Astroparticle physics
The Universe as a physics lab

Ruben Conceição

LIP

TÉCNICO LISBOA

LIP summer internship workshop, Lisboa, July 11th 2018

What is Astroparticle physics?

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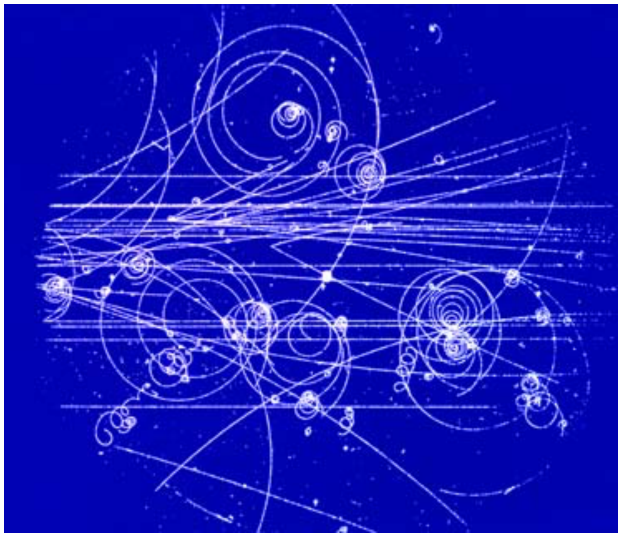
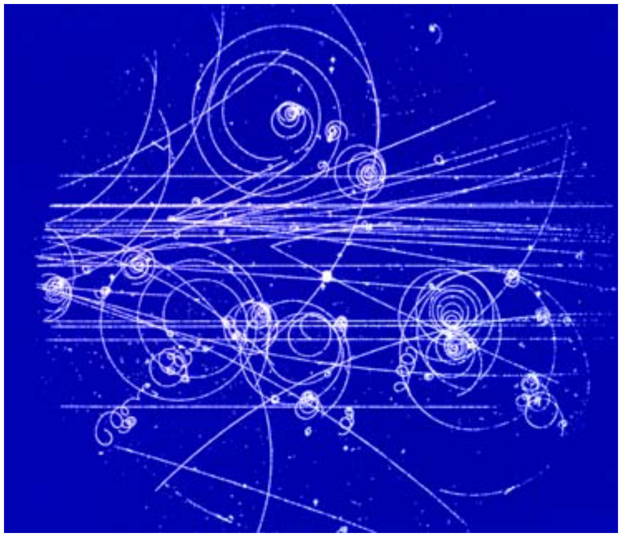
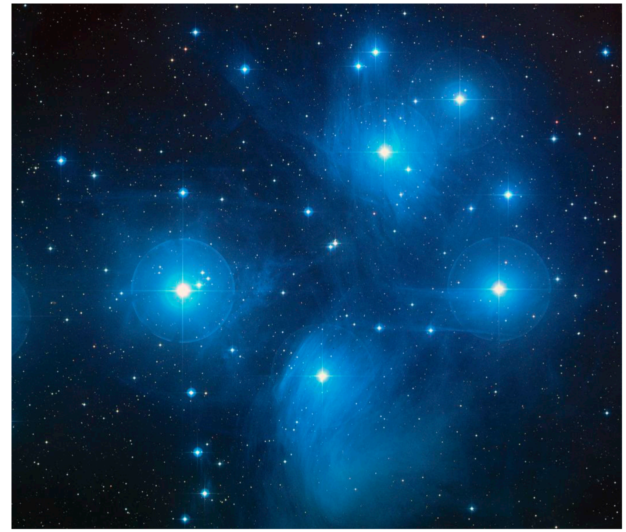


- Particle Physics
  - Study the properties of matter and interactions

What is Astroparticle physics?





- Particle Physics
  - Study the properties of matter and interactions

- Astrophysics / Cosmology
  - Study Universe's evolution and surrounding astrophysical objects

Astroparticle physics

Particle phyiscs

Astrophysics

Cosmology

Understand the dynamics of our Universe through the radiation/particles collected at Earth

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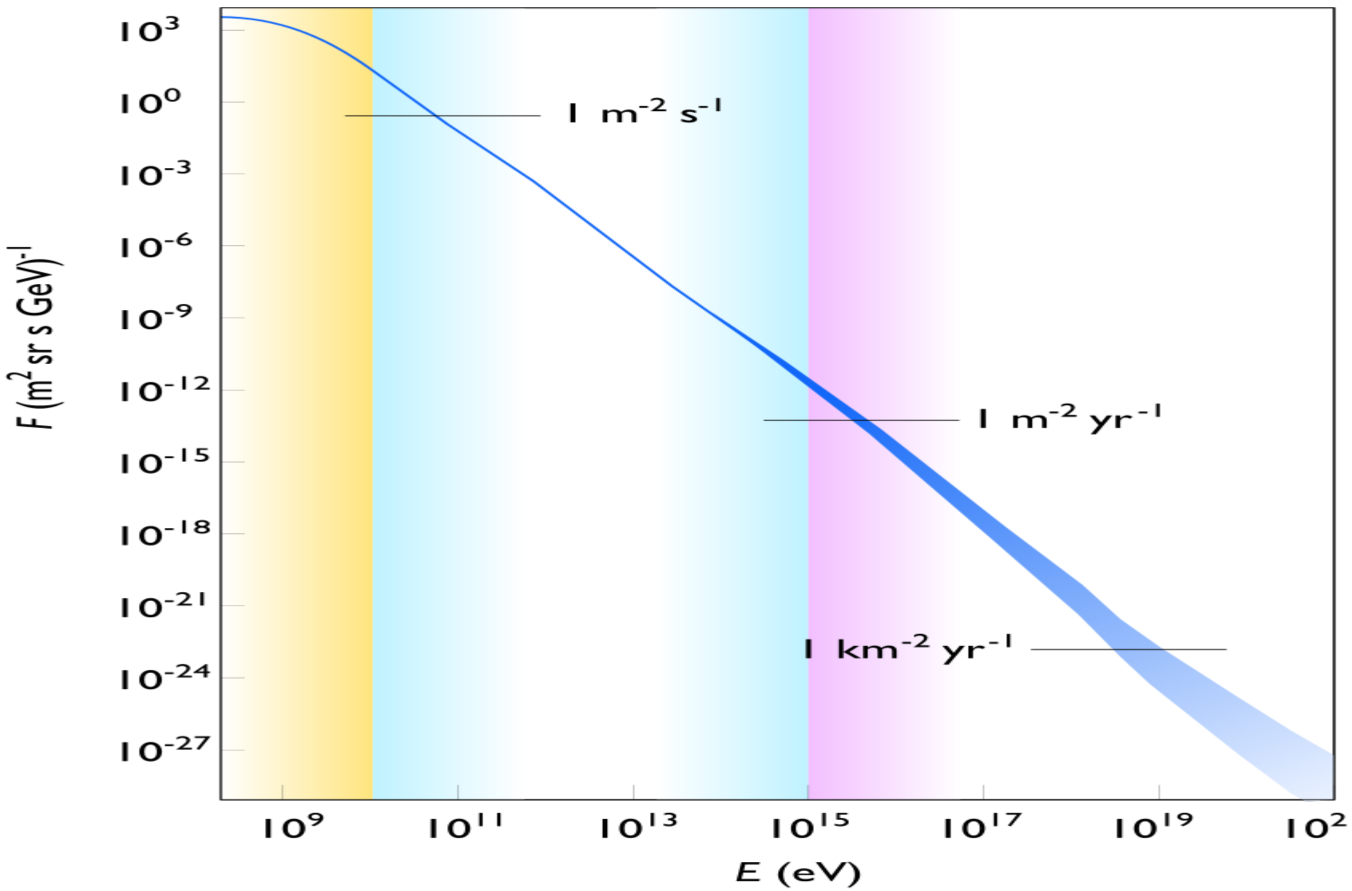
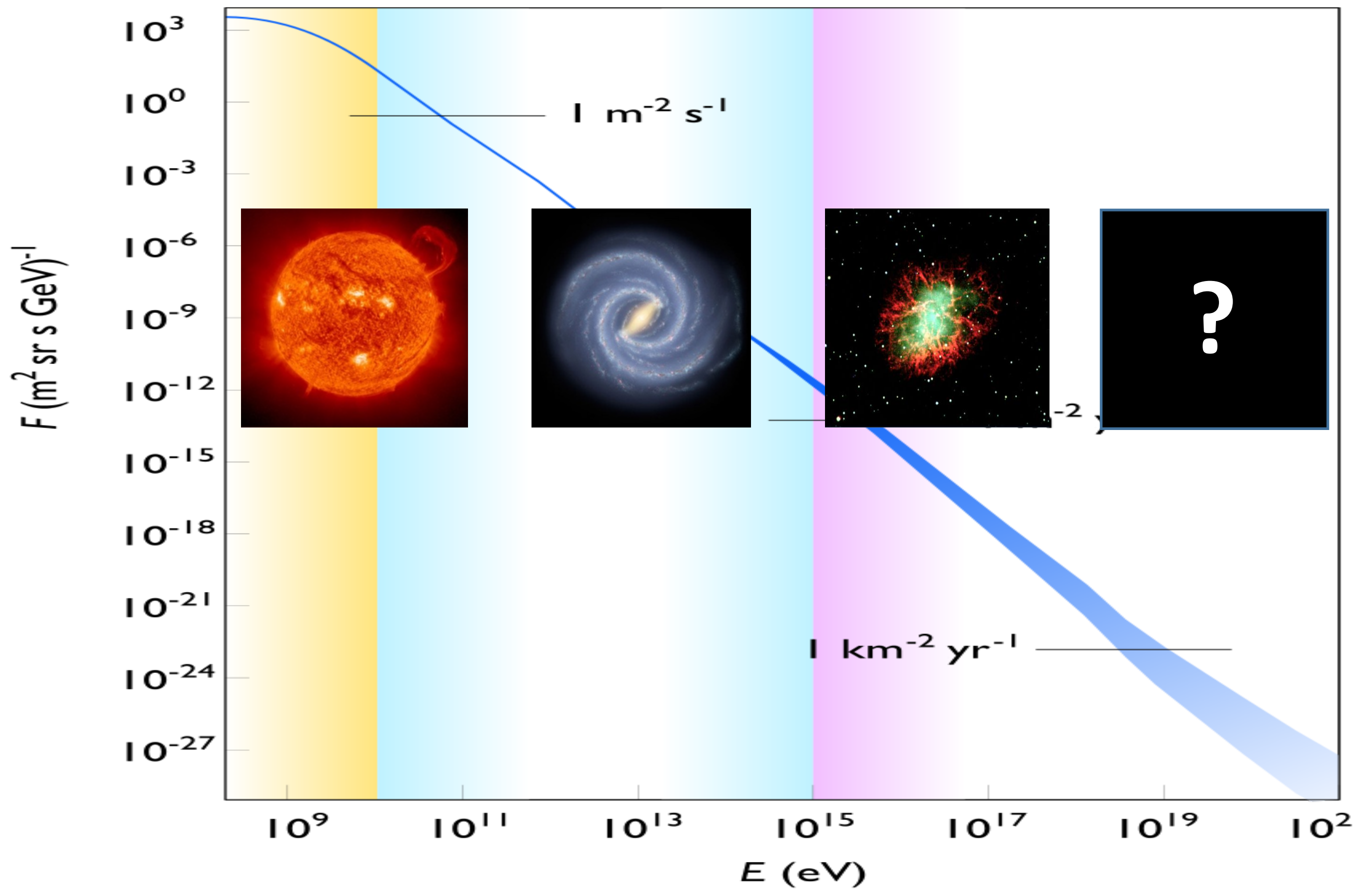
Cosmic ray energy spectrum



(Charged particles continuously bombarding Earth)

Cosmic ray energy spectrum



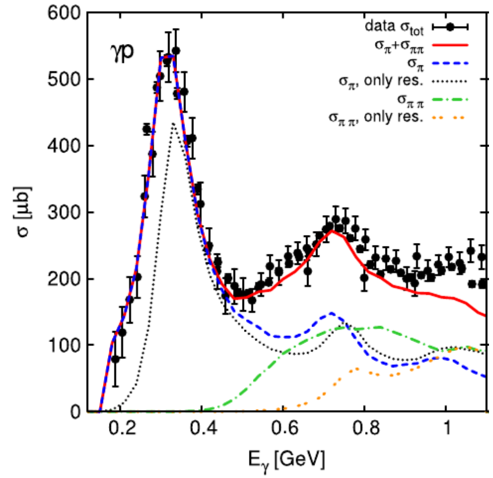
Rapidly falling energy spectrum

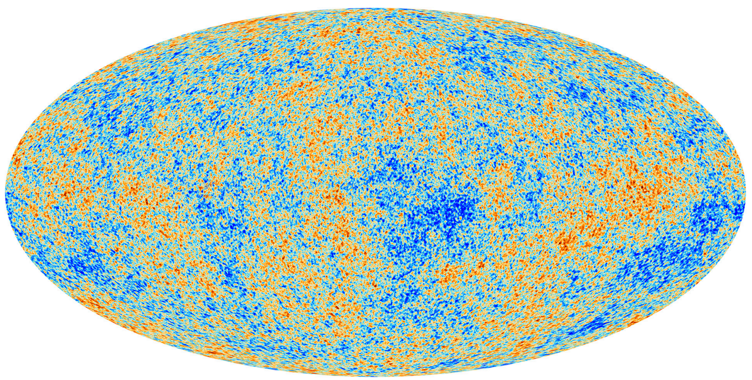
Different sources according to the energy

GZK effect

A practical example of how astroparticle physics works…

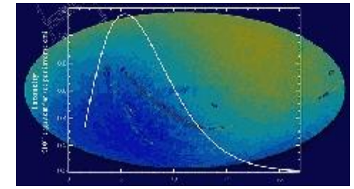
An example: GZK effect

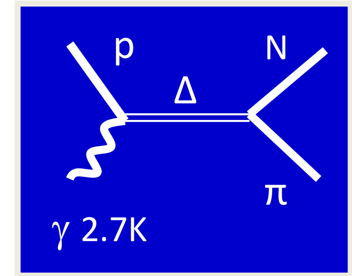




- ✧ Discovery of the Δ baryon in accelerator measurements
- ✧ Discovery of the cosmic microwave background

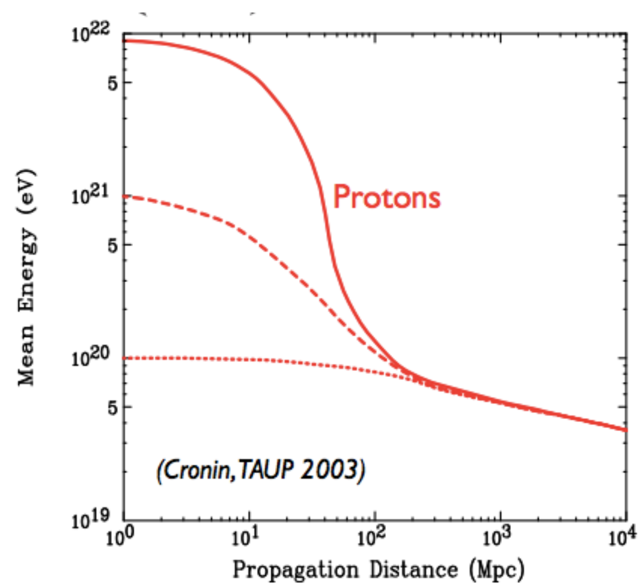
GZK effect





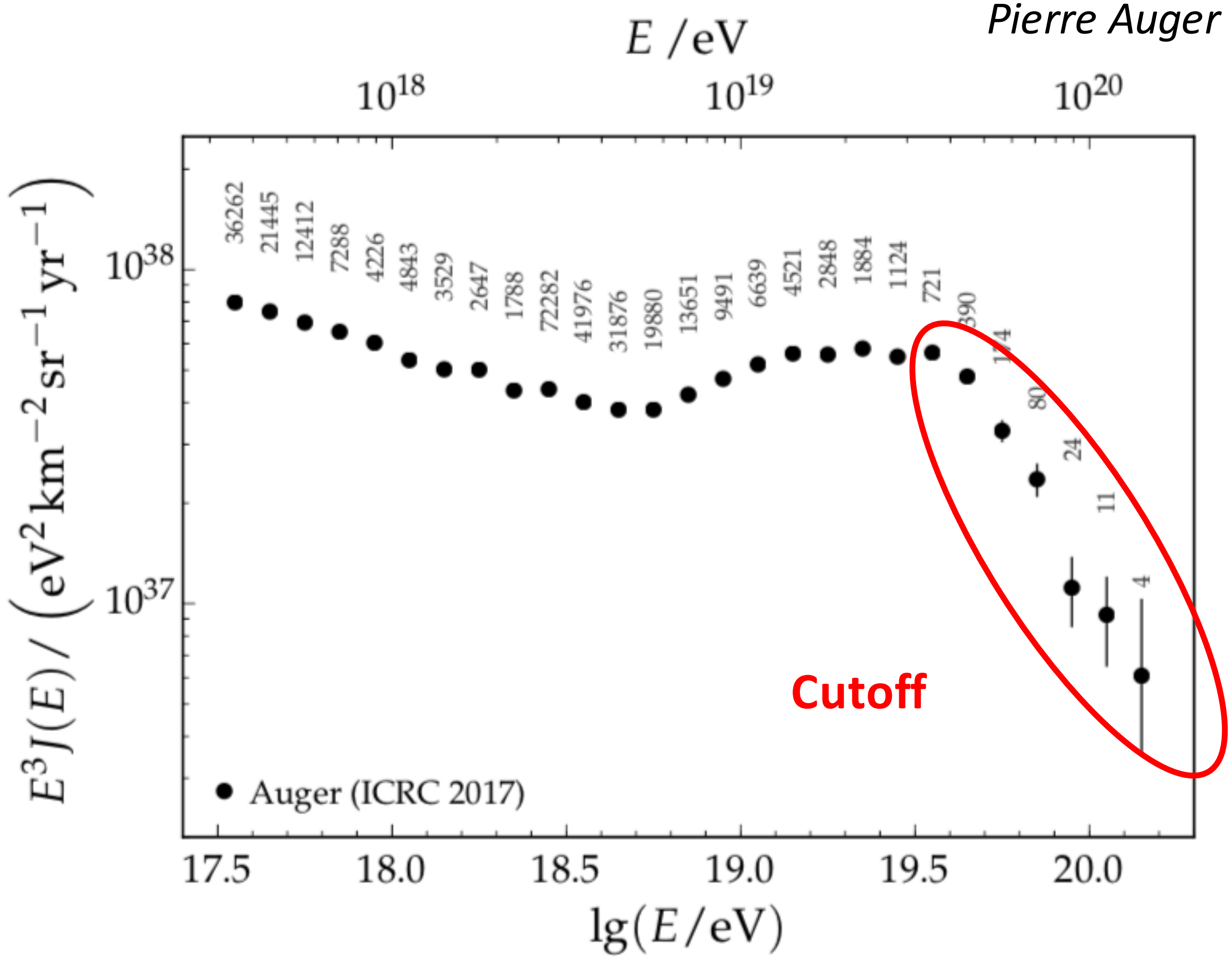
- GZK cuttoff
  - Greisen, Zatsepin, Kuz'min (1966)
  - Cosmic ray interaction with CMB
  - Energy loss process
  - Prediction: CR energy spectrum should have a cutoff around E ~ 10^{20} eV

$$p + \gamma_{CMB} \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$
$$p + \gamma_{CMB} \rightarrow \Delta^{+} \rightarrow n + \pi^{+}$$



UHECR energy spectrum

Pierre Auger Collaboration



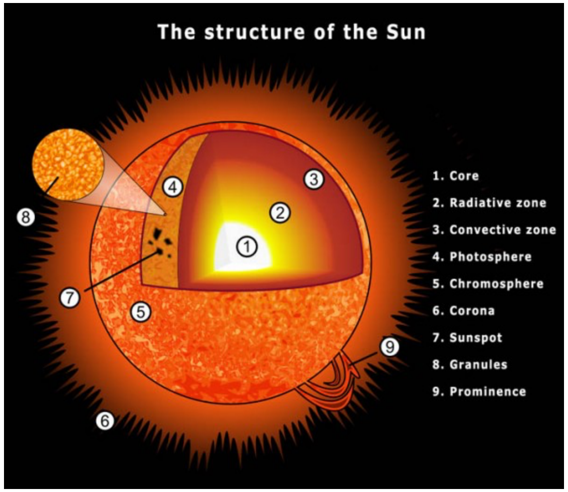
(Suppression could still be due to the source exhaustion)

Neutrino oscillations

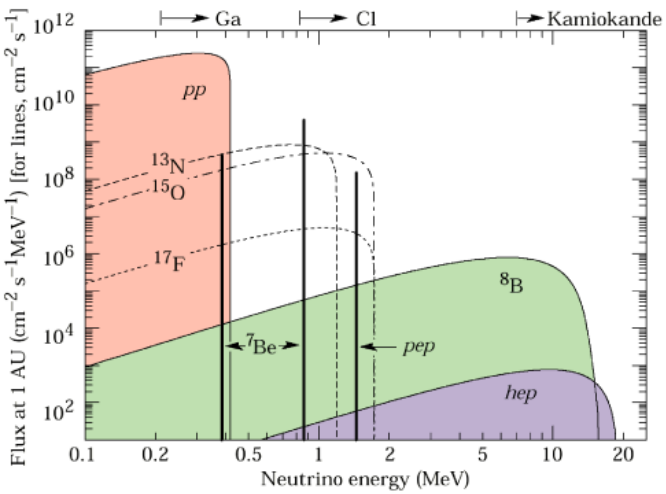
Yet another, more recent, example…

Solar Neutrinos

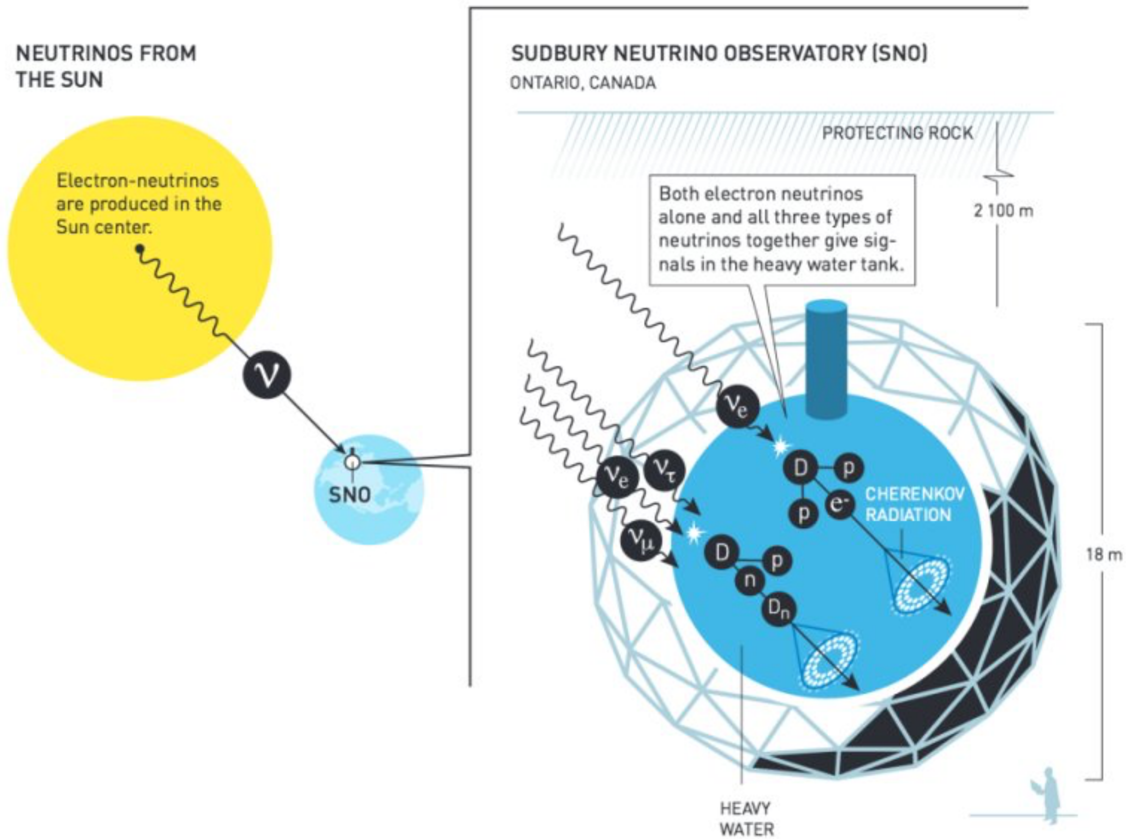
- Standard Solar Model
  - Built upon our knowledge over:
    - Solar dynamics
    - Interaction cross-sections



- It was noted since the 60's that the prediction of the flux of solar neutrino exceeded the observations



Neutrino oscillation



- Neutrino oscillation was found while trying to solve the Solar neutrino problem
- Nobel prize 2015 (A. MacDonald [SNO] ; T. Kajita [Super-Kamiokande])

Astroparticle physics allows to test our Universe combining particle physics with astrophysics

What are our probes?

