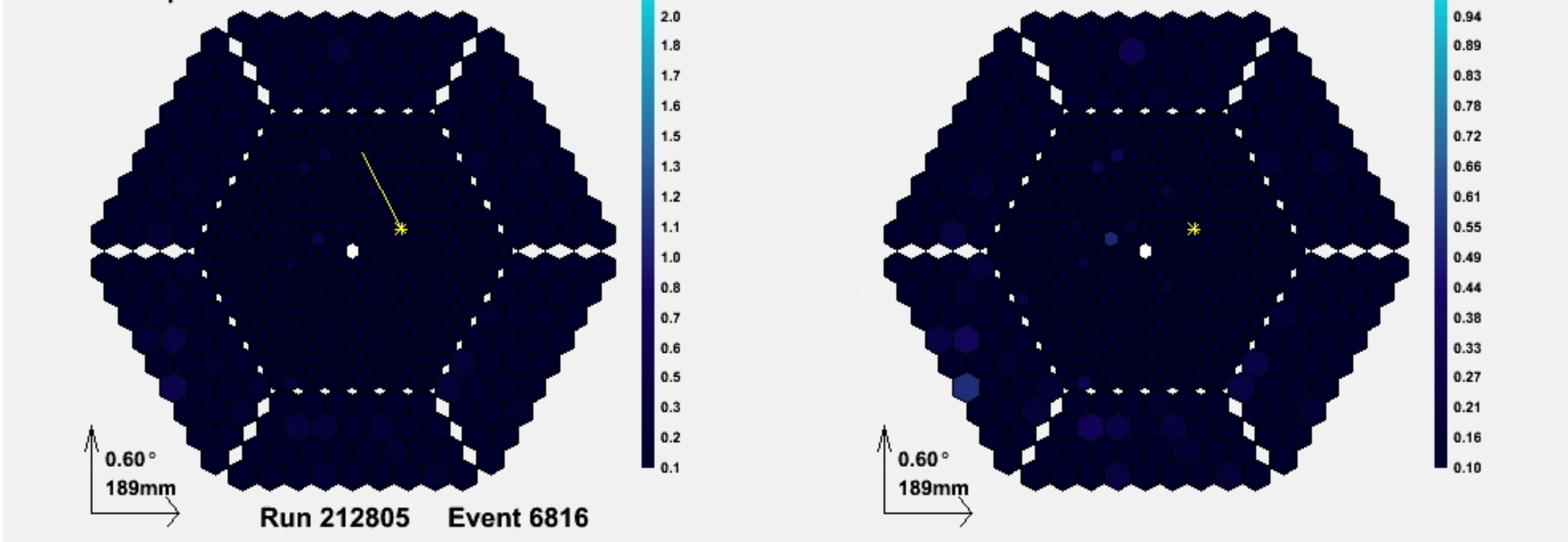
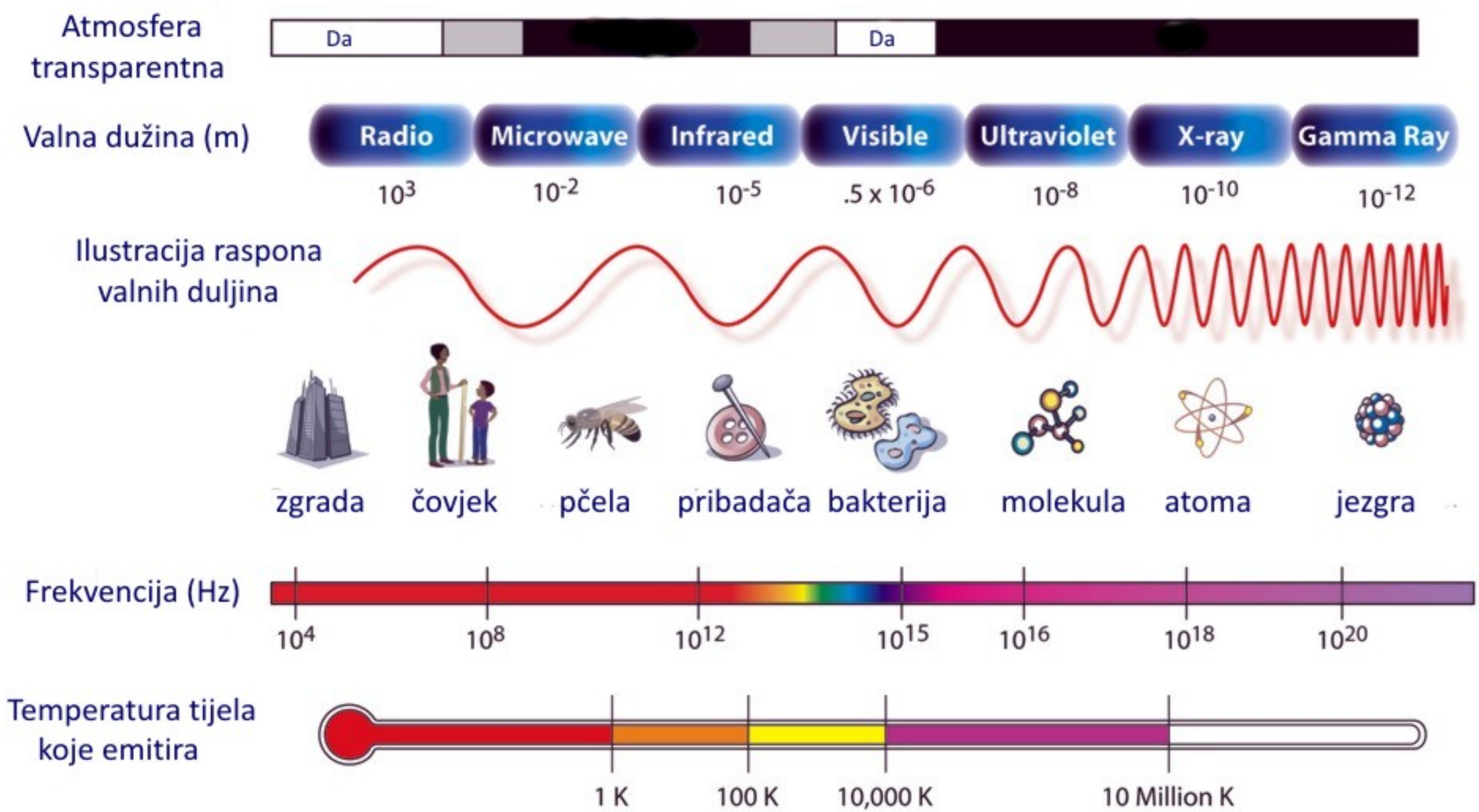


Nikola Godinović
University of Split

Electromagnetic spectrum

- Each part of the electromagnetic spectrum provides information's about process which are going on there in the Universe



Observing the whole electromagnetic spectrum

- Radio (from $\sim$ 10 MHz to $\sim$ 100 GHz) very highest spatial resolution because coherent detection of the EM field allows interferometry.

- Millimetre, sub-millimetre and far-infrared ($\sim$ 0.3 mm to $\sim$ 10 μm). Bolometers onboard satellites and high-altitude terrestrial sites.

- Infrared (10 μm to 1 μm) and optical (1 μm to 0.3 μm). Almost all of "traditional" astronomy. Most stars put out most of their energy in this range. Unsurprisingly the human eye is adapted to use these wavelengths!

- Ultraviolet (0.3 μm to $\sim$ 3 nm). Satellite-borne instruments are needed because the atmosphere is opaque now; but we can still use essentially "ordinary" telescopes.

Observing the wholw electromagnetic spectrum

- X-rays (3 nm to $\sim 3\times10^{-12}$ m; 0.4 keV to $\sim$ 100 keV). Satellite- and rocket-borne instruments are needed. Special grating-incidence mirrors are used to focus X-rays.

- Gamma-rays ($\sim$ 100 keV up to hundreds of GeV). Again telescopes are satellite-borne. Use similar detectors to particle physics experiments.

- Very high-energy photons and particles entering the Earth's atmosphere produce *Cherenkov radiation*. This is detected by very large "light bucket" telescopes which don't need finely-figured mirrors.

What about the rest ?

What could happen if we would see only, say, green color?

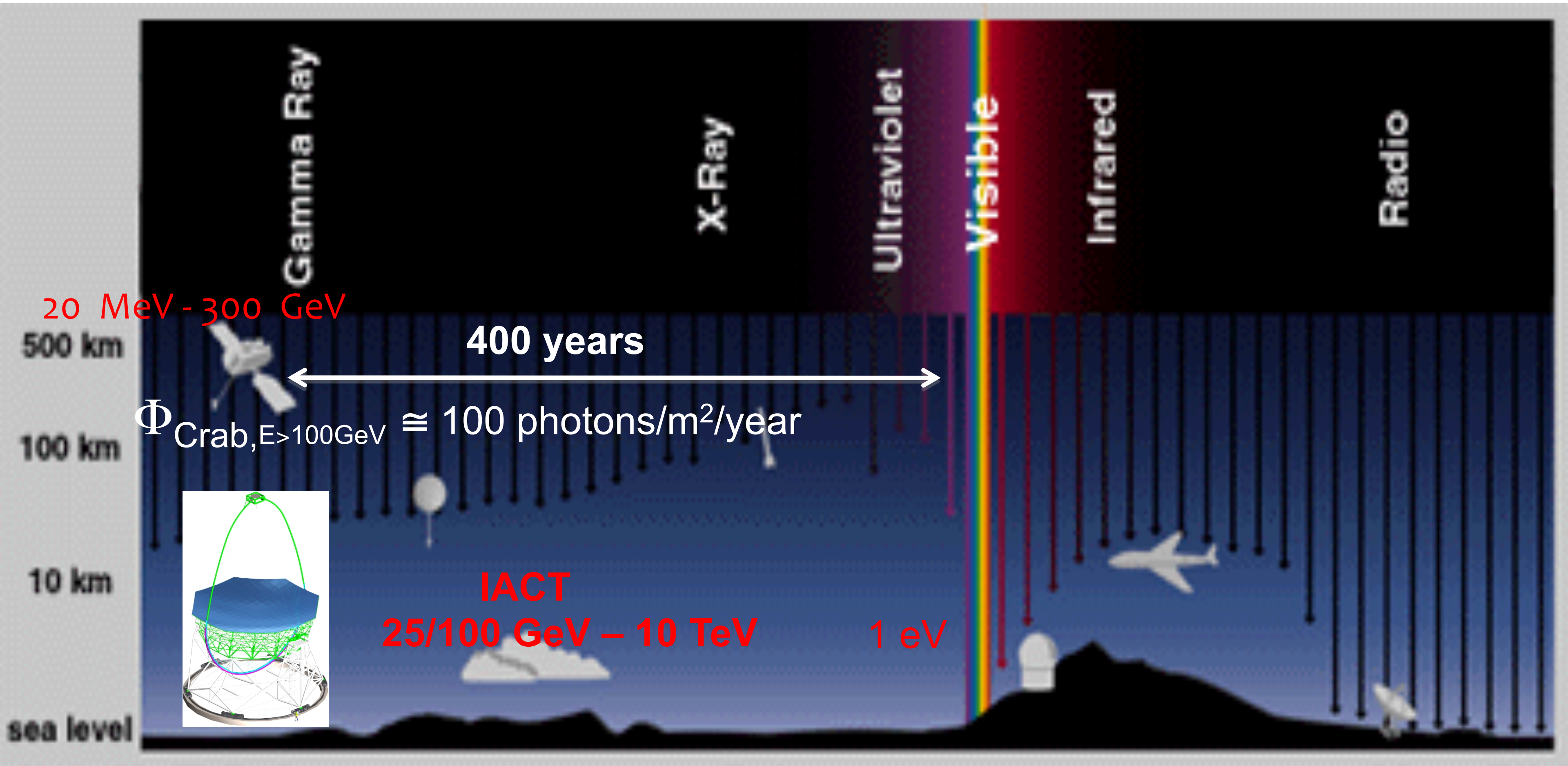
VHE gamma-ray astronomy

American spy satellites detected accidentally 1967 high-energy gamma rays during the search for radiation generated by the explosion of atomic bombs

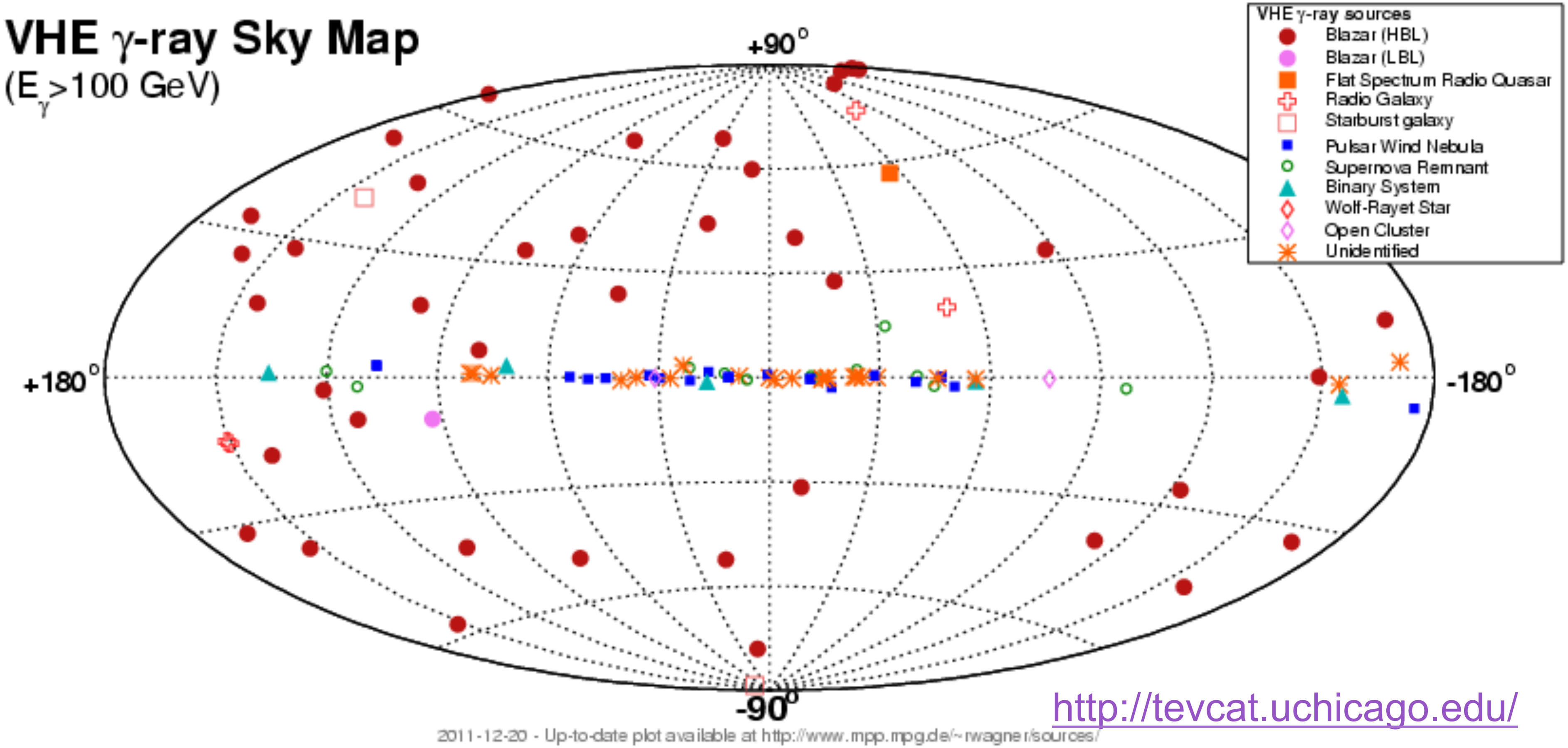
1989 Whipple Collaboration discovered 1th source of VHE gamma-ray

(T. C.Weekes et. al., ApJ 342,(379-395) 1989):

Crab nebula, standard candle E > 1TeV, flux=2 × 10^{-7} m^{-2} s^{-1} ("standard candle")



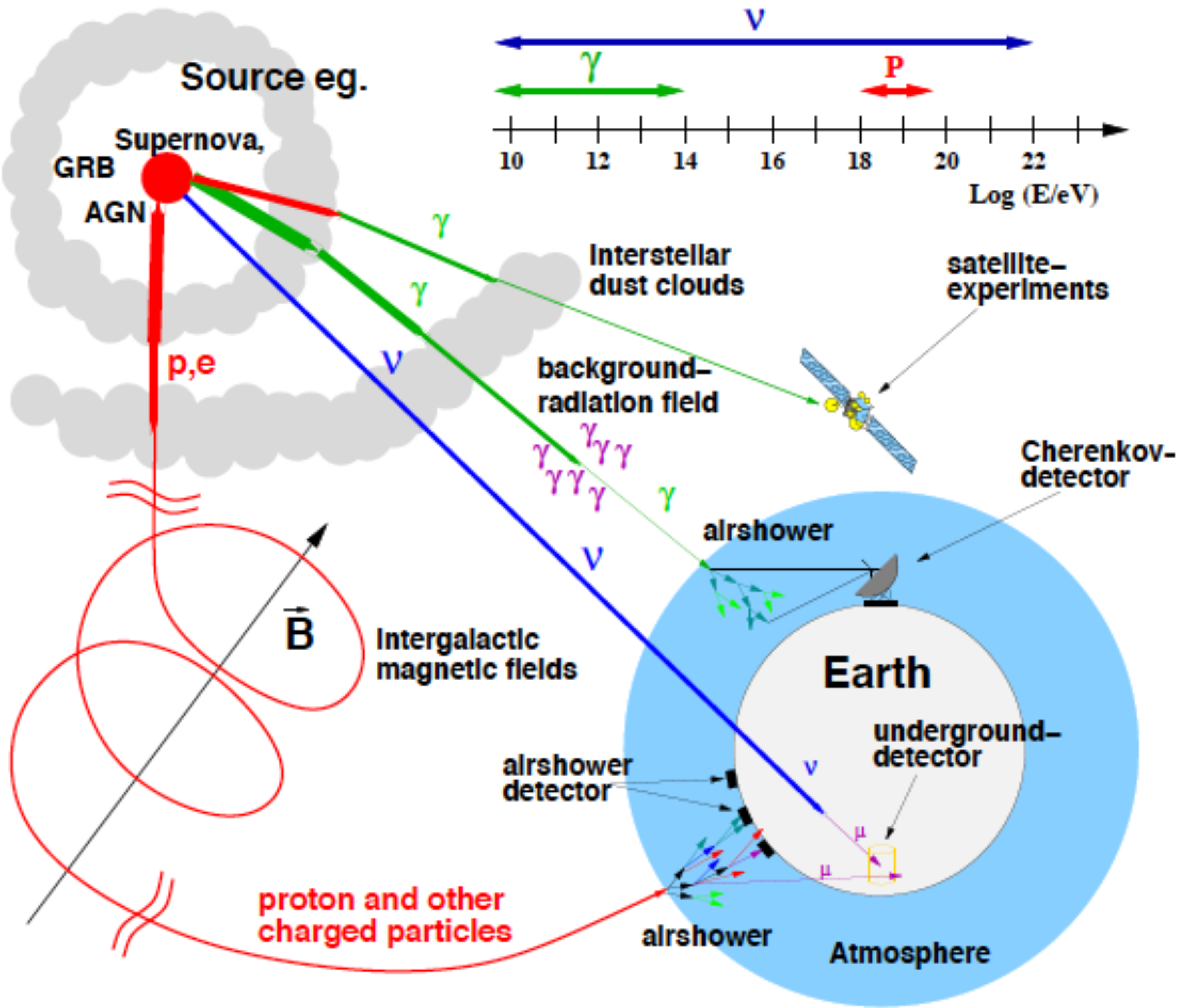
VHE Gamma-ray Sky Map



http://tevcat.uchicago.edu/

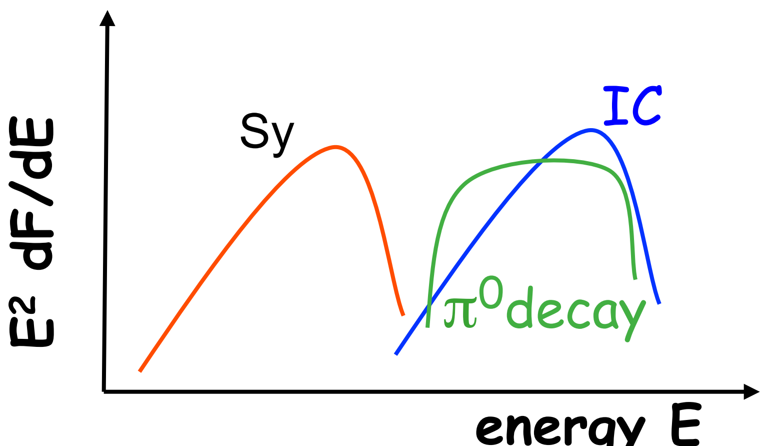
> 150 VHE gamma tay sources

Unidentified sources emits only VHE gamma ?


ν
γ
P
10
12
14
16
18
20
22
Log (E/eV)
Source eg.
Supernova,
GRB
AGN
γ
γ
Interstellar
dust clouds
satellite-
experiments
p,e
ν
background-
radiation field
Cherenkov-
detector
γ
airshower
ν
B
Intergalactic
magnetic fields
Earth
underground-
detector
ν
airshower
detector
μ
μ
proton and other
charged particles
airshower
Atmosphere

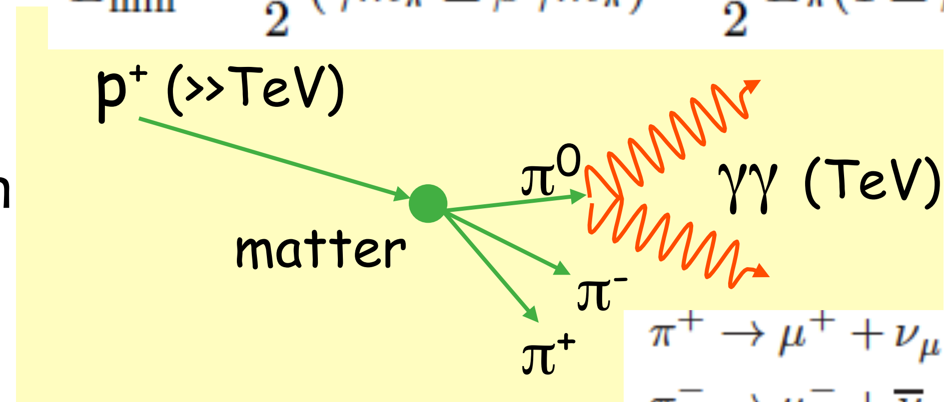
Generation of VHE gamma ray

- Hadronic model of emission
- Leptonic model of emission
  - Disentangle hadronic from leptonic gamma ray origin
    => shape of spectrum



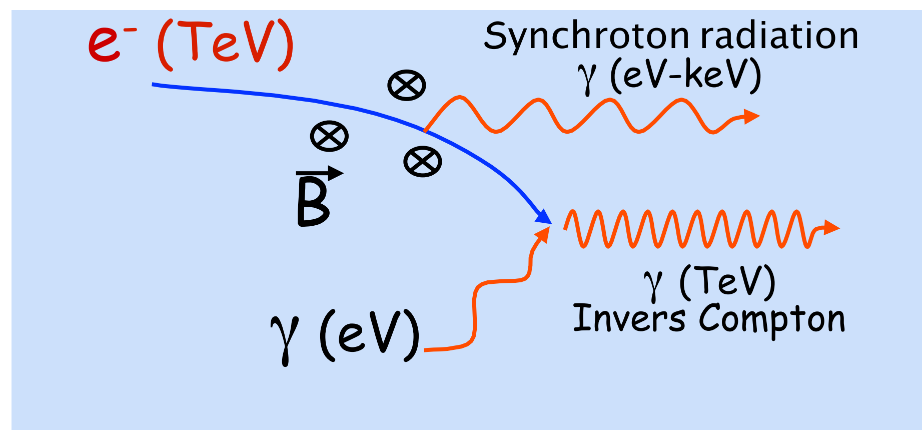
Hadronic model of γ emission

$$E^{\max}_{\min} = \frac{1}{2}(\gamma m_\pi \pm \beta\gamma m_\pi) = \frac{1}{2}E_\pi(1 \pm \beta)$$

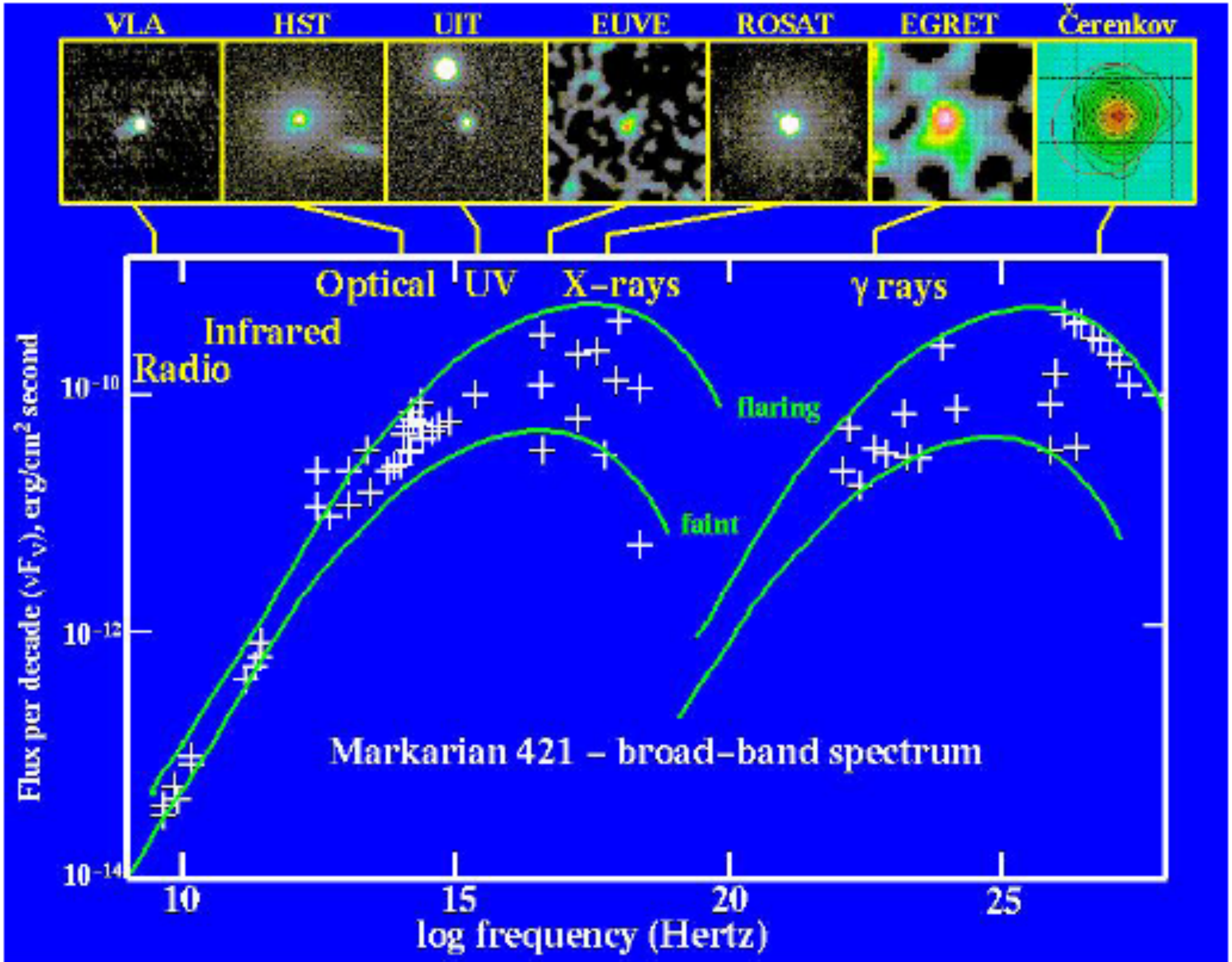


$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\pi^- \to \mu^- + \overline{\nu}_\mu$$

