Exotic needles in the gamma-ray haystack

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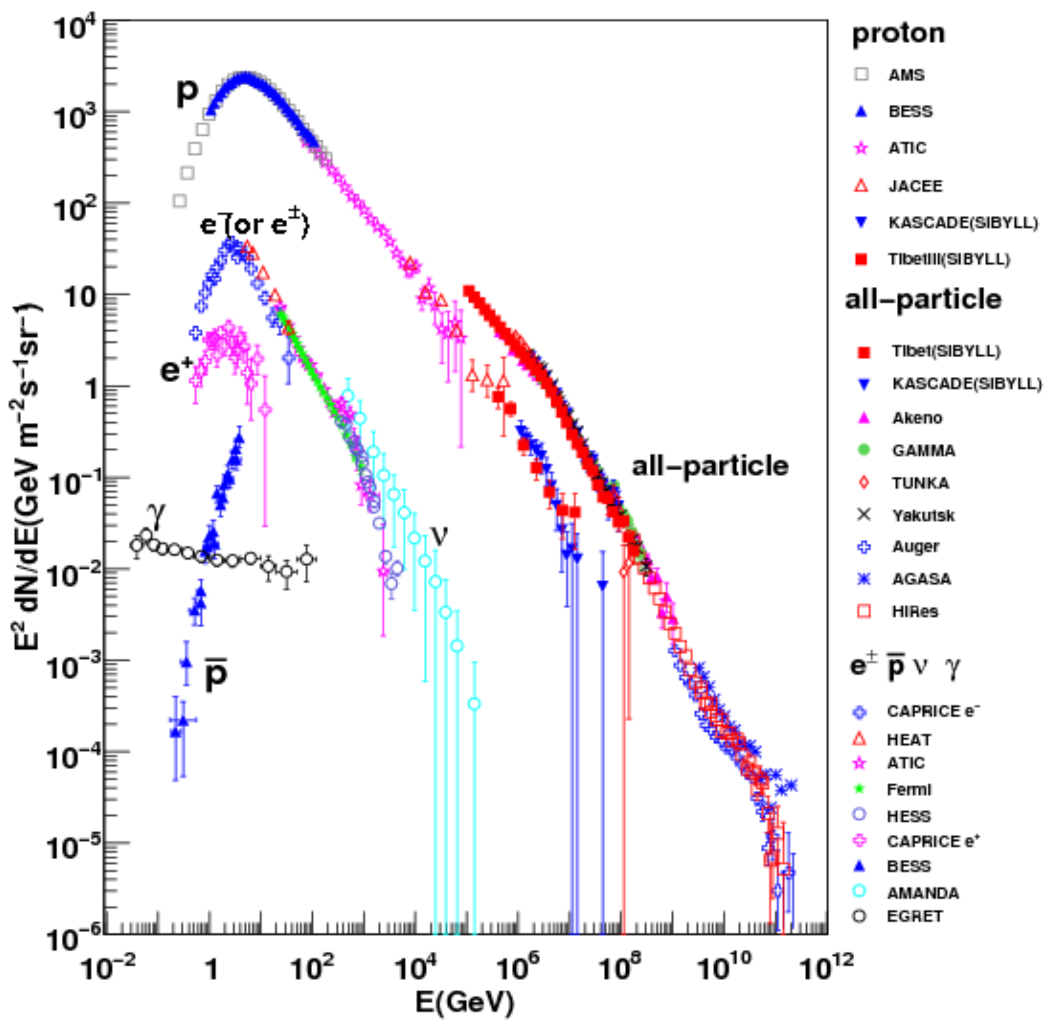
Outline

- The hunt of physics in cosmic rays
- The cosmic needles
  - Earth-skimming tau-neutrinos
  - Cosmic ray nuclei
  - Magnetic monopoles
  - Quark matter
  - Evaporating black holes
  - Fast Radio Bursts
- Challenges, Conclusions

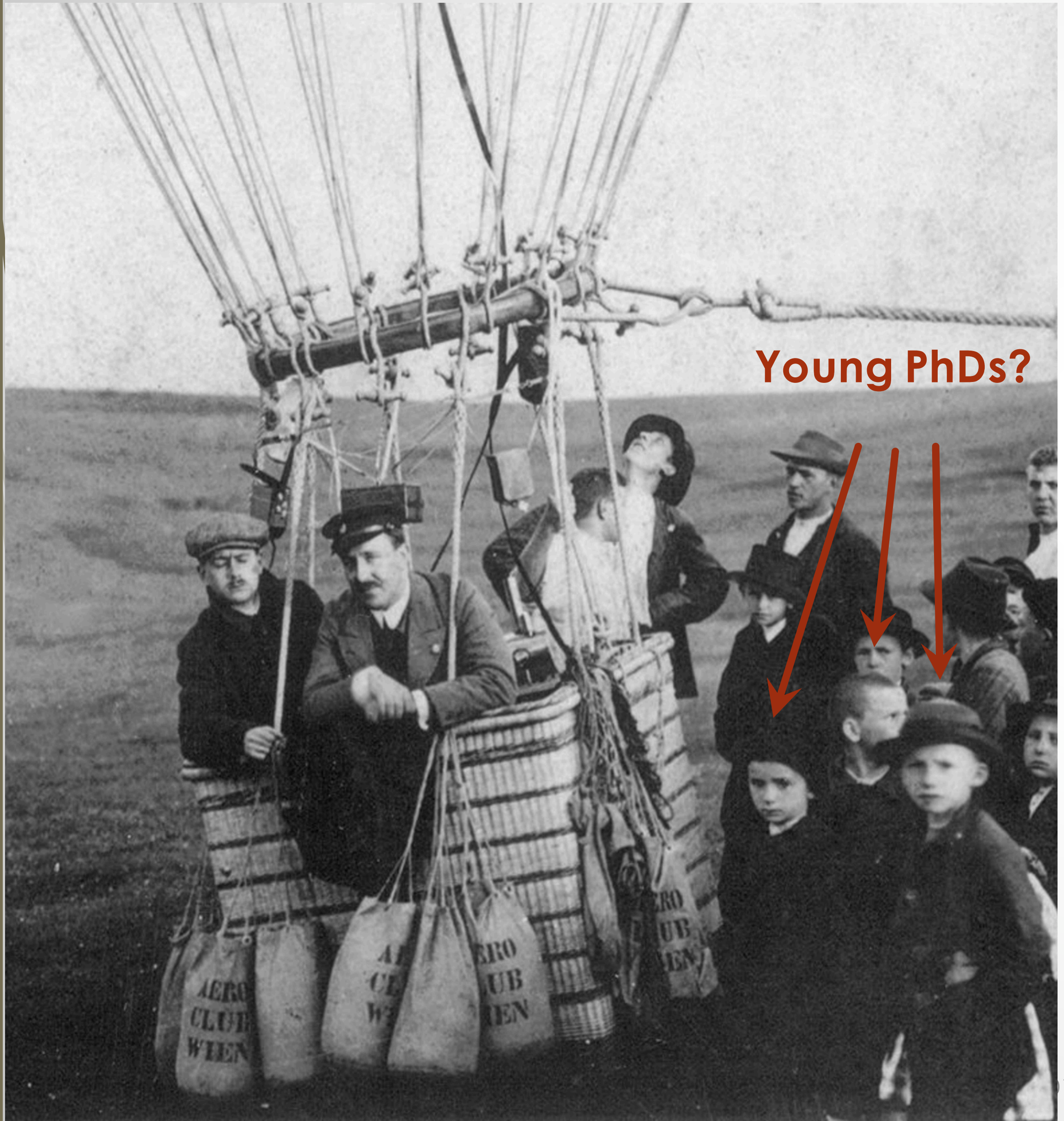
Cosmic-ray



arXiv:0911.3034 H.Hu

- **Big**
  - 14 orders of magnitude in energy
  - 10 orders of magnitude in flux, from many/cm^2/s to few/km^2/century
- How many misteries it is still hiding?
  - What is actually coming to the Earth?
  - Where were these produced (and accelerated)?
  - **Are there non-standard particle in its flux?**

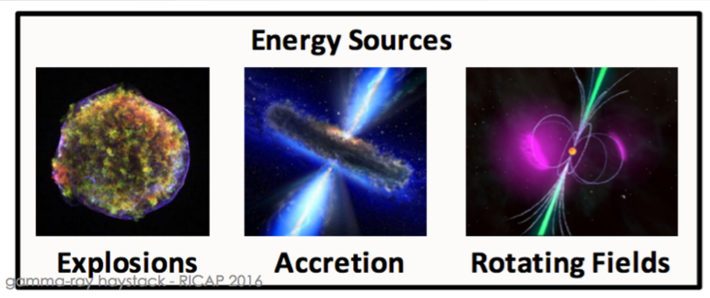
Cosmic rays



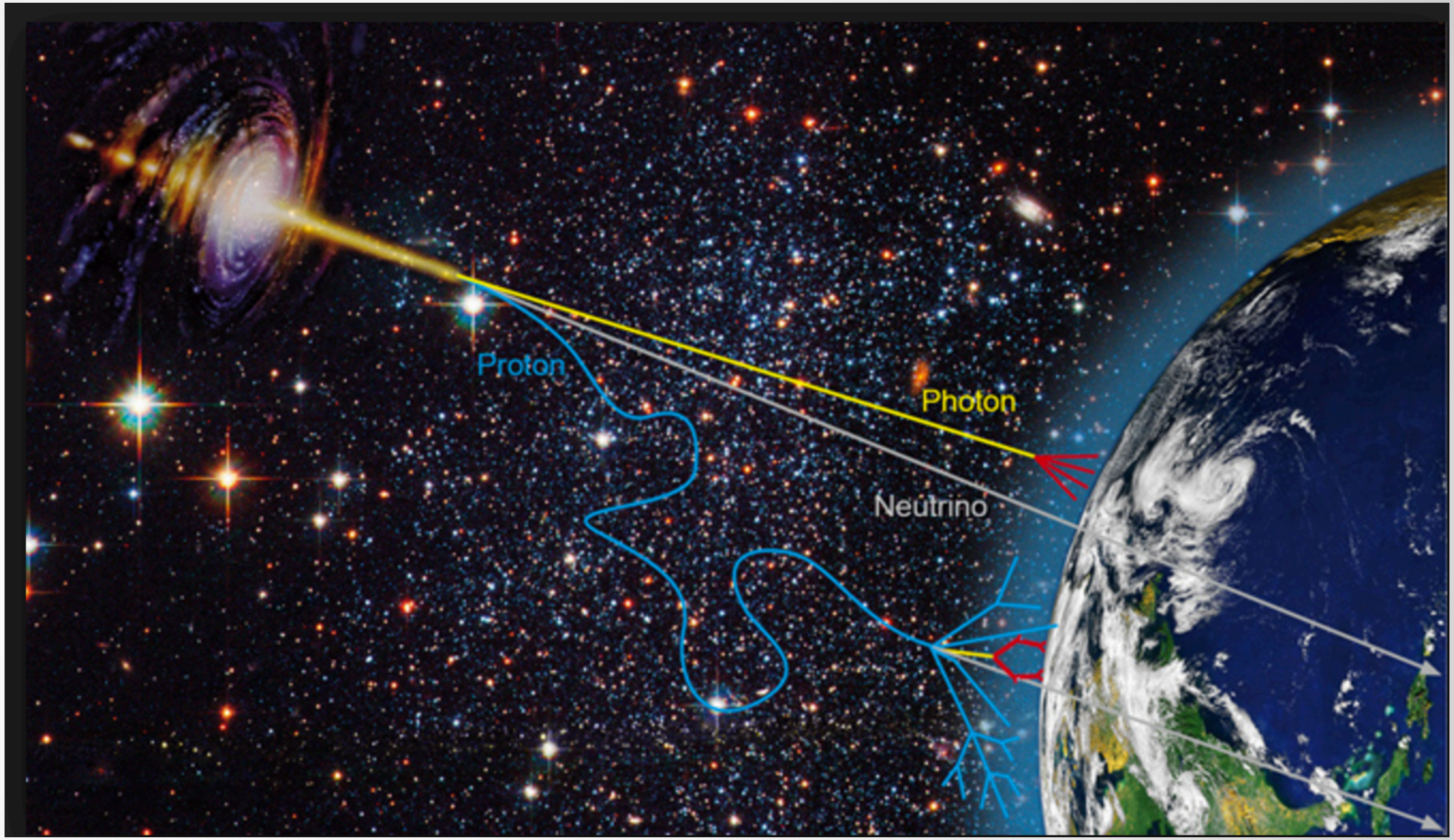
- Several very tenacious guys discovered "***An unknown radiation from space*** *with extreme penetrating power was causing the ionization of air in electrodes.*" .
  - They were *Theodor Wulf, Domenico Pacini, Albert Gockel,, and* ***finally Victor Hess (1912)***
  - Named "cosmic rays" by Millikan (that for long did not believe in them)
- **Photons or particle**? Latitude effects between Genova and Java shown CRs were charged (Clay) and then with Geiger counter (Rossi and others)
- **Breakthrough discoveries**: particle showers, pair-production, positrons, muons, pions, K-mesons

