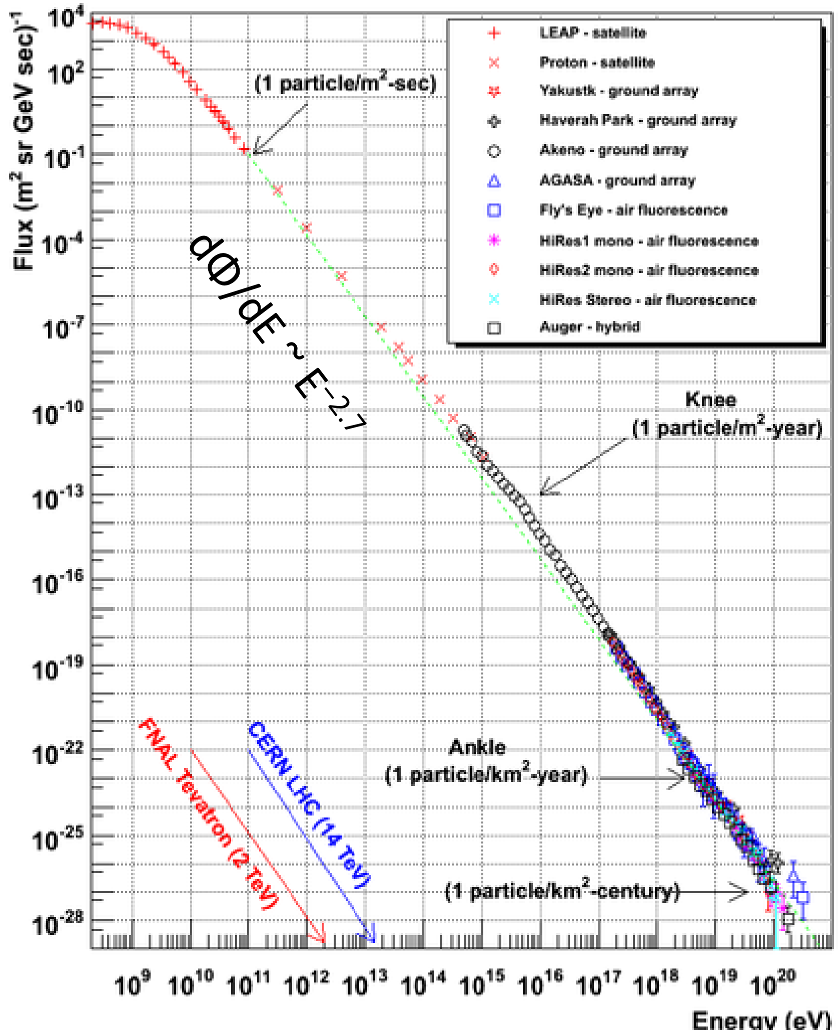
Gamma-ray observations with Imaging Atmospheric Cherenkov Telescopes

Abelardo Moralejo Olaizola
Instituto de Física de Altas Energías, Barcelona

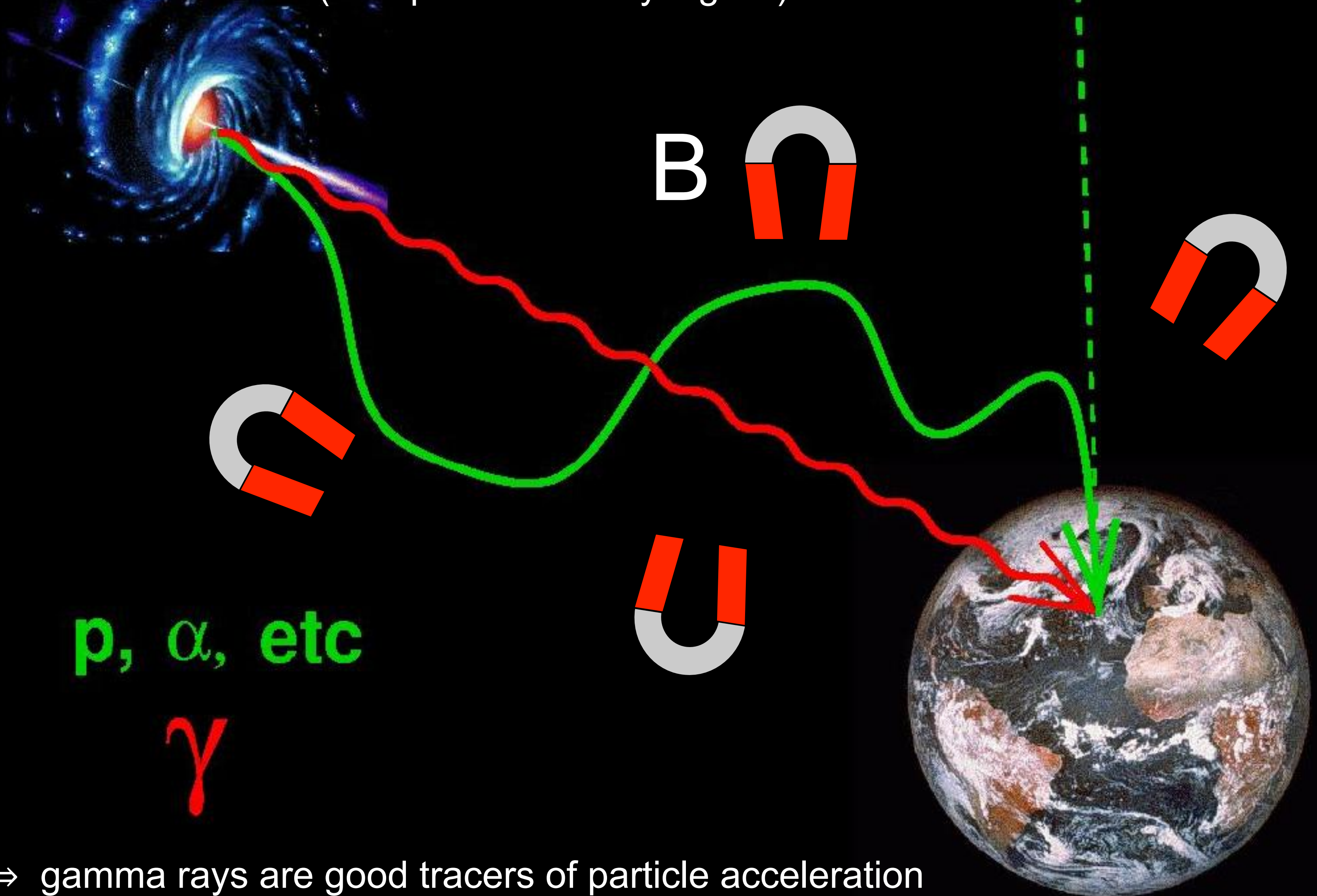
ISAPP school 2018 – LHC meets cosmic rays

Where do cosmic rays come from?



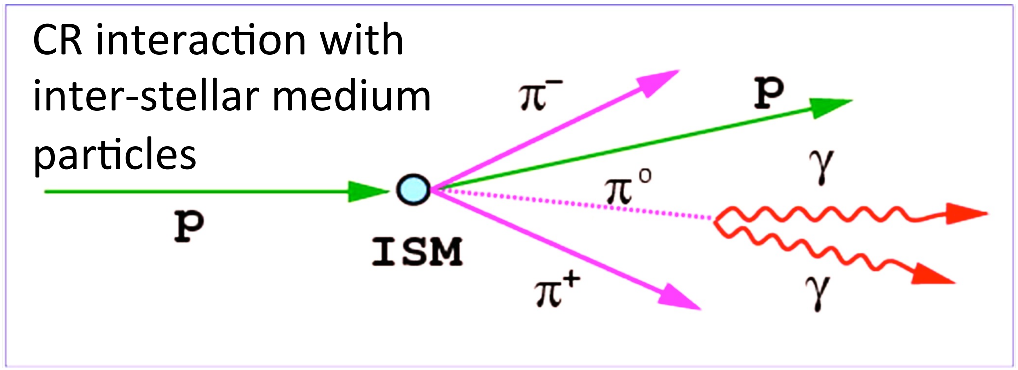
- Spectrum of cosmic-ray nuclei, coming (above few GeV) from beyond the solar system, extend over >10 decades in E
- Presumably of galactic origin up to ~few PeV ("the Knee")

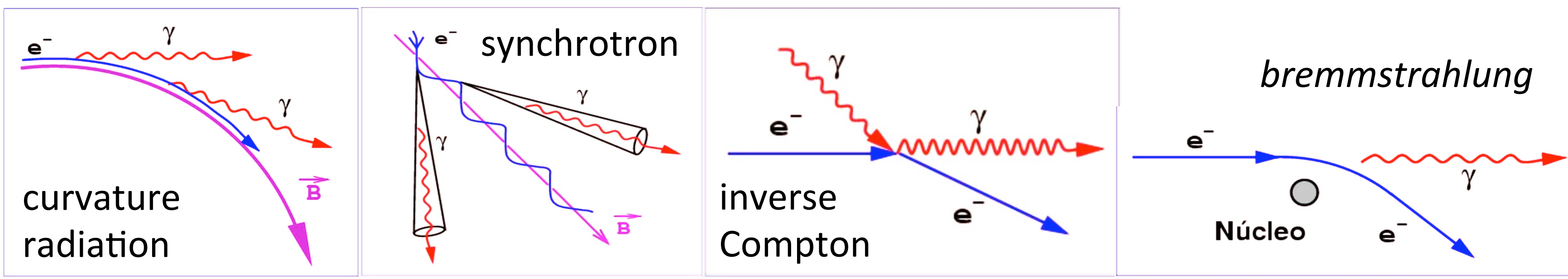
Charged cosmic rays, deviated by magnetic fields in the galaxy, provide no clue of their acceleration location (except at extremely high E)



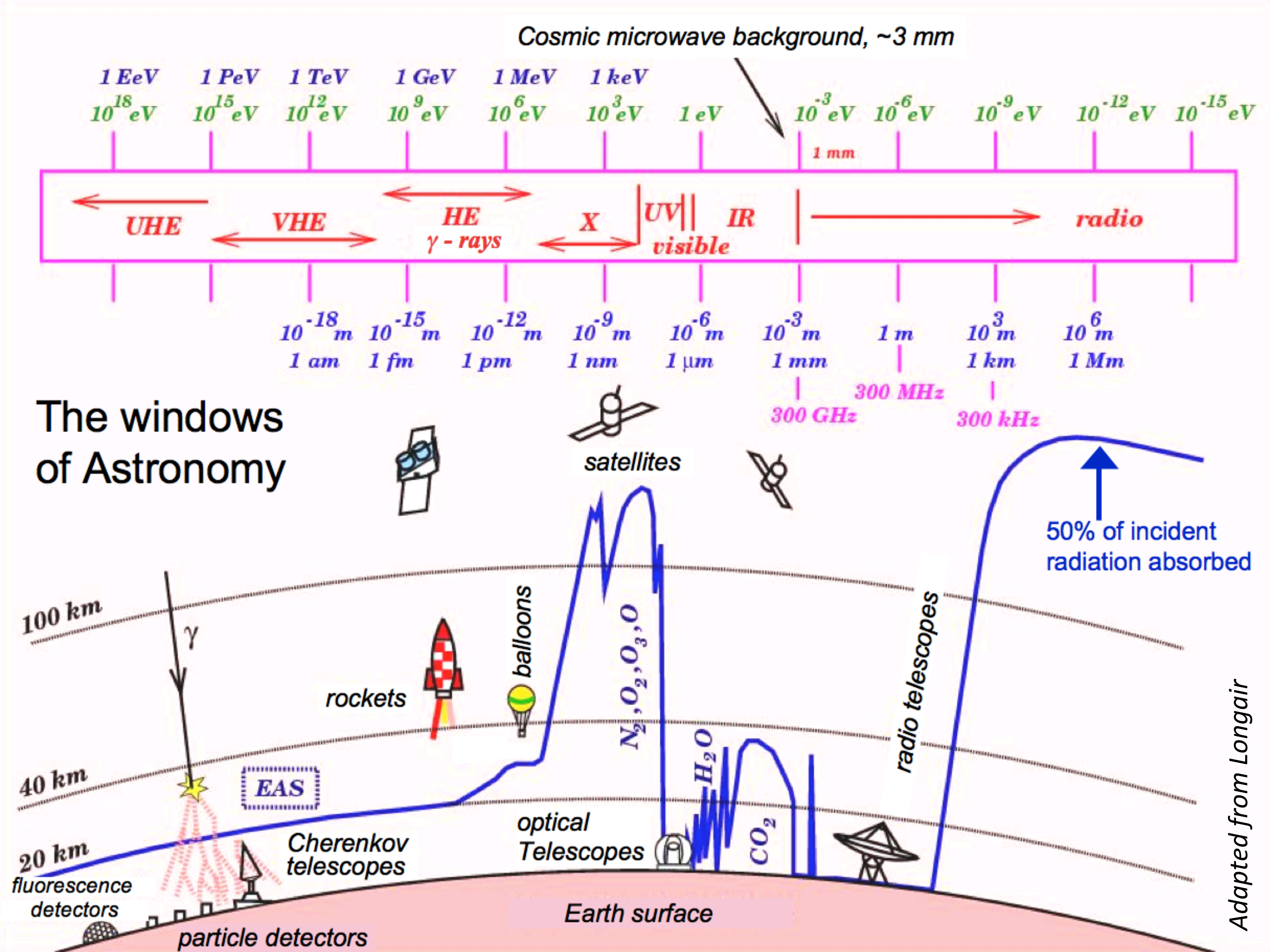
⟹ gamma rays are good tracers of particle acceleration
(so are ν's, but they are much harder to detect)

High-energy particles + target (matter, radiation or ***B*** field) ⟹ production of high-energy gamma rays





⟹ gamma rays will almost certainly be a by-product of the acceleration of charged particles



Cosmic microwave background, ~3 mm
1 EeV
1 PeV
1 TeV
1 GeV
1 MeV
1 keV
10^18 eV
10^15 eV
10^12 eV
10^9 eV
10^6 eV
10^3 eV
1 eV
10^-3 eV
10^-6 eV
10^-9 eV
10^-12 eV
10^-15 eV
1 mm
UHE
VHE
HE
γ - rays
X
UV
visible
IR
radio
10^-18 m
1 am
10^-15 m
1 fm
10^-12 m
1 pm
10^-9 m
1 nm
10^-6 m
1 µm
10^-3 m
1 mm
1 m
10^3 m
1 km
10^6 m
1 Mm
300 GHz
300 MHz
300 kHz
The windows of Astronomy
satellites
50% of incident radiation absorbed
100 km
γ
rockets
balloons
N2,O2,O3,O
radio telescopes
H2O
CO2
40 km
EAS
20 km
Cherenkov telescopes
optical Telescopes
fluorescence detectors
particle detectors
Earth surface
Adapted from Longair

X-ray and γ-ray astronomy

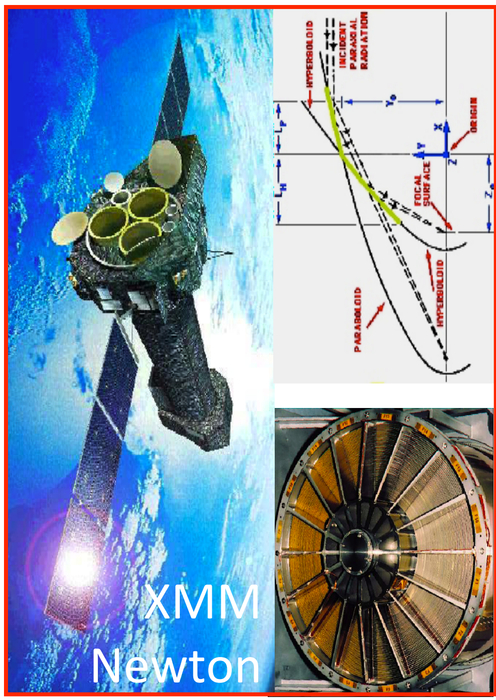
keV MeV GeV

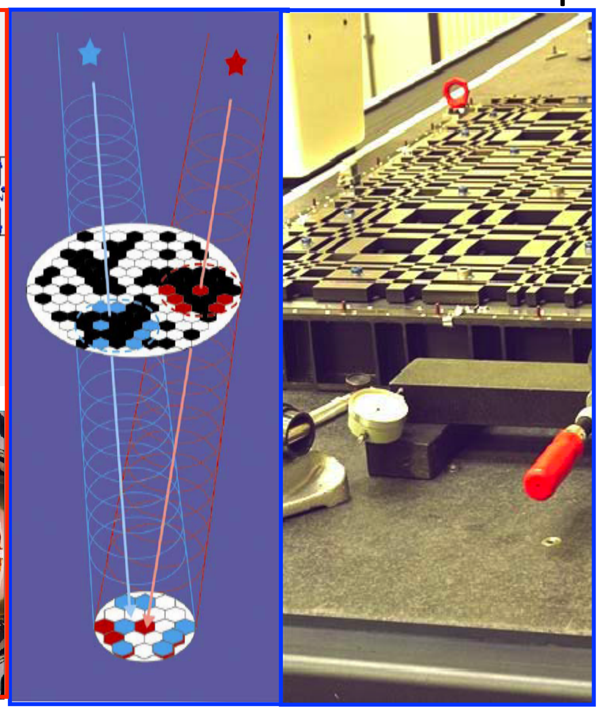
Focusing instruments

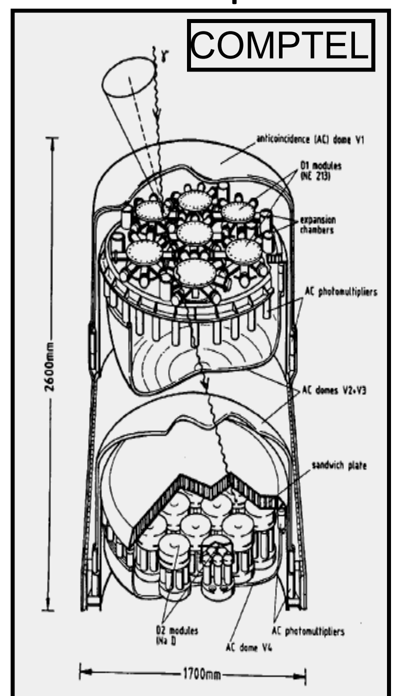
Coded masks, collimators
(i.e. INTEGRAL)

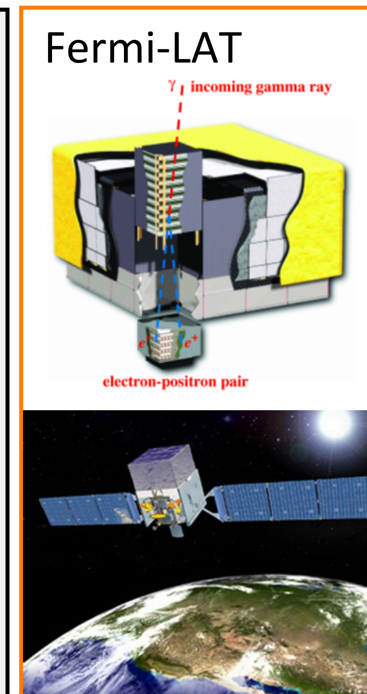
Compton telescopes

Pair conversion telescopes
(until ~300 GeV)

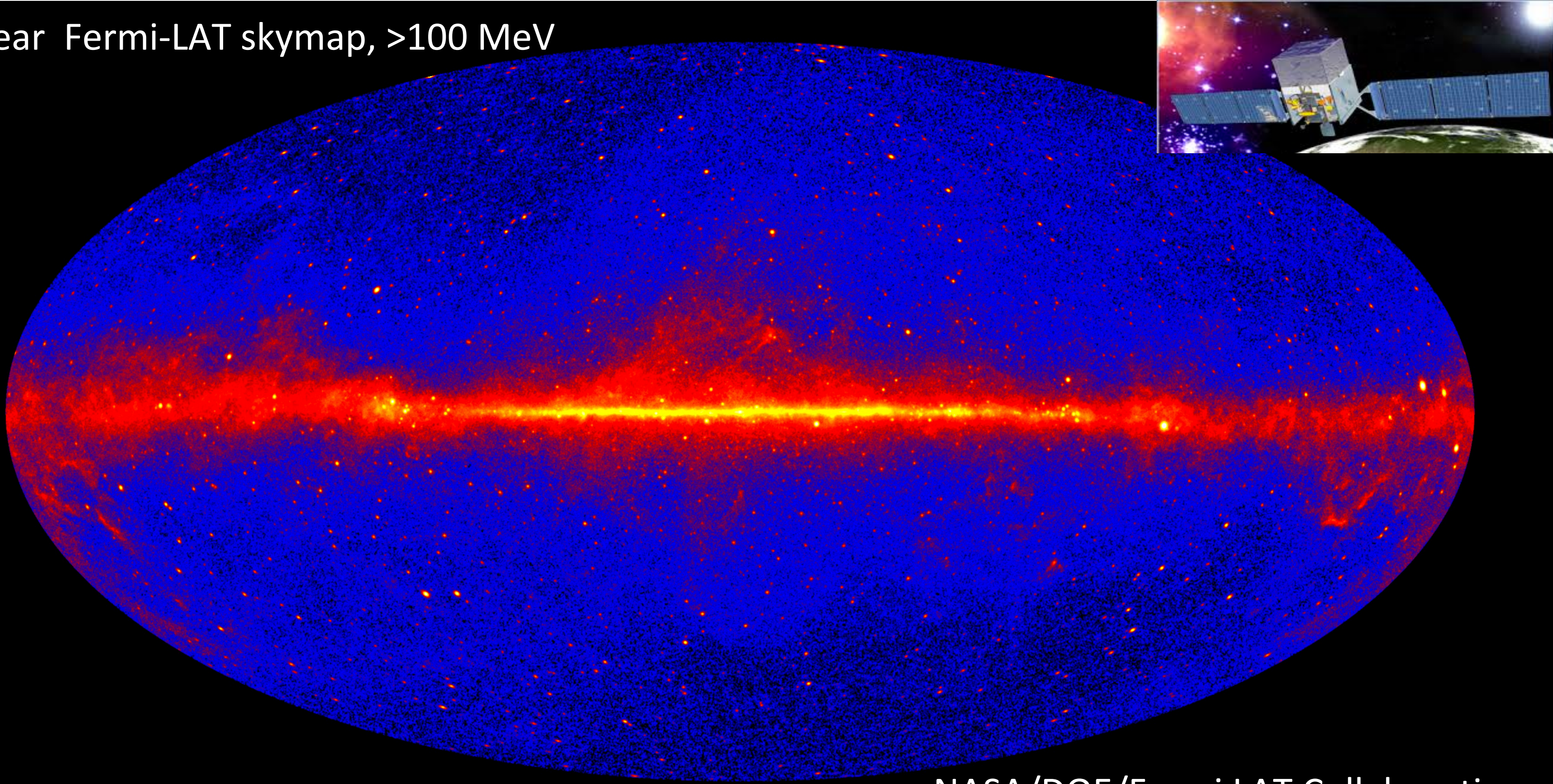






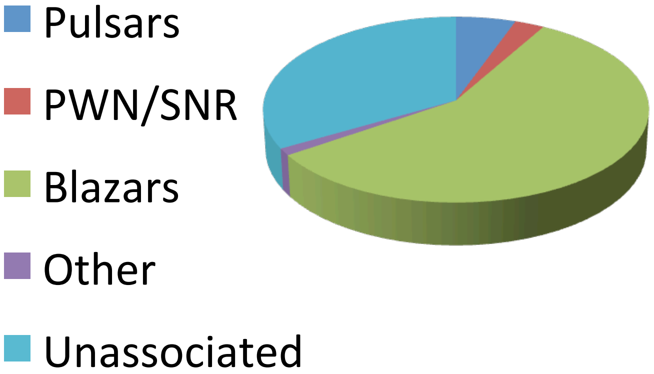


9-year Fermi-LAT skymap, >100 MeV



NASA/DOE/Fermi LAT Collaboration

- Diffuse emission + discrete sources
- As of 3FGL (4-year source catalog), 3033 sources



Fermi-LAT 2FHL catalog ApJS 222 (2016)

50 GeV – 2 TeV
360 sources

6.7 years of data
6.1×10^4 photons

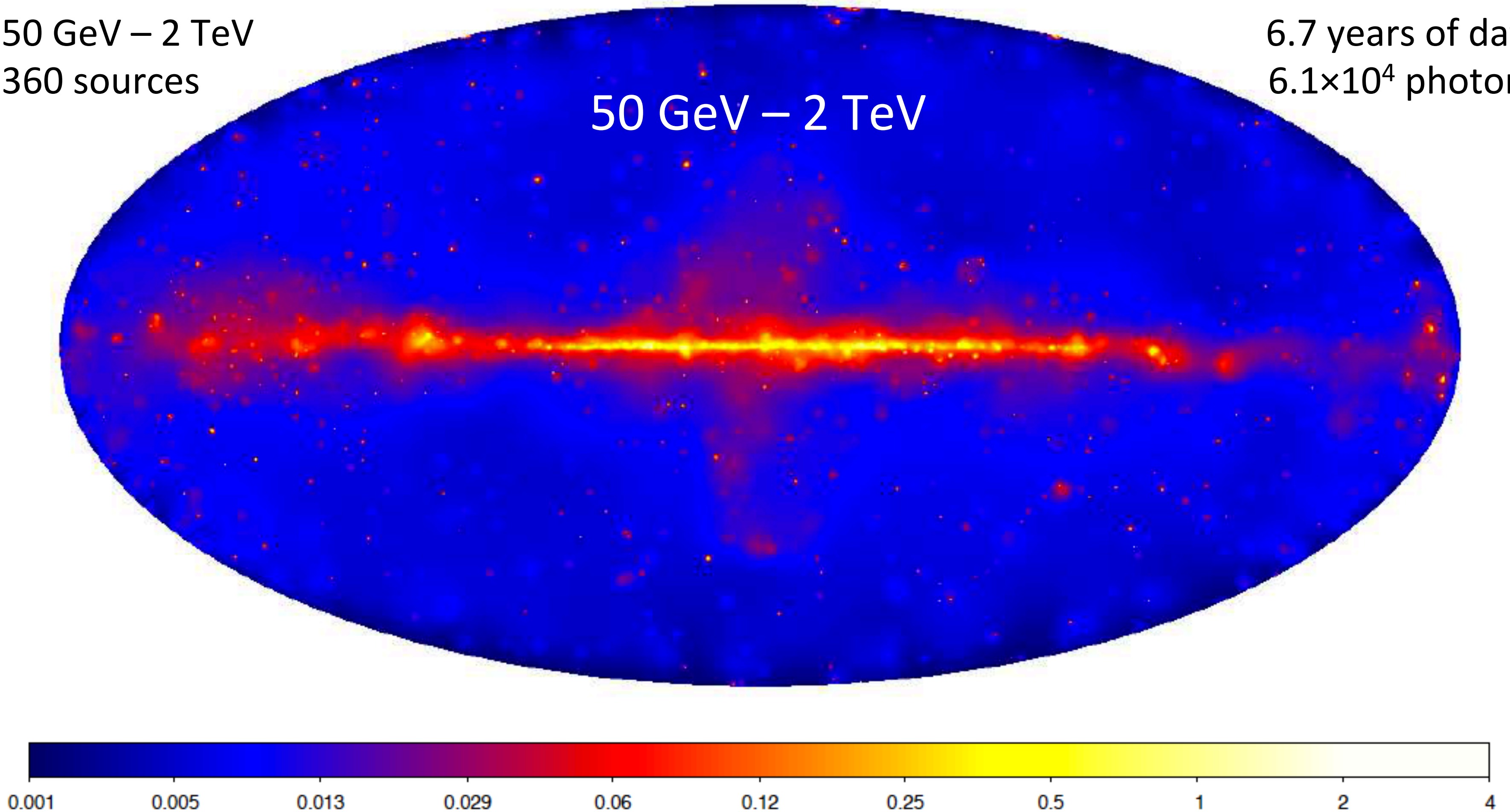


Fig. 1.— Adaptively smoothed count map in the 50 GeV–2 TeV band represented in Galactic coordinates and Hammer-Aitoff projection. The image has been smoothed with a Gaussian kernel whose size was varied to achieve a minimum signal-to-noise ratio under the kernel of 2. The color scale is logarithmic and the units are counts per $(0.1\,\mathrm{deg})^2$.

