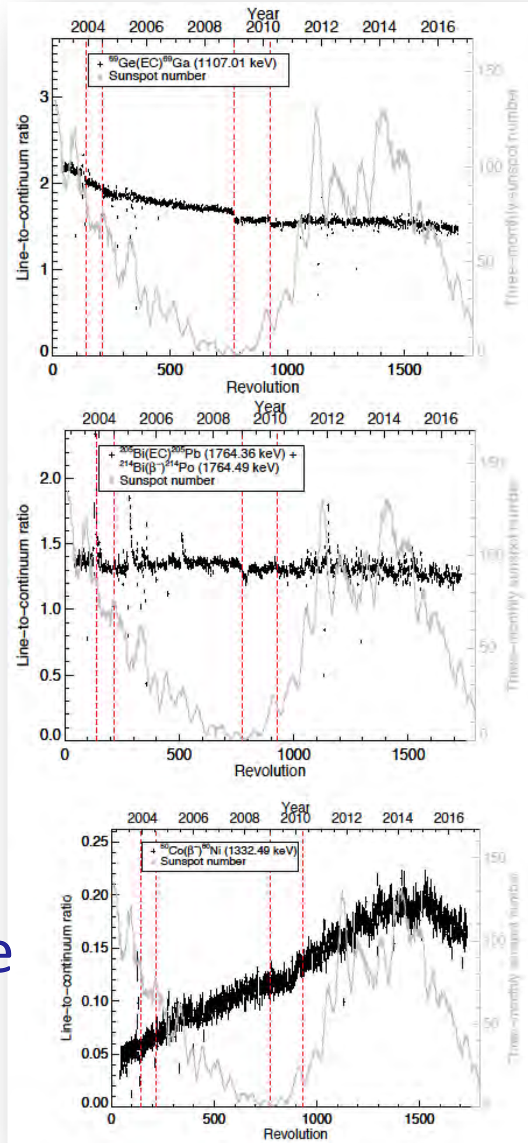


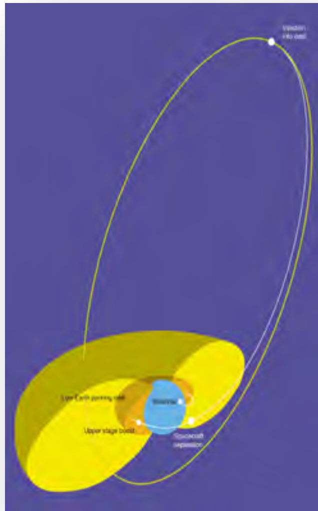
linked to solar activity

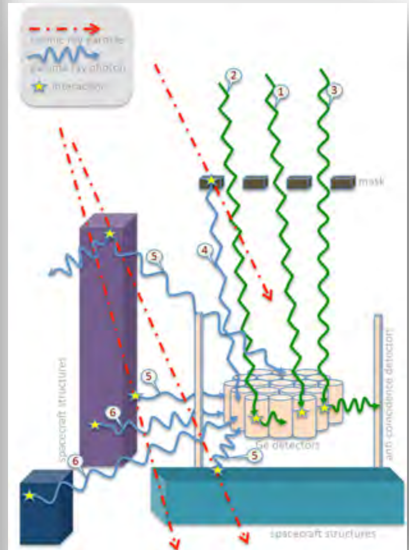
normalise with continuum

→

specific isotope characteristics





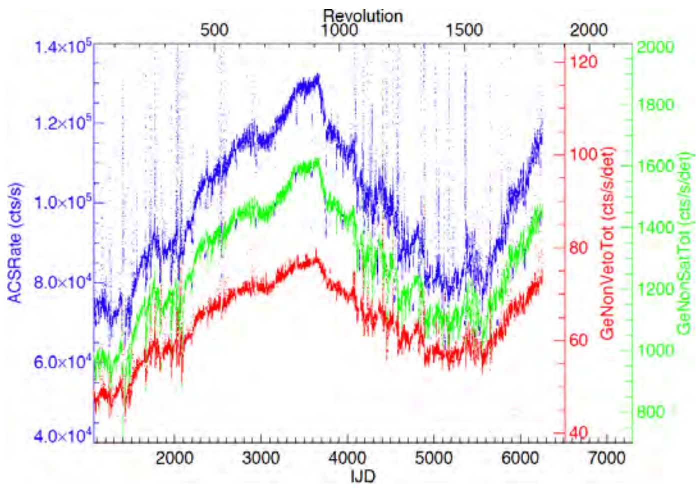


