

Experimental

**Astroparticle Physics
(a short introduction)**

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Lund 2011

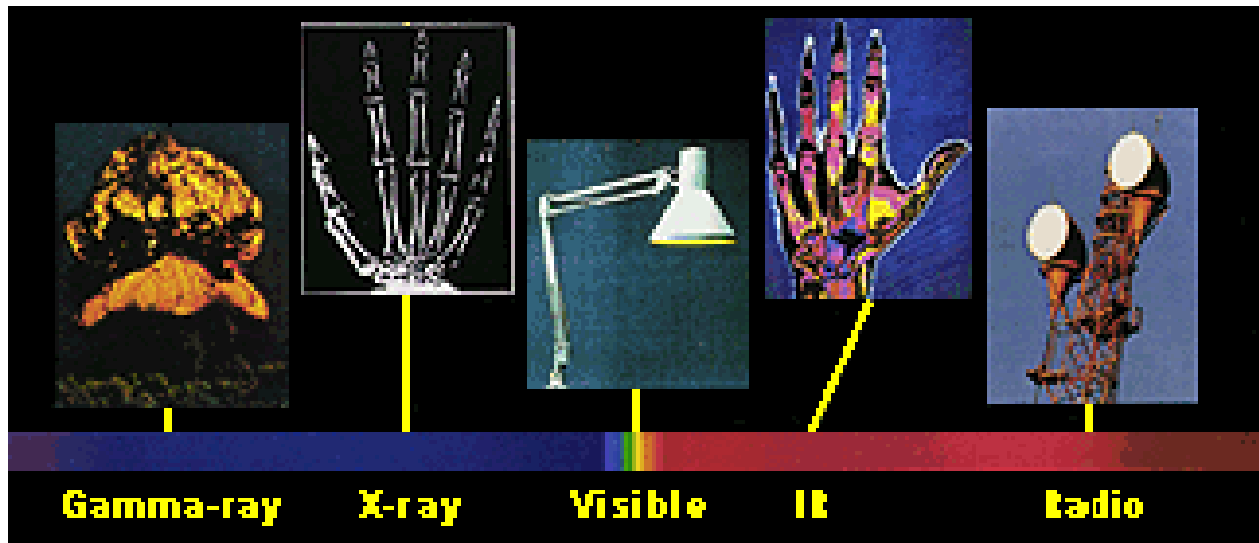
Part 4

IV

Detectors for multimessenger astrophysics

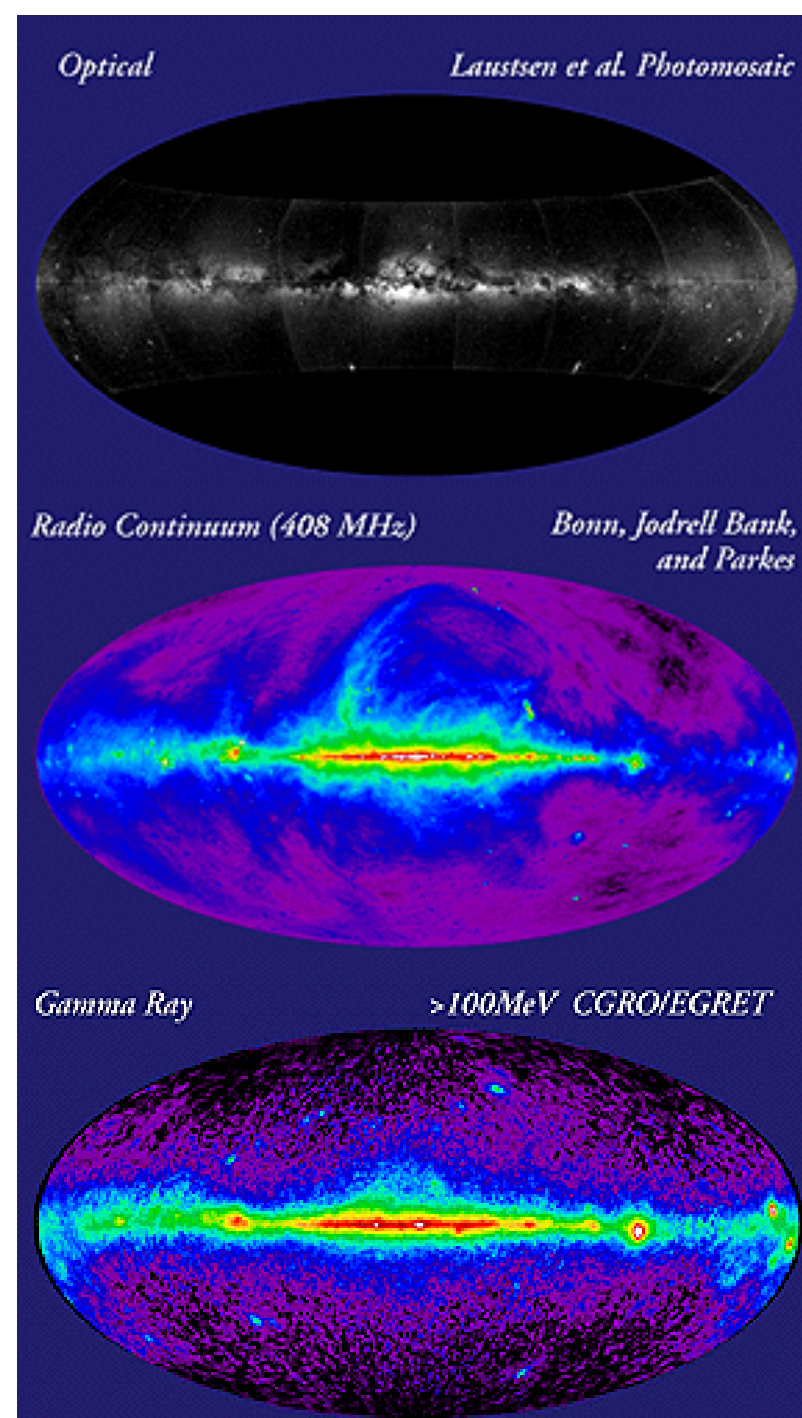
We see only partly what surrounds us

- We see only a narrow band of colors, from red to purple in the rainbow
- Also the colors we don't see have names familiar to us: we listen to the radio, we heat food in the microwave, we take pictures of our bones through X-rays...

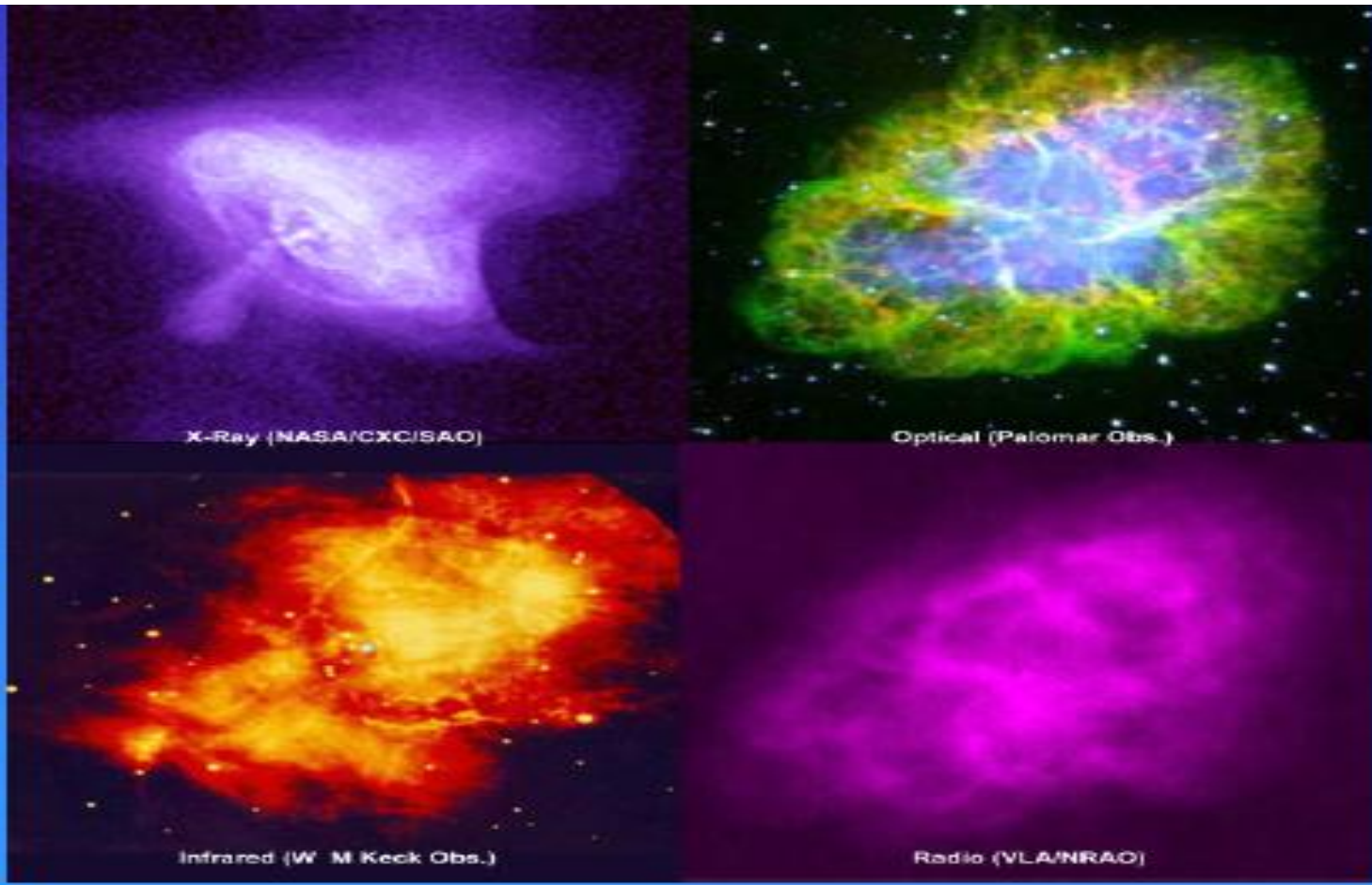
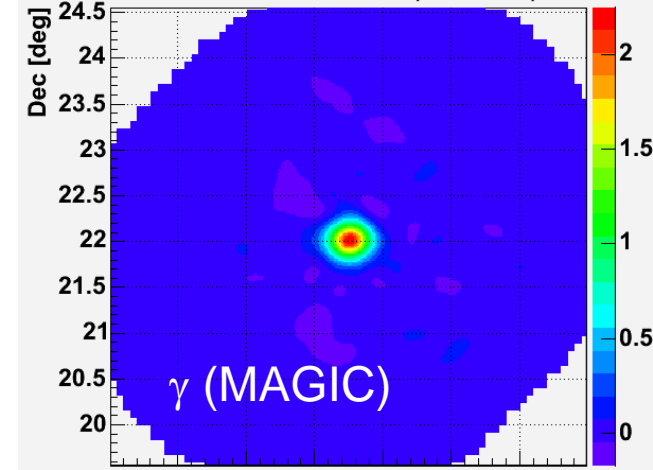


The universe we don't see

- When we take a picture we capture light (a telescope image comes as well from visible light)
- In the same way we can map into false colors the image from a “X-ray telescope”
- This can show (shows!) new objects...

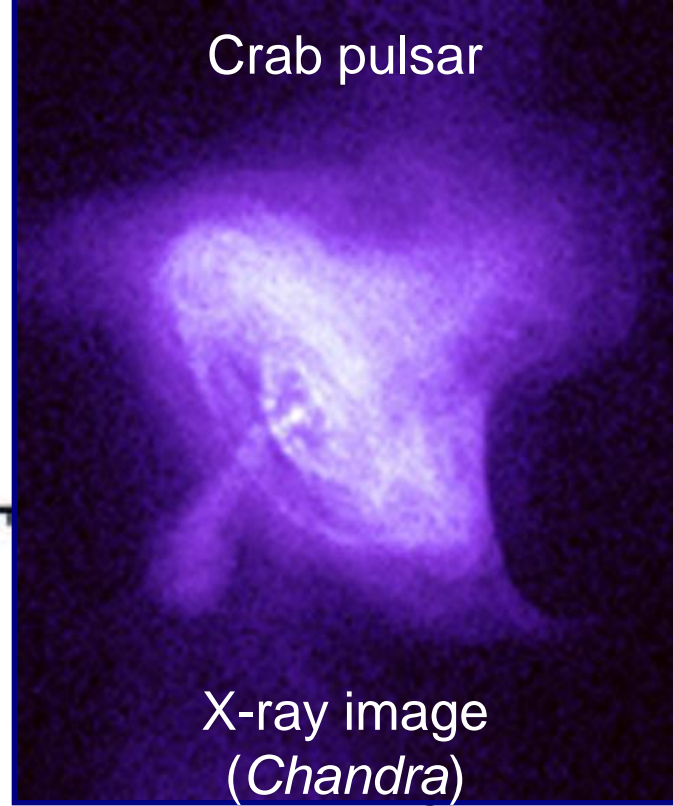
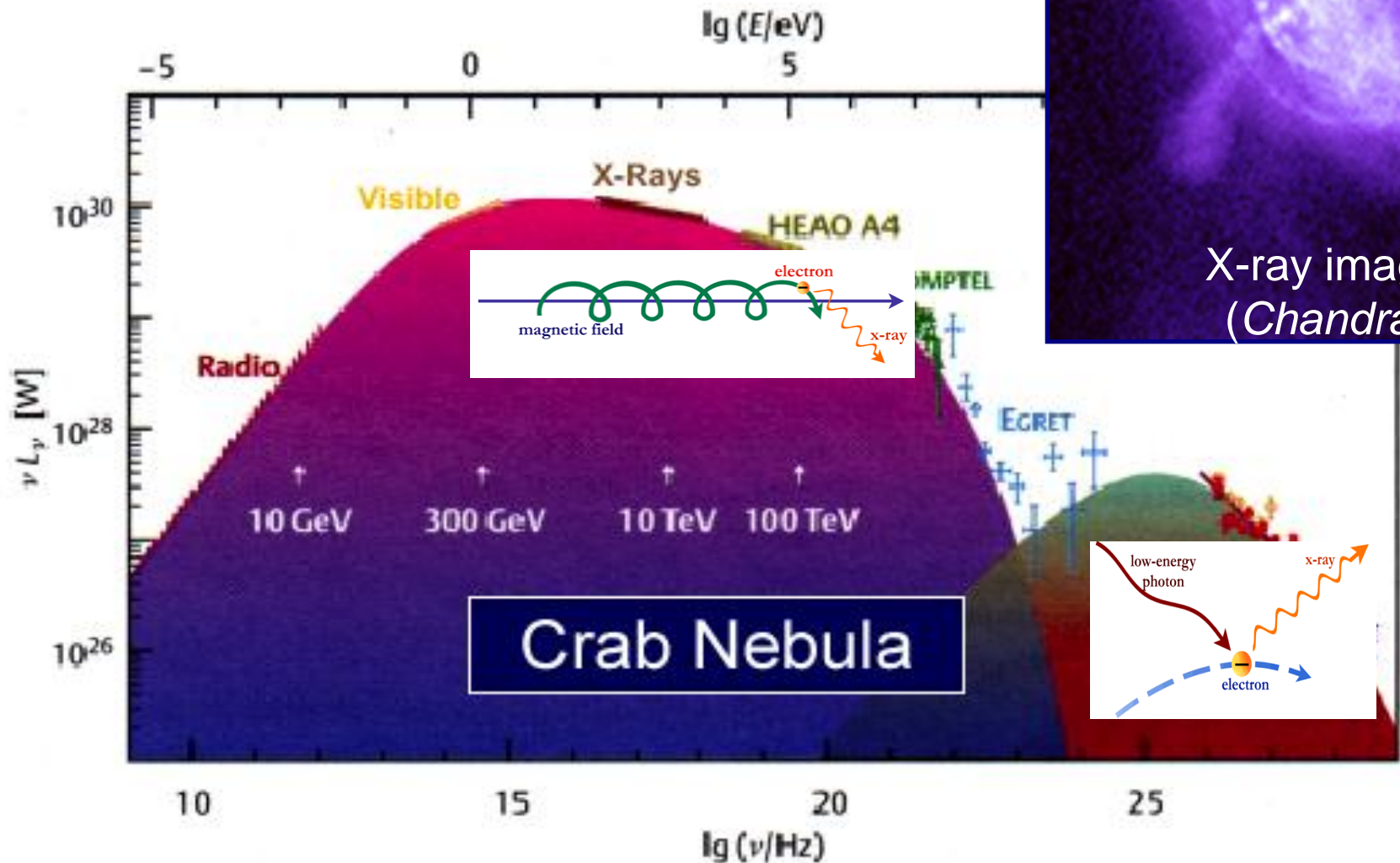


Or clarify the operation of known objects



Crab Nebula
(SN 1054)

Many sources radiate over a wide range of wavelengths

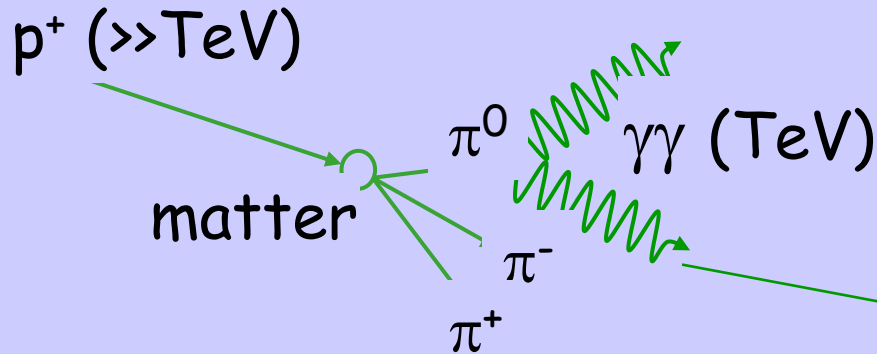


Origin of γ rays from gravitational collapses

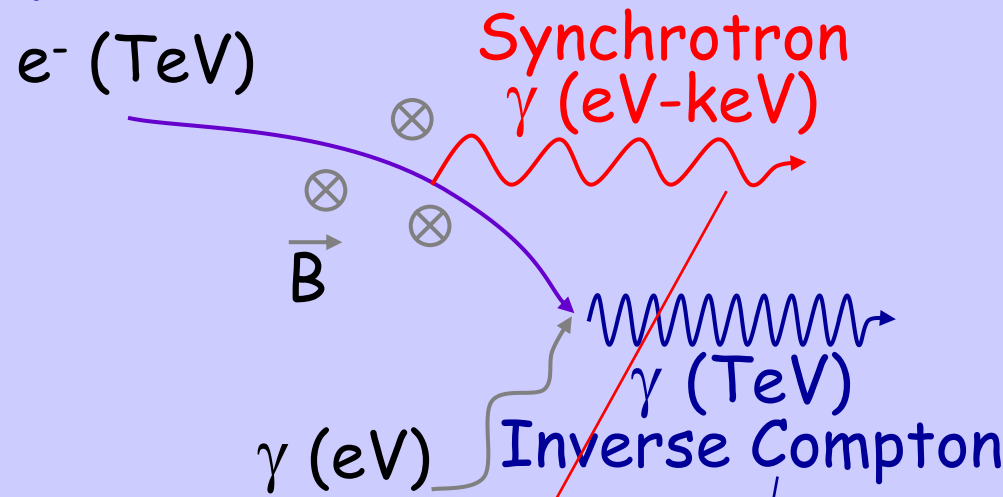
SSC: a (minimal) standard model

(0.1-1)% of energy into photons..
 SSC explains most observations,
 Maybe not the most interesting...

