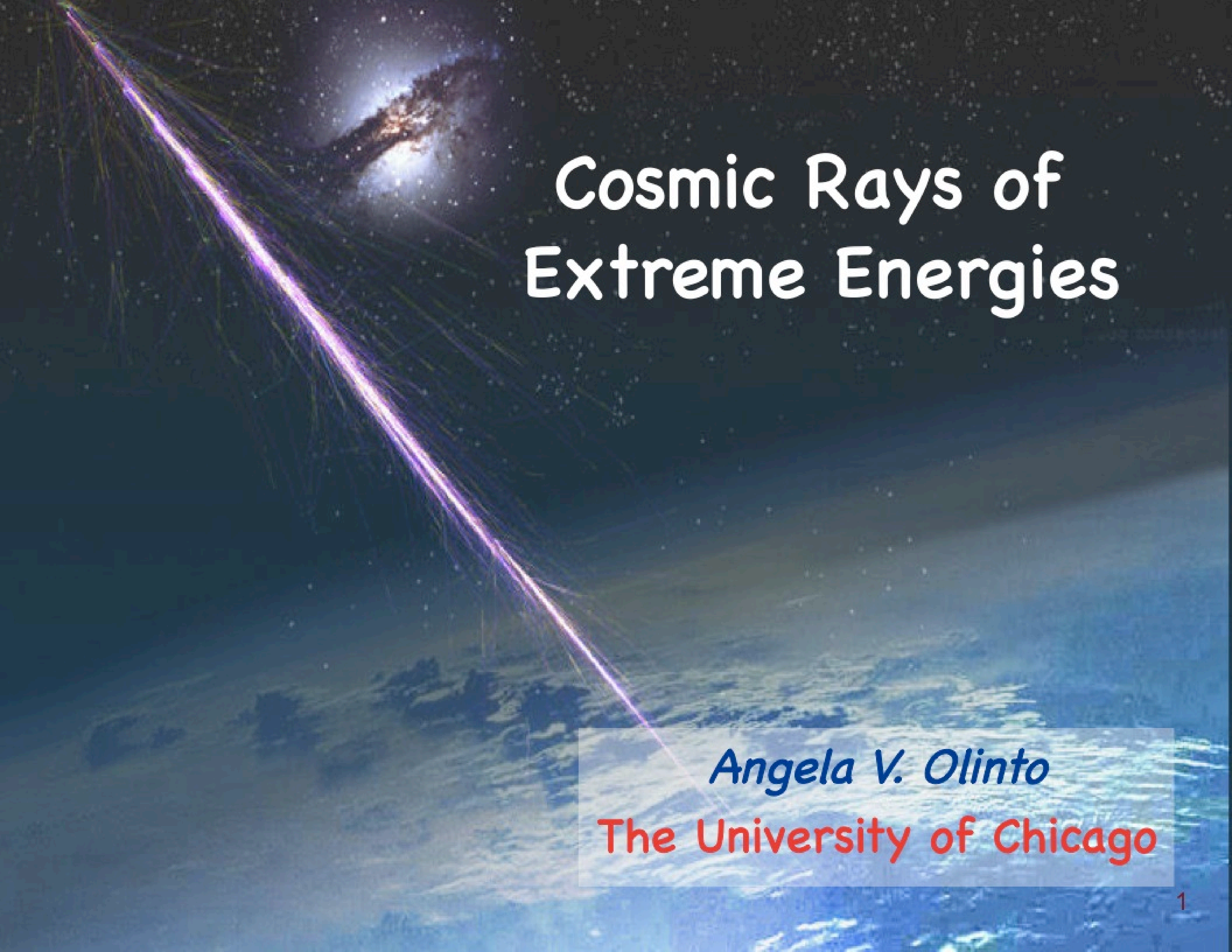
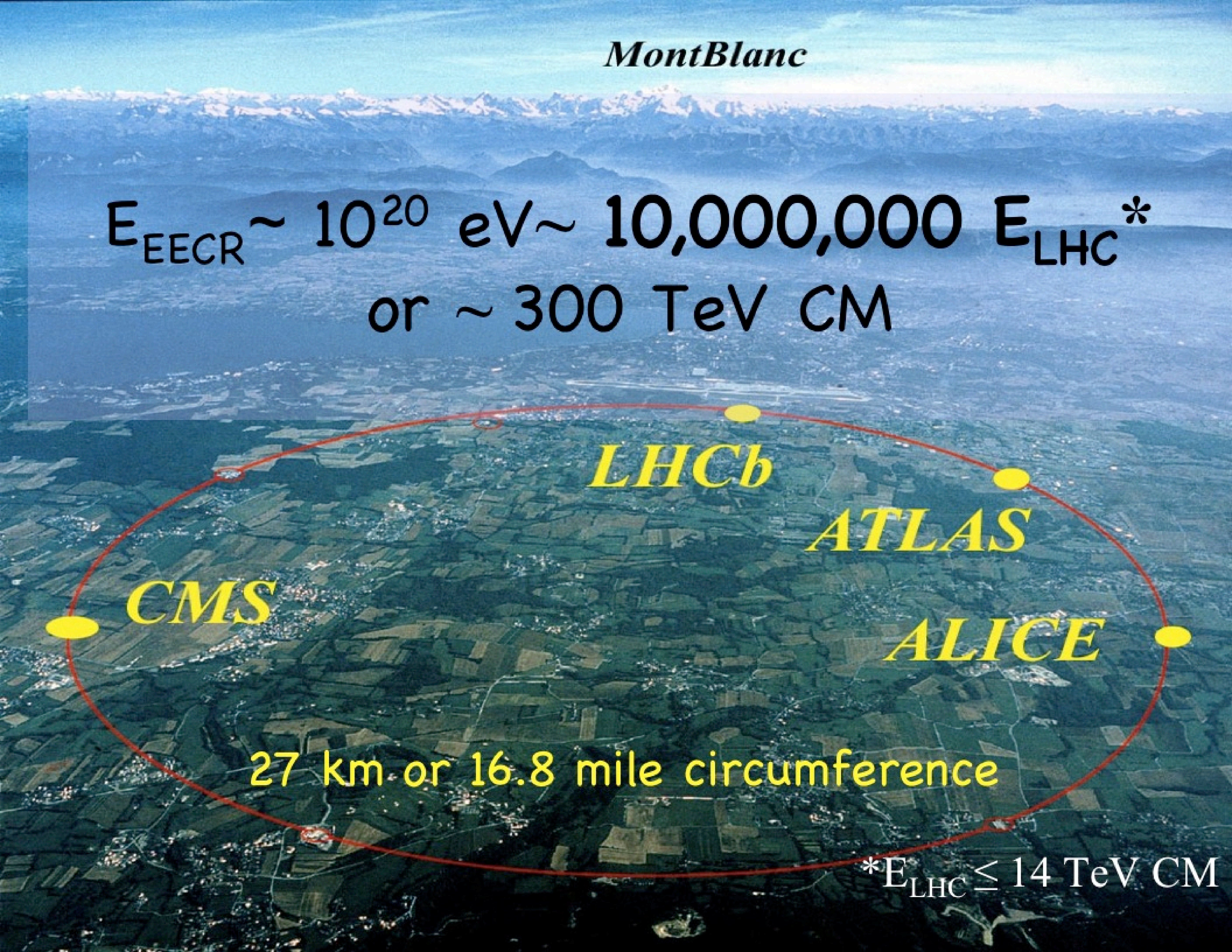


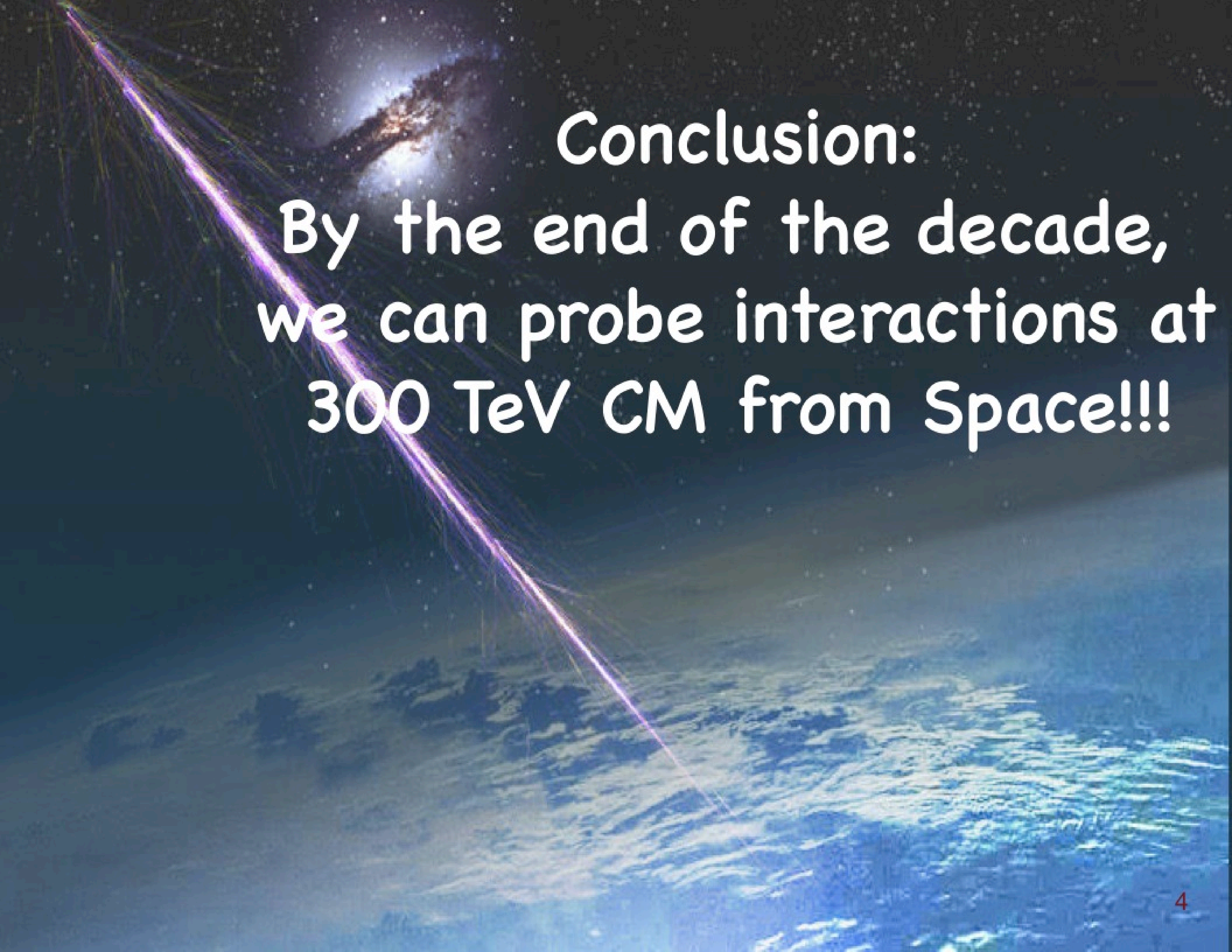
Cosmic Rays of Extreme Energies

Angela V. Olinto

The University of Chicago

How Extreme???


MontBlanc
$E_{EECR} \sim 10^{20}$ eV~ 10,000,000 E_{LHC}*
or ~ 300 TeV CM
LHCb
ATLAS
CMS
ALICE
27 km or 16.8 mile circumference
*$E_{LHC} \leq 14$ TeV CM

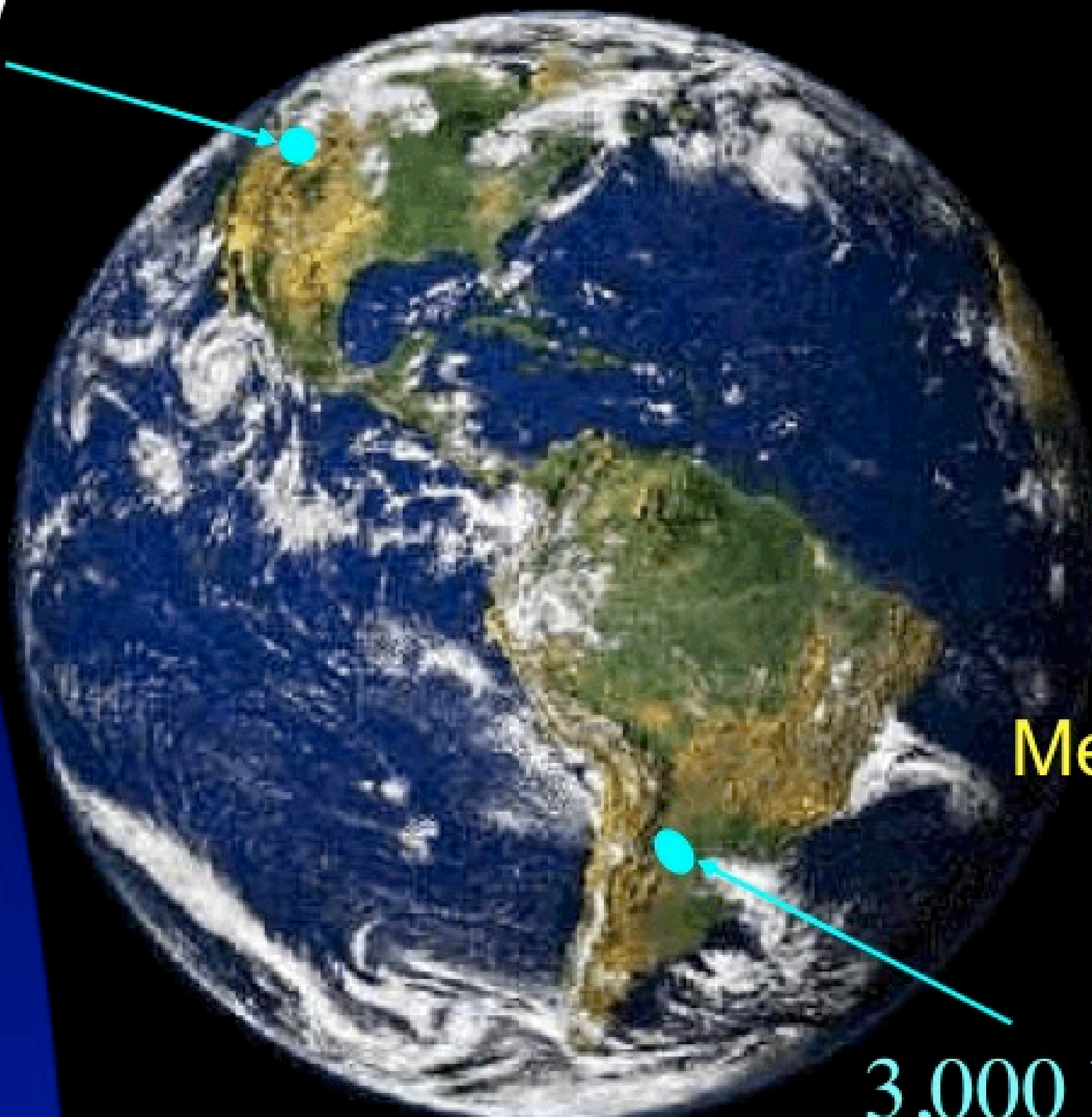

Conclusion:
By the end of the decade,
we can probe interactions at
300 TeV CM from Space!!!

Current Observatories of Ultrahigh Energy Cosmic Rays*

*UHECR:
E>EeV=10^{18} eV

Telescope Array
Utah, USA
(5 country collaboration)

700 km^2 array
3 fluorescence telescopes



Pierre Auger Observatory
Mendoza, Argentina
(19 country collaboration)

3,000 km^2 array
4 fluorescence telescopes

Current Observatories of Ultrahigh Energy Cosmic Rays

Telescope Array
Utah, USA
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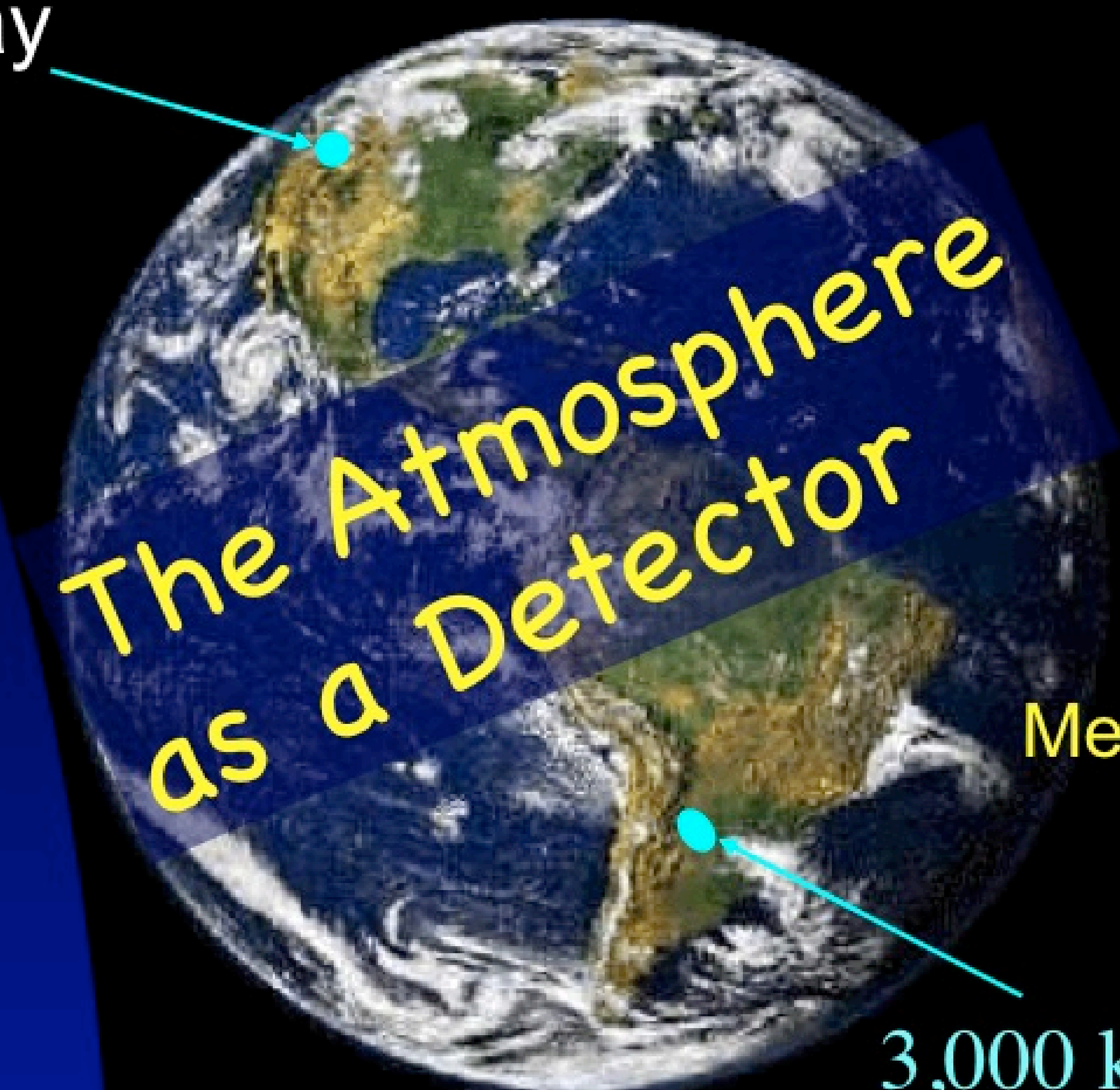
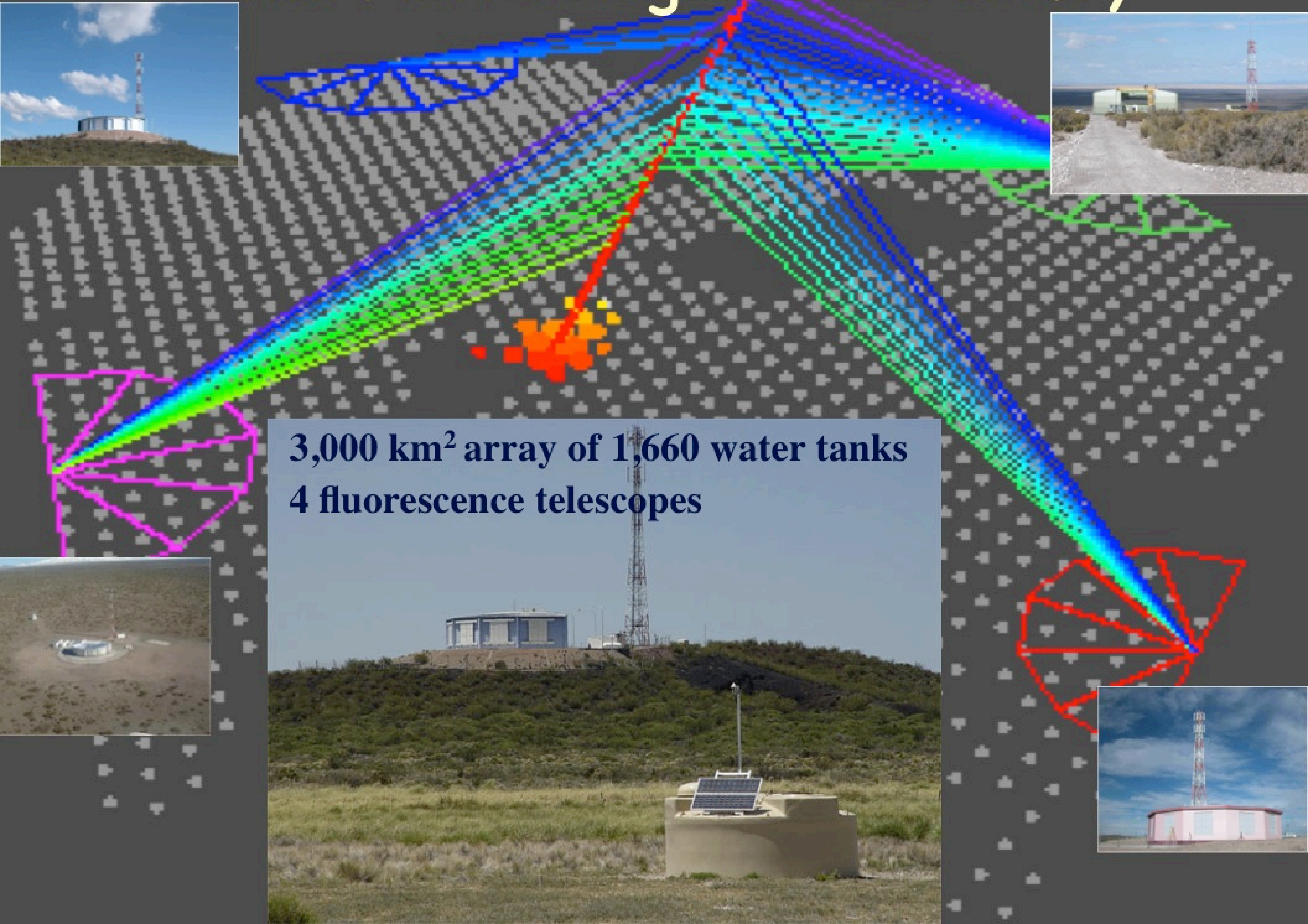


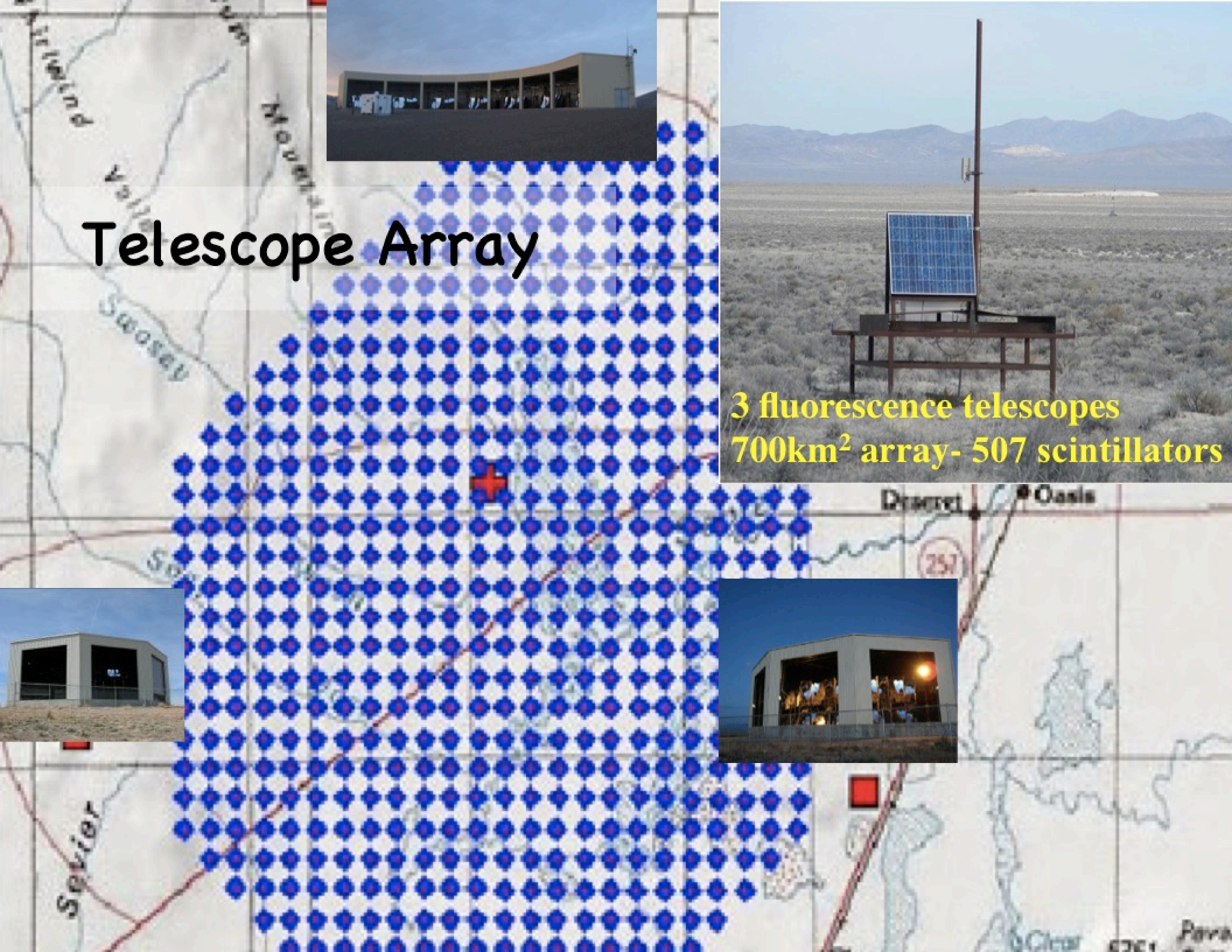
Pierre Auger Observatory
Mendoza, Argentina
(19 country collaboration)

3,000 km^2 array
4 fluorescence telescopes

The Pierre Auger Observatory



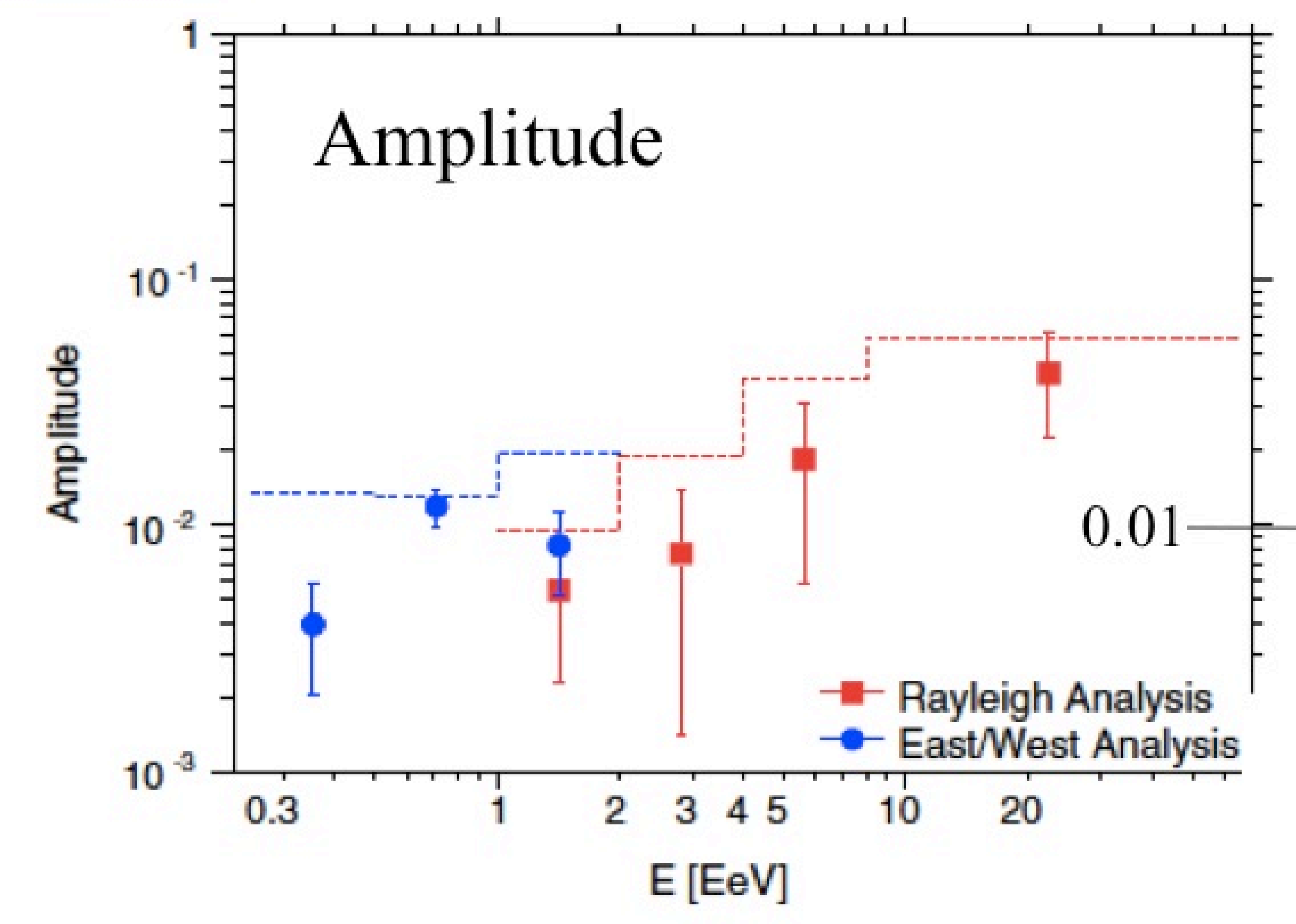
Telescope Array



EXTRA-GALATIC!

