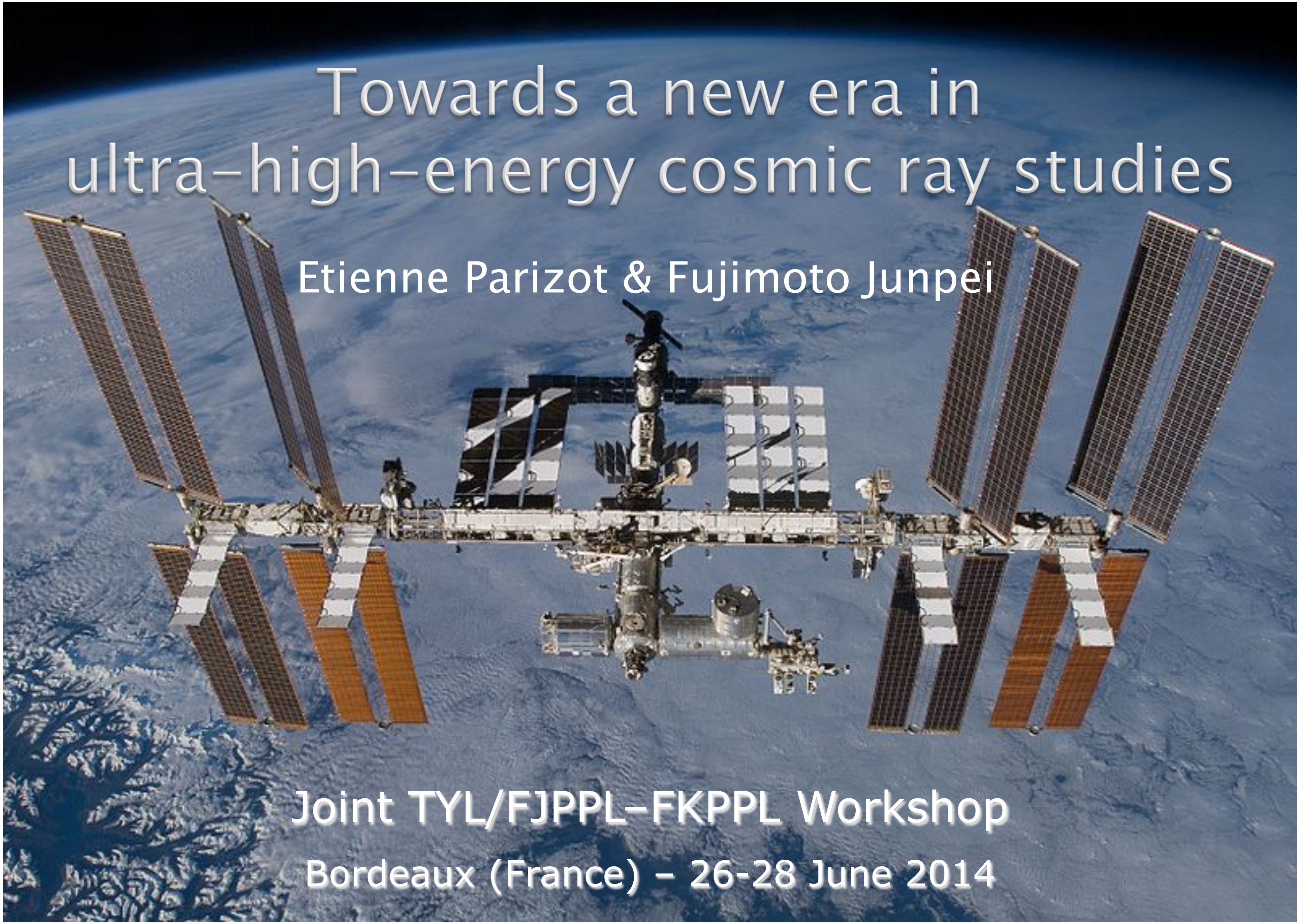
Towards a new era in ultra-high-energy cosmic ray studies

Etienne Parizot & Fujimoto Junpei



Joint TYL/FJPPL-FKPPL Workshop

Bordeaux (France) – 26-28 June 2014

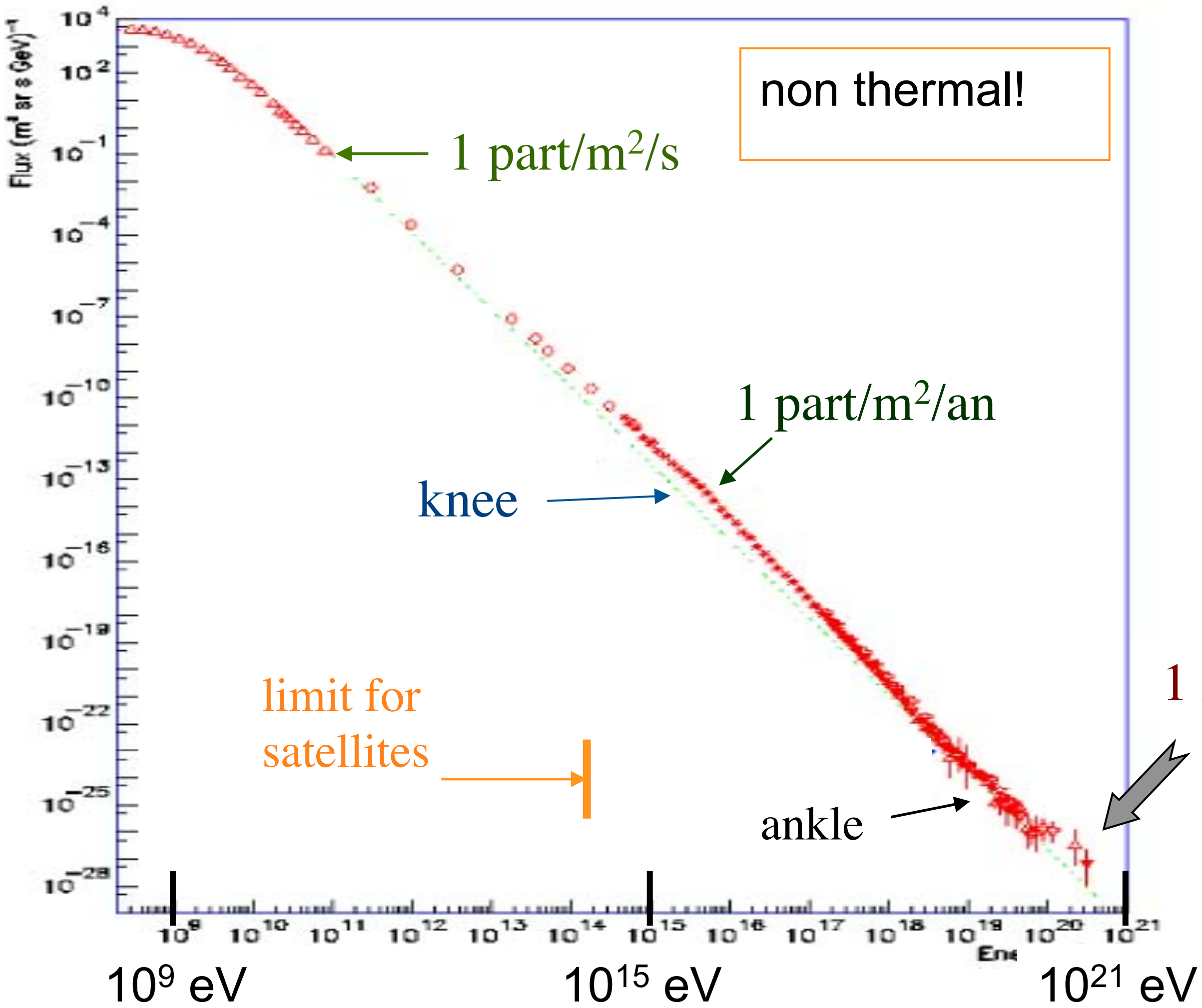
JEM-EUSO and the UHECR puzzle

A space road to the extreme universe!

(NB: UHECR = "ultra-high-energy cosmic rays")

Cosmic rays in the universe

A global phenomenon



UHECRs: a central scientific issue in astroparticle physics

- ✧ Ultra-high-energy cosmic rays → long-standing mystery
- ✧ Protons and atomic nuclei at macroscopic energies (> 10^{20} eV)

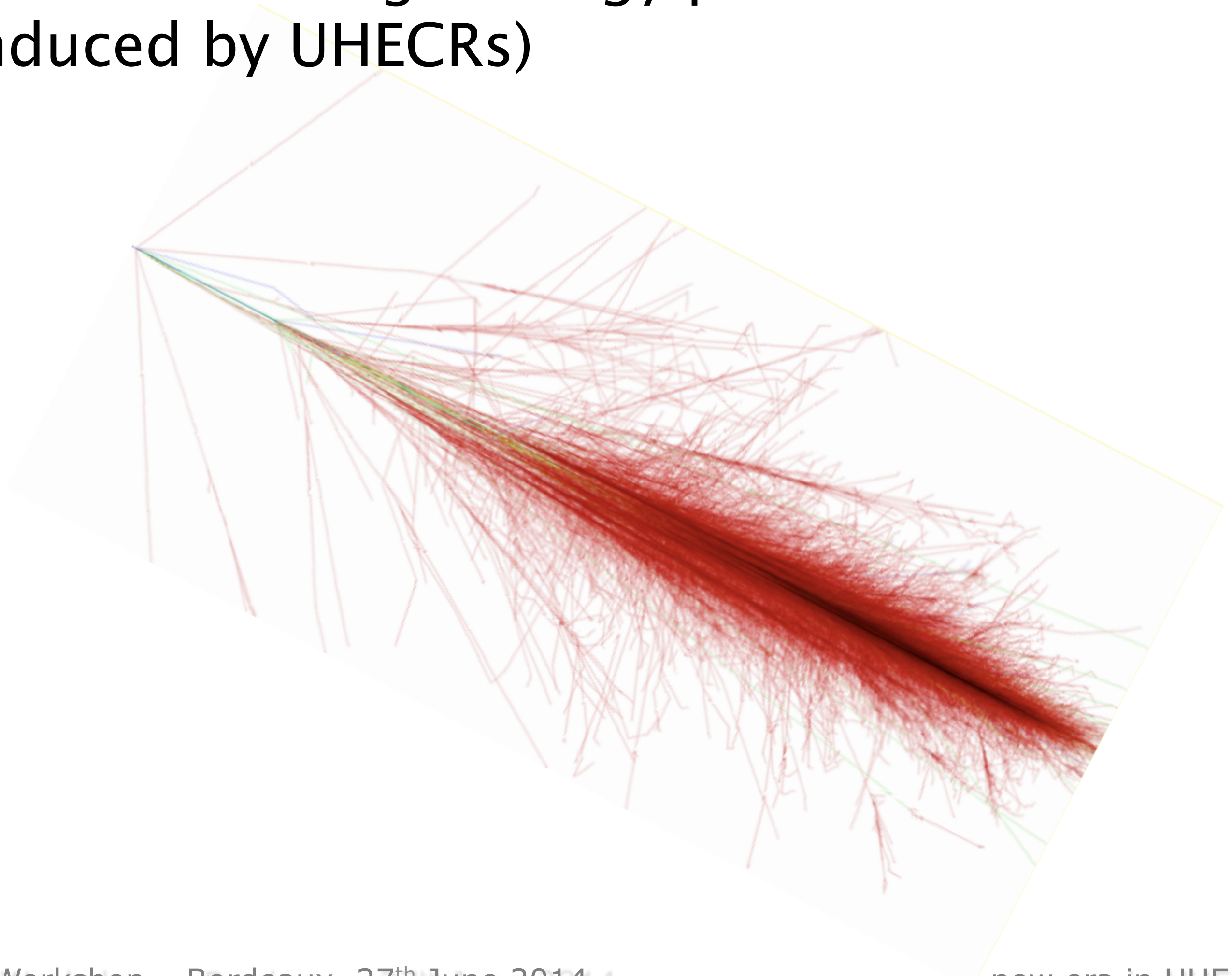
- ✧ Sources: unknown
- ✧ Acceleration process: unknown

- ✧ Extreme astrophysical sources → source modeling
- ✧ General cosmic-ray (astro)physics → particle acceleration, Galactic processes, nucleosynthesis, magnetic fields, interstellar medium, etc.
- ✧ Multi-messenger strategy

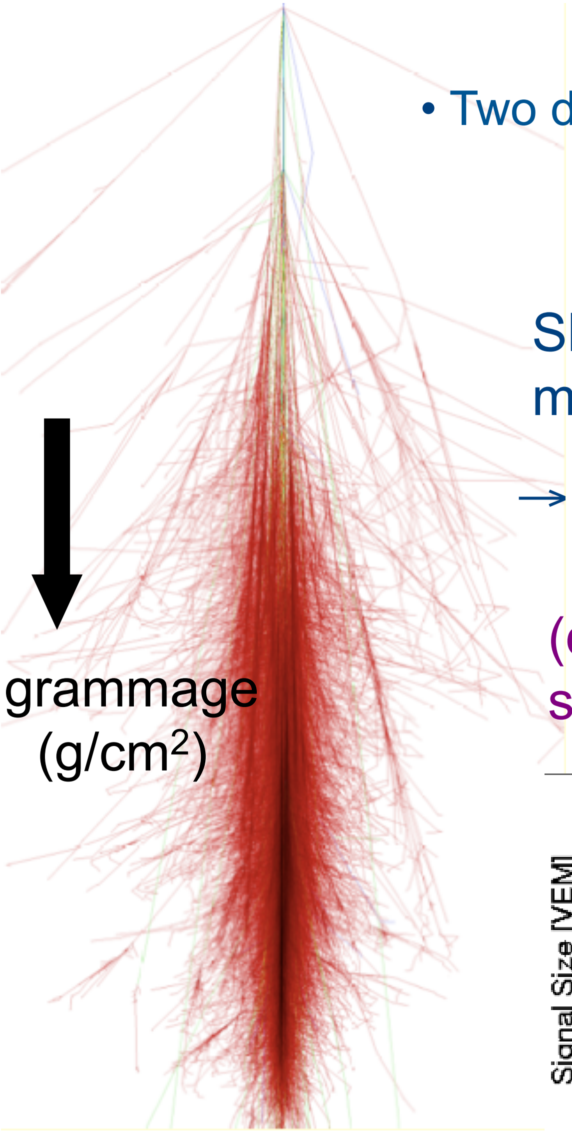
- ✧ Fundamental physics/high-energy physics/space-time physics issues