See De Angelis, Pimenta "Introduction to Particle and Astroparticle Physics, Springer

Gamma rays and cosmic rays



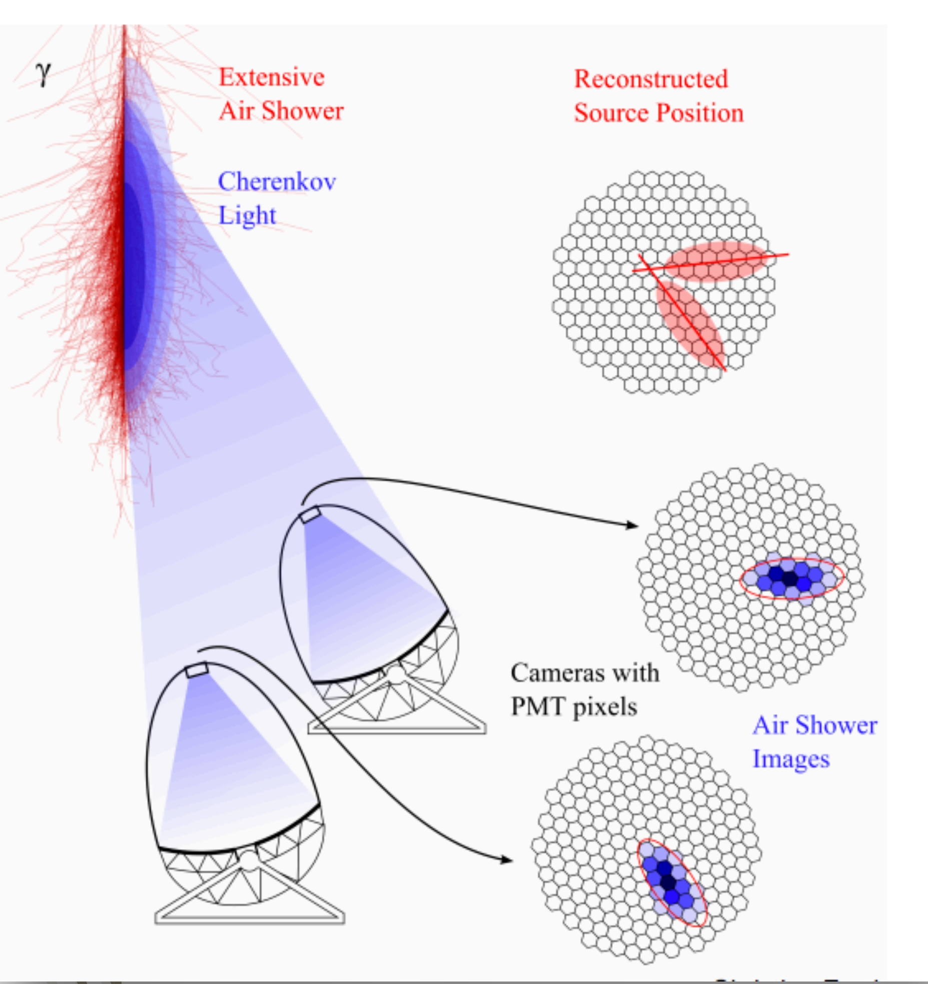
- Gamma rays are found as products in high-energy leptonic or hadronic processes (non-thermal Universe)
- **They are neutral!**
  - **Direction info**
  - **Timing info**



Hadronic high-energy particles → $\pi^0 \rightarrow \gamma\gamma$, $\pi^\pm \rightarrow \mu^\pm \nu$

Leptonic high-energy particles → *Bremsstrahlung*, *Synchrotron*, *Inverse Compton*

A question of calorimeters



- Calorimeter manmade:
  - Water Cherenkov: HAWC, LATTES, MILAGRO
  - Satellite pair-conversion instruments: Agile, Fermi-LAT
- **Calorimeter provided by nature**:
  - Imaging experiment: IACT: MAGIC, HESS, VERITAS, CTA,
- **Imaging:**
  - Showers create images in the camera whence the **shower is totally contained**
  - The **image is the event**
  - **Stereoscopy** is very important

IACTs

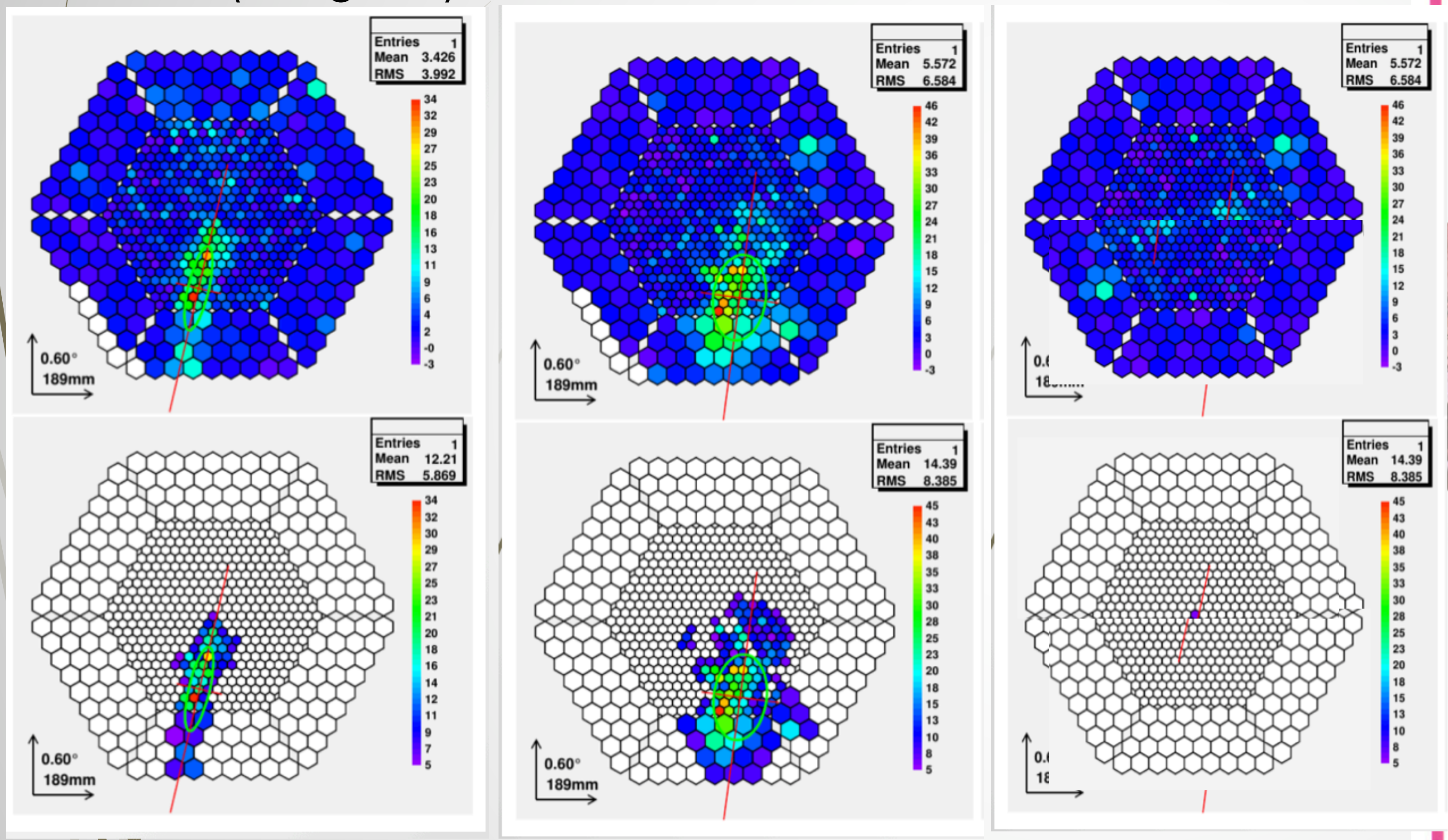
- **Array** of telescopes
  - **10^5** square meter effective area
  - **FOV** about 5 deg / **PSF** = 0.1 deg
  - Picosecond relative **timing** precision
- During data-taking, e.g., MAGIC acquires **@ 200 Hz**. *These are mostly hadronic showers. Gamma-rays are less than 1/1000 of this rate.*
- During data reconstruction, **only 1/1000 hadronic events survive** (very energy dependent)

The haystack

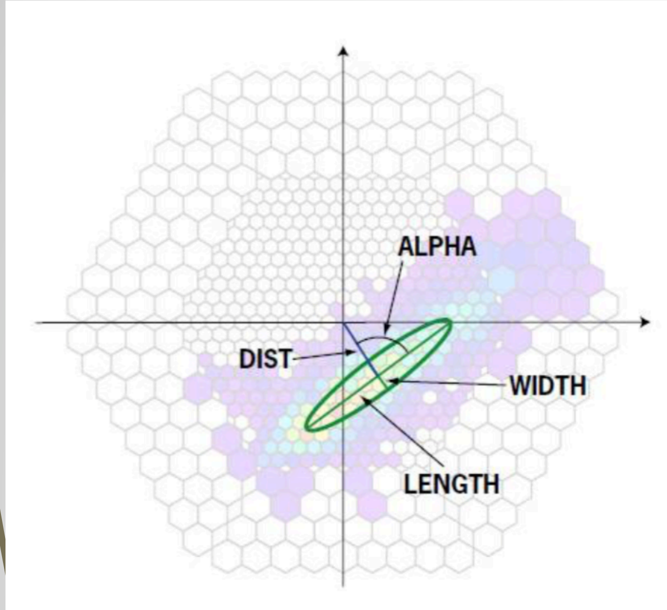
- **Background events rate**
  - One large night: 8h*3600s*200 = 5.76 MEvents
  - One month: 27days*5h*3600s*200 = 97.2 MEvents
  - One year: 1.2 Gevents
  - **Lifetime: 12 Gevents**
- In the case of MAGIC, because it is an experiment (and it can afford the disk space for now), **these billions of events are safely stored** in the database
- ← **Is this really background**? Can there be something peculiar in this haystack?

Events classes

Gamma (the good) | Hadron (the bad) | NSB (the ugly)



Event tagging

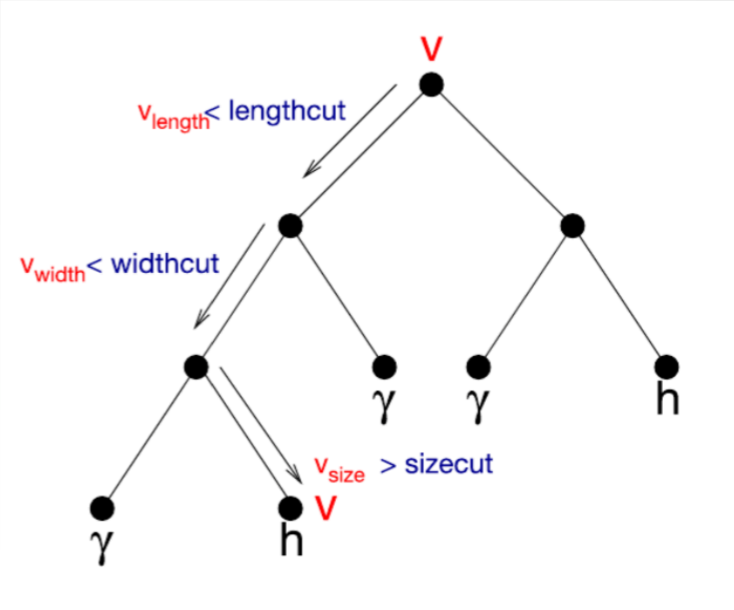


1

You "clean" the image and extract shape parameters

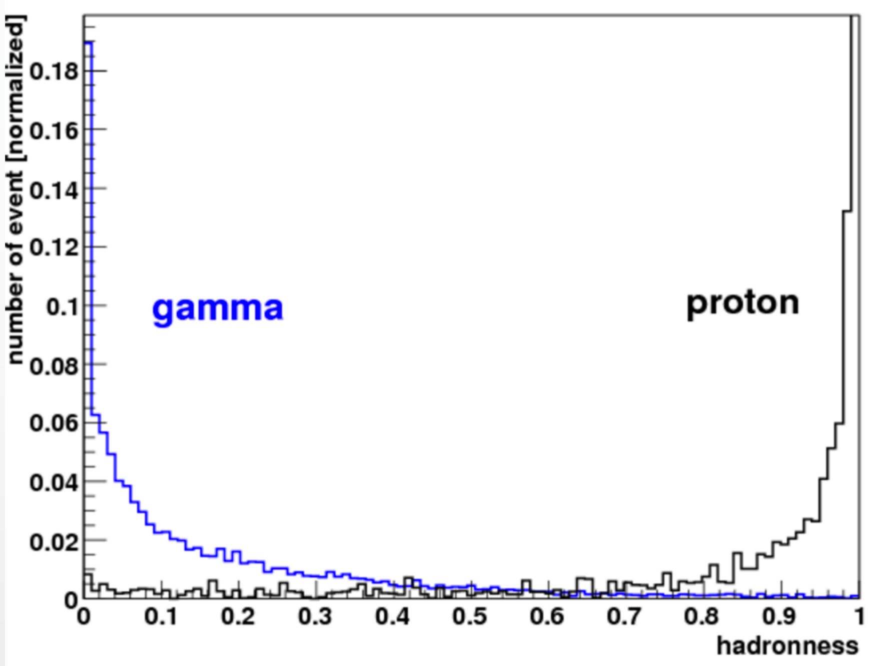
2

You make a Random Forest is a collection of decision trees, by comparing with Monte Carlo