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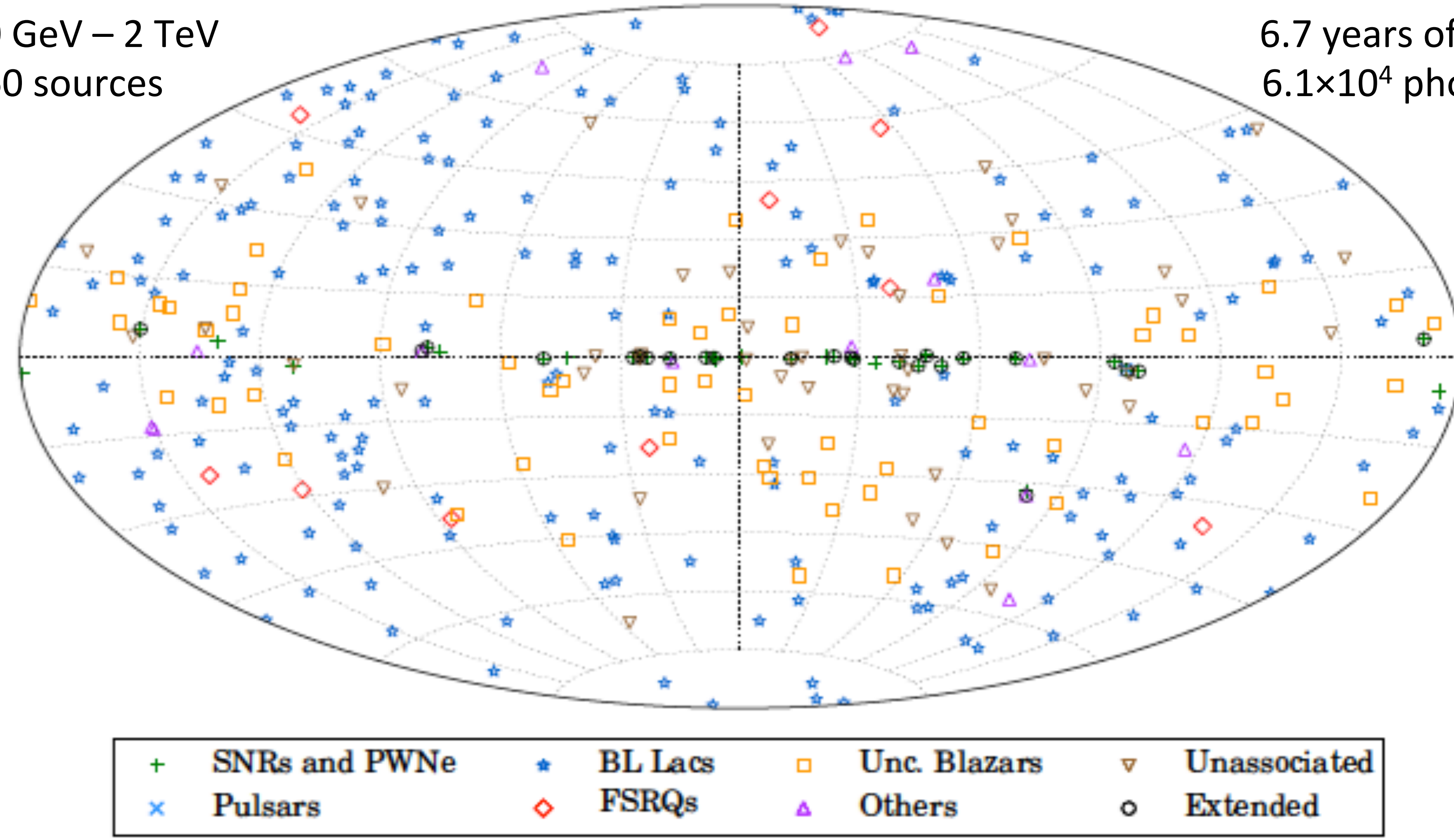


- CR accelerators are likely among these sources – do they reach high-enough energies? Where are the PeVatrons?

Limitations of space γ-ray telescopes in the VHE range (>100 GeV)

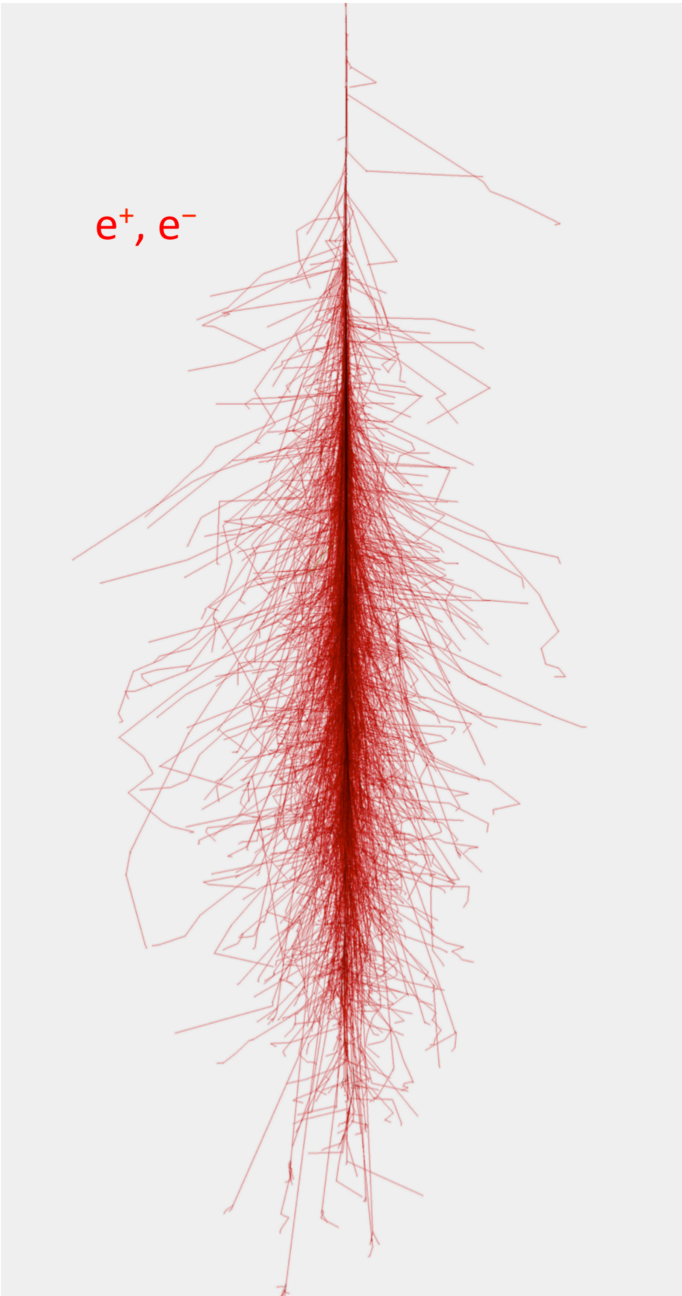
- Small effective area results in extremely low detection rates at E > 100 GeV, even for strong sources :

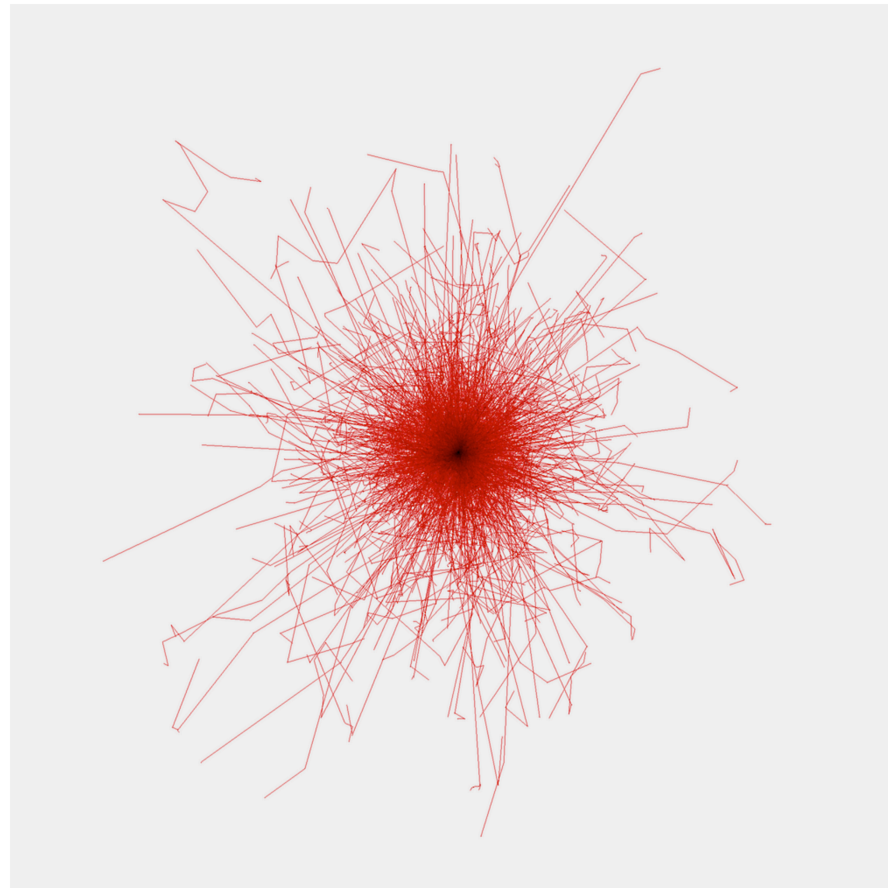
$$\Phi_{Crab,E>100GeV} \cong 100 \text{ photons/m}^2\text{/year}$$

- Calorimeter depth ≤ 10 radiation lengths (current instruments) ⇒ showers from VHE gammas leak out of the calorimeter

Fortunately, the Earth's atmosphere is *thin enough* so that the effects of the absorption of a VHE γ-ray are detectable from the ground

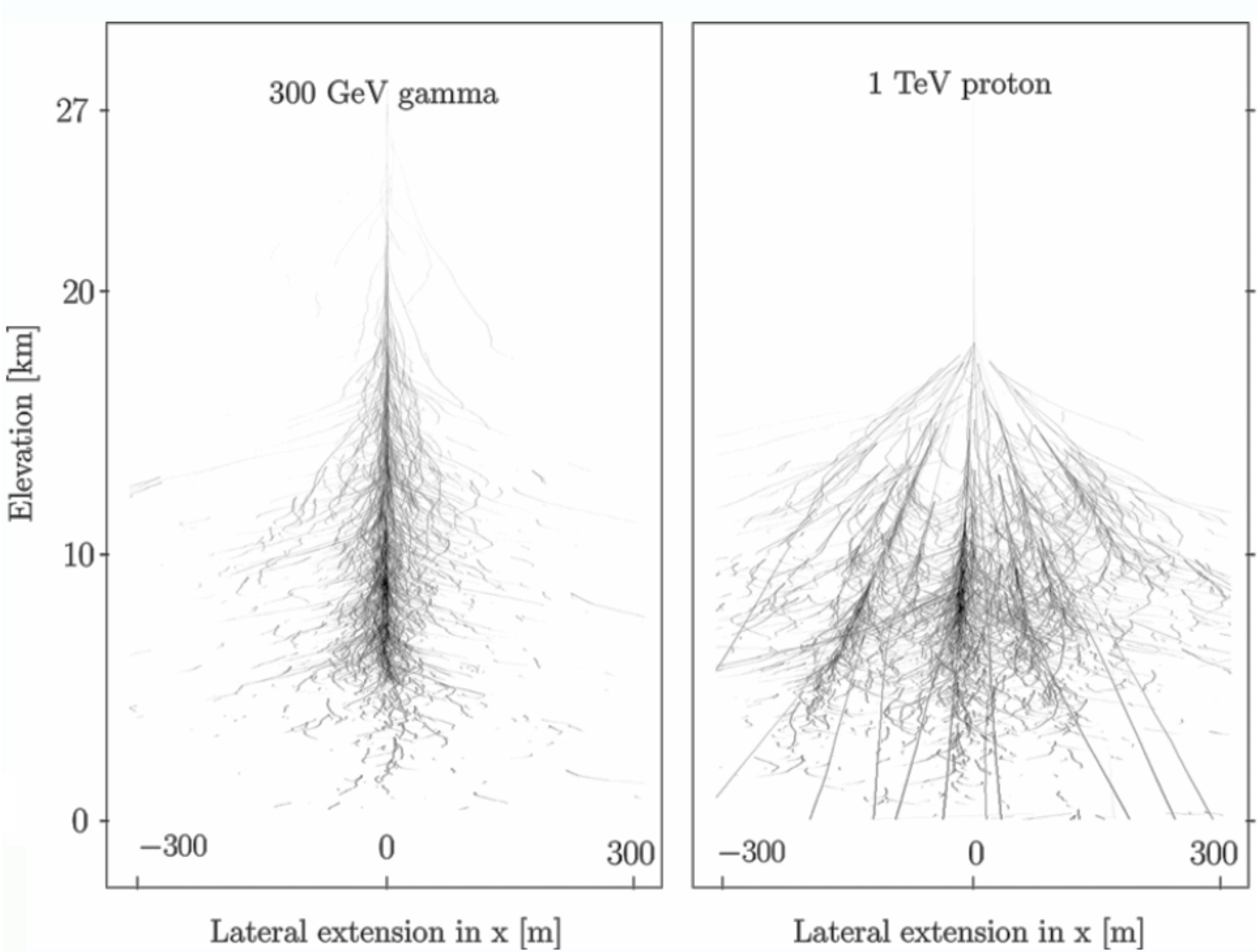
Simulated gamma 50 GeV





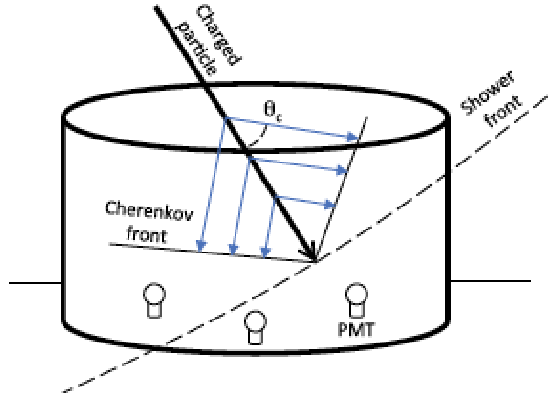
Fabian Schmidt, Leeds university

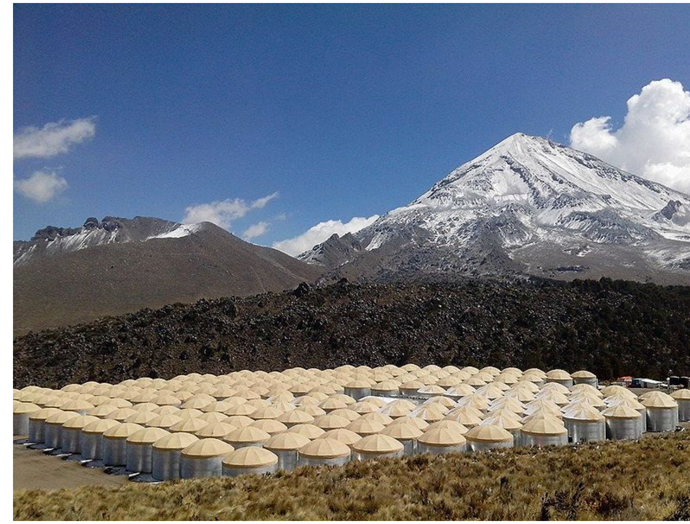
Aharonian+, Rep. Prog. Phys. 71 (2008)



Shower front sampling technique

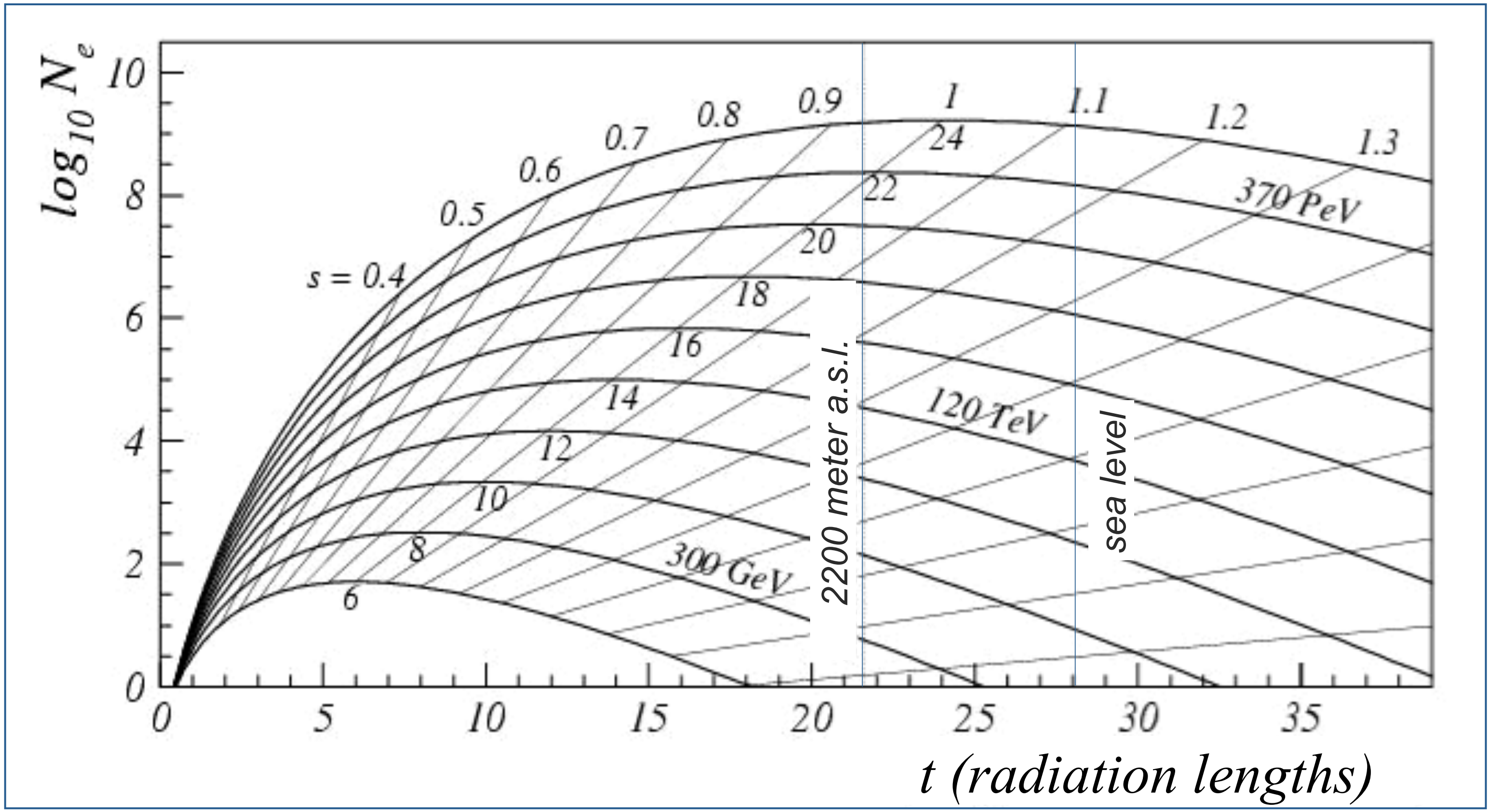
- HAWC: High-altitude (4100 m a.s.l.) + dense sampling – targets ~TeV showers





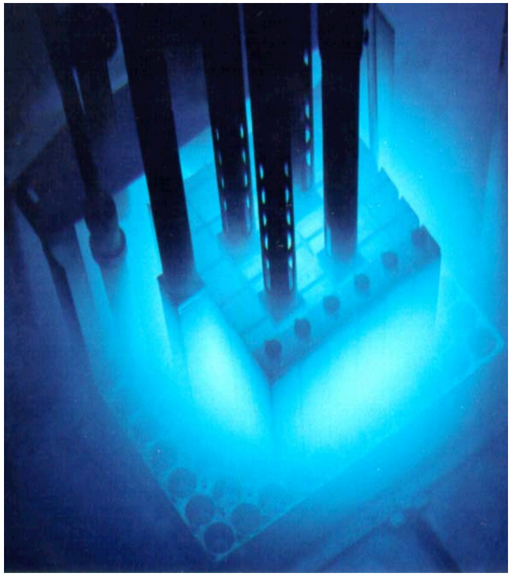
- Auger (surface detector): sparse, large footprint – targets ultra-high energy showers (10^{17} eV –)

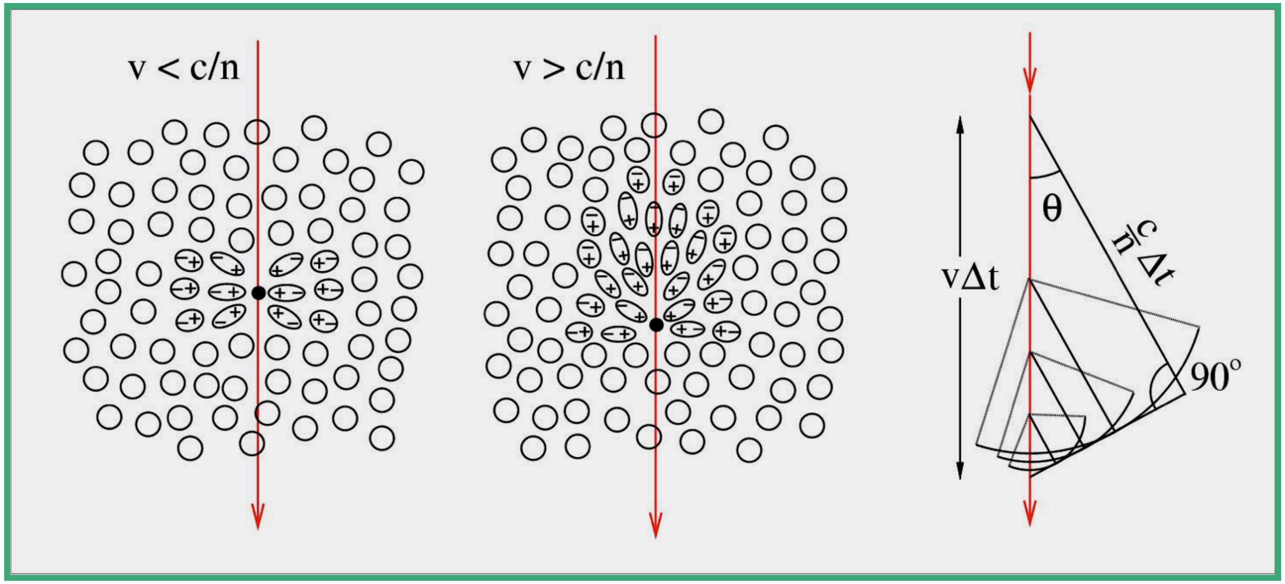
How can we detect showers in which few or no particles reach the ground?



Cherenkov Radiation

- Emitted whenever a charged particle traverses a medium at a speed larger than that of light in the medium
- The radiation results from the reorientation of electric dipoles induced by the charge in the medium. When v > c/n the contributions from different points of the trajectory arrive in phase at the observer as a narrow light pulse

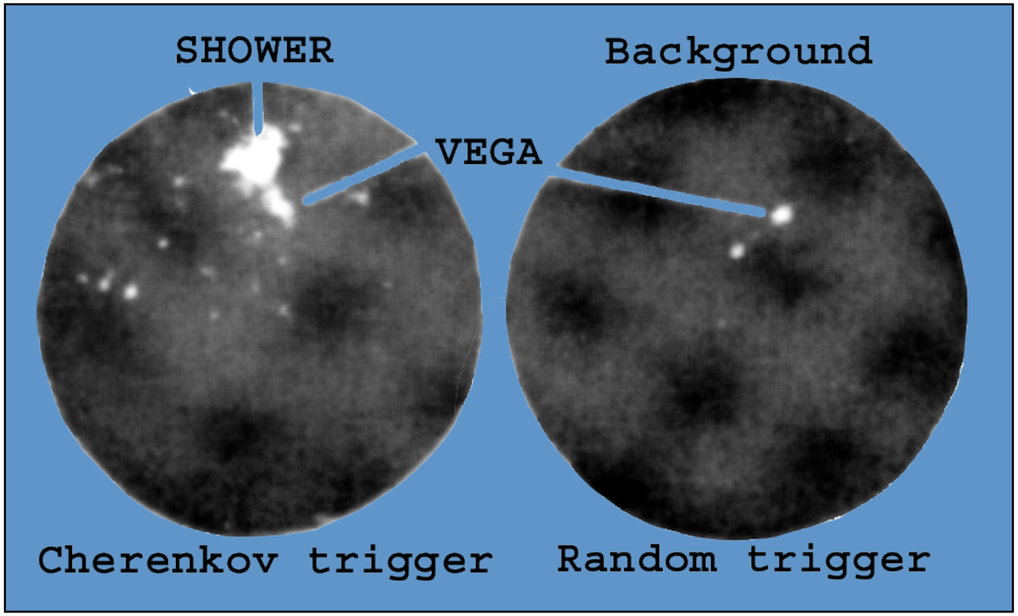




Cherenkov radiation in the atmosphere

- In 1948, P.M.S. Blackett suggested that secondary CR's should produce Cherenkov radiation which would account for a fraction 10^{-4} of the total night sky light
- In 1963 Galbraith and Jelley recorded for the first time Cherenkov light pulses from air showers, and proposed their use in gamma-ray astronomy

The existing light receiver installation at A.E.R.E., Harwell. The bank of three-foot f/0·5 mirrors is mounted equatorially for drift scans.



