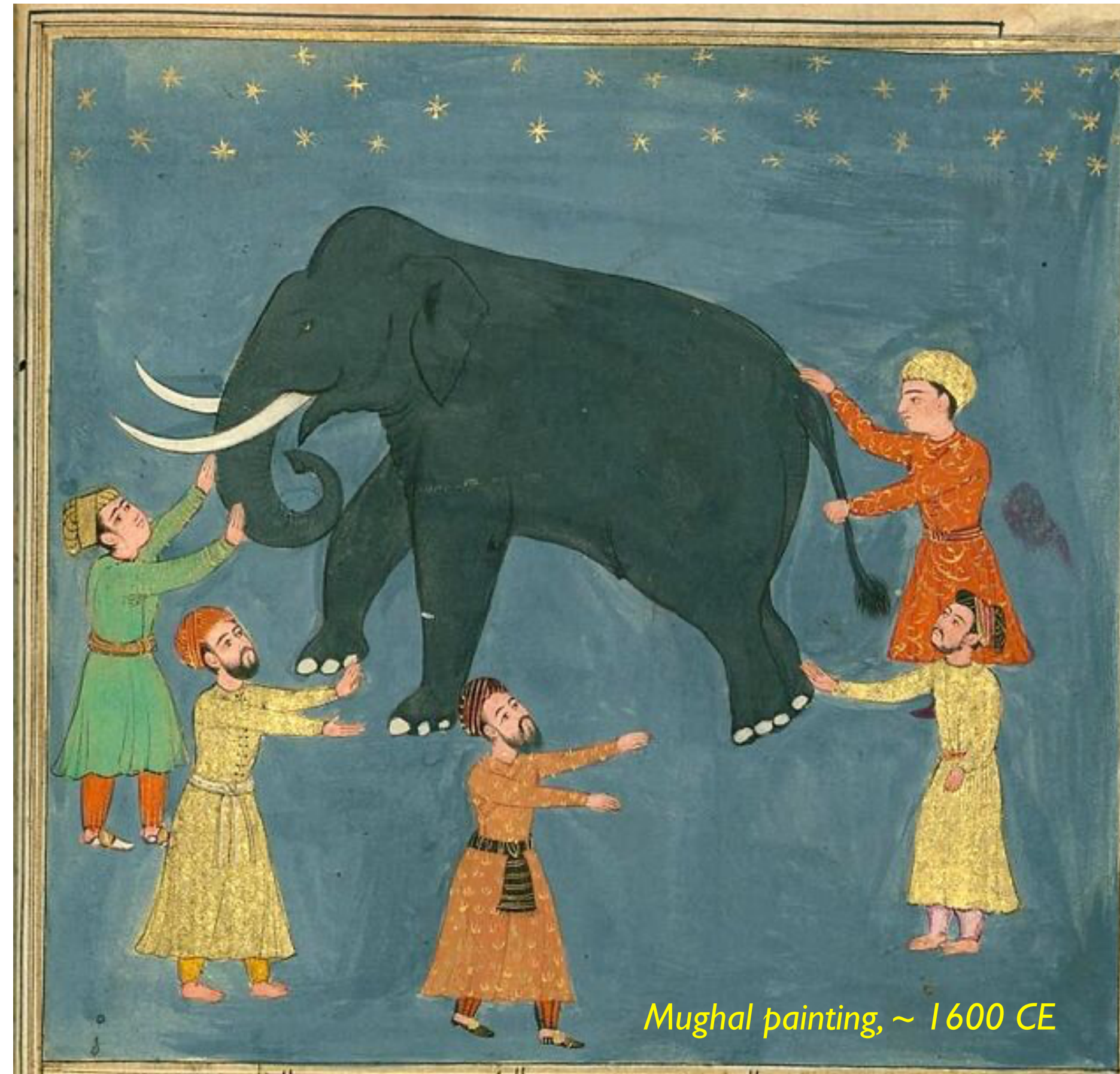


# ENIGMASS - WP 2

## GRAVITATIONAL WAVES AND MULTI-MESSENGER ASTROPHYSICS

(Virgo, HESS-CTA, AMS-02, Auger, Theory)

**Executive Summary**



Pasquale Dario Serpico (LAPTh)

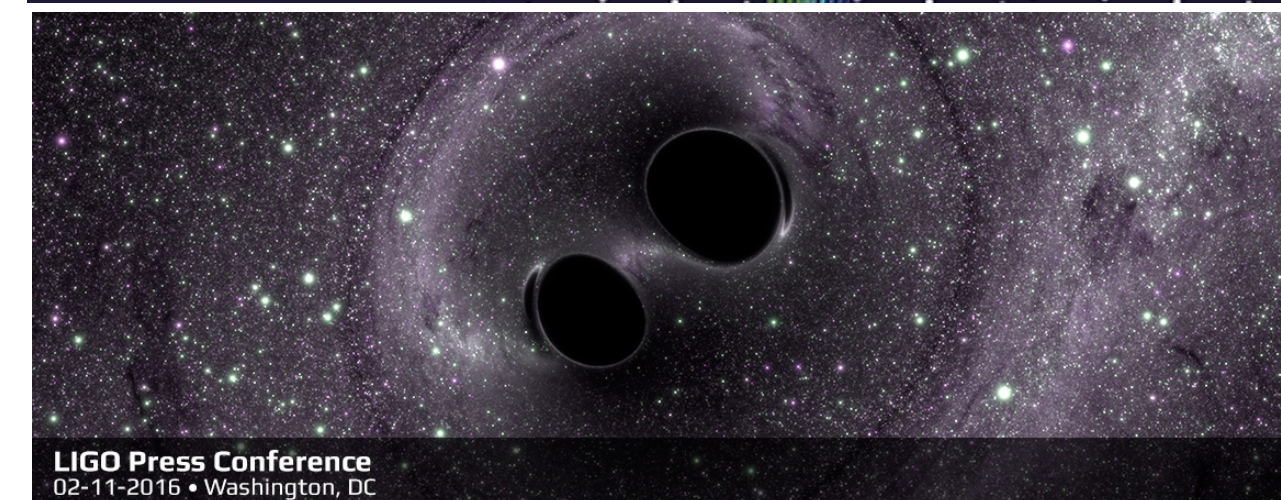
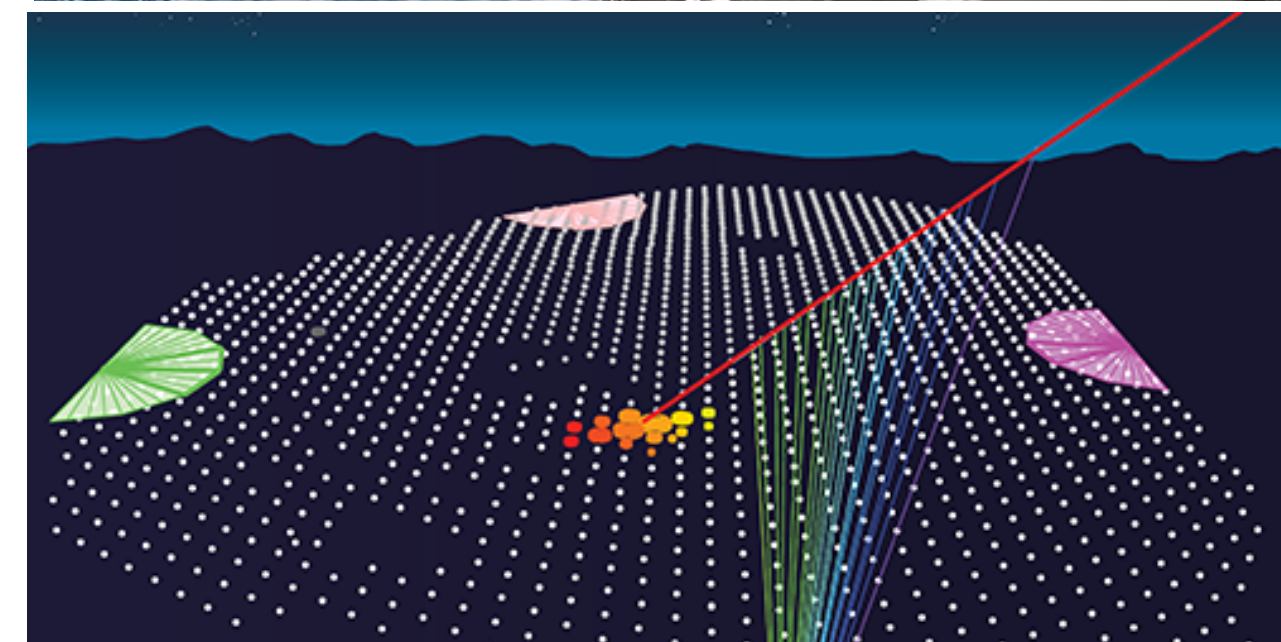
+ contributions by C. Bérat, F. Calore, L. Derome, D. Maurin, T. Regimbau, L. Rolland, D. Sanchez

# Astronomy revolutions in the XXth & XXIth century

## Looking at the sky beyond the limitation of the visible photon band

- ▶ ~1930's : Radio astronomy
- ▶ >1911: Extraterrestrial nature of cosmic rays
- ▶ >1934: Indirect (air shower) techniques
- ▶ >1957: Space Era (essential for atmospheric opacity)
- ▶ >1960's MeV Neutrinos as astrophysical messengers (Sun, SN 1987A)
- ▶ >1970's Cherenkov technique for gamma-ray showers (Whipple...HEGRA...)
- ▶ >2000 "Mature" CR direct & indirect probes, with high statistics & redundancy
- ▶ Beginning of high-energy neutrino astrophysics (IceCube >2012)
- ▶ Beginning of gravitational wave astrophysics (>2015)

