History and Status of MeV gamma-ray astrophysics

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EMMI-WS, GSI, Dec 7-8, 2011

Omnipresent MeV photons in our natural environment

... a promise for high-energy astrophysics

(high-energy sources generate large fluxes of γ-rays)

but

... a curse for experimental work!

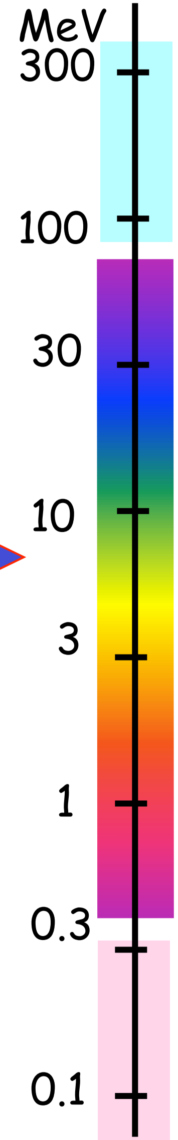
(detectors and spacecraft are flooded by background)

Astrophysics in the ‚MeV‘ region

Nuclear Processes

nuclear γ-lines

nuclear binding energy
~ 8 MeV



cosmic accelerators

non-thermal continuum

π^o – decay → 2γ
Bremsstrahlung,
synchro-cyclotron radiation,
Inverse Compton scattering

„the starting line of acceleration...“

electron restmass 0.511 MeV

Astrophysics in the ‚MeV‘ region

Nuclear processes & Nucleosynthesis

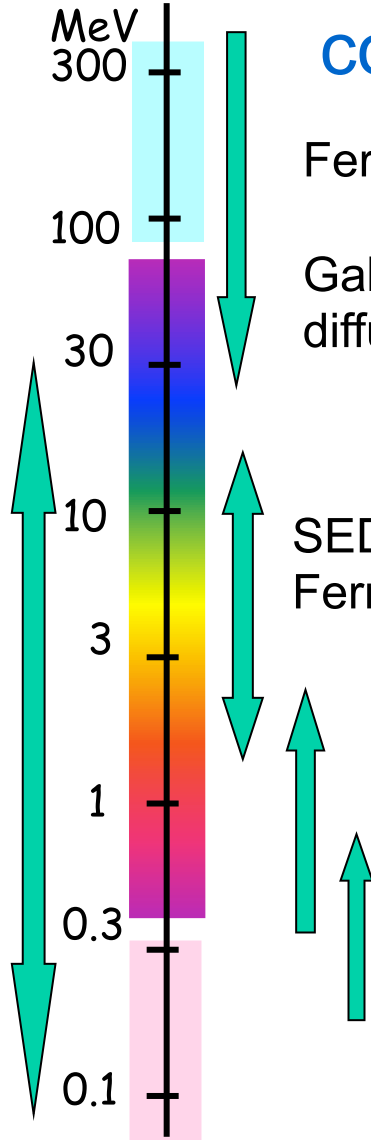
stellar & solar nuclear reactions

galactic radioactivity ^{26}Al; ^{60}Fe,
CRs & ISM

SNe
young SNRs ^{44}Ti

511 keV: novae; solar flares;
GC sources

nuclear resonance absorption



cosmic accelerators

Fermi LAT sources: pulsars, unids,
binaries, AGN, etc.

Galactic and extragalactic
diffuse background

SED maxima of many
Fermi/COMPTEL Blazars

non-thermal spectra
in black-hole binaries,
micro-quasars

GRB: spectra & polarization

History: 1940's – 1960:

The status of particle physics, cosmic ray (CR) research, and radio astronomy raised the possibility that gamma-ray observations can solve questions like:

- the origin of cosmic rays?
- the photon fraction in the CR beam?
- what powers the strong galactic radio emission?
- are there gamma-ray sources in the sky and what might be their physics?
- Is there antimatter in the Universe?

1940's – 1960:

The potential of cosmic gamma radiation from the interaction of energetic particles (cosmic rays) with matter, fields, and photons

Source processes:
Compton Scattering: Feenberg & Primakoff, Phys. Rev. 73, 449 (1948)
Meson production: Hayakawa, Prog. Theor. Phys., 8, 571 (1952)
Bremsstrahlung: Hutchinson, Phil. Mag., 43, 847 (1952)
Annihilation (e+ - e-): Anderson, Phys.Rev., 43, 491 (1933)
Nuclear transitions: excited or radioactive nuclei

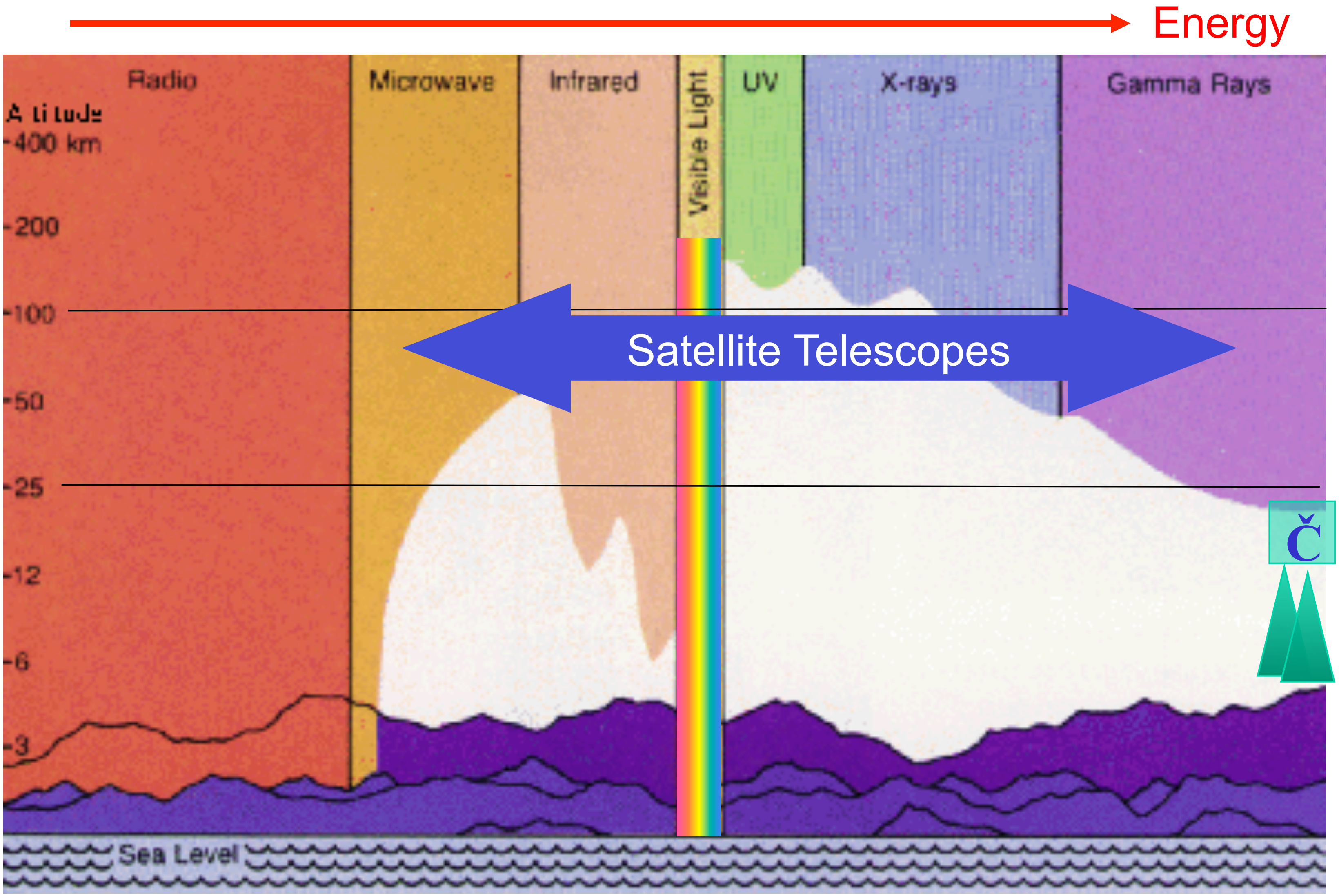
Detection:
Photoeffect (<100 keV);
Compton scattering (100kEV-30 MeV)
Pair creation (>20 MeV);
e-m Showers+Cerenkov light (>20 GeV)

Speculation on cosmic gamma-ray sources

Morrison (Nuovo Cimento, 7, 858, 1958)
(1) Synchrotron emission: $E\gamma$ > 1MeV → $(E_e/mc^2)\, B_{Gauss} > 10^{14}$
'magnetic variable stars'
(2) electron bremsstrahlung: solar flares
(3) decay of neutral π mesons
(4) de-excitation of nuclei: solar flares; radioactive debris in Crab nebula (SNRs)
(5) electron-positron annihilation: baryon symmetric universe

Pollack & Fazio (Phys.Rev., 131, 2684, 1963):
…the most probable sources of gamma rays of energy greater than 0.2 MeV are:
(1) Decay of neutral π mesons: high-energy nuclear interactions or antiparticle annihilations;
(2) electron-positron annihilations;
(3) electron bremsstrahlung
(4) synchrotron radiation (magnetic bremsstrahlung);
(5) de-excitation of nuclei
(6) Inverse Compton scattering.

Gamma-ray astronomy needs high-altitude balloon or space platforms



→ historical flux estimates: several photons / cm^2 s

present observations: confirmed for GRBs and solar flares

but about 100 times less for cosmic sources!

→ observers, failed to see the predicted intensities!

→ after a period of disapointment the development of better and larger instruments and their use on satellites produced results after ≈1970

.... how to build a good SpaceTelescope for MeV Radiation ?

- make full use of the photon interaction physics in detectors and construct systems that are selective for photons (“ efficiency “)

- measure the photon parameters (direction, energy, time) with high precision (“ resolution “)

- recognize and suppress background radiation

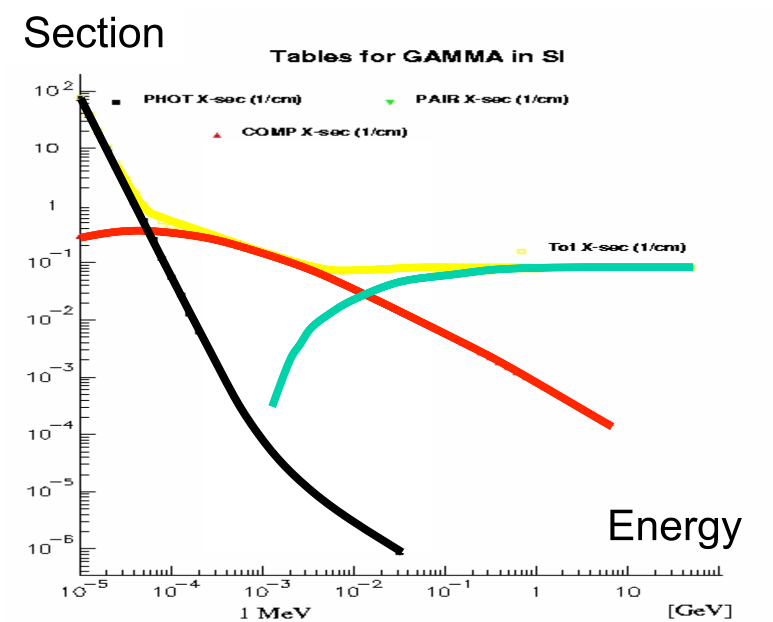
→ sensitivity

Interactions of High-Energy Photons with Matter

Type of γ Interaction / Target	Absorption	Elastic Scattering	Inelastic Scattering
Electron	**Photoelectric Effect**	Rayleigh Scattering	**Compton Effect**
Nucleon	Nuclear Photoeffect	Thomson Scattering	Nuclear Resonance Scattering
Nuclear/Electron Electric Field	**Pair Creation**	Delbrück Scattering	
Strong Field	Meson Production		

Efficiency: Detection of Gamma Radiation

Cross
Section



<u>Photoeffect(< 100 keV)</u>

Photons effectively blocked and stopped

<u>Telescopes:</u>

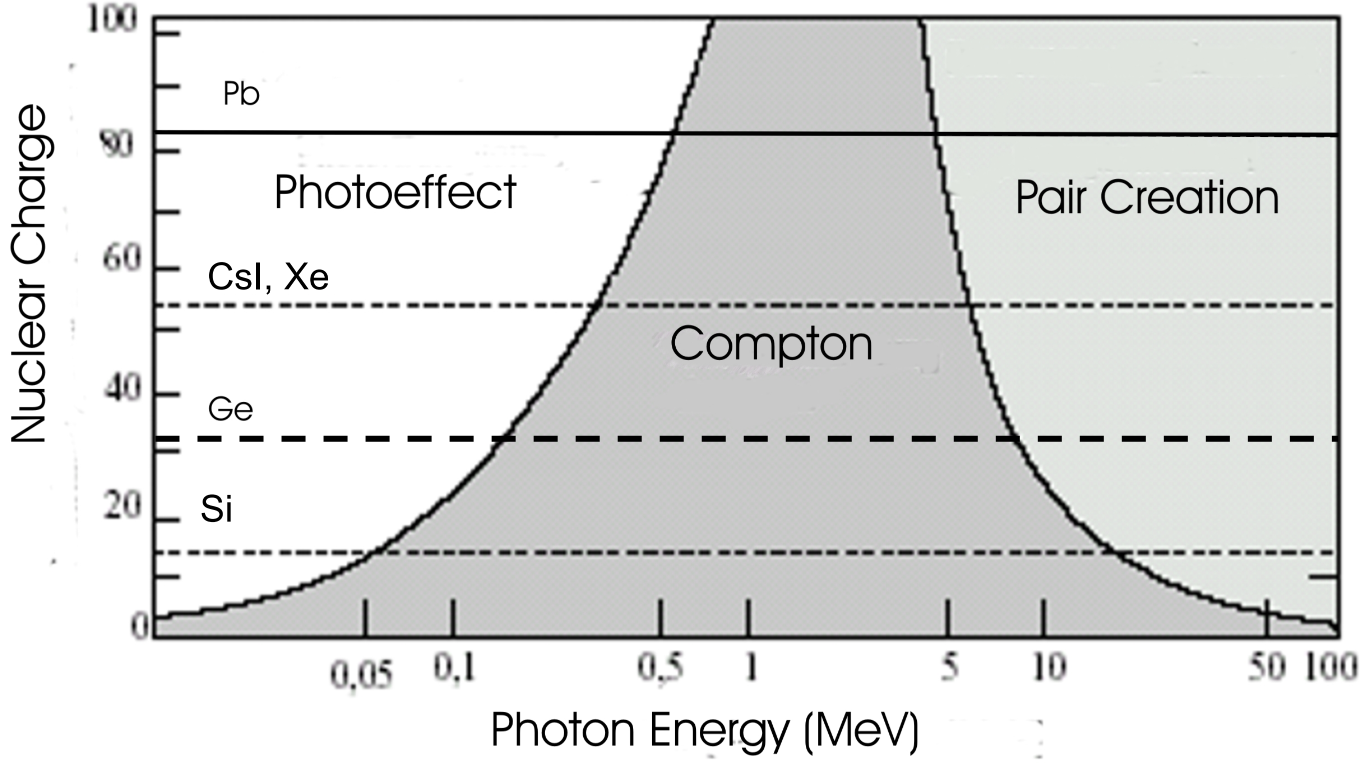
Collimators
Coded Mask Systems

<u>Compton Scattering (0.2-10 MeV)</u>
Photon Crossection Minimum
Scattered photons with long range
<u>Telescope:</u>
Compton Camera Coincidence System

<u>Pair Creation (> 10 MeV)</u>
Photons completely converted to e^+e^-

<u>Telescope:</u>
Tracking chambers to visualize the pairs

Interaction Processes vs. nuclear charge Z



Sensitivity

Source Counts: $N_s = A \, T \int I_s(E) \, \varepsilon(E) \, dE$

Geometric Area (+ Volume): limited by satellite requirements

Exposure time

Source Spectrum $\sim E^{-2}$

Efficiency

Sensitivity

Source Counts: $N_s = A\ T \int I_s(E)\ \varepsilon(E)\ dE$

Bkgnd Counts: $N_b = A\ T \int I_b(E)\ \varepsilon(E)\ dE + N_{inst}$

Instrumental Bkgnd

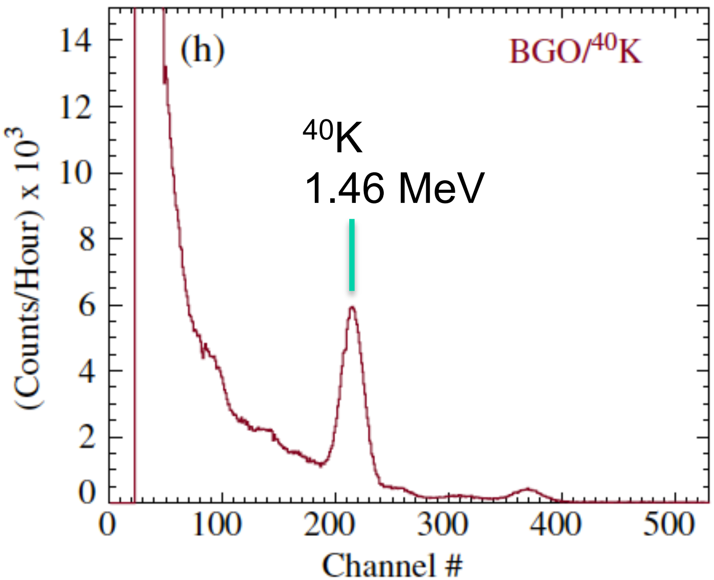
Significance: $n_\sigma = N_s / \sqrt{N_b}$

Detection Threshold:

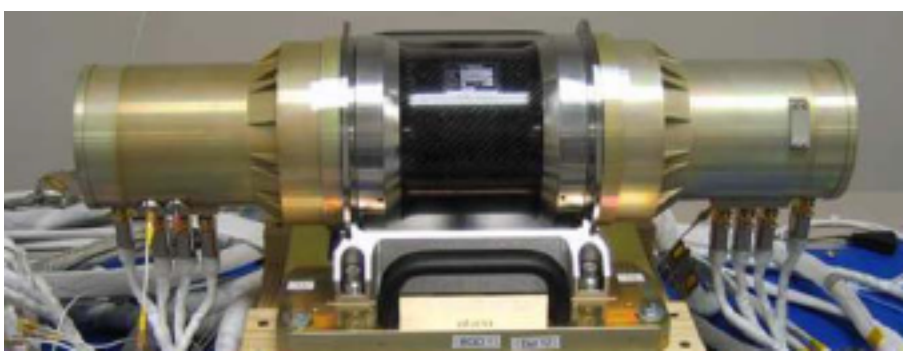
$$F_{thresh} = \frac{n_\sigma \sqrt{N_b}}{A\ \varepsilon\ T\ \Delta E}$$

γ radiation background: Fermi-GBM-BGO

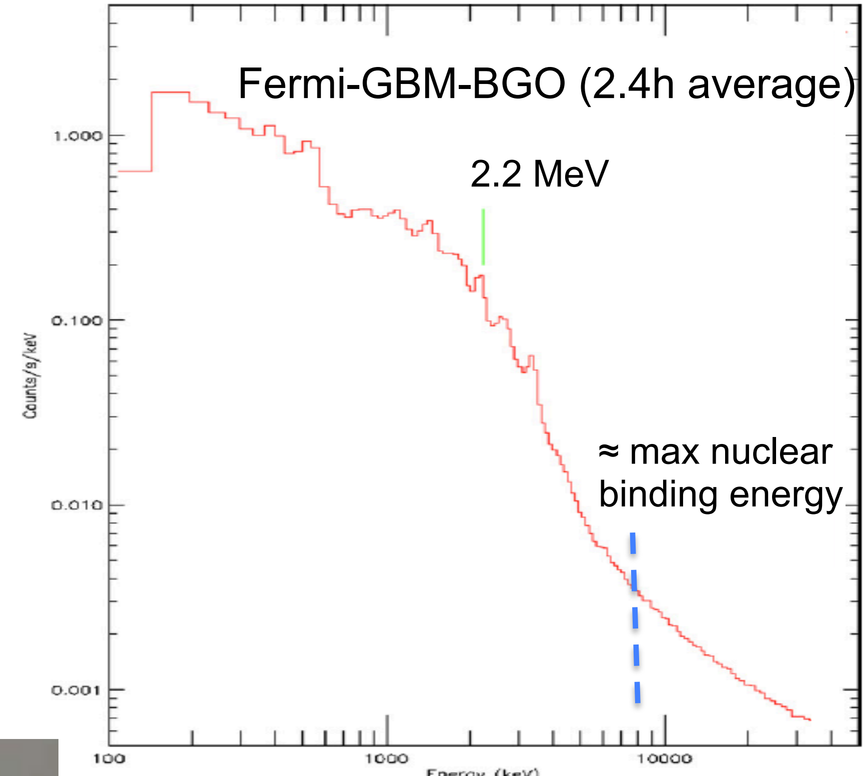
at ground level …



+ U, Th decay chains

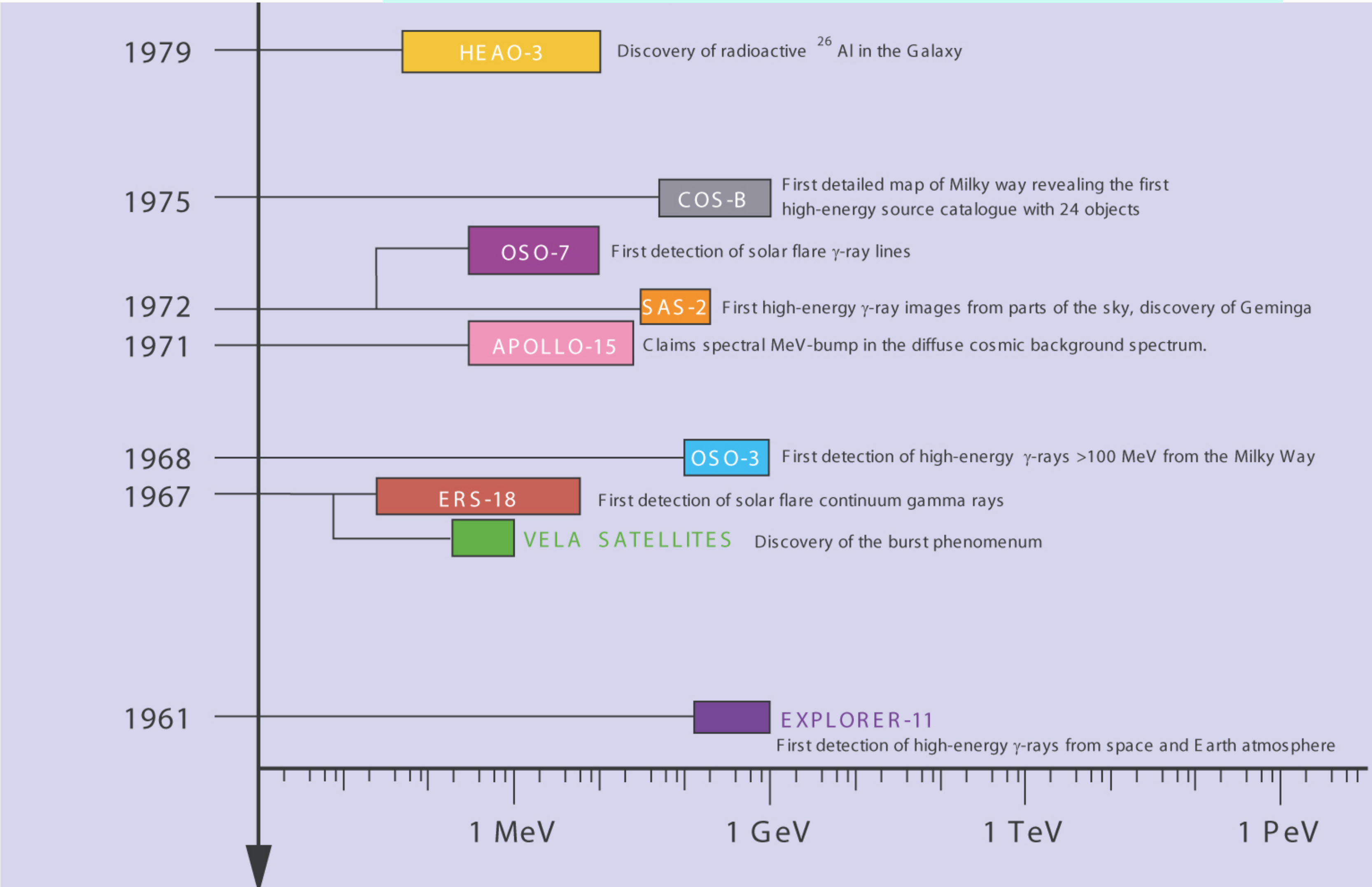


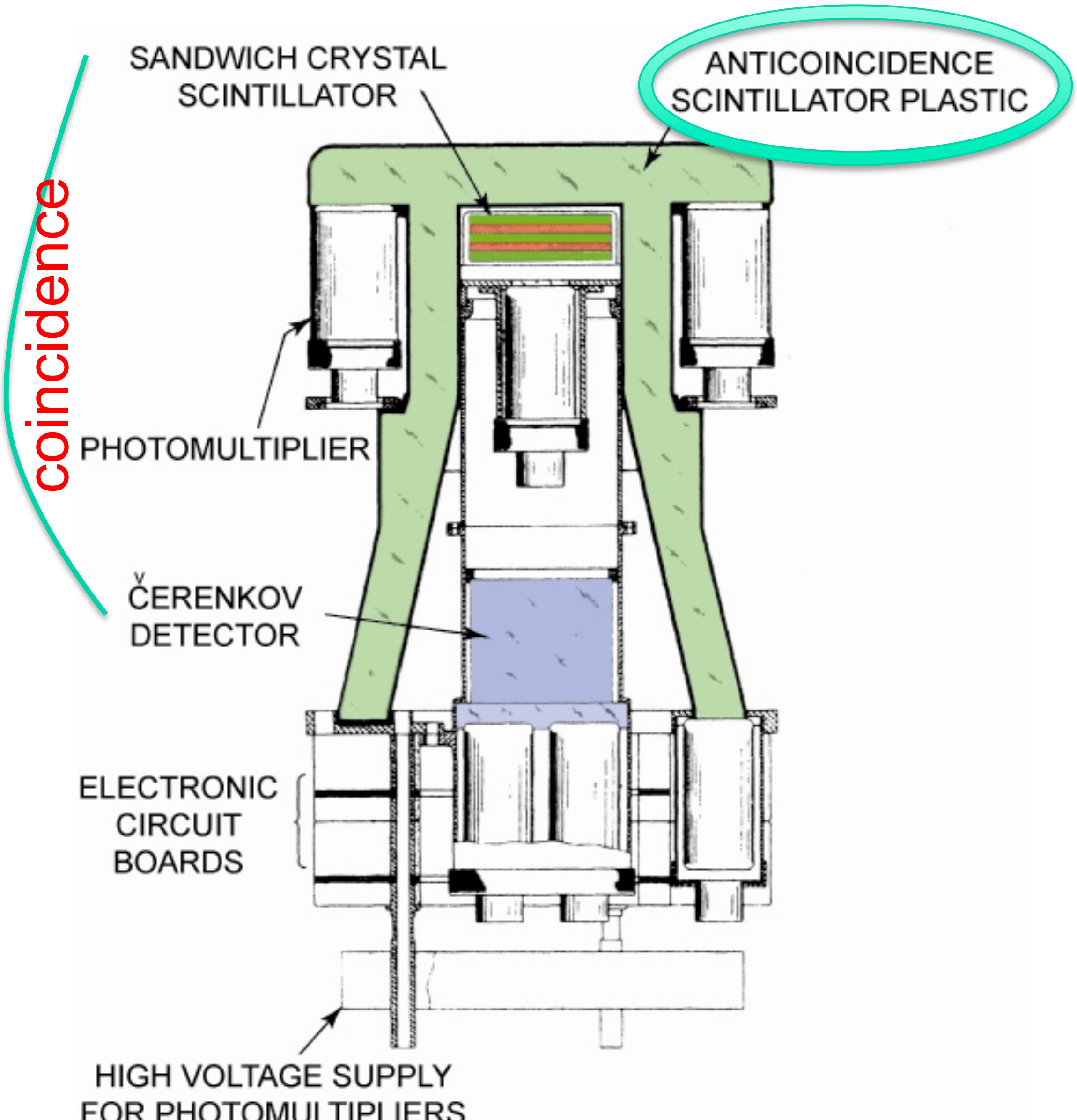
…and in space



Cosmic ray interactions, local radioactivity in spacecraft and detectors

First successful space telescopes 1960-1980:



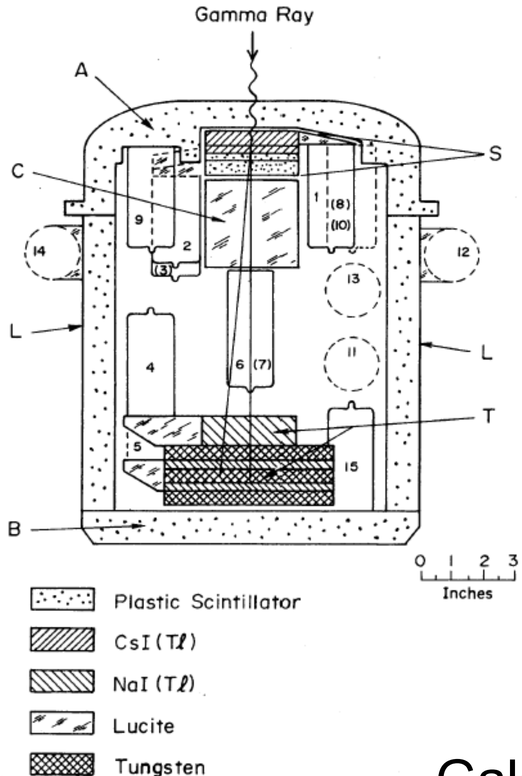


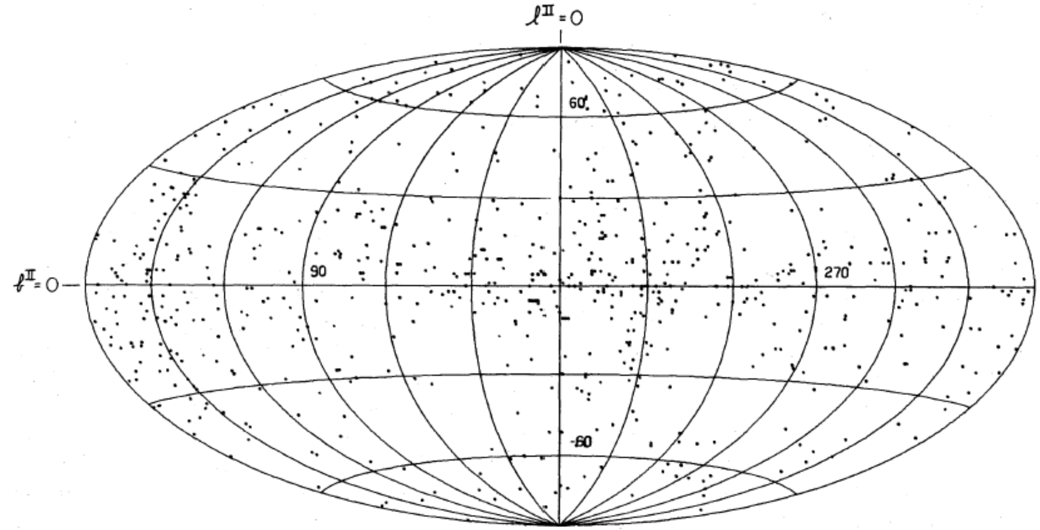
Gamma-ray detector on EXPLORER XI

Kraushaar & Clark, PRL, **8**, 106, 1962

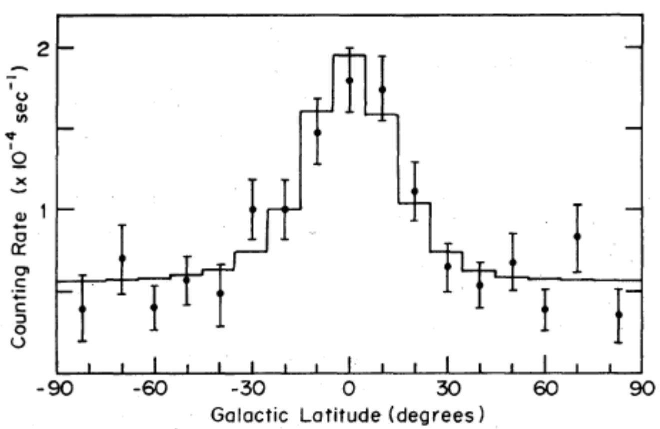
Detects first cosmic γ-rays above 100 MeV

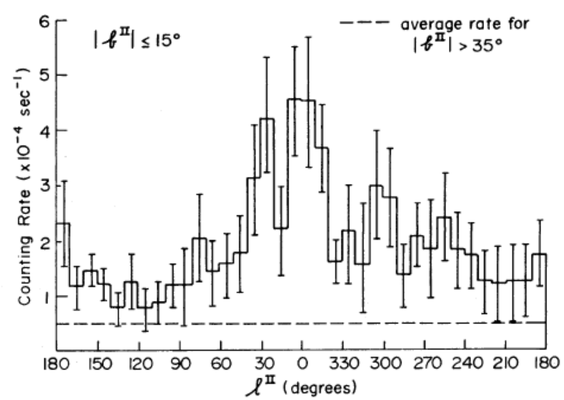
OSO-3 (1967-69)
(Kraushaar et al., ApJ, 177, 341, 1972)





Galactic Map of 621 sky events (E>50MeV)

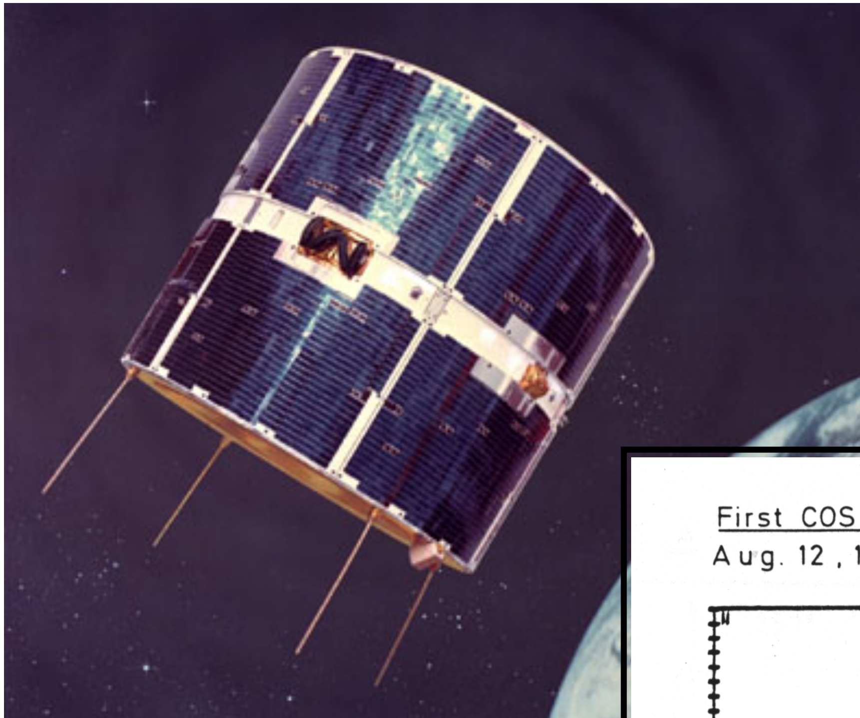


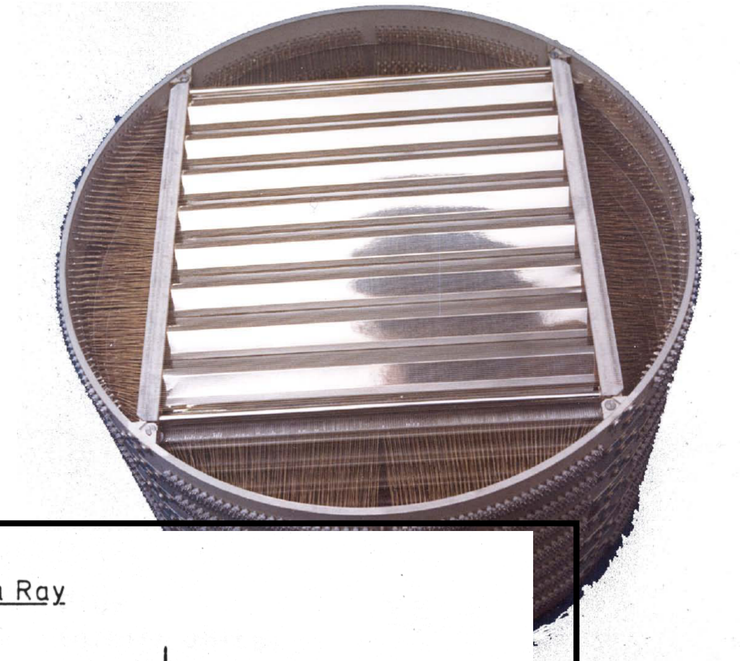


Latitude Distrib. inner Galaxy

Longitude Distrib.