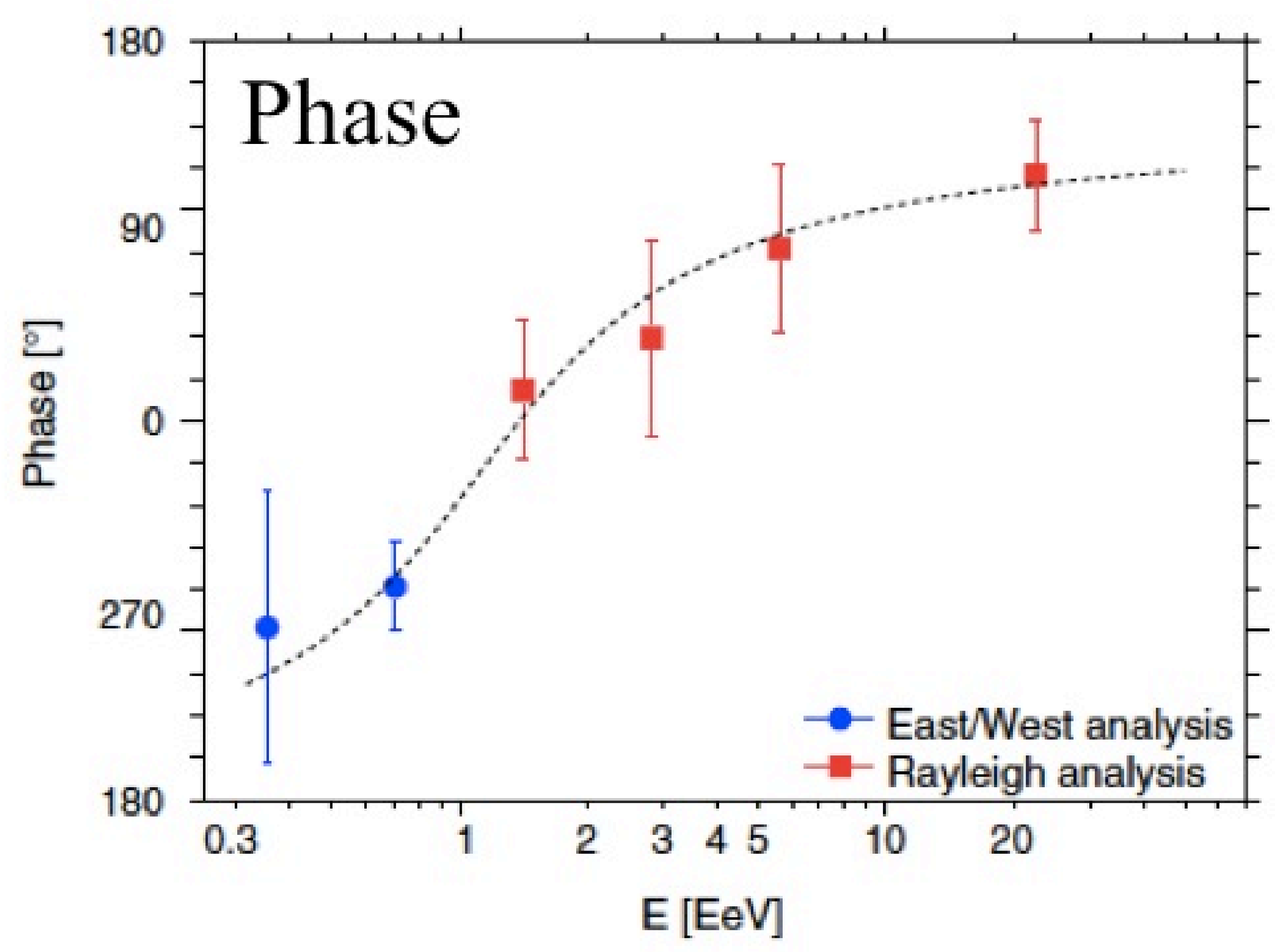
A great success of recent efforts at ultrahigh energies is establishing the extragalactic nature of UHECRs.

Auger Dipole Measurement



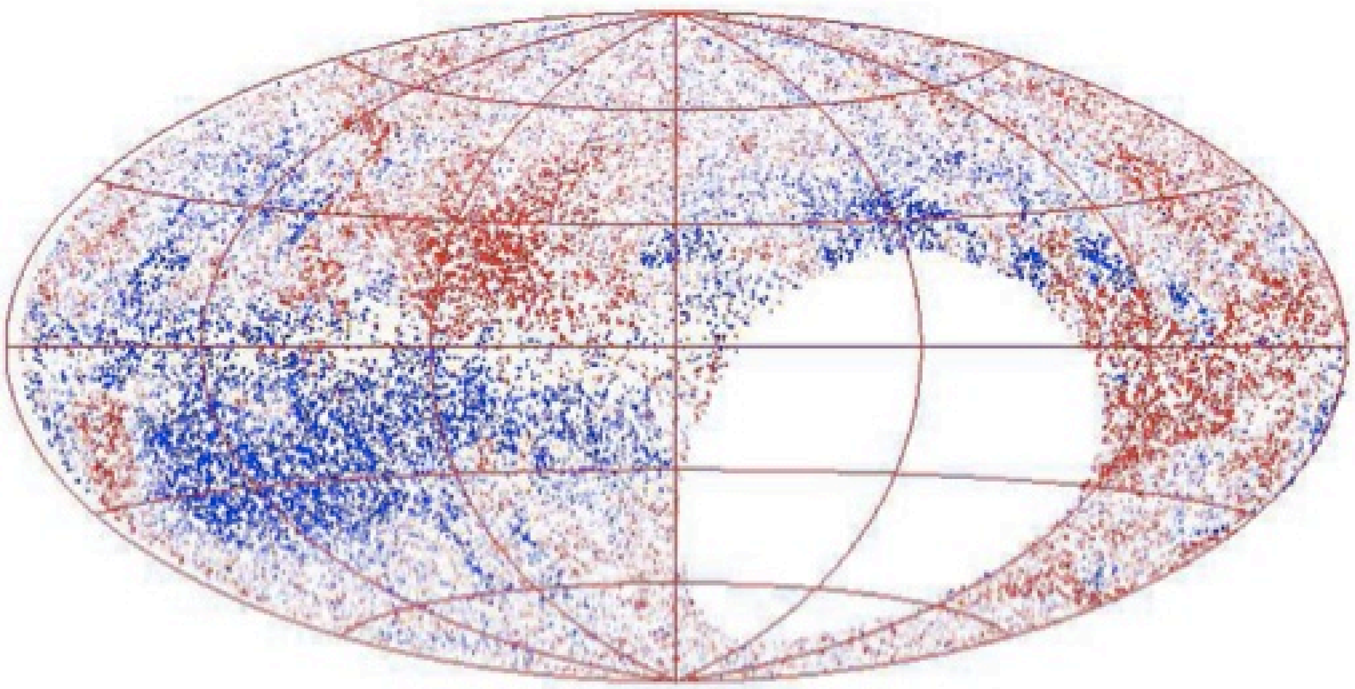
0.01

P. Abreu et al. '11

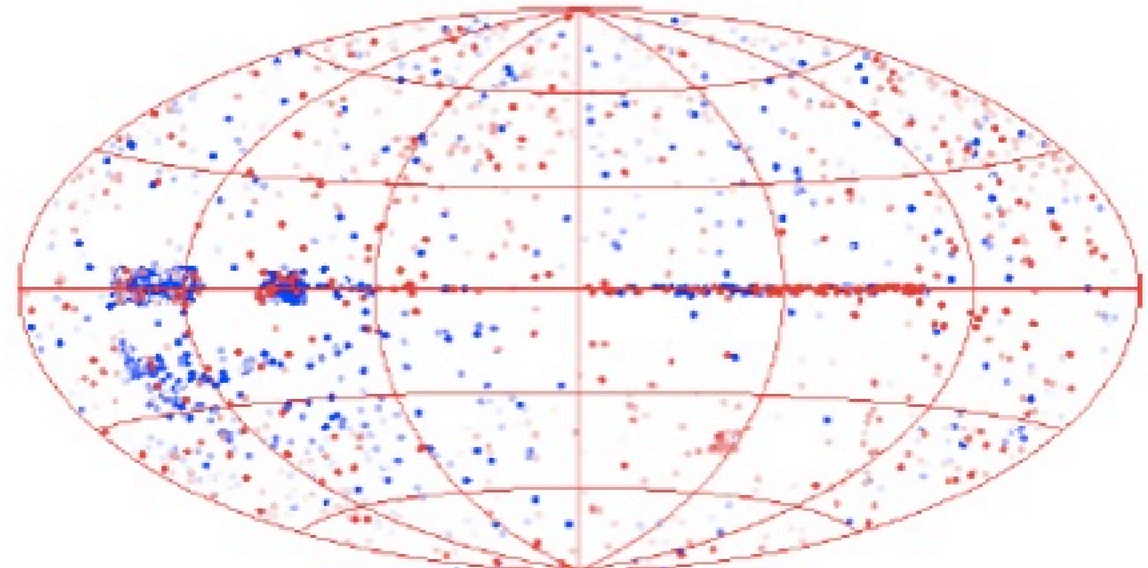


Galactic Magnetic Fields

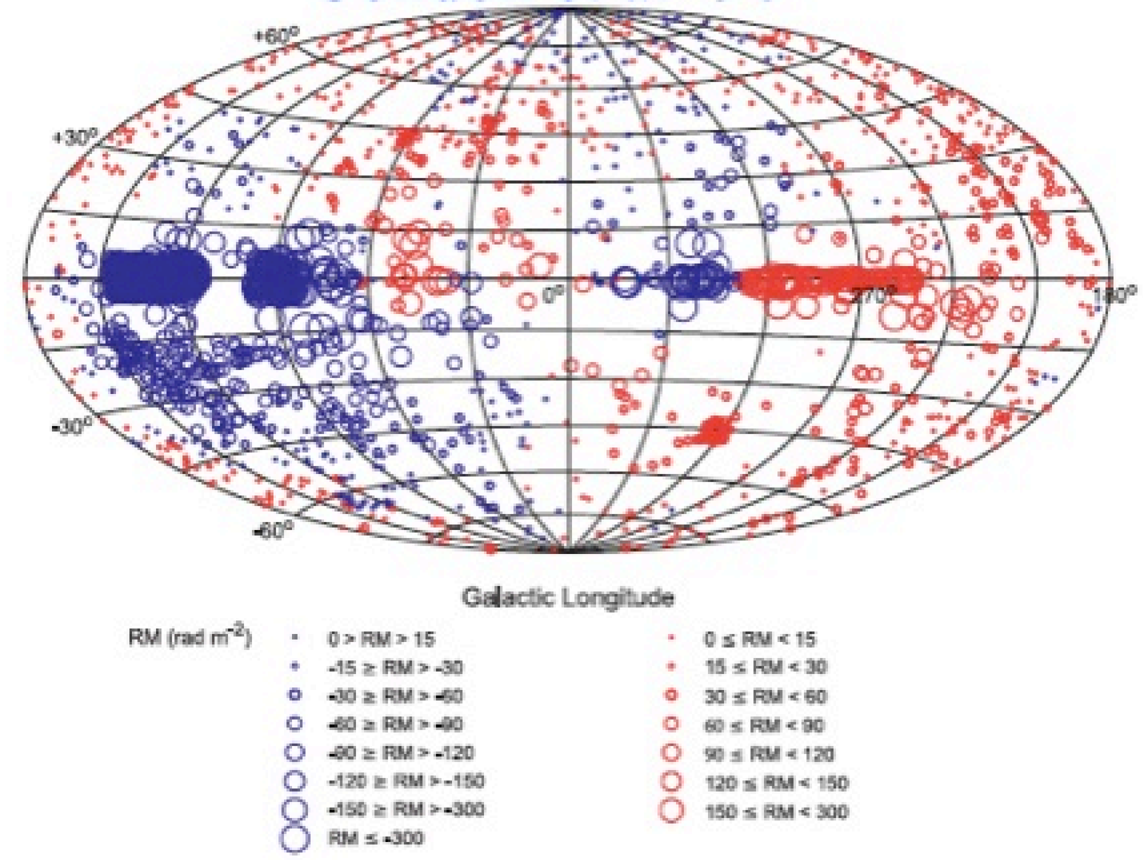
Better constrained



Taylor et al ‘09



Condon et al ‘98



Pshirkov et al ’11

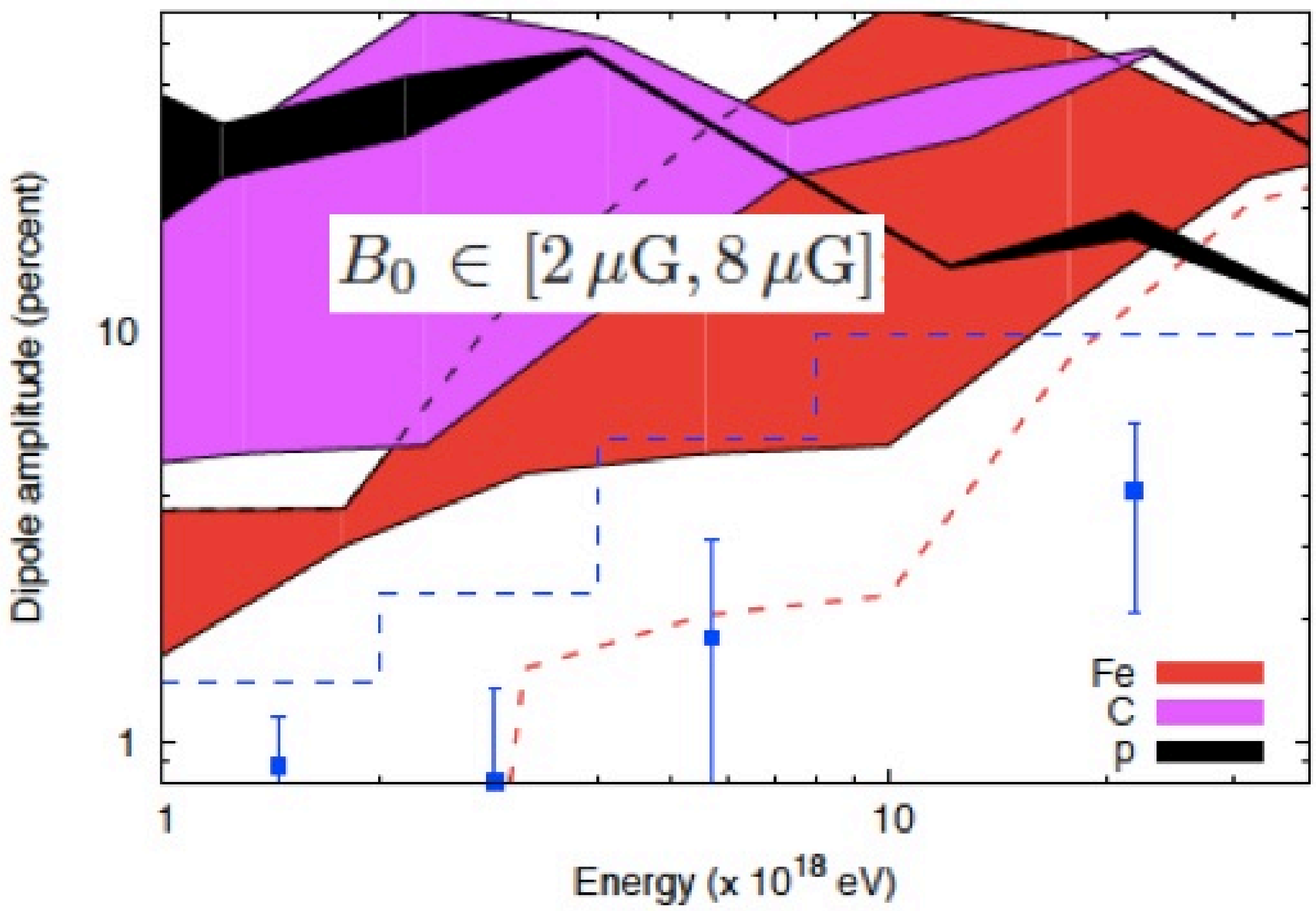
Model of Galactic Field:

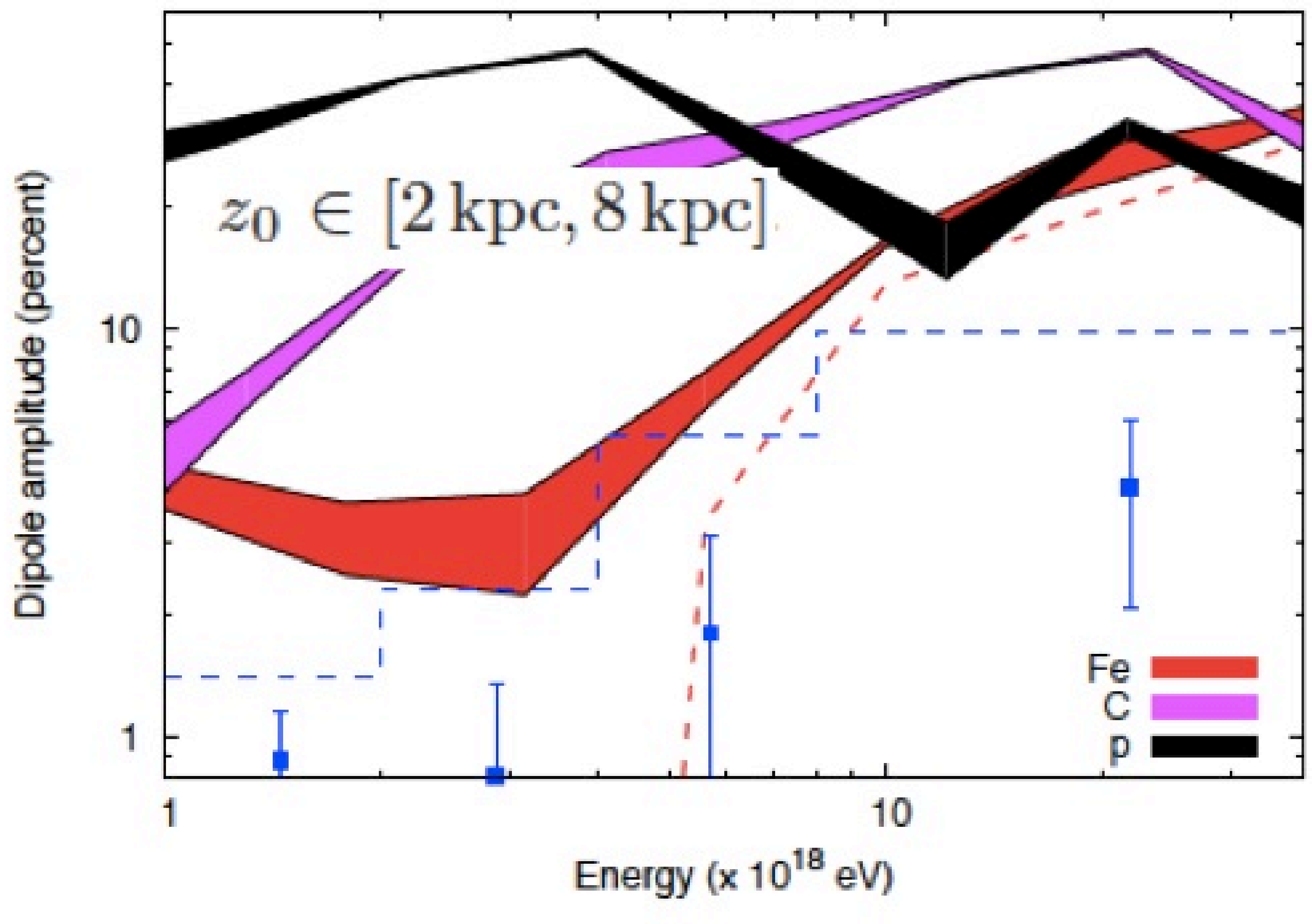
symmetric spiral disk and antisymmetric halo – reproduce best RM data.

Anisotropy Limits

rule out Galactic components of
protons to CNO as dominant CR component E >1 EeV

and Fe above ~20 EeV



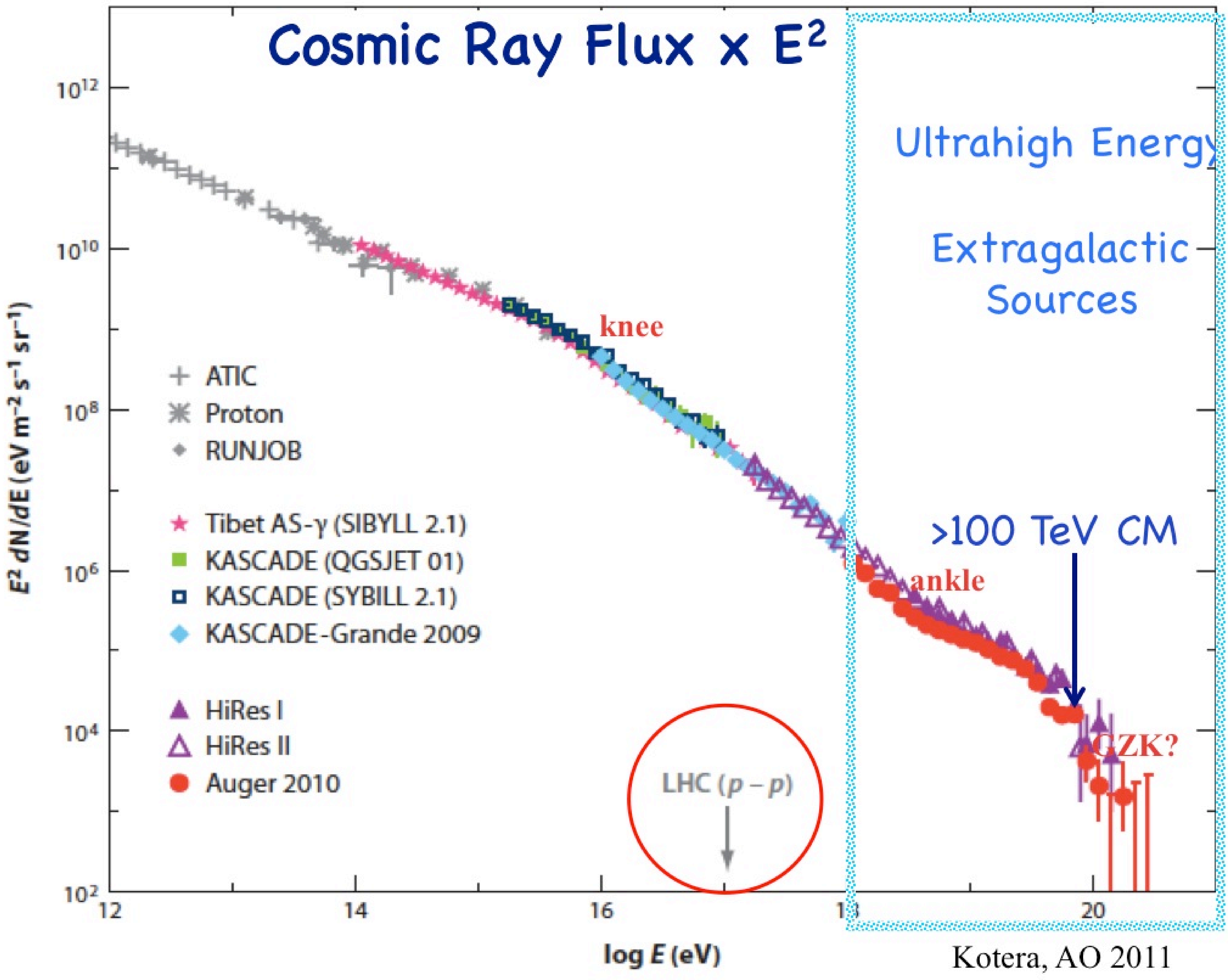


Giacinti et al '11

Recent Results

E>20 EeV Cosmic Rays are EXTRAGALACTIC*

(*unless they are much heavier than Fe!!)