**Multiwavel.-messenger: added value of combining different channels**



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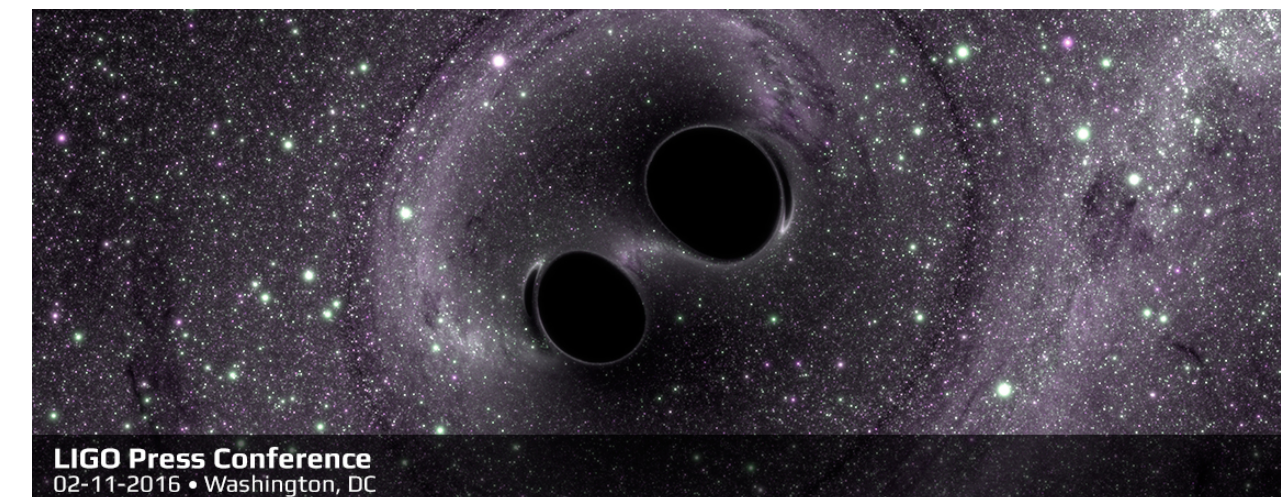
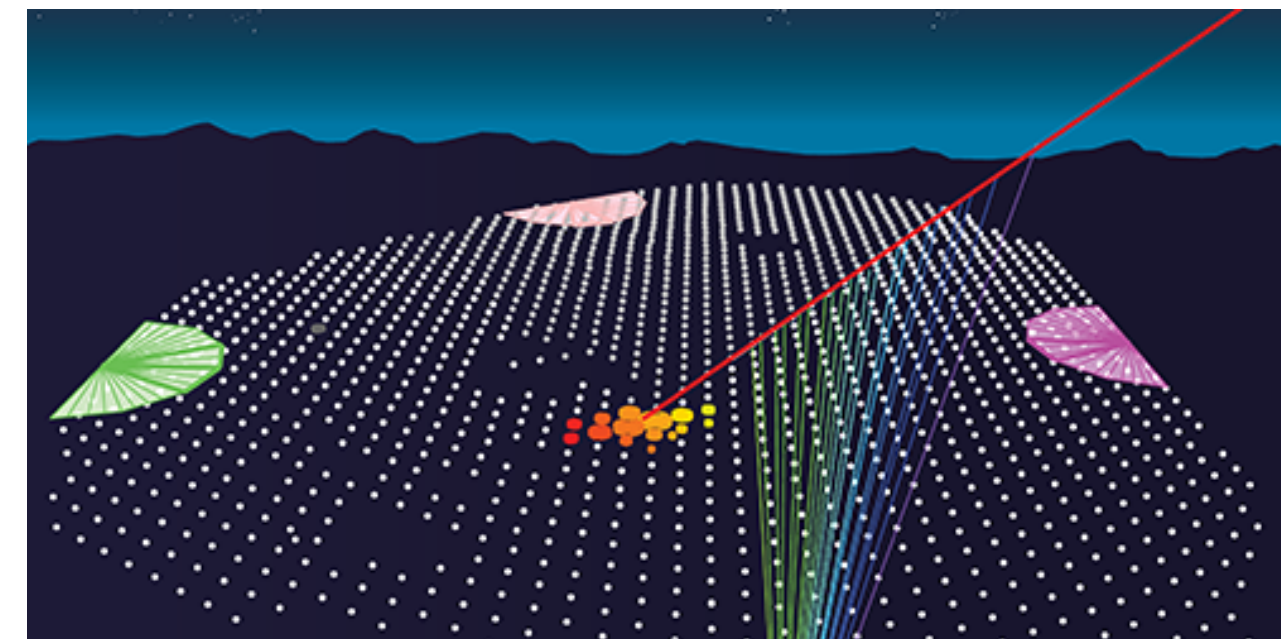
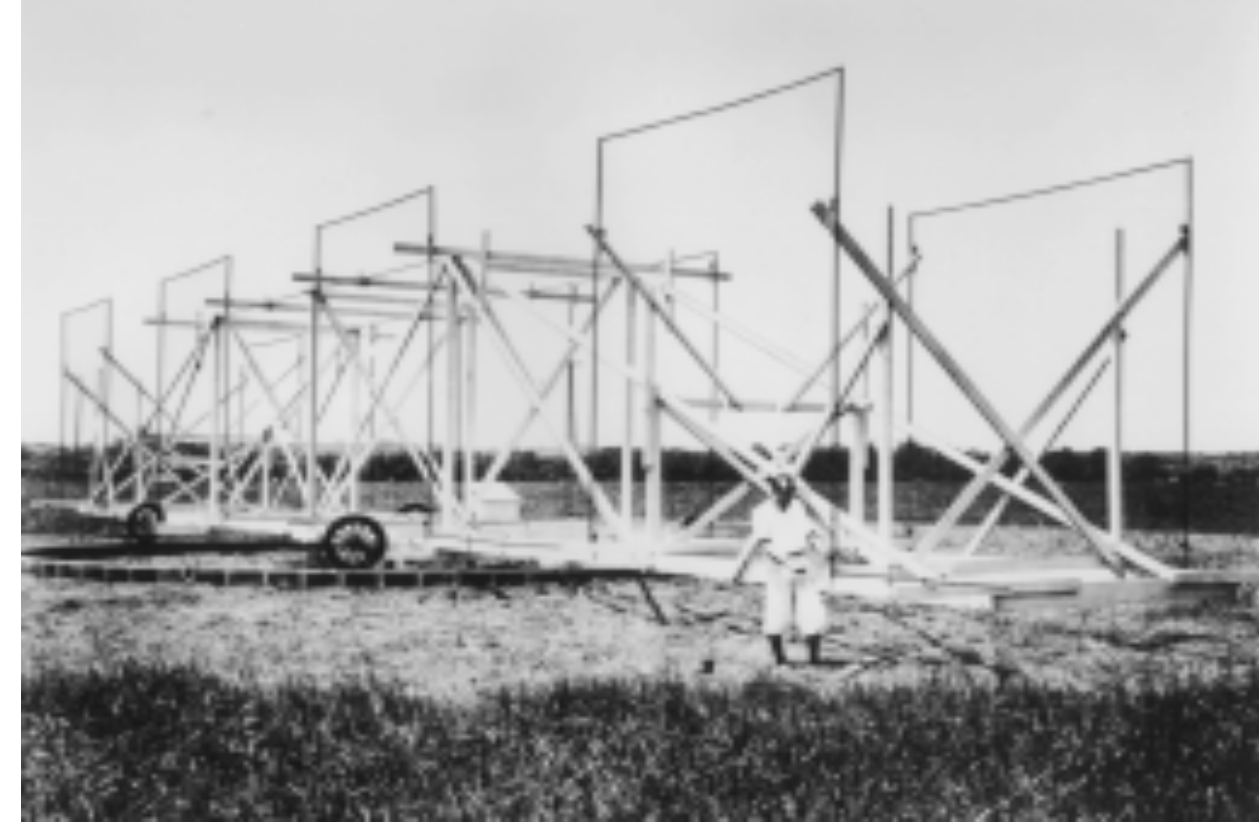
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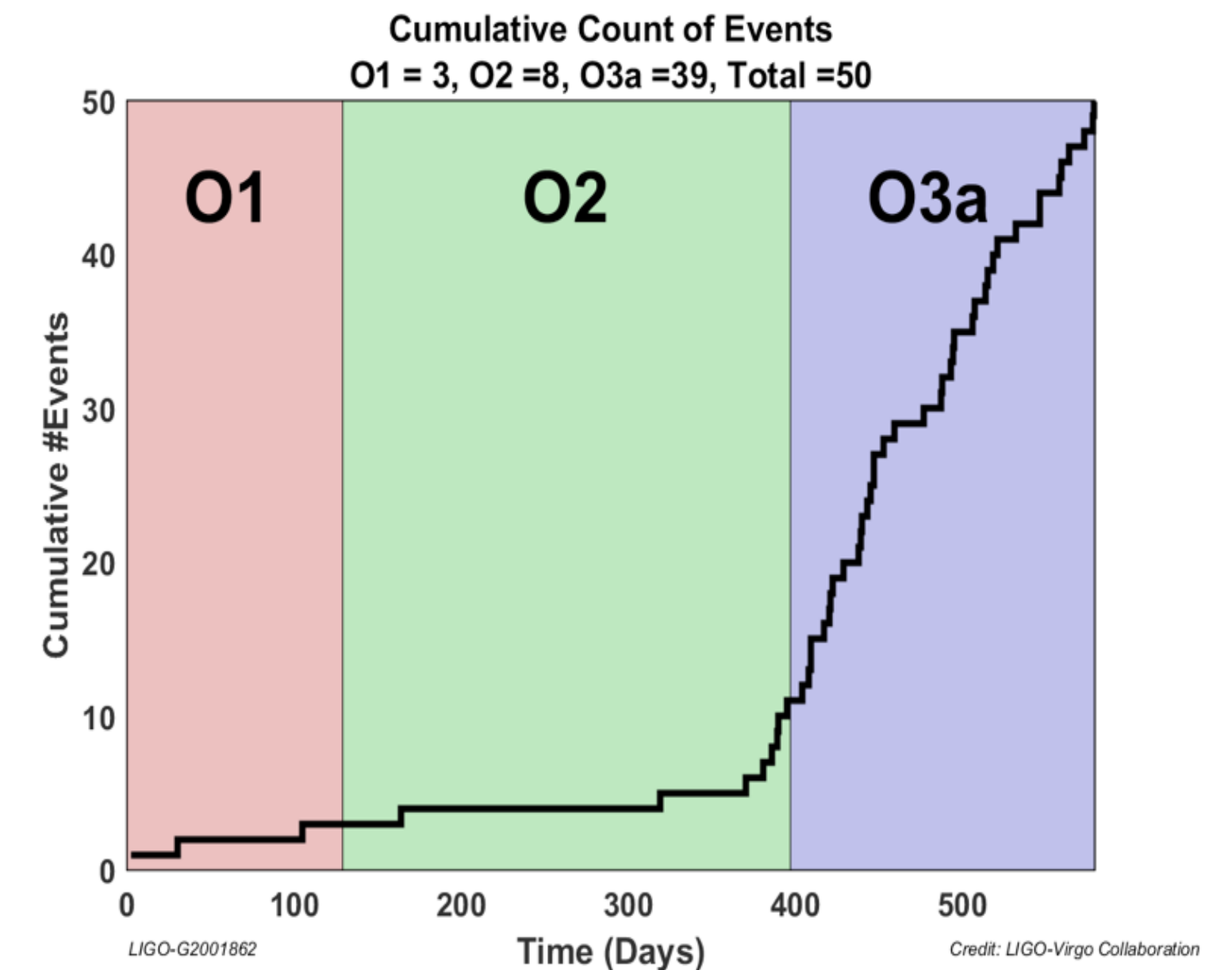
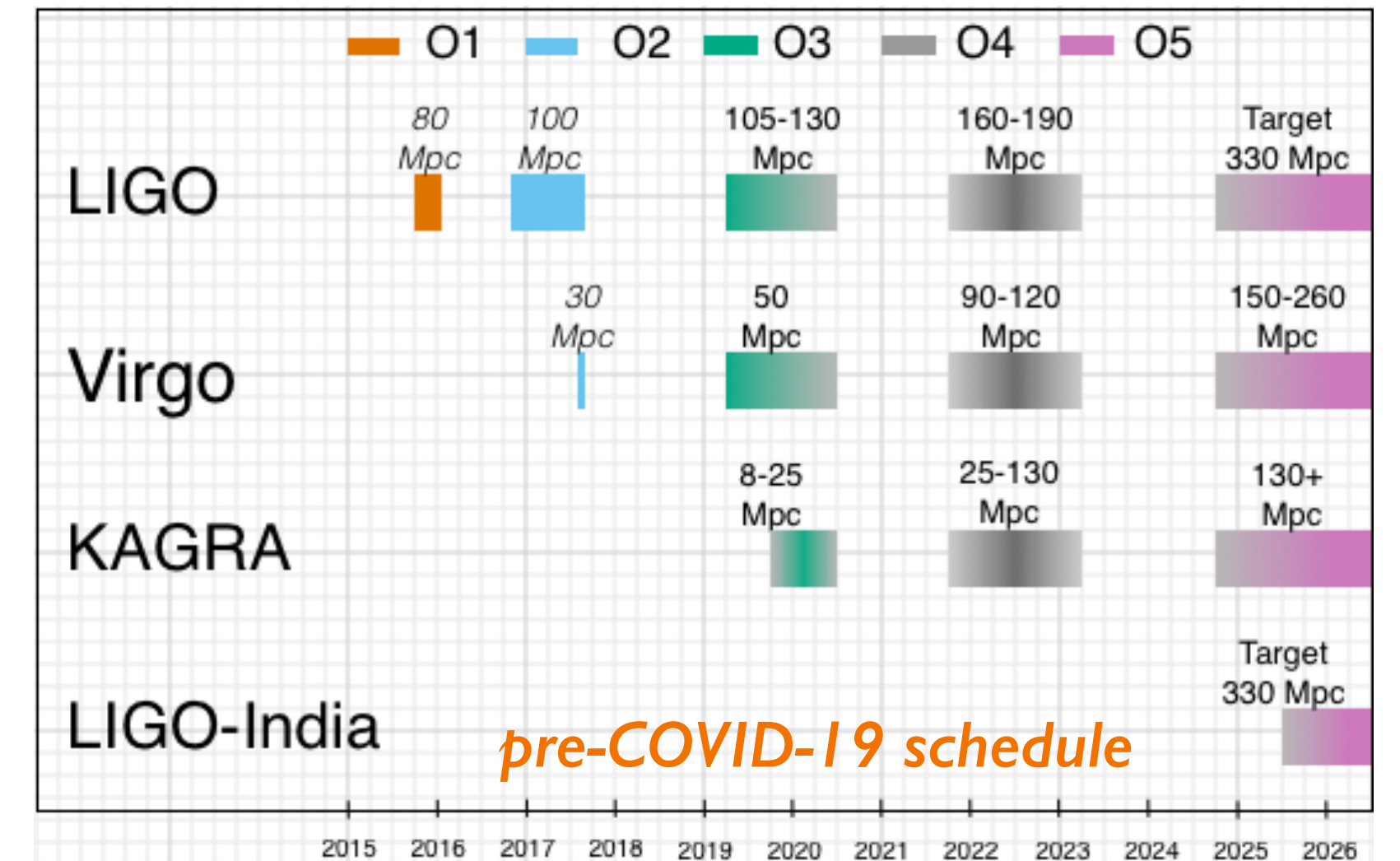
## Enigmass WP 2's activities fit in this broader context and concern:

