Air showers, exponential atmosphere, & IACT measurements

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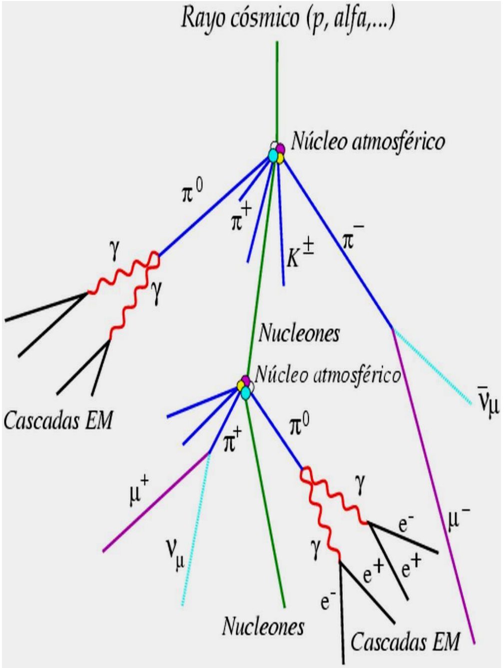
Extensive air showers (EAS)

- Discovered in 1938 by Pierre Auger

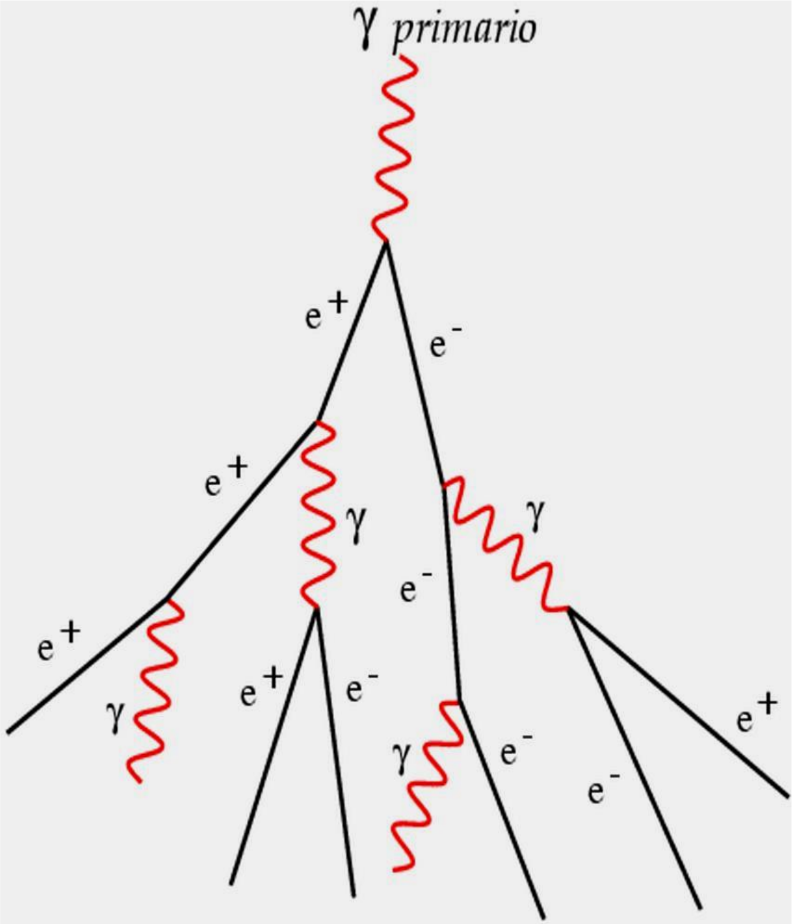


- Electromagnetic showers:
  - $\gamma \longrightarrow e^+ e^-$ (pair production)
  - $e^\pm \longrightarrow \gamma$ (*bremsstrahlung*)

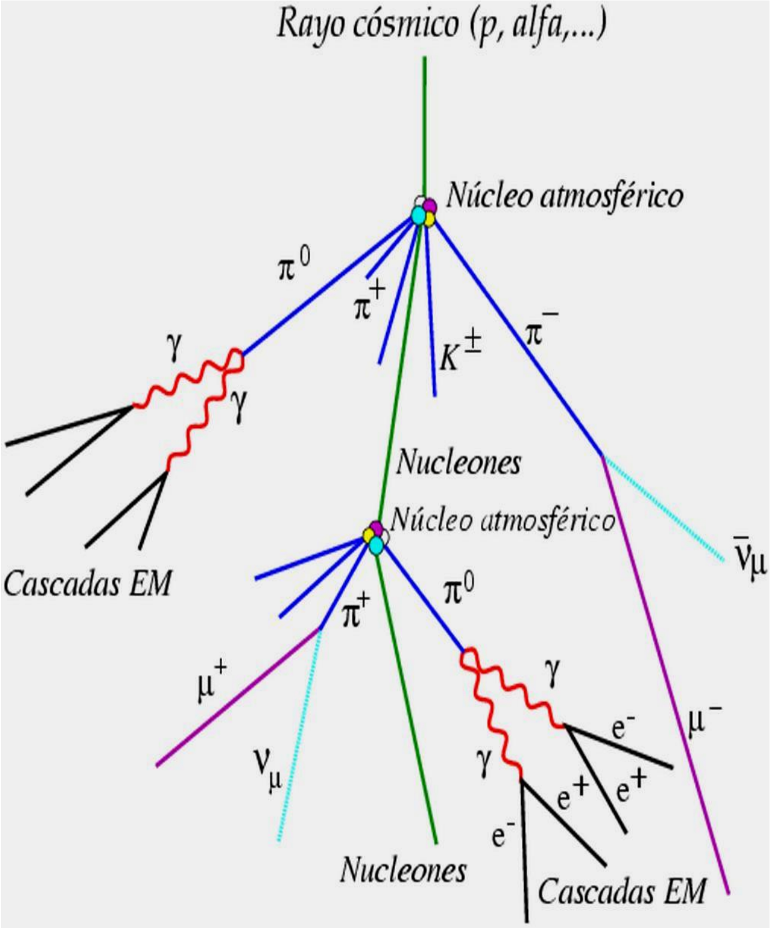
- Hadronic showers:
  - CR + atm. nucleus $\longrightarrow \pi^\circ, \pi^\pm + N^*$
  - $\pi^\pm \longrightarrow \mu^\pm + \nu$
  - $\pi^\circ \longrightarrow \gamma\,\gamma \longrightarrow$ e.m. showers

Extensive Air Showers (EAS)

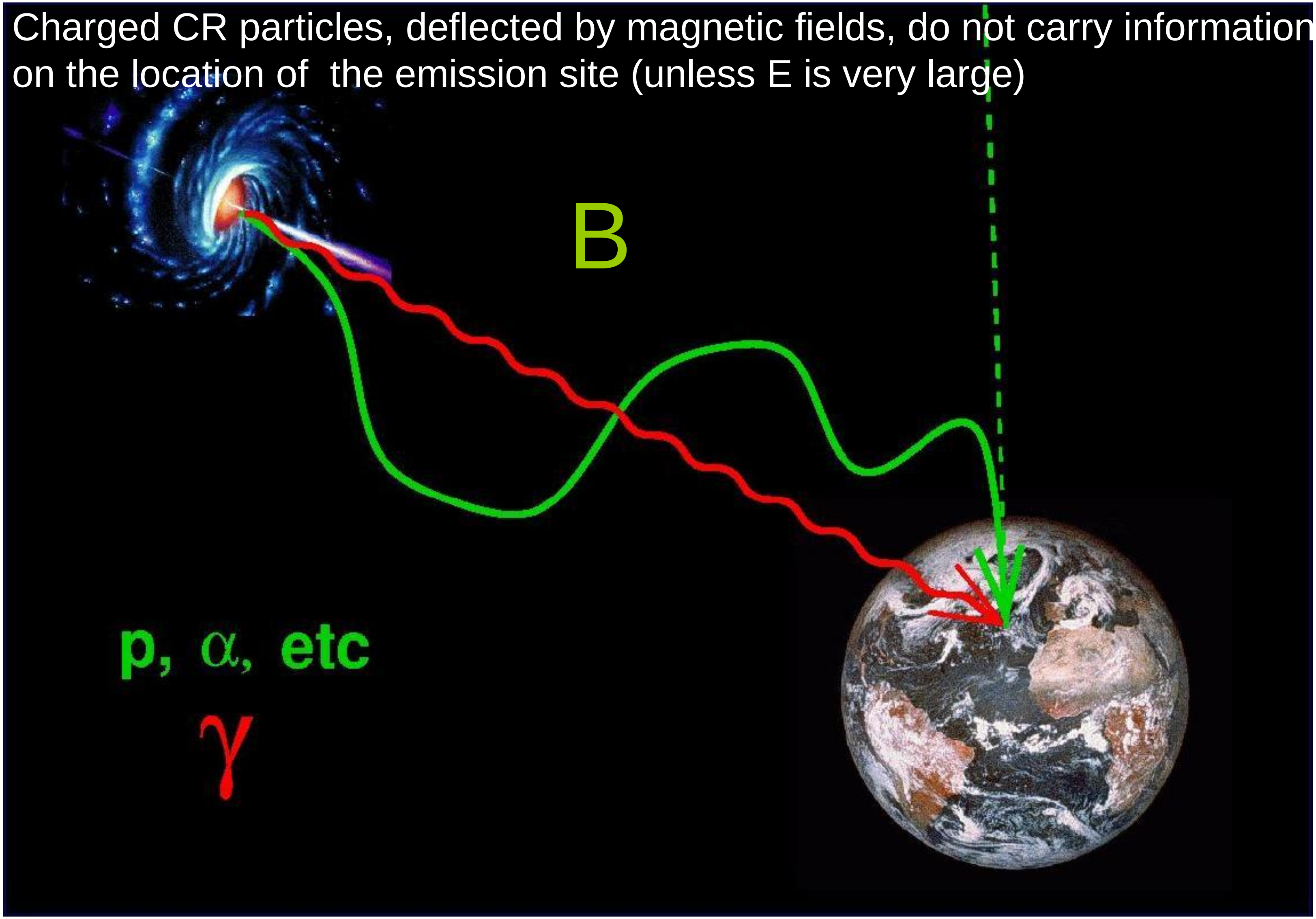
Electromagnetic



Hadronic



Why not doing charged CR astronomy?



Charged CR particles, deflected by magnetic fields, do not carry information on the location of the emission site (unless E is very large)

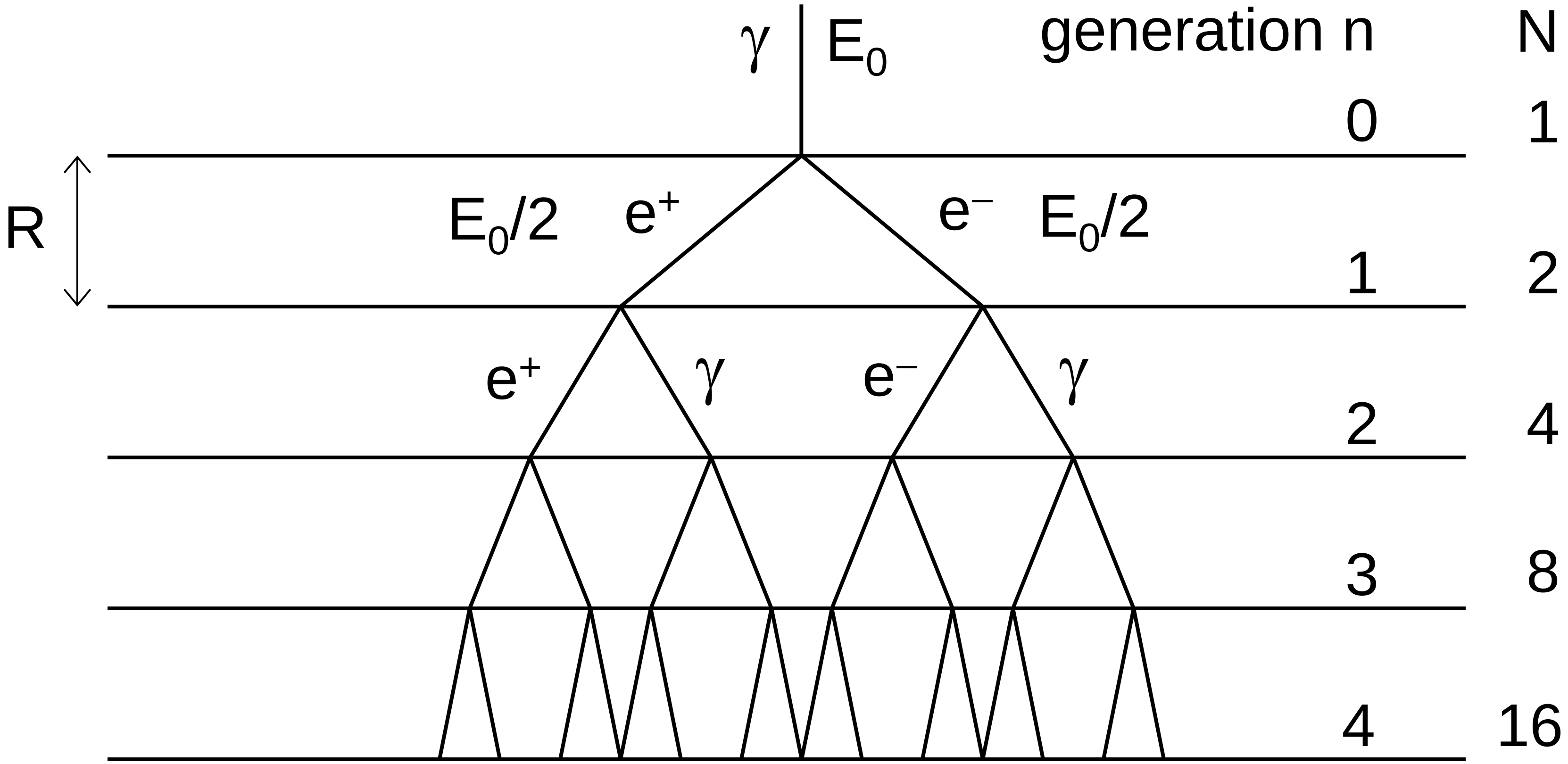
Heitler model of an electromagnetic shower

- Radiation length X_0 : average distance traversed by an electron in a medium in the time in which its energy drops by a factor **e**. That is: $E = E_0\, e^{-x/X_0}$
- For air, $X_0 = 36.7$ g/cm^2 (about 300 m at sea level)
- For ultra-relativistic electrons, X_0 roughly equals the mean free path of gammas of similar energy (m.f.p. ≈ $9/7\, X_0$)
- Heitler model assumptions:
  - Interaction probability for $e^{\pm}$ and γ is the same, and it is 1/2 after traveling a distance $R = X_0 \ln(2)$. Further simplification: one interaction exactly every R
  - Energy is equally shared between the products of each interaction

Development of an EM shower

- E_c : “critical energy” ($\cong$ 80 MeV in air) below which ionization dominates over bremsstrahlung in the energy loss of $e^{\pm}$.
- Multiplication of the number of $e^{\pm}$, N_e, goes on until $\langle E \rangle < E_c \Rightarrow N_{max} \propto E_0$ (shower maximum)
- After that, multiplication comes to an end: shower particles gradually lose their energy until the shower extinguishes.

Heitler model



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Heitler model

- In the nth generation, 2^n particles ($e^\pm$ and γ) of 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)

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Rossi & Greisen “approximation B”

(Rev. Mod. Physics 13 (1941) http://prola.aps.org/toc/RMP/v13/i4)

- Considers Bremsstrahlung and pair production
- Neglects Compton effect, photon-nucleus interactions and knock-on electrons

Number of e$^{\pm}$ vs. t (atmospheric depth):

$$N_e(t) = \frac{0.31}{\sqrt{\ln(E_0/E_c)}} \cdot \exp[t \cdot (1 - 1.5 \ln s)]$$

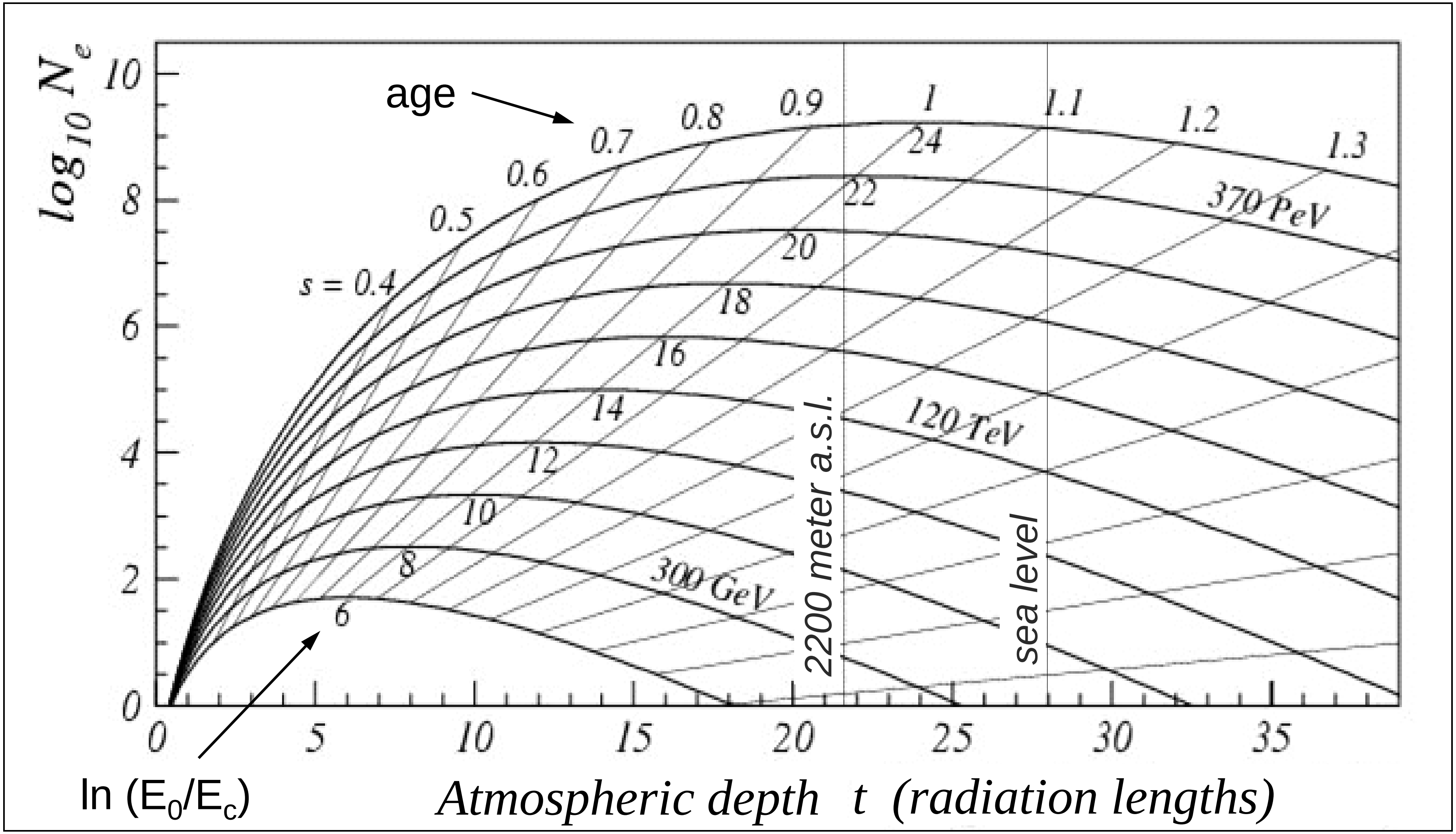
$$s = \frac{3\ t}{t + 2\ln(E_0/E_c)}$$

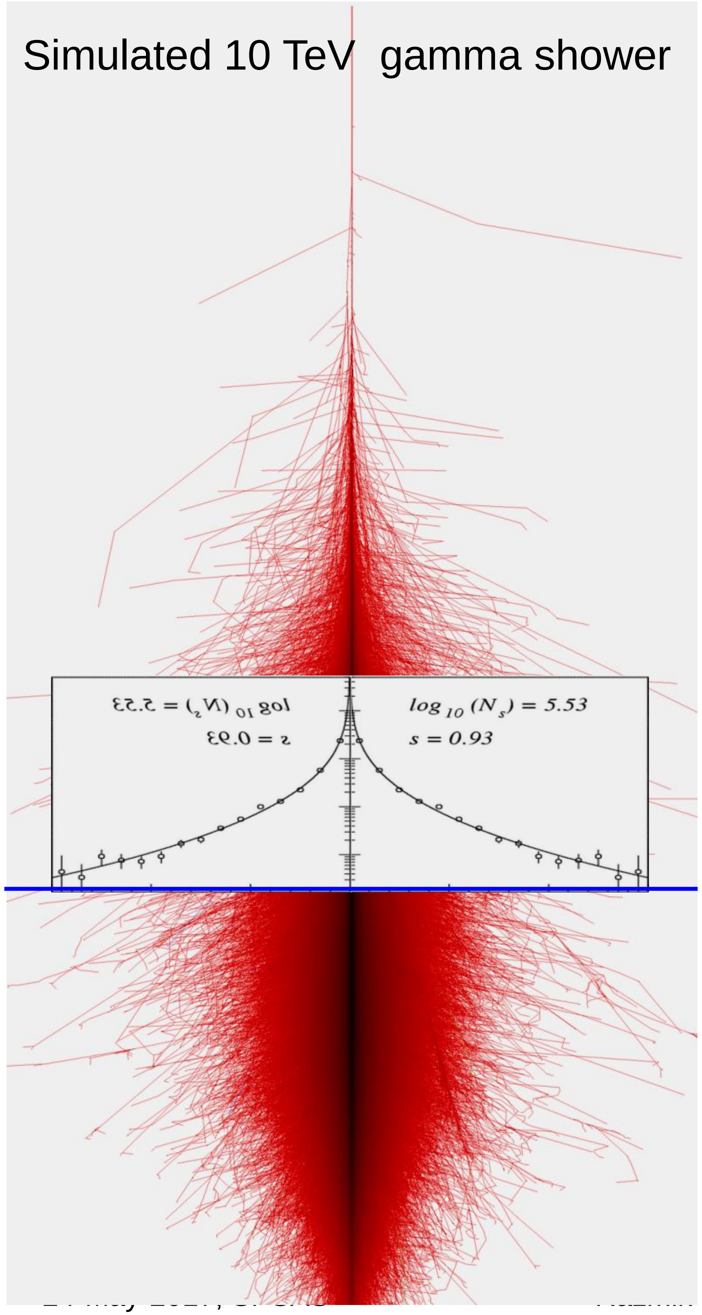
“age” of the shower

s = 0 at first interaction, 1 at maximum, 2 when $N_e < 1$

Longitudinal EM shower development

Rossi & Greisen approximation B





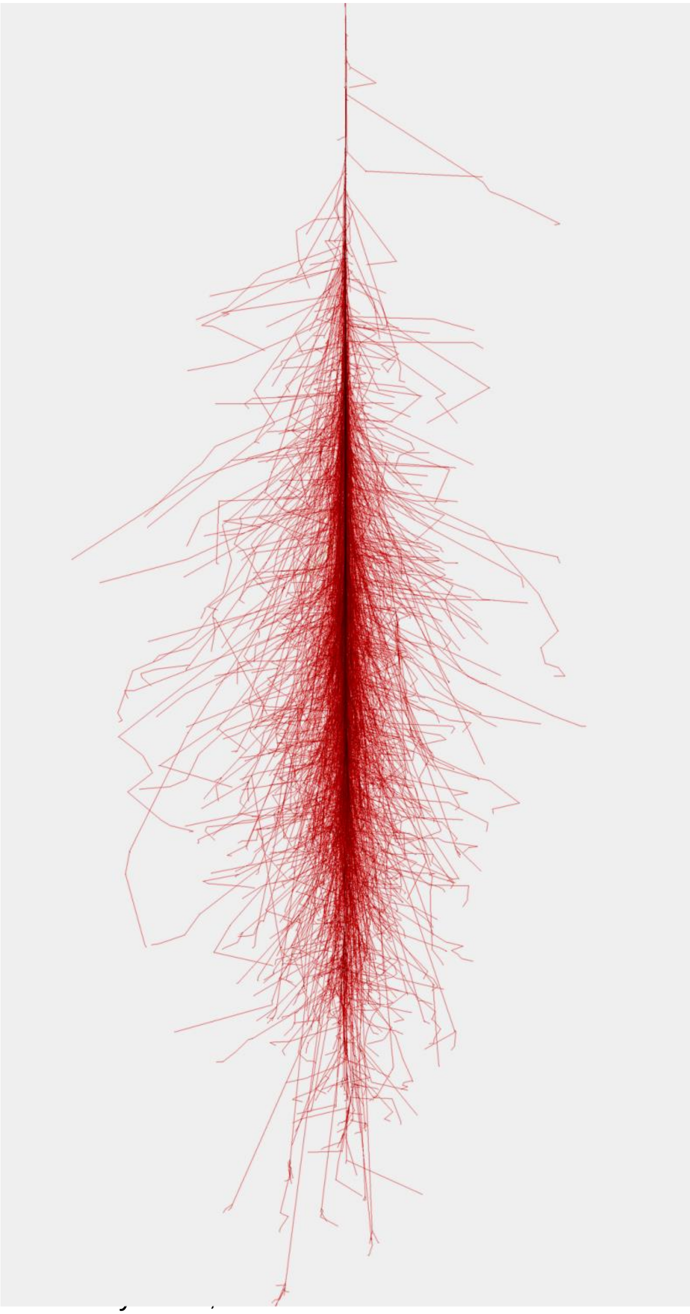
Simulated 10 TeV gamma shower

Lateral distribution: NKG formula

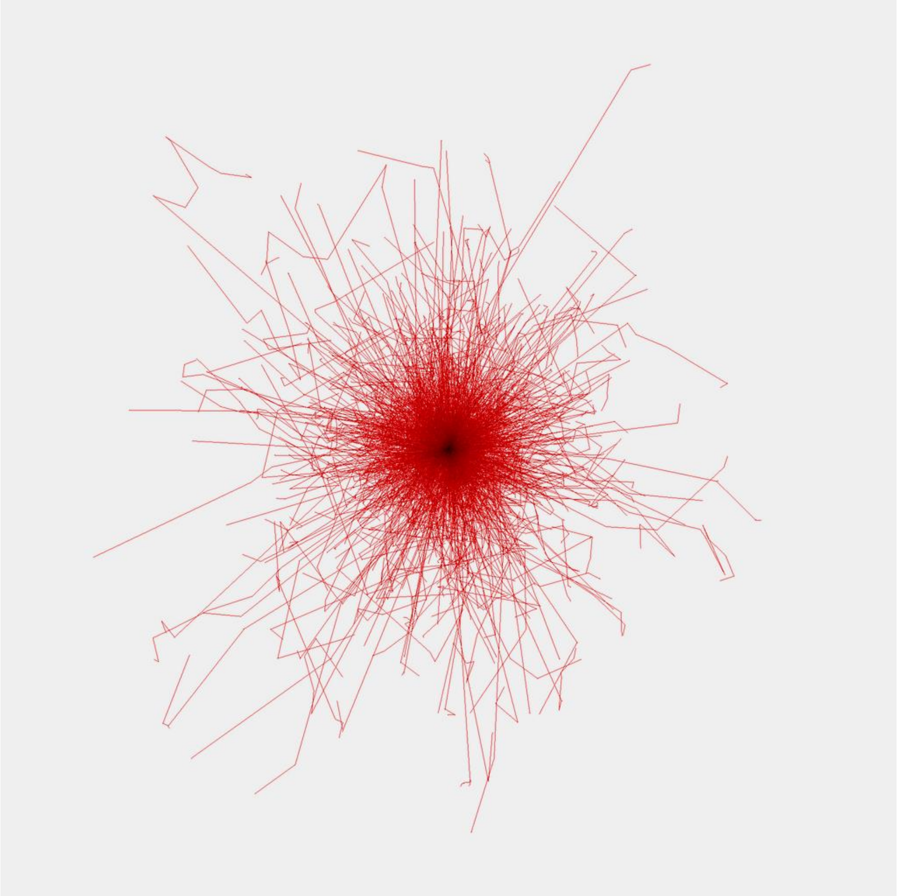
Fabian Schmidt, Leeds university
http://www.ast.leeds.ac.uk/~fs/showerimages.html

