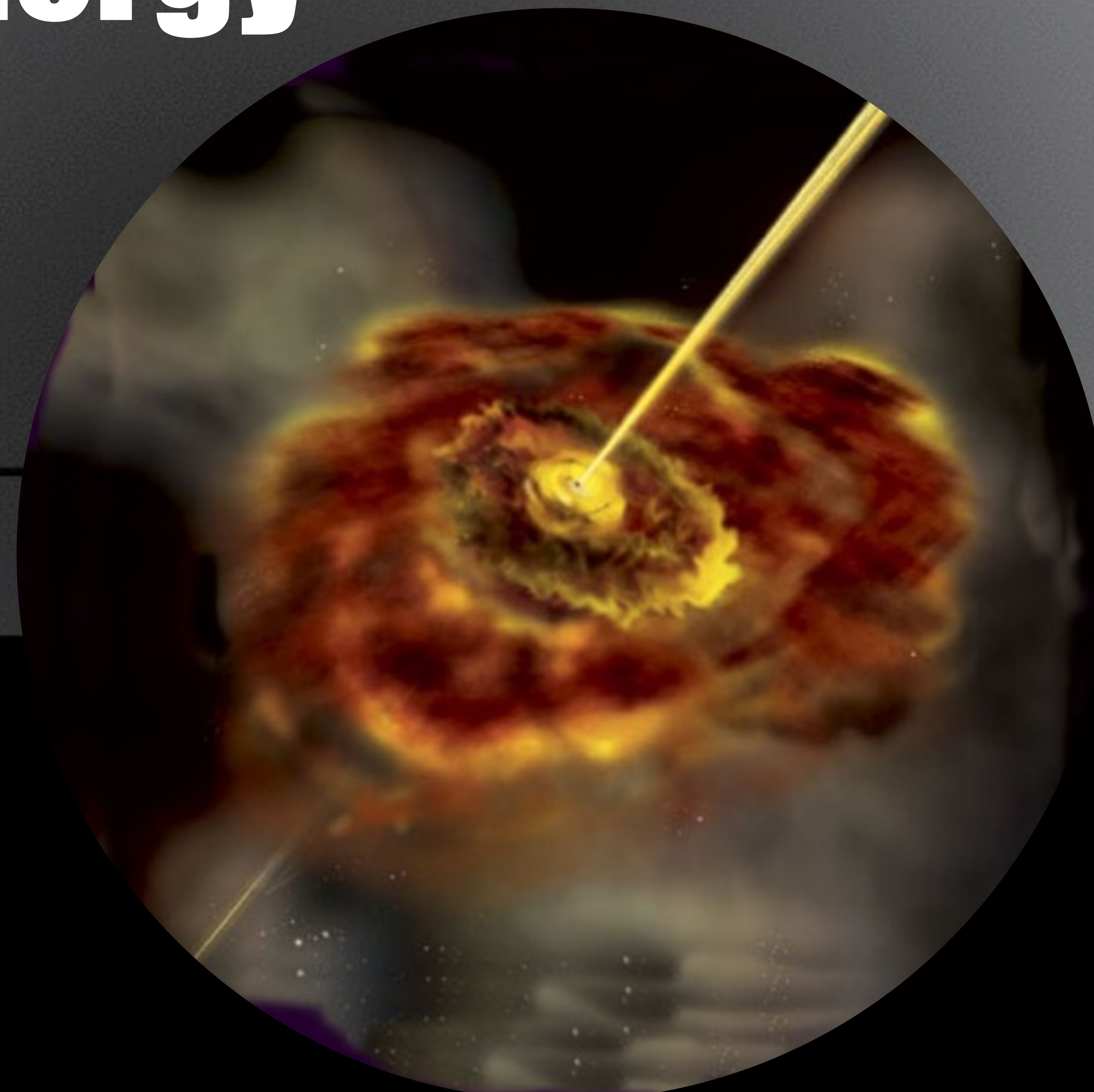
GRK 2149:Strong and Weak Interactions - from Hadrons to Dark Matter

The High-Energy Universe

Experiments, Results
Perspectives



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GRK 2149 and HE-Astroparticle Physics

- **Strong Interactions ⇔ HE Cosmic Rays**
  - Galactic and Intergalactic Propagation
  - Understanding of Extensive Air Showers
  - Forward Physics at LHC, pp cross-sections, etc.

- **Weak Interactions ⇔ HE Neutrinos**
  - Neutrino-Nucleon cross-section
  - Oscillations from Atmospheric Neutrinos
  - Mass Hierarchy, …

- **Dark Matter ⇔ HE Neutrinos, Photons, CRs**
  - DM annihilation in the Sun
  - WIMP - proton cross-sections (spin dependent & independent)
  - Super-Heavy DM searches in CRs, …

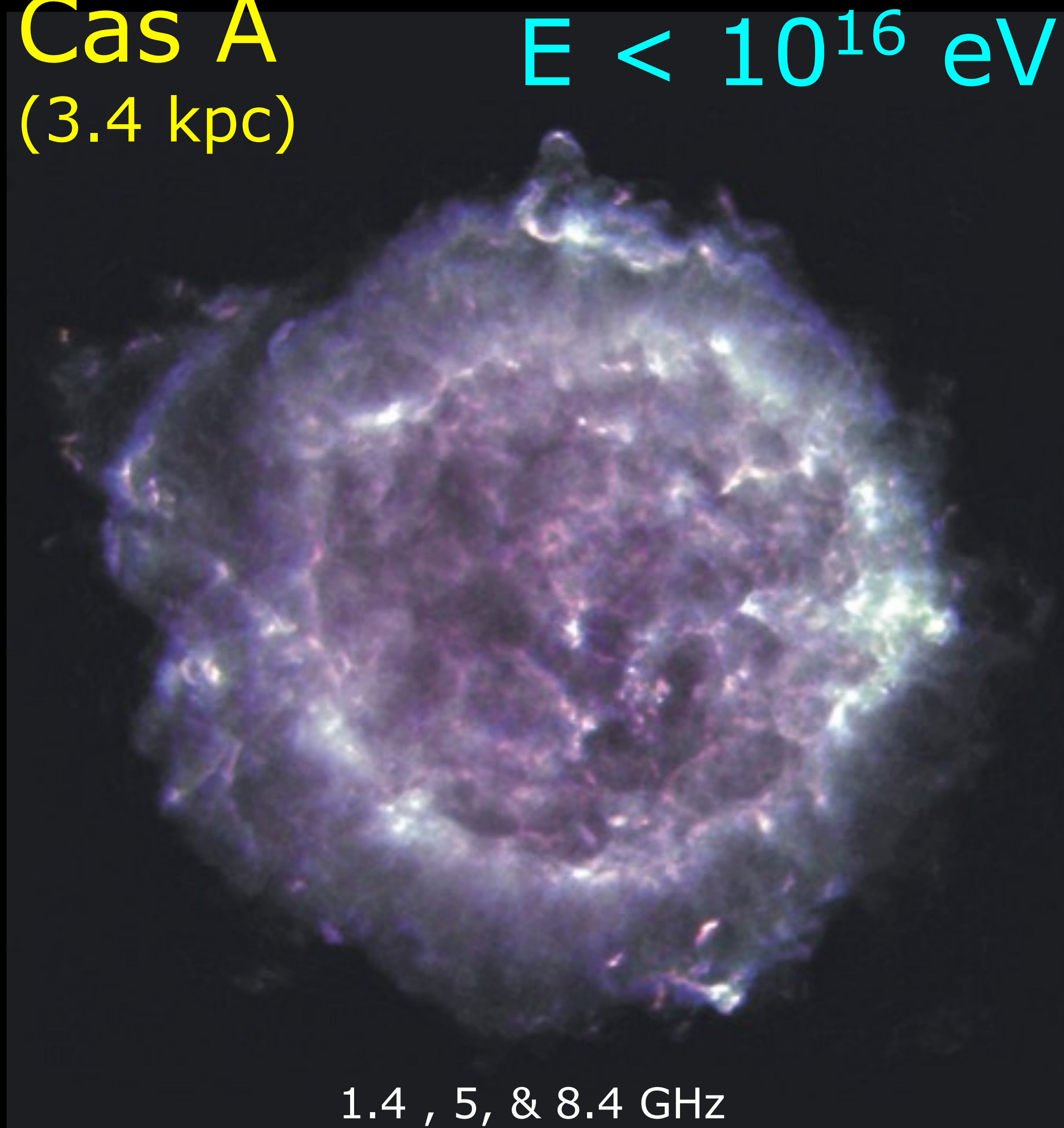
Further Themes of HE-APP

- **Cosmic Particle Acceleration**
  - How and where are cosmic rays accelerated?
  - What is their impact on the environment?
- **Probing Extreme Environments**
  - Processes close to neutron stars massive black holes?
  - Processes in relativistic jets, winds and radio-lobes?
  - Exploring cosmic magnetic fields
- **Physics Frontiers – beyond the SM**
  - Lorentz invariance violation?
  - Smoothness of Space-Time?
  - New particle physics at $\sqrt{s}$=450 TeV ?

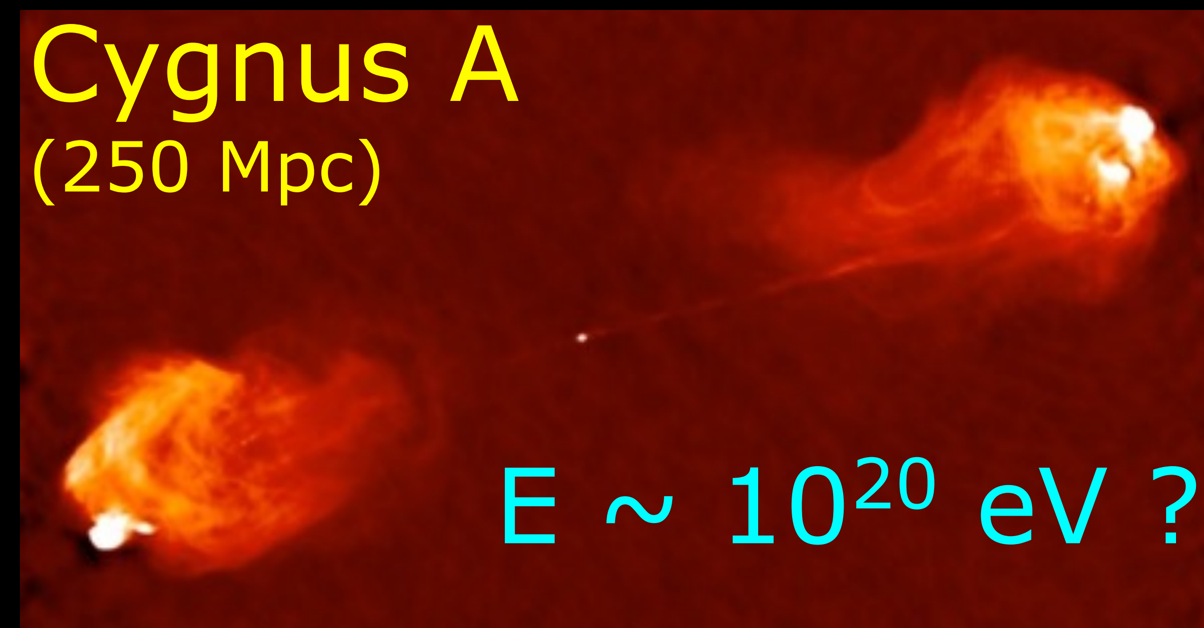
Putative

Cosmic Particle Accelerators

Supernova Remnants

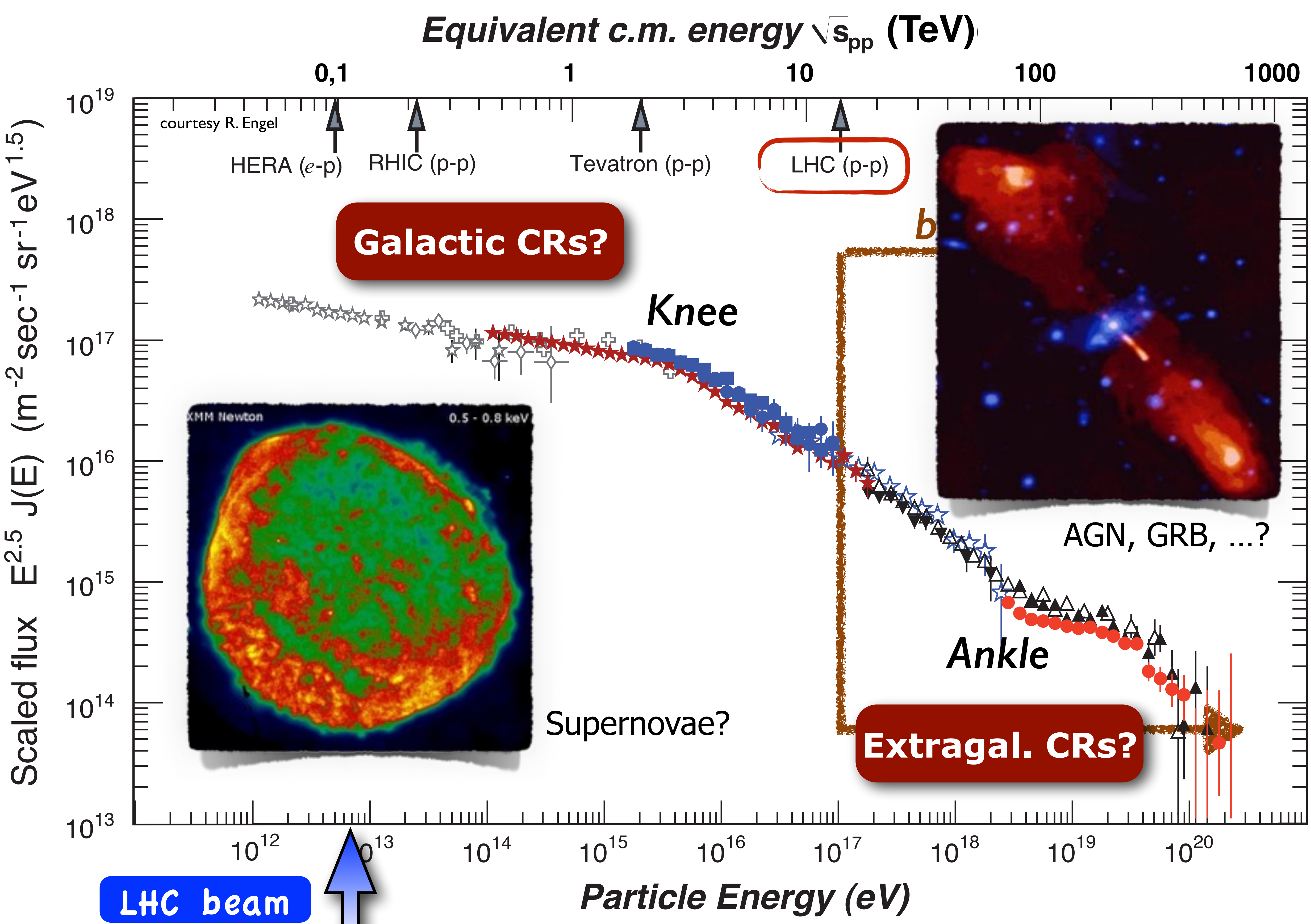


AGN and their Jets/Lobes



NRAO/AUI

Cosmic Ray Spectrum at Earth



Probes of the High-Energy Universe

Charged CRs:

⊕ direct probe. MeV≤E≤ZeV

⊕ mass composition provides vital information

⊖ get deflected in magnetic fields

don't point back to their source, unless E $\gtrsim 5 \cdot 10^{19}$ eV

(This has been the obstacle in identifying sources!)

Photons:

⊕ do point back to their sources! E_{max}~100 TeV

⊖ but origin remains ambiguous because of leptonic processes: Bremsstrahlung, synchrotron radiation, inverse Compton scattering

smoking gun: $\mathbf{p + p \to X + \pi^0 \to X + \gamma\gamma}$

Neutrinos:

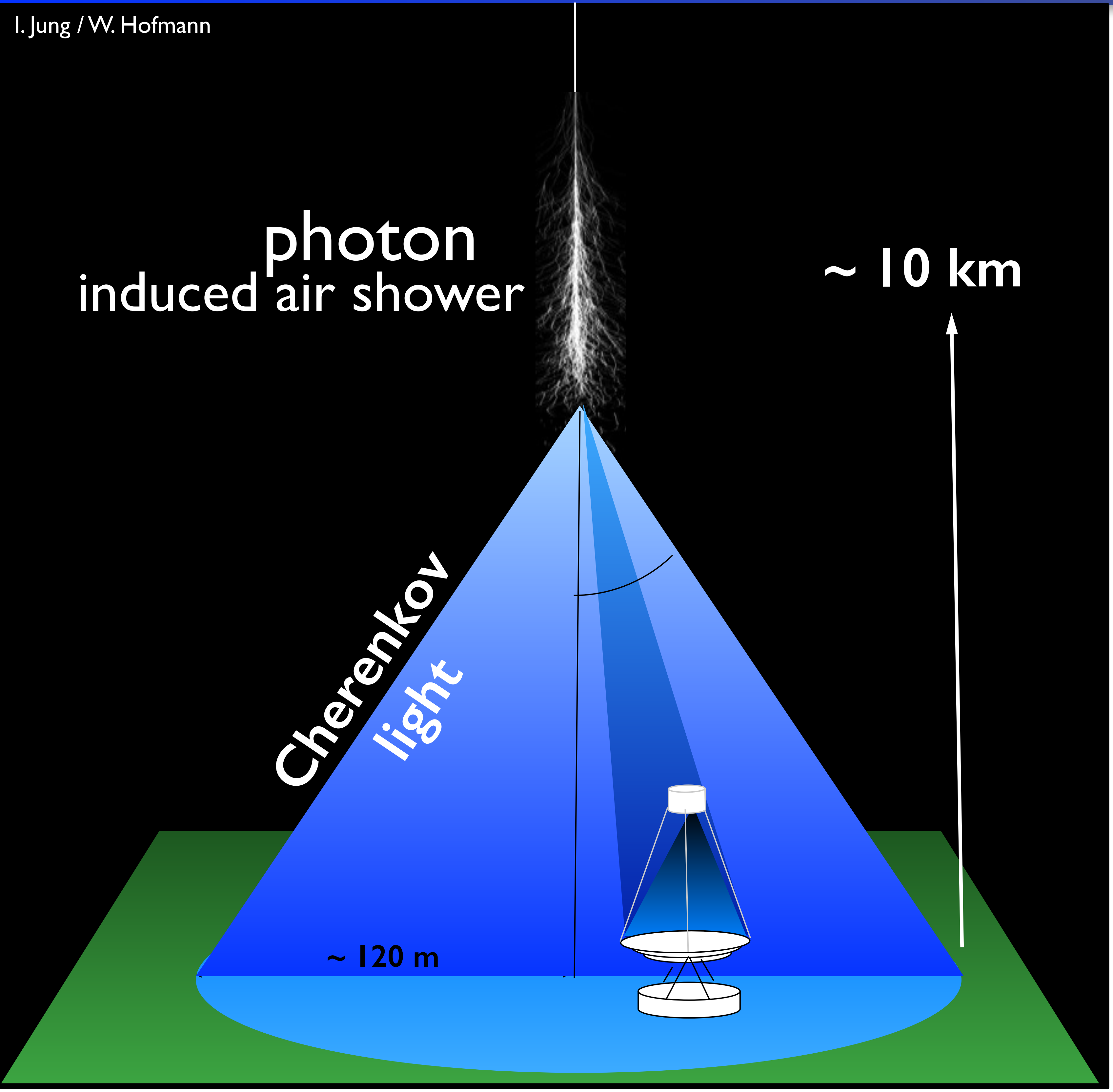
⊕ do point back to their sources. E_{max}~2 PeV

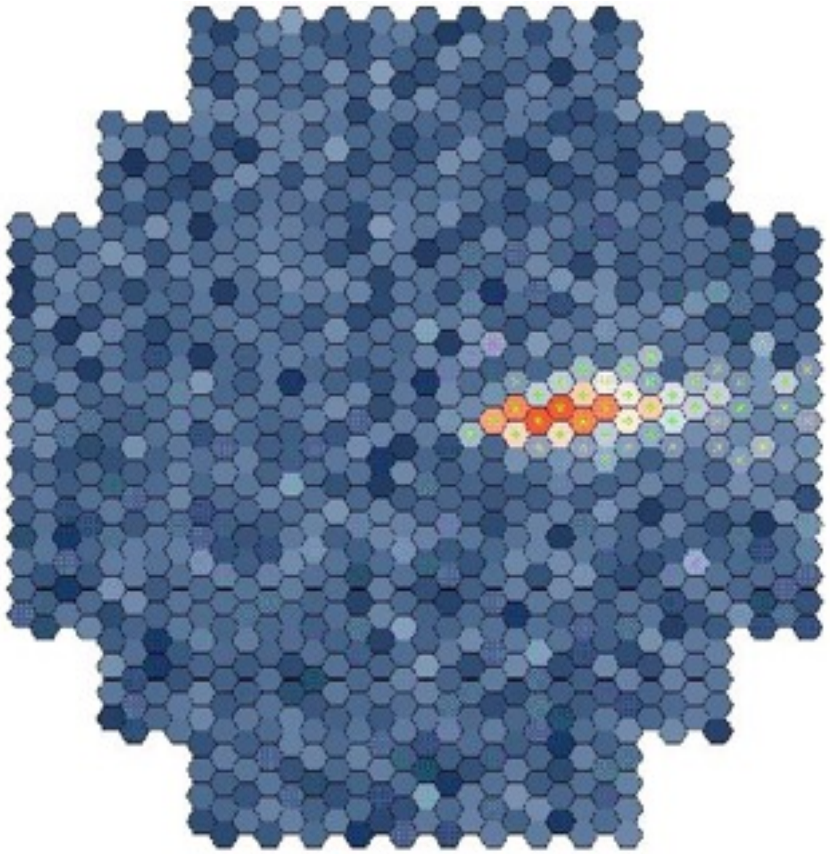
⊕ can only arise from hadronic processes

⊖ need large detector volumes

CRs, γ's, and ν's start to provide complementary information since experiments have reached similar sensitivities!

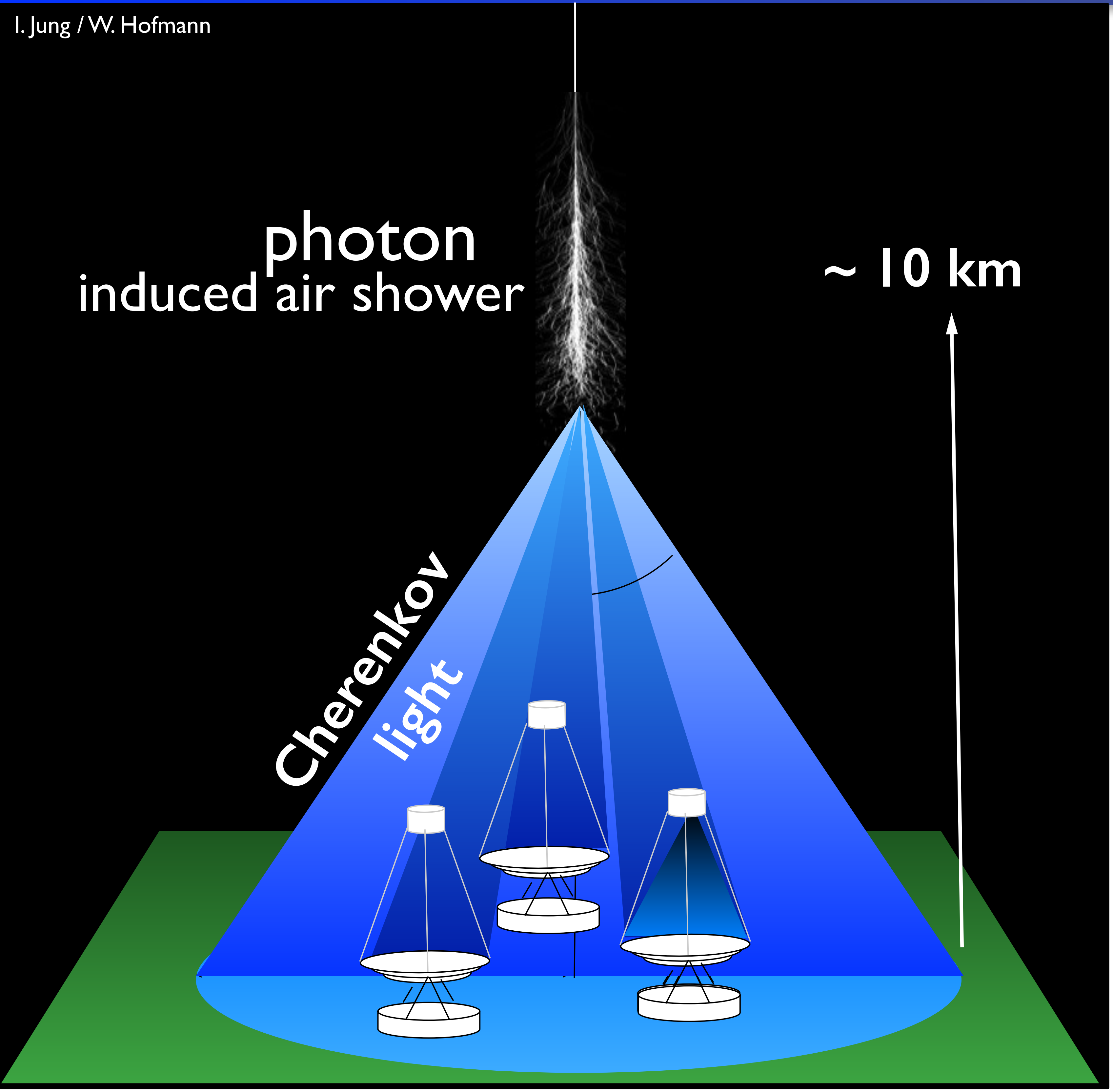
TeV γ-detection

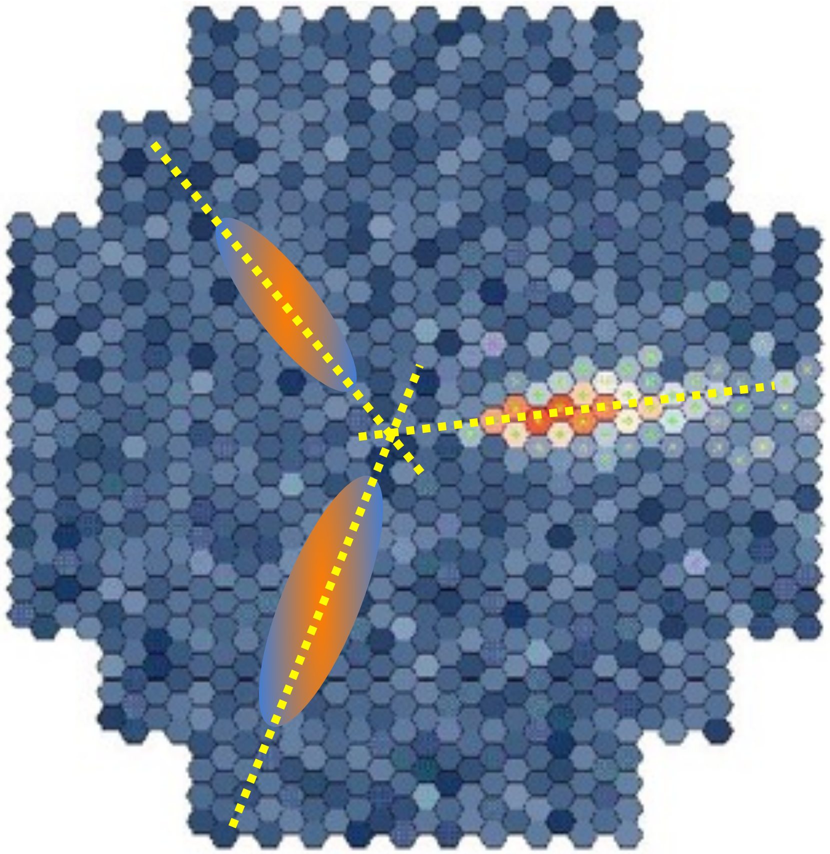




illuminated area: 10^5 m^2

TeV γ-detection

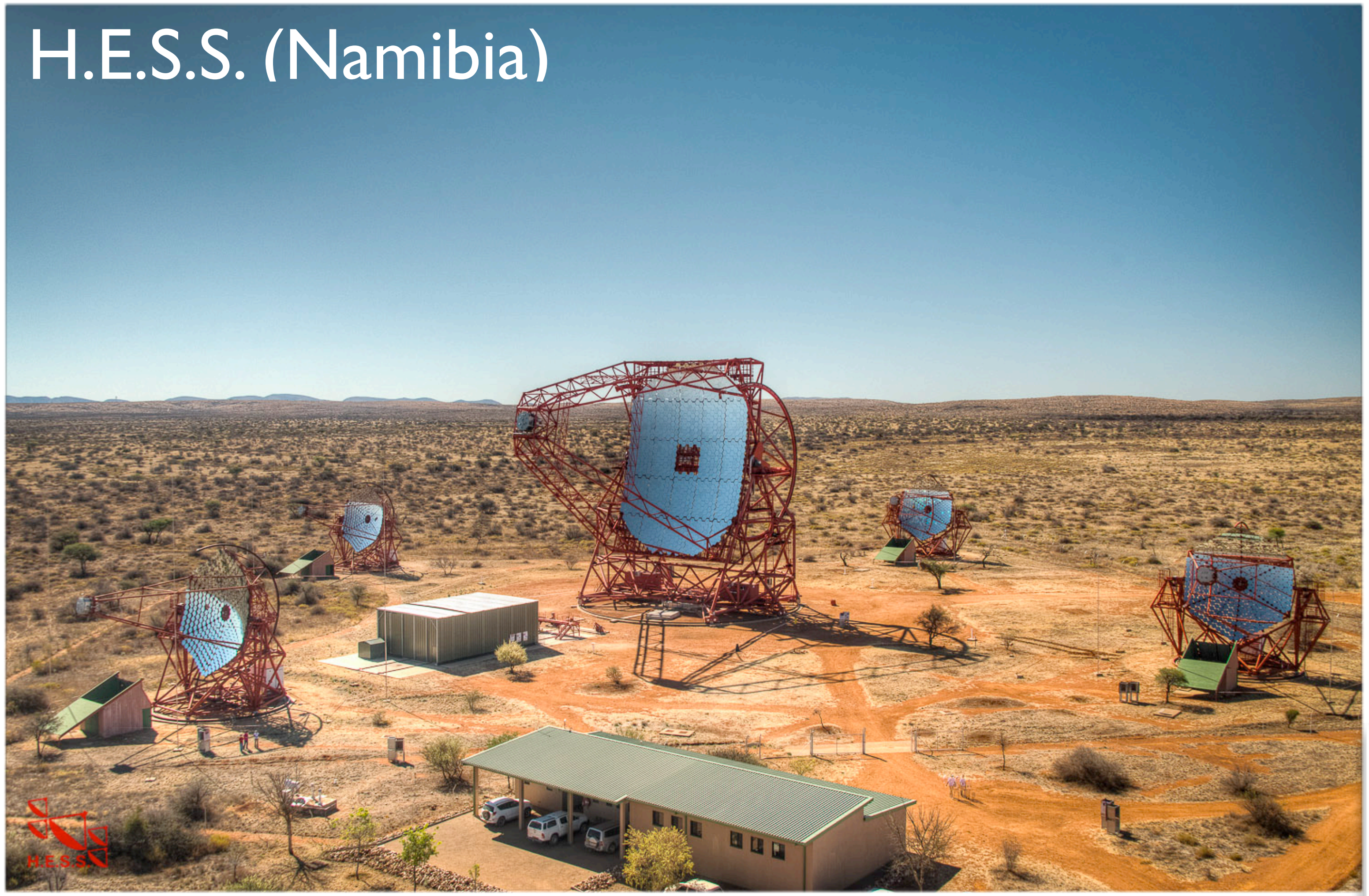




light intensity: energy
intersection: direction

shape: primary particle

H.E.S.S., MAGIC, VERITAS



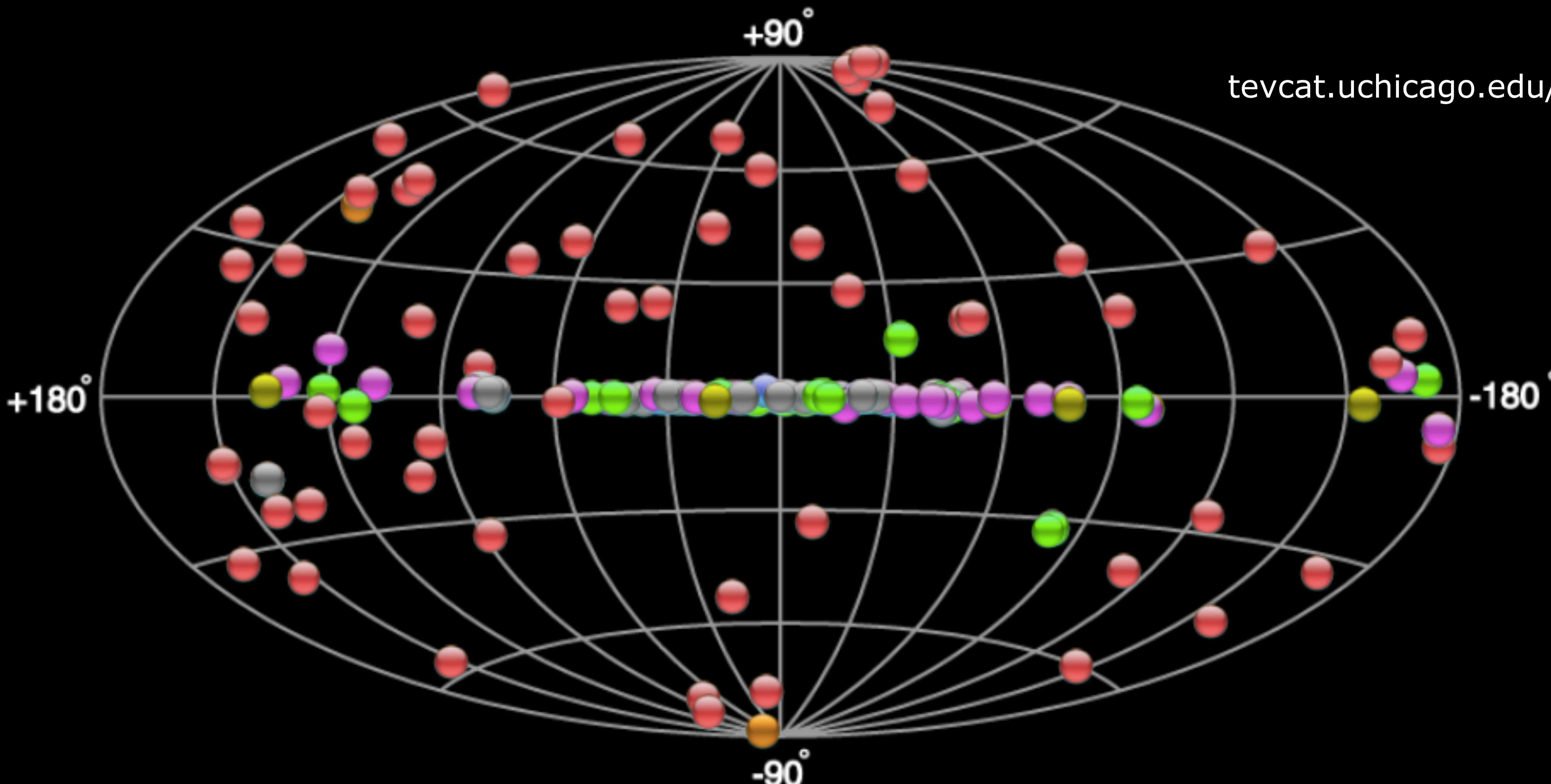
HESS-I: Ø=12 m (4 telescopes)
HESS-II: Ø=28 m (1 telescope)

