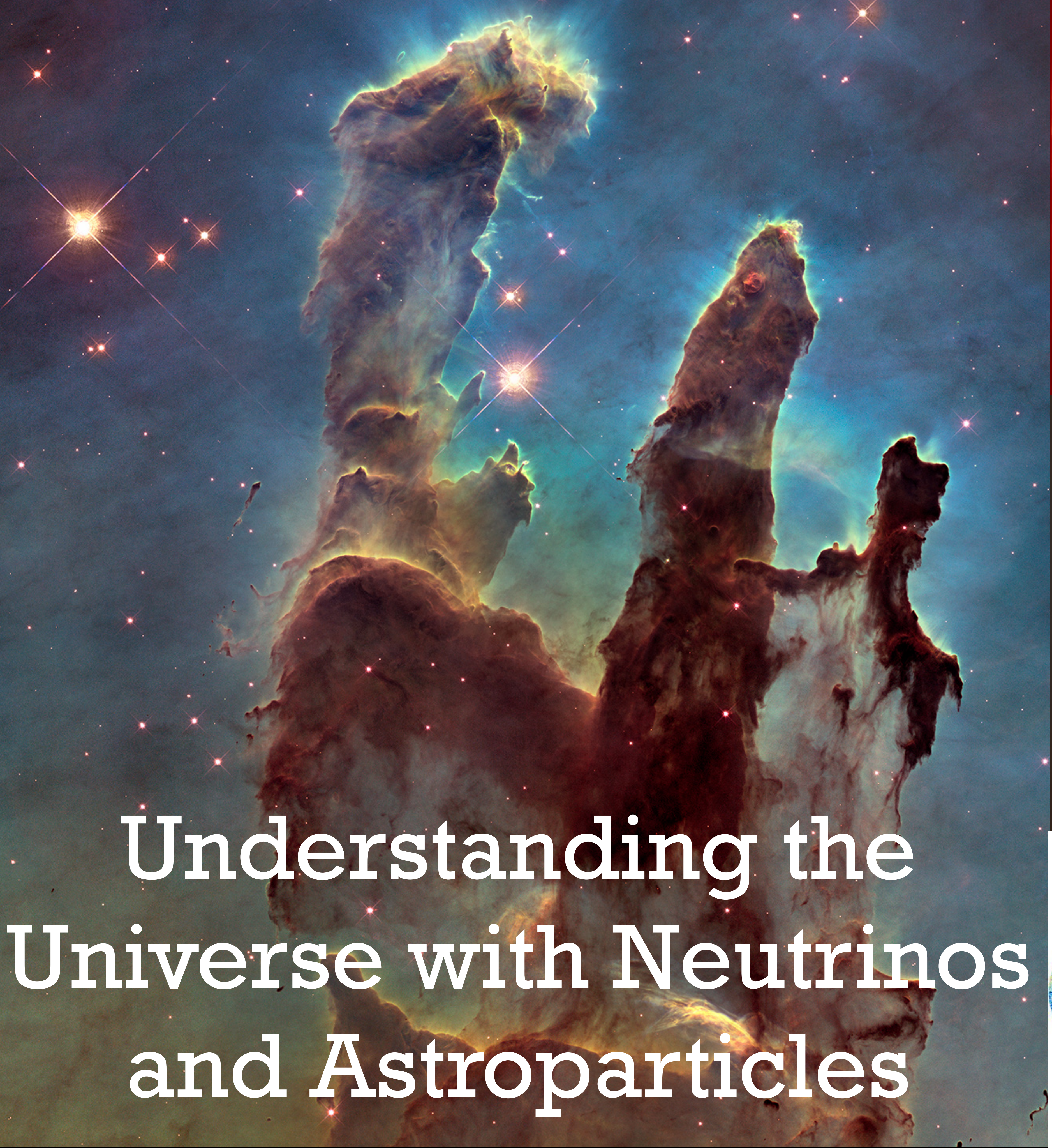
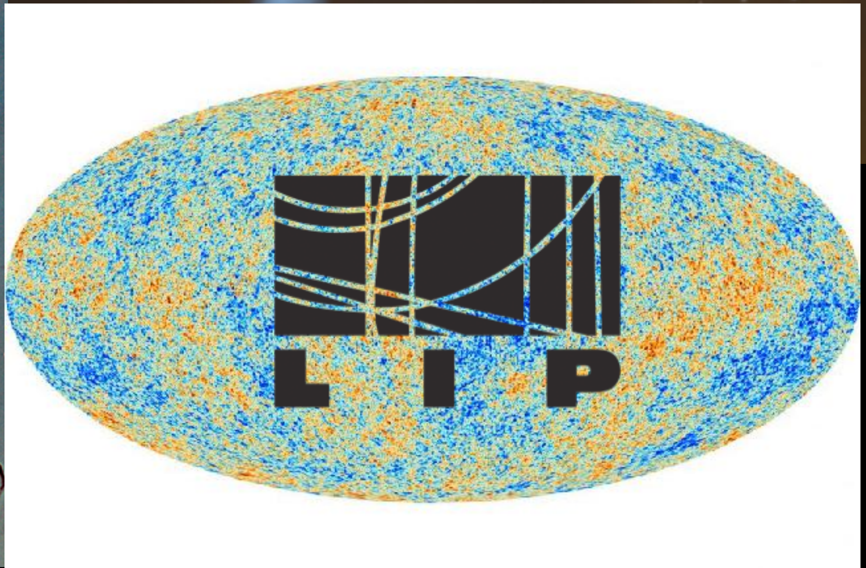


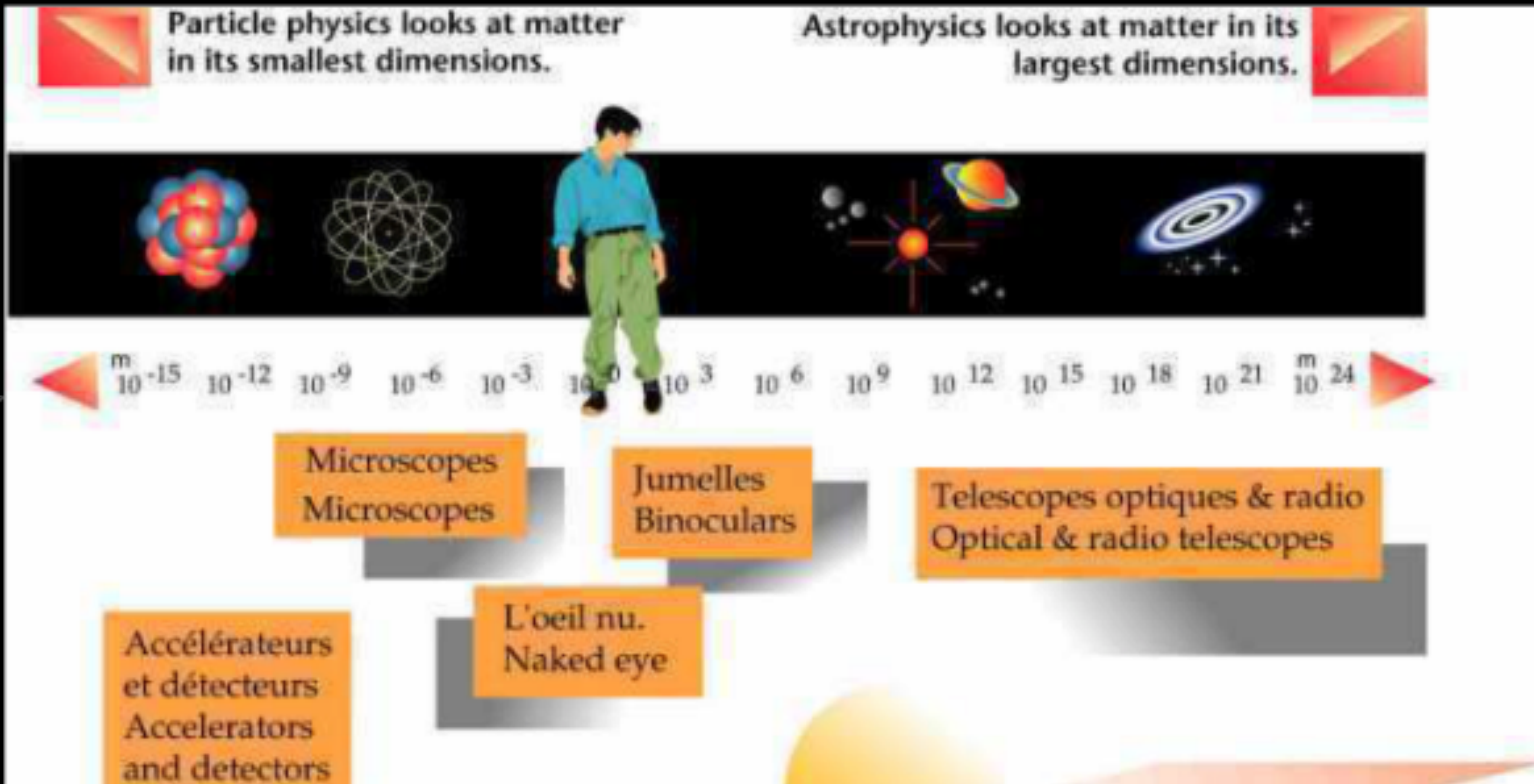
Understanding the Universe with Neutrinos and Astroparticles

J. Maneira

4th 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?

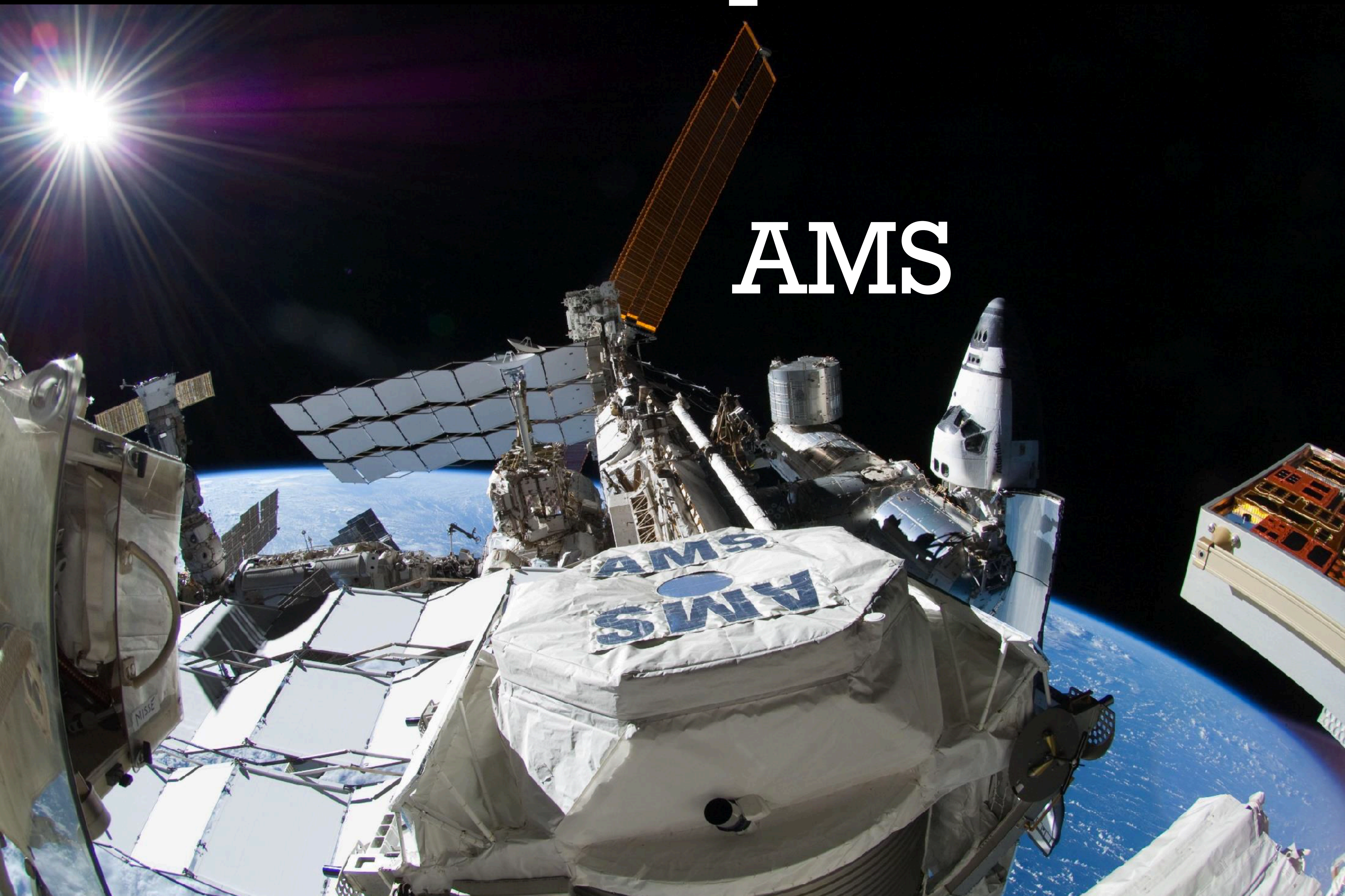
Astroparticles at LIP

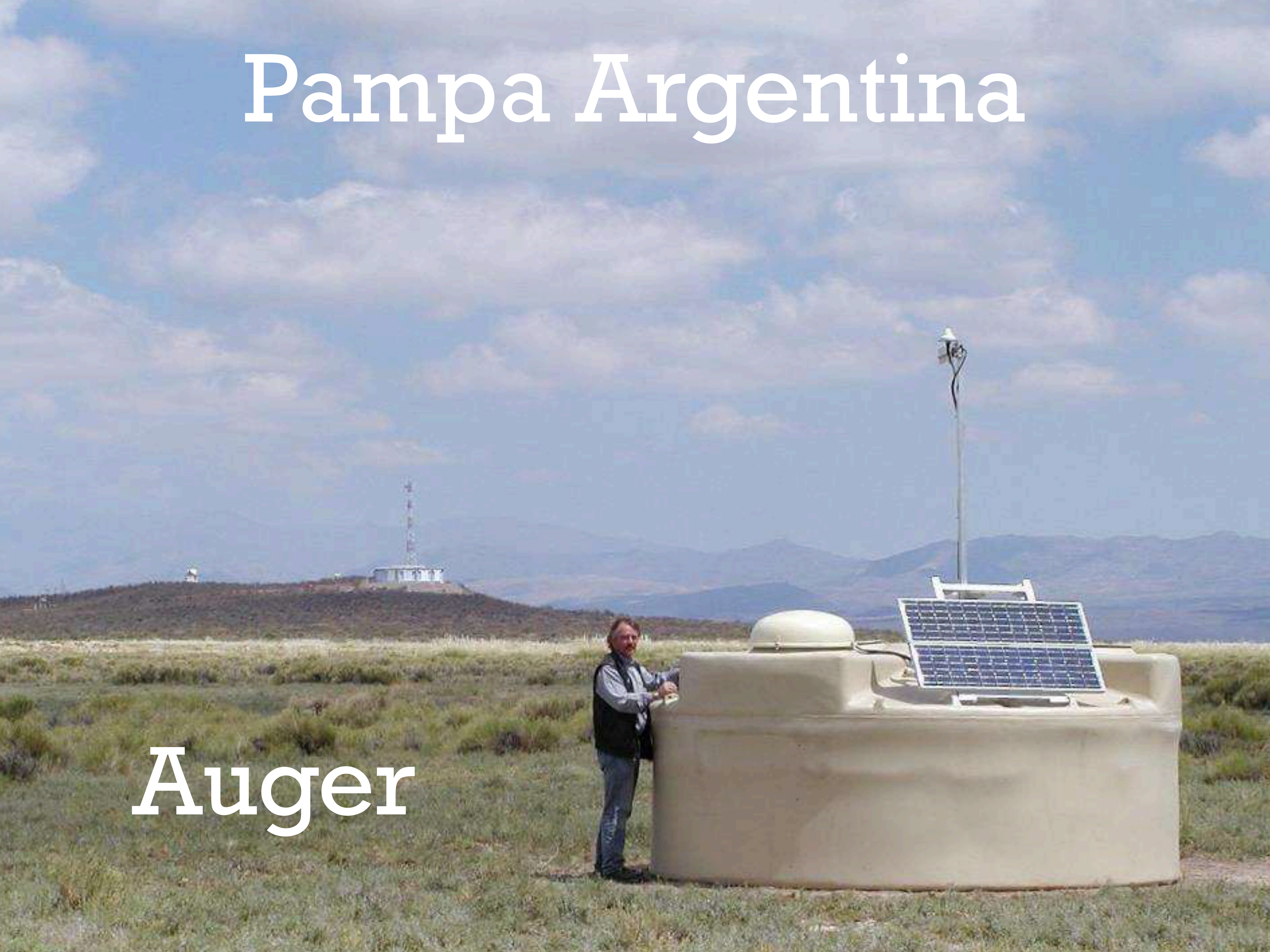
Particle	Expt.	Discover New Particle Physics	Particles as probes in Astrophysics or Cosmology
Charged cosmic rays	Auger AMS	Hadronic interactions at high energies Dark Matter search	Sources of HECR Multi-messenger Astrophysics Anti-matter search Solar Physics
Photons	LATTES	Dark Matter search	Multi-messenger 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

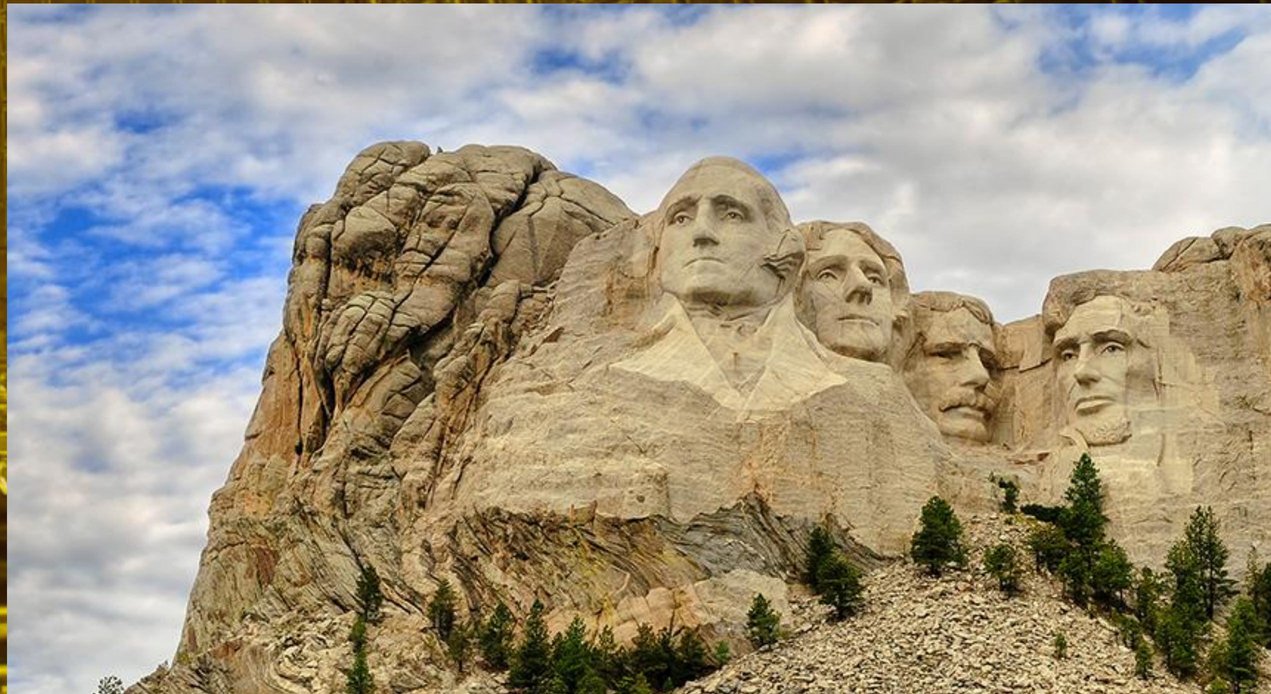
Atacama, Chile (?)

LATTES


Underground in Canada
SNO+

Fermilab to South Dakota, passing by CERN…

DUNE

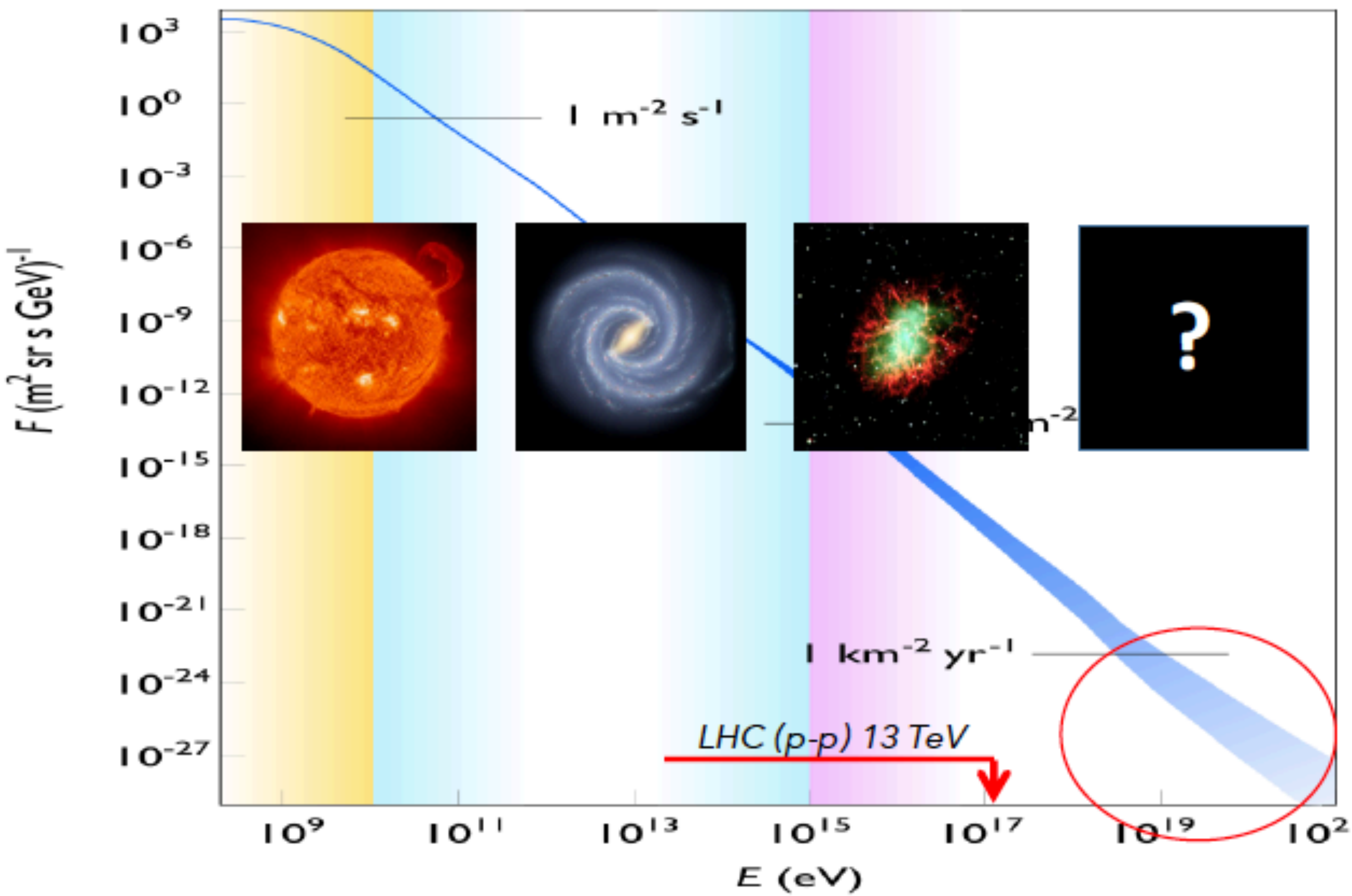


Outline

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

Ultra High Energy Cosmic Rays

Cosmic ray energy spectrum



Multi-Messenger Astronomy

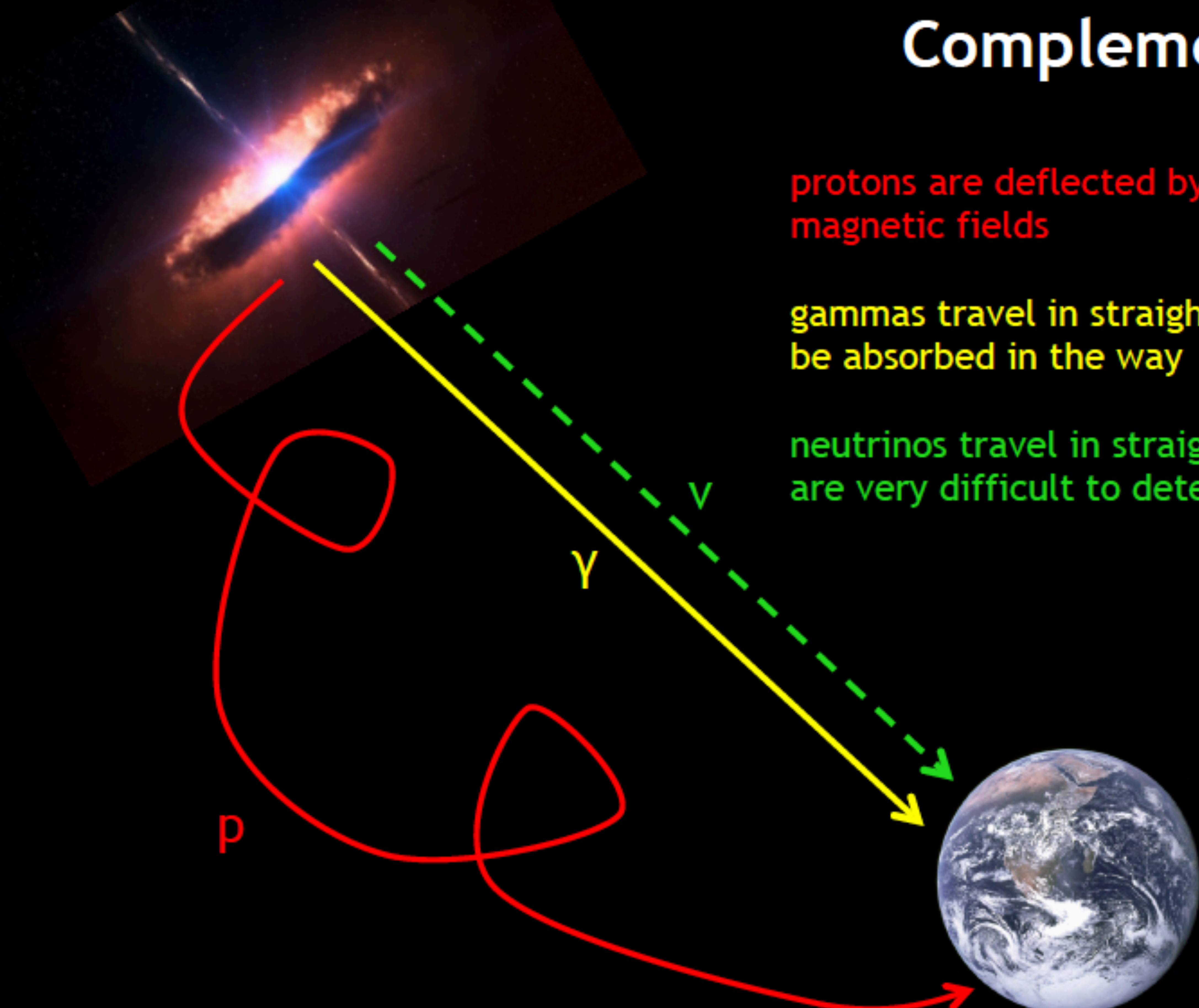
Photons

Neutrinos

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

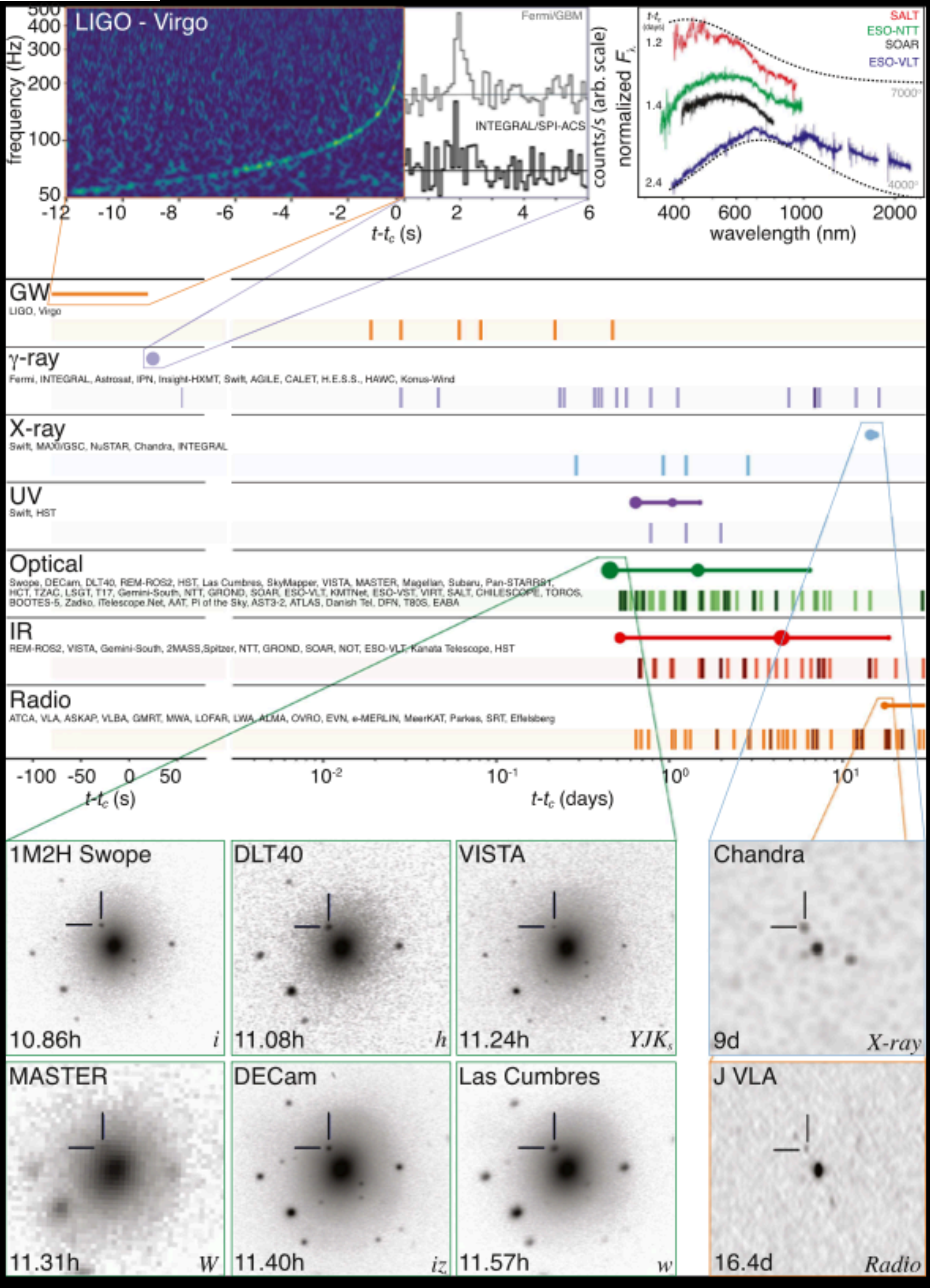
neutrinos travel in straight lines but are very difficult to detect

"Multi-messenger observation of a Binary Neutron Star Merger"

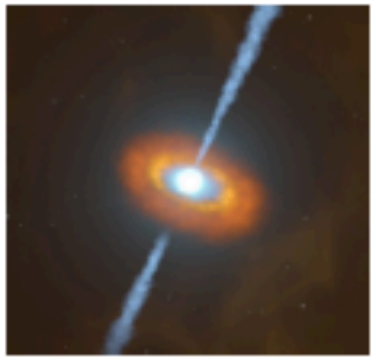
THE ASTROPHYSICAL JOURNAL LETTERS, 848:L12 (59pp), 2017 October 20

