Nuclei in the Cosmos School
2025

HIGH-ENERGY ASTROPHYSICS - II

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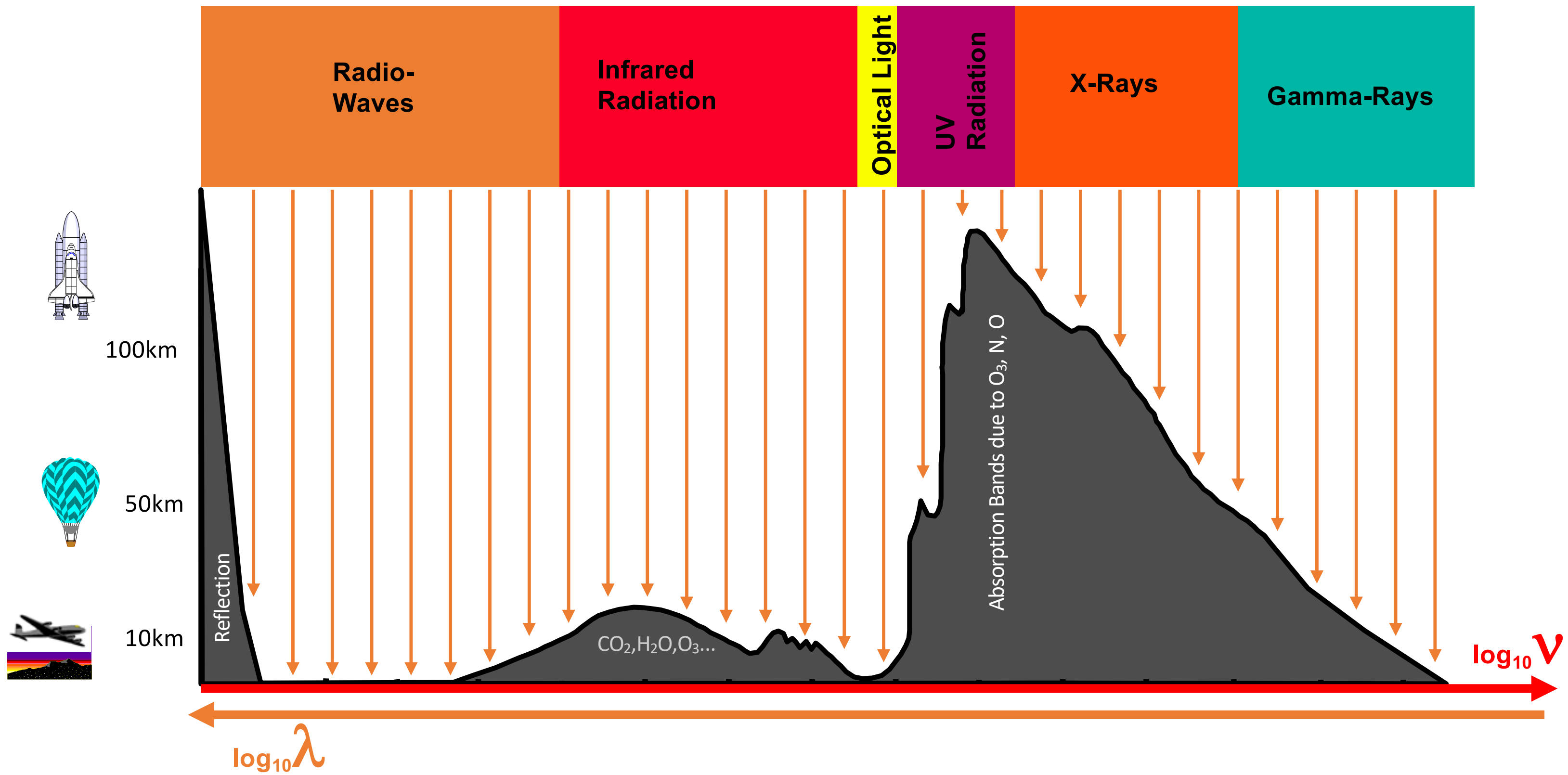
- Astrophysics at high energies
- Processes: radiation and particles
- Detectors for HE photons & particles
- Instruments and Missions
- Results in Nuclear Astrophysics
- other HE Astrophysics Results

Image Credit:NASA/Space Telescope Science Institute

- Astronomical Tools in High-Energy Astrophysics

Observational Windows



- Need a Combination of Ground-Based and Satellite Observations for Observations across Full Range
- Which Processes in Which Spectral Window?

Astronomical Instruments: X/γ-ray Space Missions

Non-focusing X-ray telescopes

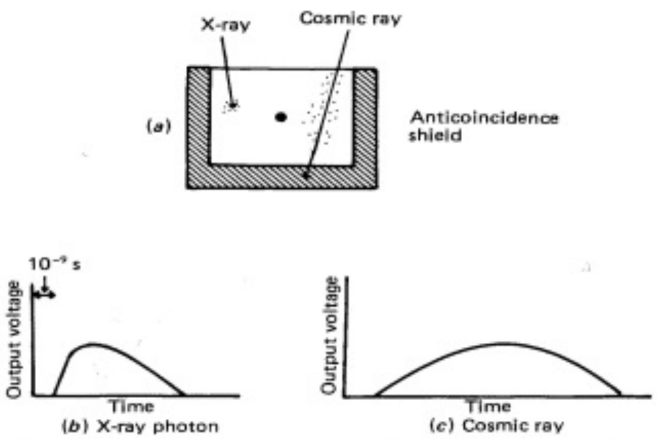
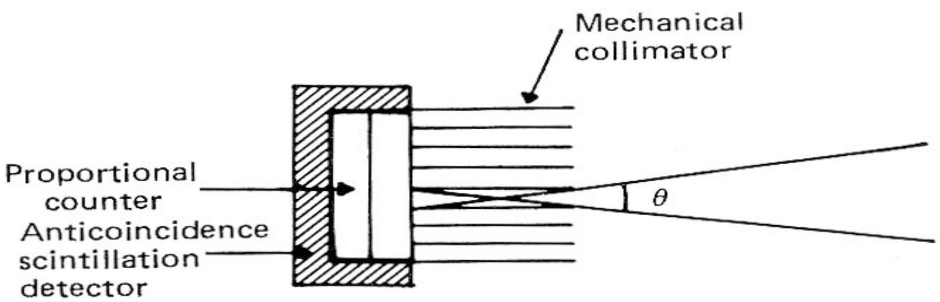


Figure 7.8. Diagrams illustrating the principles of rise-time or pulse-shape discrimination between X-rays and cosmic rays.

Two Elements (Detector, Anti-Detector)

- avoid confusion with cosmic rays
- shield works as a second “detector“
- CR's: signal in both devices
- X-rays: signal only in detector

- e.g. 'phoswich': single readout, two different detector elements
  ➡ Distinction possible



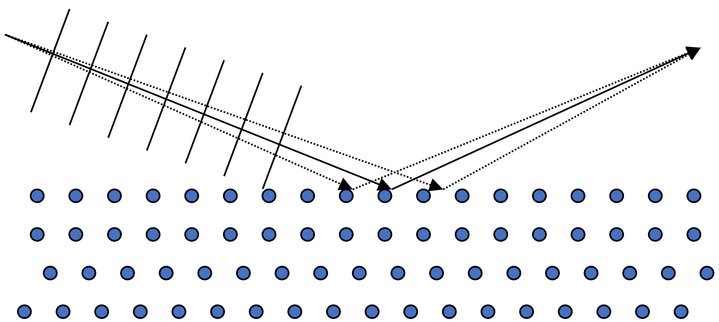
Collimators

- to avoid light from unwanted directions
- implemented with metallic tubes

Surfaces at Smaller Wavelengths (λ≲ a=atom spacing)

- Below ~1000 Å, Reflection gets more scattering than specular

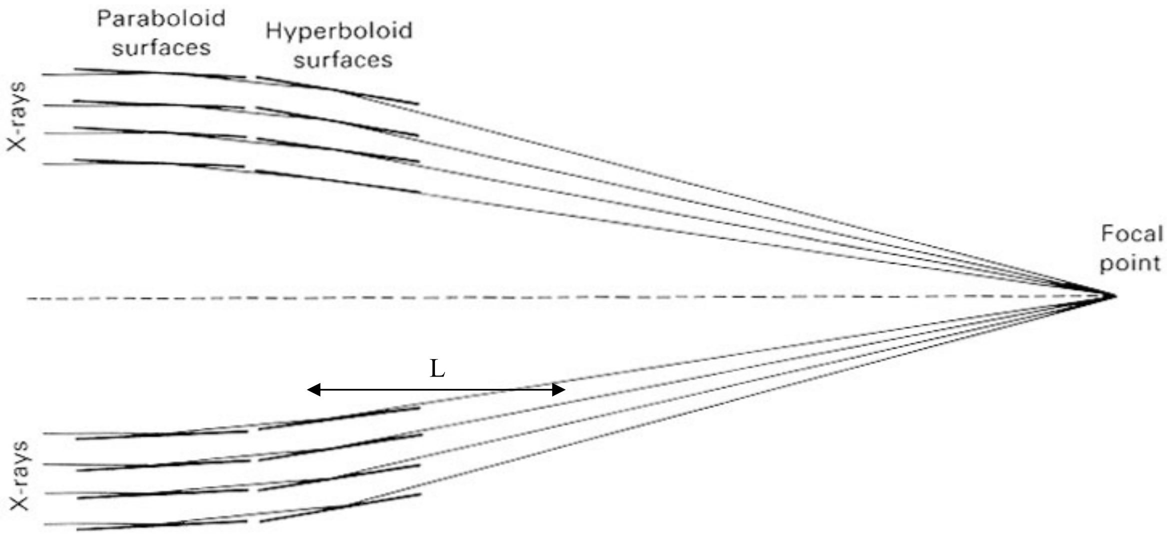
- Physical reason:
  When λ is of the order of the structure of the "surface" of a mirror: -> No cancellations of "indirect" paths of the e.m. wave functions (in QED picture)



- "Trick" at X-ray Energies: Grazing Incidence
  - ✓ This shifts the problem to somewhat higher energies (~100 keV)

☞ https://www.mpe.mpg.de/~rod/05_ROLAND_Looking_Stars_v02HD.mp4
a movie illustration created in Barcelona 2022

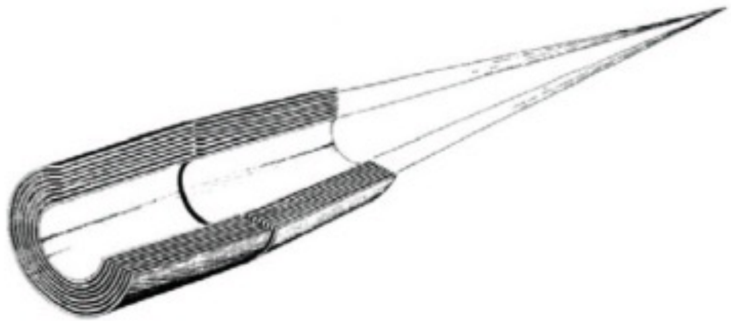
Wolter type I telescopes (II)



- effective area A_{eff} (per shell) is given by

$$A_{eff} = 8\pi \cdot F \cdot L \cdot \theta^2 \cdot Refl.^2$$

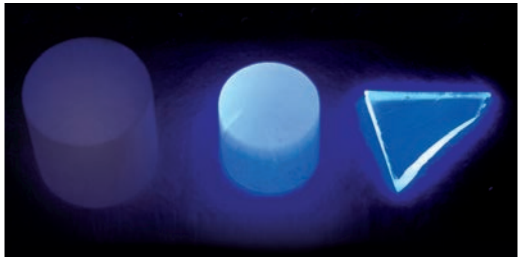
- solution: nesting many confocal mirror shells can maximise the effective (collecting) area !!

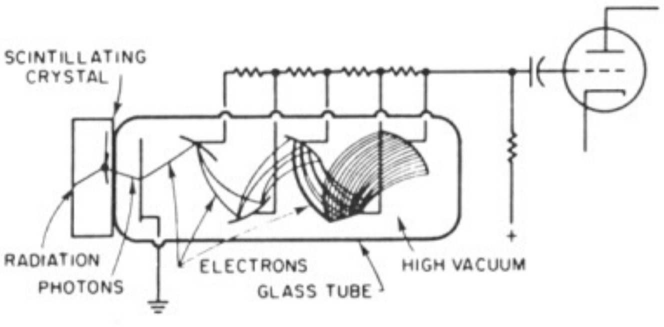


Example: The XMM-Newton mirrors

- segmented thin mirrors
- mirror material: Nickel – coating with Au
- 3 moduls with 58(!) shells/module
- shell thickness: 0.5 mm and 1 mm (very close!)
- focal length = 750 cm, max. diameter = 70 cm
- effective Area @ 1 keV = 1475 cm^2 /module

Scintillator Detectors & Photomultiplier Signals





Photomultiplier

converting X-ray energy into visible light using material fluorescence

- organic scintillators (plastics)
  almost exclusively used as anti-coincidence shields

- inorganic scintillators (crystals: NaI, CsI, BGO, $LaBr_3$ ...)
  for HE photon detection

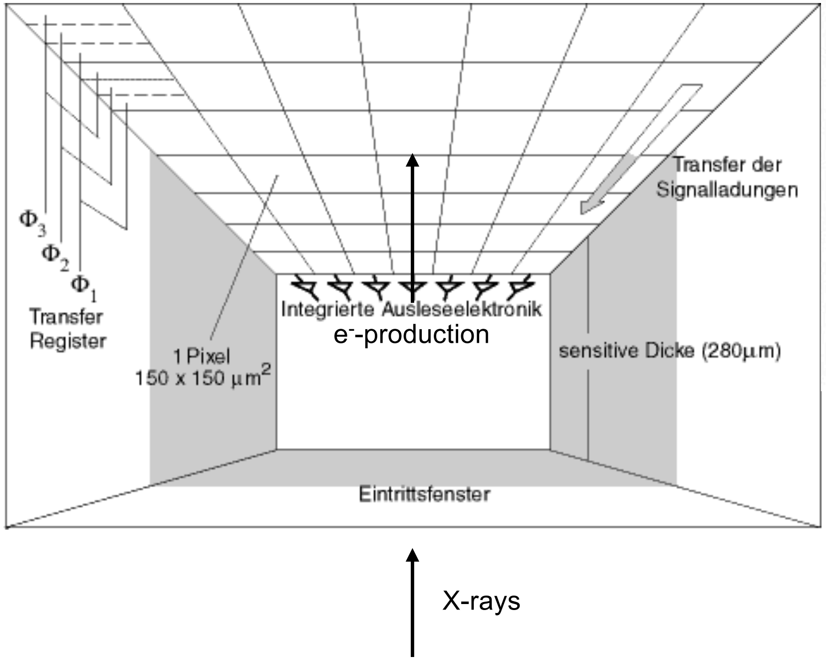
Alkali halides: NaI, CsI
- can be made into large area crystals: NaI(Tl), CsI(Na)
- good X/γ-ray stopping power
- efficient light producers → blue light

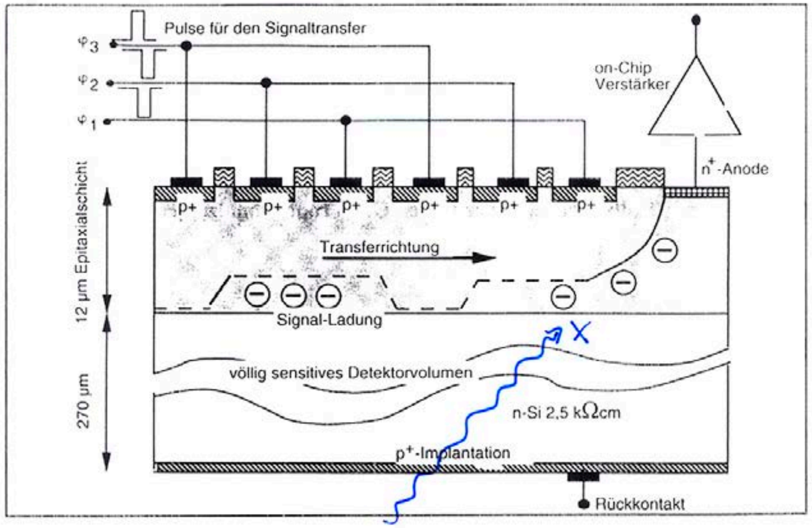
- photo-electron creates scintillation pulse with
  different decay times for different materials (~20ns for $LaBr_3$)

- total light output proportional to energy input
  (up to 60000 ph/MeV (for $LaBr_3$))

pn-CCD Operating Principle

view from inside the CCD, from the n-side

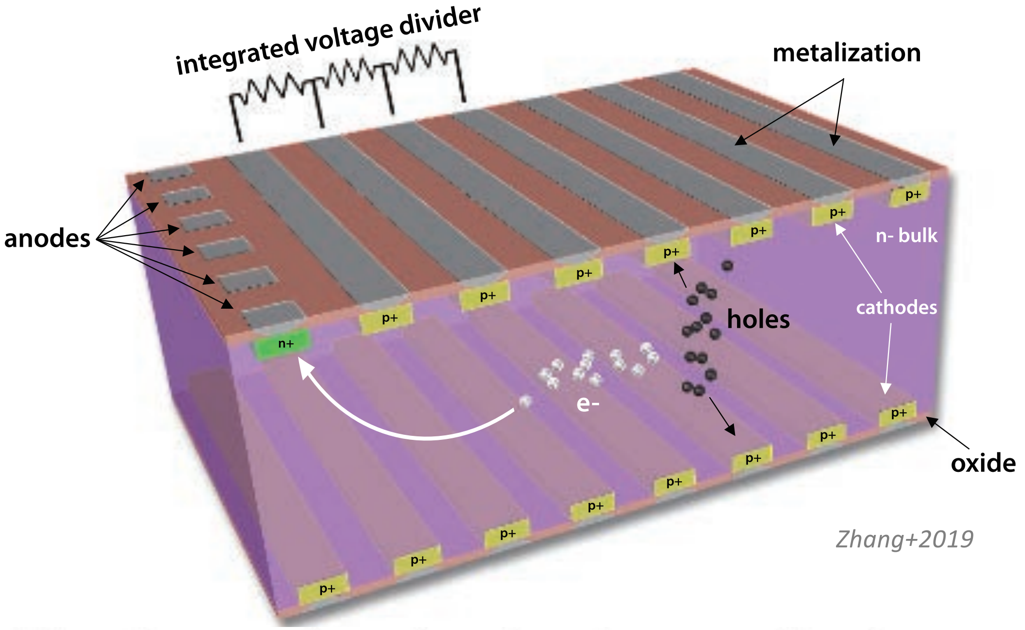




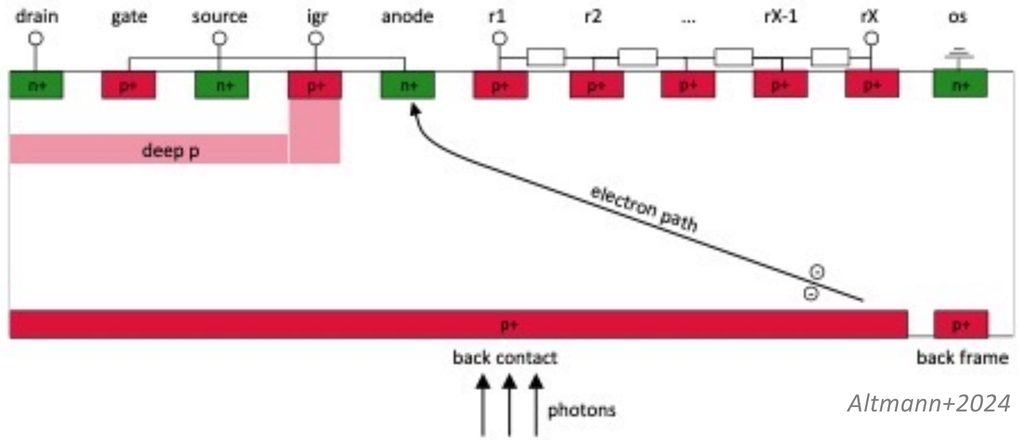
- applying an electric field in the Si sensitive region
- transfer of the created charges to the gate
- cycling the voltages of the electrodes
  - ➡ move of the charges to the read-out