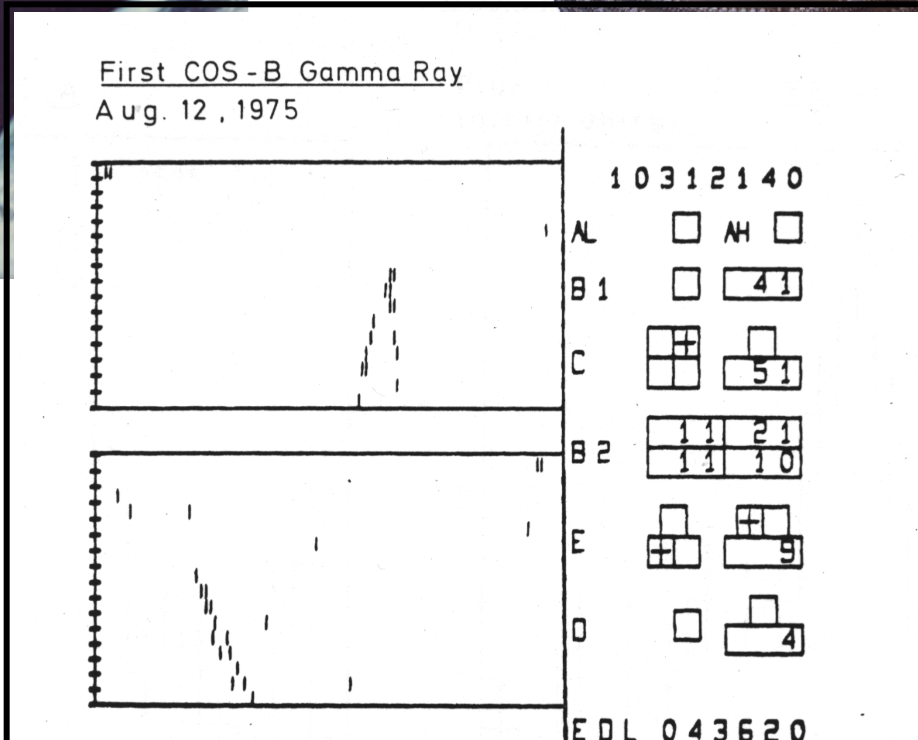
COS-B: 1975-81



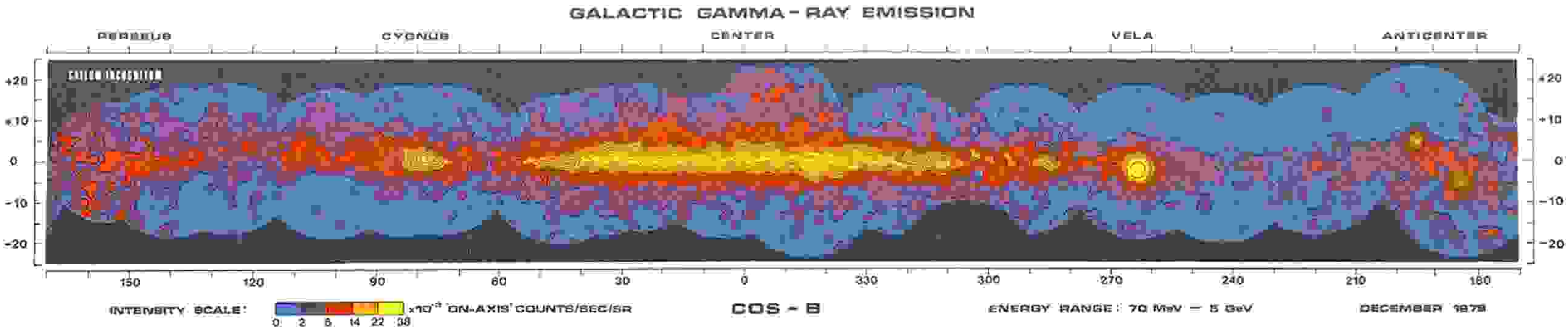


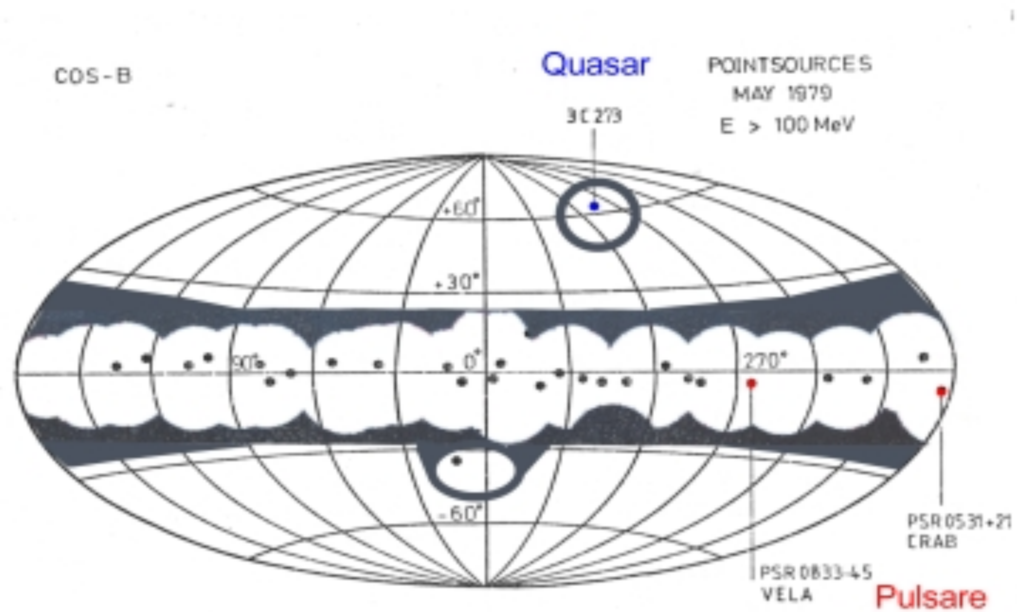
Single Experiment Satellite devoted to Gamma-Ray Astronomy:

Collaboration:
Noordwijk (ESTEC), Leyden (Uni), Paris (Saclay), Garching (MPE), Milano, Palermo



Most important results from COS-B: galactic survey, pointsources



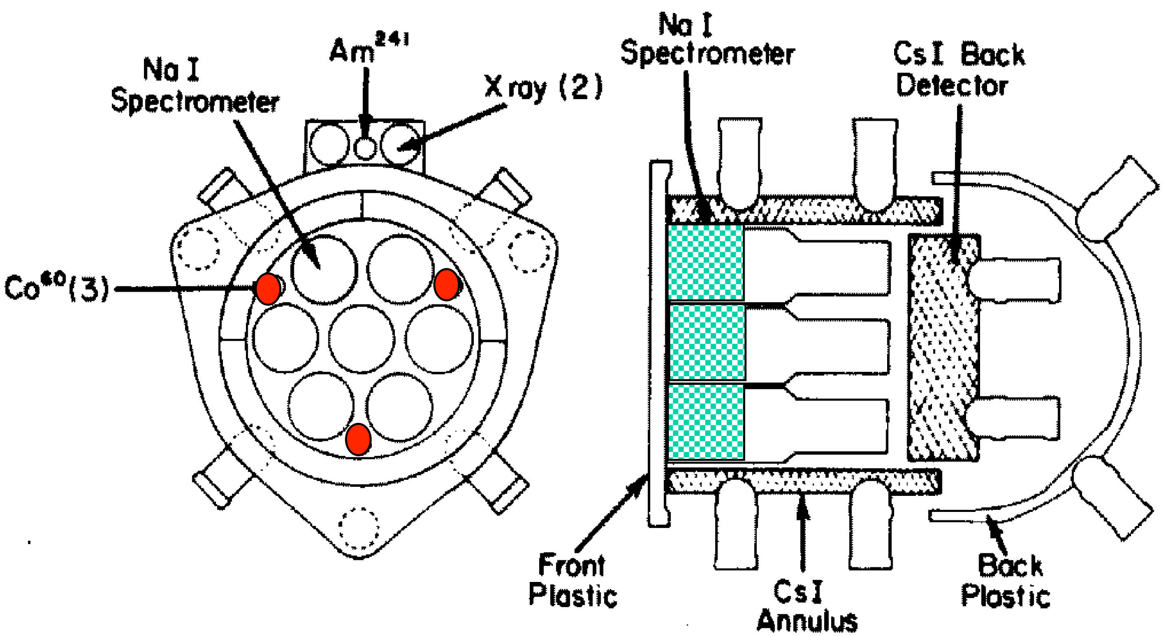


Solar flare spectroscopy:

OSO-7 (1972, first discovery of γ-lines)

Solar-Maximum-Mission Gamma-Ray Spectrometer (NASA, 1981-90)

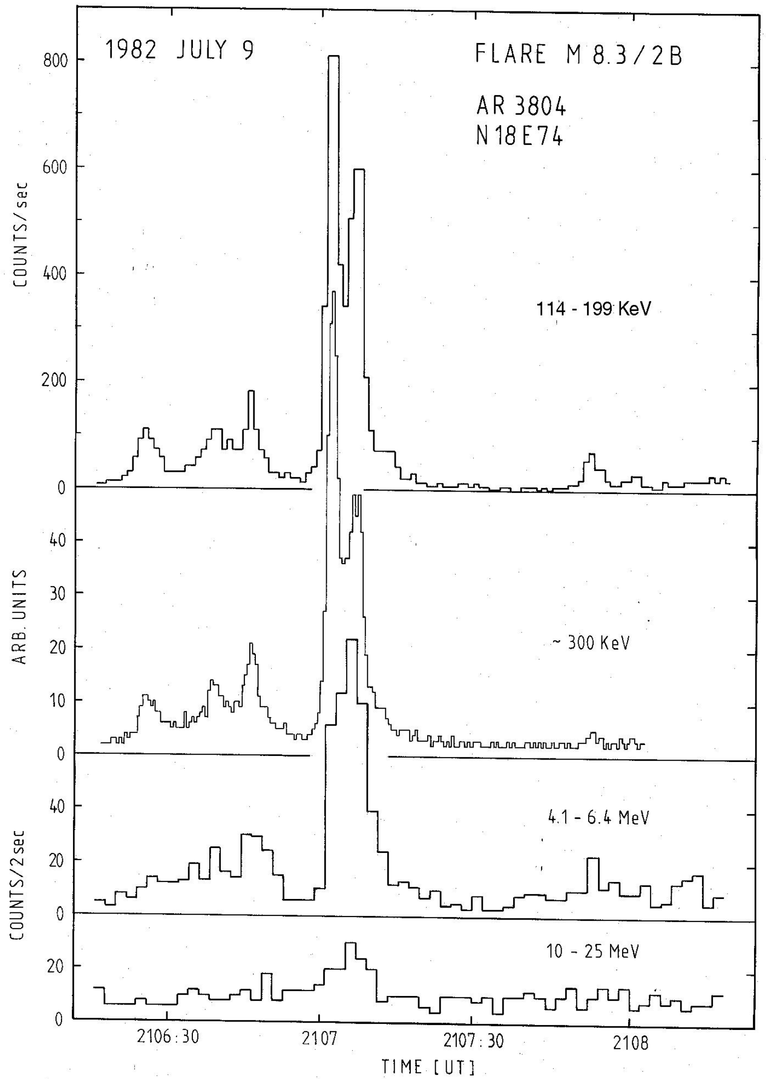
14 keV-140 MeV
ΔE/E ~ 7% @ 662 keV
f.o.v. ~130°

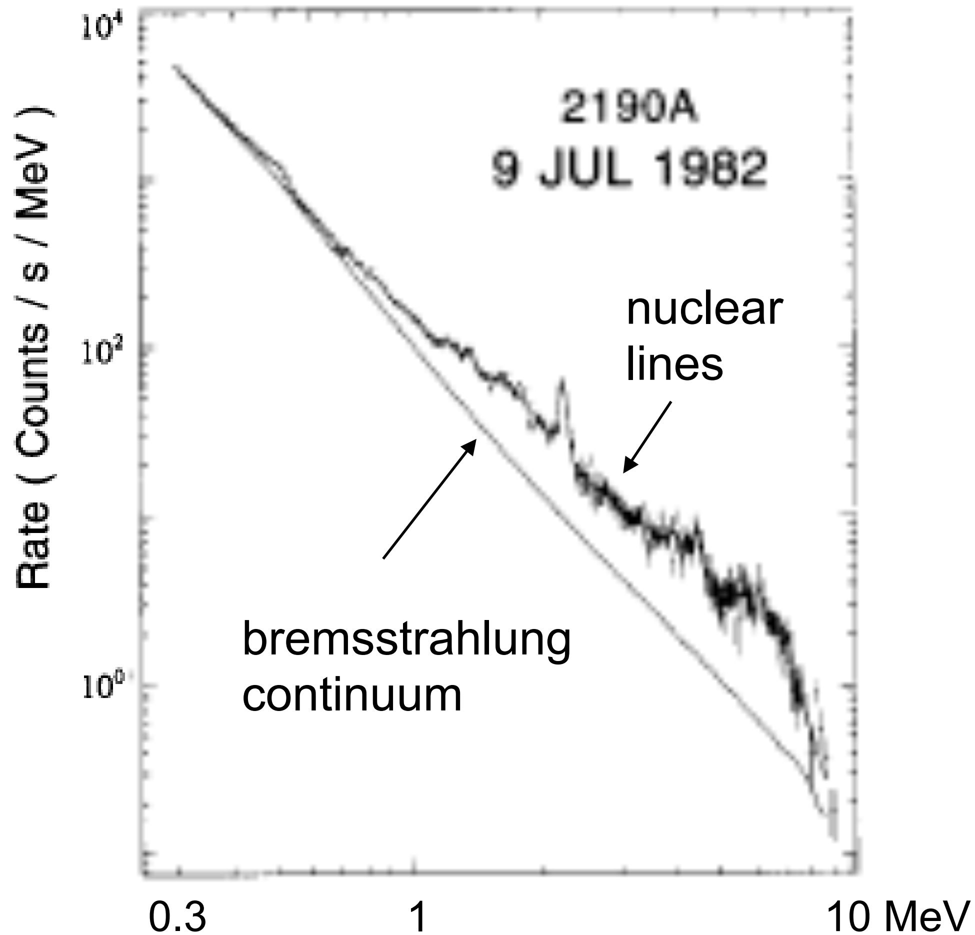


Detected solar flares:
258 (>0.3 MeV)
25 (>10 MeV)
6 (up to 140 MeV)

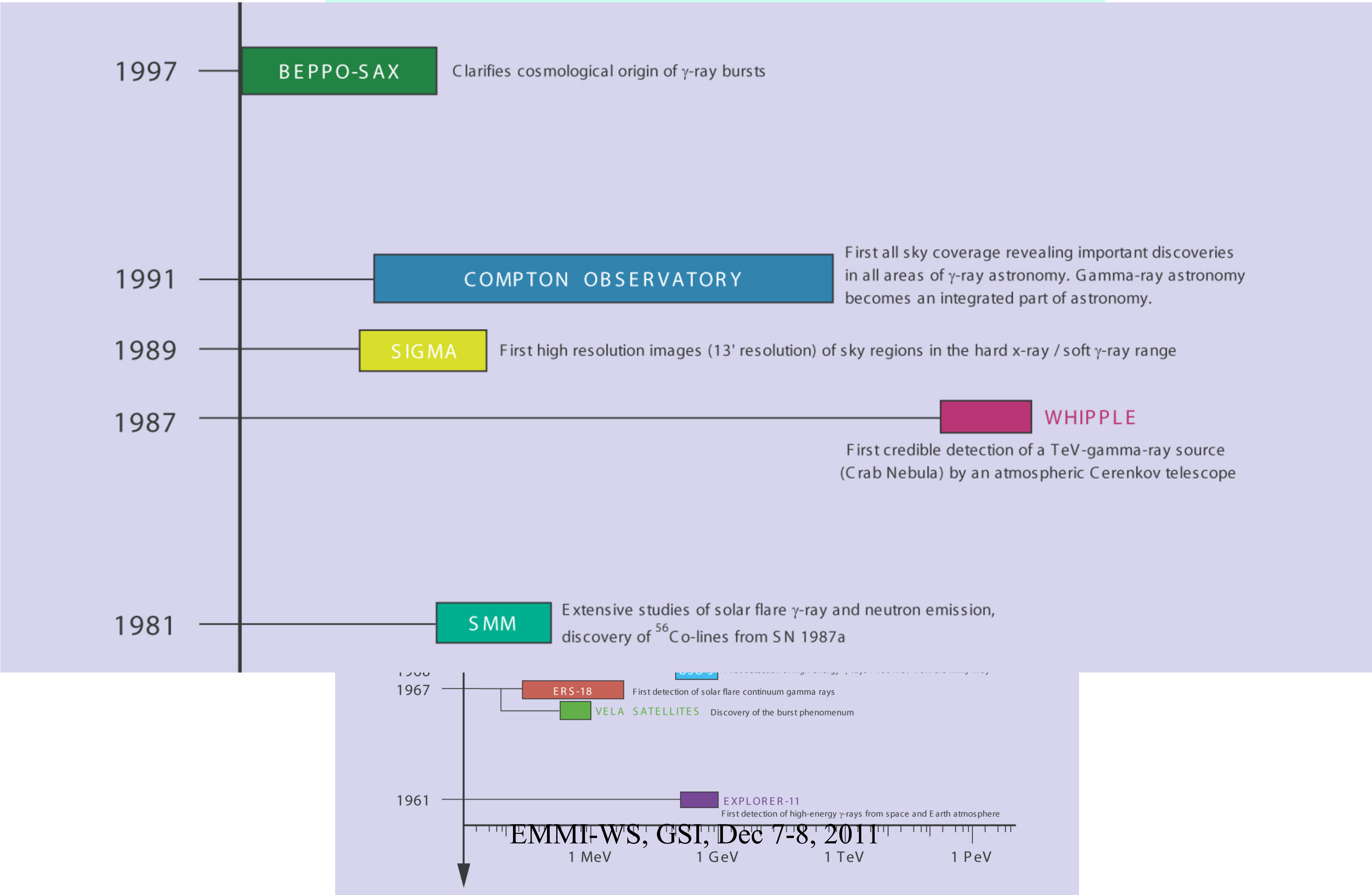
Vestrand et al., 1999

Nuclear line flare measured by SMM (NaI resolution)

