Ground based cosmic ray experiments: results and perspectives

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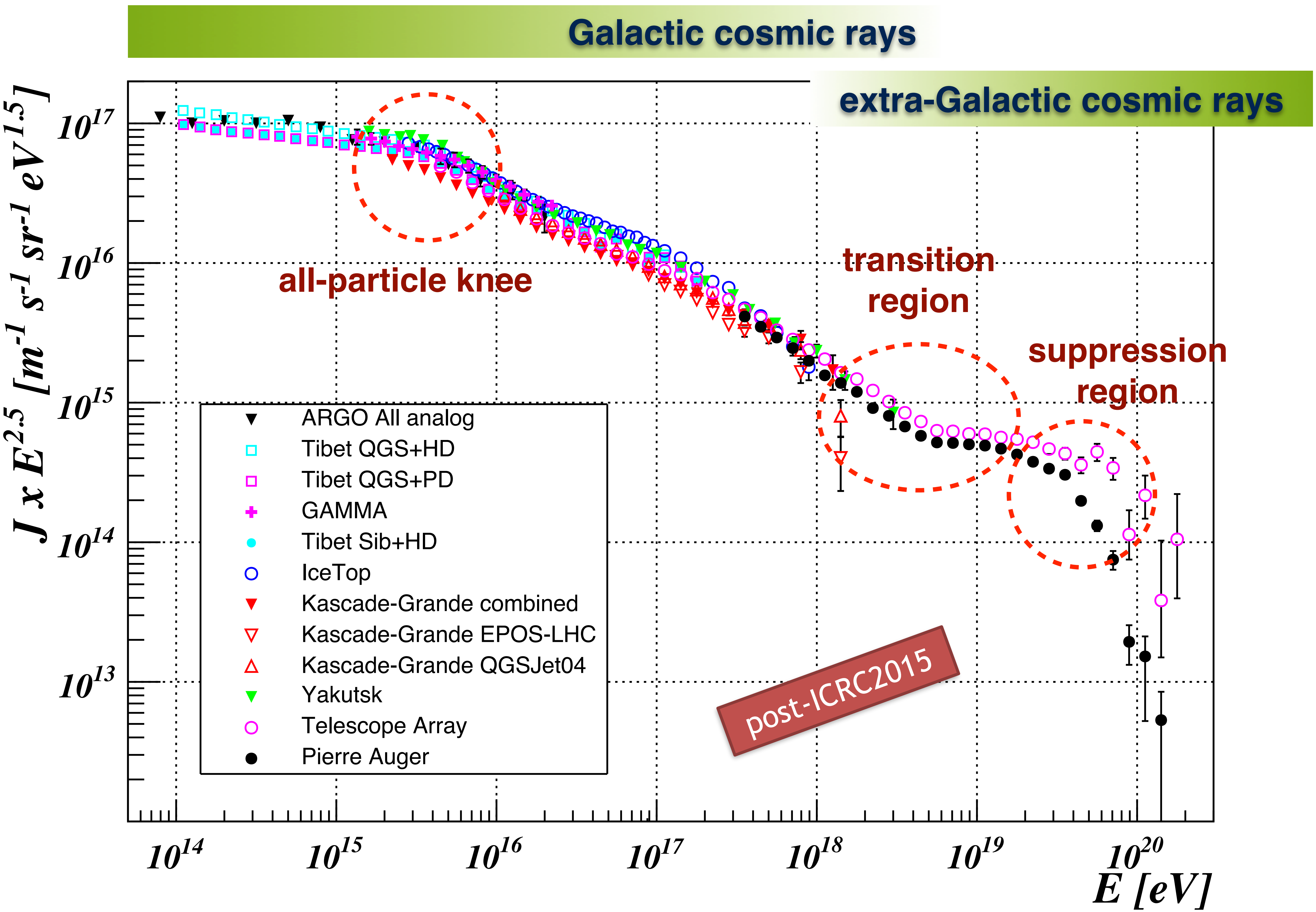
The experimental challenge



The air shower detectors

Array	*g cm^-2*	*Detector*	*ΔE [eV]*	*Area [km²]*
ARGO	*600*	*RPC hybrid (LLASHO)*	*0.3-5 10^{15}*	*0.0056*
Tibet-ASγ	*600*	*Scintillator/burst detector*	*1-200 10^{15}*	*0.0037 [0.5 phase III]*
EasTop	*820*	*scintillator/muon*	*1-100 10^{15}*	*0.01*
GAMMA	*700*	*scintillator/muon*	*3-200 10^{15}*	*0.03*
KASCADE	*1020*	*scintillator/muon*	*2-90 10^{15}*	*0.04*
CASA-MIA	*860*	*scintillator/muon*	*0.1-100 10^{15}*	*0.25*
Kascade-Grande	*1020*	*scintillator/muon*	*10^{16}-10^{18}*	*0.49*
IceTop	*680*	*ice Cher.tanks*	*10^{16}-10^{18}*	*1*
Tunka	*900*	*unshielded PMTs*	*10^{15}-10^{18}*	*3*
Yakutsk	*1020*	*scintillator/unshielded PMTs*	*10^{15}-10^{19}*	*~40*
Telescope Array +TALE	*880*	*scintillator+ fluorescence tel.*	*4 10^{15}-10^{20}*	*700*
Auger +Infill	*840*	*water Cher.tanks fluorescence tel.*	*10^{17}-10^{20}*	*3000*

