The Universe at the Highest Energies

Ralph Engel

Karlsruhe Institute of Technology (KIT)

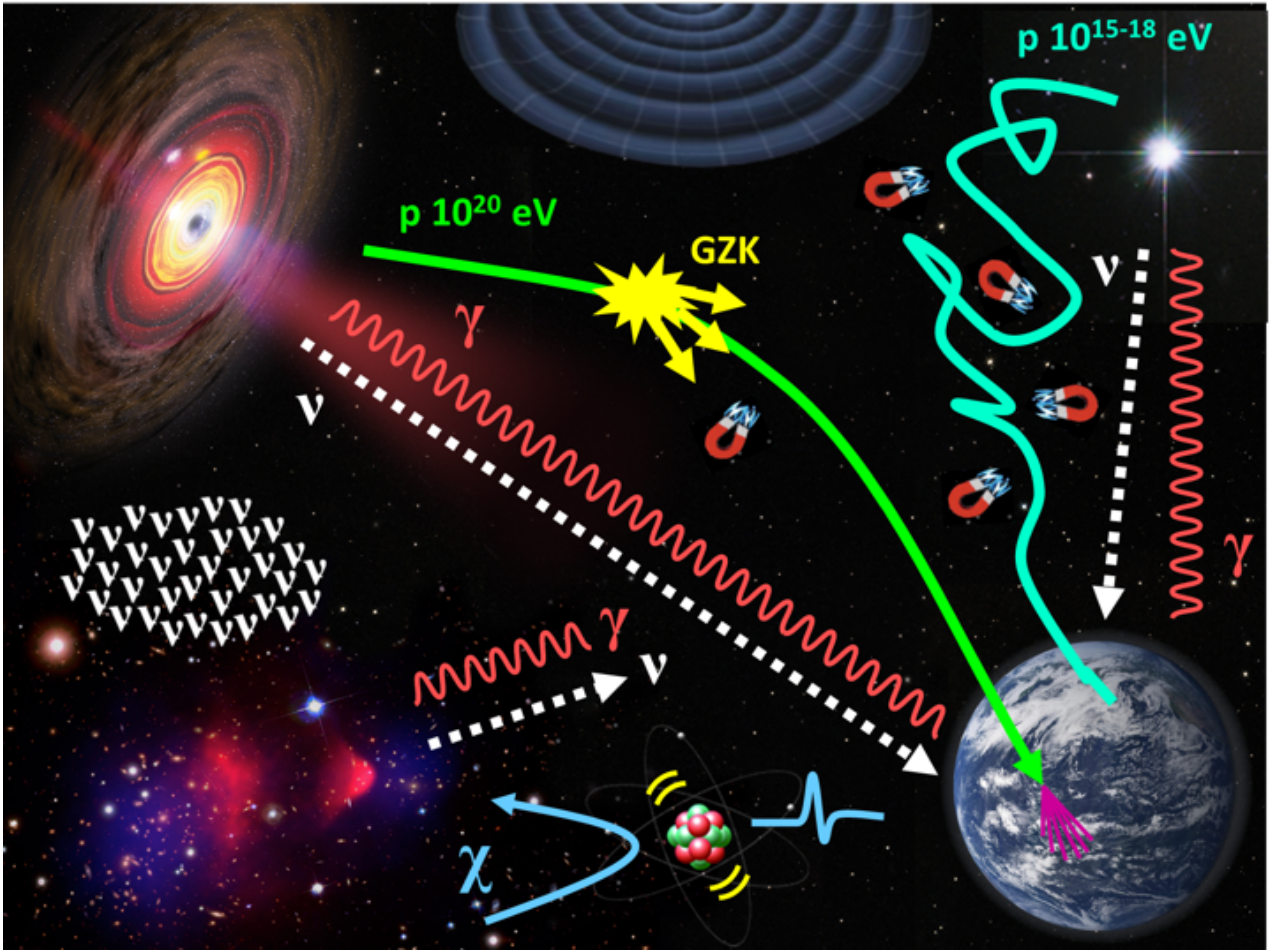
Astroparticle physics

Very rapidly developing field
Largely driven by observations

Enormous diversity
- Cosmic rays
- Gamma rays
- Neutrinos
- Gravitational waves
- Dark Matter
- Axions etc.
- Astrophysical objects
- Quantum gravity &
  Space-time fluctuations

Multi-messenger physics

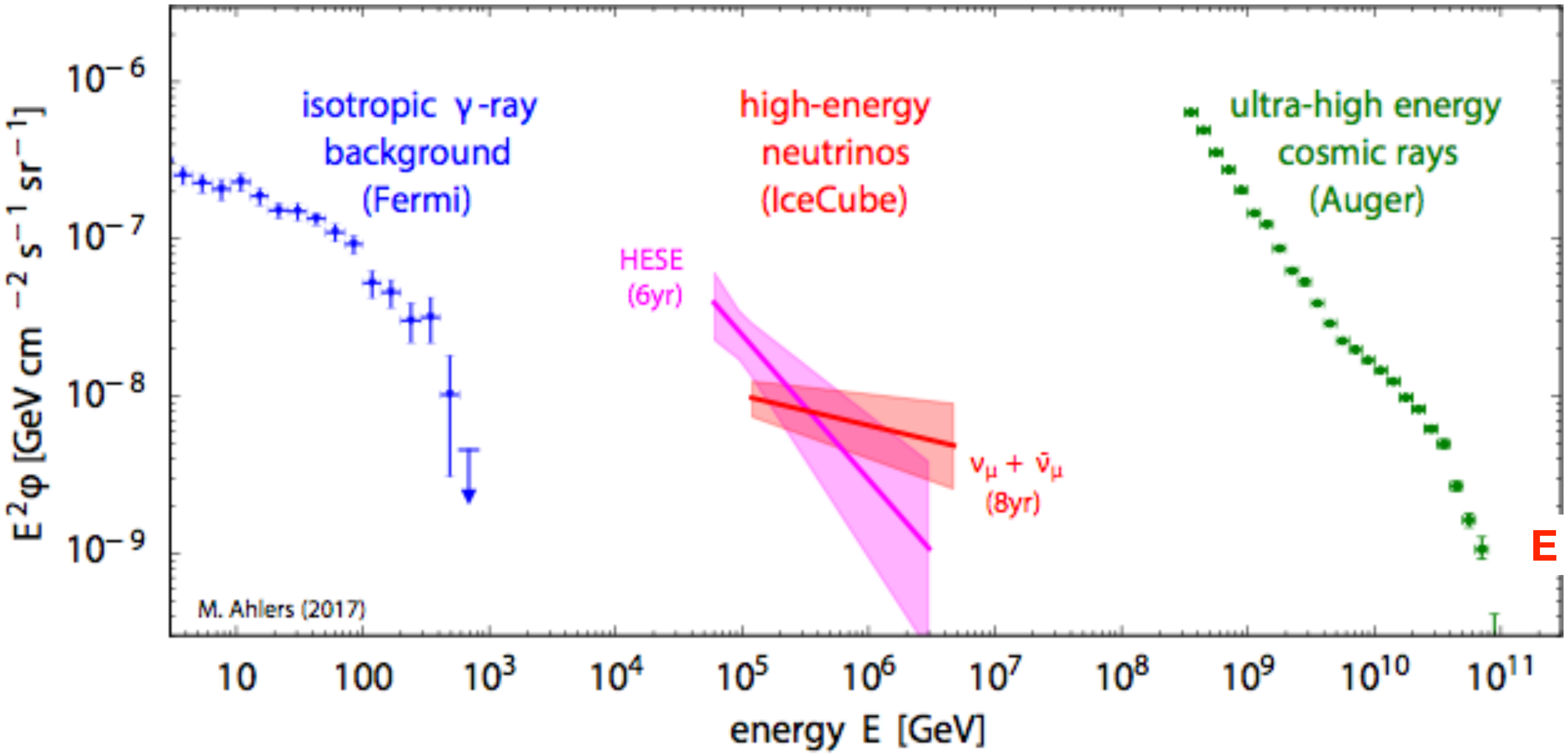
(J. Blümer)



This talk: The Universe at the highest energies

Particle flux multiplied by E^2

$$E^2 \frac{\mathrm{d}N}{\mathrm{d}E} = E \frac{\mathrm{d}N}{\mathrm{d}\ln E}$$



E = 10^{20} eV

Energy density per decade

$$\rho_{\mathrm{decade}} = \int_{\mathrm{decade}} E \frac{\mathrm{d}N}{\mathrm{d}\ln E} \, \mathrm{d}\ln E$$

Energy density per decade similar in all three messenger particles

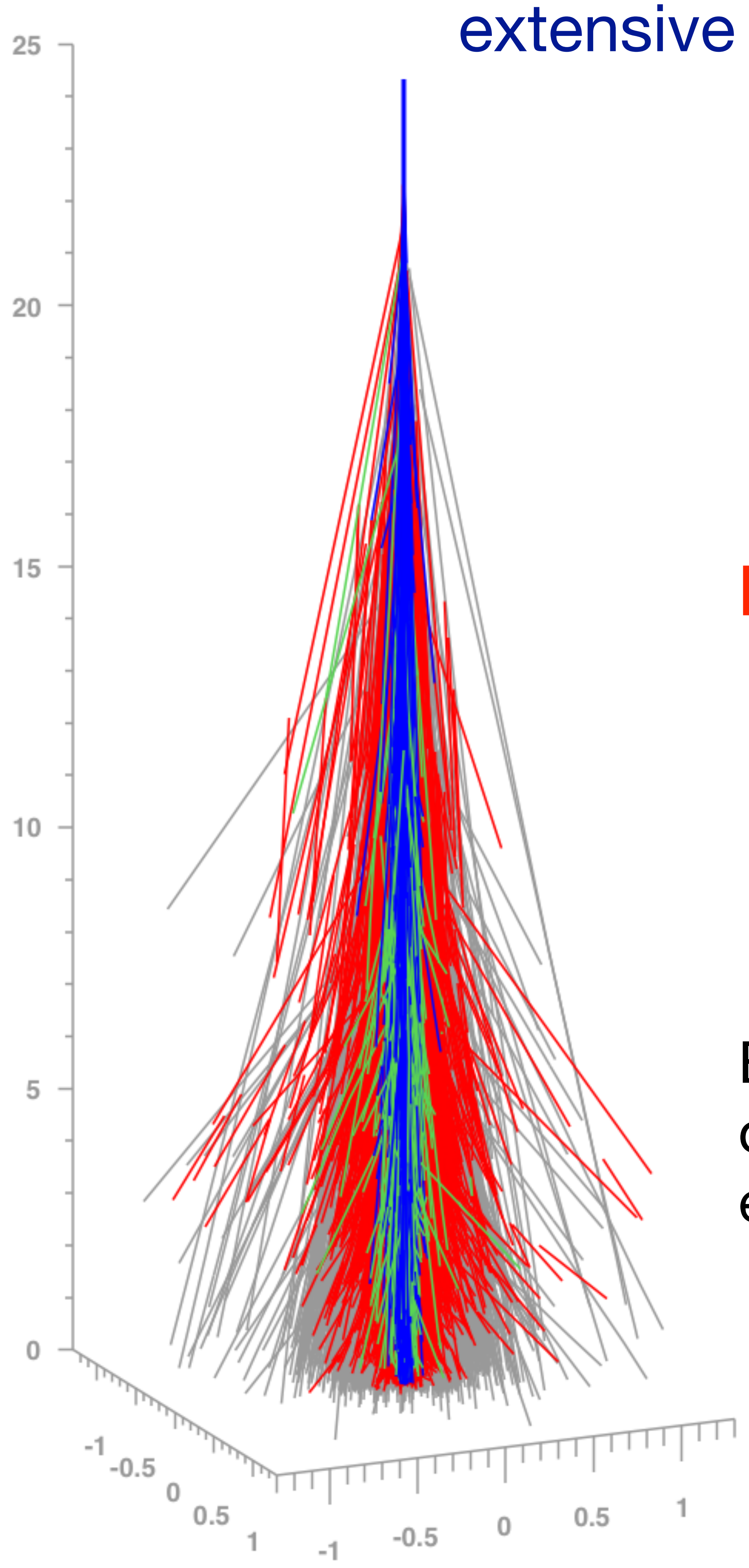
The first cosmic particle of ultra-high energy

VOLUME 10, NUMBER 4 PHYSICAL REVIEW LETTERS 15 FEBRUARY 1963

EVIDENCE FOR A PRIMARY COSMIC-RAY PARTICLE WITH ENERGY 10^{20} eV†

John Linsley
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 10 January 1963)

Cascade of secondary particles: extensive air shower



E = 10^{20} eV

Energy conservation, overall energy estimate robust

Cosmic rays of 10^{20} eV energy exist !

VOLUME 10, NUMBER 4 PHYSICAL REVIEW LETTERS 15 FEBRUARY 1963

EVIDENCE FOR A PRIMARY COSMIC-RAY PARTICLE WITH ENERGY 10^{20} eV†

John Linsley
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 10 January 1963)

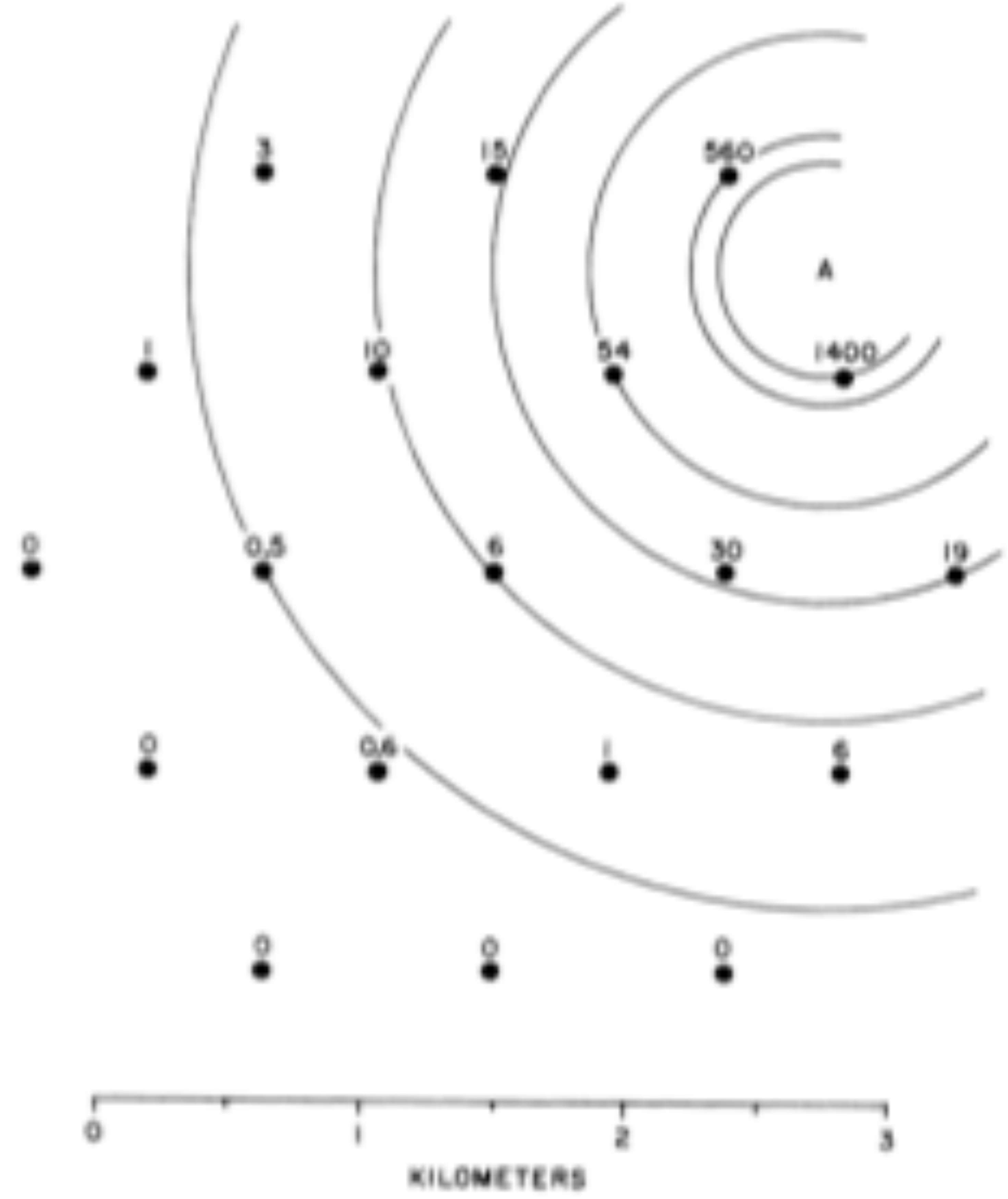


FIG. 1. Plan of the Volcano Ranch array in February 1962. The circles represent 3.3-m² scintillation detectors. The numbers near the circles are the shower densities (particles/m²) registered in this event, No. 2-4834. Point "A" is the estimated location of the shower core. The circular contours about that point aid in verifying the core location by inspection.

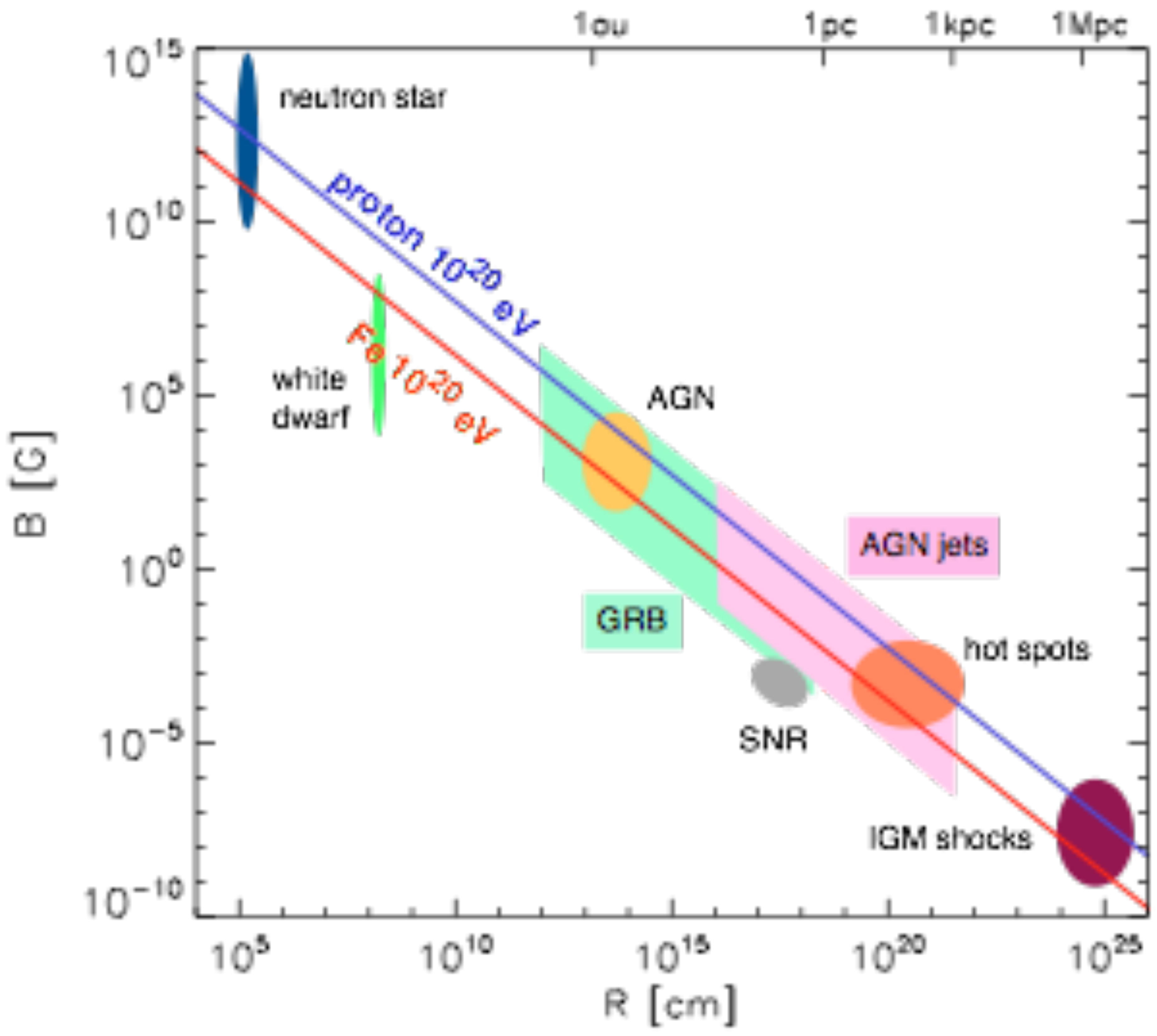
How to accelerate particles to 10^{20} eV

Large Hadron Collider (LHC), 27 km circumference, superconducting magnets

Need accelerator of size of Mercury orbit to reach 10^{20} eV with LHC technology

Hillas plot (1984)

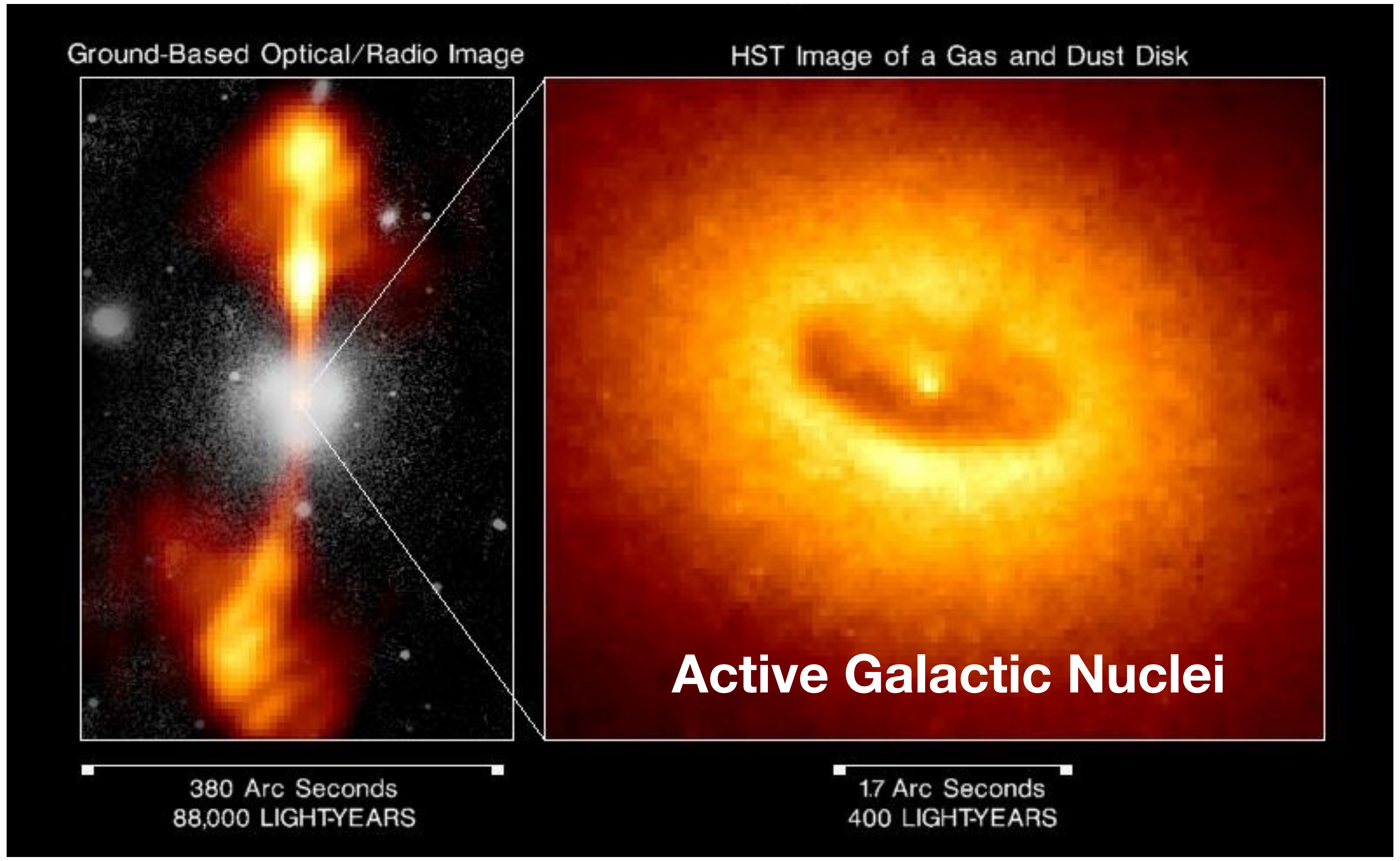
$$E_{\max} \sim \beta_s Z B R$$

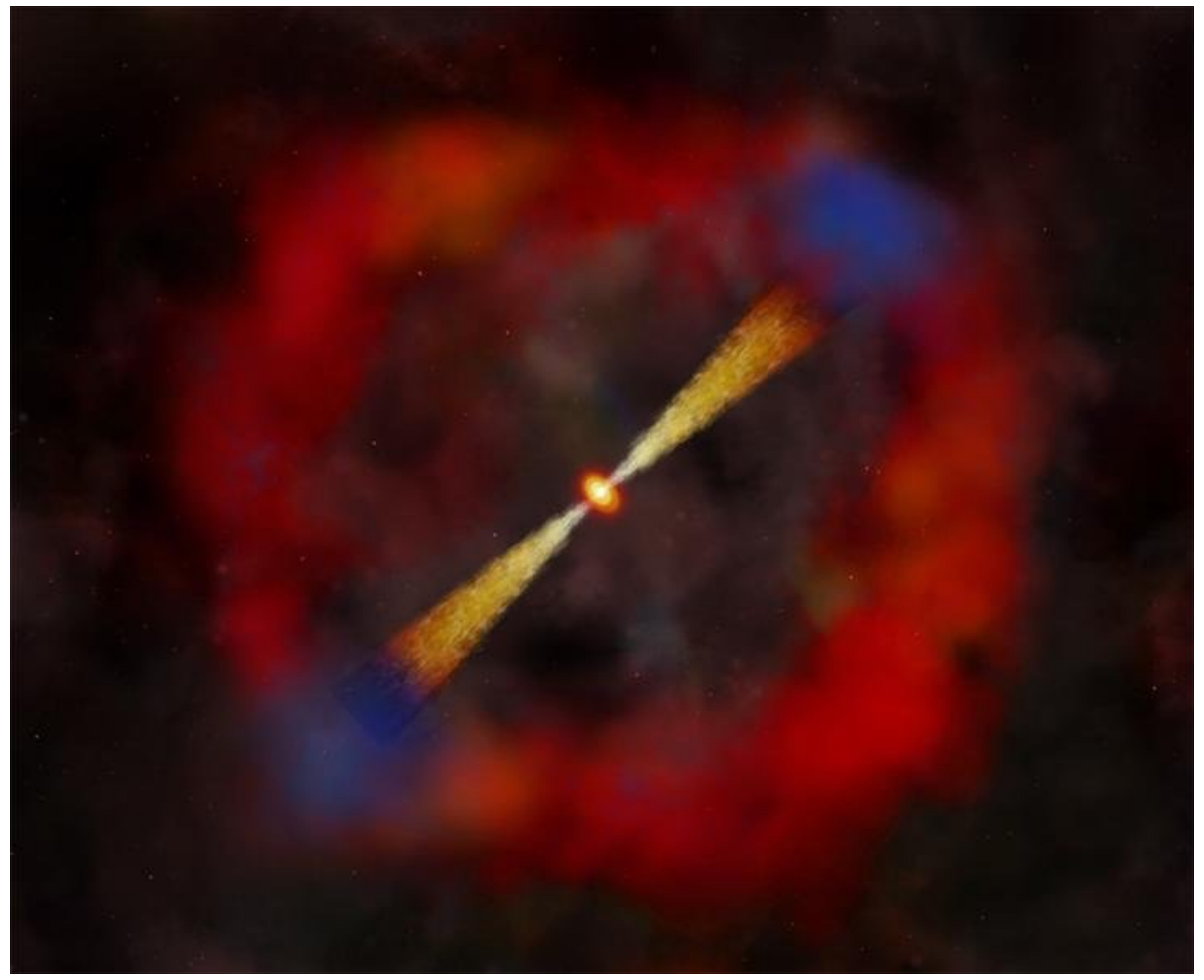


(Kotera & Olinto, ARAA 2011)

Examples of astrophysical source candidates

Diffusive shock acceleration

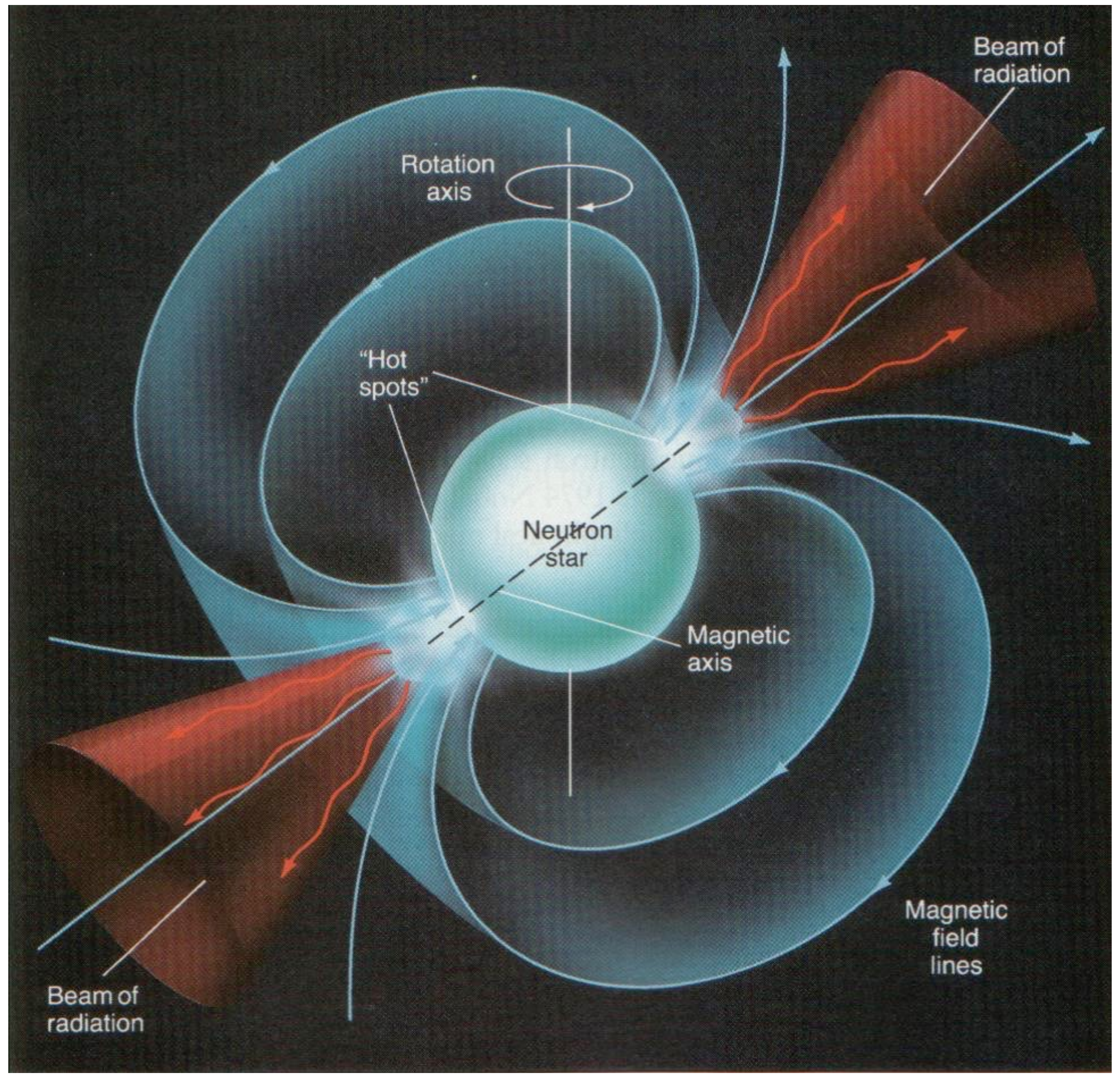




$$\frac{\mathrm{d}N_{\mathrm{inj}}}{\mathrm{d}E} \sim E^{-2}$$

Gamma ray bursts (GRBs)

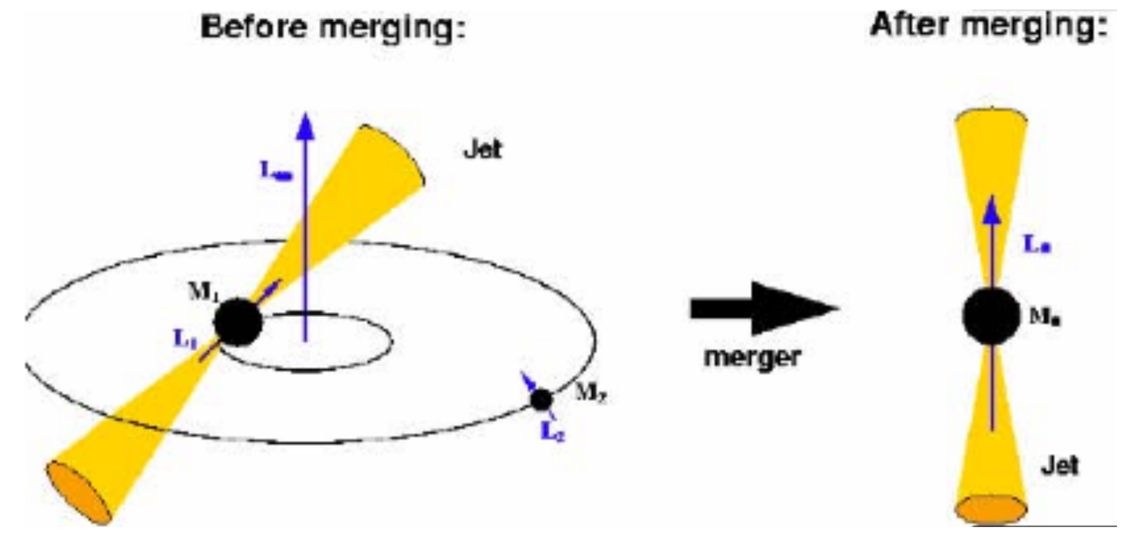
Inductive acceleration

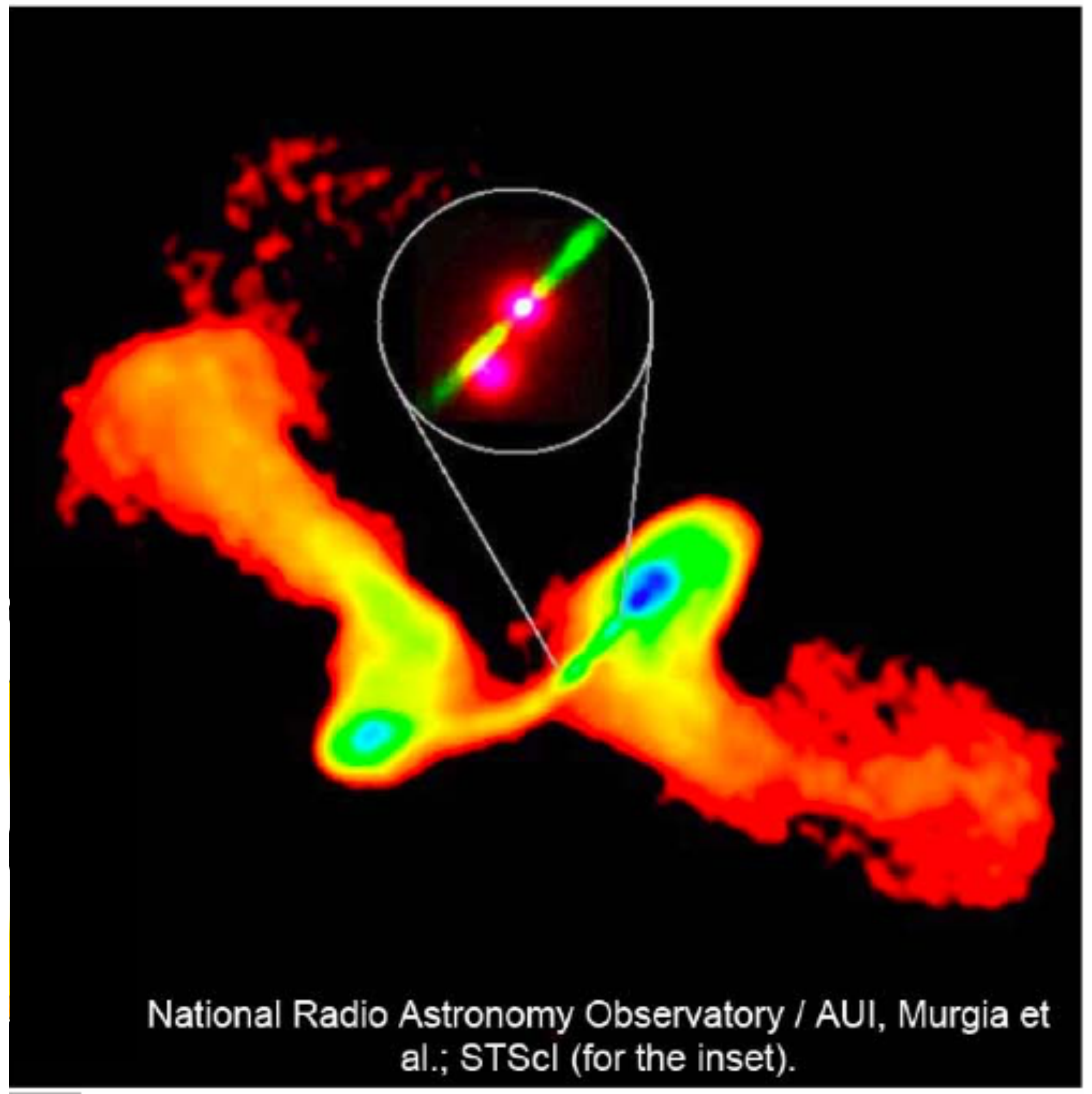


Rapidly spinning neutron stars

$$\frac{\mathrm{d}N_{\mathrm{inj}}}{\mathrm{d}E} \sim E^{-1}\left(1+\frac{E}{E_g}\right)^{-1}$$

Single (relativistic) reflection





Tidal disruption events (TDEs)