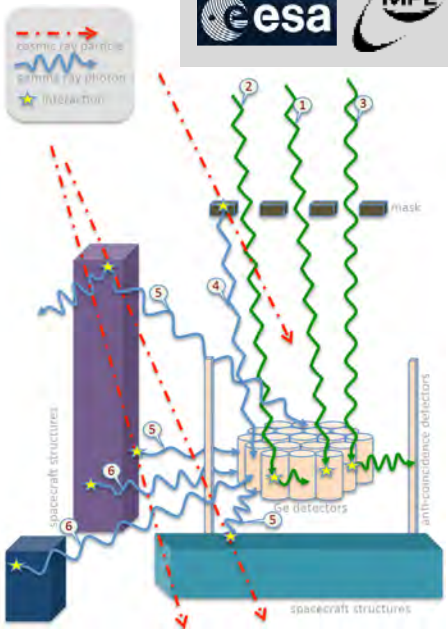
Diehl+, A&A (2018)

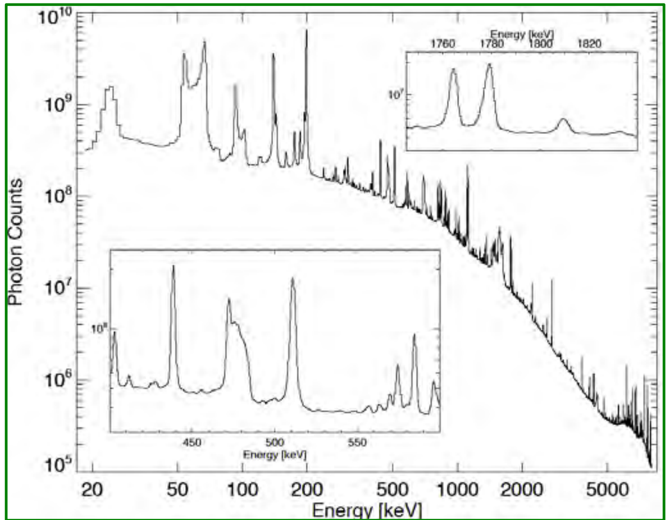
The SPI γ-ray spectrometer instrument on INTEGRAL

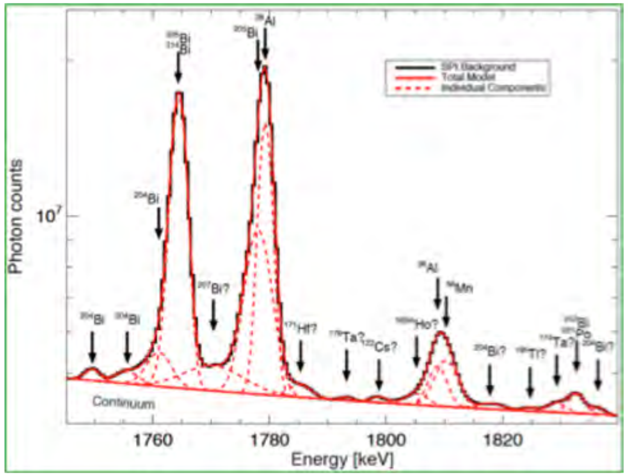
20 keV – 8000 keV, ~30° field of view, ~2.7° PSF, E/δE~800