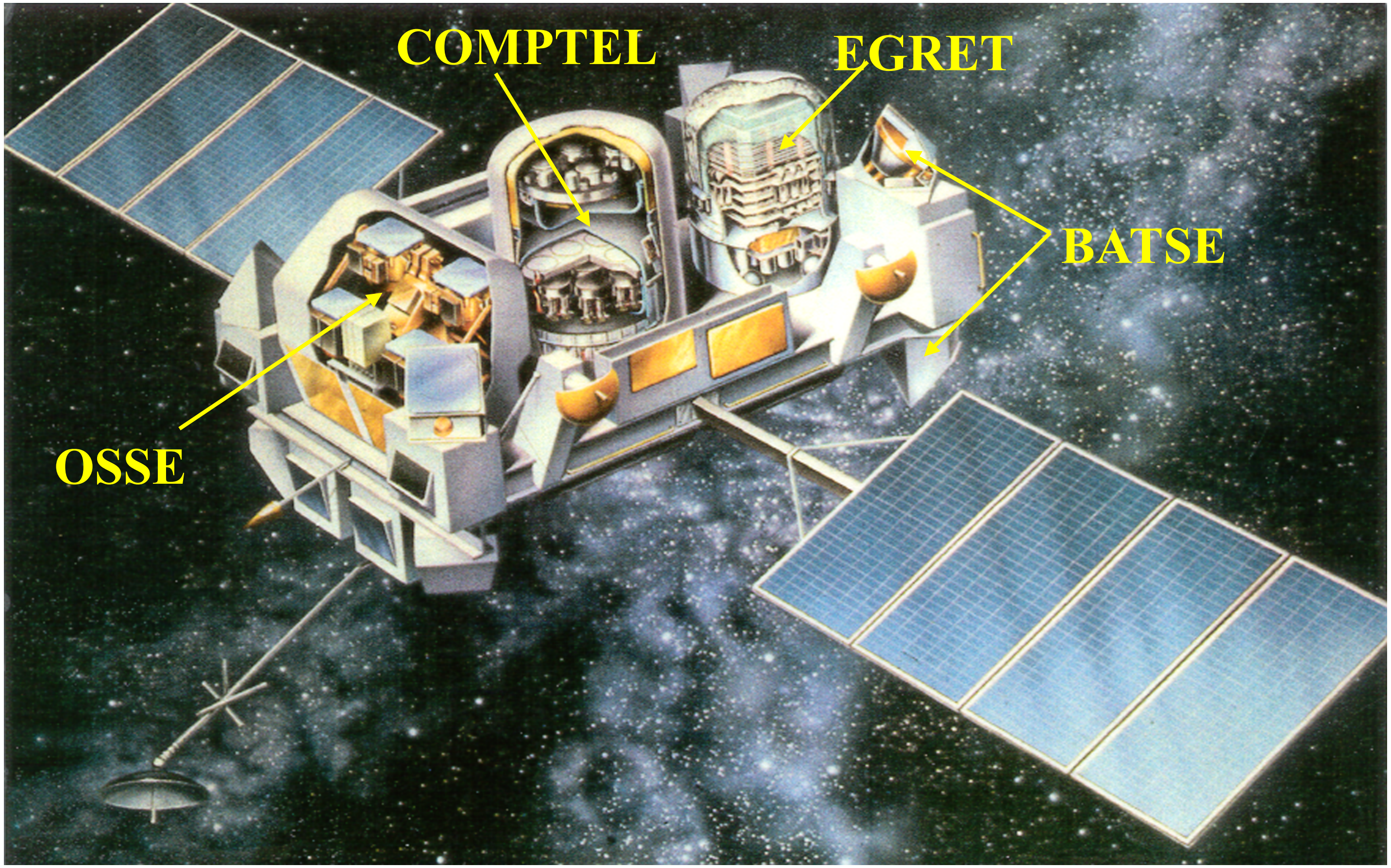


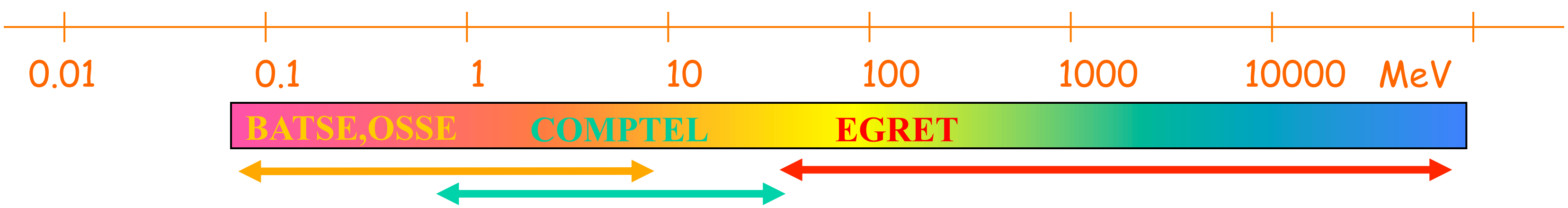


1980-2000


1997
BEPPO-SAX
Clarifies cosmological origin of γ-ray bursts
1991
COMPTON OBSERVATORY
First all sky coverage revealing important discoveries in all areas of γ-ray astronomy. Gamma-ray astronomy becomes an integrated part of astronomy.
1989
SIGMA
First high resolution images (13' resolution) of sky regions in the hard x-ray / soft γ-ray range
1987
WHIPPLE
First credible detection of a TeV-gamma-ray source (Crab Nebula) by an atmospheric Cerenkov telescope
1981
SMM
Extensive studies of solar flare γ-ray and neutron emission, discovery of 56Co-lines from SN 1987a
1967
ERS-18
First detection of solar flare continuum gamma rays
VELA SATELLITES
Discovery of the burst phenomenum
1961
EXPLORER-11
First detection of high-energy γ-rays from space and Earth atmosphere
1 MeV
1 GeV
1 TeV
1 PeV

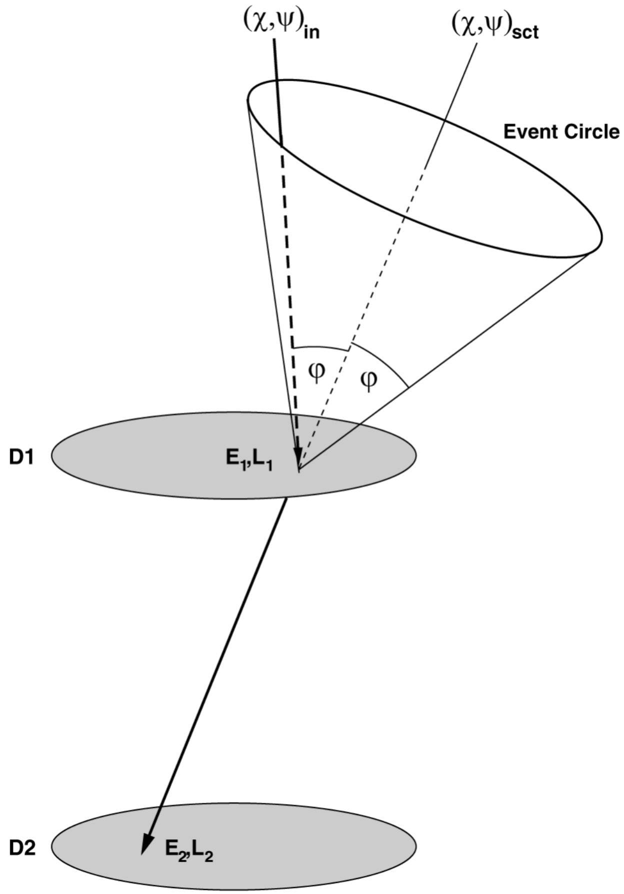
Compton Gamma-Ray Observatory (1991-2000)



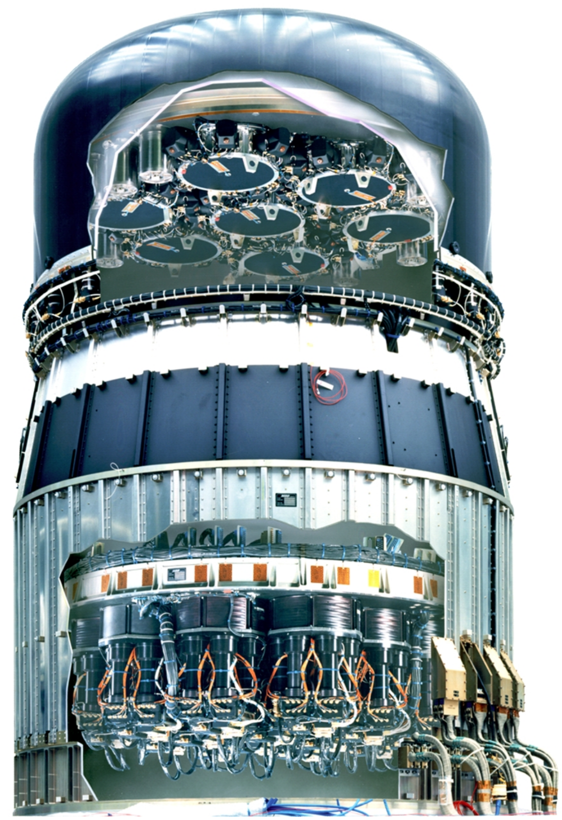


CGRO

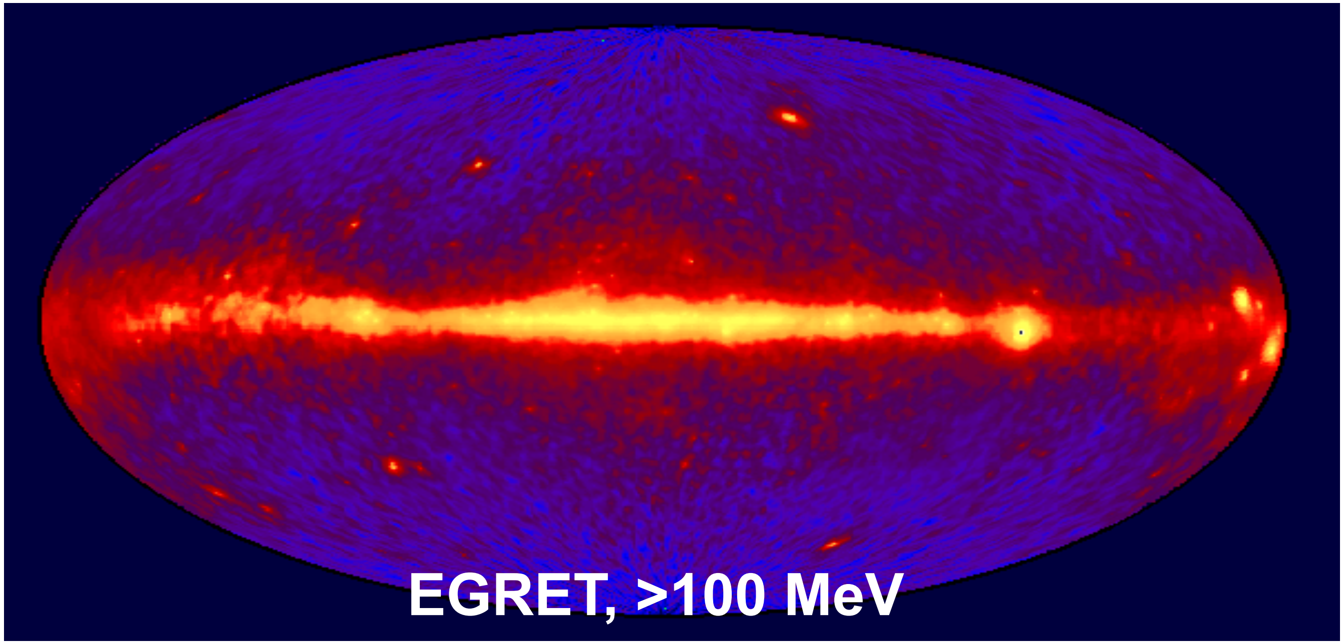
COMPTEL

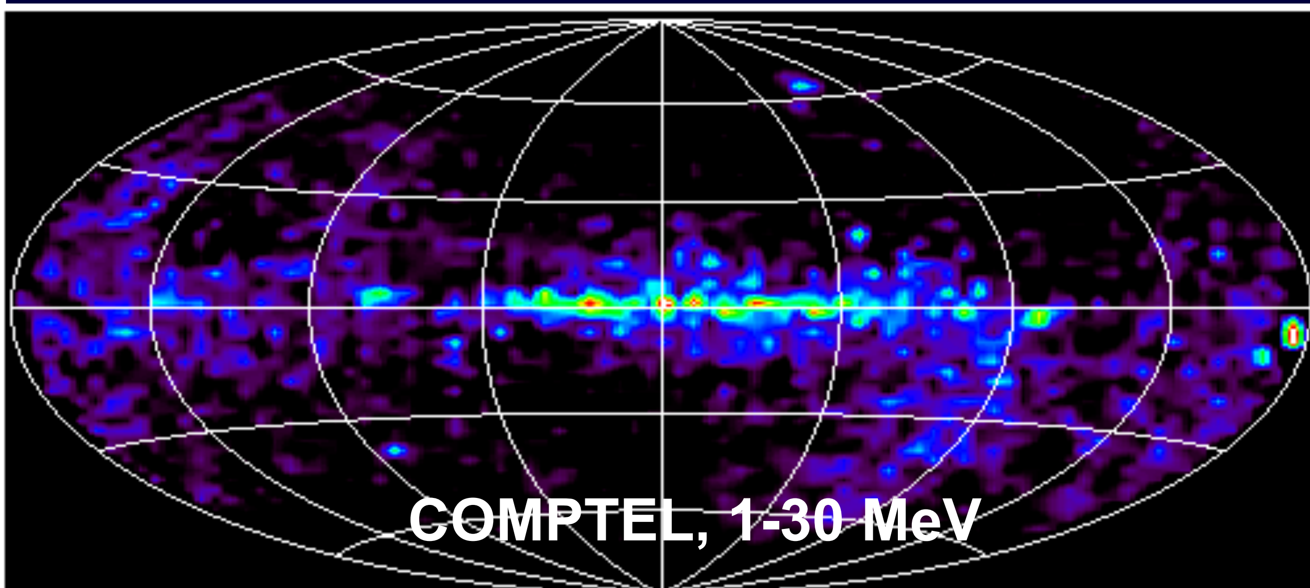


$$\cos\varphi = 1 - m_0 c^2 \left(\frac{1}{\varepsilon_1 + \Delta} - \frac{1}{\varepsilon_0 + \Delta} \right)$$