Cosmic Ray Flux x E²
Ultrahigh Energy
Extragalactic
Sources
knee
ankle
>100 TeV CM
GZK?
LHC (p – p)
ATIC
Proton
RUNJOB
Tibet AS-γ (SIBYLL 2.1)
KASCADE (QGSJET 01)
KASCADE (SYBILL 2.1)
KASCADE-Grande 2009
HiRes I
HiRes II
Auger 2010
E² dN/dE (eV m⁻² s⁻¹ sr⁻¹)
log E (eV)
10¹²
10¹⁰
10⁸
10⁶
10⁴
10²
12
14
16
18
20
Kotera, AO 2011

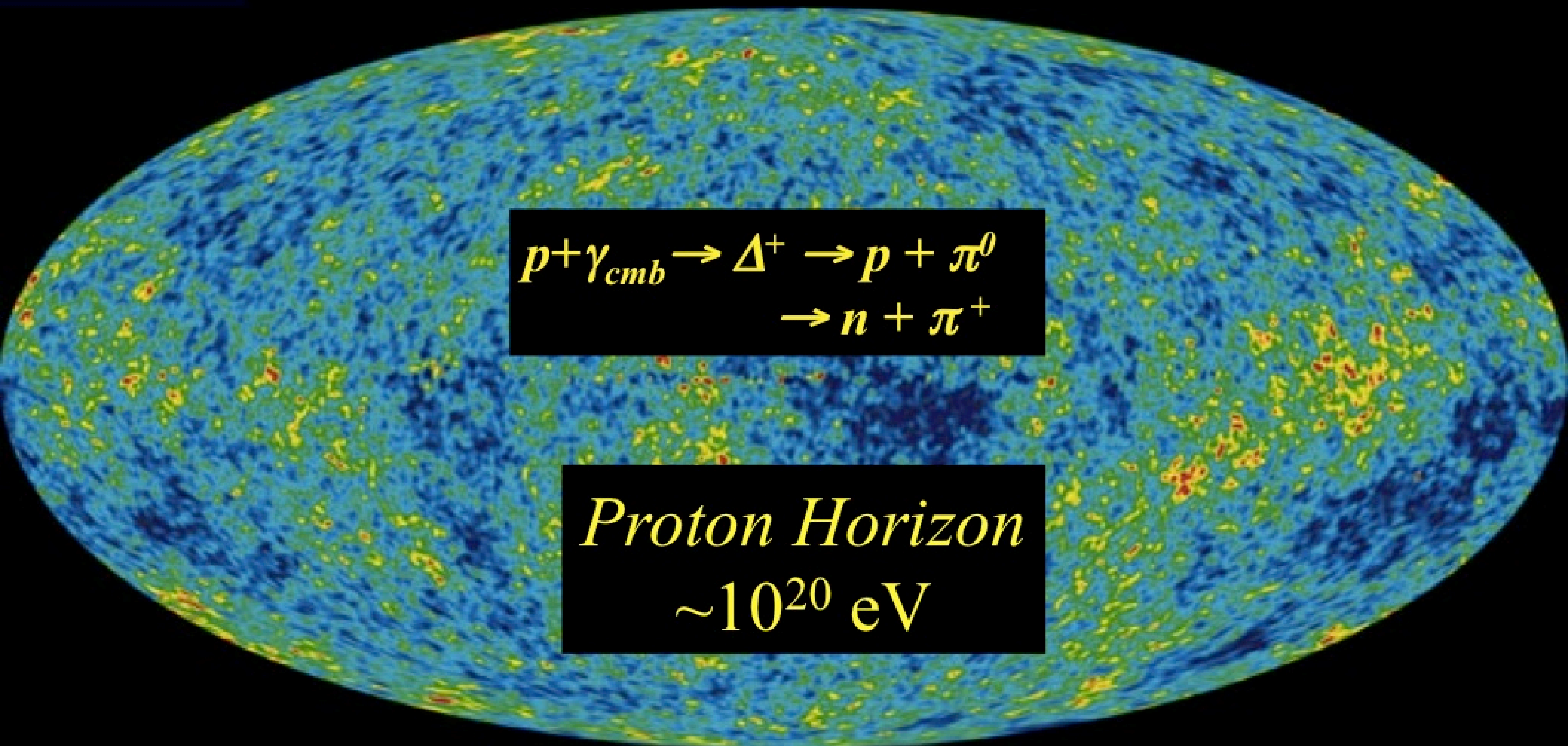
Recent Results

E>20 EeV Cosmic Rays are EXTRAGALACTIC

Implies a GZK* feature in the spectrum

(*Greisen-Zatsepin-Kuzmin)

"Cosmologically Meaningful Termination"

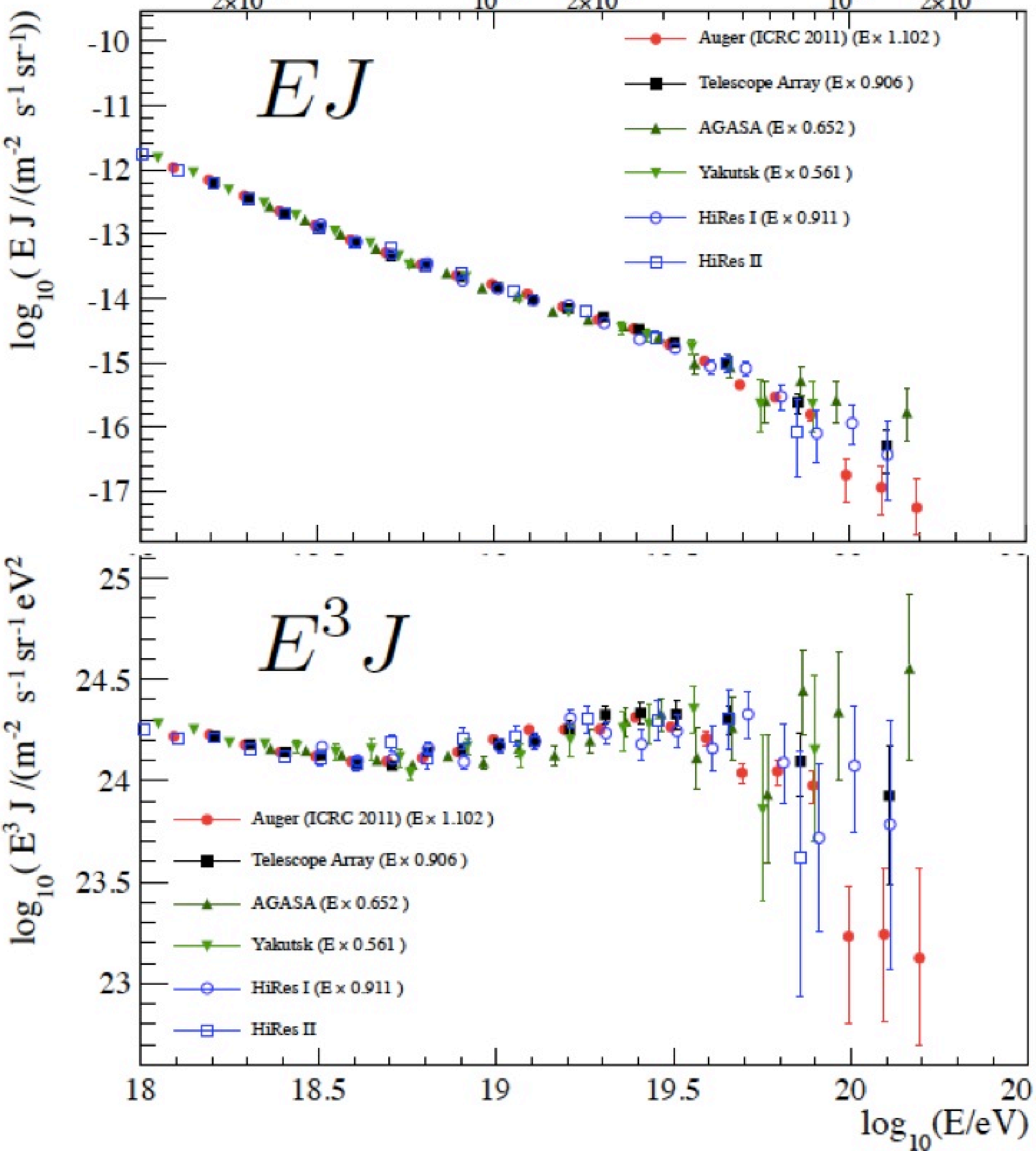


GZK Cutoff

Greisen, Zatsepin, Kuzmin

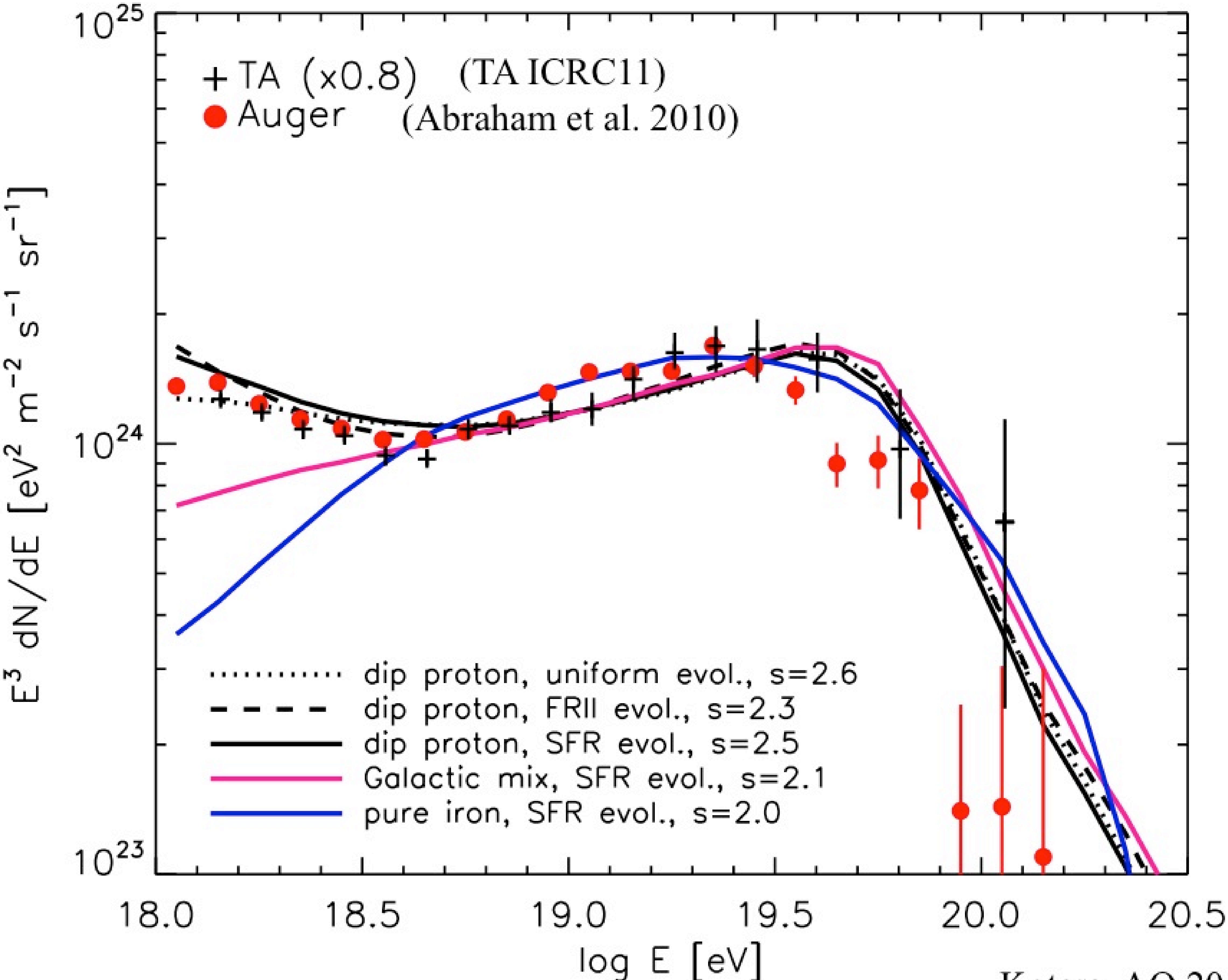
1966

UHECR 2012 CERN Feb.



Tsunesada et al. CERN WG '12

Composition and Transition from Gal to XGal



Kotera, AO 2011

Recent Results

E>20 EeV Cosmic Rays are EXTRAGALACTIC 

E>40 EeV GZK-like feature in the spectrum 

Recent Results

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or end of the injected spectrum, E_{max}?

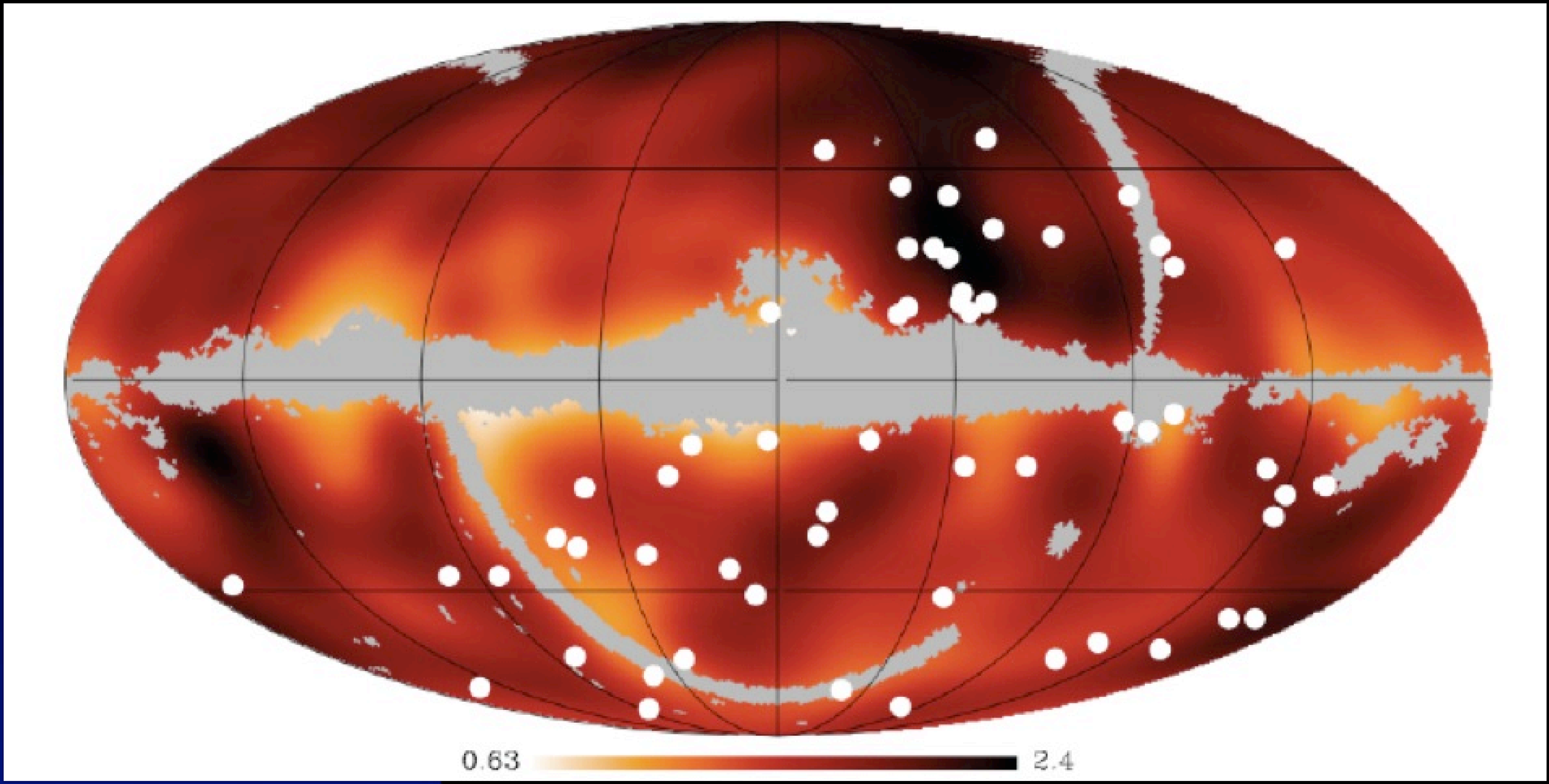
Recent Results

E>20 EeV Cosmic Rays are EXTRAGALACTIC 

E>40 EeV GZK-like feature in the spectrum 
or end of the injected spectrum, E_{max}? 

GZK implies anisotropies since GZK limits distance < 100 Mpc and matter distributed anisotropically in these scales!

Above 60 EeV

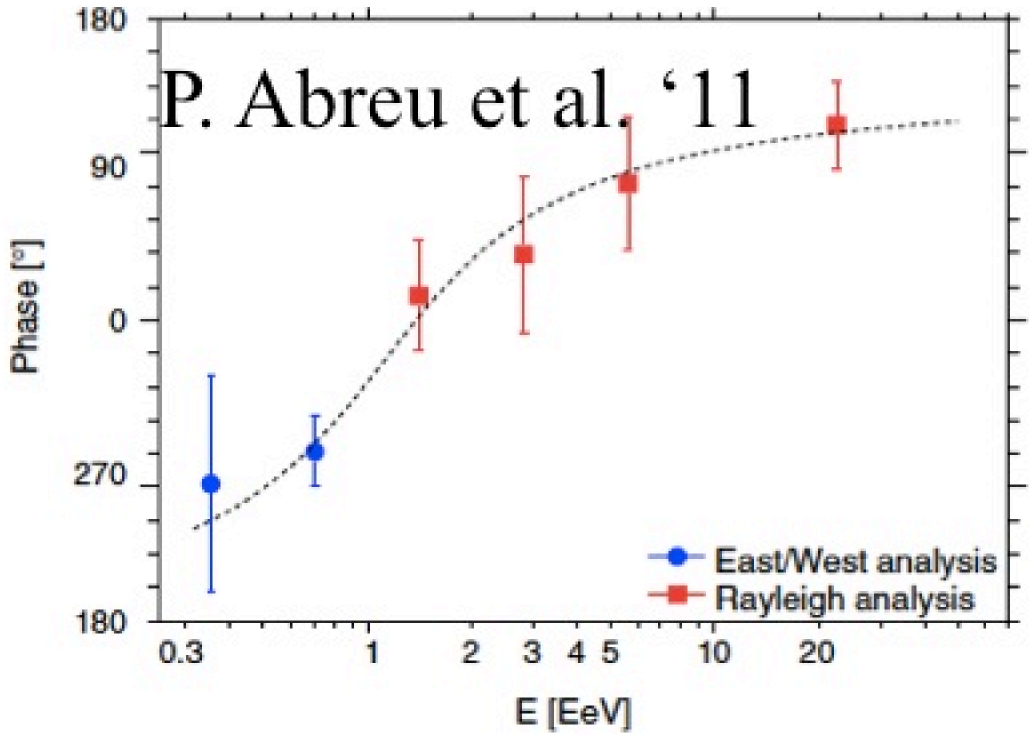


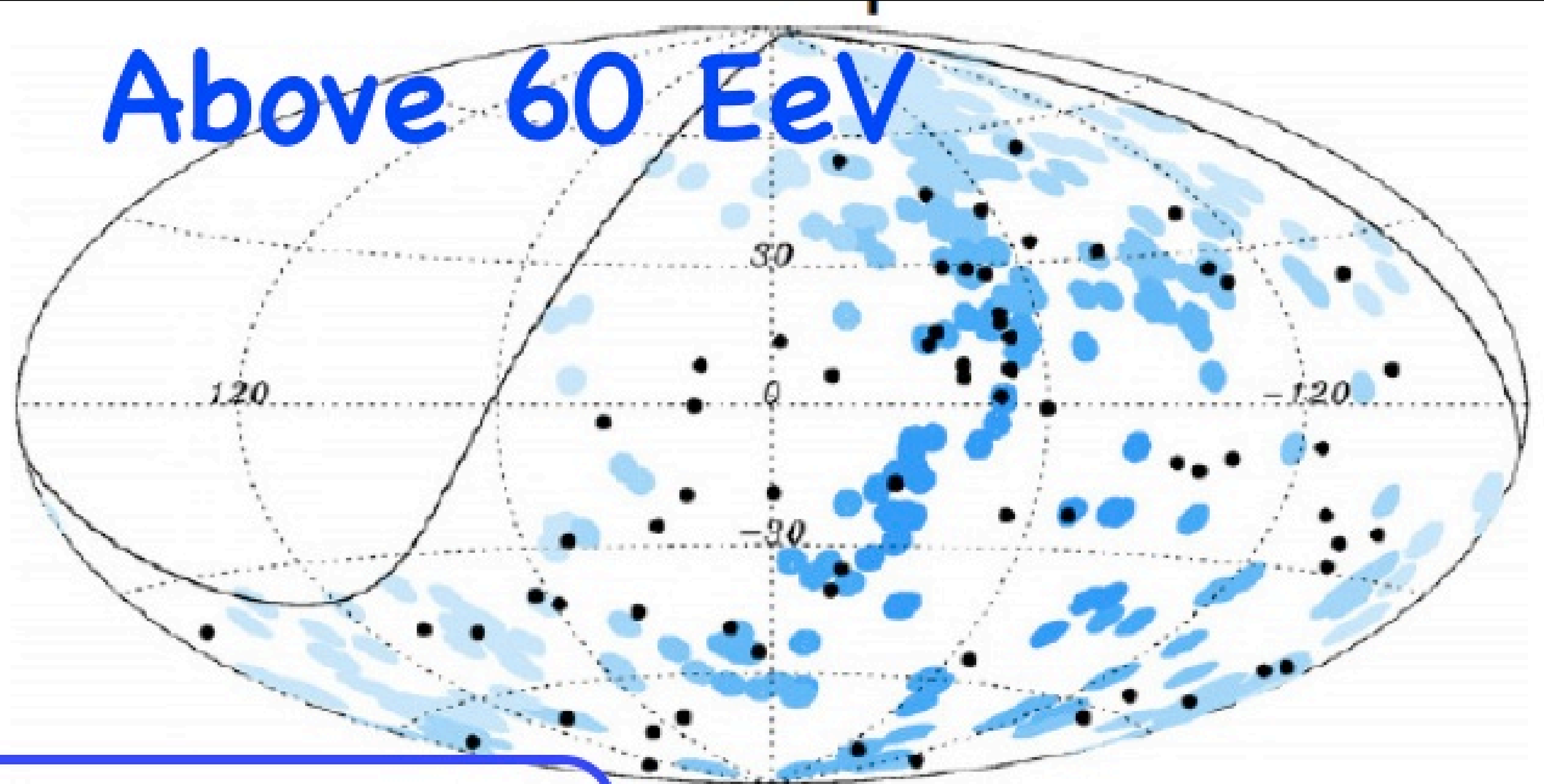
Angular deviations for protons less than 3 degrees