Quarterly Journal of the Royal Astronomical Society, 4 (1963)

Cherenkov radiation in the atmosphere

Air density: $\rho(h) = \rho_0 \cdot e^{-\frac{h}{h_0}}$ $h_0 = 7.1$ km

Refractive index:

$$n = 1 + \eta_h = 1 + \eta_0 \cdot e^{-\frac{h}{h_0}} \text{ , with } \eta_0 = 2.9 \cdot 10^{-4}$$

Threshold for Cherenkov emission:

$$E_{min} = \frac{m_e c^2}{\sqrt{1-\beta_{min}^2}} = \frac{m_e c^2}{\sqrt{1-n^{-2}}} \simeq \frac{0.511\ MeV}{\sqrt{2\ \eta_h}}$$ (≈ 35 MeV at h_0)

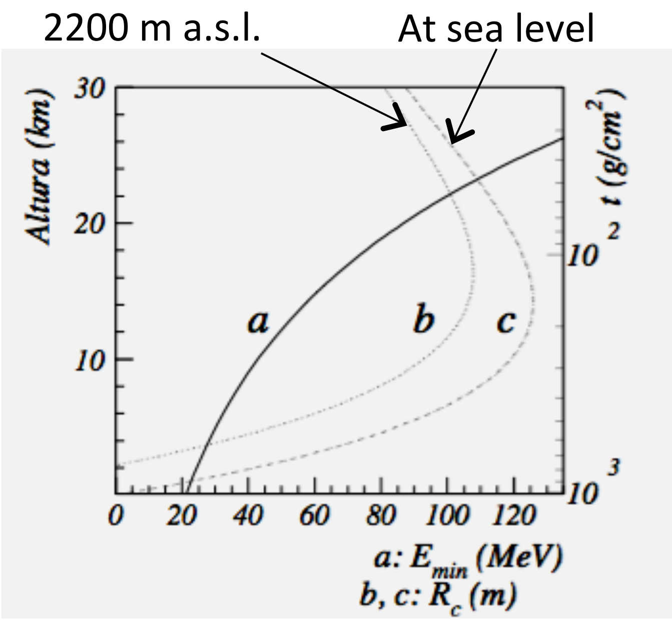
Cherenkov angle for $\beta = 1$:

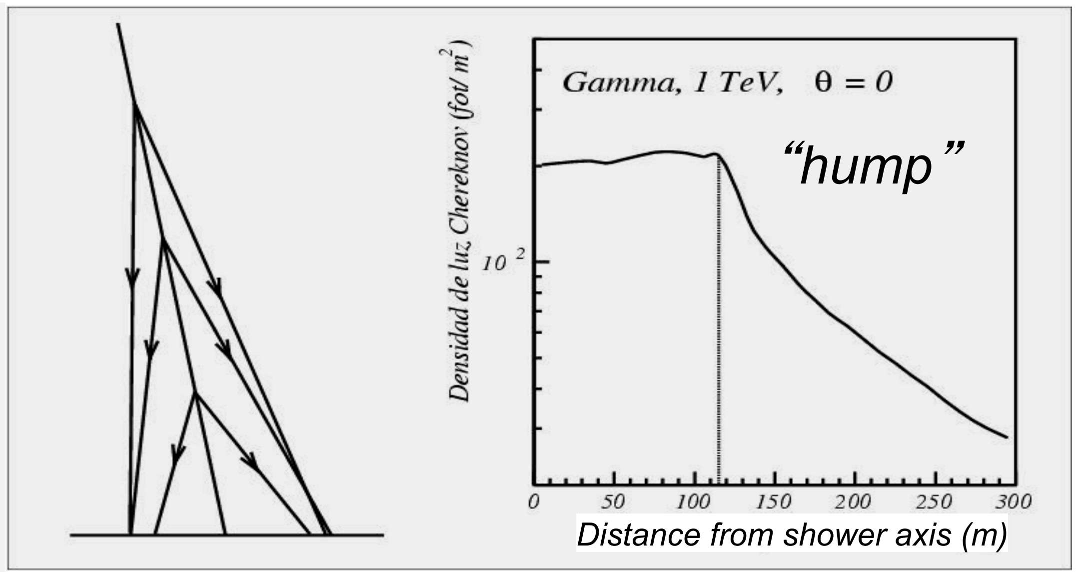
$$\cos\theta_{max} = \frac{1}{n} = \frac{1}{1+\eta_h} \simeq 1 - \eta_h$$ ($\theta_{max} \approx 0.8°$ at h_0)

Cherenkov radiation in the atmosphere

R_c: Distance from particle trajectory at which the C-photons hit the ground

$$R_c \equiv (h - h_{obs}) \cdot \tan\theta_{max} \quad \text{for } \beta = 1$$



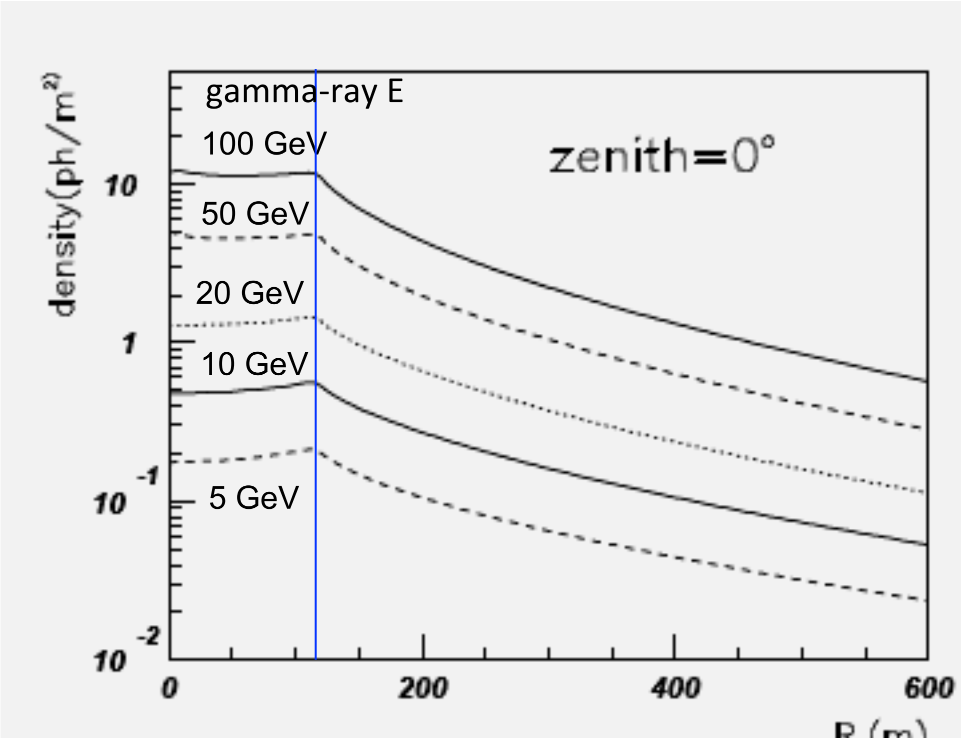


(note: angular distribution of $e^{\pm}$ due to multiple scattering also matters!)

Hump position depends on observation altitude (but not on E_0)

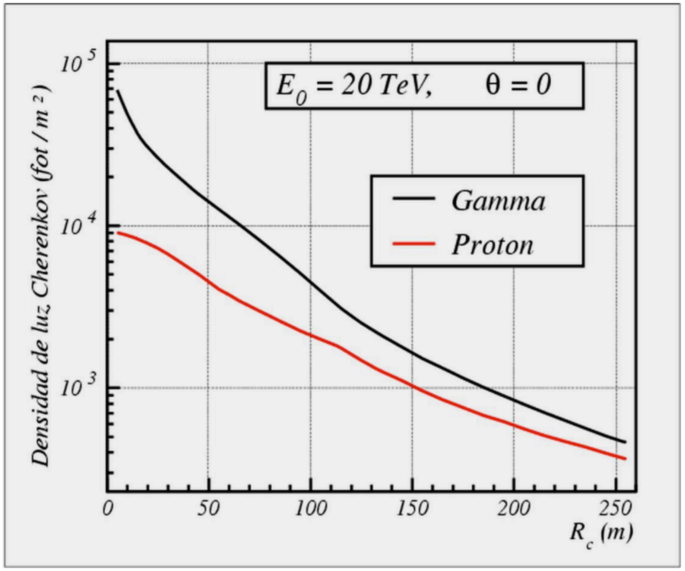
Lateral distribution of C-light

If e± shower extinguishes before reaching observation level (E< a few TeV) : Plateau up to the hump, then fast drop



D. Sobczynska, CORSIKA simulations

Else, C-light density is maximum at shower core and drops exponentially with R

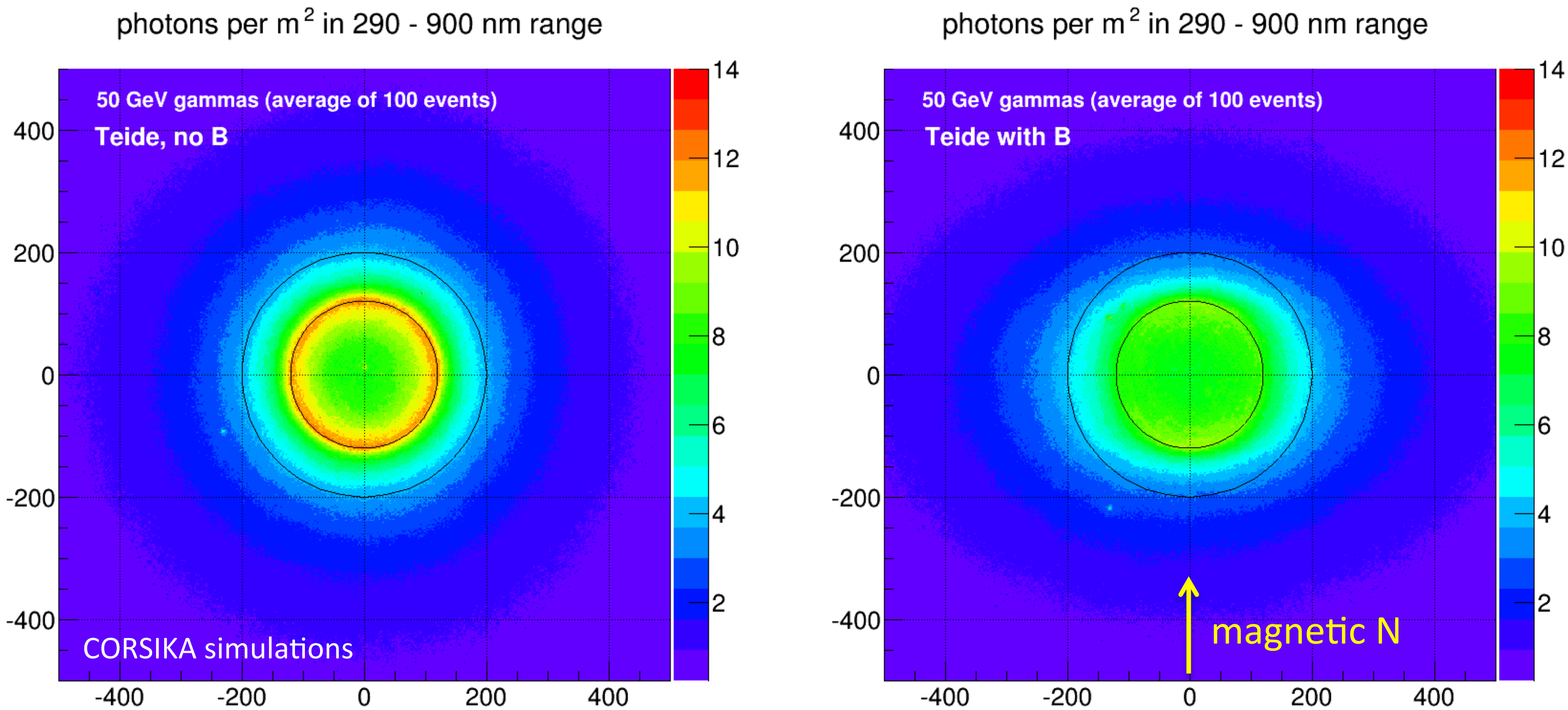


Note: for a given E_0, a γ-ray produces far more light than a p

Good correlation of the light density (given R) with the gamma-ray energy ⟹ calorimetric measurement

Effect of geomagnetic field

Light pool, B=0 vs. B=30.8 μT (La Palma)

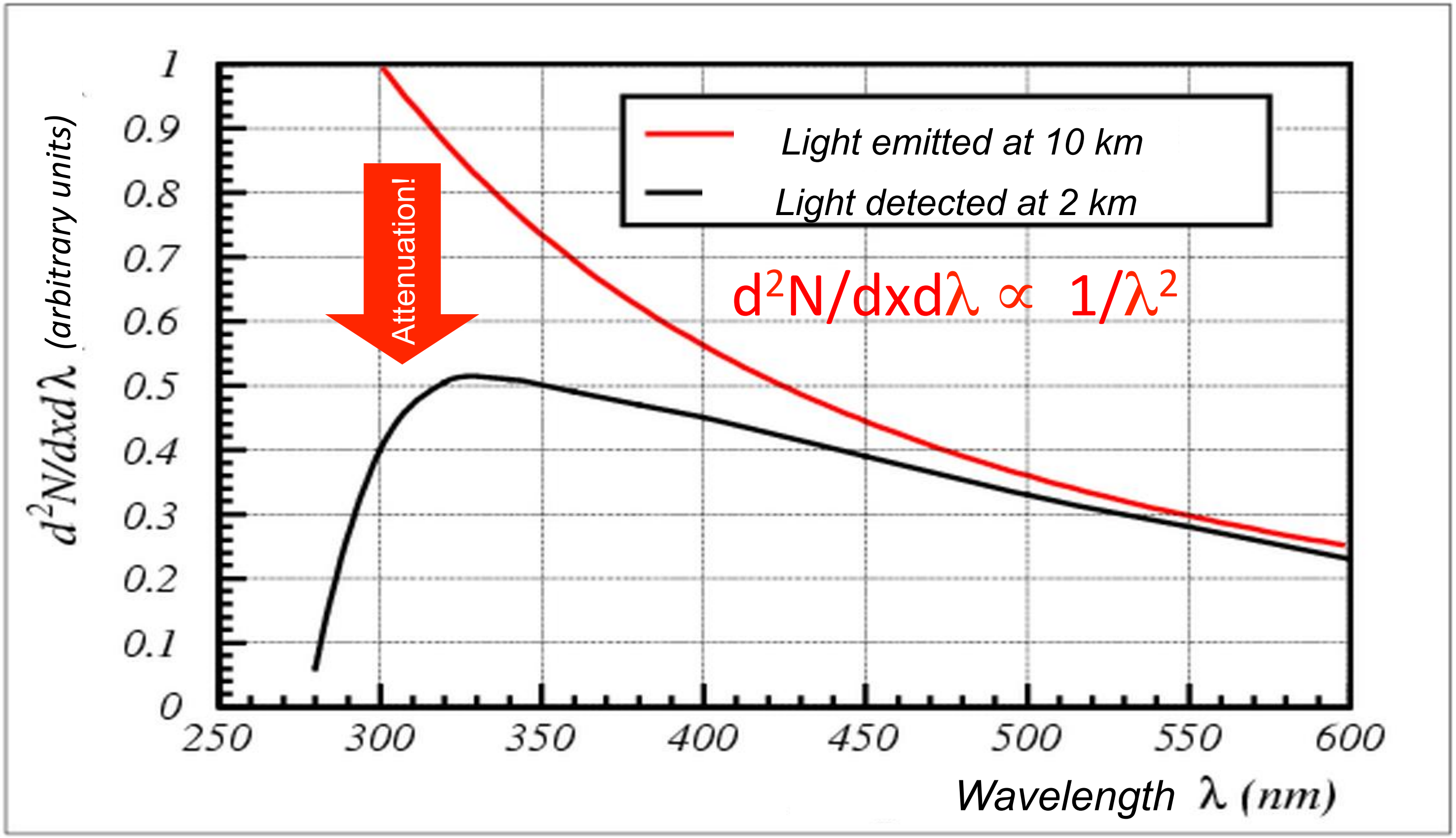


- B-field separates + and – charges in the E-W direction
- Shown above is the *average* effect – a given pool can be very E-W asymmetric

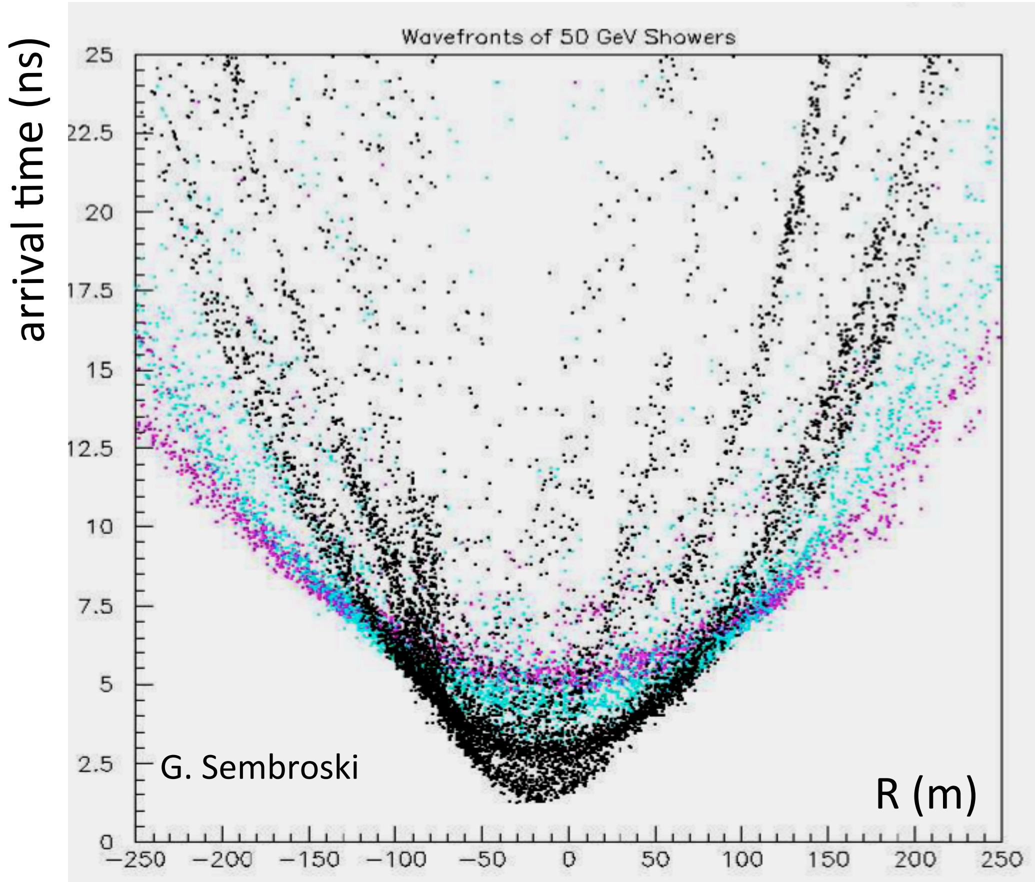
Attenuation of C-light in the atmosphere

Three relevant processes:

- Mie scattering (by dust particles)
- Rayleigh scattering (by air molecules)
- Absorption by Ozone (but EAS develops mostly below O_3 layer)



Time structure of the C-light front



Light emitted above 10 km

Light emitted at 6-10 km

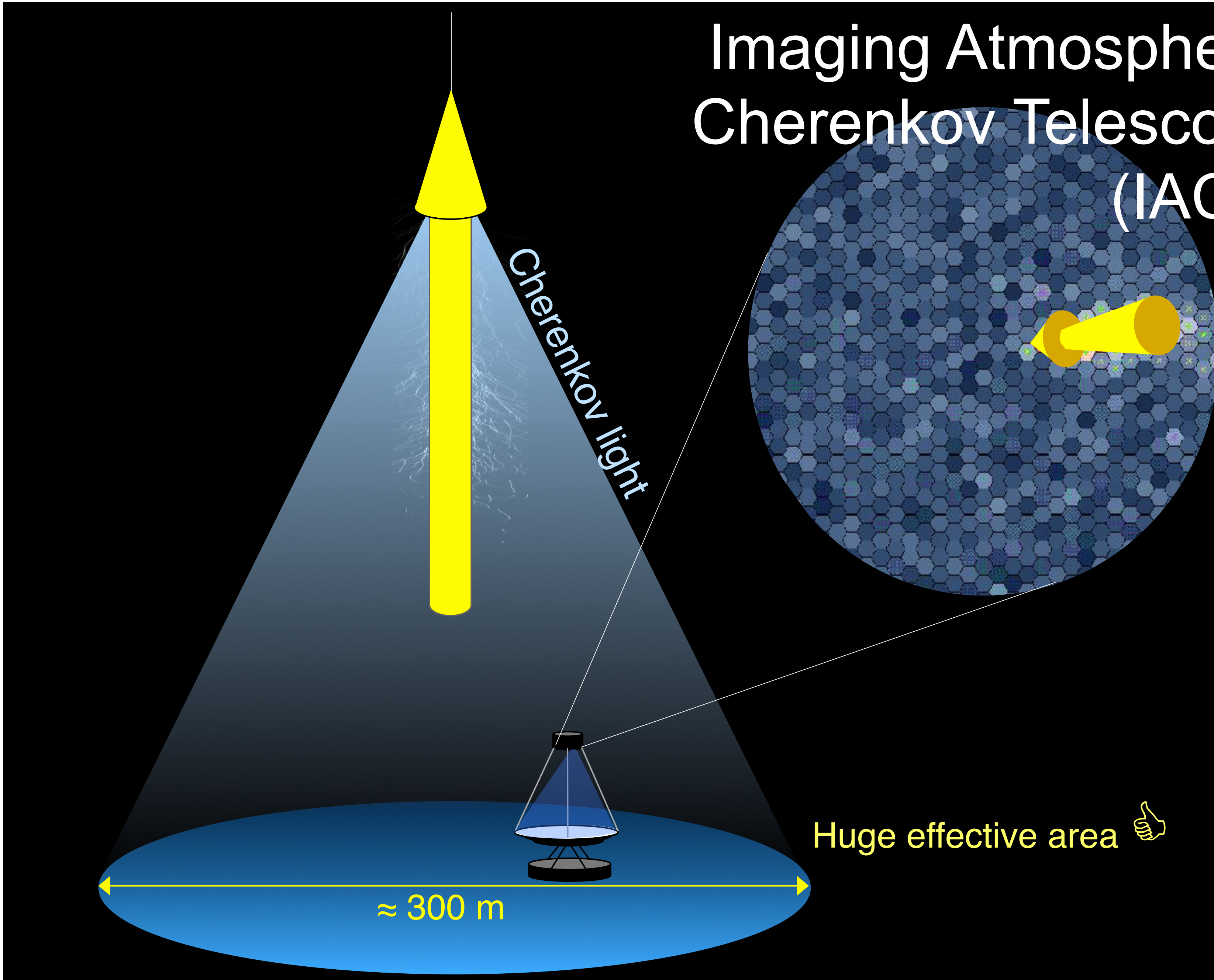
Light emitted below 6 km

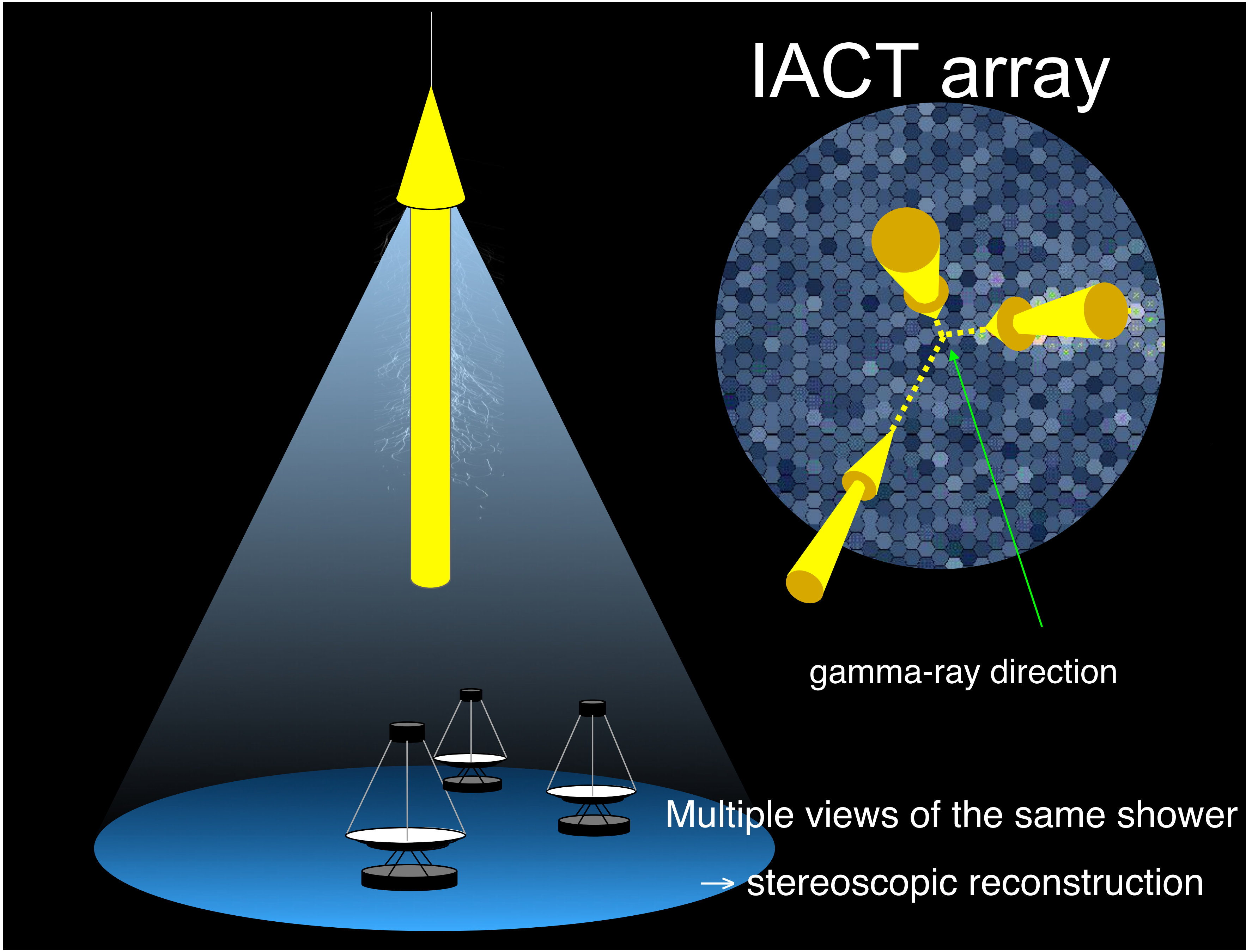
Close to shower core: light from shower tail arrives first

Far from shower core: light from top of the shower arrives first

- Cherenkov pulse duration O(ns) $\Longrightarrow$ fast photodetectors (PMTs or SiPMS)
- If placed at the focal plane of an imaging optical system (e.g. a parabollic mirror) allows to obtain an image of the EAS

Imaging Atmospheric Cherenkov Telescope (IACT)

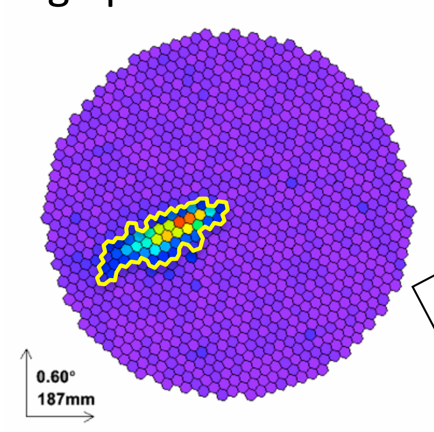



IACT array
gamma-ray direction
Multiple views of the same shower
→ stereoscopic reconstruction

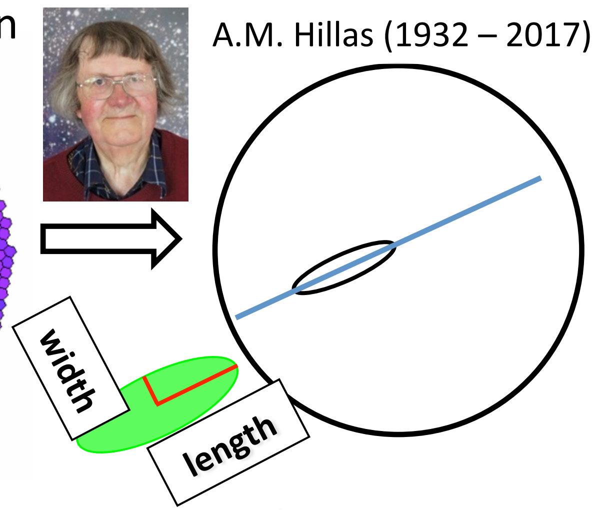
Simplest IACT event reconstruction

– 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 (2nd order moments - "Hillas parameters"), time gradient along major axis...

