

# POEMMA & EUISO-SPB SPACE PROBES OF THE HIGHEST ENERGY PARTICLES

Proton

Photon

Neutrino

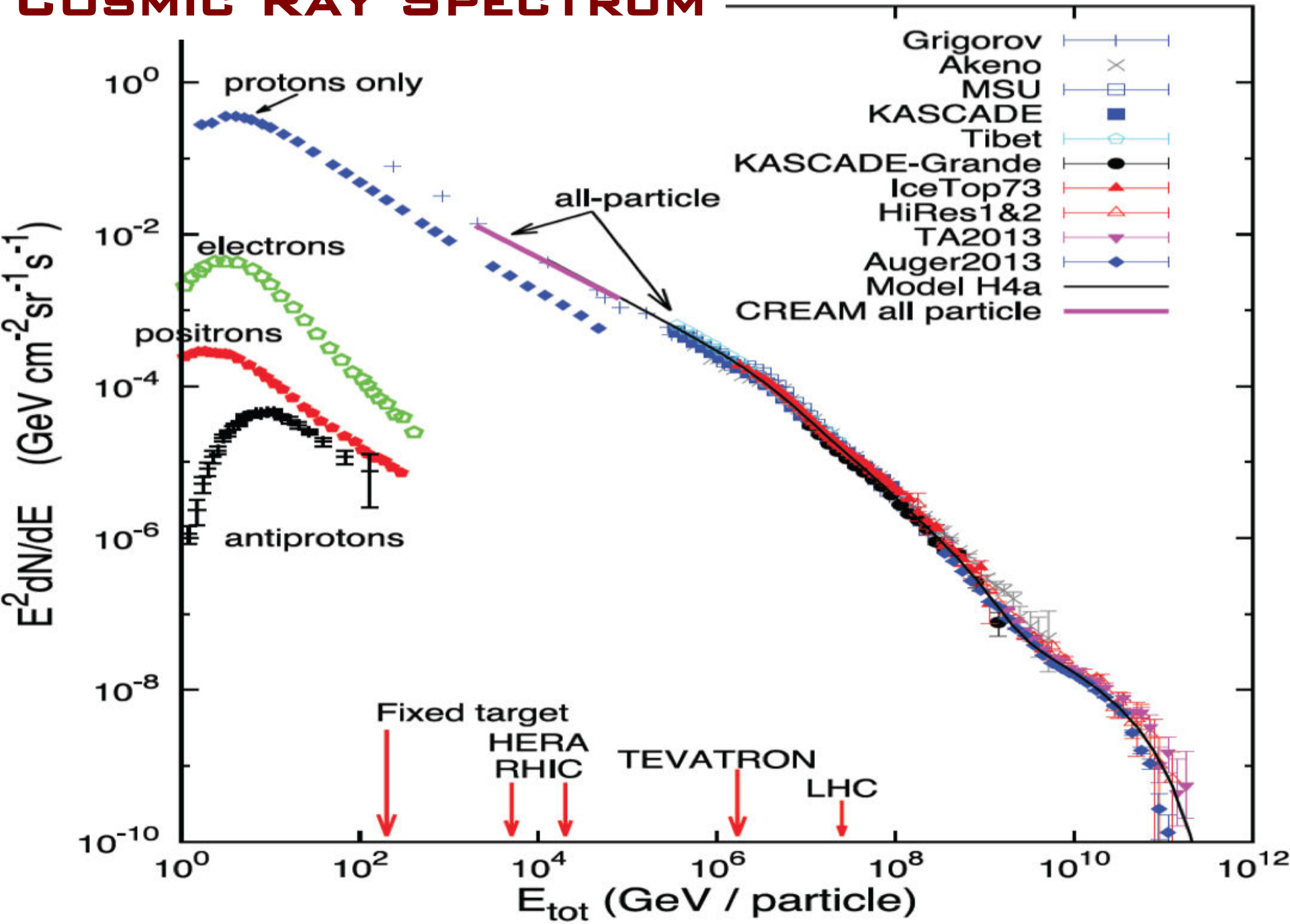
VULCANO 2018

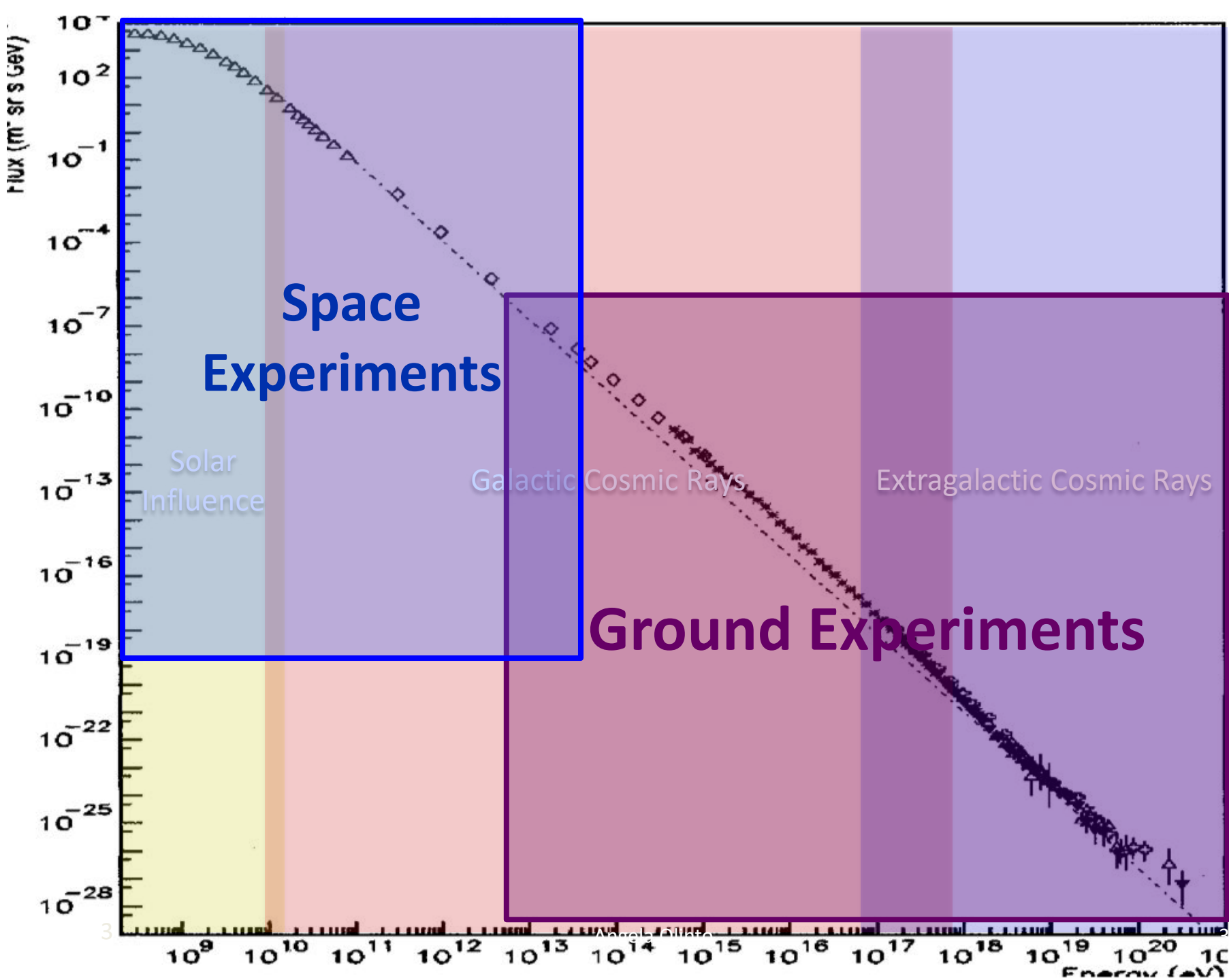
ANGELA V. OLINTO

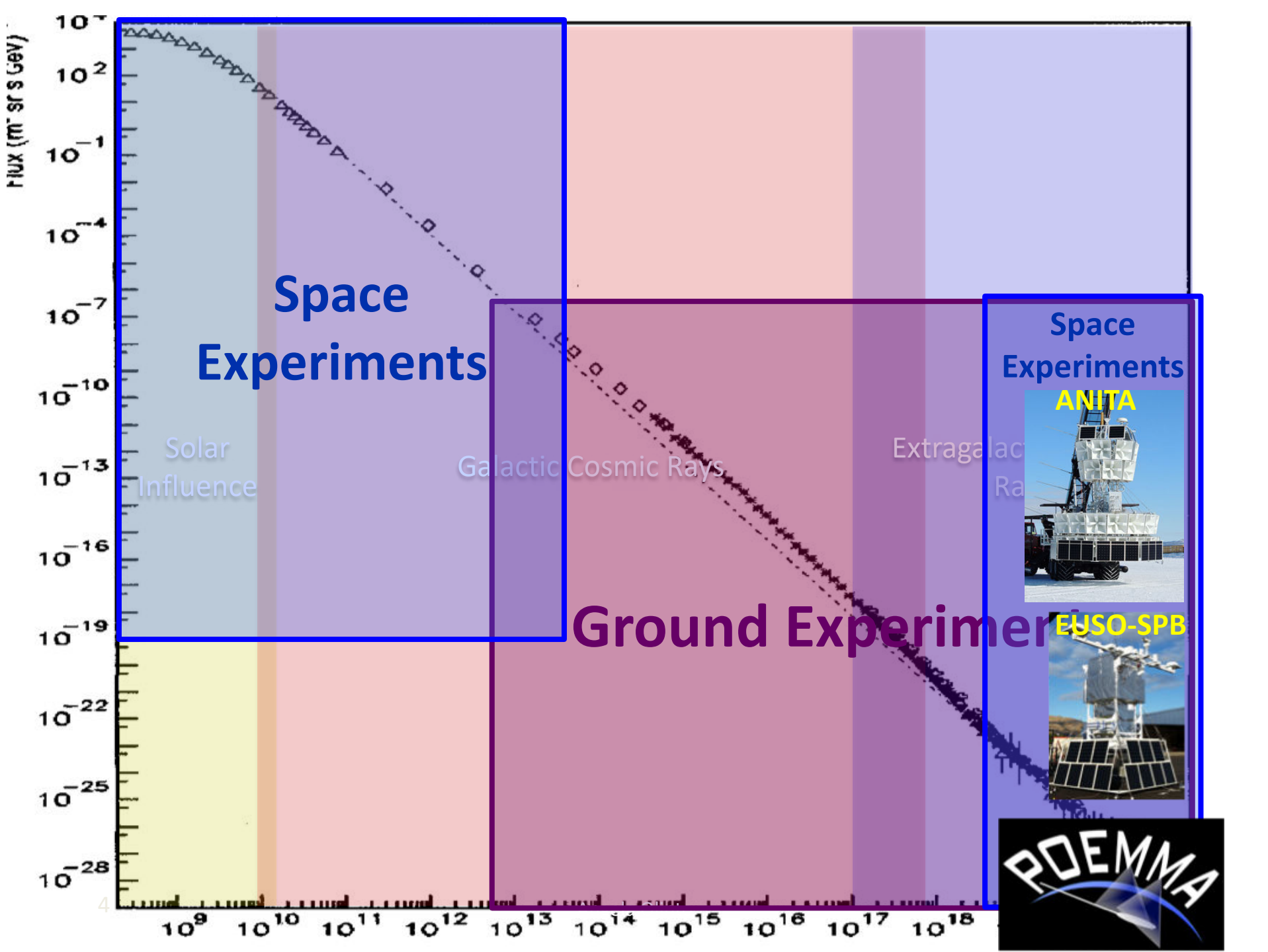


THE UNIVERSITY OF  
CHICAGO

# COSMIC RAY SPECTRUM

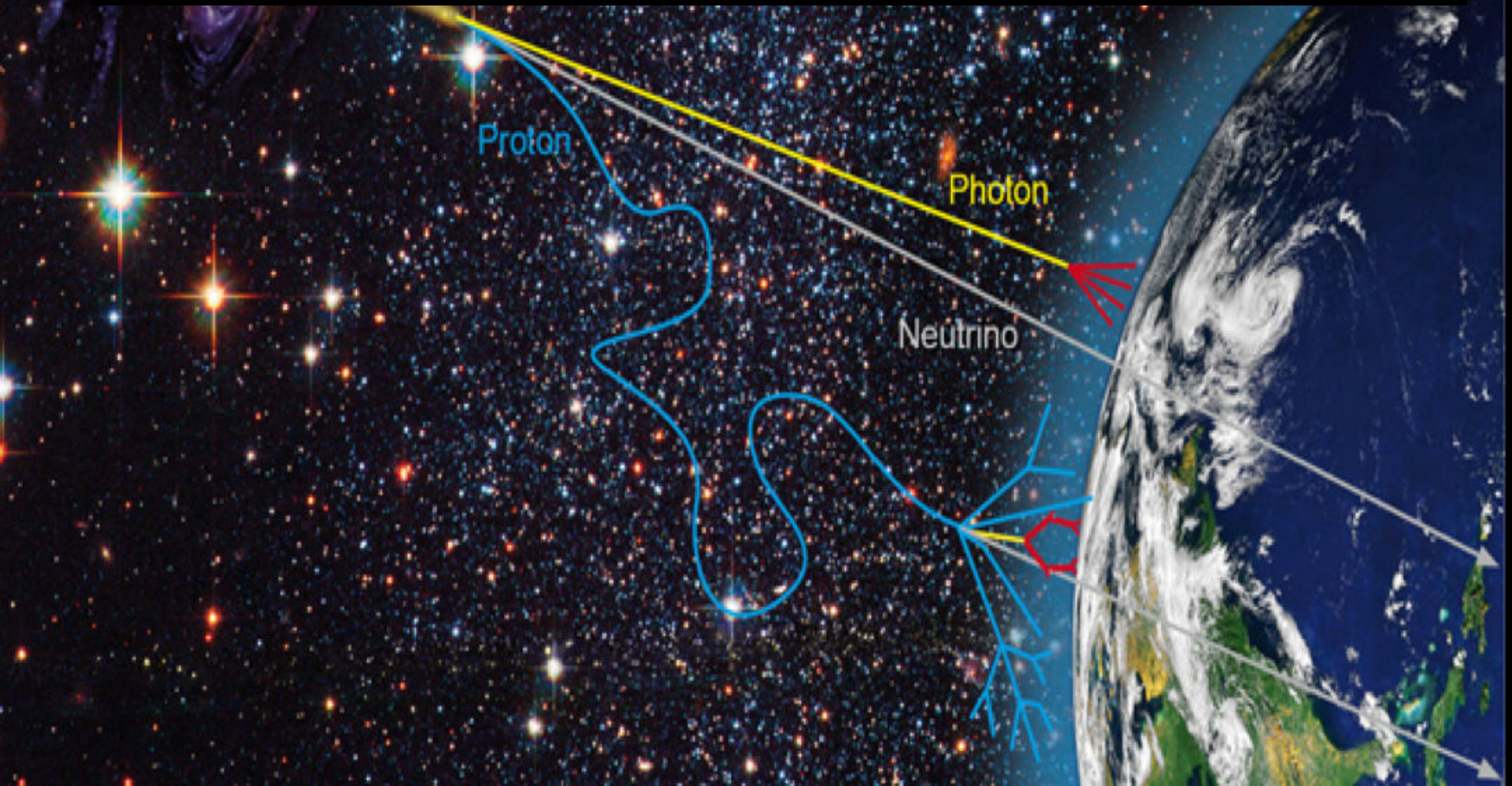






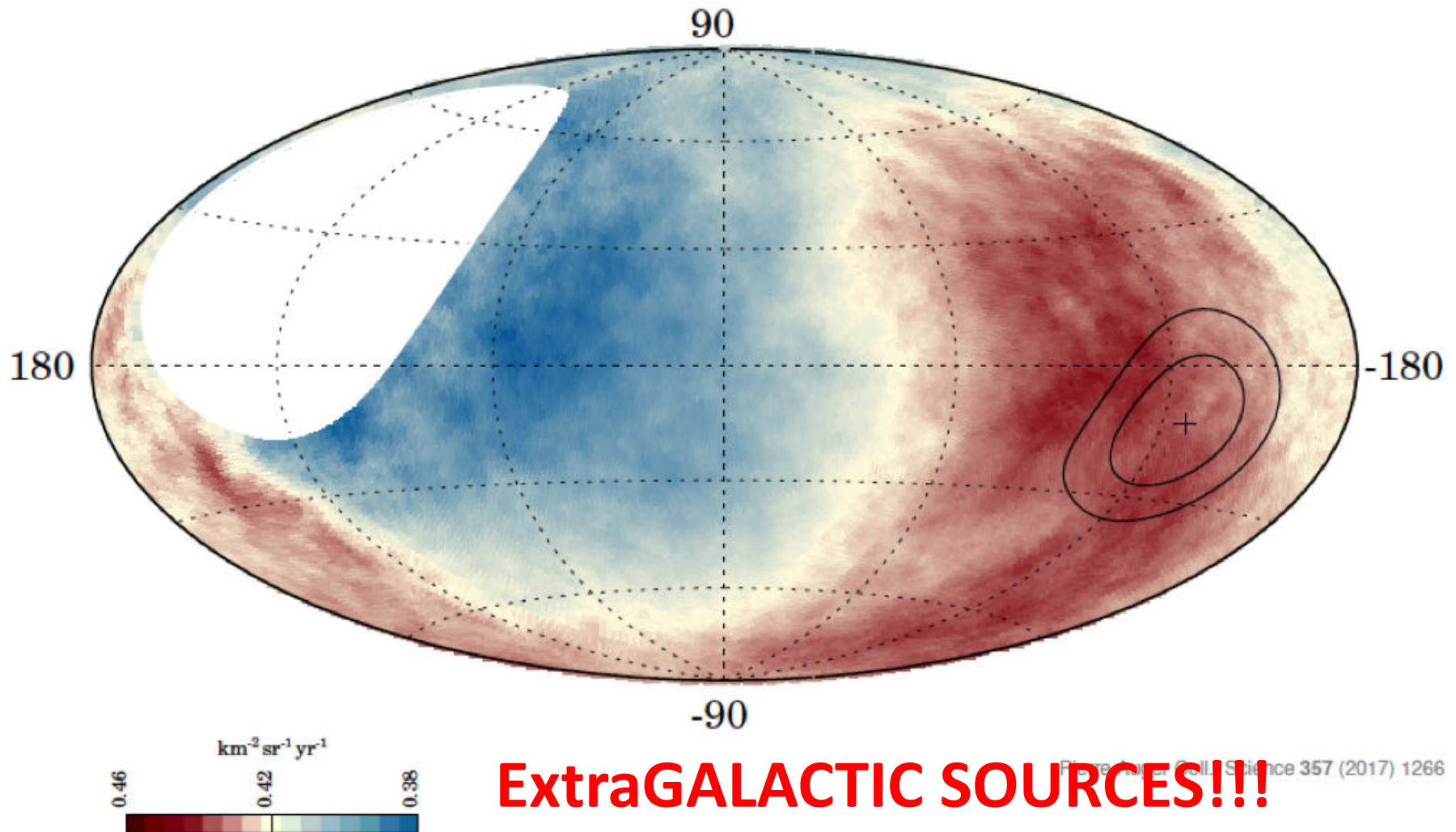
2010s

# WHAT ARE THE SOURCES OF THE HIGHEST ENERGY COSMIC RAYS ?



Dipole Above 8 EeV =  $5.2\sigma$ !!

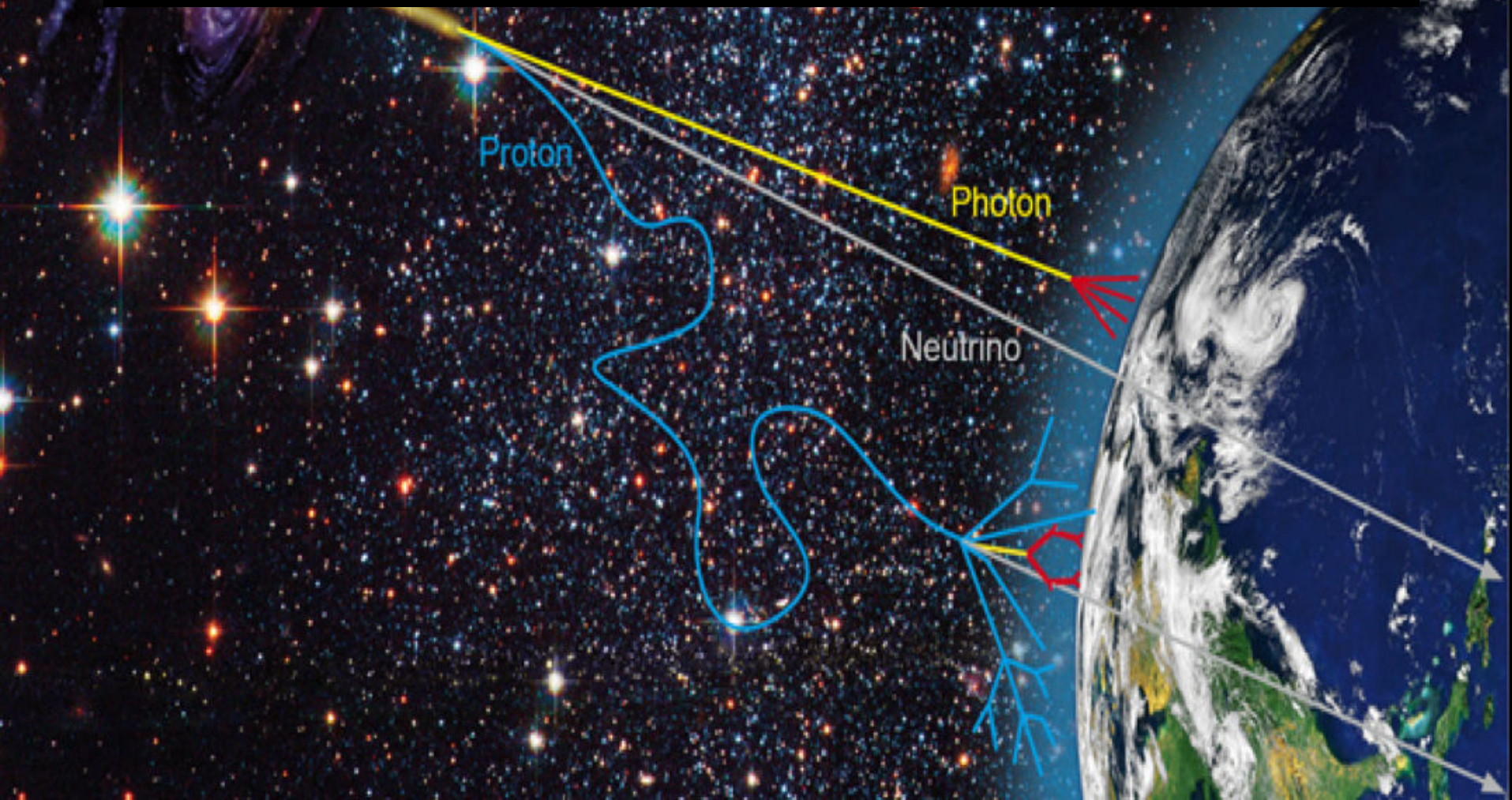
Auger Large-scale Anisotropy ( $E > 8$  EeV,  $(6.5^{+1.3}_{-0.9})\%$ ,  $5.2 \sigma$ )



**ExtraGALACTIC SOURCES!!!**

2020s

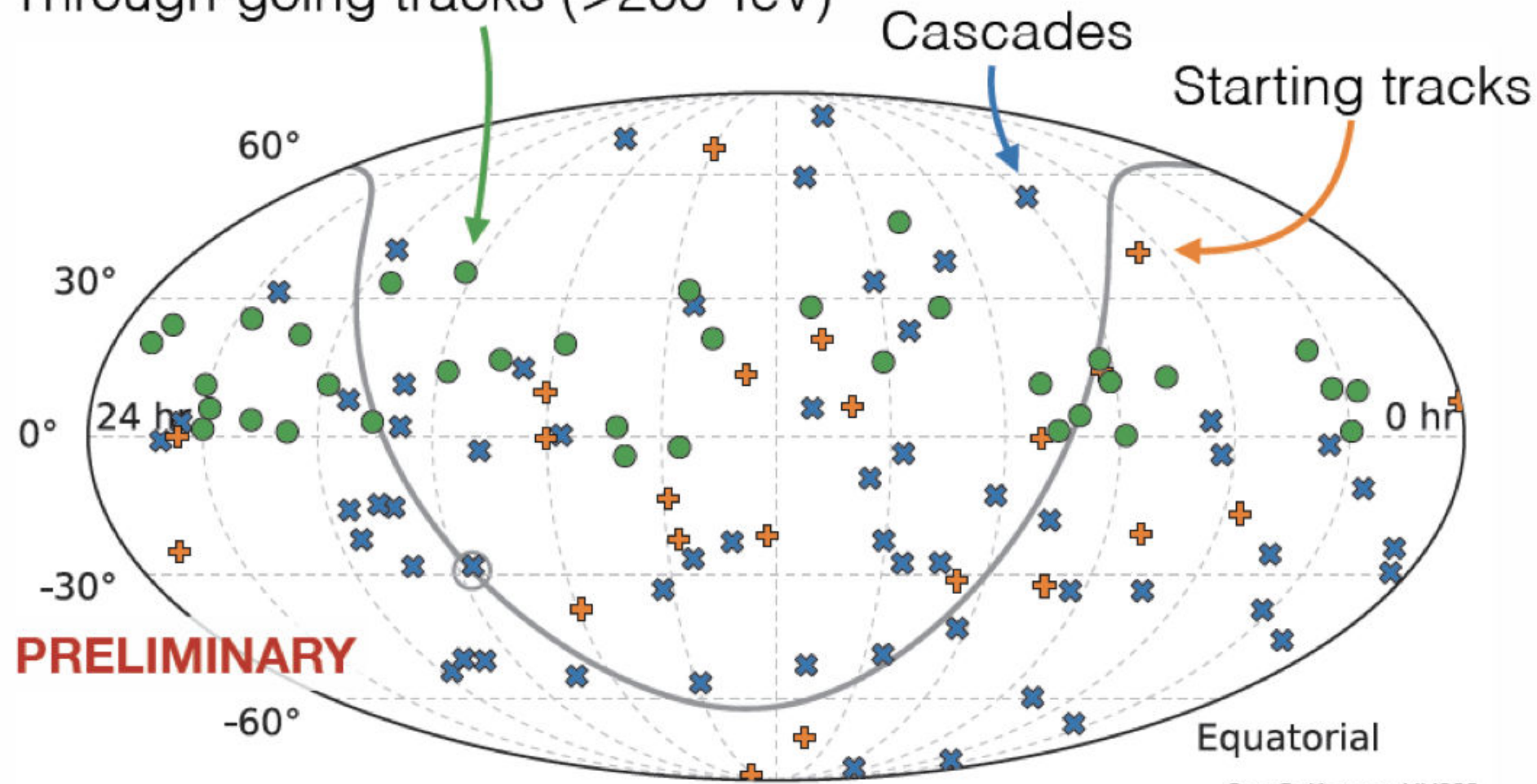
# WHAT ARE THE SOURCES OF THE **EXTRAGALACTIC** COSMIC RAYS ?







## Through-going tracks (>200 TeV)



No evidence of clustering in high-energy neutrino directions (> 50% astrophysical).

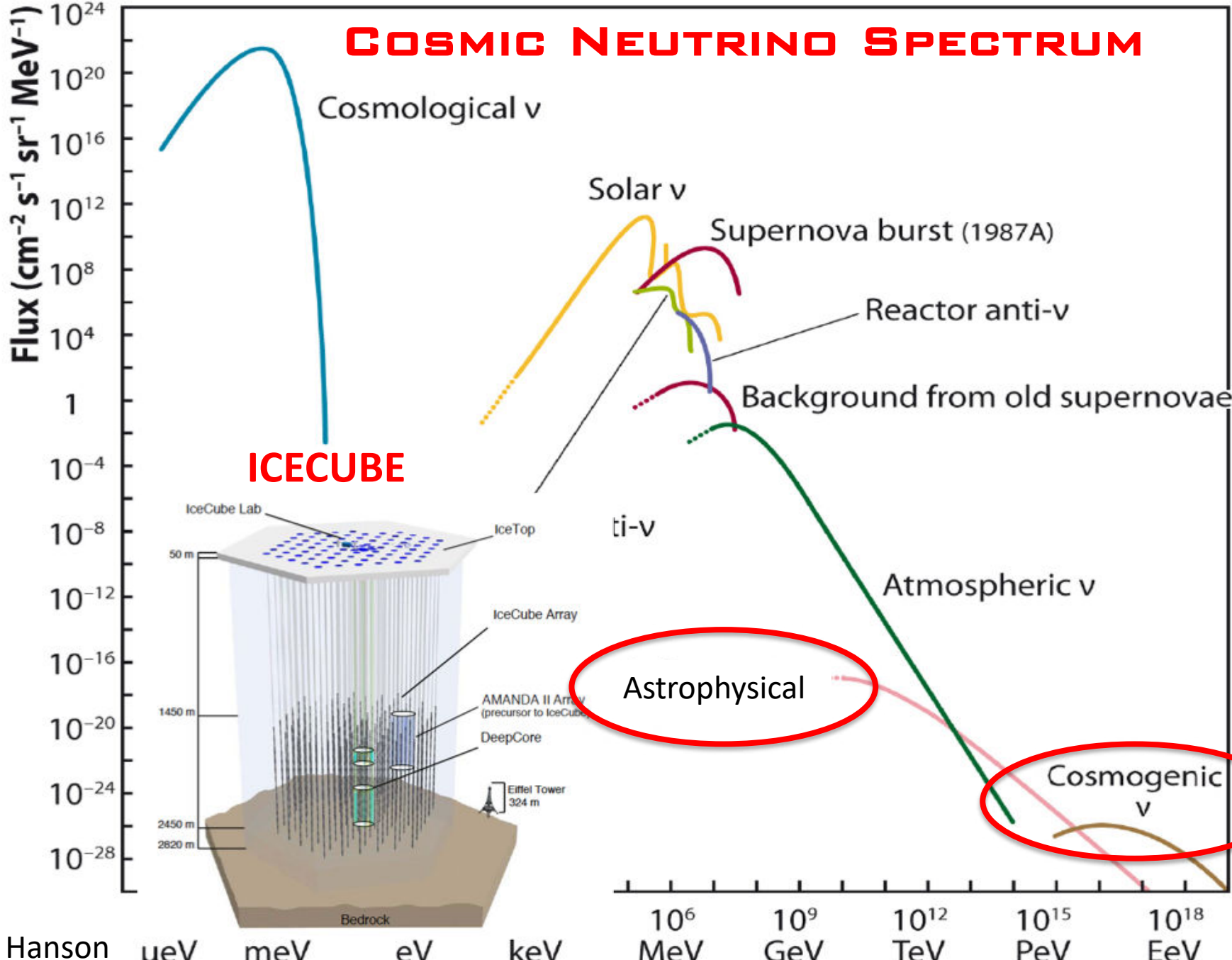
2020s

WHAT ARE THE SOURCES OF THE  
**EXTRAGALACTIC** COSMIC RAYS ?

WHAT ARE **ALL** THE SOURCES OF  
**ICECUBE NEUTRINOS**?

WHAT IS THE FLUX OF COSMOGENIC  
**NEUTRINOS**?

# COSMIC NEUTRINO SPECTRUM



**ICECUBE**

K. Hanson

$\mu\text{eV}$     $\text{meV}$     $\text{eV}$     $\text{keV}$     $10^6 \text{ MeV}$     $10^9 \text{ GeV}$     $10^{12} \text{ TeV}$     $10^{15} \text{ PeV}$     $10^{18} \text{ EeV}$

**Neutrino energy**

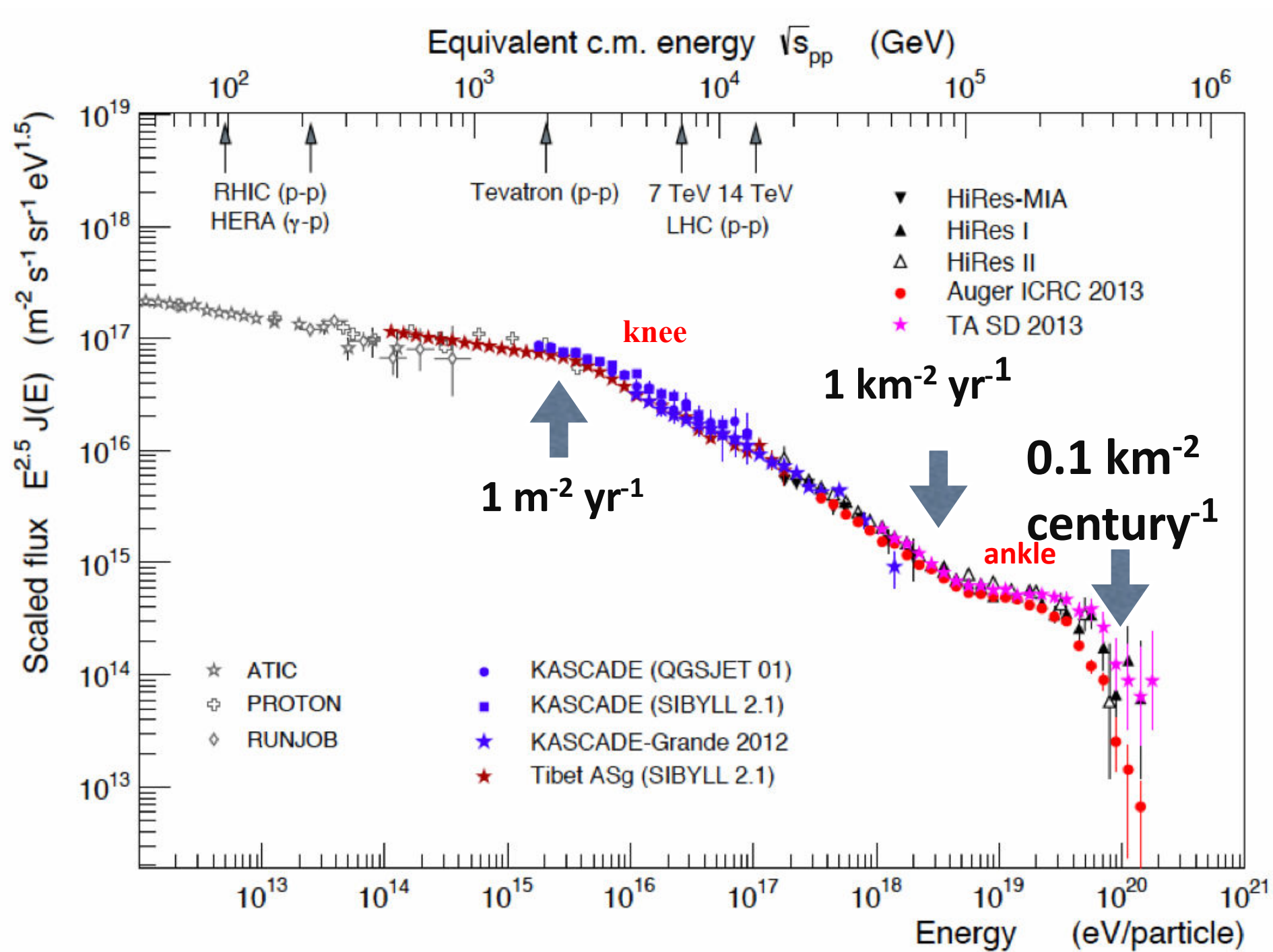
2020s

WHAT ARE THE SOURCES OF THE  
**EXTRAGALACTIC COSMIC RAYS ?**

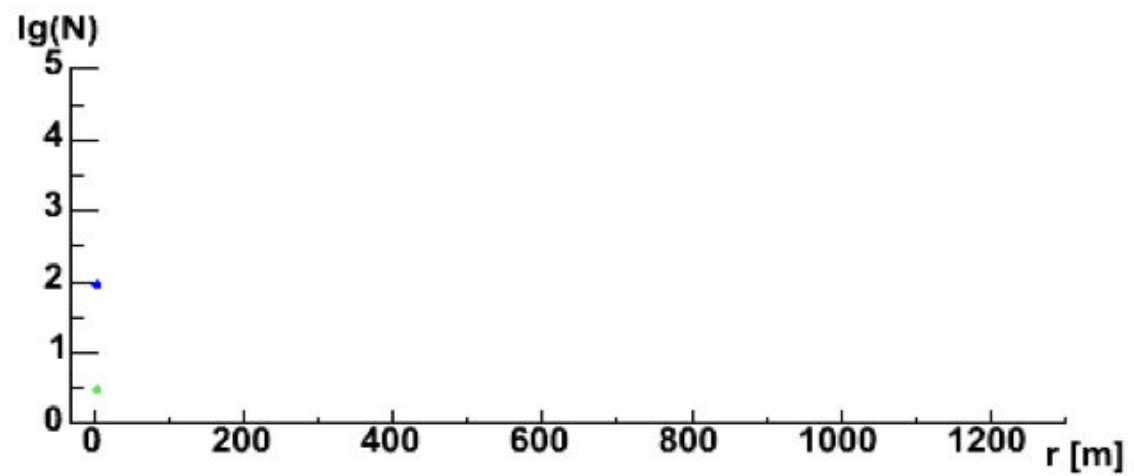
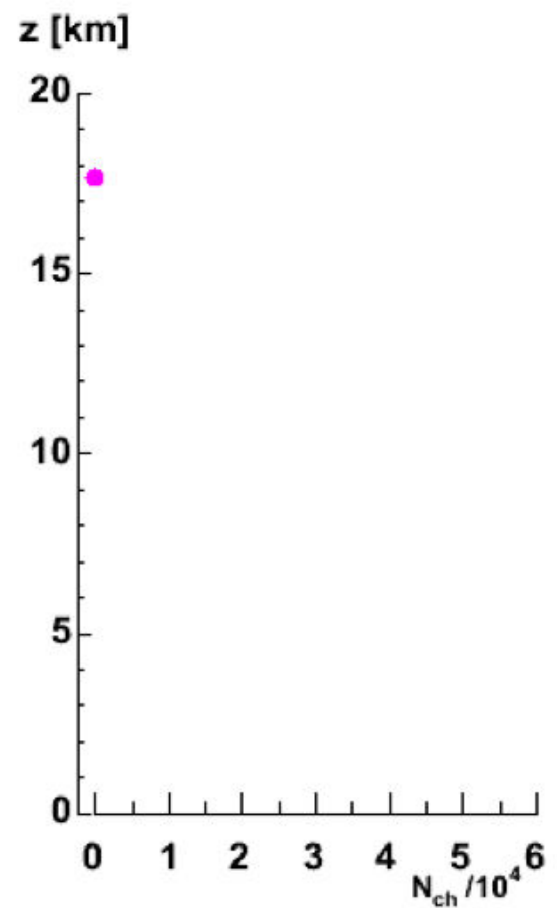
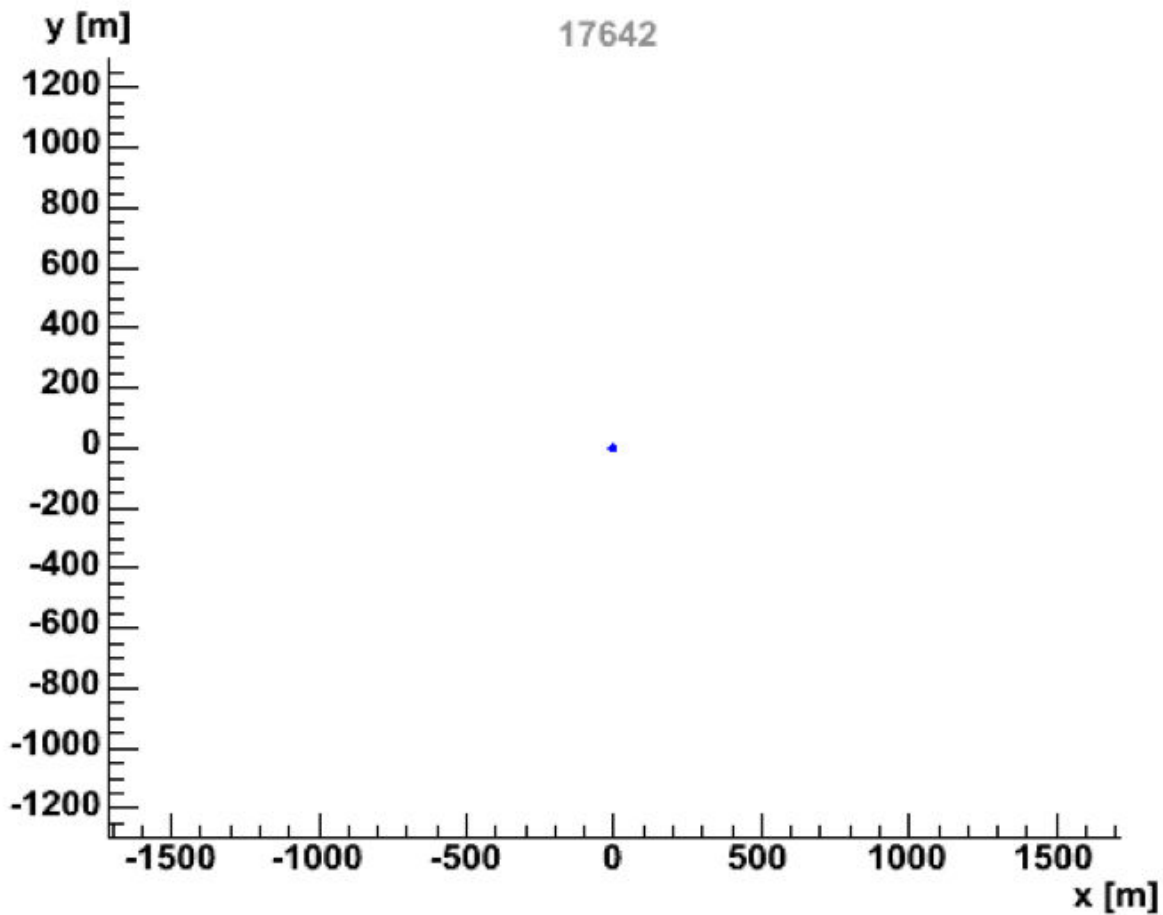
WHAT ARE **ALL** THE SOURCES OF  
**ICECUBE NEUTRINOS?**