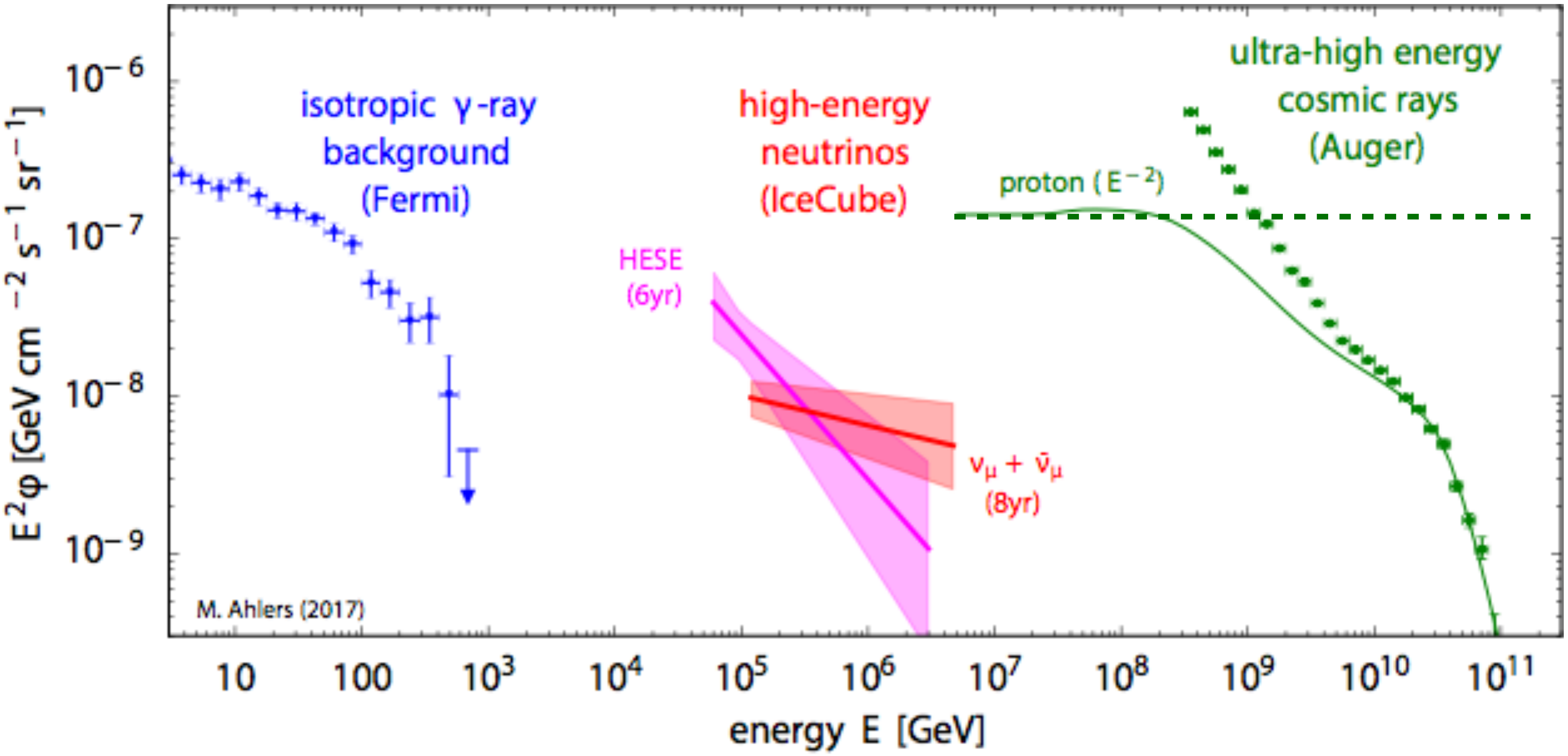
Fermi acceleration – a simplified view

First order Fermi acceleration at large-scale shock fronts

(shown is second order Fermi acceleration)

$$\frac{\mathrm{d}N_{\mathrm{inj}}}{\mathrm{d}E} \sim E^{-2}$$

Cosmic rays at the highest energies: extragalactic sources

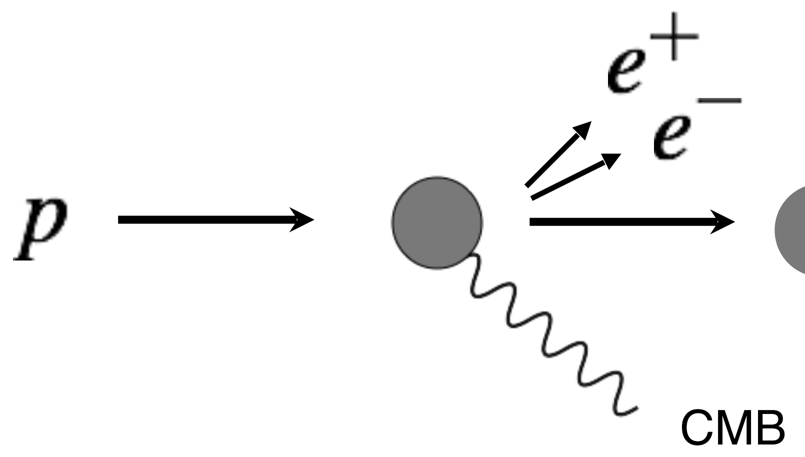


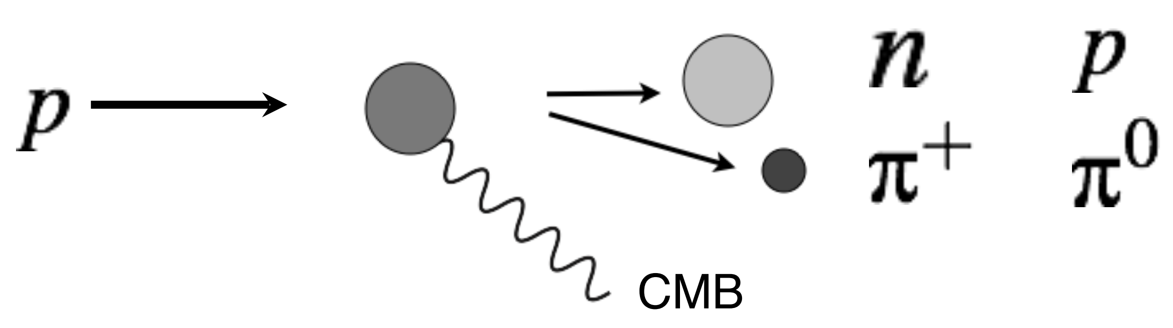
Energy spectrum of protons injected by sources

$$\frac{dN_{inj}}{dE} \sim E^{-2}$$

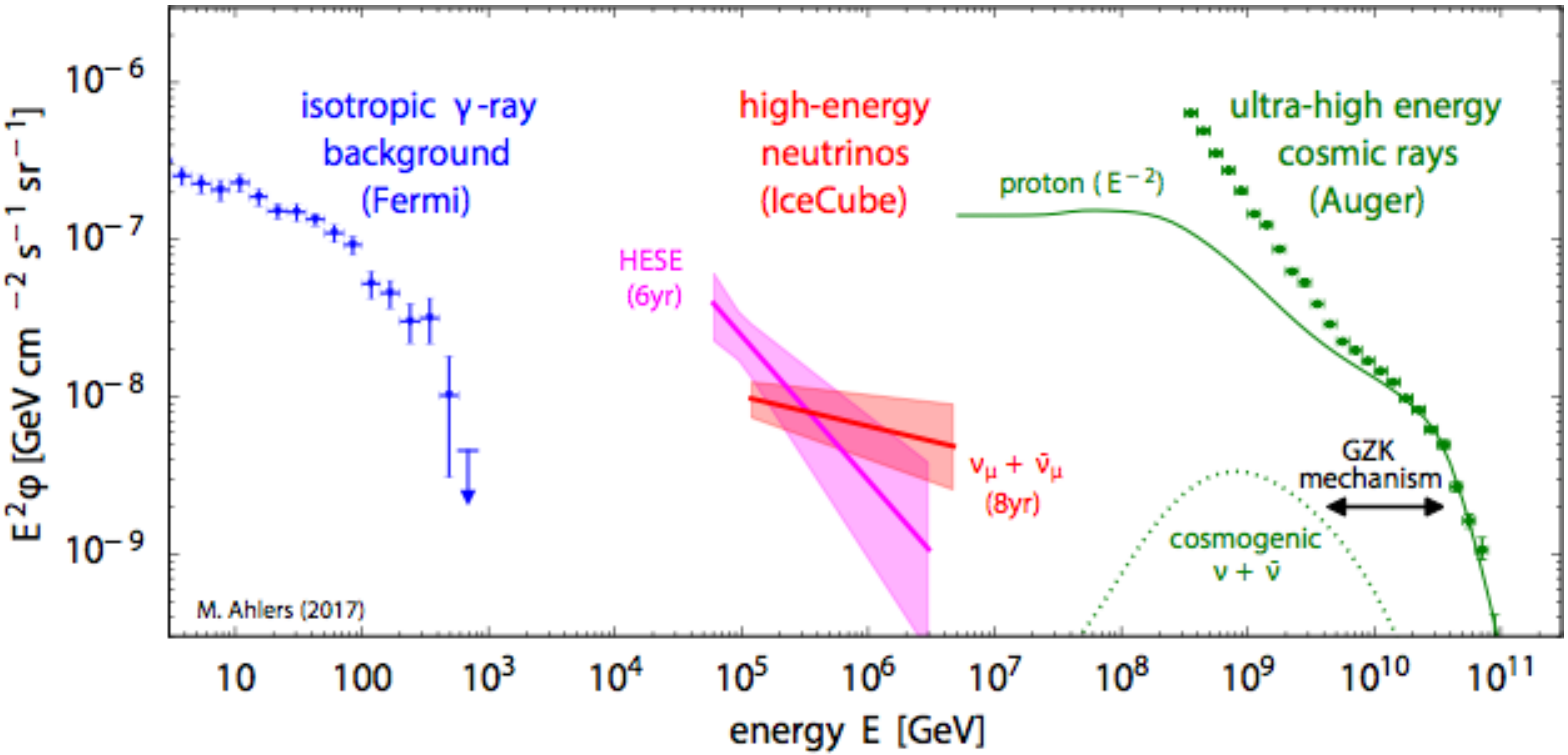
GZK effect:
Photo-pion production
(mainly Δ resonance)

Just a toy model to illustrate power of multi-messenger studies





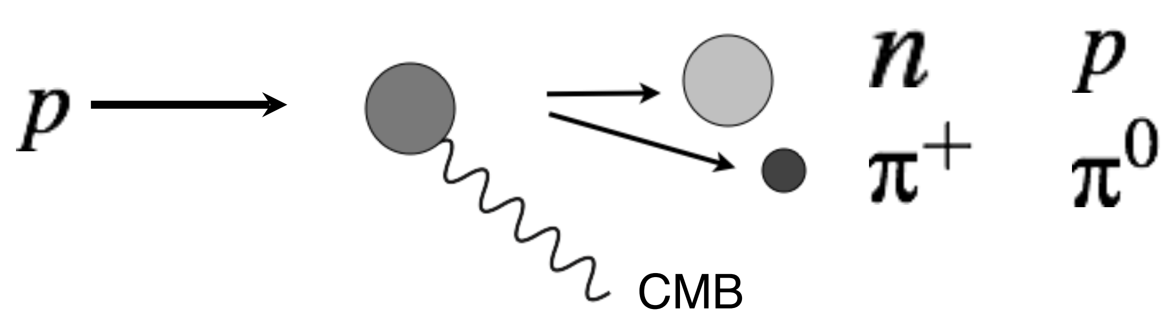
Neutrino production due to cosmic ray propagation



Energy spectrum of protons injected by sources

$$\frac{dN_{\rm inj}}{dE} \sim E^{-2}$$

GZK effect:
Photo-pion production (mainly Δ resonance)



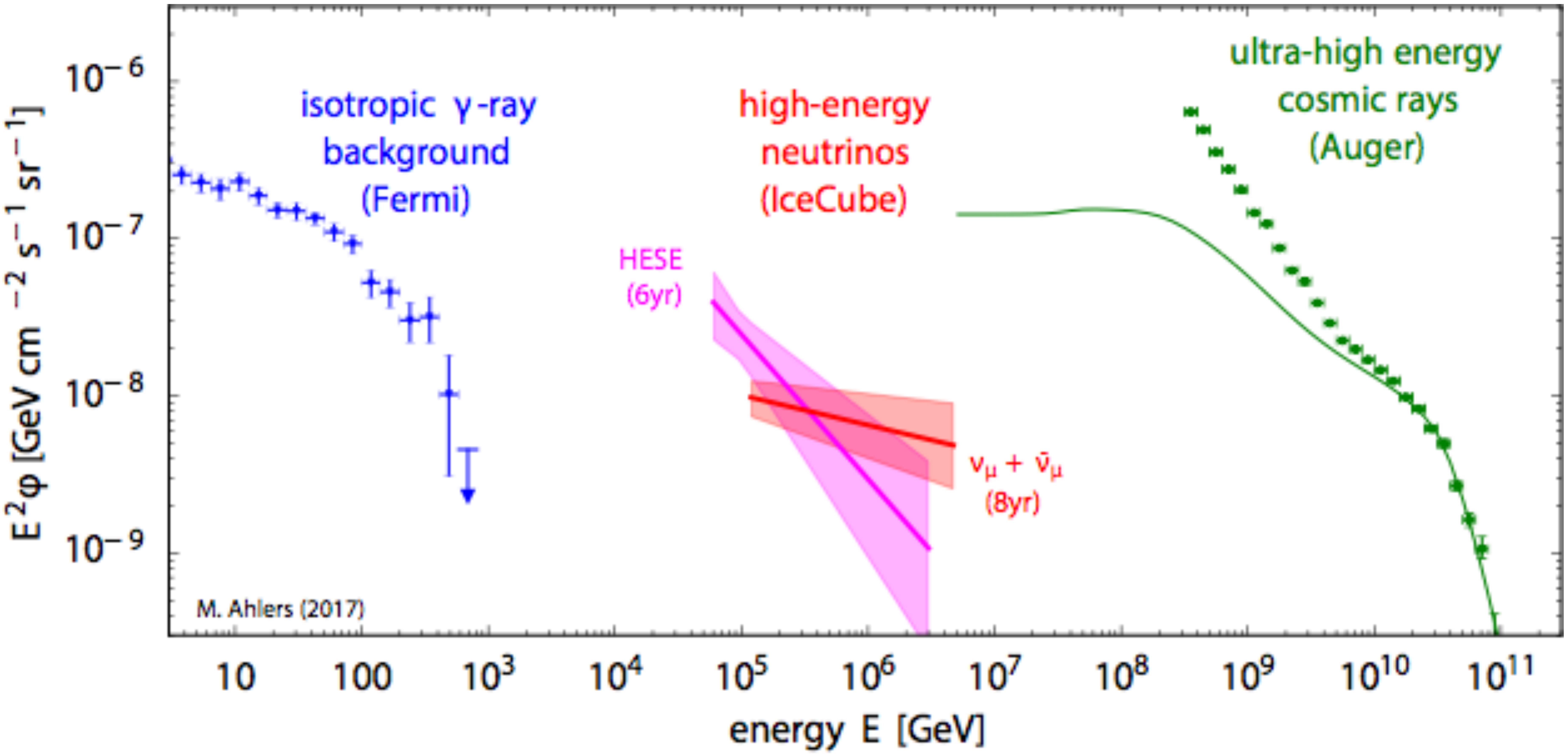
$$\pi^0 \longrightarrow \gamma\gamma$$

$$\pi^+ \longrightarrow \mu^+ \nu_\mu \longrightarrow e^+ \nu_e \nu_\mu \bar{\nu}_\mu$$

$$\boxed{\nu_\mu : \nu_e \sim 2:1}$$

(neutrino + antineutrino flavor)

Neutrino production due to cosmic ray propagation



Energy spectrum of protons injected by sources

$$\frac{\mathrm{d}N_{\mathrm{inj}}}{\mathrm{d}E} \sim E^{-2}$$

Very similar energy loss for nuclei,
but different physics process (very few neutrinos)

Iron

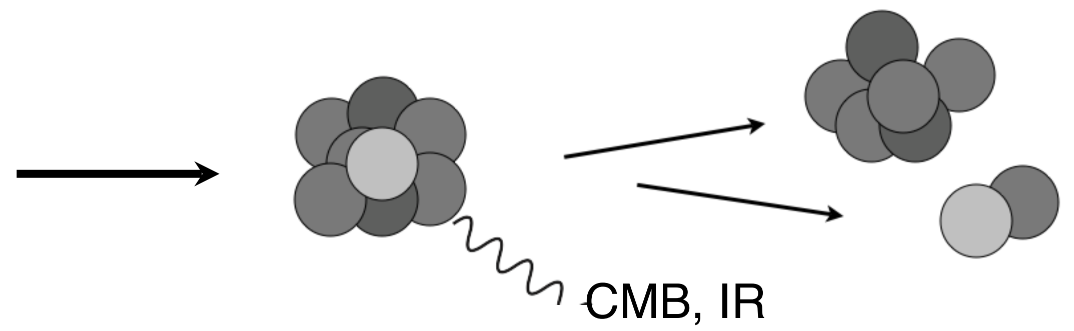
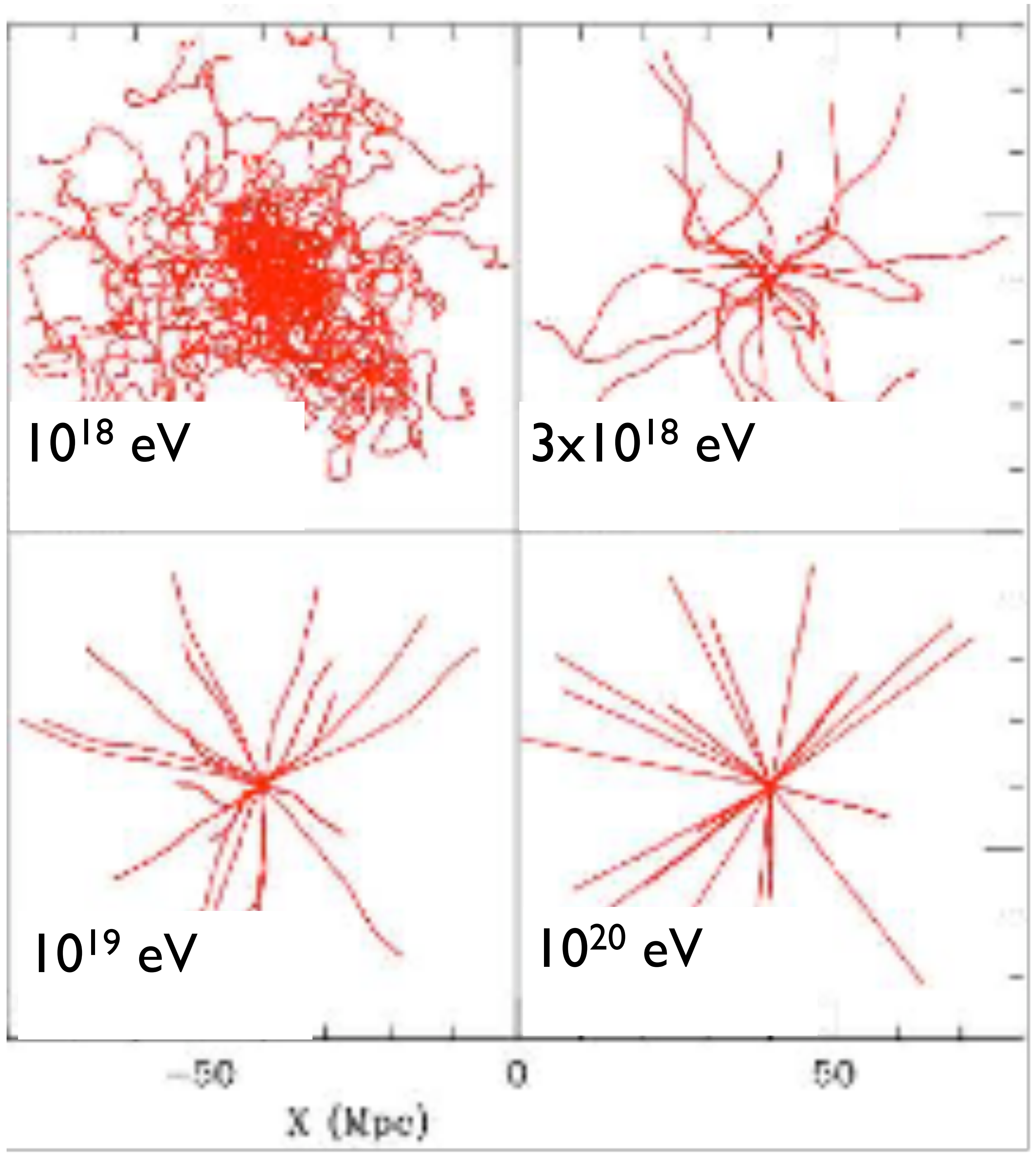


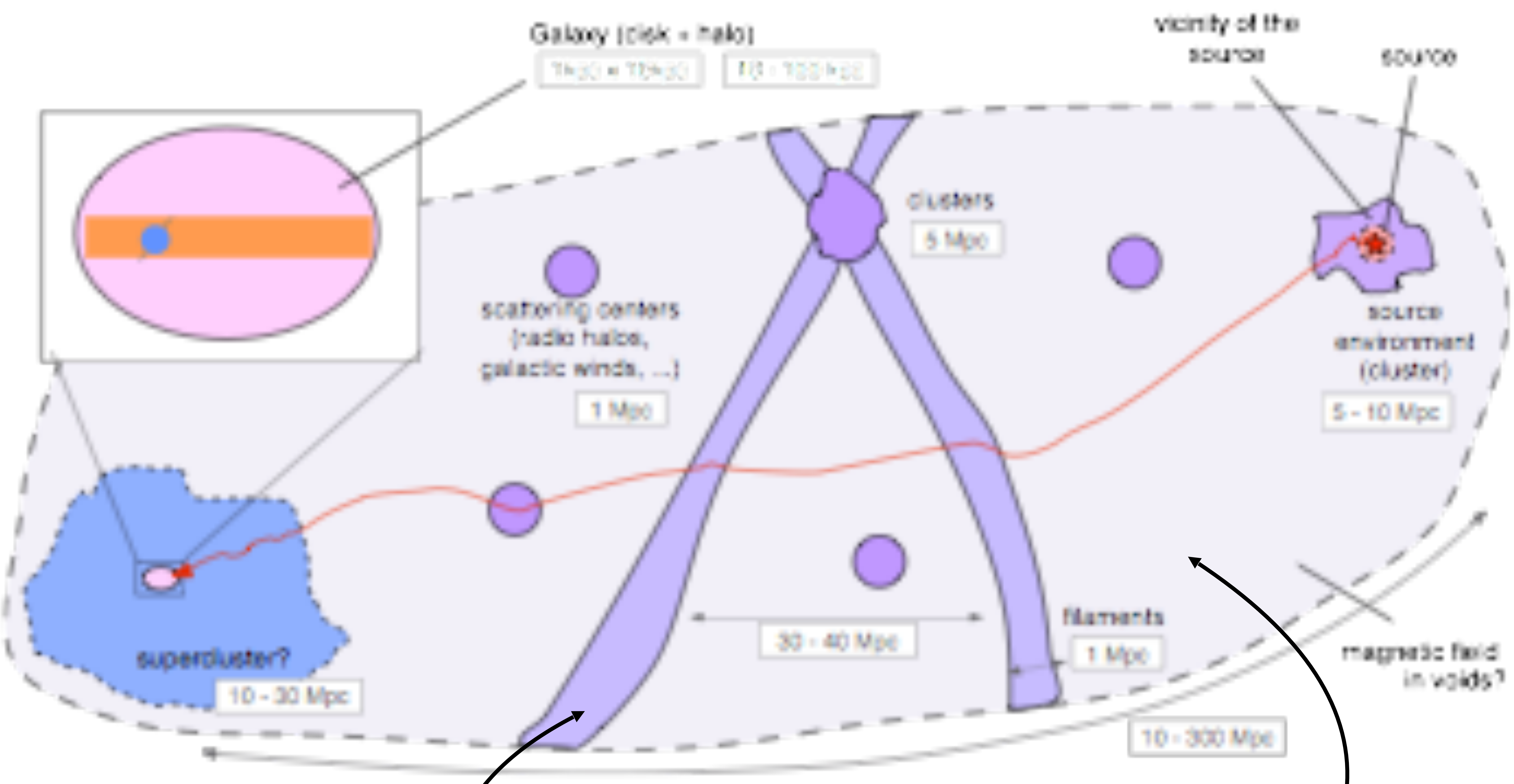
Photo-dissociation
(giant dipole resonance)

How to identify sources of ultra-high-energy cosmic rays

Deflection in Galactic and extragalactic mag. fields

protons





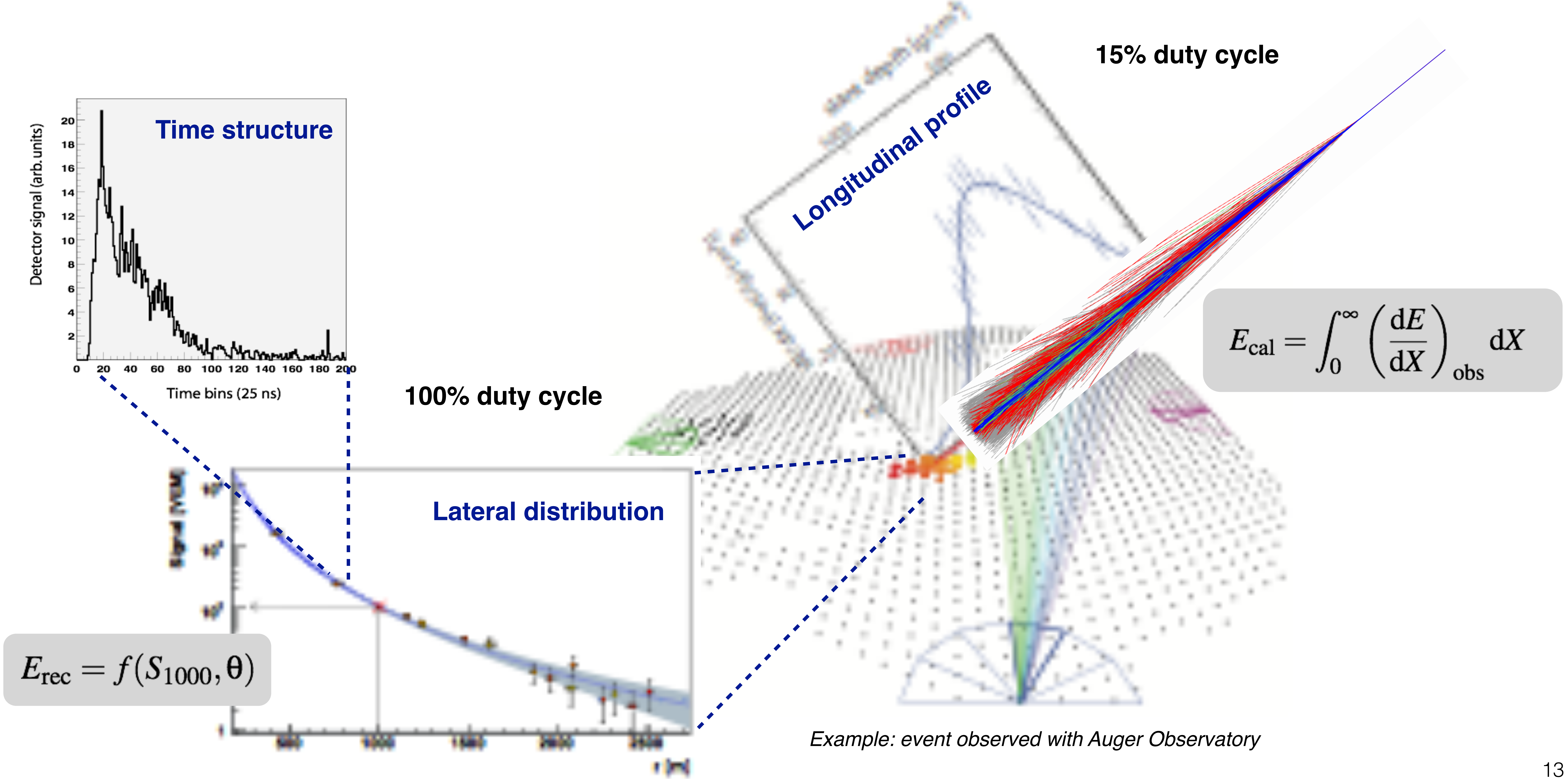
(Kotera & Olinto, ARAA 2011)

$B \sim 10^{-6}\,\mathrm{G}$

$B \leq 10^{-9}\,\mathrm{G}$

Anisotropy in arrival direction distribution on small, intermediate and large scales

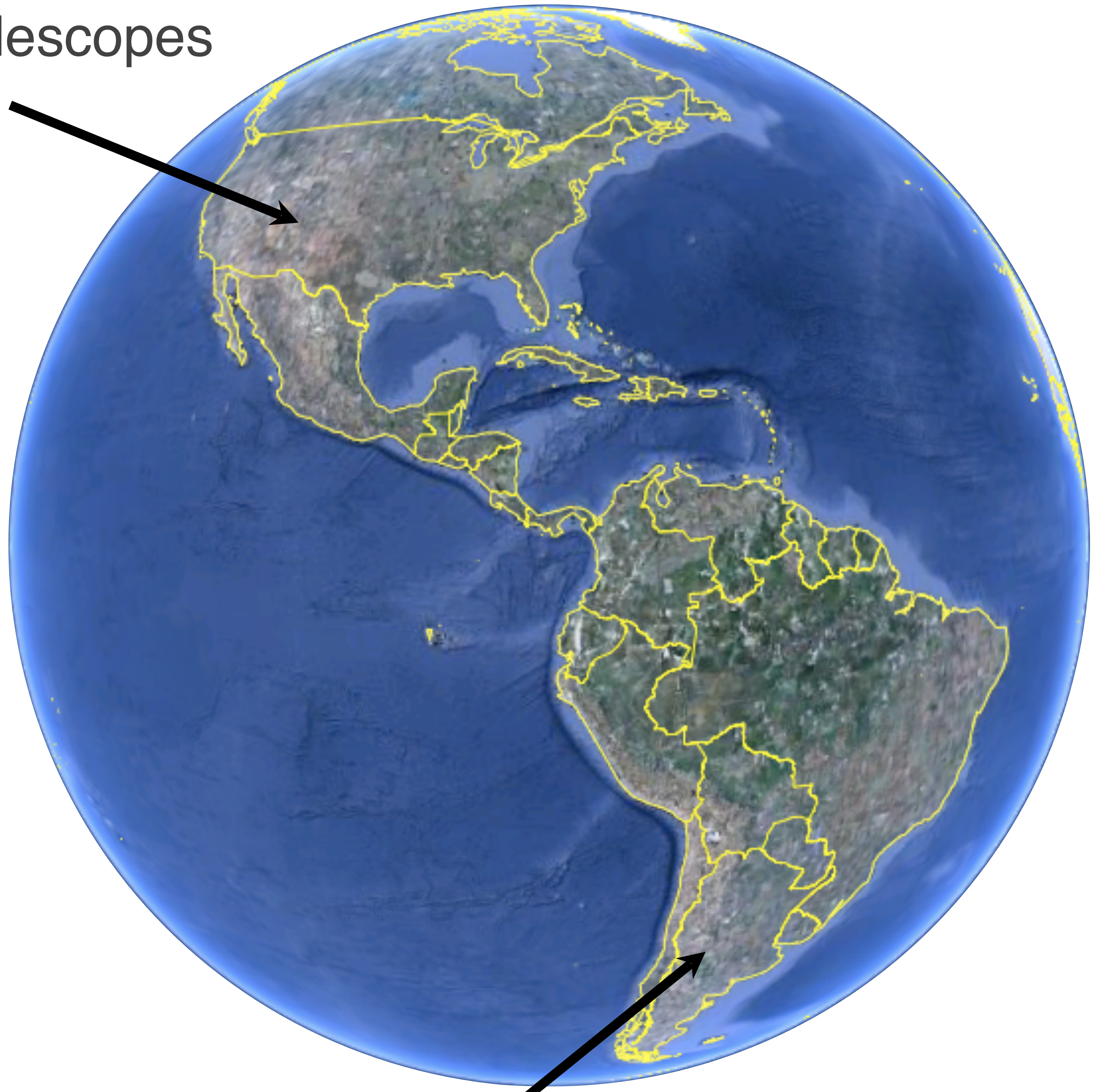
How to detect ultra-high-energy cosmic rays



Example: event observed with Auger Observatory

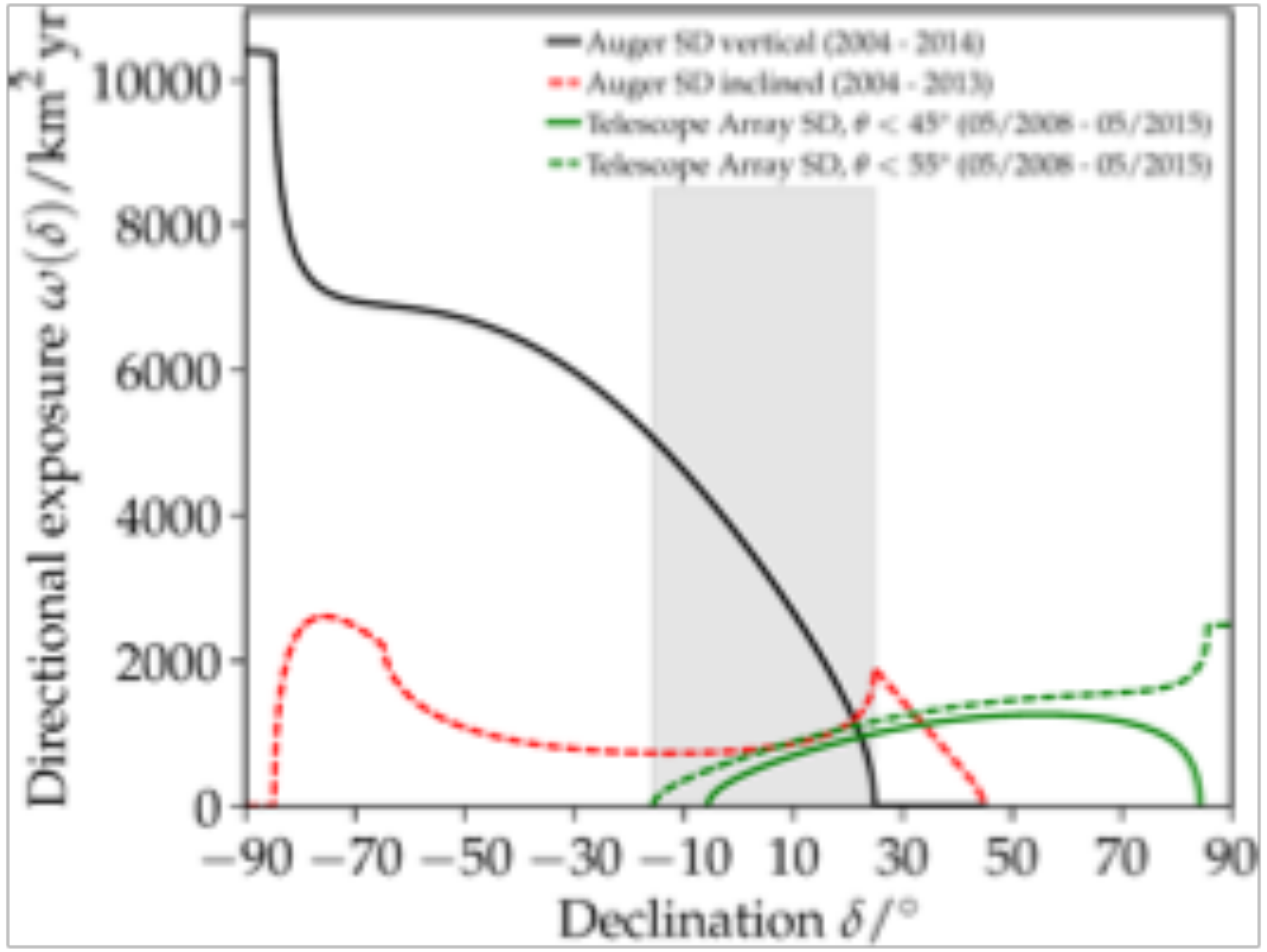
Pierre Auger Observatory and Telescope Array

Telescope Array (TA)
Delta, UT, USA
507 detector stations, 680 km^2
36 fluorescence telescopes



Pierre Auger Observatory
Province Mendoza, Argentina
1660 detector stations, 3000 km^2
27 fluorescence telescopes

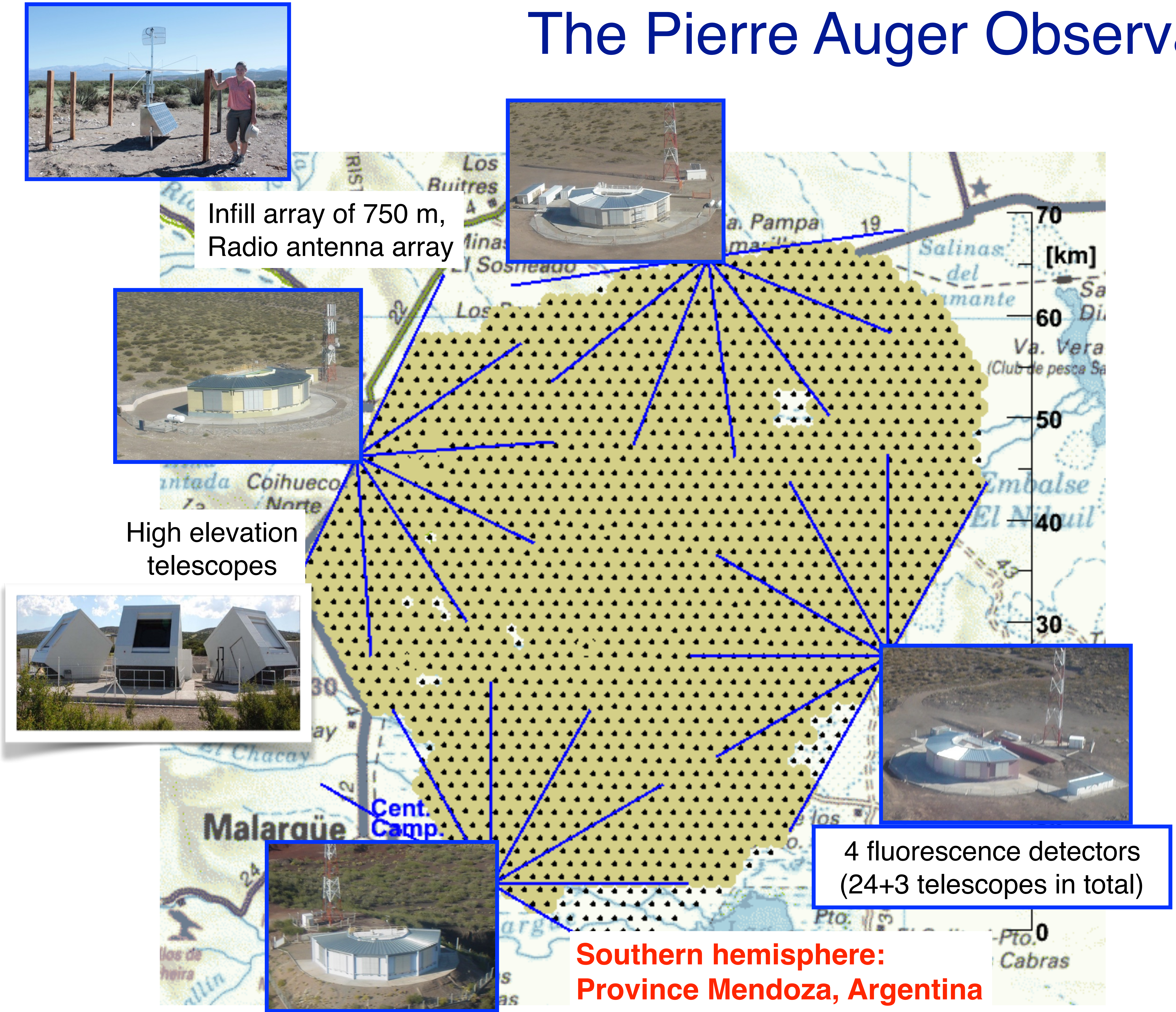
Together full sky coverage

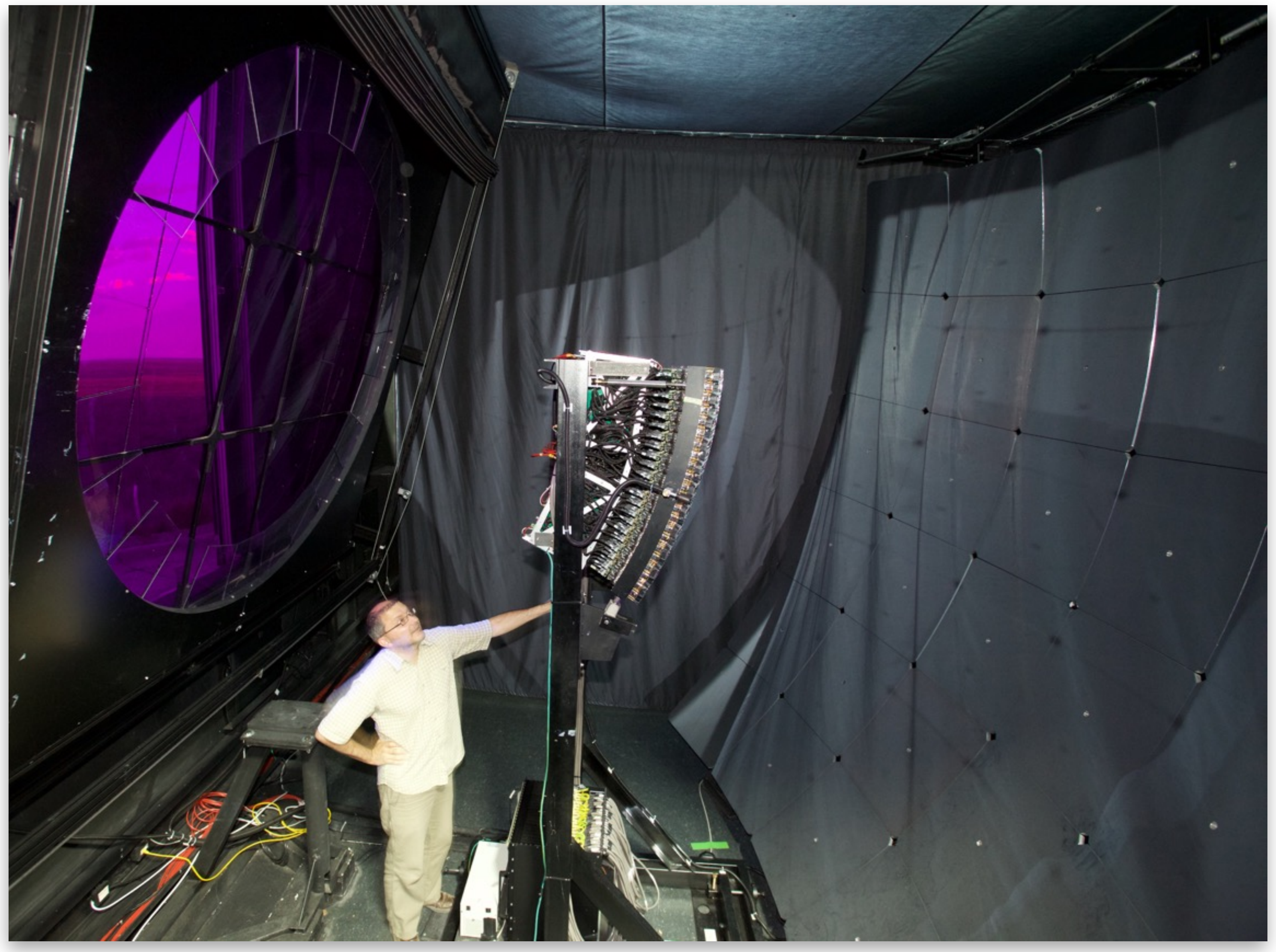


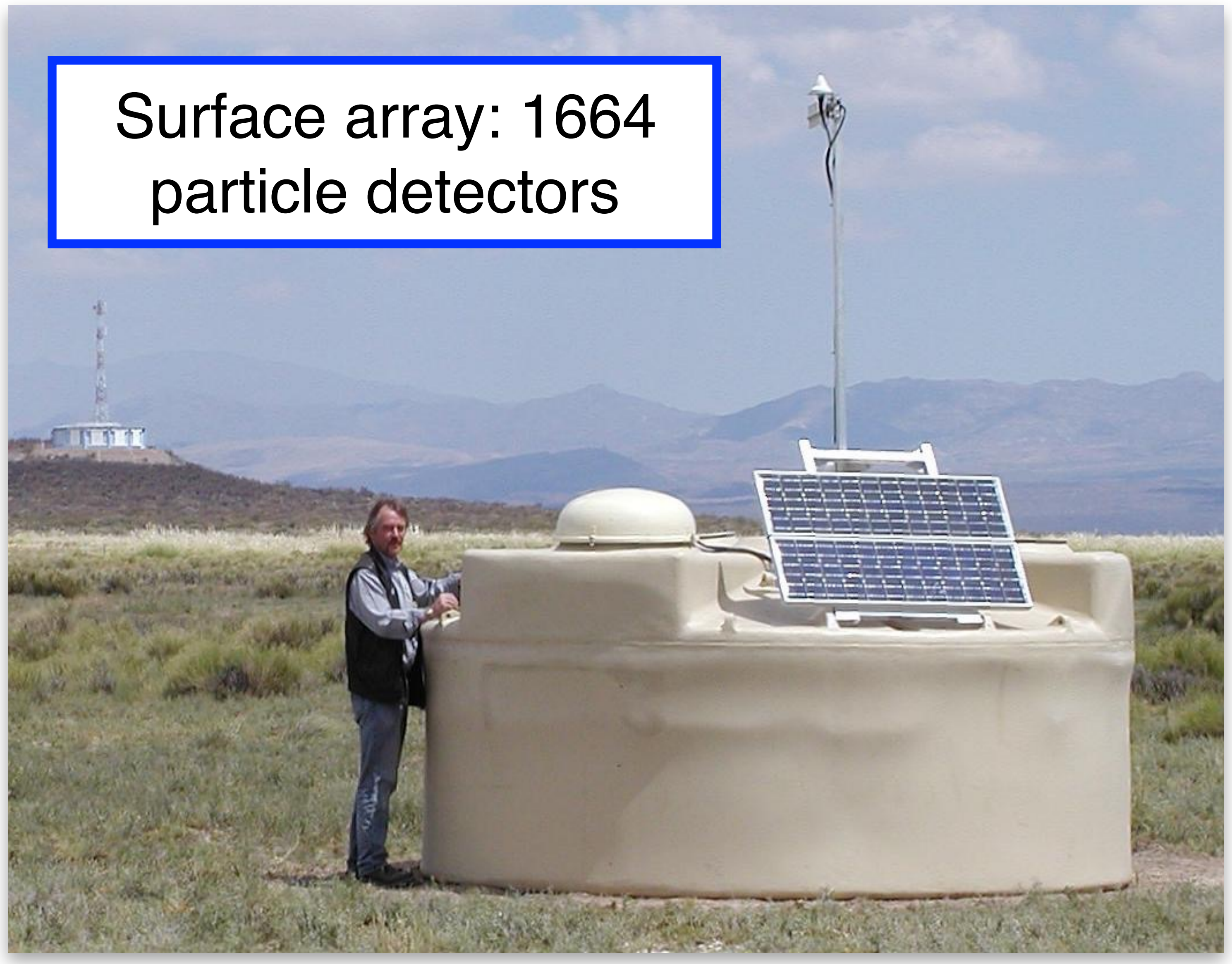
Auger:
- 6.7 x 10^4 km^2 sr yr (spectrum)
- 9 x 10^4 km^2 sr yr (anisotropy)