CR detection at high energy

- Detection of "extensive atmospheric showers"
  (cascades of high energy particles in the atmosphere, induced by UHECRs)



CR detection at high energy



- Two detection techniques for "extensive atmospheric showers"

Shower particle density, measured on the ground

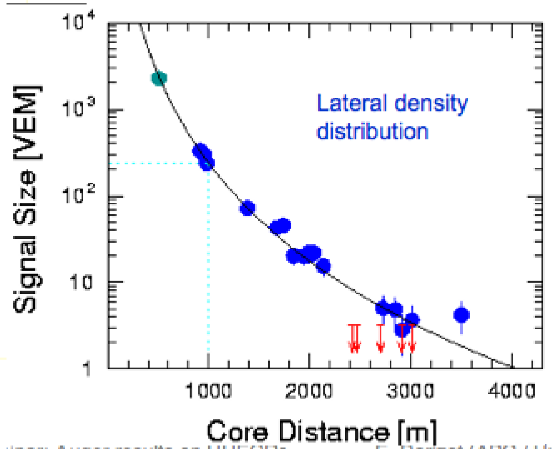
→ lateral distribution

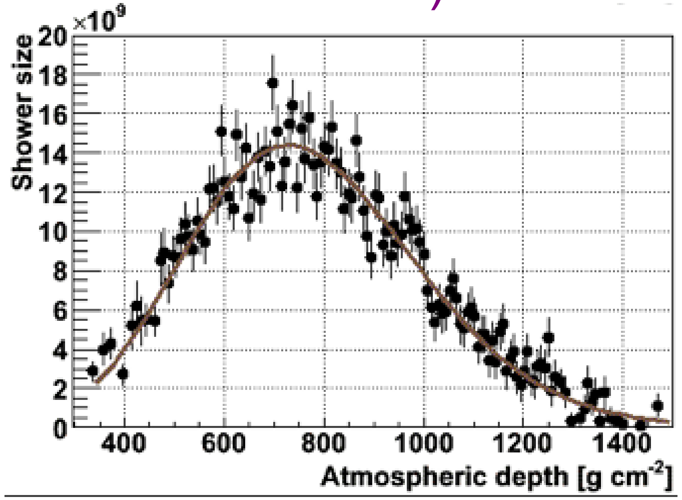
(depends on hadronic sub-shower)

fluorescence photons in the atmosphere

→ longitudinal development

(depends on EM sub-shower)

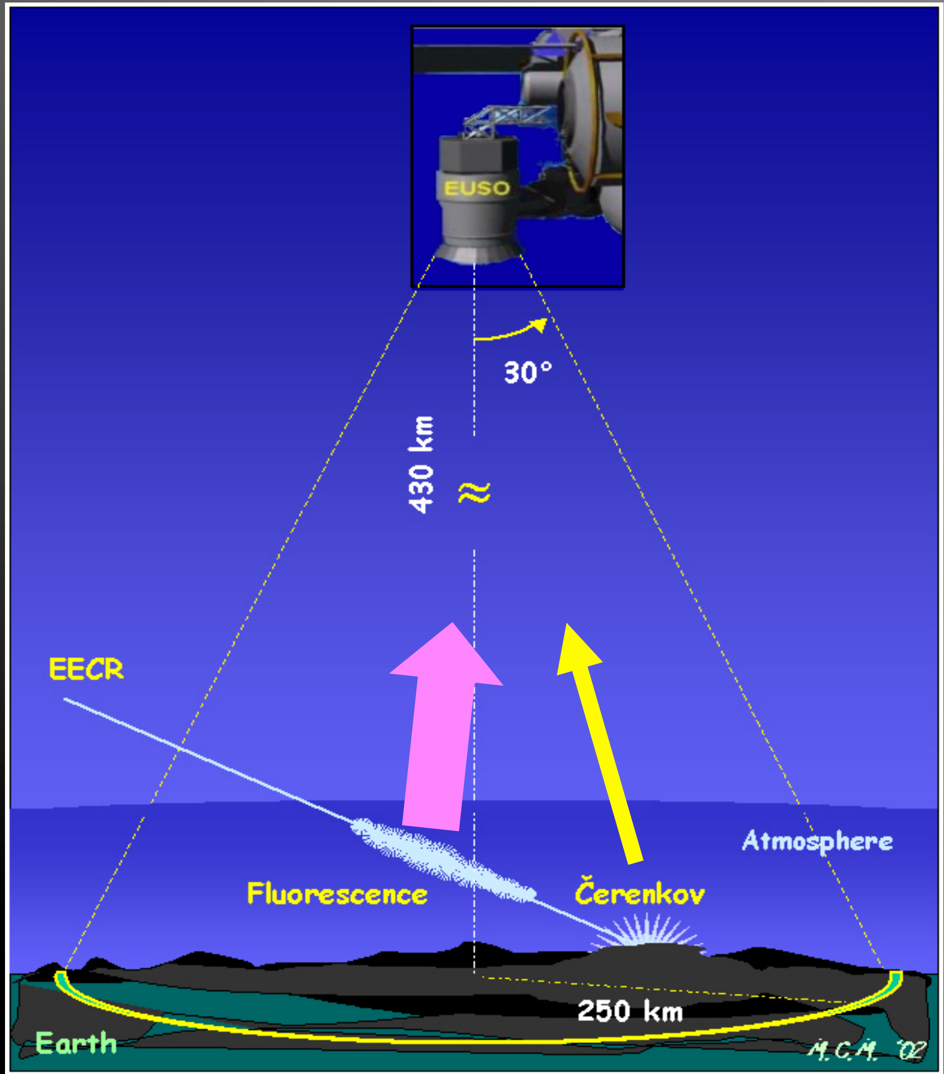




JEM-EUSO: from space!

Huge detection volume!

190 000 km^2



Only works by moonless nights…

~14% duty cycle

UV Fluorescence 300 - 400 nm (+ Cherenkov)

Scientific context

- Detection of UHECR-induced showers by the fluorescence technique **from space**

- UV telescope onboard the ISS, with Fresnel refractive optics and > 300 000 pixels (single photoelectron sensitive PMTs)
  - ±30° field-of-view, ISS altitude (400 km), ~190 000 km^2, 60 000 km^2 sr yr per year

- Acceptance: ~10 times Auger
- Energy range: E > 30 EeV
- Uniform full-sky coverage (both hemispheres)
- Performances and duty cycle now properly worked out

[main refereed paper: Astropart. Phys. 44, 76 (2013)]

- UHECRs + transient high-energy atmospheric phenomena + meteorites + exotic physics

UHECRs: current status

- ∃ steepening above ~60 EeV (probably GZK ⊗ E_{max})

  Compatible with standard astrophysical expectations

  ⇒ very low fluxes, but also good news! (much fewer sources at UHE)

- Very limited statistics at ~100 EeV !

- Low level of anisotropy ⇒ ∃ hints, mostly with unclear status

  ⇒ Does not generate info about sources

  ⇒ Current experiments have shown that there is something to see at UHE, but much larger statistics will be needed to actually see it!

- CR composition becomes heavier at UHE (or showers not understood)

  ⇒ Important information!

  ⇒ Does not help the observation of clear, meaningful anisotropies easier!

  But does not prevent it either!

Disclaimer

∃ good and precious science to be done at lower energy! (Auger, TA)

- hadronic physics, composition studies, shower physics, Galactic/extragalactic transition…

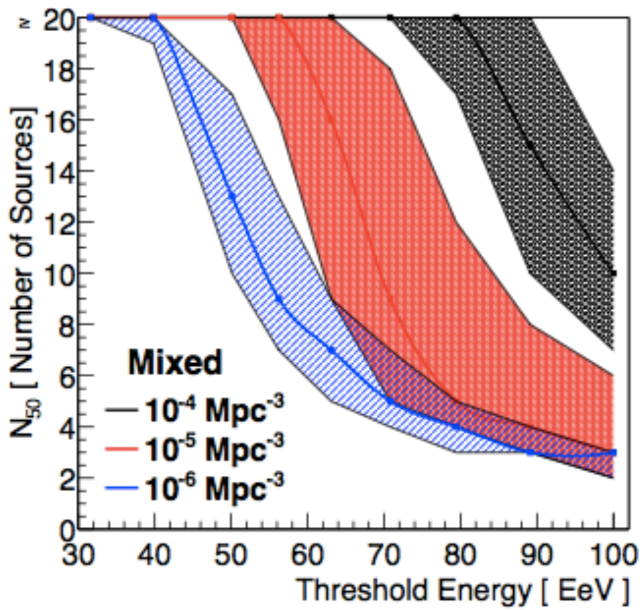
But our main interest here is:

- extreme energy cosmic rays (~100 EeV)
- the exploration of the UHE universe
- the perspective of actually studying the sources

Nota Bene

Take advantage of the GZK cutoff!

- At 100 EeV, most of the events come from a handful of events!
- Blaksley & Parizot (2013)



Anisotropy studies with large stat.

- Aim of the study:

A Assume
- 300 000 km^2 sr yr of exposure
- ~ uniform full-sky coverage
- even with limited reconstruction performance: $\Delta\theta = 3°$, $\Delta E/E = 30\%$

⇒ Chosen with JEM-EUSO in mind (next major step in the quest for UHECR sources and the exploration of the UHE universe)

⇒ We also assume the JEM-EUSO detection efficiency as a function of E

[NB: JEM-EUSO's performances will be better (and even much better in a significant subset of events), but we keep low perf. on individual showers to avoid irrelevant objections and show that in the above-mentioned quest, statistics is what matters the most!]

B Explore a range of astrophysical models for the origin of UHECRs, compatible with current data.

⇒ Source spectrum
⇒ Source composition
⇒ Source density
⇒ Intervening magnetic fields

Anisotropy studies with large stat.

C Compute UHECR propagation taking into account energy losses, charge modification, magnetic deflections and secondary particles

(cf. the standard APC propagation code, Allard et al.)

D Build expected sky maps with the relevant statistics at different energies (500 realizations of each astrophysical model framework, to understood the associated “cosmic variance”)

E Study the resulting anisotropies through the 2-pt correlation function analysis

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Ω Result: For all models, significant anisotropies can be observed!

→ There is a lot to gain if we can reach an exposure of 300 000 km^2 sr yr indeed!

The models explored

- Sources are assumed to be “standard candles”

  (not reasonable, but consequences are understood and under control)

  - UHECRs have a mixed composition at their sources

    cf. Galactic cosmic rays

    known acceleration mechanisms are not strongly nuclear-type specific

- Maximum energy is proportional to charge

(i.e. the acceleration is not limited by energy loss processes) $E_{\max}\left({}^{A}_{Z}X\right) = Z \times E_{\max}(p)$

If $E_{max}(p) \geq 100$ EeV ⇒ protons dominate at all accessible energies

If $E_{max}(p) < E_{GZK}$ ⇒ transition to heavier nuclei

⇒ Fe nuclei dominate at the highest energies

The models explored

If $E_{max}(p) \geq 100$ EeV → protons dominate at all accessible energies

If $E_{max}(p) < E_{GZK}$ → transition to heavier nuclei

→ Fe nuclei dominate at the highest energies

- 3 classes of models

E_{max}= 4 EeV	E_{max}= 15 EeV	E_{max}= 300 EeV
Fe-dominated at 60 EeV	CNO present at 60 EeV	proton-dominated

- 2 additional classes of models:

"pure protons"

→ similar results as with large E_{max}

NB: appears at odds with Auger results, but may be possible if the showers are not well understood…

"pure Fe"

∃ secondary protons → simulates sub-dominant proton component

→ (could easily exist: different sources should have different E_{max})

The models explored

- Source distribution

UHECR sources are assumed to be distributed like matter in the nearby universe: we use the 2MRS catalog (Huchra et al., 2012)

- Source density The lower the density, the stronger the anisotropies!

Various densities: $n_s = 10^{-4}$ Mpc^{-3} | $n_s = 10^{-5}$ Mpc^{-3} | $n_s = 10^{-6}$ Mpc^{-3}

- Magnetic fields

Extragalactic magnetic field: Kolmogorov-like turbulent field with 1 Mpc coherence length and intensities ranging from 0.1 to 3 nG
→ found to have little incidence on anisotropies

Galactic magnetic field: dominant effect!