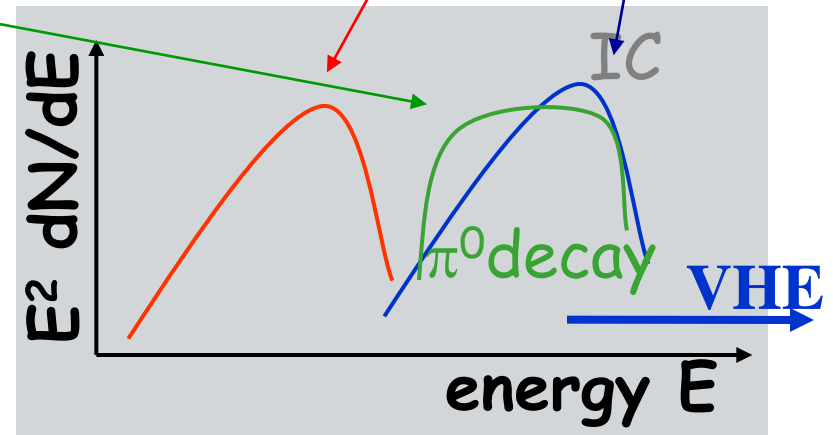
hadronic acceleration



leptonic acceleration

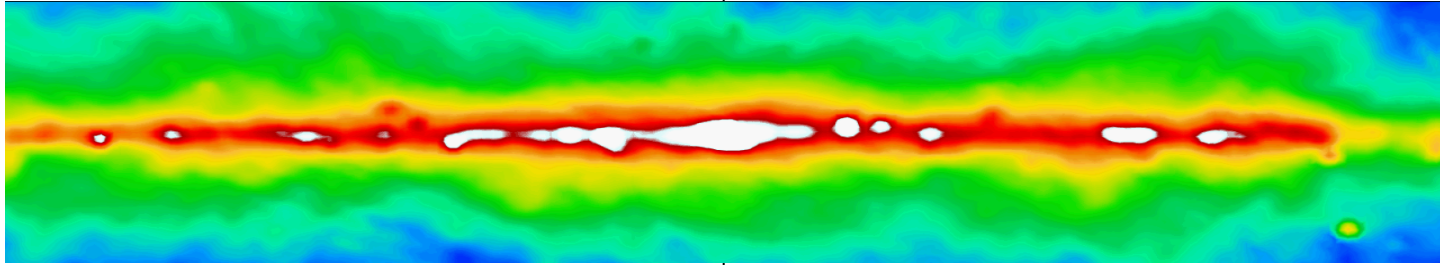


In the VHE region,
 $dN/dE \sim E^{-\Gamma}$ (Γ : spectral index)

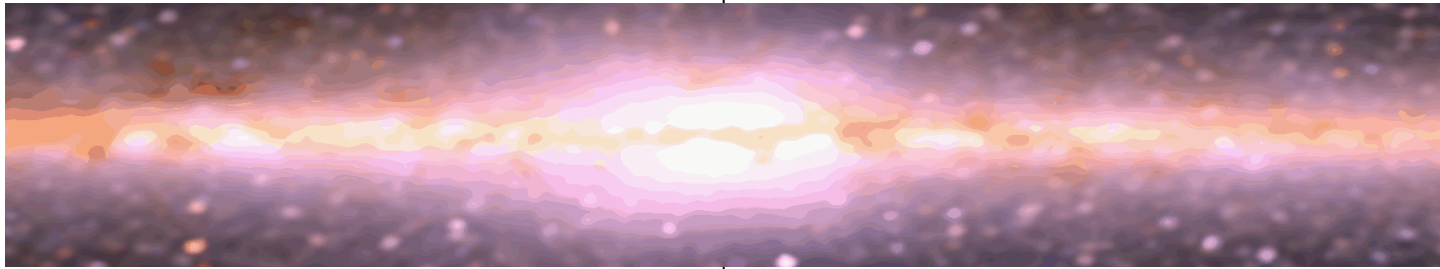


Centre of Galaxy in Different Photon Wavelengths

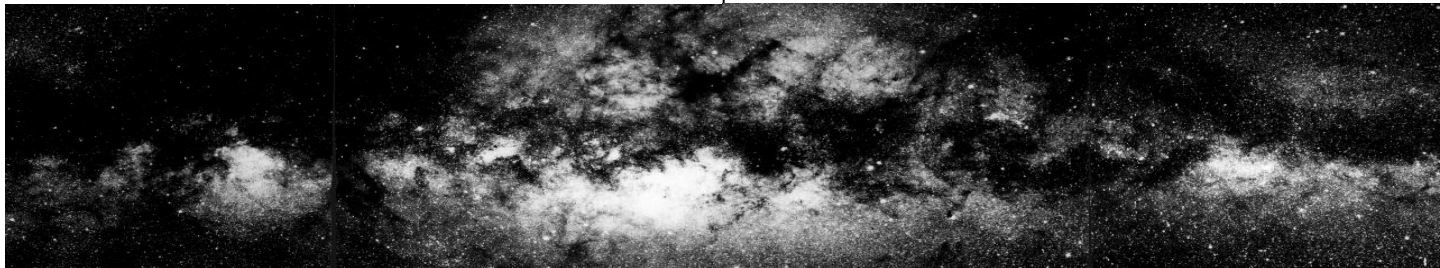
Radio 408 Mhz



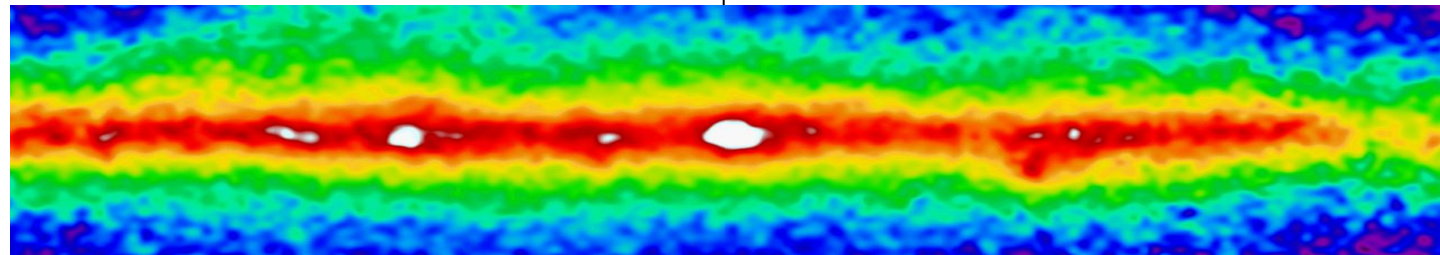
Infrared 1-3 μm



Visible Light



Gamma Rays



Surprises in history of astrophysics

New instruments often give unexpected results:

Telescope	User	date	Intended Use	Actual use
Optical	Galileo	1608	Navigation	Moons of Jupiter
Optical	Hubble	1929	Nebulae	Expanding Universe
Radio	Jansky	1932	Noise	Radio galaxies
Micro-wave	Penzias, Wilson	1965	Radio-galaxies, noise	3K cosmic background
X-ray	Giacconi ...	1965	Sun, moon	neutron stars accreting binaires
Radio	Hewish,Bell	1967	Ionosphere	Pulsars
γ -rays	military	1960?	Thermonuclear explosions	Gamma ray bursts

With future new detector can again hope for completely new discoveries

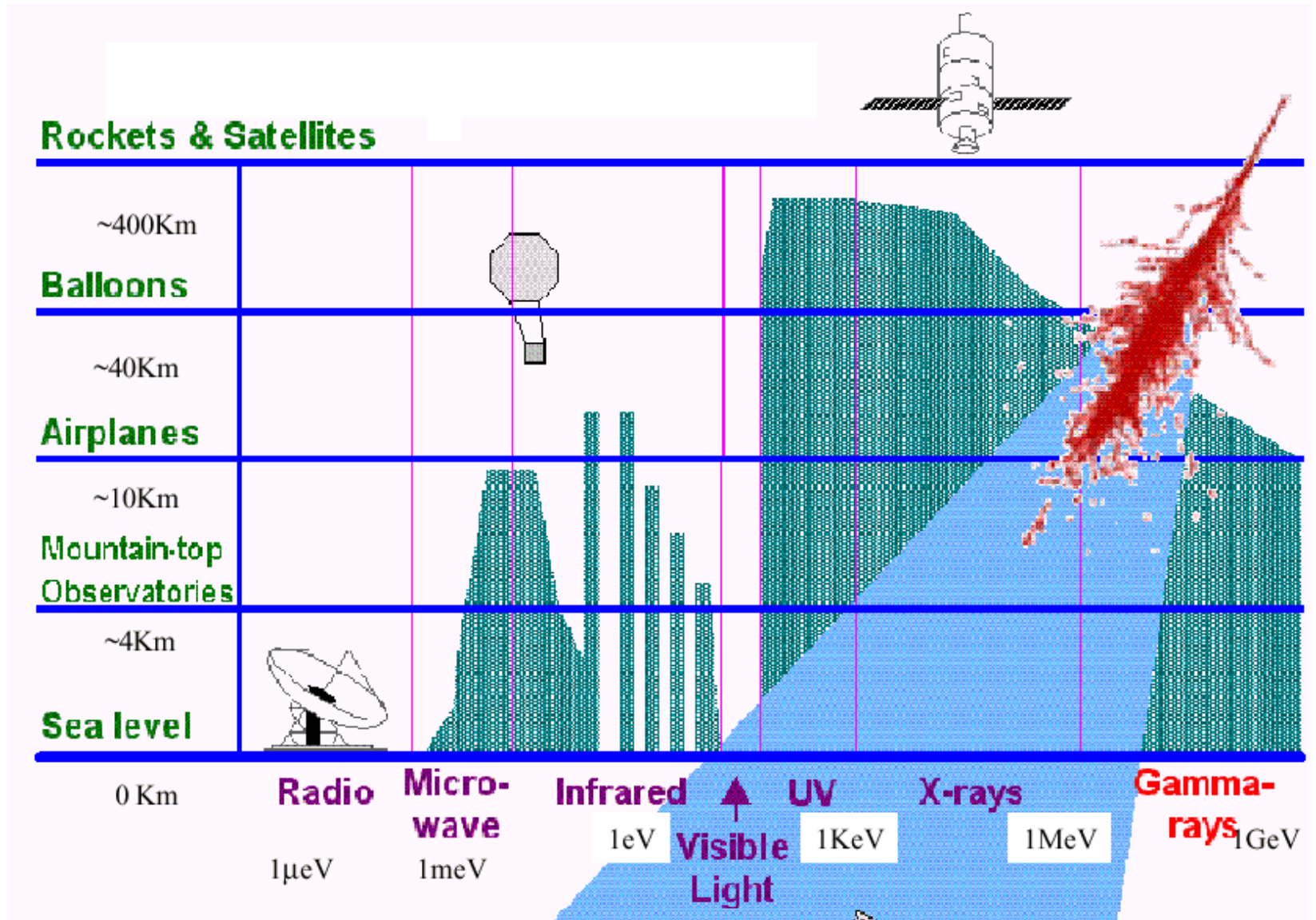
The high-energy γ spectrum

$$E_\gamma > 30 \text{ keV} \quad (\lambda \sim 0.4 \text{ \AA}, \nu \sim 7 \cdot 10^9 \text{ GHz})$$

Although arbitrary, this limit reflects astrophysical and experimental facts:

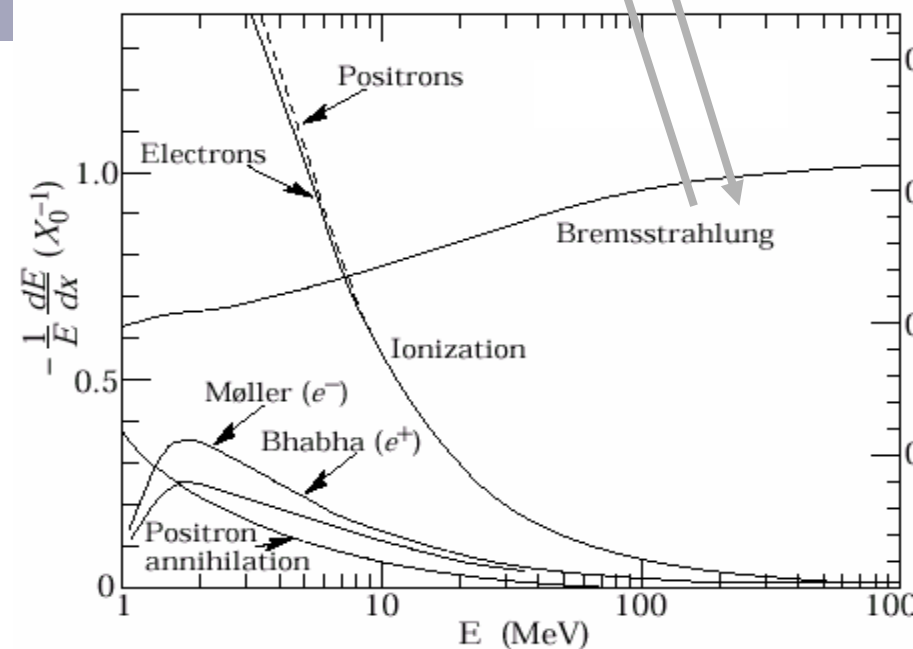
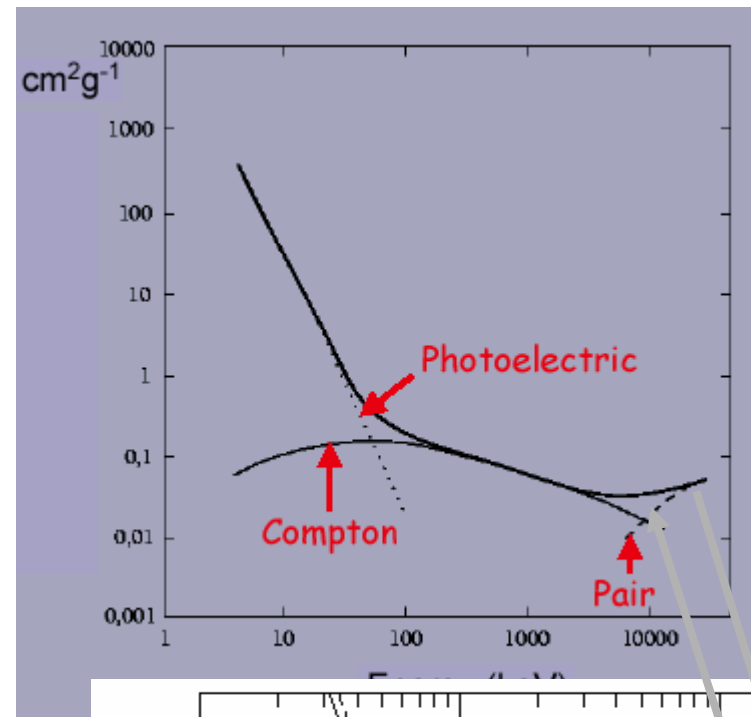
- Thermal emission \rightarrow nonthermal emission
- Problems to concentrate photons (\rightarrow telescopes radically different from larger wavelengths)
- Large background from cosmic particles

Transparency of the atmosphere

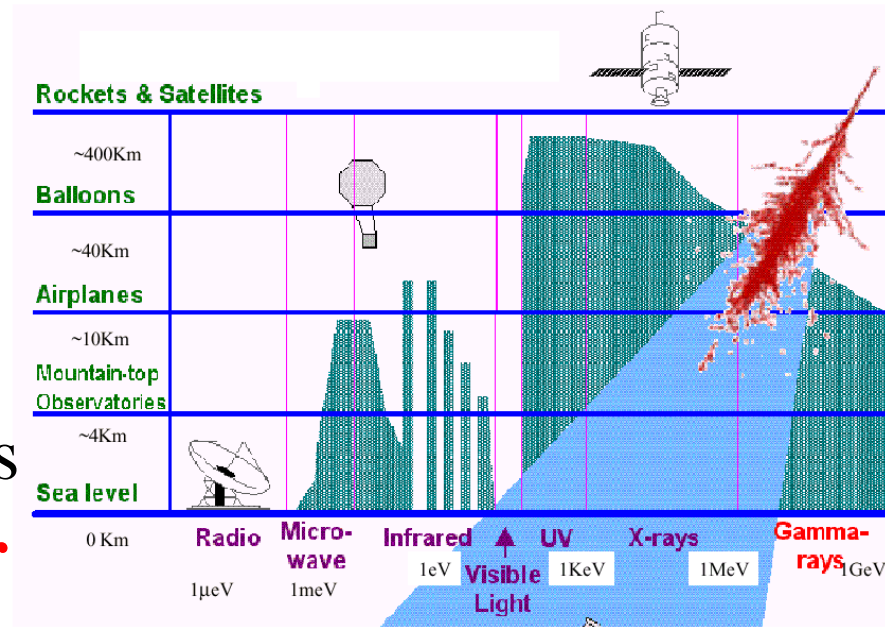


Detection of a high E photon

- Above the UV and below “50 GeV”, shielding from the atmosphere
 - Below the e^+e^- threshold + some phase space (“10 MeV”), Compton/scintillation
 - Above “10 MeV”, pair production
- Above “50 GeV”, atmospheric showers
 - Pair \leftrightarrow Brem



Consequences on the techniques



- The earth atmosphere ($28 X_0$ at sea level) is opaque to X/γ Thus **only a satellite-based detector can detect primary X/γ**

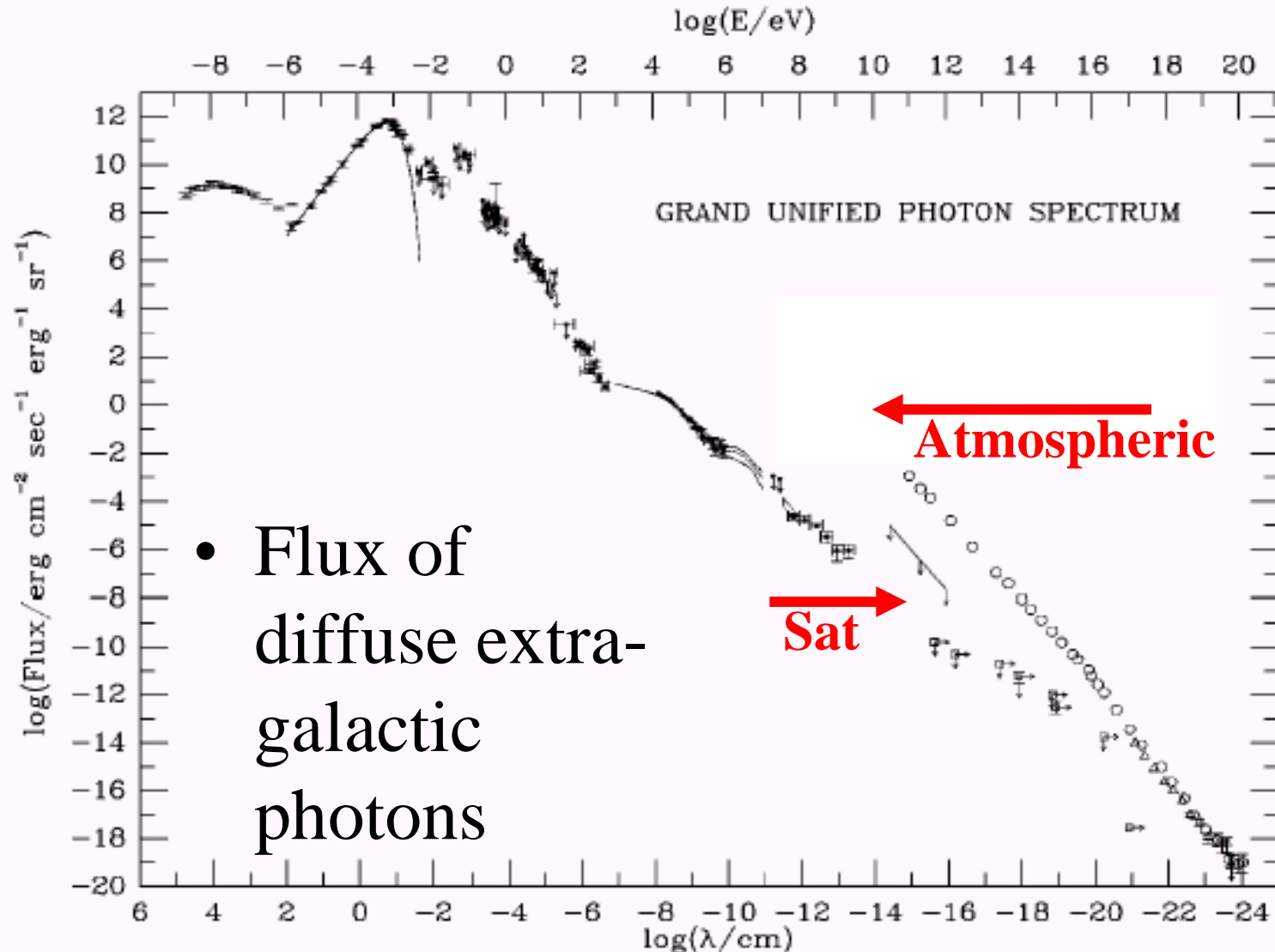
- The fluxes of h.e. γ are low and decrease rapidly with energy
 - Vela, the strongest γ source in the sky, has a flux above 100 MeV of $1.3 \cdot 10^{-5}$ photons/(cm^2s), falling with $E^{-1.89} \Rightarrow$ a 1m^2 detector would detect only 1 photon/2h above 10 GeV

\Rightarrow with the present space technology, VHE and UHE gammas can be detected only from atmospheric showers

- Earth-based detectors, atmospheric shower satellites

- The flux from high energy cosmic rays is much larger

Satellite-based and atmospheric: complementary, w/ moving boundaries



- Flux of diffuse extra-galactic photons

Satellite-based detectors: figures of merit

- Effective area, or equivalent area for the detection of γ

$$A_{\text{eff}}(E) = A \times \text{eff.}$$

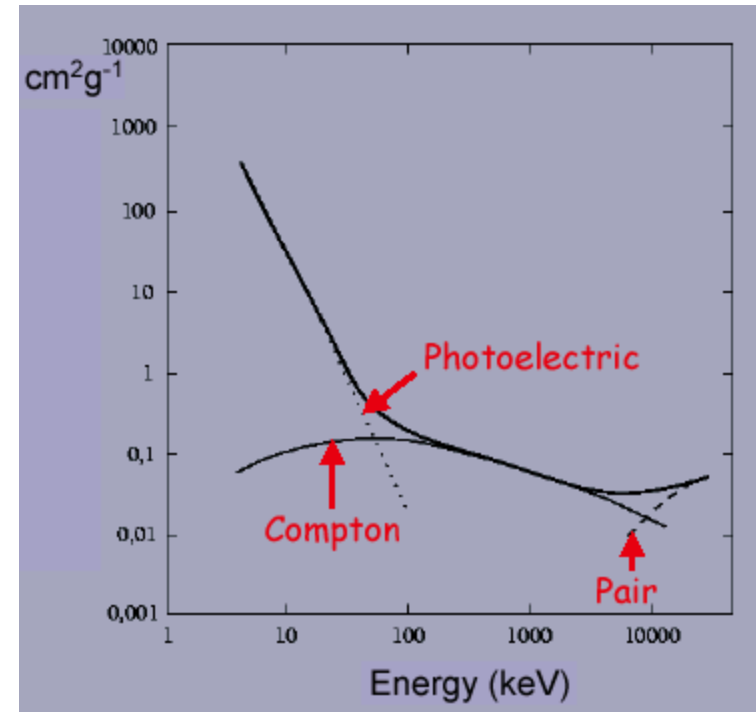
- Angular resolution is important for identifying the γ sources and for reducing the diffuse background
- Energy resolution
- Time resolution

X detectors

- The electrons ejected or created by the incident gamma rays lose energy mainly in ionizing the surrounding atoms; secondary electrons may in turn ionize the material, producing an amplification effect
- Most space X-ray telescopes consist of detection materials which take advantage of ionization process but the way to measure the total ionization loss differ with the nature of the material

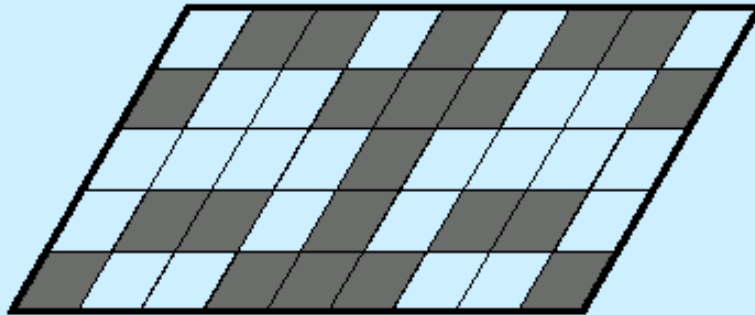
Commonly used detection devices are...