WHAT IS THE FLUX OF COSMOGENIC  
**NEUTRINOS?**

WHAT ARE **NEUTRINO AND HADRONIC**  
**INTERACTIONS AT LARGER ENERGIES?**



17642



**Proton 10<sup>14</sup> eV**

$h^{1st} = 17642$  m

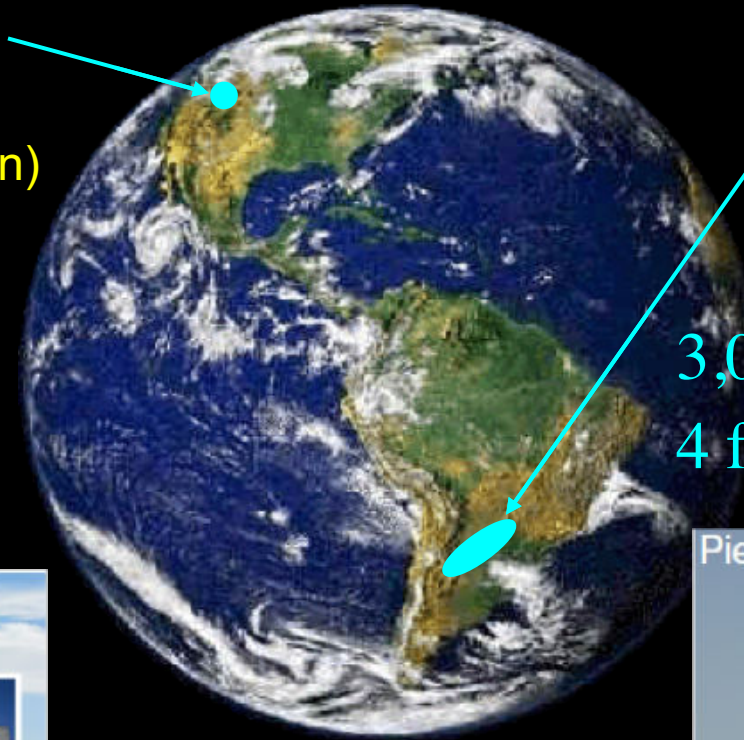
**hadrons**    **muons**  
**neutrons**   **electrs**



# Leading Observatories of Ultrahigh Energy Cosmic Rays

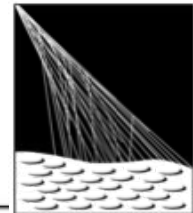


Telescope Array  
Utah, USA  
(5 country collaboration)  
700 km<sup>2</sup> array  
3 fluorescence  
telescopes

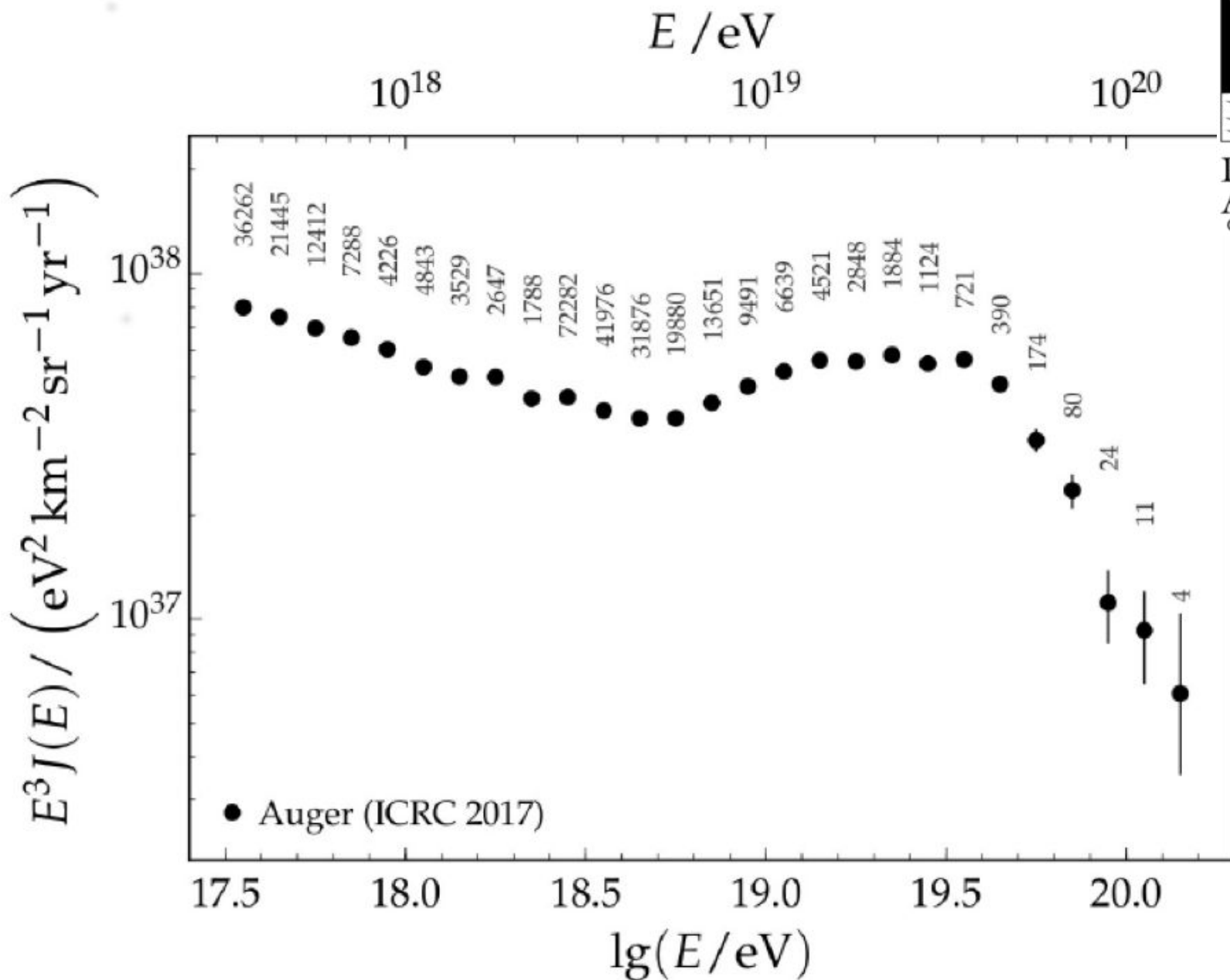


Pierre Auger  
Observatory  
Mendoza, Argentina  
(19 country collaboration)  
3,000 km<sup>2</sup> array  
4 fluorescence telescopes





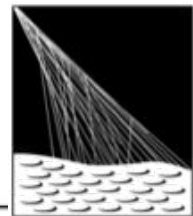
PIERRE  
AUGER  
OBSERVATORY



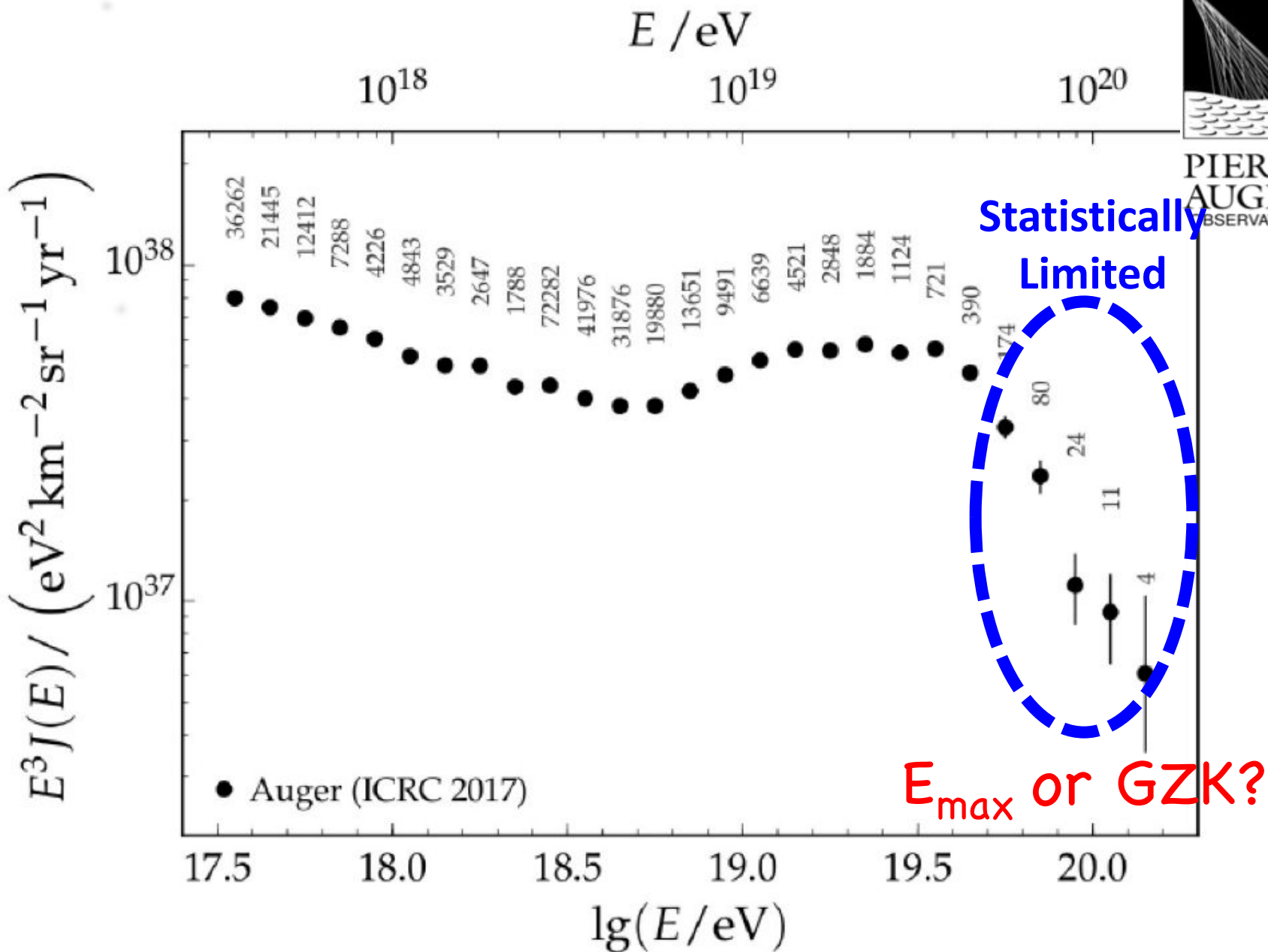
Exposure = 67000  $\text{km}^2 \text{ sr yr}$

302,000 EVENTS





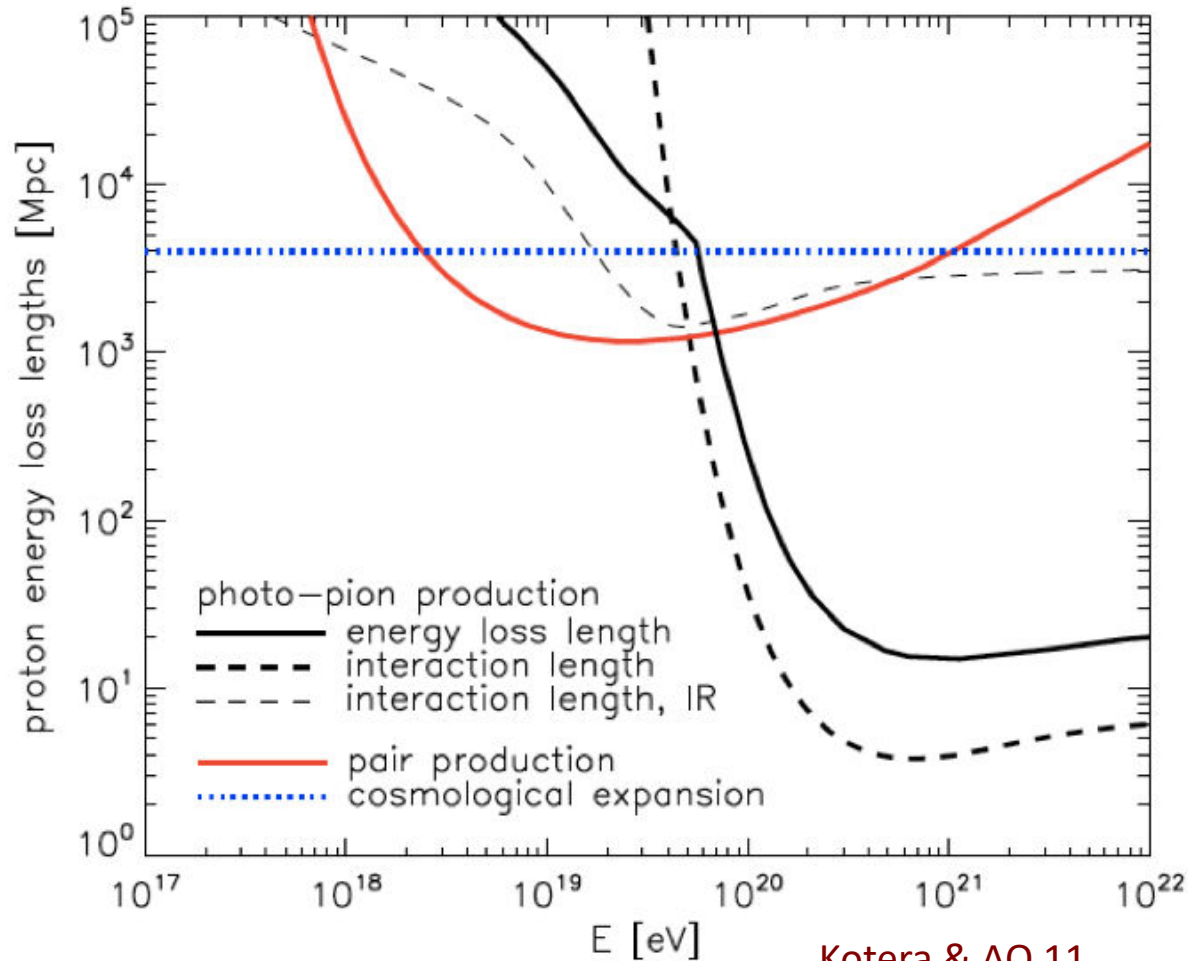
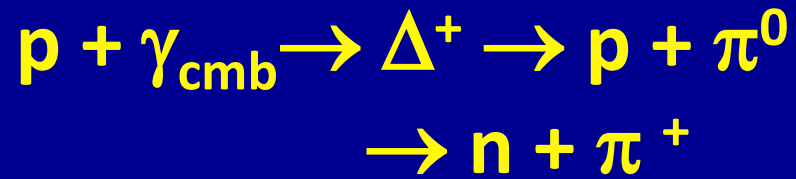
PIERRE  
AUGER  
OBSERVATORY



Exposure = 67000  $\text{km}^2 \text{ sr yr}$

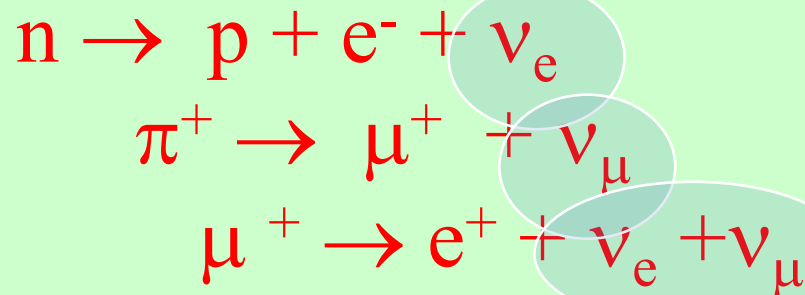
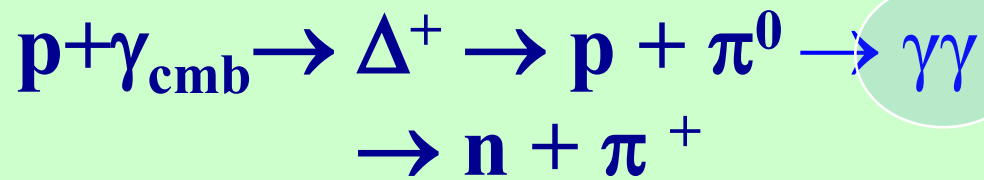
302,000 EVENTS

# GREISEN-ZATSEPIN-KUZMIN EFFECT



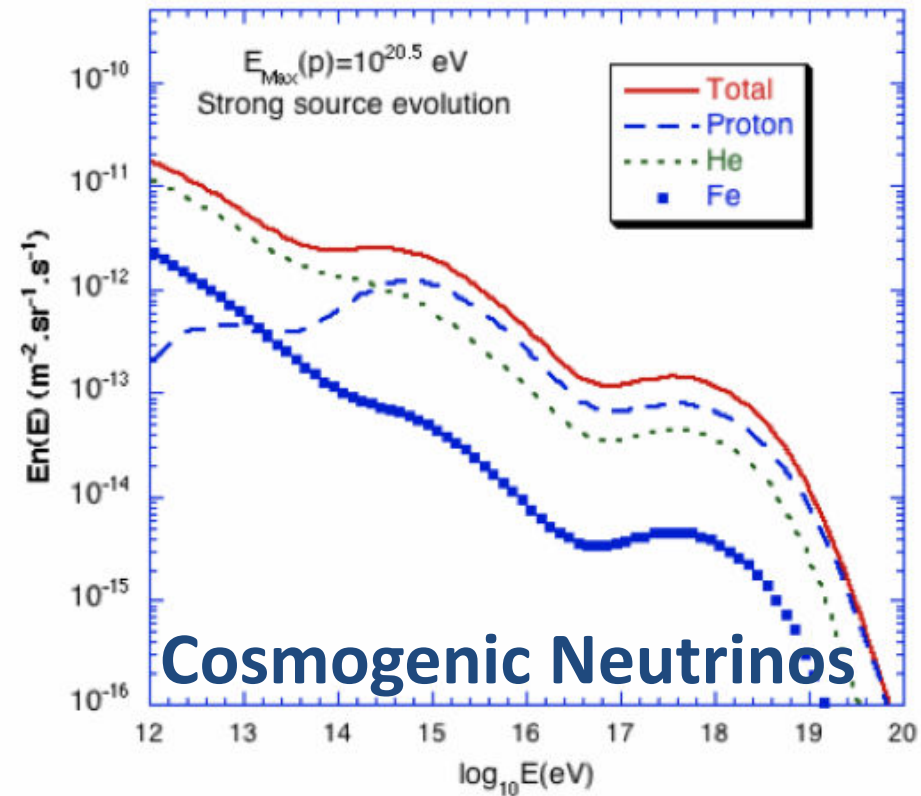
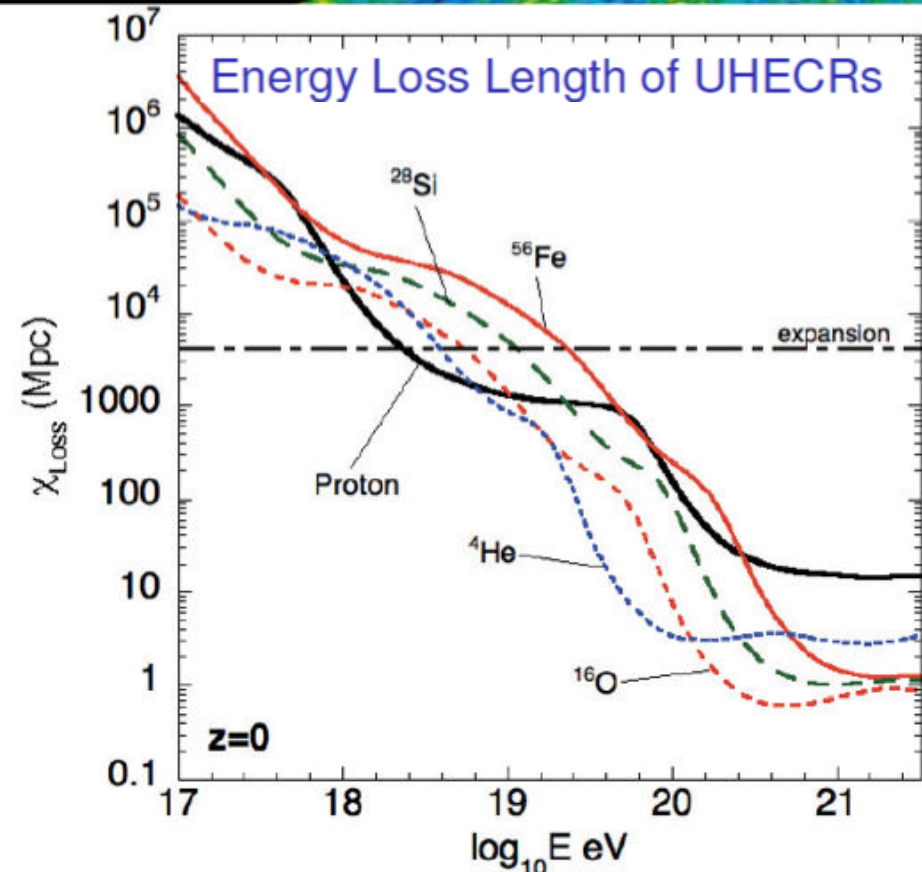
Kotera & AO 11

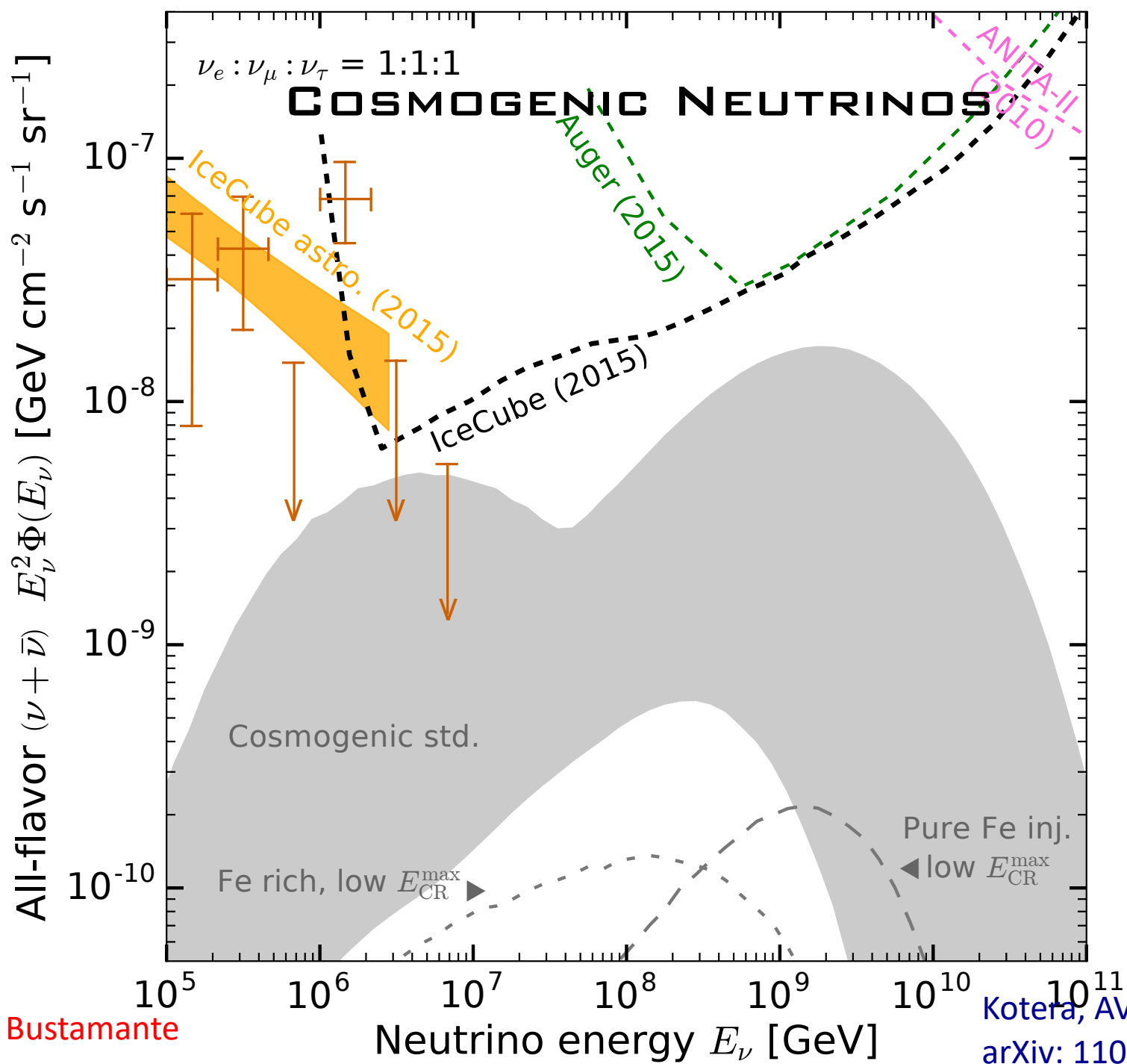
# Cosmogenic (BZ\*) Neutrinos & Photons



# GREISEN-ZATSEPIN-KUZMIN EFFECT

## Nuclei: Photo-dissociation

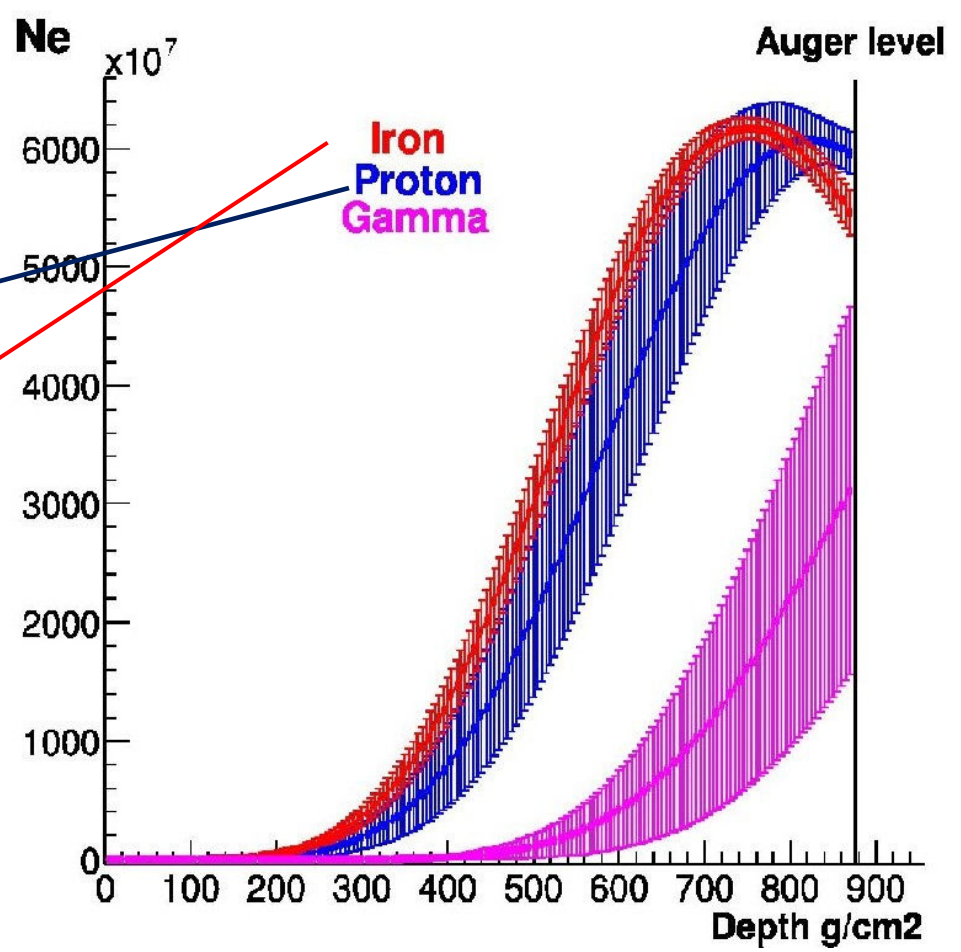
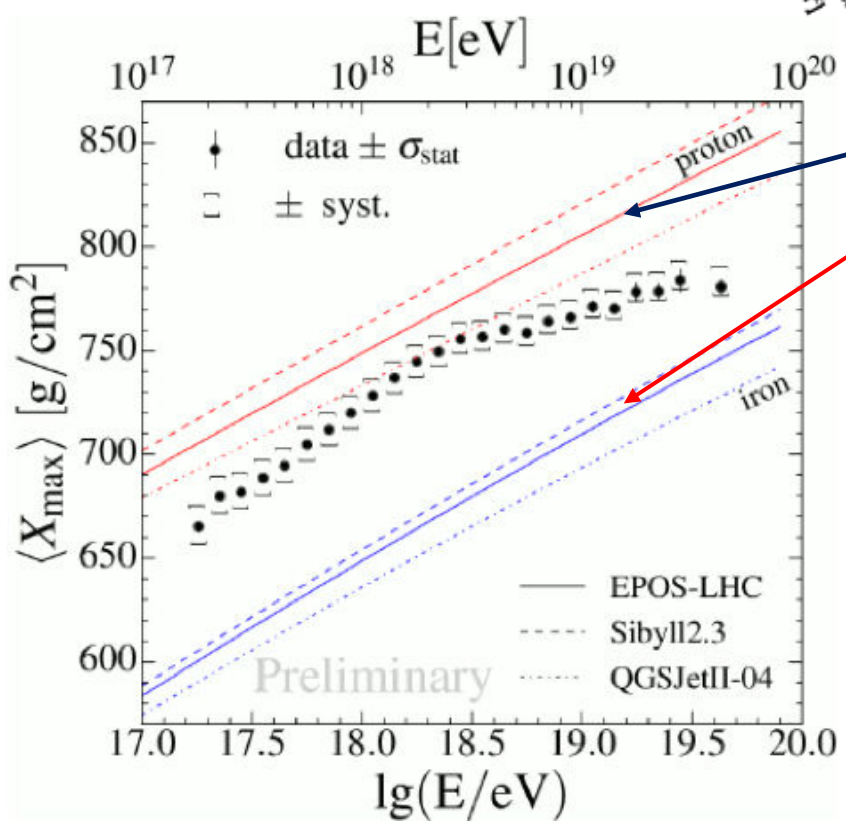
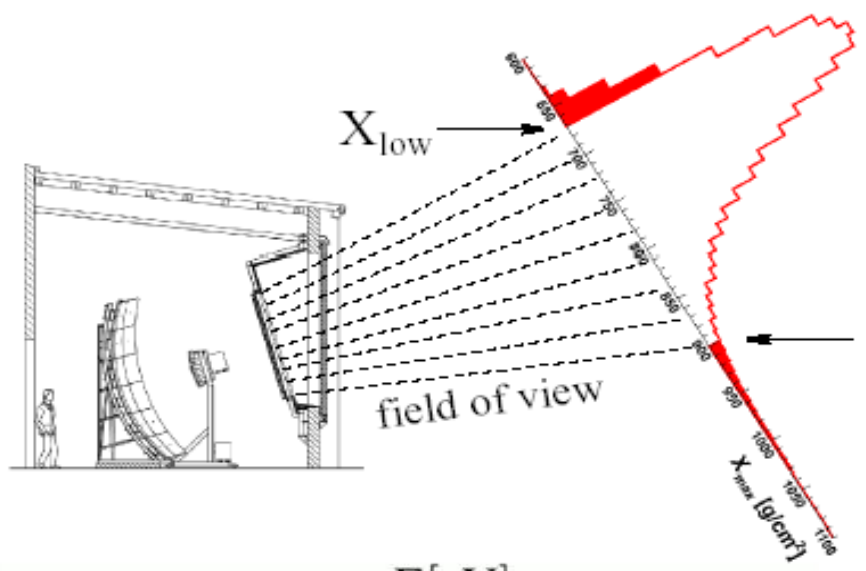