Silicon Drift Detectors for X-rays

- Active volume registers ionisation tracks, collecting ion (timing trigger) and electron signals in surface electrodes
- Analogue signal: electron cloud as enlarged by electric field as it drifts though the volume before reaching the anodes
  - ☞typical drift voltage ~370 V/cm → 5mm/µs
  - ☞location of photon incidence from timing
- Originally developed at CERN for ALICE, now applied for many high-energy photon and particle detectors
  - ✓ faster readout compared to CCDs
  - ✓ light weight
  - ✓ broad range of applications/users

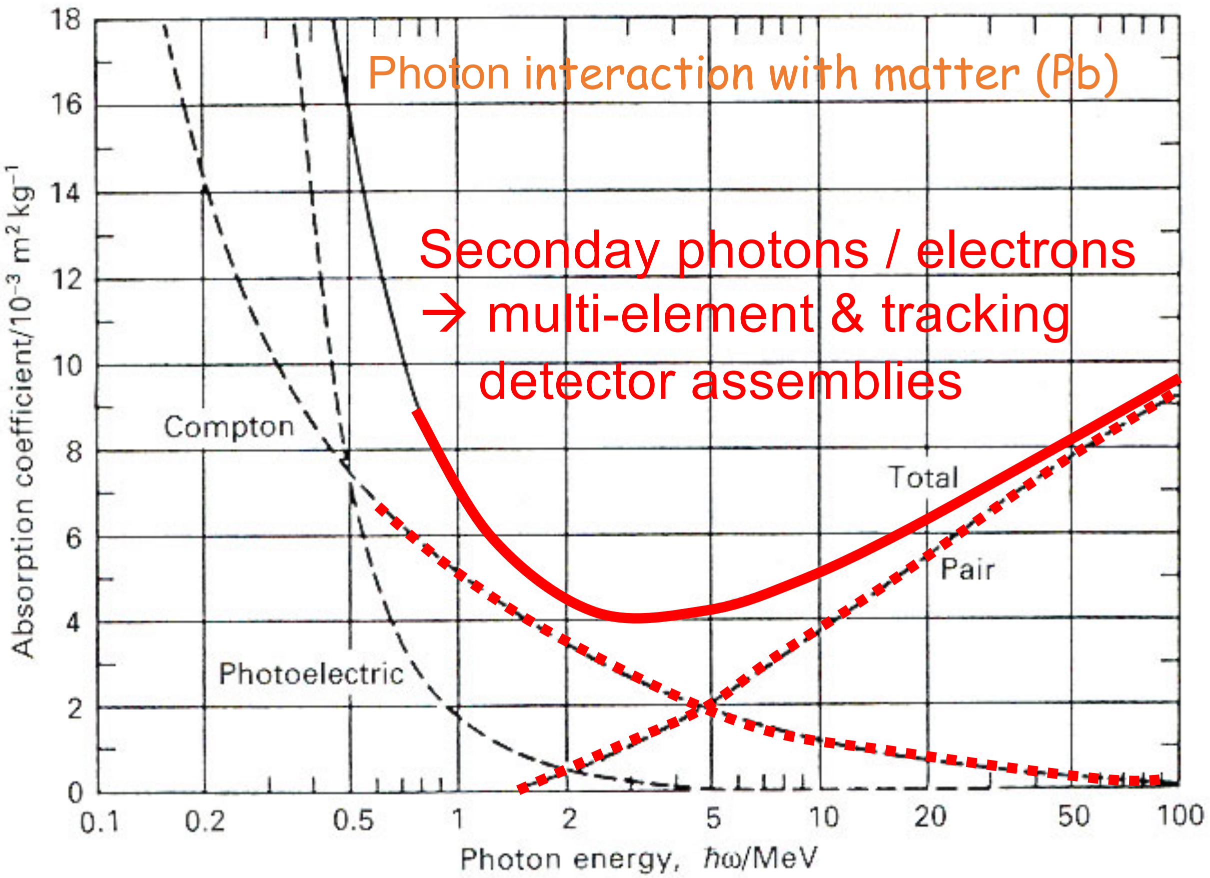


Zhang+2019



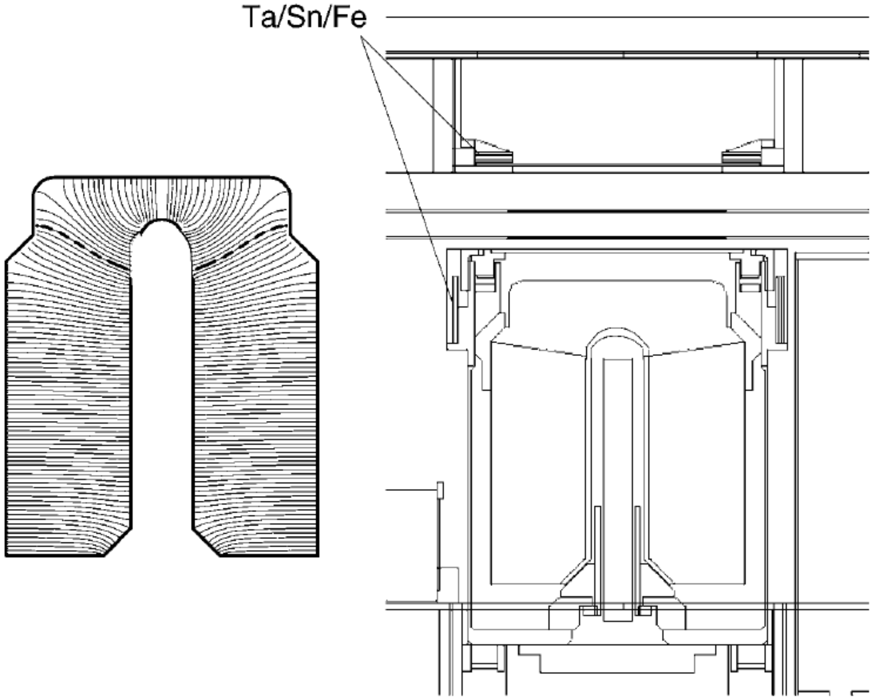
Altmann+2024

Gamma-Ray Astronomical Telescopes:
Interaction of high-energy photons with matter



→ Secondary Particles … → e.m. cascade

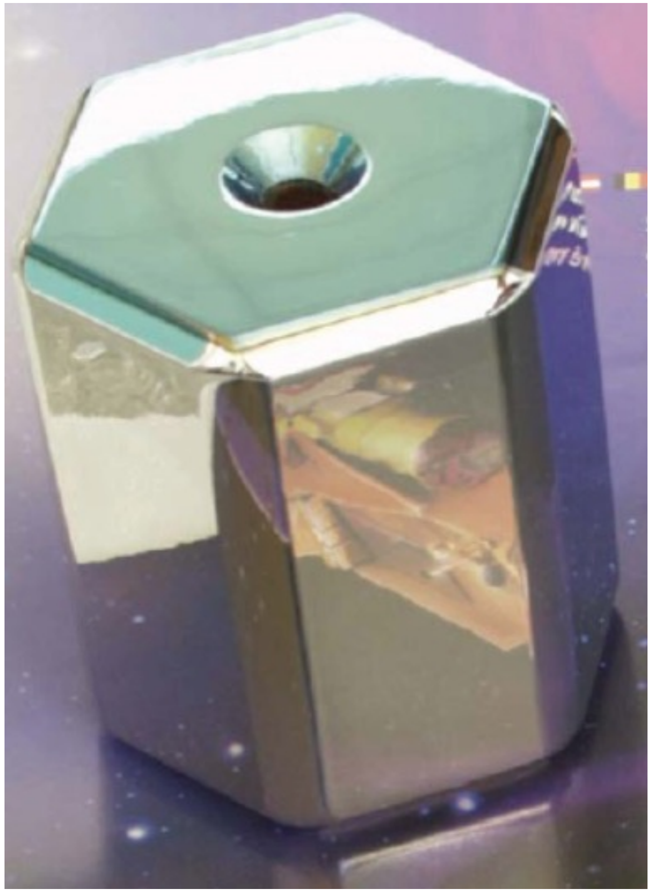
Ge Detectors in Space Telescopes



Detector Cross Section

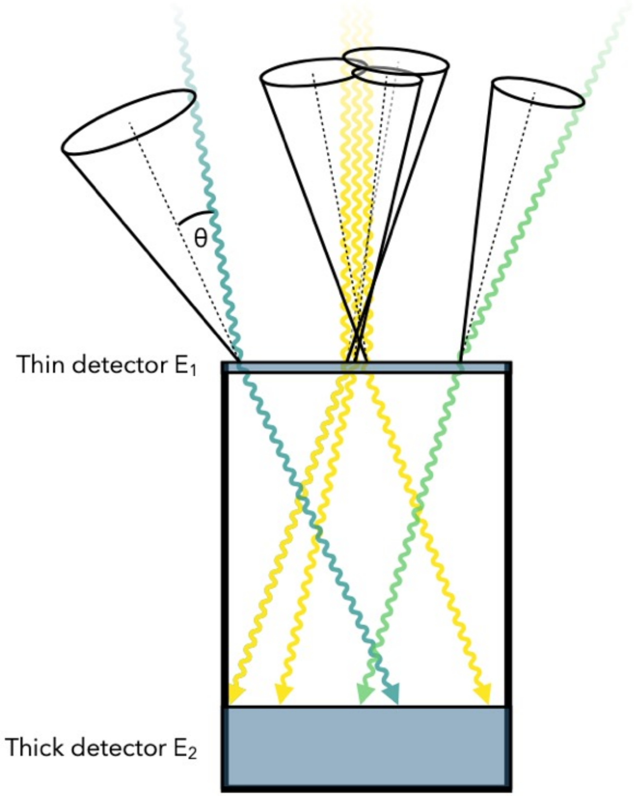
- Electric potential
- Mechanics
- (RHESSI)

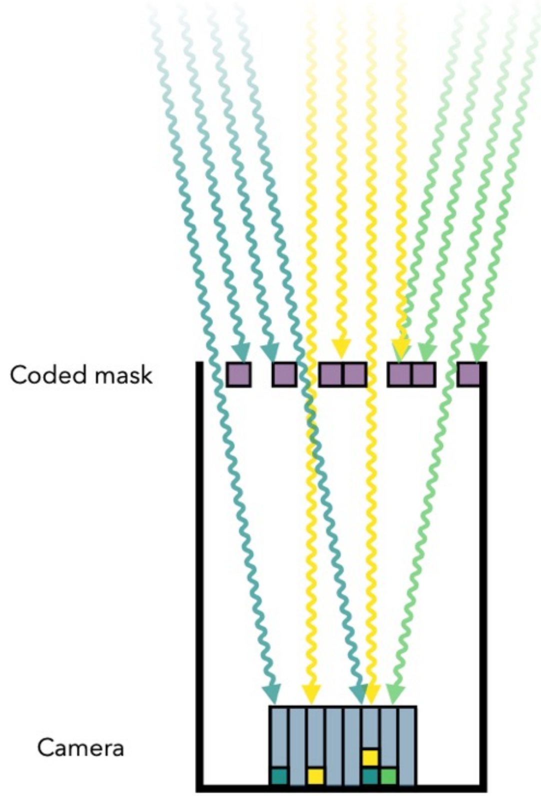
Detector of SPI/INTEGRAL



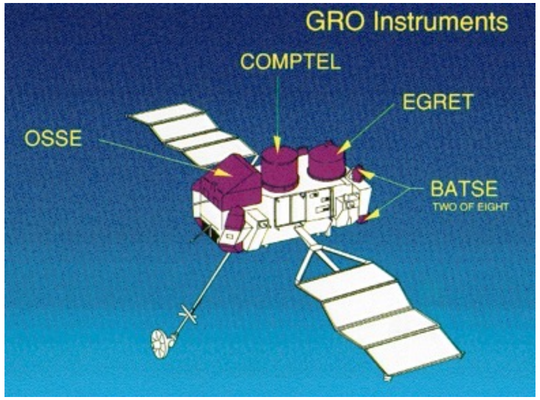
MeV Range Gamma-Ray Telescope Imaging Principles

Compton Telescopes and Coded-Mask Telescopes



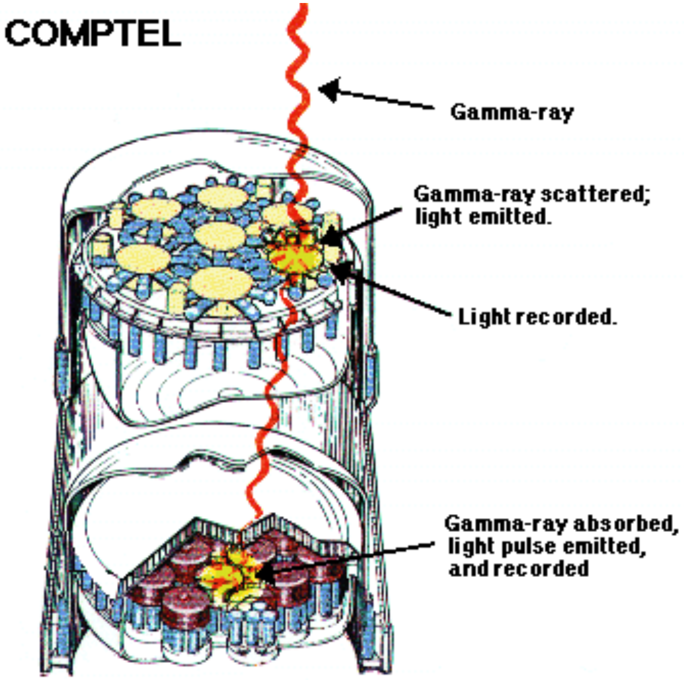


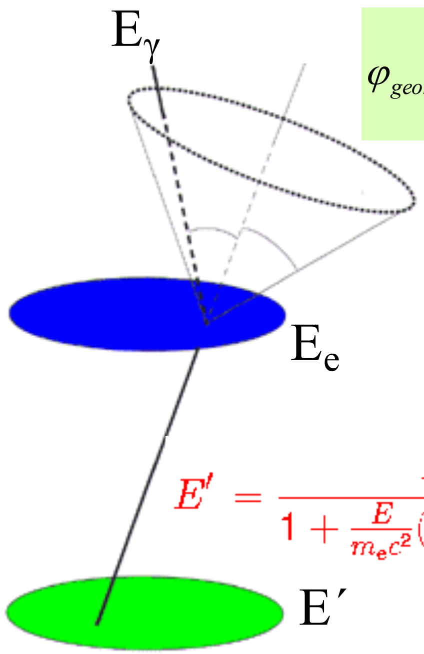
Currently achieved: Sensitivity ~10^{-5} ph cm^{-2} s^{-1} Angular Resolution ≥ deg



The Compton Telescope on CGRO

Compton Scattering → Detector-Coincidence Instruments





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

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

projected 'event circles'