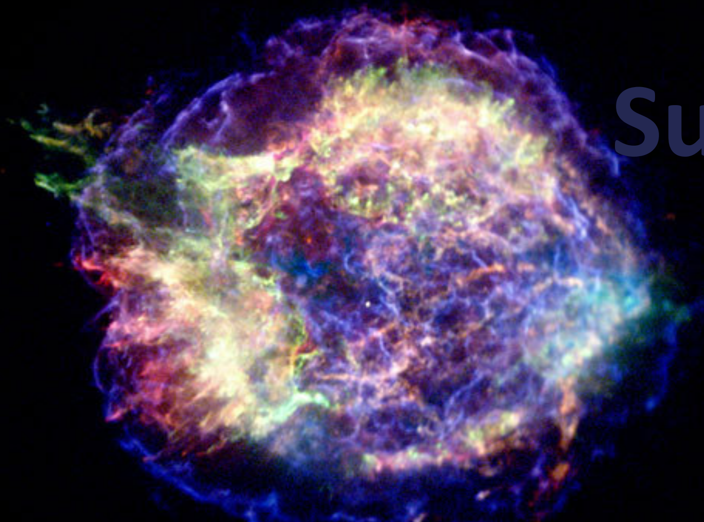
Leptonic model γ emission

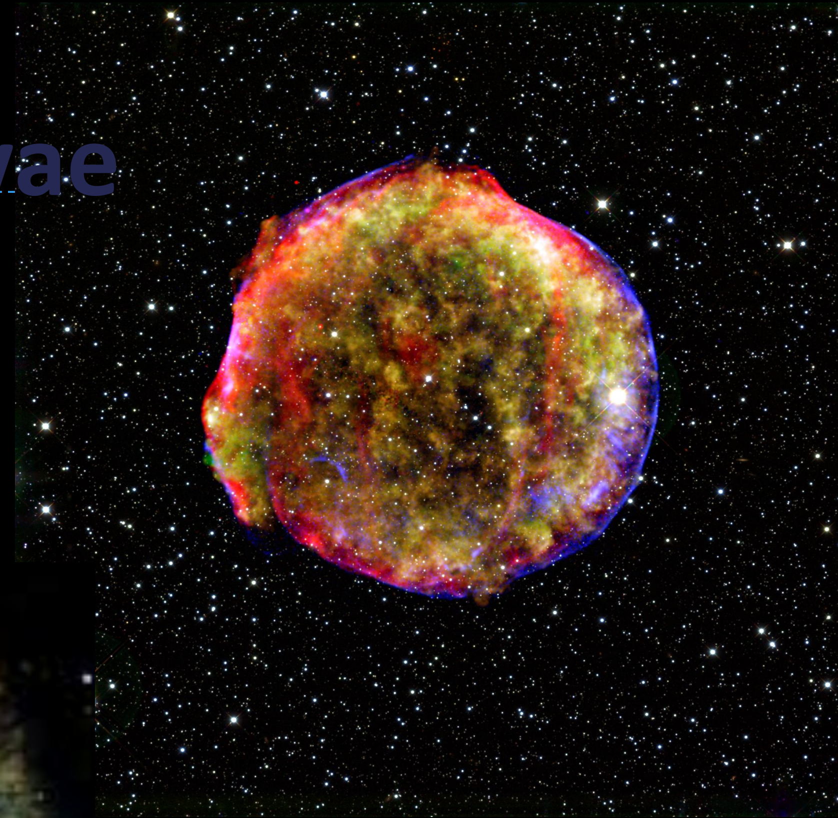


Active galactic nucleai – broad band spectra

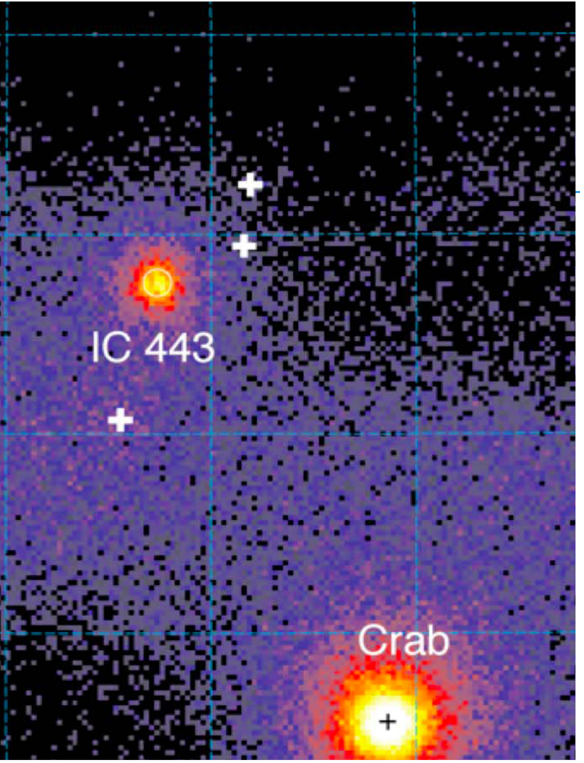


Super-novae





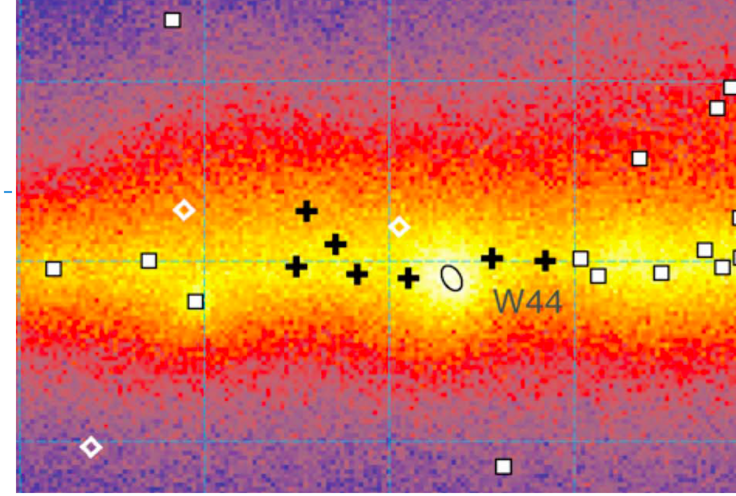
Cosmic Rays from Super-novae
Baade & Zwicky (1934)

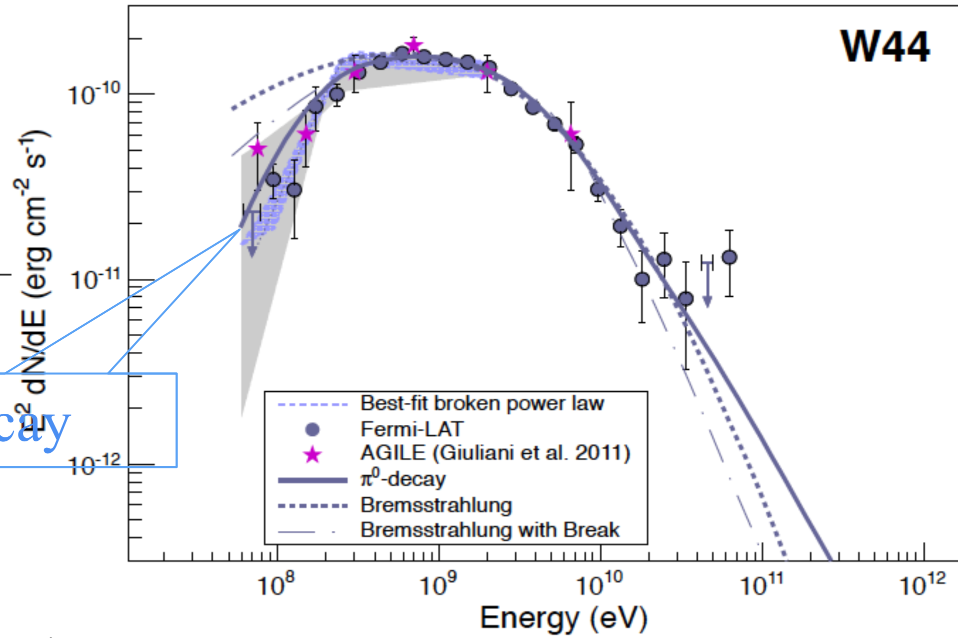


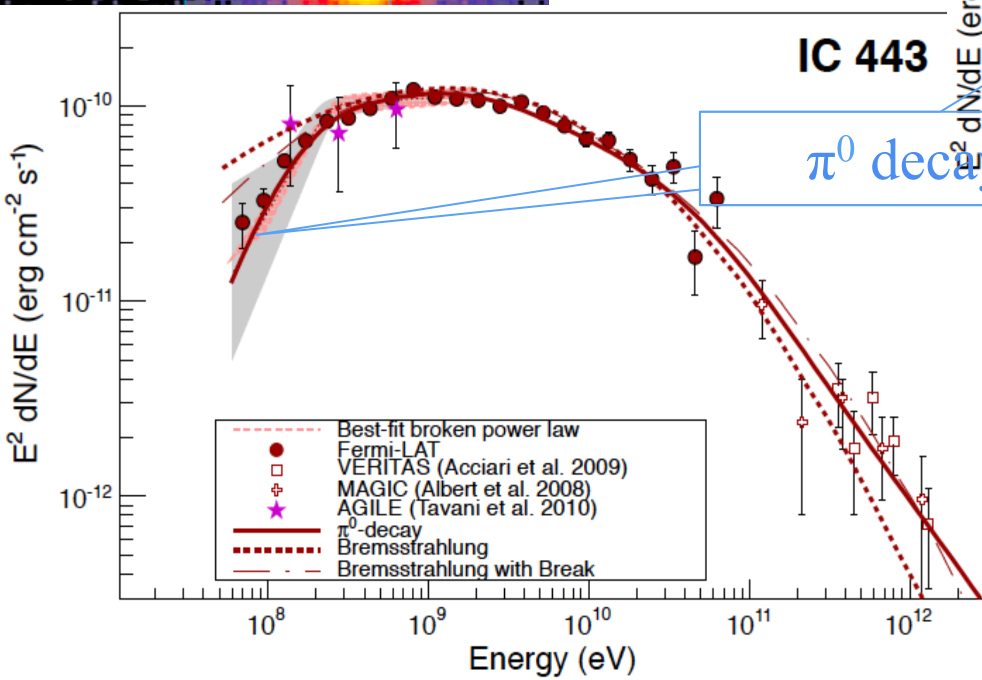
π^0 decay!

IC 443 & W44

Fermi & AGILE



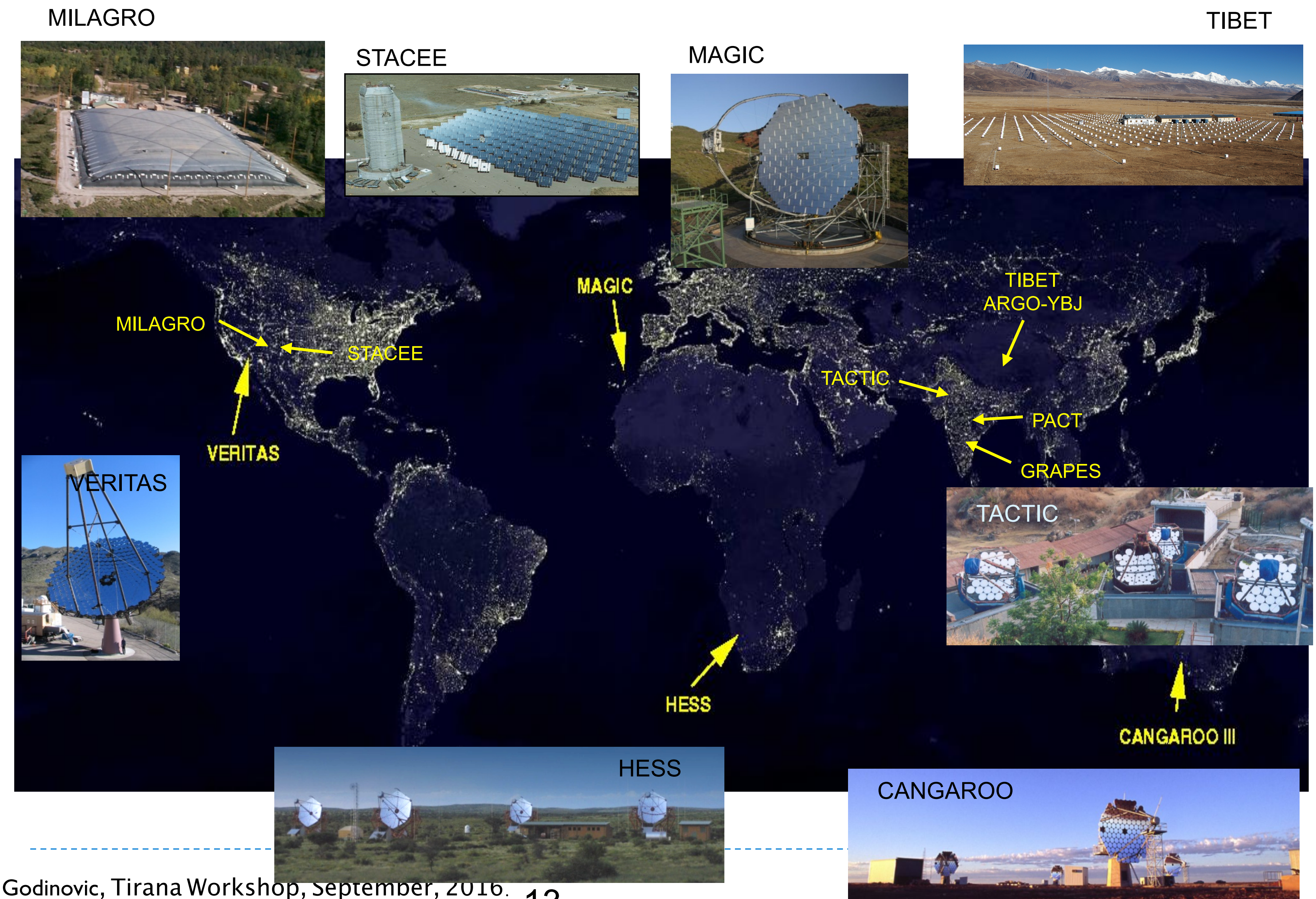




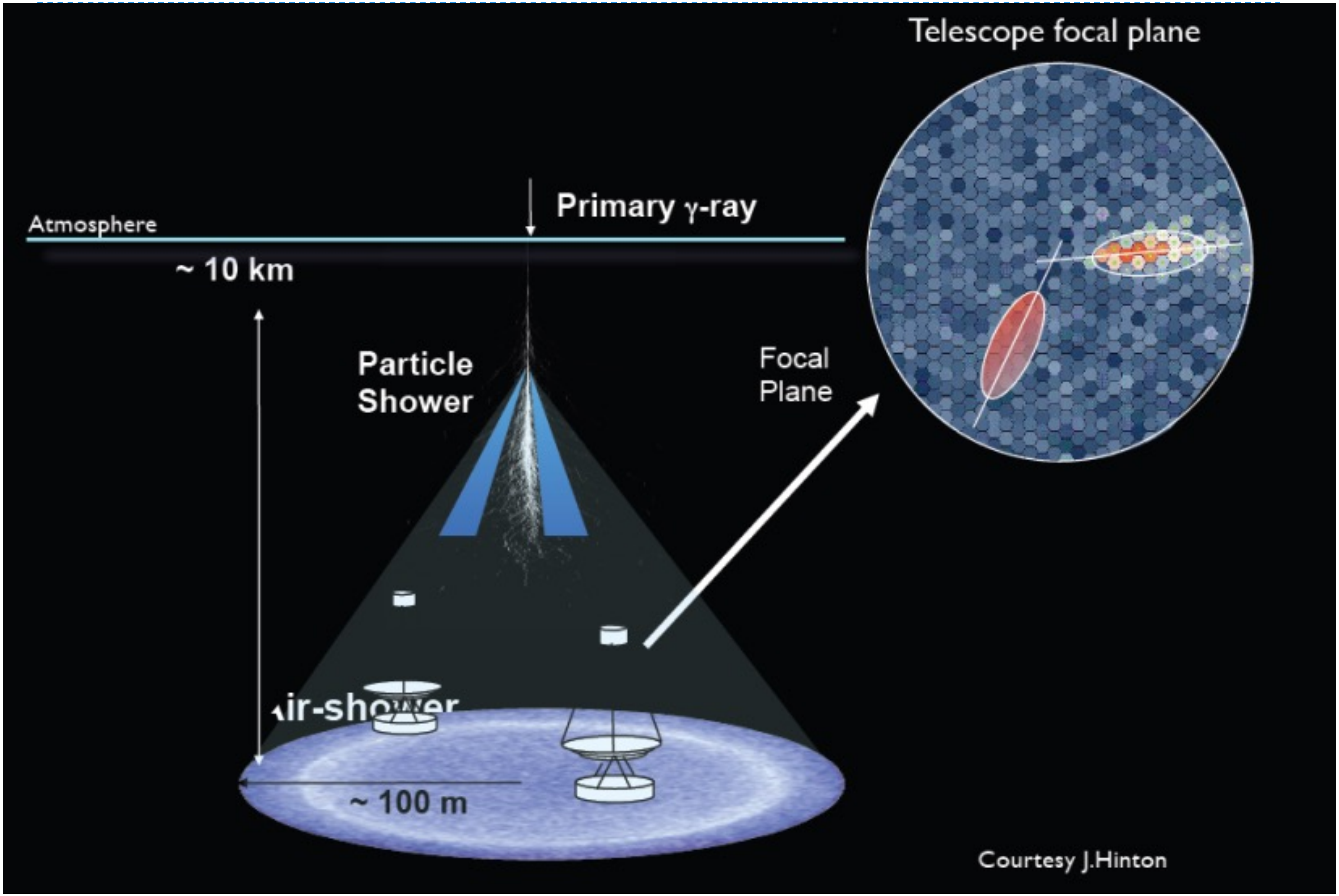
π^0 decay

Ackermann et al (Fermi Collab) '13
arXiv:1302.3307

VHE Gamma-ray telescopies (GeV-TeV)



IACT technique (1)



Cherenkov (Č) detectors
Cherenkov light from γ showers

Č light is produced by particles faster than light in air

Limiting angle $\cos\theta_c \sim 1/n$

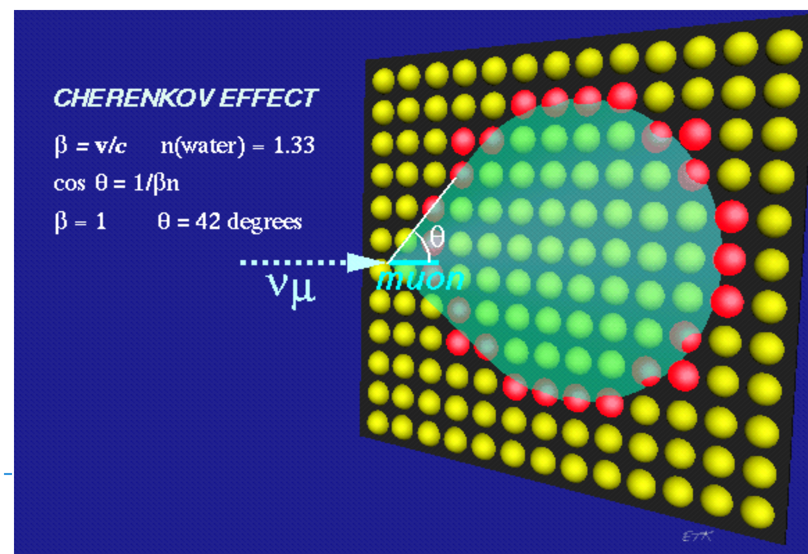
- $\theta_c \sim 1°$ at sea level, 1.3° at 8 km asl
- Threshold @ sea level : 21 MeV for e, 44 GeV for μ

Maximum of a 1 TeV γ shower ~ 8 Km asl

200 photons/m² in the visible range

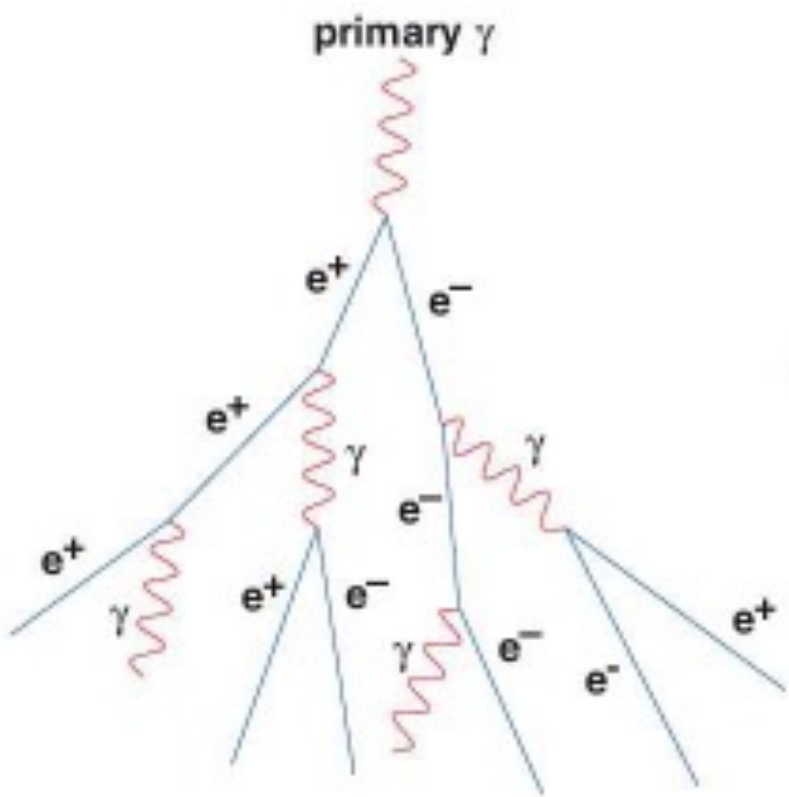
Duration ~ 2 ns

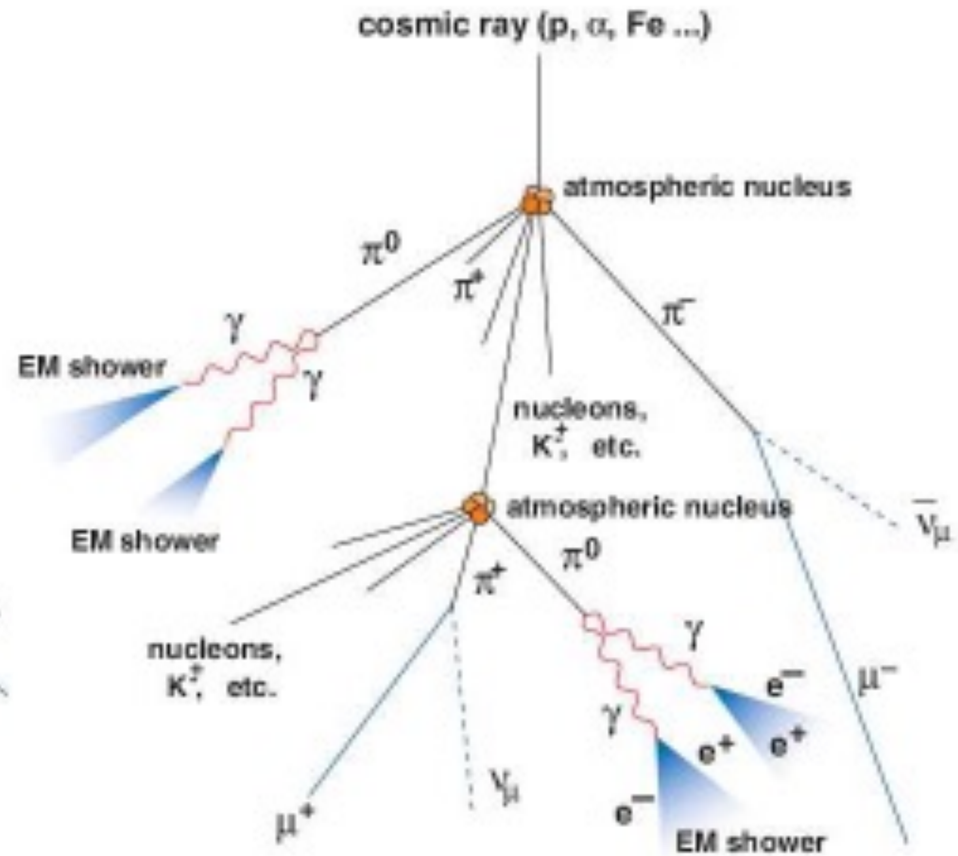
Angular spread ~ 0.5°



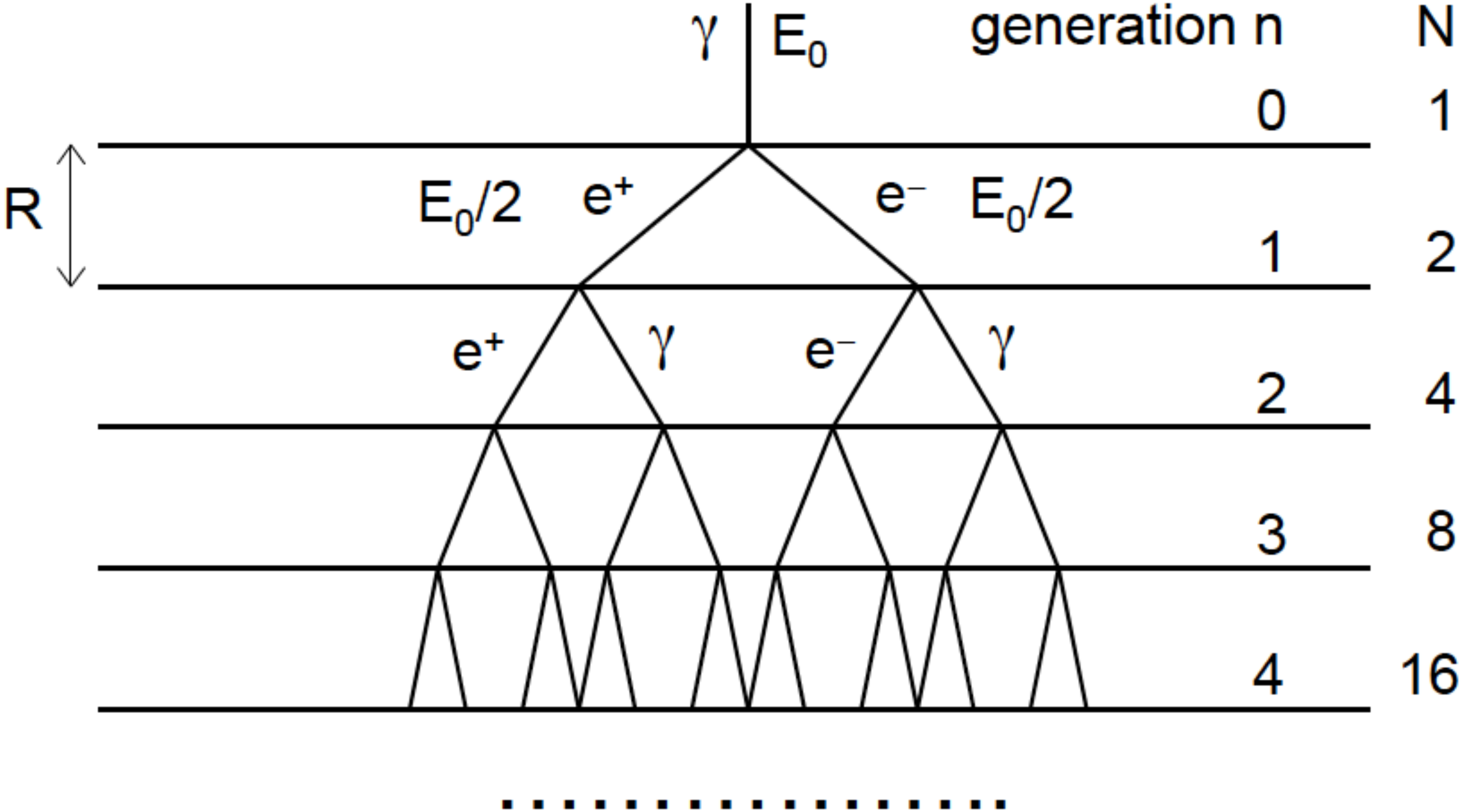
IACT technique (2)