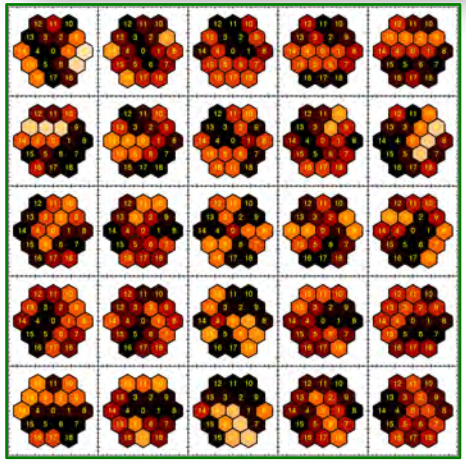
- ☆ Coded-mask imaging
- ☆ Ge detector spectroscopy





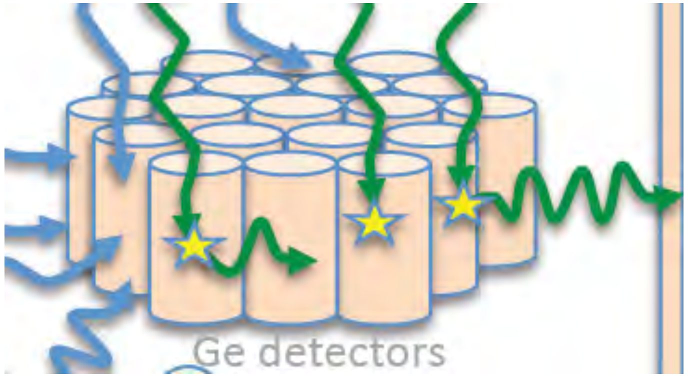


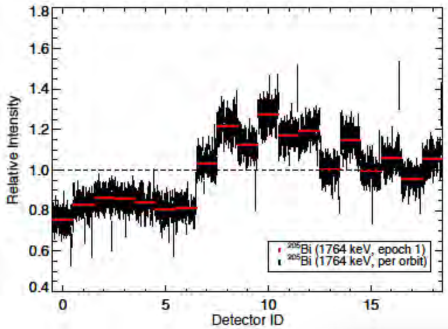


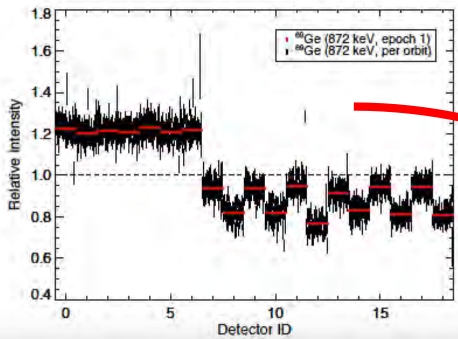


Analysis = Discriminating Background and Sky Signals

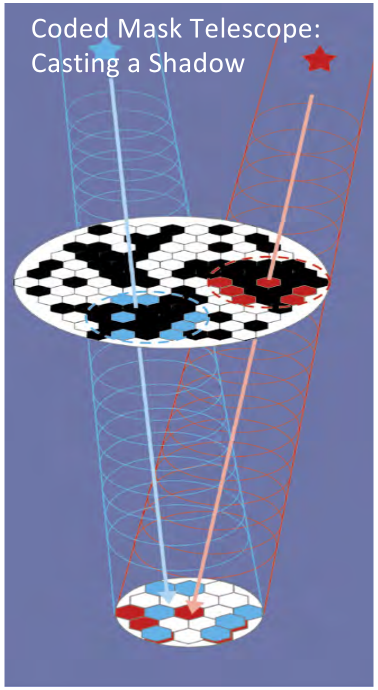
Tracking the relative count rate ratios among detectors ('coding pattern')