- gas detectors
- scintillation counters
- semiconductor detectors

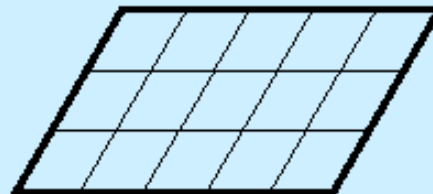


X detection (direction-sensitive)

A **coded mask** (array of opaque blocks) is disposed so that a point source at infinity projects on a position sensitive detector a **pattern characteristic of the source direction**

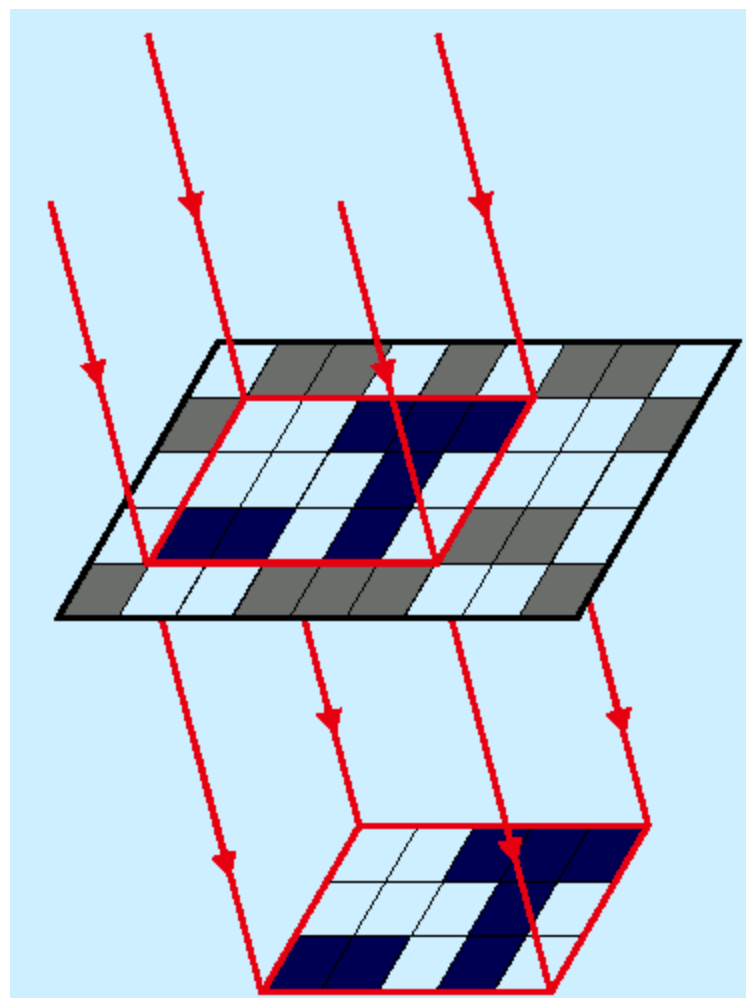
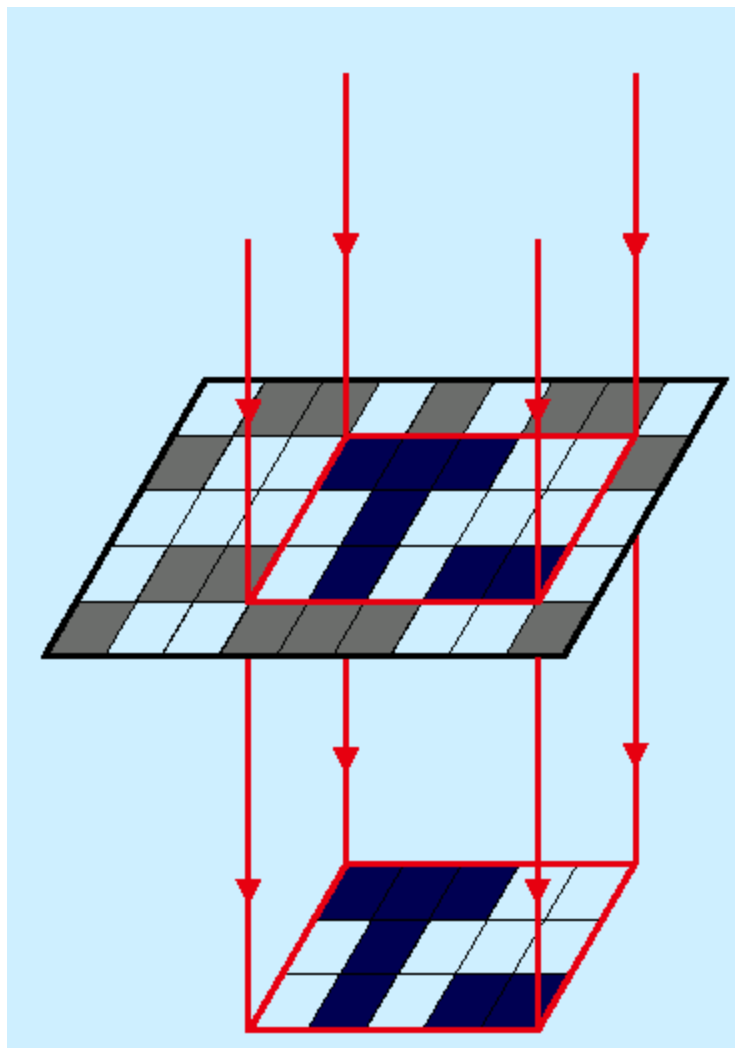


Coded mask



Position sensitive detector

X detection (direction-sensitive)



Unfolding is a nice mathematical problem !₁₈

γ satellite-based detectors: engineering

- Techniques taken from particle physics

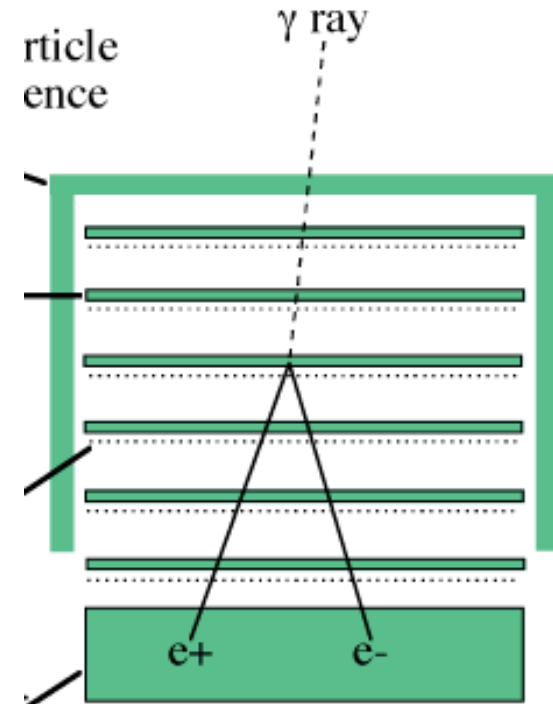
- γ direction is mostly determined by e^+e^- conversion

- Veto against charged particles by an ACD
- Angular resolution given by
 - Opening angle of the pair $m/E \ln(E/m)$
 - Multiple scattering $(20/p\beta) (L/X_0)^{1/2}$ (dominant)

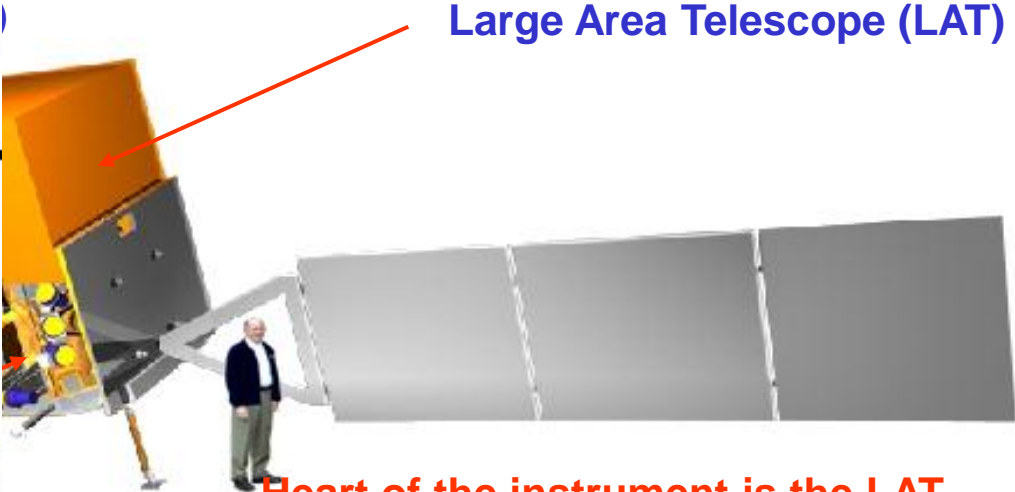
=> large number of thin converters, but the # of channel increases
(power consumption \ll 1 kW)

- If possible, a calorimeter in the bottom to get E resolution, but watch the weight (leakage => deteriorated resolution)

Smart techniques to measure E w/o calorimeters (AGILE)

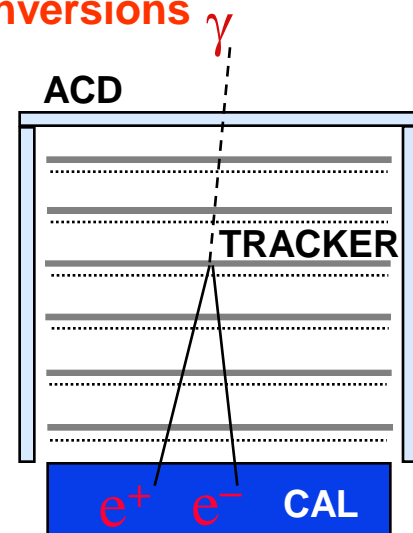


The GLAST/Fermi observatory and the LAT



Heart of the instrument is the LAT, detecting gamma conversions γ

e Center
min)



International collaboration USA-Italy-France-Japan-Sweden
(it has a small precursor: the all-Italian AGILE)

LAT overview

Si-strip Tracker (TKR)

18 planes XY ~ 1.7 x 1.7 m² w/ converter
Single-sided Si strips 228 μm pitch, ~10⁶ channels

Measurement of the gamma direction



Astroparticle groups
INFN/University Bari,
Padova, Perugia, Pisa,
Roma2, Udine/Trieste

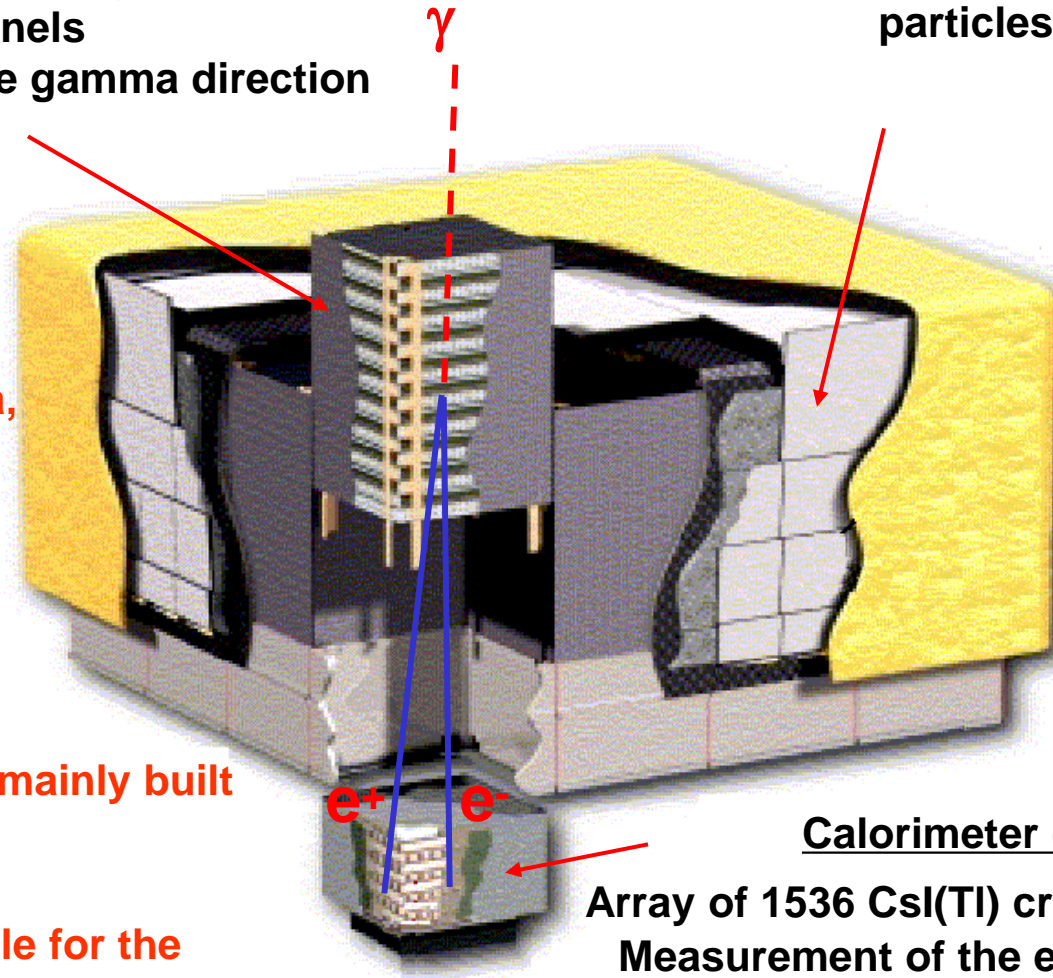
The Silicon tracker is mainly built
in Italy

Italy is also responsible for the
detector simulation, event display
and GRB physics

AntiCoincidence Detector (ACD)

89 scintillator tiles around the TKR

Reduction of the background from charged
particles



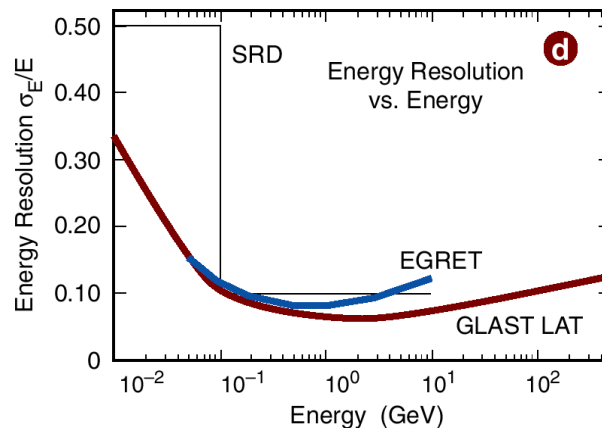
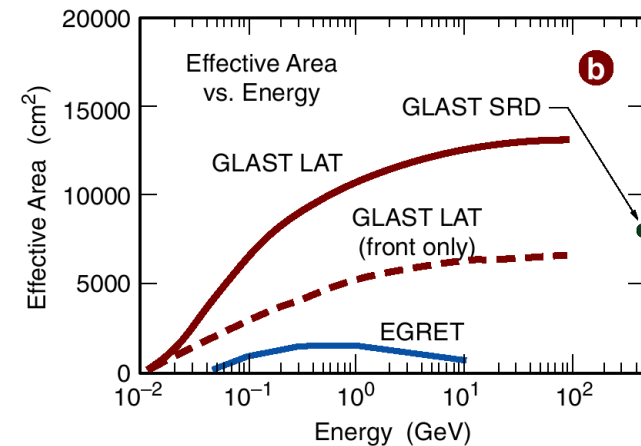
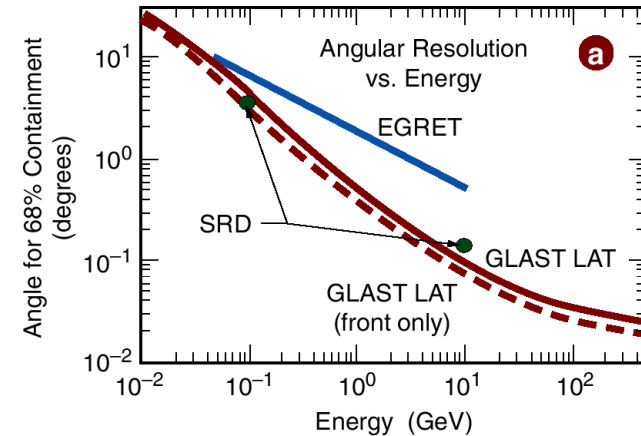
Calorimeter (CAL)

Array of 1536 CsI(Tl) crystals in 8 layers
Measurement of the electron energy



The Fermi LAT outperforms the previous reference, EGRET, by two orders of magnitude

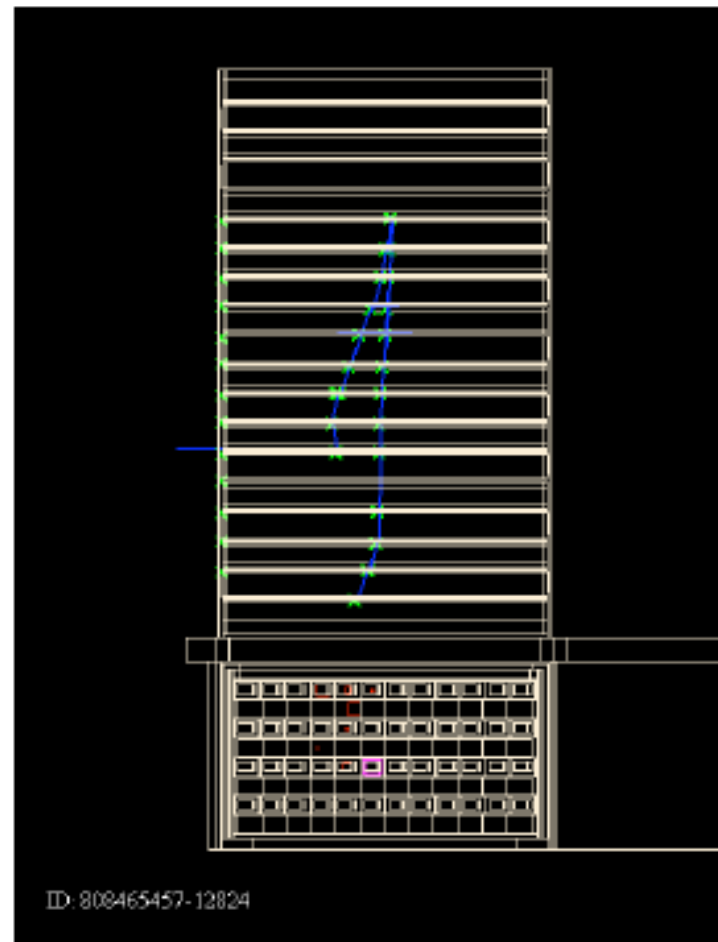
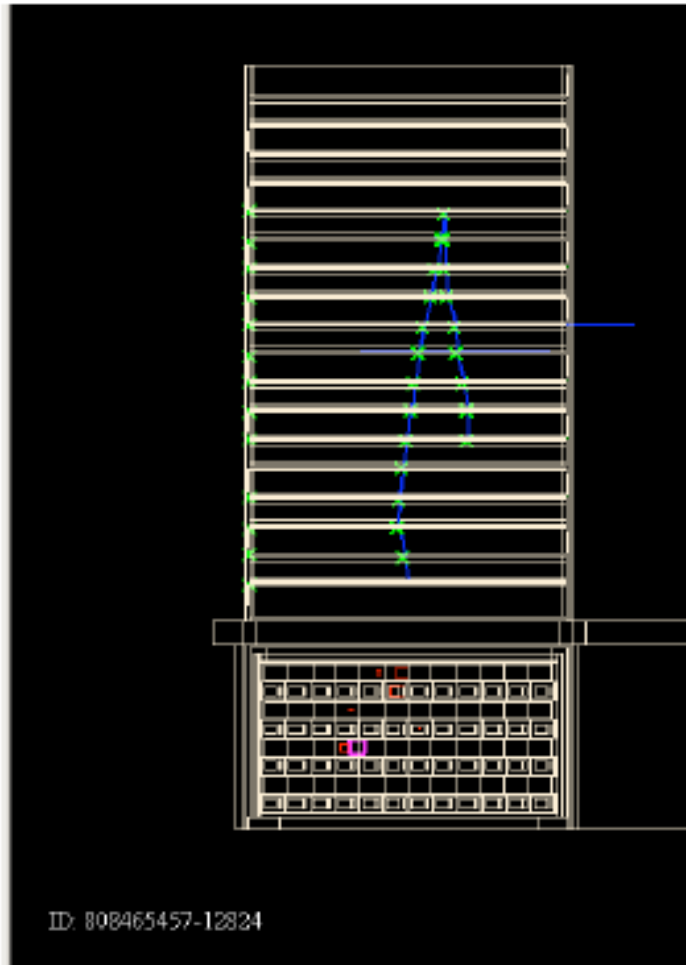
Quantity	GLAST	EGRET
Energy range	20 MeV- > 300 GeV	20 MeV- 30 GeV
Energy resolution	10 % (E>100 MeV)	10%
Peak Effective Area	> 8000 cm ² (E>1 GeV)	1500 cm ²
Single photon angular resolution (68%, on-axis)	<3.5 deg (100 MeV) <0.15 deg (E>10 GeV)	5.8 deg (100 MeV)
*Field of view (FOV)	> 2 sr	0.5 sr
Time resolution	10 microseconds	0.1 milliseconds
Dead time	< 20 microsec/event	100 ms/event



Launch of GLAST/Fermi (Cape Canaveral, June 2008)



Detection of a gamma-ray



Ground-based telescopes still needed for VHE...