Messengers from the Universe

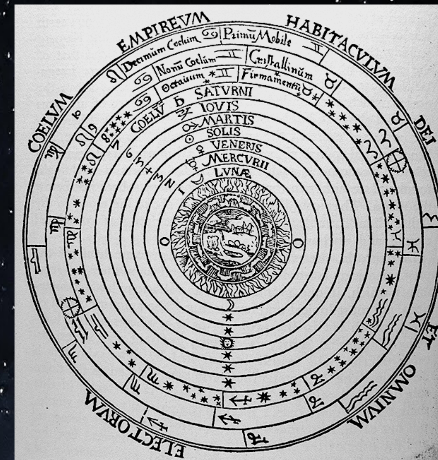
Photons

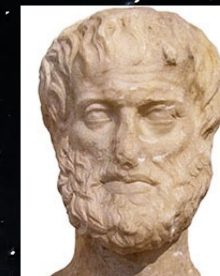
(visible light)

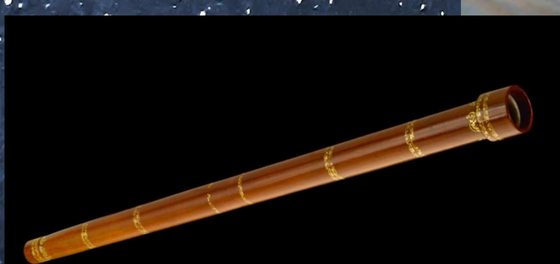
Messengers from the Universe

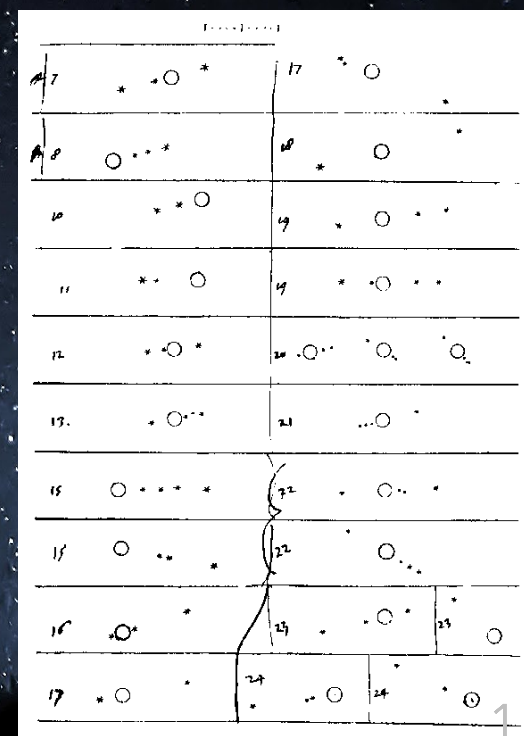
Photons

(visible light)



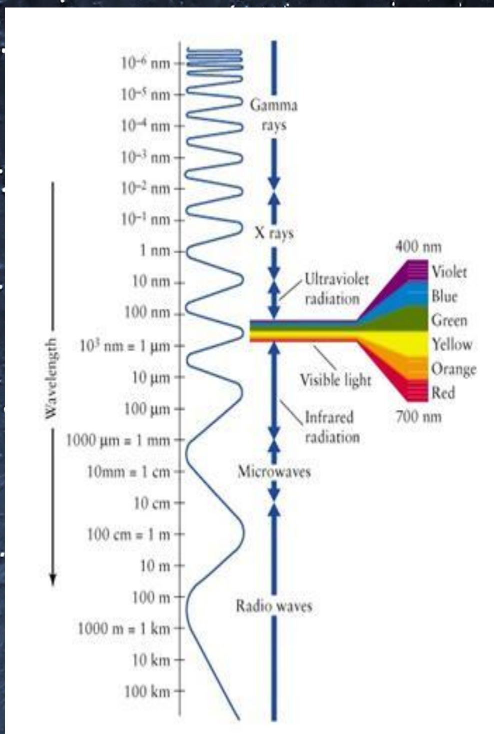


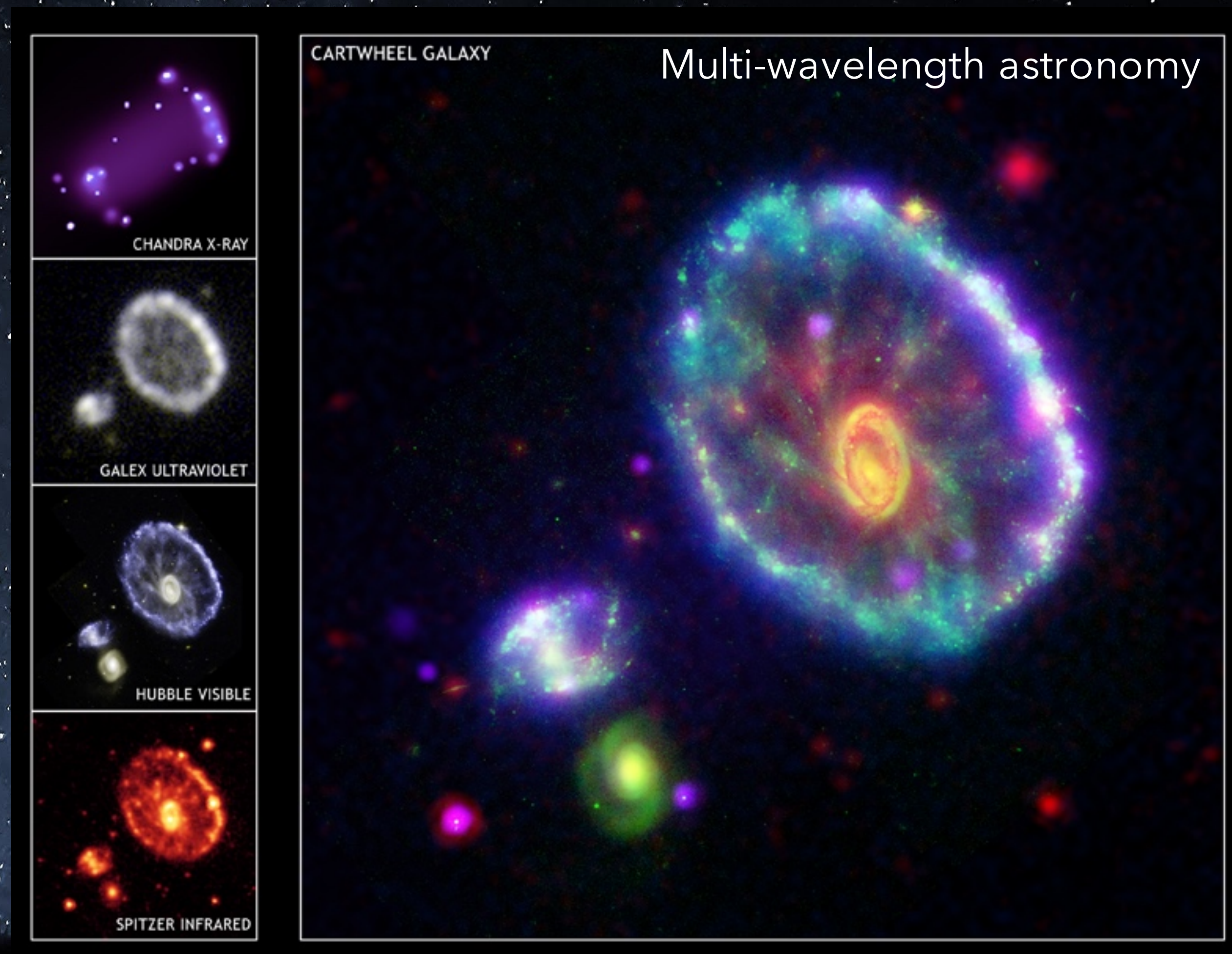




Messengers from the Universe

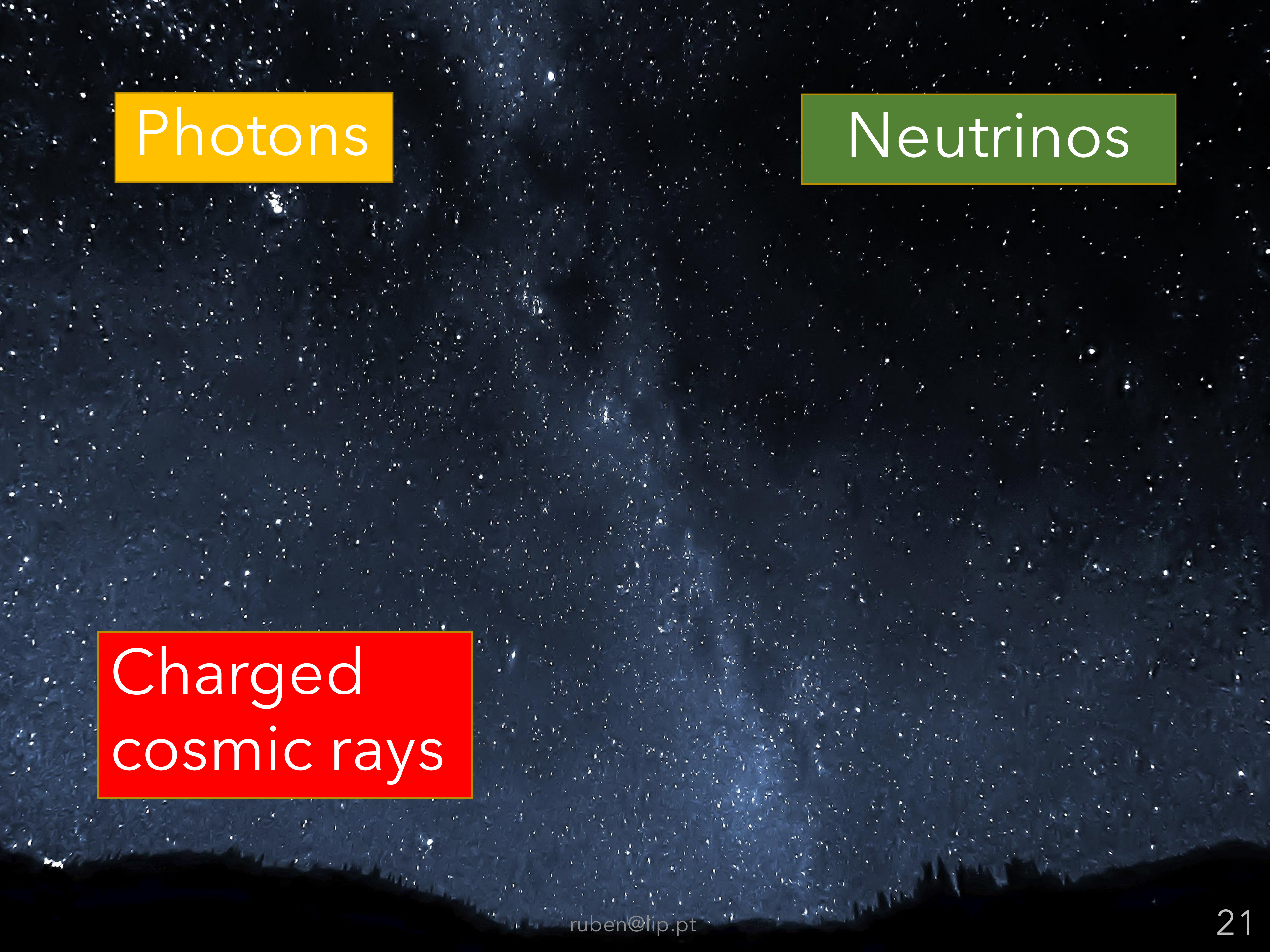
Photons (other wavelengths)





Photons


Photons
Charged cosmic rays



Photons

Neutrinos

Charged cosmic rays

Photons

Neutrinos

Charged cosmic rays

Gravitational waves

Photons

Neutrinos

Multi-messenger approach

Test the dynamics of our cosmos

Charged cosmic rays

Gravitational waves

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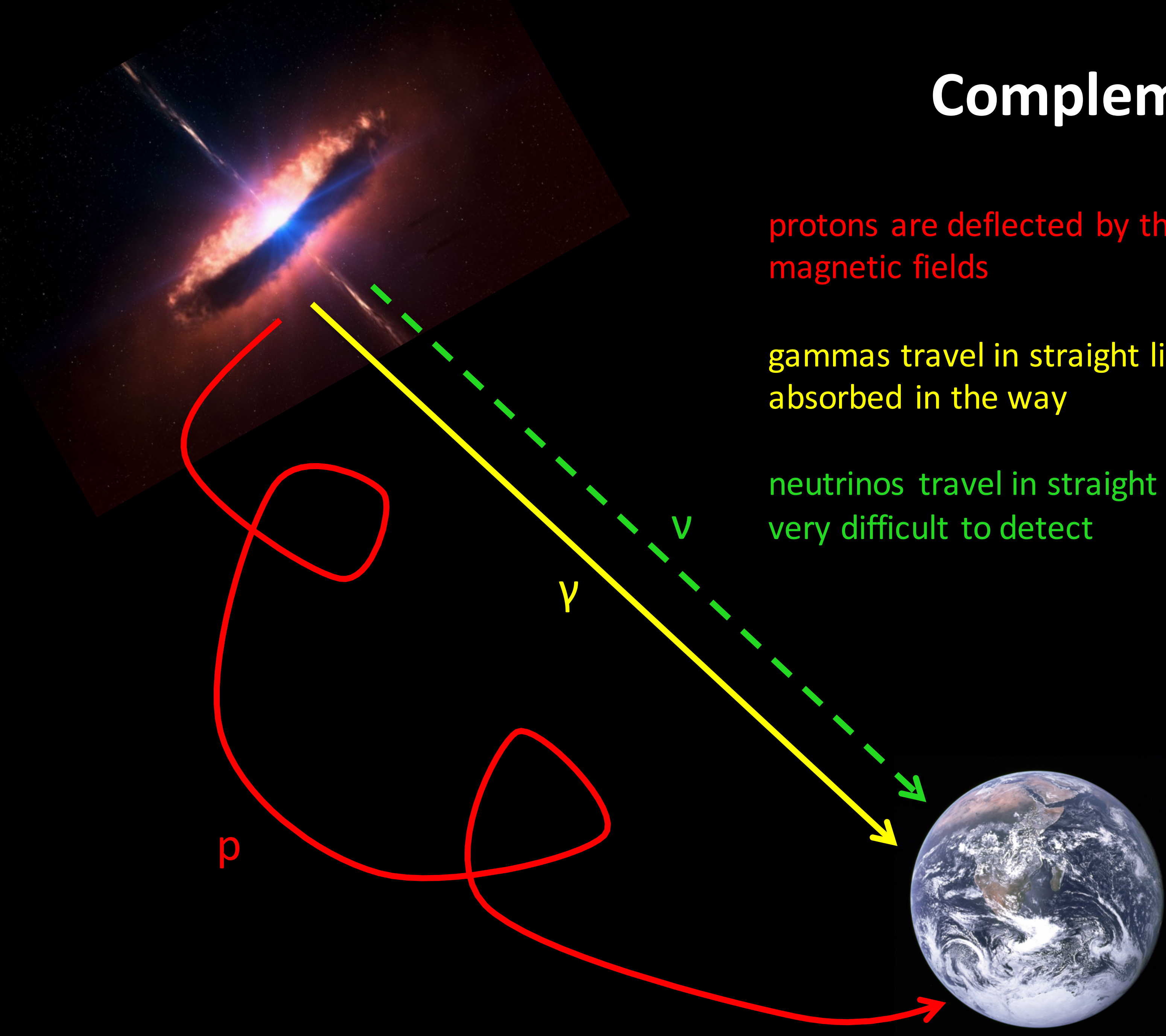
Complementarity

protons are deflected by the galactic magnetic fields

gammas travel in straight lines but can be absorbed in the way

neutrinos travel in straight lines but are very difficult to detect



Photons

Neutrinos

Examples of astroparticle experiments

Charged cosmic rays

Gravitational waves

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In this talk…

- (Very) high-energy gamma-rays
  - Probe some of the most violent astrophysical phenomena
    - SuperNovae (SN) & SuperNovae Remnants (SNR)
    - Gamma-ray bursts (GRB)
- Ultra high-energy cosmic rays
  - Universe greatest accelerators
    - Nature and origin still a mystery
  - Opportunity to do particle physics above the human-made accelerator energies

Very High-Energy Gamma-rays

(Very) High Energy Gamma Rays

- Astrophysical gamma rays
  - Energy region of interest from GeVs to hundreds TeVs

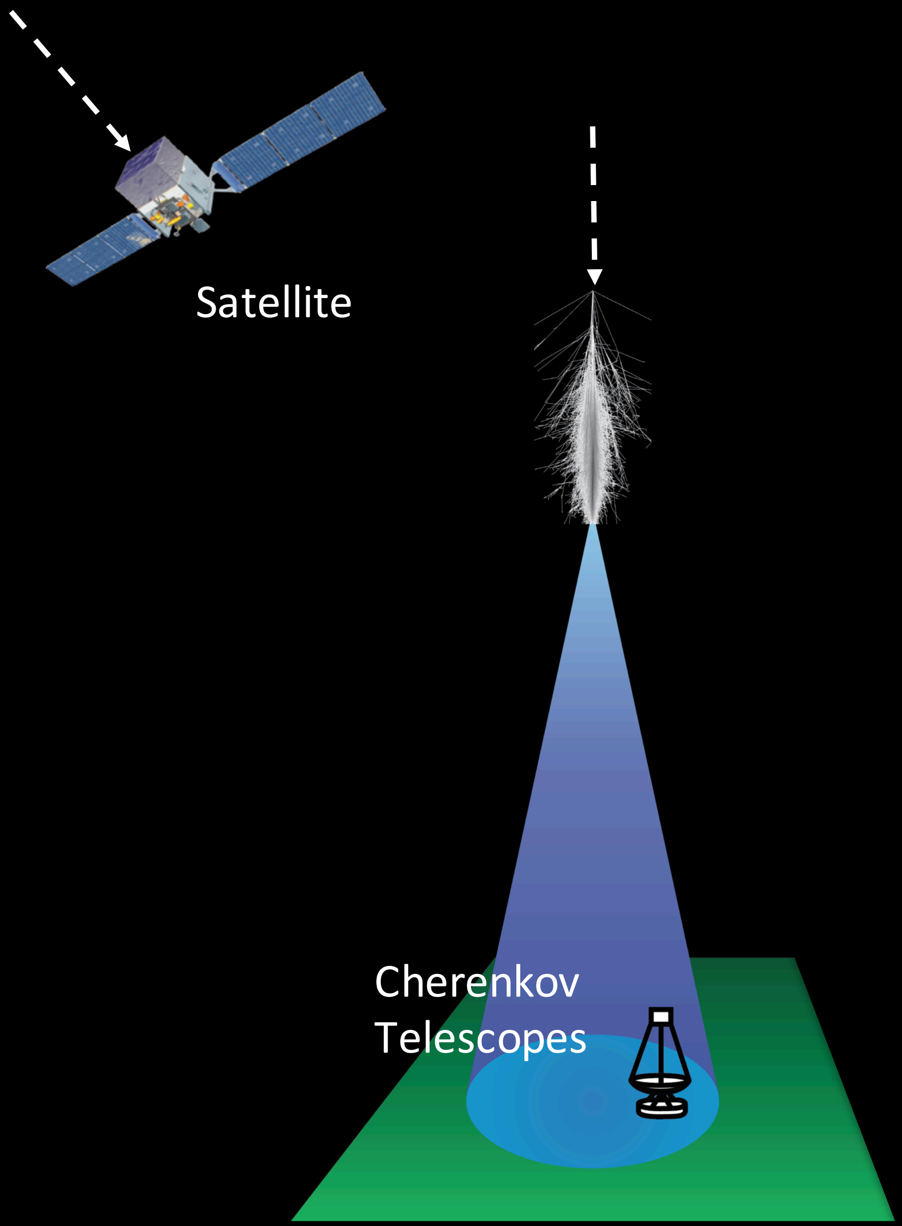
(Very) High Energy Gamma Rays

- Astrophysical gamma rays
  - Energy region of interest from GeVs to hundreds TeVs
- Scientific interest:
  - Key to understand the **acceleration mechanism** of cosmic rays in our galaxy
  - Violent astrophysical phenomena: pulsars and black holes
  - Galactic magnetic fields
  - Photon radiation fields in the Universe
  - Indirect search of **dark matter** (WIMP interactions)
  - Test fundamental properties of quantum gravity
  - …