- 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



Photon + neutrino

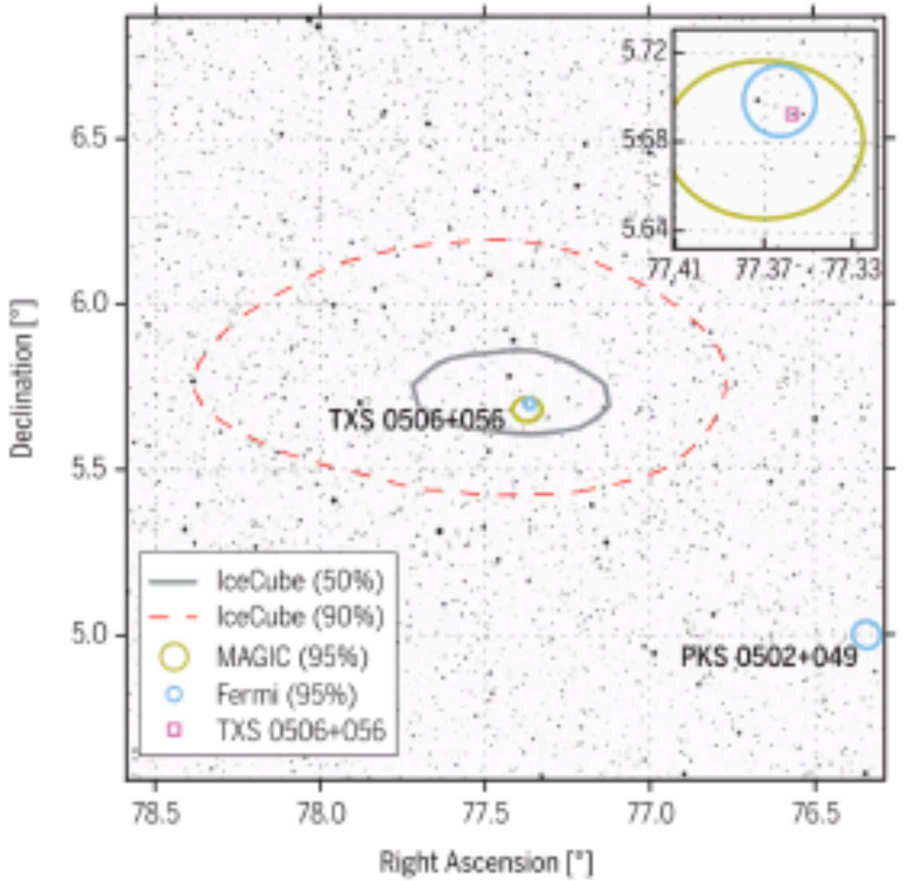


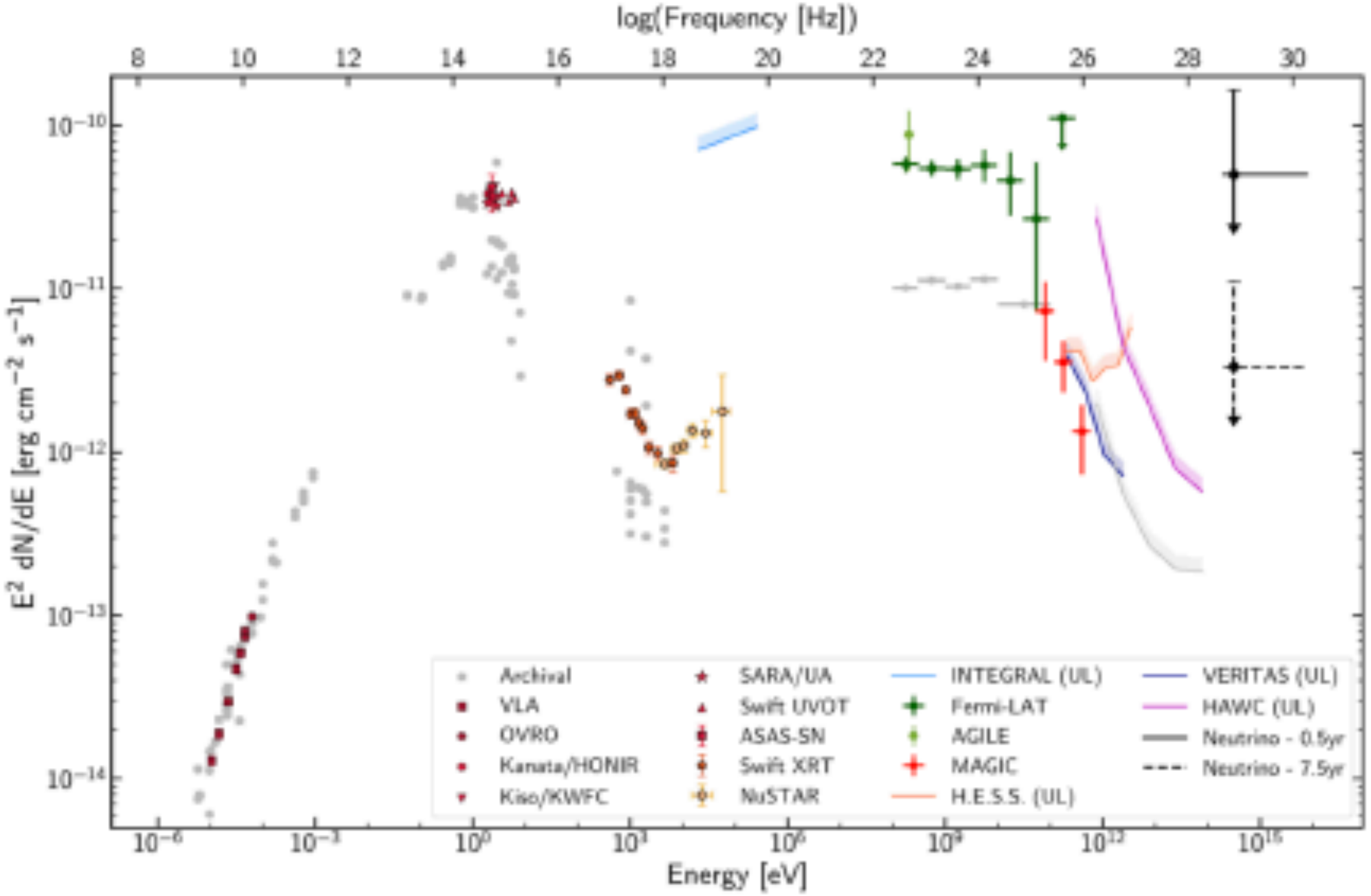
Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S., *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†

Science 361 (2018) no.6398

Observation occurred on September, 22nd 2017





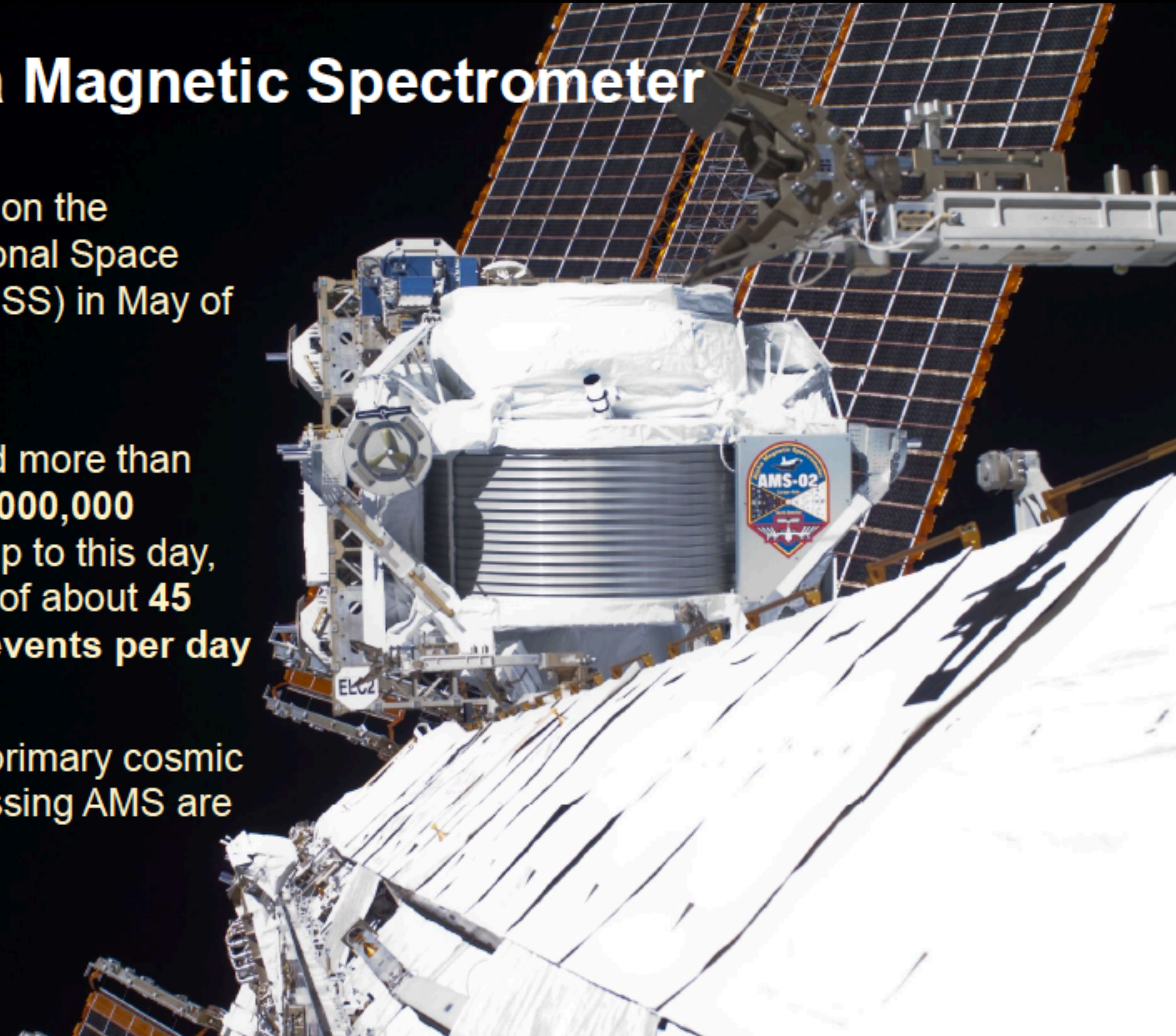
AMS

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**

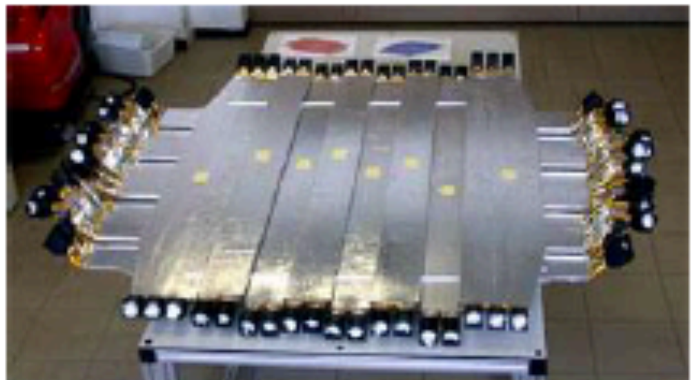
Most of primary cosmic rays crossing AMS are protons

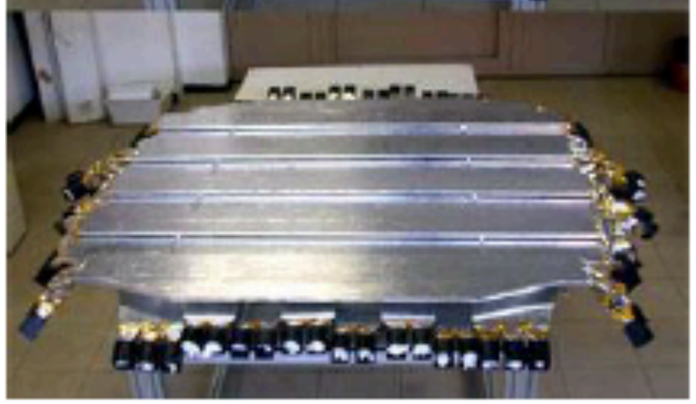


AMS detector

Transition Radiation Detector

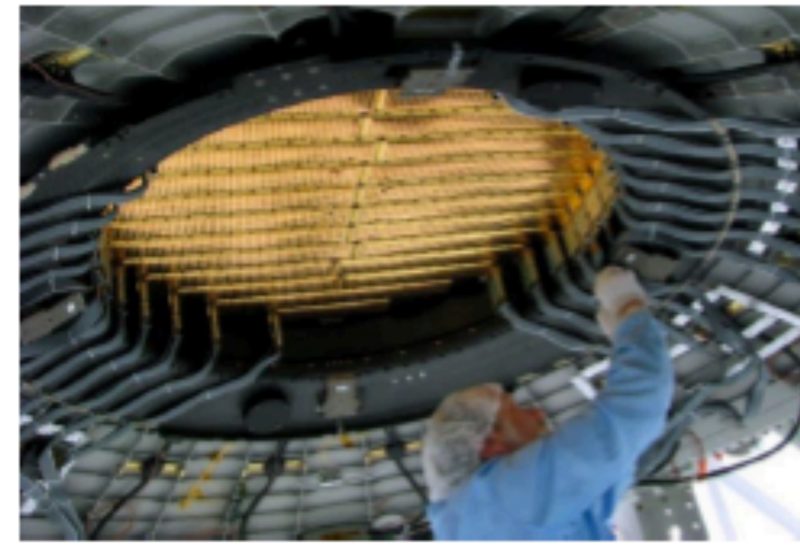
Upper TOF

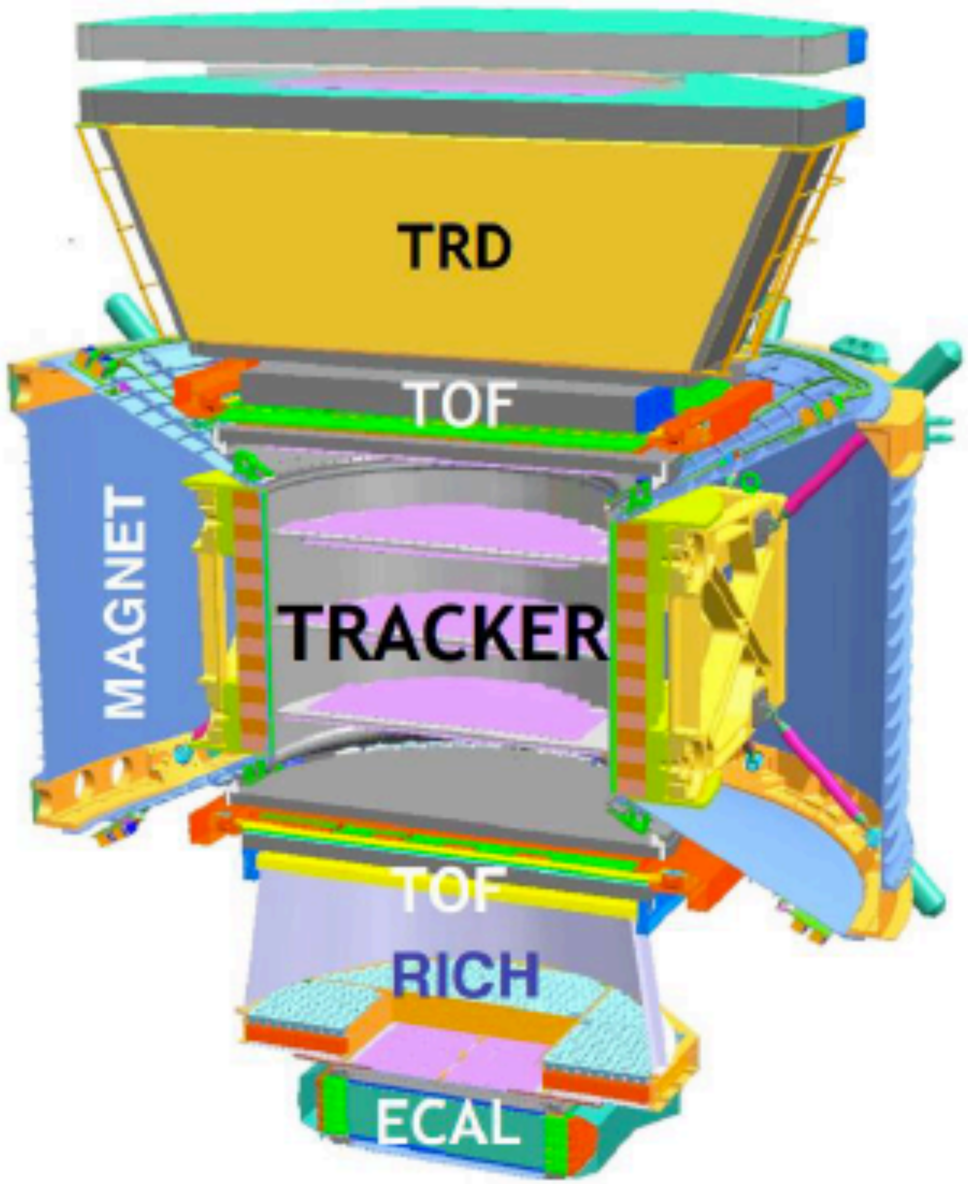




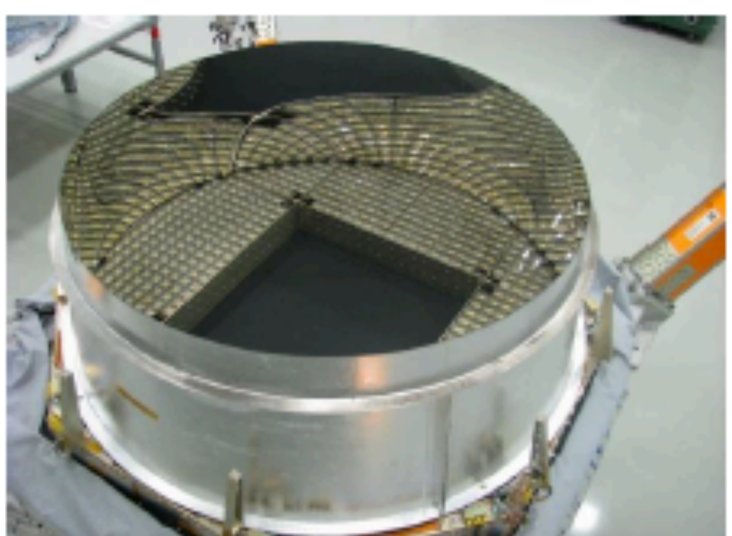
Lower TOF

Sillicon Tracker

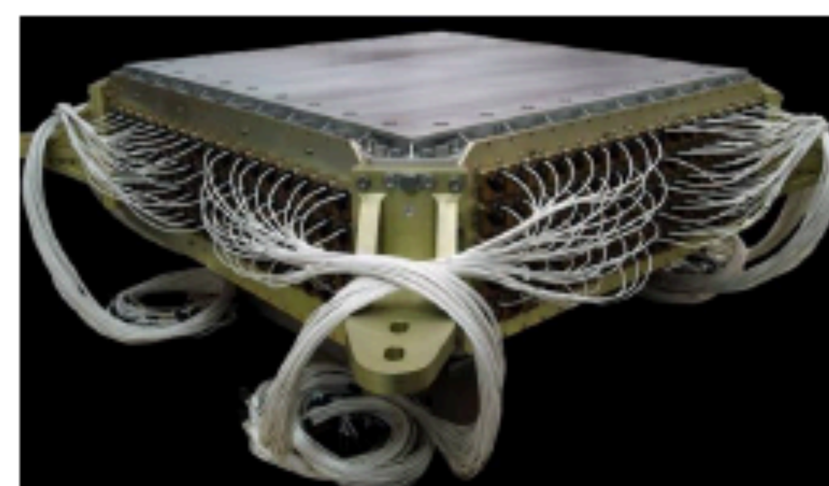




Ring-Imaging Cherenkov Detector

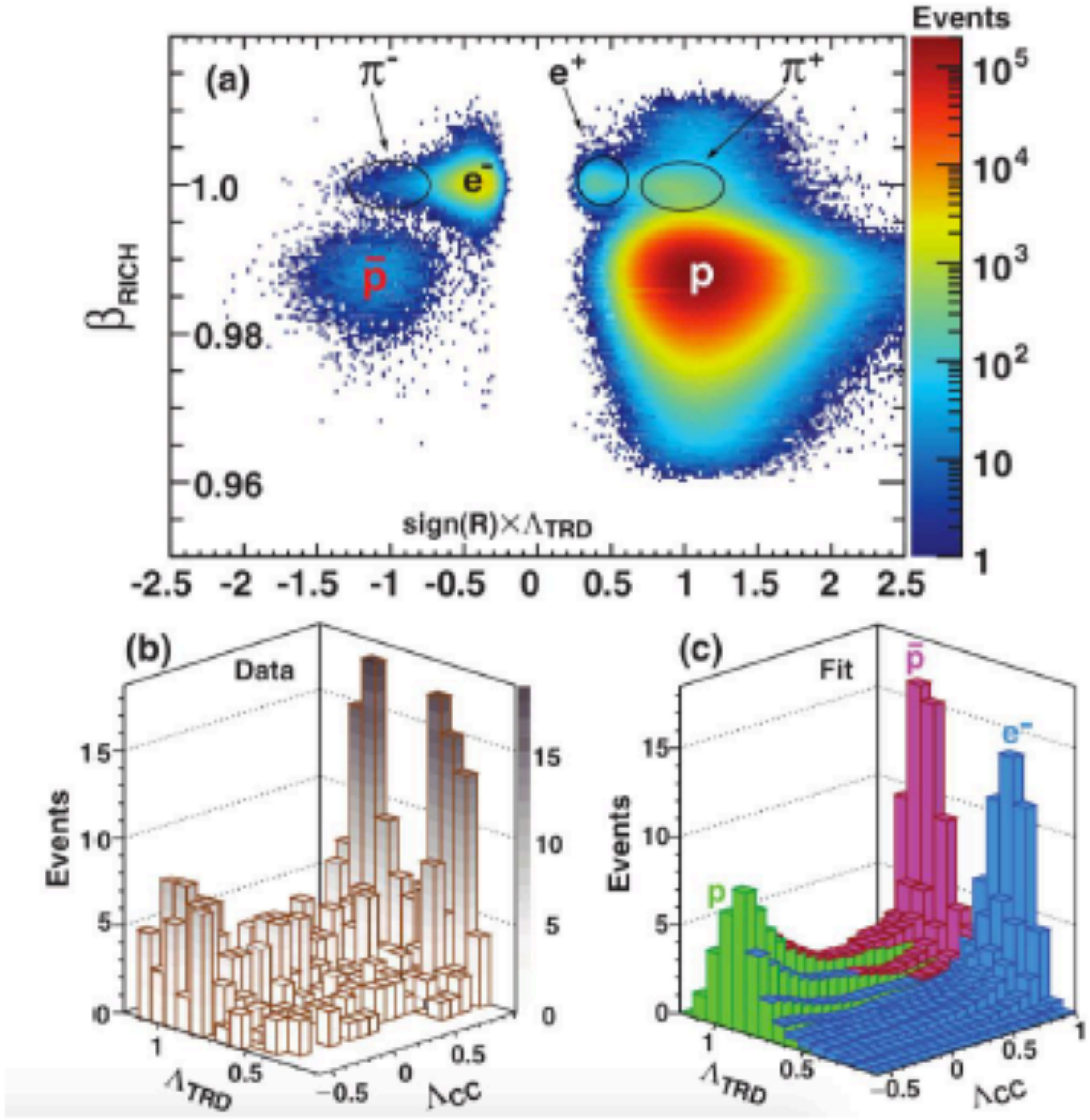


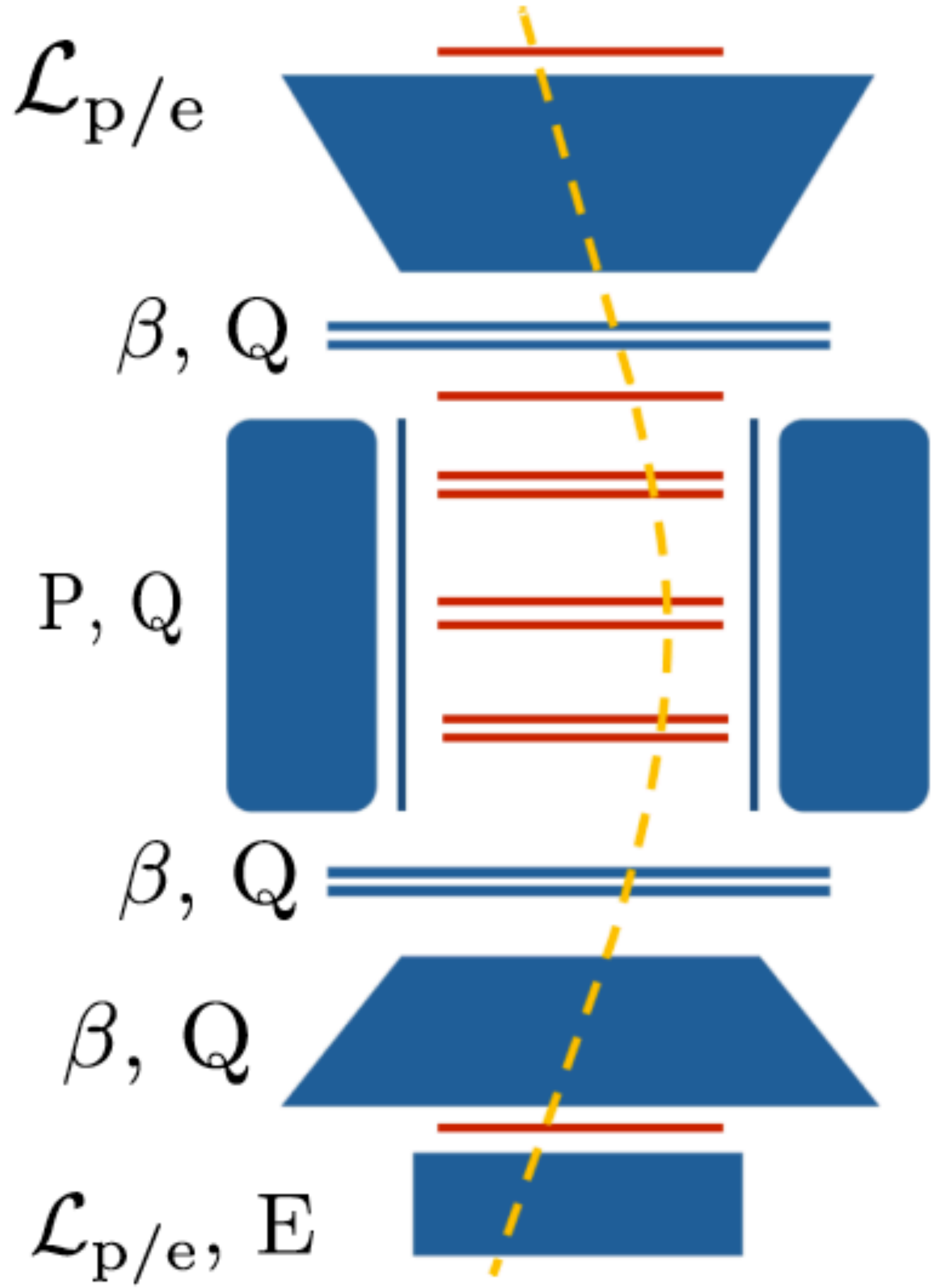
Electromagnetic Calorimeter



AMS results

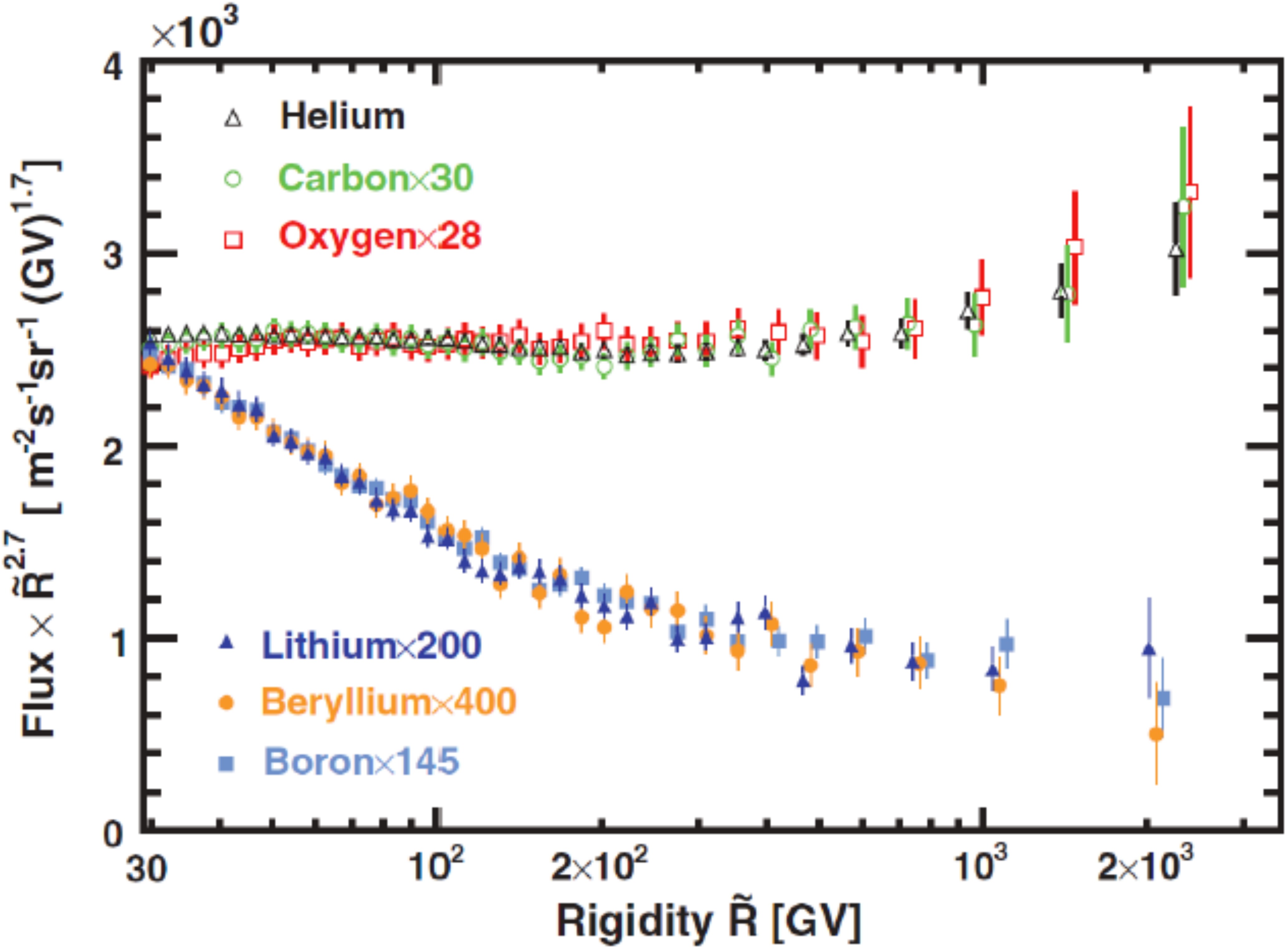
electron/positron
vs
proton/antiproton separation