TA:
- 8.1 x 10^3 km^2 sr yr (spectrum)
- 8.6 x 10^3 km^2 sr yr (anisotropy)

The Pierre Auger Observatory







Telescope Array (TA)

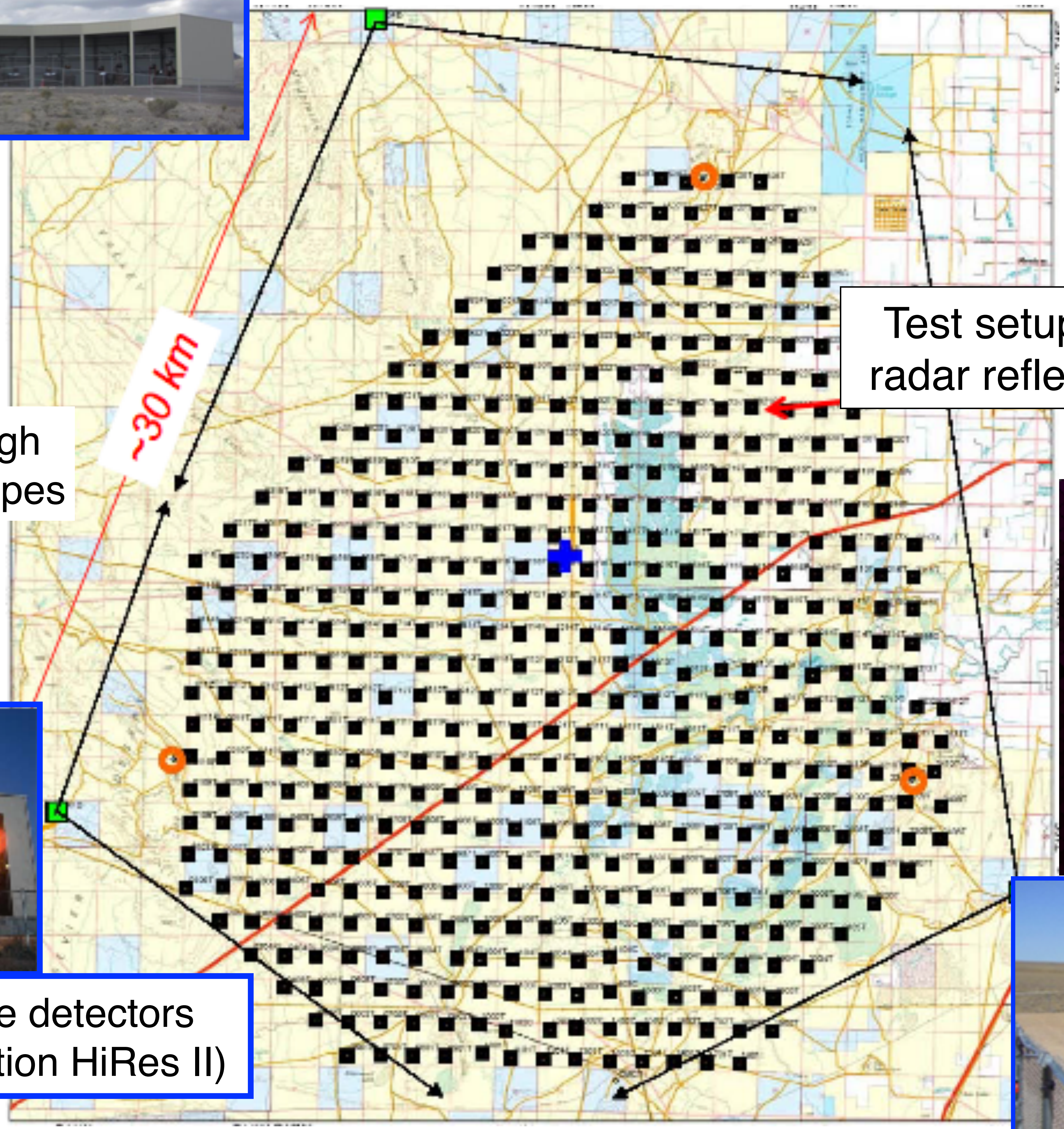
Talk by Abu-Zayyad

Middle Drum: based on HiRes II

TALE (TA low energy extension)

LIDAR
Laser facility

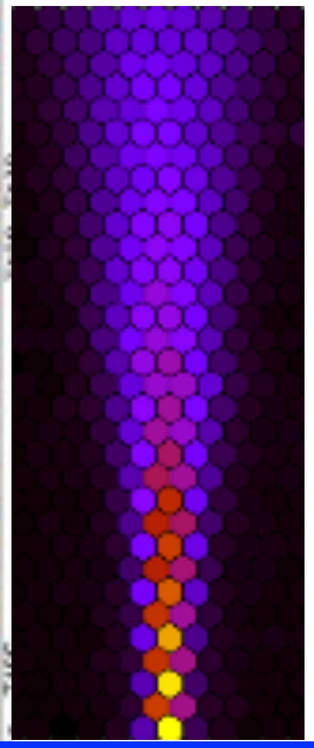
Infill array and high
elevation telescopes



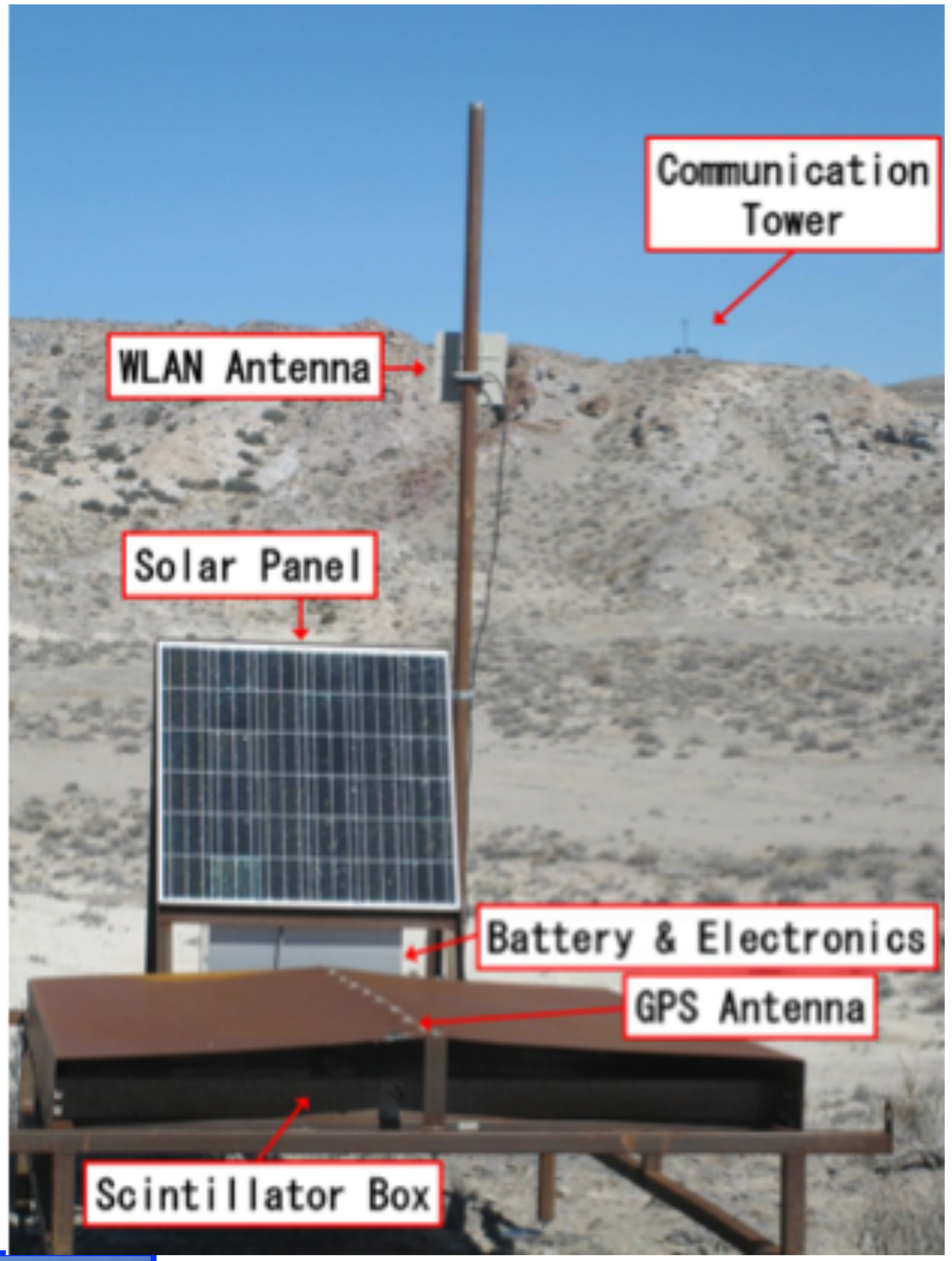
Test setup for
radar reflection

3 fluorescence detectors
(2 new, one station HiRes II)

Northern hemisphere: Utah, USA



Electron light
source (ELS):
~40 MeV



507 surface detectors:
double-layer scintillators
(grid of 1.2 km, 680 km^2)

Results: Flux strongly suppressed, change of mass composition

(RE, Nijmegen Summer School, 2004)

Events per year
(based on AGASA spectrum)

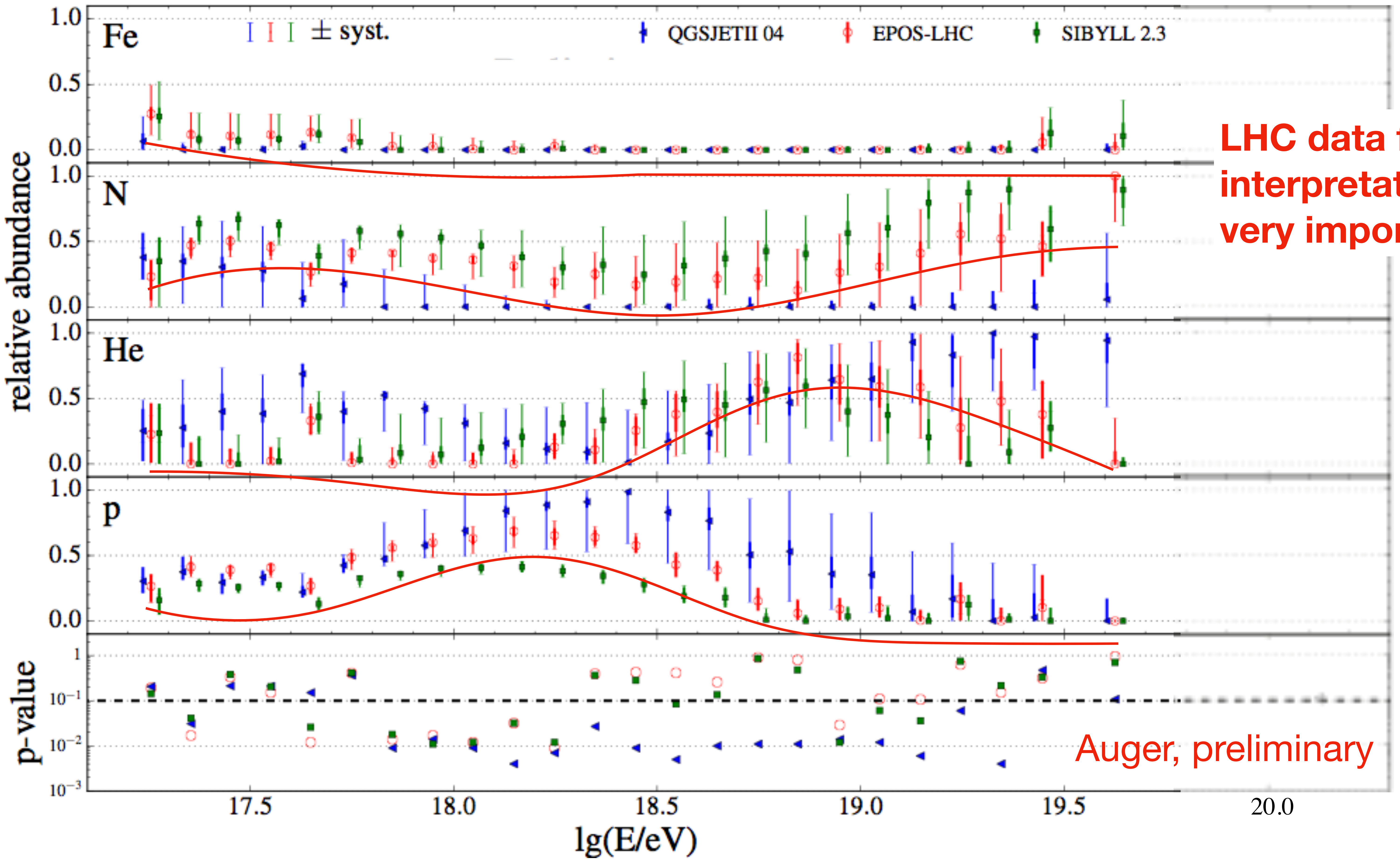
	SD only	SD + ≥1 FD
> 6 x 10^{17} eV	0	45000
> 10^{18} eV	0	30000
> 3 x 10^{18} eV	15000	4700
> 10^{19} eV	5150	515
> 2 x 10^{19} eV	1590	159
> 5 x 10^{19} eV	490	49
> 10^{20} eV	103	10
> 2 x 10^{20} eV	32	3
> 5 x 10^{20} eV	10	1

FD *2 tanks with 4 VEM and
10% duty cycle
SD *5 tanks with each 4 VEM

zenith angle >60°: + 50%

Expected 1100, have ~14 events

Composition based on fluorescence telescope data (15% duty cycle)



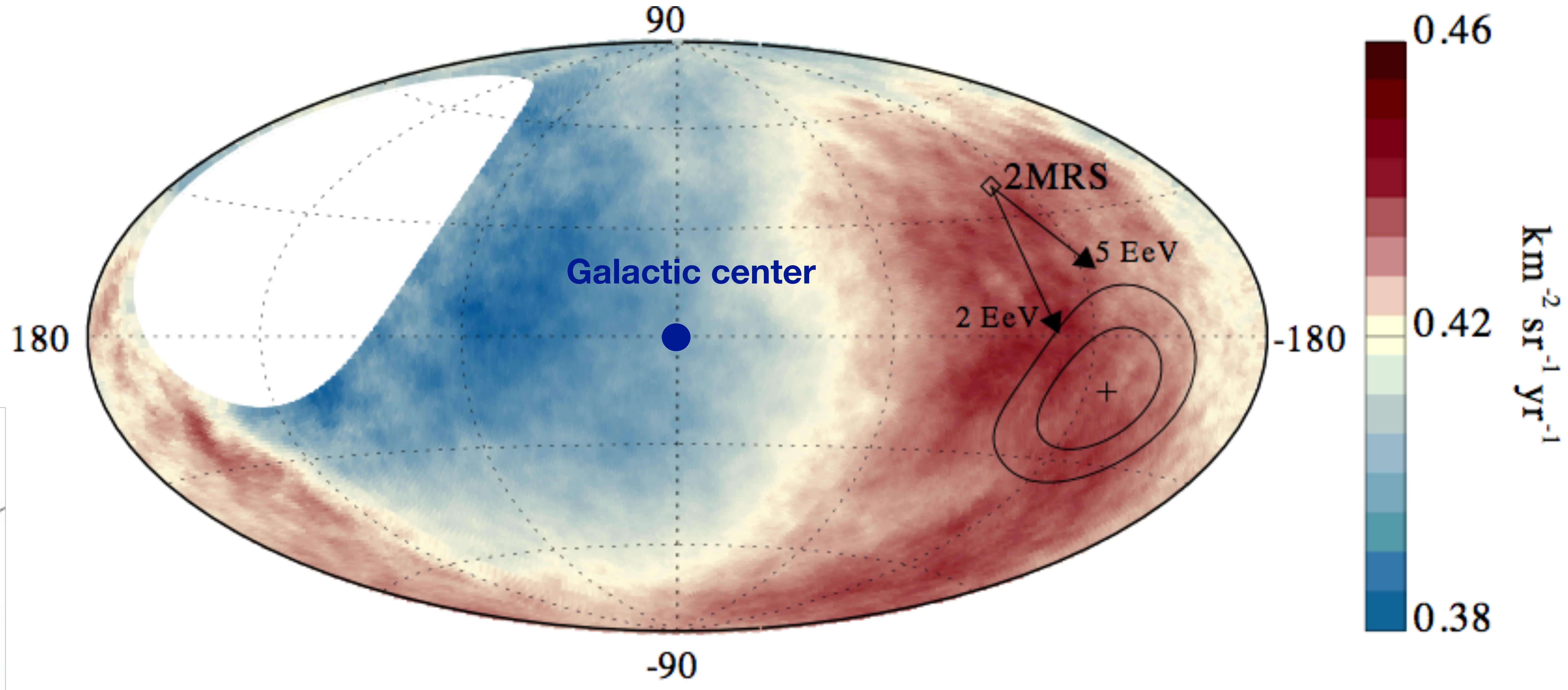
LHC data for interpretation very important

Composition could be explained by disintegration of ~ C or Si nuclei, very hard energy spectrum at injection favored (~ *E*$^{-1}$)

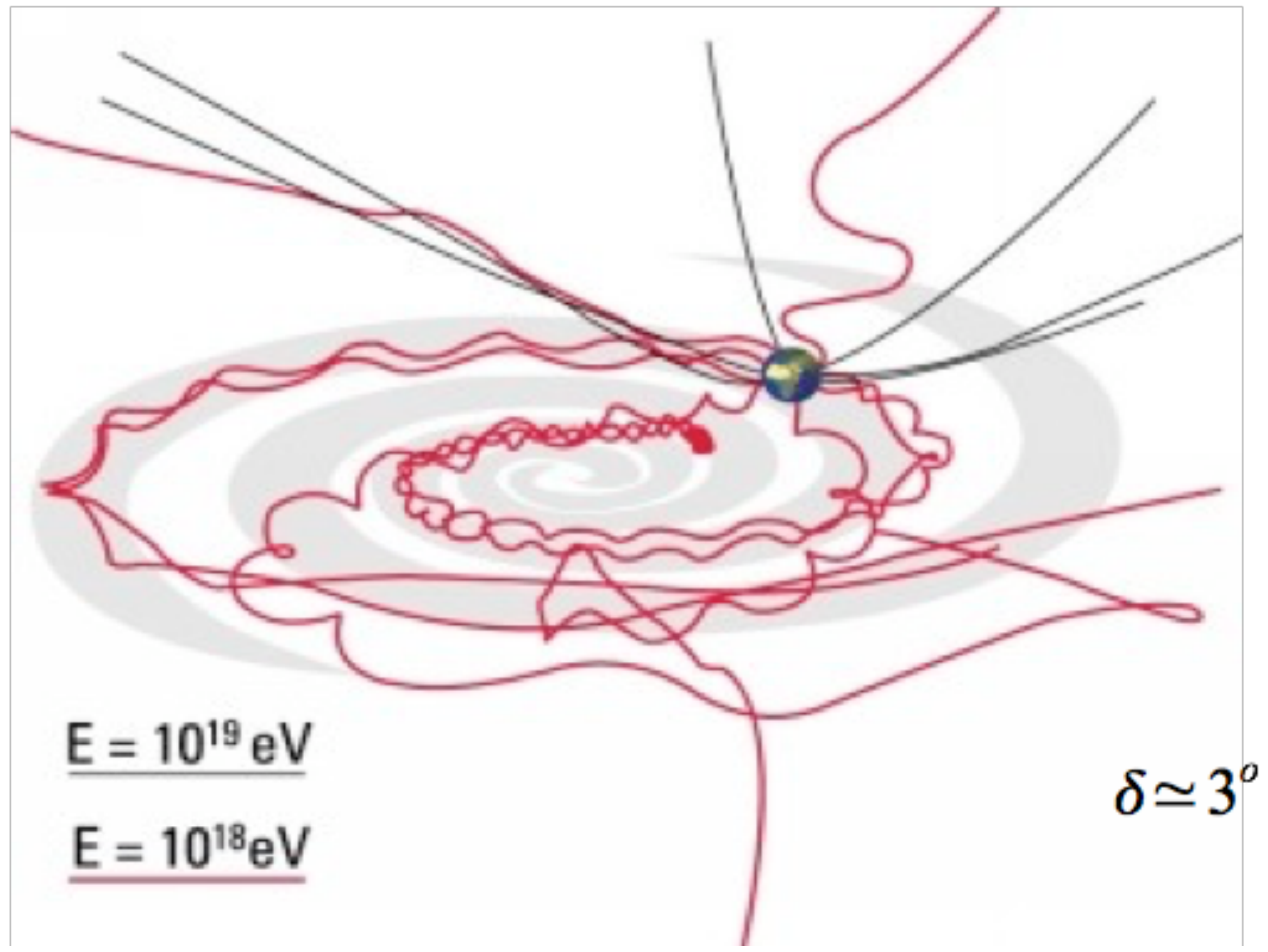
Results: Particles are of extragalactic origin

6.5% dipole at 5.2 sigma
Science 357 (2017) 1266

$E > 8 \times 10^{18}\,\mathrm{eV}$



Estimated deflection in galactic mag. field

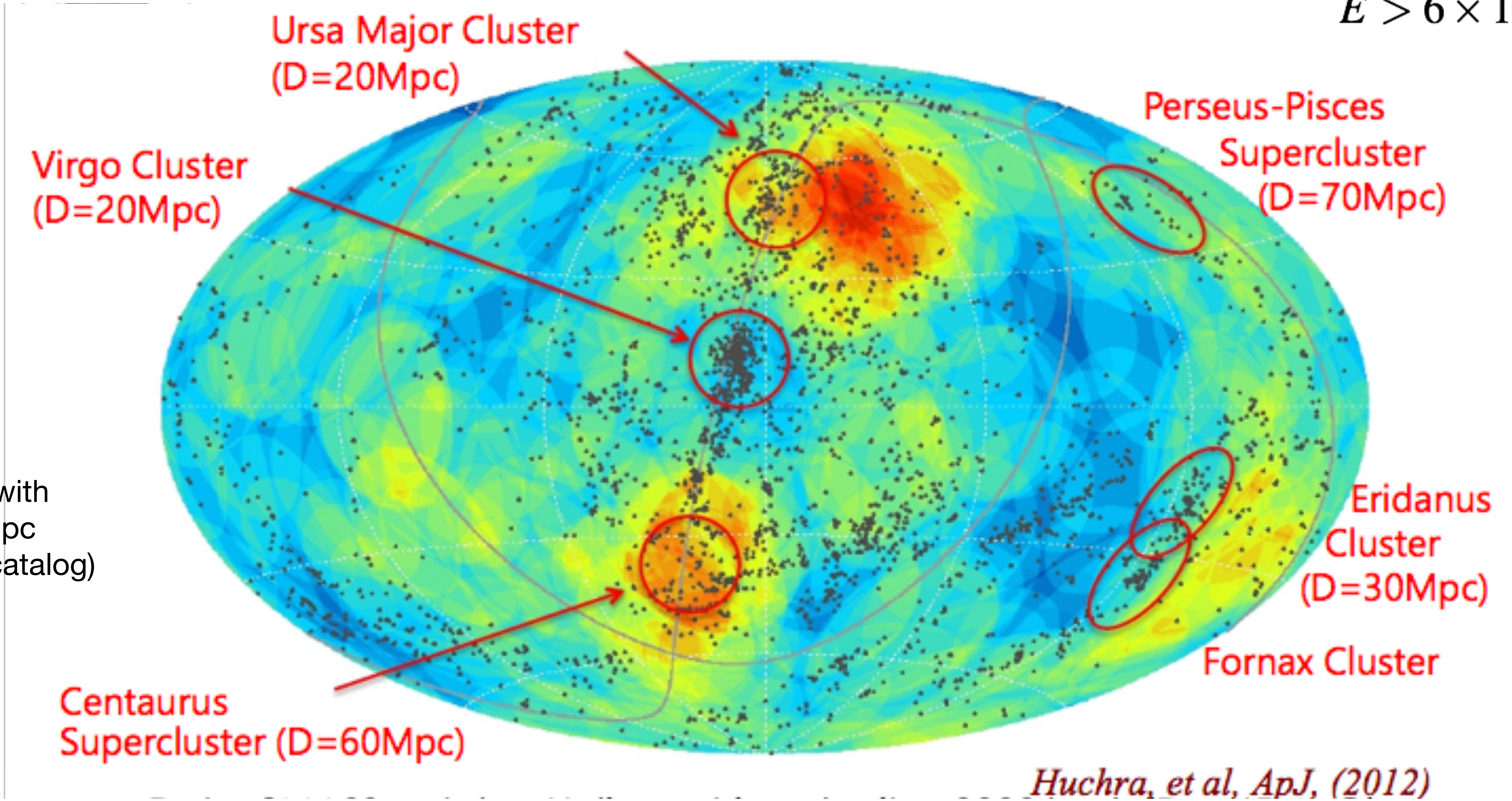


$$\delta \simeq 3^{o}\,\frac{B}{3\,\mu G}\,\frac{L}{kpc}\,\frac{6\times10^{19}eV}{E/Z}$$

Arrival directions follow mass distribution of near-by galaxies

Intermediate-scale anisotropy: over-densities ~20° size

$E > 6 \times 10^{19}\,\mathrm{eV}$



Galaxies with
D < 45 Mpc
(2MASS catalog)

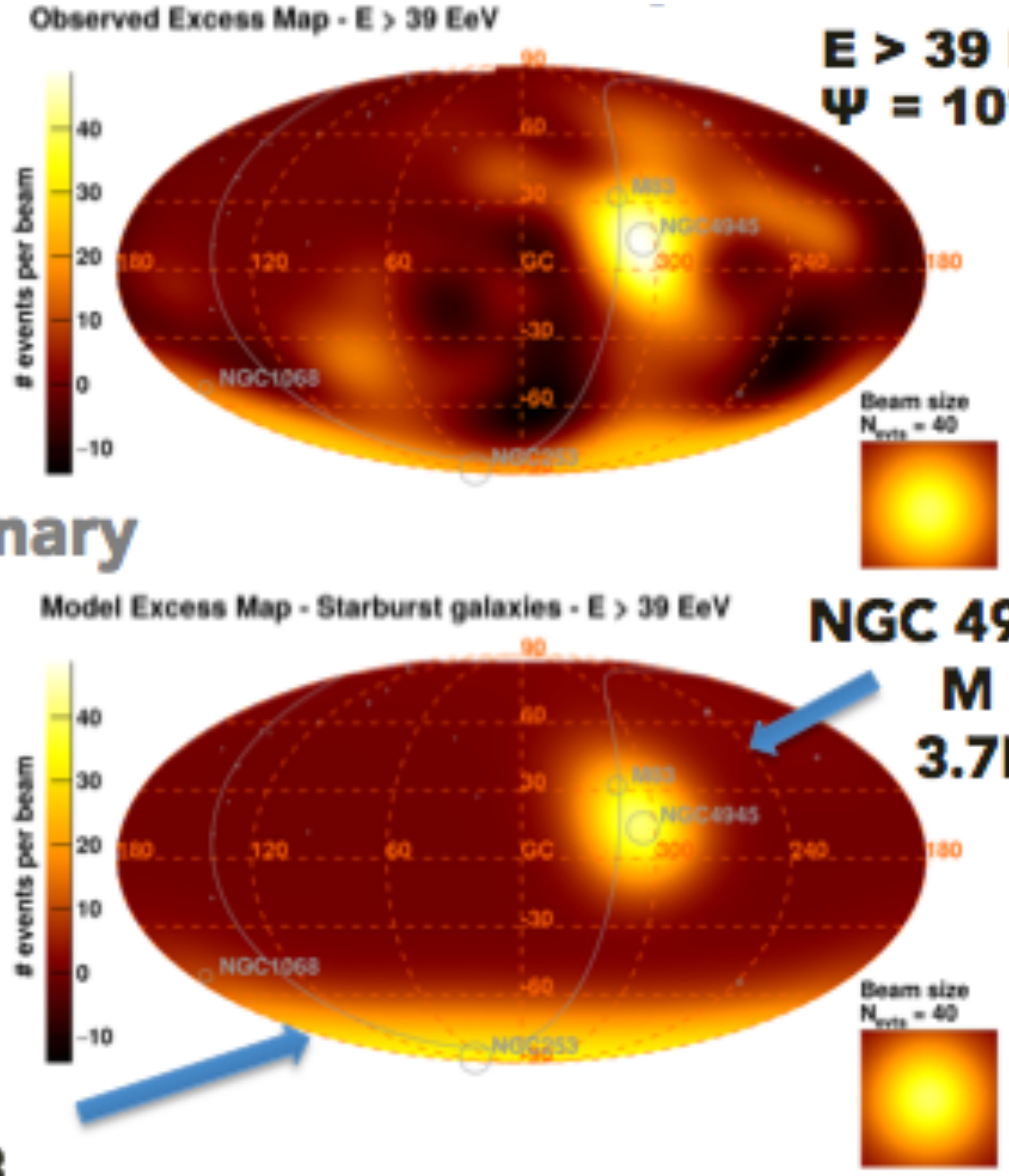
Huchra, et al, ApJ, (2012)

Anisotropy – Correlation with catalogs (Auger data)

Starburst galaxies

E > 39 EeV
Ψ = 10°

preliminary



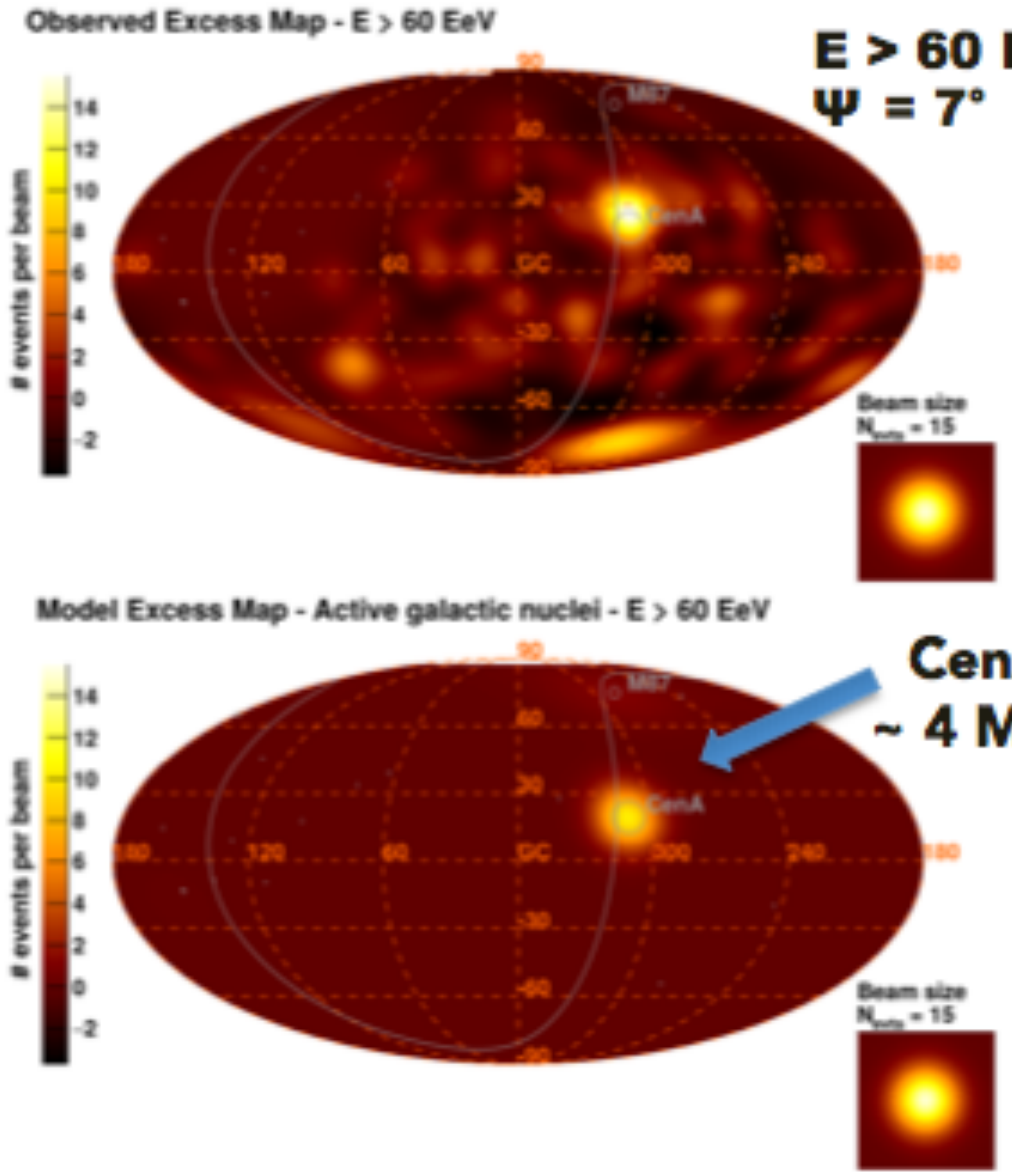
NGC 4945
M 83
3.7Mpc

NGC 253
2.5 Mpc

NGC 1068
16.7 Mpc

AGNs

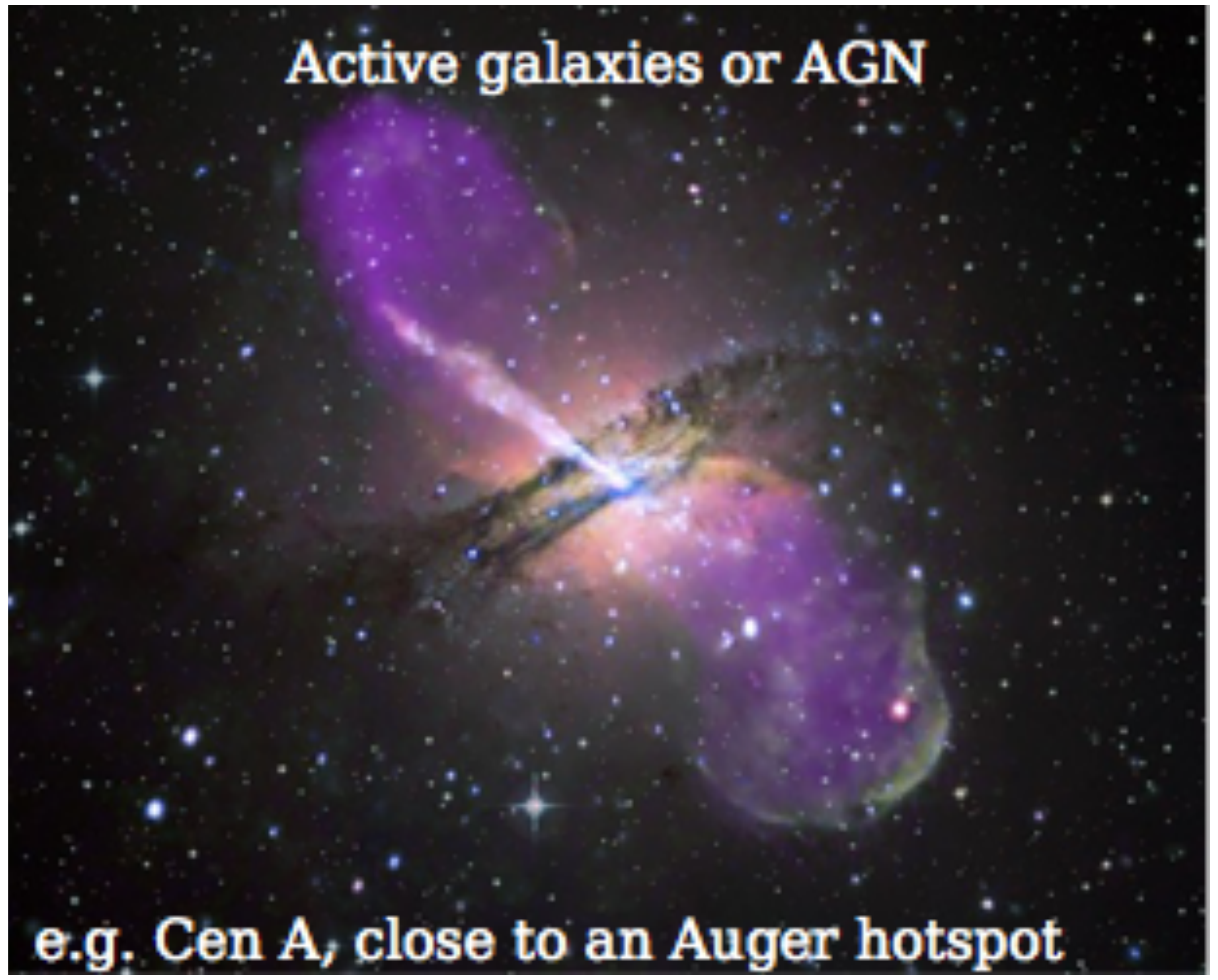
E > 60 EeV
Ψ = 7°



CenA
~ 4 Mpc

(Giaccari ICRC 2017)

Results: Hints for sources or source regions?

