Gamma-Ray Observations of

COSMIC Accelerators

SLAC Summer Institute, August 4th - August 15, 2008

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Literature (phenomenologist's menu):

Schönfelder, V.: The Universe in Gamma Rays *Springer 2001*

Weekes, T.S.: Very High Energy Gamma Ray Astronomy *IoP 2003*

Aharonian, F.: Very High Energy Cosmic Gamma Radiation *World Scientific 2003*

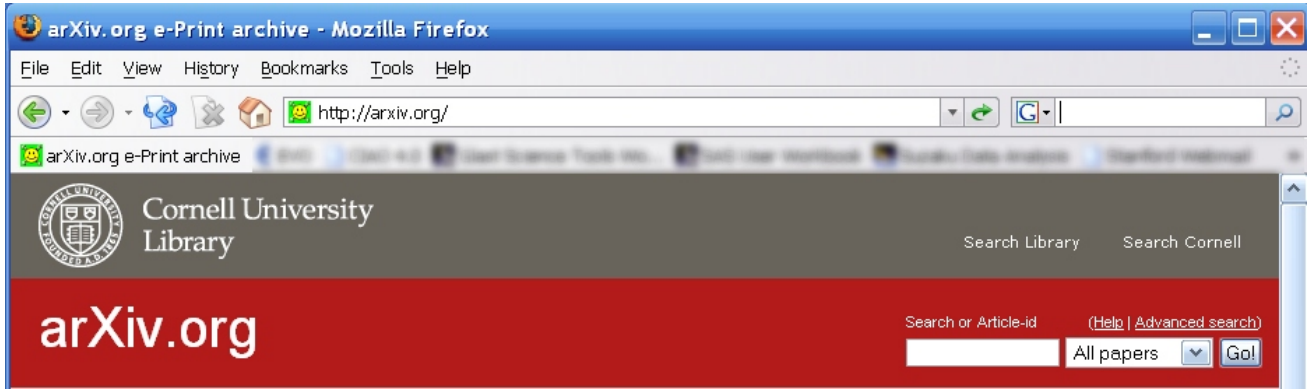
Longair, M.S.: High Energy Astrophysics 1 & 2 *Cambridge University Press 1992/1994*

Stanev, T.: High Energy Cosmic Rays *Springer 2004*

Wall, J.V. & Jenkins, C.R.: Practical Statistics for Astronomers *Cambridge 2003*

James, F.: Statistical Methods in Experimental Physics *World Scientific 2006*

+ lots of *up-to-date topical reviews* in arXiv!



Outline of Lectures

Gamma-rays as messengers of the energetic universe

Better observations as result of progress in instrumentation

→ the chronological perspective (not yet with 1st GLAST results)

Observables in gamma-ray astronomy – what do we actually measure?

→ the observers perspective

→ three regimes: 511 keV ↔ ~30 MeV ↔ ~50 GeV ↔ 100 TeV

Cosmic accelerators observed through γ-rays – the global picture

→ the perspective involving primary particles/nuclei: Cosmic Rays

Taxonomy: The zoo of cosmic gamma-ray sources

→ identifying γ-ray sources with astronomical objects

→ periodic variable γ-ray sources

→ stochastic variable & transient γ-ray sources

→ steady γ-ray emitter & our anticipation of new source classes

Commons of gamma and particle astrophysics

Unlike many branches of physics founded on elaboration and analysis of experiments, particle astrophysics is a science of observation, based on the detection and study of messengers sent by celestial bodies

Messengers of the energetic universe

- Electromagnetic radiation (from radio waves to gamma rays)
- Particles (protons & nuclei, electrons, neutrons, neutrinos, …)
- Gravitational waves

Observables in gamma astronomy

- Direction of arrival
- Energy
- Time of arrival
- Flux

That's it! Nothing else!

1st Observable: Photon arrival direction

Locate celestial sources: astrometry

Unfortunately, source localization in HE astrophysics not good
(→ source confusion, ambiguity in source identifications, diffuse processes vs. unresolved sources)

products: celestial images / skymaps / source catalogs

Study morphologies: diffuse, extended, point-like

Allows us to study spatial multiwaveband associations
→ signatures of non-thermal emission mechanisms
(synchrotron features? expanding shocks? jets? …)
→ decisive clue to its identification

1st Observable: Photon arrival direction

Point sources

Angular size smaller than the instrument point spread function (PSF)

Background is a severe issue (except for focusing instruments)

Extended sources

Angular size > PSF, the source is resolved into many pixels

The statistics per image element is usually rather low

Background is a much more severe issue, instrumental sensitivity loss

Main sources of background

Charged particles within the detector

Actual messengers produced in the close environment

Actual messengers produced in the atmosphere

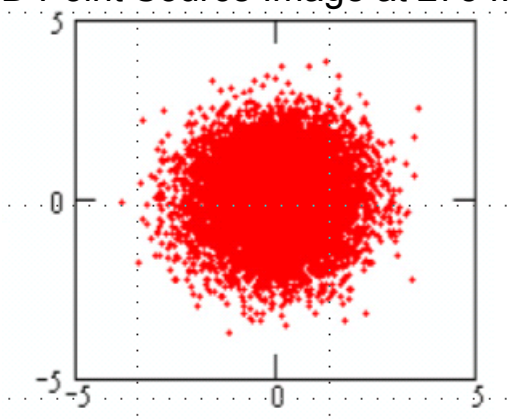
Actual messengers produced in the Galaxy

Actual messengers produced in the universe (cosmic background)

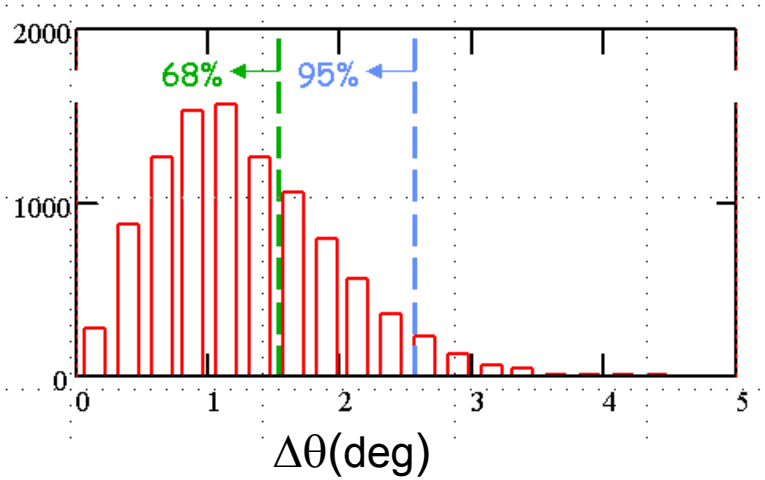
The Point Spread Function

Point Spread Function (PSF)

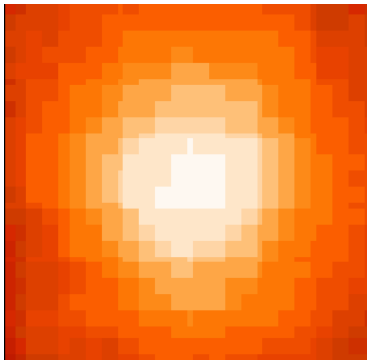
2D Point Source Image at 275 MeV



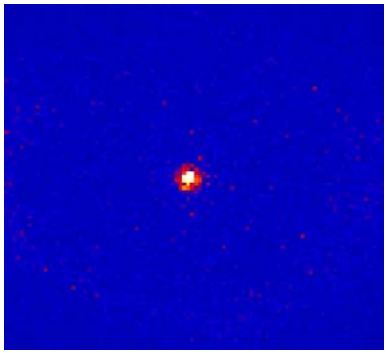
PSF Characterized by 68% & 95% Containment



Crab viewed with EGRET



Crab viewed with HEGRA-IACT



… and yes, they are in scale!

2nd Observable: Photon energy

Lines spectra: basis of astrophysics

Atomic physics of emitting (absorbing) media, Doppler shift, redshifts (cosmological, gravitational), …

HE domain: cyclotron features, nuclear lines (nuclear astrophysics), Annihilation lines

Continuum spectra: basis of HE astrophysics

Signature of non-thermal emission mechanisms

Signature of absorption processes

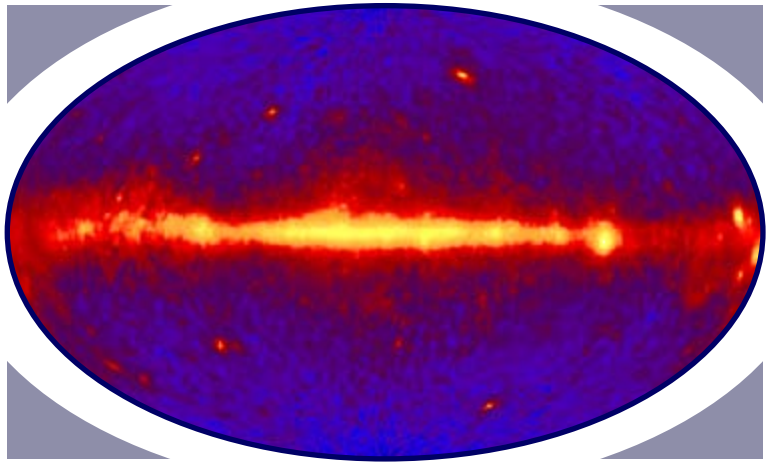
Responses of HE telescopes

HE telescopes generally answer in a rather complex manner to the photons (particles) released by cosmic sources

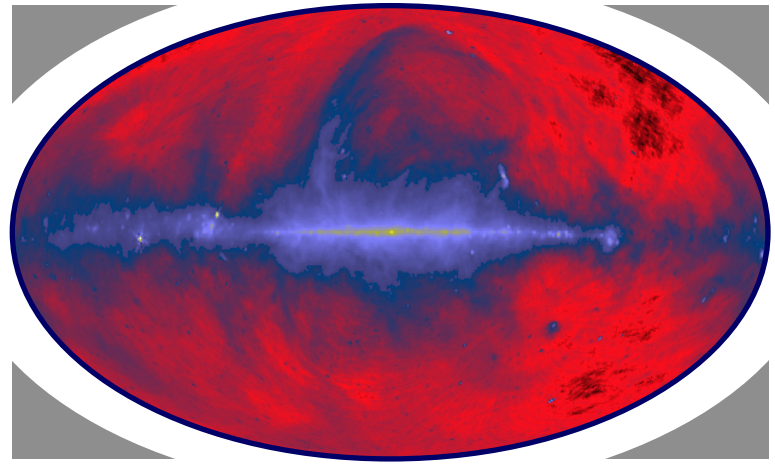
In particular, the count energy spectra differ markedly from the incident photon (particle) spectra

products: photon or energy spectrum, width in γ-ray lines

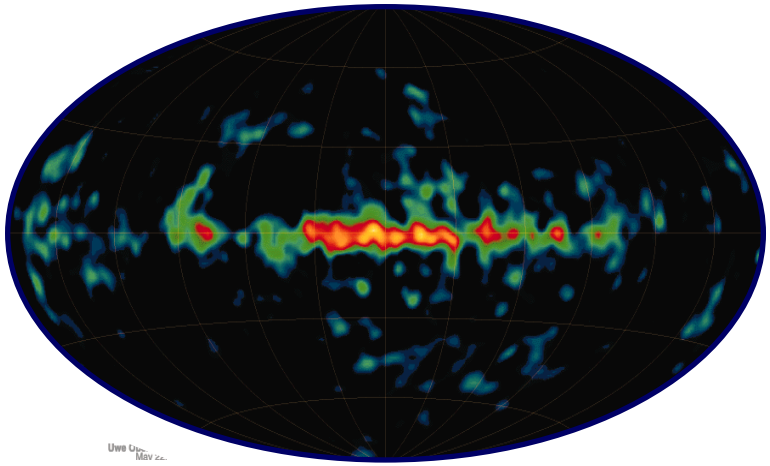
Two observables used: arrival direction & energy



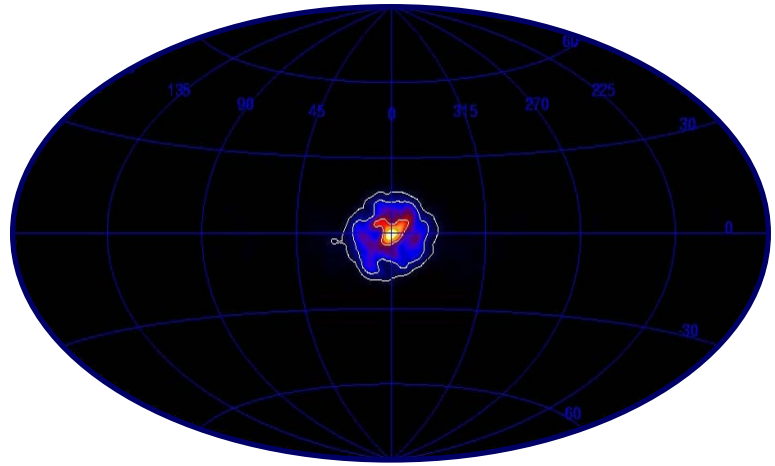
Gamma rays ($E\gamma$ > 100 MeV)



Radio waves (408 MHz)



Gamma rays ($E\gamma$ = 1.8 MeV)



Gamma rays ($E\gamma$ = 511 keV)

3rd Observable: Arrival Time

An extremely powerful observable

Source size upper limit

Periodic behavior (binaries, pulsars, …)

Pseudo periodic behavior (QPO)

Source identification (light curve similarities)

Source identification (transient emission in coincidence)

Timing is well adapted to HE astrophysics

Many phenomena in γ-ray sources are highly variable

HE telescopes operate in an event by event manner*

Long observation time, survey capabilities

products: rate changes, light curves, phase-folded signals

4th Observable: Flux

In single photon counting experiments: Just count and keep time!

Problem: celestial and instrumental backgrounds

Calibrations (ground, Monte-Carlo, sky, relative vs. absolute)

Different responses to different phenomena (e.g. coded mask ↔ source extension)

Monitoring of activity states → flux/time domain: alerts, campaigns

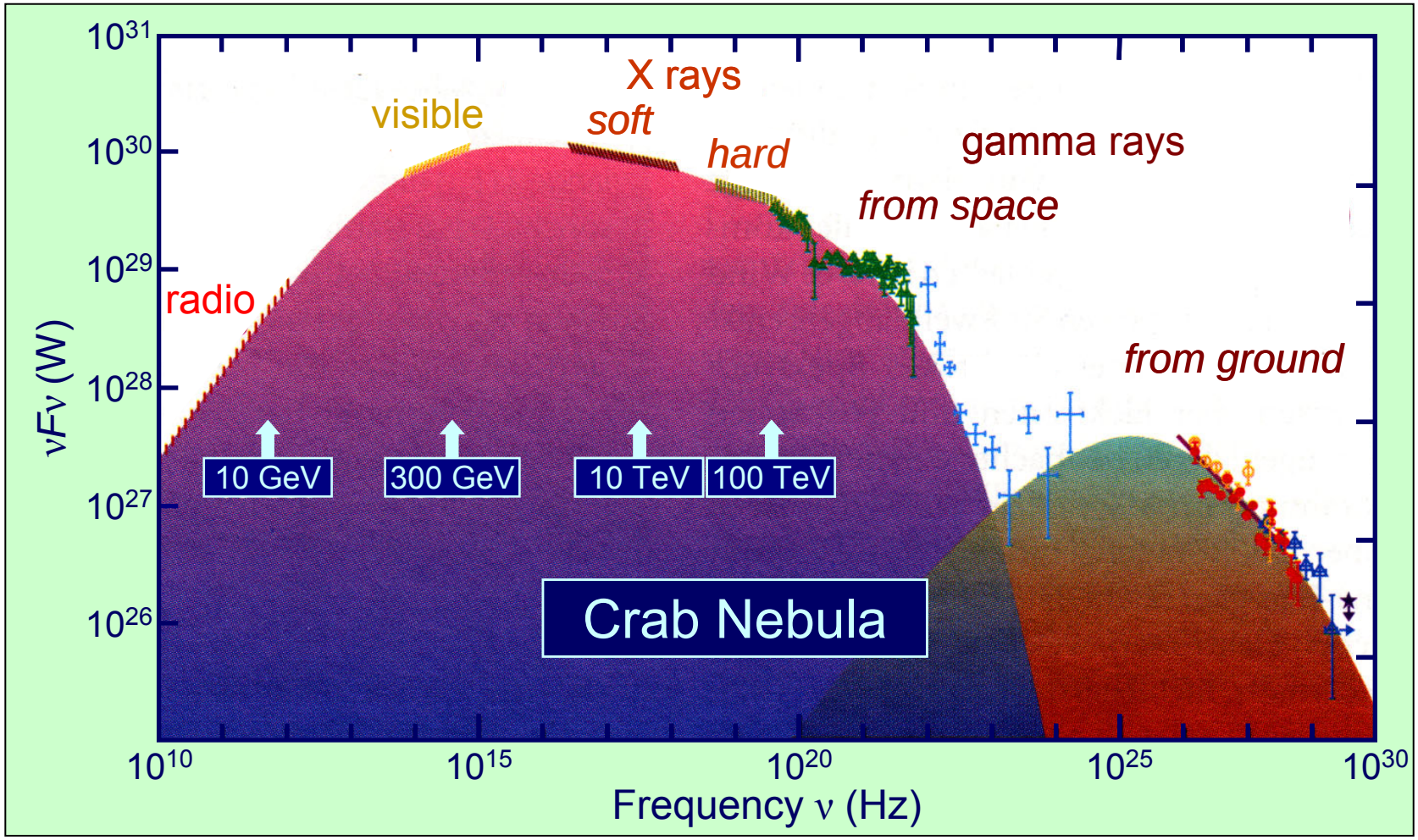
Intensity ↔ distance estimates from astronomical tools

Interstellar absorption

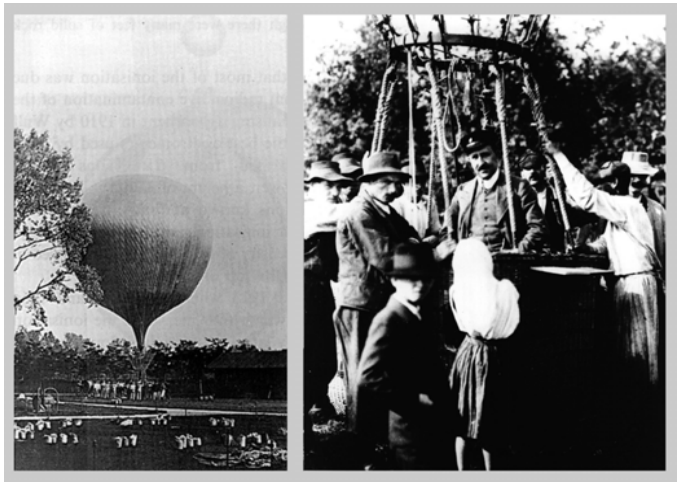
Galactic rotation

products: fluxes (and flux uncertainties) → spectral energy distribution

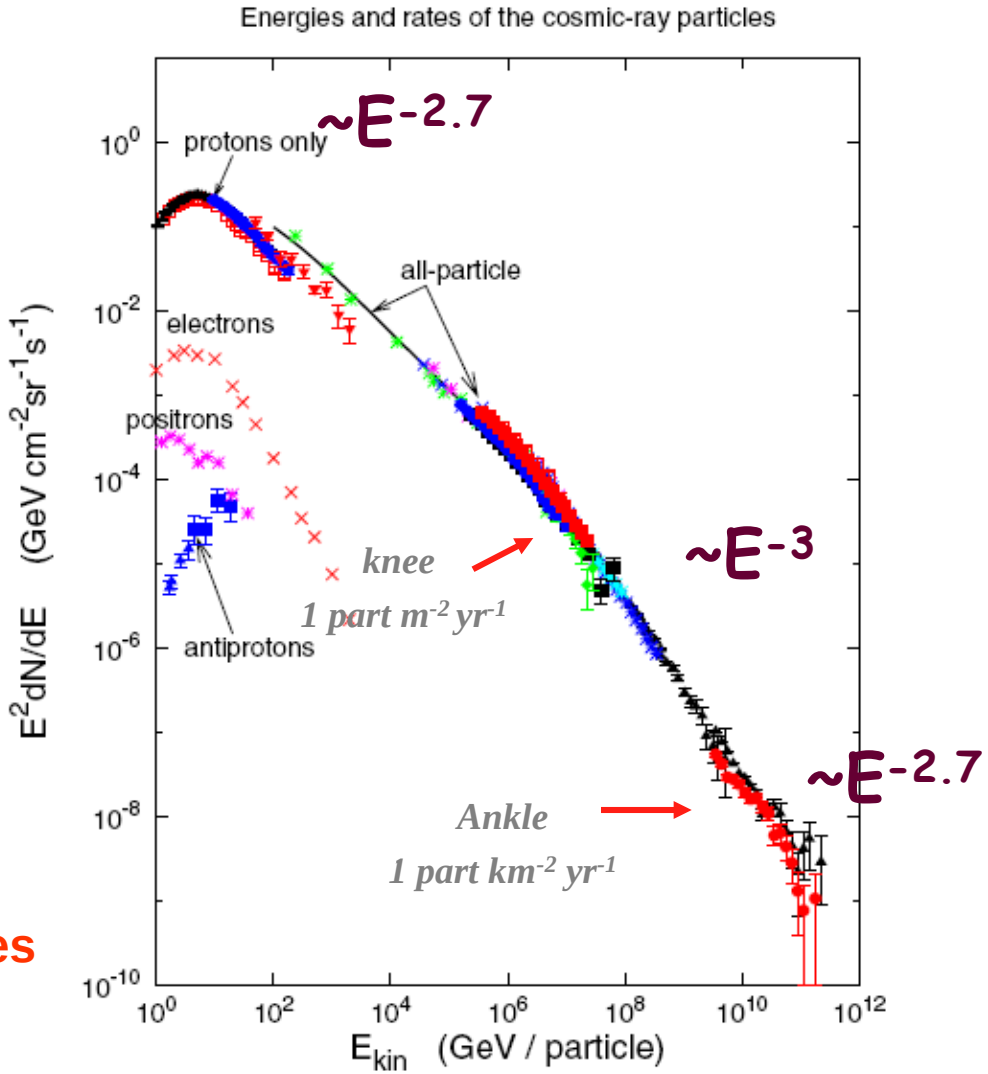
Cosmic source of calibration



Cosmic Rays and particle acceleration in our Universe



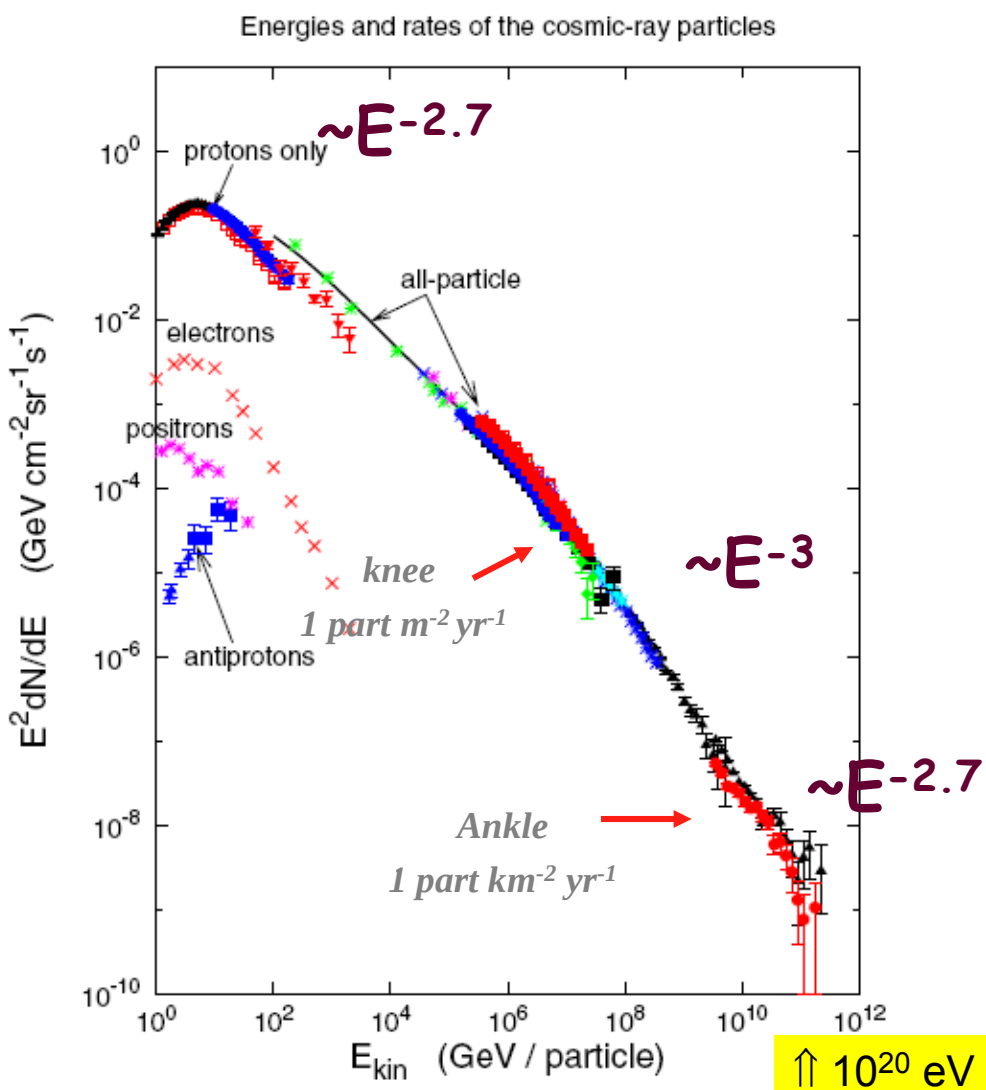
"The results of my observations are best explained by the assumption that a radiation of very great penetrating power enters our atmosphere from above."
Victor Franz Hess (1912)



[adapted from Gaisser'05]

But we still fail to settle on the sources & acceleration of Cosmic Rays!