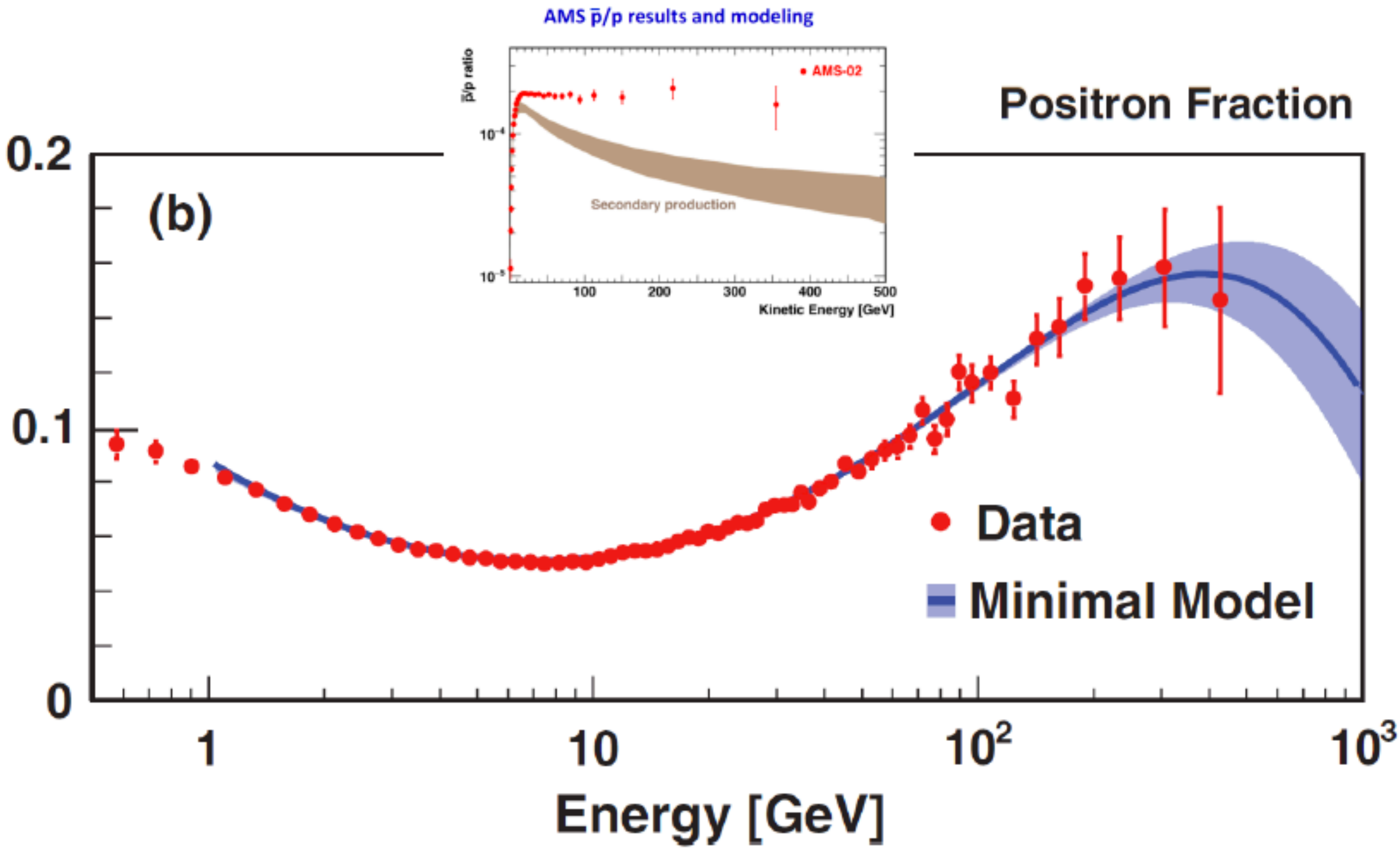


Z>1 fluxes

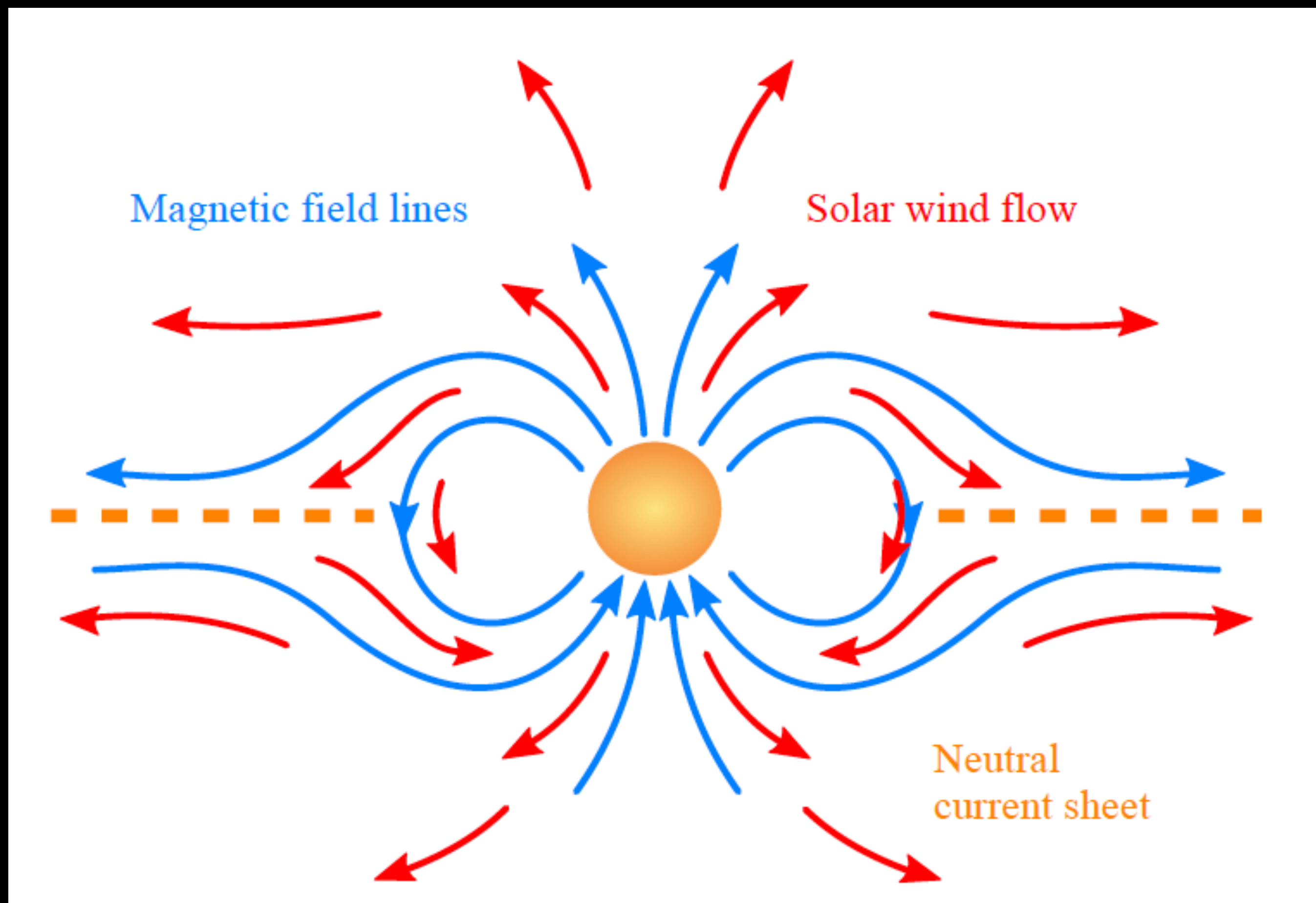
Primary (He, C, O) and secondary nuclei (Li, Be, B)



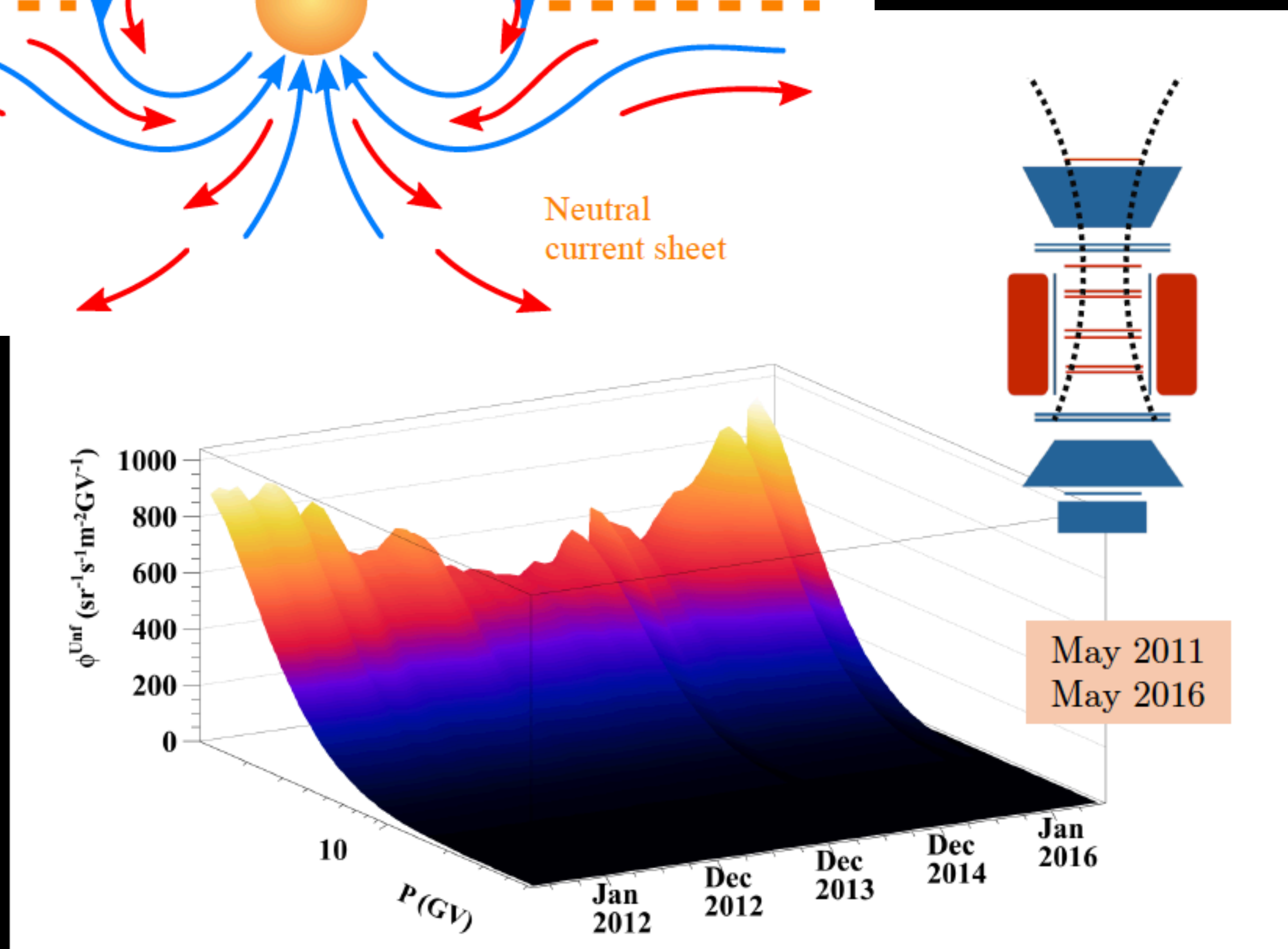
Positrons and antiprotons



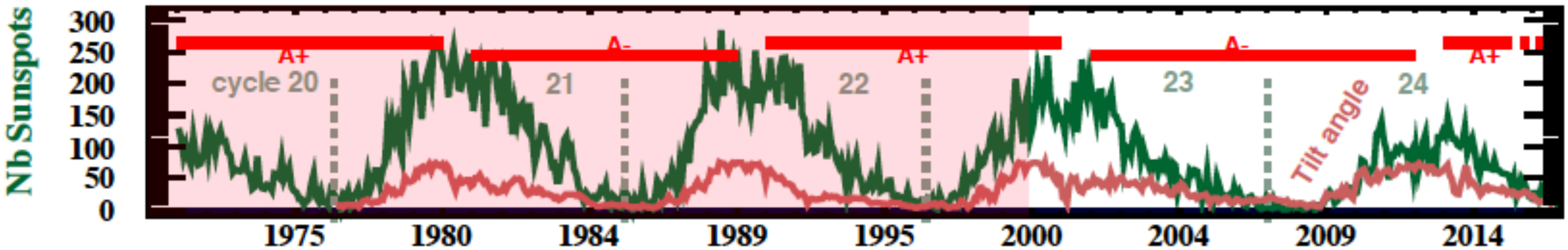
Solar modulation

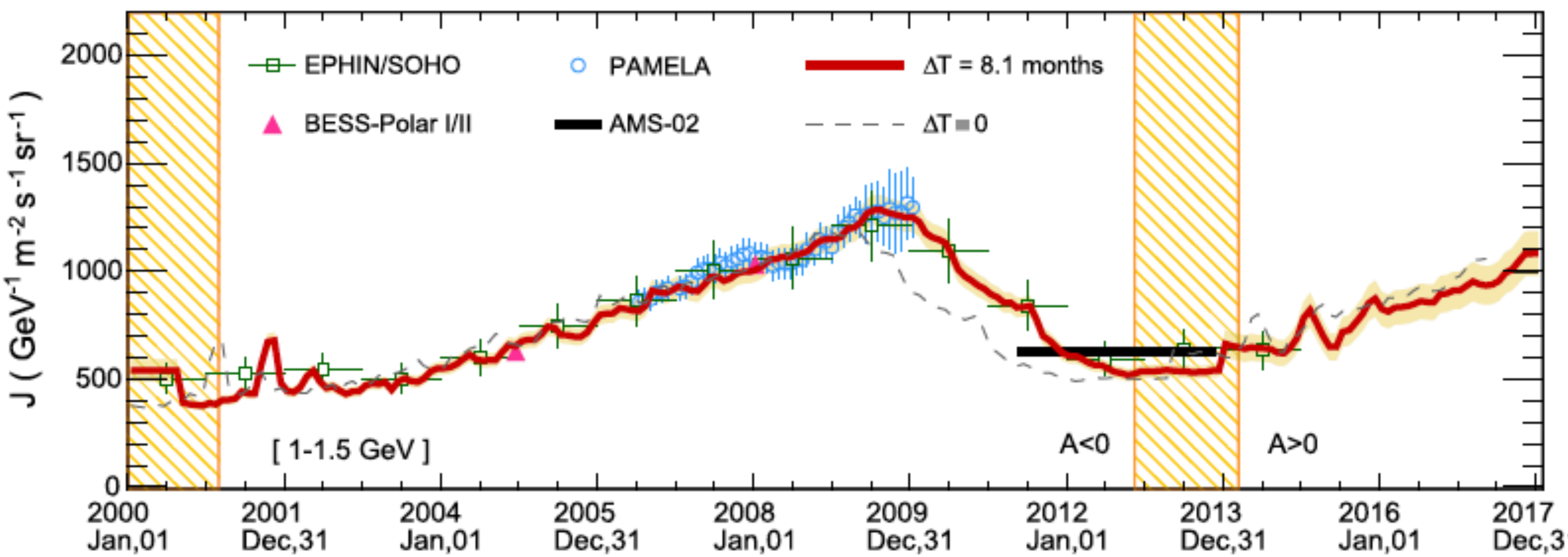


Solar modulation is prevaling up to 30 GV



EVIDENCE OF A TIME DELAY

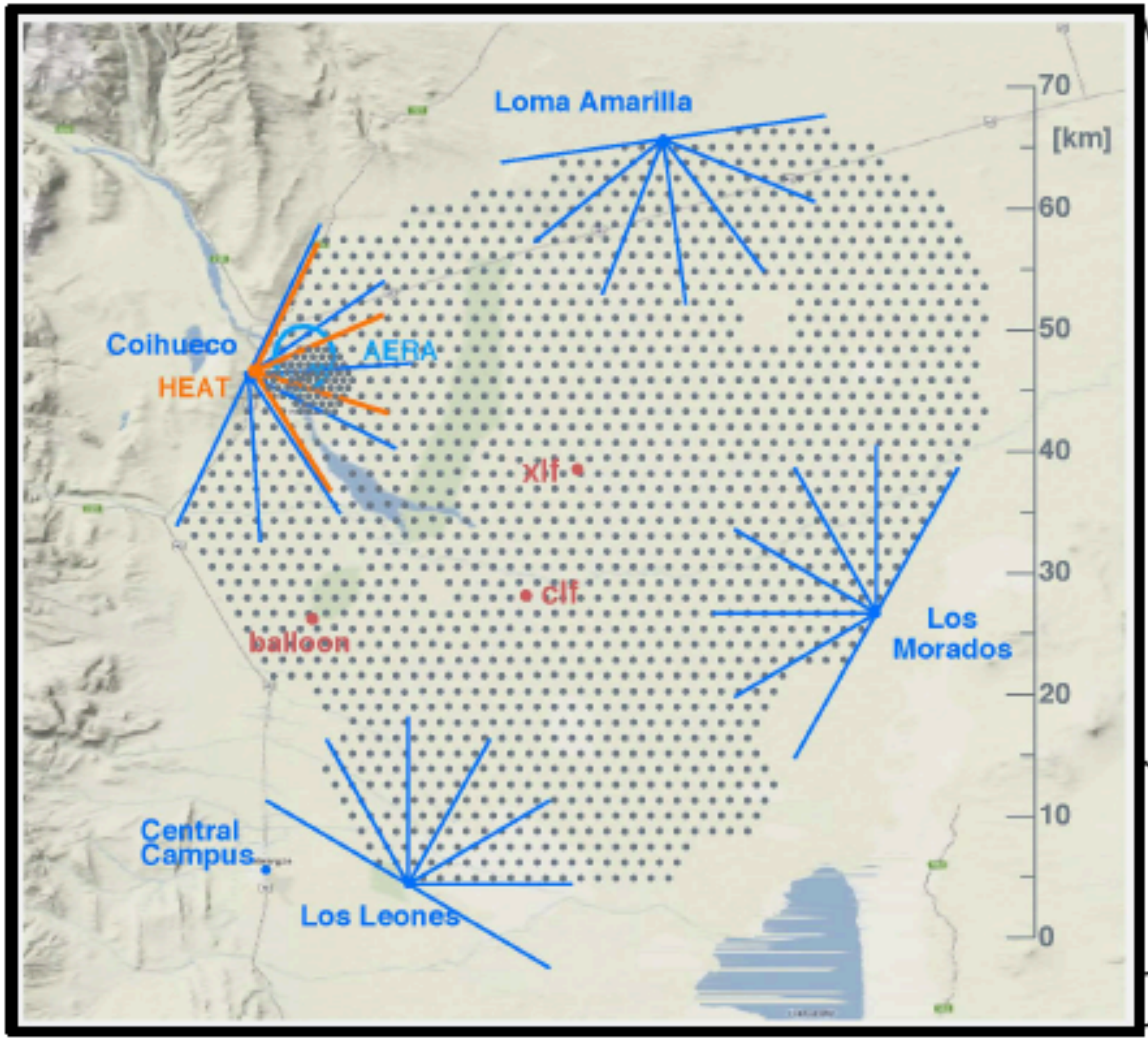




$$\Delta t \sim 8.1\,\mathrm{months}$$

Auger

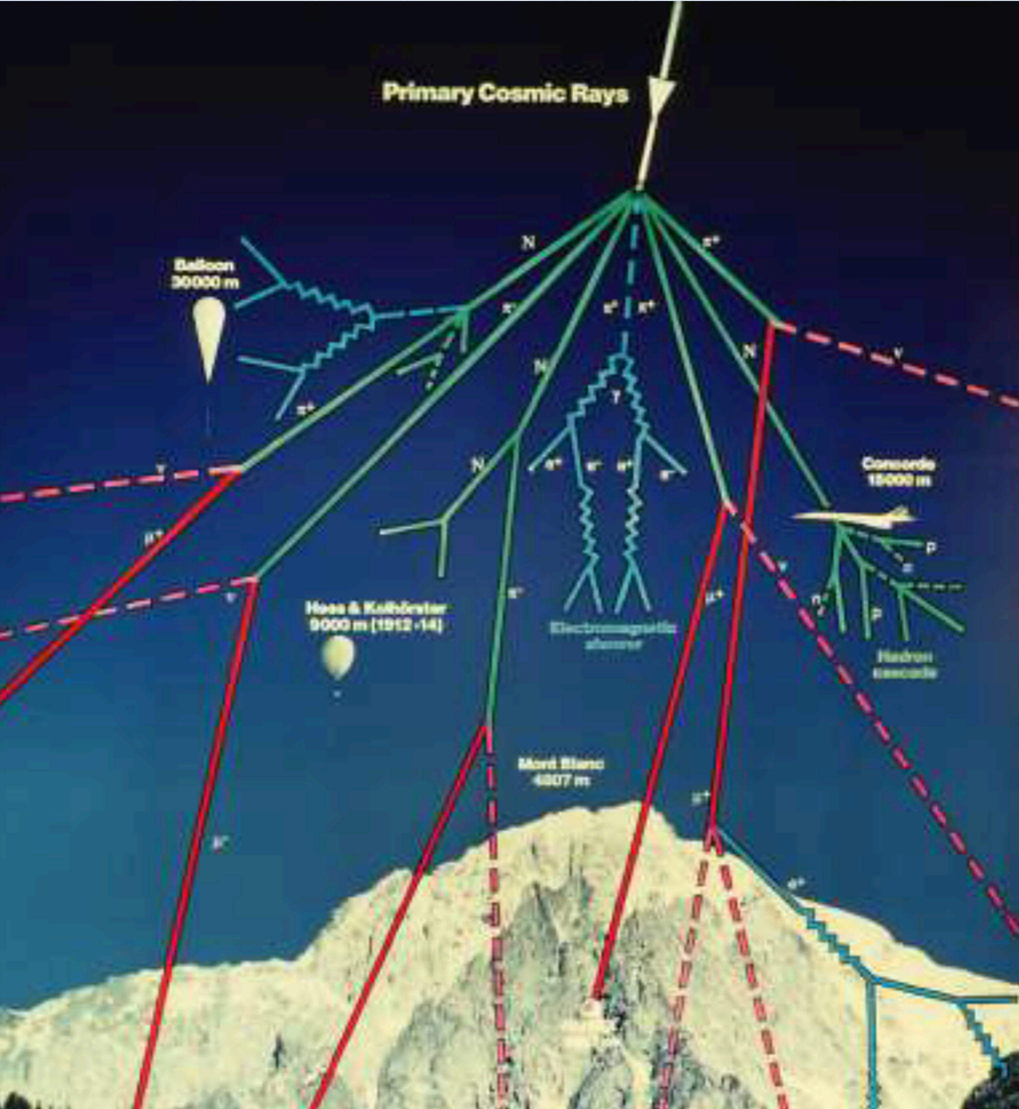
Pierre Auger Observatory



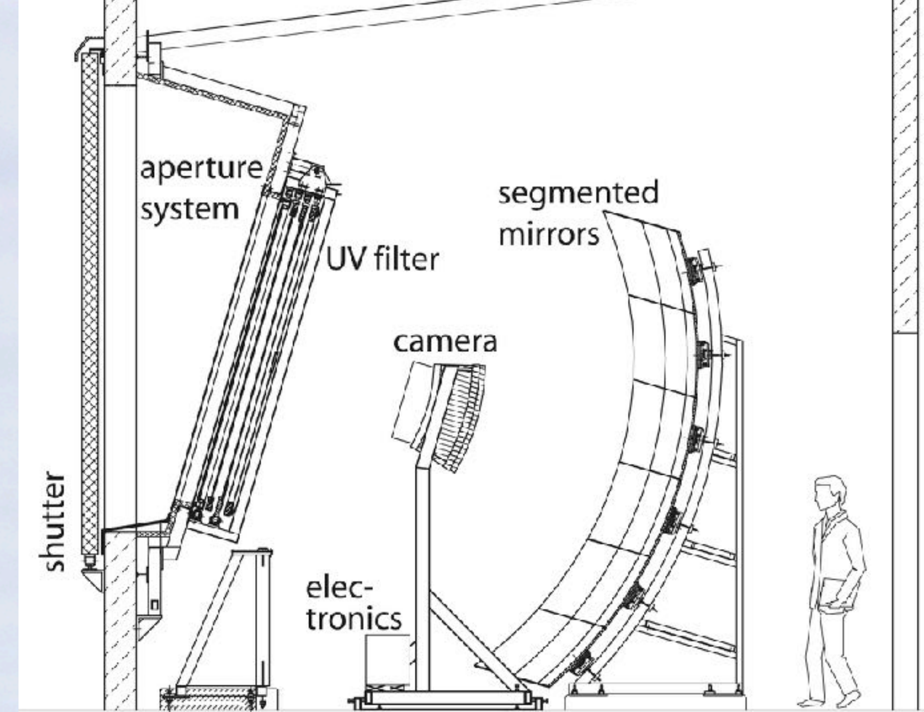
Area: 3000 km^2

Located in the Pampa Amarilla, Mendoza, Argentina

Altitude: 1400 m a.s.l.

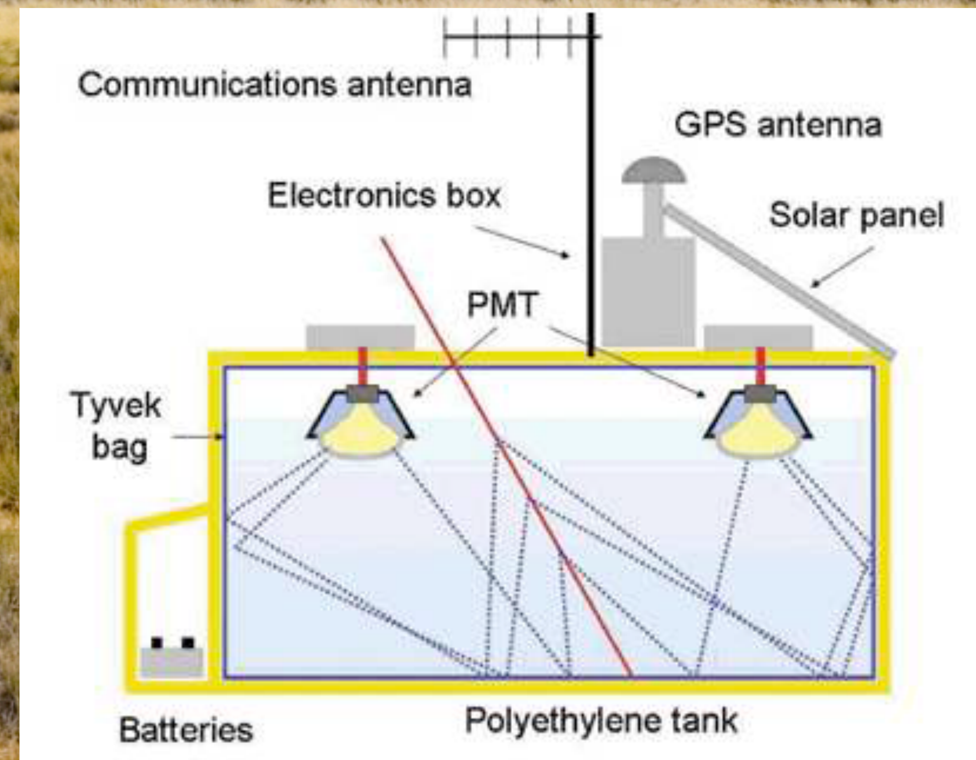


Hybrid detector



Fluorescence detector (FD) for scintillation light

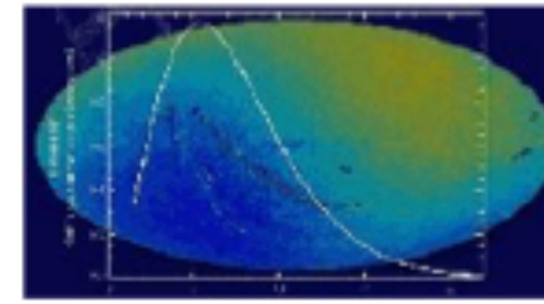
Surface detector (SD) for charged particles

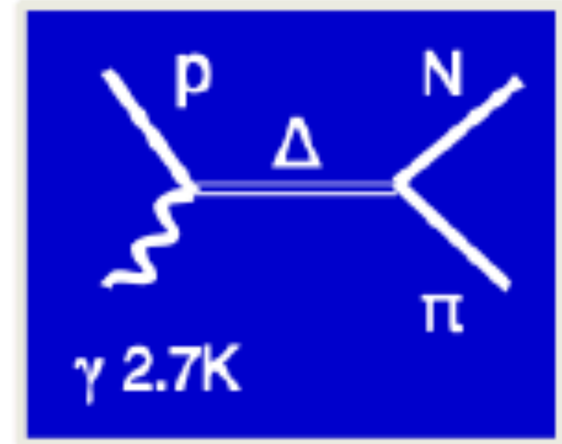


GZK effect

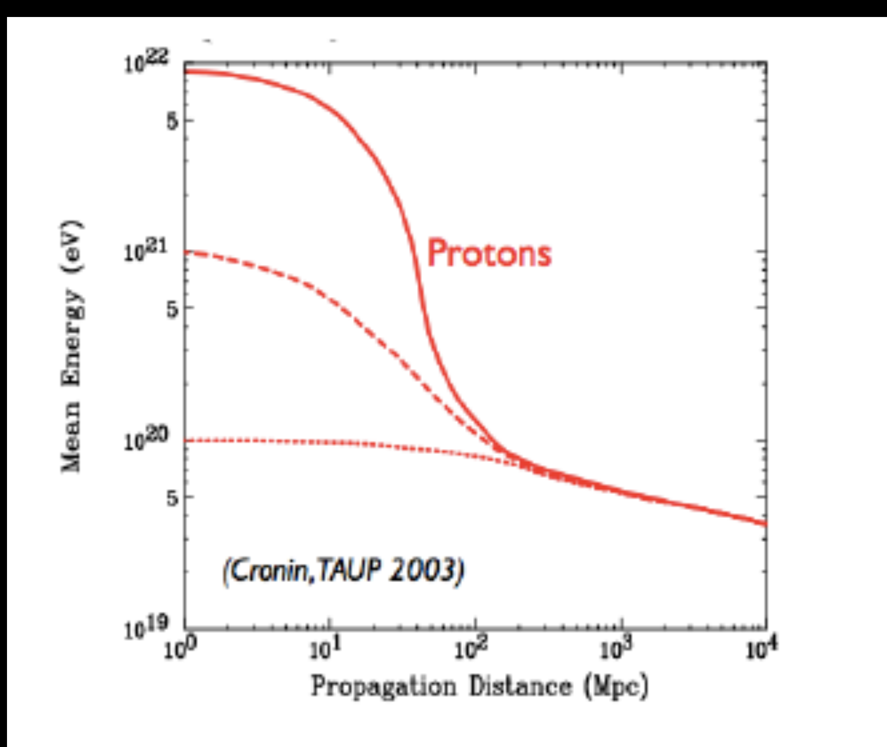
- Cosmic ray interaction with Cosmic Microwave Background (CMB)
  - Greisen, Zatsepin, Kuz'min (1966)
- Cross-section increases at $E_{CM} > m_{\Delta} = 1.23$ GeV, or $E_p \sim 10^{19.5}$ eV
- Energy loss vs. distance