- Virgo @ LAPP
- Pierre Auger Observatory @ LSPC
- HESS/CTA @ LAPP
- AMS-02 @ LPSC
- Some interdisciplinary topics (e.g. transients)
- Theoretical and phenomenological analyses (LAPTh, LAPP, LPSC)



# LIGO/Virgo:O3 News

- steep increase in event rate in O3a due to the hard work between O2 and O3 to upgrade the detectors.
- detection of 39 candidates in O3a consistent with merger rate inferred from O1+O2.
- Second GW catalog (O1+O2+O3a): 50 events
  - ▶ O1 (4 months): 3 BBHs
  - ▶ O2 (8 m.): 7 BBHs and 1 BNS
  - ▶ O3a (6 m.): 36 BBHs, 1 BNS, 2 BH + lighter object



- BBHs with large mass asymmetry (radiation beyond main quadrupolar order, tests of General Relativity)
- Object of  $\sim 2.5-3 M_{\odot}$  : either heaviest NS or lightest BH!
- Black hole of  $85 M_{\odot}$  : « forbidden » mass (pair instability)
- $M_{\text{fin}} = 142 M_{\odot}$  : intermediate mass black hole

# Synoptic view of LAPP activities in Virgo: towards better sensitivity and precision for GW analyses

Optical benches and sensors

Output mode-cleaner cavities

Injection of squeezed light

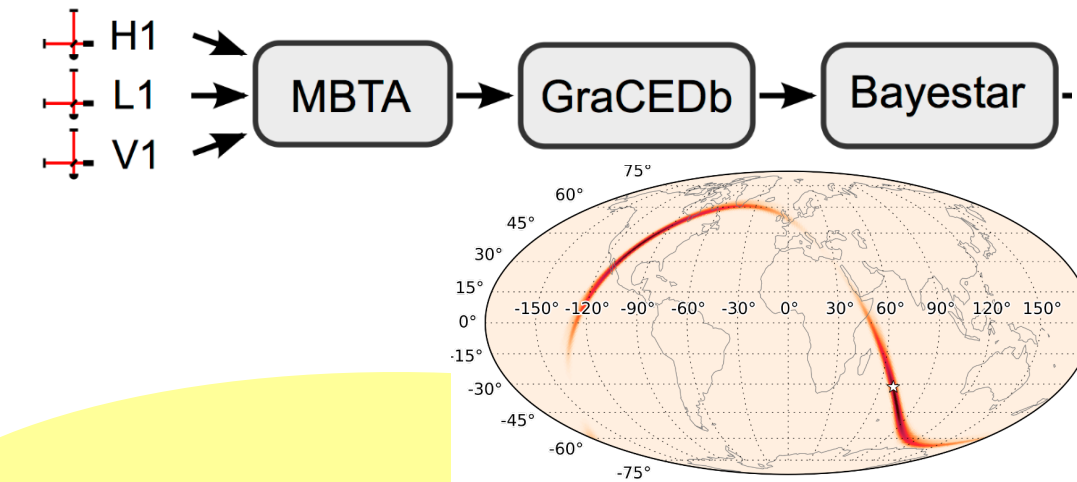
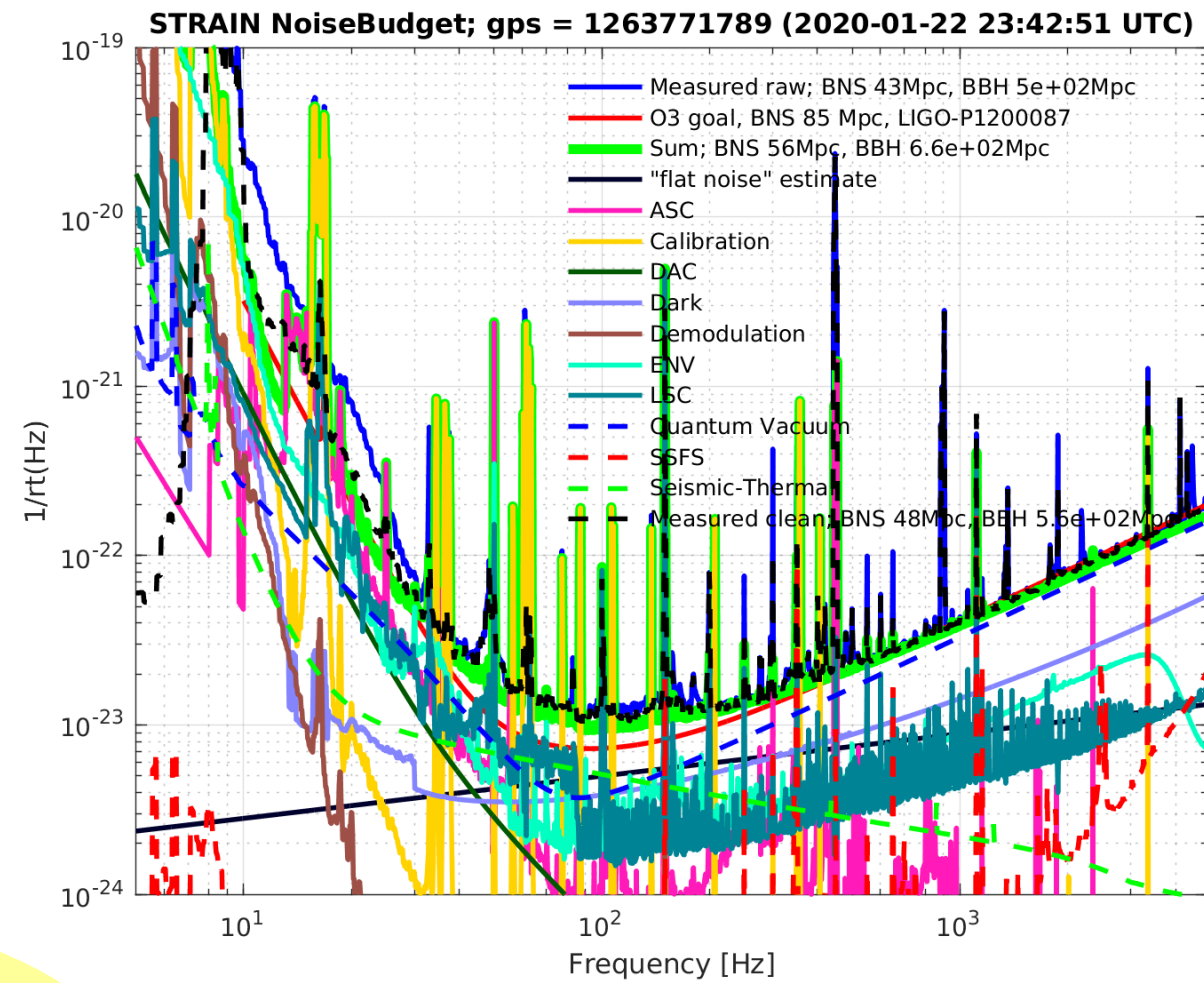
**Detector**  
Design, construction, installation, commissioning