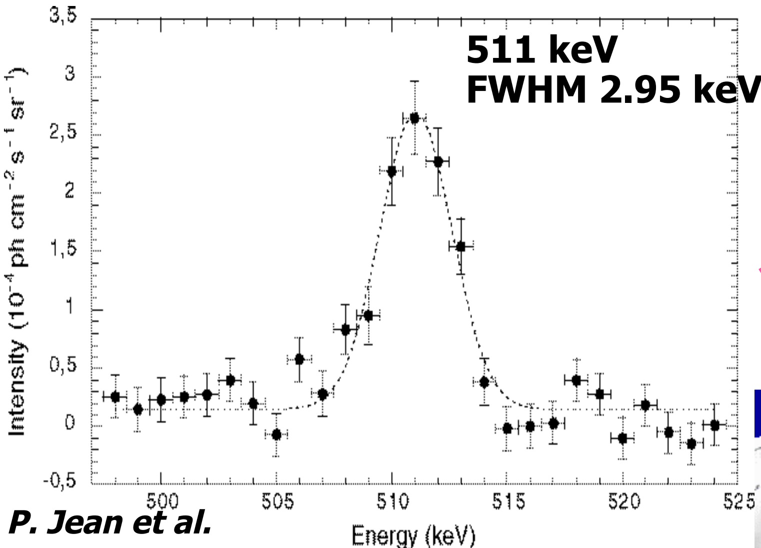


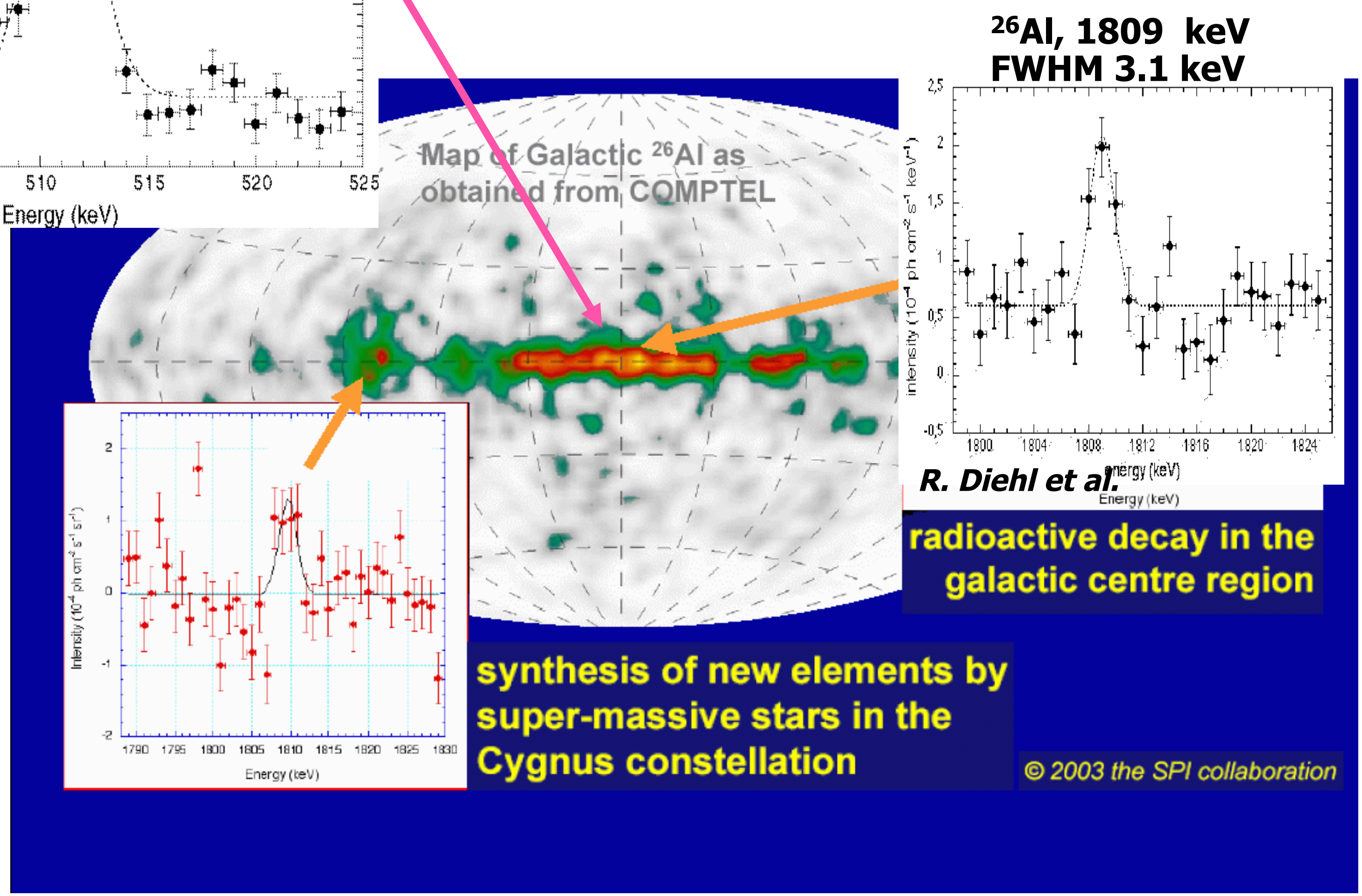
Trigger:
t.o.f. delayed coincidence


EGRET, >100 MeV

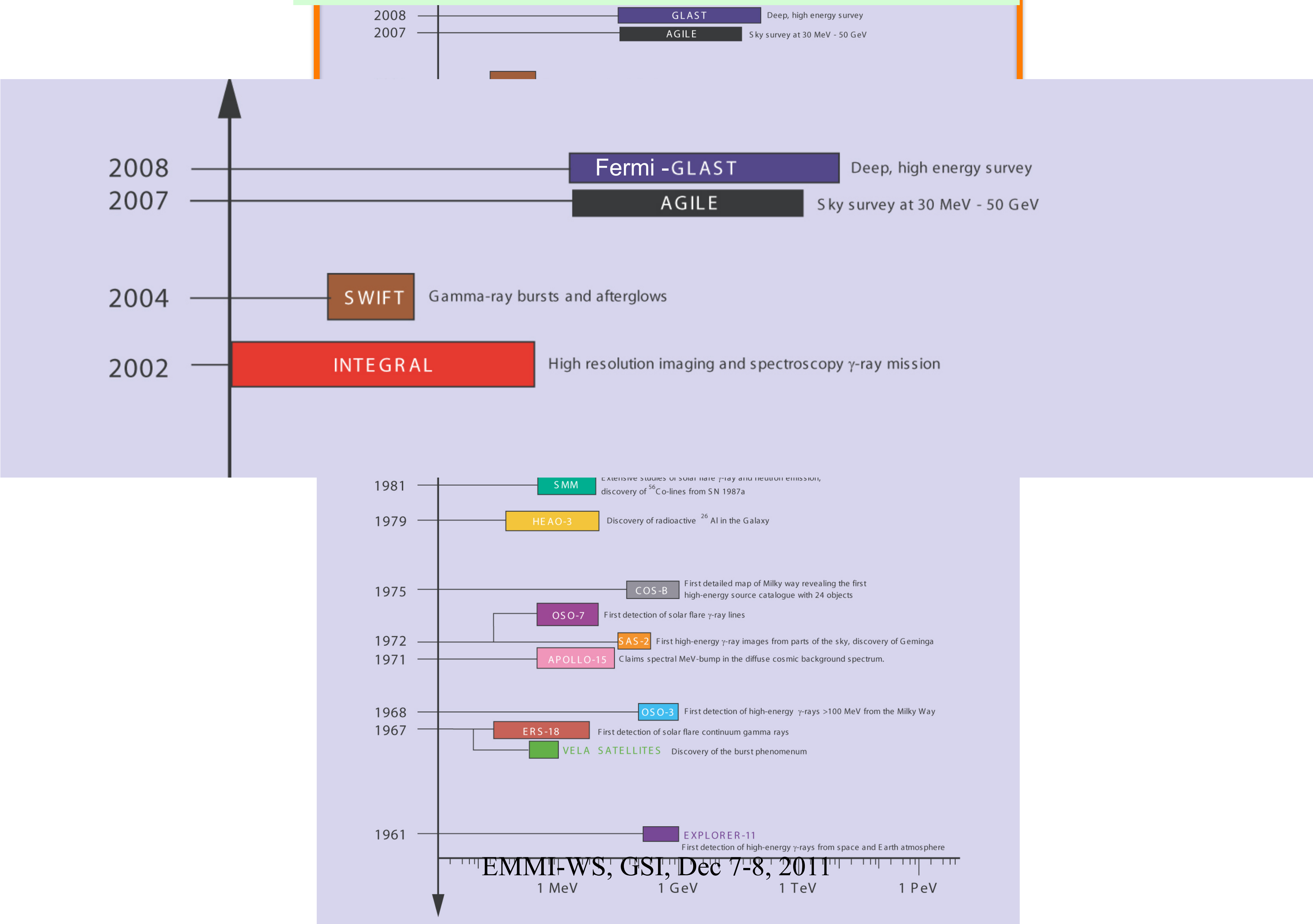

COMPTEL, 1-30 MeV

Galactic γ-ray line emission

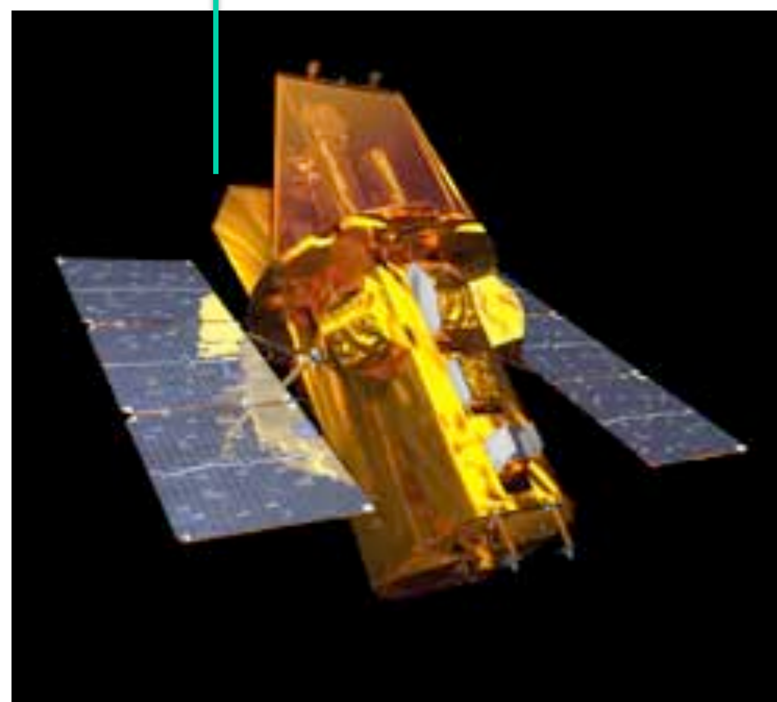




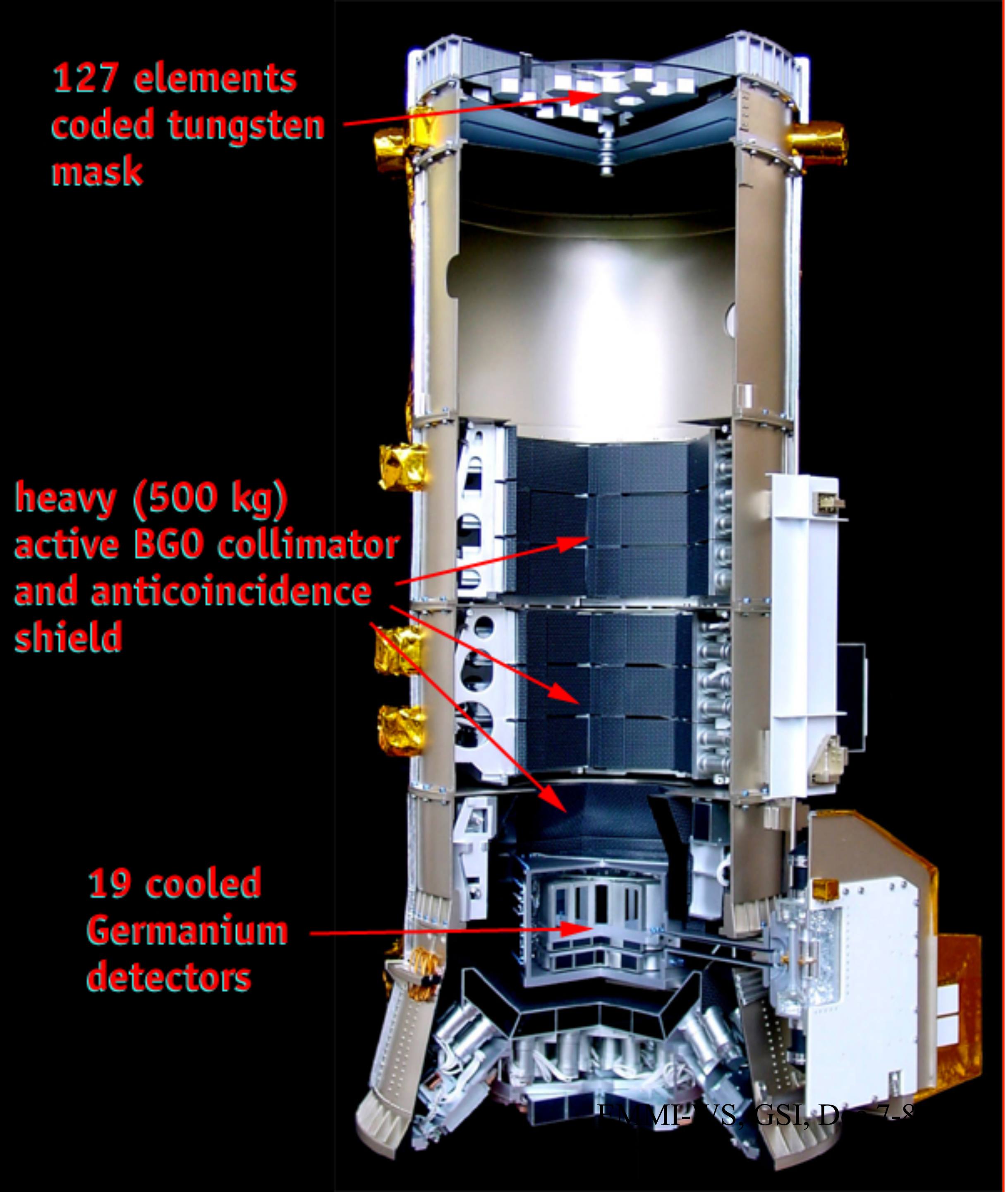
2000-2020


2008
Fermi -GLAST
Deep, high energy survey
2007
AGILE
Sky survey at 30 MeV - 50 GeV
2004
SWIFT
Gamma-ray bursts and afterglows
2002
INTEGRAL
High resolution imaging and spectroscopy γ-ray mission
2008
GLAST
Deep, high energy survey
2007
AGILE
Sky survey at 30 MeV - 50 GeV
1981
SMM
discovery of 56Co-lines from SN 1987a
1979
HEAO-3
Discovery of radioactive 26Al in the Galaxy
1975
COS-B
First detailed map of Milky way revealing the first high-energy source catalogue with 24 objects
OSO-7
First detection of solar flare γ-ray lines
1972
SAS-2
First high-energy γ-ray images from parts of the sky, discovery of Geminga
1971
APOLLO-15
Claims spectral MeV-bump in the diffuse cosmic background spectrum.
1968
OSO-3
First detection of high-energy γ-rays >100 MeV from the Milky Way
1967
ERS-18
First detection of solar flare continuum gamma rays
VELA SATELLITES
Discovery of the burst phenomenum
1961
EXPLORER-11
First detection of high-energy γ-rays from space and Earth atmosphere
1 MeV
1 GeV
1 TeV
1 PeV

Swift: launch Nov. 2004
BAT: large area GRB monitor
(15-150 keV)
XRT: imaging X-ray telescope
OMC: opt. monitor



INTEGRAL: launch Oct 2002
IBIS: 15 keV-10 MeV, Imager
SPI: 20 keV- 8 MeV, Spectrom.
JEM-X, OMC



INTEGRAL

launched October 2002

SPI

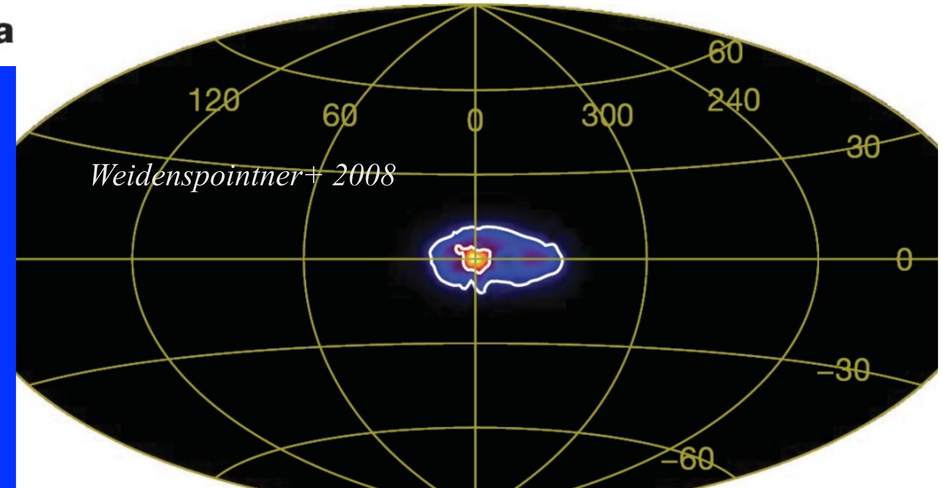
Spectrometer
Pour
INTEGRAL

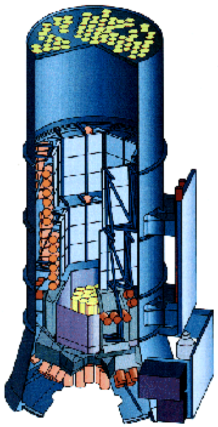
SPectroscopy
and
Imaging

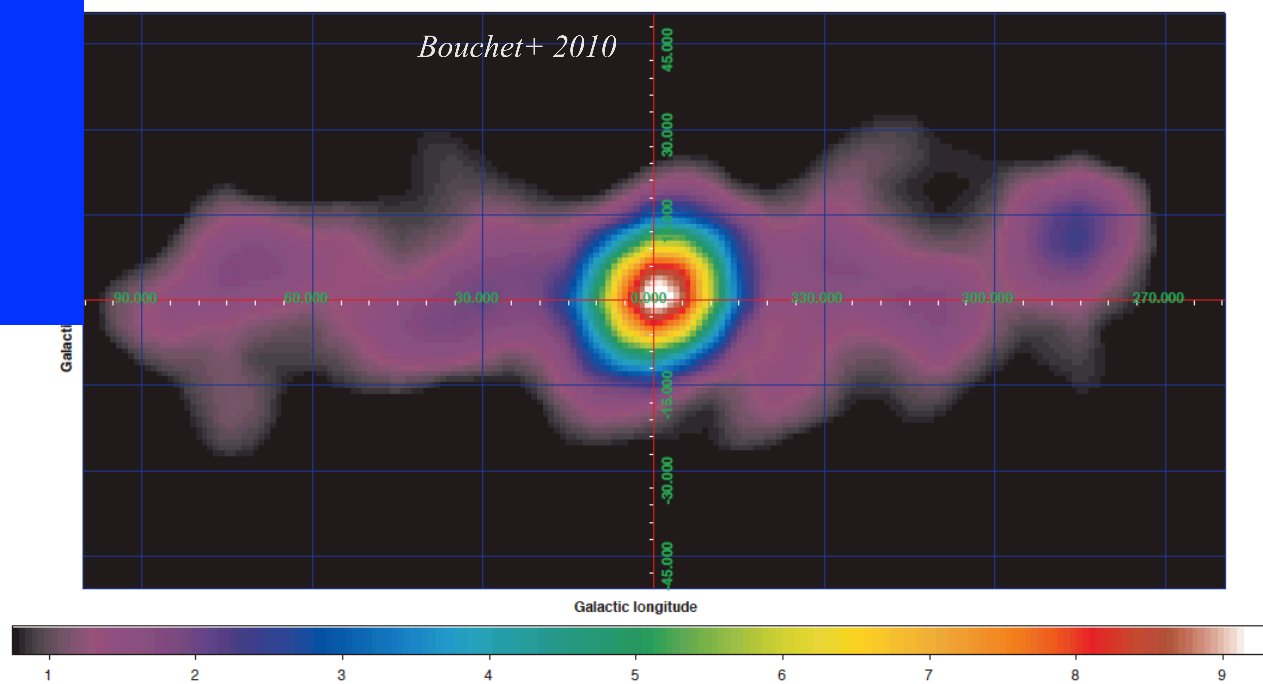
INTEGRAL-SPI: extended 511 keV Emission region around the galactic center

