“Astroparticle Physics Review”

DIS 2016, DESY Hamburg

Johannes Knapp

Astro-Particles

energetic (elementary) **particles**
from space (Sun, Milky Way, distant galaxies)
bombard Earth continuously.

Energies from MeV .... >10^{20} eV

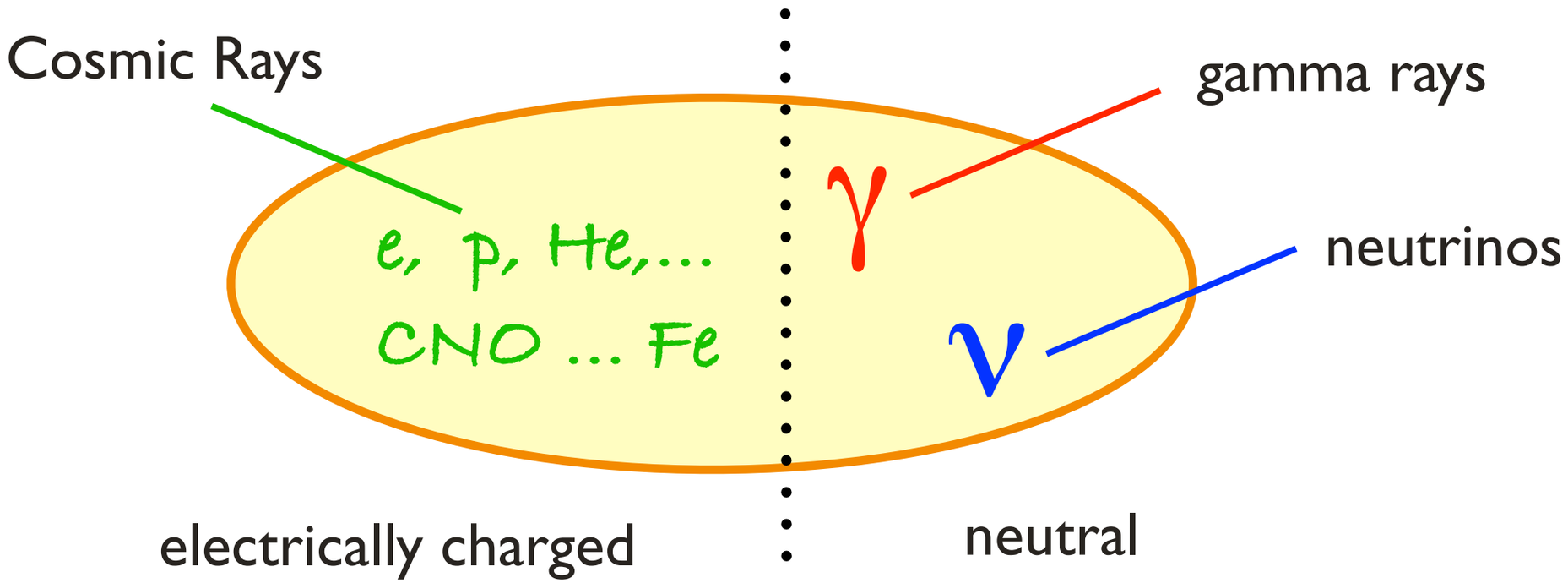
most relativistic particles in the Universe

Astrophysics with photons and particles.

Particle physics with probes of astrophysical origin.

What are these cosmic particles?

must be stable (to survive travel to us)



+ can be accelerated in el.mag. fields
– are deflected in magnetic fields

+ **move in straight lines**
– secondaries

Energy scale:

radio

IR visible light UV

X rays

γ rays

the range of astroparticle physics

meV ... eV ... keV ... MeV ... GeV ... TeV ... PeV ... EeV ... ZeV

10^{-3} ... 1 ... 10^{3} ... 10^{6} ... 10^{9} ... 10^{12} ... 10^{15} ... 10^{18} ... 10^{21} eV

non-thermal processes

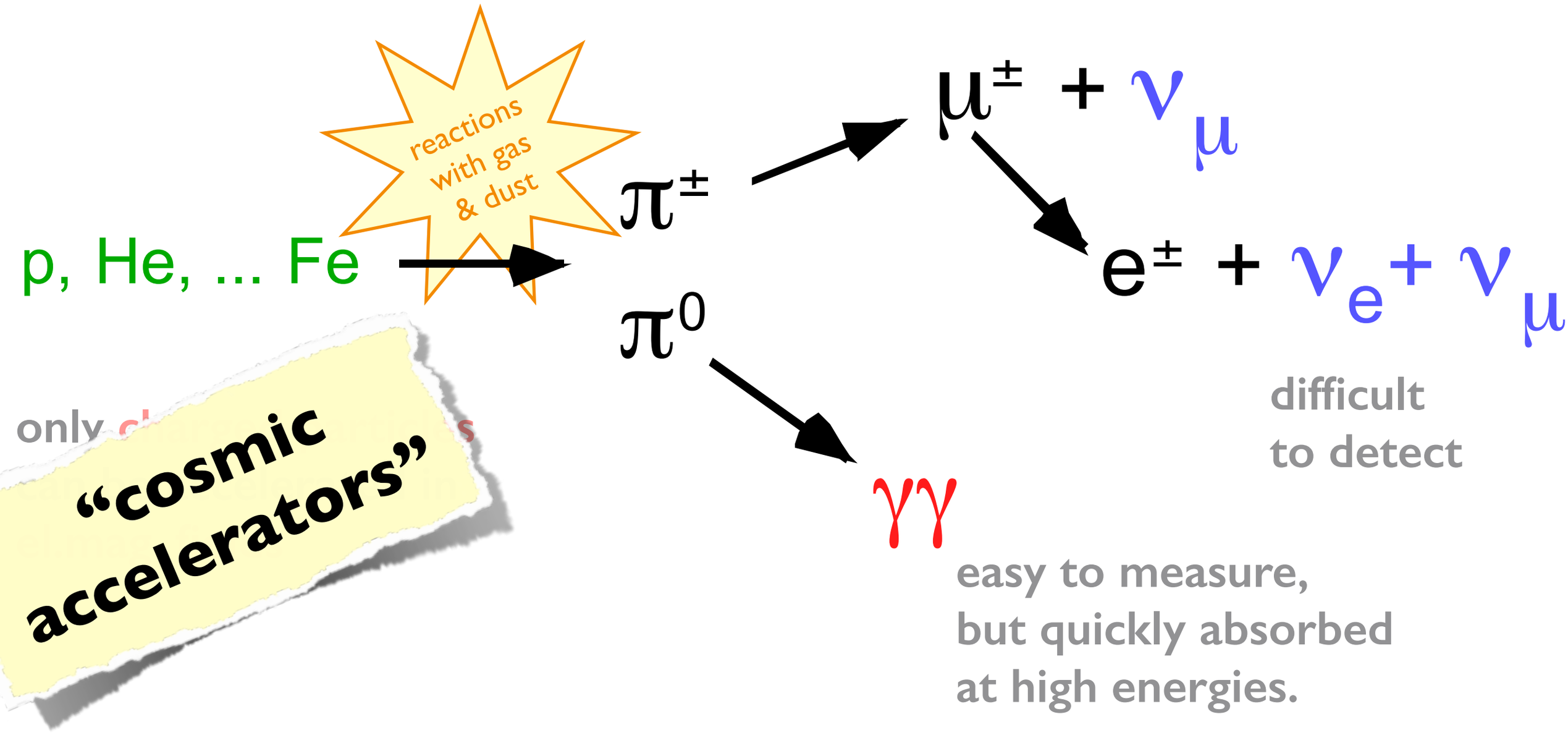
Photons: astronomy

charged: p, He, ... Fe, ... completely ionised nuclei

electrons

Neutrinos:

Cosmic rays, gamma rays und neutrinos are closely connected:



γ and ν travel in straight lines, i.e. point back to sources.

Charged particles are deflected in cosmic magnetic fields.

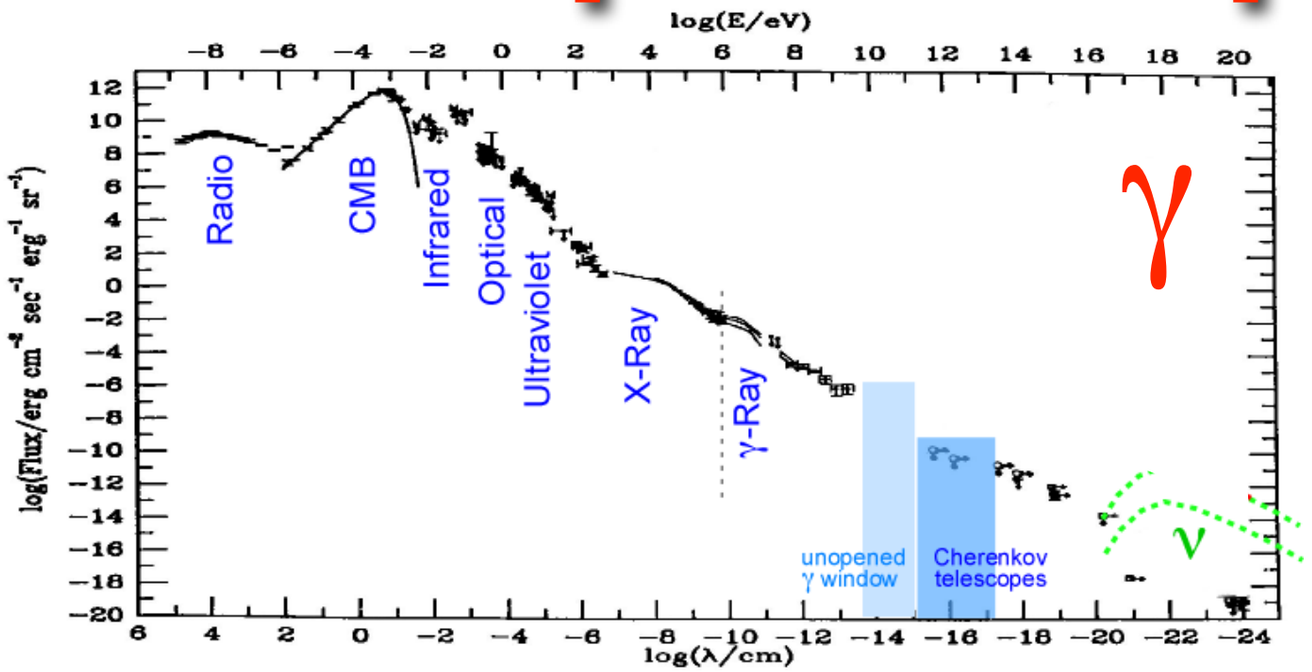
Cosmic accelerators

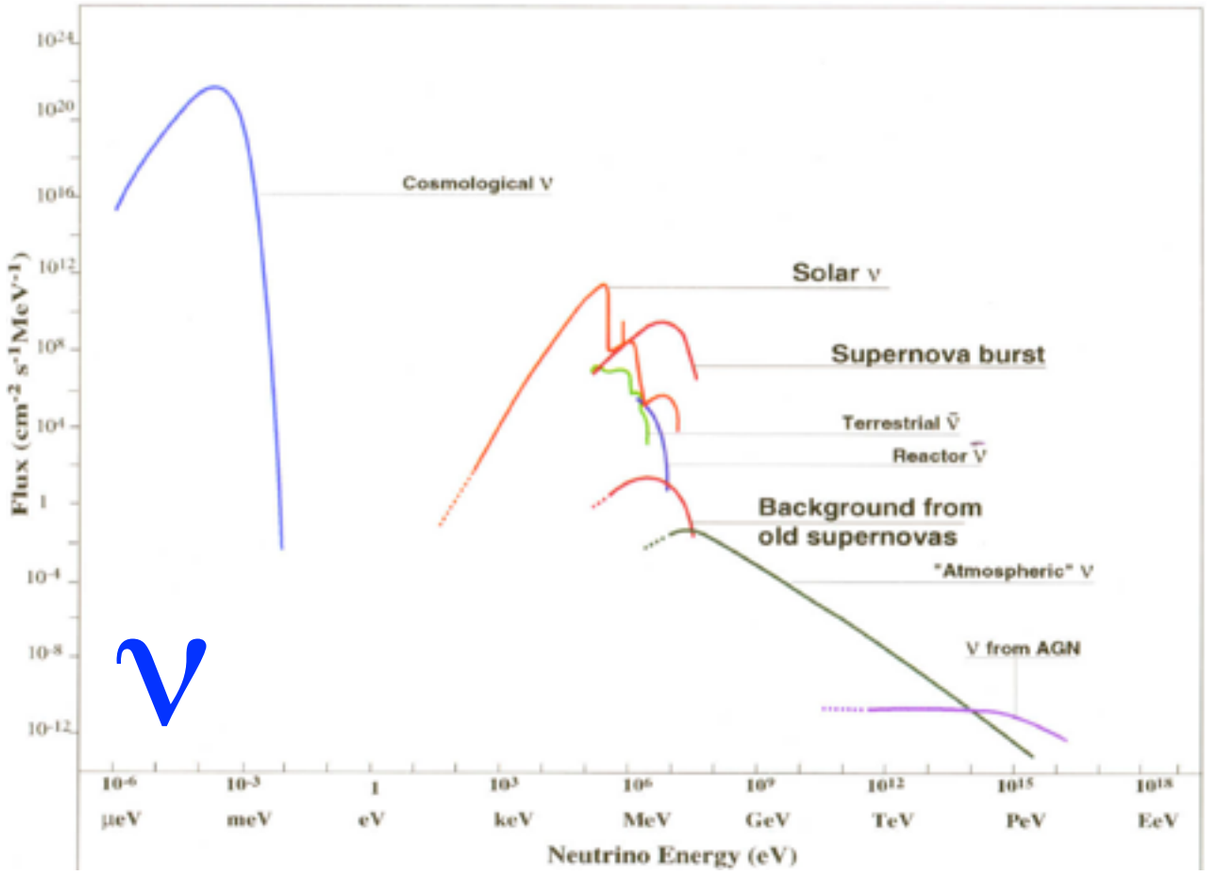
The highest-energy particles come from the most violent environments (physics in extreme conditions)

The highest-energy CRs, γ and ν come likely from the same sources.

"multi-messenger" approach

Cosmic particle spectra



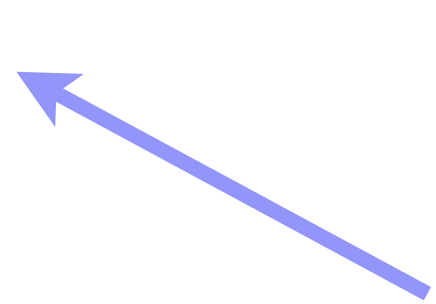


steeply falling spectra,
low fluxes at high energies

require huge detectors

Large, natural volumes become part of the detectors:

atmosphere,
ice shields,
oceans,
...



instrument (sparsely)
to record secondaries
produced by
particle interactions

understand / monitor
the “target”

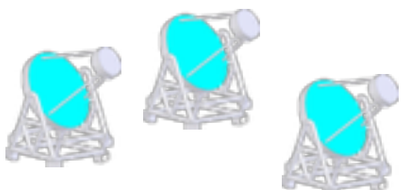
primary particle: E, type, θ, φ

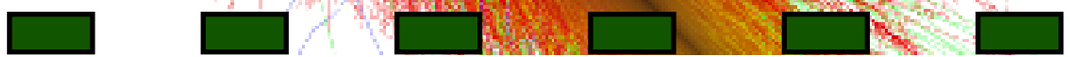
indirect measurement:
extensive showers

(in air, ice, water, …)

measure the shower
to identify the primary

Energy:	shower size
Direction:	timing
Type:	shower shape & particle contents





CRs: each CR makes an air shower, easy to detect

(difficult to identify the primary)

γ : each γ makes an air shower, easy to detect

(but 100 -10000 x more CRs, separate them from γ)

ν: only very few ν interact in/near detector,

high-energy e, μ, τ make showers in ice

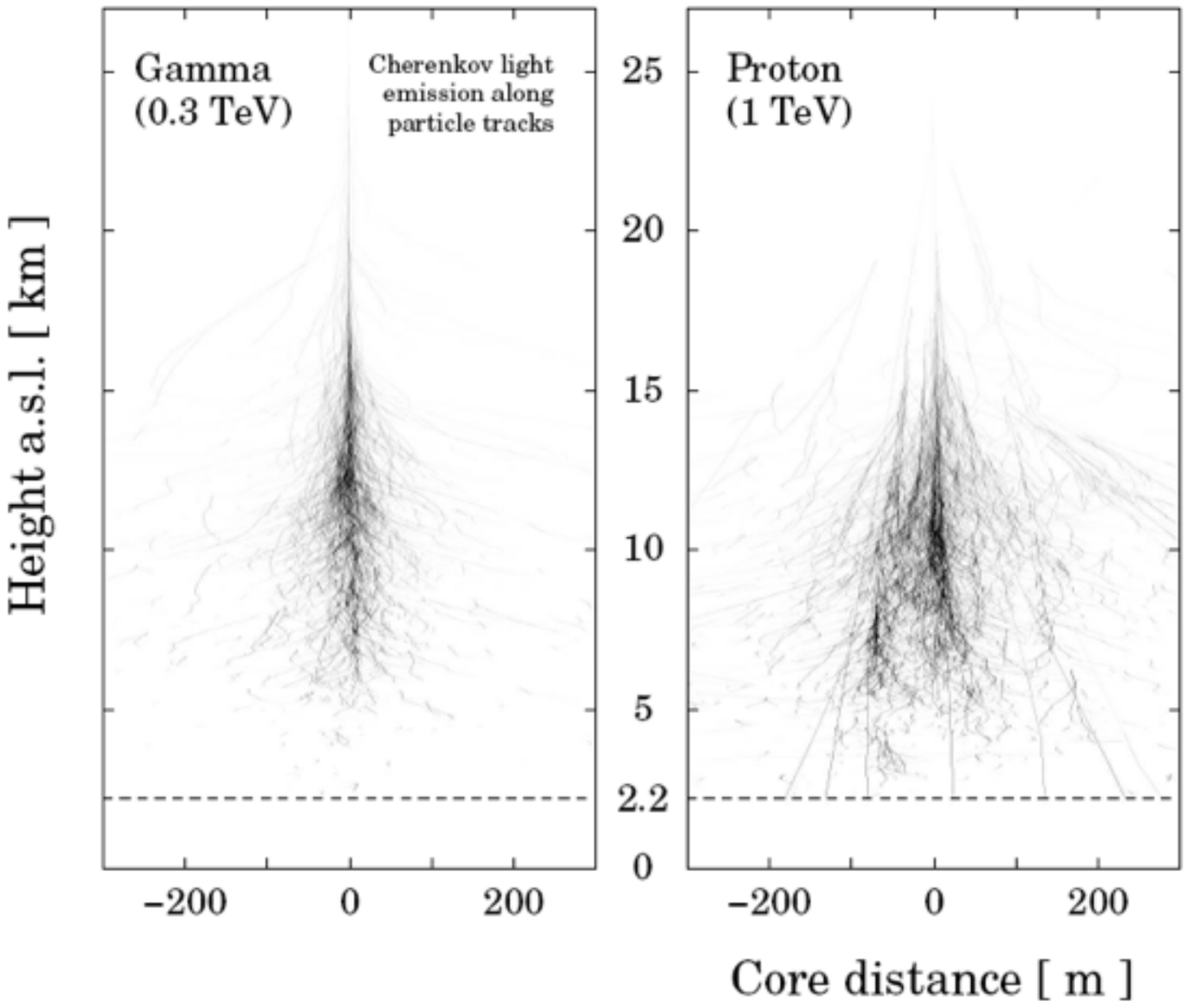
(but many atmospheric neutrinos from CR interactions)

serious backgrounds

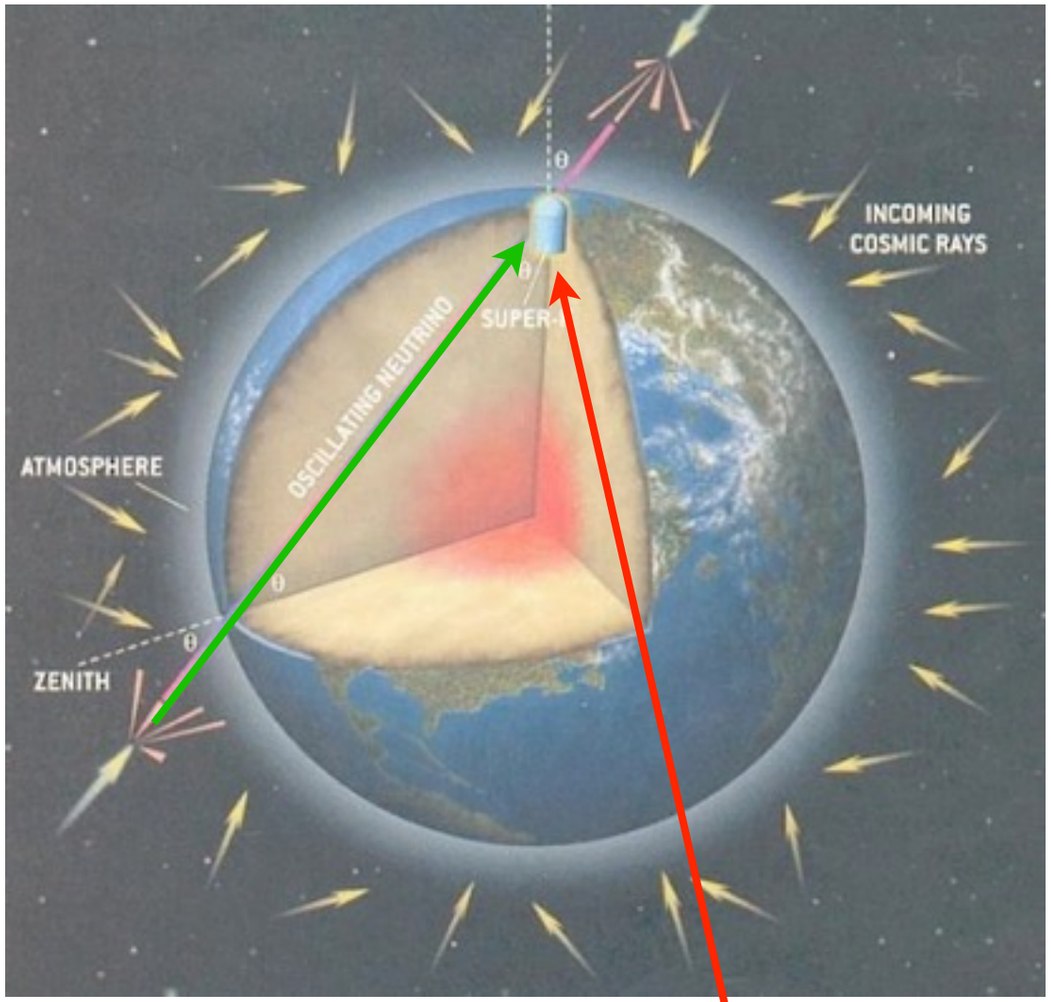
Backgrounds

gamma rays
(pointing back at source)

nuclei
(diffuse)



10000x more



atmospheric ν

astrophysical ν

(dominant at high energies)

Hadronic Interactions ...

hadrons,
muons,
e^+, e^-, γ

from MeV … 10^{20} eV
very forward directions (~0°)

diffractive / non diffractive / nuclear

heavy quark production and decay

fragmentation, p_T, baryons, heavy quarks…

for all particles (primary & secondaries)

needed to connect observables to primary particle.