High altitude experiments

- N_{part} ~ indip of composition
- close to maximum of EAS: low fluctuations

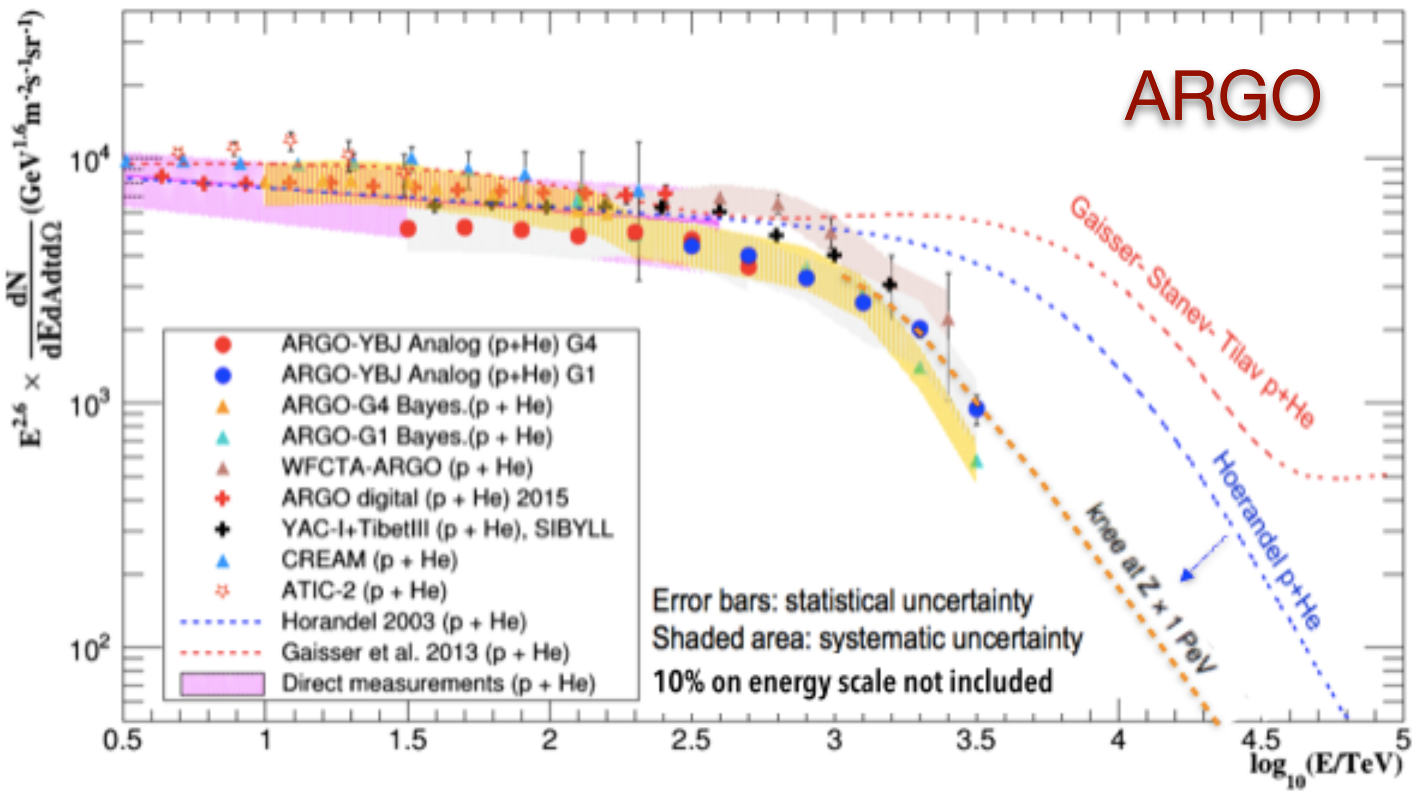
energy resolution

Sea level experiments

- N_{part} ~ indip of composition
- EAS after maximum
- exploit longitudinal distribution differencies for different primaries