Data acquisition

Digital electronics and software for real-time controls

**Detector characterisation**  
« Noise budget », noise search, software tools

**Detector calibration &  $h(t)$  reconstruction**



**Data analysis**

Low-latency search for binary coalescences (MBTA)

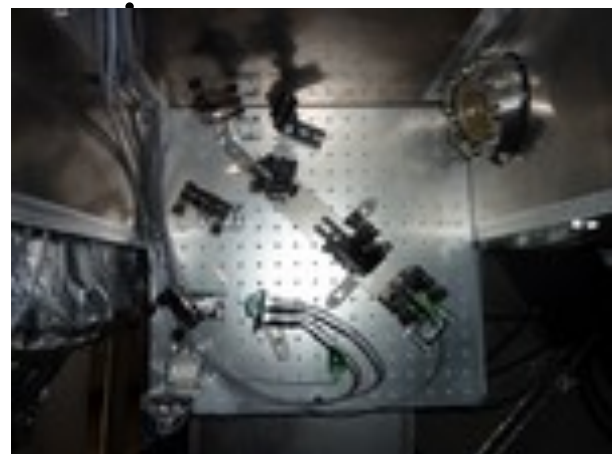
GRB studies

Stochastic background search

Gravitational wave alerts

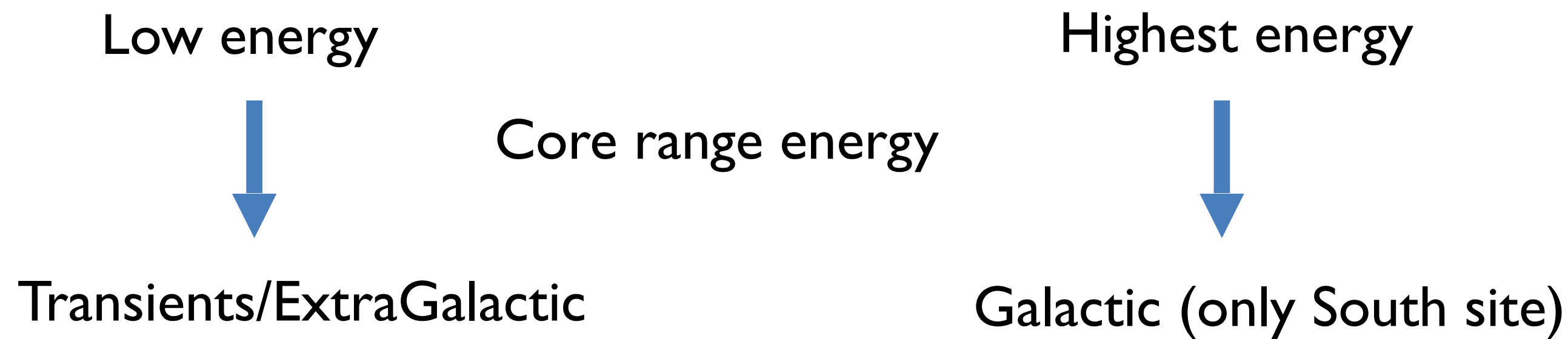
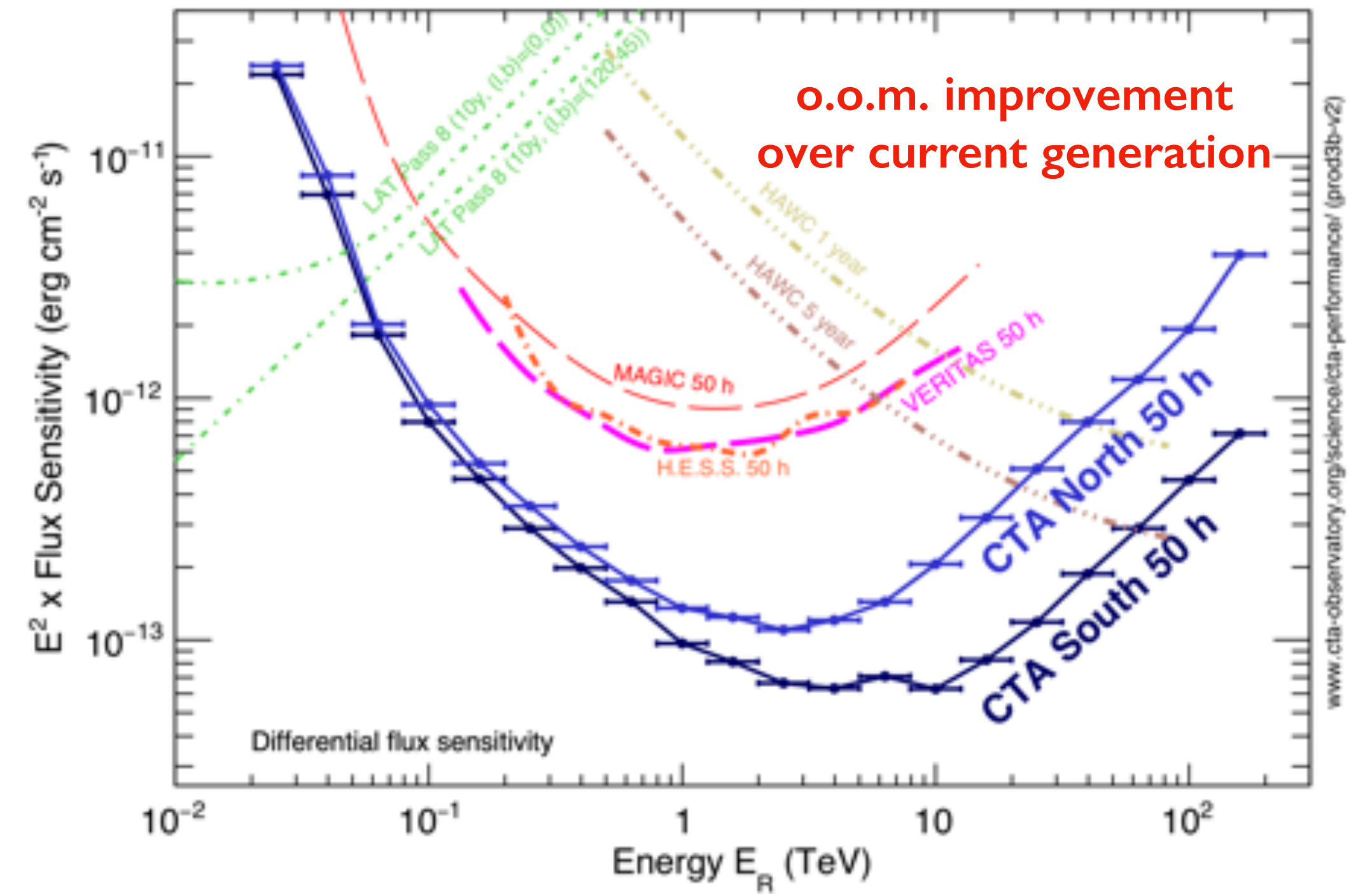
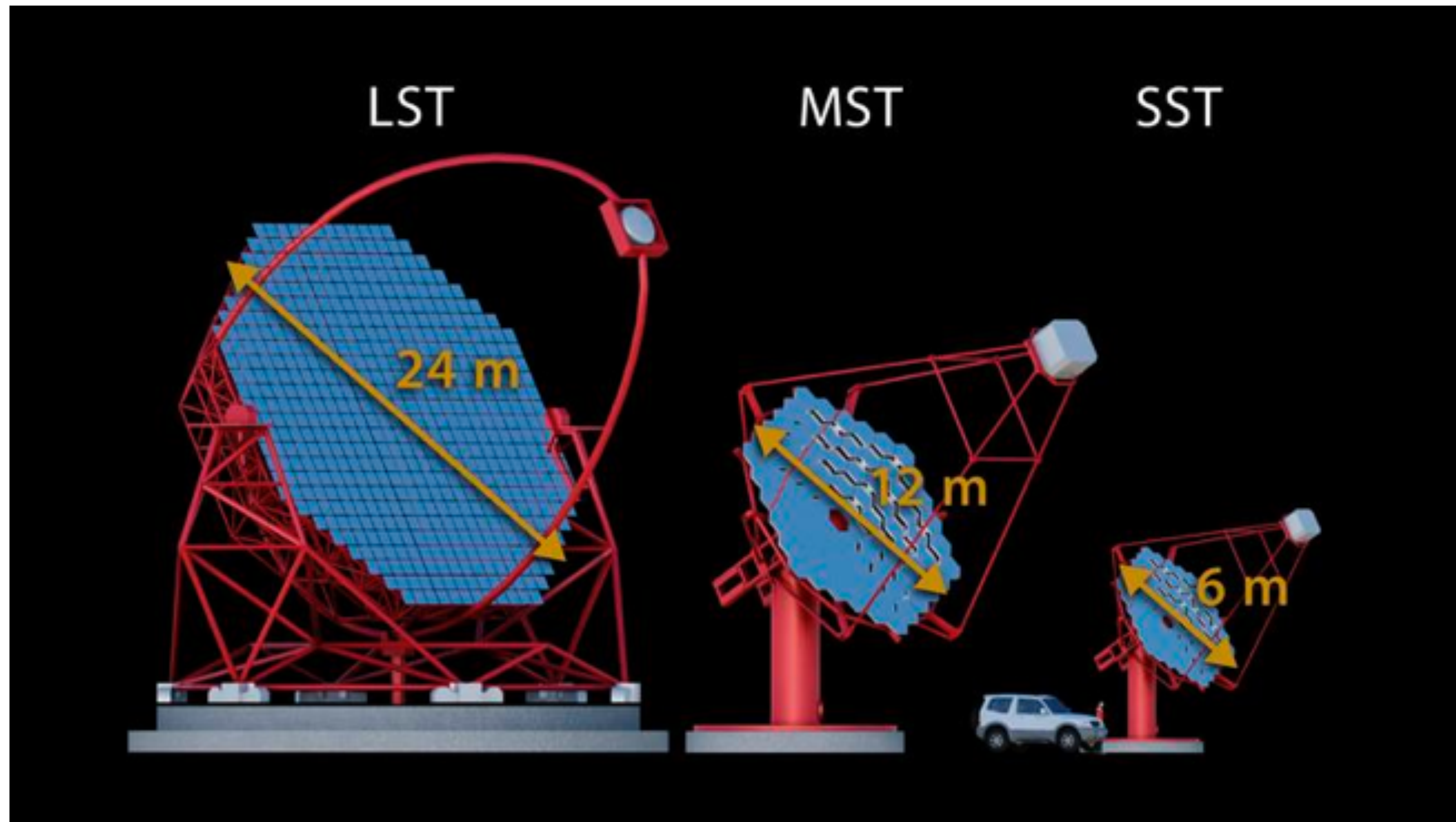