⇒ Model of Jansson & Farrar (2012)

⇒ + random field + striated field

Galactic deflections

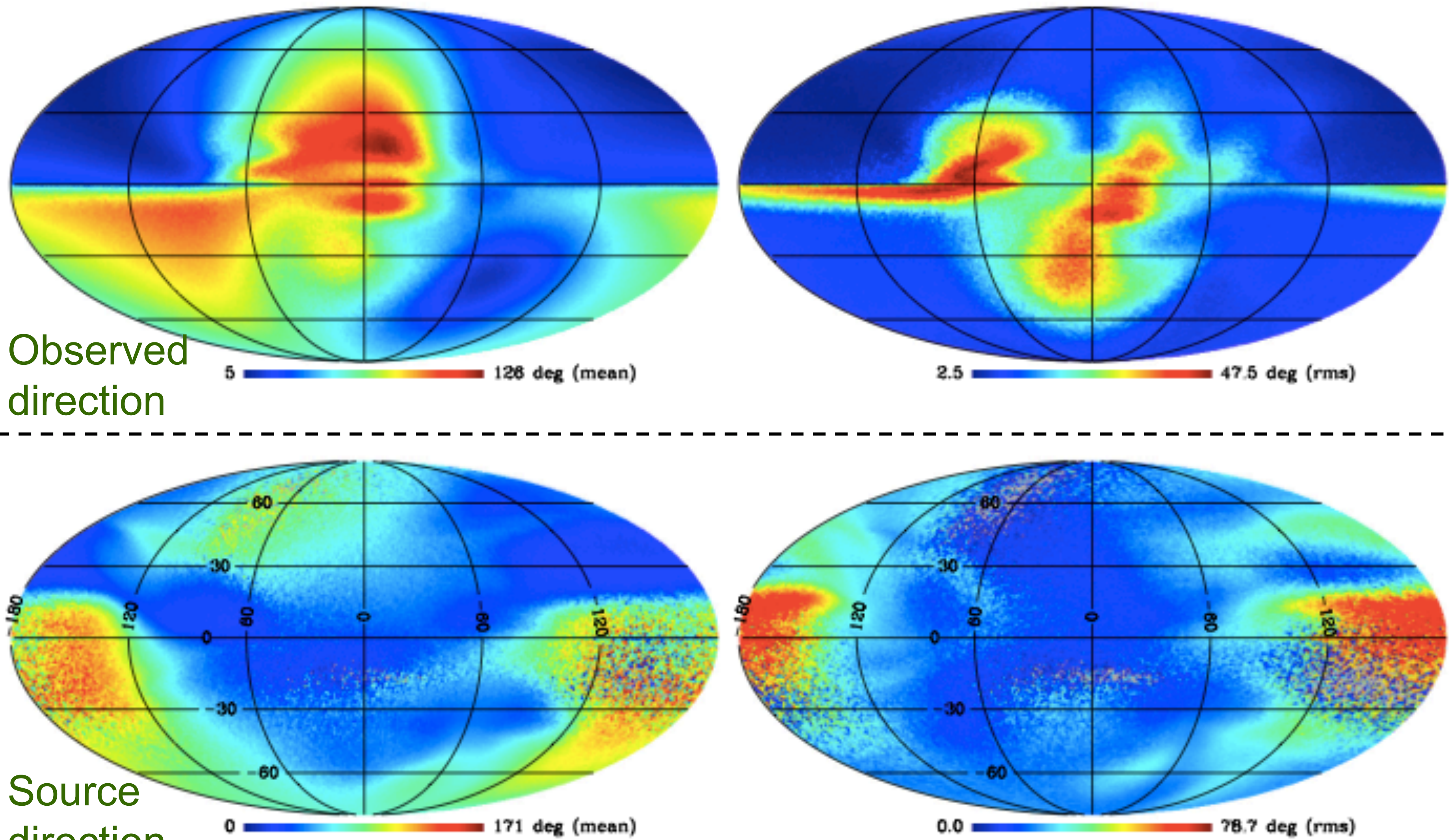
Mean deflection

(For protons at 5 EeV or Fe at 130 EeV)

Standard deviation

Observed direction

Source direction



Simulated sky maps

• 300 000 km^2 sr yr means typically (somewhat model-dependent):

Auger energy scale → 1100 / 250 / 100 events above 50 / 80 / 100 EeV

HiRes/TA energy scale → 2100 / 580 / 260 events above 50 / 80 / 100 EeV

→ We simulate 500 realizations of each astrophysical model, randomly drawing the positions of the sources with the assumed source density

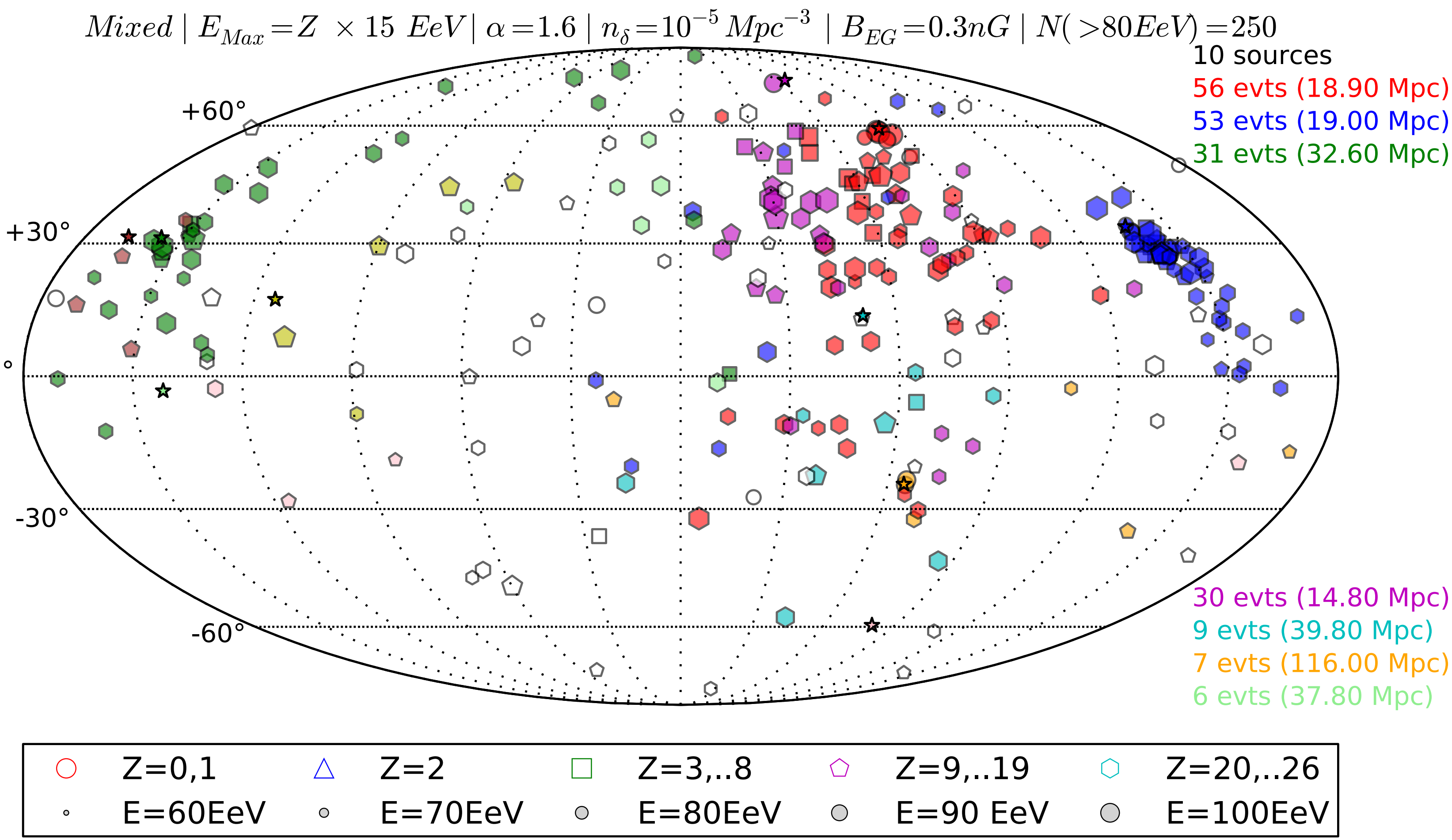
→ For each realization, we draw the resulting UHECR sky map with the above statistics (taking into account the detector's angular resolution and energy resolution)

→ Then we quantify the associated anisotropy according to the 2-pt correlation function analysis, by comparing with the expectations for an underlying isotropic model (with the same UHECR statistics)

Simulated sky maps

Example for $E_{max}(p)$ = 15 EeV and $n_s = 10^{-5}$ Mpc^{-3}

Sky-map above 80 EeV (Auger energy scale)

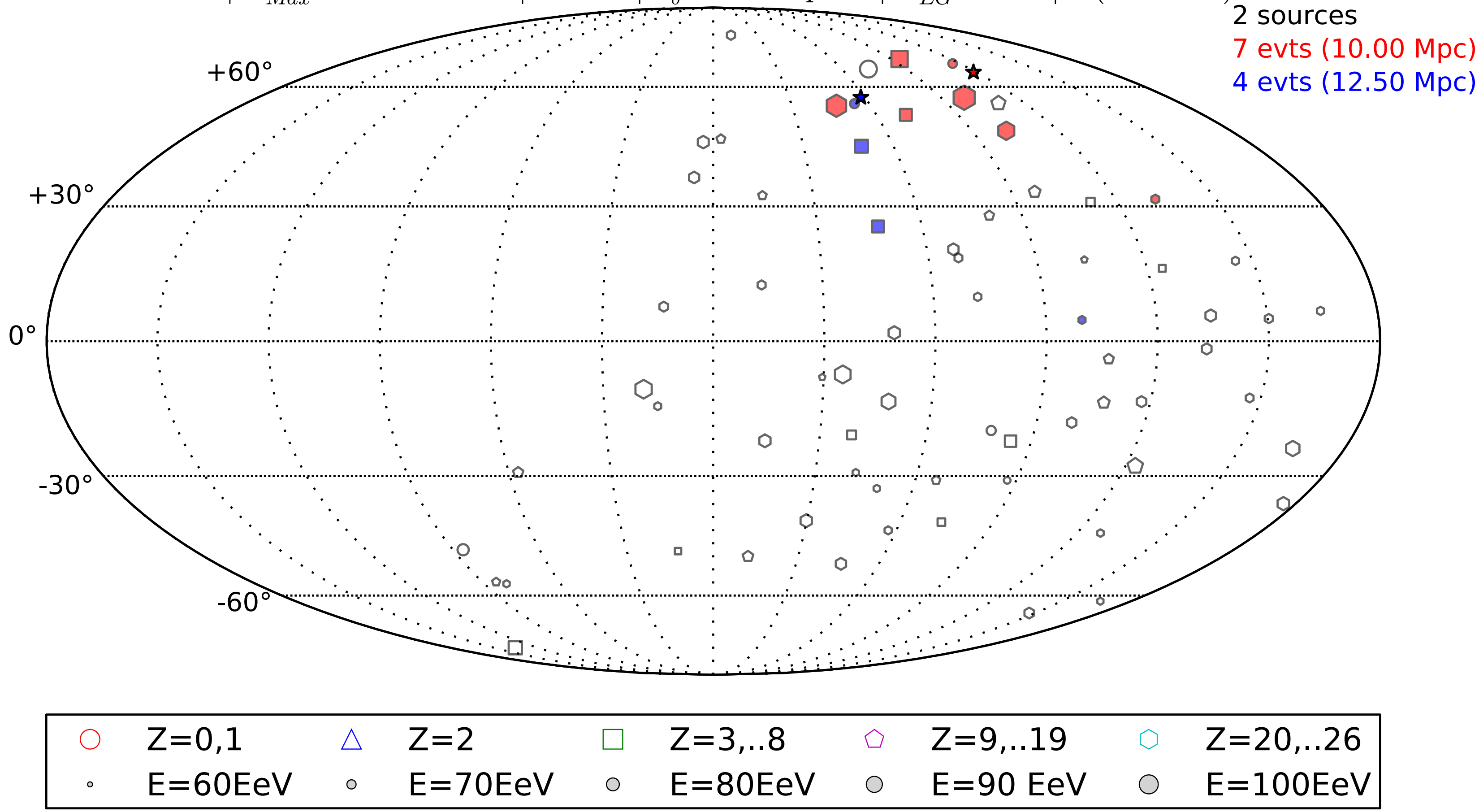


Simulated sky maps

Example for $E_{max}(p)$ = 15 EeV and $n_s = 10^{-4}$ Mpc^{-3}

"Auger statistics": 69 events above 55 EeV

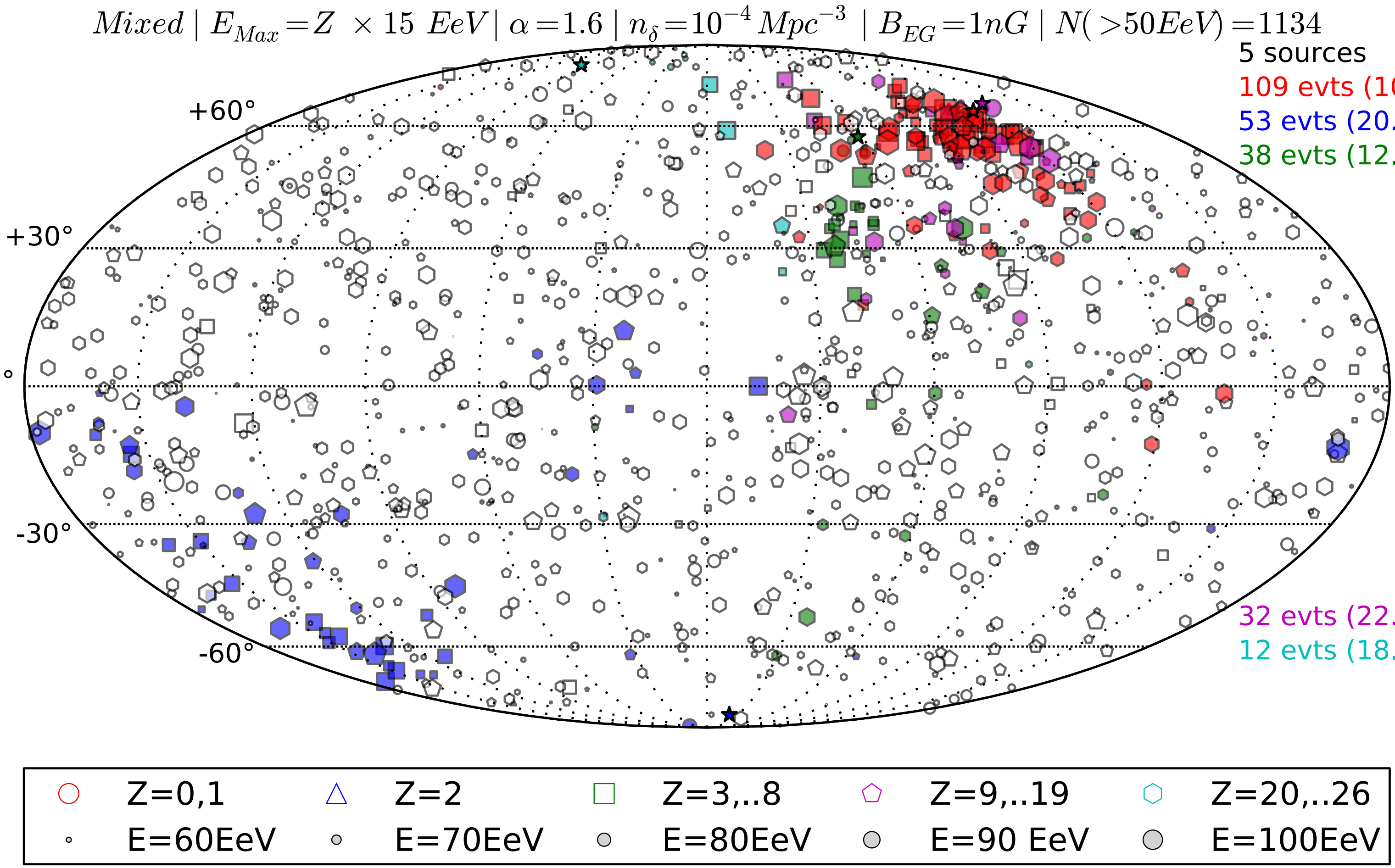
$Mixed \mid E_{Max} = Z \times 15\ EeV \mid \alpha = 1.6 \mid n_\delta = 10^{-4}\ Mpc^{-3} \mid B_{EG} = 1nG \mid N(>55EeV) = 69$