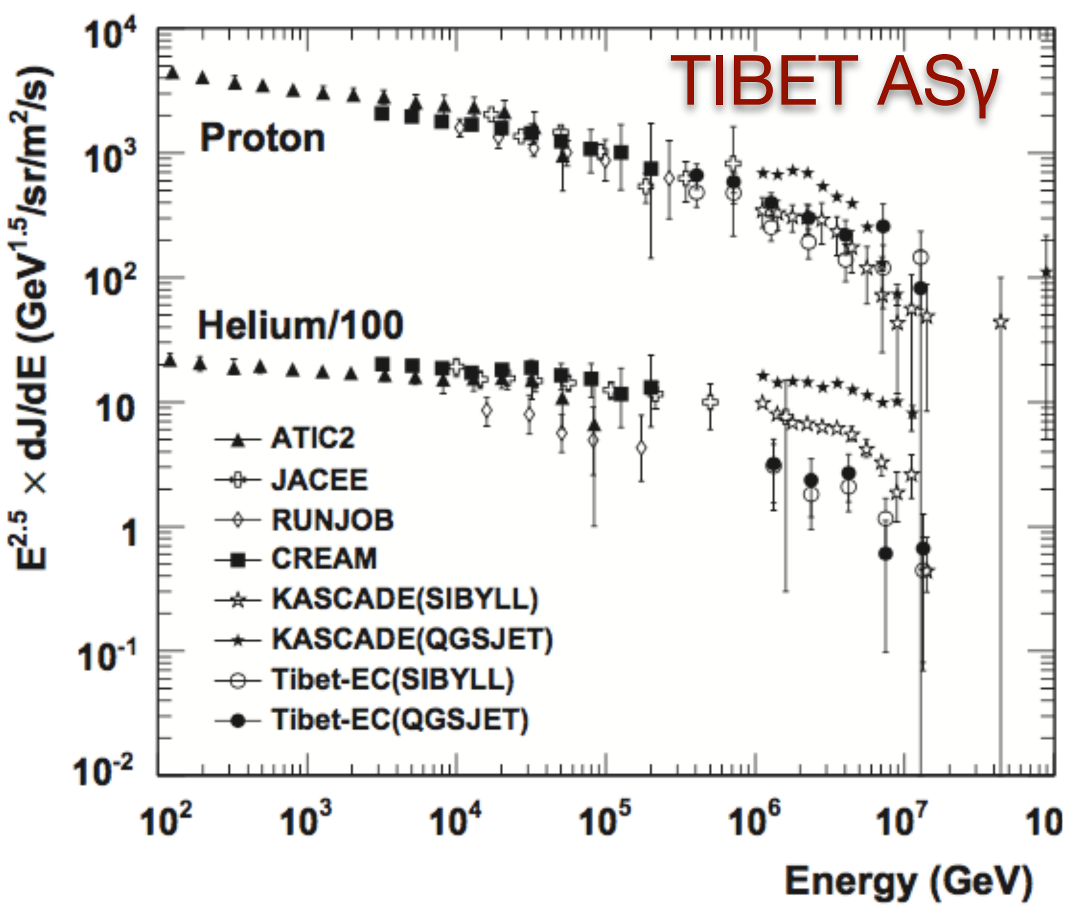
composition

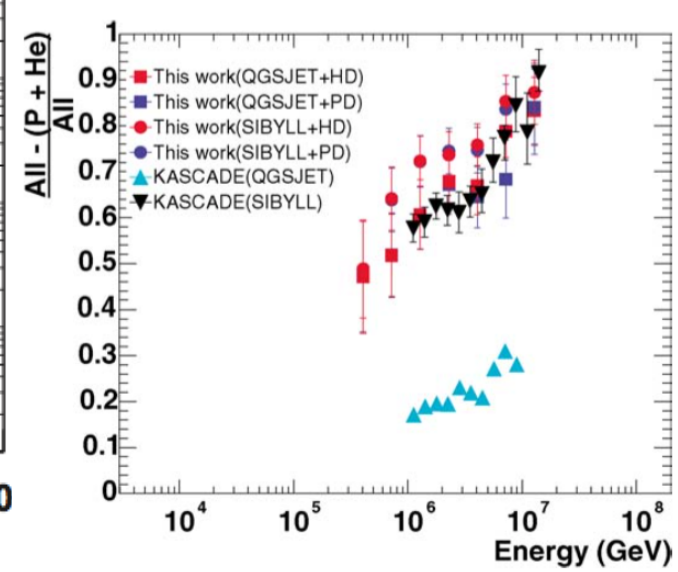
The knee region



- evidence for a **proton knee at E_k=(700 ±230) TeV** at variance with E_k(p) ~ E_k(all-particle)
- γ from (-2.56±0.05) to (-3.24±0.36)
- compatible with JH2003 spectrum with proton knee at 1 PeV

Data	σ(E)	σ^{sys} (E scale)	σ^{sys} (flux)
Hybrid	25%	- 9.7%	-28%
Analog	15%	5%	20%