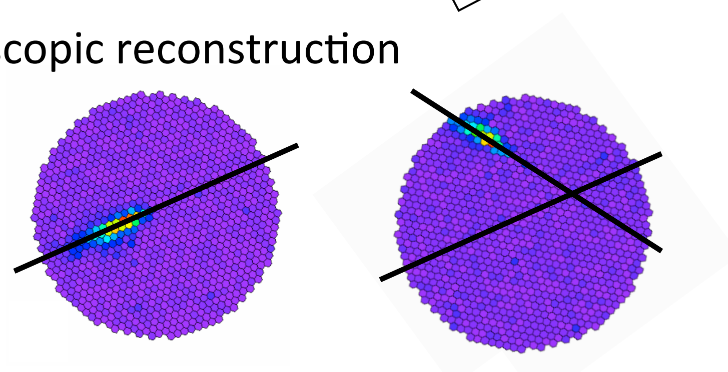
Image parametrization

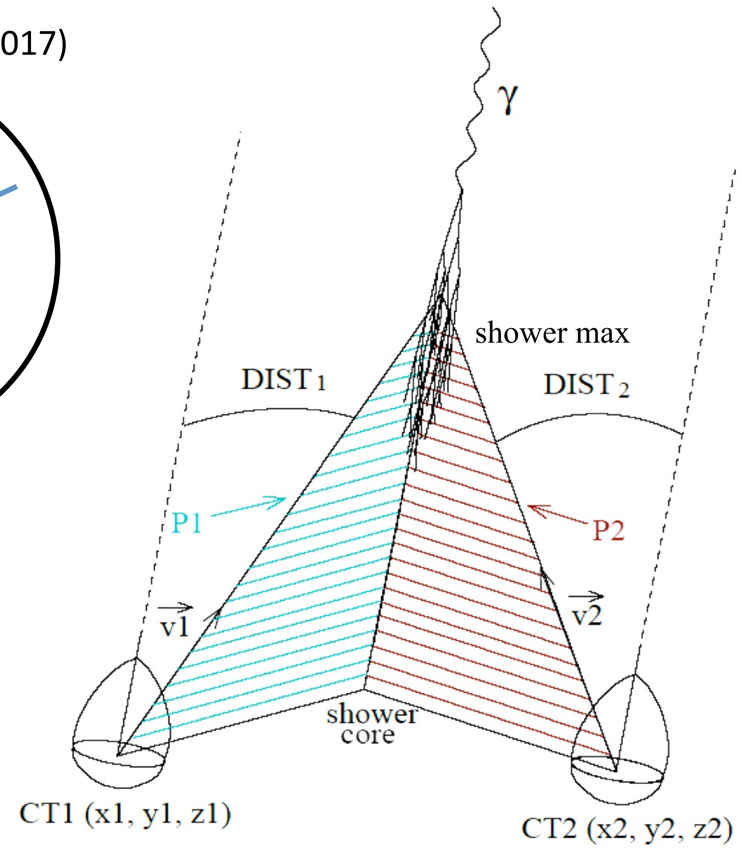


A.M. Hillas (1932 – 2017)



Stereoscopic reconstruction





Monte Carlo simulations

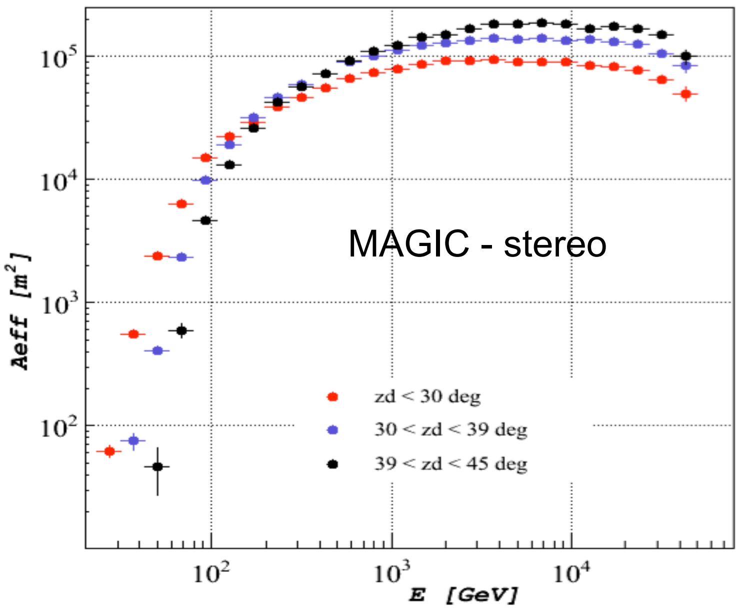
No test-beam to calibrate the atmosphere + IACTs system

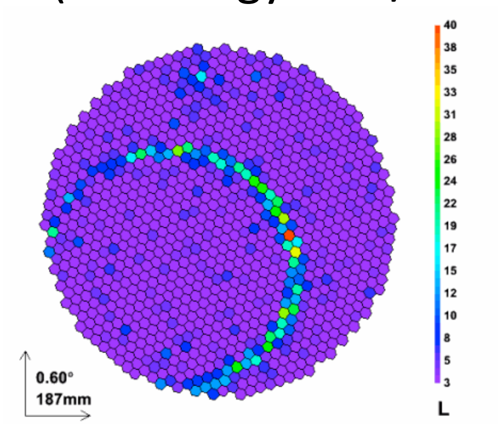
⟹ key role of MC of shower development and detector response

- needed to correlate the observed quantities with the properties of the primary gamma (or cosmic ray), e.g. its energy

- ⟹ MC allows to calculate the effective area of the IACT array (vs. Energy, Zenith...)

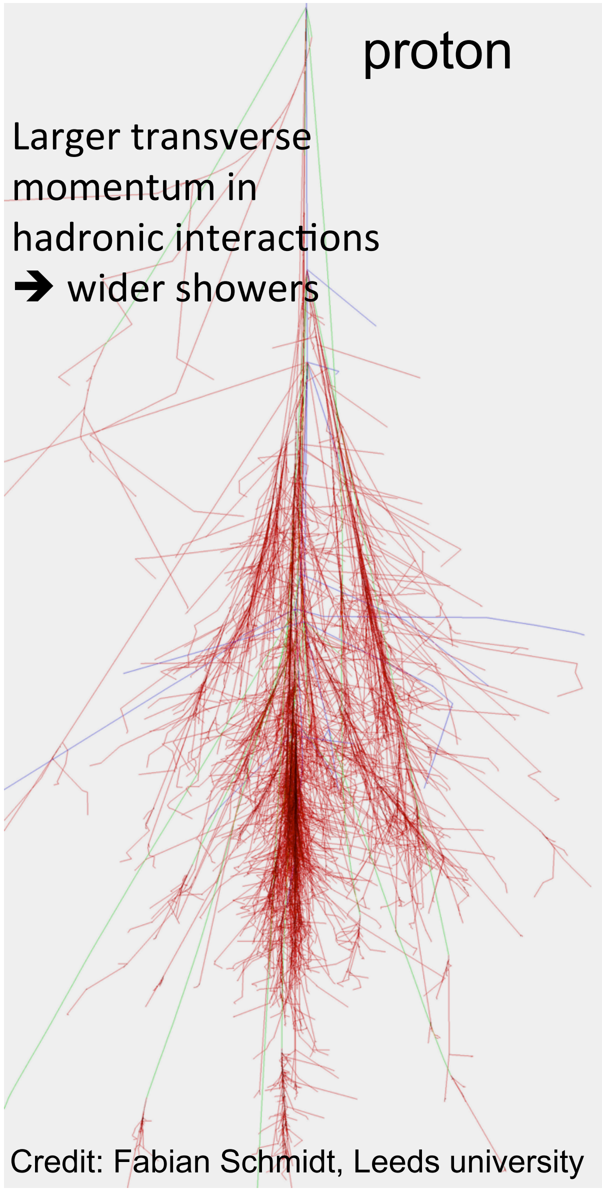
- ⟹ Convert the observed gamma-ray rates into an estimate of the source flux (vs. energy and/or time)

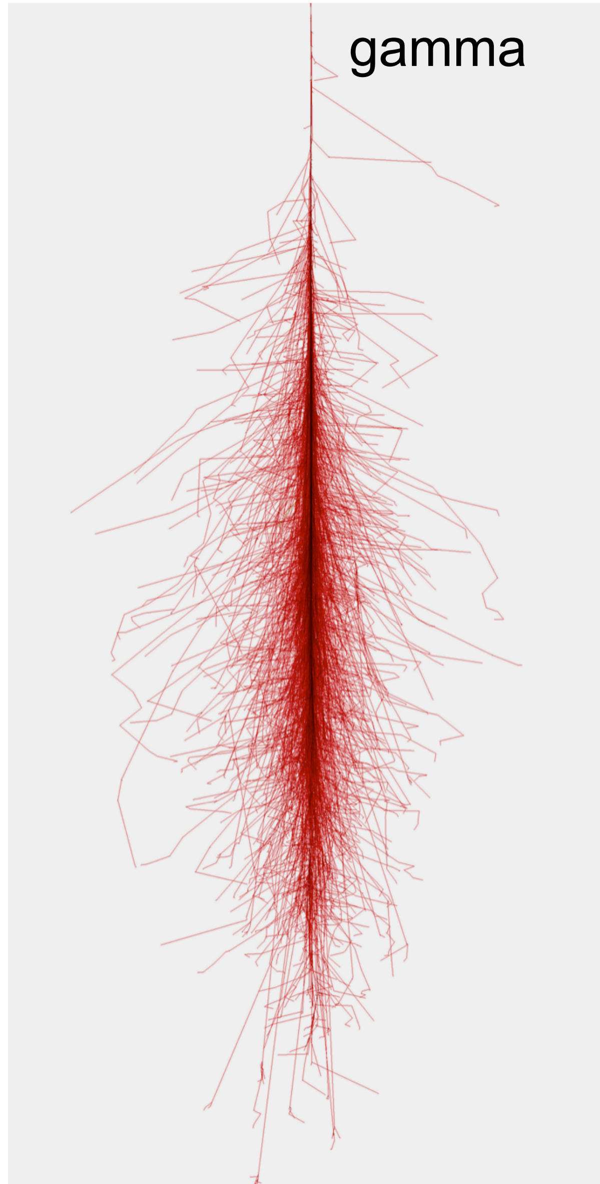




MC parameters need to be tuned to match the telescopes performance ⟹ use muon ring events, check Crab Nebula (standard candle) observations...

Suppression of charged CR background



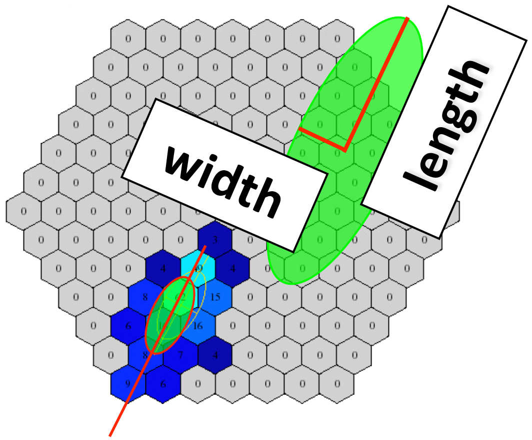


The isotropic flux of CRs

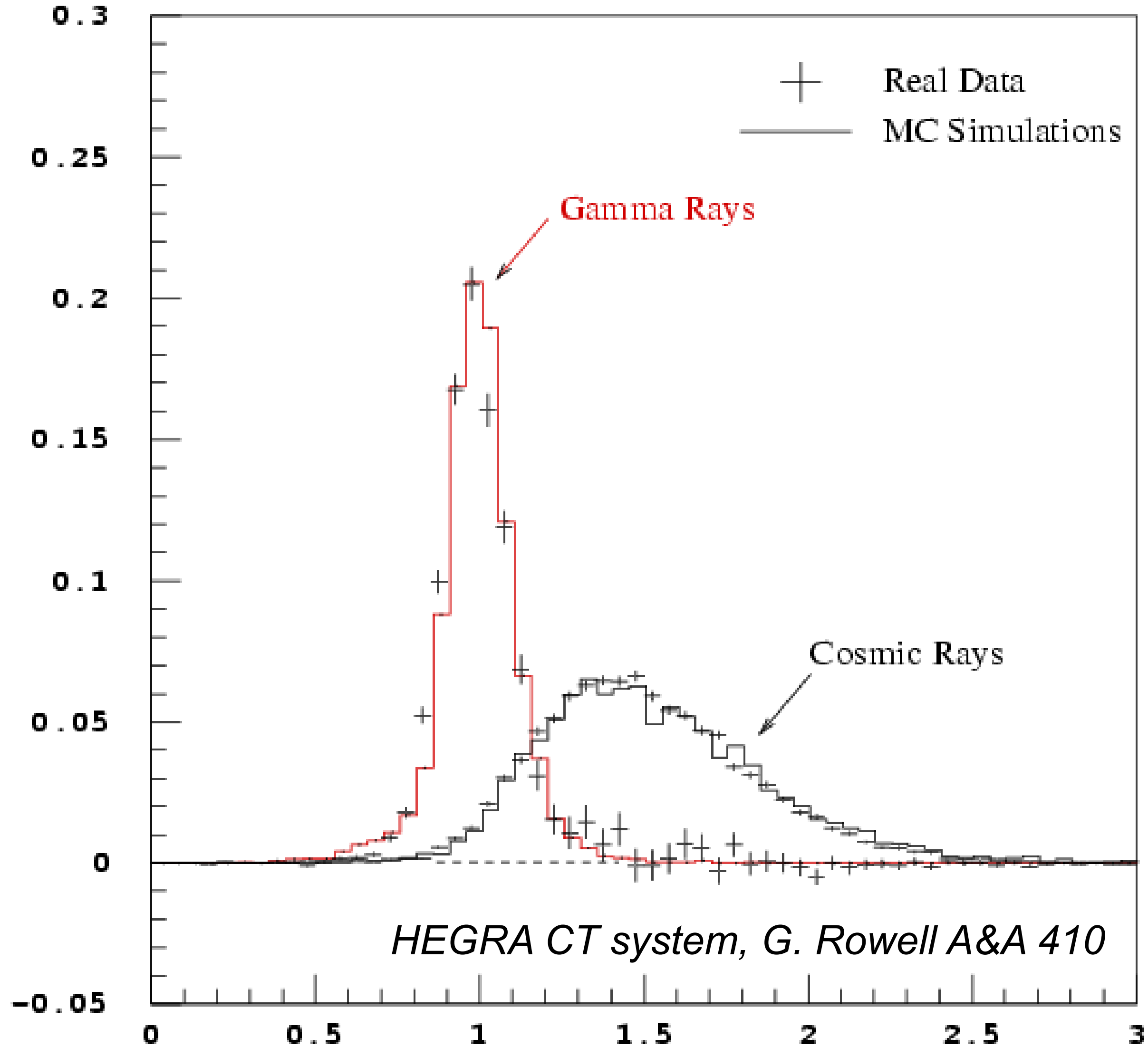
Based on the different lateral and longitudinal development of gamma- and hadron-initiated showers

⇒ different distributions of image parameters for gammas & CRs

Suppression of charged CR background



- background suppression factor 100 - 1000
- Much better than any other ground-based gamma-ray detection technique (because of handle on shower *development*)

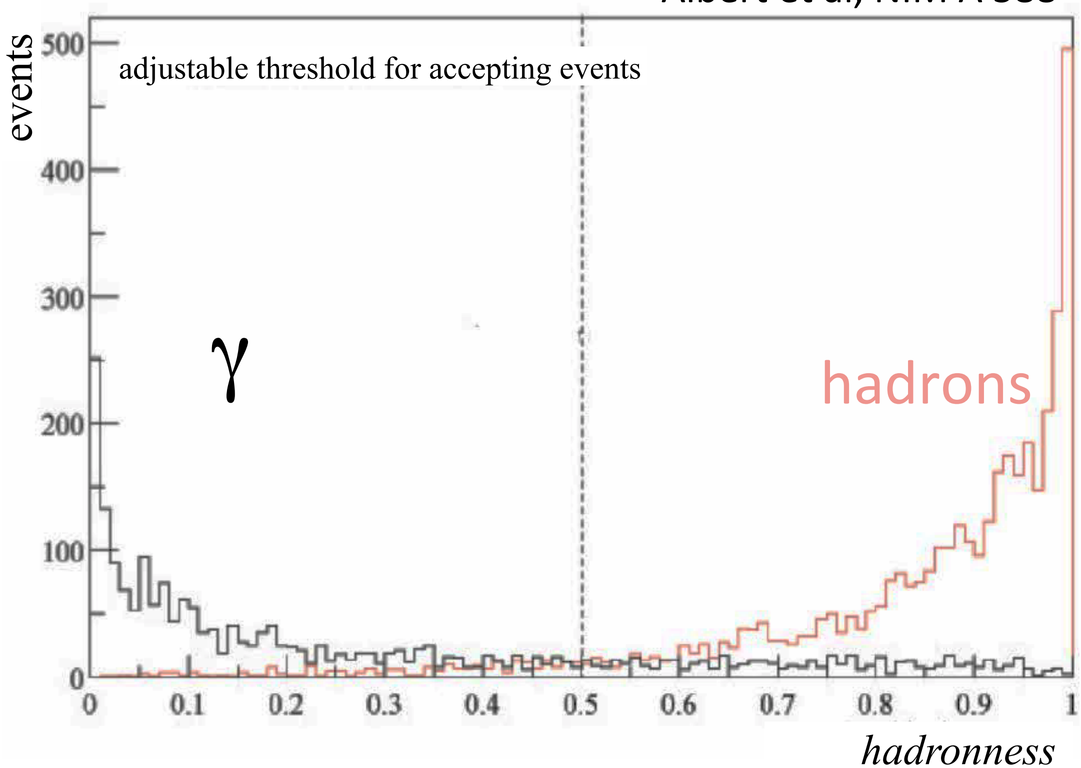


Mean scaled image width: scaled to the expectation for gammas at given impact parameter & image Size)

Suppression of charged CR background

- Image parameters (from different telescopes) can be combined by multivariate classification methods (like Random Forest, or BDTs) to derive a single cut parameter (dubbed *hadronness* below)
- The algorithms are trained using MC-simulated gammas, and real (or MC) background events

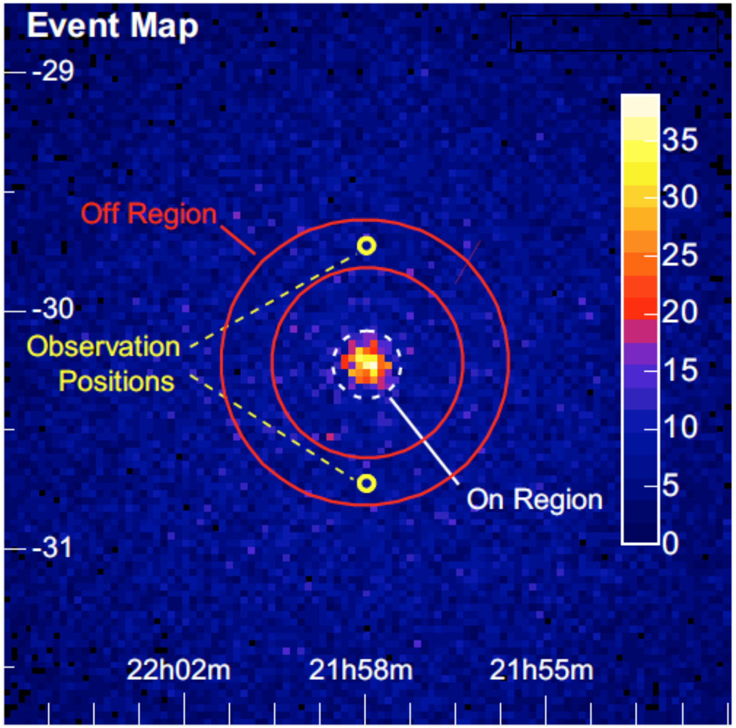
Albert et al, NIM A 588

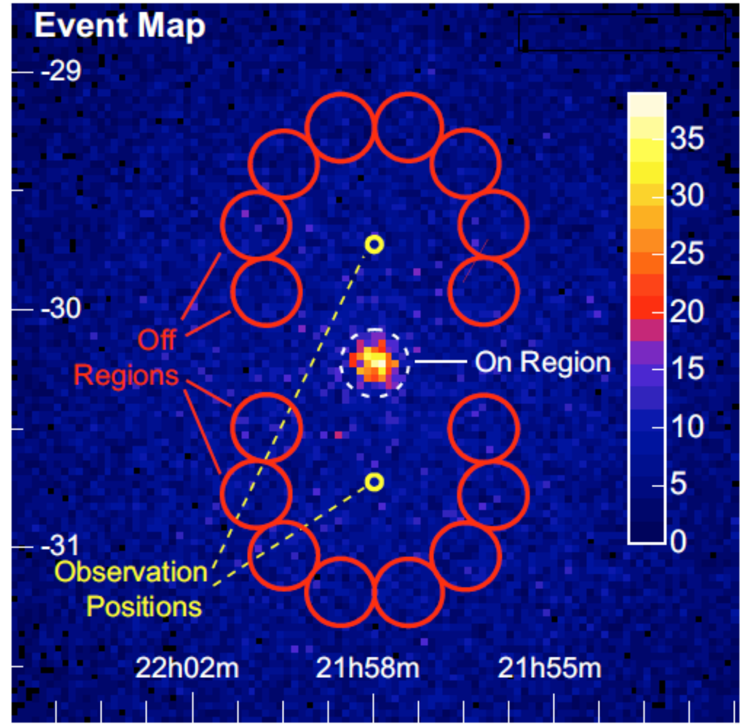


- There are also more sophisticated IACT analysis methods than the classical one here described:
- see e.g. Parsons & Hinton, Astroparticle Physics 56 (2014) – maximum likelihood method using MC library of image templates

Higher-level IACT analysis

Berge+ A&A 466 (2007)

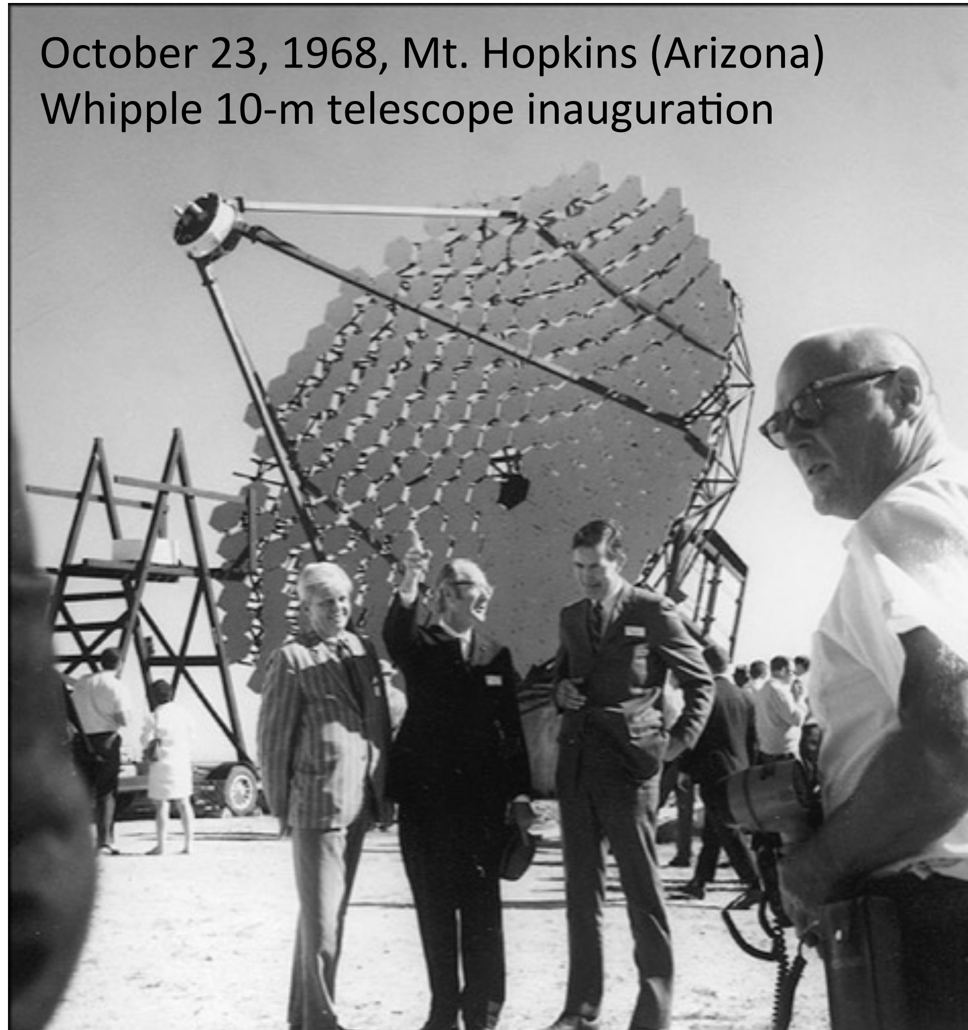




- After CR suppresion cuts we are left with a list of events (t, E_{rec}, RA_{rec}, δ_{rec}) with both VHE gammas and *gamma-like background* ($e^{\pm}$-initiated showers, EM subshowers from CR-initiated showers) – limit of IACTs in their core energy range
- Aperture photometry (on / off) or background modelling used to estimate gamma-ray fluxes; translated into spectra & light curves using MC-generated instrument response functions.