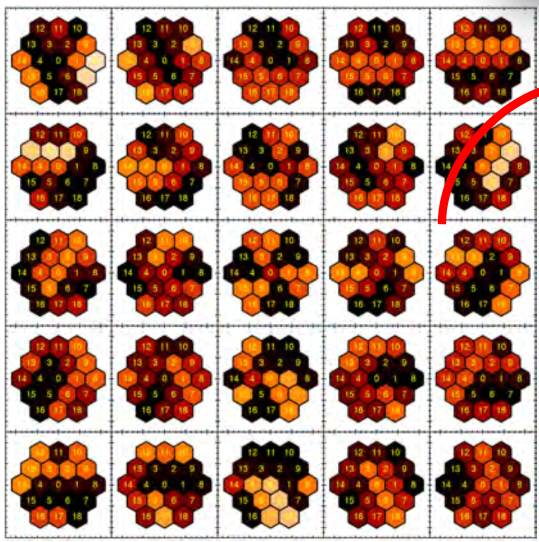


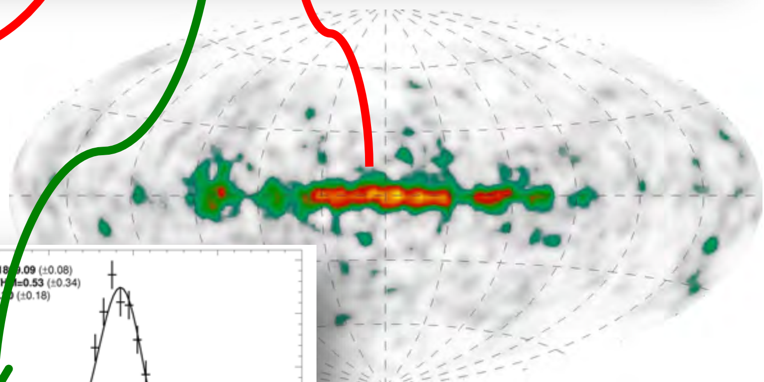


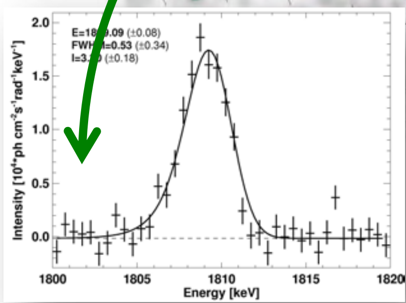


$$d_k = \sum_j R_{jk} \sum_{i=1}^{N_I} \theta_i M_{ij} + \sum_t \sum_{i=N_I+1}^{N_I+N_B} \theta_{i,t} B_{ik}$$





