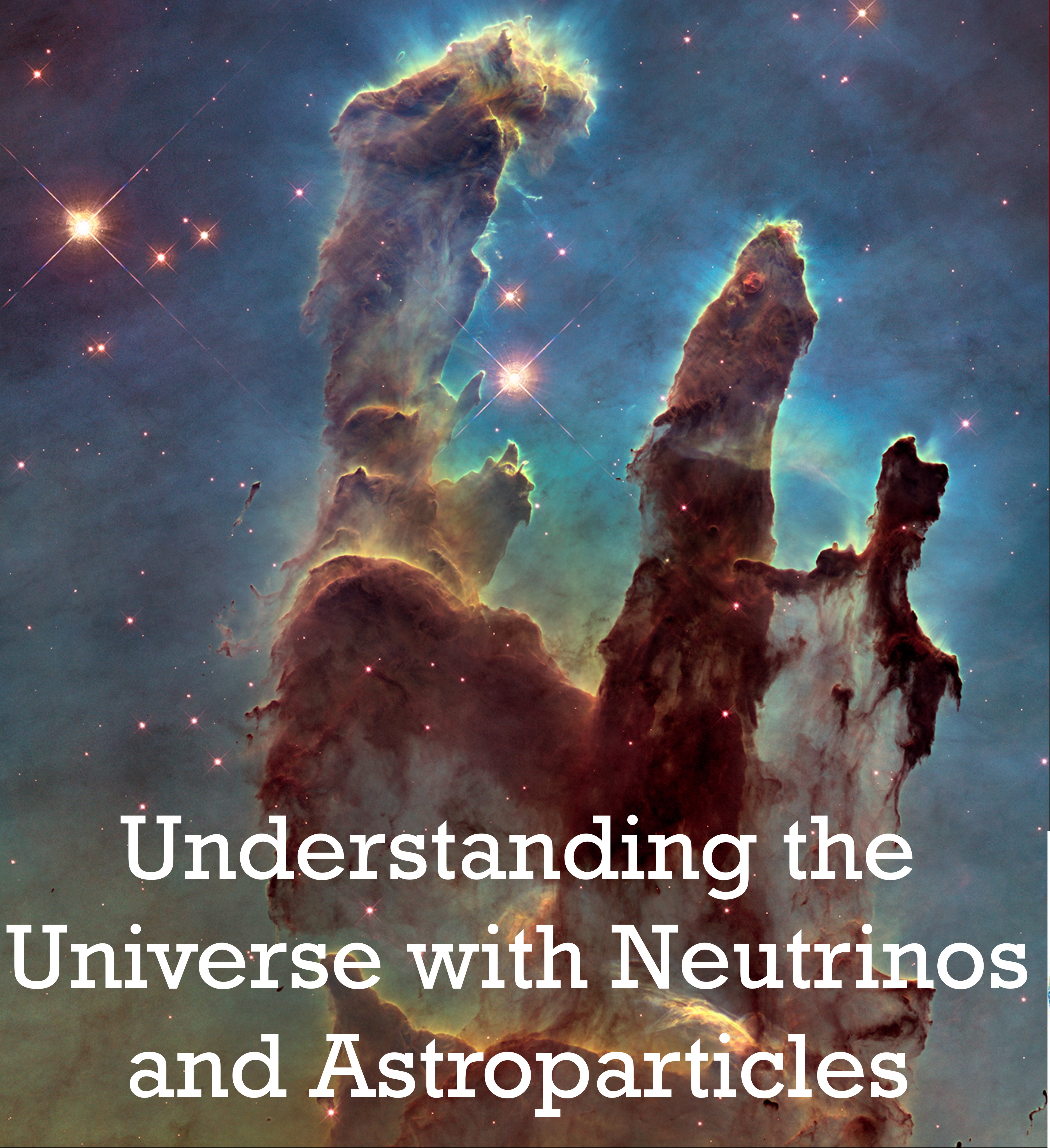
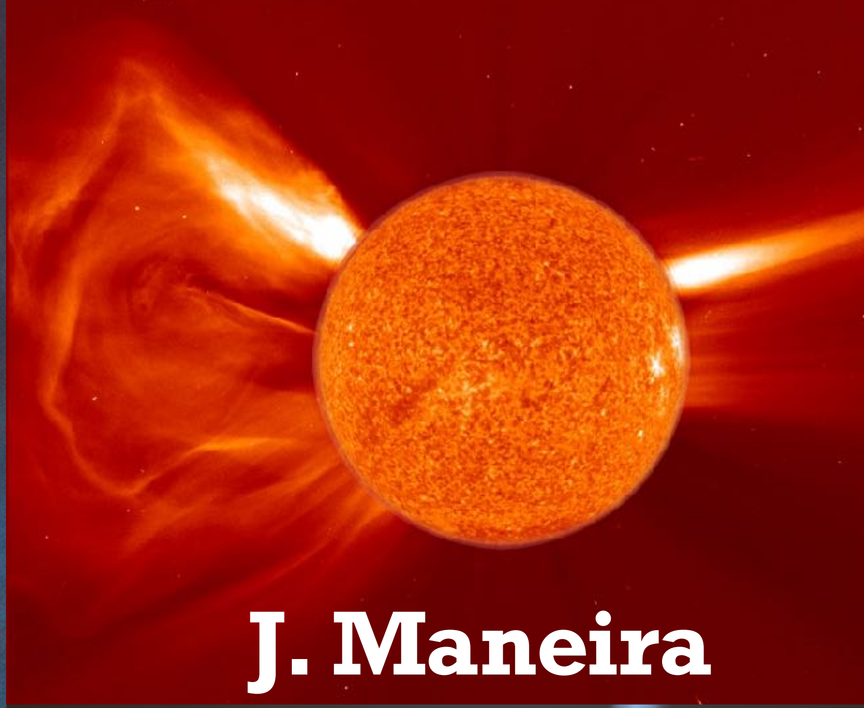
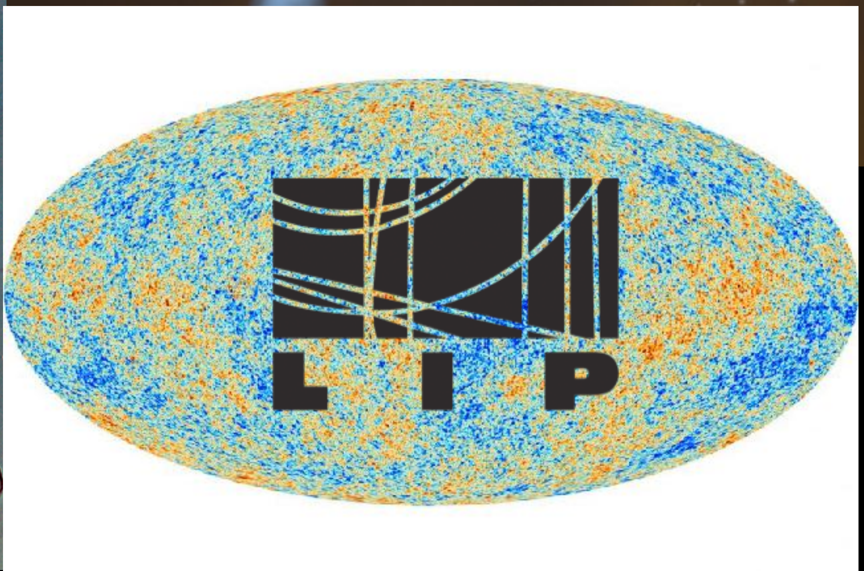


Understanding the Universe with Neutrinos and Astroparticles

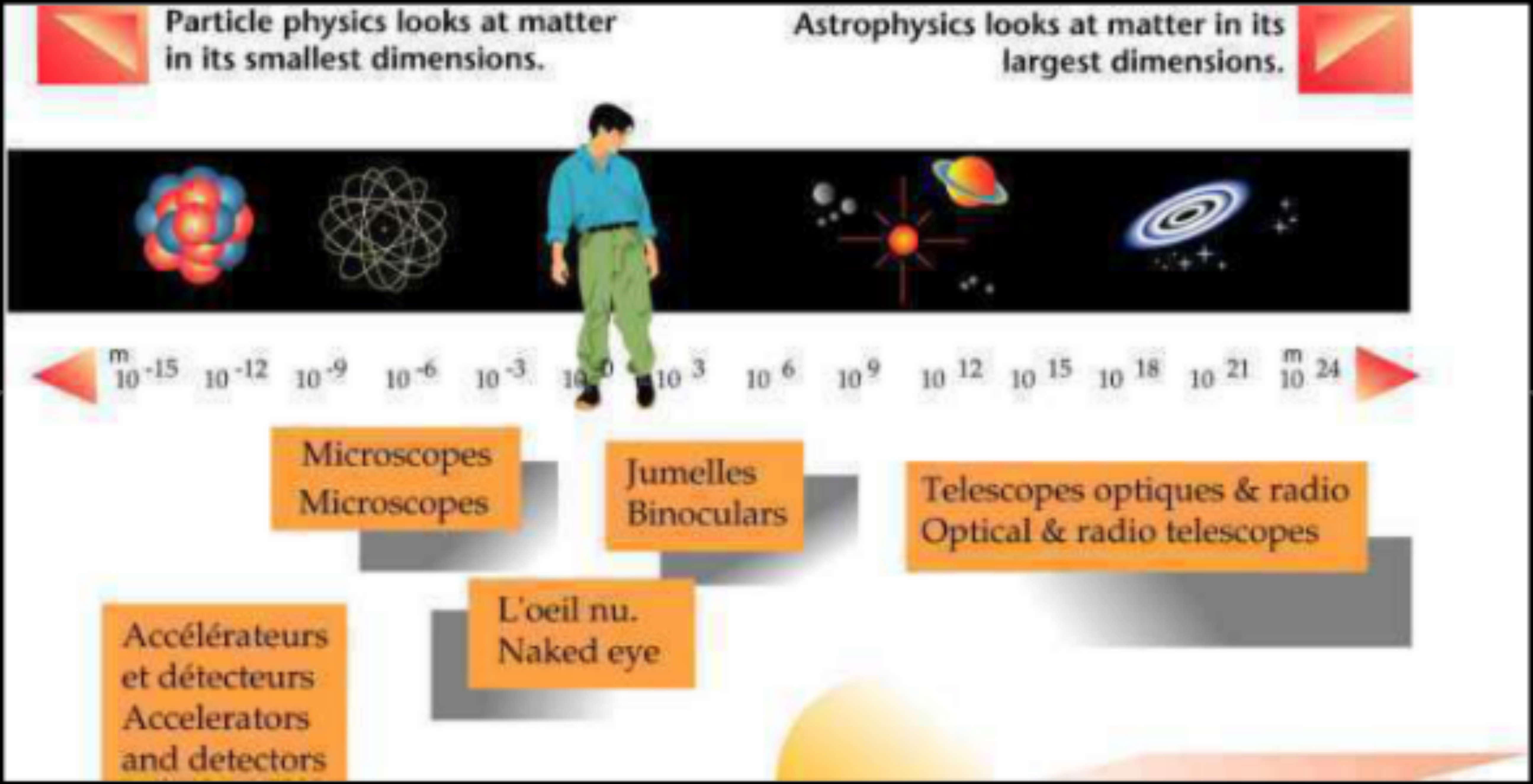


J. Maneira

6h Lisbon miniSchool on Particle and Astroparticle Physics



The two frontiers



- Need to understand the "infinitely small" to understand the "infinitely large"

What Physics do we do?

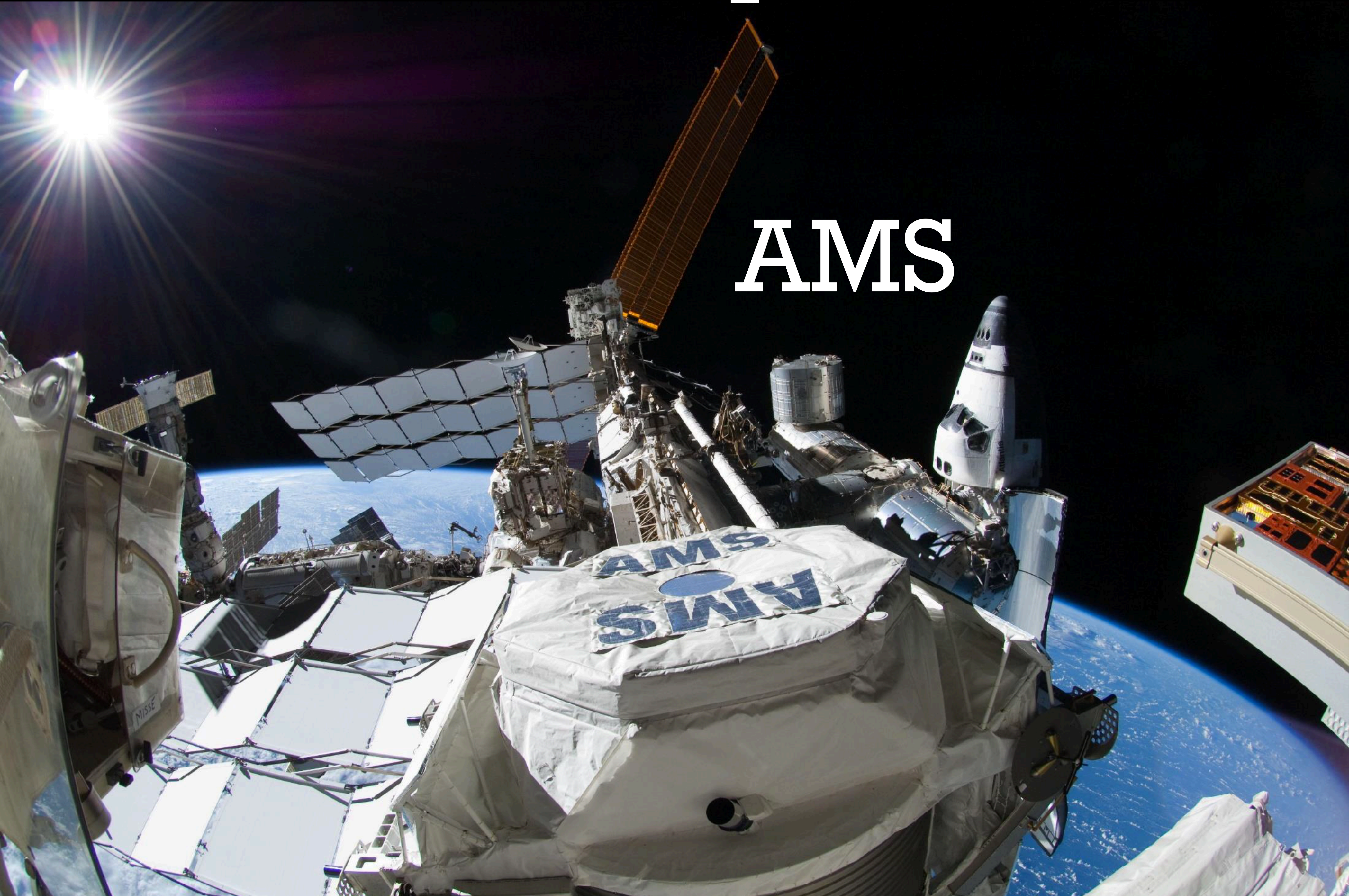
Astroparticles at LIP

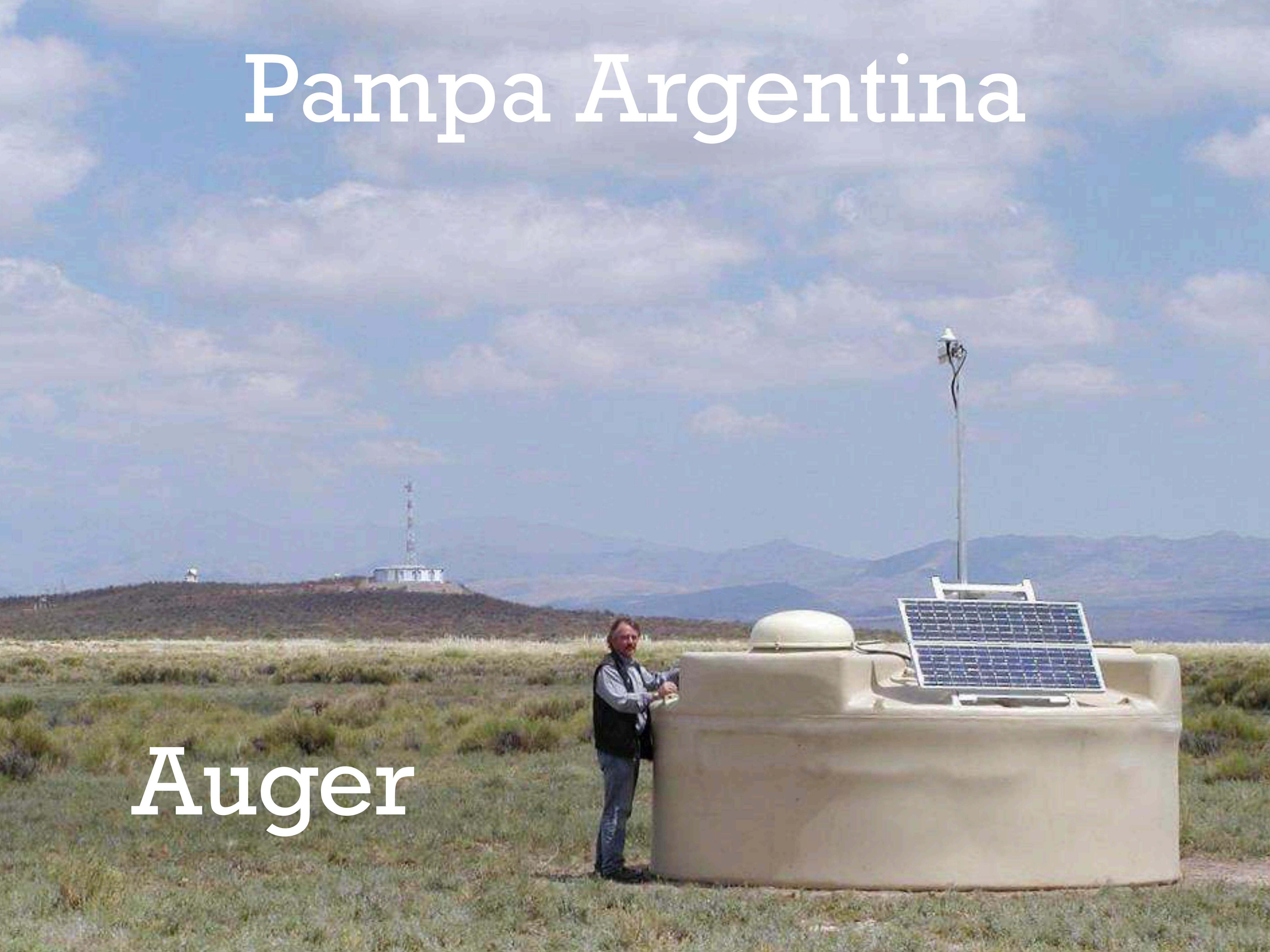
Particle	Expt.	Discover New Particle Physics	Particles as probes in Astrophysics or Cosmology
Charged cosmic rays	Auger AMS	Hadronic interactions at high energies Dark Matter search	Sources of HECR Multi-messenger Astrophysics Anti-matter search Solar Physics
Photons	SWGO	Dark Matter search	Multi-messenger Astrophysics
Neutrinos	SNO+ DUNE	Oscillations and mass Majorana neutrinos CP violation and leptogenesis Nucleon decay search	Sun, Earth and Supernova Physics Matter/antimatter in early Universe

Thanks to: P. Assis, F. Barão, N. Barros, R. Conceição

Where we do it?