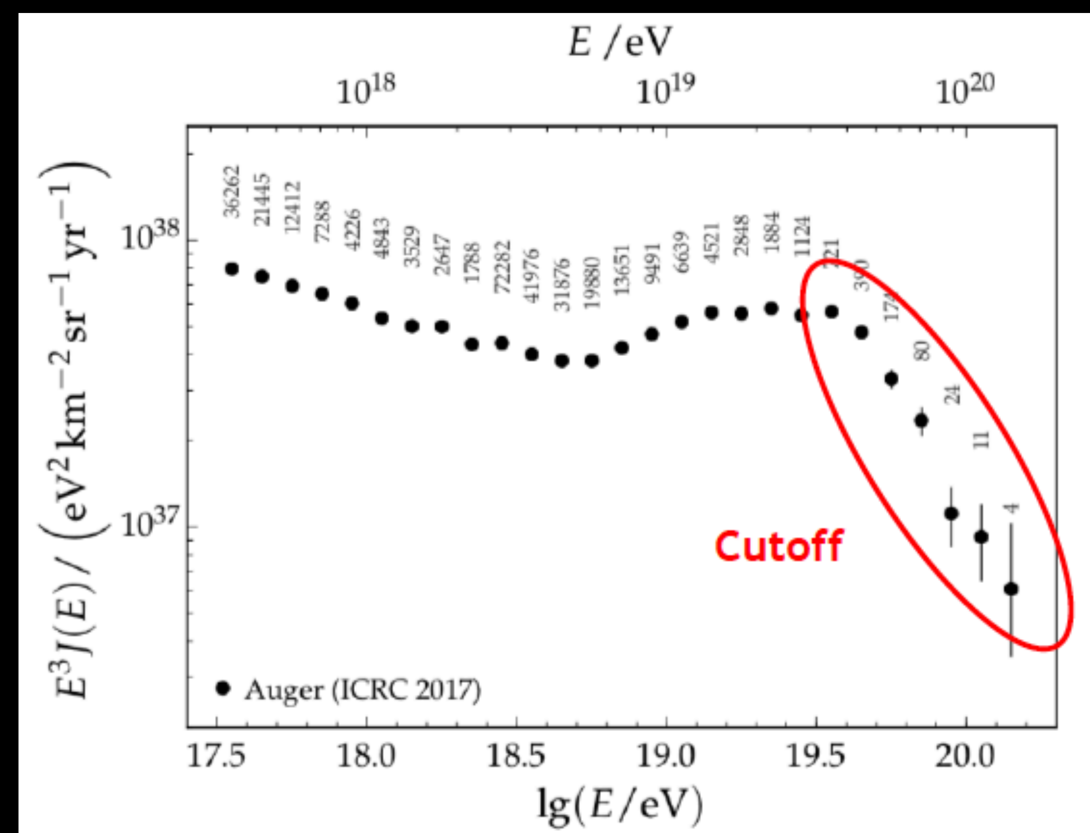
$E_{\gamma} \sim 1$ meV





$m_{\Delta} = 1.23$ GeV

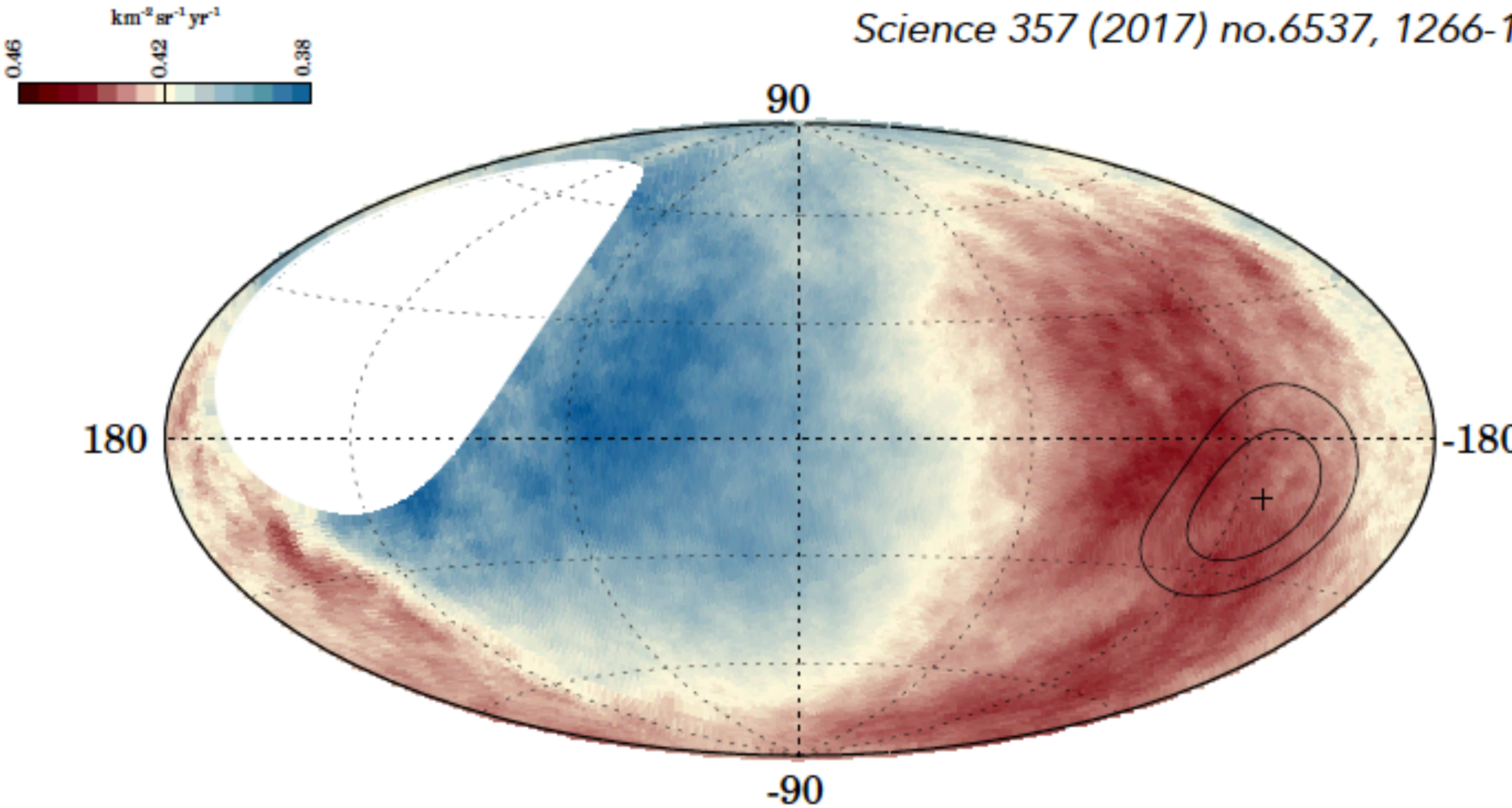




(Suppression could still be due to the source exhaustion)

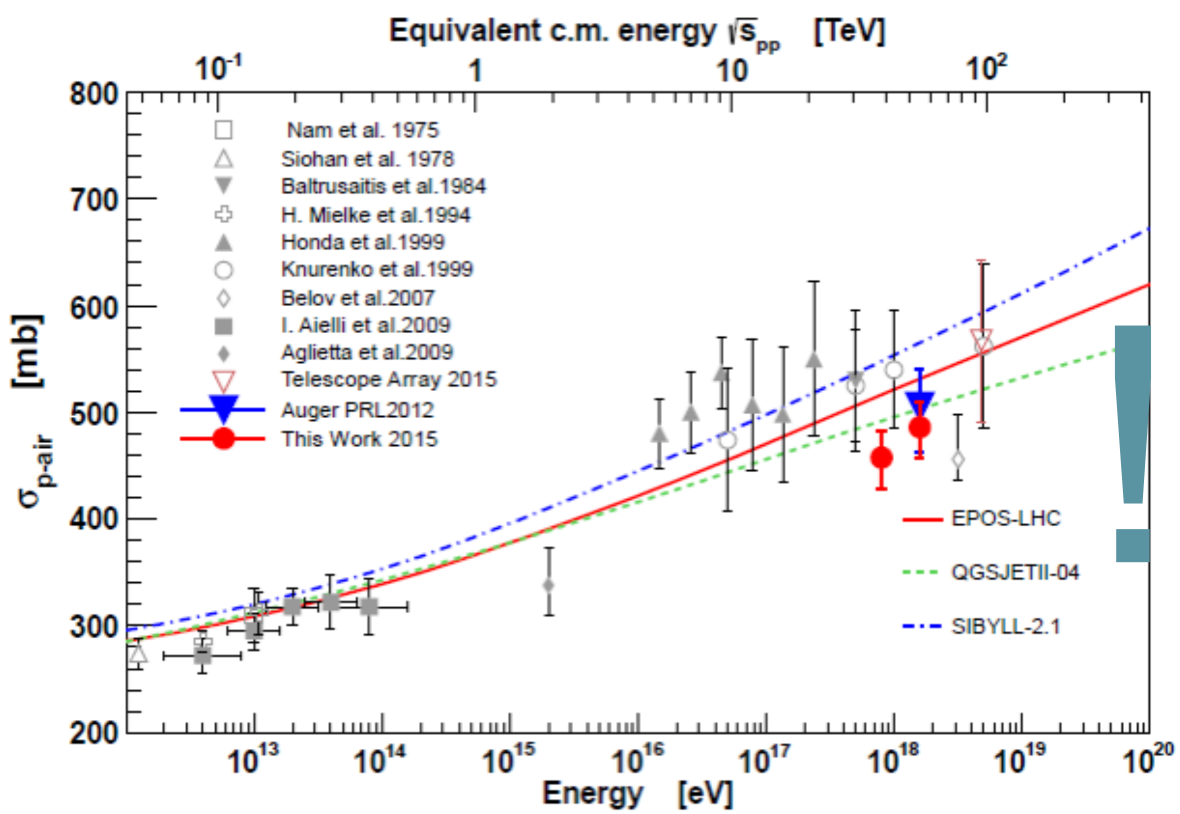
Observation of dipolar anisotropy

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

!!!

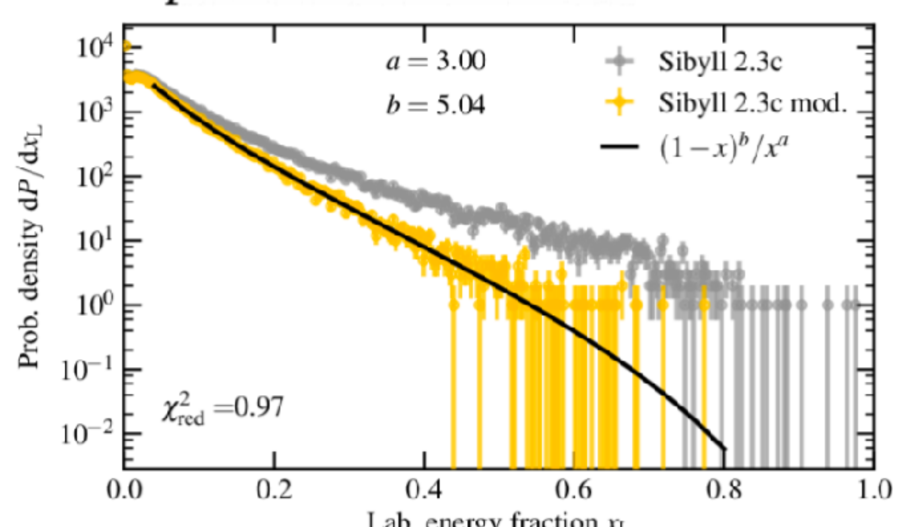
First measurement of p-air cross-section at 10^{18} eV

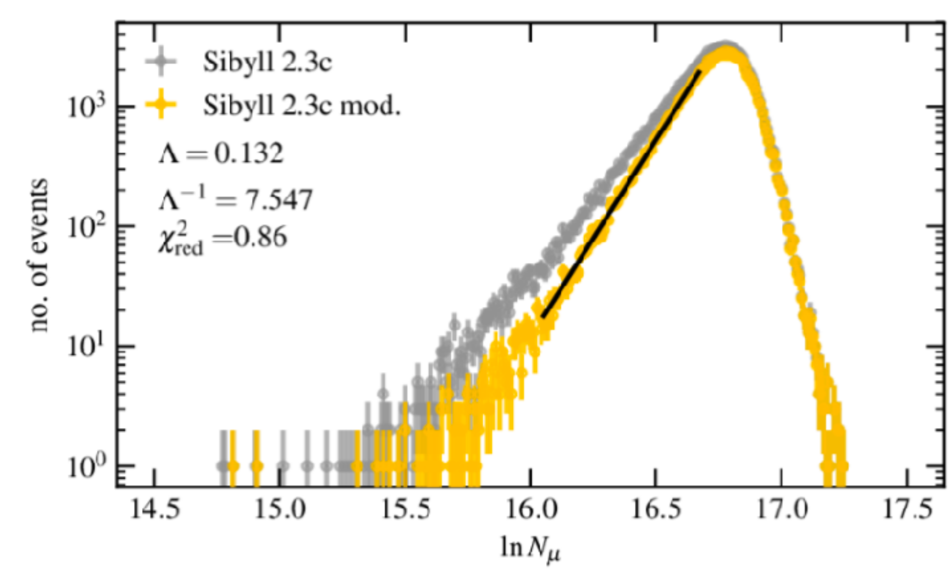
π^0 energy spectrum

Just now…

The output of first interactions dictate the muon distribution!

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



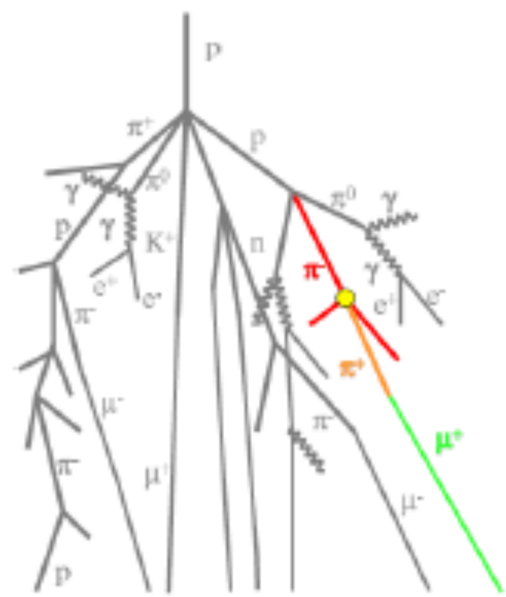


Measure the muons → Estimate π^0 Energy Spectrum

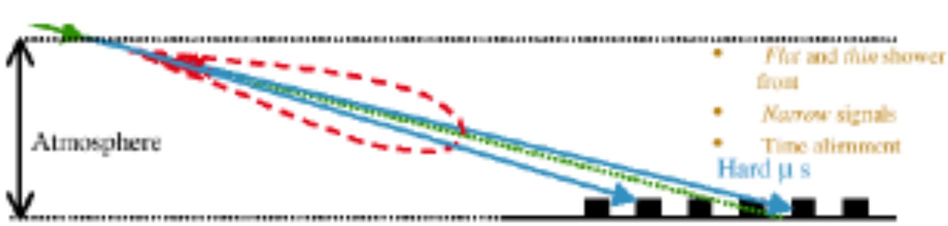
Particle Physics at the highest energies

Muon content in air showers

- Muons → Assess Hadronic interaction models (HIM)

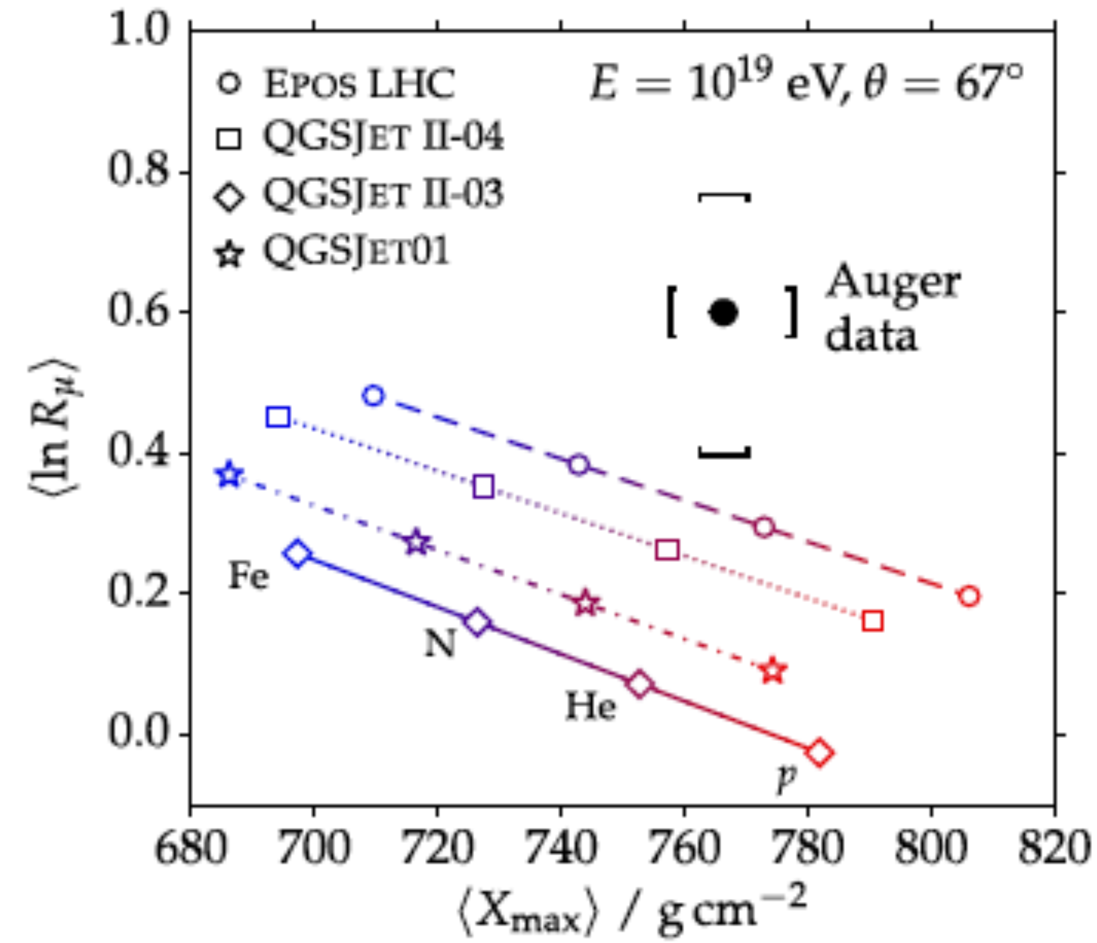


- Inclined shower → Muons



Surface Detector

Phys.Rev. D91 (2015) 3, 032003

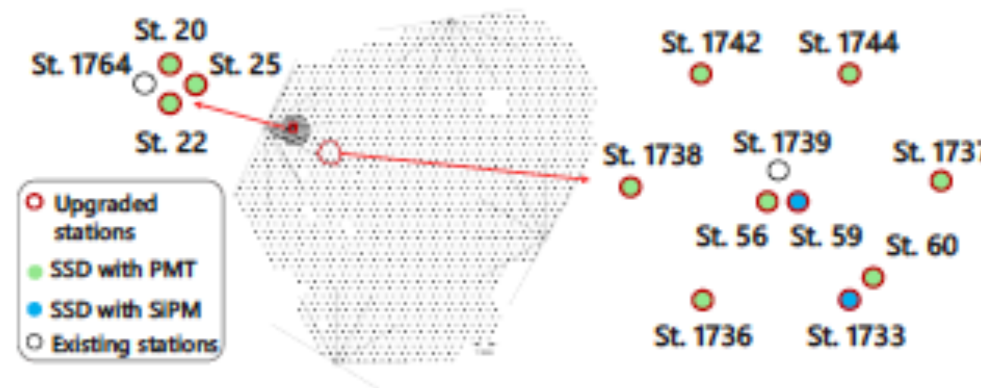


Fluorescence Detector

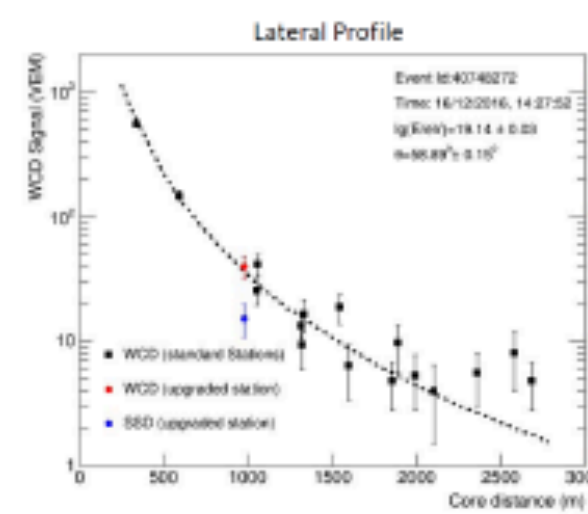
- Combination of the R_μ (number of muons) with X_{max} shows tension between data and all hadronic interaction models

The future: AugerPrime

- "Primary cosmic Ray Identification through Muons and Electrons"
- Two complementary detectors:
  - Scintillator on top of the tank: signal dominated by e.m. component
  - WCD sensitive to e.m. + muon
- The goal:
  - Enhance primary identification
  - Improve shower description
  - Reduce systematic uncertainties
- Engineering array taking data



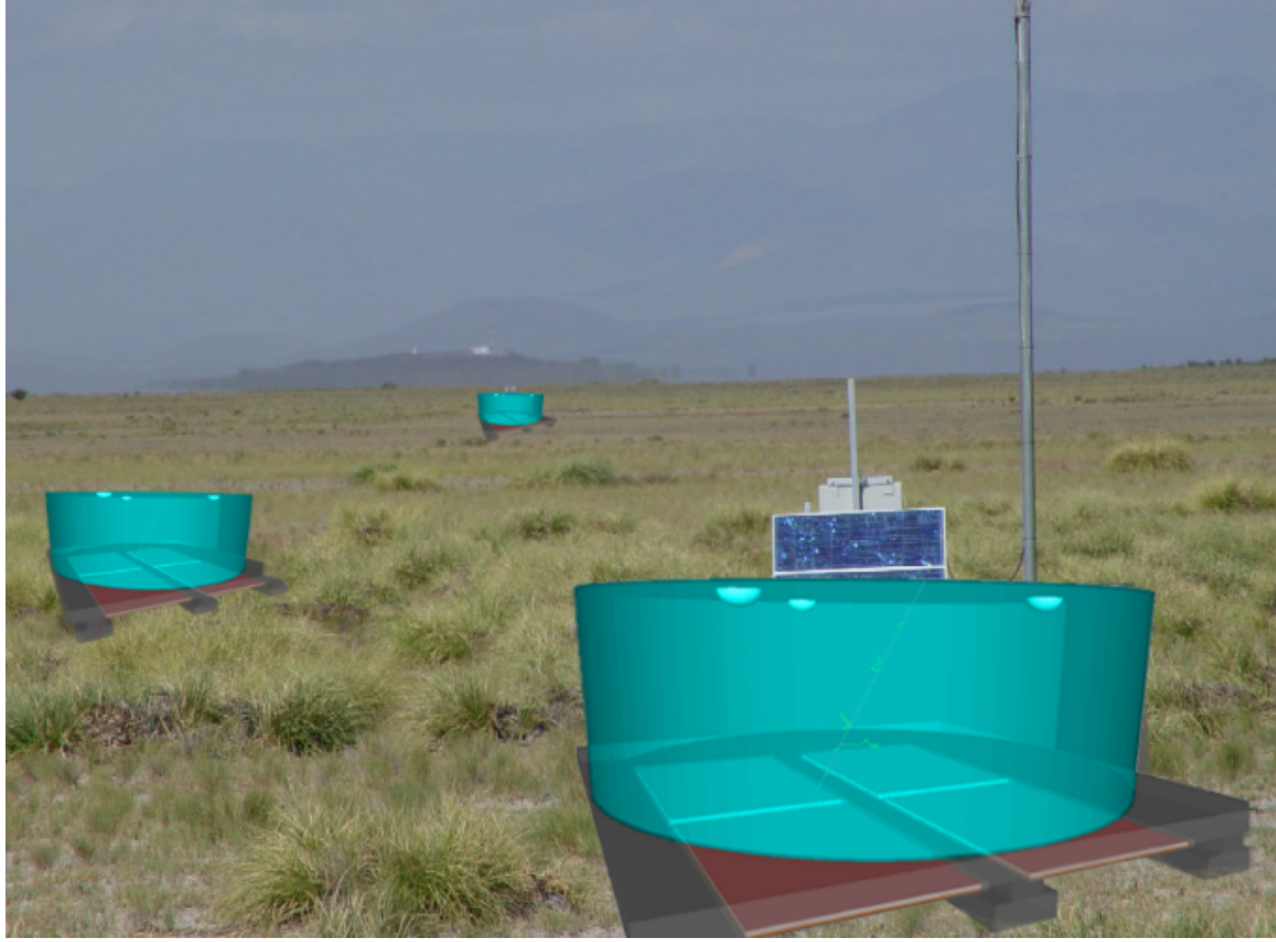
35th ICRC, PoS (2017) 383

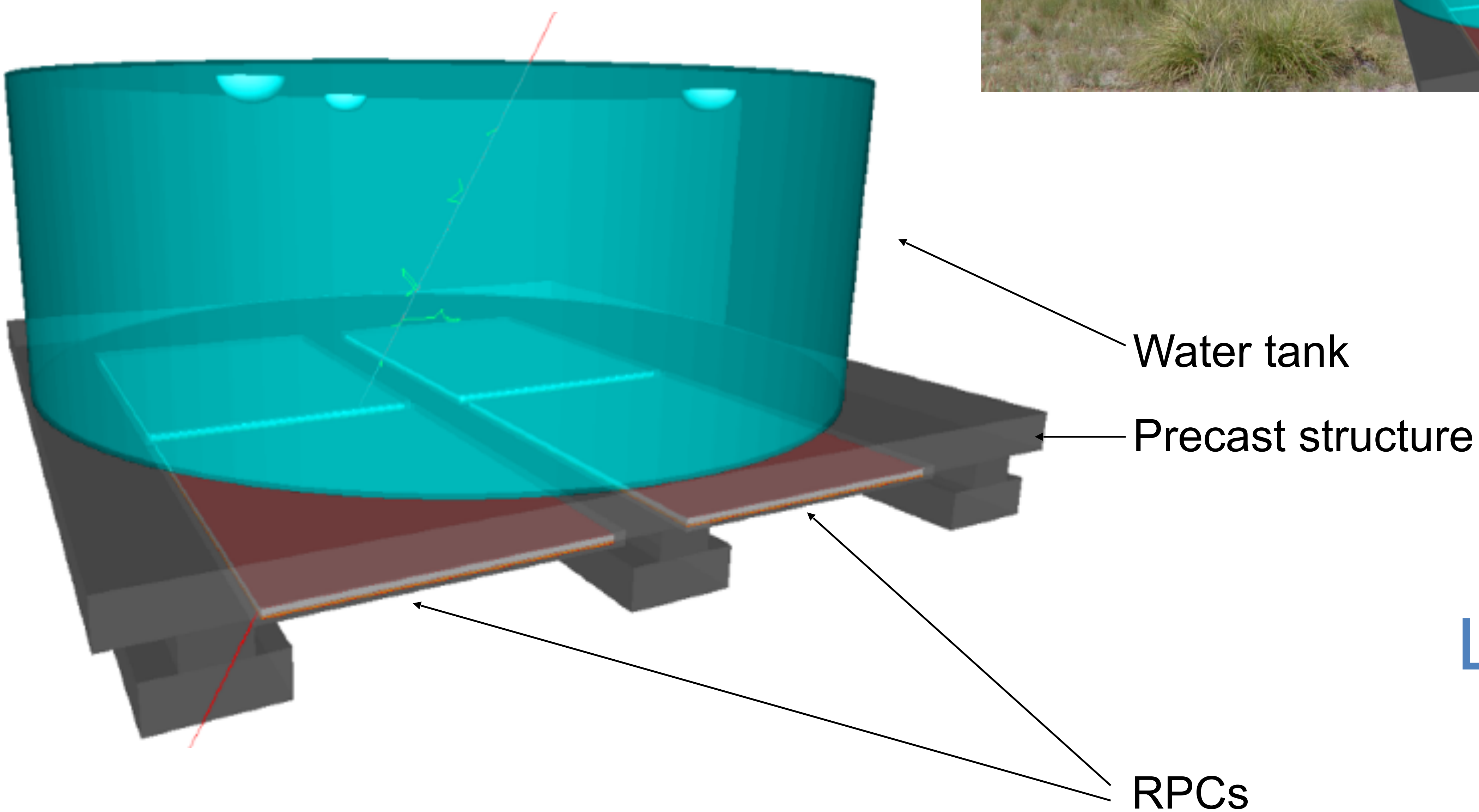


Measuring Muons : MARTA

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

Cost-effective.





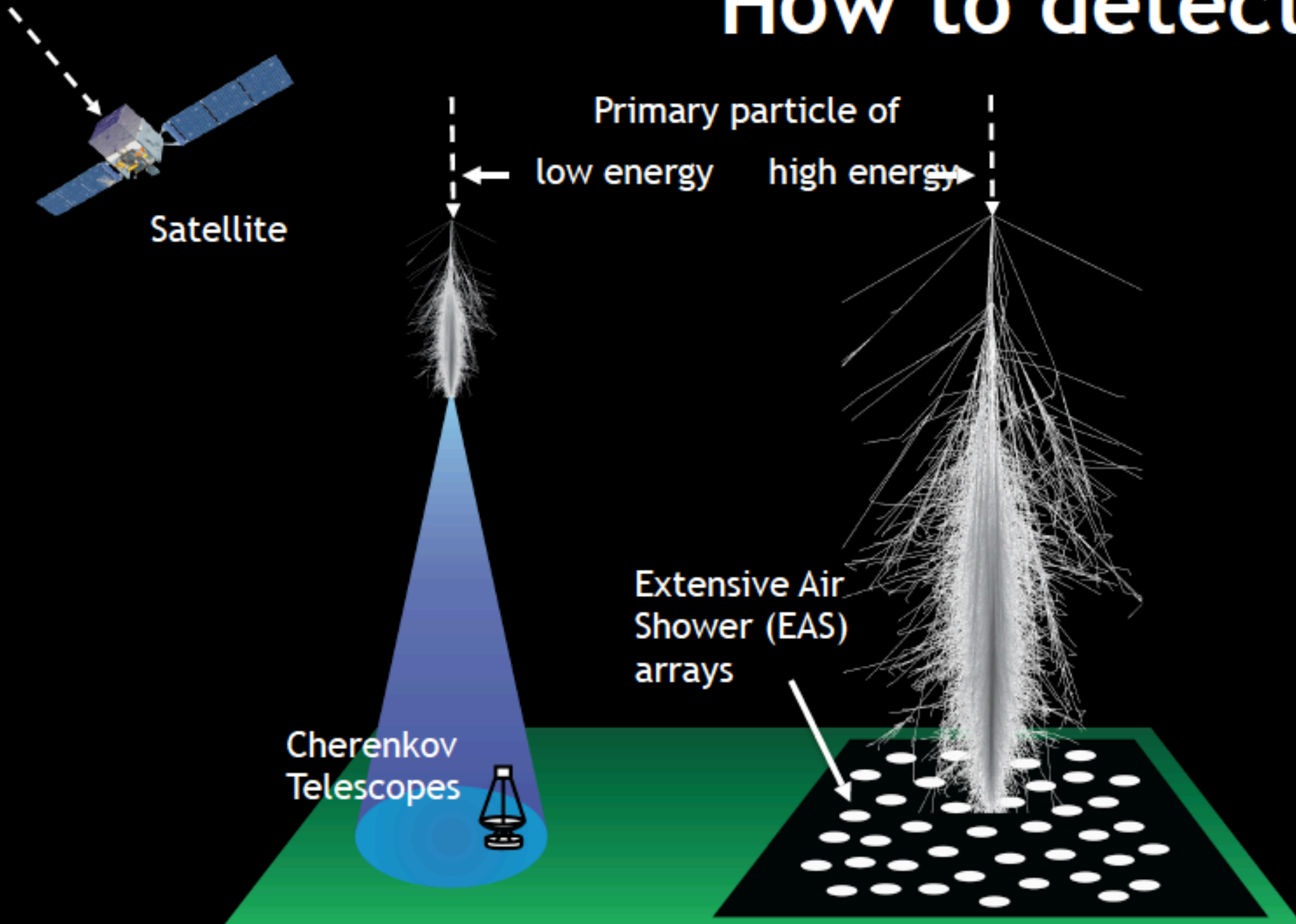
Led by LIP

LATTES

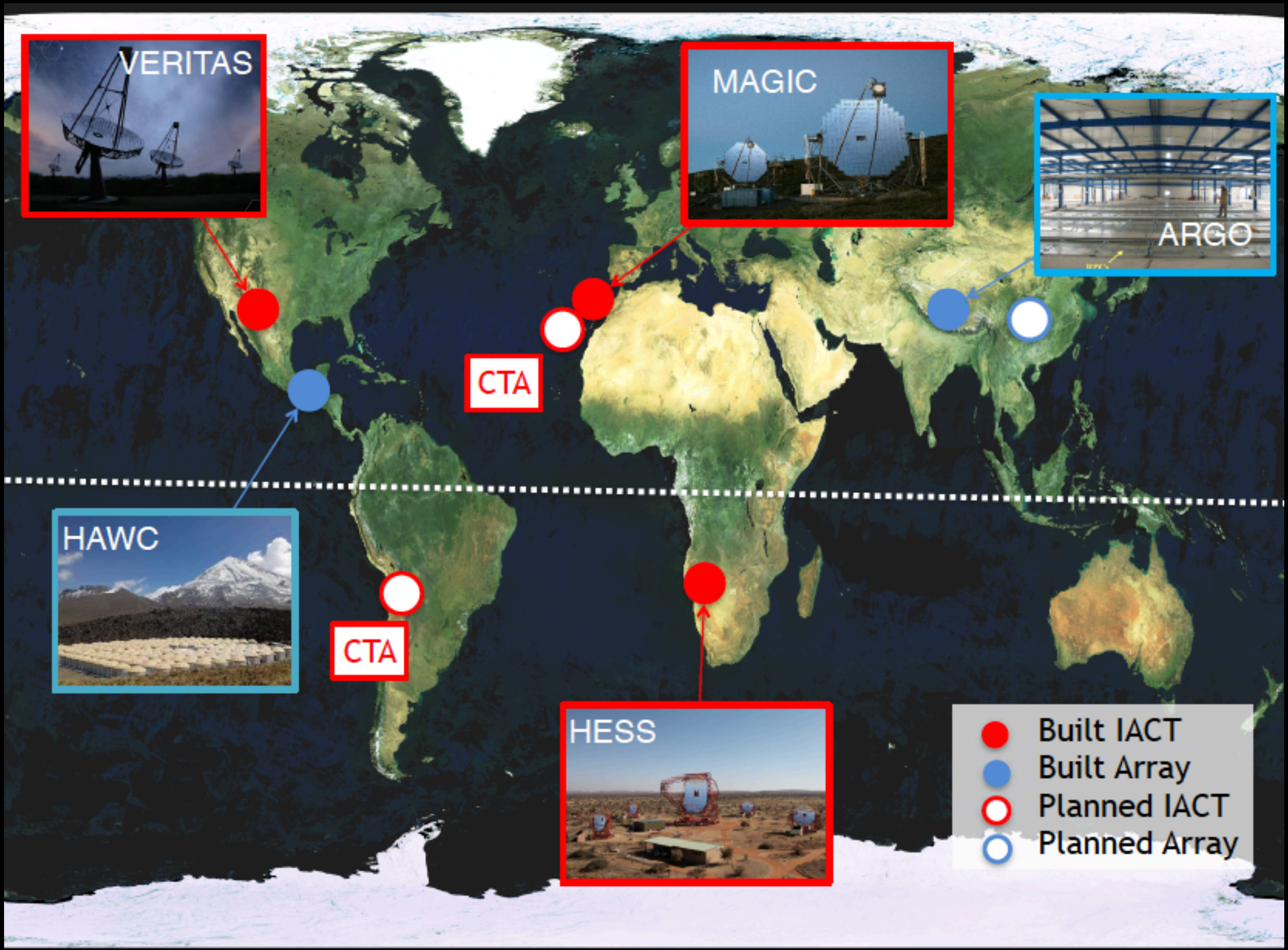
(Very) High Energy Gamma Rays

- 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; black holes,…
  - Galactic magnetic fields
  - Photon radiation fields in the Universe
  - Indirect search of **dark matter** (WIMP interactions)
  - Test fundamental properties of quantum gravity
  - …