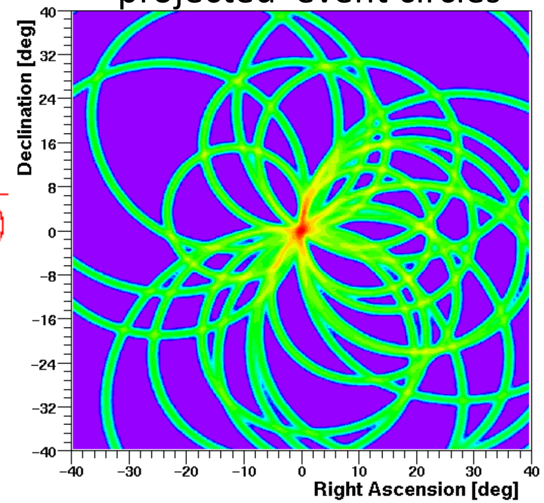


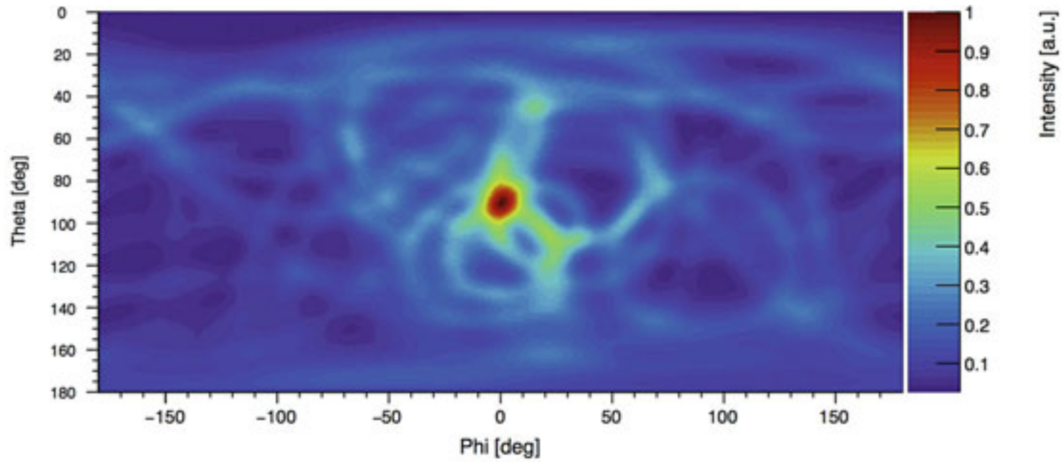
Image Generation with Compton Telescope events

example:

point source

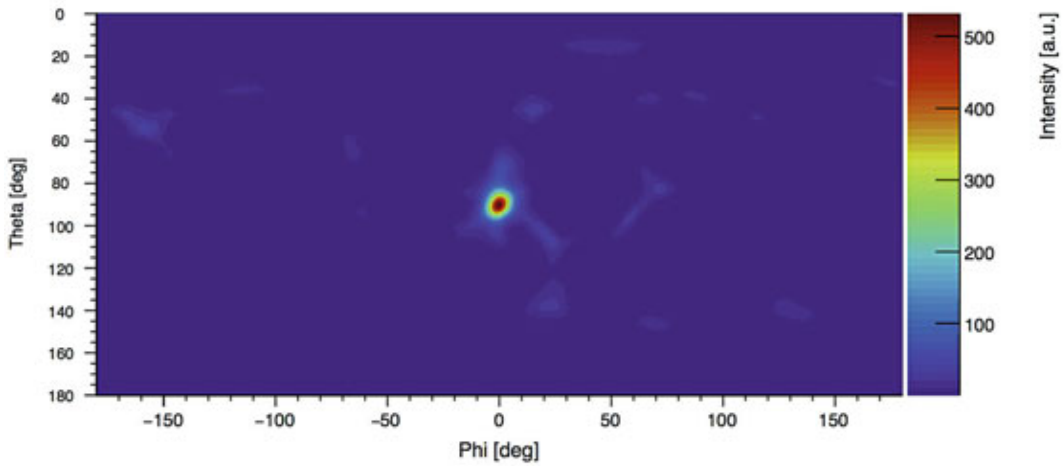
500 keV incident E

200 events



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

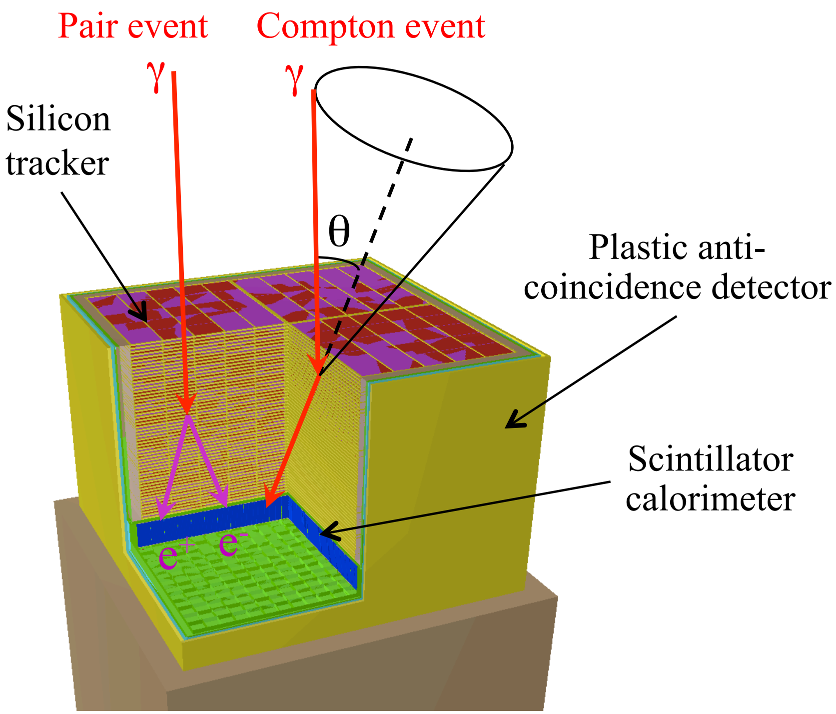
Kierans, Takahashi, Kanbach 2022

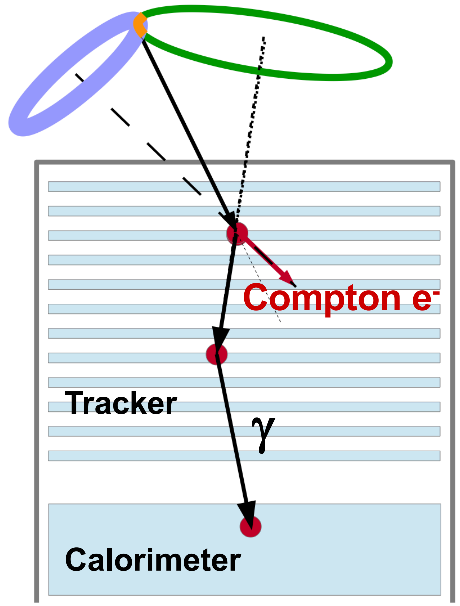


(b) Image obtained after 5 iterations of the LM-ML-EM algorithm.

e-ASTROGAM (proposed ESA M Mission, not realised)

de Angelis+ 2017

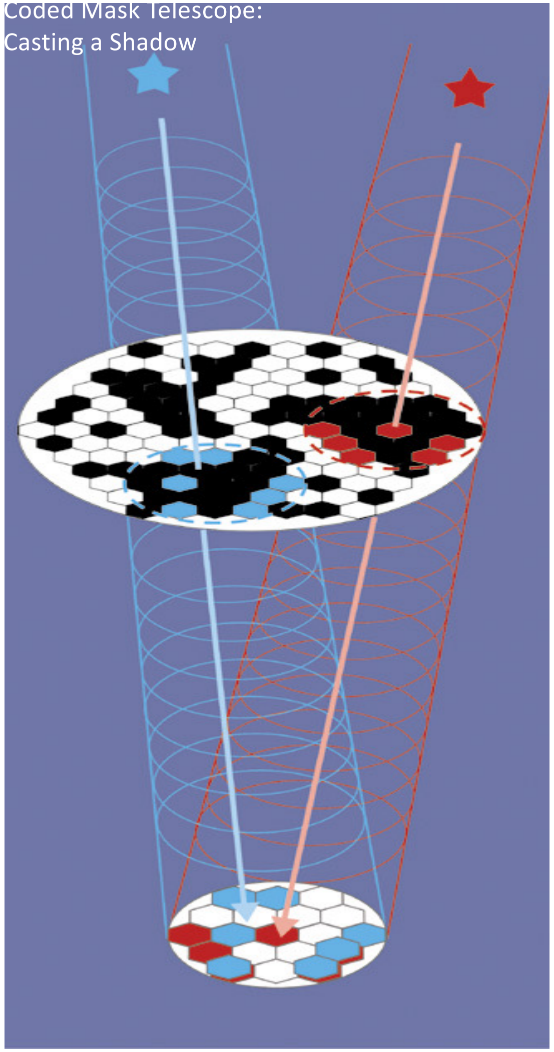




Tracked Compton event

- **Tracker** → Double sided Si strip detectors (DSSDs) for excellent spectral resolution and fine 3-D position resolution
- **Calorimeter** – High-Z material for an efficient absorption of the scattered photon → CsI(Tl) scintillation crystals readout by Si Drift Diodes for better energy resolution
- **Anticoincidence detector** to veto charged-particle induced background → plastic scintillators readout by Si photomultipliers

INTEGRAL ESA Mission: The SPI Ge γ-ray Spectrometer



Coded-Mask Telescope

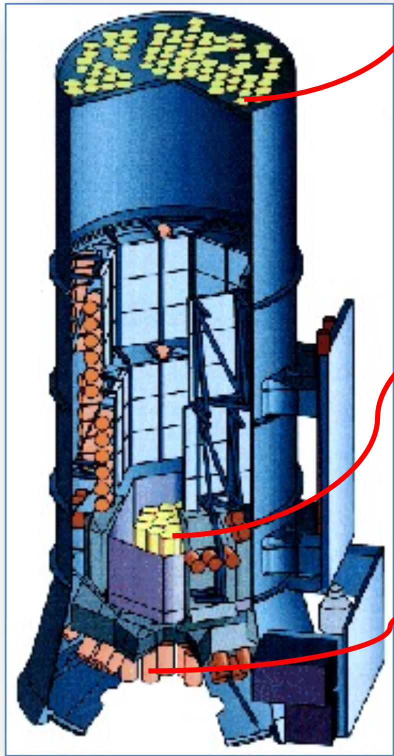
Ge Detectors, Energy Range 15-8000 keV

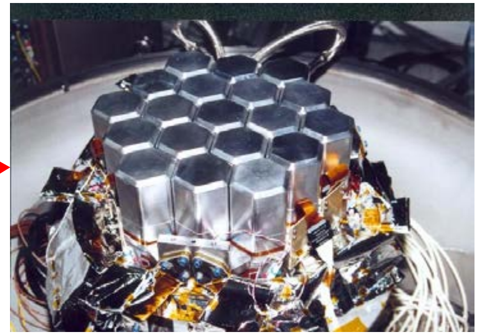
Energy Resolution ~2.2 keV @ 662 keV

Spatial Precision 2.6° / ~2 arcmin

Field-of-View 16x16°

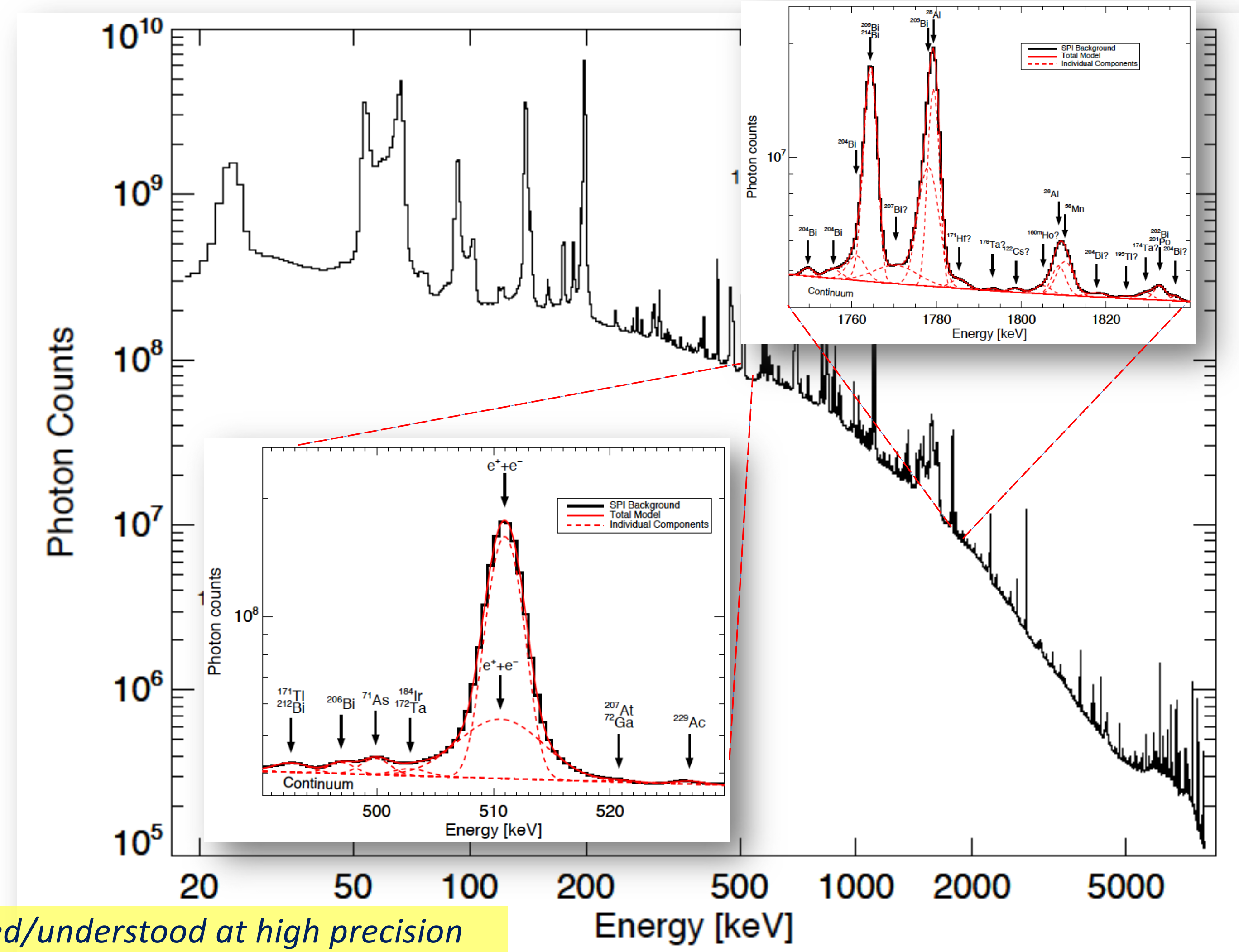
BGO active Shield





INTEGRAL: Dominance of instrumental background

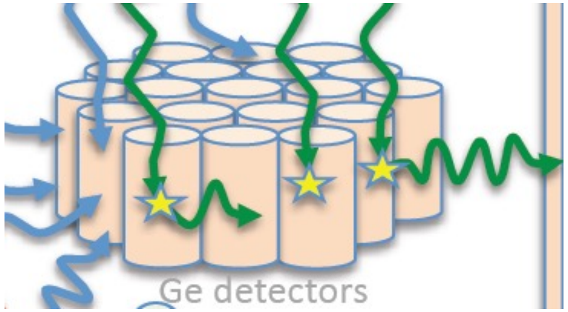
SPI Ge detector spectra

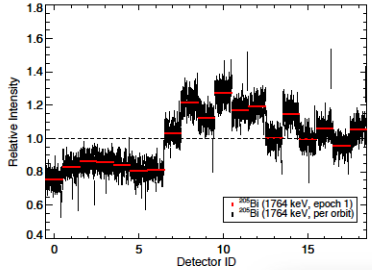


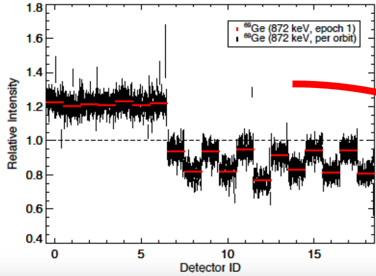
Modelled/understood at high precision

Discriminating Background and Sky Signals in SPI Data

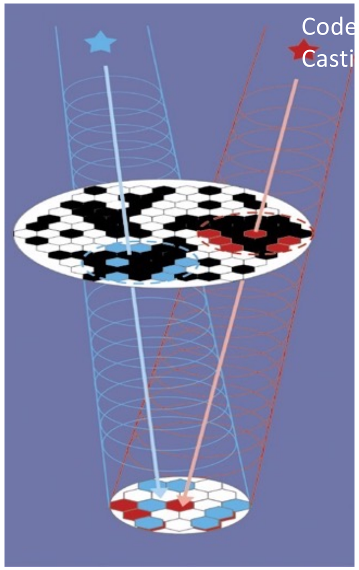
- Tracking the relative count rate ratios among detectors
  - ✓ characteristic signatures from celestial sources withcoded mask, and from background events

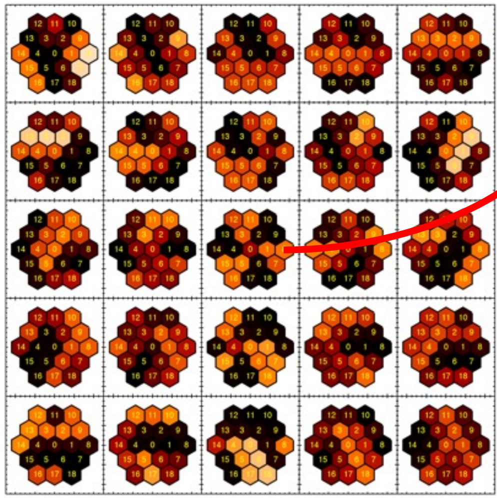


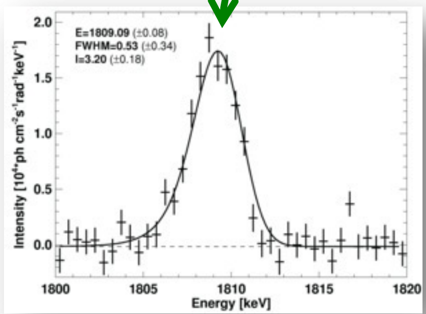


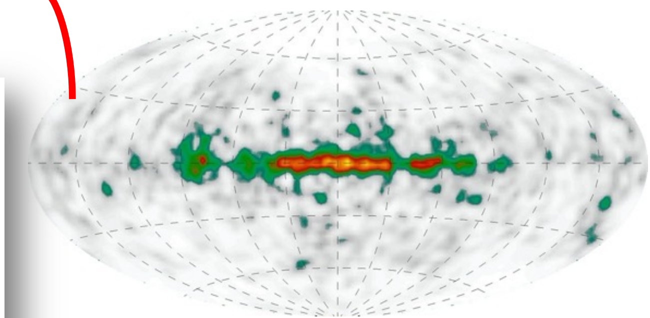


$$d_k = \sum_j R_{jk} \sum_{i=1}^{N_I} \theta_i M_{ij} + \sum_t \sum_{i=N_I+1}^{N_I+N_B} \theta_{i,t} B_{ik}$$







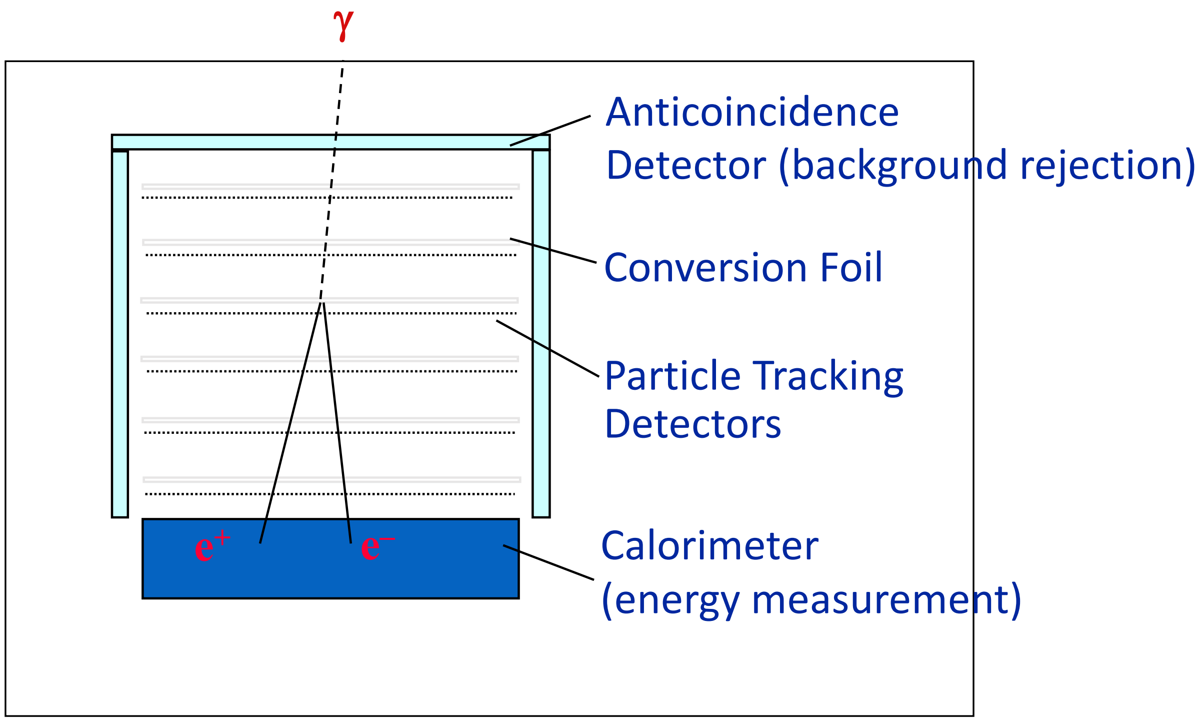


Detecting Cosmic High-Energy Photons

- *The Physical Processes behind...*
  - UV and X-Rays: eV ... 100 keV
    - ✓ Space-resolved Charge Collection in Imaging Plane of Focussing Optics
    - ✓ Using Photo-Electric Effect, i.e. Atomic-Ionization Charges
  - Low-Energy Gamma-Rays 20 keV ... 30 MeV
    - ✓ Energy Transfers in Photon Collisions -> High-Energy Secondaries
    - ✓ Compton Electron Detection & Tracking
  - Medium-Energy Gamma-Rays 20 MeV ... 300 GeV
    - ✓ Pair Production as Most-Likely Initial Interaction with Matter
    - ✓ Trace Ionization Tracks of Secondary e^-e^+
  - High-Energy Gamma-Rays 50 GeV ... PeV
    - ✓ Electromagnetic Cascade is Extended & Penetrating
    - ✓ Use Earth Atmosphere as Interaction Volume, Observe Showers