International Space Station



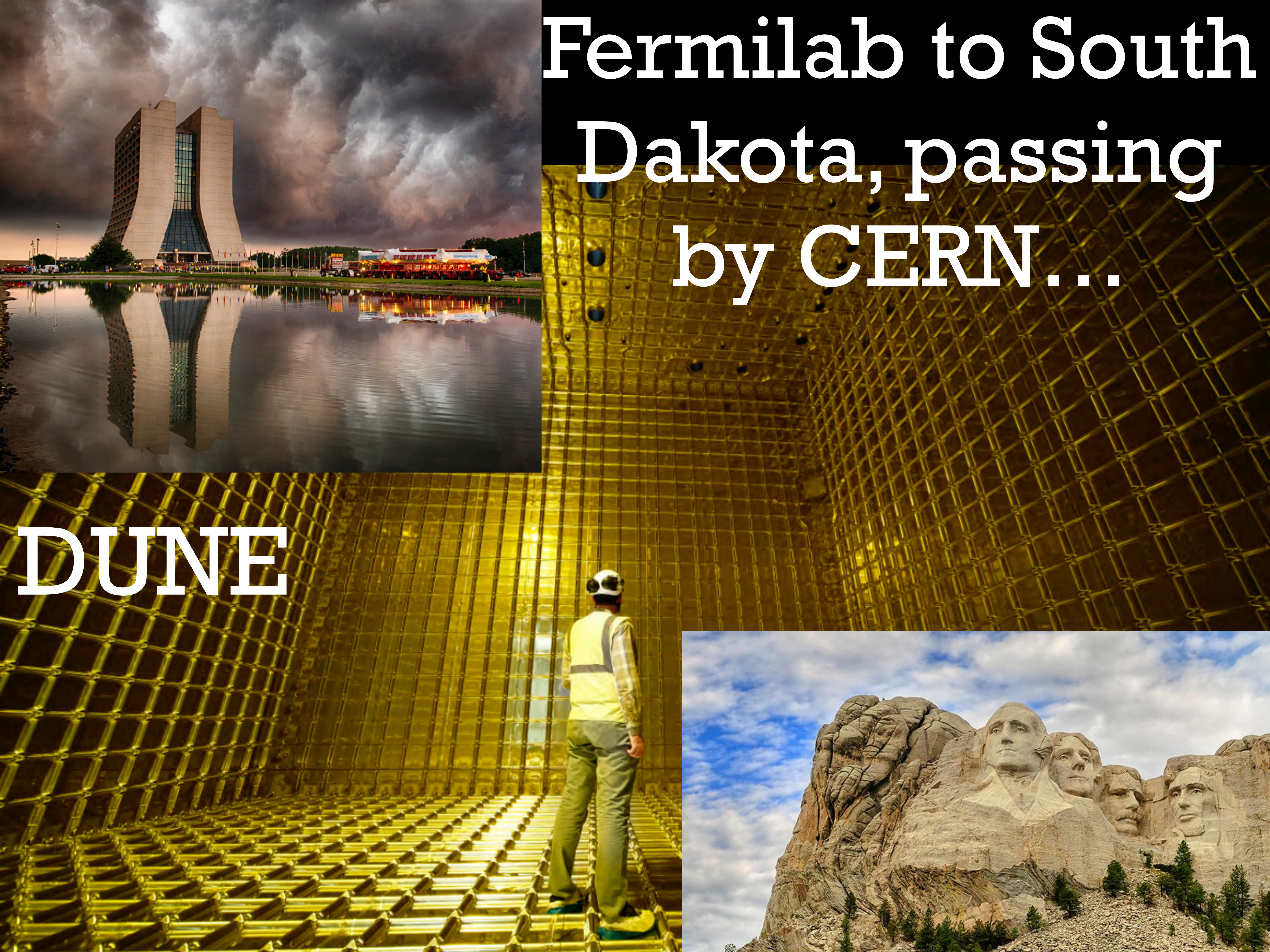

Pampa Argentina
Auger

Atacama, Chile (?)

SWGO


Underground in Canada
SNO+

Fermilab to South Dakota, passing by CERN…

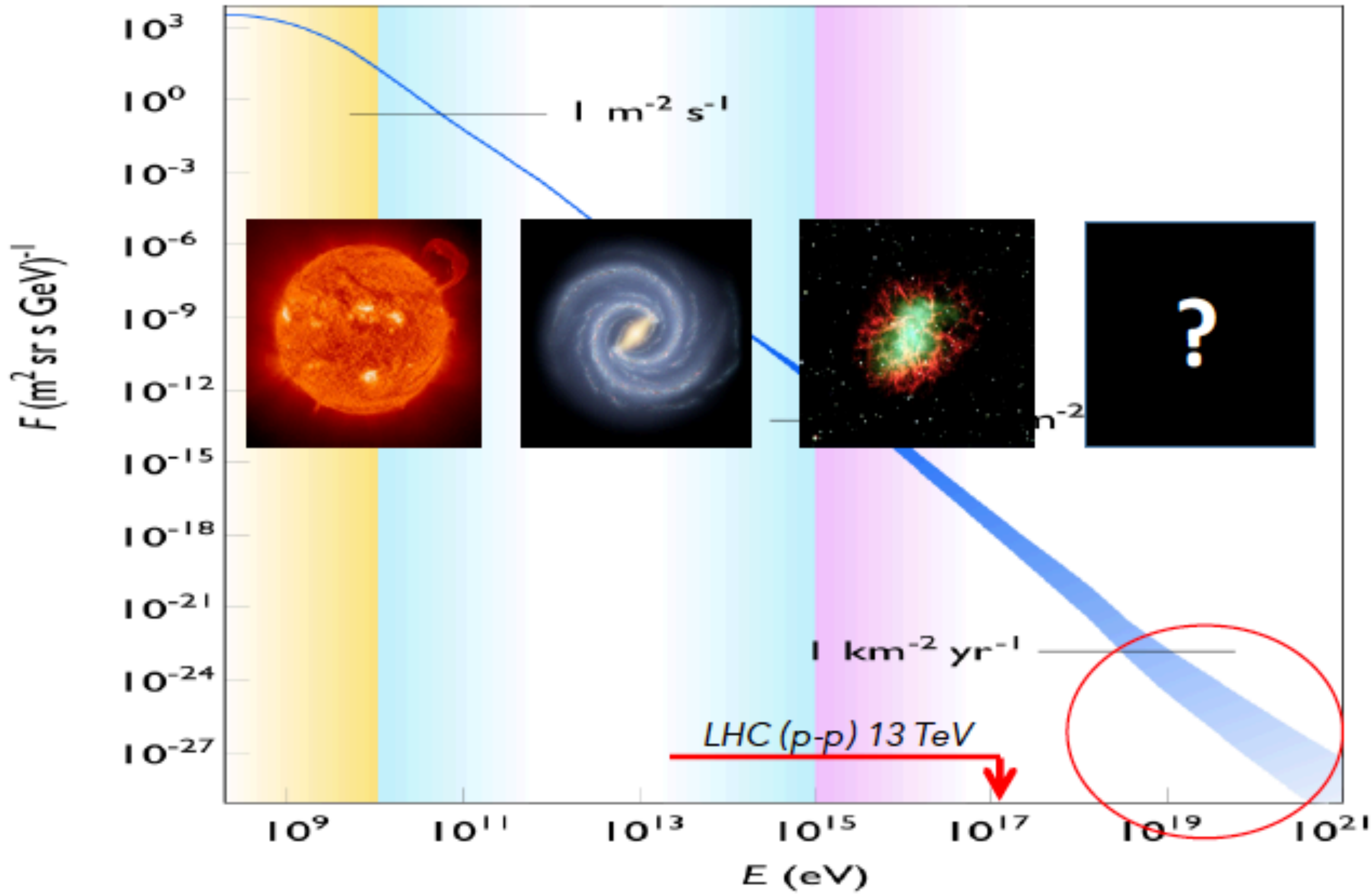


Outline

- Introduction 1: Multi-Messenger Astronomy
  - AMS
  - Auger
  - SWGO
- Introduction 2: Neutrino Physics
  - SNO+
  - DUNE

Ultra High Energy Cosmic Rays

Cosmic ray energy spectrum



Photons

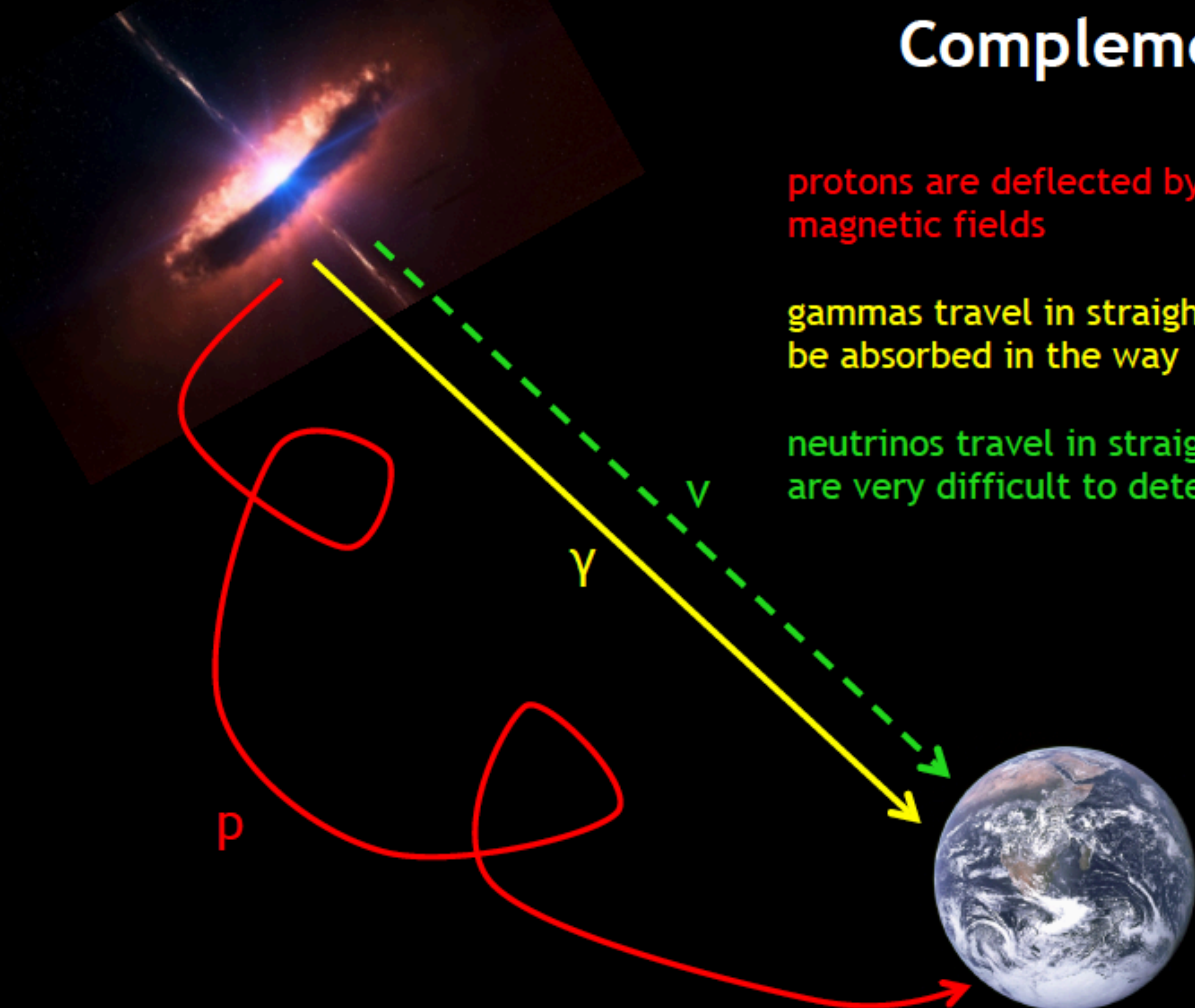
Neutrinos

Multi-Messenger Astronomy

Charged Cosmic Rays

Gravitational Waves

Complementarity



protons are deflected by the galactic magnetic fields

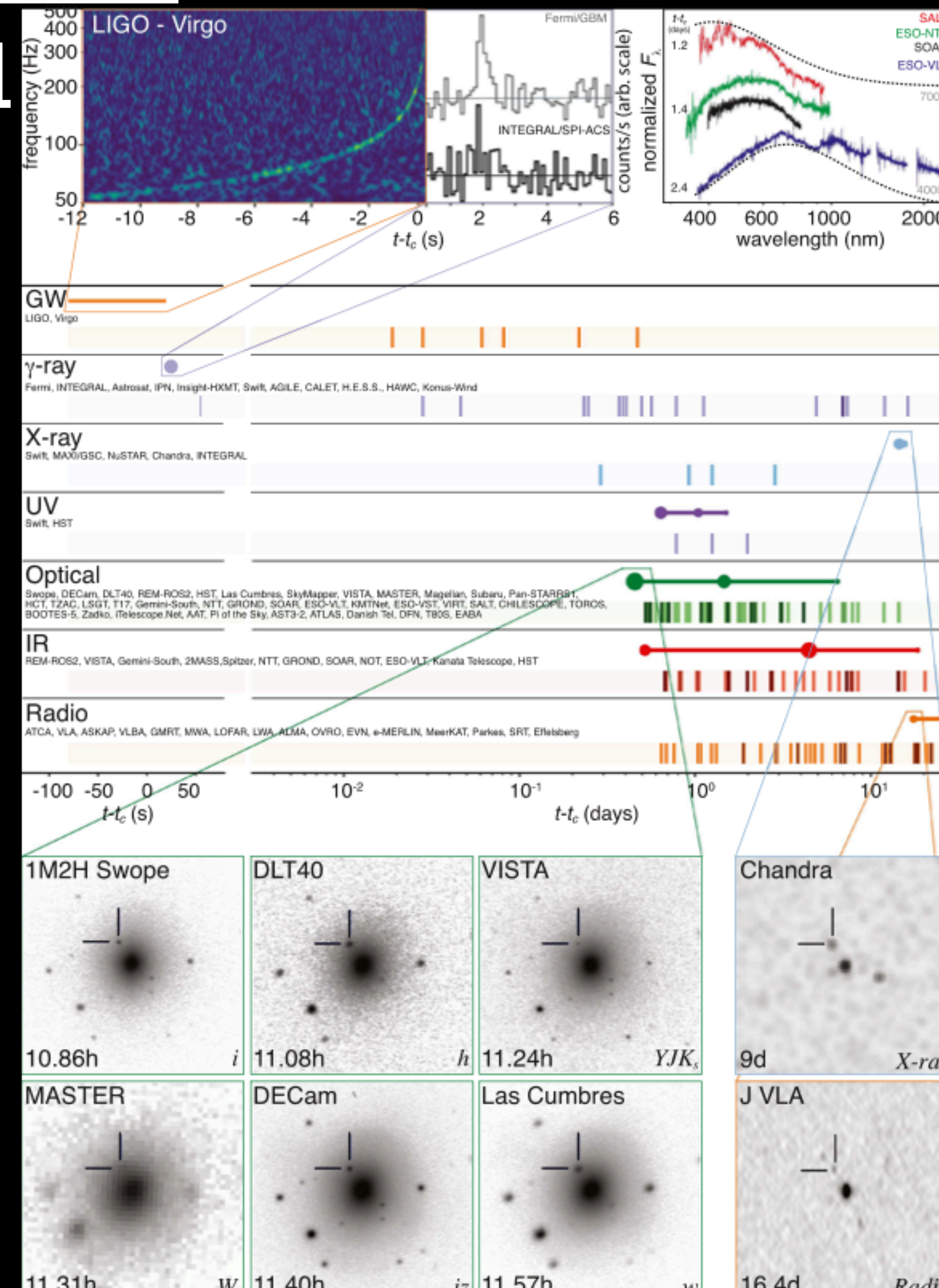
gammas travel in straight lines but can be absorbed in the way

neutrinos travel in straight lines but are very difficult to detect

“Multi-messenger observation of a Binary Neutron Star Merger”

THE ASTROPHYSICAL JOURNAL LETTERS, 848:L12 (59pp), 2017 October 20

- Joint observation of GW and EM signals by many collaborations
  - different wavelengths, different physics
  - much richer understanding of the astrophysical phenomena
- Birth of a new era!



physicsworld
BREAKTHROUGH OF THE YEAR 2017

AMS

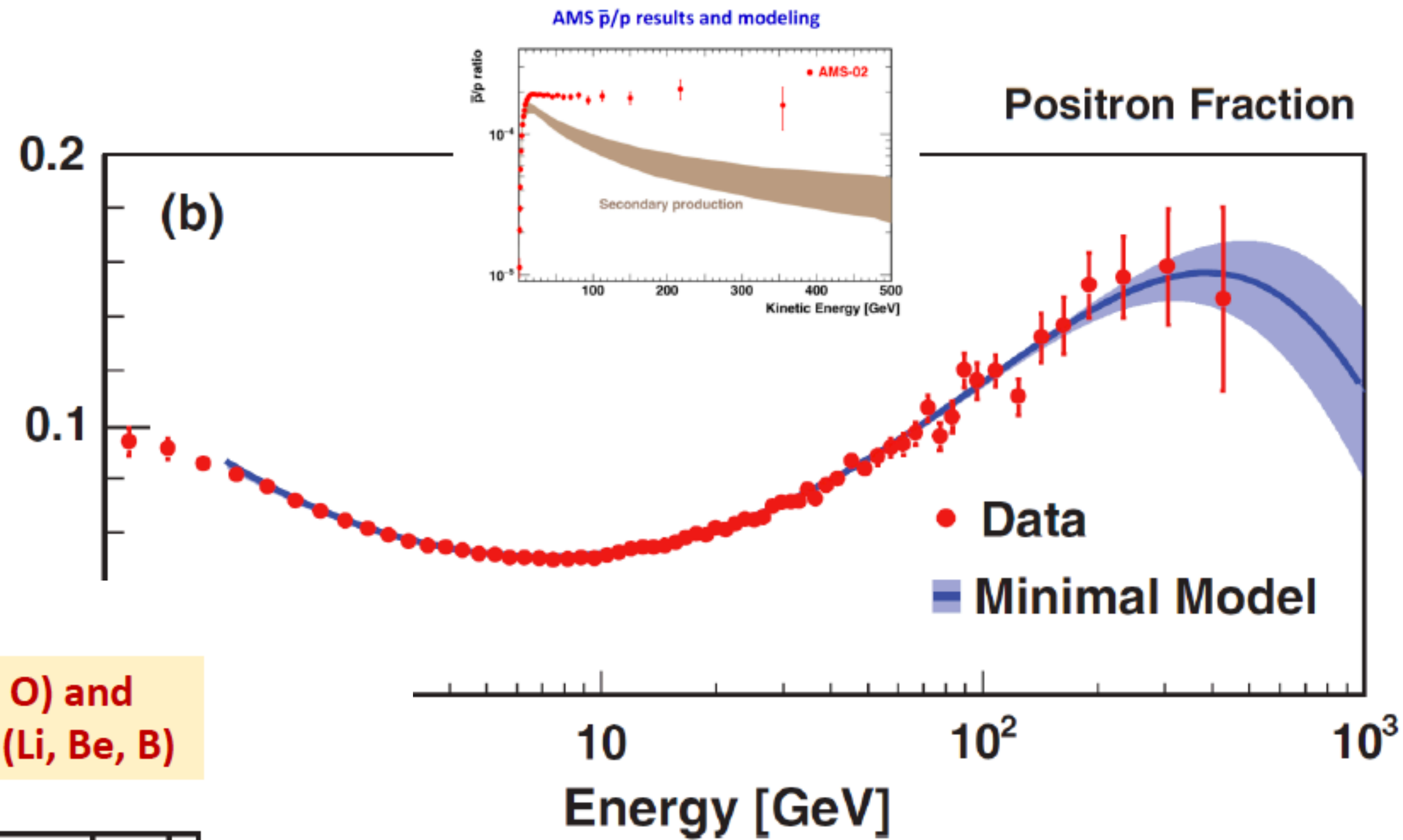
Alpha Magnetic Spectrometer

Installed on the International Space Station (ISS) in May of 2011

Collected more than **112,500,000,000 events** up to this day, at a rate of about **45 million events per day**

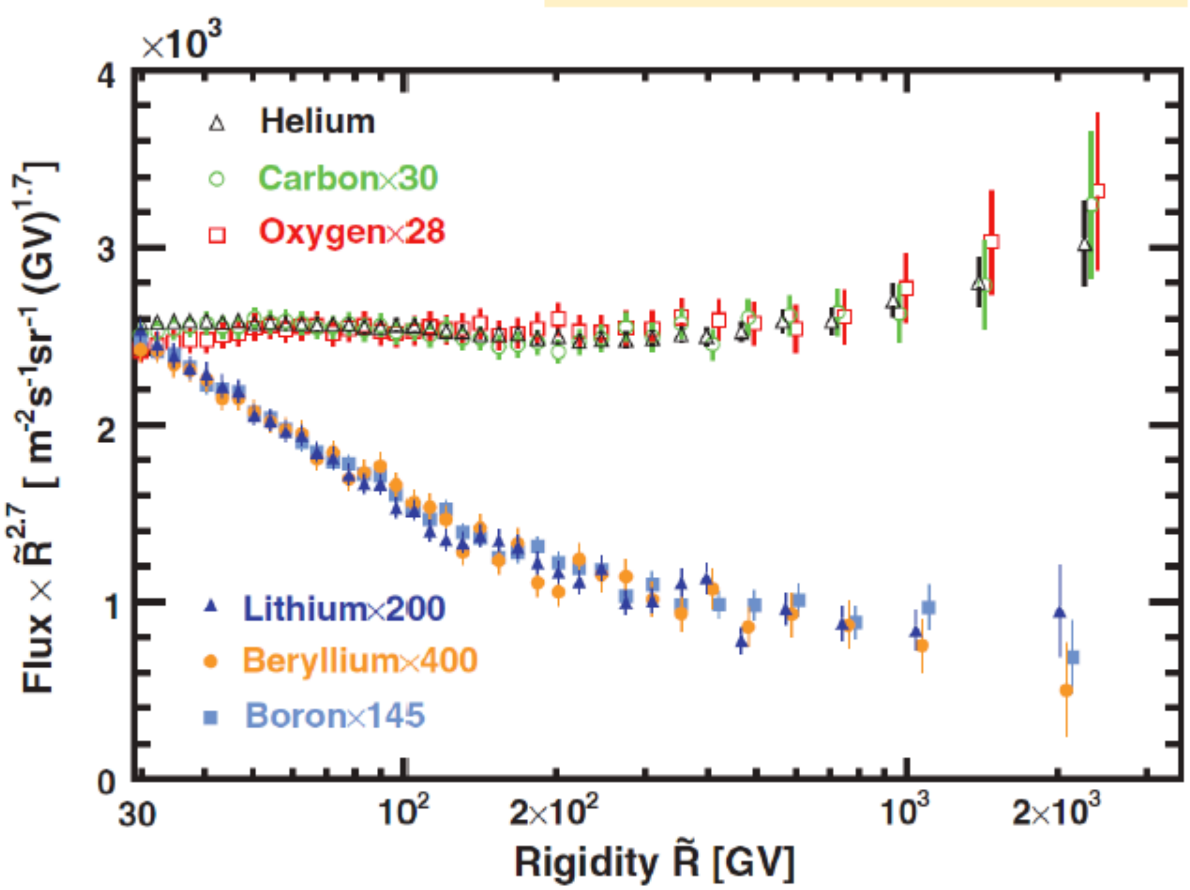
Most of primary cosmic rays crossing AMS are protons