Hadron-initiated showers

- Muons, resulting mainly from charged pions, have a half-life of 2.2 μs in their own reference system ⇒ many arrive at the ground before decaying (and account for 75% of all secondary CR 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
- Detailed study requires a full Monte Carlo simulation

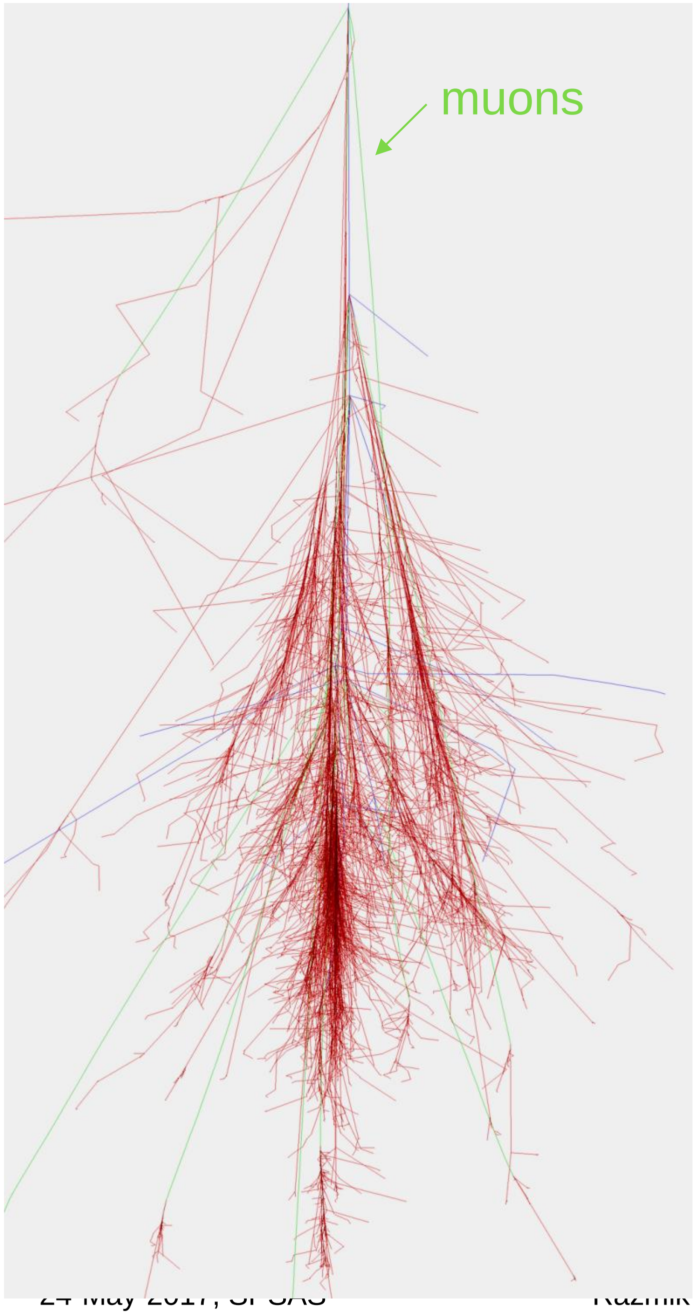


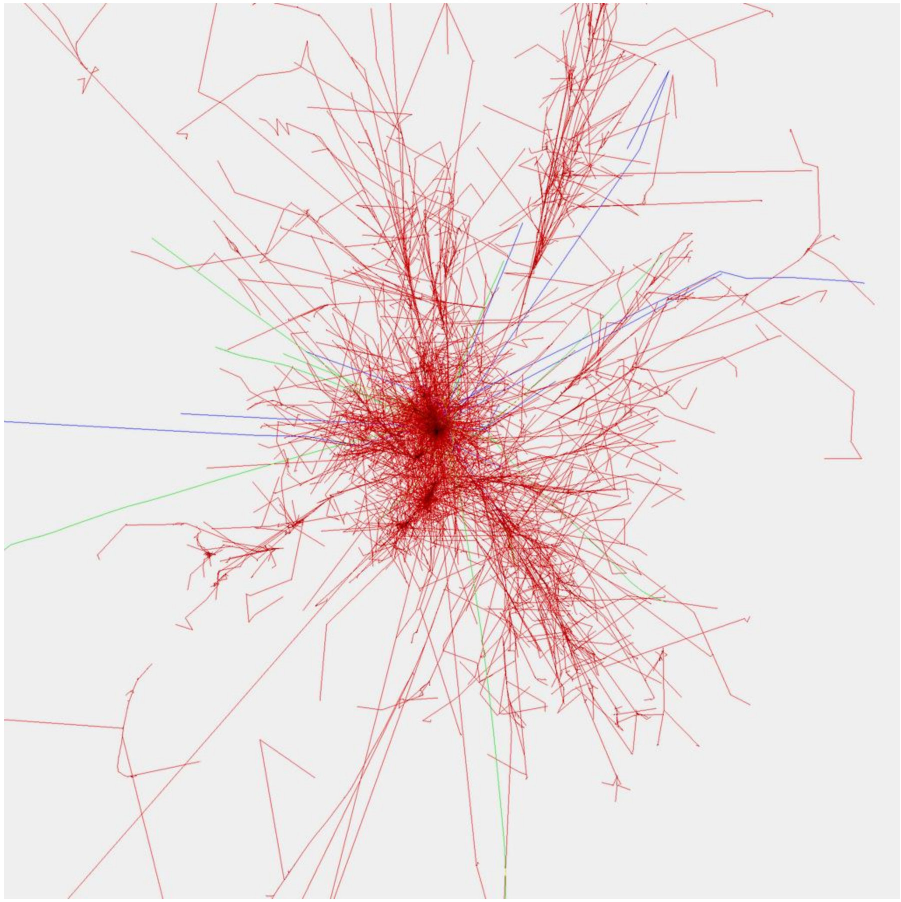
Simulated gamma 50 GeV



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

Simulated proton 100 GeV





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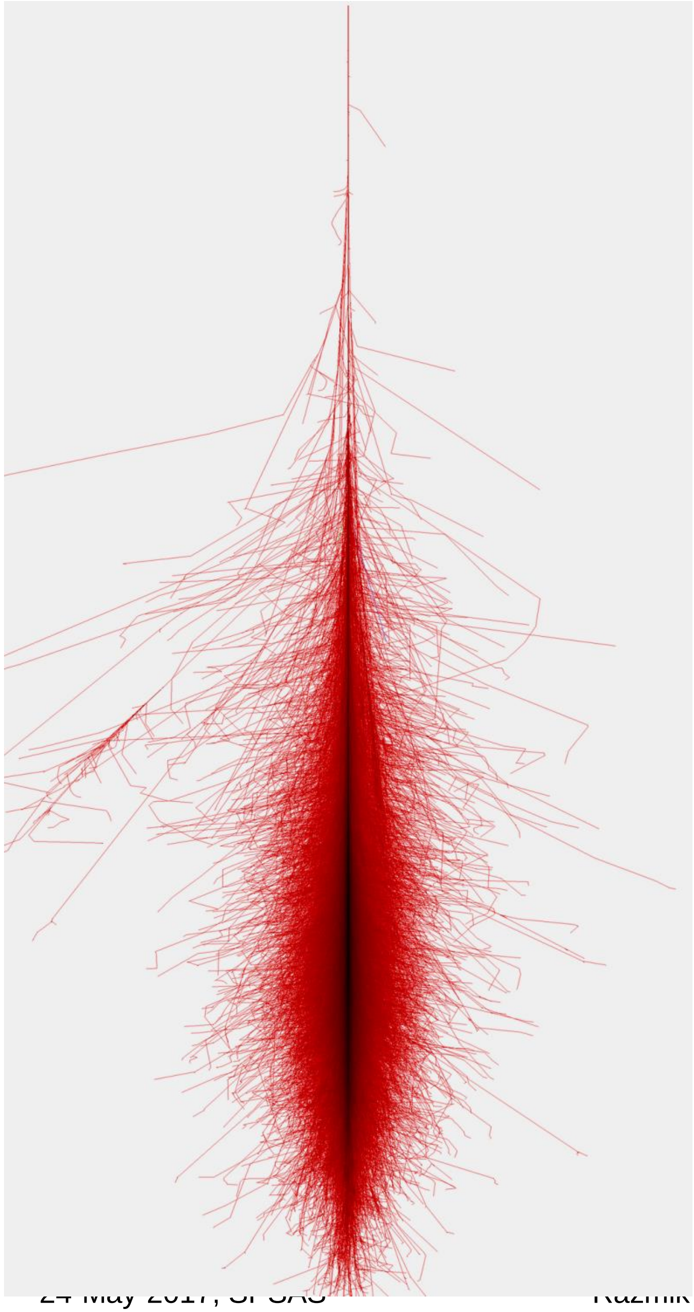
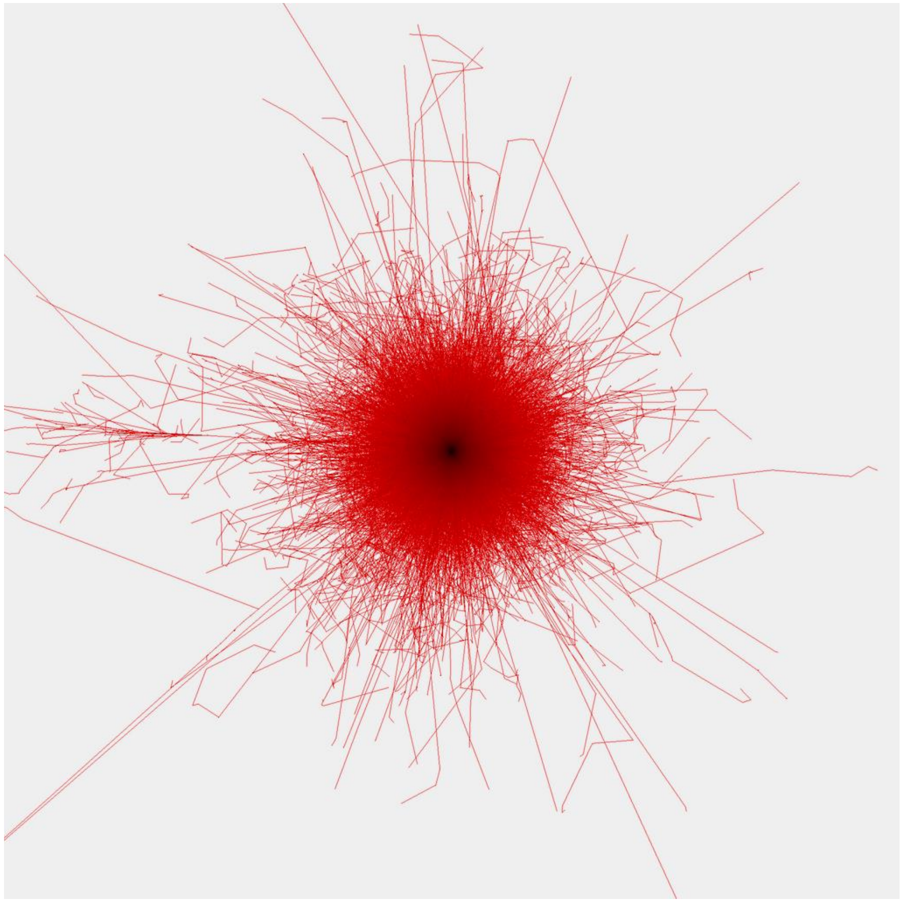


Simulated gamma
1 TeV



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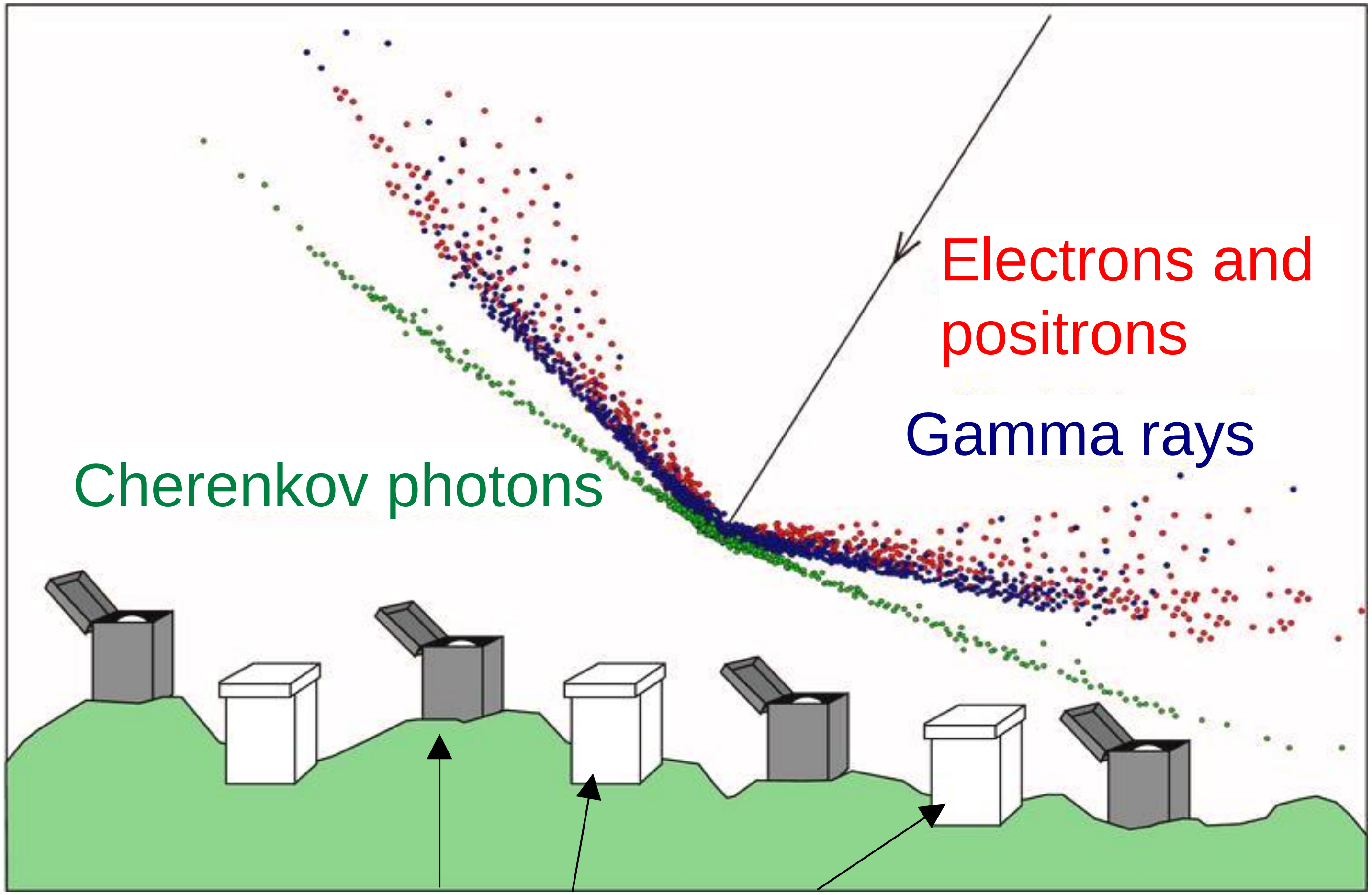
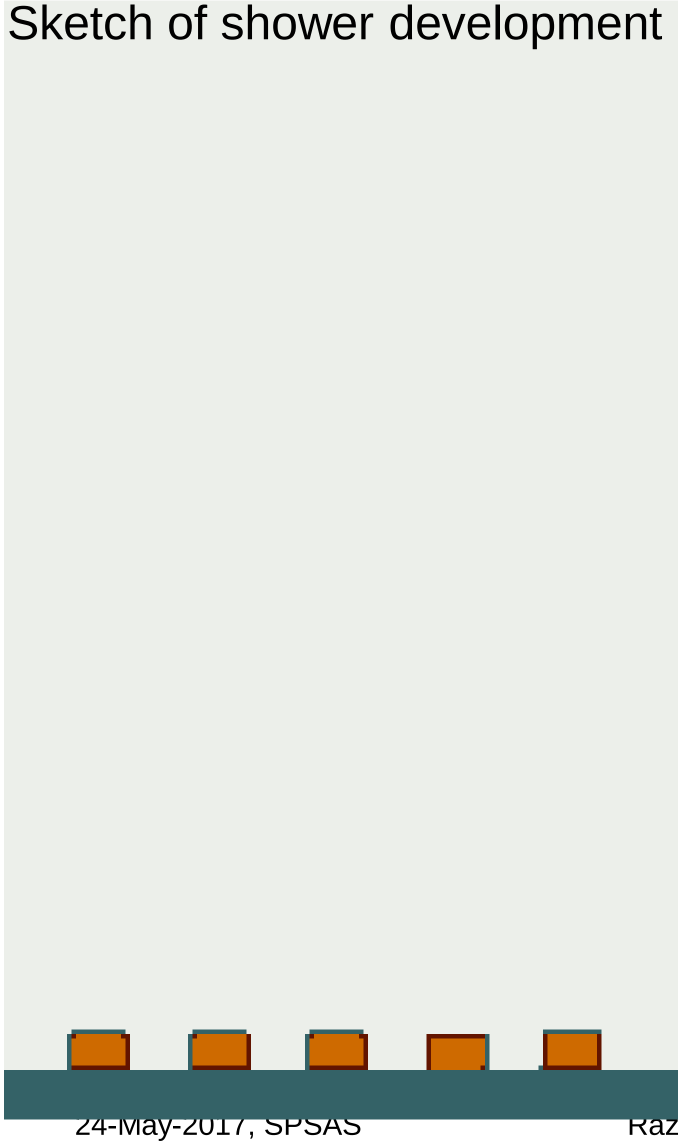
Air shower hit ground-based detectors



Particle or light Cherenkov light detectors

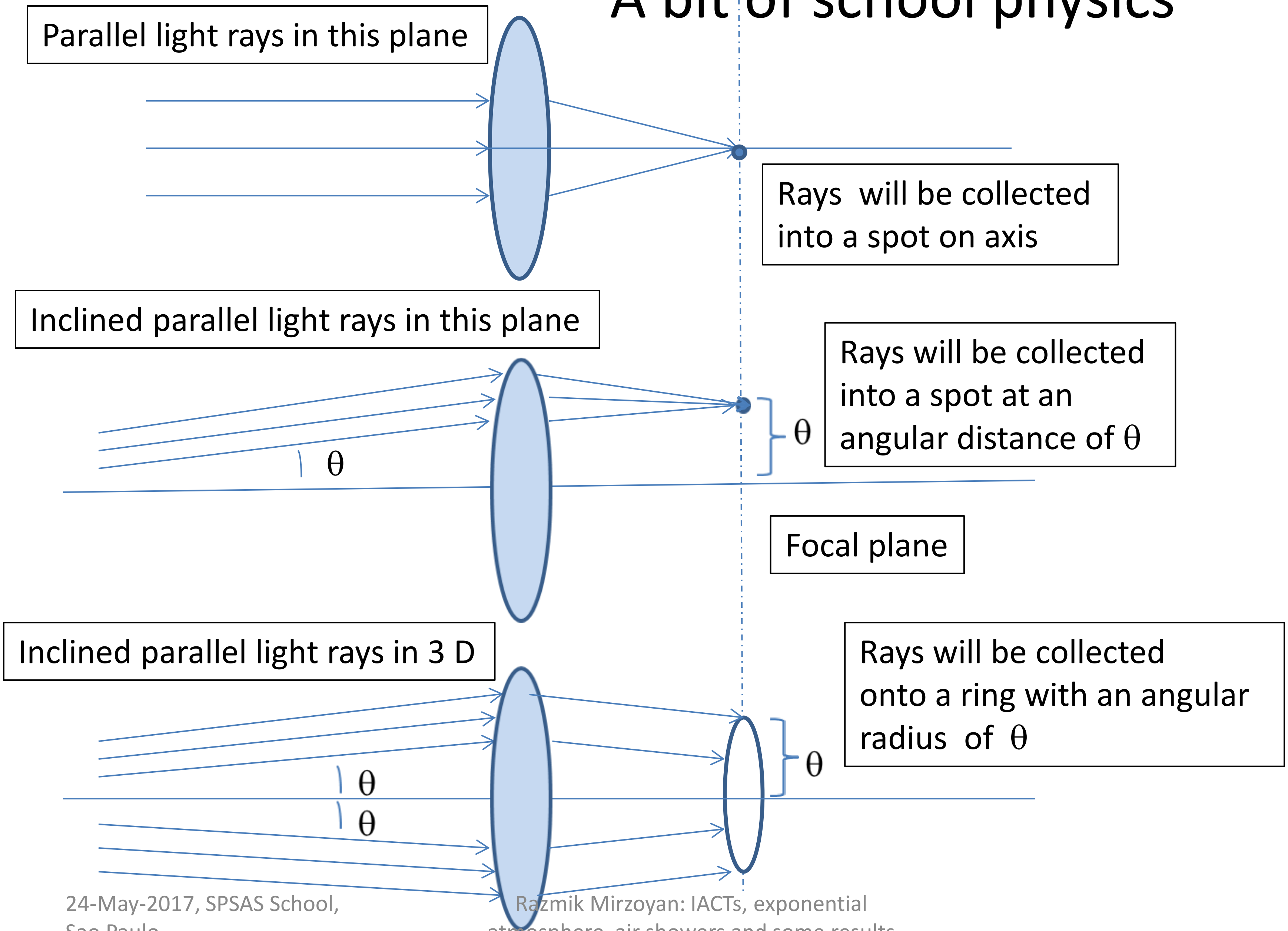
Shower front evolution



Sketch of shower development

Shower particles form roughly a disk-shaped conical front (a rather flat one) of **few** ns thickness, traveling at speed ≈c towards the ground

A bit of school physics



Parallel light rays in this plane

Rays will be collected into a spot on axis

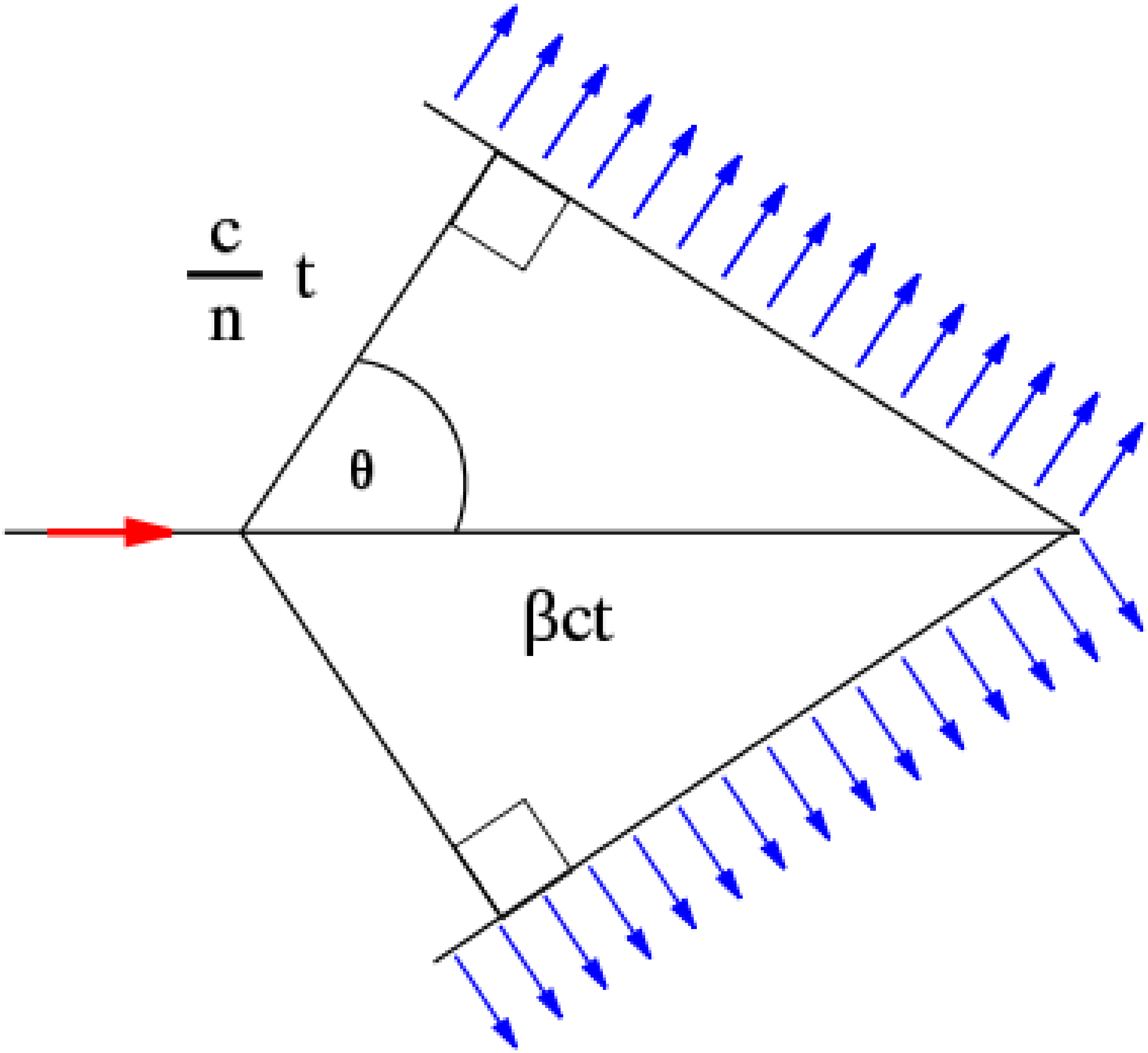
Inclined parallel light rays in this plane