30 GeV < E_γ < 10 TeV

Two telescopes,
mirror: Ø=17 m

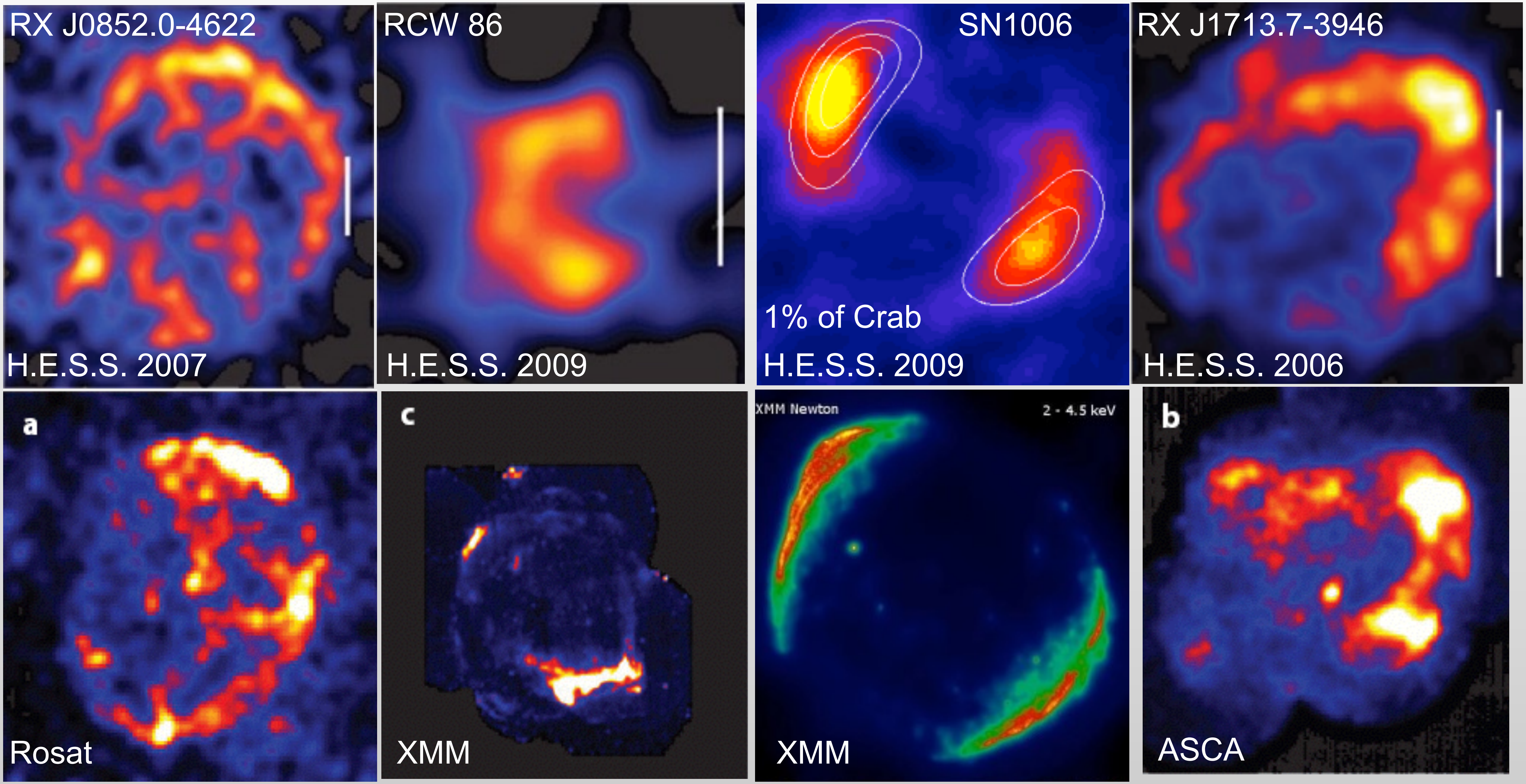
A new branch of astronomy has emerged

157 sources known by now (130 of which were discovered in last 10 yrs)



large variety of sources types and mechanisms
(PWN, starbursts, globular clusters, SNR, AGN, molec. clouds, XRB, …)

SNR Morphologies: TeV vs X-ray



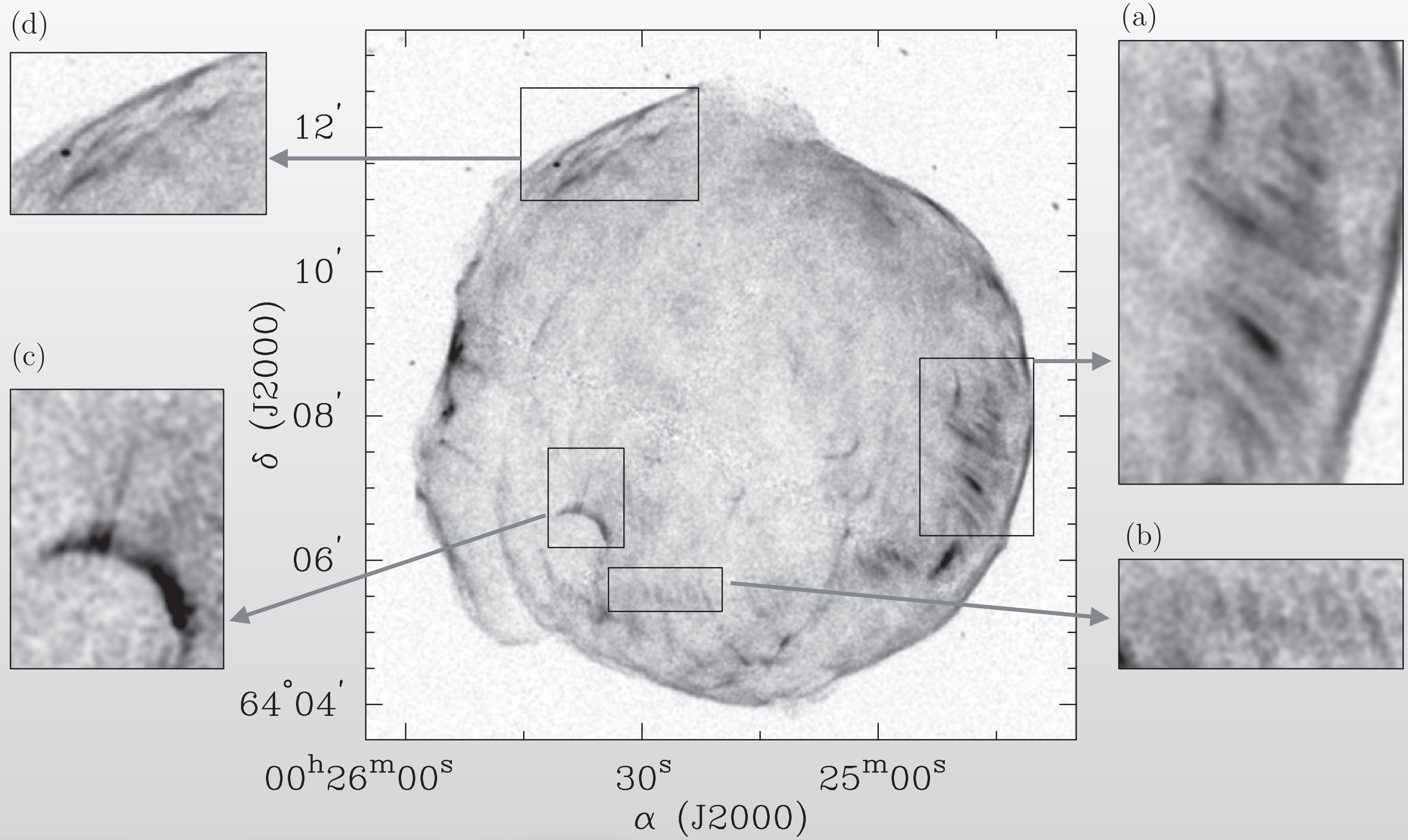
Very similar morphologies in TeV and X-Ray

Open Key Question: are these the sources of galactic cosmic rays ?

Note: TeV photons may result from inverse Compton at TeV electrons!

X-ray images pin down acceleration sites

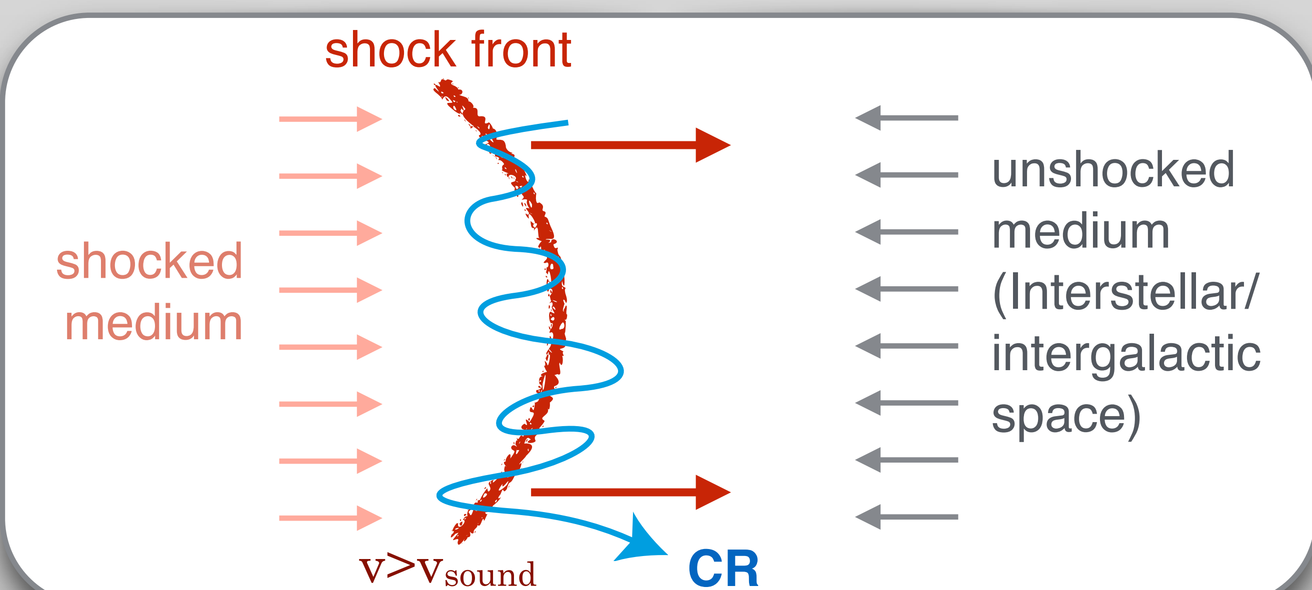
Chandra X-ray image of Tycho SNR (d=4 kpc, v_s=5700 km/s); Kristoffer et al, ApJ 728 (2011) L28



non-thermal X-ray spectra observed

stripes due to plasma instabilities ?

separation ≙ gyro-radius of E_p~10^{15} eV



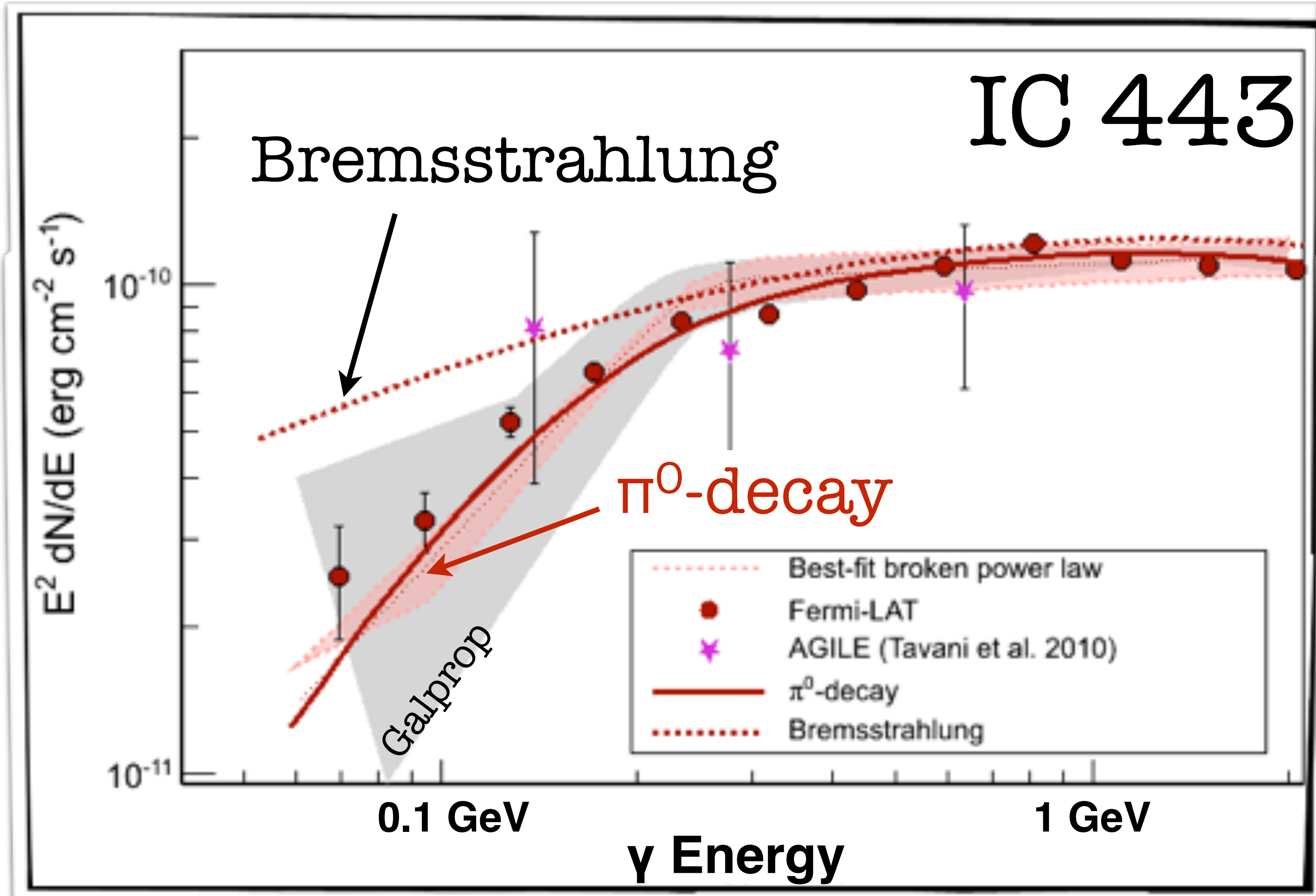
Mechanism of shock acceleration well established

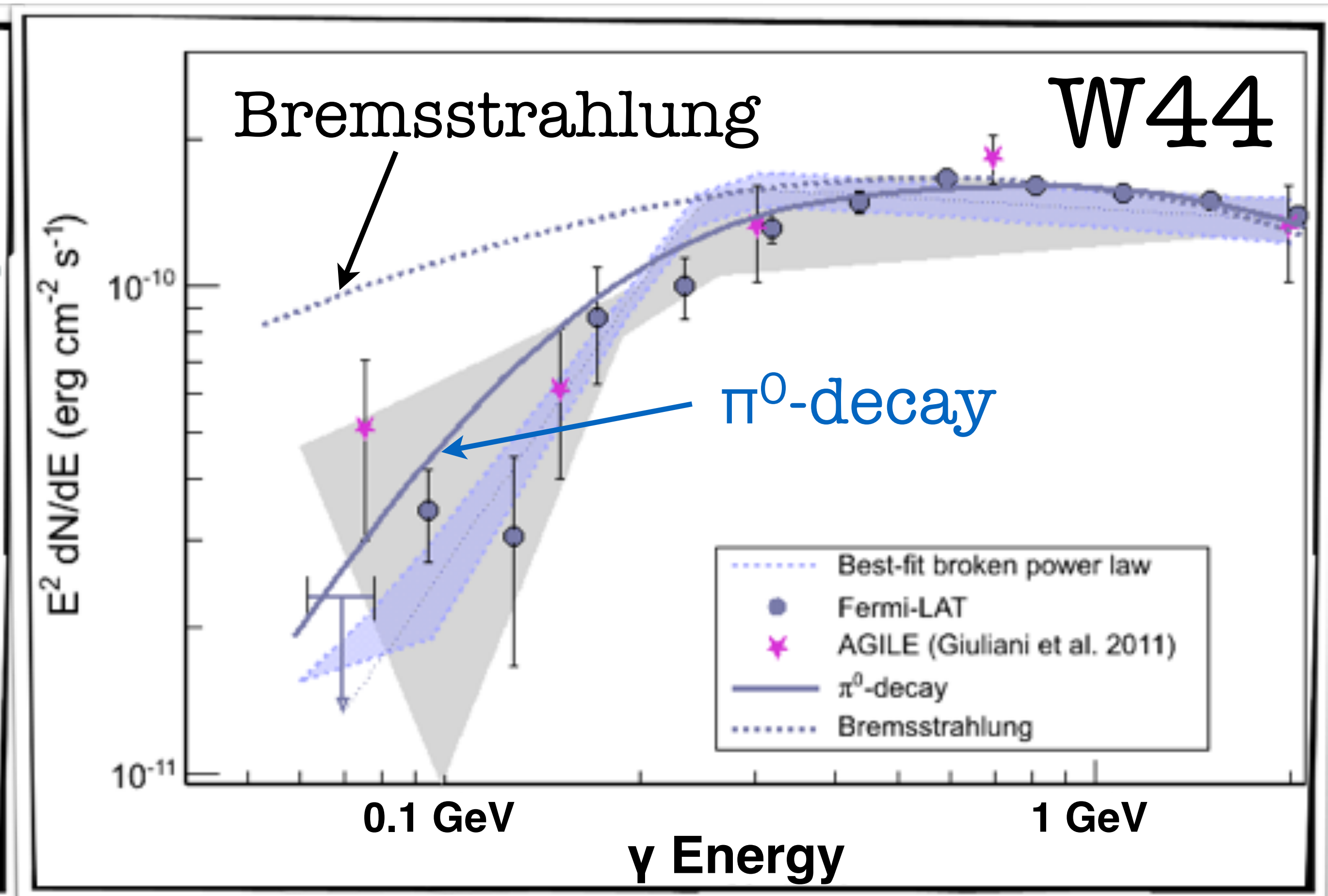
Magnetic field amplification by particle acceleration

First glimpse of hadron acceleration?

Seeing the π^0 hump: $p_{CR} + p_{medium} \rightarrow X + \pi^0 \rightarrow X + \gamma\gamma$

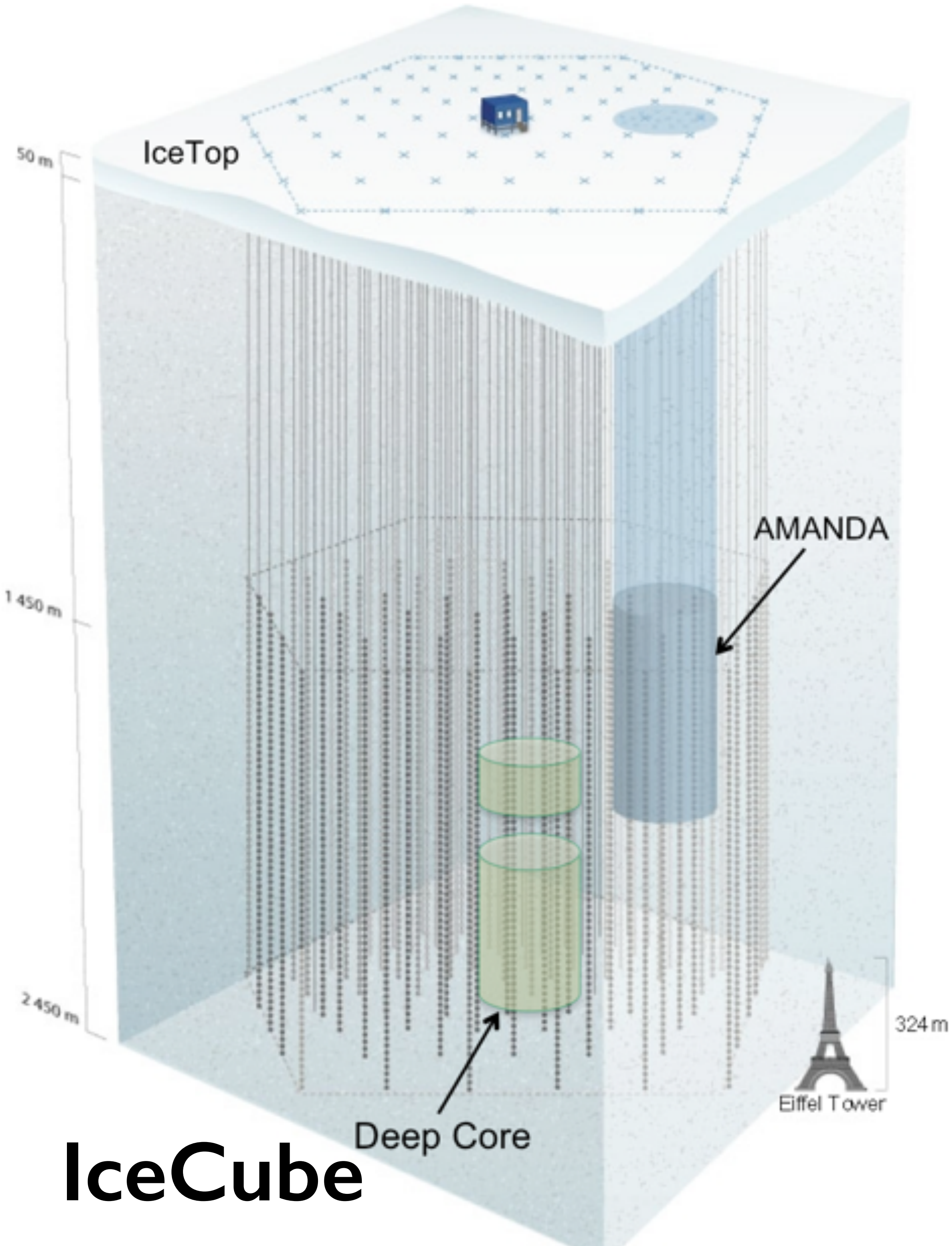
Ackermann et al. (Fermi-LAT collaboration), Science 339 (2013) 807



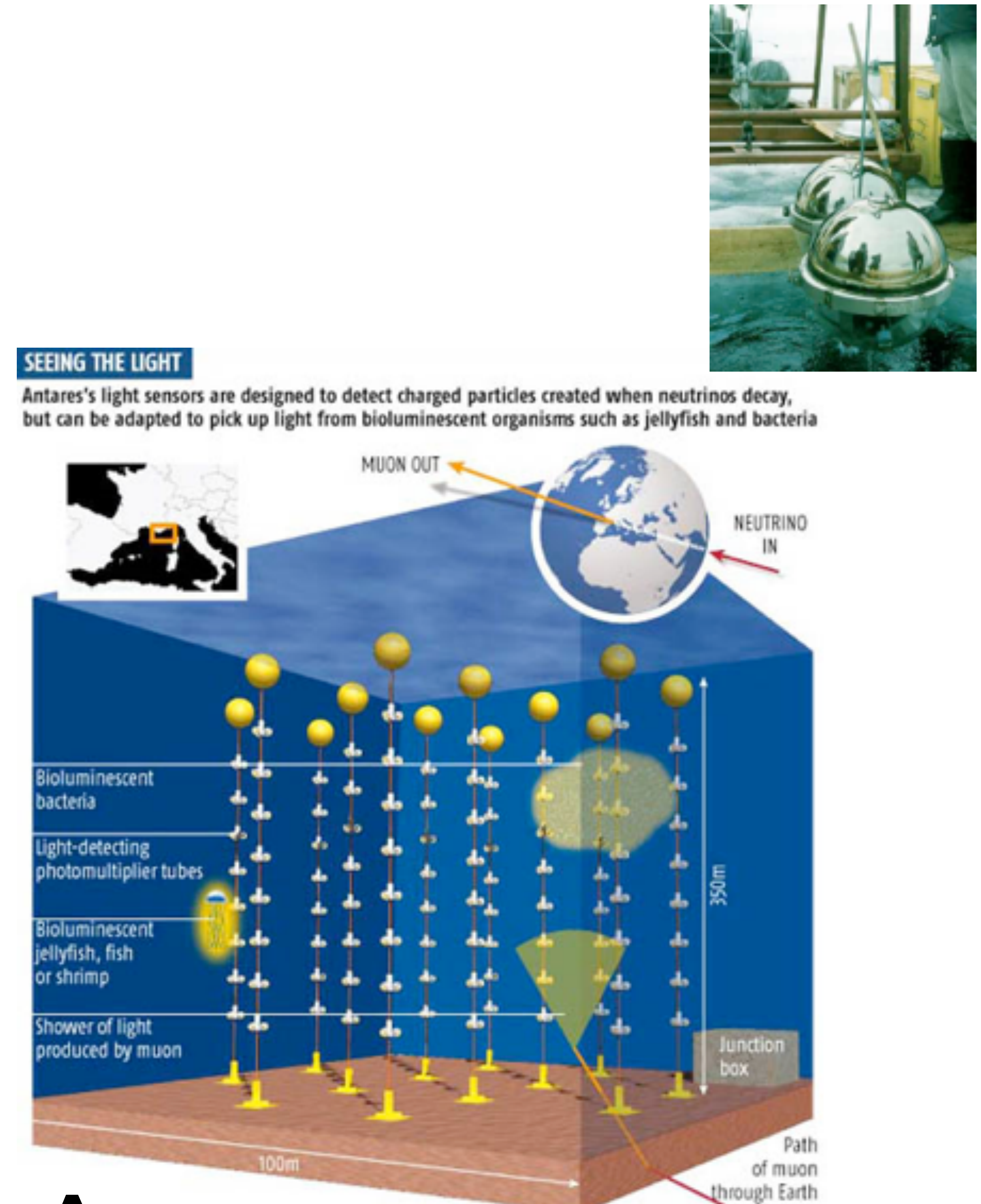


Is this a rock solid proof for a 100 year old problem?
Neutrinos may provide the final proof