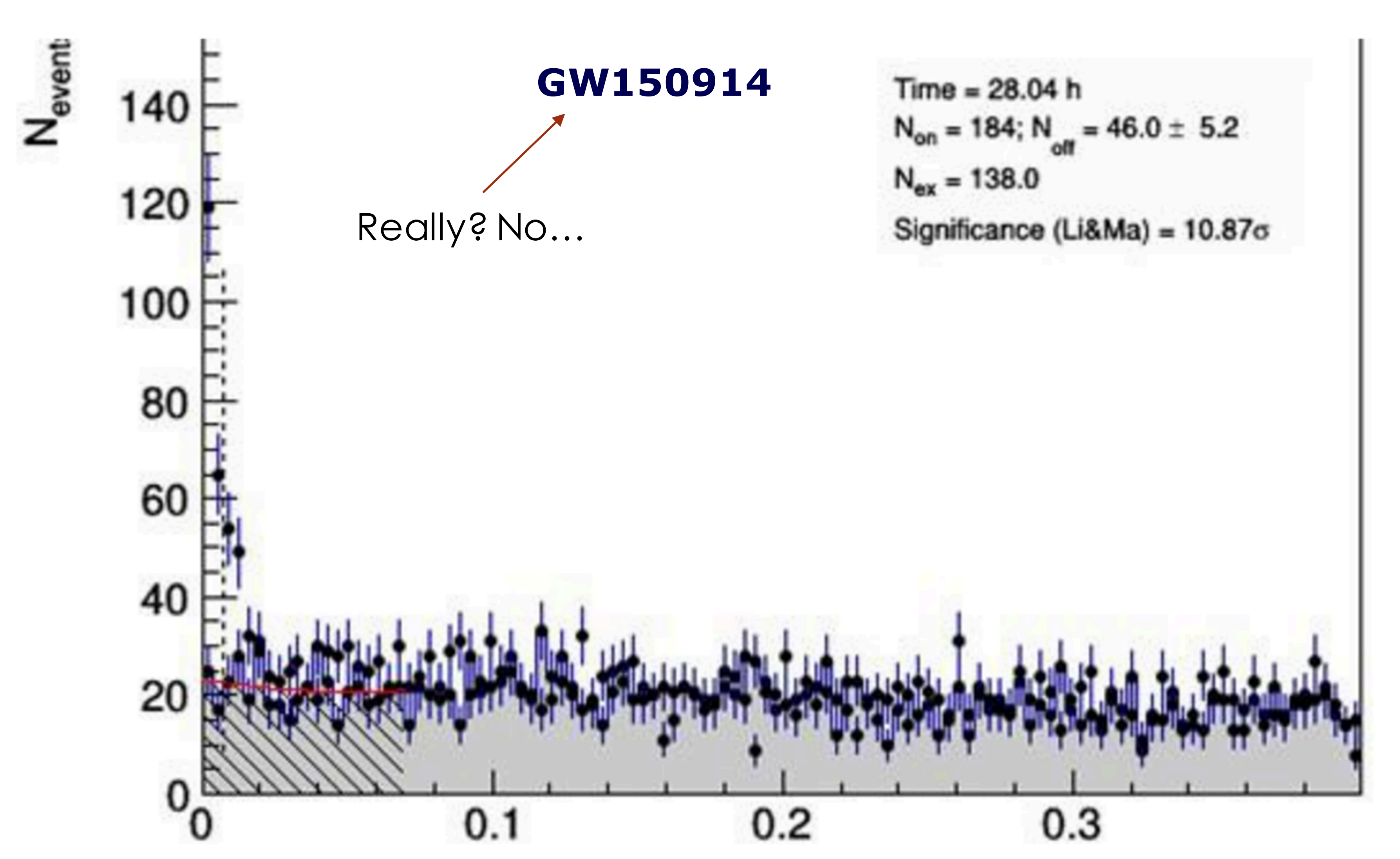


3

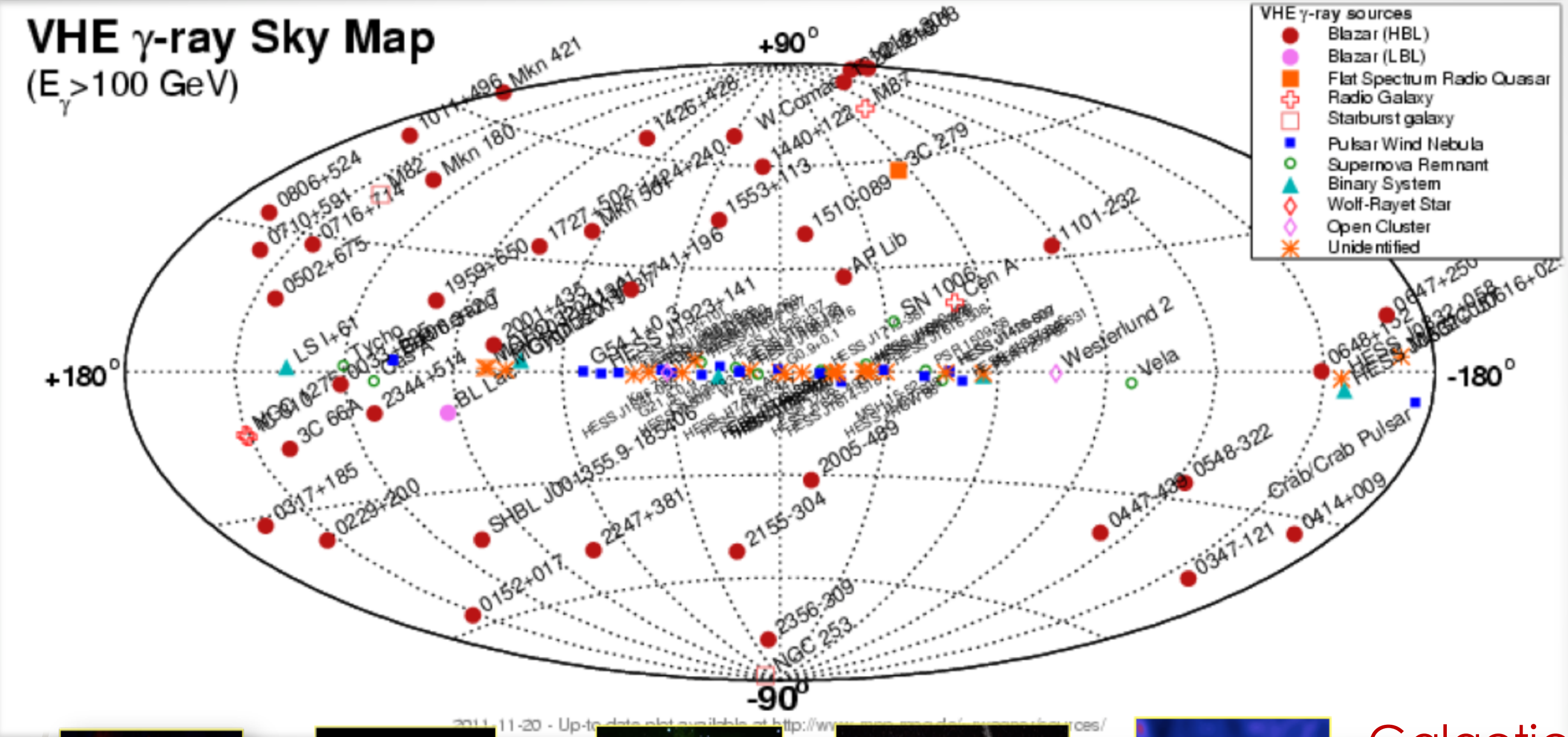
You have classified events according to "hadronness" and start to make cuts