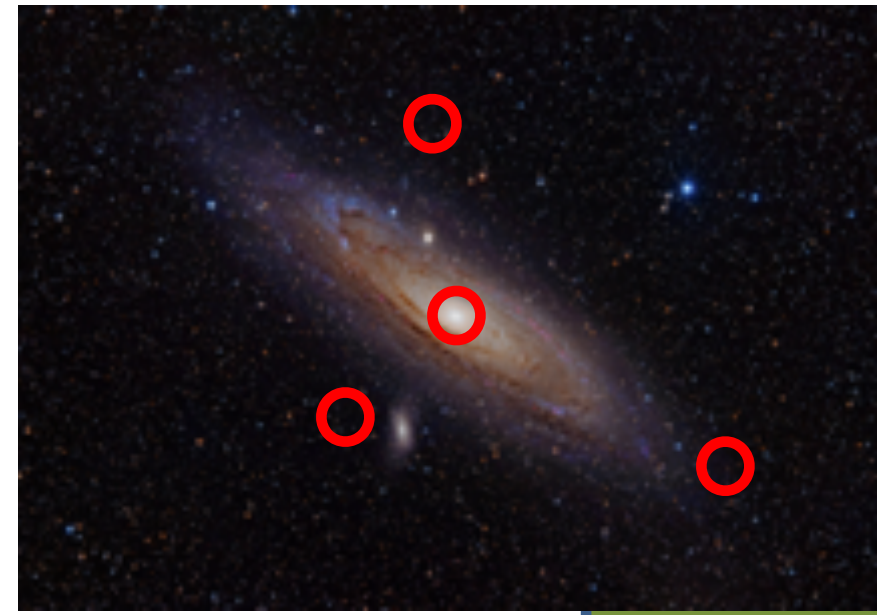
Photon calibrators



# New gamma-ray observatory: The CTA Project

- 2 sites for full & complementary sky coverage
- 3 telescope sizes to cover a large energy range

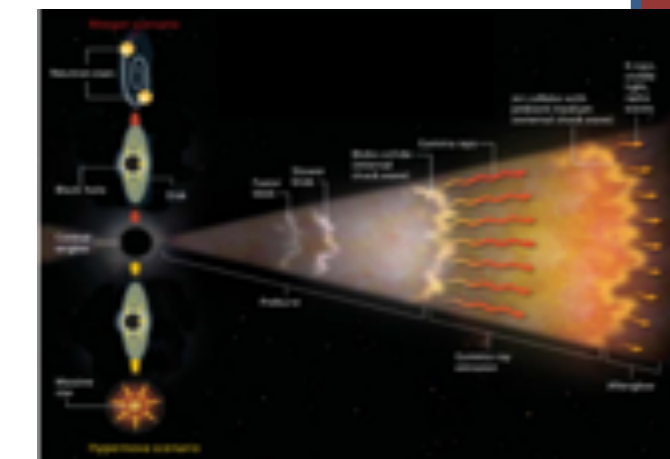
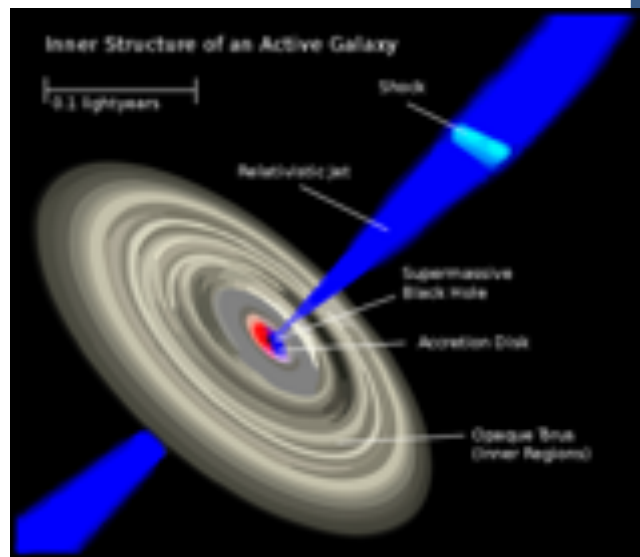




Dark Matter

AGN  
(variability, jet)

GRB/GW  
(jet)