High-Energy Neutrino-Astronomy

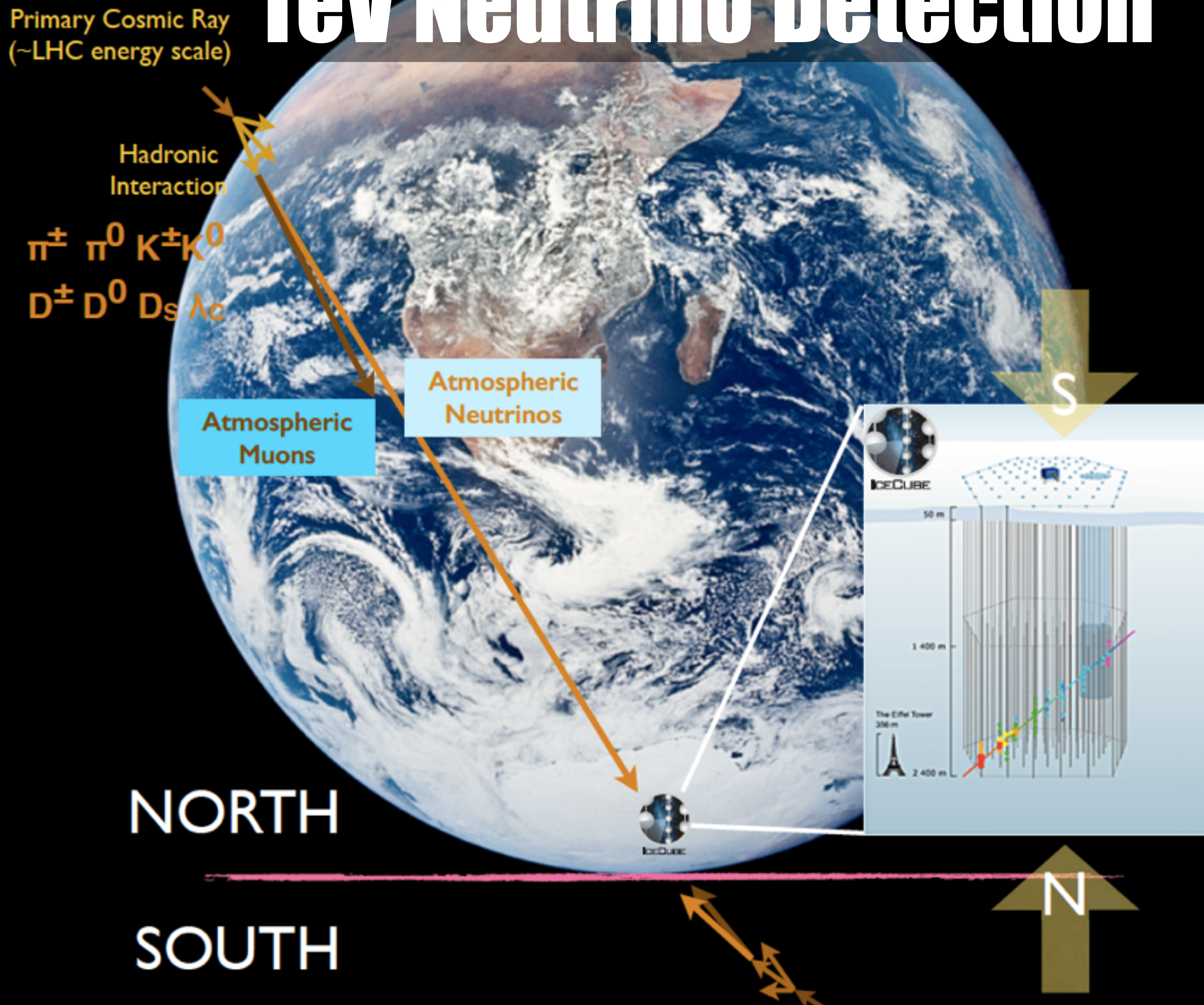


IceCube



Antares

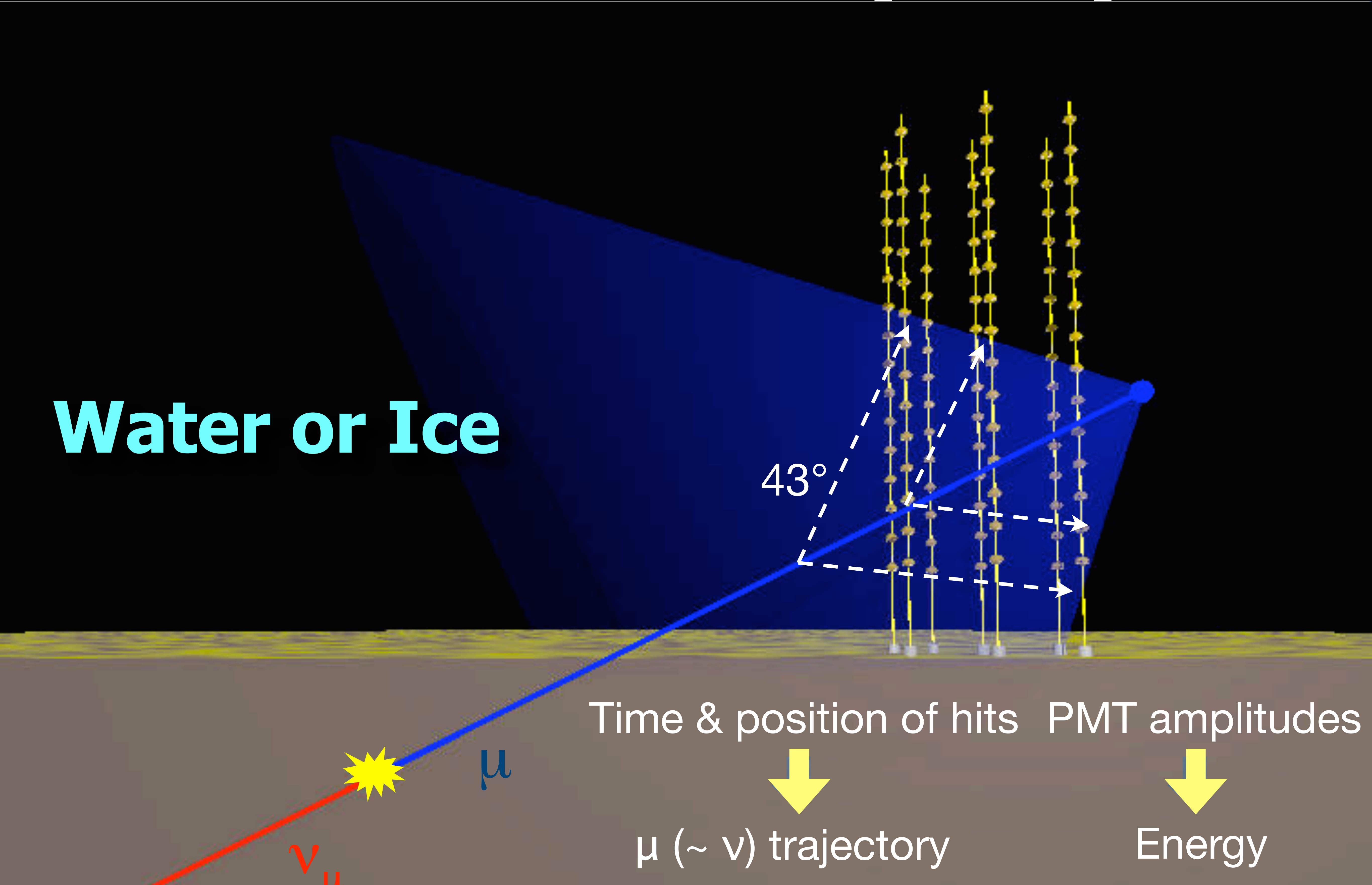
TeV Neutrino Detection



Karl-Hein:

courtesy: E. Resconi

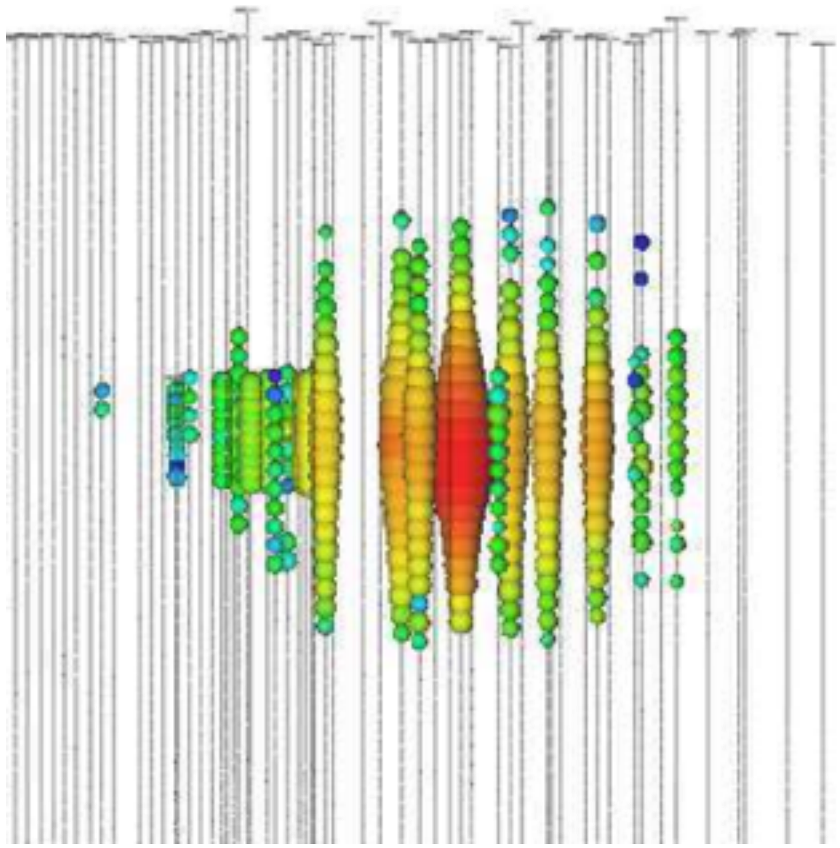
Neutrino Detection (principle)



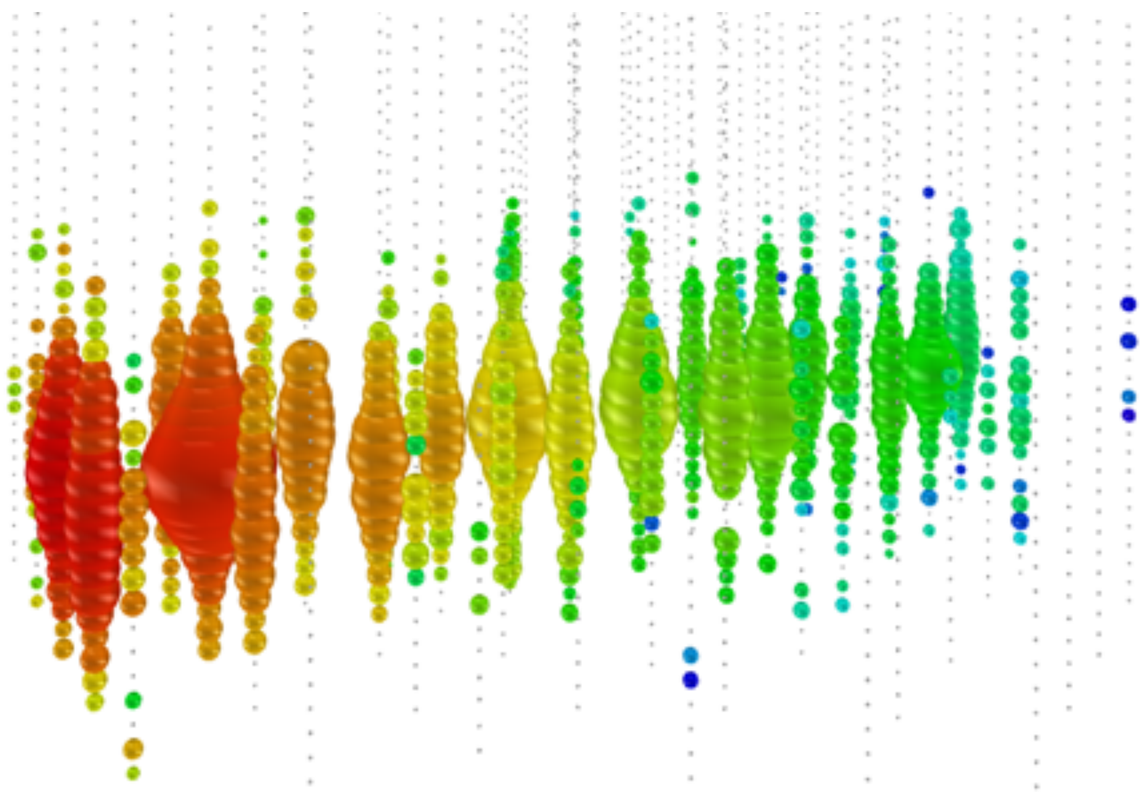
Discovery of HE extraterrestrial neutrinos

37 events in 3 yrs IceCube sample

color: arrival time ; blob size: no. of photons



cascade like pattern from e.g. $\nu_e \rightarrow e$
(NC interaction)

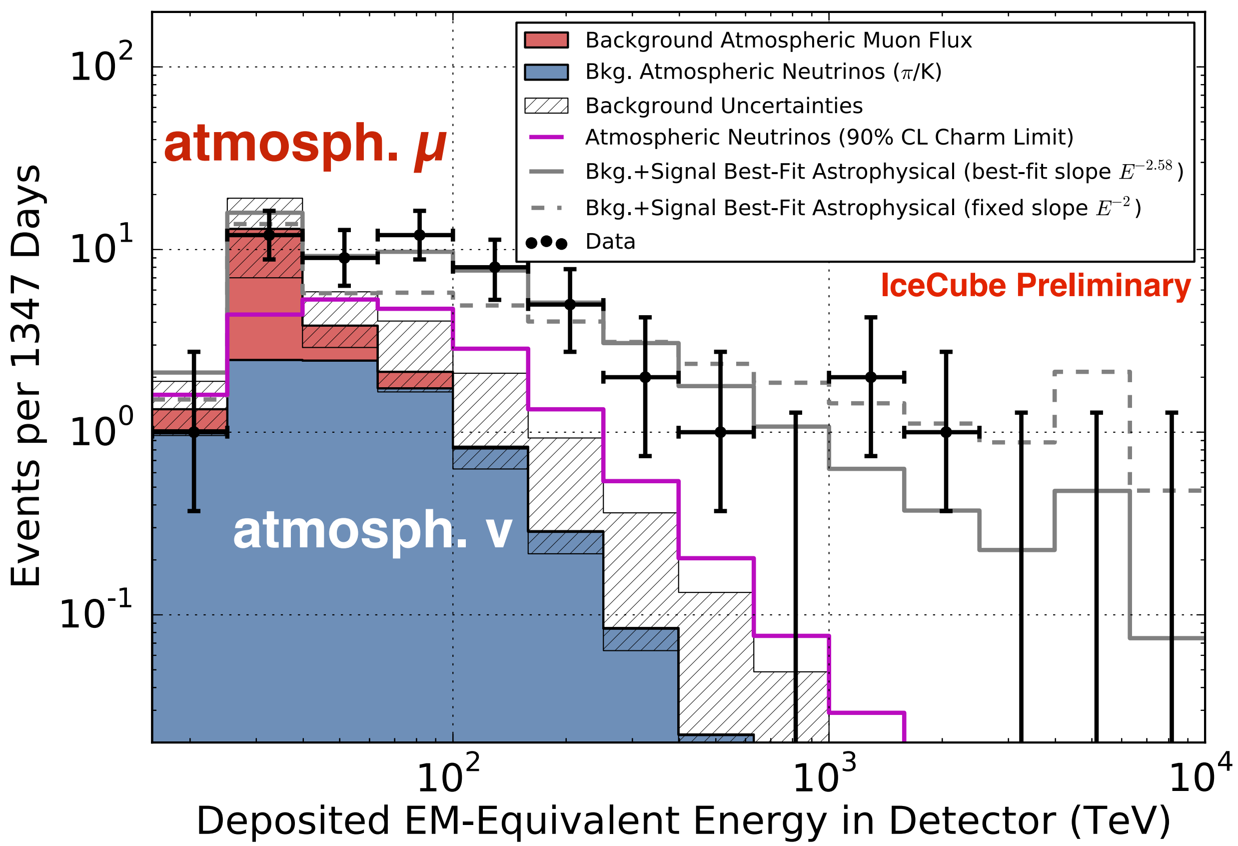


track like pattern from $\nu_\mu \rightarrow \mu$
(CC interaction)

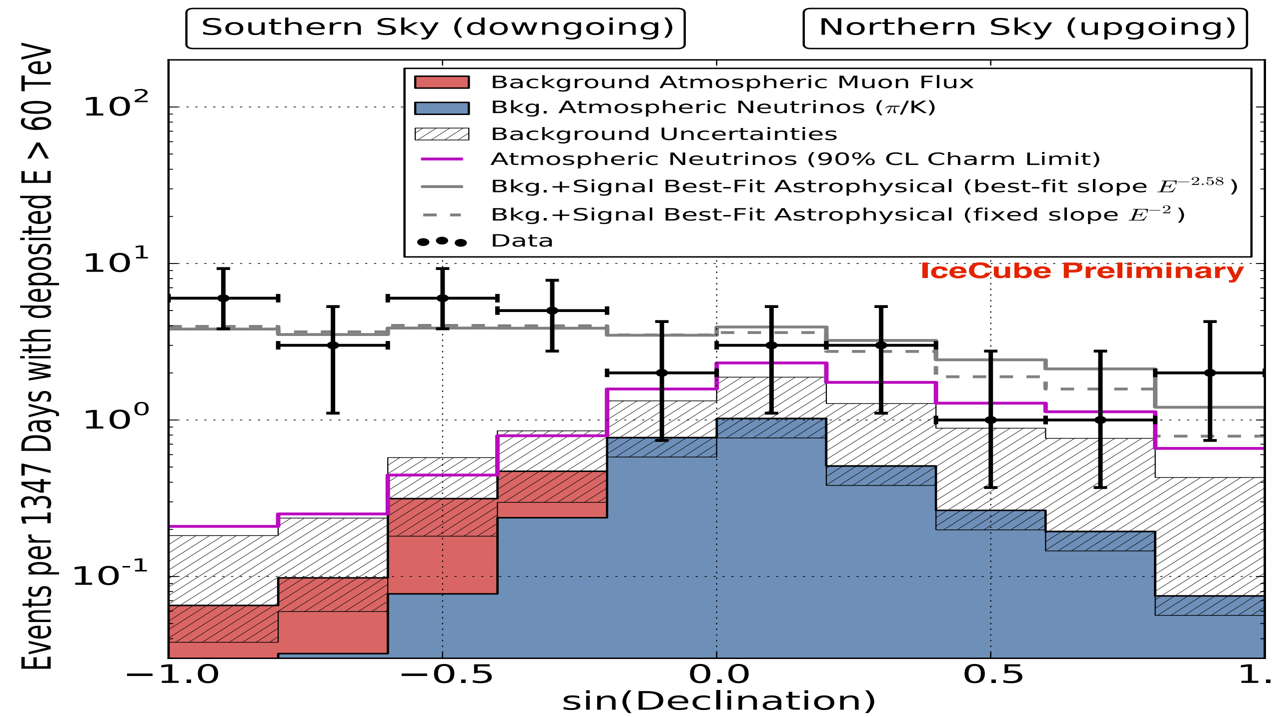
IceCube-Collaboration, Phys. Rev. Lett. 111, 021103 (2013).

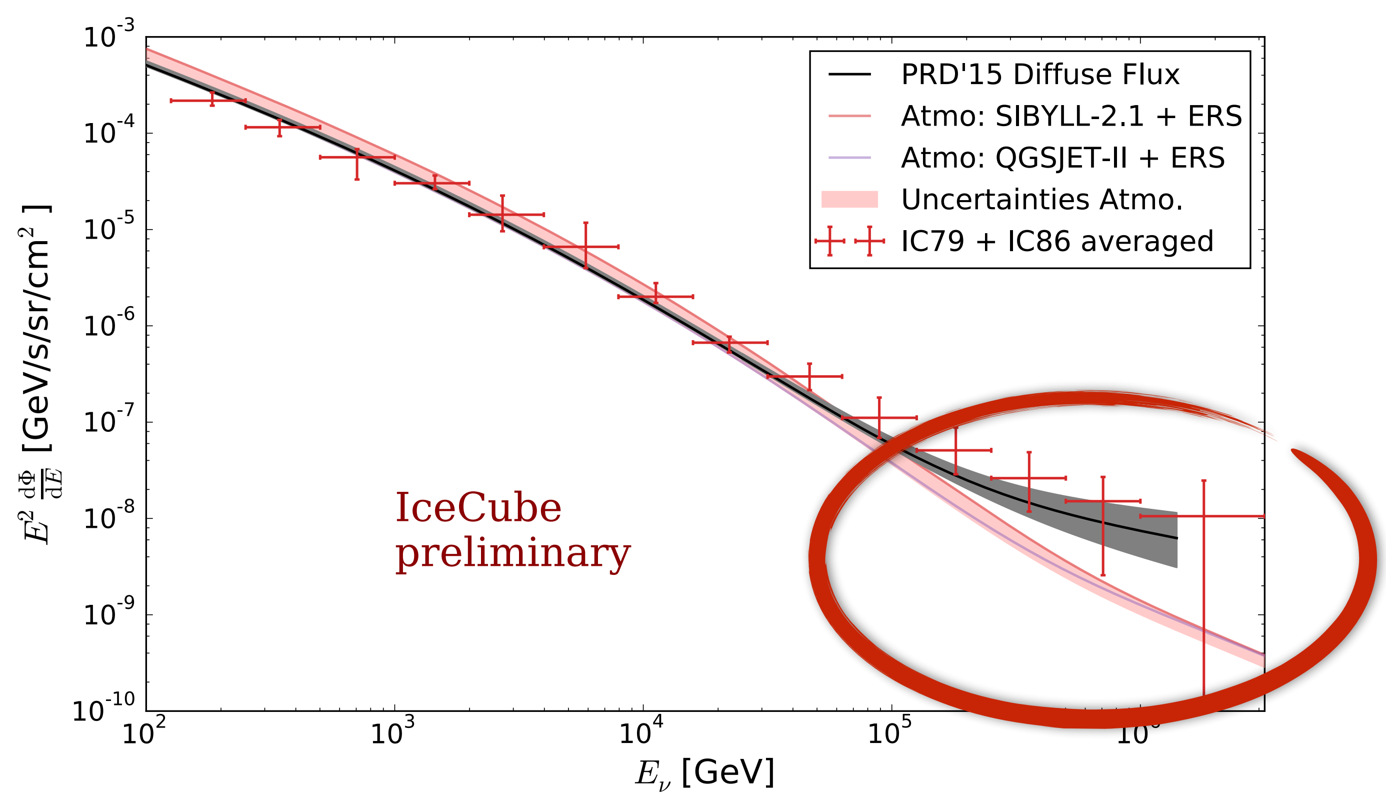
Energy Spec & Declination dependence

> 5 σ excess



IceCube Collaboration:
Phys. Rev. Lett. 113 (2014) 101101; ICRC2015





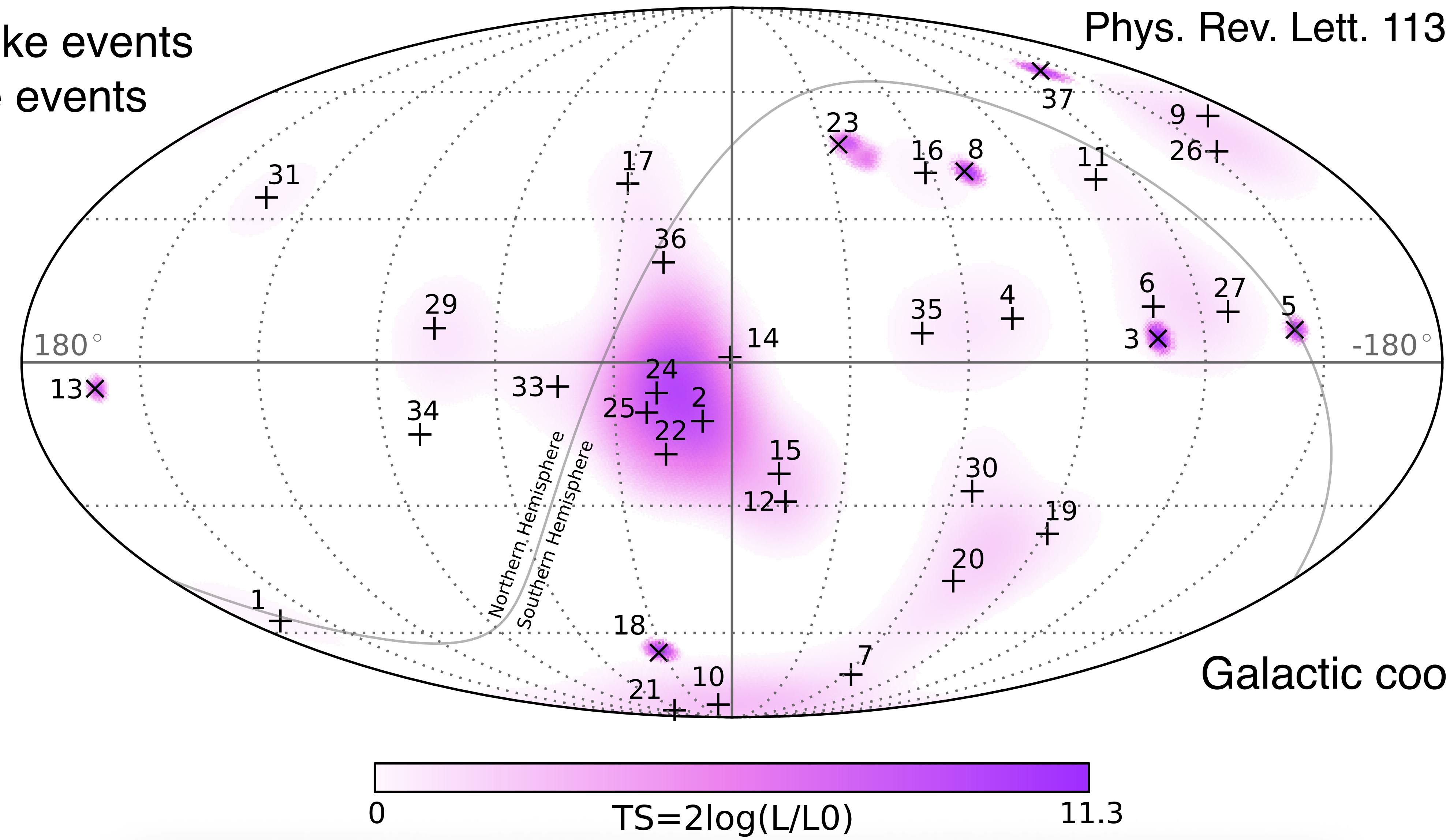
Data consistent with (f_e,f_μ,f_τ)=(1:1:1) flavor ratio at Earth

Atmospheric and astrophysical neutrino fluxes

Neutrino Sky-Map

IceCube Collaboration:
Phys. Rev. Lett. 113 (2014) 101101

+: Shower like events
x: Track like events



Galactic coordinates

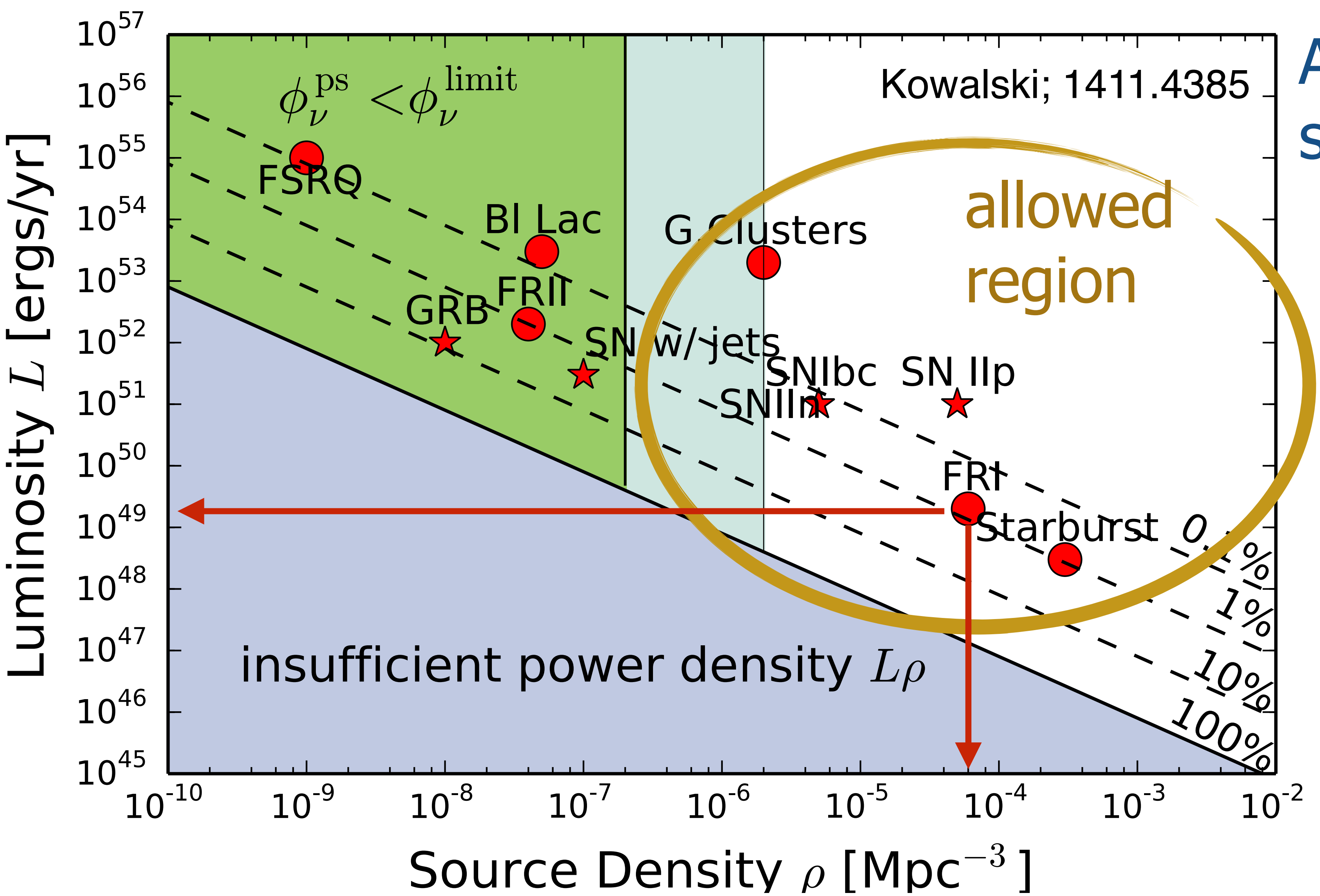
No significant clustering seen (p=84%)

cross correlations to catalogs ⇛ no signal yet

… to UHECRs ⇛ may be…

Constraints from Neutrino-Isotropy

High level of Isotropy ⇛ source density must be fairly high
Integral Flux F=ρ·L is known ⇛ Mean Luminosity per source must be low

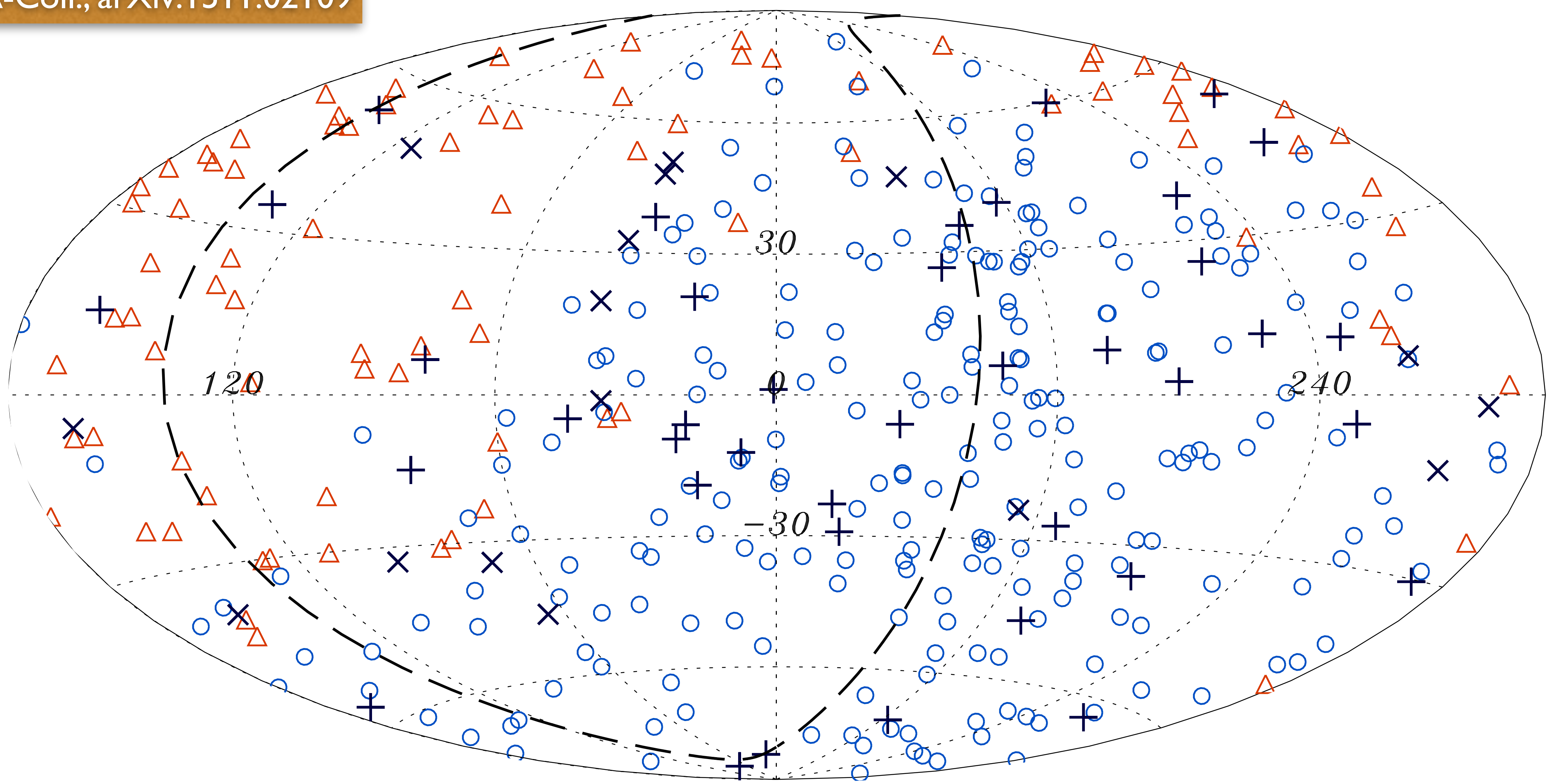


Assumption:
steady point sources

Numbers compare well to UHECRs !

UHECR-Neutrino correlations?