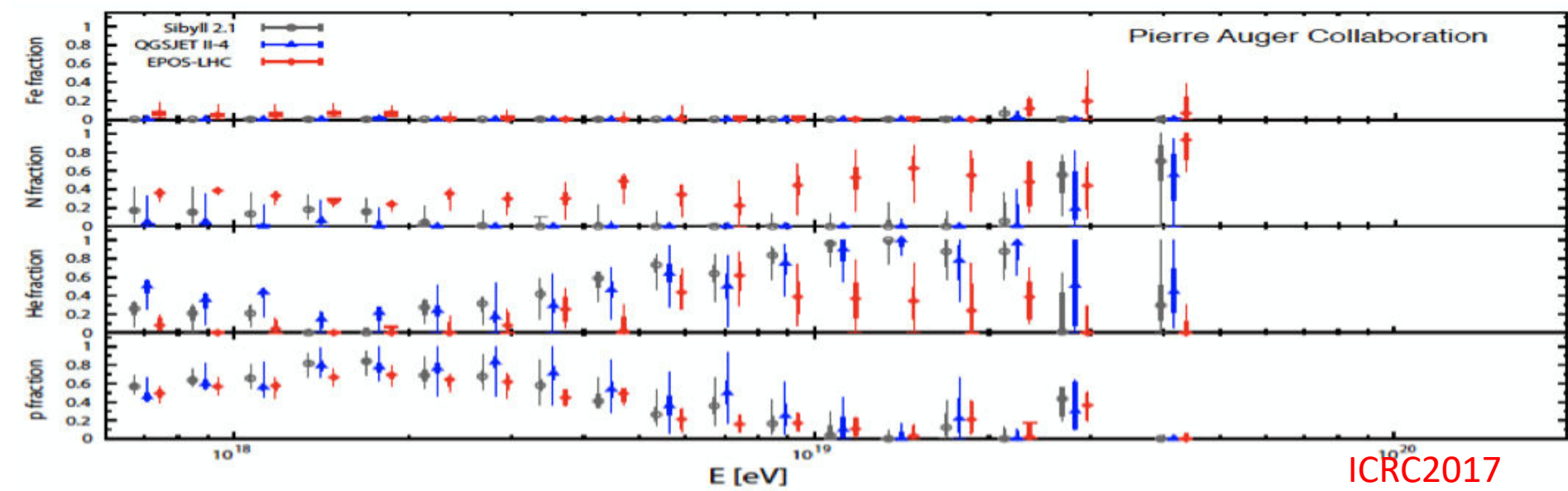
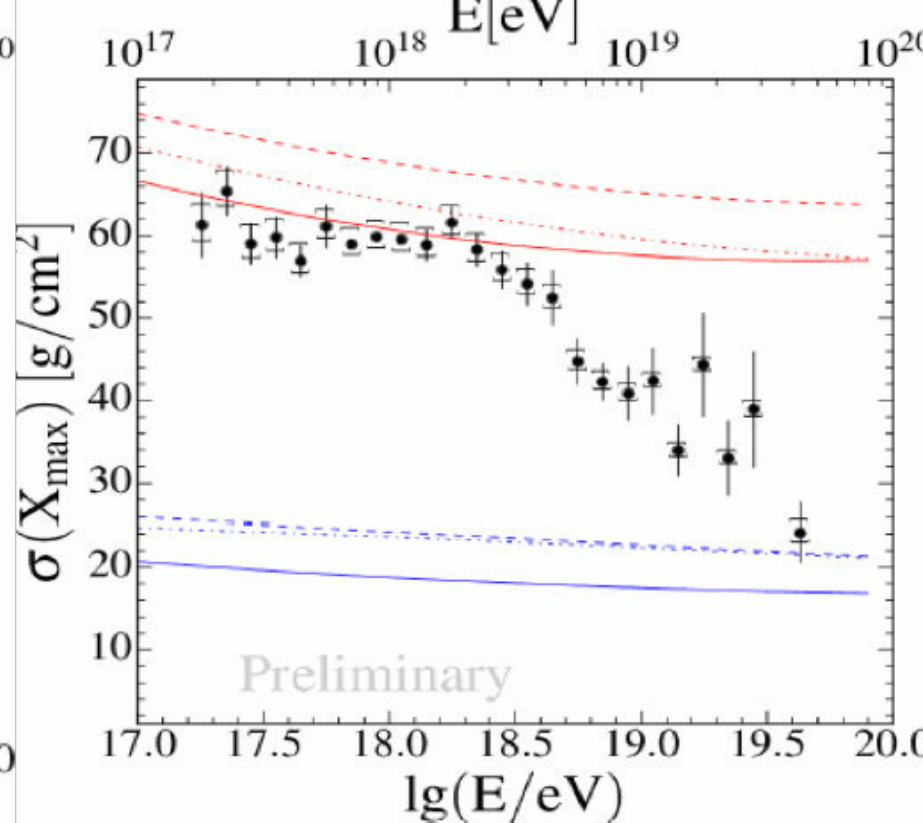
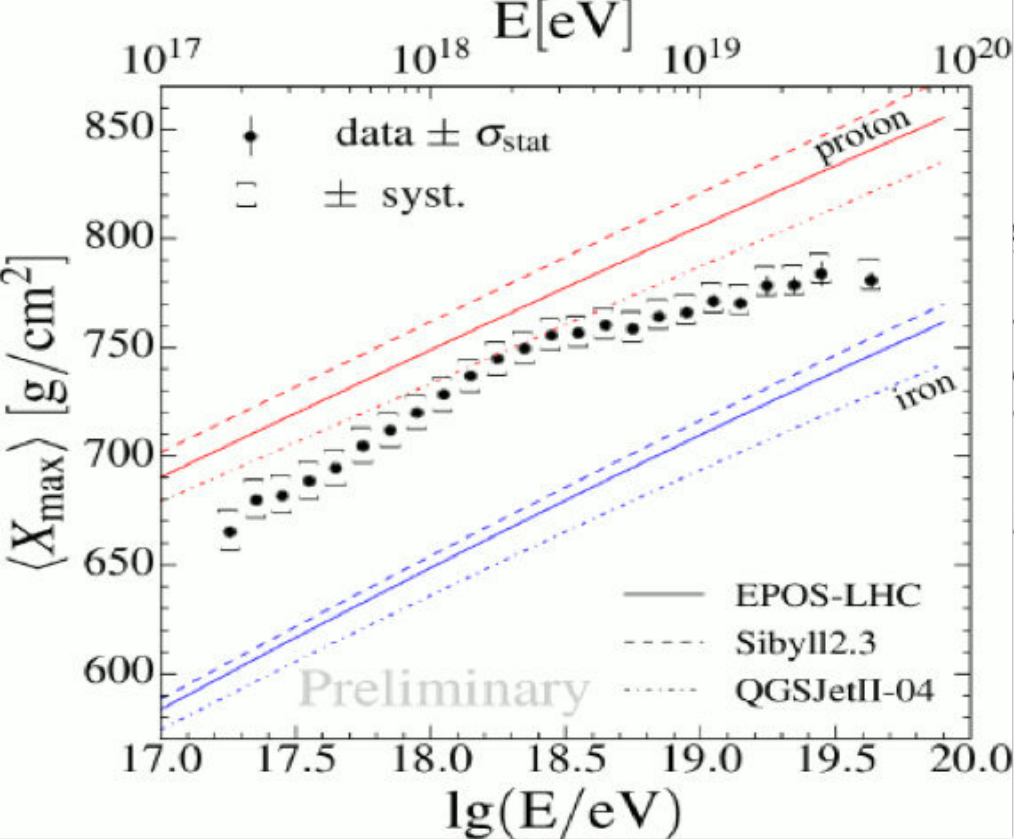


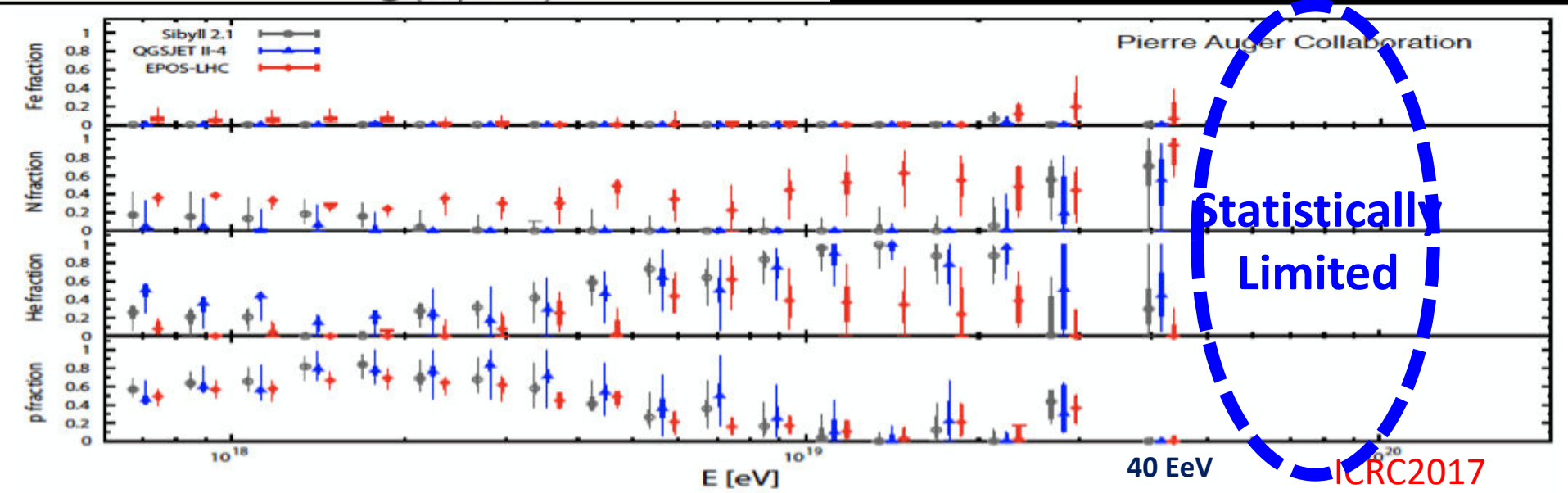
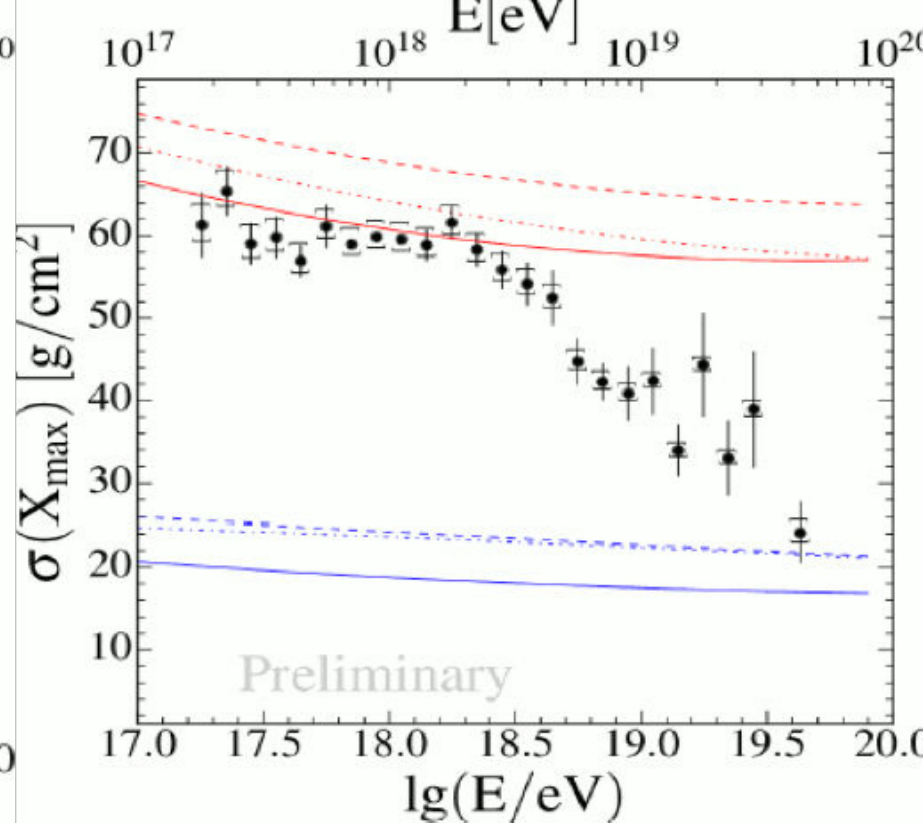
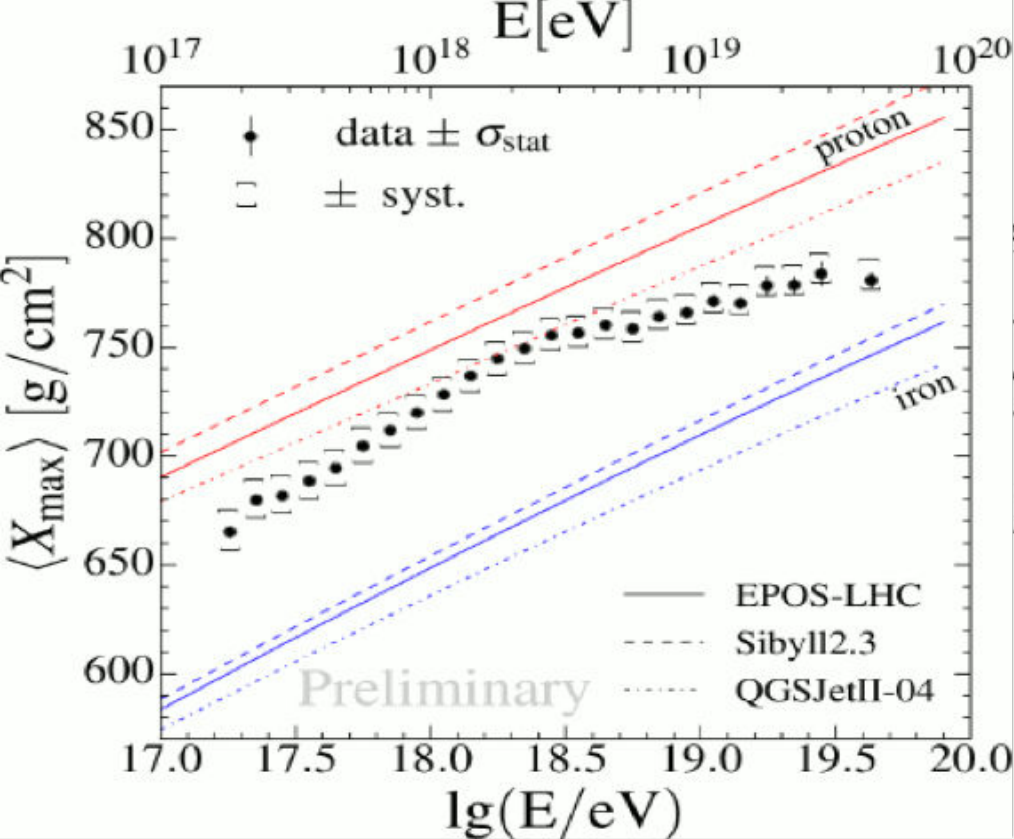
credit M. Bustamante

Kotera, AVO  
arXiv: 1101.4256

Composition observable:  
depth of shower maximum  
average and fluctuations

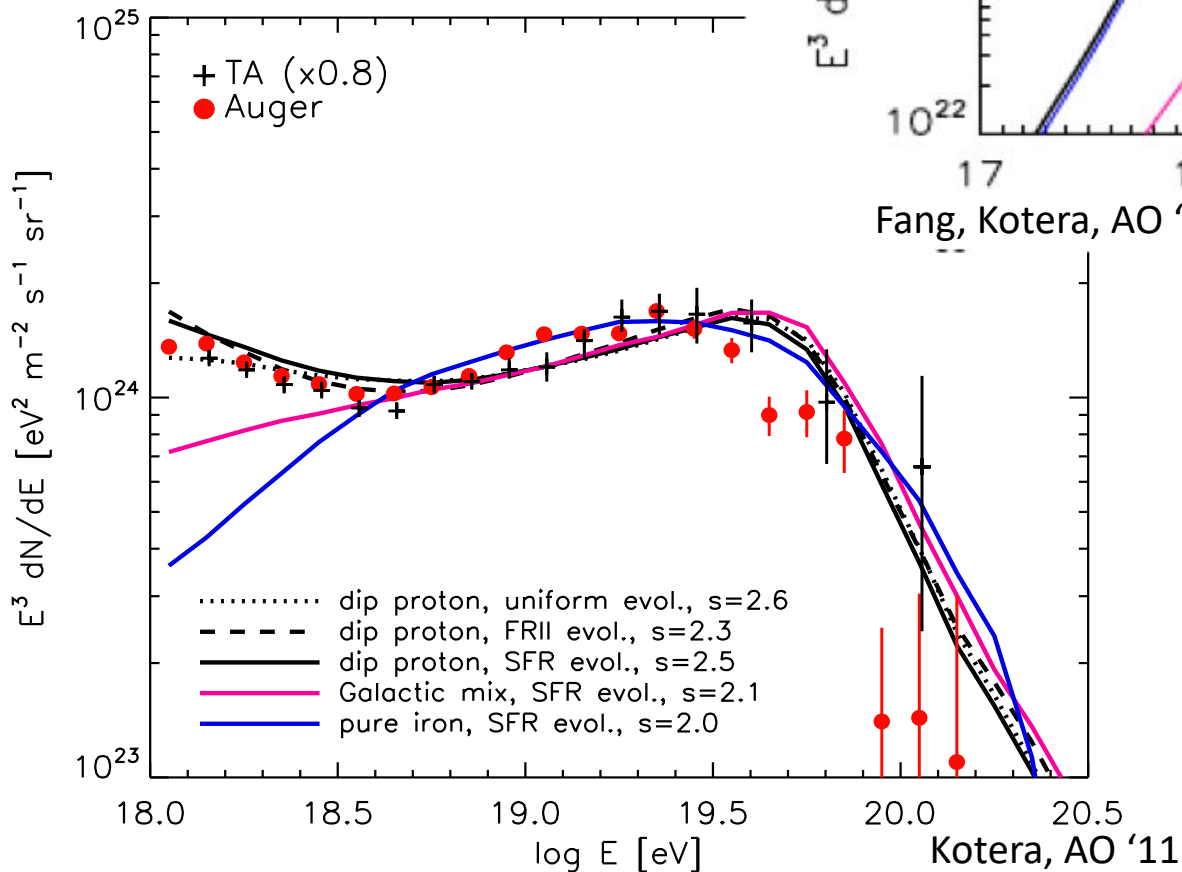
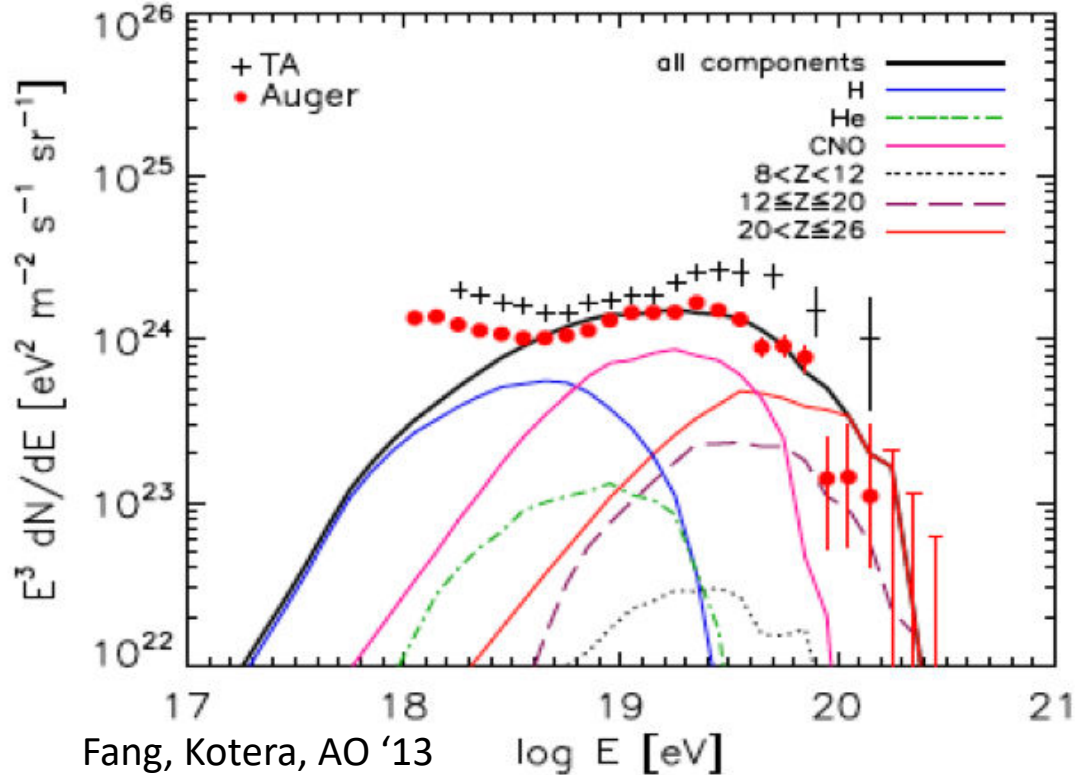








# GZK or $E_{\max}$ ?

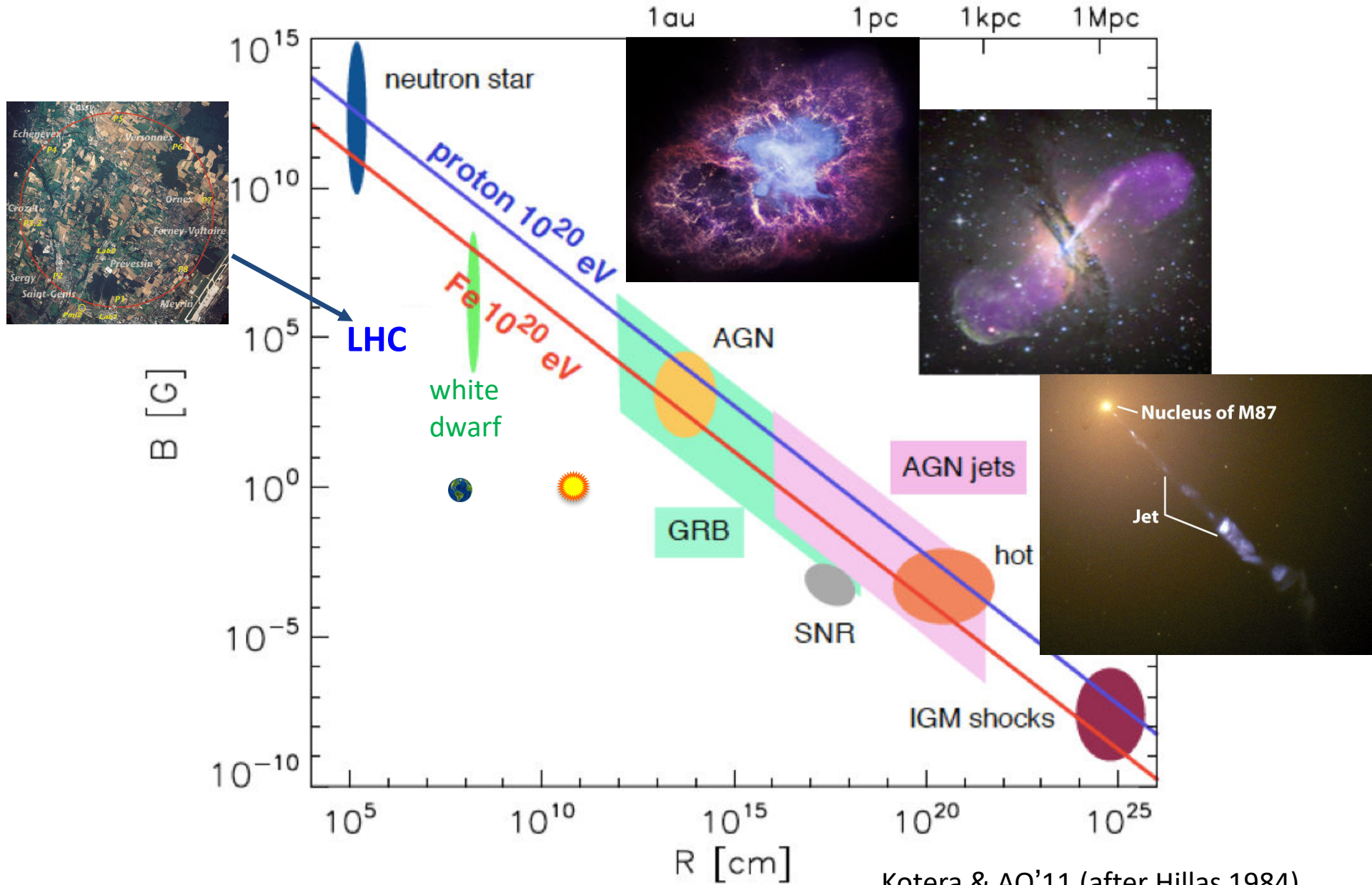


$R_{\max} \sim 5 \cdot 10^{19} \text{ eV}$

Hard Spectra  $\sim E^{-1.x}$

Source density: **negative evolution**

# Hillas Plot: $E_{\max}$ required



# UHECRs Current Status

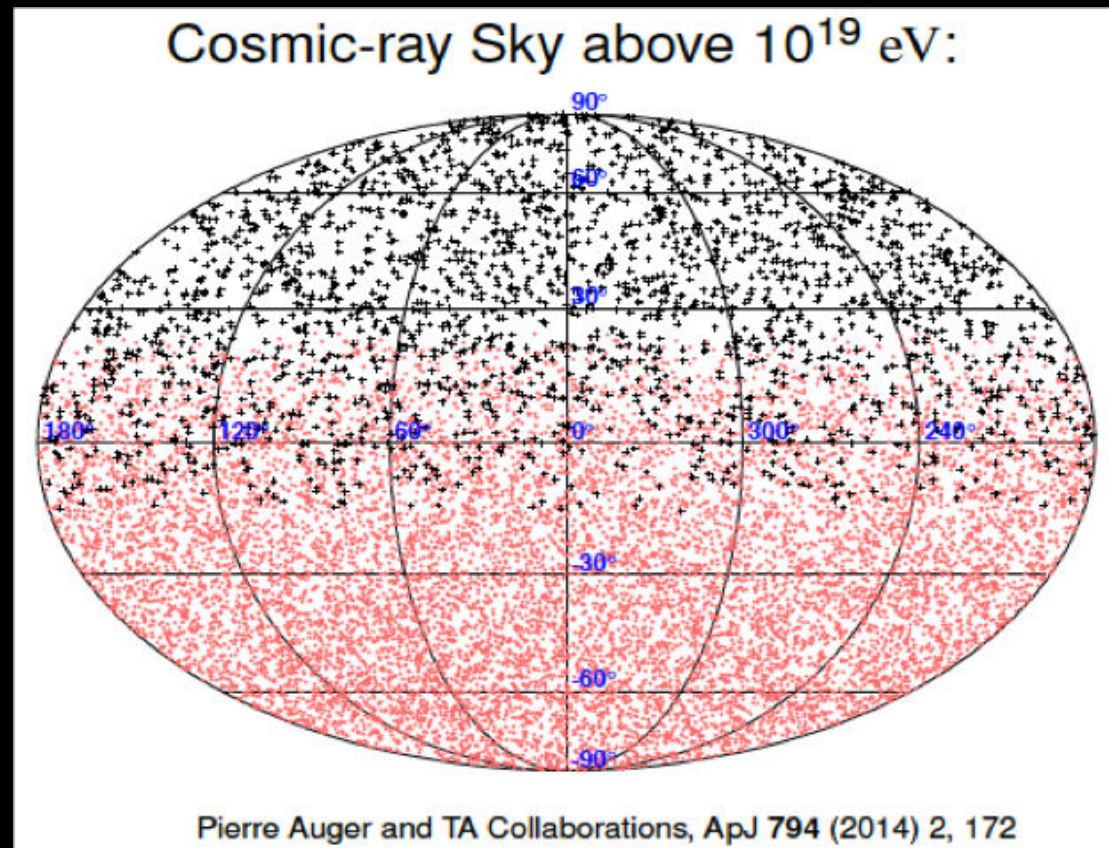
**Spectrum:** ankle and "GZK like" feature

**Composition:** transition to mixed at highest energies

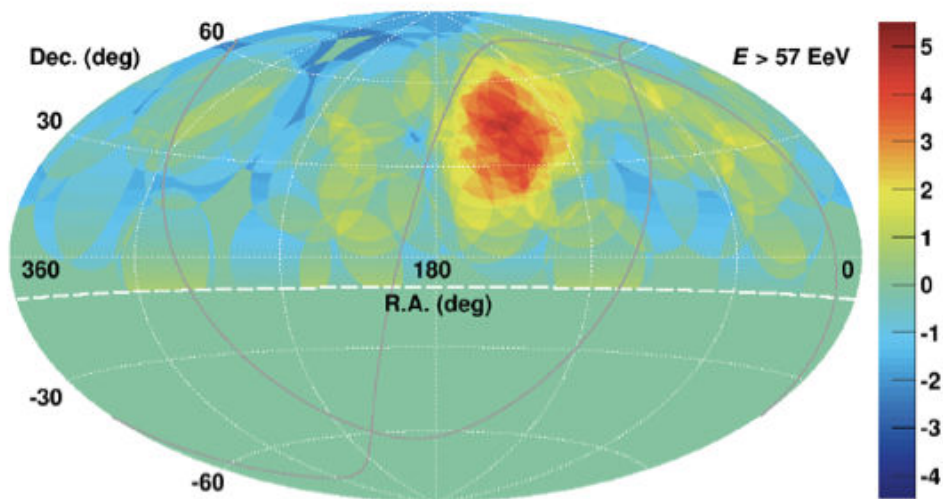
**Anisotropies?**

From  $\sim 3\sigma$  to

$5.2\sigma$



# TA "Hot Spot" 2014 ( $E > 57$ EeV, $\sim 3 \sigma$ )

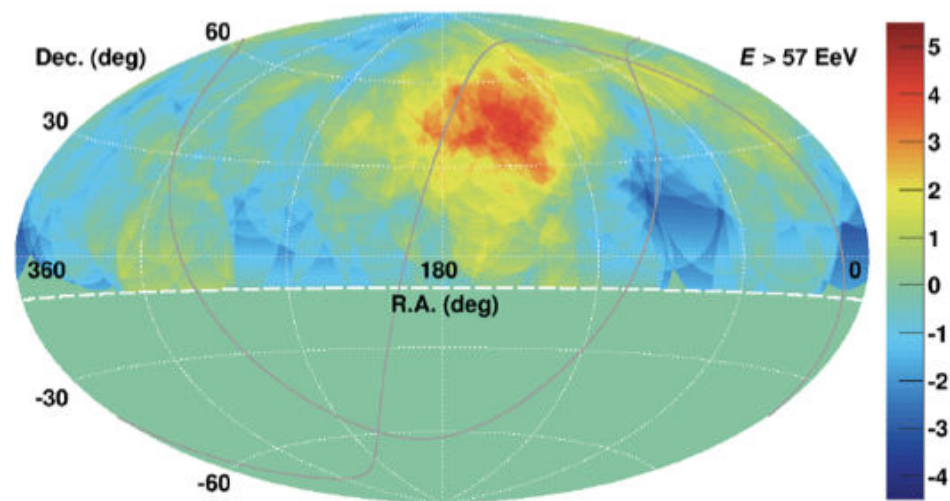


Above 57 EeV  
 $\sim 3\sigma$

Total events: 72  
Observed: 19  
Expected : 4.5

Best circle center: RA=146°  
Best circle radius: 20°  
Local significance : 5  $\sigma$   
Global significance : 3  $\sigma$

# TA "Hot Spot" 2017 ( $E > 57$ EeV, $\sim 3 \sigma$ )



Total events: 143  
Observed: 34  
Expected : 13.5

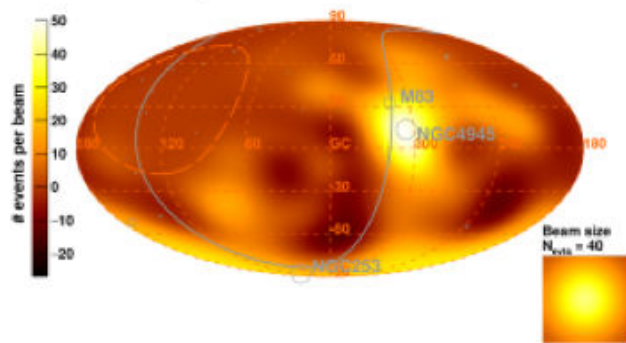
Best circle center: RA=144.3°, Dec=+40.3°  
Best circle radius: 25°  
Local significance : 5  $\sigma$   
Global significance : 3  $\sigma$

# Above 39 EeV $\sim 4\sigma$

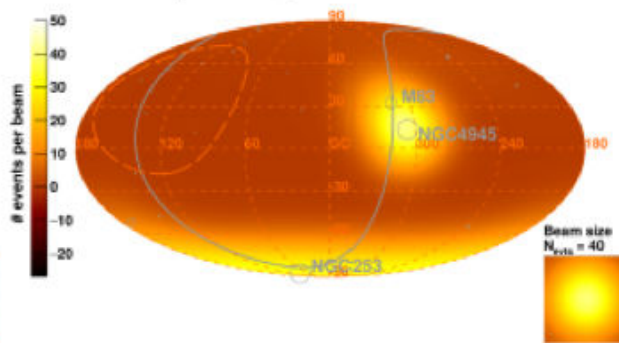
## Auger Intermediate-scale Anisotropy ( $E > 39$ EeV, $\sim 4\sigma$ )

starburst galaxies ( $E > 39$  EeV, 9.7%,  $12.9^\circ$ ,  $4.0\sigma$ )

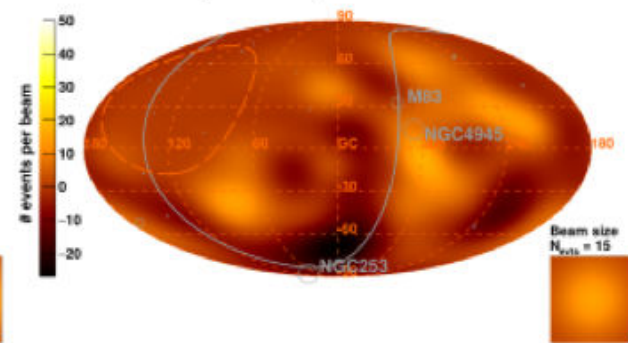
Observed Excess Map -  $E > 39$  EeV



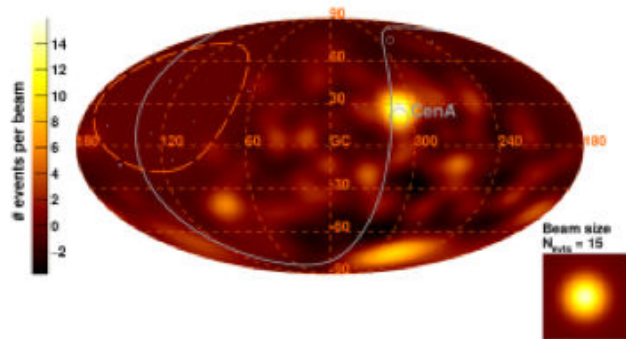
Model Excess Map - Starburst galaxies -  $E > 39$  EeV



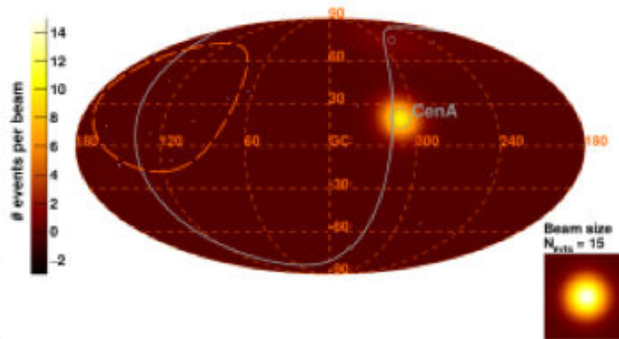
Residual Excess Map - Starburst galaxies -  $E > 39$  EeV



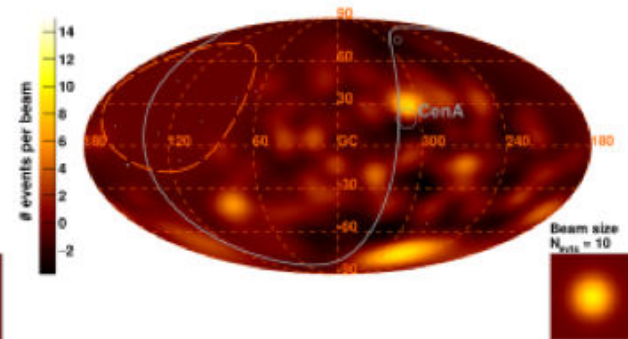
Observed Excess Map -  $E > 60$  EeV



Model Excess Map - Active galactic nuclei -  $E > 60$  EeV



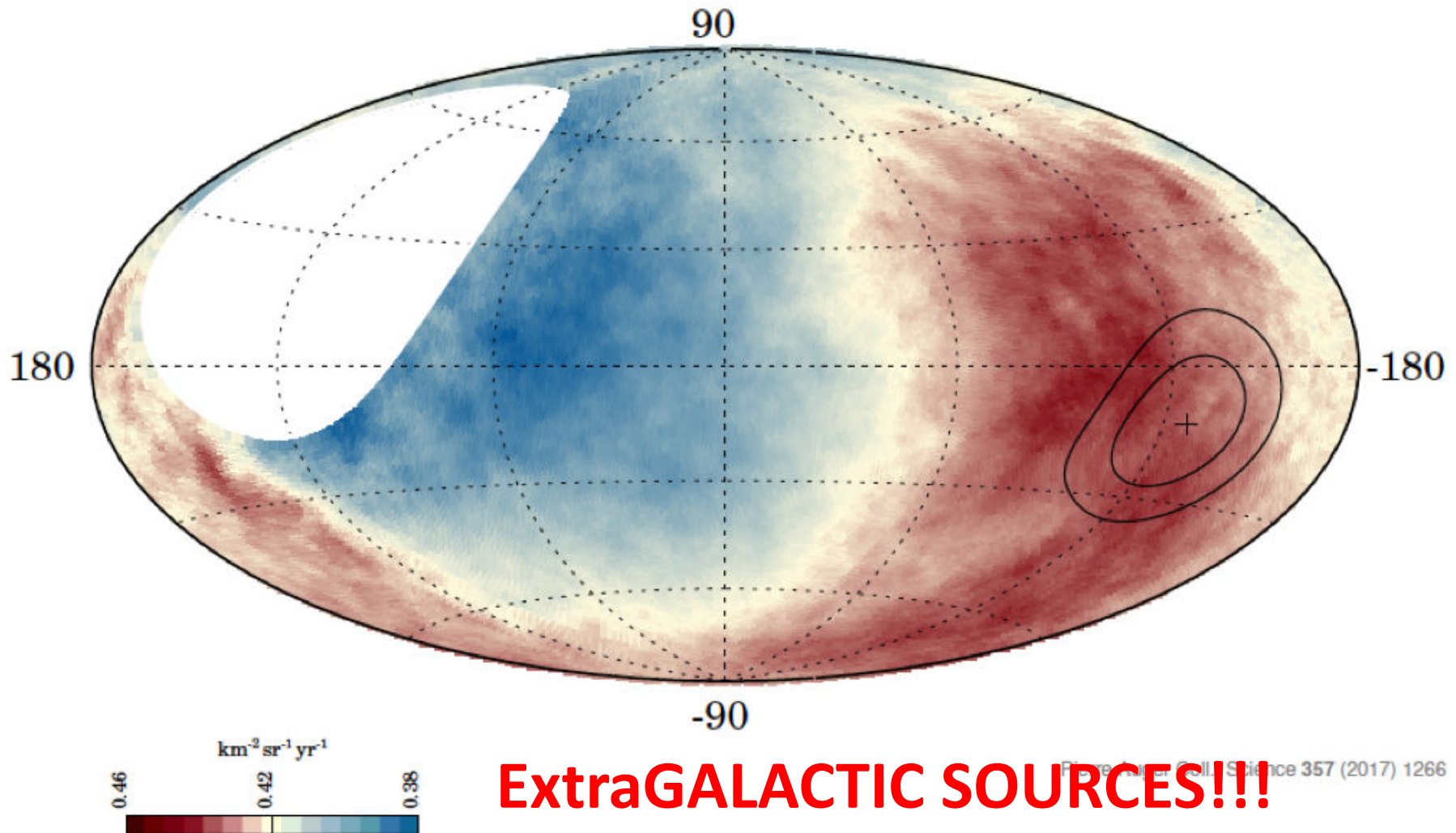
Residual Excess Map - Active galactic nuclei -  $E > 60$  EeV



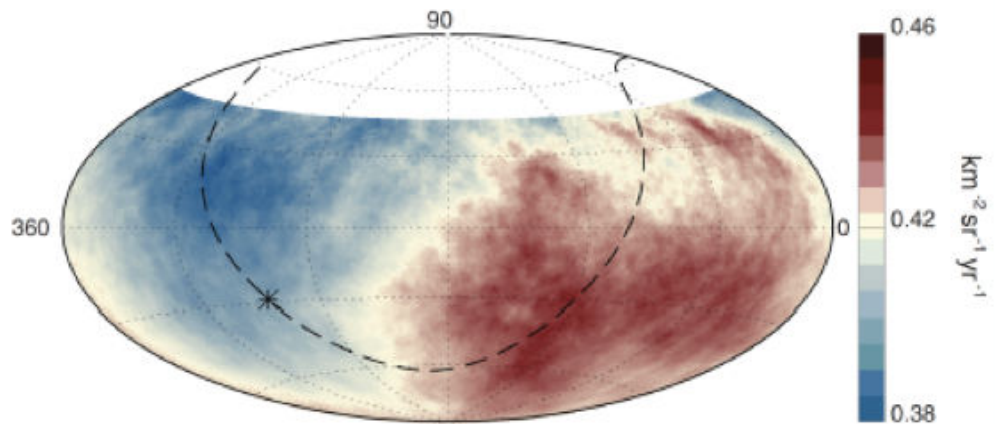
$\gamma$ AGN ( $E > 60$  EeV, 6.7%,  $6.9^\circ$ ,  $2.7\sigma$ )

Dipole Above 8 EeV =  $5.2\sigma$ !!