Rays will be collected into a spot at an angular distance of θ

Focal plane

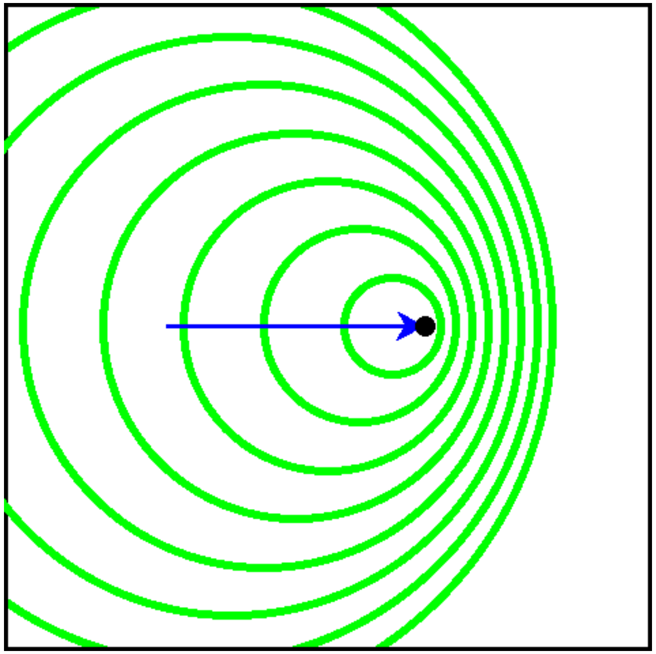
Inclined parallel light rays in 3 D

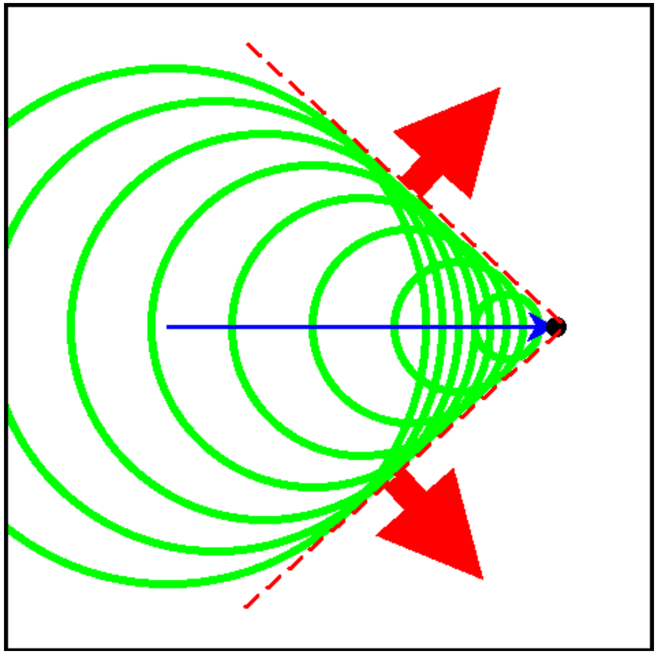
Rays will be collected onto a ring with an angular radius of θ


$\frac{c}{n}t$
θ
βct

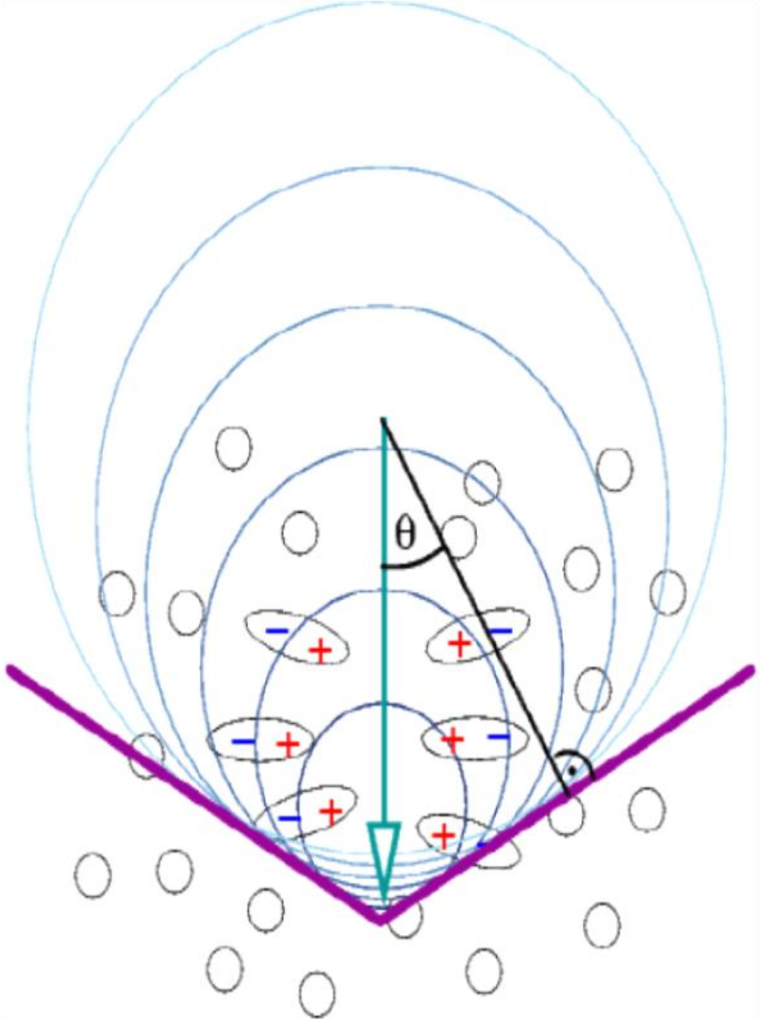
An e-m wave spreads out
from each point on the particle's track.
As the particle is travelling slower
than the ***c*** in that medium,
the radiation from earlier times is
always outside that emitted later.
No interference is possible.

An e-m wave spreads
out from each point on the particle's
track. For a particle travelling faster
than ***c***, it overtakes the electromagnetic wave. At a certain angle
(red dotted line), the waves all add
coherently. This corresponds to
Cherenkov radiation, travelling
in the direction shown by red arrows.



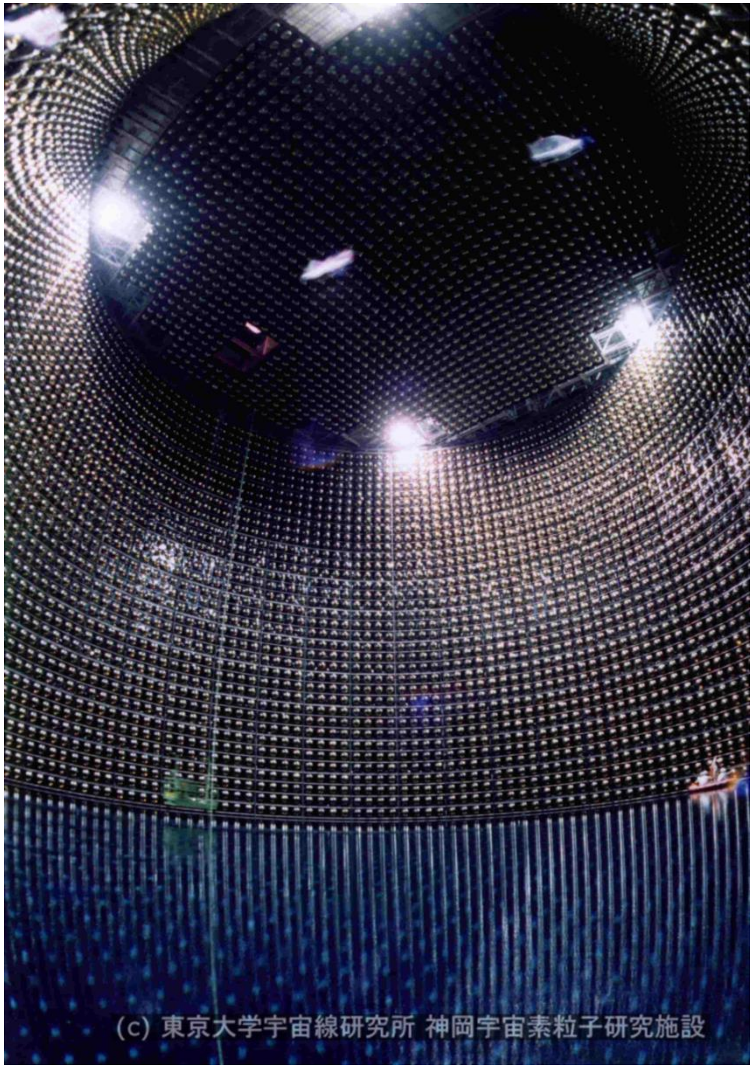


The geometry of the Cherenkov wave front is defined by the particle velocity vp= βc and the speed of light in the medium vl=c/n:



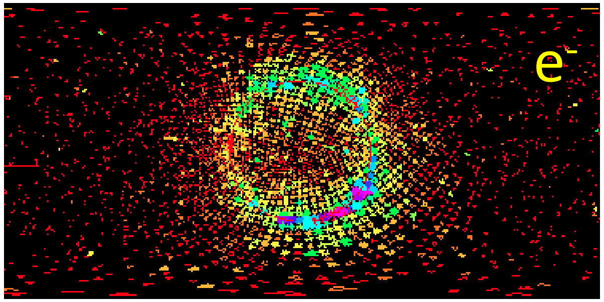
$\cos\theta = c/nv_p$

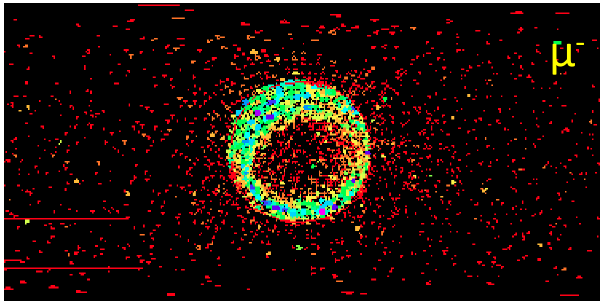
Homogeneous medium – water


(c) 東京大学宇宙線研究所 神岡宇宙素粒子研究施設

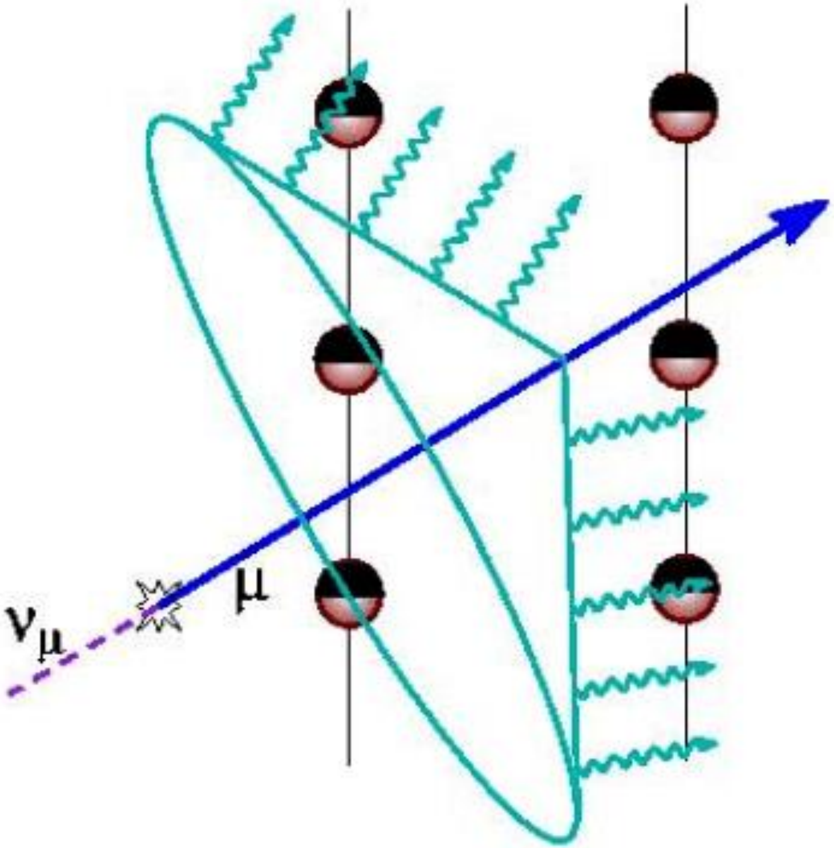
Super **Kamiokande** detector in Japan
11200 PMTs, each 0.5m in diameter

It is a H2O Cherenkov detector which discovered *v* oscillations. Ring gives incident *v* direction & its sharpness provides e- versus μ- discrimination





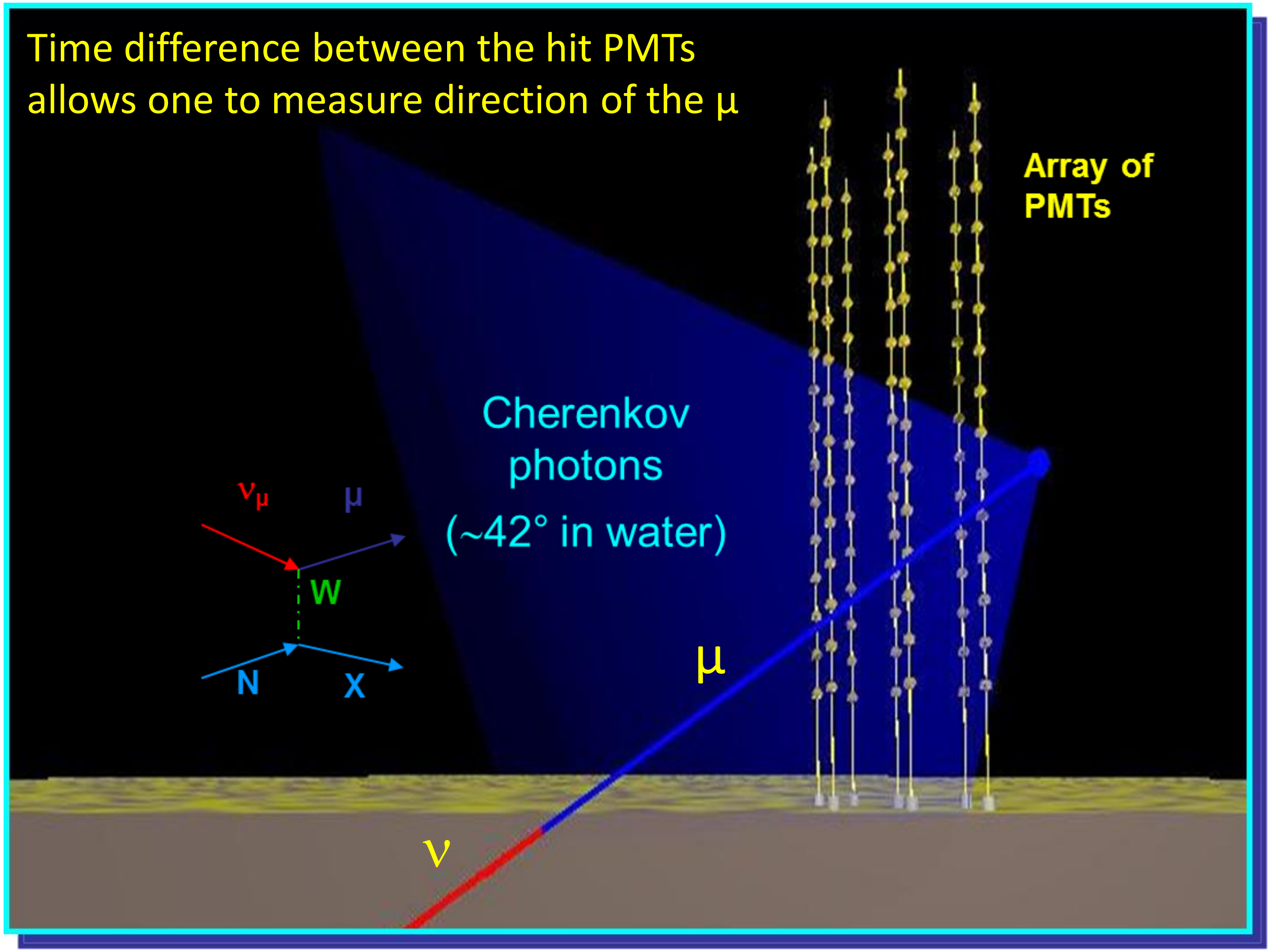
Neutrinos generate muons (μ) in the water which produce flashes of Cherenkov Radiation



Flashes are picked up by the light detectors

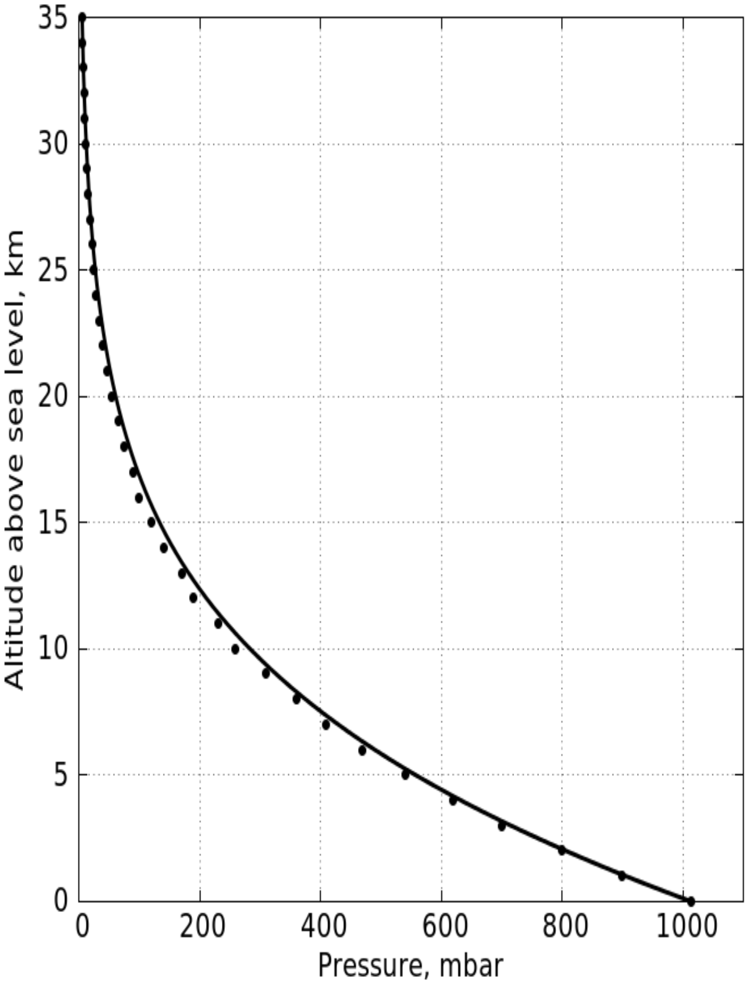
Detection principle of ν in water or in ice

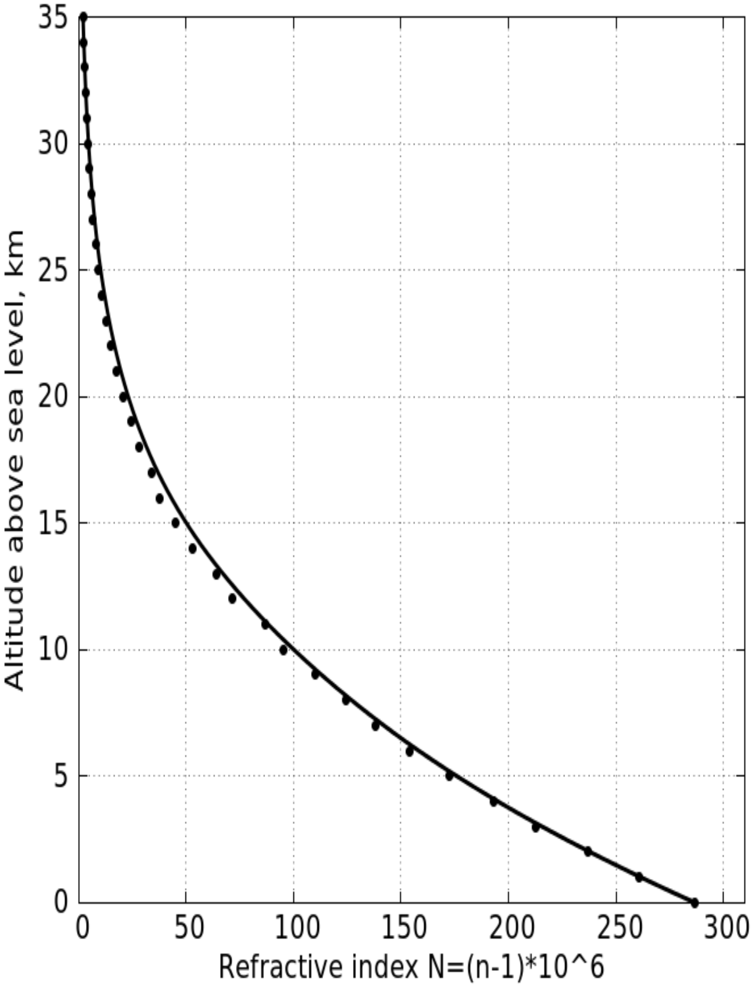
Baikal GVD, IceCube, Antares, Nestor, KM3NeT



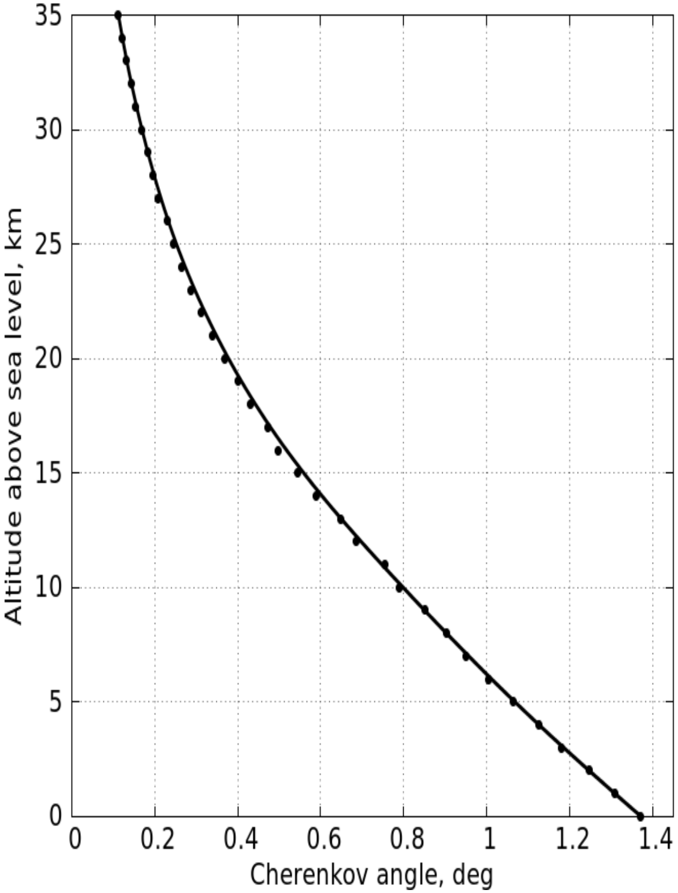
Time difference between the hit PMTs allows one to measure direction of the μ

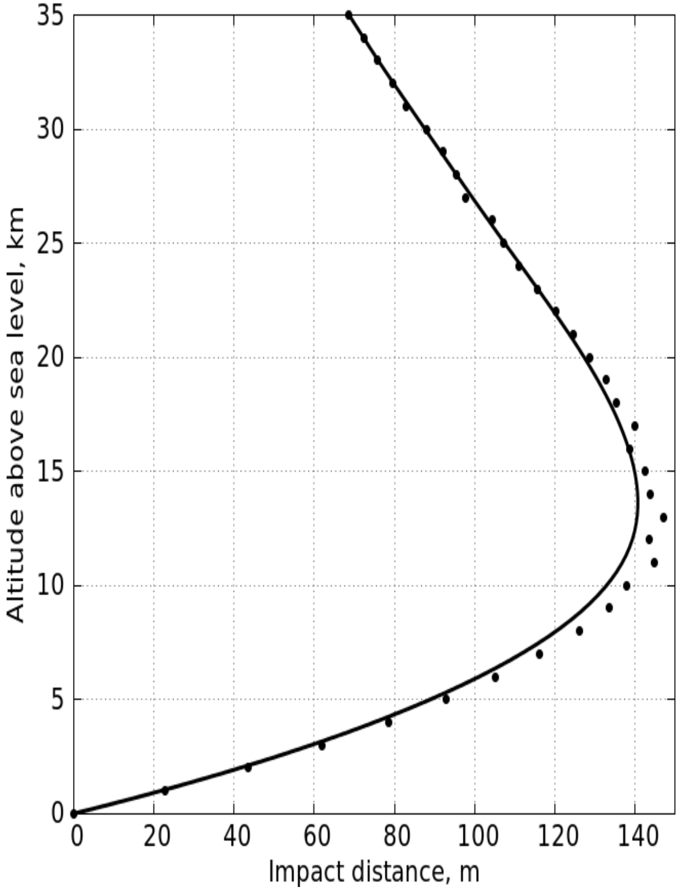
Air pressure & refractive index vs. height in atmosphere





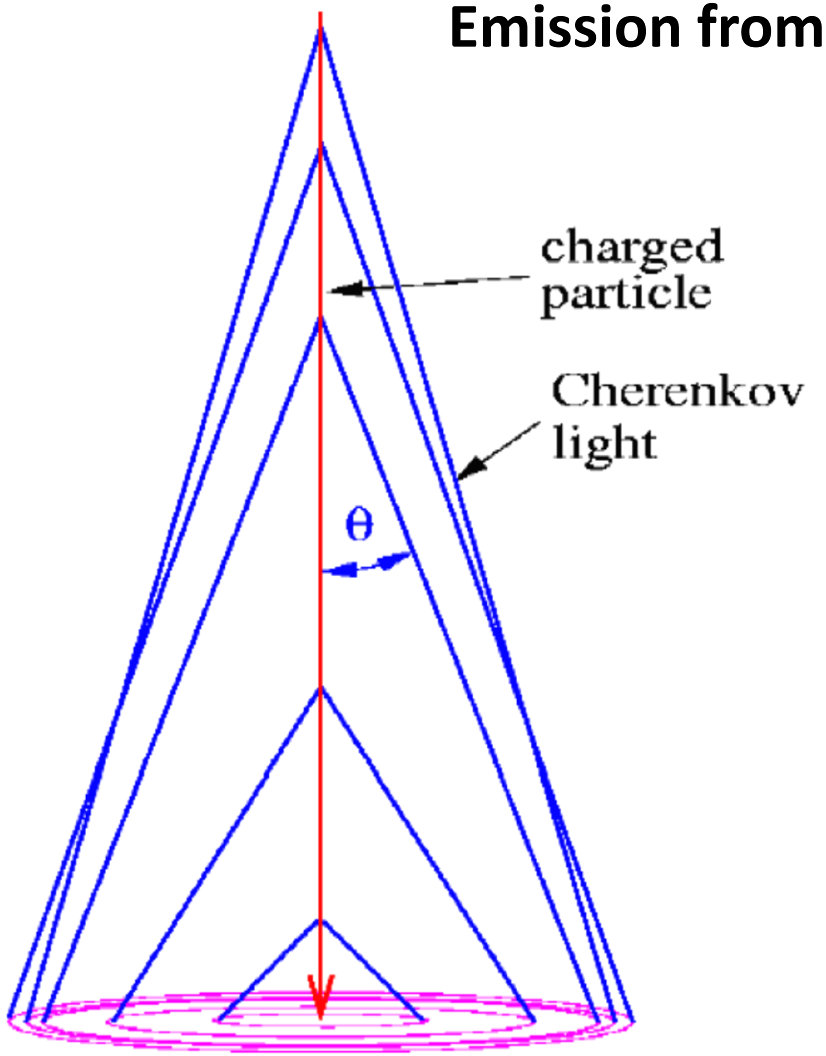
Cherenkov angle and photon impact point on the ground vs. height in atmosphere





Cherenkov Radiation

Emission from a single μ

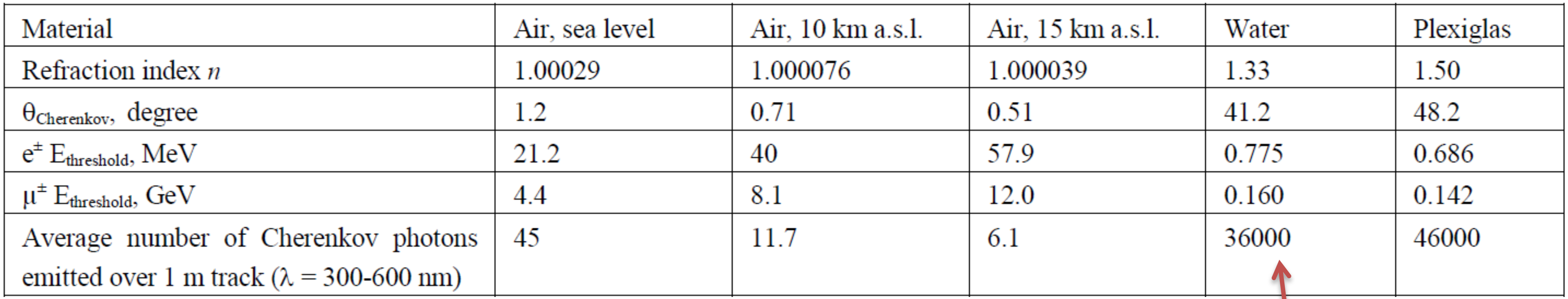


n - 1 is proportional to air density.