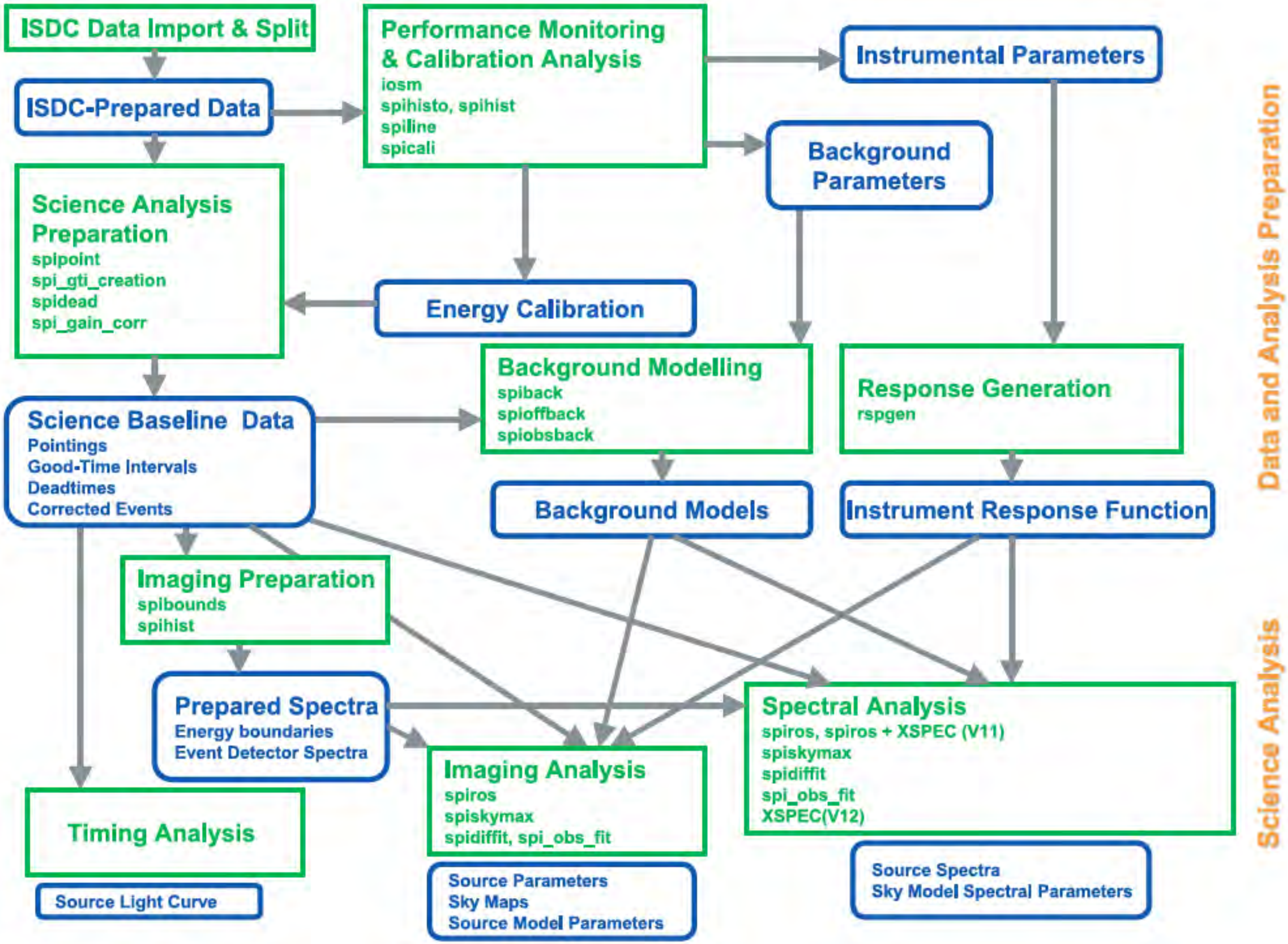




see, e.g., Diehl et al. A&A (2018)