Link with Virgo

Enigmass postdoc being recruited

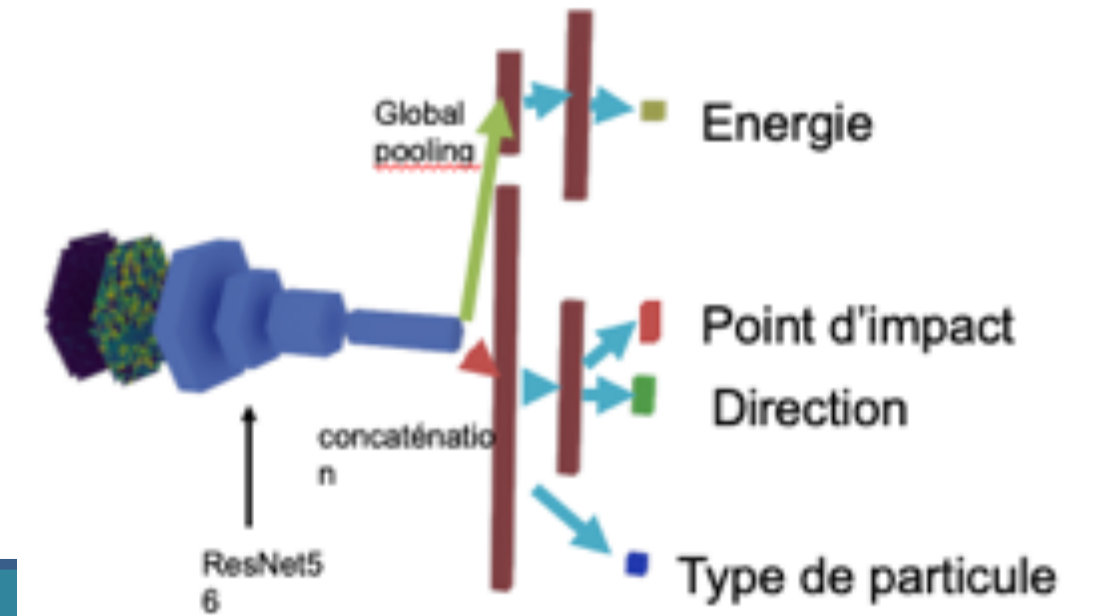
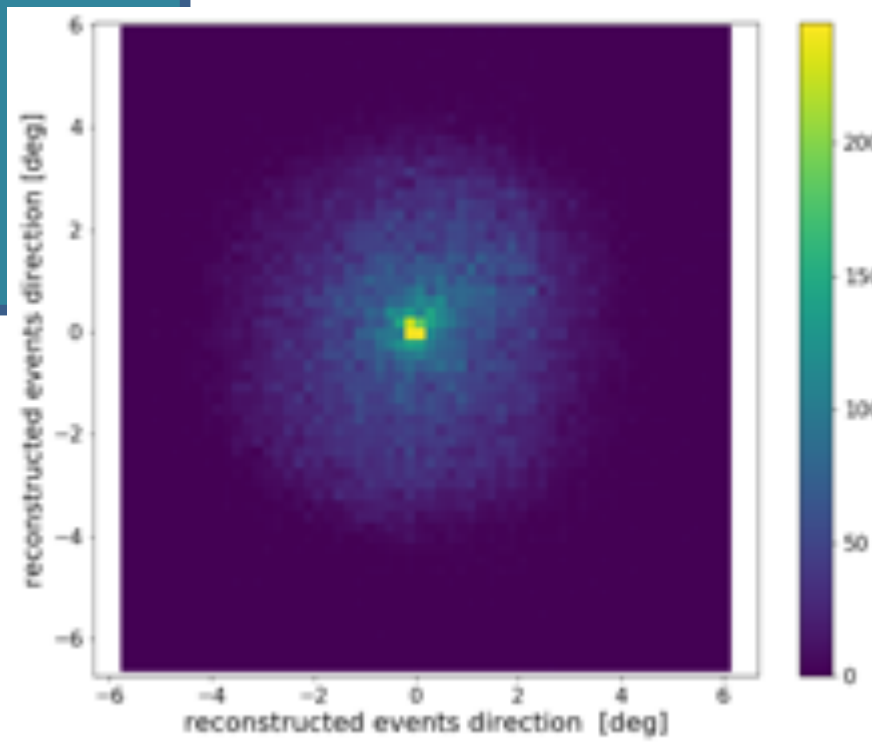
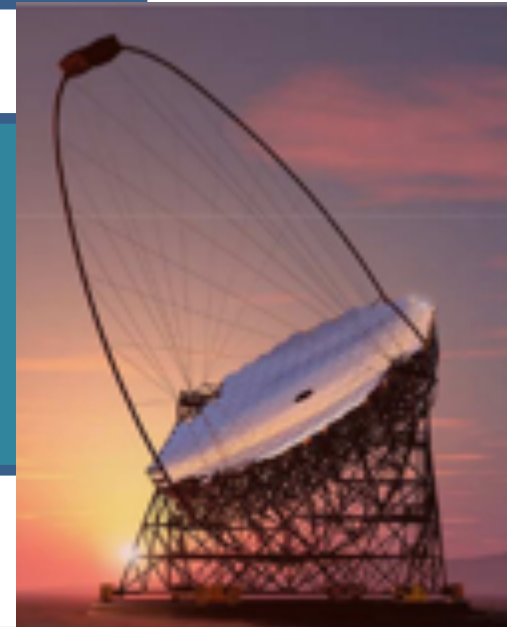
Low Energy

Transients

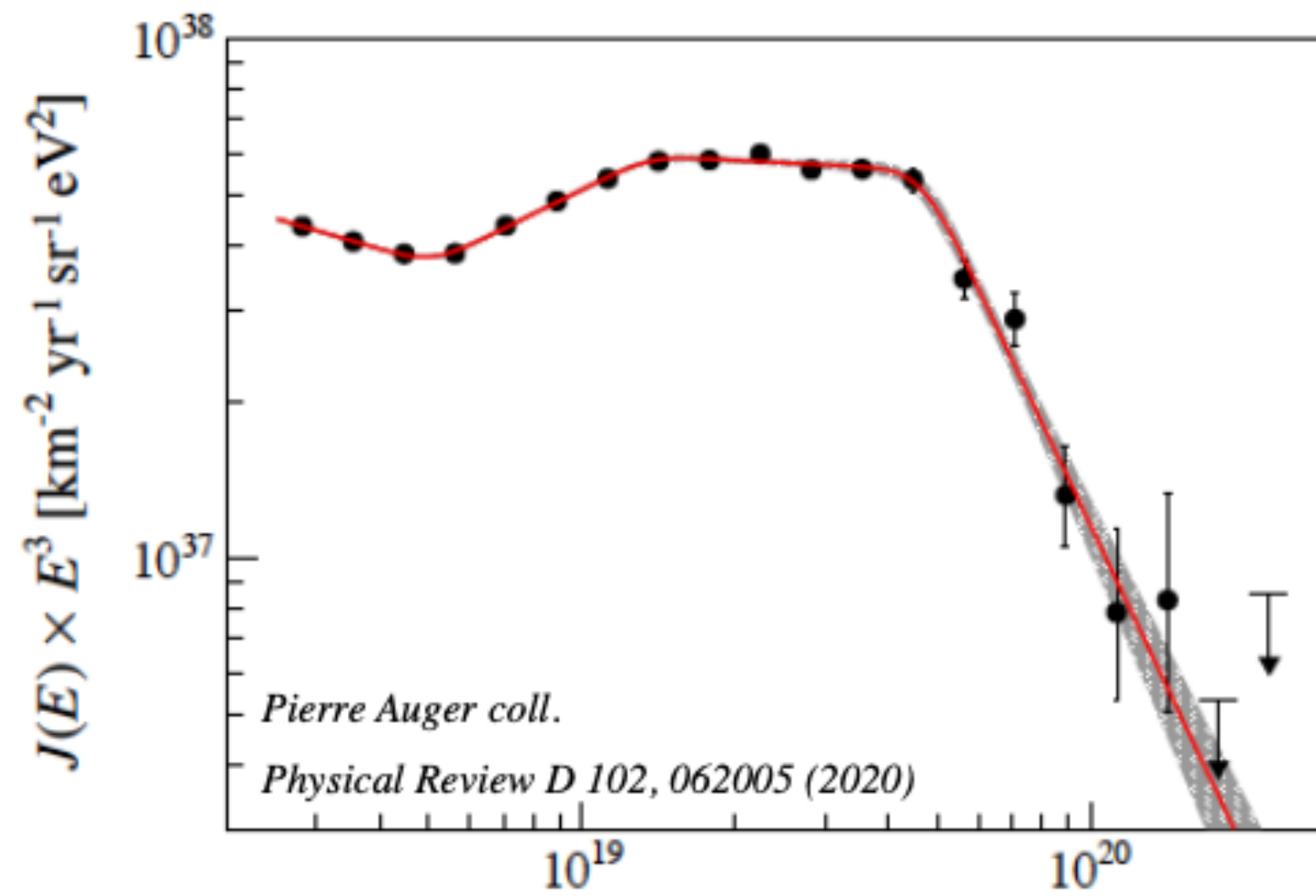
Deep-Learning

LST

Real time  
Analysis



# Ultra-high-energy cosmic rays (UHECRs)



## Main goal:

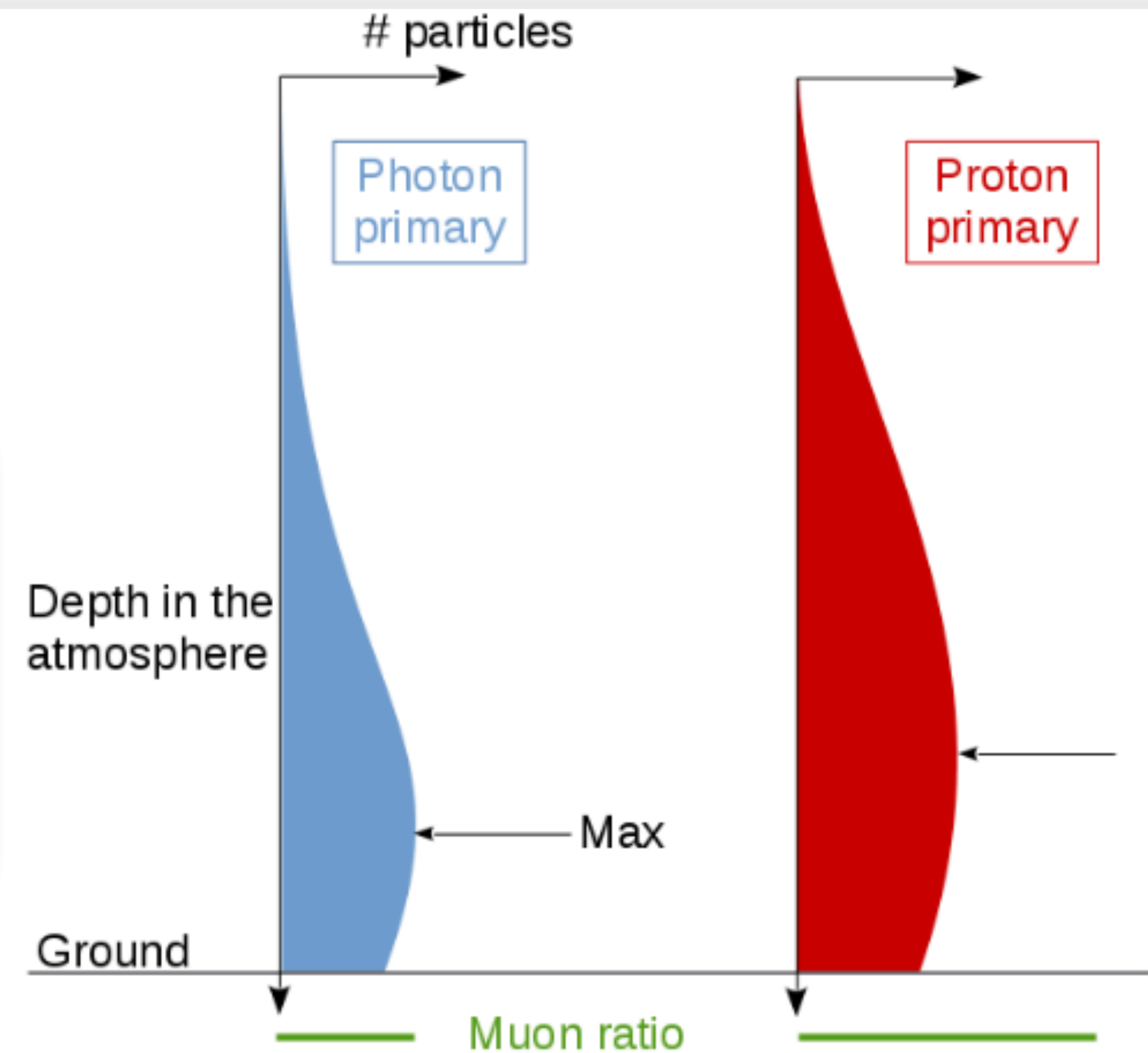
- Understand their origin and nature

## Issues:

- Astrophysics: sources, acceleration, propagation processes.
- New fundamental physics at UHE?