The Cherenkov opening angle θ is increasing downwards.

For a particle moving vertically downwards, the largest ring on the ground near sea level is from 12 to 15 km height.

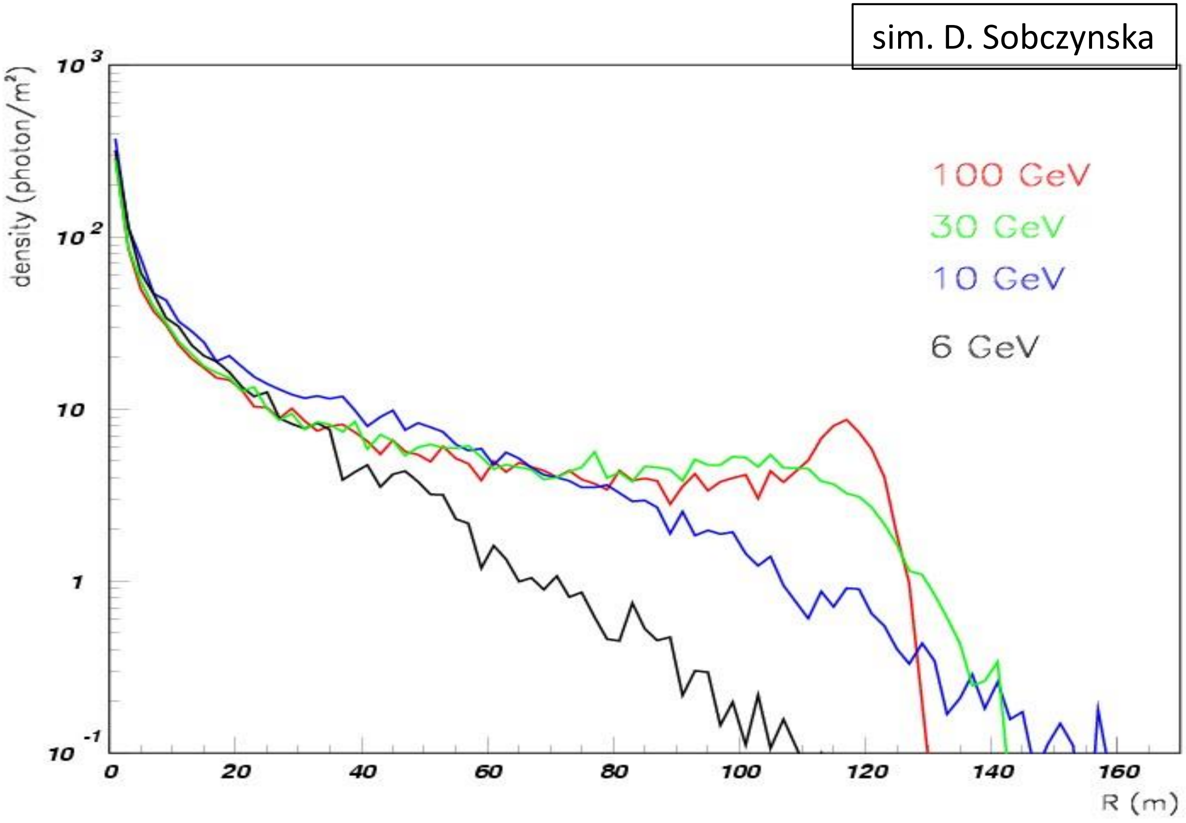
Cherenkov light emission from $e^{\pm}$ and $\mu^{\pm}$ in atmosphere @ 3 different heights and in Plexiglas

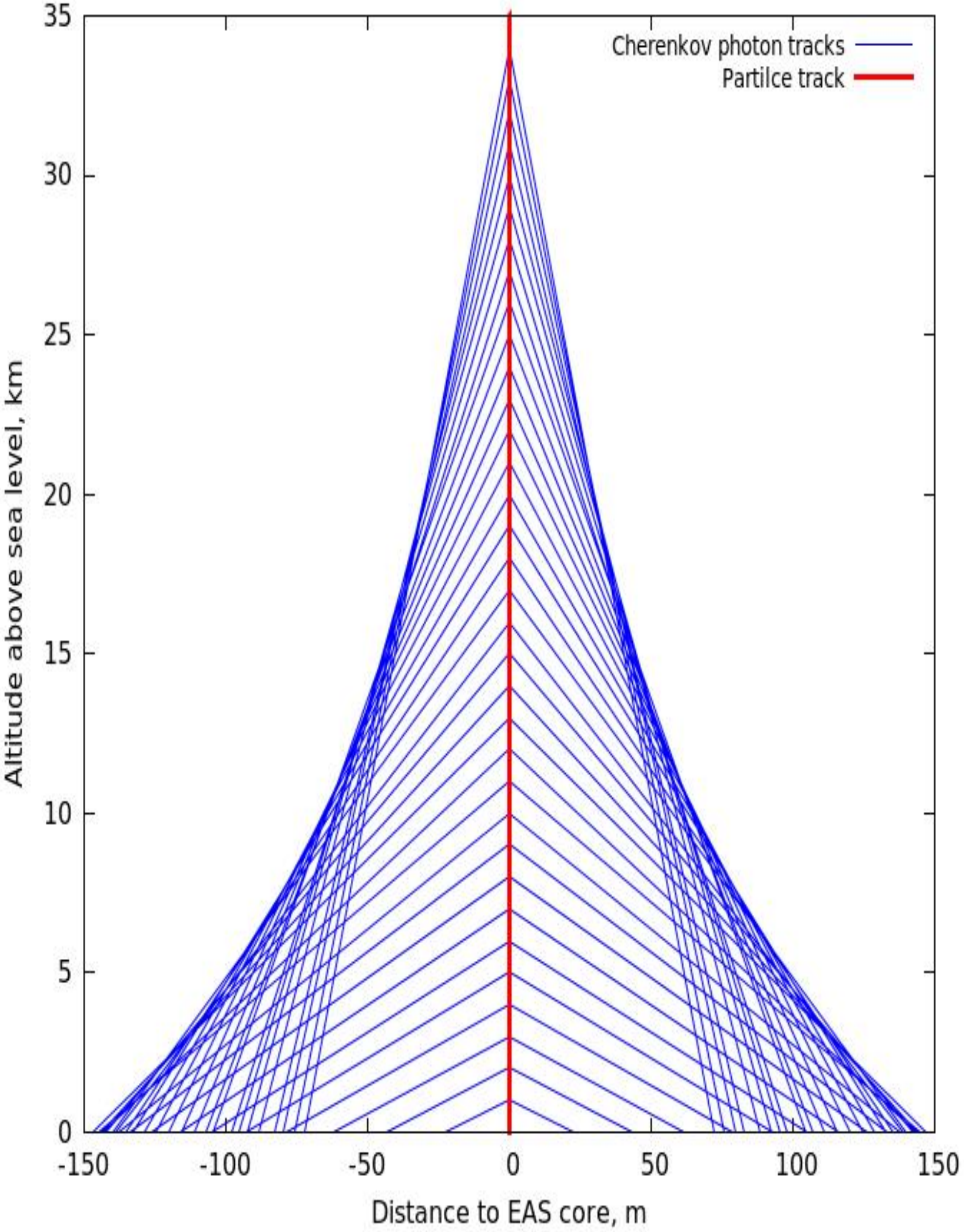


Material	Air, sea level	Air, 10 km a.s.l.	Air, 15 km a.s.l.	Water	Plexiglas
Refraction index n	1.00029	1.000076	1.000039	1.33	1.50
$\theta_{Cherenkov}$, degree	1.2	0.71	0.51	41.2	48.2
$e^{\pm}$ $E_{threshold}$, MeV	21.2	40	57.9	0.775	0.686
$\mu^{\pm}$ $E_{threshold}$, GeV	4.4	8.1	12.0	0.160	0.142
Average number of Cherenkov photons emitted over 1 m track (λ = 300-600 nm)	45	11.7	6.1	36000	46000

The very high intensity is the remarkable feature of the Cherenkov emission; in 1m of water it produces 36000 photons!

Single μ induced Cherenkov light on the ground

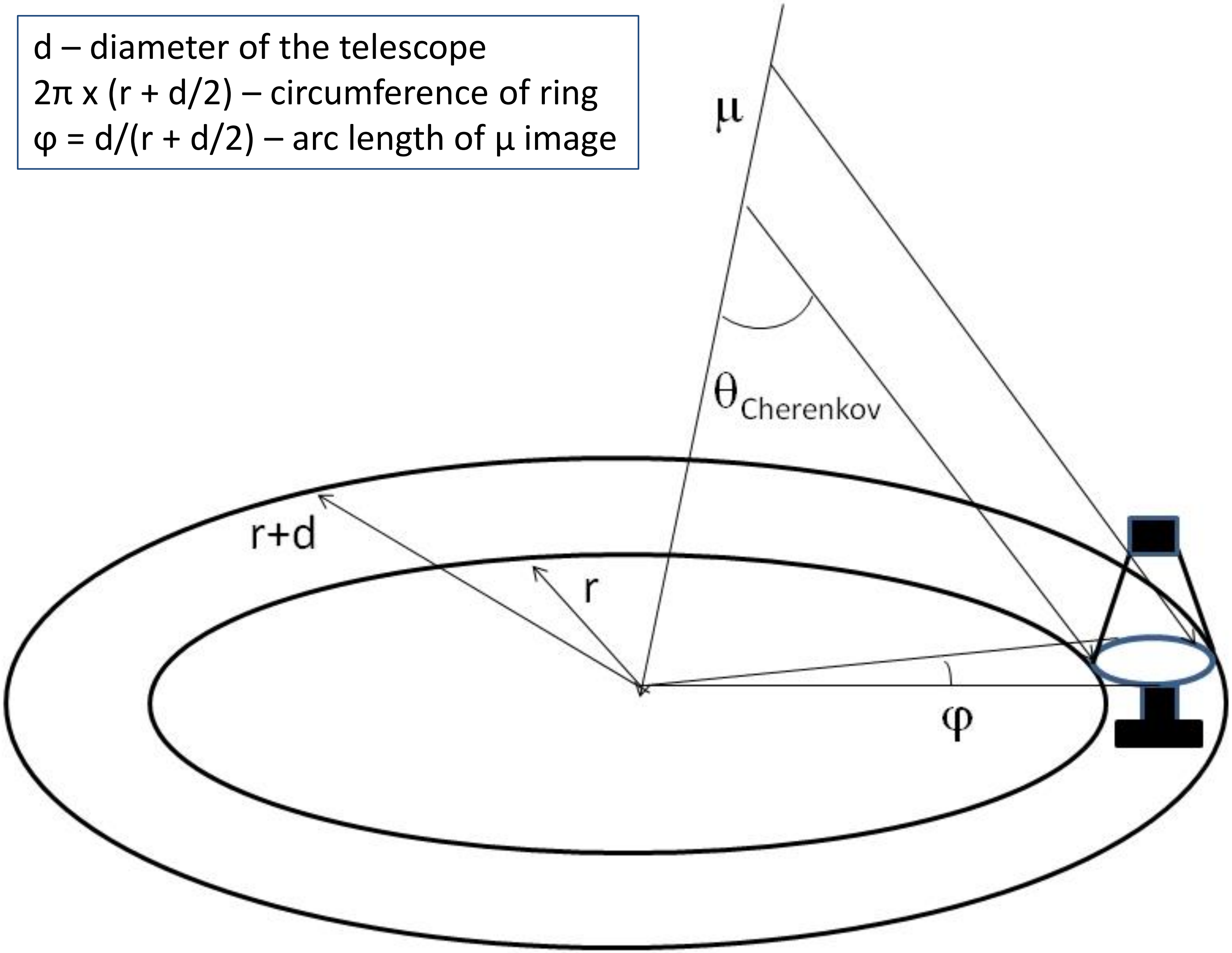




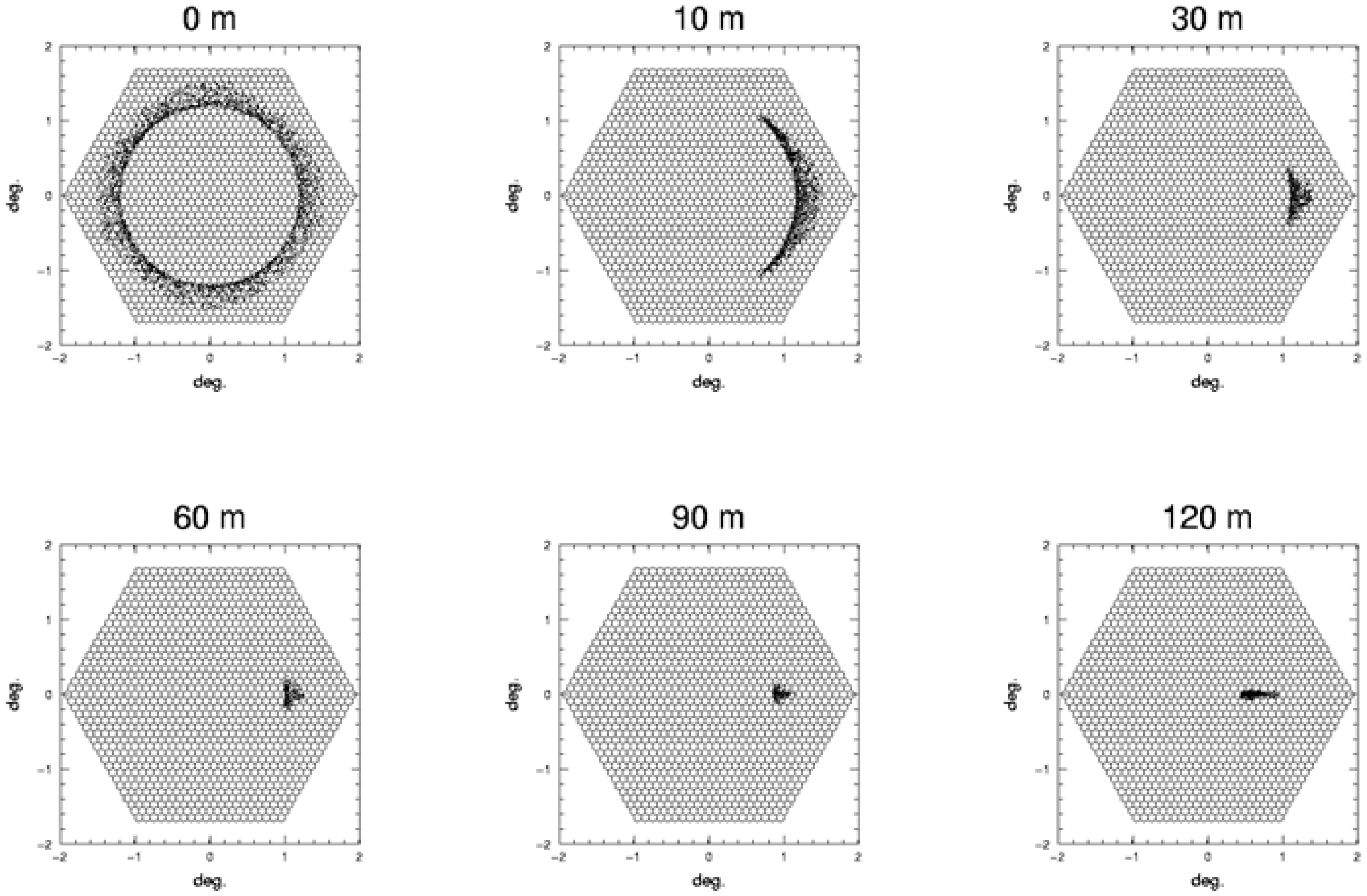
Cherenkov photon lateral distribution produced by a single μ on the ground

Note the focusing effect centered at about 100m distance

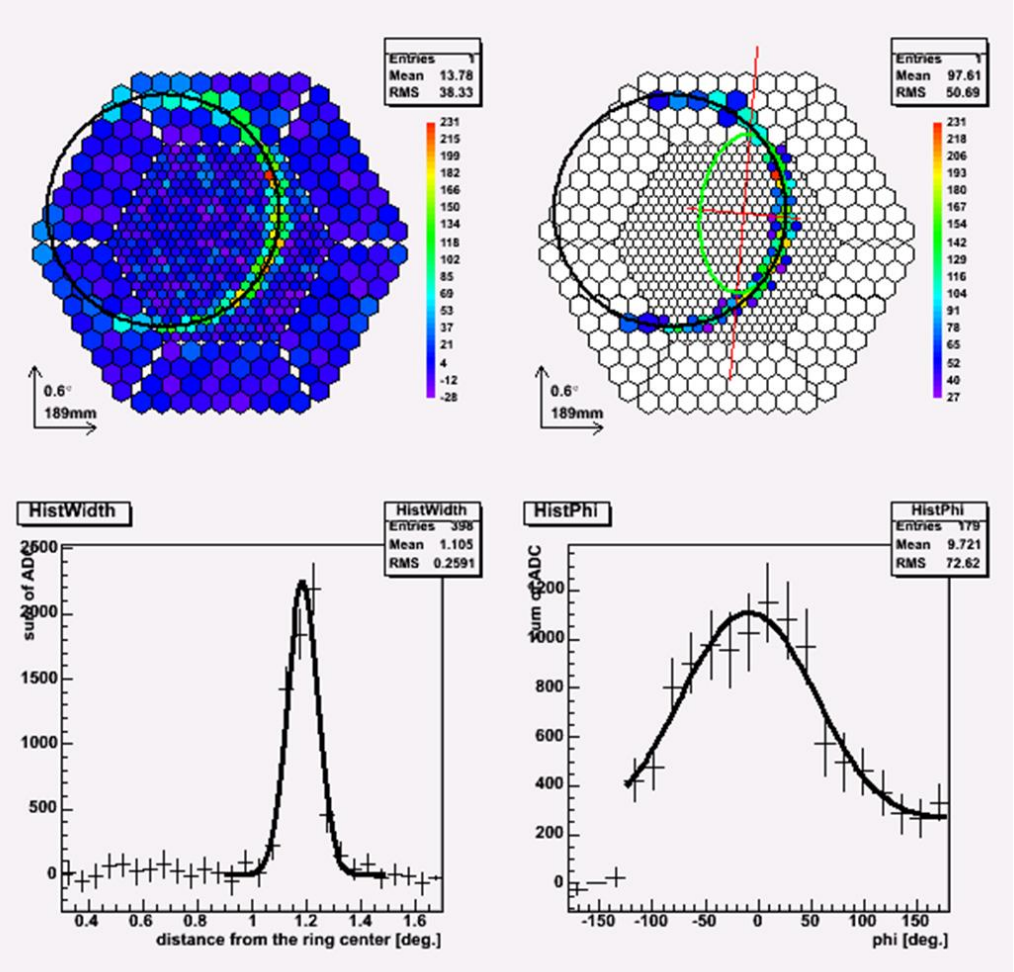
d – diameter of the telescope
$2\pi \times (r + d/2)$ – circumference of ring
$\varphi = d/(r + d/2)$ – arc length of μ image



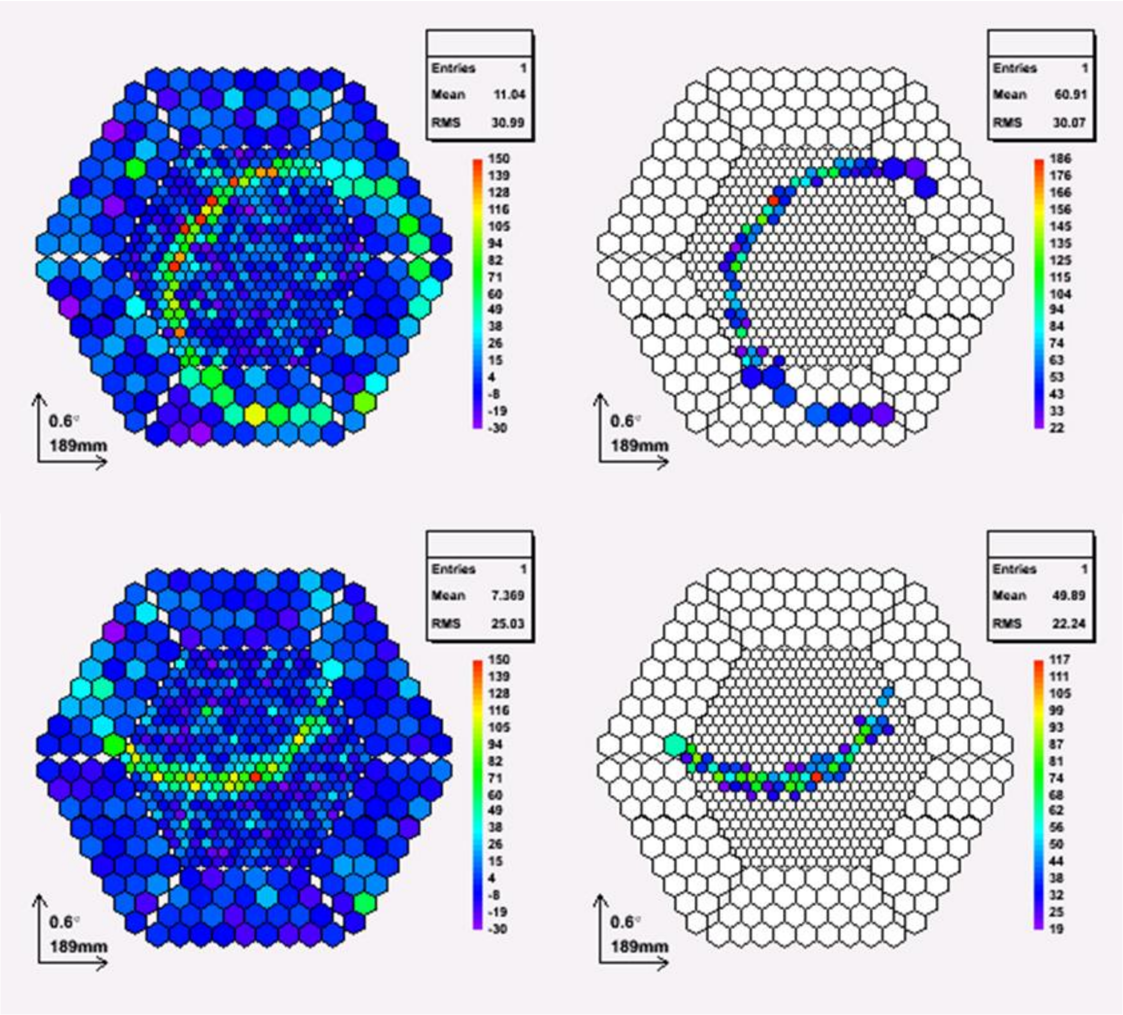
Images produced by a single μ from different impact points