SPI Data Processing and Analysis Tools

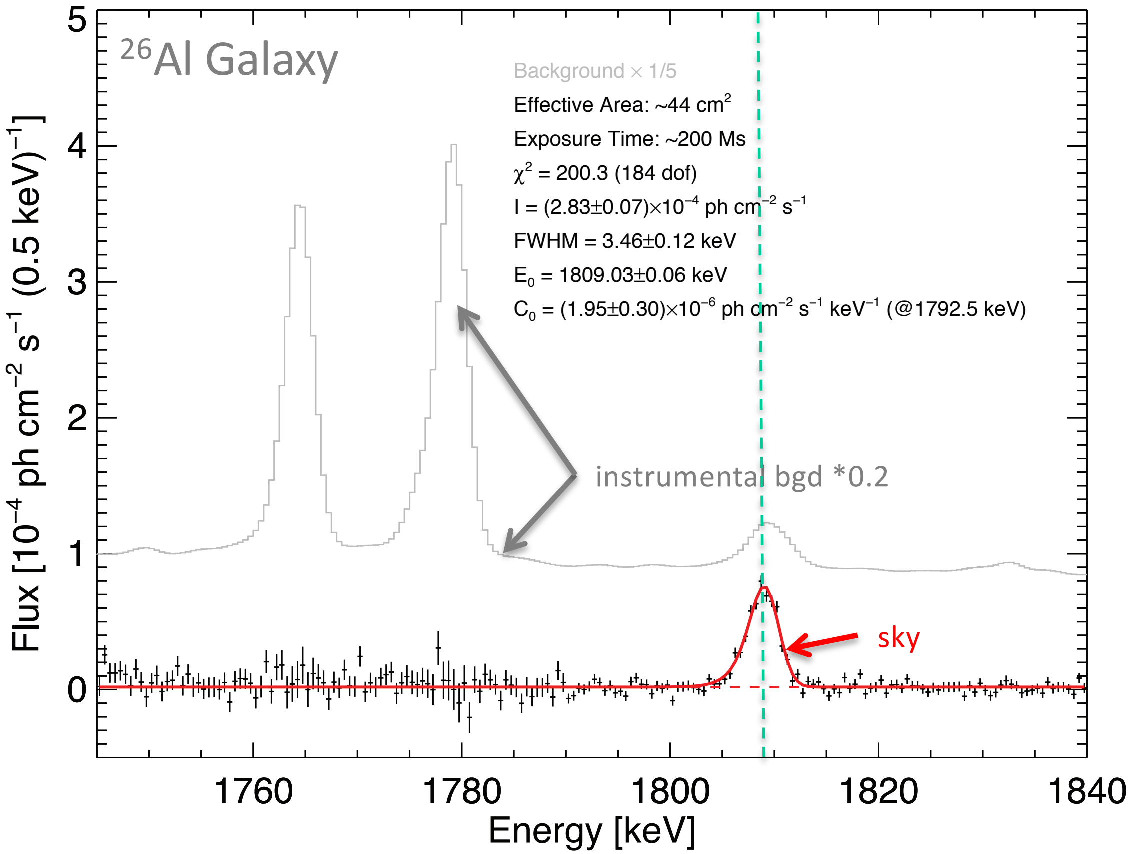
•

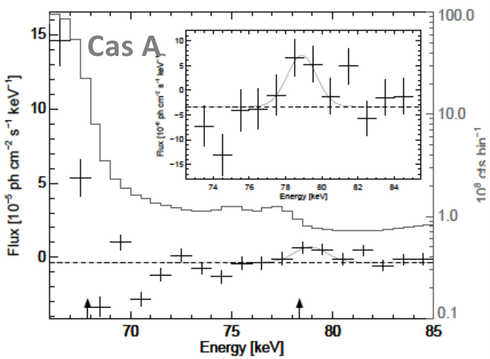


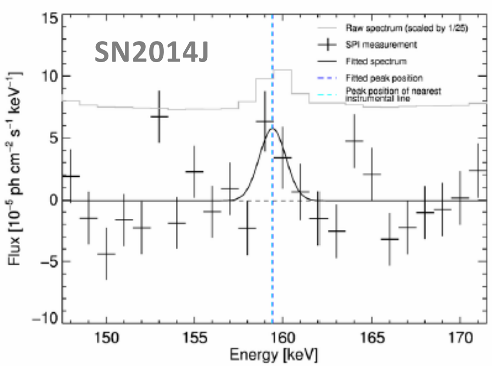
Gamma ray spectroscopy with SPI

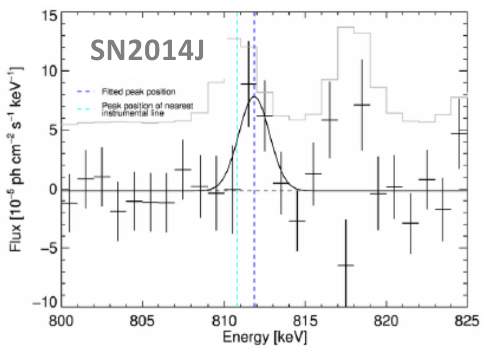
…it works!