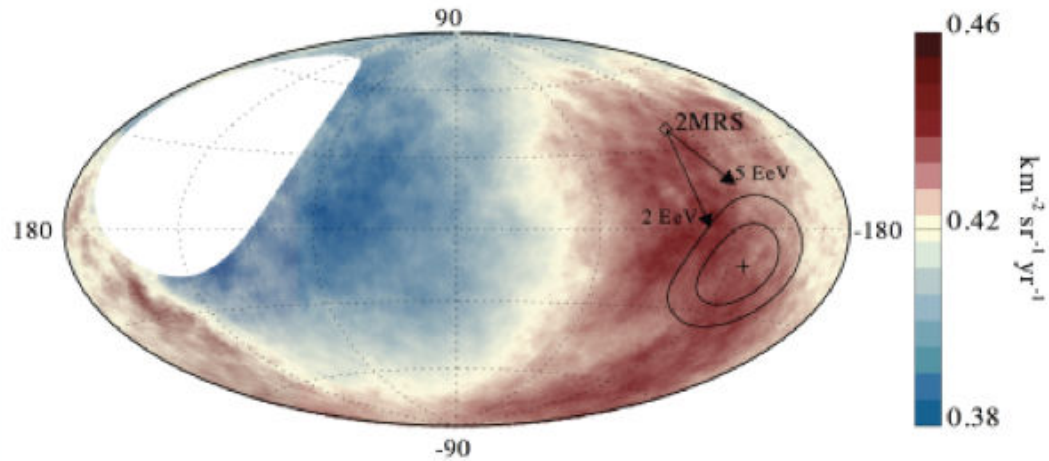
Auger Large-scale Anisotropy ( $E > 8$  EeV,  $(6.5^{+1.3}_{-0.9})\%$ ,  $5.2 \sigma$ )



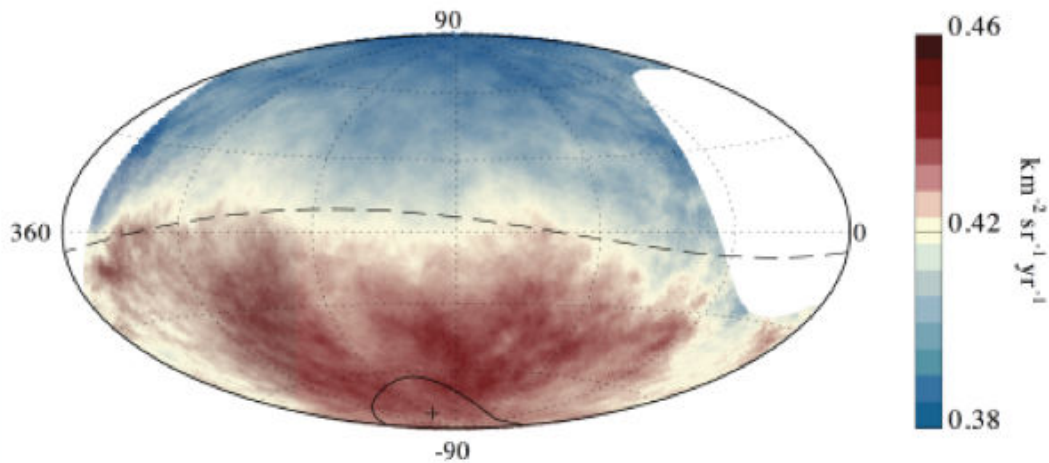
Equatorial

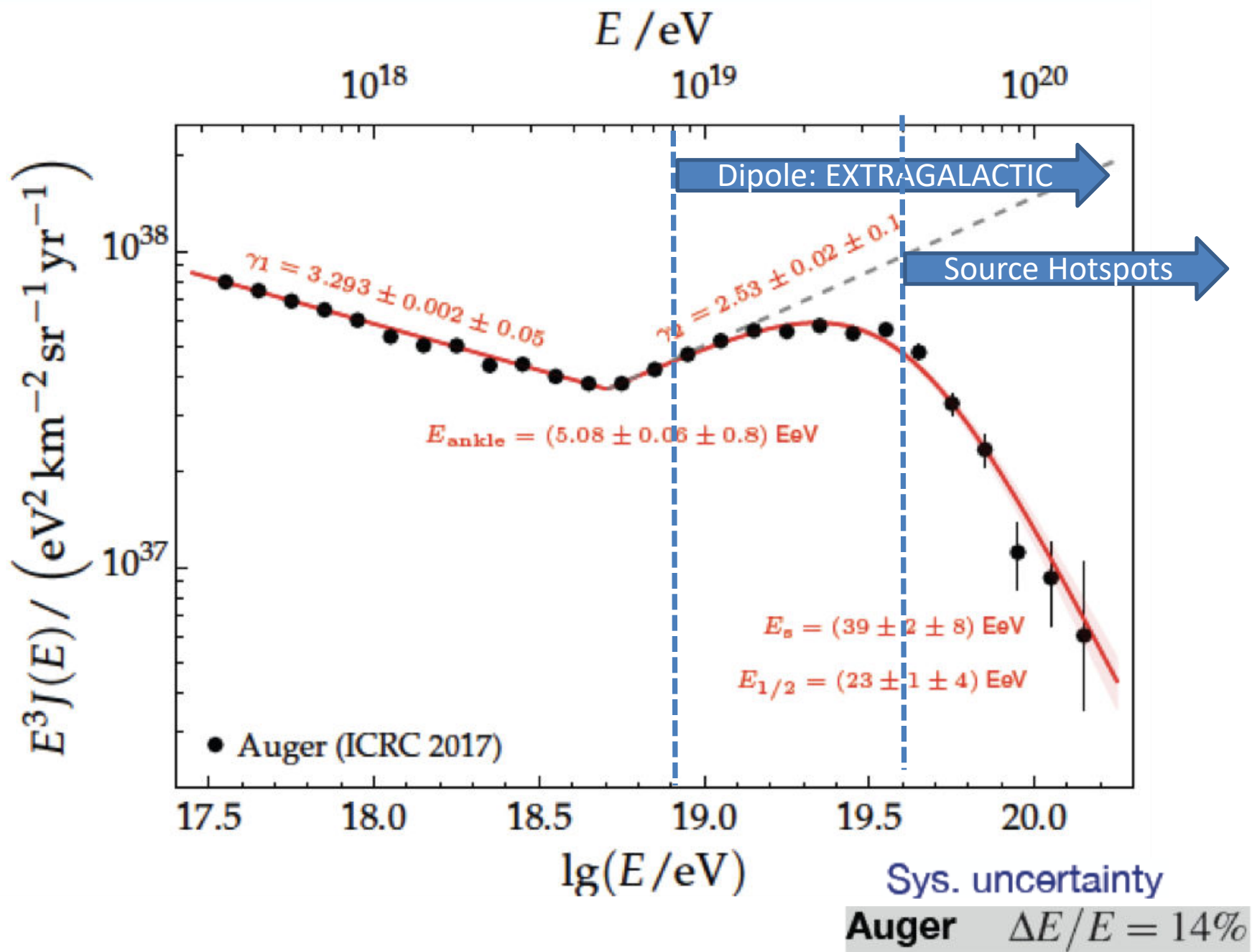


Galactic



Super Galactic







# UHECRs Current Status

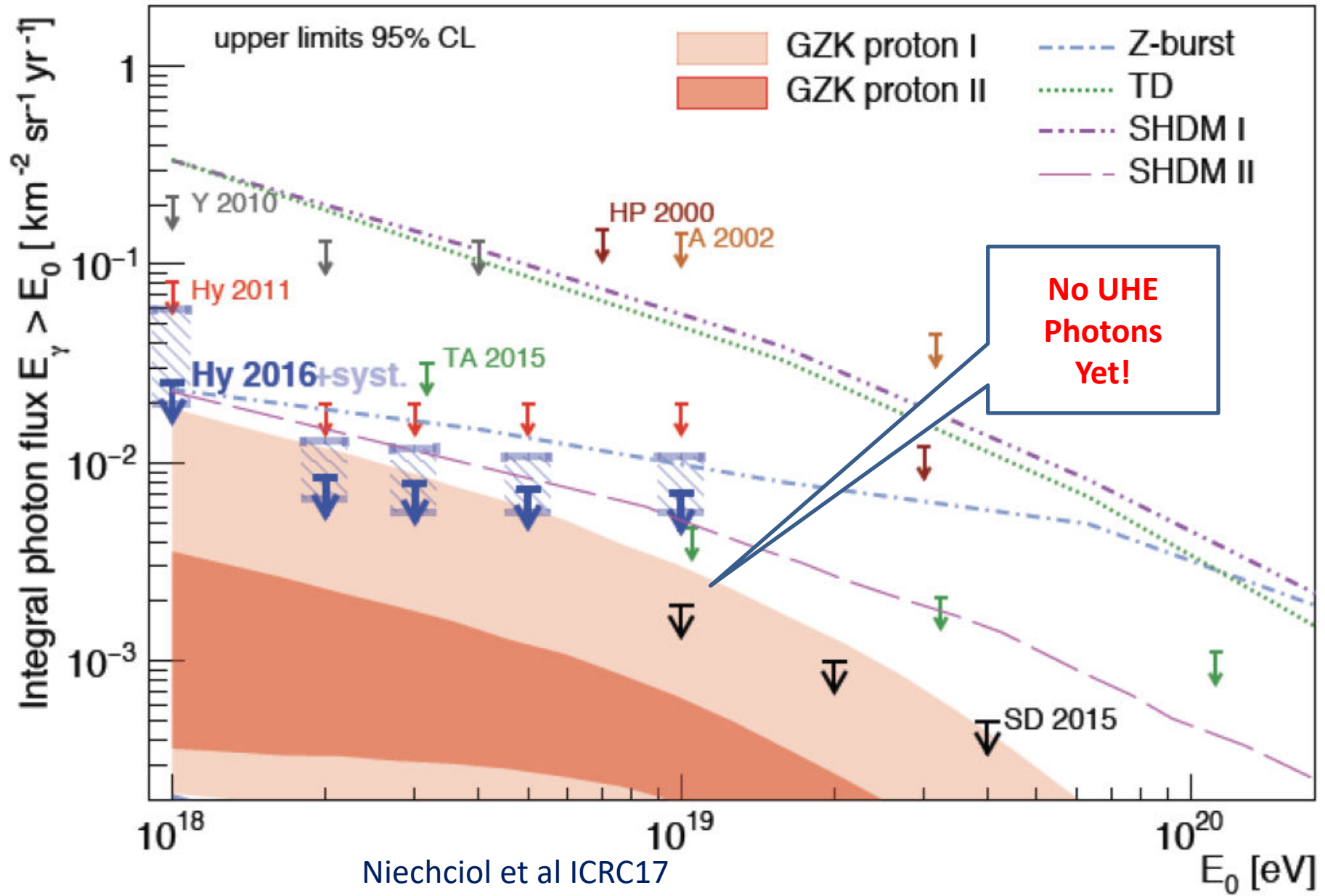
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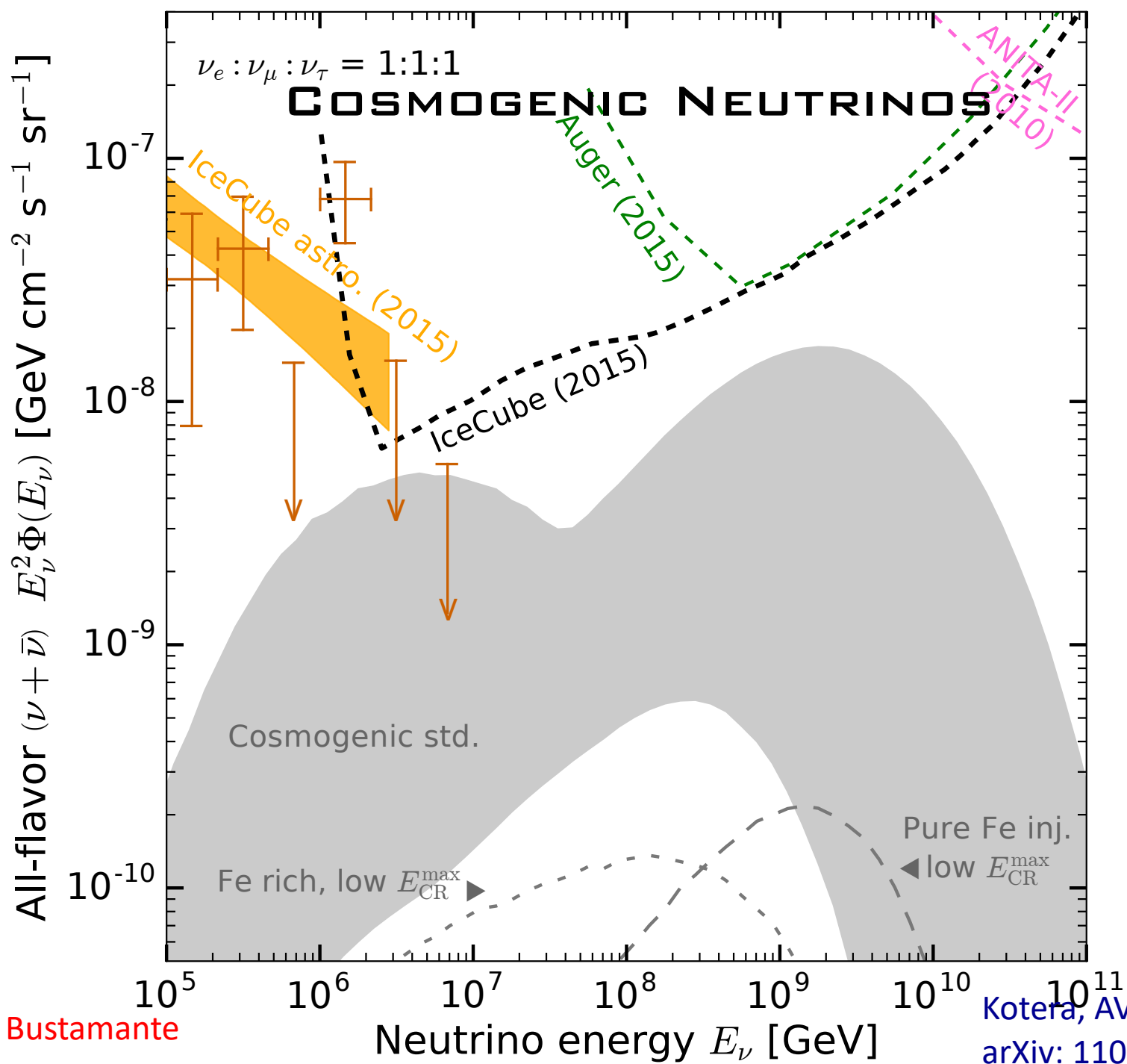
**Composition:** transition to mixed at highest energies

**Anisotropies:** Auger Dipole  $E > 8 \text{ EeV}$ ;  
above  $\sim 50 \text{ EeV}$ : TA hotspot?

**Multi-messengers?**

# AUGER PHOTON LIMITS





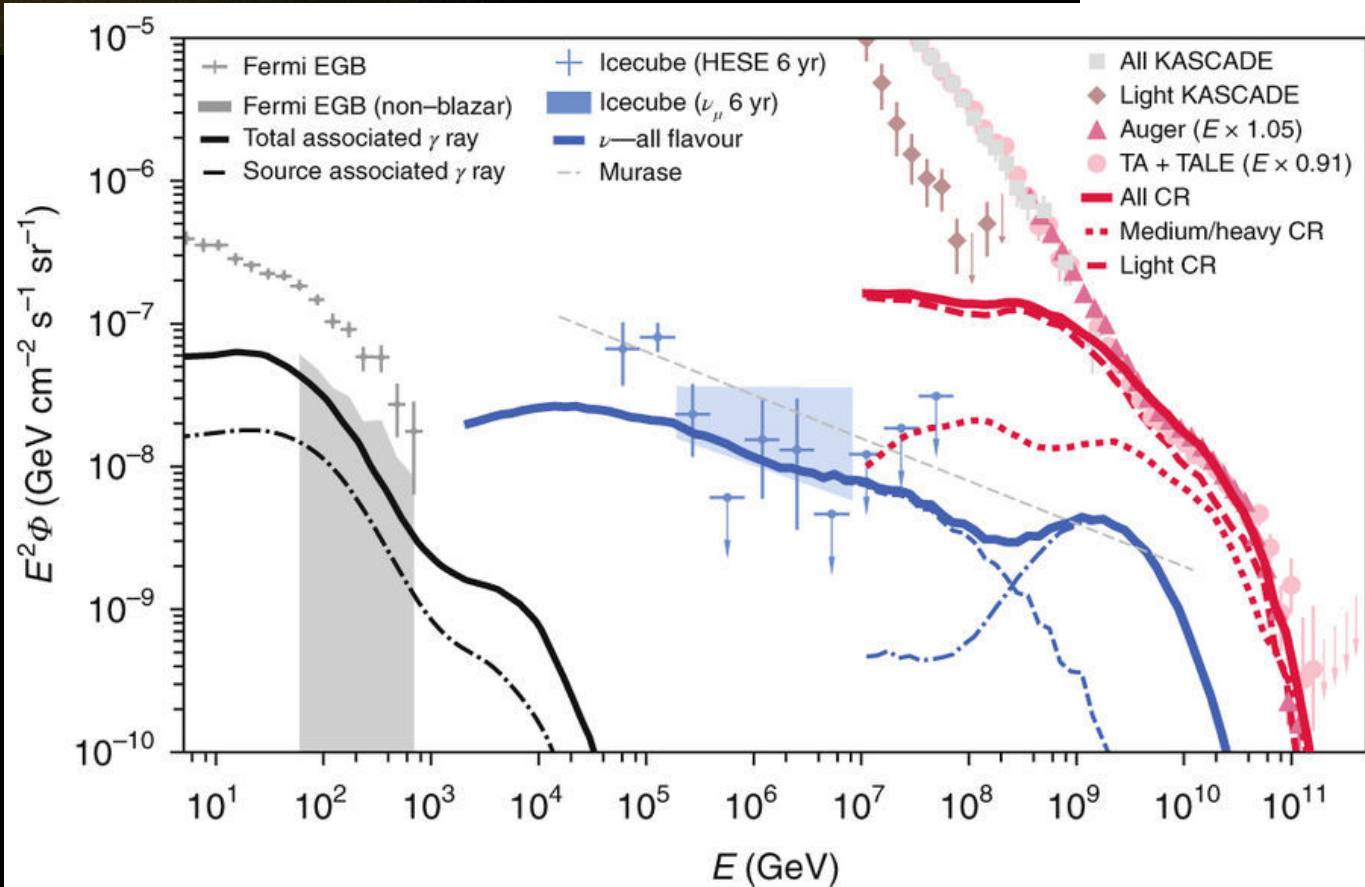
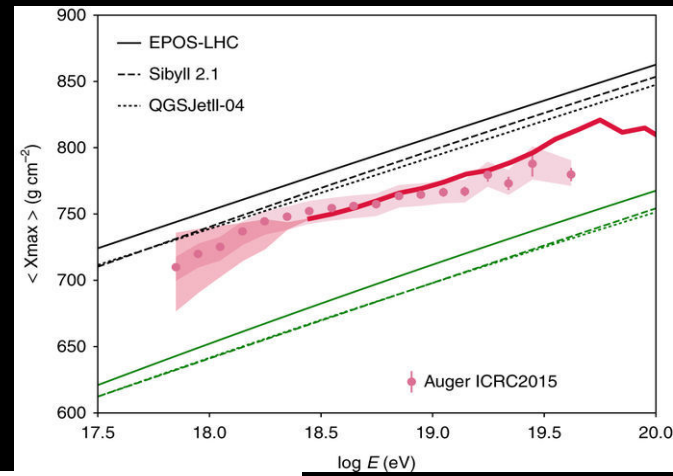
credit M. Bustamante

Kotera, AVO  
arXiv: 1101.4256



# Grand Unified Models!

## Jets in clusters



Fang & Murase  
2017

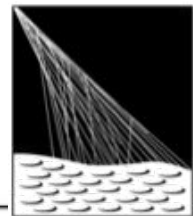
2020s

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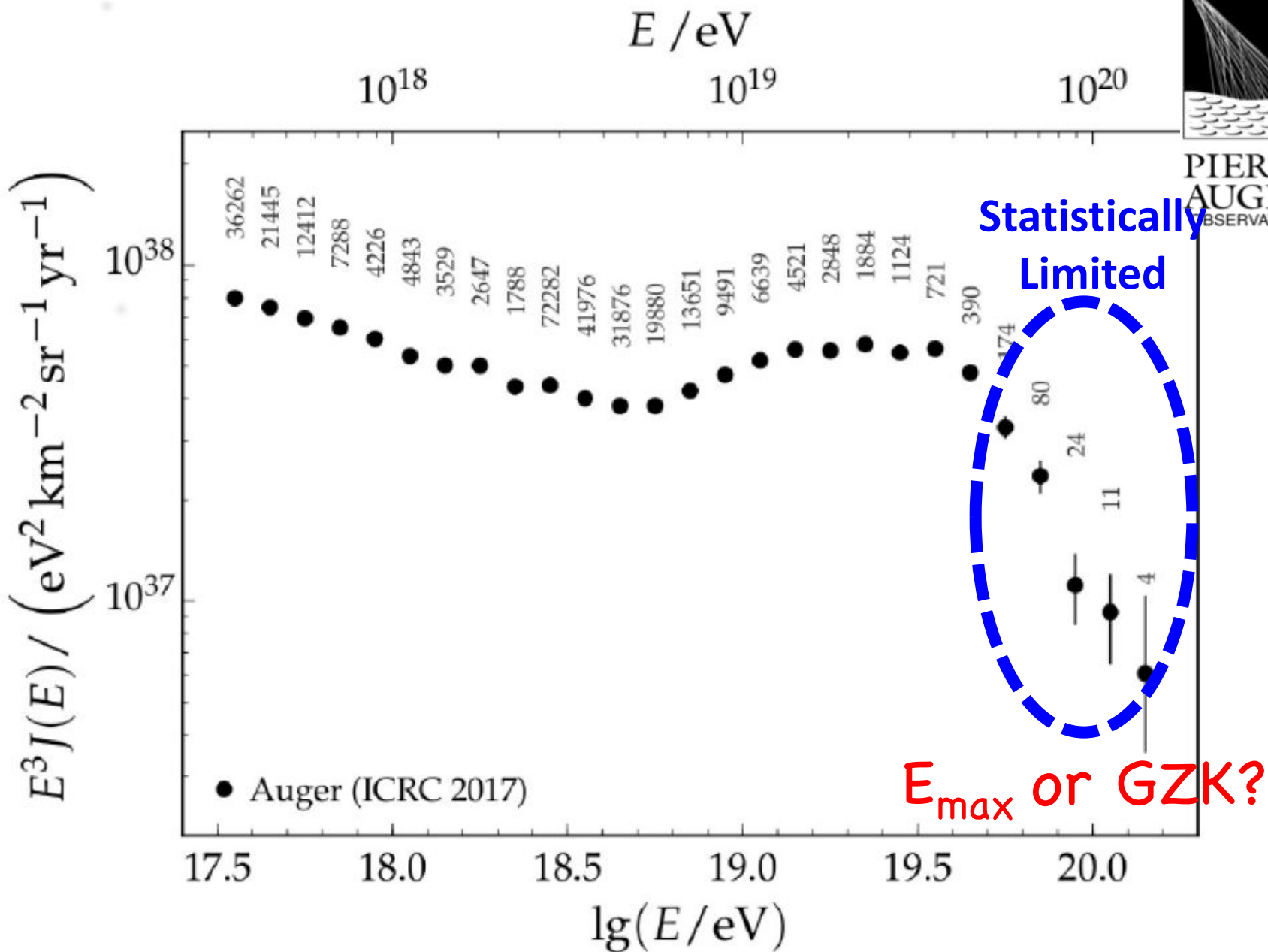
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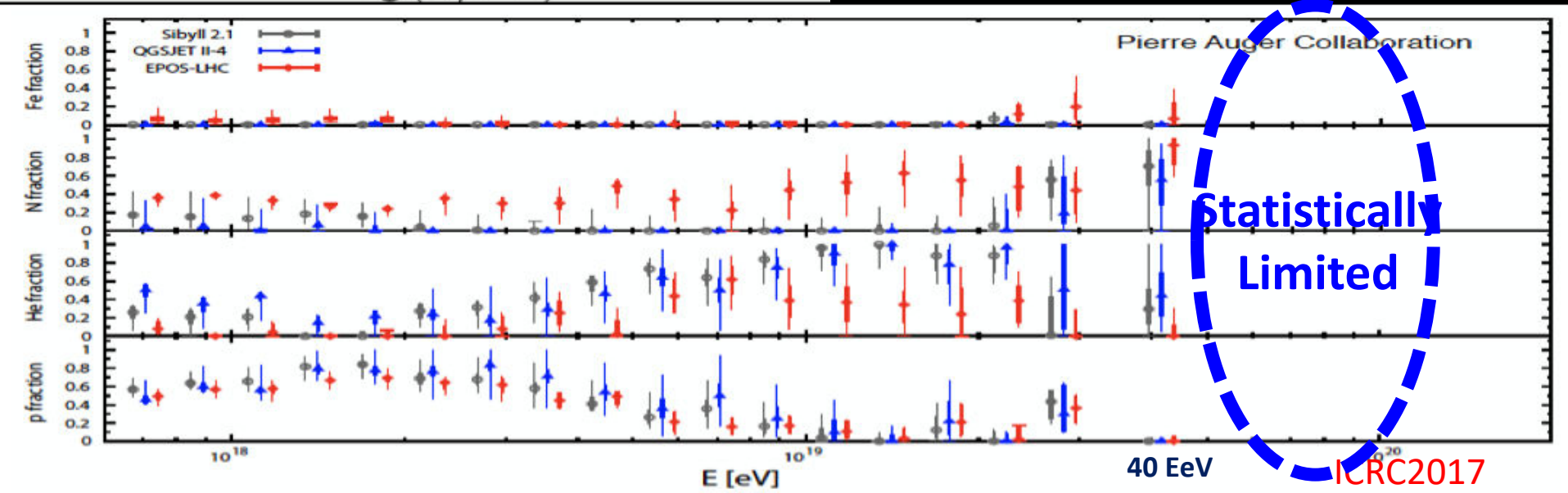
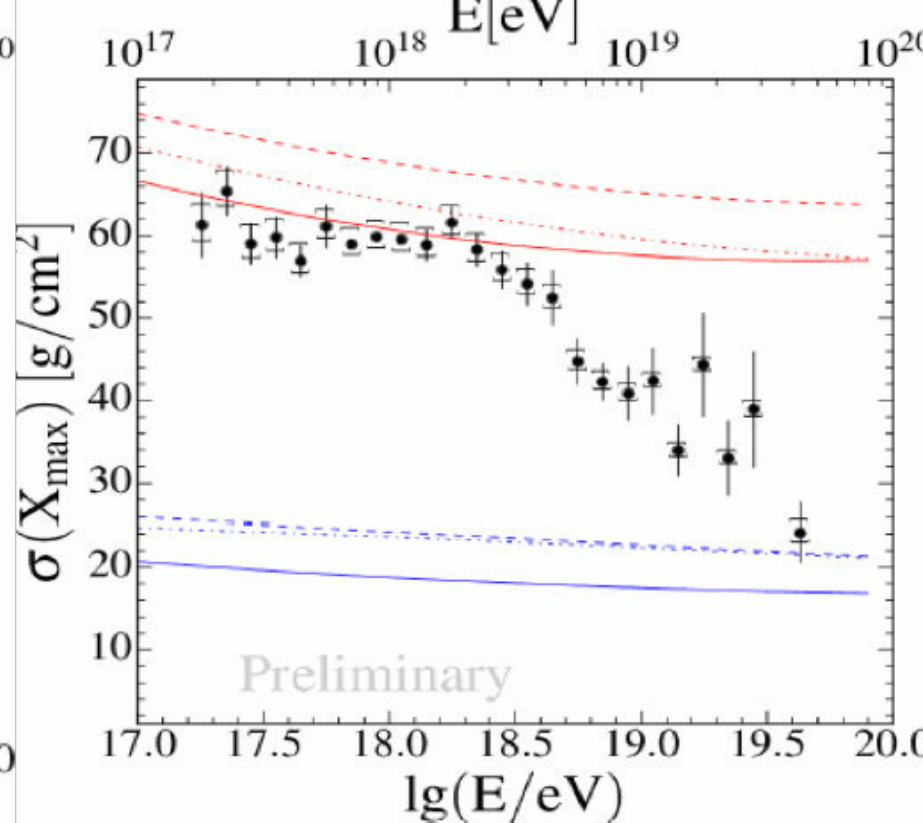
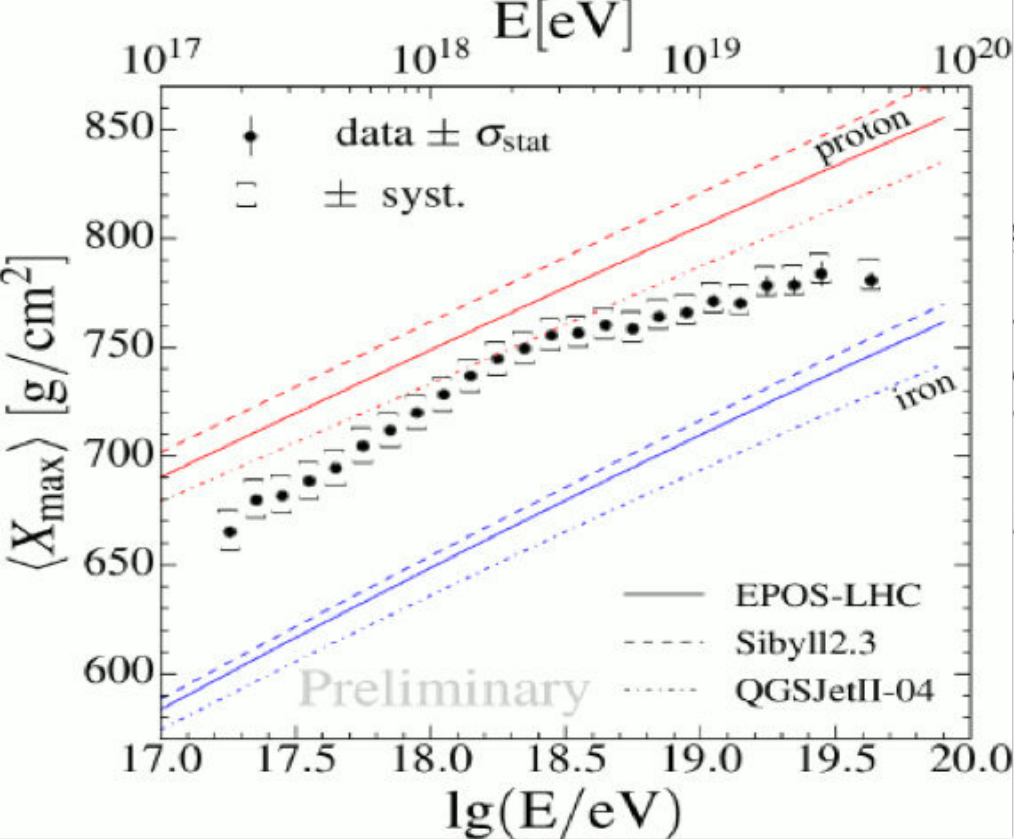