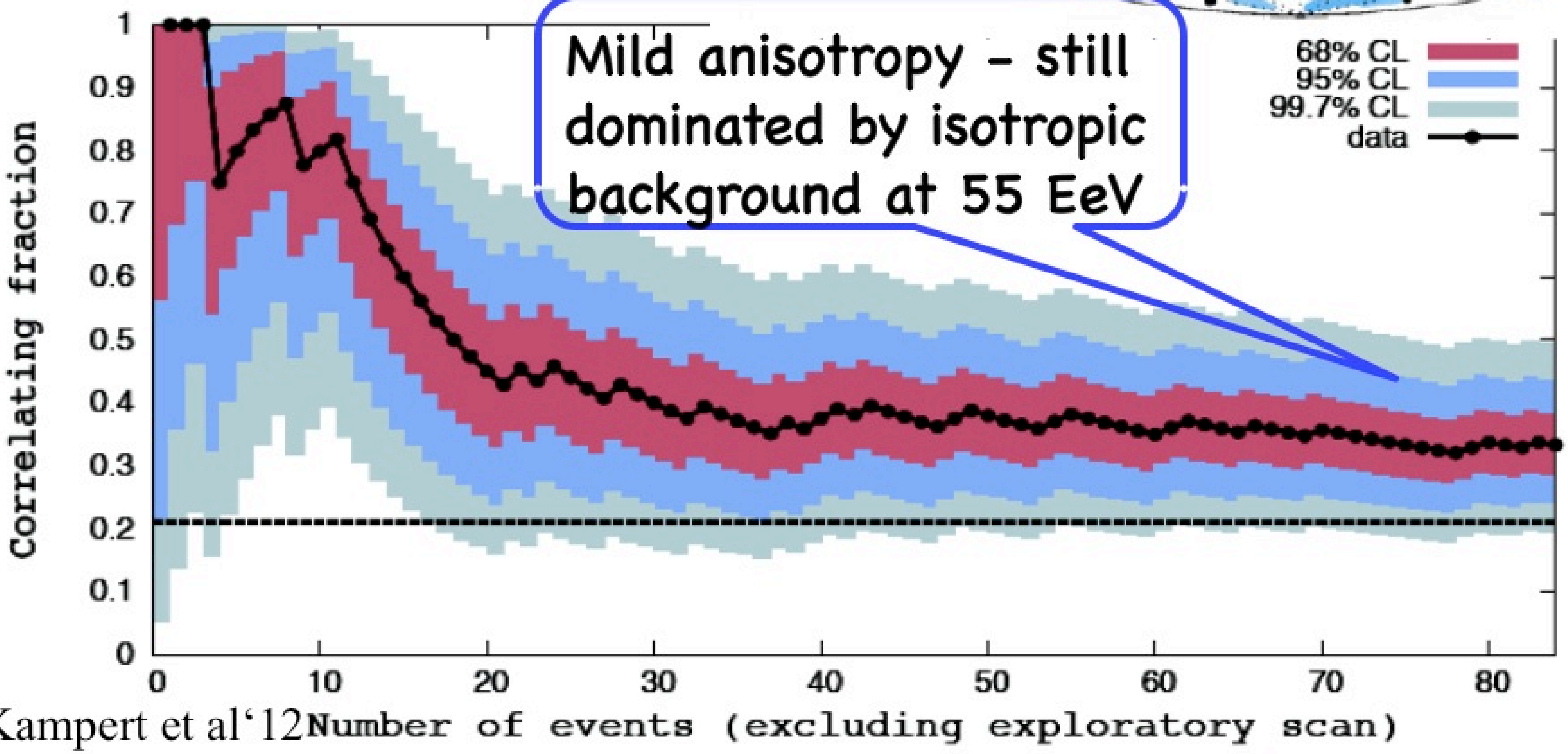
Kotera & AVO '11

Kotera & Lemoine '08

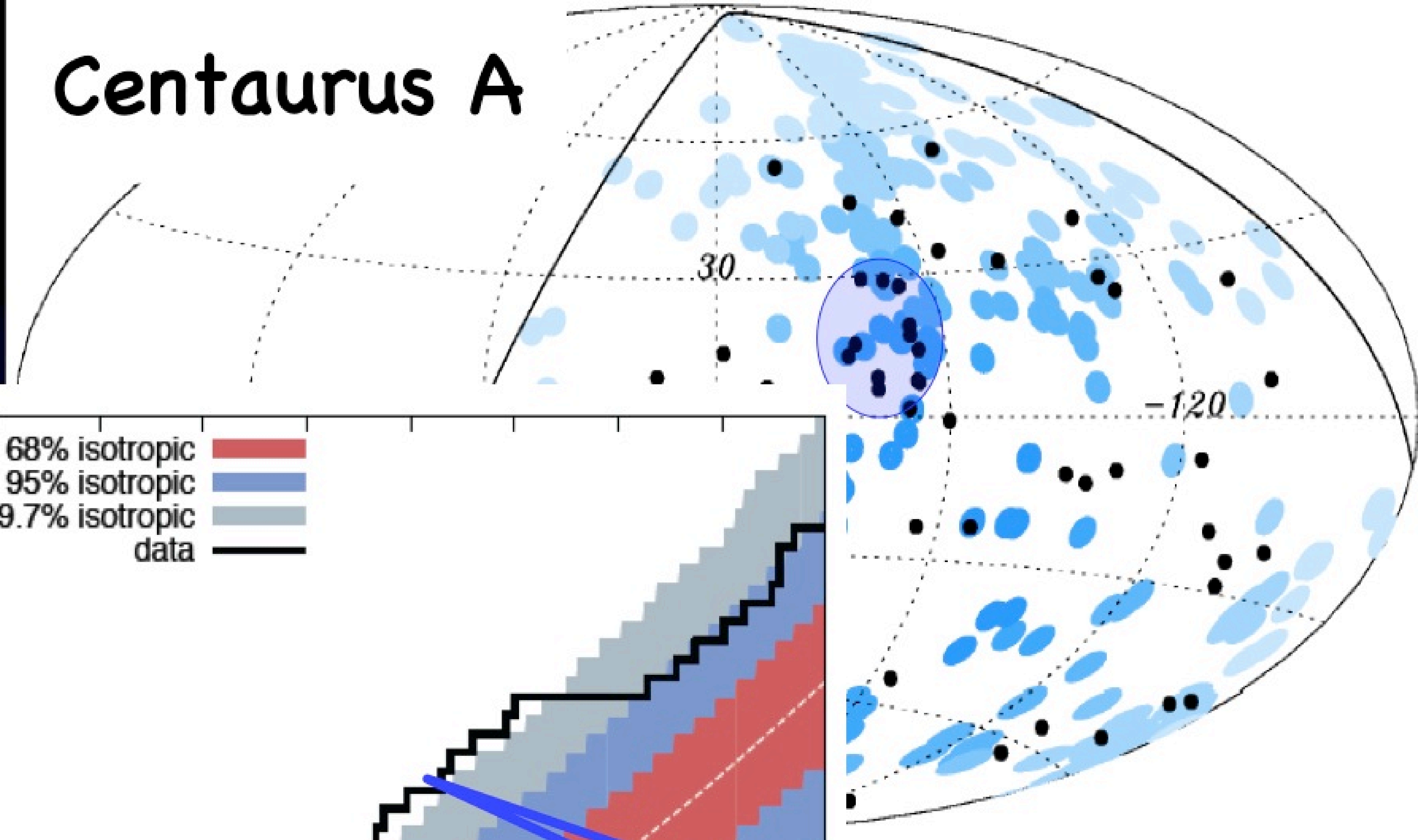
Auger Anisotropy Hints

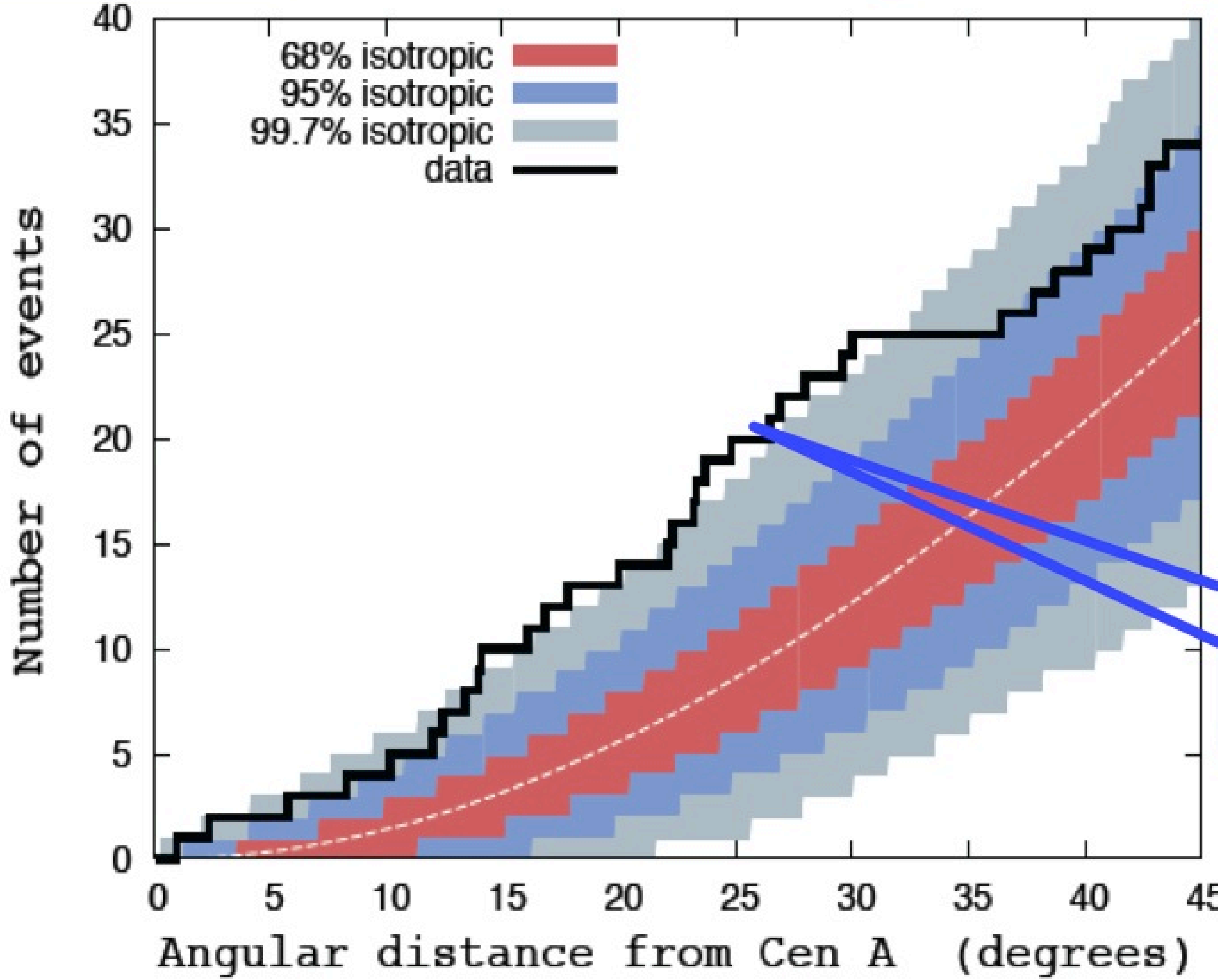






Centaurus A

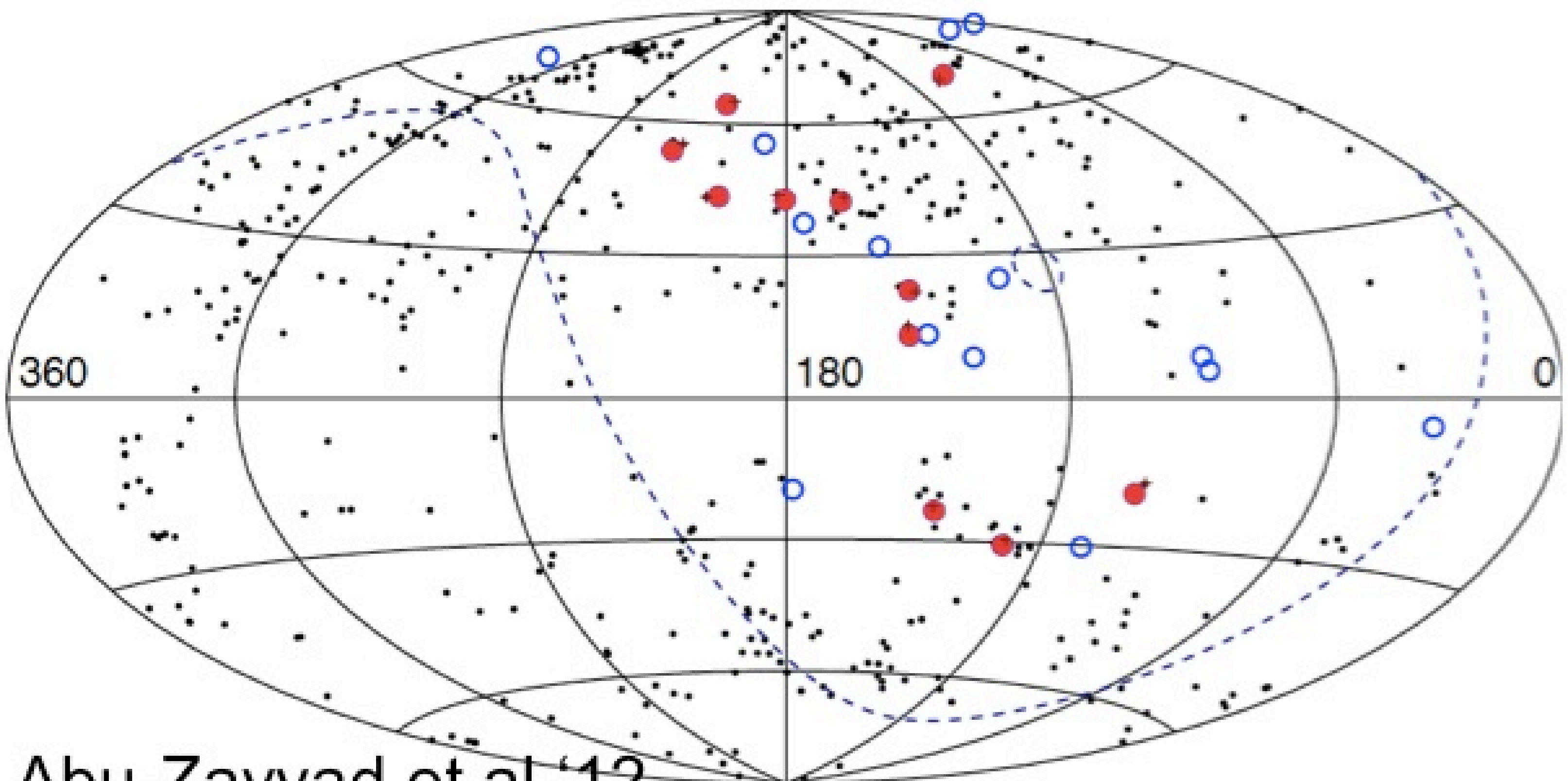


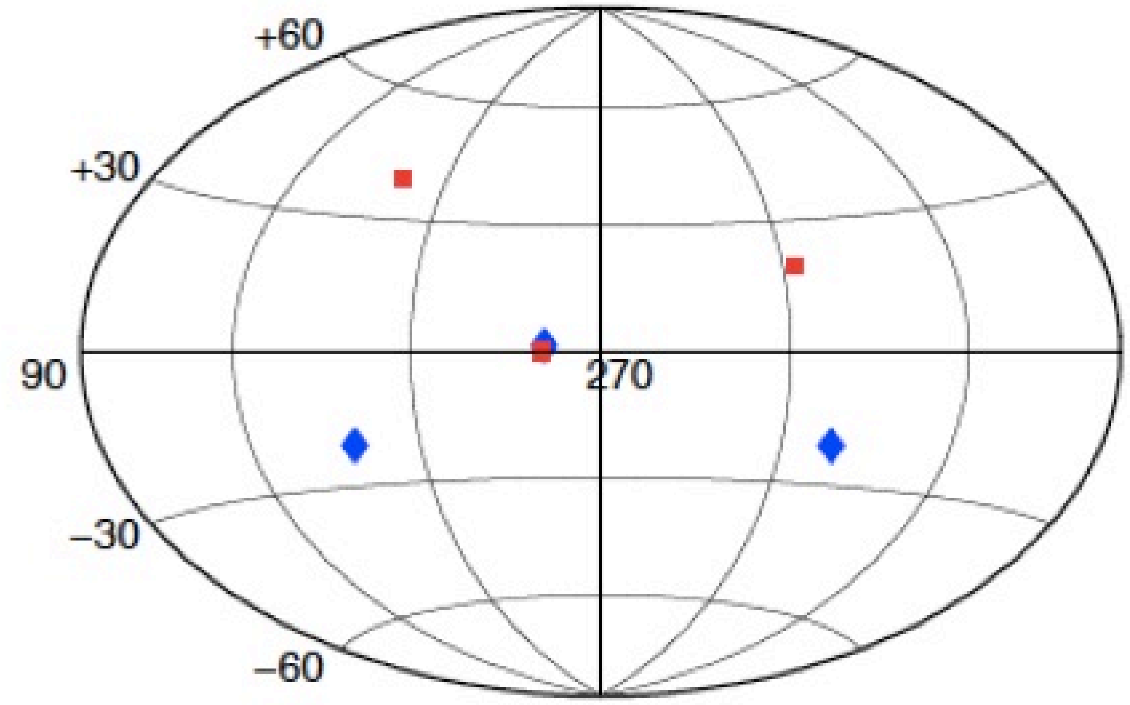


Large Scale Structure or Point source smeared by B??

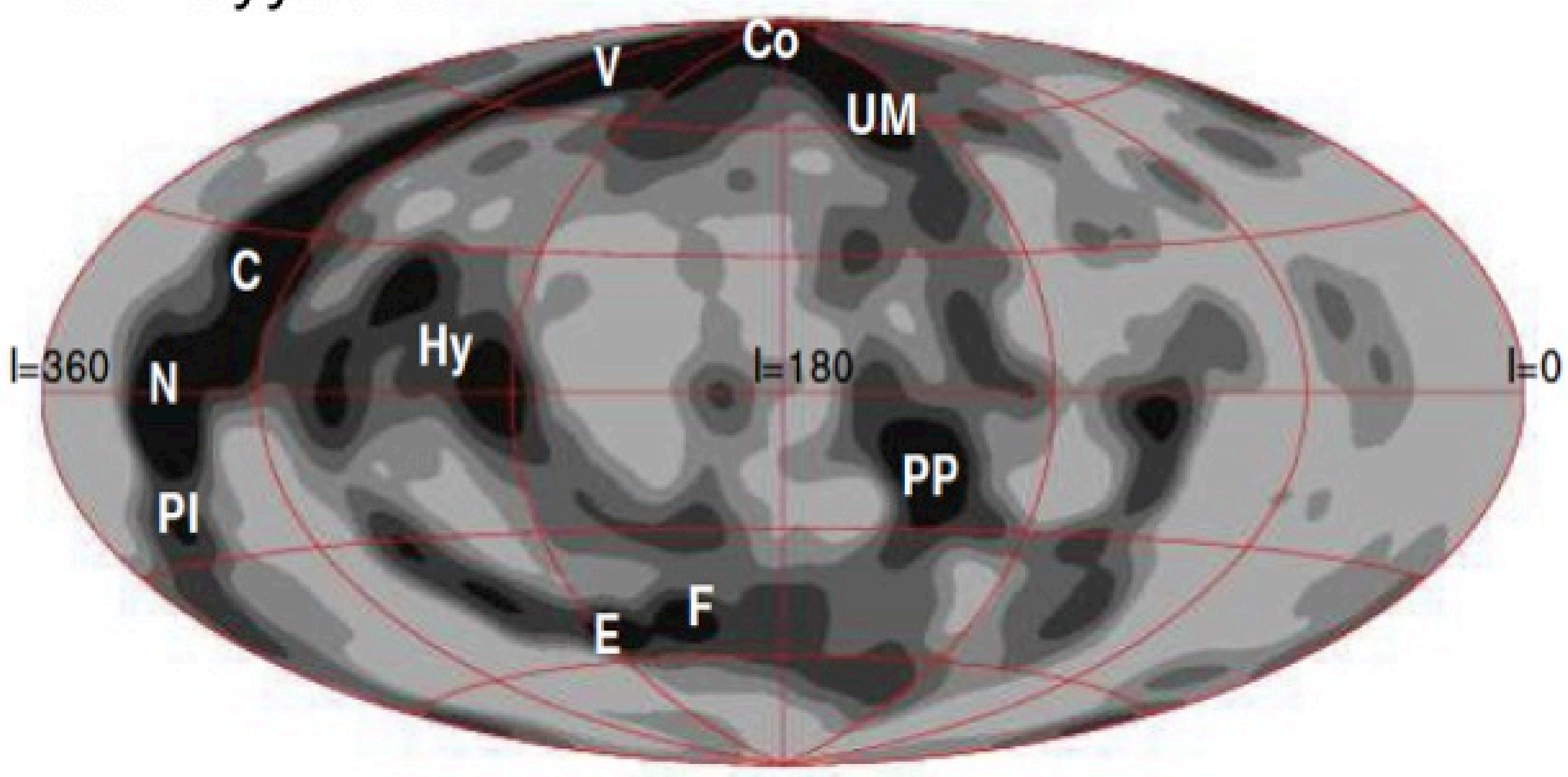
Telescope Array

25 events above 57 EeV - consitent with LSS





Abu-Zayyad et al '12



above 100 EeV
Auger/TA doublet

$P \approx 3.7 \times 10^{-3}$

Troitsky '12

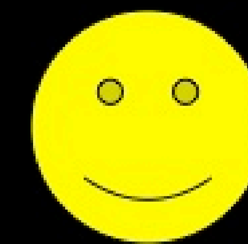
Recent Results

E>20 EeV Cosmic Rays are EXTRAGALACTIC 

E>40 EeV GZK-like feature in the spectrum 
or end of the injected spectrum, E_{max}? 

E>60 EeV Anisotropy Hints 

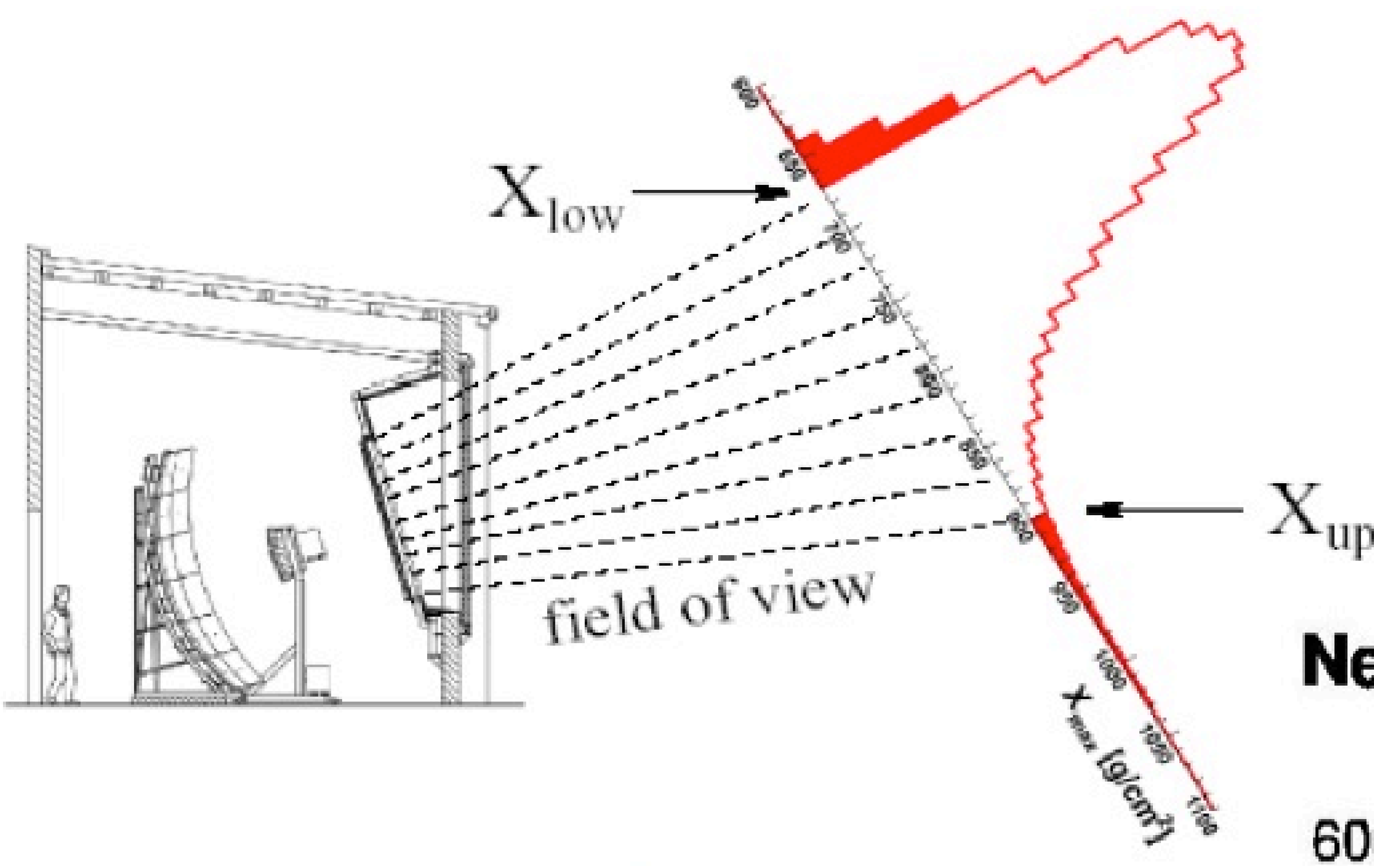
Recent Results

E>20 EeV Cosmic Rays are EXTRAGALACTIC 

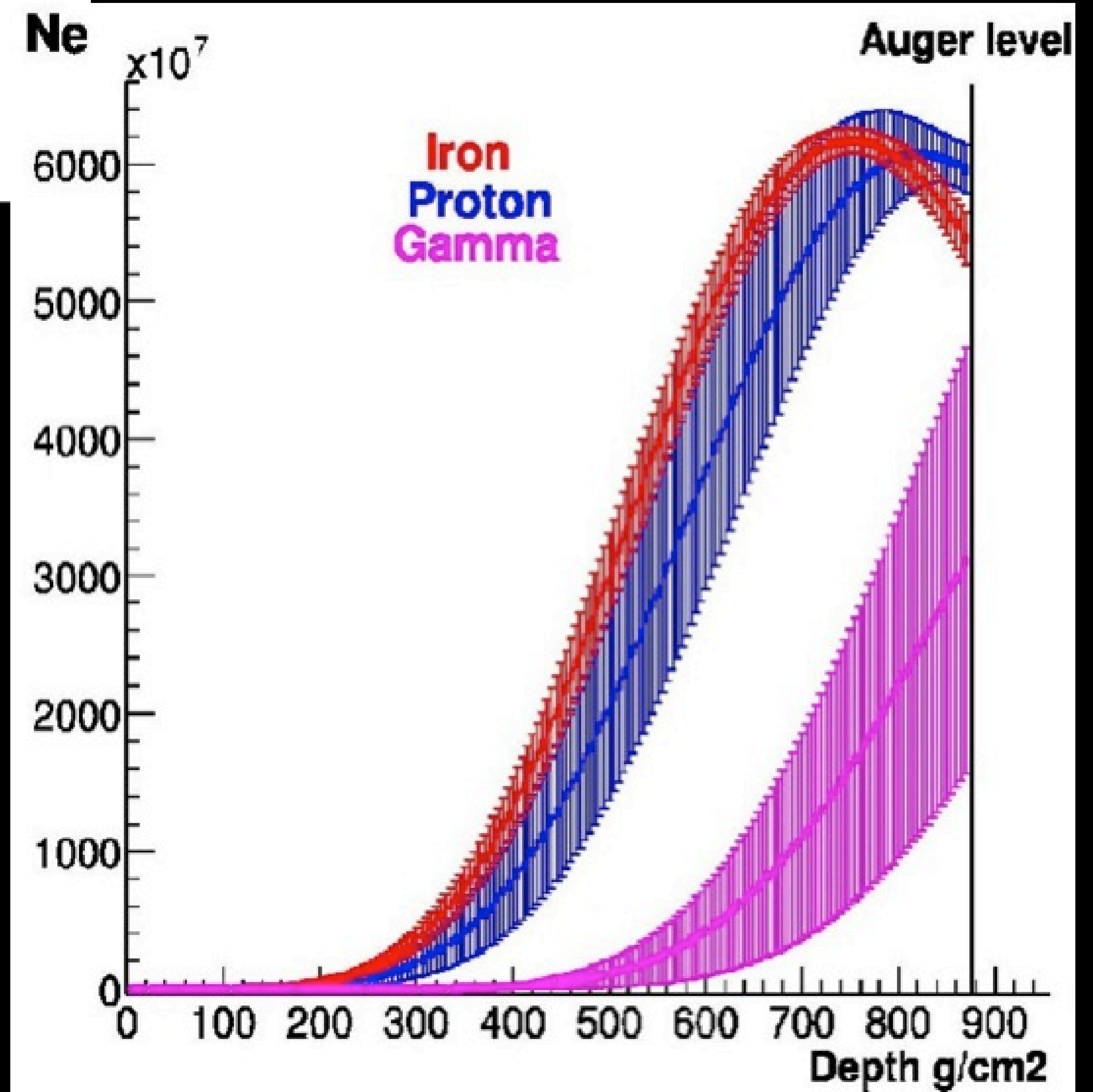
E>40 EeV GZK-like feature in the spectrum 
or end of the injected spectrum, E_{max}? 

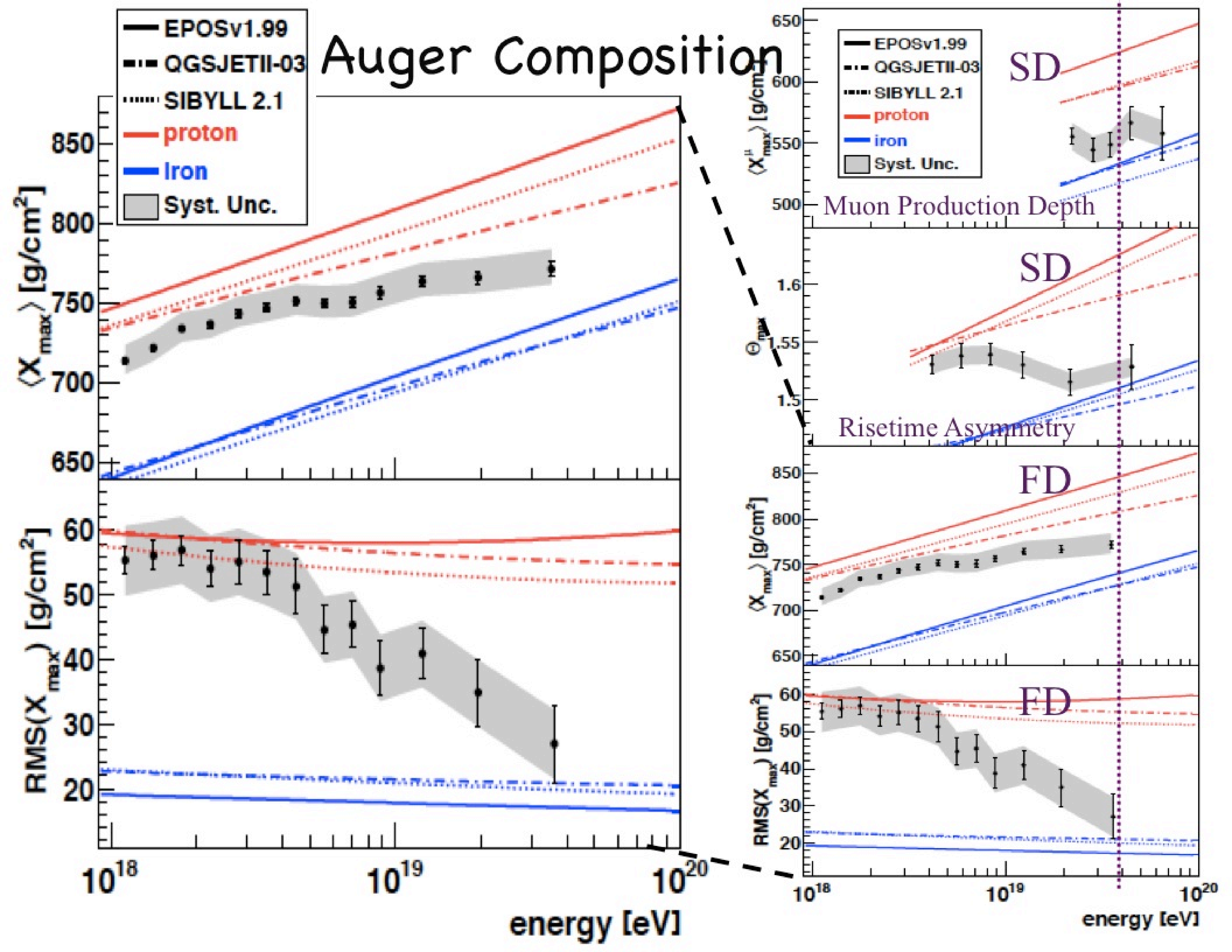
E>60 EeV Anisotropy Hints 

E>40 EeV Composition may be changing! 