Pair-Conversion γ-ray Telescopes

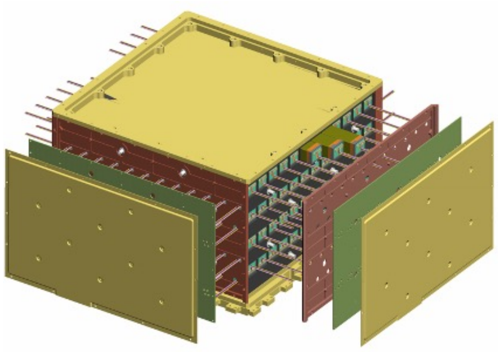
e.g. the Fermi Large Area Telescope (LAT)

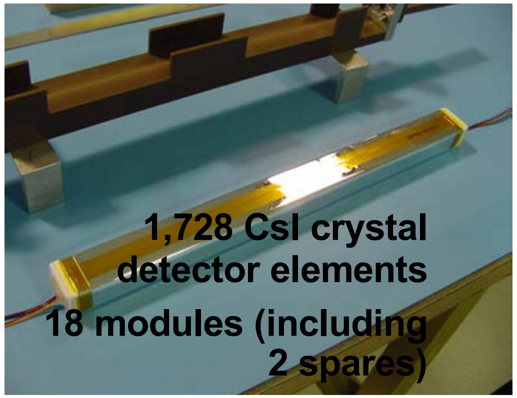


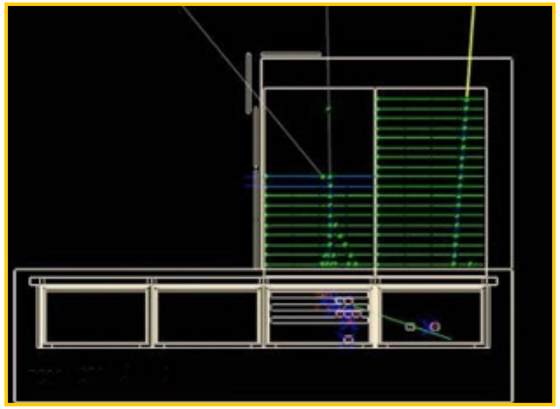
- Gamma-rays >10 MeV interact mainly through pair production
- the gamma-ray energy is converted into two charged particles – an electron and a positron (its antiparticle)
- LAT is a particle tracker, e^+/e^- tracks diverge following the magnetic field

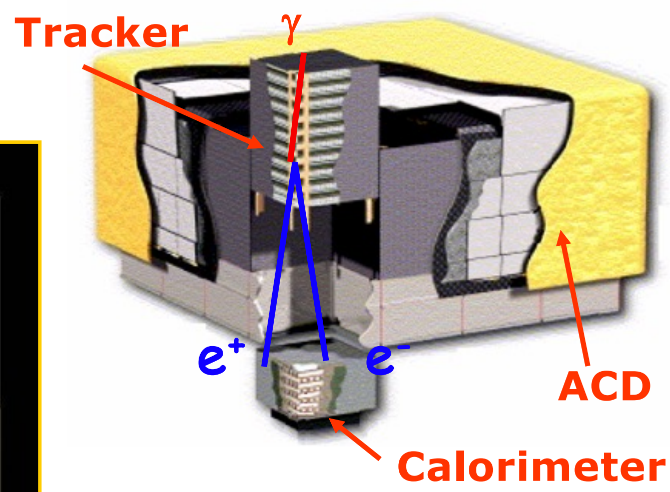
GeV γ ray Measurements: Tracking e+e- pair interactions
The Fermi Large-Area Telescope (LAT)

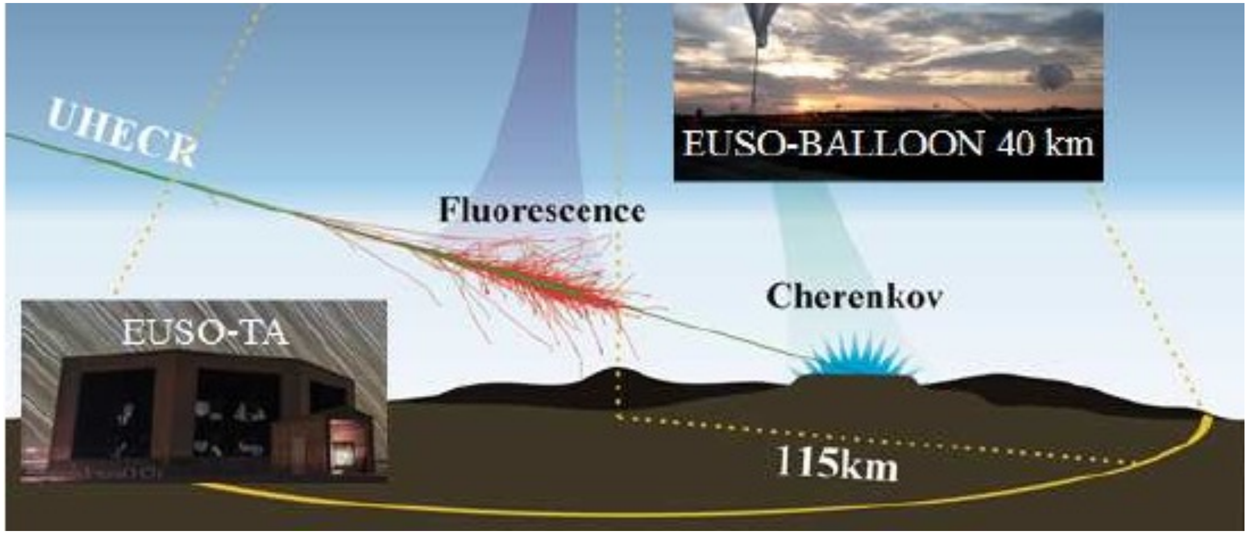
- Pair Conversion
  - Detect photons between ~20 MeV - 300GeV
- Tracking system
  - Silicon-Strip Detectors (880000 channels)
- Calorimeter
  - CsI Crystals (8.4 r.l., hodoscopic array)
- Anticoincidence
  - Segmented ACD veto counters









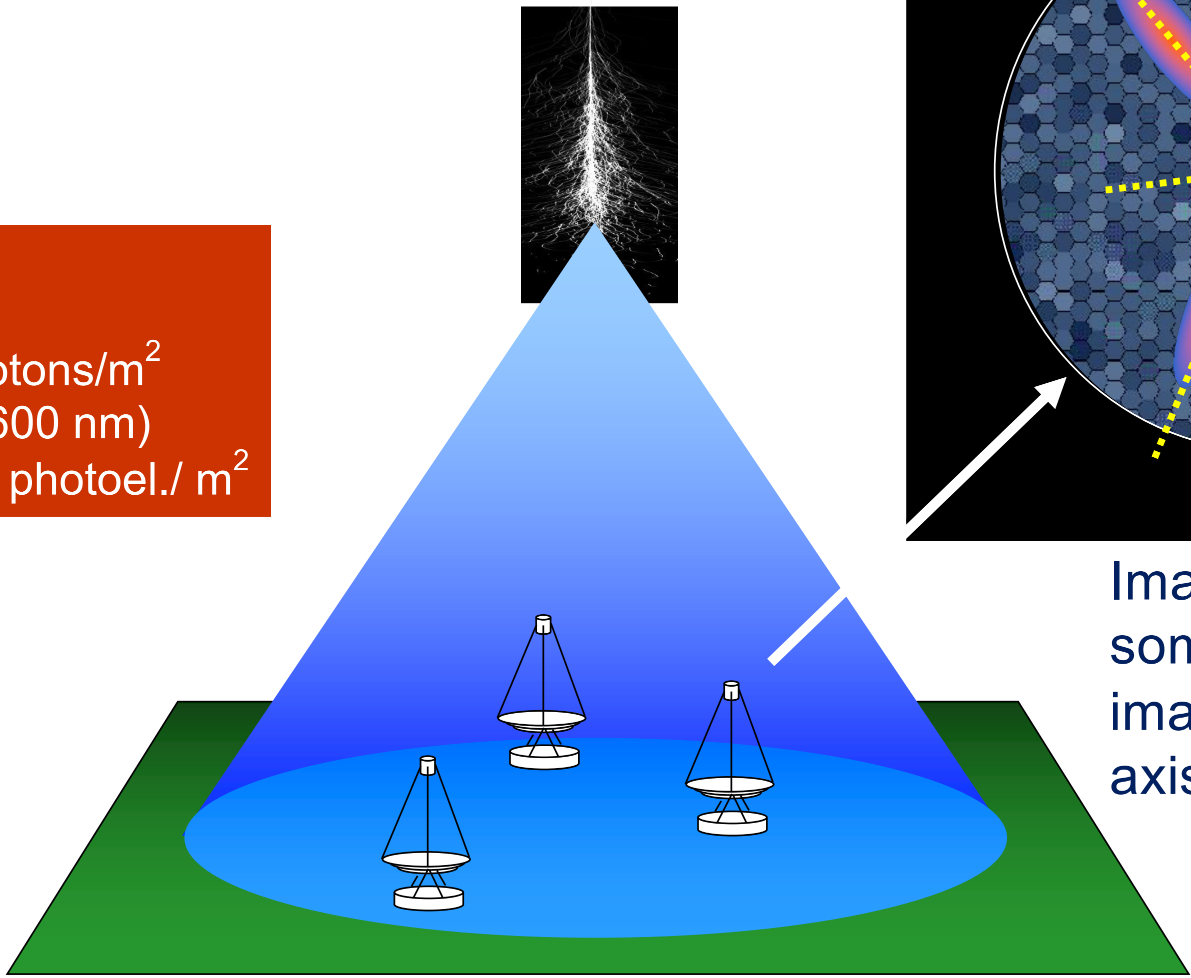


- E.m. particle-photon shower
  - detection by surface detectors
- Fluorescence from, e.g., N atoms
  - at several km altitude
  - Converting the total ionization power of incident particle
  - X_{max} ~ E; I ~ yield; atmo transparency
- Continuum from Cerenkov radiation
  - in a cone around shower axis
-

Systems of Čerenkov telescopes and stereoscopy

at 1 TeV

~ 100 photons/m^2
(300 – 600 nm)
~ 10 – 20 photoel./ m^2



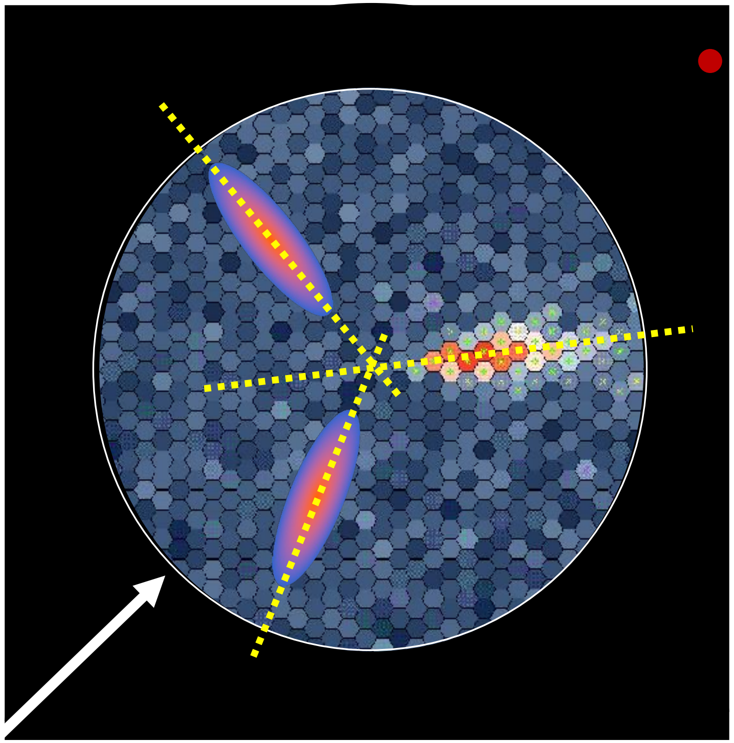
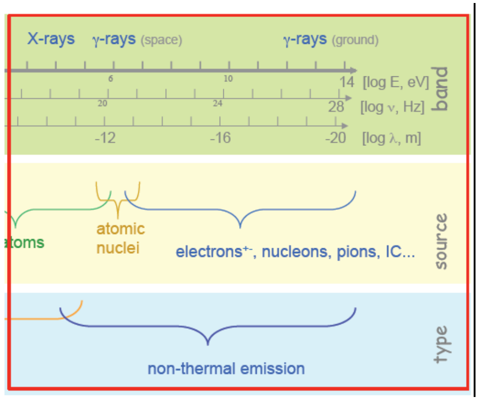


Image of source is somewere along image of shower axis ...

→ Use more aspects to locate the source!