Cosmic Rays and particle acceleration in our Universe



[adapted from Gaisser'05]

Energy density	erg cm^{-3}
Cosmic Rays:	~1.0×10^{-12}
starlight:	~0.7×10^{-12}
ISM pressure:	~0.4×10^{-12}
B:	~1.0×10^{-12}

Galactic luminosity:

stars:	~ 10^{44} erg/s
CR sources:	~ 10^{41} erg/s

CRs seem to be blend of many galactic / extragalactic accelerators !

⇑ 10^{20} eV = 16 J (lift 1 kg by 1.5m!)

Cosmic-ray orgin?

observables

- Arrival direction
- Intensity
- Energy spectrum
- Composition

- energy density: $\rho_{CR} \sim 1.8$ eV/cm^3

  $\rho_{CR} \sim \rho_B \sim \rho_P$
- galactic CR energy content:

  $\rho \times$(15 kpc $\times$ 15 kpc $\times$ 3 kpc), renewed every 10^7 years

  $\Rightarrow$ 2×10^{41} erg/s

1 SN of 10^{51} erg every 30 years $\Rightarrow$ 10^{42} erg/s

$\Rightarrow$ 20% of the SN energy could energize galactic cosmic-rays

How to approach the enigmatic cosmic accelerators?

Theoretical: processes and conditions for particle acceleration

Experimental:

build an accelerator and study how it works

visit a ‚natural' accelerator and measure the energetic particles directly:

- lightning flashes
- earth magnetosphere – bow shock
- interplanetary shock waves
- solar flares

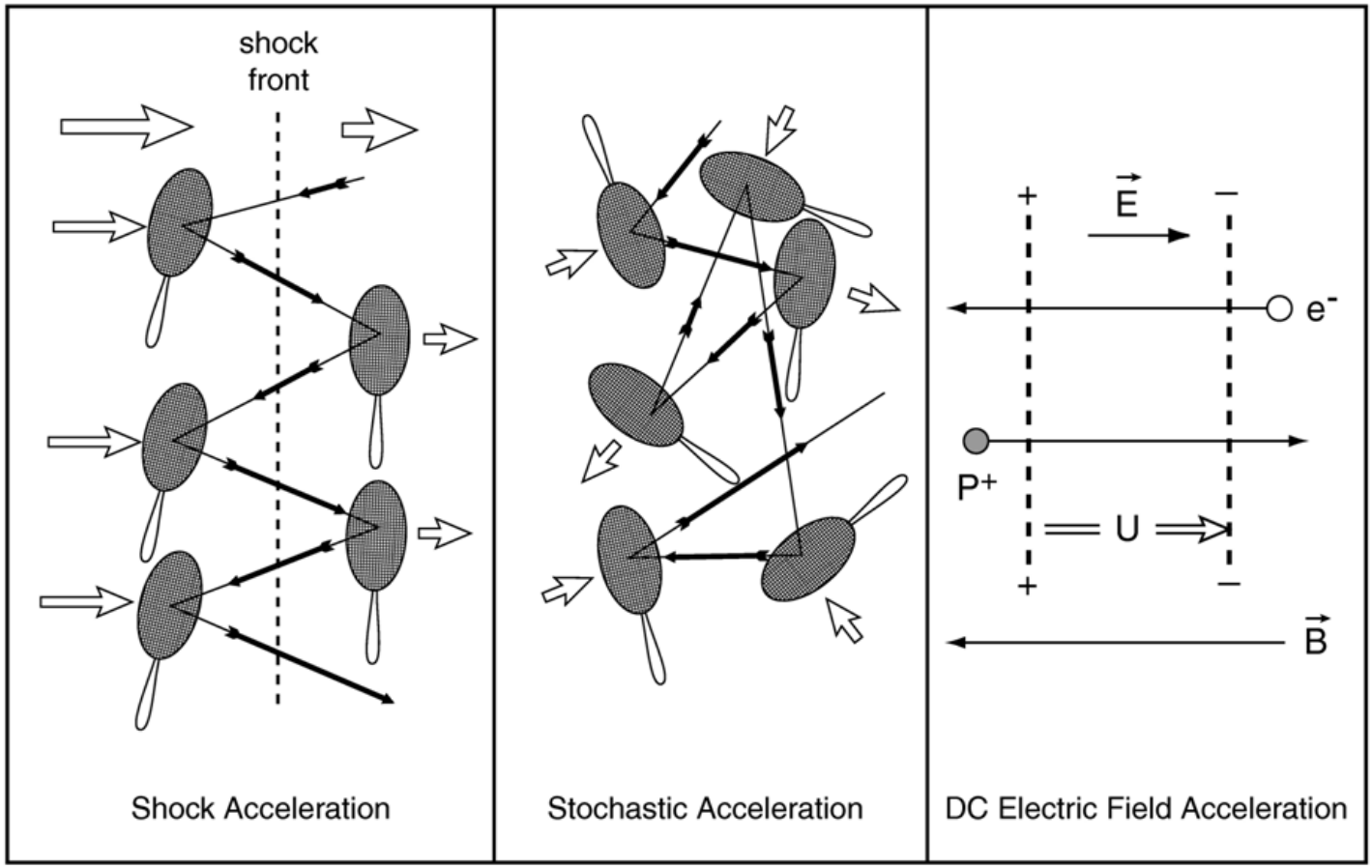
look at secondary emission:

- electromagnetic spectrum (from radio to gamma-rays)
- neutrinos *(tough!)*

look at our most pristine primaries:

- UHECRs *(tough!)*
- gravitational waves *(toughest!)*

Basic Cosmic Accelerator Schemes



Fermi – I:
momentum
convection

Fermi – II:
momentum
diffusion

EM Accelerator

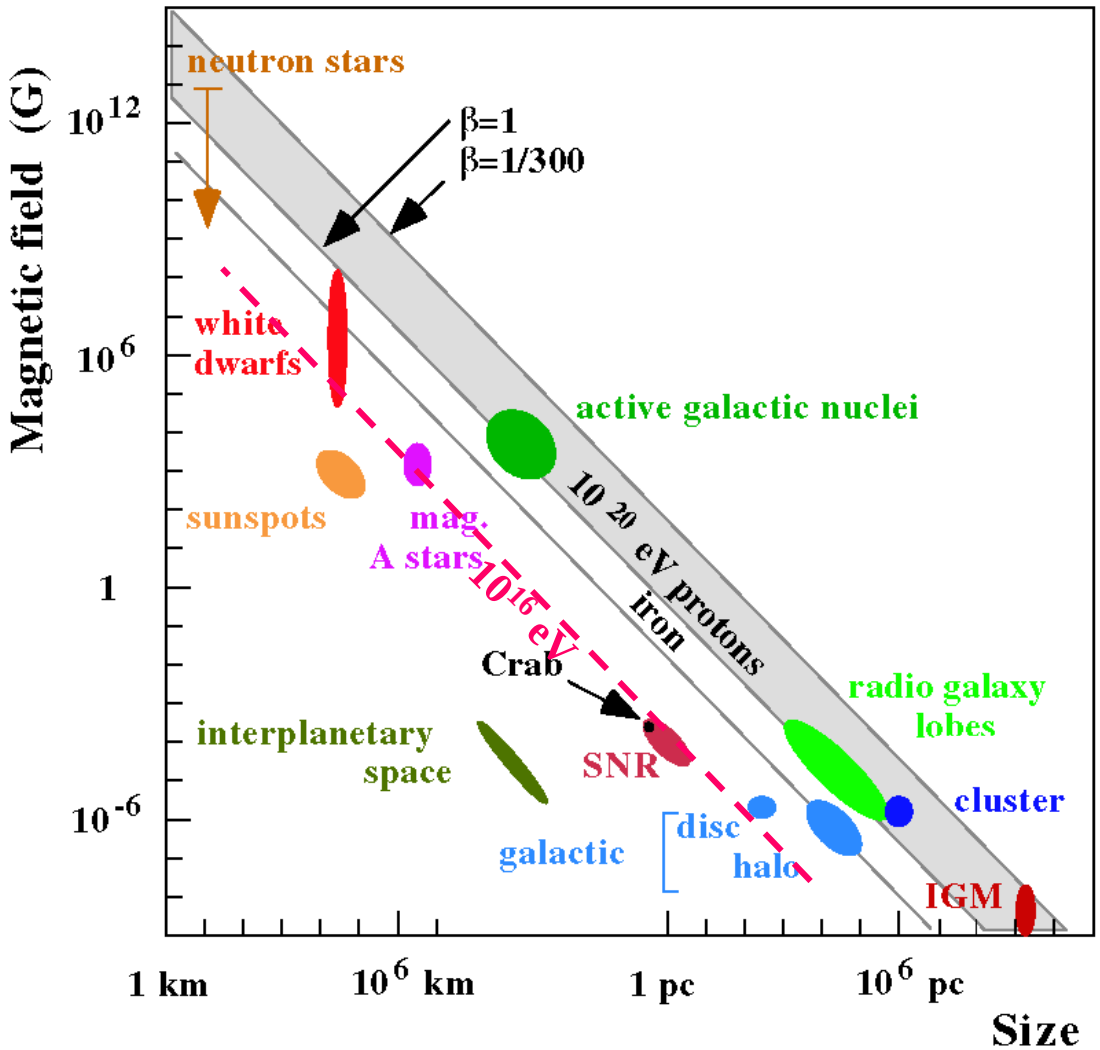
Cosmic Acceleration environments

- Electrostatic Fields
  - Pulsars

- Magnetic Fields
  - Near Compact Stars → … ~10^{13}G
  - Stellar Environments & SNe → … ~ G
  - Galactic and Intergalactic Space → … ~mG
  - Turbulent Magnetic Fields in Shocked Gas
    - Jets (AGN, μQSOs , GRB, …)
    - SNR, stellar wind blown bubbles, superbubbles ?

Spectral shapes and evolution are coupled to the size, temporal evolution and geometry of the accelerating sources!

Cosmic Particle Accelerators?



[after Hillas 1984]

Size ~ Gyro-Radius

$$E_{max} \propto \beta \cdot Ze \cdot B \cdot L$$

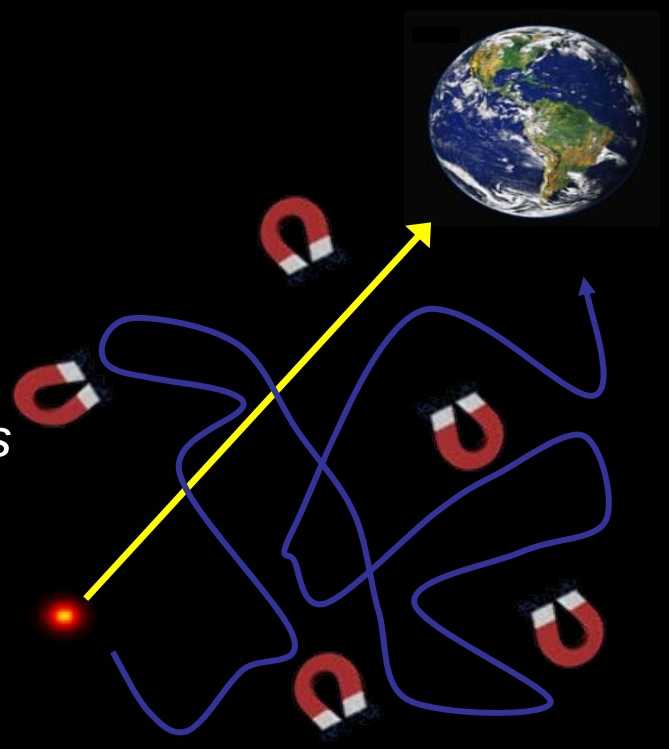
Where and what are the CR sources?

- Deflection of charged particles in interstellar magnetic fields

- For a given interstellar or intergalactic magnetic field and a given energy:

  $\rightarrow$ *expect anisotropies at highest energies (AUGER results!)*

  $\rightarrow$ *however: arrival direction of particles isotropized (10^{-3} at 1 TeV)*

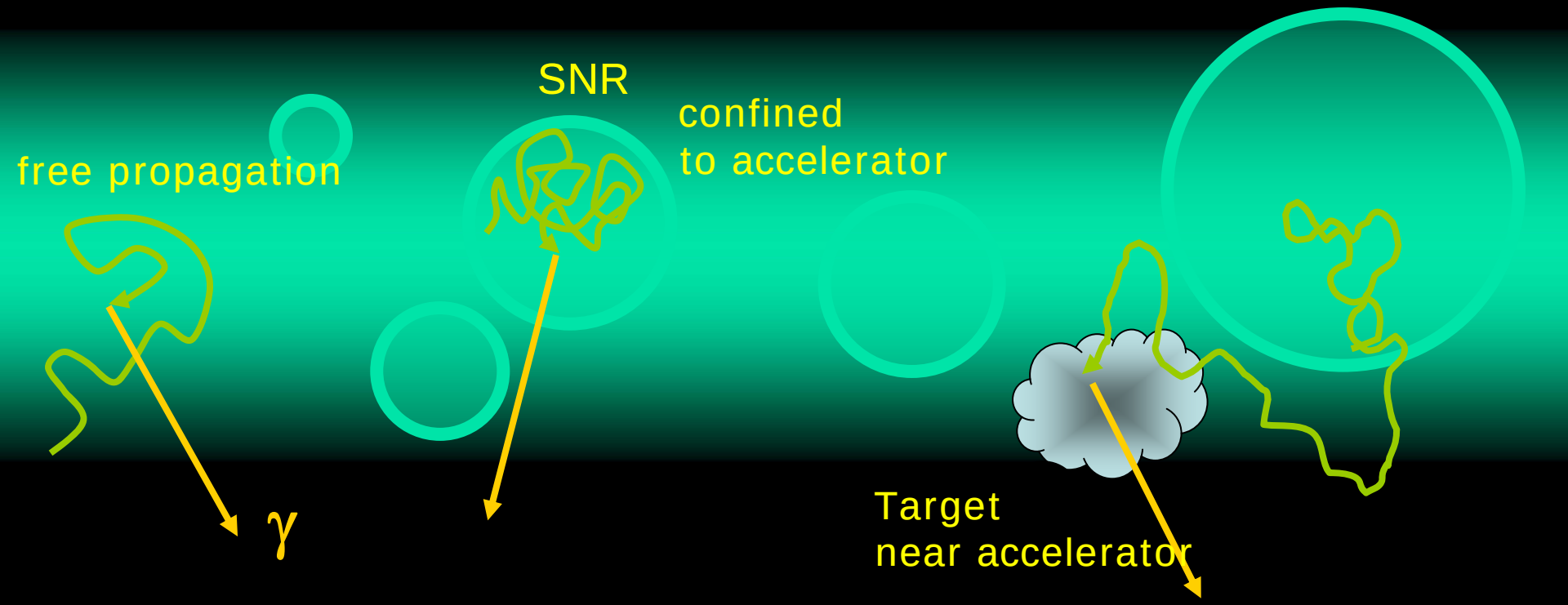


- Turn to neutral messengers:

  Photons
  - Radio
  - X-rays
  - γ -rays

  or … Neutrinos

CR origin and propagation



γ-rays from secondary interactions:

p: π^o production and decay

e: Inverse Compton scattering and bremsstrahlung

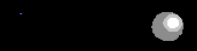
→ trace beam density x target density

The main photon production processes

- Proton accelerator:
  - Hadronic interaction, π_0-decay

$$p + p \rightarrow \pi^o + X + \ldots \pi^{\pm}$$
$$\hookrightarrow \gamma + \gamma \quad \hookrightarrow \nu_\mu + \nu_e \ldots$$

π^0 -decay

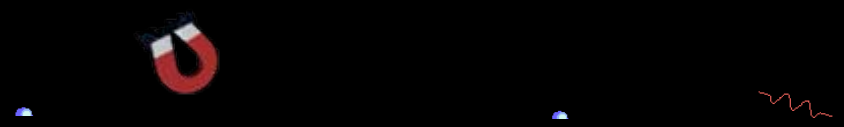


γ-rays and Neutrinos

- Electron accelerator:
  - Synchrotron emission in magnetic field at radio to X-ray energies
  - Inverse Compton scattering off photon fields (CMB, …) at γ-ray energies

Synchrotron
(B-field)

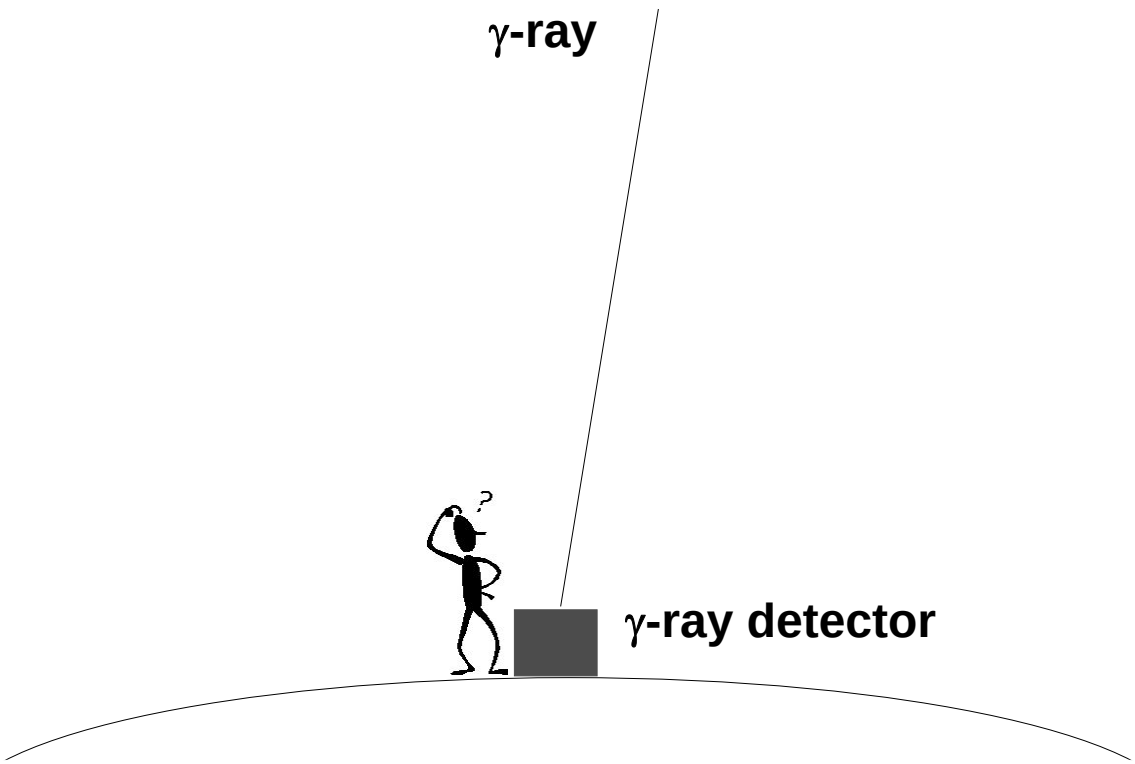
Inv Compton
(photon-field)