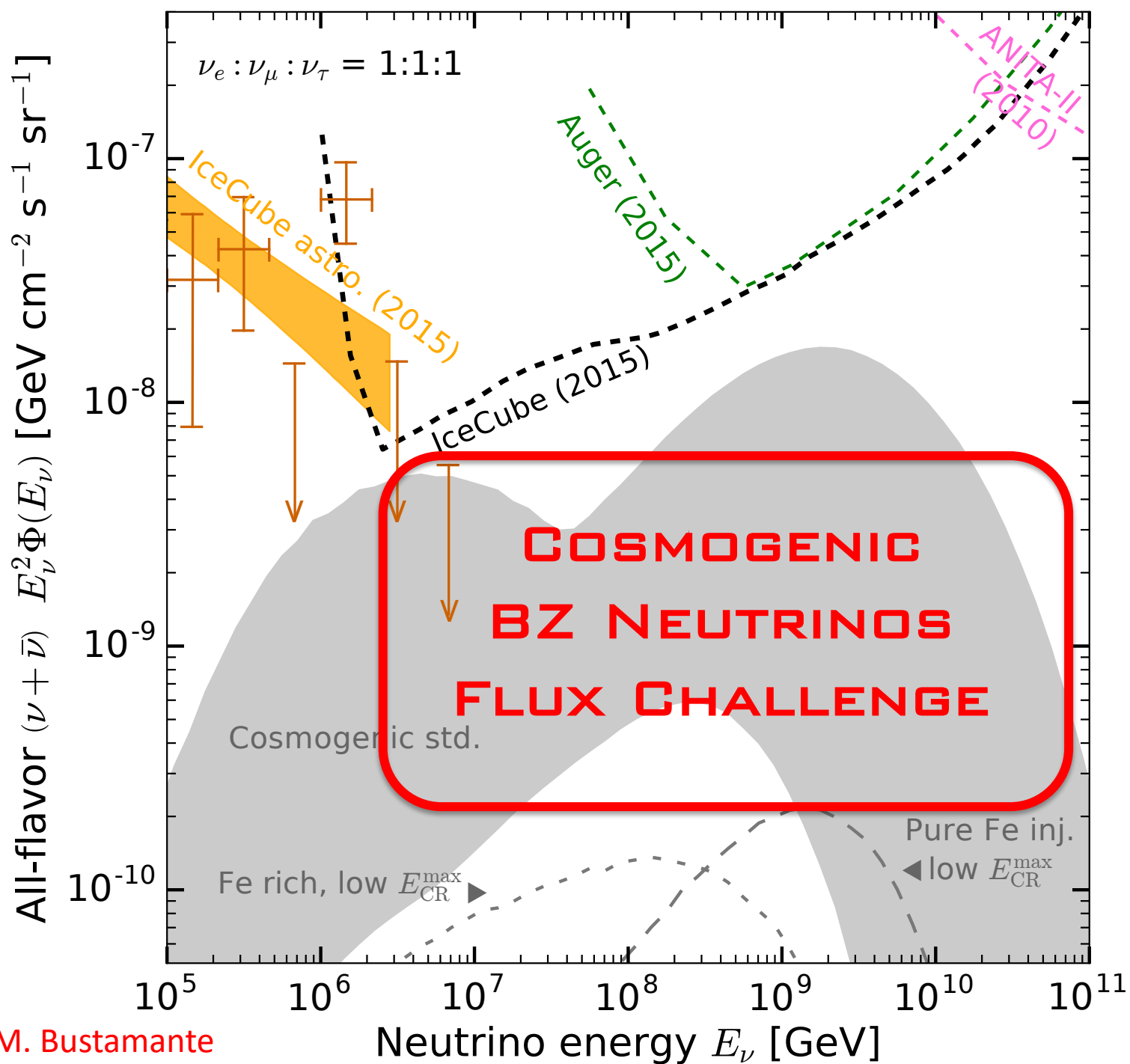
PIERRE  
AUGER  
OBSERVATORY



Exposure = 67000  $\text{km}^2 \text{ sr yr}$

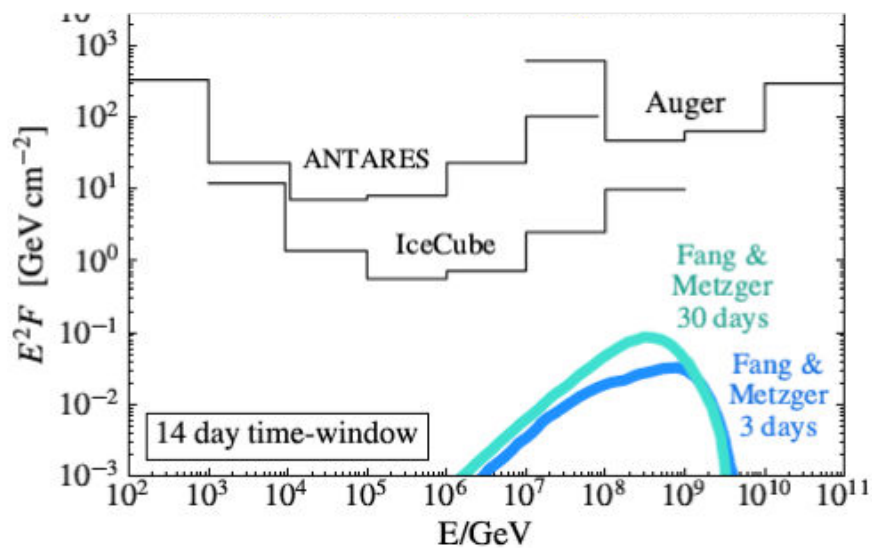
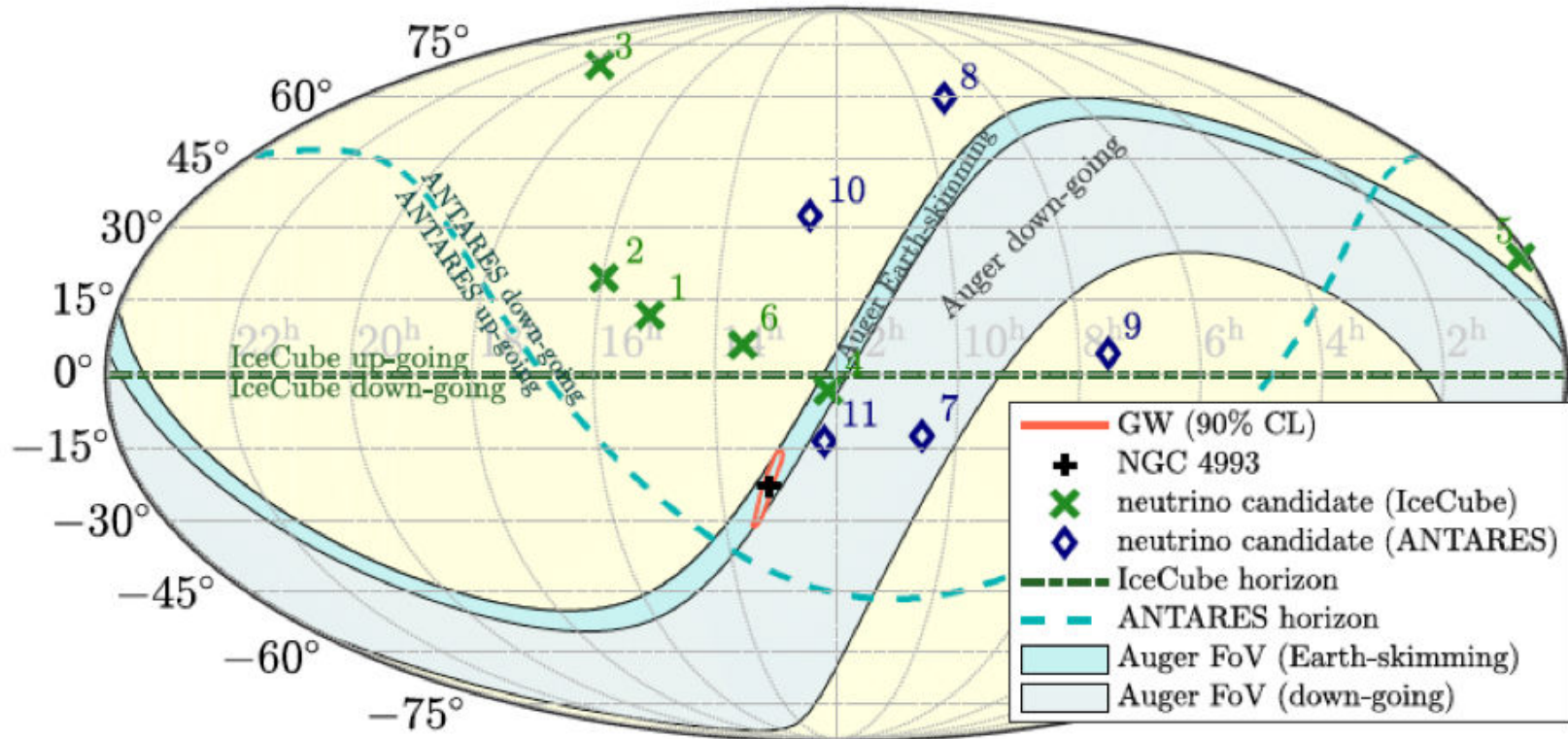
302,000 EVENTS





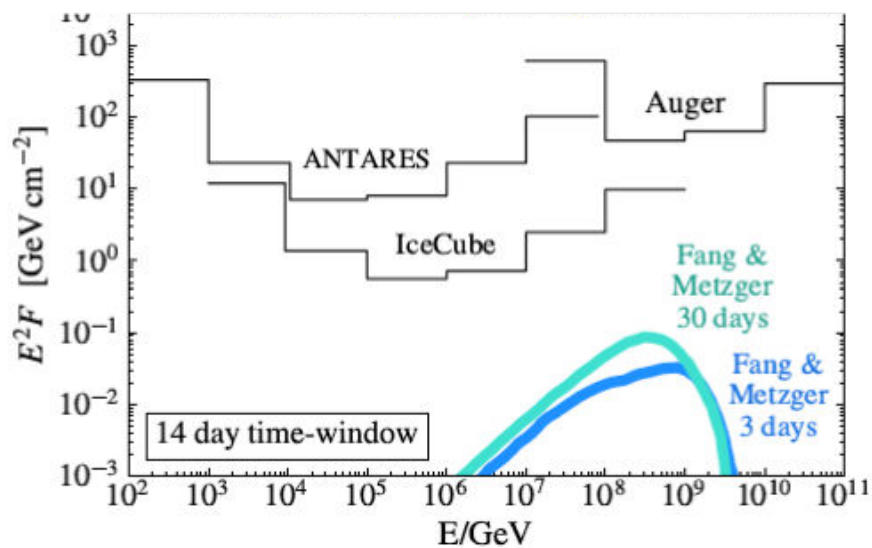
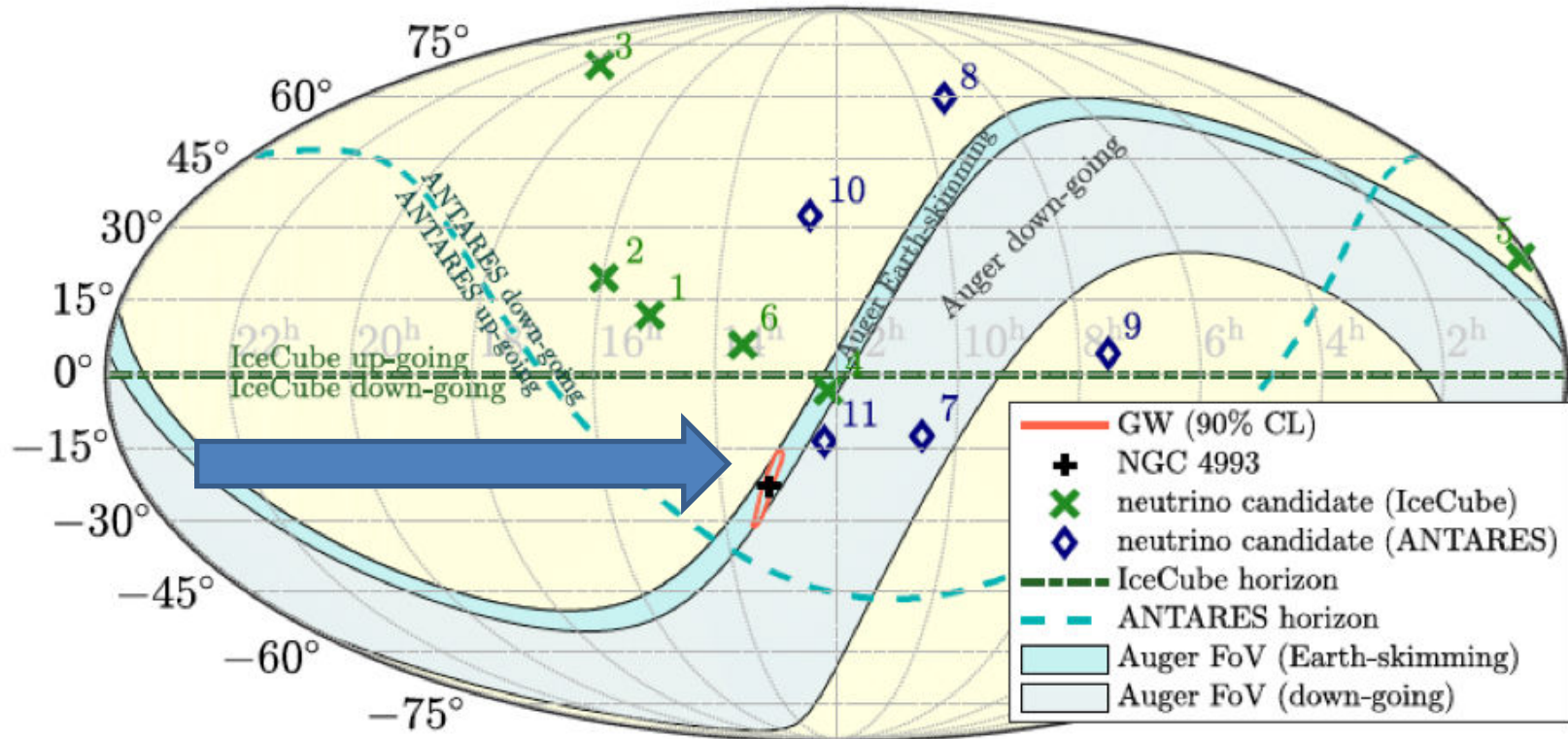
credit M. Bustamante





arXiv:1710.05839

**GW170817 follow up w  
ANTARES, ICECUBE, AUGER**



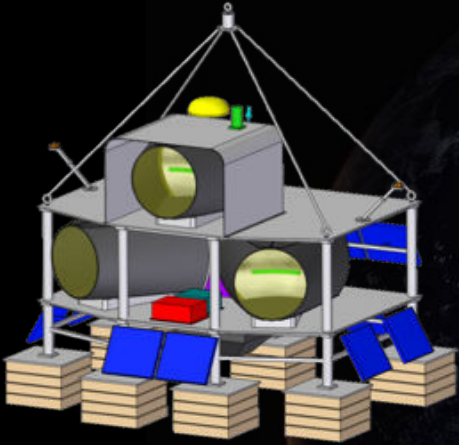
arXiv:1710.05839

**GW170817 follow up w  
ANTARES, ICECUBE, AUGER**

# TOWARDS SPACE PROBES OF UHECRS AND NEUTRINOS SOURCES AND INTERACTIONS

POEMMA

EUSO-SPB2



EUSO-SPB1



THE EARTH ATMOSPHERE  
AS AN EXTREME ENERGY  
PARTICLE OBSERVATORY

POEMMA

The logo for POEMMA, featuring the word "POEMMA" in a white, sans-serif font, arched over a stylized blue and white graphic that resembles a satellite or a probe.

**POEMMA:**  
**PROBE OF EXTREME MULTI-MESSENGER**  
**ASTROPHYSICS**  
**UHECRs AND NEUTRINOS**



# POEMMA: STUDY COLLABORATION

University of Chicago: *Angela V. Olinto (PI)*

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University of Alabama, Huntsville: James Adams, Patrick Reardon, Evgeny Kuznetsov, J. Watts Jr., J. Tubbs, M. Mastafa

NASA/GSFC: John W. Mitchell, John Krizmanic, Jeremy S Perkins, Julie McEnery, Elizabeth Hays, Floyd Stecker, Stan Hunter, Jonathan Ormes

University of Utah: Doug Bergman, John Matthews

Colorado School of Mines: Lawrence Wiencke, Frederic Sarazin

City University of New York, Lehman College: Luis Anchordoqu, Thomas C. Paul

Georgia Institute of Technology: A. Nepomuk Otte

Space Sciences Laboratory, University of California, Berkeley: Eleanor Judd

University of Iowa: Mary Hall Reno

Jet Propulsion Laboratory: Insoo Jun, L. M. Martinez-Sierra

Vanderbilt University: Steven E Csorna

APC Univerite de Paris 7: Etienne Parizot, Guillaume Prevot

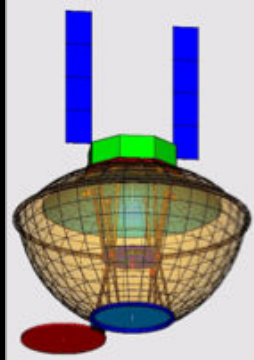
Universita di Torino: Mario Edoardo Bertaina, Francesco Fenu, Kenji Shinozaki

University of Geneva: Andrii Neronov

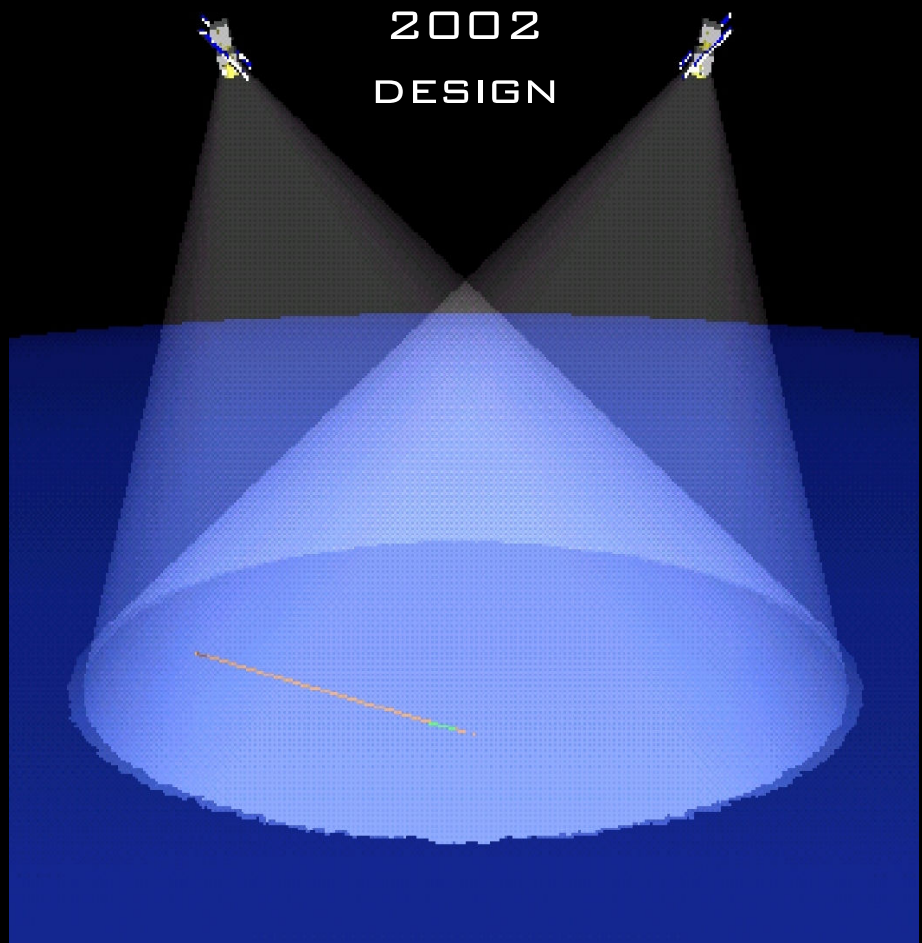
Gran Sasso Science Institute: Roberto Aloisio

**SCIENTISTS FROM 16+ INSTITUTIONS FROM  
OWL, JEM-EUSO, AUGER, TA, VERITAS, CTA, FERMI, THEORY**

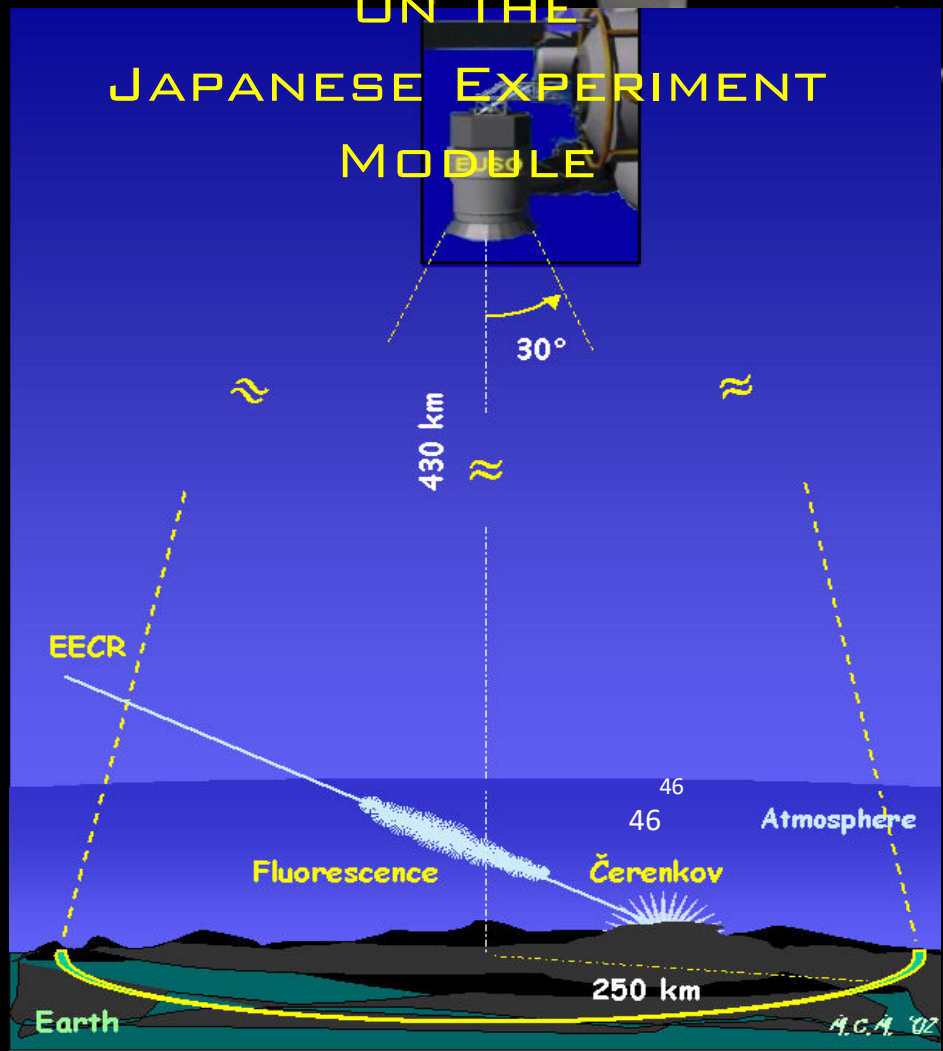
# EXTENSIVE AIR-SHOWER FLUORESCENCE FROM SPACE



OWL  
2002  
DESIGN

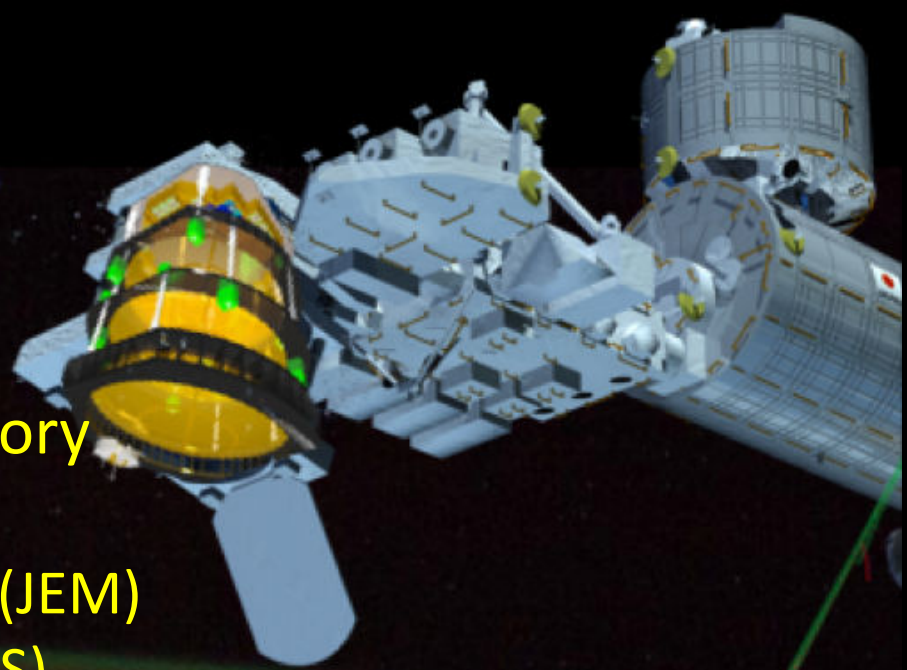


EUSO  
ON THE  
JAPANESE EXPERIMENT  
MODULE



# JEM-EUSO

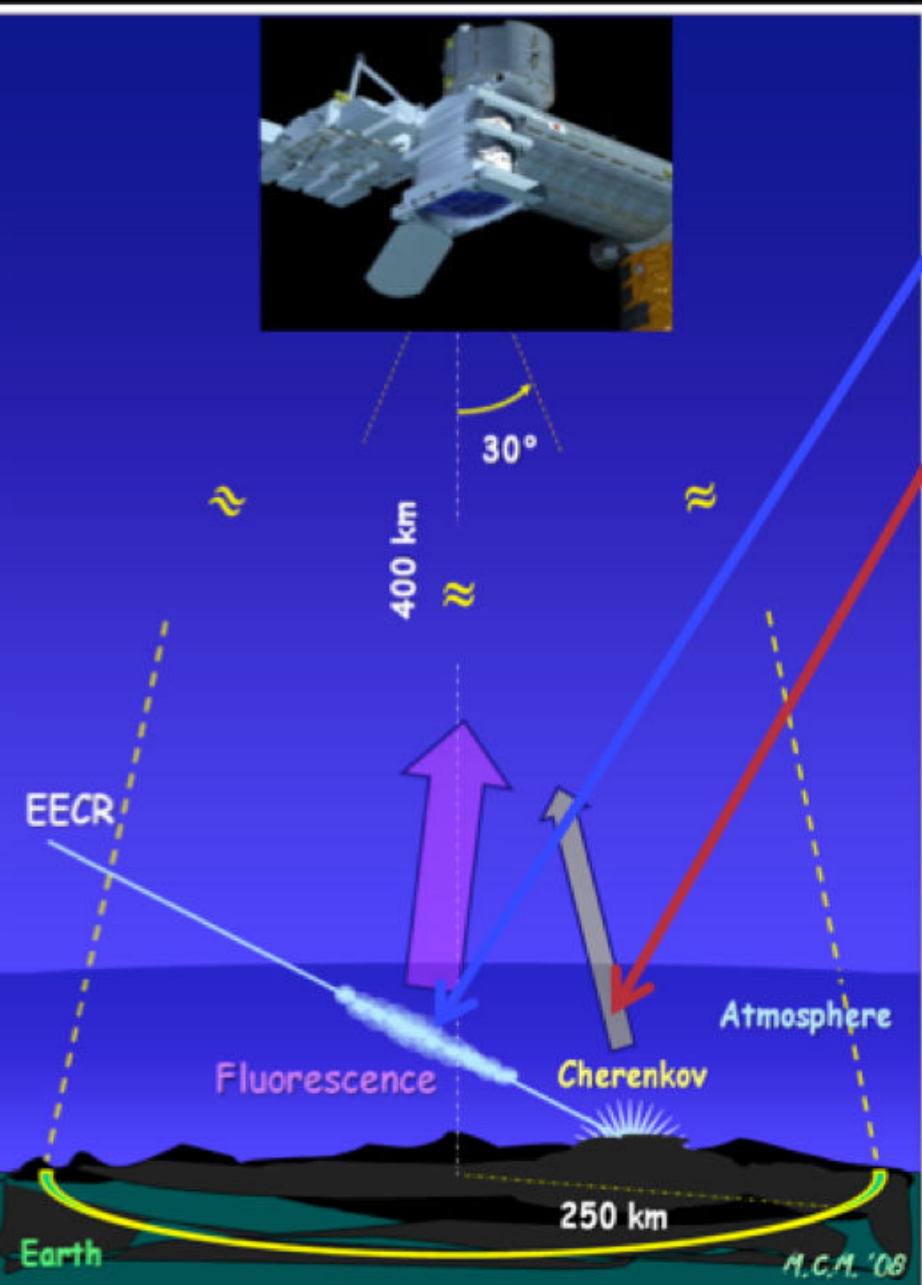
Extreme Universe Space Observatory  
(EUSO)  
in the Japanese Experiment Module (JEM)  
of the International Space Station (ISS)



Collaboration: 16 Countries, 95 Institutes, 358 Researchers  
Refractor Fresnel Lenses large FOV and large MAPMT camera  
with 0.3M pixels

16 Countries, 95 Institutes, 358 Researchers

# Fluorescence from SPACE

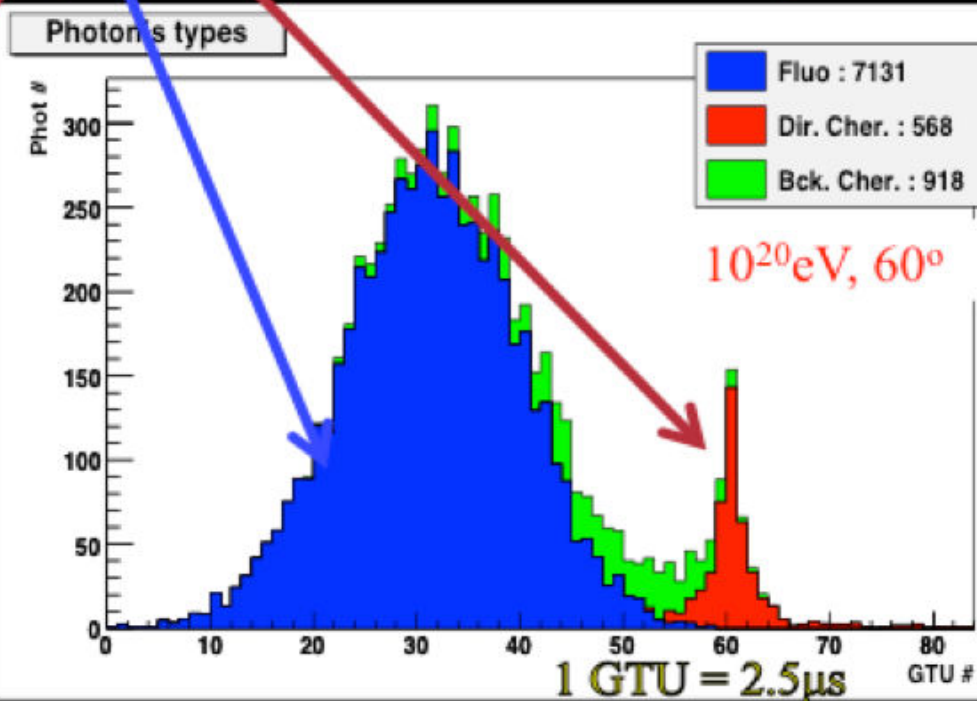


Fast Signal: 50 -150  $\mu$ s

a) Fluorescence

b) Scattered Cherenkov

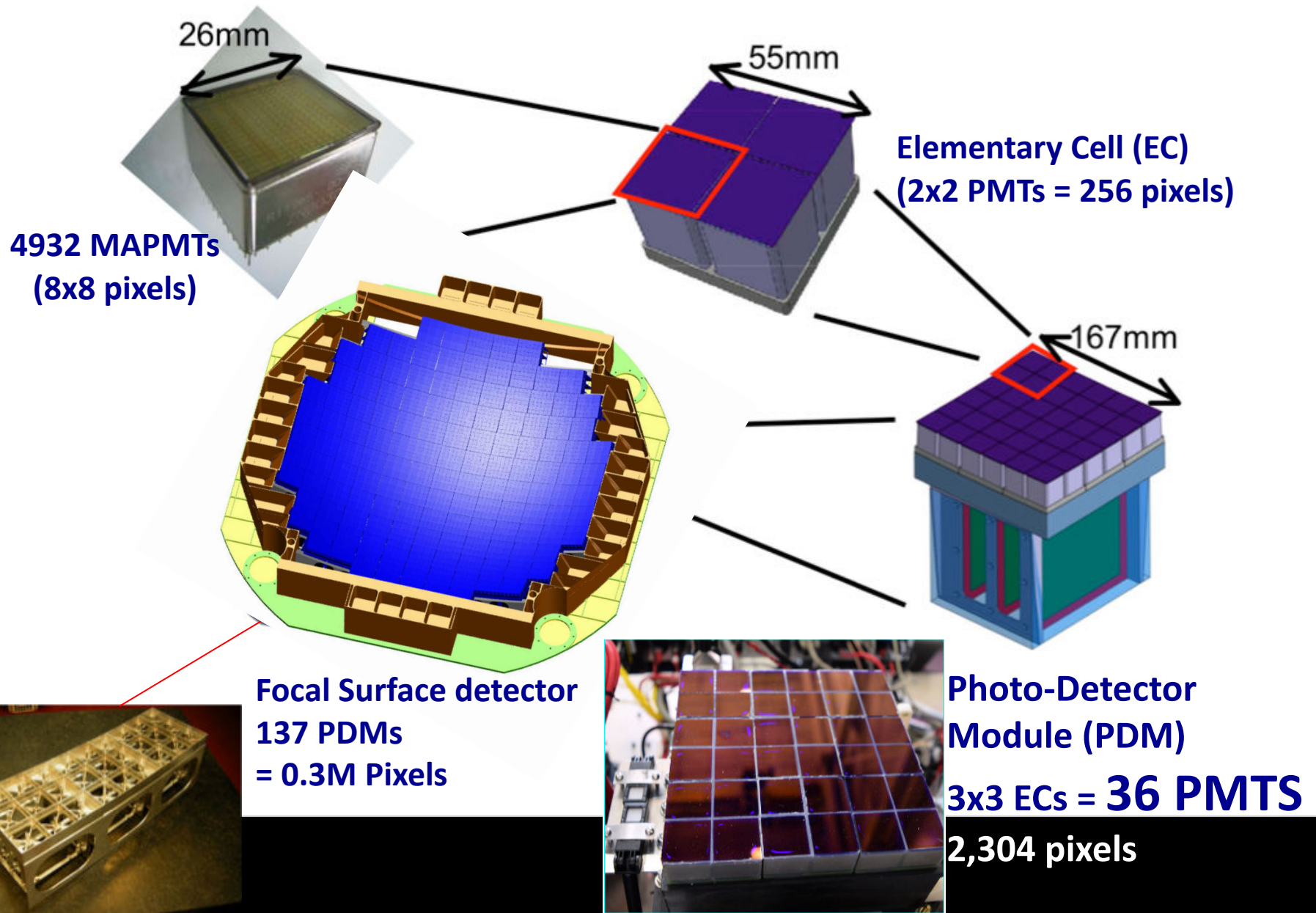
c) Direct (reflected Cherenkov)



Background: 500 /m<sup>2</sup> sr ns



# Focal Surface Detector



# JEM-EUSO PROGRAM

EUSO-TA (2013- )

EUSO-Balloon (2014)

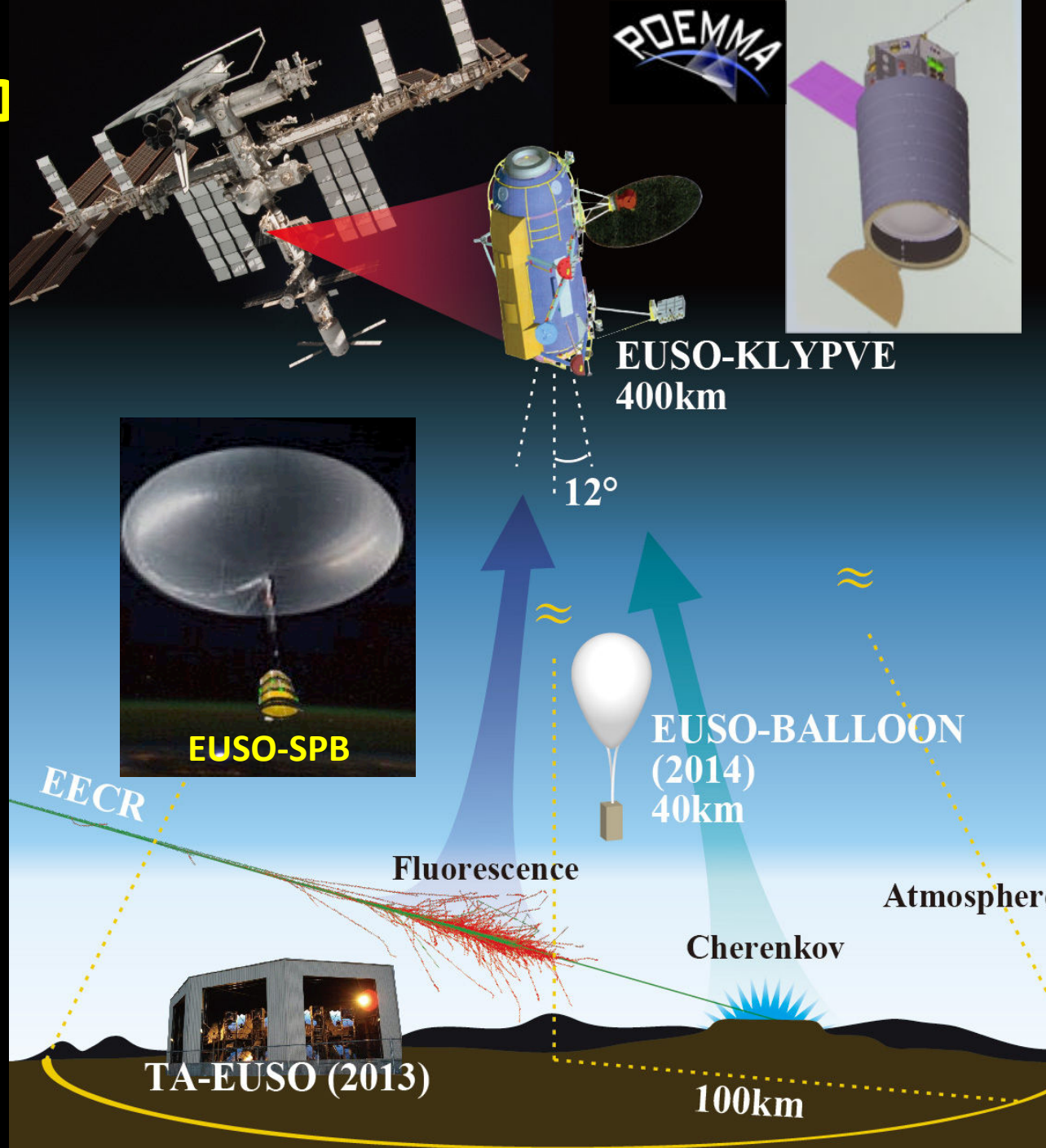
EUSO-SPB1 (2017)

Mini-EUSO (2018-19)

EUSO-SPB2 (2020-22)

K-EUSO (2023+)

POEMMA (2028+)