1 gamma-ray in 1000 - 10 000 CR





Heitler model of em shower



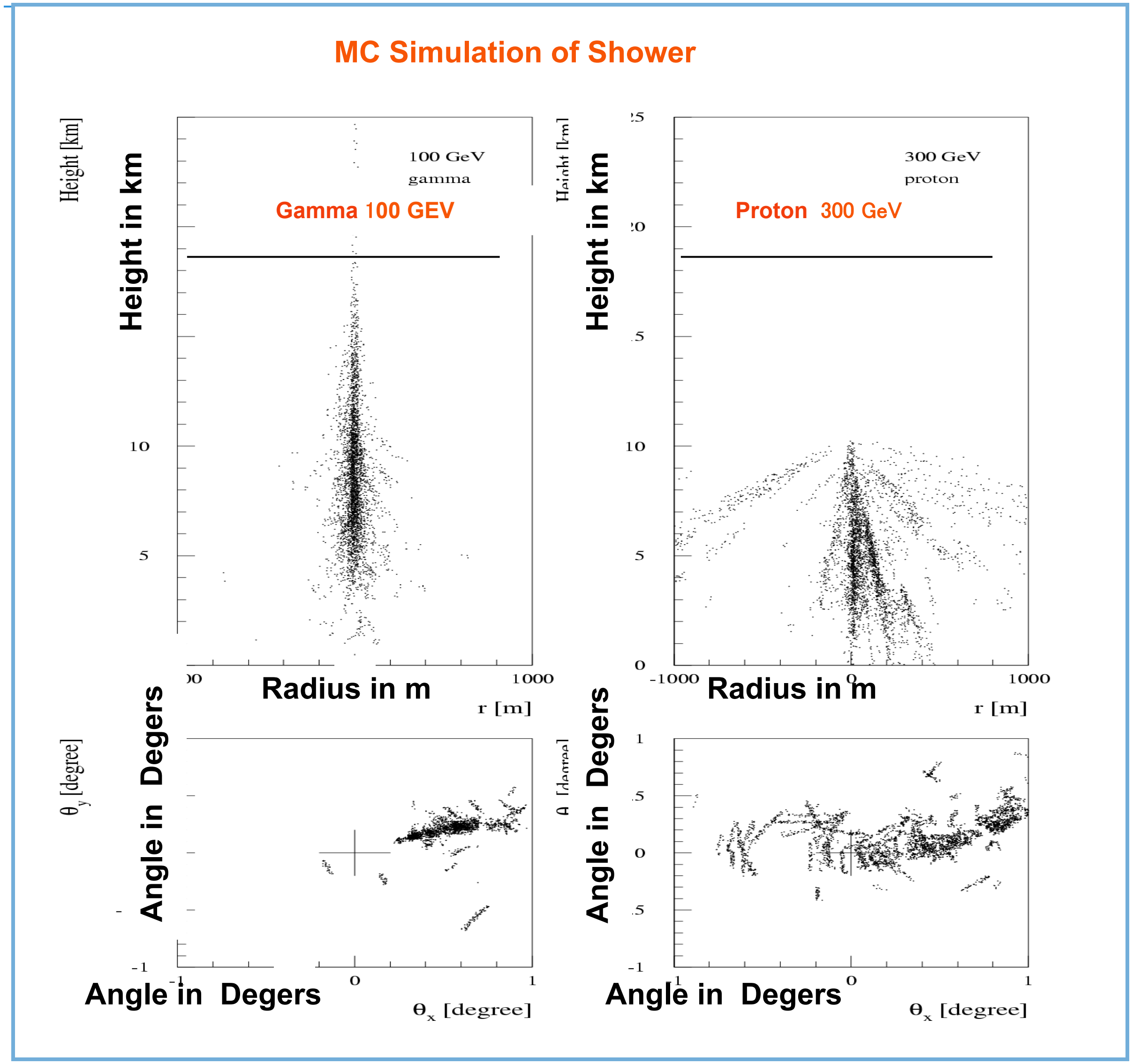
Heitler model of em shower

- In the n^{th} generation, 2^n particles ($e^{\pm}$ and γ) o energy $E_0 / 2^n$
- Shower maximum reached when E_c is reached, hence $E_0 / 2^{n_{max}} = E_c$
- Number of generations until shower maximum: $n_{max} = \ln (E_0 / E_c) / \ln(2)$
- Atmospheric depth of shower maximum:

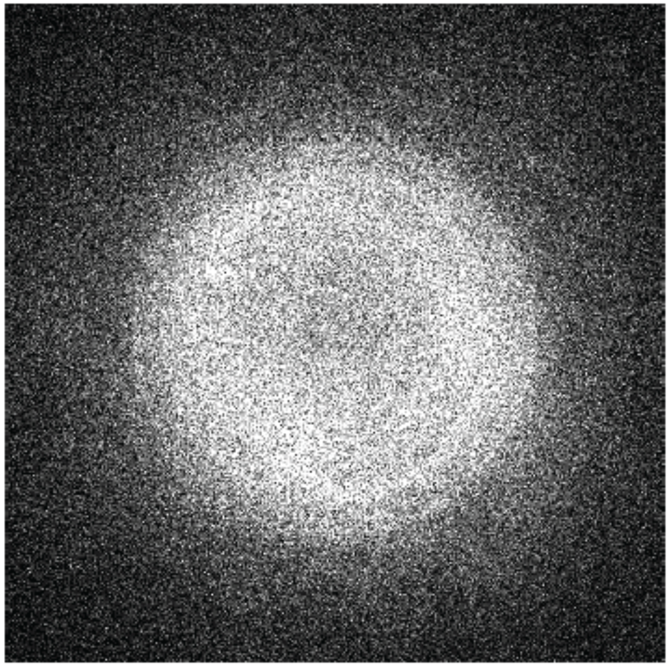
$$X_{max} \cong n_{max} \cdot R = X_0 \ln (E_0 / E_c)$$

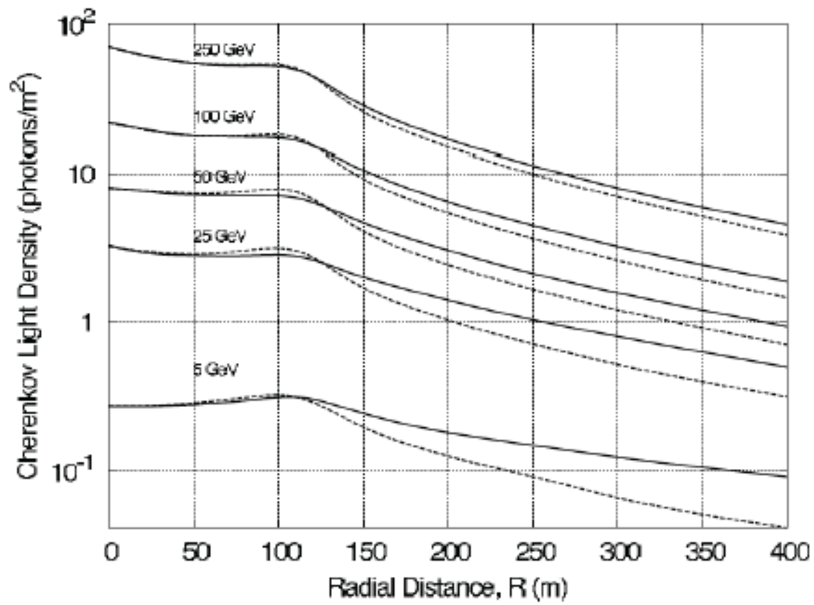
(depends logarithmically on E_0)

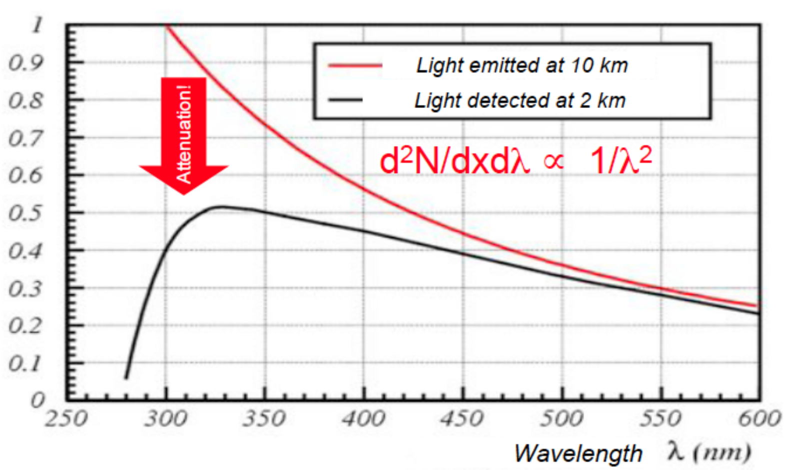
IACT – Technique (3)

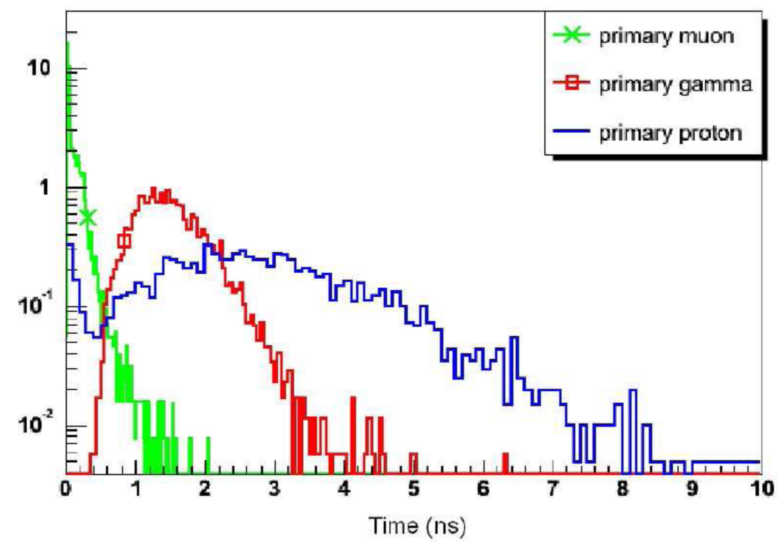


Density of Cherenkov photons

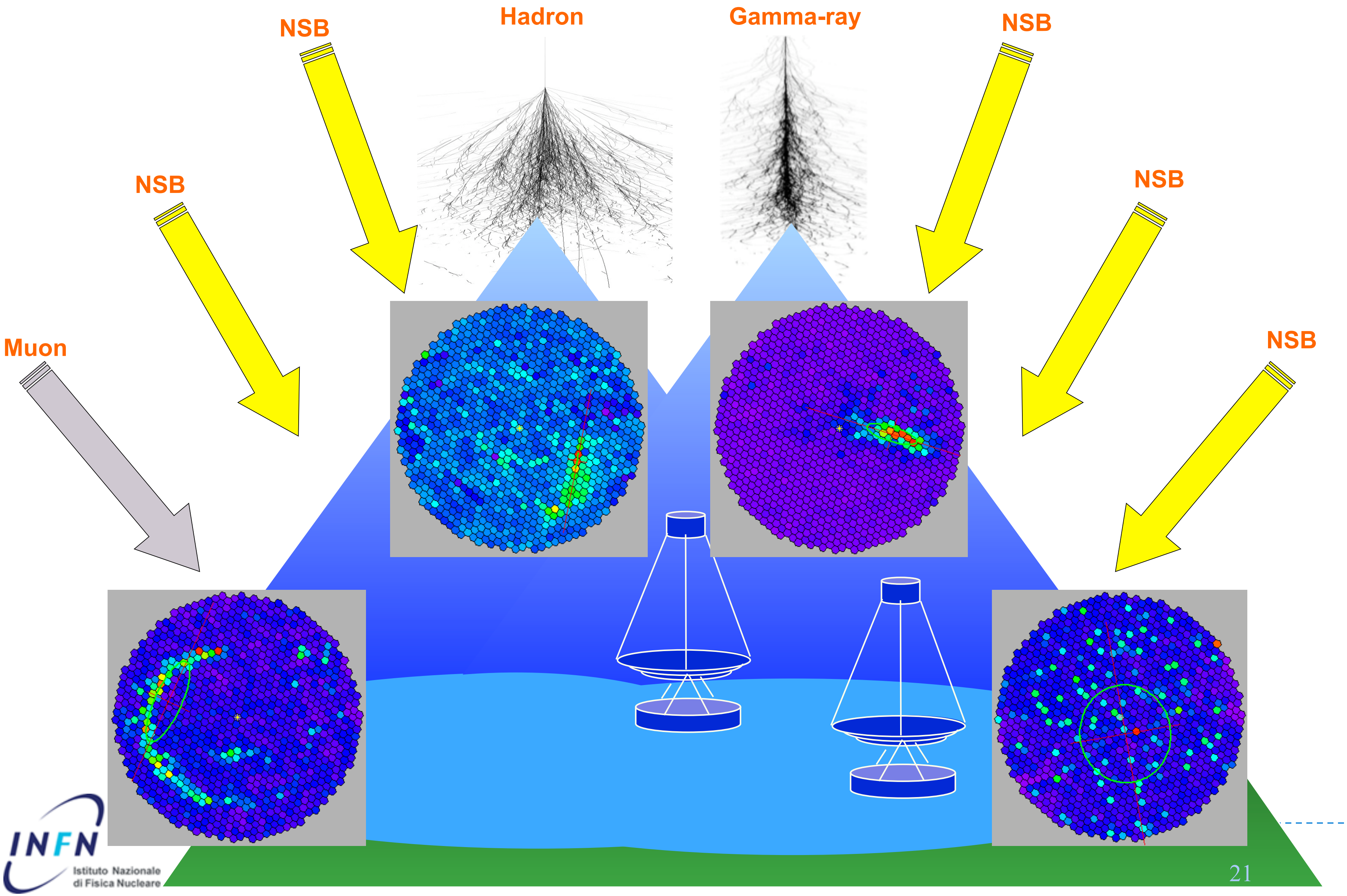








IACT technique



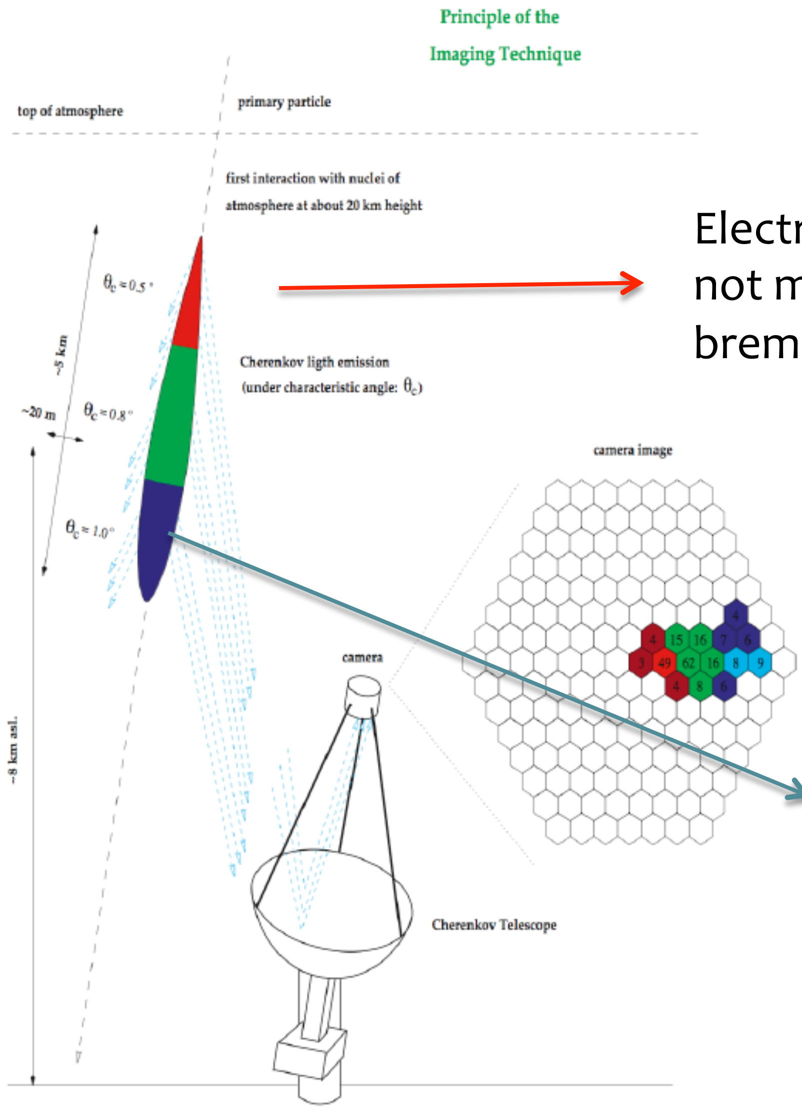
Sensitivity of IACT

- Φ ($sr^{-1}s^{-1}$,m^{-2}) –NSB flux
- Ω – solid angle viewd by detector
- τ – integration (exposure) time
- F (m^{-2}) – density of Cherenkov photons
- A- light collection area
- ε – light collection efficiency (reflectivity,QE,…)
- Number of background photons $N_B = \phi\Omega A\varepsilon \pm \sqrt{\phi\Omega A\varepsilon}$
- Number of detected Cherenkov/signal photons N=FεA

$$\frac{S}{B} \equiv \frac{N}{\sqrt{N_B}} \; \frac{FA\varepsilon}{\sqrt{\phi\Omega A\varepsilon\tau}} = \sqrt{\frac{F\varepsilon A}{\phi\Omega\tau}}$$

$$E_{th} \sim \sqrt{\frac{\phi\Omega\tau}{\varepsilon A}}$$

Shower development

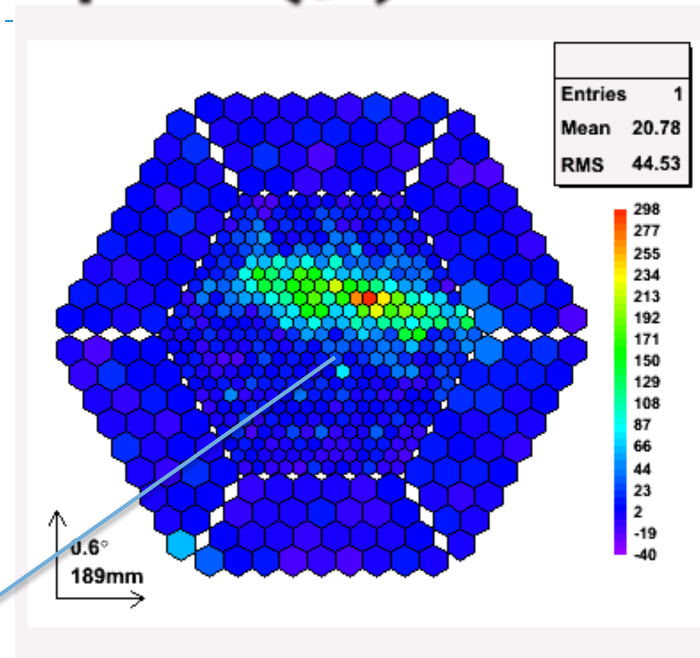


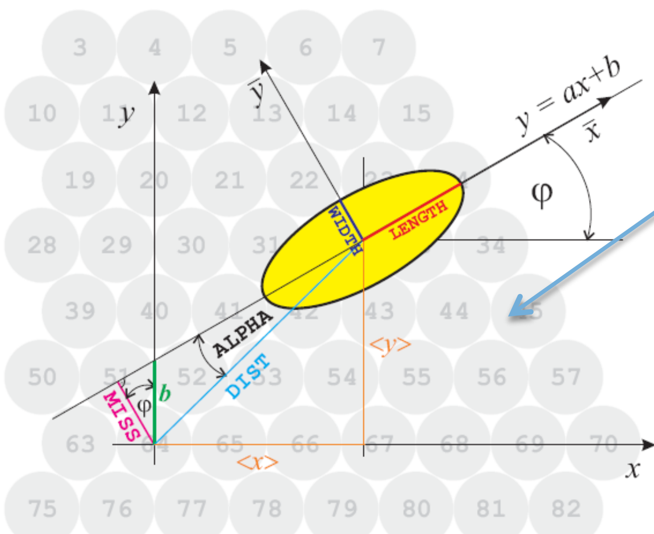
Electrons energetic and not much deflected by bremmstrahlung

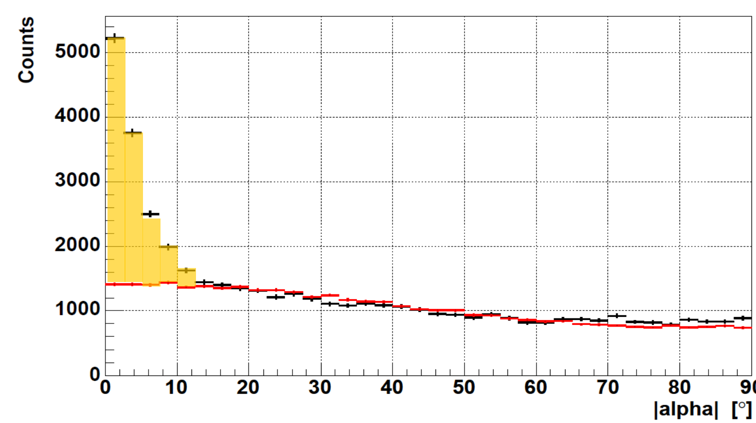
$$\alpha_{scattering}(n) \simeq \frac{1}{\gamma} = \frac{m_e c^2}{E(n)}$$

Electrons less energetic deflected by bremmstrahlung
Some photone deflected for 6 equivalent pixel away forn the original trajectory

IACT Technique (5)