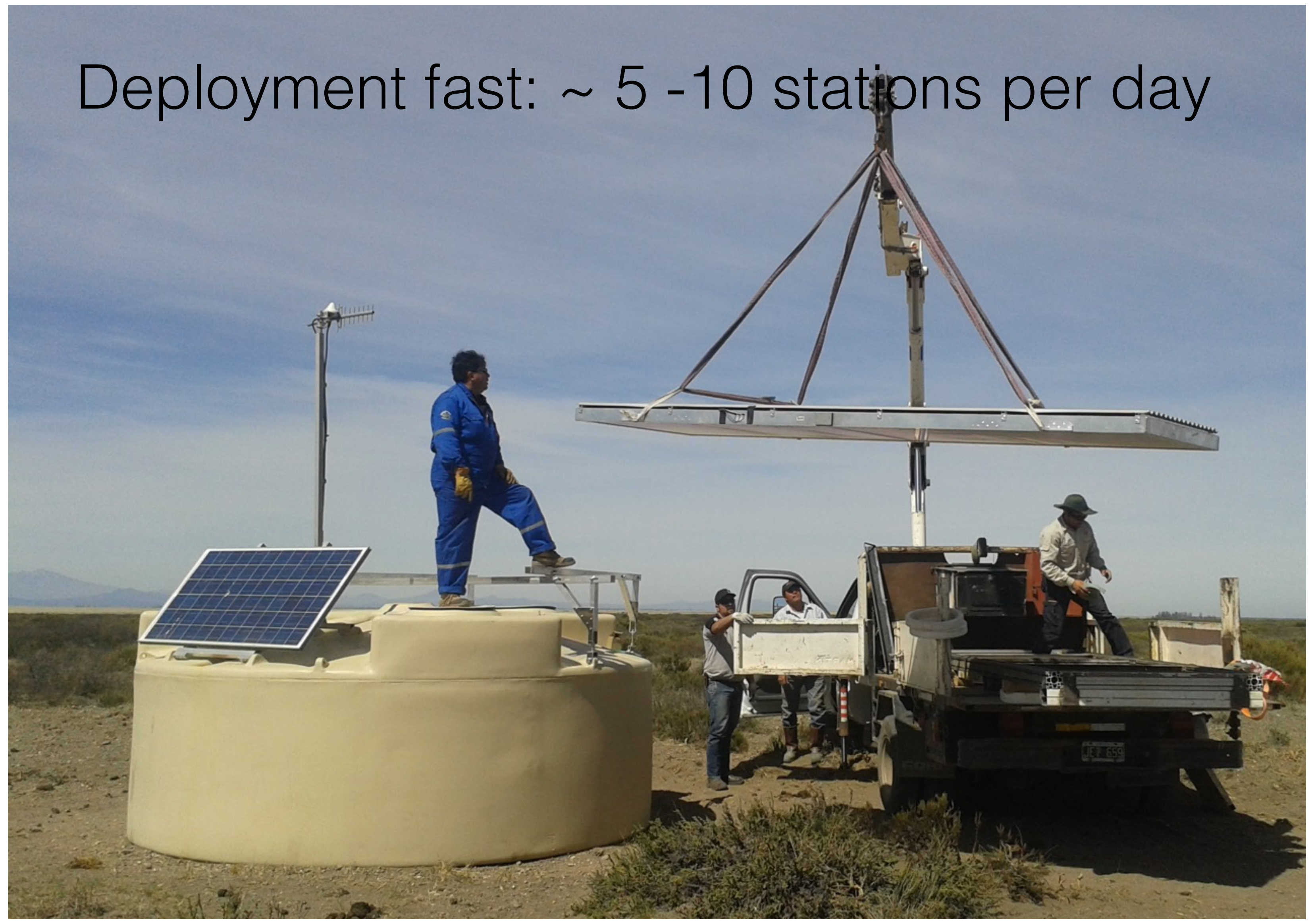


Significance of correlation with starburst galaxies

Upgrade of Auger Observatory: AugerPrime

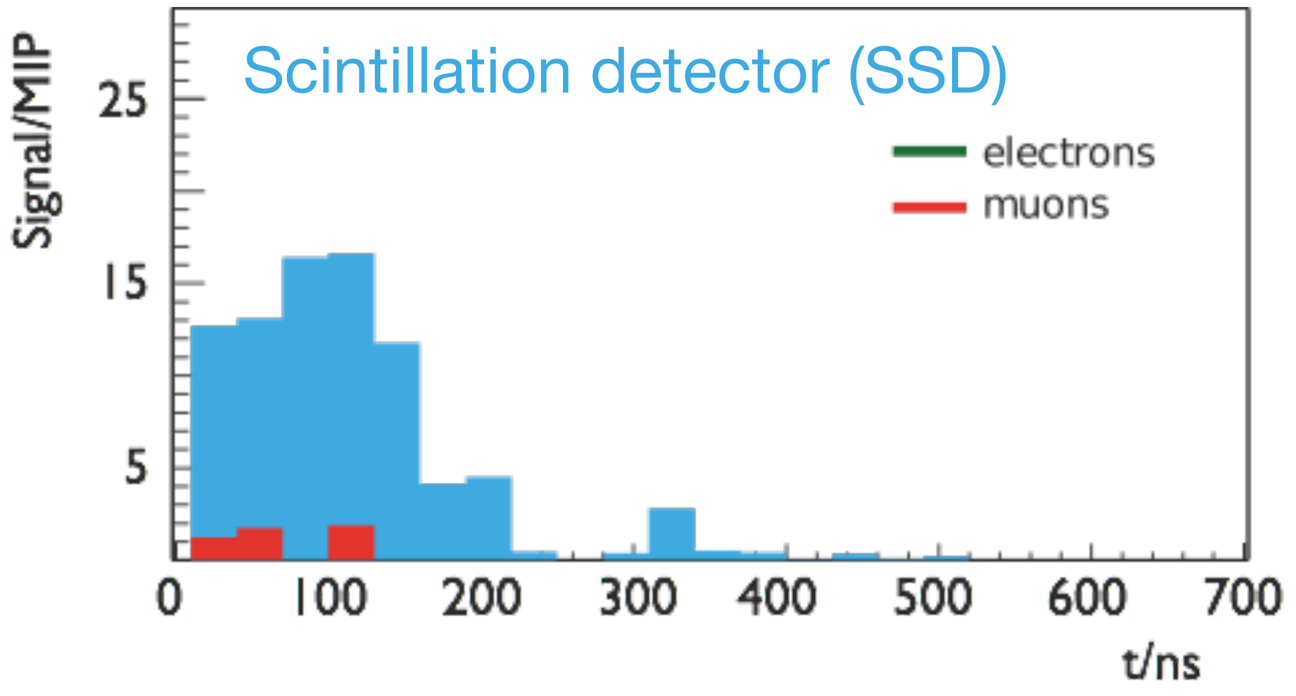
15% duty cycle

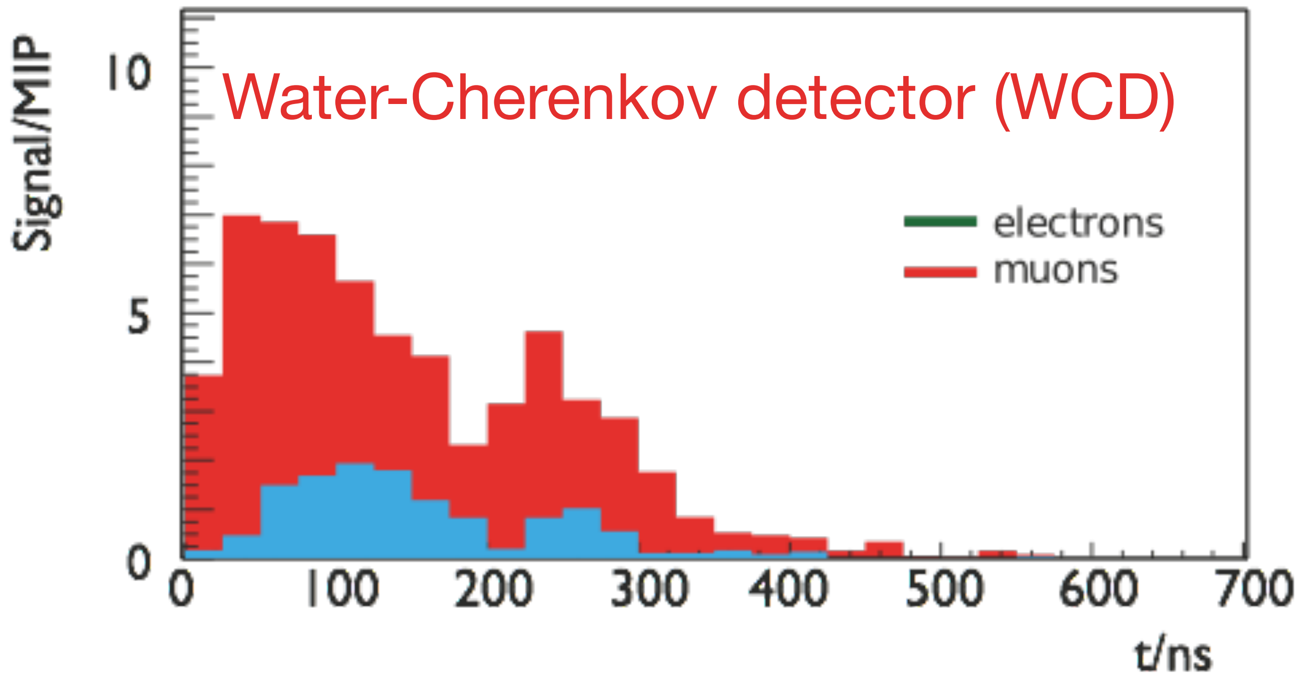
100% duty cycle

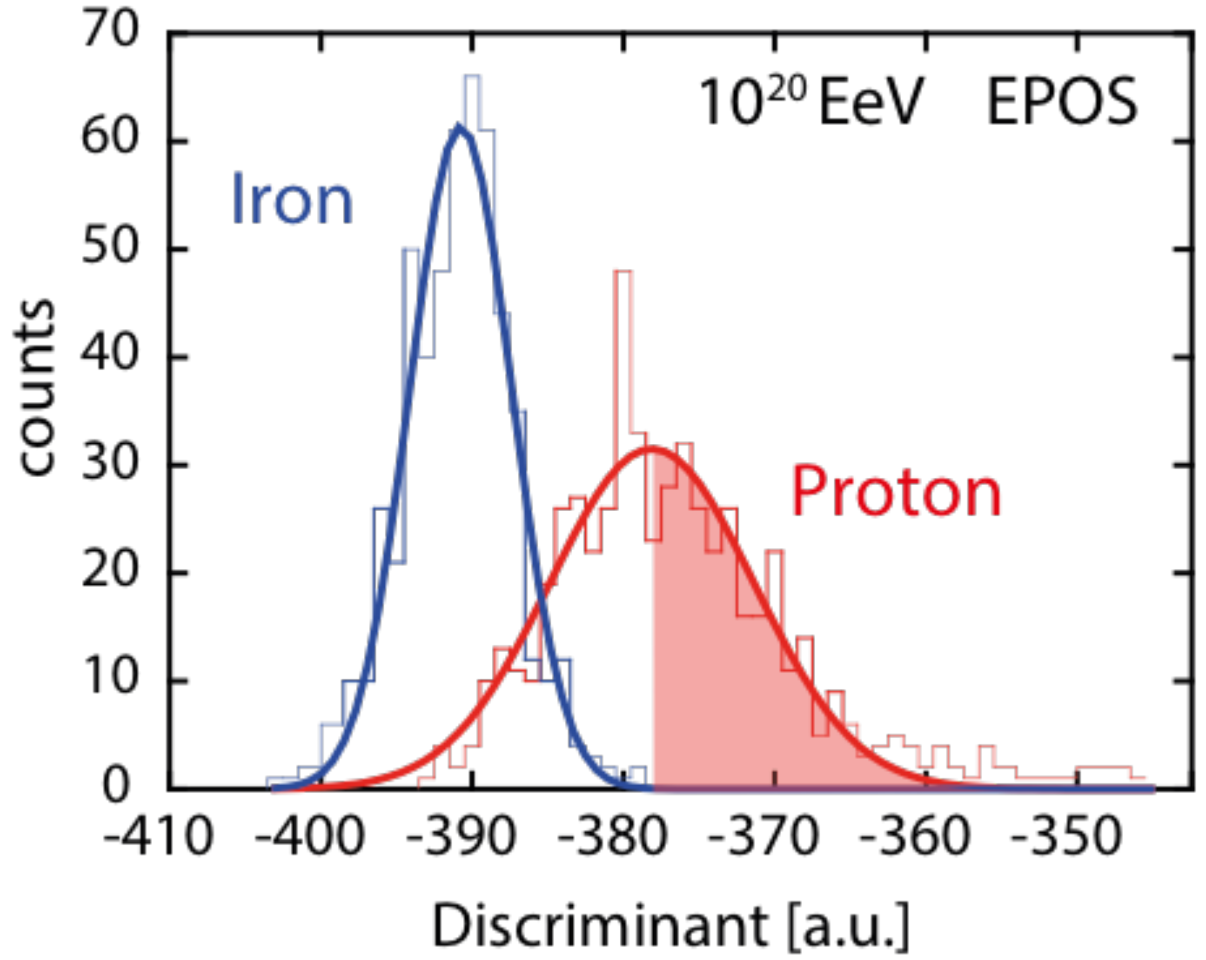


Deployment fast: ~ 5 -10 stations per day

2016-09-15: first station in field







- **Composition measurement up to 10^{20} eV**
- **Composition selected anisotropy**
- **Particle physics with air showers**

(AugerPrime design report 1604.03637)

TAx4 Project

TA SD (~3000 km²): Quadruple area

Approved in Japan 2015

500 scintillator SDs

2.08 km spacing

3 yrs construction, first 173 SDs have arrived in Utah for final assembly, next 77 SD to be prepared at Akeno Obs. (U.Tokyo) 2017-08 and shipped to Utah

2 FD stations (12 HiRes Telescopes)

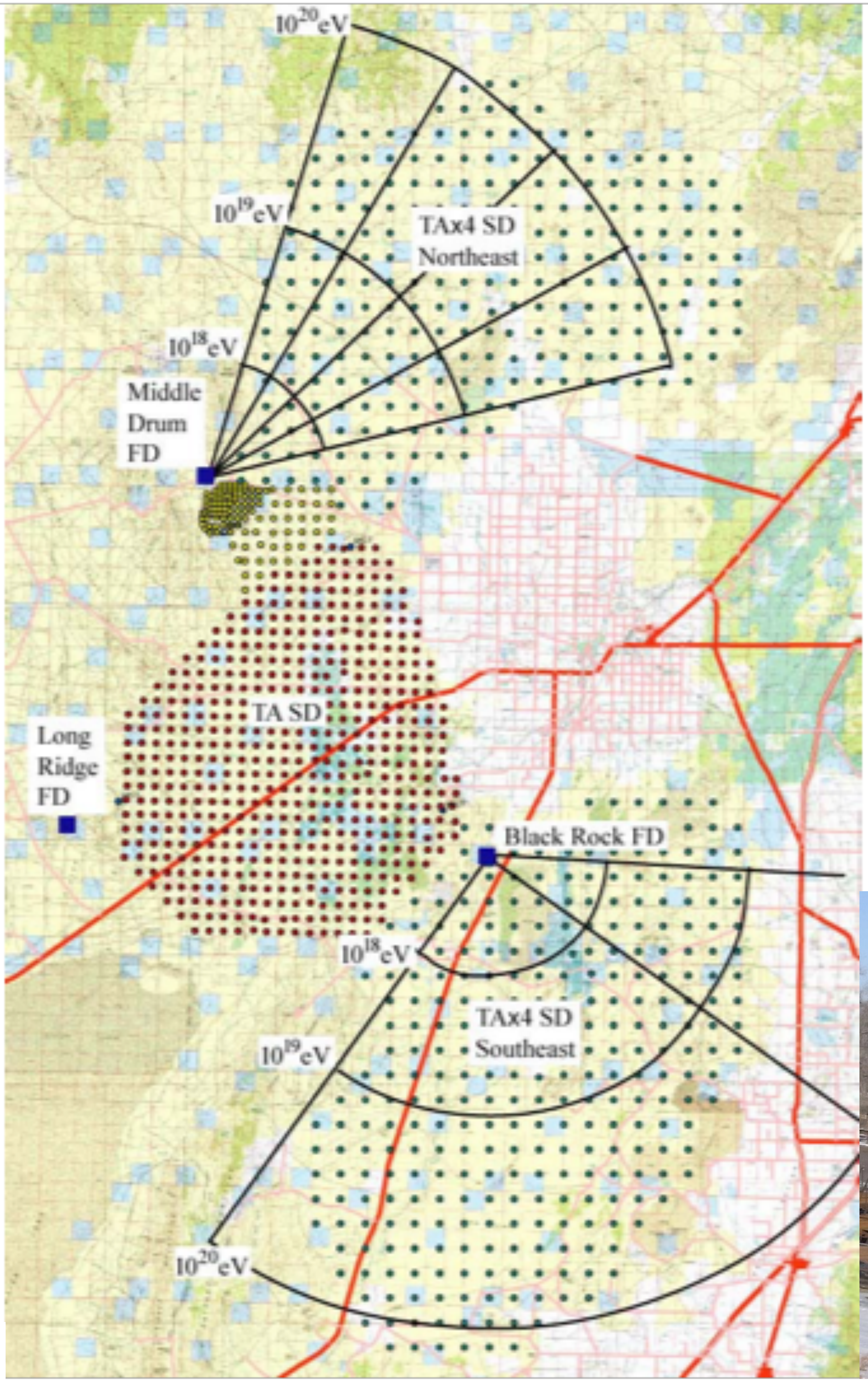
Approved US NSF 2016

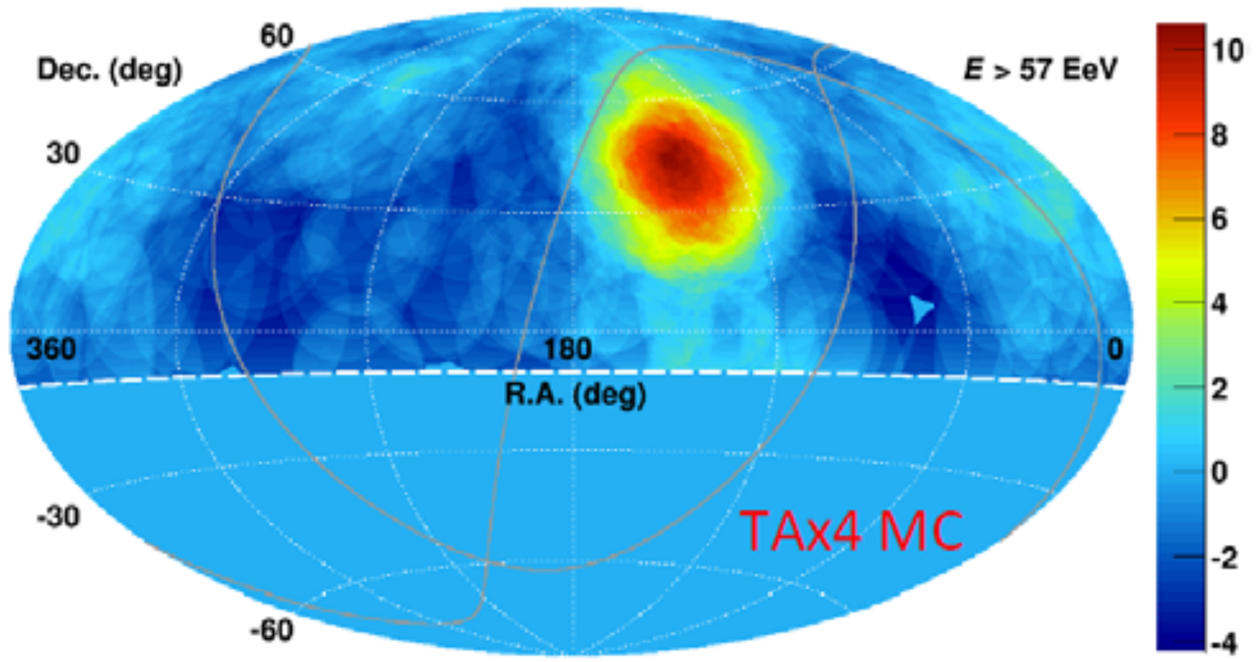
Telescopes/electronics being prepared at Univ. Utah

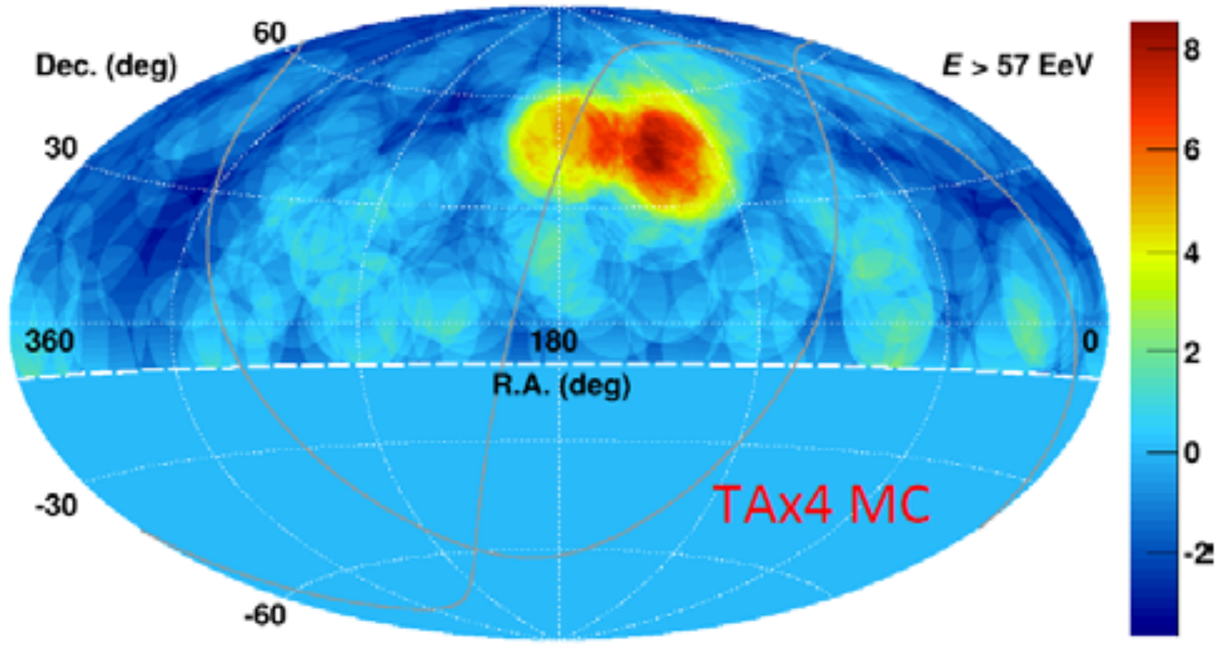
Site construction underway at the northern station.

Get 19 TA-equiv years of SD data by 2020

Get 16.3 (current) TA years of hybrid data



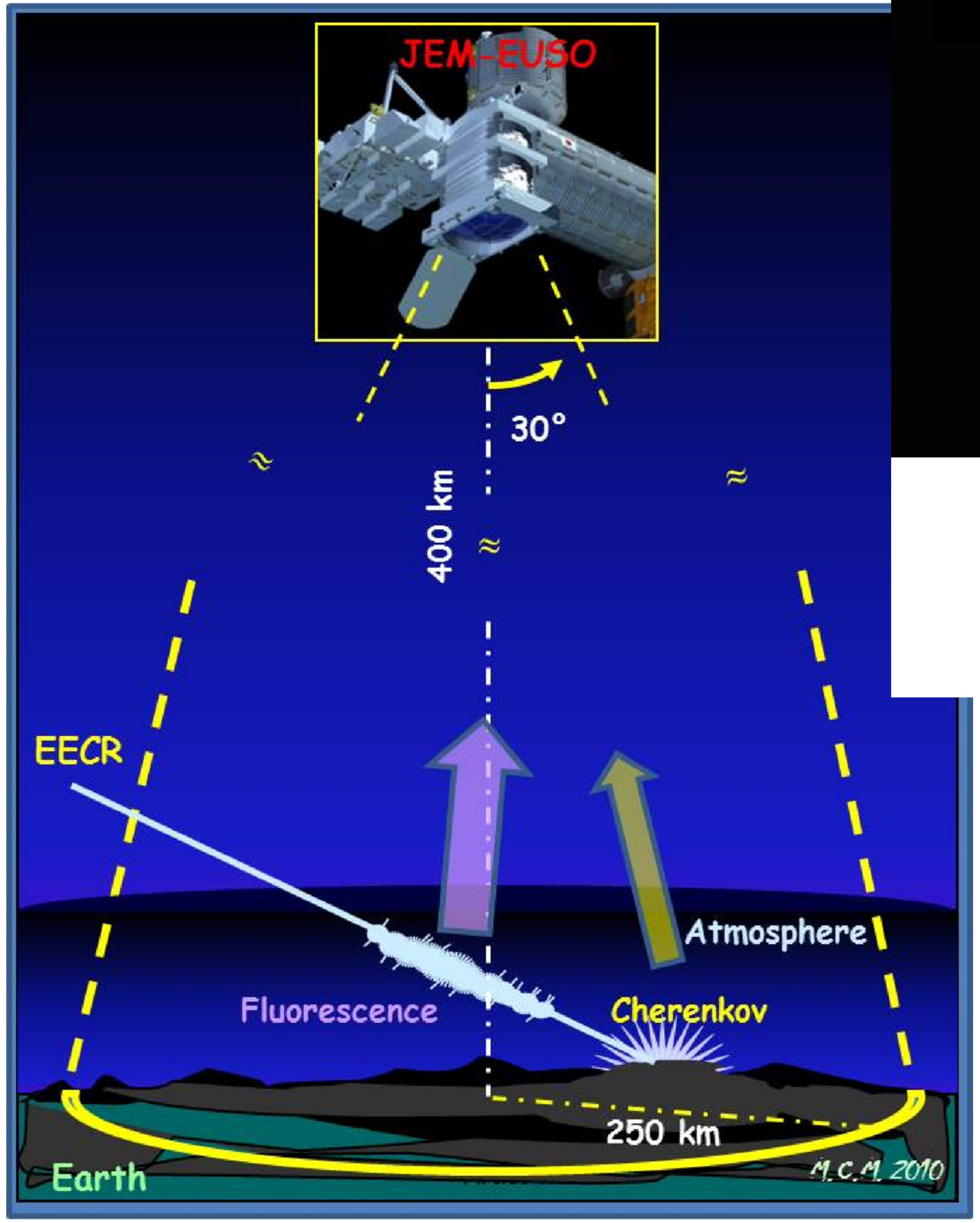




(Kido, Matthews ICRC 2017)

The quest for an instrument of ultimately large aperture

JEM-EUSO (status unclear)

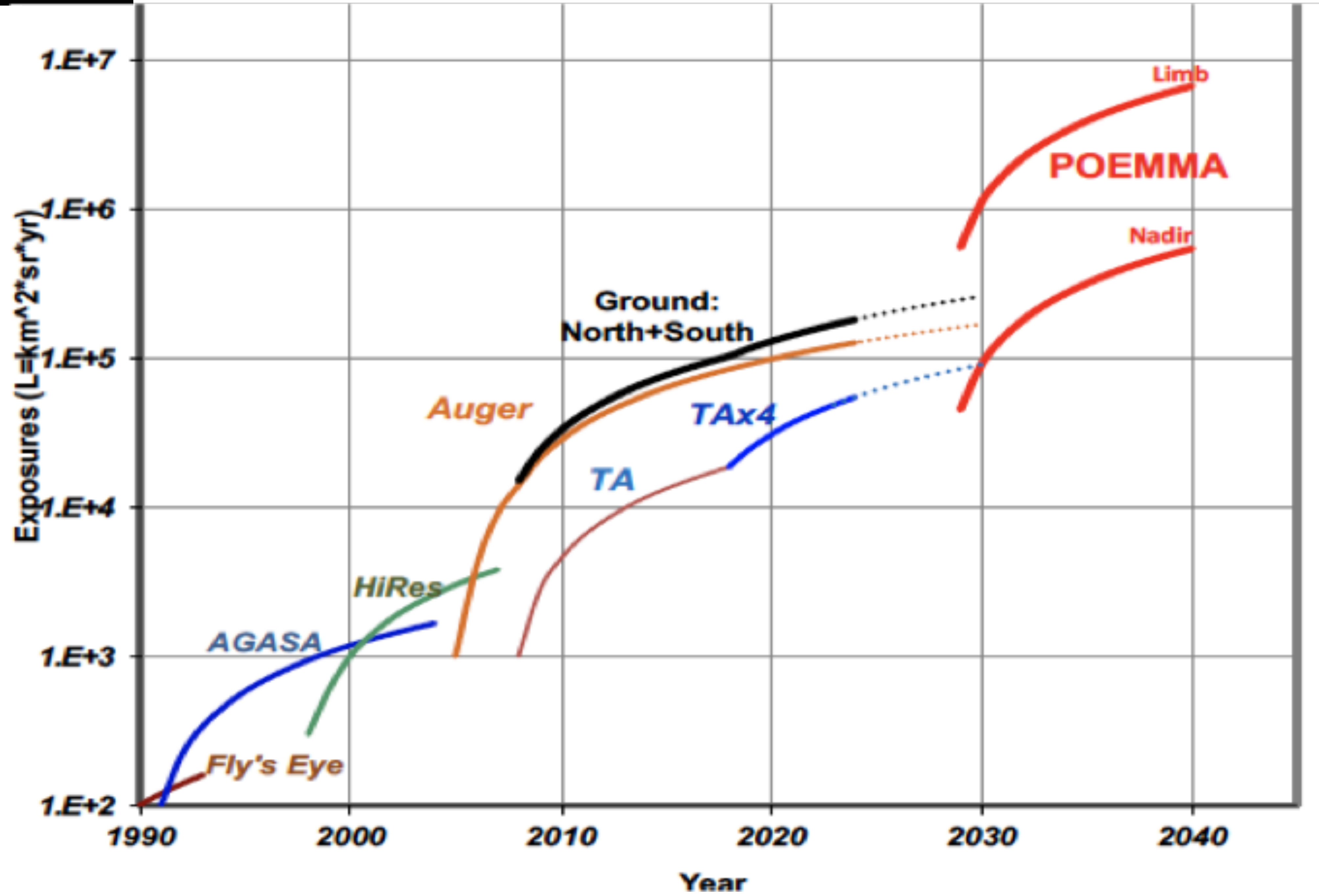


POEMMA:
Probe of Extreme Multi-Messenger Astrophysics UHECRs and Neutrinos

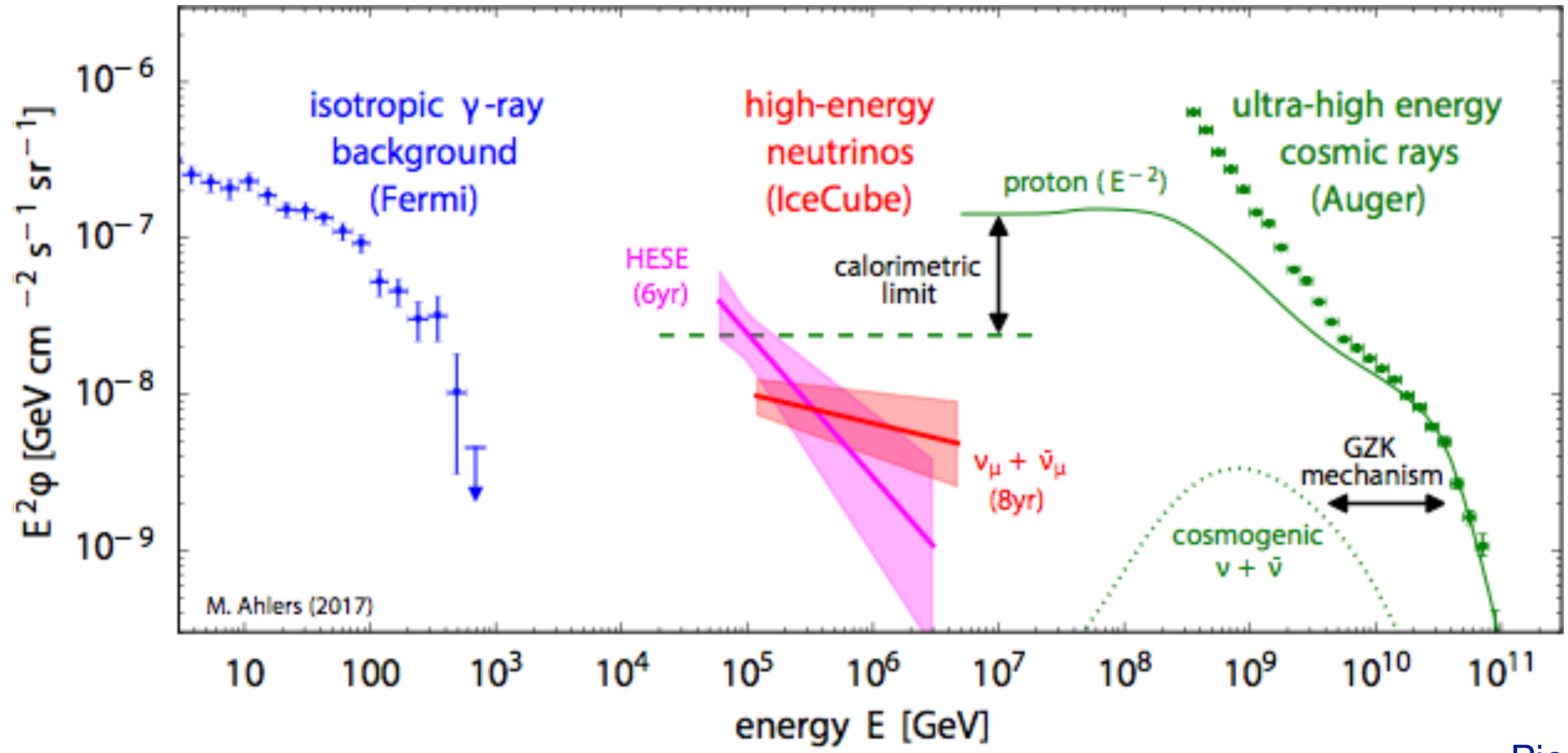
NASA-supported design study

K-EUSO
(Russian Space Agency)

Worldwide distributed hybrid arrays



Neutrino production due to cosmic ray propagation



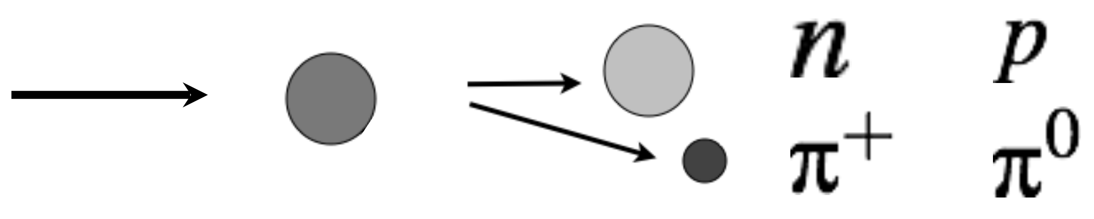
Interplay of

interaction in source

vs.

escape from source

Pion production on any target



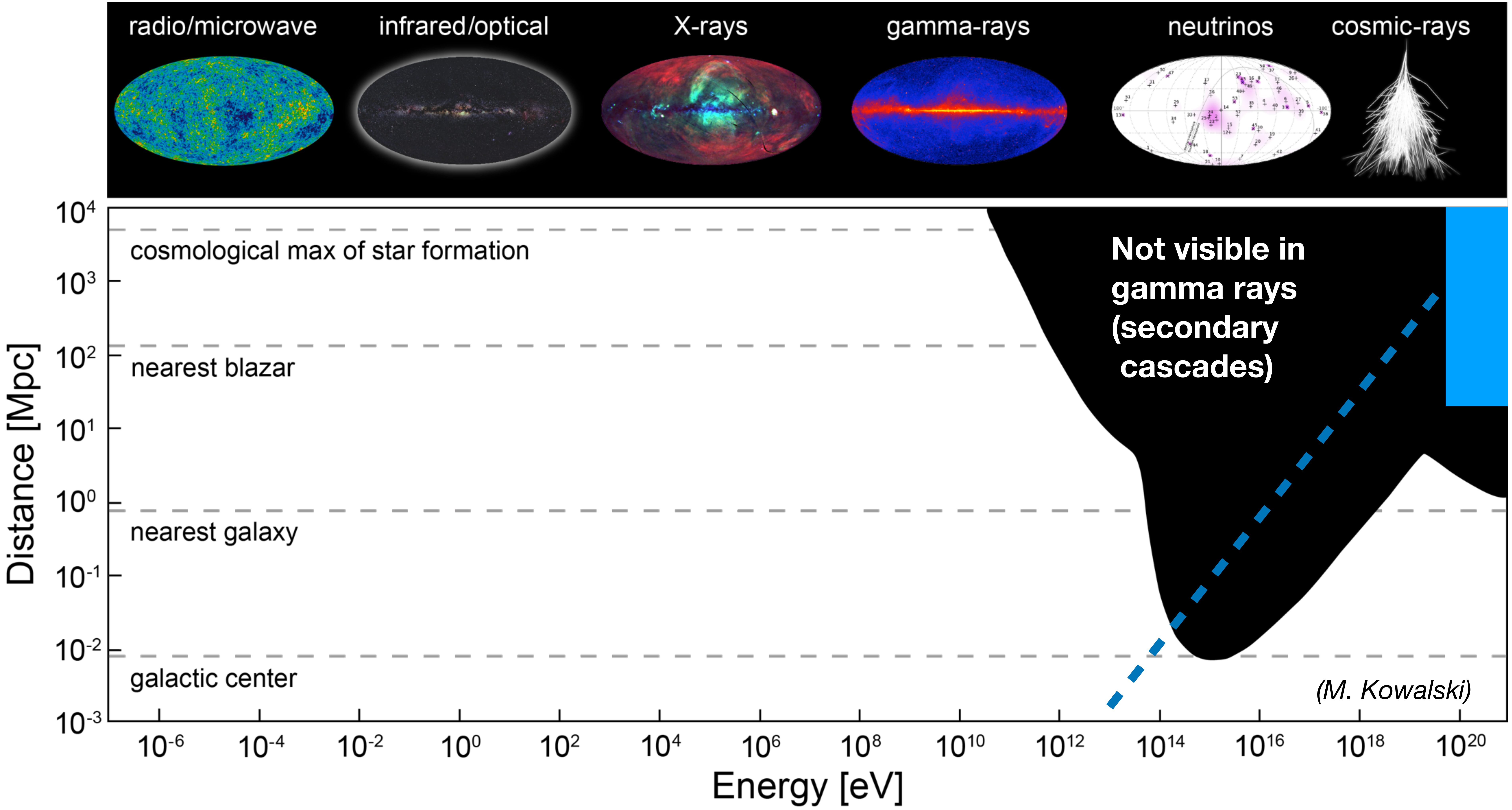
$$\pi^0 \longrightarrow \gamma\gamma$$

$$\pi^+ \longrightarrow \mu^+ \nu_\mu \longrightarrow e^+ \nu_e \nu_\mu \bar{\nu}_\mu$$

$$\boxed{\nu_\mu : \nu_e \sim 2:1}$$

(neutrino + antineutrino flavor)

Propagation distances of different messenger particles

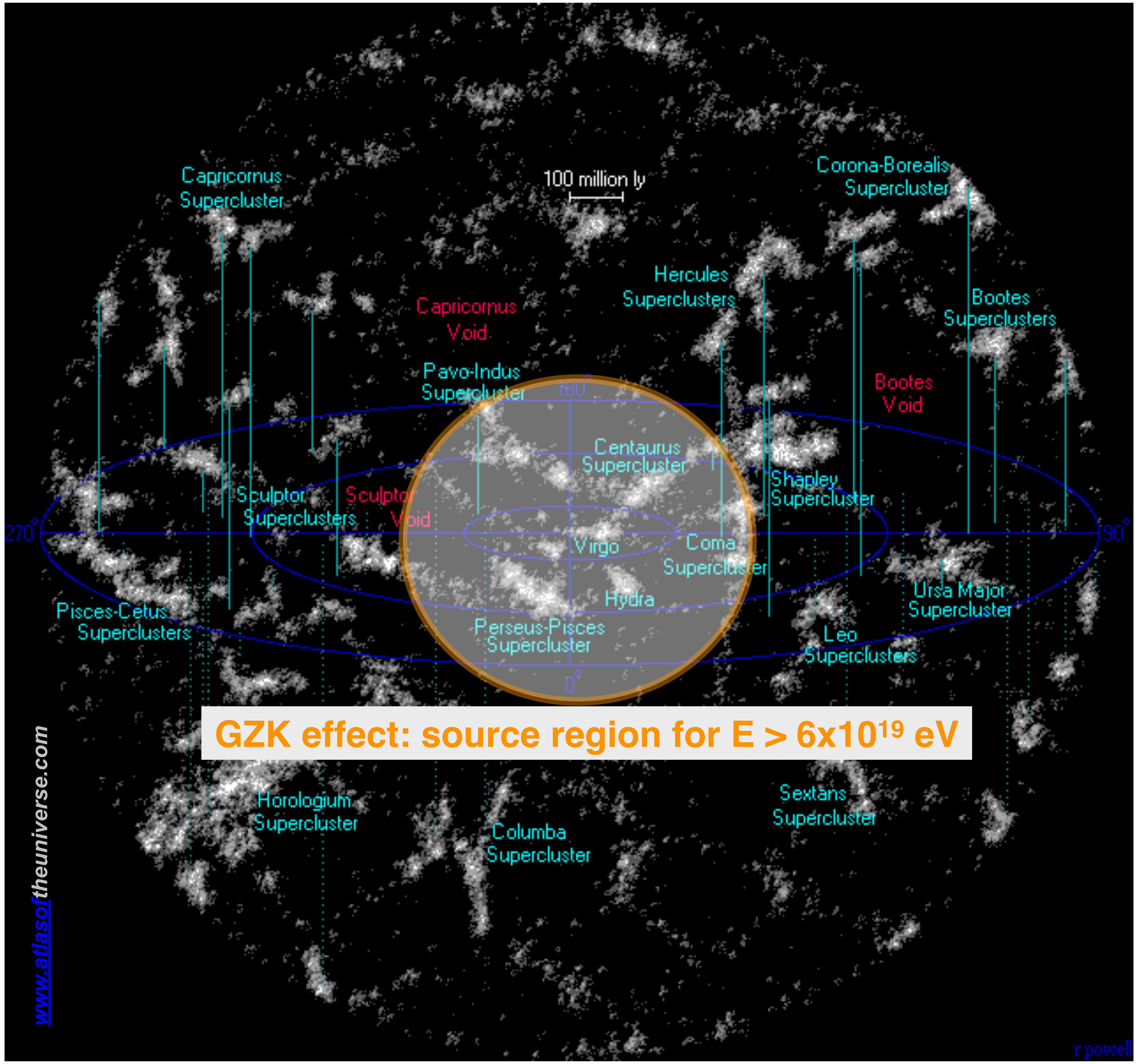


Not visible in in cosmic rays (energy loss effects)