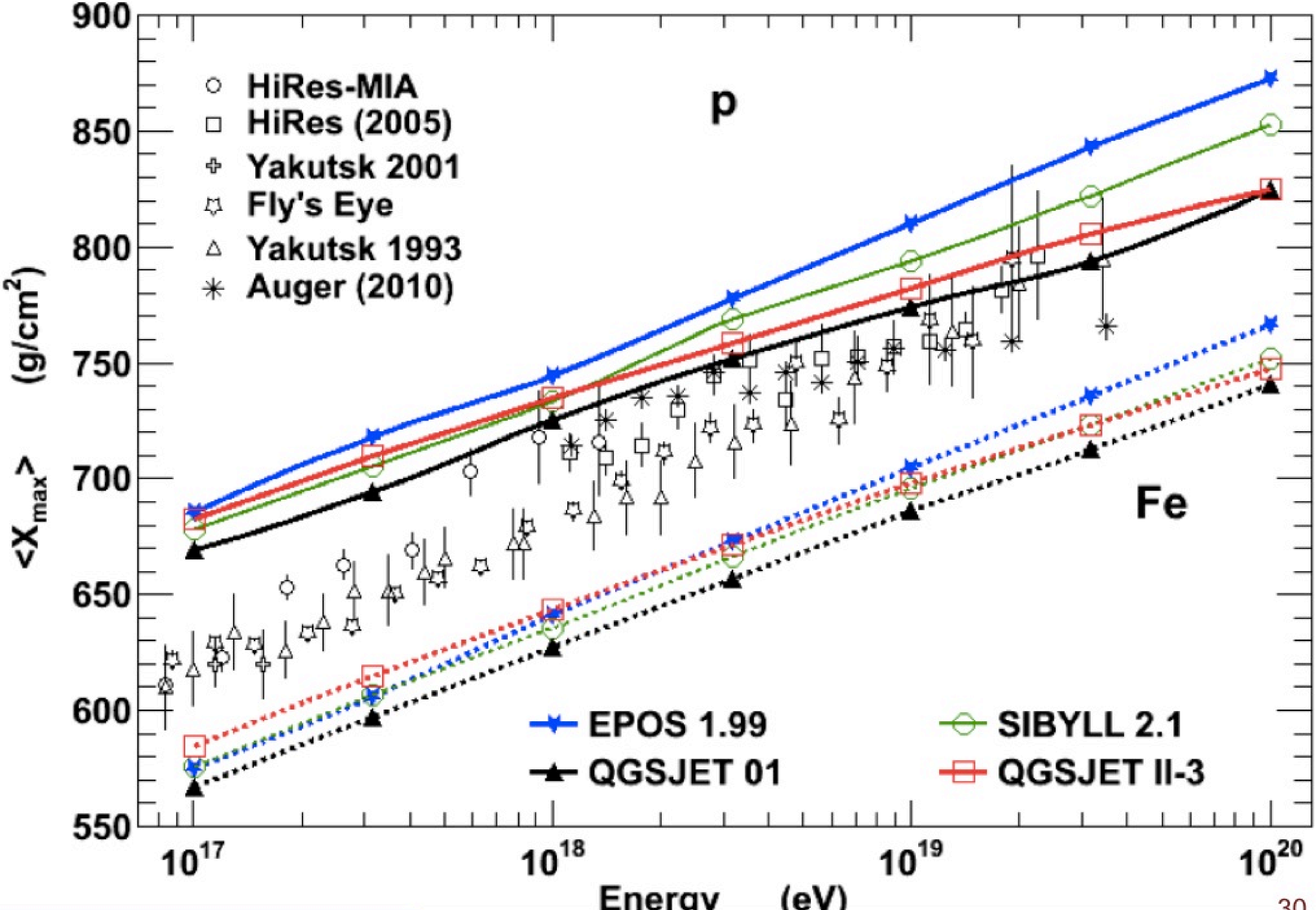
Composition observable: shower maximum $\langle X_{max} \rangle$ & RMS(X_{max})



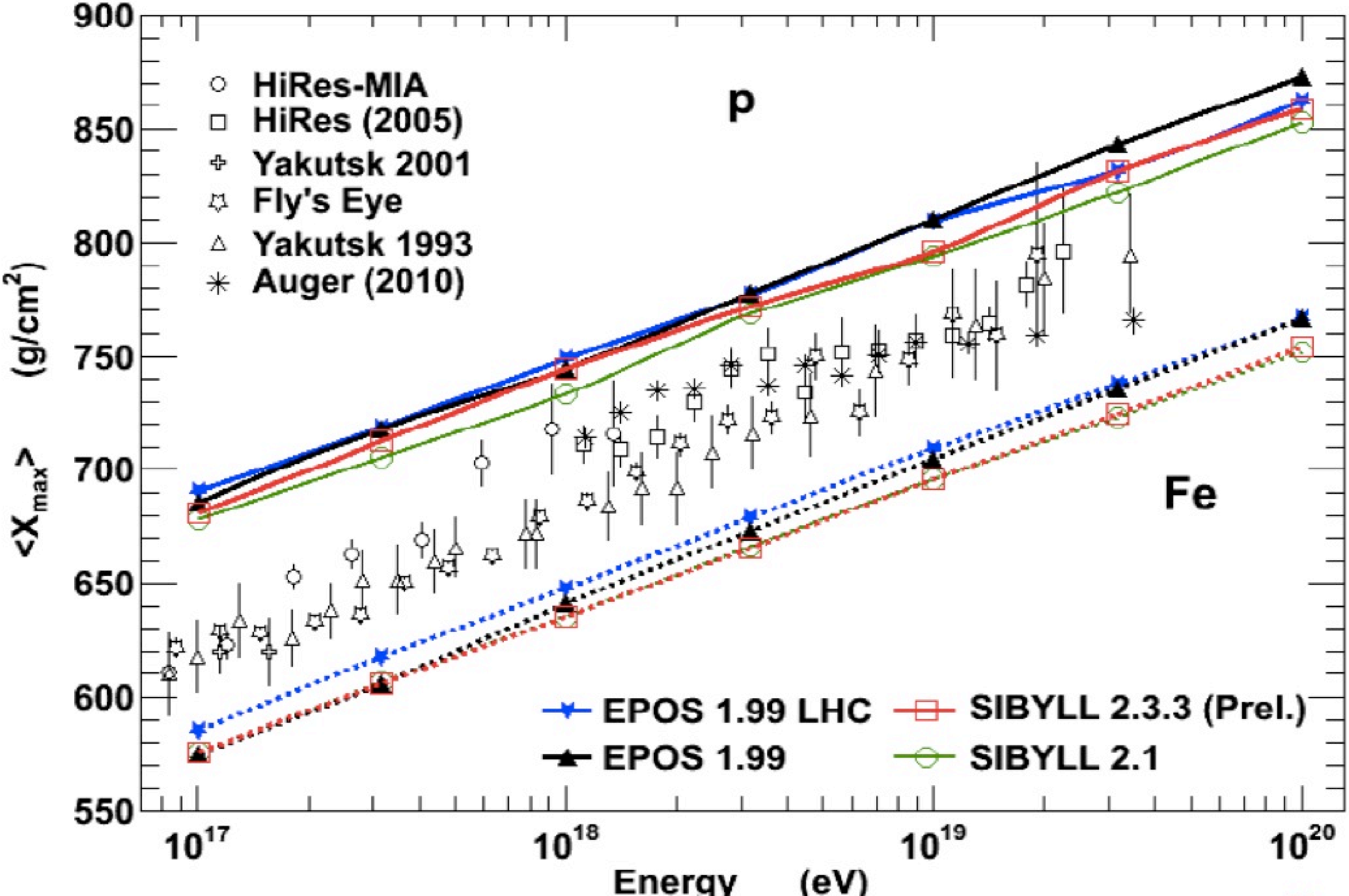


Auger Composition
EPOSv1.99
QGSJETII-03
SIBYLL 2.1
proton
Iron
Syst. Unc.
⟨X_max⟩ [g/cm²]
RMS(X_max) [g/cm²]
energy [eV]
SD
Muon Production Depth
SD
Risetime Asymmetry
FD
FD

Before LHC

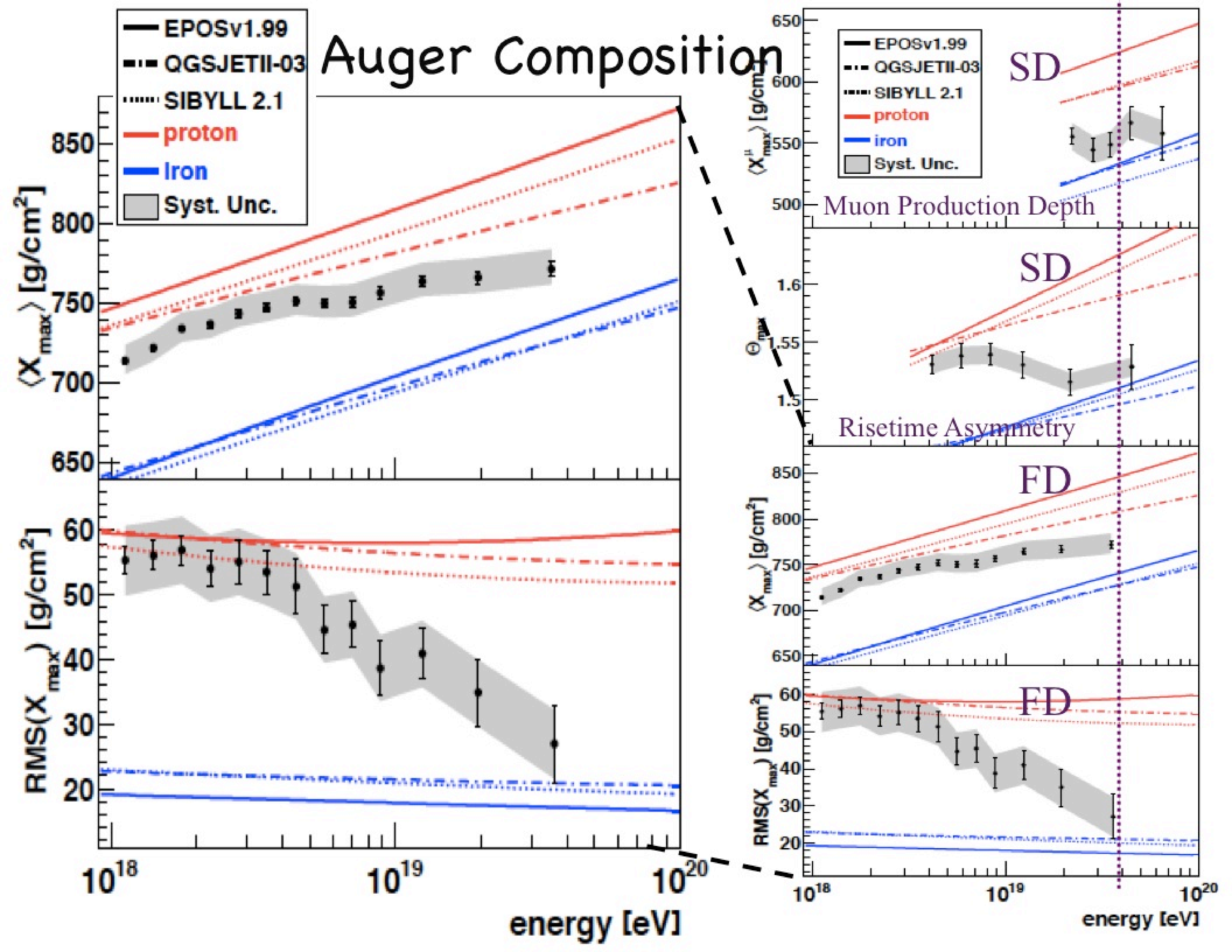

HiRes-MIA
HiRes (2005)
Yakutsk 2001
Fly's Eye
Yakutsk 1993
Auger (2010)
p
Fe
EPOS 1.99
QGSJET 01
SIBYLL 2.1
QGSJET II-3
900
850
800
750
700
650
600
550
$<X_{max}>$ (g/cm^2)
10^{17}
10^{18}
10^{19}
10^{20}
Energy (eV)

After LHC



900
850
800
750
700
650
600
550
$\langle X_{max} \rangle$ (g/cm^2)
HiRes-MIA
HiRes (2005)
Yakutsk 2001
Fly's Eye
Yakutsk 1993
Auger (2010)
p
Fe
EPOS 1.99 LHC
EPOS 1.99
SIBYLL 2.3.3 (Prel.)
SIBYLL 2.1
10^{17}
10^{18}
10^{19}
10^{20}
Energy (eV)

Auger Composition



Recent Results

E>20 EeV Cosmic Rays are EXTRAGALACTIC

E>40 EeV GZK-like feature in the spectrum
or end of the injected spectrum, E_{max}?

E>60 EeV Anisotropy Hints

E>40 EeV Composition may be changing!

Or maybe the HE interactions are changing!

How do we solve this Conundrum?

How do we solve this Conundrum?

GET A LOT MORE DATA above 60 EeV!!!!

How do we solve this Conundrum?

GET A LOT MORE DATA above 60 EeV!!!!

GET A LOT MORE DATA above 60 EeV!!!!

GET A LOT MORE DATA above 60 EeV!!!!

GET A LOT MORE DATA above 60 EeV!!!!

OVER THE WHOLE SKY !!!!

How many EECRs > 60 EeV?

Before we see a source?

How many EECRs > 60 EeV?

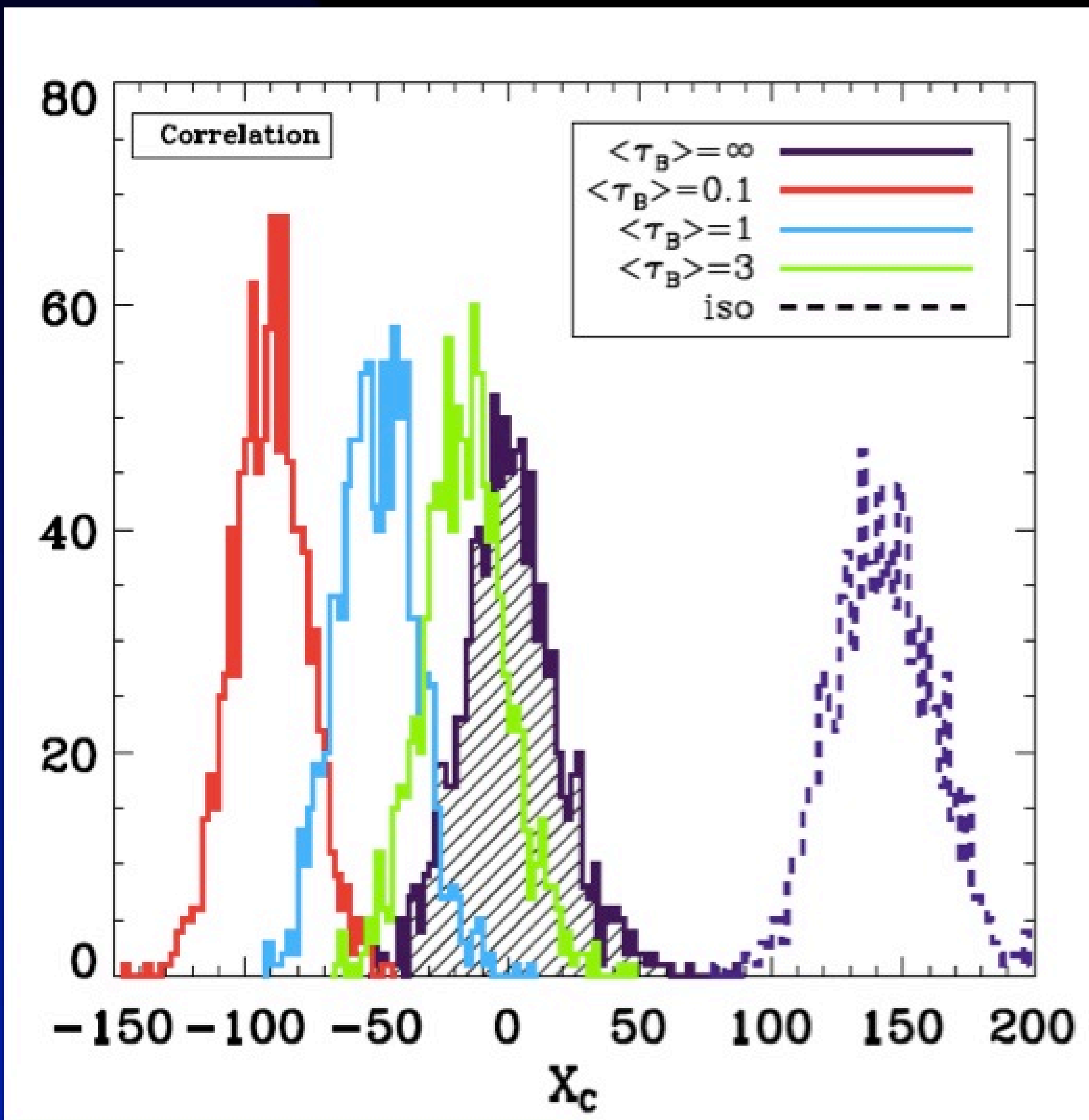
Before we see a source?

1,000 is a good o.o.m. estimate

How many EECRs > 60 EeV?

Before we see a source?

1,000 is a good o.o.m. estimate



1,000 simulated events
>60 EeV
can separate populations
even for transient sources

Kalli, Lemoine, Kotera, '11

How many EECRs > 60 EeV?

Before we see a source?

1,000 is a good o.o.m. estimate

Dipole from direction of Cen A in Auger >60 EeV:

(a posteriori) right ascension harmonic analyses

Anchordoqui, Goldberg & Weiler '11

$$\alpha_d \, \hat{d} = \frac{3}{\mathcal{N}} \int J(\hat{u}) \; \hat{u} \; d\Omega$$

$\alpha_d = 0.25$

5σ discovery requires 1,000 events

(with whole sky coverage)

How many EECRs > 60 EeV?

Auger w/ 3,000 km^2

~20 events > 55 EeV/ yr

Telescope Array w/ 700 km^2

~4.6 events > 55 EeV/ yr

TOTAL ~30 events/yr

How many EECRs > 60 EeV?

Auger w/ 3,000 km^2

~20 events > 55 EeV/ yr

Telescope Array w/ 700 km^2

~4.6 events > 55 EeV/ yr

TOTAL ~30 events/yr

It will take 30 years to reach 1,000!

How many EECRs > 60 EeV?

Auger w/ 3,000 km^2

~20 events > 55 EeV/ yr

Telescope Array w/ 700 km^2

~4.6 events > 55 EeV/ yr

TOTAL ~30 events/yr

Earth - surface ~ $5\ 10^8$ km^2

~$3.4\ 10^6$ events/yr

How many EECRs > 60 EeV?

Auger w/ 3,000 km^2

~20 events > 55 EeV/ yr

Telescope Array w/ 700 km^2

~4.6 events > 55 EeV/ yr

TOTAL ~30 events/yr

5 o.o.m to go!

Earth surface ~ 5 10^8 km^2

~3.4 10^6 events/yr

Go to SPACE!

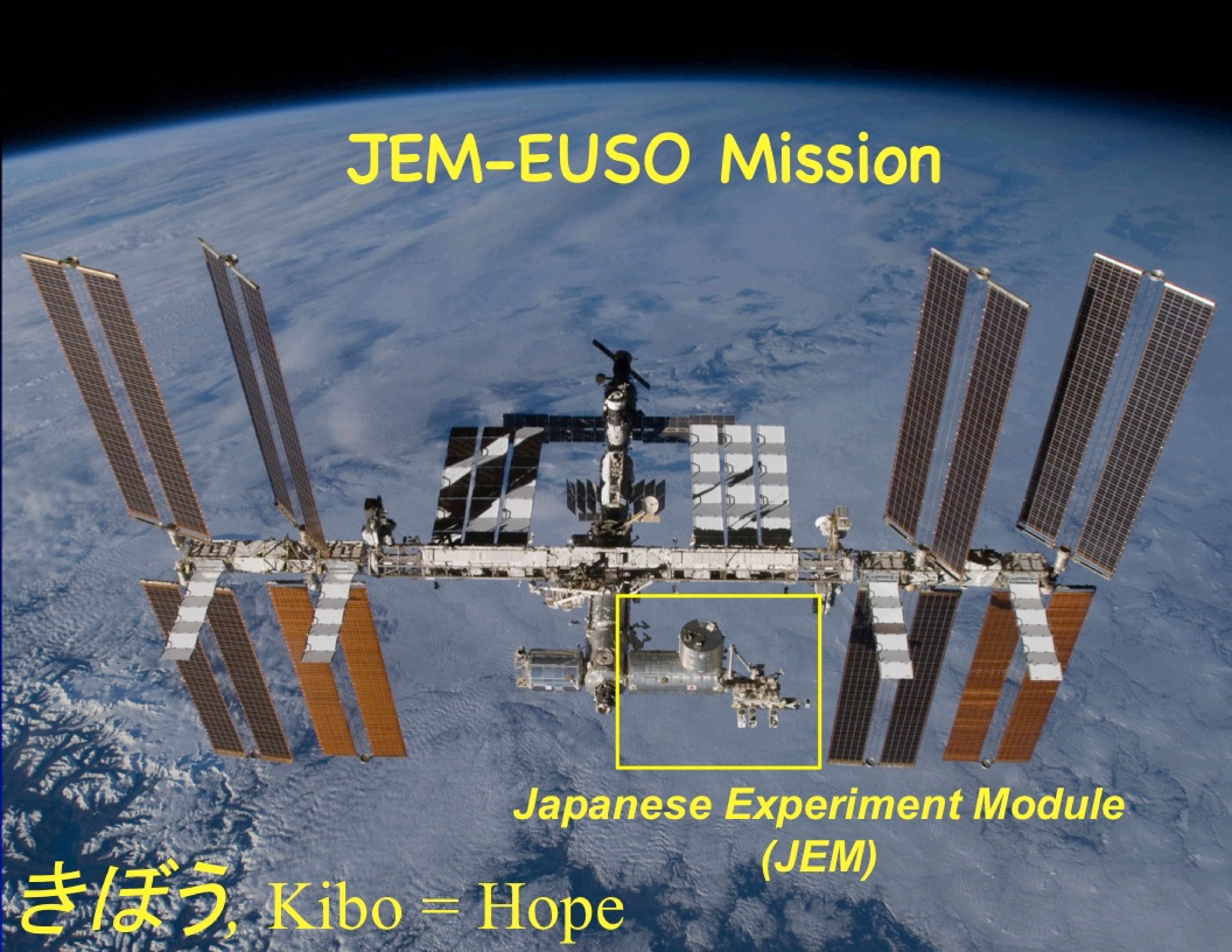
To look down on the Atmosphere!

The JEM-EUSO Mission

RIKEN, NASA, JAXA, ESA, ROSCOSMOS

JEM-EUSO

Extreme Universe Space Observatory (EUSO) in the Japanese Experiment Module (JEM)


JEM-EUSO Mission
Japanese Experiment Module
(JEM)
きぼう, Kibo = Hope

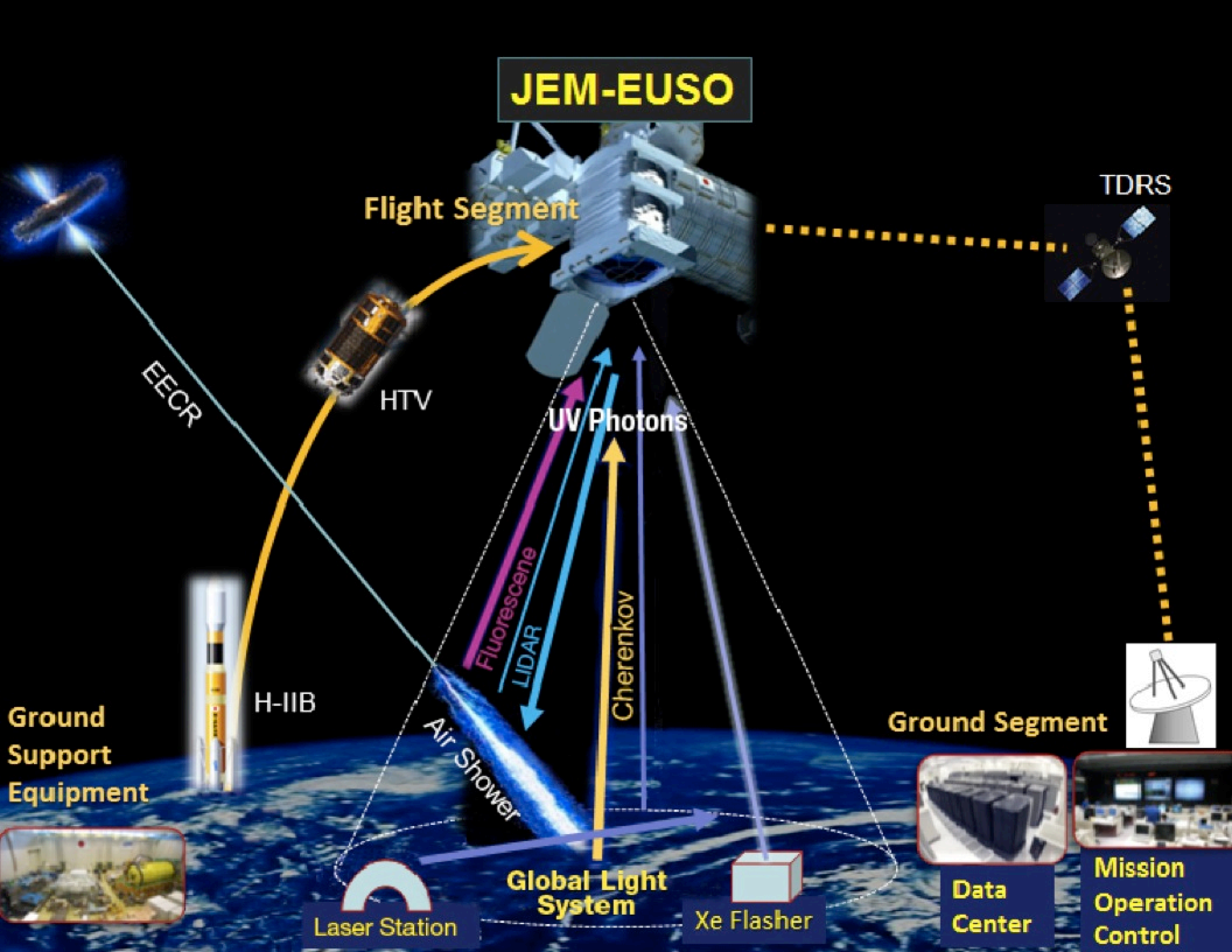
JEM-EUSO Collaboration

Japan, USA, Korea, Mexico, Russia
Europe: Bulgaria, France, Germany, Italy, Poland, Slovakia, Spain, Switzerland