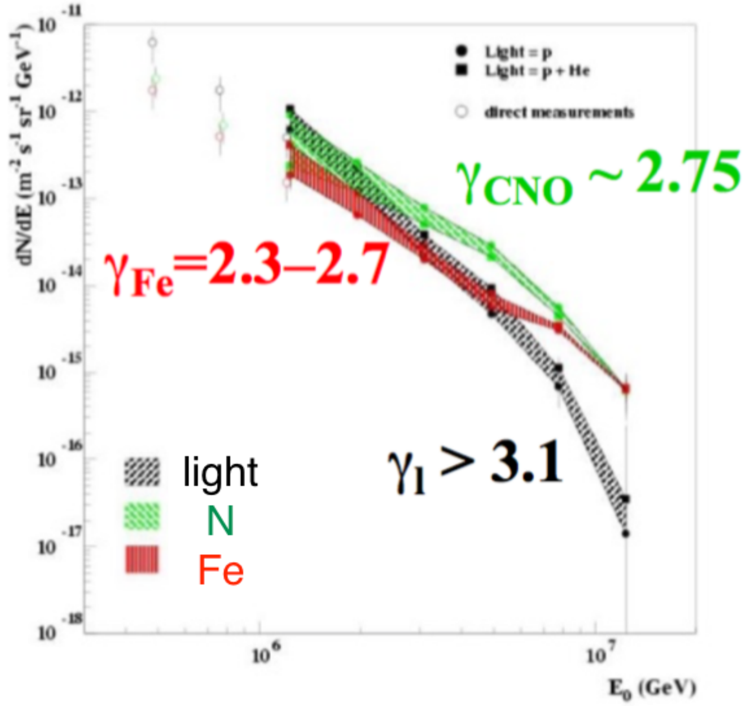




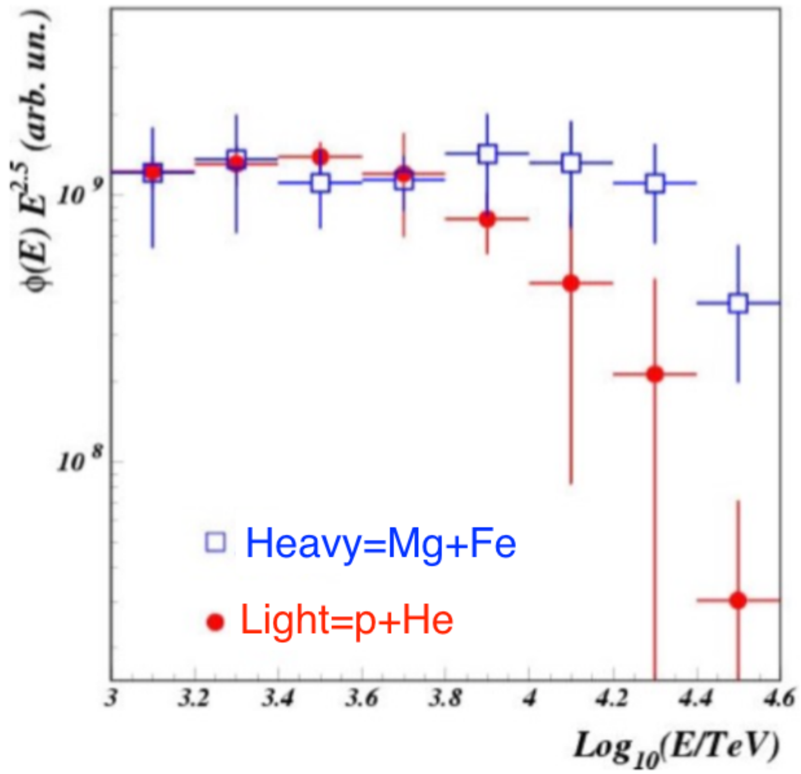
- power index for light spectrum steeper wrt all-particle one: E_k(light) < E_k(all)
- heavy component dominates the all particle knee

The knee region - old results

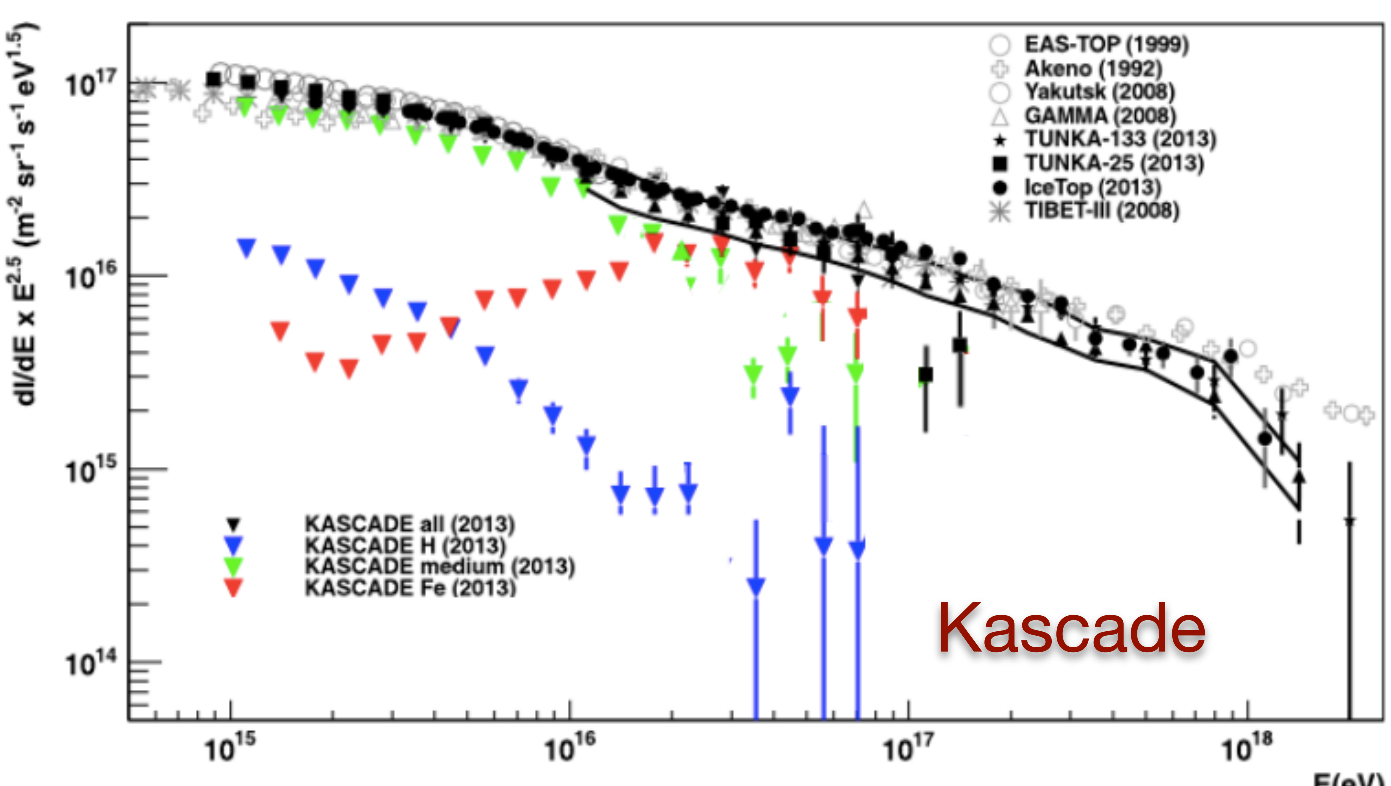
EAS-TOP Ne-Nμ (GeV)
[M.Aglietta et al., Astrop.Phys.21 (2004) 583]