## Extensive atmospheric air shower

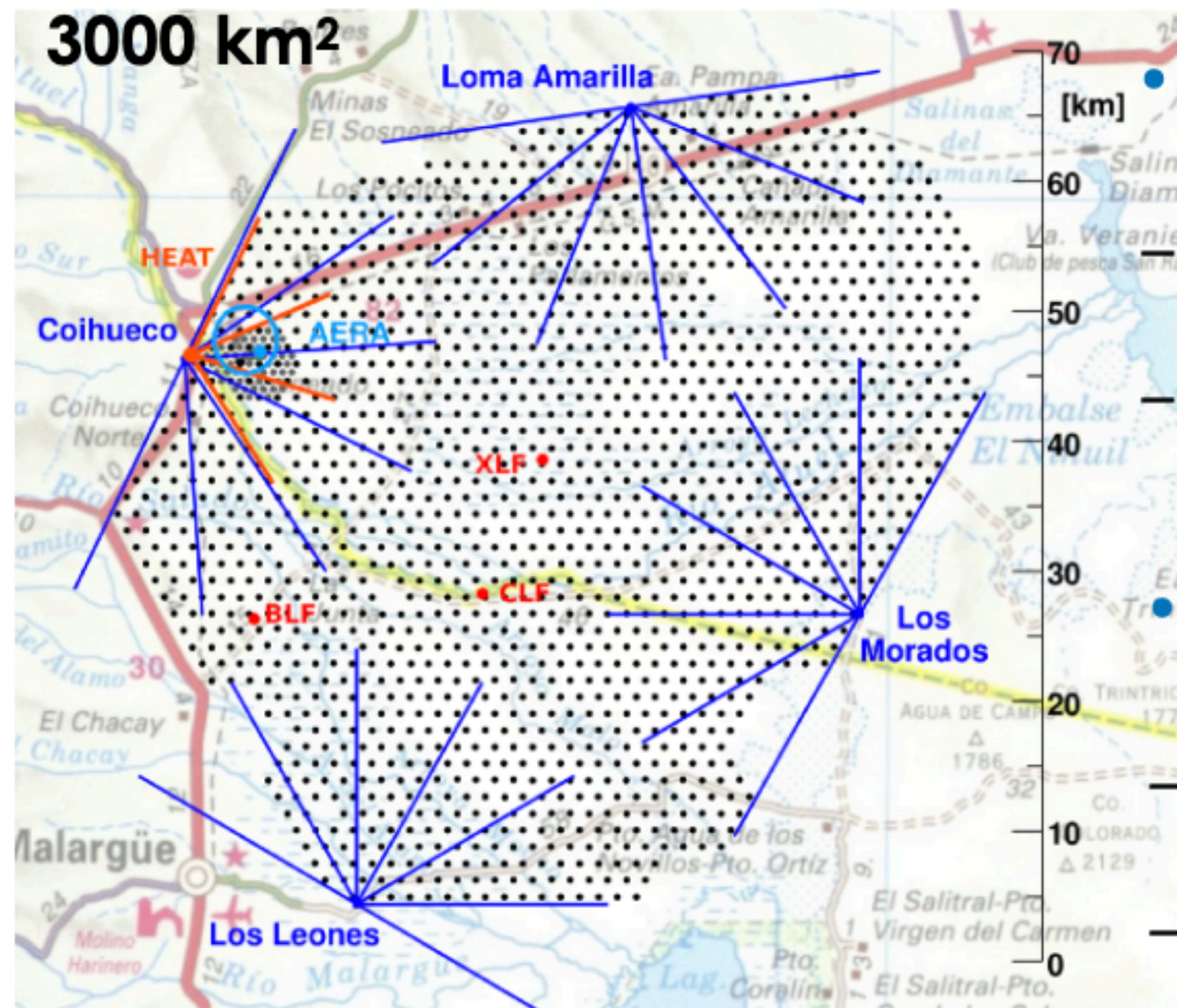
- ▶ One measures features of the particle shower induced by primaries interacting in the atmosphere
- ▶ They develop differently for different primaries, offering identification capability.





# Pierre Auger Observatory & $\gamma_{UHE}$ searches

## Key role of hybrid detection



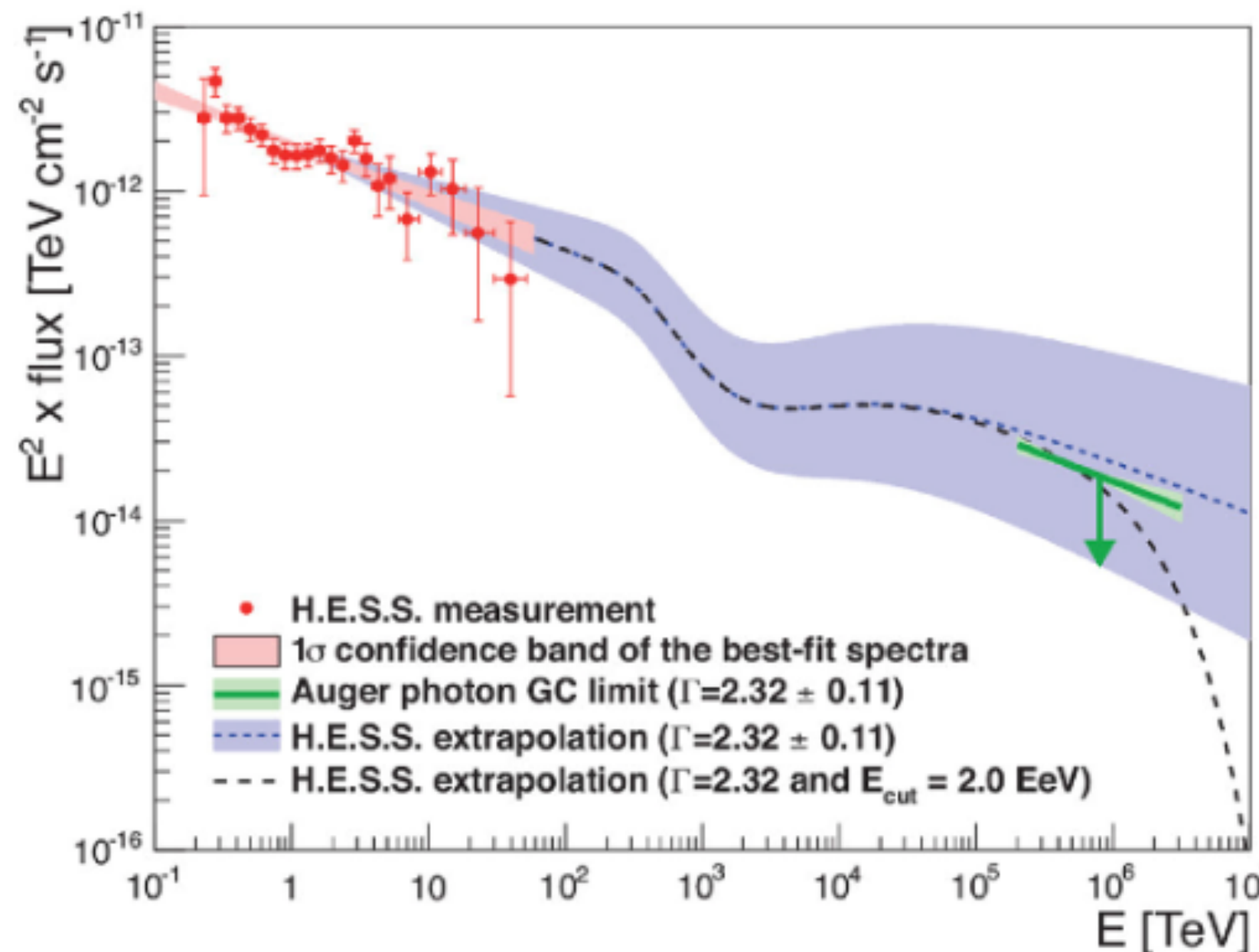
17 countries, 81 institutions, >500 researchers

27 Fluorescence Detectors (FD)  
~13% duty cycle

1660 Surface Detectors (SD)  
~100% duty cycle

## Interest for $\gamma_{UHE}$

- Unavoidably produced in association to the GZK “propagation-induced” suppression at  $E > 5 \times 10^{19}$  eV = 50 EeV, but in local (tens of Mpc) universe
- If produced near the sources, could allow for source identification. Directional & time correlation searches with sources/events detected by multiple observatories (GW, gamma’s, neutrinos...)
- None identified, yet: sufficient to exclude dominant top-down production



## AugerPrime upgrade

Addition of scintillators (SSD) on Cherenkov detectors  
New radio electronics, buried detectors...