EUSO Balloon:  
1<sup>st</sup> flight and first light on 24-25.8.2014

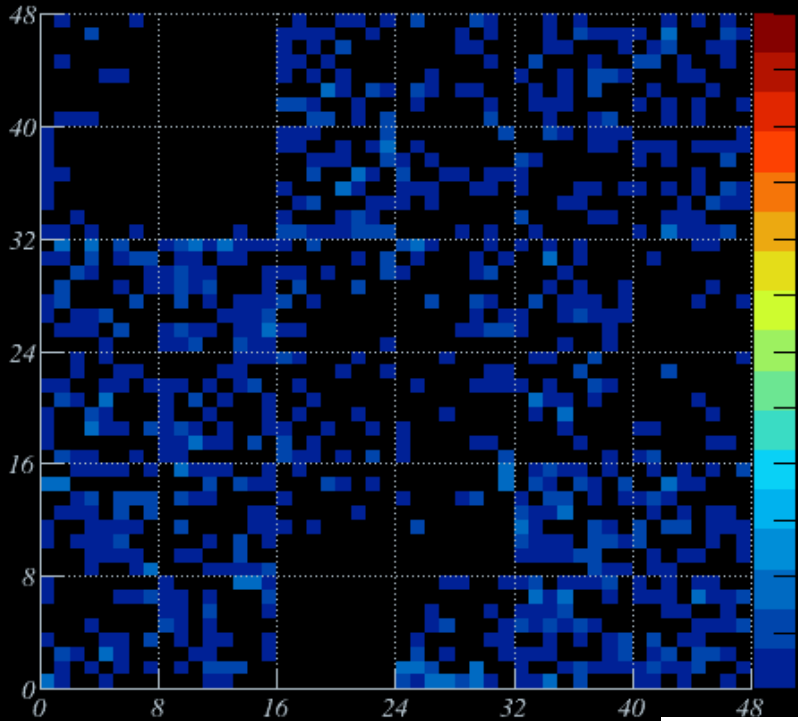


# EUSO-BALLOON 2014

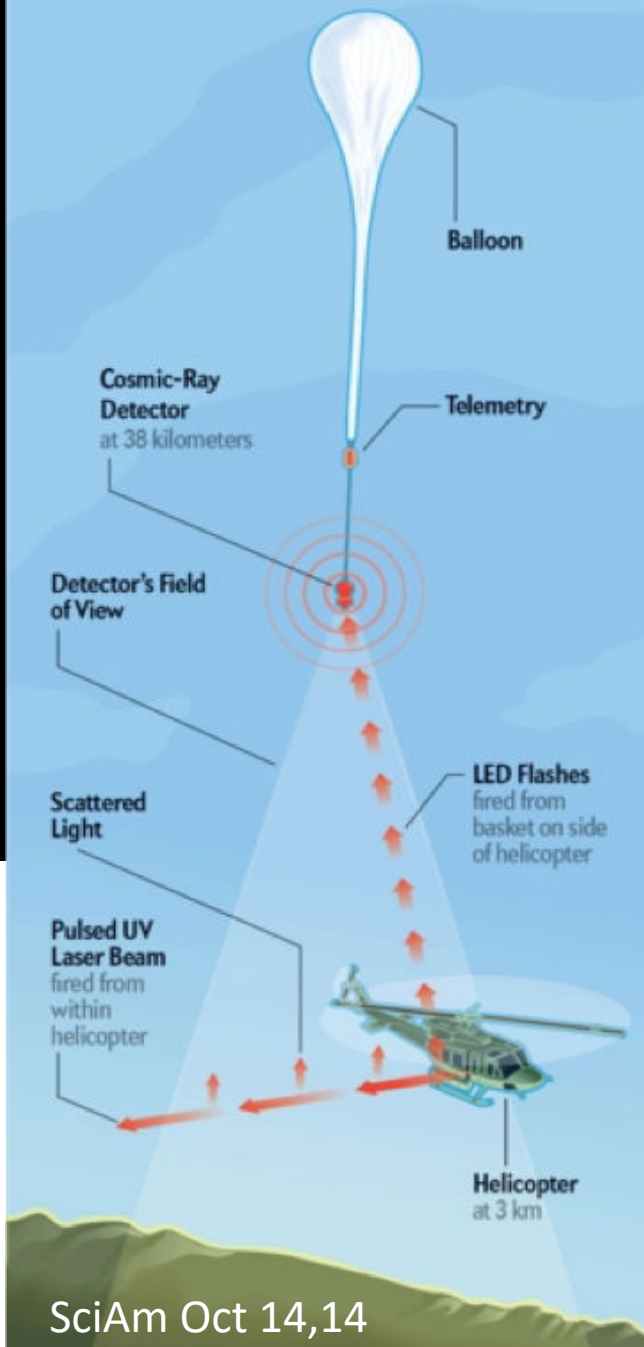
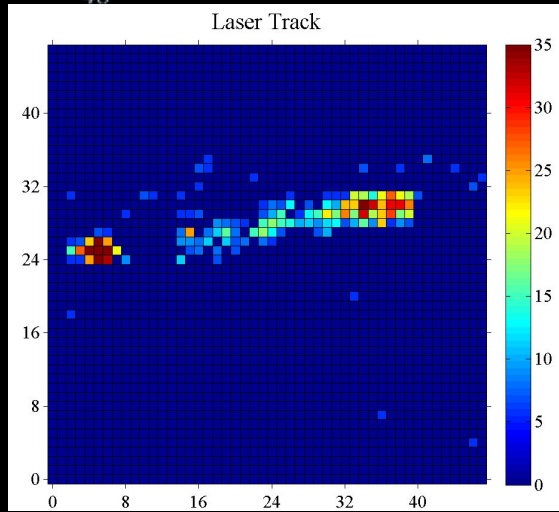
## FLASHER & LASER EVENTS

Aver.Count: 0.442

GTU : 0

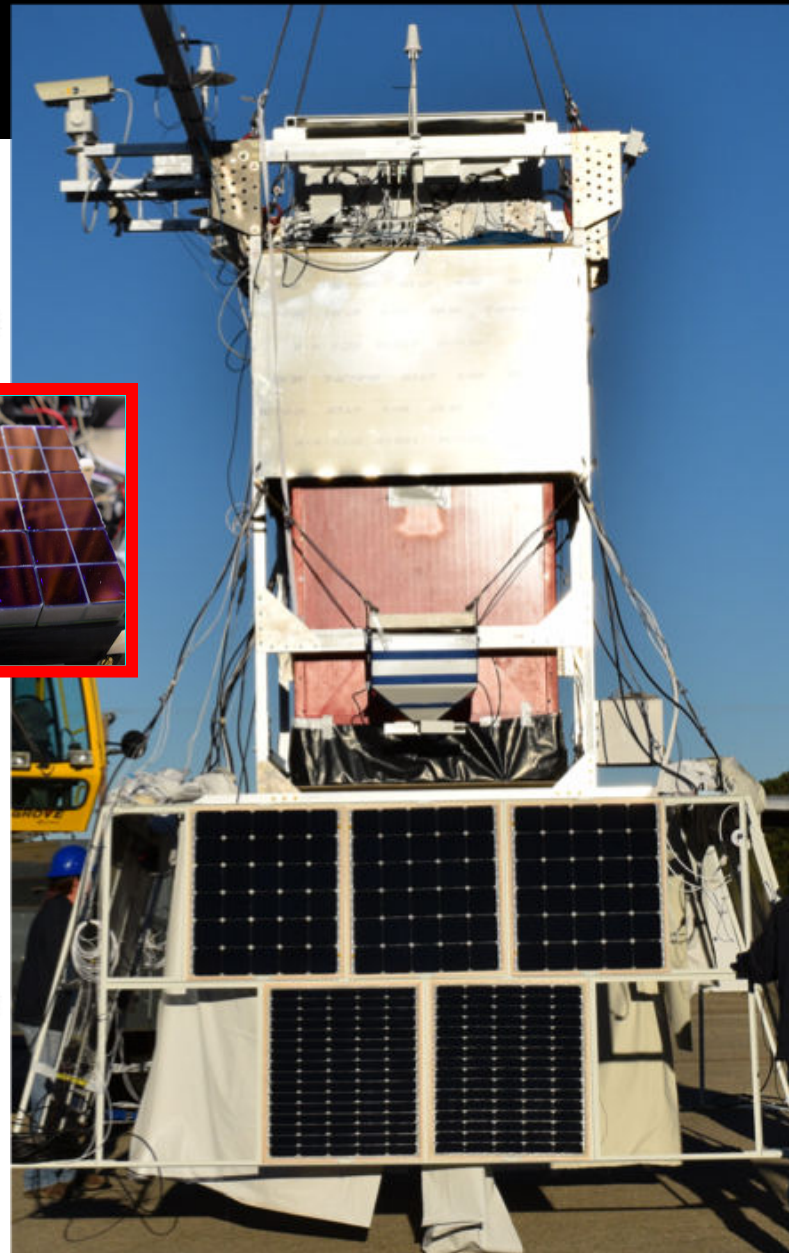
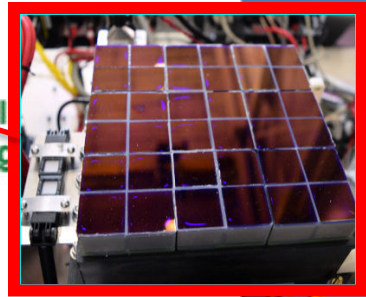
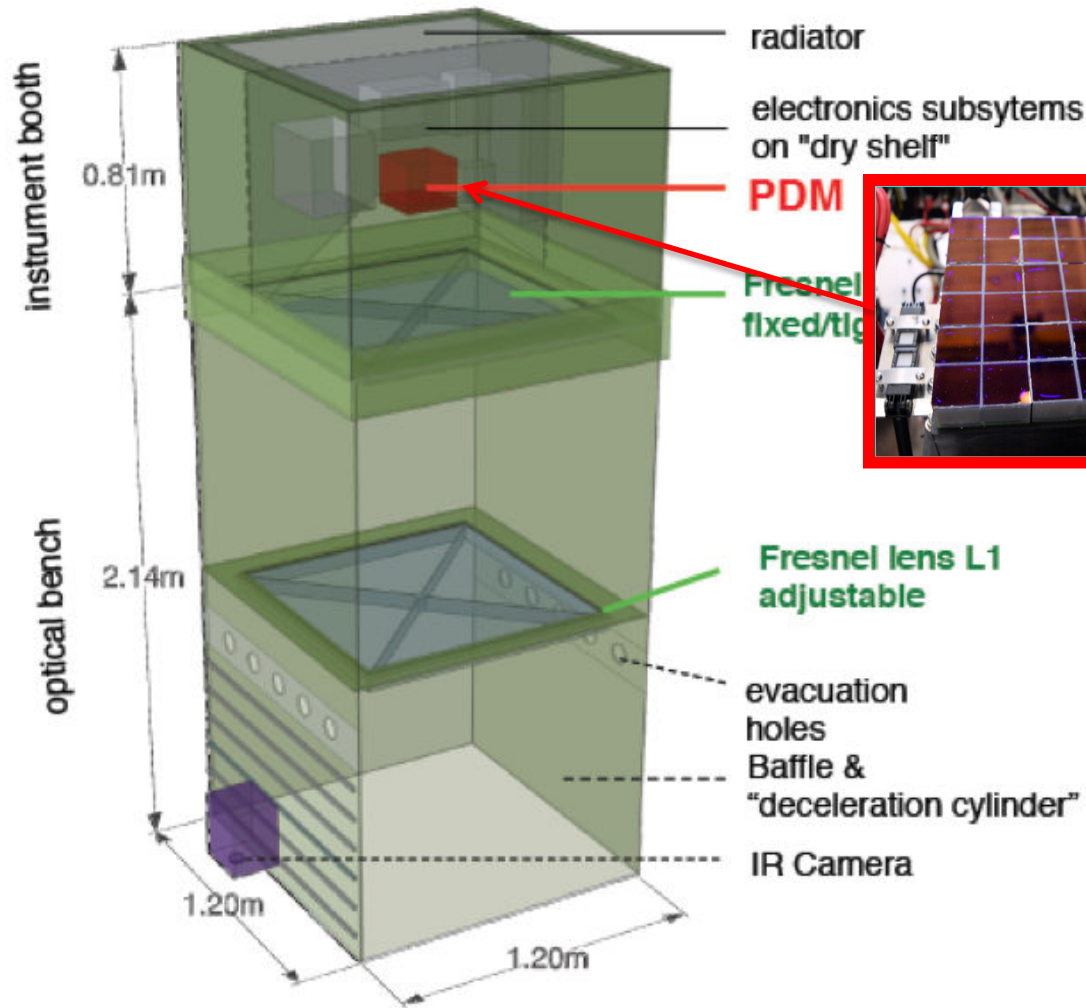


355nm Laser:  
~ $10^{20}$  eV equivalent brightness



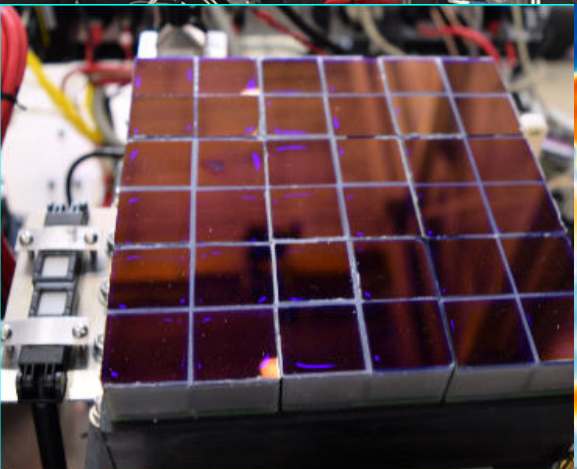
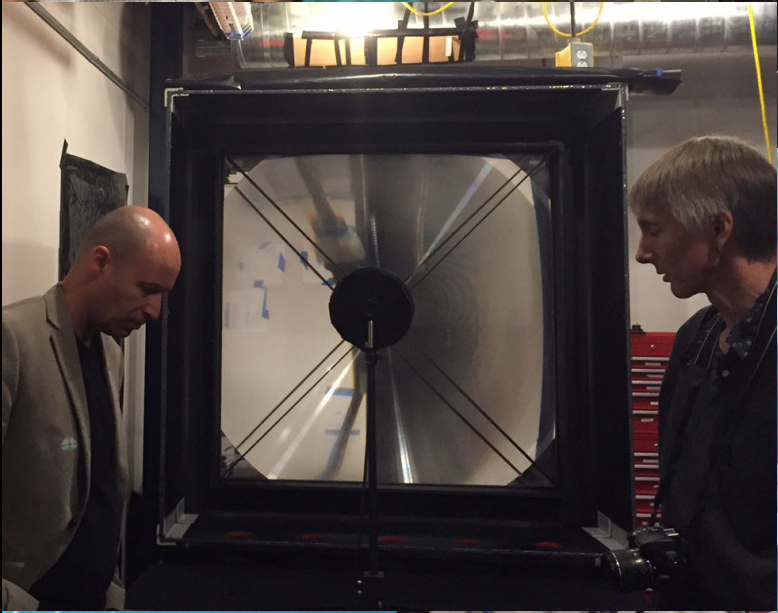
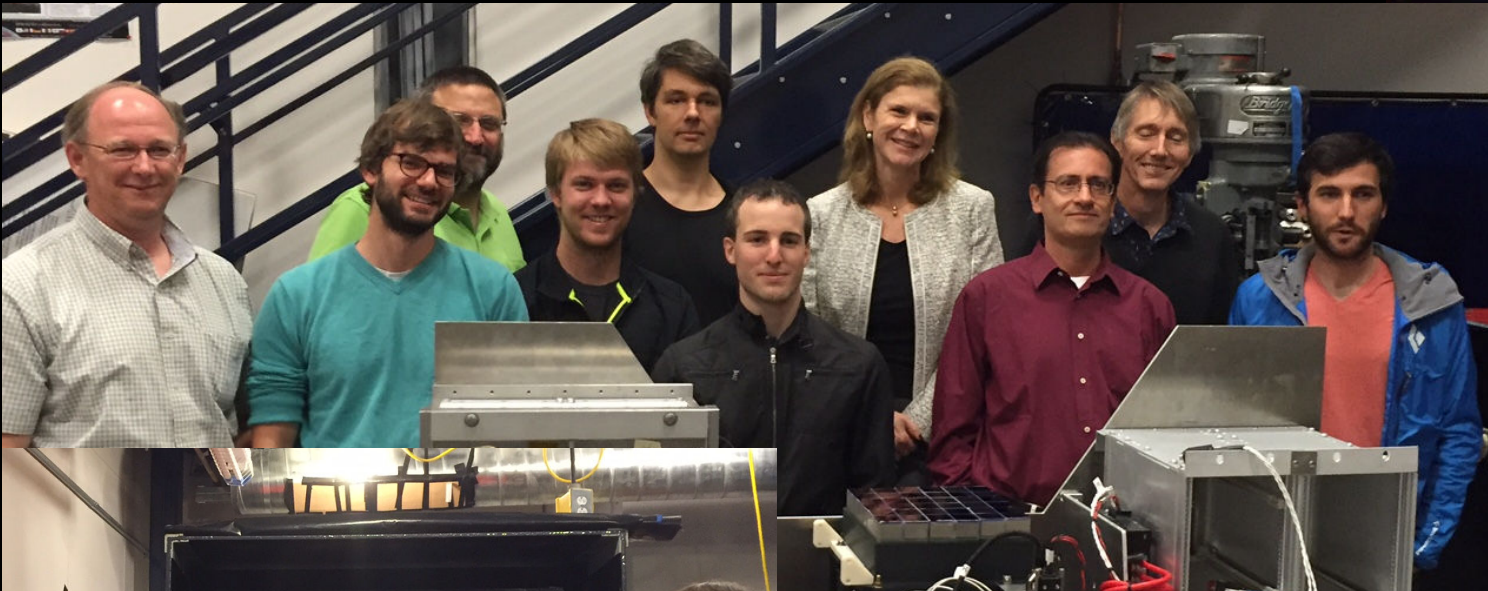
SciAm Oct 14,14

# EUSO-SPB Extreme Universe Space Observatory on a Super Pressure Balloon



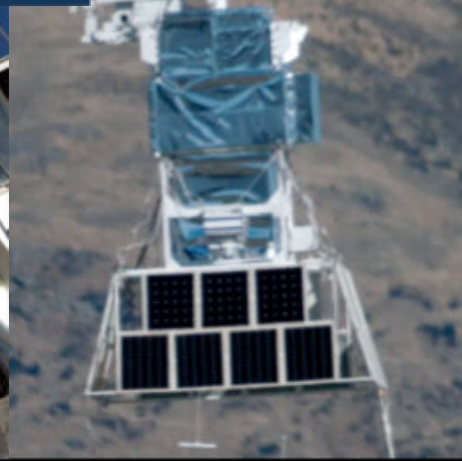
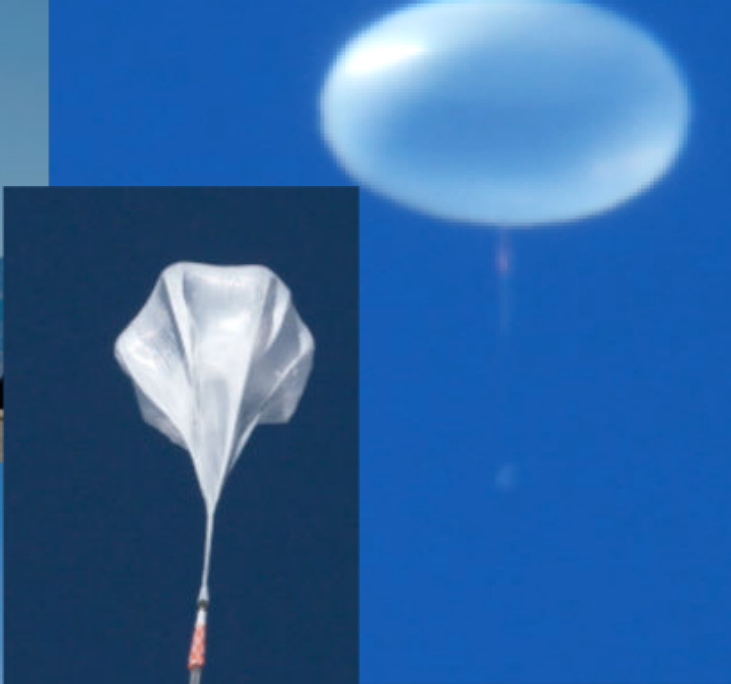
# EUSO-SPB Extreme Universe Space Observatory on a Super Pressure Balloon

Ultrafast Camera: Photo-Detector Module (PDM)  
(3x3 ECs = 36 MAPMTs ; 2,304 pixels)



# EUSO-SPB Extreme Universe Space Observatory on a Super Pressure Balloon



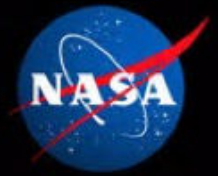


EUSO-SPB  
LAUNCH,  
APRIL 24,  
2017  
23:51 UTC



# WANAKA 2017 Campaign

## Super Pressure Balloon (SPB) EUSO mission



2015

NASA Engineering Flight



32 d 5 h

2016

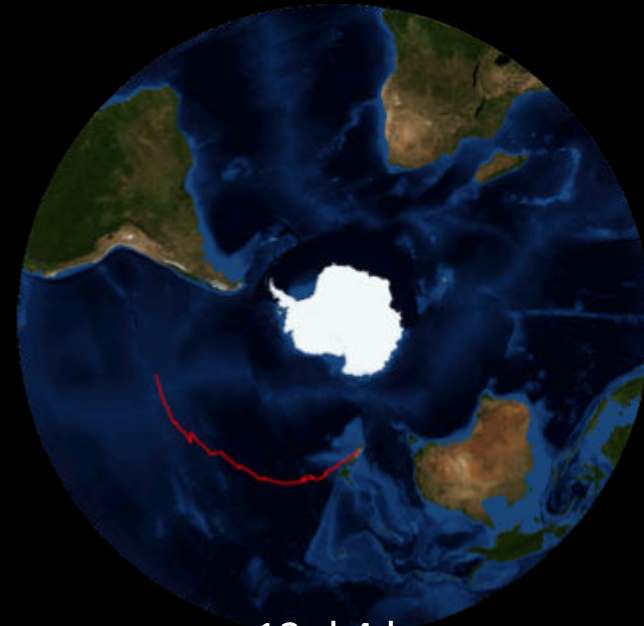
COSI



46 d 20 h

2017

EUSO-SPB

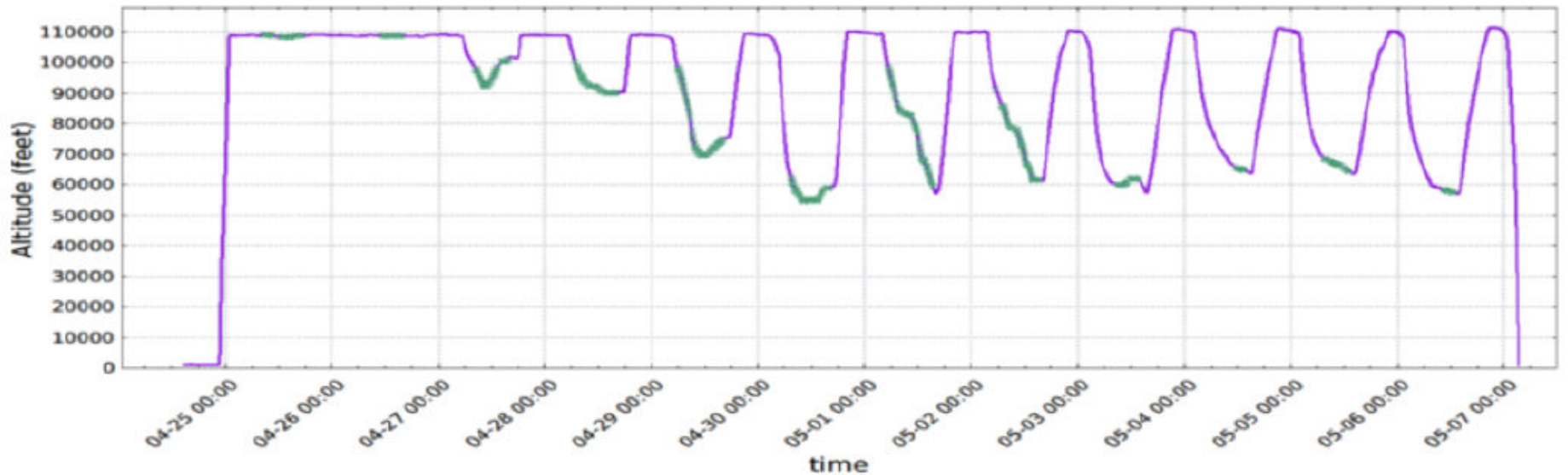


12 d 4 h

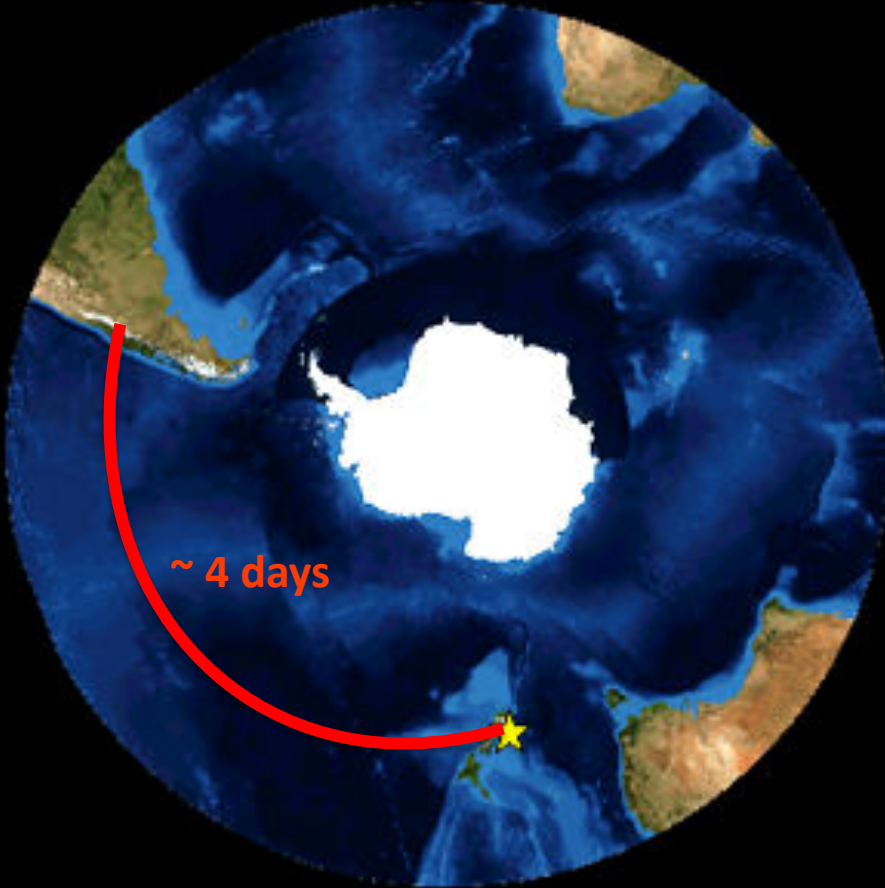
NASA completed its third mid-latitude Super Pressure Balloon (SPB) flight a 11:24 p.m. EDT, Saturday, May 6, after 12 days, 4 hours and 34 minutes aloft



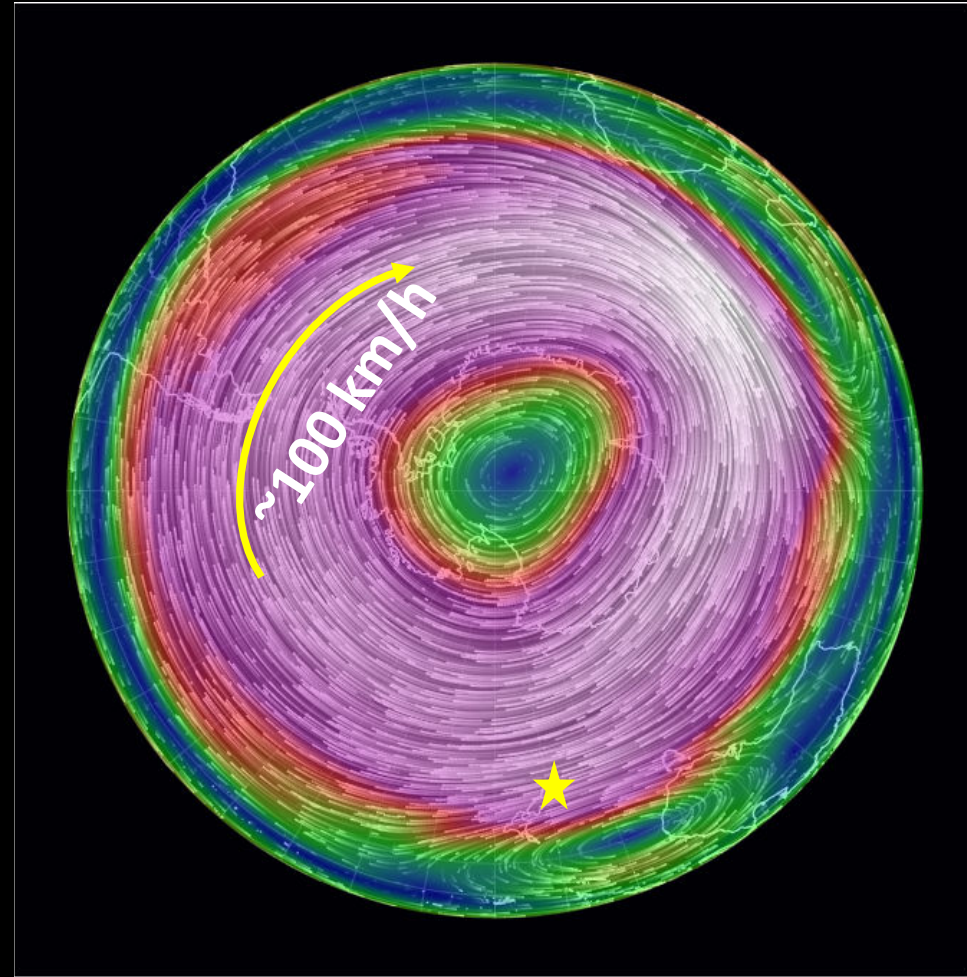
Flight Data Status



# Why New Zealand?



Wanaka  
South Island  
New Zealand

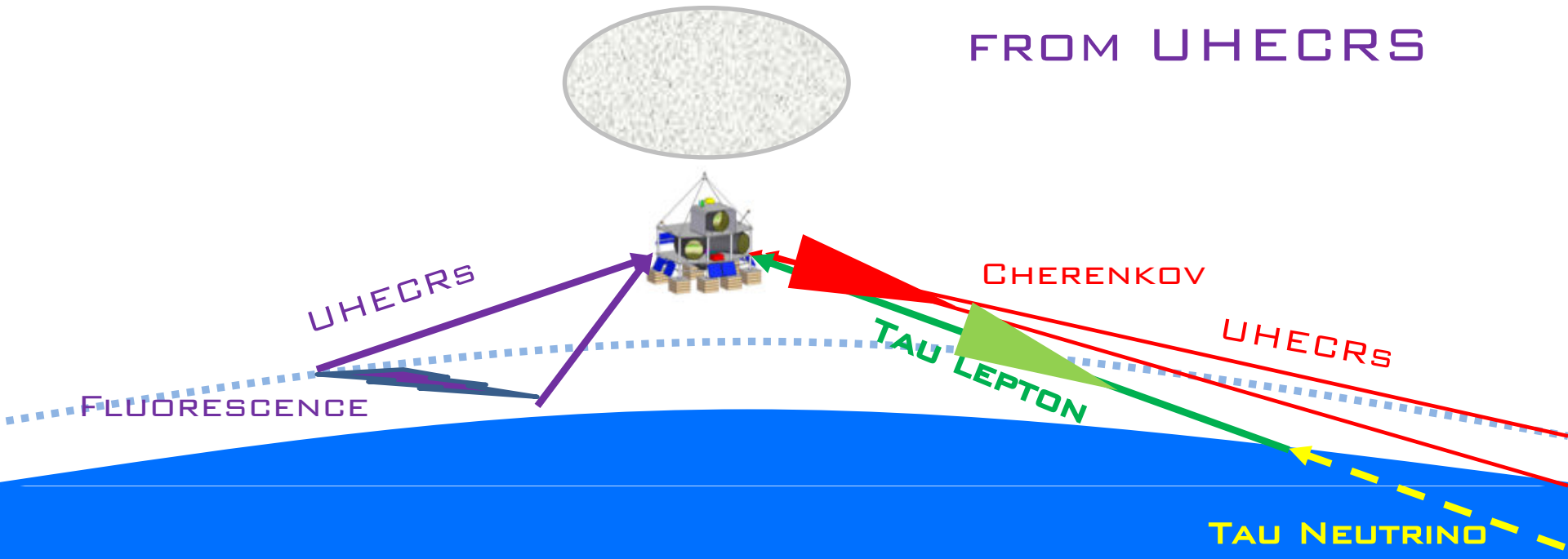
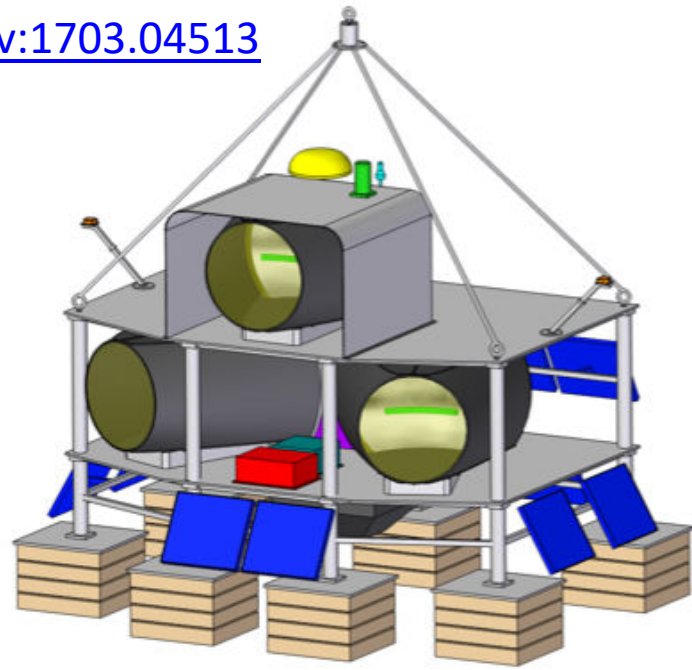


air flow at ~30 km June 9<sup>th</sup> 2017

<https://earth.nullschool.net/#current/wind/isobaric/10hPa/orthographic=180,-90,300>