IC+ Auger+TA-Coll., arXiv:1511.02109



△ TA >57EeV ; ○ Auger >52EeV; × IceCube cascades ; + IceCube tracks

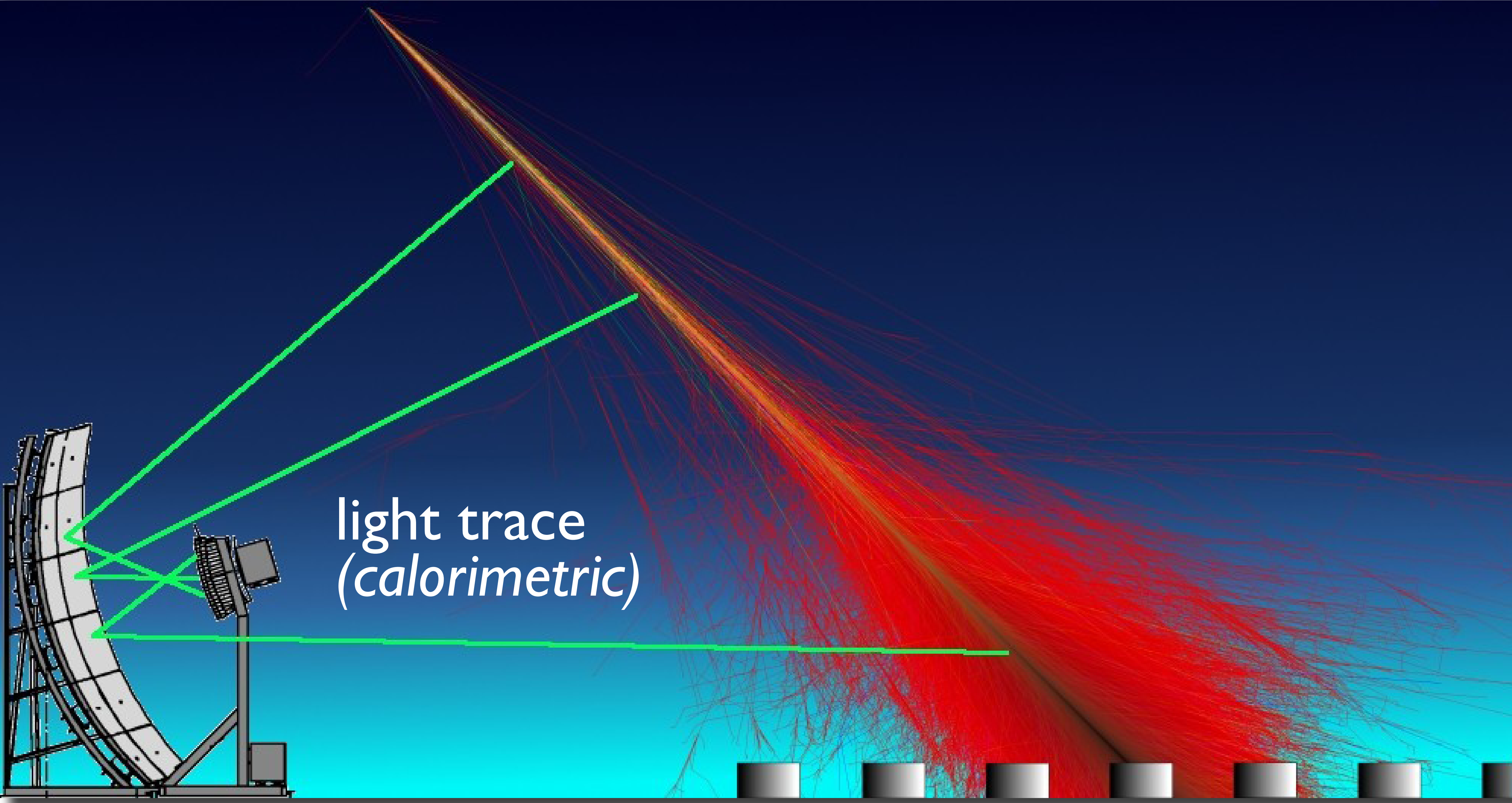
cross correlation and stacking analysis was performed

cascade events: smallest pre-trial value for 22°: 575 pairs observed, 490 expected

⇒ **post-trial p-value of $5 \cdot 10^{-4}$** ($8.5 \cdot 10^{-3}$) **assuming isotropic CRs** (ν's)

Potentially interesting, will be monitored

Observation of Extensive Air Showers

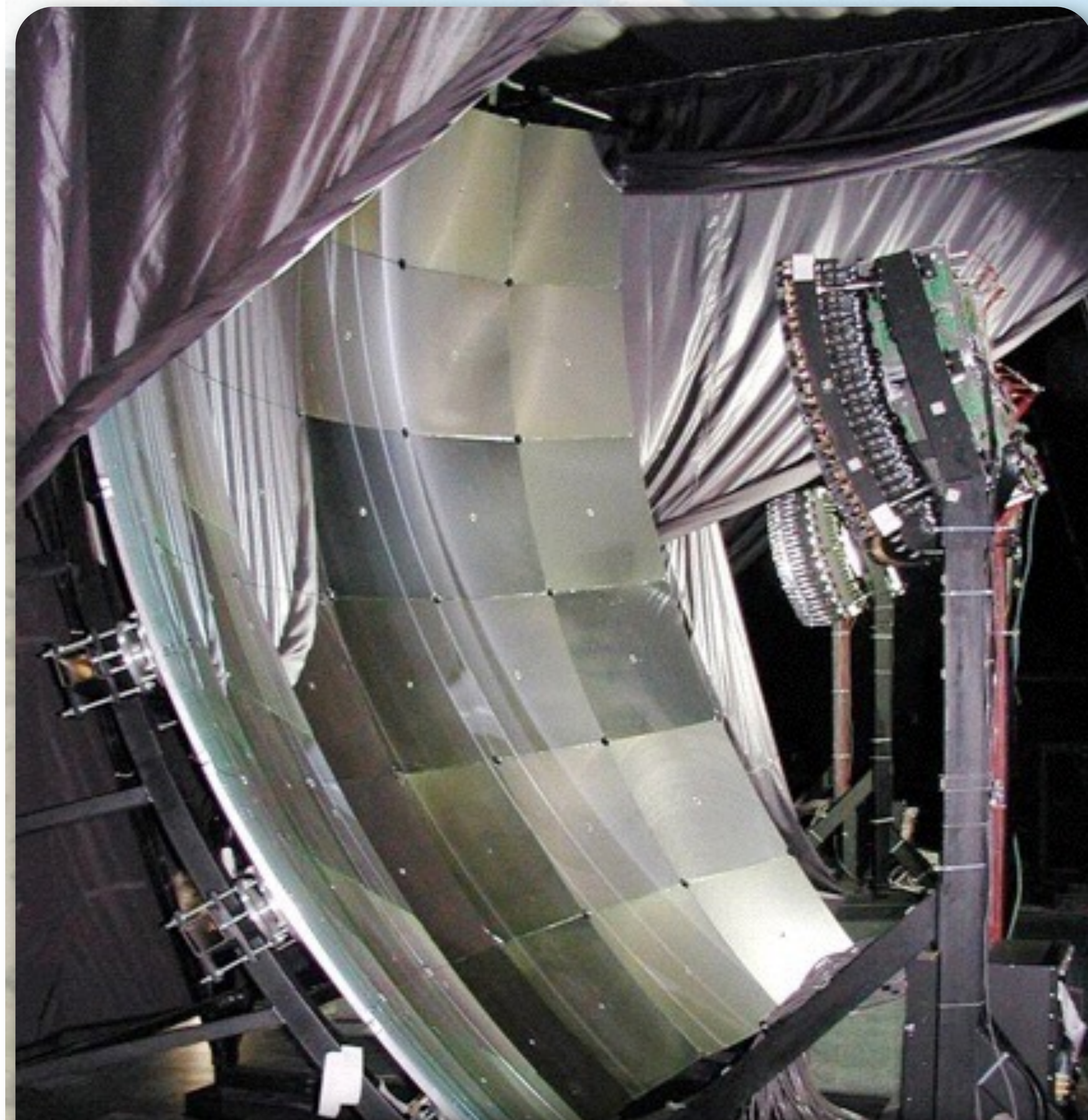


particle density and composition measured at ground

Also:
Observation of radio signals

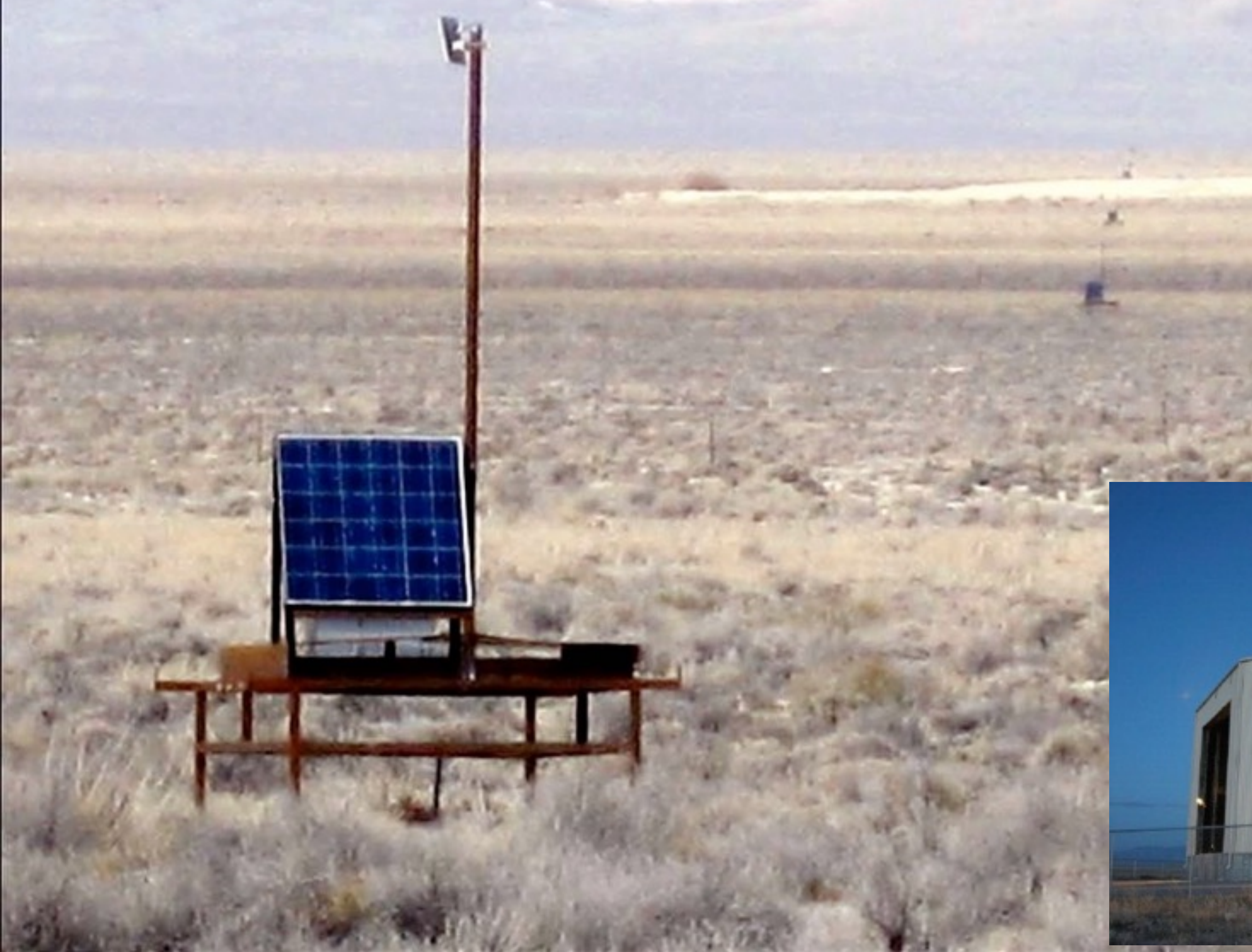
Auger Hybrid Observatory

3000 km^2 area, Argentina
27 fluorescence telescopes plus
...1660 Water Cherenkov tanks, 10 m^2

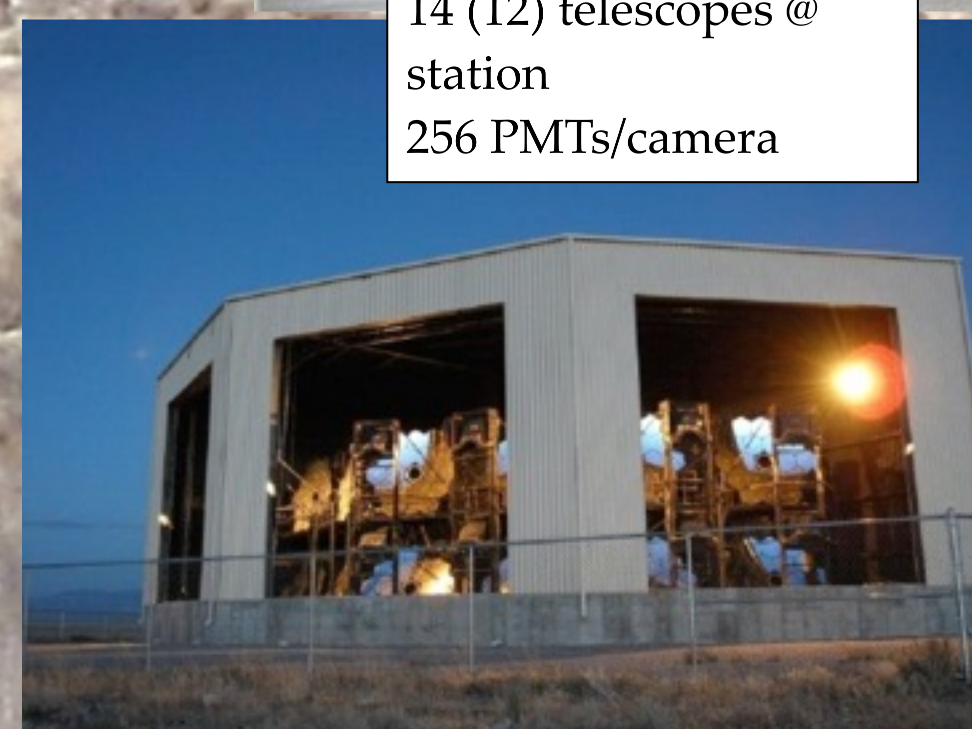


Telescope Array

700 km^2, Utah (USA)
3 m^2 Scintillator Detectors
on a 1.2 km square grid



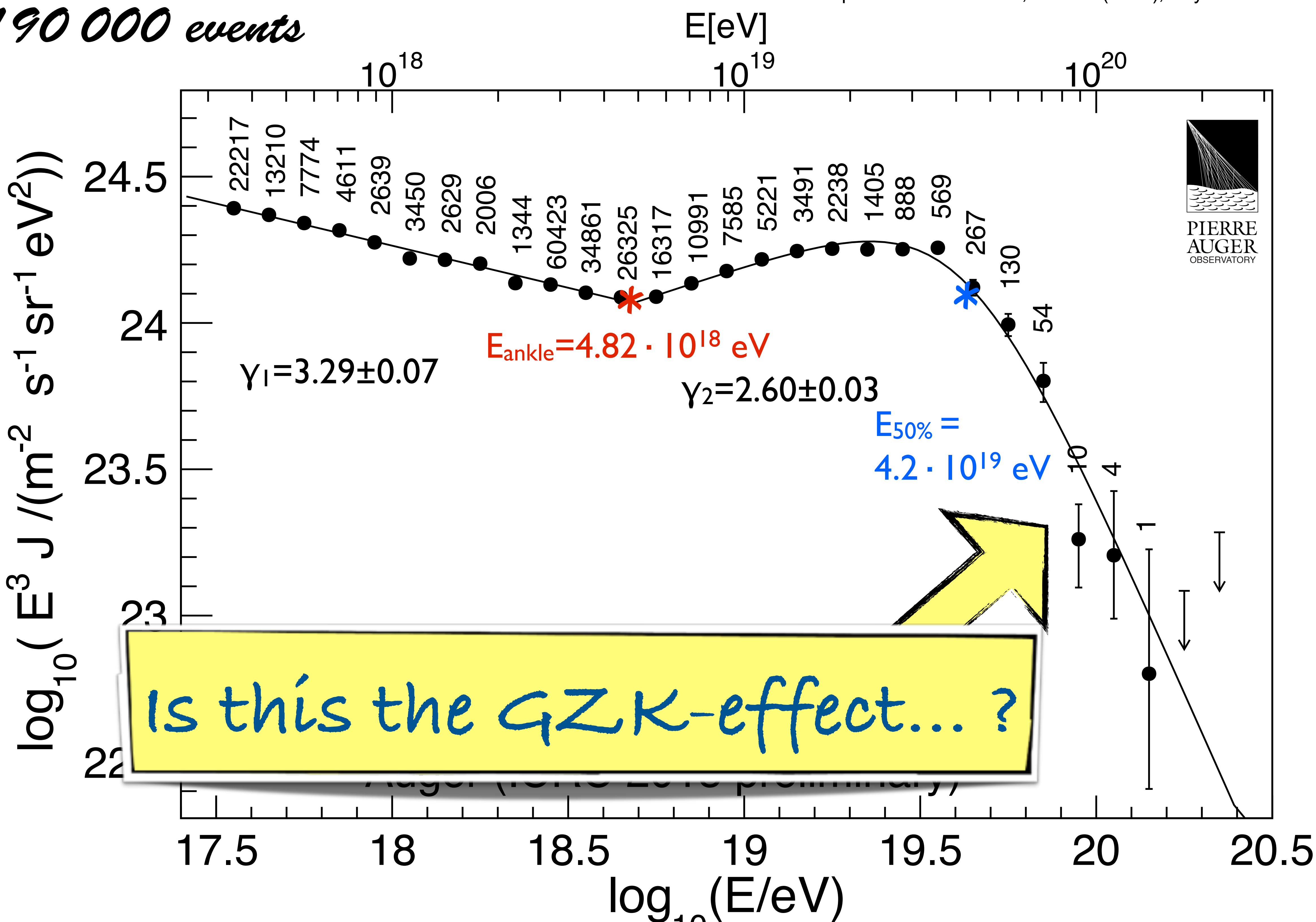
14 (12) telescopes @ station
256 PMTs/camera



End of the CR-Spectrum

Update from: PRL 101, 061101 (2008), Physics Letters B 685 (2010) 239

190 000 events



combined from: infill+hybrid+vertical+inclined events

GZK-Effect: Energy losses in CMB

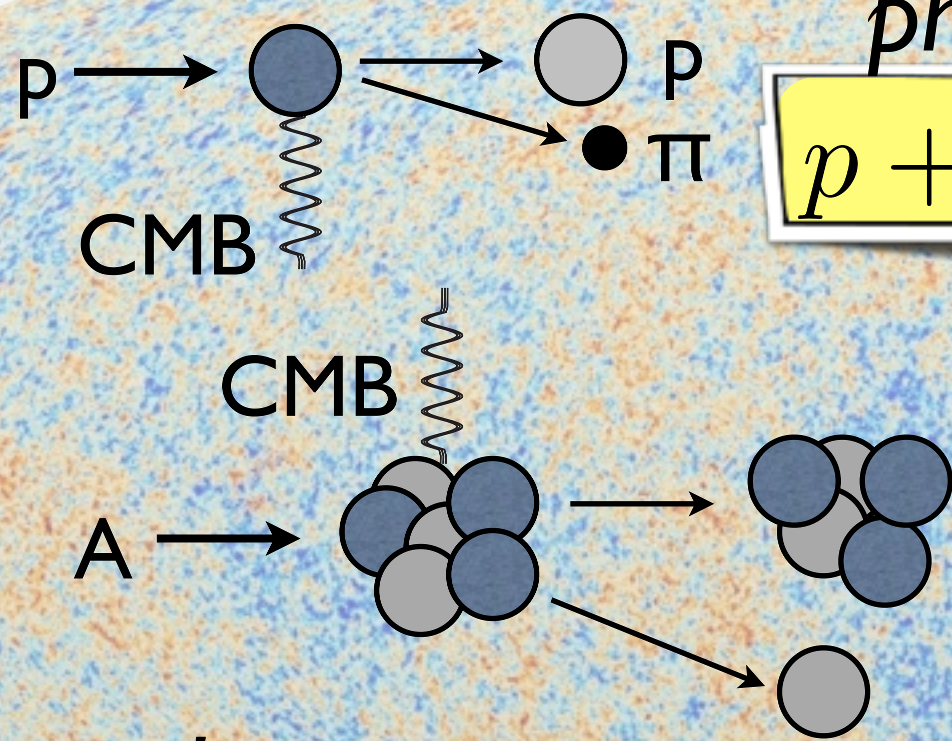


photo-pion production

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

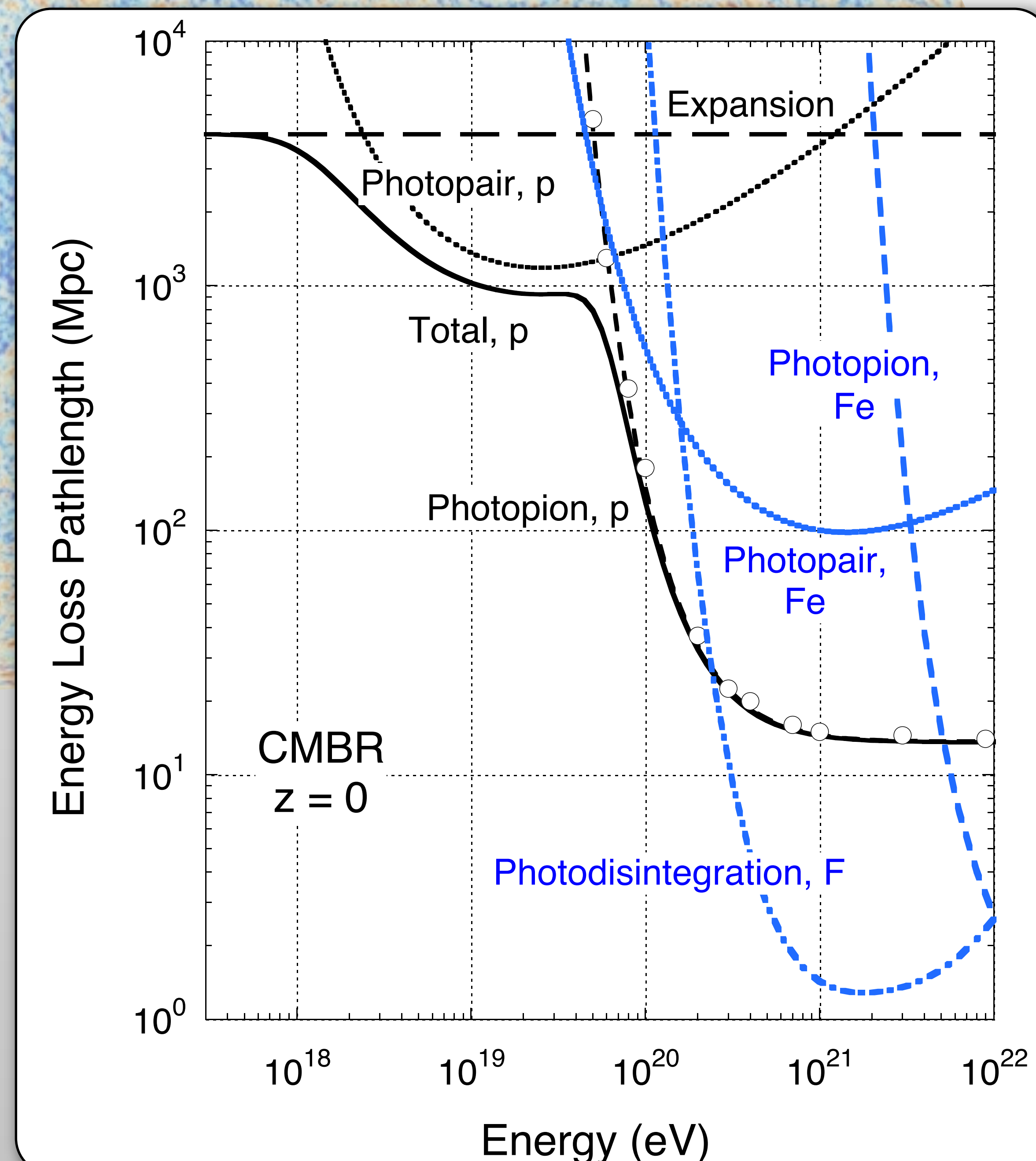
photo disintegration

$$A + \gamma_{\mathrm{CMB}} \rightarrow (A - 1) + n \ldots$$

Greisen-Zatsepin-Kuz'min (1966)

threshold: $E_p E_\gamma > (m_\Delta^2 - m_p^2)$

$\Rightarrow E_{\mathrm{GZK}} \approx 6 \cdot 10^{19}$ eV

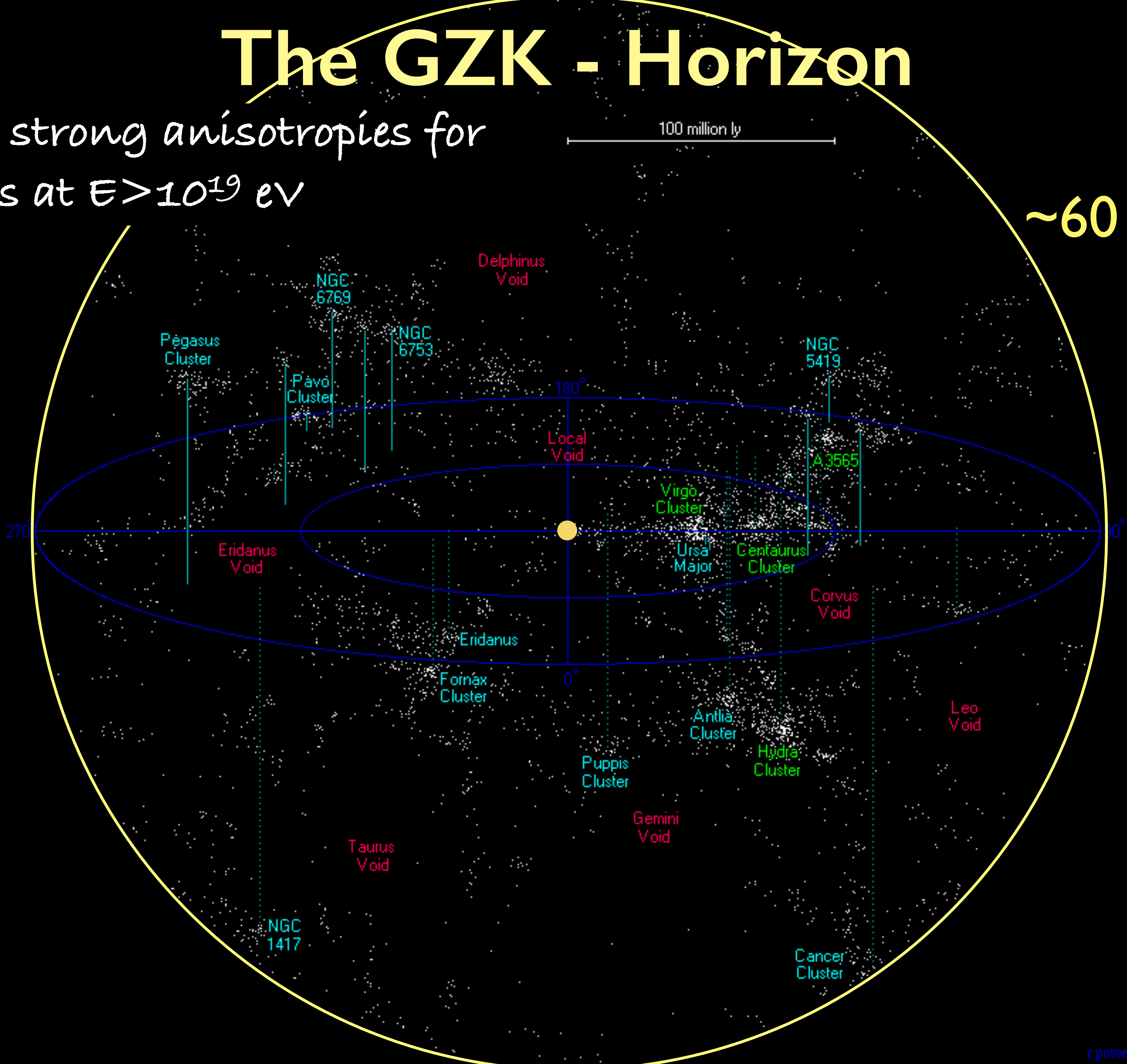


➙ GZK-Horizon ~ $(n_\gamma \sigma_\Delta)^{-1}$ ~ 60 Mpc

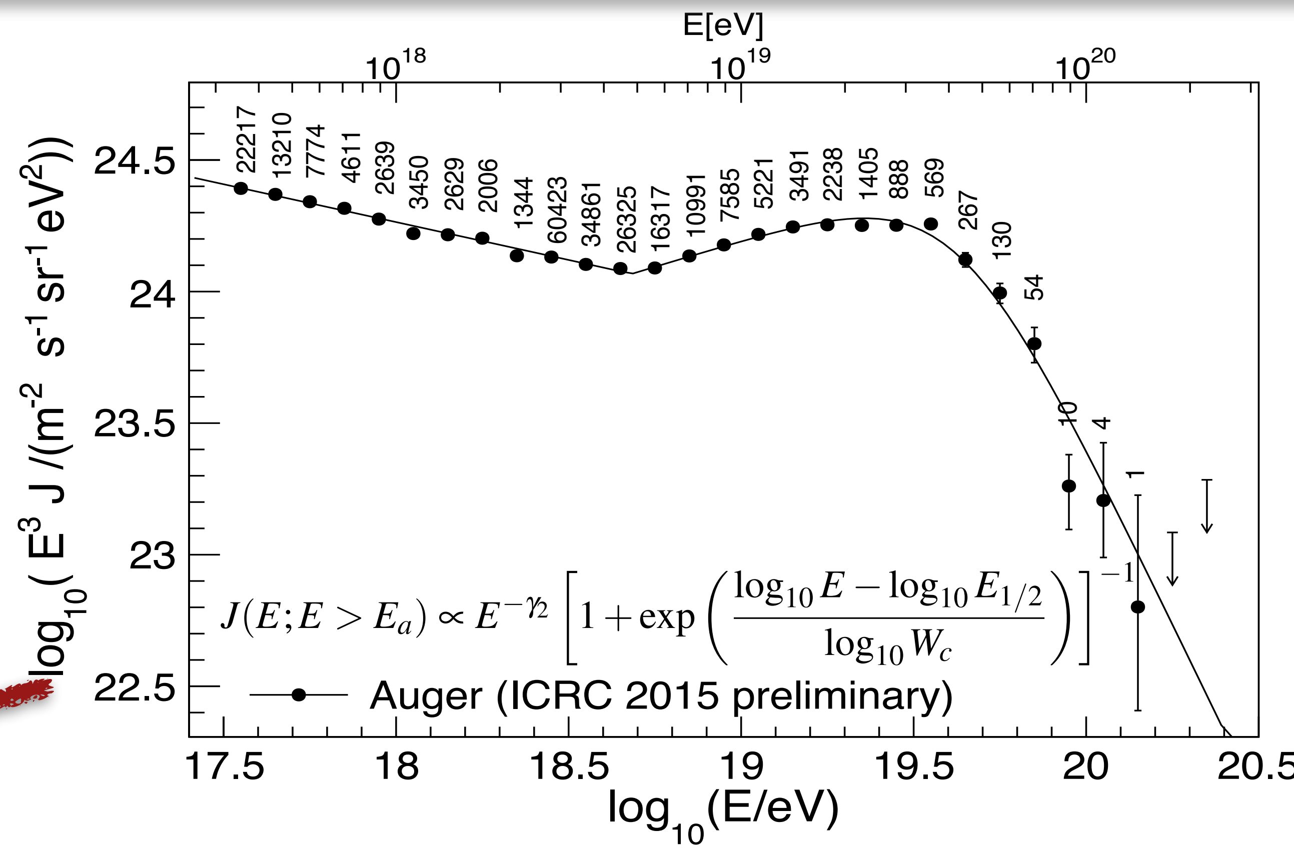
The GZK - Horizon

Expect strong anisotropies for protons at $E>10^{19}$ eV

~60 Mpc

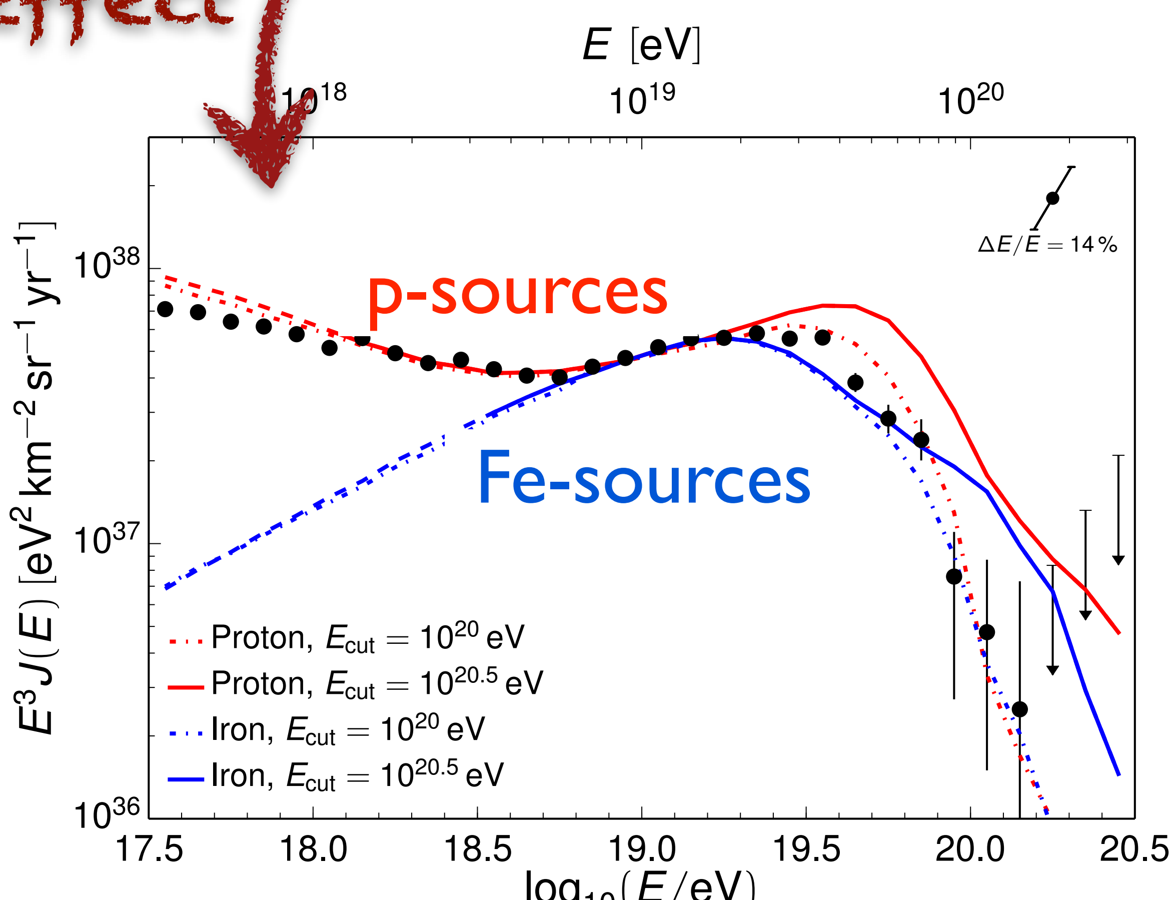


GZK-Effect or Exhausted Sources?