CORSIKA:

A Monte Carlo Code to Simulate Extensive Air Showers
Forschungszentrum Karlsruhe Report **FZKA 6019 (1998)**
with interaction models: QGSJET, EPOS, FLUKA, …

"Particle physics with astroparticles"

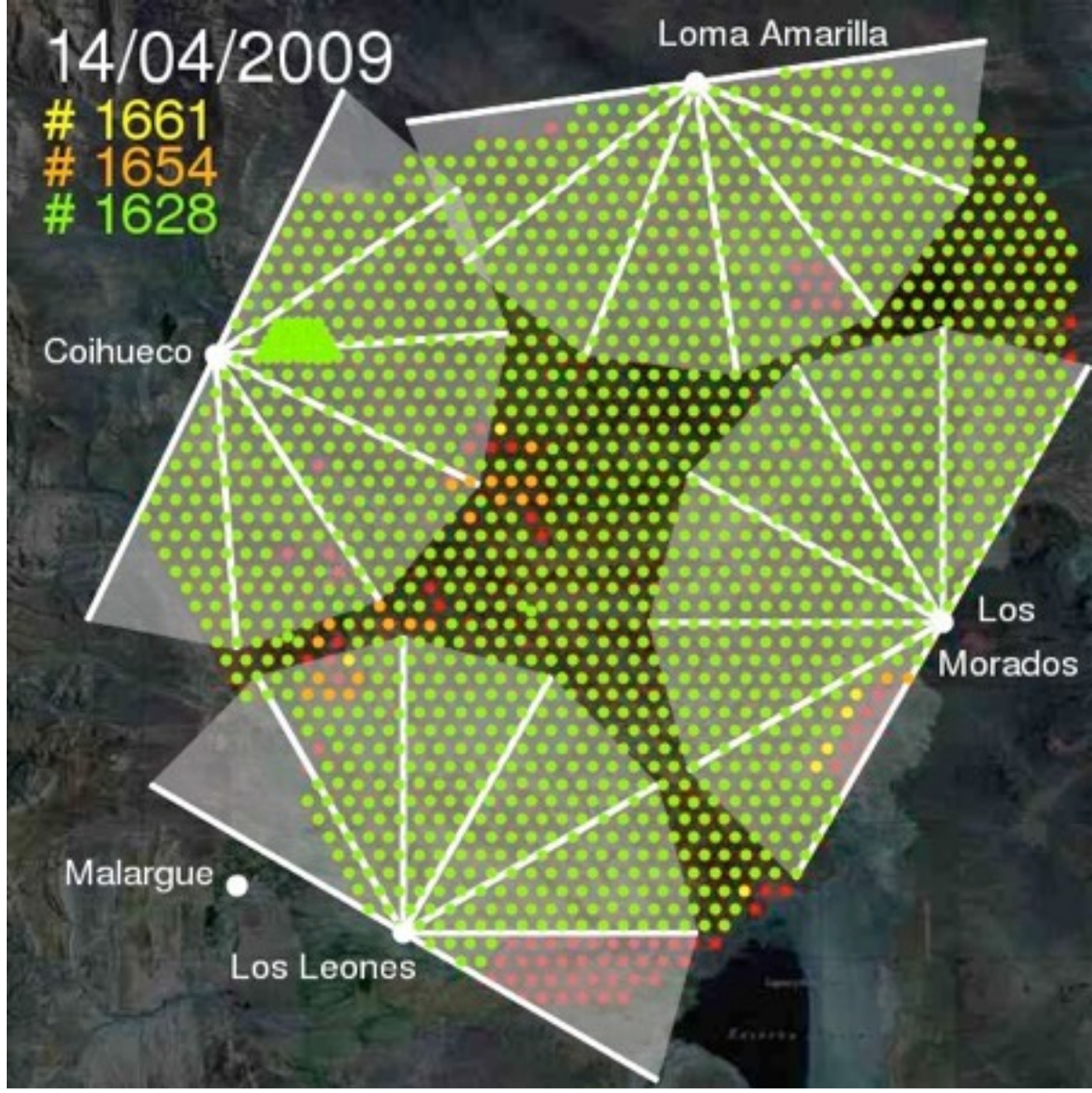
Cosmic Rays

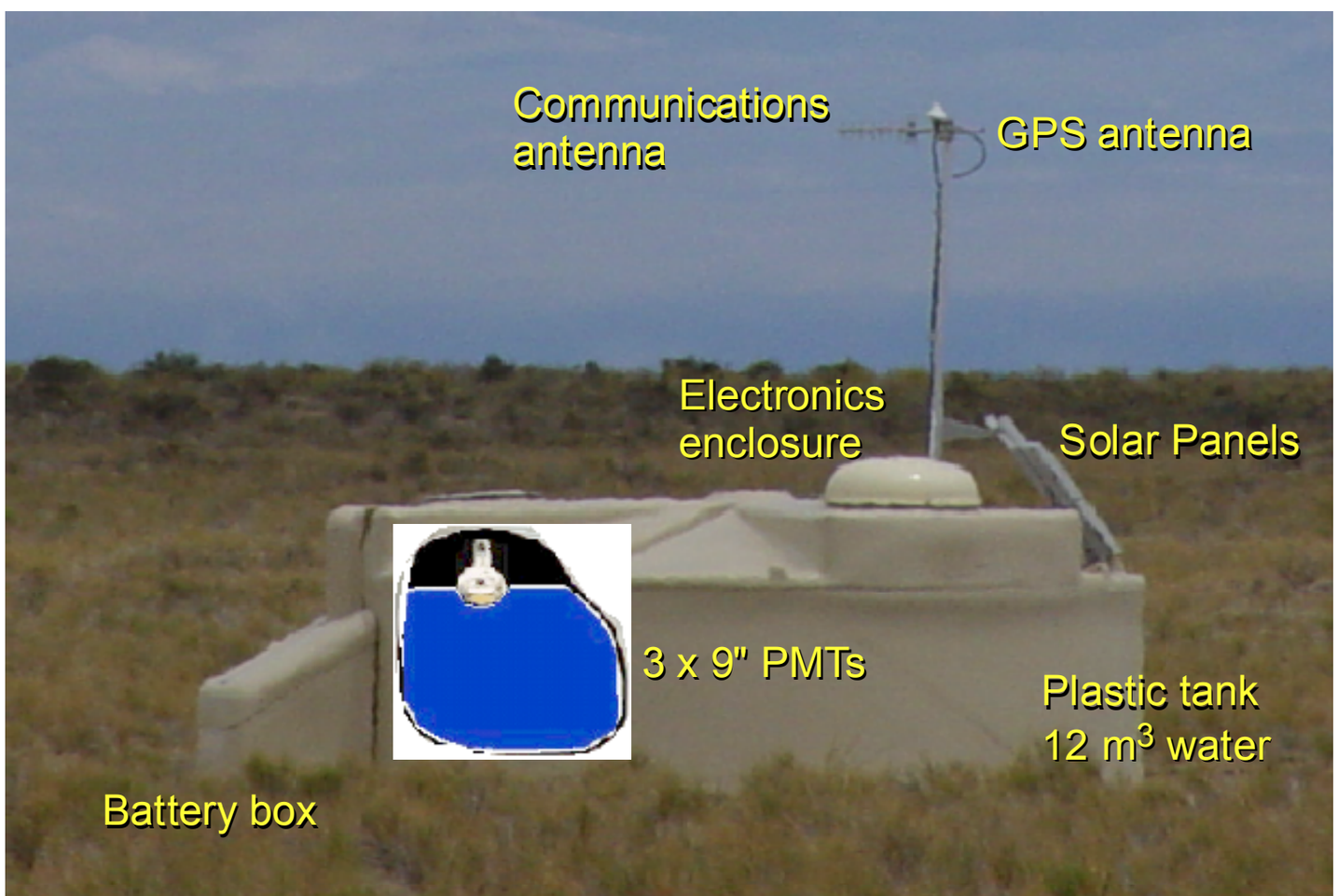
Pierre Auger Observatory
Argentina: 3000 km^2

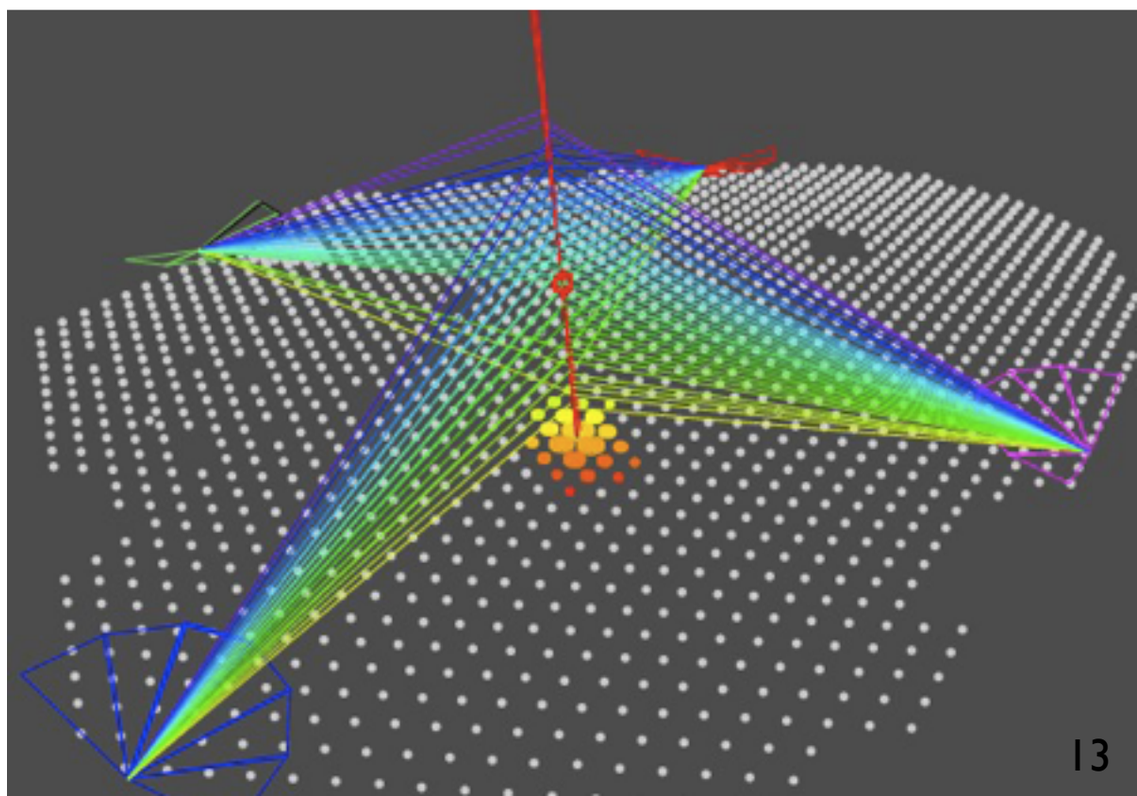
1600 particle detectors +

27 fluorescence telescopes

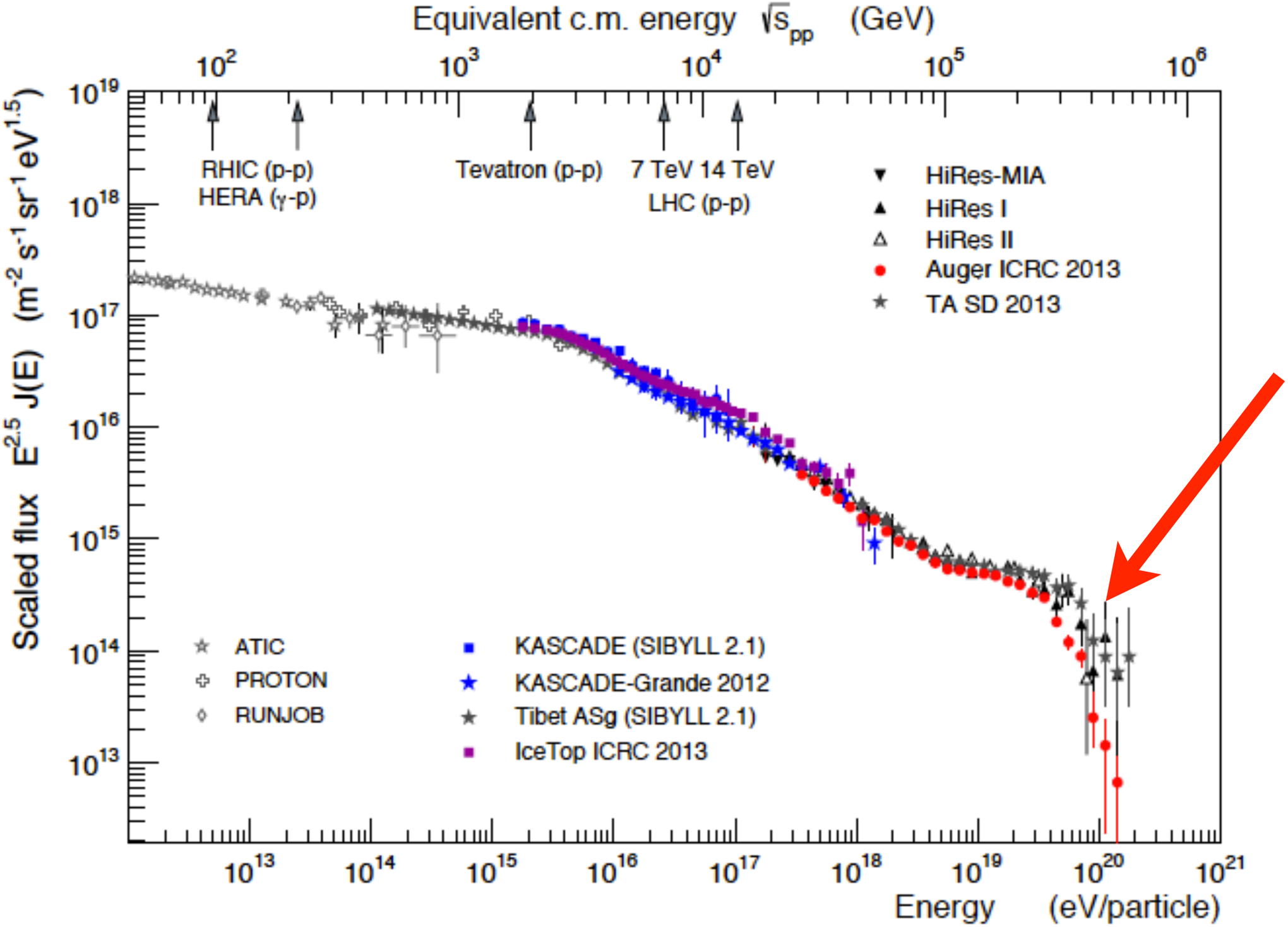
Ultra High Energy cosmic particles
($E > 10^{18}$ eV)







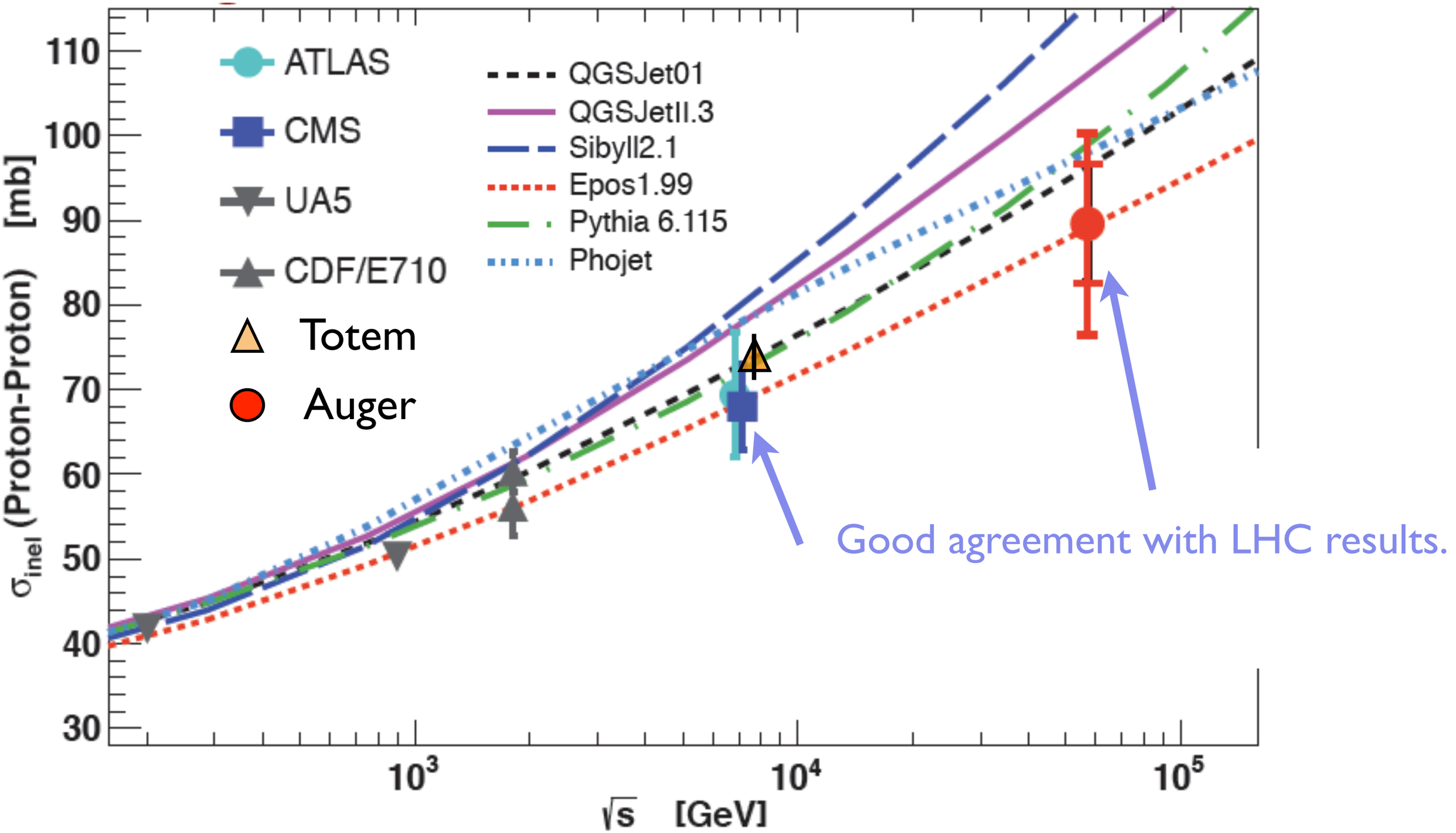
The spectrum cuts off ...



isotropic arrival, sources ??

composition nuclear, but variable. upper limits on neutrino, gammas

p-p cross-section



$\sigma(p\text{-}p) = 90 \pm 7 \pm 10$ mb (@ $E_{cm} \approx 57$ TeV)

Astroparticle Physics Zeuthen

https://astro.desy.de

γ ray astrophysics

HESS, VERITAS, MAGIC, Fermi, CTA

ν astrophysics

IceCube, Pingu, Gen2

+ astroparticle physics theory

γ rays

large angle telescope

Fermi - LAT

pair-conversion telescope with:

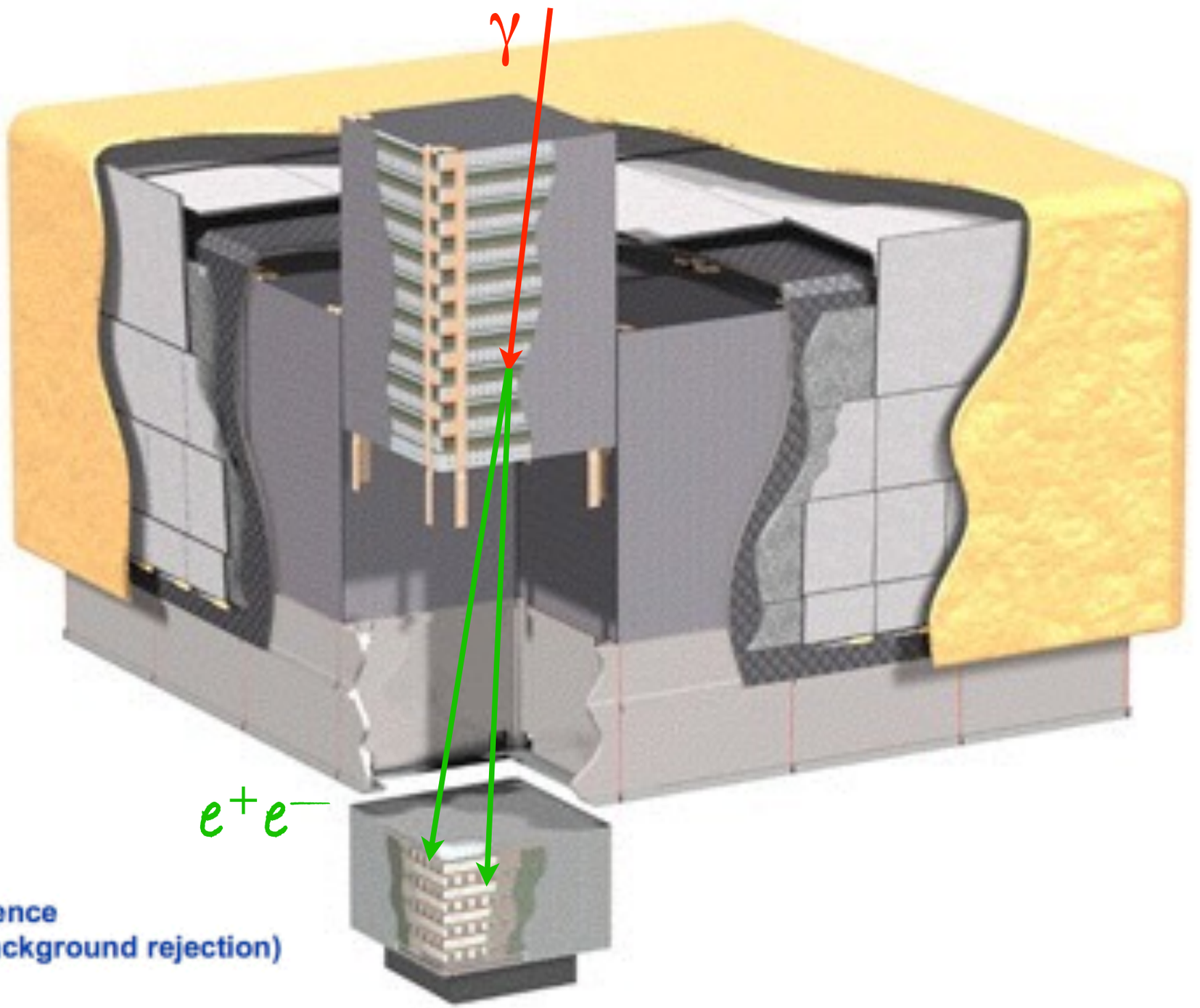
precision trackers

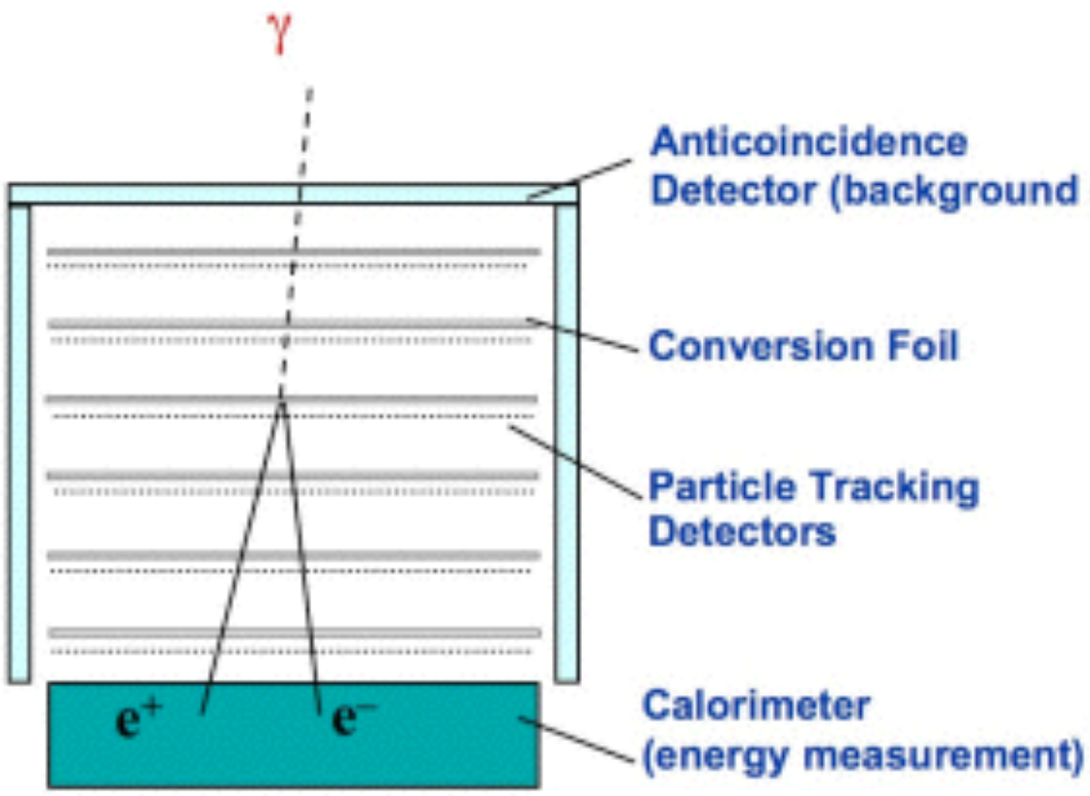
18 layers tungsten converters and x, y silicon strip detectors.

calorimeter

96 CsI(Tl) crystals in an 8 layer hodoscope (depth: 8.6 X_0)

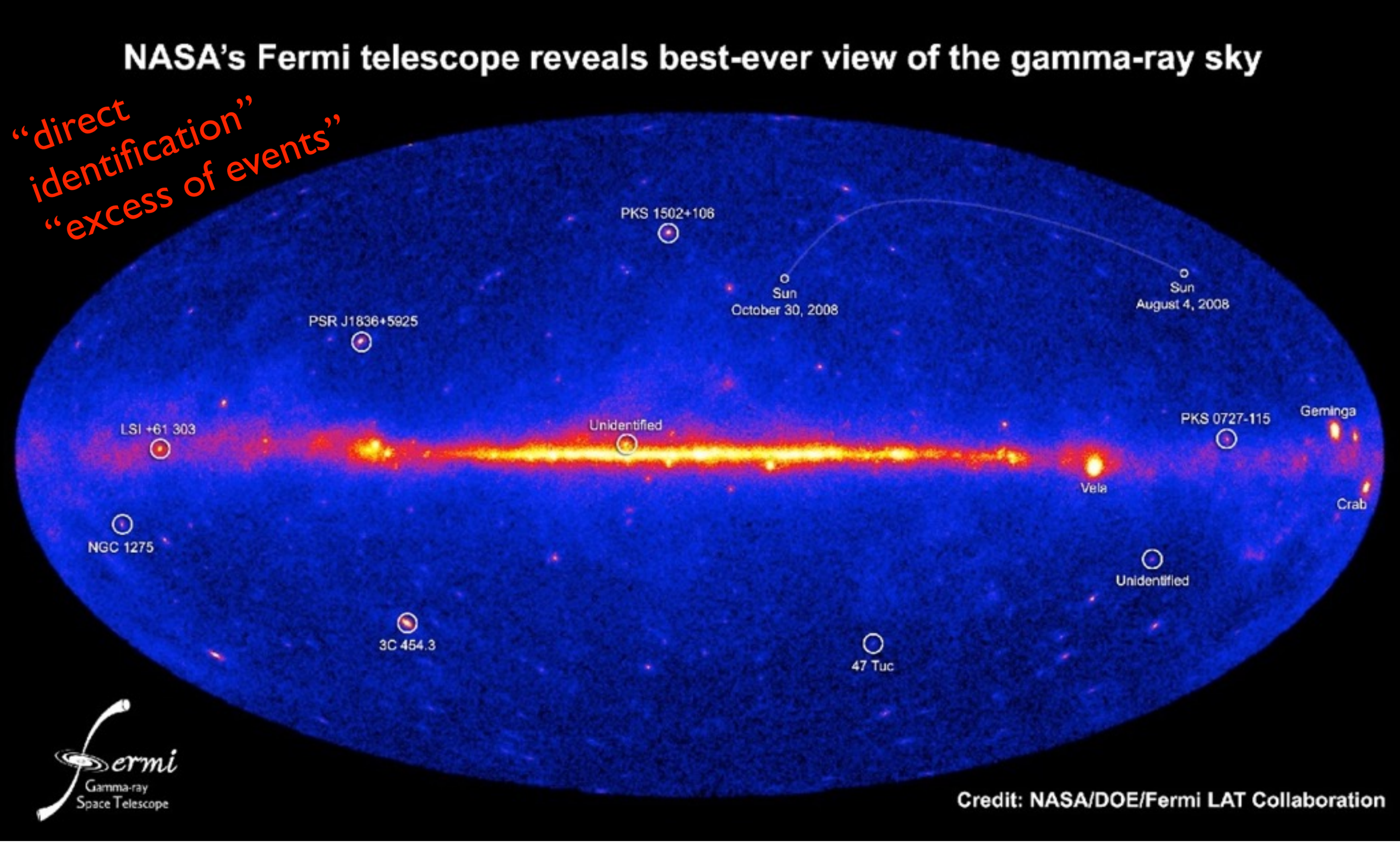
4x4 modules covered by anti-coincidence shield





≈ 1 m² 2.5 sr

near-perfect rejection of charged primaries



Satellite experiment: 100 MeV - 100 GeV
point sources, extended sources and diffuse emission, ...

Cherenkov Telescopes

most sensitive instruments for gamma ray astronomy.

30 GeV .... 300 TeV

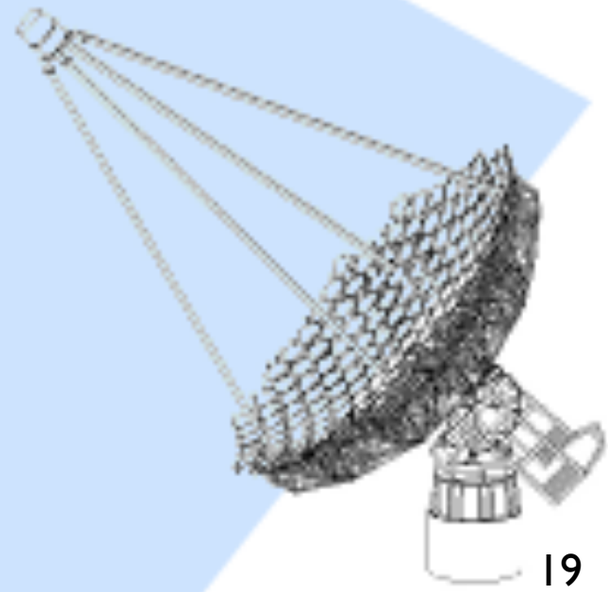
air shower

only in dark nights
(10% duty cycle)
require good knowledge of atmosphere

Fast charged particles in shower produce Cherenkov light.
(forward emission)

"Photograph" shower with an imaging telescope.

Reconstruct identity (γ, p, ...) and energy of primary and direction to source.



Cherenkov light

Detection principle

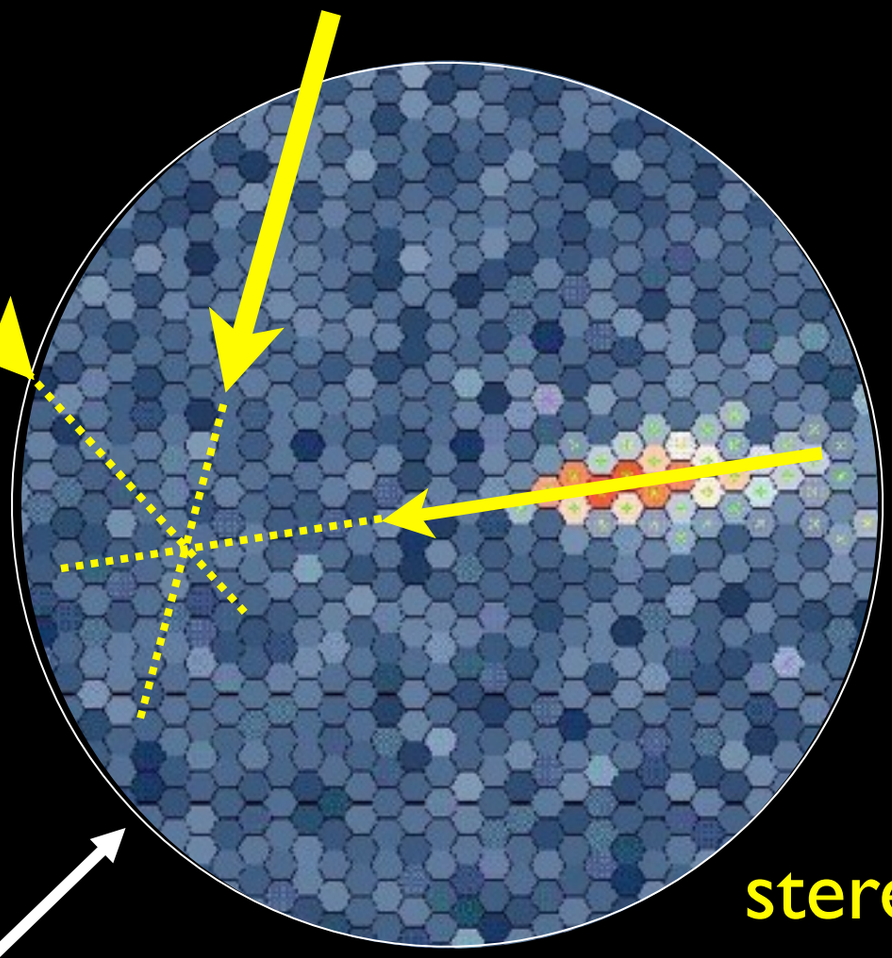
Photon

≈ 1 m²

particle shower

~ 10 km

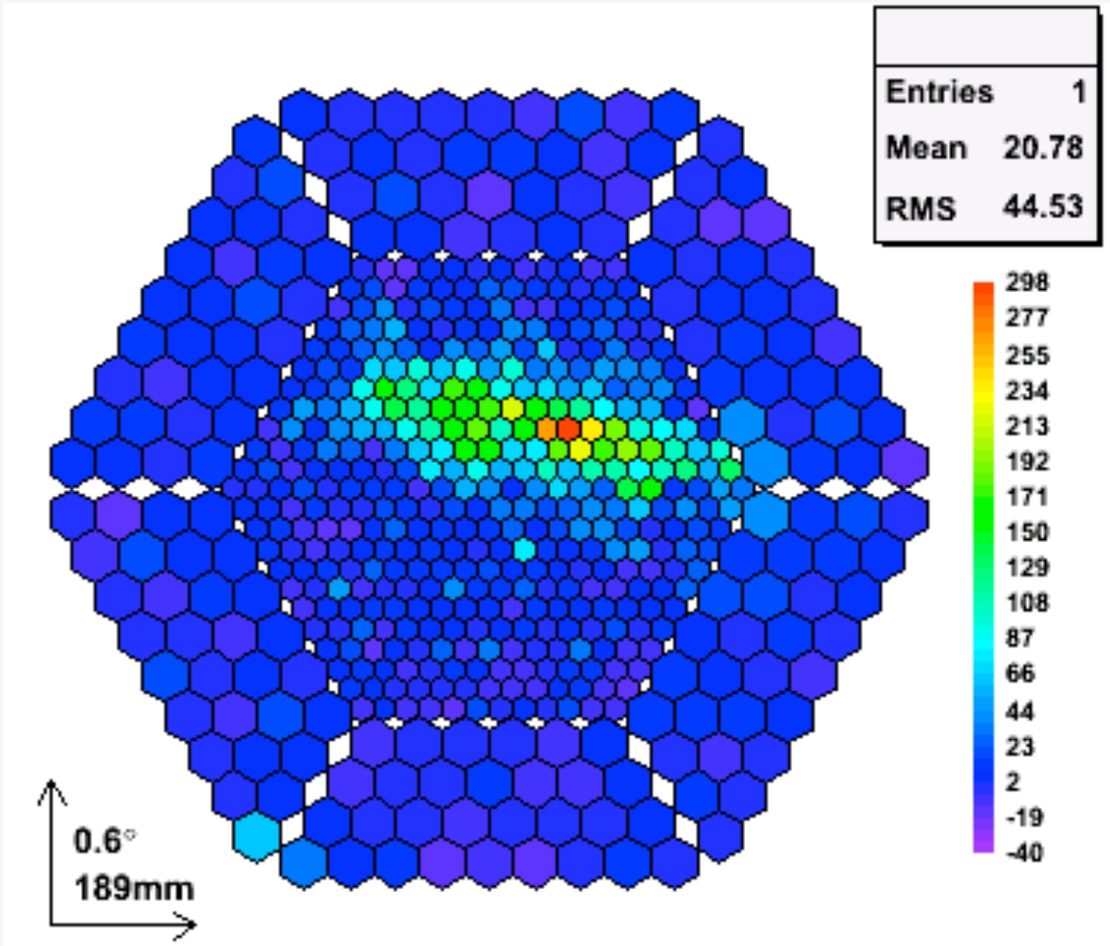
Cherenkov light



stereo

large effective detector area ≈ 10^5 m²

Shower images in a PMT camera



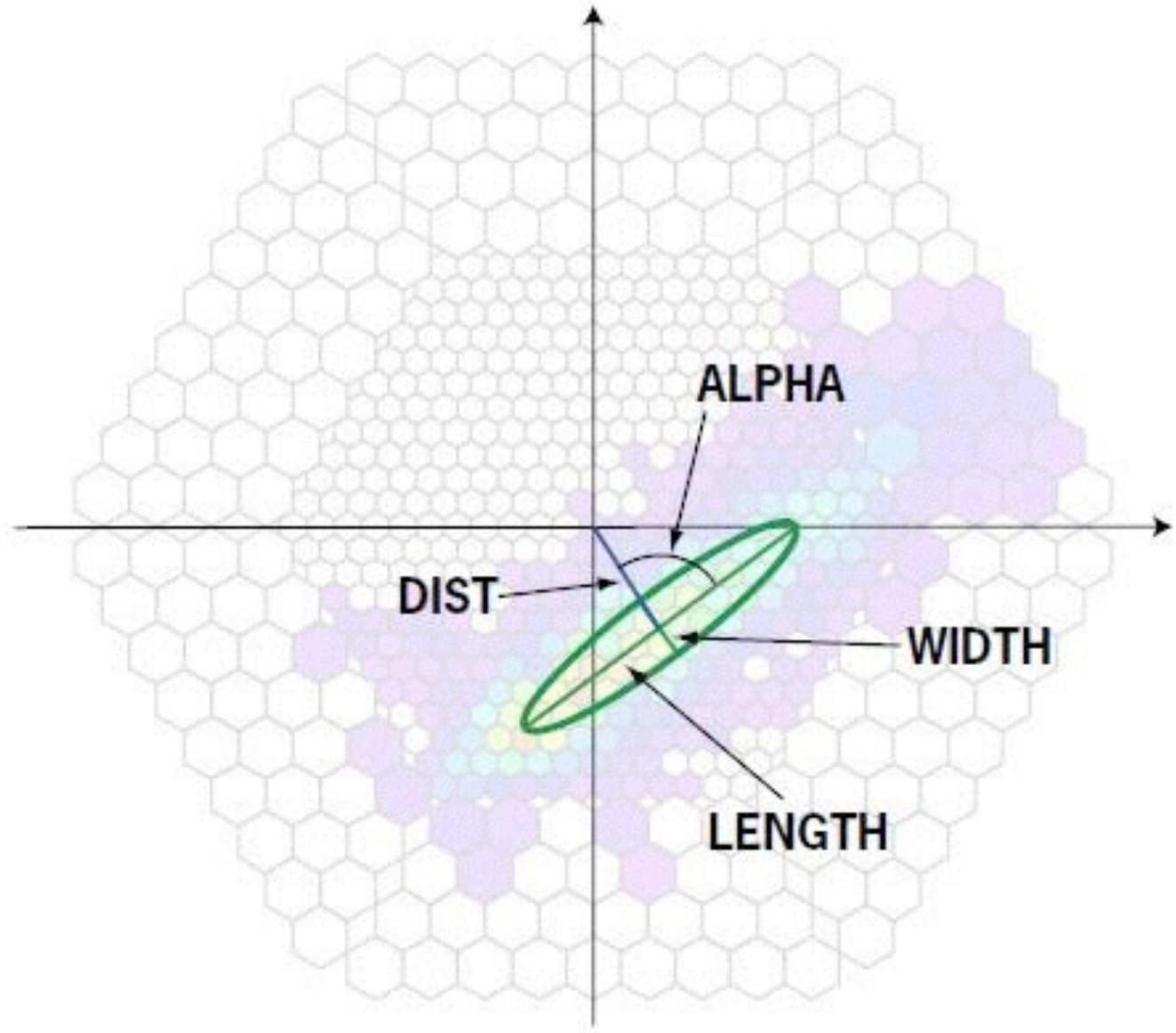


image analysis:
form and orientation

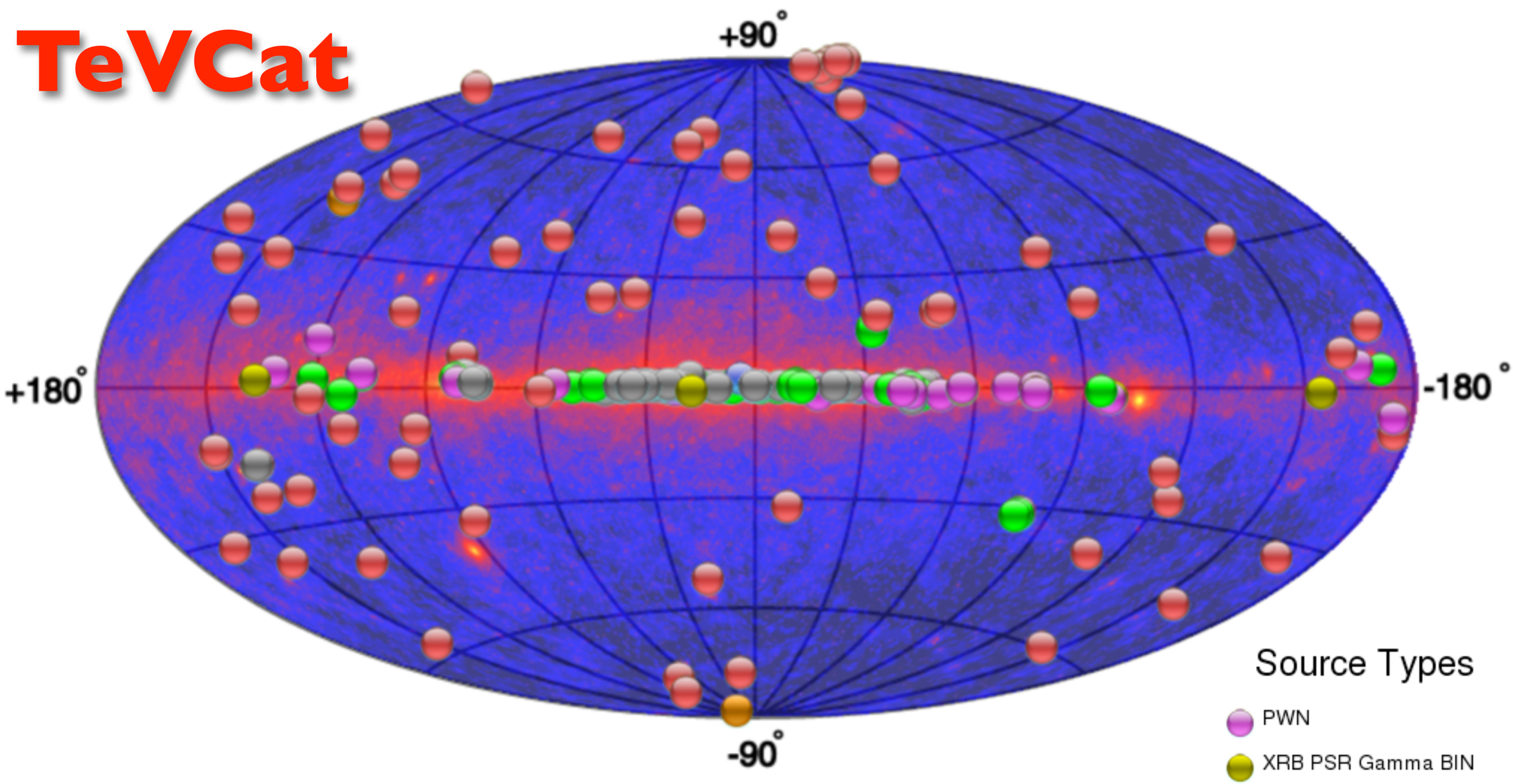
VERITAS

MAGIC

HESS

Current imaging Cherenkov Telescopes

TeVCat



Source Types

- PWN
- XRB PSR Gamma BIN
- HBL IBL FRI FSRQ LBL AGN (unknown type)
- Shell SNR/Molec. Cloud
- Starburst
- DARK UNID Other
- uQuasar Star Forming Region Globular Cluster Cat. Var. Massive Star Cluster BIN BL Lac (class unclear) WR

background image:
Fermi sky map (MeV-GeV)

now: >170 sources (> 100 GeV)
gal. / extragal. / unid.