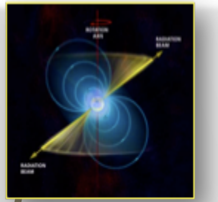


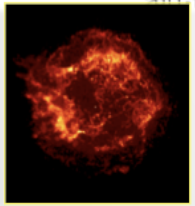
Some background survives

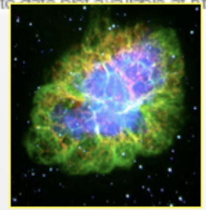


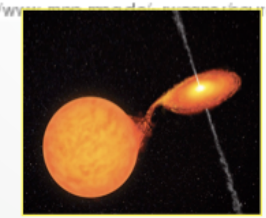
Astronomical targets in our TeV sky

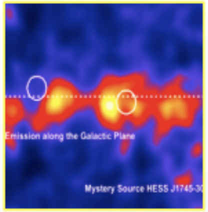



Pulsar


Supernova Remnants


Pulsar wind nebulae

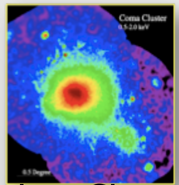

Micro-quasars



Galactic center

Galactic targets


Active Galactic Nuclei



Galaxy Cluster

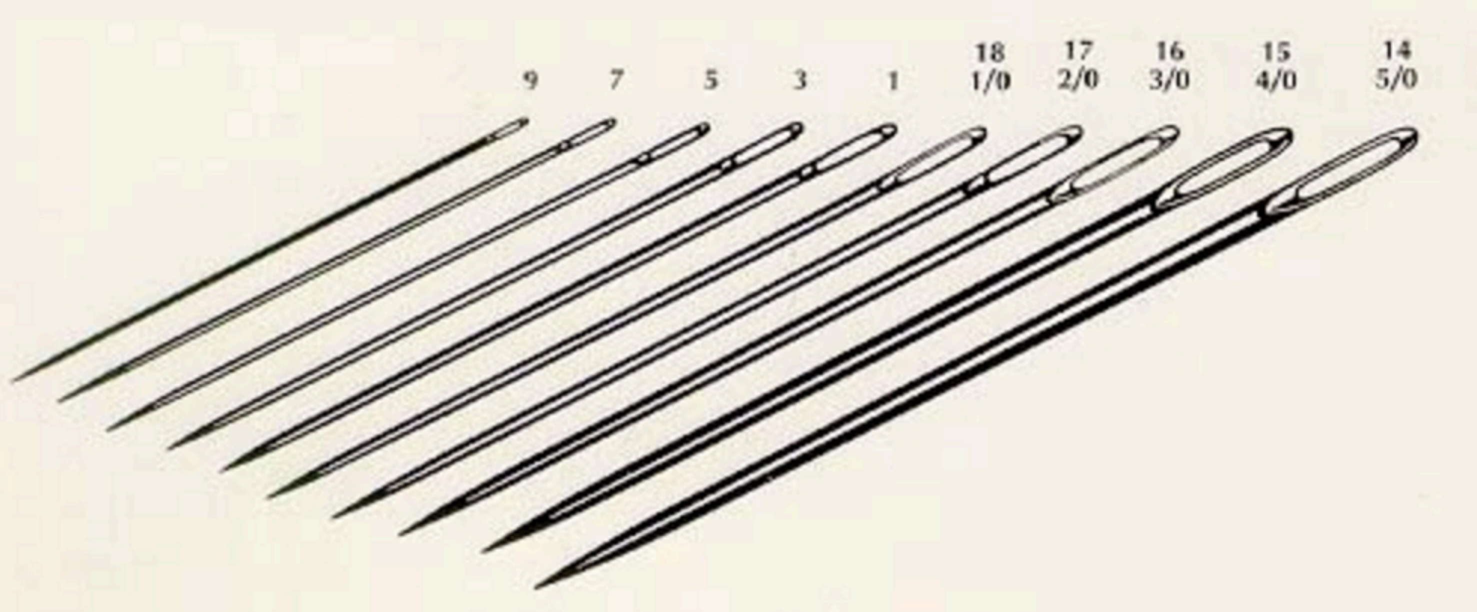

Starburst galaxies


Merging Galaxies


Gamma-ray Bursts

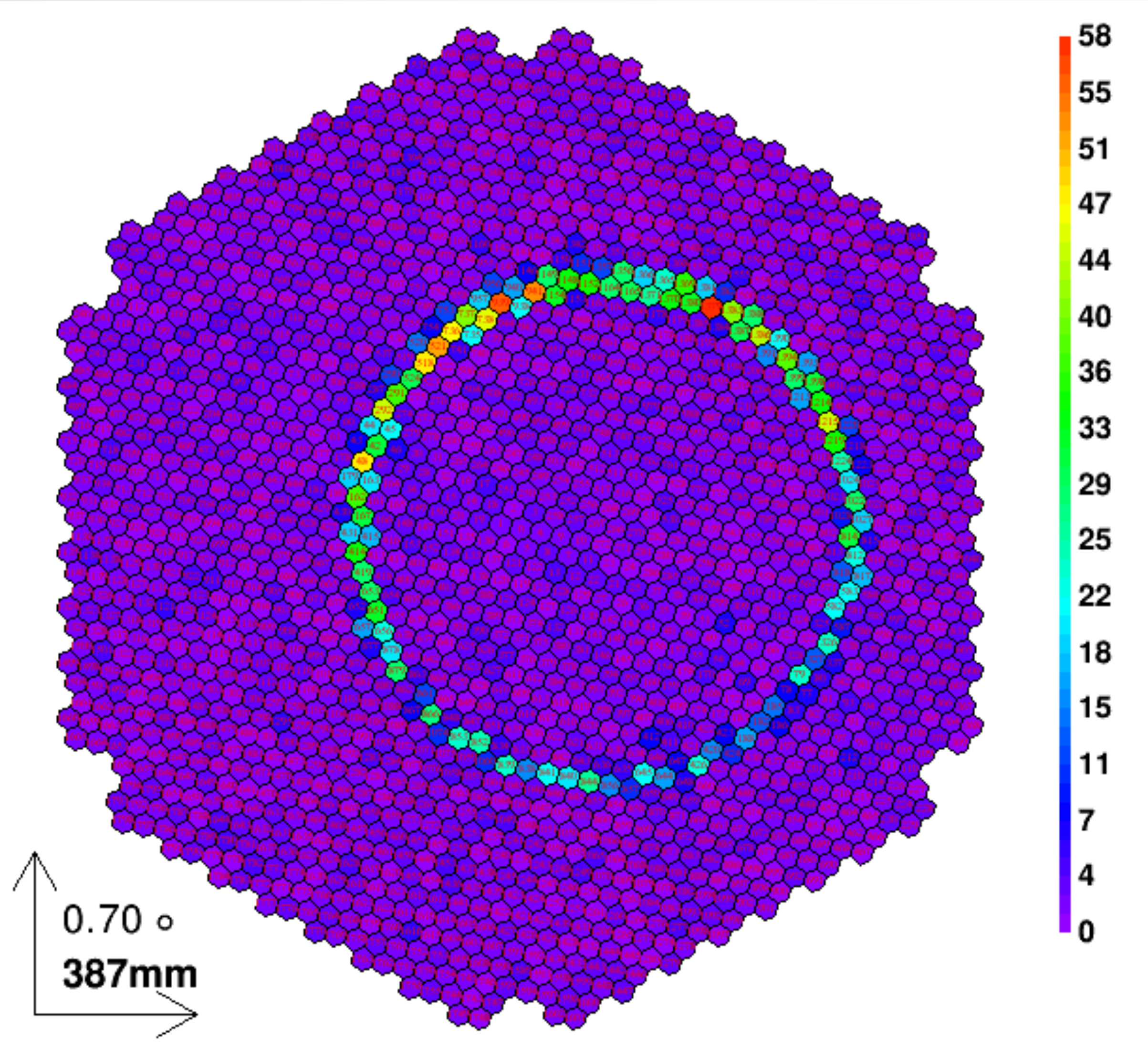
Extragalactic targets

- IACTs have a huge astroparticle physics program
- Aims is answering questions on where and how CRs are accelerated
- But strong program of fundamental particle physics
- **Focusing most efforts and results**



The needles

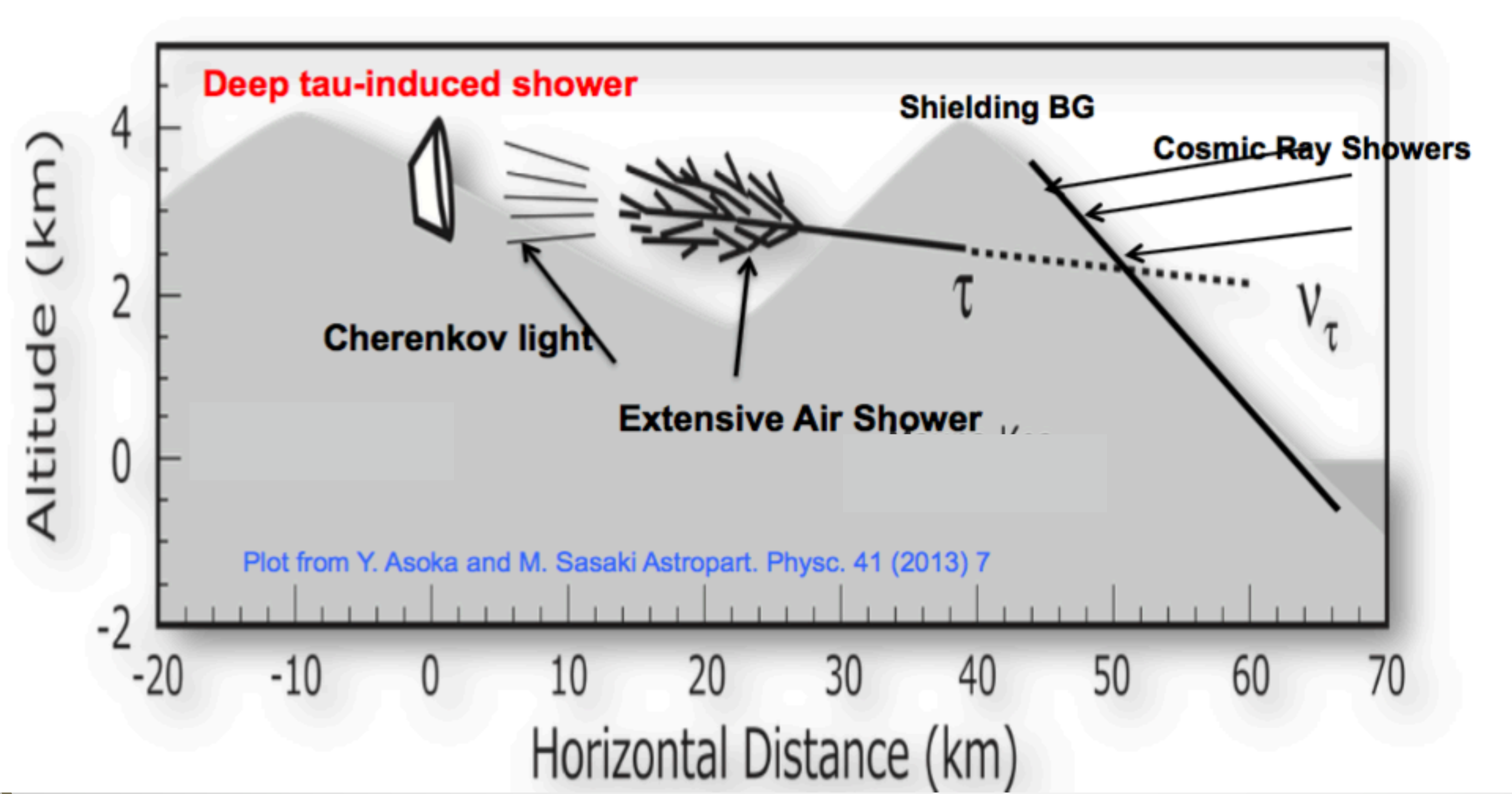
Known events: muons



- For example, there are already special events in our data
- This is the **Cherenkov light ring produced by a muon** right above the mirror of the telescope
- The muon was generated in a hadronic shower
- ***Muons are used for monitoring and calibration purposes***, *but…*

N1: Earth skimming tau-neutrinos

- **Tau neutrinos may** reach Earth from space from energetic engines (AGNs, GRBs) from decay of charged pions. At Earth $\nu_e : \nu_\mu : \nu_\tau \sim 1:1:1$
- If crossing the right amount of matter, **can convert to tau-lepton in ground** and if exiting the ground again, can **generate atmospheric showers**
- Neutrinos should be at the **PeV** or above



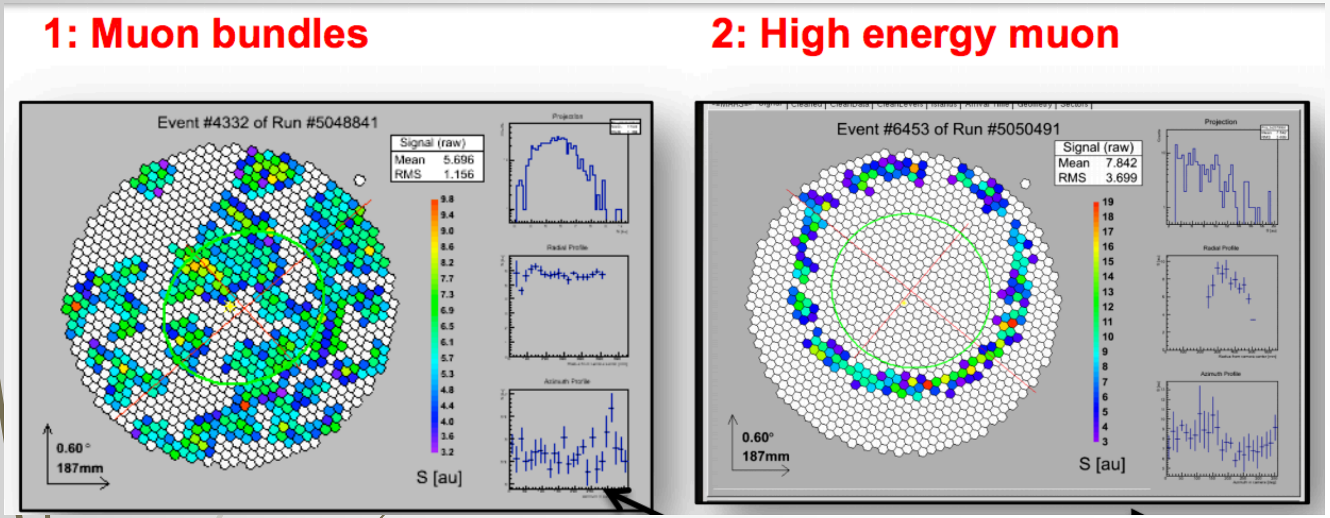
- **Complexity in MC simulations** (atmosphere, shower model, interactions, orography)
- All solved in Gora+ Astropart.Phys. 26 (2007) 402-413

D. Fargion, Astrophys.J. 570, 909 (2002).
X. Bertou et al., Astropart.Phys. 17, 183 (2002).
E. Zas, New J.Phys. 7, 130

Portraits of tau-neutrinos

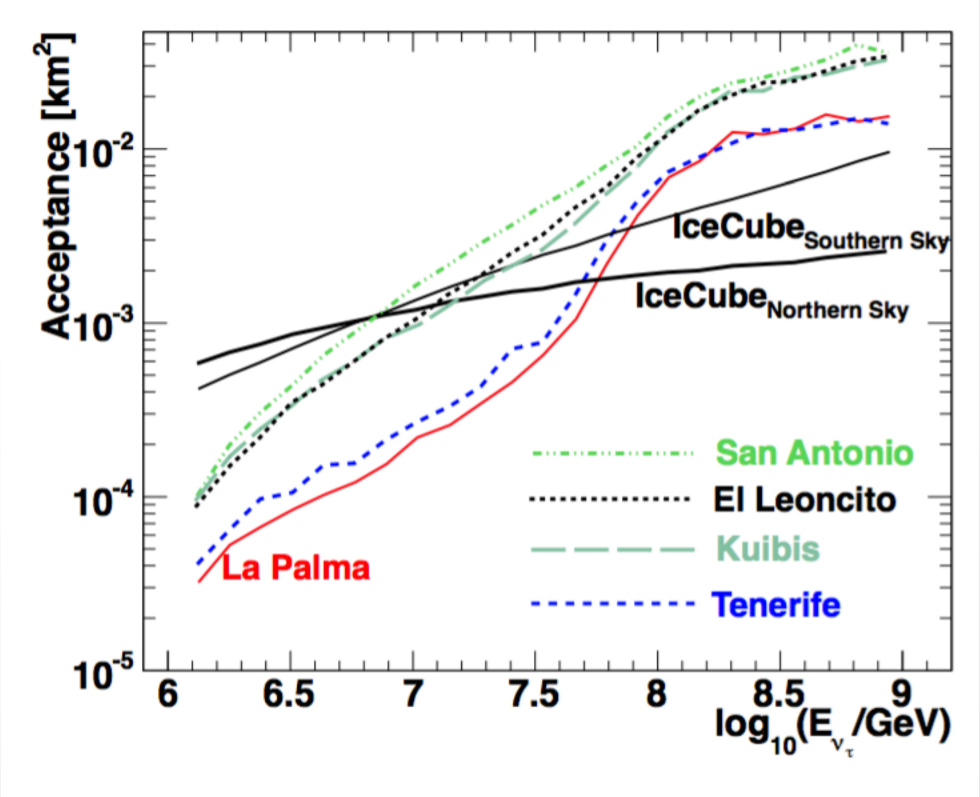
arXiv:1606.01676

Gora, Bernardini



- According to the radiative loss, the tau-lepton can have **multiple signatures in IACT**
  - High energy muons
  - Muon bundles
- MAGIC is able to disentangle the signatures from protons (Gora+ in prep.)