IACT, a few milestones

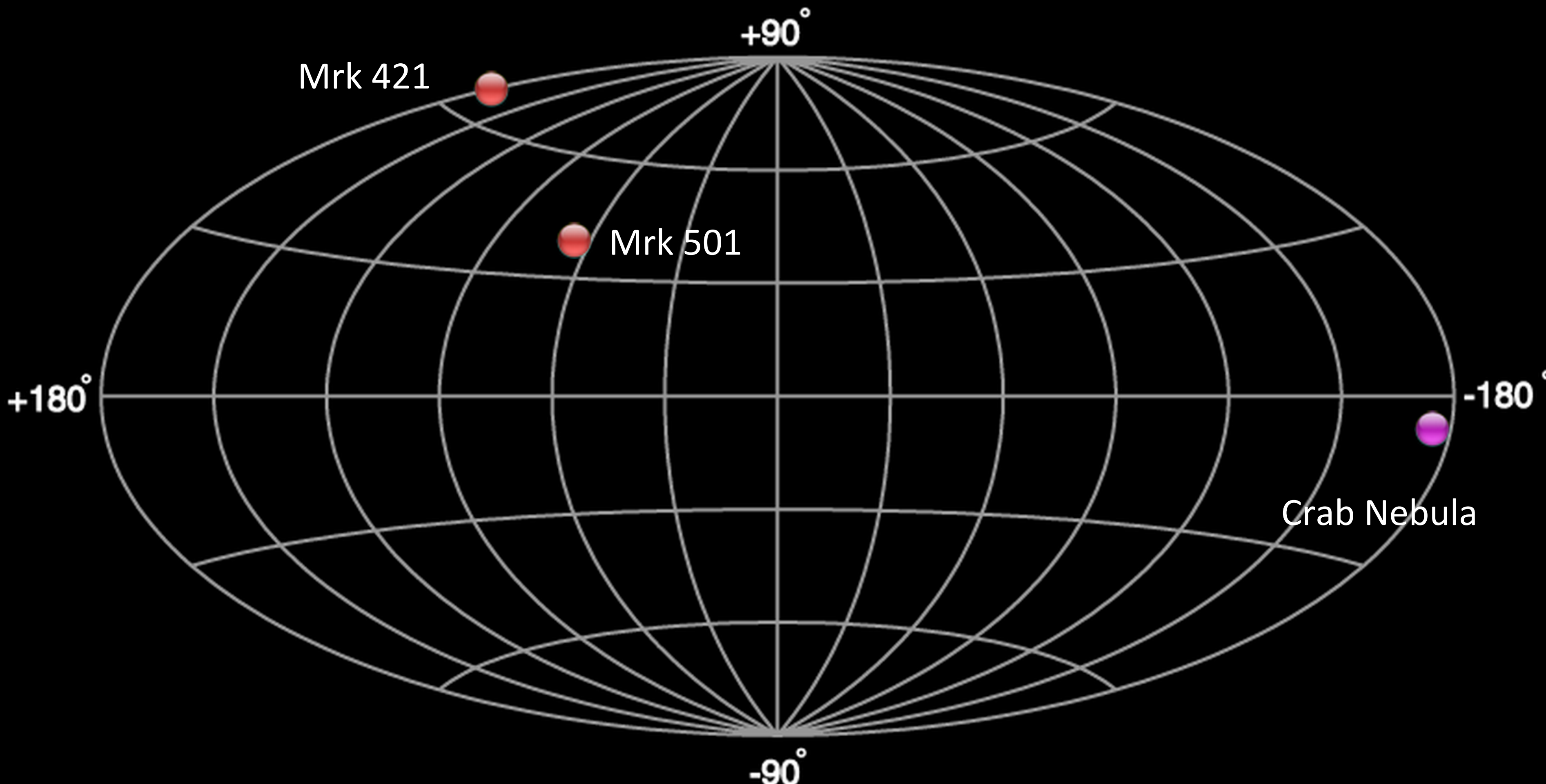
- **1968**: inauguration of the Whipple 10-m telescope
- **1989**: Whipple reports first γ-ray source detection: the Crab Nebula
- **1997-2002**: HEGRA array. first successful application of stereoscopy
- **2002 – today**: second-generation of IACT arrays (HESS, MAGIC, VERITAS)



Current generation of IACT arrays

- Energy threshold E_γ = ~25 to 100 GeV
- Point-source integral flux sensitivity: 0.5 to 1.0 % of the Crab Nebula flux in 50 h (above 200 GeV, >100 times more sensitive than Fermi-LAT in one year)
- Modest field of view (few degrees) ⟹ pointing instruments
- Angular resolution < 0.1°   Energy resolution ≈ 15%

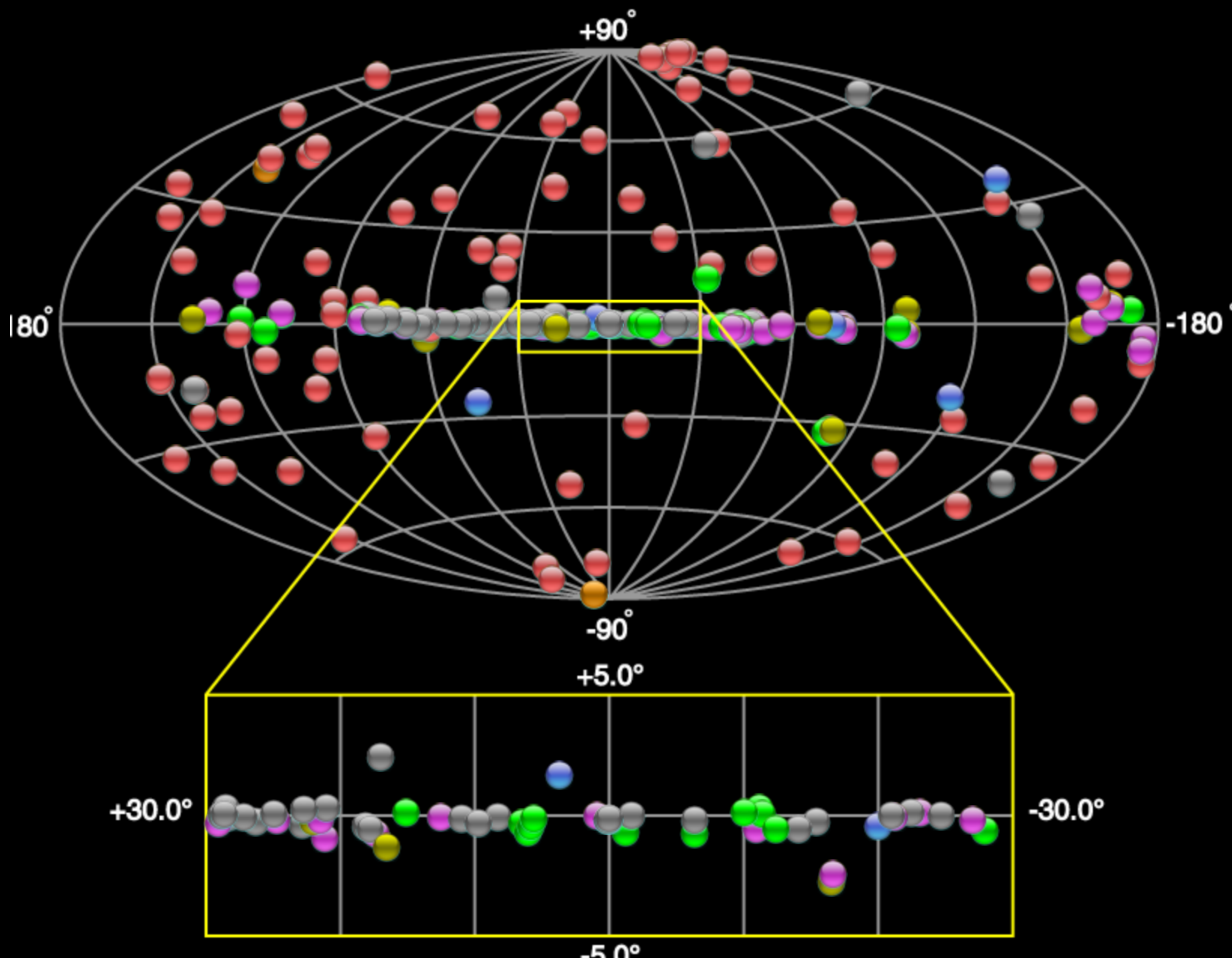
The TeV sky 1995



Detected by the Whipple telescope in Arizona

The TeV sky 2018

http://tevcat.uchicago.edu



Extended TeV Halo, PWN
Starburst
HBL, IBL, FRI, Blazar, FSRQ, LBL, AGN (unknown type)
Globular Cluster, Star Forming Region, uQuasar, Cat. Var., Massive Star Cluster, BIN, BL Lac (class unclear), WR
Shell, SNR/Molec. Cloud, Composite SNR, Superbubble
DARK, UNID, Other
Binary, XRB, PSR, Gamma BIN

>200 sources as of April' 18

The TeV sky as of April 2018

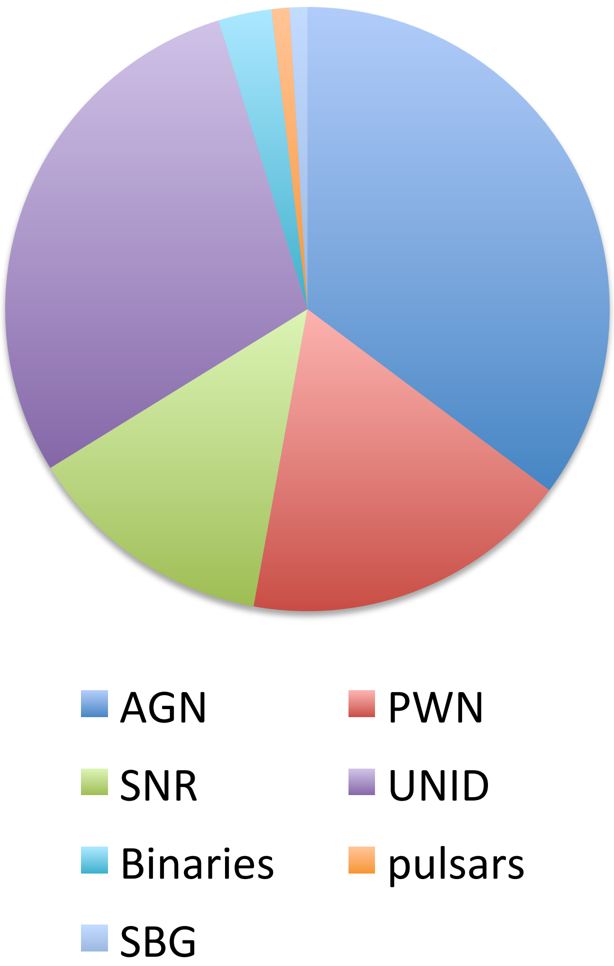
source: http://tevcat.uchicago.edu

Extragalactic:

- 74 AGN (mostly blazars)
- 2 starburst galaxies

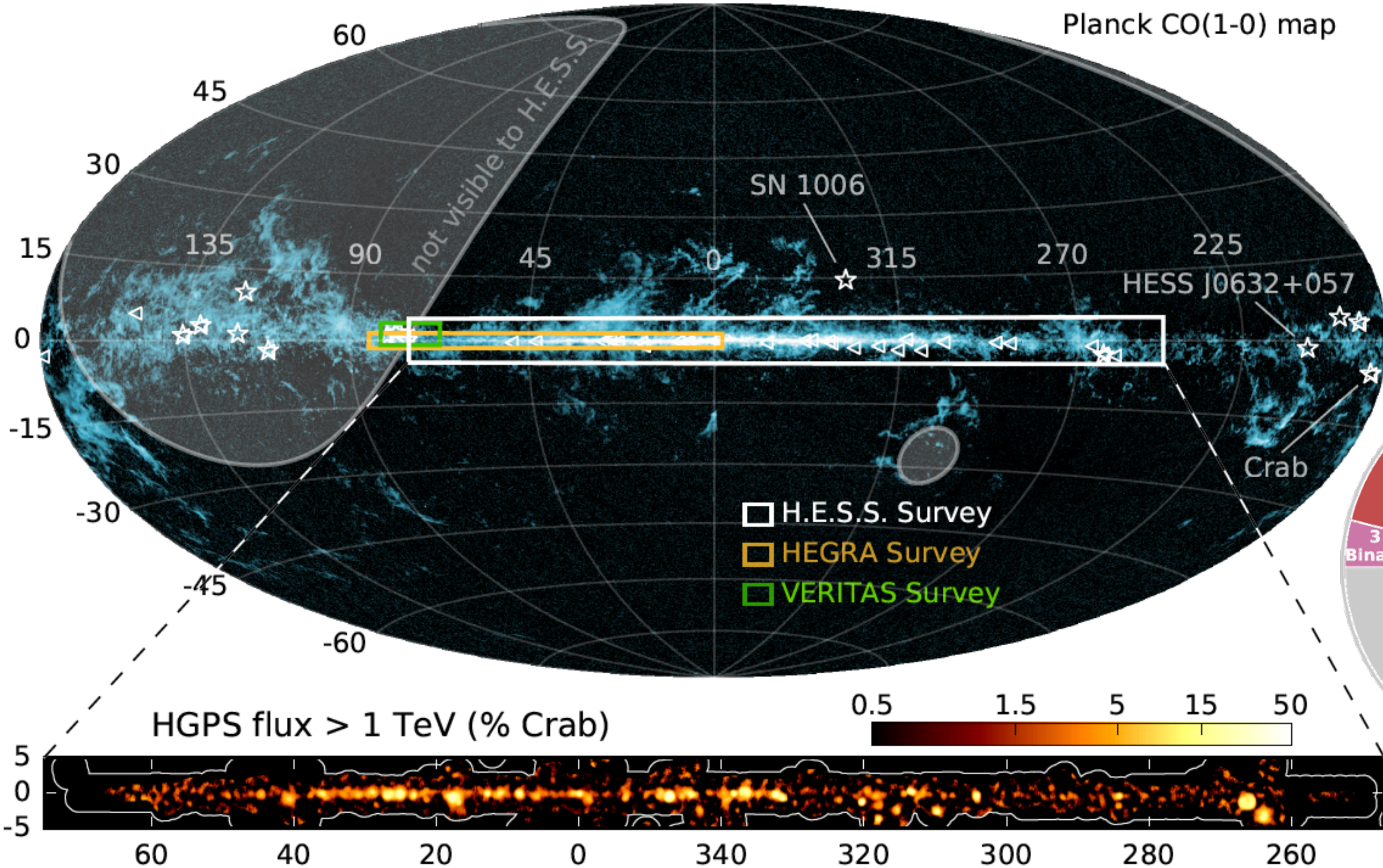
Galactic:

- 37 Pulsar Wind Nebulae
- 28 shell-type SNR, composite SNR, SNR/Molecular cloud
- 61 Unidentified
- 6 binaries
- 2 pulsars



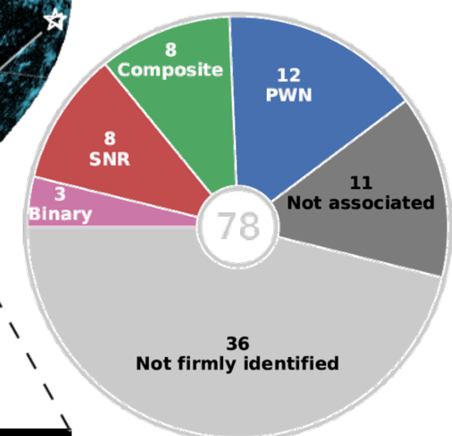
The H.E.S.S. galactic plane survey

HESS coll., A&A 612, A1 (2018)



l = −110 to +70°
b = −5 to +5°

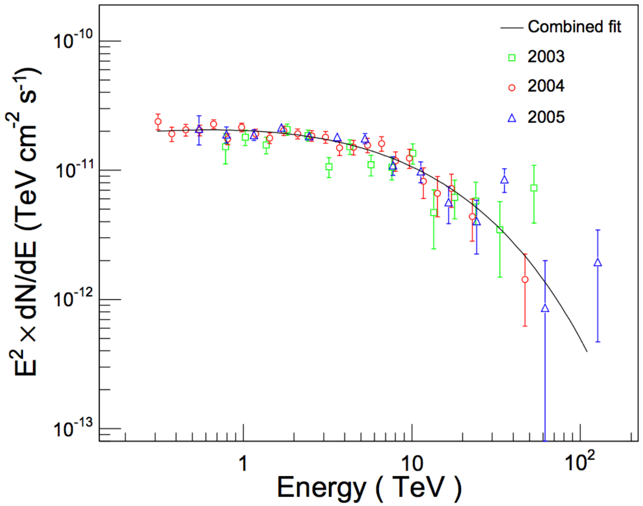
2673 h of good-quality data acquired over a decade

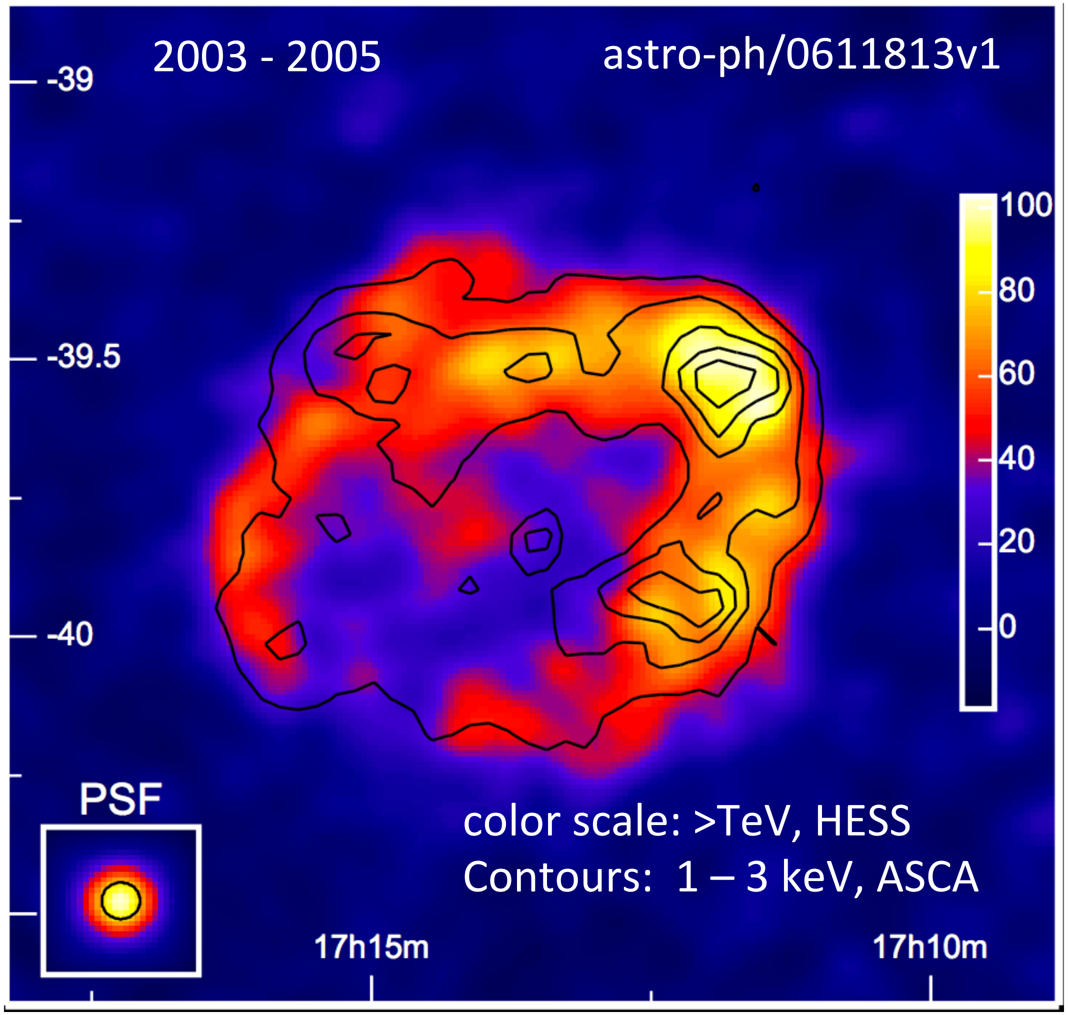


- Most identified sources are SNRs
- Maps made publicly available in FITS format

SNR RX J1713-3946 seen by H.E.S.S.

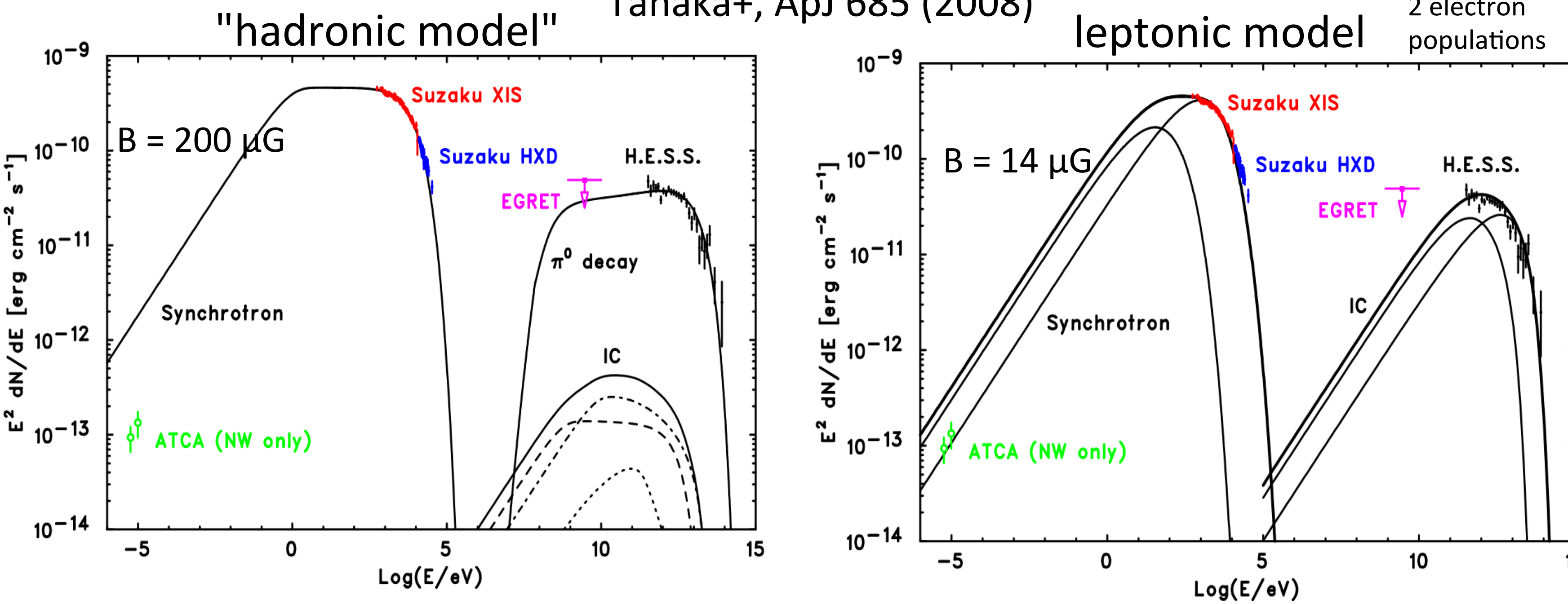
- First resolved SNR shell at TeV energies
- Spectrum extends to >30 TeV
- Implies particle acceleration at least up to 100 TeV





H.E.S.S. RX J1713-3946
protons or electrons?

Tanaka+, ApJ 685 (2008)

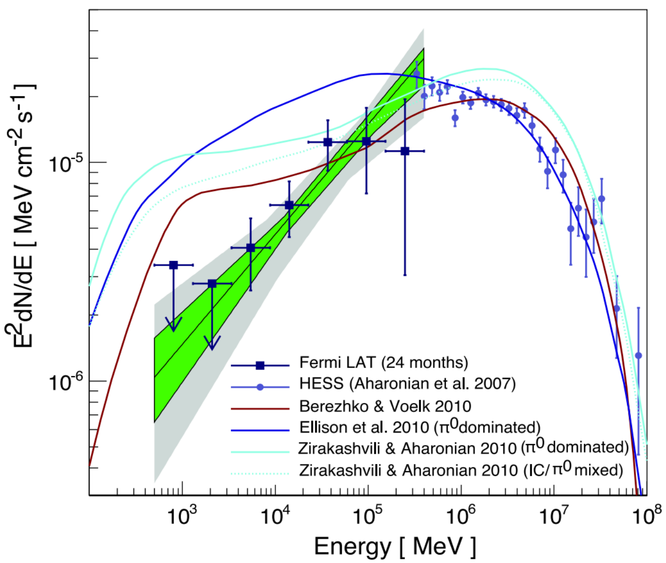


Situation unclear before Fermi-LAT

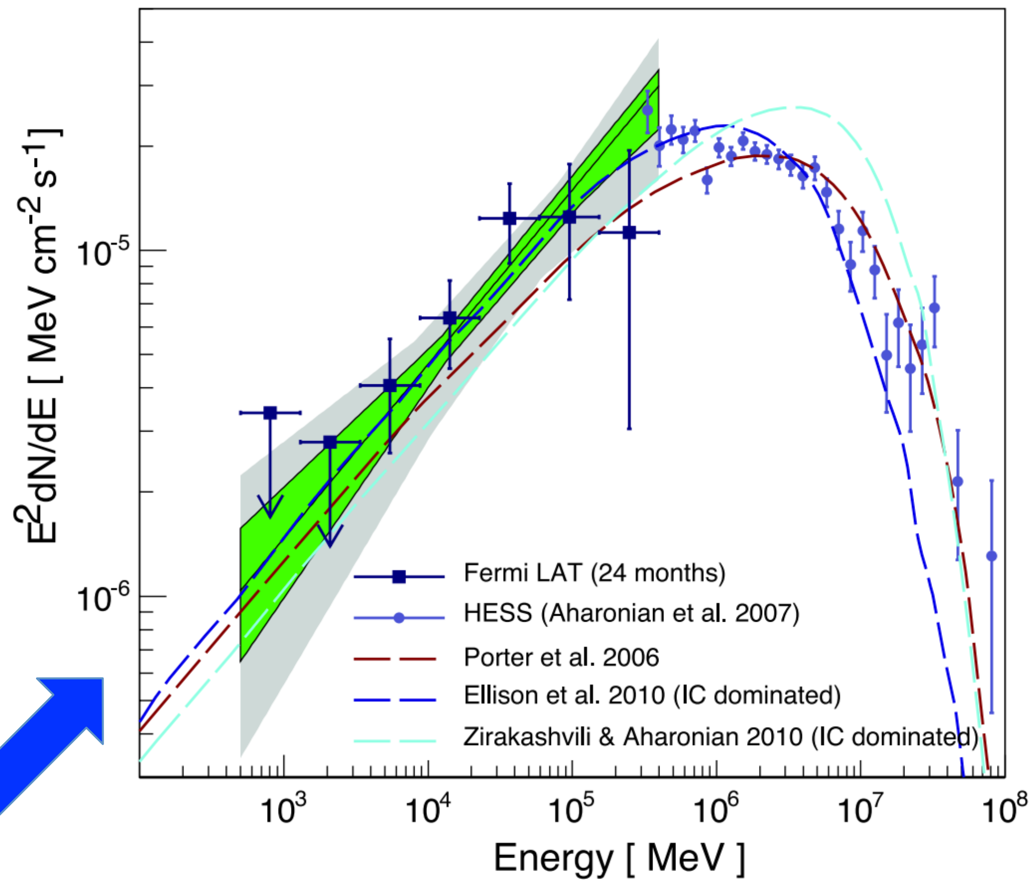
- No doubt about the synchrotron origin of the X-rays
- Gamma rays might be either of hadronic or leptonic origin
  - if leptonic, no proof of hadronic CR acceleration

H.E.S.S. RX J1713-3946
protons or electrons?