Simulated sky maps

Example for $E_{max}(p)$ = 15 EeV and $n_s = 10^{-4}$ Mpc^{-3}

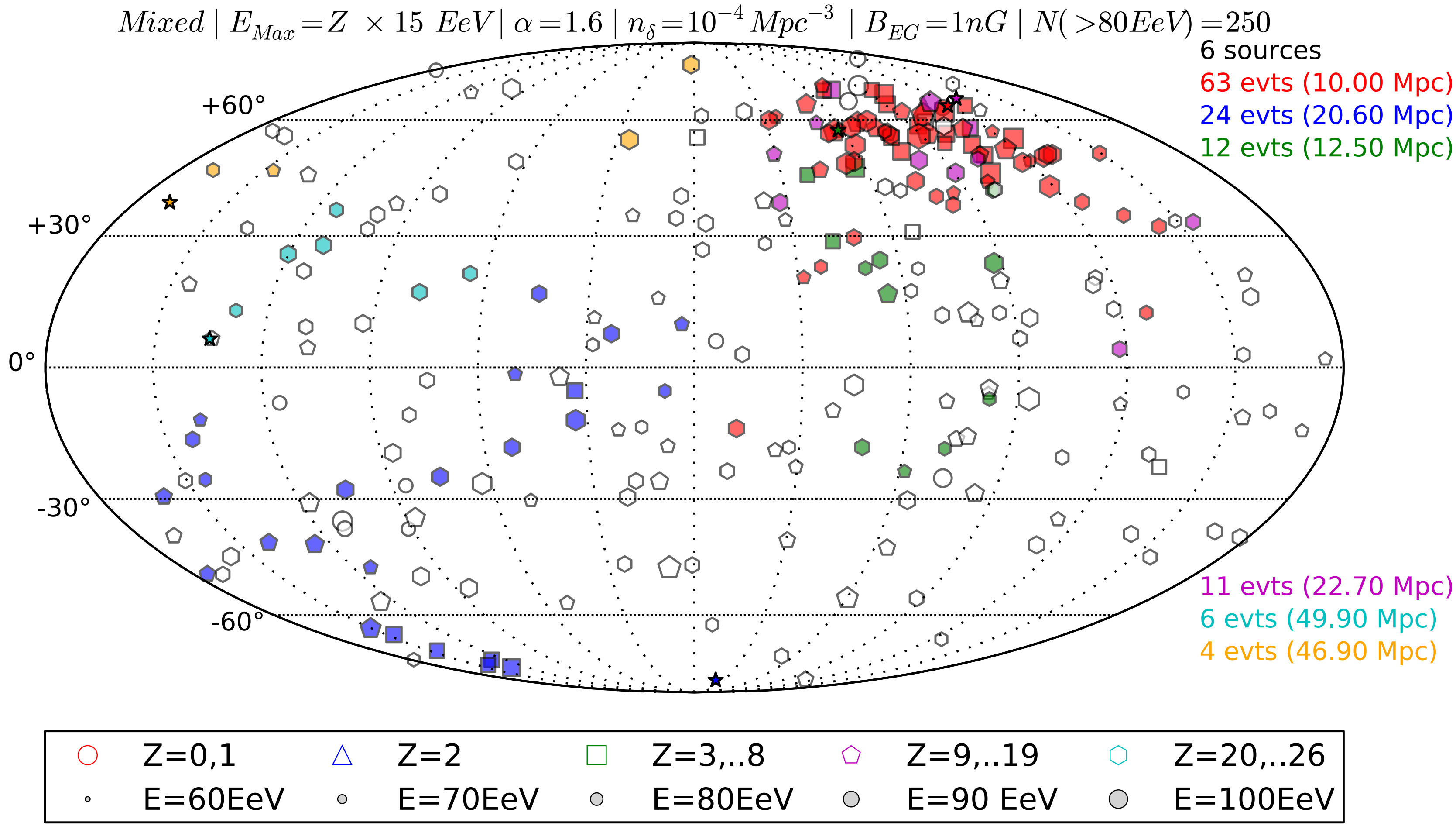
"JEM-EUSO statistics": 1100 events above 50 EeV (Auger energy scale)



Simulated sky maps

Example for $E_{max}(p)$ = 15 EeV and $n_s = 10^{-4}$ Mpc^{-3}

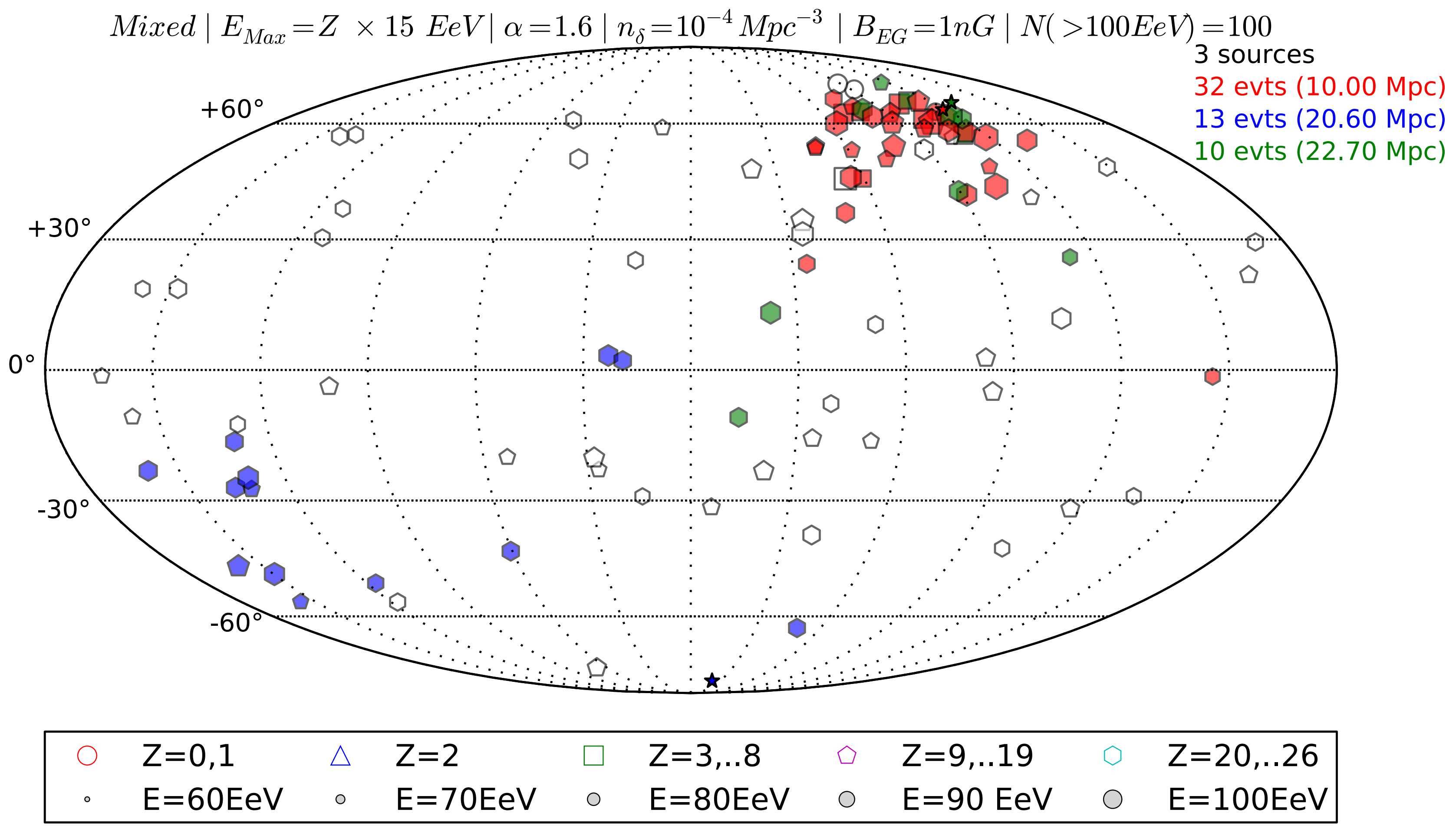
"JEM-EUSO statistics": 250 events above 80 EeV (Auger energy scale)



Simulated sky maps

Example for $E_{max}(p)$ = 15 EeV and $n_s = 10^{-4}$ Mpc^{-3}

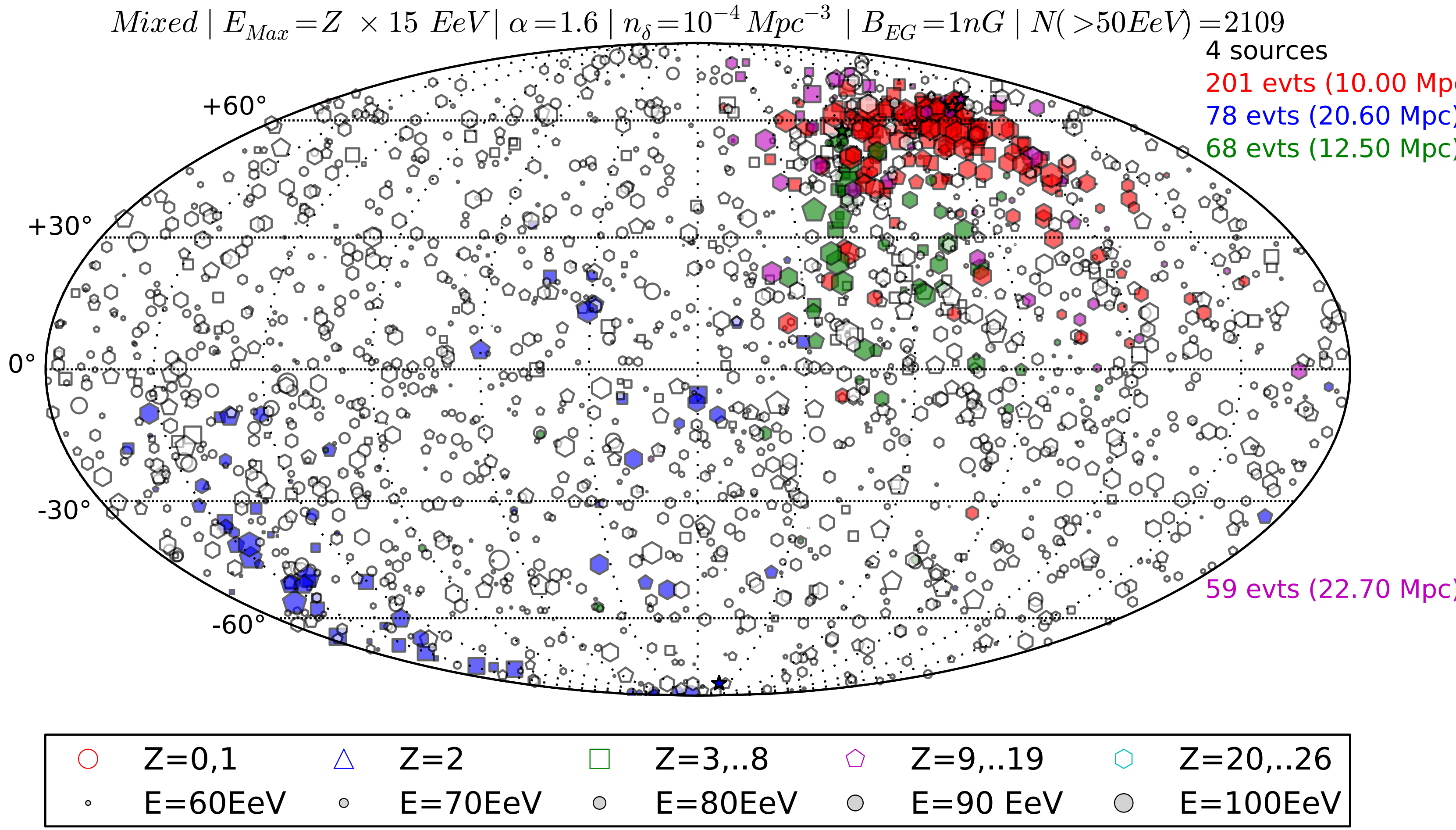
"JEM-EUSO statistics": 100 events above 100 EeV (Auger energy scale)