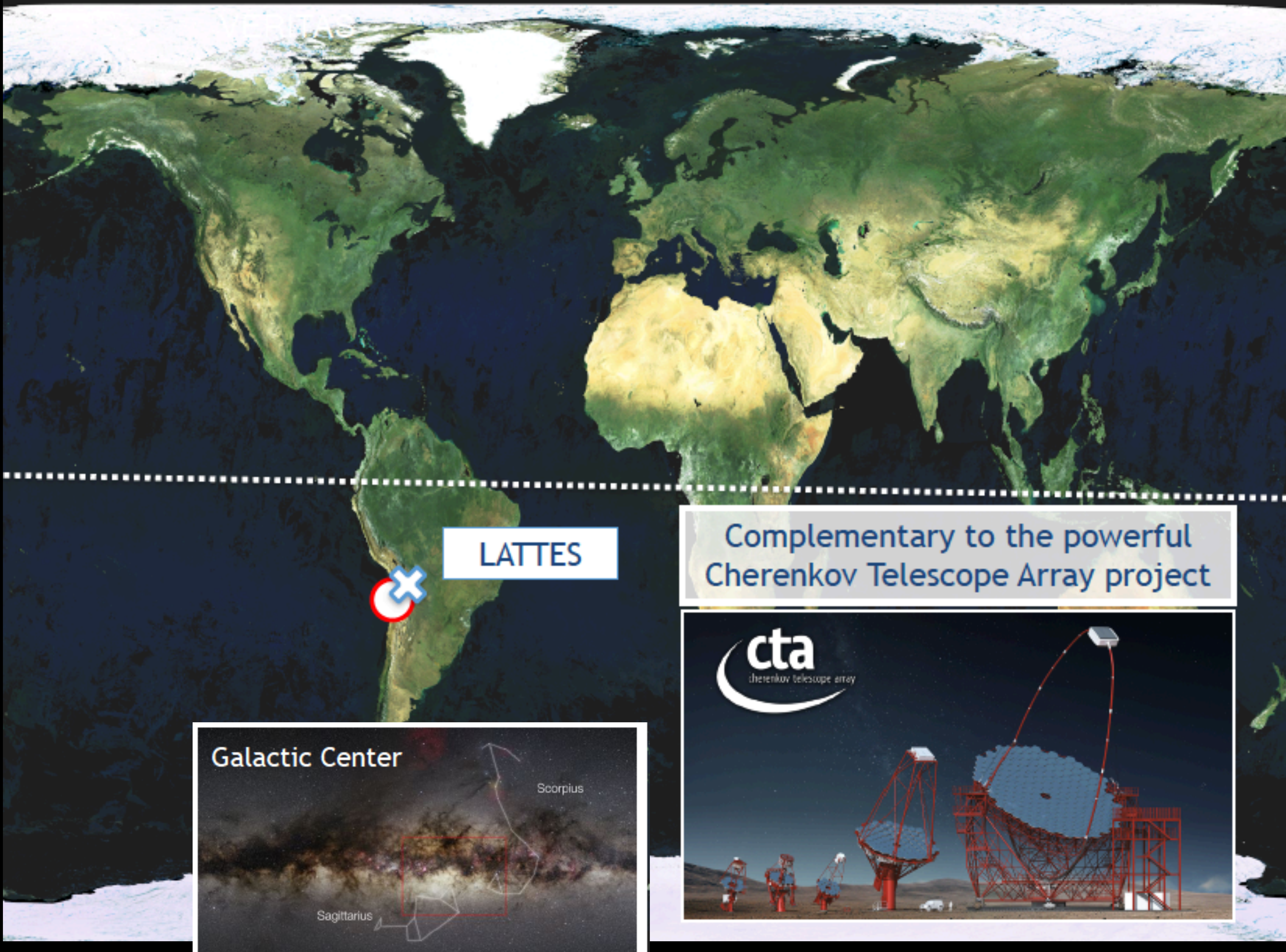
How to detect?



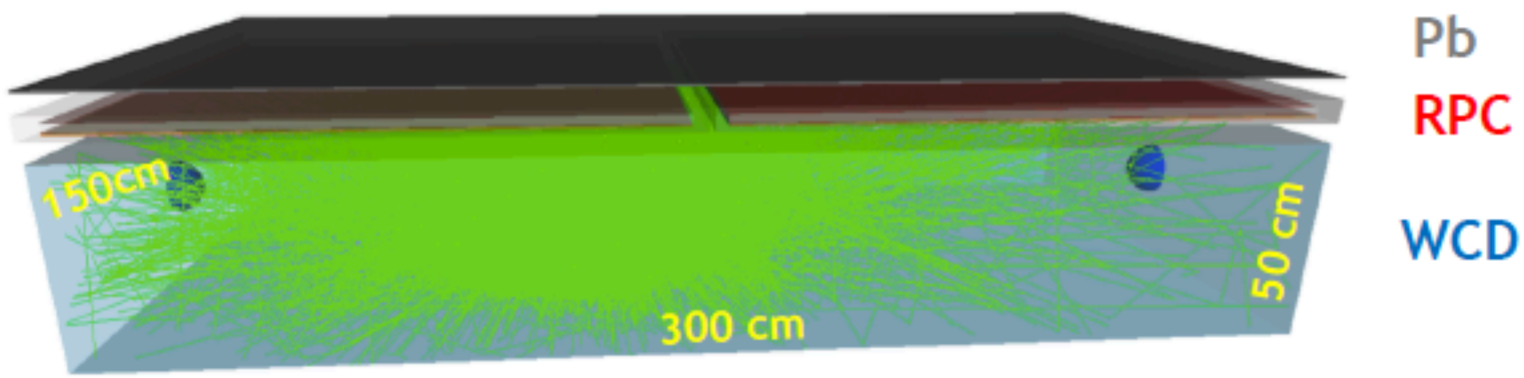
Arrays at high-altitude = large field of view + large duty cycle + low energy



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


LATTES
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

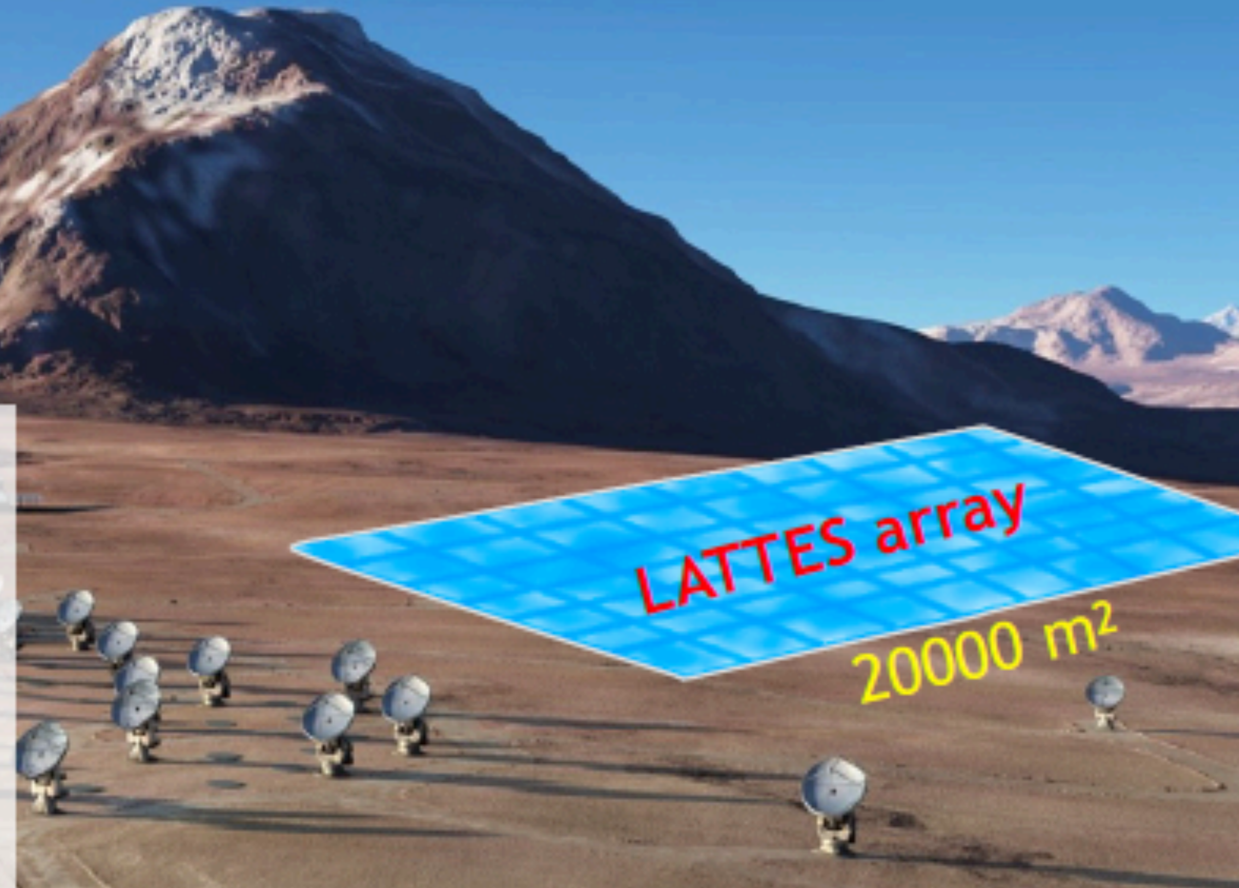
WCDs: e.m. energy, g/h discrimination and trigger

LATTES @ ALMA site

Large Array Telescope for Tracking Energetic Sources

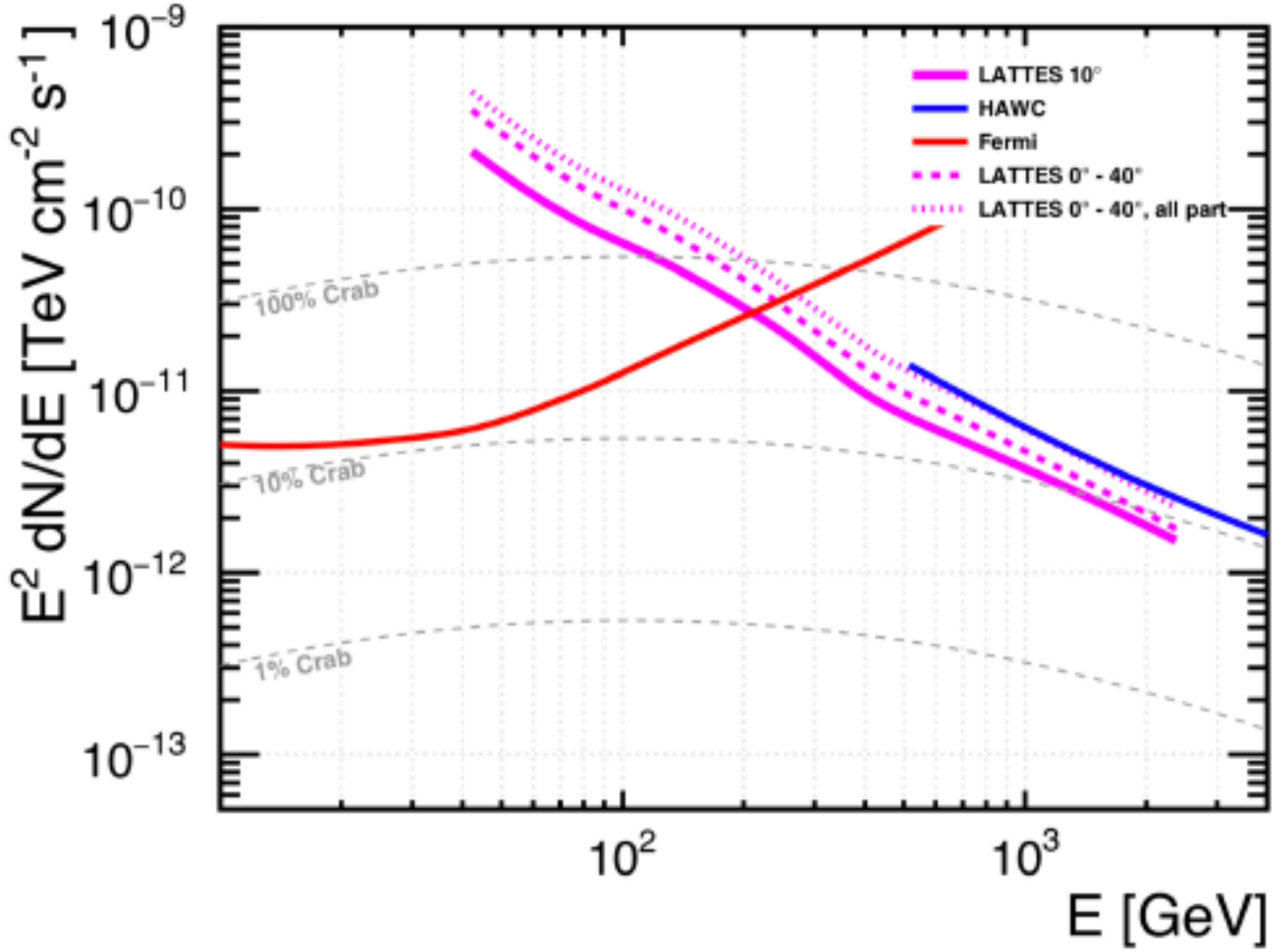
- Joint Brazil / Italy / Portugal initiative
- Interest from Czech group

- Possible site:
  - Atacama Large Millimeter Array site
  - Chajnantor plateau
  - 5200 meters altitude in north Chile
  - Good position to survey the Galactic Center



LATTES sensitivity

Astropart.Phys. 99 (2018) 34-42



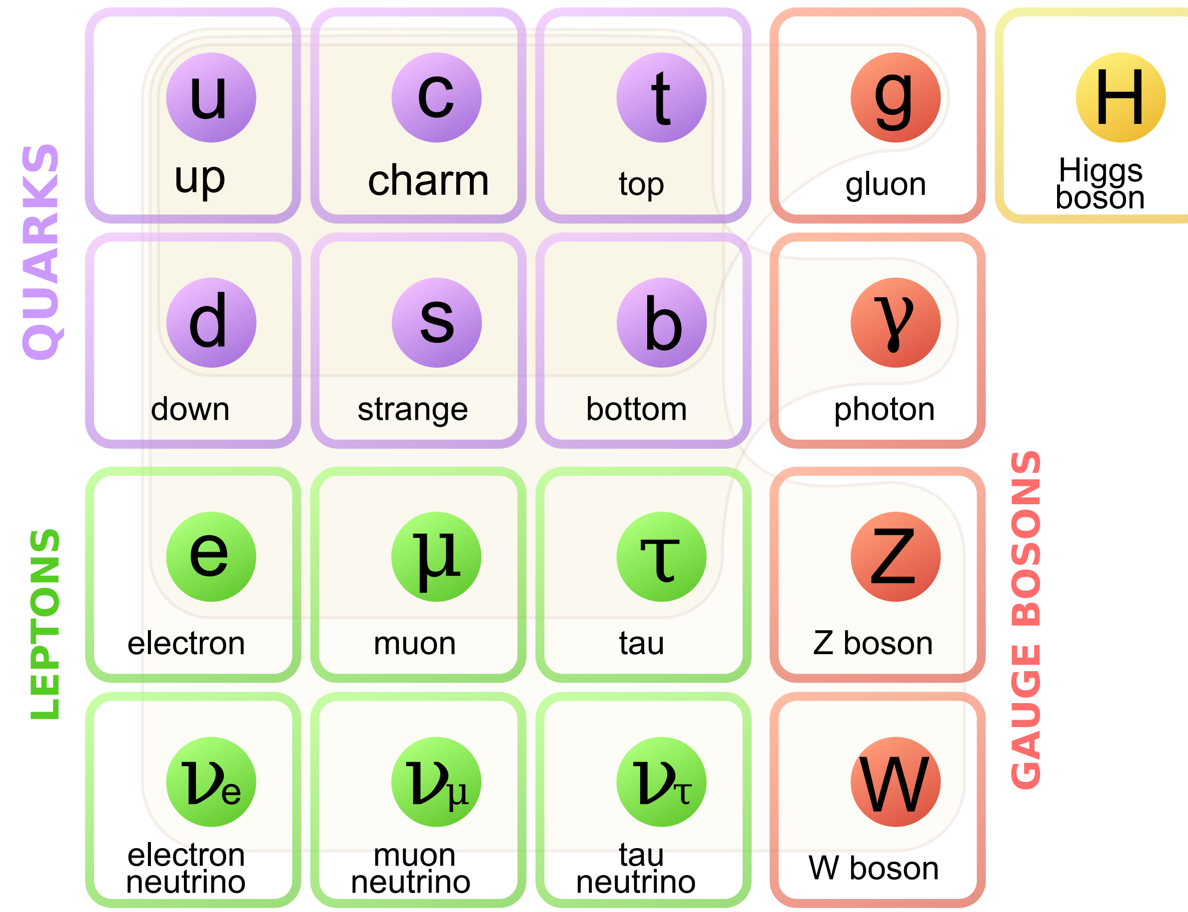
LATTES concept **can cover the energy gap** between satellite borne and ground base experiments

Neutrinos


For every proton/neutron/electron
the Universe contains a billion of
neutrinos from the Big Bang

What do we know about neutrinos?

- Have no charge - do not participate in electromagnetism.
  - Could be their own anti-particles.
- Come in three flavors
- Are very light
- Interact very weakly
- Neutrinos (ν) are always left-handed and anti-neutrinos ($\bar{\nu}$) are always right-handed

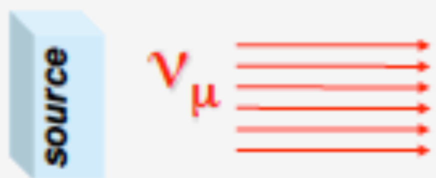


Neutrino oscillations

Requirements: Massive neutrinos & different masses

weak Hamiltonian

E_ν



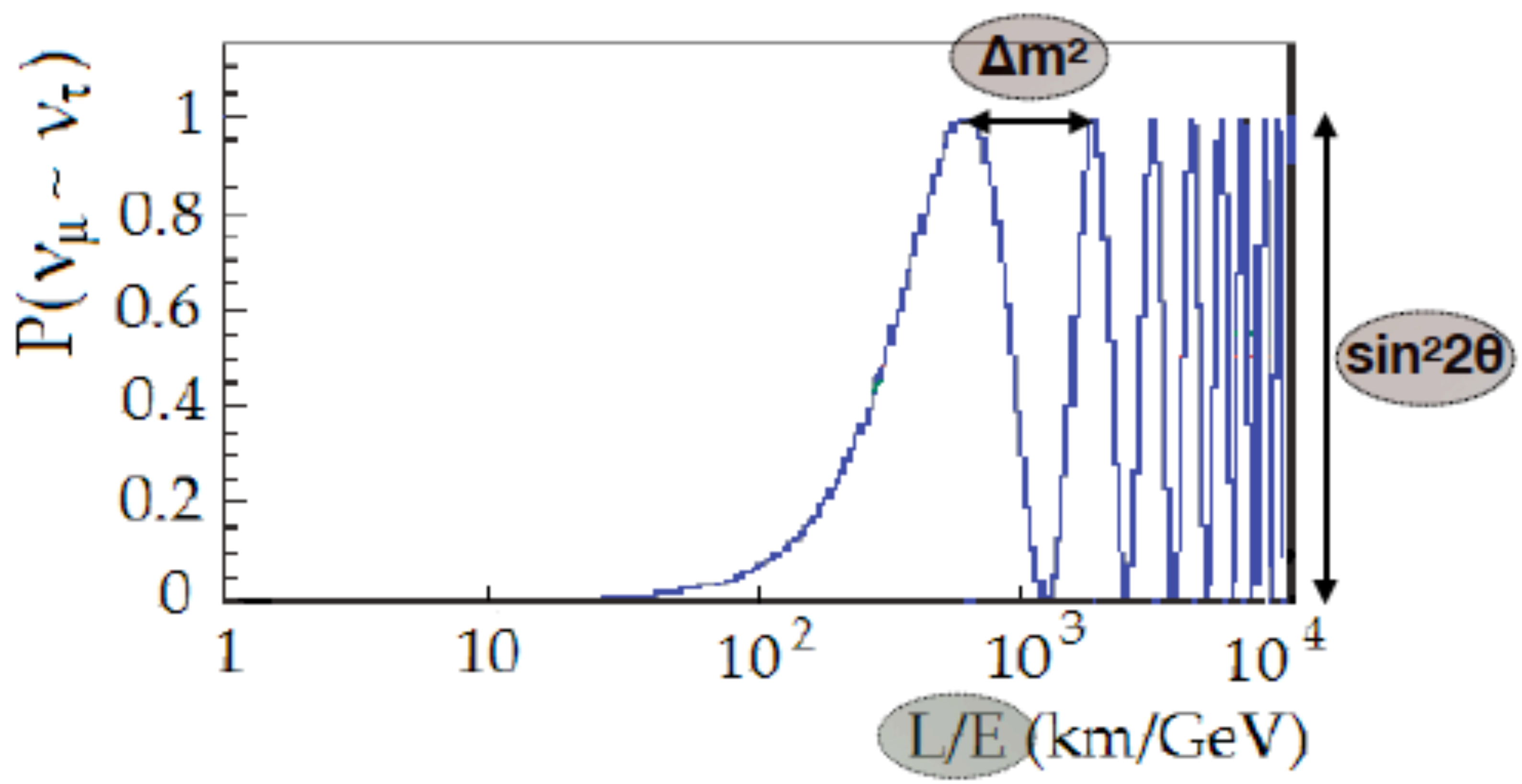
free Hamiltonian
(mass eigenstates)

$$P_{\nu_\mu \nu} \sim \sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m^2 \cdot L}{4E_\nu}\right)$$

2-family approx. for illustration purposes

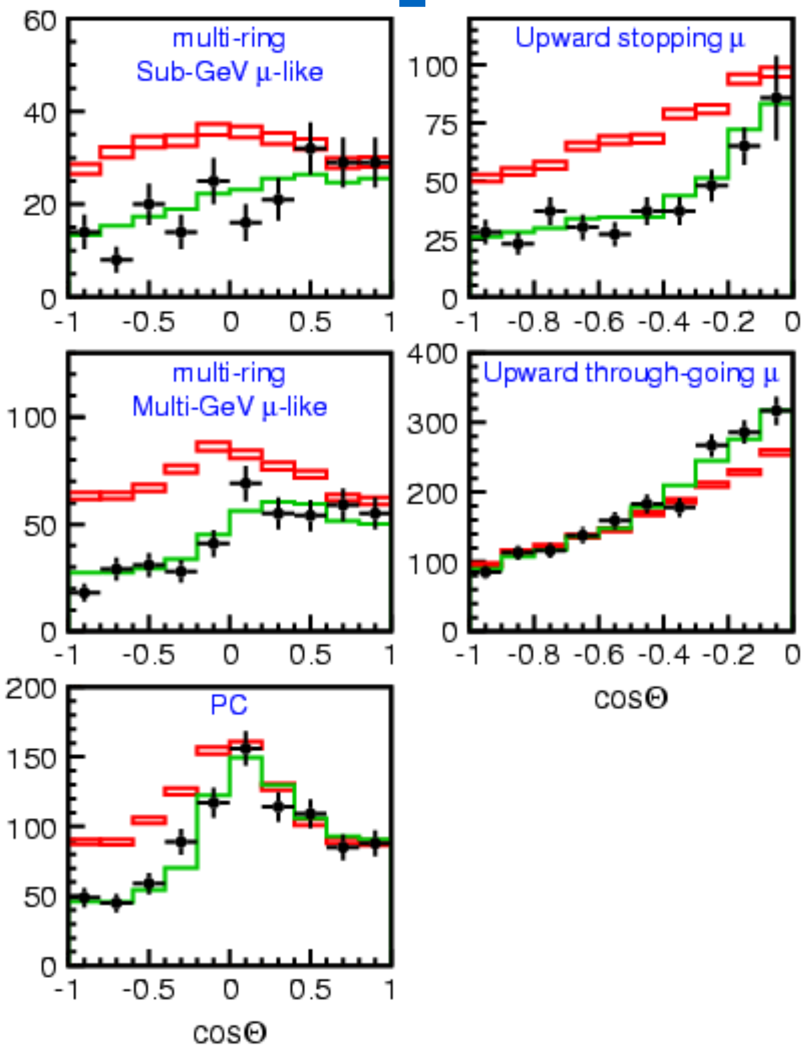
weak Hamiltonian

L

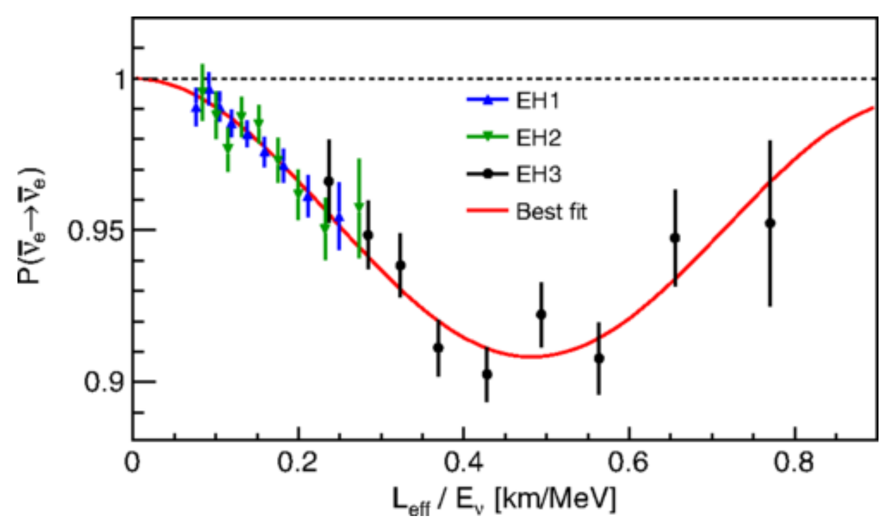


What have we learned in the last ~20 years

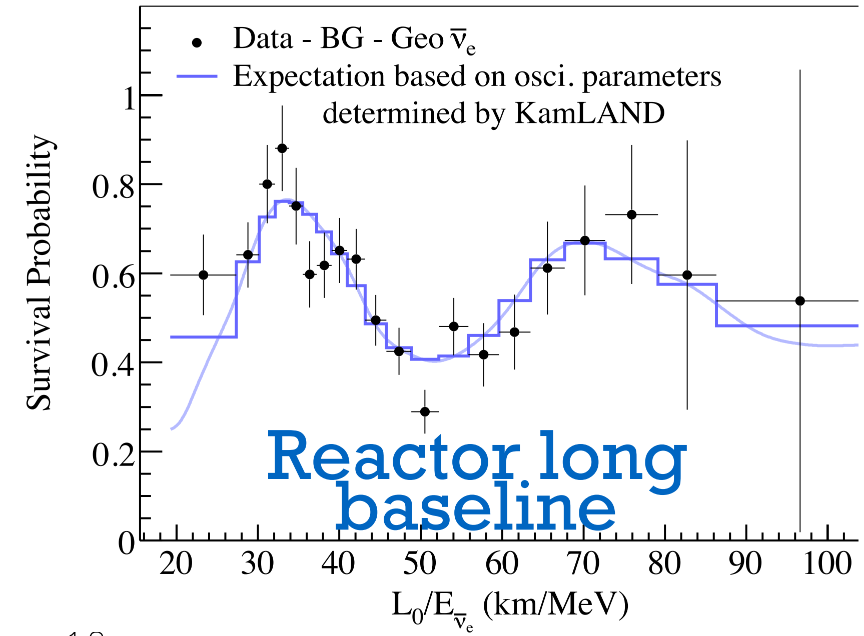
Atmospheric



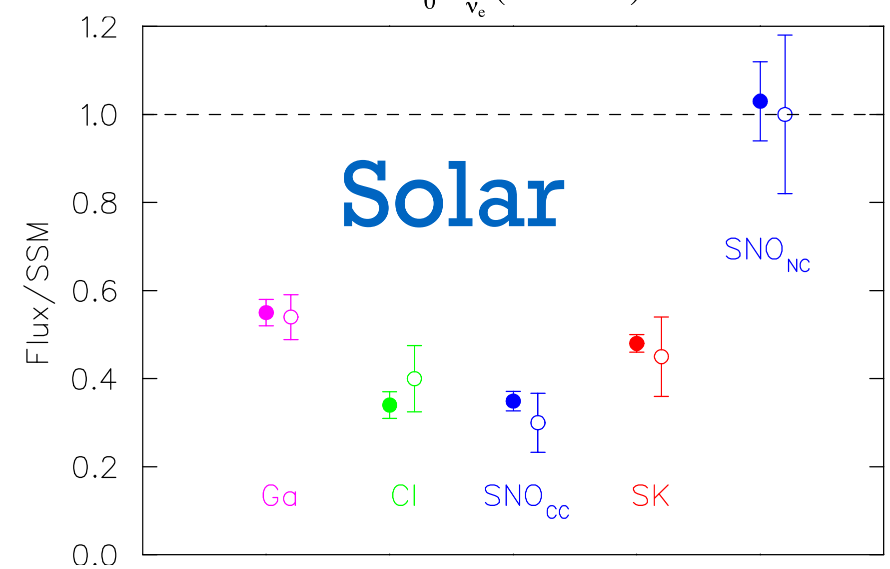
Reactor short baseline



Reactor long baseline



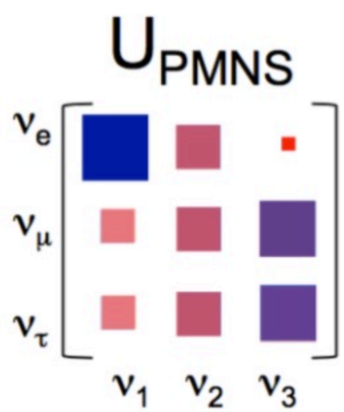
Solar



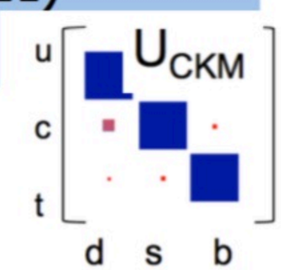
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\text{Accelerator and Atmospheric}} \underbrace{\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}}_{\text{SBL reactor}} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{Solar + LBL reactor}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

What **haven't** we learned yet

- Is there CP violation in the lepton sector?
- Which mass hierarchy is correct?
- What are the precise values of the neutrino mixing parameters?