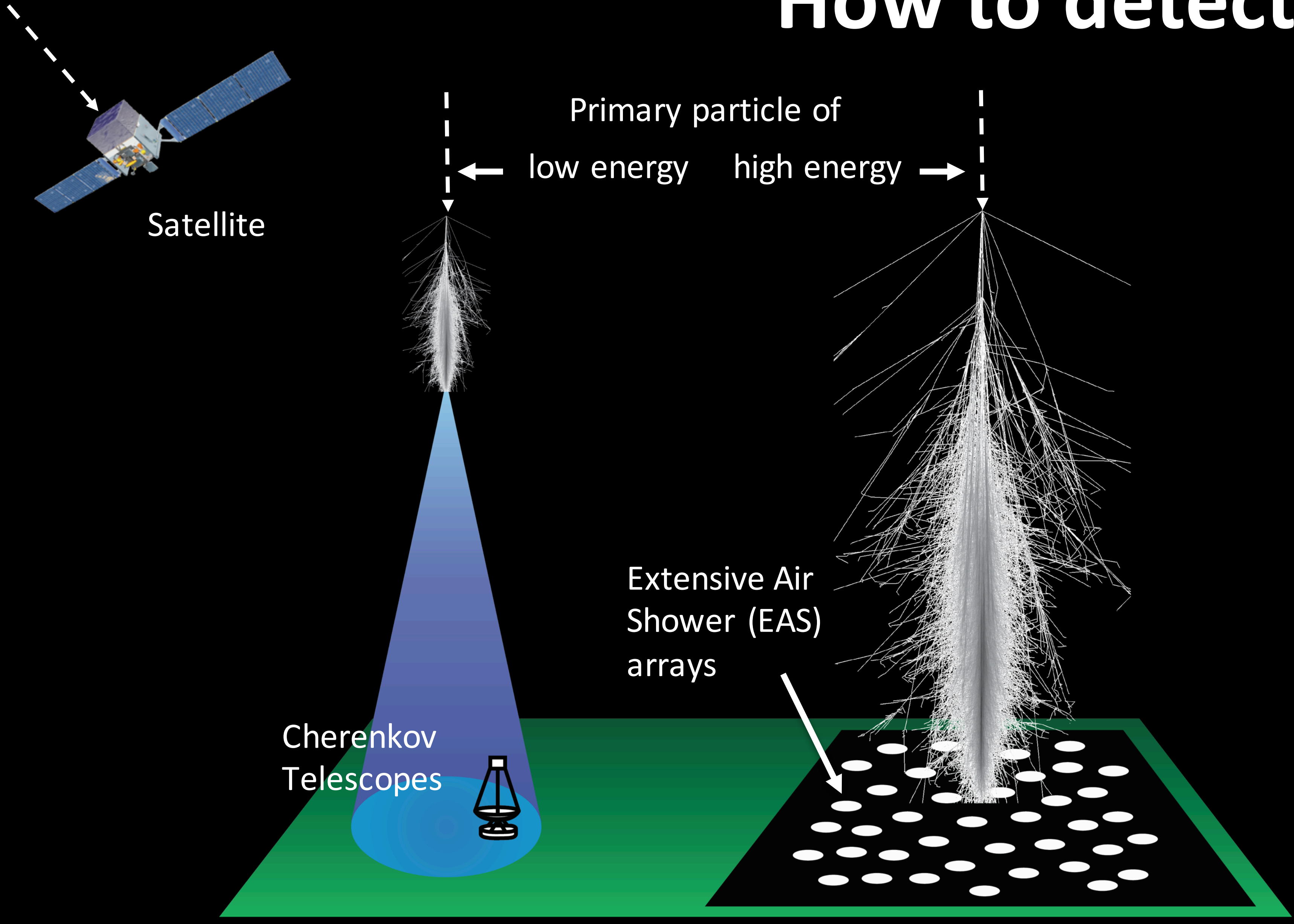
How to detect?

Satellite

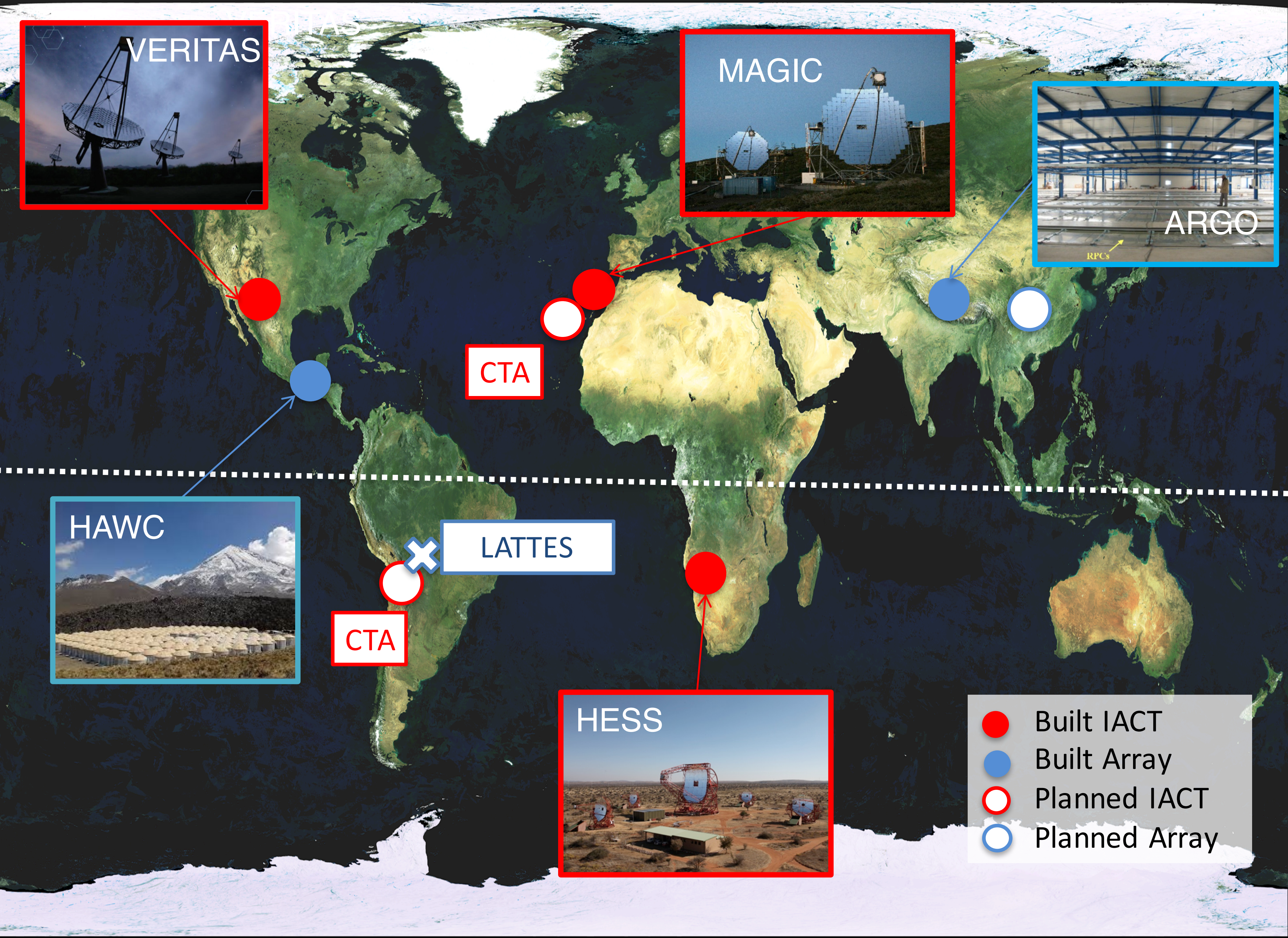
How to detect?



How to detect?

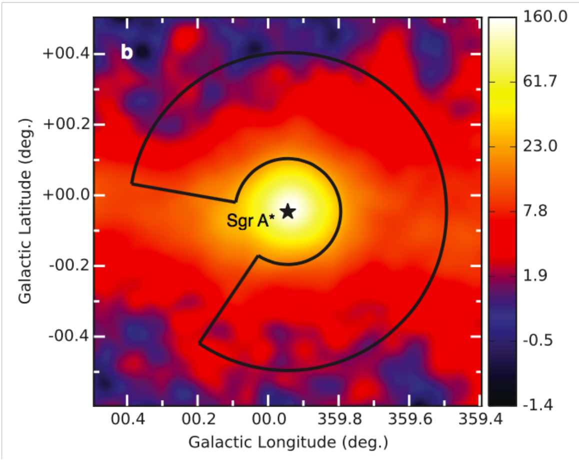


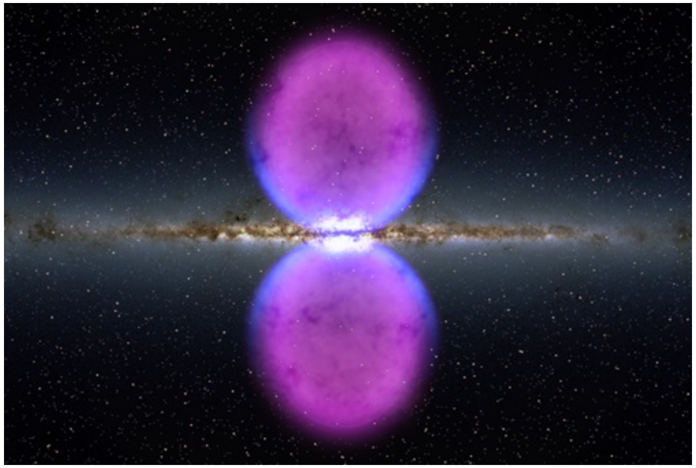
Arrays at high-altitude = large field of view + large duty cycle + low energy


VERITAS
MAGIC
ARGO
RPCs
CTA
HAWC
LATTES
CTA
HESS
Built IACT
Built Array
Planned IACT
Planned Array

What we know so far...

- Protons are known to be accelerated in the galaxy up to PeV energies (E = 10^{15} eV)
- All current acceleration models encounter non-trivial difficulties at these energies
- HESS data suggests that there might be a PeVatron source in the galactic center
- Fermi bubbles - gamma ray emission in outbursts from our galaxy

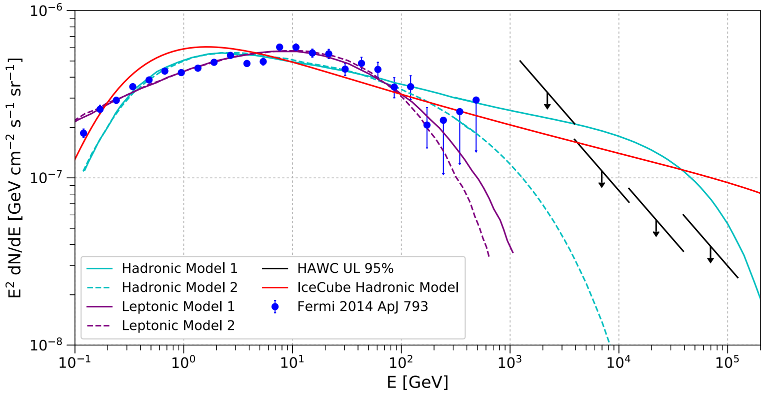




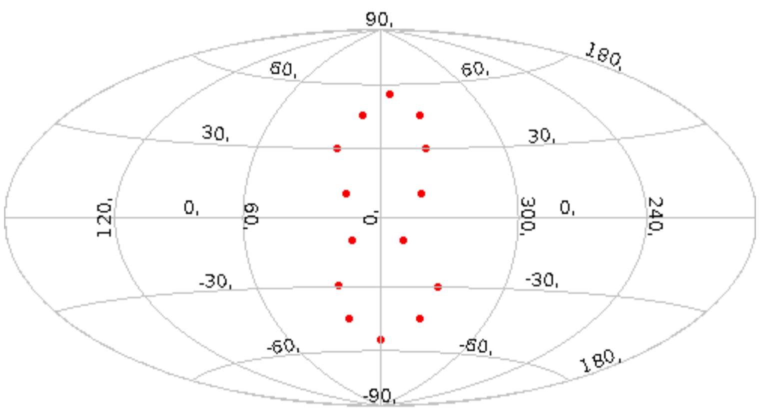
The future…

- Higher sensitivity experiments planned to be built in the Southern Hemisphere
  - CTA
  - LATTES (LIP w/ leading role)…

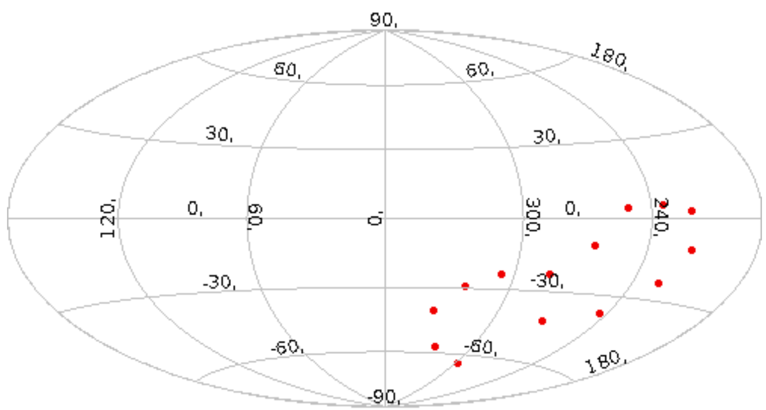
Fermi bubbles



Galactic Coordinates

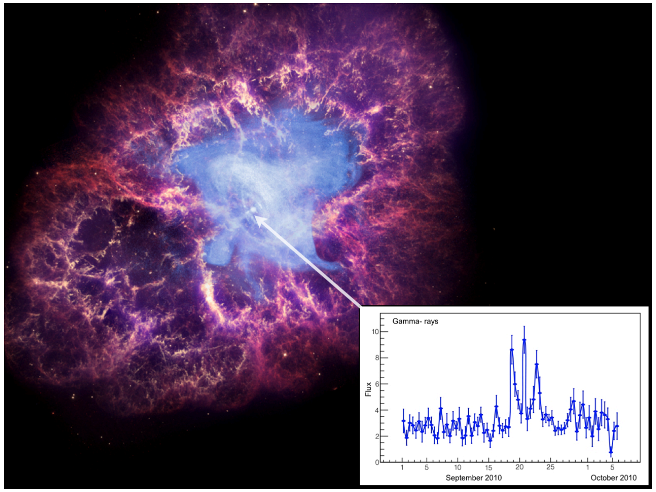


Equatorial Coordinates



The future…

- Higher sensitivity experiments planned to be built in the Southern Hemisphere
  - CTA
  - LATTES (LIP w/ leading role)…
- Detect and follow transient phenomena
  - Large field of view



The future…

- Higher sensitivity experiments planned to be built in the Southern Hemisphere
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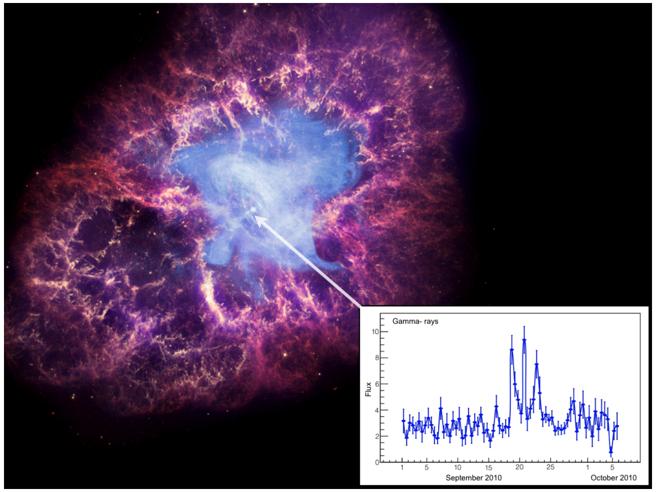
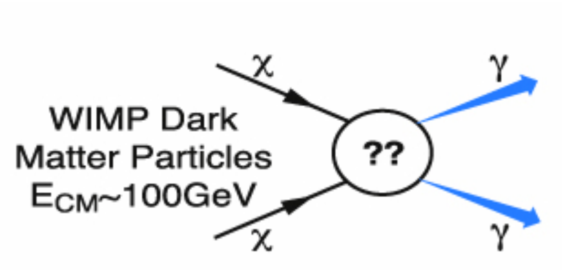
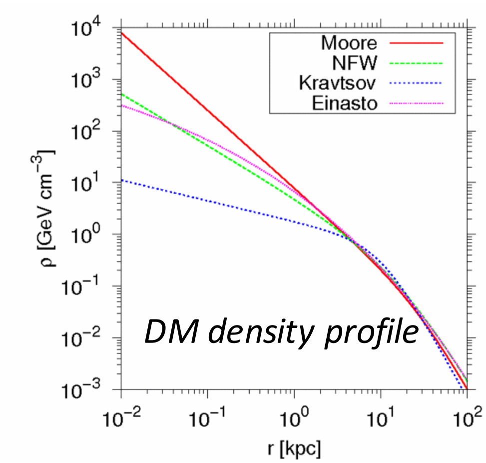
  - LATTES (LIP w/ leading role)…



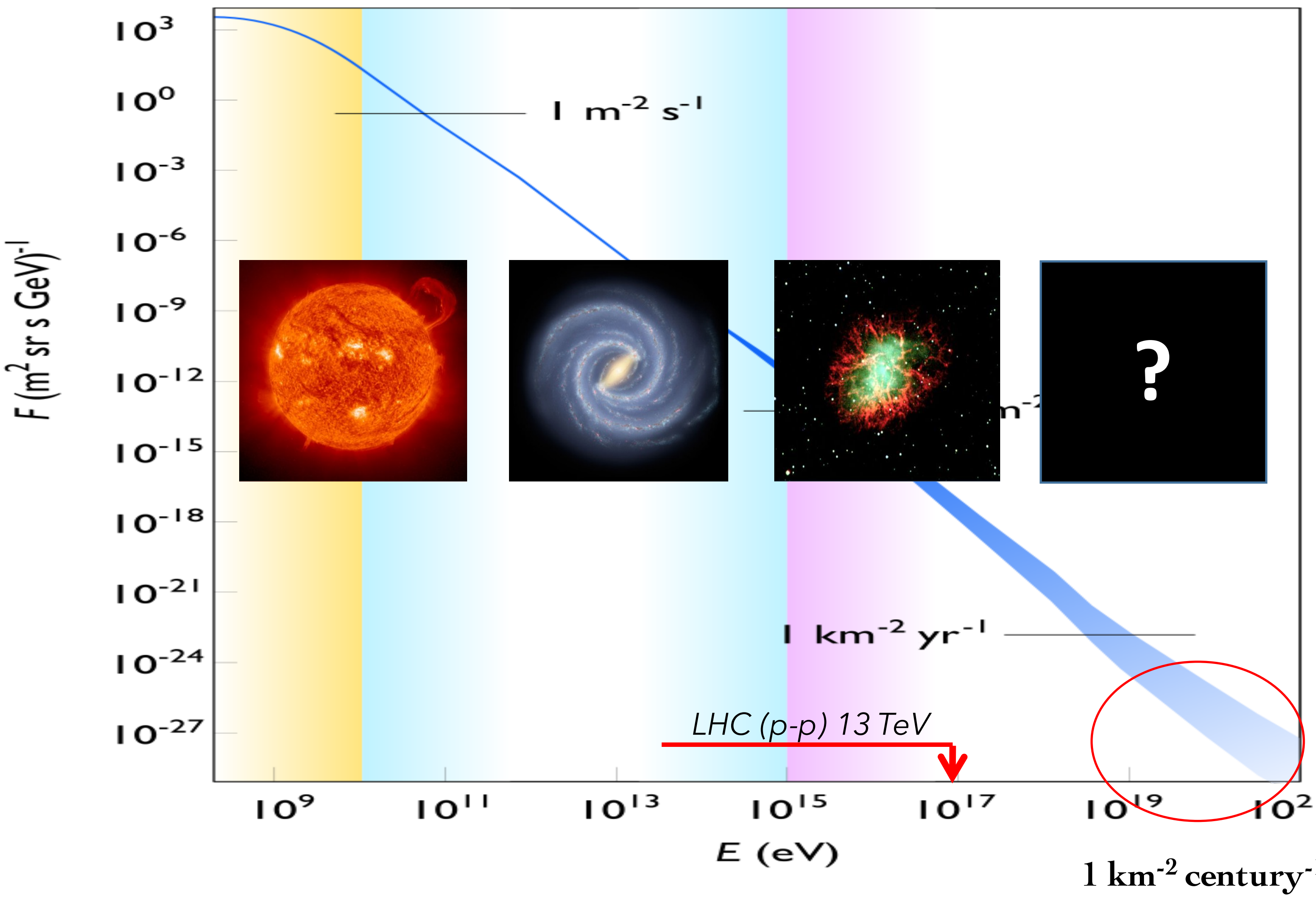
- Detect and follow transient phenomena
  - Large field of view
- Look for dark matter at the center of the galaxy