Simulated sky maps

Example for $E_{max}(p)$ = 15 EeV and $n_s = 10^{-4}$ Mpc^{-3}

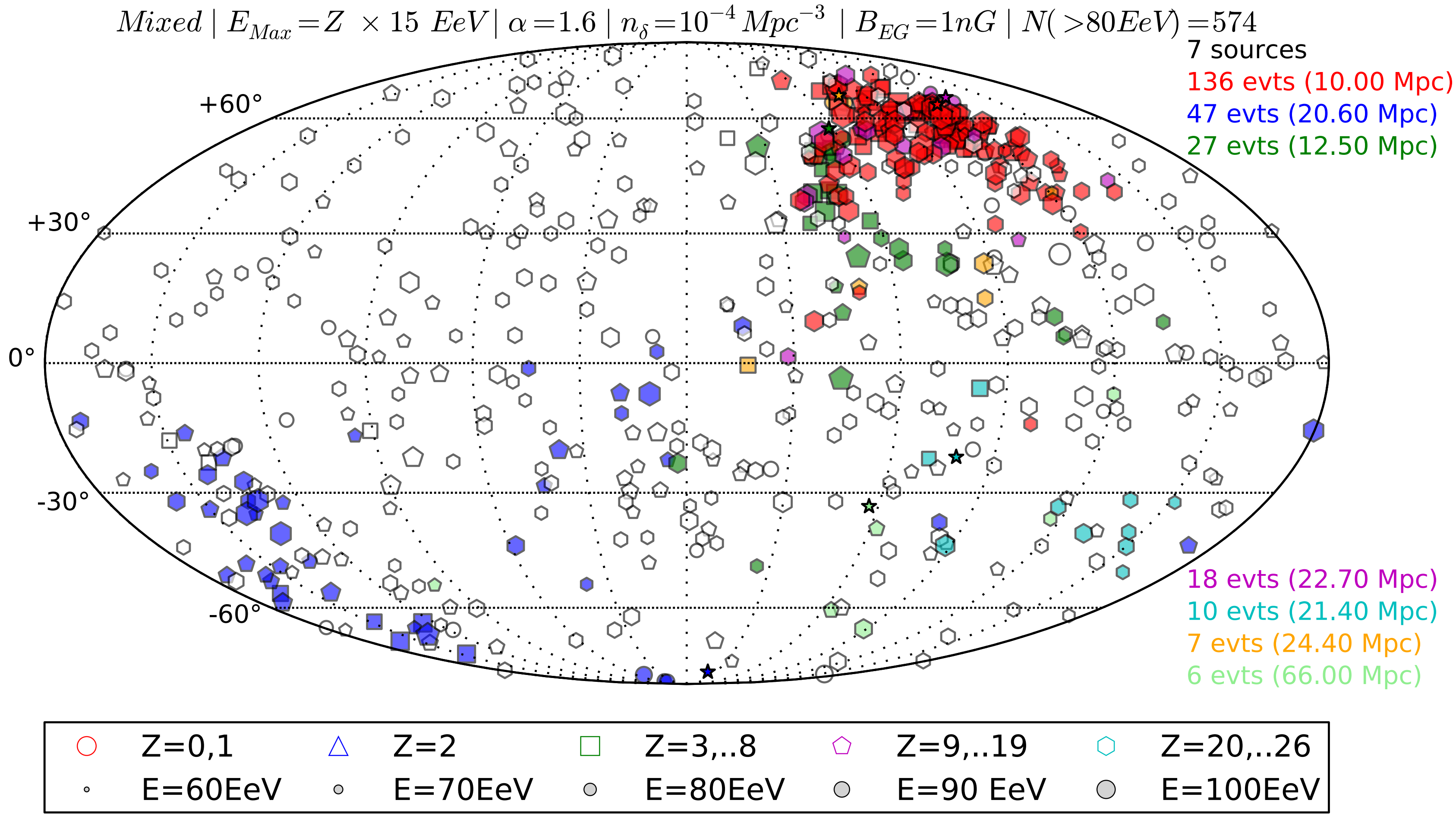
“JEM-EUSO statistics”: 2100 events above 50 EeV (HiRes/TA energy scale)



Simulated sky maps

Example for $E_{max}(p)$ = 15 EeV and $n_s = 10^{-4}$ Mpc^{-3}

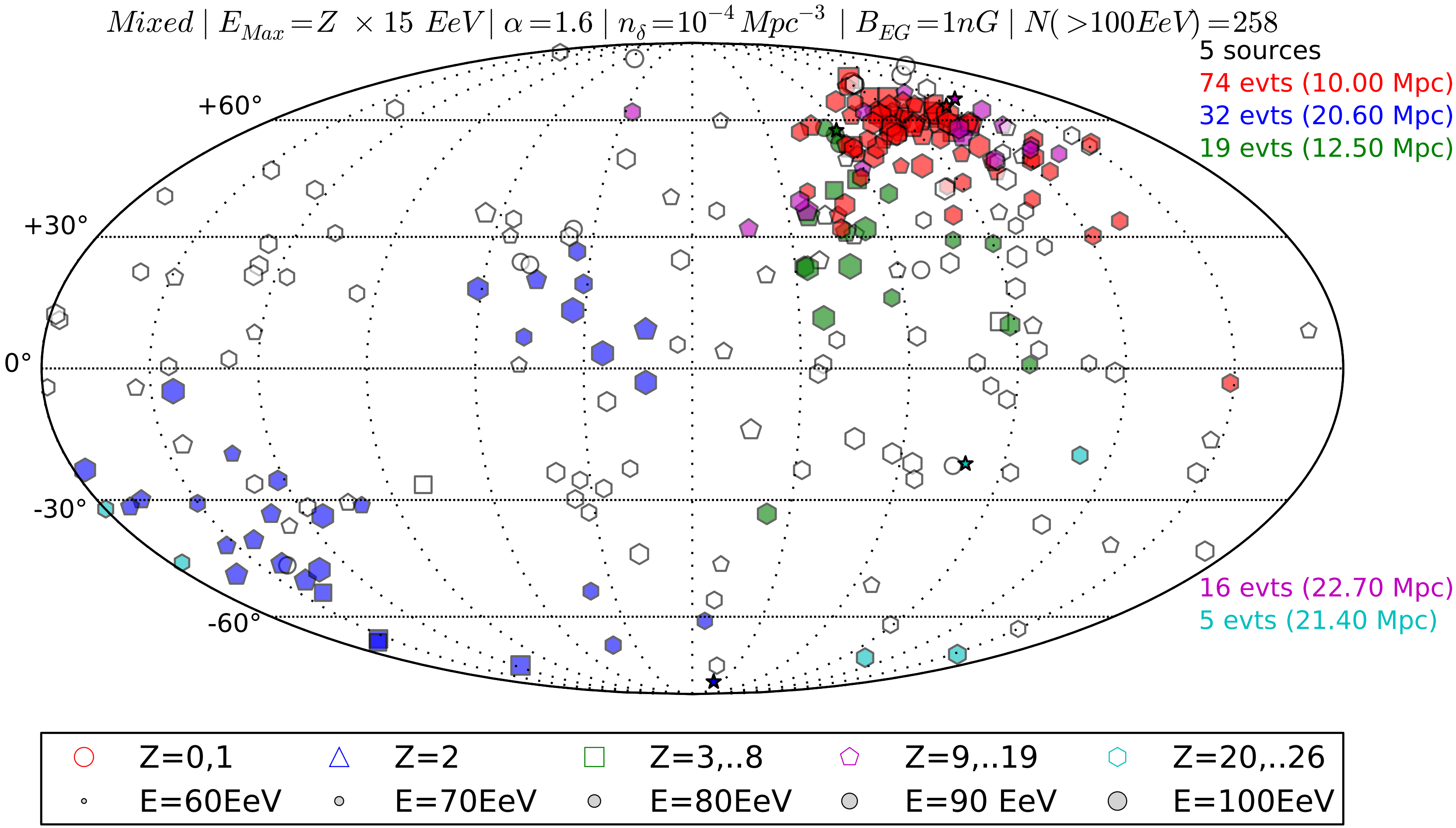
"JEM-EUSO statistics": 570 events above 80 EeV (HiRes/TA energy scale)



Simulated sky maps

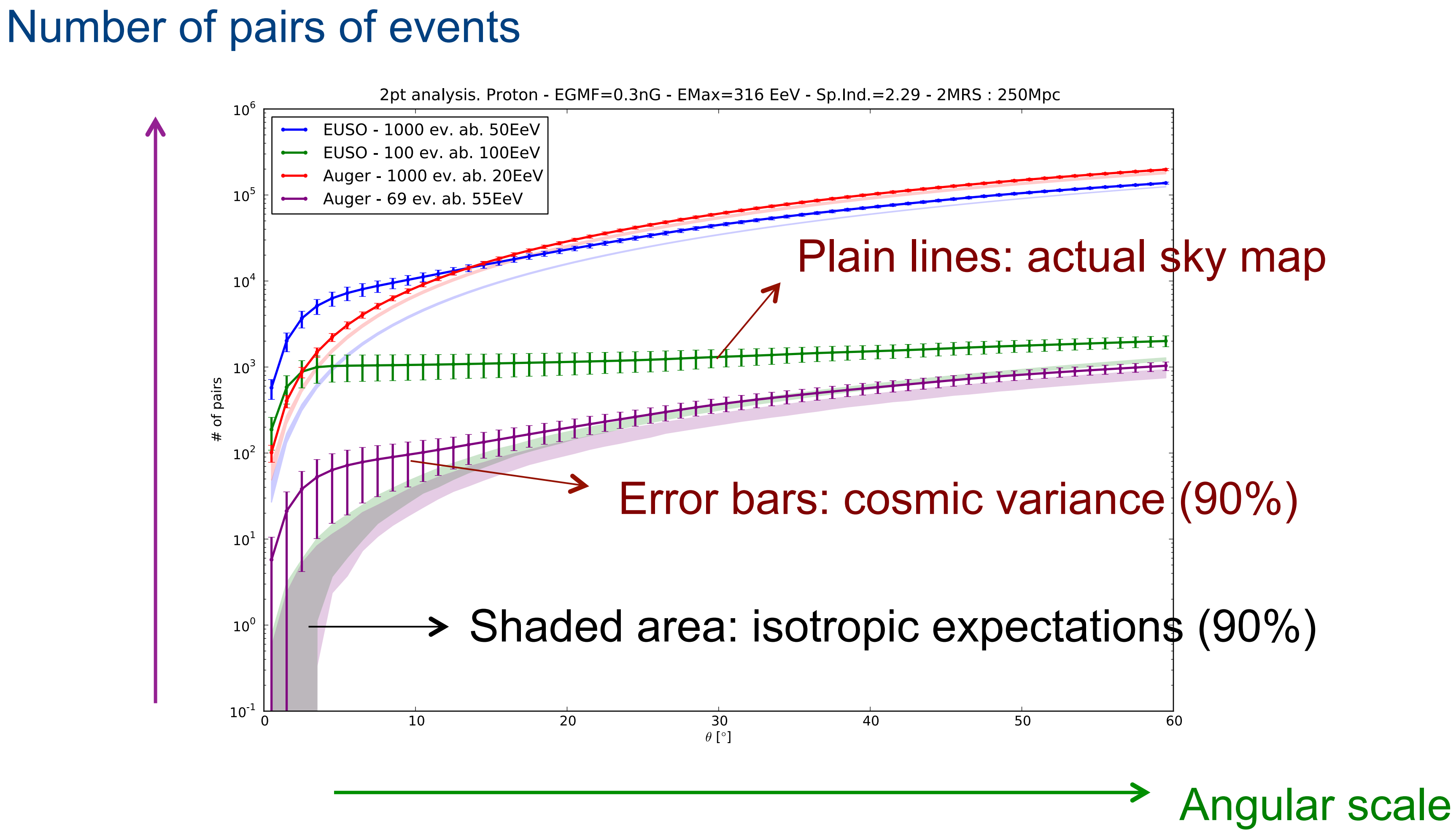
Example for $E_{max}(p)$ = 15 EeV and $n_s = 10^{-4}$ Mpc^{-3}

"JEM-EUSO statistics": 260 events above 100 EeV (HiRes/TA energy scale)



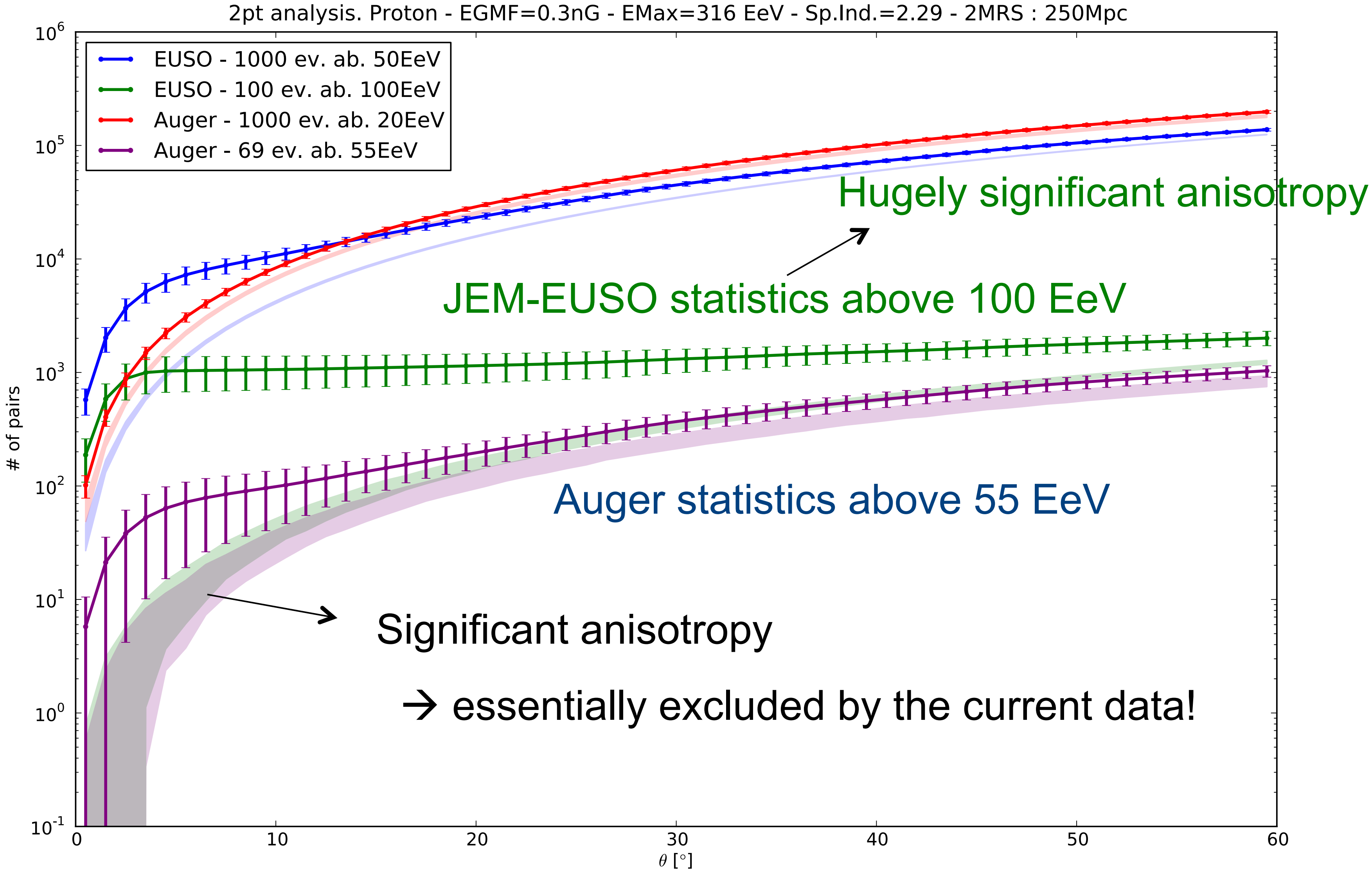
UHECR anisotropy

The 2-pt correlation function analysis is (just) one way to assess and quantify the anisotropy of a given sky map.