EAS-TOP/MACRO Ne-Nμ (TeV)
[M.Aglietta et al., Astrop.Phys.20 (2004) 641]



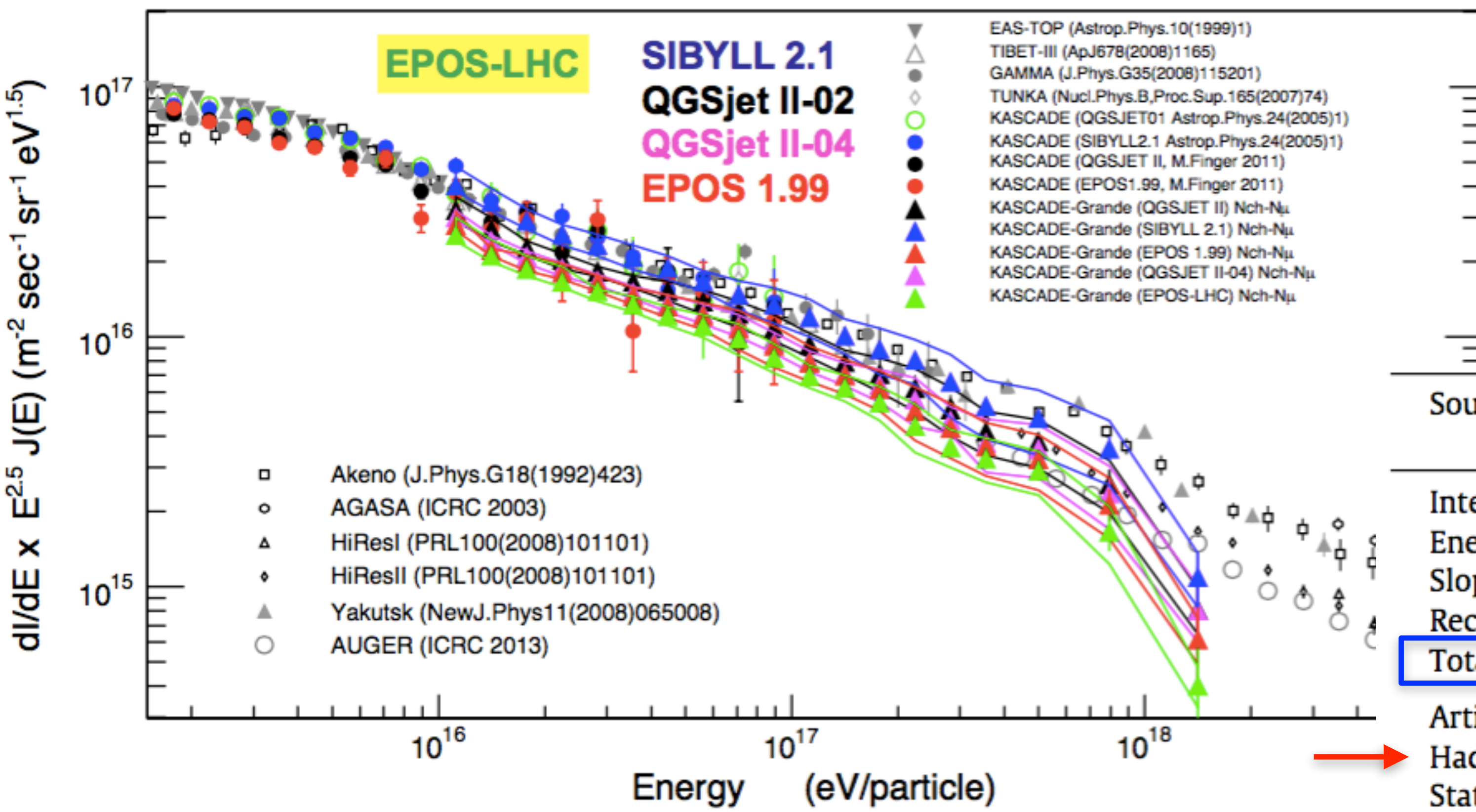
- **light knee around few PeV**
- harder spectrum for heavier nuclei: indication for $E_k \propto Z$
- old models, lower resolution