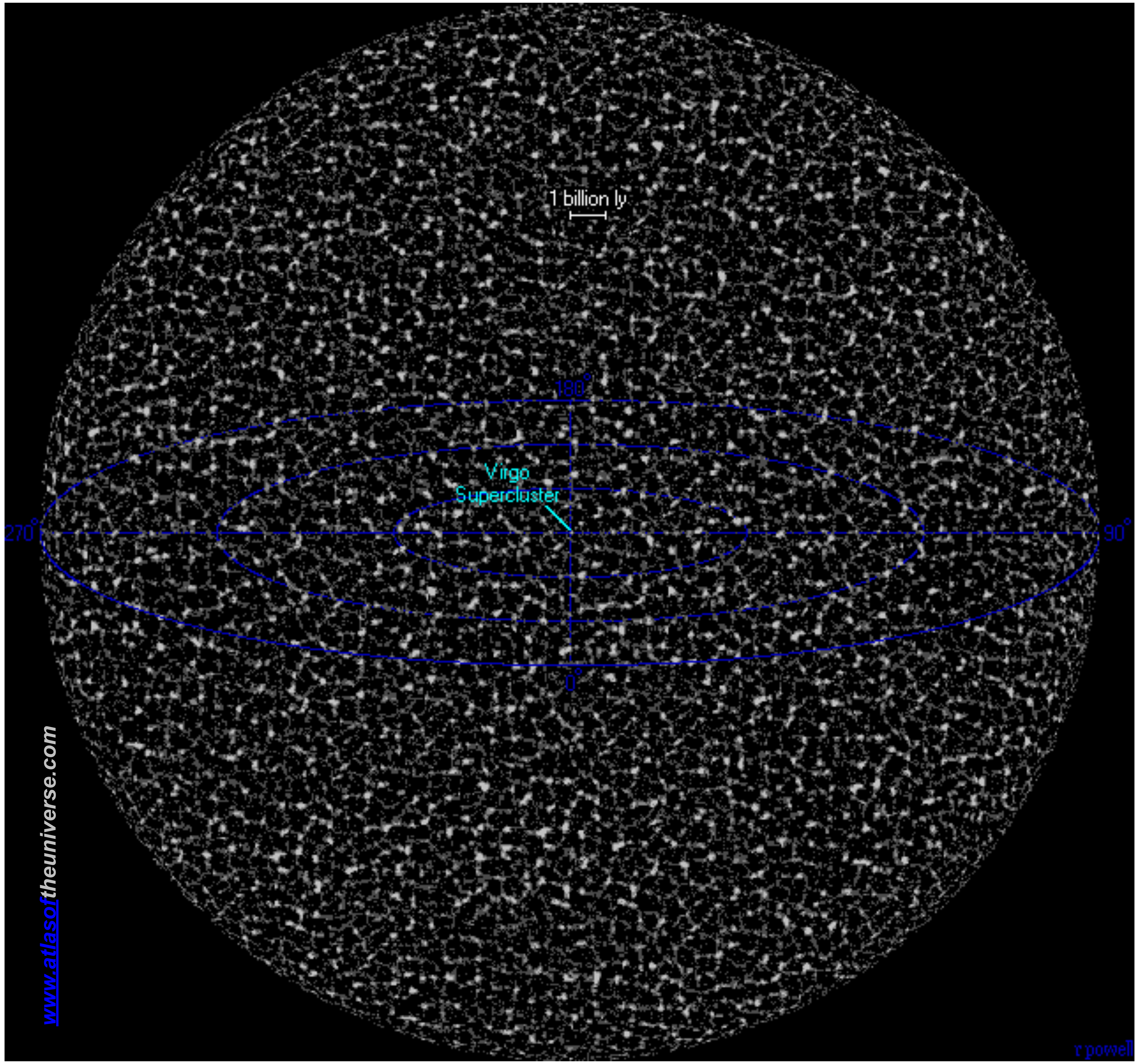
Cosmological evolution of sources important

Magnetic horizon for cosmic rays (diffusion time exceeds lifetime of Galaxy / Universe)

Distance ranges and matter distribution in the Universe



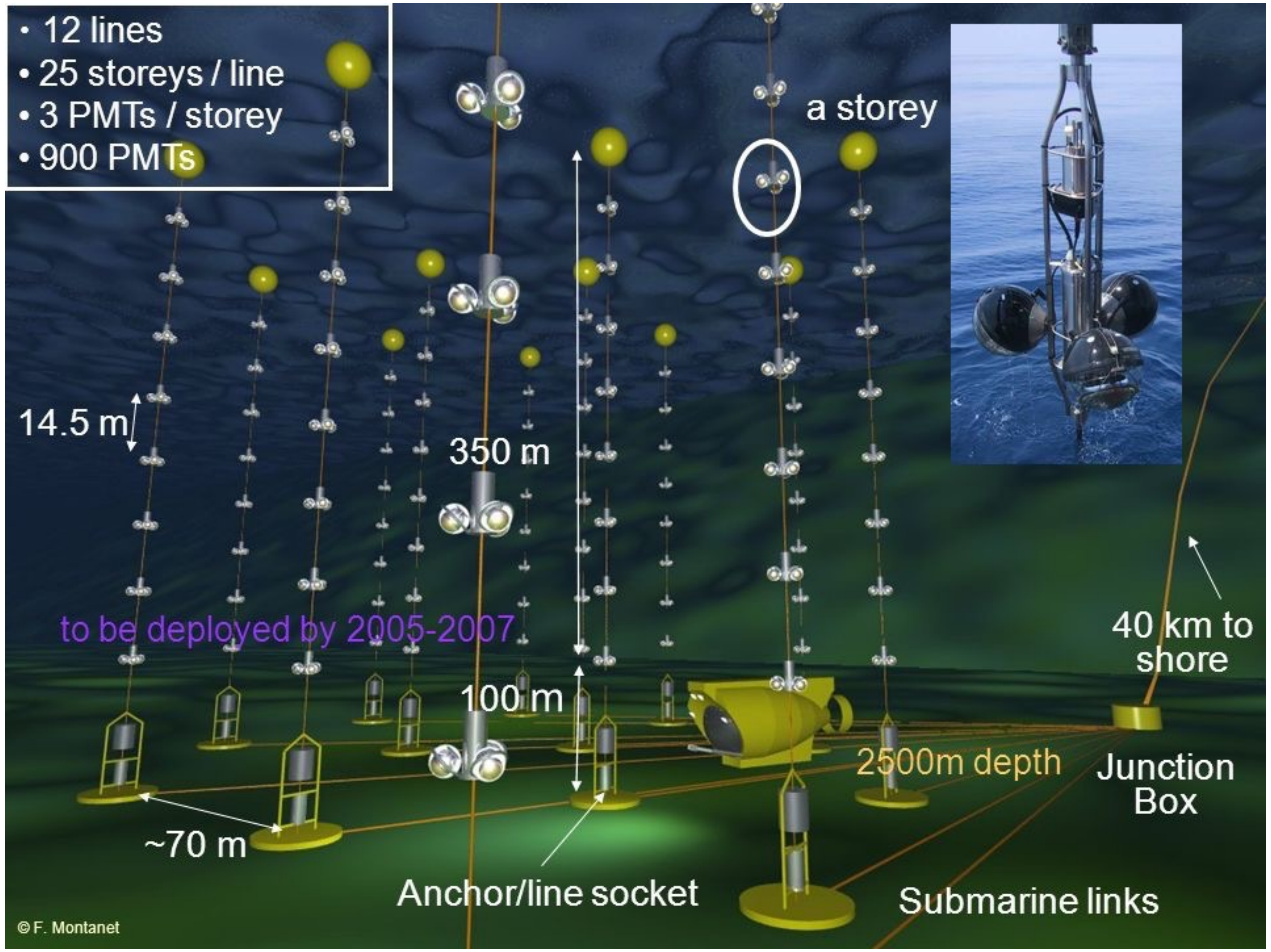
Cosmic rays, gamma-rays

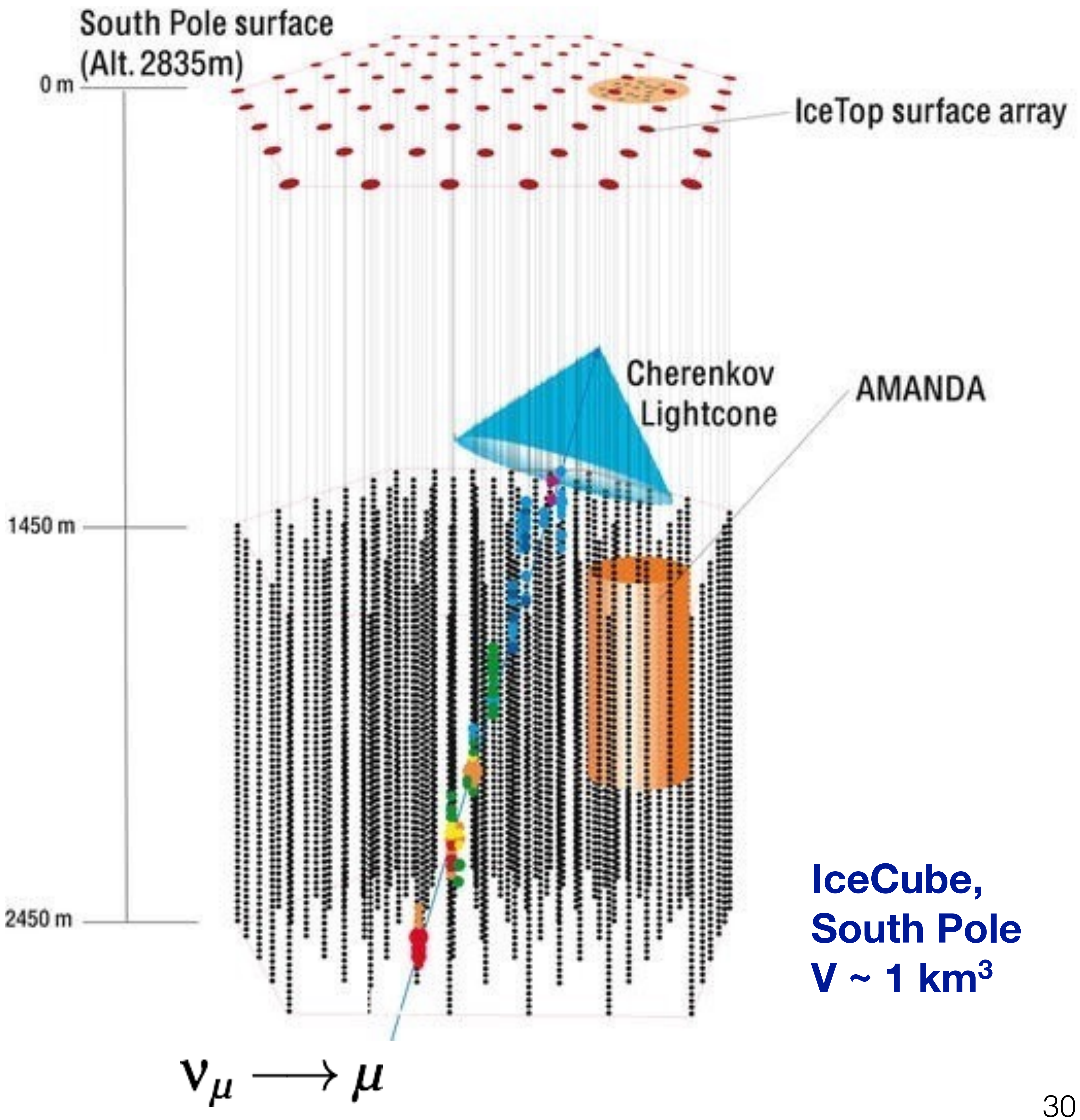


Neutrinos

High-energy neutrino telescopes

ANTARES, Mediterranean Sea, V ~1/100 km^3

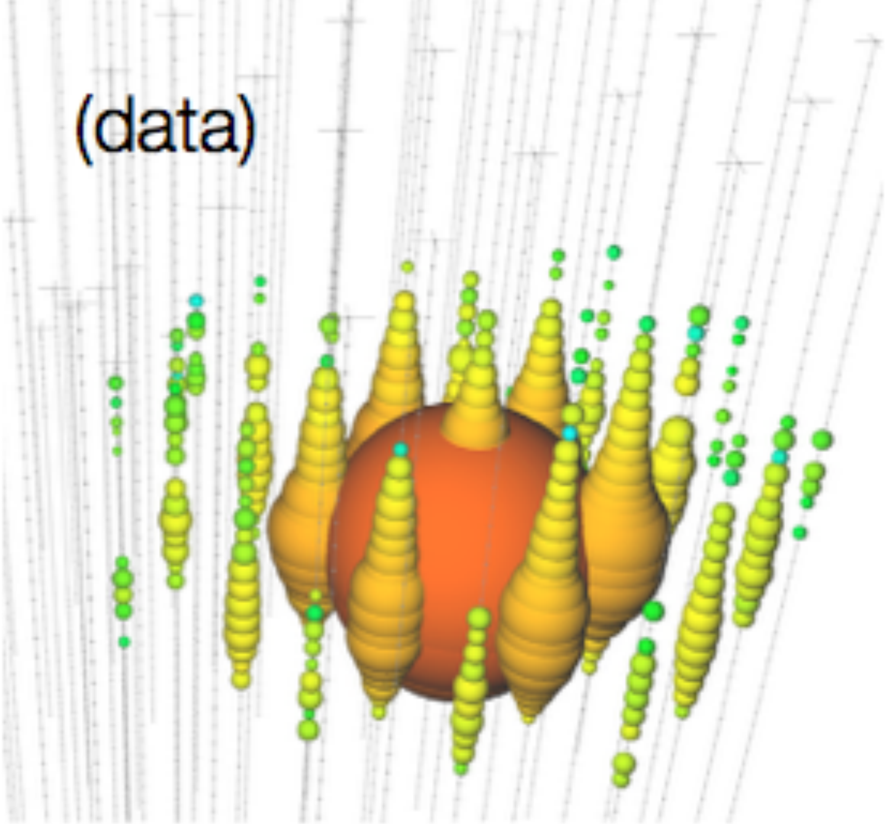




IceCube, South Pole V ~ 1 km^3

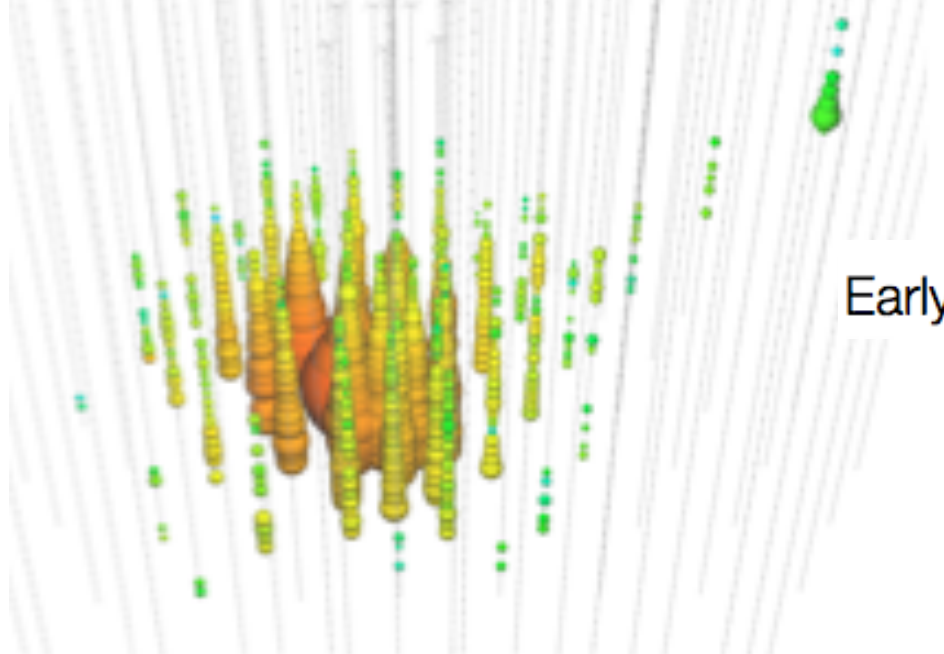
IceCube measurement techniques

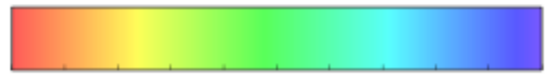
Charged current ν_e interaction



electron neutrinos
(NC muon & tau neutrinos)

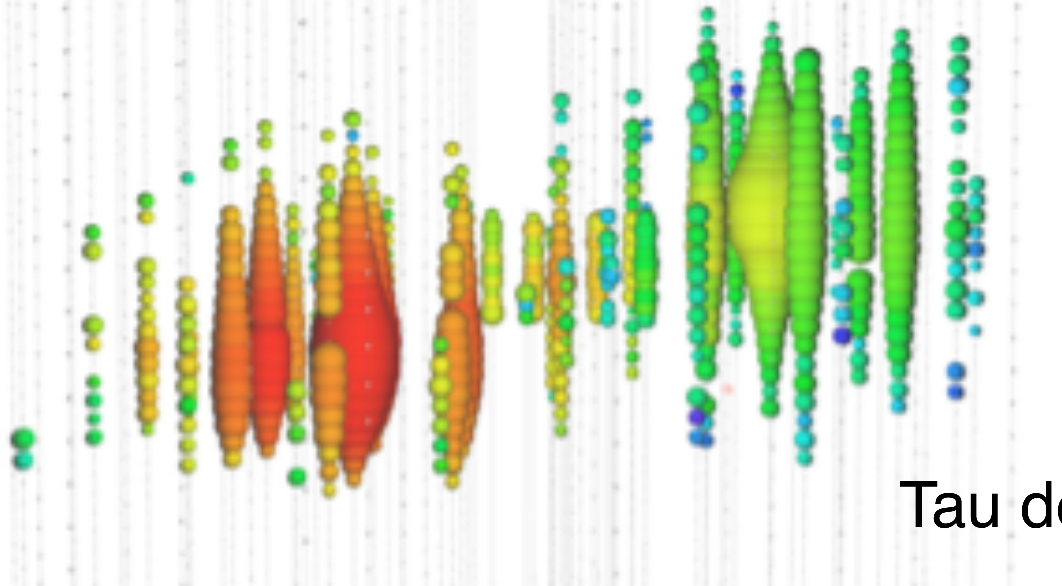
Charged current ν_μ interaction





Only muon neutrinos

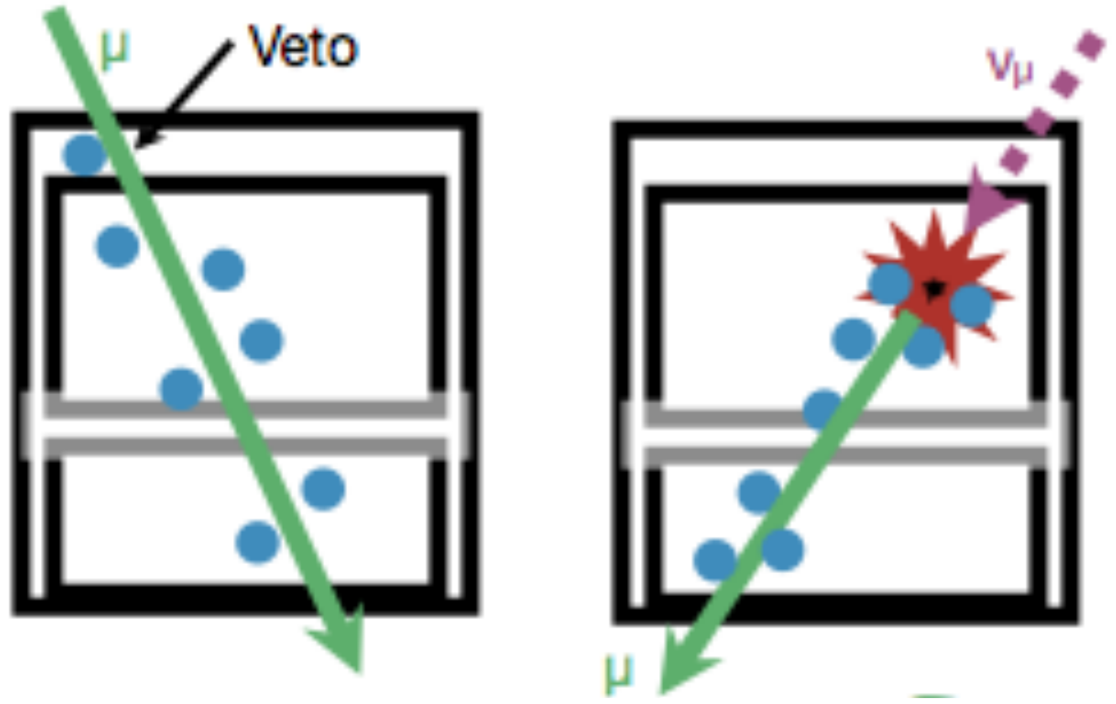
Charged current ν_τ interaction



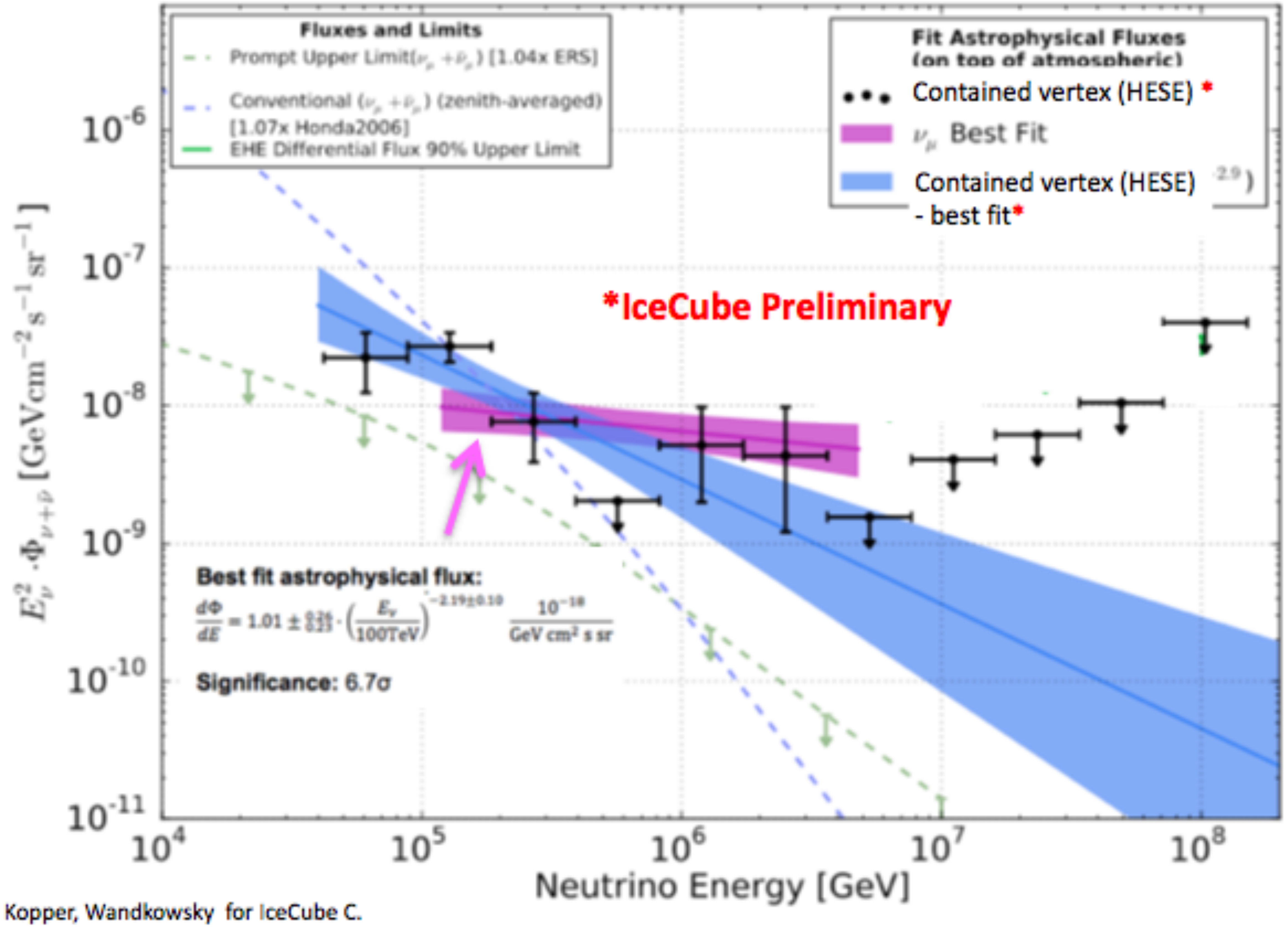
Tau decay length ~50m/10^{15} eV

Veto technique

High energy starting events (HESE)

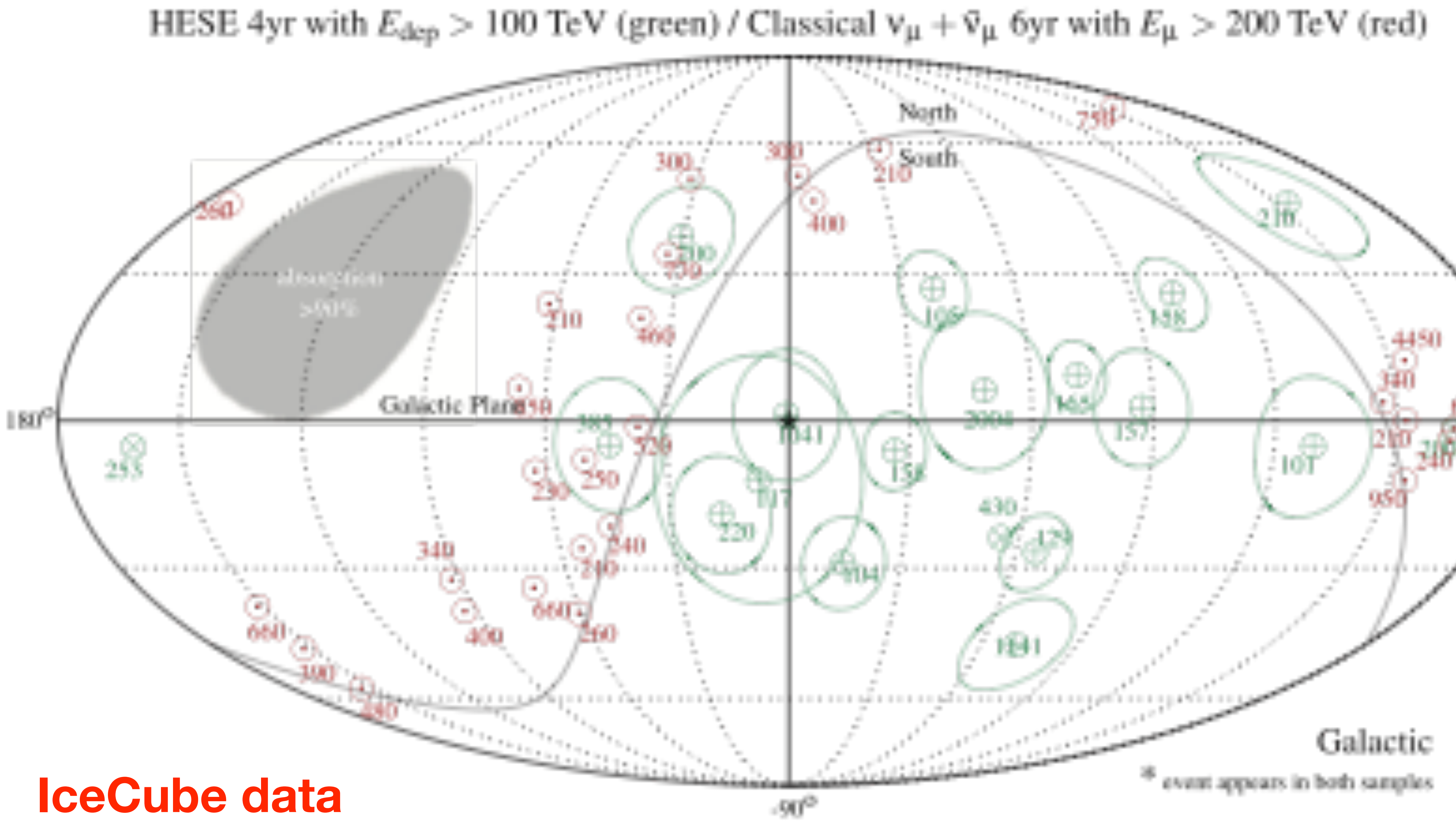


Breakthrough in 2013



ICRC 2017: Kopper, Wandkowsky for IceCube C.
ICRC 2017: Haack for IceCube C.

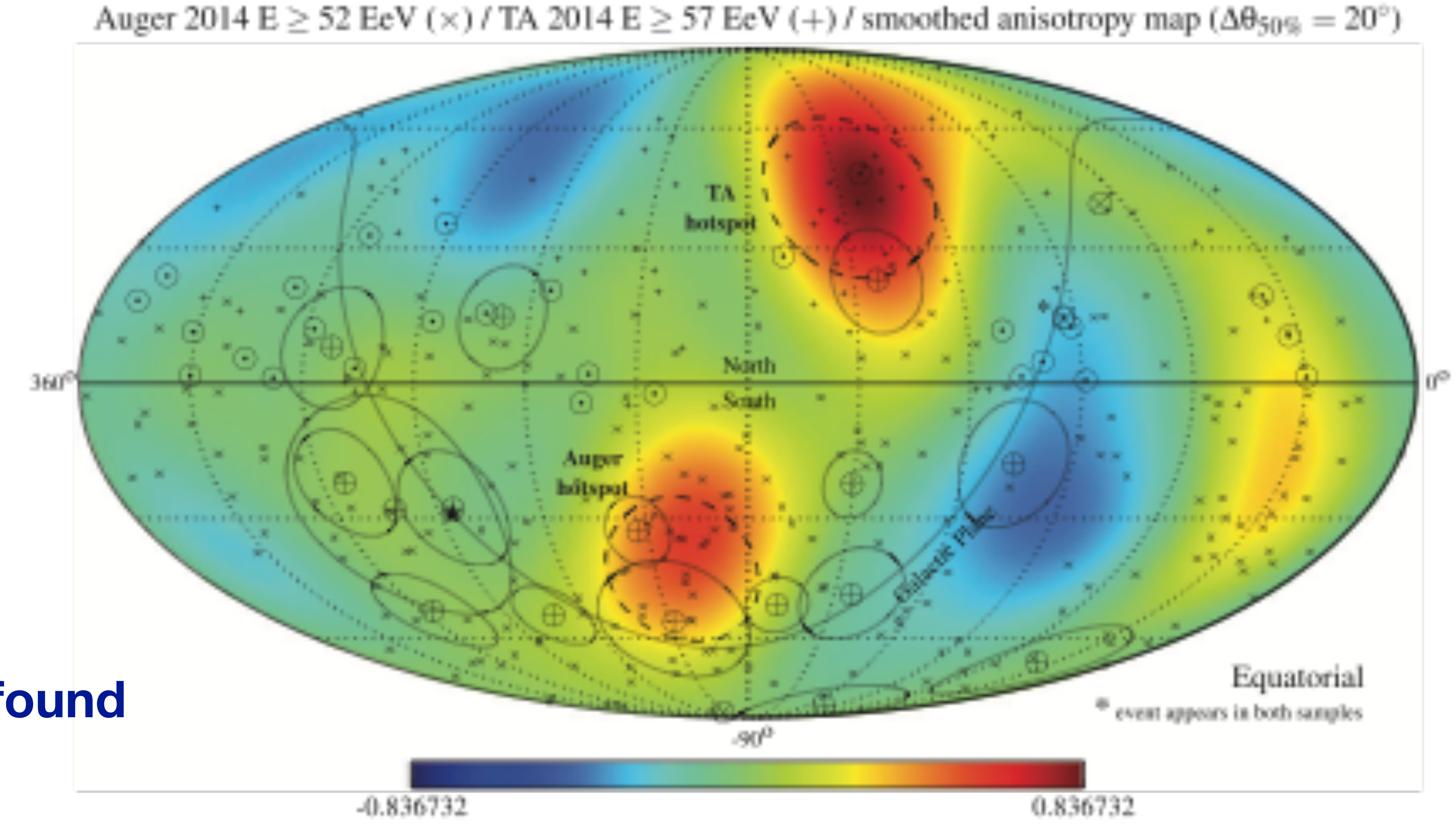
Results: Neutrino arrival directions (i)



Some neutrinos are background events

Different detection techniques for different sky regions

No obvious clustering with Galactic plane or Center



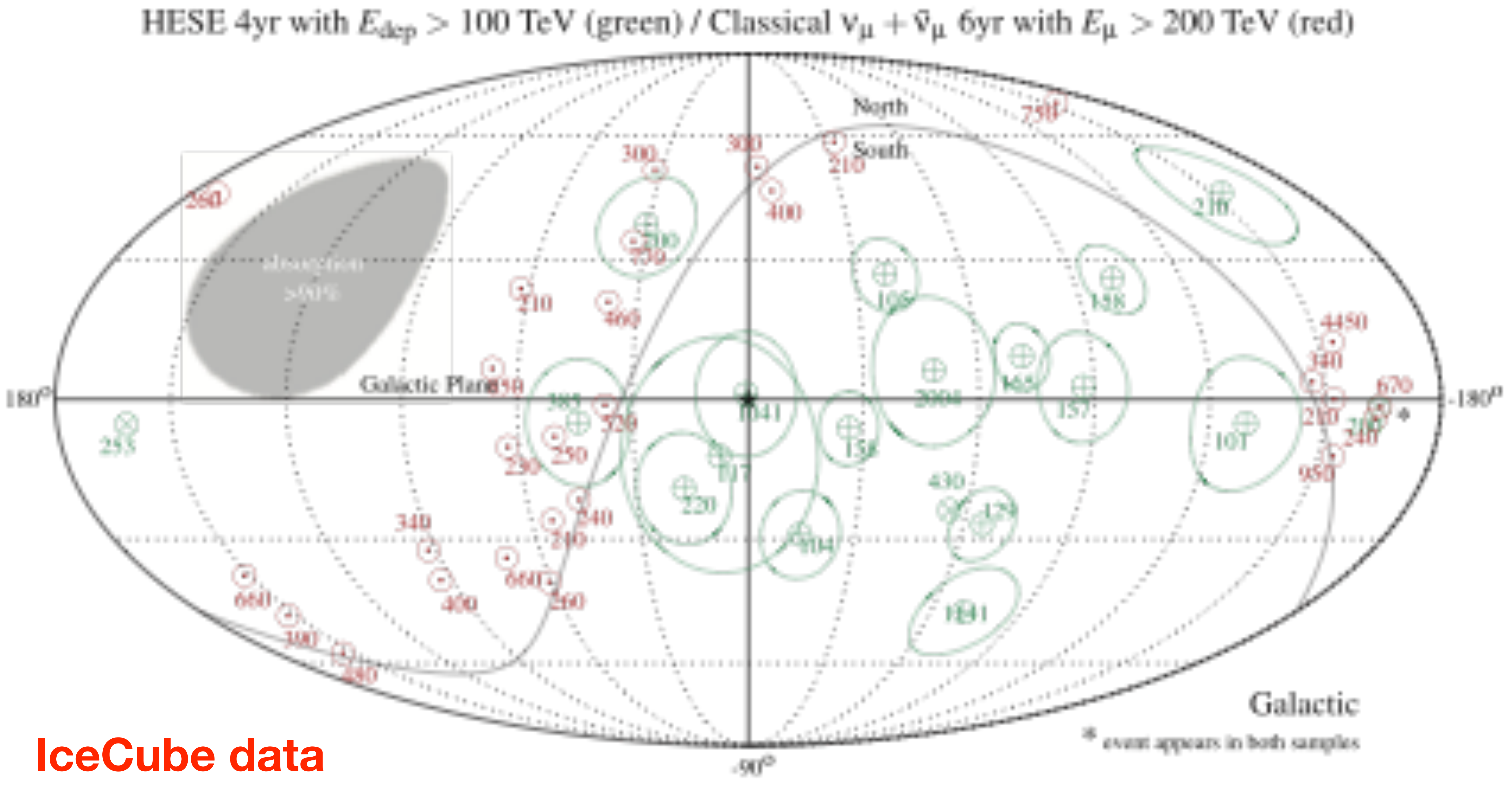
IceCube data

No significant correlation with UHECRs found

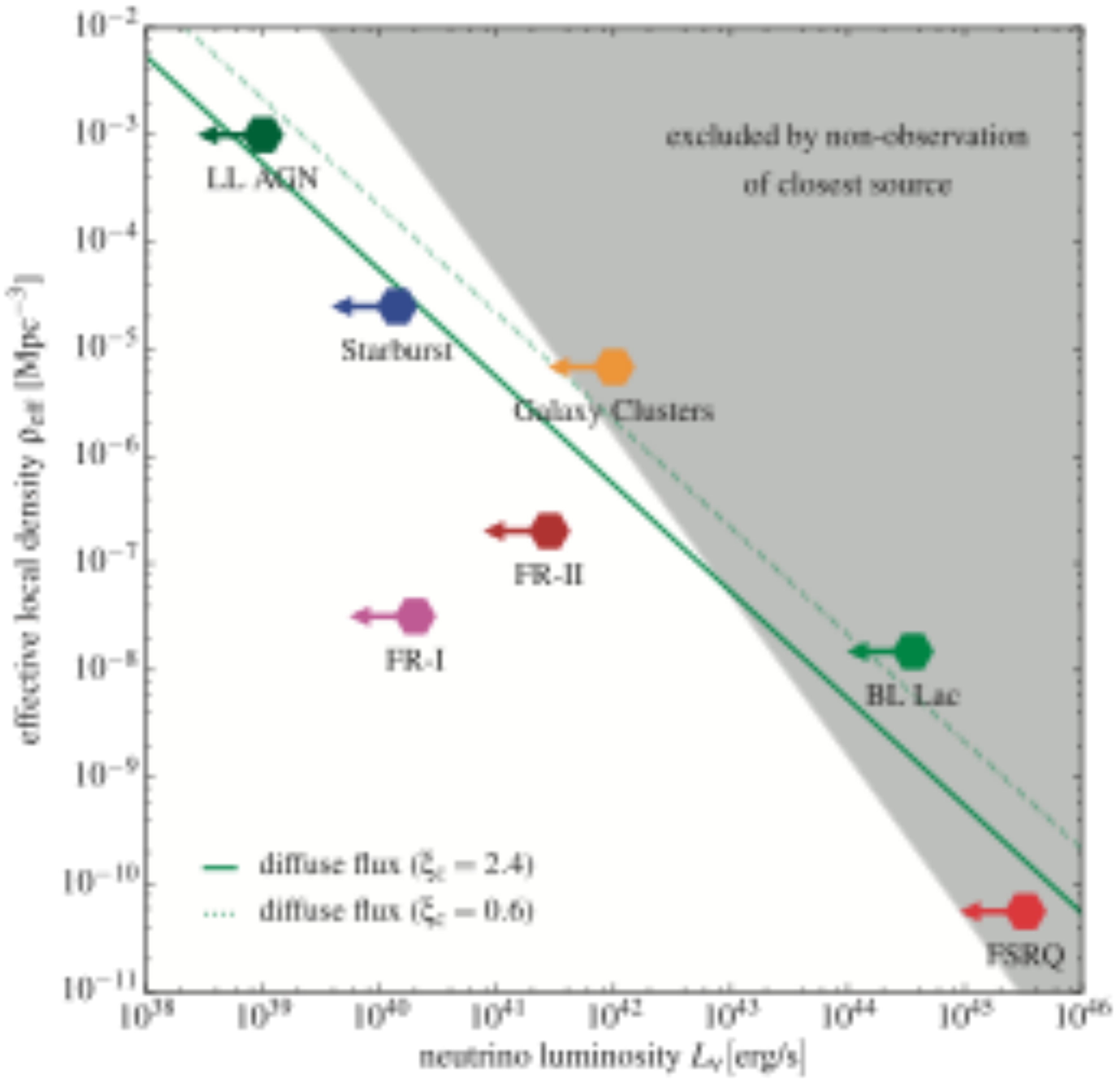
(Ahlers & Halzen, PTEP 2017)