Ultra High-Energy Cosmic Rays

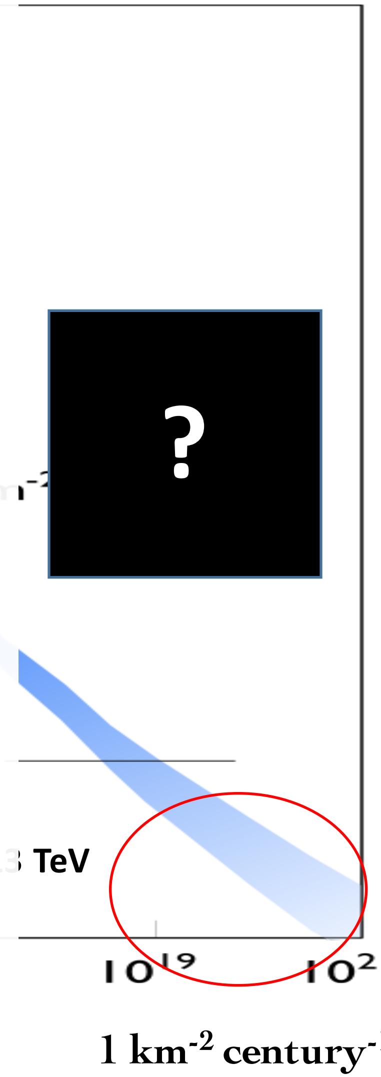
Ultra High Energy Cosmic Rays



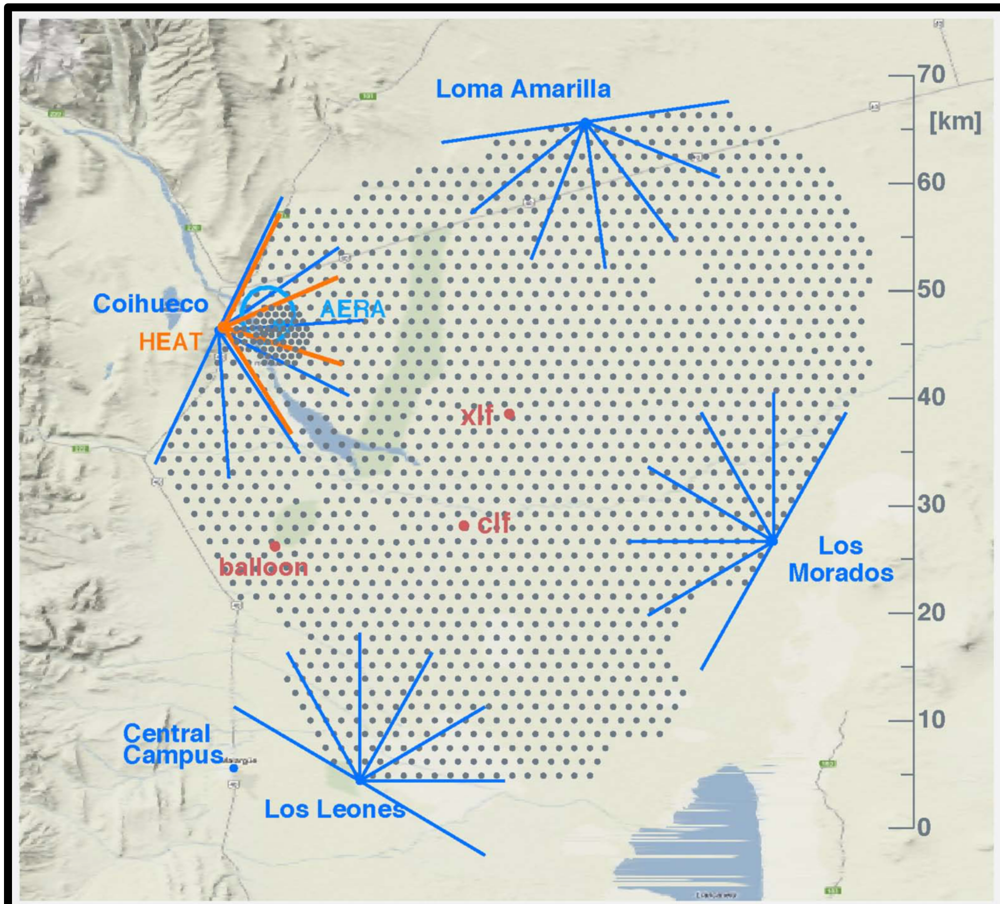
Ultra High Energy Cosmic Rays

- Opportunity to understand high-energy Universe
  - Production (sources; acceleration mechanisms…)
  - Propagation (Magnetic fields…)

- Opportunity to test particle physics at energies above the LHC
  - High-energy interactions
    - $E = 10^{19}$ eV => sqrt(s) ~ 130 TeV
  - Different kinematic regimes
    - E_{beam} up to 10^{8} TeV



Pierre Auger Observatory

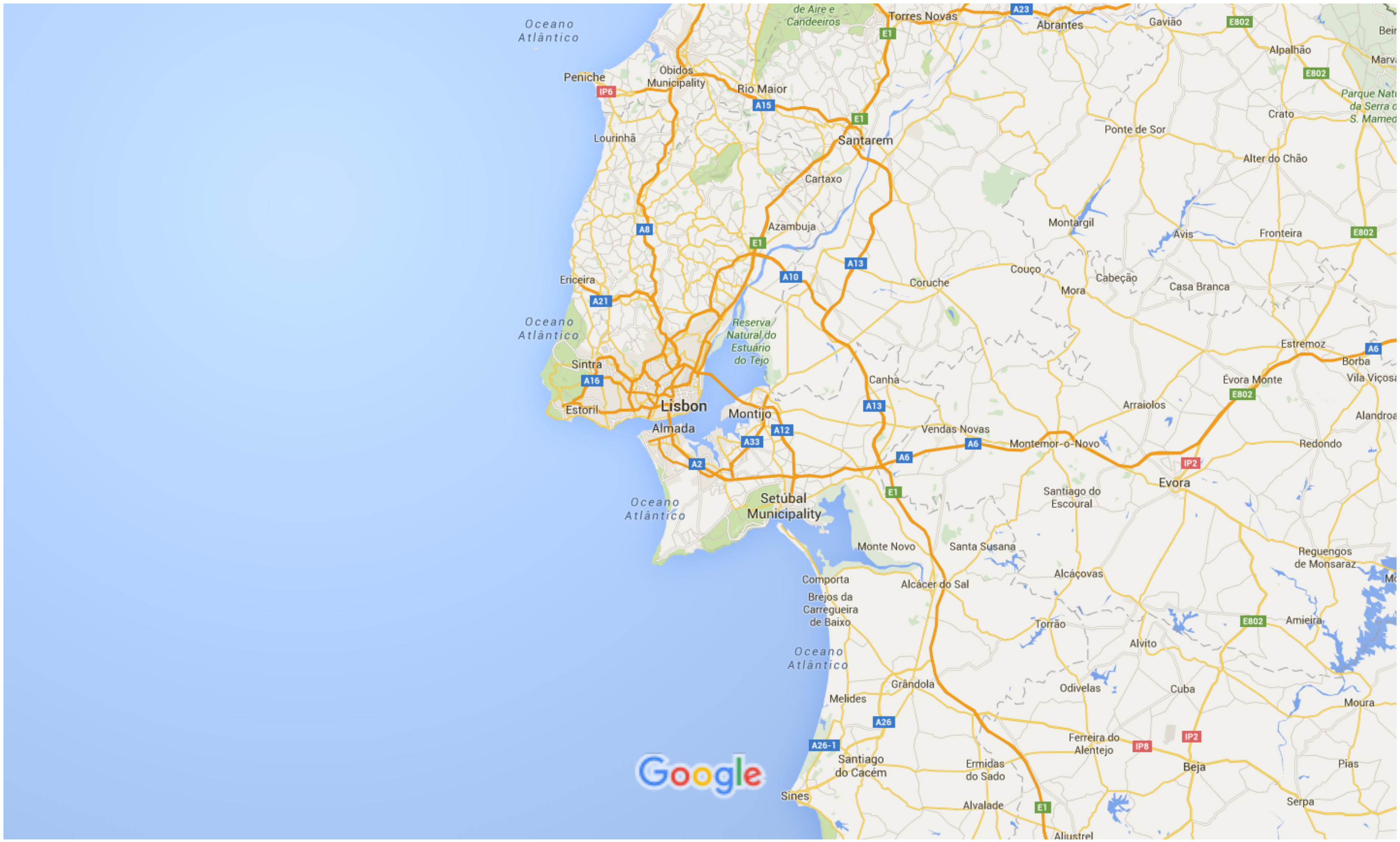


Area: 3000 km^2

Located in the Pampa Amarilla, Mendoza, Argentina

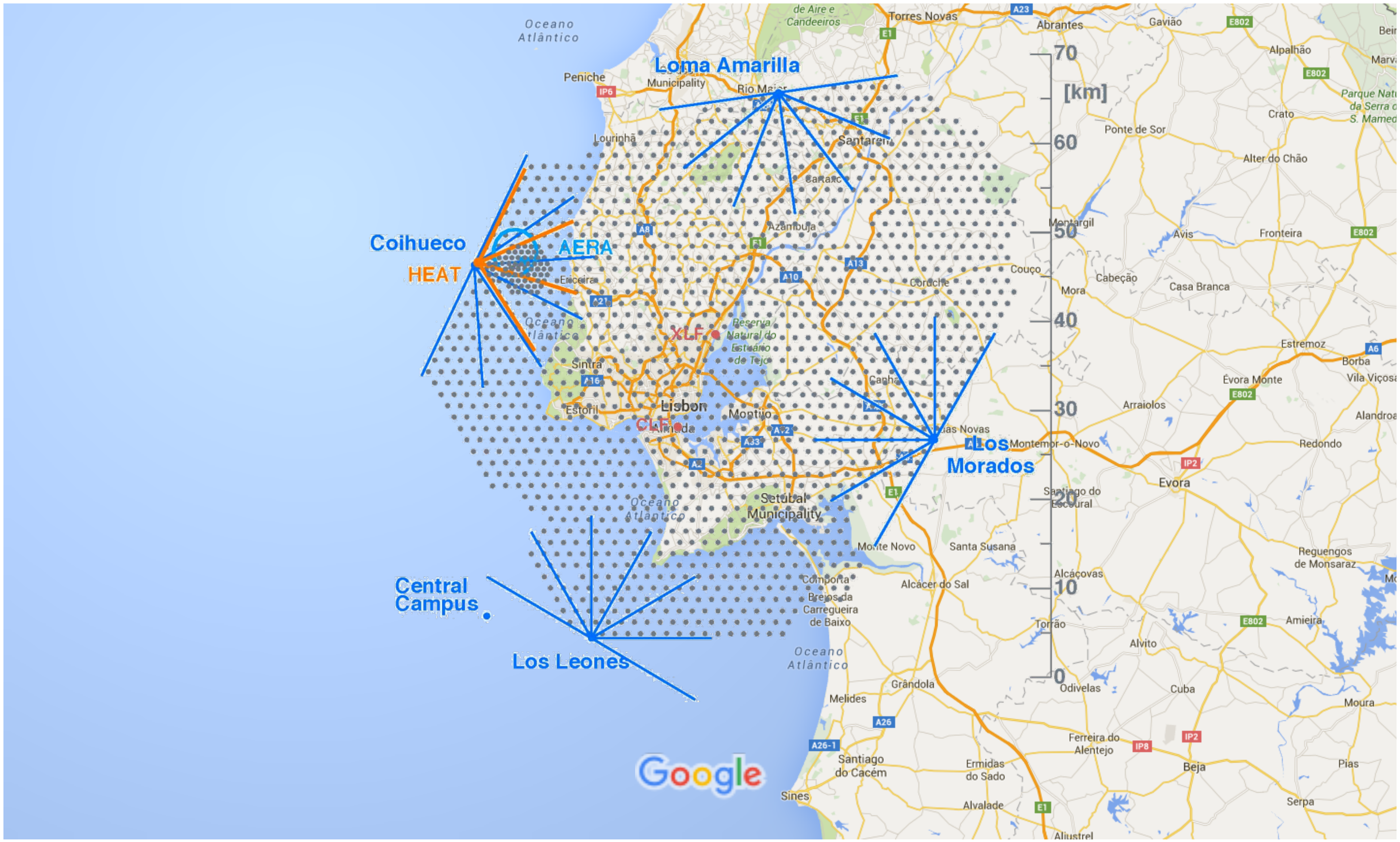
Altitude: 1400 m a.s.l.

How big is it?



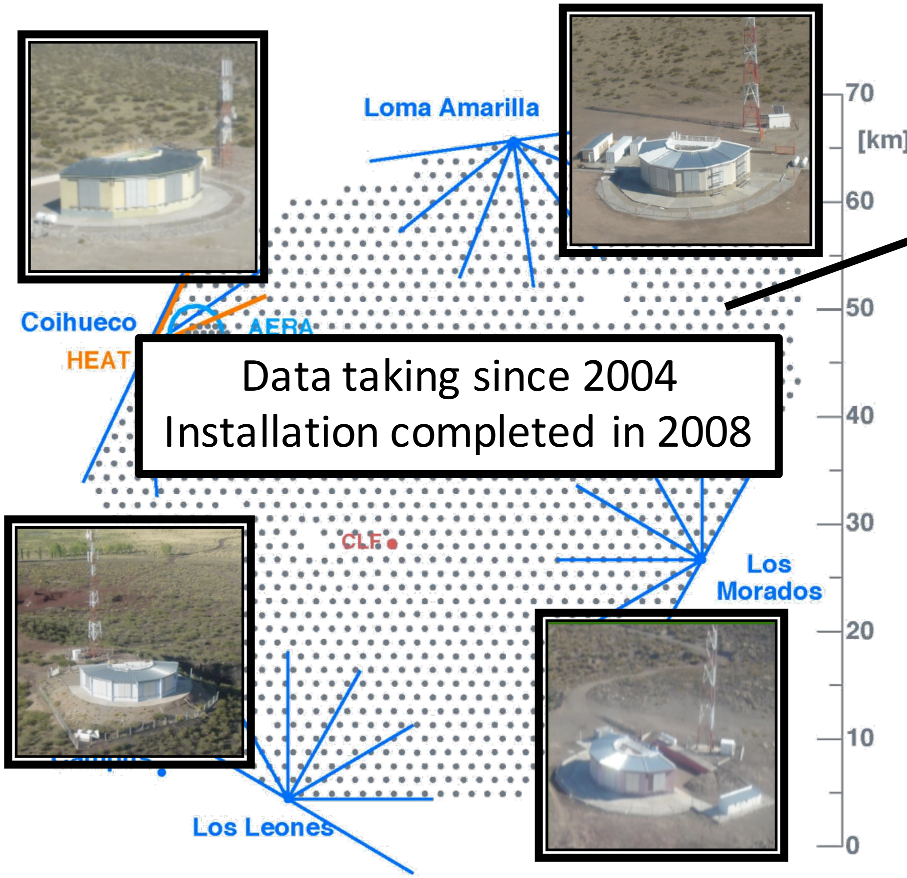
Map data ©2016 Google, Inst. Geogr. Nacional 20 km

Really big!!



Map data ©2016 Google, Inst. Geogr. Nacional 20 km

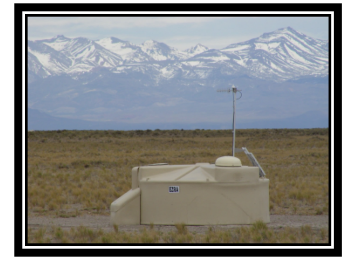
Pierre Auger Observatory



Data taking since 2004
Installation completed in 2008

~ 60 km

- 4 Fluorescence Detectors (FD)
- 6 x 4 Fluorescence Telescopes

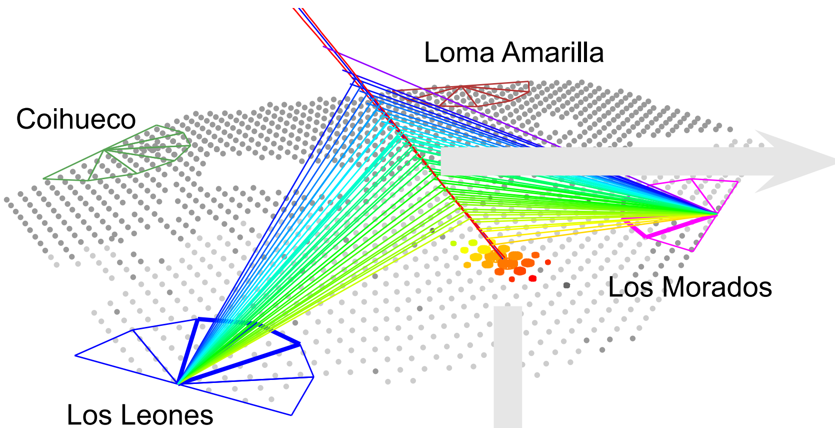


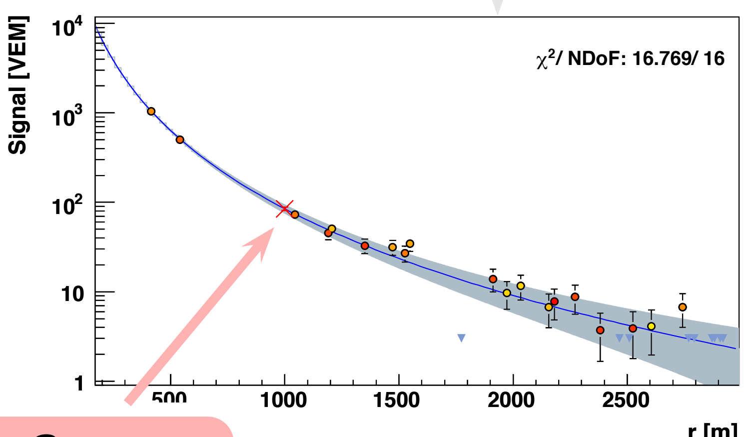
- ~ 1600 Surface Detector (SD) Stations
- 1.5 km spacing
- 3000 km^2

Low energy extension

- ✧ Aim to E ≈ 10^{17} eV
- ✧ AMIGA
  - ✧ Denser array plus muon detectors
- ✧ HEAT
  - ✧ 3 additional FD telescopes with a high elevation FoV

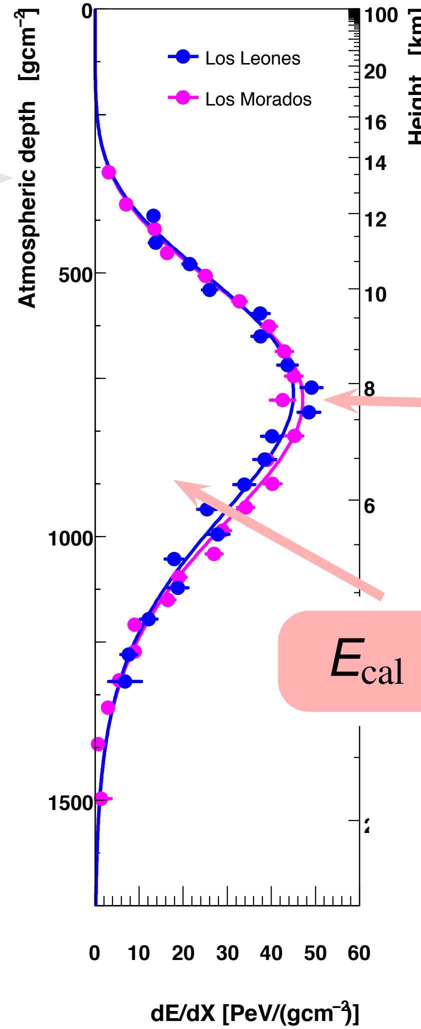
Hybrid Technique





S_{1000}

$E_{\rm surface} = f(S_{1000},\ \theta)$



$\sigma_{X_{\rm max}} \leq 20\,{\rm g/cm^2}$
$\Delta_{\rm sys} \leq 10\,{\rm g/cm^2}$

$X_{\rm max}$

$E_{\rm cal} = \int \frac{dE}{dX}\,dX$

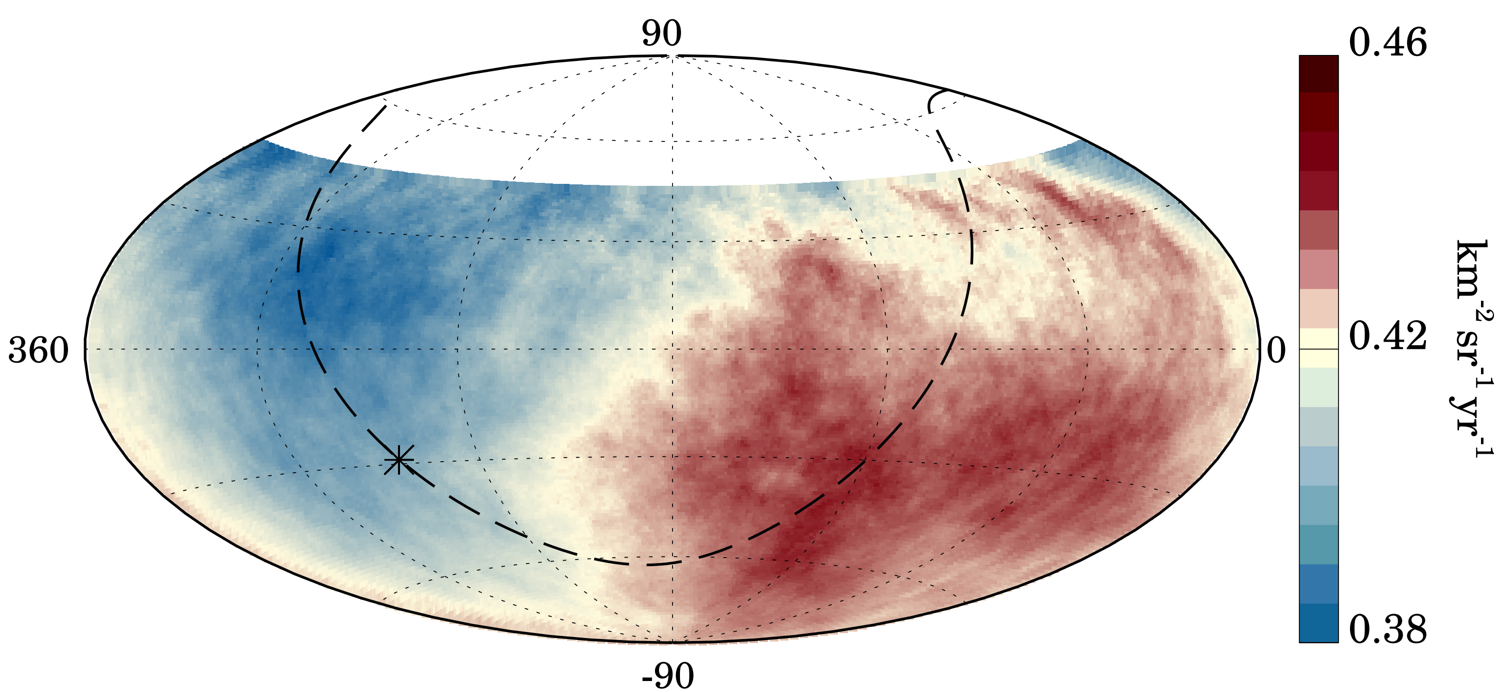
$\sigma_E/E \sim 8\,\%$
$\Delta_{\rm sys} \approx 15\,\%$