- all-particle knee ~ 4 10^{15} eV
- **p knee around few PeV, heavier knee not visible (no statistics)**
- if Peters cycles, E_k(Fe) must be found at ~ Z x E_k(p) ~ 7-10 10^{16} eV

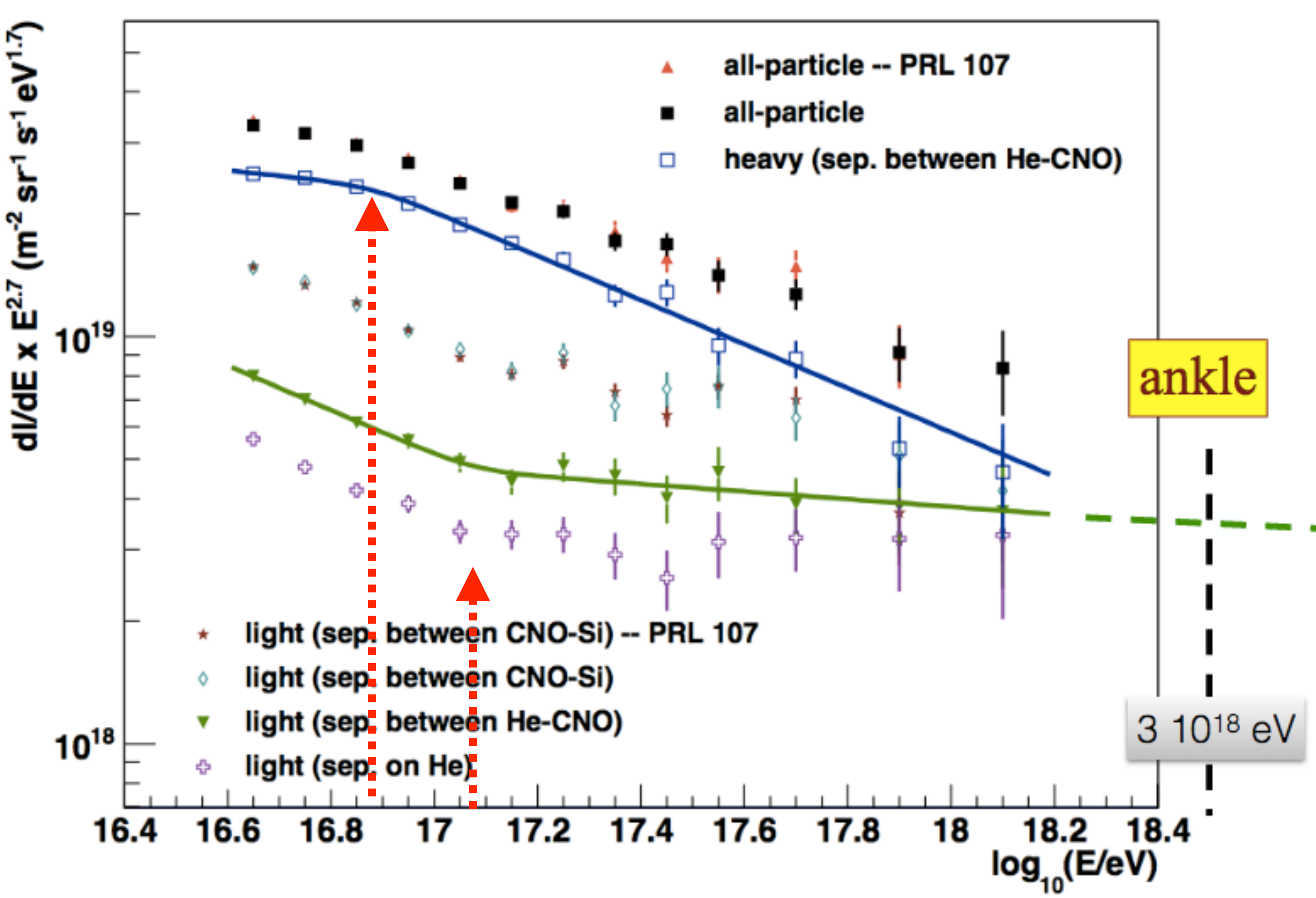
similar results in Casa-MIA, Gamma experiments

The transition region



Kascade-Grande

Source of uncertainty	10^{16} eV (%)	10^{17} eV (%)	10^{18} eV (%)
Intensity in different angular bins (attenuation)	−0/+6.5	10.9	21.3
Energy calibration and composition	10.3	5.8	13.4
Slope of the primary spectrum	4.0	2.0	1.9
Reconstruction (core and shower sizes)	0.1	1.4	6.5
Total	−11.1/+12.8	12.6	26.1
Artificial spectrum structures (extreme cases)		<10	
Hadronic interaction model (EPOS-QGSJet)	−5.3	−16.9	−14.6
Statistical error	0.6	2.7	17.0
Energy resolution (mixed composition)	24.7	18.6	13.6