Results: Neutrino arrival directions (ii)

Some neutrinos are background events
Different detection techniques for different sky regions
No obvious clustering with Galactic plane or Center
First source candidates can be excluded



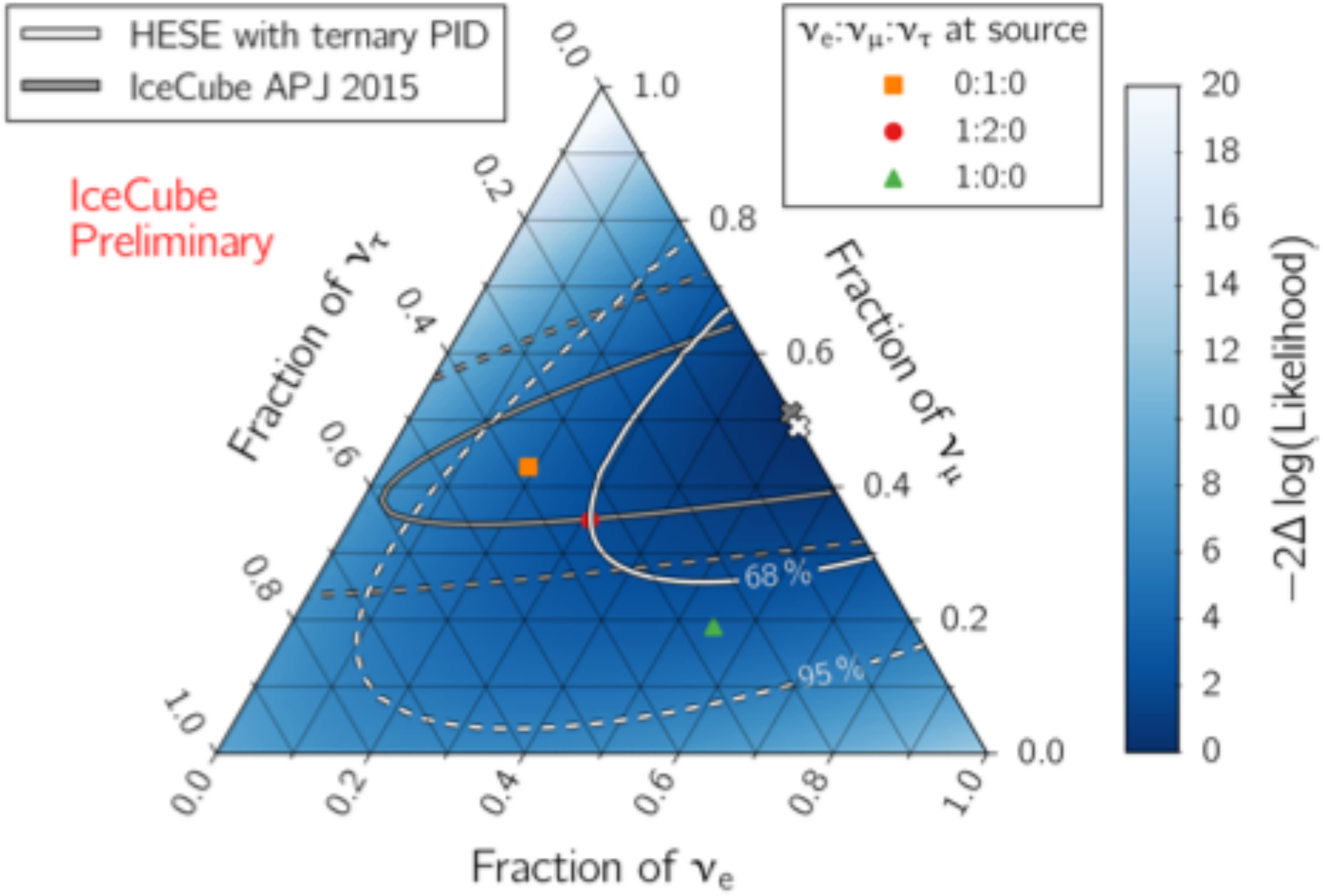
IceCube data



Assumption:
IceCube flux is diffuse,
no local source seen

(Ahlers & Halzen, PTEP 2017)

Results: Neutrino flavor mixture as observed at Earth



$$\pi^+ \longrightarrow \mu^+ \nu_\mu \longrightarrow e^+ \nu_e \nu_\mu \bar{\nu}_\mu$$

Neutrino oscillations from source to Earth

- **0:1:0 only pion decay, strong muon cooling**
- **1:2:0 classic pion and muon decay**
- **1:0:0 neutron decay (anti-neutrinos_e)**

IceCube:
2.83 tau-neutrinos expected,
0 observed

$$f_{\nu_e} = 0.51^{+0.12}_{-0.13}$$

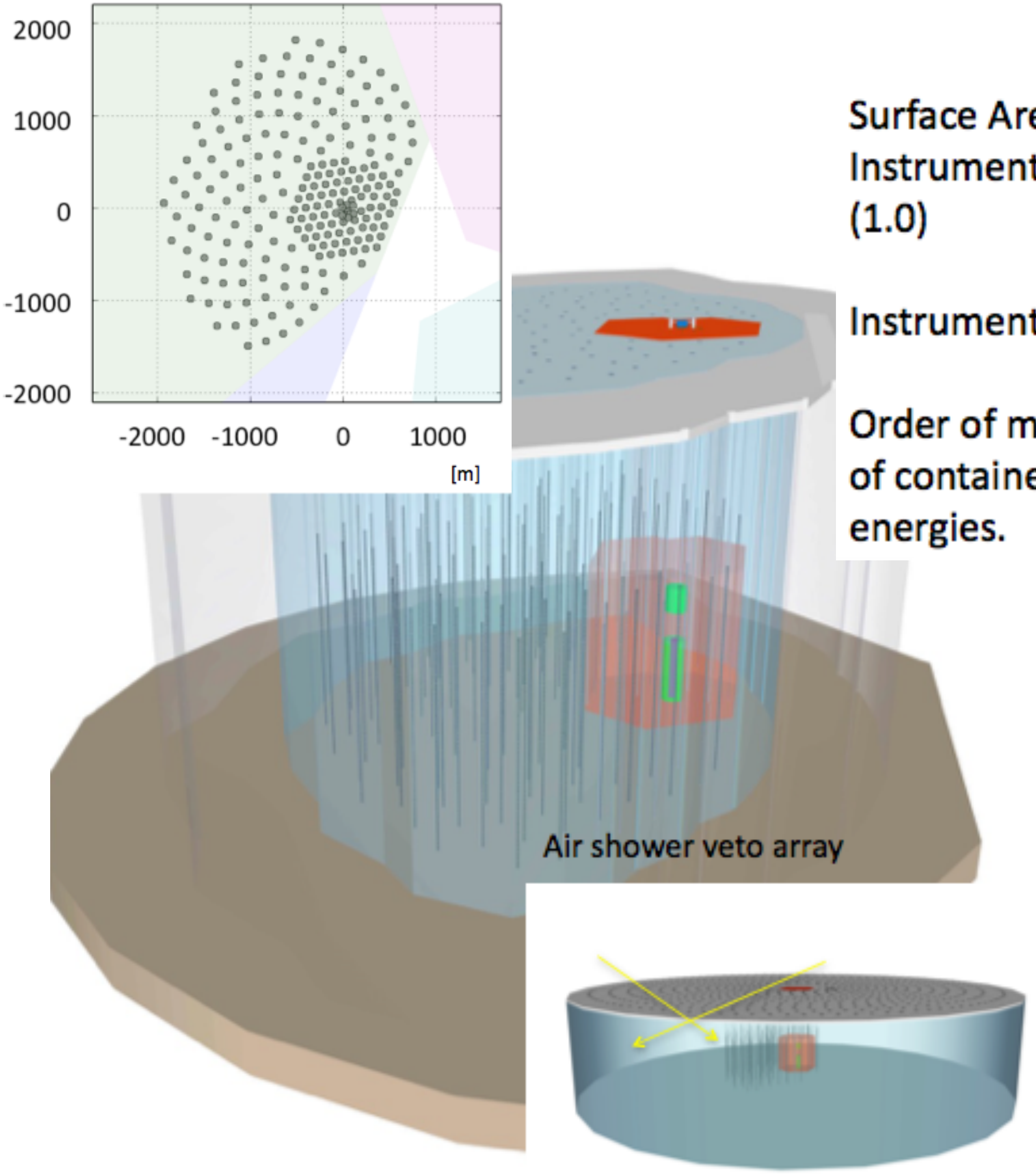
$$f_{\nu_\mu} = 0.49^{+0.12}_{-0.13}$$

$$f_{\nu_\tau} = 0.00^{+0.16}_{-0.00}$$

(Bustamante, MIAPP 2018)

(IceCube, ICRC 2017)

IceCube Generation 2 (Gen-2)



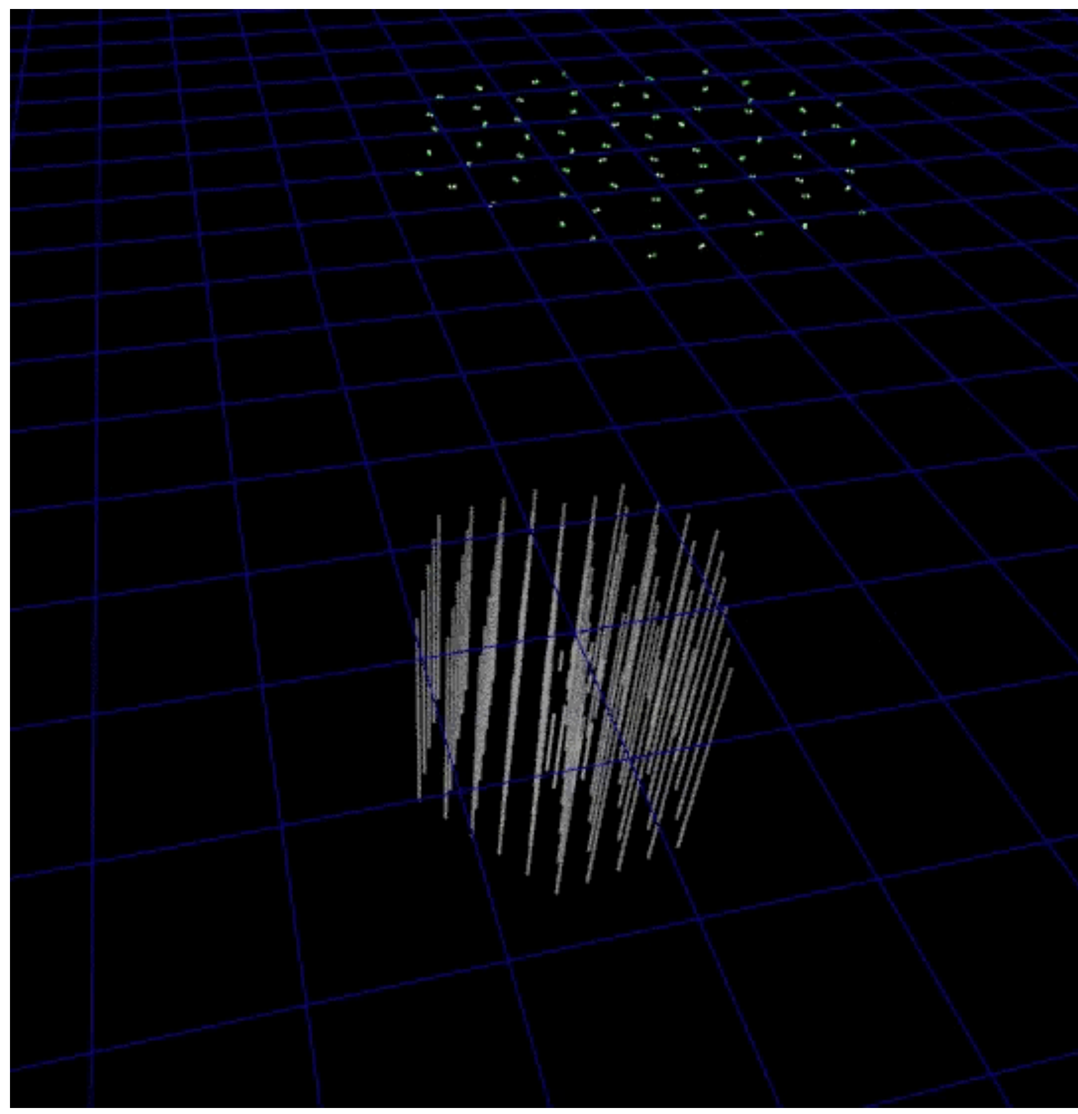
Surface Area: ~6.5km^2 (0.9)
Instrumented depth: 1.26 km (1.0)

Instrumented Volume: 8 km^3

Order of magnitude increase of contained event rate at high energies.

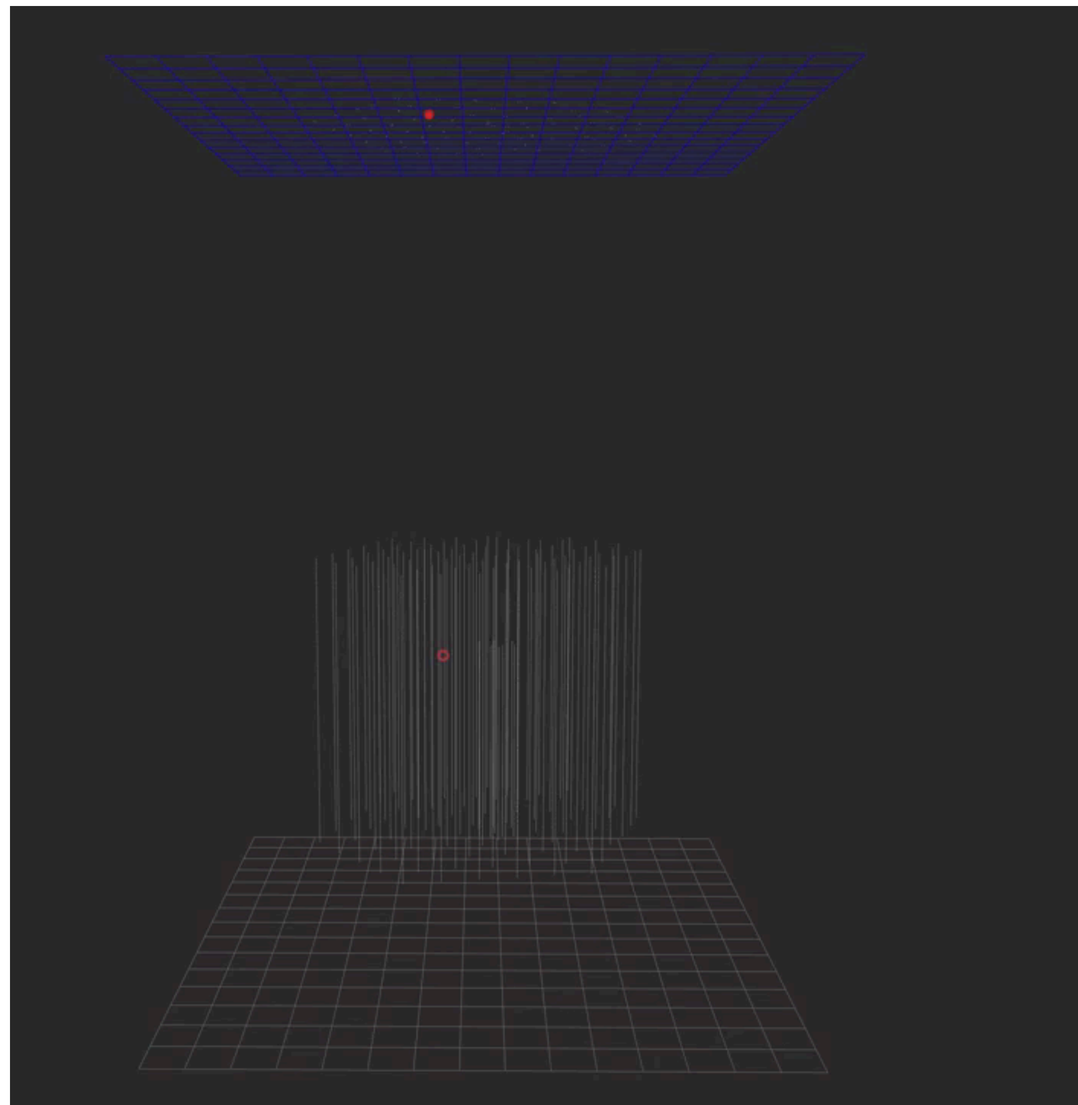
(Karle, MIAPP 2018)

Importance of veto array



Air shower event

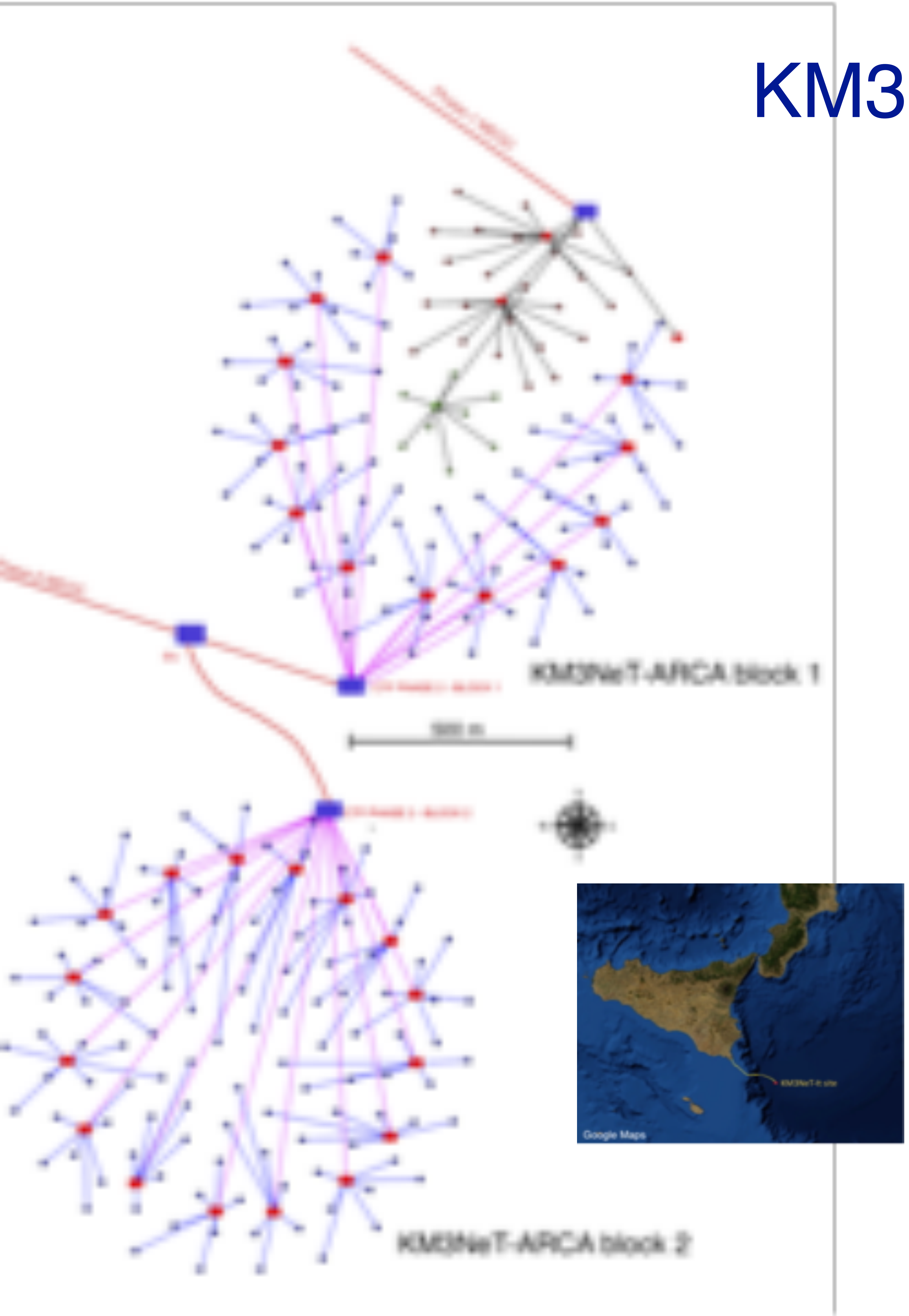
- IceTop: $E_\mu \sim 1$ GeV
- IceCube: $E_\mu \sim 500$ GeV



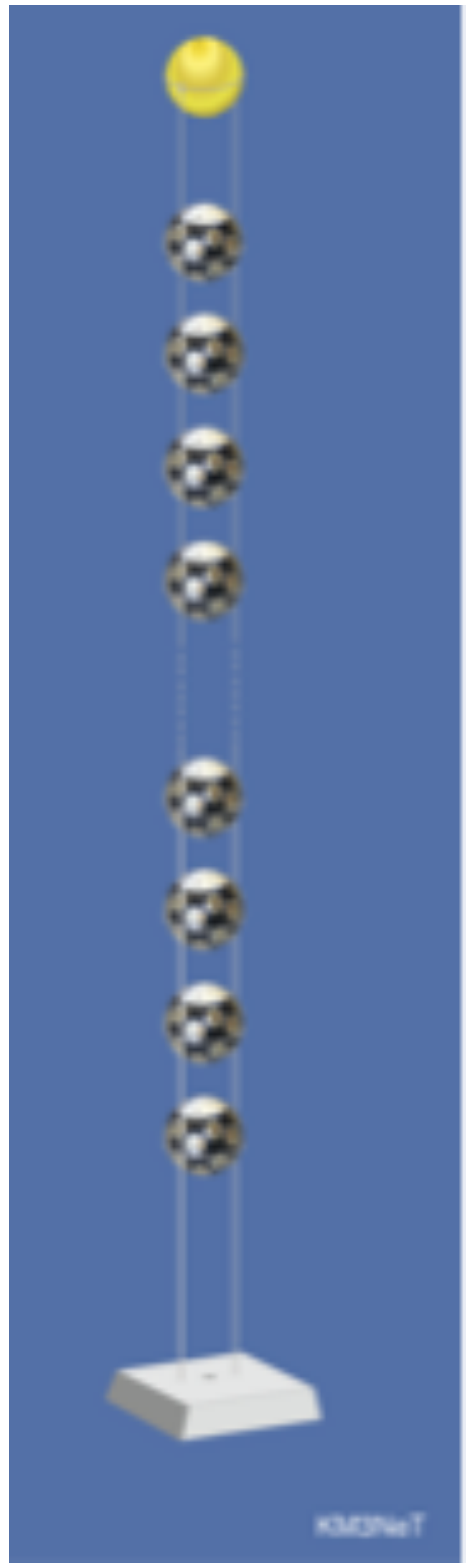
Astrophysical neutrino event (simulation)

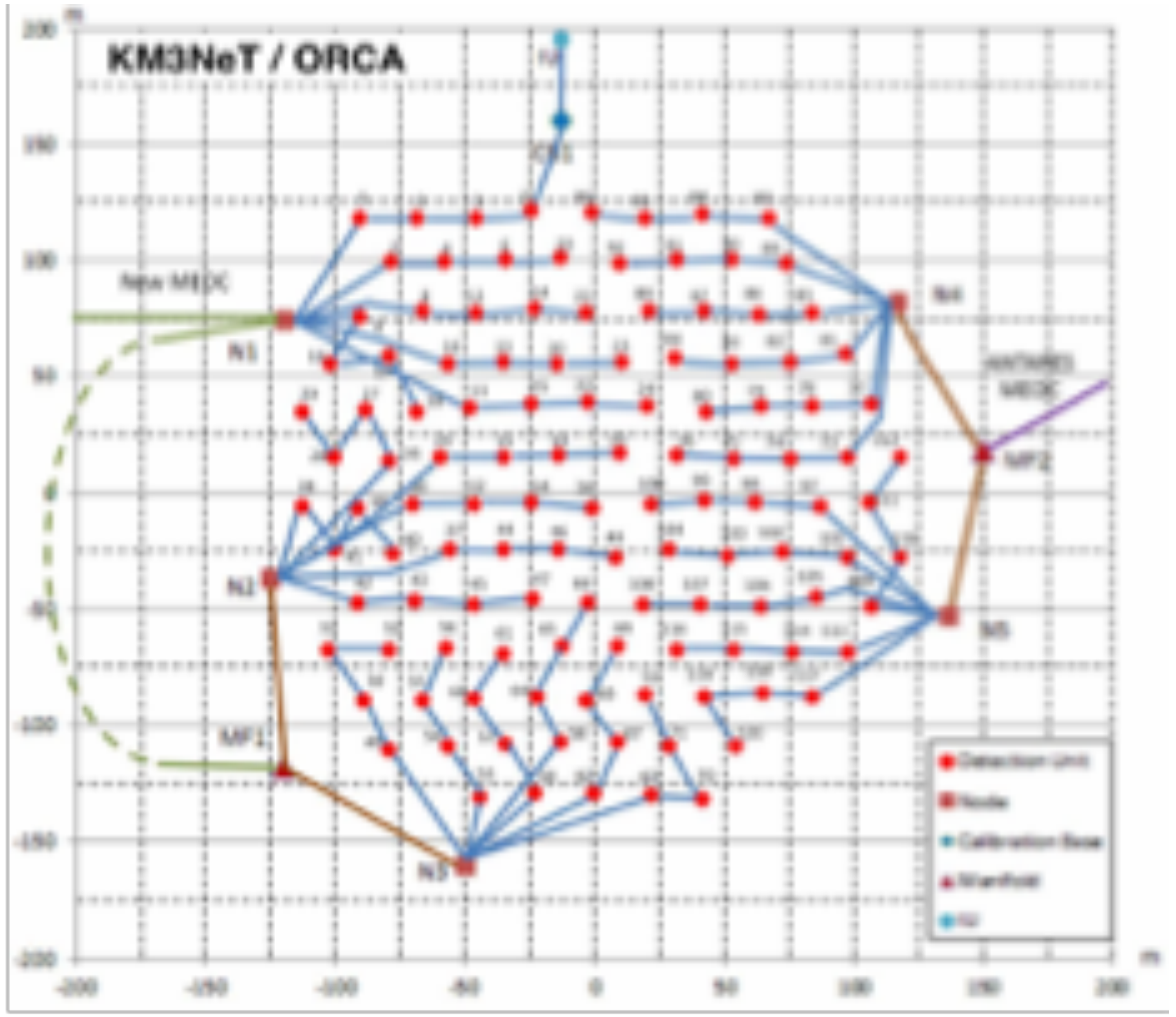
- IceTop: veto array
- IceCube: neutrino track or cascade

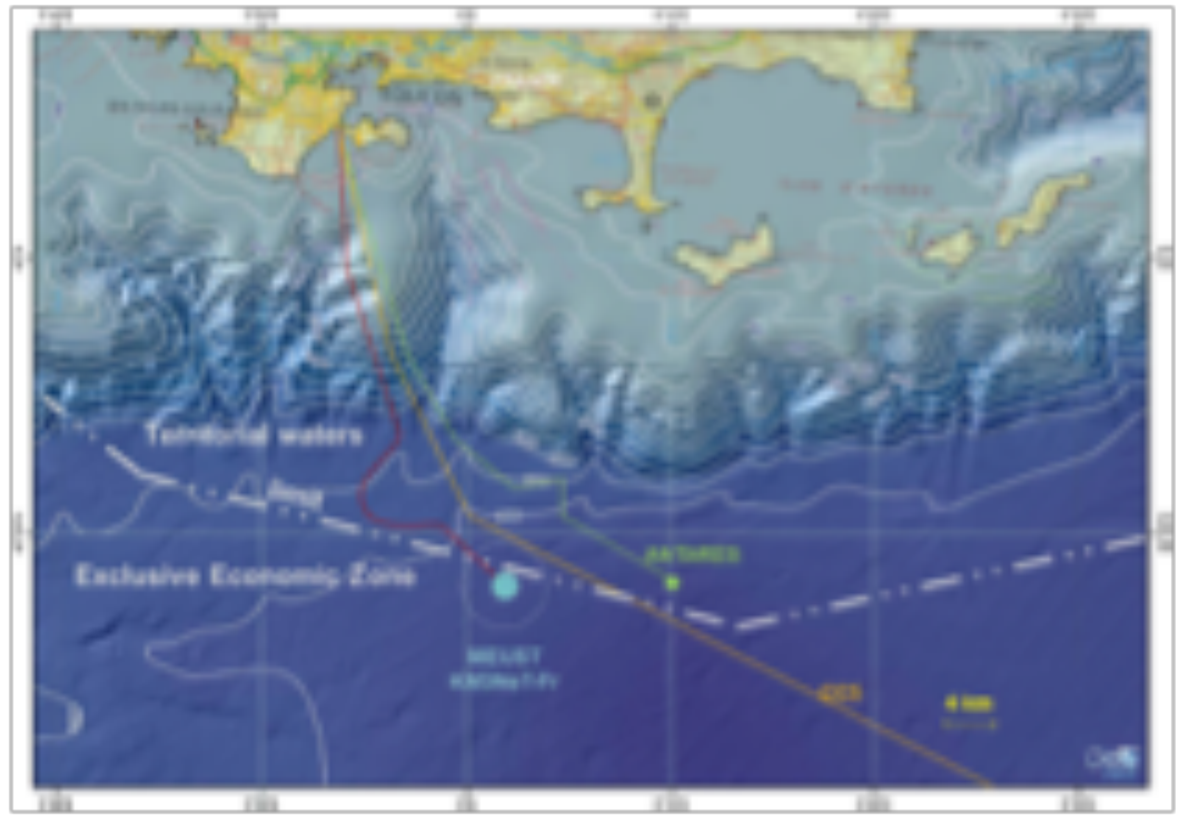
KM3NeT: ARCA and ORCA



ORCA could be first experiment to determine neutrino mass hierarchy

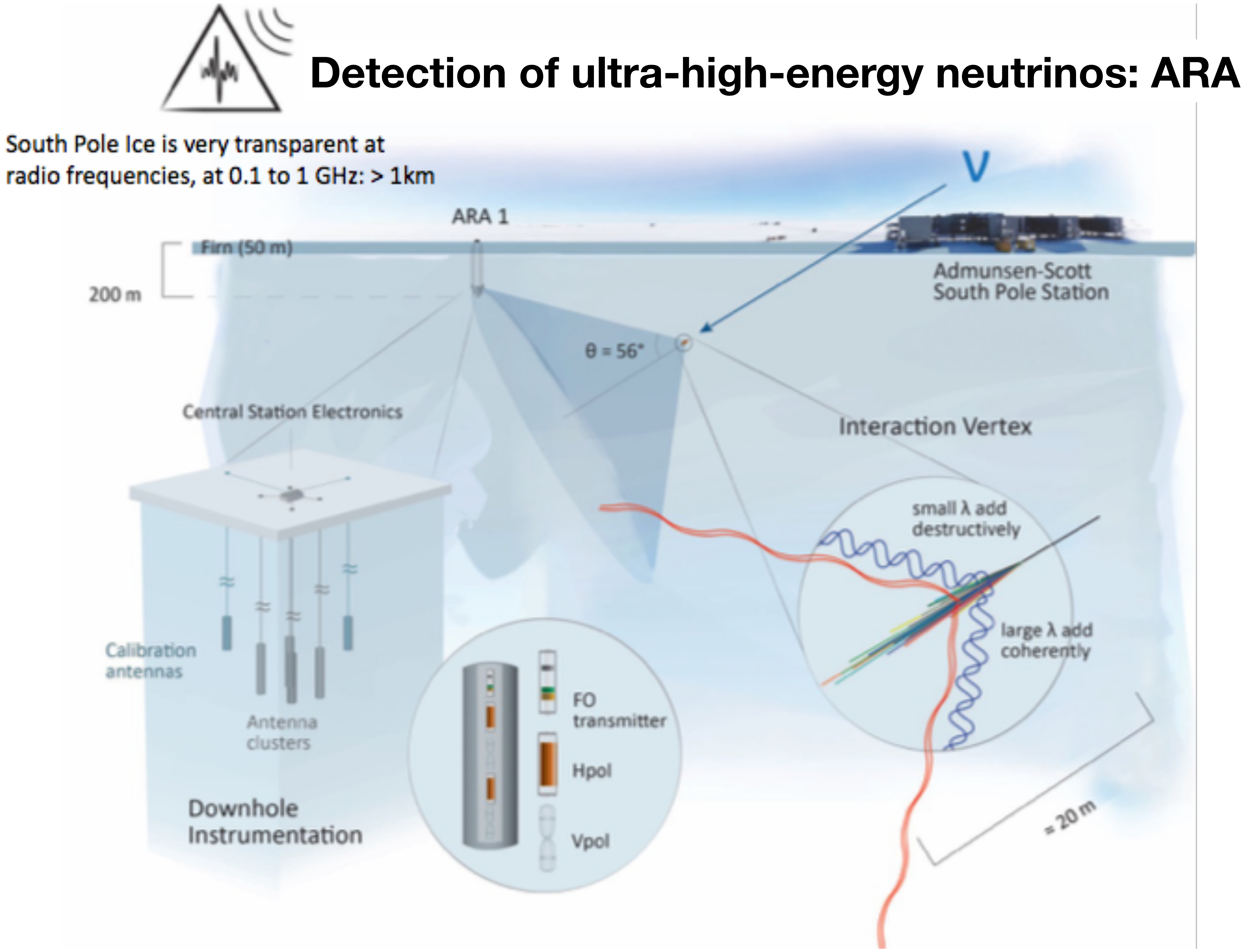






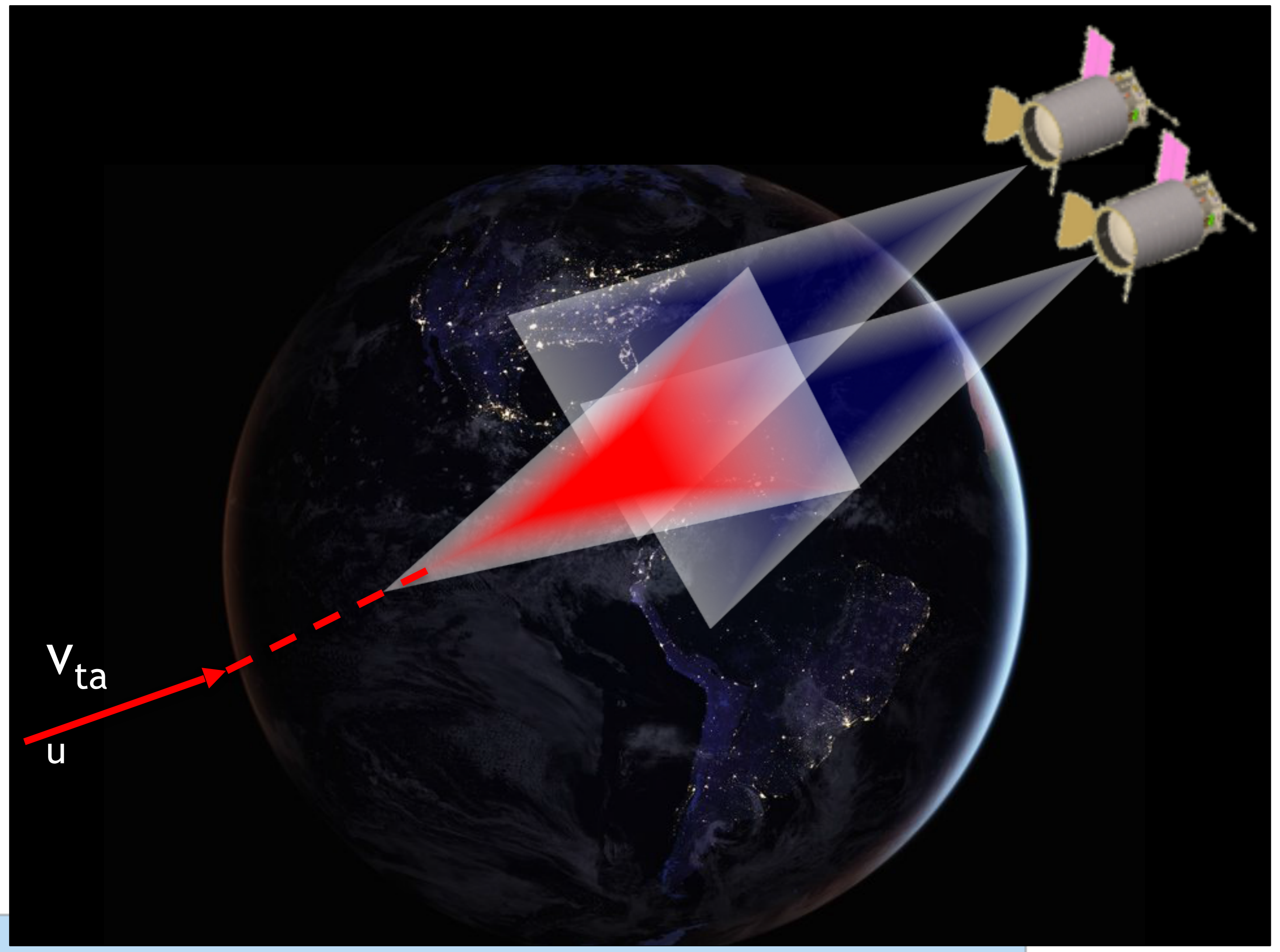
Detection of neutrinos of ultra-high energy