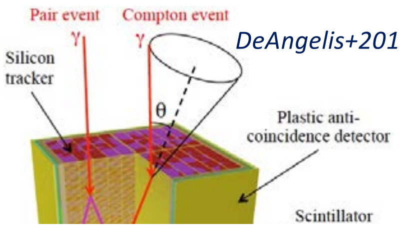
Perspectives of High-Energy Astronomy



Nuclear range:
Compton Telescope most promising

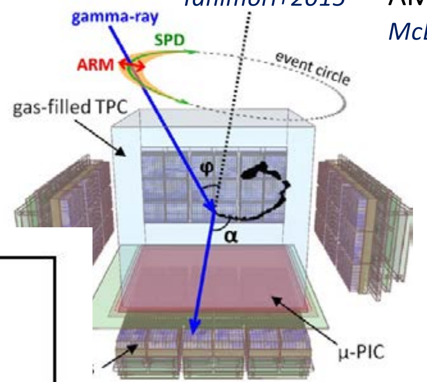
eAstrogam

DeAngelis+2017, 2018



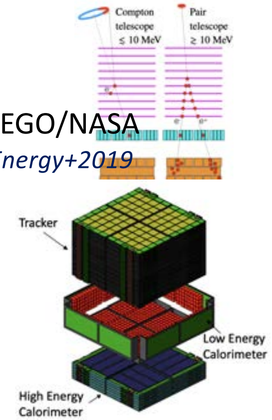
ETCC

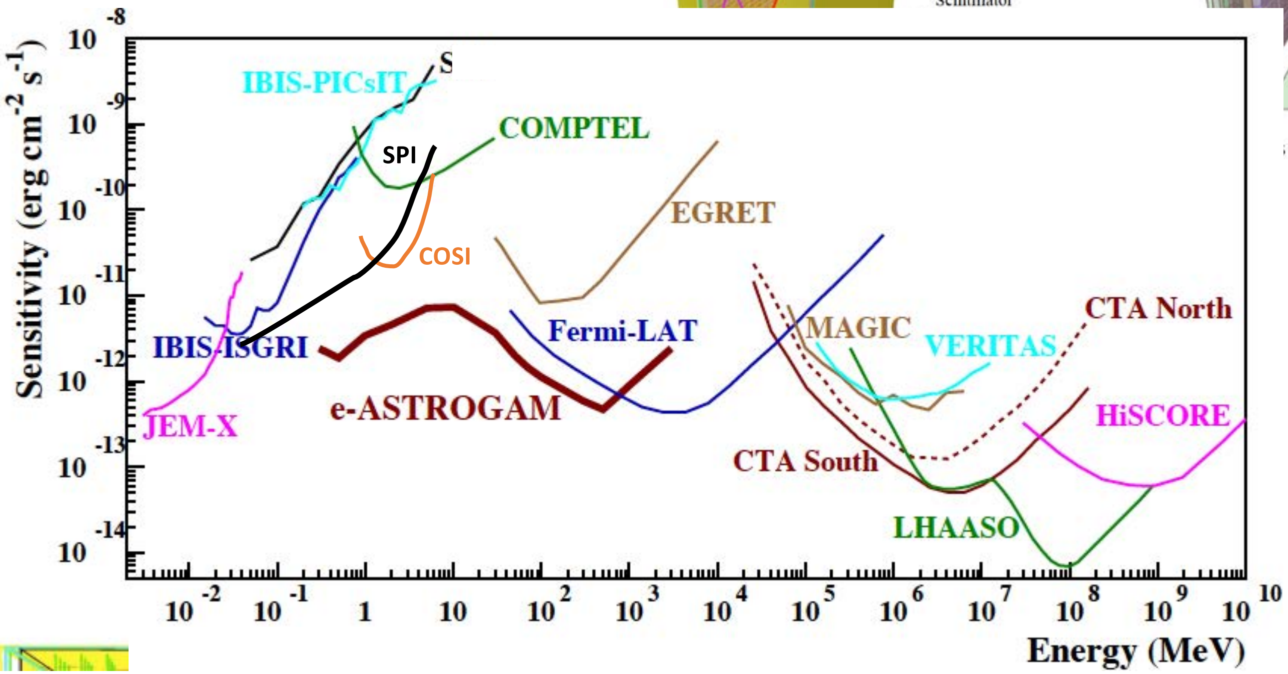
Tanimori+2015



AMEGO/NASA

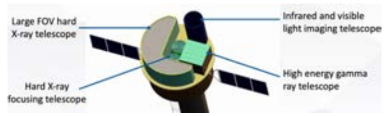
McEnergy+2019

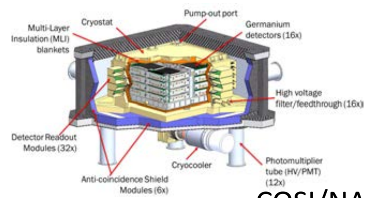




CAST/CNSA

Peng+2020



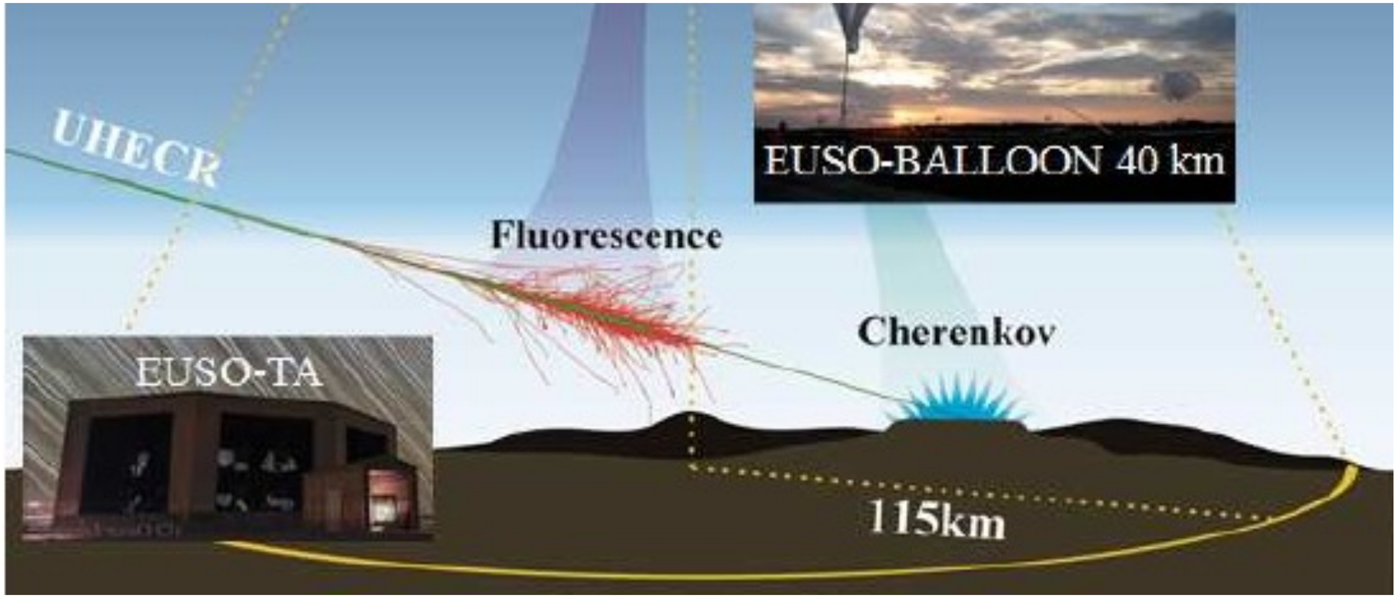


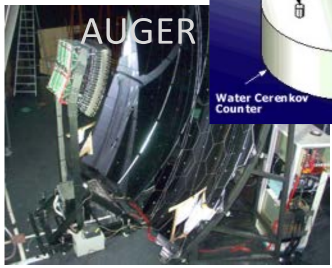
COSI/NASA

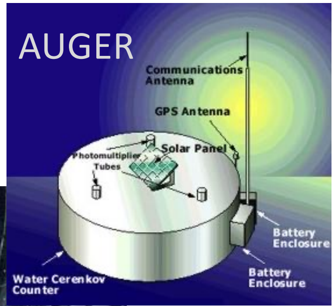
Tomsick+2021

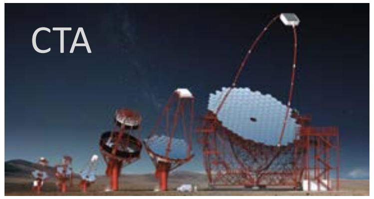
Charged particles and their signatures in the atmosphere

- Secondary particles from
  - ➢ pair creation
  - ➢ spallation
- Secondary photons from
  - ➢ bremsstrahlung
  - ➢ fluorescence
  - ➢ Cerenkov radiation
- Detectors:
  - ➢ Charged particle detectors on the ground
    - ✓ scintillators
    - ✓ tracking chambers, ...
  - ➢ Photon detectors
    - ✓ mirrors with PMTs
    - ✓ telescopes



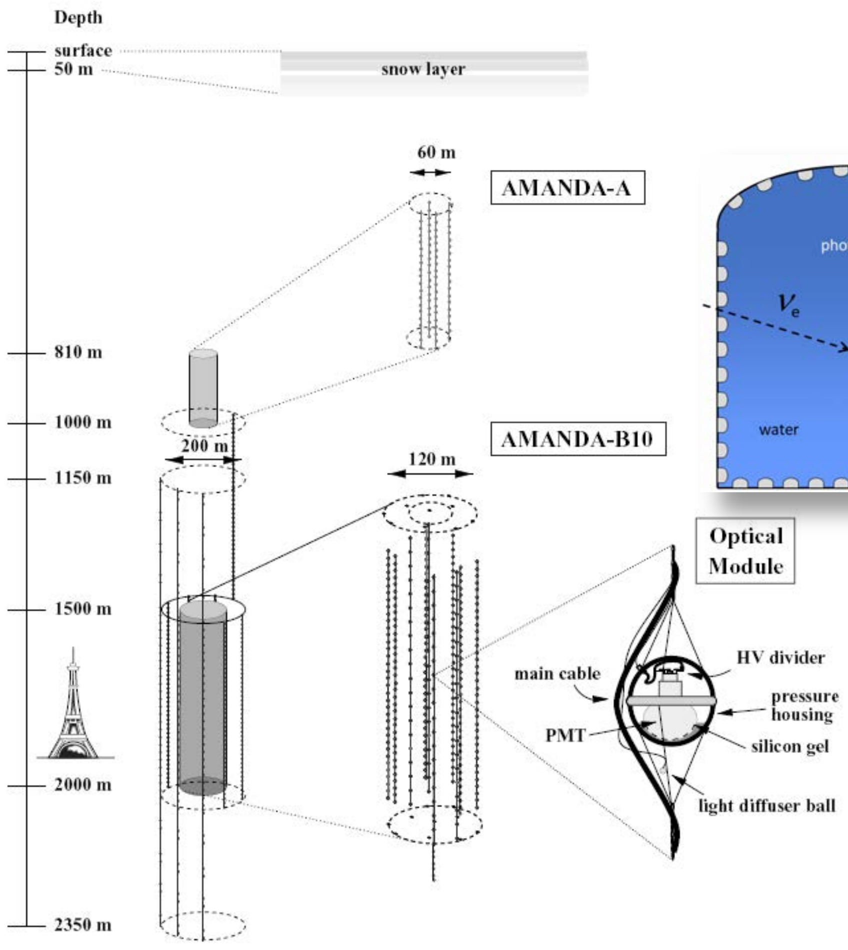






Detecting High-Energy Neutrinos

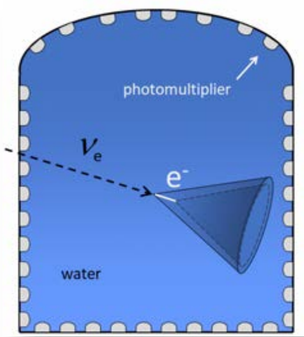
KM3NET & IceCube



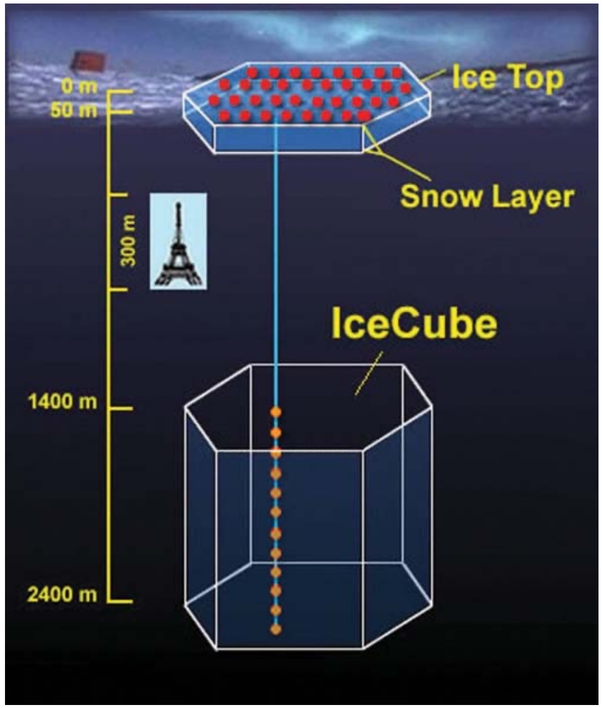
AMANDA as of 2000
Eiffel Tower as comparison
(true scaling)

zoomed in on
AMANDA-A (top)
AMANDA-B10 (bottom)

zoomed in on one
optical module (OM)

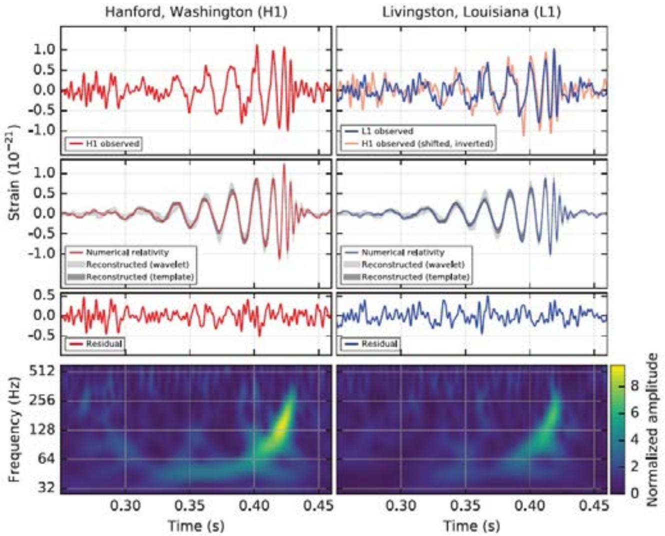


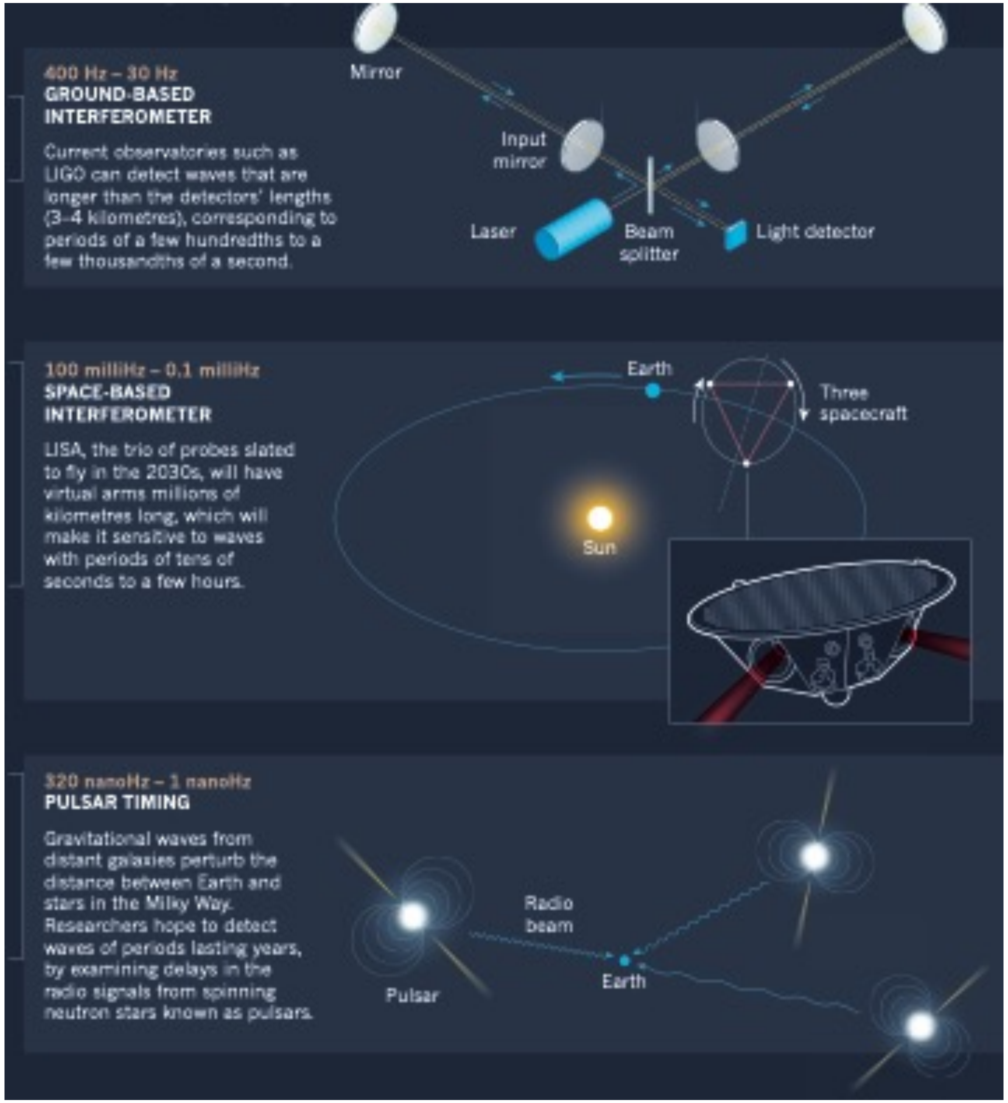
- ➢ Cerenkov radiation detection by PMTs on strings
  - ✓ Amanda/KM3NET in Mediterranean Sea 2000+ 7 10^6 m^3
    - ☞ORCA: off Sicily, 3500m depth, 115 units 20*9m
    - ☞ARCA: off Toulon (F), 2500 m depth
  - ✓ IceCube in Antarctica Ice 2010+
  - ✓ Super-Kamiokande Japan 1996+



Measuring Gravitational Waves

- Detecting tiny distortions of space
  - ✓ comparing templates as expected from sources to observed signals
  - ✓ example: NS binary coalencence 2017:

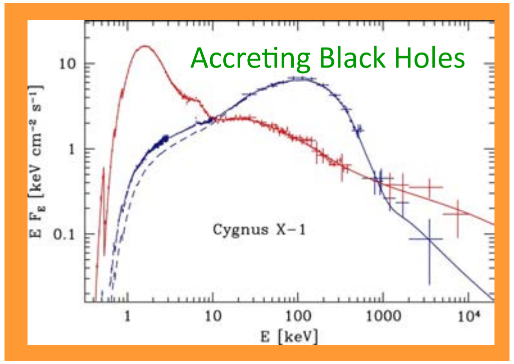


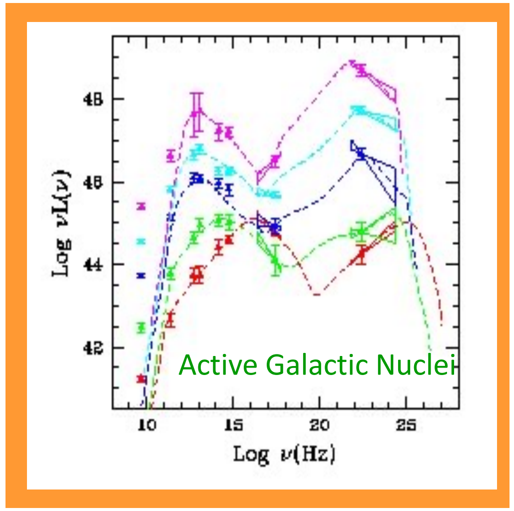


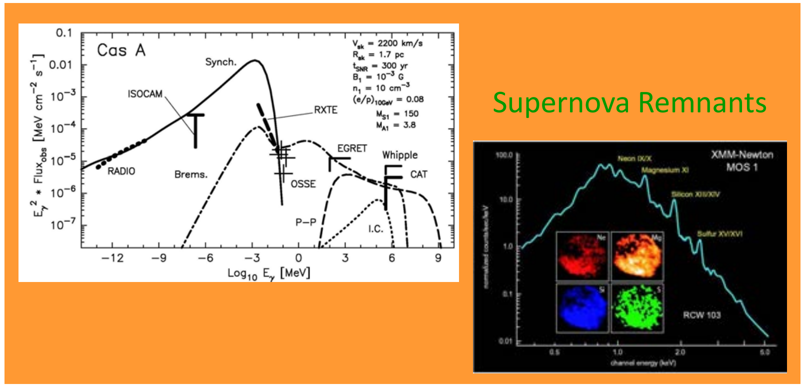
- Connecting cosmic objects to processes

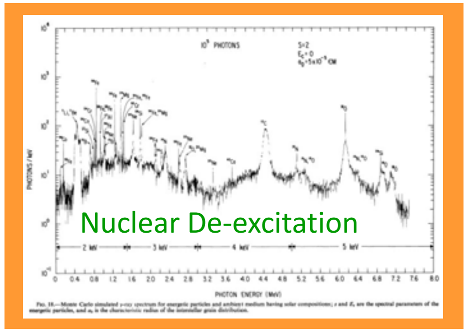
Typical High-Energy-Source Energy Spectra

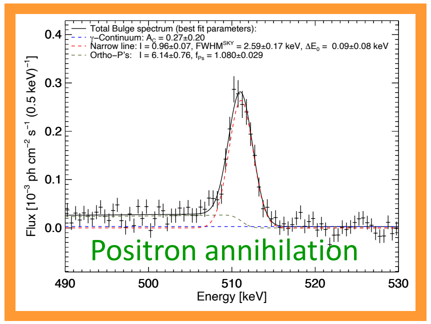
- Thermal Components
  - ✓ Compact-star surfaces heated by accretion/explosions
  - ✓ Binary-system accretion Disks
  - ✓ Plasma bubbles after supernova explosions
- Non-Thermal Components
  - ➢ Accelerated Particles
    - ✓ Synchrotron Radiation
    - ✓ Bremsstrahlung
  - ➢ De-excitation Lines