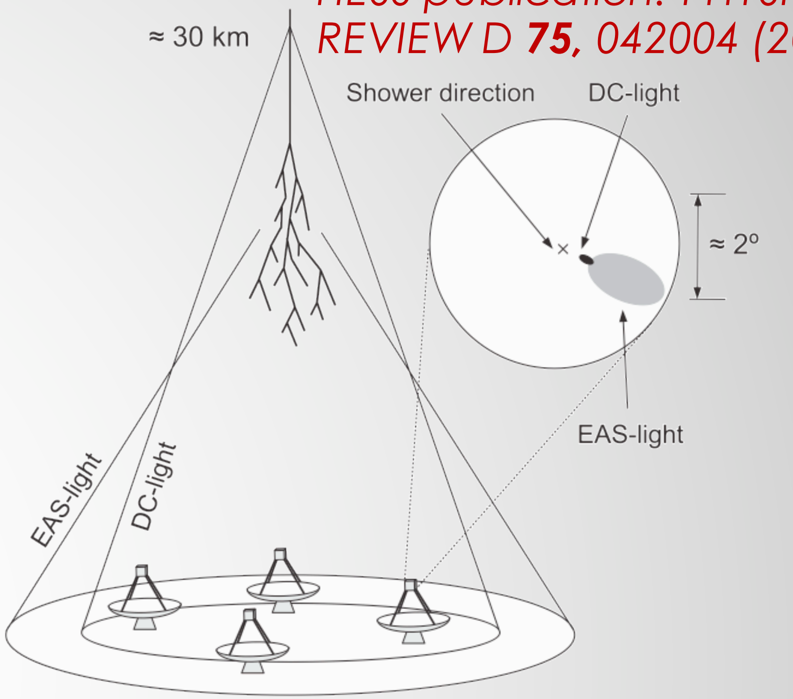
- **IACTs** may have larger **acceptance** than Icecube for short burst (Auger out of scale here)
- Problem due to low flux anyhow, so very few events expected



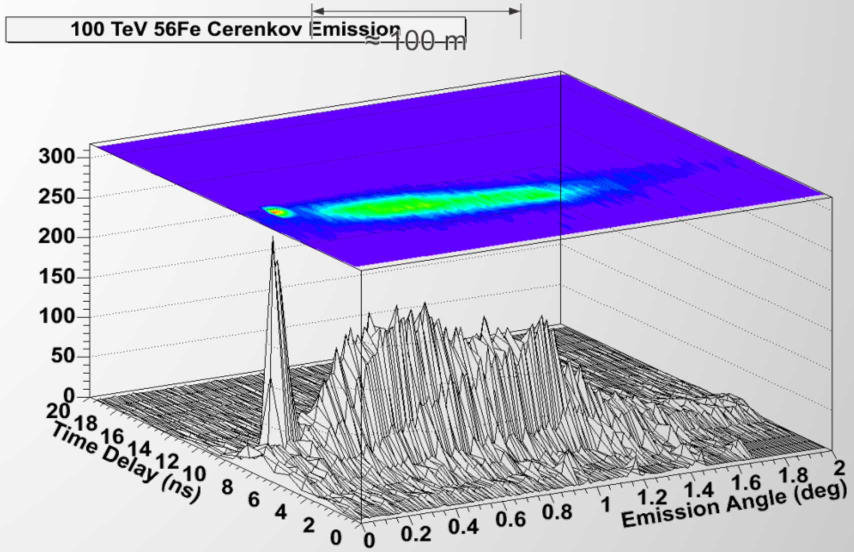
A.N. Cillis,S. J. Sciutto, (astro-ph/0010488) P. Kiraly, M.G. Thompson and A.W. Wolfendale,, Journal of Physics A: General Physics V. 4 Num. 3 (1971) 367.

N2: Iron nuclei

HESS publication: PHYSICAL REVIEW D **75**, 042004 (2007)

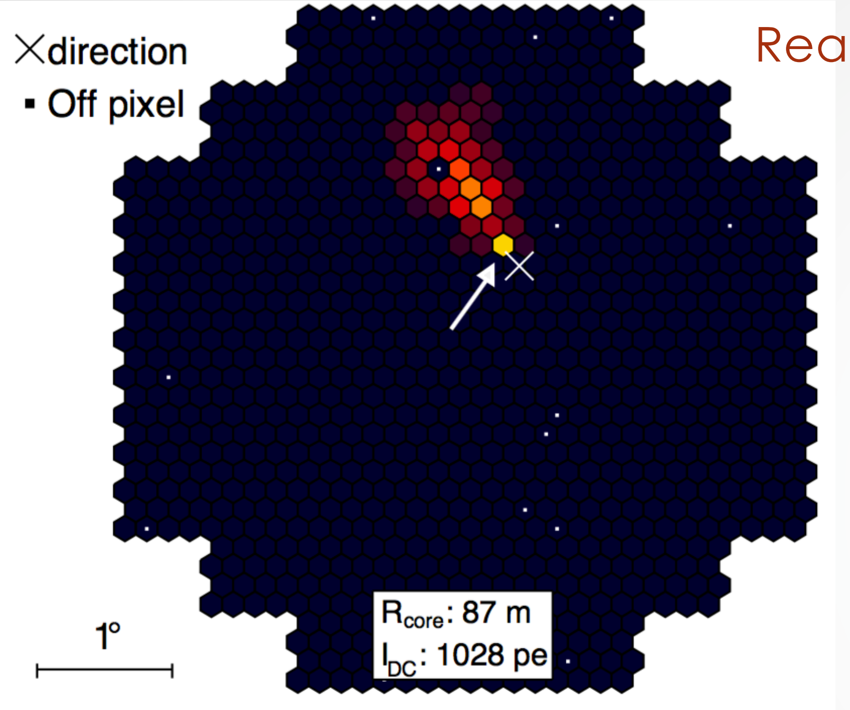


- Cosmic nuclei can emit **Direct Cherenkov** light in the high atmosphere and narrow angle, followed by an EAS
  - Image is double: Prompt Direct Chernekov emission followed by atmospheric showers (delay 3-5 ns)
- Two constraints:
  - $Intensity \propto Z^2$ and Flux decrease with Z
  - Because of their large atomic number and high flux compared to other heavy elements, **iron nuclei** are well suited for DC-light detection.
- Shower image shows saturated peak toward the center of the camera: 1000 phe in 1 pixel



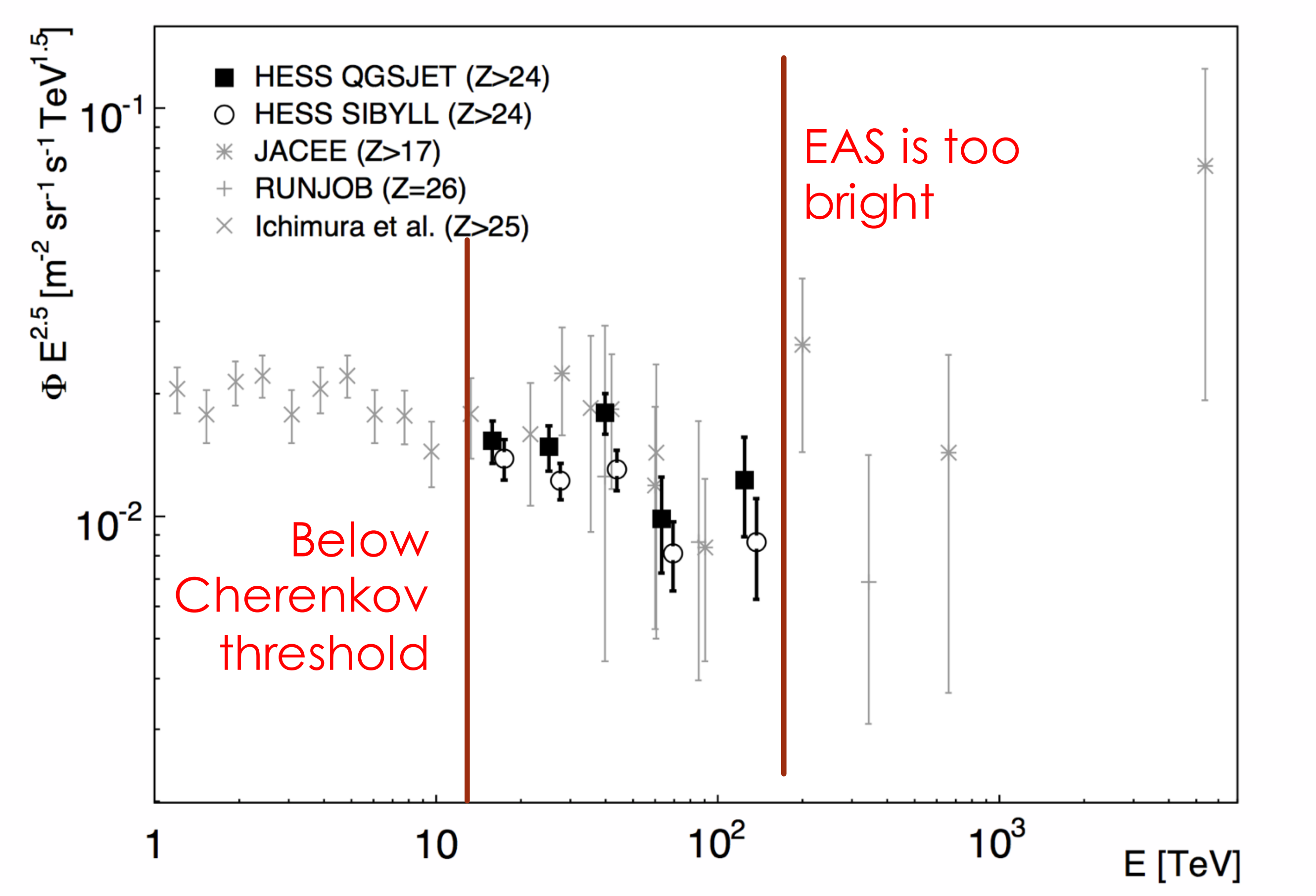
D. B. Kieda, S. P. Swordy, and S. P. Wakely, Astropart. Phys. **15**, 287 (2001).

The needle Iron event



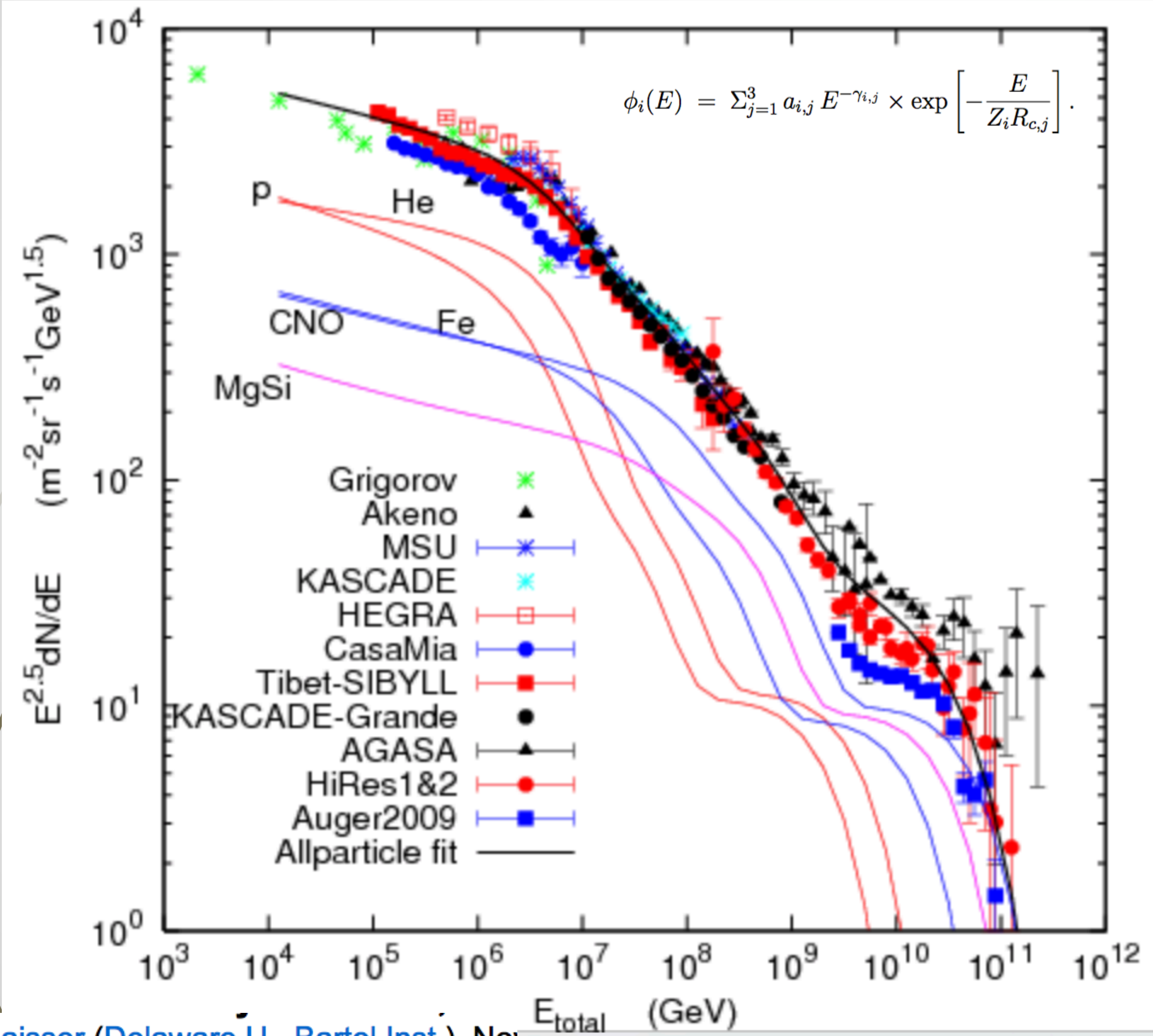
Real HESS event

HESS Coll. PRD 75 (2007) 042004")



- 357 hours of observation time.
- 35364 events passed the selection criteria
- energy range of 13 to 200 TeV

What about CNO, MgSi?