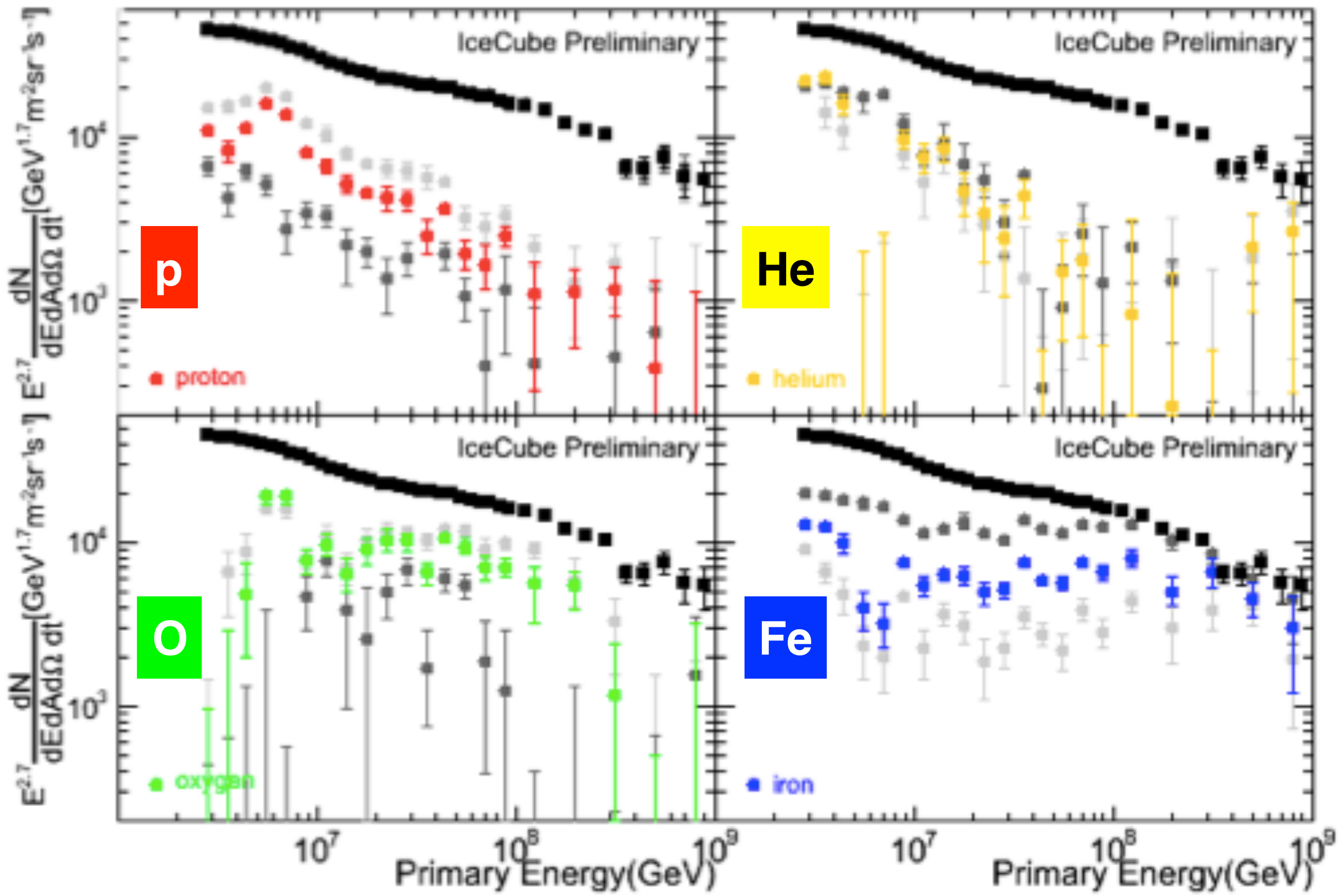
- ***(heavy+medium) component knee ~$10^{16.88}$ eV*** *compatible with previous result*
- ***light component hardening ~$10^{17.08}$ eV,*** *$\Delta\gamma$=0.46 (from -3.25 to -2.79) —> 5.8σ : start of the transition ?*