13 Countries, 73 Institutions, 250 researchers

Leading institution: RIKEN
PI: Piergiorgio Picozza

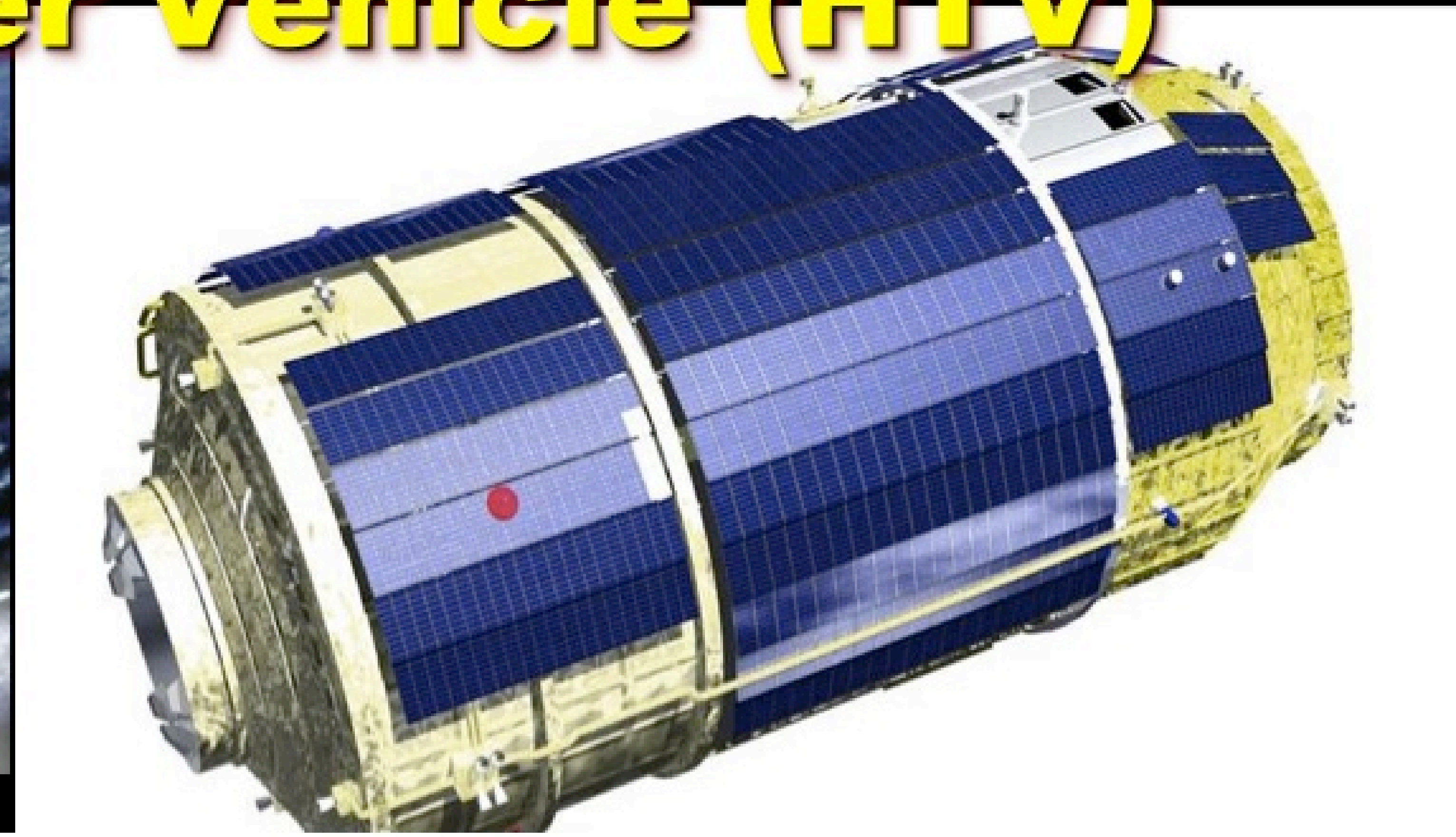
launch 2017


JEM-EUSO
Flight Segment
TDRS
EECR
HTV
UV Photons
Fluorescene
LIDAR
Cherenkov
H-IIB
Air Shower
Ground Support Equipment
Ground Segment
Global Light System
Laser Station
Xe Flasher
Data Center
Mission Operation Control

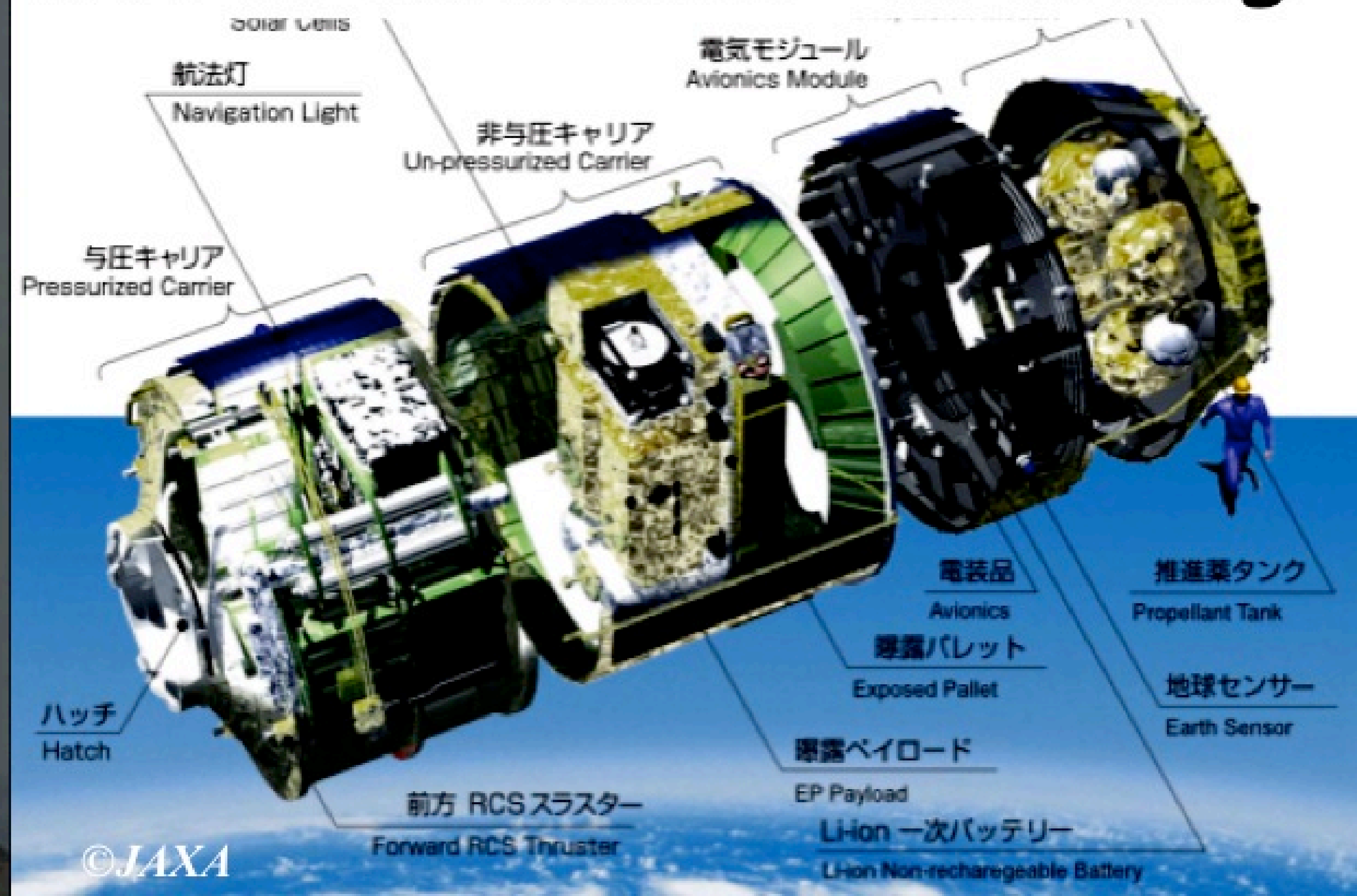
Mission Studies

Parameter	Value
Launch date	2017
Mission Lifetime	3+2 years
Rocket	H2B
Transport Vehicle	HTV
Accommodation on JEM	EF#2
Mass	1938 kg
Power	926 W (op.) 352 W (non op.)
Data rate	285 kbps (+ on board storage)
Orbit	400 km
Inclination of the Orbit	51.6°
Operation Temperature	-10° to +50°

H-II Transfer Vehicle (HTV)



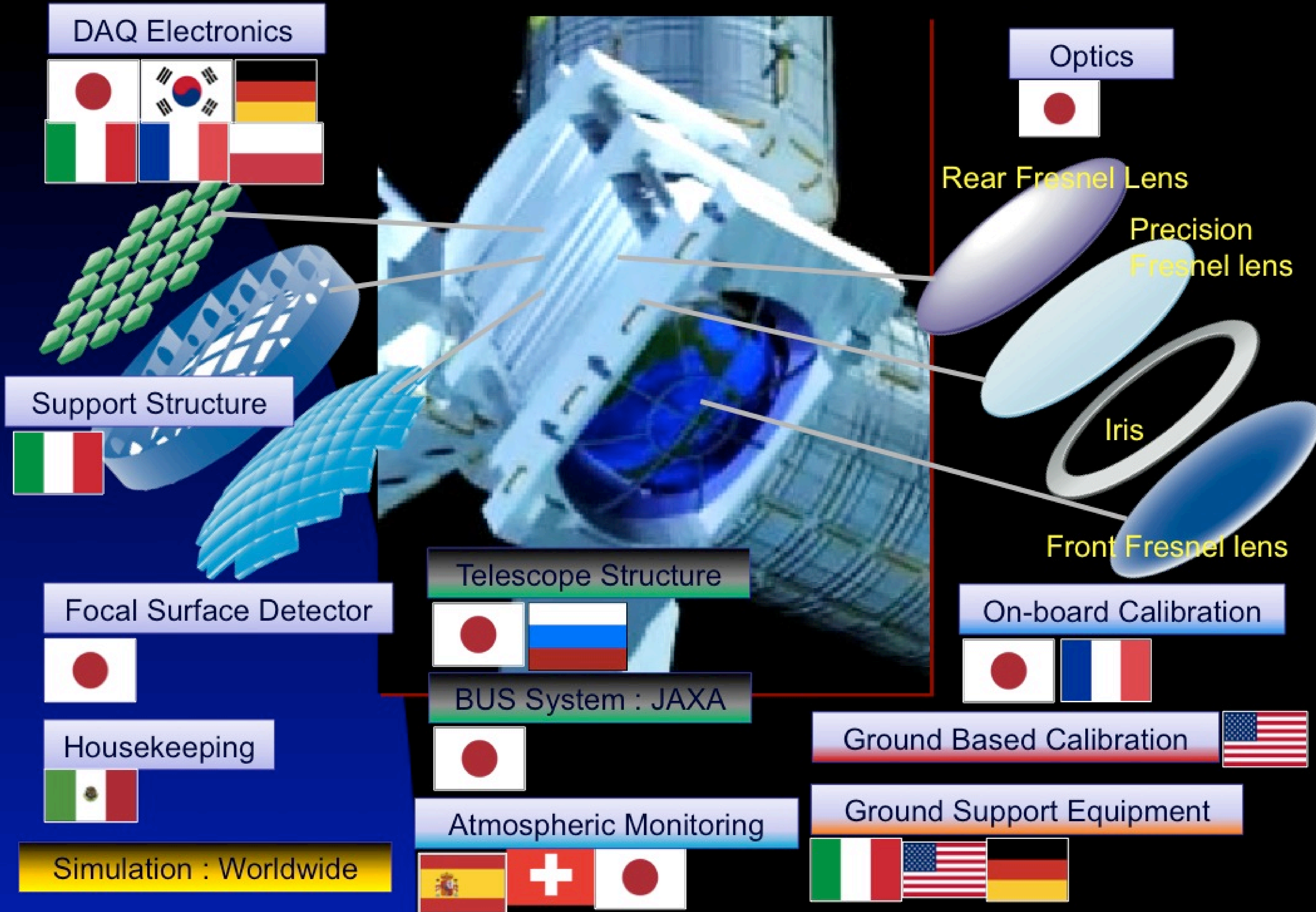
HTV is 4m across ~10 m long



UV Telescope Parameters

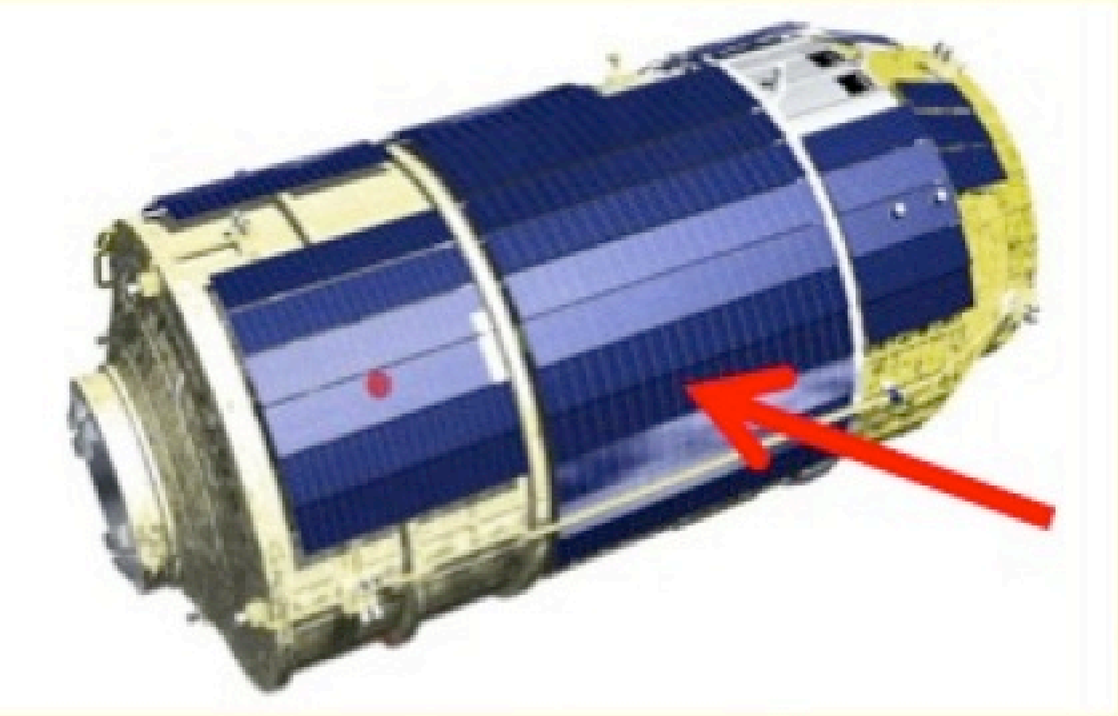
Parameter	Value
Field of View	±30°
Monitored Area	>1.3×10^5 km^2
Telescope aperture	≥2.5 m
Operational wavelength	300-400 nm
Resolution in angle	0.075°
Focal Plane Area	4.5 m^2
Pixel Size	<3 mm
Number of Pixels	≈3×10^5
Pixel size on ground	≈560 m
Time Resolution	2.5 μs
Dead Time	<3%
Photo-detector Efficiency	≥20%

International Role Sharing



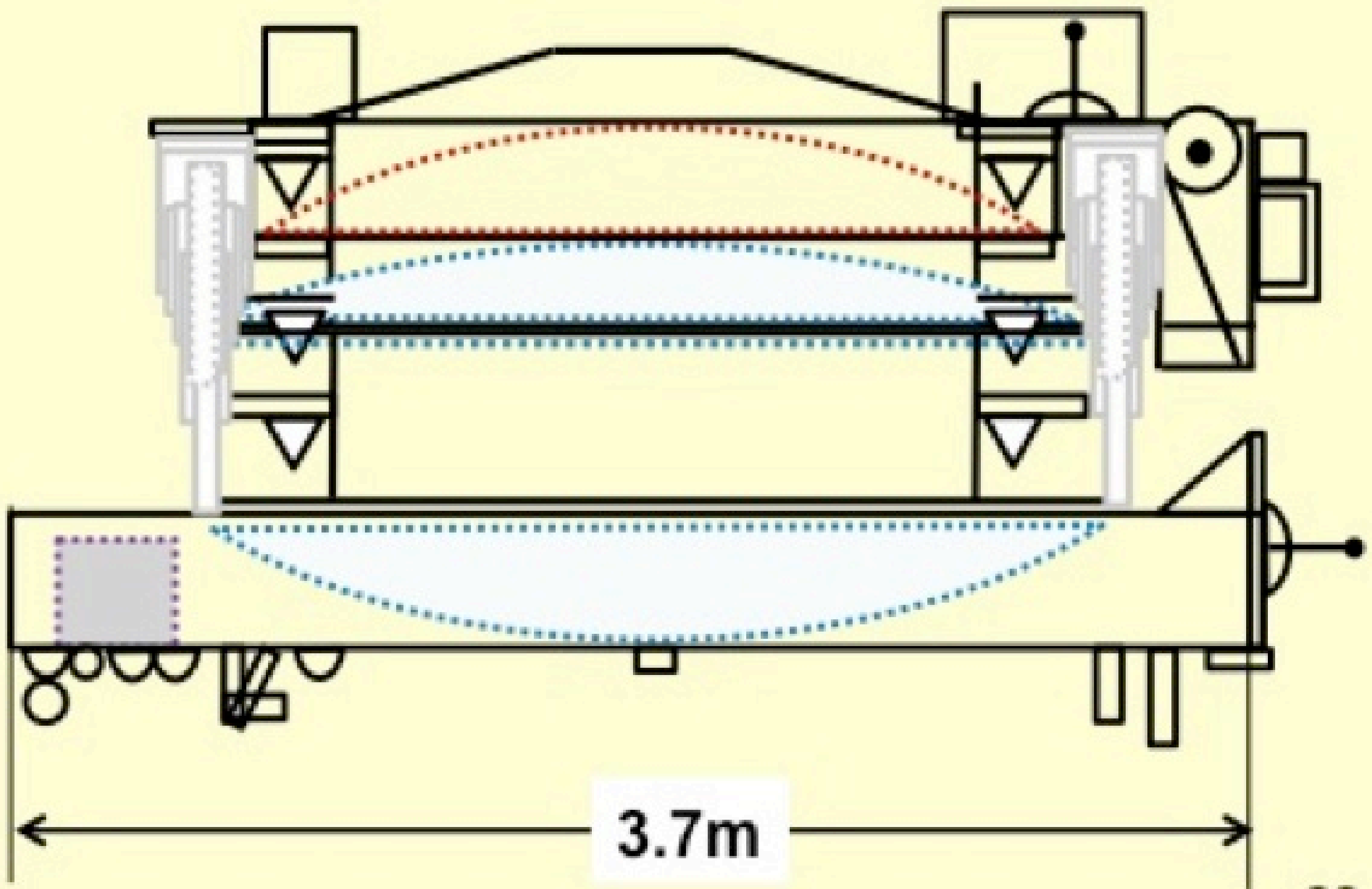
Science Instrument on HTV

Stowing configuration
to carry by HTV

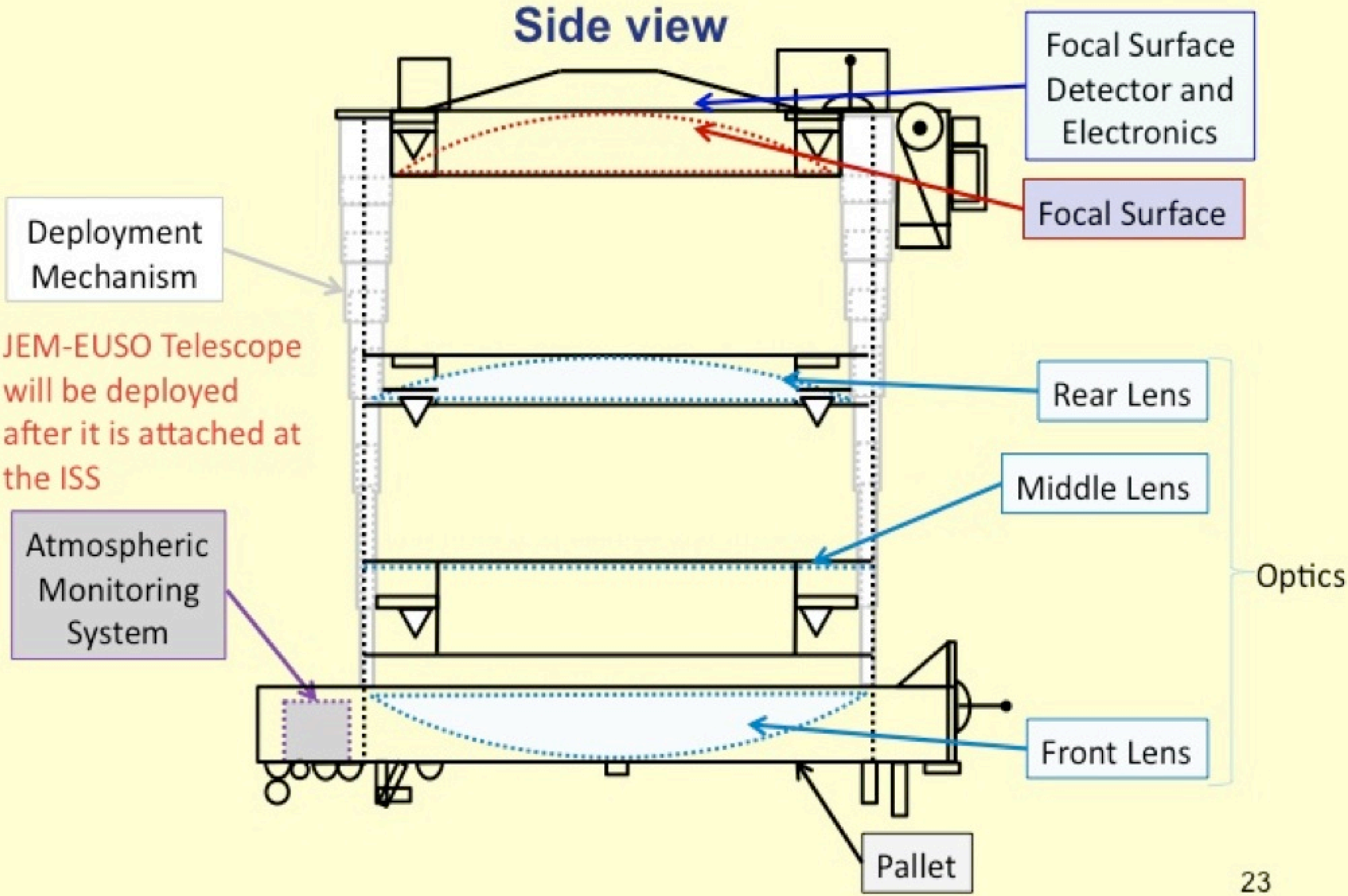


H2B Transfer
Vehicle (HTV)

Side view



Science Instrument

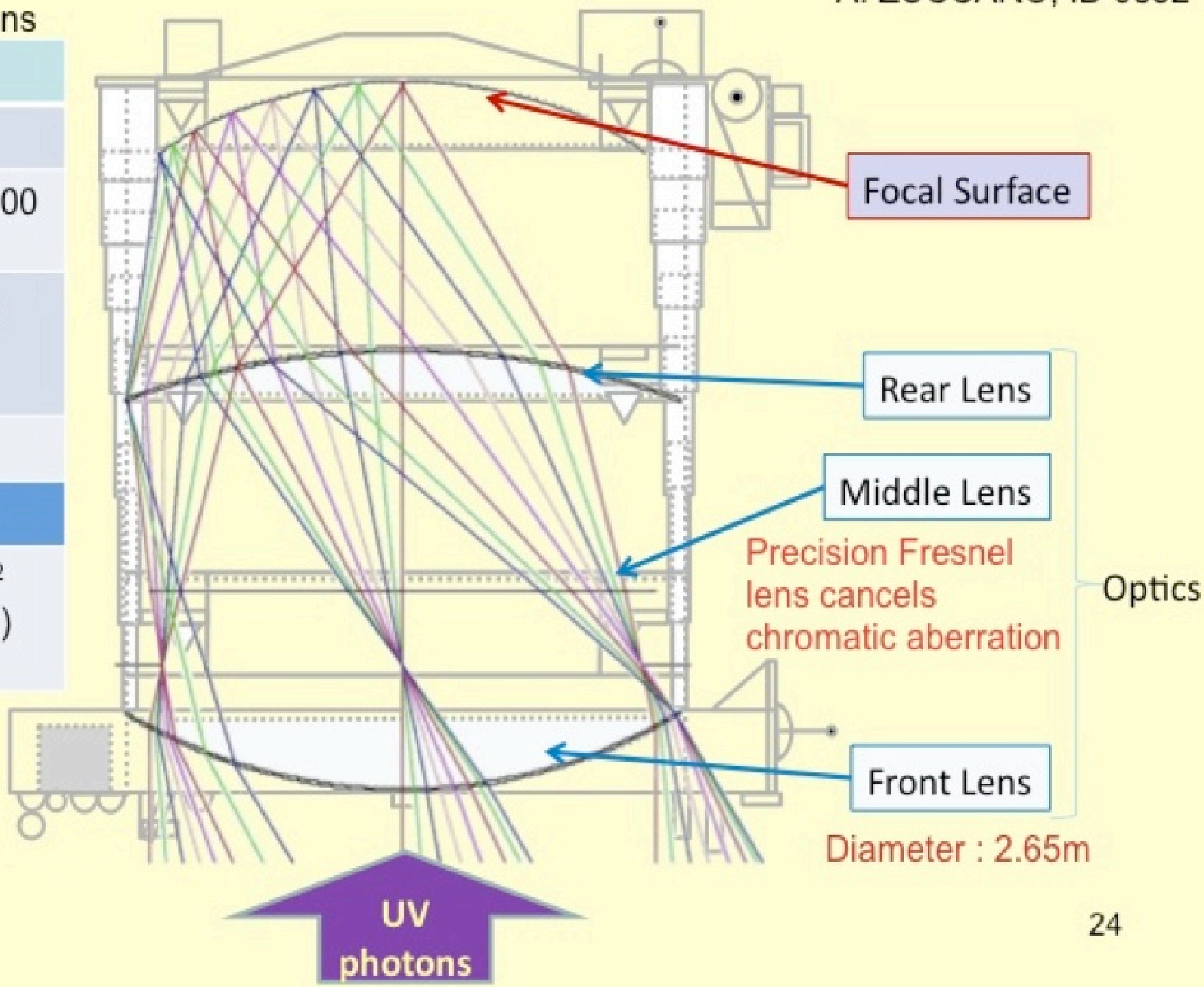


Optics design by ray tracing

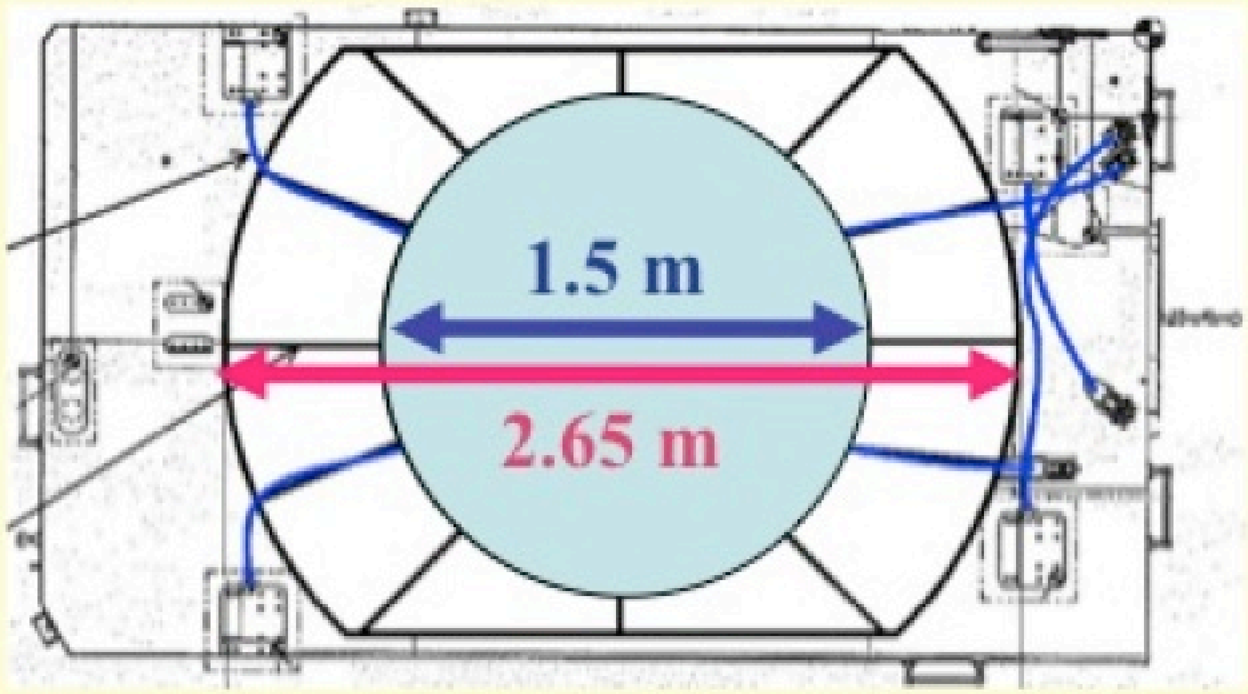
A. ZUCCARO, ID 0852

Simulation conditions

Optics	
FOV	±30
Optical bandwidth	330 ÷ 400 nm
Entrance Pupil Diameter	≥ 2.3 m
F/number	≤1
Focal surface	
Focal surface area	~4.5 m² (curved)