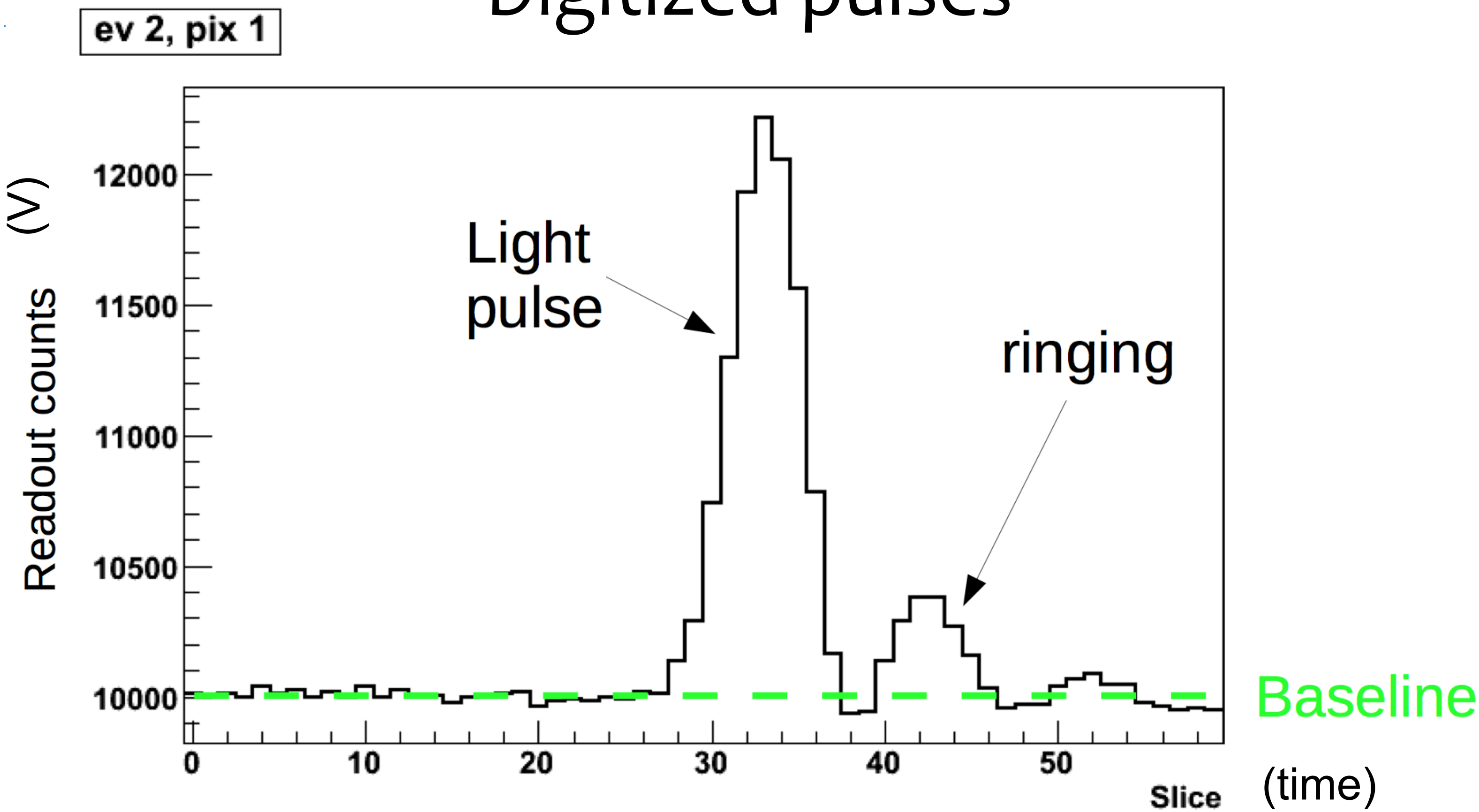




IACT data analysis

in short

Digitized pulses



- For every triggered event, one such digitized pulse is saved for all pixels in both telescopes
- The light recorded by the pixel is ~proportional to the area of the first pulse above the baseline (= pedestal)

Camera calibration

Using dedicated calibration and pedestal runs…

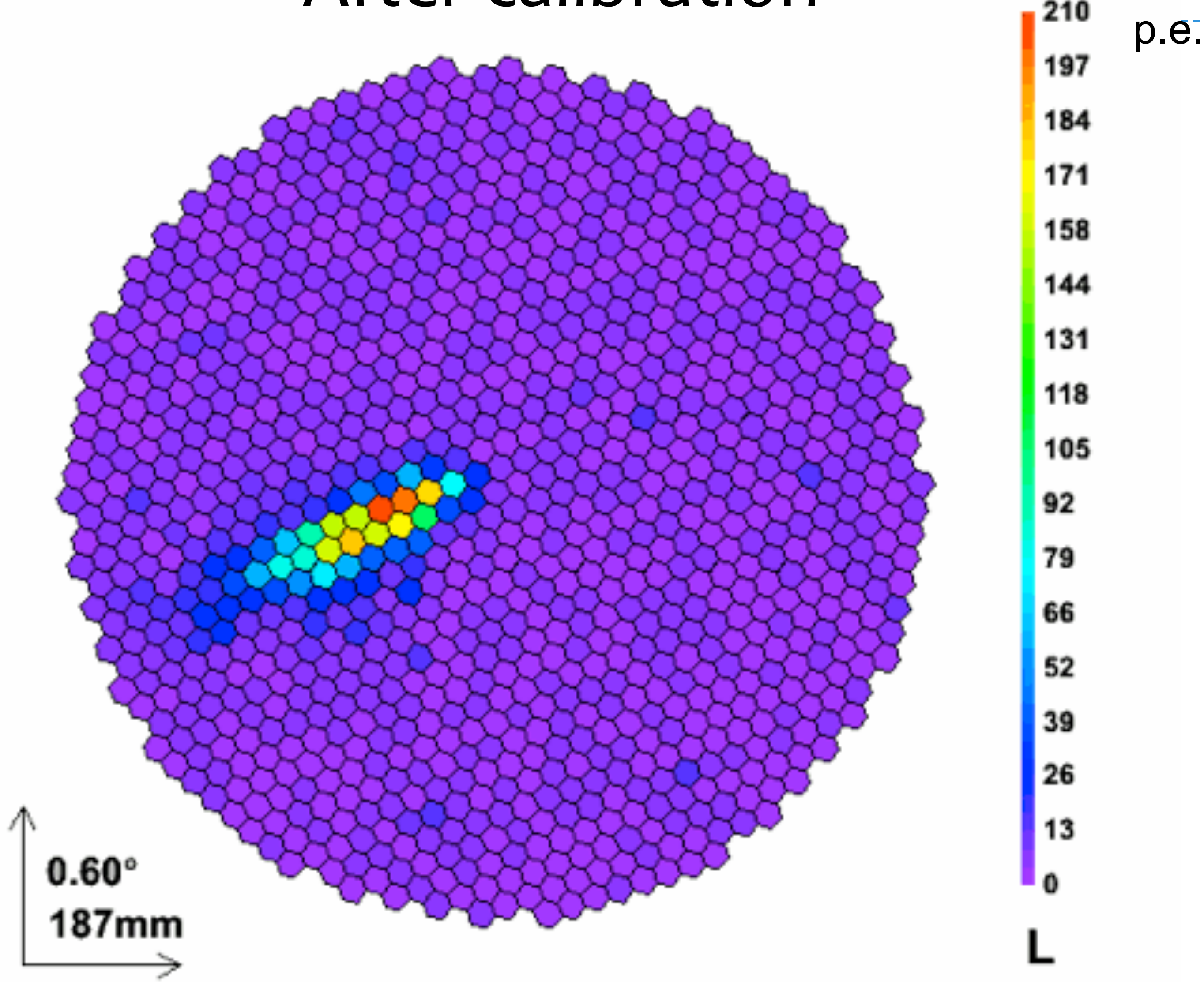
- Pedestal (baseline) calculation
- Software flat-fielding of camera ⇒ uniform response
- Calculate conversion factors p.e. / ADC count
- Adjust relative time delays among pixels

Apply calibration to shower images in regular runs

- Subtract pedestal & integrate signal ⇒ # of p.e. and arrival time in each pixel

Note: the calibration constants are updated through the analysis of pedestal and calibration events interleaved (@25+25 Hz) with the shower events

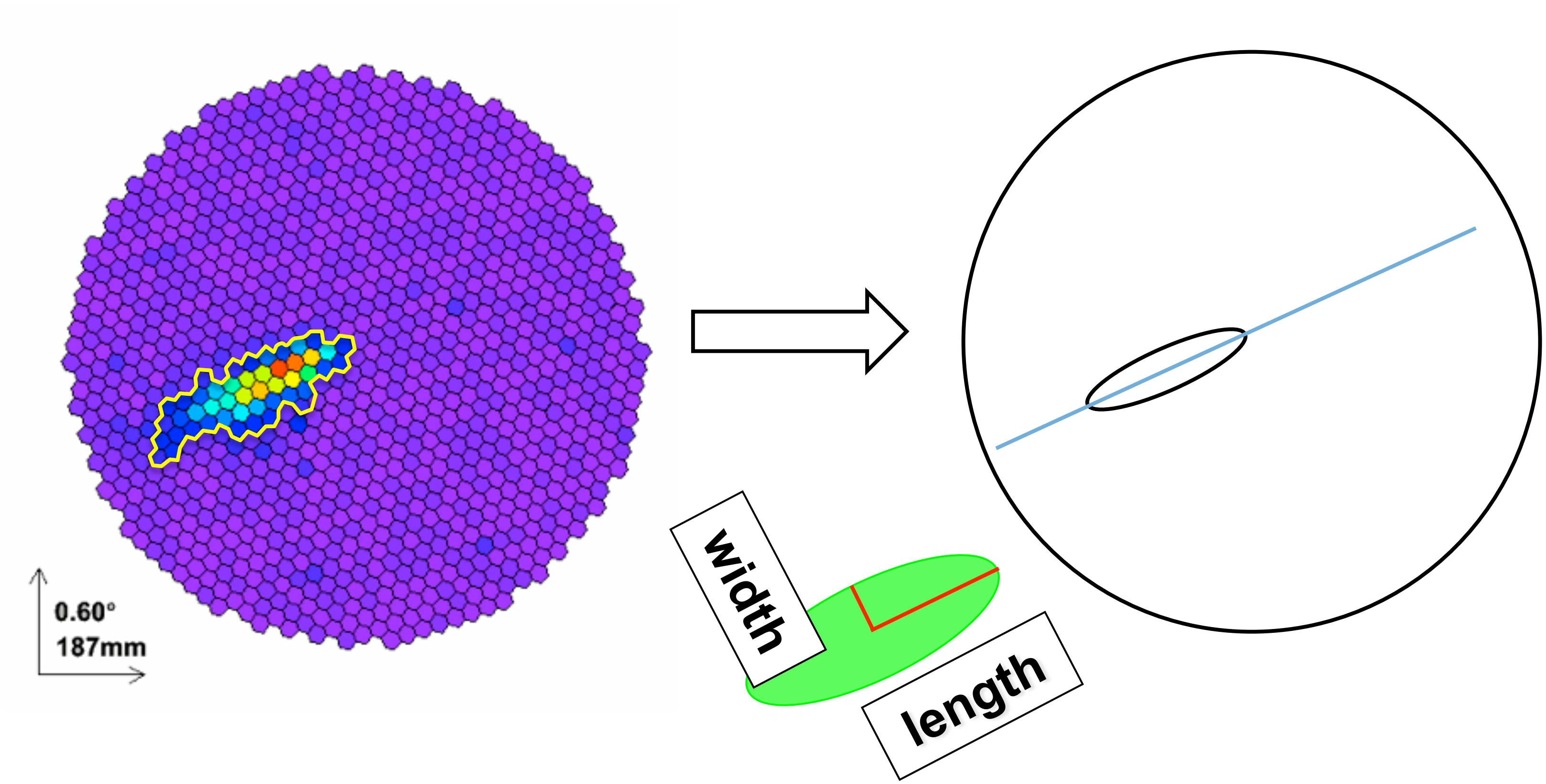
After calibration



one calibrated image (# of p.e. & time) per telescope

Image cleaning & parametrization

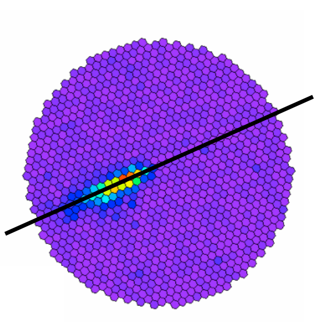
- Keep only pixels significantly above the background light fluctuations
- Calculate a small set of parameters describing the image: Size (total # of p.e.), main axis, Width, Length (2^{nd} order moments - "Hillas parameters"), time gradient along major axis...

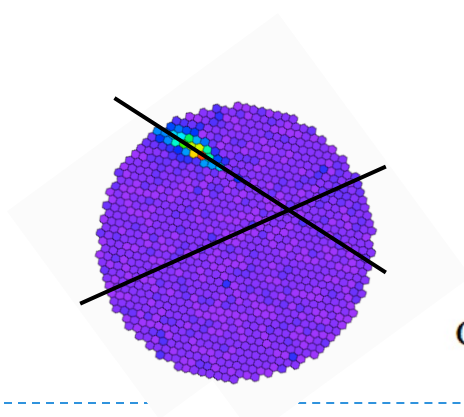


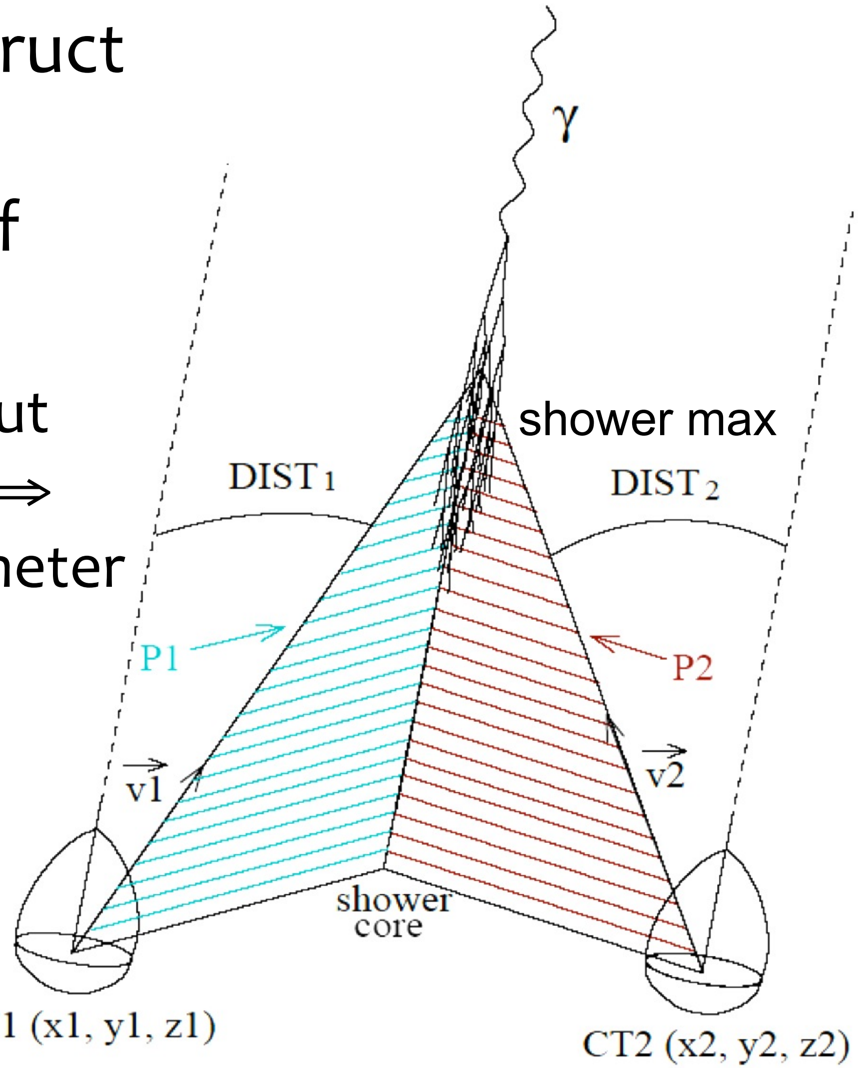
Stereoscopic reconstruction)

From the 2 images, reconstruct the shower axis (direction, core position) and height of maximum

- May use not only *geometry*, but also pixel timing information ⇒ extra handle on impact parameter & shower direction





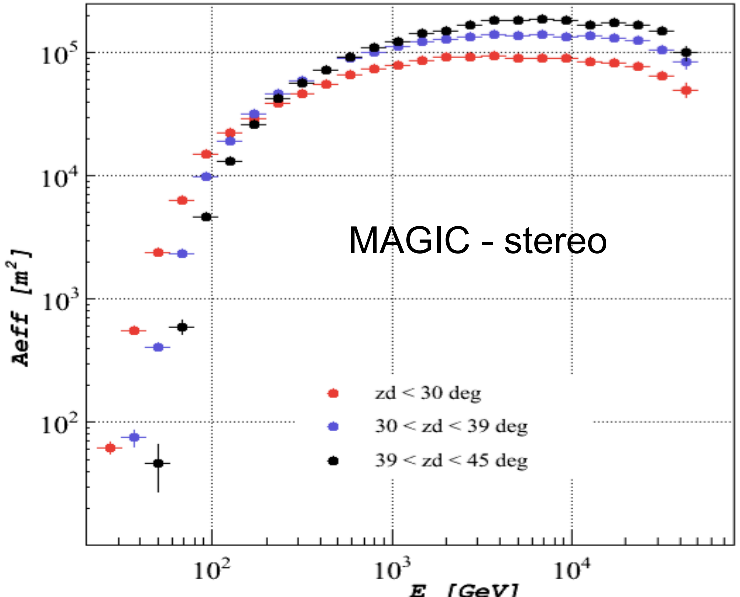


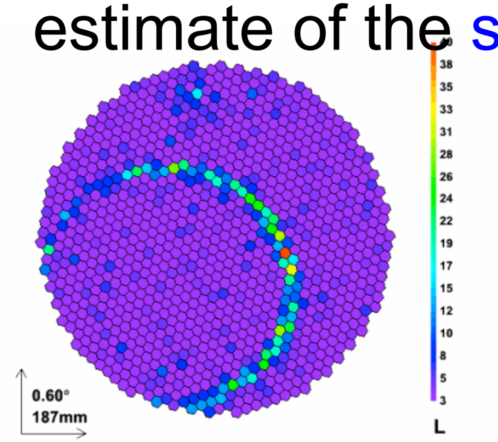
Monte Carlo simulations

MC of shower development and detector response...

needed to correlate the observed quantities to the properties of the primary gamma (or cosmic ray)

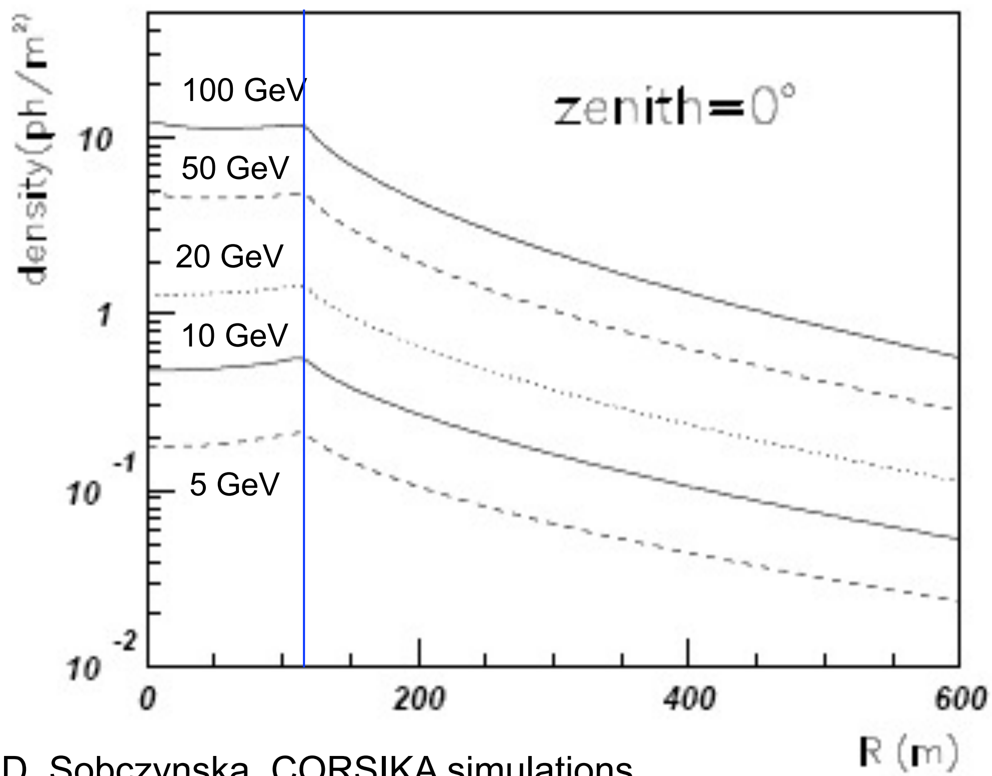
- ⇒ MC allows to calculate the effective area of the IACT array (vs. Energy, Zenith...)
- ⇒ Convert the observed gamma-ray rates into an estimate of the source flux





MC parameters need to be tuned to match the telescopes performance! ⇒ use muon ring events, check Crab Nebula observations...

Energy reconstruction



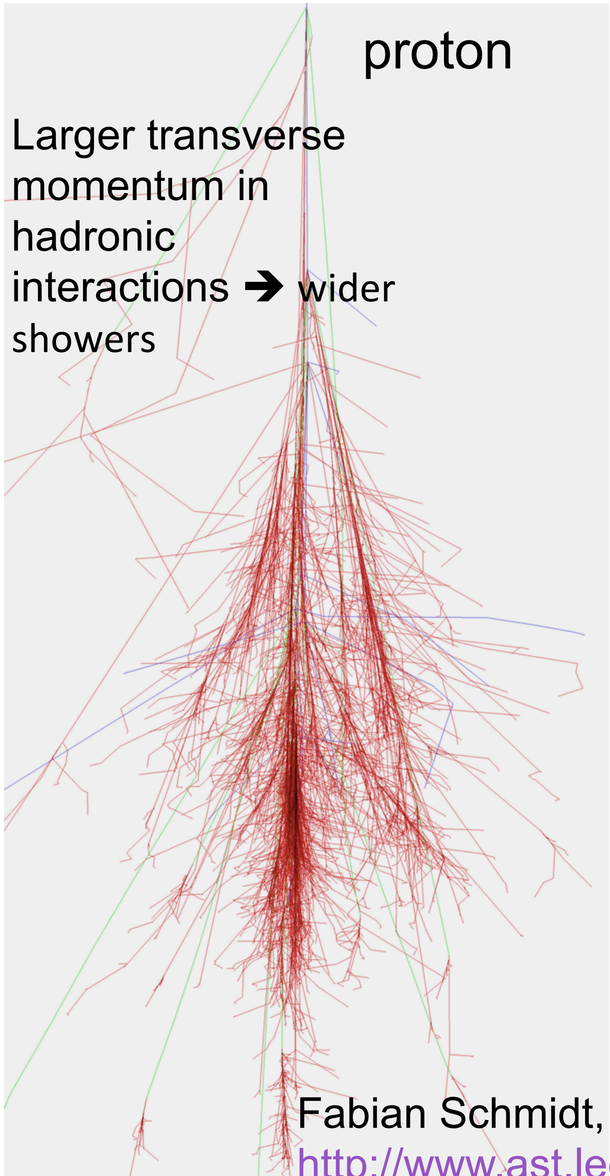
D. Sobczynska, CORSIKA simulations

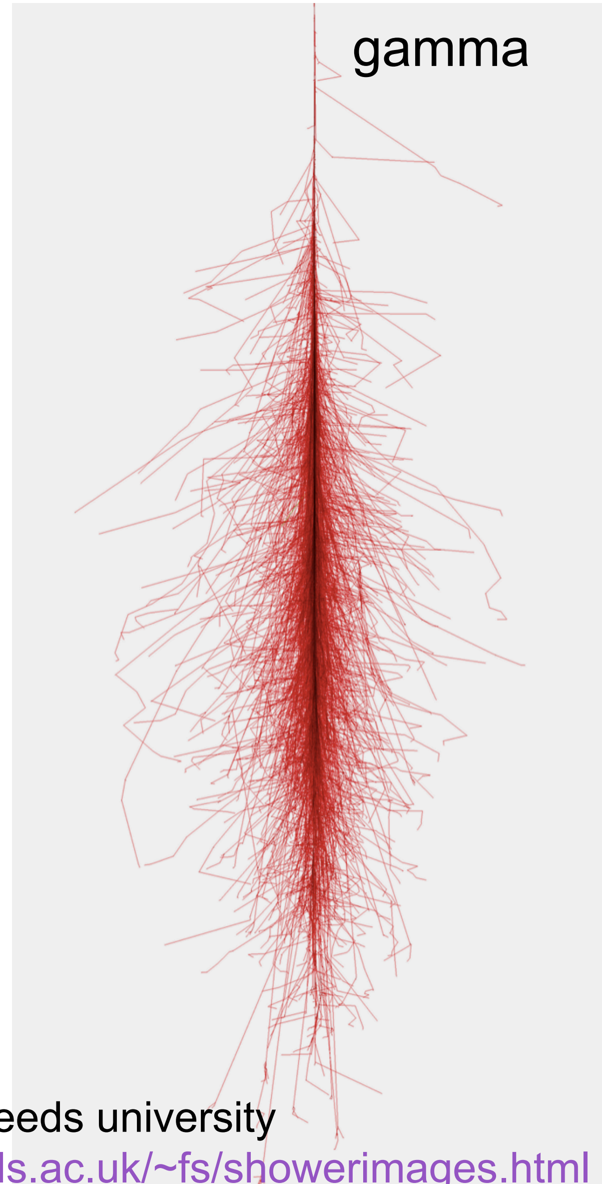
Based on the very good correlation between the number of collected photons (*Size*) and the energy, for a given impact parameter.

E_{est} obtained from MC-trained Look-Up Tables (or multivariate regression methods) on Size, i.p., zenith angle, height of shower maximum

Note: actually the light pool is not, even in average, exactly round: the geomagnetic field separates + and – charges in the E-W direction! But this is usually disregarded in the reconstruction.