Active participation of LPSC  
(Electronics, SSD assembly and test)

# Activities $\gamma_{UHE}$ @ LPSC

2 staff, 1 postdoc, 1 PhD

## Current analyses

- ▶ Discriminating variables to identify  $\gamma$ @ SD
- ▶ Multivariate analysis (PhD thesis defended)
- ▶ Study of irreducible background noise

## R&D related to AugerPrime

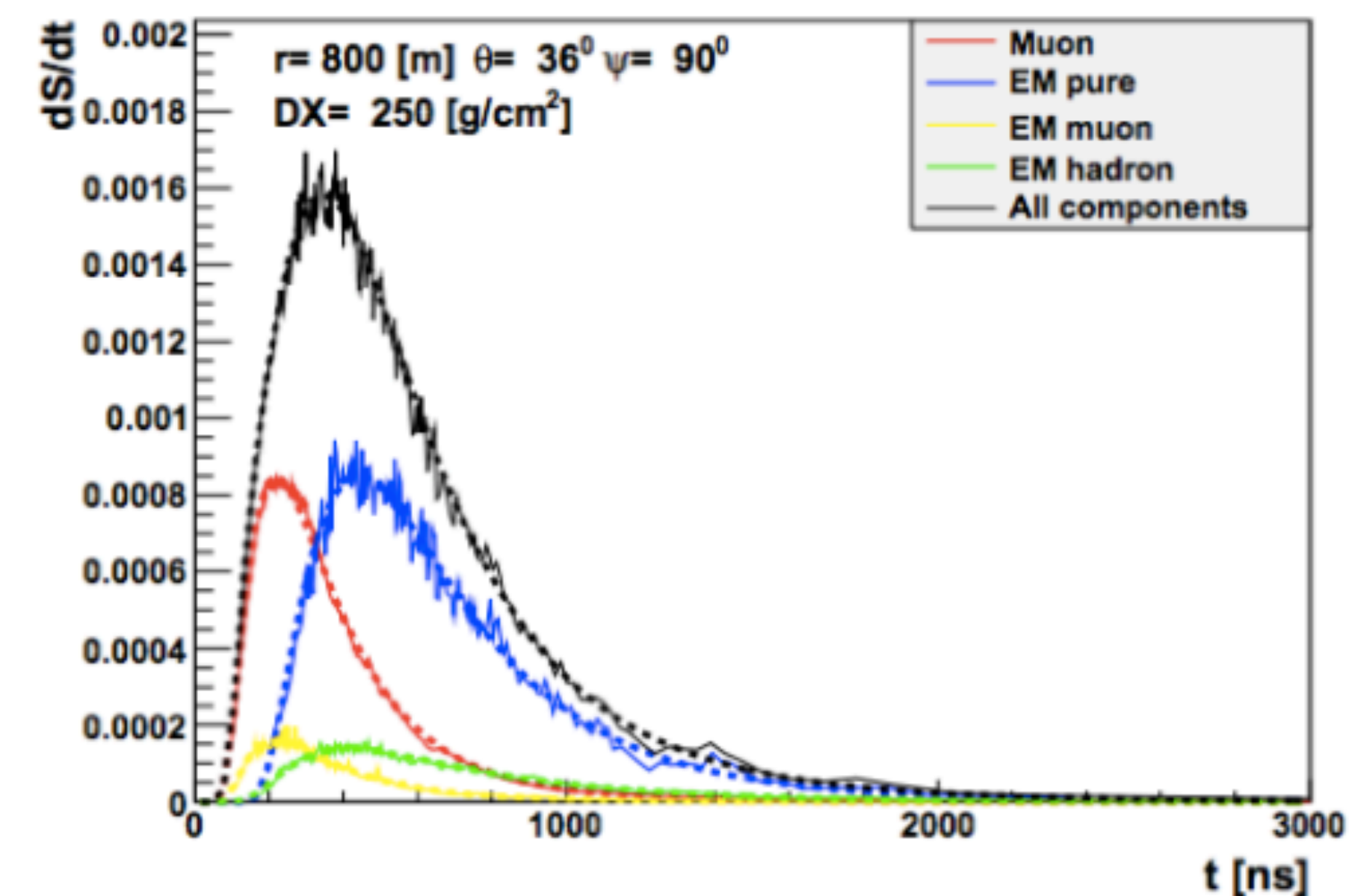
- ▶ Shower dependence from key parameters ( $E$ ,  $X_{\max}$ , direction,  $\# \mu$ )
- ▶ Identified universal components enter the MICRO project

## $\gamma$ shower reconstruction via universality principle

- ▶ Feasibility and validity for  $\gamma$  searches
- ▶ Using complementary measurements from AugerPrime
- ▶ On line alert performing analysis (PhD thesis Labex 2020-23: Zoé Torrès)
- ▶ Multimessenger exploration of UHECR origin (ANR project)

Signal total = Signal e.m. (pur)

- + composante muonique
- + produits de désintégration de muons
- + produits de désintégration de hadrons



# Galactic Cosmic Rays: AMS-02

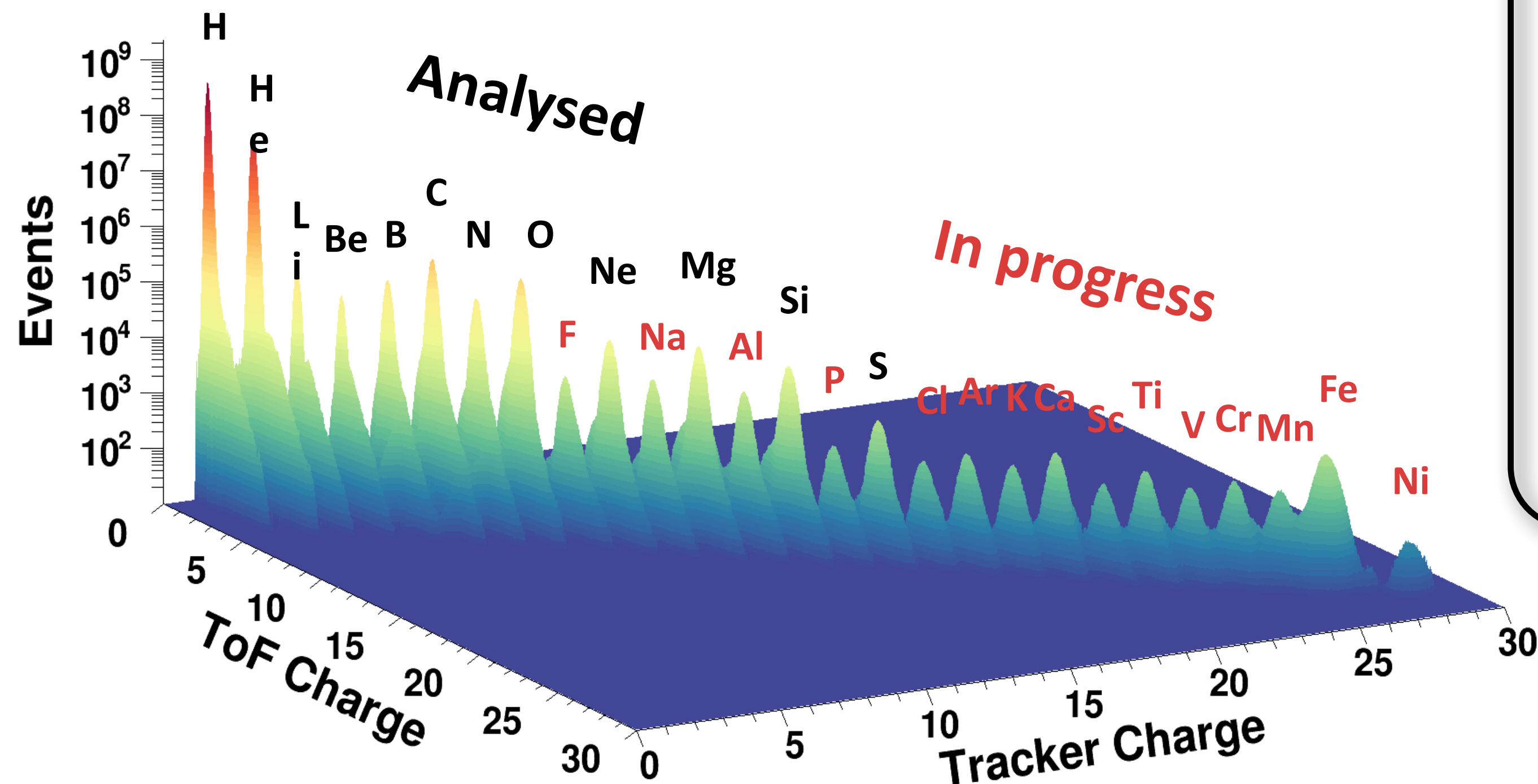
High statistics (large acceptance, long exposure time) and high precision data:

- Elemental fluxes from H to Ni
- Isotopic fluxes for light nuclei
- Low energy time dependance

**Intrinsically multi-messenger !**

LPSC Involvement in data analysis:

- Elements from H to O
- He, Li, and Be Isotopes



- LAPP/LAPTh/**LPSC**/LUPM collaboration for the exploitation of AMS-02 data:
  - GCR propagation code **USINE**: <http://lpsc.in2p3.fr/usine>
  - Search for dark matter contributions in the rare components of the CR (**see WP 3**)
- Large impact and visibility (9 publications), many contributions in conferences
- Some original contributions:
  - Treatment of data systematics
  - Impact of the model's systematics
  - Combined fit of different species
  - Reference propagation models
  - Identification of nuclear cross sections to improve (XSCRC19 at CERN)
  - CR database <http://lpsc.in2p3.fr/crdb>

# Theory & pheno studies

No 'dedicated-WP2' theory group at any of the labs, yet regular activity, notably with inter-Lab collaborations:

## Some examples:

- ▶ A longstanding one on CR data analysis
- ▶ On multi-wavelength aspects of gamma-rays (source variability, models of diffuse gamma-ray background based on Fermi-LAT and IACT observations...)
- ▶ Exploratory studies in multimessenger astrophysics, within a Idex UGA grant, a junior ANR... (e.g.: role in the investigation of gamma-ray excess at Galactic center, cross-correlation studies GW / cosmological surveys)

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**Thank you for your attention!**