- Annihilation γ-rays are dominated by a Bright Inner-Galaxy Component
- The ^{26}Al e+ Produced in the Disk (82%) are a Minor Contribution
- Annihilation γ-ray Emission Presents a Puzzle:
  - e+ Sources ?
  - Propagation !!
  - Annihilation

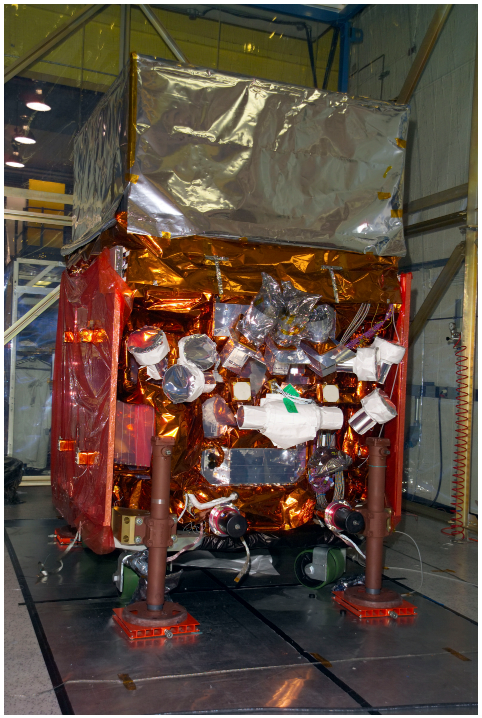
a

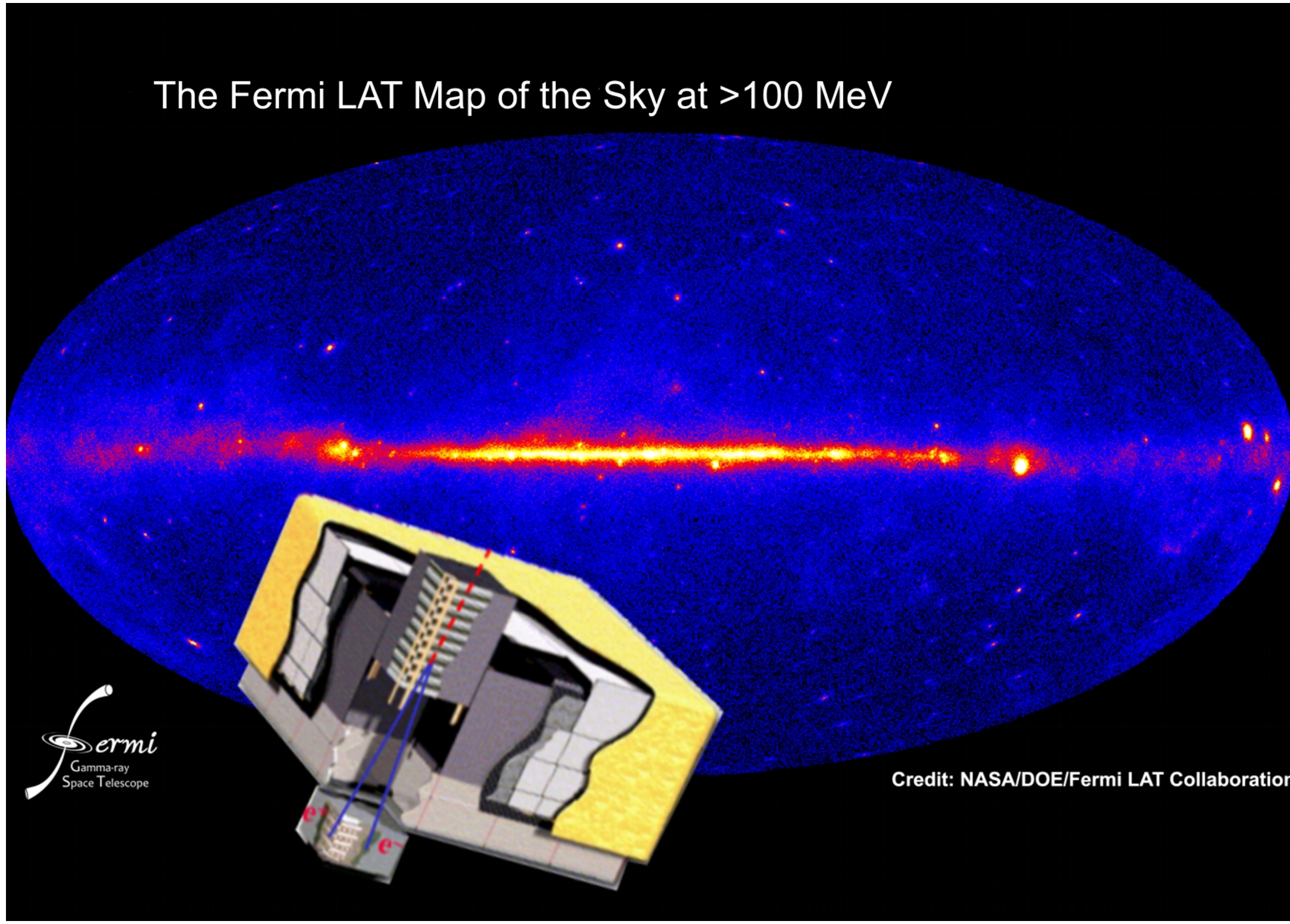


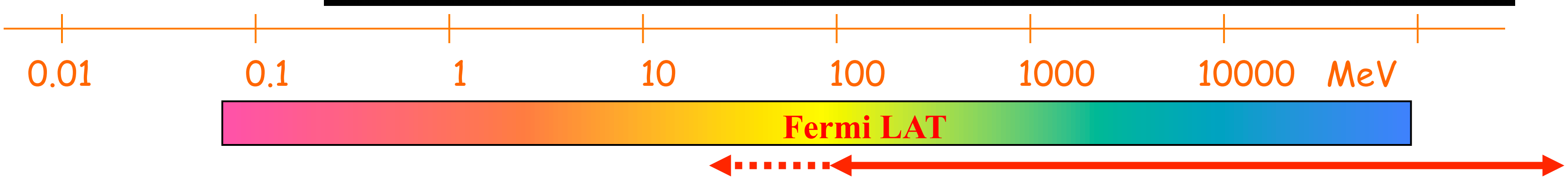




Fermi Gamma-Ray Space Telescope: LAT & GBM (2008 -)



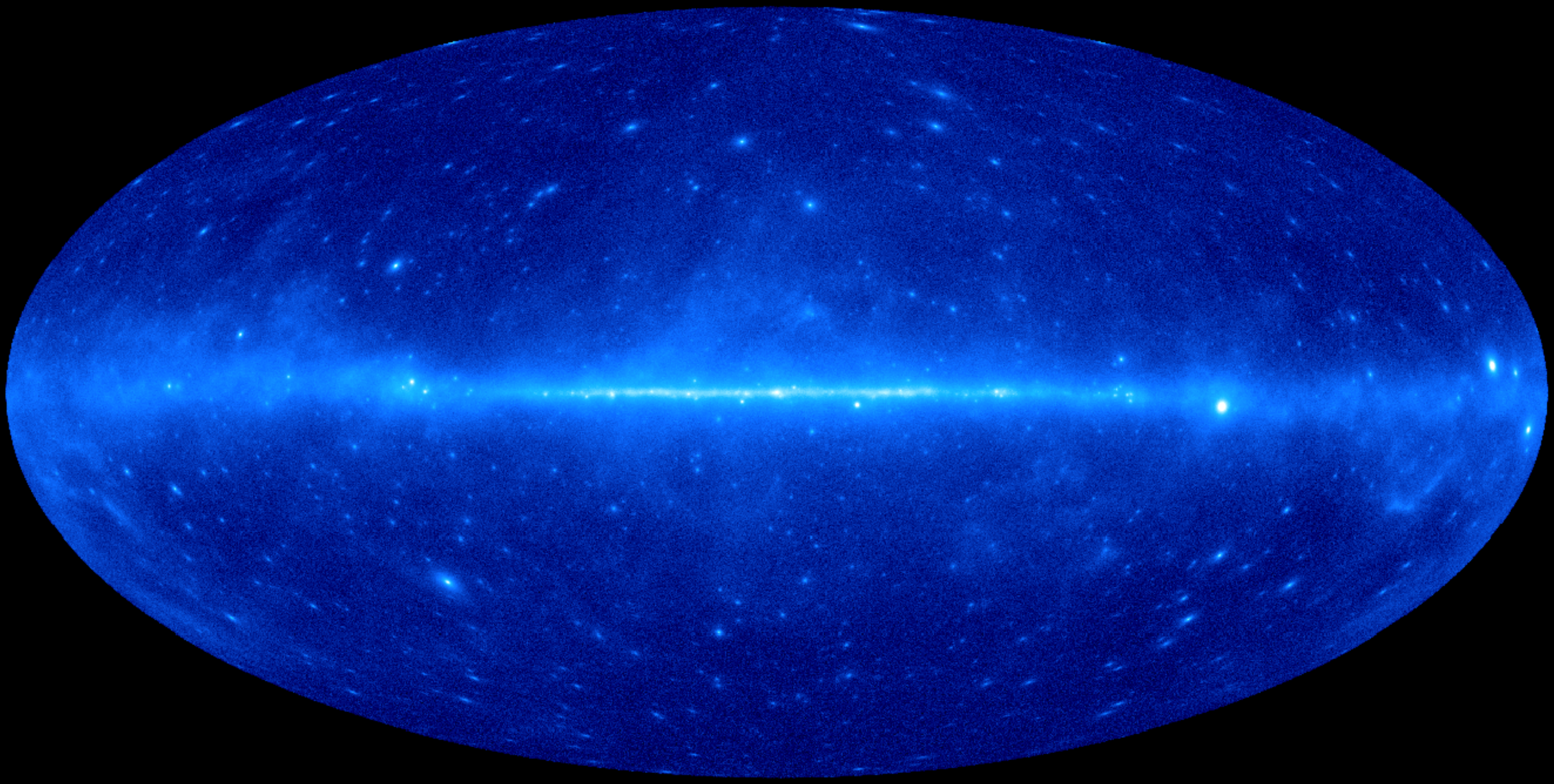




CGRO

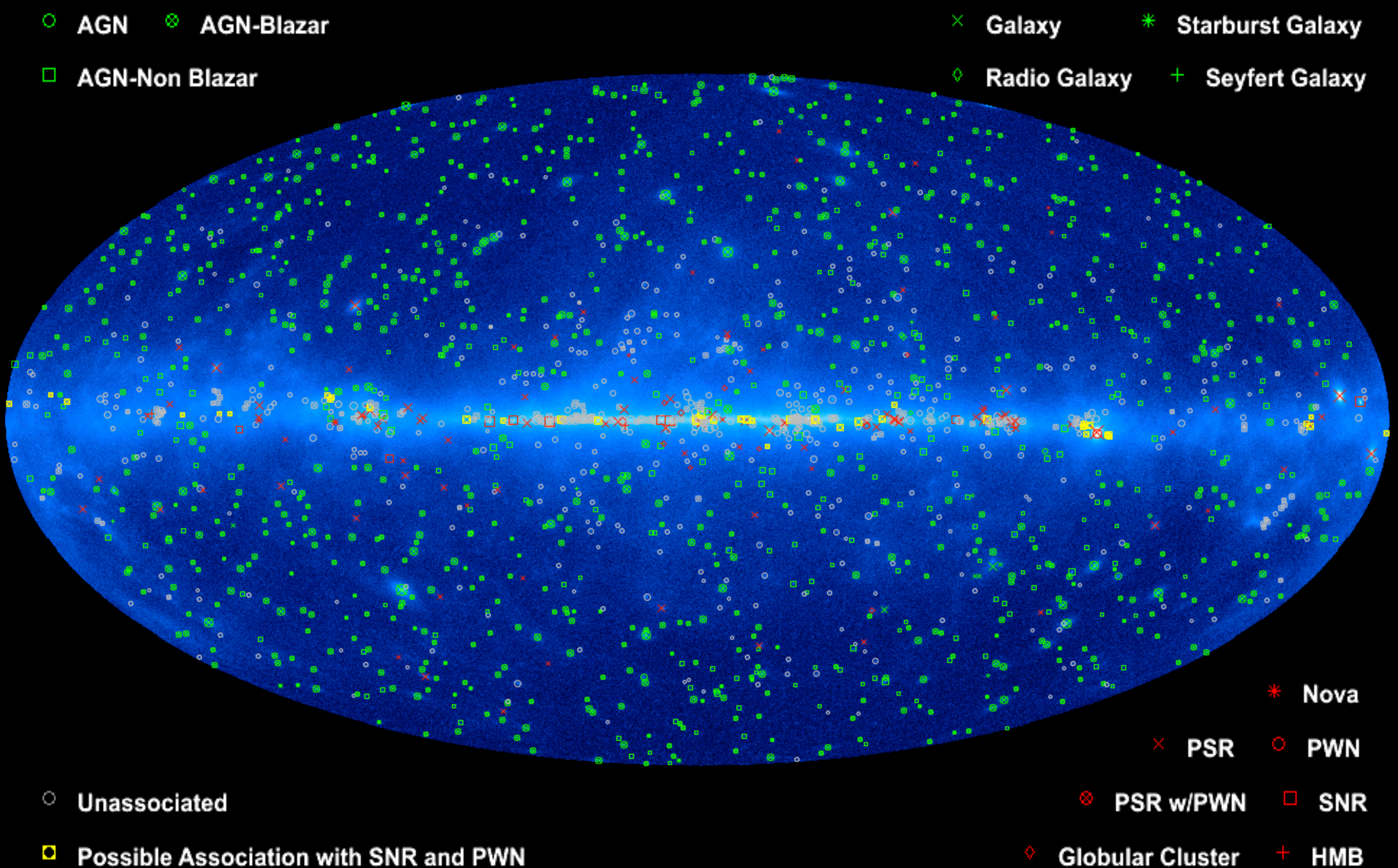
Fermi Large Area Telescope: 2 year survey

>100 MeV



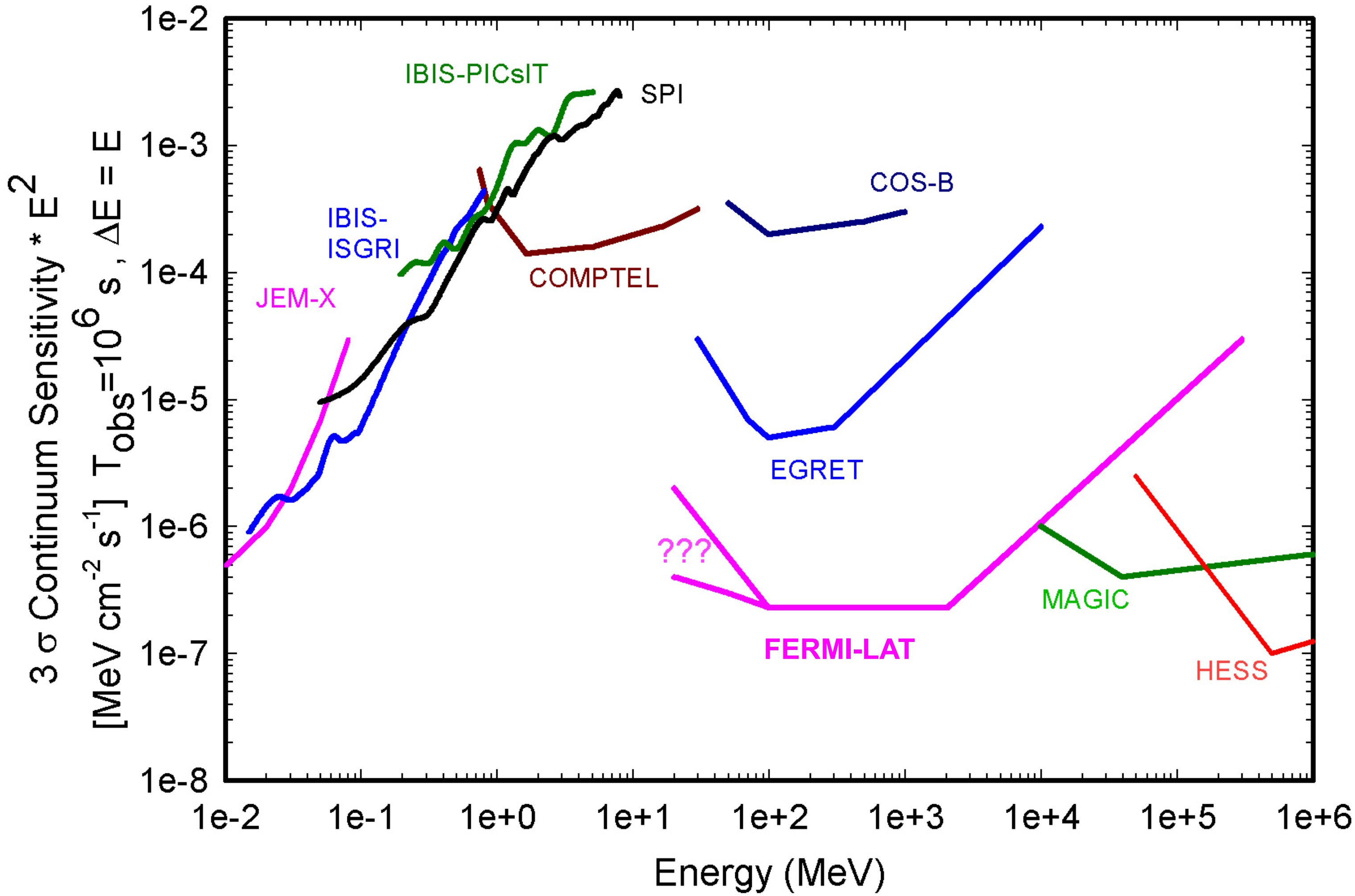
Credit: Fermi Large Area Telescope Collaboration