gamma ray emission is present
wherever there are shocks and relativistic flows

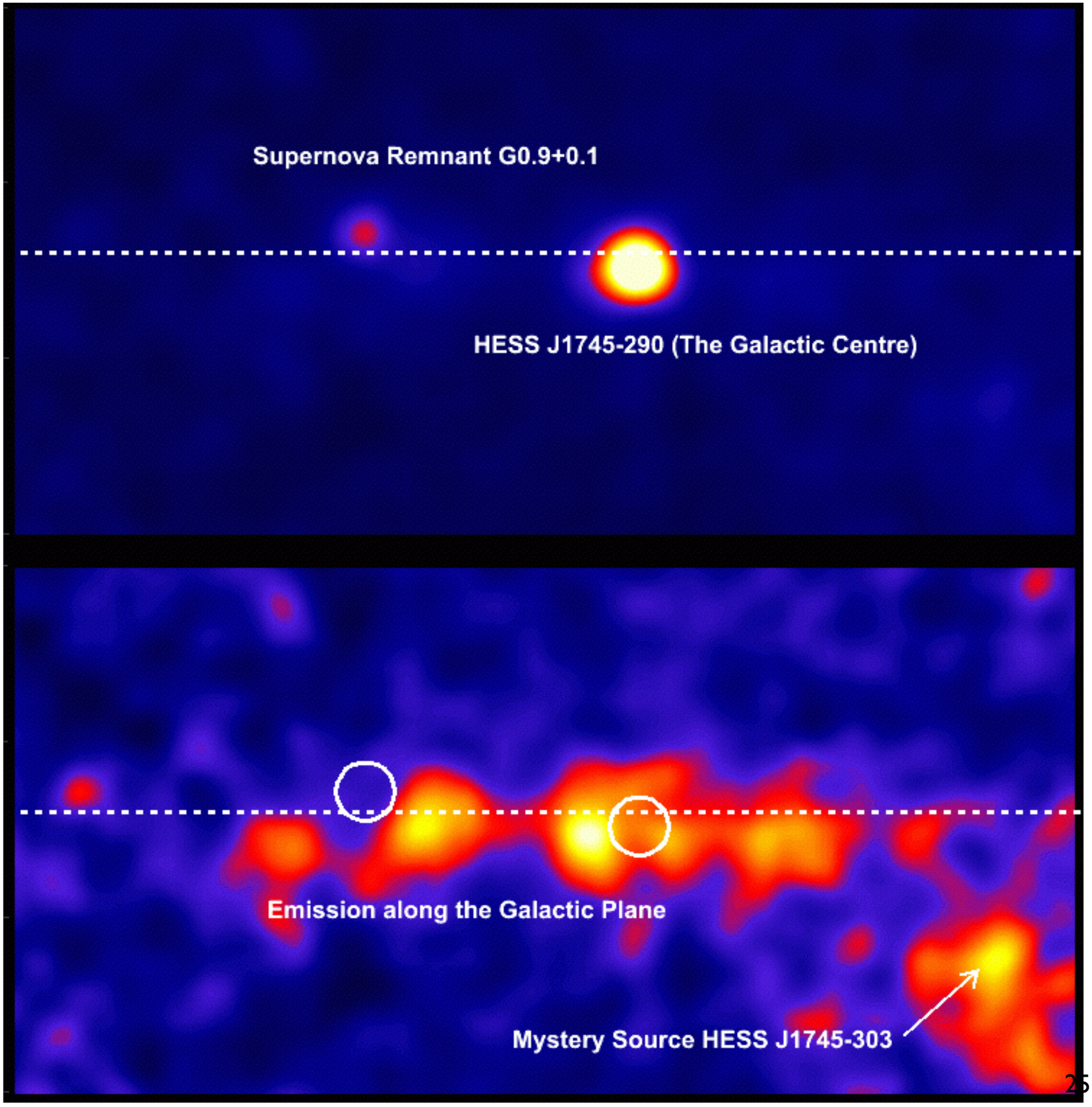
Supernovae produce TeV γ rays

RX J1713.7-3946

a supernova remnant shell

Galactic centre
(H.E.S.S.)

CRs interact with molecular clouds



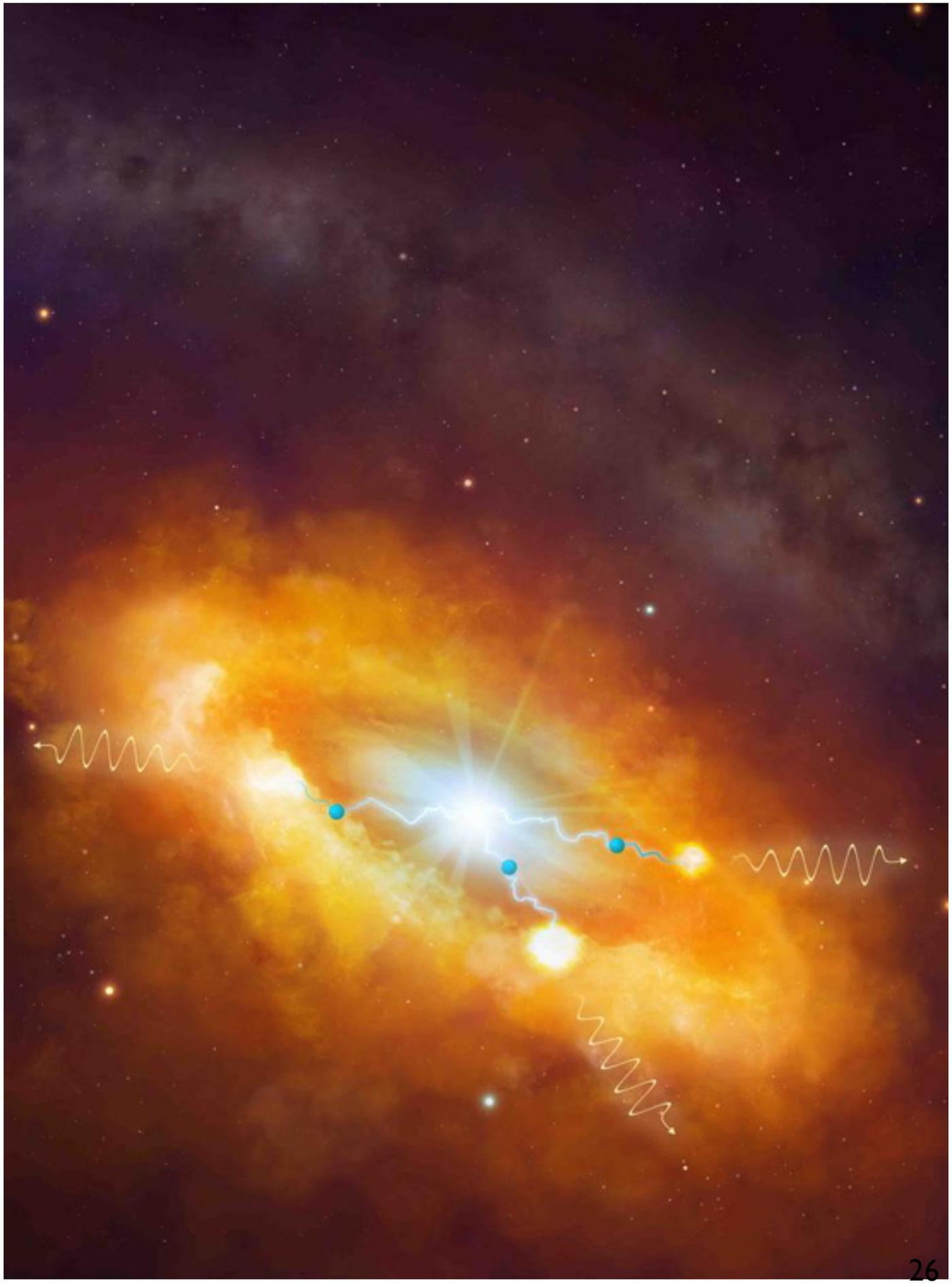
A PeV-atron in the Galactic centre

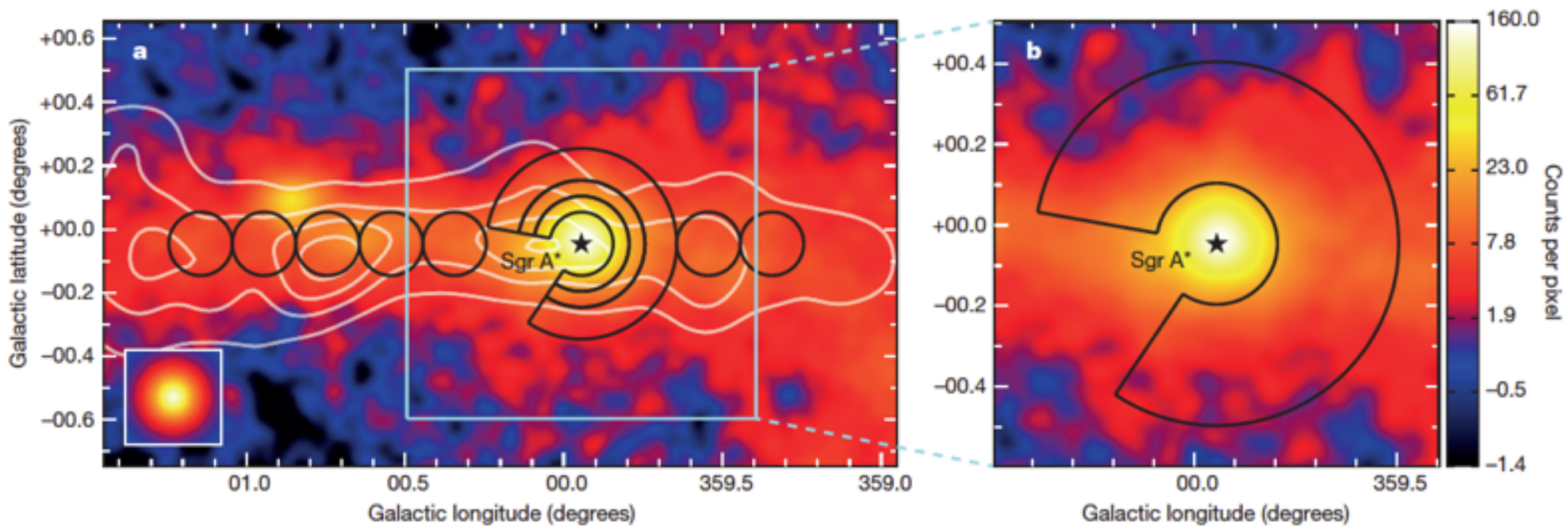
Nature 531, 476-479 (2016

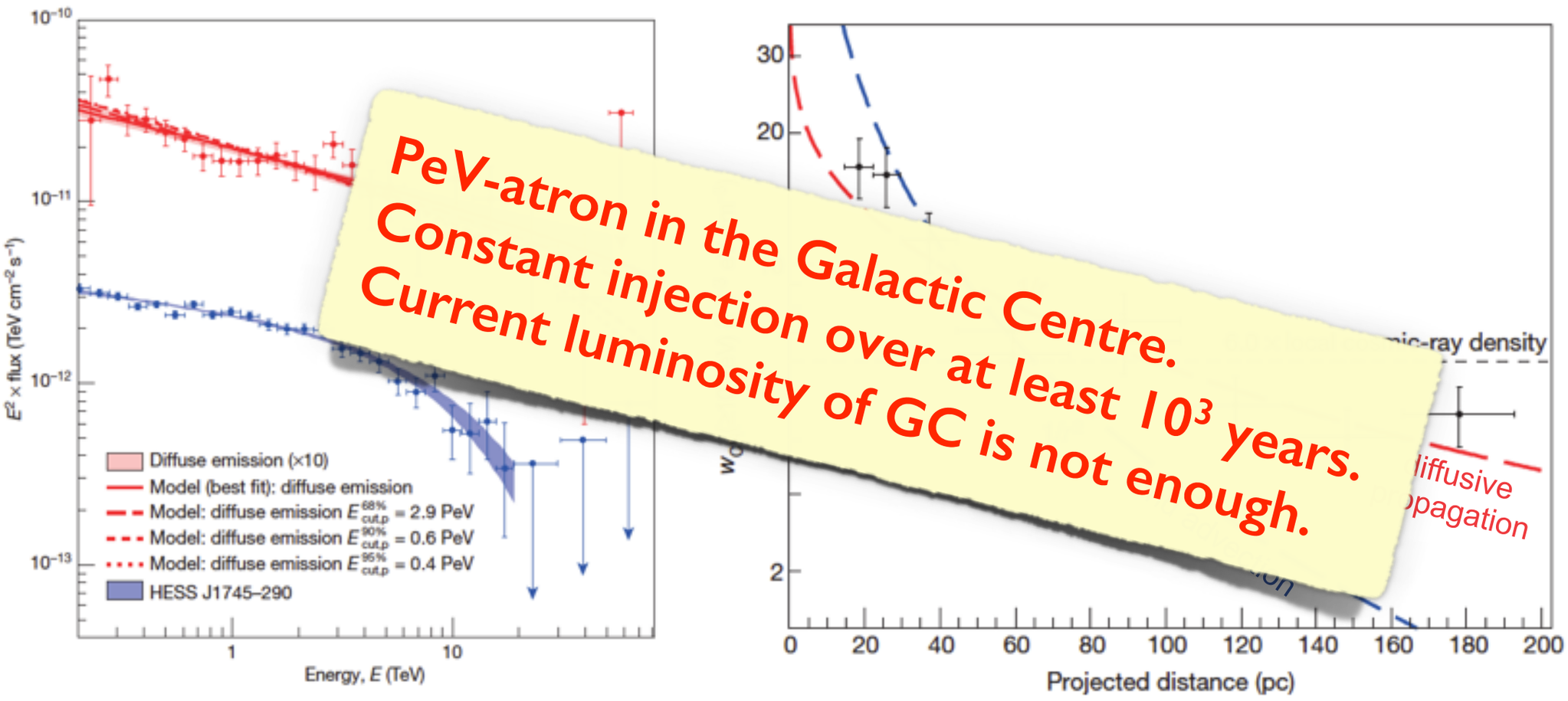
H.E.S.S. 2016:
diffuse emission in
Galactic Centre Ridge region

Presence of protons of ≈ 10^{15} eV

Dataset: 2004 - 2015





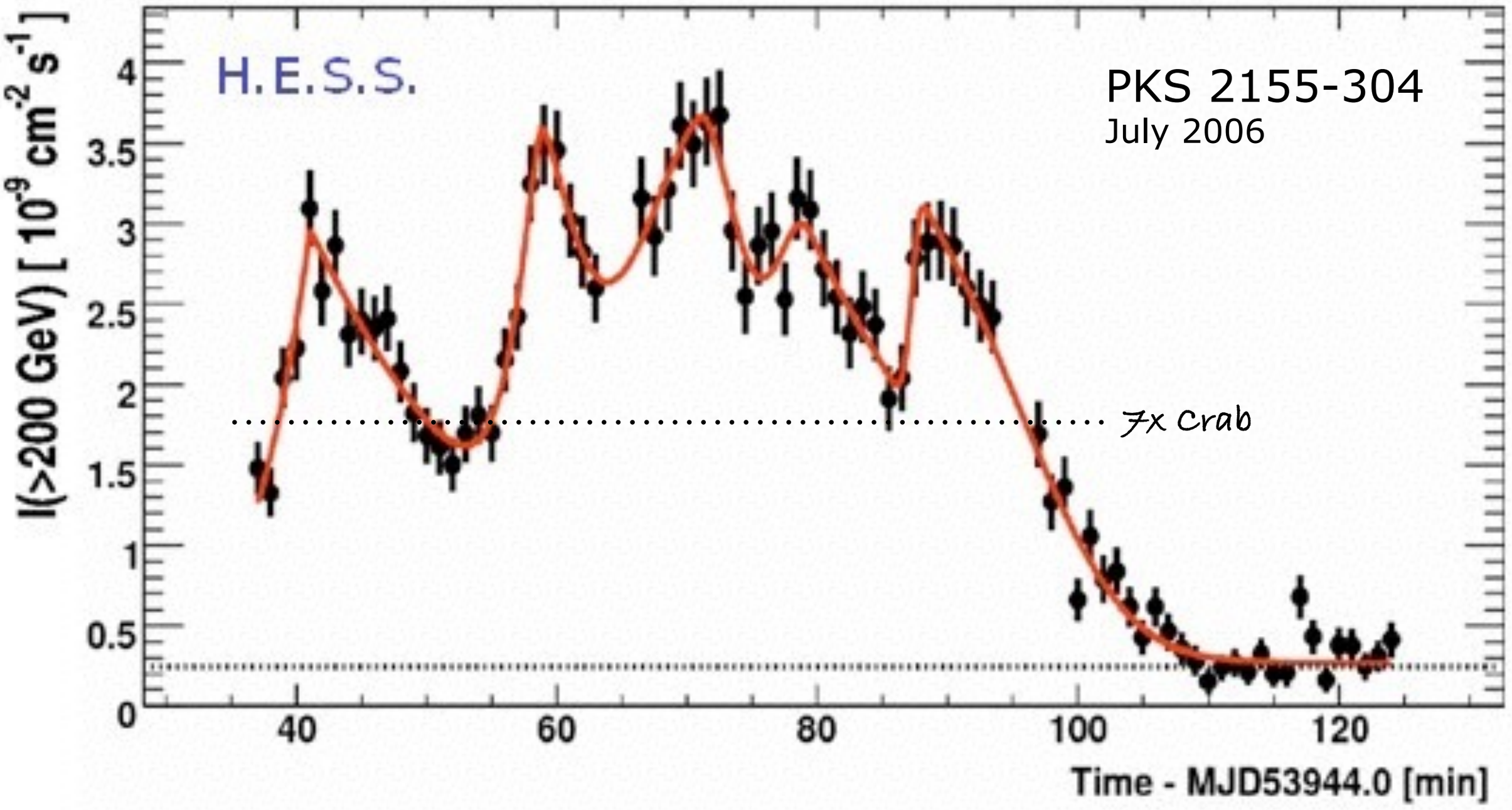


PeV-atron in the Galactic Centre.
Constant injection over at least 10^3 years.
Current luminosity of GC is not enough.

Very hard emission, no cutoff, untypical for extended emission

Cosmic ray density profile using matter densities from molecular line surveys.

Variability



BL Lac object $z = 0.116$

bursts on minute scales

$\Gamma \geq 100$ are required

Science Areas:

Cosmic energetic particles

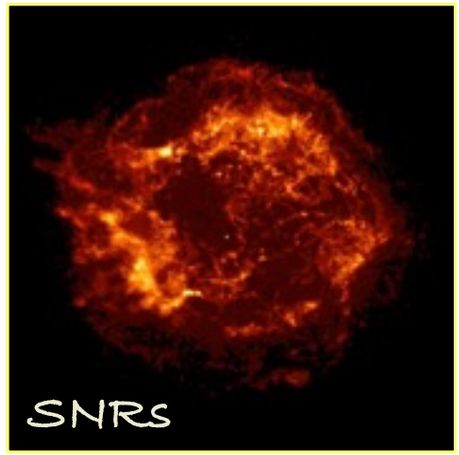
- Origin of the galactic cosmic rays
  - Also UHECR signatures
- Role of ultra-relativistic particles in
- in clusters of galaxies, AGN, Starbursts…
- The physics of (relativistic) jets and shocks

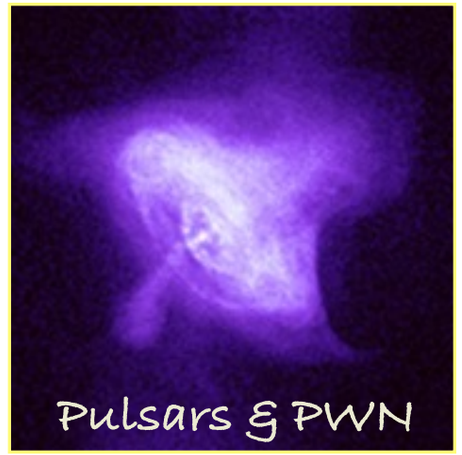
Fundamental Physics

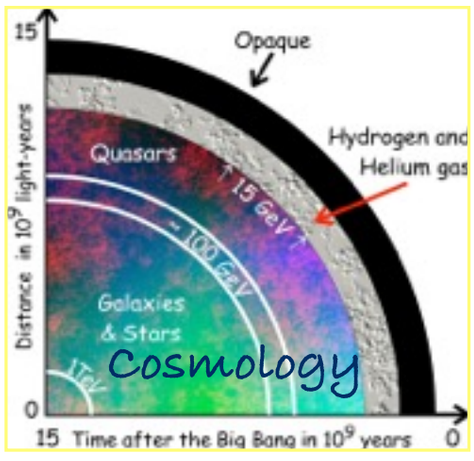
- Dark Matter annihilation / decay
- Lorentz Invariance violation

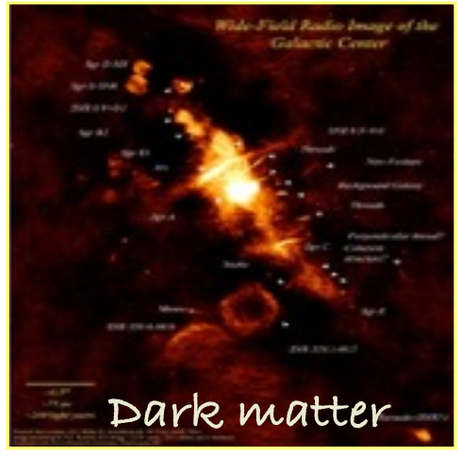
Cosmology

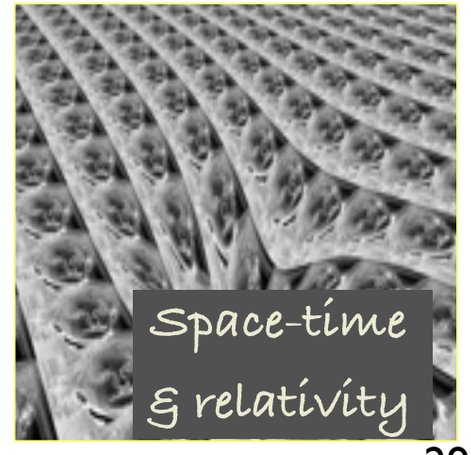
- cosmic FIR-UV radiation,
- cosmic magnetism











The future with …

cta
cherenkov telescope array

… an advanced facility for ground-based gamma-ray astronomy

CTA is the global, next-generation project with
largely enhanced performance,
two observatories (South and North)

probing the extreme universe with huge potential for
extreme astronomy and fundamental physics with TeV photons.