- Peak eff. area of Fermi: 0.8 m^2

From strongest flare ever recorded(*) of very high energy (VHE) γ -rays:

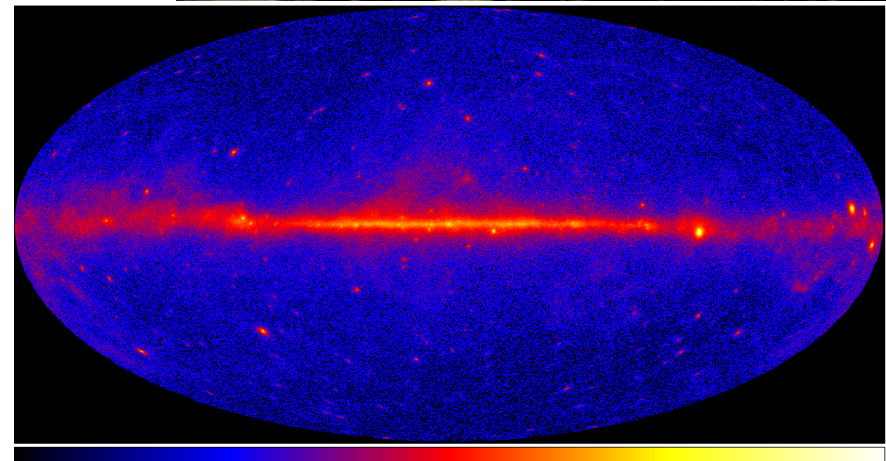
1 photon / m^2 in 8 h above 200 GeV

(PKS 2155, July 2006)

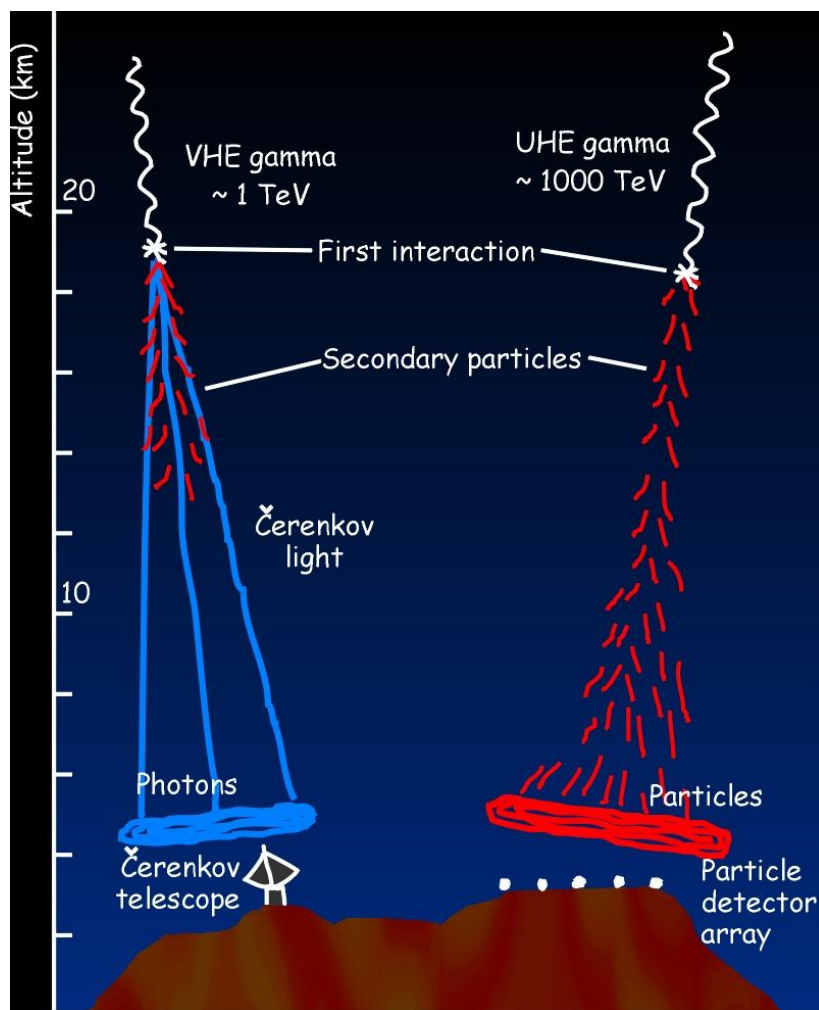
- The strongest *steady* sources are > 1 order of magnitude weaker!
- Besides: calorimeter depth $\leq 10 X_0$

\Rightarrow VHE astrophysics (in the energy region above 100 GeV) can be done only at ground

(*) Up to November 2009...



Ground detectors: EAS vs. IACT

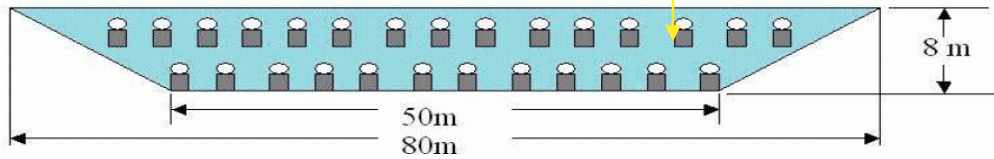


- EAS (Extensive Air Shower): detection of the charged particles in the shower
- Čerenkov detectors: (IACT): detection of the Čerenkov light from charged particles in the atmospheric showers

EAS

MILAGRO (New Mexico @ 2600m)
water Cherenkov,
 $60 \times 80 \text{m}^2$ + outriggers,
 γ/h : Muon-identification
in second layer)

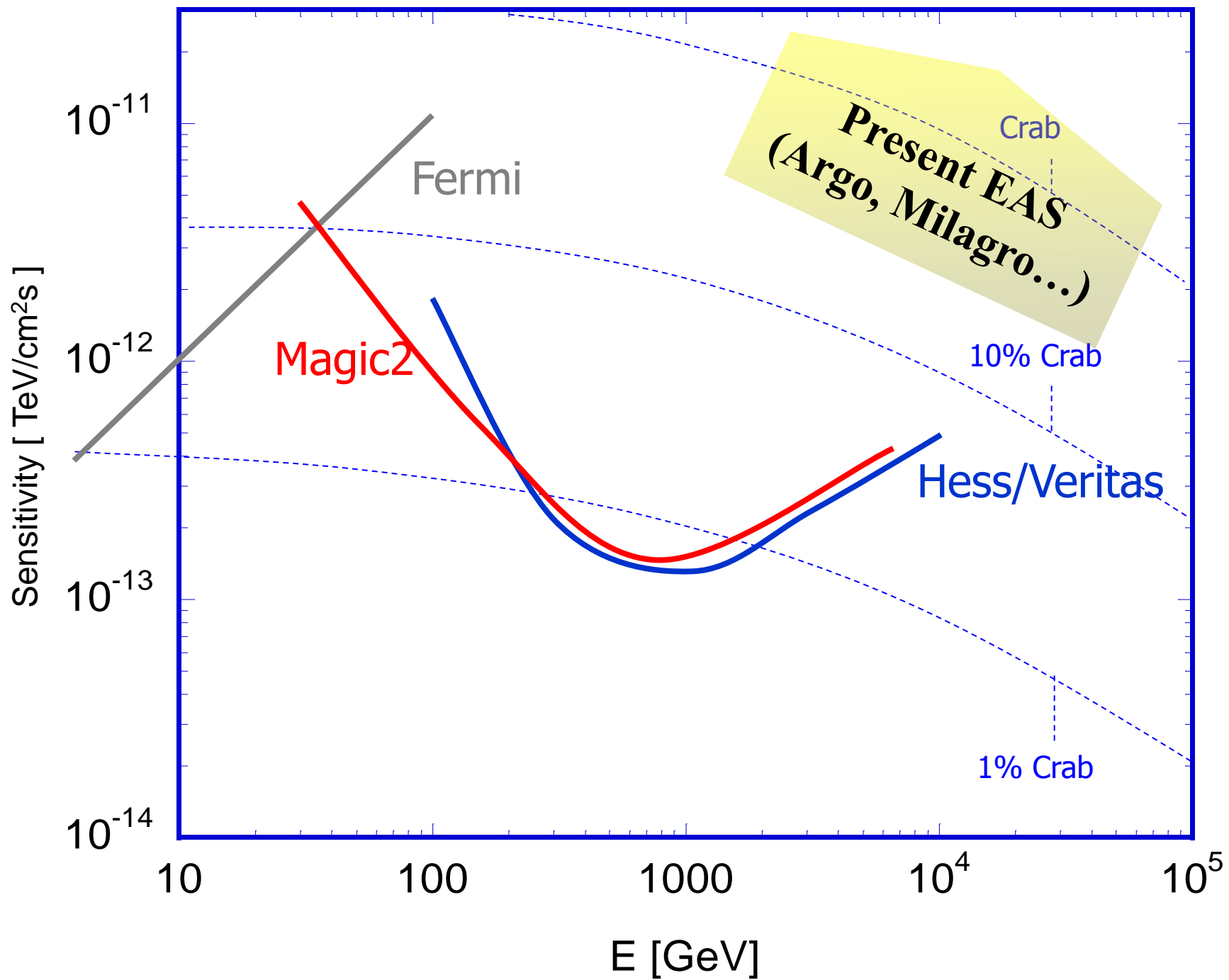
Proposed: HAWC
10x bigger @ 4500m a.s.l.



TIBET-AS (@4300M A.S.L.)
SCINTILLATOR-ARRAY, $350 \times 350 \text{M}^2$
SEE: CRAB, MKN421

SOON:
ARGO-YBJ
 6500M^2 RPC





Cherenkov (Č) detectors

Cherenkov light from γ showers

- Č light is produced by particles faster than light in air
- Limiting angle $\cos \theta_c \sim 1/n$

□ $\theta_c \sim 1^\circ$

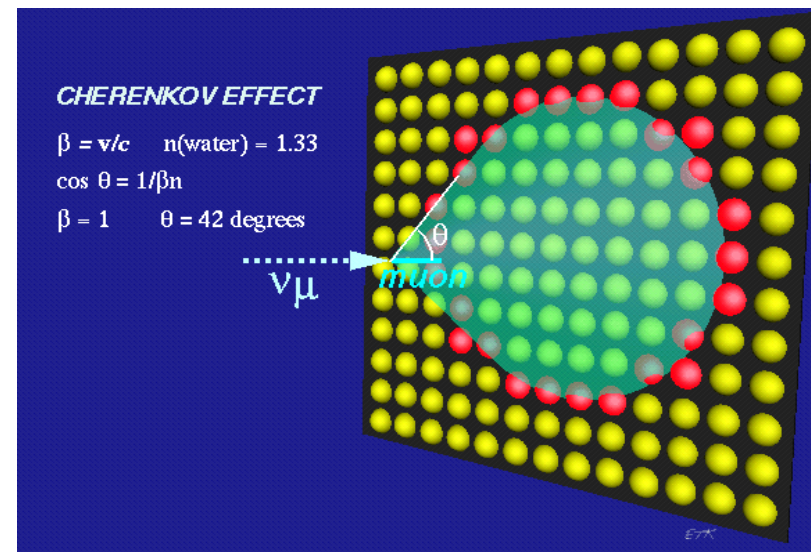
– Threshold @ sea level : 21 MeV for e, 44 GeV for μ

Maximum of a 1 TeV γ shower ~ 8 Km asl

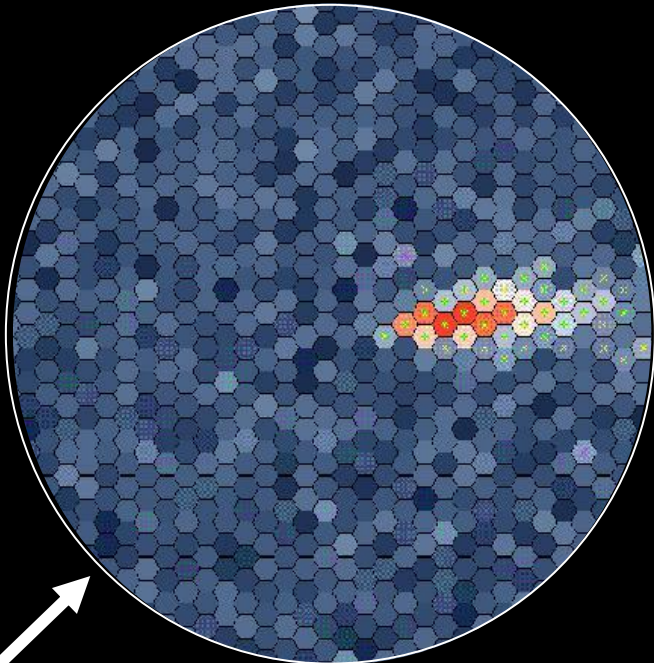
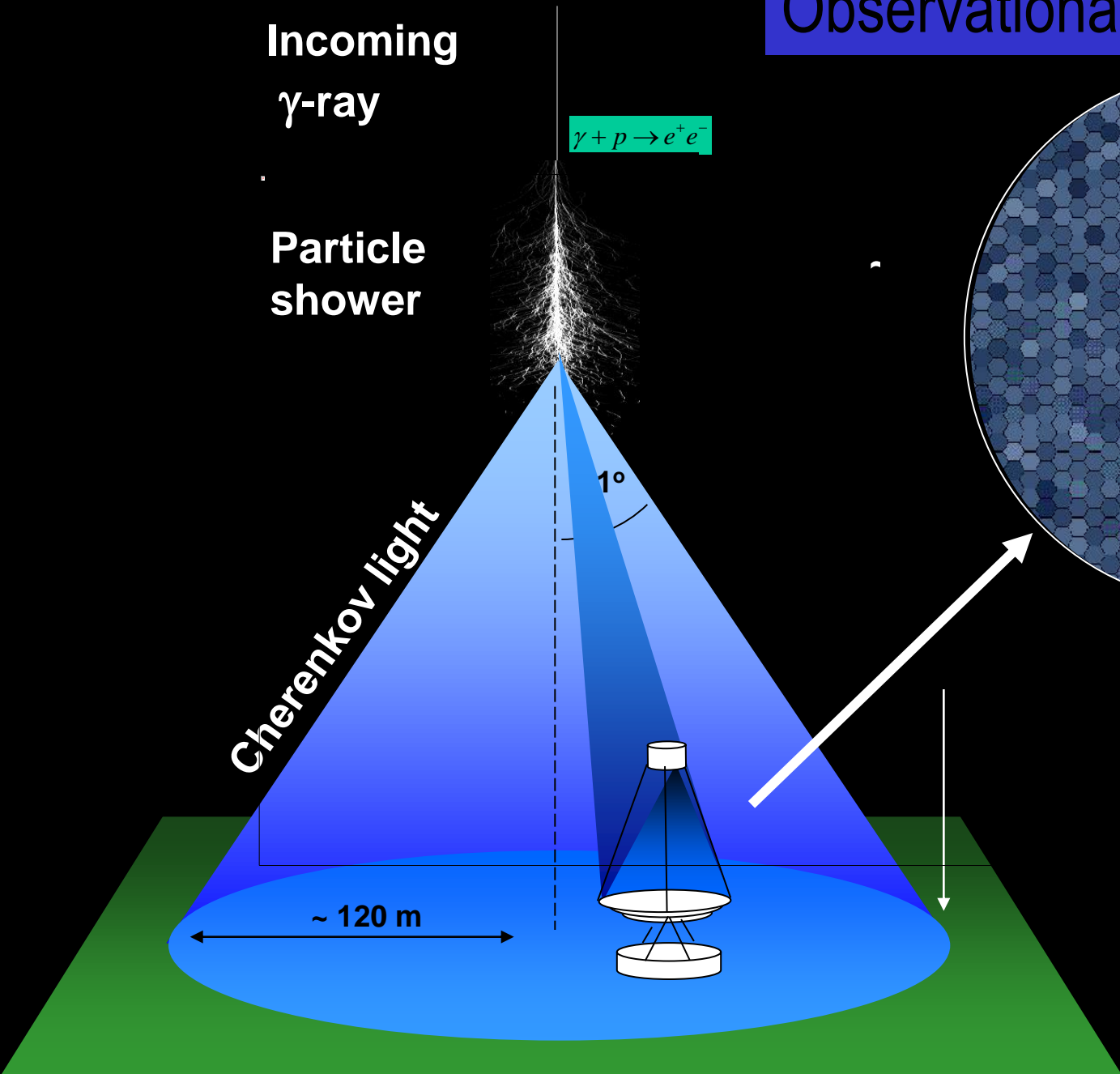
200 photons/m² in the visible

Duration ~ 2 ns

Angular spread $\sim 0.5^\circ$

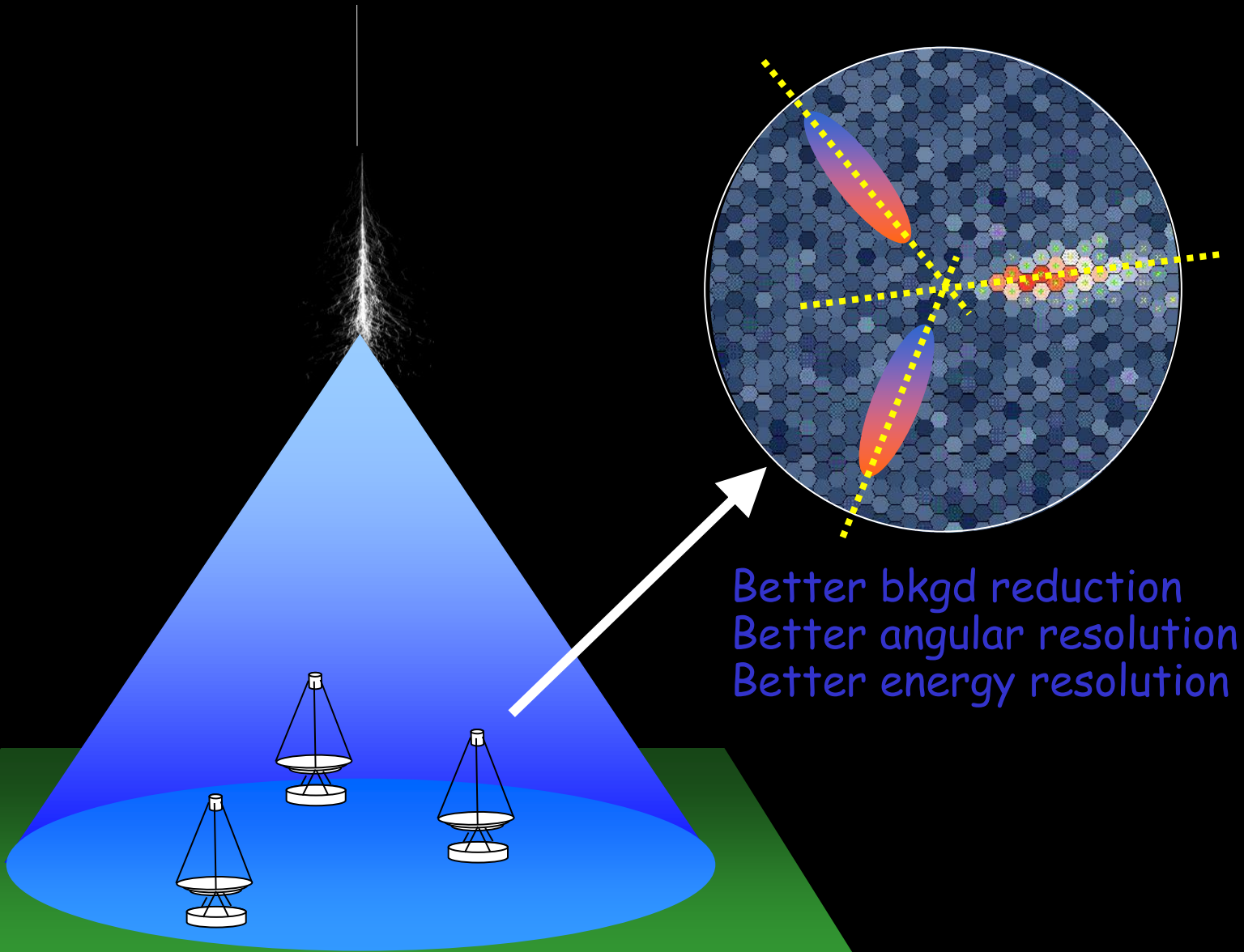


Observational Technique



- Image intensity \rightarrow Shower energy
- Image orientation \rightarrow Shower direction
- Image shape \rightarrow Primary particle

Systems of Cherenkov telescopes

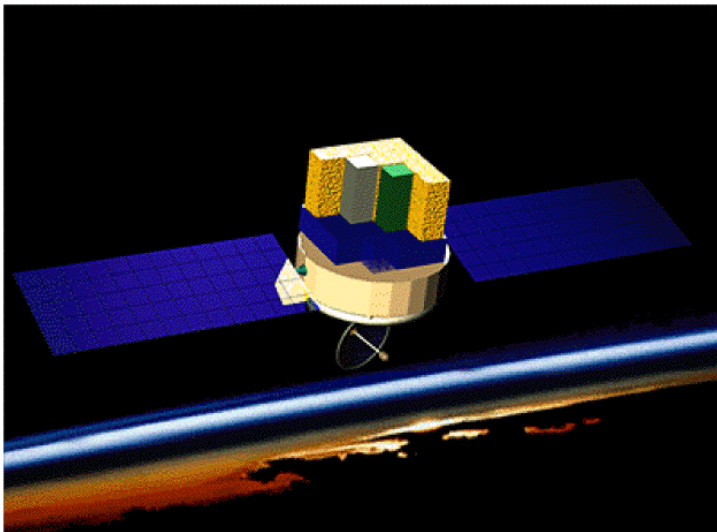


Better bkgd reduction
Better angular resolution
Better energy resolution

IACT vs Satellite

- Satellite :

- primary detection
- small effective area $\sim 1\text{m}^2$
 - lower sensitivity
- large angular opening
 - search
- large duty-cycle
- large cost
- lower energy
- low bkg



- IACT/ground based

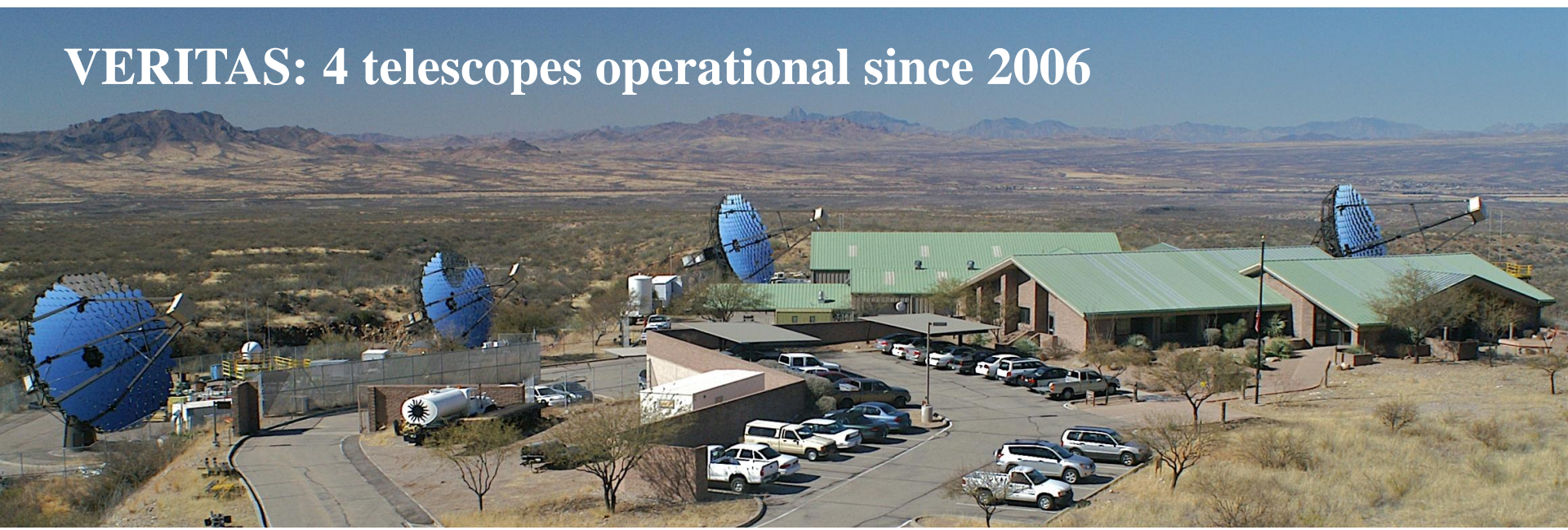
- secondary detection
- huge effective area $\sim 10^4\text{m}^2$
 - Higher sensitivity
- small angular opening
 - Serendipity search
- small duty-cycle
- low cost
- high energy
- high bkg





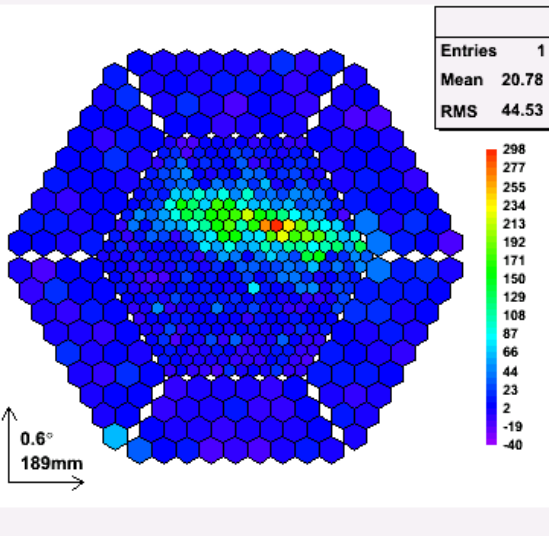
H.E.S.S.: 4 telescopes operational since 2003

The VHE connection...