Fermi Large Area Telescope 2FGL catalog

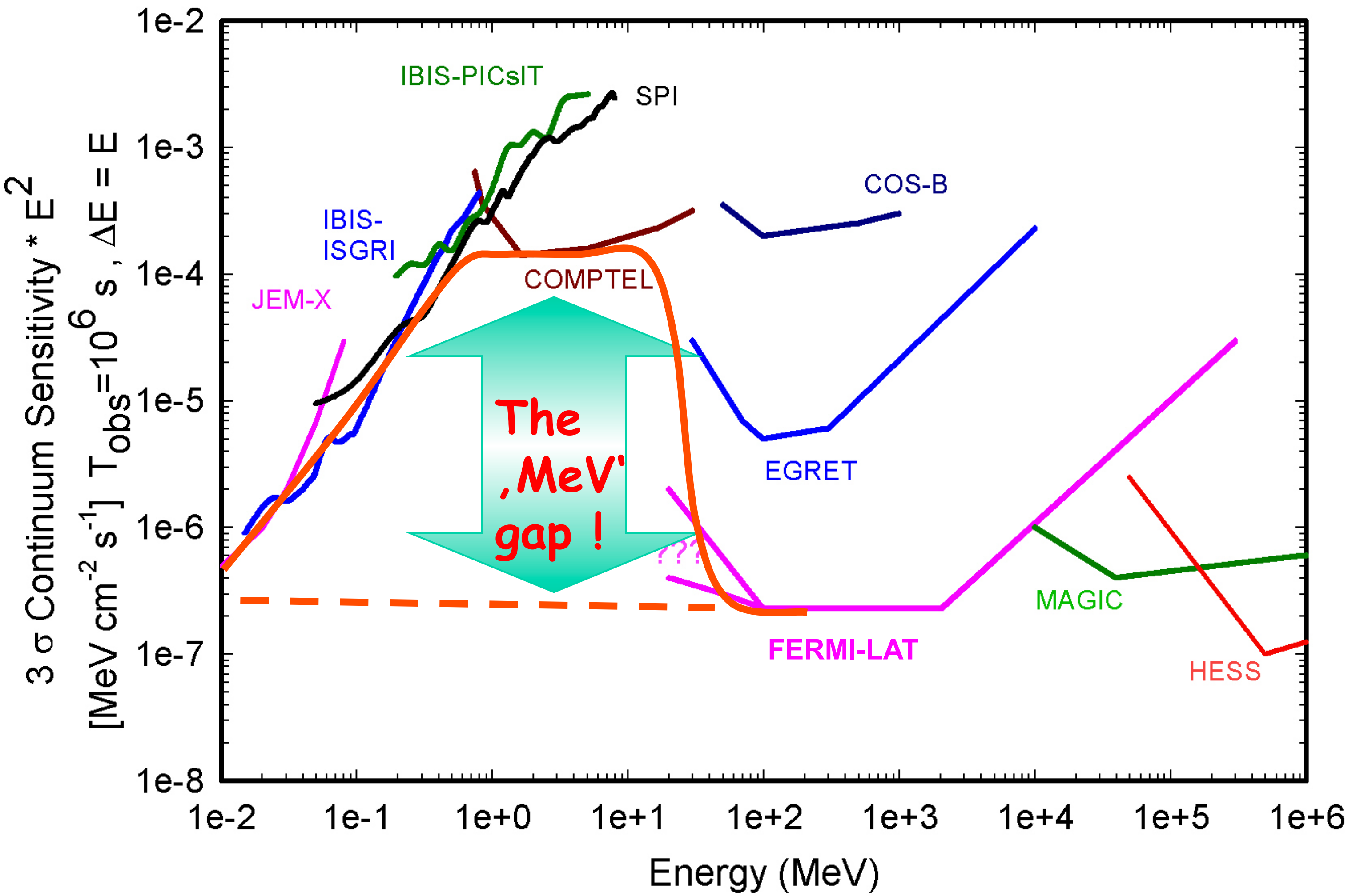


Credit: Fermi Large Area Telescope Collaboration

Current sensitivity of multi-wavelength High-Energy Astronomy:



Severe sensitivity deficit at MeV energies!



Why is the sensitivity in the MeV region still so low?

- photon interaction cross-sections go through a minimum
- double Compton scattering efficiencies low
- Compton event reconstruction incomplete and limited by Doppler broadening
- Pair events limited by nuclear recoil

- Instrumental background in space is strong

MeV Telescope Improvements:

Sensitivity→ reduce background
→ higher efficiency

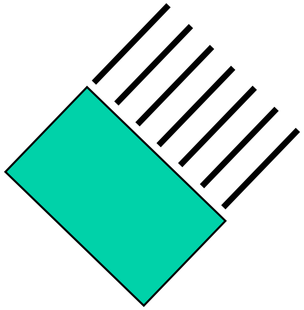
angular resolution → better imaging

energy resolution over large E range
→better spectroscopy

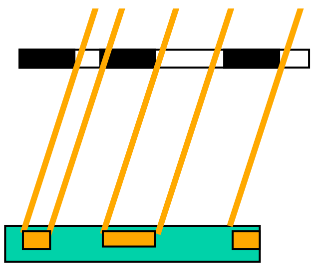
→Polarimetry

Current and new MeV Telescope Concepts

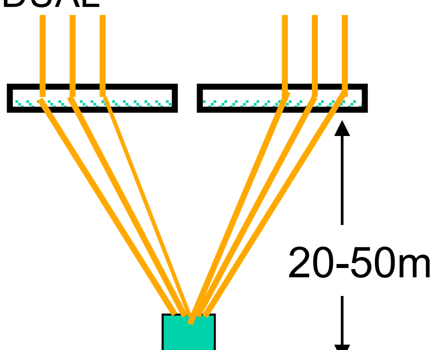
Collimated Detectors:
HEAO-3,OSSE, RHESSI, ASTRO-H



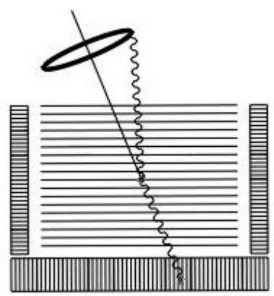
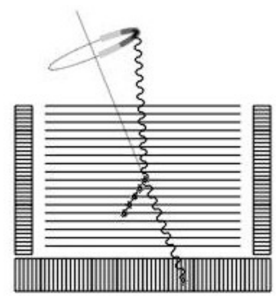
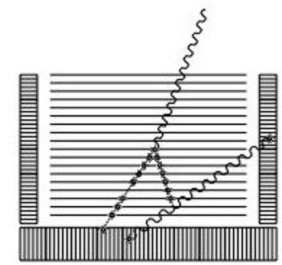
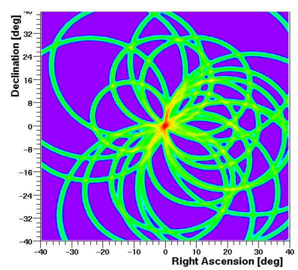
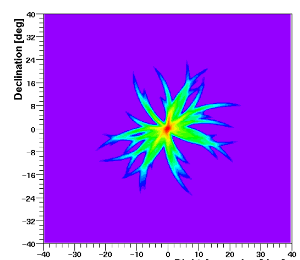
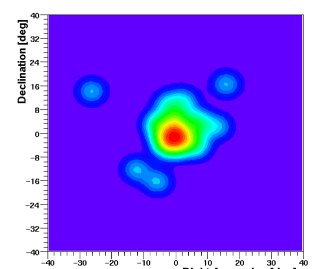
Coded Mask Systems:
INTEGRAL, SWIFT



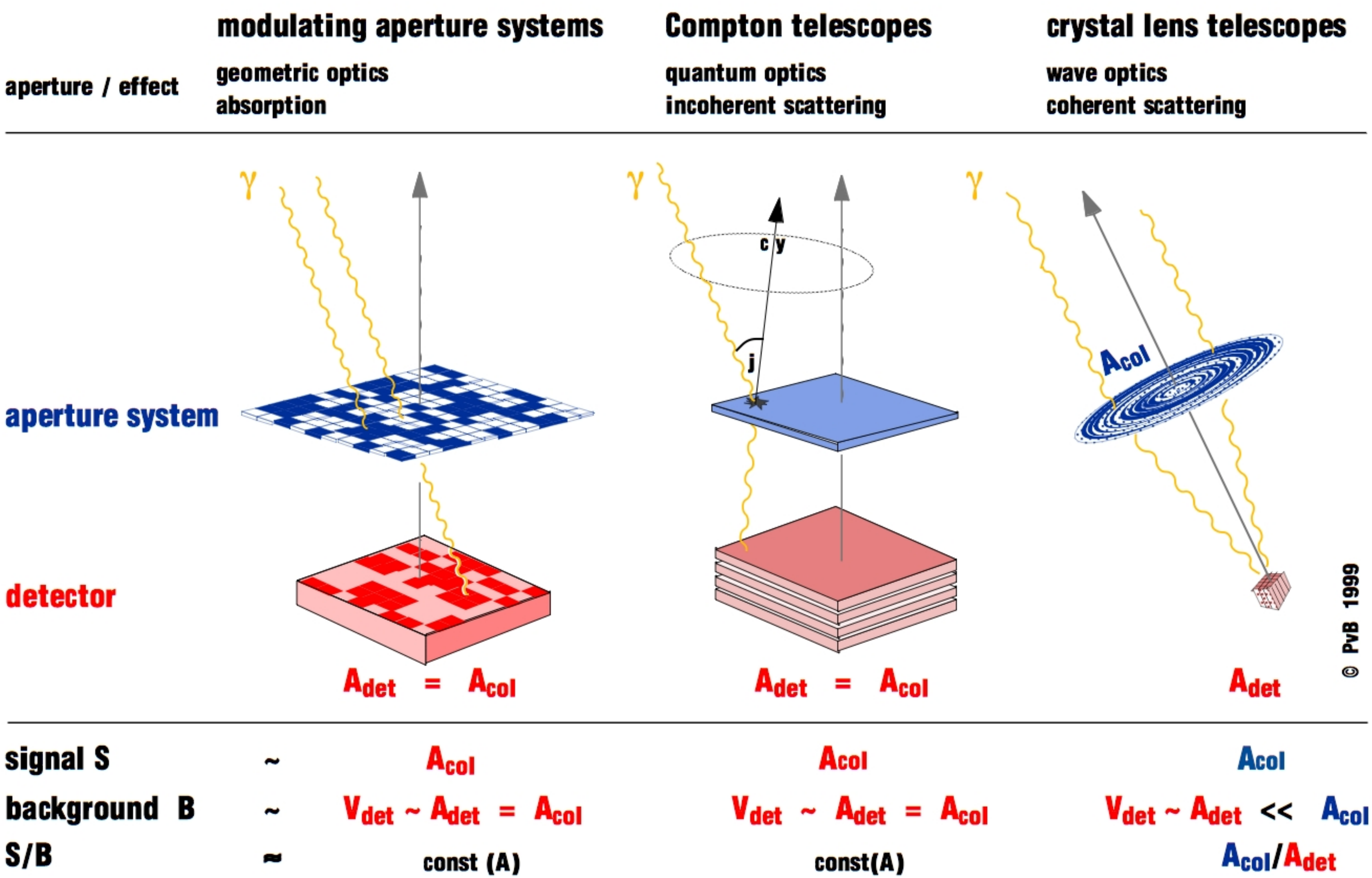
Laue Lens Telescope:
DUAL



Detectors using Compton Scattering and Pair Creation
COMPTEL, EGRET, LAT

Classical Compton Event Circles (no electron tracking)	Compton arcs for events with electron track or 3rd interaction	Direct imaging of pair-creation events
		
		

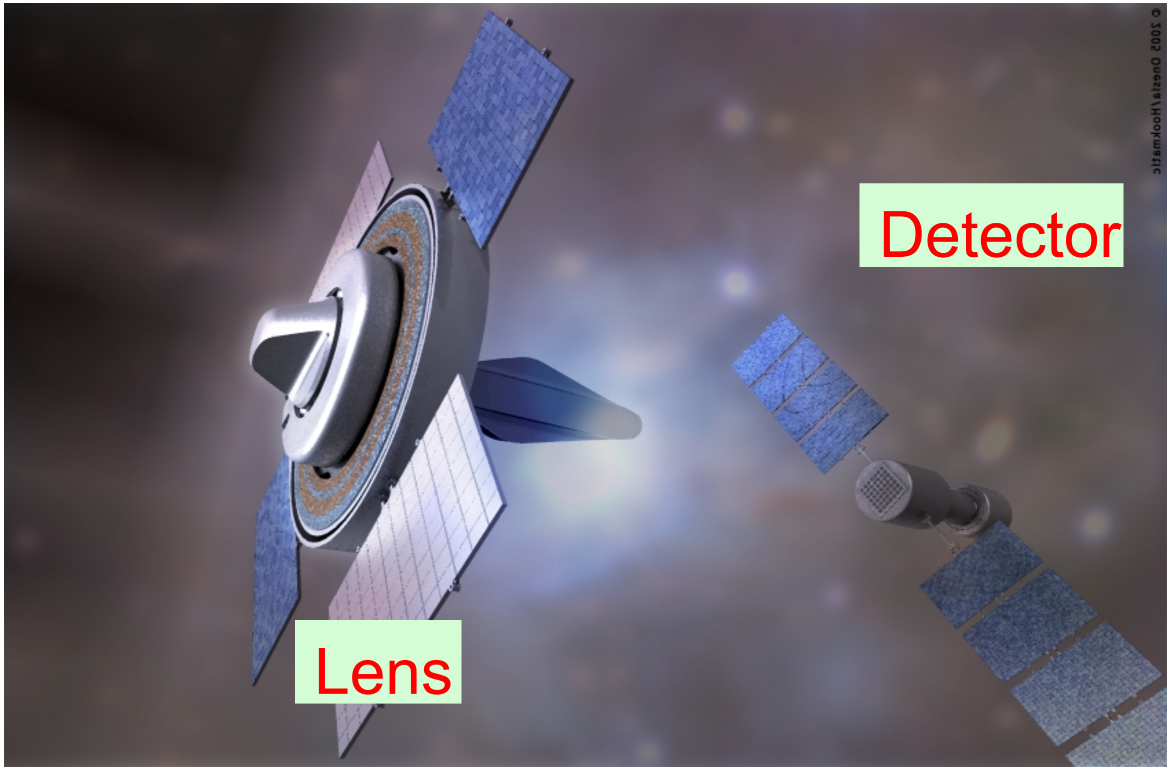
Sensitivity for coded mask, Compton, and Lens



Courtesy: Peter von Ballmoos

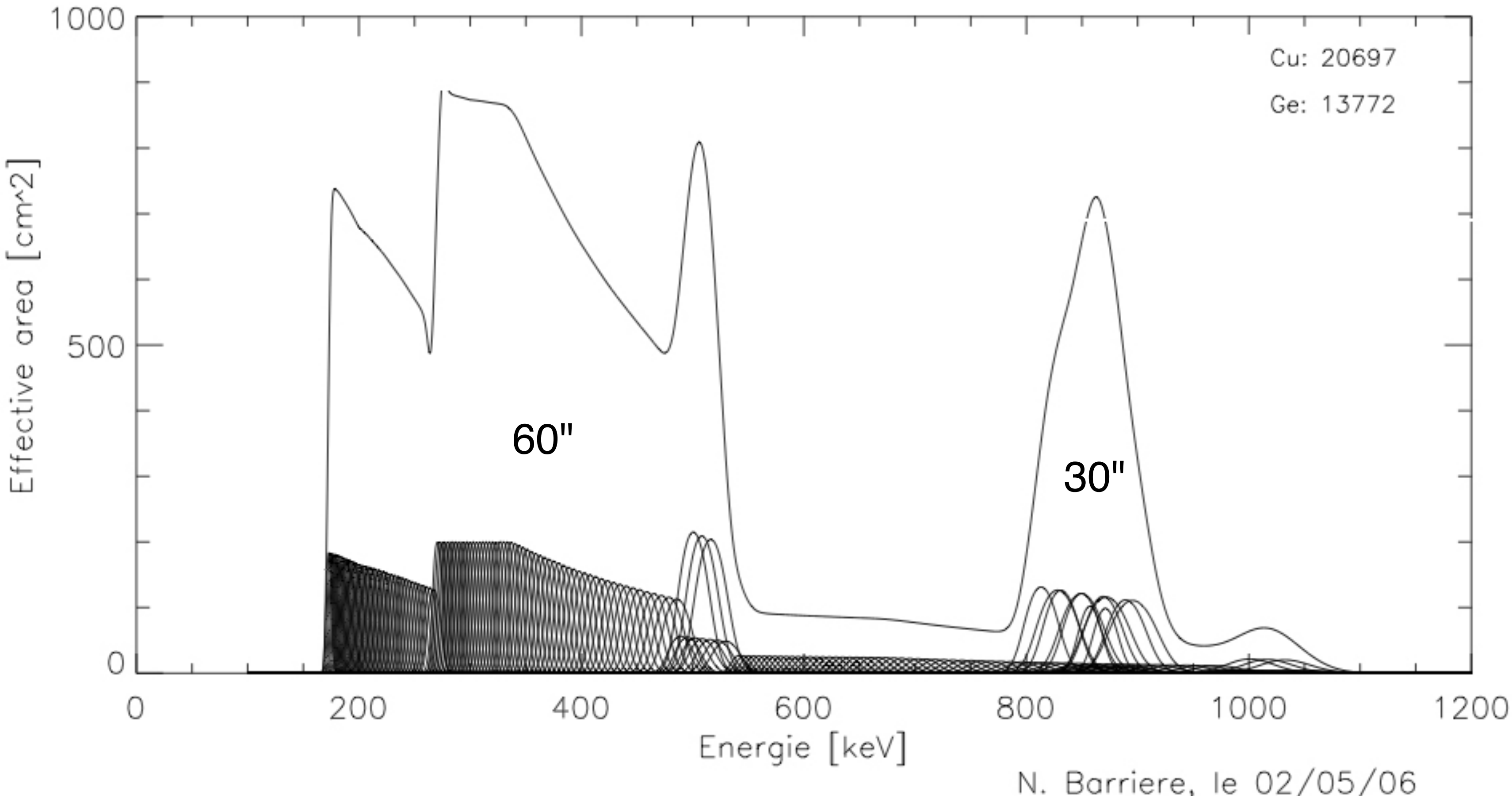
GRI: the Gamma-Ray Imager Mission

Proposal for ESA's Cosmic Vision (PI: Peter von Ballmoos, CESR)