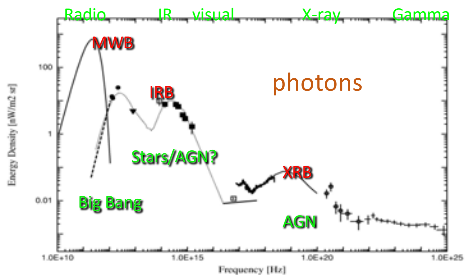


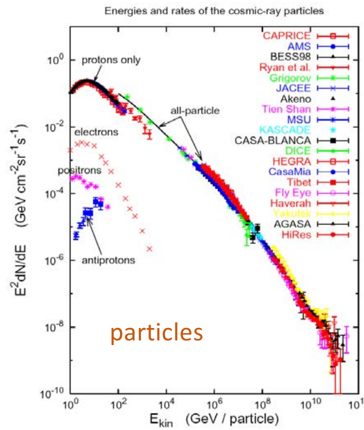








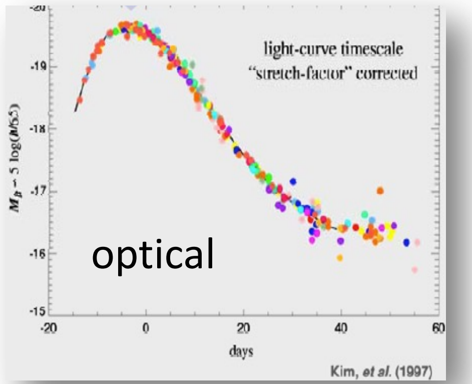


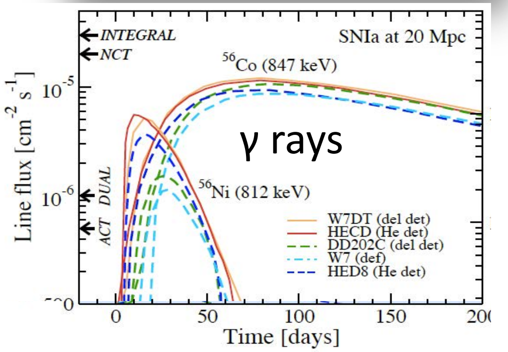


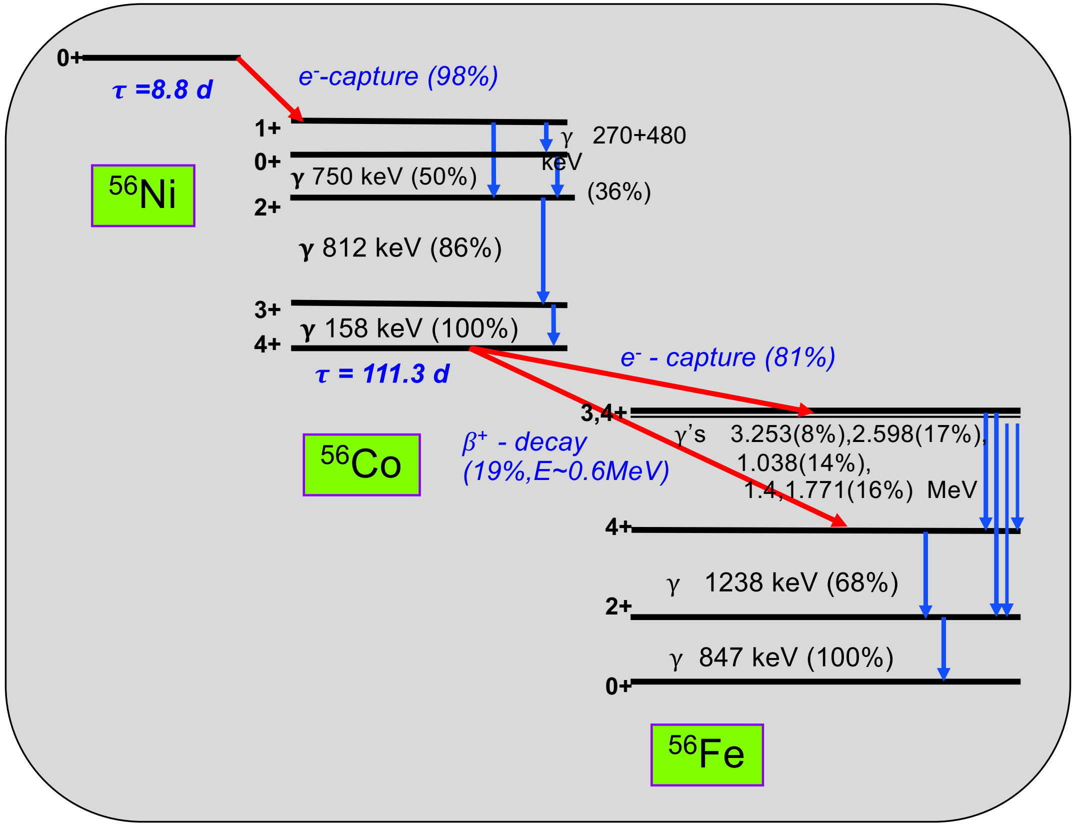
- ➢ Positron Annihilation

^{56}Ni radioactivity → γ-Rays, e$^+$ → leakage/deposit evolution

SN Ia



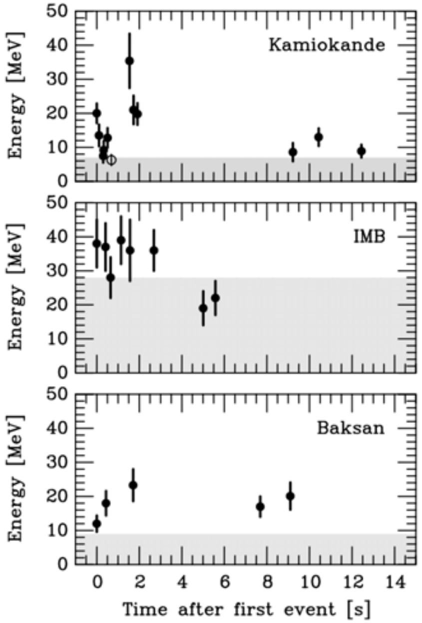




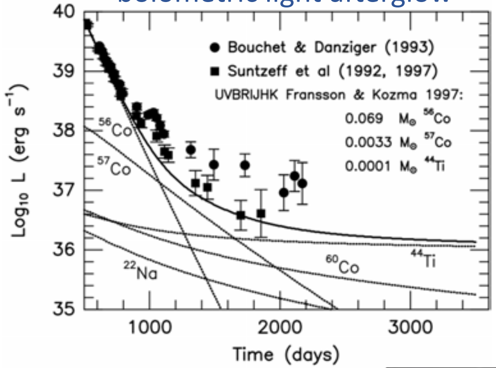
- ✓ Nuclear BE release from 0.6$M_\odot$ [C,O → ^{56}Ni] = ~1.1 10^{51} erg (>2*BE_{WD})
- ✓ Deposit of γ rays and e+ in expanding/diluting envelope
- ✓ Re-radiation of deposited energy in low-energy (thermal) radiation

SN1987A: Gravitational Collapse Supernova

- Witnessing the final core collapse of a massive star of mass 22 $M_\odot$ in Feb 1987

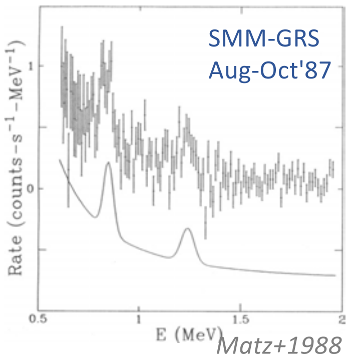


bolometric light afterglow

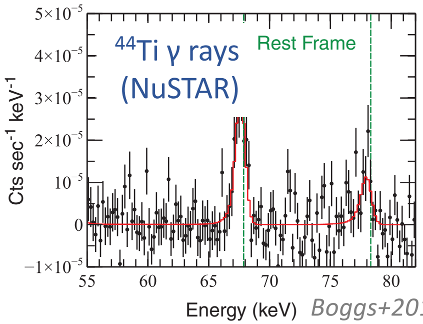


- Witness neutrino burst from core collapse

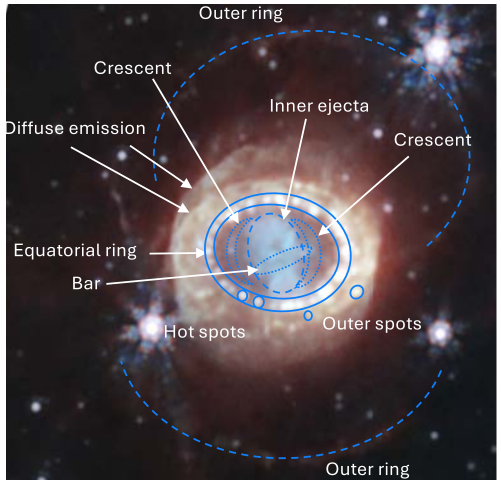
- Witness radioactively-powered SN afterglow and γ rays as its source



Matz+1988



Boggs+2015



CSM, dust, ejecta (ALMA)

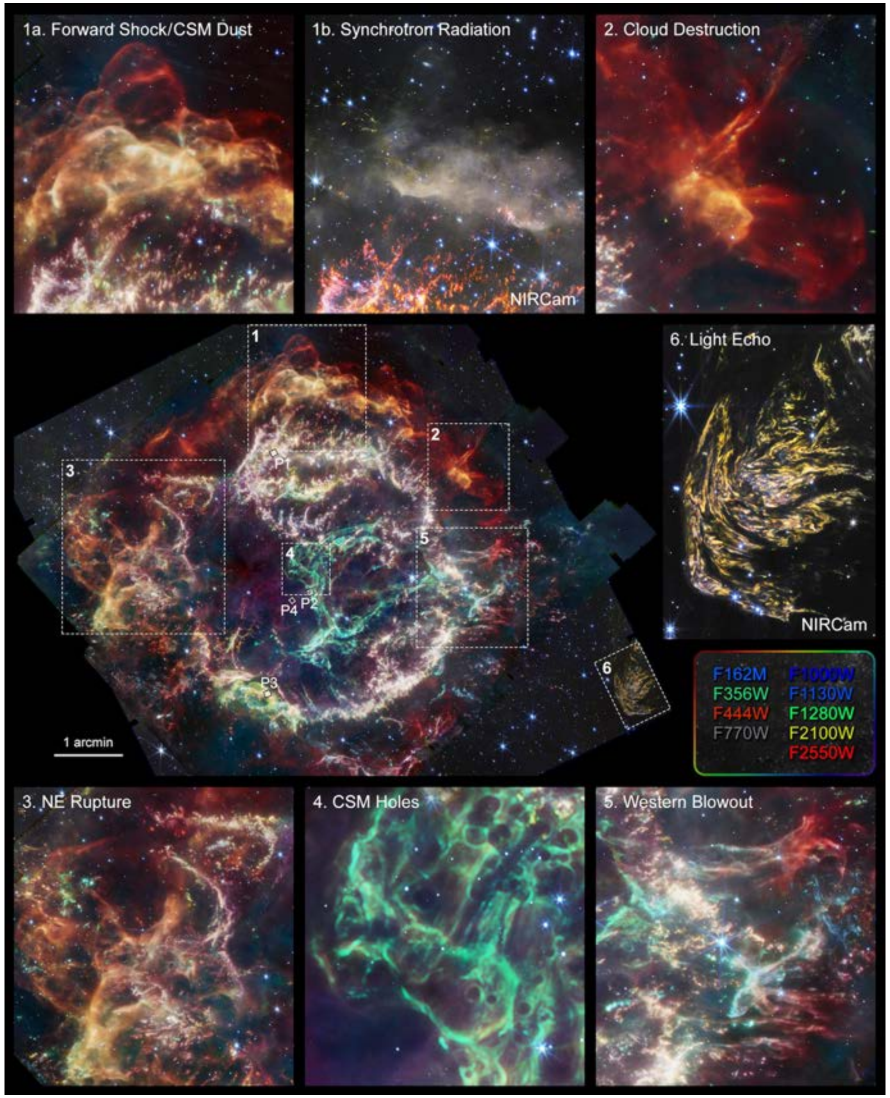
Matsuura+2024

Cas A with JWST

The Cas A SNR displays a great variety of features that reflect the ccSN explosion history and dynamics

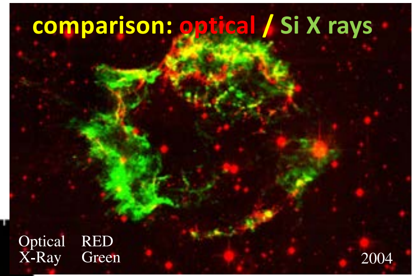
- interaction of the SN shock with surrounding CSM
  - shock and dust
  - synchrotron emission
  - destruction of ISM clouds
- internal dynamics of the expanding remnant
  - CSM structure remains
  - explosion asymmetry remains
  - RT lobes
  - jets
  - reverse-shocked ejecta
- light echoes

Milisavljevic+2023



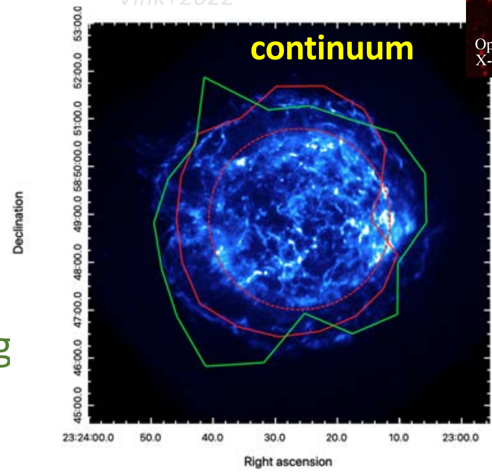
Cas A in X rays

- Cas A SNR composition and dynamics is reflected in X rays
  - ➢ interaction of the SN shock with surrounding CSM
    - ✓ shock acceleration (e^-)
    - ✓ synchrotron emission, non-thermal Bremsstrahlung
  - ➢ composition of remnant



Patnaude&Fesen2014

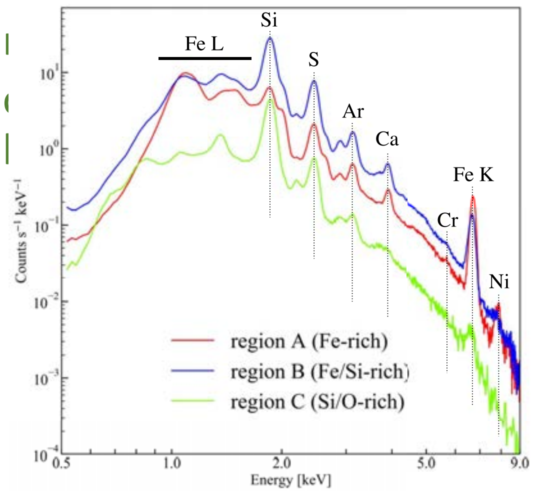
Vink+2022



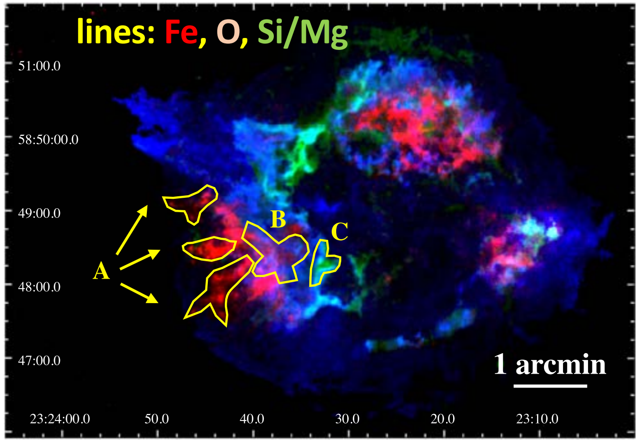
➔ complex shock dynamics

➔ overturn of ejecta material (shells)?

0.9- 9 keV, Chandra



Tsuchioka+2022



Beyond X rays: Locating the inner Ejecta in Cas A

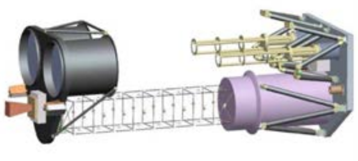


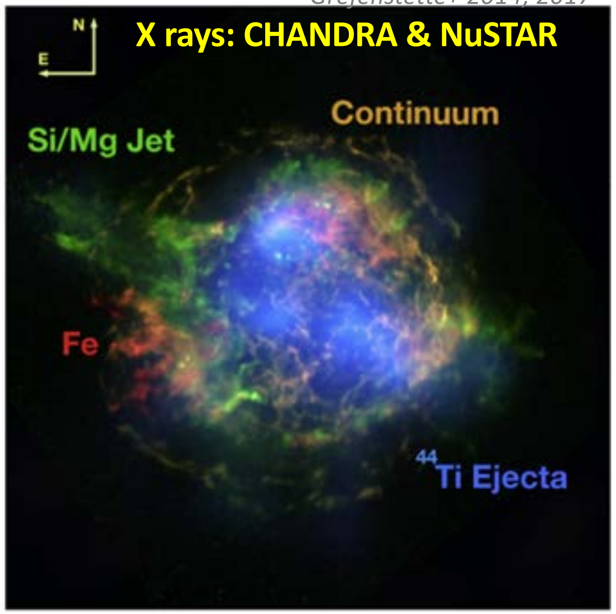
Fig. 1. NuSTAR telescopes in deployed configuration

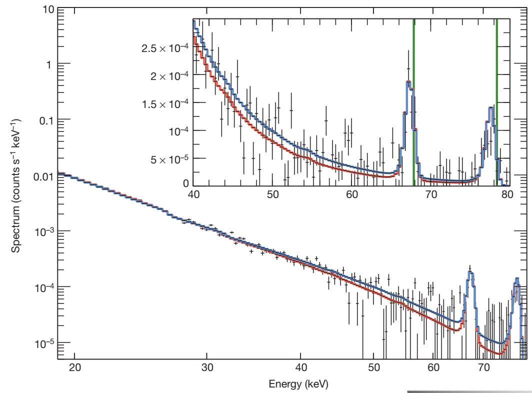
NuSTAR Imaging in 3-79 keV; ^{44}Ti lines at 68,78 keV

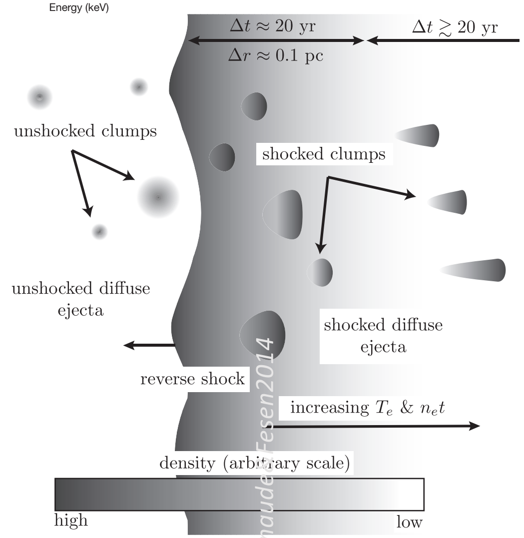
✓first mapping of radioactivity in a young SNR

- Both ^{44}Ti lines detected
- redshift ~0.5 keV
  → 2000 km/s asymmetry
- ^{44}Ti flux consistent with earlier measurements
- Doppler broadening: (5350 ±1610) km s^{-1}
- Different from Fe-X rays!!