High-energies
10 km^2 area at
>100 TeV
70 4-m telescopes

Low-energies
>30 GeV
few 23-m telescopes

central energy range:
mCrab sensitivity
0.1–10 TeV
25 12-m telescopes

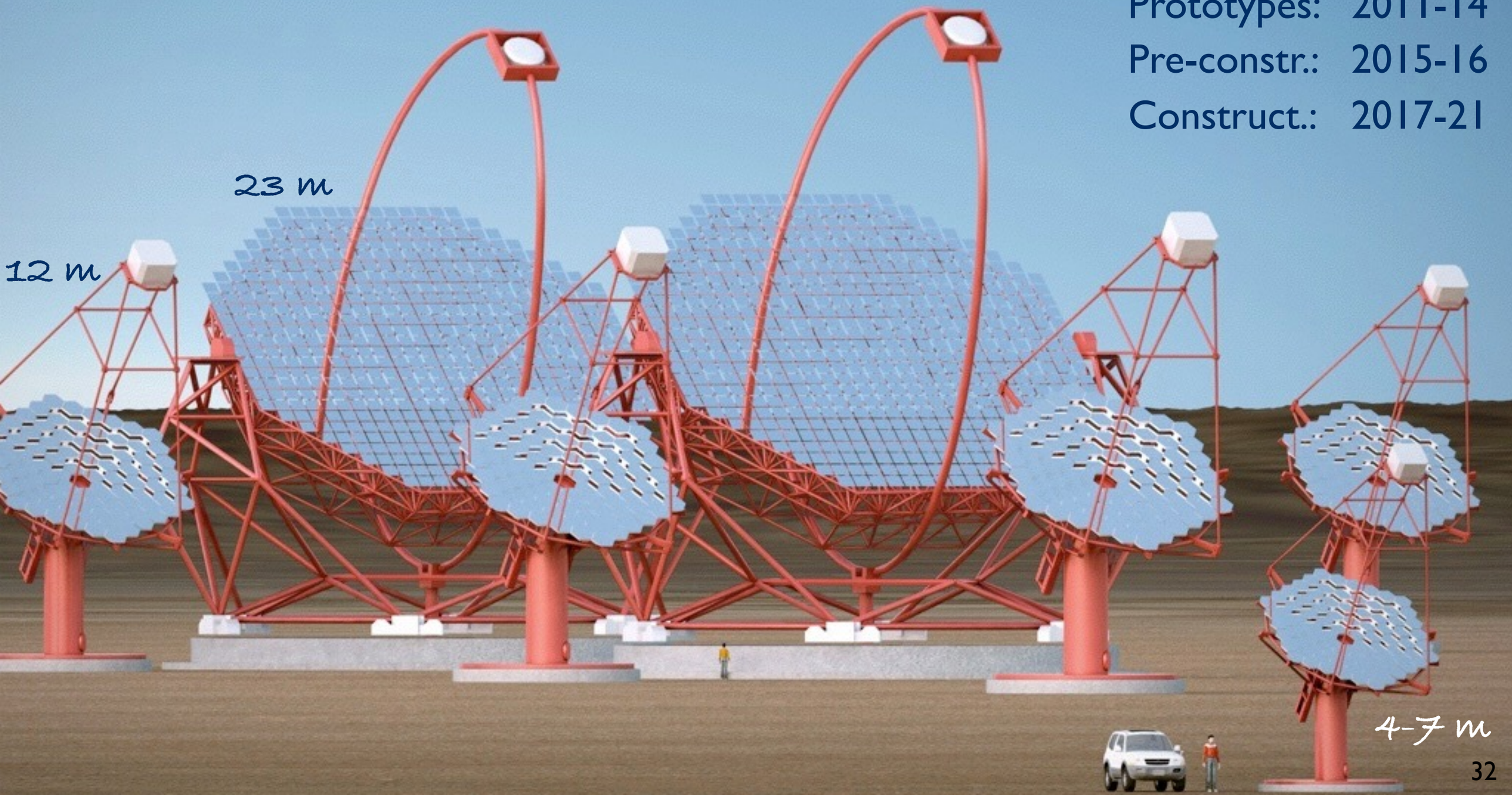
30 GeV … 300 TeV

Not to scale !

CTA

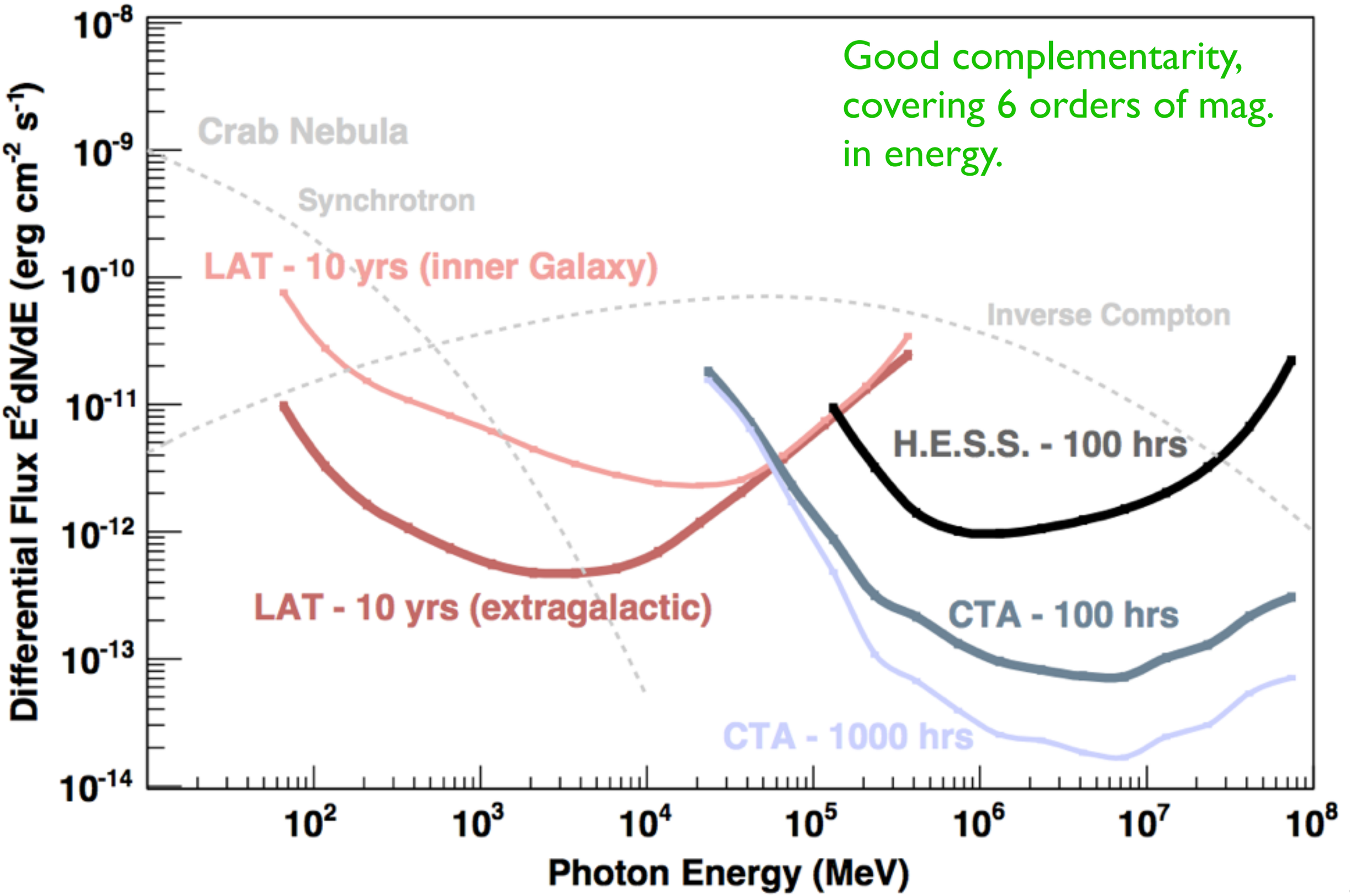
10x more sensitive than current instruments,
much **wider energy coverage** and **field of view**,
substantially **better angular and energy resolution.**

Design:	2008-12
Prototypes:	2011-14
Pre-constr.:	2015-16
Construct.:	2017-21



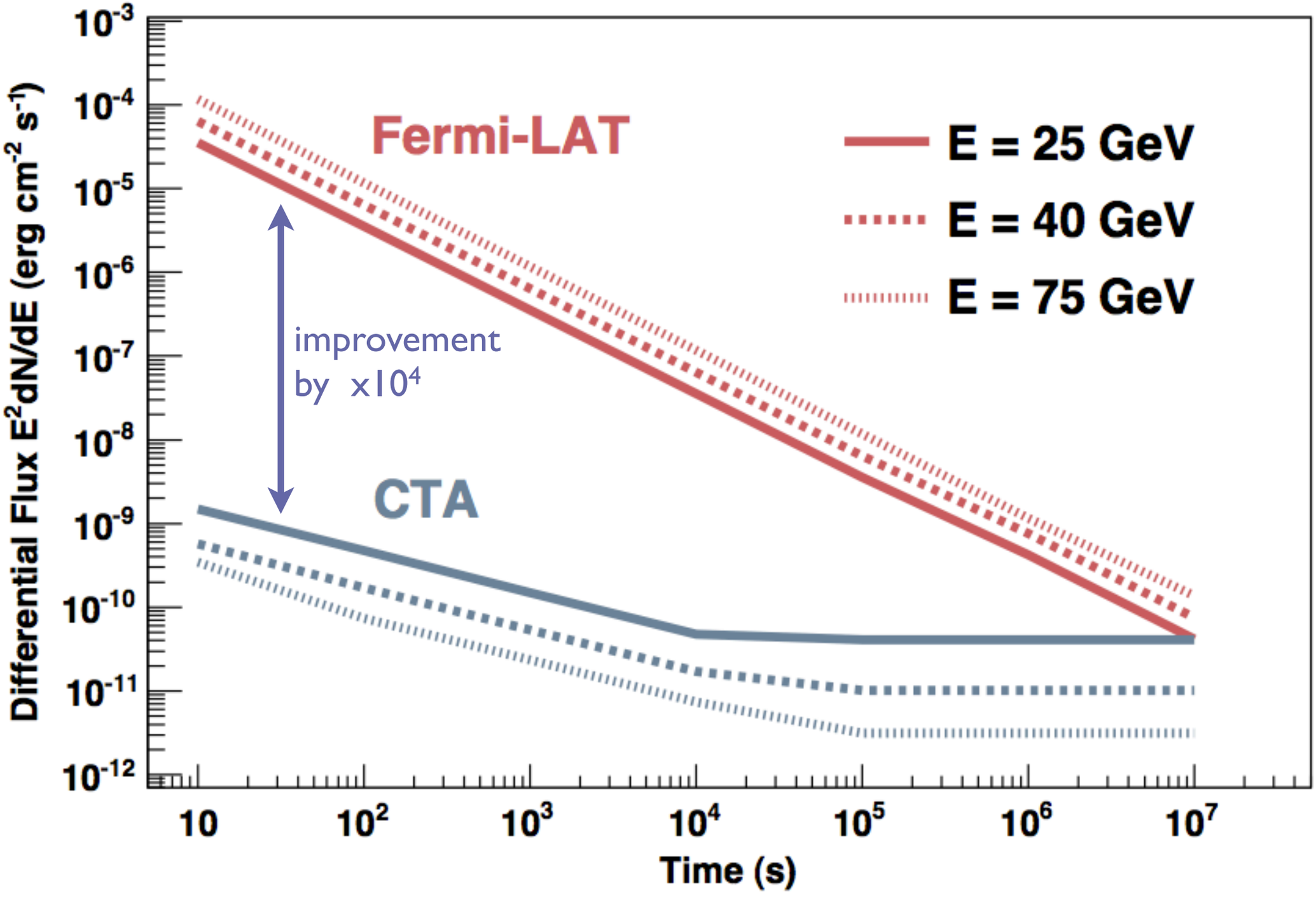
CTA and Fermi

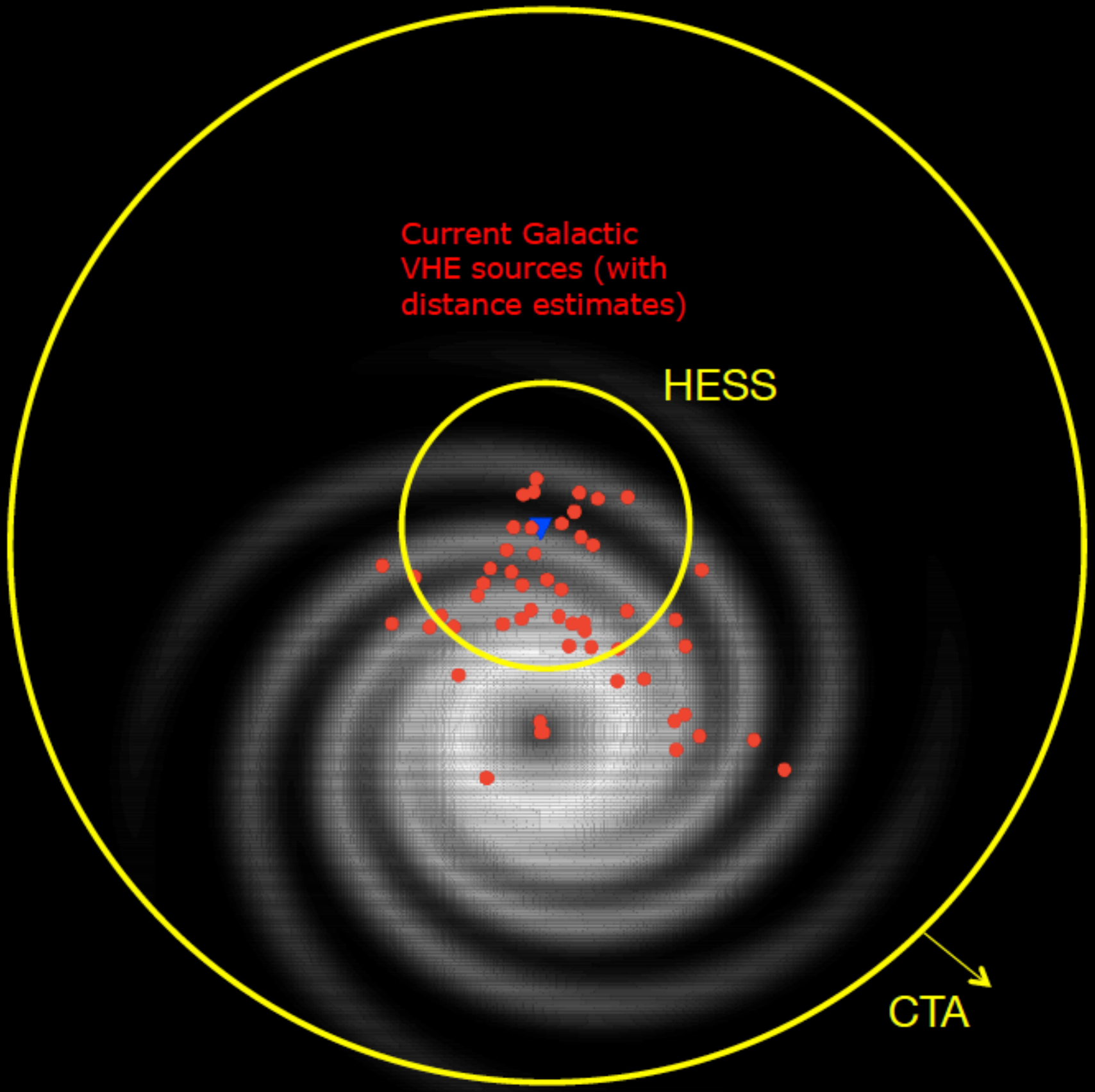
(Steady sources)



Variability and Short-Timescale Phenomena

(flares, GRBs, ... all sorts of transients)





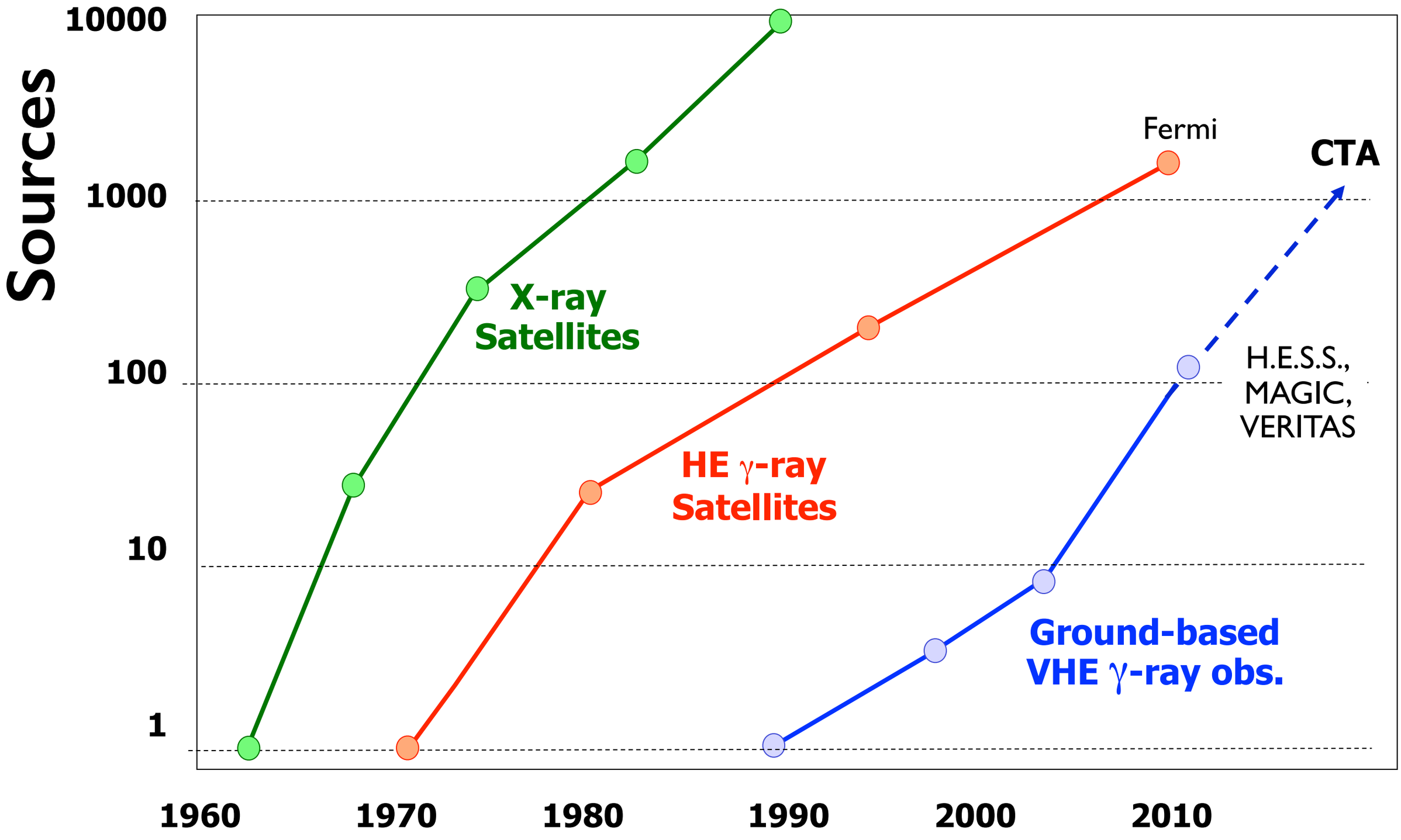
CTA will be the
ultimate instrument

for surveys
400x faster than HESS

for transients
at 25 GeV,
10^4x better than Fermi

Source Number

Ground-based gamma ray astronomy becomes “mainstream”.