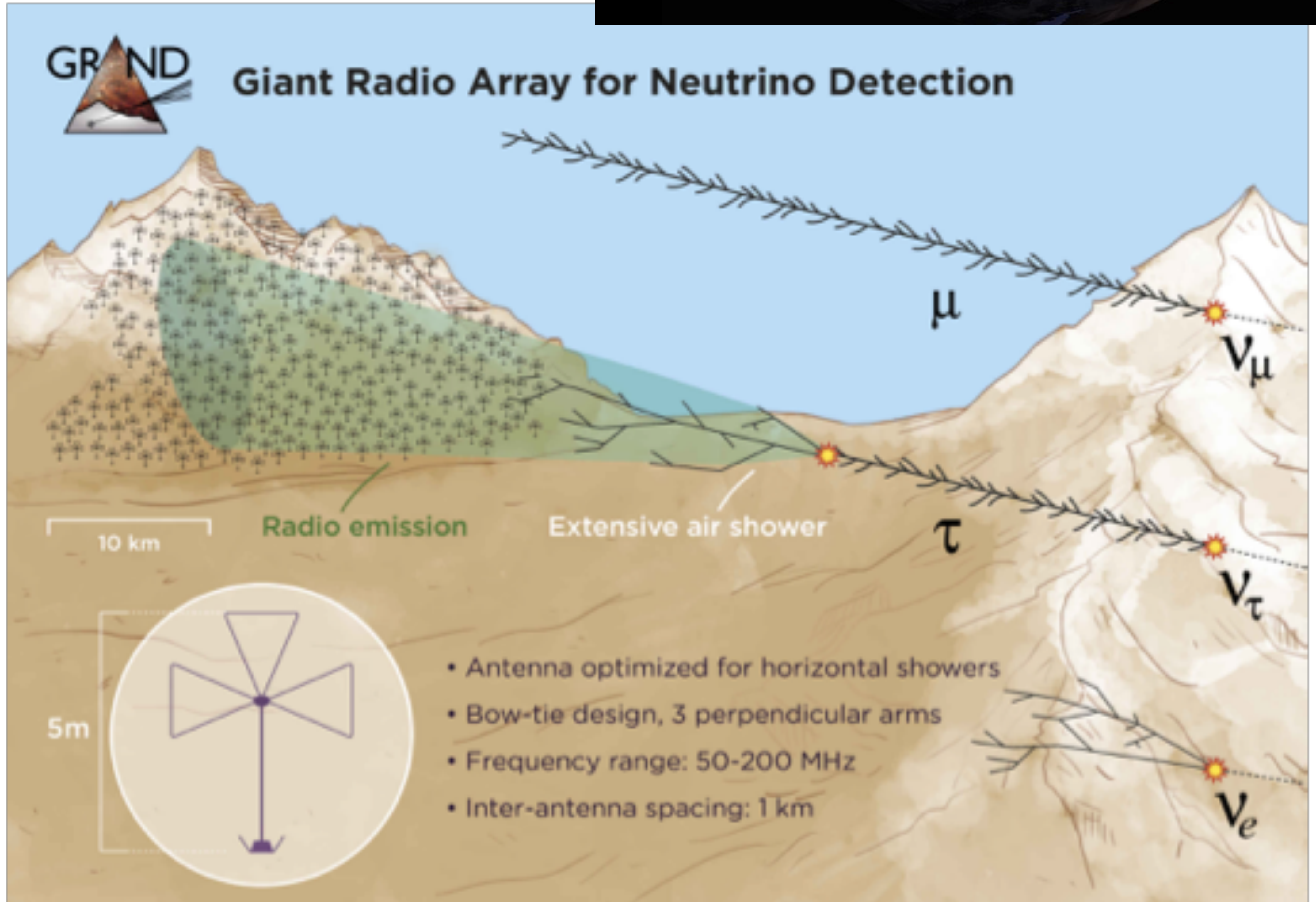
ANITA balloon flights



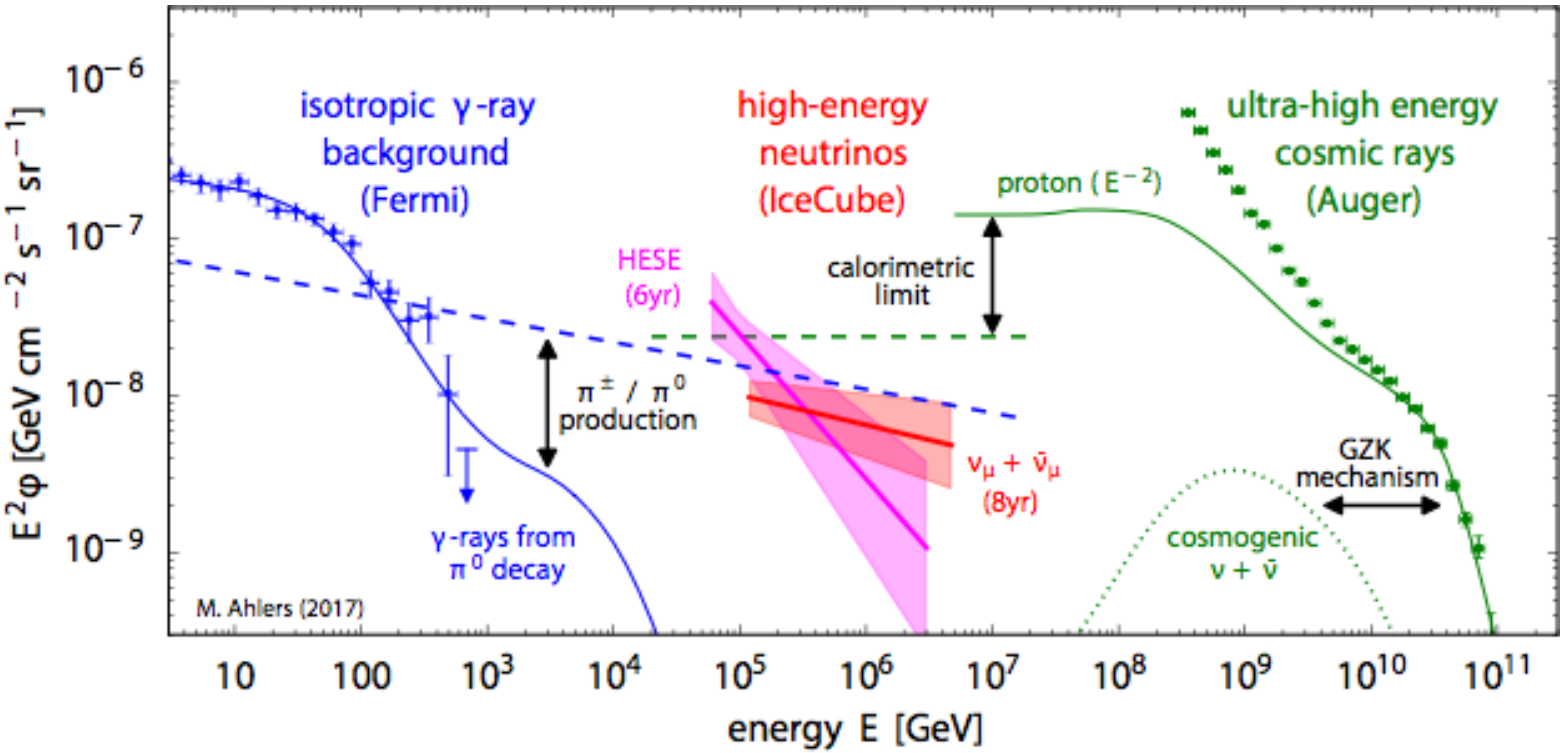
Different concept in ice: ARIANNA

POEMMA
neutrino detection





Gamma-ray production due to cosmic ray propagation



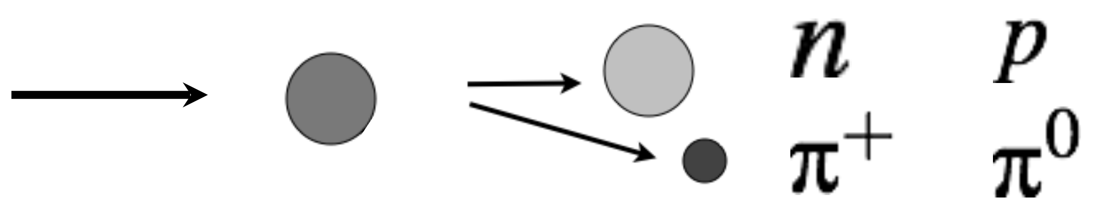
Interplay of

interaction in source

vs.

escape from source

Pion production on any target



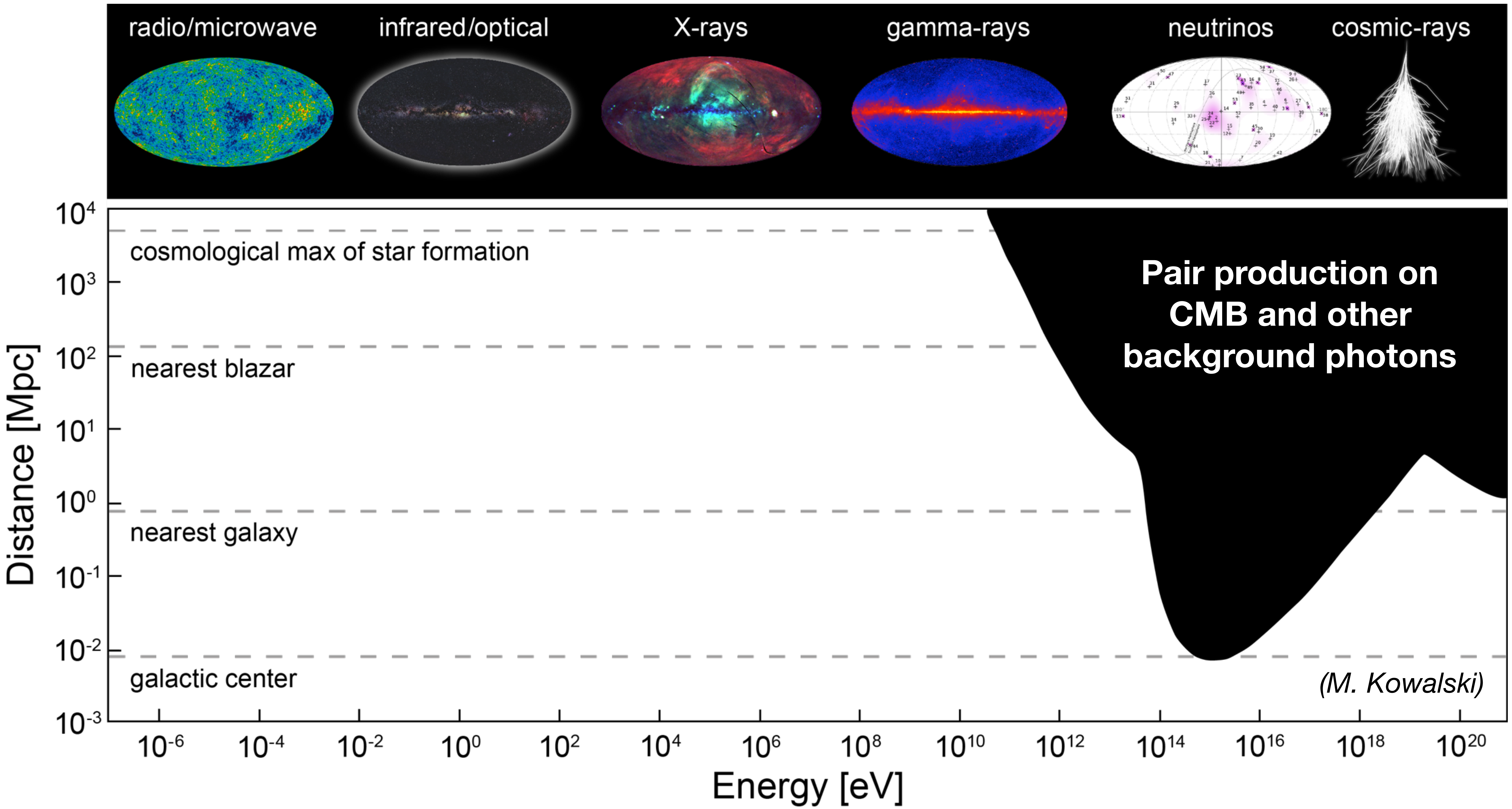
$$\pi^0 \longrightarrow \gamma\gamma$$

$$\pi^+ \longrightarrow \mu^+ \nu_\mu \longrightarrow e^+ \nu_e \nu_\mu \bar{\nu}_\mu$$

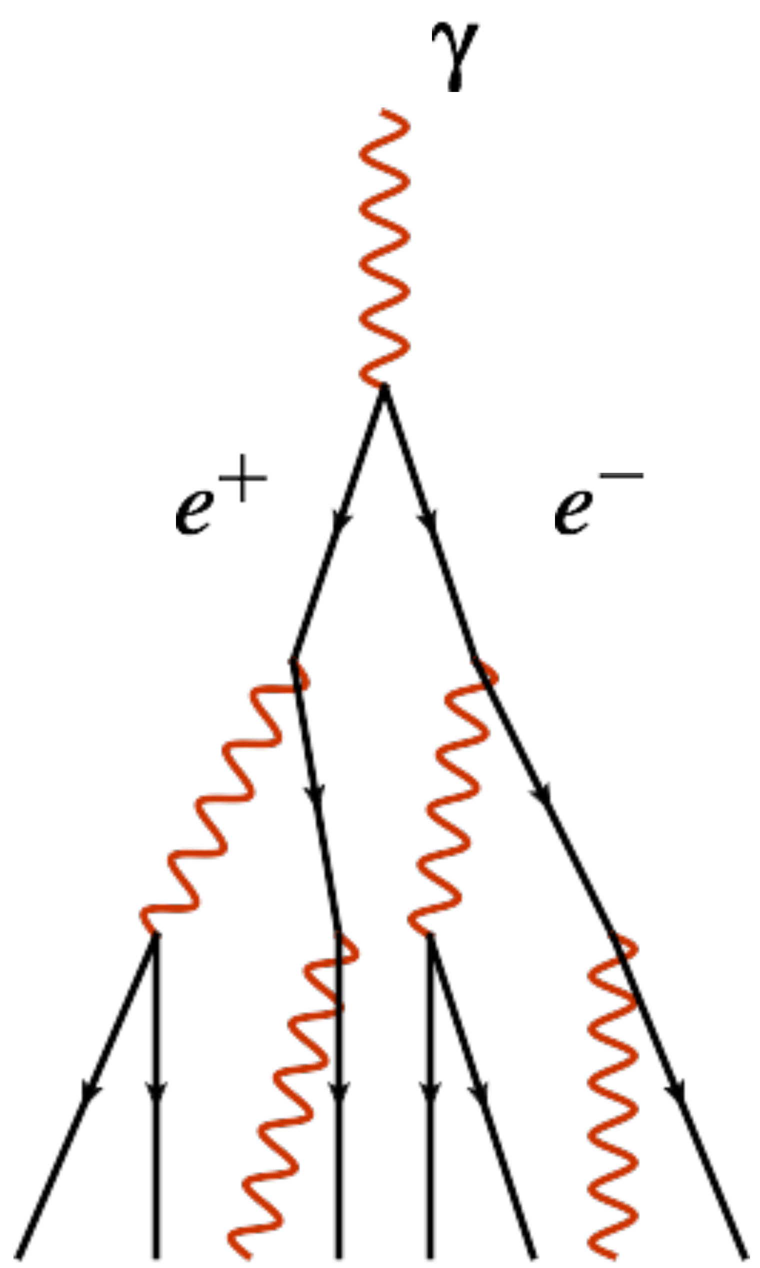
$$\boxed{\nu_\mu : \nu_e \sim 2:1}$$

(neutrino + antineutrino flavor)

Gamma-ray cascading down to ~ 100 GeV

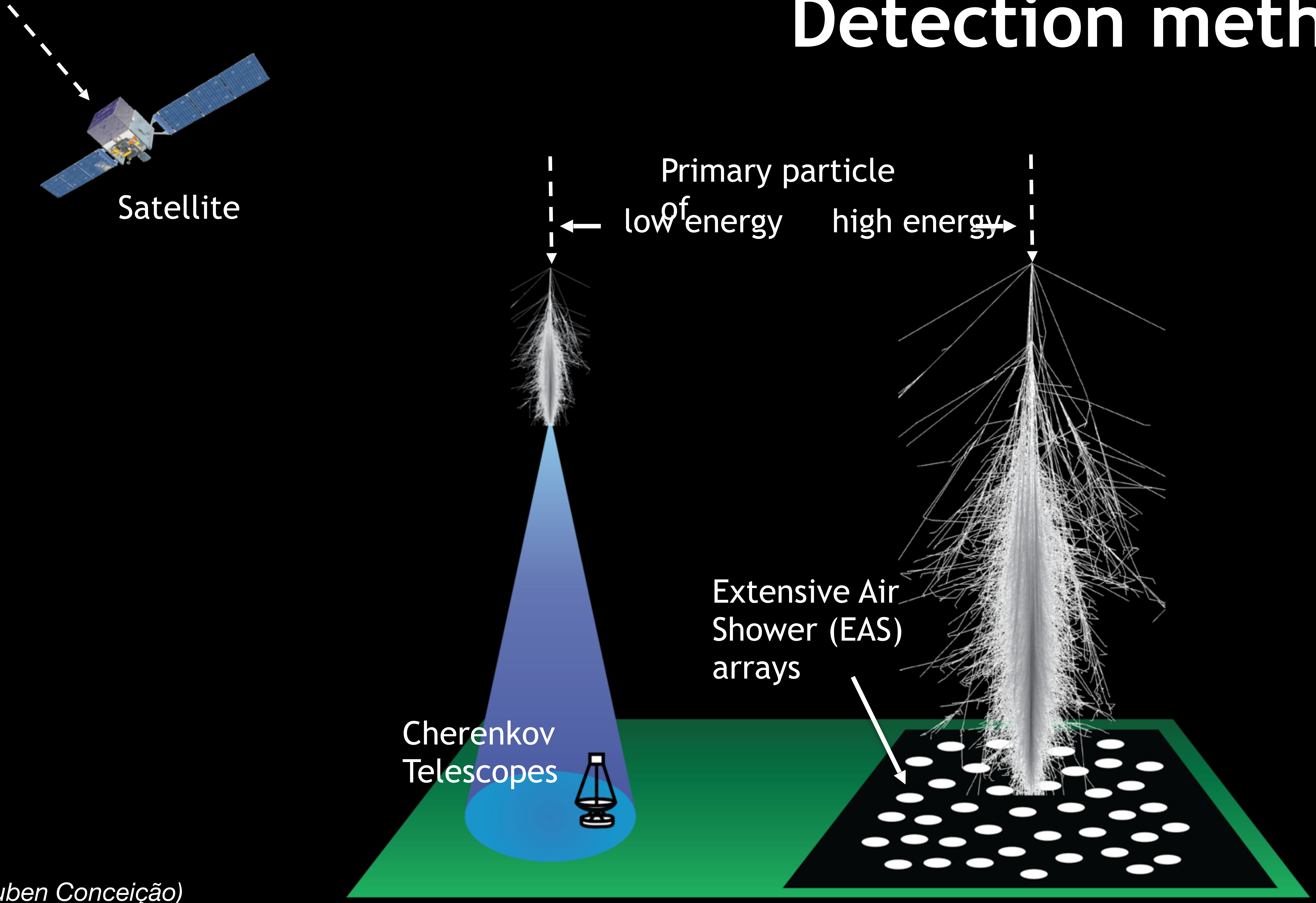


Em. Cascade of pair production and synchrotron radiation in external magnetic fields



Photons "pile up" at low energy

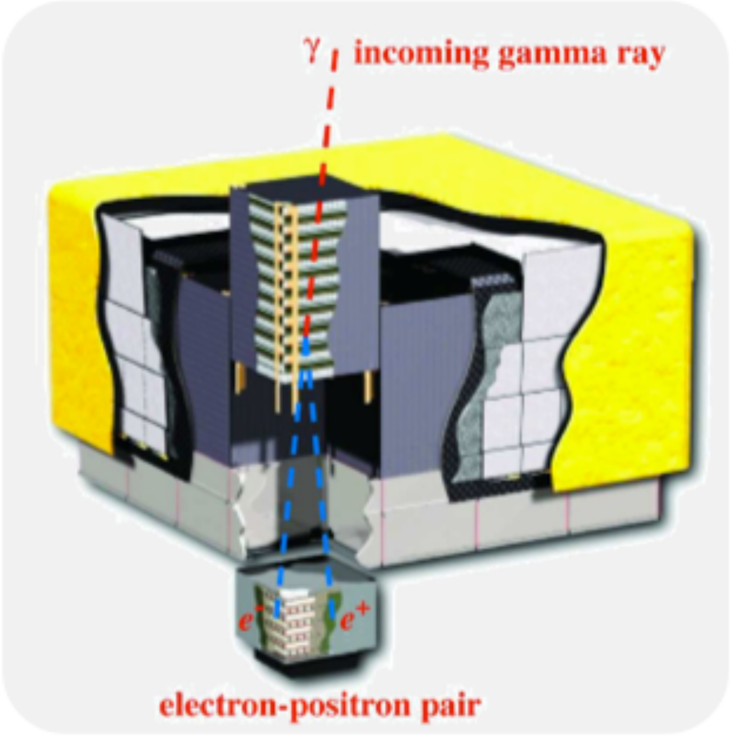
Detection methods

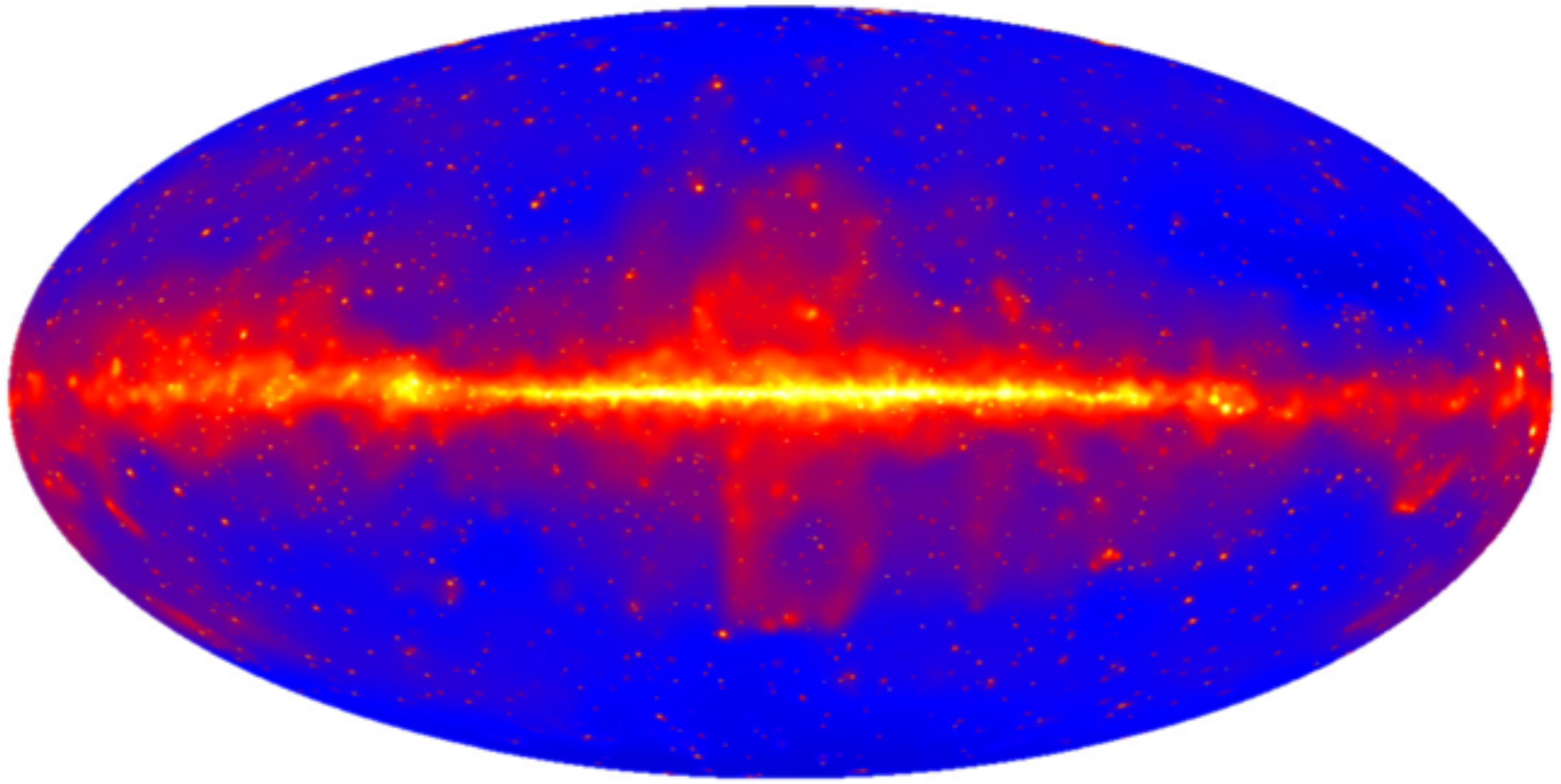


(slide by Ruben Conceição)

Results: Examples of measurements

MAGIC telescopes

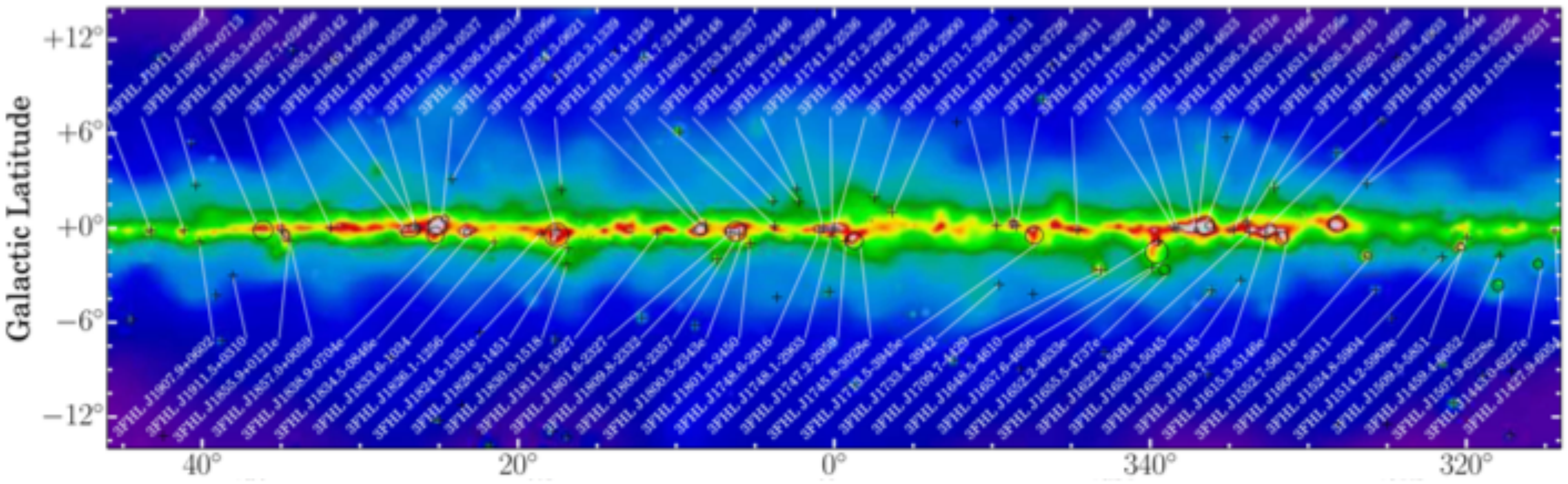


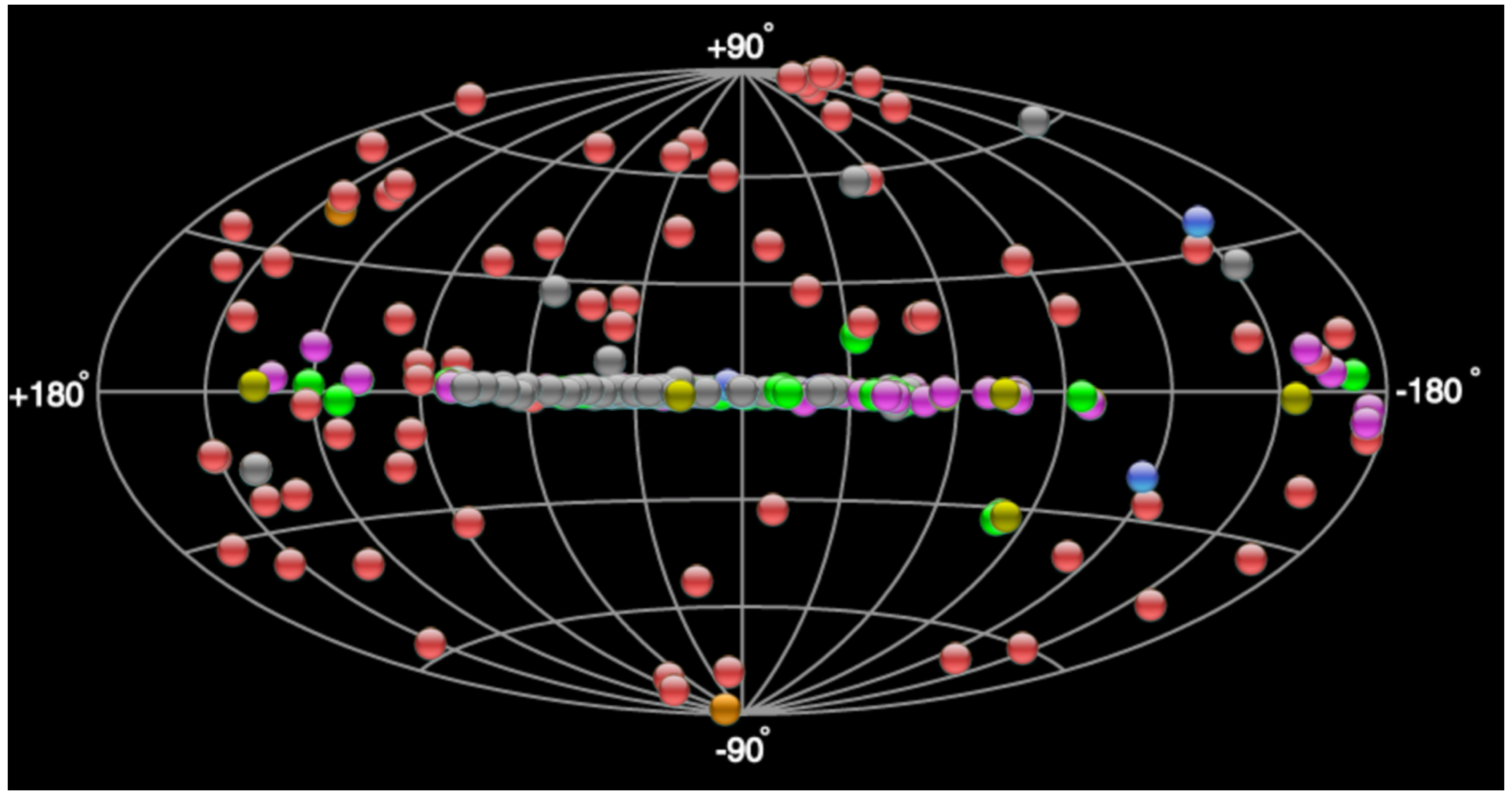


Fermi Large Area Telescope

Today: 210 sources in TeV catalog

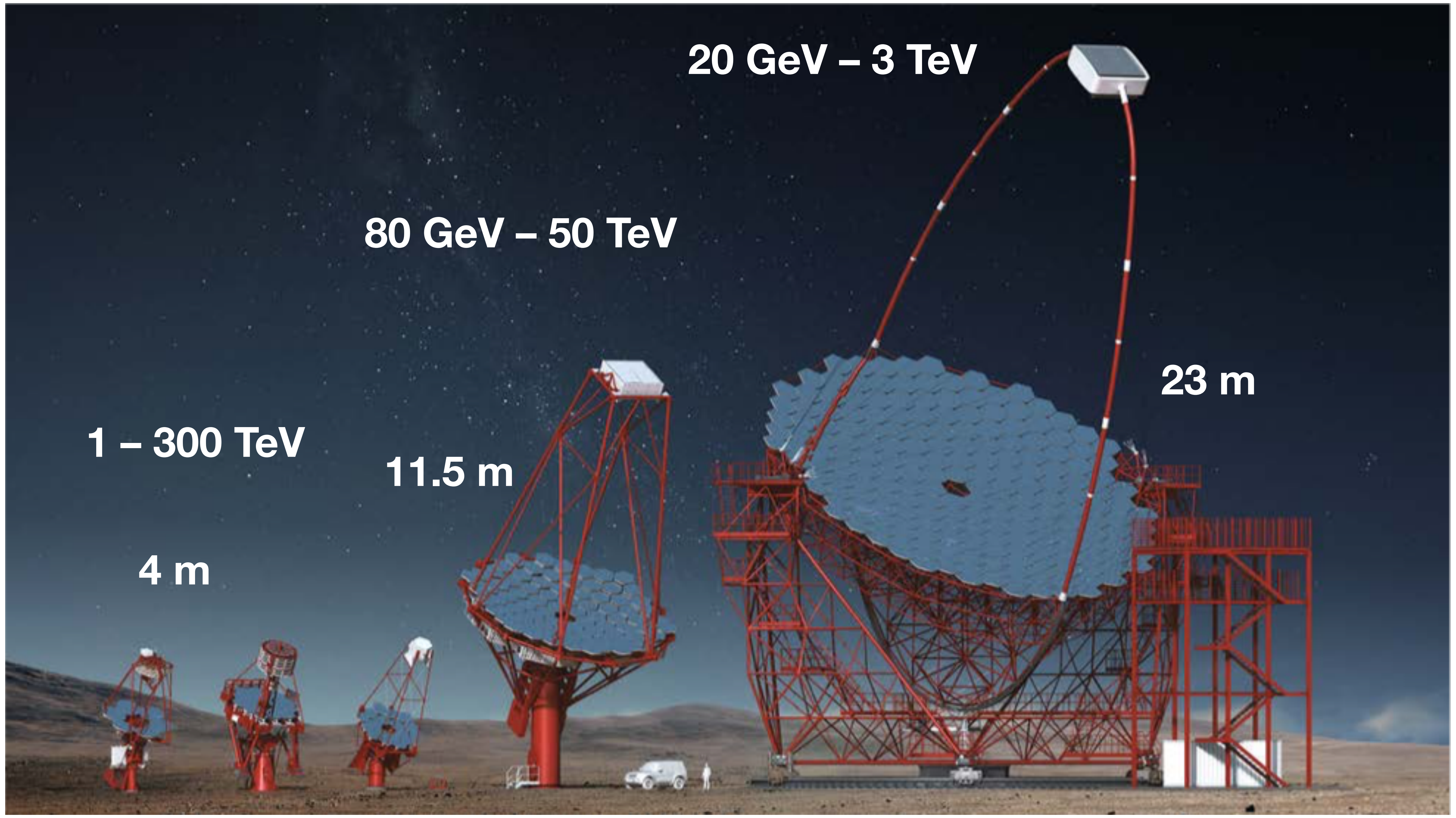
3FHL: 1556 sources in catalog






VERITAS
MAGIC
RPCs
ARGO
RPCs
LHASSO
HAWC
WCDs
HESS
Built IACT
Built Array
Planned IACT
Planned
Array
(slide by Ruben Conceição)

Cherenkov Telescope Array (CTA)

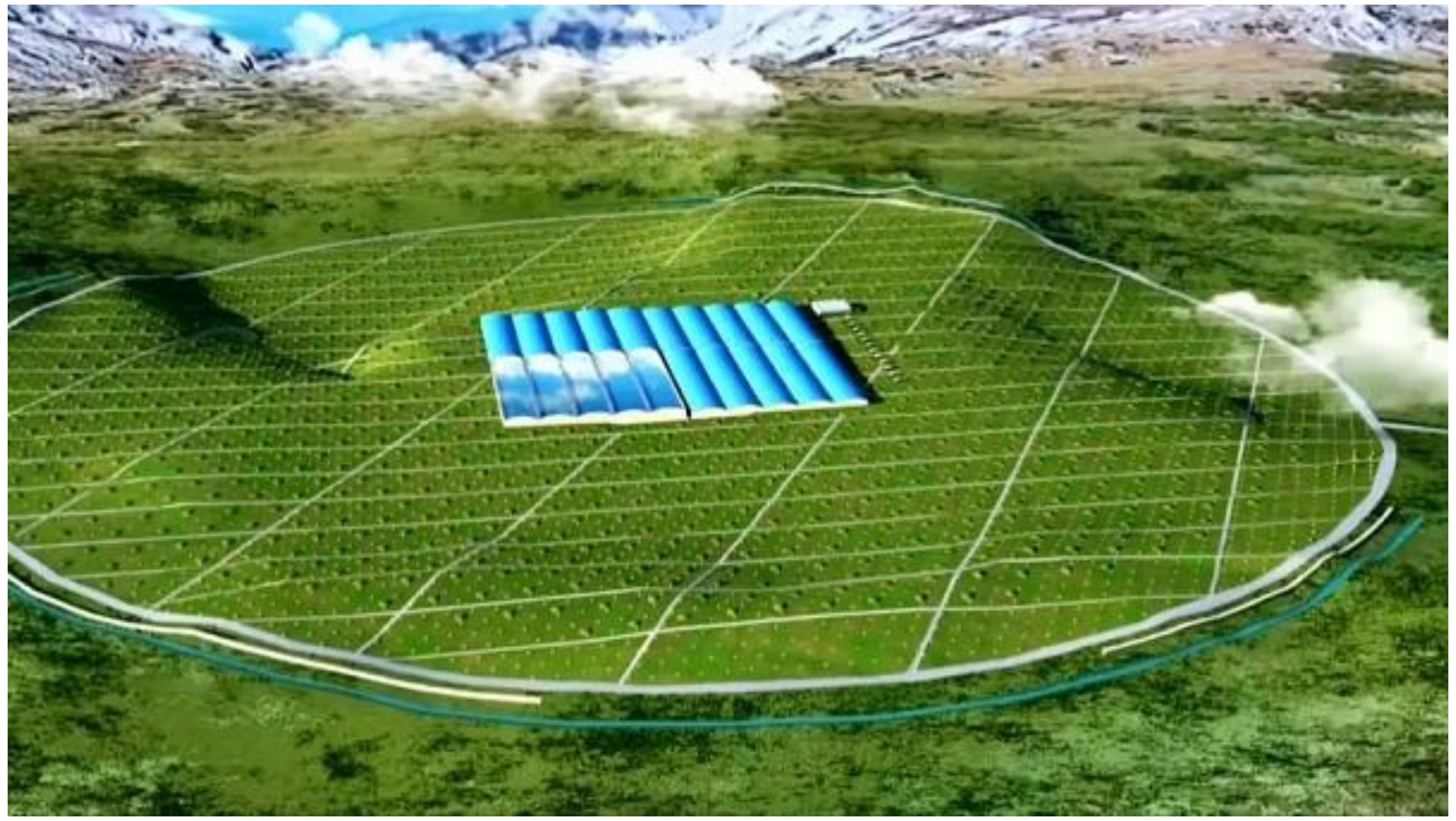


Northern site:
- 4 LST
- 15 MST

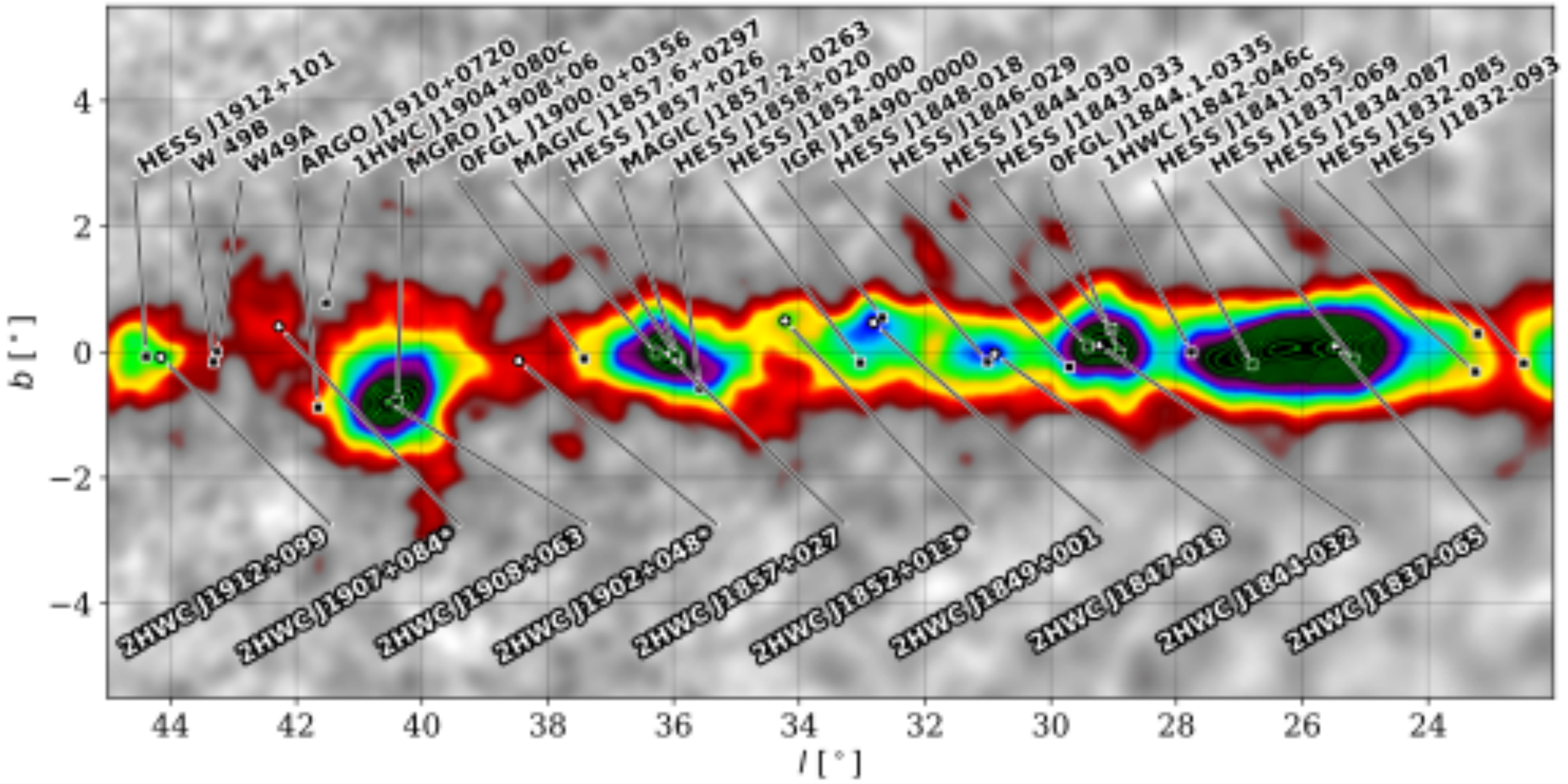
Southern site:
- 4 LST
- 25 MST
- 70 SST

HAWC, LHAASO, Southern Gamma-Ray Observatory

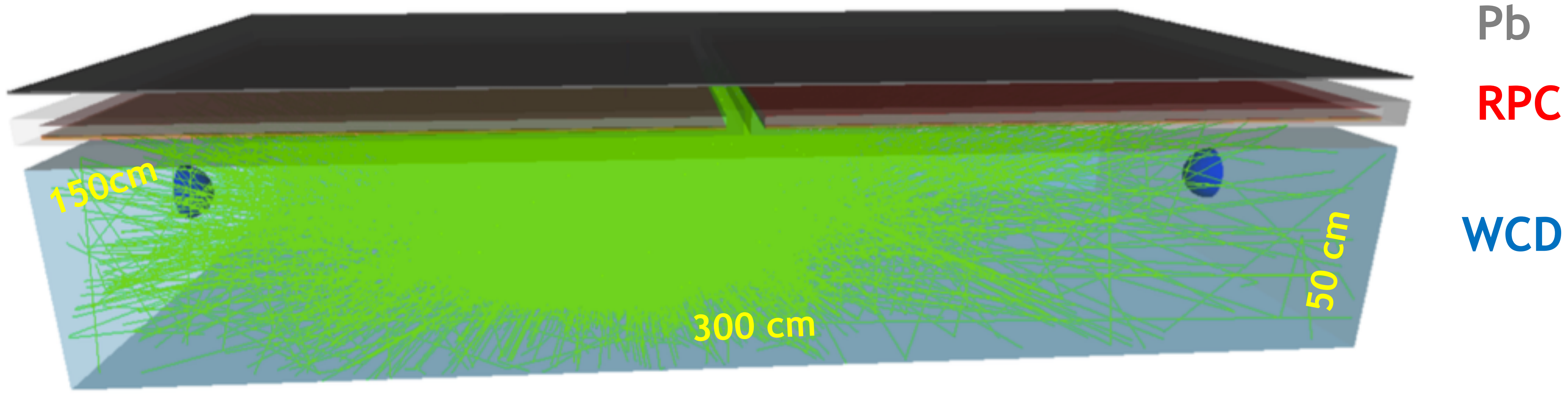
300 tanks,
5m x 7m
22 000 m^2
4100 m



LHAASO in China (under construction)