Radio, X-rays, γ-rays

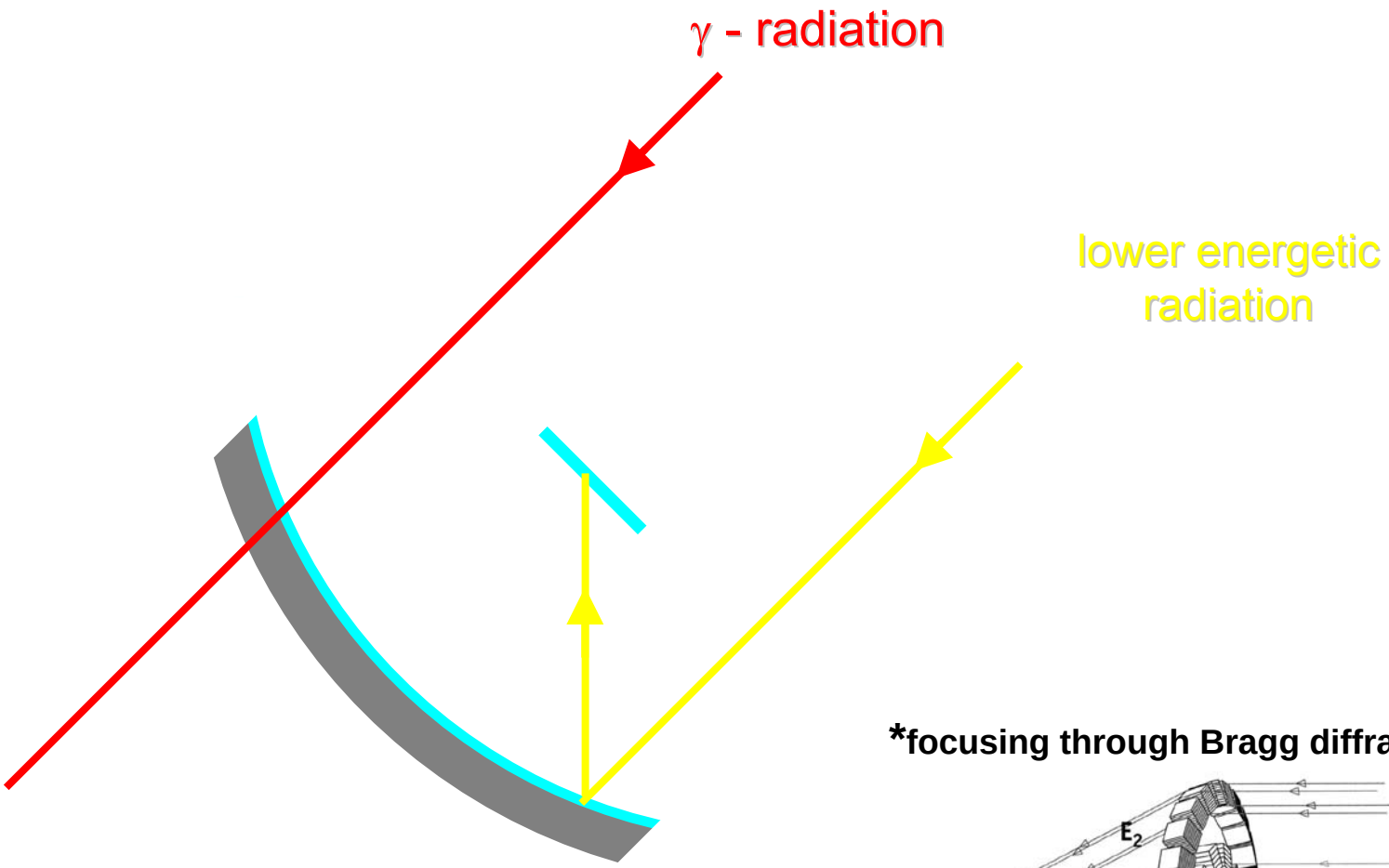
[From W. Hofmann]

The technical challenges in observational gamma-ray astronomy

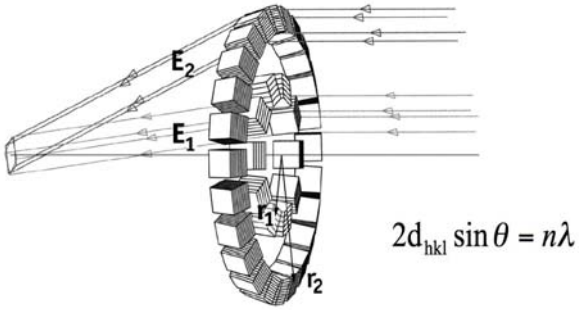


No Optics: Detector Area = Collection Area

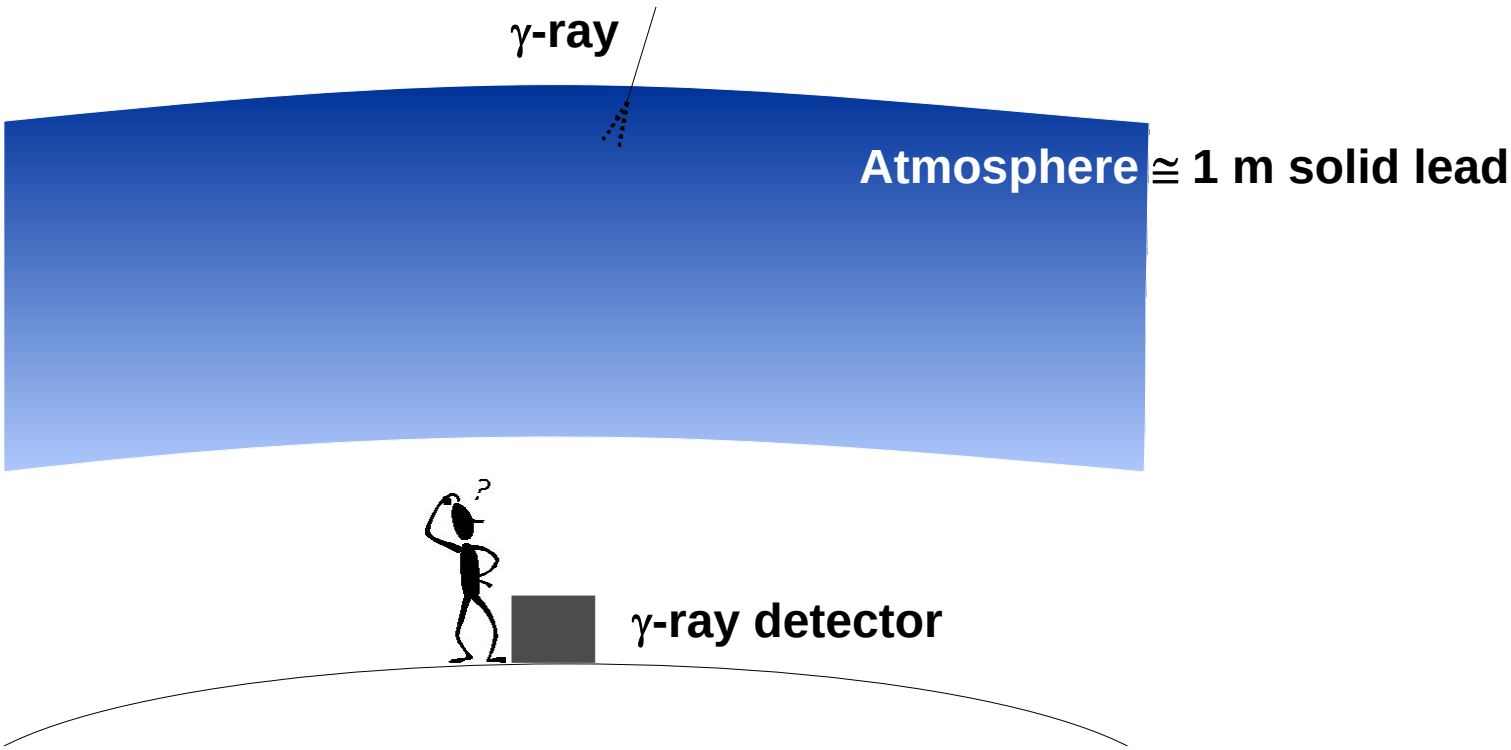
How to catch a γ-ray?



***focusing through Bragg diffraction**

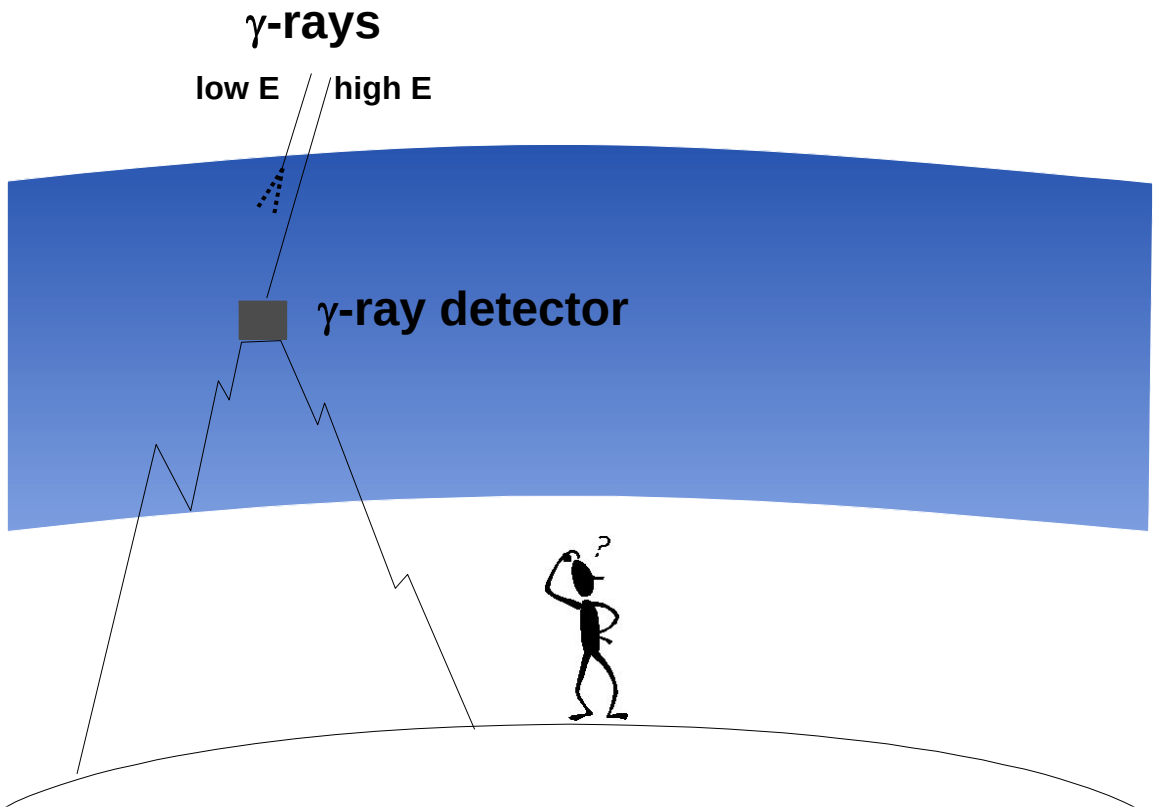


Gamma rays cannot be detected directly on the ground



No celestial photons* reach the ground.

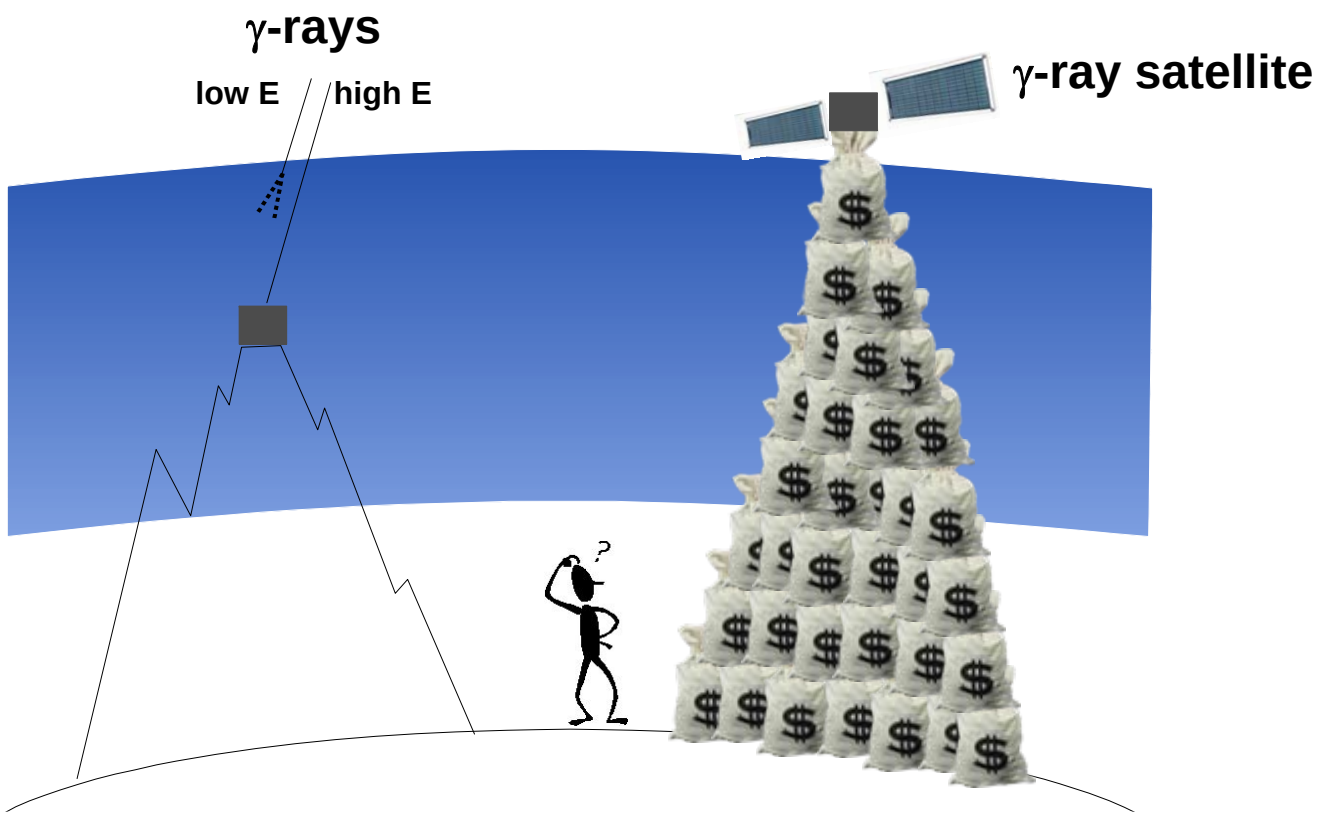
Solutions to problem of Atmosphere



Move detectors up!

…but even Mt. Everest is below half an atmosphere

One solution to problem of Atmosphere

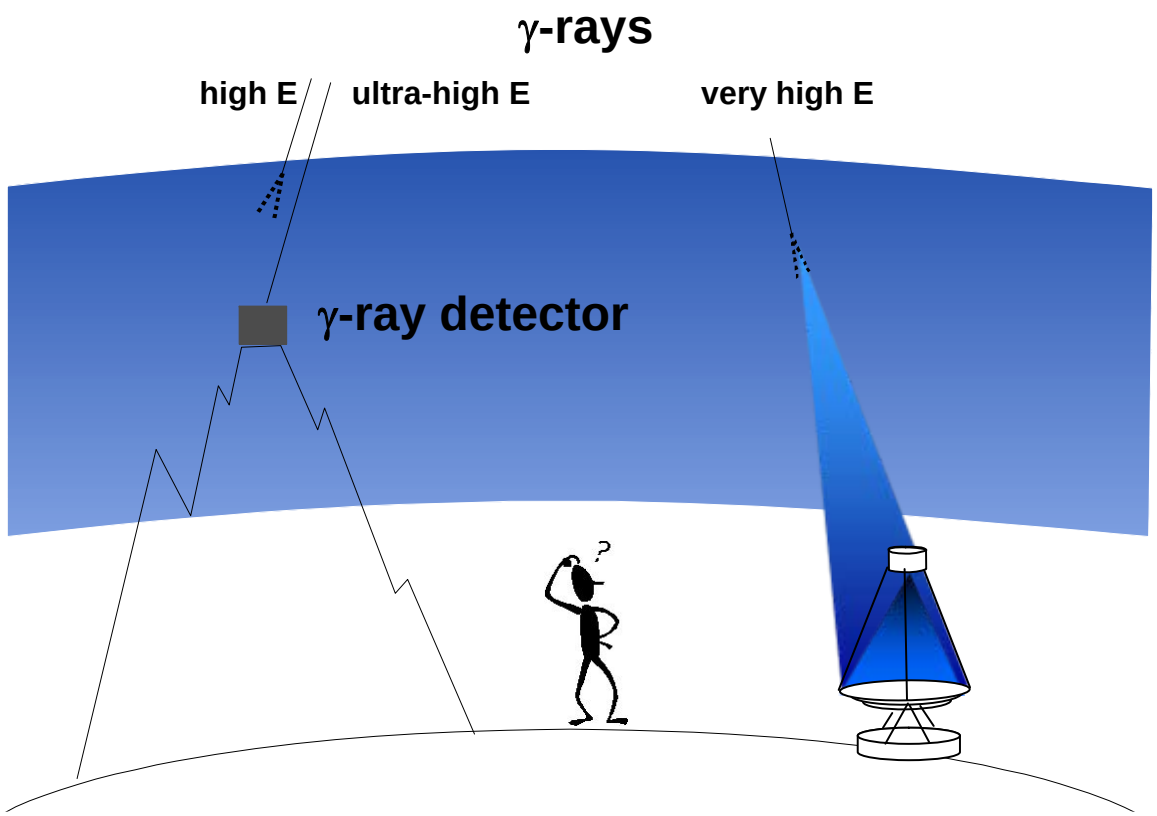


Move detectors up!
..but even Mt. Everest is below half an atmosphere

Artificial mountain!
Mountain of money :=
space-based γ-ray astronomy*

*quote by Trevor Weekes

Another solution to problem of Atmosphere

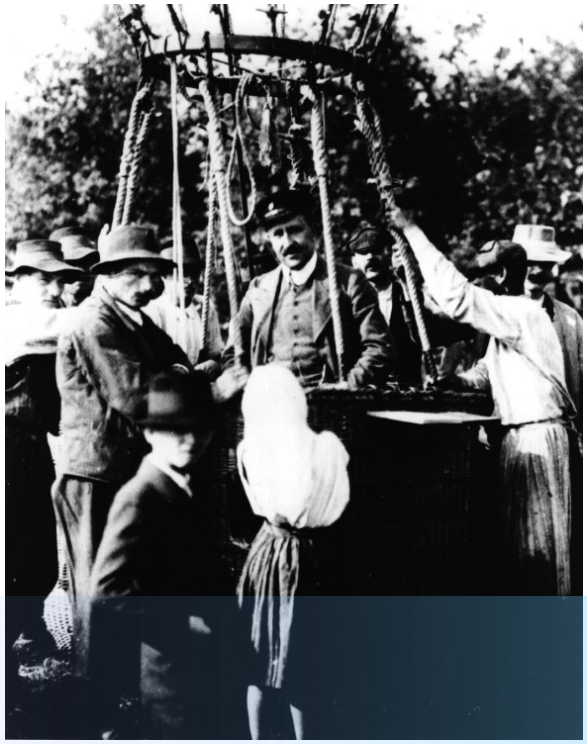


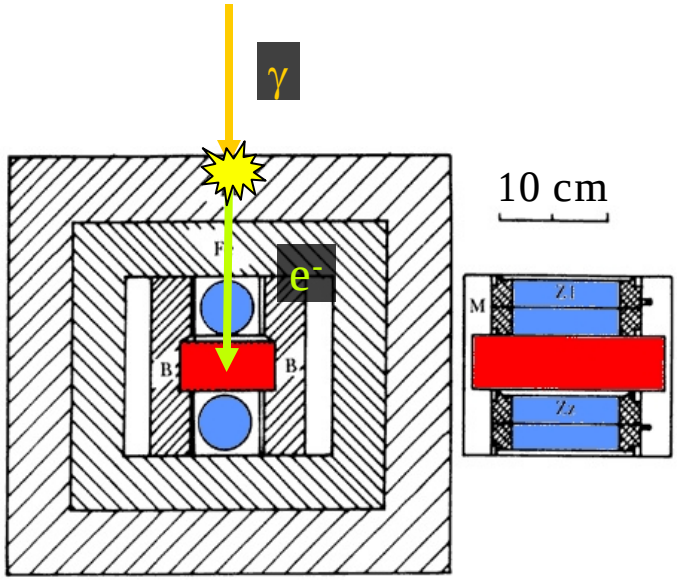
Use atmosphere!

Detect secondaries (Cherenkov light) from the secondaries (photon messenger) of our cosmic particle accelerators!

...and thereby gaining a huge collection area...

A misleading name – and a controversy





The New York Times

VOL. LXXXII...No. 27,370. December 31, 1932

MILLIKAN RETORTS HOTLY TO COMPTON IN COSMIC RAY CLASH

Debate of Rival Theorists Brings Drama to Session of Nation's Scientists.

THEIR DATA AT VARIANCE

New Findings of His Ex-Pupil Lead to Thrust by Millikan at 'Less Cautious' Work.

1912

Discovery of Cosmic Rays
by Victor Franz Hess
« Ultragamma-Strahlung »

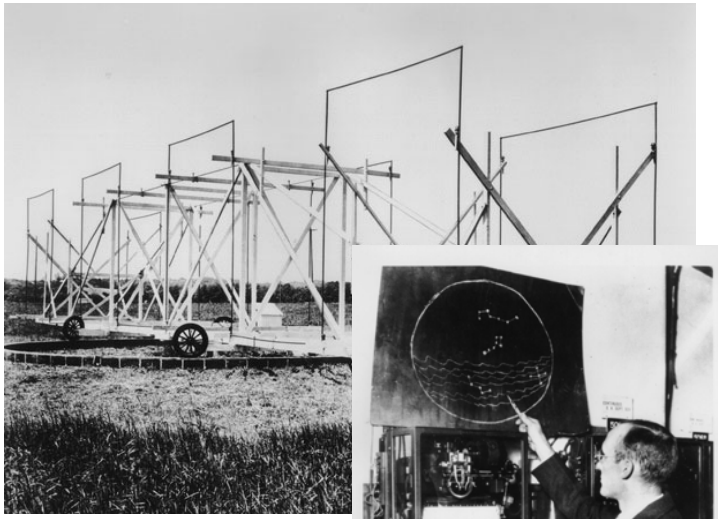
1929

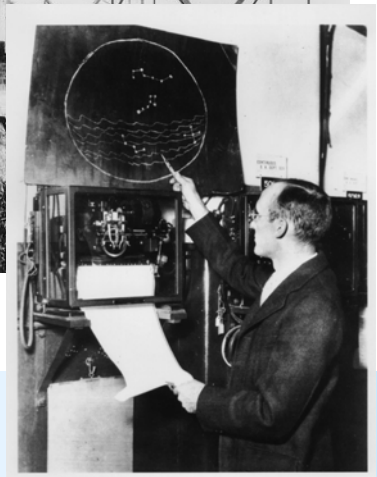
Bothe and Kolhörster
proof charged particle
nature of Cosmic Rays

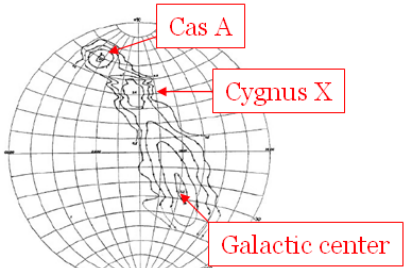
1932

The dispute on the
nature of Cosmic Rays
erupts again

Radio astronomy leads the way





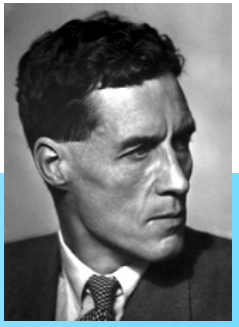


Cosmic Rays as the Source of General Galactic Radio Emission

K. O. Kiepenheuer

Yerkes Observatory, University of Chicago, Williams Bay, Wisconsin

June 20, 1950



1933

Jansky discovers radio emission from our own Galaxy

1944

Reber produces first radio sky maps

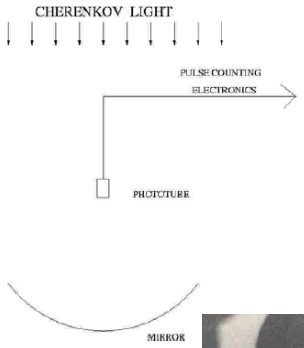
1948

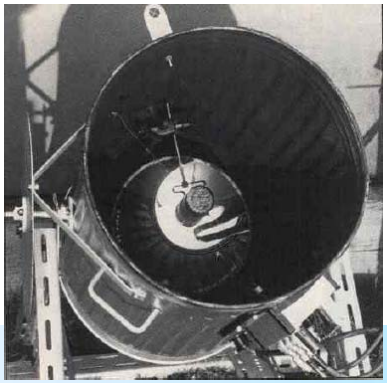
P.M.S. Blackett: Cherenkov radiation constitutes small fraction of night sky light

1950

Kiepenheuer suggests CR e^- as comon source of radio emission

An astronomical discipline?