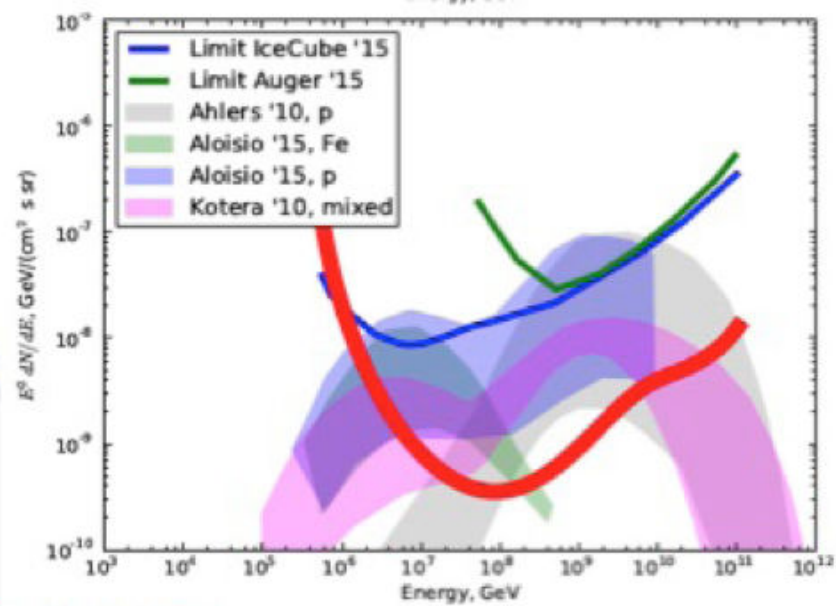
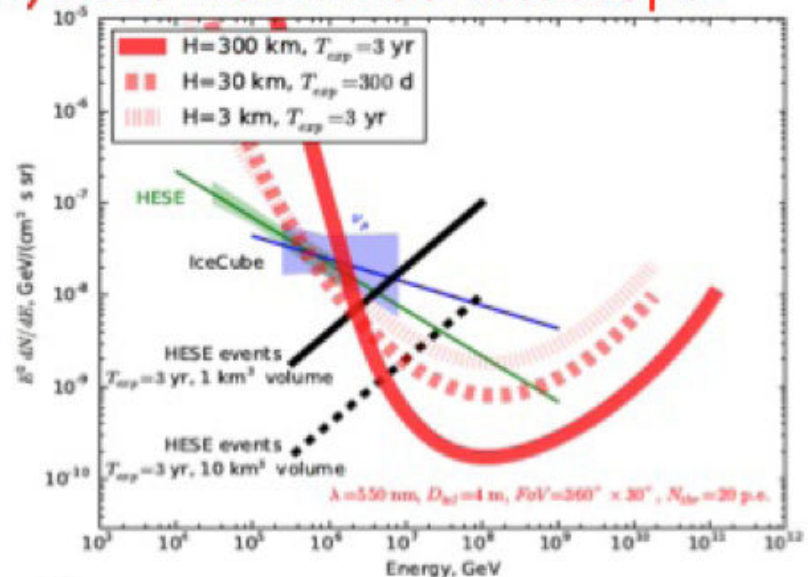
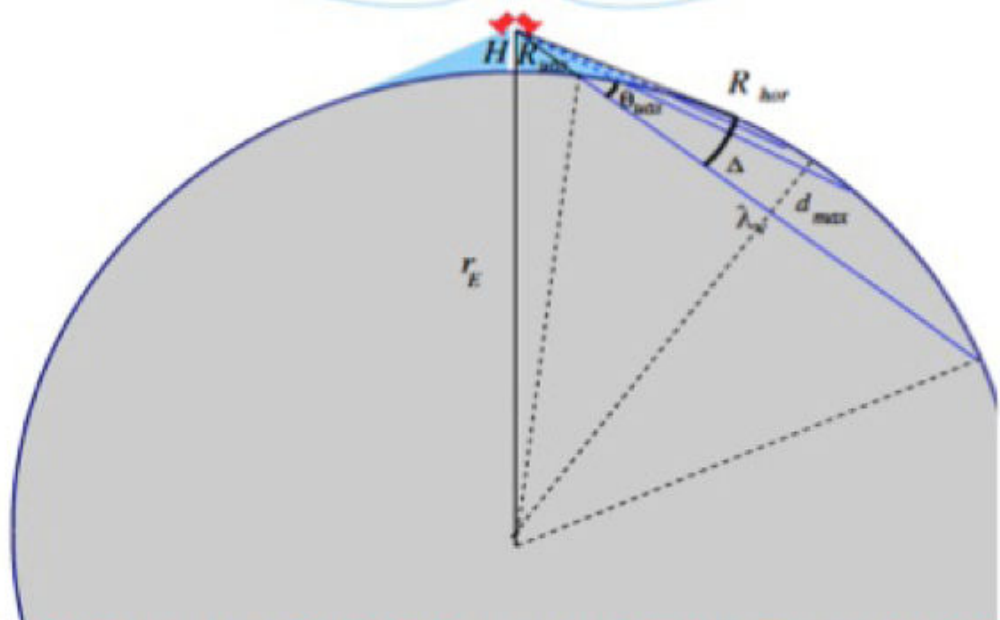
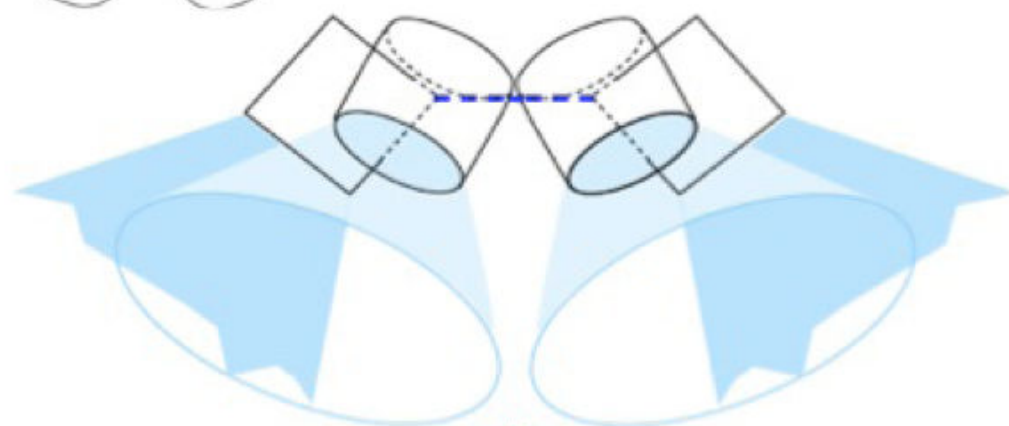
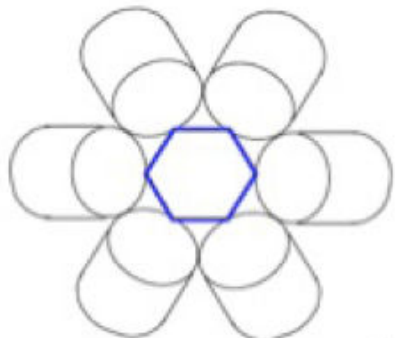
# EUSO-SPB2

CHERENKOV EMISSION  
FROM UHECRs  
TAU NEUTRINO  
BACKGROUND  
FLUORESCENCE  
FROM UHECRs



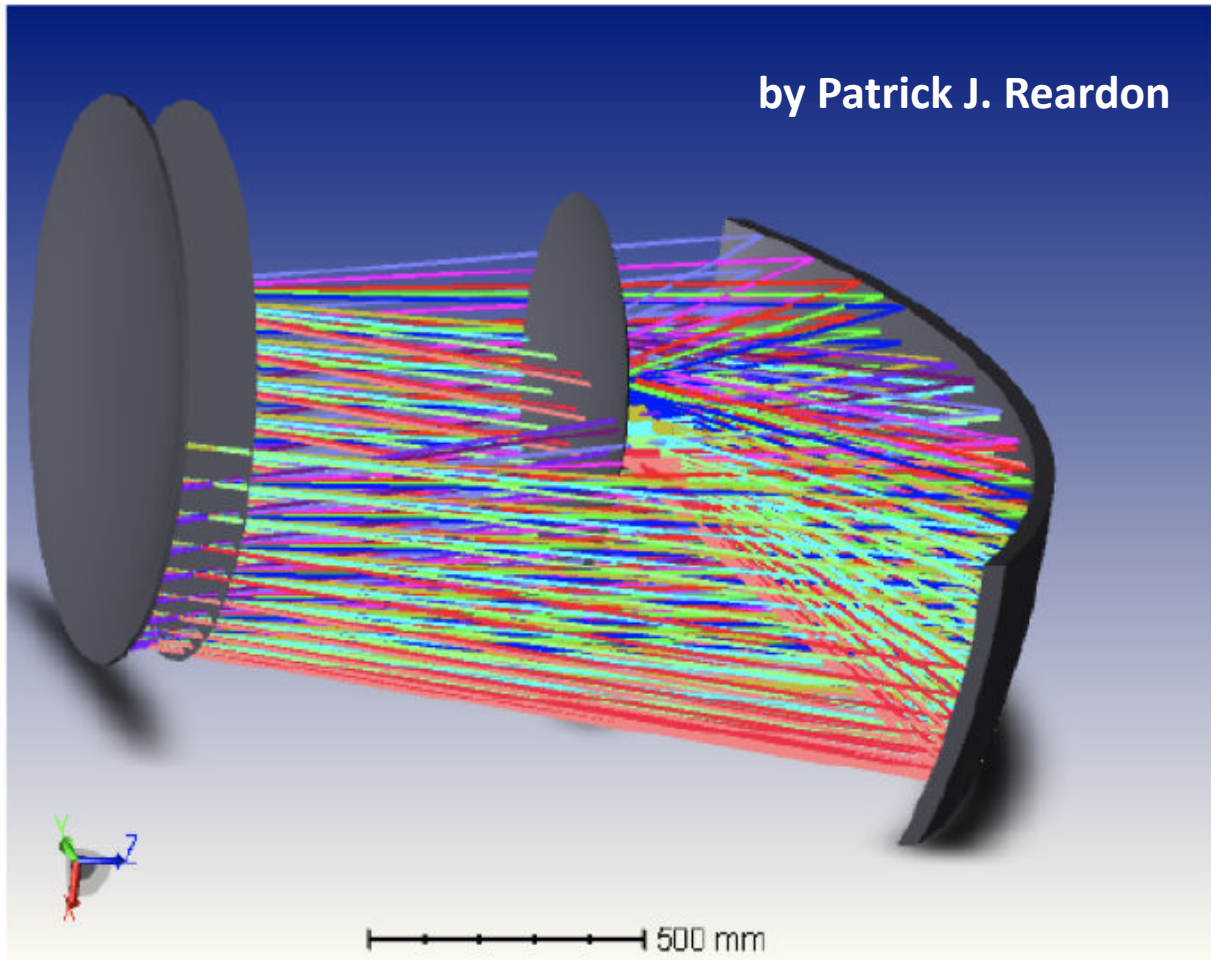
# CHANT

## Cherenkov from Astrophysical Neutrinos Telescope



# Bifocal Design

by Patrick J. Reardon



## Cherenkov Telescopes

FoV  $5^\circ \times 45^\circ$  bi-focal mirror

FoV  $5^\circ \times 45^\circ$  normal mirror

## Focal Surface

7cm x 70cm

## Fluorescence Telescope

FoV  $15^\circ \times 45^\circ$  normal mirror

Corrector Plate:  $1\text{m}^2$

Image resolution:  $\sim$  few mm

Pixel size:  $\sim 3\text{mm}$  square

## Challenges/Opportunities:

Space qualified SiPMs, ultra-fast ASICs, corrector lens development, bifocal mirror  
SPB stability

POEMMA

The logo for POEMMA, featuring the word "POEMMA" in a white, sans-serif font, arched over a stylized blue and white graphic that resembles a satellite or a probe.

**POEMMA:**  
**PROBE OF EXTREME MULTI-MESSENGER**  
**ASTROPHYSICS**  
**UHECRs AND NEUTRINOS**



# POEMMA

## PROBE OF EXTREME MULTI-MESSENGER ASTROPHYSICS

**Class B Mission**

**2 observatories: Stereo Observations**

**3-year Prime Mission,**

**5-year Mission Goal**

**LEO 525 km, 28.5° inclination**

**300 km to 25 km separation**

**Controlled re-entry/decommission**

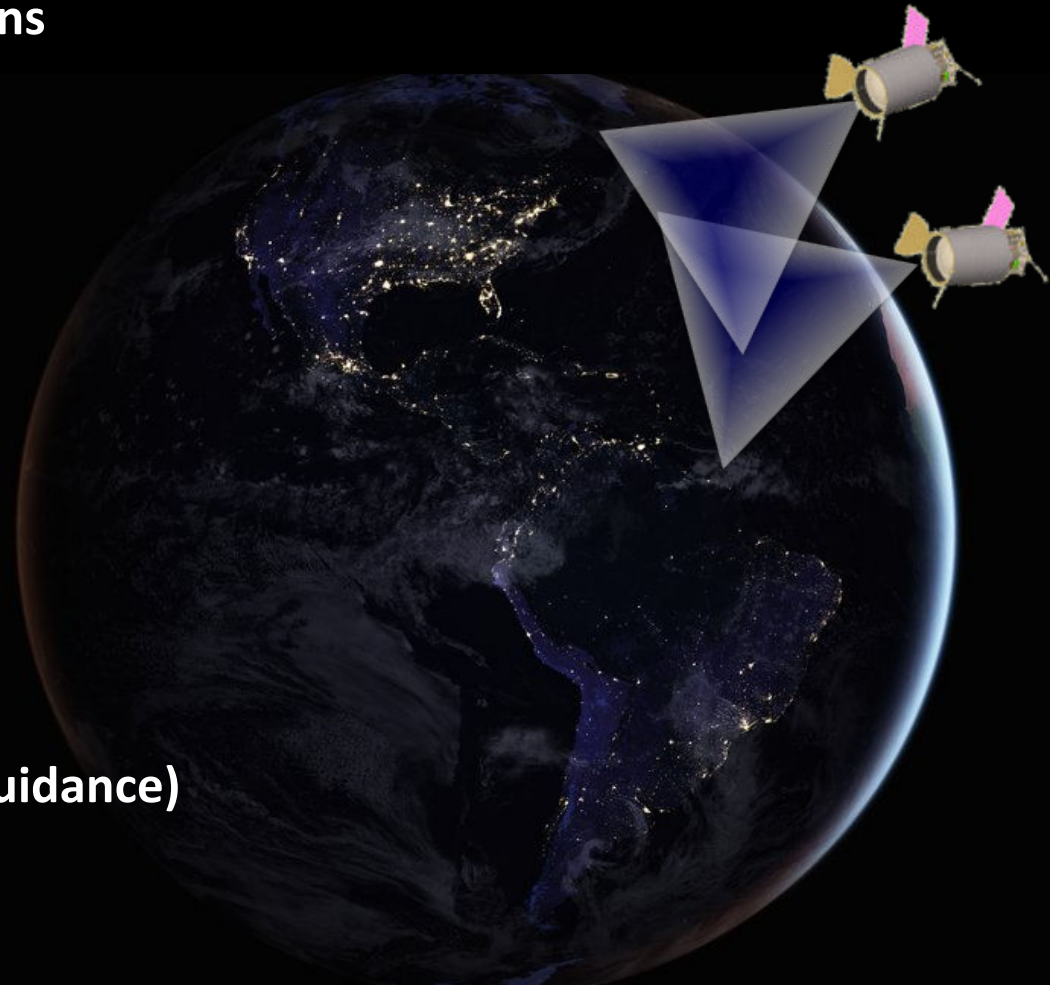
**4 meter f/0.64 Schmidt telescope**

**45° FoV**

**MAPMT and SiPM focal surface**

**Phase A start 10/2023 (NASA HQ guidance)**

**Launch 11/2029 (MDL forecast)**



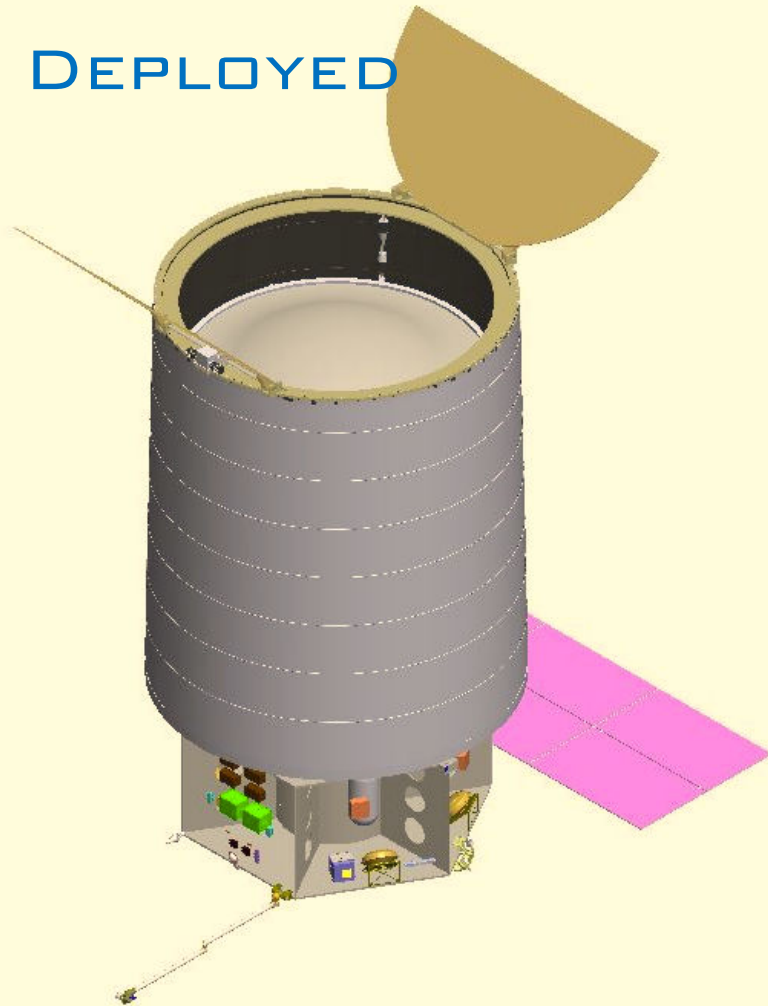




# POEMMA

## PROBE OF EXTREME MULTI-MESSENGER ASTROPHYSICS

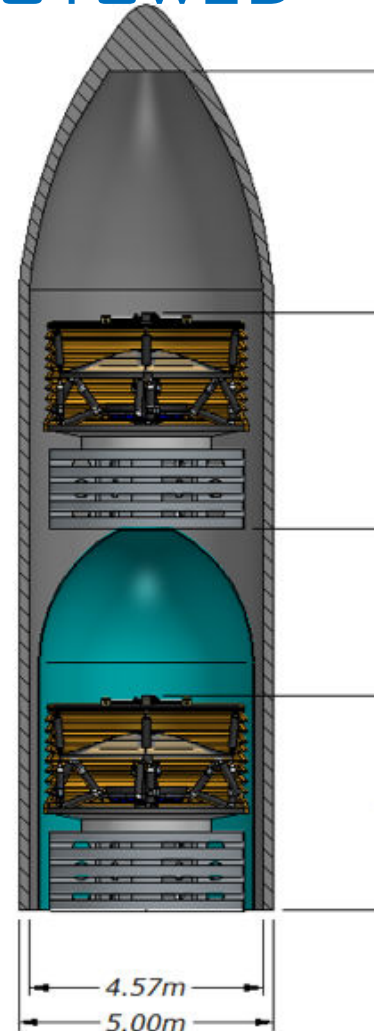
DEPLOYED

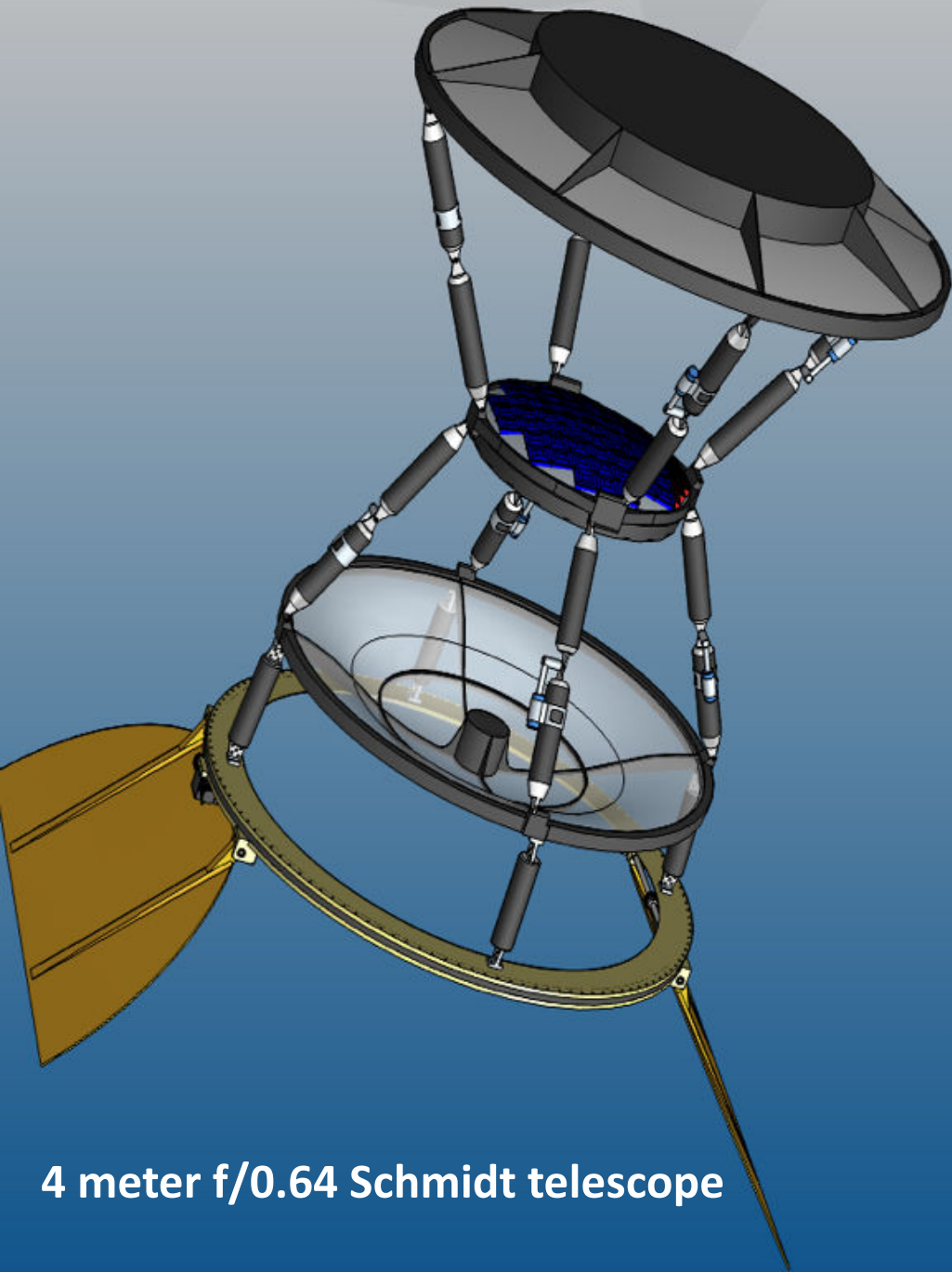


POEMMA	
Mass/Instrument	1547 kg
Primary Mirror	4 m
Corrector Lens	3.3 m
Focal Surface	1.6 m
Aperture (m <sup>2</sup> )	6 to 2
Power	550 W
Data (MB/day)	1043

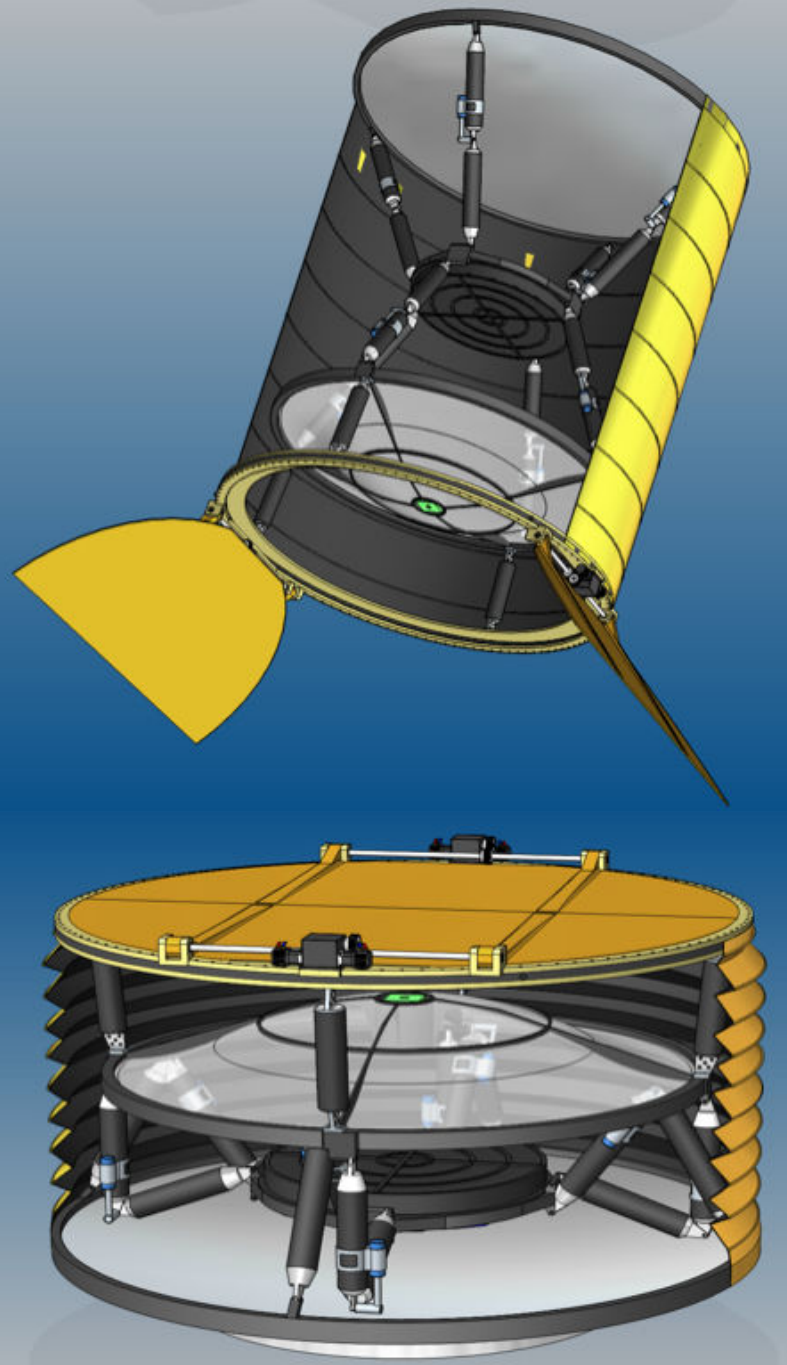
Dual Manifest in  
ATLAS V LPF

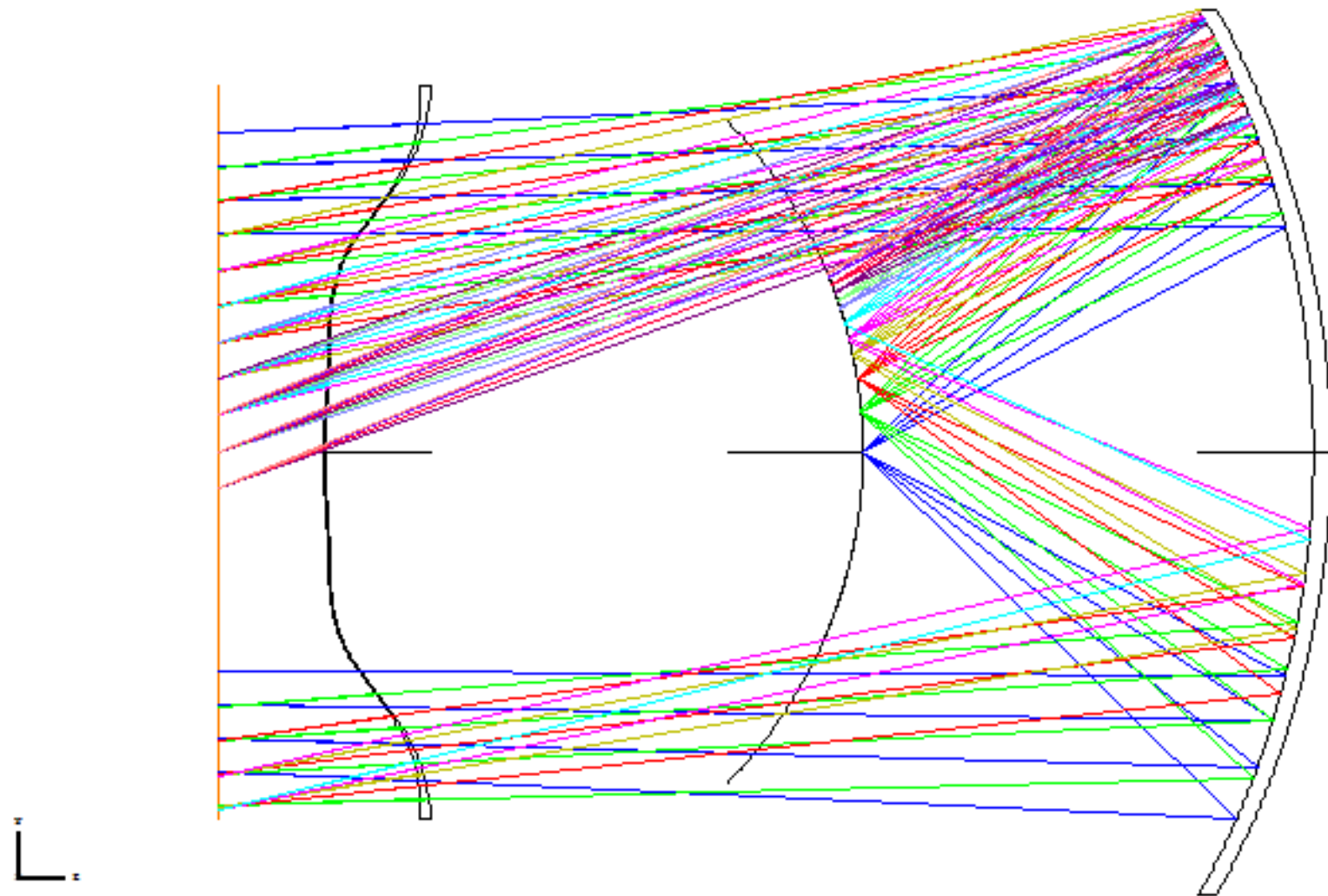
STOWED





4 meter f/0.64 Schmidt telescope





3D Layout

F/0.64, EFL=2.08m, EPD=3.3m, UV: 3.3m Corrector

Center for Applied Optics

University of Alabama in Huntsville  
Patrick J. Reardon

DeScopePOEMMA Start R01S02FT.zmx  
Configuration 1 of 1



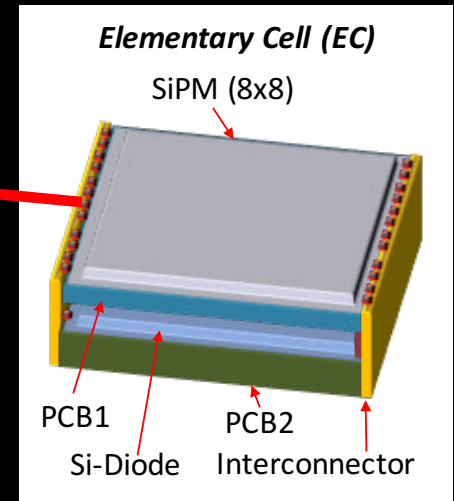
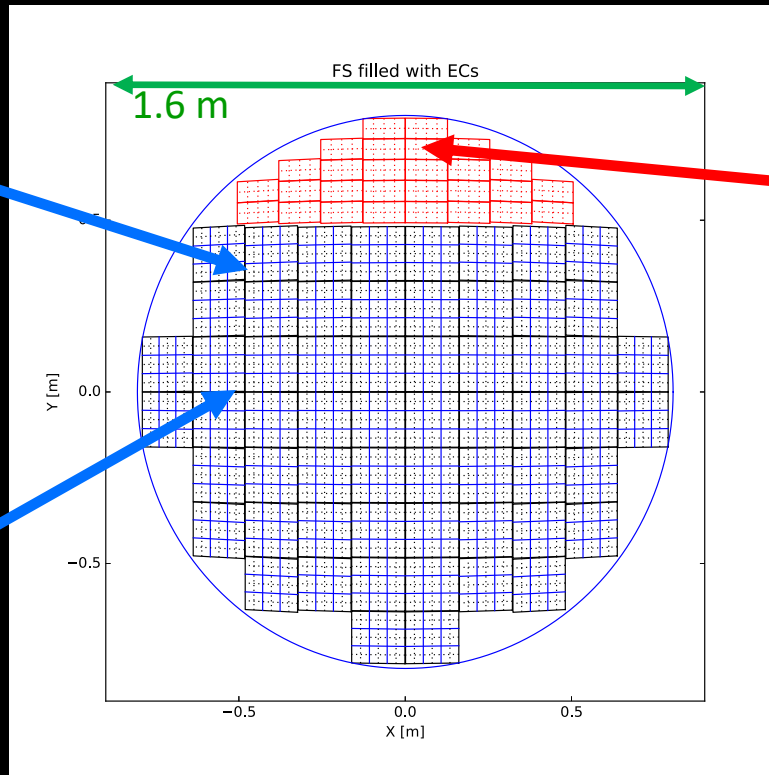
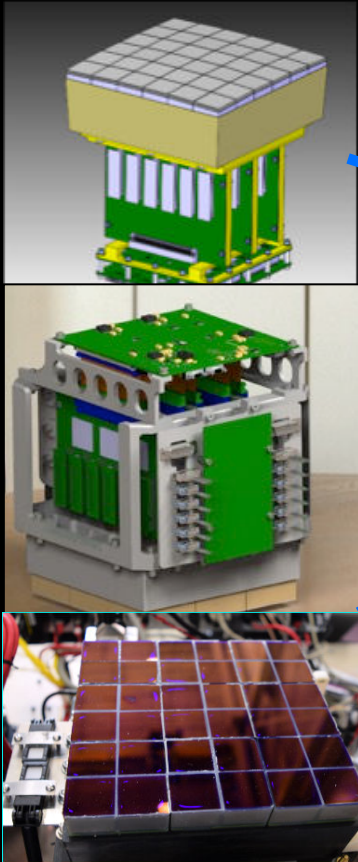
# POEMMA

## HYBRID MM FOCAL SURFACE

UV FLUORESCENCE  
DETECTION WITH MAPMTs

CHERENKOV DETECTION  
WITH SIPMs

~ 150k pixels



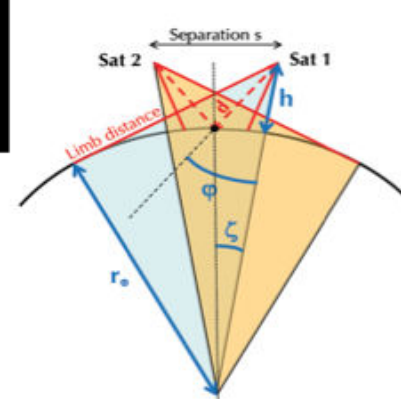
28 SIPM FOCAL  
SURFACE UNITS  
TOTAL 14,336 PIXELS  
512 PIXELS PER FSU  
(64x4x2)