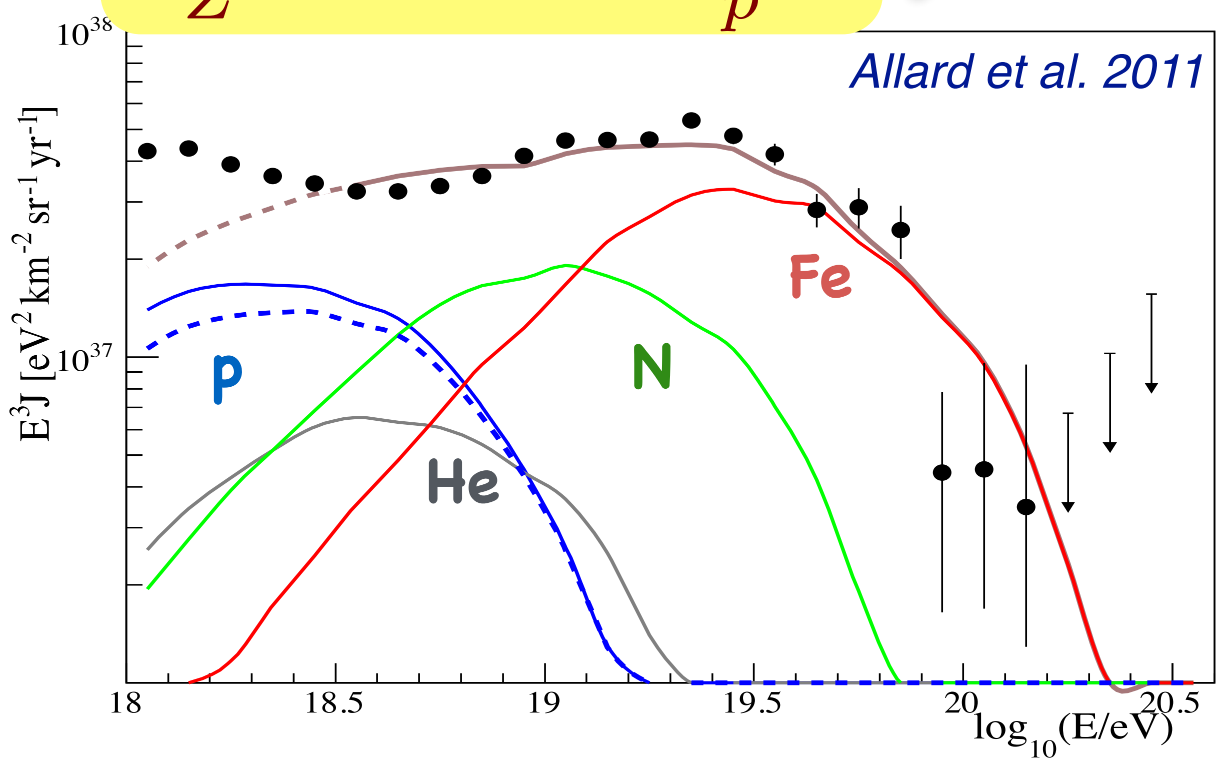


GZK-effect

exhausted sources

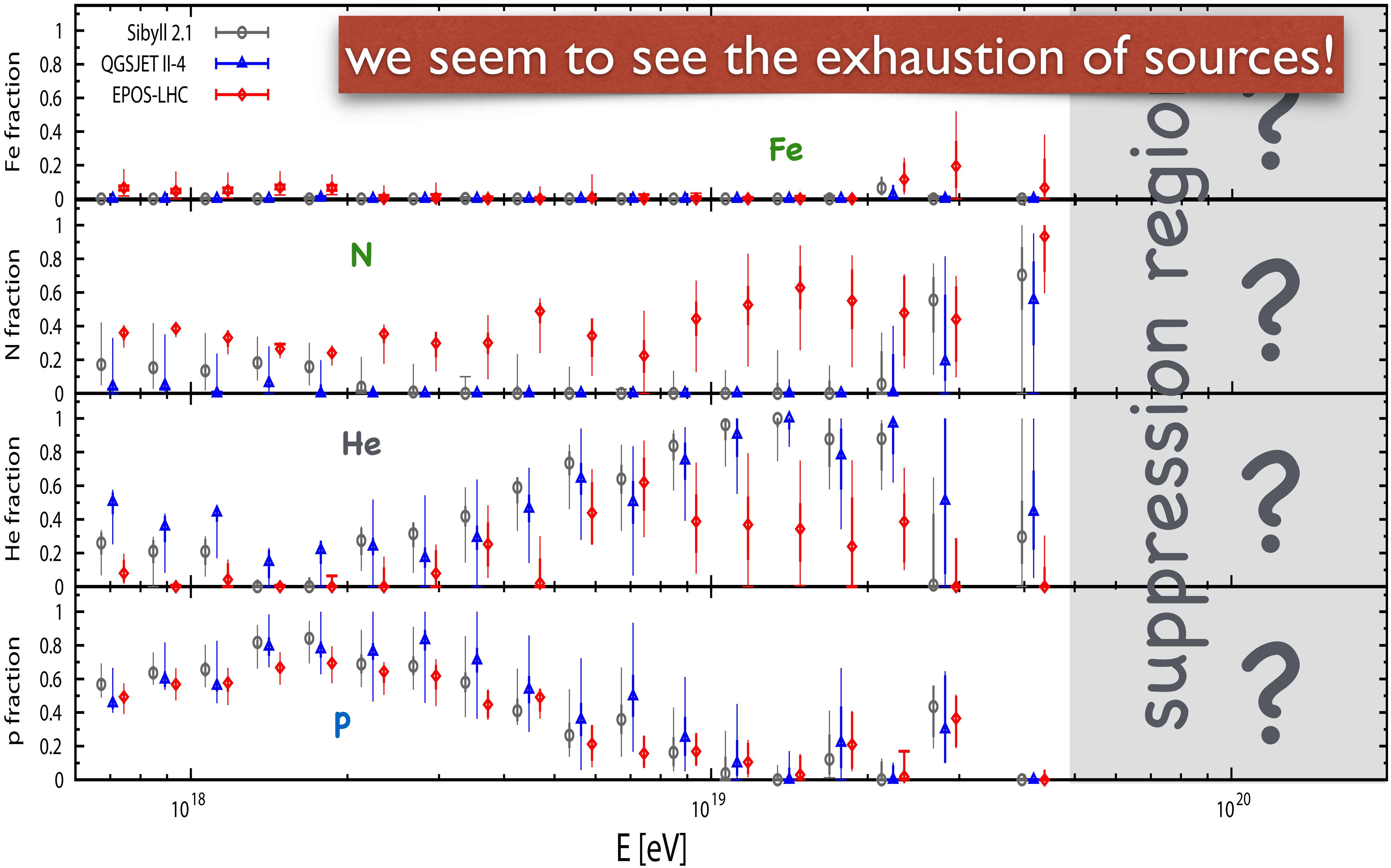


$$E_Z^{\max} \propto Z \times E_p^{\max}$$



Decomposition of X_{max}-Distributions

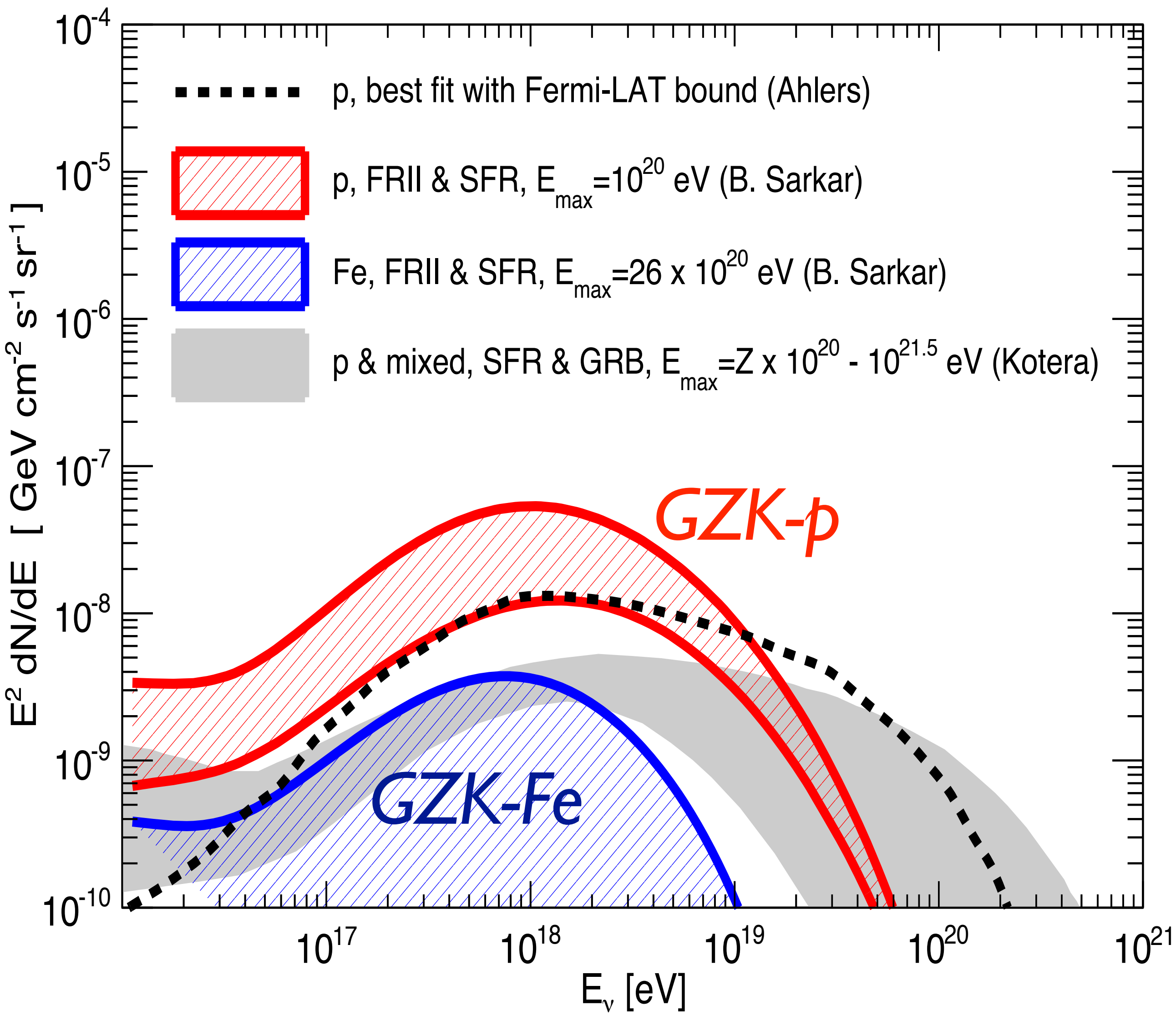
Auger collaboration, Phys. Rev. D 90, 122006 (2014)

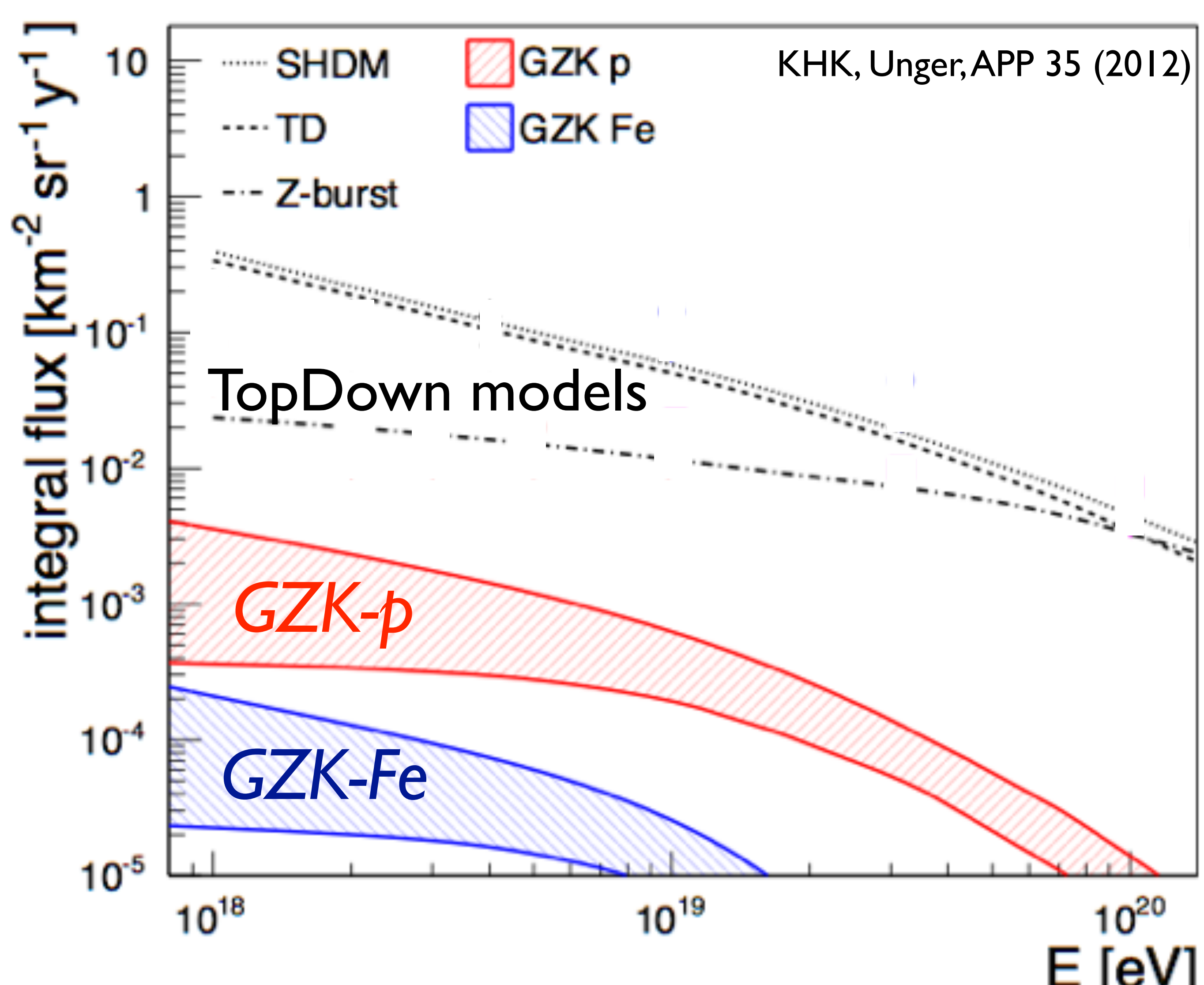


Cosmogenic Neutrinos and Photons
– a guaranteed signal in presence of GZK –

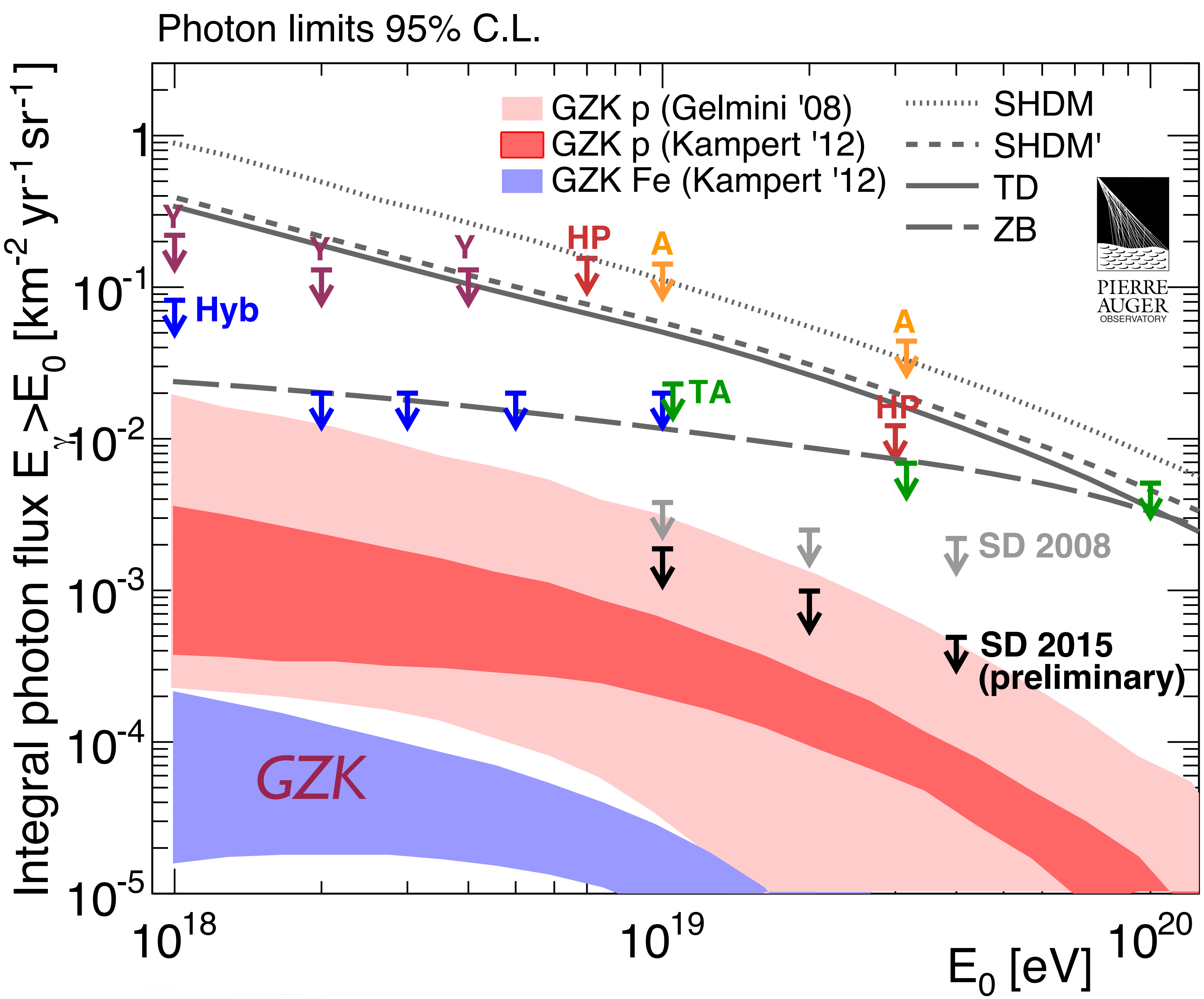
$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta \rightarrow$$

$$\rightarrow n + \pi^{+} \rightarrow \nu_{\mathrm{EeV}} \qquad \rightarrow p + \pi^{0} \rightarrow \gamma_{\mathrm{EeV}}$$





Experimental Upper Limits (photons)



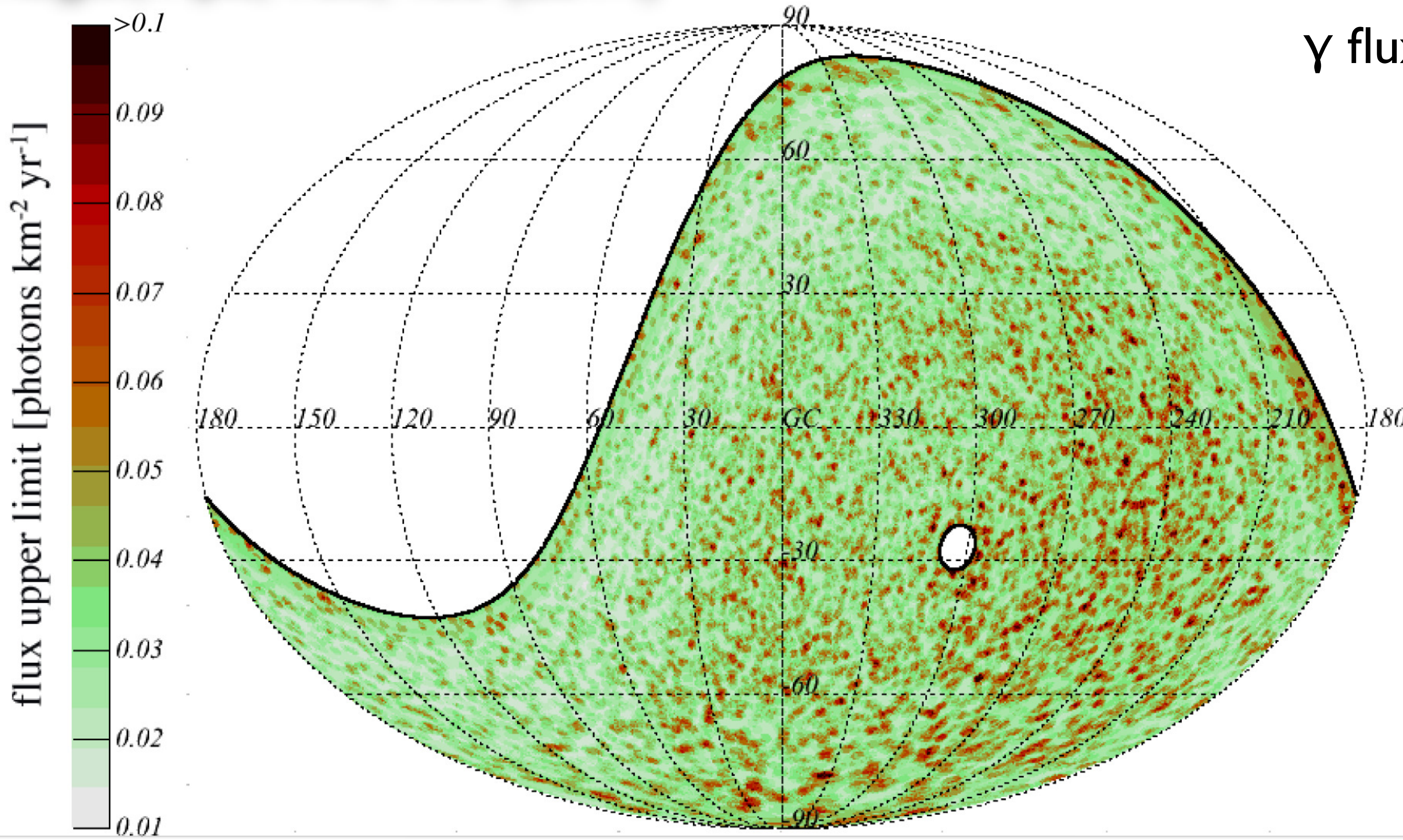
Auger @ ICRC2015:
arXiv1509.03732

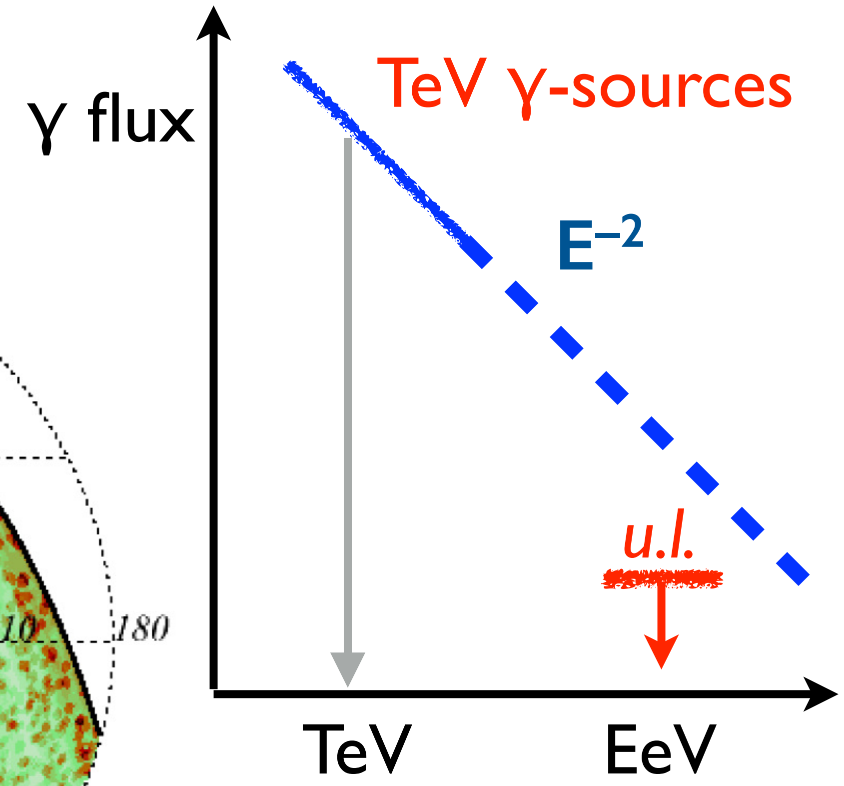
2 orders of magnitude improvement during last 10 years!

Photon upper limits rule out Top-Down Models and start to constrain GZK-fluxes

Search for EeV γ-point sources

Auger, ApJ, 789, 160 (2014)



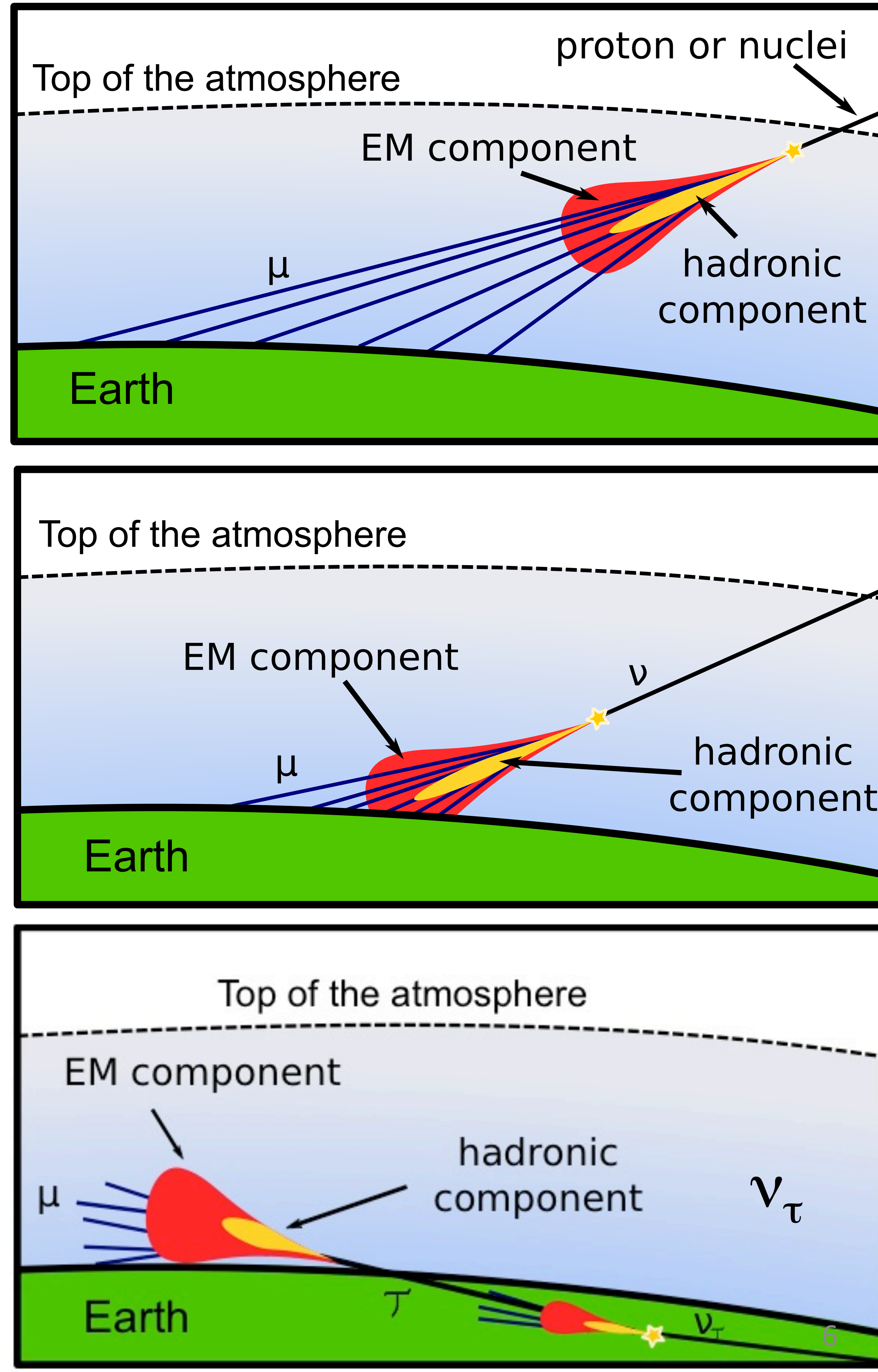


Energy flux of 0.25 eV/cm^{2}s would yield a 5σ excess (assuming E^{-2} spectr.)
Note, some Galactic TeV sources exceed 1 eV/cm^{2}s !