Positrons and antiprotons

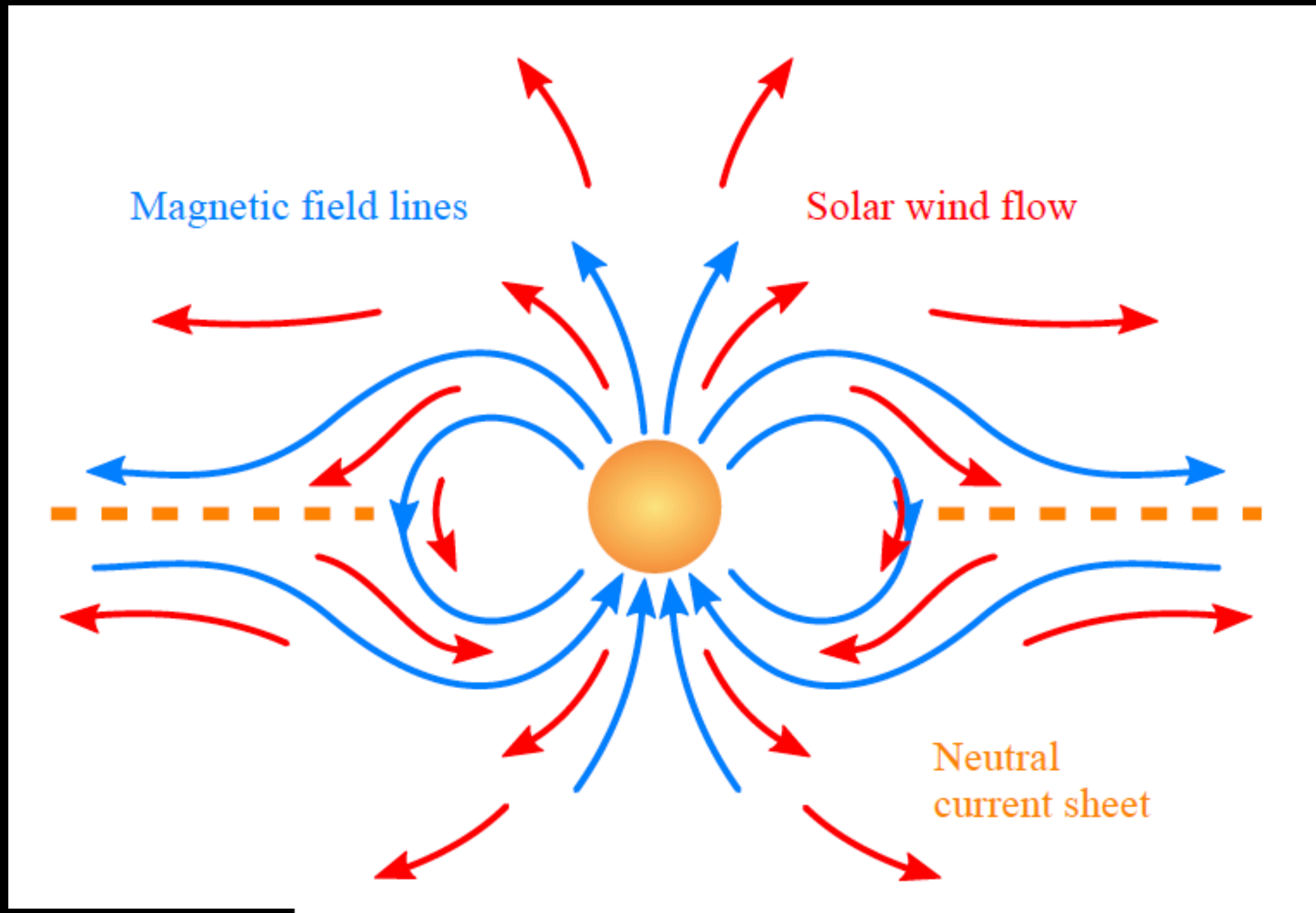


Z>1 fluxes

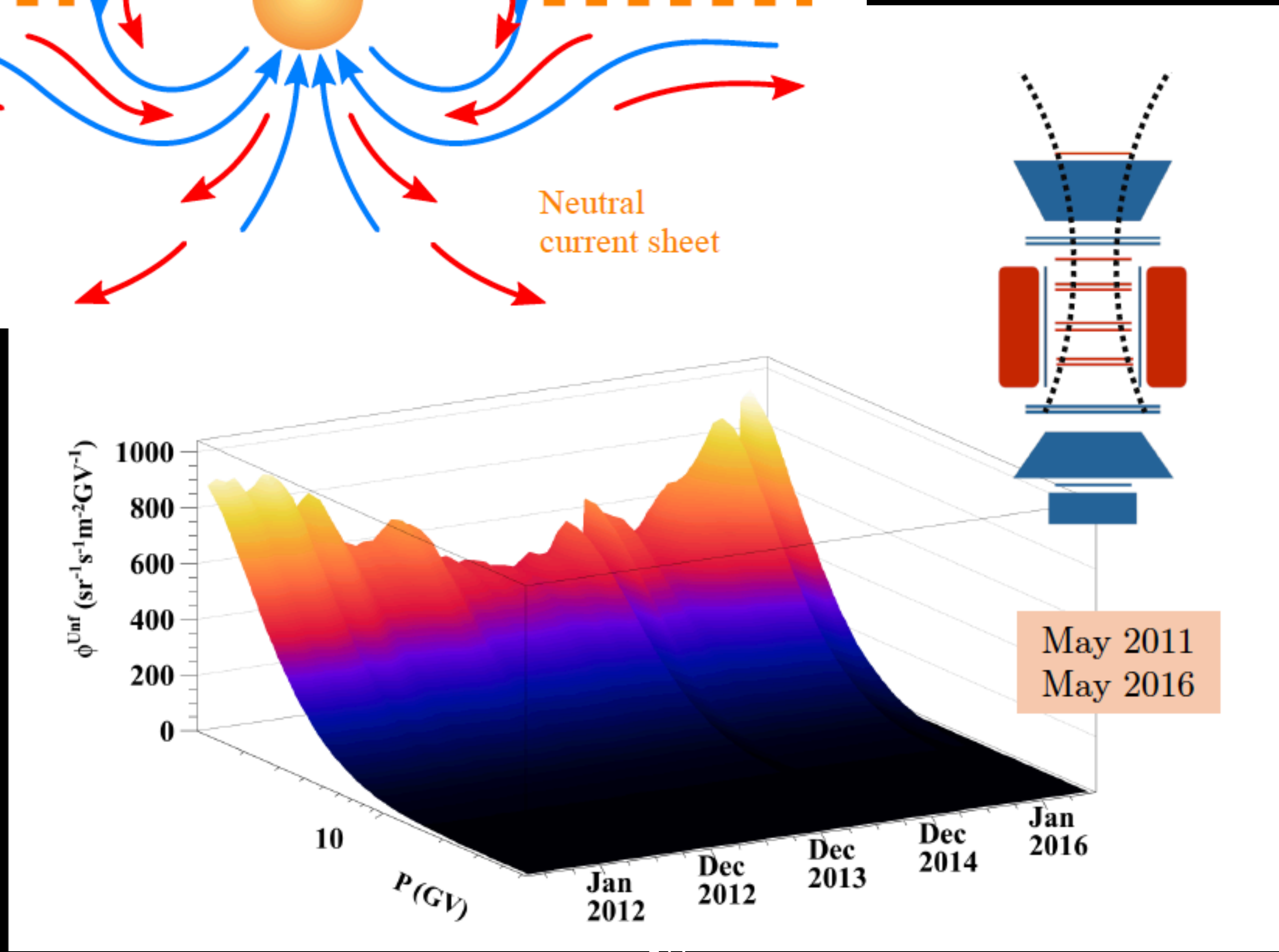
Primary (He, C, O) and secondary nuclei (Li, Be, B)



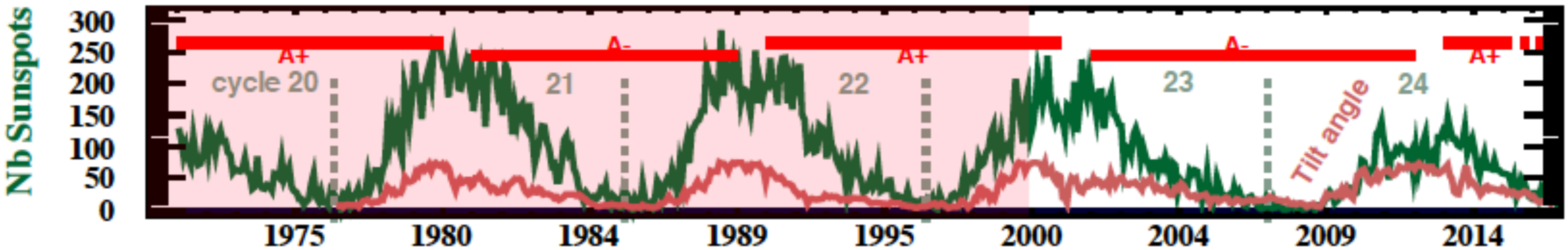
Solar modulation

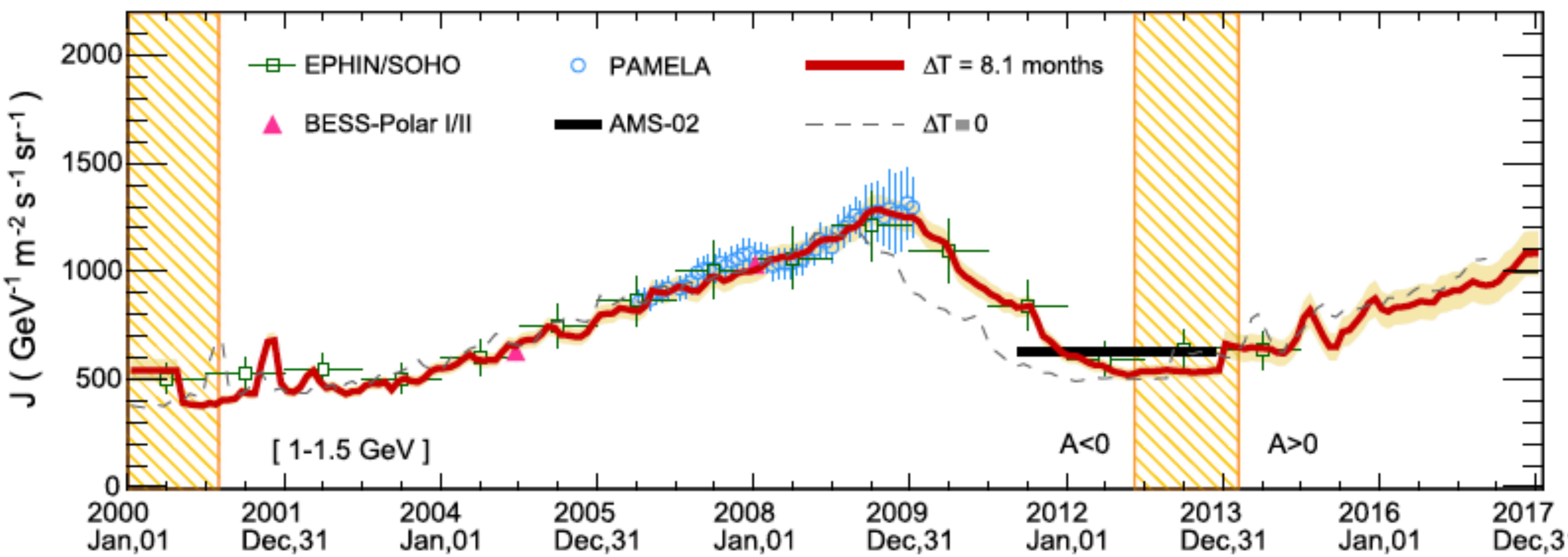


Solar modulation is prevaling up to 30 GV



EVIDENCE OF A TIME DELAY

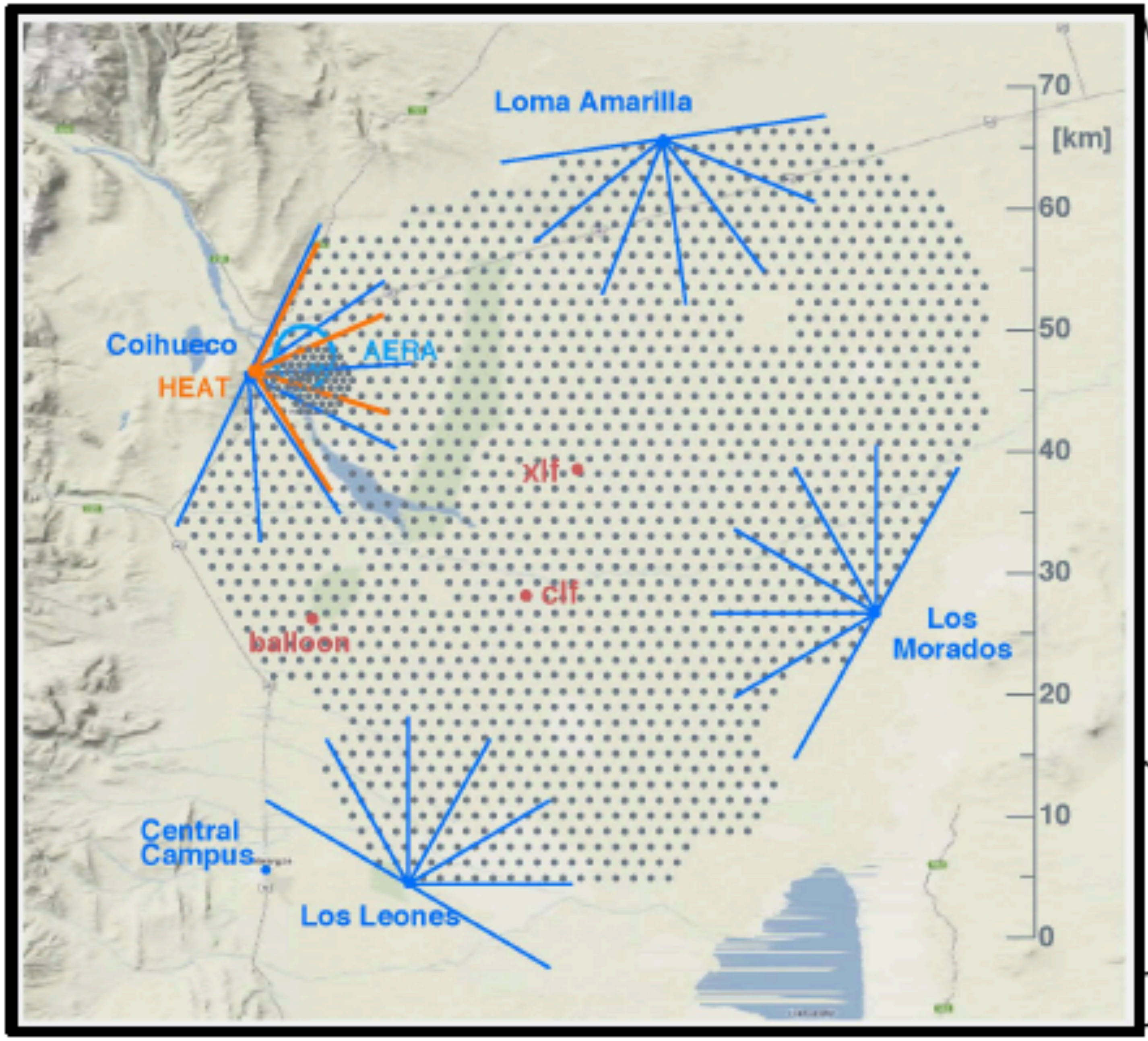




$$\Delta t \sim 8.1\,\mathrm{months}$$

Auger

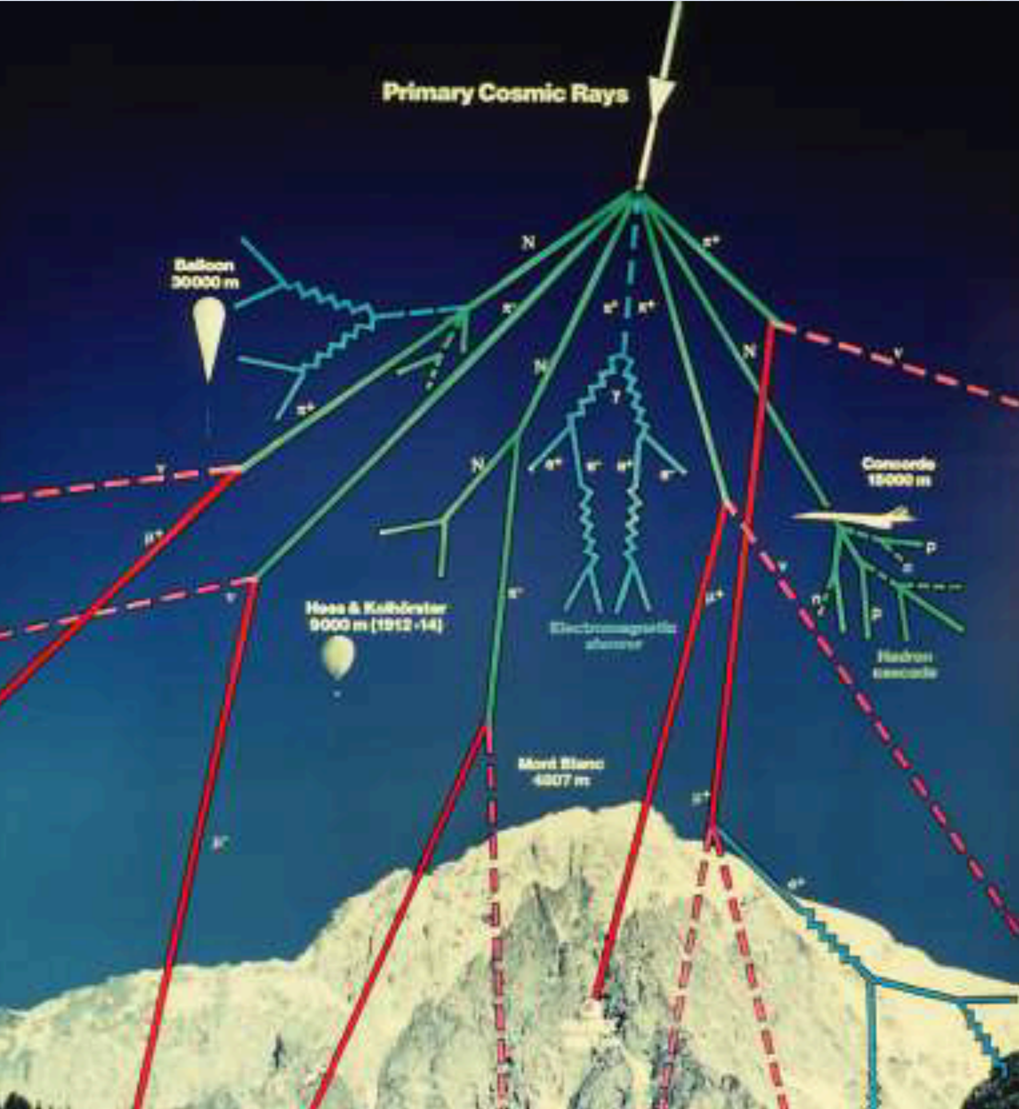
Pierre Auger Observatory



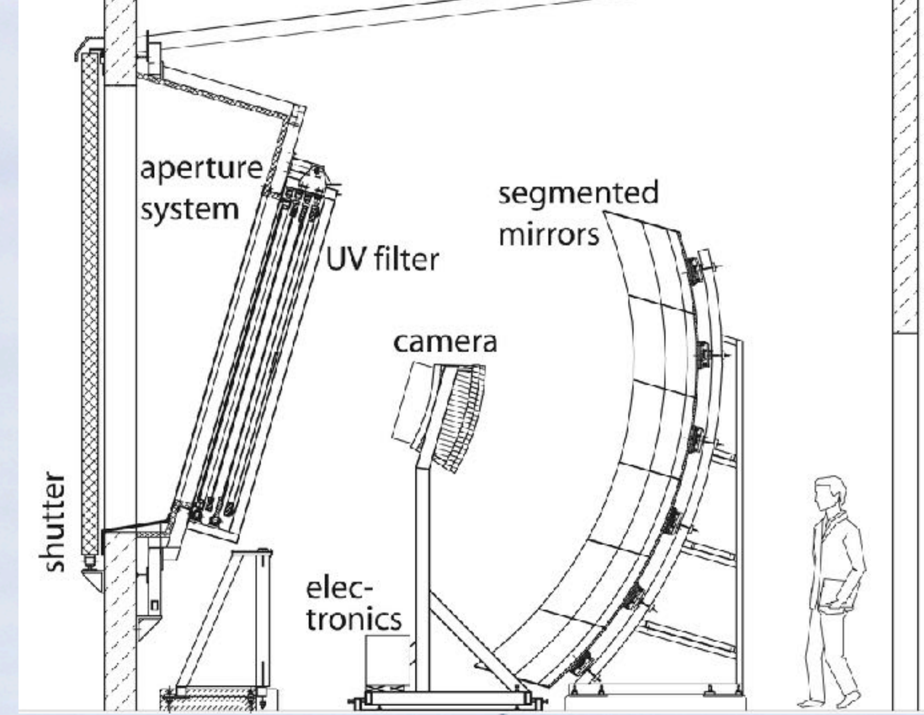
Area: 3000 km^2

Located in the Pampa Amarilla, Mendoza, Argentina

Altitude: 1400 m a.s.l.