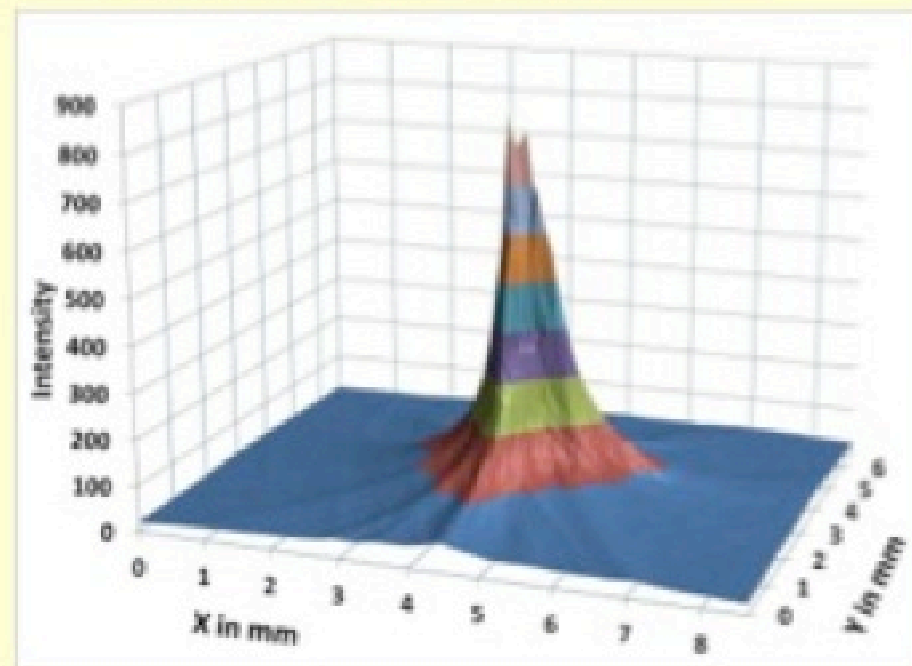


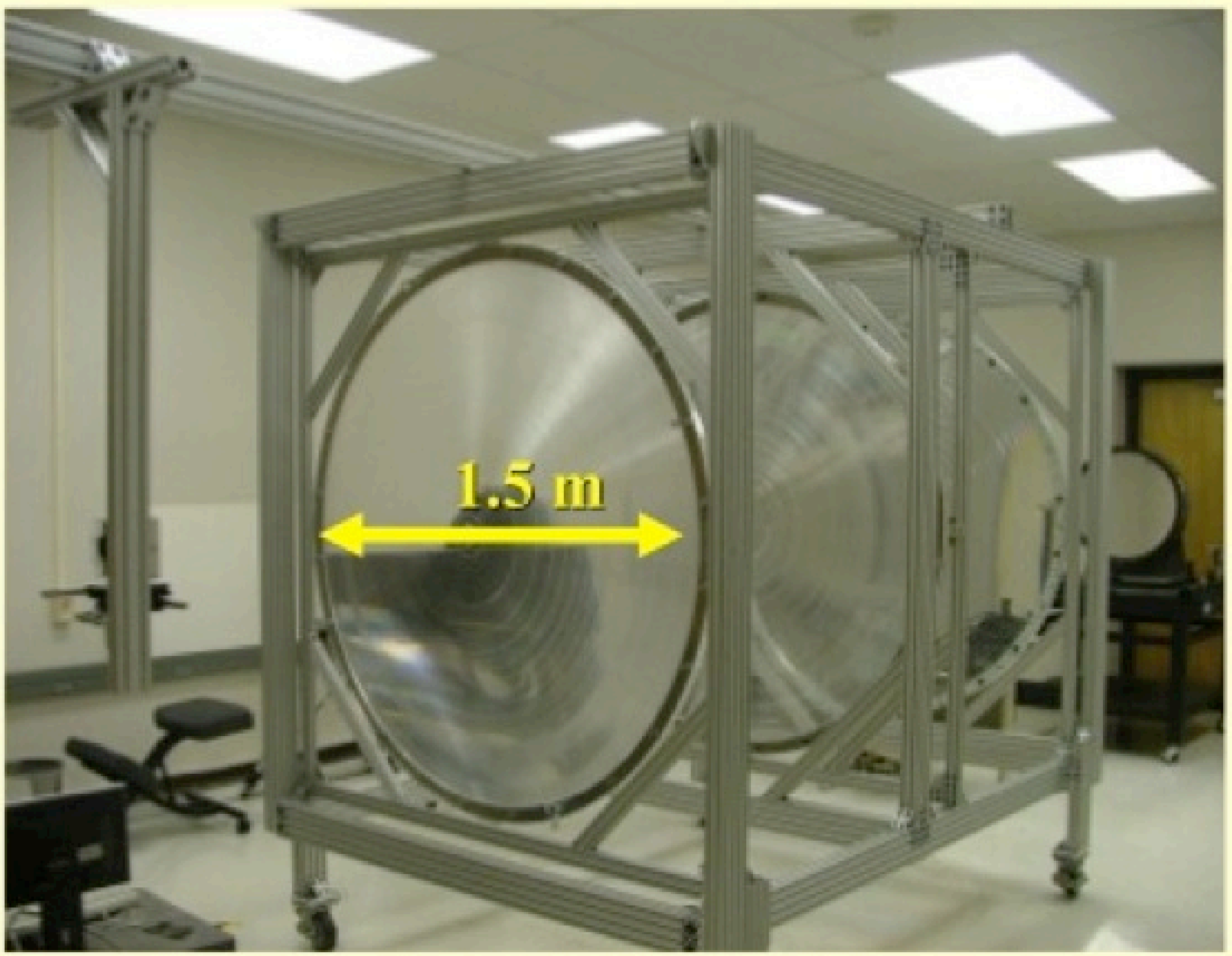
Test of Breadboard Model Lenses



J.H. Adams, ID 1100
Y. Hachisu, ID 0874

3 Breadboard Model (BBM) Fresnel lenses (1.5m ϕ) are manufactured and tested.



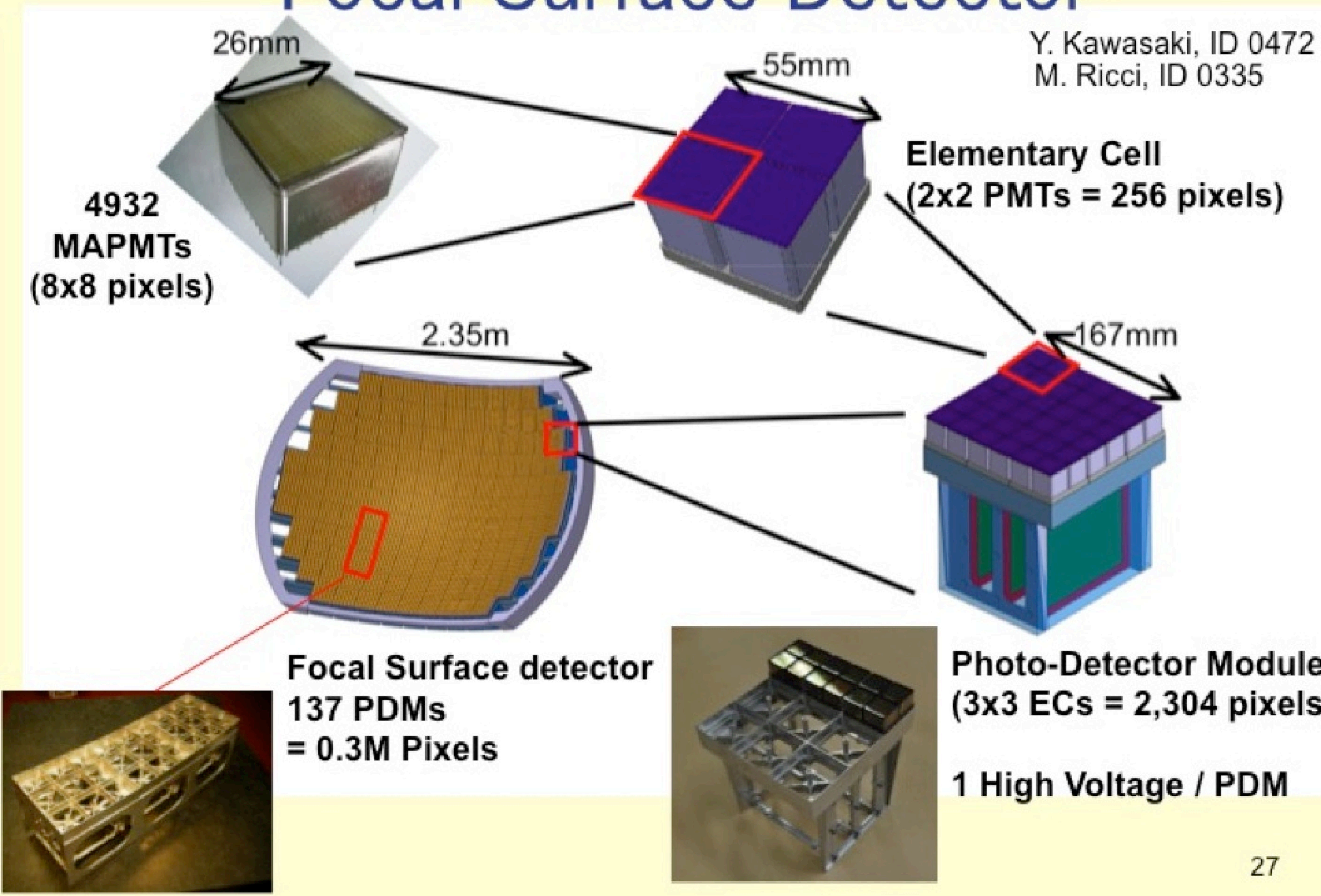


Tested performances meet the requirements or are close to it.

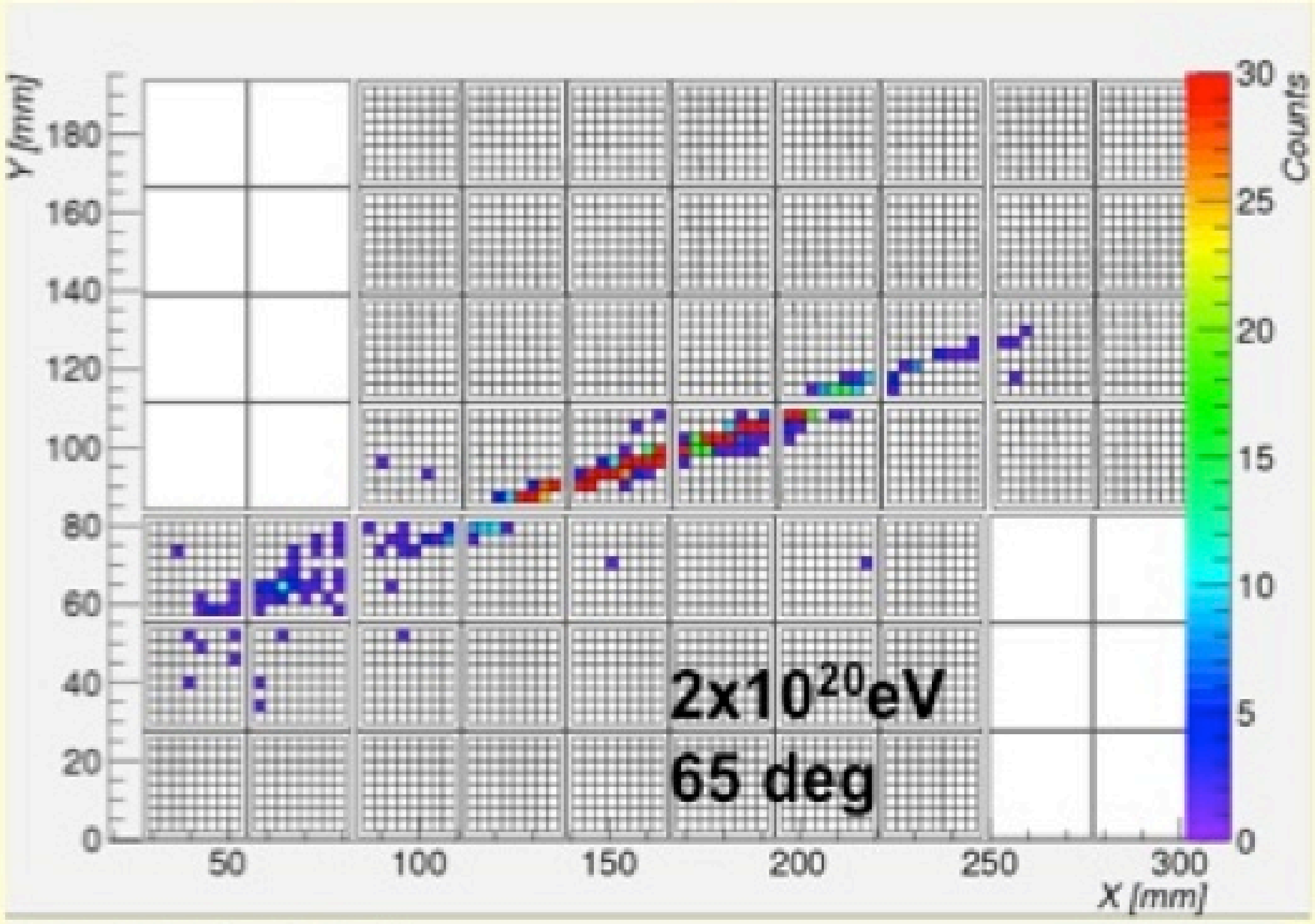
Result: ~3mm RMS

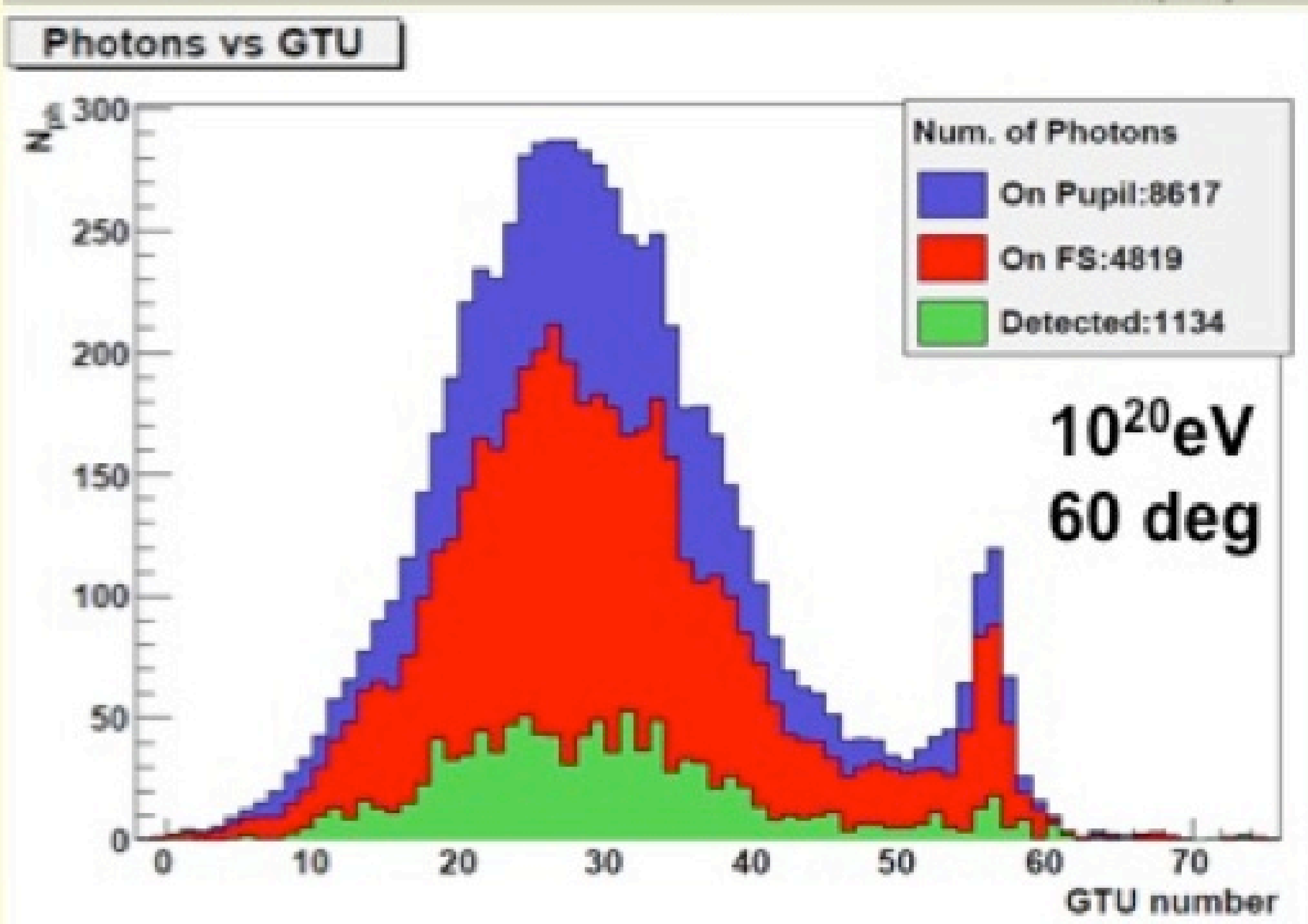
Req. : 4.6mm RMS

Focal Surface Detector



Result of end-to-end simulation



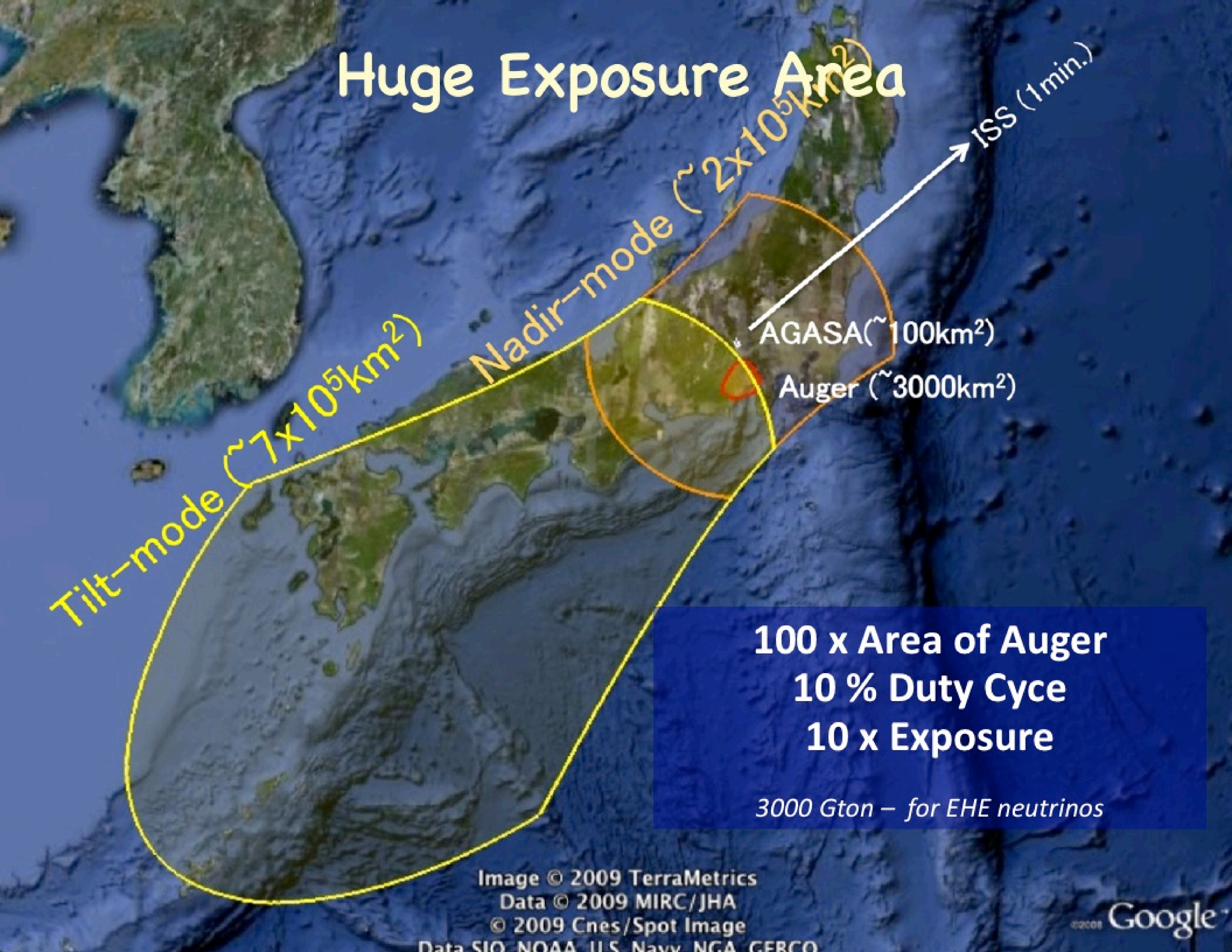


F. Fenu, ID 0829
K. Higashide, ID 1240
T. Mernik, ID 0633

Simulated air shower image on the focal surface detector.

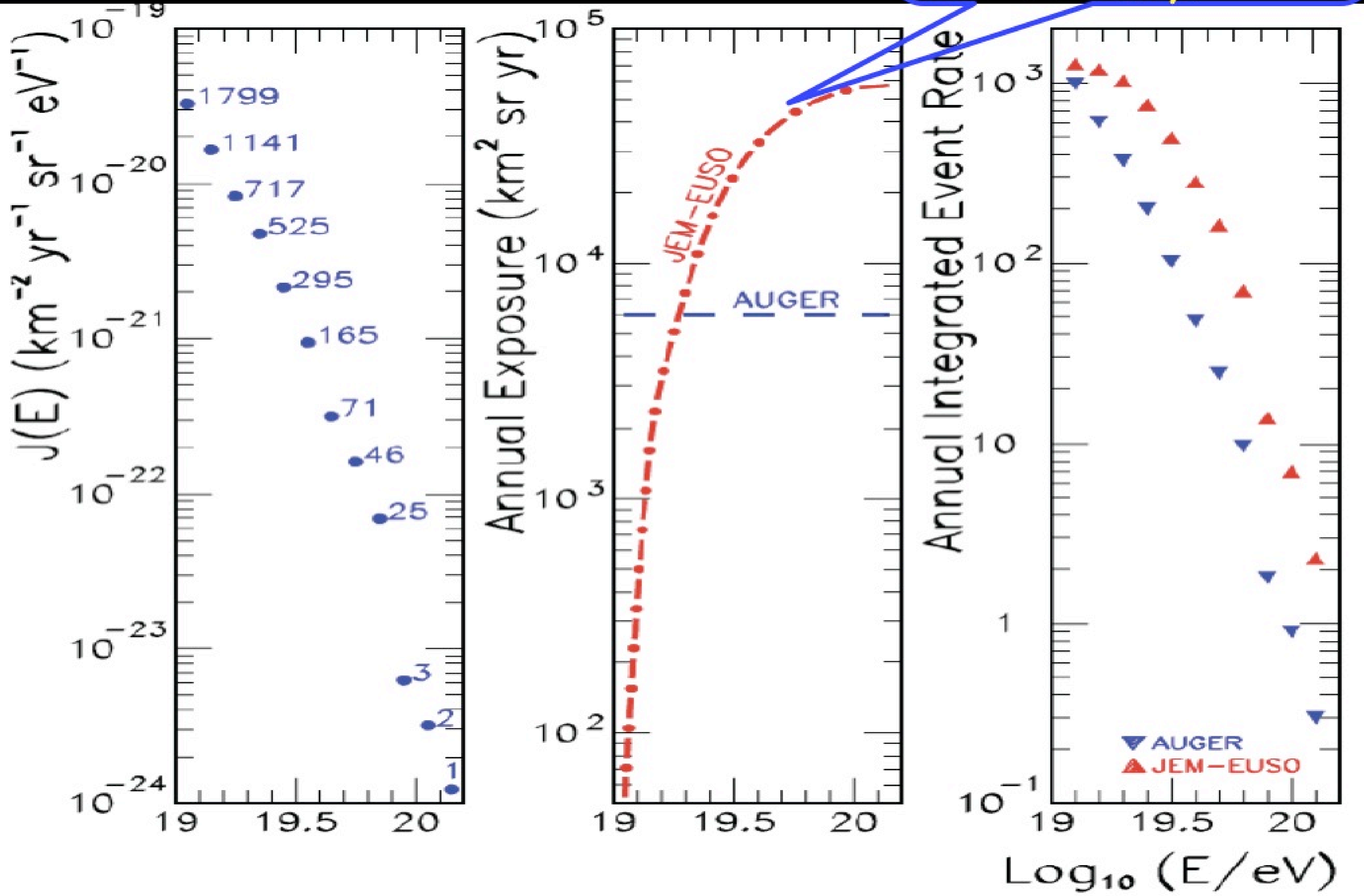
Detected photoelectrons are recorded every Gate Time Unit (GTU) of 2.5μs continuously.