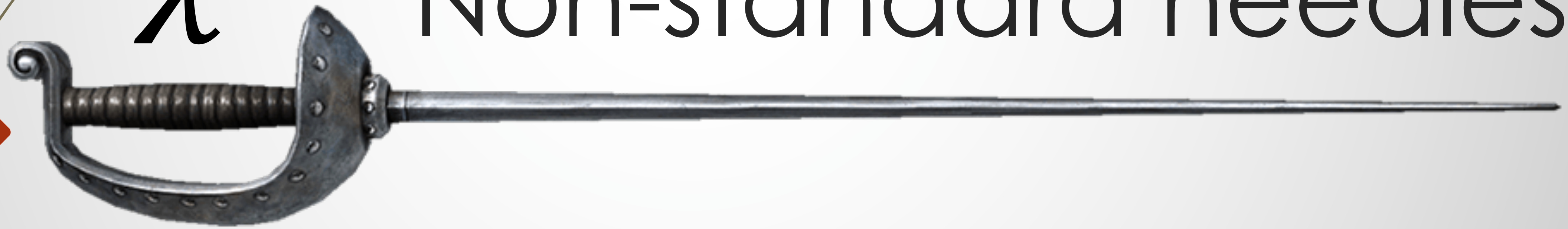


Thomas K. Gaisser (Delaware U., Bartol Inst.). No
Published in **Astropart.Phys. 35 (2012) 801-806**

- **Future improvements** of could extend to 1 PeV on Iron
- MgSi, CNO, could in principle be detectable, although with much lower flux
- **Improved** timing, improved pixelization, better shower reconstruction etc could allow this measurements→**CTA!**

χ

Non-standard needles



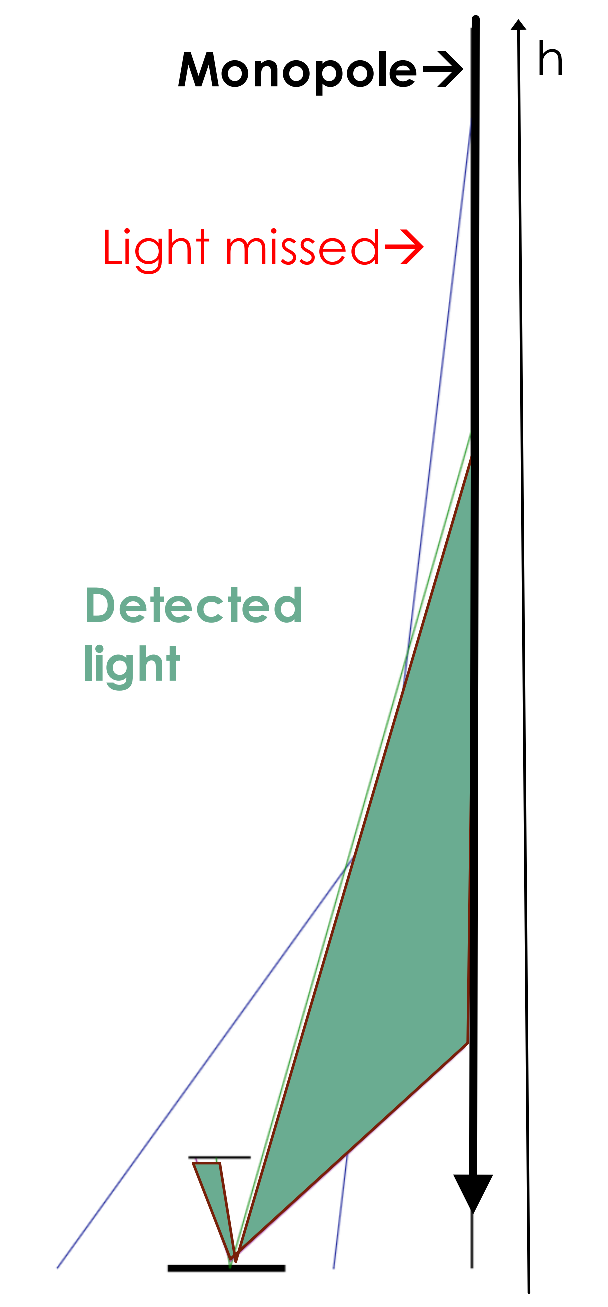
G. Spengler, U. Schwanke, 32 ICRC

N3: Magnetic monopoles

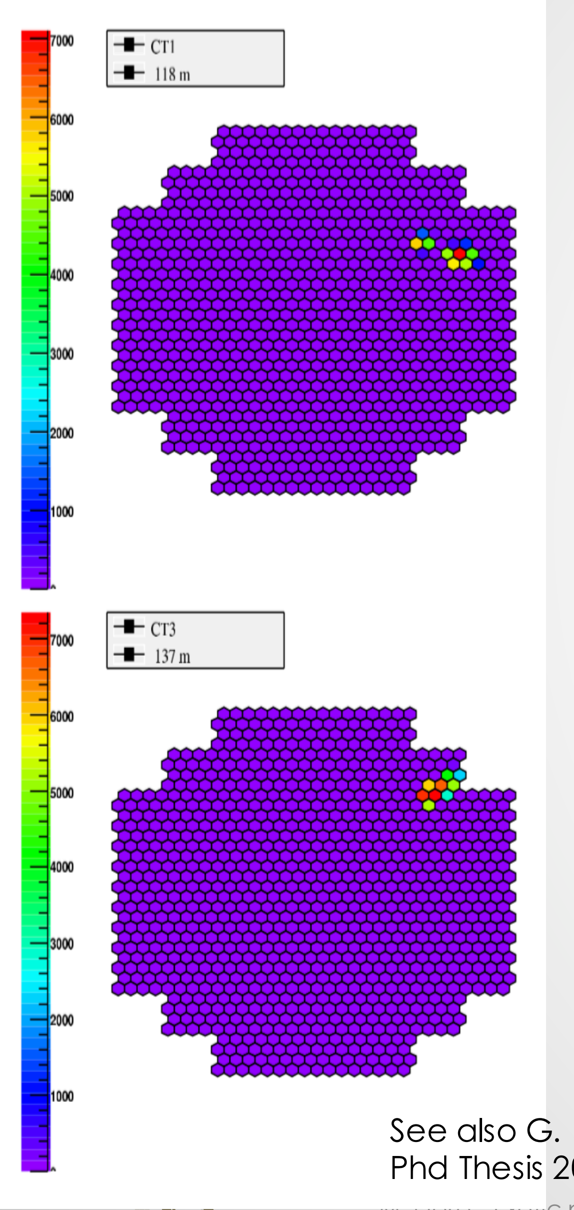
- **In 1931, Dirac** introduced **magnetic monopoles** to explain electric charge quantization. Later on, many theories (specially GUT) predict its existence
- Thomkins predicted that a magnetic monopole will produce **4700 times the Cherenkov light of an electron**, without producing any secondary particle

$$\left.\frac{d^2N}{dxd\lambda}\right|_{\text{Monopole}}^{\text{Air}} \approx 4700 \left.\frac{d^2N}{dxd\lambda}\right|_{\text{Electric}}$$

- Cherenkov emission happens deep in atmosphere and only $\gamma > 10^3$ and $m > 1\,TeV$ can be probed
- Only a fraction of Cherenkov light can be seen

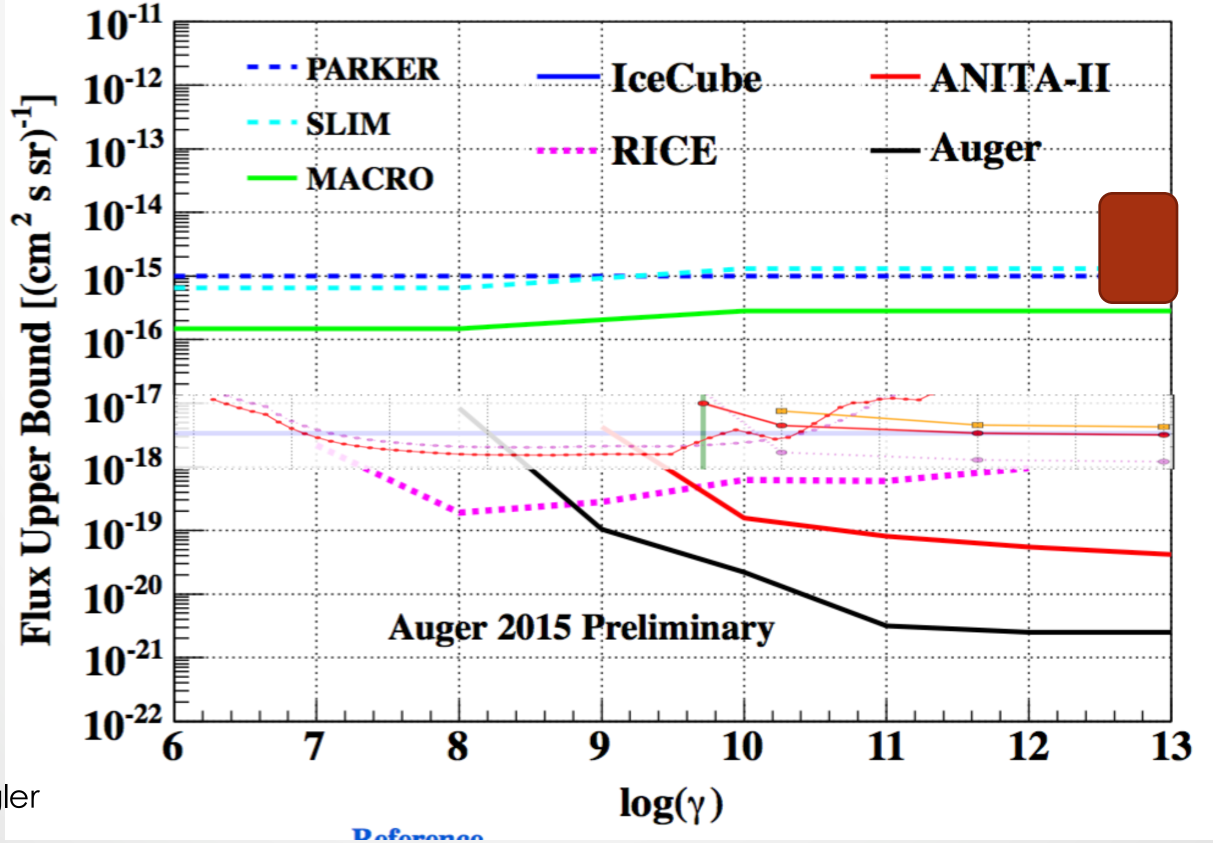


'ctd



See also G. Spengler Phd Thesis 2009

- Several instruments are sensitive
- Sensitivity prospects in gamma-rays are not competitive, but would be independent



← Estimated CTA sensitivity

(MD+ Astroparticle Physics 43 (2013) 189–214)