Adapted from Tadashi Kifune

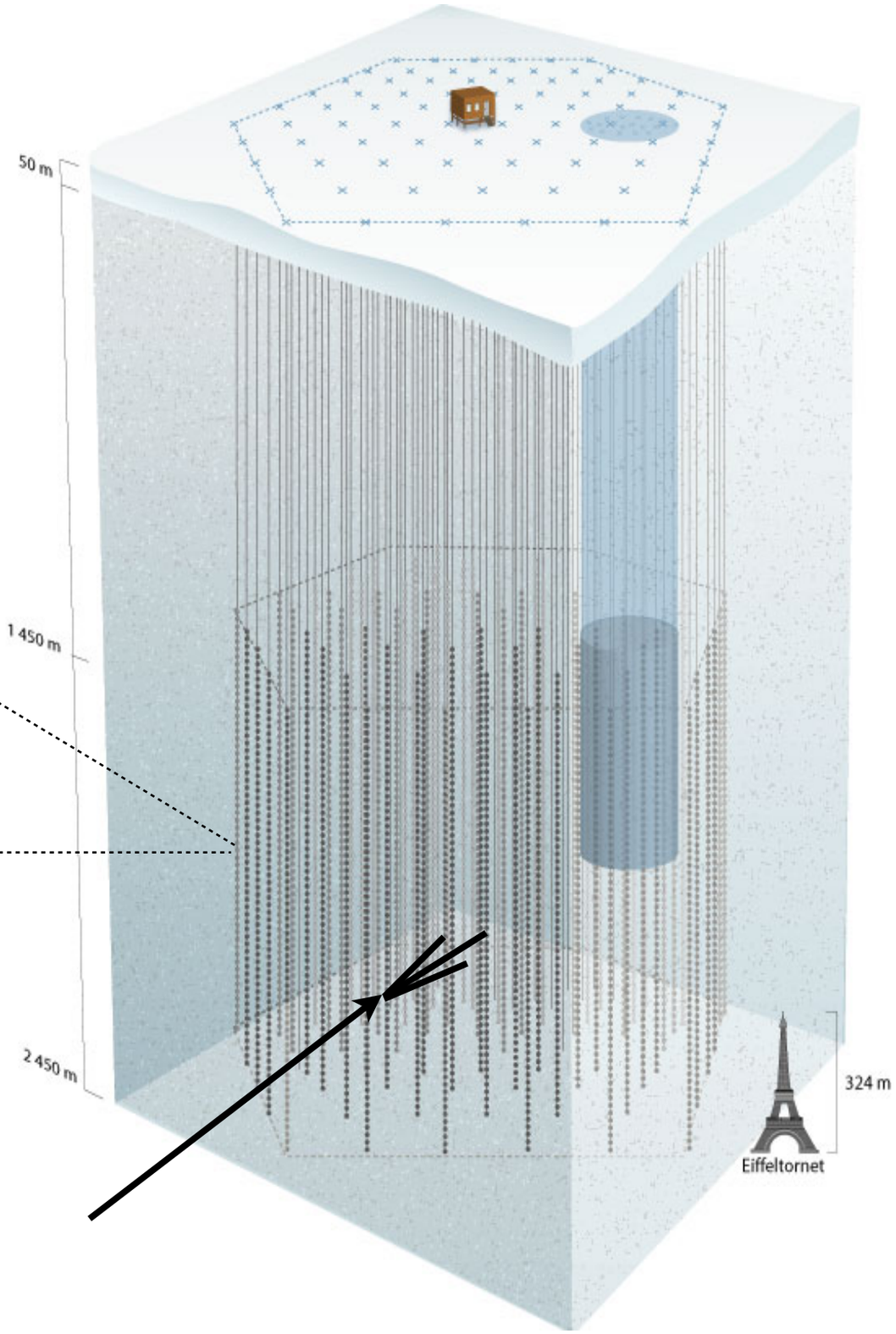
Neutrinos

IceCube @ South Pole

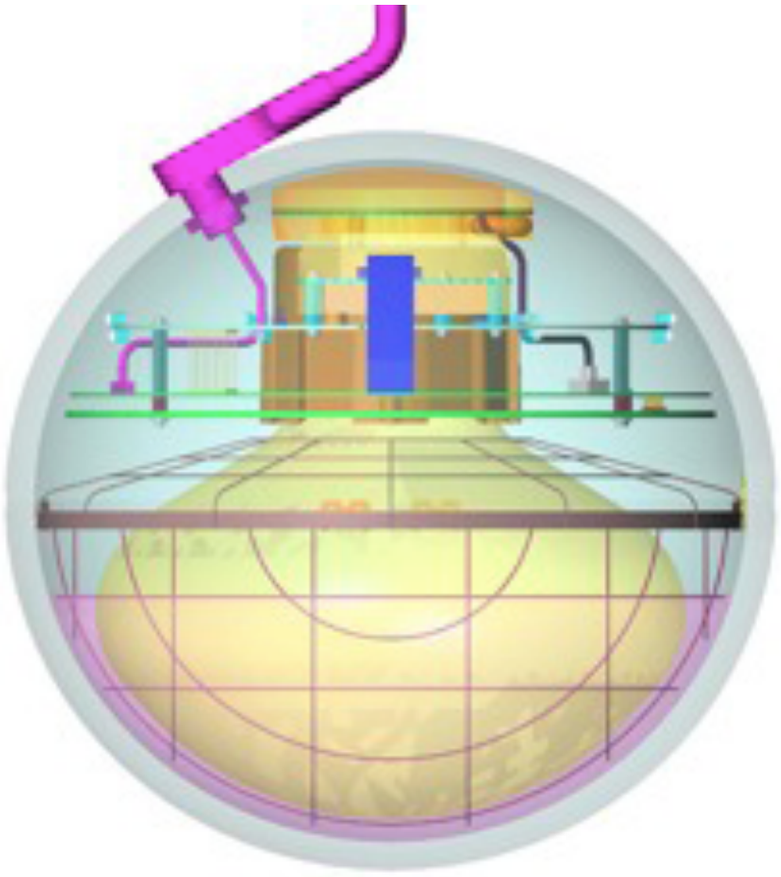
1 km^3 5160 sensors,
~2 km deep in ice

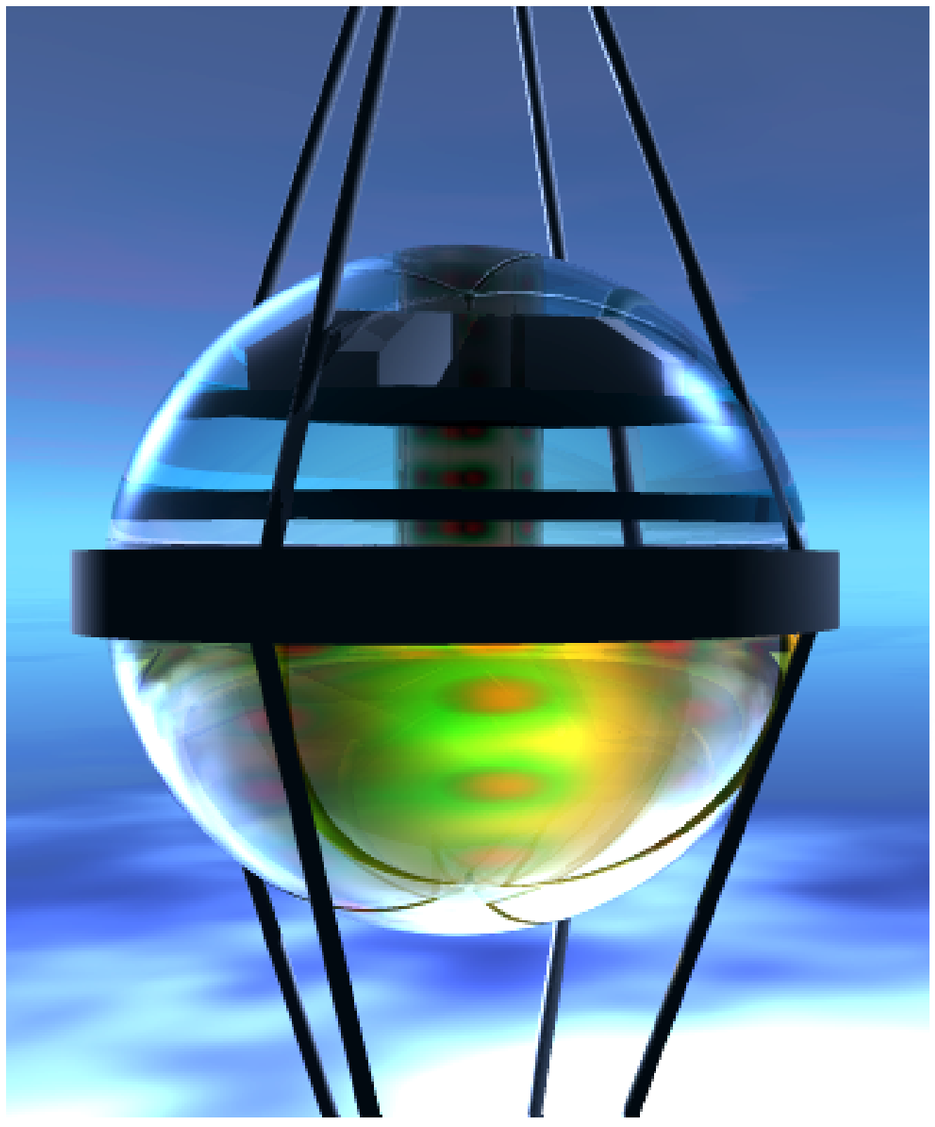
Neutrinos go through the earth.
(E ≈ 10^{11}–10^{15} eV)

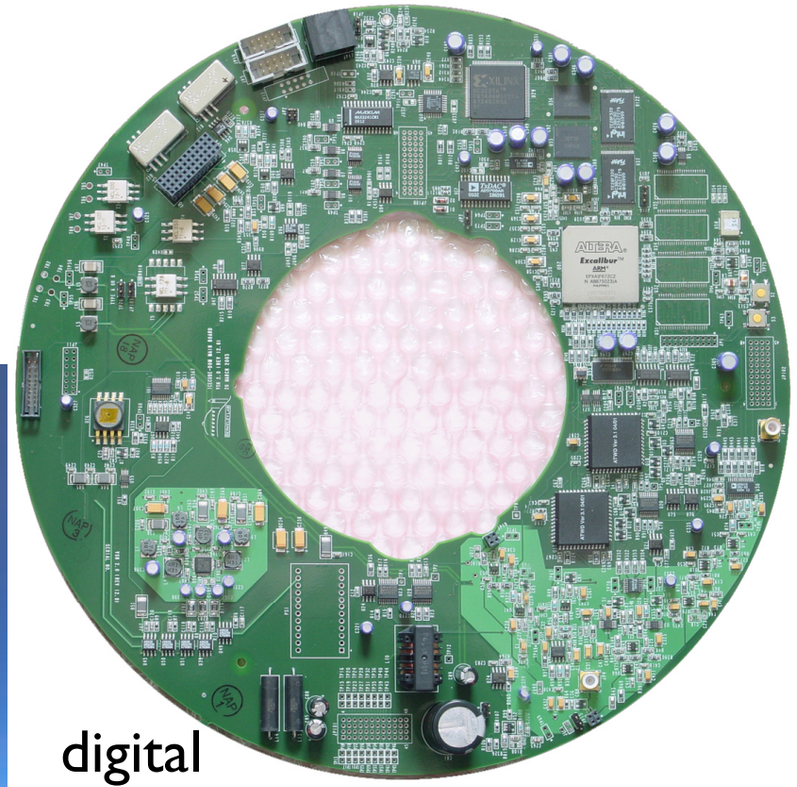
digital optical module
with 10 inch PMT



digital optical module







digital
electronics

10 inch PMT
(Light sensors)

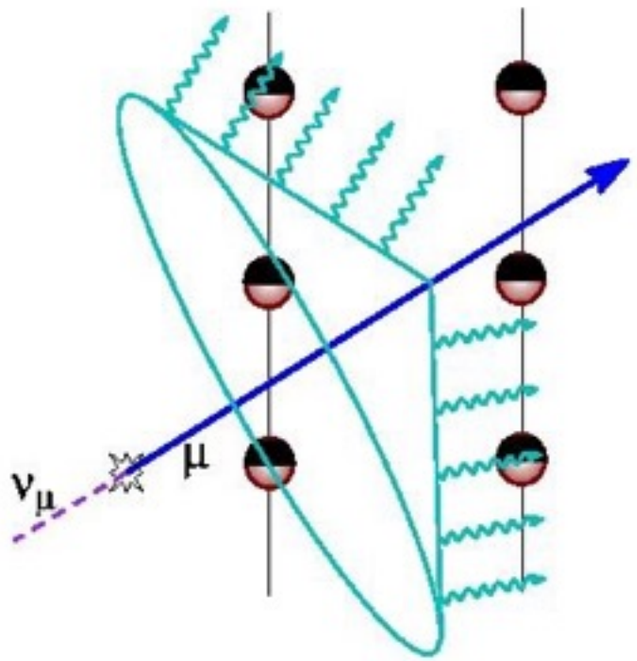
86 strings with 60 sensors each

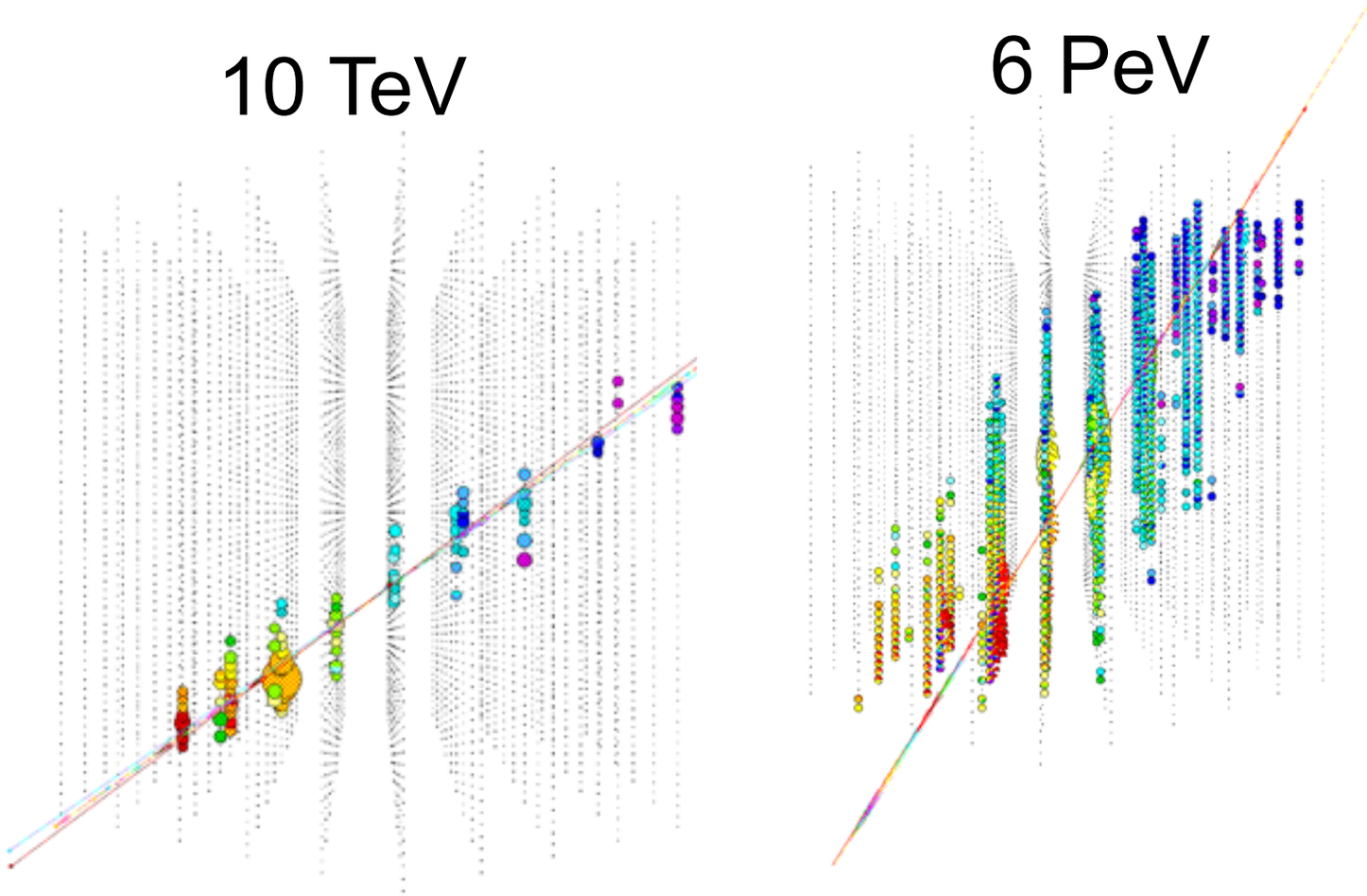
Neutrinos create charged particles
which in turn produce Cherenkov light.

Muon-tracks

good pointing (<1 degree)

large event rates due to long muon tracks



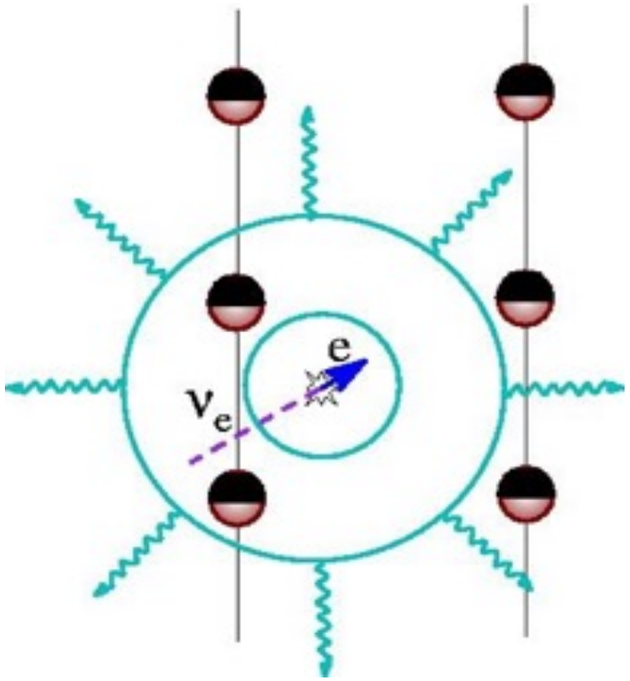


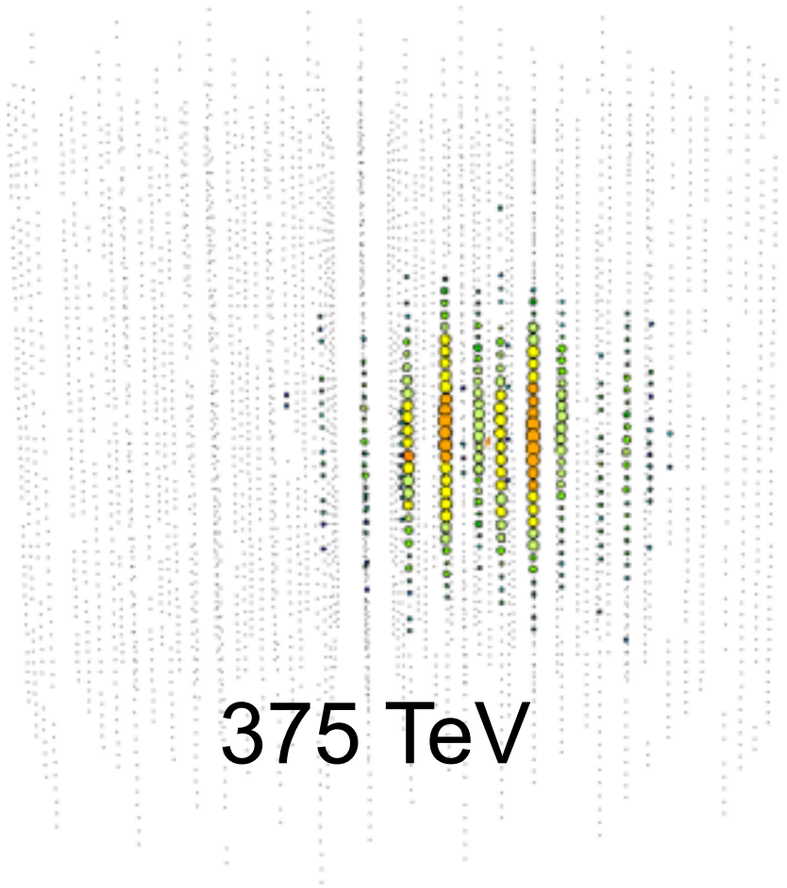
signature of ν_μ

Particle cascades

ν_e , ν_τ

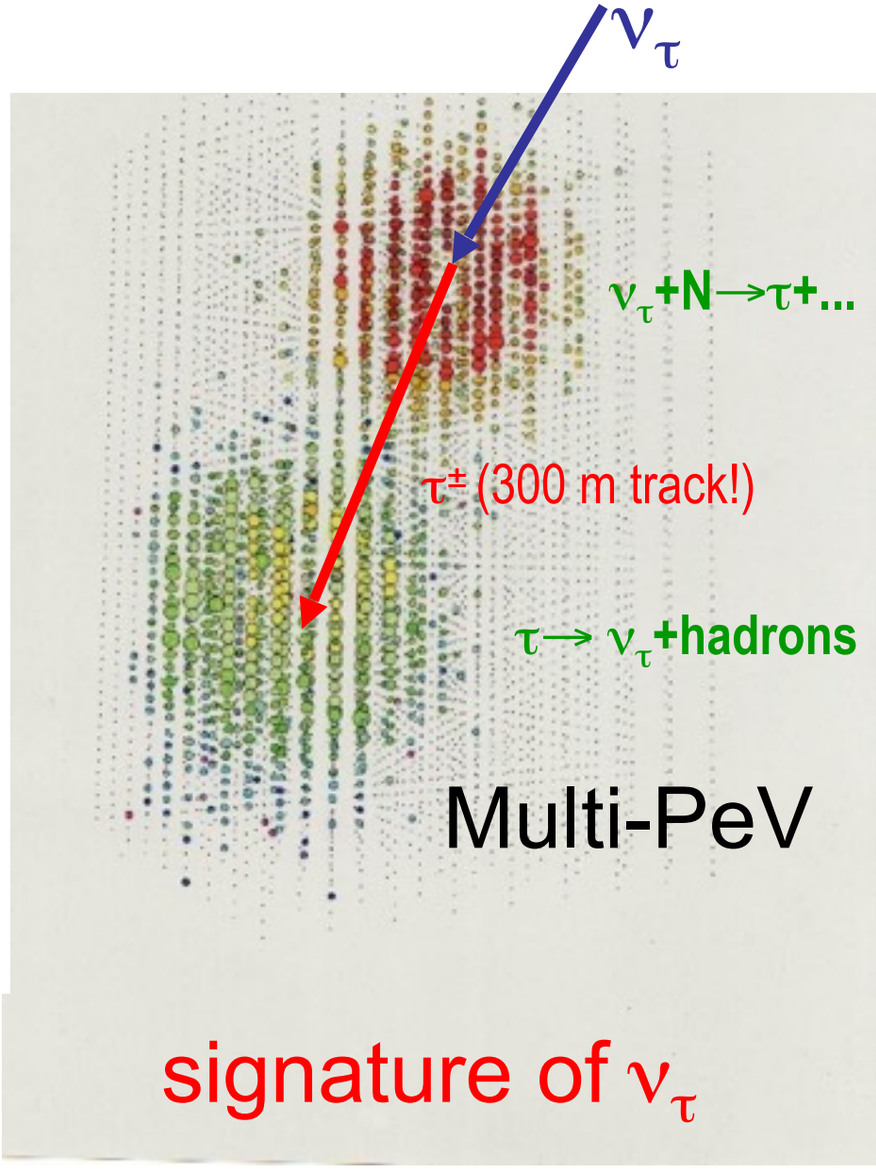
good energy resolution,
little background





375 TeV

signature of ν_e



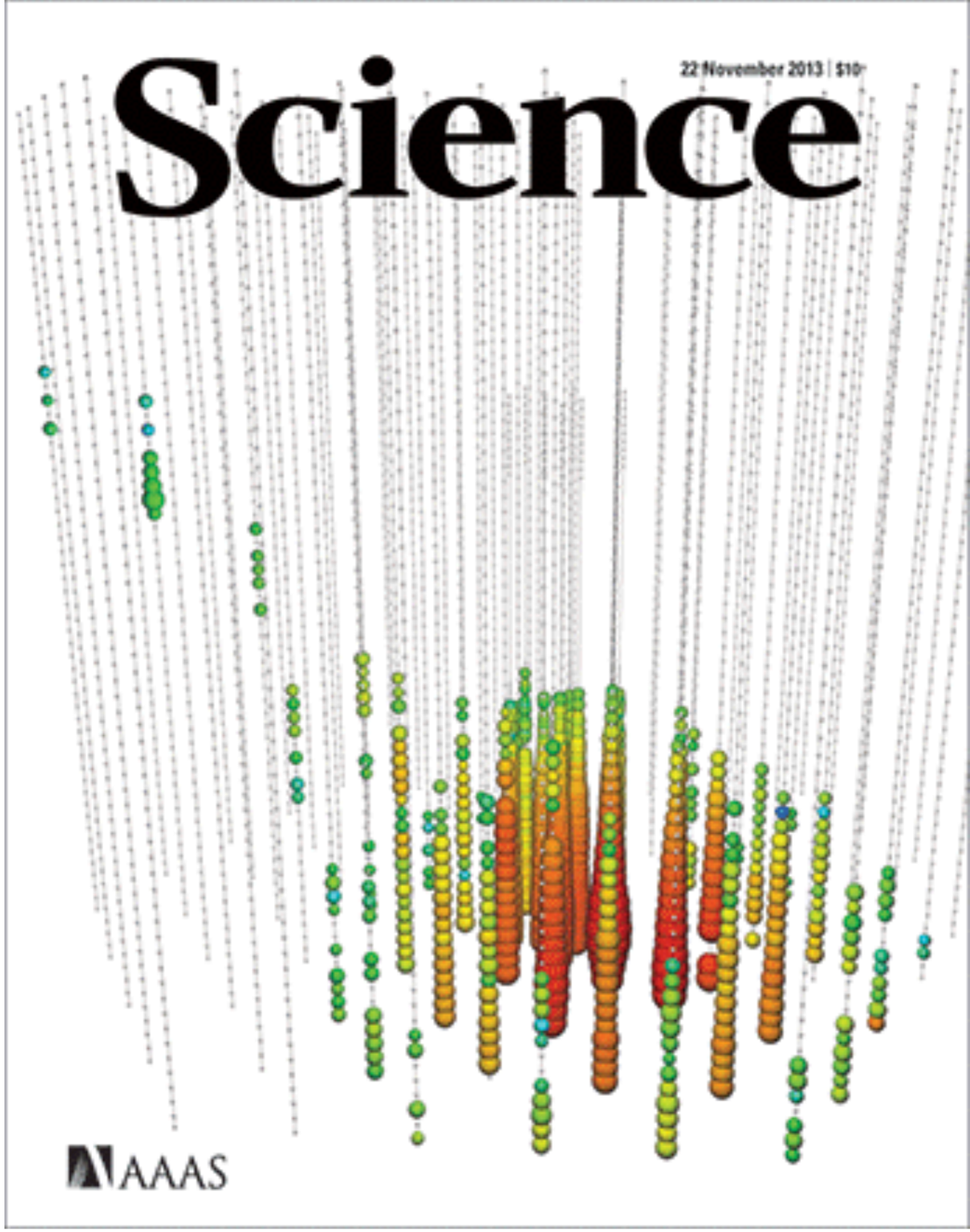
Multi-PeV

signature of ν_τ

High-energy νs detected.

