Exotic needles in the gamma-ray haystack

Michele Doro
University and INFN Padova
michele.doro@pd.infn.it

RICAP Conference, Rome, 2016
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

- **Big**
  - 14 orders of magnitude in energy
  - 10 orders of magnitude in flux, from many/cm²/s to few/km²/century

- **How many mysteries 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?

---

arXiv:0911.3034 H.Hu
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
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: \(8 \text{h} \times 3600 \text{s} \times 200 = 5.76 \text{MEvents}\)
  - One month: \(27 \text{days} \times 5 \text{h} \times 3600 \text{s} \times 200 = 97.2 \text{MEvents}\)
  - 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)
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

GW150914

Really? No...
Astronomical targets in our TeV sky

- 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

Galactic targets

Extragalactic targets

- Pulsar
- Supernova Remnants
- Pulsar wind nebulae
- Micro-quasars
- Galactic center

- Active Galactic Nuclei
- Galaxy Cluster
- Starburst galaxies
- Merging Galaxies
- Gamma-ray Bursts
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+

\[ \text{Astropart.Phys. 26 (2007) 402-413} \]

---

E. Zas, New J.Phys. 7, 130
Portraits of tau-neutrinos

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
**N2: Iron nuclei**

- Cosmic nuclei can emit **Direct Cherenkov light** in the high atmosphere and narrow angle, followed by an EAS
  - Image is double: Prompt Direct Cherenkov 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

M. Doro - Exotic needles in the gamma-ray haystack - RICAP 2016

The needle Iron event

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

Real HESS event

EAS is too bright

Below Cherenkov threshold

HESS Coll. PRD 75 (2007) 042004’’

M. Doro - Exotic needles in the gamma-ray haystack - RICAP 2016
What about CNO, MgSi?

- **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!
Non-standard needles
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.

Cherenkov emission happens deep in atmosphere and only $\gamma > 10^3$ and $m > 1 \text{ TeV}$ can be probed.

Only a fraction of Cherenkov light can be seen.
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)

See also G. Spengler Phd Thesis 2009

Fujii, ICRC 2015
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: $< 5 \times 5 \text{ deg}^2$
- If they are very bright, they are detected by-eye, if faint or short-lived, they *need a dedicated analysis*
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)

\[ \text{Gamma-ray spectrum for various PBH remaining lifetimes ranging from 0.001 s to 100 s.} \]

\[ \text{Short Bursting signal anywhere in the FOV} \]


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 explosion rate \((pc^3 y^{-1})\)

Currently most sensitive searches (\(\sim 10^5 pc^3 y^{-1}\)) are performed with Milagro and HAWC

**CTA is competitive** because of the enhanced sensitivity to transients
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

- strangelets
- branons
- heavy matter
- highly accelerated dust
- All-electrons spectrum
- Positron exceed
- Anti-p spectrum
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 will have a N-hemisphere site and a S-hemisphere site. About 100 telescopes.

CTA will see more, better showers \(\rightarrow\) very good

However, the data-mill will be too large. CTA will need to delete hadronic background events \(\rightarrow\) clever algorithm should be envisaged to make rare events survive