Suppression of charged CR background



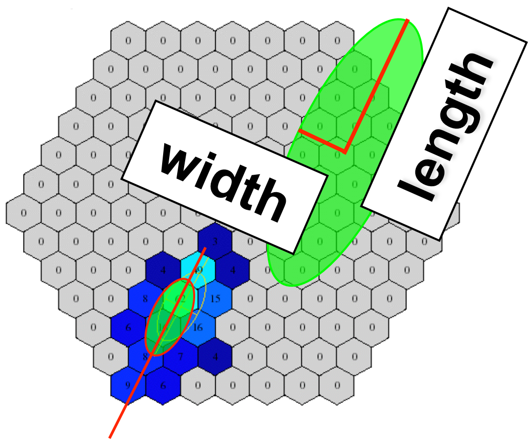


Fabian Schmidt, Leeds university
http://www.ast.leeds.ac.uk/~fs/showerimages.html

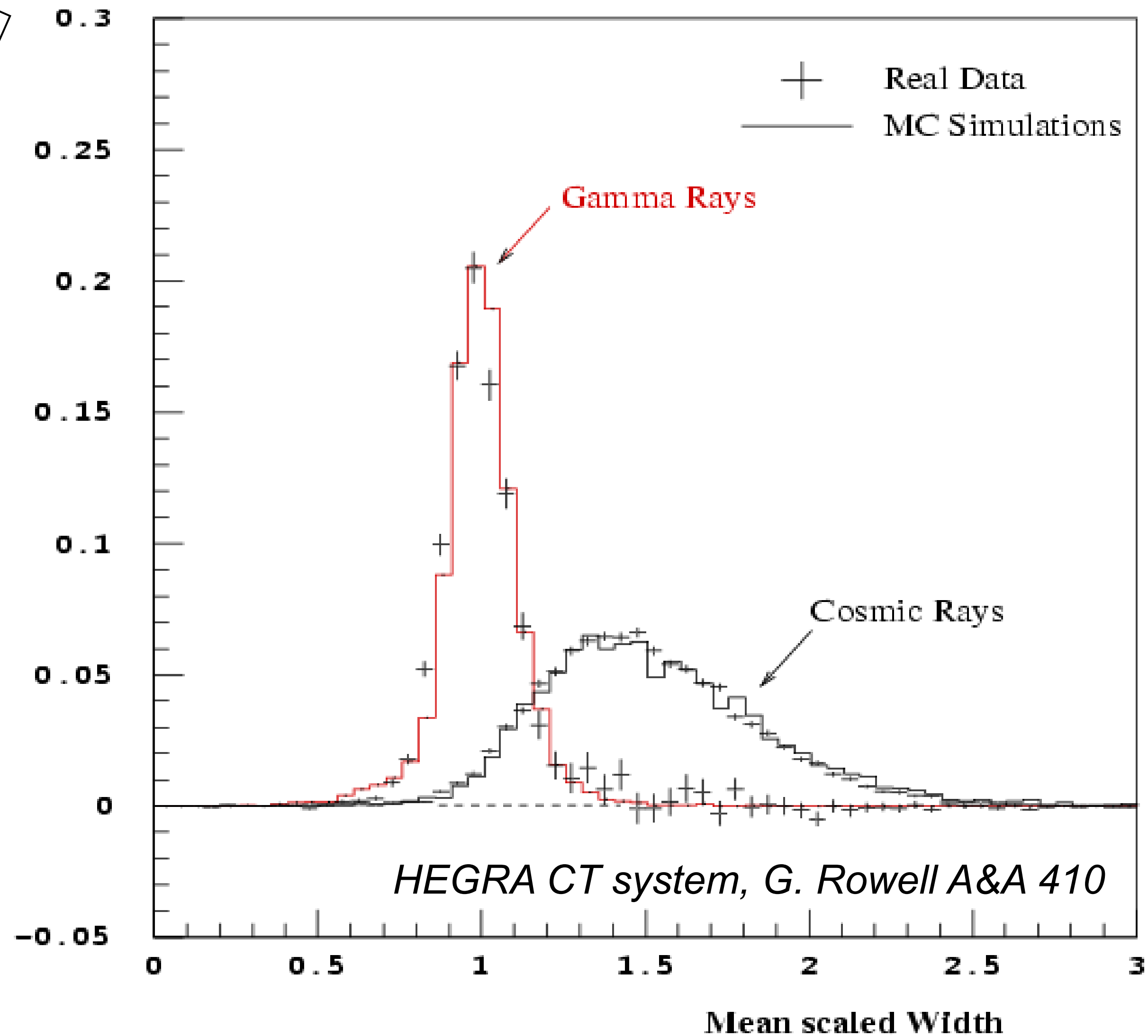
Based on the different lateral and longitudinal development of gamma- and hadron- initiated showers

⇒ different distributions of Hillas parameters for gammas & CRs

Suppression of charged CR background

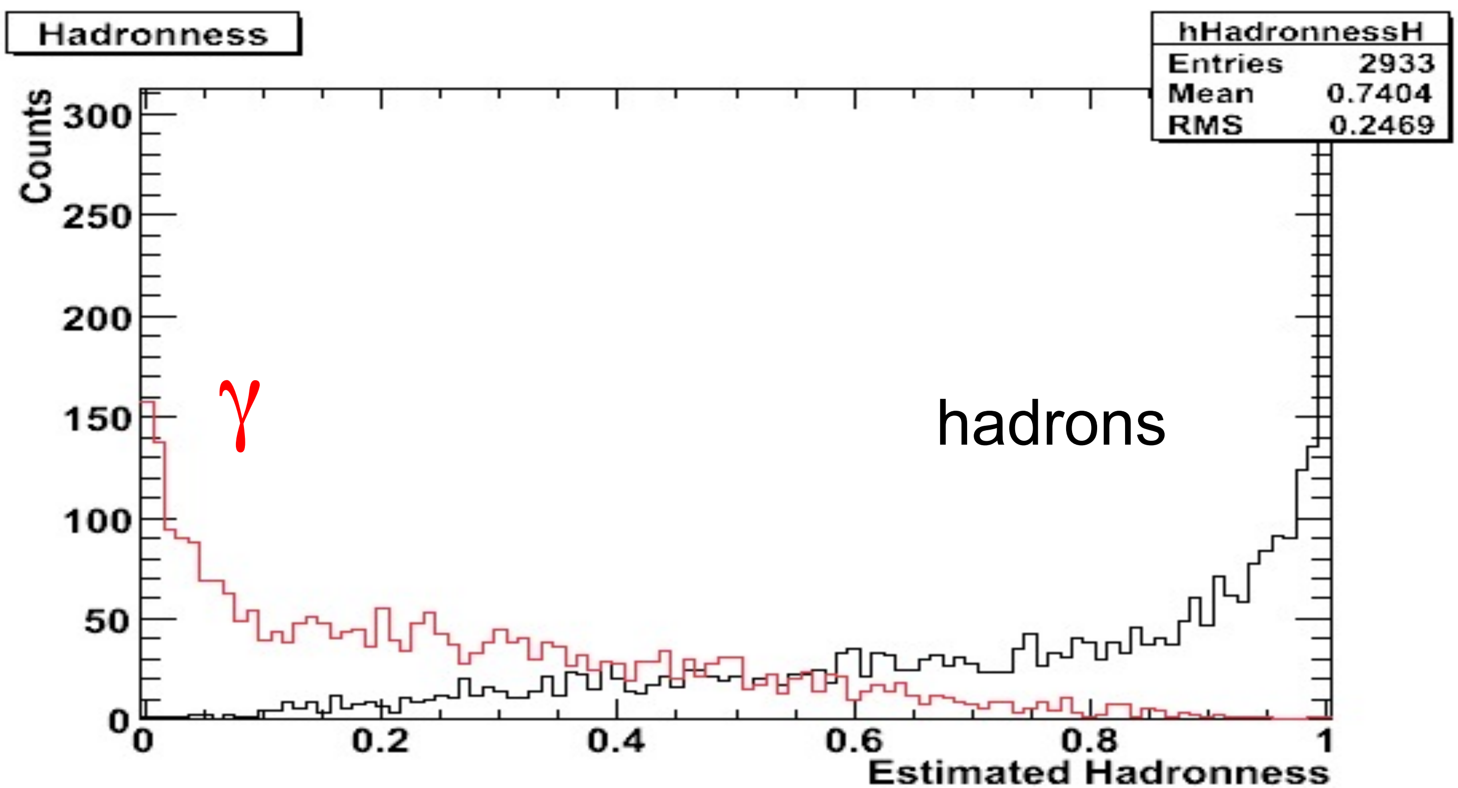


background suppression factor 100 - 1000



Suppression of charged CR background

- Several image parameters (even from different telescopes) can be combined by multivariate classification methods (like Random Forest) to derive a single cut parameter
- The algorithms are usually trained using real background events and MC gammas , then applied to the observations



After this process, the basic information per event is:

- an estimated energy
- an estimated incident direction
- a measure of how "gamma-like" the event is (in MAGIC, the *hadronness*)
- its arrival time

With these quantities, and the help of MC, we want to obtain

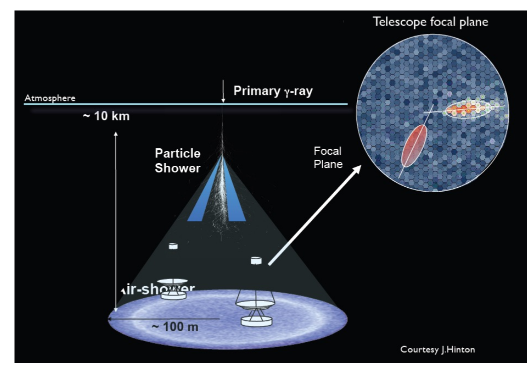
- A sky map of the observed sky region

If there is a (significant enough) source in the FoV:

- The energy spectrum of the source (flux vs. E)
- The light curve (flux vs. t)

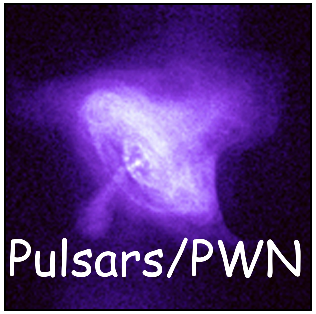
The MAGIC γ-ray telescopes

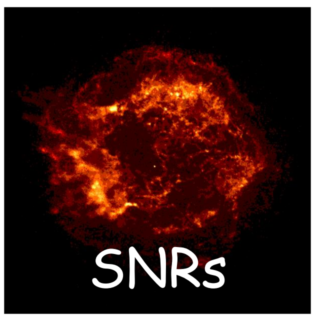
- Telescope array: M1 & M2
- Largest CT, 17 m ø mirror dish
  M1: 236.0 m^2 reflector
  M2: 241.5 m^2 reflector
- 3.5° FoV
  M1: 1039 coated PMT's
  M2: 1039 enhanced QE PMTs
- Fast repositioning for GRBs:
  M1: 30 s for 180° Az
  M2: ~30 faster
- Trigger threshold
  M1: **50 - 60 GeV**
  (25 GeV sumtrigger)
  M2: not measured yet
- Sensitivity: 0.7 % Crab / 50 h
- γ-PSF: ~ 0.1°
- Energy resolution: 20 %

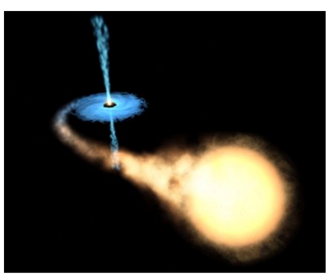


Scientific scope

Galactic

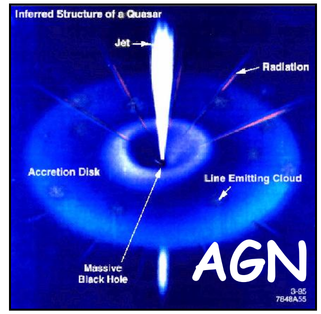


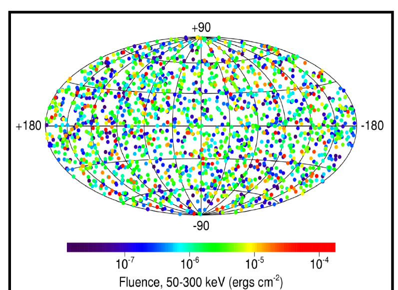




Binary systems

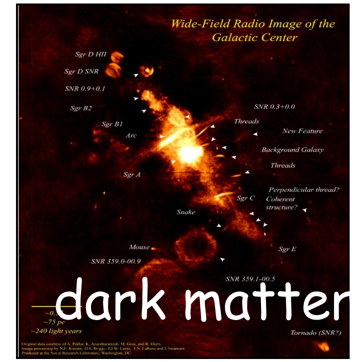
Extragalactic

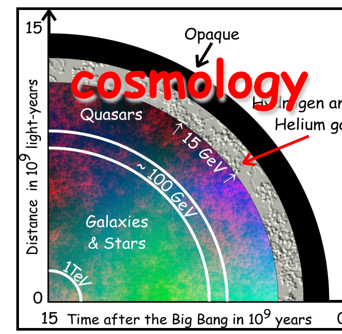


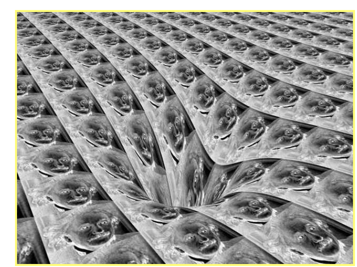


GRBs

Fundamental





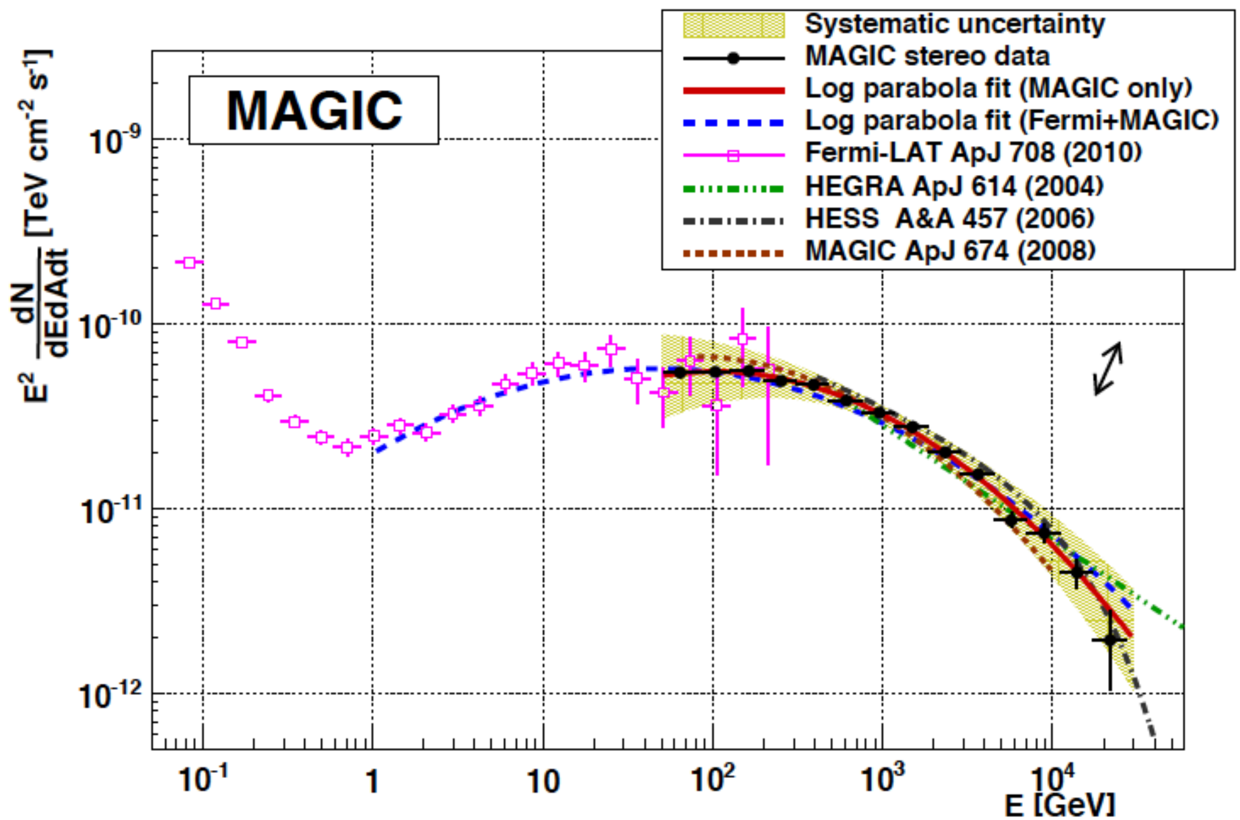


Qantum Gravity Effect

Crab Nebula -Spectral Energy Distribution

- Dominated by systematic uncertainties
- Given the systematic impossible to exclude the cutoff at E > 10 TeV
- Inverse Compton peak estimation (MAGIC + Fermi): **52.5 ± 2.6GeV** stat. err. only

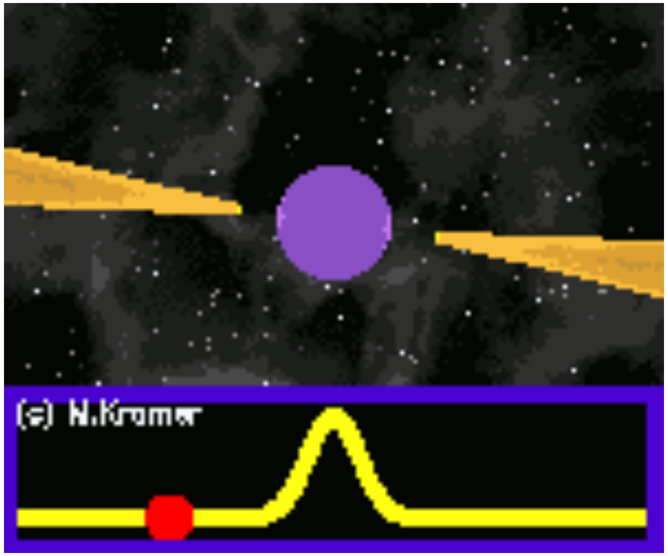
MOST PRECISE IC PEAK MEASUREMENT SO FAR

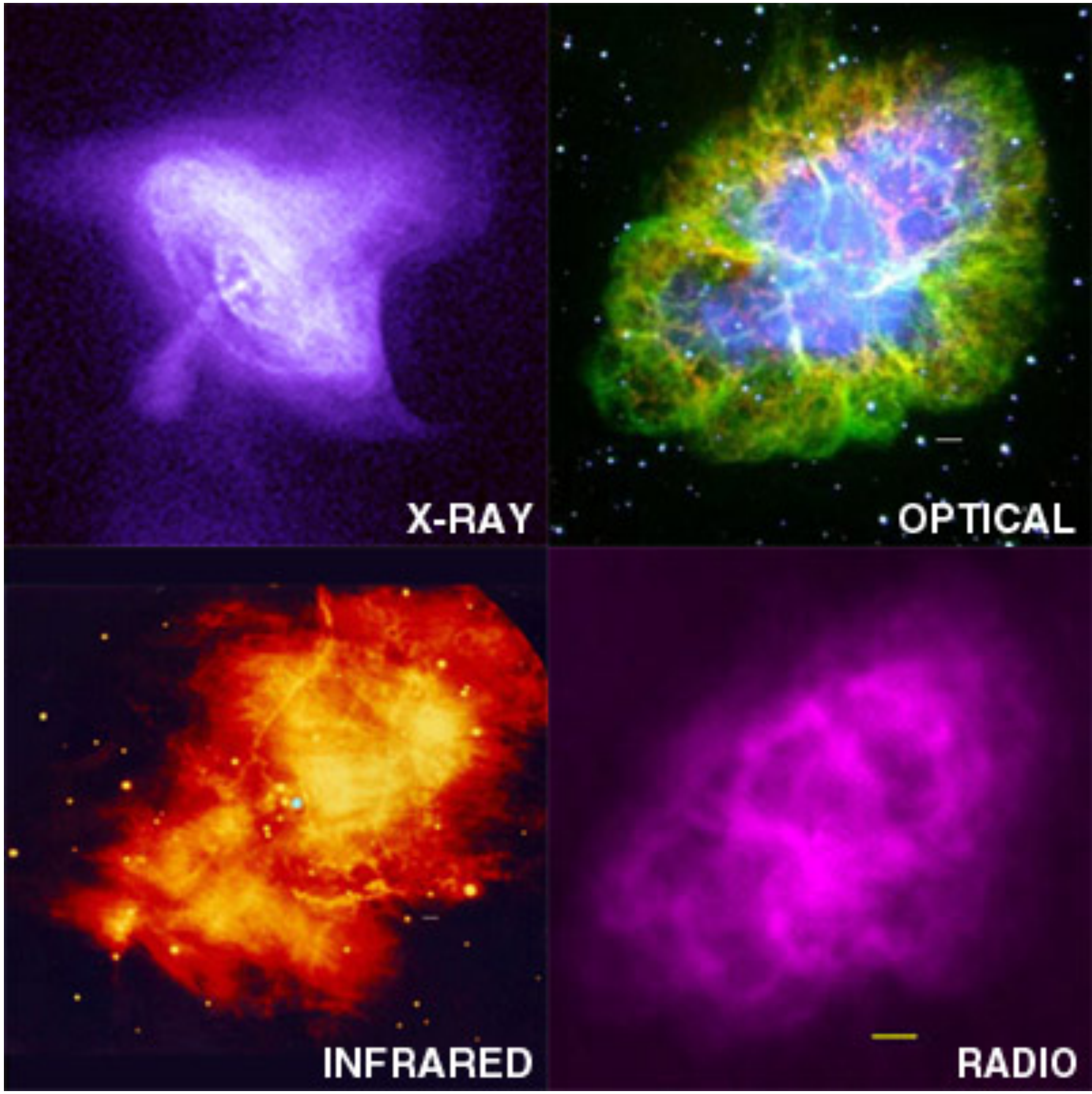


Zanin et al. arXiv:1110.2987

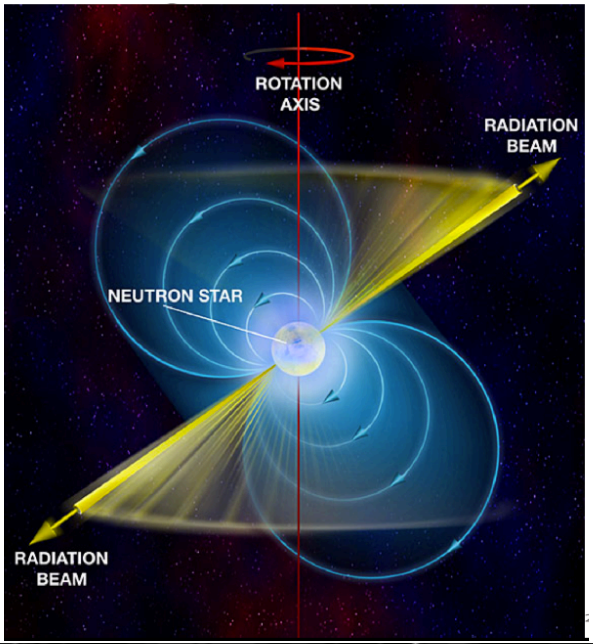
Crab nebula

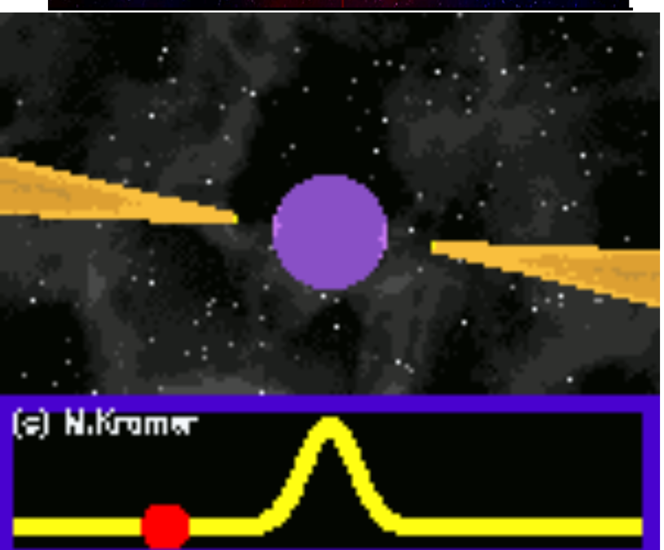
Supernove in 1054
Neutron star - engine
T=33 ms
Radius: ~12 km
Density: ~10^{14} x Sun
Gravity: ~10^{11}x Earth
B = 10^{12} x Earth
Tempeture: 10^{12} K (initial)