What have we learned so far…

What have we learned so far…

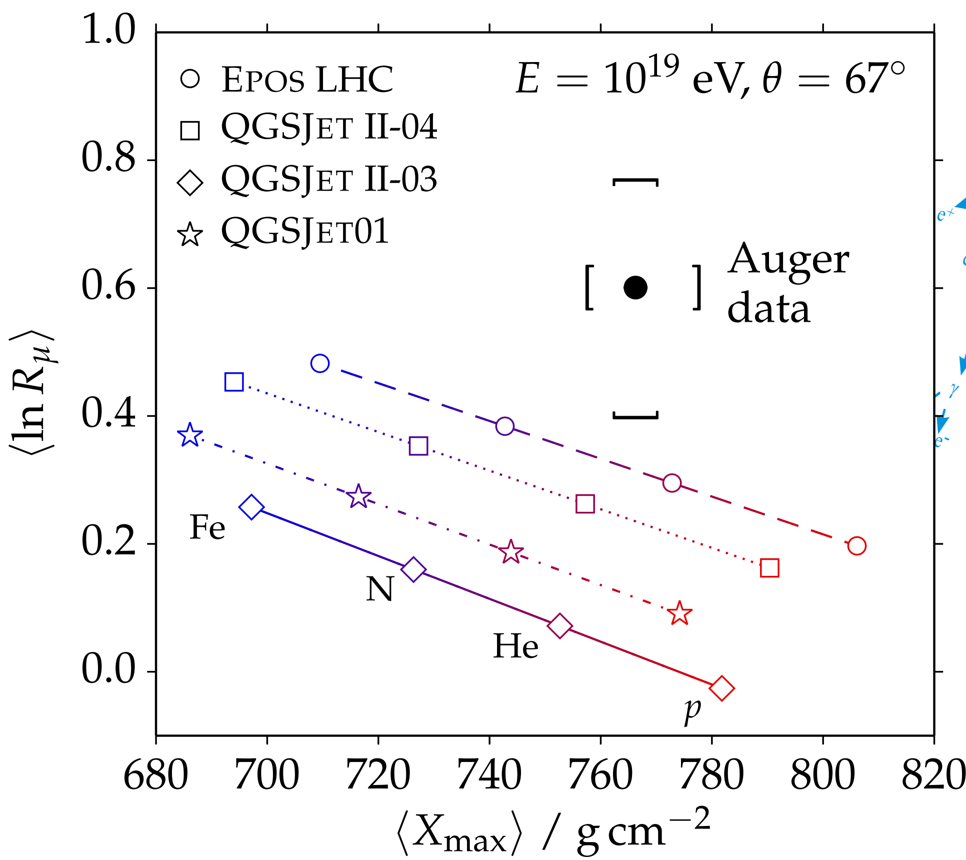
- UHECRs are accelerated:
  - somewhere in our Universe
    - from the photon and neutrino limits
  - Outside the galaxy

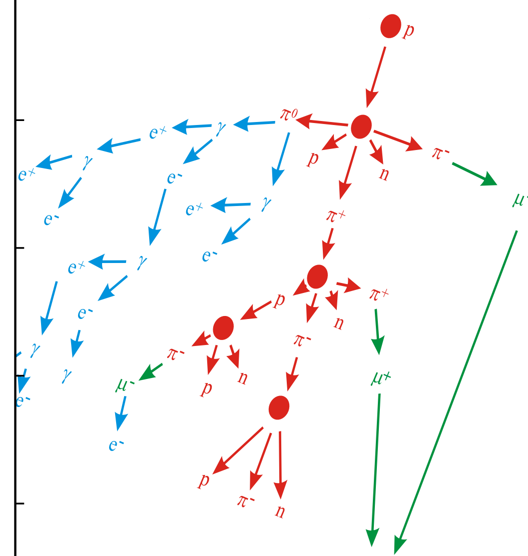
Science 357 (2017) no.6537, 1266-1270



Composition vs Hadronic interactions

Surface Detector





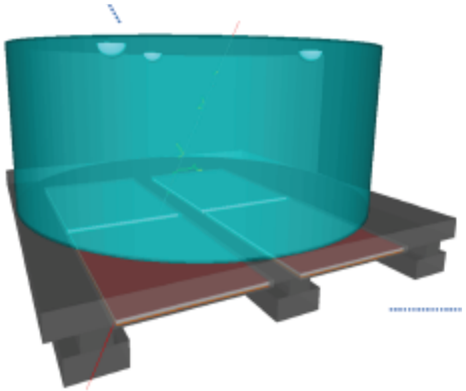
Fluorescence Detector

Combination of the number of muons R_μ with X_{max} reveals tension between data and all hadronic interaction models

The future of UHECRs…

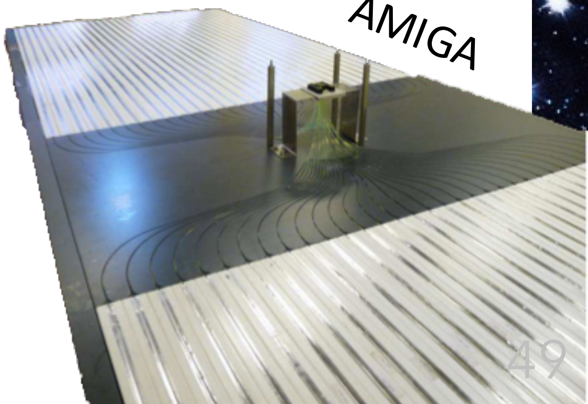
- Gain better understanding over the shower physical mechanisms
  - Use LHC data to better tune the hadronic interaction models at low energy
  - Auger upgrade
    - Auger PRIME (operates until 2025)
    - Put a scintillator on top of the SD
    - Complementary information to separate the muon from the e.m. shower component
  - Several R&D projects
    - EAS radio detection
    - MARTA engineering array
      - RPCs below the tank
    - AMIGA
      - Scintillators below the ground

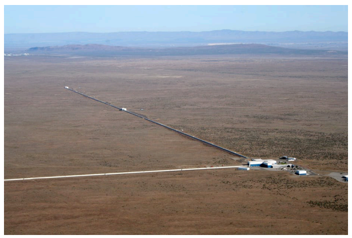
Auger PRIME SSD



MARTA

AMIGA







Multi-messengers

The opening of a new era…

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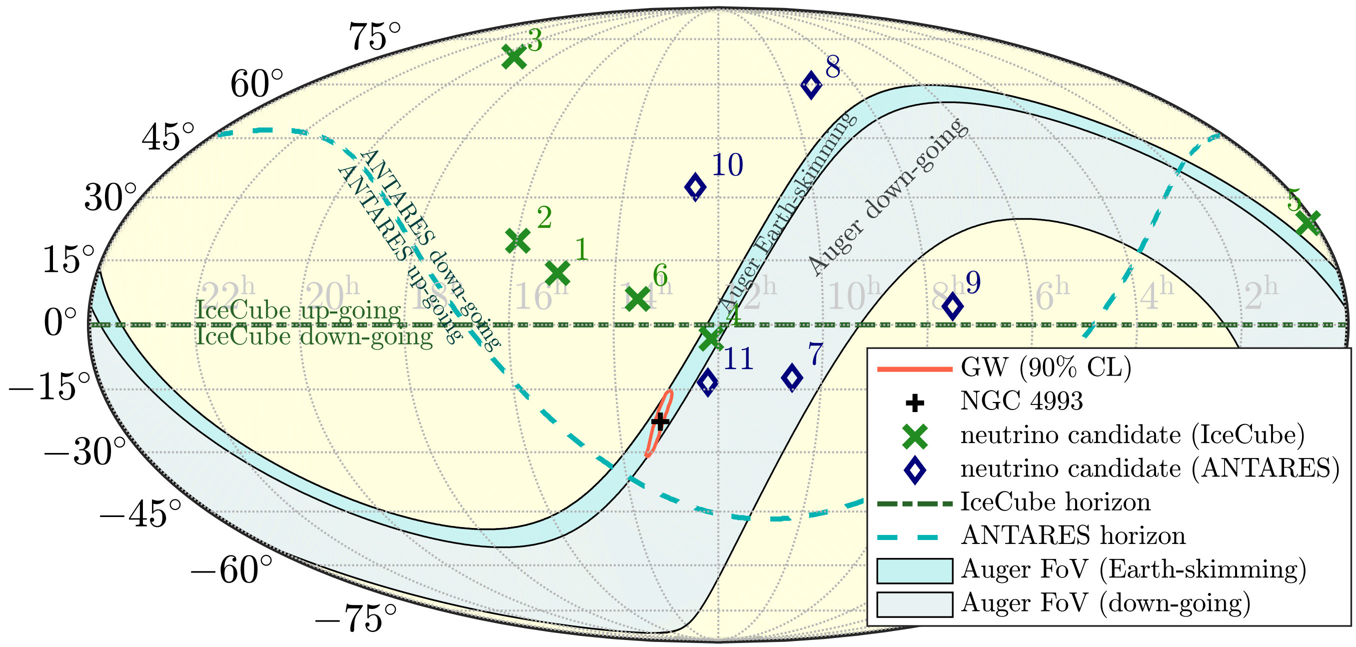
Multi-messenger observation of a Binary Neutron Star Merger



- ✧ Non-detection of high-energy neutrinos correlated with the Gravitational Wave (GW)
- ✧ Observations consistent with theoretical expectation

Multi-messenger observation of a Binary Neutron Star Merger

THE ASTROPHYSICAL JOURNAL LETTERS, 848:L12 (59pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa91c9

Multi-messenger Observations of a Binary Neutron Star Merger

LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech-NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT
(See the end matter for the full list of authors.)

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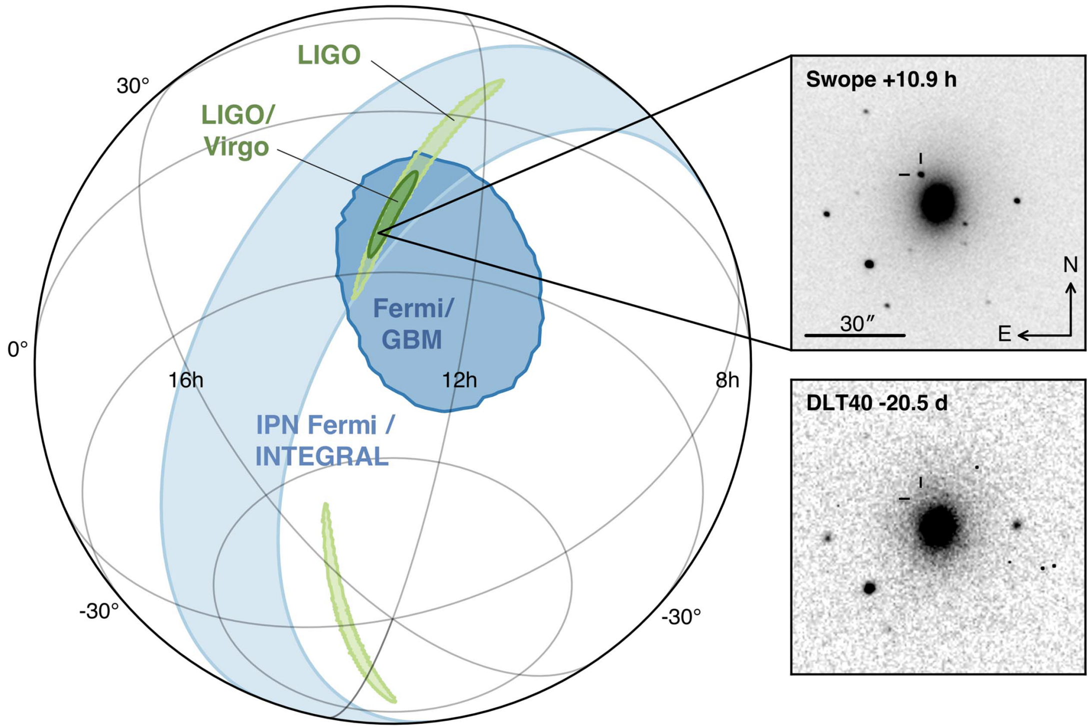
- Paper appeared in arXiv in October 2017
- Already with about 350 citations

Multi-messenger observation of a Binary Neutron Star Merger

physicsworld
BREAKTHROUGH OF THE YEAR 2017

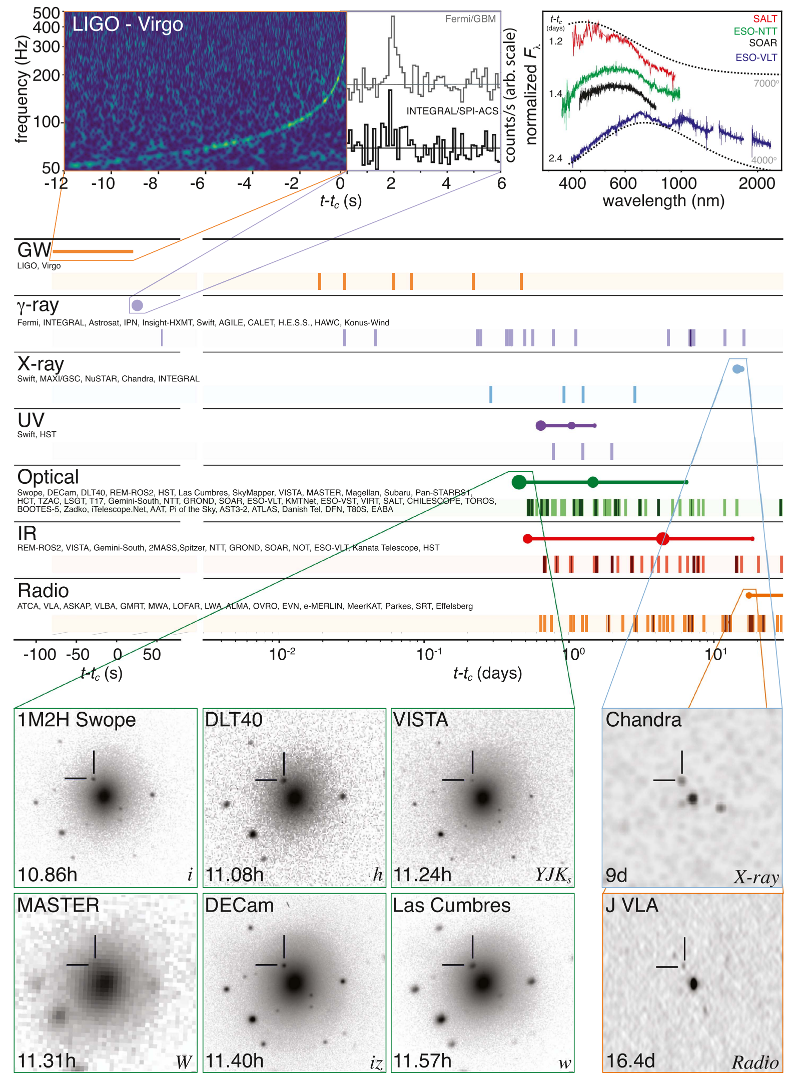
Joint publication of LIGO, VIRGO, INTEGRAL, Fermi, IceCube, Pierre Auger …



- Simultaneous observation of a Gravitational Wave + electromagnetic counter parts
- Allows to test the dynamics of our surrounding Universe
- Study of transient phenomena in all energy regions is one of the main ingredients

Multi-messenger observation of a Binary Neutron Star Merger

- ✧ Observe the same phenomenon with different instruments
- ✧ Follow the evolution in time
- ✧ Different wavelengths ⇒ different kind of interactions ⇒ different phenomena



Summary

- Astroparticle physics (Multi-Messengers)
  - Use astrophysical messengers and known particle physics to gain a deeper understanding of the dynamics of our Universe
  - Rapidly evolving field
  - Lots of ambitious projects
  - Will soon provide important tests to our knowledge over fundamental physics

Acknowledgements

FCT
Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

COMPETE
PROGRAMA OPERACIONAL FACTORES DE COMPETITIVIDADE

QREN
QUADRO DE REFERÊNCIA ESTRATÉGICO NACIONAL
PORTUGAL 2007.2013

UNIÃO EUROPEIA
Fundo Europeu de Desenvolvimento Regional

LIP

TÉCNICO LISBOA

Backup slides

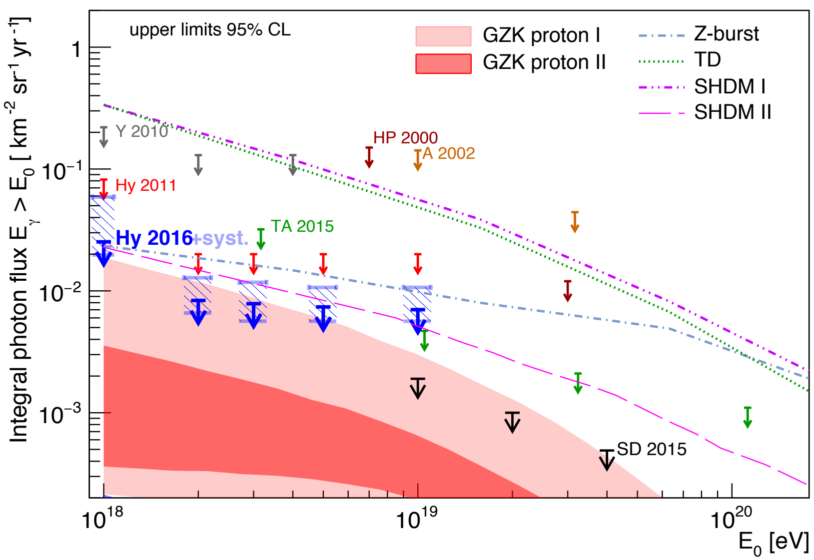
Pierre Auger Observatory

UHE Photons/Neutrinos

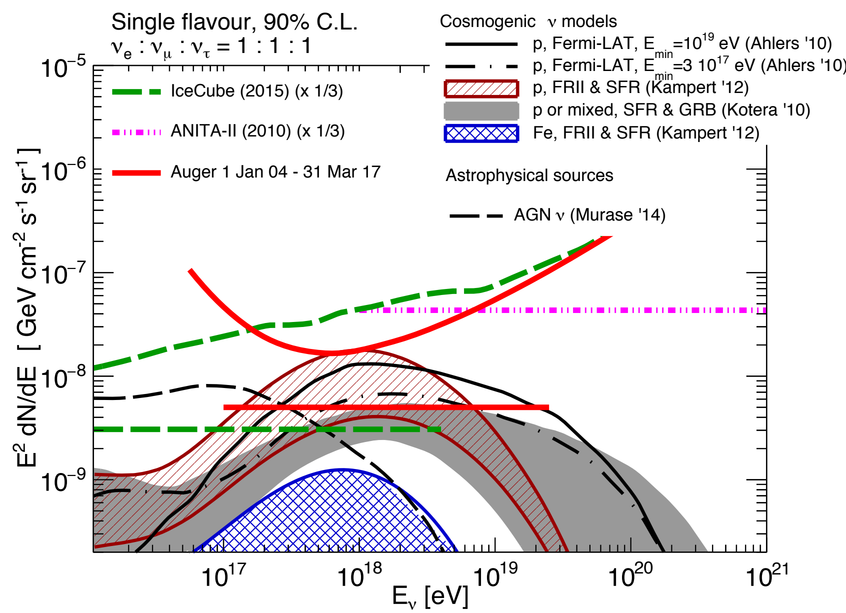
35th ICRC, PoS (2017) 517

35th ICRC, PoS (2017) 972

Photons



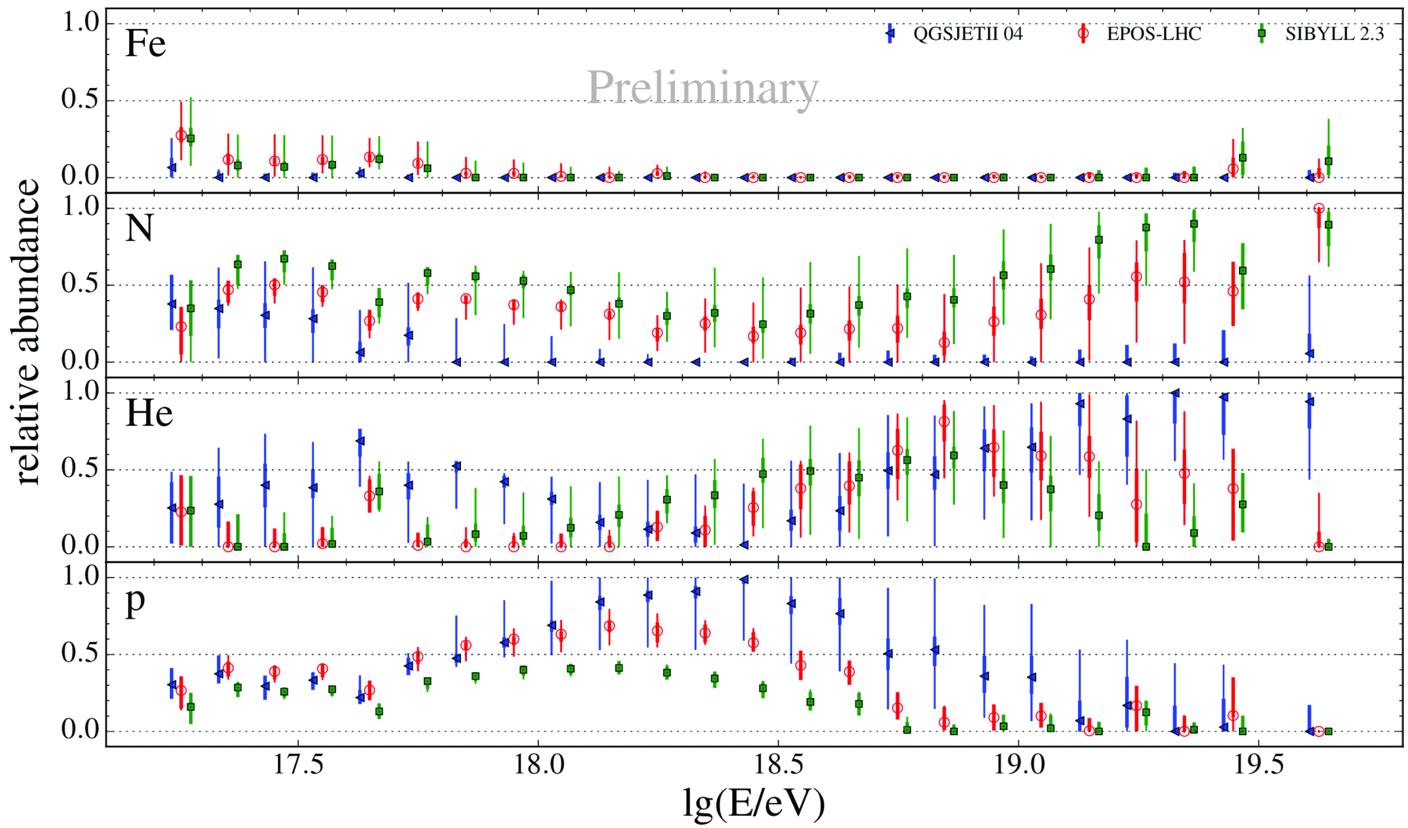
Neutrinos

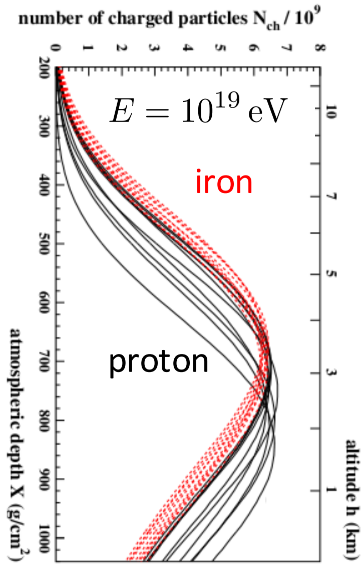


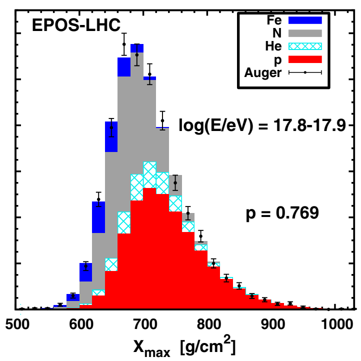
✧ The absence of photons and neutrinos strongly disfavors top-down acceleration models