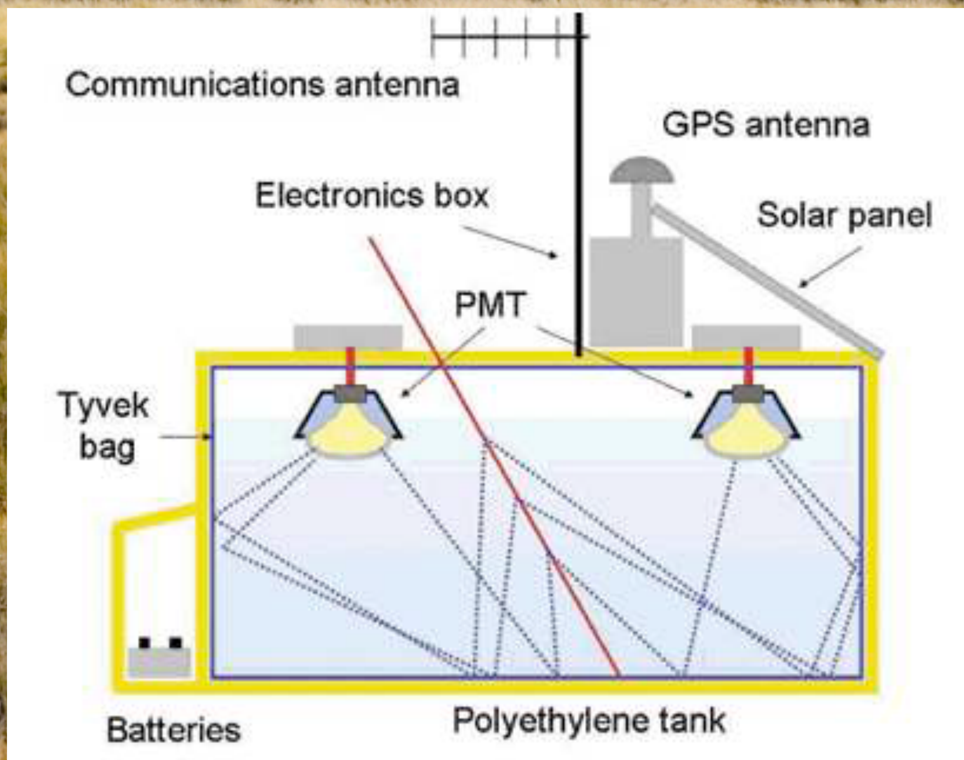


Hybrid detector



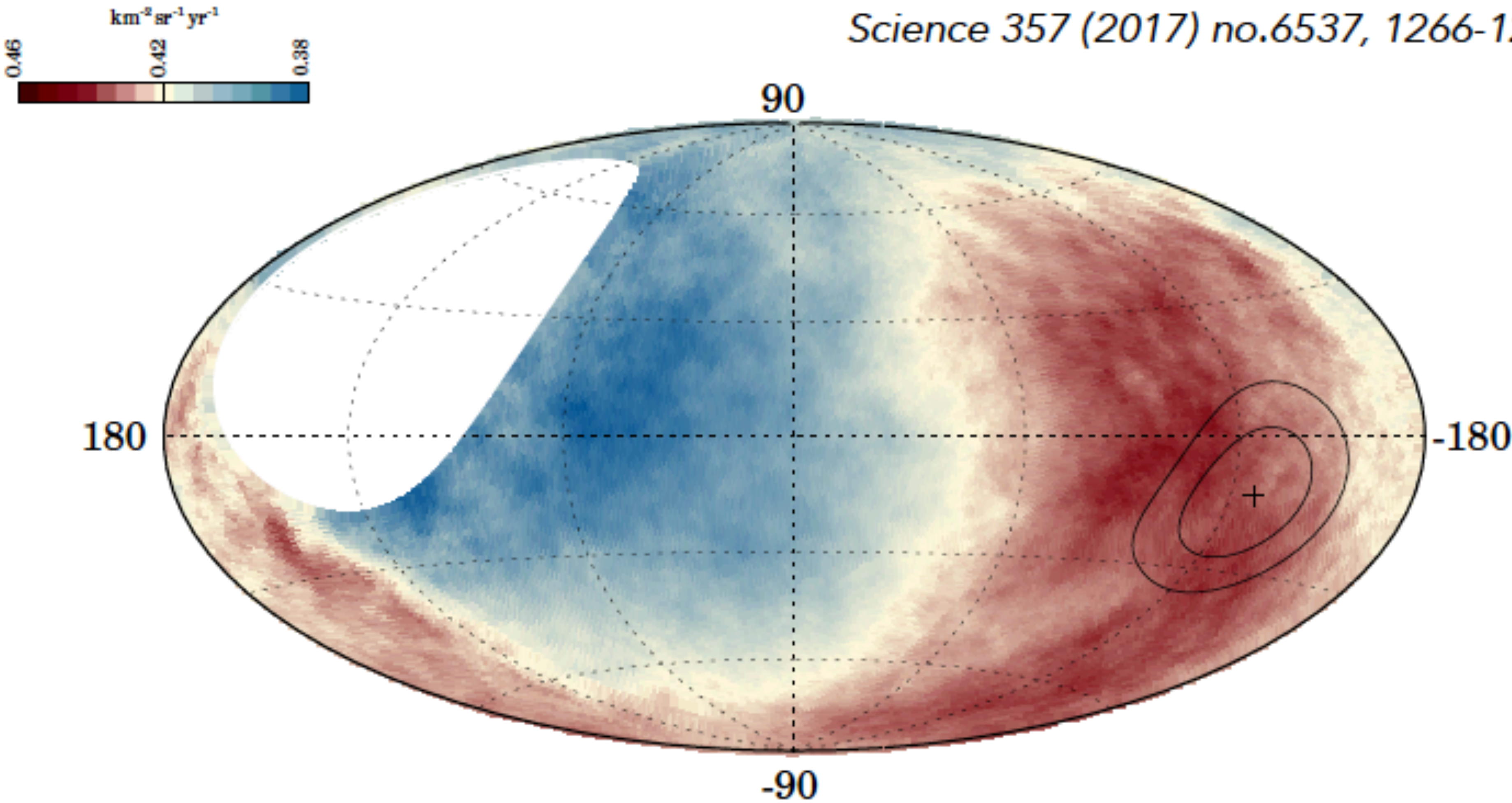
Fluorescence detector (FD) for scintillation light

Surface detector (SD) for charged particles



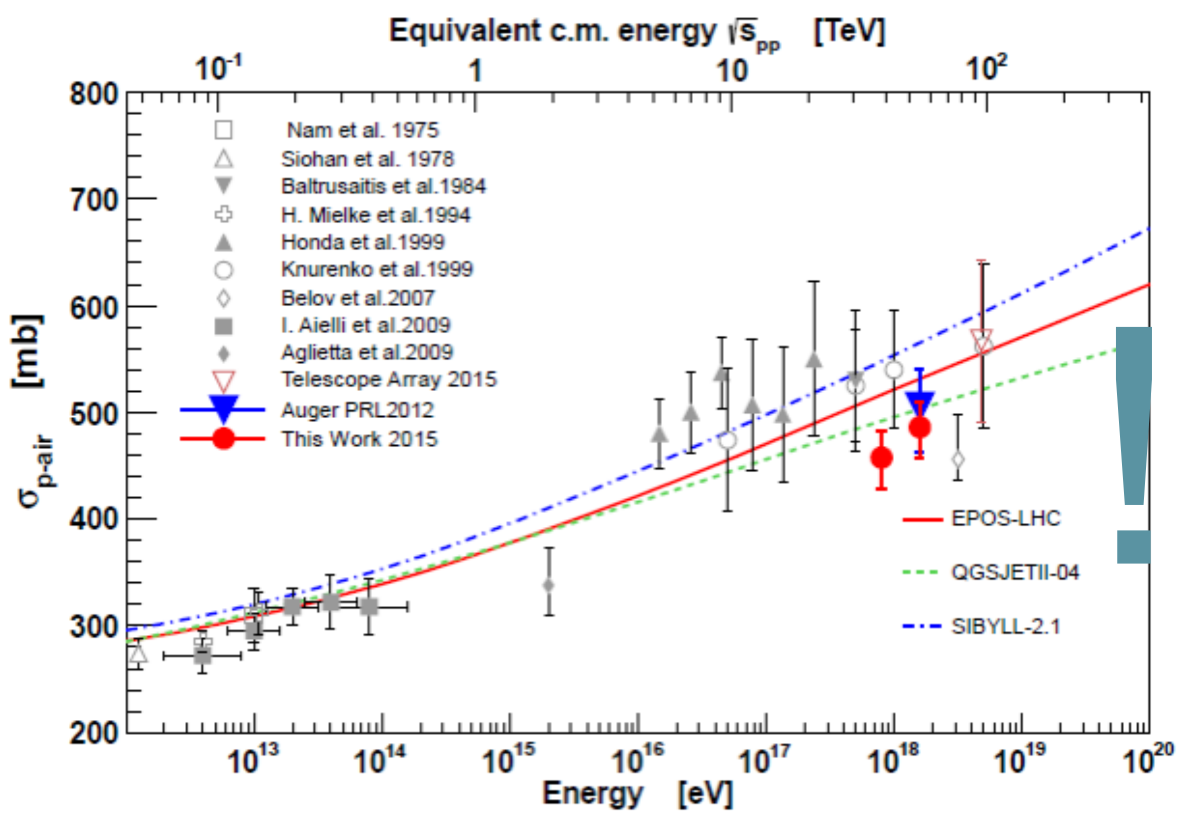
Observation of dipolar anisotropy

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



- Harmonic analysis shows a dipole for energies above 8 EeV
  - Significance: 5.2 σ (post-trial ; with penalization for energy bins exploration)
- Evidence for UHECRs origin outside the galaxy

Measurement (!) of cross-section



Few years ago… before LHC got it

!!!

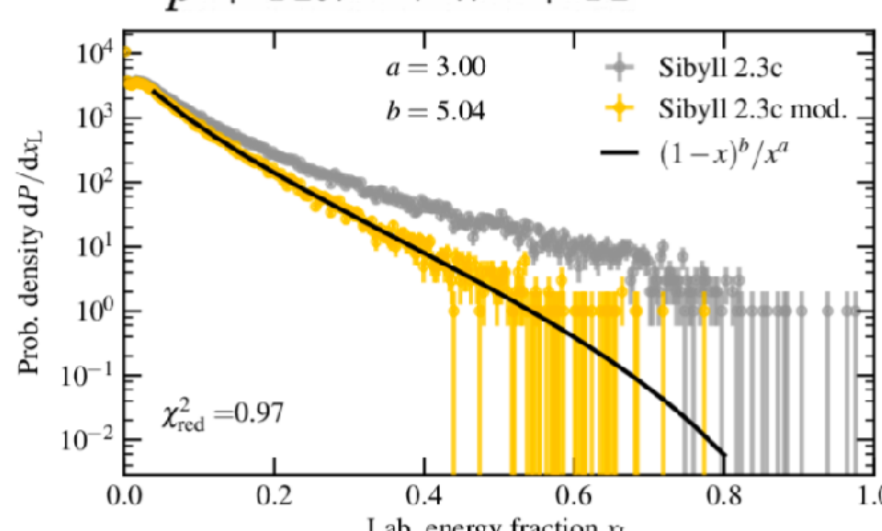
First measurement of p-air cross-section at 10^{18} eV

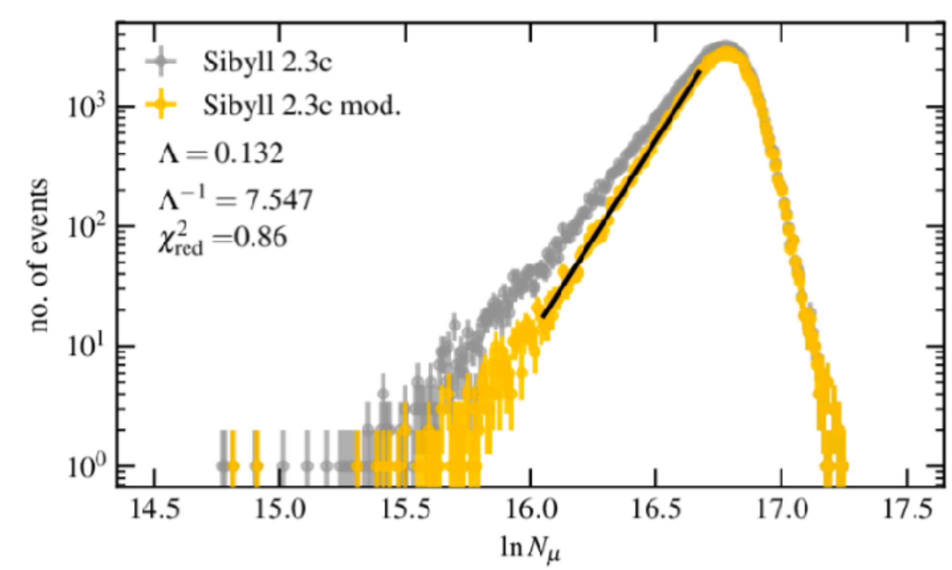
π^0 energy spectrum

Just now…

The output of first interactions dictate the muon distribution!

$$p + Air \rightarrow \pi^0 + X$$



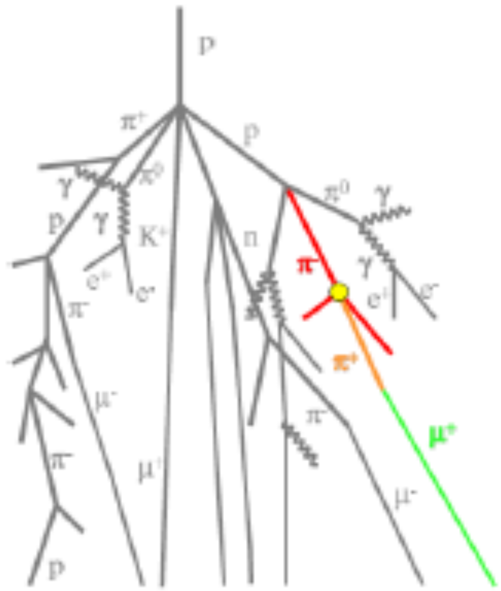


Measure the muons → Estimate π^0 Energy Spectrum

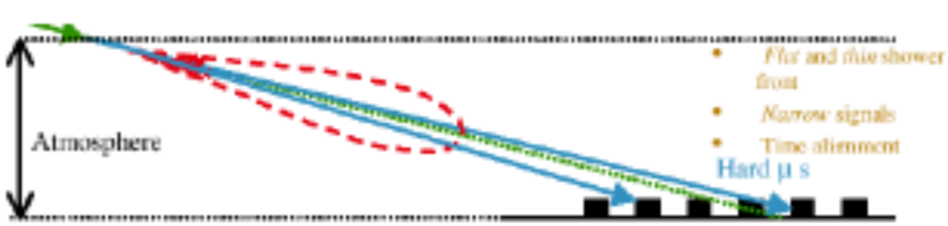
Particle Physics at the highest energies

Muon content in air showers

- Muons → Assess Hadronic interaction models (HIM)