Mixing	Neutrinos	Quarks
θ_{12}	$(33.6 \pm 0.8)^o$	$(13.04 \pm 0.05)^o$
θ_{23}	$(45 \pm 3)^o$	$(2.38 \pm 0.06)^o$
θ_{13}	$(8.5 \pm 0.15)^o$	$(0.201 \pm 0.011)^o$
δ_{CP}	$(-90\ ?\ )^o$	$(67 \pm 5)^o$



→ Test 3 flavor paradigm
→ Measure symmetry between 2nd and 3rd generation
→ Search for new/unexpected physics

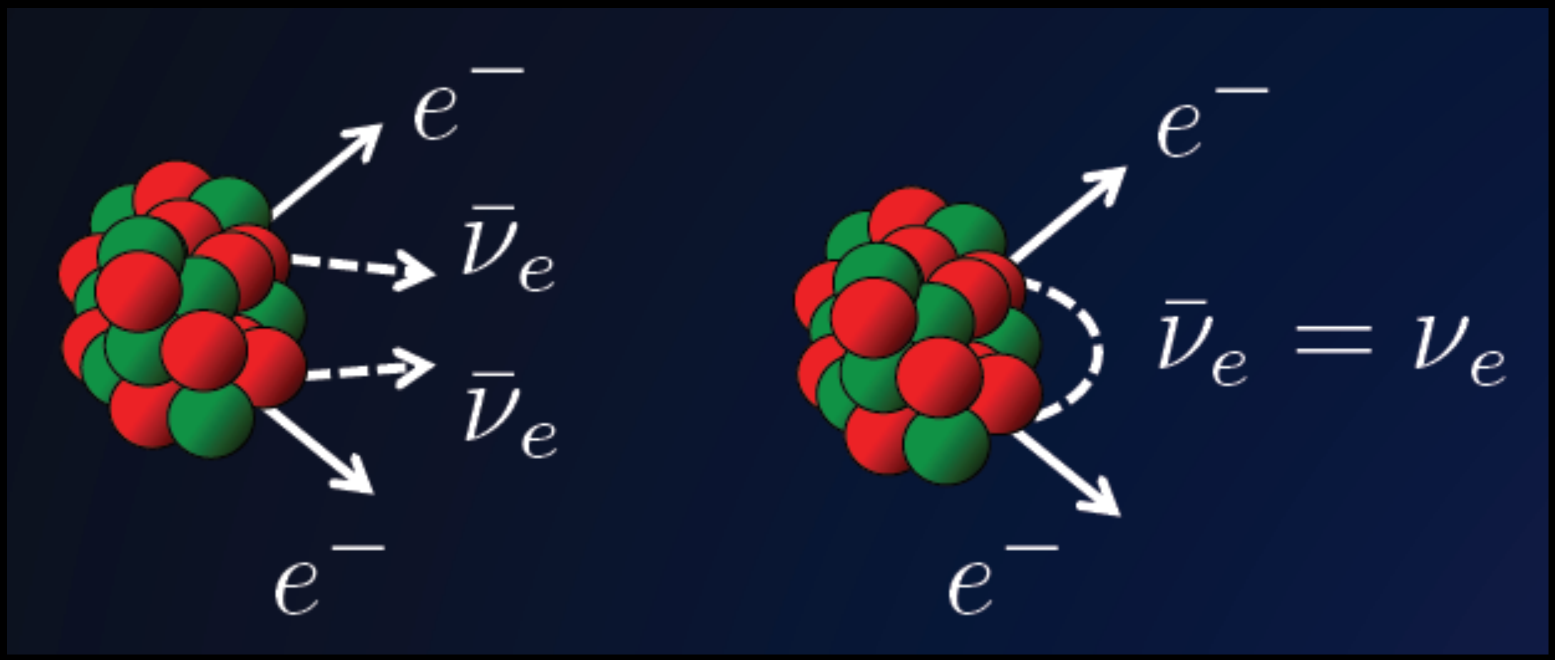
- What is the absolute mass scale?
- Are neutrinos Majorana or Dirac particles?

DUNE

SNO+

SNO+

Neutrino-less double beta decay



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

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

Half-life

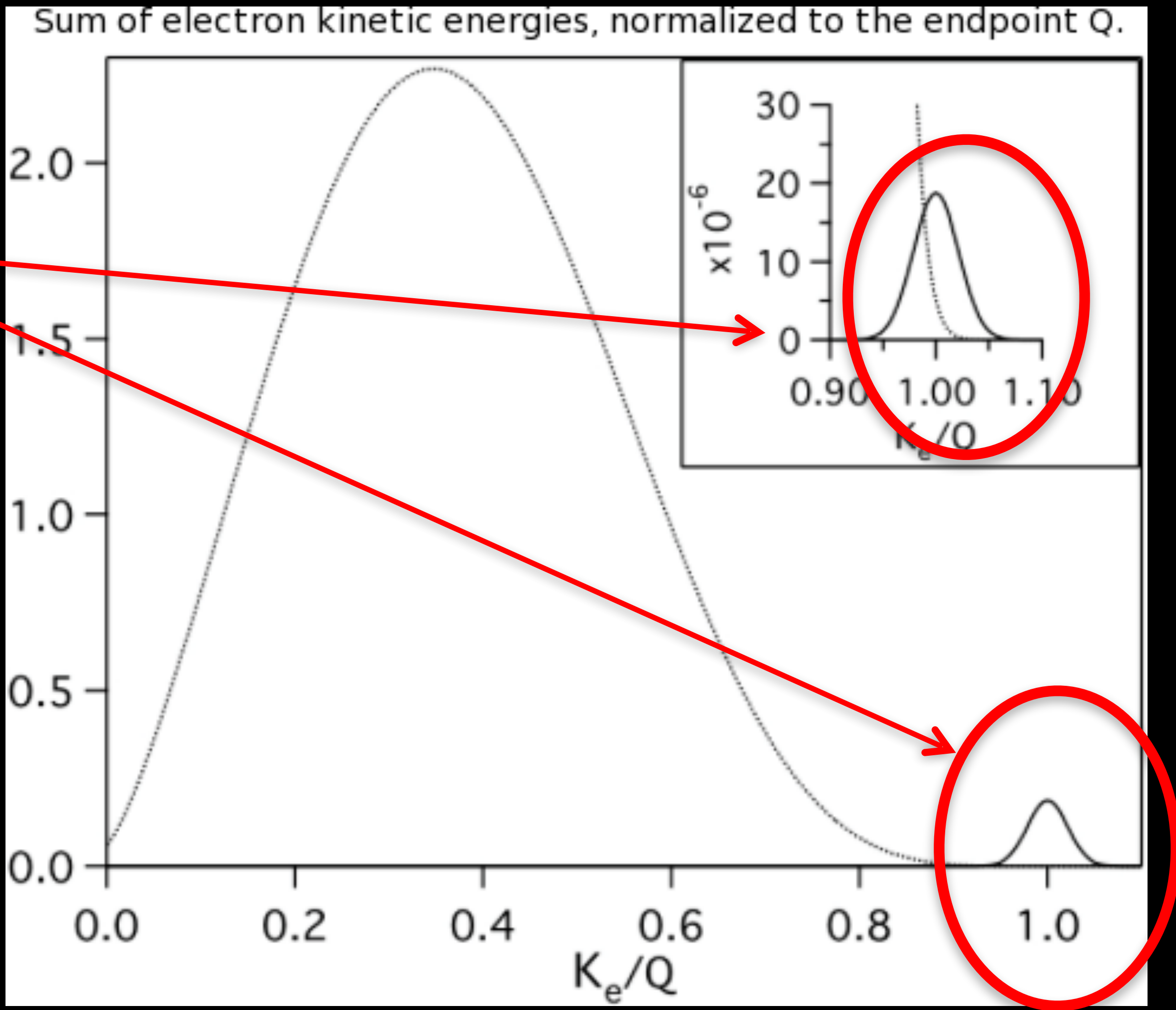
Nuclear Physics terms

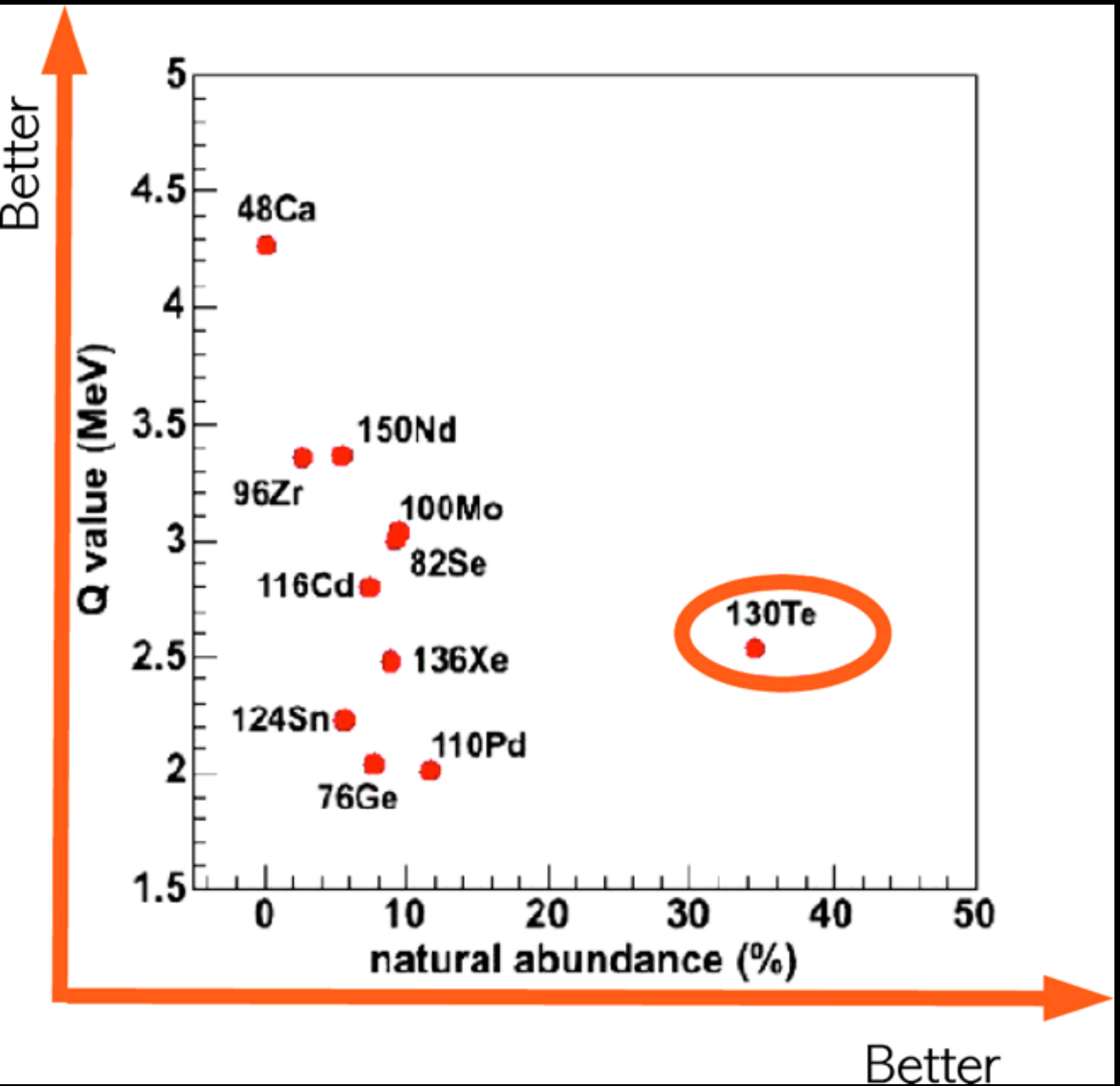
Particle Physics term
Effective Majorana mass
Depends on masses m1, m2, m3
also on neutrino mixing parameters

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

Searching for NLDBD

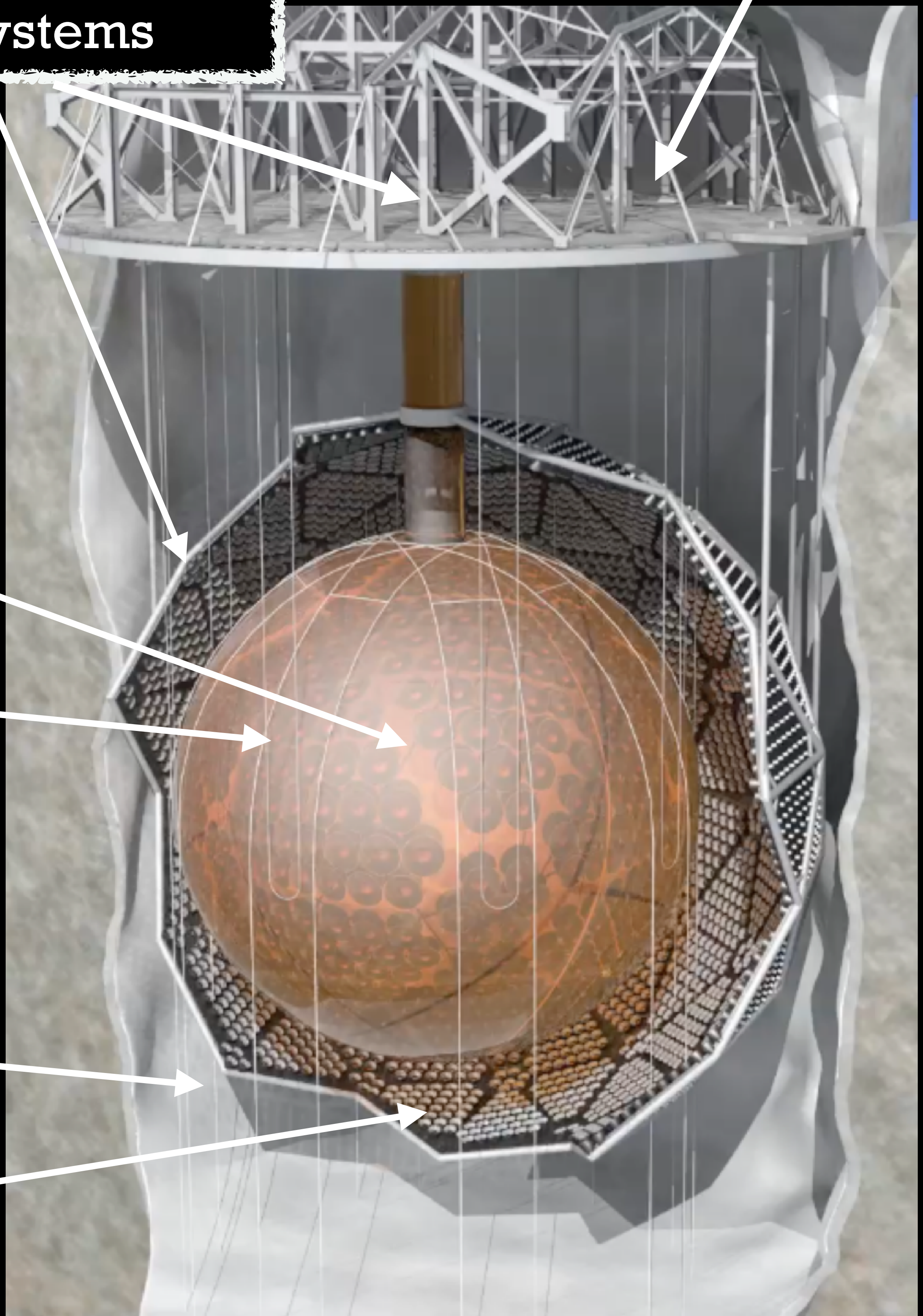
- Method
  - Search for a peak in the energy spectrum (sum of the two electrons)
  - Acquire data for a long time and with high quantities of isotope





- Choice of isotope
  – Natural abundance, energy
- Low backgrounds
  – Underground location
  – Low radioactivity

SNO+ detector



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

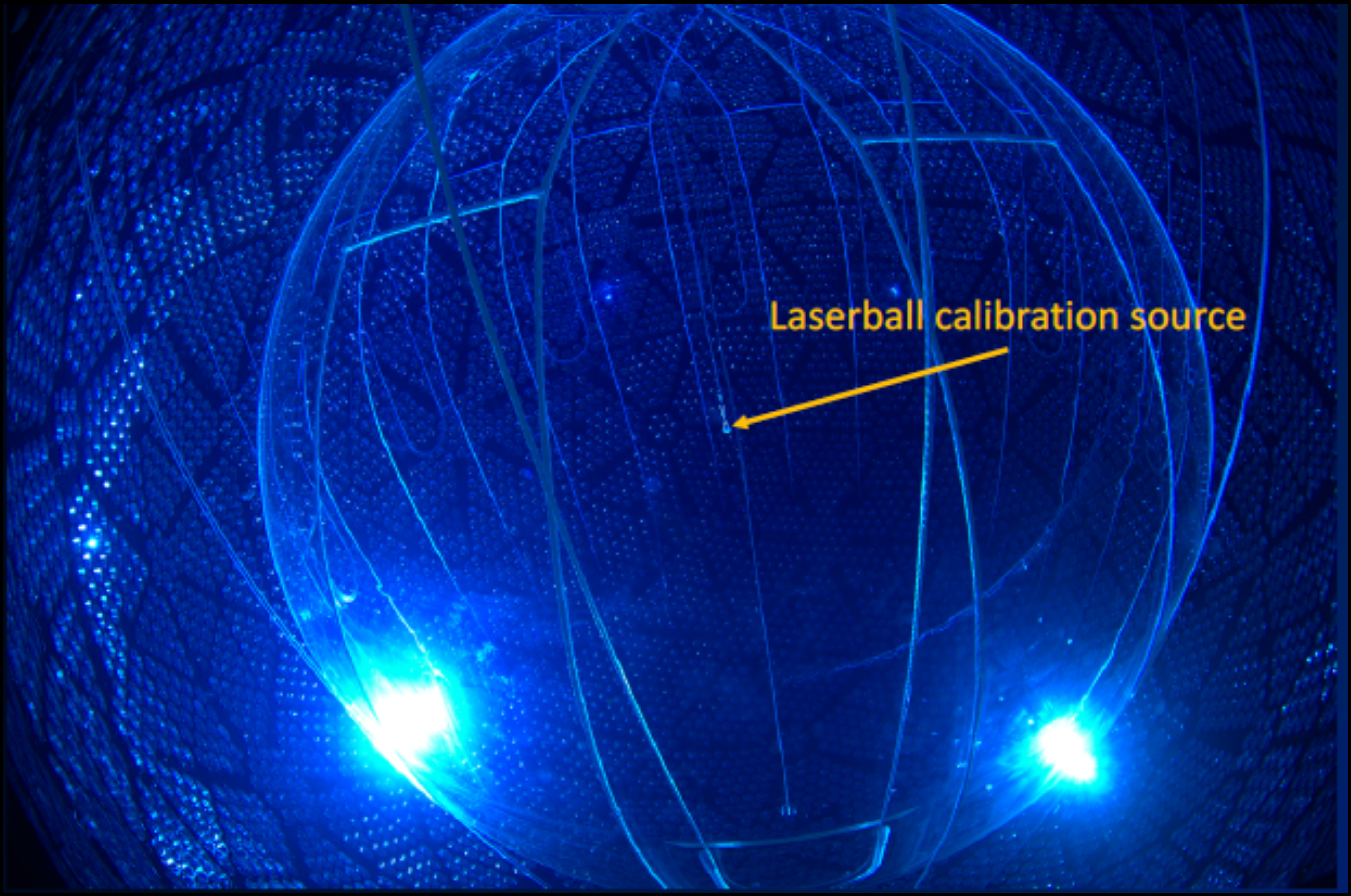
viewed by ~ **9300 PMTs** (8")

mounted on 17 m diam. structure

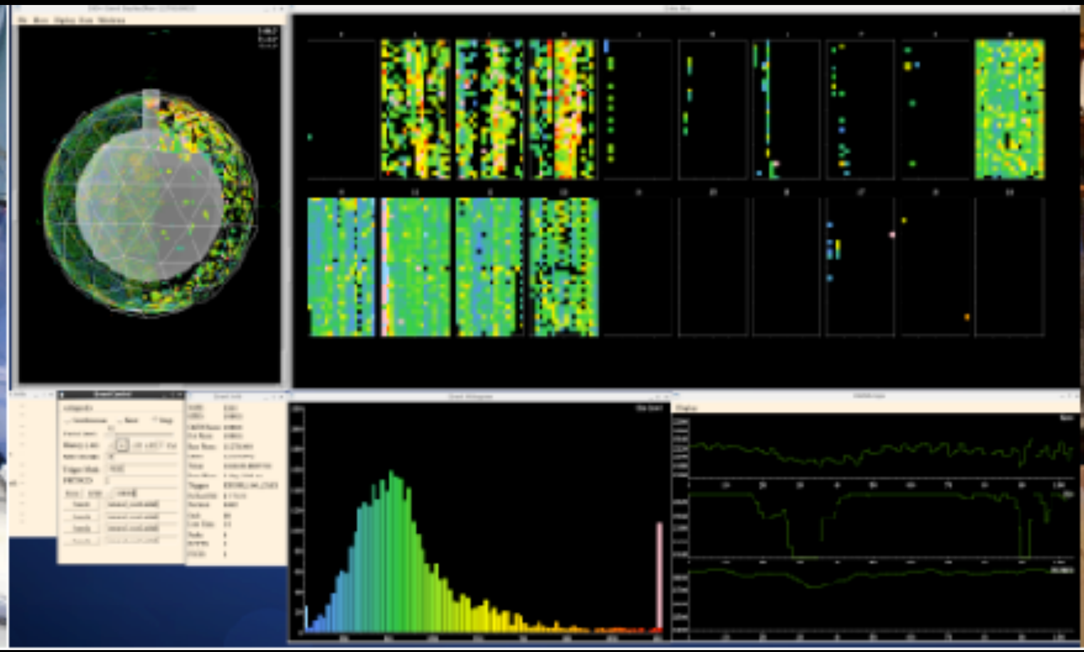
new calibration systems

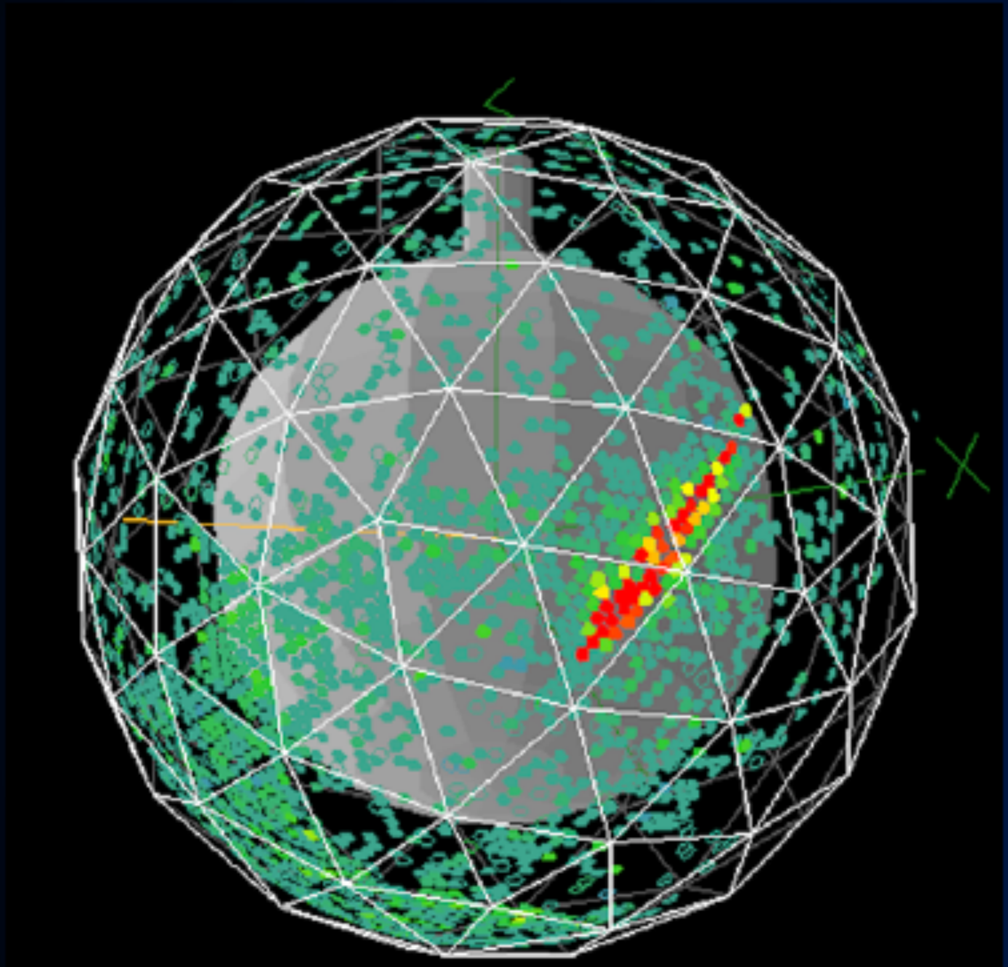
new DAQ and readout cards

Water phase data!

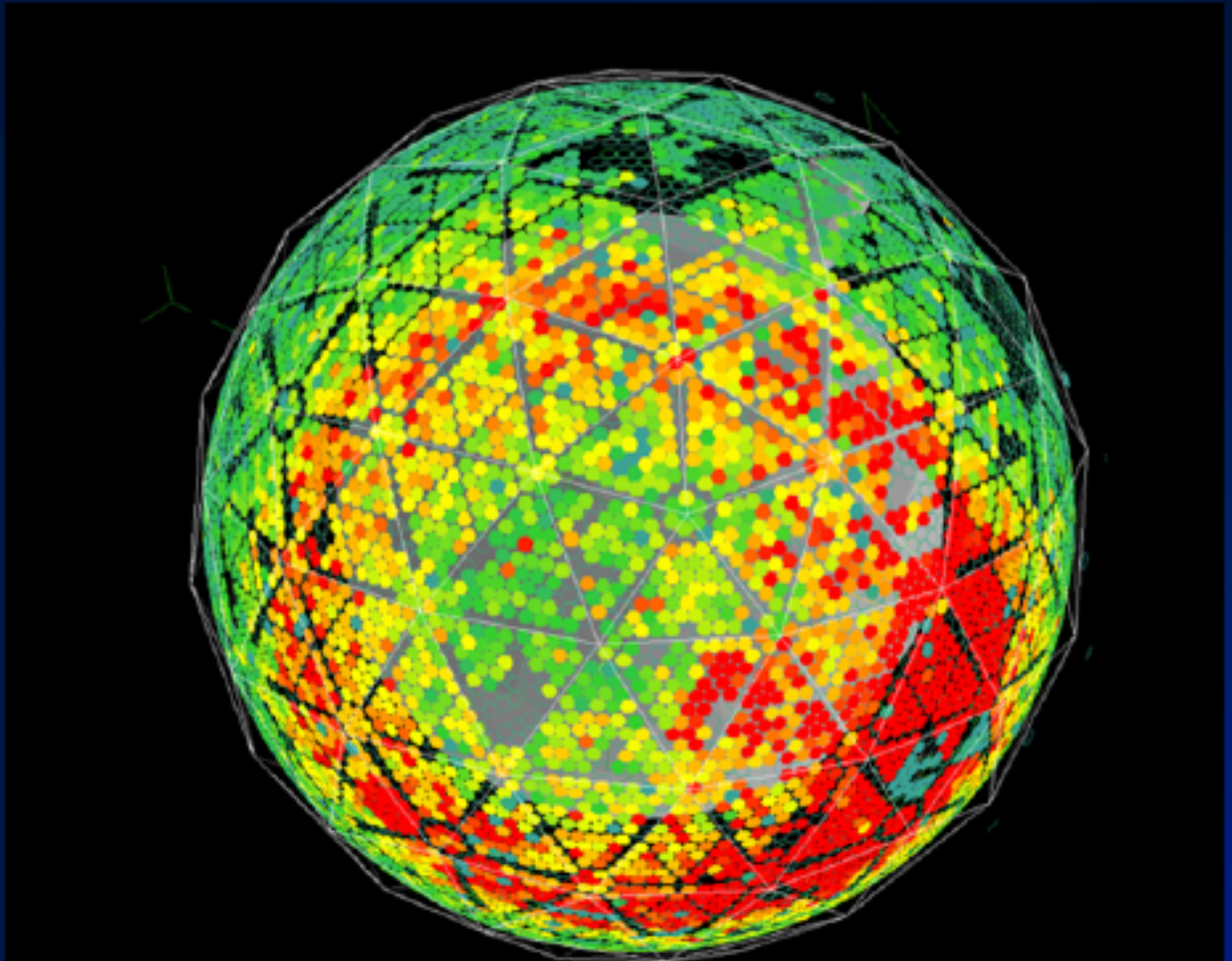


Data-taking!





Muon candidate grazing the detector

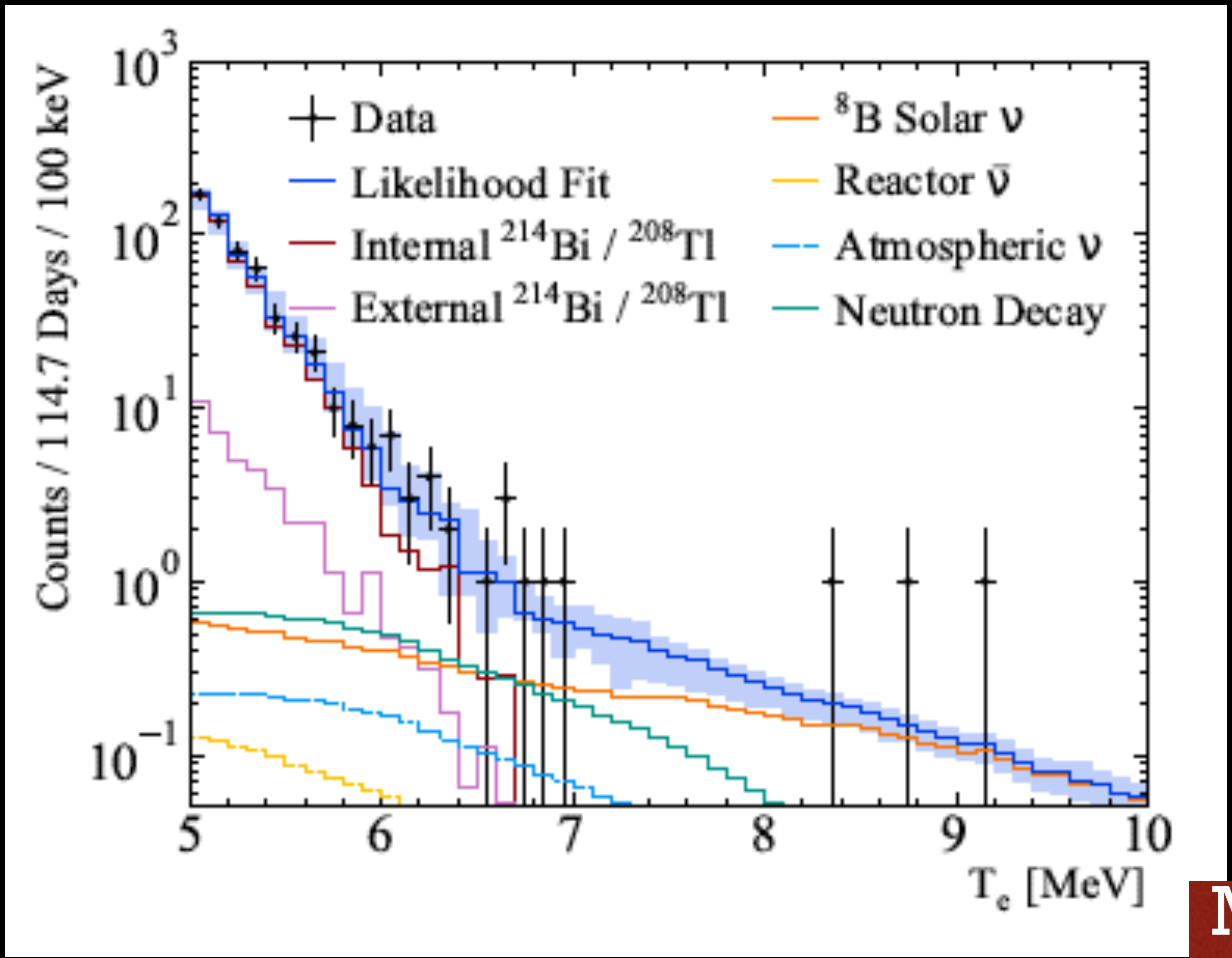


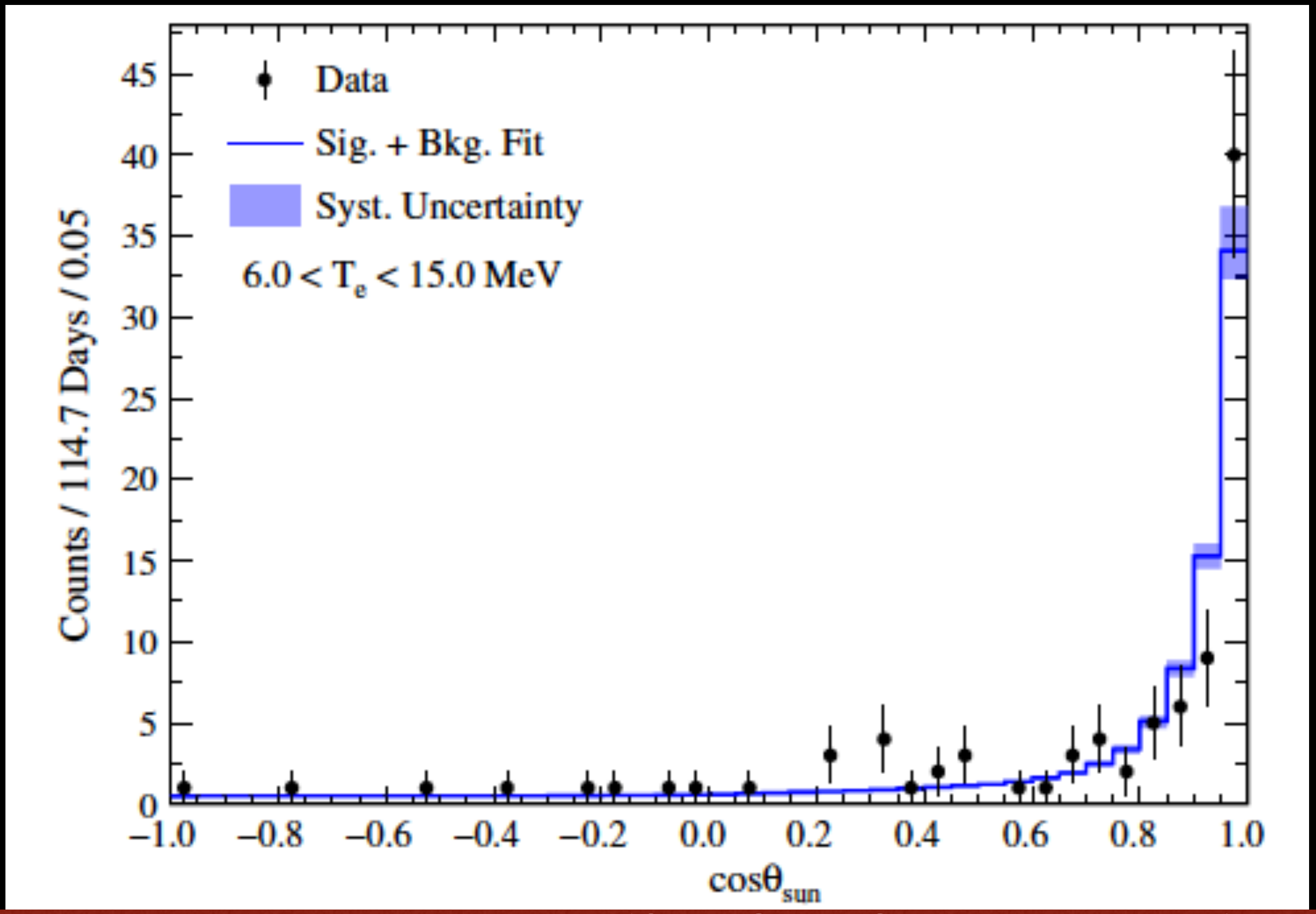
Another muon candidate

New results!