60 PHOTO DETECTOR MODULES (PDMs) =  
138,240 PIXELS

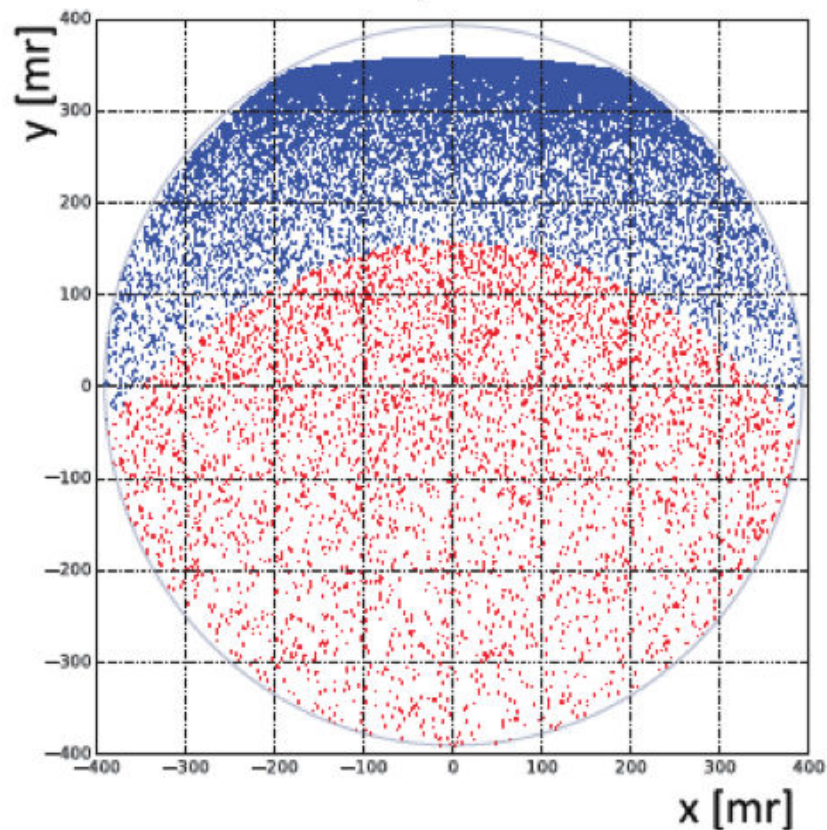
1 PDM = 36 MAPMTs = 2,304 PIXELS

# FOV 2° above limb

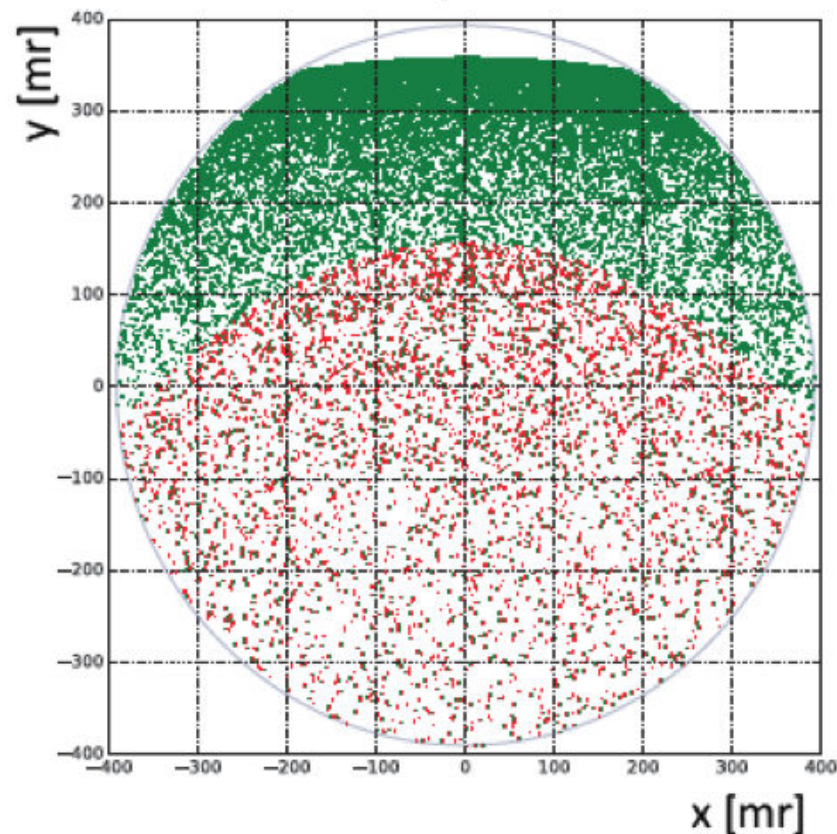
Focal surface coordinates



Eye 1

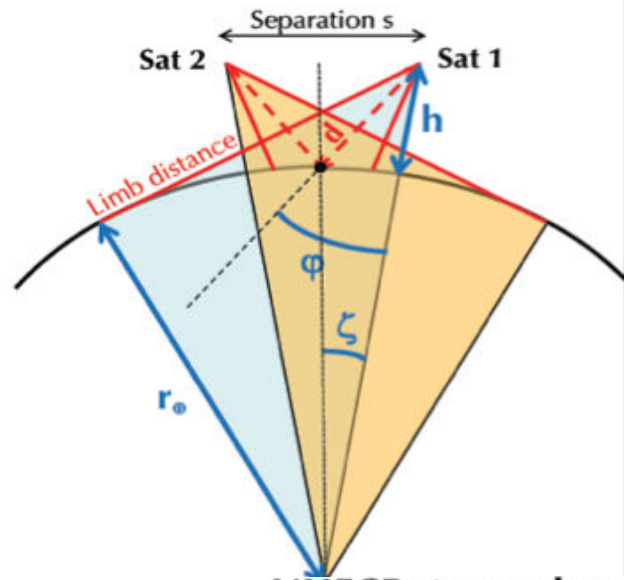


Eye 2



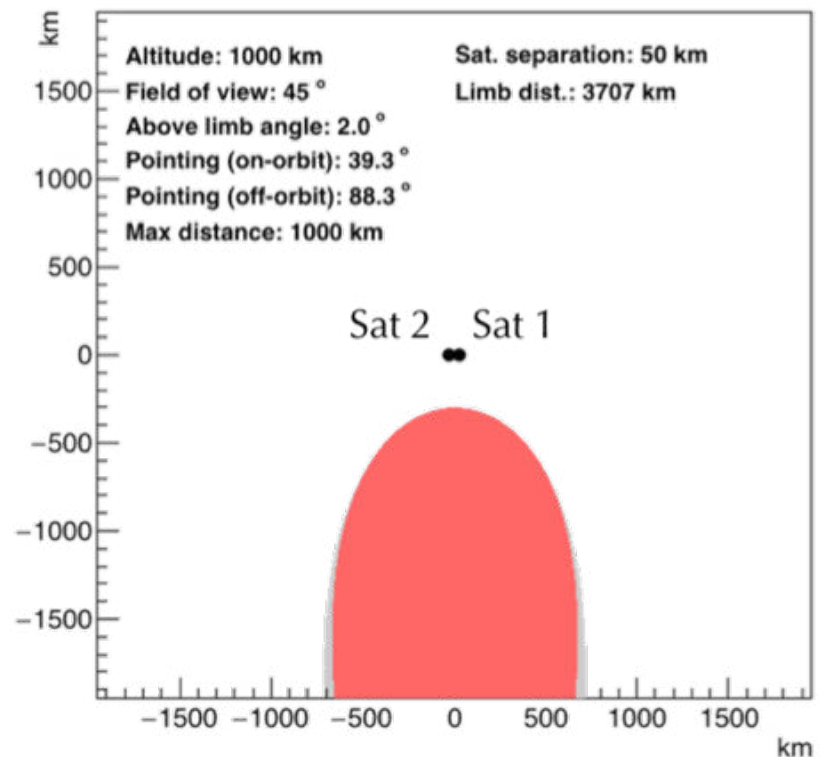
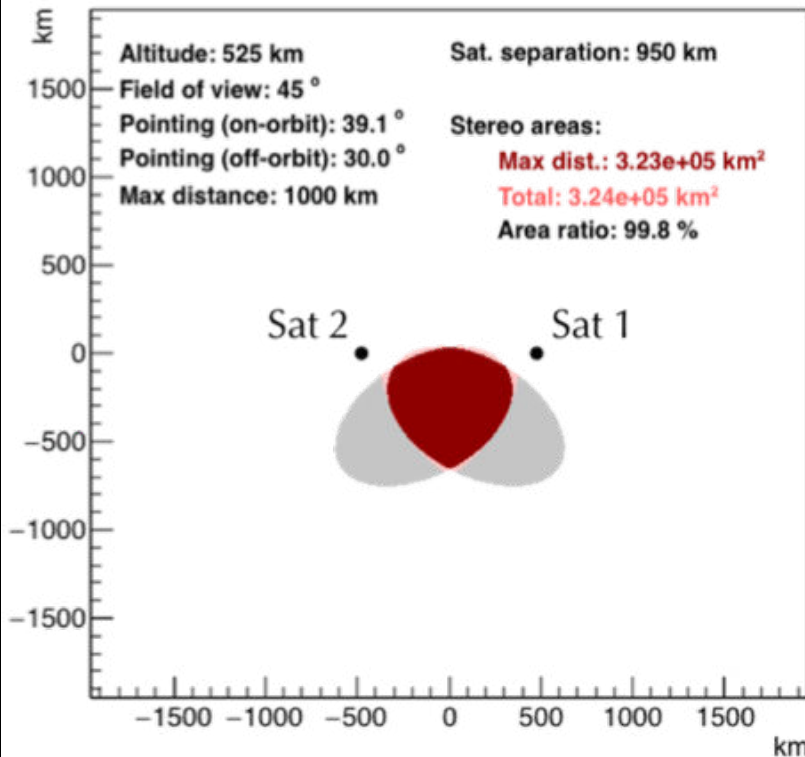
# POEMMA MISSION DESIGN TO OPTIMIZE SCIENCE PRIORITIES

Orbits from 525 km altitude, inclin 28.5°  
 UHECR cross-calibration with ground  
 UHECR sky map, composition above 10 EeV  
 UHECR flux at 100 EeV  
 Below limb: Tau decay search  
 Above limb: horizontal showers

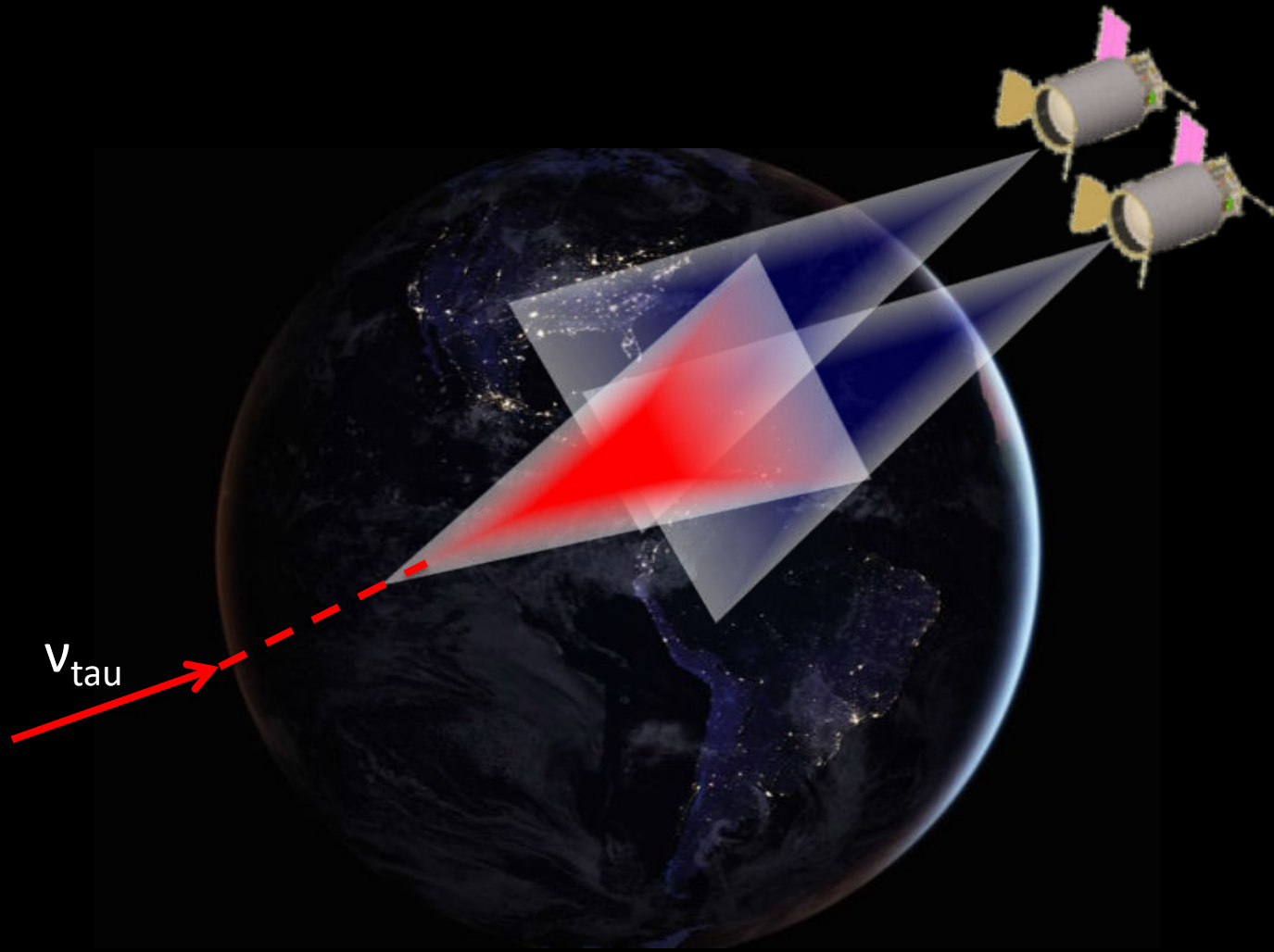


UHECR stereo observation mode

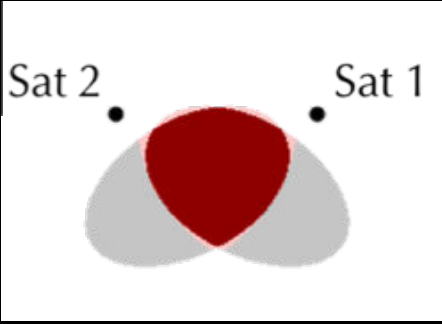
Neutrino stereo observation mode



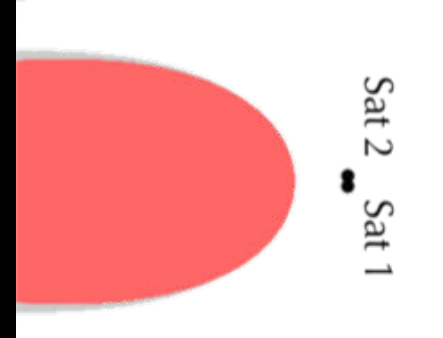
# POEMMA



OPTICAL CHERENKOV SIGNAL FROM TAU NEUTRINOS  
PEV  $\rightarrow$  HIGHEST ENERGIES

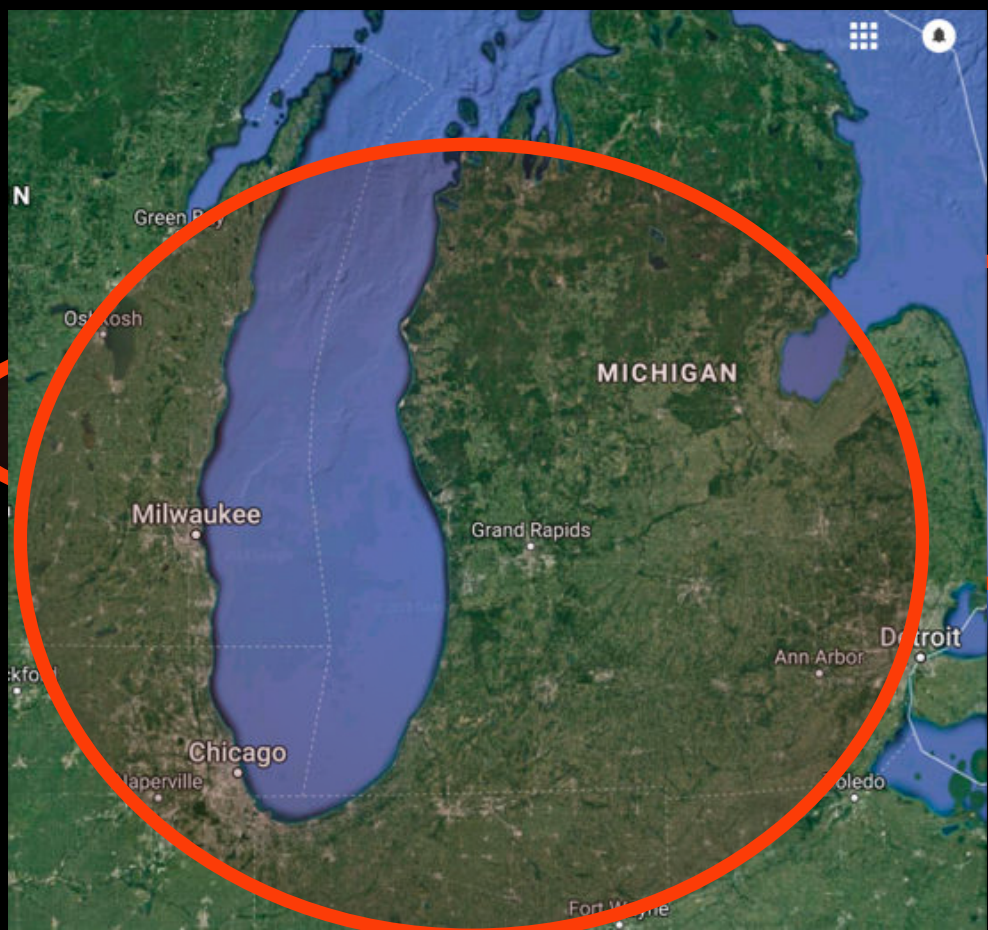


# POEMMA



**NADIR FOR UHECR:  
RADIUS 200-400 KM**

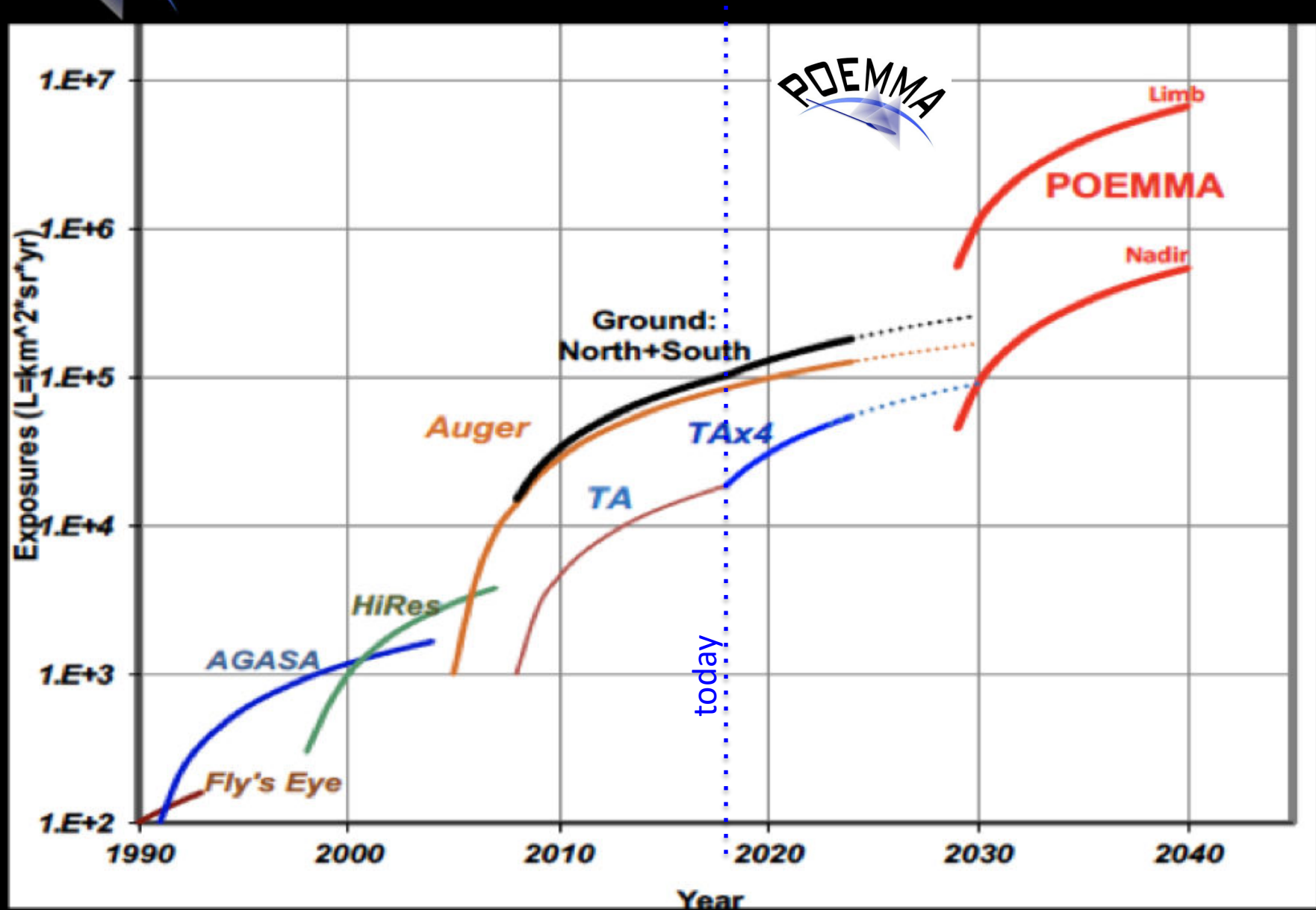
**LIMB FOR NEUTRINOS:  
RADIUS 2.6-3.7  $10^3$  KM**

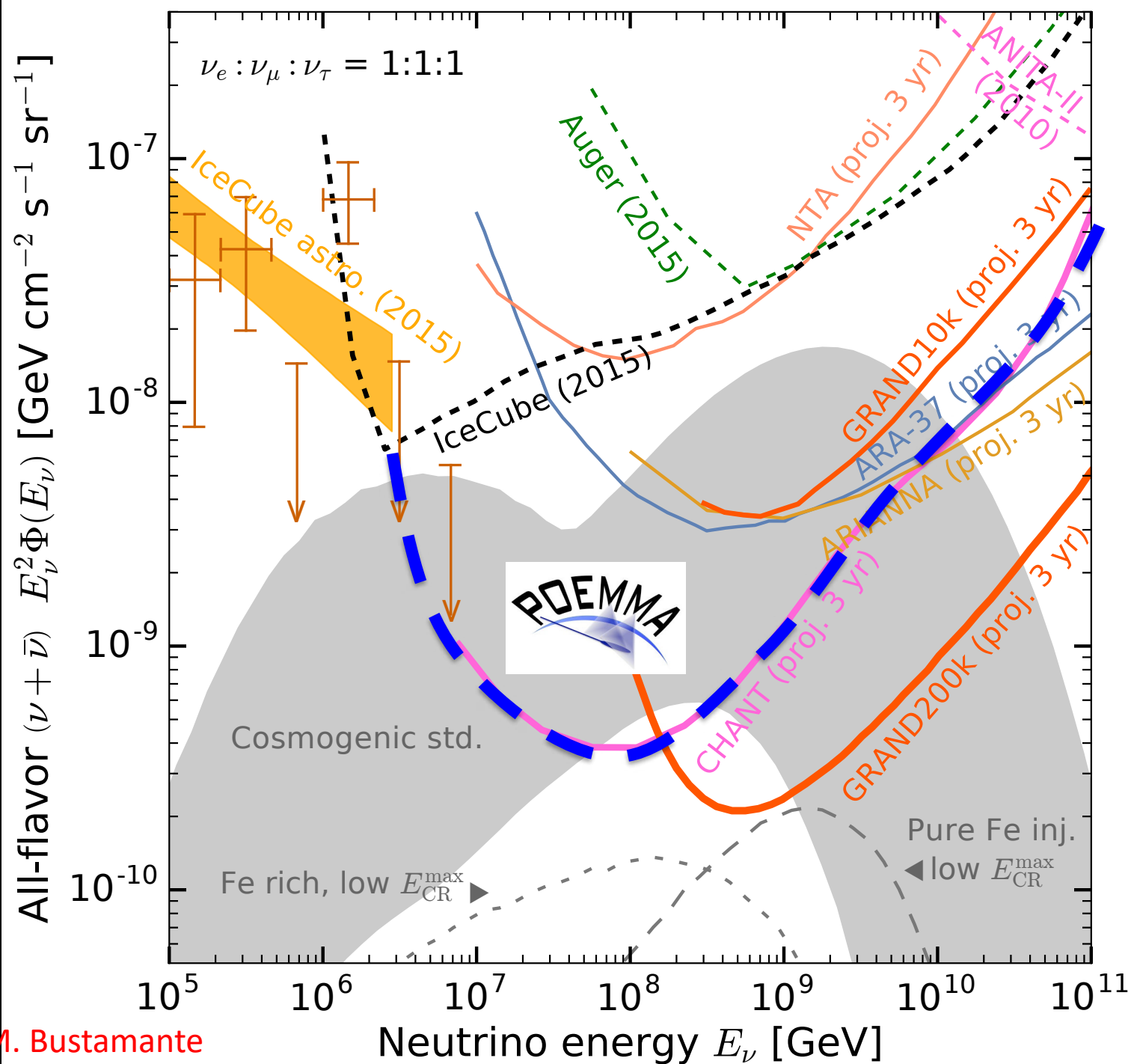




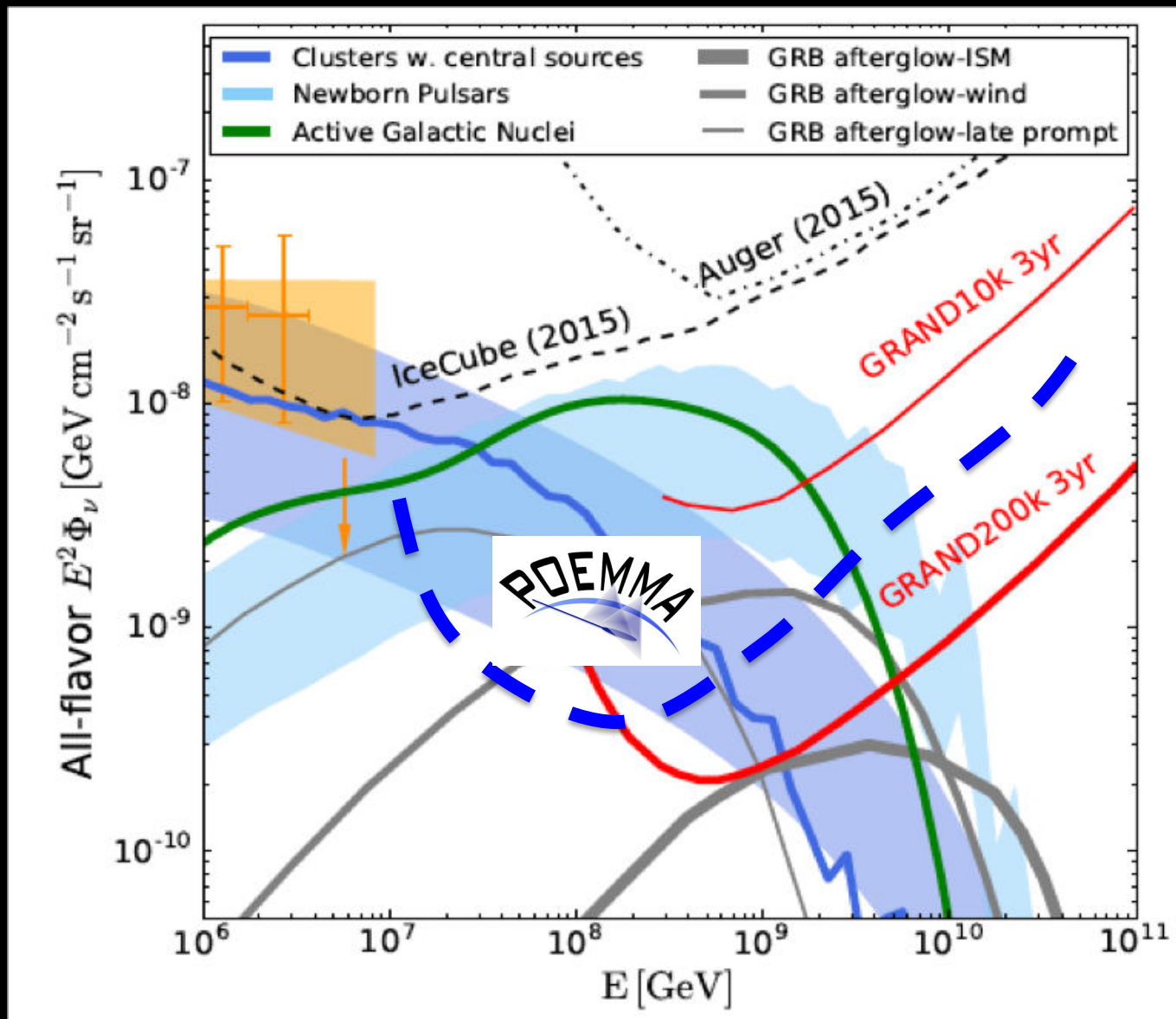


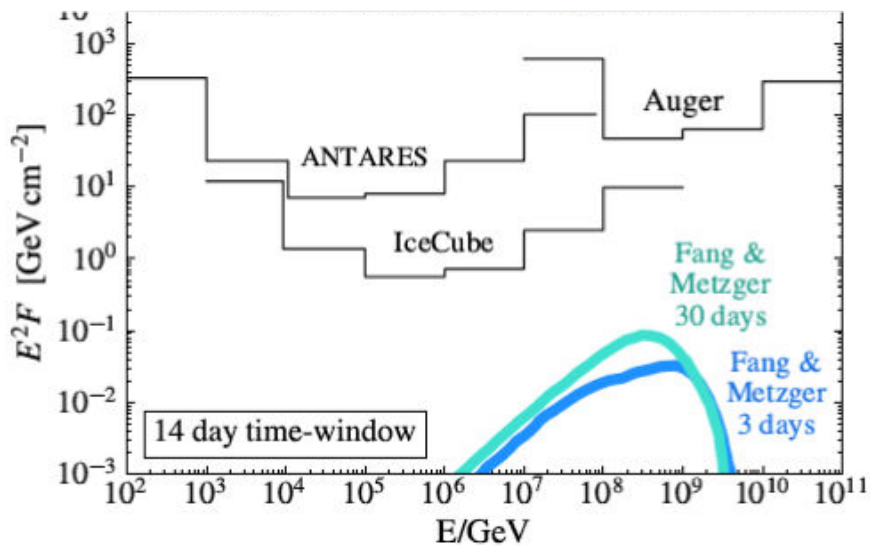
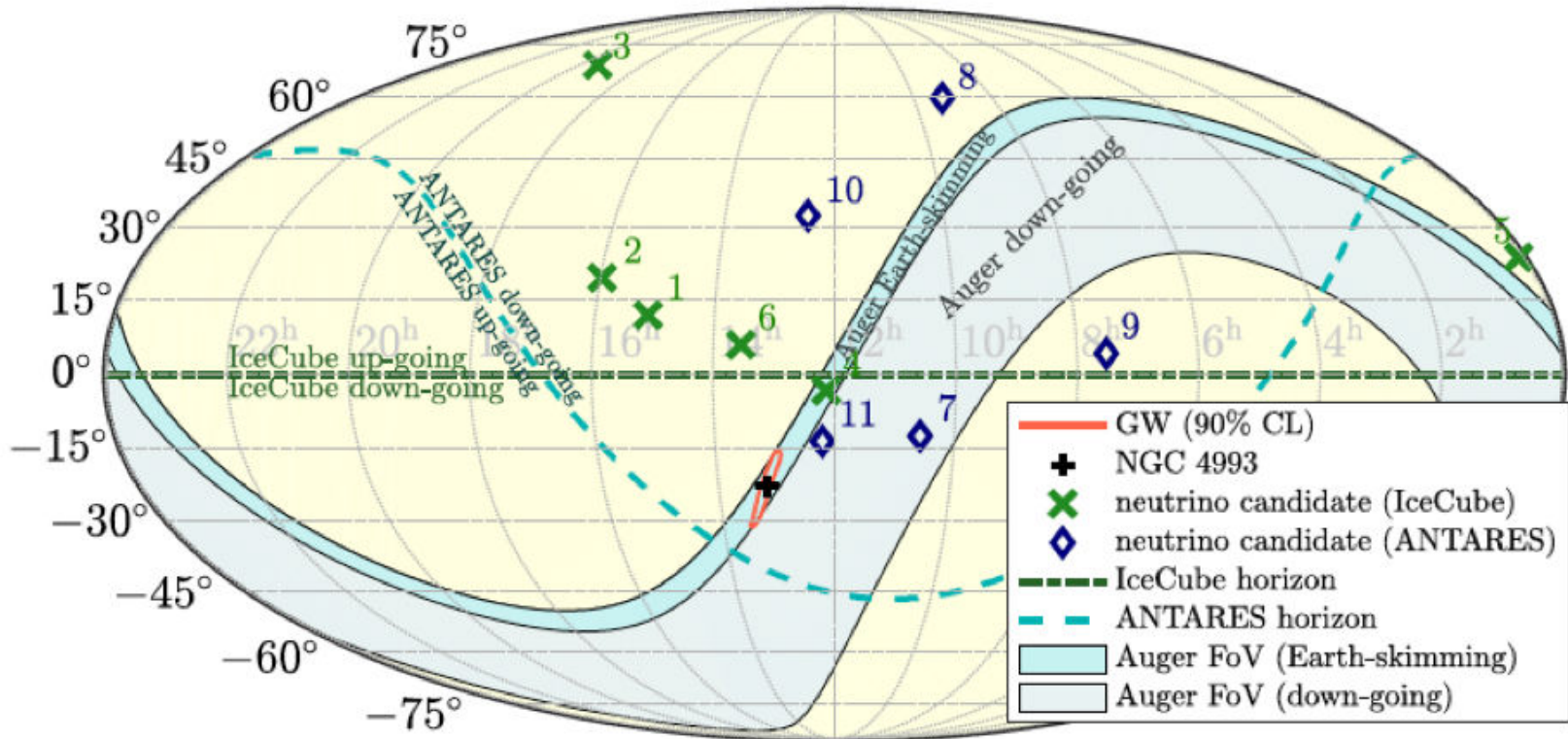
# UHECR EXPOSURE HISTORY





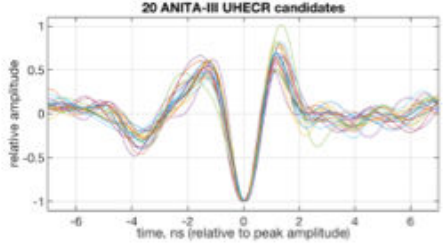
# NEUTRINOS FROM UHECR MAY BE SEEN FIRST





arXiv:1710.05839

GW170817 follow up w  
ANTARES, ICECUBE, AUGER

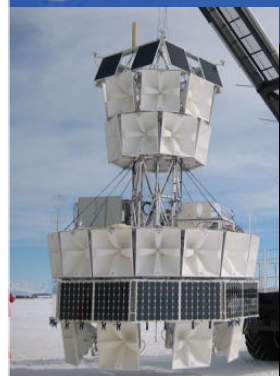
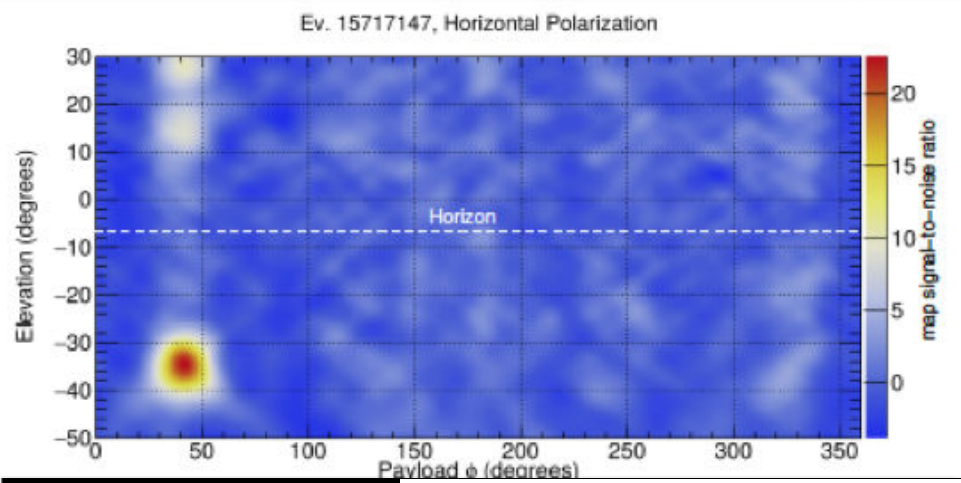
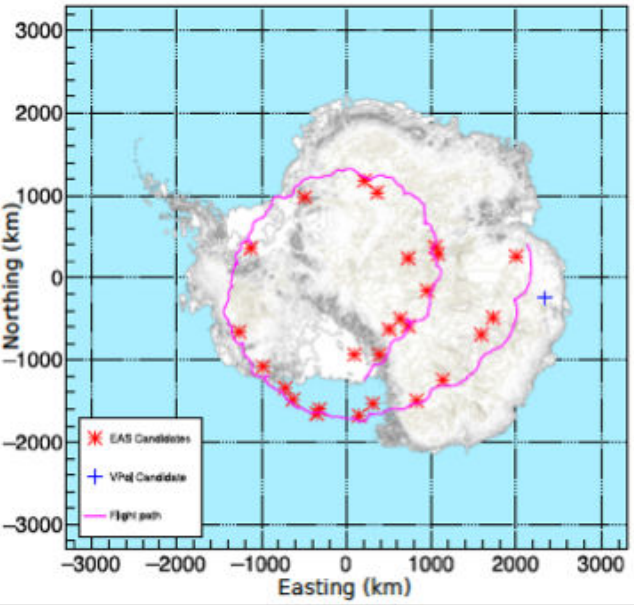


# ANITA 1 & 3

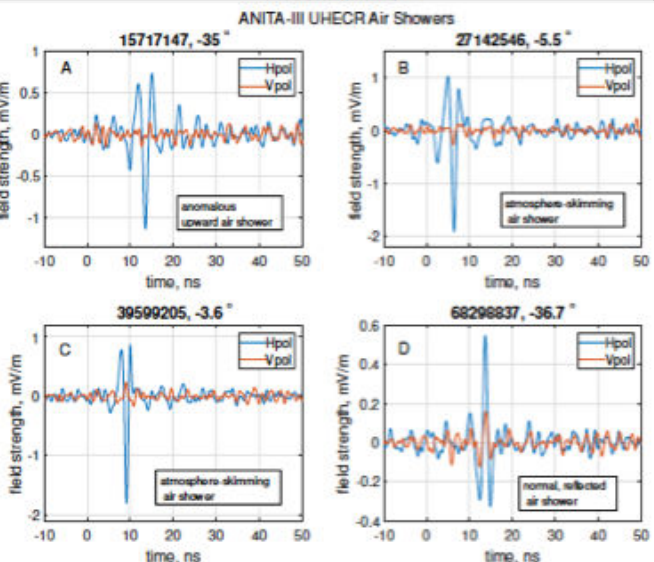
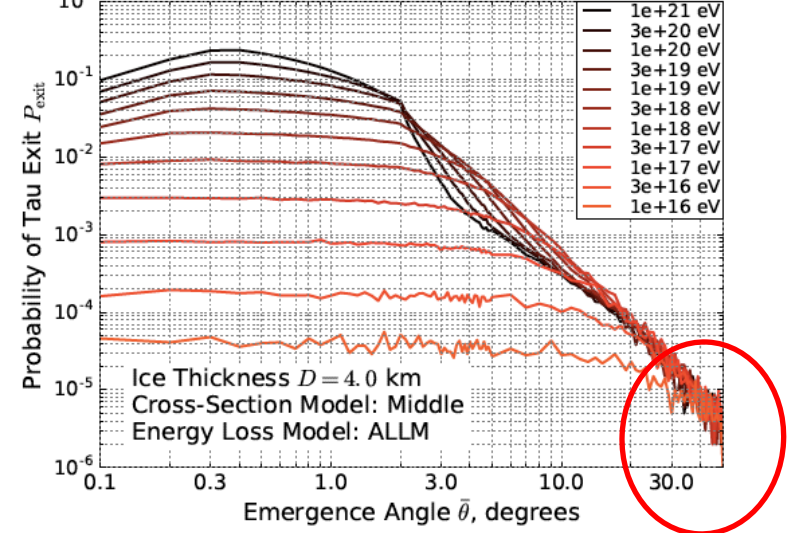
EeV CRs + 2 Unusual Events

ANITA1: 16 CRs >  $10^{18}$  eV

ANITA3: 26 CRs >  $10^{18}$  eV



Alvarez-Muniz et al, arxiv 1707.00334.pdf



Gorham et al  
1803.05088



# POEMMA

## UHECR AND NEUTRINO OBSERVATIONS

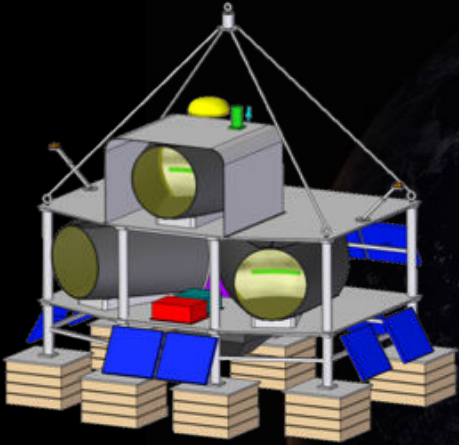


GRAZIE!

# TOWARDS SPACE PROBES OF UHECRS AND NEUTRINOS SOURCES AND INTERACTIONS

POEMMA

EUSO-SPB2



EUSO-SPB1



THE EARTH ATMOSPHERE  
AS AN EXTREME ENERGY  
PARTICLE OBSERVATORY

EUSO-SPB1 LAUNCH FROM WANAKA, NZ  
APRIL 24, 2017