Abdo+ (Fermi-LAT coll.), arXiv:1103.5727v1, ApJ, 734, 28 (2011)



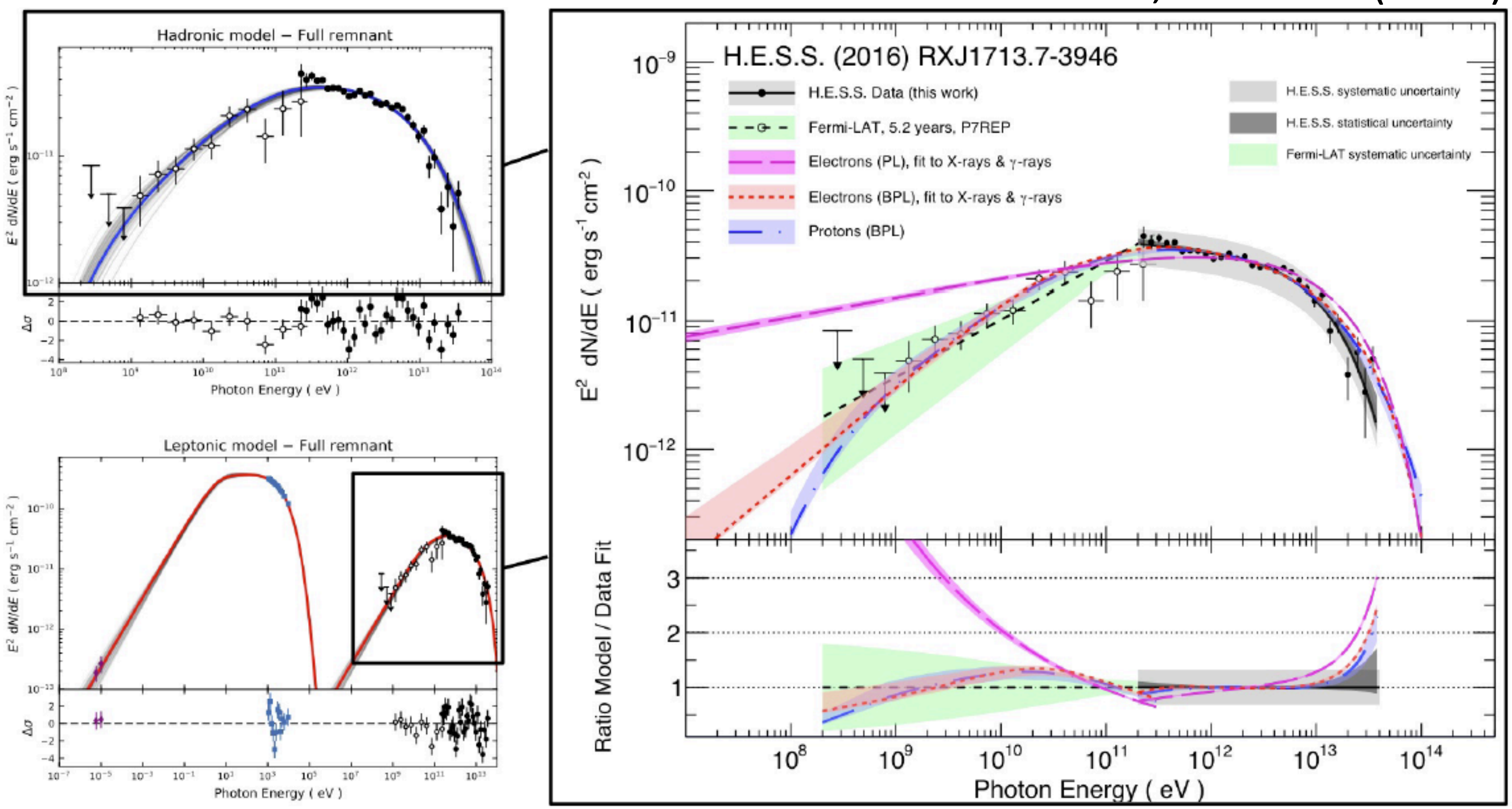
A few pre-Fermi hadronic models



Leptonic models apparently favored by Fermi-LAT observations, but...

H.E.S.S. RX J1713-3946
protons or electrons?

H.E.S.S. coll., A&A 612 (2018)

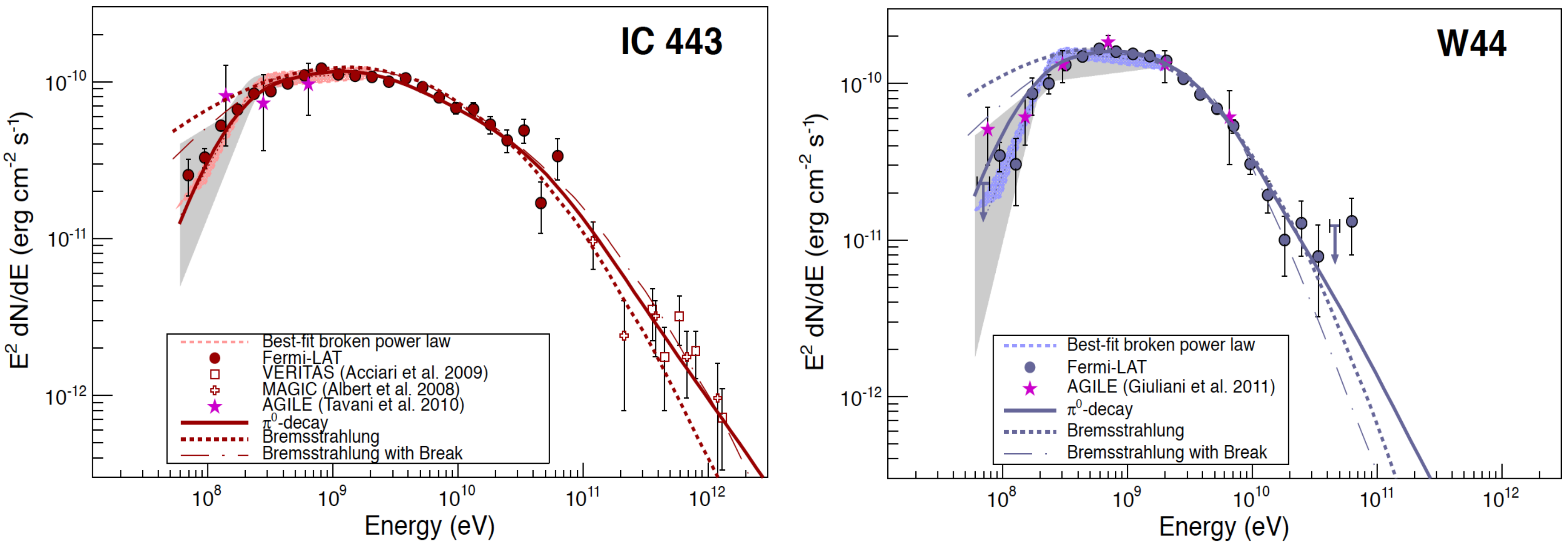


- Hadronic scenario still plausible
- Also: first-time evidence of VHE particles beyond the X-ray shell

Fermi-LAT: detection of the "pion bump"

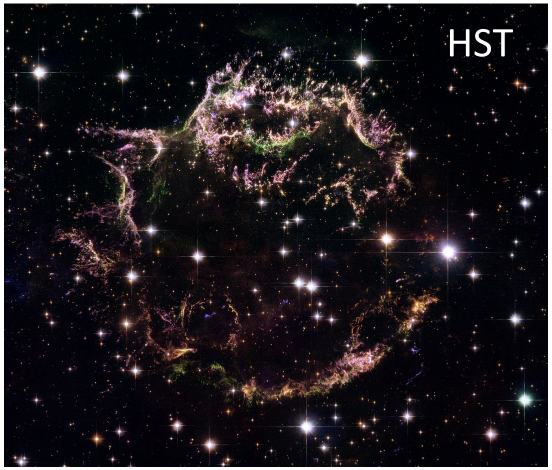
- SNRs IC 443 and W44 observed by Fermi-LAT from ~ 0.1 to 50 GeV

Science 339 (2013) arXiv:1302.3307v1



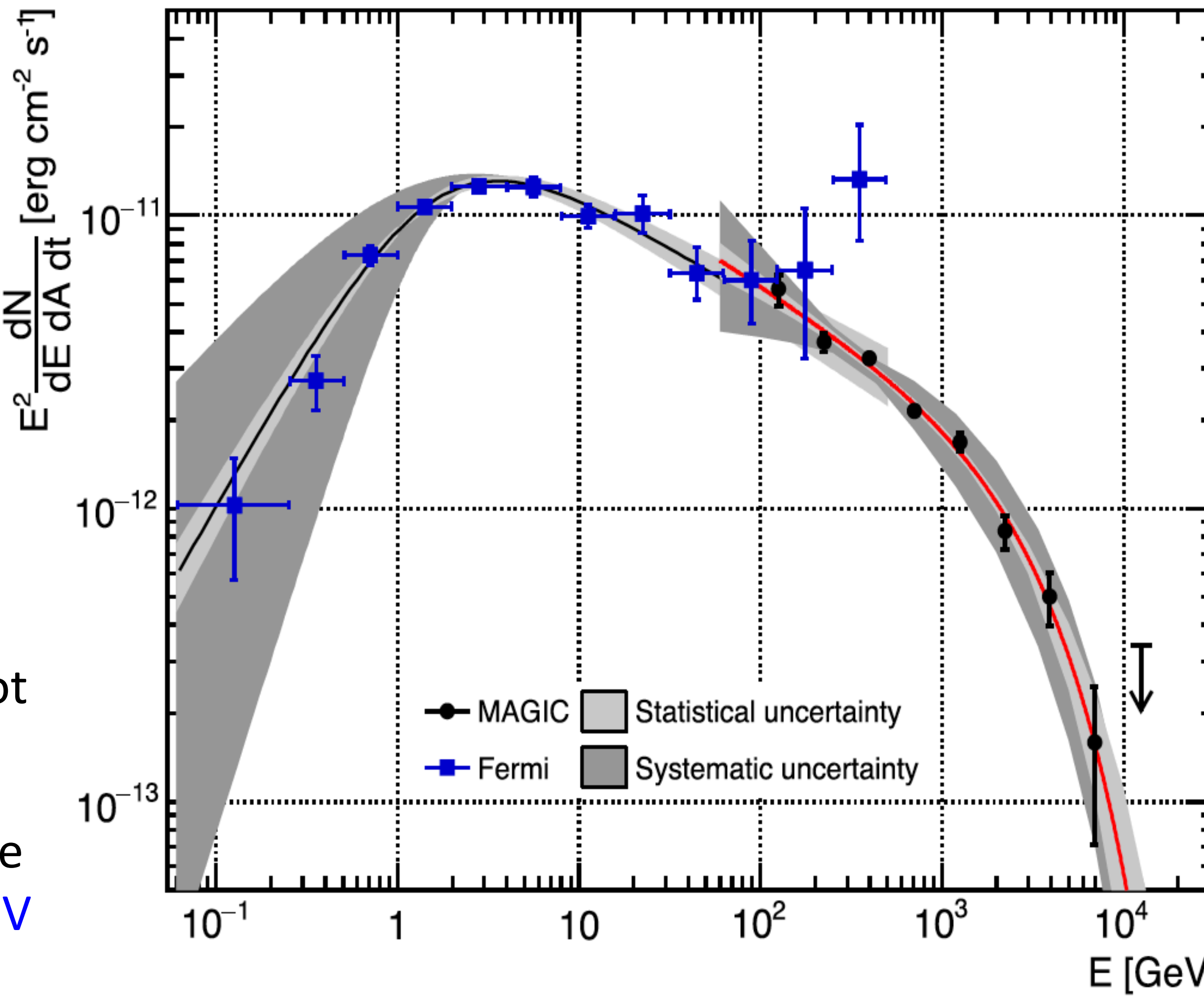
- Fast-rising SED below 0.2 GeV is a characteristic signature of π^0 decay
- Hadronic models fit significantly better than leptonic models ⟹ evidence of proton acceleration at these SNRs – but to what energies?
- IACTs needed to probe the highest energies – search for PeVatrons

Cas-A: MAGIC +Fermi-LAT spectrum



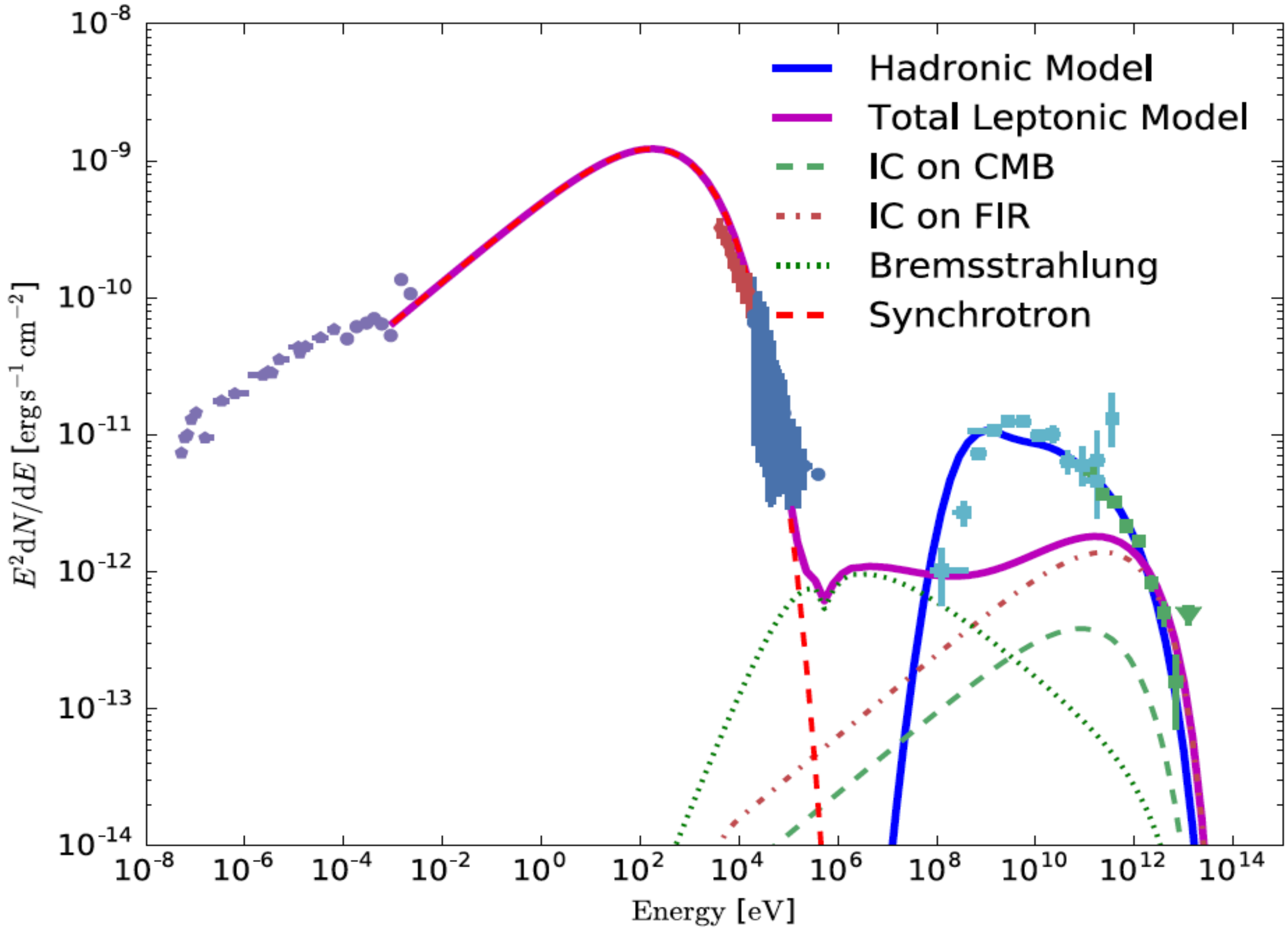
- Remnant of a core-collapse SN (330 yr. old)
- Shell has 5 arcmin ∅ , not resolved in gamma band
- Clear cut-off visible in the VHE spectrum at ~3.5 TeV

MAGIC coll., MNRAS 472 (2017)



Cas-A, broadband spectrum: not a PeVatron

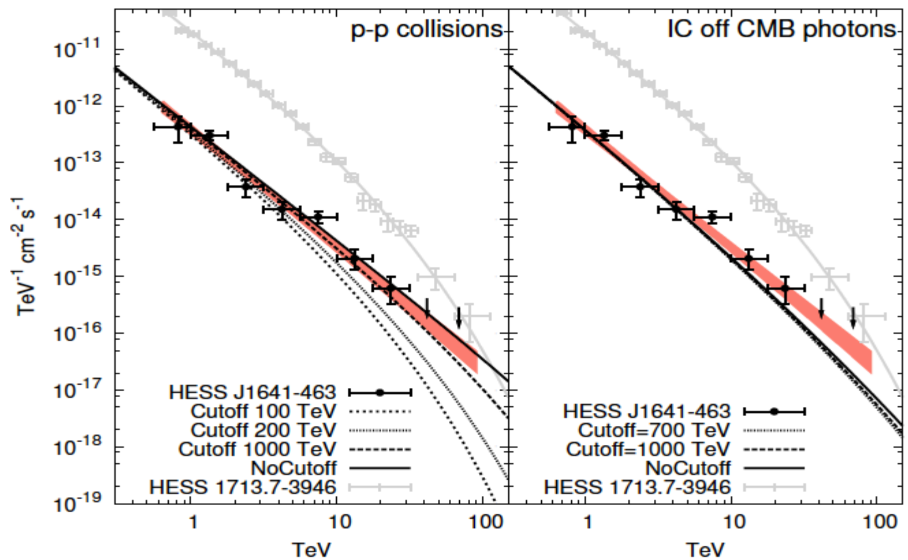
Hadronic model favoured, but cut-off in gamma spectrum suggests cut-off at ~12 TeV in parent proton spectrum (i.e., well below the *knee*)



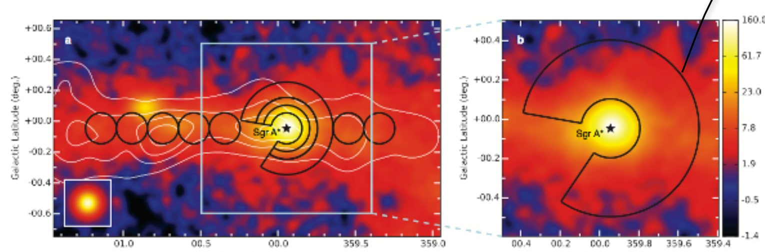
Any promising PeVatron candidates?

- Some galactic sources show a hard spectrum and no hint of a cut-off
- Example: HESS J1641 (PWN or unresolved shell SNR)
- Next generation IACT (CTA) needed for establishing maximum E reached

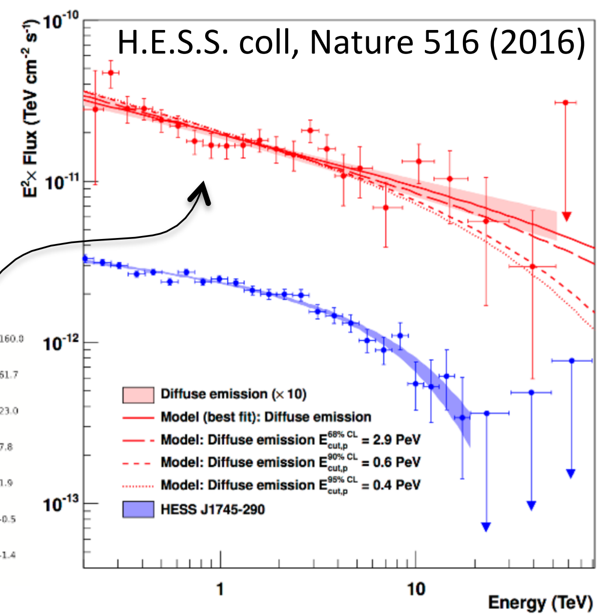
HESS J1641-463 H.E.S.S. coll., ApJL 794 (2014)



- Another Pevatron candidate is the galactic center region
- Assuming hadronic origin of the diffuse gamma emission, spectrum implies a cutoff >0.4 PeV at 95% C.L.



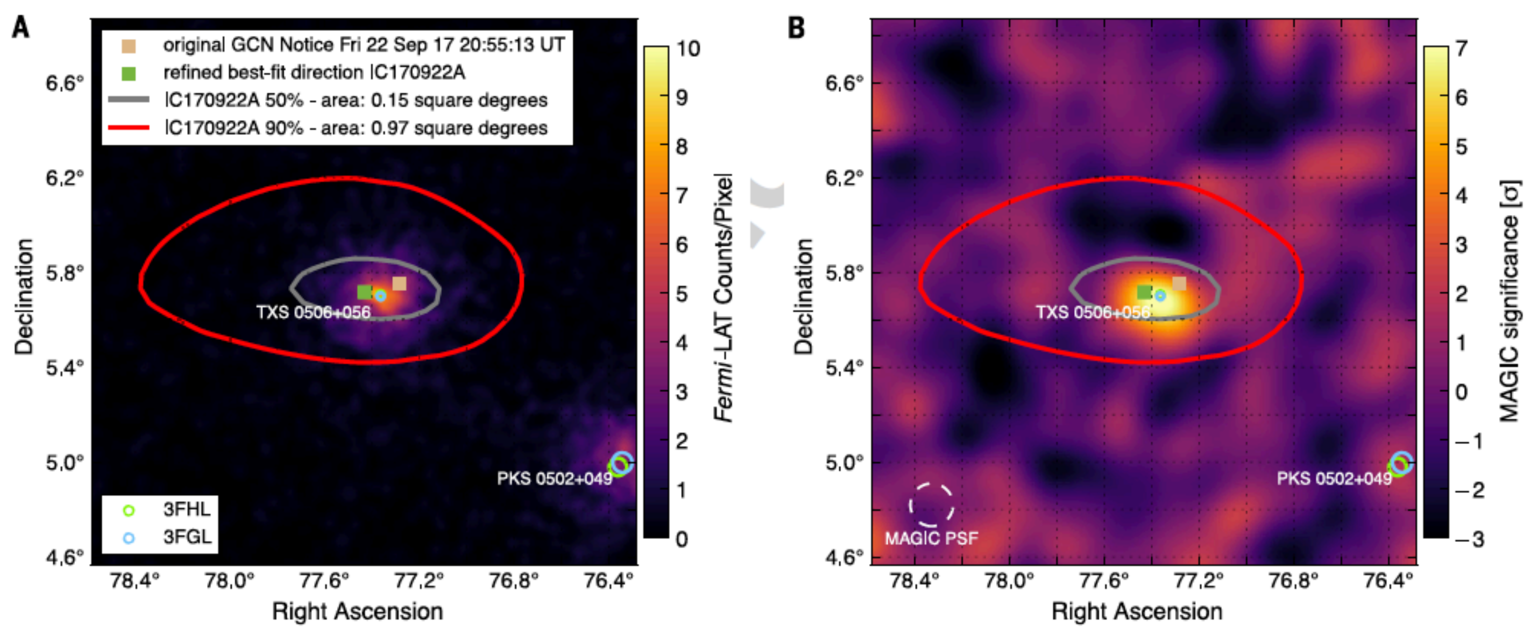
H.E.S.S. coll, Nature 516 (2016)



IceCube-170922A: dawn of VHE neutrino astronomy?