Limits on invisible nucleon decay
World-leading on proton:
$T(p \rightarrow inv.) \geq 3.6 \times 10^{29}$ yr (90% CL)

^{8}B solar neutrinos.
Consistent with SK and SNO.
Lowest backgrounds ever
> 6 MeV

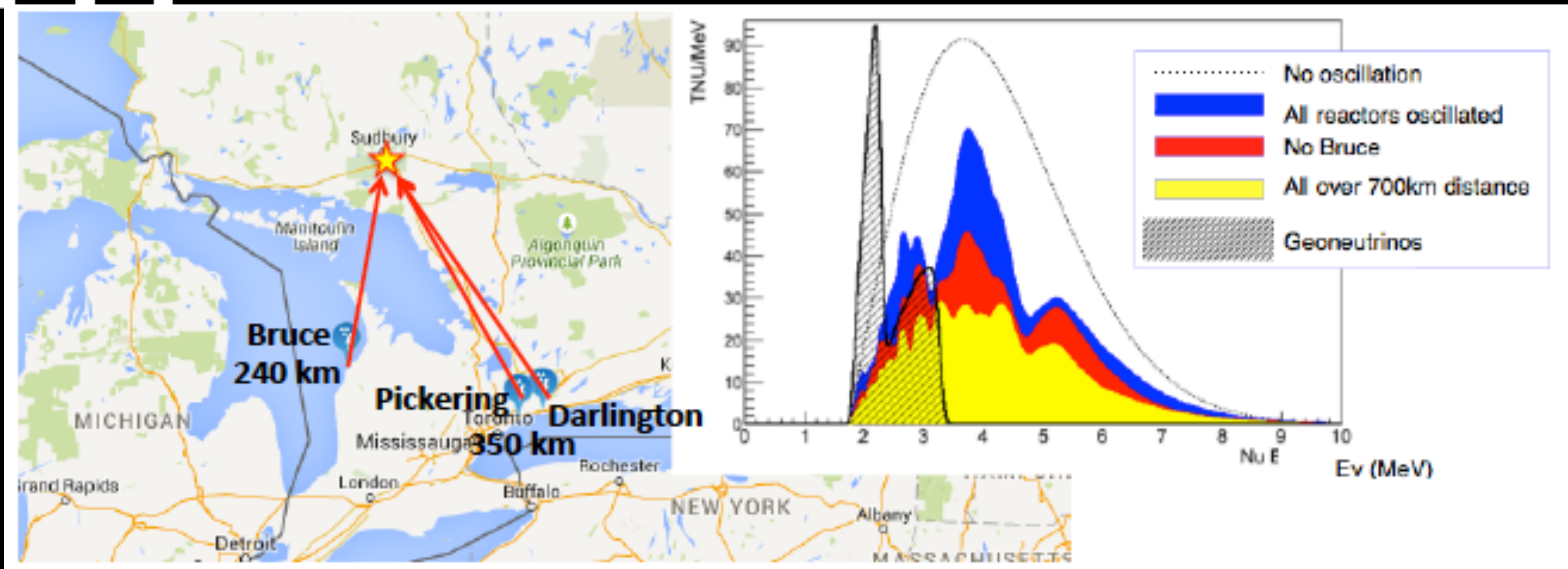


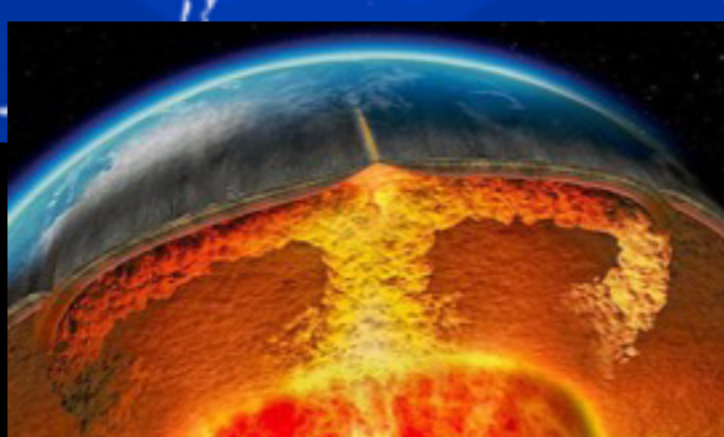


https://arxiv.org/abs/1812.05552

M. Anderson *et al.* (SNO+ Collaboration)
Phys. Rev. D 99, 012012 (2019)

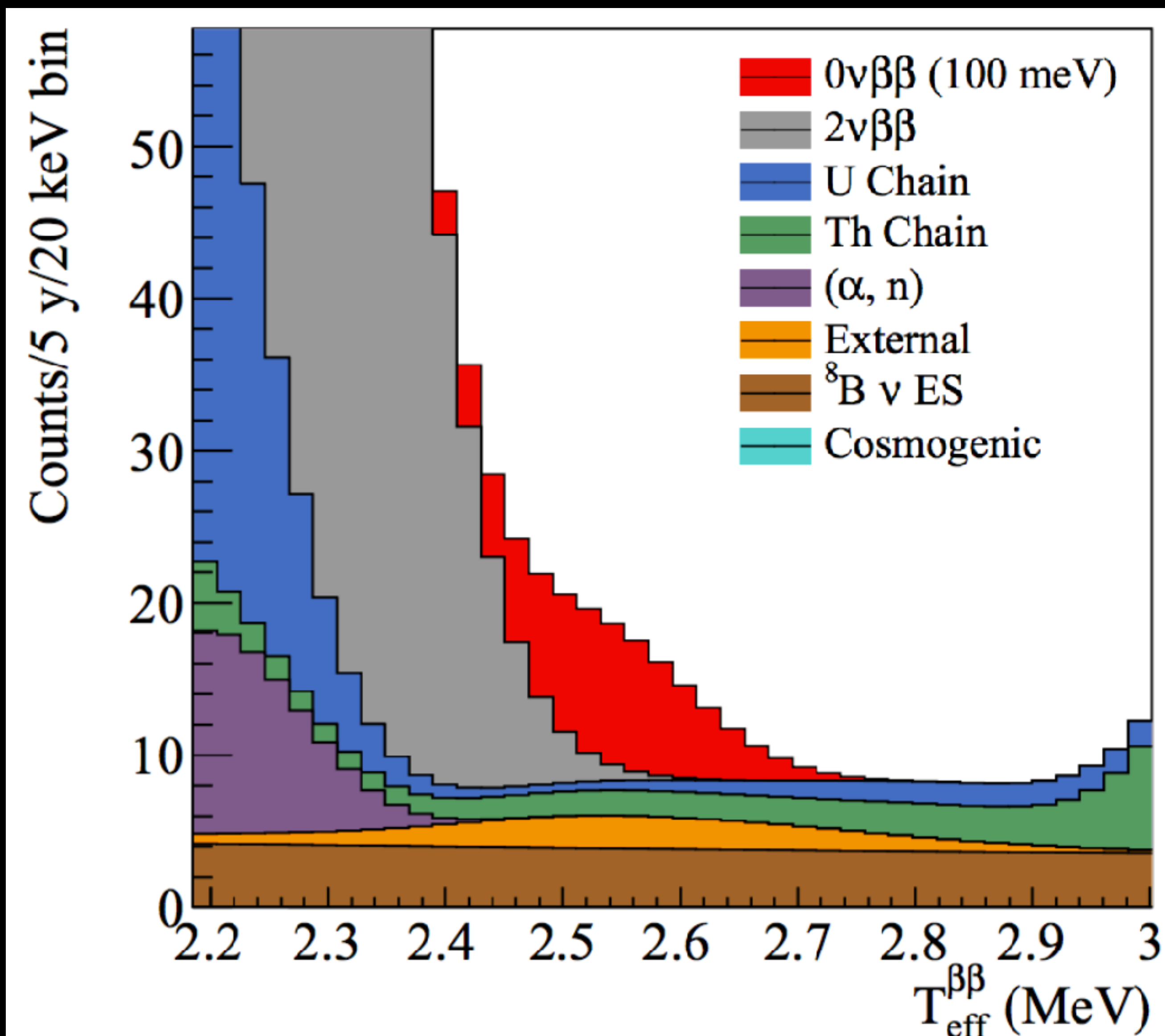
Anti-neutrinos





- from nuclear reactors and natural Earth radioactivity
- improve oscillation measurements
- constrain Earth heat models

Double Beta Decay Sensitivity



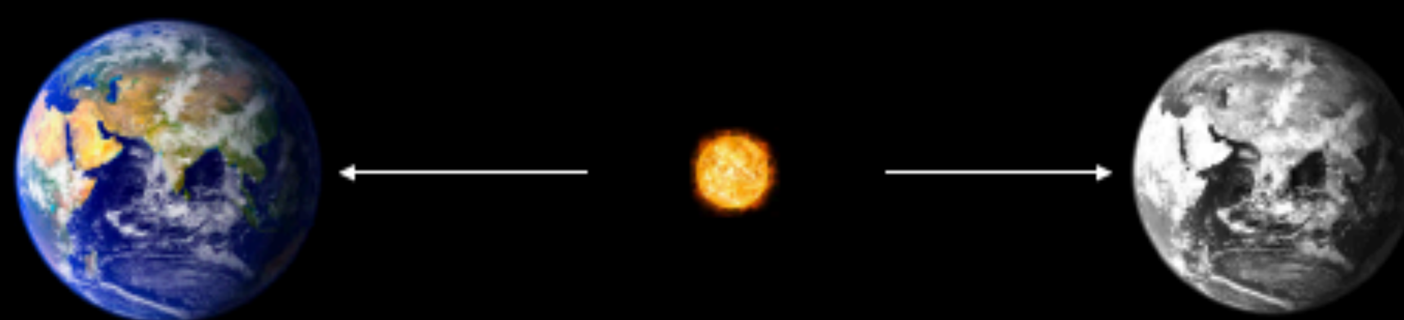
$T_{1/2} \geq 2 \times 10^{26}$ yr (90% CL, 5 yr)

$m_{\beta\beta} \approx$ **40 – 90 meV**

- Tellurium phase: 2020
- After 5 years, expect best ^{130}Te DBD half-life limit, probing top of inverted hierarchy neutrino masses
  - Upgrade: x5 better
- Complementary to searches with ^{136}Xe and ^{76}Ge

DUNE

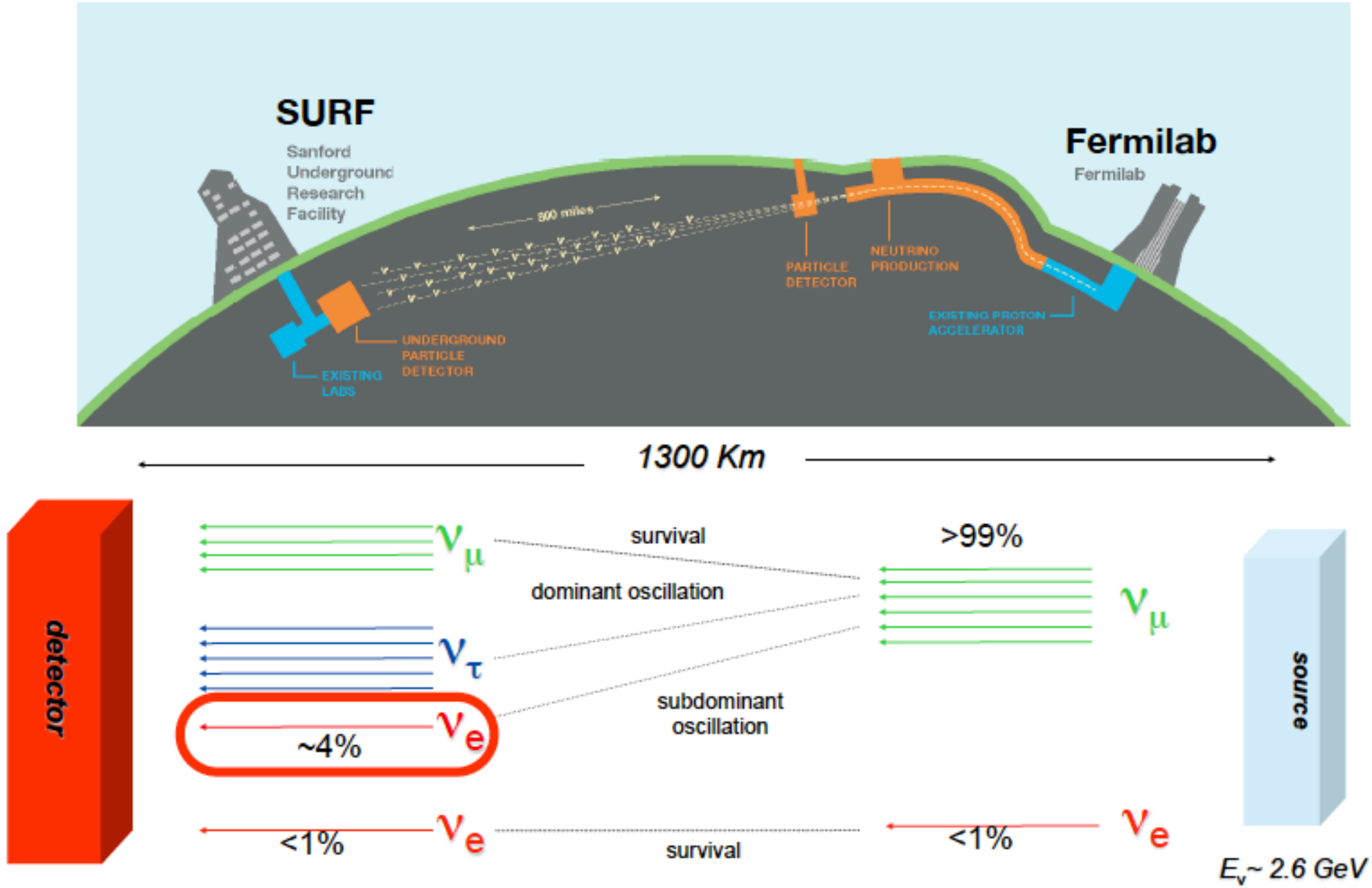
The big bang produced equal amounts of matter and antimatter



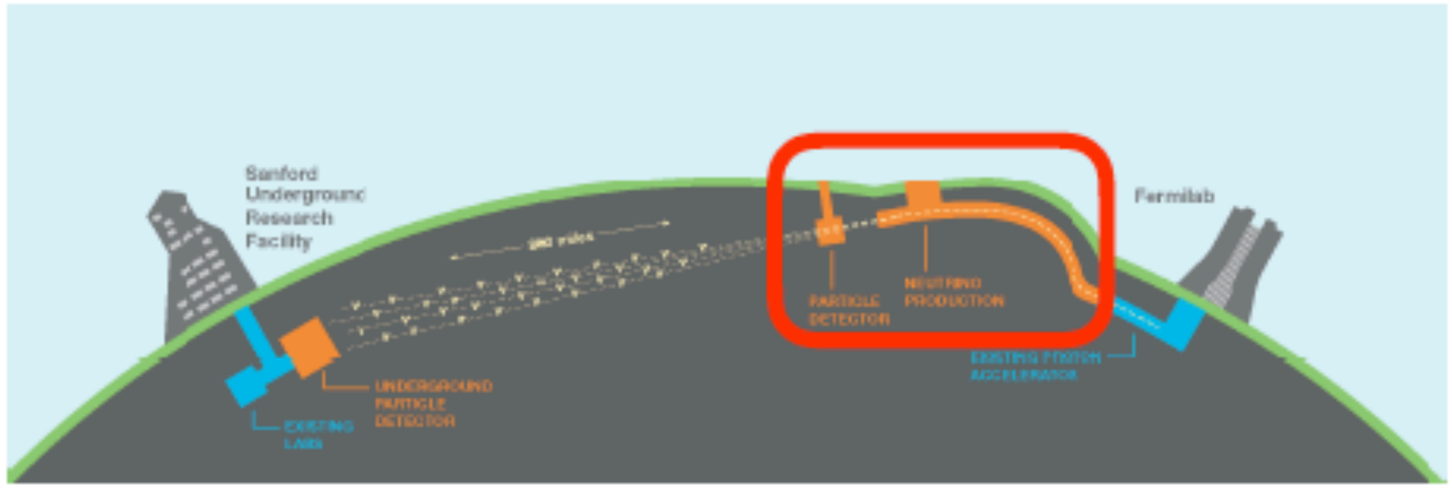
For some reason antimatter was annihilated. Why ?

Neutrinos may have the answer: **CP violation**

Oscillation modes in DUNE

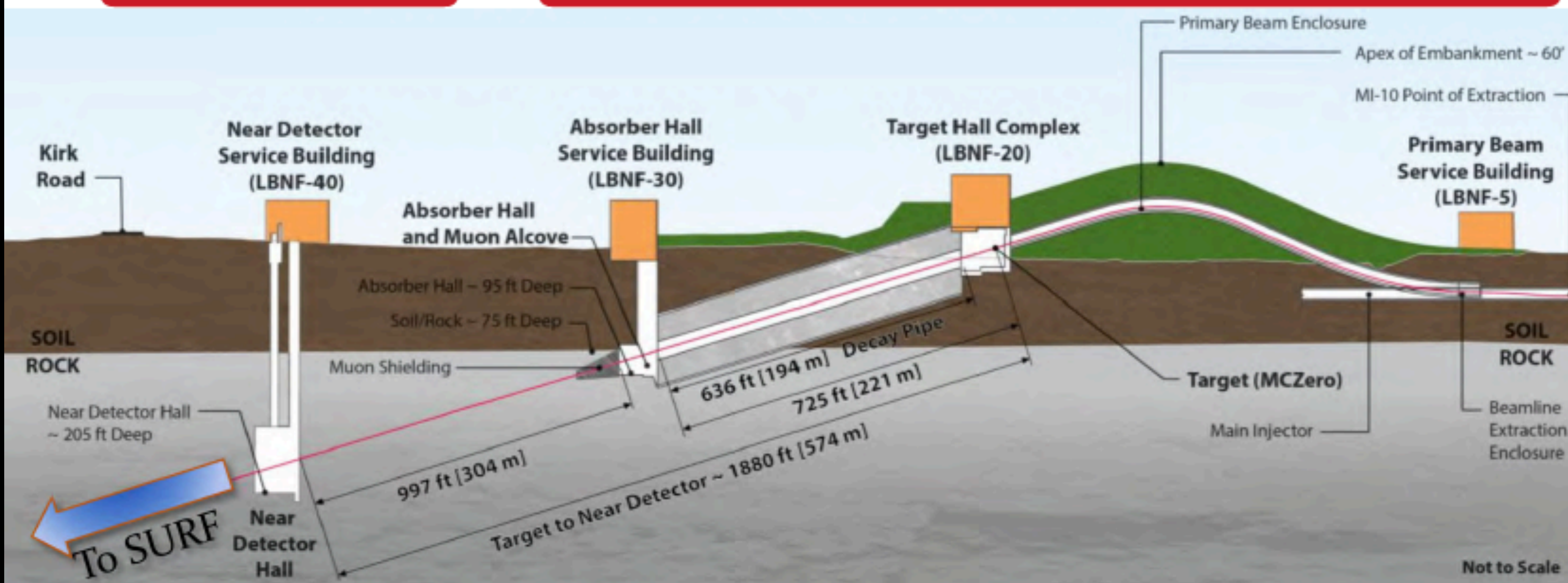


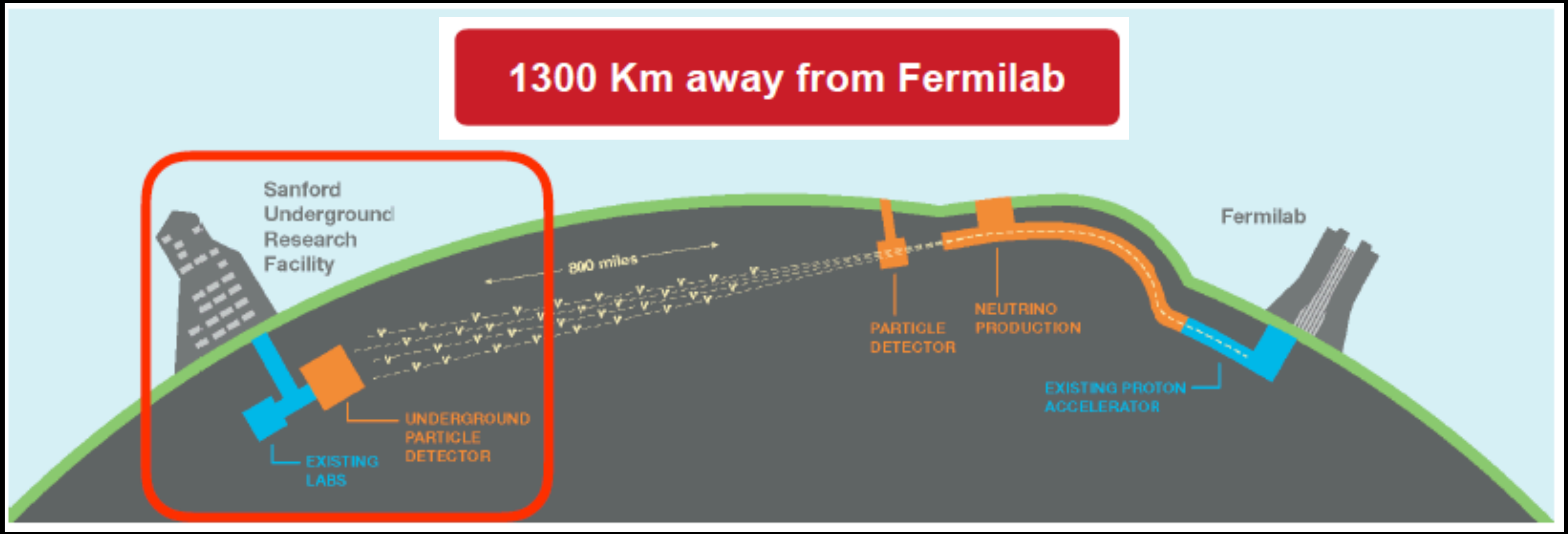
Fermilab

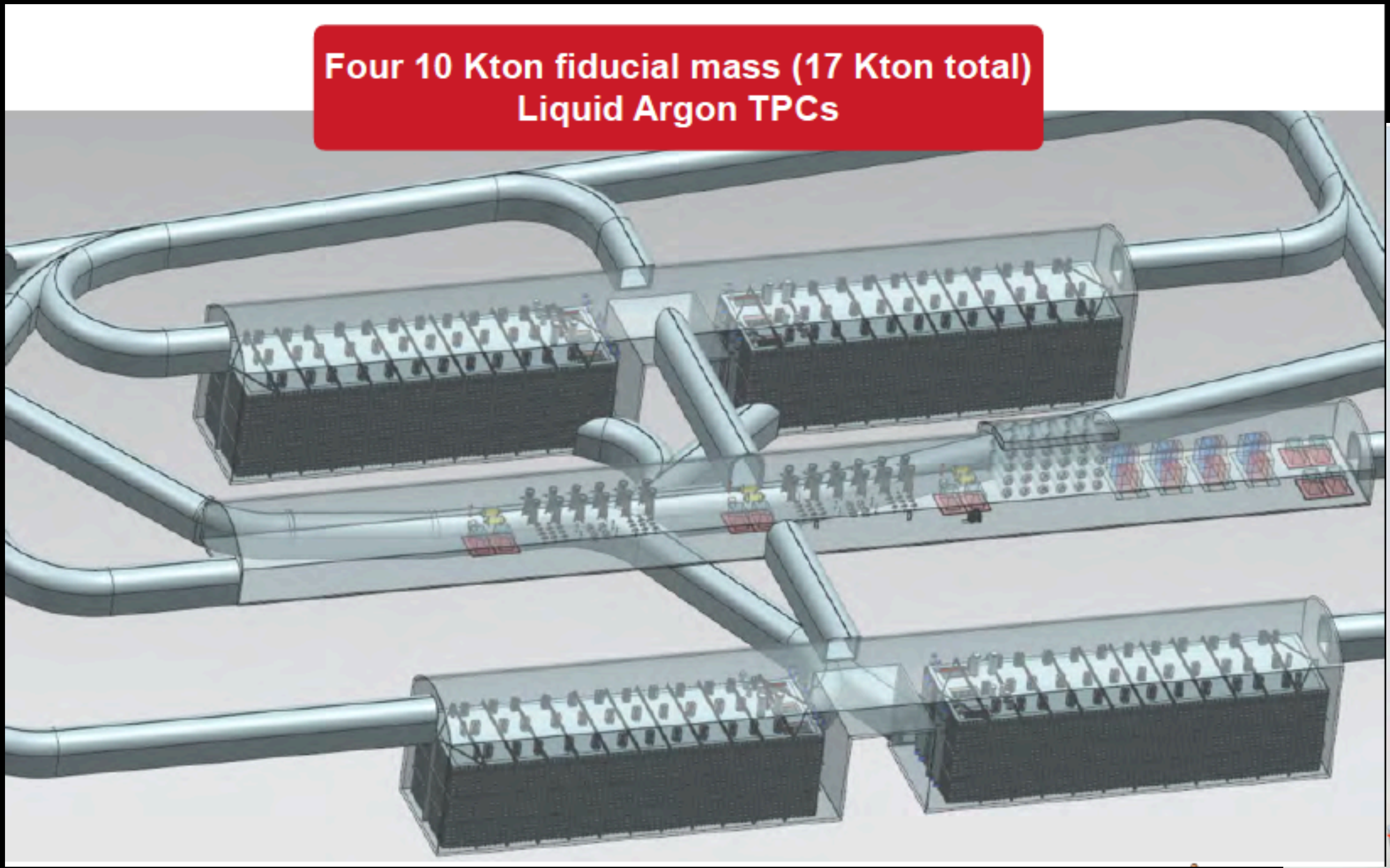


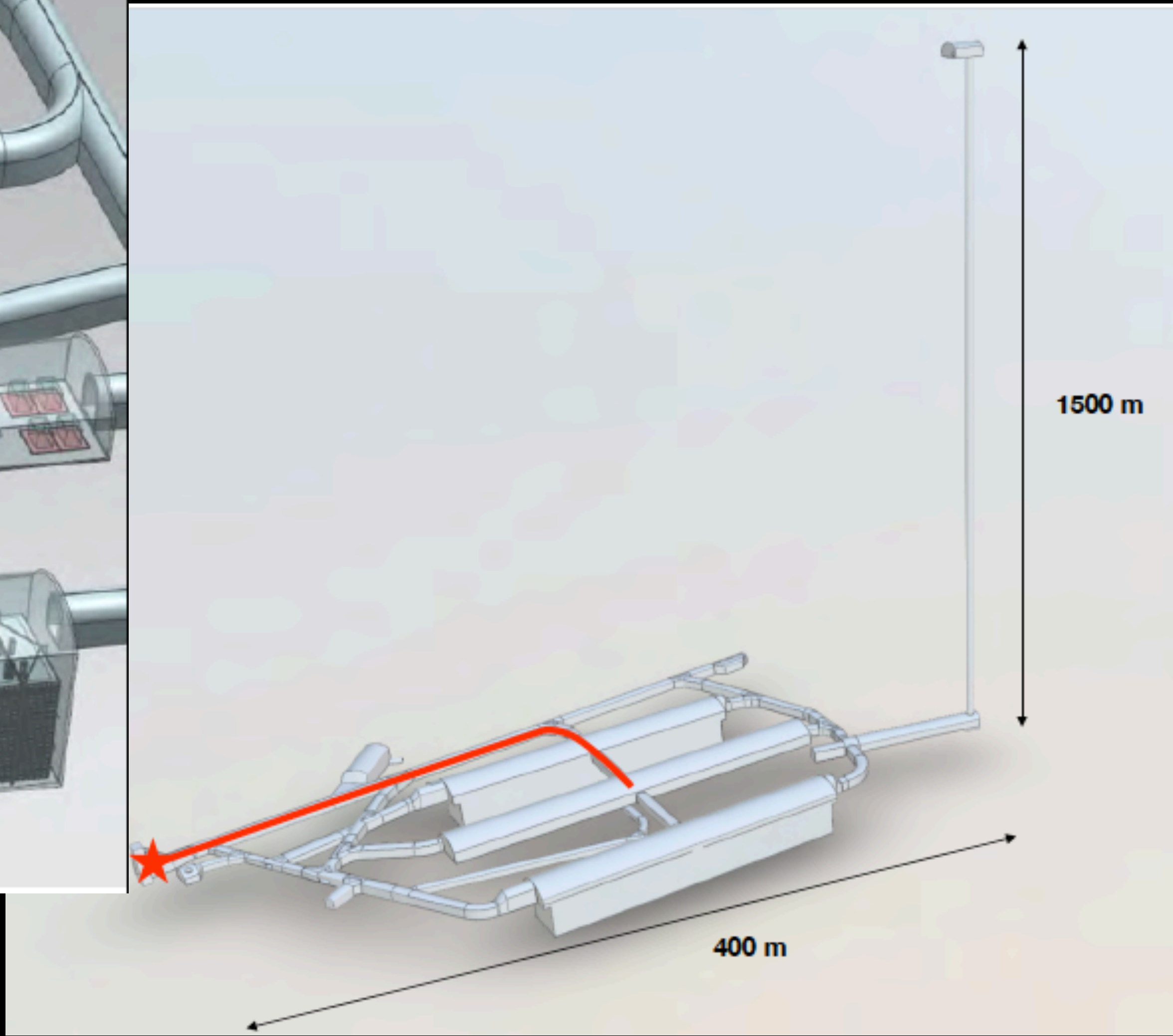
LBNF= Long Baseline Neutrino Facility

Near Detectors | **LBNF Neutrino beam-line**




1300 Km away from Fermilab
Sanford
Underground
Research
Facility
800 miles
Fermilab
PARTICLE
DETECTOR
NEUTRINO
PRODUCTION
UNDERGROUND
PARTICLE
DETECTOR
EXISTING
LABS
EXISTING PROTON
ACCELERATOR