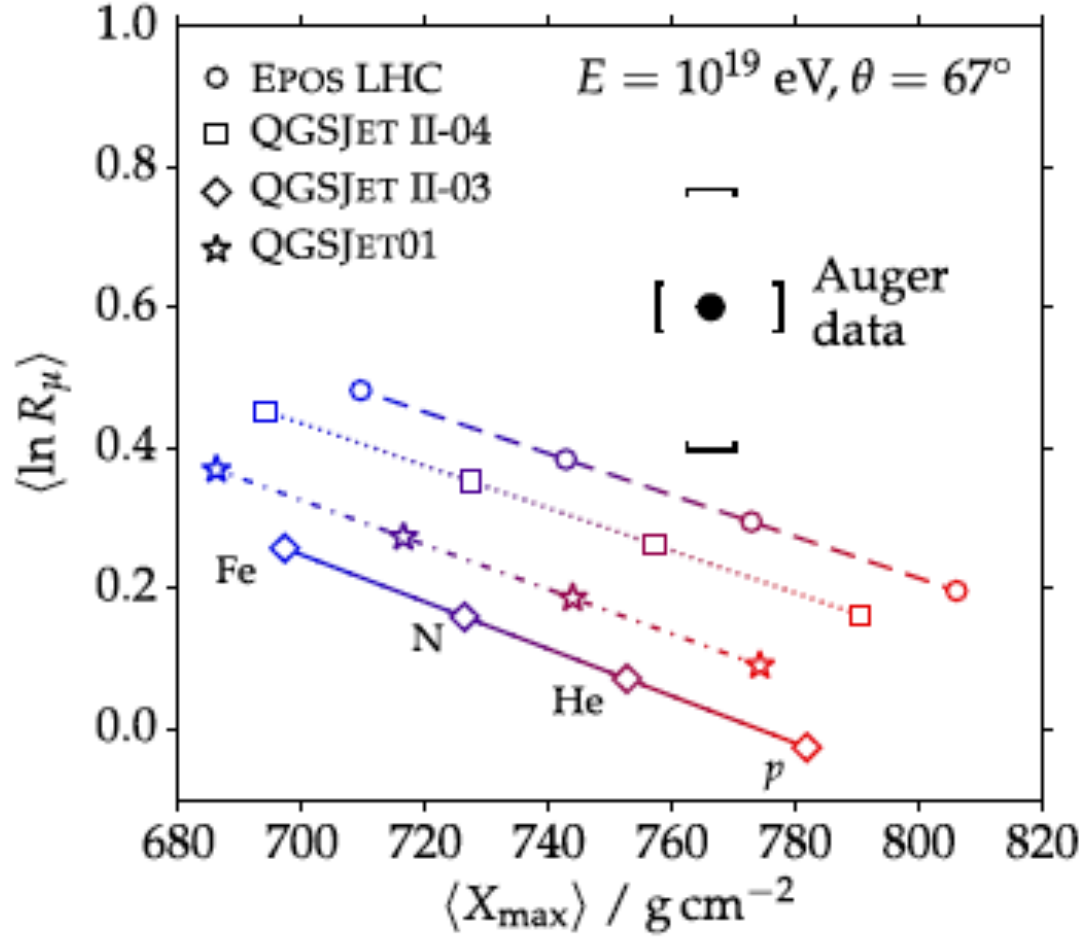


- Inclined shower → Muons



Surface Detector

Phys.Rev. D91 (2015) 3, 032003



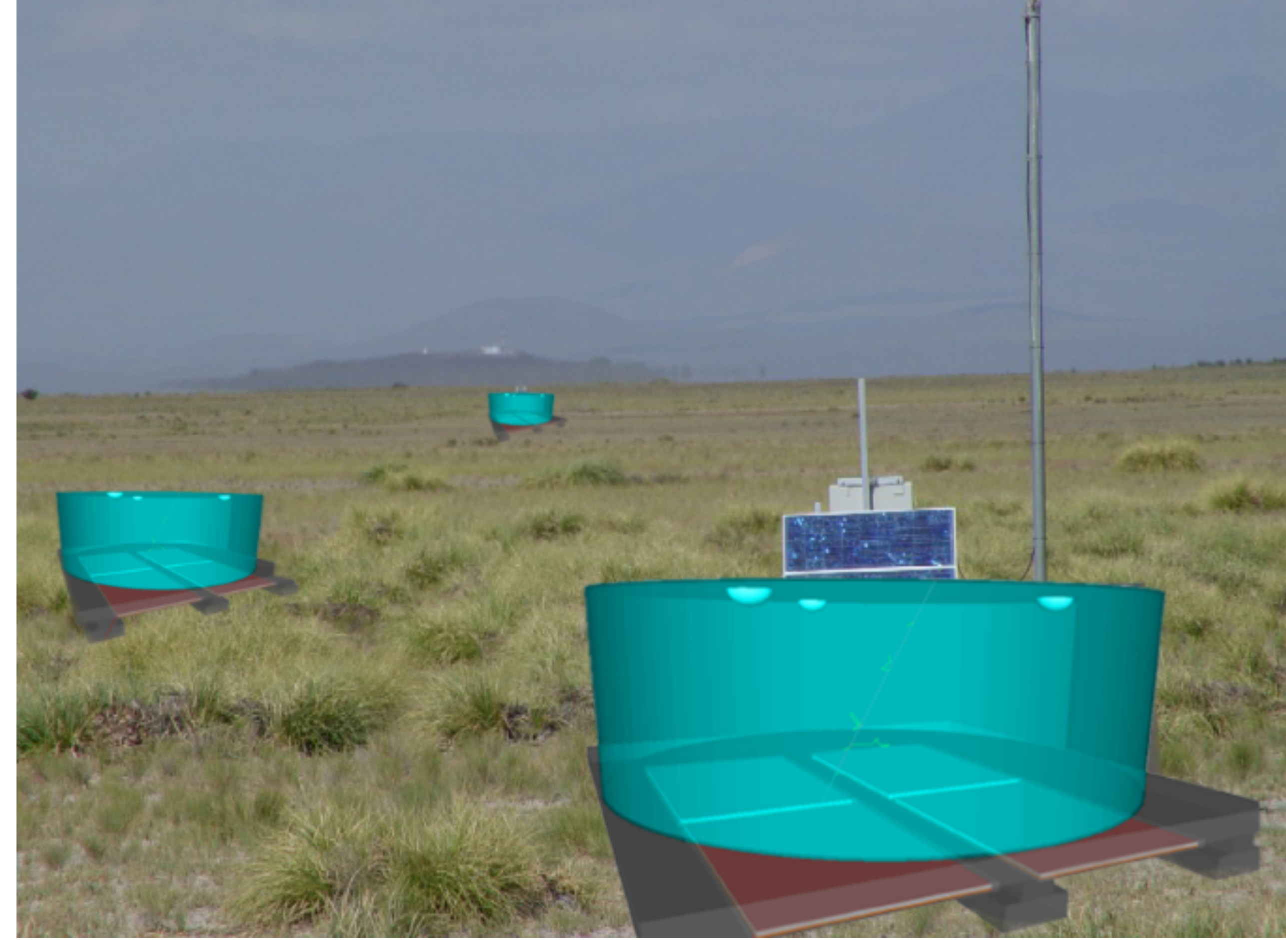
Fluorescence Detector

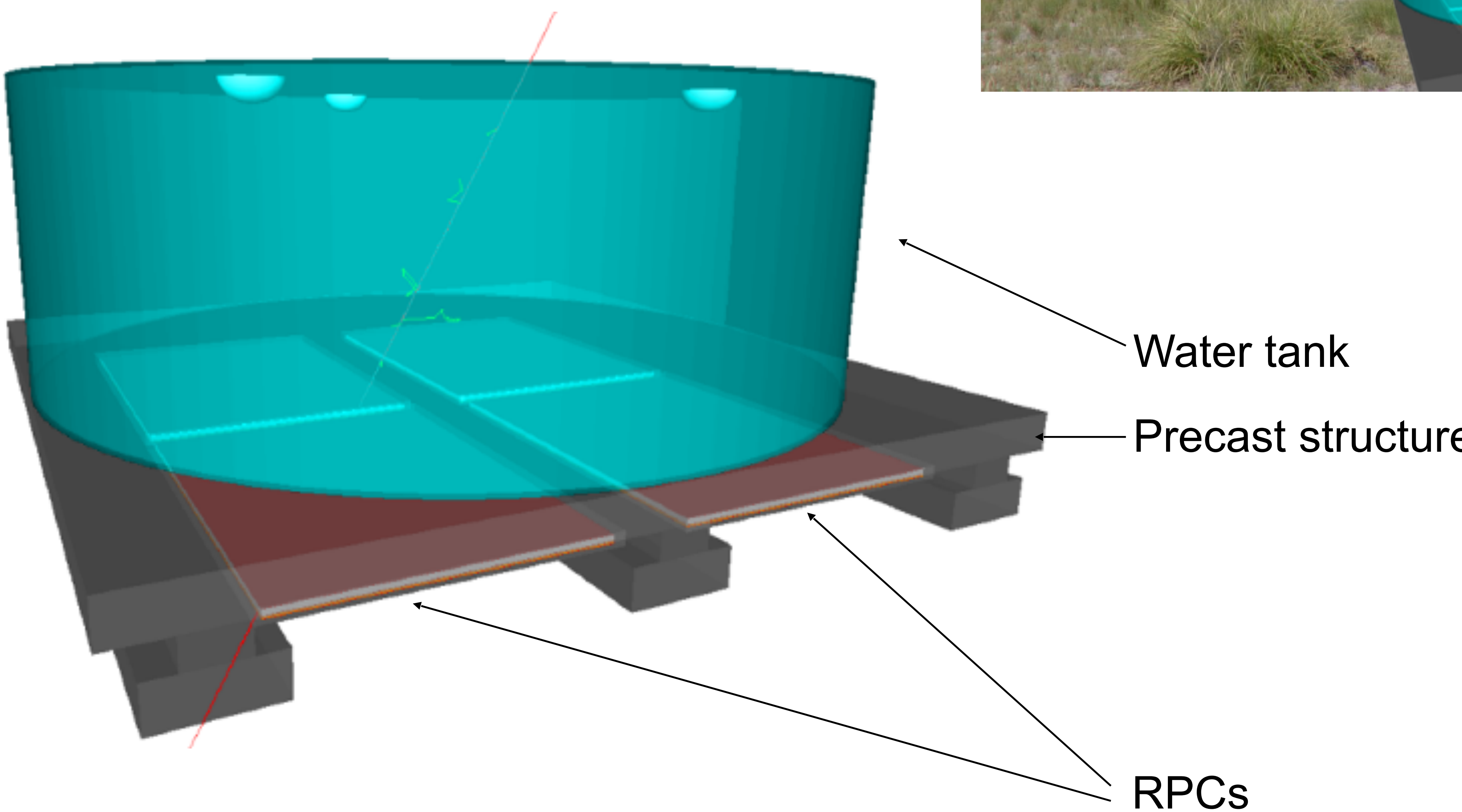
- Combination of the R_μ (number of muons) with X_{max} shows tension between data and all hadronic interaction models

Measuring Muons : MARTA

A dedicated muon detector:
An array of particle detector installed beneath the tanks.

Cost-effective.

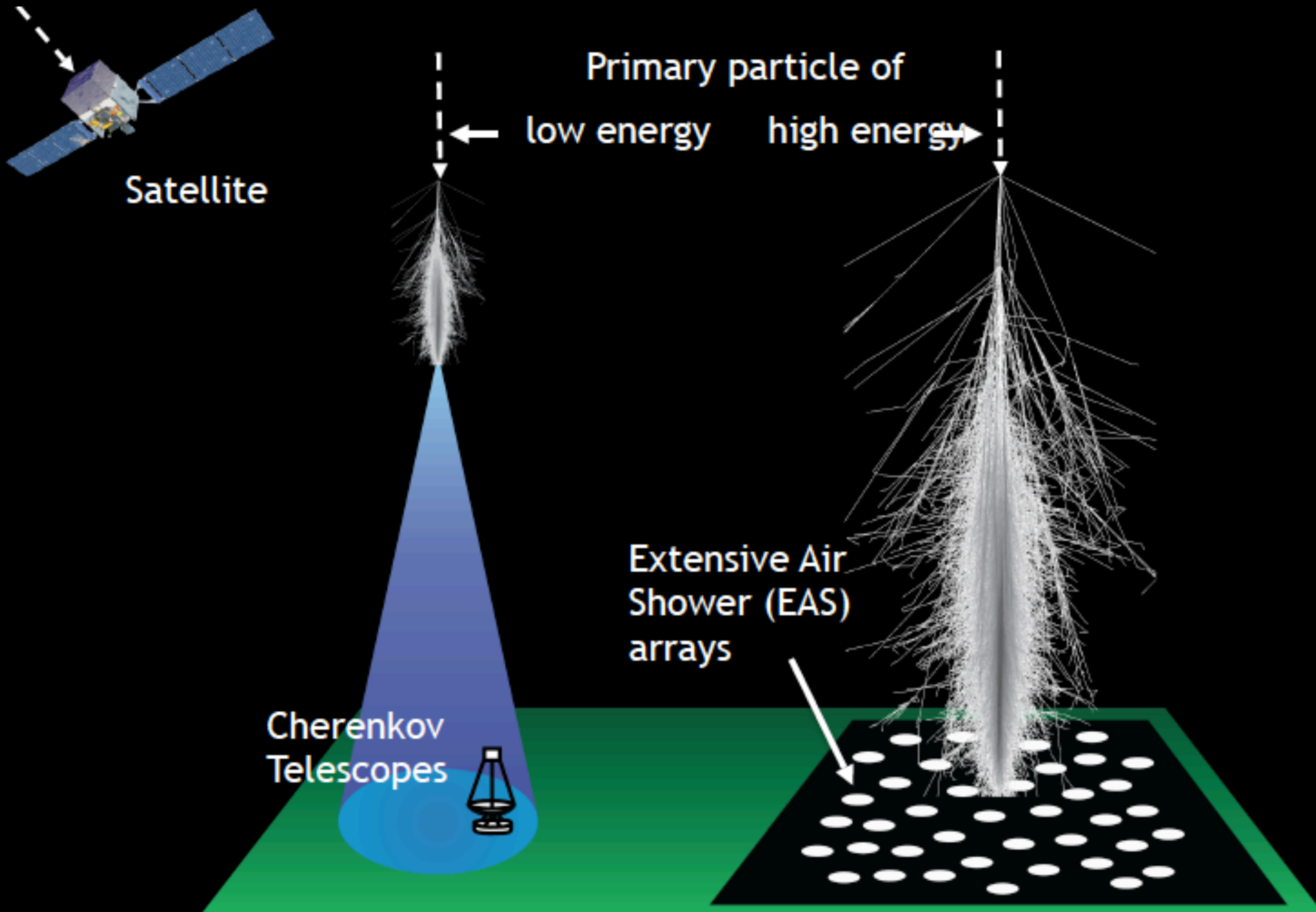




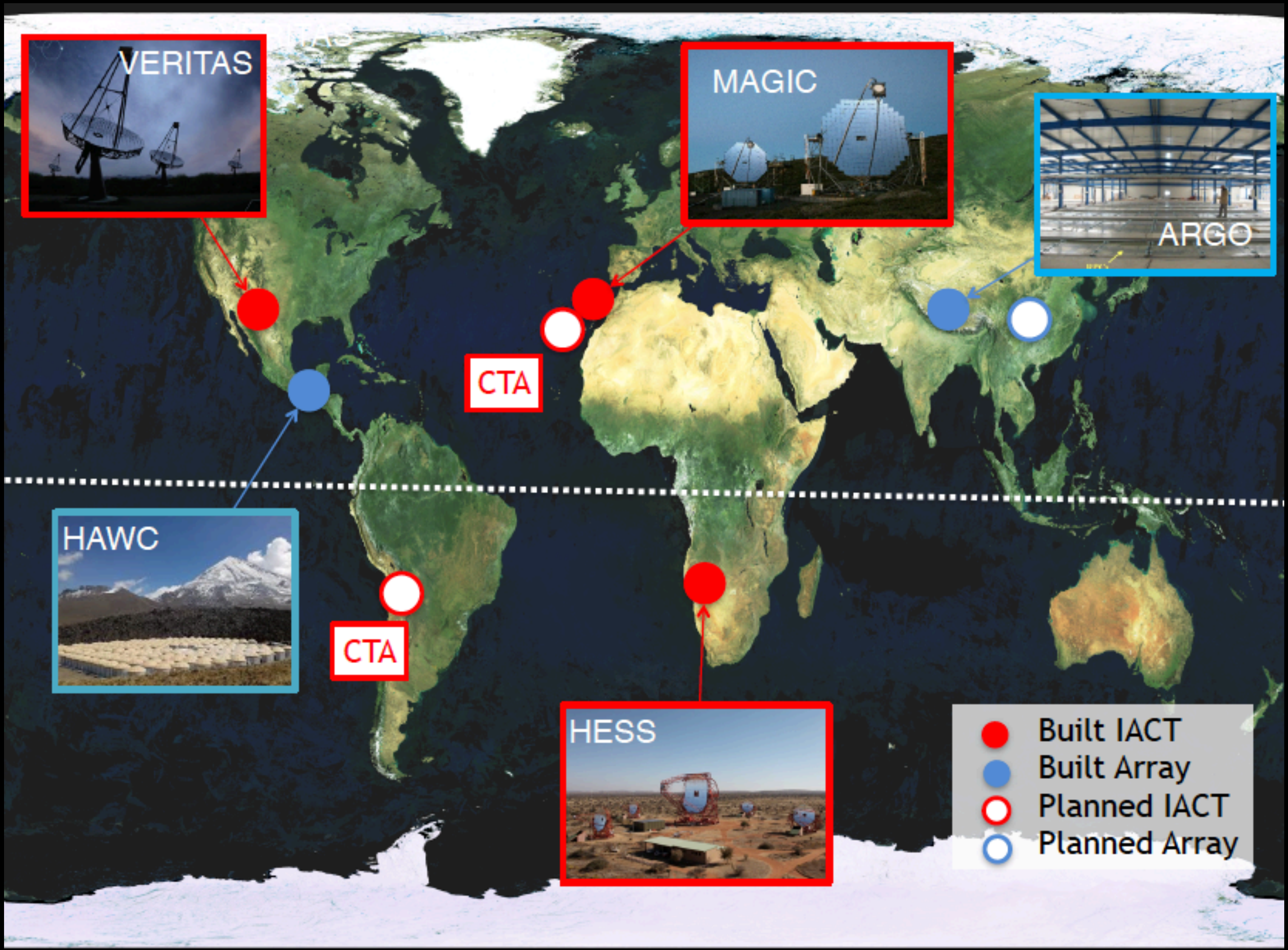
Led by LIP

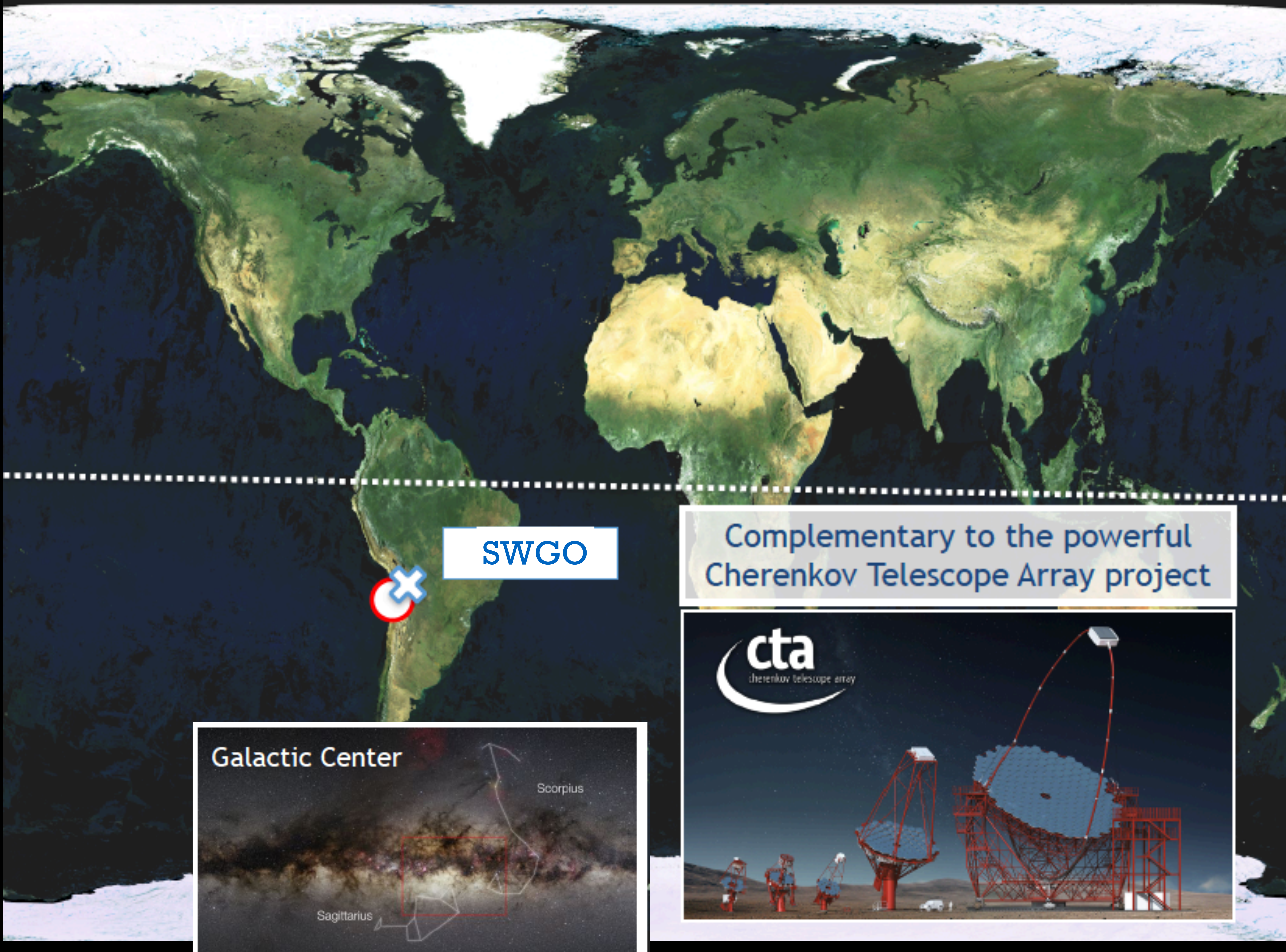
SWGO

How to detect VHE gamma rays?