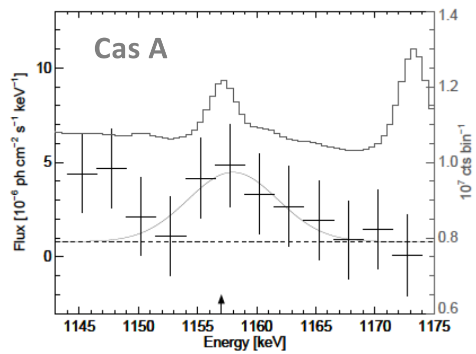
- ☆ ^{26}Al line 1808.6 keV
- ☆ instrumental lines
  - ☞ 1810 keV (!!)
  - ☞ 1779 keV
  - ☞ 1764 keV
- ☆ …also: SN ^{56}Ni, ^{44}Ti











Measuring Cosmic Radioactive Isotopes

Isotope-Decay Gamma Rays

- ☆ Radioactive decay in current interstellar medium (few My) and explosions
  - *Mahoney et al., ApJ (1979); Diehl et al., Springer AASL (2018)*

Mass Spectrometry of Meteorite Material

- ☆ Daughter isotope abundances in inclusions formed at solar-system formation
  - *Dauphas & Chaussidon, AnnRevEarthPlanSci (2011)*

Mass Spectrometry of Cosmic Rays

- ☆ Isotope flux in current interplanetary space
  - *Binns et al., Sci (2016)*

Mass Spectrometry of Lunar and Terrestrial Sediments

- ☆ History of interplanetary particle flux (~10 My)
  - *Knie et al., PRD (2004); Wallner et al., Nat (2015)*

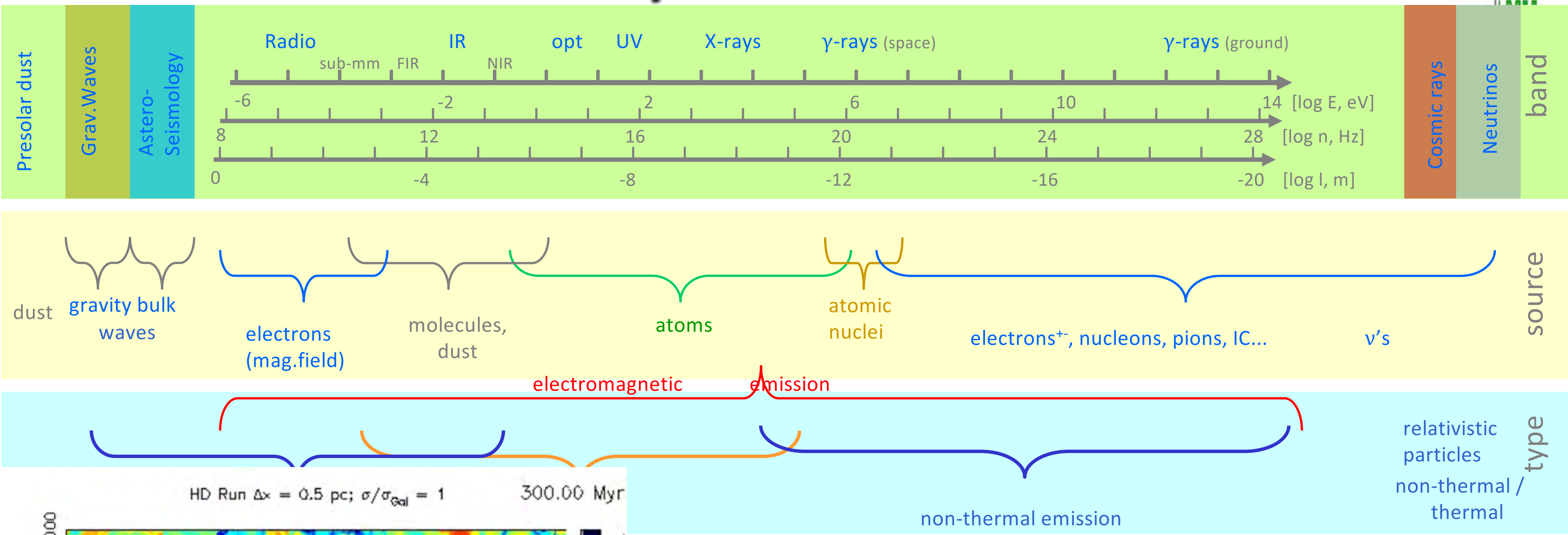
Molecular Isotopic Lines in sub-mm Radio Waves