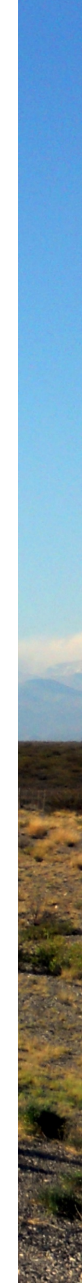
Composition fits to X_{max}

35th ICRC, PoS (2017) 506



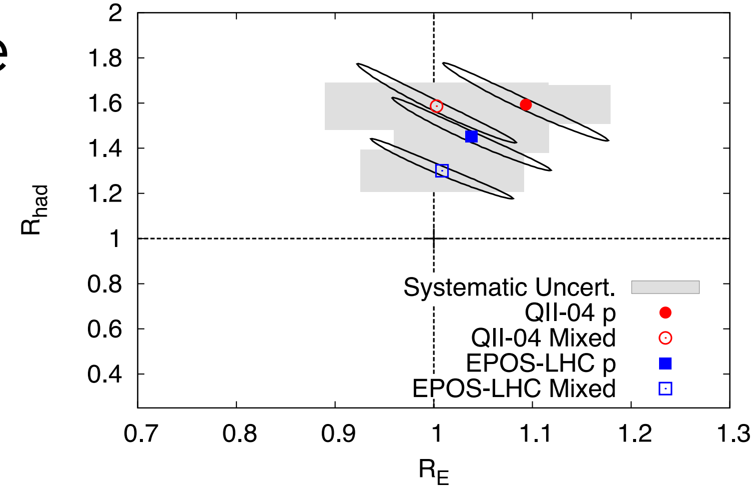






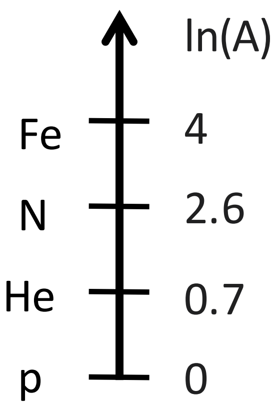
More trouble for Hadronic Interaction Models…

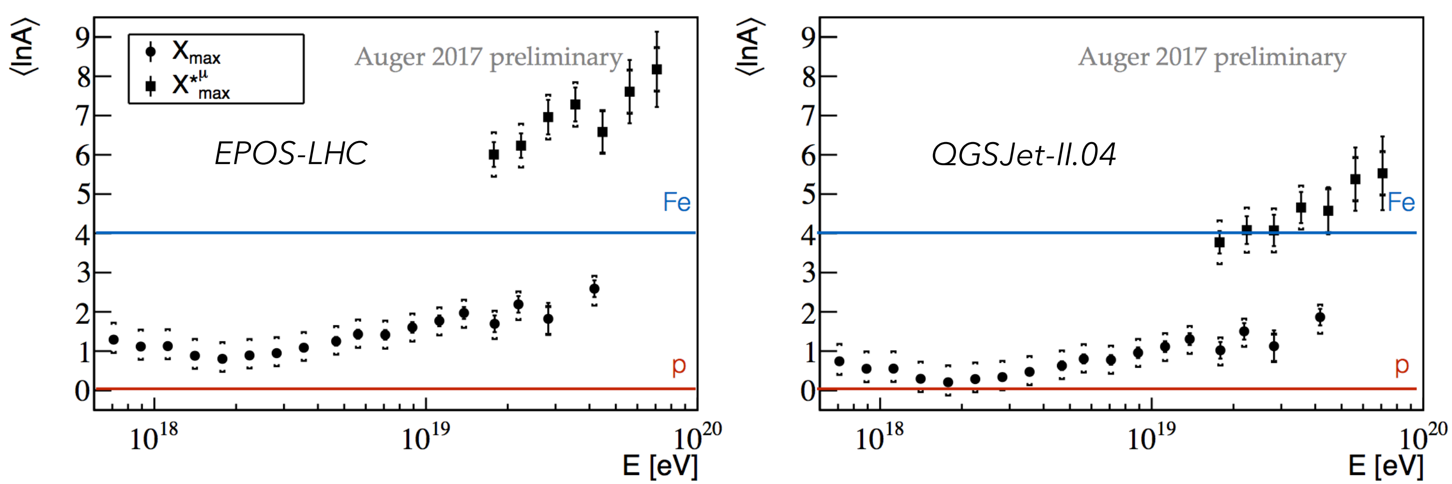
Phys.Rev.Lett. 117 (2016) no.19, 192001

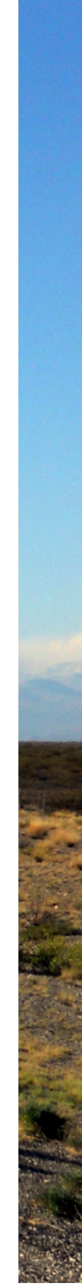


- ✧ Combined fit of energy scale (R_E) and hadronic component rescaling (R_{had}) [Hybrid: SD + FD]
- ✧ Depth of maximum of muon production depth ($X^{*\mu}_{max}$)

35th ICRC, PoS (2017) 398





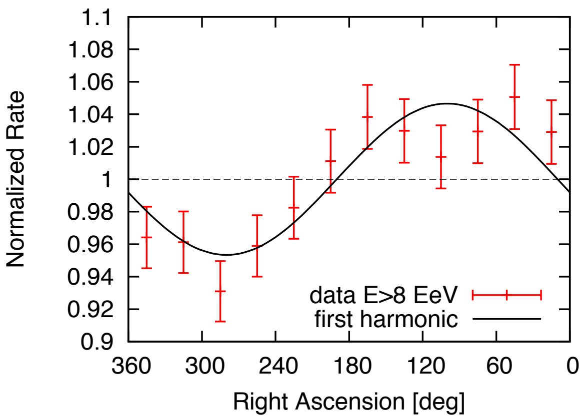


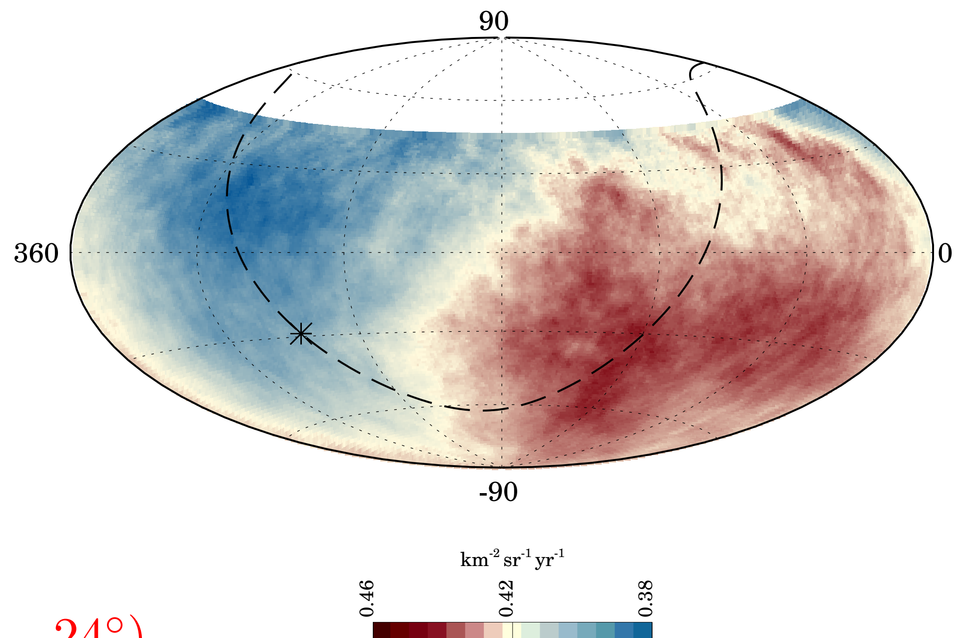
UHECRs dipole

Harmonic analysis in right ascension α

E [EeV]	events	amplitude r	phase [deg.]	$P(\geq r)$
4-8	81701	$0.005^{+0.006}_{-0.002}$	80 ± 60	0.60
> 8	32187	$0.047^{+0.008}_{-0.007}$	100 ± 10	2.6×10^{-8}

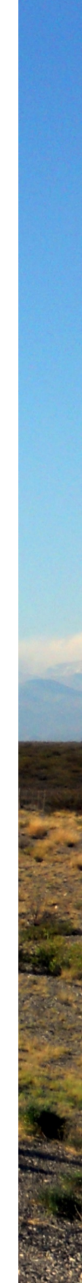
significant modulation at 5.2σ (5.6σ before penalization for energy bins explored)



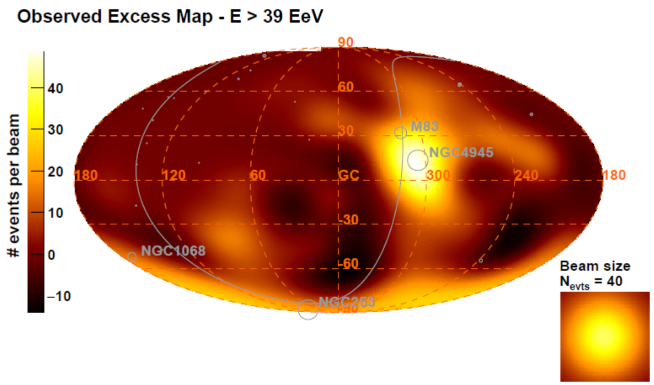


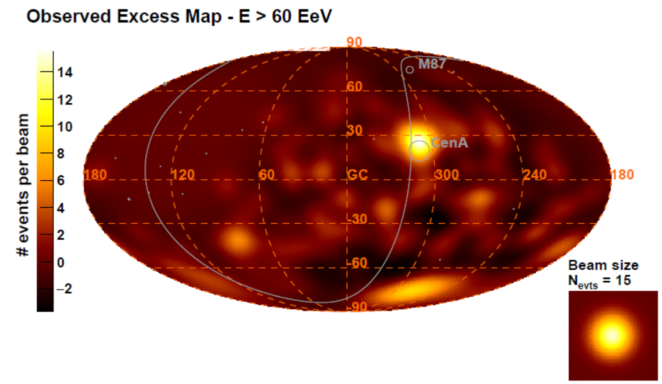
3-d dipole above 8 EeV:

$(6.5^{+1.3}_{-0.9})\%$ at $(\alpha, \delta) = (100°, -24°)$

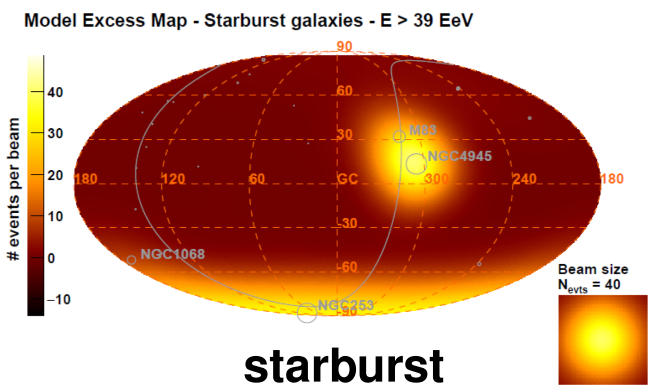


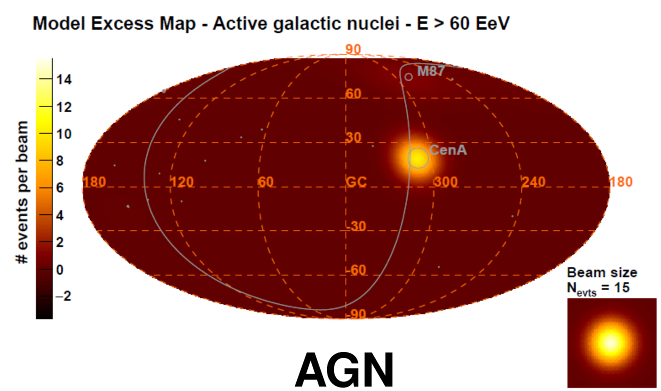
Search for intermediate scale anisotropy





preliminary



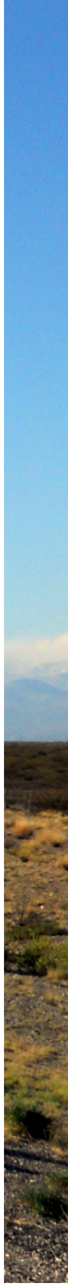


starburst

$f = 10\%,\ \psi = 13°$
pre-trial* p-value: 4×10^{-6}
post-trial** p-value: 4×10^{-5}
post-trial** significance: $3.9\,\sigma$

AGN

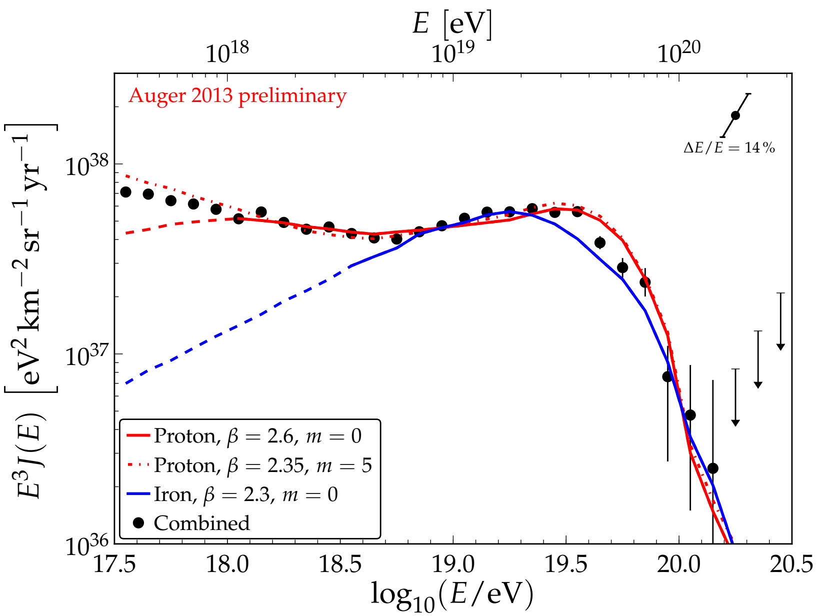
$f = 7\%,\ \psi = 7°$
pre-trial* p-value: 5×10^{-4}
post-trial** p-value: 3×10^{-3}
post-trial** significance: $2.7\,\sigma$



Two possible scenarios

Pure proton or Fe nuclei at source

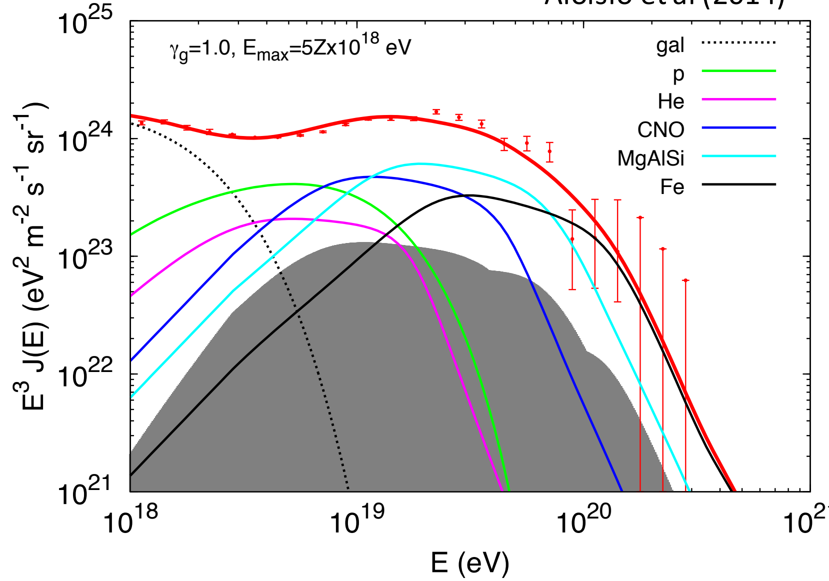
Cutoff caused by **GZK or photo-disintegration**

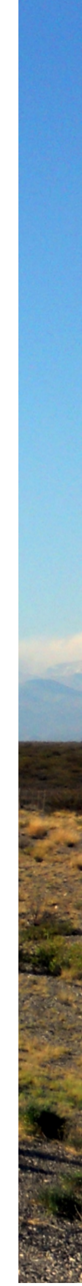


Mixed composition at source

Cutoff caused by **source energy exhaustion**

Aloisio et al (2014)

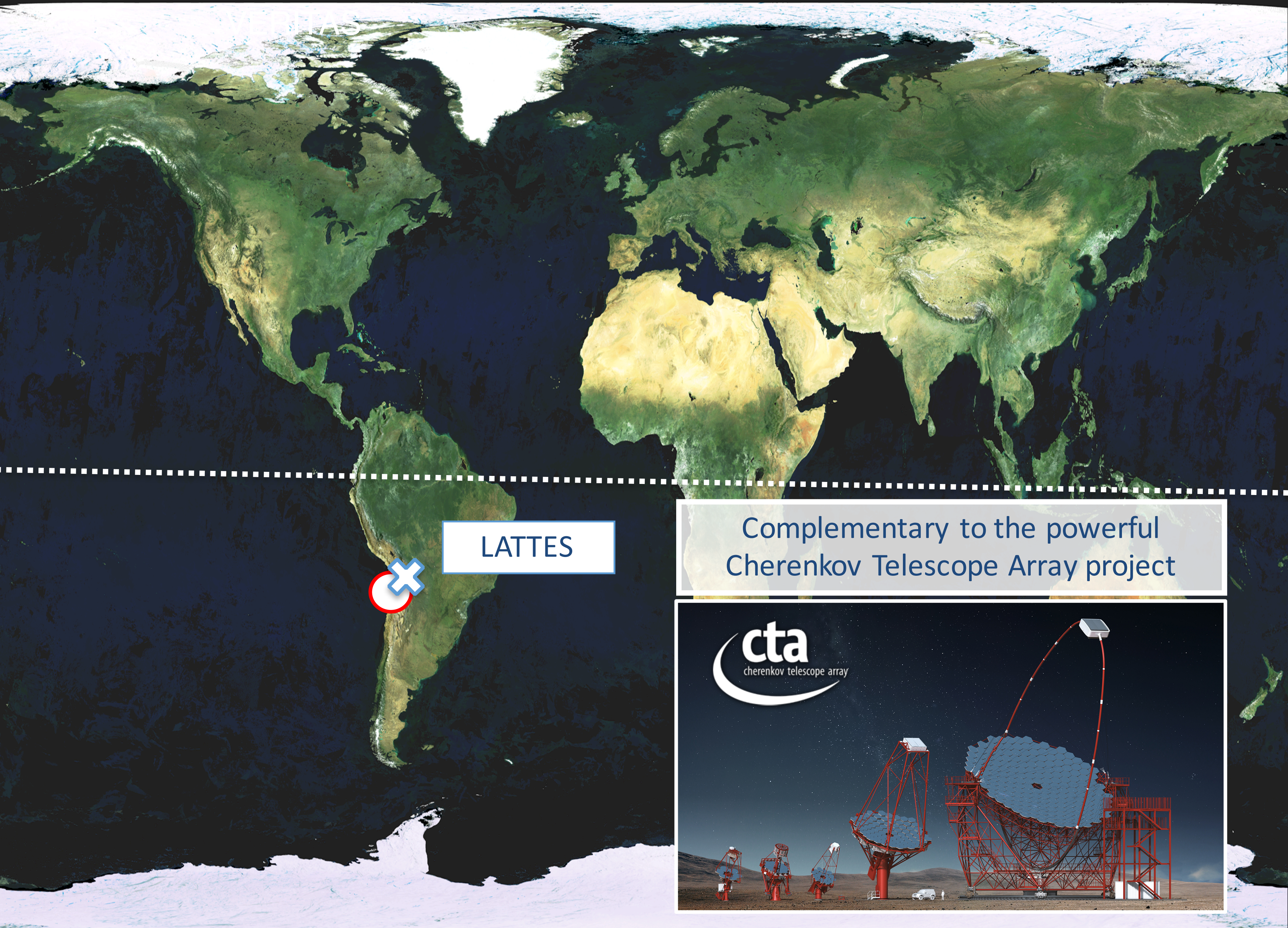




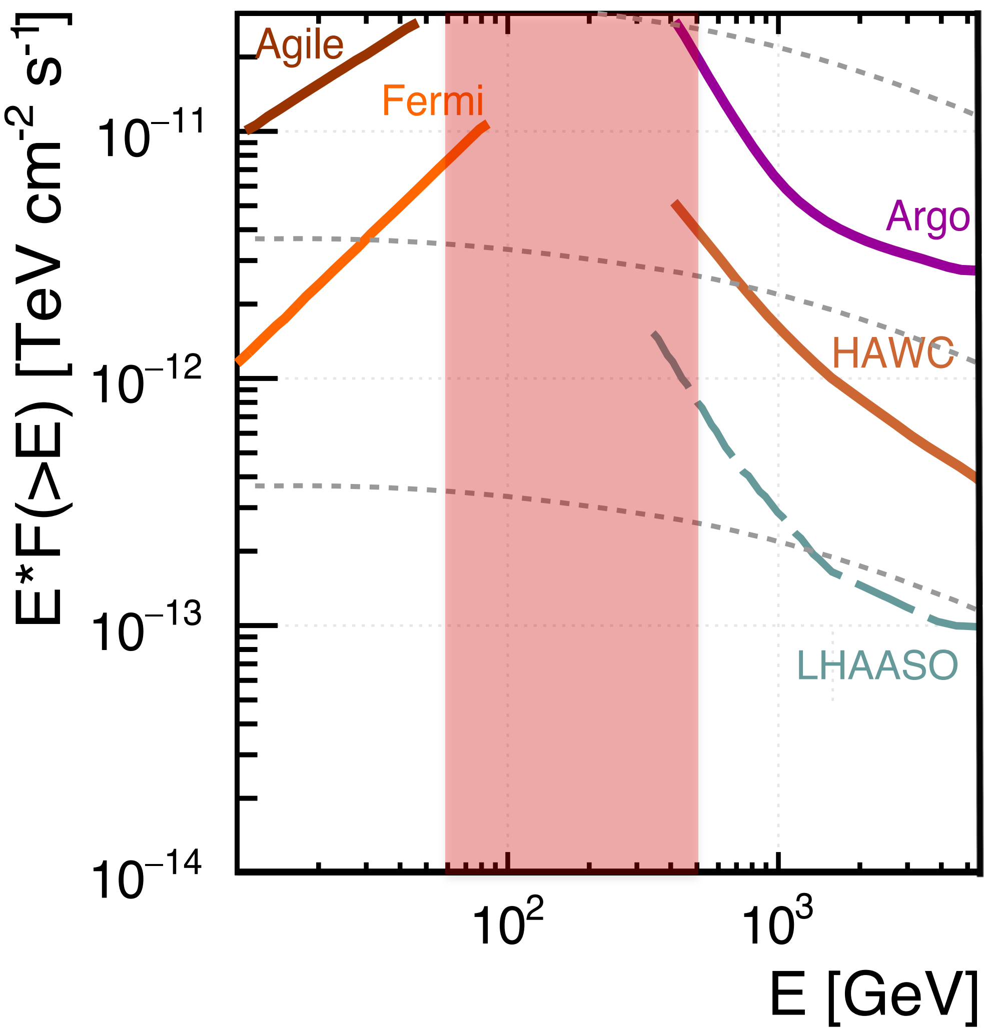
The UHECR composition is essential to understand the spectrum features cause