VERITAS: 4 telescopes operational since 2006

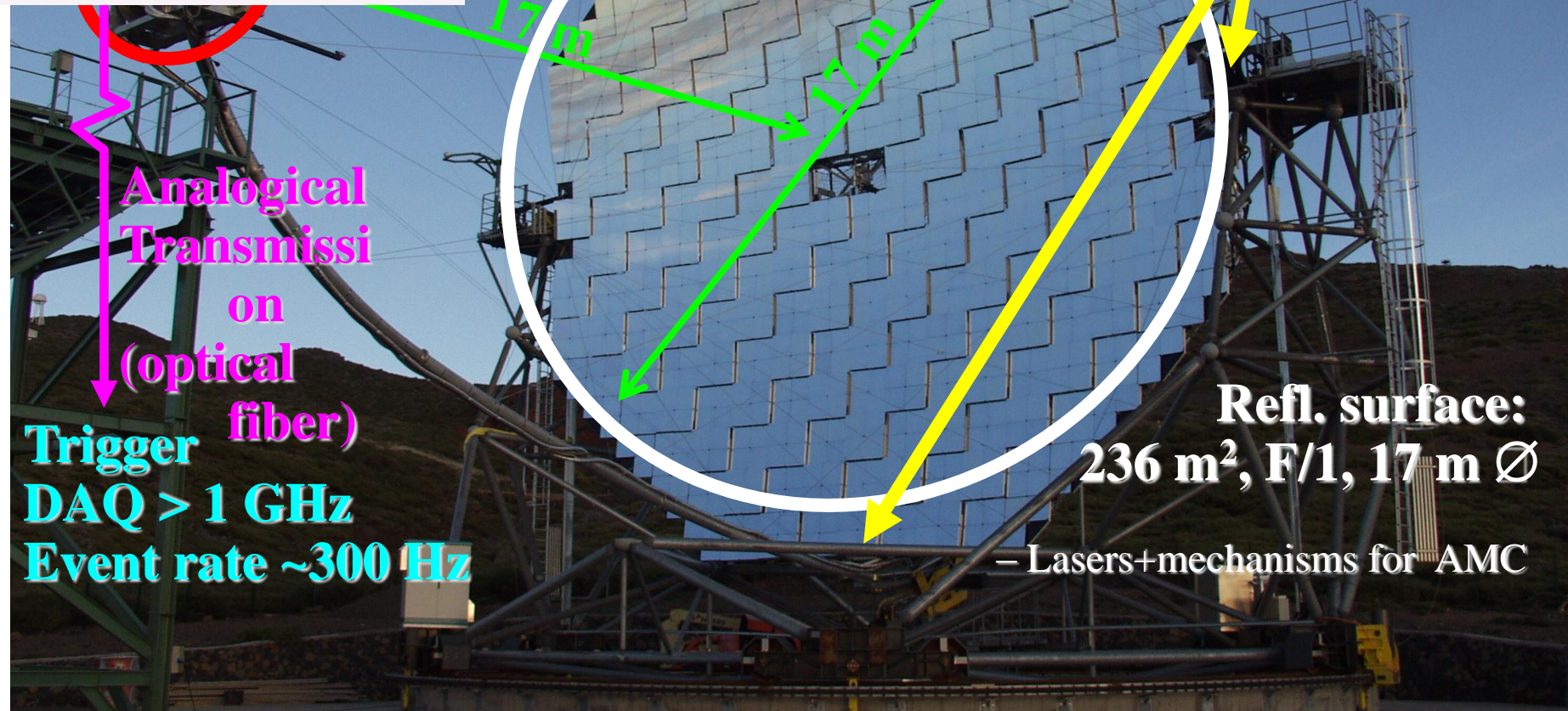
MAGIC



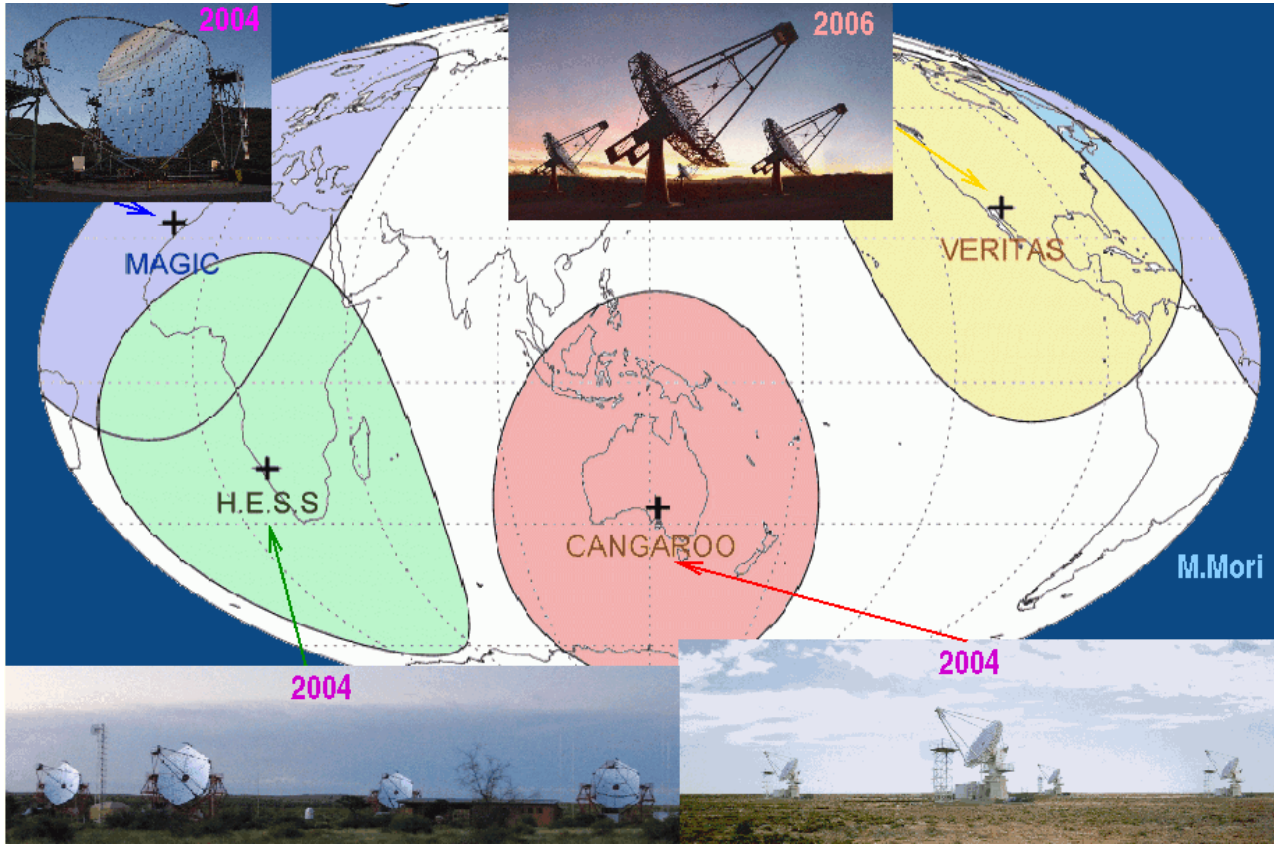
3.5° FoV

Rapid pointing

- Carbon fiber structure
- Active Mirror Control
⇒ 20 ÷ 30 seconds



Instr.	Tels. #	Tel. A (m ²)	FoV (°)	Tot A (m ²)	Thresh. (TeV)	PSF (°)	Sens. (%Crab)
H.E.S.S.	4	107	5	428	0.1	0.06	0.7
MAGIC	2	236	3.5	472	0.05(0.03)	0.06	0.8
VERITAS	4	106	4	424	0.1	0.07	0.7



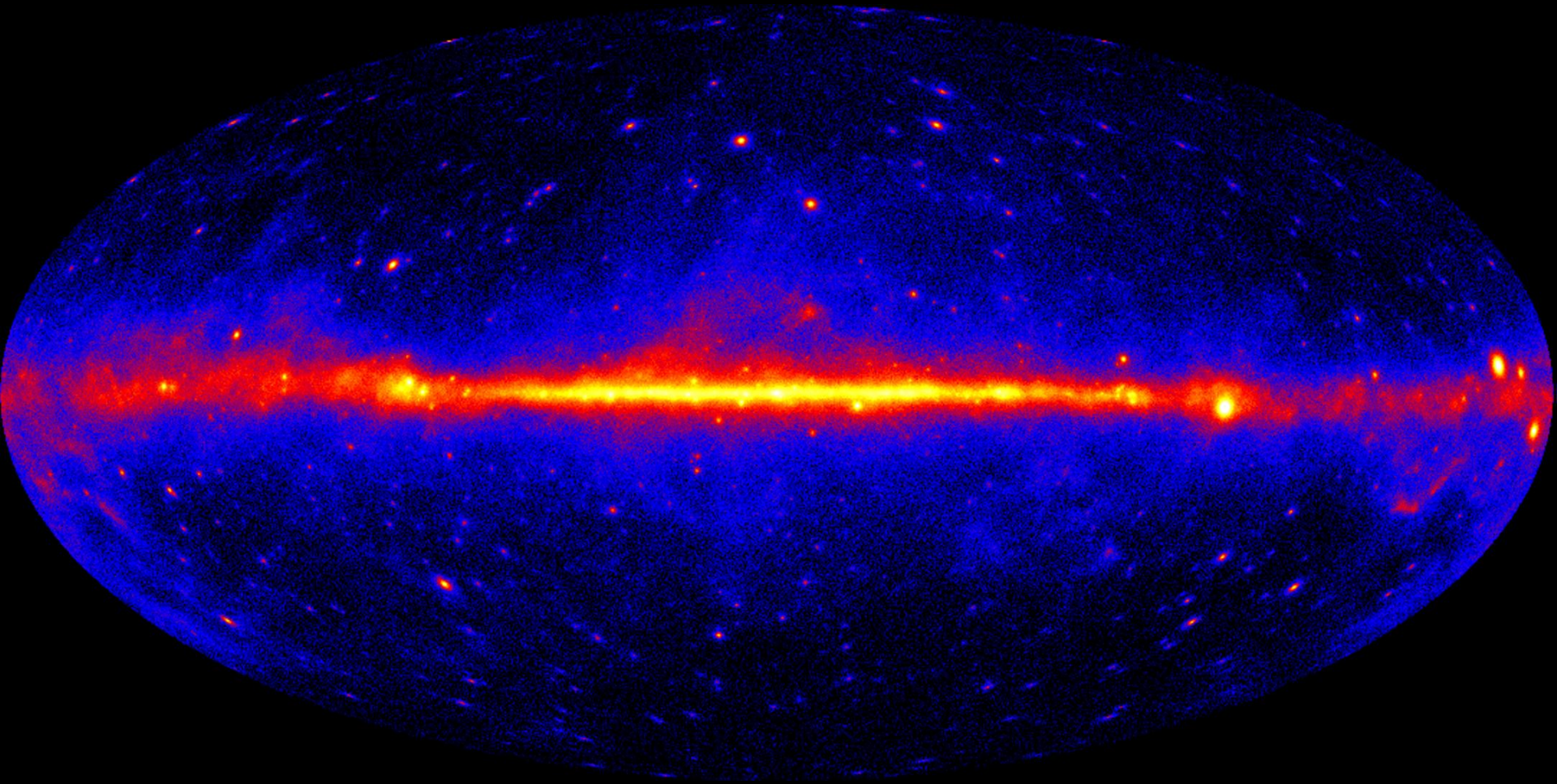
MAGIC looks farthest away: $z \sim 1.2$ (wrt $z \sim 0.8$ Of H.E.S.S.)

M
A
G
I
C

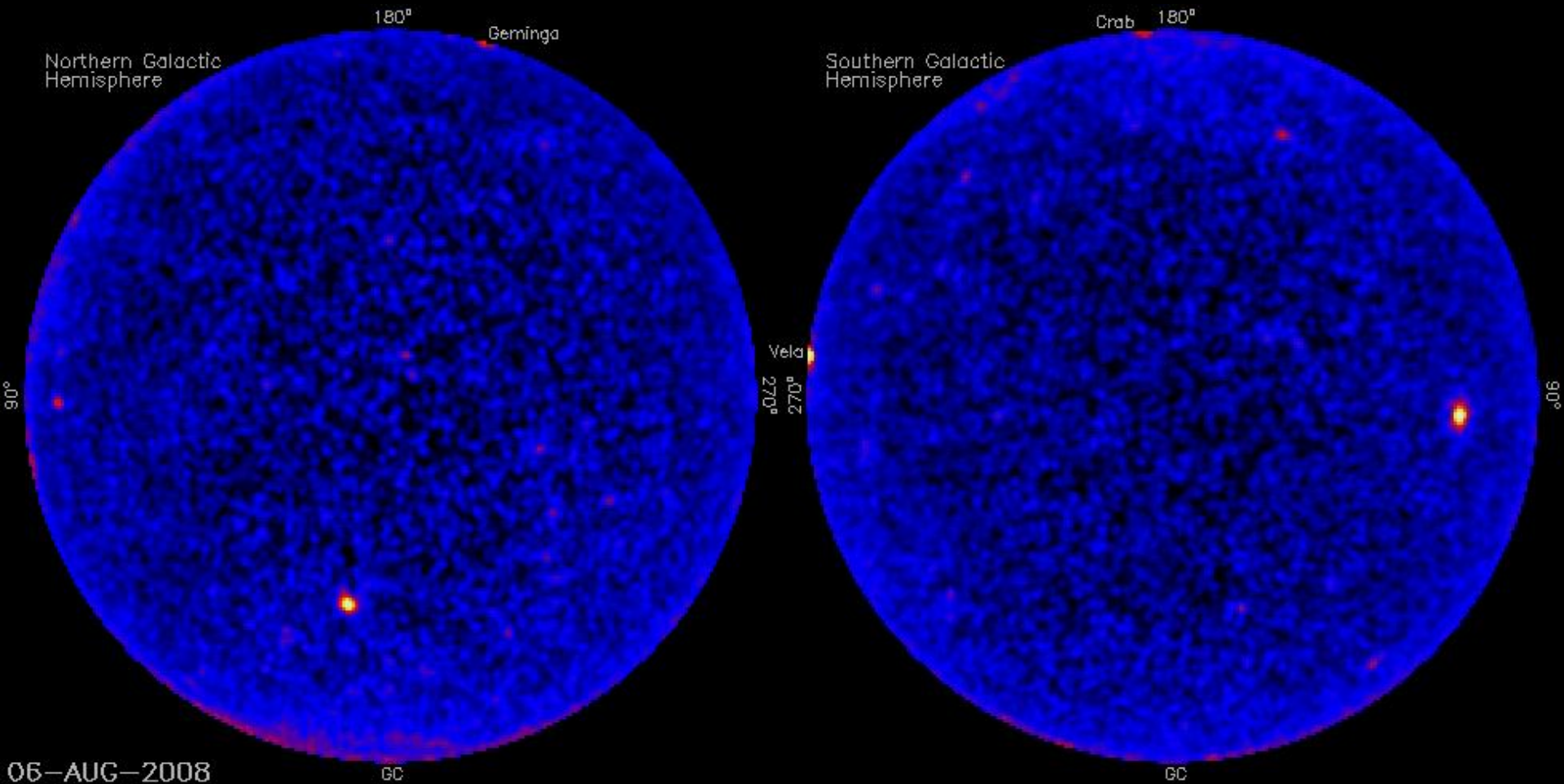


Very fast movement (< 30 s)

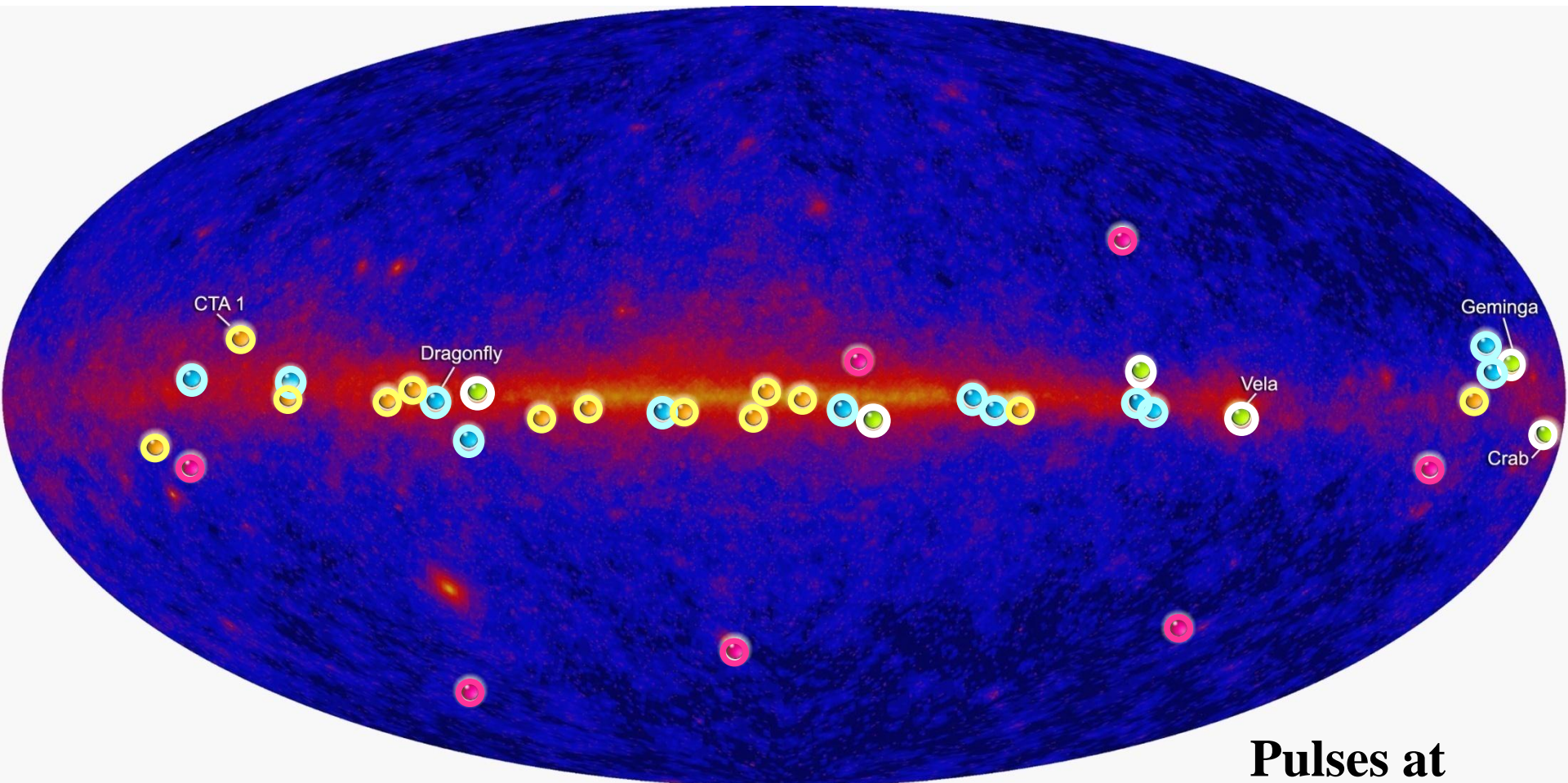
Dec 2009: release of the 1st Fermi catalog **above 100 MeV** (1451 sources, more than half extragalactic: EGRETx5)



Day-by-day variability ($> 1/3$ extrag)