Grefenstette+ 2014; 2017







Patnaude Fesen2014

✓^{44}Ti→ TRUE locations of inner-SN ejecta

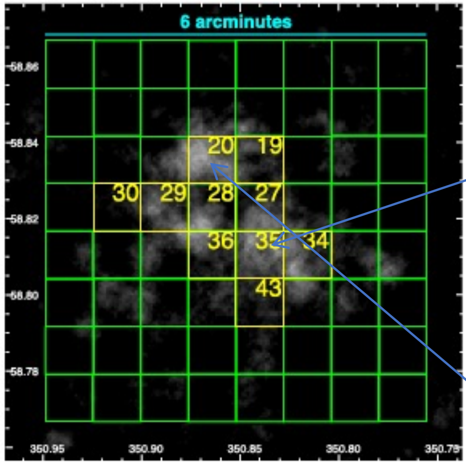
✓atomic-line X-rays are biased from ionization of plasma by reverse shock

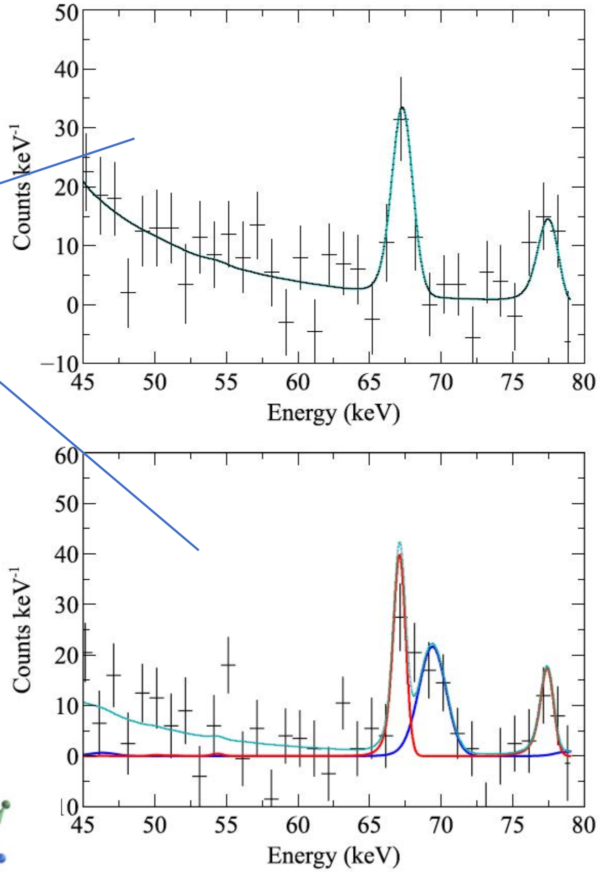
NuSTAR details on ^{44}Ti in Cas A

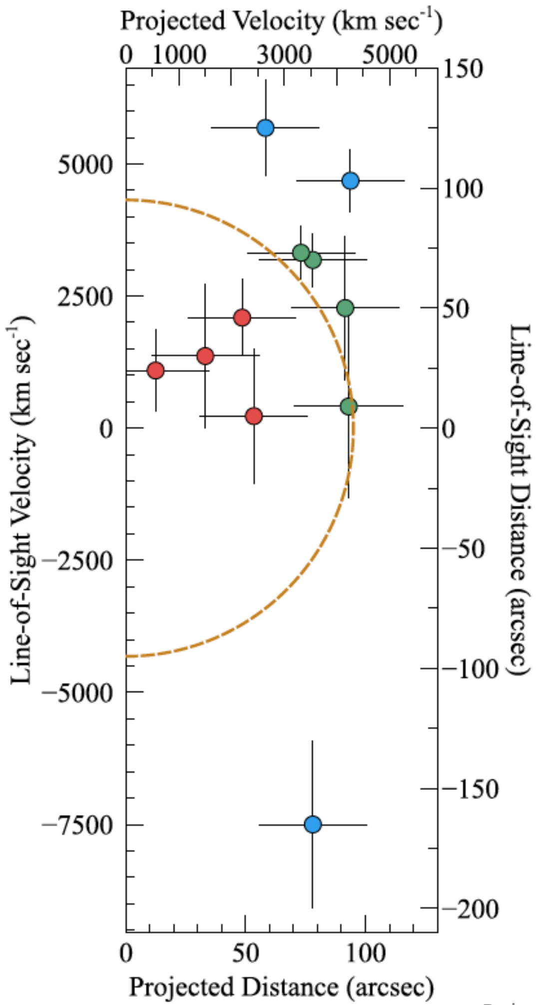
NuSTAR FOV ≈ $\emptyset_{Cas\ A}$

- Imaging resolution allows to spatially resolve Cas A's ^{44}Ti:

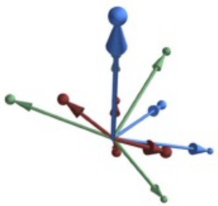
2.4 Msec NuSTAR campaign
Grefenstette et al. 2017



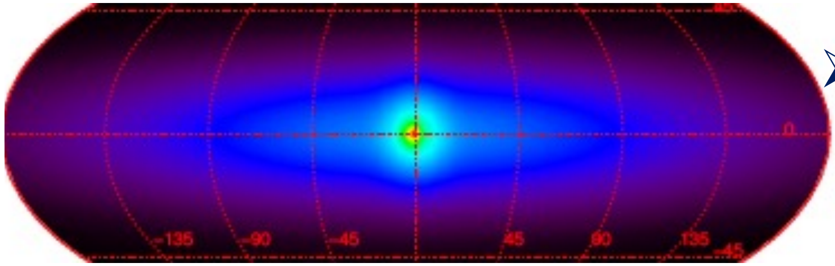




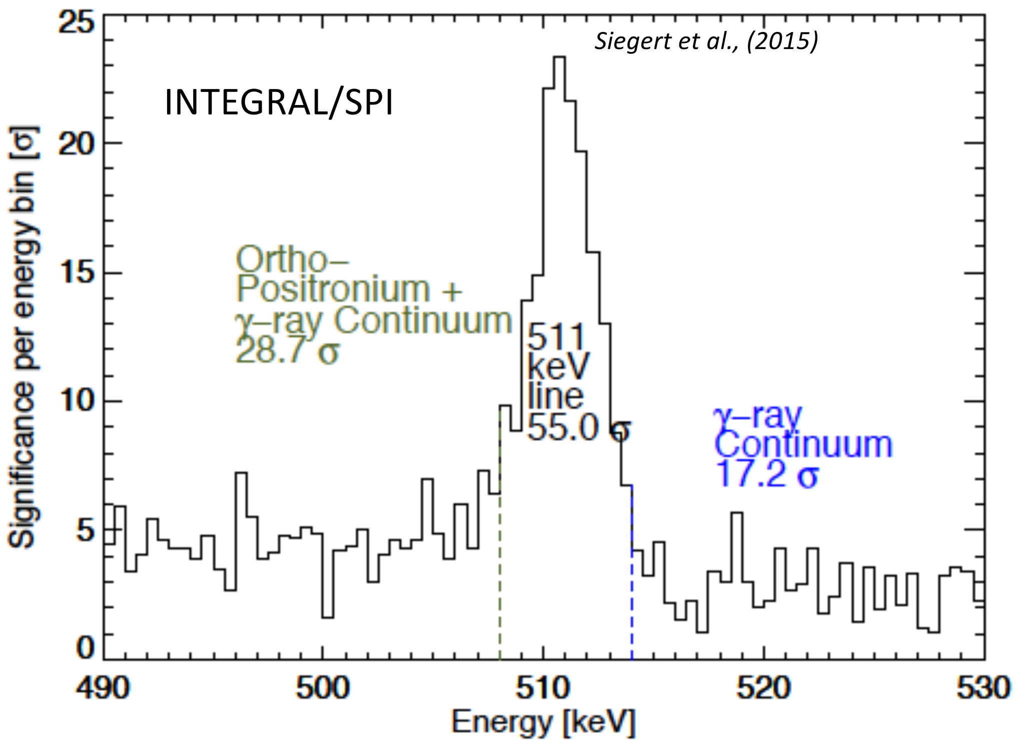
→ motion away from us, and in clumps

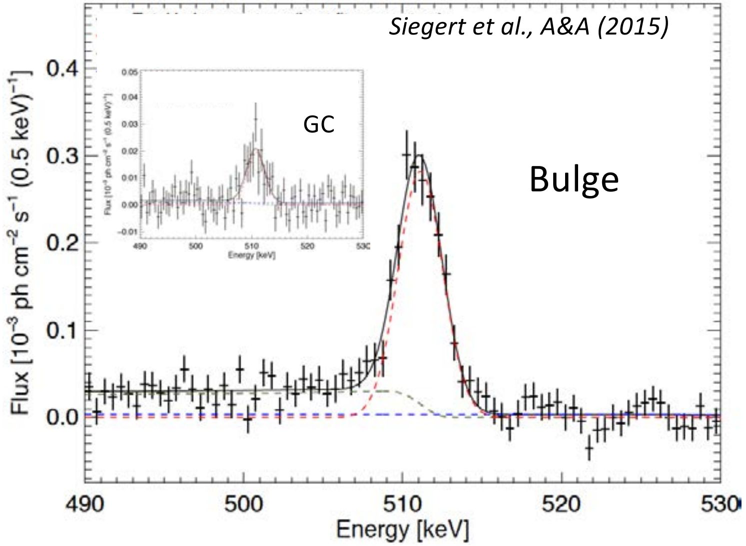


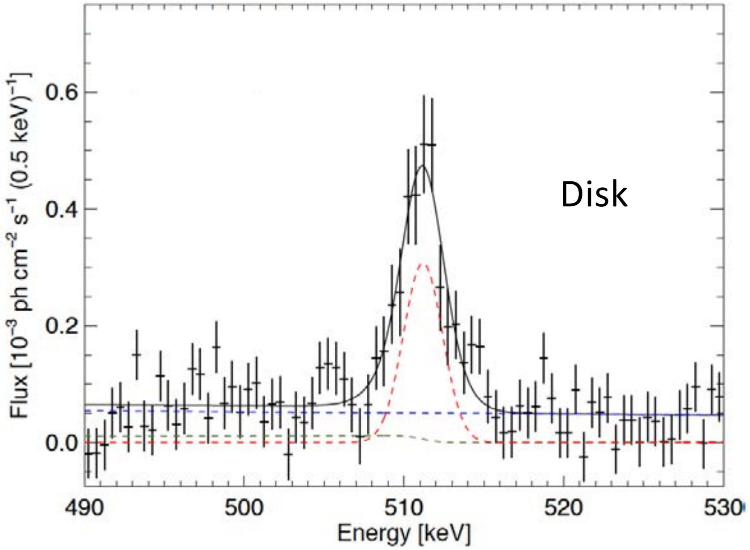
Positron annihilation within our Galaxy



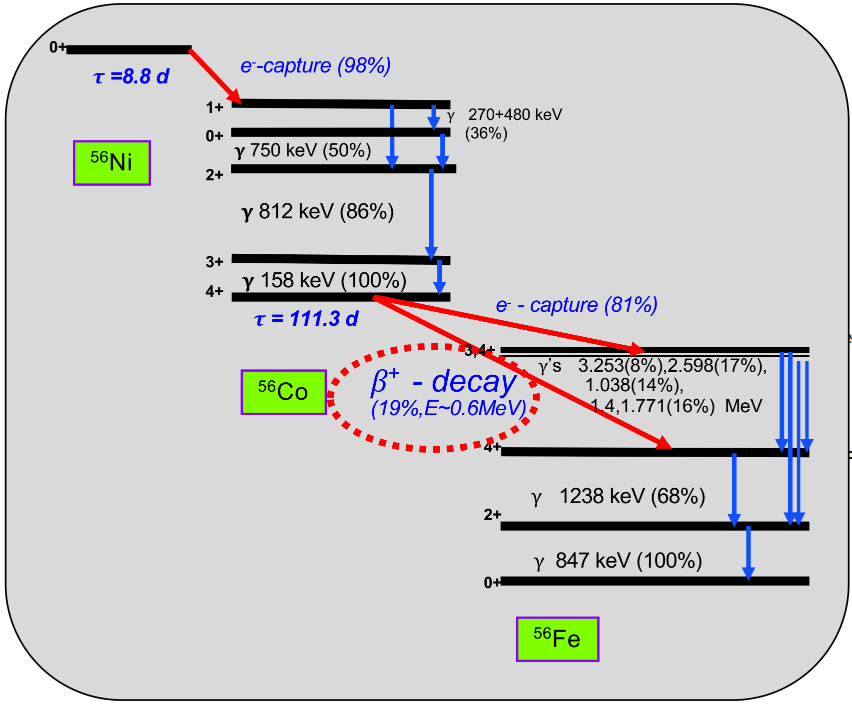
- Derive/discriminate spectra from different regions

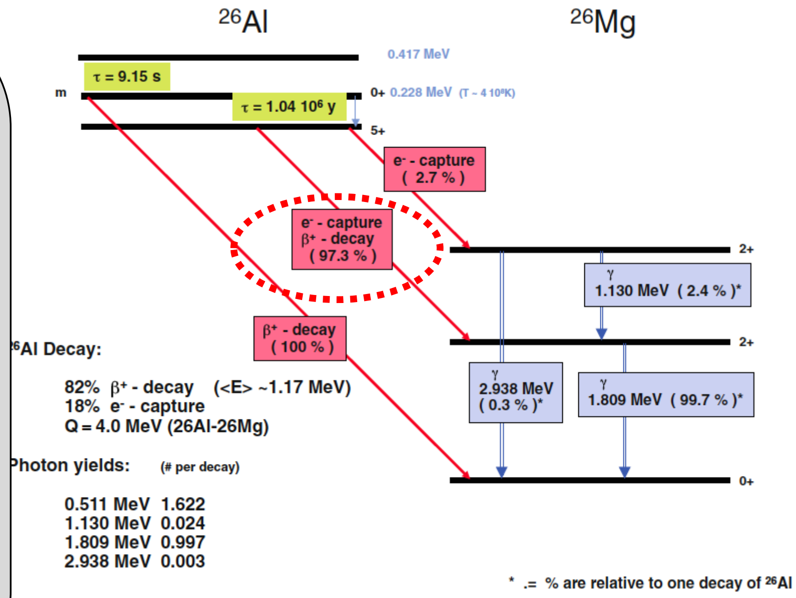






radioactive decay → energy sources = γ rays and positrons

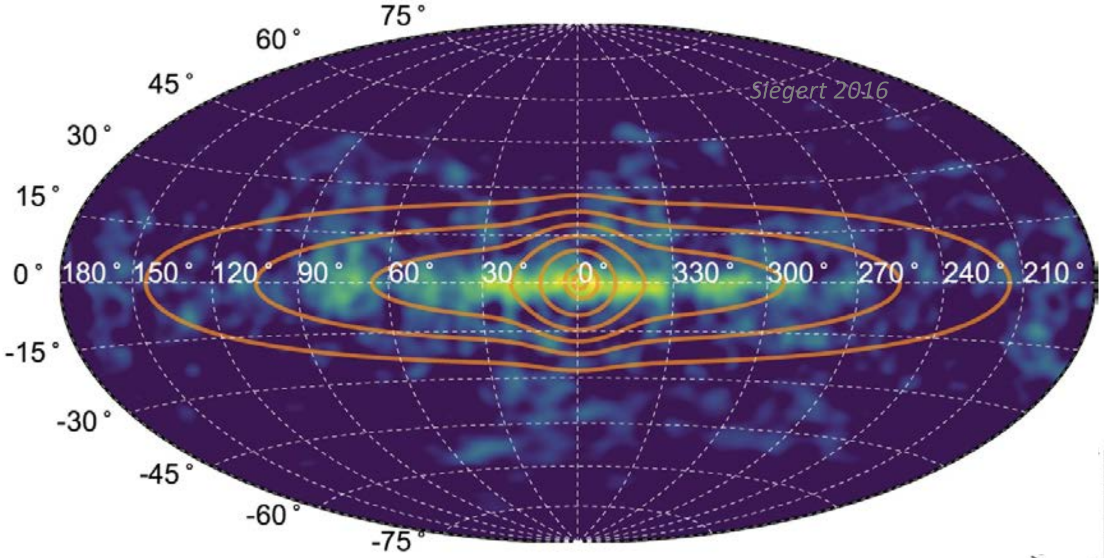


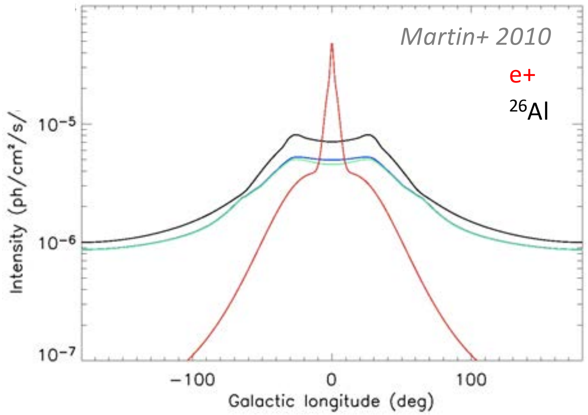


photons *and positrons* may escape into interstellar medium

The Galactic Positron Annihilation

Is it all from ^{26}Al?