DUAL: configuration 2008 (with lens on boom)

Lens perfomances



Lens summary (optimisation studies still ongoing):

- 13772 Ge crystals, 20697 Cu crystals
- Lens effective area:
  500 - 900 cm^2 @ 160 - 520 keV & 700 cm^2 @ 800 - 900 keV
- Mosaicity (= angular resolution): 30" (high-energy) - 60" (low-energy)

Gamma Ray Lens Telescope:

Pro:
- Very good sensitivity in limited energy bands
- angular resolution of ≈1 arcmin

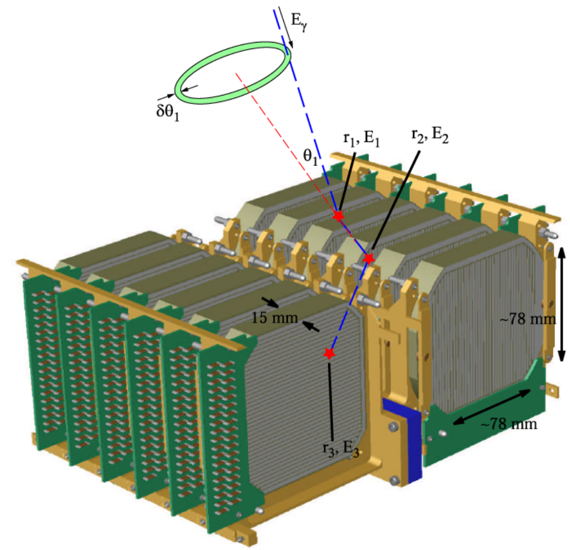
Contra:
- Small field of view (few arcmin)
- Large satellite structure

→ Specialized telescope for the observation of known pointsources with nuclear line emissions: e.g. SNe, binaries

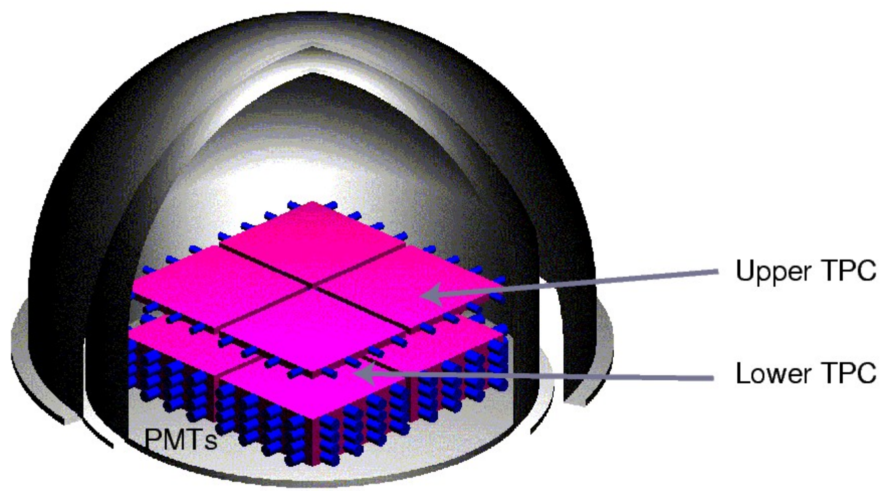
Advanced Compton Telescope (ACT) studies: Instrument Concepts (1)

<u>High spectral resolution:</u>
$\Delta E/E \sim 1\%$
E: 0.2-2MeV

- Compton telescope with position sensitive Ge detectors (Boggs et al, UCB)

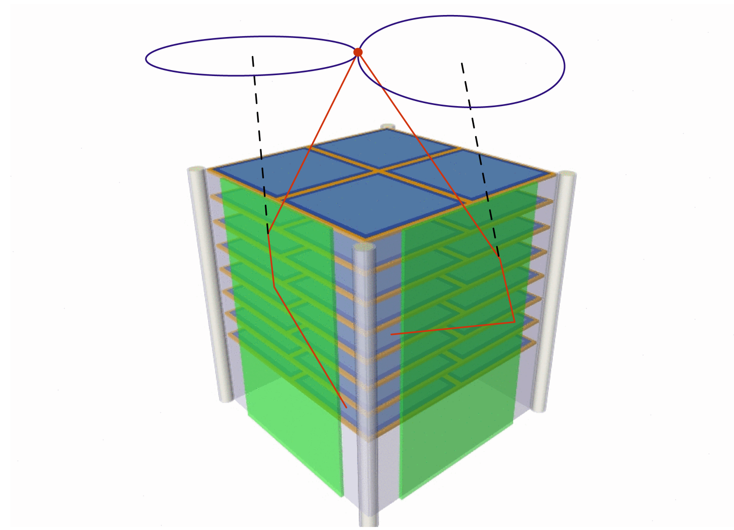


- Liquid Xe detector: time projection chamber to resolve interactions (Aprile, Oberlack et al., Columbia U.)

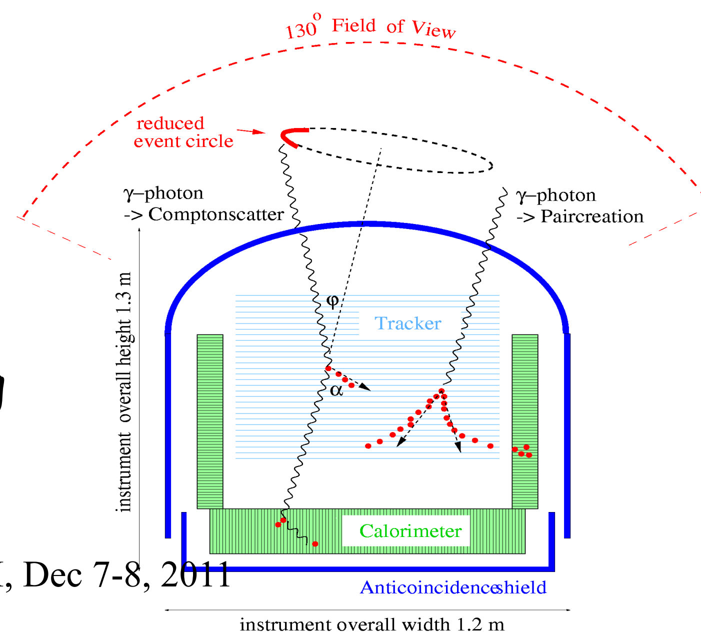


ACT Instrument Concepts (2)

- thick Si(Li) doublesided strip detectors -> record multiple Compton scatterings (Kurfess et al., NRL)



- Electron tracking – Calorimeter detectors (MEGA, TIGRE) MPE, Garching; UCR:
  Energy range from 0.4 to 50 MeV
  Background suppression by tracking



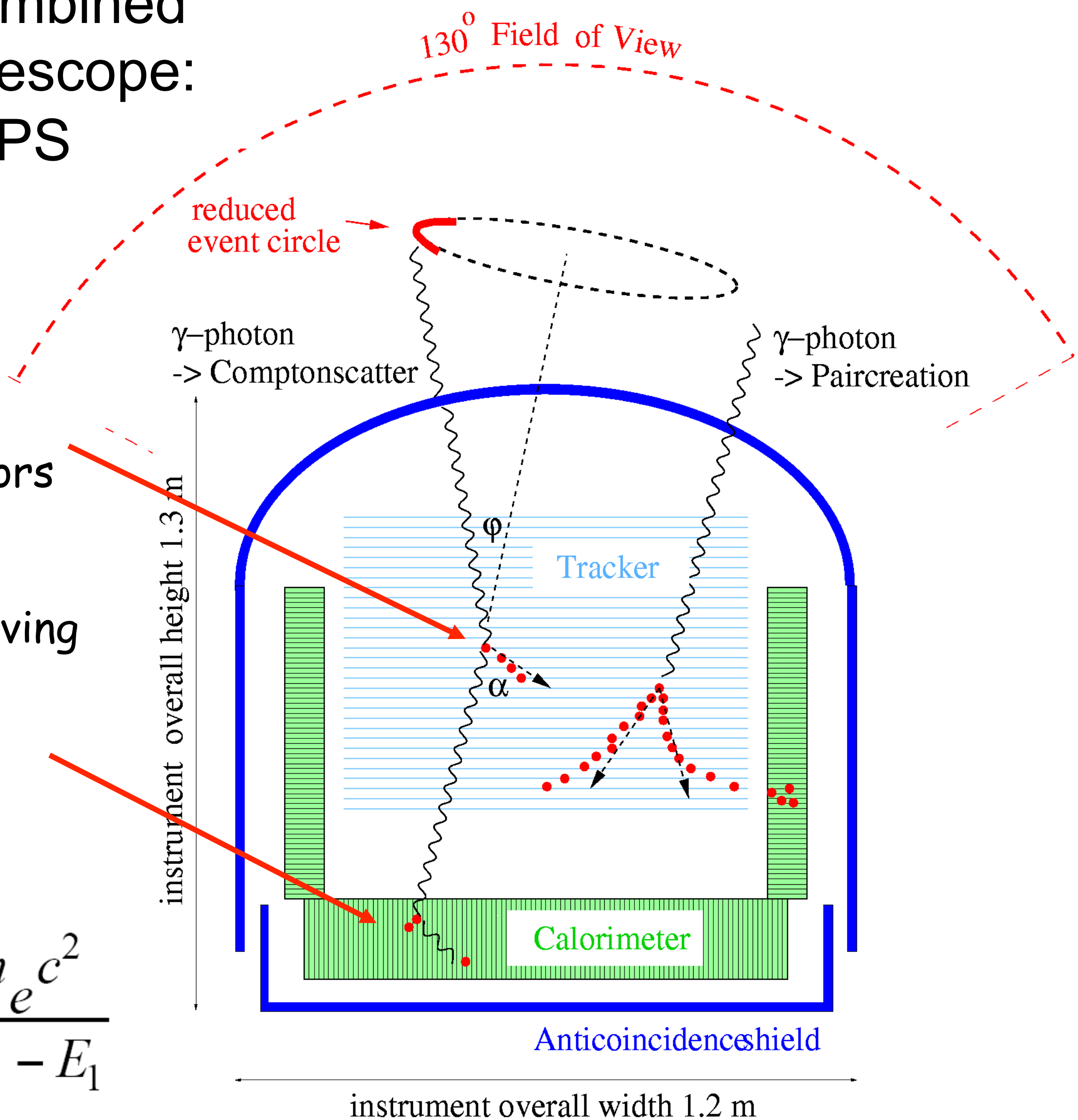
Concept for a combined Compton/Pair telescope: MEGA, GRIPS

Tracker: double sided Si strip detectors

Calorimeter: 2(3)D resolving voxel array

Compton Scattering:

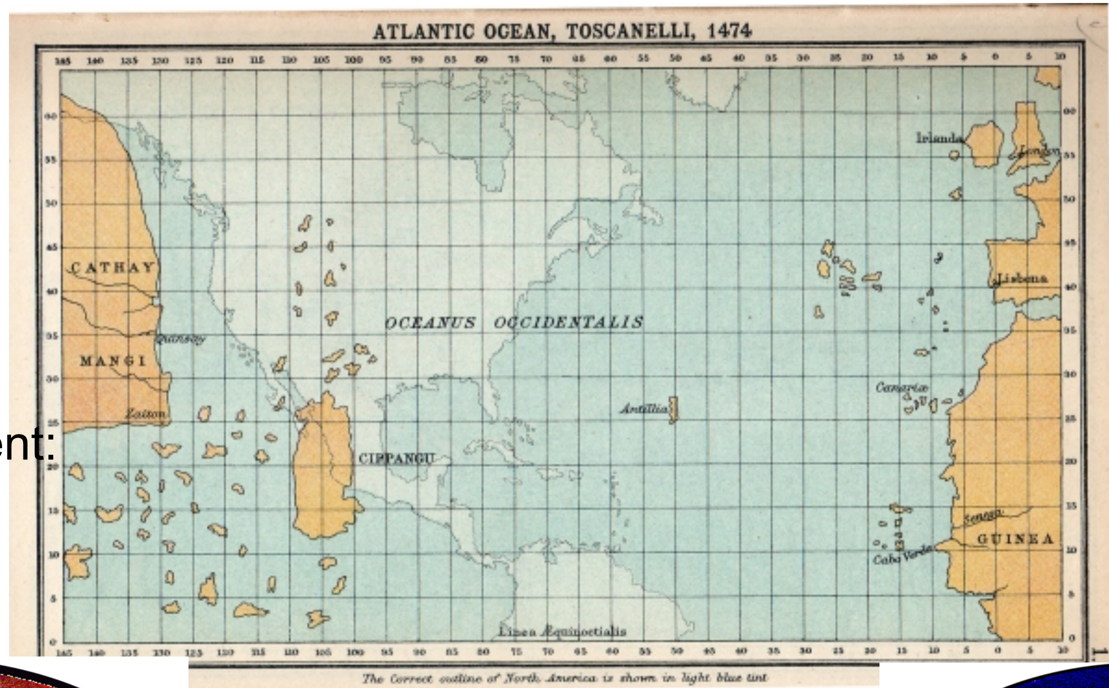
$$\cos\varphi = 1 + \frac{m_e c^2}{E_\gamma} - \frac{m_e c^2}{E_\gamma - E_1}$$



Goals: Imaging, Timing, Spectroscopy, Polarimetry

- Mapping the Sky:
  deep, continuous, survey from ~0.3-100 MeV
  Diffuse and localized sources
- Variability
  fast: GRBs, transients, SGRs, Novae
  solar flares, pulsars (periodic)
  slow: AGN, SNe
- Broadband spectra:
  SED characteristic for particles, fields & geometry
- Narrowband spectra:
  Cosmic radioactivity with short and long half-lives
  Nuclear resonance absorption
- Polarization: Pulsars, GRBs, AGN

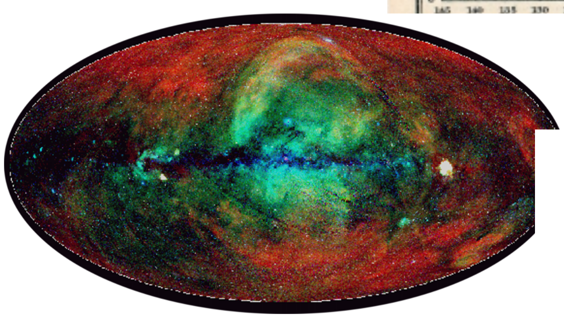
Toscanelli's World Map, 1474



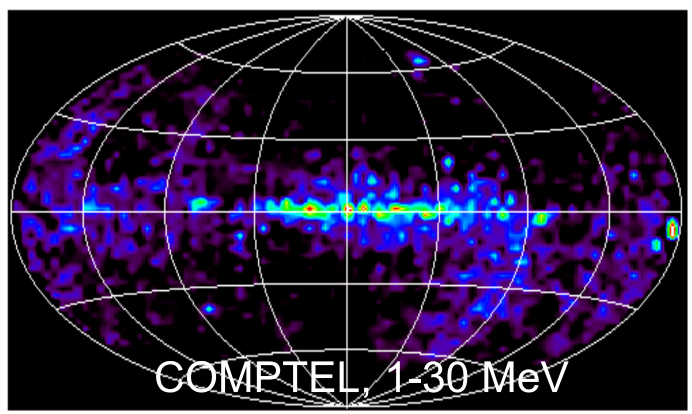
the X-ray continent:
~100 ev to
~100 keV

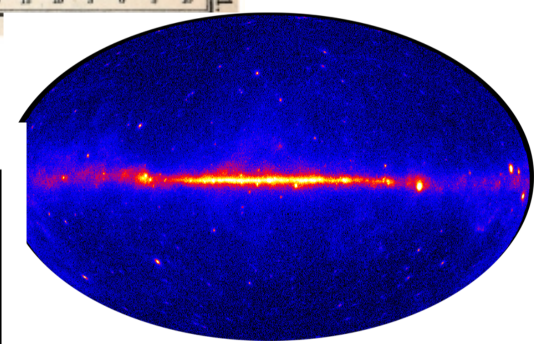
the gamma-ray
mainland:
~50 Mev to ~TeV

the MeV continent



ROSAT PSPC
0.1-2 keV
also:
SWIFT, INTEGRAL
coming: NuStar, Astro-H





Fermi. sky survey
>100 MeV
also:
Air Cerenkov Telescopes
HESS, Veritas, Magic

"*Tutte le verità sono facili da capire una volta scoperte – il punto è scopirle !*

All truths are easy to understand once they are discovered - the point is to discover them!"

Galileo Galilei (1564-1642)

Thank You for your attention

... concepts and a prototype for current technology MeV detectors later in the program ...

END