⇒ Galactic TeV sources don't stick out to EeV energies

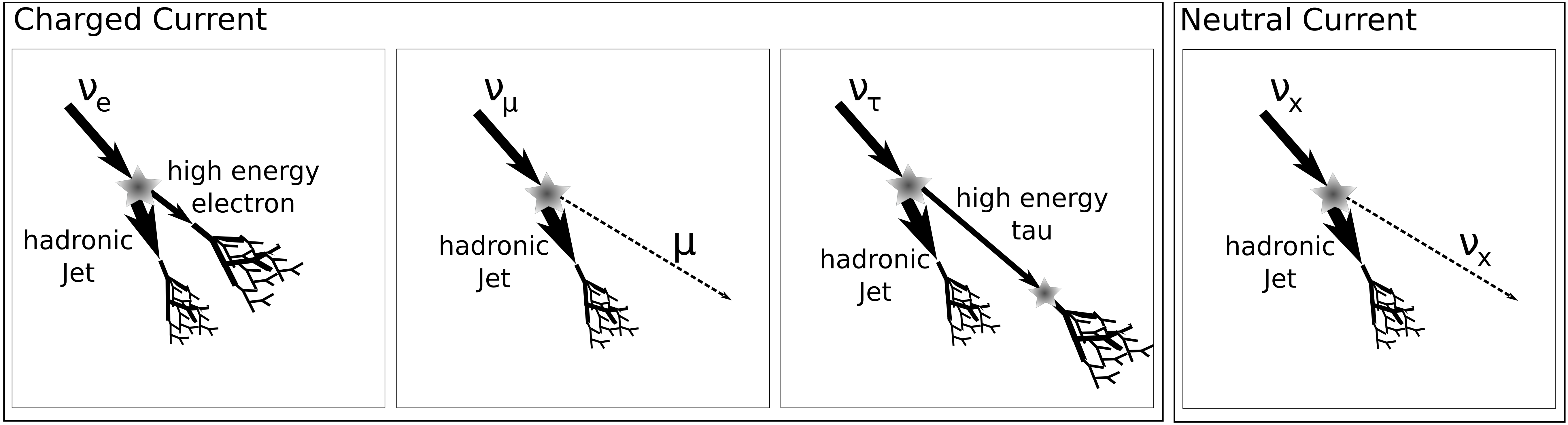
Search for EeV Neutrinos in inclined showers

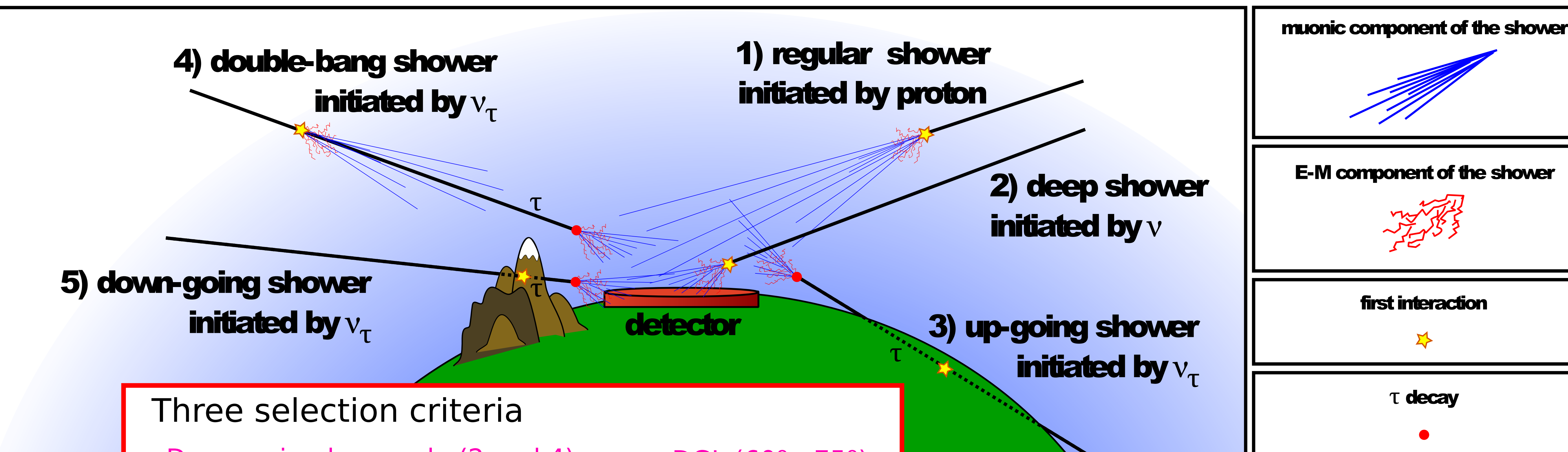
- Protons & nuclei initiate showers high in the atmosphere.
  - Shower front at ground:
    - mainly composed of muons
    - electromagnetic component absorbed in atmosphere.
- Neutrinos can initiate "deep" showers close to ground.
  - Shower front at ground: electromagnetic + muonic components



Searching for neutrinos ⇒ searching for inclined showers with electromagnetic component

Sensitivity to all ν flavors and channels

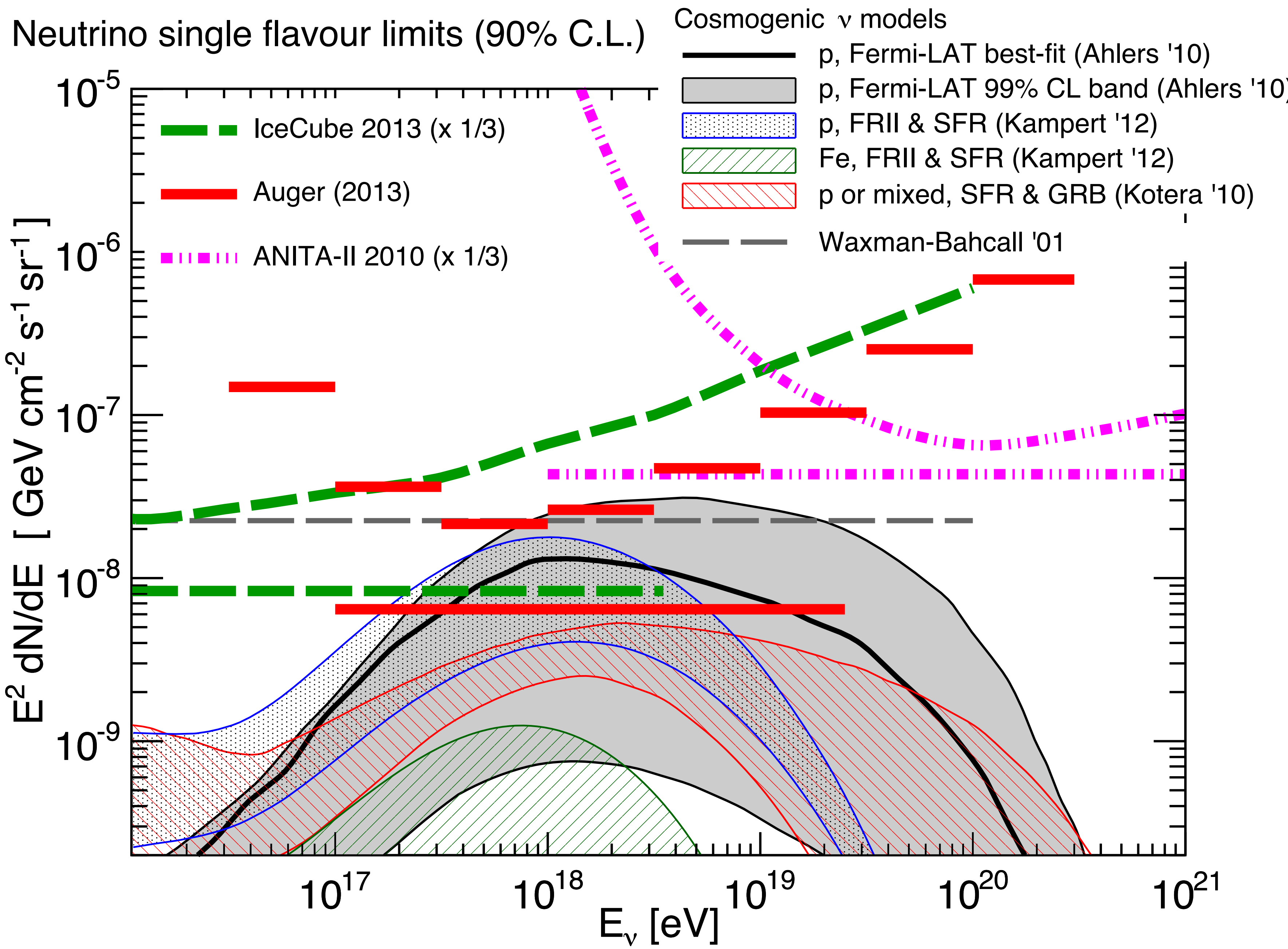




Three selection criteria

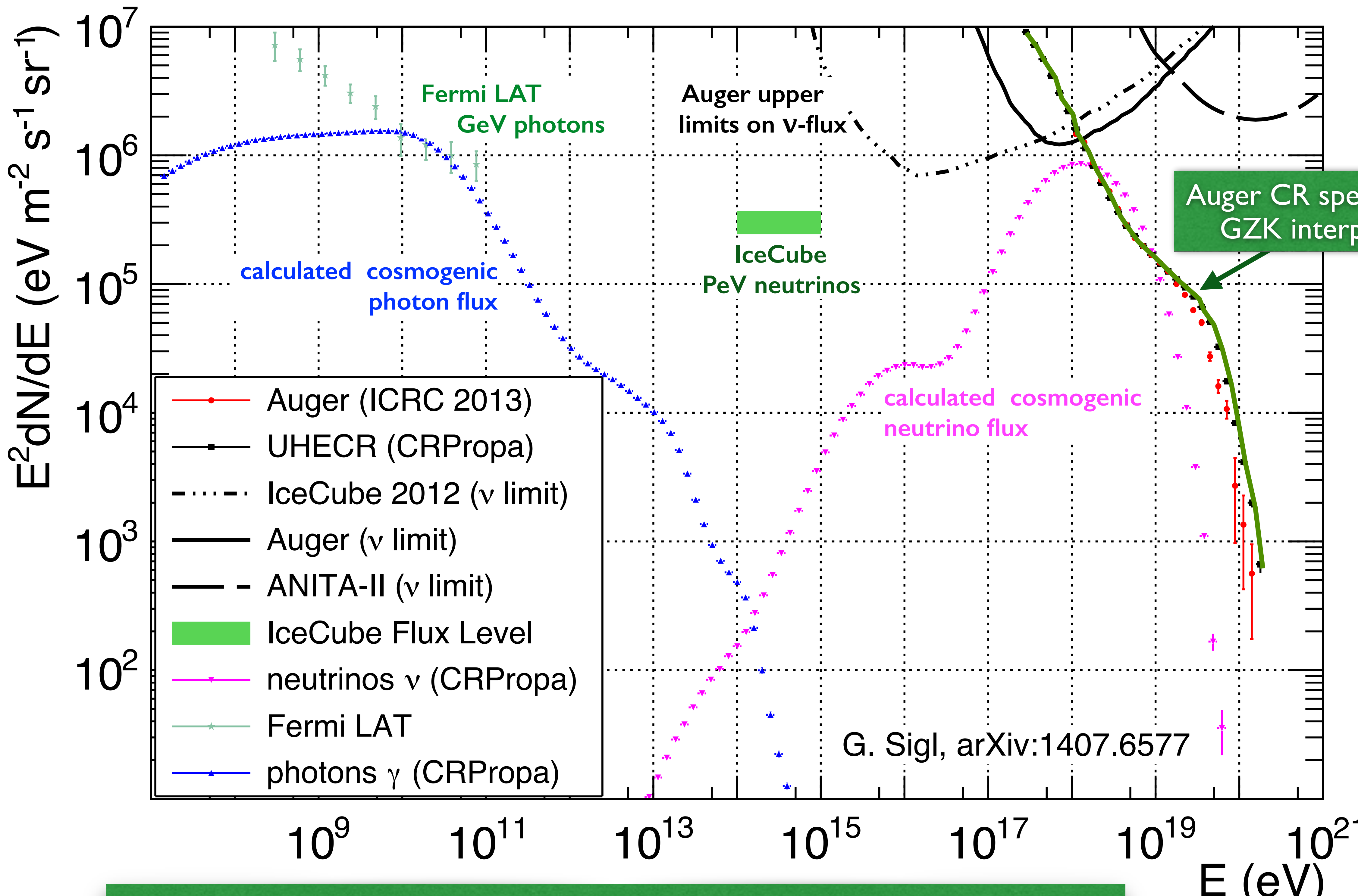
Down-going low angle (2 and 4) ⟶ DGL (60º - 75º)
Down-going high angle (2, 4 and 5) ⟶ DGH (75º - 90º)
Earth-skimming (3) ⟶ ES (90º - 95º)

EeV neutrino limits start to constrain GZK



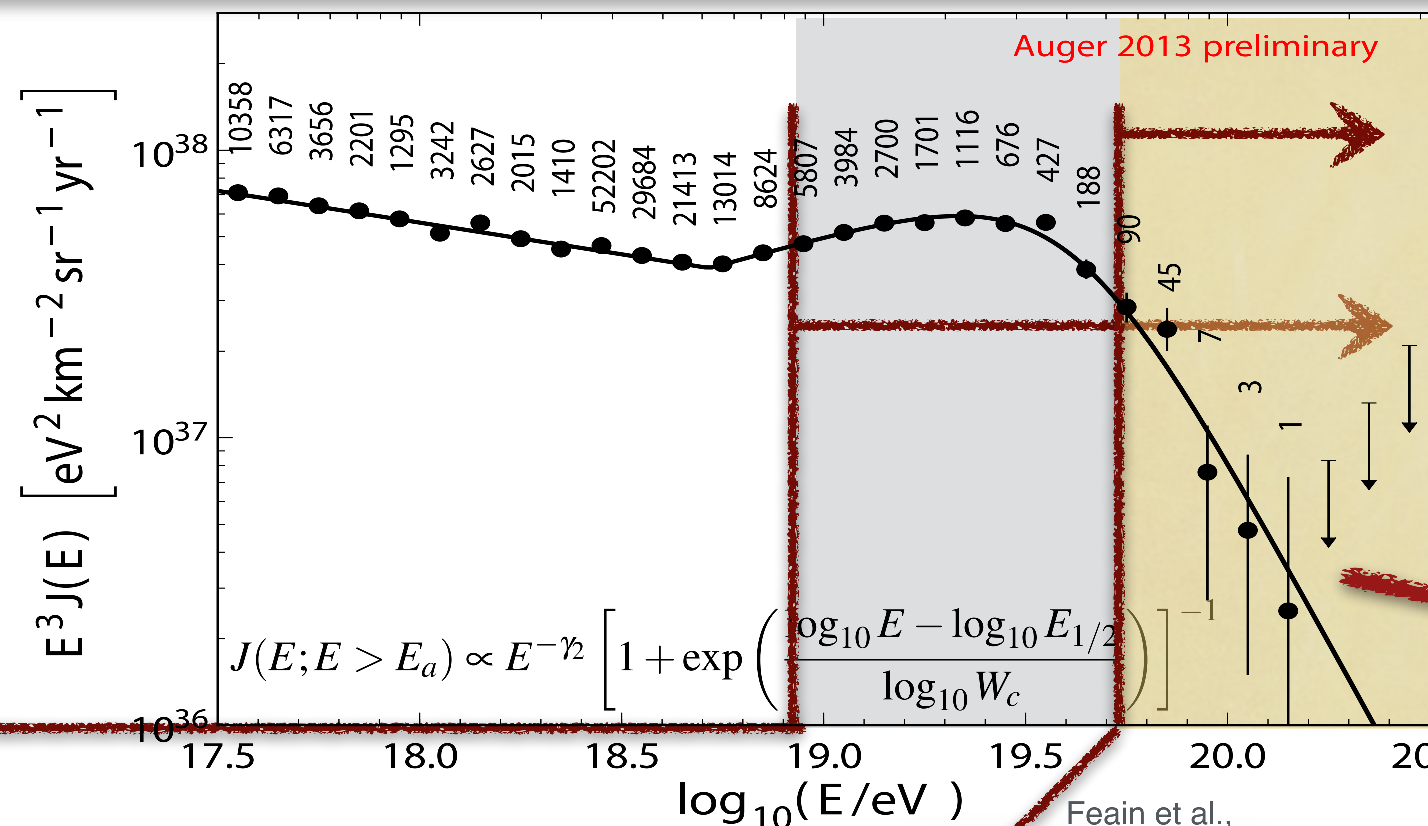
Neutrino upper limits start to constrain GZK-fluxes

CRs and cosmogenic neutrinos & photons



- GZK also constrained by Fermi-LAT data
- IceCube ν's are no GZK-neutrinos

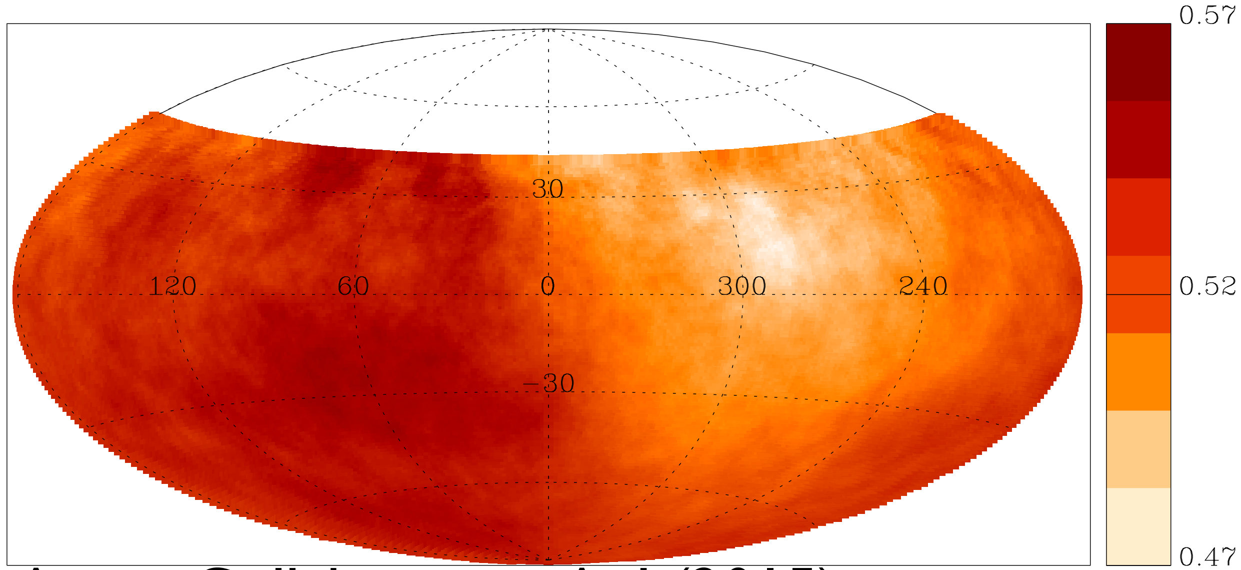
UHECR Sky surprisingly isotropic



hot/warm spot

dipole like anisotropy

E>8 EeV

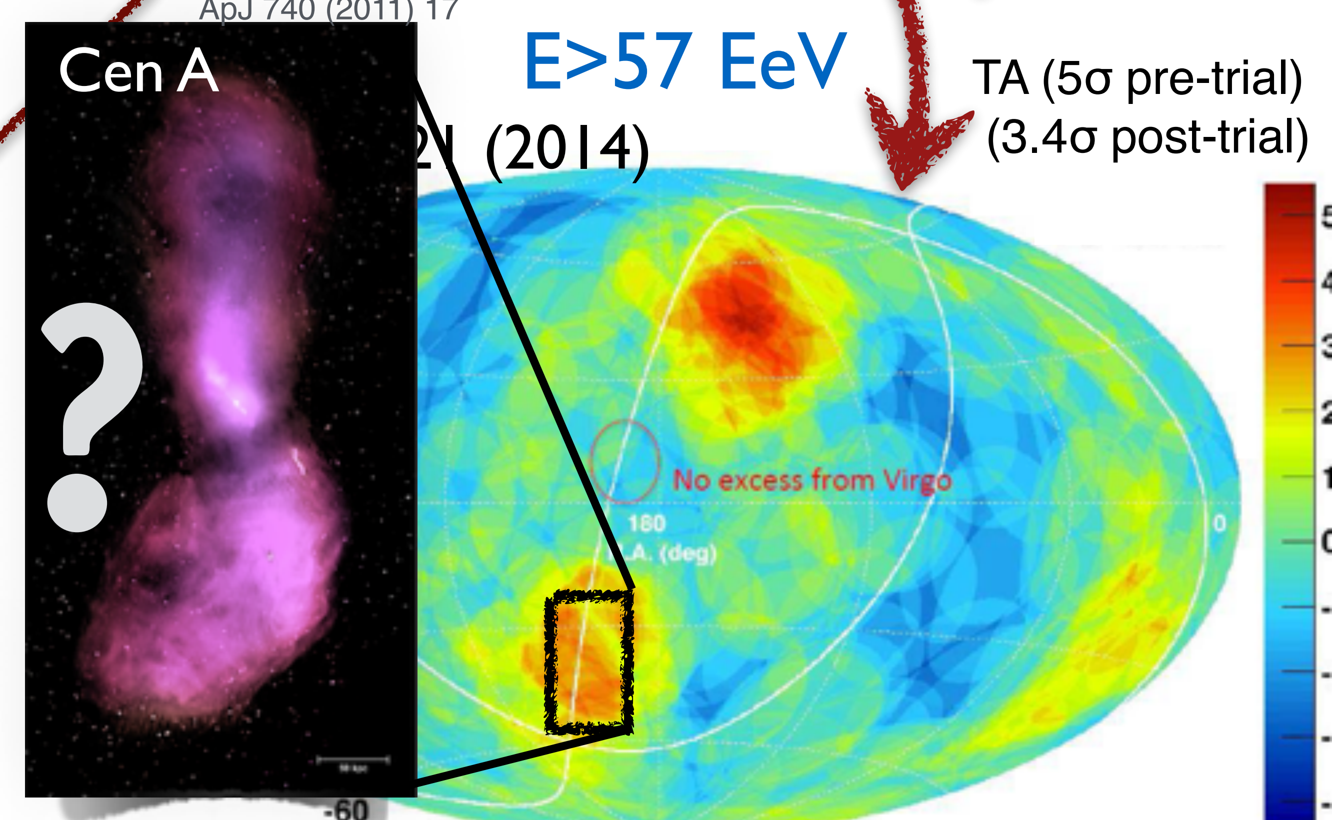


Auger Collaboration ApJ (2015) in press
Amplitude: (4.4±1.0)%; p=6.4 · 10^{-5}

Feain et al., ApJ 740 (2011) 17

E>57 EeV

TA (5σ pre-trial) (3.4σ post-trial)

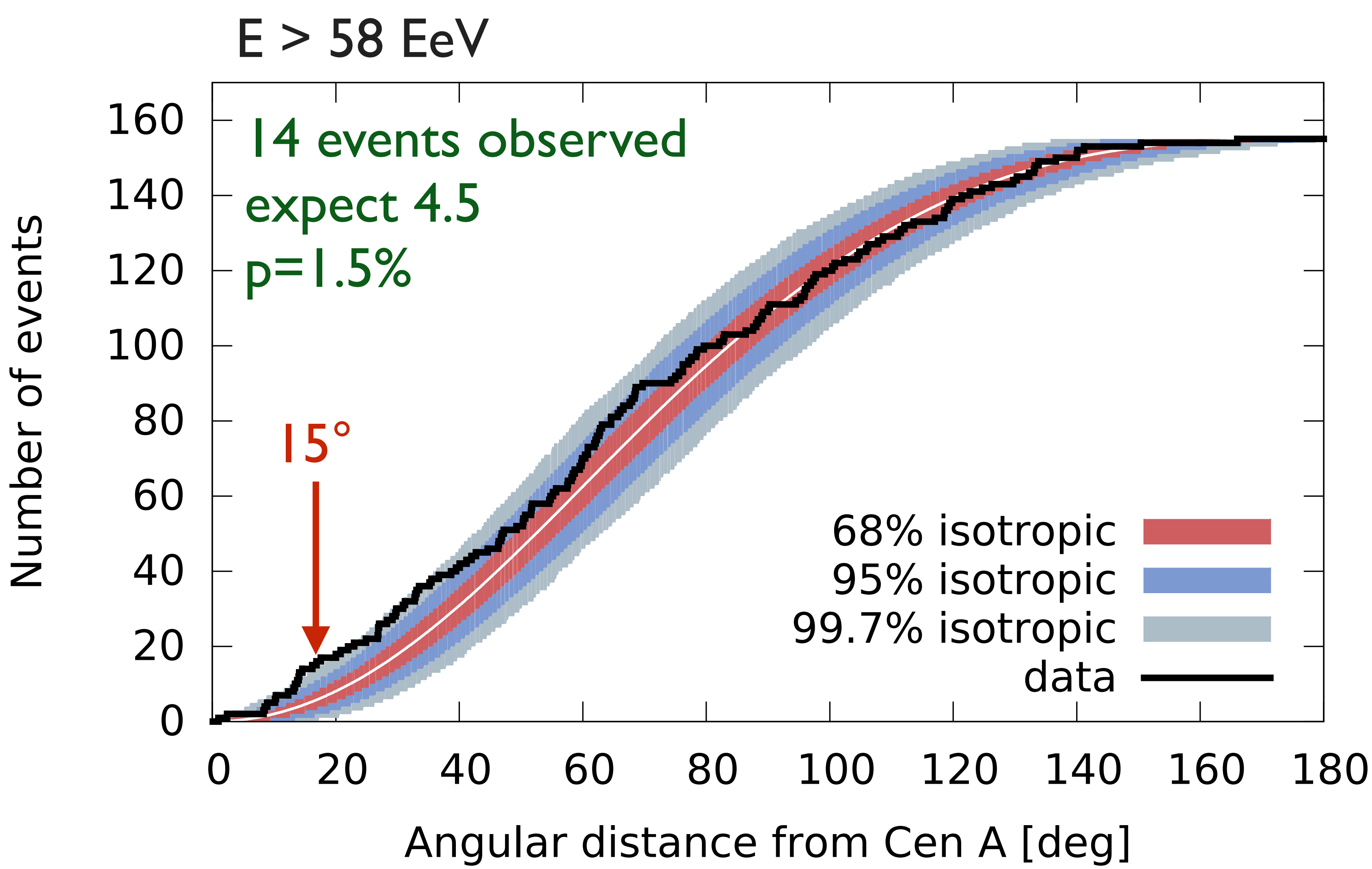


Auger (3σ pre-trial)

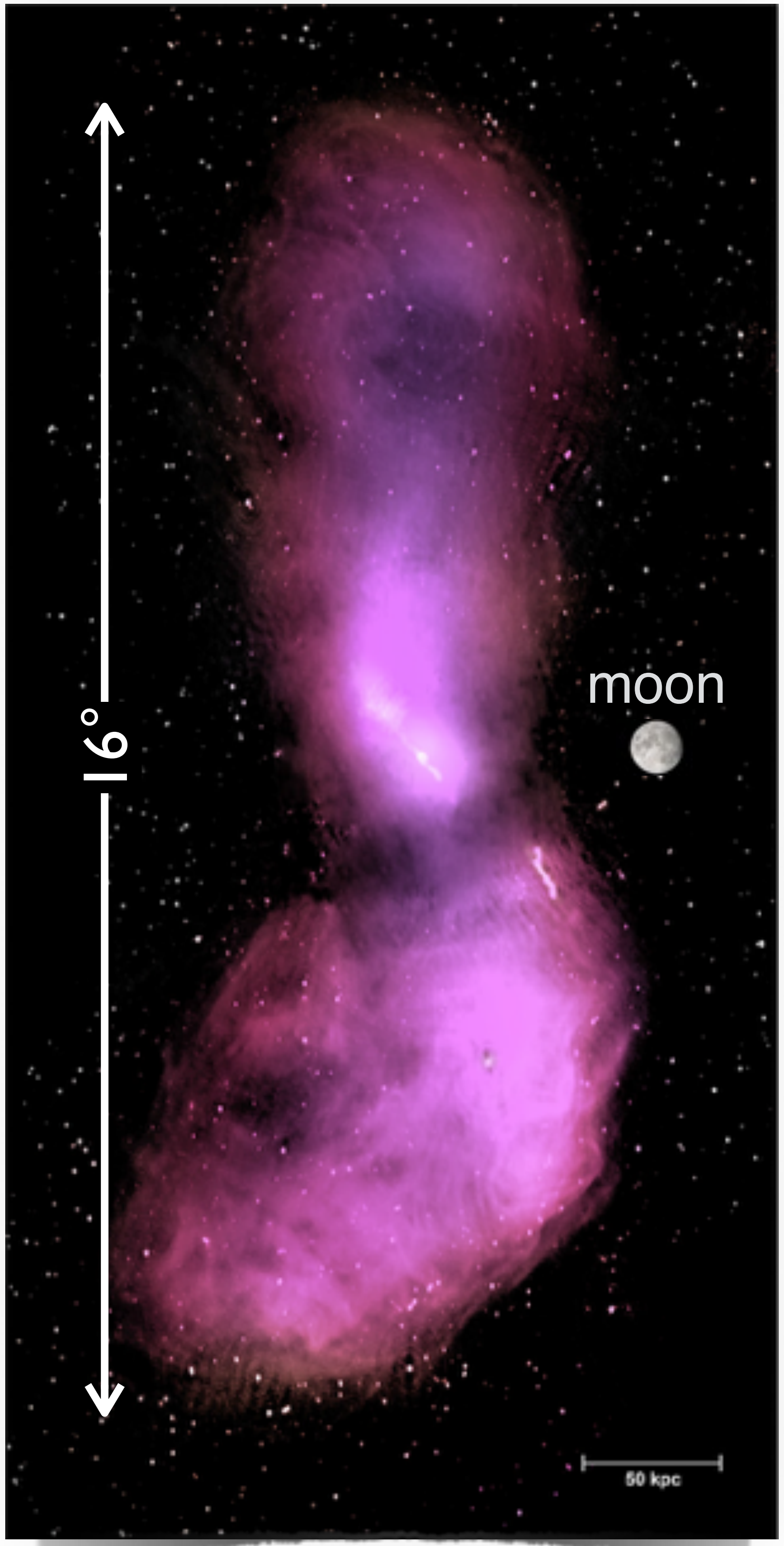
Auger: APP 34(2010) 314

Weak excess of events around Cen A

giant lobes ~ 280 kpc
physical age ~ 560 Myr
distance ~ 3.8 Mpc



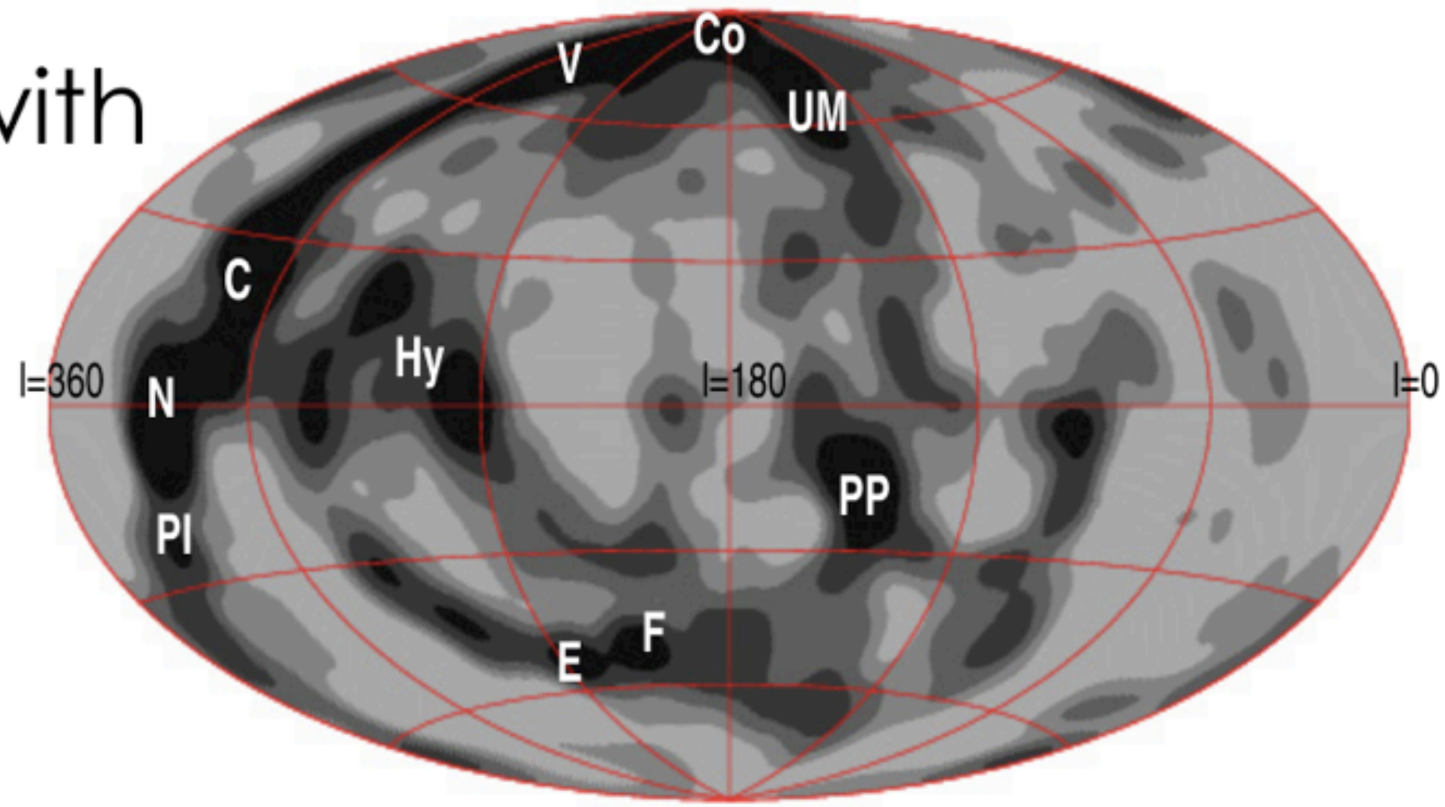
Auger Coll.; ApJ 84 (2015) 15



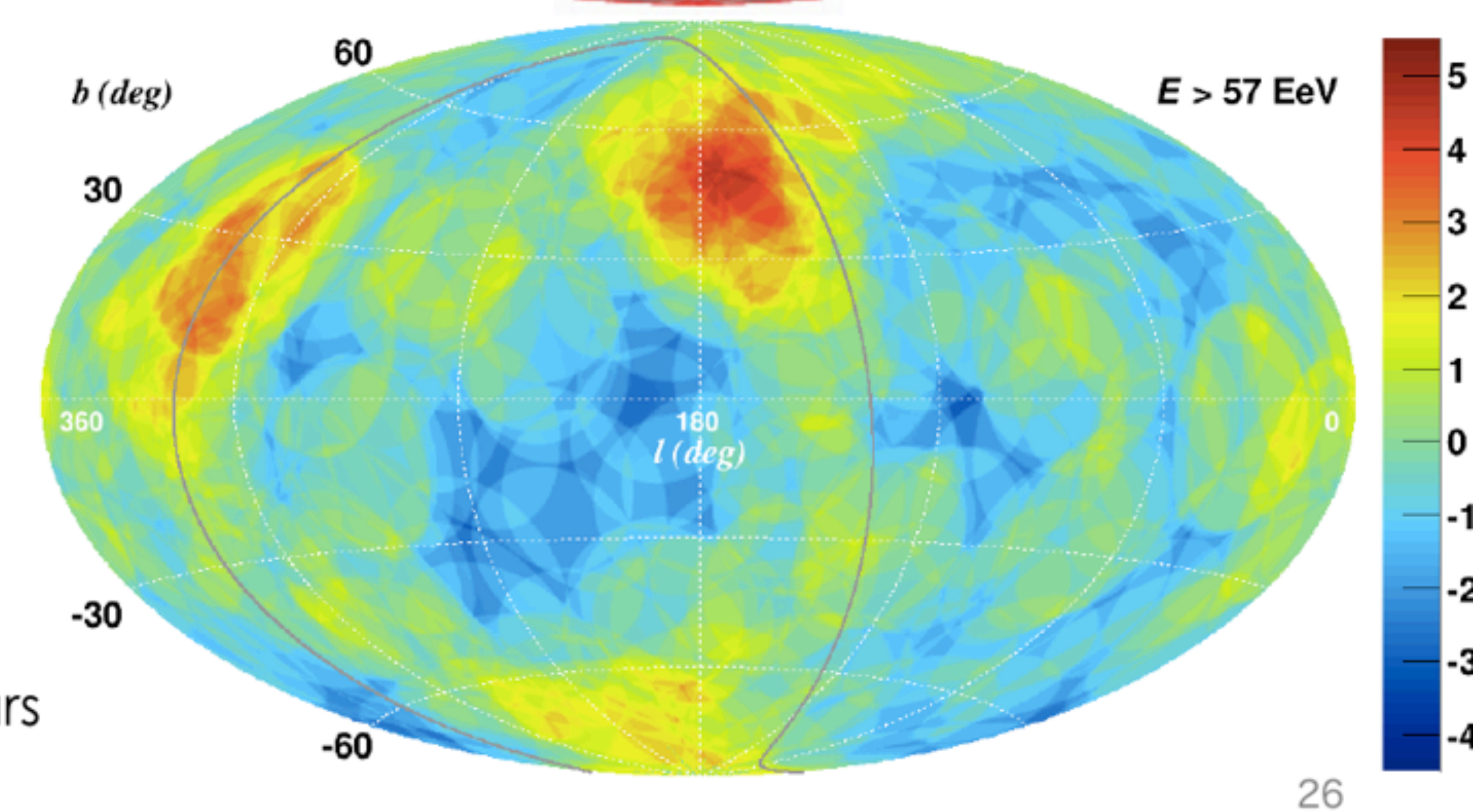
Feain et al., ApJ 740 (2011) 17

Auger/TA: small/intermediate-scales

Comparison with Large-Scale Structure



Sky map of expected flux at E > 57 EeV (Galactic coordinates). The smearing angle is 6°. The letters indicate the nearby structures as follows: C: Centaurus supercluster (60 Mpc); Co: Coma cluster (90 Mpc); E: Eridanus cluster (30 Mpc); F: Fornax cluster (20 Mpc); Hy: Hydra supercluster (50 Mpc); N: Norma supercluster (65 Mpc); PI: Pavo-Indus supercluster (70 Mpc); PP: Perseus-Pisces supercluster (70 Mpc); UM: Ursa Major (20 Mpc); and V: Virgo cluster (20 Mpc).