Finding out μ parameters for calibration purposes



Images produced by a single μ



VHE γ-astrophysics with IACTs is possible thanks to exponential atmosphere

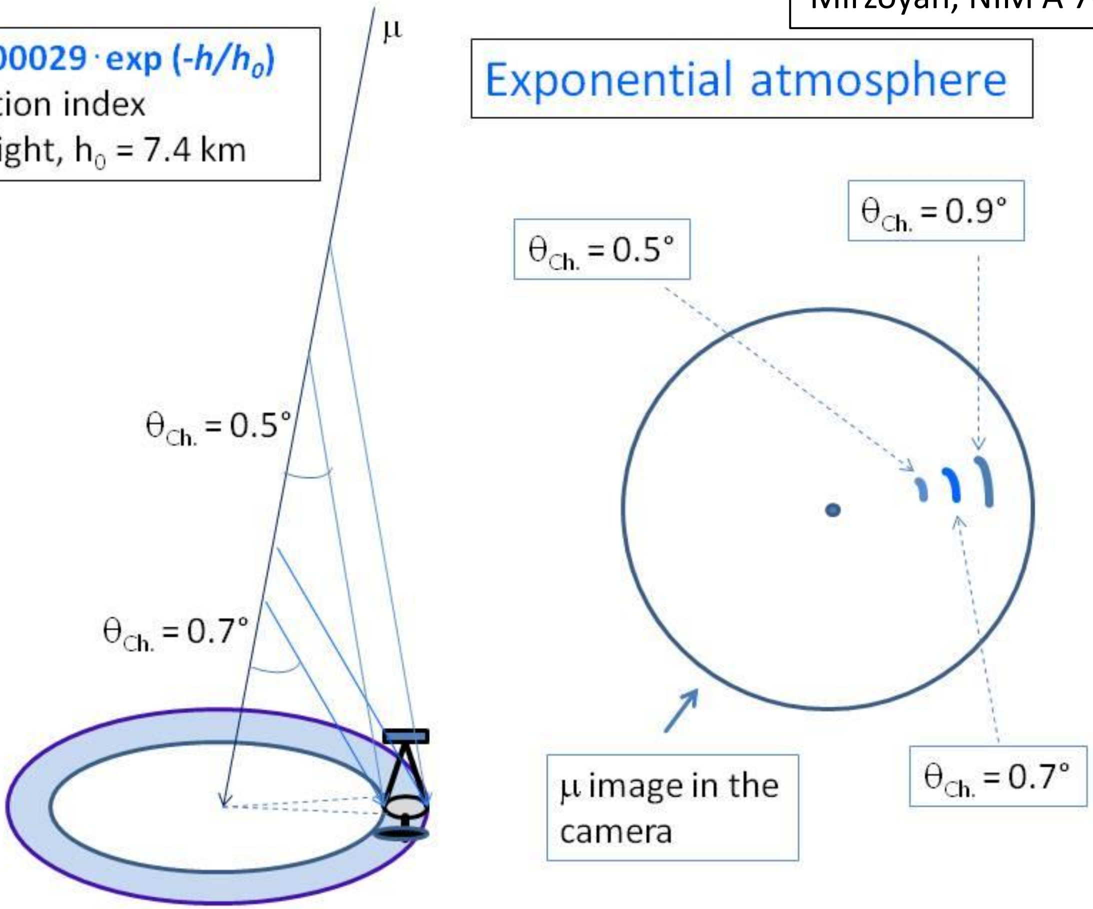
Mirzoyan, NIM A 766 (2014)

$n(h) = 1 + 0.00029 \cdot \exp(-h/h_0)$

n(h) – refraction index

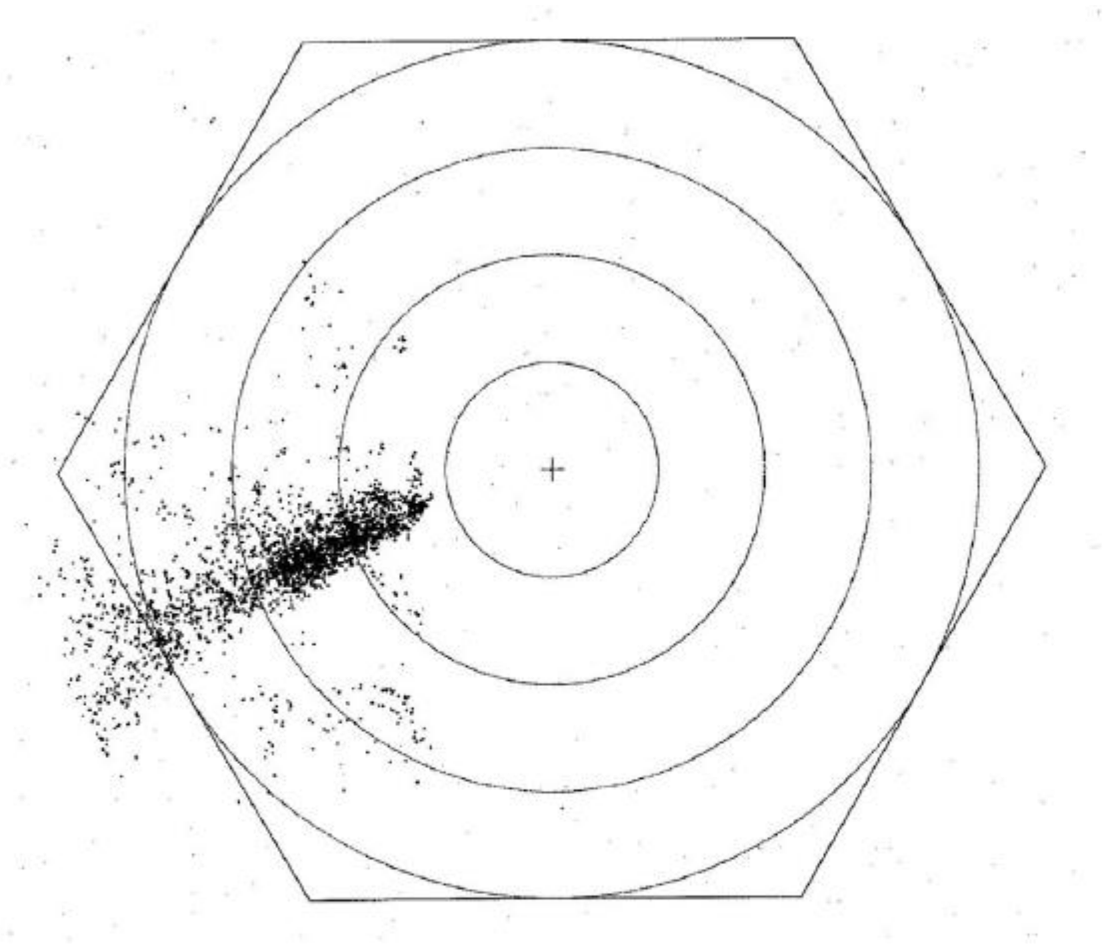
h_0 – scale height, h_0 = 7.4 km

Exponential atmosphere

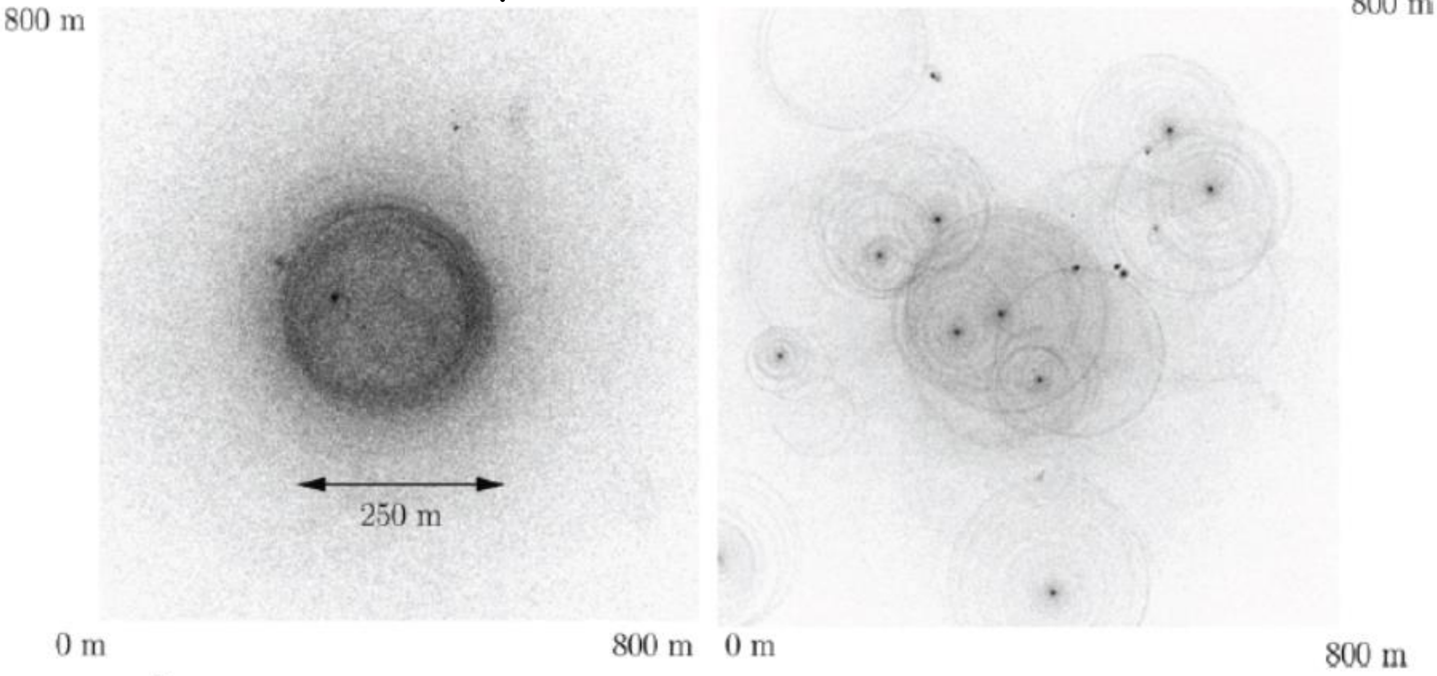


μ image in the camera

A typical γ-image from an IACT



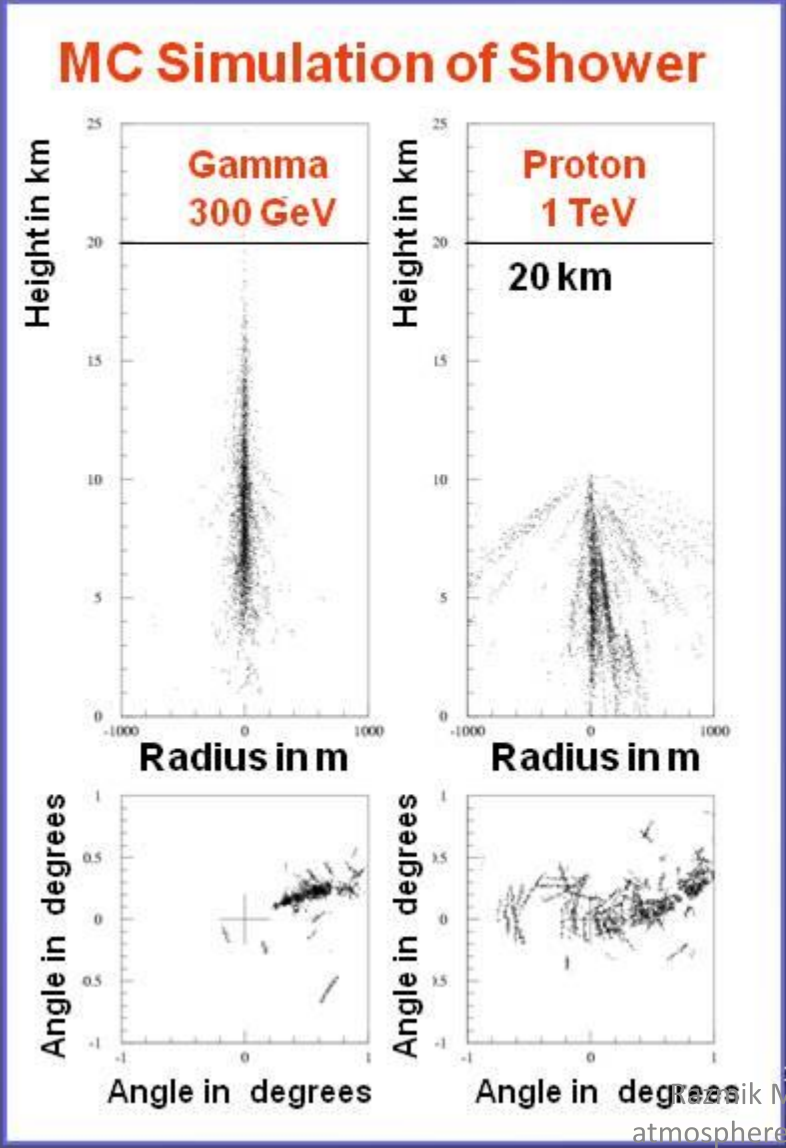
Monte Carlo simulation of Cherenkov photon distribution on the ground from air showers



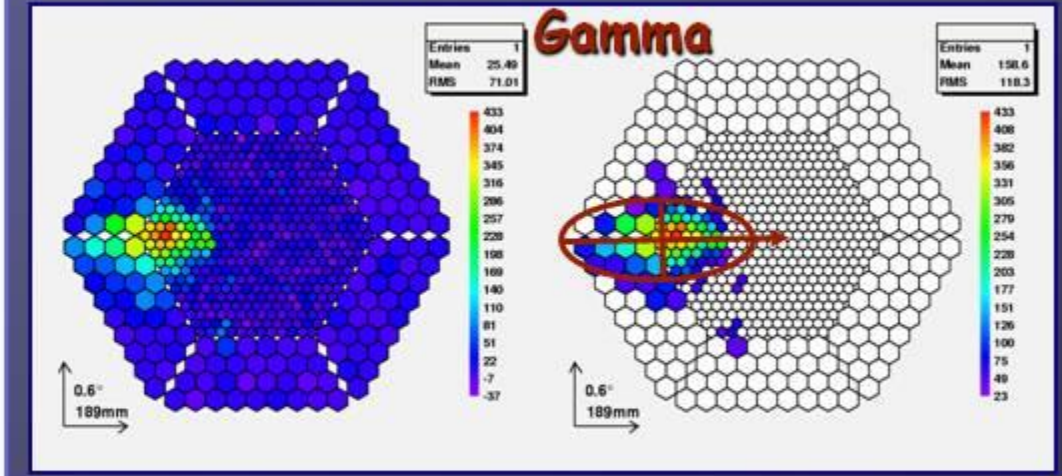
300 GeV γ

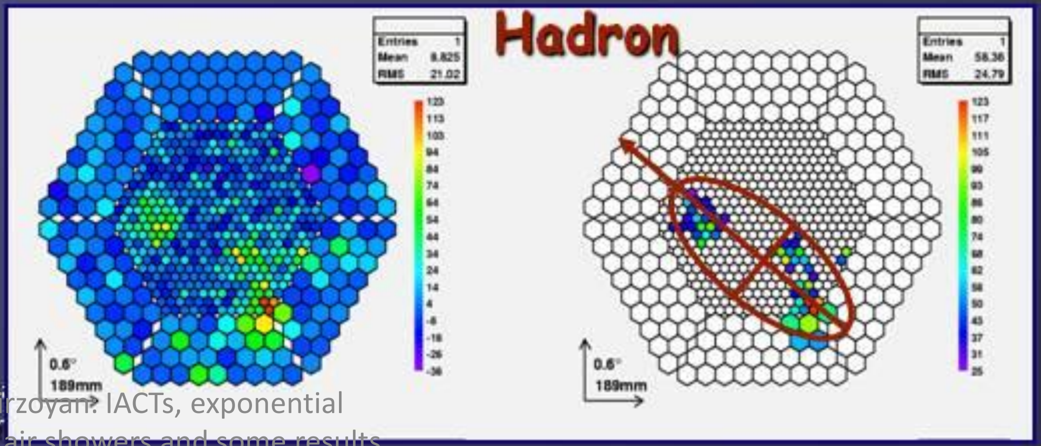
1 TeV proton

Gamma and hadron images and their separation



Hadron Rejection by Image Shape + Orientation ~ 99.9 %



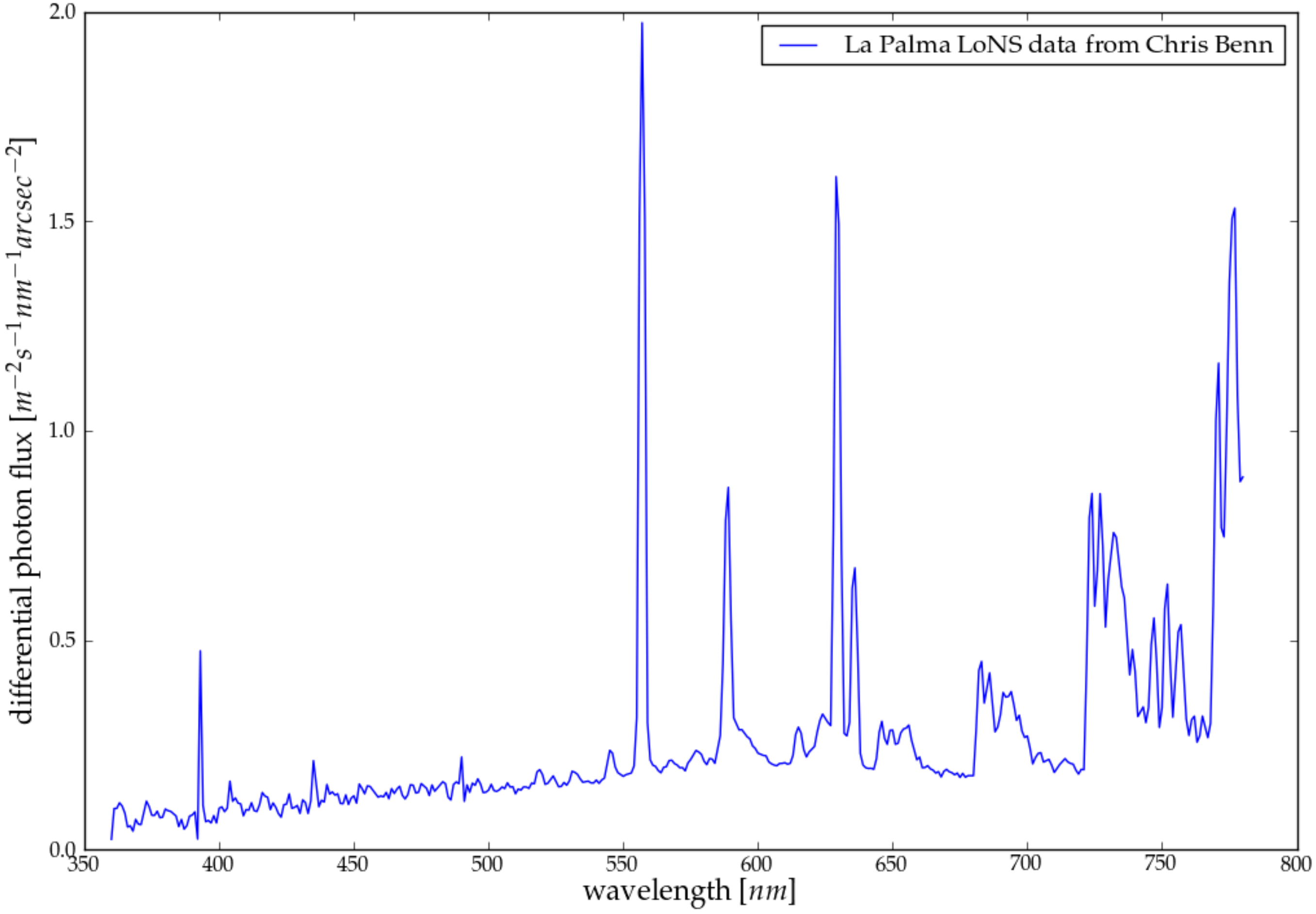


Exponential atmosphere & IACTs

- IACT technique exists thanks to the **exponential distribution** of pressure and refraction index in the atmosphere
- IACT images display the **differential development** of the air showers in height in atmosphere
- The **differences between γ & hadron shower developments in height** are reflected in respective images
- In a uniform medium (say, for example, in water or in horizontal atmosphere) the Cherenkov emission angle of all relativistic particles will be the same, their tracks (arcs) will overlay on top of each other and one cannot obtain an image in a “common IACT” sense and the prominent γ/h separation power will strongly deteriorate

Light of Night Sky (LoNS) is a strong background emission

Integral of LoNS in 300-600nm: 2×10^{12} ph/m²·sr·s



The 1st important background for an IACT, influencing its trigger

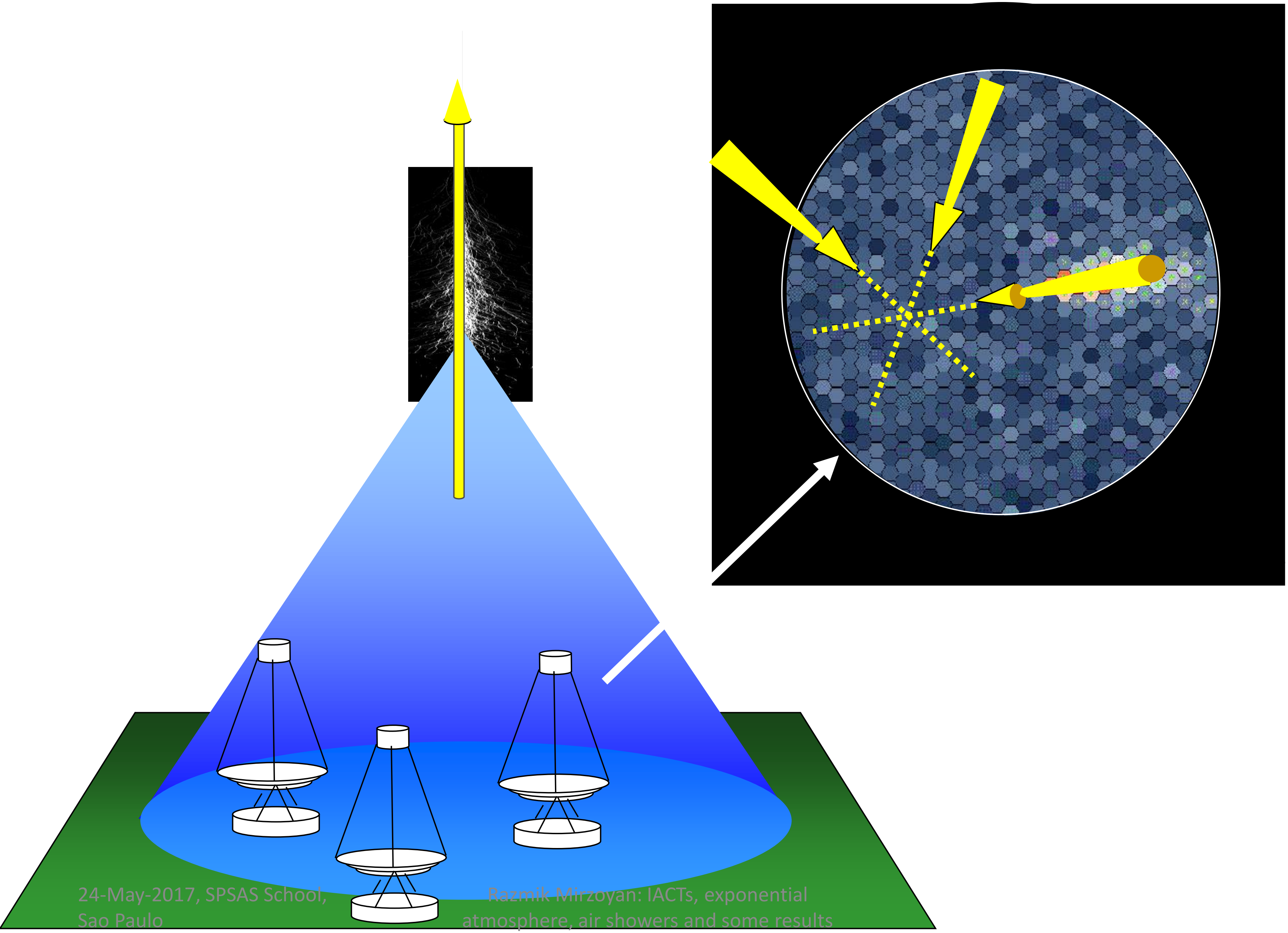
- The 1^{st} important background for an IACT is due to the steady emission from LoNS; a self-trigger scheme of the telescope shall be designed as to minimize the **triggers** due to the LoNS.
- Example: PMT-based pixels of the MAGIC telescope collect charge from the LoNS at a rate of 0.13 ph.e./ns (from extragalactic dark patch).
- So we use a very fast (FADC) readout scheme (operated at 1.67 GSample/s) for integrating Cherenkov signals for a duration of only a few ns (~3ns) for minimizing LoNS noise contribution
- (in ~3ns we will integrate **on average** 0.4 ph.e.; fluctuations of this number (1,2,3,4,… ph.e.) will contribute into the signal

The 2nd important backgrounds for an IACT, hadron showers

- The 2nd important background is due to the hadrons.
- The trigger rate of MAGIC telescopes is ~300 Hz (mostly hadrons, coming isotopically from all directions)
- When observing the strongest source in our galaxy, the Crab nebula, we measure ~20 gammas/minute above 100 GeV
- So even when observing the strongest source, roughly we have 1g event against 1000 hadron events (which will be strongly, say ~2000 times, discriminated)

The 2nd important backgrounds for an IACT, hadron showers

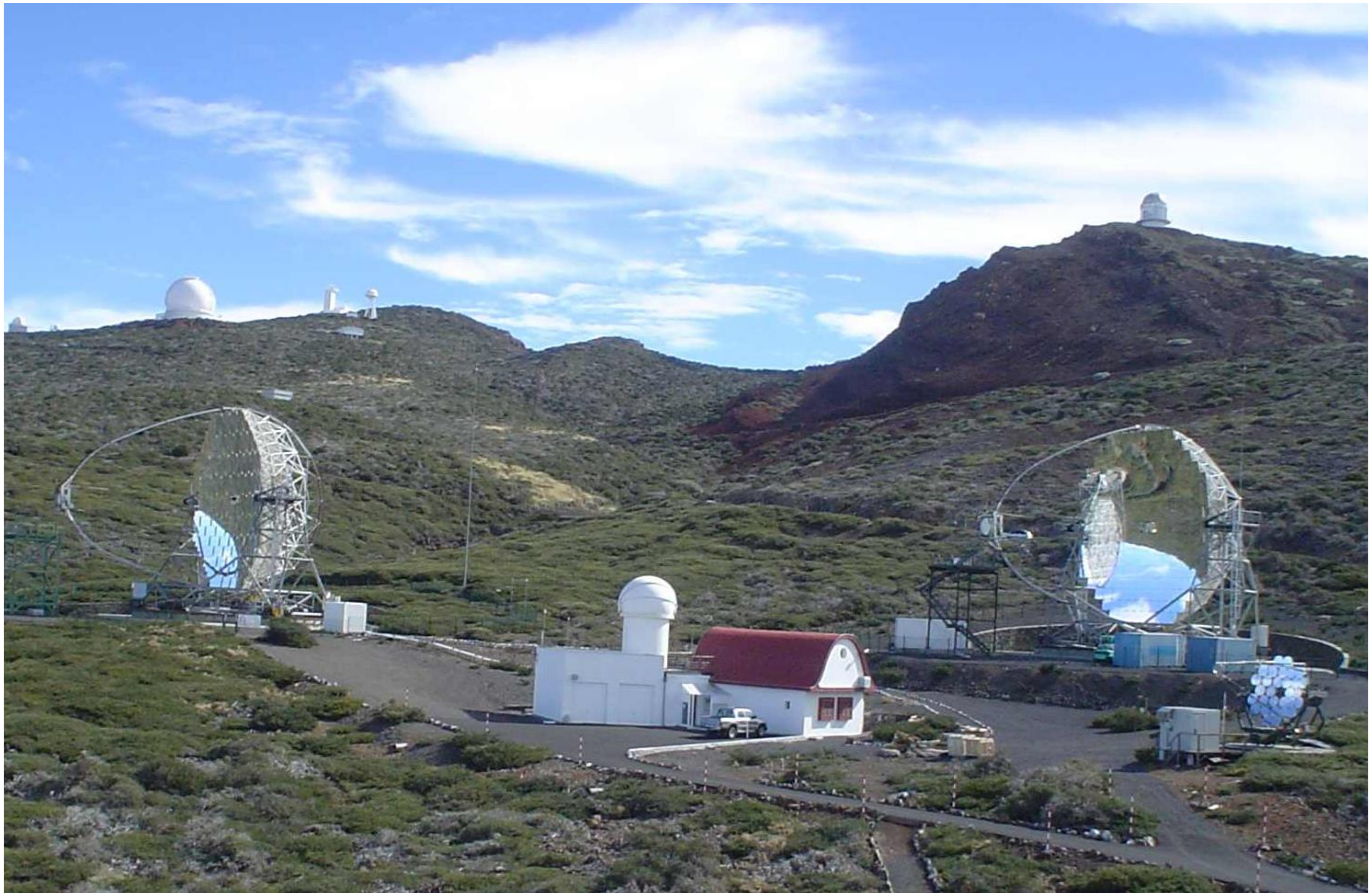
- We obtain a significant signal from Crab in ~ 1 minute observation time
- Imagine the situation with the weak sources, let us say on the intensity level of 1/100 of Crab; the signal to noise ratio can improve only statistically, over long observation time.
- In 50h observations we can reveal a source with an intensity of 6/1000 of Crab