LATTES probable site


RPCs
ARGO
RPCs
LHASSO
HAWC
WCDs
LATTES
Scorpius
Sagittarius
Galactic Center

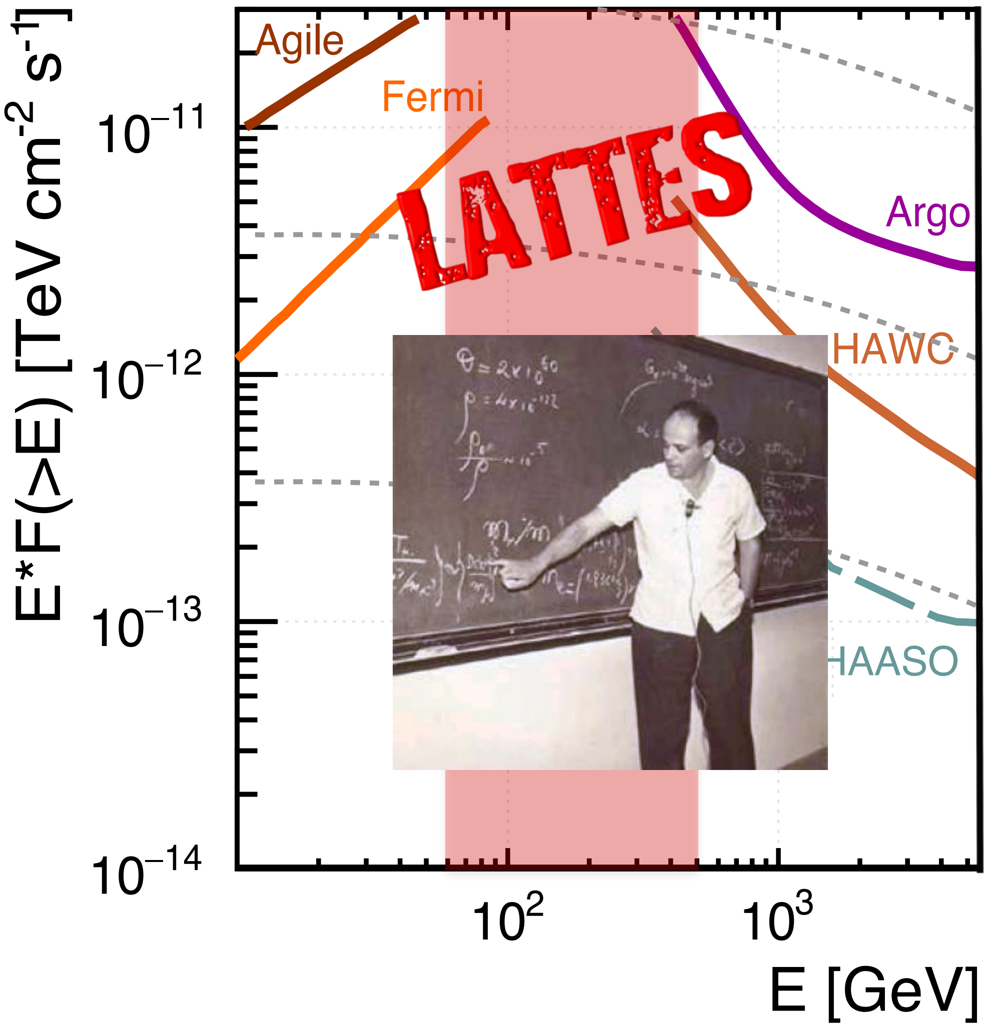

LATTES
Complementary to the powerful
Cherenkov Telescope Array project
cta
cherenkov telescope array

Requirements to build a Wide FoV gamma-ray observatory



- Located in the South Hemisphere
- Low energy threshold:
  - High altitude
  - Next generation detector concept

Requirements to build a Wide FoV gamma-ray observatory

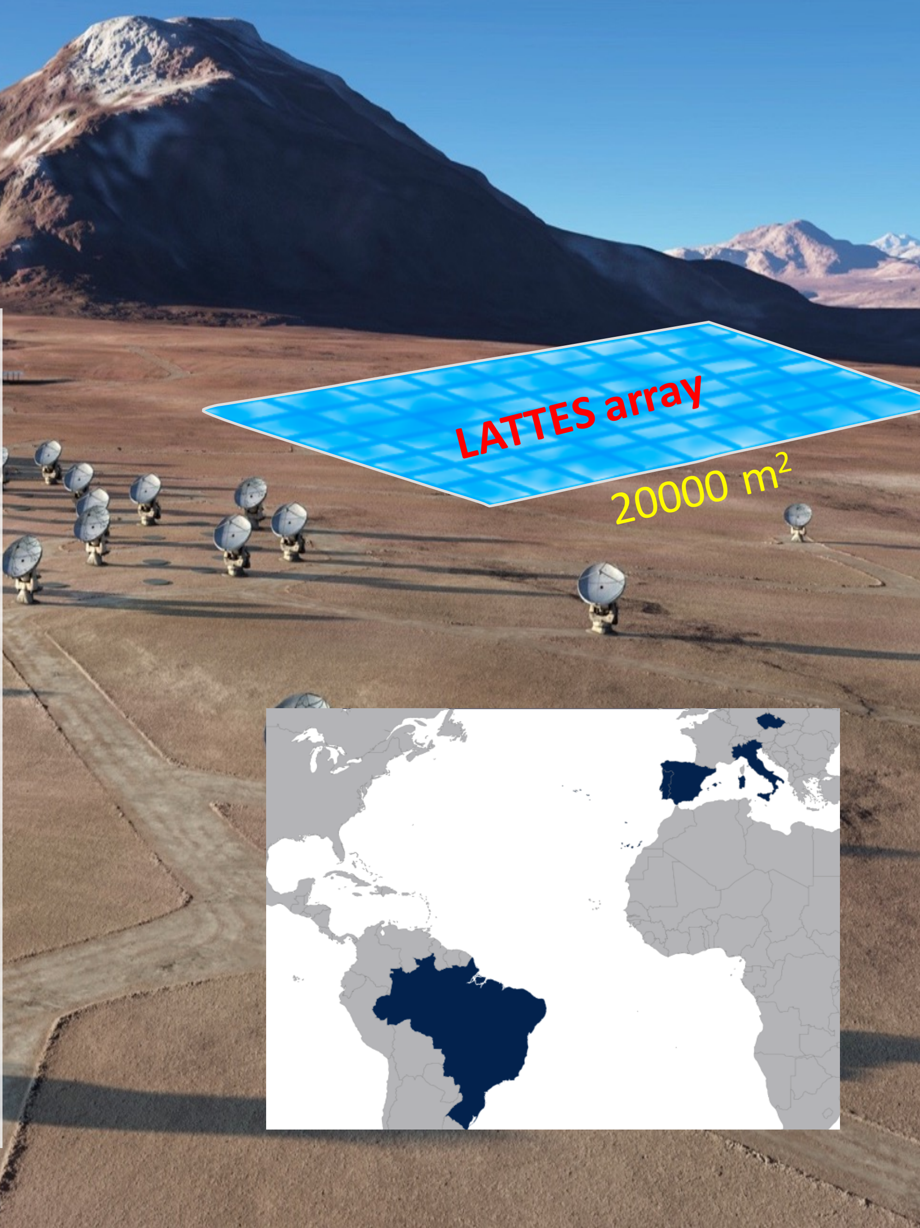


- Located in the South Hemisphere ✓
- Low energy threshold:
  - High altitude ✓
  - Next generation detector concept ✓

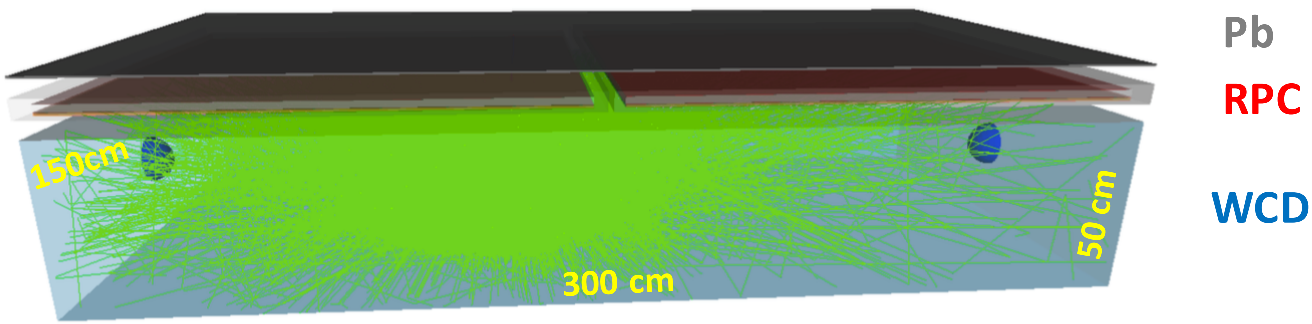
LATTES @ ALMA site

Large Array Telescope for Tracking Energetic Sources

- Joint Brazil / Italy / Portugal initiative
- Interest from Czech group
- Possible site:
  - Atacama Large Millimeter Array site
  - Chajnantor plateau
  - 5200 meters altitude in north Chile
  - Good position to survey the Galactic Center



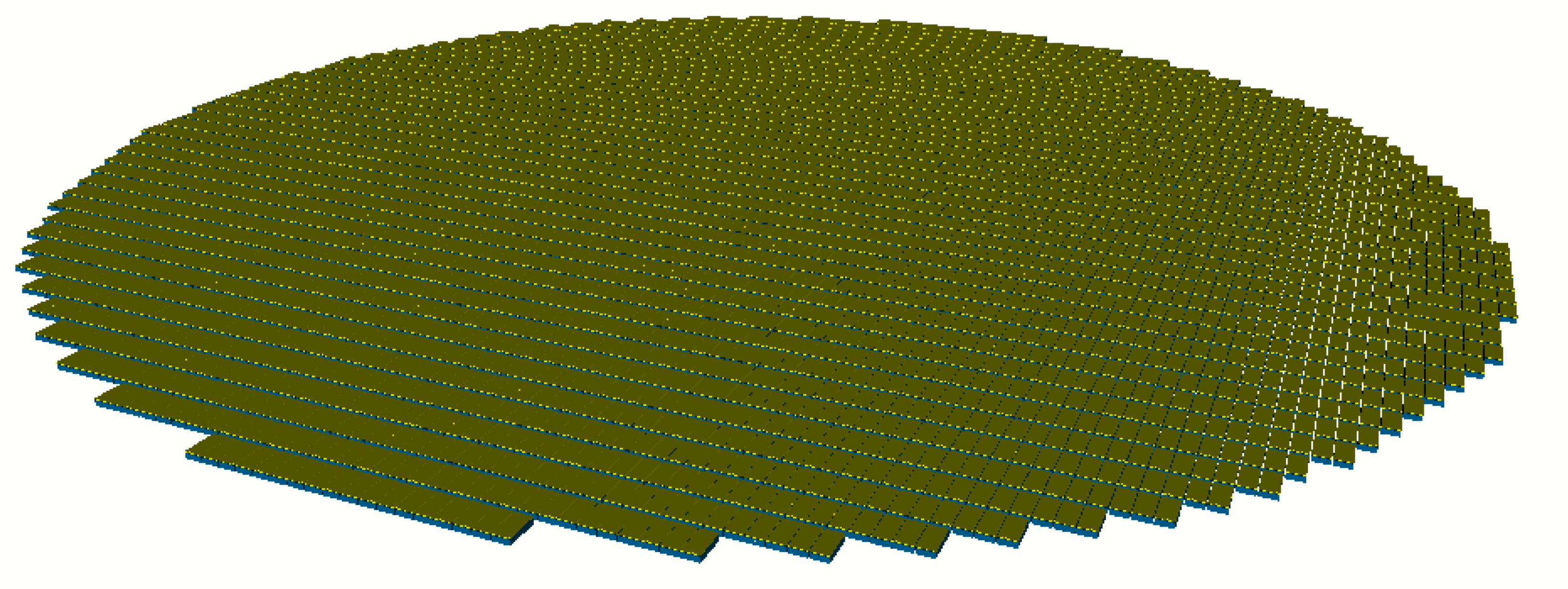
The concept: a hybrid detector



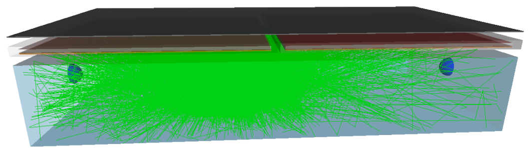
RPCs : time and spatial resolution

WCDs: e.m. energy, g/h discrimination and trigger

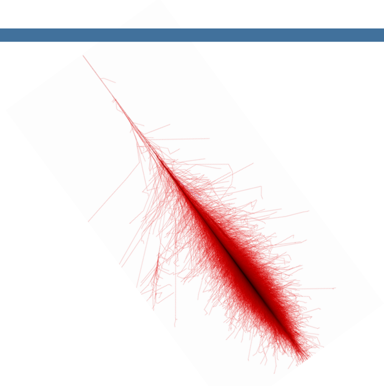
Array configuration



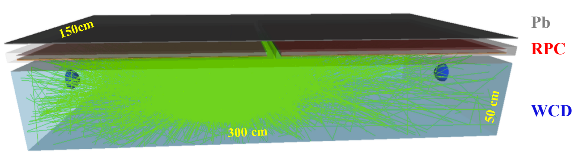
- LATTES compact core array
  - 3600 LATTES stations
  - Array of roughly 20 000 m^2



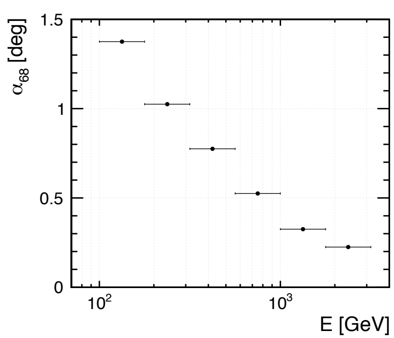
Towards LATTES sensitivity…



Shower simulation (CORSIKA)



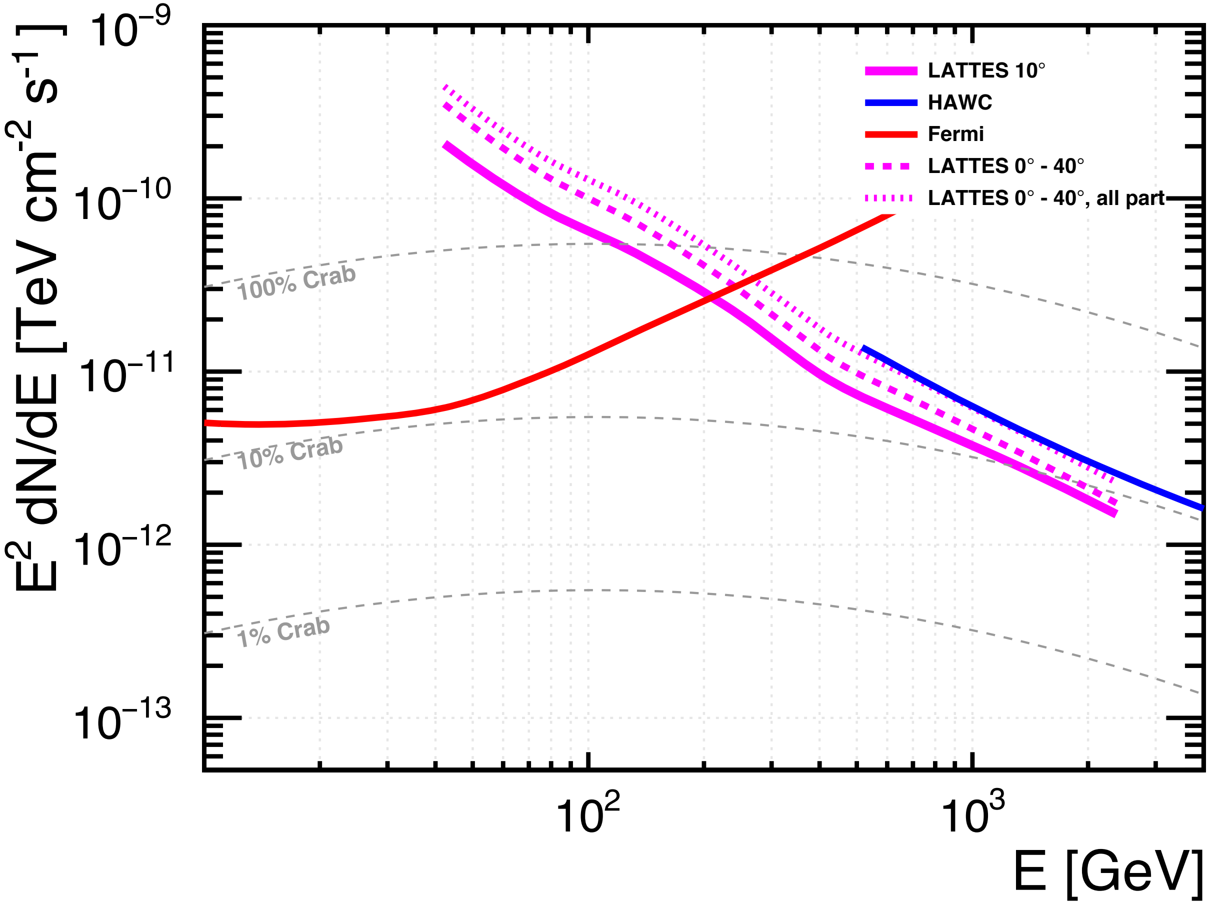
Detector simulation (Geant4)



Shower reconstruction (LATTESrec)

LATTES sensitivity

(accepted to publication on Astropart. Phys.)