Fujii, ICRC 2015

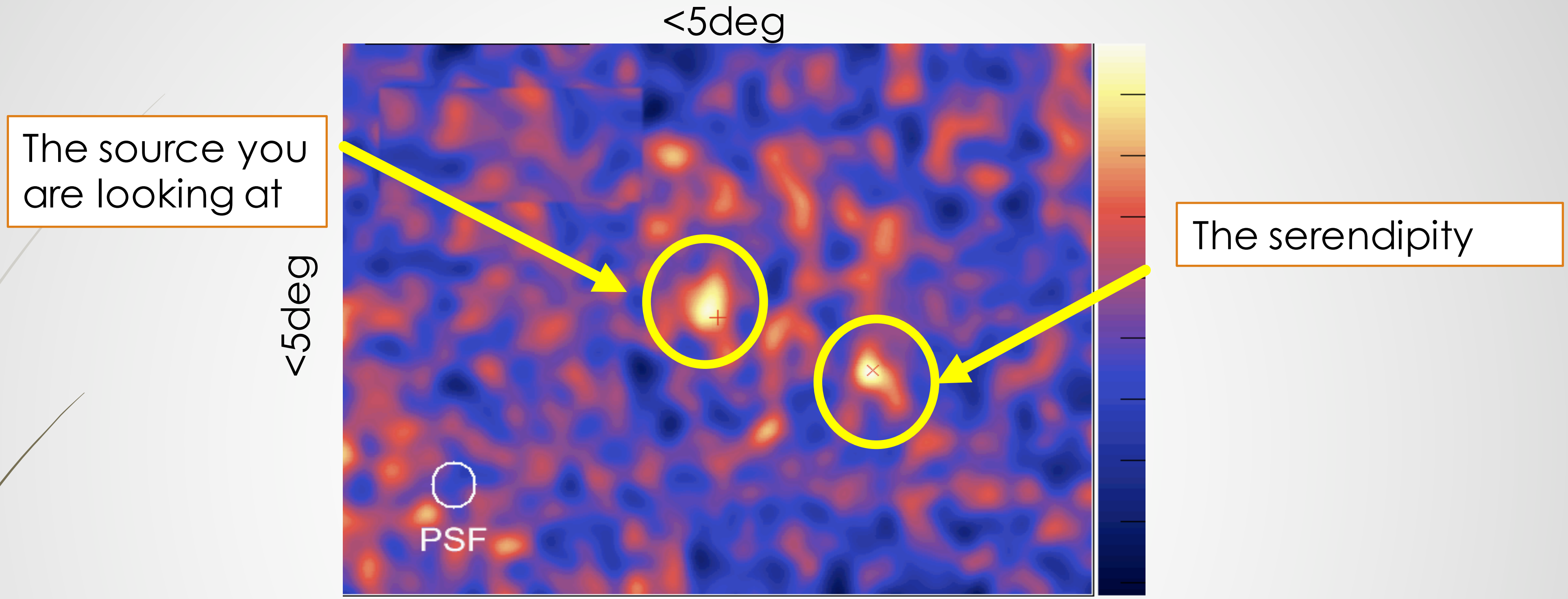
N3: Quark nuggets

Kyle Lawson (British Columbia U.). Nov 2010.
Published in **Phys.Rev. D83 (2011) 103520**

- Quark nuggets are **stable bound states of quarks or antiquarks** generated in the early universe: 10^{20} quarks inside.
- Globally neutral, with expected **charge excess on the surface**: nuggets will be dressed with leptons
- Big and heavy…
- **When crossing the atmosphere**, the energy deposited by annihilations can be quite large : **an extensive air shower will be produced**.
  - K. Lawson 2009-2015 papers+

Some other needles, in the field-of-view

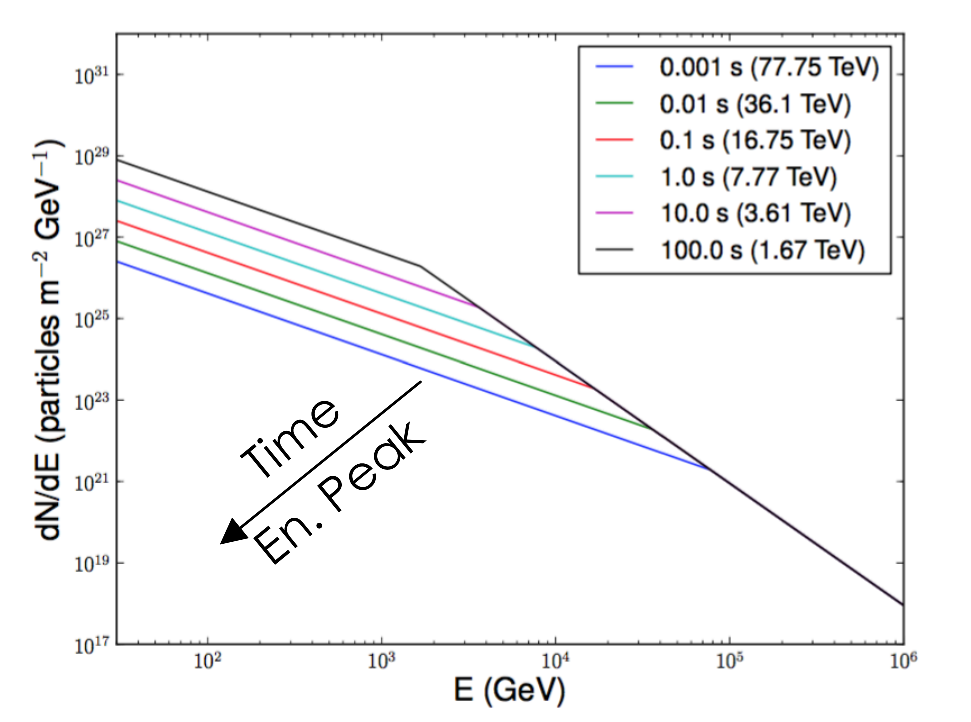
The field of view



- Interesting surprise could as (**brief) bursts in the FOV** of the telescopes: $< 5x5\ \mathrm{deg}^2$
- If they are very bright, they are detected by-eye, if faint or short-lived, **they need a dedicated analysis**

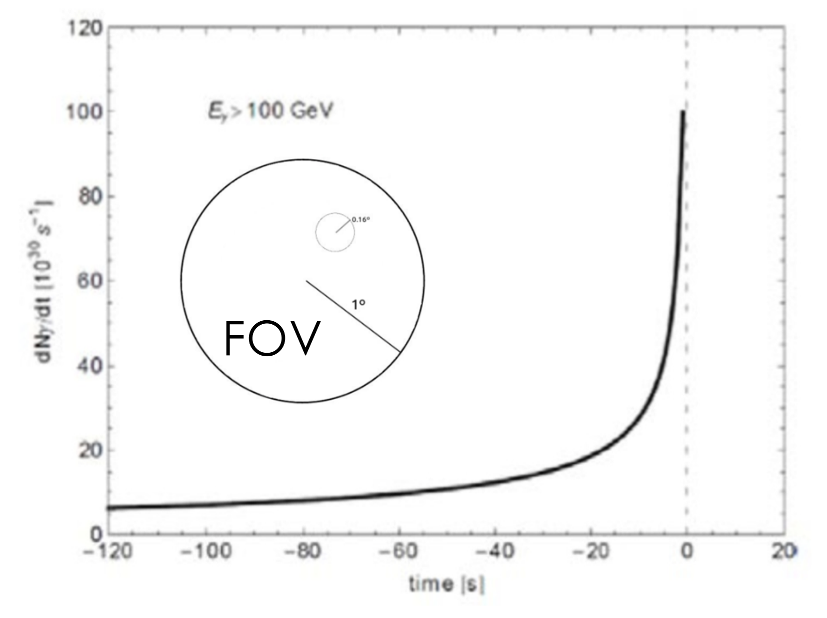
N4: Evaporating PBH

- Formed in the early Universe, because of the Hawing radiation, those with a specific mass could be evaporating today
  - Brief bursts of gamma rays (similar to short GRBs)



- ← Gamma-ray spectrum for various PBH remaining lifetimes ranging from 0.001 s to 100 s.

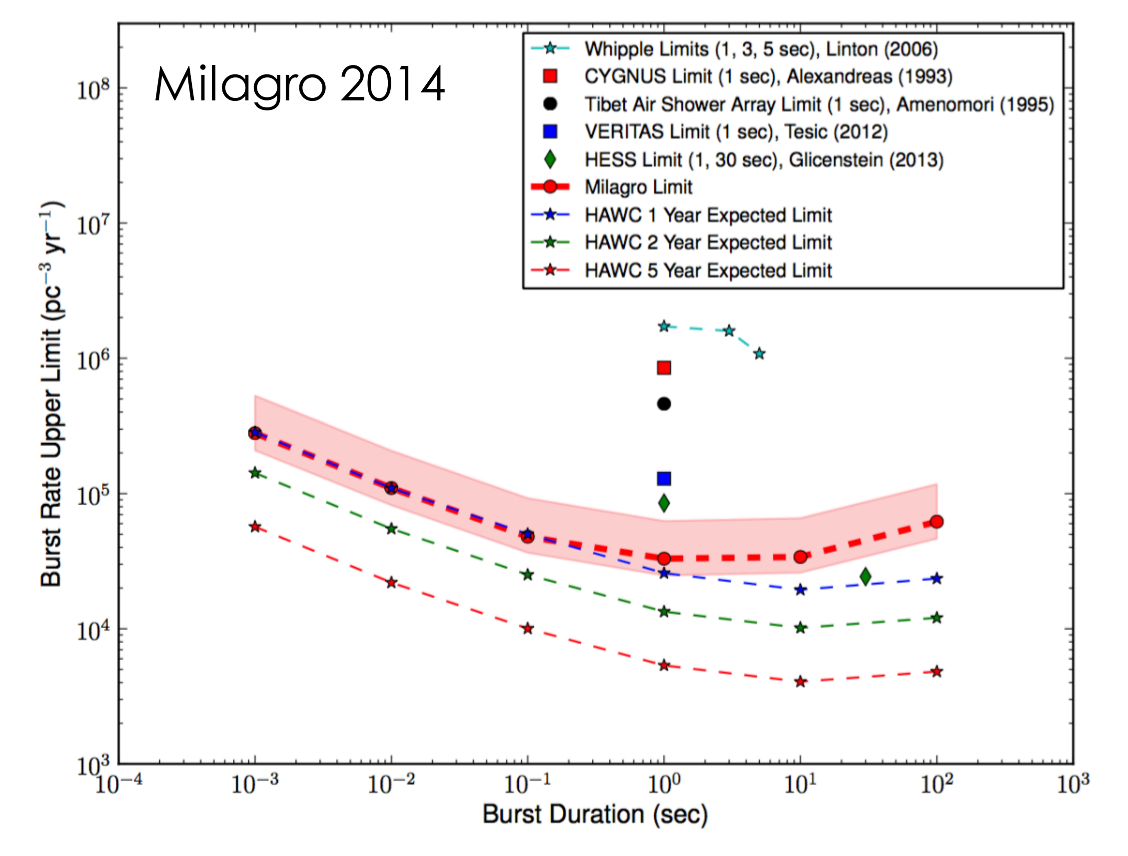
- → Short Bursting signal anywhere in the FOV



V. B. Petkov et al., Astronomy Letters, vol. 34, pp. 509–514, Aug. 2008; Abdo et al. Astroparticle Physics, Volume 64, p. 4-12. 2015

MacGibbon, PRD44, 991.