IL NUOVO CIMENTO Vol. VII, N. 6 16 Marzo 1958

On Gamma-Ray Astronomy.

P. Morrison
Department of Physics, Cornell University - Ithaca, N. Y.

(ricevuto il 22 Dicembre 1957)

Summary. — Photons in the visible range form the basis of astronomy. They move in straight lines, which preserves source information, but they arise only very indirectly from nuclear or high-energy processes. Cosmic-ray particles, on the other hand, arise directly from high-energy processes in astronomical objects of various classes, but carry no information about source direction. Radio emissions are still more complex in origin. But γ-rays arise rather directly in nuclear or high-energy processes, and yet travel in straight lines. Processes which might give rise to continuous and discrete γ-ray spectra in astronomical objects are described, and possible source directions and intensities are estimated. Present limits were set by observations with little energy or angular discrimination; γ-ray studies made at balloon altitudes, with feasible discrimination, promise valuable information not otherwise attainable.

*A trashcan setup made it into **Nature** !*

the active Sun, Crab nebula, Cyg A, continuum

…predates birth of X-ray astronomy !

1952

Hutchinson: Prediction of diffuse γ-ray emission from CR via bremsstrahlung

Hayakawa: Prediction of diffuse γ-ray emission from π_0 decay in Galaxy

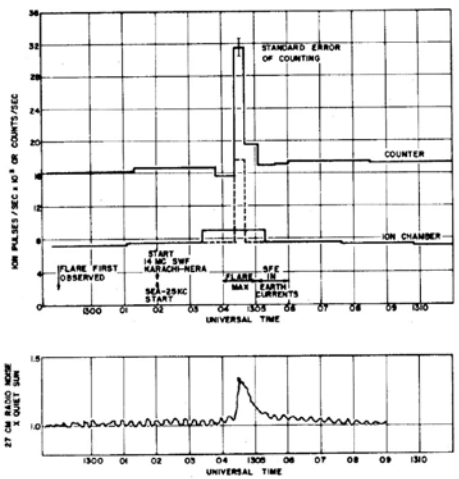
1953

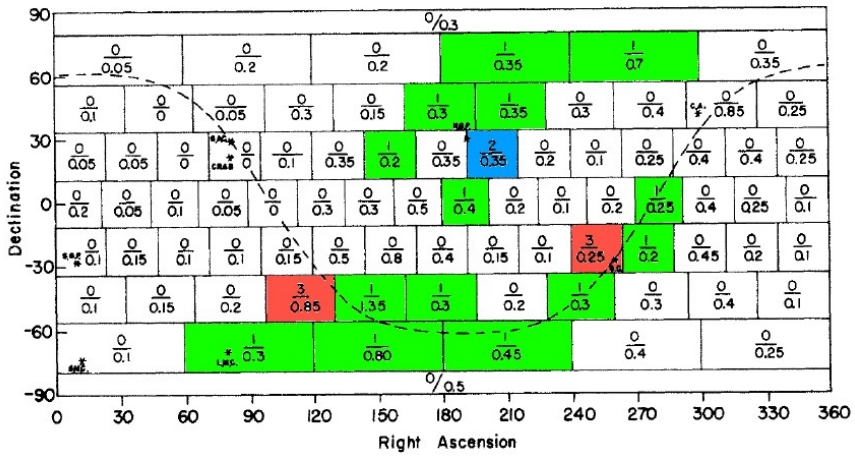
Galbraith & Jelley 1953: “Light Pulses from the Night Sky associated with Cosmic Rays”

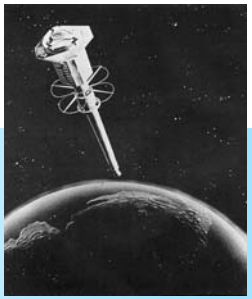
1958

Morrison:
« On Gamma-Ray Astronomy »

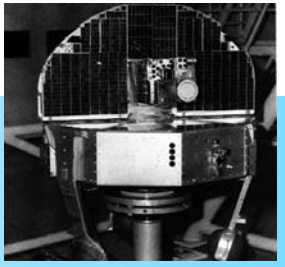
The 60ies: Photon counting

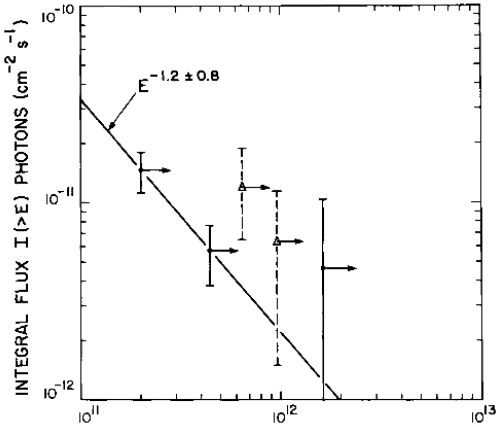






OSO-3





621 photons ...

1958

Peterson & Winckler
Solar flare γ-ray outburst by balloon experiment

1962

Arnold et al.
0.4 – 2 MeV γ-ray spectra

1968

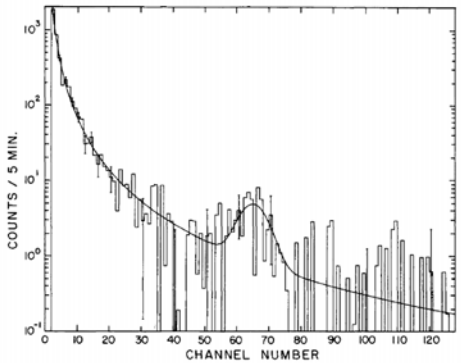
Kraushaar & Clark
22 high-energy photons by Explorer 11

1972

Crab nebula in TeV:
Grindlay (1971, 1972)
Fazio et al. (1972)

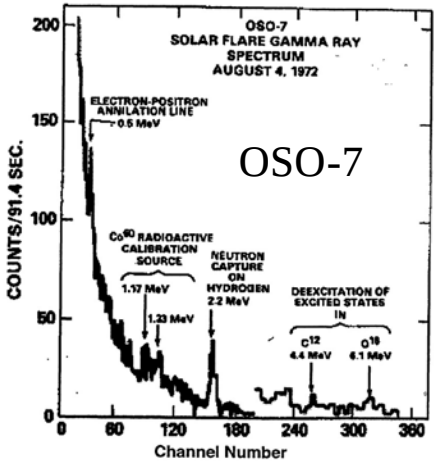
1970 to 1990 : Discoveries turn in

$e^+ e^-$ annihilation line



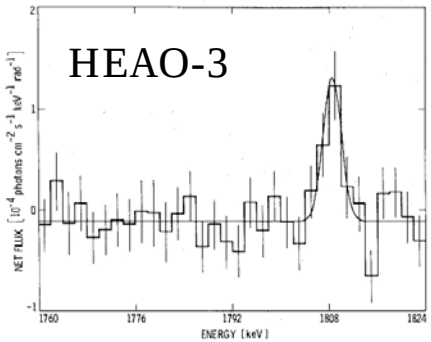
Johnson et al. (1972)

Nuclear lines



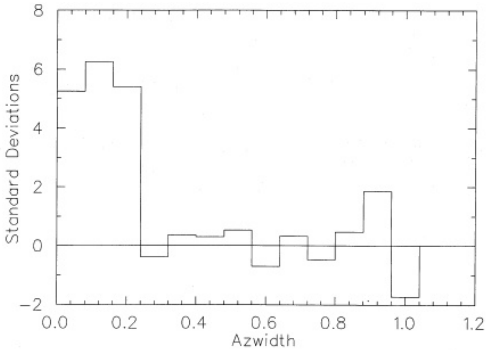
Chupp et al. (1973)

Radioactive ^{26}Al

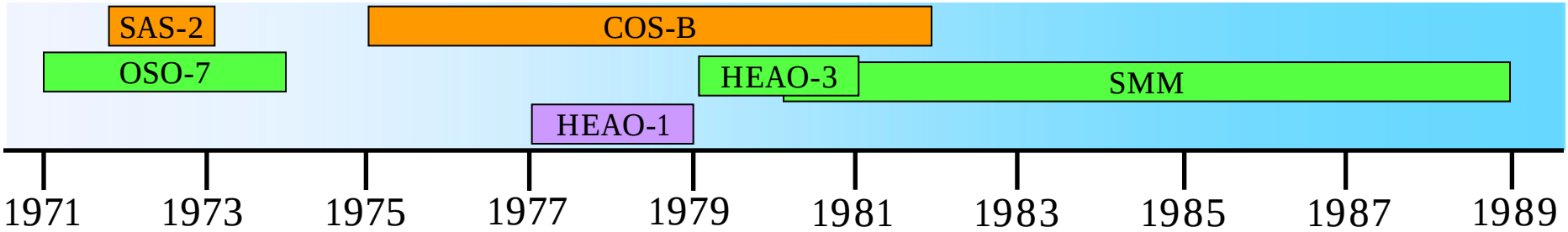


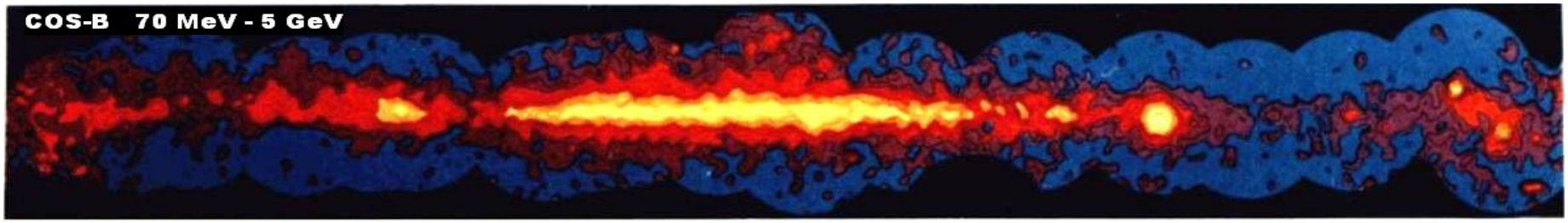
Mahoney et al. (1984)

Crab nebula > 700 GeV



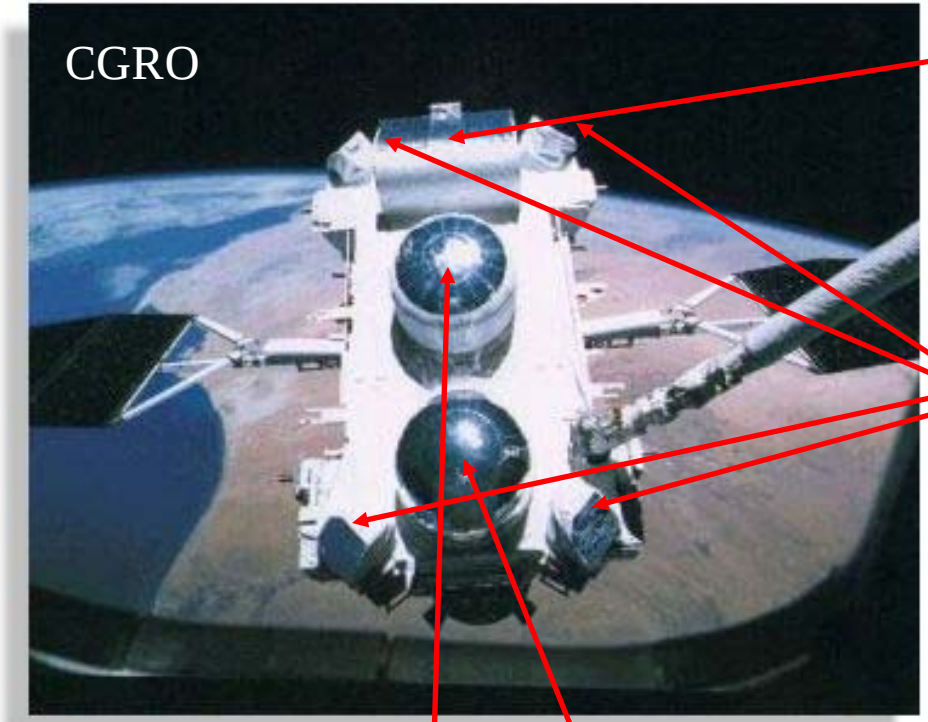
Weekes et al. (1989)





Mayer-Hasselwander et al. (1982)

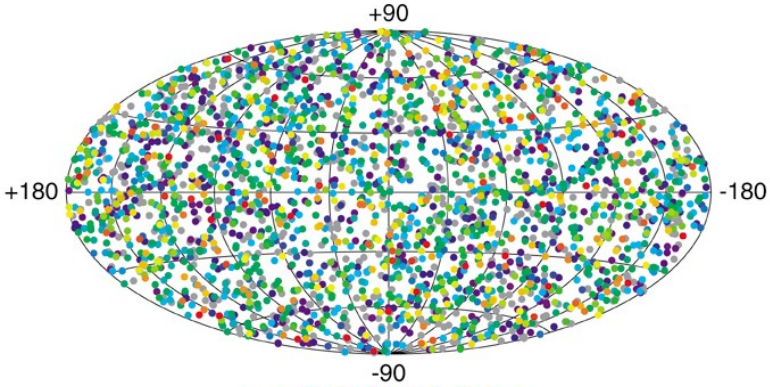
The 90ies: An observatory in orbit, finally



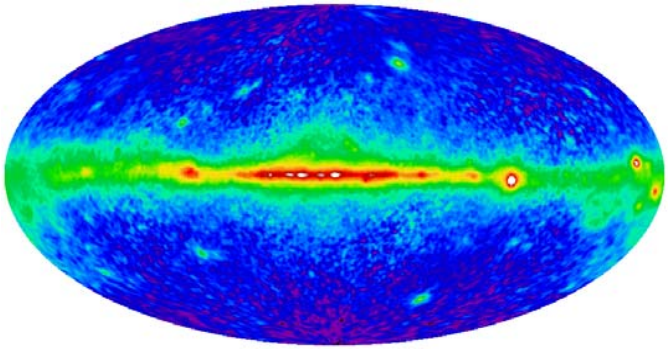
April 5, 1991

OSSE :
keV to MeV
spectroscopy

BATSE : loacting 2704 γ-ray bursts



COMPTEL :
mapping th sky in MeV



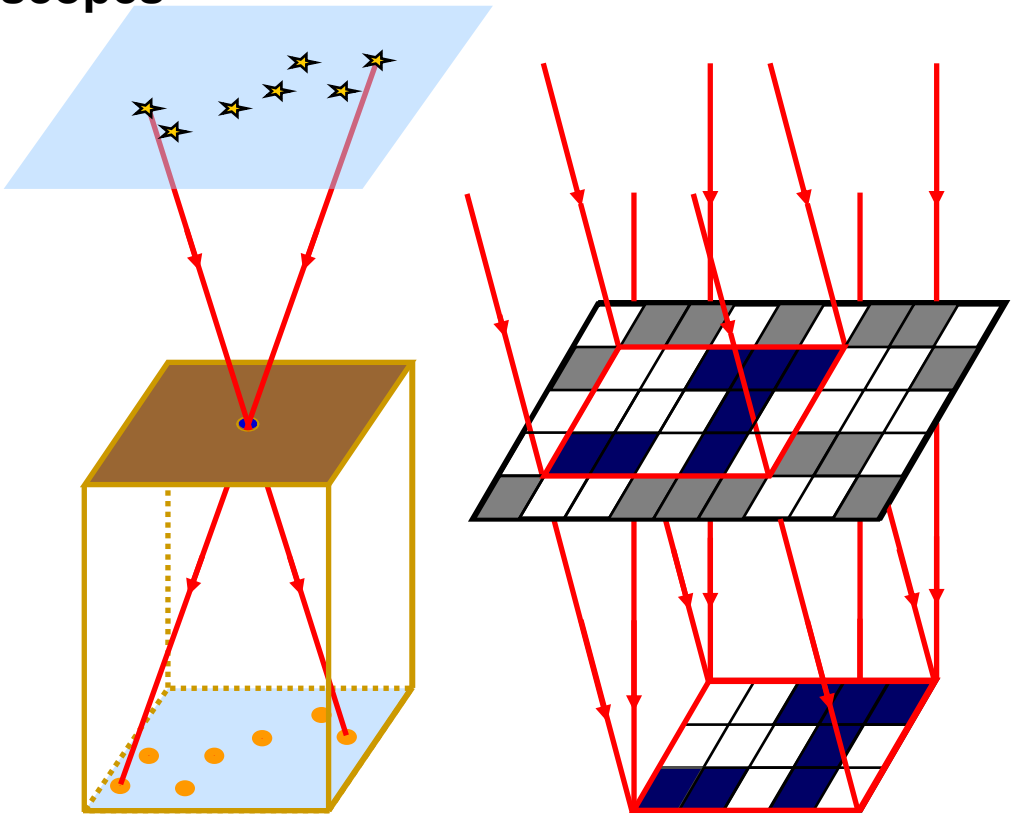
EGRET :
mapping the sky above 100 MeV

Three major branches

511 keV … 30 MeV	30 MeV … 50 GeV	50 GeV…100 TeV
nucleosynthesis	**satellite-based**	**ground-based**
"γ-ray line observations"	**"HE γ-ray observations"**	**"VHE γ-ray observations"**

Coded mask **& Compton**

telescopes



Principle realized in

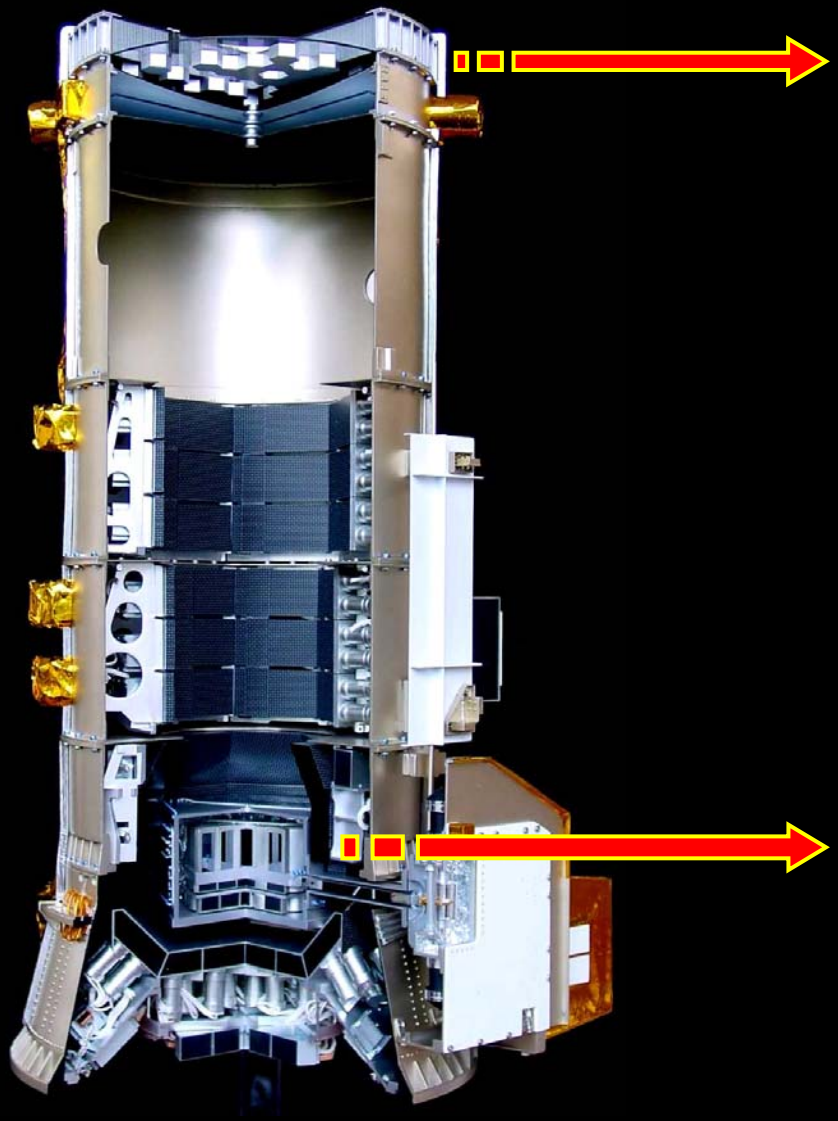
INTEGRAL

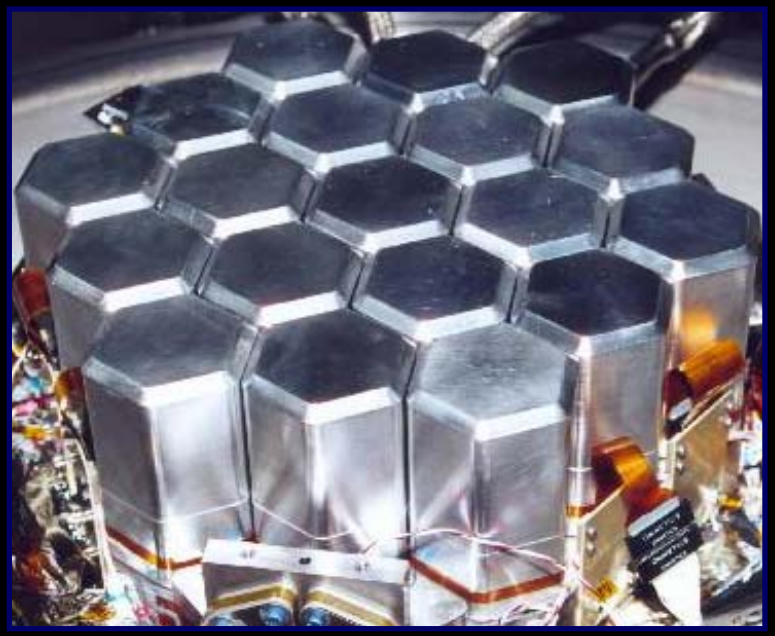
SWIFT

HETE

(in orbit)