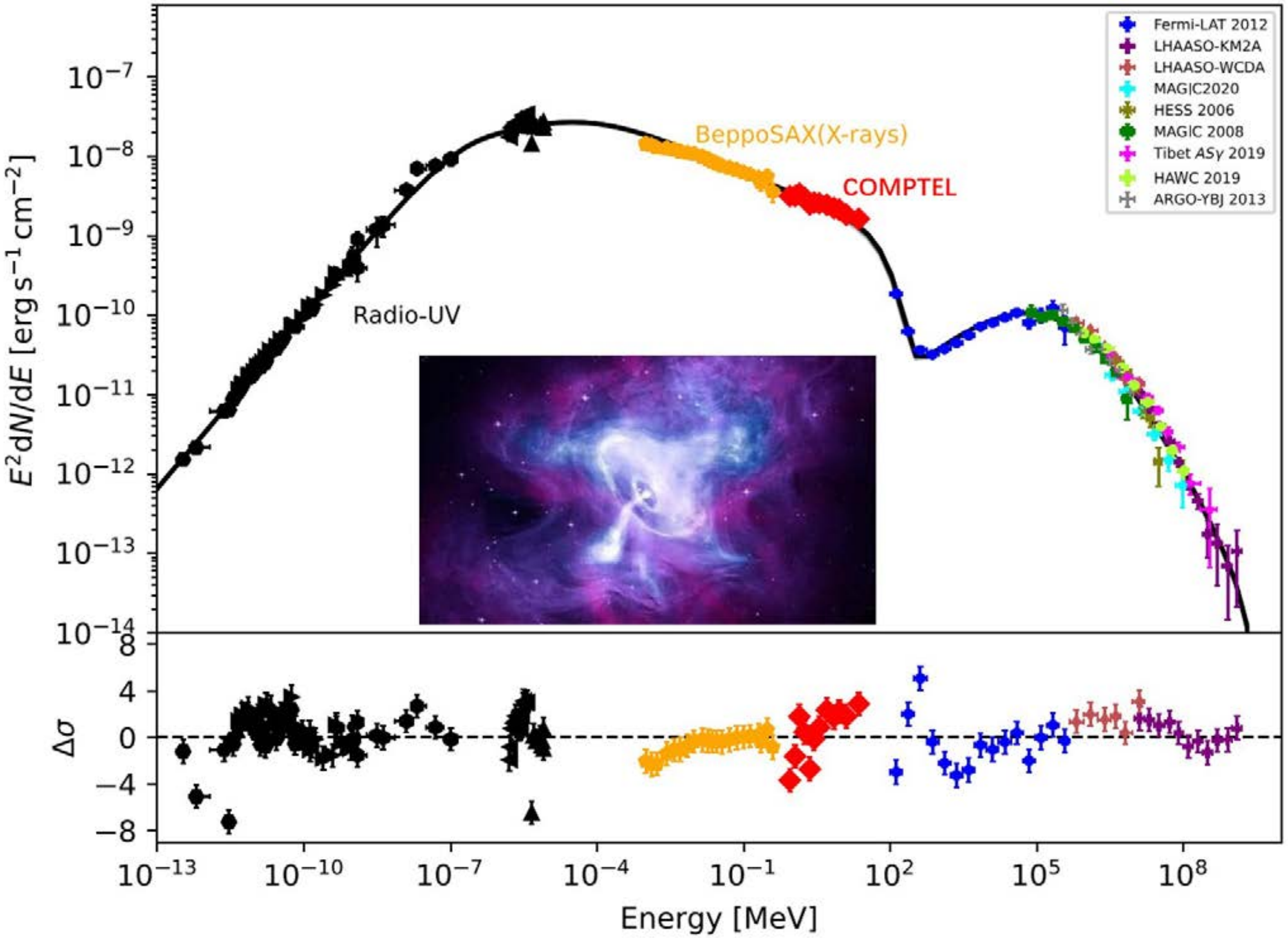


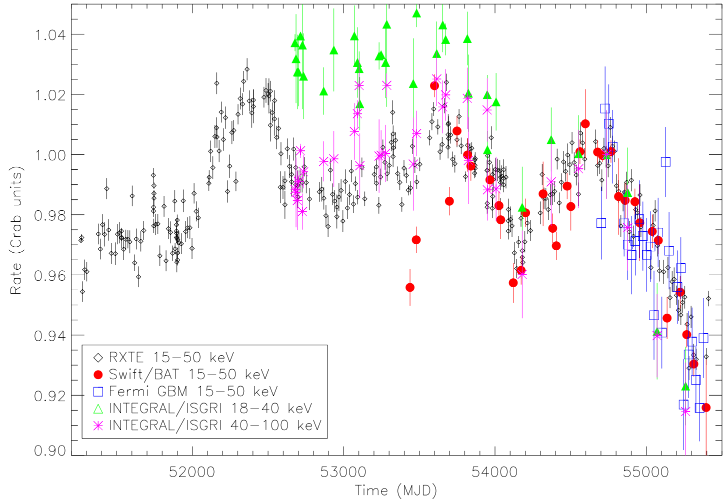


Morphology of emissions is different

→ annihilation astrophysics + other sources

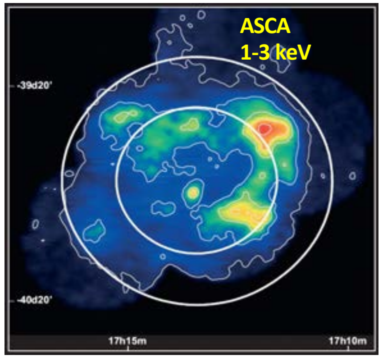
Crab: the standard high-energy source

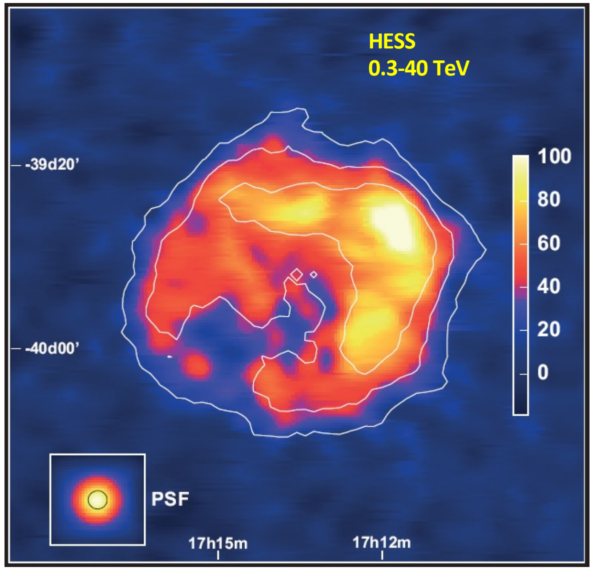




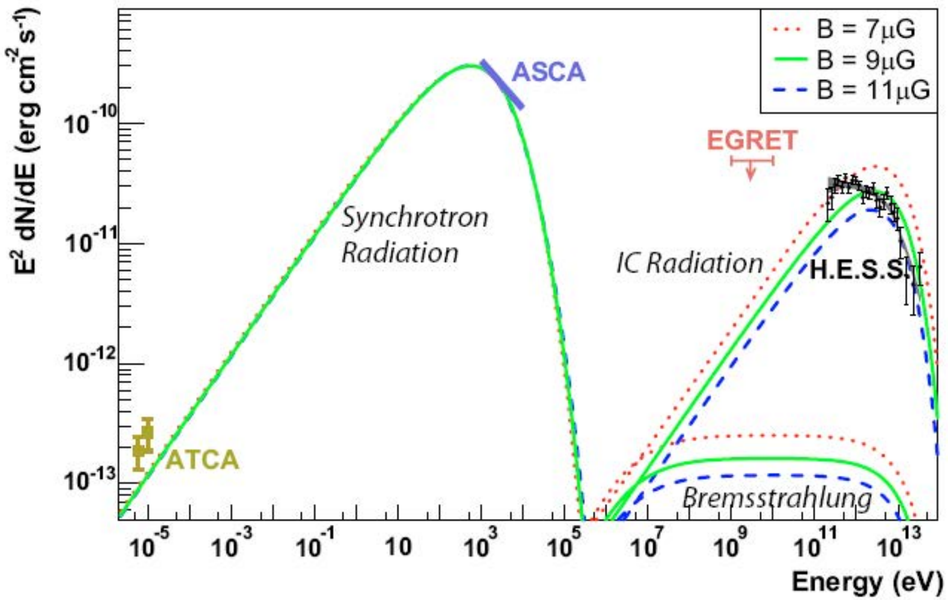
- Emission over entire e.m. spectrum
  - μeV... PeV = 21 o.o.m.
  - different processes, electrons mostly causing the emission
- Gamma-ray intensity appears to "flicker"

Cosmic-Ray Acceleration in SNR RX J1731.7

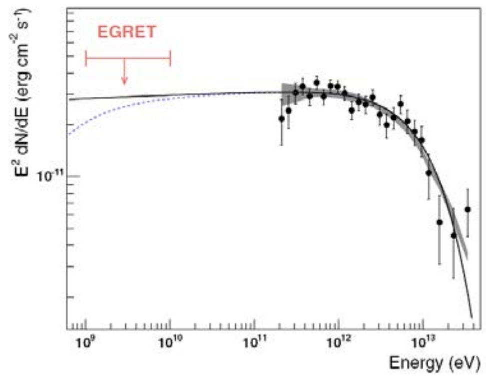




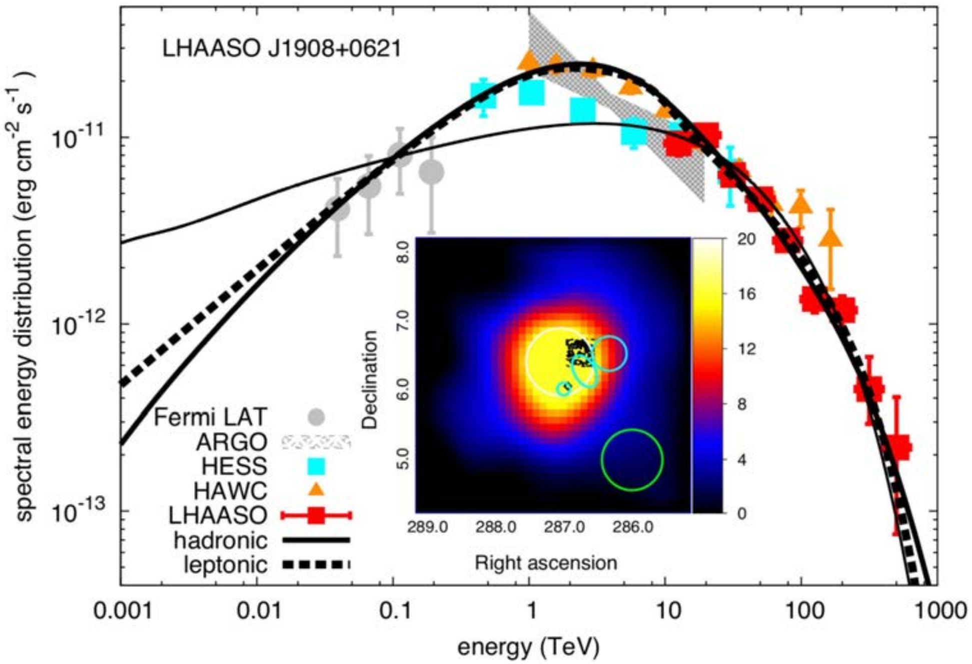
Aharonian et al. 2006



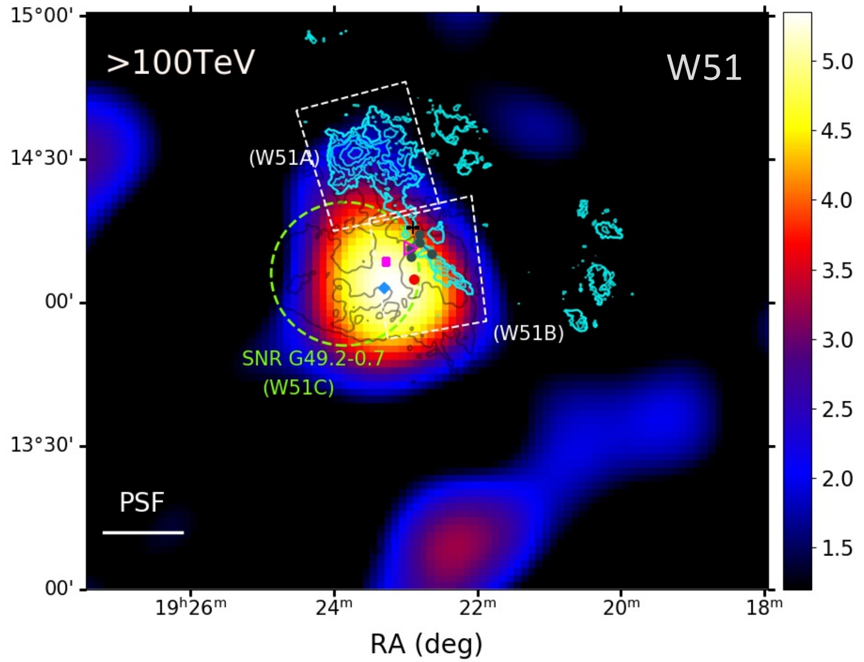
- ➢ TeV Emission Mapped to Conform to SNR X-ray Morphology
  - ✓ Identical Particle-Acceleration and γ-ray Production Regions
- ➢ Gamma-ray Spectrum is rather Flat at TeV Energies
  - ✓ IC Leptonic Model Seems OK;
    Proton Acceleration Origin more Plausible (?)
  - ✓ Systematic Uncertainties (magnetic field, …)

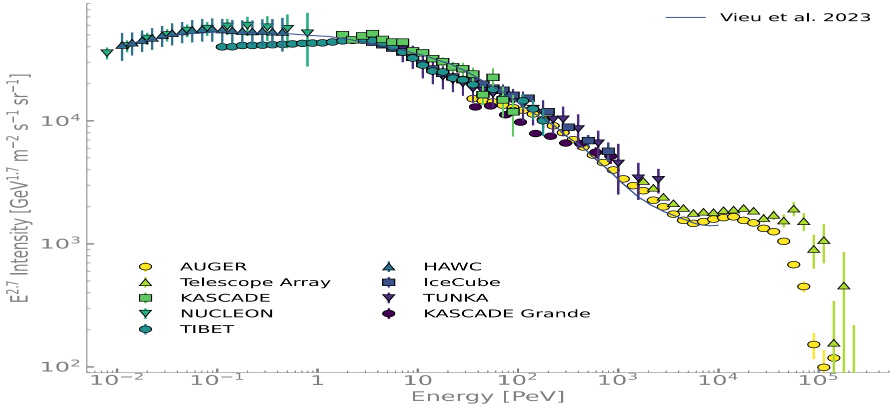


Observations of PeVatrons: Cosmic-Ray Accelerators in the Galaxy



LHAASO collab. 2024

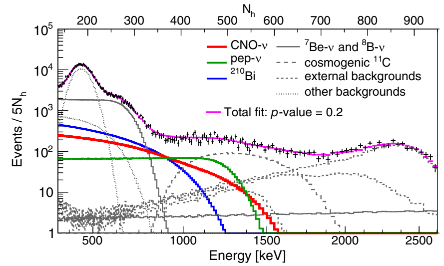




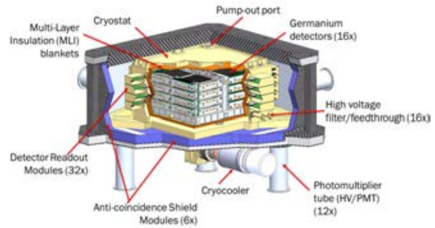
- ~PeV Emission confirms SNR being particle accelerators to PeV energies
  - e^- energy losses make leptonic models unlikely
  - turn-off of p spectrum >200 PeV?
- Proton origin of γ rays more plausible
  - Systematic offset towards molecular clouds in W51 suggest 'target model'

(W51 SRF @ 5.5 kpc)

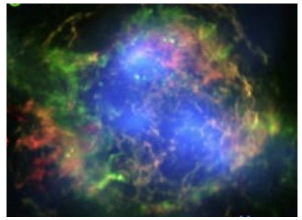
High-Energy Astrophysics- Summary



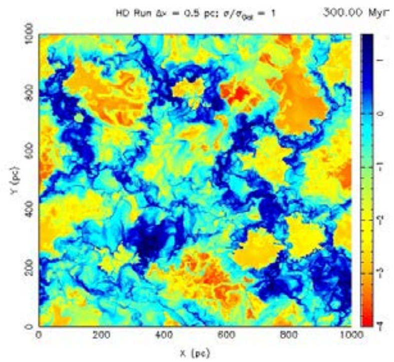
- ➢Radiation processes from nuclear transitions are superimposed on charged-particle processes of a variety



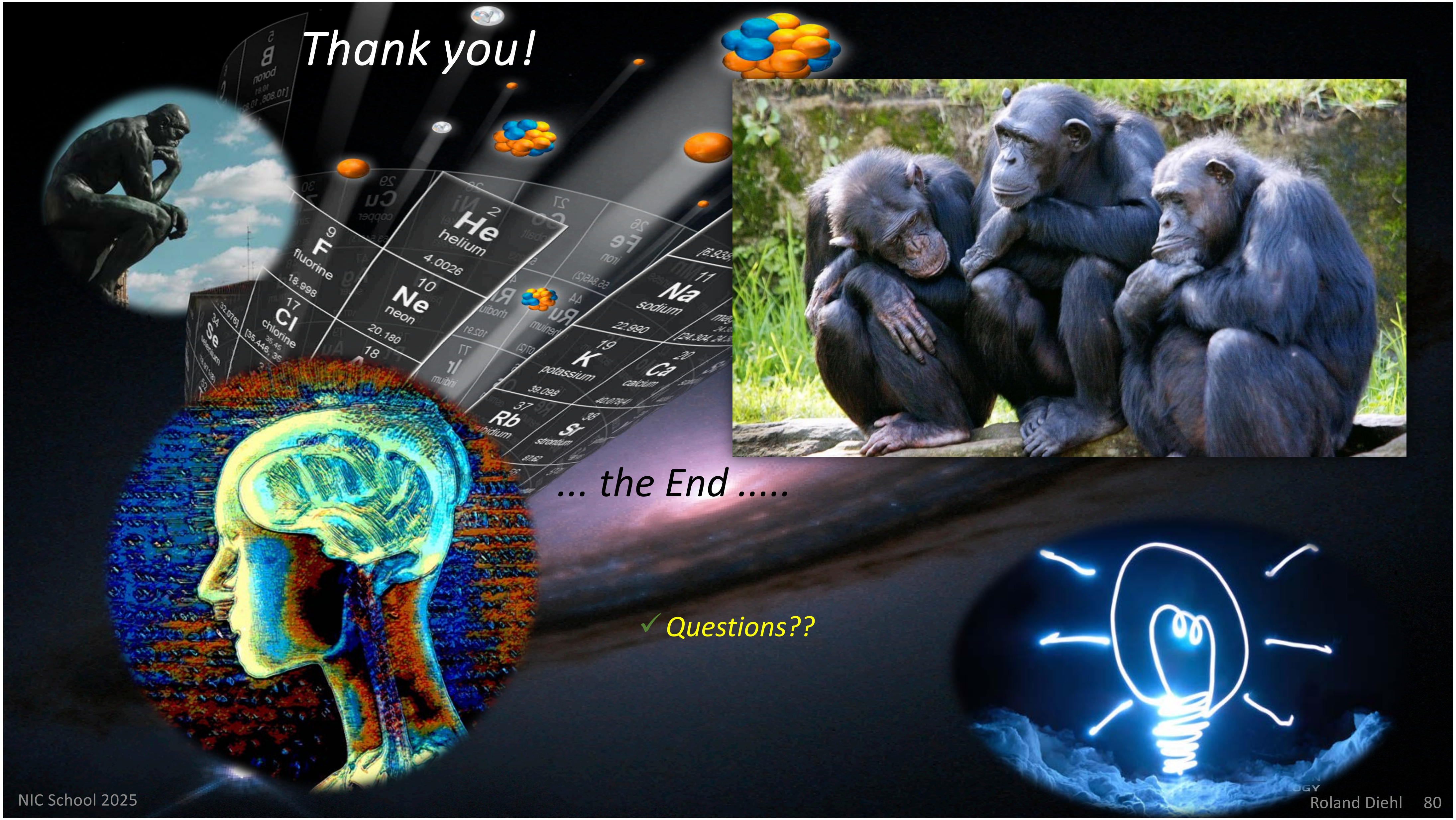
- ➢Instruments and their detectors are complex devices measuring multiple interactions of photons with materials, simultaneously discriminating against backgrounds



- ➢Cosmic nuclear-reaction sites have revealed several tantalising direct signals in high-energy instruments



- ➢A variety of astronomies as well as theory and astrophysical models are required to extract knowledge about high-energy astrophysics objects


Thank you!
... the End .....
✓ Questions??