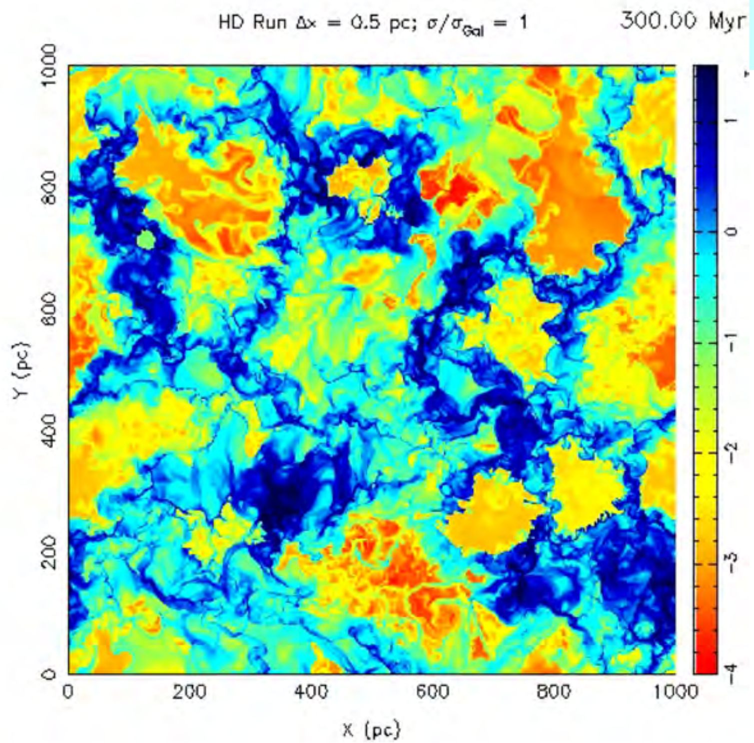
- ☆ Isotope ratios in dust/molecule-forming sites
  - *Kamiński et al., Nat Astr (2018)*

High-resolution Spectroscopy of Stellar Photospheres

- ☆ Isotopic abundance (line shoulders; light isotopes) at formation time of a star
  - *Lind et al., A&A (2013)*

The variety of astronomies



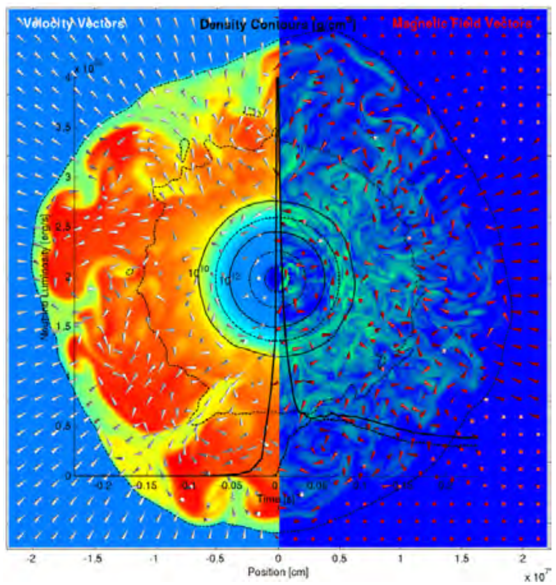


The variety of astrophysics

here:

stellar explosions

cosmic matter cycle



- End of Lecture II