SPI aboard INTEGRAL





First detected, still puzzling: e^+e^- annihilation at 511 keV

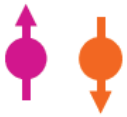
Either **directly** (2 γ of E = 511 keV each),
or, after formation of **Positronium (Ps)**, with probability **f**

Probability: 1/4

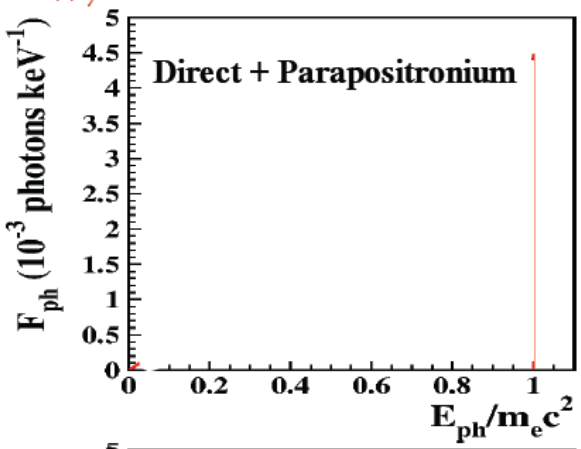
Parapositronium

S=0 (singlet)

$^1S_0$



$T = 1.25\ 10^{-10}\ s \Longrightarrow 2\ \gamma$ of $E = 511$ keV



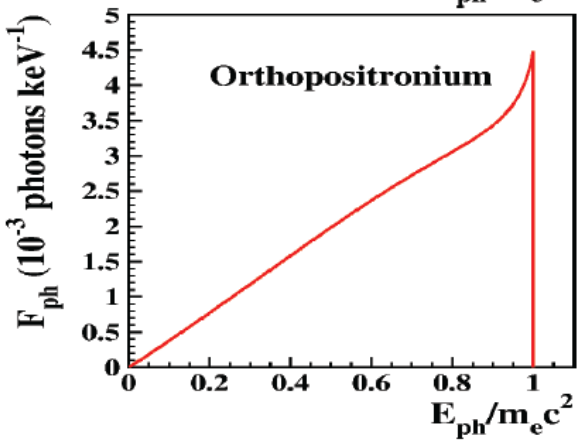
Probability: 3/4

Orthopositronium

S=1 (triplet)

$^3S_1$

$T = 1.4\ 10^{-7}\ s \Longrightarrow 3\ \gamma$ of $E \leq 511$ keV



$$F_{2\gamma} = \underbrace{2(1-f)}_{\text{direct}} + \underbrace{\tfrac{3}{4}\ 2f}_{\text{paraPs}}$$

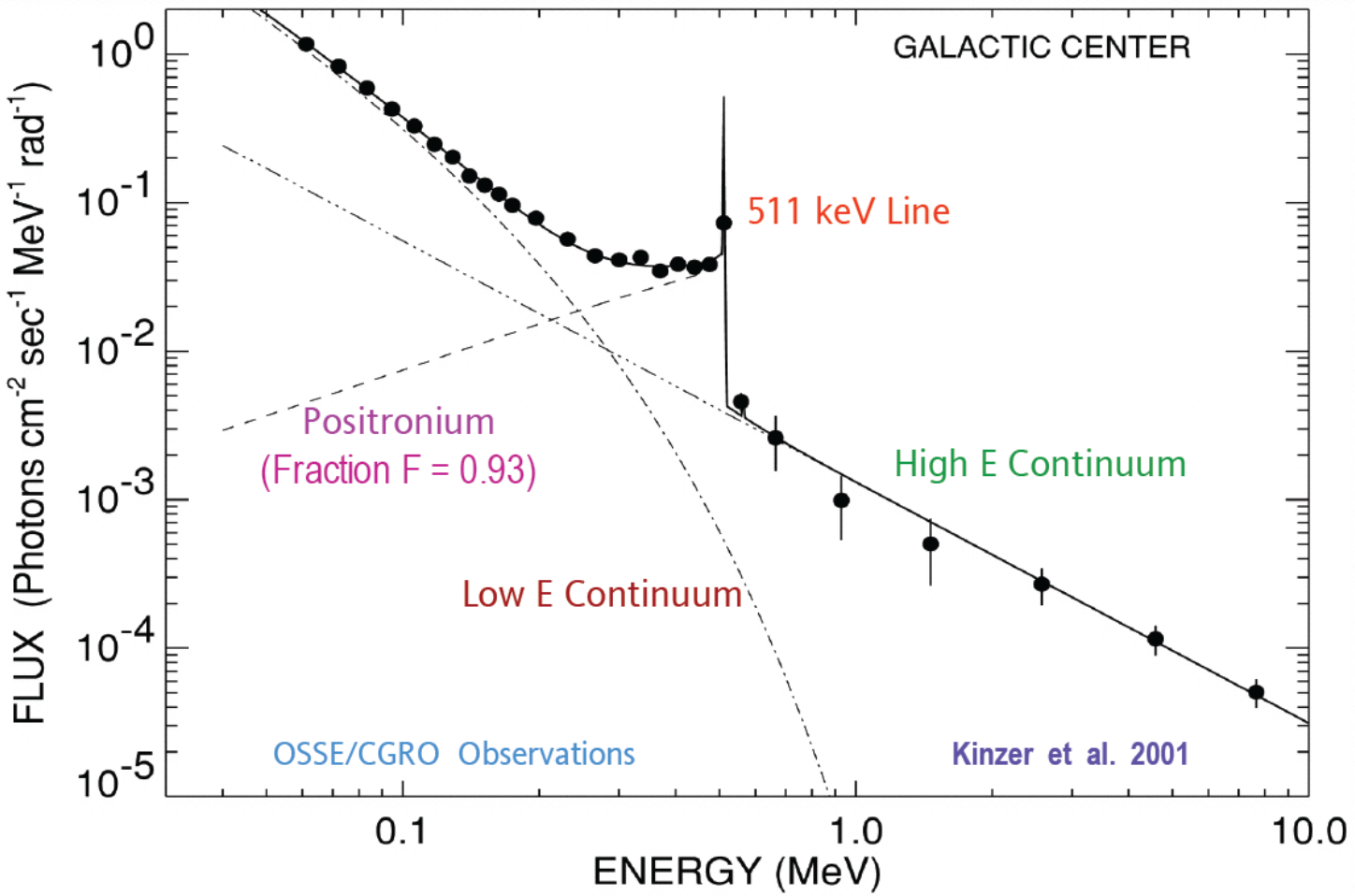
$$F_{3\gamma} = \underbrace{\tfrac{3}{4}\ 3f}_{\text{orthoPs}}$$

$$f = \frac{2}{1.5 + 2.25(F_{2\gamma}/F_{3\gamma})}$$

Positronium fraction

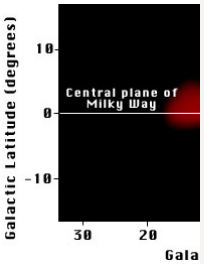
[from Prantzos]

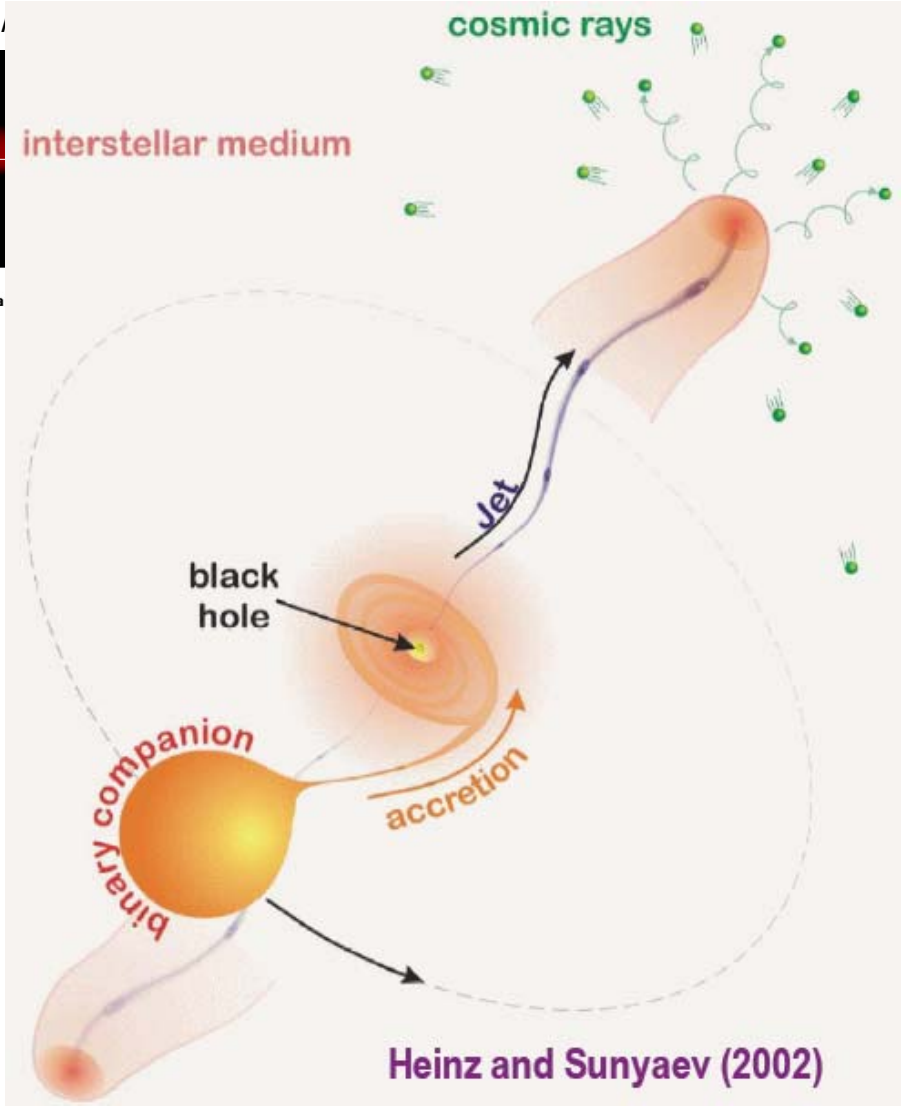
Impressive spectral signature...



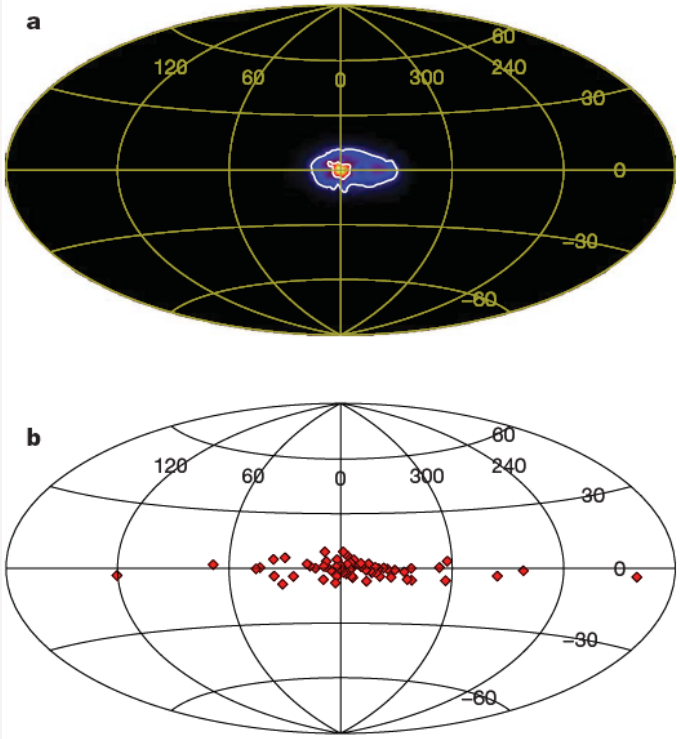
...but imaging the 511 keV line is hard!

1997: OSSE/





This years feature:

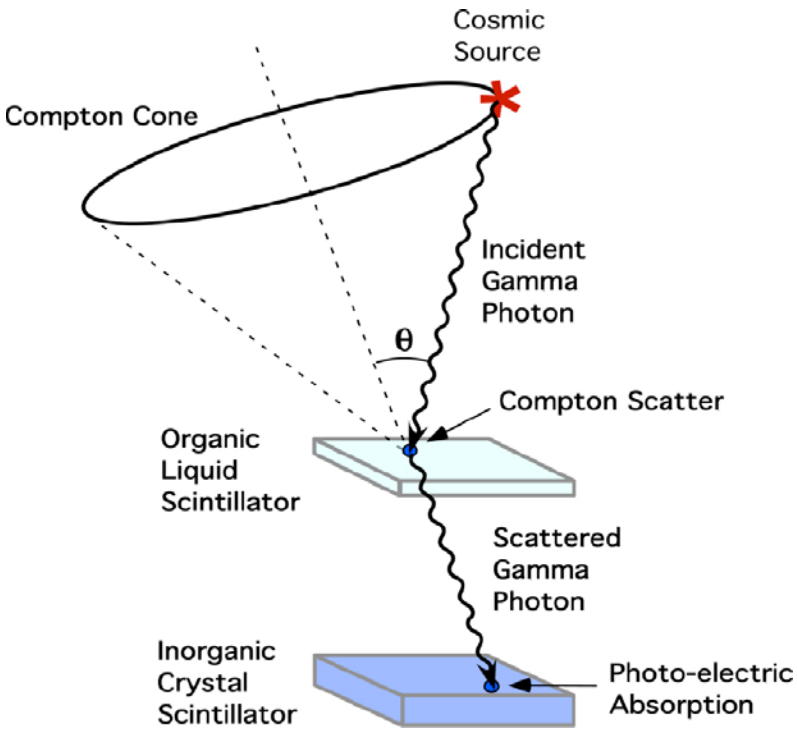


But are the hard X-ray detected LMXBs dominated by leptonic jet emission?

Three major branches

511 keV … 30 MeV	30 MeV … 50 GeV	50 GeV…100 TeV
nucleosynthesis	**satellite-based**	**ground-based**
"γ-ray line observations"	**"HE γ-ray observations"**	**"VHE γ-ray observations"**

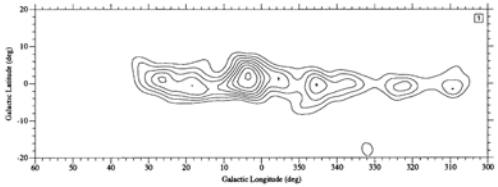
Coded mask & Compton telescopes



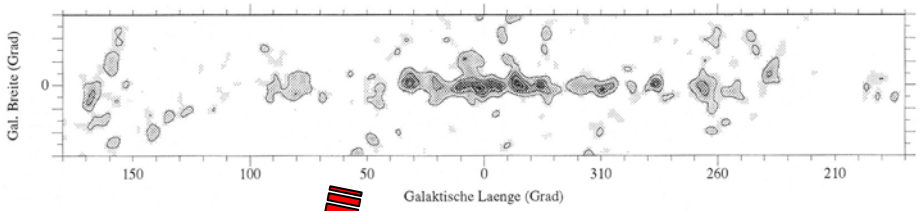
COMPTEL (1991-2000)

Mapping the sky at 1,809 MeV

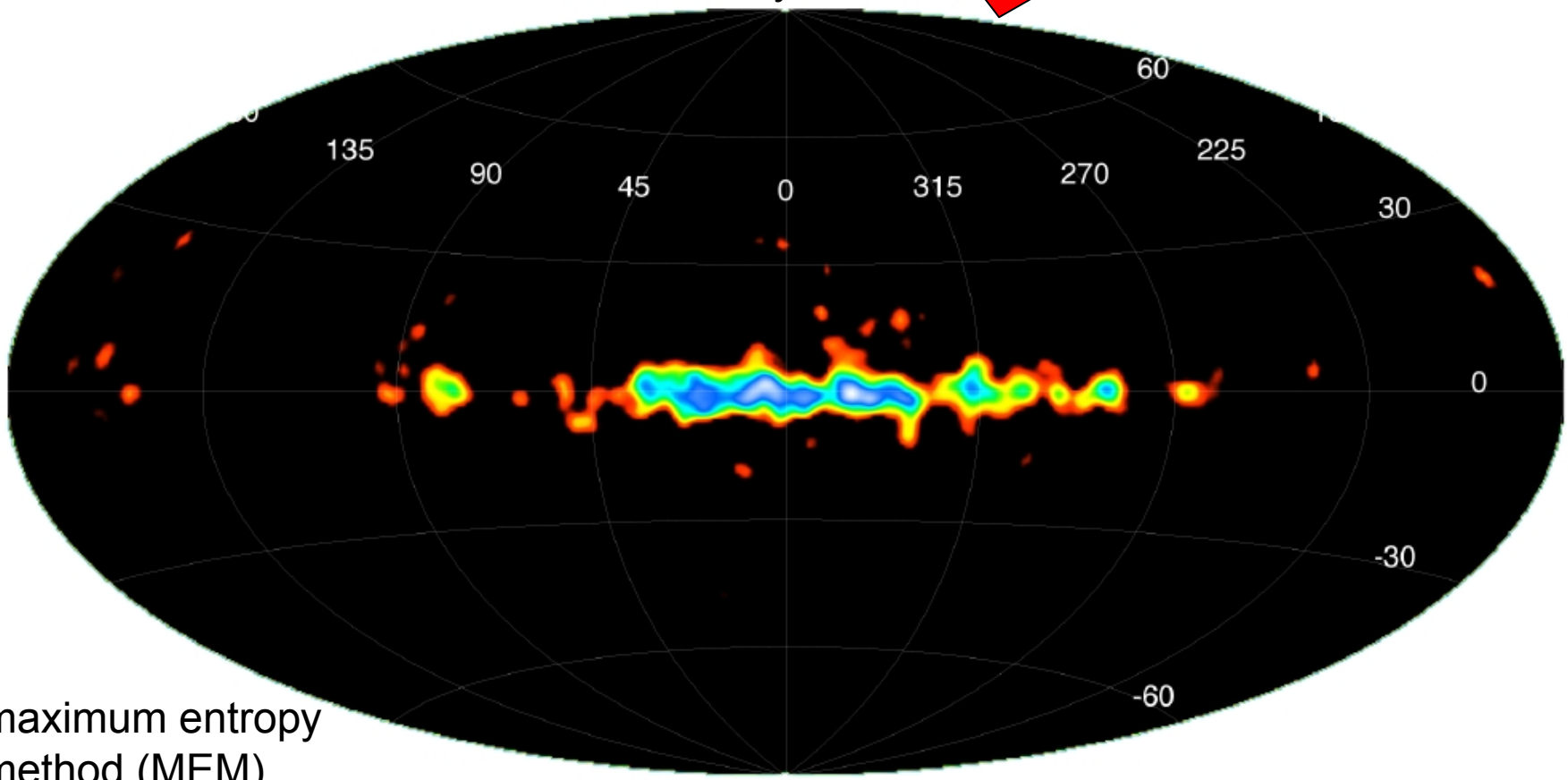
just weeks: COMPTEL



2 years: COMPTEL

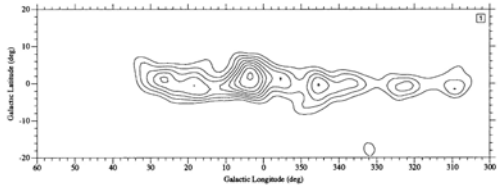


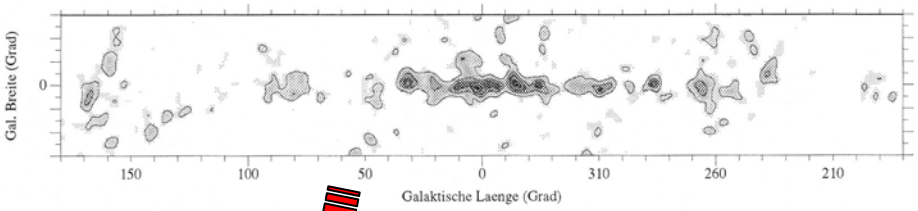
... 5 years

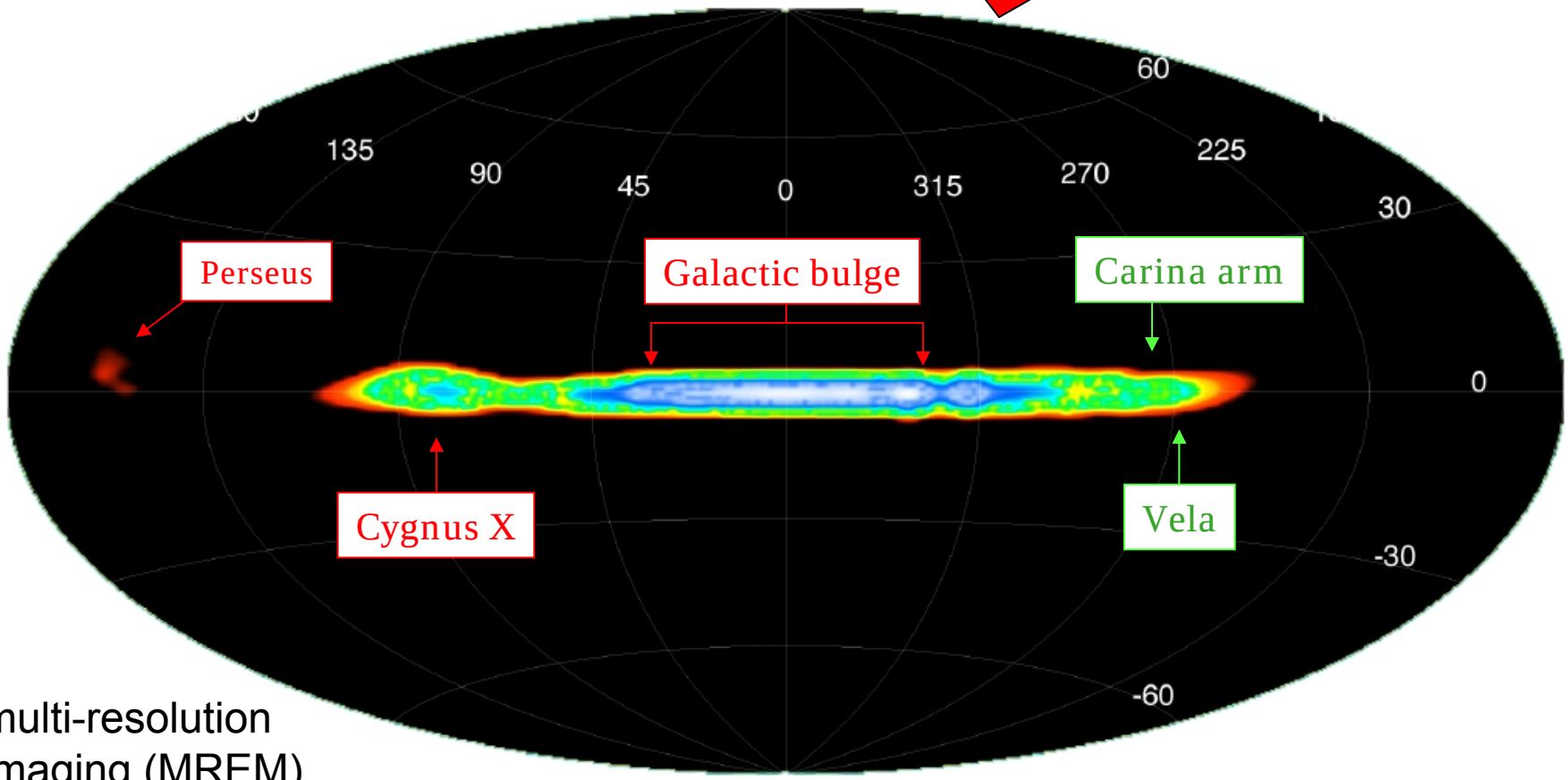


maximum entropy method (MEM)