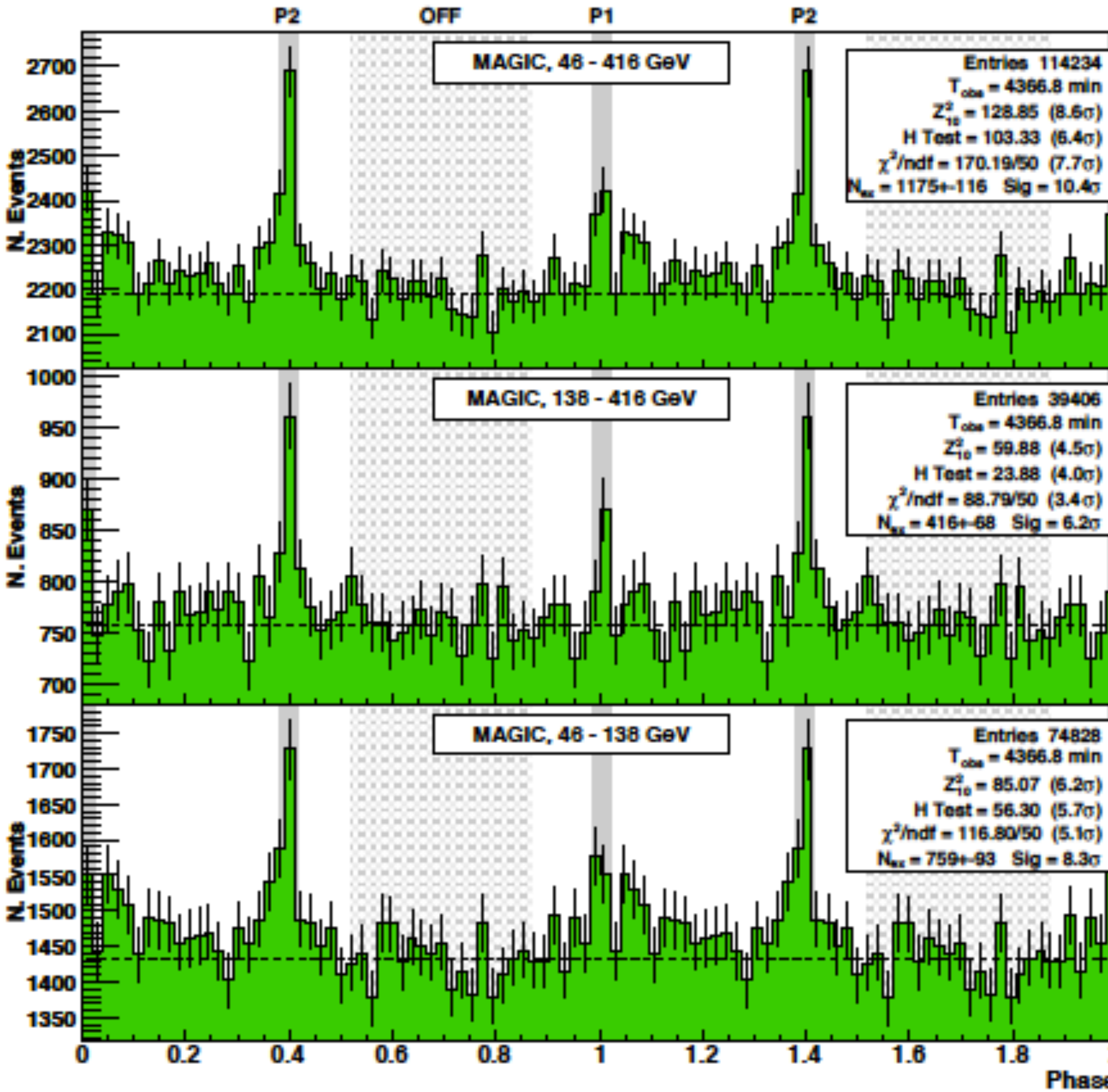




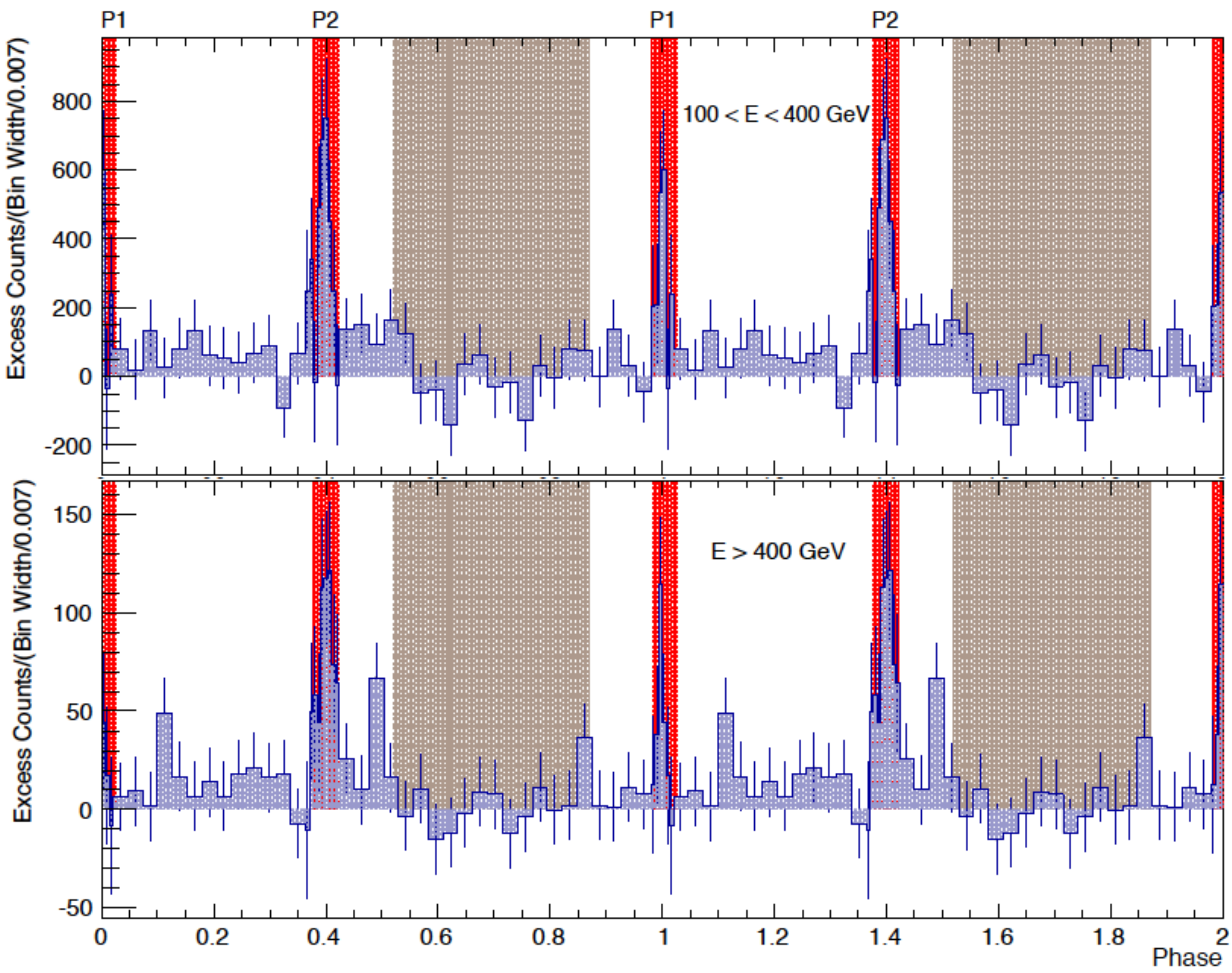
Crab pulsar is bursting with energy



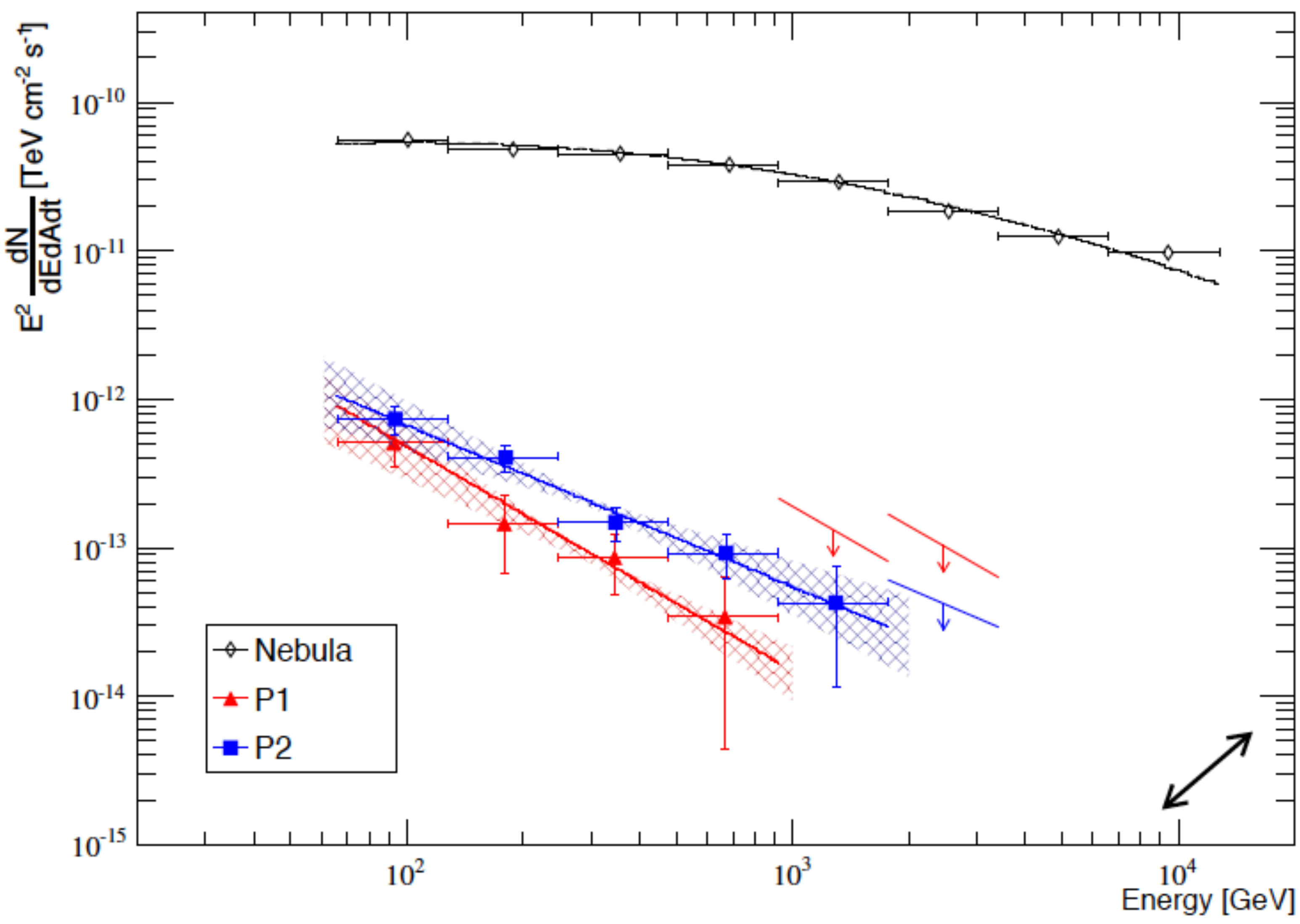




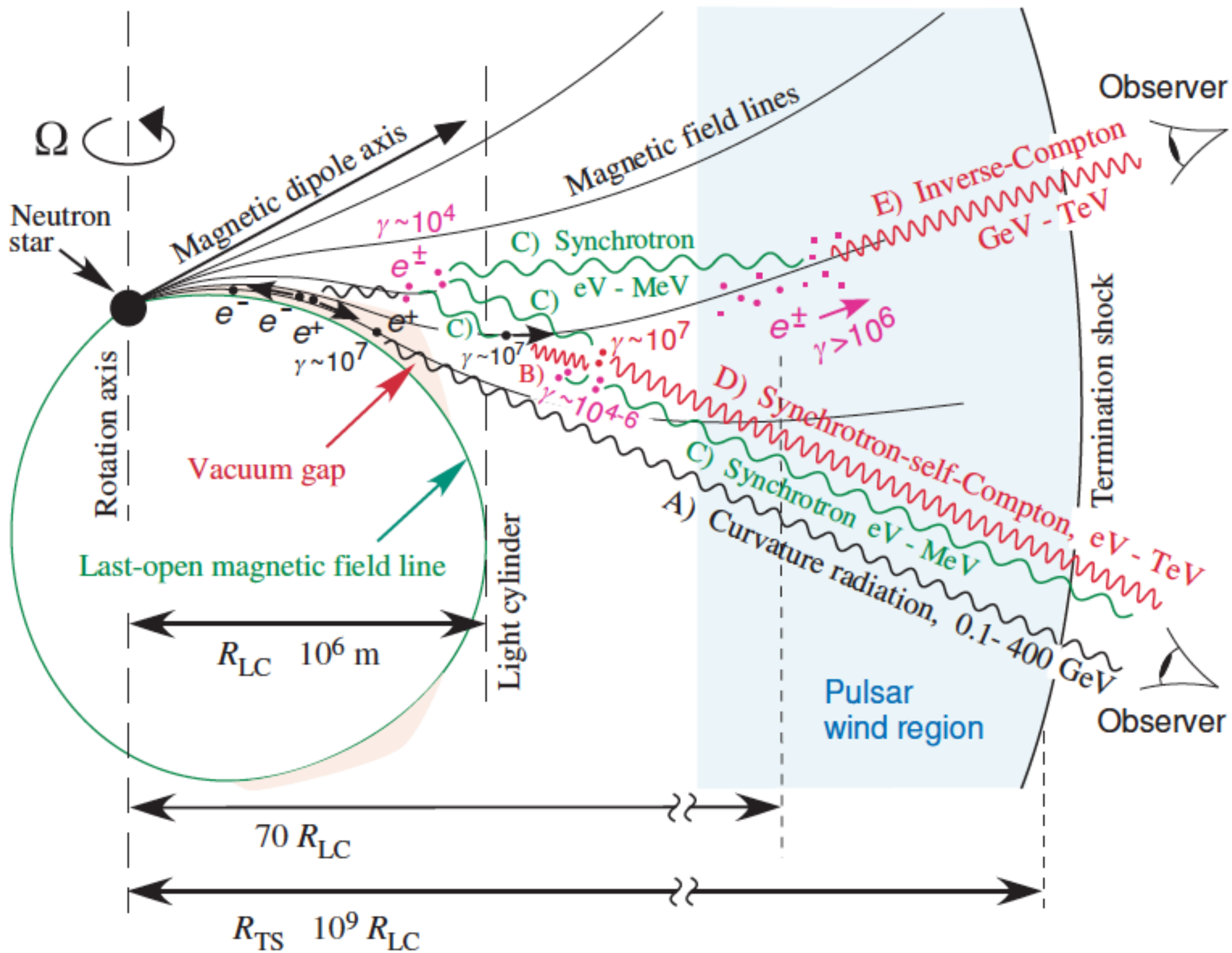
Pulsno svjetlo najveće energije dosada



Pulsno svjetlo najveće energije dosada

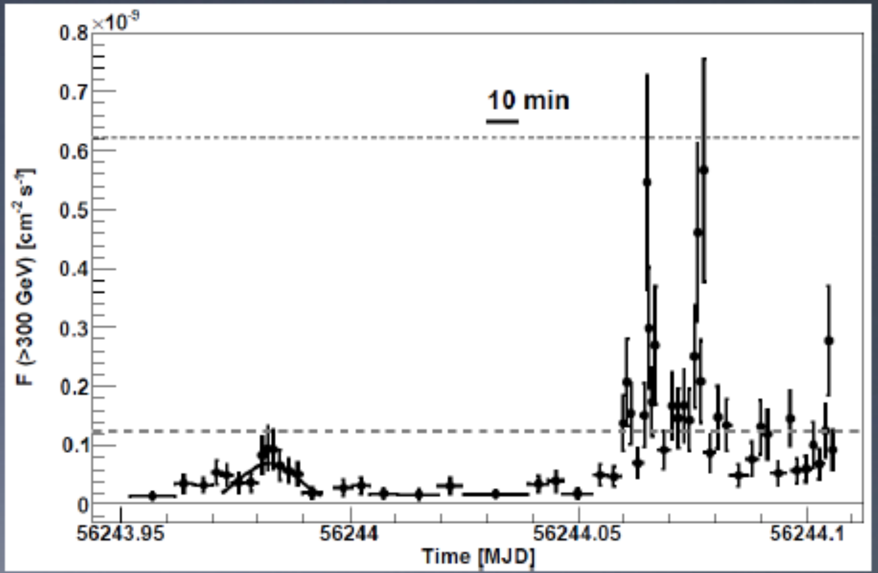


Crab Pulsar: Emission Model

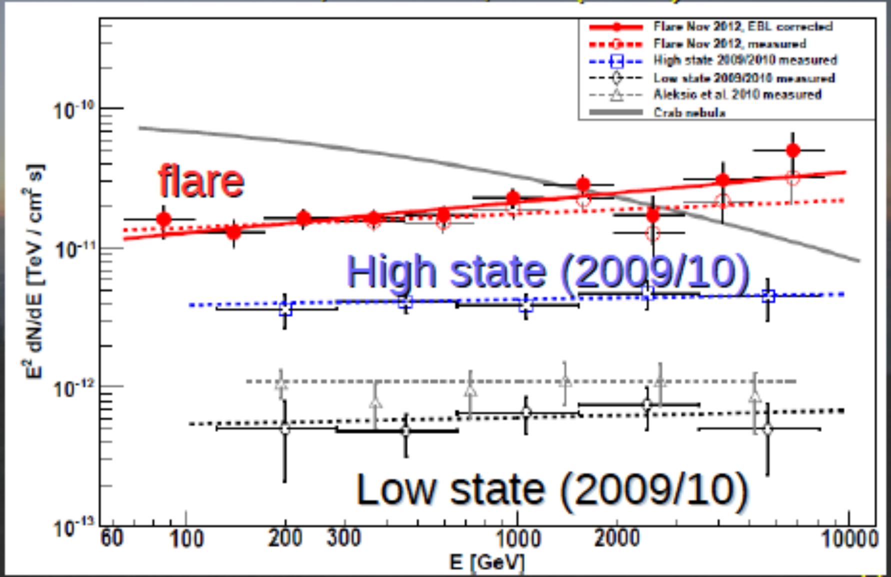


Extreme flare from radio galaxy IC 310

- IC 310 is a nearby (z=0.018) radio galaxy seen at the angle of 10-20°
- In the end of 2012 MAGIC saw a strong flare from IC 310
- Variability time scale < 4.8 min is shorter than the light crossing time of the event horizon of the IC 310 central black hole
- Hard spectrum without a cut-off up to TeV energies

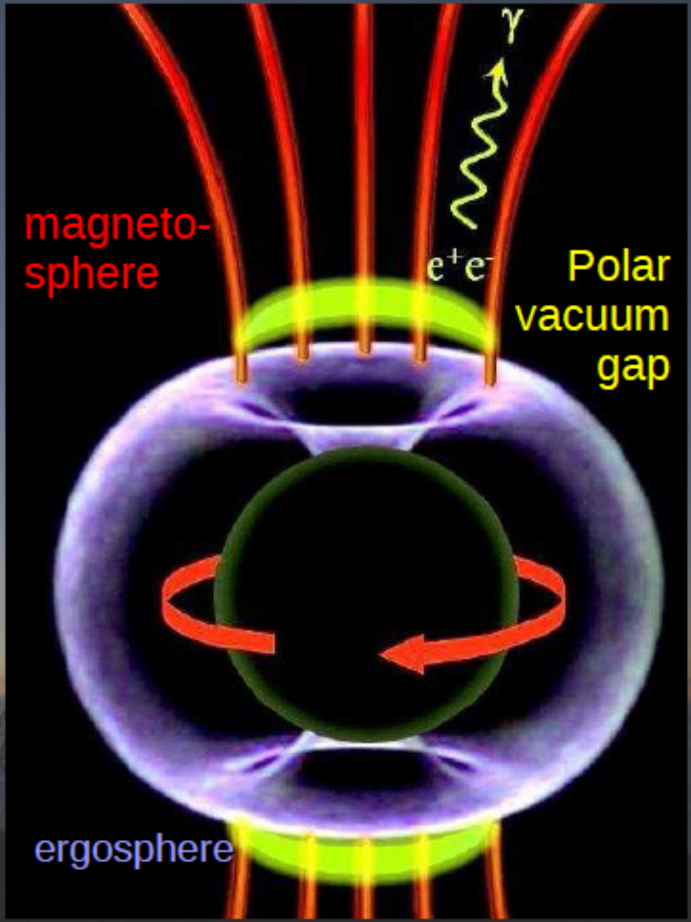


Aleksić et al., Science, 346(2014) 1080



Extreme flare from radio galaxy IC 310

- Shock in the jet models have troubles explaining IC 310 flare
- Plausible alternative: pulsar-like emission from the magnetosphere of the BH (e.g. Levinson & Rieger 2011, Hirotani & Pu 2016):
  - e^+e^- are accelerated in strong electric field across a gap in charge carrier density
  - Gamma-rays are produced in an electromagnetic cascade
  - Variability can occur due to shortening of the gap by secondary e^+e^- pairs and/or dependence of the gap height on the accretion rate

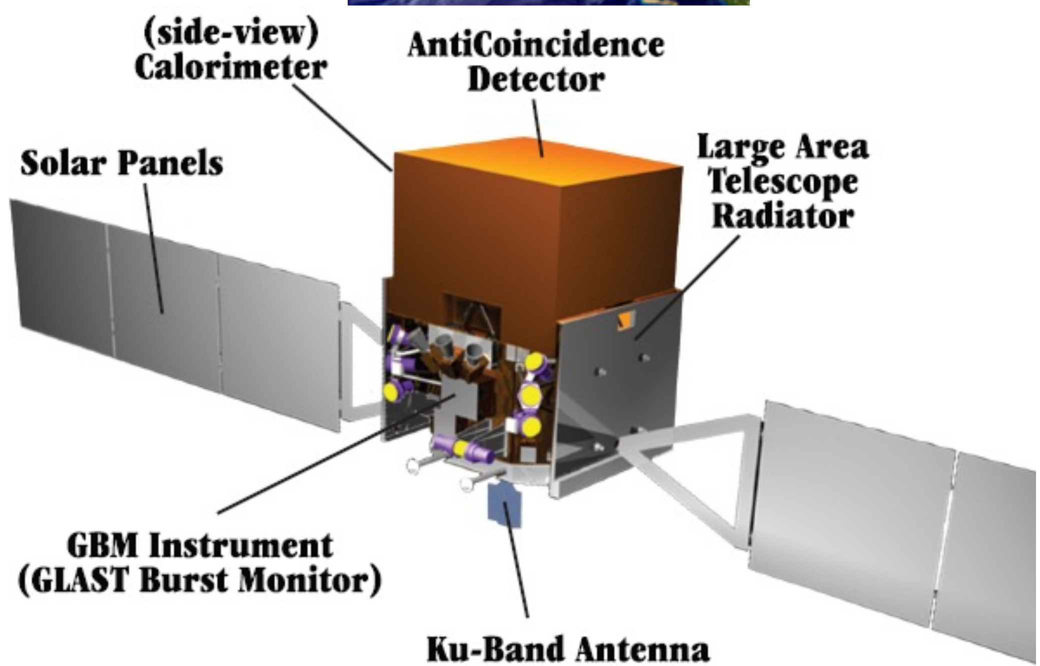


Aleksić et al., Science, 346(2014) 1080

FERMI – gamma telescope on board satelite

At the height 565 km

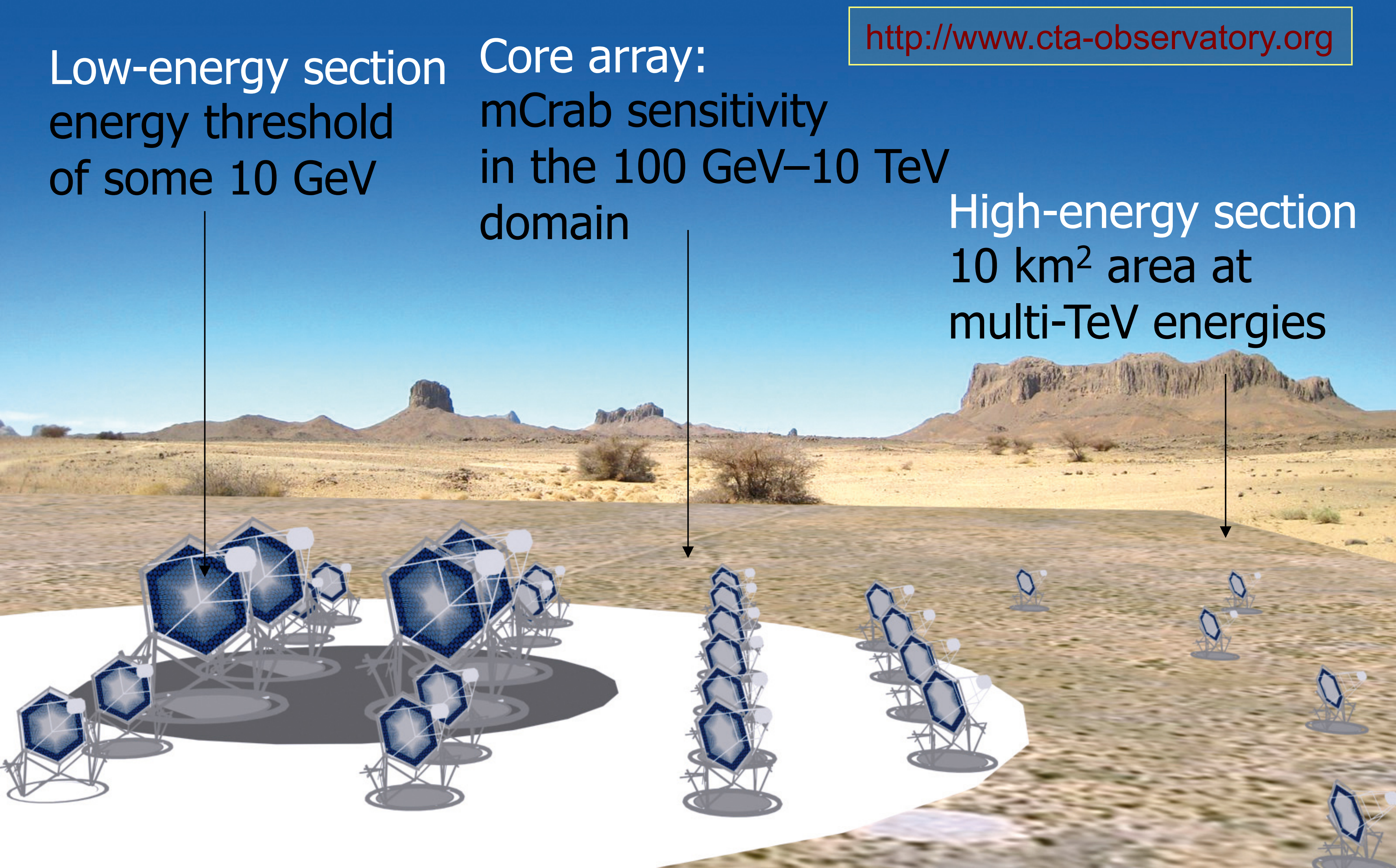
- Period 90 min
- Scan of whole sky in 3 hours
- Energy range:
  - **20 MeV – 300 GeV**



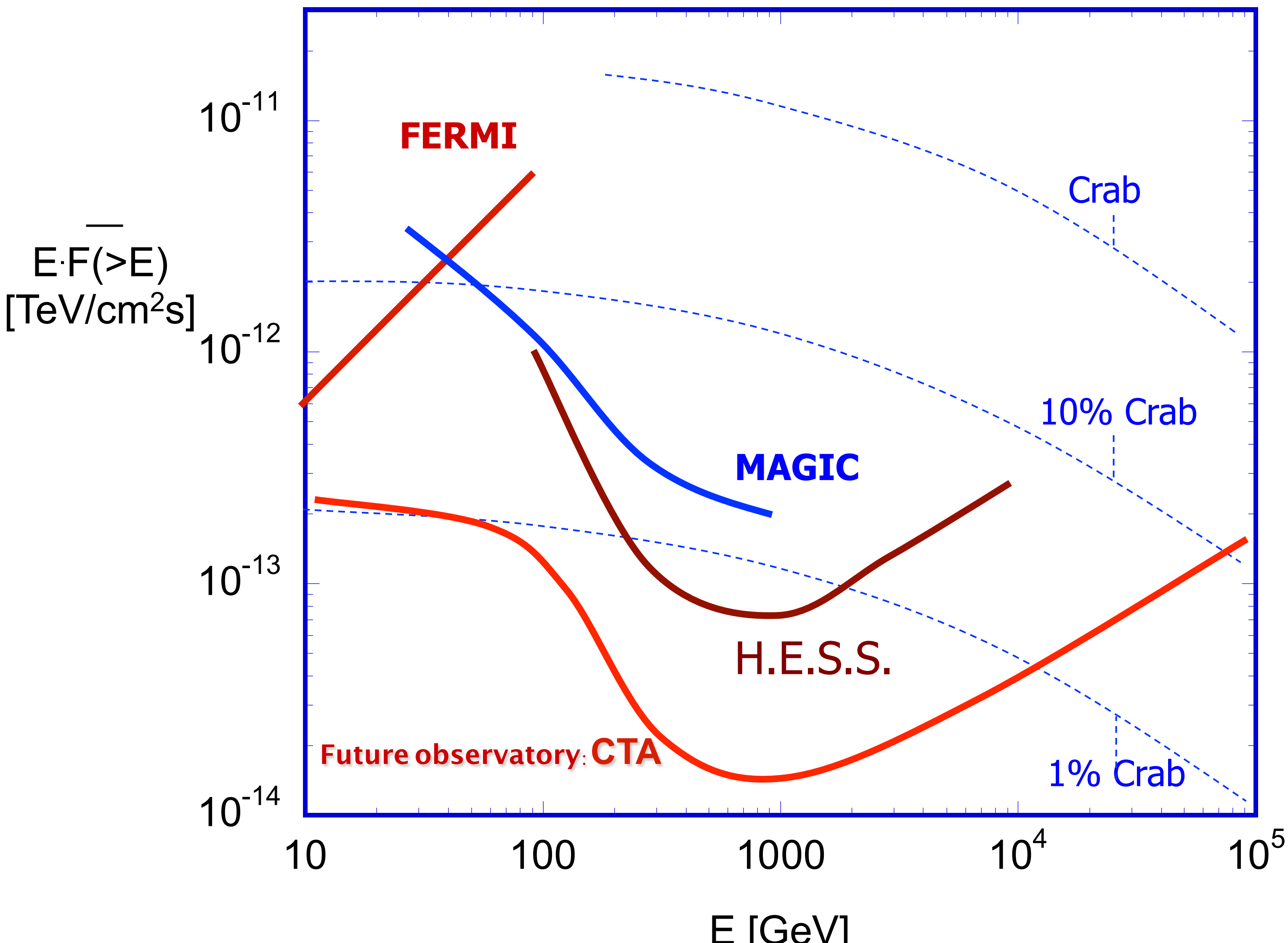
H.E.S.S. , MAGIC, VERITAS

	H.E.S.S. (I+II)	MAGIC	VERITAS
# telescopes	4 + 1	2	4
Field of view	5° + 3.2°	3.5°	3.5°
Dish diameter	12 m + 28 m	17 m	12 m
Energy threshold	160 + <100 GeV	50 GeV	85 GeV
Sensitivity	0.8% Crab Unit (25 h, H.E.S.S.-I)	0.8% Crab Unit (50 h, E ≥ 220 GeV)	1% Crab Unit (25 h)