Millisecond variability



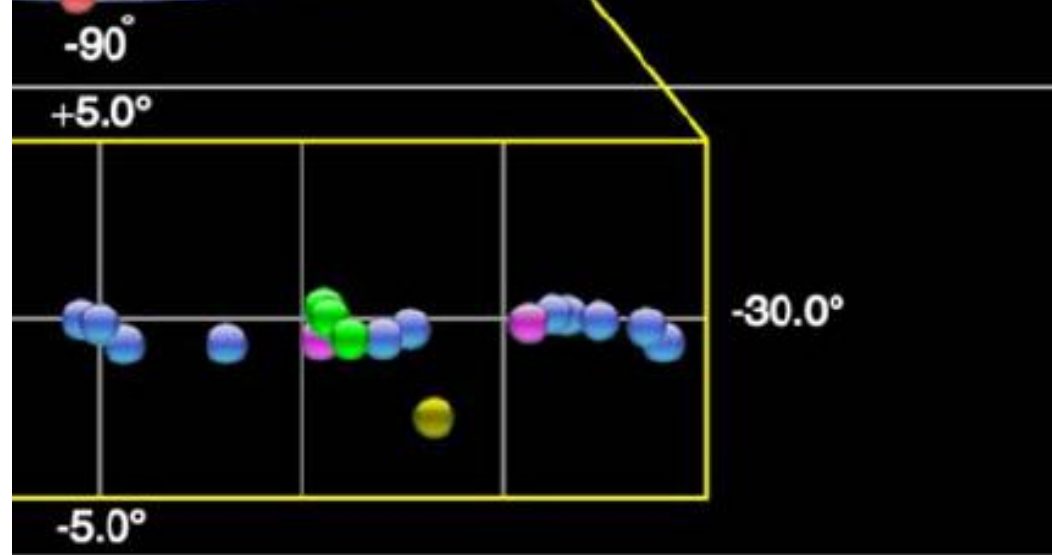
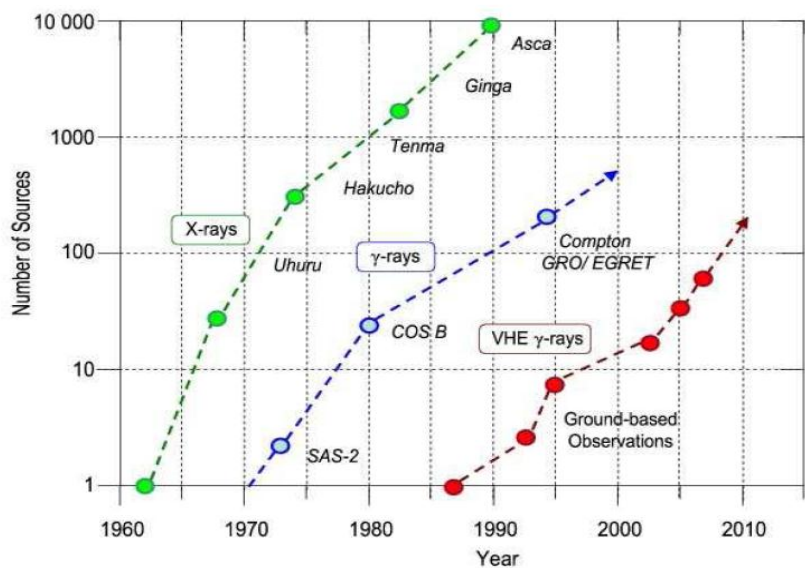
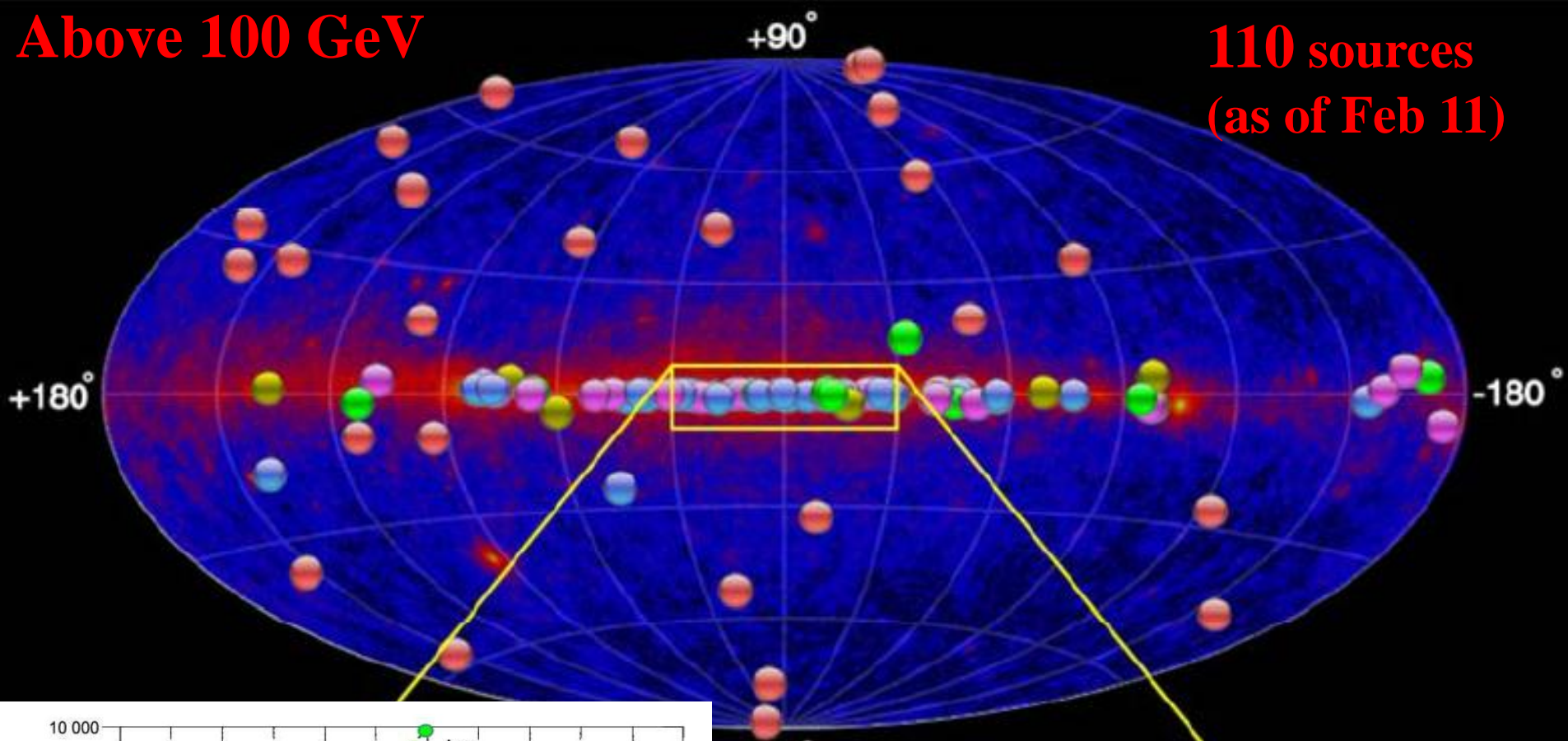
Fermi Pulsar Detections

- New pulsars discovered in a blind search
- Millisecond radio pulsars
- Young radio pulsars
- Confirmed pulsars seen by Compton Observatory EGRET instrument

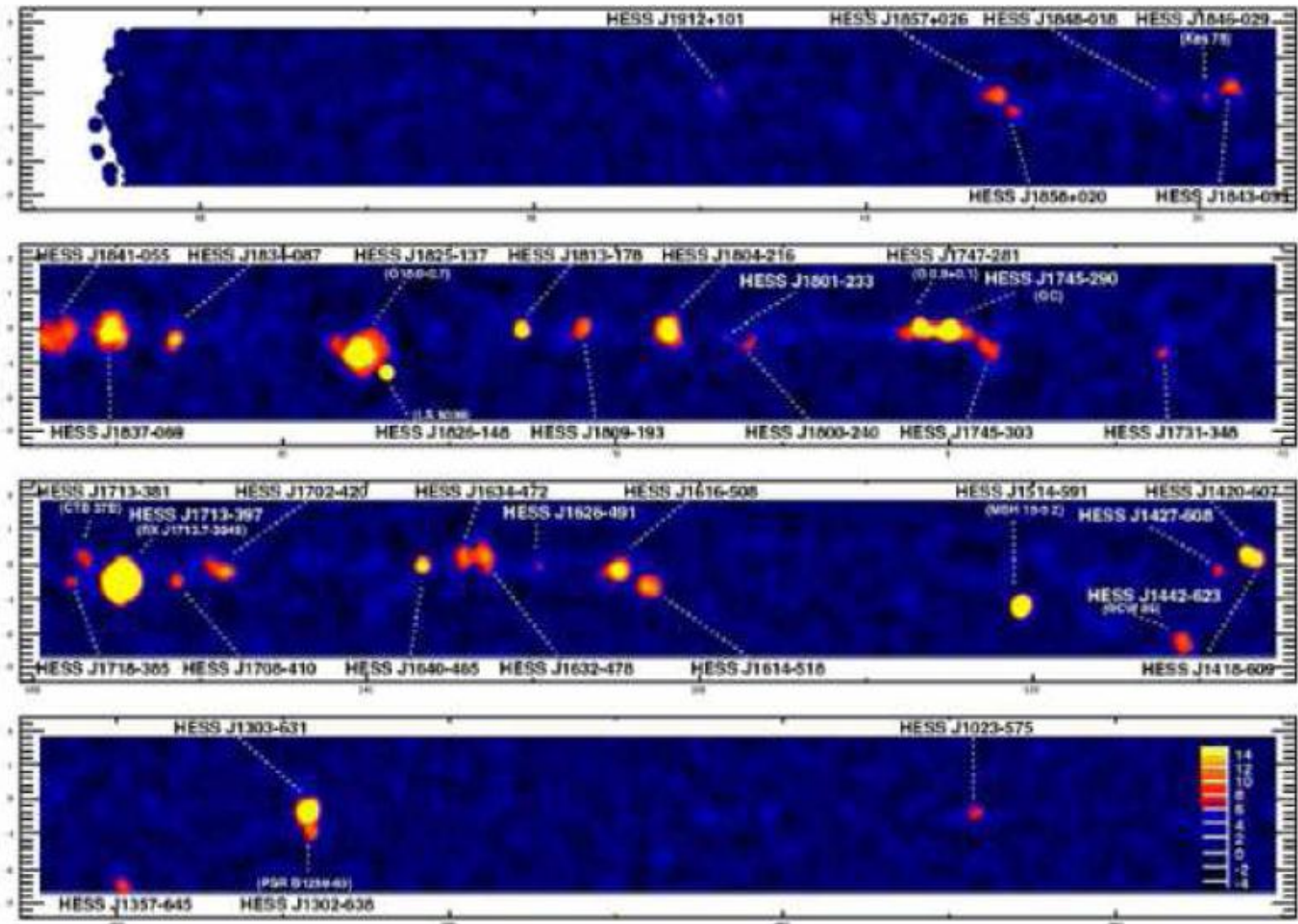
Pulses at
 $1/10^{\text{th}}$ true
rate

Above 100 GeV

110 sources (as of Feb 11)



HESS' galactic scan (2003-2007)



Standard Model of galactic Cosmic Rays

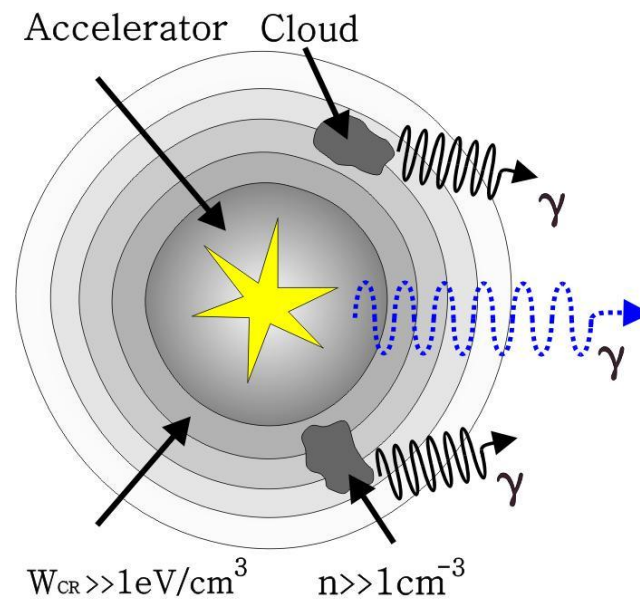
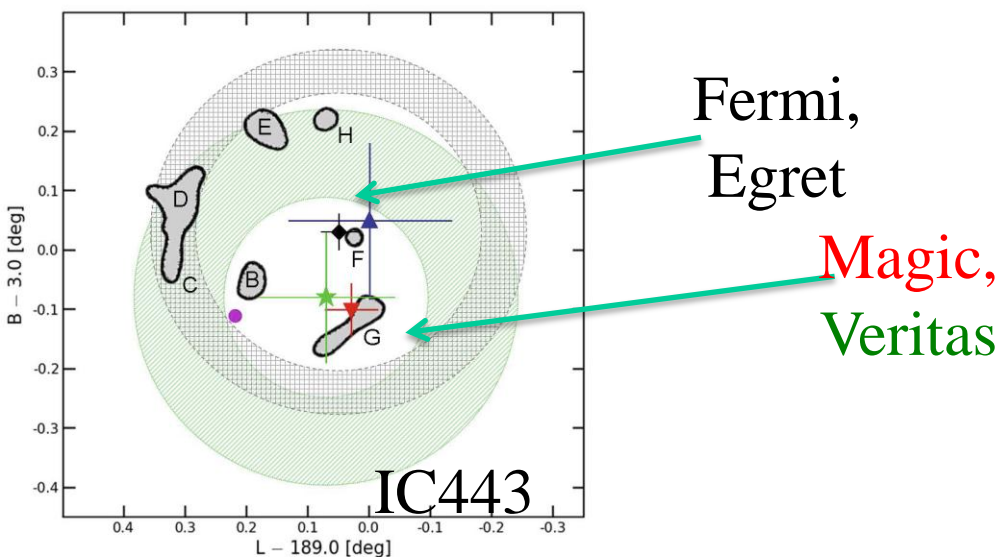
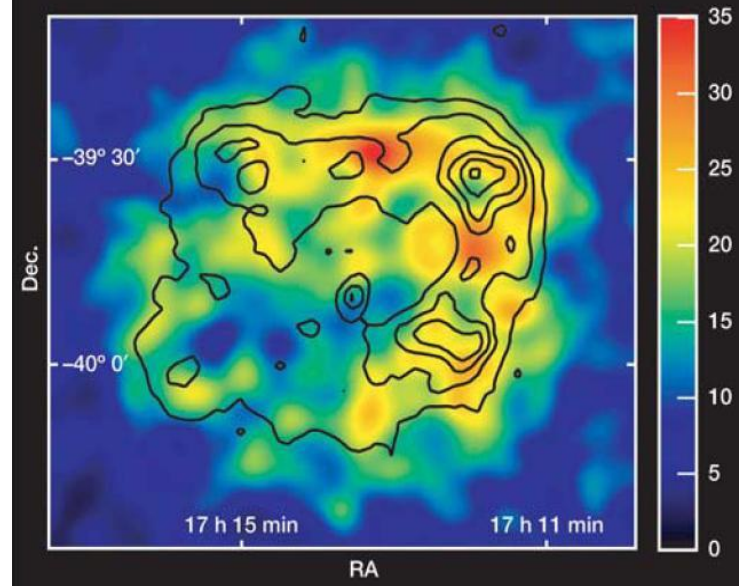
- Galaxy is a leaky box
 - Energy-dependent escape of CR from the Galaxy
 - CR source spectra $dN/dE = E^{-2.1 \text{ to } -2.4}$, consistent w/ Fermi acceleration mechanism, (*) matches $E^{-2.7}$ CR spectrum measured at Earth
- Supernova Remnants accelerate cosmic rays
 - Acceleration of CR in shock produced with external medium that lasts ~ 1000 years
 - SN rate of 1/30 years means ~ 30 SNR are needed to maintain cosmic ray flux
 - Confirmed by gamma-rays up to 50 TeV observed by HESS
- Model explains most observations, and is consistent with many details

(*) [^](#) E. Fermi, 1949 On the Origin of the Cosmic Radiation, Phys. Rev. vol. 75, p. 1169

Sources of CR up to the knee

Gamma & X spectra

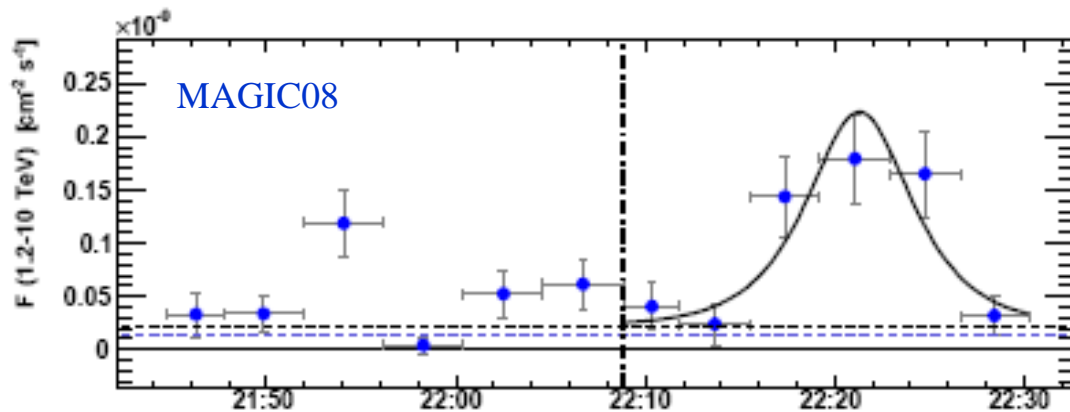
- Evidence that SNR are sources of CR up to ~ 1000 TeV came from morphology studies of RX J1713-3946 (H.E.S.S. 2004)
- Striking evidence from the morphology of IC443 (MAGIC + Fermi/Agile 2010)



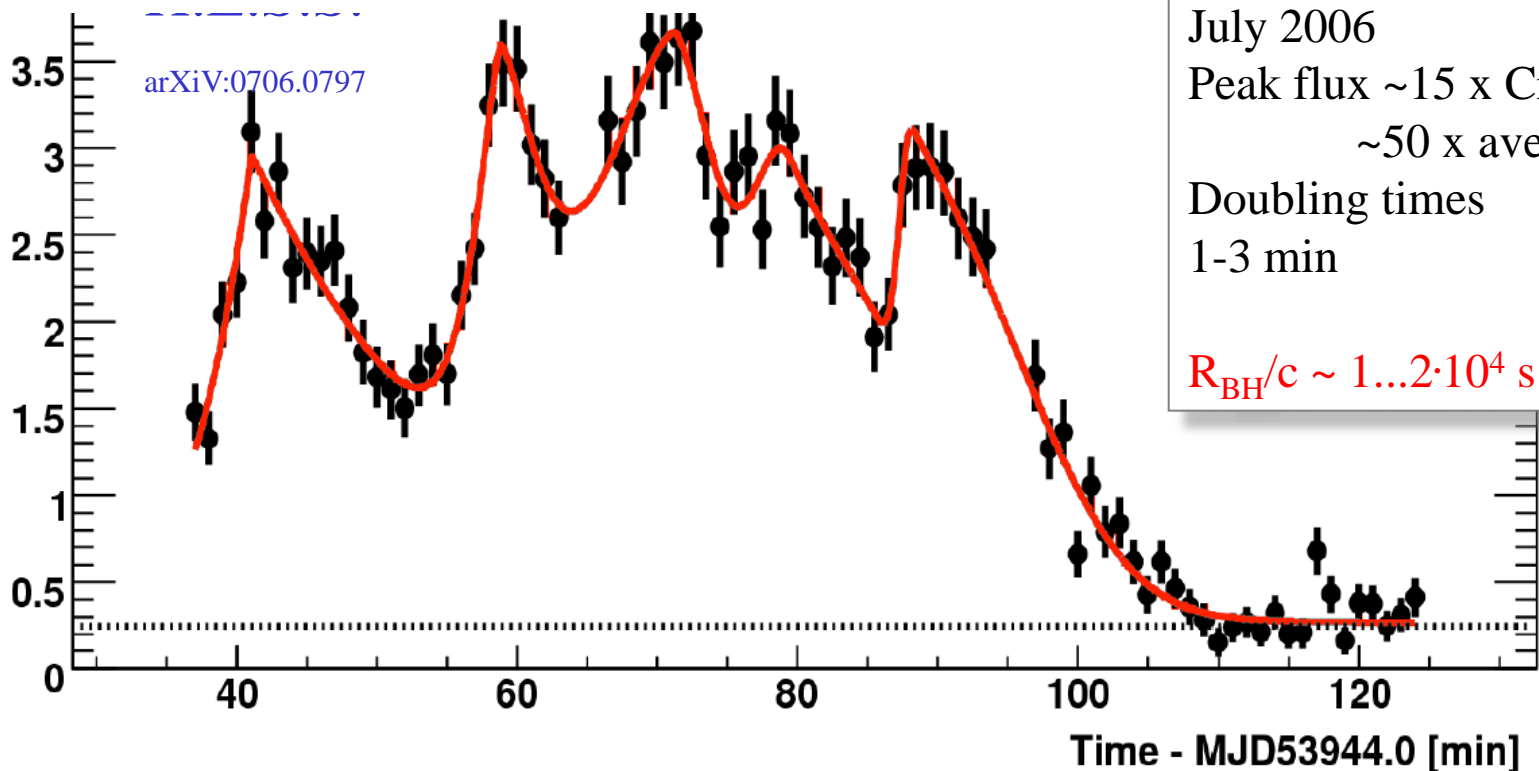
**HINTS OF
NEW
PHYSICS?**



Rapid variability



MAGIC, Mkn 501
Doubling time ~ 2 min



HESS PKS 2155

$z = 0.116$

July 2006

Peak flux $\sim 15 \times$ Crab

$\sim 50 \times$ average

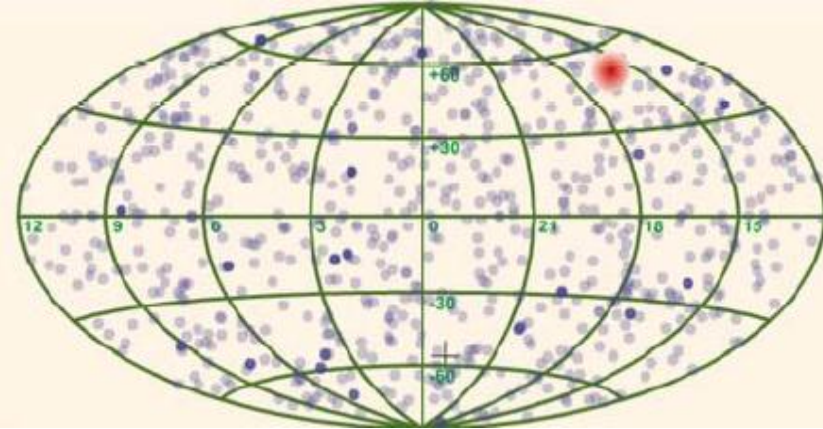
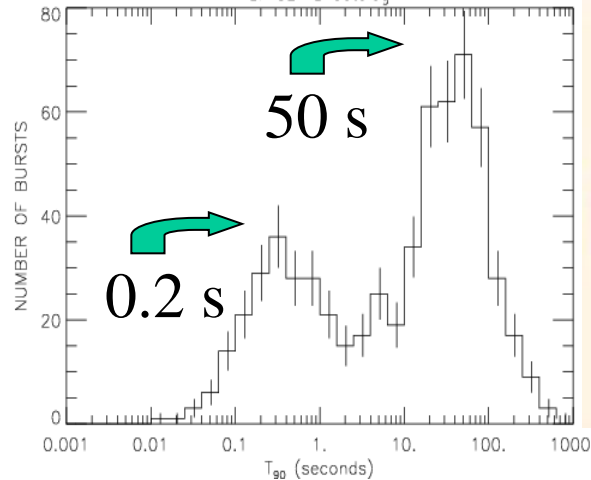
Doubling times

1-3 min

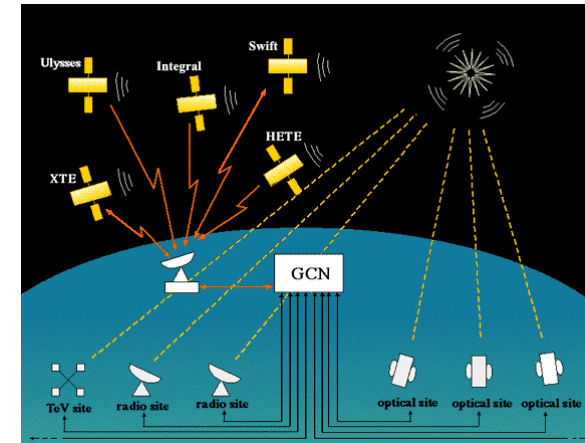
$R_{\text{BH}}/c \sim 1 \dots 2 \cdot 10^4 \text{ s}$

HESS08

GRBs



- Long GRBs (lasting > 2 s) are associated with the explosive deaths of massive stars. The core collapses, and it forms a BH or a n star. The gamma rays are produced by shock waves created from material colliding within the jet.
- Short GRBs may originate from a variety of processes
 - merger of two n stars, or the merger of a BH and a n star
 - collapse of the core of a massive star into a black hole
- Many crucial questions remain unanswered
 - What types of stars die as GRBs?
 - What is the composition of the jets?
 - How are the gamma rays in the initial burst produced?
 - What is the total energy budget of a GRB? How wide are the jet opening angles?