...but when using another imaging technique



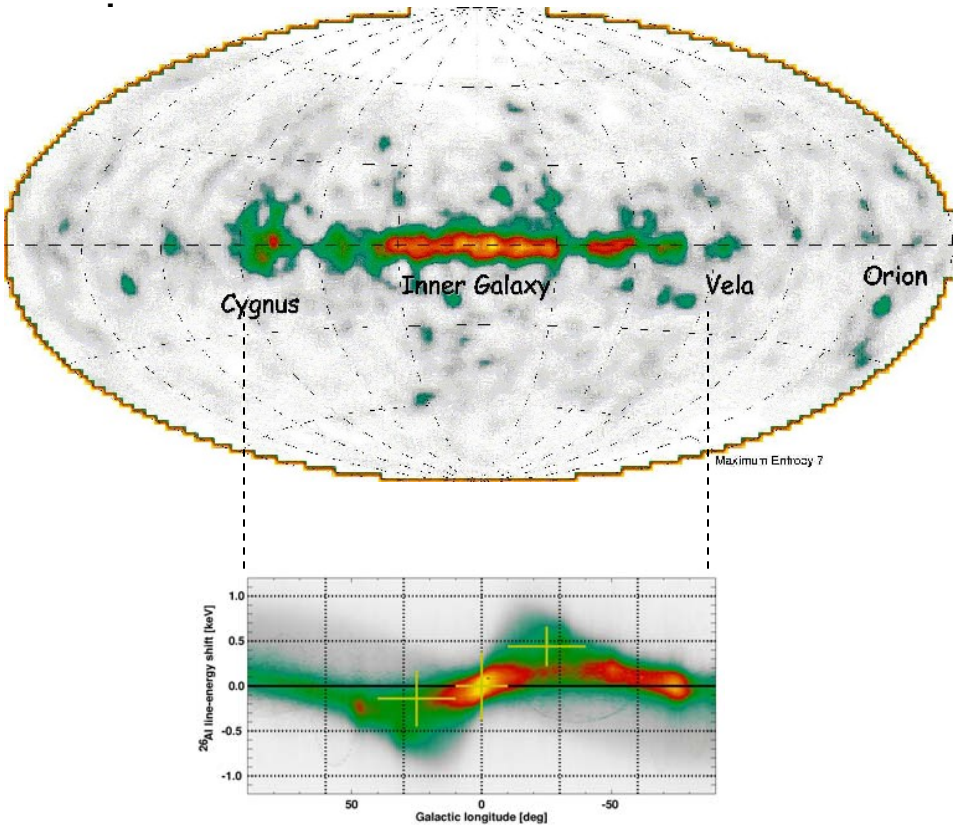




multi-resolution imaging (MREM)

Mapping the sky at 1,809 MeV

The 1.809 MeV line emission of ^{26}Al ($\tau_{1/2}$~720000 y)
:



COMPTEL (~2001)

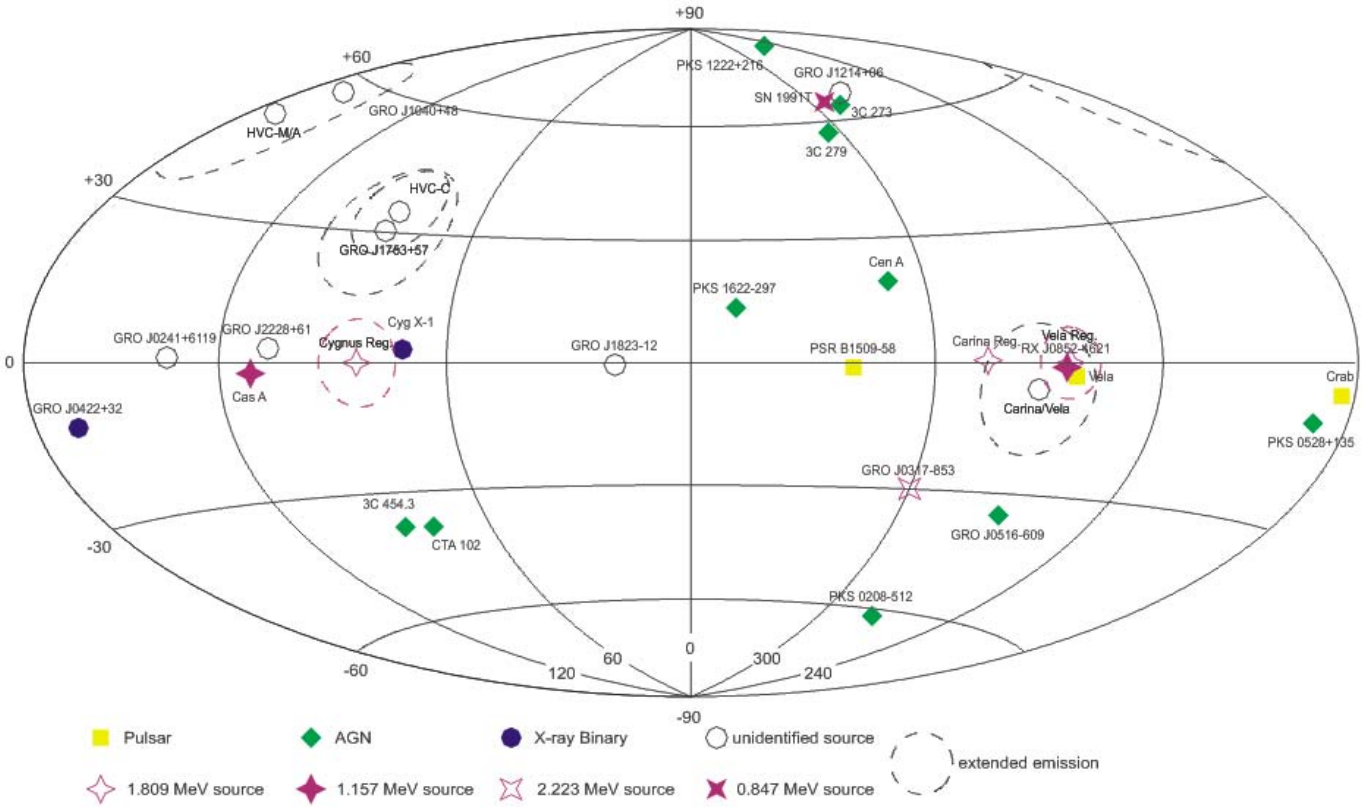
- demonstrates that this radioactivity reflects an entire population of massive, young stars in the Galaxy
- massive stars reach the terminal phases of their evolution and finally explode as supernovae
- corresponds to a rate of supernovae from massive stars (i.e. "Types Ib/c and II") of two per century

INTEGRAL (2006)

- ^{26}Al source regions co-rotate with the Galaxy → Galaxy-wide origin

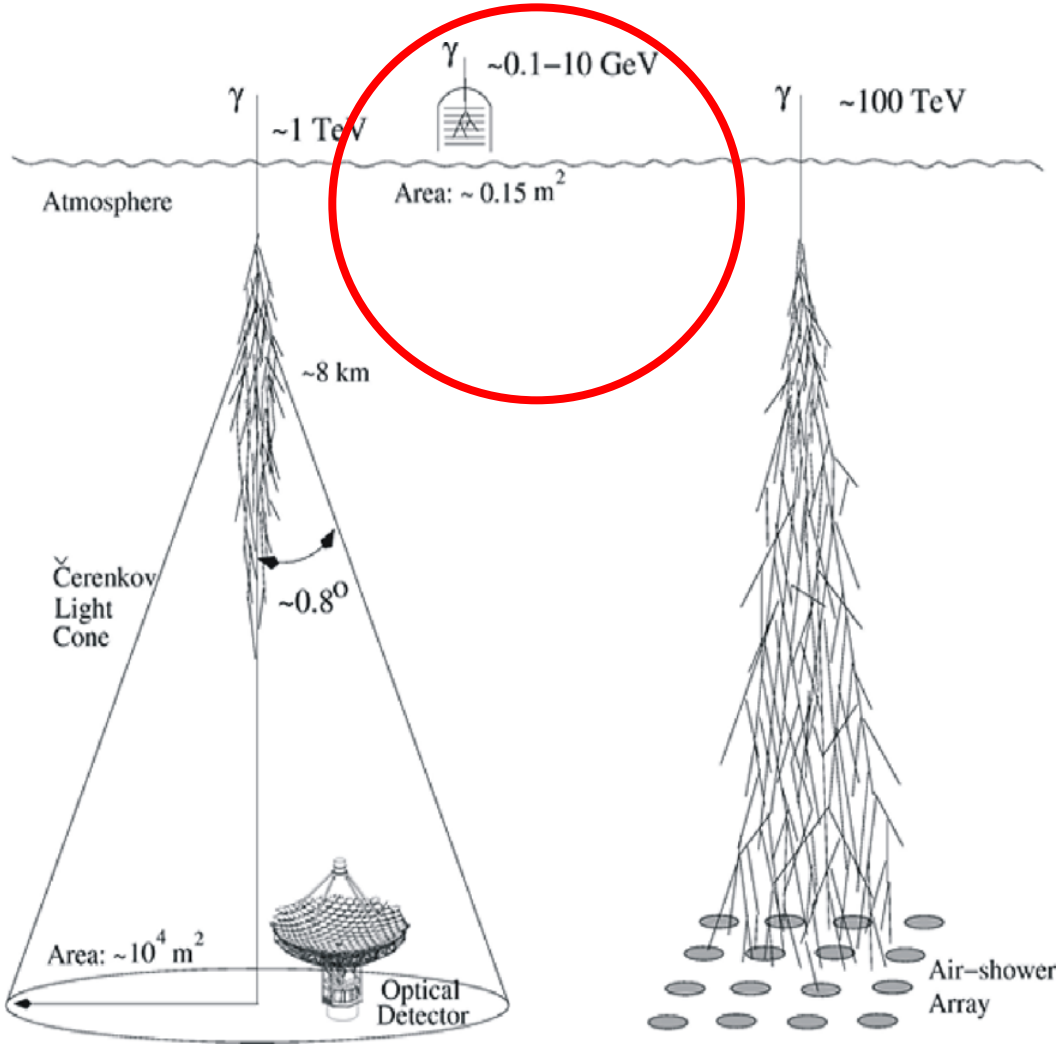
→ confirm our understanding of nucleosynthesis, not CR acceleration up to the knee

Gamma-ray sources from 0.75 to 30 MeV



Three major branches

511 keV … 30 MeV	30 MeV … 50 GeV	50 GeV…100 TeV
nucleosynthesis	satellite-based	ground-based
"γ-ray line observations"	"HE γ-ray observations"	"VHE γ-ray observations"



cross section for pair production dominamt at E_γ > 10 MeV

cross section saturates at ~ E_γ > 1 GeV

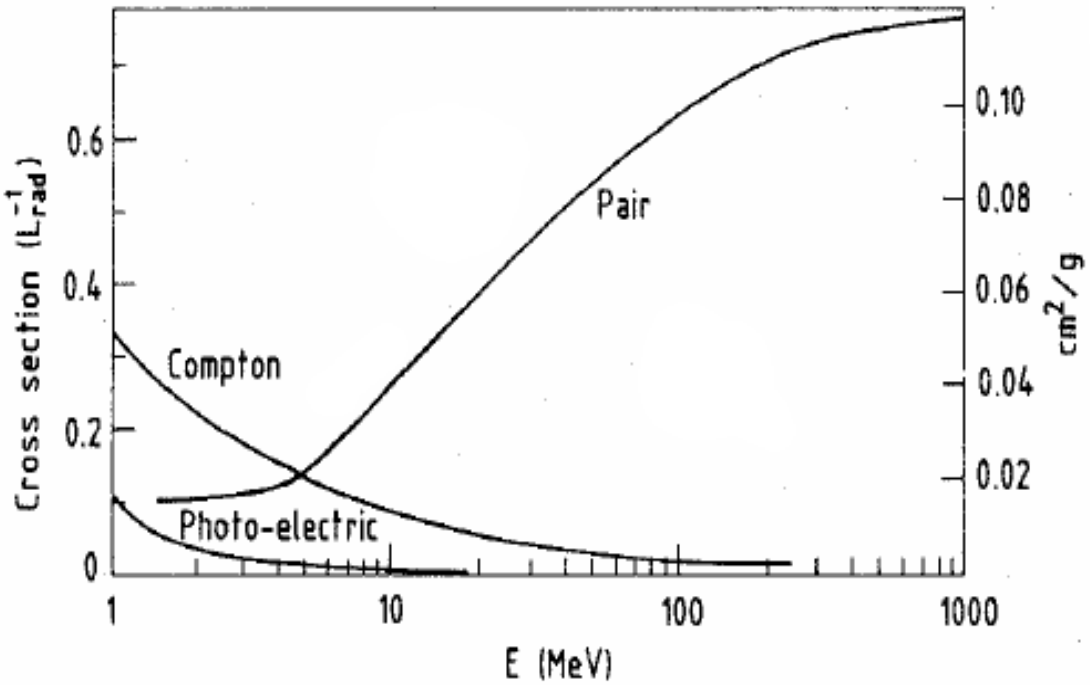


Fig. 2: Photon cross-section σ in lead as a function of photon energy. The intensity of photons can be expressed as $I = I_0 \exp(-\sigma x)$, where x is the path length in radiation lengths. (Review of Particle Properties, April 1980 edition).

→ (e^+e^-) pair production telescopes

Past Gamma-Ray Satellites (size about in proportion)

- **1967-1968**, OSO-3
  Detected Milky Way as an extended γ-ray source

  621 γ-rays
- **1972-1973**, SAS-2,

  ~8,000 γ-rays

  + the Pulsars: Crab, Vela
- **1975-1982**, COS-B

  orbit resulted in a large and variable background of charged particles

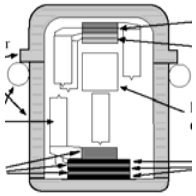
  + the 1st AGN:3C273

  ~200,000 γ-rays
- **1991-2000**, EGRET

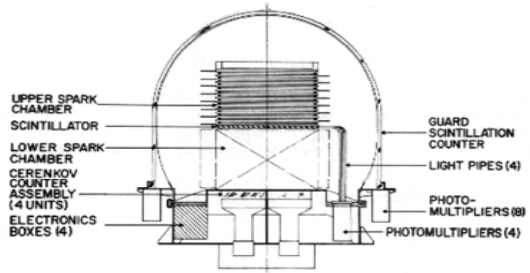
  Large effective area, good PSF, long mission life, excellent background rejection