H.E.S.S. in Namibia

Veritas in Arizona

MAGIC in La Palma, Canary islands

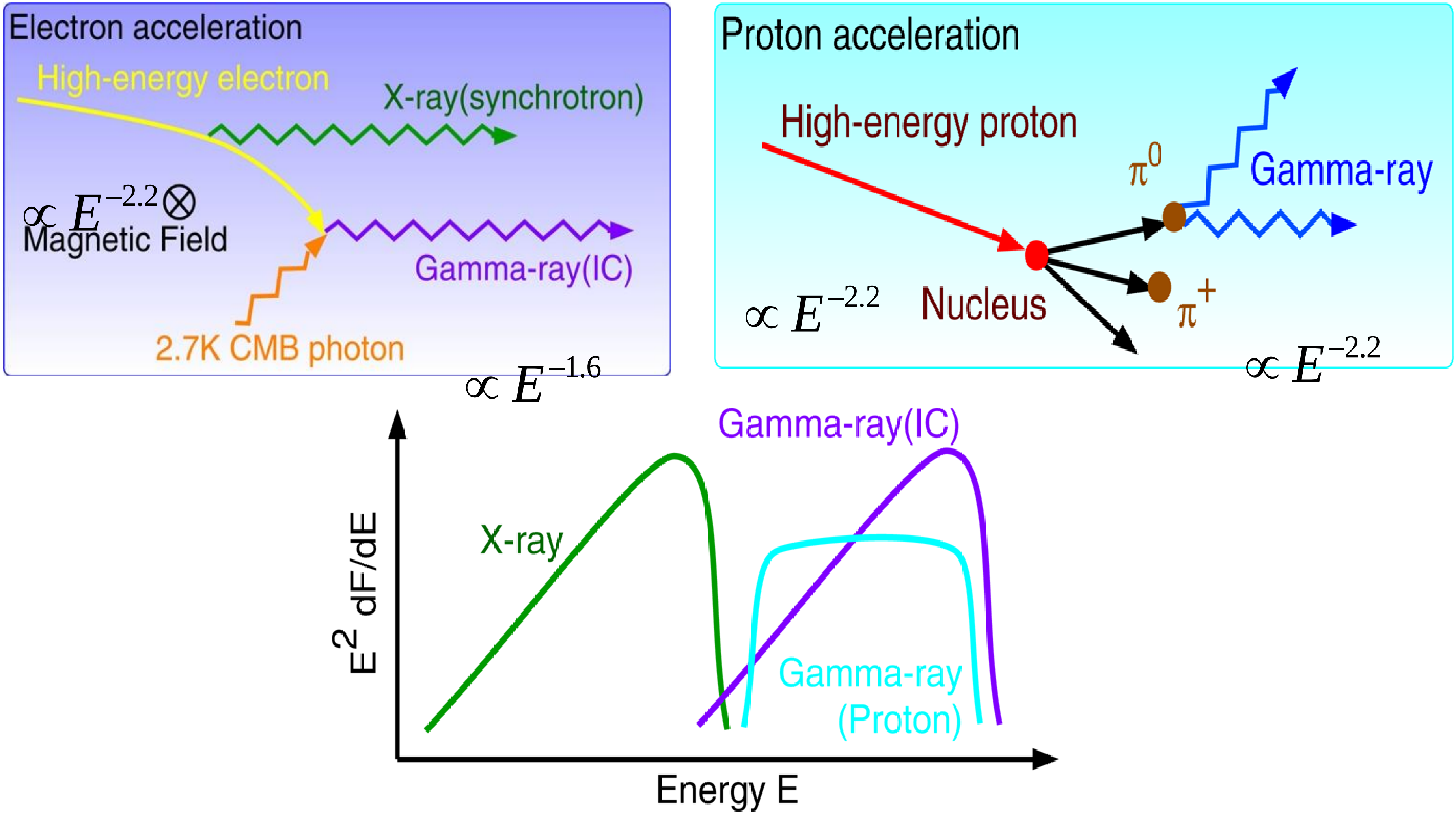


System of 2 MAGICs: the main parameters

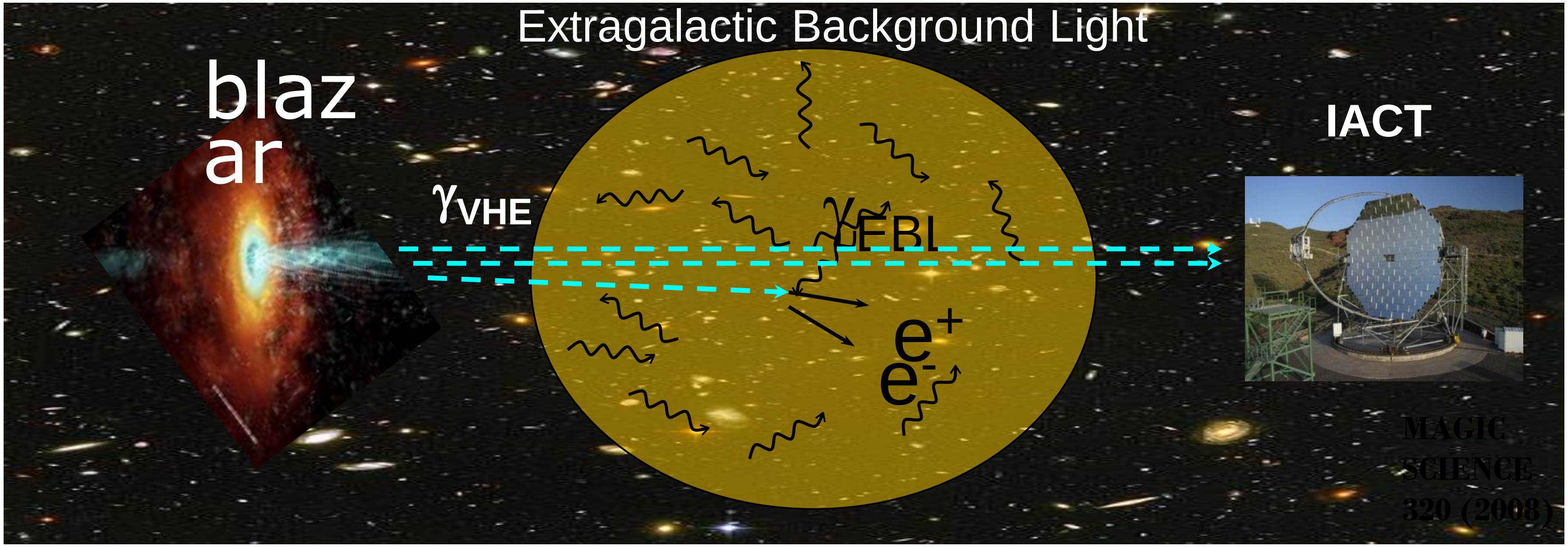
- Energy threshold (trigger): ~ 50 GeV
- Energy threshold in *"Sum-Trigger"* modus: 30 - 35 GeV
- Energy resolution: 15 % - 23 % for E ≤ 10 TeV
- Angular resolution: 0.07° for E ≥ 300 GeV;   0.05° @ 1 TeV
- Sensitivity: source with 6/1000 of Crab Nebula 5σ in 50h
- Light-weight construction, only ~ 70 T
- Fast re-positioning to any coordinates in the sky: 25s/180°
- Opto-electric design optimized to provide ~ 2.5ns FWHM pulses
- Data digitized by using DRS4 chips operated at 1.67 GigaSample/s
- Producing ~ 1 TB data per observation night per telescope

Fast Rotation of MAGIC to„catch“ GRB

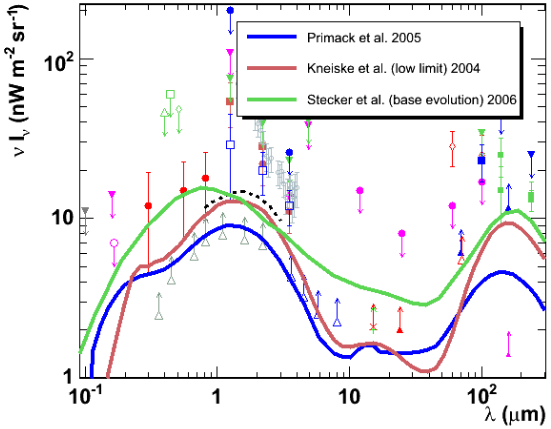
Gamma-Ray Emission Processes
Astrophysical process

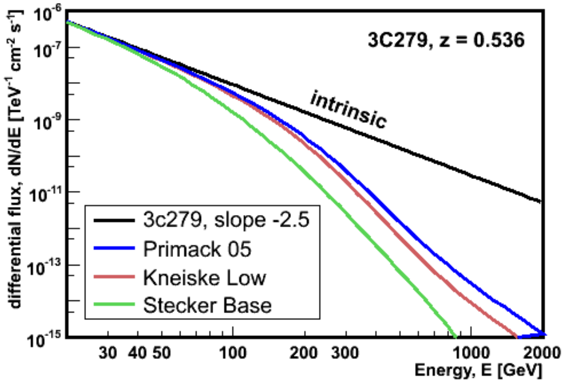


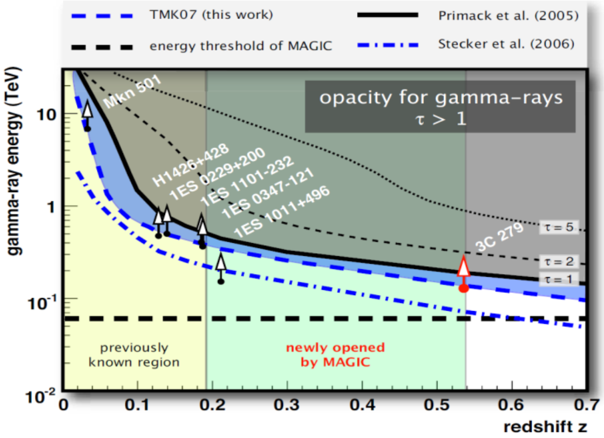
Gamma Ray Absorption by EBL



MAGIC SCIENCE 320 (2008)







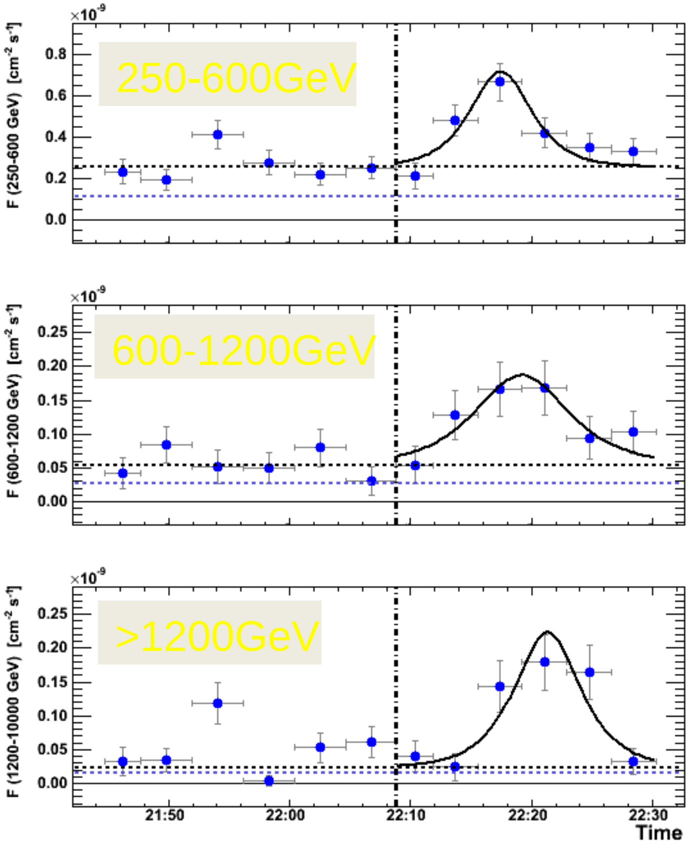
Fast time variation of VHE γ from AGN Mrk-501 by MAGIC, PKS 2155 by HESS

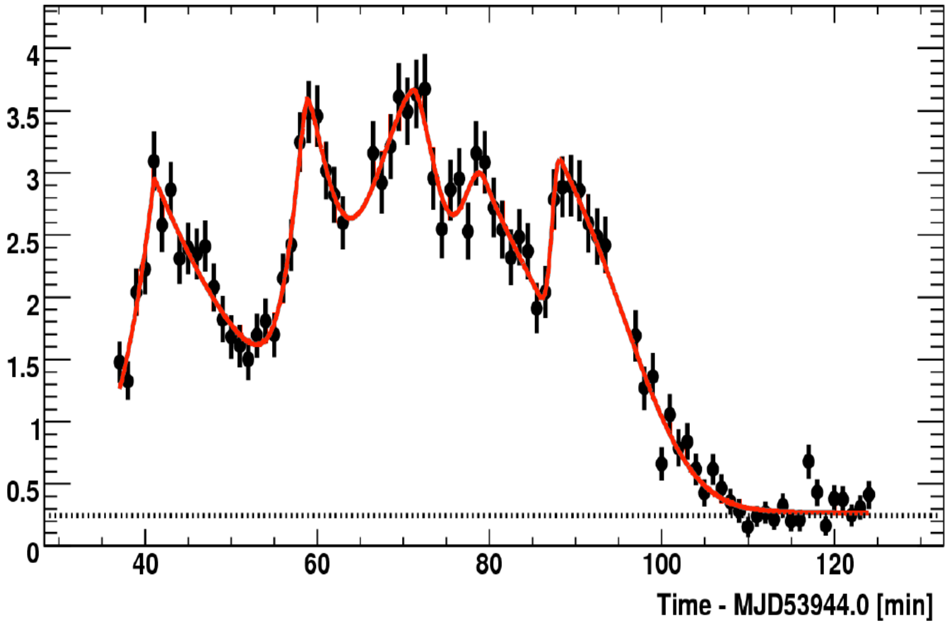
Mrk501(z=0.03) MAGIC observation

$M_{QG1} > 0.26 \times 10^{18}$GeV

PKS2155(z=0.116) HESS observation

$M_{QG1} > 0.72 \times 10^{18}$GeV

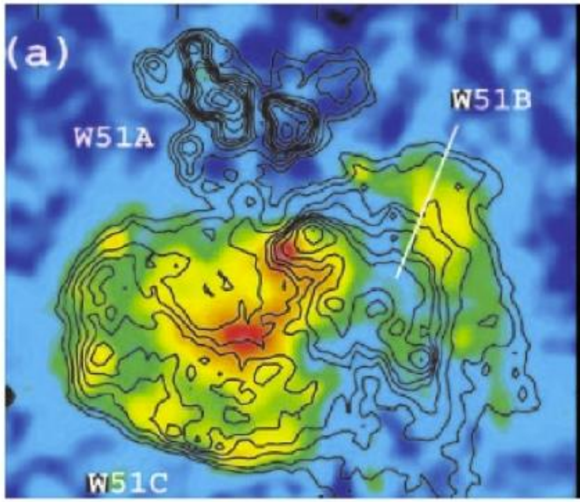




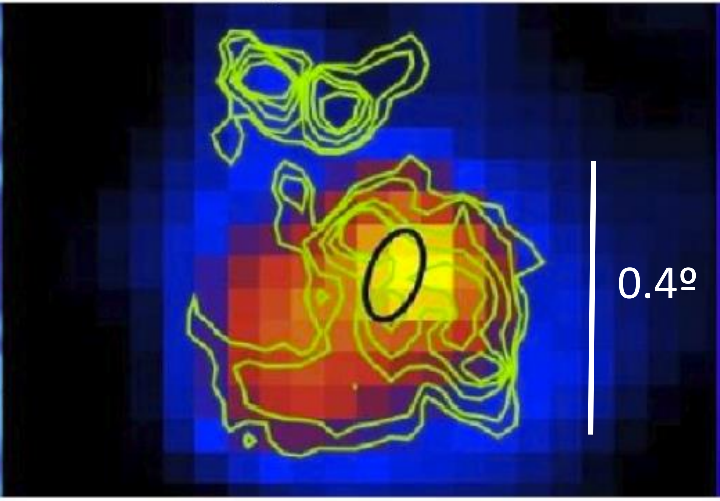
CTA can provide ~10sec time resolution for the fast variation

W51

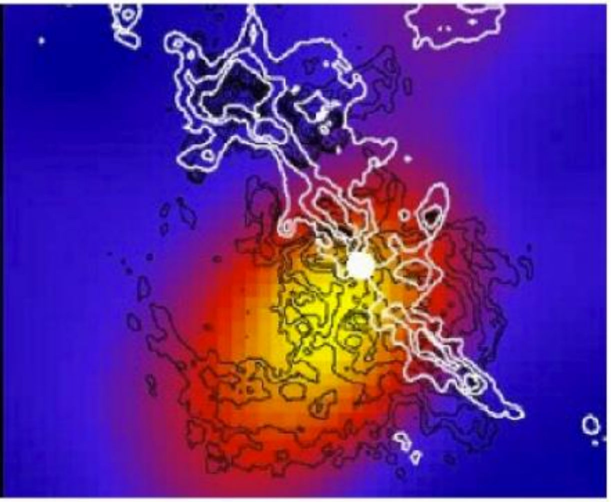
ROSAT 0.7-2.5 keV
Koo et al. 2002



Fermi / LAT 2-10 GeV
Uchiyama et al. 2011



H.E.S.S. >1 TeV
Fiasson et al. ICRC 2009

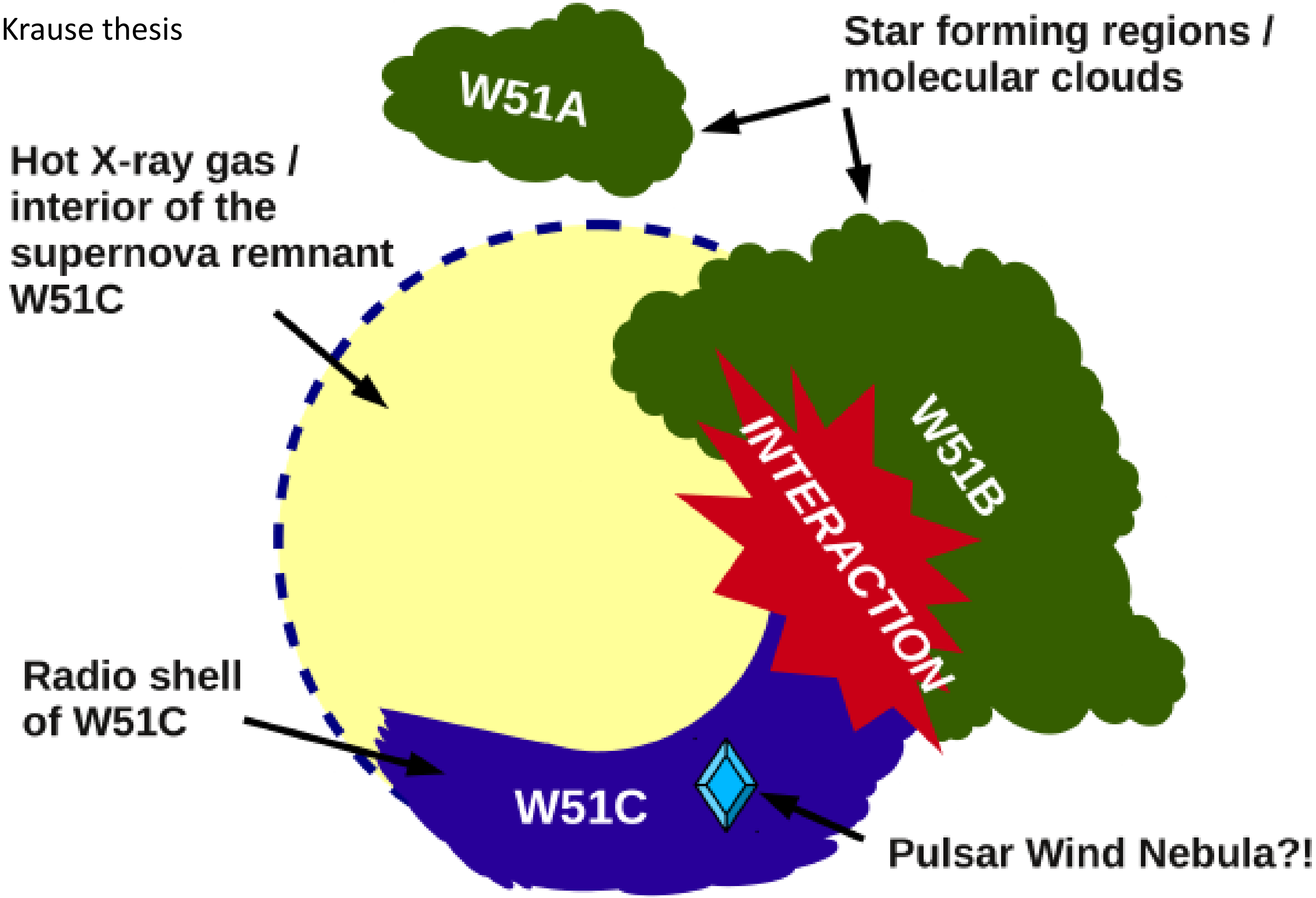


- W51A & W51B: star forming regions, W51C medium-age (~30kyr) SNR @ ~5.5 Kpc.
- Possible PWN CXO J192318.5+1403035 maybe associated with W51C (*Koo et al 2005*)
- The SNR appears to be interacting with W51B (*Koo et al. 1997, Green et al. 1997*)
- High Cosmic Ray ionization, ~100xISM value (*Ceccarelli et al. 2011*)

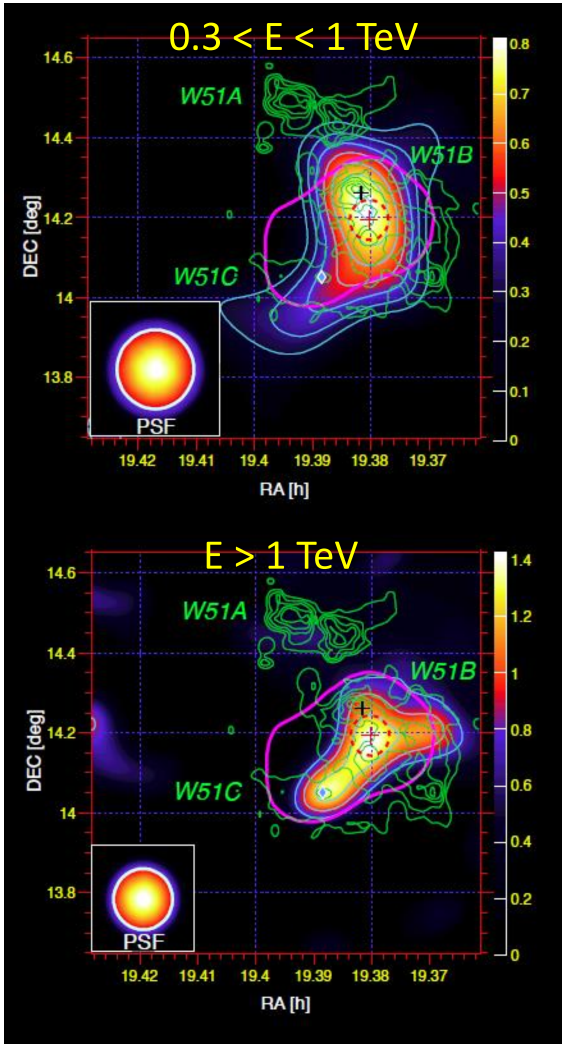
MAGIC stereo data taken in 2010 and 2011 (53h), 11 σ signal

The morphology cartoon of W51

J.Krause thesis

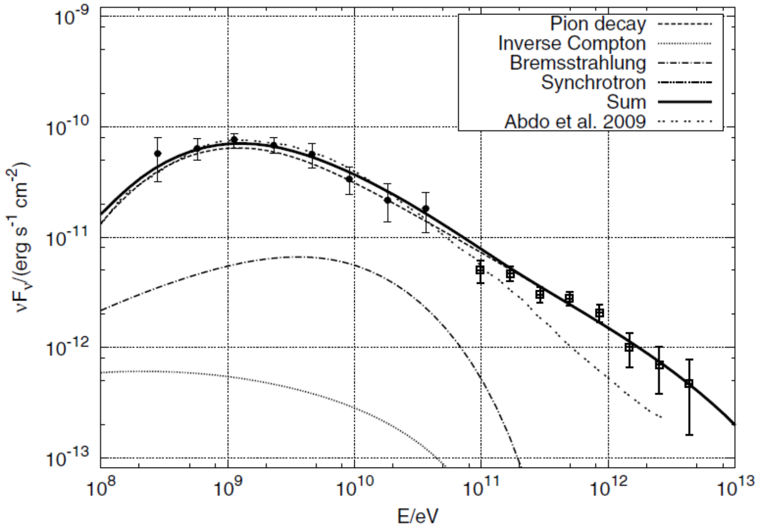


W51 as seen by MAGIC



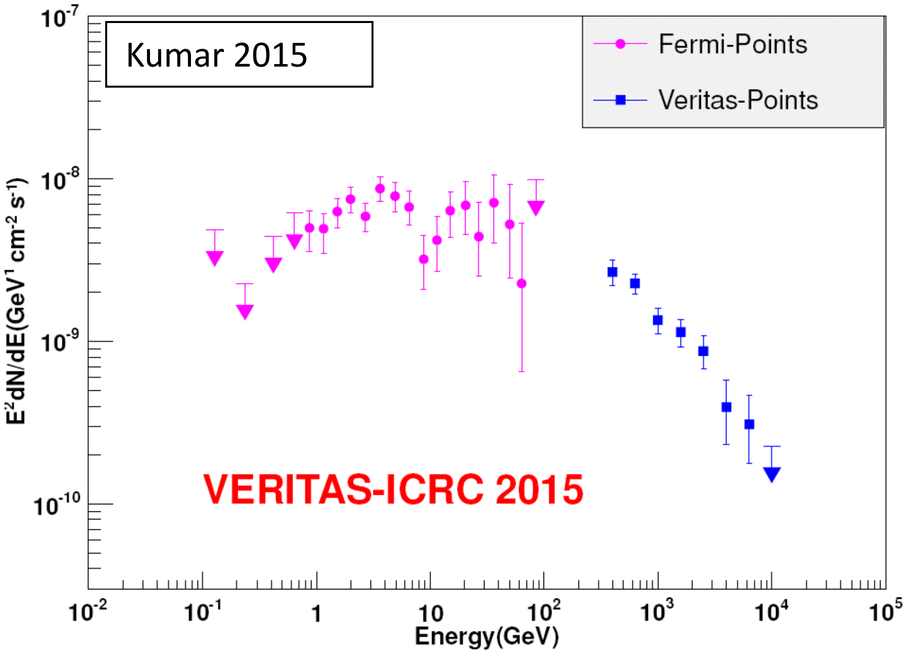
W51: SNR W51C interacts with molecular clouds in W51B The broad-band spectral energy distribution can be explained *only* (1-zone) with a hadronic model. This implies proton acceleration ≥ 50 TeV. This result, together with the morphology of the source, tentatively suggests that we are observing ongoing acceleration of ions in the interaction zone between the supernova remnant and the cloud.