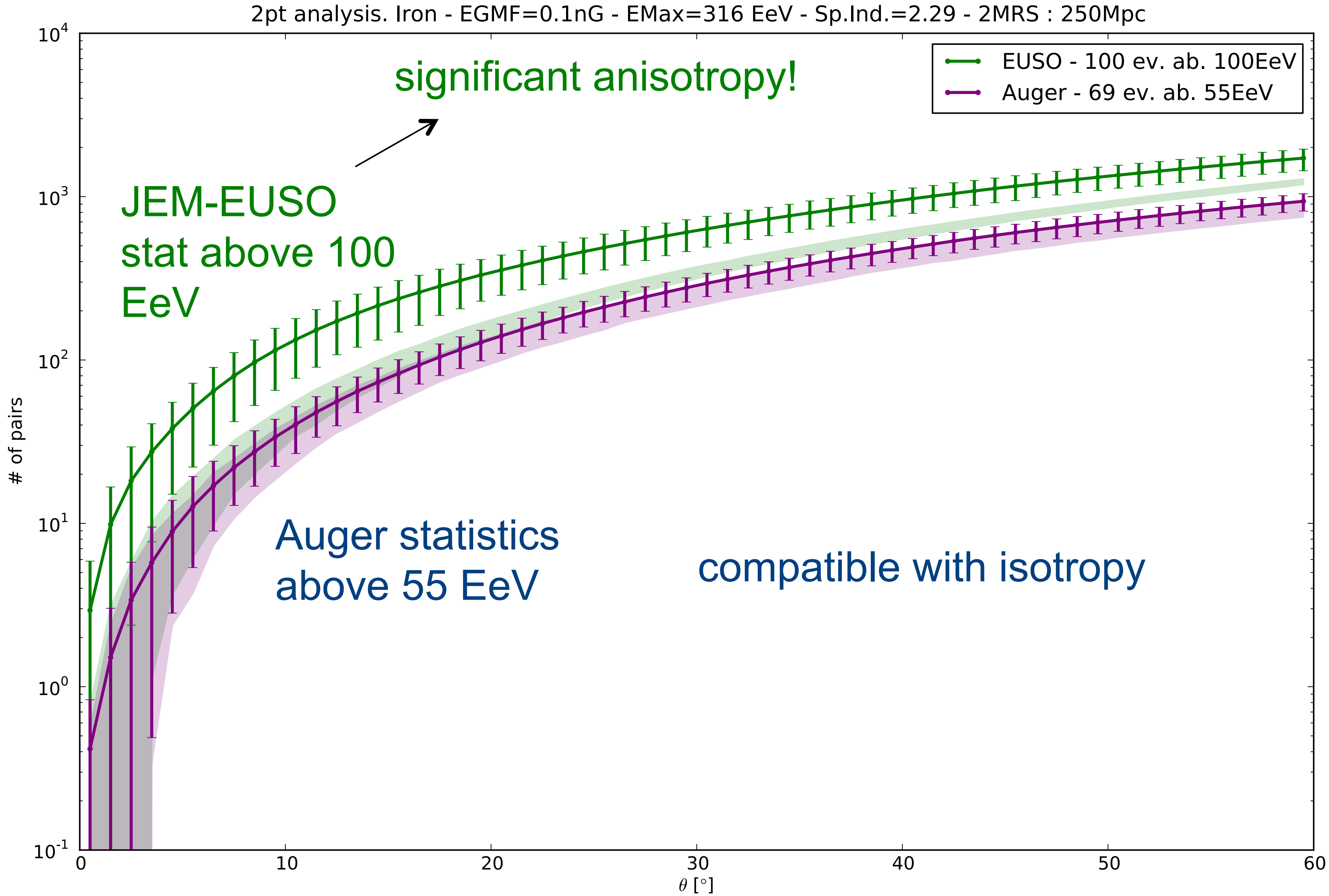
UHECR anisotropy

Proton-dominated (E_{max} = 300 EeV), $n_s = 10^{-5}$ Mpc^{-3}



UHECR anisotropy: unfavorable case

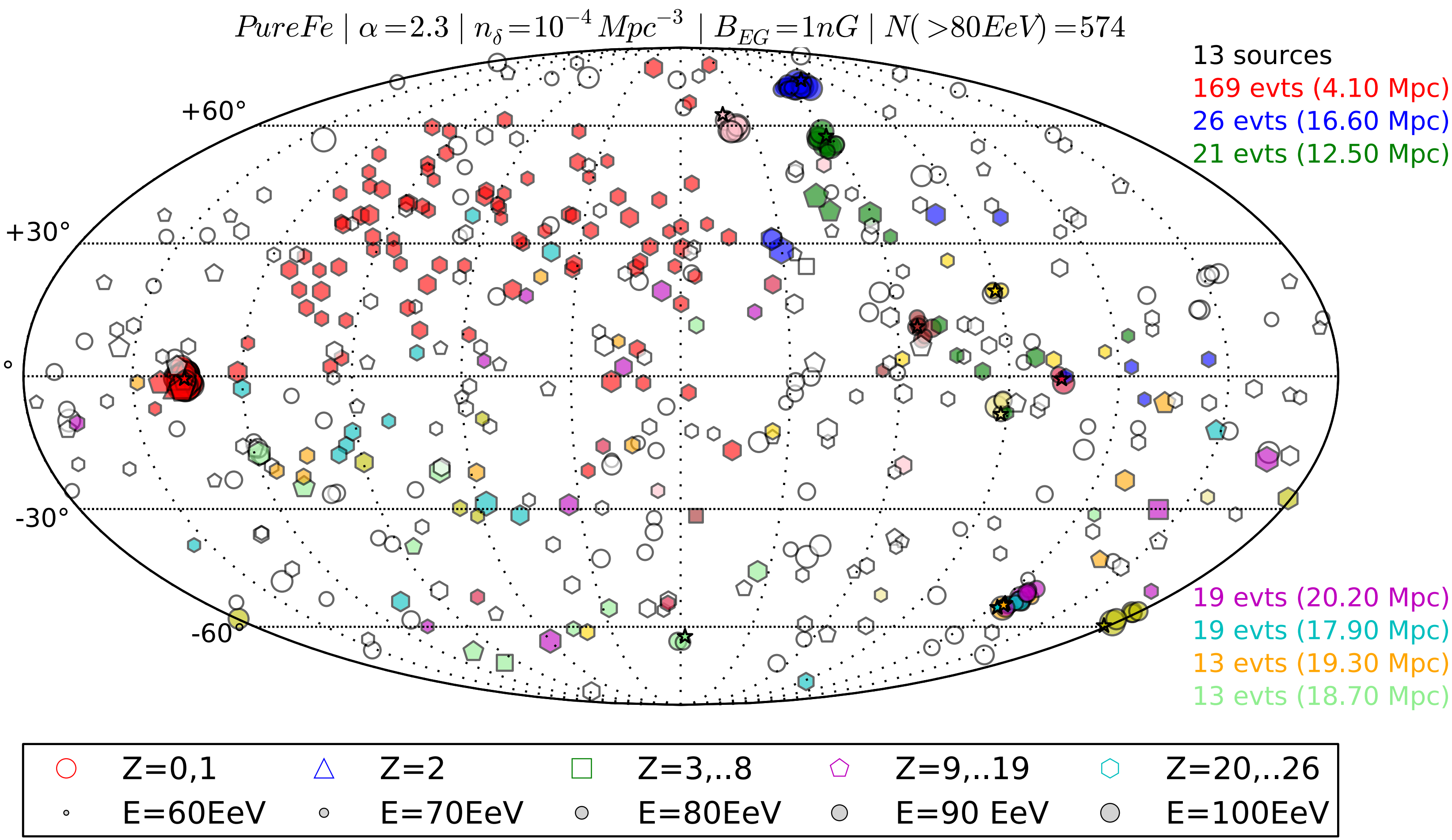
"Pure Fe" model, $n_s = 10^{-5}$ Mpc^{-3}



Simulated sky maps

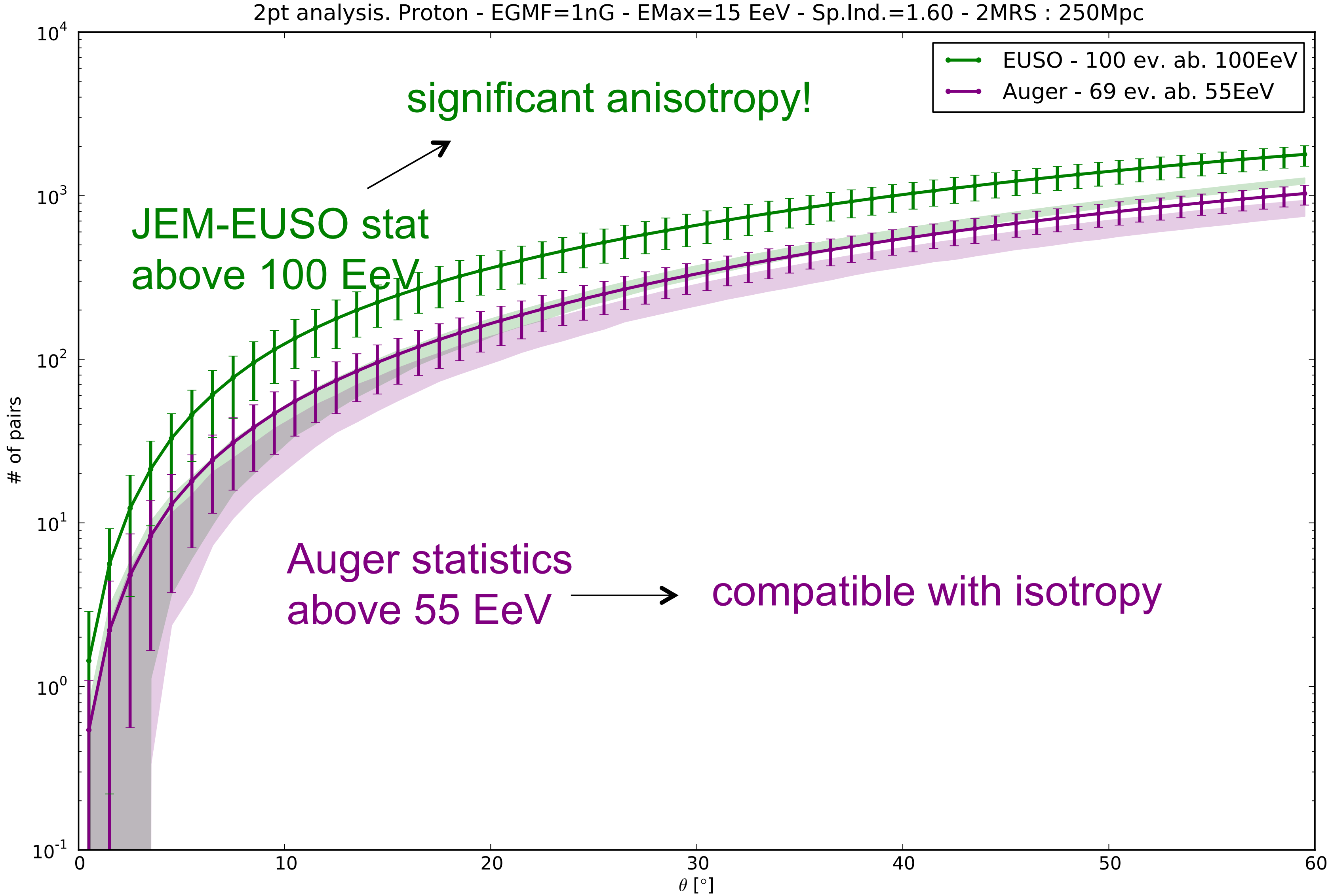
Example for the "Pure Fe" model, with $n_s = 10^{-4}$ Mpc^{-3}

"JEM-EUSO statistics": 570 events above 80 EeV (HiRes/TA energy scale)



UHECR anisotropy: even less favorable case!