Huge Exposure Area



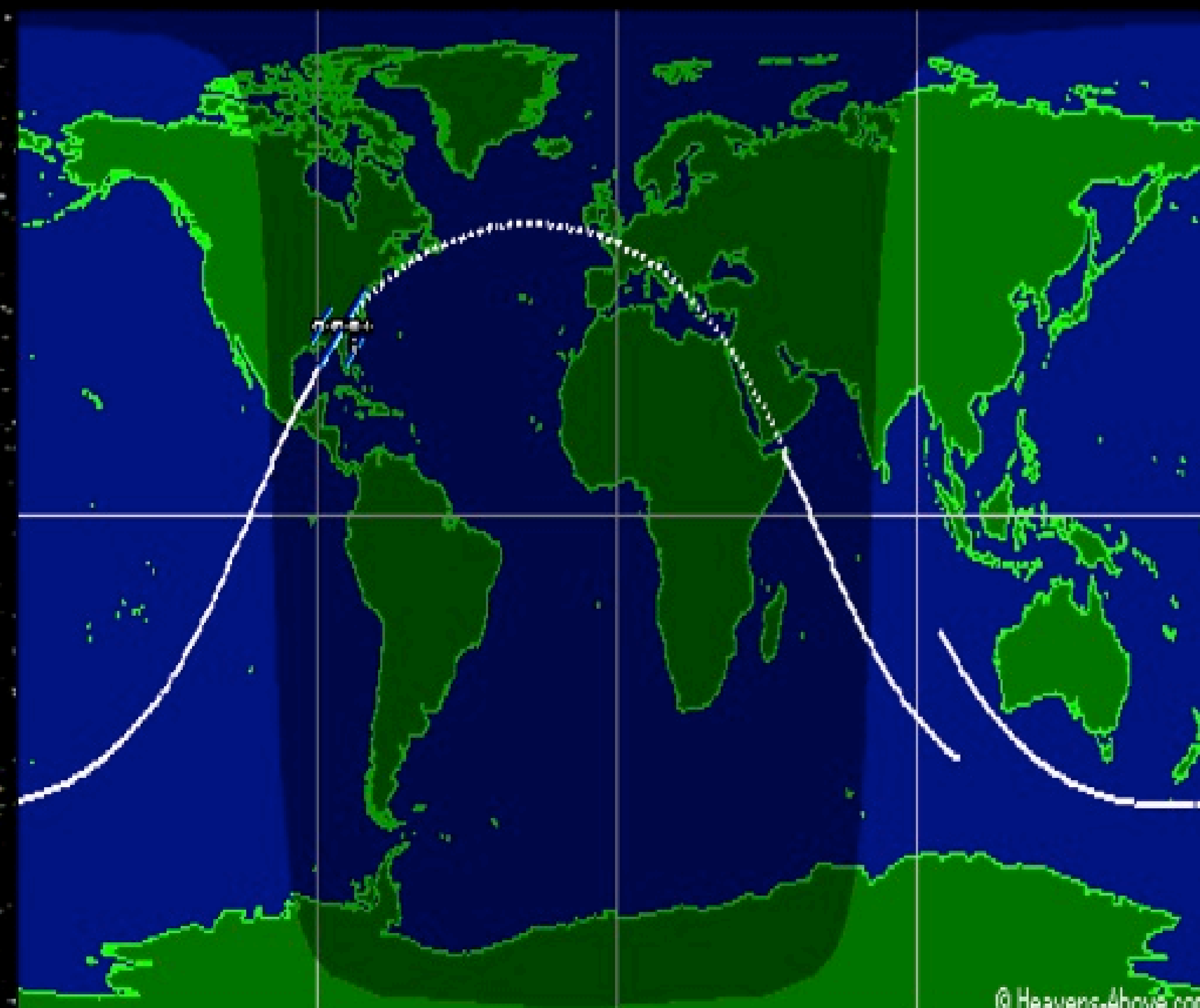
JEM-EUSO

annual exposure =
10 x Auger
$6\ 10^4\ km^2\ sr\ yr$



Full Sky Coverage
with nearly uniform exposure

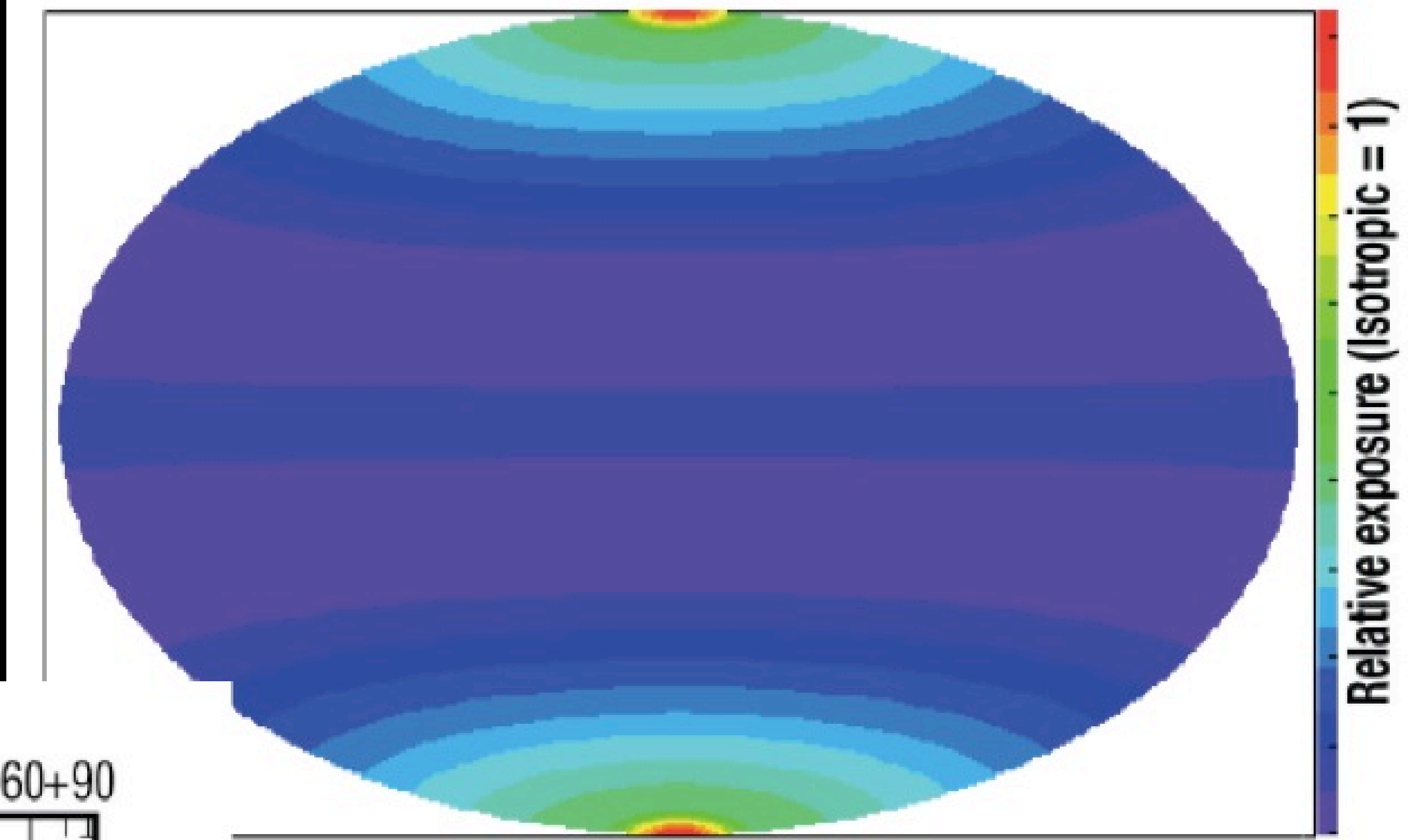
The ISS ORBIT

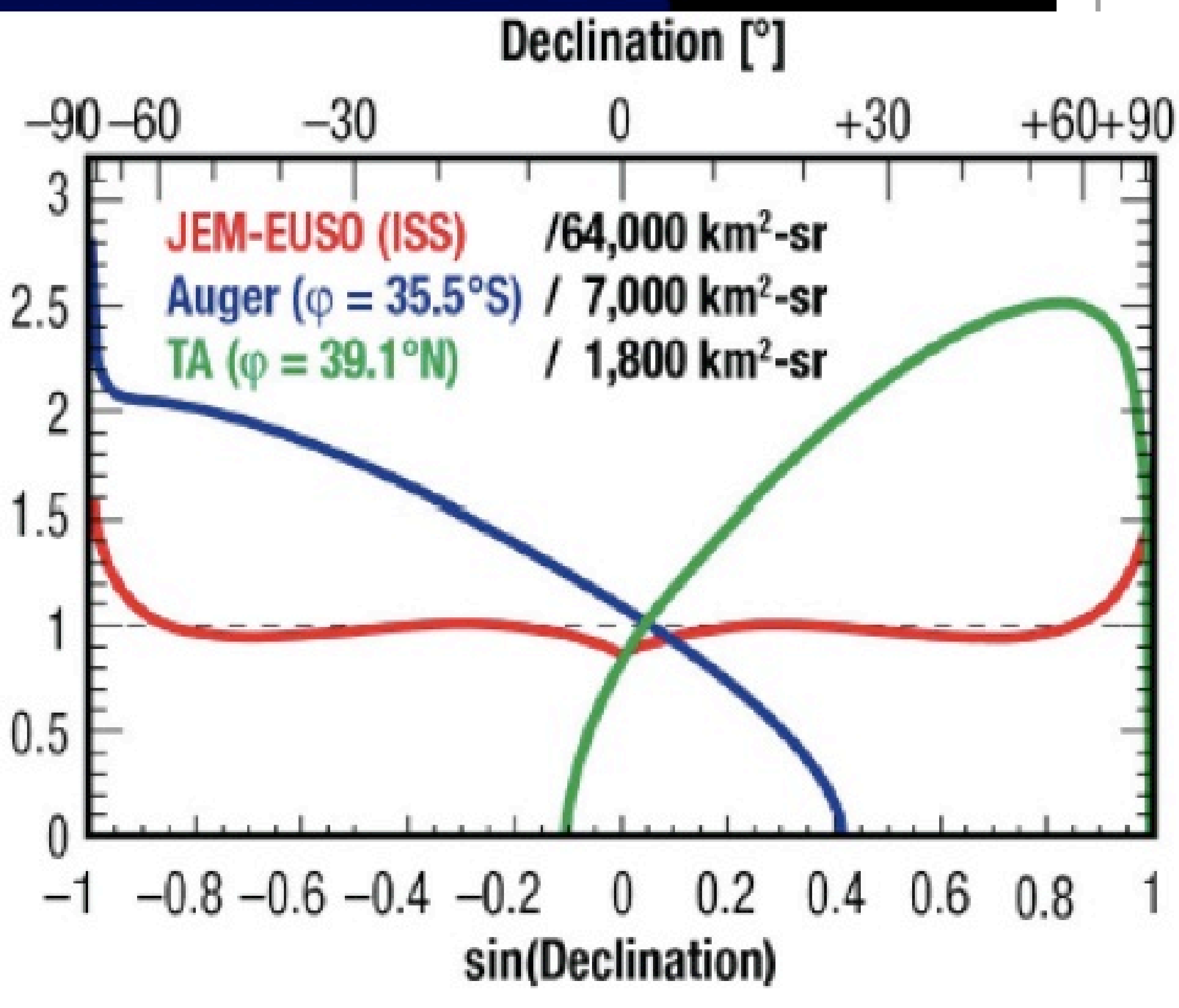


Inclination: 51.6°
Height: ~400km

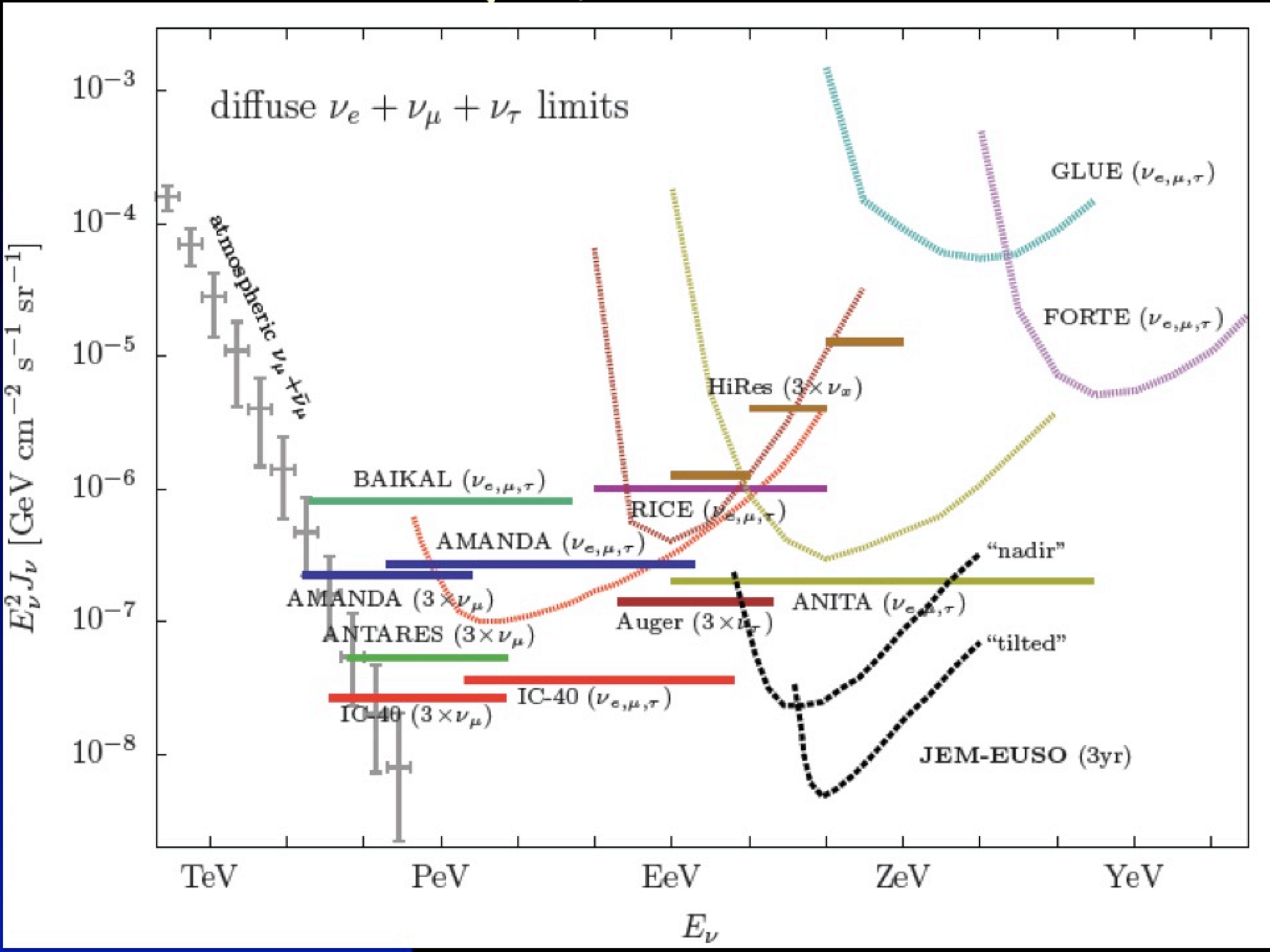
JEM-EUSO

Full sky coverage





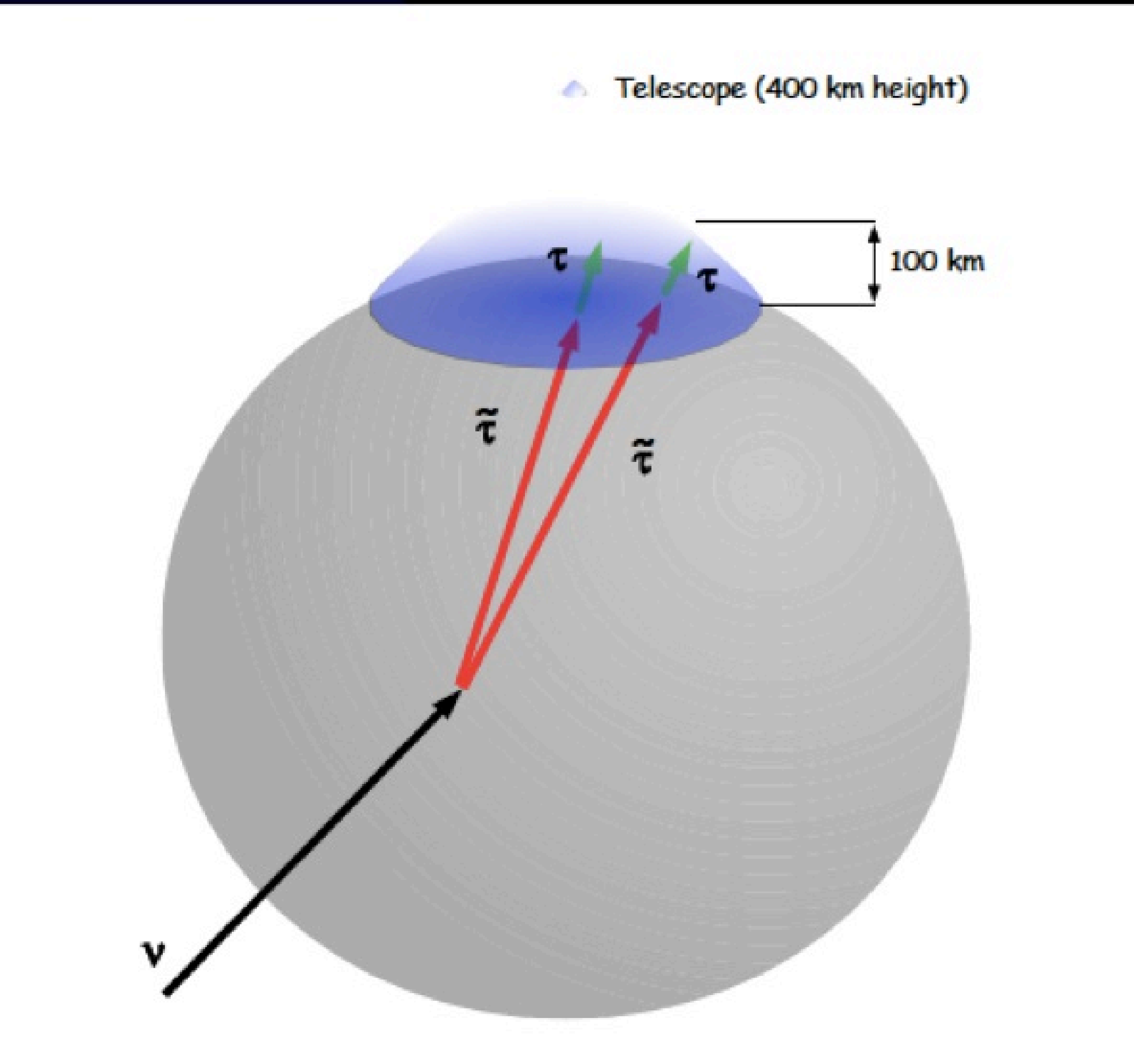
Serendipity: ZeV neutrinos



Serendipity: NLSP slepton

Gravitino is LSP (lightest supersymmetric particle)
slepton is the next to lightest (NLSP) long lived
SUSY breaking @ 5 10^6 GeV

signature:
coincident upwards taus



Albuquerque & de Souza '12

EUSO Balloon – pathfinder

PI: P. von Ballmoos

How many EECRs > 60 EeV?

Auger w/ 3,000 km²

~20 events > 55 EeV/ yr

Telescope Array w/ 700 km²

~4.6 events > 55 EeV/ yr

TOTAL ~30 events/yr

5 o.o.m to go!

Earth surface ~ 5 10^8 km²

~3.4 10^6 events/yr

How many EECRs > 60 EeV?

JEM-EUSO

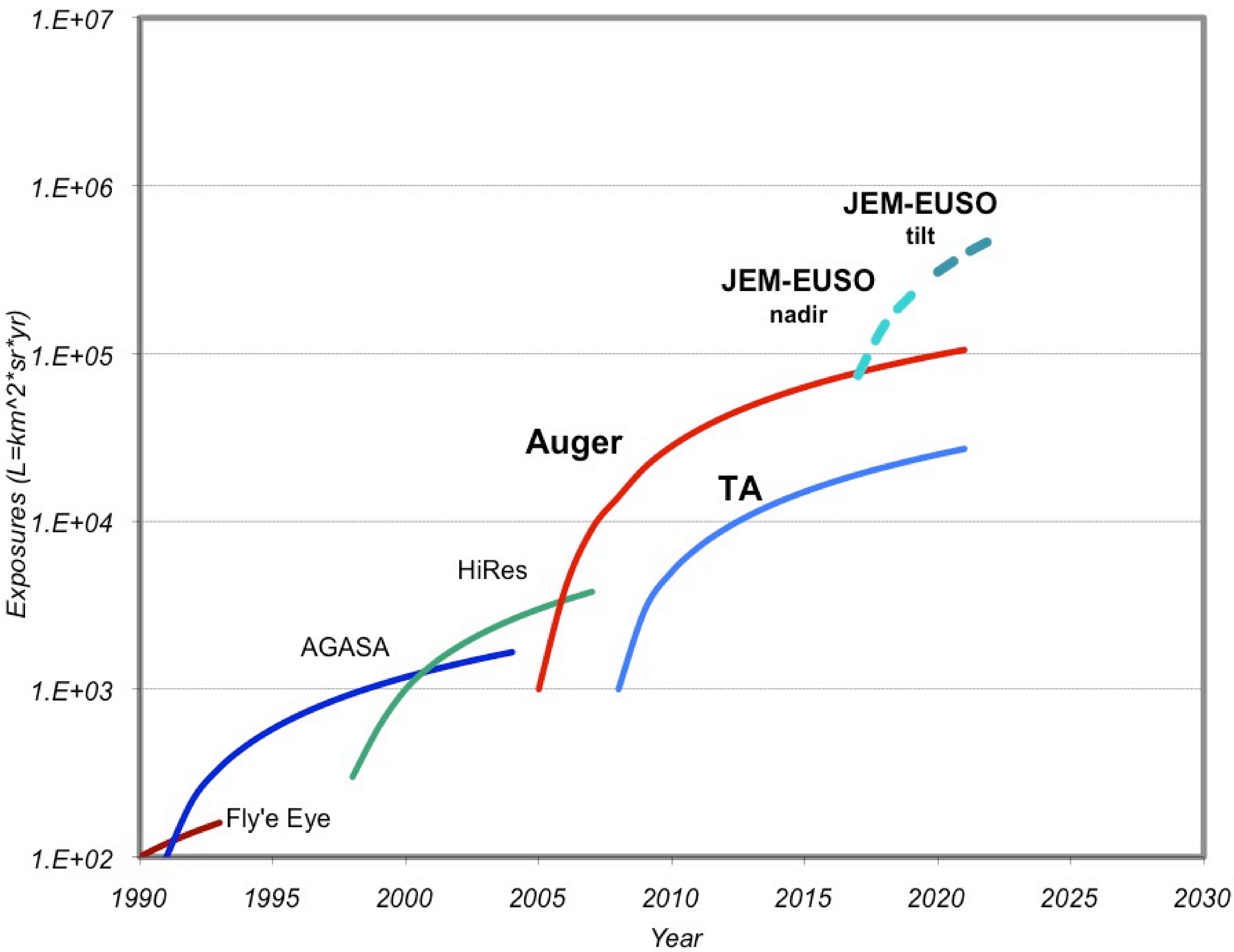
~200 events > 55 EeV/ yr

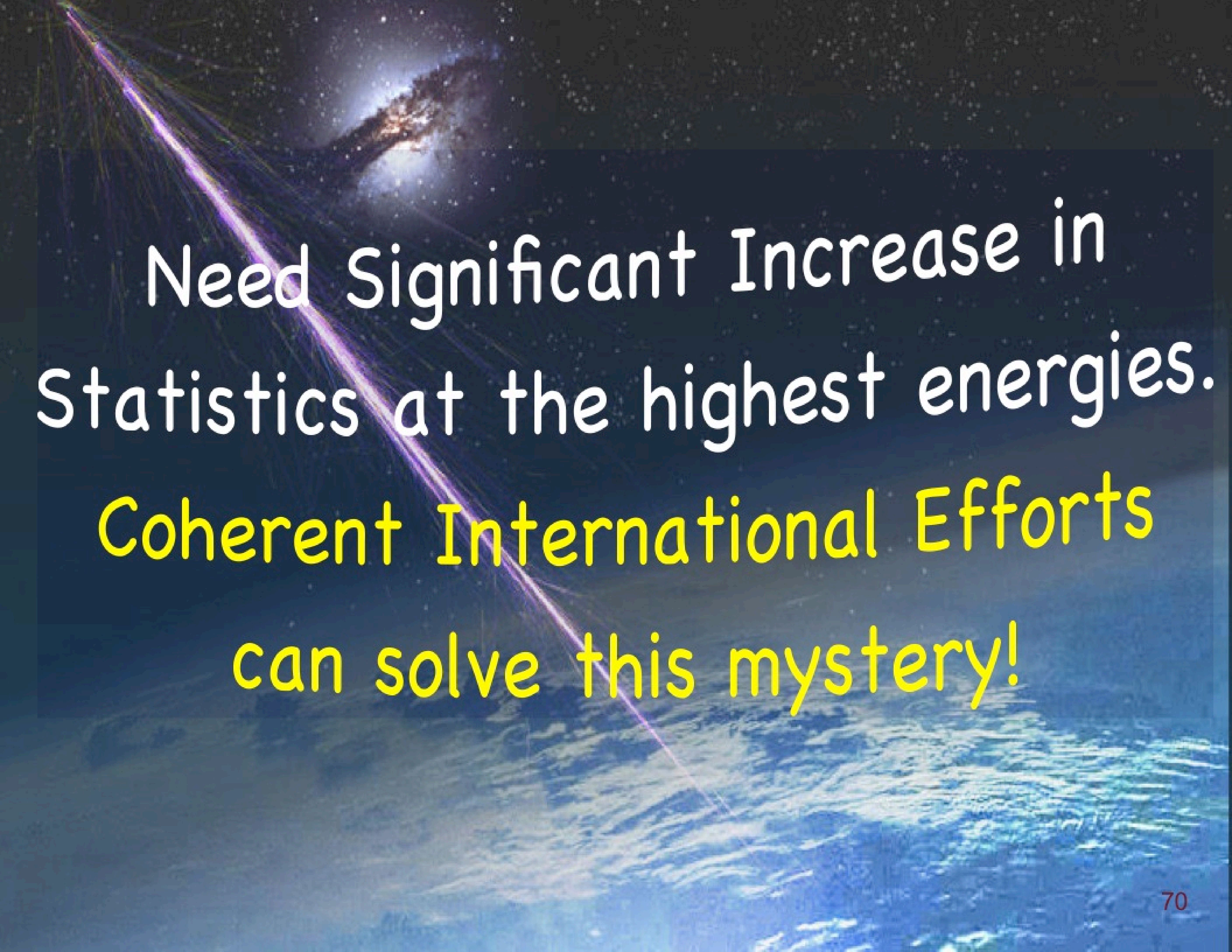
4 o.o.m to go!

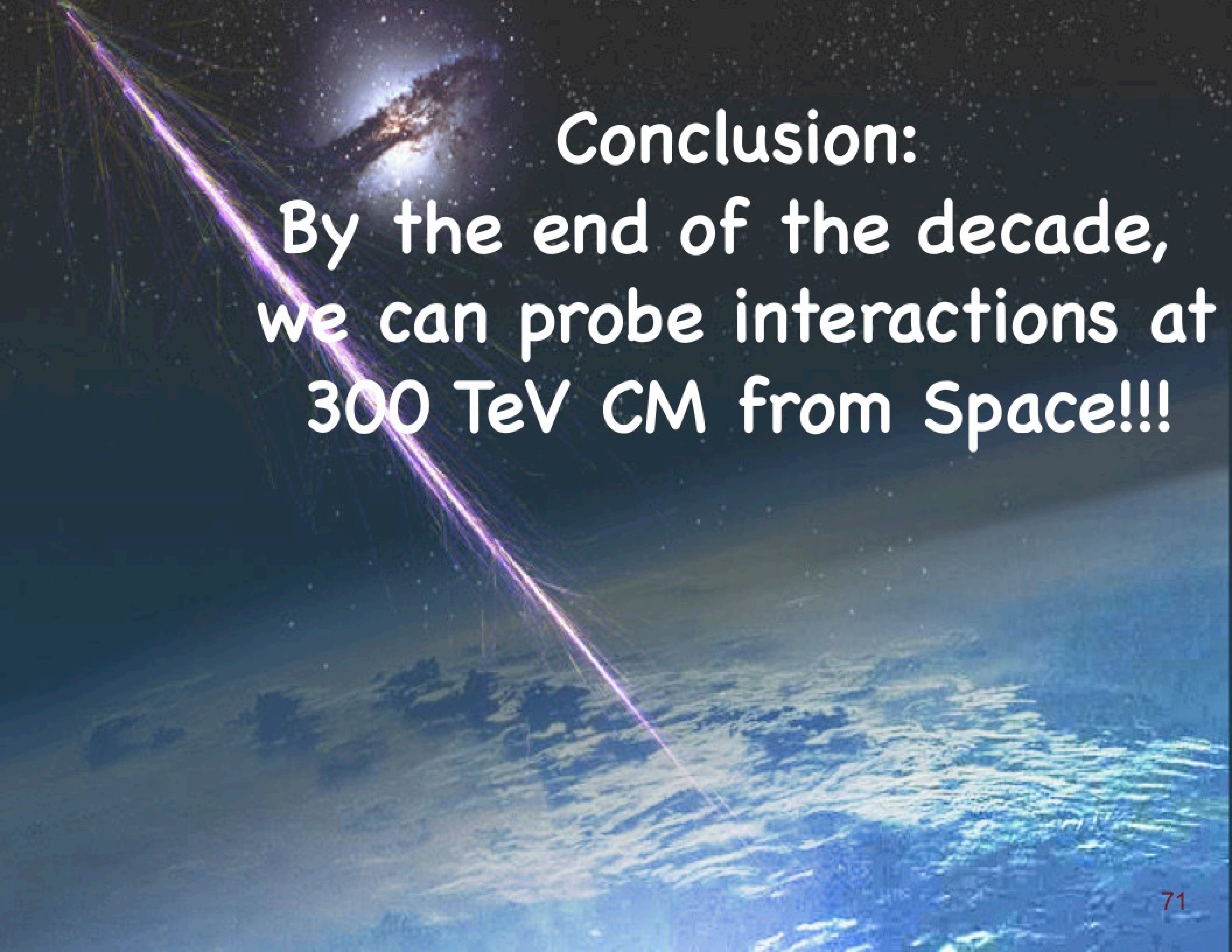
Earth - surface ~ 5 10^8 km^2

~3.4 10^6 events/yr

Exposure History




Need Significant Increase in
Statistics at the highest energies.
Coherent International Efforts
can solve this mystery!



Conclusion:

By the end of the decade, we can probe interactions at 300 TeV CM from Space!!!


Thanks !