  >1.4 × 10^6 γ-rays

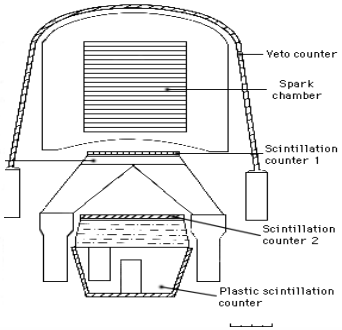
OSO-3



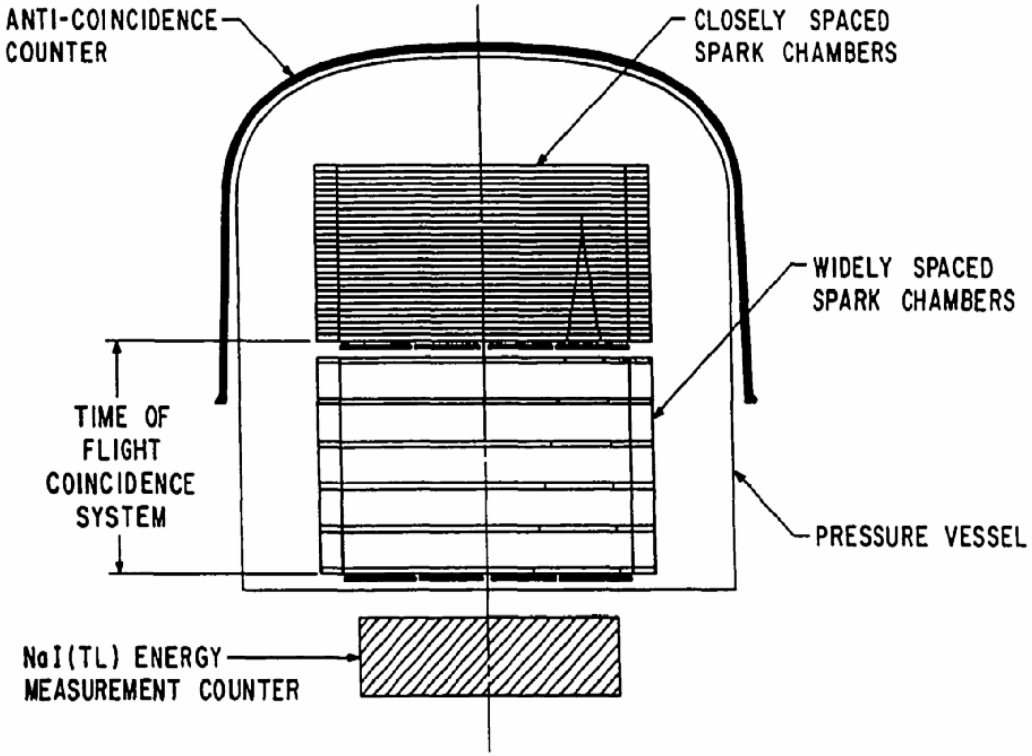
SAS-2



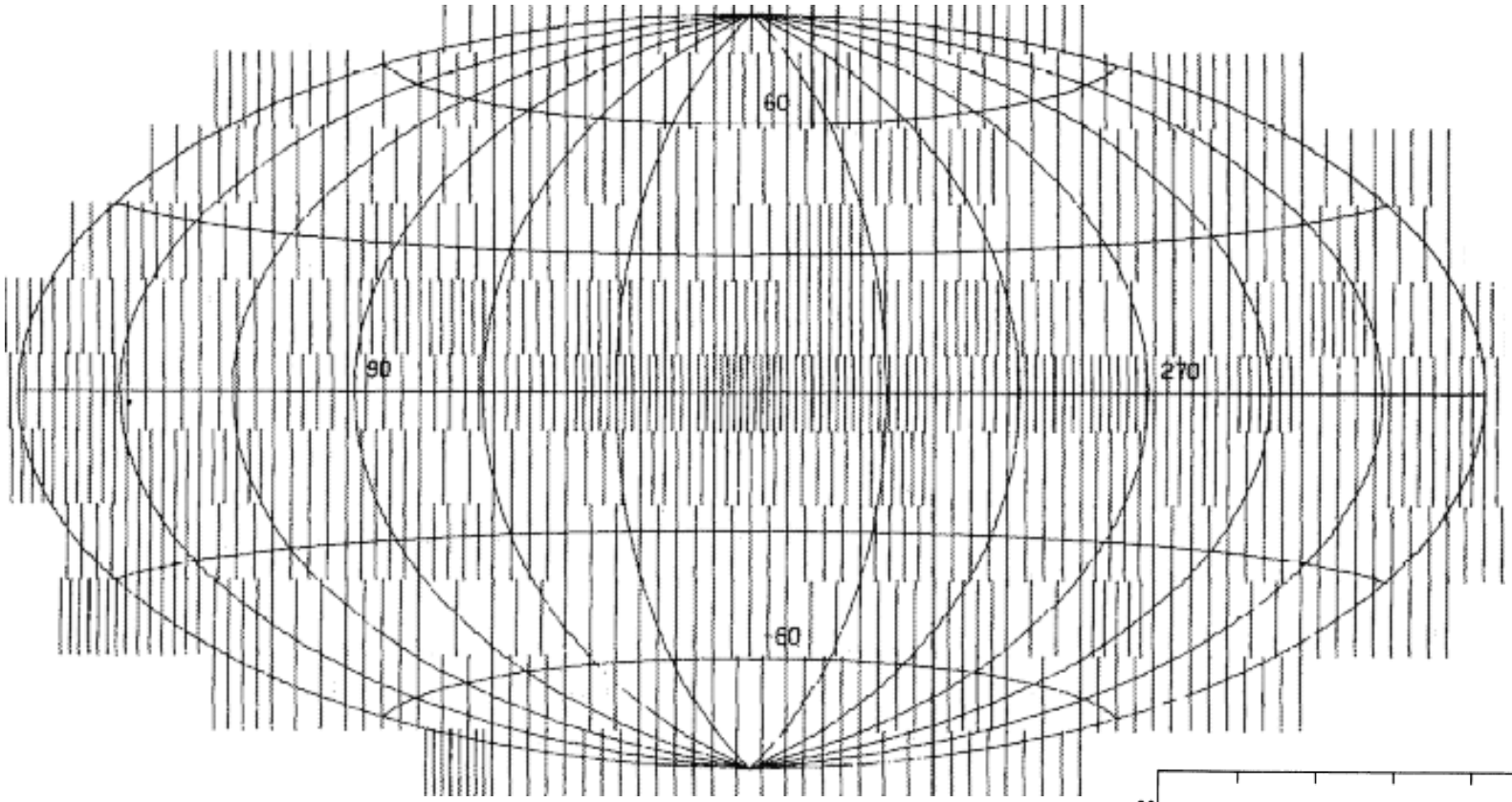
COS-B

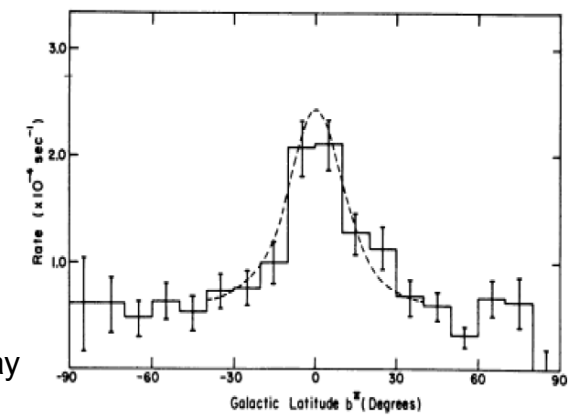


EGRET



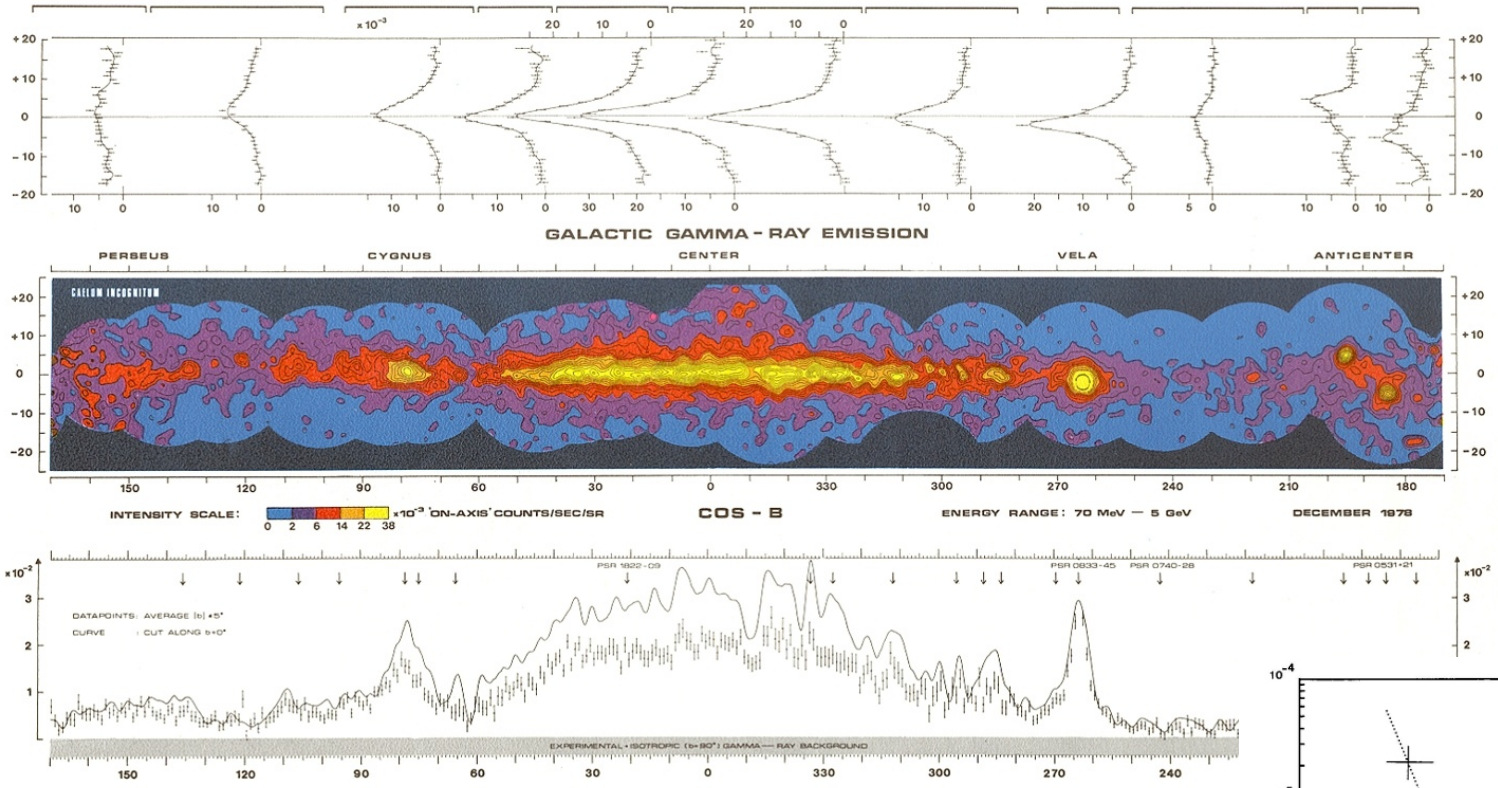
OSO-III 1967-1968

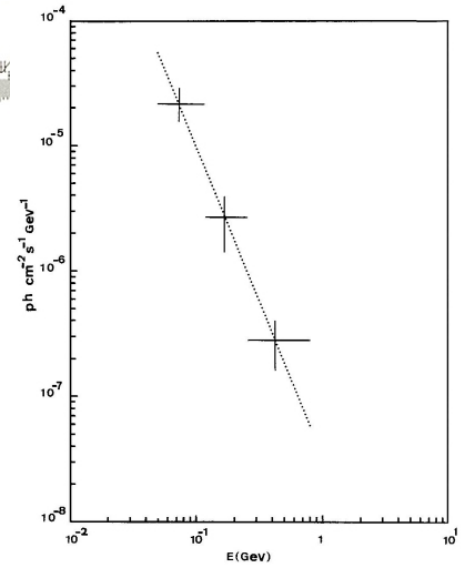




The begin of galactic γ-ray astronomy: Milkyway

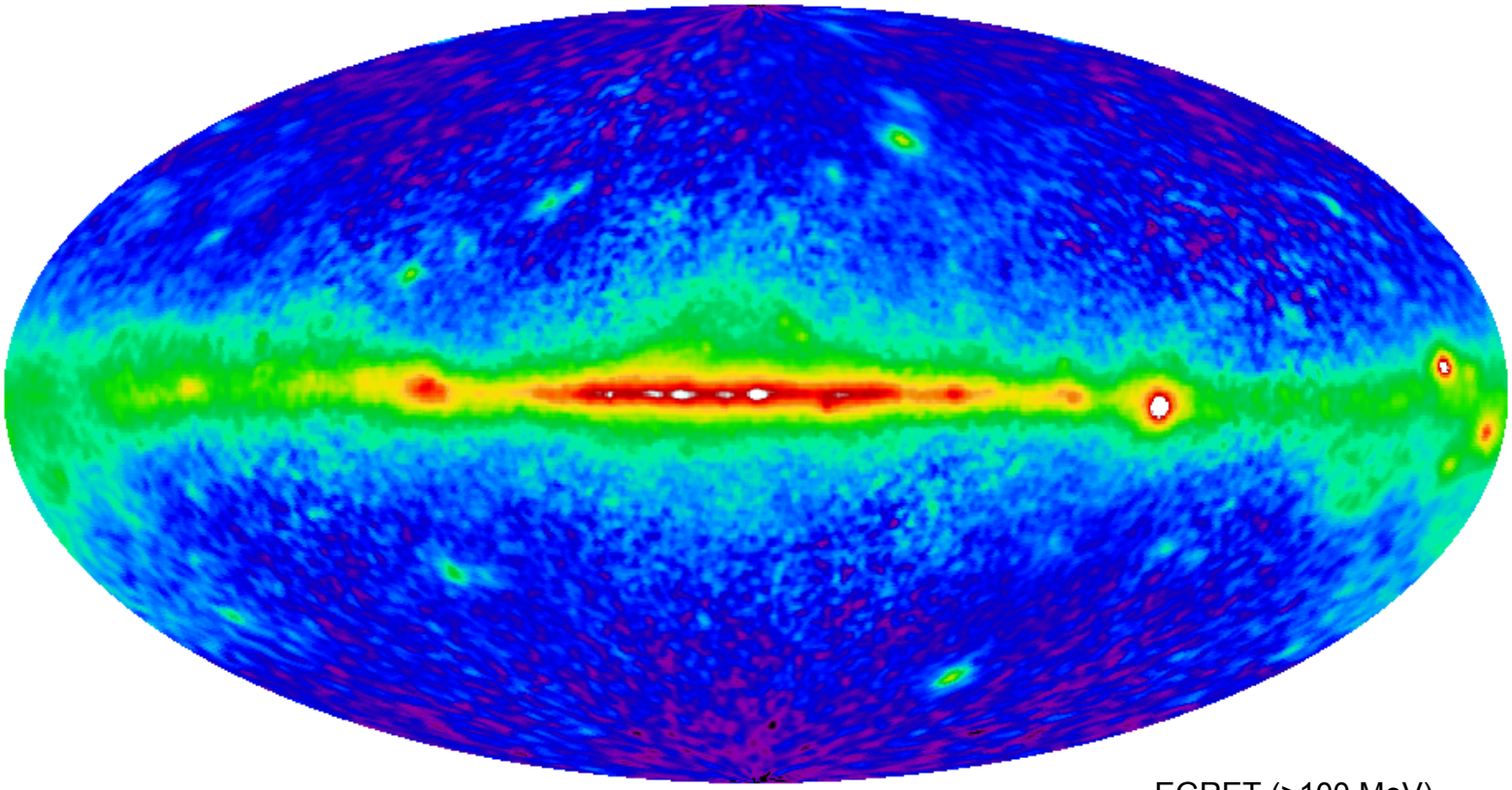
COS-B 1975-1982





The begin of extragalactic γ-ray astronomy: 3C273

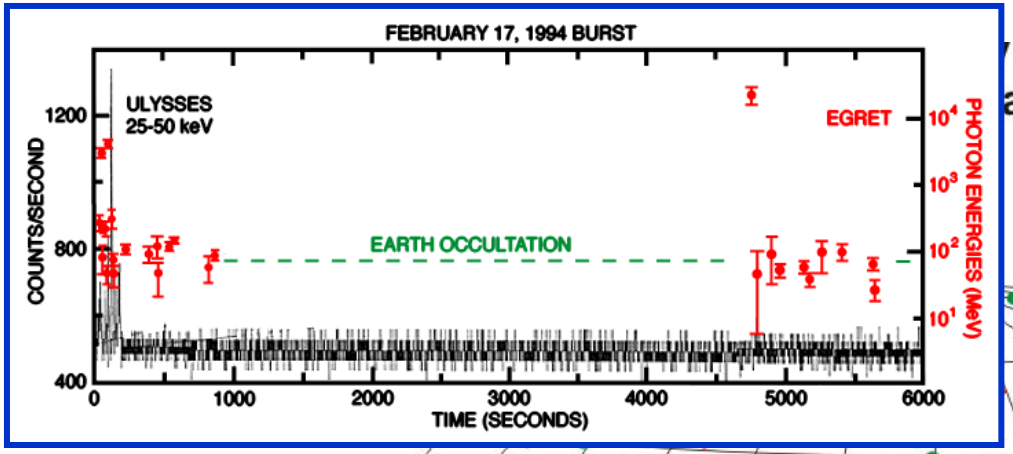
EGRET – 1991-2000

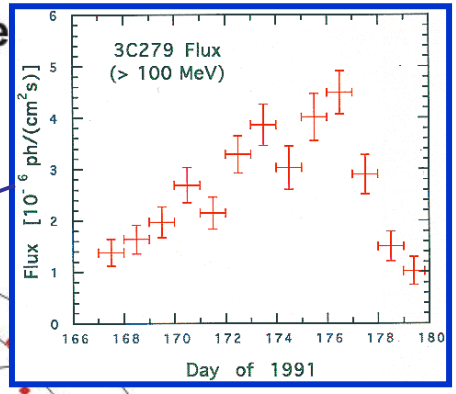


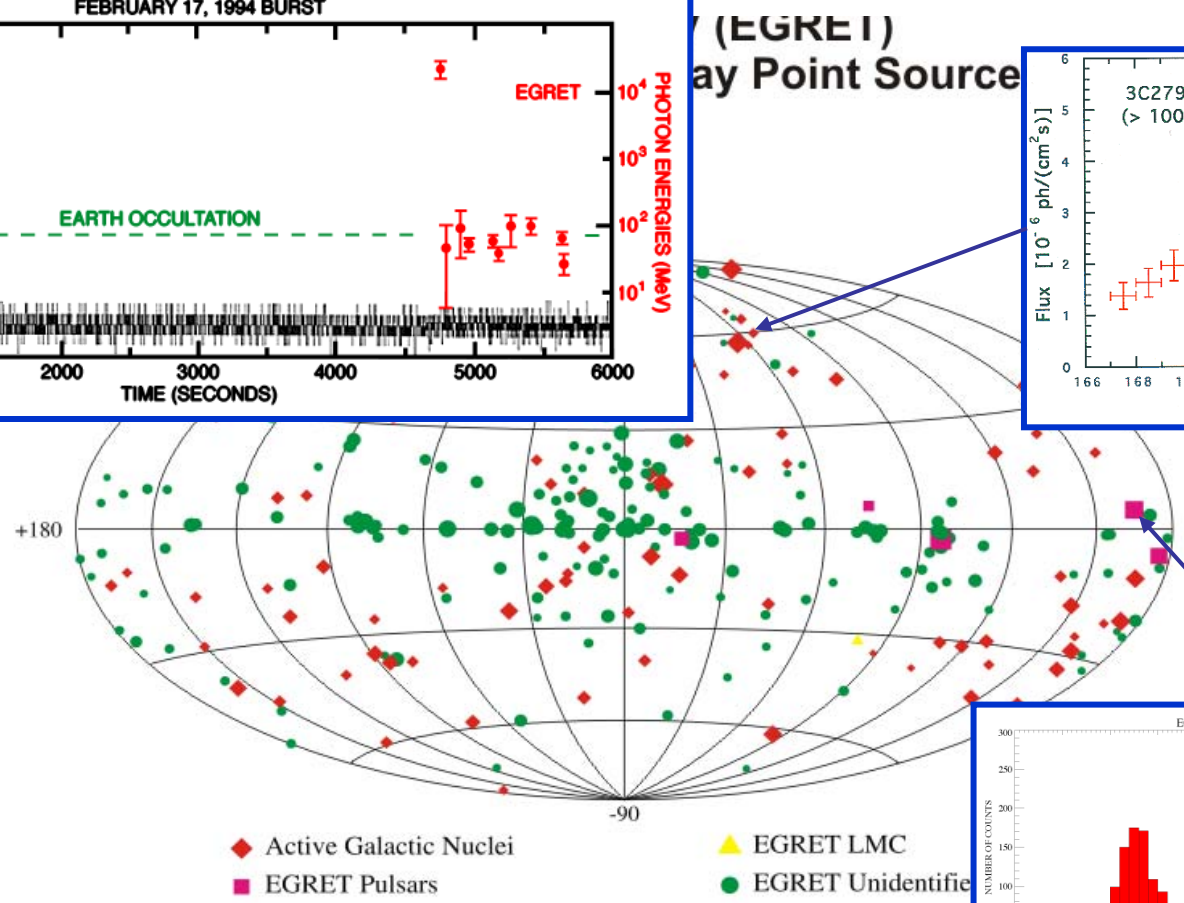
EGRET (>100 MeV)

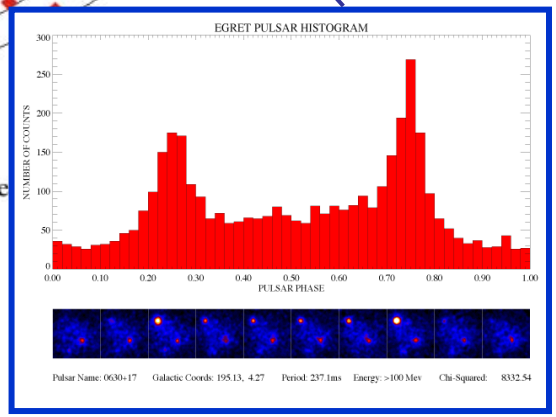
- ~1.4x10^6 γ, ~60% interstellar emission from the MW
- ~10% are cataloged (3EG) point sources

Different phenomena at E > 100 MeV









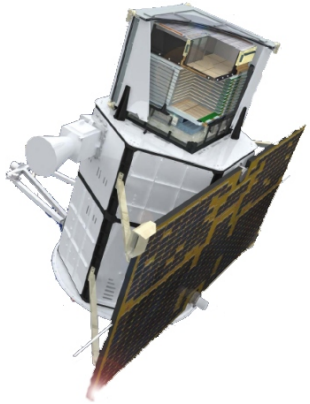
Present Gamma-Ray Satellites

- **2007-…,** AGILE

  30 kg instrument, small detector size compensated through precise track detector (Si-strip), larger indicidence angle possible

  ”-” mini-calorimeter

  ”+” SUPER-AGILE

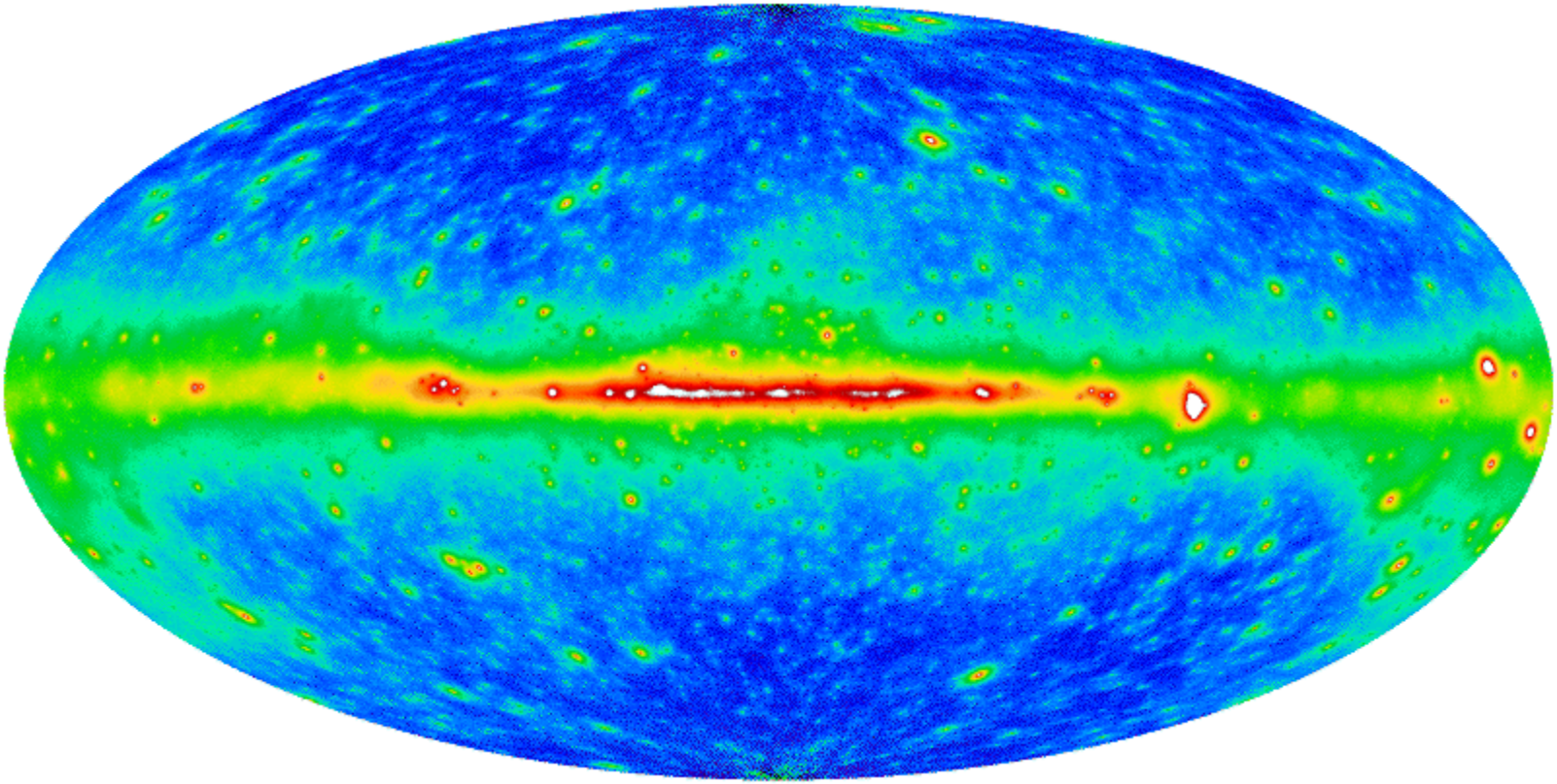


- **2008-…, GLAST**

  got it all (large collection area, precision tracker, deep calorimeter, modularity, wide field of view, default observation mode survey, high time reolution, wide spectral coverage *GBM+LAT*)

! Dedicated GLAST lecture Aug 14 !

Still simulated, but only days before entering the scene: GLAST 2008-2013…18…?

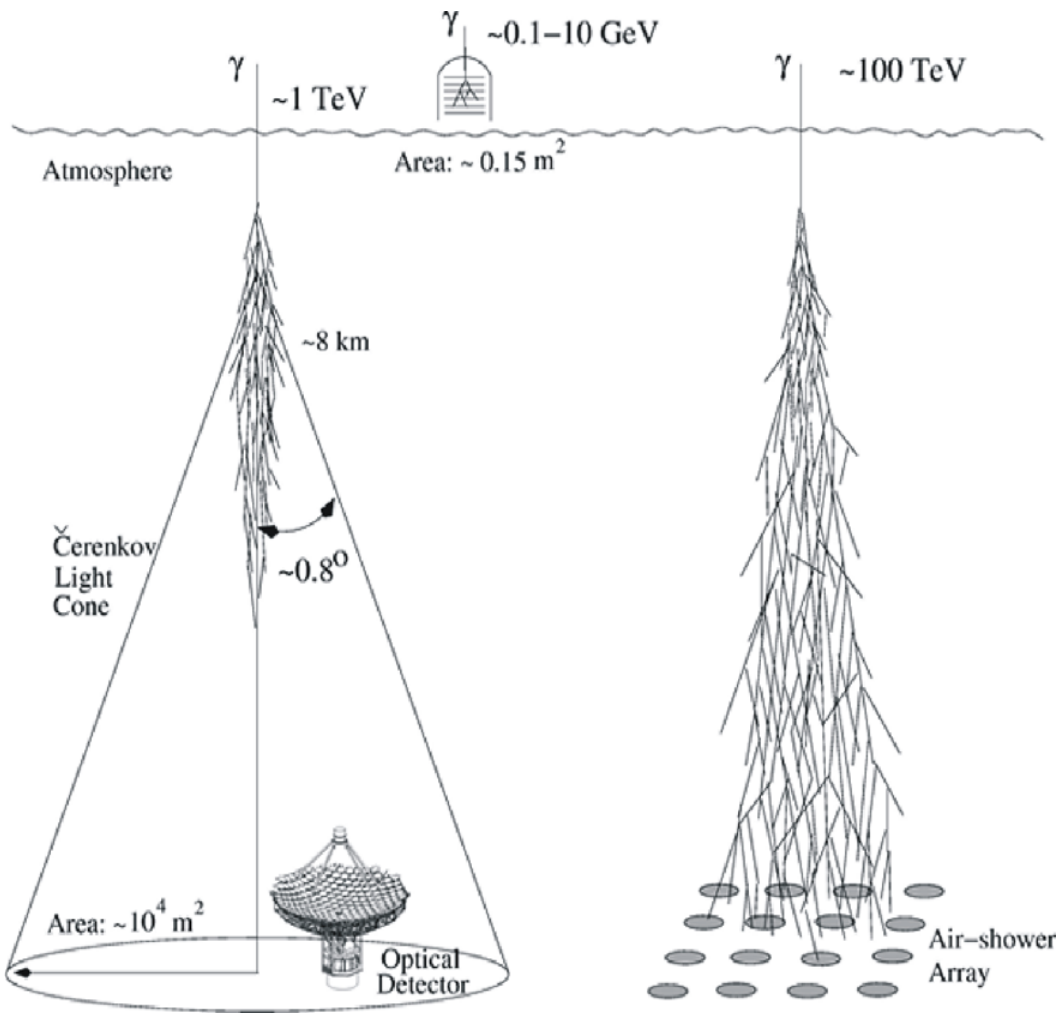


GLAST simulation, (> 100 MeV)

- Based on what we know so far, and anticipate from instrument performance
- Surprises ahead, it may look different, when looked at close

Three major branches

511 keV … 30 MeV	30 MeV … 50 GeV	**50 GeV…100 TeV**
nucleosynthesis	satellite-based	**ground-based**
"γ-ray line observations"	"HE γ-ray observations"	**"VHE γ-ray observations"**



The VHE frontier

- First Generation Systems 1960 – 1985
  - Weak or no discrimination
  - Lebedev, Glencullen, Whipple, Narrabri, Crimea,..