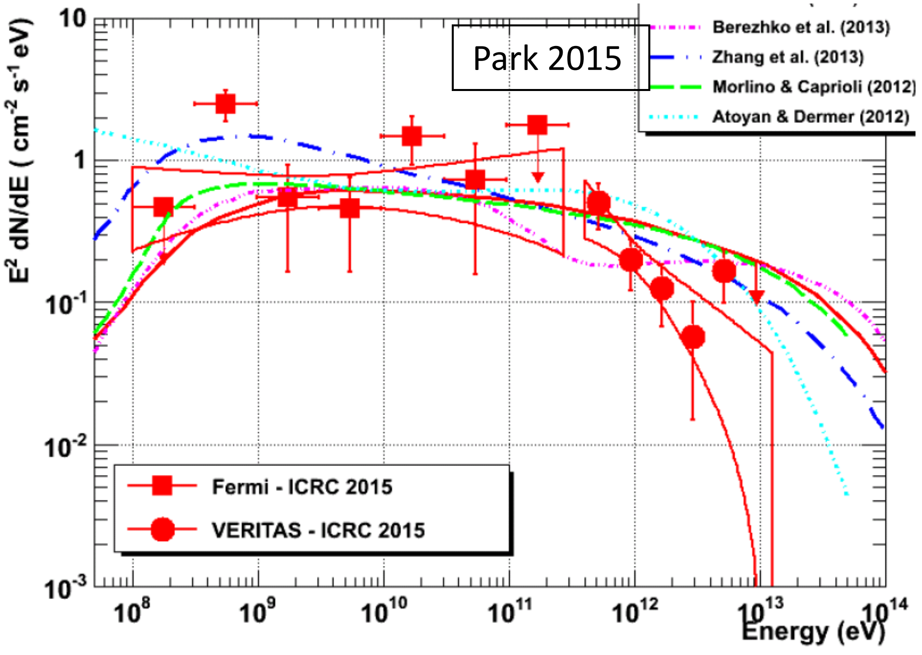
Aleksic, et al, 1012



Young SNRs in denser medium

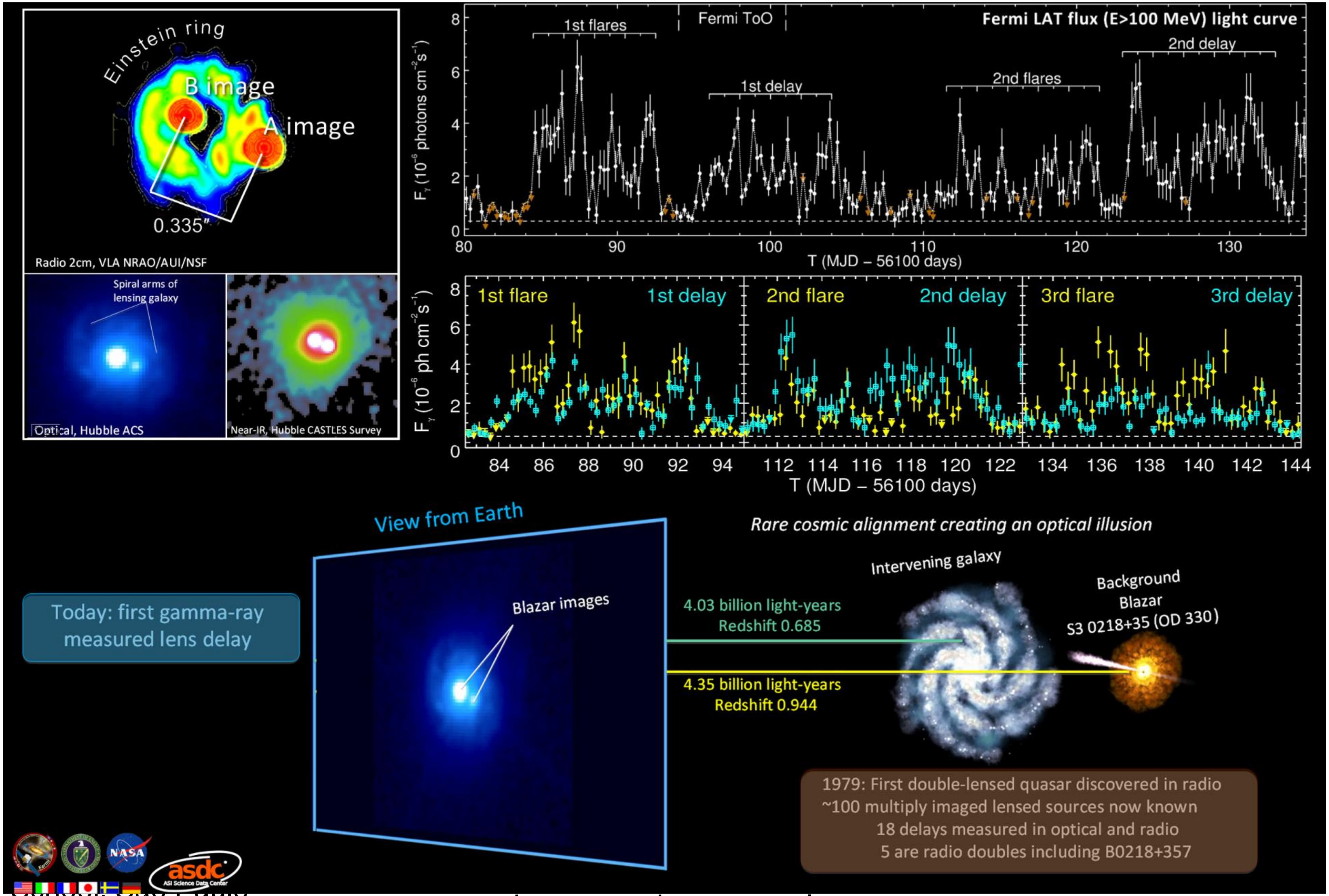
Cas A T=350 yr $n_H \sim 0.3\text{-}1\ \mathrm{cm}^{-3}$ **Tycho T=444 yr**





- Hadronic origin of gamma-emission, spectral breaks at $E_b \sim 300$ GeV are observed.
- Poor proton accelerators at multi-TeV energies

Gravitational lense system S3 0218 (also known as B0218+357)

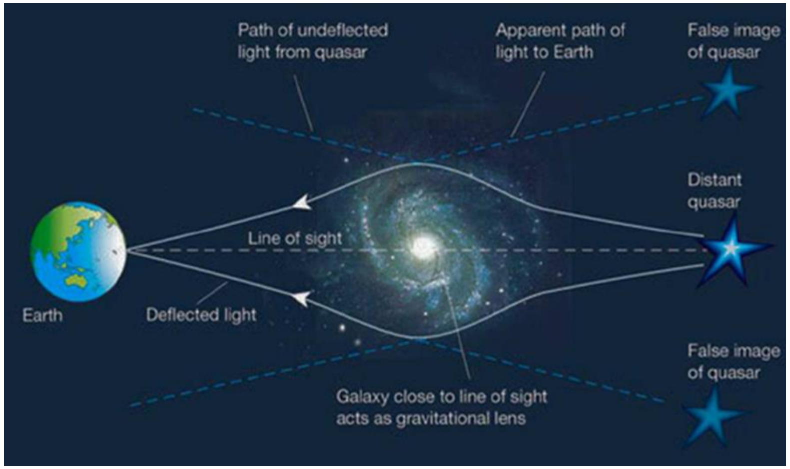


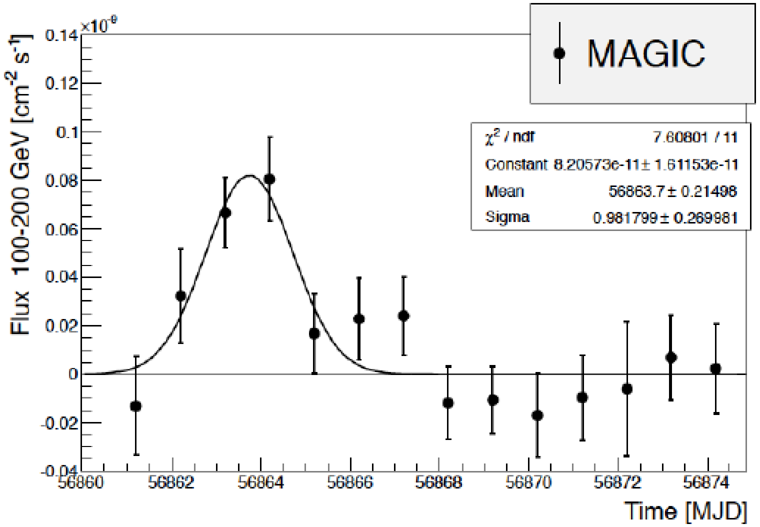
Today: first gamma-ray measured lens delay

1979: First double-lensed quasar discovered in radio
~100 multiply imaged lensed sources now known
18 delays measured in optical and radio
5 are radio doubles including B0218+357

Discovery of Gravitationally Lensed Blazar S3 0218+357 residing at the red shift 0.944

- In 2012 Fermi observed high state, with many overlapping flares
- Fermi claimed 11.46 ± 0.16 days delay for the lensed component
- On July 13/14 2014 Fermi again observed a high state
- Magic started observing 2 days before the predicted delayed signal and kept on-going till 5th of August





Oldest VHE γ-rays in Universe from a source at red shift of $z = 0.944$ detected

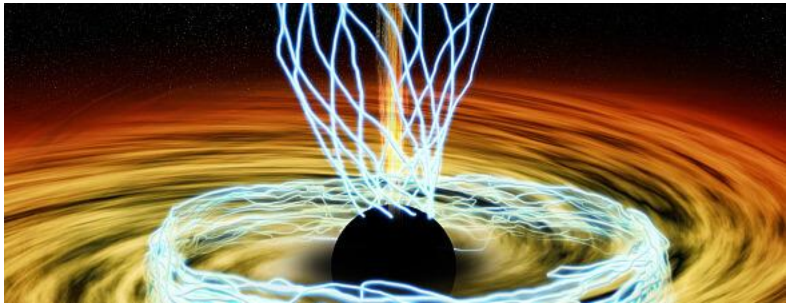
Discovery of Very High Energy Gamma-Ray Emission From Gravitationally Lensed Blazar S3 0218+357 With the MAGIC Telescopes

ATel #6349; ***Razmik Mirzoyan (Max-Planck-Institute for Physics) On Behalf of the MAGIC Collaboration***

on 28 Jul 2014; 14:20 UT

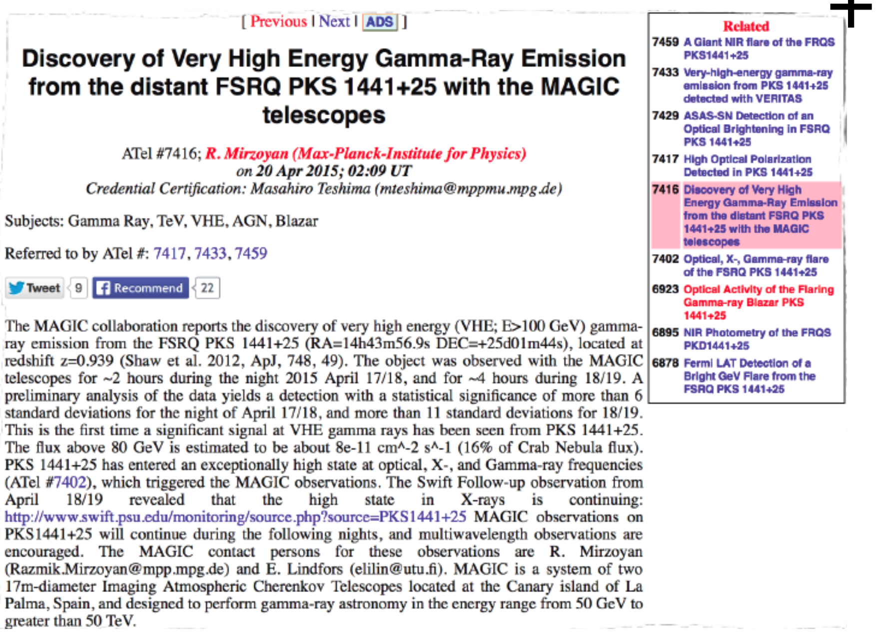
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

- On a few occasions Fermi mission measured flares of the blazar S3 0218+357 *with a time lag of 11.5 days*.
- This was interpreted as due to the gravitational lensing effect
- 2 weeks ago MAGIC detected a flare with $> 5\,\sigma$ at the anticipated time of the arrival of Fermi gravitational lense echo
- The most distant source discovered @ VHE !



Discovery of FSRQ PKS-1441 +25

- Along with S3 0218 +357, z = 0.944, this is the most distant VHE source: **z = 0.939**
- Started observing on April 17th after alert from Fermi, for 10 days



[Previous | Next | ADS]

Discovery of Very High Energy Gamma-Ray Emission from the distant FSRQ PKS 1441+25 with the MAGIC telescopes

ATel #7416; ***R. Mirzoyan (Max-Planck-Institute for Physics)***
on 20 Apr 2015; 02:09 UT
Credential Certification: Masahiro Teshima (mteshima@mppmu.mpg.de)

Subjects: Gamma Ray, TeV, VHE, AGN, Blazar

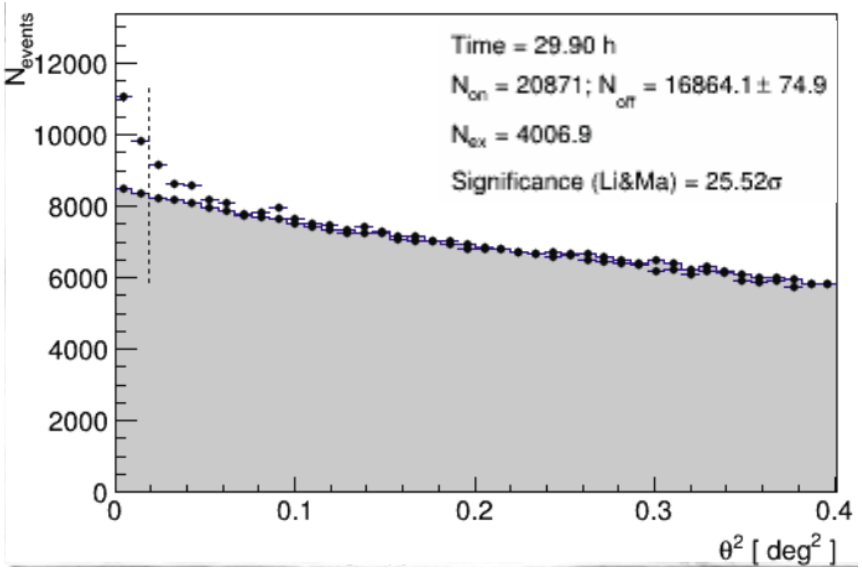
Referred to by ATel #: 7417, 7433, 7459

Tweet 9 Recommend 22

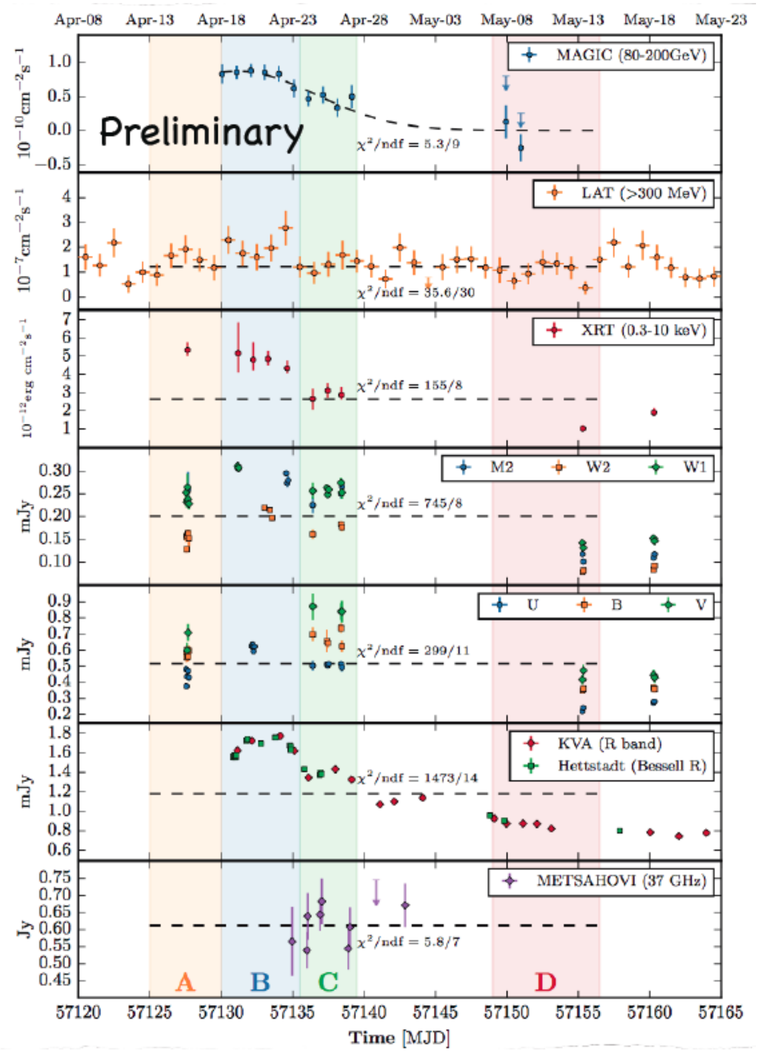
The MAGIC collaboration reports the discovery of very high energy (VHE; E>100 GeV) gamma-ray emission from the FSRQ PKS 1441+25 (RA=14h43m56.9s DEC=+25d01m44s), located at redshift z=0.939 (Shaw et al. 2012, ApJ, 748, 49). The object was observed with the MAGIC telescopes for ~2 hours during the night 2015 April 17/18, and for ~4 hours during 18/19. A preliminary analysis of the data yields a detection with a statistical significance of more than 6 standard deviations for the night of April 17/18, and more than 11 standard deviations for 18/19. This is the first time a significant signal at VHE gamma rays has been seen from PKS 1441+25. The flux above 80 GeV is estimated to be about 8e-11 cm^-2 s^-1 (16% of Crab Nebula flux). PKS 1441+25 has entered an exceptionally high state at optical, X-, and Gamma-ray frequencies (ATel #7402), which triggered the MAGIC observations. The Swift Follow-up observation from April 18/19 revealed that the high state in X-rays is continuing: http://www.swift.psu.edu/monitoring/source.php?source=PKS1441+25 MAGIC observations on PKS1441+25 will continue during the following nights, and multiwavelength observations are encouraged. The MAGIC contact persons for these observations are R. Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de) and E. Lindfors (elilin@utu.fi). MAGIC is a system of two 17m-diameter Imaging Atmospheric Cherenkov Telescopes located at the Canary island of La Palma, Spain, and designed to perform gamma-ray astronomy in the energy range from 50 GeV to greater than 50 TeV.

Related

7459	A Giant NIR flare of the FRQS PKS1441+25
7433	Very-high-energy gamma-ray emission from PKS 1441+25 detected with VERITAS
7429	ASAS-SN Detection of an Optical Brightening in FSRQ PKS 1441+25
7417	High Optical Polarization Detected in PKS 1441+25
7416	Discovery of Very High Energy Gamma-Ray Emission from the distant FSRQ PKS 1441+25 with the MAGIC telescopes
7402	Optical, X-, Gamma-ray flare of the FSRQ PKS 1441+25
6923	Optical Activity of the Flaring Gamma-ray Blazar PKS 1441+25
6895	NIR Photometry of the FRQS PKD1441+25
6878	Fermi LAT Detection of a Bright GeV Flare from the FSRQ PKS 1441+25



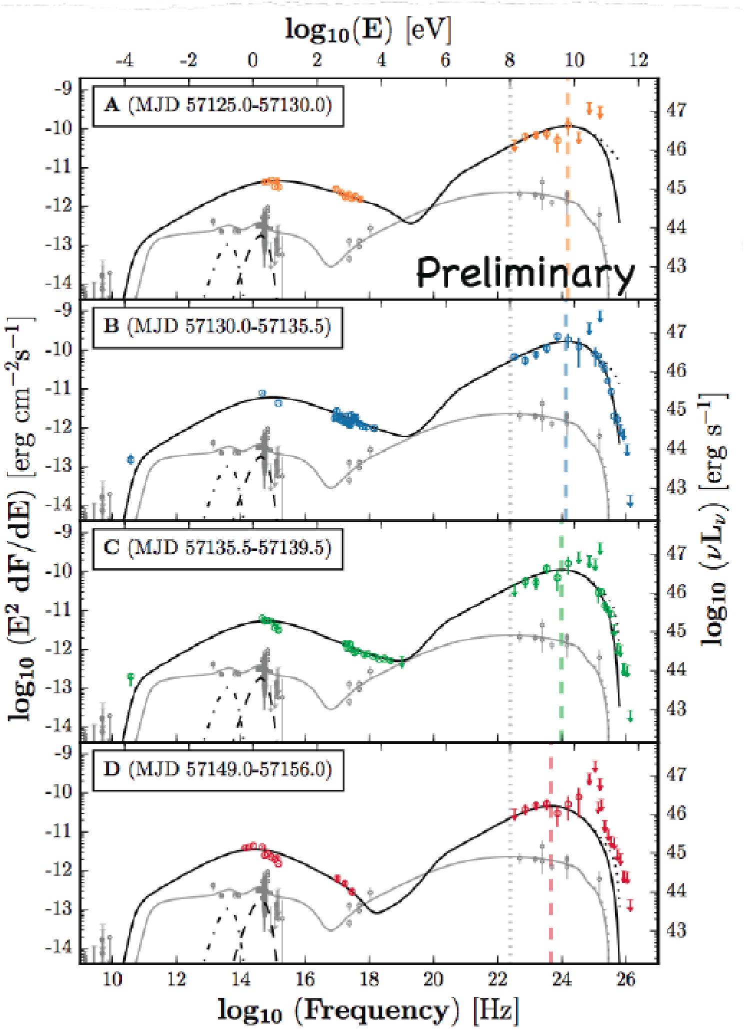
25 σ, > **4000** γ events
Spectrum measured in
40 – 250 GeV energy range



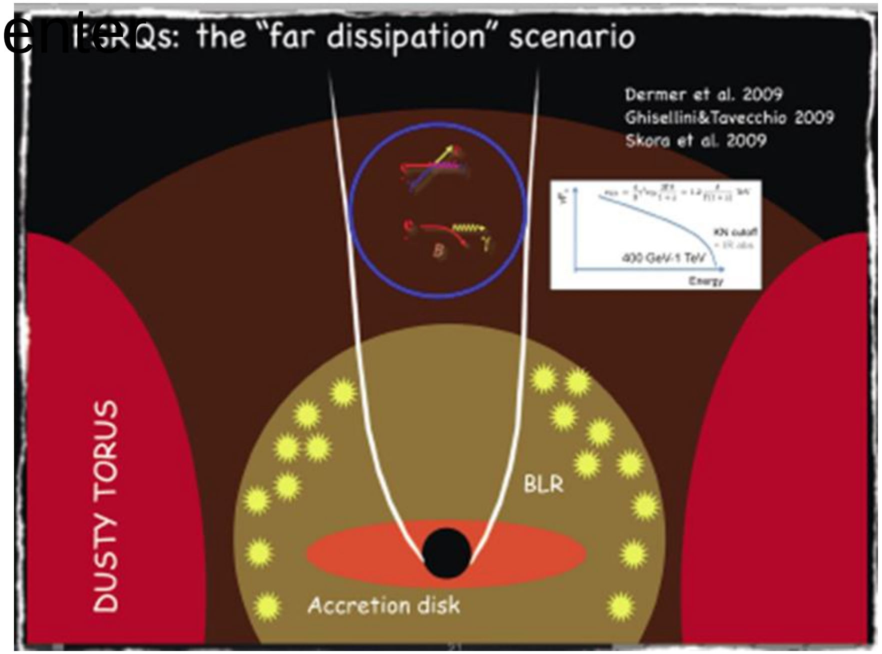
PKS-1441 +25

- Two flux states can be distinguised during the flare
- Flux halving time is ~ 6 days
- No signal after the moon-break period