Violation of the Lorentz Invariance?

Light dispersion expected in some QG models, but interesting “per-se”

$$V = c [1 + \xi (E/E_{s1}) - \xi_2 (E/E_{s2})^2 + \dots]$$

1st order

$$(\Delta t)_{\text{obs}} = \frac{\Delta E}{E_{s1}} H_0^{-1} \int_0^z \frac{(1+z) dz}{\sqrt{\Omega_\Lambda + \Omega_m(1+z)^3}}$$

MAGIC Mkn 501, PLB08

$$E_{s1} \sim 0.03 M_p$$

$$E_{s1} > 0.02 M_p$$

HESS PKS 2155, PRL08

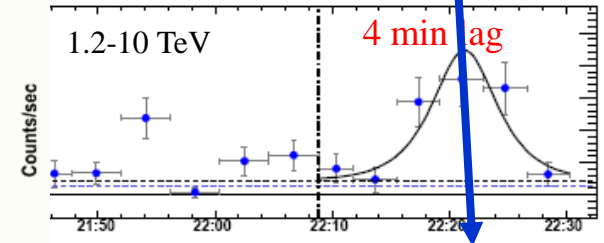
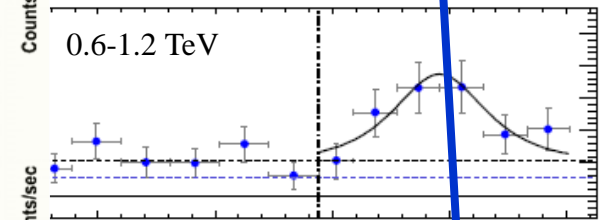
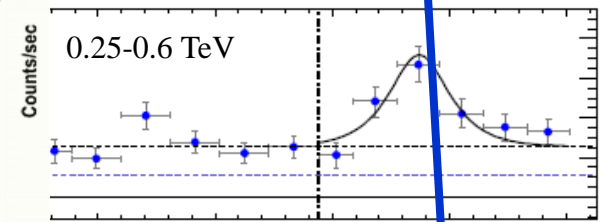
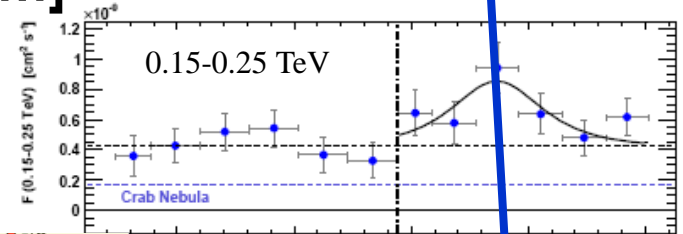
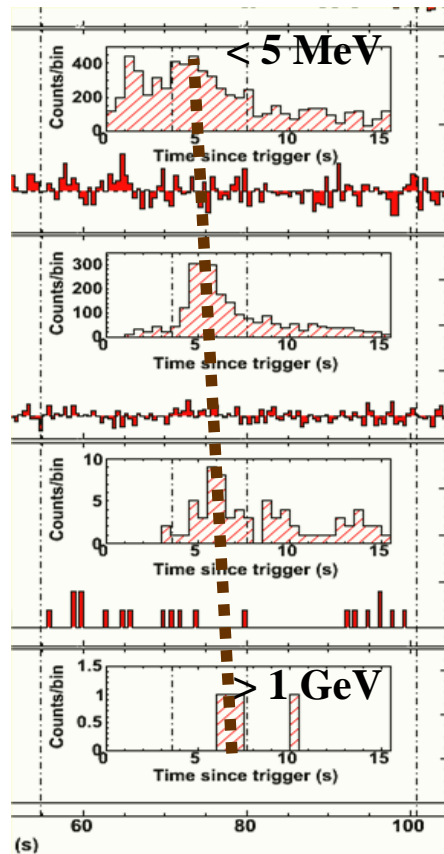
$$E_{s1} > 0.06 M_p$$

anyway in most scenarios

$$\Delta t \sim (E/E_{s\alpha})^\alpha, \alpha > 1$$

▶ VHE gamma rays are the probe

▶ Mrk 501: $E_{s2} > 3 \cdot 10^{-9} M_p$, $\alpha=2$



LIV in Fermi vs. MAGIC+HESS

- GRB080916C at $z \sim 4.2$: 13.2 GeV photon detected by Fermi 16.5 s after GBM trigger.

At 1st order

$$(\Delta t)_{\text{obs}} = \frac{\Delta E}{E_{s1}} H_0^{-1} \int_0^z \frac{(1+z) dz}{\sqrt{\Omega_\Lambda + \Omega_m (1+z)^3}} \sim z$$

- The MAGIC result for Mkn501 at $z = 0.034$ is $\Delta t = (0.030 \pm 0.012)$ s/GeV; for HESS at $z \sim 0.116$, according to Ellis et al., Feb 09, $\Delta t = (0.030 \pm 0.027)$ s/GeV
- $\Delta t \sim (0.43 \pm 0.19)$ K(z) s/GeV

Extrapolating, you get from Fermi (26 ± 11) s (J. Ellis et al., Feb 2009)

SURPRISINGLY CONSISTENT:

DIFFERENT SOURCE TYPE

DIFFERENT ENERGY RANGE

DIFFERENT DISTANCE

Fermi: GRB 090510

Nature 2009

- $z = 0.903 \pm 0.003$
- prompt spectrum detected, significant deviation from Band function at high E
- High energy photon detected:
31 GeV at $T_0 + 0.83$ s
[expected from Ellis & al. (12 ± 5) s]
- tight constraint on Lorentz Invariance Violation:
 - $M_{QG} \gtrsim x M_{\text{Planck}}$ [$x = O(1)$]

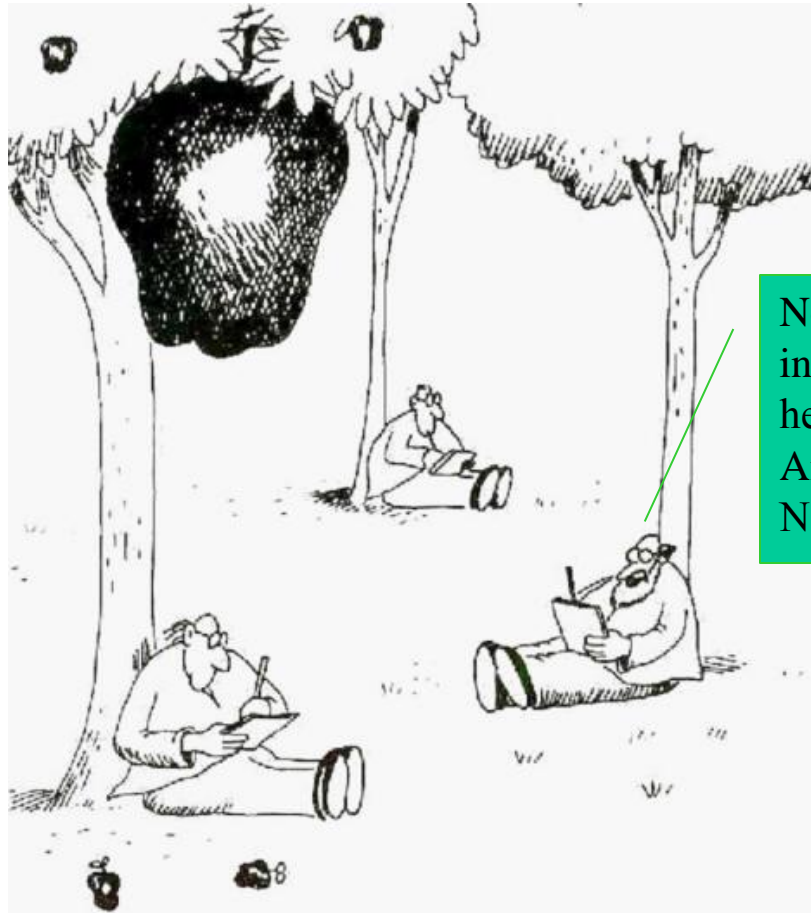
GRB 090902

Nature 2009

- $z = 1.8 \pm 0.4$
- one of the brightest GRBs observed by LAT
- after prompt phase, power-law emission persists in the LAT data as late as 1 ks post trigger:
highest E photon so far detected: 33.4 GeV, 82 s after GBM trigger
[expected from Ellis & al. (26 ± 13) s]
- much weaker constraints on LIV E_s (EBL constraints)

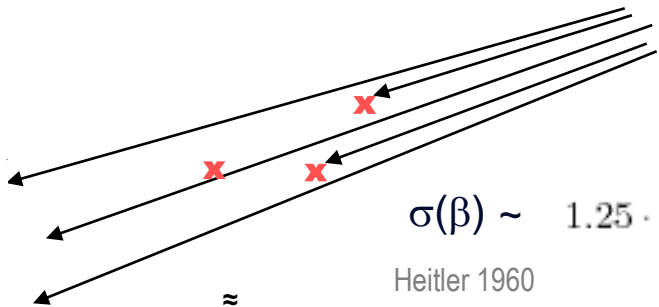
Interpretation of the results on rapid variability

- The most likely interpretation is that the delay is due to physics at the source
 - By the way, a puzzle for astrophysicists
- However
 - We are sensitive to effects at the Planck mass scale
 - More observations of flares will clarify the situation



Nothing interesting here... Any new stuff, Newt'?

Propagation of γ -rays



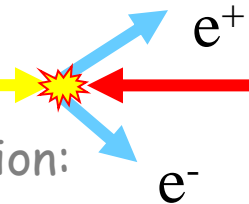
$$\sigma(\beta) \sim 1.25 \cdot 10^{-25} (1 - \beta^2) \cdot \left[2\beta(\beta^2 - 2) + (3 - \beta^4) \ln \left(\frac{1 + \beta}{1 - \beta} \right) \right] \text{cm}^2$$

Heitler 1960

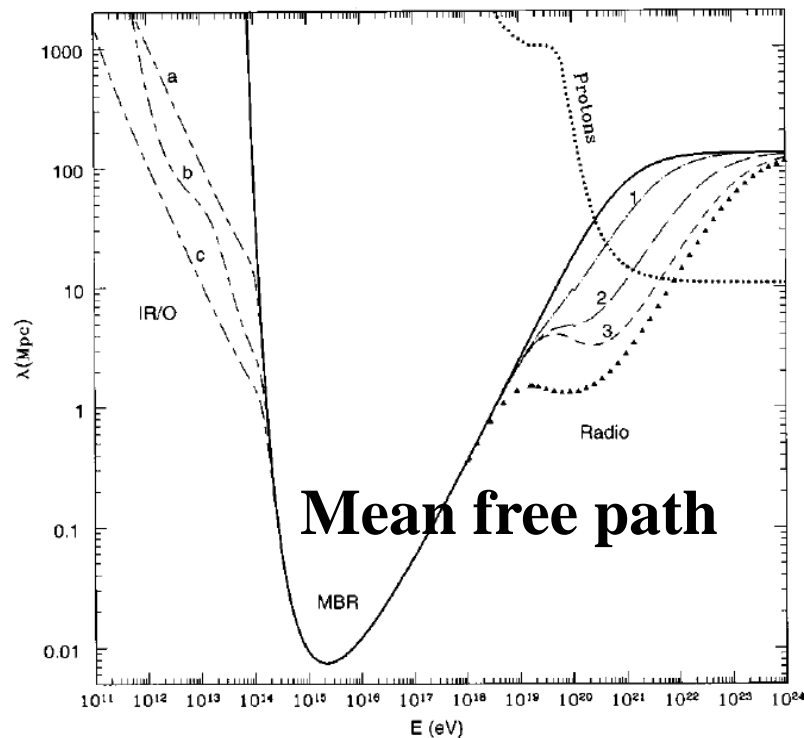
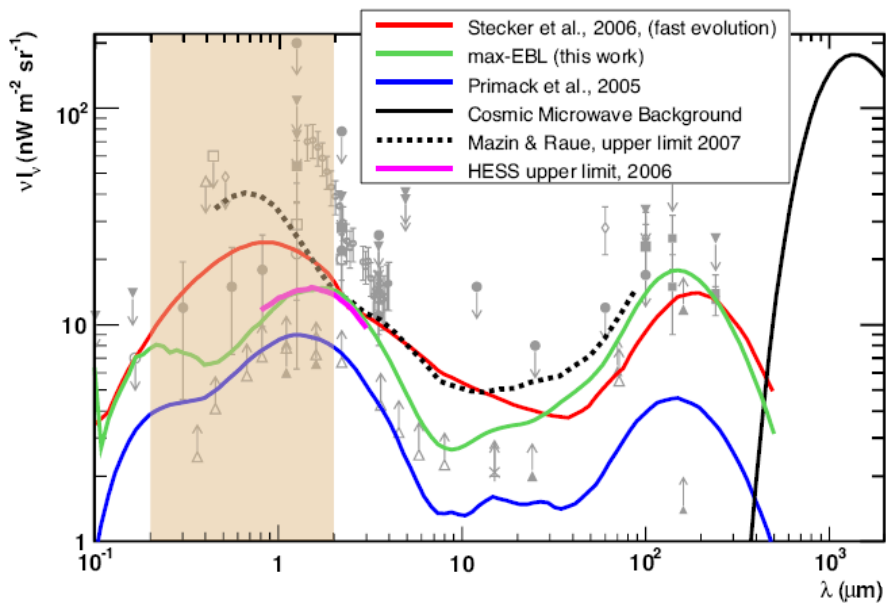
maximal for:

$$\epsilon \simeq \frac{2m_e^2 c^4}{E} \simeq \left(\frac{500 \text{ GeV}}{E} \right) \text{eV}$$

dominant process for absorption:



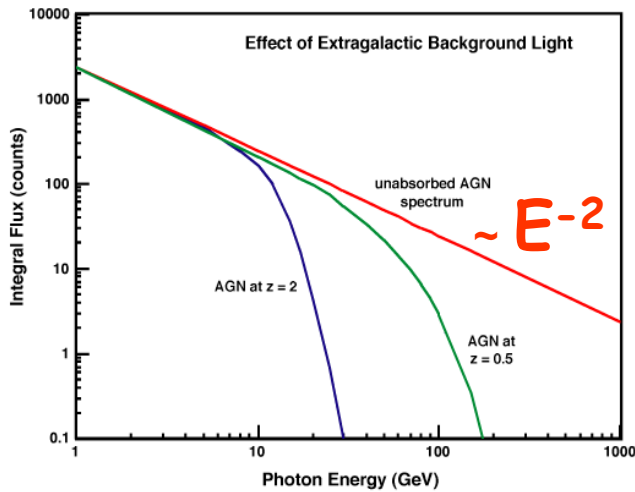
- For γ -rays, relevant background component is **optical/infrared** (EBL)
- different models for EBL: minimum density given by cosmology/star formation



Are our AGN observations consistent with theory?

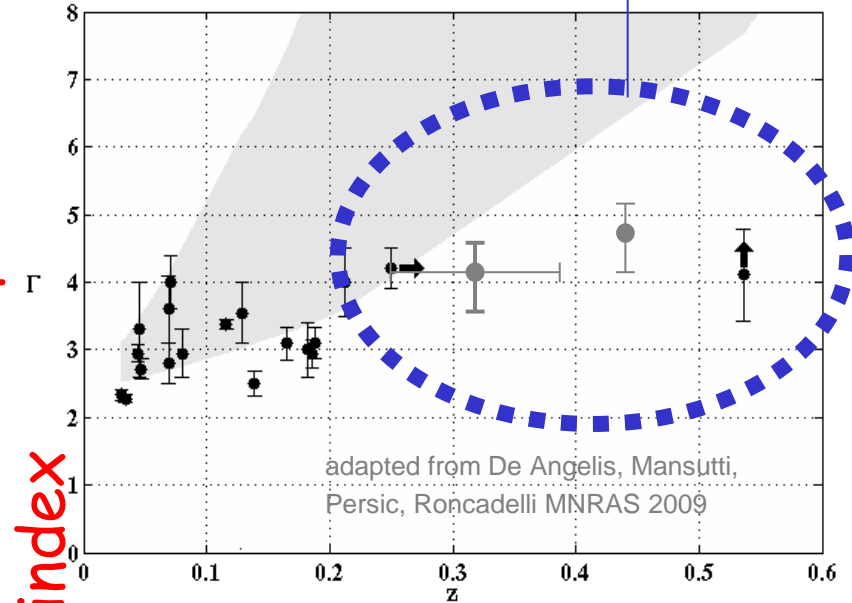
Selection bias?
New physics?

Measured spectra affected by attenuation in the EBL:

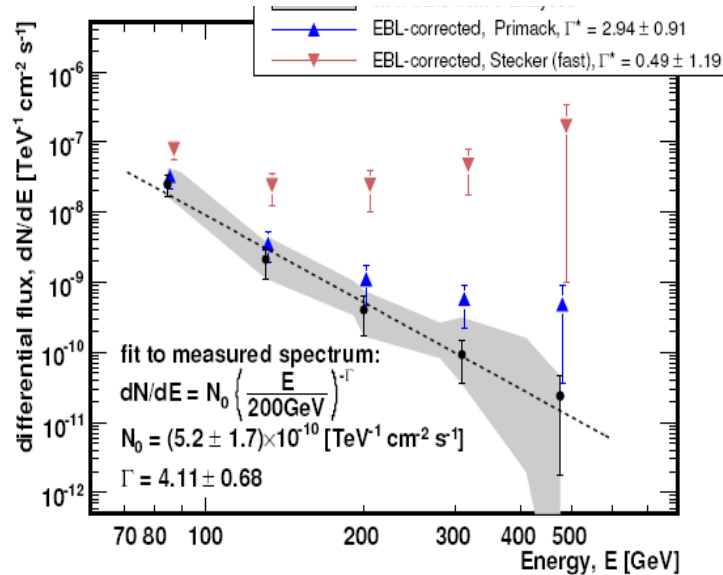


The most distant:
MAGIC 3C 279 ($z=0.54$)

observed spectral index

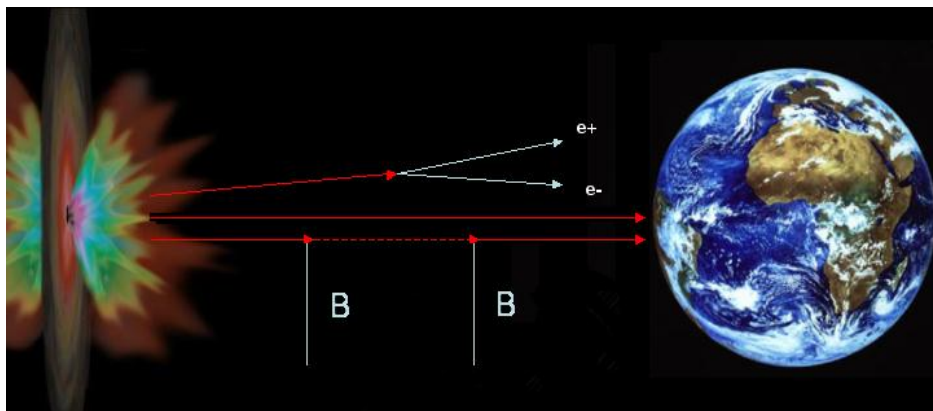
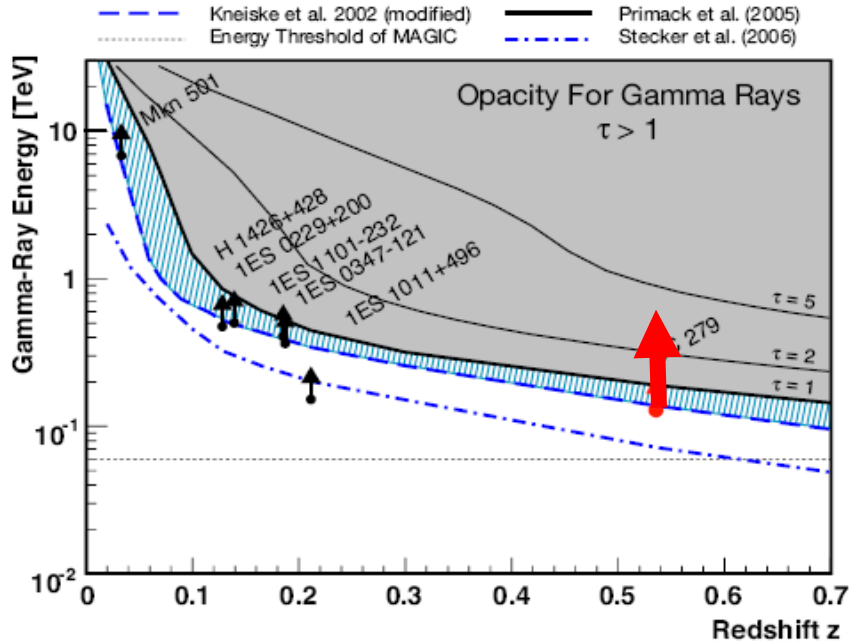
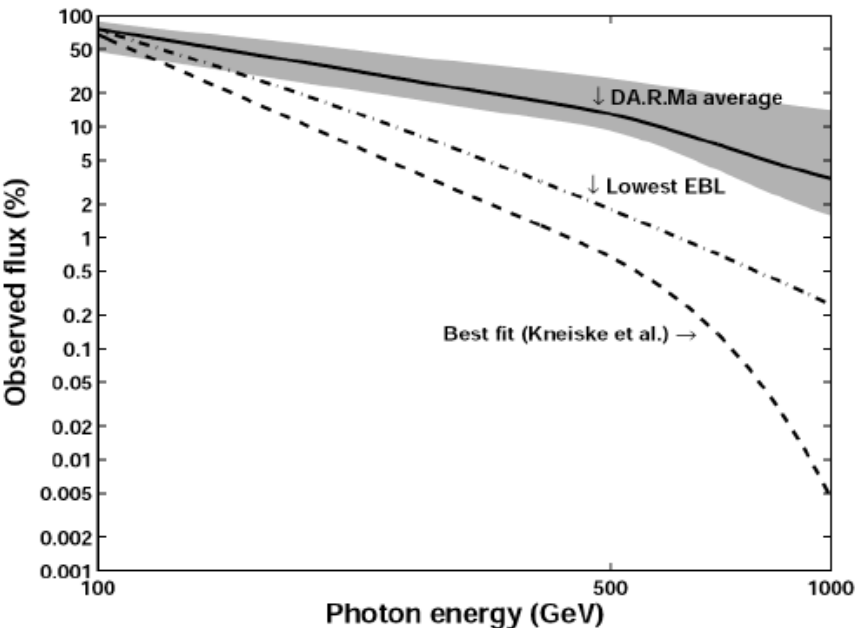


redshift



Could it be seen?