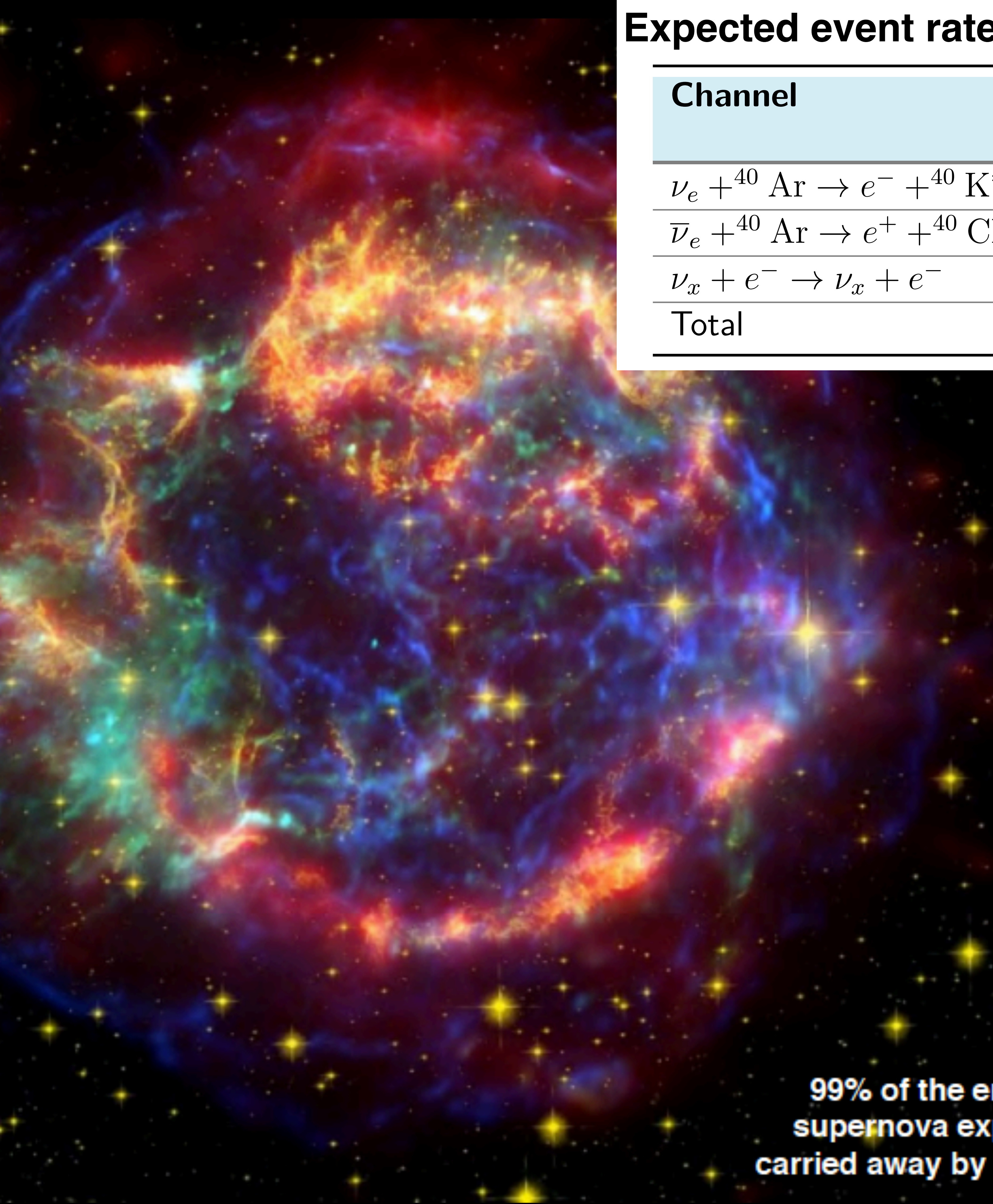

Four 10 Kton fiducial mass (17 Kton total)
Liquid Argon TPCs

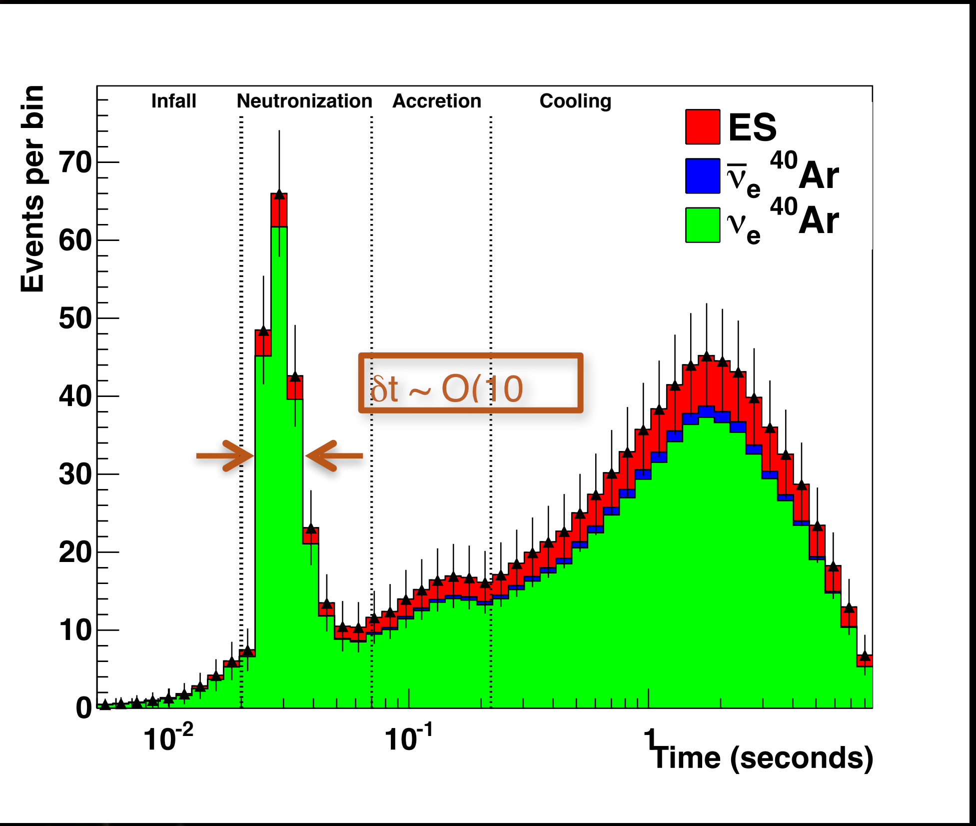

1500 m
400 m

Expected event rates (without oscillations) at 10 kpc:

Channel	Events "Livermore" model	Events "GKVM" model
$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$	2720	3350
$\overline{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$	230	160
$\nu_x + e^- \rightarrow \nu_x + e^-$	350	260
Total	3300	3770

Supernovae

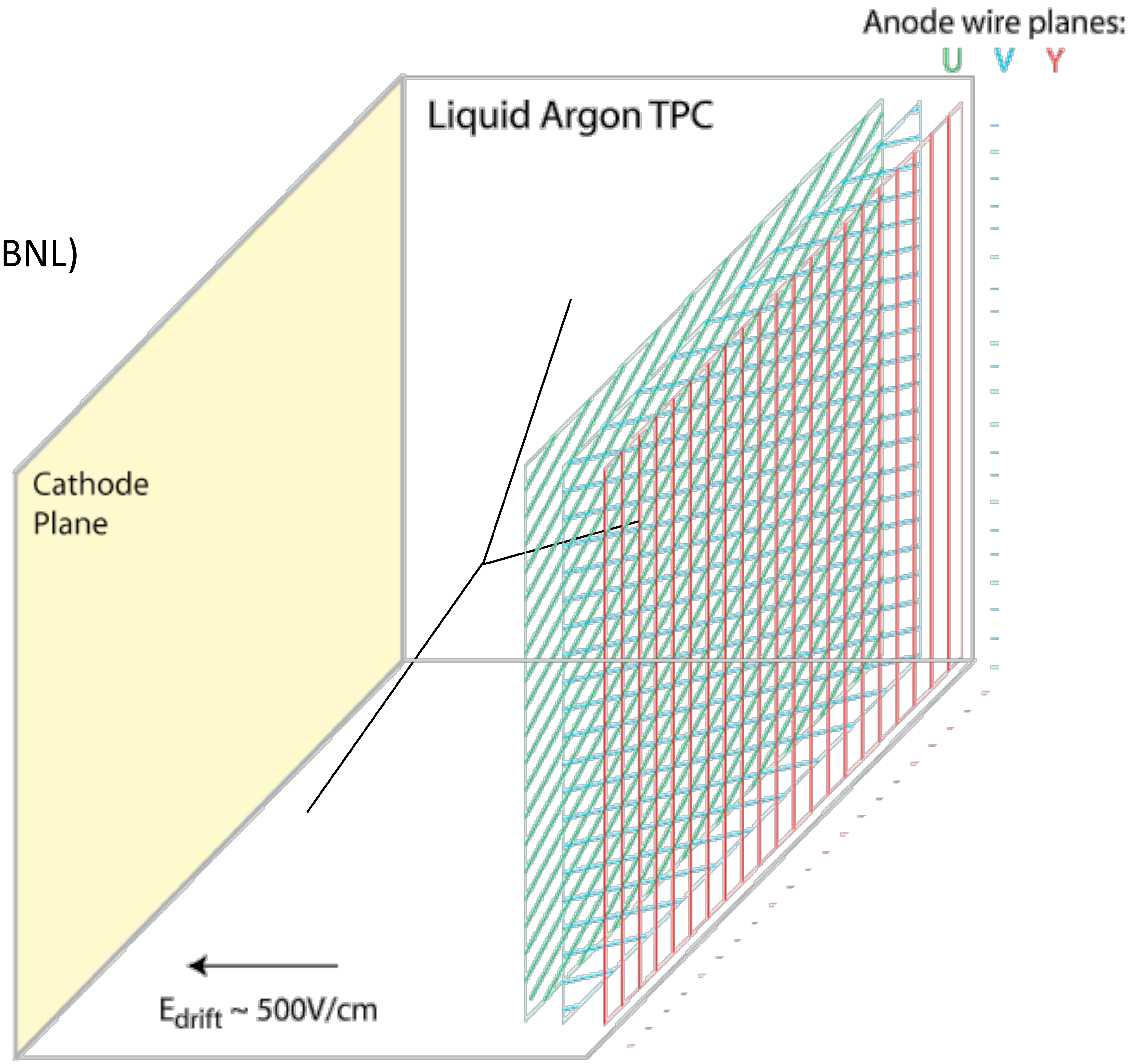




99% of the energy in a supernova explosion is carried away by neutrinos

How Does a LArTPC Work?

Bo Yu (BNL)



CERN COURIER | International high-energy physics | IOP

FEATURE

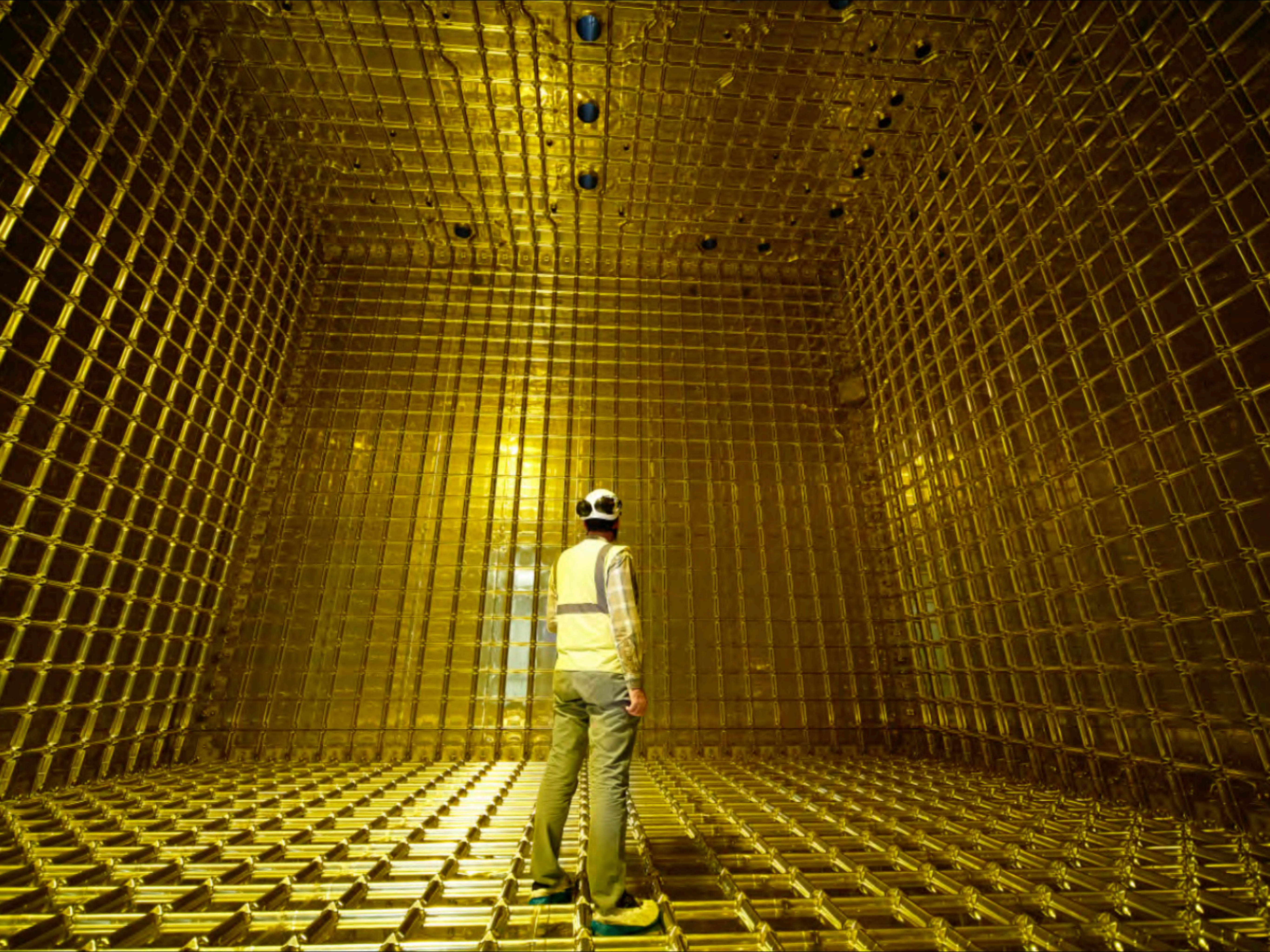
ProtoDUNE revealed

15 February 2017

CERN makes rapid progress toward prototype DUNE detectors.

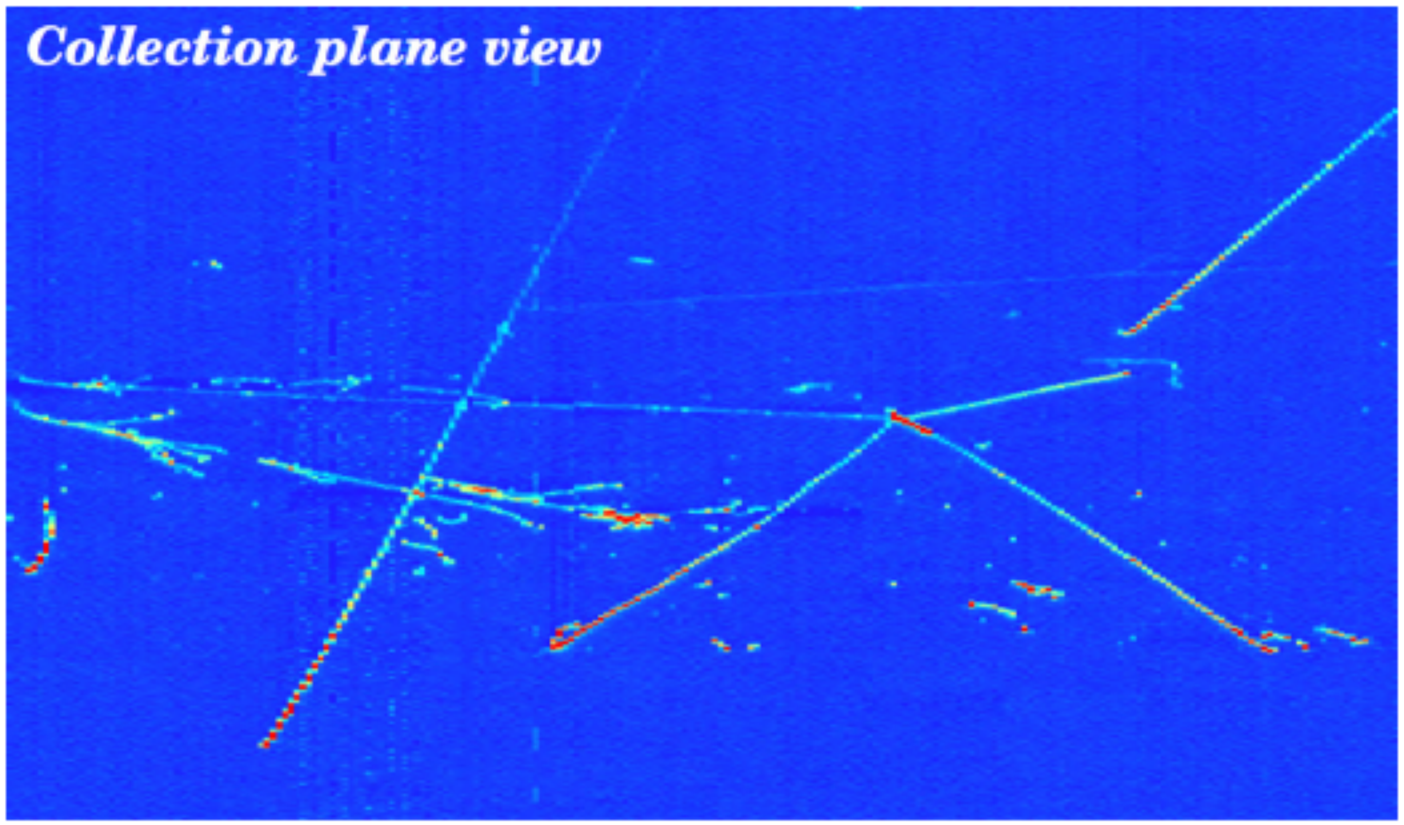
Latest Articles

Meet the Extremely Brilliant Source
Cosmic research poles apart
The tale of a billion-trillion protons
Viewpoint: Fixing gender in theory
The deepest clean lab in the world
Doubly-strange baryon observed in Japan
Inside Story: On the Courier's new future



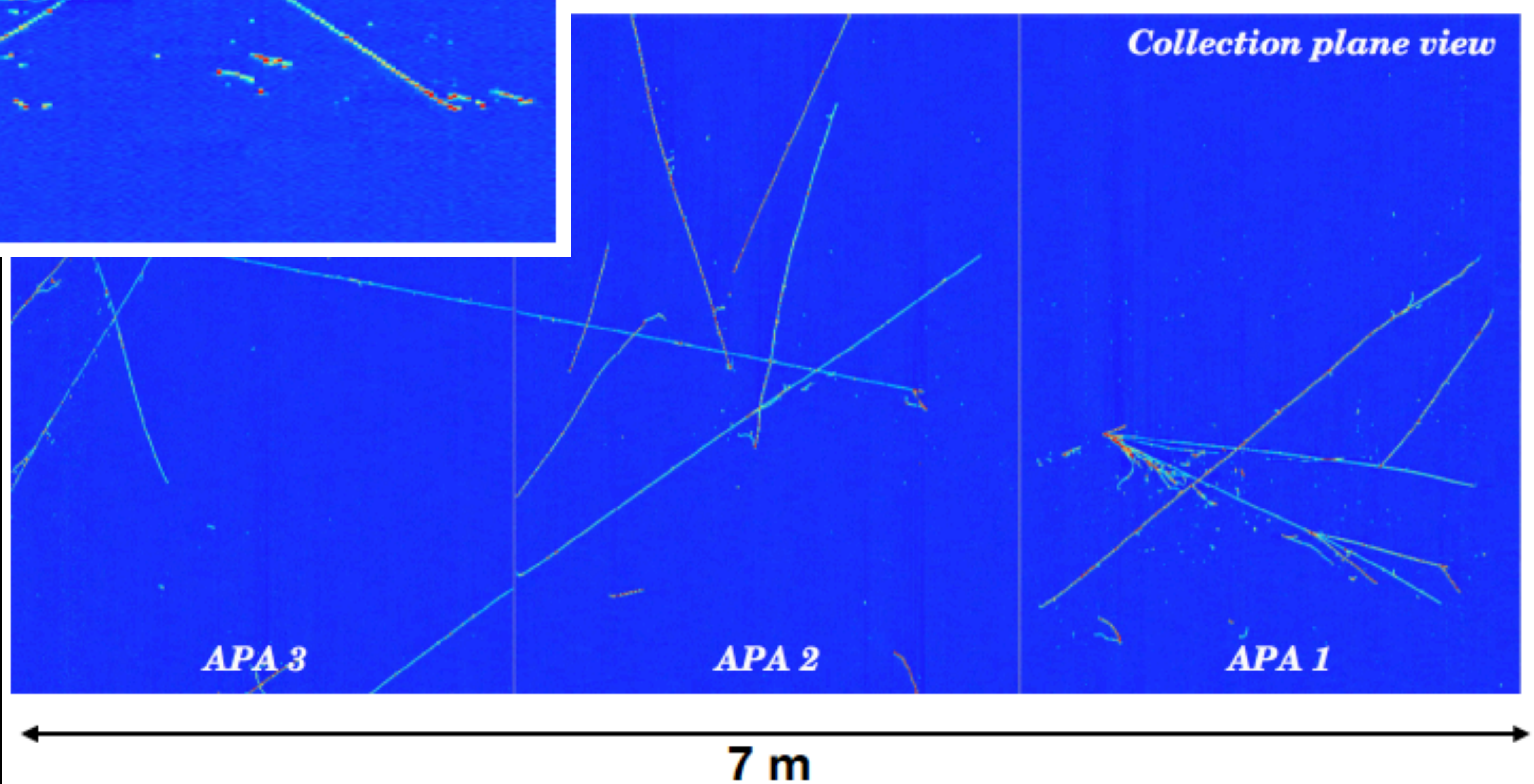
protoDUNE data !

2 EM showers and a pion
interaction with 4 outcoming particles



pion and proton beam
events mixed with cosmics

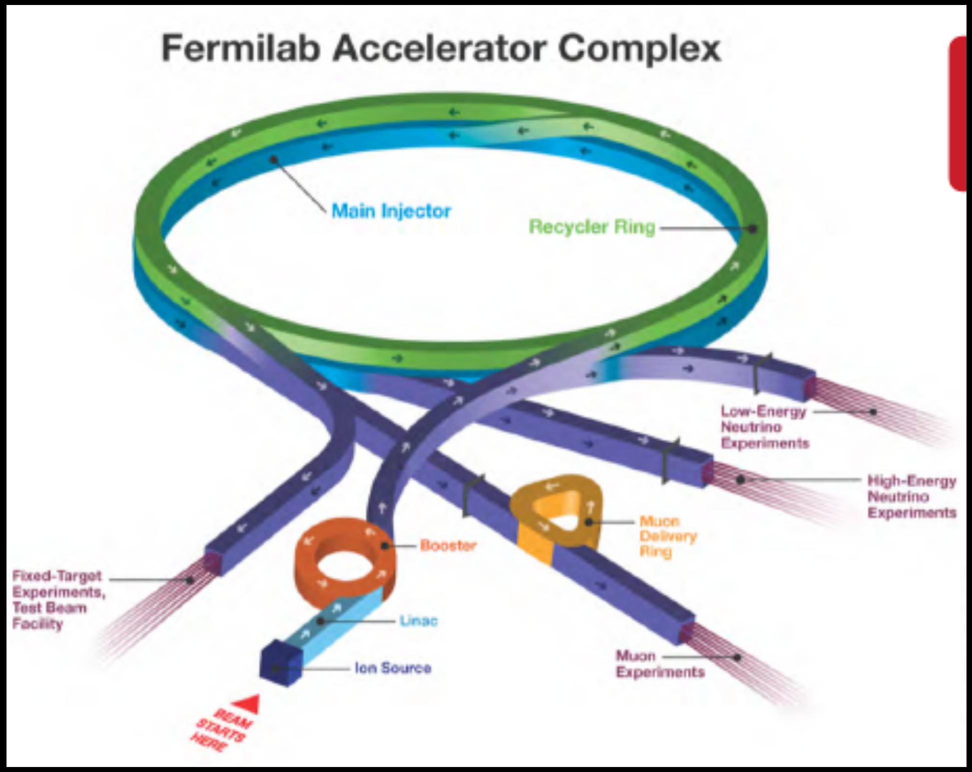
7 GeV beam proton

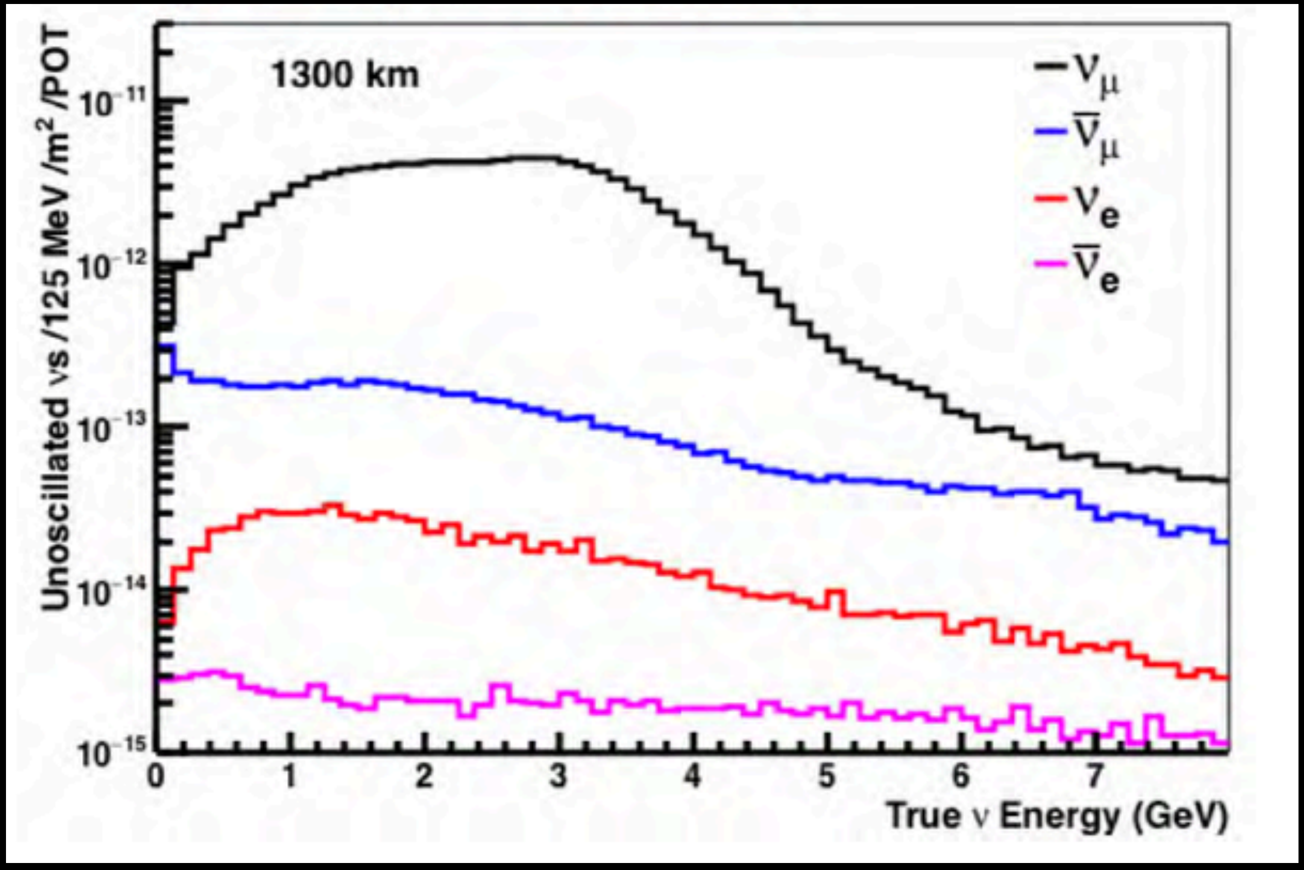


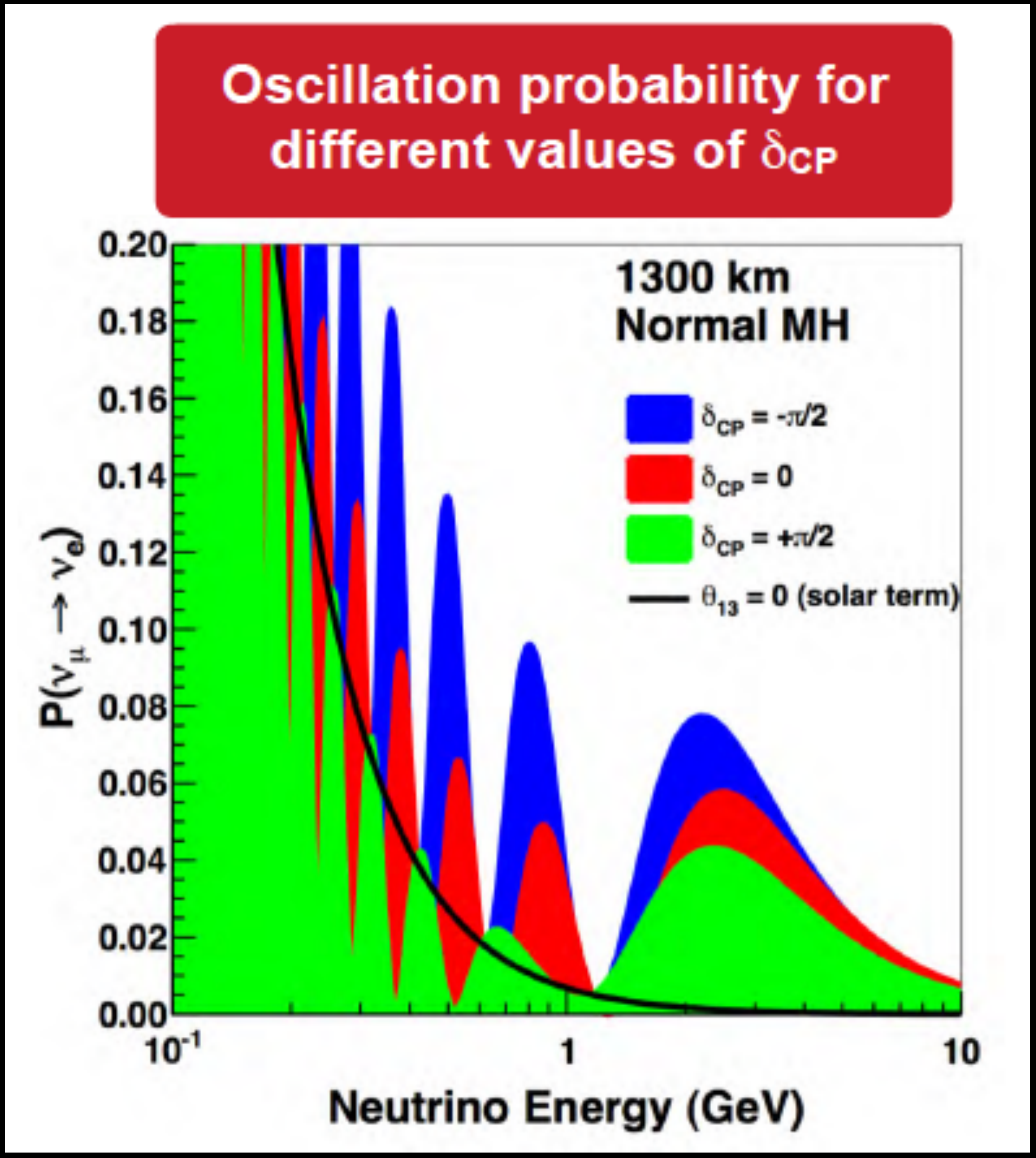
Outlook

- 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

Neutrino beam / oscillations







Yellow light becomes green