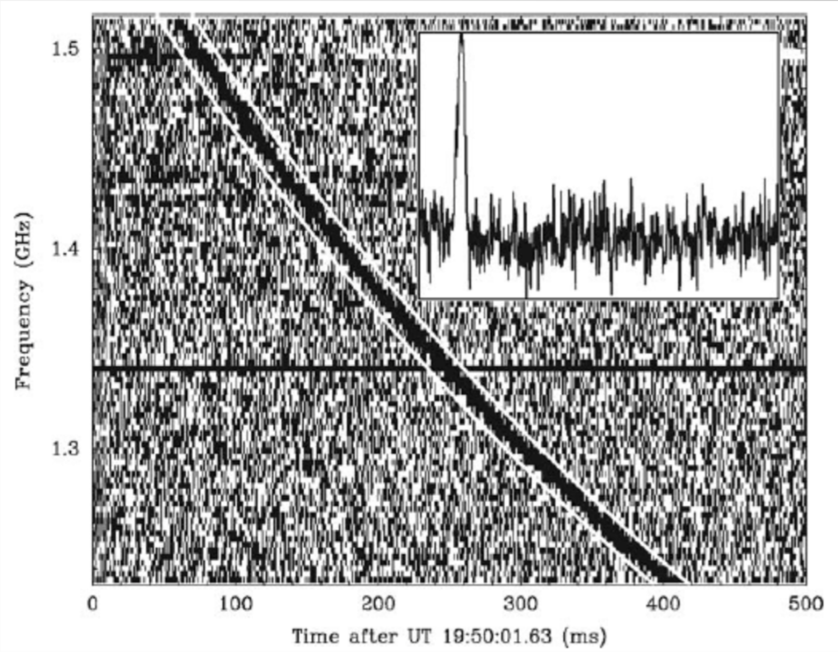
- A dedicated search for short burst anywhere in the FOV can provide a serendipity detection
- Upper limits are given in PBH density exploion rate $(pc^3 y^{-1})$



- Currently most sensitivite searches $(\sim 10^5 pc^3 y^{-1})$ are performed with Milagro and HAWC
- **CTA is competitive** because of the enhanced sensitivity to transients

N5: Fast Radio Bursts (FRBs)

- In 2007 (*analyzing archival data!*) Lorimer discovered a radio burst at 1 GHz with
  - Duration below 1ms
  - Time dispersion
- ..now a catalog of **17 FRBs** is public online
- The **dispersion measurement** provide clues to **distance**: they are likely **extragalactic**
- Association/Nature:
  - FRBs are seen to repeat from the same target! Cannot be a destroying event
  - No clear counterparts at other wl
  - Small size (stellar BH)

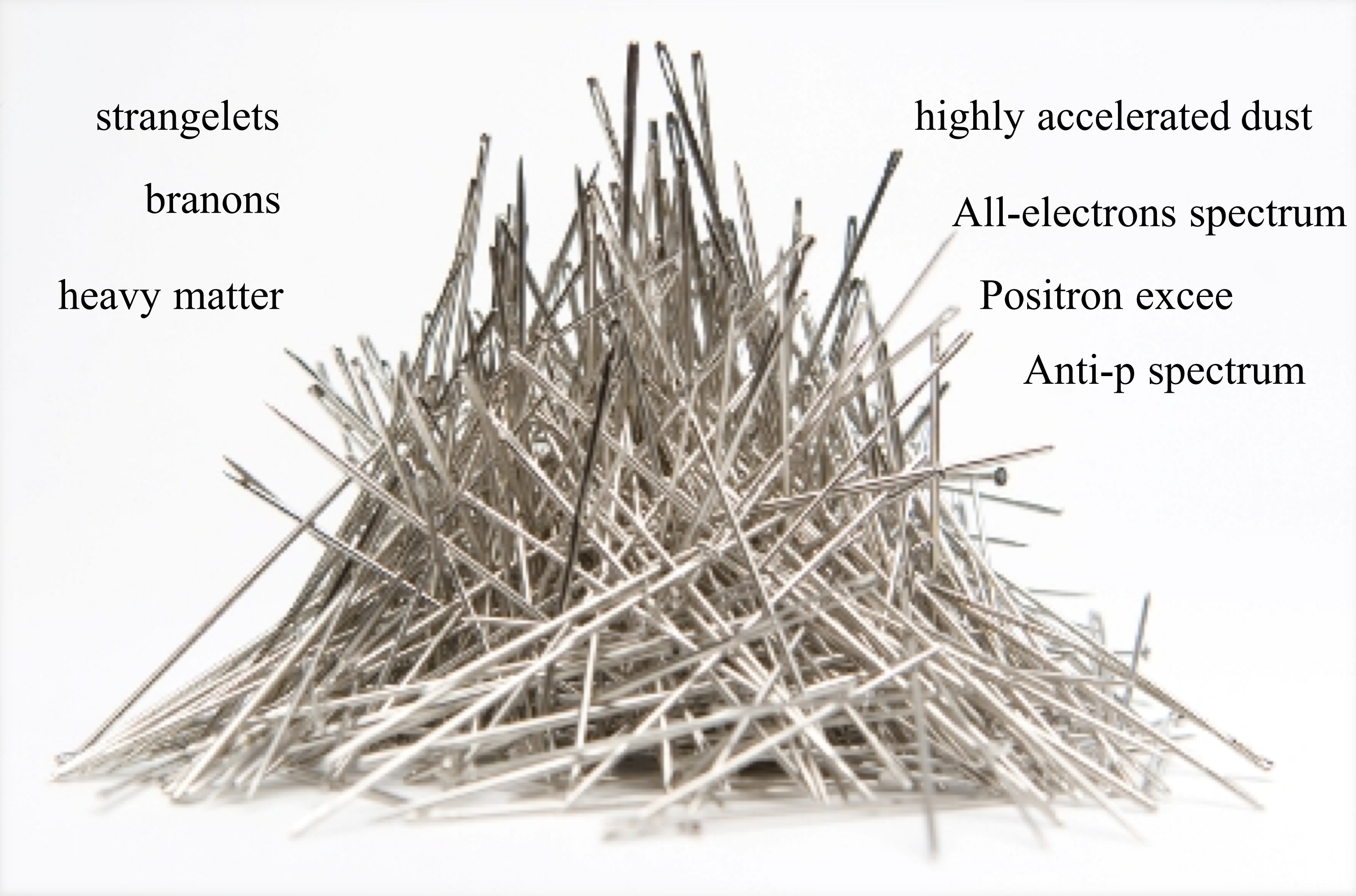


VHE emission if FRBs are associated to magnetar-like sources. → serendipitous events in the FOV?

Murase 2016

And and and…

- Of course there's more

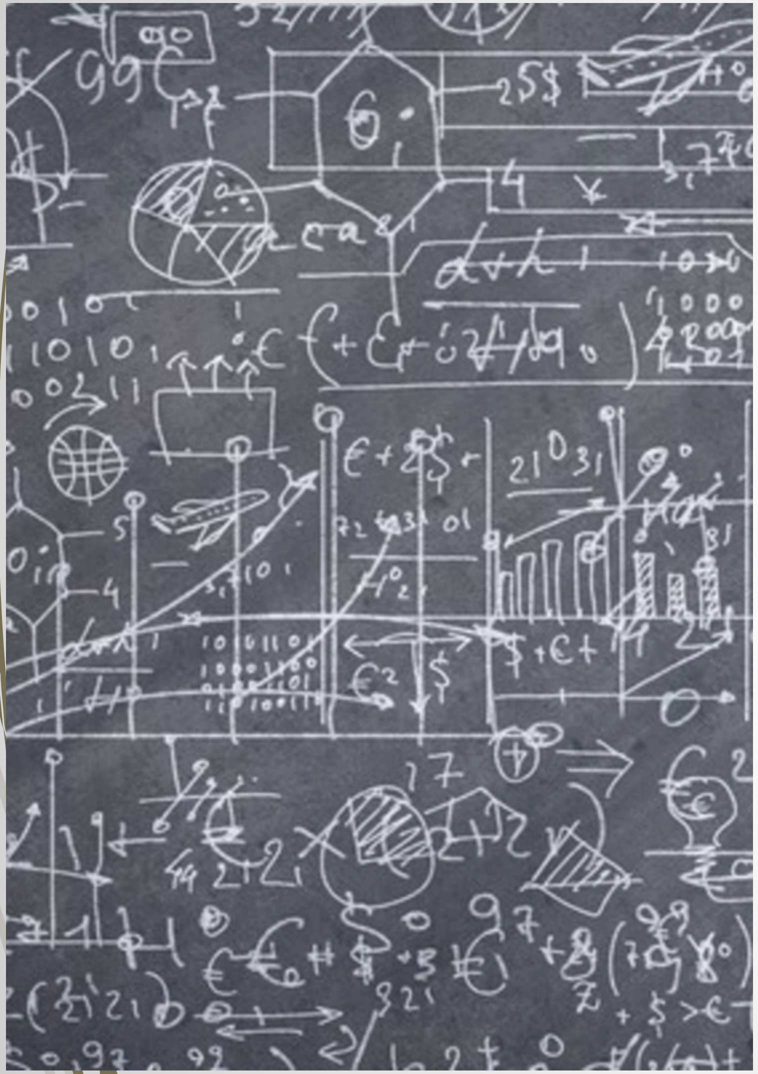


WHAT ARE THE CHALLENGES THEN?

What's good

- You may have realized that in many cases, we don't need to **point the telescope**, just run a **careful check on data**:
  - Peculiar images
  - Peculiar temporal structure
  - Objects in the FOV

What's hard



- **Preparing the model** is complex
  - Huge theoretical uncertainties
  - Complex implementation of MC codes
- Adaptation of **analyses methods** sometimes not trivial
- Faint and rare signal should anyhow be searched for above the **systematics** and are to get sufficient S/N.
- IACTs are not exactly counting experiment…hard to address **single events**
- After convincing yourself, you should also *convince the community…*

What's even harder

- Often are **long-term** projects.
- Phd does not want to make them…

Conclusions

Can be a long journey to discovery

- The bus that Bruno Rossi set-up to carry the experimental equipment to measure Cosmic Rays to the summit of Mount Evans in Colorado (4,348 m).
- *He brought his family too!*

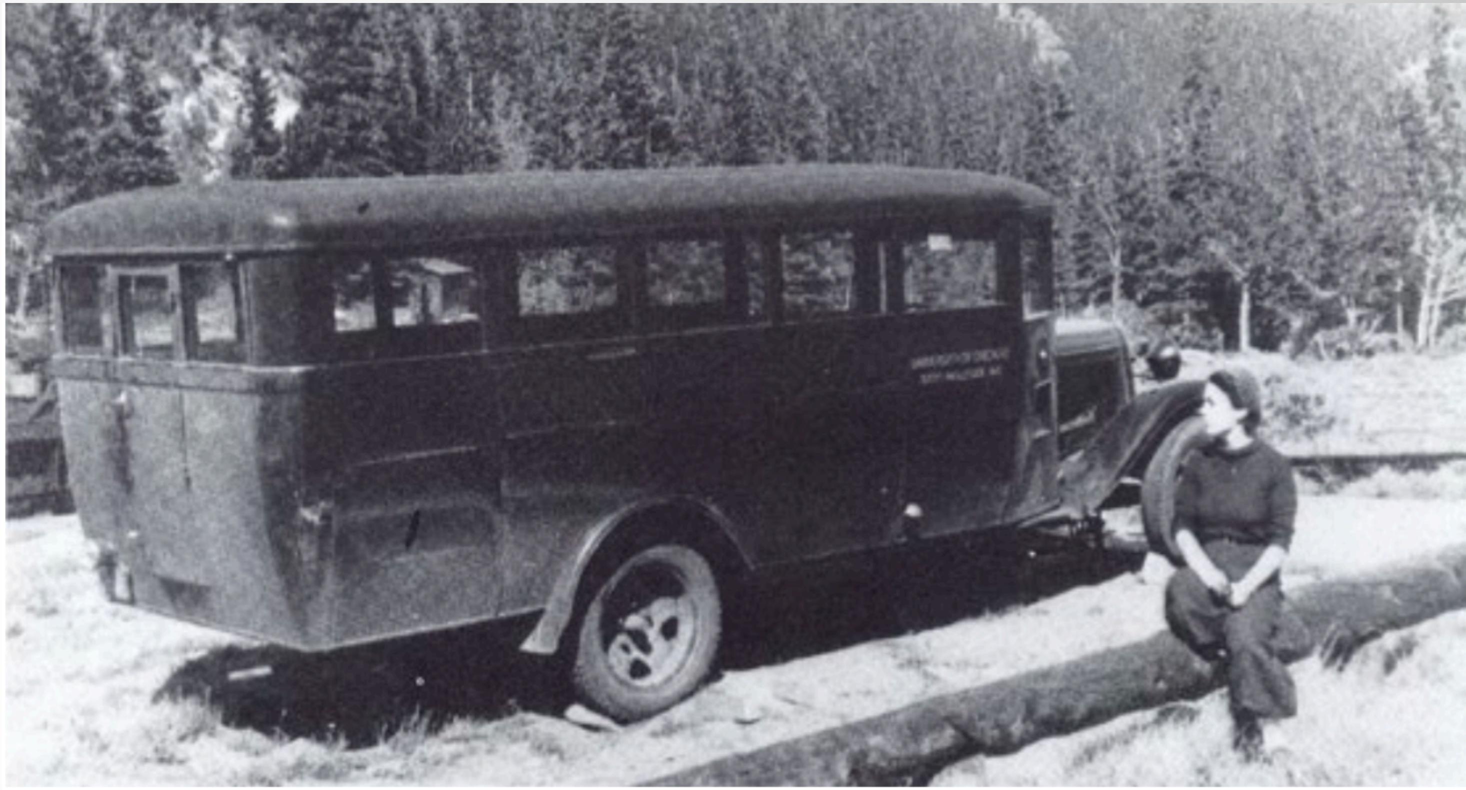


Figure 3. The bus equipped for the measurements at different altitudes up to the summit of Mount Evans. Here at Echo Lake, 1939, together with Nora Rossi (reproduced from B. Rossi, *Moments in the Life of a Scientist*, Cambridge University Press, New York 1990).

Conclusions

- We should not forget that for each photon we save on disk, we also save a lot of background data.
- We should prepare the data analysis to look **for these elusive events**
- All in all, we are looking at the most violent Universe

- **Need to find the right idea to find the needles!**

Thanks!

Backups

CTA

- CTA will have a N-hemisphere site and a S-hemisphere site. About 100 telescopes.
- CTA will see more, better showers → very good
- However, the data-mill will be too large. CTA will need to delete hadronic background events → clever algorithm should be envisaged to make rare events survive