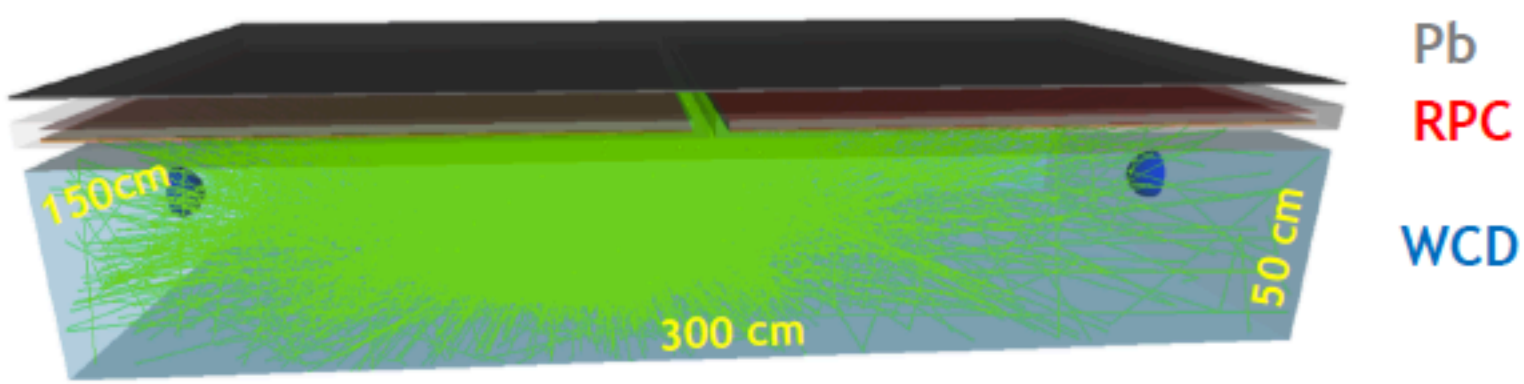


Arrays at high-altitude = large field of view + large duty cycle + low energy


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


SWGO
Complementary to the powerful Cherenkov Telescope Array project
cta
cherenkov telescope array
Galactic Center
Scorpius
Sagittarius

The concept: a hybrid detector



RPCs : time and spatial resolution

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

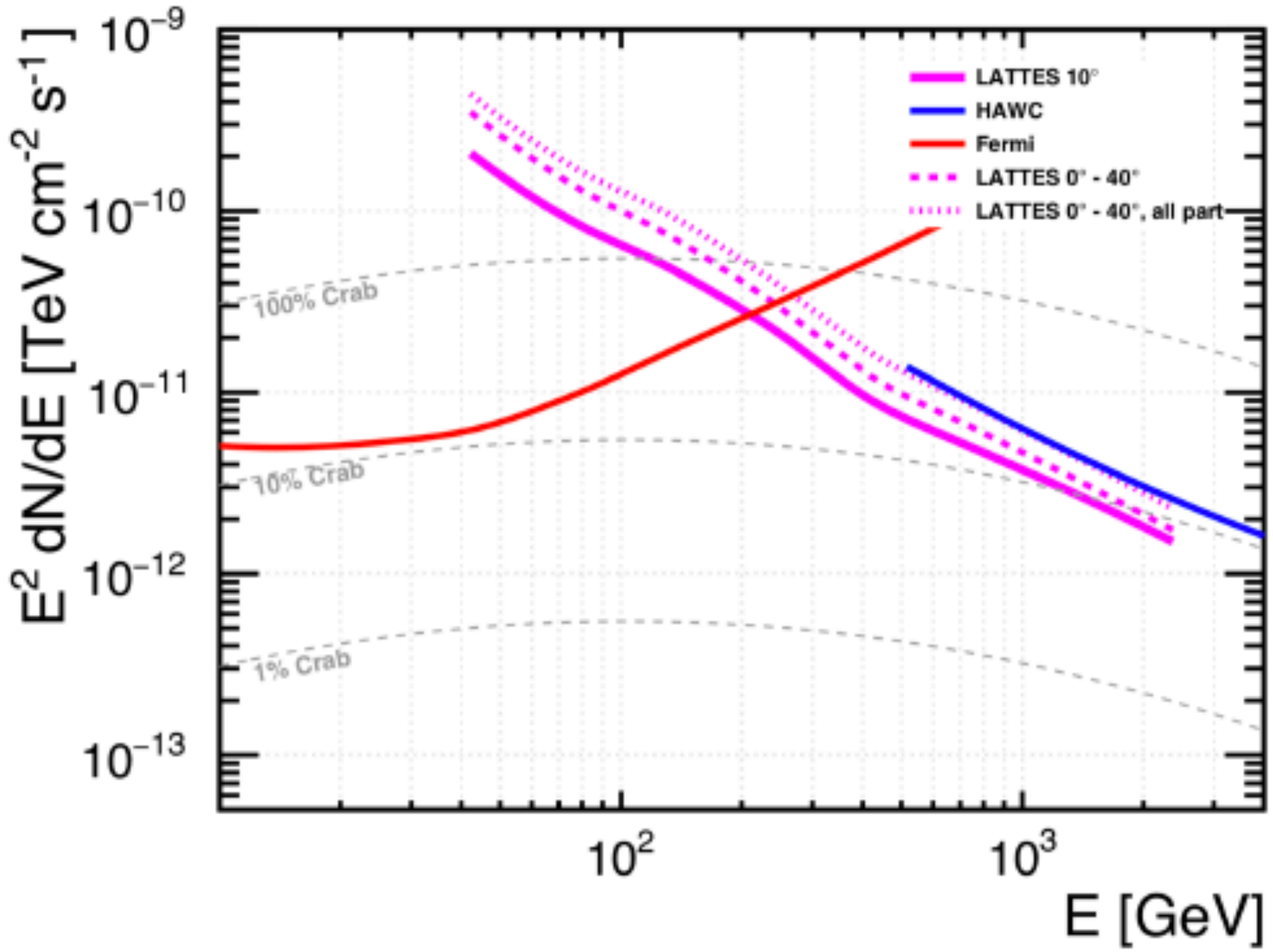
SWGO @ ALMA site

Southern Wide-field Gamma Observatory

- 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

SWGO sensitivity

Astropart.Phys. 99 (2018) 34-42

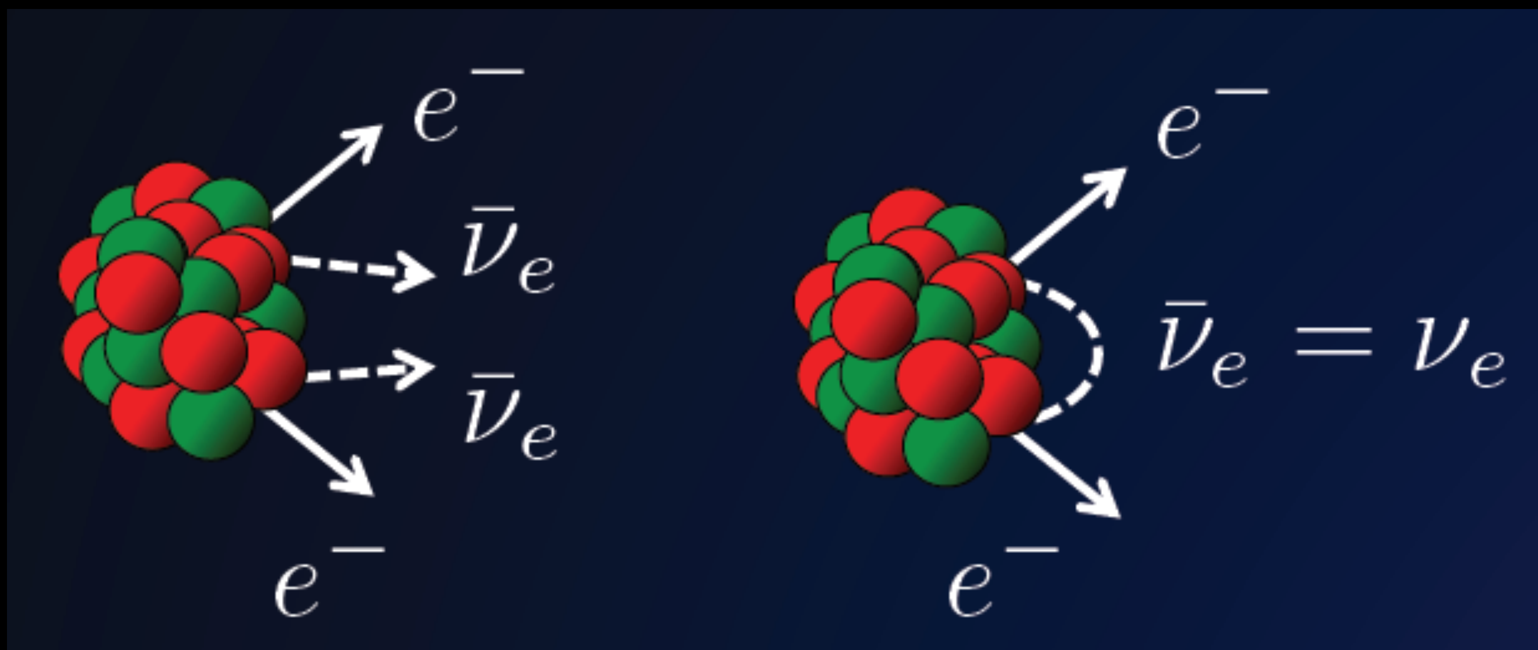


SWGO concept **can cover the energy gap** between satellite borne and ground base experiments

ruben@lip.pt

SNO+

Neutrino-less double beta decay



- Only happens if neutrinos are of Majorana type
- Half-life depends on the neutrino mass

$$\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu}|\mathcal{M}_\nu|^2 \left|\frac{m^\nu_{\mathrm{ee}}}{m_\mathrm{e}}\right|^2$$

Half-life

Nuclear Physics terms

Particle Physics term
Effective Majorana mass
Depends on masses m1, m2, m3
also on neutrino mixing parameters

$$m^\nu_{\mathrm{ee}} = m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{2i\alpha_2} + m_3 s_{13}^2 e^{2i(\alpha_3+\delta)}$$

SNO+ detector

new calibration systems

new DAQ and readout cards

780 tons of **liquid scintillator**

loaded with double-beta decay isotope (Te130)

contained in an **acrylic vessel (AV)**

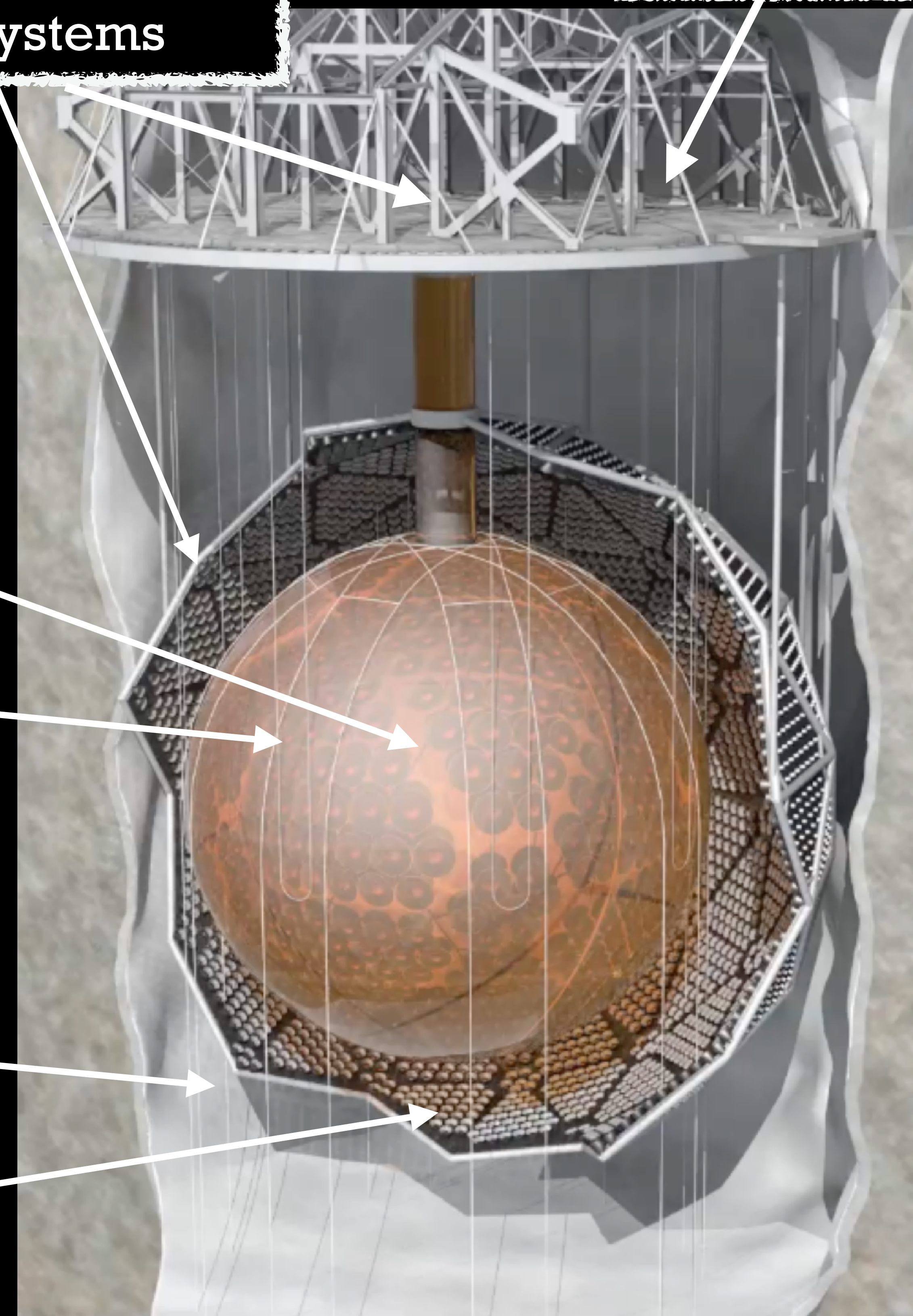
12 m diameter

held-down by **new rope system**

shielded by 7 kt ultra-pure water

viewed by ~ **9300 PMTs** (8”)

mounted on 17 m diam. structure



SNO+ Timeline

2016 — Dec. 2016: Started taking commissioning data

2017 — May 2017: Start of the Water Phase

2019 — Start of Scintillator Fill

2021 — End of Scintillator Fill

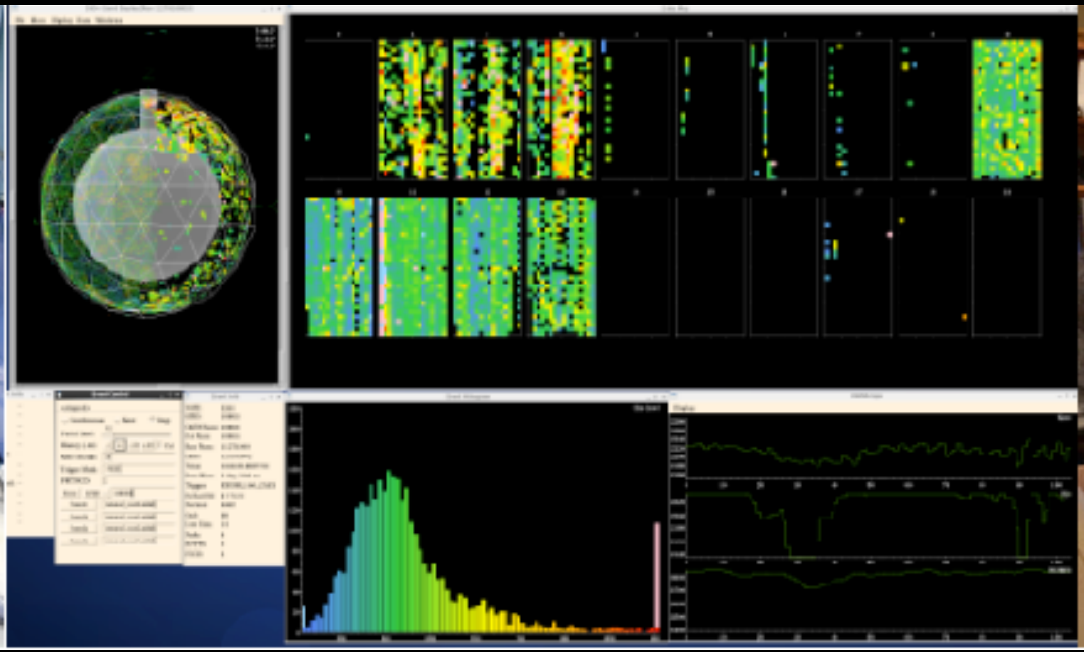
2022 — Tellurium is added to the scintillator