2HWC catalog 2017



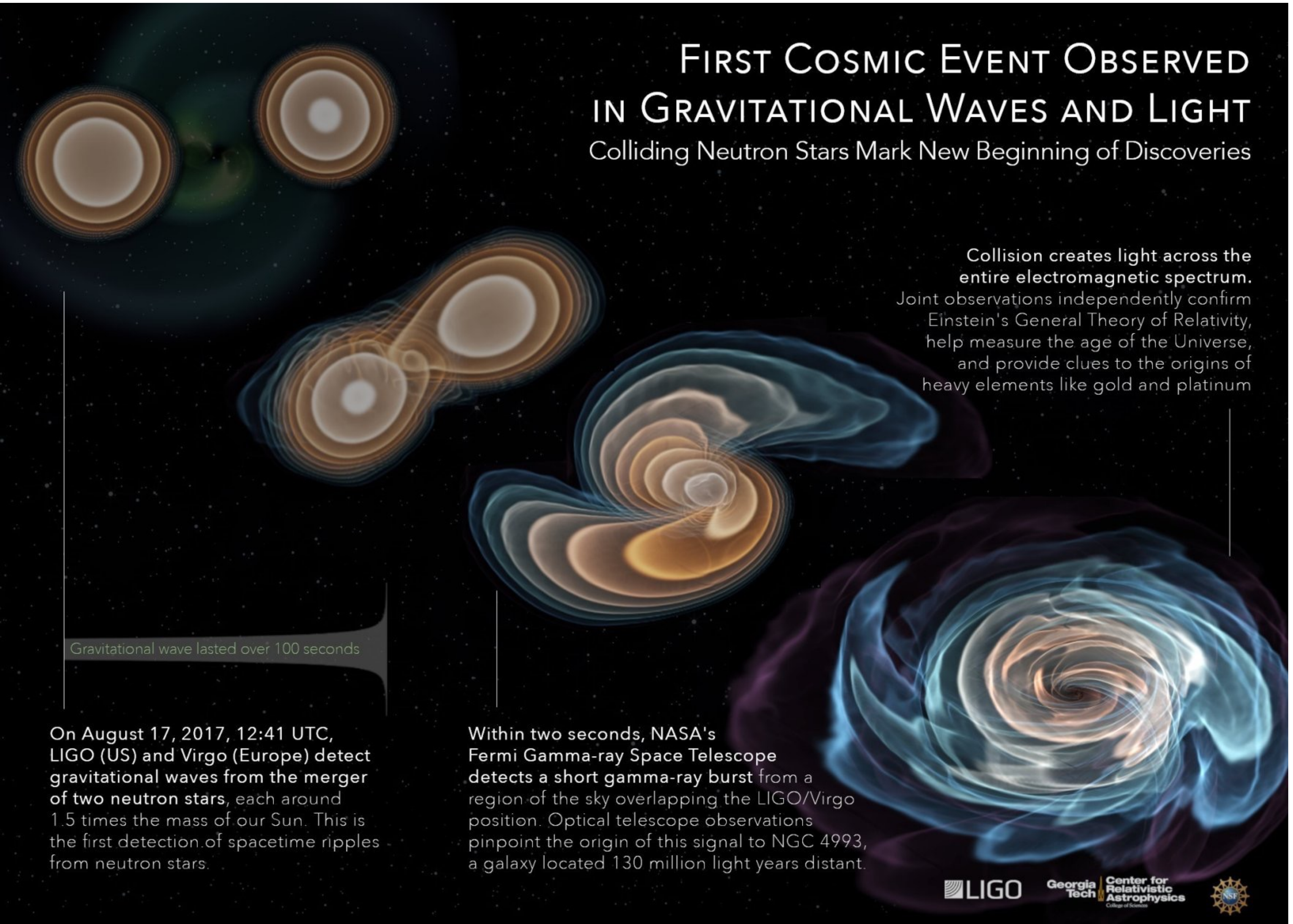
LATTES concept for southern observatory (LIP)
3600 stations (very compact)
Total area ~20 000 m^2

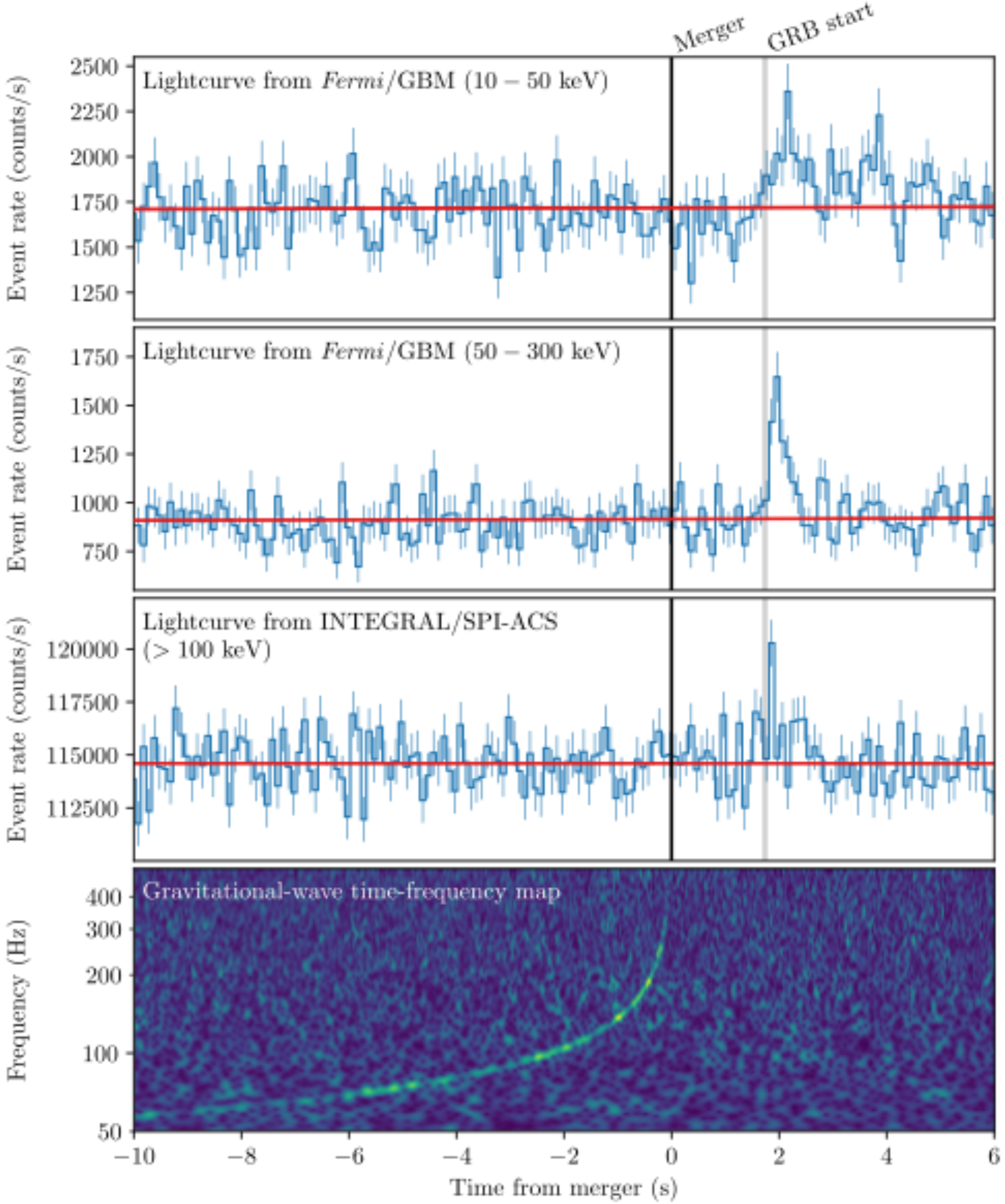
Multi-messenger astrophysics with gravitational waves

Publication 16 Oct 2017 in ApJL

70 collaborations, 953 Institutes, 3500+ Autoren

Auger: limits on neutrinos (and photons)





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

OPEN ACCESS

CrossMark

Multi-messenger Observations of a Binary Neutron Star Merger

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

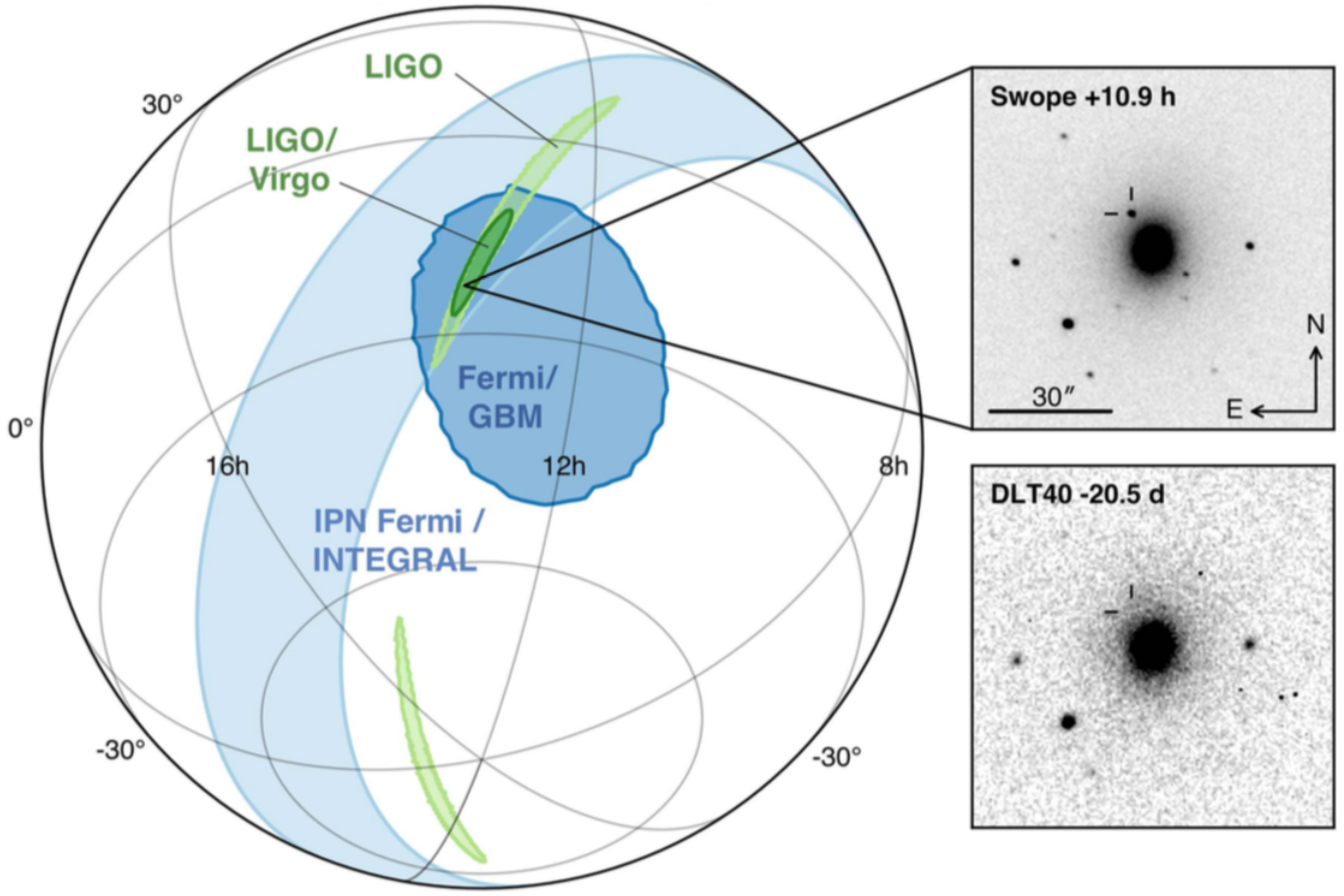
Received 2017 October 3; revised 2017 October 6; accepted 2017 October 6; published 2017 October 16

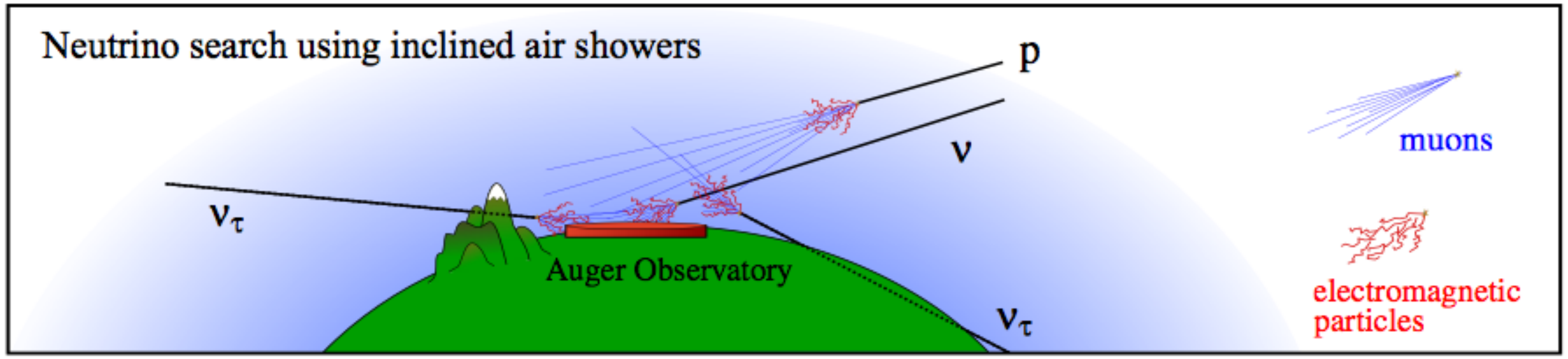
Abstract

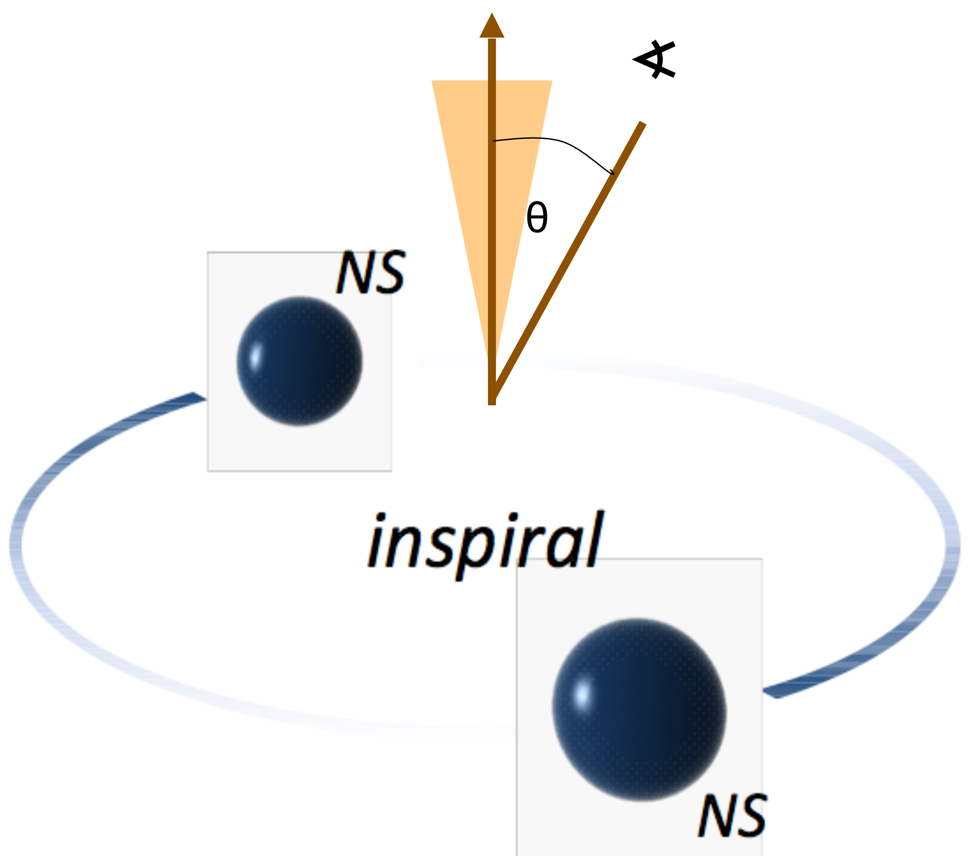
On 2017 August 17 a binary neutron star coalescence candidate (later designated GW170817) with merger time 12:41:04 UTC was observed through gravitational waves by the Advanced LIGO and Advanced Virgo detectors. The *Fermi* Gamma-ray Burst Monitor independently detected a gamma-ray burst (GRB 170817A) with a time delay of $\sim$1.7 s with respect to the merger time. From the gravitational-wave signal, the source was initially localized to a sky region of 31 deg^2 at a luminosity distance of 40^{+8}_{-8} Mpc and with component masses consistent with neutron stars. The component masses were later measured to be in the range 0.86 to 2.26 $M_\odot$. An extensive observing campaign was launched across the electromagnetic spectrum leading to the discovery of a bright optical transient (SSS17a, now with

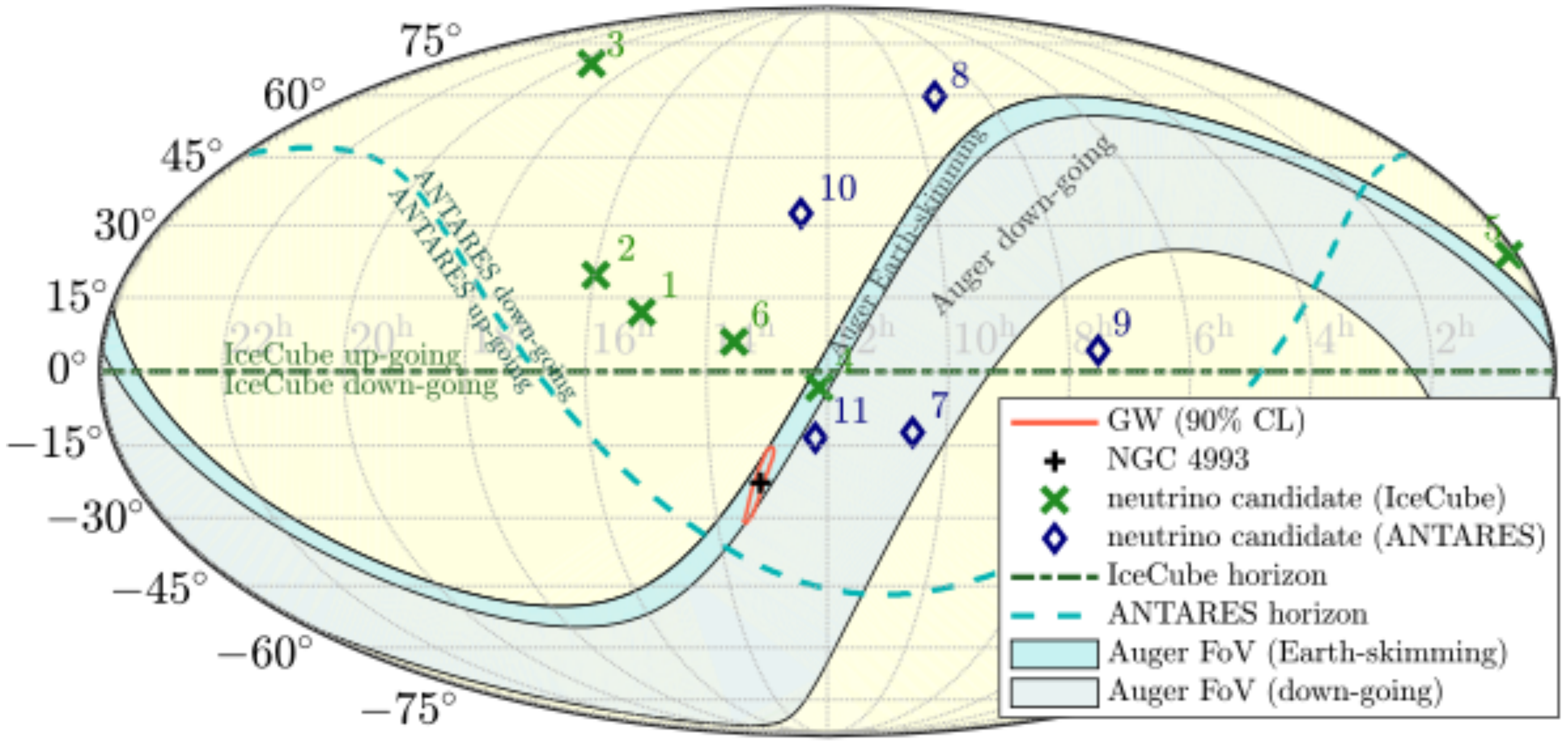
physicsworld TOP 10 BREAKTHROUGH 2017

GW170817: Neutrino flux limits by Auger Observatory

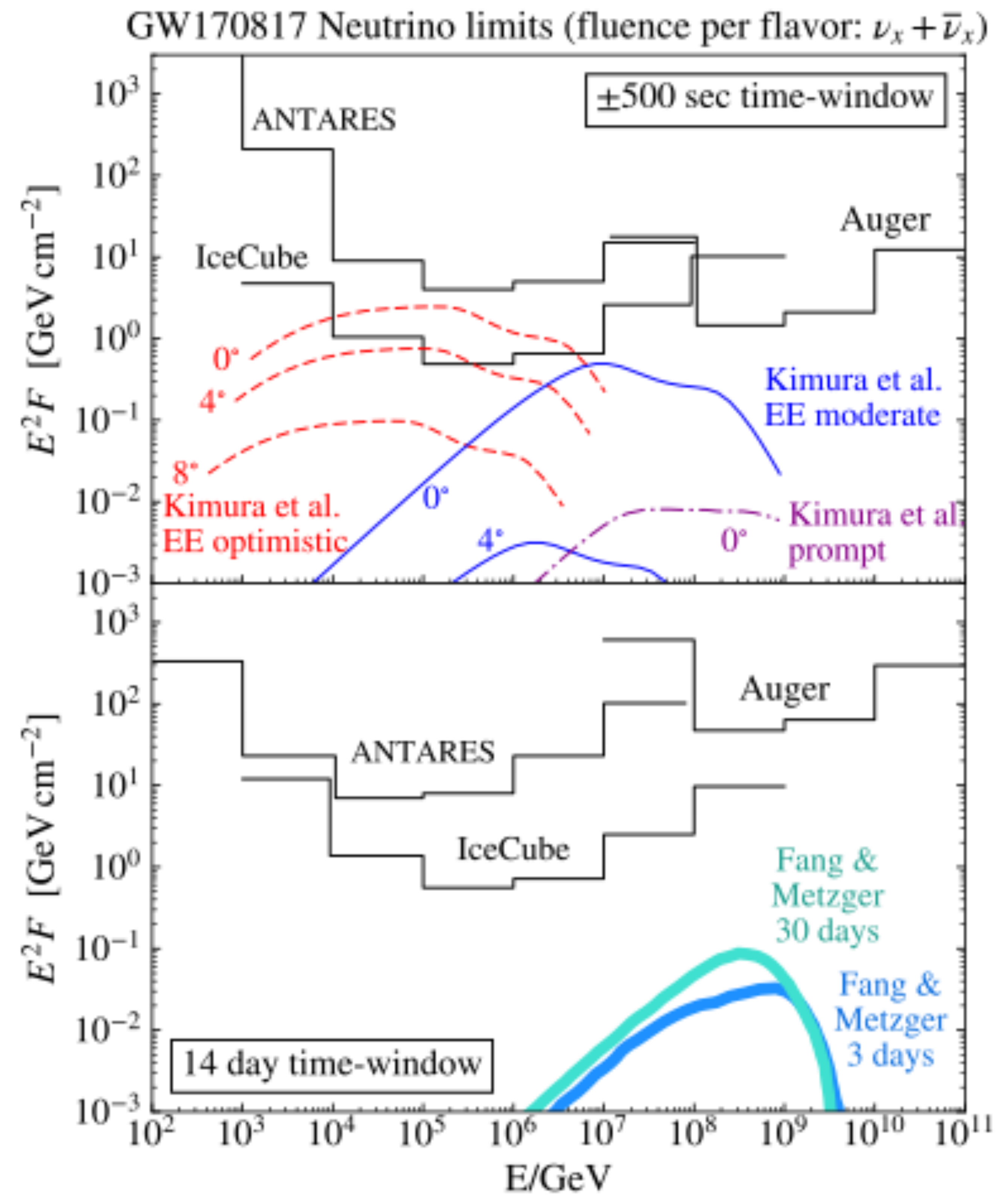






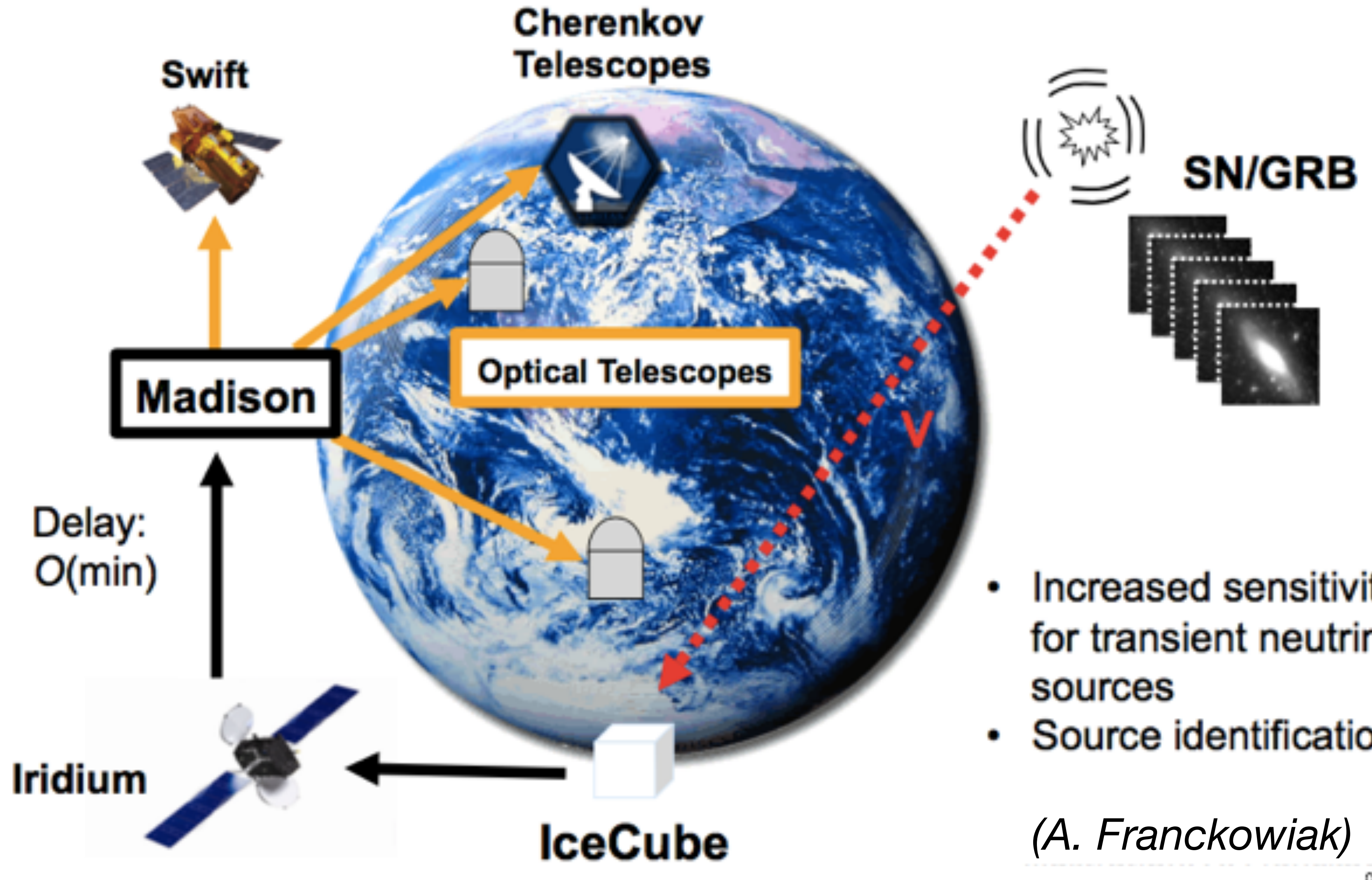


Data of all relevant detectors, including Auger



ApJL (2017), special issue (70 collaborations)

First source of astrophysical neutrinos at high energy?

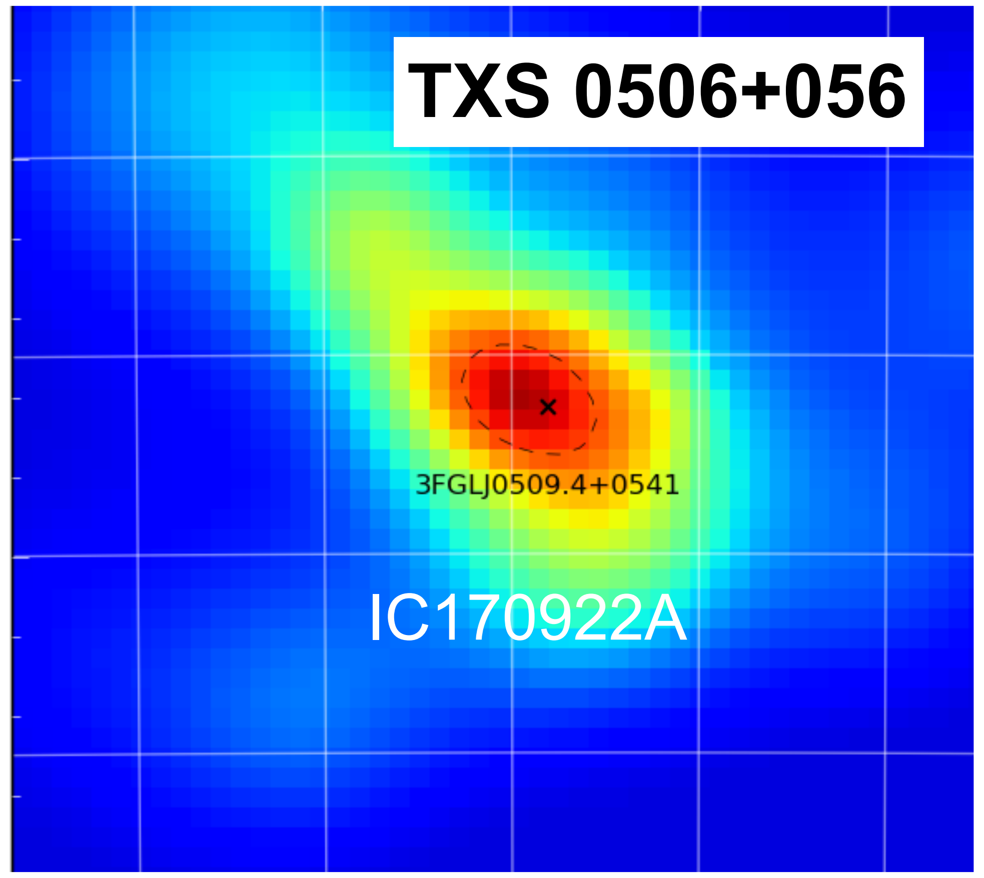


- Increased sensitivity for transient neutrino sources
- Source identification

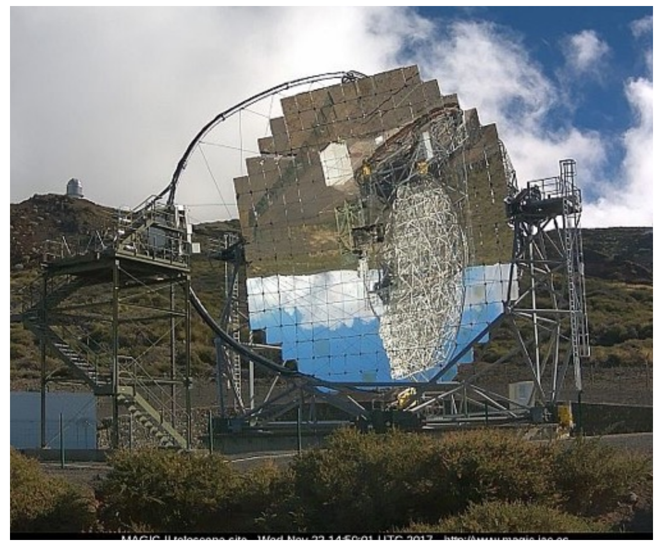
(A. Franckowiak)

09.05.18, 13:33

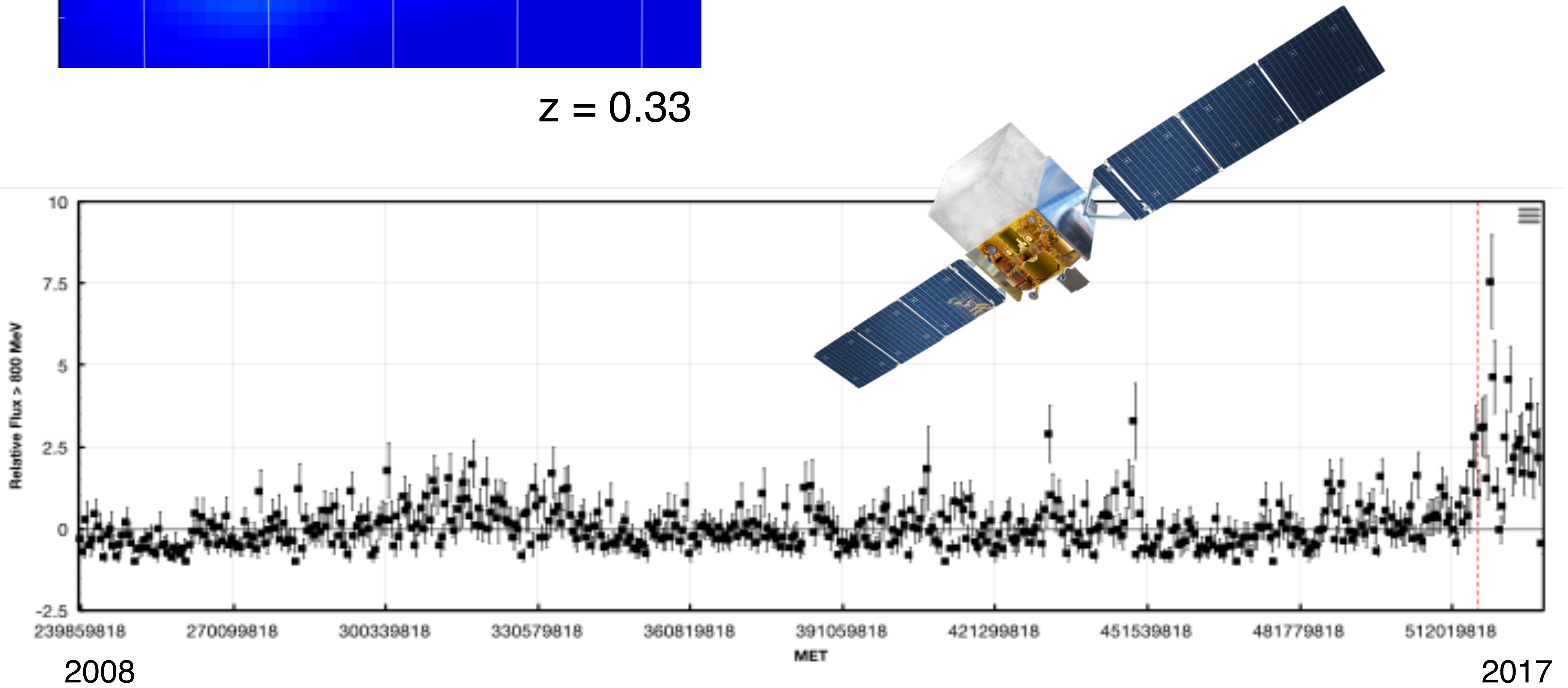
```
TITLE:   GCN CIRCULAR
NUMBER:  21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy neutrino candidate event
DATE:    17/09/23 01:09:26 GMT
FROM:    Erik Blaufuss at U. Maryland/IceCube  <blaufuss@icecube.umd.edu>

Claudio Kopper (University of Alberta) and Erik Blaufuss (University of  Maryland) report on
behalf of the IceCube Collaboration (http://icecube.wisc.edu/).

On 22 Sep, 2017 IceCube detected a track-like, very-high-energy event with a high probability
of being of astrophysical origin. The event was identified by the  Extremely High Energy
(EHE) track event selection. The IceCube detector was in a normal operating state. EHE events
typically have a neutrino interaction vertex that is outside the detector, produce a muon
that traverses the detector volume, and have a high light level (a proxy for energy).

After the initial automated alert
(https://gcn.gsfc.nasa.gov/notices_amon/50579430_130033.amon), more
sophisticated reconstruction algorithms have been applied offline, with the direction refined
to:

Date: 22 Sep, 2017
Time: 20:54:30.43 UTC
RA: 77.43 deg (-0.80 deg/+1.30 deg  90% PSF containment) J2000
Dec: 5.72 deg (-0.40 deg/+0.70 deg 90% PSF containment) J2000

We encourage follow-up by ground and space-based instruments to help identify a possible
astrophysical source for the candidate neutrino.
```



z = 0.33



MAGIC: flare E > 100 GeV



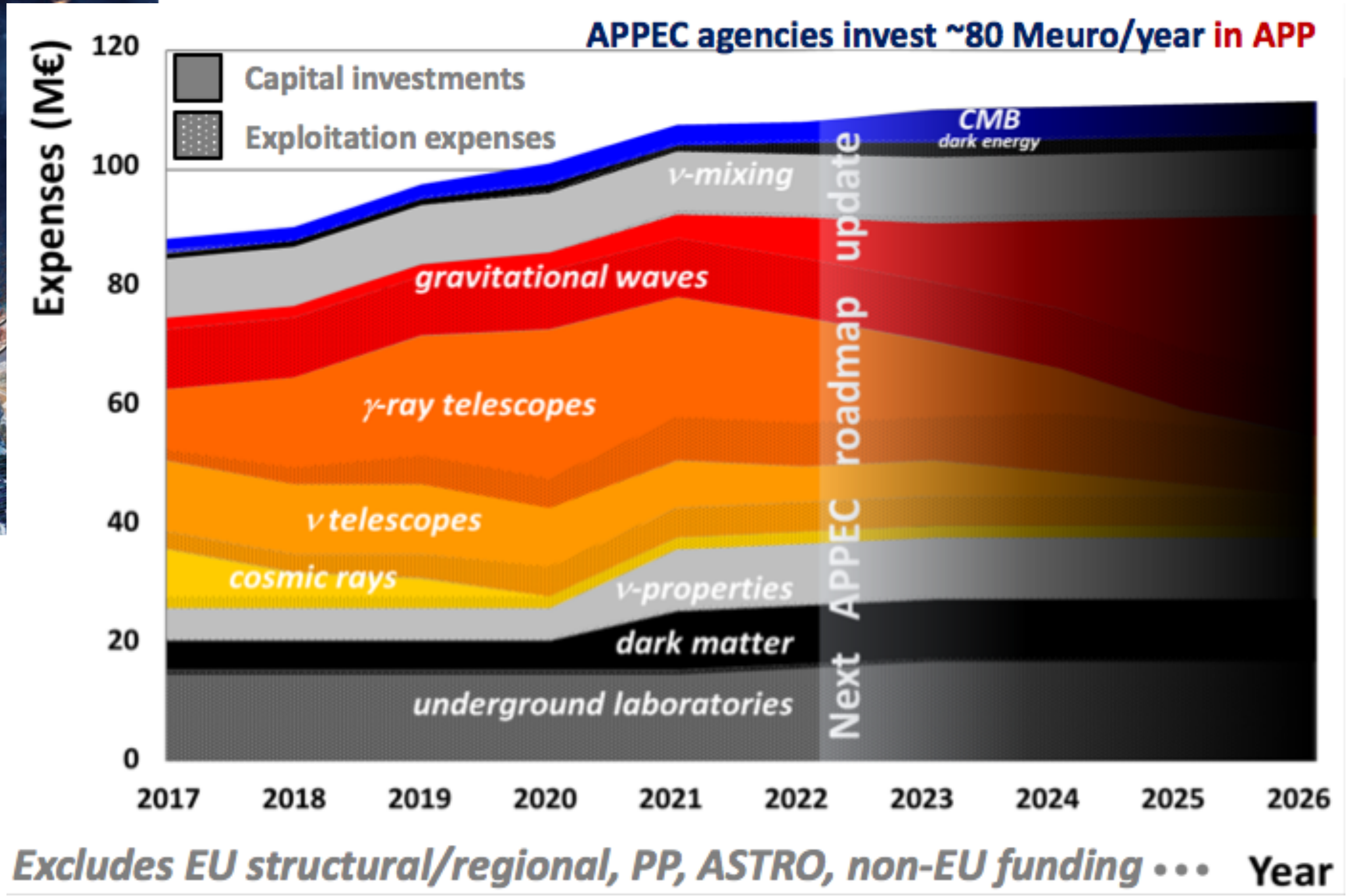
FERMI: flare (found 6 days later)

IceCube 1709922A, publications in preparation

APPEC Roadmap for Astroparticle Physics

APPEC – AstroParticle Physics European Consortium

Roadmap, Brussels, Jan 2018



Very rapid progress in understanding

Largely driven by observations

Actively observed messengers

- Cosmic rays
- Gamma rays
- Neutrinos
- Gravitational waves

Multi-messenger physics of transient phenomena is the next step

Powerful detectors for all messenger particle needed to optimally use scientific and financial investment