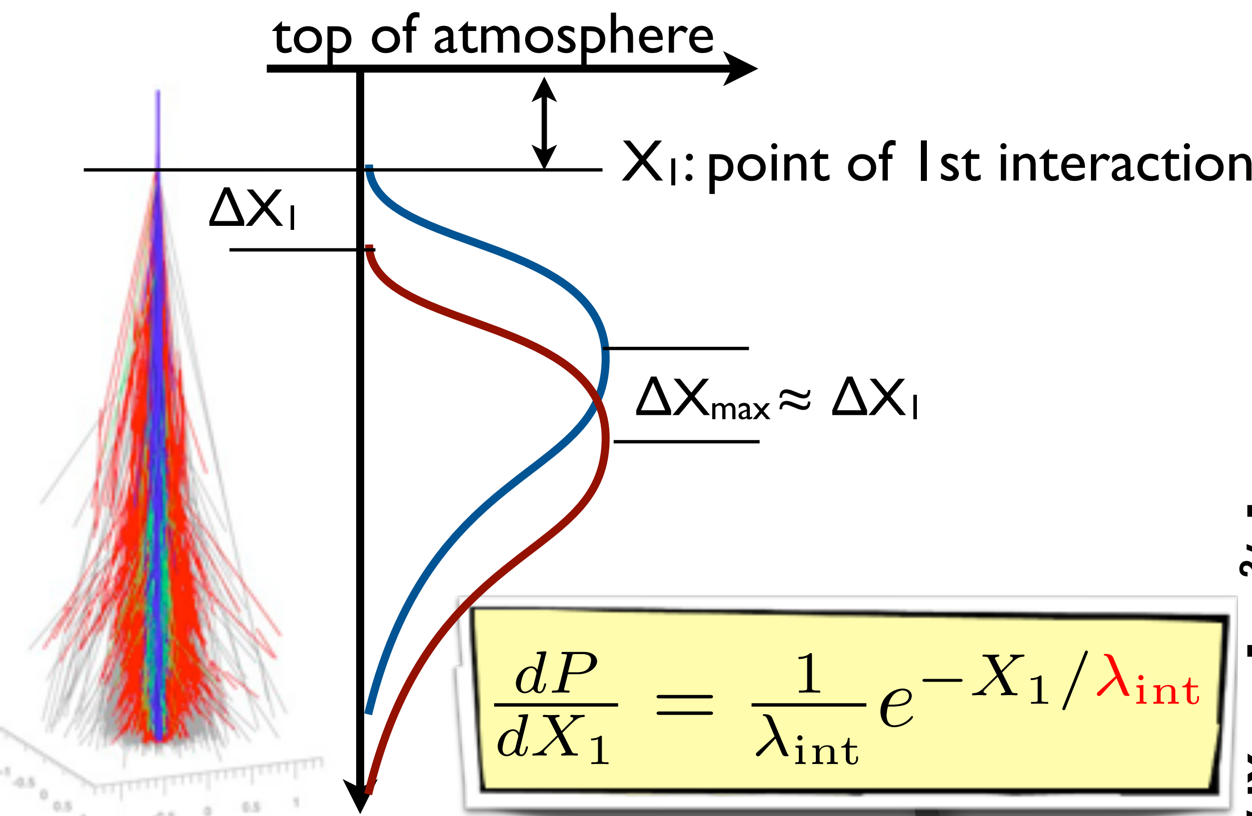


TA 7 years + PAO 10 years

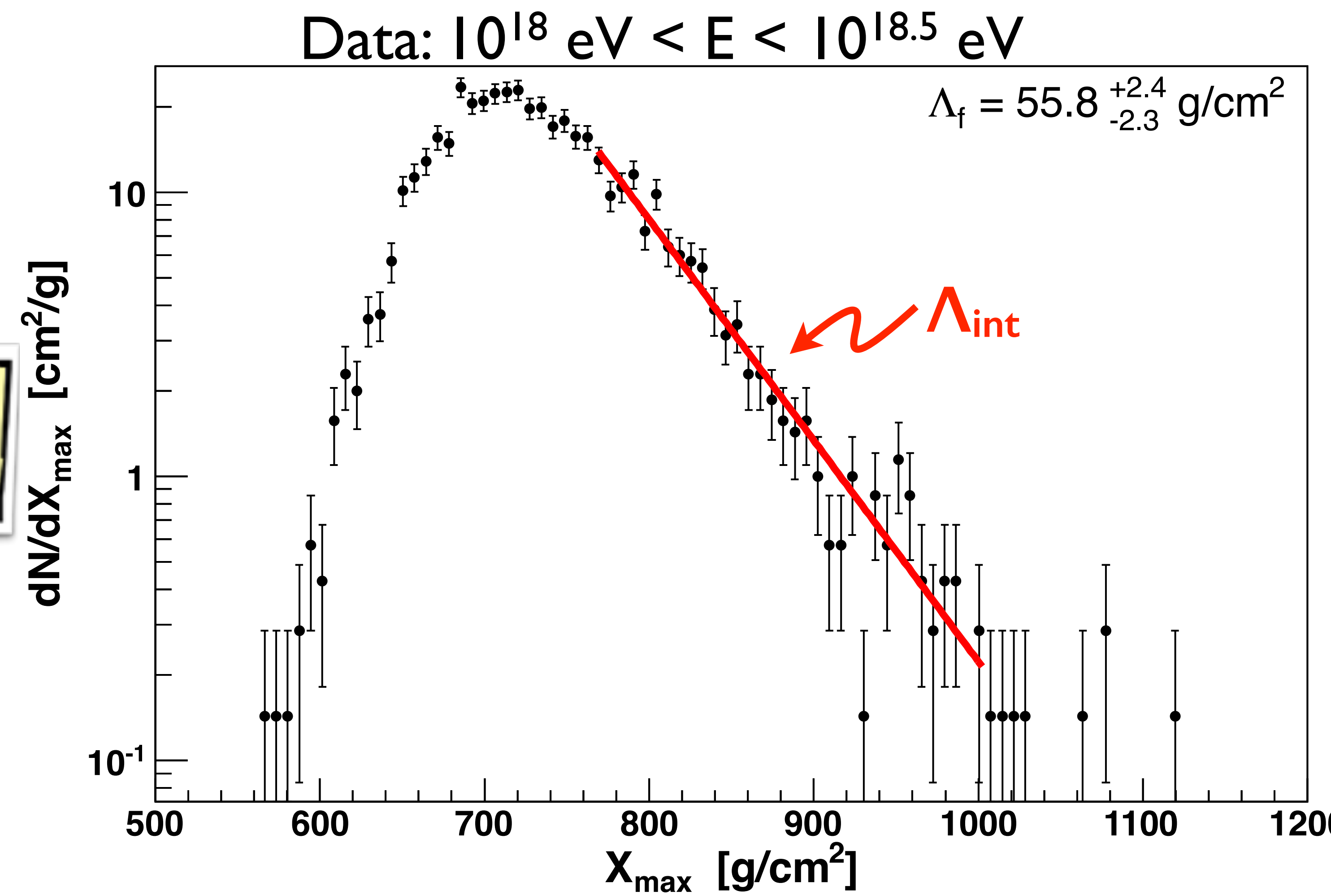
Themes of HE-Astroparticle Physics

- **Cosmic Particle Acceleration**
  - How and where are cosmic rays accelerated?
  - How do they propagate?
  - What is their impact on the environment?
- **Probing Extreme Environments**
  - Processes close to neutron stars massive black holes?
  - Processes in relativistic jets, winds and explosions?
  - Exploring cosmic magnetic fields
- **Physics Frontiers – beyond the SM**
  - What is the nature of Dark Matter? How is it distributed?
  - Lorentz invariance violation? Smoothness of Space-Time?
  - New particle physics at $\sqrt{s}$=450 TeV ?

p-Air Cross-Section from X_{max} distribution



$$\frac{dP}{dX_1} = \frac{1}{\lambda_{\text{int}}} e^{-X_1/\lambda_{\text{int}}}$$



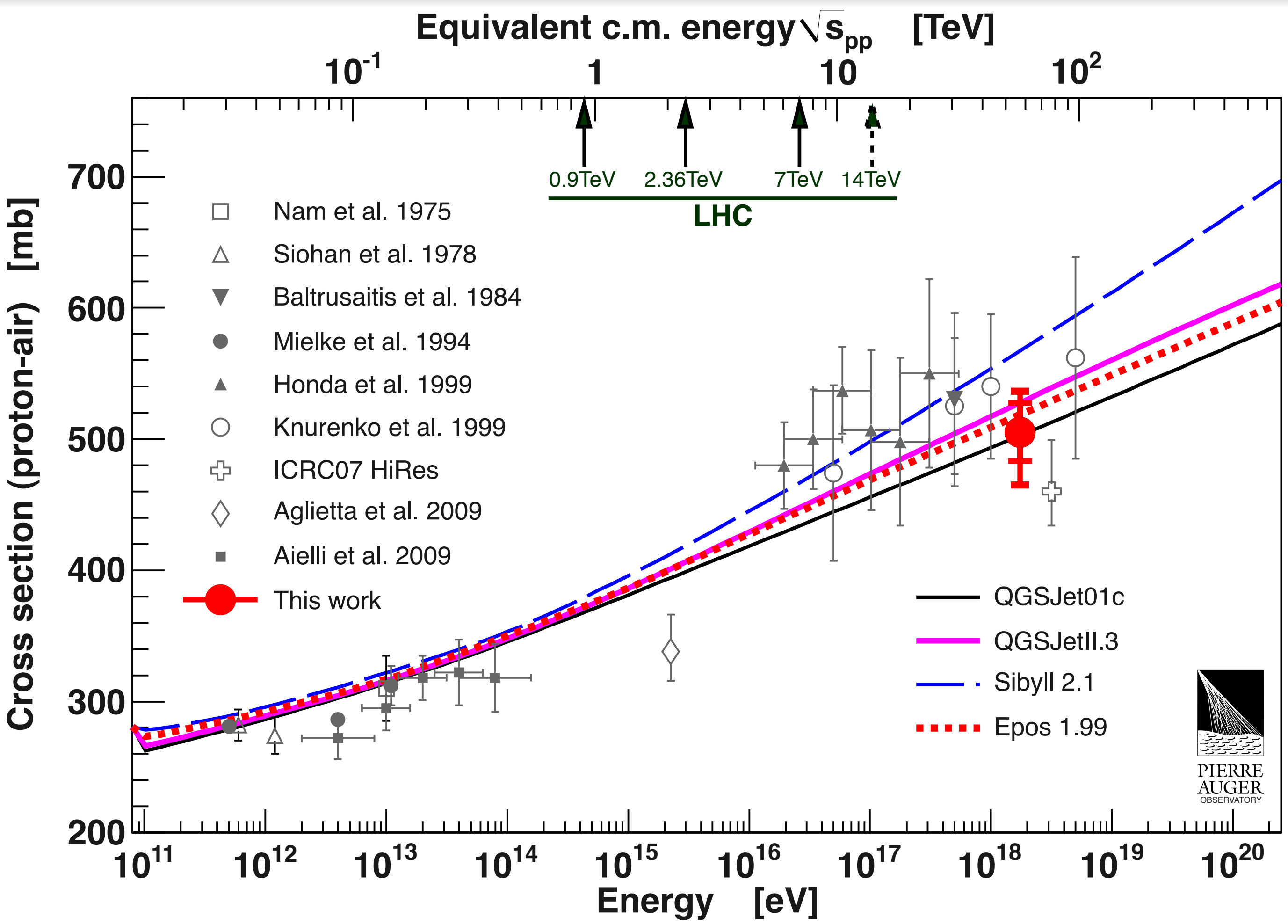
Difficulties:

- mass composition can alter Λ
- fluctuations in X_{max}
- experimental resolution ~ 20 g/cm²

$$\sigma_{p-Air} = \frac{\langle m_{Air} \rangle}{\lambda_{int}}$$

In practice: $\sigma_{p\text{-}Air}$ by tuning models to describe Λ seen in data

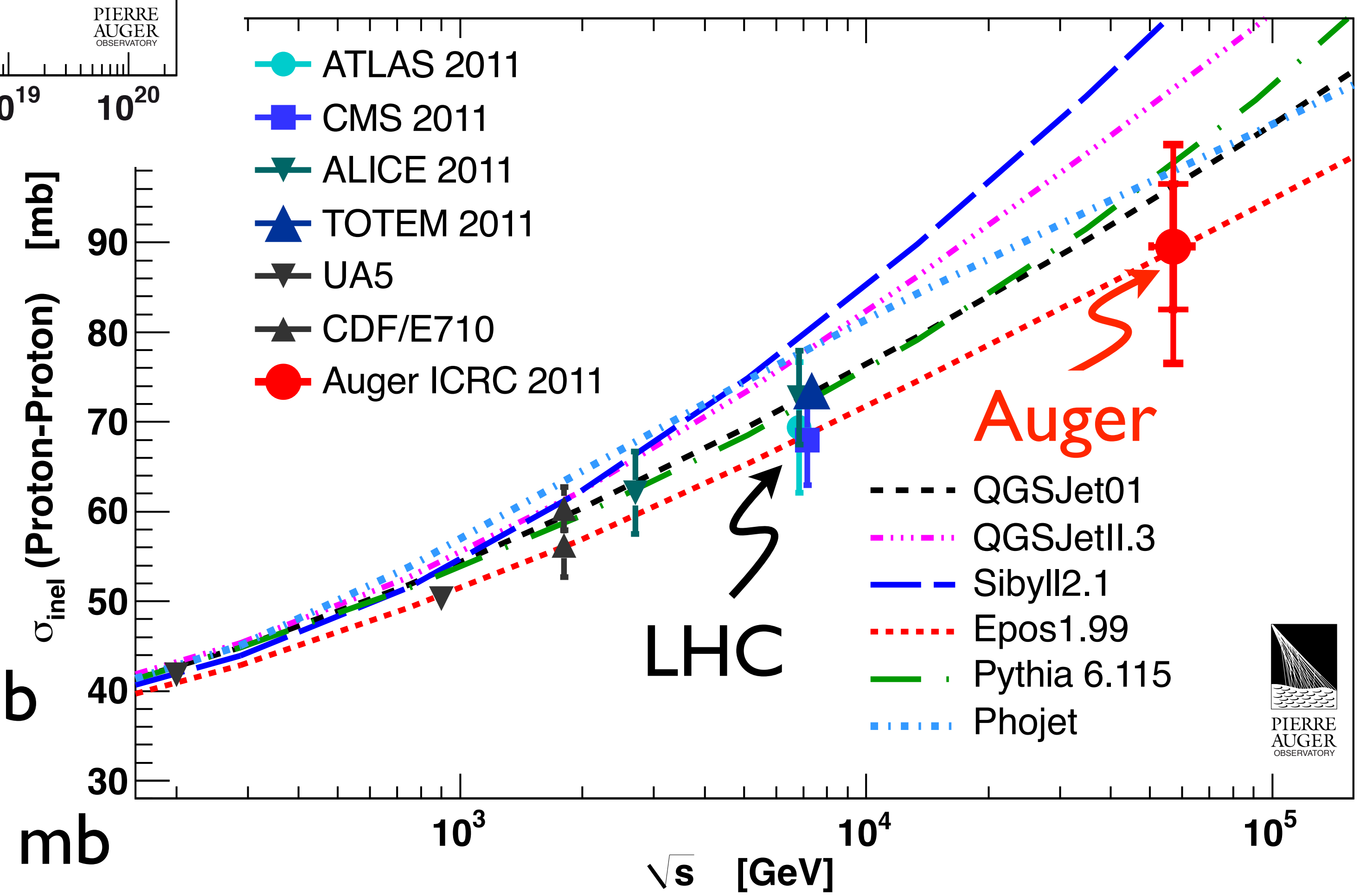
p-Air and pp Cross section @ $\sqrt{s}$=57 TeV



Auger Collaboration, PRL 109, 062002 (2012)
Update: ICRC 2015

Conversion from p-air to p-p cross section by Glauber-approach

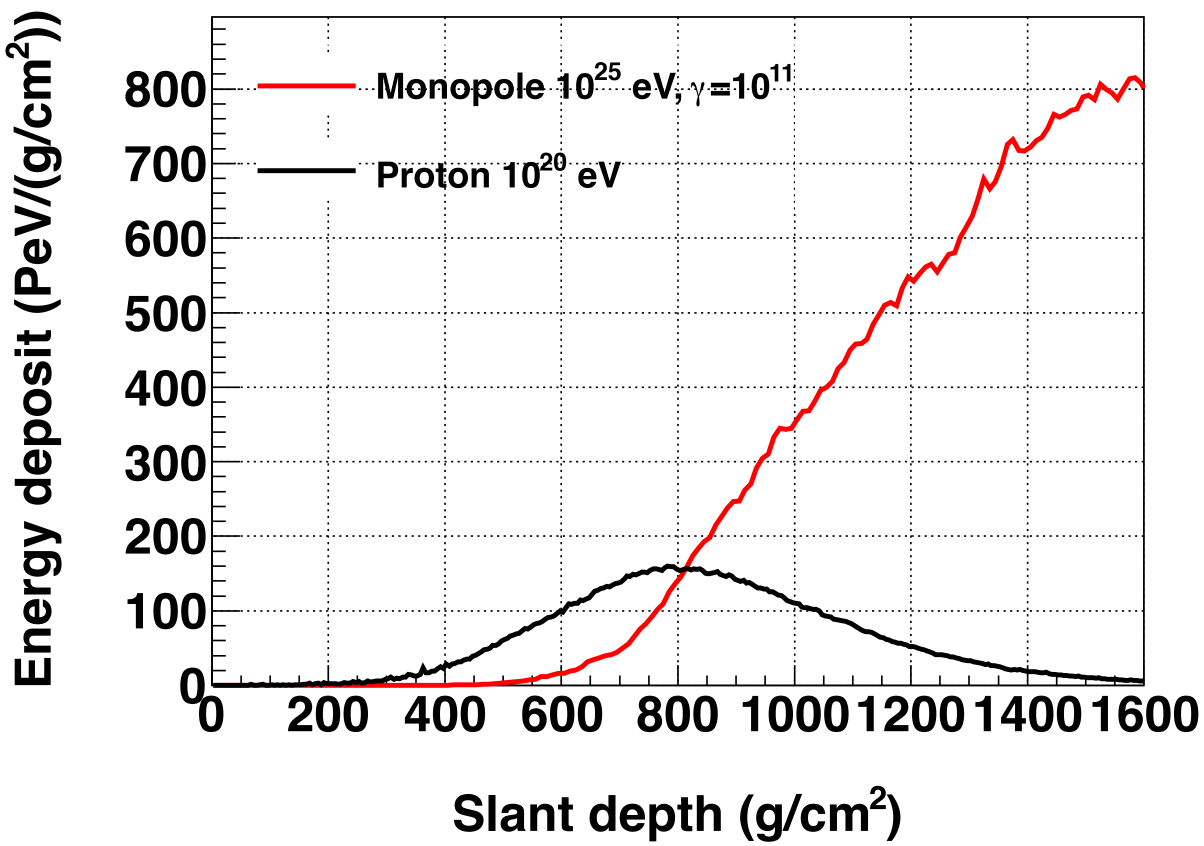
$$\sigma^{prod}_{p\text{-}Air} = (505 \pm 22_{stat} \left(^{+26}_{-34}\right)_{sys}) \text{ mb}$$



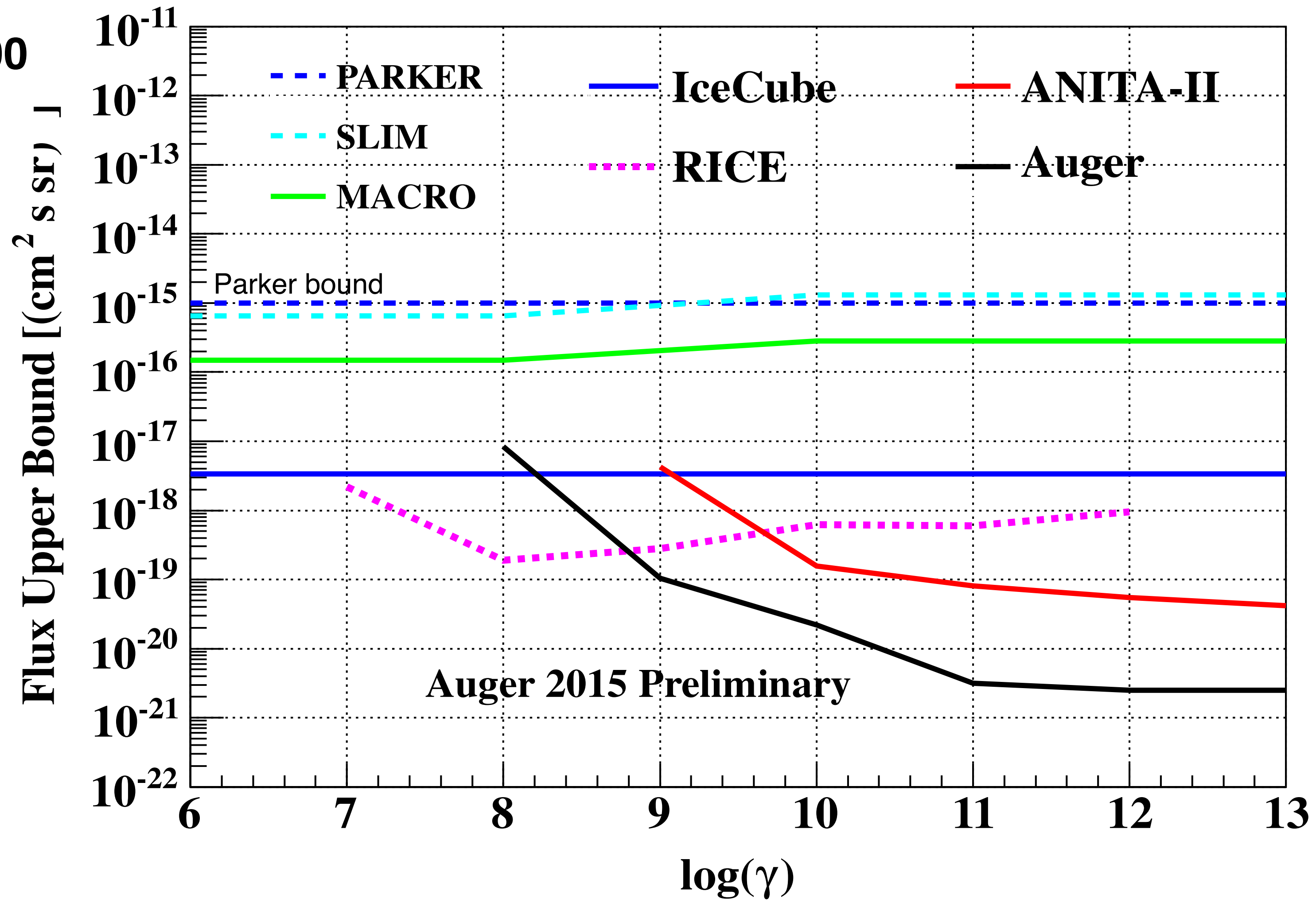
$$\sigma^{inel}_{pp} = [92 \pm 7_{stat} \left(^{+9}_{-11}\right)_{sys} \pm 7.0_{Glauber}] \text{ mb}$$

$$\sigma^{tot}_{pp} = [133 \pm 13_{stat} \left(^{+17}_{-20}\right)_{sys} \pm 16_{Glauber}] \text{ mb}$$

Search for Magnetic Monopoles



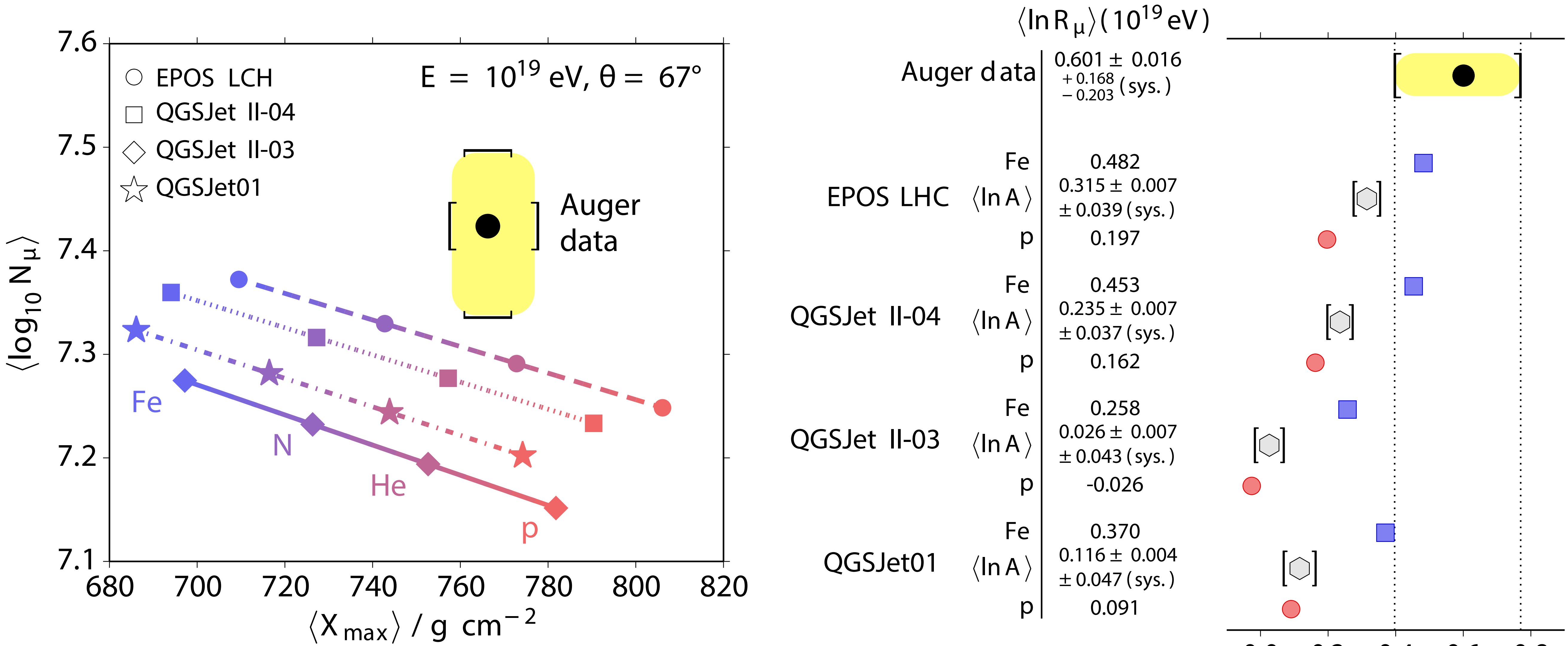
Expect very deeply generating showers with high light intensity



best present limits
by 3 orders of magnitude
to be submitted to PRD

Interaction Models lack Muons in EAS

Auger Collaboration, Phys. Rev. D 91, 032003 (2015); editors suggestion



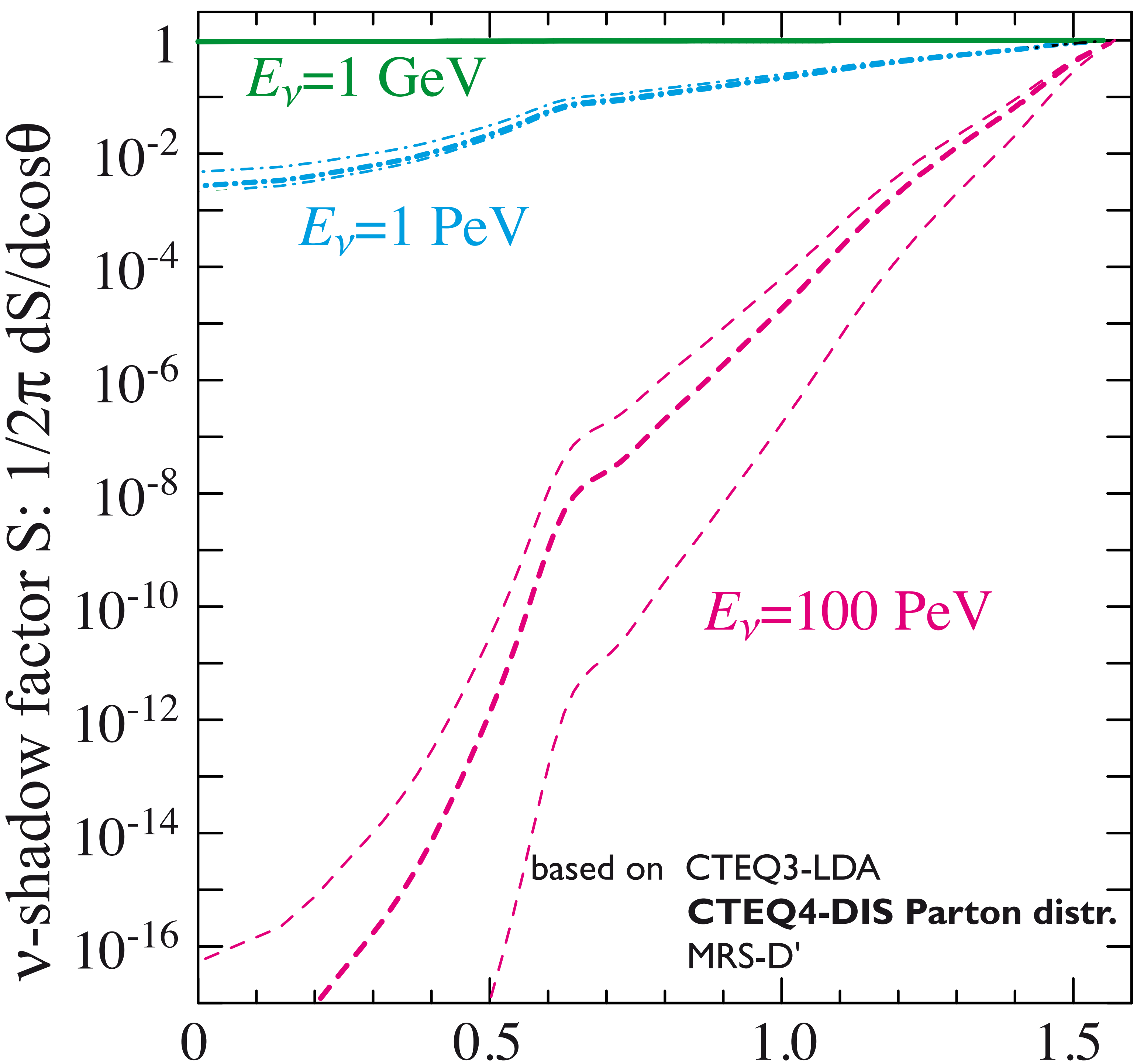
μ-deficit points to deficiencies of hadronic interaction models