$E_{max}(p)$= 15 EeV (heavy-dominated) $n_s = 10^{-5}$ Mpc^{-3}



Conclusion

- With a full sky coverage and a total exposure of 300 000 km^2 sr yr (or more!), a next-generation UHECR detector would be able to measure significant anisotropies in all the scenarios that we investigated (even for the least favourable source composition and source density)

  → gather key information and constraints on individual sources and source properties!

- Such a detector would make a ***qualitative*** difference thanks to a ***quantitative*** difference

  → Initiate multi-messenger studies with cosmic rays!

- Excellent precision is not crucial!

  In all the above studies, a 30% resolution was assumed → it proved to be good enough!

- The next step in UHECR science is within reach!

  Simulation show that JEM-EUSO appears to have the potential to make that step, and in addition to prepare for even larger exposures, from space!

JEM–EUSO

- Detection of UHECR-induced showers by the fluorescence technique **from space**

- UV telescope onboard the ISS, with Fresnel refractive optics and > 300 000 pixels (single photoelectron sensitive PMTs)
  - ±30° field-of-view, ISS altitude (400 km), ~190 000 km^2, 60 000 km^2 sr yr per year

- Acceptance: ~10 times Auger
- Energy range: E > 30 EeV
- Uniform full-sky coverage (both hemispheres)
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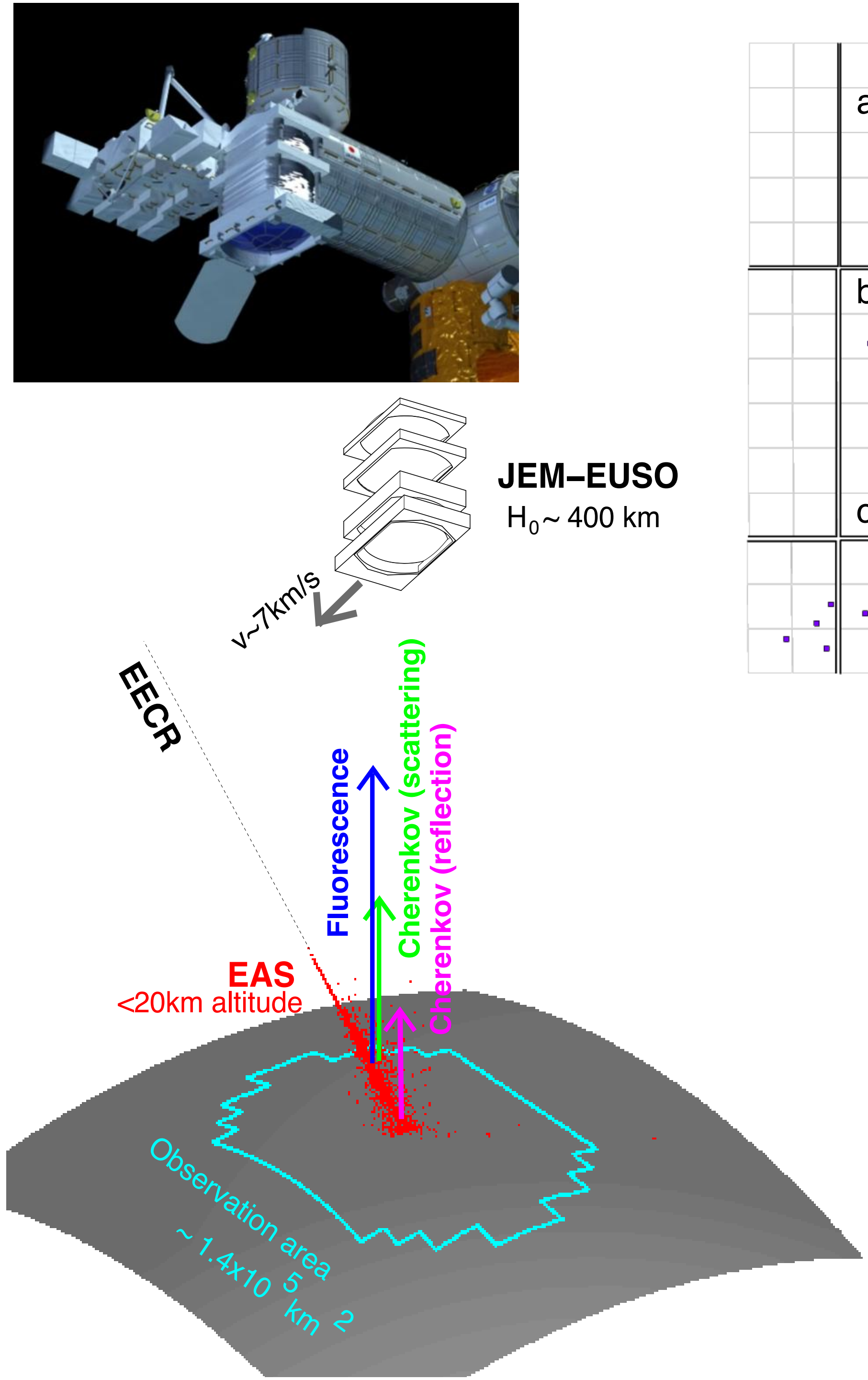
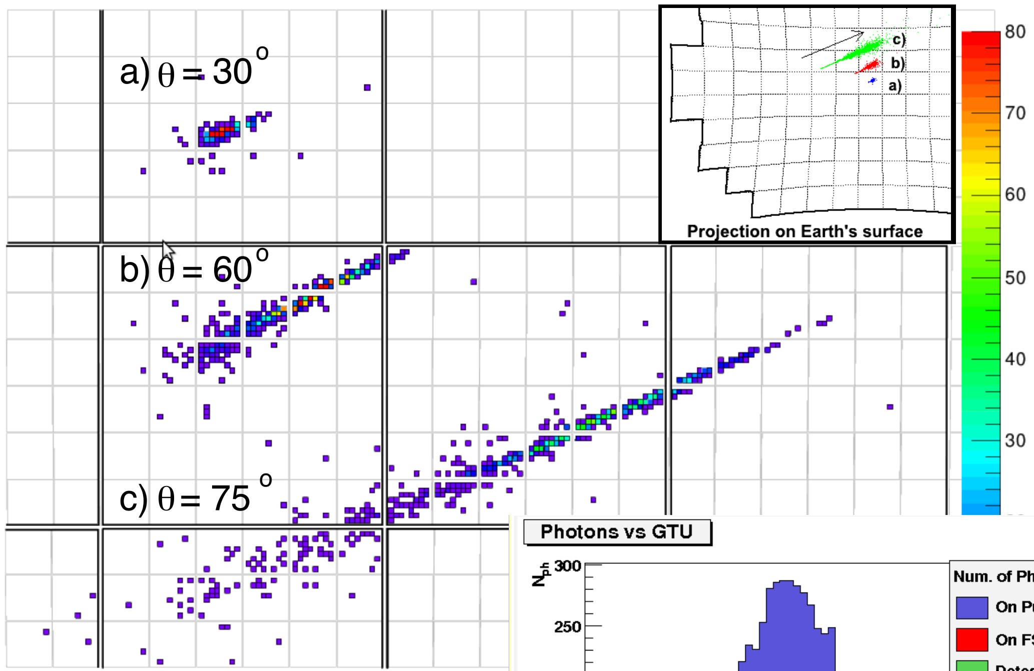
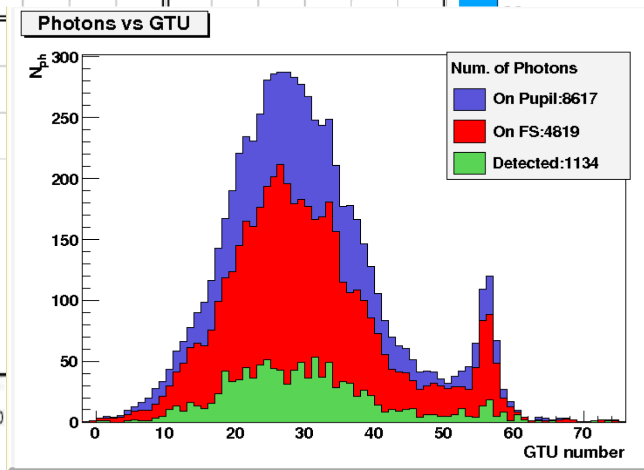
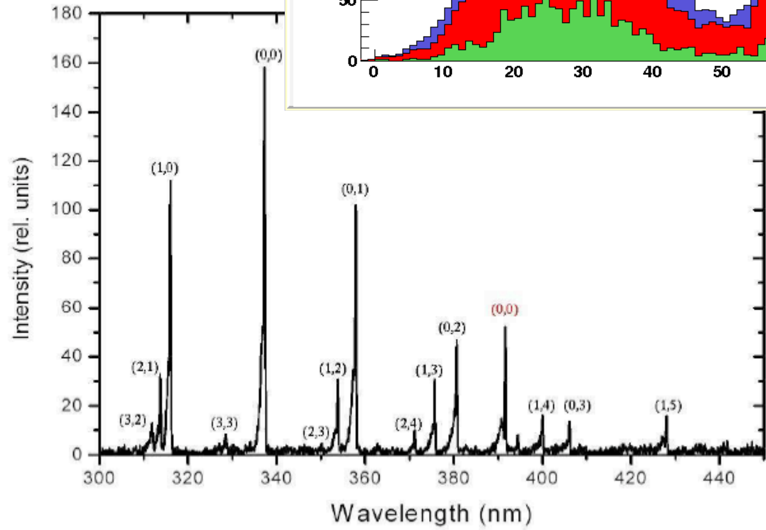
[main refereed paper: Astropart. Phys. 44, 76 (2013)]

- UHECRs + transient high-energy atmospheric phenomena + meteorites + exotic physics


JEM–EUSO
H_0 ~ 400 km
v~7km/s
EECR
Fluorescence
Cherenkov (scattering)
Cherenkov (reflection)
EAS
<20km altitude
Observation area
~ 1.4x10 5 km 2


a) θ = 30°
b) θ = 60°
c) θ = 75°
Projection on Earth's surface
c)
b)
a)
80
70
60
50
40
30


Photons vs GTU
N_{ph}
Num. of Photons
On Pupil:8617
On FS:4819
Detected:1134
GTU number


Intensity (rel. units)
Wavelength (nm)

Parizot

International collaboration: strong and active (14 countries, 80 institutions, >250 researchers)

Japan	Lenses, PMTs *(ISS resources)*, EUSO-TA pathfinder
Korea	Electronics, PDM board
France	Front-end electronics, calibration, Balloon pathfinder
Italy	Mechanics, data processing, triggers
Germany	Electronics, cluster control board
Spain	Atmospheric monitoring, IR camera
USA	Flashers/laser shots, onboard calibration, *ISS resources*
Russia	Mechanical structure, extension mechanism, *ISS res.*

International collaboration: strong and active (14 countries, 80 institutions, >250 researchers)

 Switzerland — Atmospheric monitoring, lidar system

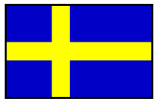
 Poland — High voltage power supply

 Mexico — Low voltage power supply, House-keeping

 Algeria — Electronics, simulations

 Slovakia — Simulations

 Bulgaria — Simulations

 Sweden — TBD

International collaboration: strong and active (14 countries, 80 institutions, >250 researchers)

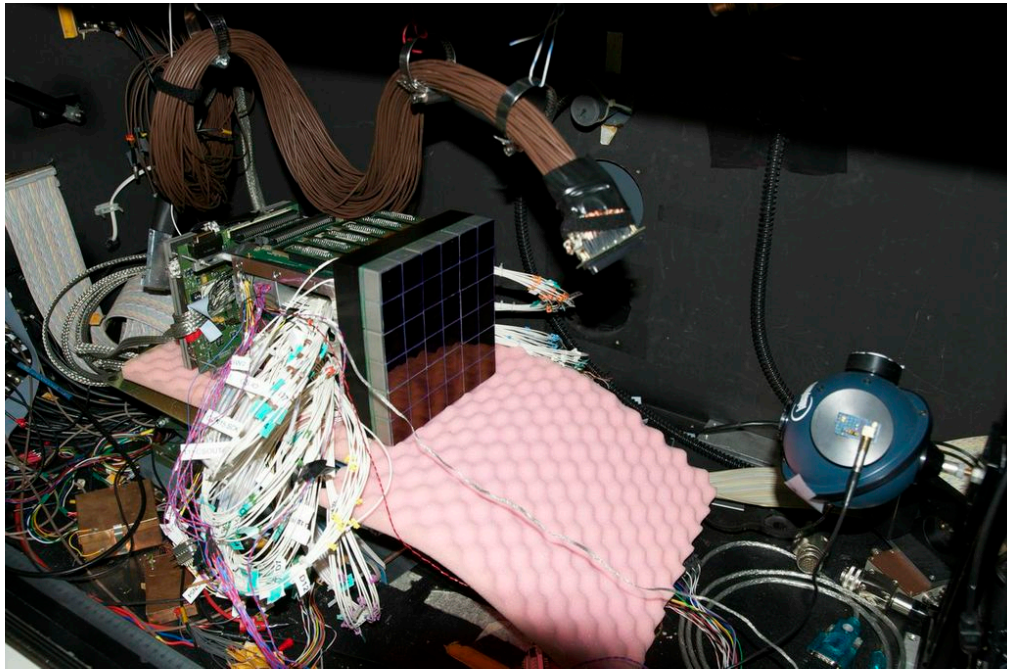
- ✧ All technical studies, R&D and prototypes have been officially approved and successfully <u>funded by the national agencies</u>

→ Successful development of a complete, fully operational pre-flight model (with all subsystems, hardware and software)

→ Successful integration of the focal surface (Feb./March 2014)
→ EUSO-Balloon (CNES mission, to fly in Aug. 2014)

PDM = photo-detection module

(flight model!)