Future: Cherenkov Telescope Array (CTA)



Sensitivity of gamma ray telescopes

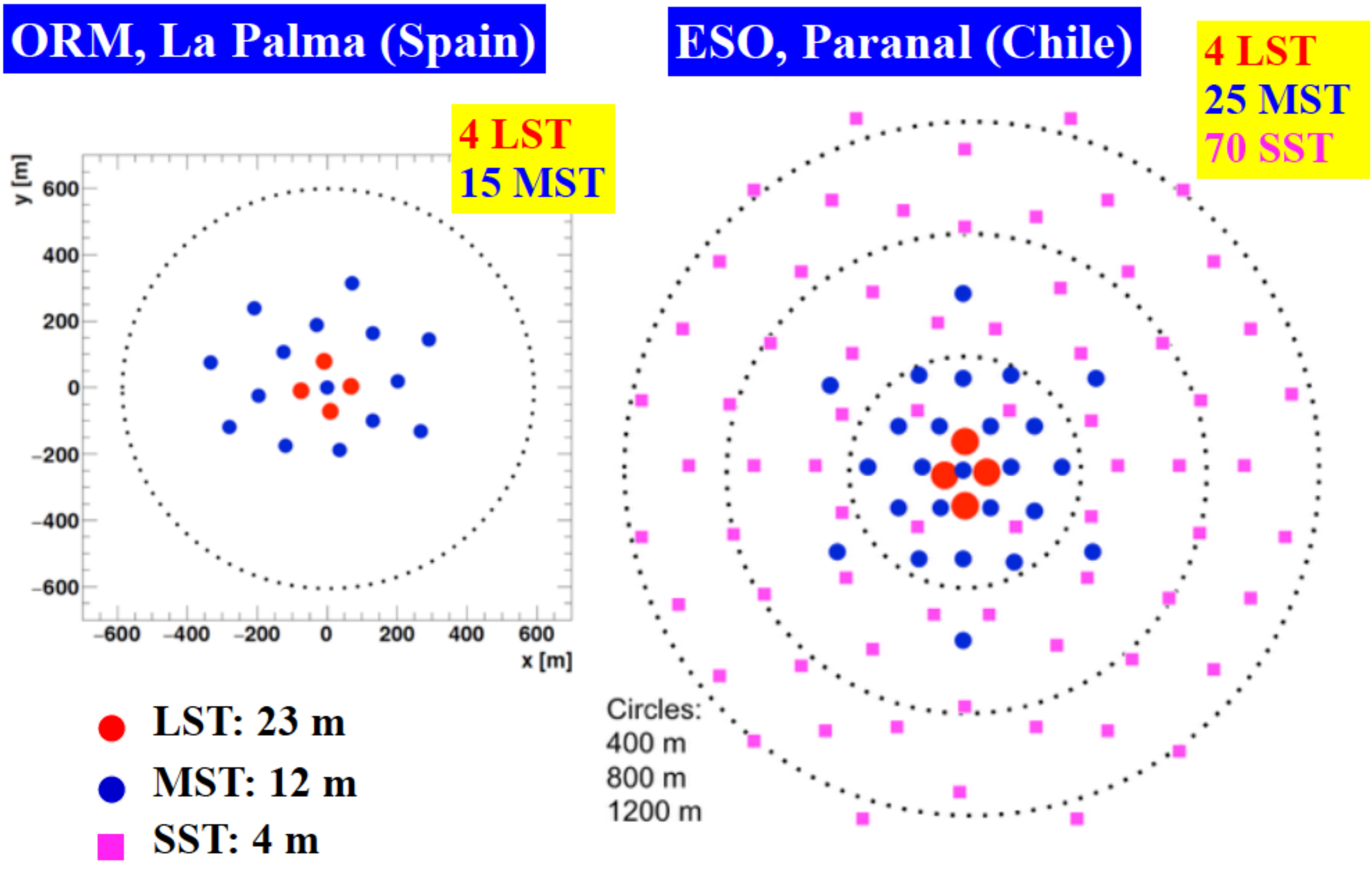


N. Godinovic, Tirana Workshop, September, 2016.

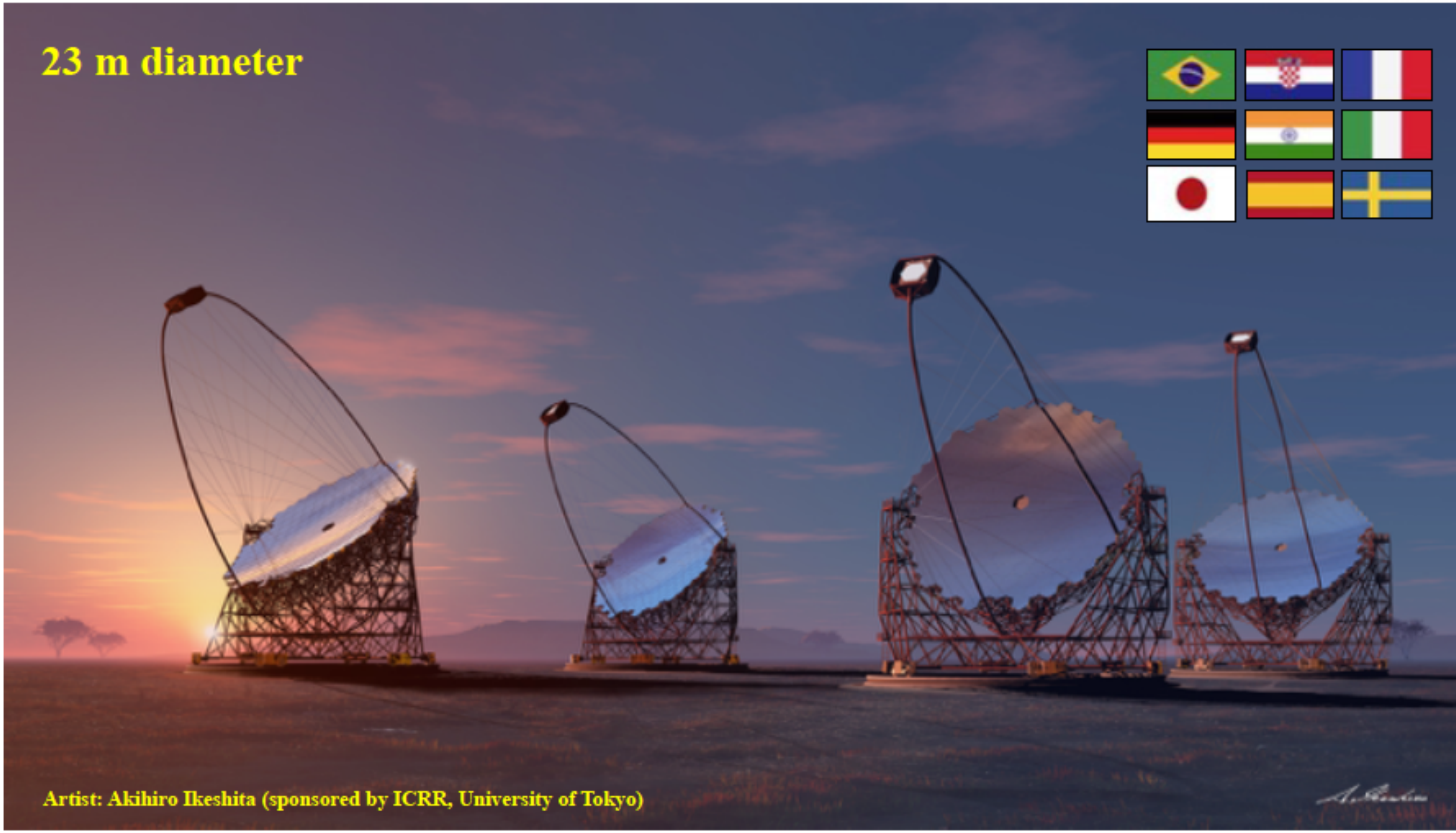
CTA telescopes types

Telescope	Large	Medium		Small		
	LST	MST	SCT	SST-1M	ASTRI	GCT
Energy range	20 - 200 GeV	200 GeV - 5 TeV		5 - 300 TeV		
No. telescopes (N/S)	4 / 4	15 / 25	TBD	0 / 70		
Optics type	Parabola	Davies-Cotton	Schwarzschild-Couder	Davies-Cotton	Schwarzschild-Couder	Schwarzschild-Couder
Focal length / Primary Mirror diameter [m]	28 / 23	16 / 13.8	5.6 / 9.7	5.6 / 4	2.15 / 4.3	2.28 / 4
Field of View [deg]	4.5	7.7 (FlashCam) 8.0 (NectarCam)	8.0	9.1	9.6	8.5 - 9.2
Pixel [deg] (detector)	0.1 (PMT)	0.18 (PMT)	0.07 (SiPM)	0.24 (SiPM)	0.17 (SiPM)	0.15 - 0.20 (SiPM)
No. of pixels	1855	1764 (F) 1855 (N)	11328	1296	1984	2048
Sampling rate	GHz	250 MHz (F) GHz (N)	GHz	250 MHz	(Integrated)	GHz
Weight	100	85	~85	9	15	8
Time for reposition [s]	<20	<90	<90	<60	<80	<60

CTA sites

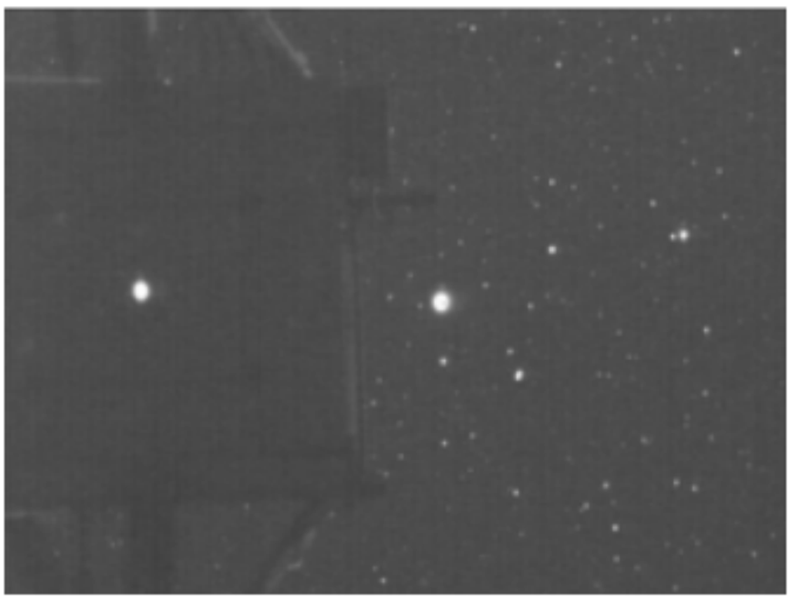

ORM, La Palma (Spain)
4 LST
15 MST
y [m]
600
400
200
0
−200
−400
−600
−600
−400
−200
0
200
400
600
x [m]
LST: 23 m
MST: 12 m
SST: 4 m
ESO, Paranal (Chile)
4 LST
25 MST
70 SST
Circles:
400 m
800 m
1200 m

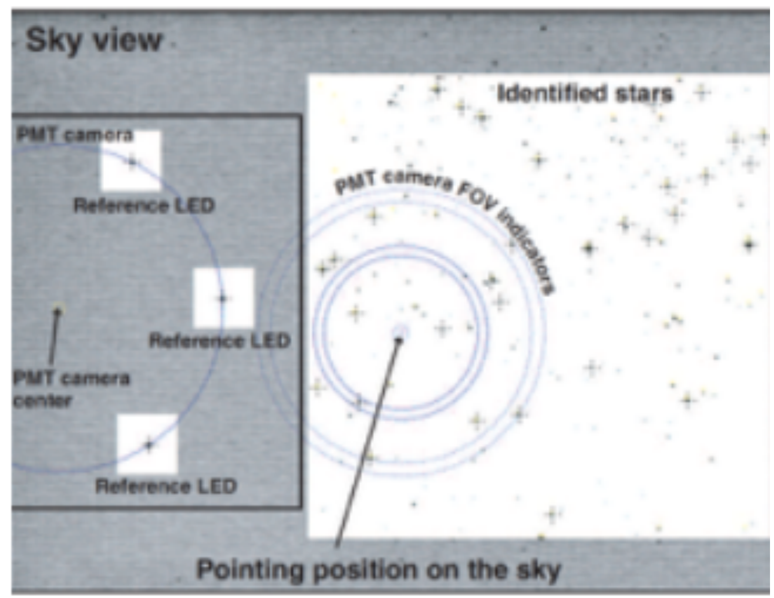
CTA – Large Size Telescope (LST)



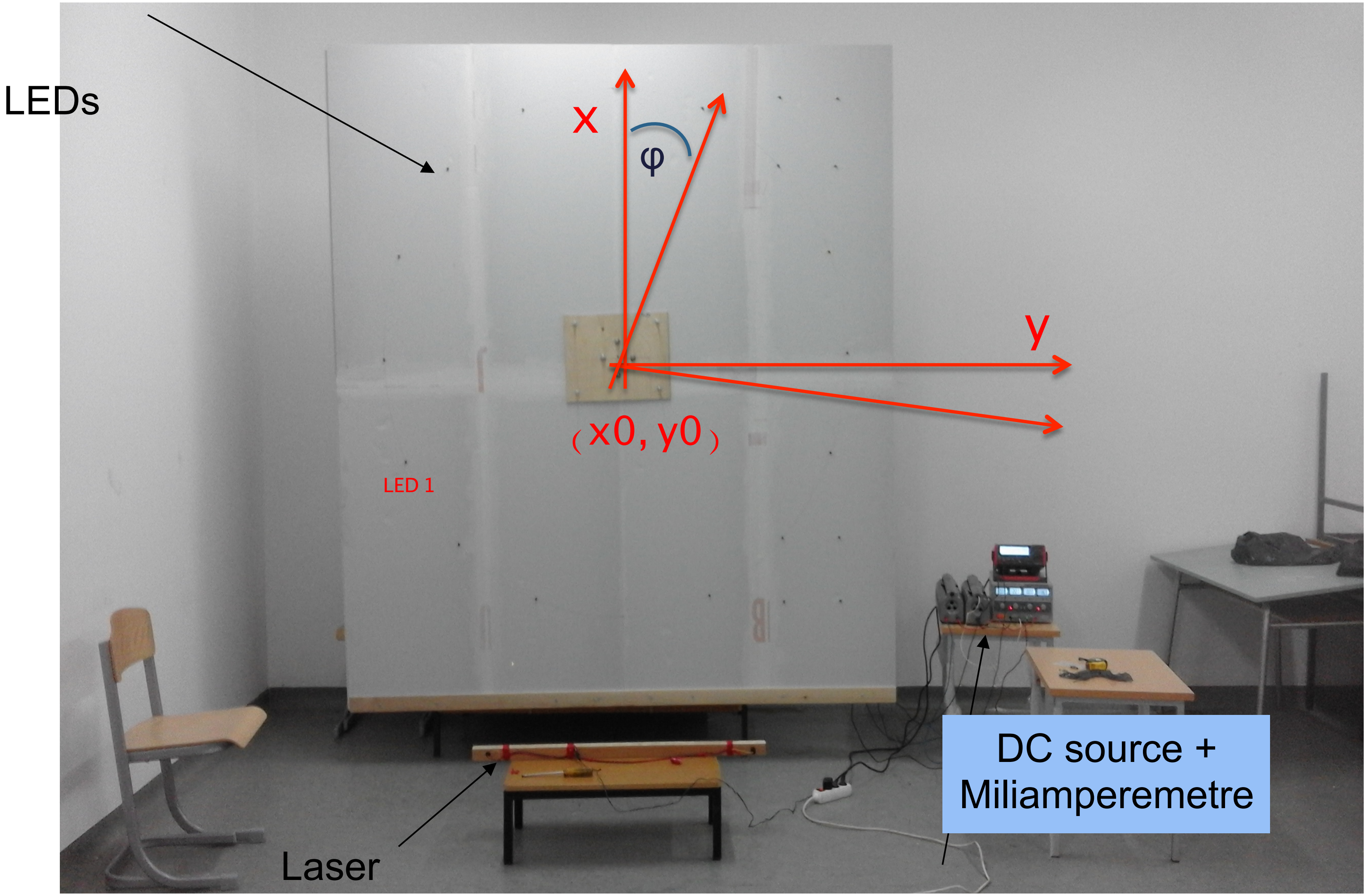
LST pointing precision – Croatian contribution

- LST pointing accuracy requirements: 10 arsec per axis
- Camera Displacement Monitor

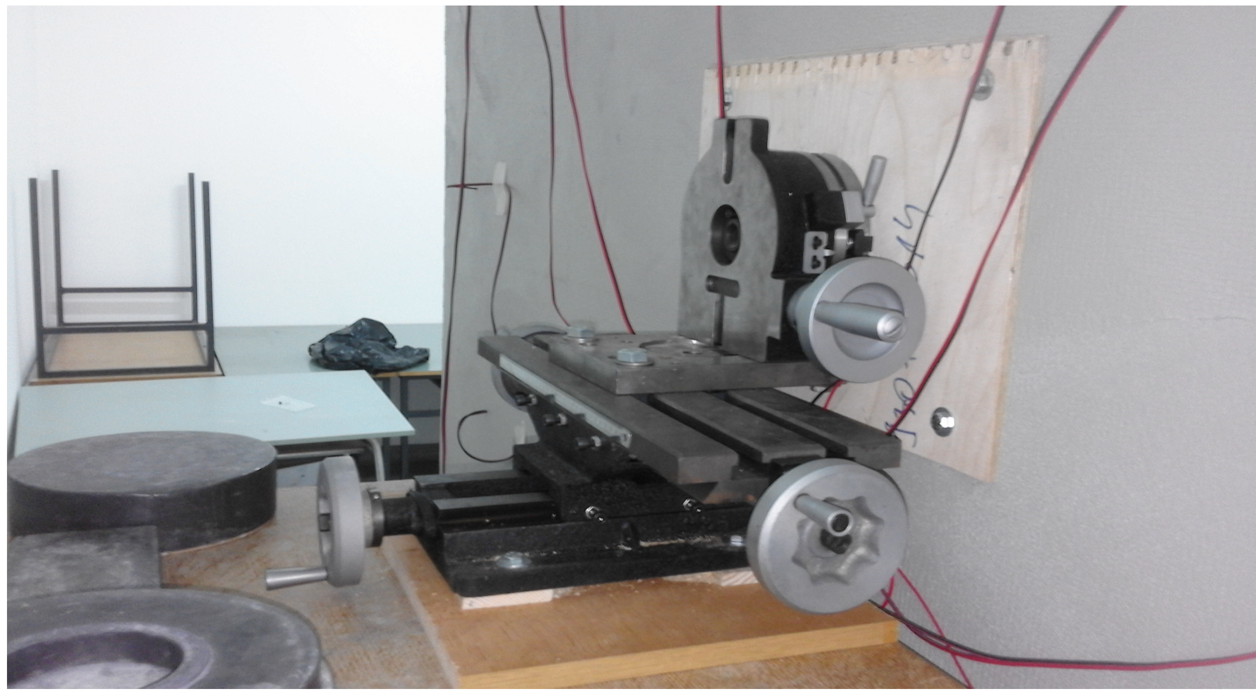




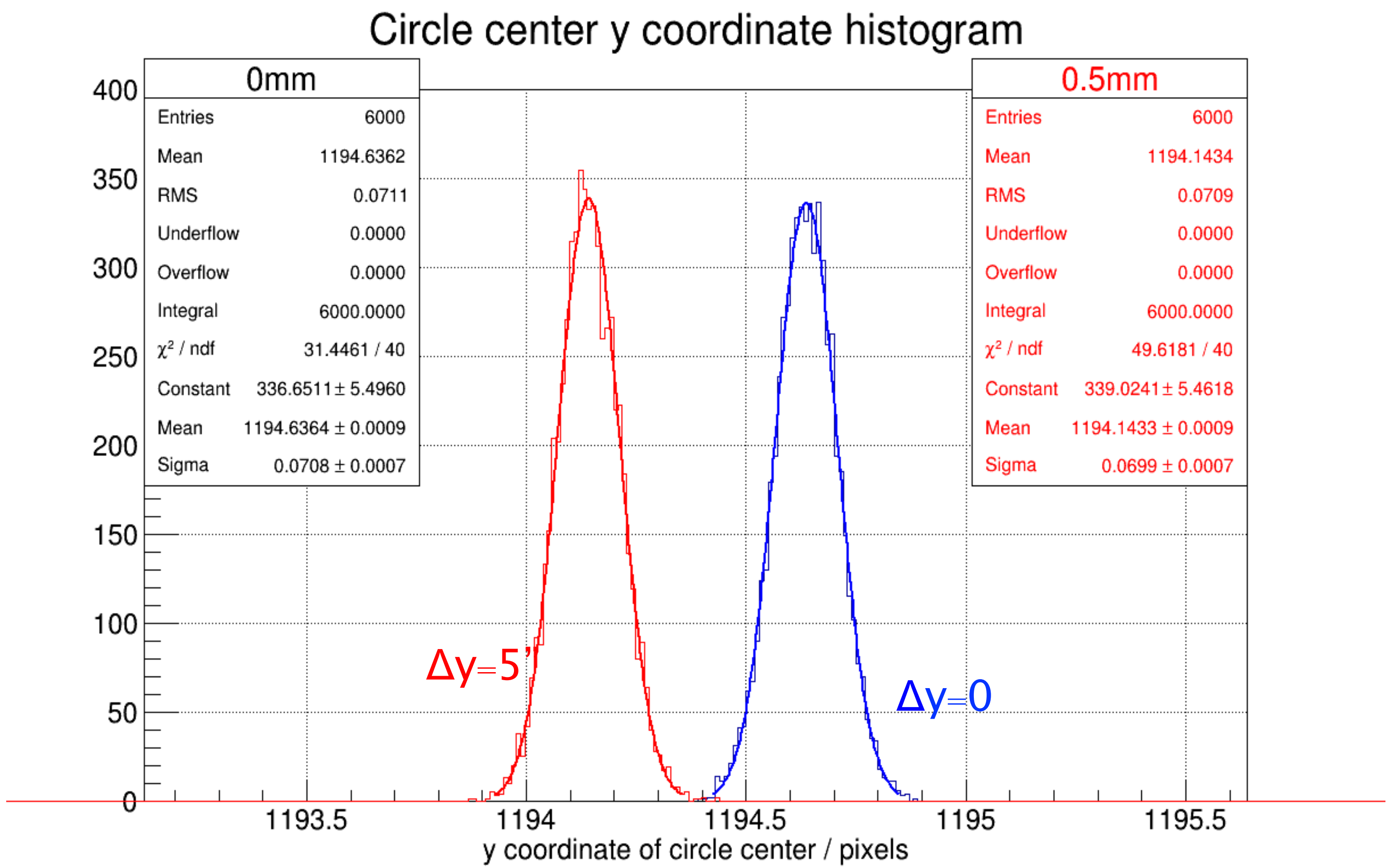
Setup & CDM coordinates



Lab set-up inSplit



Coordinates of the center of LED circle @ translation: Δx=0", Δy=5"



We can observe displacement with required precision of 5“

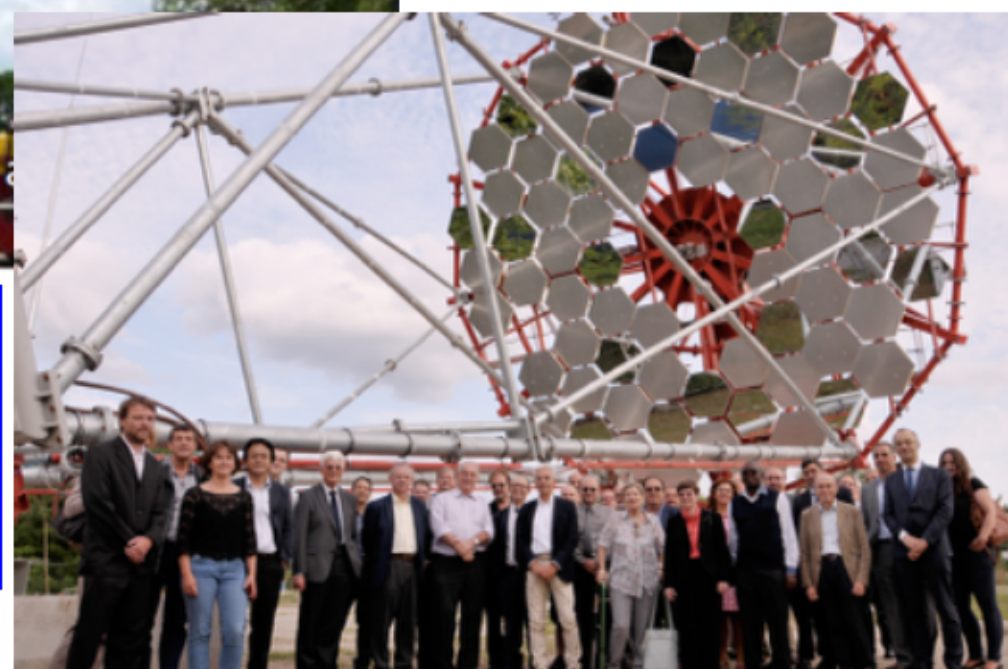
LST construction is ongoing

Medium Size Telescope (MST)