Clear evidence for astrophysical origin

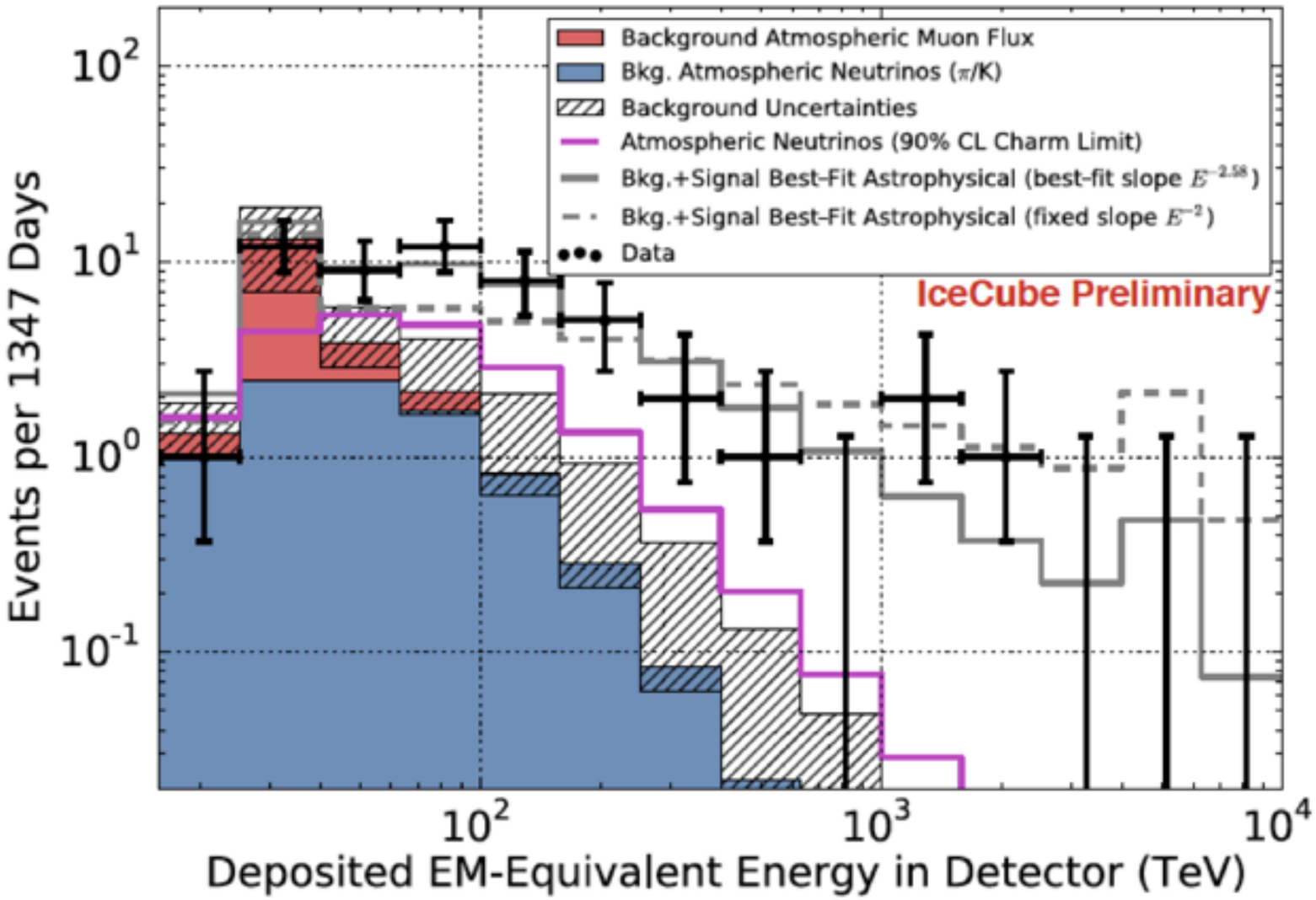
(>5σ)



Nov 2013

Spectrum

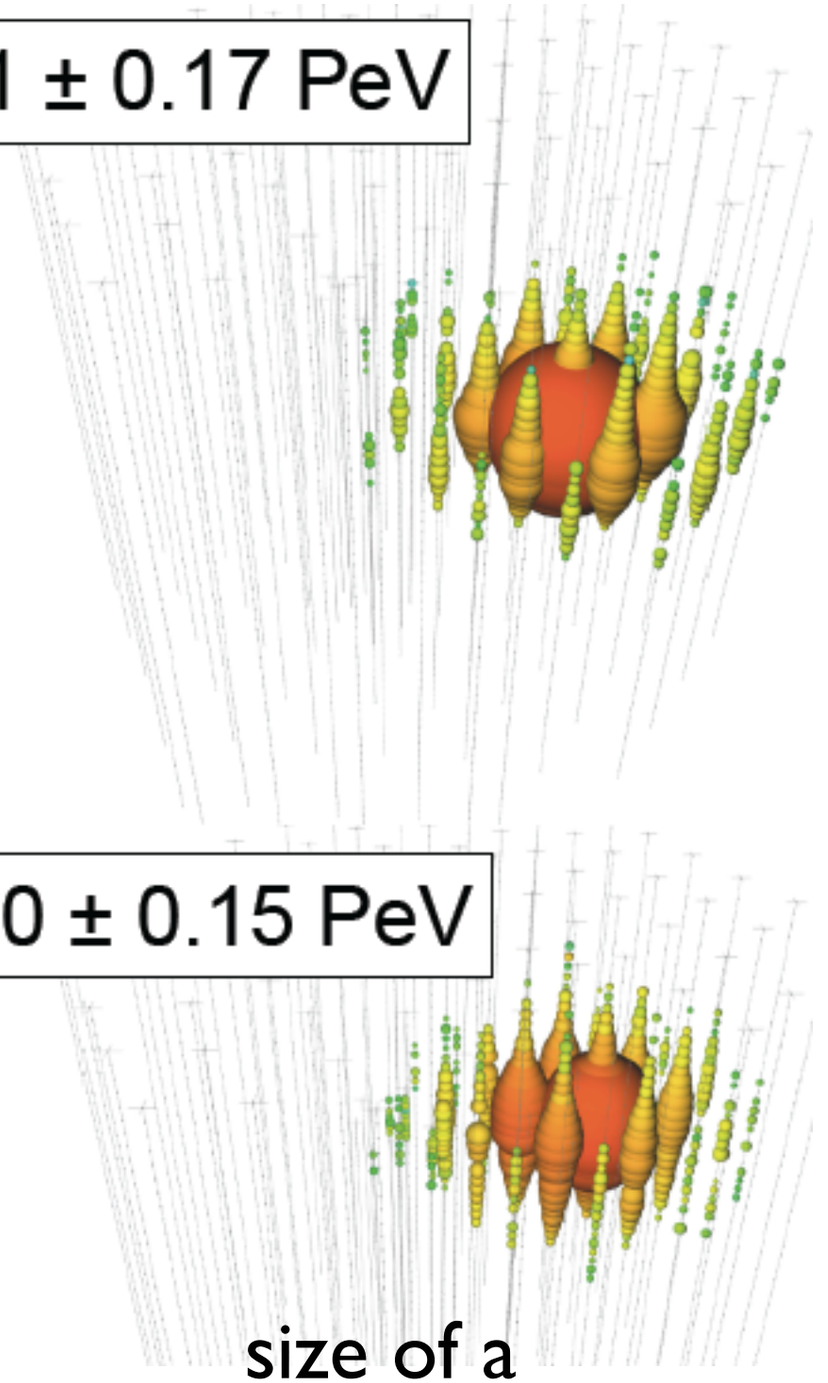
54 events observed,
20±6 expected from atmosphere



now: ~7 σ evidence for
extra-terrestrial ν

$E \geq 10^{15}$ eV

1.1 ± 0.17 PeV

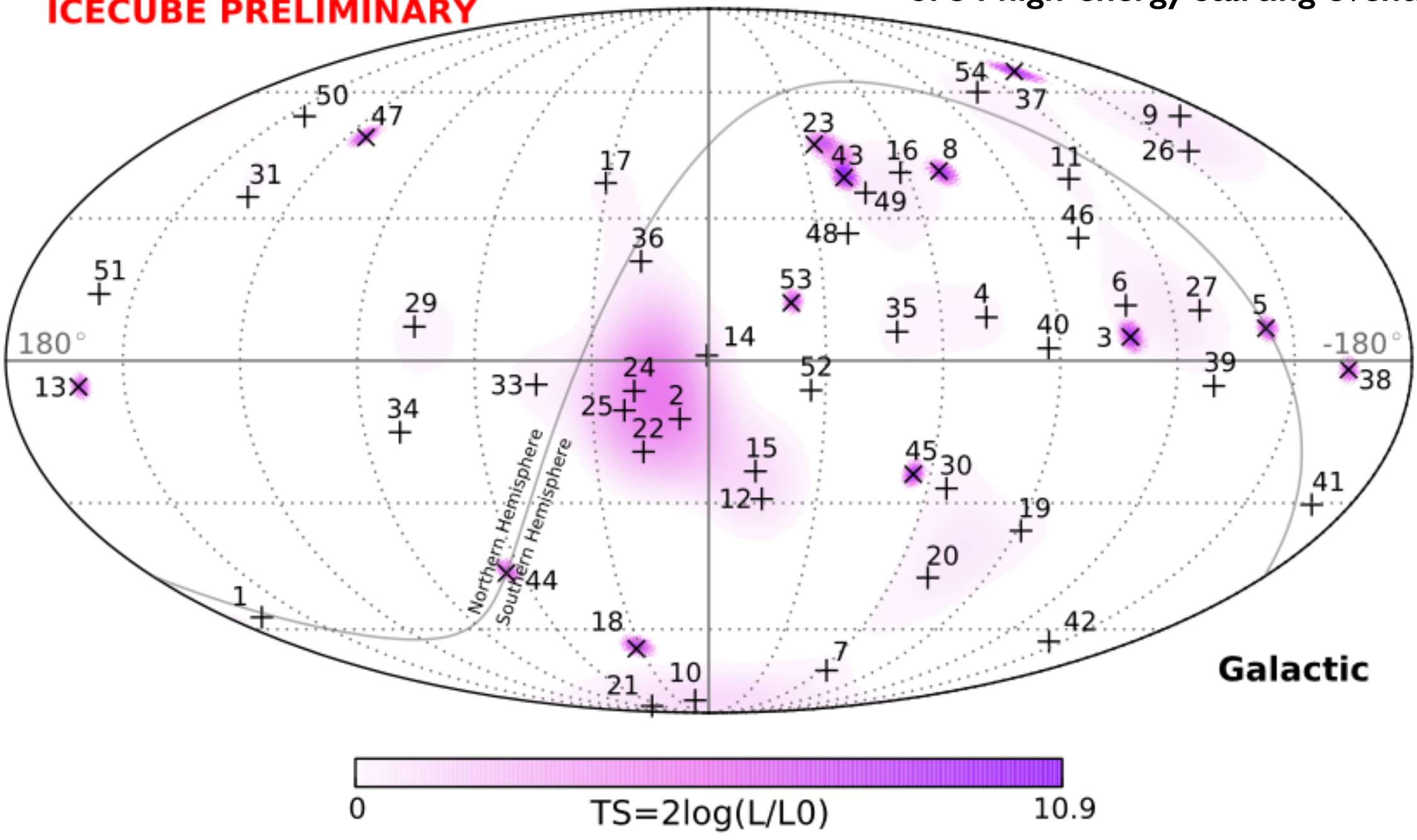


1.0 ± 0.15 PeV

size of a
football stadium

Sky Map

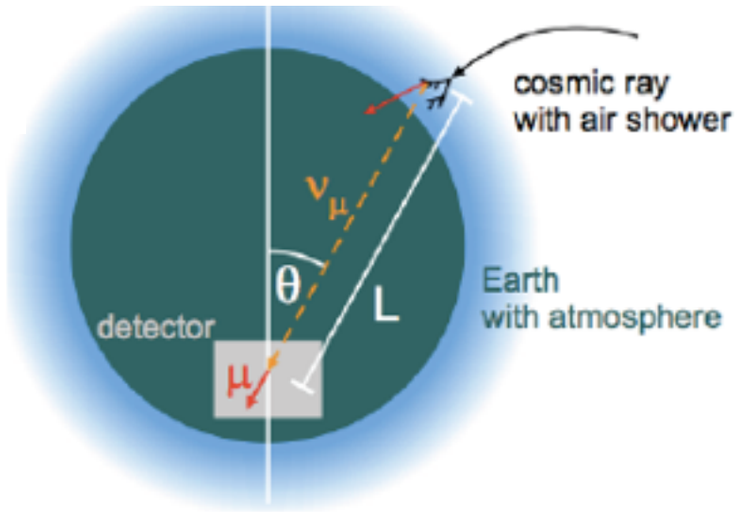
of 54 high-energy starting events

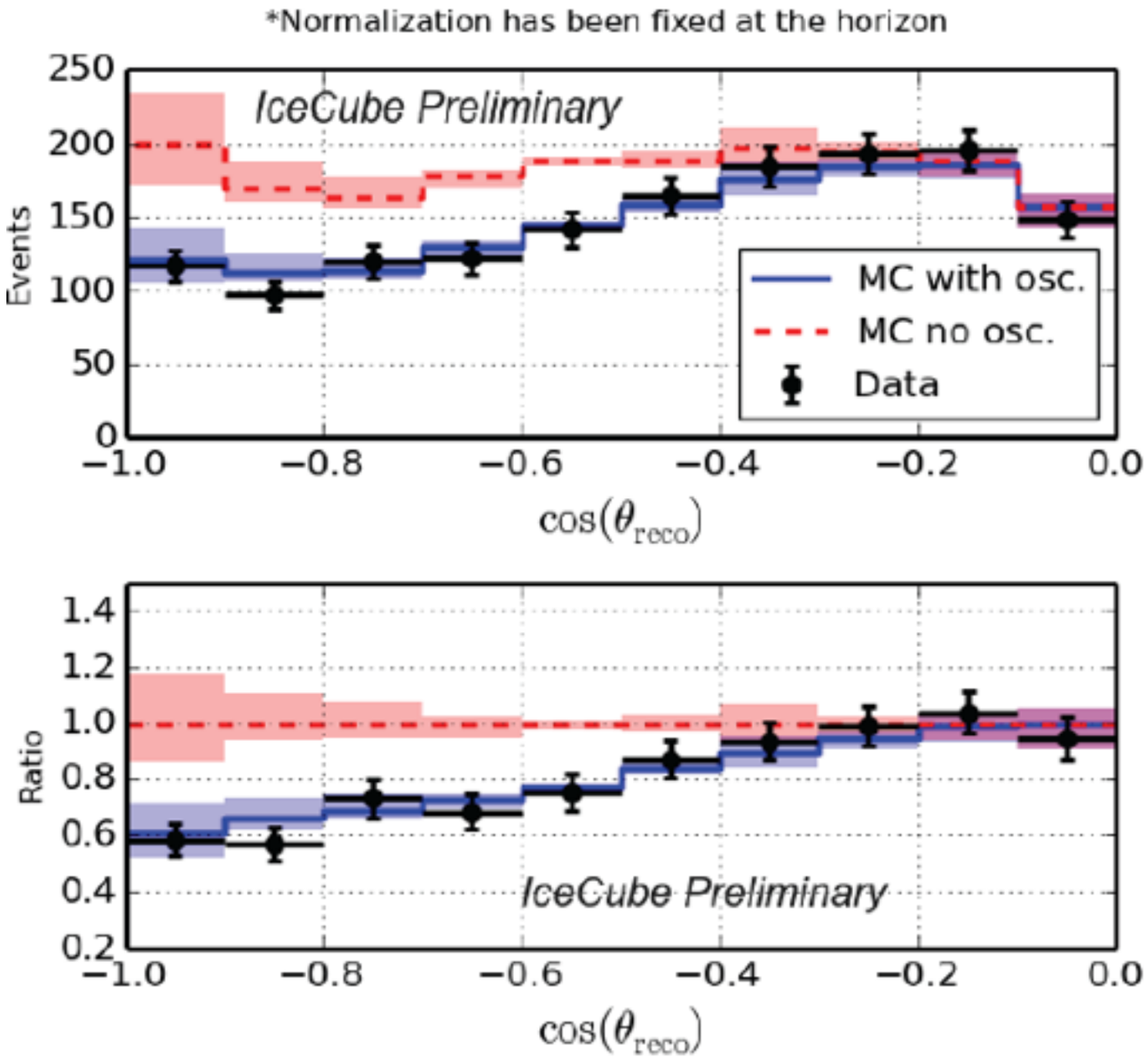


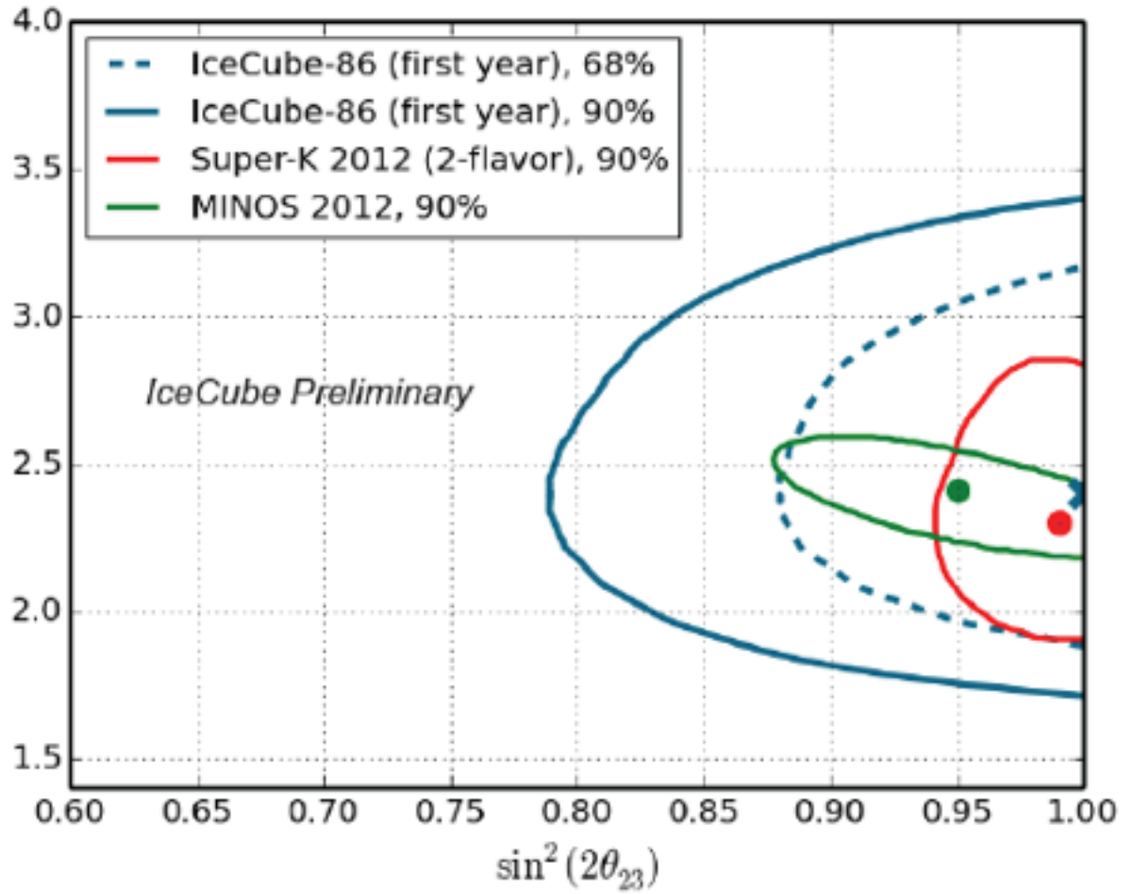
Largely isotropic ⇒ extragalactic origin

+ cascades
x track-like

Neutrino properties





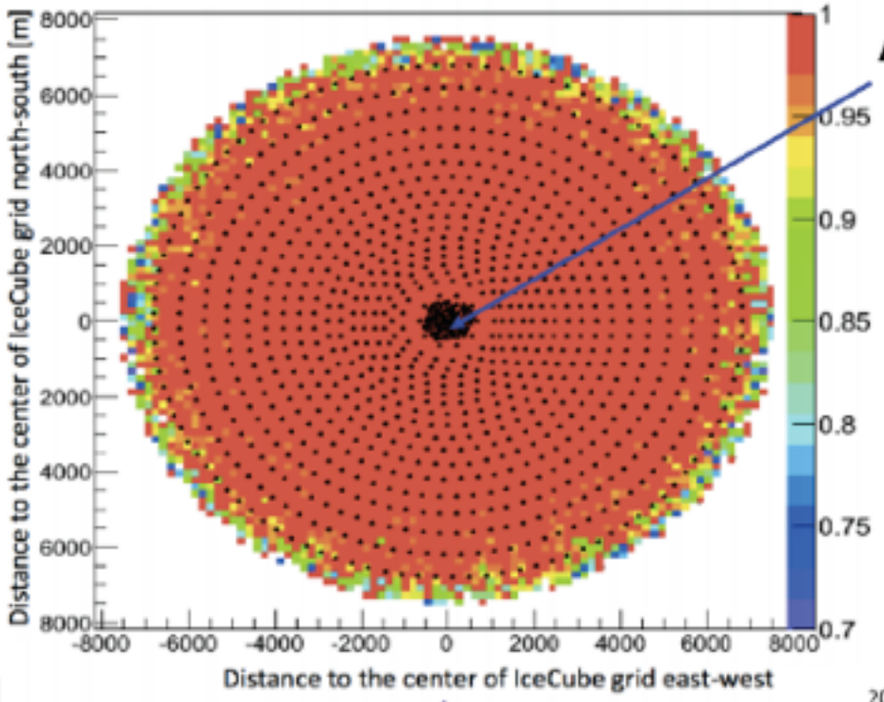


First determination of θ_{23} and Δm^2 with a neutrino telescope.