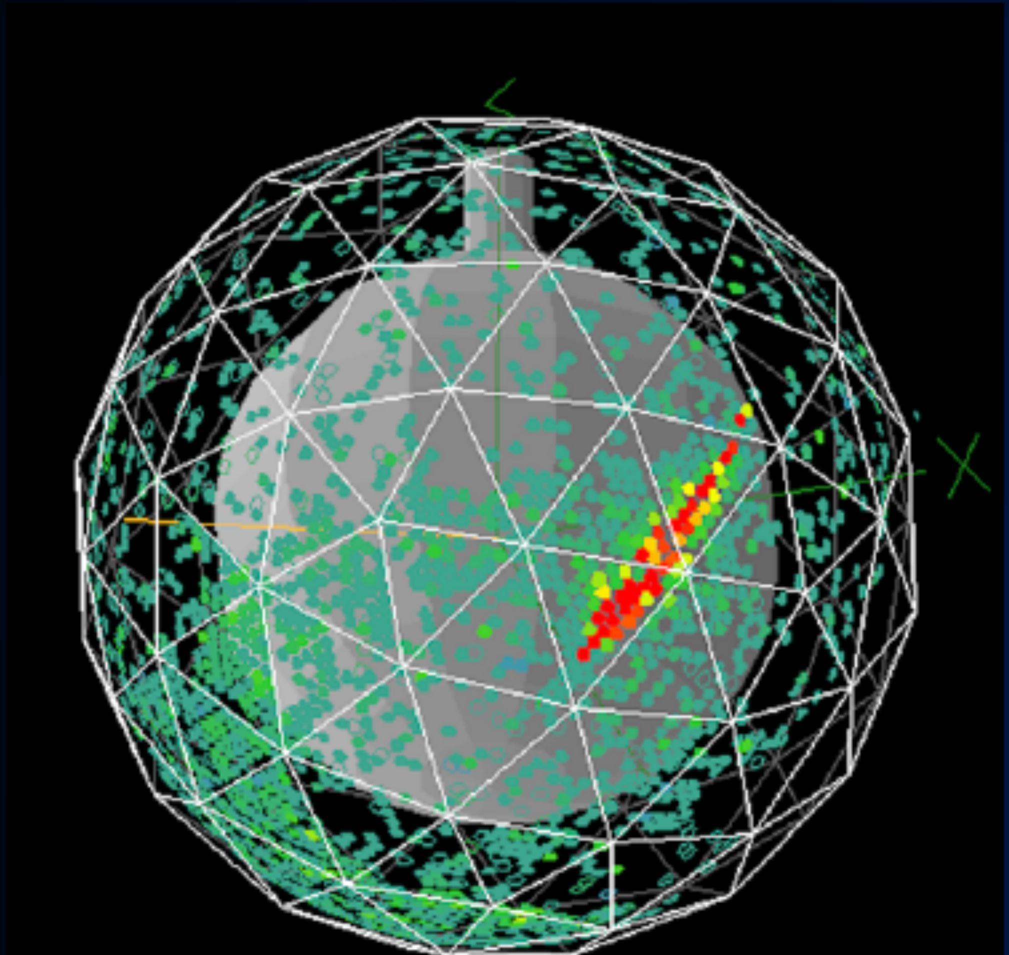
780 tonnes of LAB+PPO

+0.5% Te loading

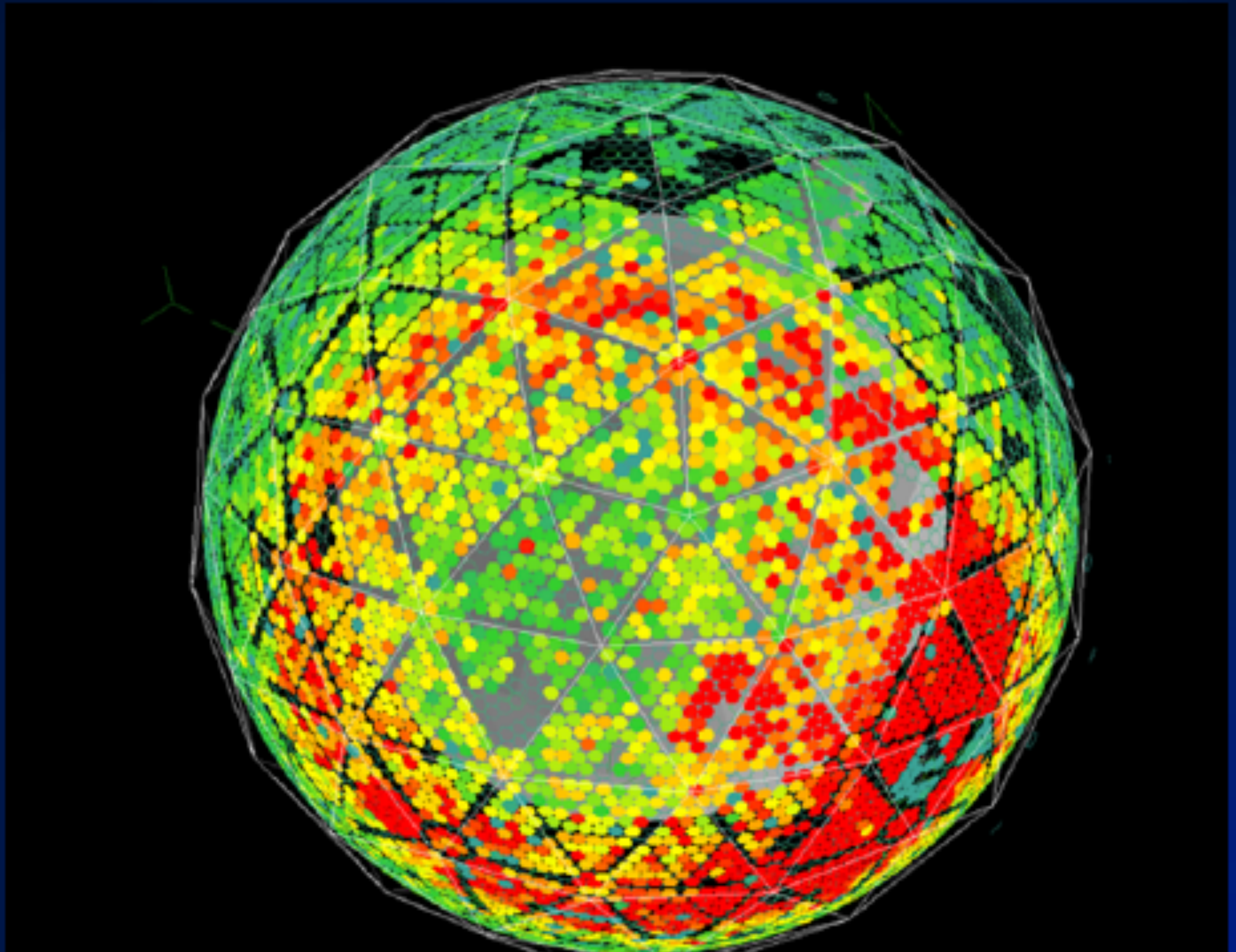
$0\nu\beta\beta$ Searches

UG @ SNOLAB



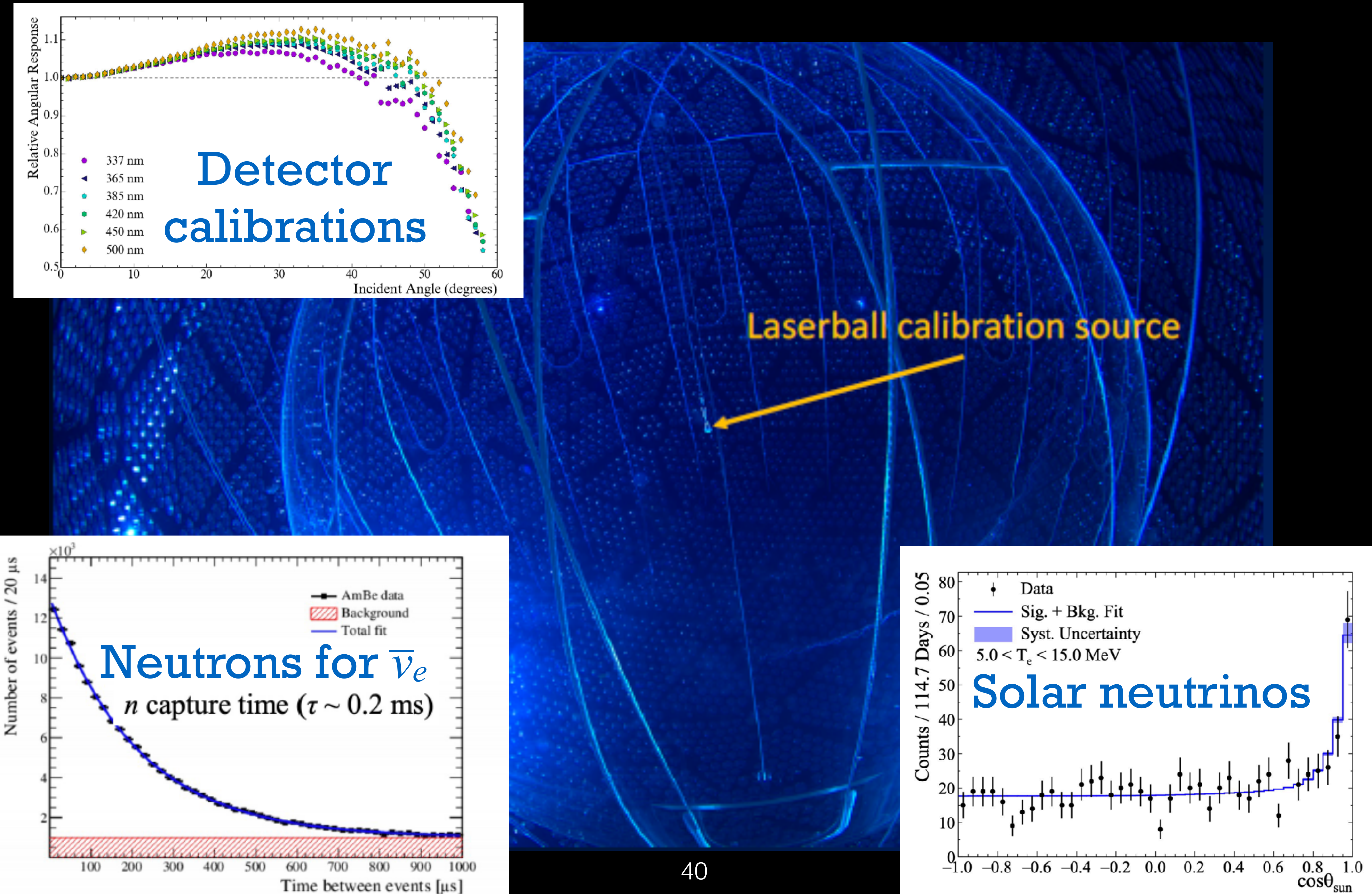


Muon candidate grazing the detector

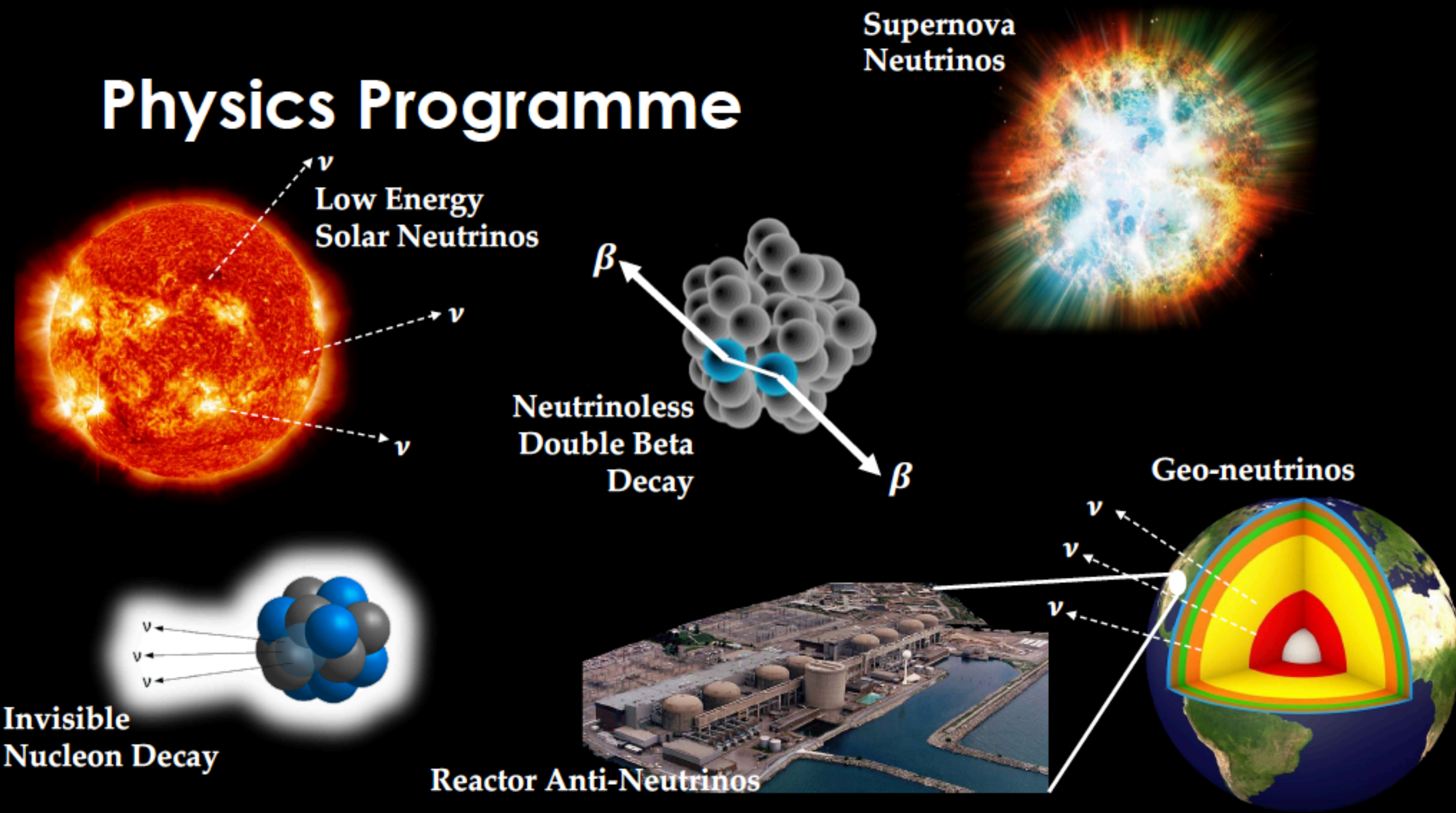


Another muon candidate

We have data!


Relative Angular Response
Incident Angle (degrees)
337 nm
365 nm
385 nm
420 nm
450 nm
500 nm
Detector calibrations
Laserball calibration source
Number of events / 20 µs
Time between events [µs]
AmBe data
Background
Total fit
Neutrons for $\overline{\nu}_e$
n capture time ($\tau \sim 0.2$ ms)
Counts / 114.7 Days / 0.05
$\cos\theta_{sun}$
Data
Sig. + Bkg. Fit
Syst. Uncertainty
$5.0 < T_e < 15.0$ MeV
Solar neutrinos

SNO+


Physics Programme
Supernova
Neutrinos
ν
Low Energy
Solar Neutrinos
ν
ν
β
β
Neutrinoless
Double Beta
Decay
Geo-neutrinos
ν
ν
ν
Invisible
Nucleon Decay
Reactor Anti-Neutrinos

DUNE

Long-baseline oscillations
Electron neutrino appearance

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2}\Delta_{31}^2$$

$$+ \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12} \times \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)}\Delta_{31} \times \frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31} \pm \delta_{CP})$$

$$+ \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2$$

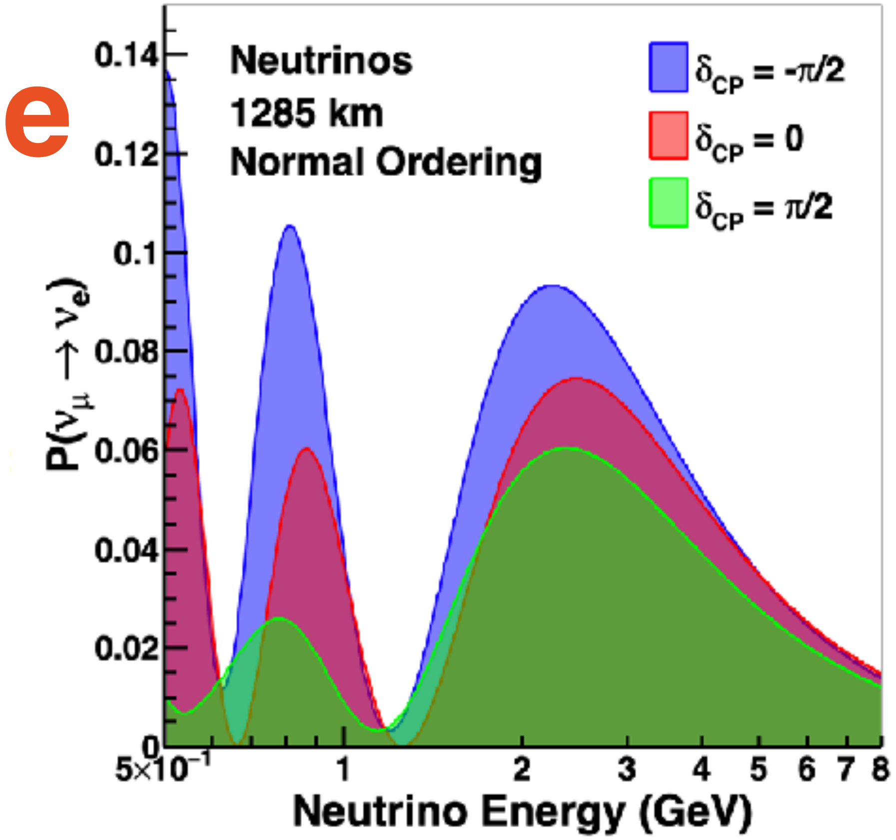
$$a = \pm\frac{G_F N_e}{\sqrt{2}}$$

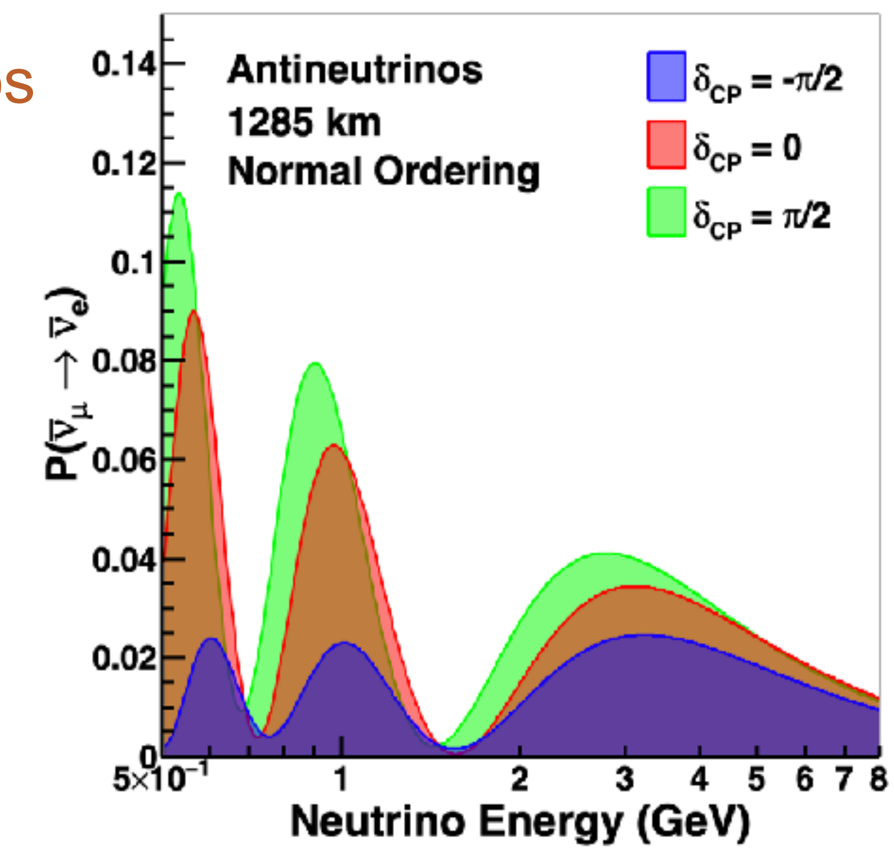
$$\Delta_{ij} = 1.267\,\Delta m_{ij}^2 L/E_\nu$$

Matter Effects

+ Neutrinos
− Antineutrinos

CP violation

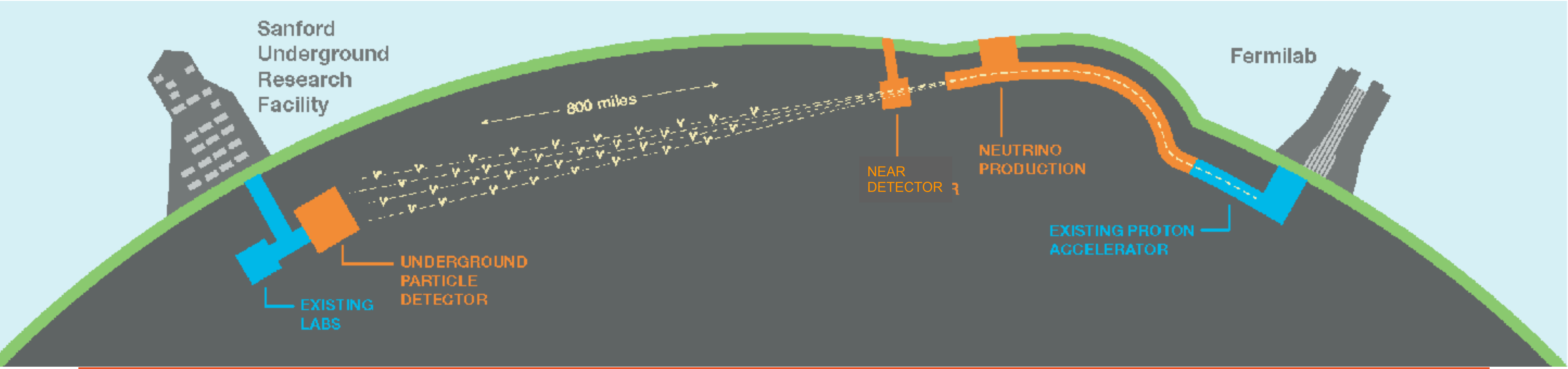




Deep Underground Neutrino Experiment

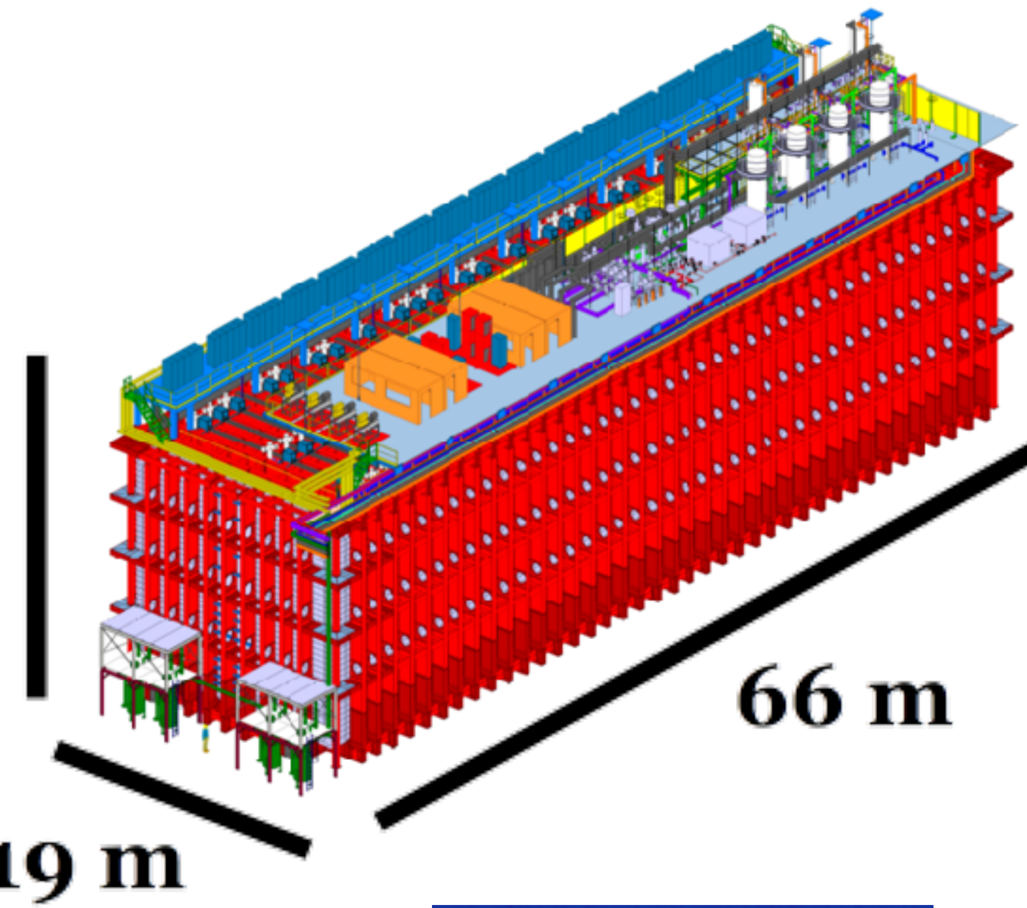
- DUNE in a nutshell
  - Fermilab makes intense neutrino and antineutrino beams
  - Near Detector characterizes beam and cross-sections
  - Beams reach Sanford lab, 1285 km away, 1.5 km underground
  - 70 kt Far Detector, divided in 4 modules