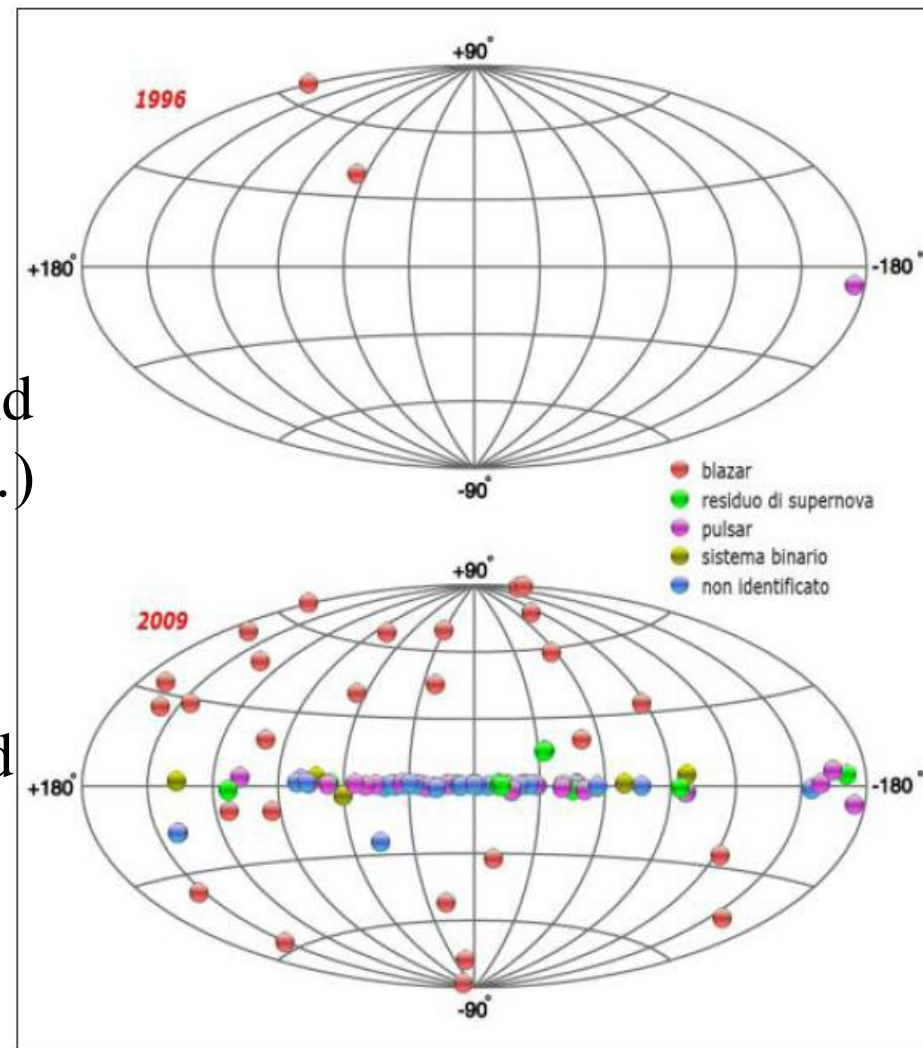
- Explanations go from the standard ones
 - very hard emission mechanisms with intrinsic slope < 1.5 (Stecker 2008)
 - Very low EBL
- to possible evidence for new physics
 - Oscillation to a light “axion”? (DA, Roncadelli & Mansutti [DARMA], PLB2008, PRD2008)
 - » Axion emission (Hooper et al., PRD2008)



What next?

- Fermi has been a great success (and now years to analyze & improve...)

- Cherenkov telescopes have opened the new VHE window



- No hope to build a 10x better satellite soon, while it is ~easy to build a 10x better Cherenkov: a huge Cherenkov Telescope Array (CTA)

A first (minimal) design: Core Array



Low-energy section

mCrab sensitivity in the
100 GeV–10 TeV
domain



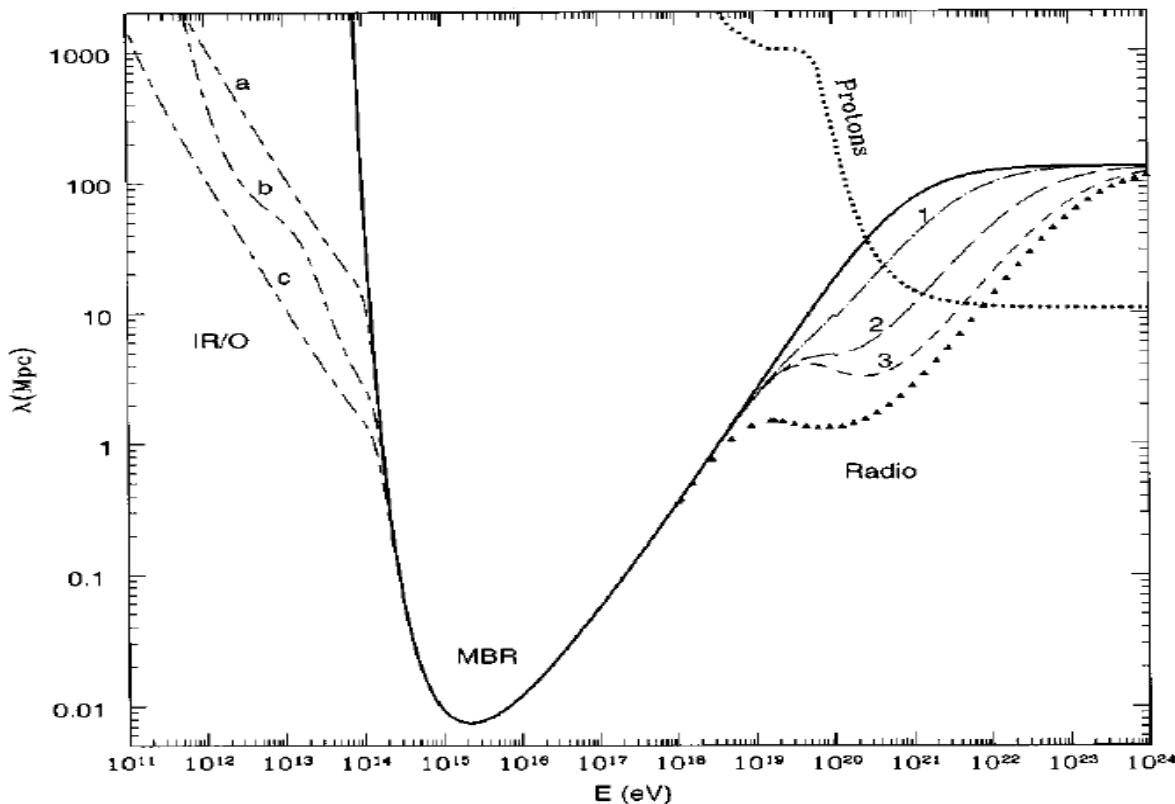
O(12-14m) telescopes
energy threshold
of some 10 GeV
(a) bigger dishes
(b) dense-pack and/or
(c) high-QE sensors

Very very high-energy
section: 10 km² area at
multi-TeV energies

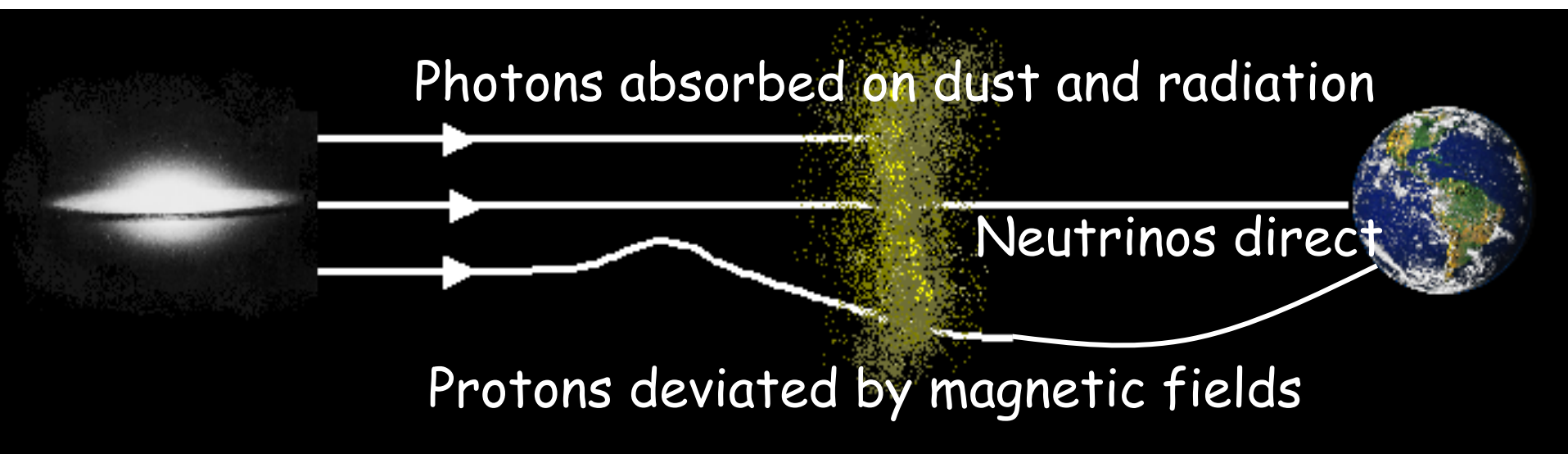
CTA



Not to scale !



In the 100 TeV -
100 PeV region...



Neutrino Telescope Projects

ANTARES La-Seyne-sur-Mer, France
(NEMO Catania, Italy)

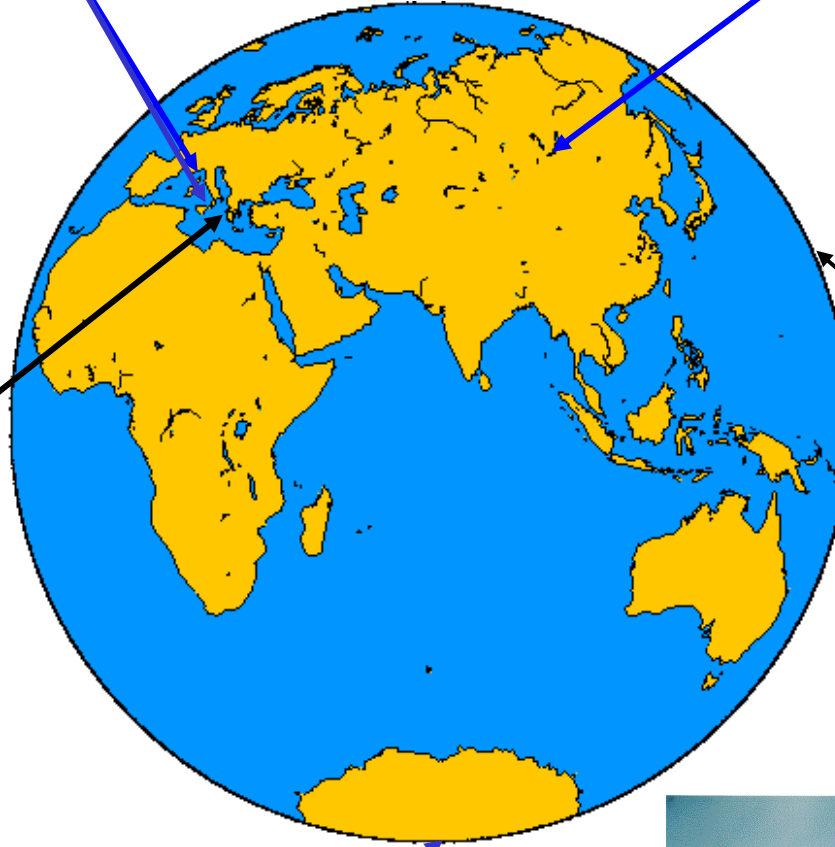
BAIKAL: Lake Baikal, Siberia



NESTOR : Pylos, Greece

DUMAND, Hawaii
(cancelled 1995)

AMANDA, South Pole, Antarctica



AMANDA -> ICECUBE

South Pole: glacial ice

1993 First strings AMANDA A

1998 AMANDA B10 ~ 300 Optical Modules

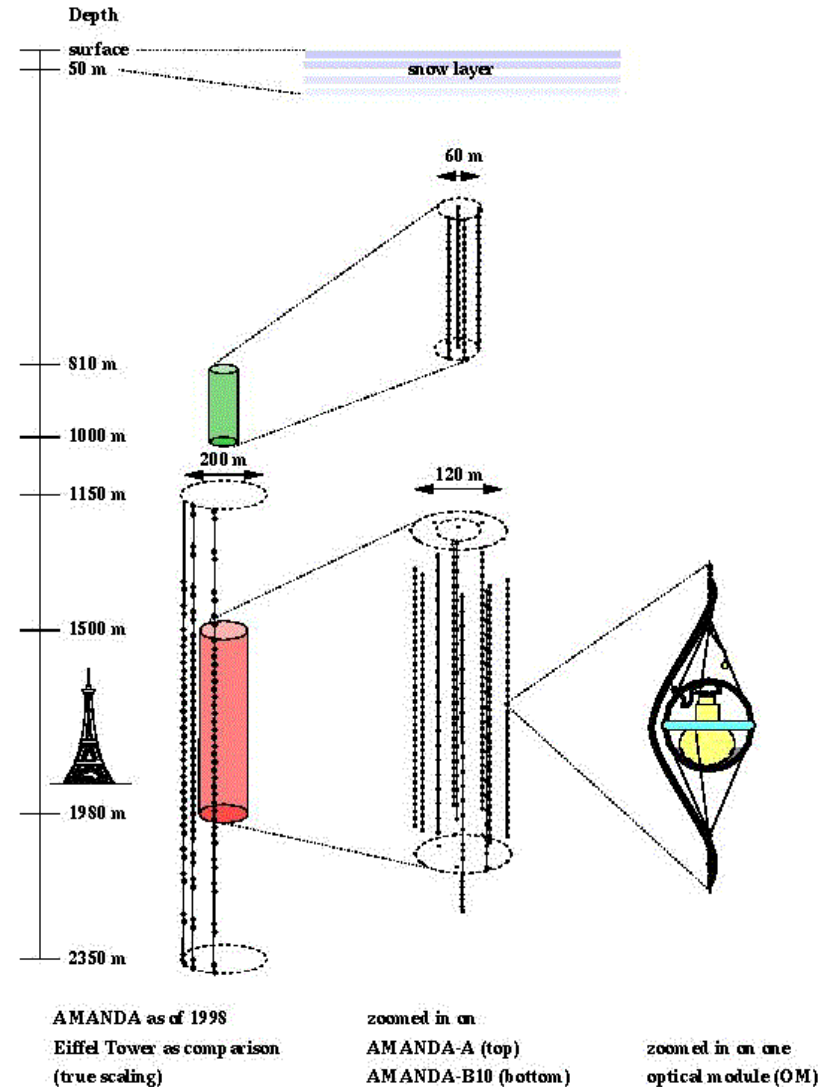
2000 ~ 700 Optical Modules

→ICECUBE 8000 Optical Modules

→Inaugurated in 2011



AMANDA
 $\nu > 50\text{GeV}$

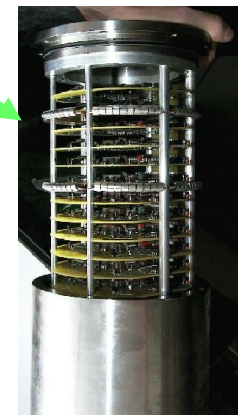
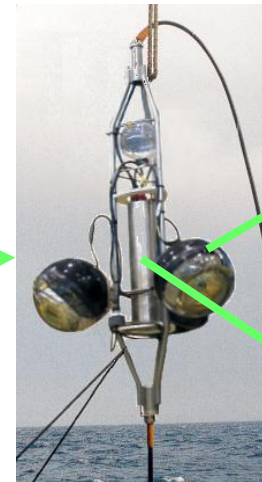
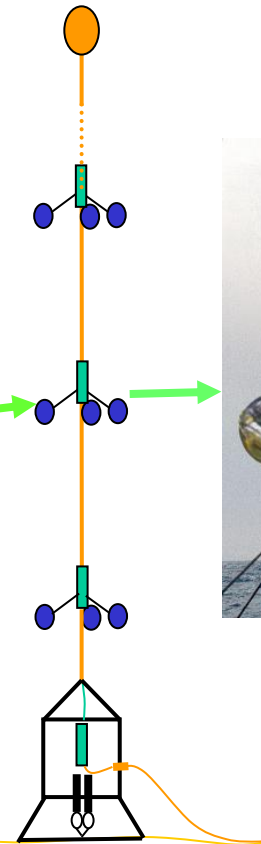
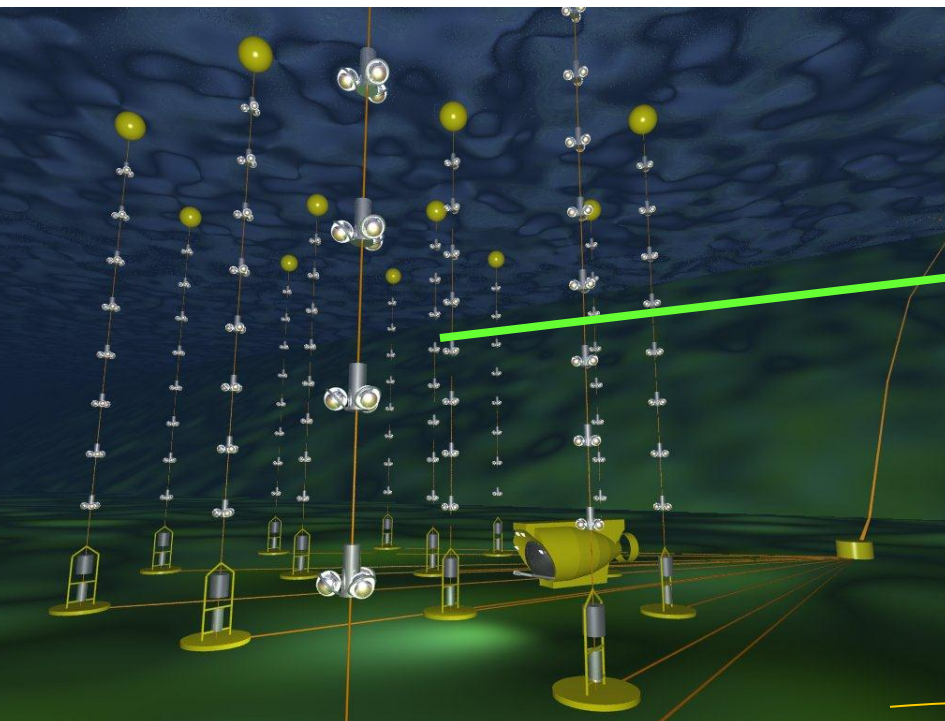


Future in ν telescopes: ANTARES



- 1996 Started
- 1996 - 2000 Site exploration and demonstrator line
- 2001 - 2004 Construction of 10 line detector, area $\sim 0.1 \text{ km}^2$ on Toulon site
- future 1 km^3 in Mediterranean (2 or 3 sites)?

Angular resolution $< 0.4^\circ$ for $E > 10 \text{ TeV}$



To know more...

- Not to ingenerate confusion, just a book
 - It's swedish, and it connects well to Martin & Shaw:
Bengström & Goobar, Cosmology and Particle
Astrophysics, Wiley
 - (If you don't like it, another book: Perkins, Particle
Astrophysics, Oxford)
- But careful: the field is in fast evolution...