New technology:

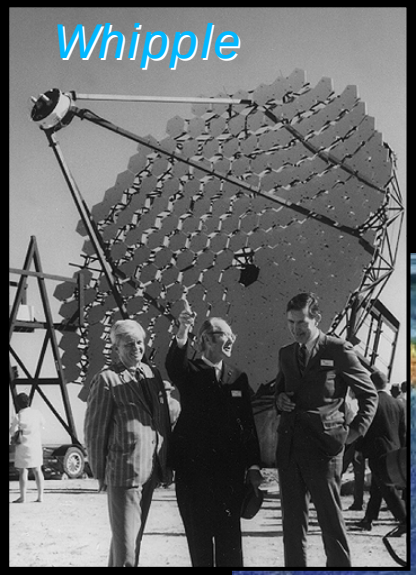
- Second Generation Systems 1985 – 2003
  Atmospheric Cherenkov Imaging Telescopes
  - Whipple, Crimea, CAT, Durham, CANGAROO
  - Stereoscopy: HEGRA
  - A sideway: Celeste, Stacee, Cactus, Graal
  - Wavefront sensing shower arrays: Milagrito

Zero

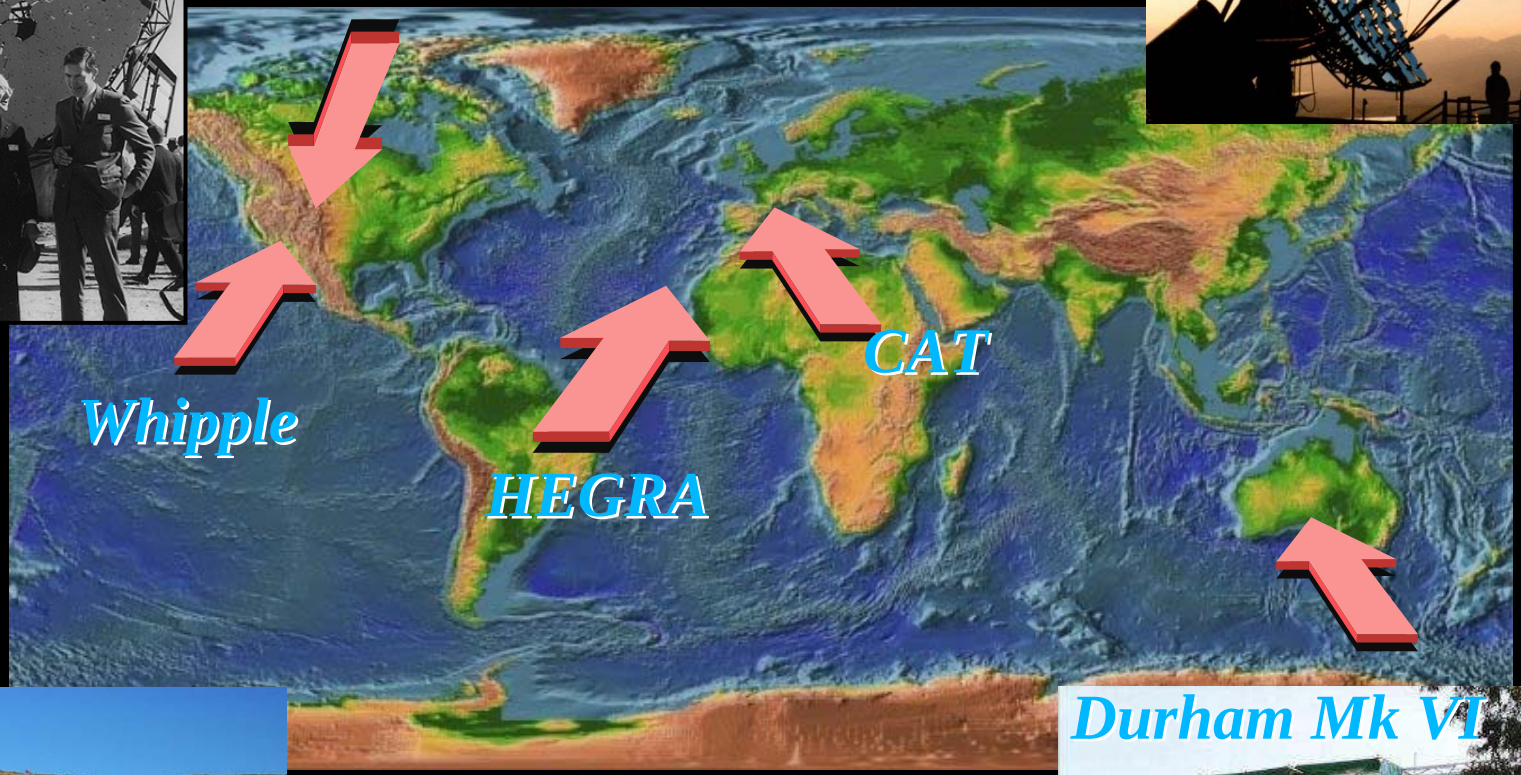
~ 12

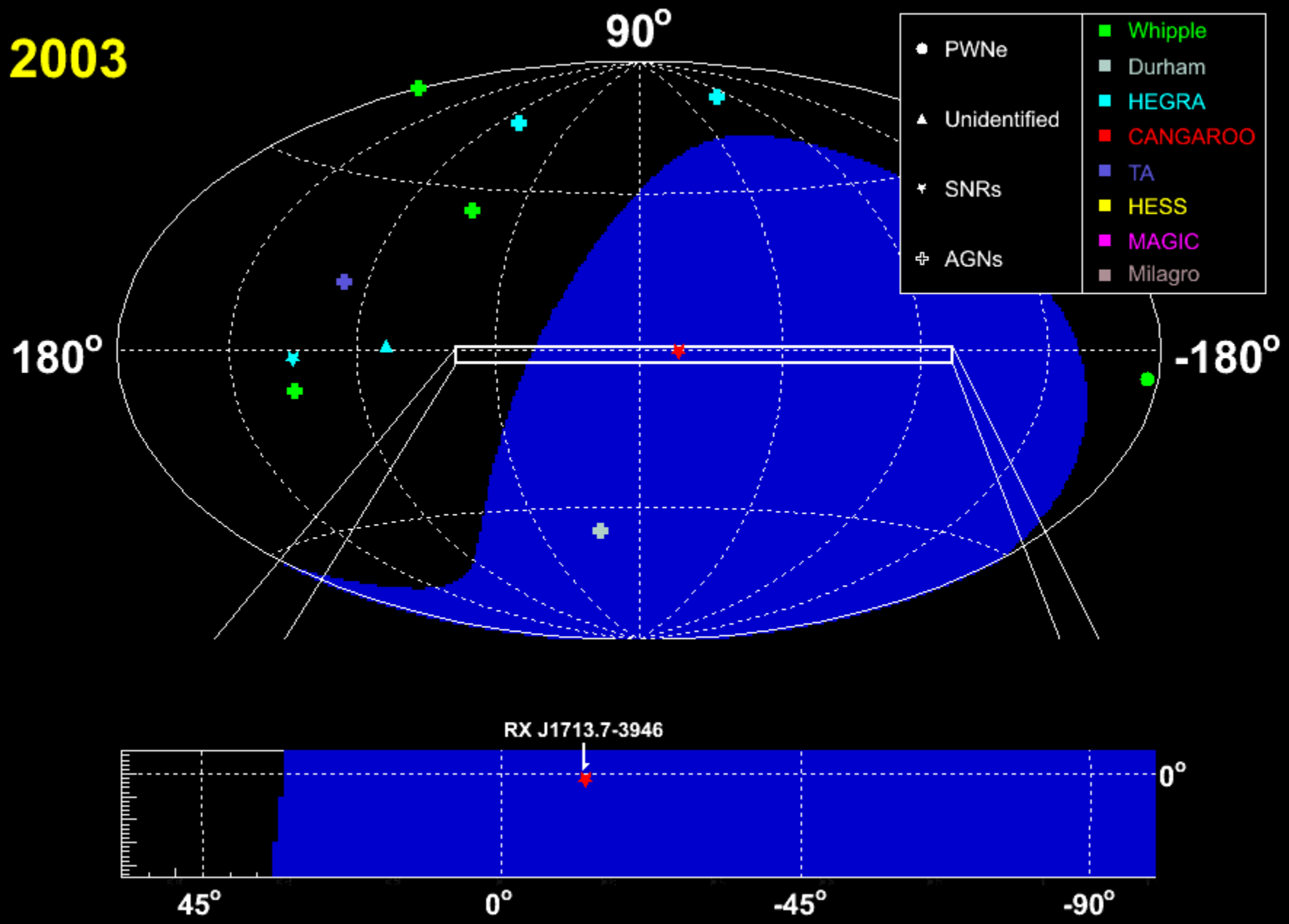
TeV sources

Past sensitive ACT detectors



... i.e. those having discovered or made major contributions to field





[From J. Hinton]

The VHE frontier

- First Generation Systems 1960 – 1985
  - Weak or no discrimination
  - Lebedev, Glencullen, Whipple, Narrabri, Crimea,..

Zero

New technology:

- Second Generation Systems 1985 – 2003
  Atmospheric Cherenkov Imaging Telescopes
  - Whipple, Crimea, CAT, Durham, CANGAROO
  - Stereoscopy: HEGRA
  - A sideway: Celeste, Stacee, Cactus, Graal
  - Wavefront sensing shower arrays: Milagrito

~ 12

Increase in Scale:

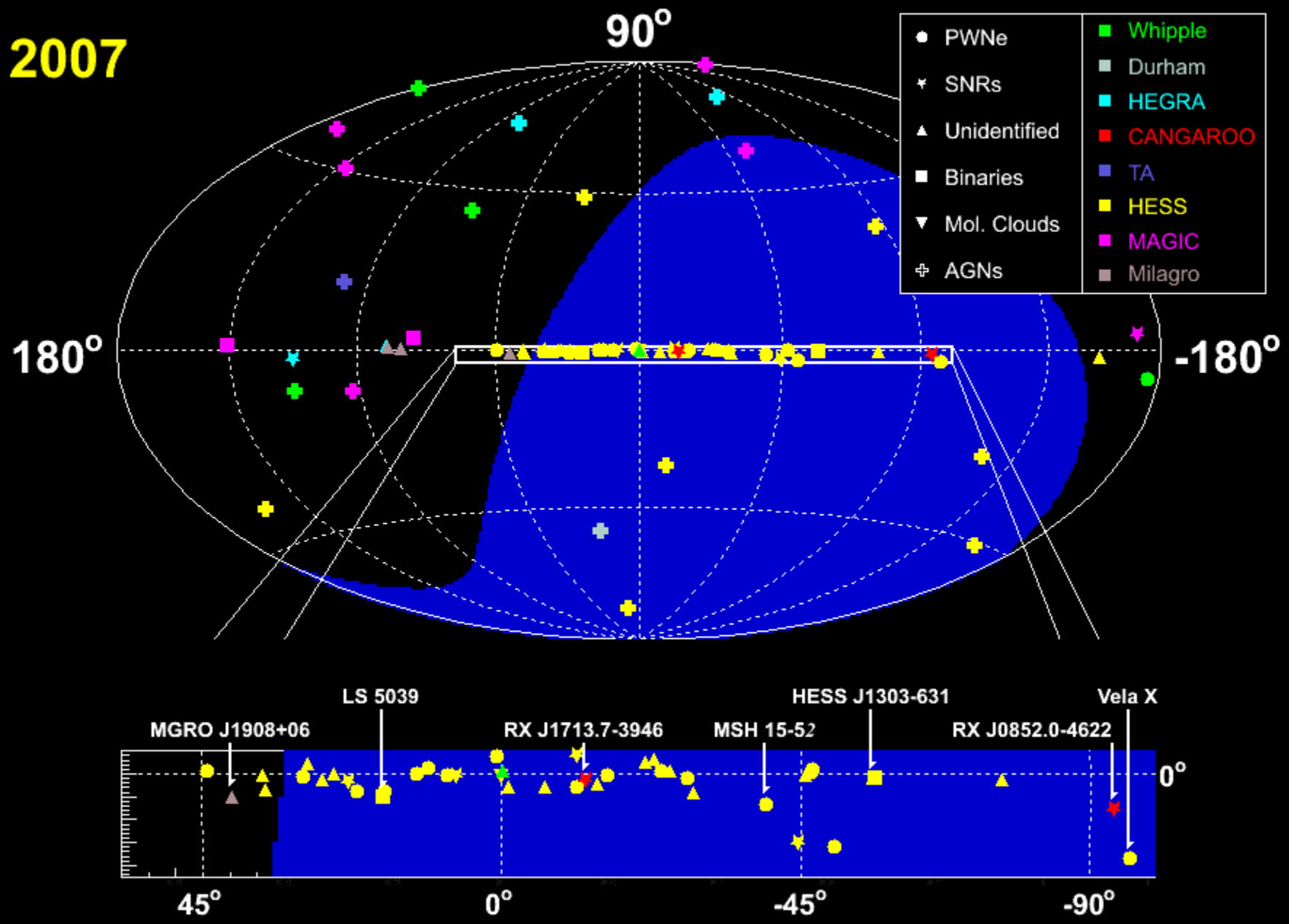
- Third Generation Systems 2003 – 201x
  - CANGAROO-III, HESS-4, MAGIC, VERITAS-4
  - Extensions: MAGIC-2, HESS-5
  - overcome gamma/hadron separation problem: Milagro, Argo

> 100?

TeV sources

Current VHE γ-ray world

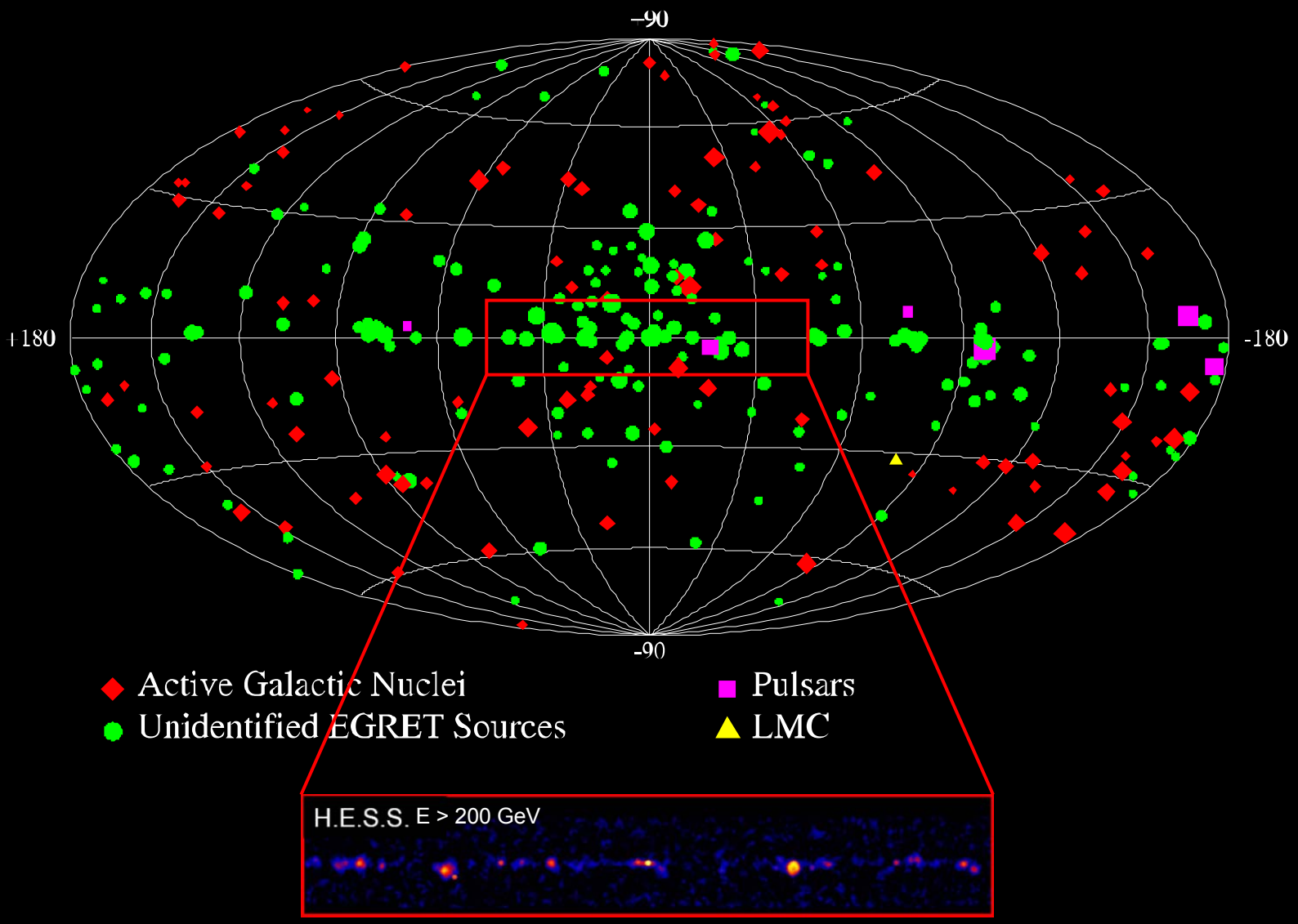
CANGAROO-III

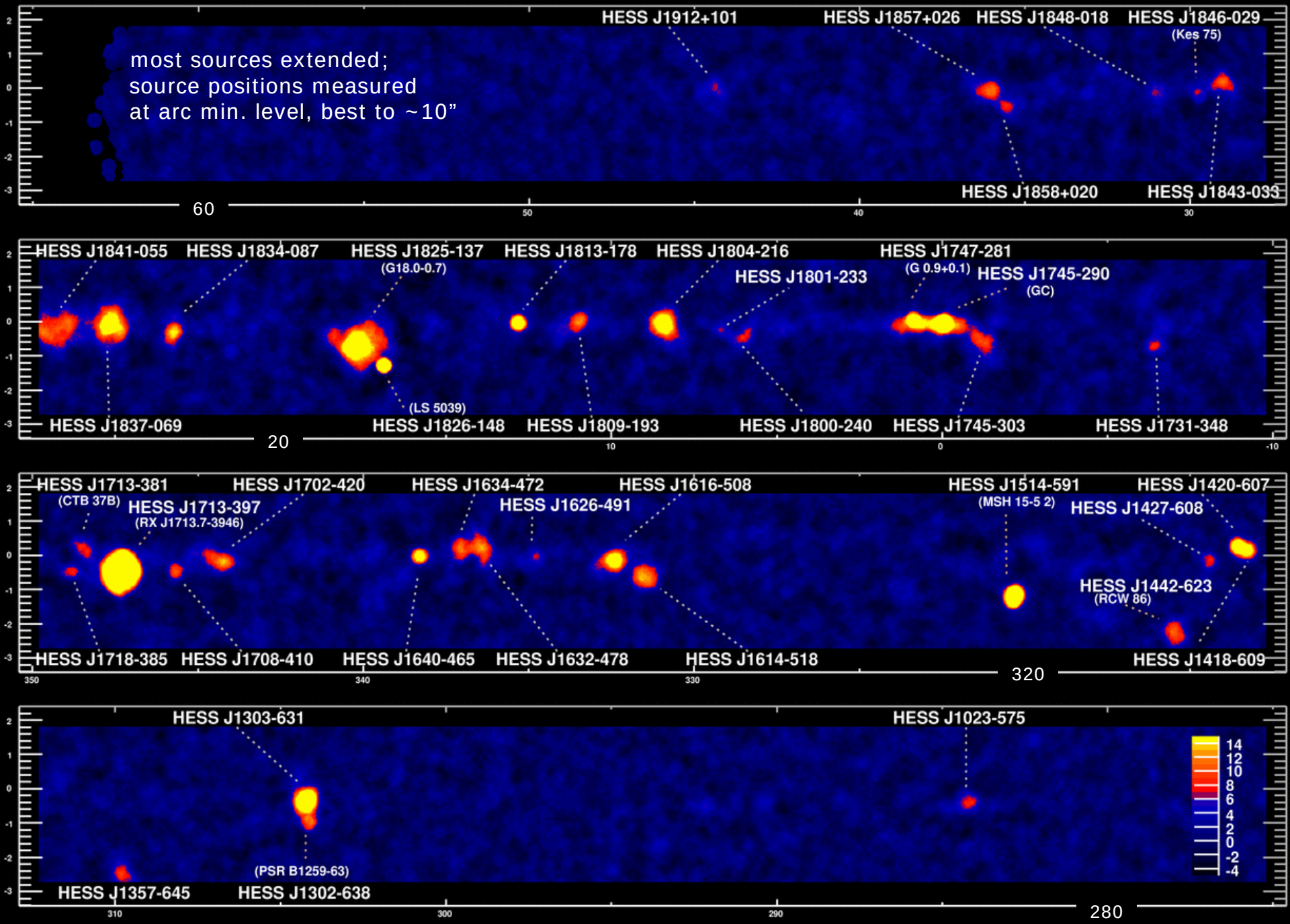


[From J. Hinton]

Third EGRET Catalog

E > 100 MeV




most sources extended;
source positions measured
at arc min. level, best to ~10”
HESS J1912+101
HESS J1857+026
HESS J1848-018
HESS J1846-029
(Kes 75)
HESS J1858+020
HESS J1843-033
60
50
40
30
HESS J1841-055
HESS J1834-087
HESS J1825-137
(G18.0-0.7)
HESS J1813-178
HESS J1804-216
HESS J1747-281
(G 0.9+0.1)
HESS J1801-233
HESS J1745-290
(GC)
(LS 5039)
HESS J1837-069
HESS J1826-148
HESS J1809-193
HESS J1800-240
HESS J1745-303
HESS J1731-348
20
10
0
-10
HESS J1713-381
(CTB 37B)
HESS J1713-397
(RX J1713.7-3946)
HESS J1702-420
HESS J1634-472
HESS J1626-491
HESS J1616-508
HESS J1514-591
(MSH 15-5 2)
HESS J1420-607
HESS J1427-608
HESS J1442-623
(RCW 86)
HESS J1718-385
HESS J1708-410
HESS J1640-465
HESS J1632-478
HESS J1614-518
HESS J1418-609
350
340
330
320
HESS J1303-631
HESS J1023-575
(PSR B1259-63)
HESS J1357-645
HESS J1302-638
310
300
290
280
14
12
10
8
6
4
2
0
-2
-4