- Detection of ν's would be a smoking gun evidence of hadron acceleration
- IceCube-170922A alert, ~290 TeV neutrino with 56.5% *signalness*
- Direction compatible with flaring blazar TXS 0506+056 reported by Fermi-LAT
- Follow-up observations by MAGIC show gamma spectrum extends to ~400 GeV (source not previously known in VHE).
- Post-trial significance of coincidence ~3 σ

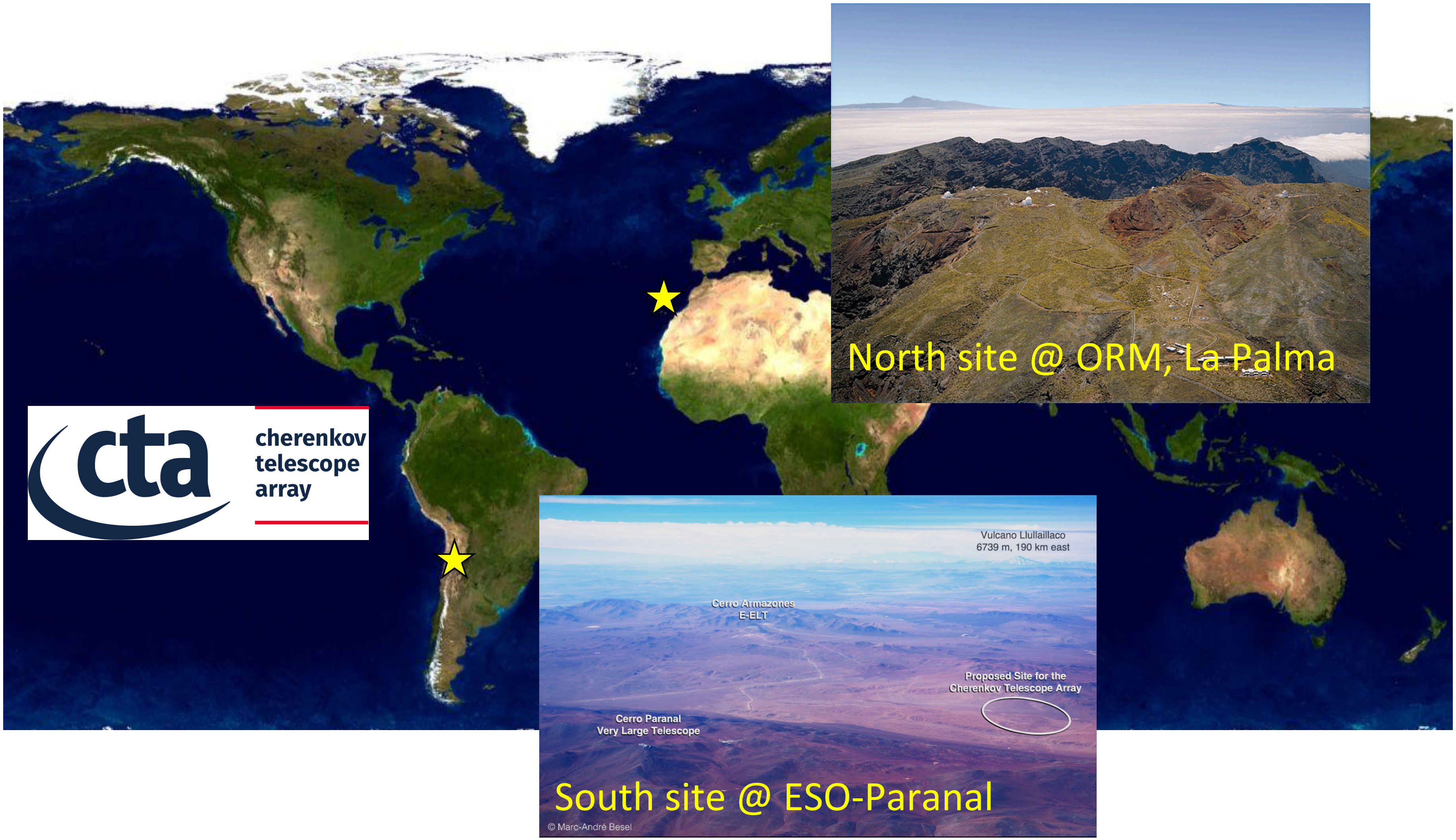
Science 361 (2018)



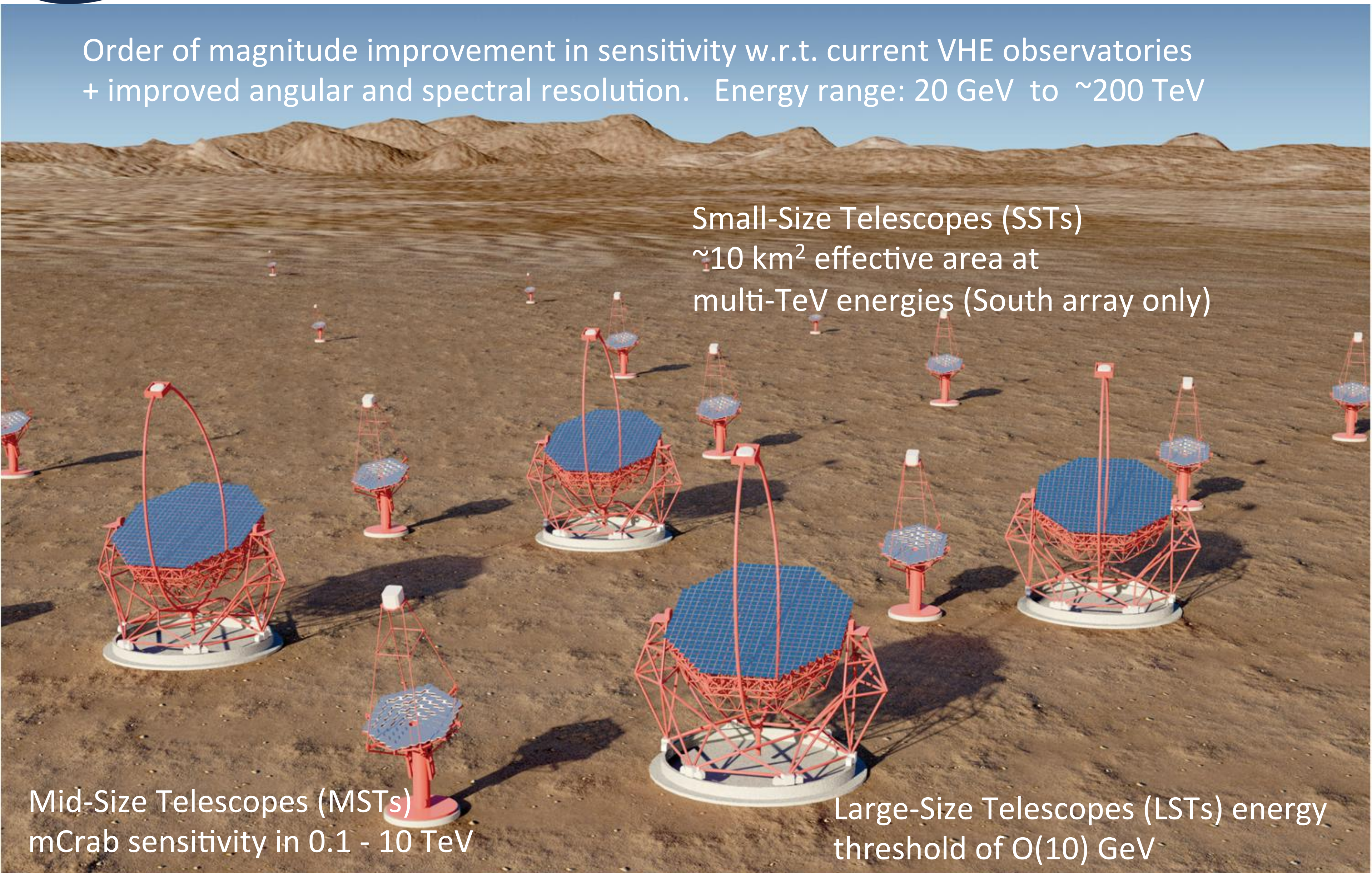
- Looking on archival data, IceCube reported another excess from the same direction (Sept 2014 – March 2015, 3.5 σ post-trials) - but with no associated ϒ activity

The future: the Cherenkov Telescope Array

the next-generation VHE observatory



The CTA concept

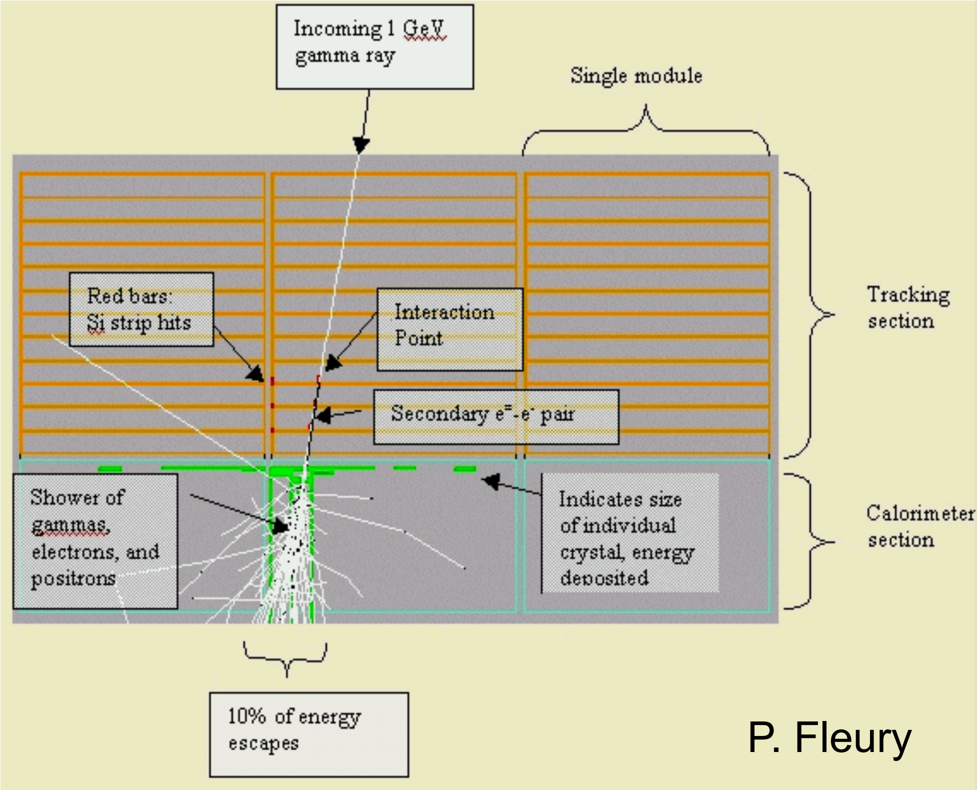



CTA-LST1 in La Palma
inaugurated Oct 10th, 2018
First CTA telescope on-site
Thanks!

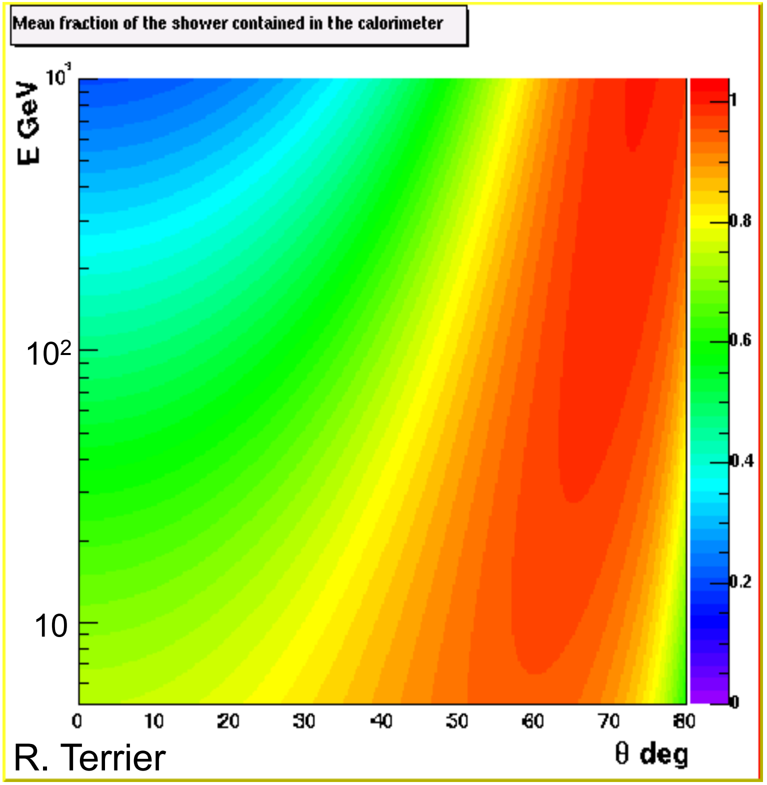
Back-up

Limitations of space γ-ray telescopes in the VHE range (>100 GeV)

Realistic MC simulation of the materialization of a 1 GeV γ-ray in a structure like that of LAT (or EGRET)

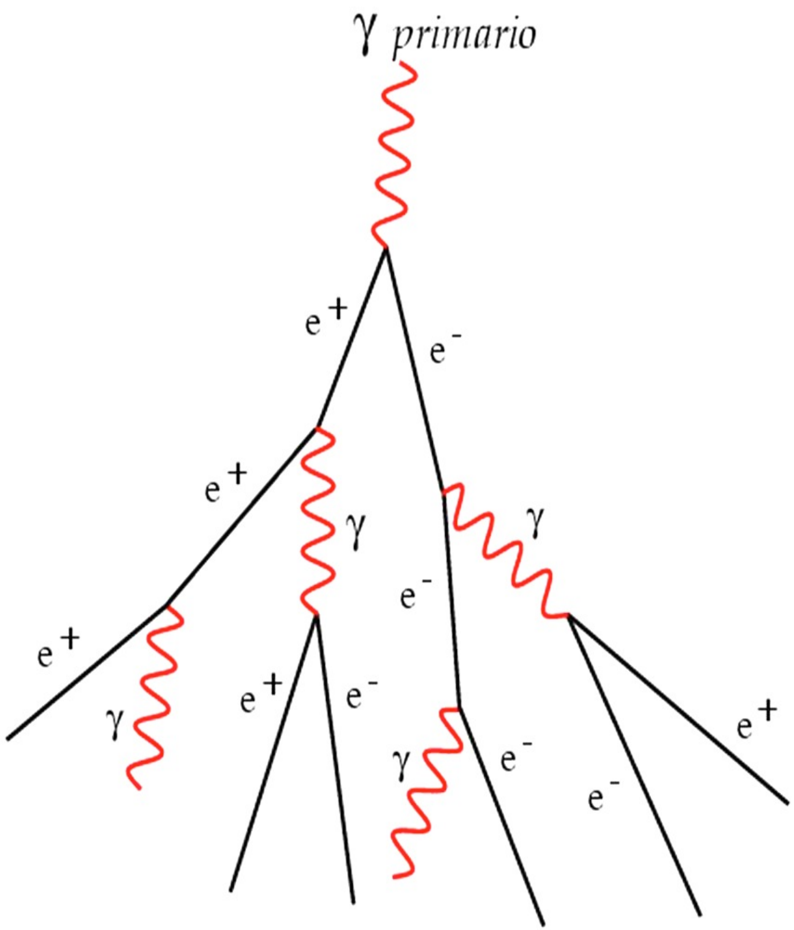


Fermi LAT, mean fraction of the shower contained in the calorimeter vs. incidence angle

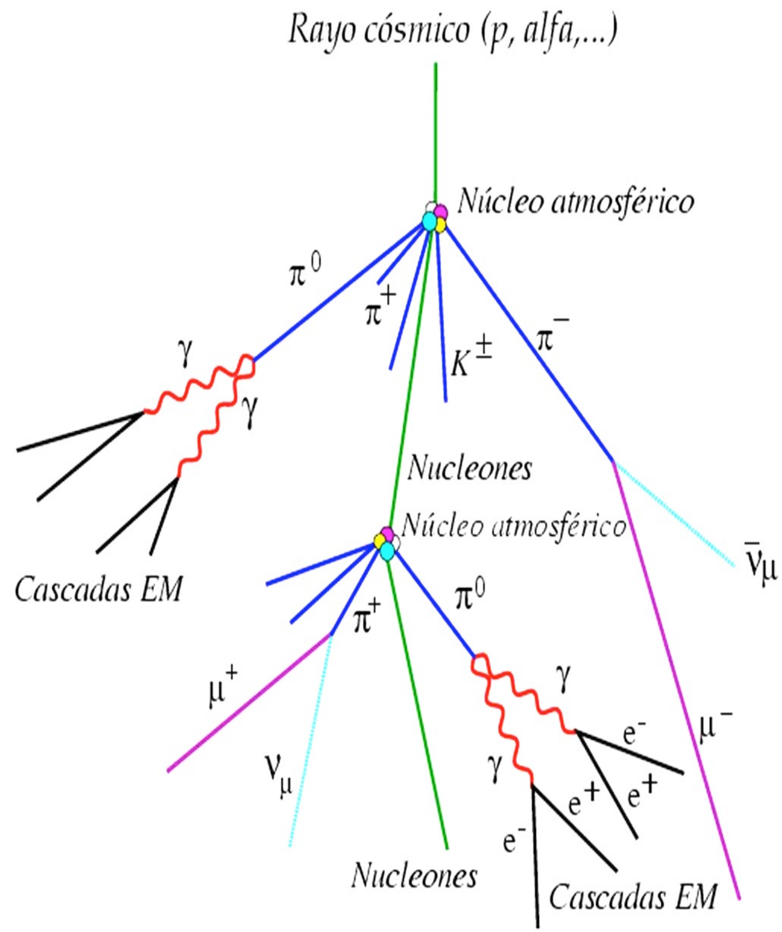


Extensive Air Showers (EAS)

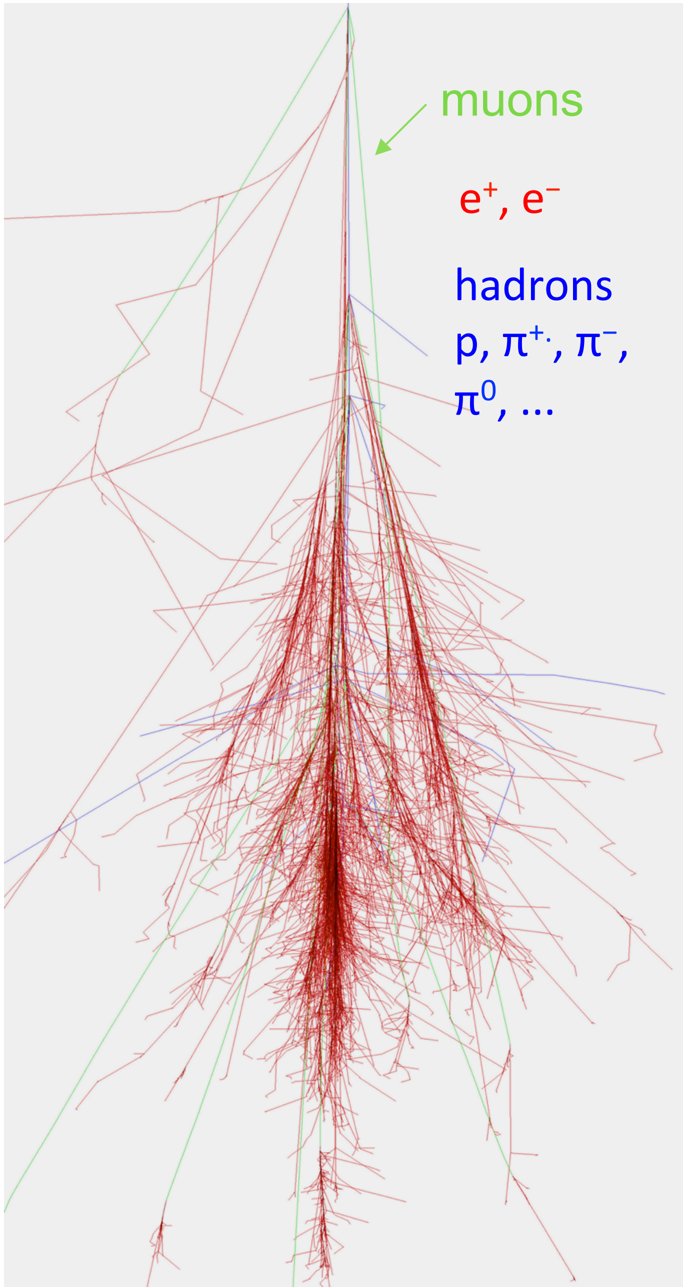
Electromagnetic (EM)

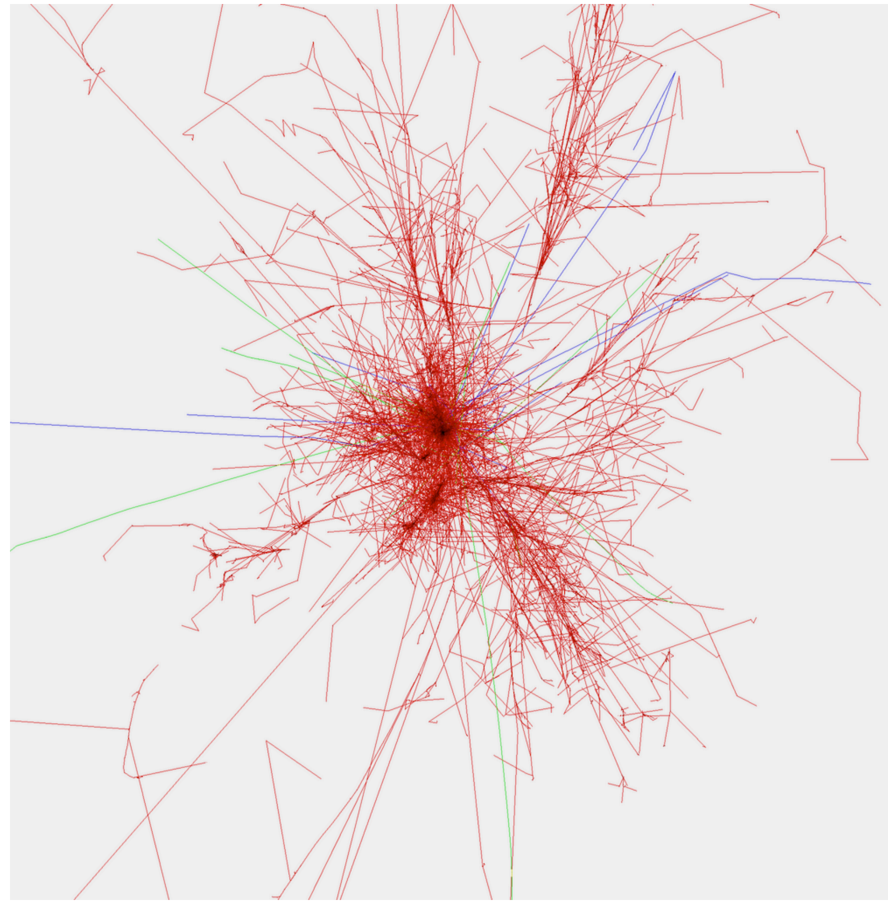


Hadronic



Simulated proton 100 GeV





Fabian Schmidt, Leeds university

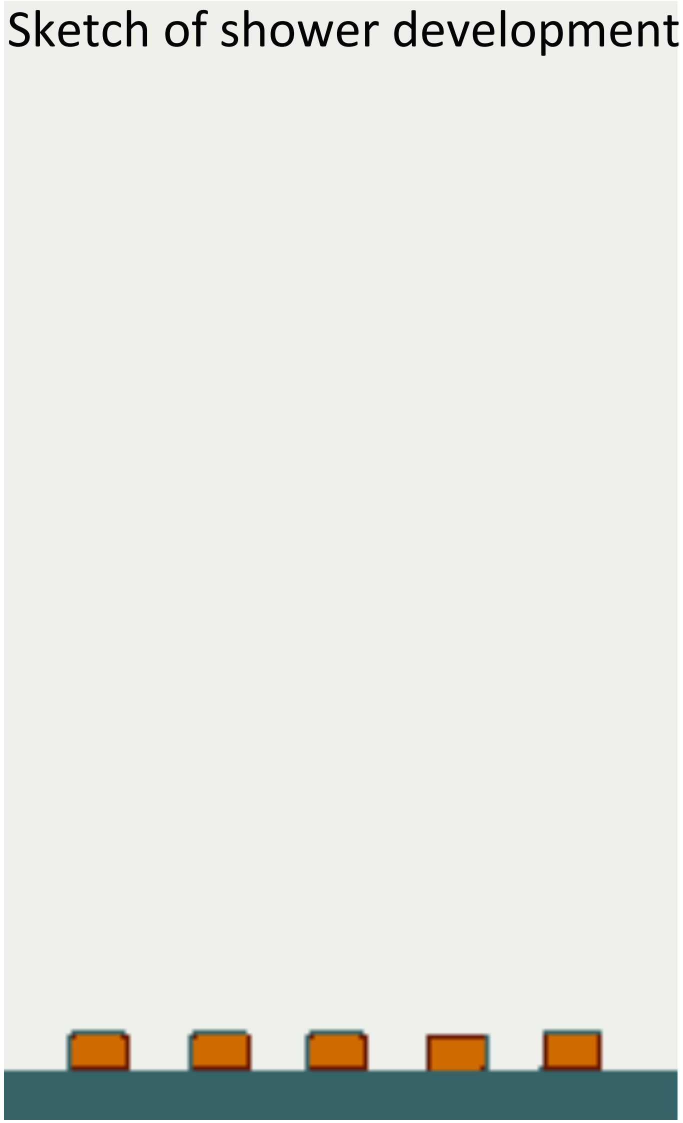
Hadron-initiated showers

- Muons, resulting mainly from charged pions, have a half-life of 2.2 μs in their own reference frame ⇒ many arrive at the ground before decaying (and account for 75% of all secondary CRs detected at sea level)

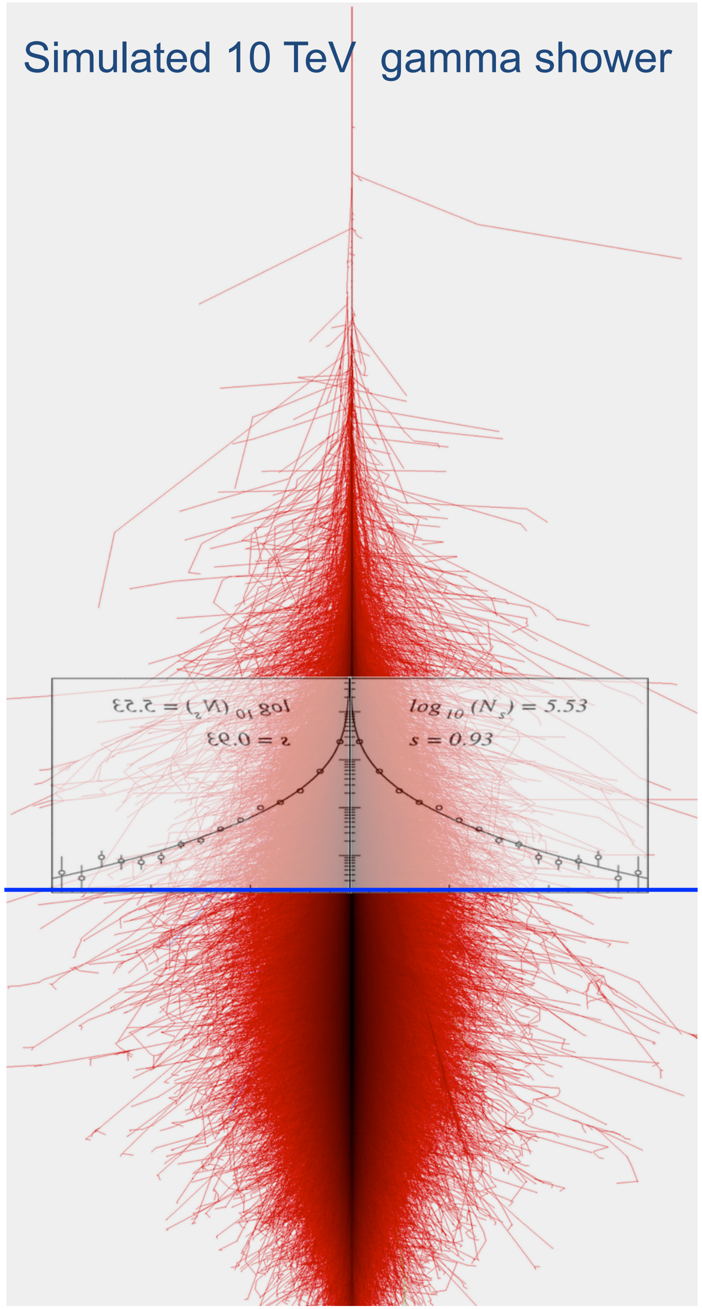
- Neutral pions decay (most often) in 2 γ, resulting in EM subshowers at some angle w.r.t. the shower axis (carrying in average 1/3 of E_0)

- Detailed study of extensive air showers requires a full Monte Carlo simulation (e.g. *Corsika*)

Shower front sampling technique



- Both in EM & hadronic showers secondary particles form roughly a disk-shaped front (or very flat cone) of few ns thickness, traveling at speed ≈ c towards the ground
- Extensive air showers can be detected using arrays of particle detectors on the ground (e.g. Auger, HAWC)
- Site altitude determines the energy threshold



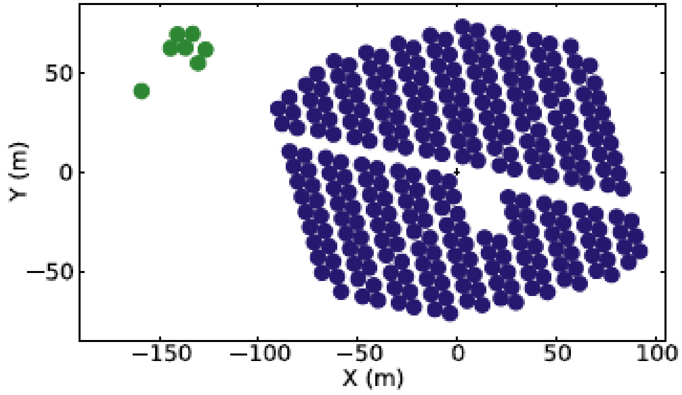
Lateral distribution: NKG formula

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

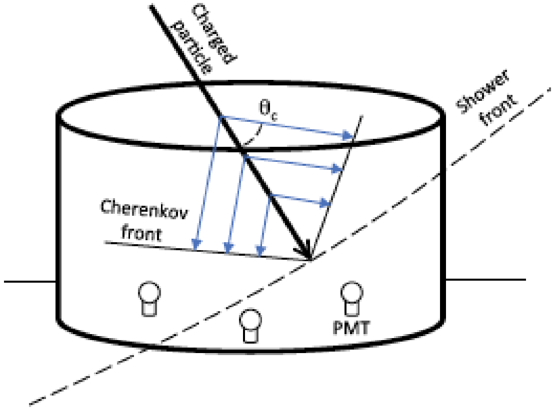
Shower front sampling technique: HAWC

High-altitude and dense sampling - detect as many particles as possible

- 4100 m a.s.l. in *Sierra Negra,* México
- 300 close-packed water-Cherenkov tanks
- Instantaneous FoV ≈2sr
- Can survey 40% of the sky every year
- Sensitivity (1 yr.): 5% Crab above 2 TeV



(a) HAWC tank layout.