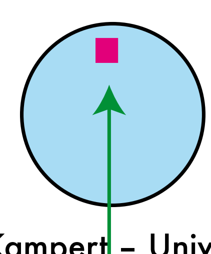
LHC forward physics program highly relevant

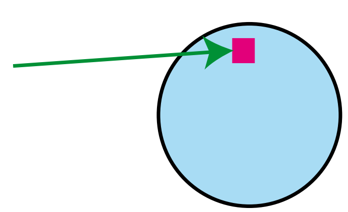
joint efforts by people from both communities

Neutrino Absorption in Earth

nach Gandhi et al., Fermilab-Pub-98-087-T

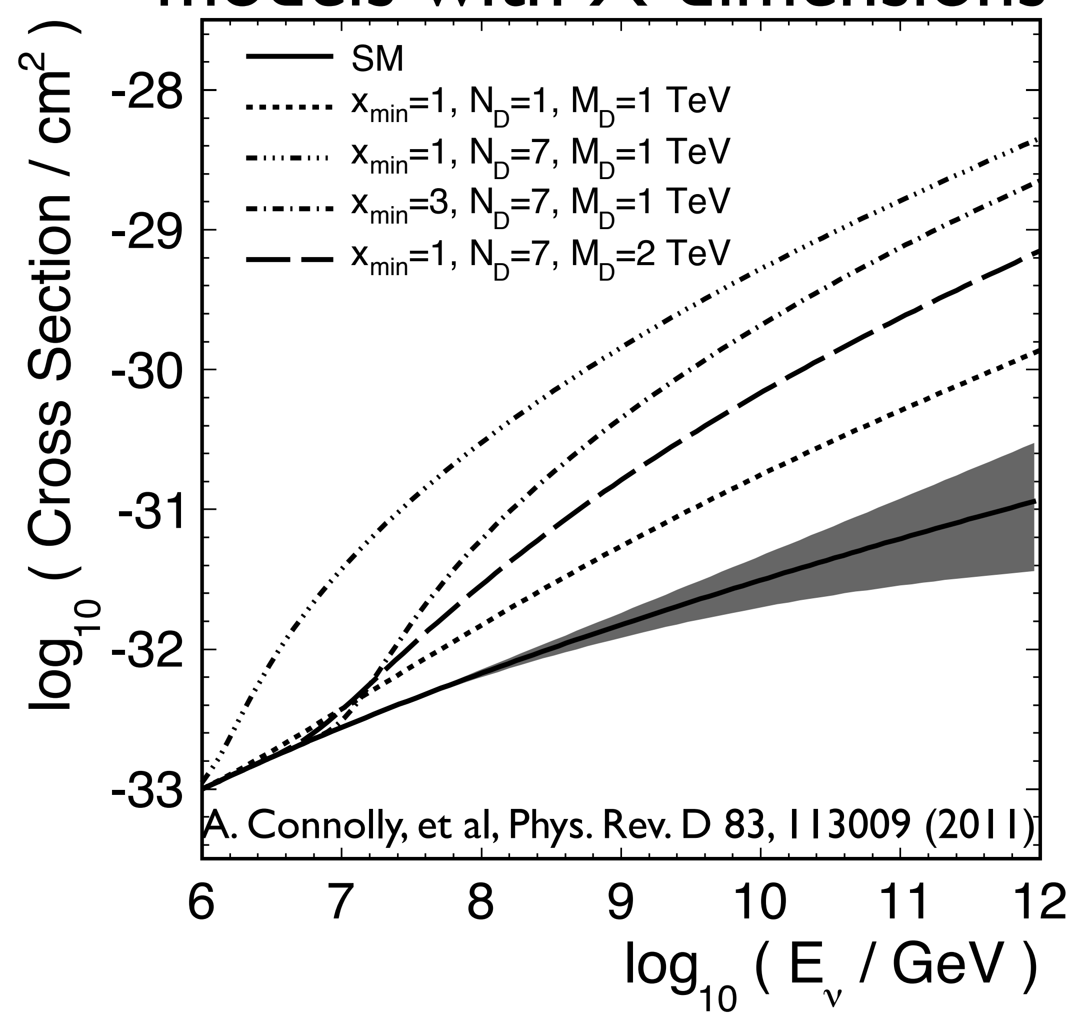






Earth becomes opaque at $E_\nu \gtrsim 100$ TeV

enhanced cross section in models with X-dimensions



Bounds on LIV and Smoothness of Class. Space-Time

Klinkhamer/Risse; PRD77 (2008) 016002; 117901; Klinkhamer, AIP Conf.Proc.977:181-201,2008

Observation of 10^{20} eV events
proofs absence of Vacuum Cherenkov-Radiation
→ Provides limits on smoothness of space & LIV-effects

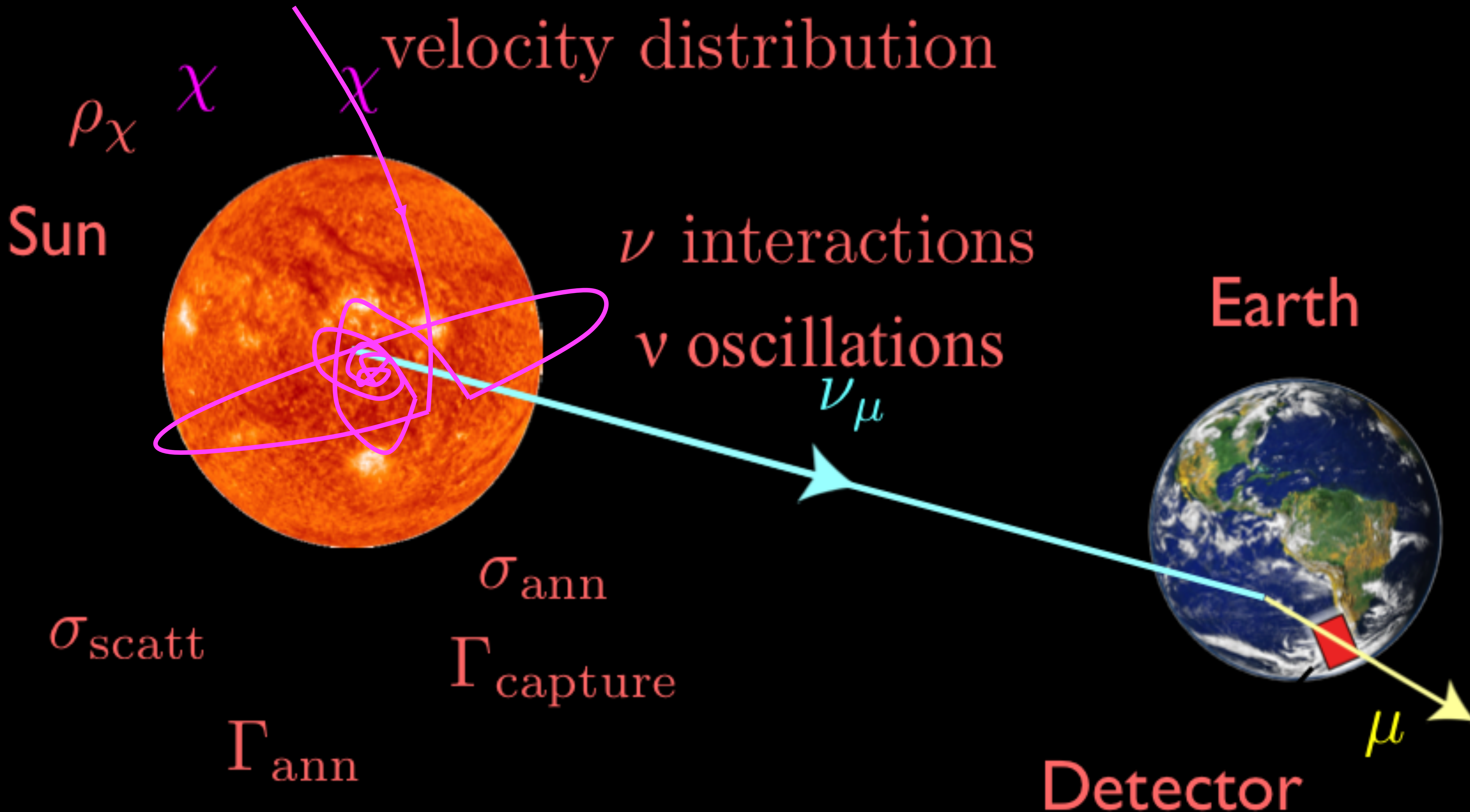
- Conservative limit on any small-scale structure of space:
  LEP/LHC: $\ell \leq 10^{-19}$ m $\approx \hbar c/(1\ \text{TeV})$.
- Use published 27 Auger events + 1 AGASA + 1 Fly's-Eye
  ↪ single scale classical space-time foam at
  UHECRs: $b \leq 10^{-26}$ m $\approx \hbar c/(2 \cdot 10^{10}\ \text{GeV})$

by far best (3 to 8 orders of magn.!) existing bounds of Standard Model Extension parameters of nonbirefringent modified Maxwell theory

Results complemented by TeV γ-rays

- **Conjecture:** fundamental length scale of quantum space time may be different from Planck length and may be linked to cosmological constant

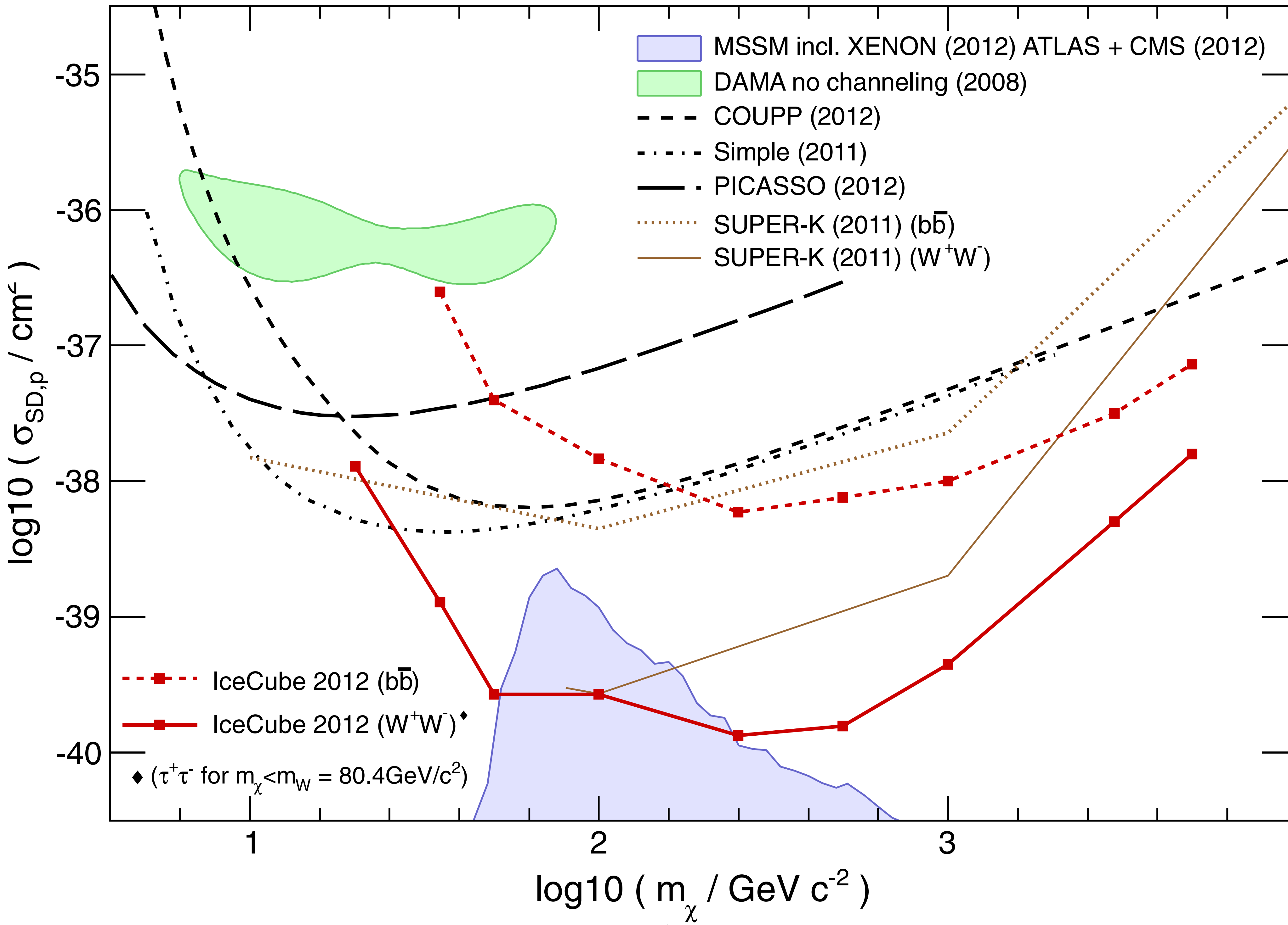
Dark Matter Annihilations in the Sun



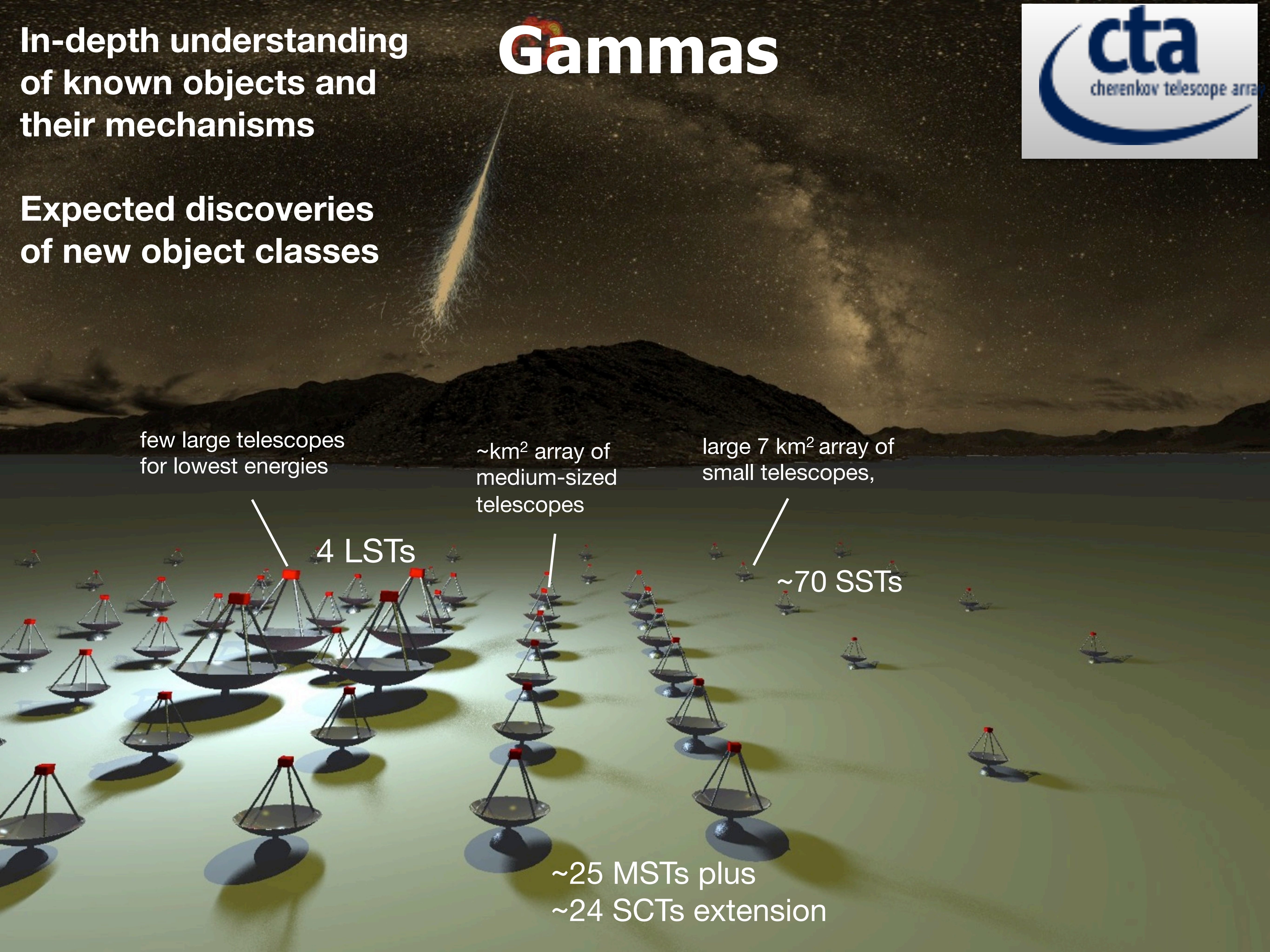
WIMP-proton cross section limits

IceCube-Collaboration, Phys. Rev. Lett. 110, 131302 (2013)

upper limits for spin dependent WIMP X-section for WIMPs annihilating into W^+W^- or $\tau^+\tau^-$

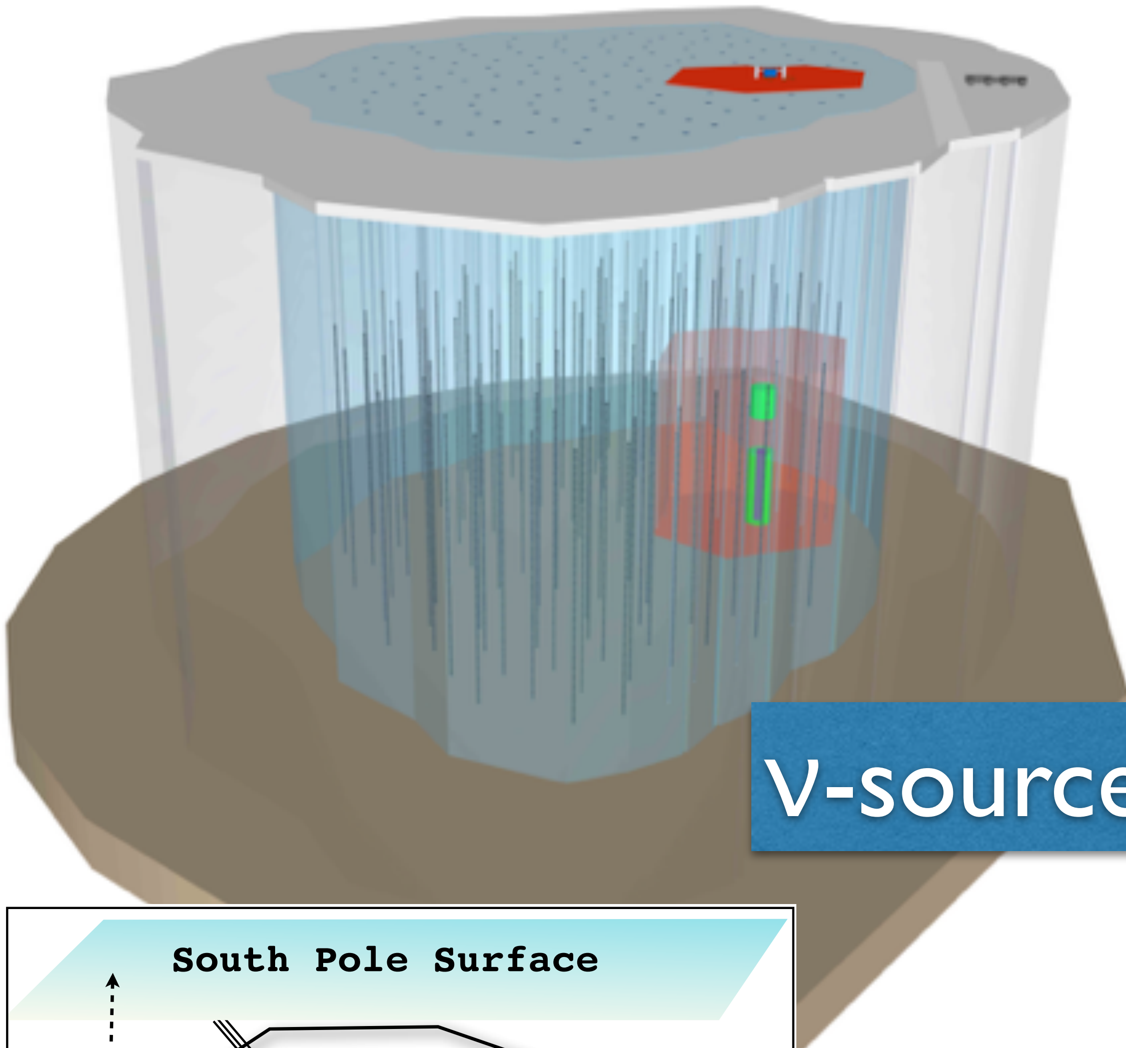


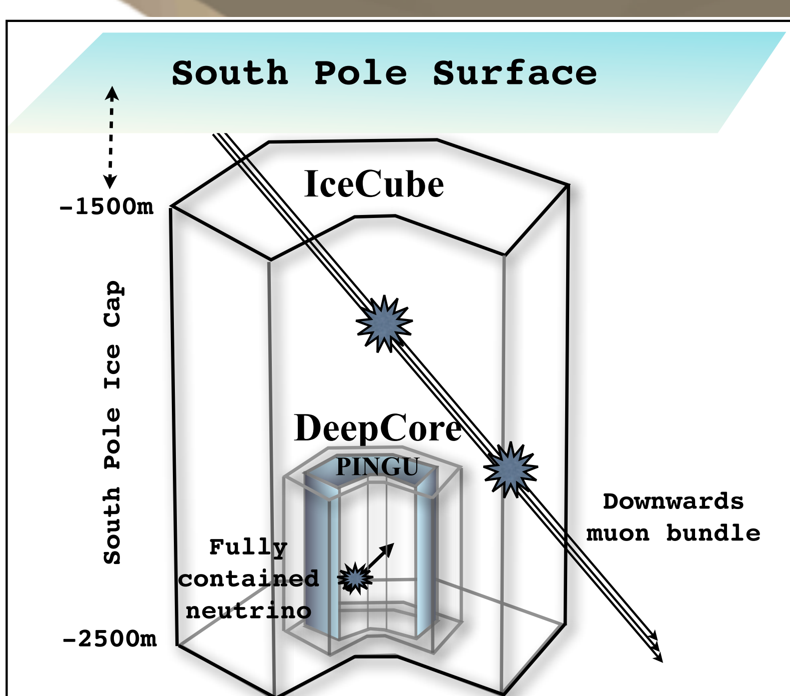

CRs
γ
ν
The next steps
with complementary probes of the high energy Universe
many recent discoveries and surprises


Gammas
In-depth understanding of known objects and their mechanisms
Expected discoveries of new object classes
cta
cherenkov telescope array
few large telescopes for lowest energies
~km^2 array of medium-sized telescopes
large 7 km^2 array of small telescopes,
4 LSTs
~70 SSTs
~25 MSTs plus
~24 SCTs extension

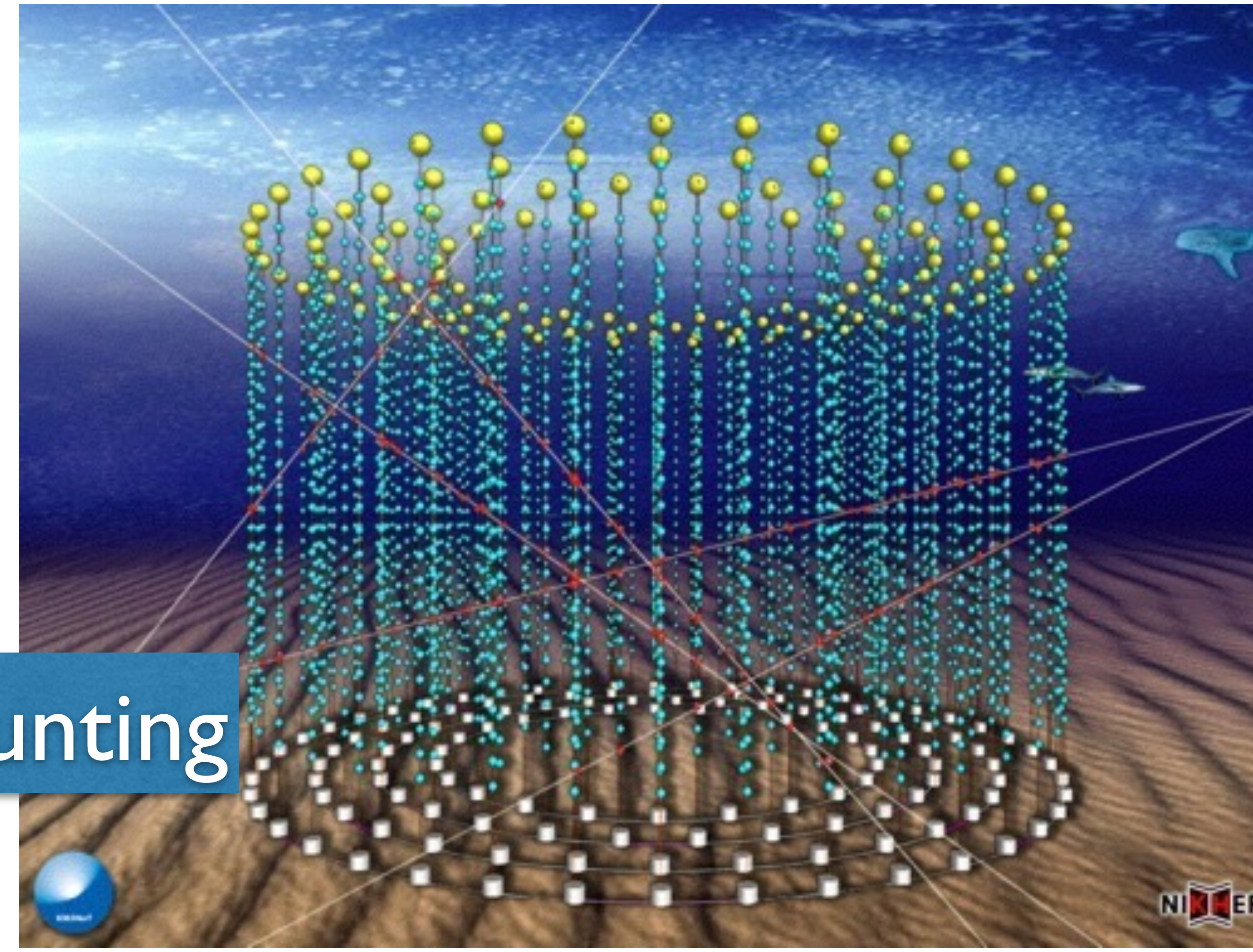
Neutrinos

10 km³ IceCube





Km3Net

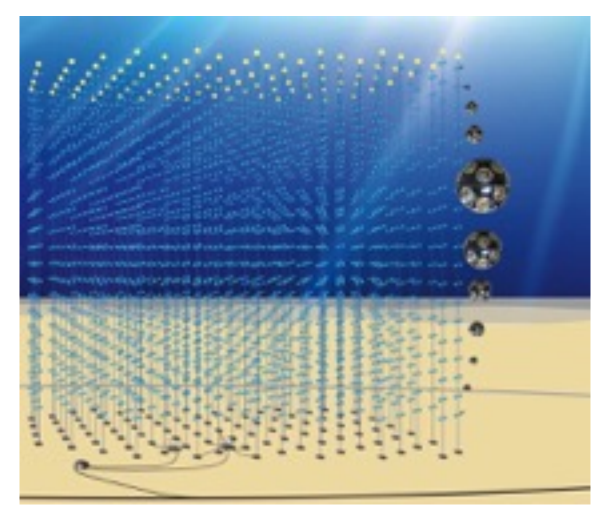


ν-source hunting

ν-mass hierarchy

PINGU

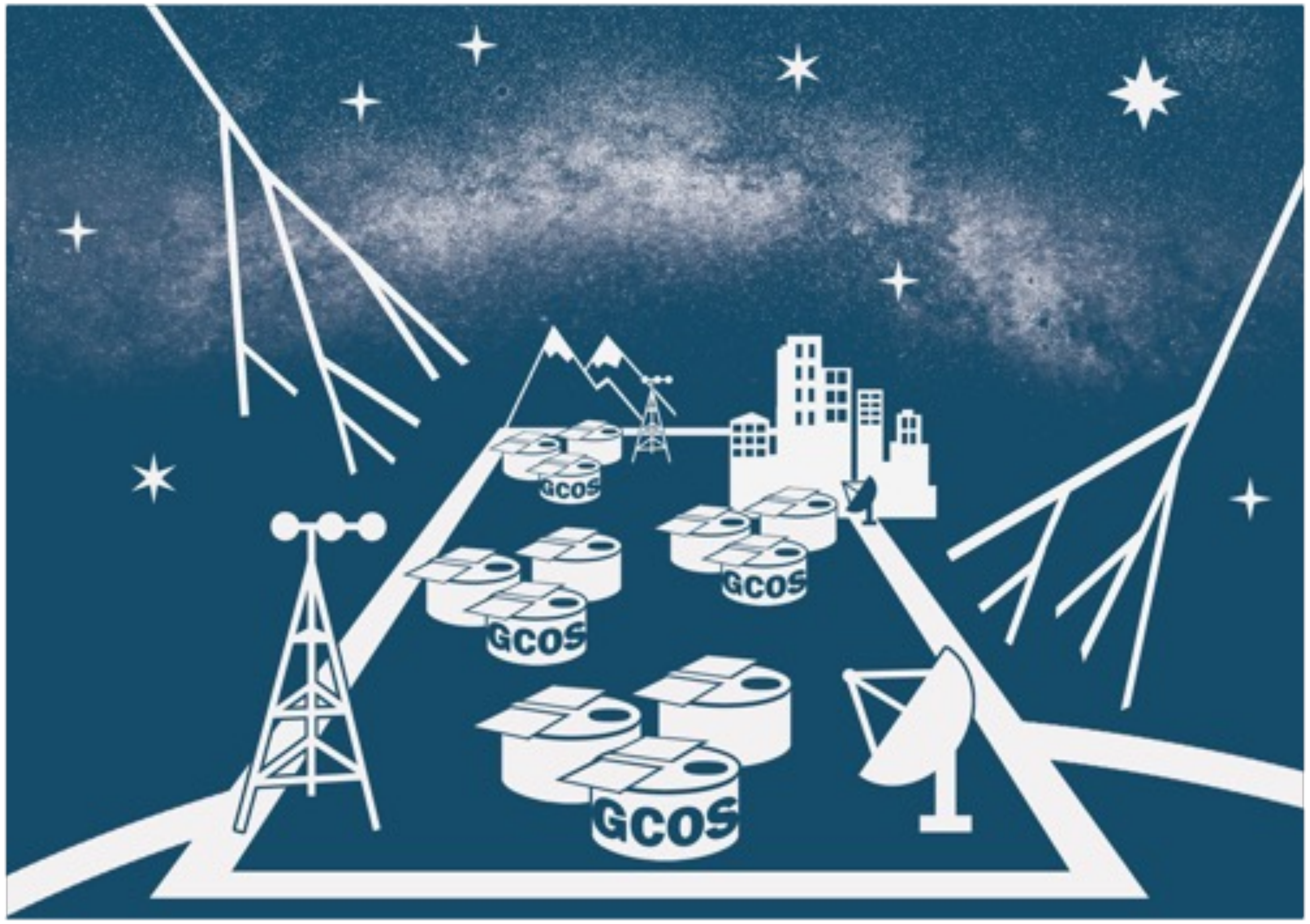
ORCA



UHECRs

AugerPrime: mass composition with ground array

Global Cosmic Ray Observatory few sites in N+S, 90 000 km^2



origin of the flux suppression

hadronic interactions beyond LHC

p-astronomy of sources source physics

Summary & Conclusion

- Major break throughs and discoveries made during last years
- Multi-Messenger observations have become real and improve our understanding further
- Besides Astrophysics, also key observations in fundamental physics and in BSM (B-LHC)
- Major new projects under construction and in preparation
- Exciting years & thesis topics for GRK2149