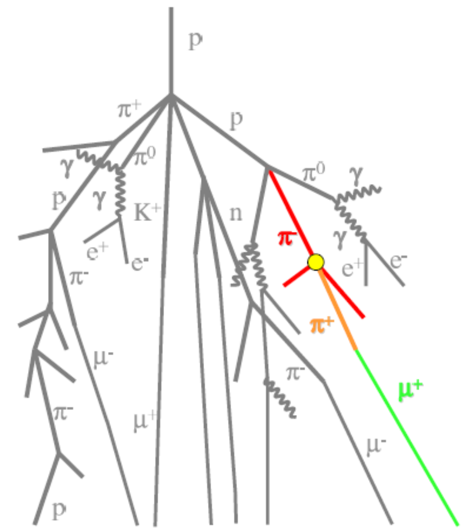


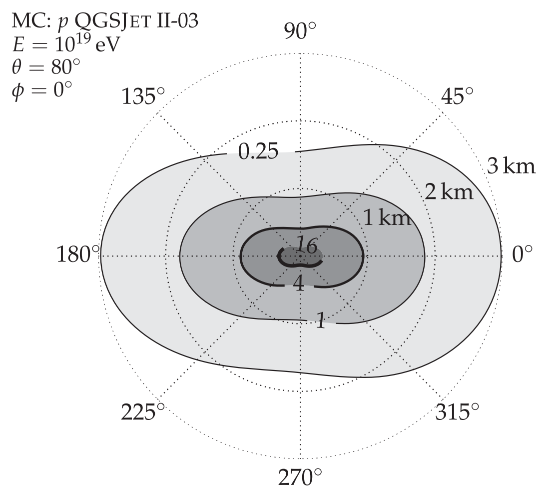
LATTES concept **can cover the energy gap** between satellite borne and ground base experiments

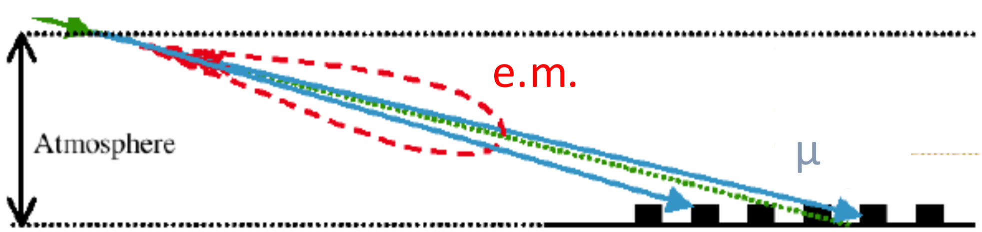
Muon content in air showers

- Muon EAS content is directly related with the hadronic shower component

- Through inclined showers is possible to measure directly the muon content (R_{μ}) in the SD
  - Electromagnetic shower component gets attenuated

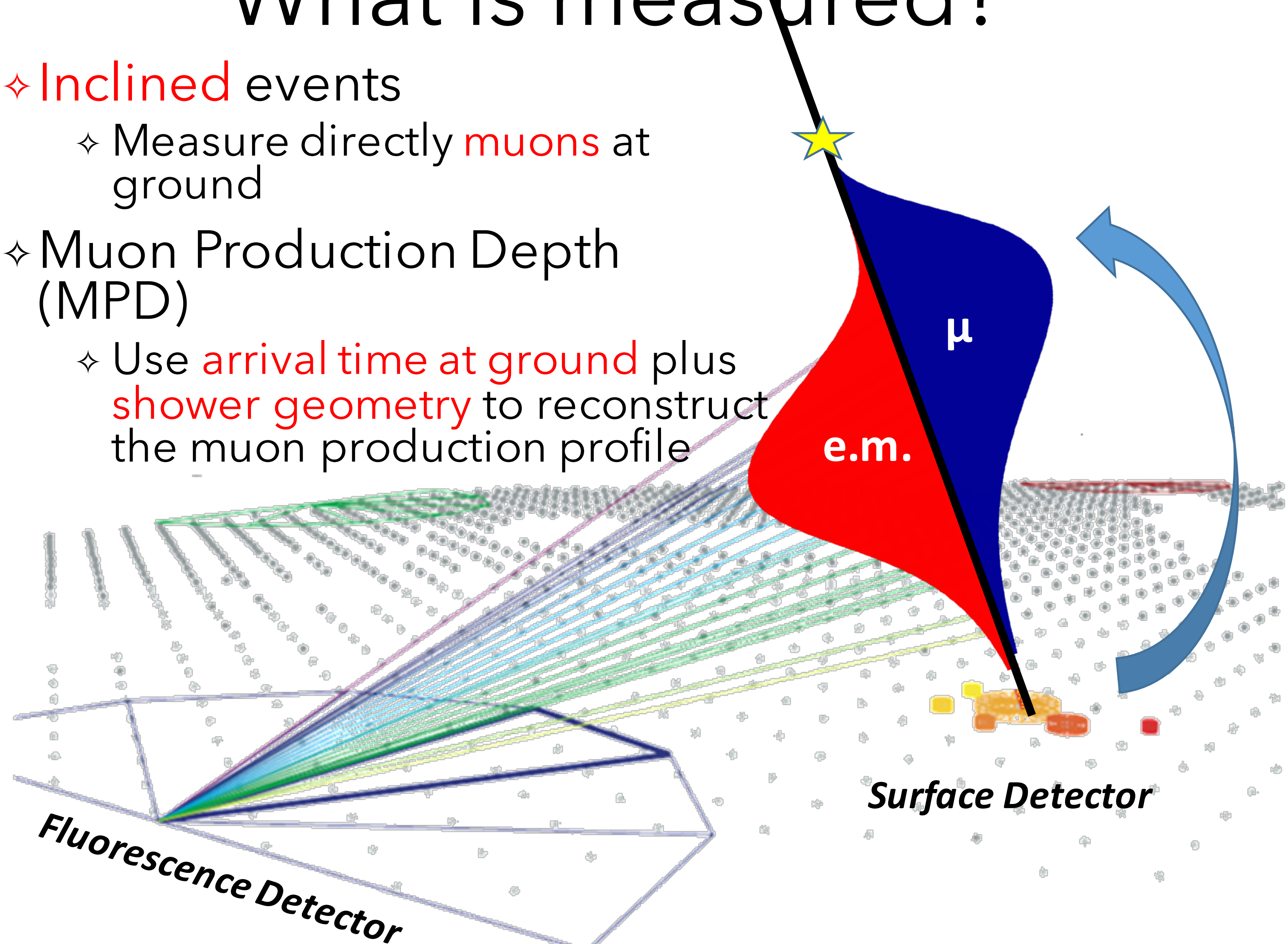






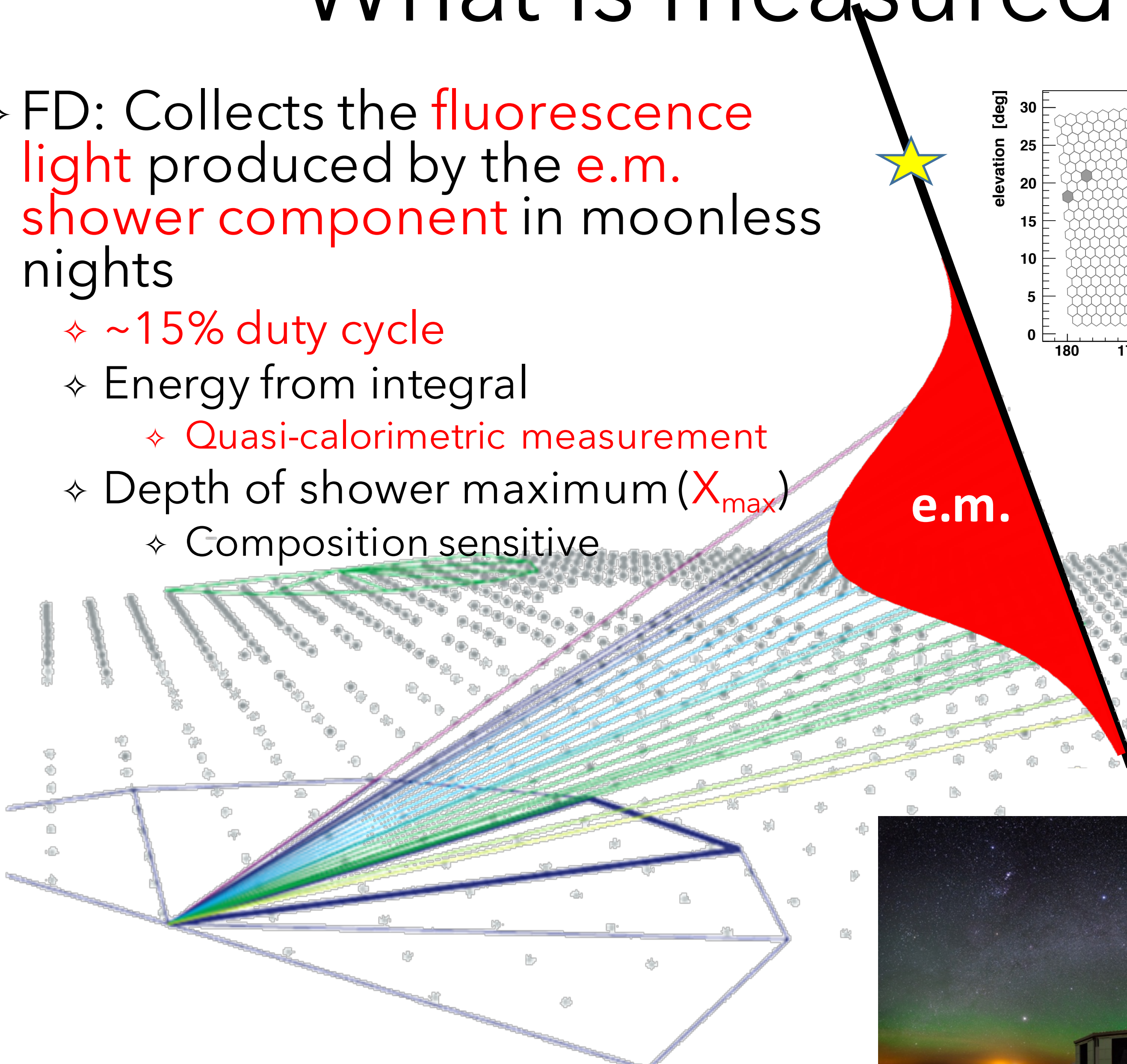
What is measured?

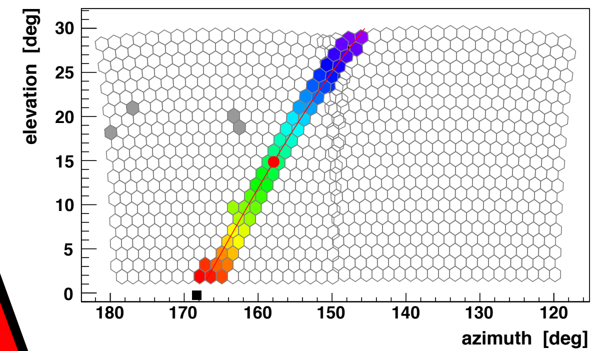
- ✧ Inclined events
  - ✧ Measure directly muons at ground
- ✧ Muon Production Depth (MPD)
  - ✧ Use arrival time at ground plus shower geometry to reconstruct the muon production profile

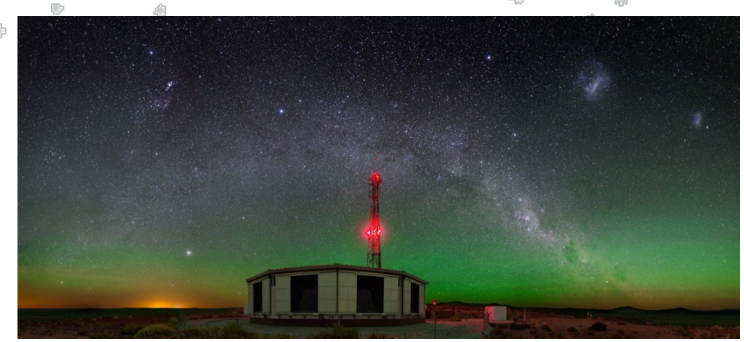


What is measured?

- FD: Collects the fluorescence light produced by the e.m. shower component in moonless nights
  - ~15% duty cycle
  - Energy from integral
    - Quasi-calorimetric measurement
  - Depth of shower maximum (X_{max})
    - Composition sensitive

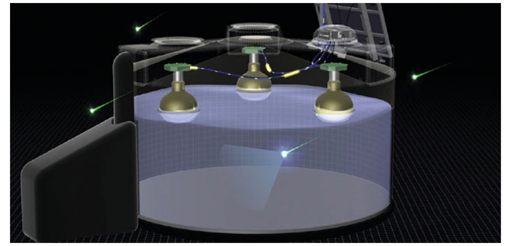


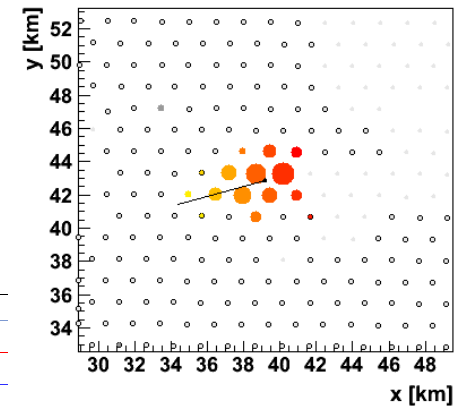


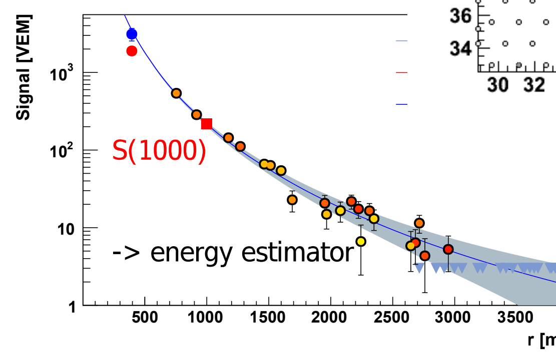


What is measured?

- SD: Sample the charged secondary particles that arrive at ground
  - 100% duty cycle
  - Shower direction: from arrival time
  - Energy estimator: signal at 1000 m from the core

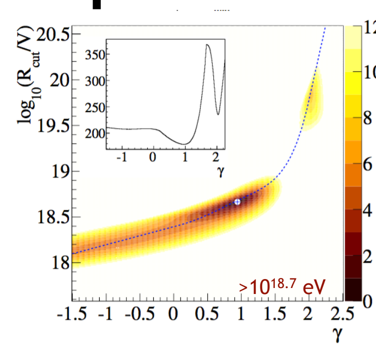


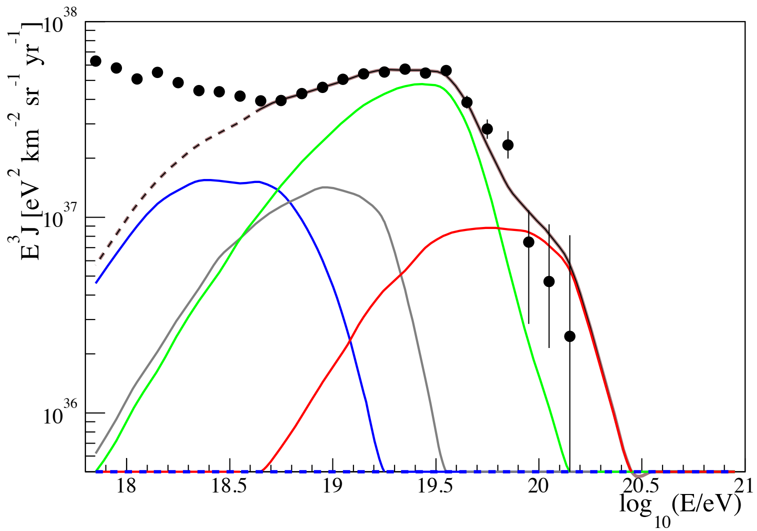


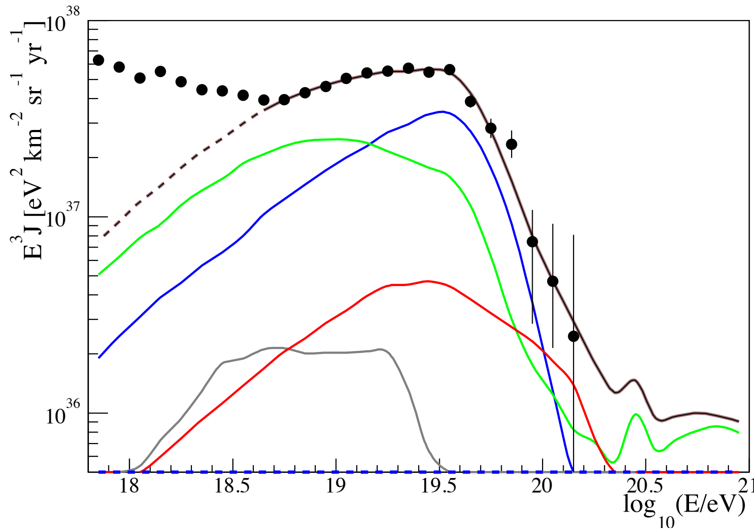


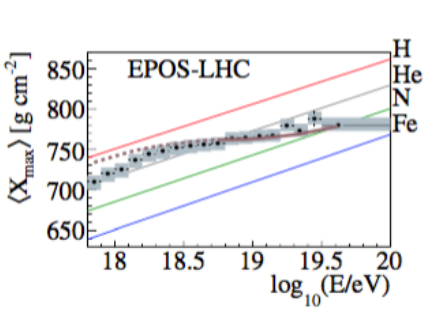
Combined spectrum + comp fits

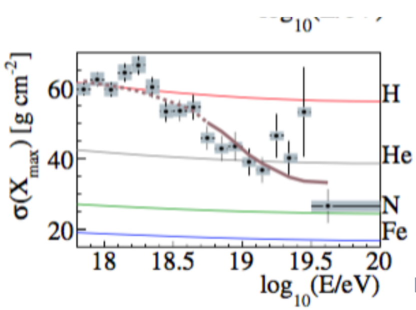
Protons (blue)
Helium (gray)
Nitrogen (green)
Iron (red)

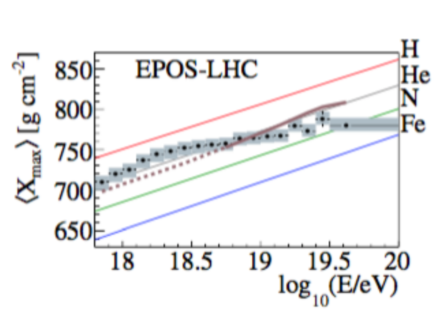


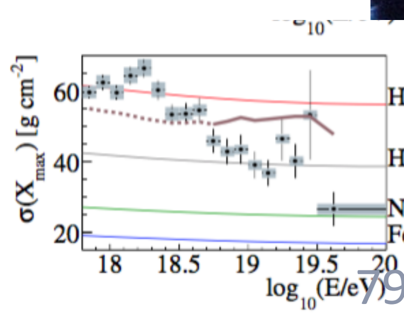








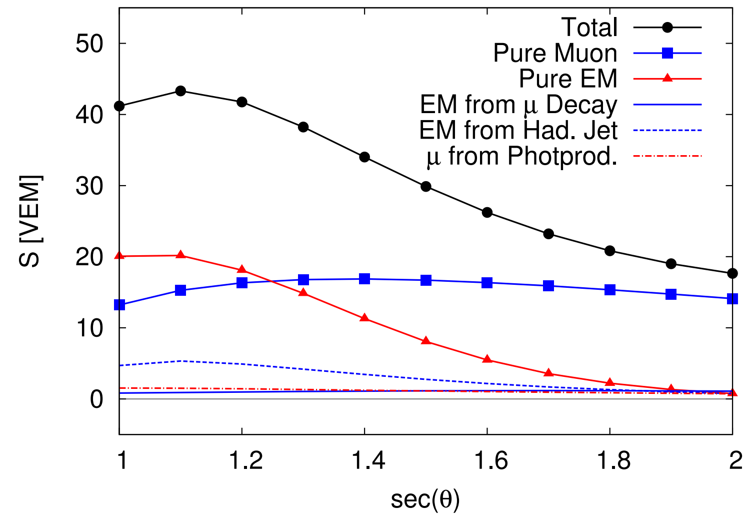




Explore hybrid events

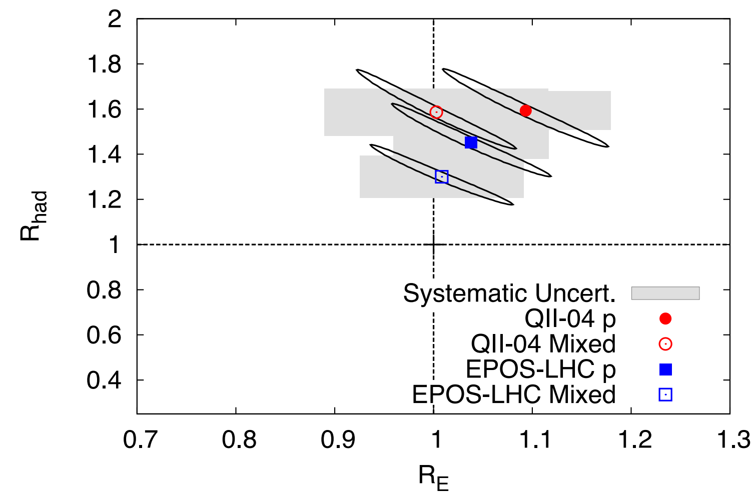
- Combined fit of energy scale (R_E) and hadronic component rescaling (R_{had})

$$S_{\text{resc}}(R_E, R_{\text{had}})_{i,j} \equiv R_E\, S_{EM,i,j} + R_{\text{had}}\, R_E^{\alpha}\, S_{\text{had},i,j}$$

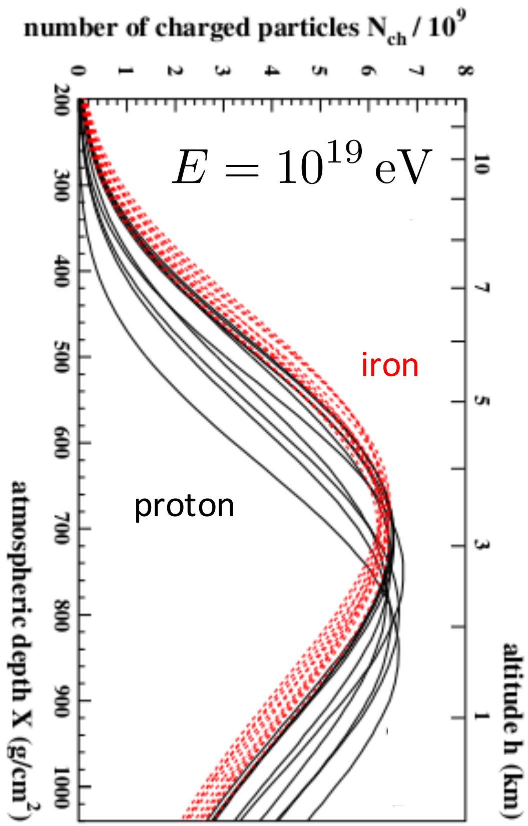


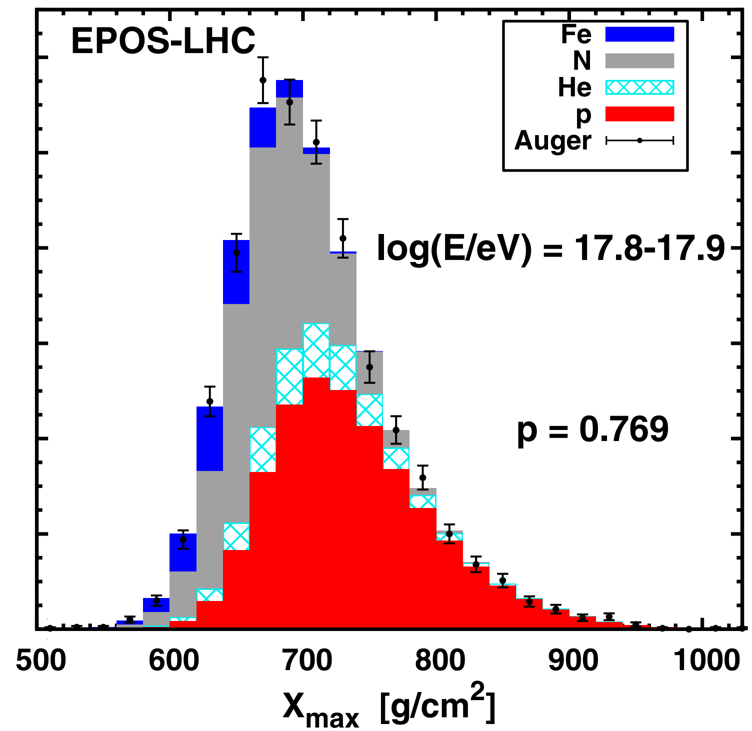
- Findings:
  - No need for an energy rescaling
  - Hadronic signal in data is significantly larger with respect to simulations

Model	R_E	R_{had}
QII-04 p	$1.09 \pm 0.08 \pm 0.09$	$1.59 \pm 0.17 \pm 0.09$
QII-04 Mixed	$1.00 \pm 0.08 \pm 0.11$	$1.61 \pm 0.18 \pm 0.11$
EPOS p	$1.04 \pm 0.08 \pm 0.08$	$1.45 \pm 0.16 \pm 0.08$
EPOS Mixed	$1.00 \pm 0.07 \pm 0.08$	$1.33 \pm 0.13 \pm 0.09$



Mass composition interpretation





- ✧ Interpretation of the X_{max} distribution in terms of mass composition
  - ✧ Proton showers have deeper X_{max} than iron induced showers
  - ✧ X_{max} fluctuates more for proton induced showers