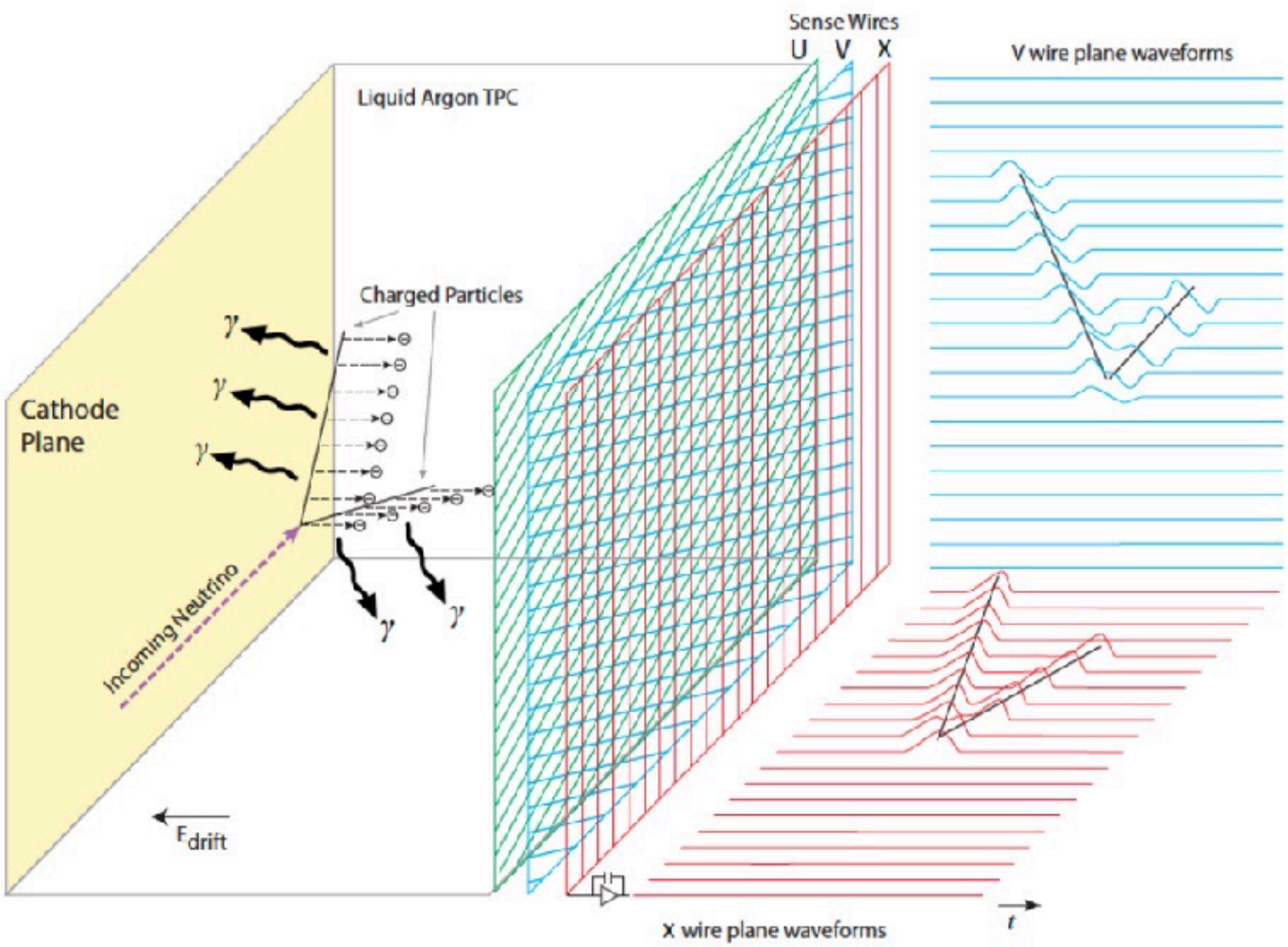
- Physics goals
  - Measure ν_e / $\overline{\nu}_e$ appearance and ν_μ / $\overline{\nu}_\mu$ disappearance
  - Measure mass ordering, CP violation and neutrino mixing parameters in a single experiment
  - Large, deep underground detector is sensitive to rare and low-energy physics (Supernova bursts, nucleon decay and more)

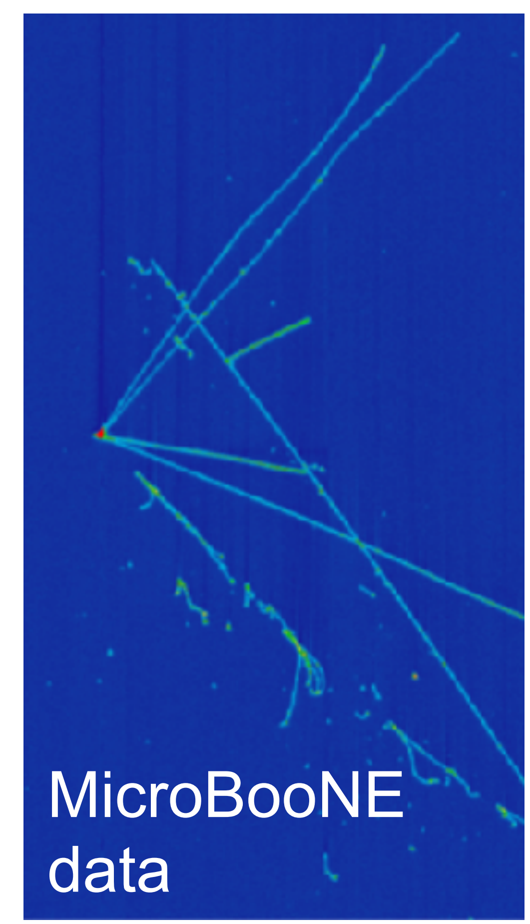


DUNE Far Detector

- Four detector modules, 17 kt each
- Modules #1, #2, and #3: Liquid Argon Time Projection Chamber
  - Precision tracking and calorimetry
- Ongoing R&D for #4 Module of Opportunity

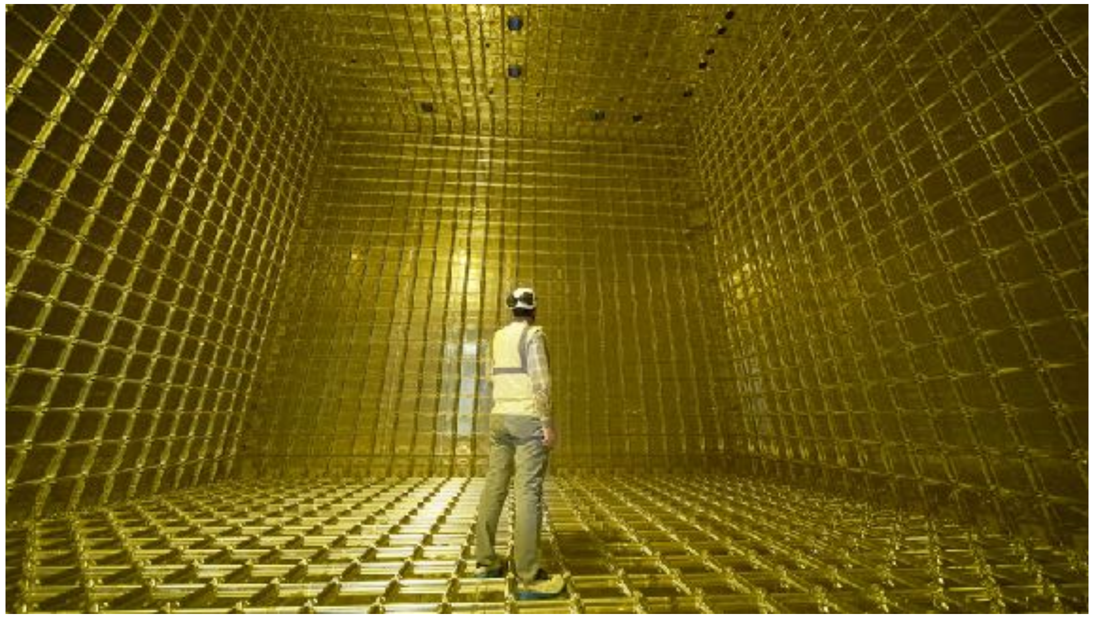






ProtoDUNE(s) at CERN

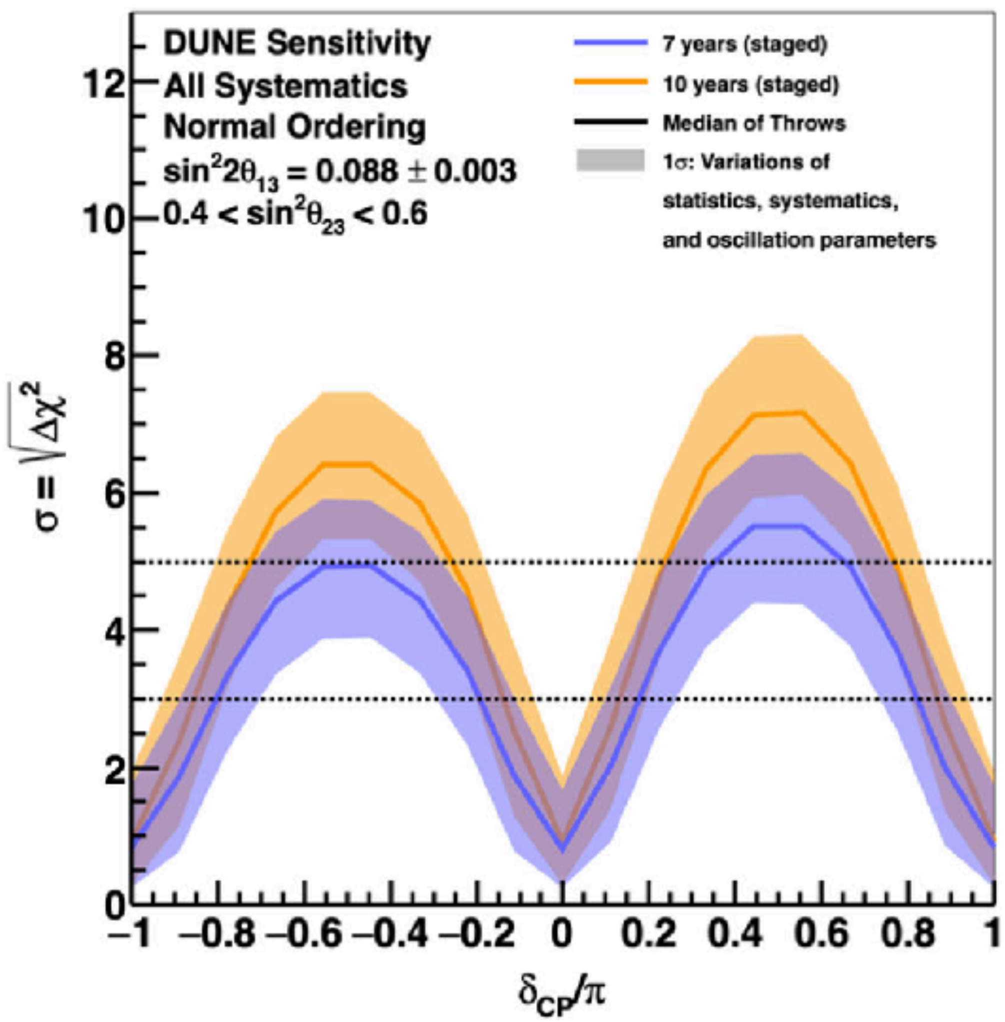
- Two ~1 kt prototypes 6x6x6 m
  - Design validation at (component) full scale
- Single-phase (HD) 2018-20
  - Charged particle beam + cosmics
  - Event reconstruction, full analysis
  - Neutron calibration, Xe doping, HV tests
  - Phase-II starting 2022
- Dual-phase 2019-20
  - Develop CRP technology, very HV
  - Evolved into SP-Vertical Drift

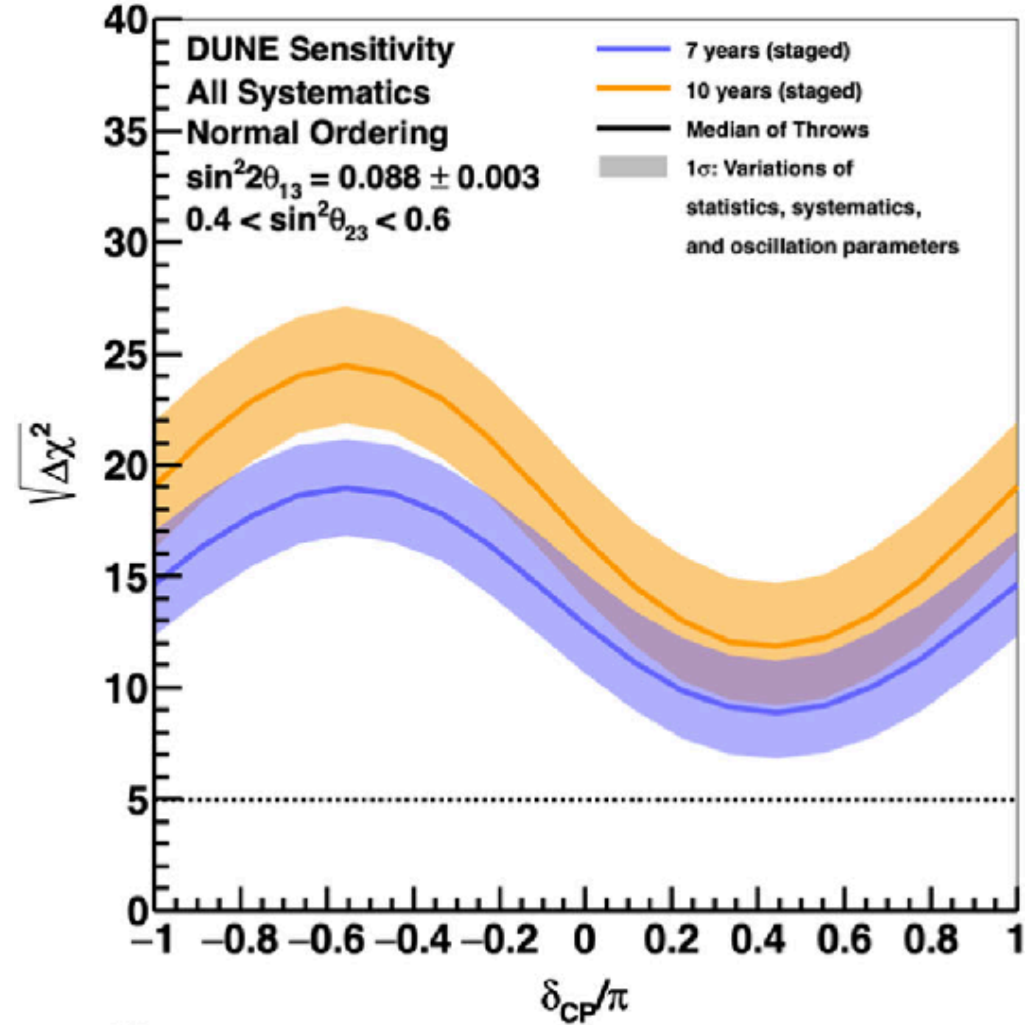


JINST 15 (2020) 12, P12004

Eur. Phys. J. C (2020) 80:978

CP violation and Mass Ordering





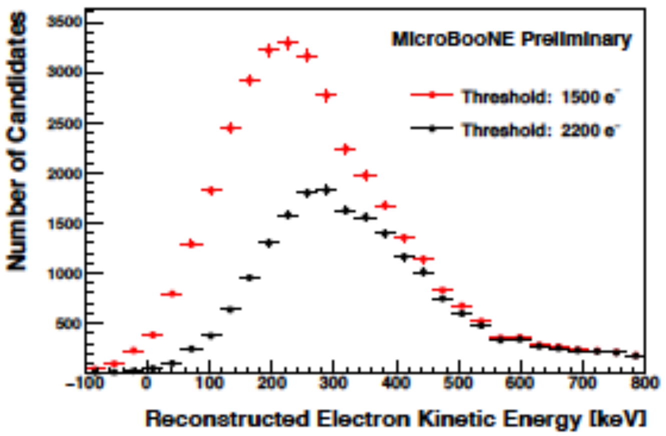
- **CP violation** discovery in wide range of δ_{CP} over 7-10 yrs
- Definitive determination of **mass ordering** for all parameters

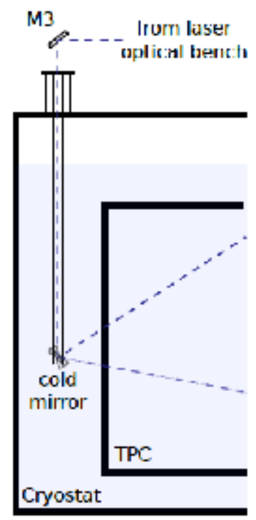
Due to long baseline and wideband beam, CPV and MO degeneracies are broken and DUNE can determine both these effects in the same experiment.

Calibration and Monitoring

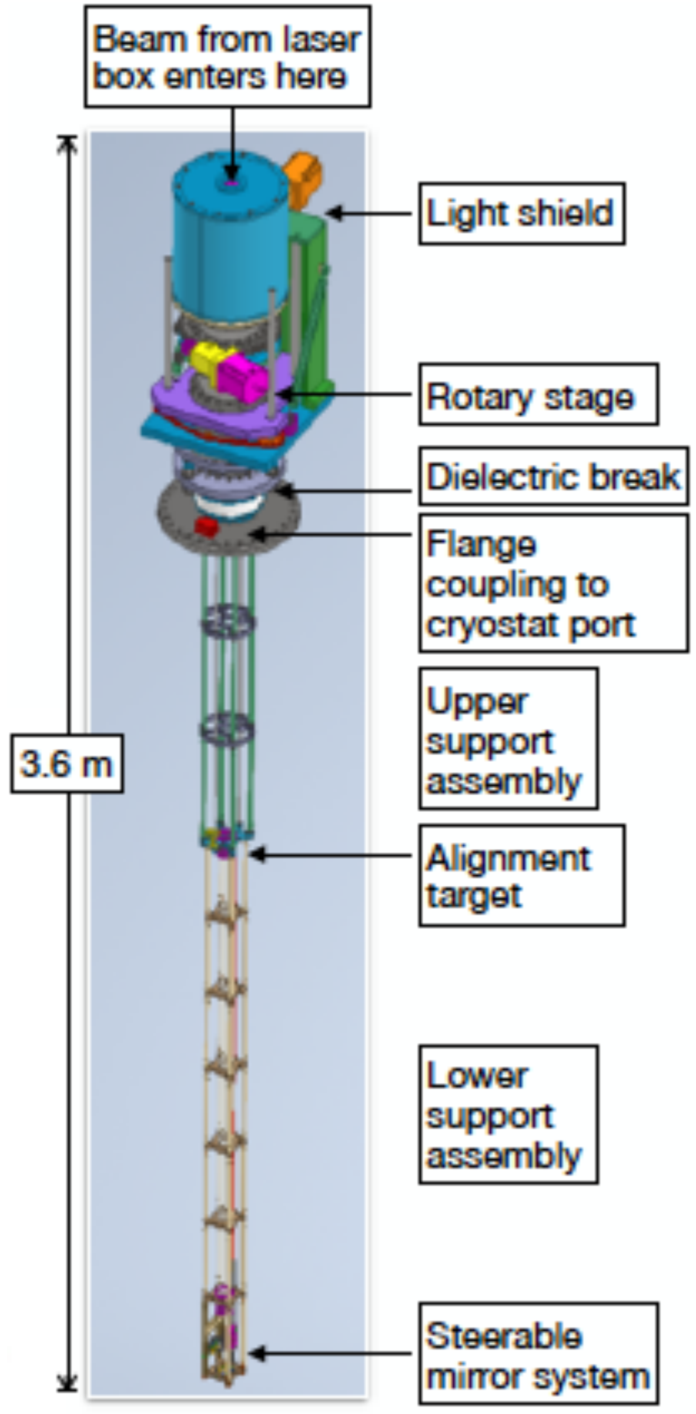
- Use of “natural” sources
  - Cosmic ray muons
  - Beam-induced muons
  - ^{39}Ar radioactivity
- Cryogenic instrumentation
  - Array of temperature sensors constraining Computational Fluid Dynamics simulations
  - Purity monitors (i.e., miniature TPCs) measure electron lifetime.
- Dedicated calibration hardware
  - Intense laser beams steered into active volume. Ionization tracks to monitor detector performance
  - External neutron source for low energy response
  - Possibly deployed sources

MICROBOONE-NOTE-1050-PUB





DD neutron generator



LIP LABORATÓRIO DE INSTRUMENTAÇÃO E FÍSICA EXPERIMENTAL DE PARTÍCULAS DUNE

Outlook

- Neutrino and astroparticle experiments have a very wide range of:
  - Energy ranges and techniques
    - Scintillator/low energy, Liquid Argon
    - Trackers/spectrometers/calorimeters (in space!!)
    - RPC, water Cherenkov tanks
  - Particle Physics discovery potential
    - hadronic interactions, dark matter, leptogenesis
    - neutrino oscillations, mass, Majorana
  - Capabilities for Astrophysics
    - Multi-messenger studies of sources and propagation
    - Sun, Earth, Supernova