(b) Water Cherenkov Detection Principle.

Intensity of atmospheric C-light

An electron traveling at speed β in a medium of refractive index n emits, between wavelengths λ_1 and λ_2, per unit length:

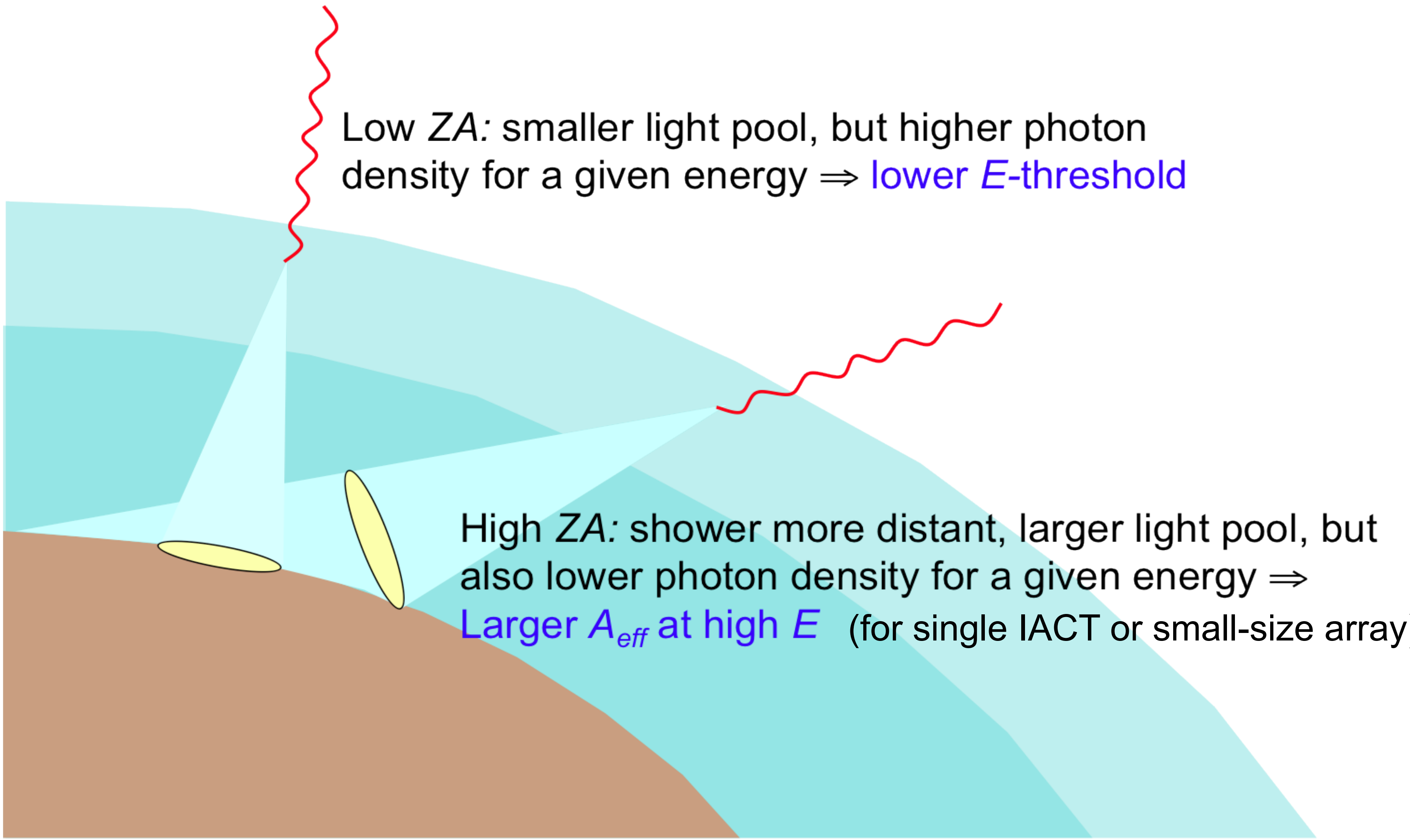
$$\frac{dN}{dx} = 2\pi\alpha \cdot \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right) \cdot \left(1 - \frac{1}{\beta^2 n^2}\right)$$

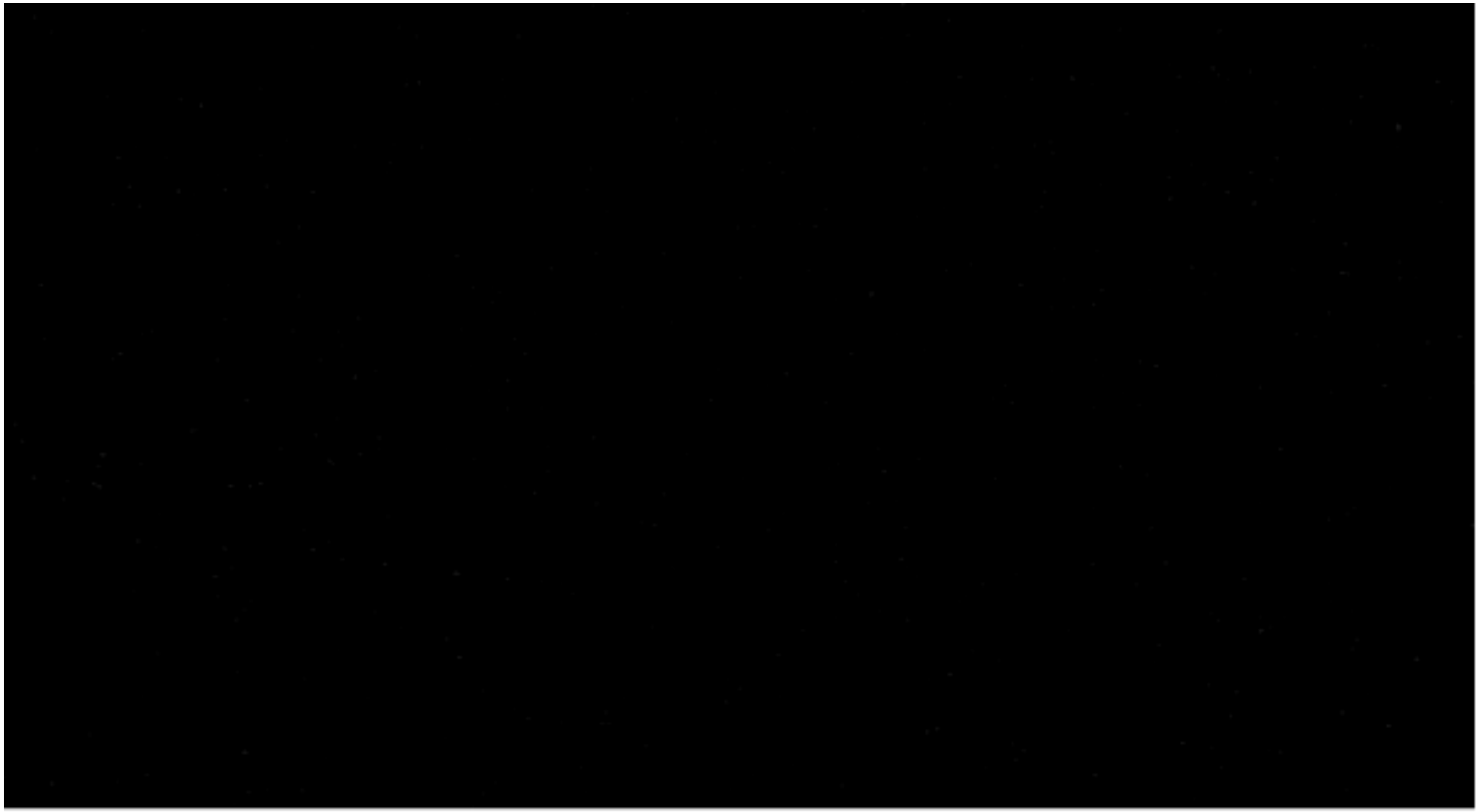
For λ_1 = 300 nm, λ_2 = 450 nm, in air, β = 1, exponential atmosphere ρ profile:

$$\frac{dN}{dx} \simeq 30 \cdot e^{-\frac{h}{h_0}} \text{ photons / m} = \boxed{30 \cdot \frac{t}{t_0} \text{ photons / m}}$$

t: atmospheric depth, t_0 = 1024 g/cm^2

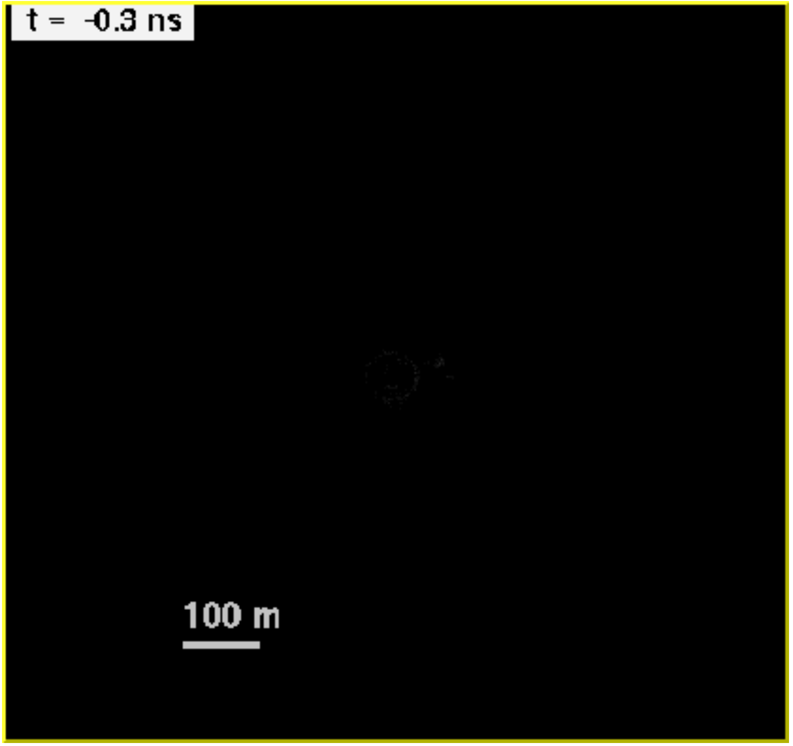
Effect of Zenith angle





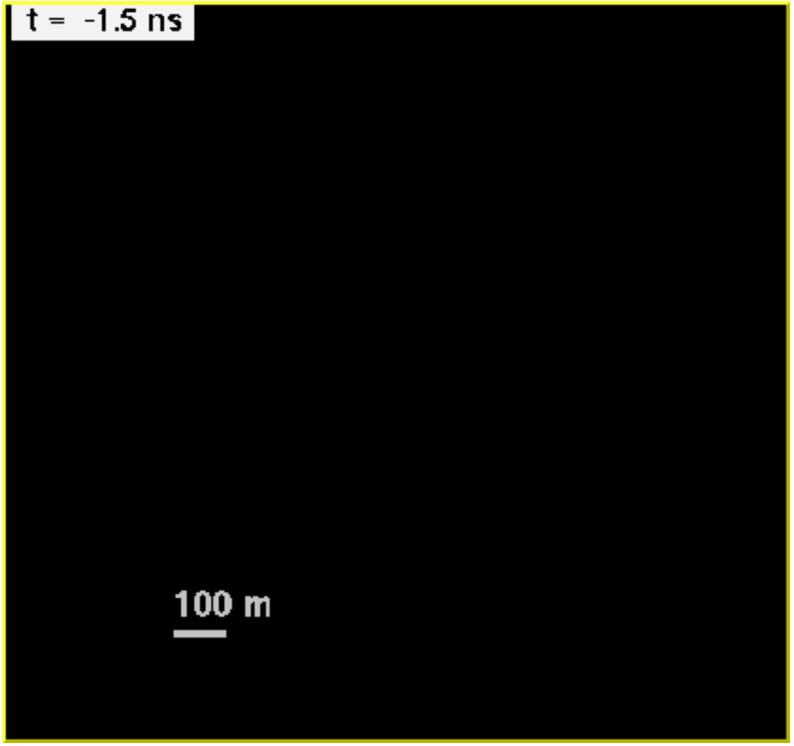
Arrival of C-photons at the ground

Gamma 100 GeV



CORSIKA simulation

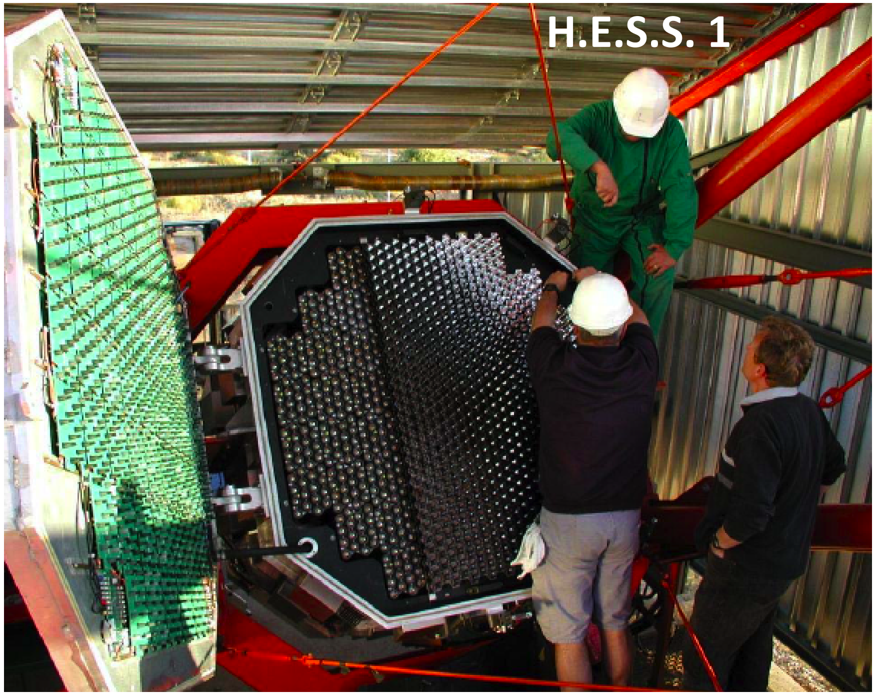
Proton 200 GeV



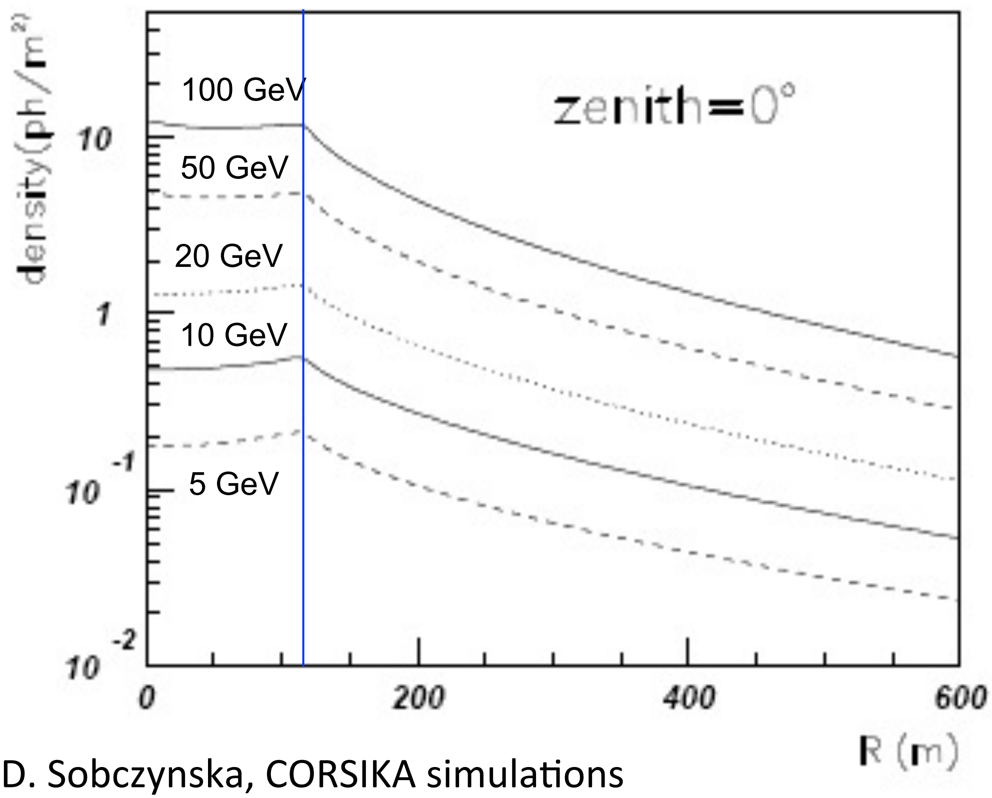
CORSIKA simulation,

- Cherenkov pulse duration O(ns) ⟹ fast photodetectors needed (PMTs or SiPMS)
- If placed at the focal plane of an imaging optical system (e.g. a parabollic mirror) allows to obtain an image of the EAS

IACT cameras



Energy reconstruction



D. Sobczynska, CORSIKA simulations

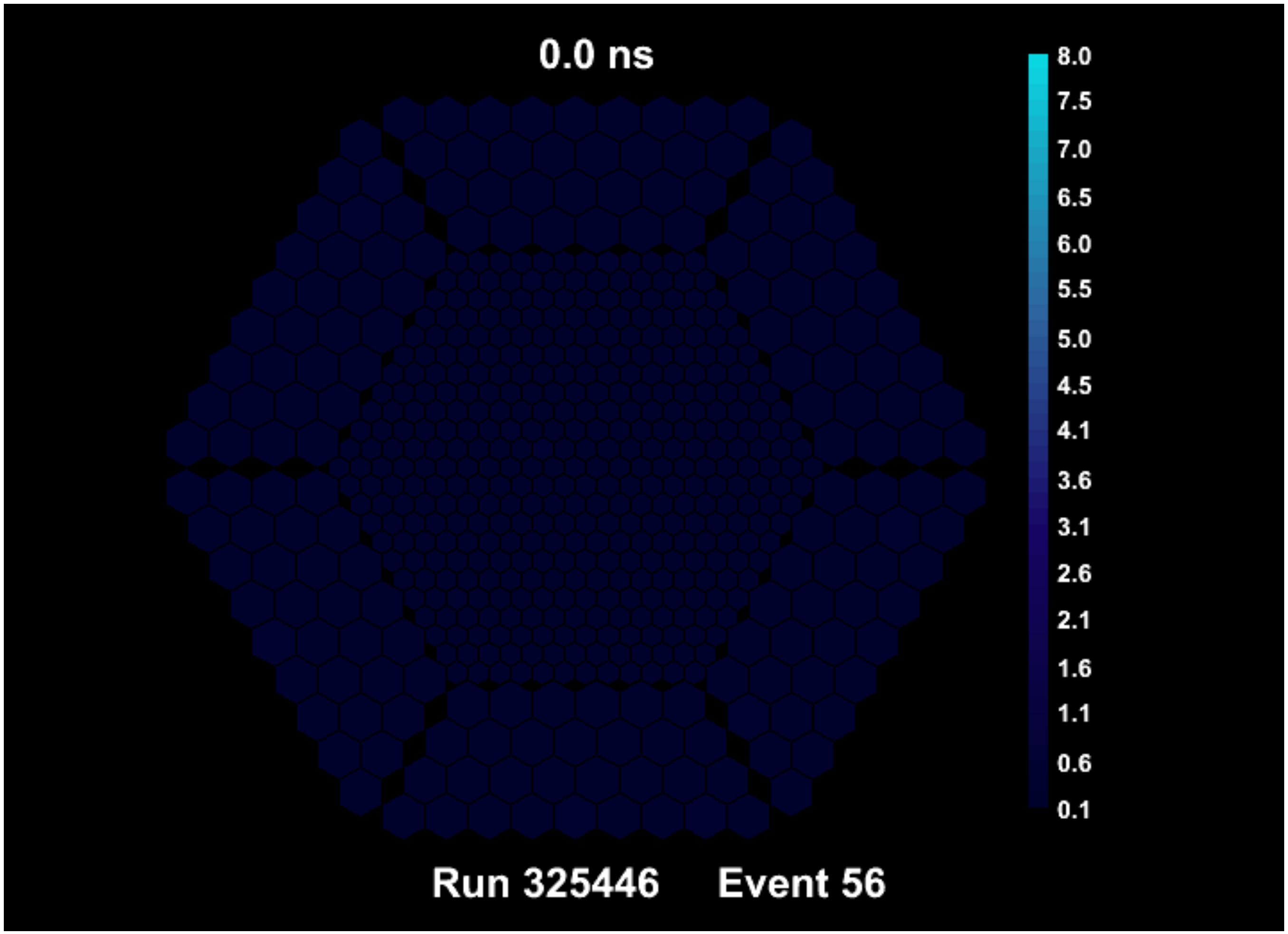
Based on the very good correlation between the number of collected C-photons *(Size)* and the energy, for a given impact parameter.

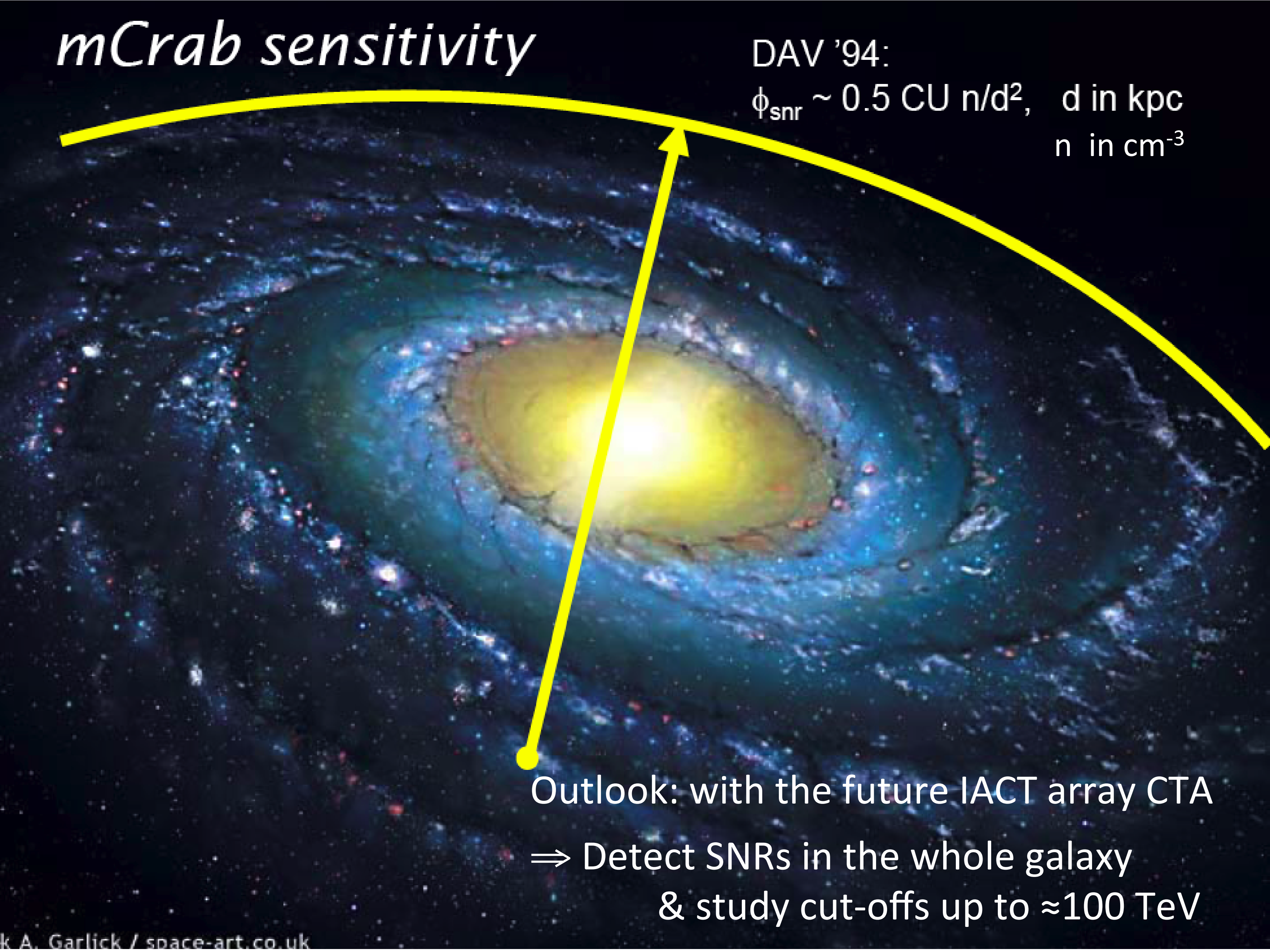
E_{est} obtained from MC-trained Look-Up Tables (or multivariate regression methods like random forest) on Size, i.p., zenith angle, height of shower maximum

Note: actually the light pool is not, even in average, exactly round: the geomagnetic field separates + and – charges in the E-W direction. This is taken into account (via a parametrized correctin) in the LUT-based E reconstruction

IACT camera (MAGIC-I)

2000 million frames per second γ-candidates




mCrab sensitivity
DAV '94:
$\phi_{snr} \sim 0.5$ CU n/d^2, d in kpc
n in cm^{-3}
Outlook: with the future IACT array CTA
⇒ Detect SNRs in the whole galaxy
& study cut-offs up to ≈100 TeV
k A. Garlick / space-art.co.uk