Beyond IceCube: Gen2

... a multi-purpose research infrastructure at the South Pole.

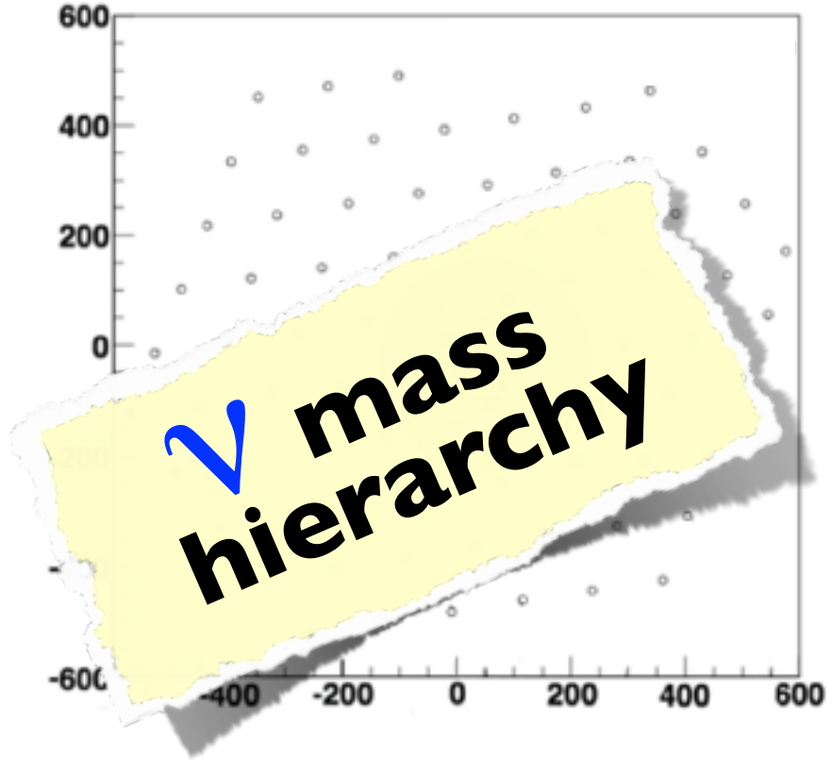
Multi-km² Surface Detector

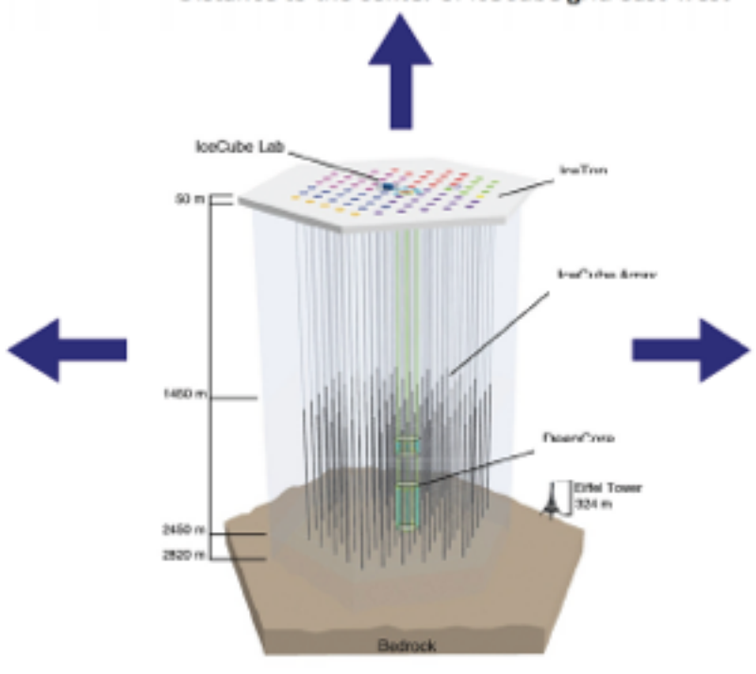


Atm. neutrino veto
CR physics

PINGU

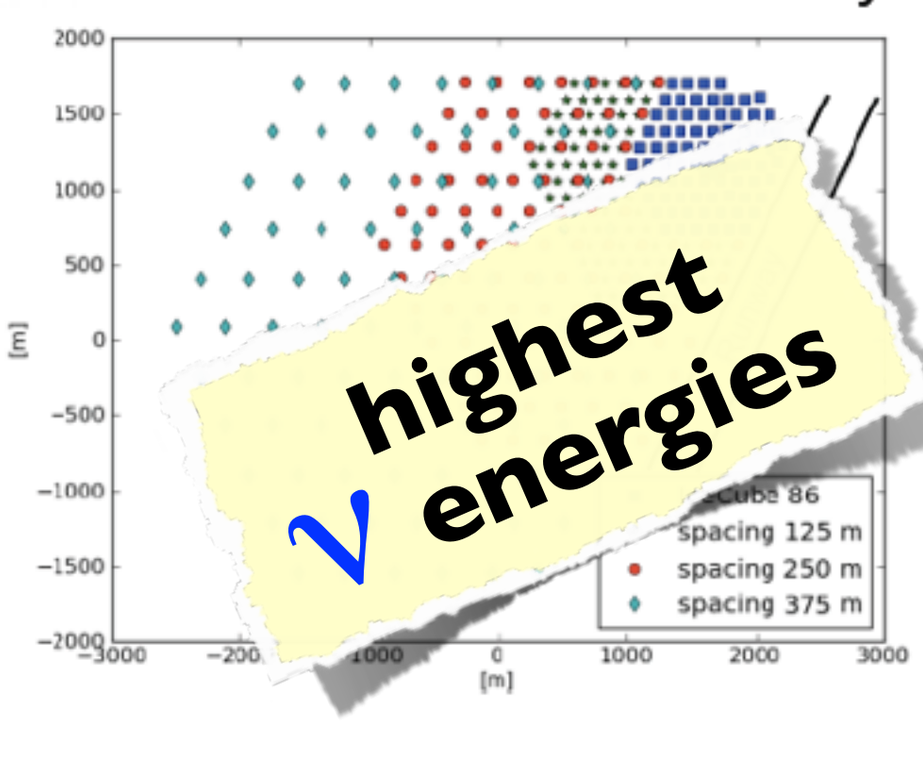
Neutrino properties





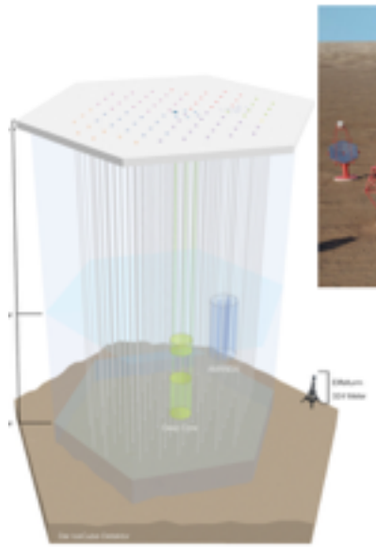
Multi-km³ Neutrino Telescope

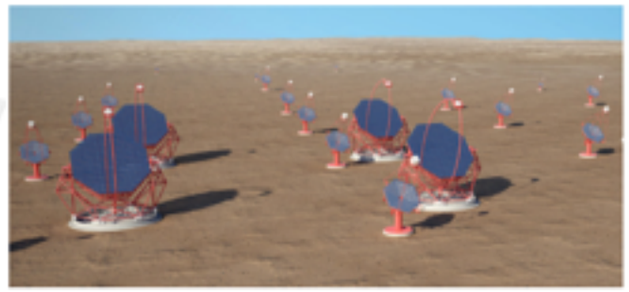
Neutrino astronomy

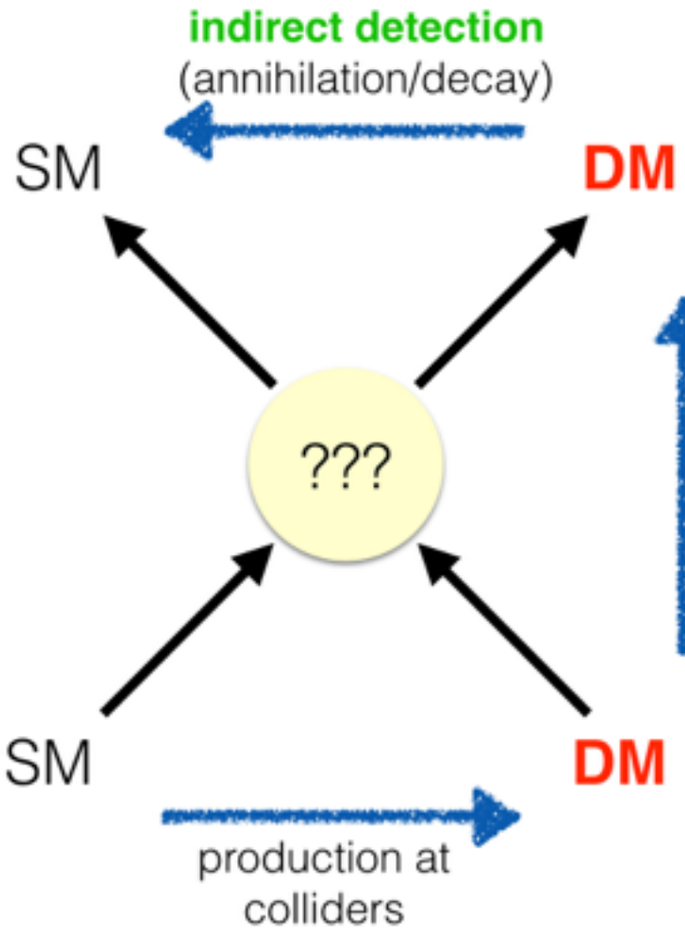


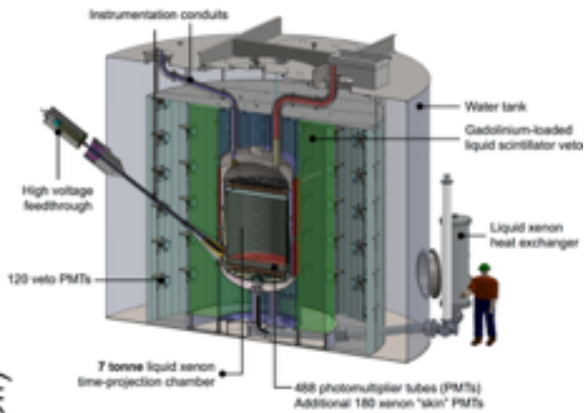
Other “astro particles”:

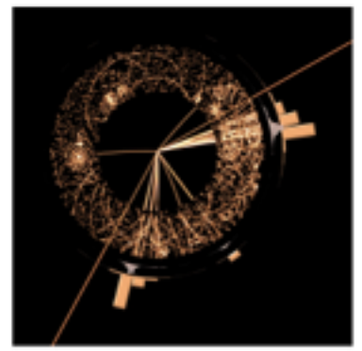
Dark Matter :











Wimps ?

No signs of Wimp DM
in any type of search.

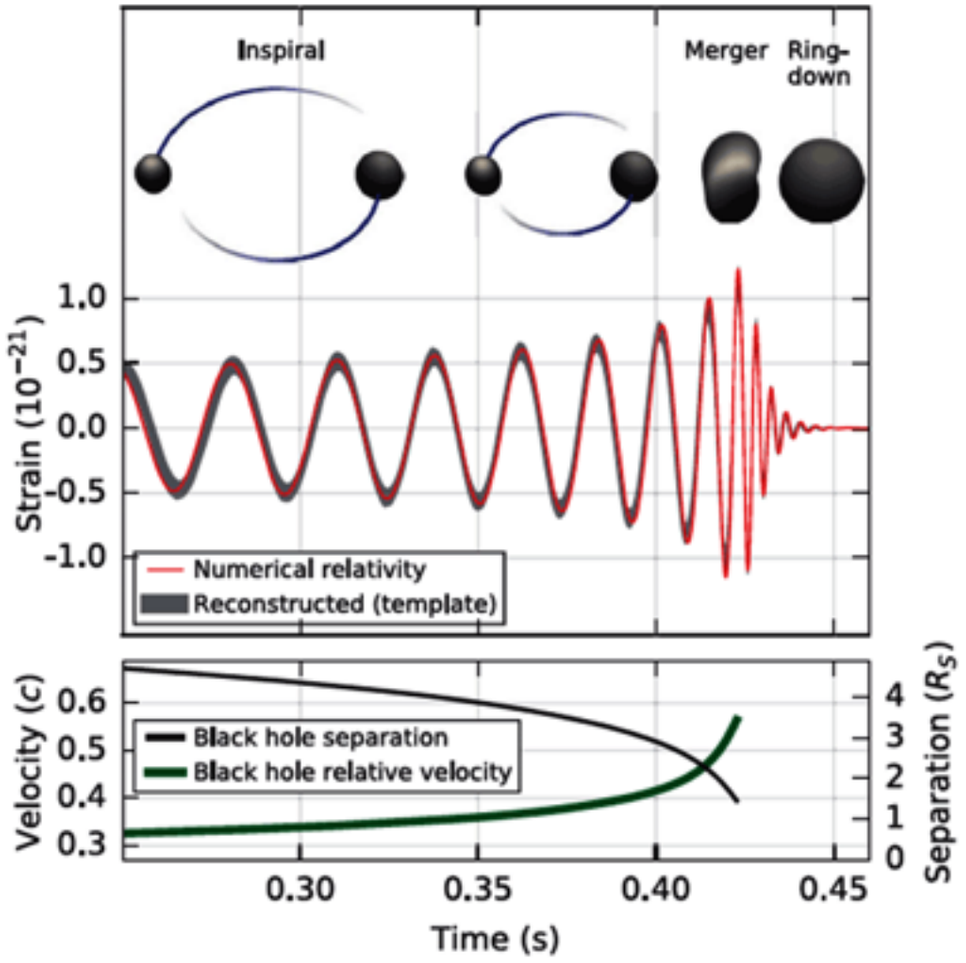
Stringent upper limits
for $m\chi = 1 \ldots 10^4$ GeV

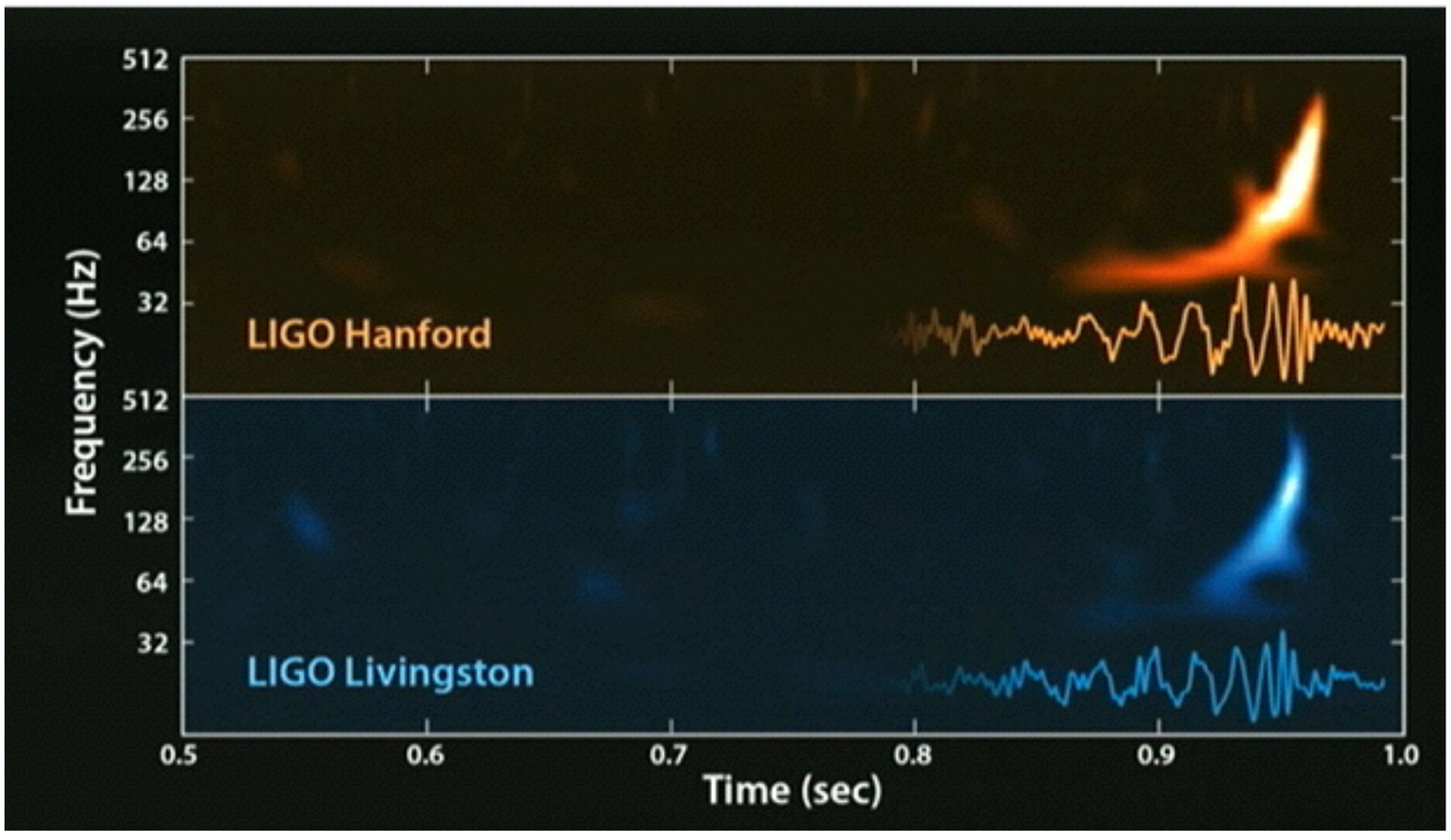
Gravitational Waves:

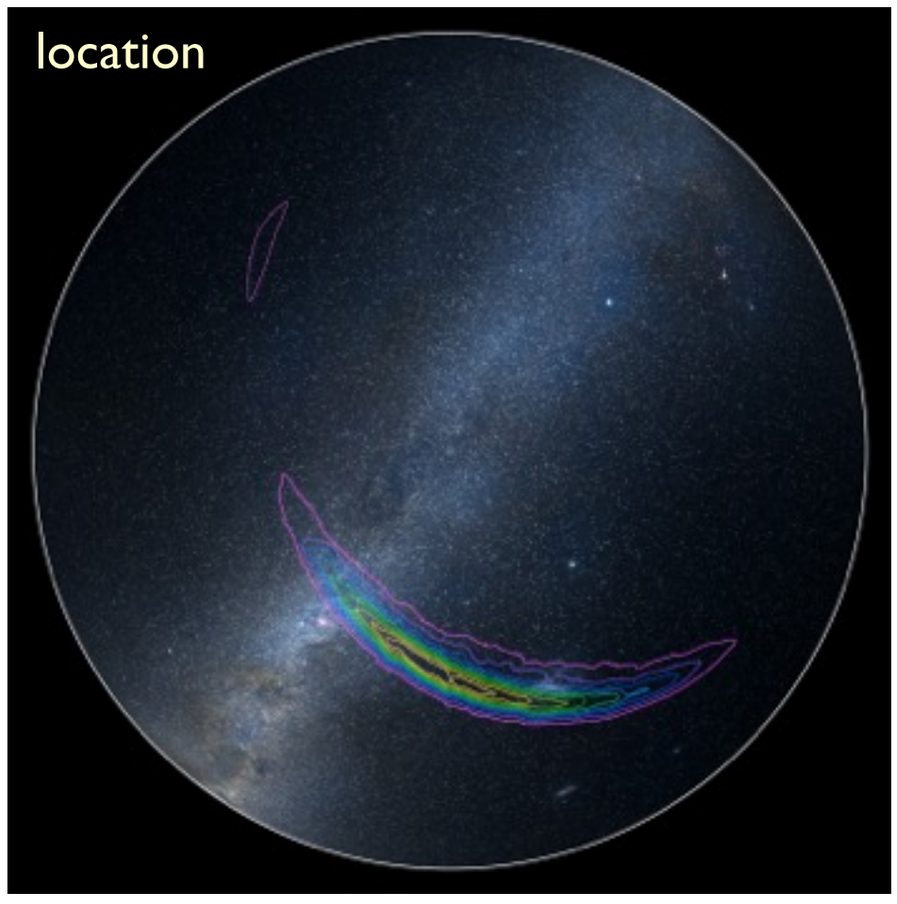
event GW150914 : Merger of two black holes
29 and 36 solar masses
1.3 x 10^9 light years away

New messenger in the multi-messenger approach
to high-energy astrophysics.

Do grav. events produce also other measurable outputs
(light, neutrinos, gamma rays)? Some might …







Summary:

Astroparticle Physics is a highly productive and exciting field.

Highest-energy particles …

- probe the most violent environments in the universe
- are rare & difficult to detect
- provide most energetic particles in universe
- Energetic CRs, gamma rays & neutrinos are connected (likely from the same sources).

Experiments are getting better in detecting them and identifying their origin.

Multi-messenger approach to appreciate all aspects of sources.

Thanks to M Kowalski, T Karg, S Klepser for slides and inputs.