Modified Davies-Cotton design

- **12 m diameter**
- **90 m² effective mirror area**
- **1.2 m mirror facets**
- **16 m focal length**
- **8° field of view with 0.18° PMT pixels**

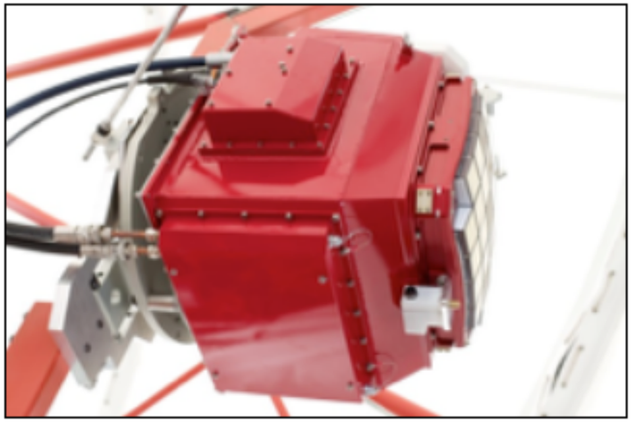
Mid energies (100 GeV – 10 TeV)
DM, AGN, Super Nova Remnant, Pulsar Wind Nebulae, binaries, starbursts, Extragalactic Background Light, InterGalactic Matter



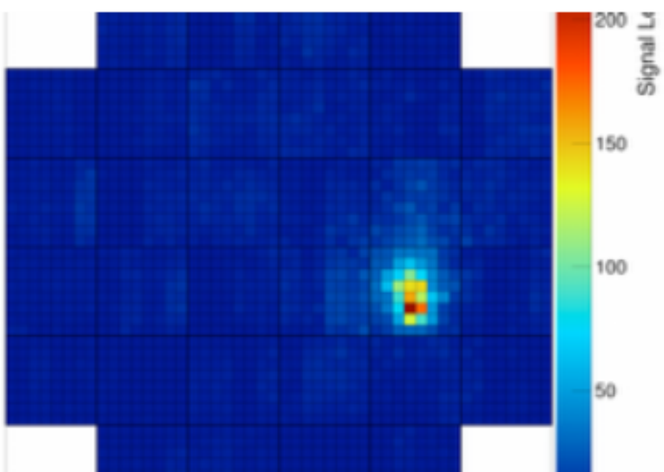
Prototype DESY Zeuthen

Small Size Telescope - GTC

Camera



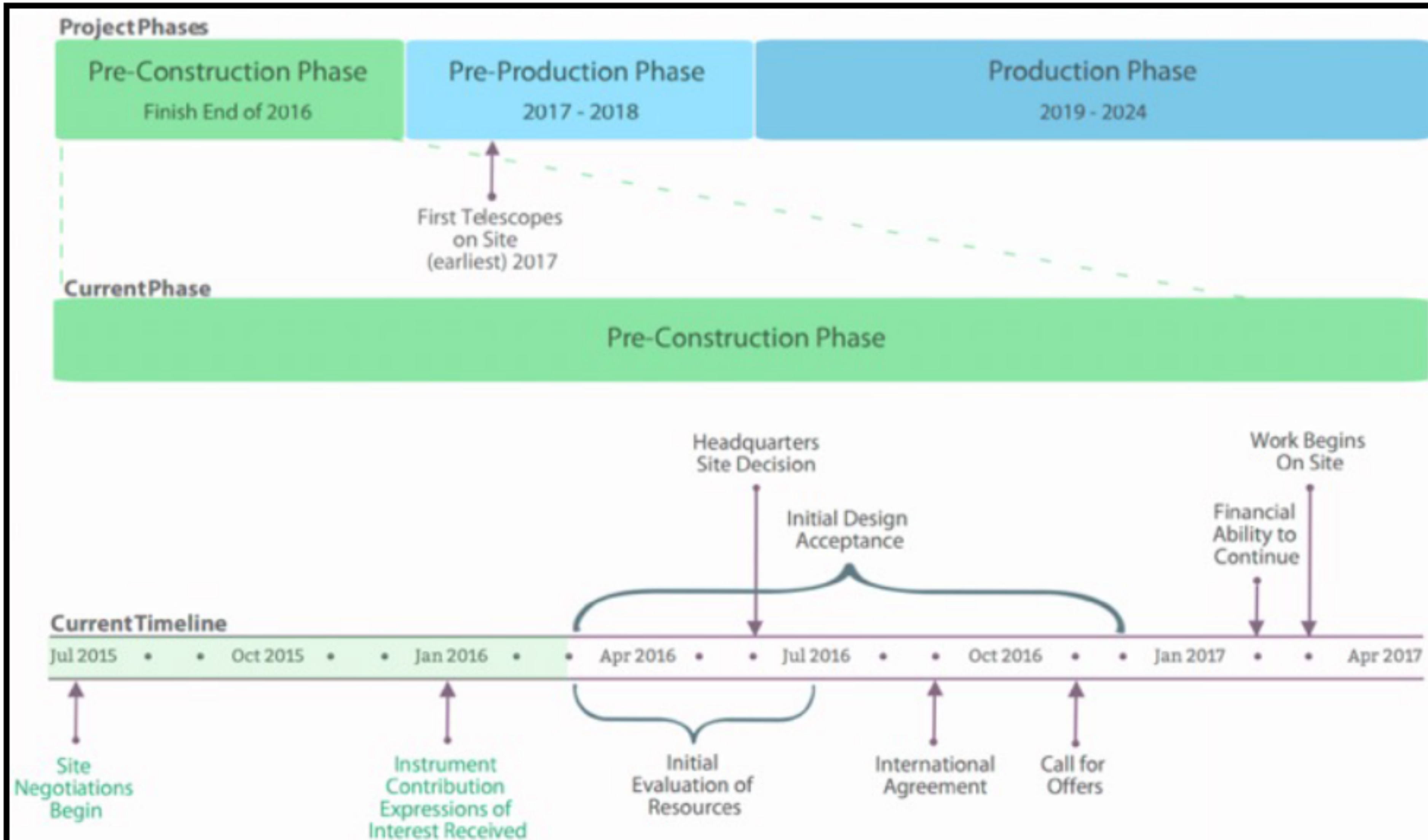
26/11/2015: First light!



GCT prototype: Observatoire de Paris, Meudon

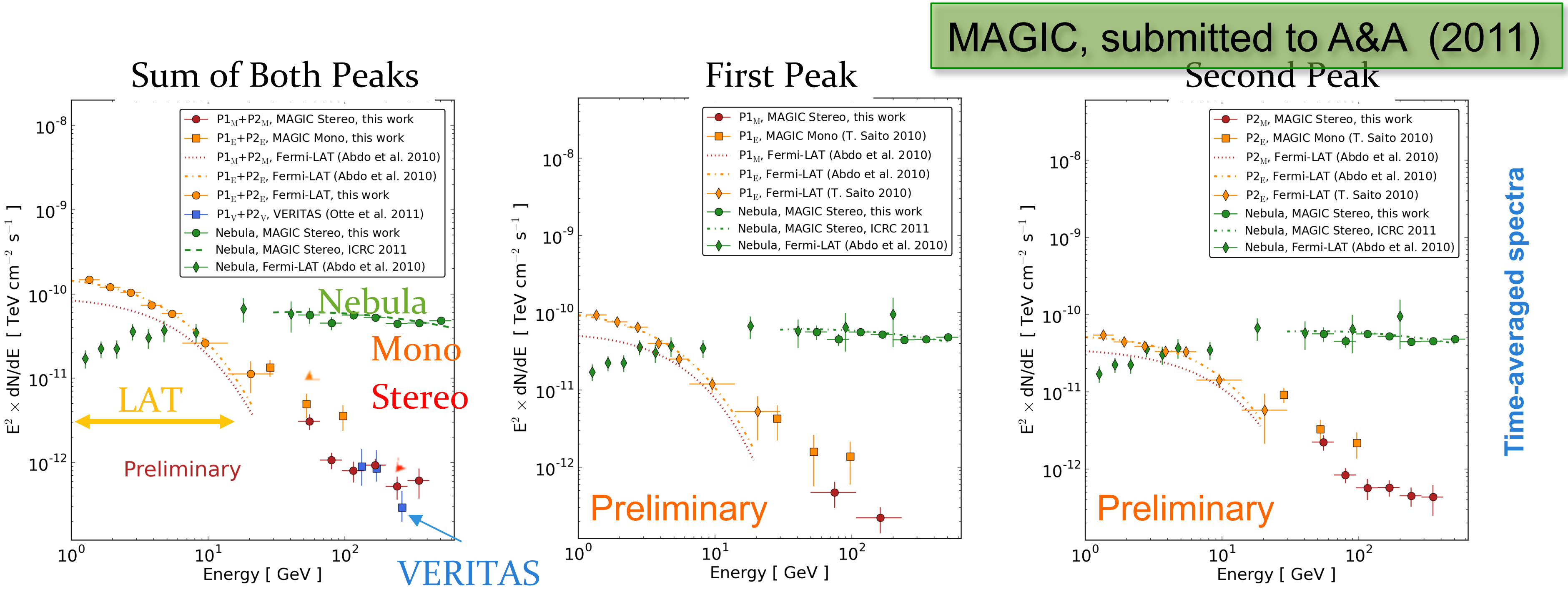
- **4 m primary diameter, 2 m secondary diameter**
- **6 m² effective mirror area**
- **2.3 m focal length**
- **8.6° field of view**
- **0.16° MAPM/SiPM pixels**

CTA timeline



Thanks

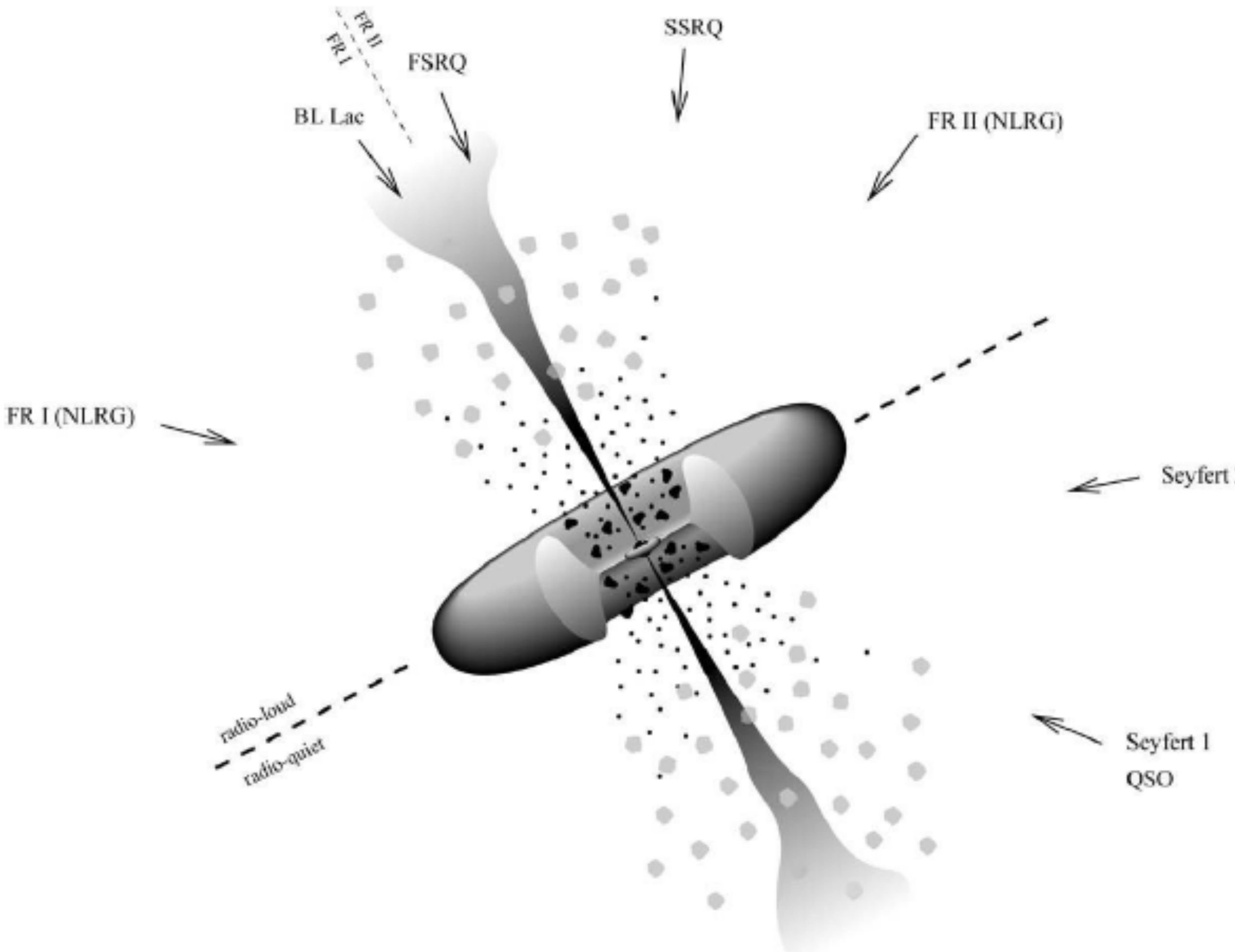
Crab pulsar (73 hours of stereo data)



- Stereo data provides precise spectra up to 400 GeV.
- No gap between Fermi and MAGIC.
- We can even produce spectra for both peaks separately.
- Mono/stereo spectra agree… and go well beyond a cutoff at few GeV!

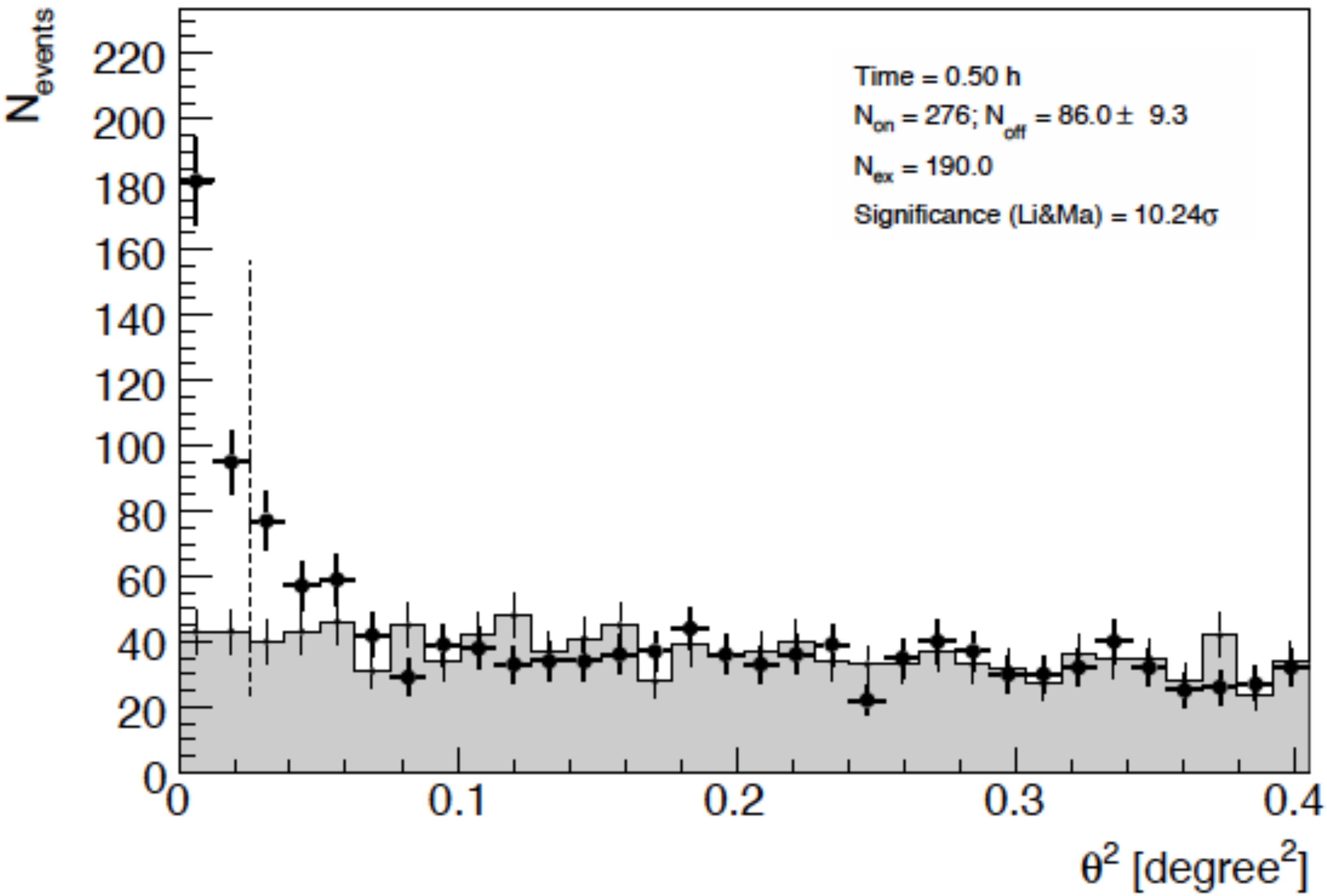
Active galactic nucleai

Active galactic nucleai



FSRQ – PKS1222+21 ($C21.35, z=0,432)

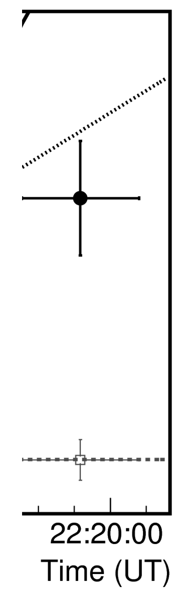
- PKS1222+21 – discovered by MAGIC within cca. 30 min. 10.2σ



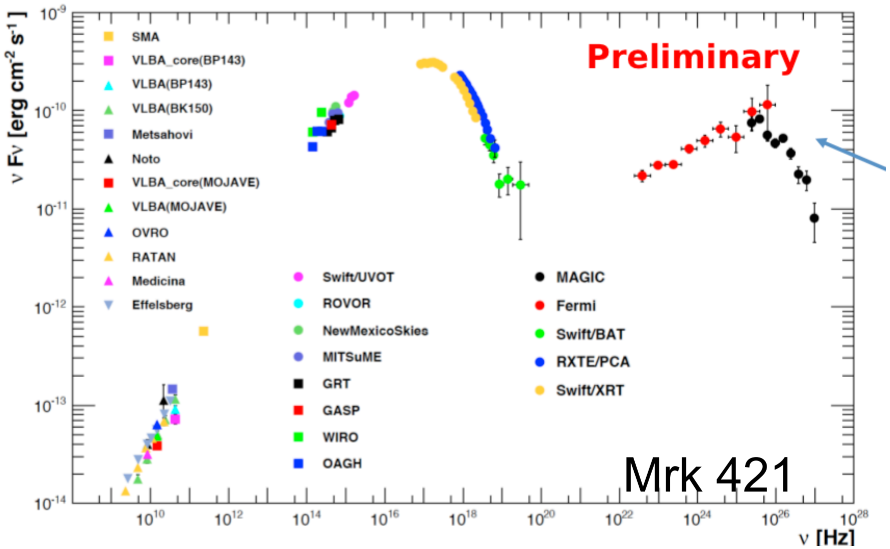
) VHE

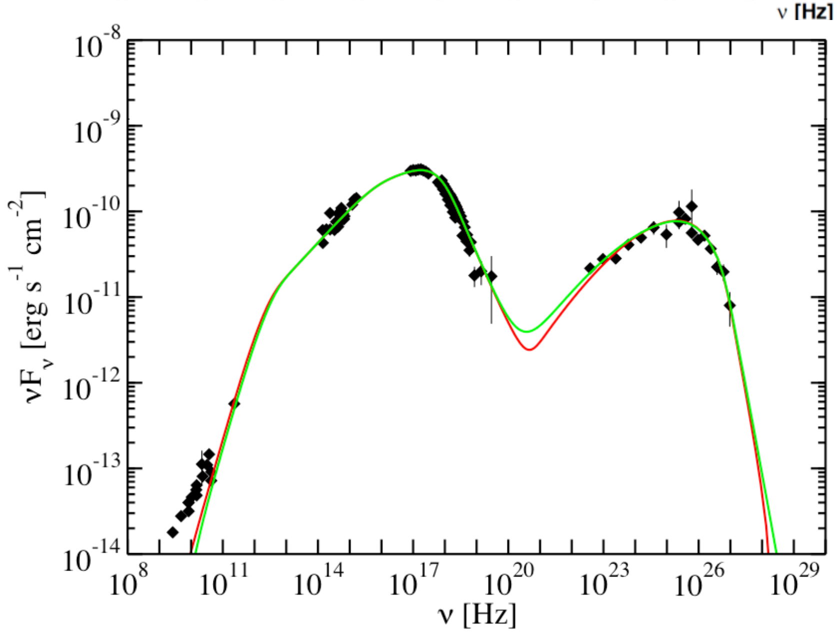
hift ”

cm^{-2}s^{-1})



Multiwavelenght observations





MWL observations involving many instruments, lately also Fermi, allow to generate more detailed SEDs of sources.

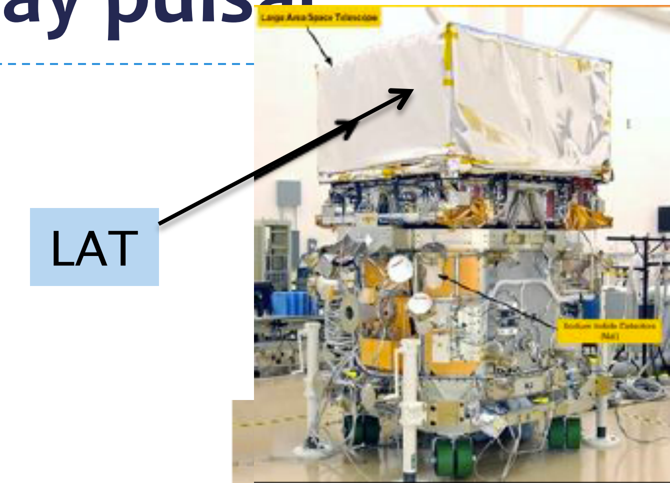
Illustration: Abdo et al 2011, ApJ 736, 131

Unprecedented SED sampling demands modeling with a double broken power law electron distribution and allows to put tight constraints on the model parameter space.

Most complete SED ever collected

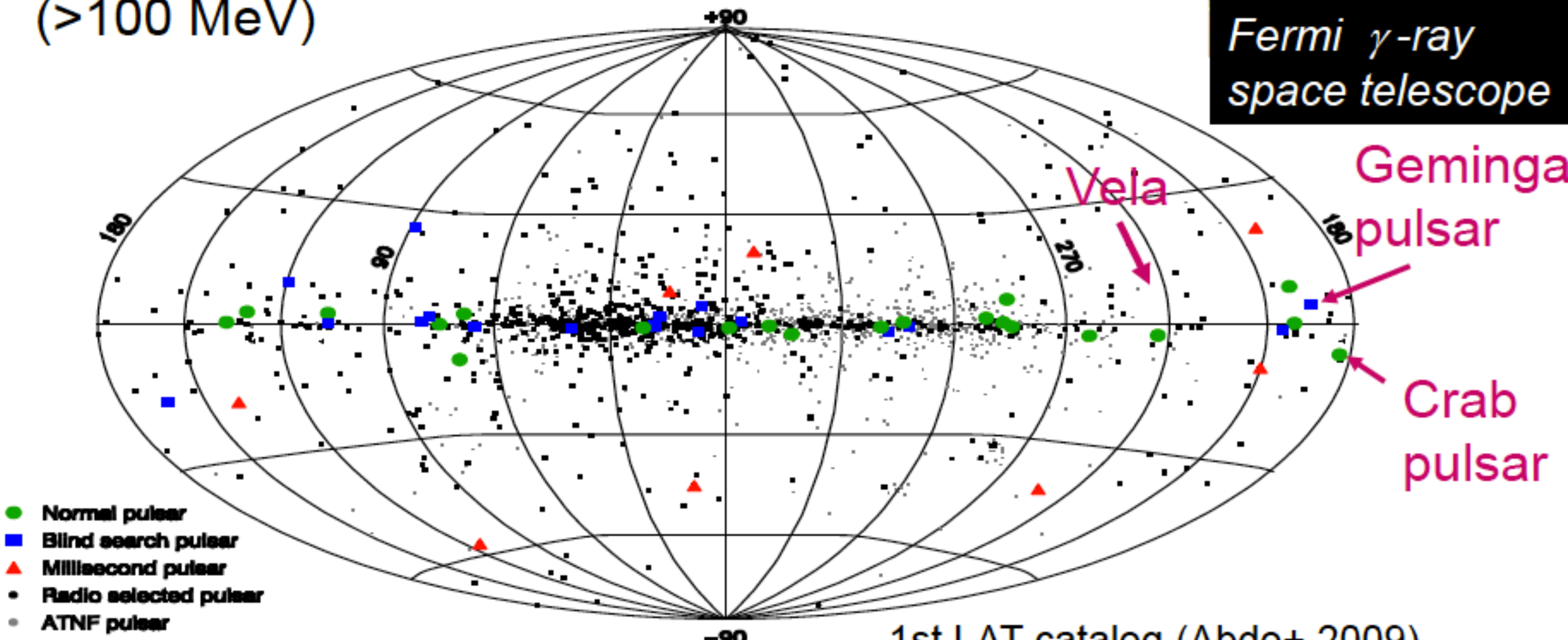
Fermi catalog of gamma-ray pulsar

After 2008 LAT onboard Fermi detected
> 100 pulsar with E > 100 MeV



Fermi γ-ray space telescope

Fermi/LAT point sources (>100 MeV)



1st LAT catalog (Abdo+ 2009)

Final remark

- Particle physics started as astroparticle physics and it is coming back … EHE particle comes for free from space, make use of them …
- Advance of technology and understanding of elementary particle physics allow us to study the most violent process in the universe which are inaccessible in the laboratory
- Ground based (Imaging Atmospheric Cherenkov Telescope) IACT technique is inexpensive and becoming more and more mature technique to explore the non-thermal universe – the most violent processes in the universe