PDM = 36 PMT = 2304 pixels

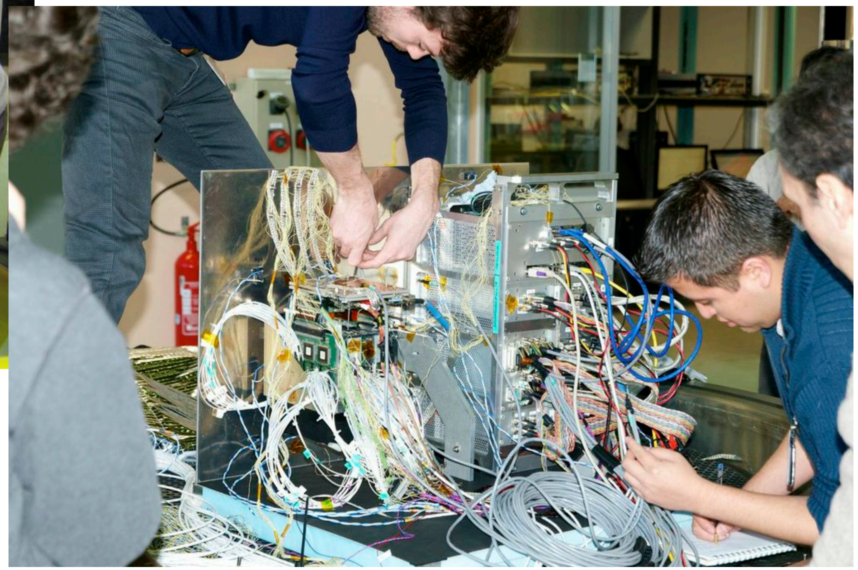
(focal surface of EUSO-Balloon)

Integrated electronics

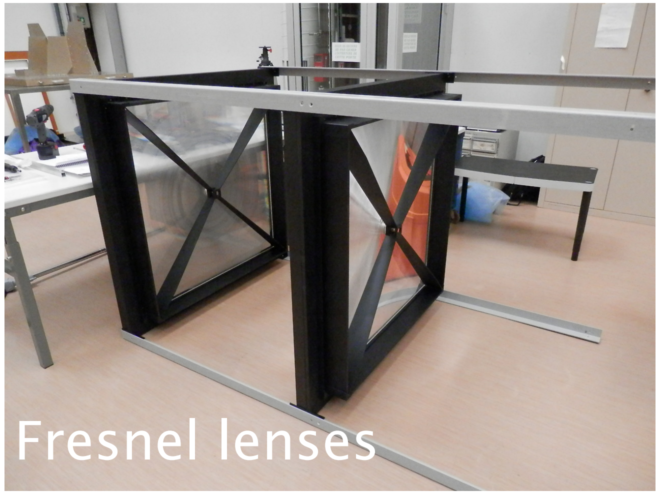
Japan: PMTs
Korea: PDM boards
France: front-end electronics

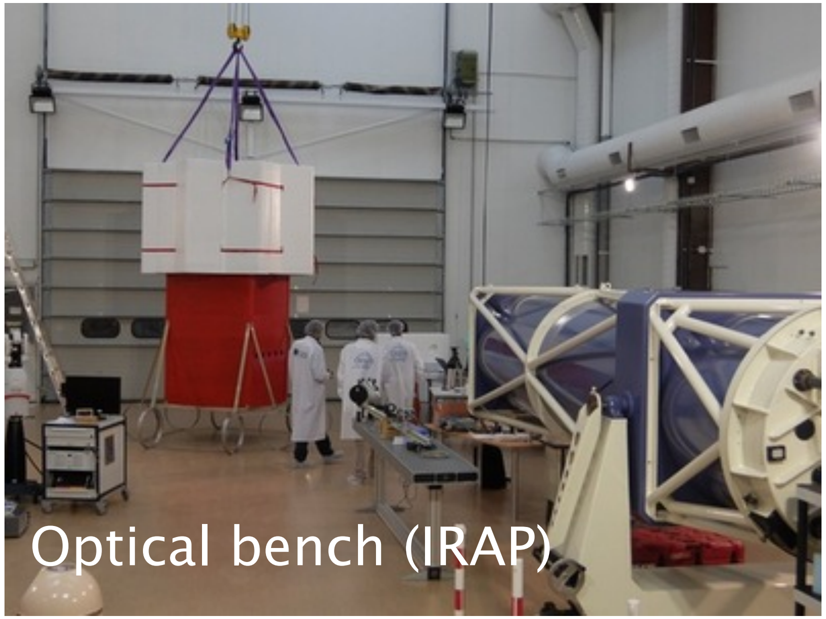
- ✧Installation in the APC black box (photo-detection lab)
- ✧Ultra-precise calibration system (<5%) with integrating sphere

Thermal and vacuum tests at CNES (Toulouse)



EUSO-Balloon





JEM–EUSO pathfinders

- EUSO–TA

- Japan/USA initiative and funding ✓
- 1 PDM (photo-detection module) of JEM–EUSO, 2 Fresnel lenses
- Cross-calibration with the Telescope array UHECR experiment in Utah
- Tests and measurements with artificial showers → end of 2014

- EUSO–Balloon

- French initiative, funded by CNES ✓
- 1 PDM of JEM–EUSO, 3 Fresnel lenses
- UV background measurement over various landscape/albedo
- Complete test of hardware and trigger software (+ flashers signal)

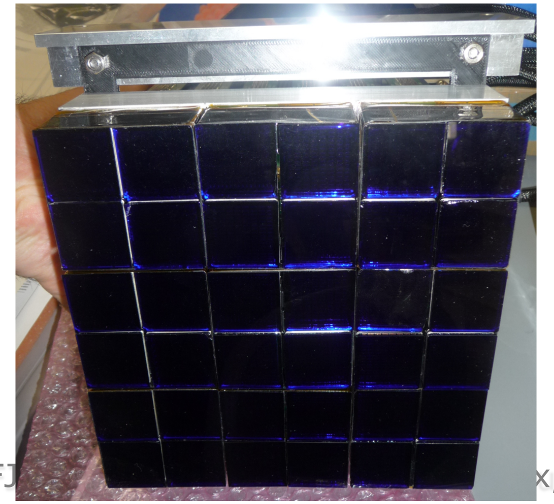
Mini-EUSO:

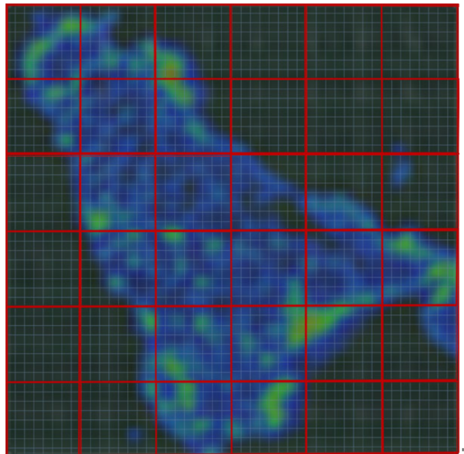
✓

- ✧ Italian initiative: selected by ASI
- ✧ 1 PDM (photo-detection module) of JEM-EUSO, 2 Fresnel lenses

Inside the ISS (quartz window for UV transmission): 2017

- + ANR Proposal: selected at first stage (2014)
- + European Proposal (H2020) to build the instrument (2015-2016)





Future: NASA-led mission?

✓

- NASA: ISS/HSMD is willing to put the JEM-EUSO instrument onboard the ISS if the instrument exists

  (cf. ISS-CREAM)

  → the JEM-EUSO collaboration is seeking a framework to fund the building of the instrument (~100 M€)

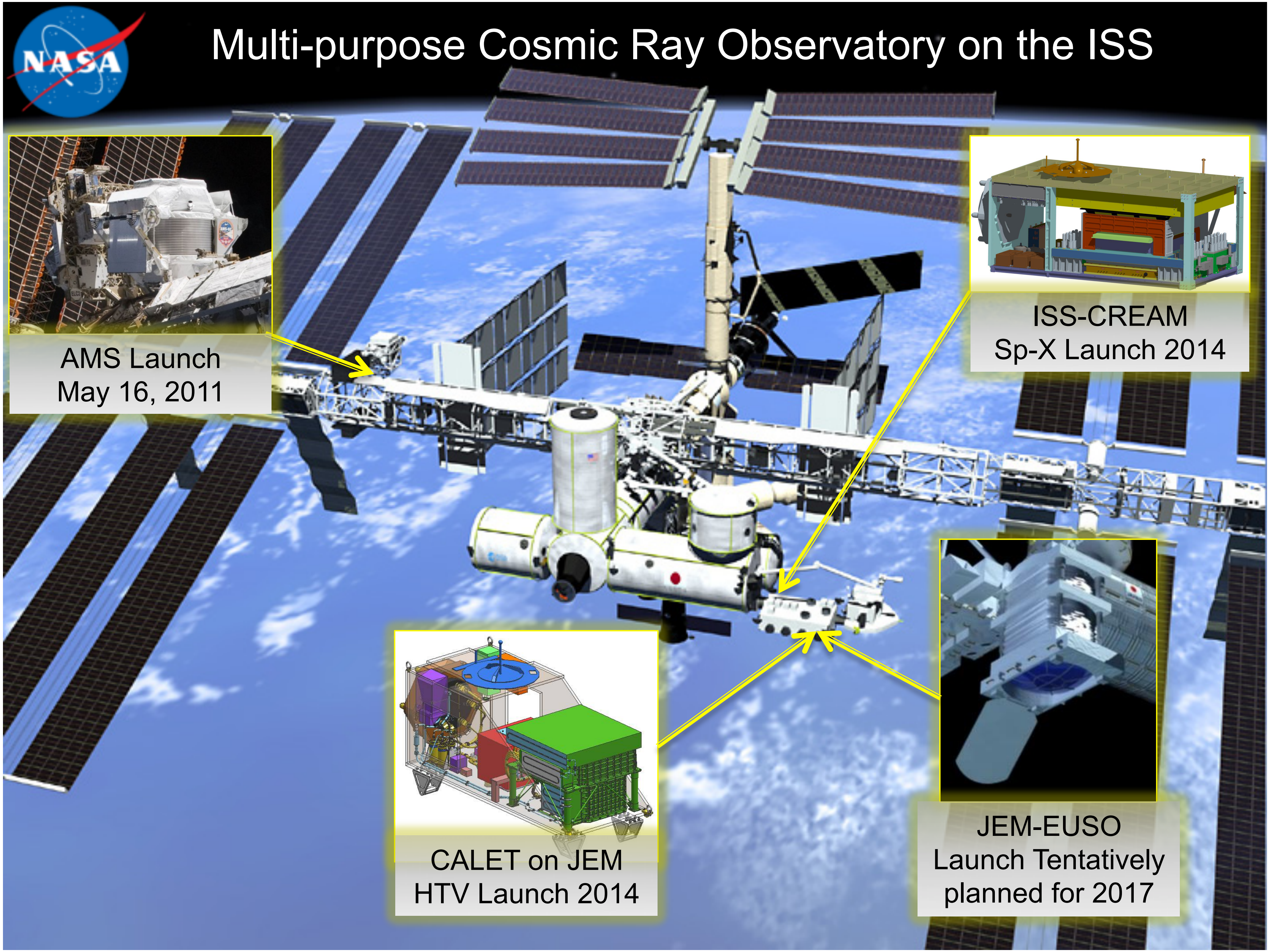
  → Multi-agency agreement for “flag ship mission”?

  → ISS

- Active international collaboration: Japan, USA, Europe (9 countries), Korea, Mexico, Russia, Algeria

- NASA vision of a multi-purpose/multi-instrument cosmic-ray observatory on the ISS

  → JEM-EUSO included in NASA’s road map (dec. 2013)


NASA
Multi-purpose Cosmic Ray Observatory on the ISS
AMS Launch
May 16, 2011
ISS-CREAM
Sp-X Launch 2014
CALET on JEM
HTV Launch 2014
JEM-EUSO
Launch Tentatively
planned for 2017

Mid- and long term

- ✧ Develop the space road for UHECR studies

- ✧ NB: parallel effort in Russia: ROSCOSMOS program "KLYPVE"
- ✧ → JAXA/ISAS proposal for "KLYPVE-EUSO

- ✧ Increase performances (SiPM?, free flyer?, stereo instrument?)
- ✧ We have "5 orders of magnitude in aperture to go!" (A. Olinto)

  (between the size of Auger and the Earth-wide capacity offered by space)

- ✧ Free-flyer version → "Super-EUSO"
- ✧ Revival of the "OWL" concept in the USA

Proposal for 2014-2015

- 2014 is a key year in the development of UHECR studies from space:
  - EUSO-Balloon in operation in space (August 2014)
  - TA-EUSO in operation on the ground (Summer-Fall 2014)
- Sharing of experience between France and Japan: instrumental aspects
- Joint data analysis and software development
- Develop a common plan for the future of the field, based on the results and experience from EUSO-Balloon and EUSO-TA

  → Assessment of performances

  → Identify accessible instrumental improvements (PMTs, HW, SF + electronics (also with Korea)

  → Develop deeper understanding of UHECR phenomenology/theory

  → Define the "best compromise" with scientific objectives

Proposal for 2014-2015

- Additional theoretical studies:
  - Energy spectra associated with the simulated sky maps
  - Spectrum fluctuations and spectrum differences
  - Identify discriminating variables

- Link between UHECRs and other messengers
- High-energy astrophysics
- X-ray and gamma-ray astronomy
- AGNs and GRBs
  - particle acceleration
  - source modeling

} Complementary expertise in Japan and in France!

- Key instrumental work: study of new ASIC (SPACIROC 3 developed by OMEGA + new version of the Korean PDM board)

- NB: student from the Korean team currently doing a PhD in Paris!

French Group			Japanese Group		
Name	**Title**	**Lab./Organis.**	**Name**	**Title**	**Lab/Organis.**
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Albert Jean-Noël	DR	APC/IN2P3			
Kegl Balazs	CR	LAL/IN2P3			
Semikoz Dmitry	CR	APC/IN2P3			

JEM–EUSO and its pathfinders…