SED PKS-1441 +25

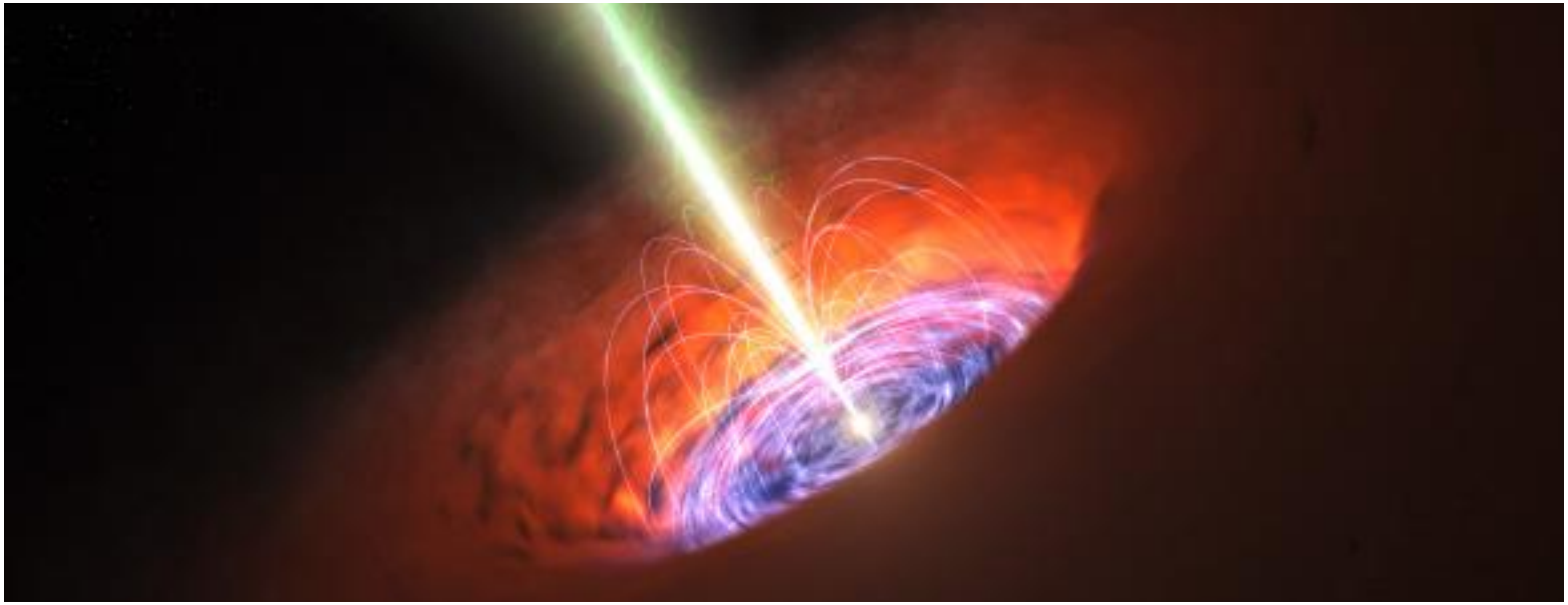


Lack of absorption features in the measured HE - VHE γ-ray spectra allows one to constrain the location of emitting region to be far from the center



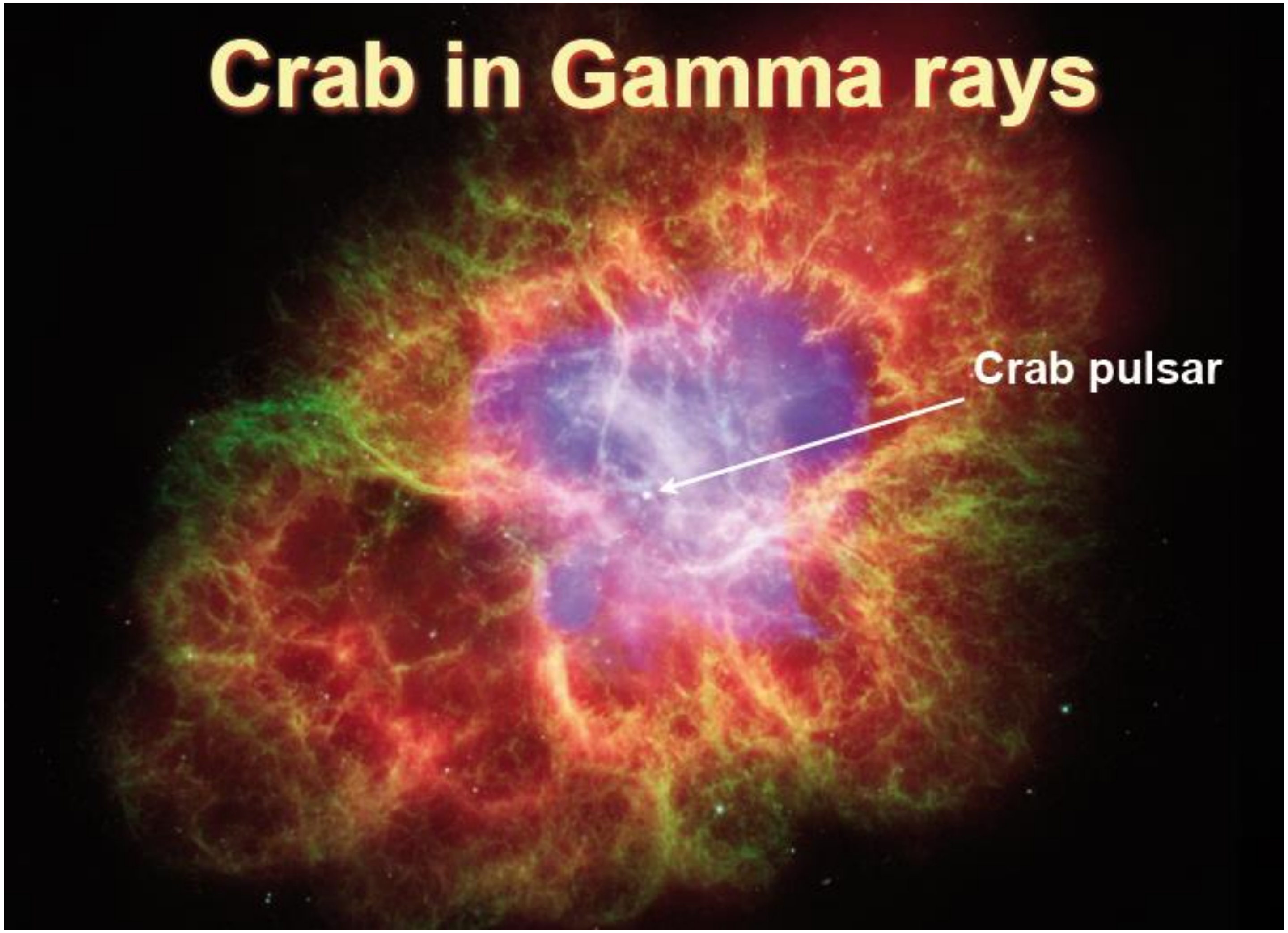
External Compton scenario

Joint NASA-MAGIC-VERITAS press-release on PKS-1441 +25 on 15th Dec. 2015

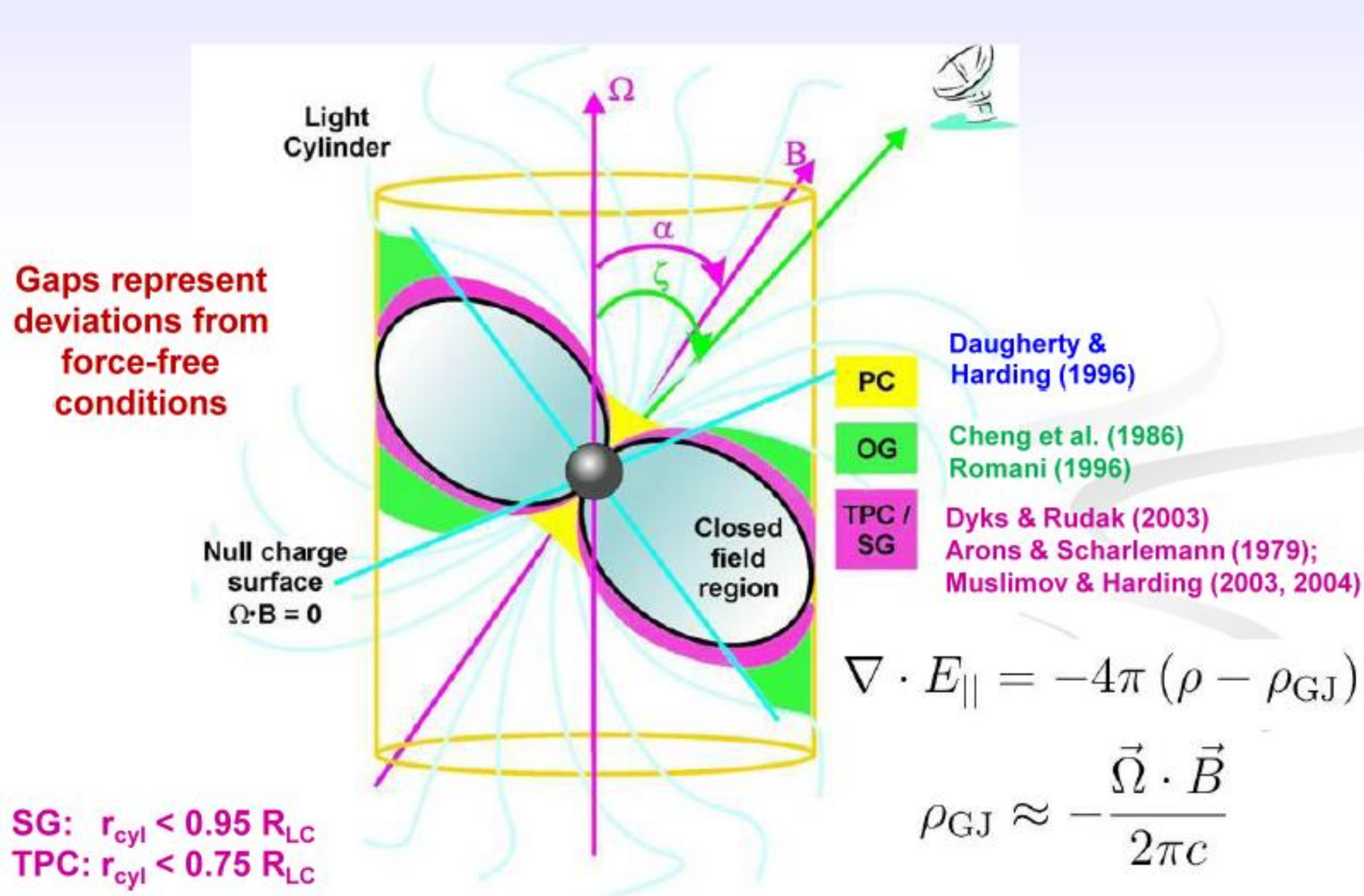


FineCut4-NASA-8PM-11-Dec-15.mp4

Composite figure of Crab Nebula



Cartoon of a pulsar



Gaps represent deviations from force-free conditions

PC: Daugherty & Harding (1996)

OG: Cheng et al. (1986)
Romani (1996)

TPC / SG: Dyks & Rudak (2003)
Arons & Scharlemann (1979);
Muslimov & Harding (2003, 2004)

$$\nabla \cdot E_{||} = -4\pi\left(\rho - \rho_{\mathrm{GJ}}\right)$$

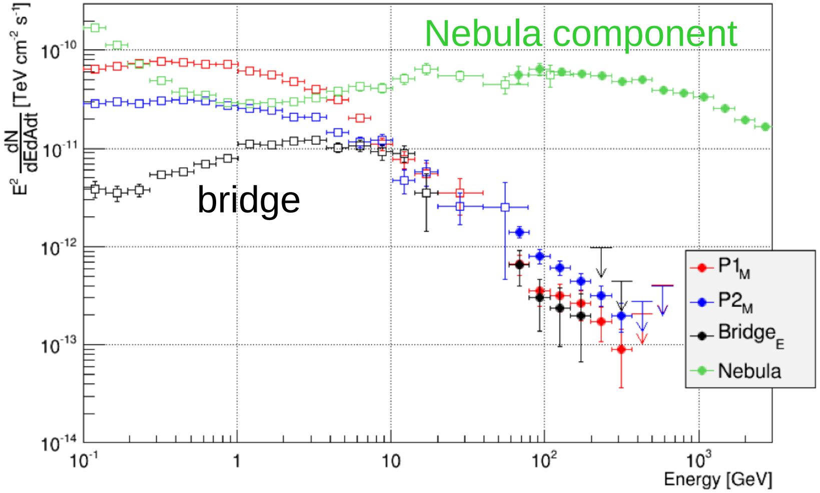
$$\rho_{\mathrm{GJ}} \approx -\frac{\vec{\Omega} \cdot \vec{B}}{2\pi c}$$

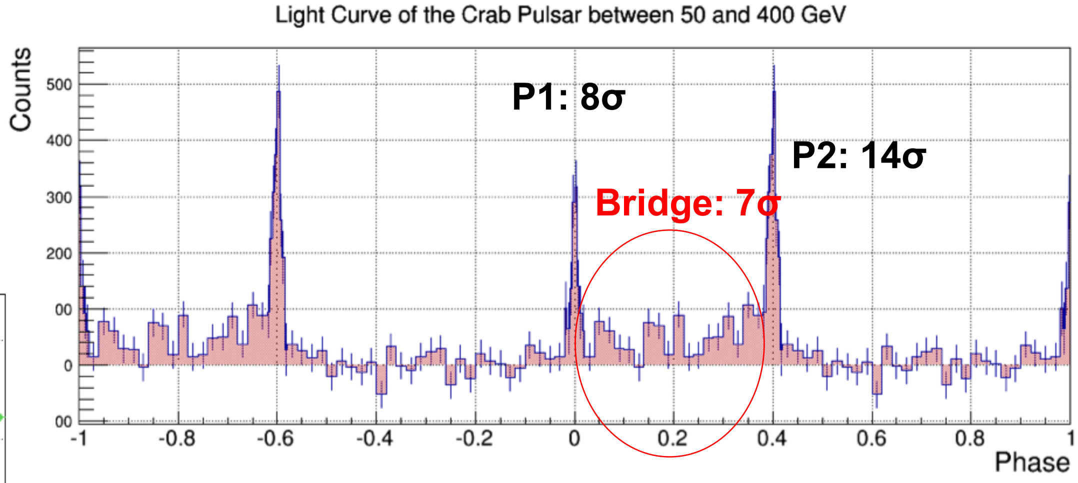
SG: $r_{cyl} < 0.95\ R_{LC}$
TPC: $r_{cyl} < 0.75\ R_{LC}$

MAGIC bridge emission & very narrow pulses

J. Aleksic, et al., arXiv:1402.4219

Fermi bridge emission becomes strong above few GeV

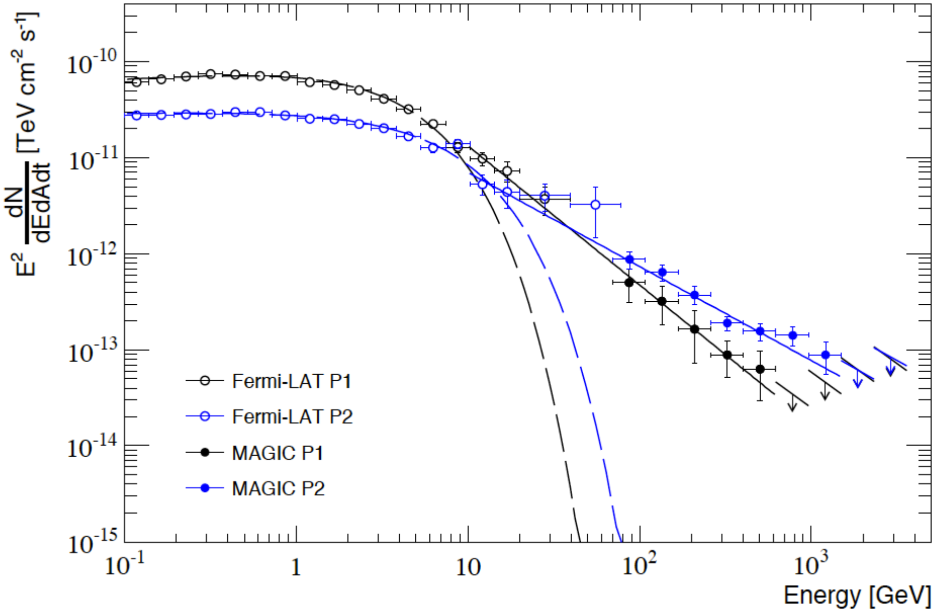




- bridge hints on toroidal bending of magnetic lines near LC
- This result set a quest for precision Crab pulsar theories

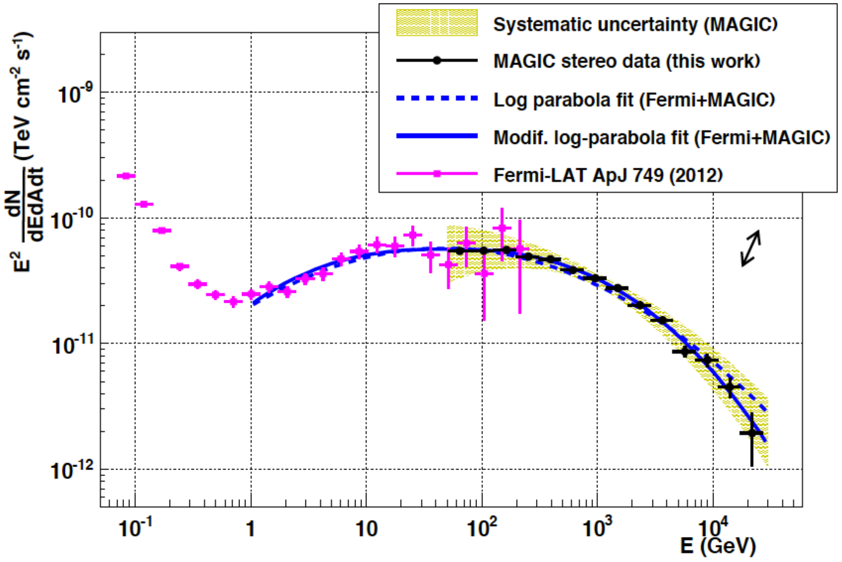
The last word is not yet said: soon new results, new insights…

MAGIC established the Crab pulsar as the most compact accelerator of TeV γ rays



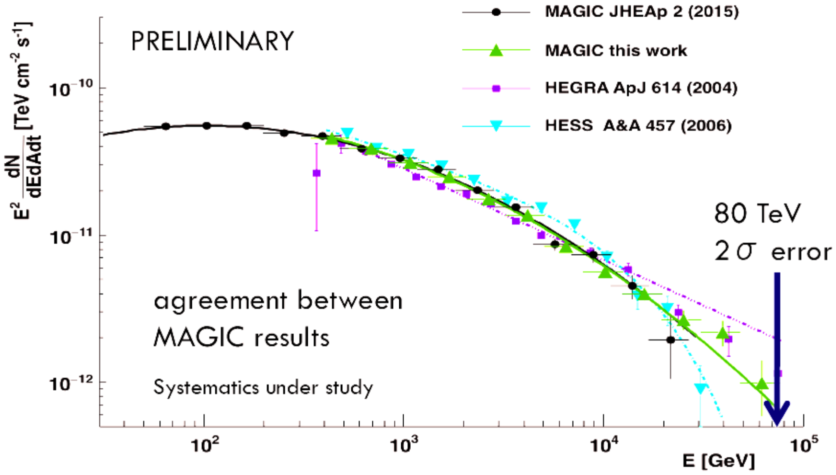
- Discovered pulsed emission from Crab, spectrum extending ≥ 1.2 TeV
- Challenging the emission models
- MAGIC-Fermi fit shows IC emission from ~10 GeV to ≥ 1 TeV
- Emission from the neighborhood of Light Cylinder (r ~1600km)
- TeV pulsation is used to put quadratic limits for Lorentz Invariance Violation (LIV): EQG2 > 4.4 x 10^{10} GeV: this is only factor 3 below current best limit from Fermi

MAGIC & Crab Nebula



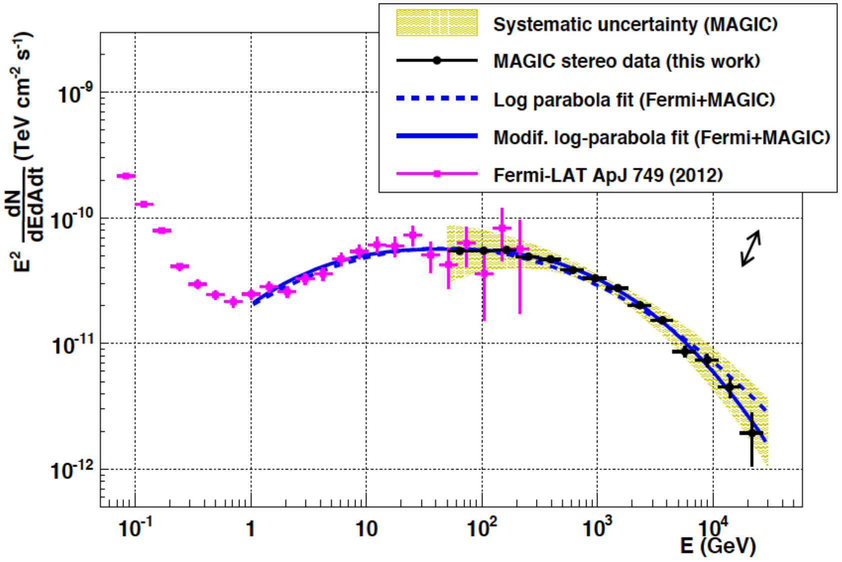
Aleksic et al. (MAGIC) JHEAP, 5, 2015

- Crab Nebula spectrum from 60 GeV till 30 TeV
- Together with Fermi LAT precision definition of the IC peak



Large zenith angle observations $\theta \leq 70°$ for exploring the E range ~80 TeV

MAGIC & Crab Nebula



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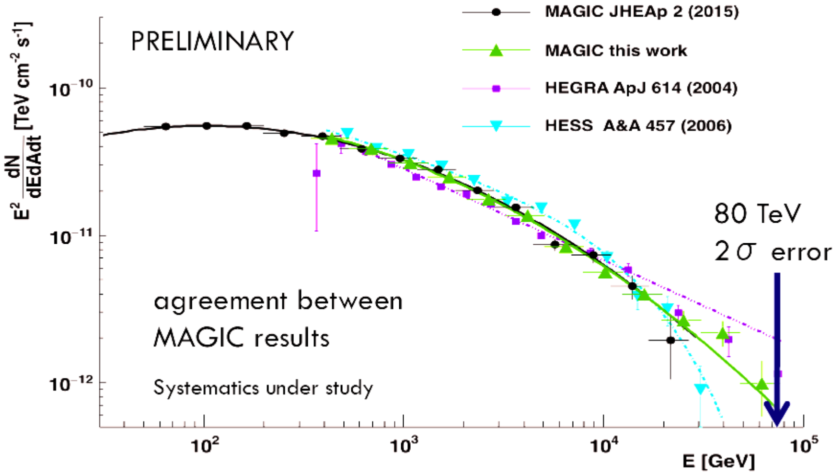
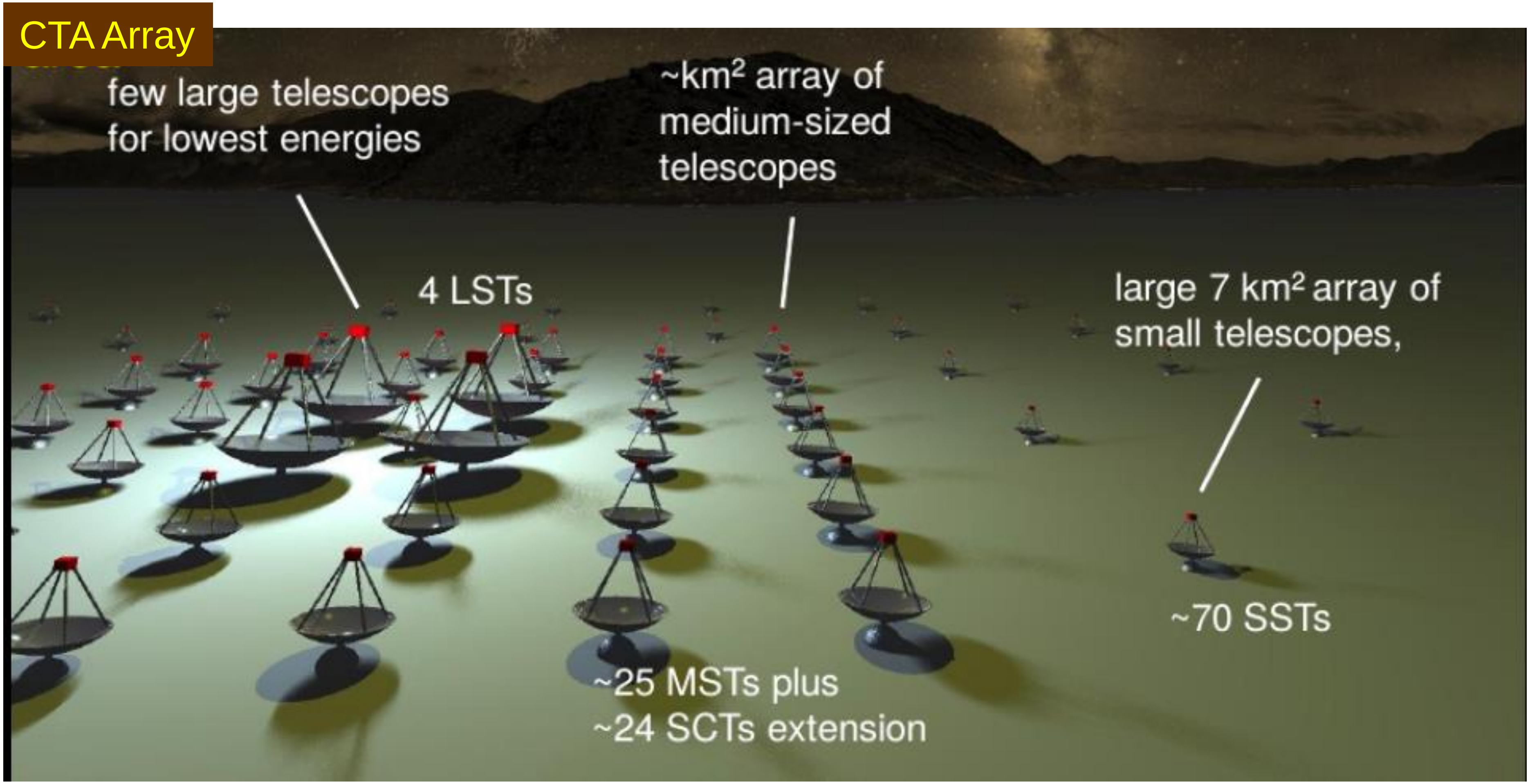


Next ~ 5 years

- Planning smooth operation of MAGIC for at least next ~ 5 years, until CTA telescopes in the North and South locations will start producing data with better sensitivity
- Successful source hunting and deep observation of diverse source types entered in its best phase with the current generation of telescopes

CTA with its several times higher sensitivity compared to existing instruments is on becoming reality



Welcome to join the CTA Collaboration !