The transition region

IceTop

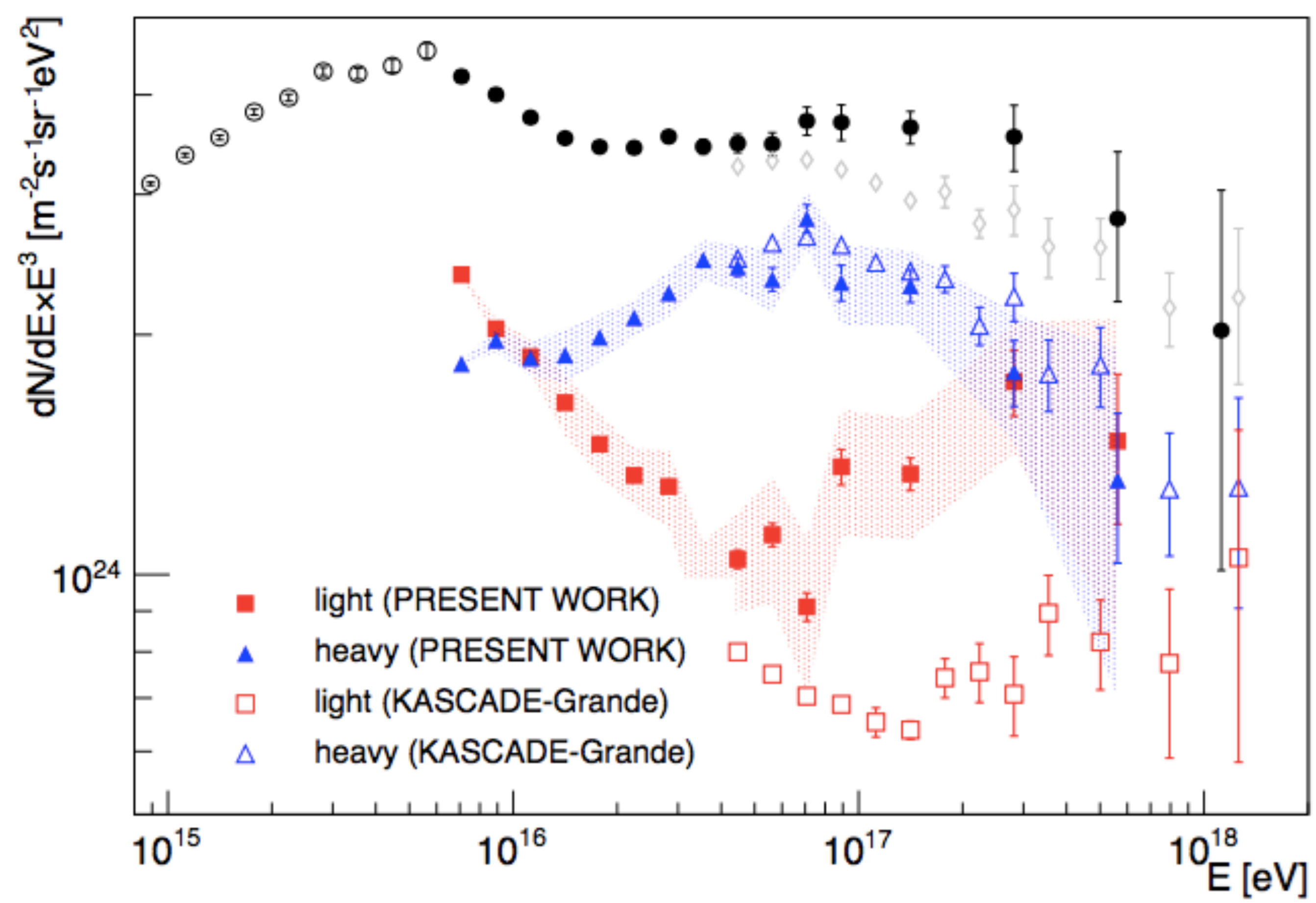
- KG features confirmed in both standalone and combined analysis
- Light spectra steeper
- problem with iron component?

Systematics: +9.6% -12.5%
(dominant effect light yield in the in-ice detectors)



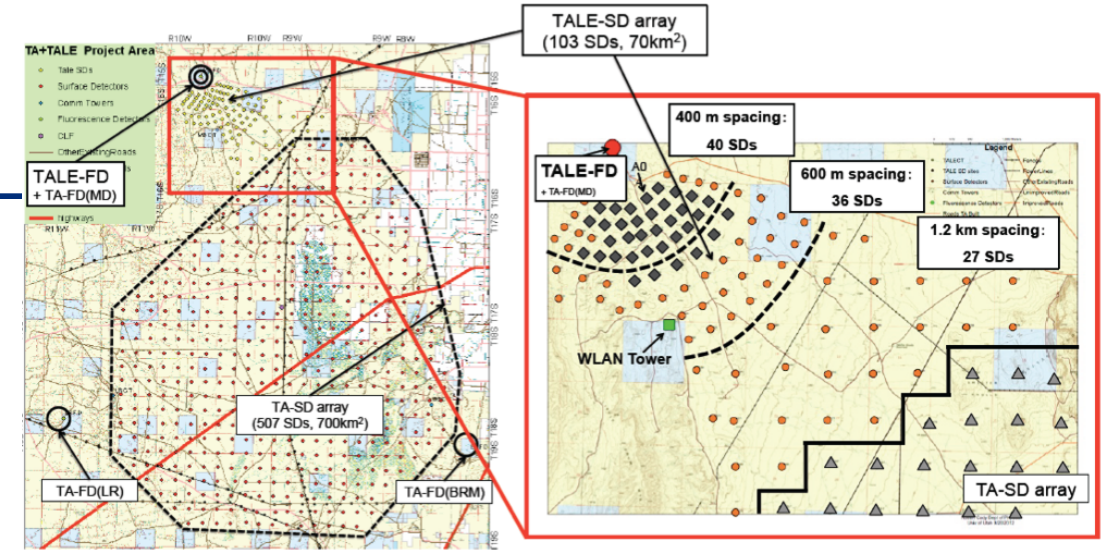
Tunka

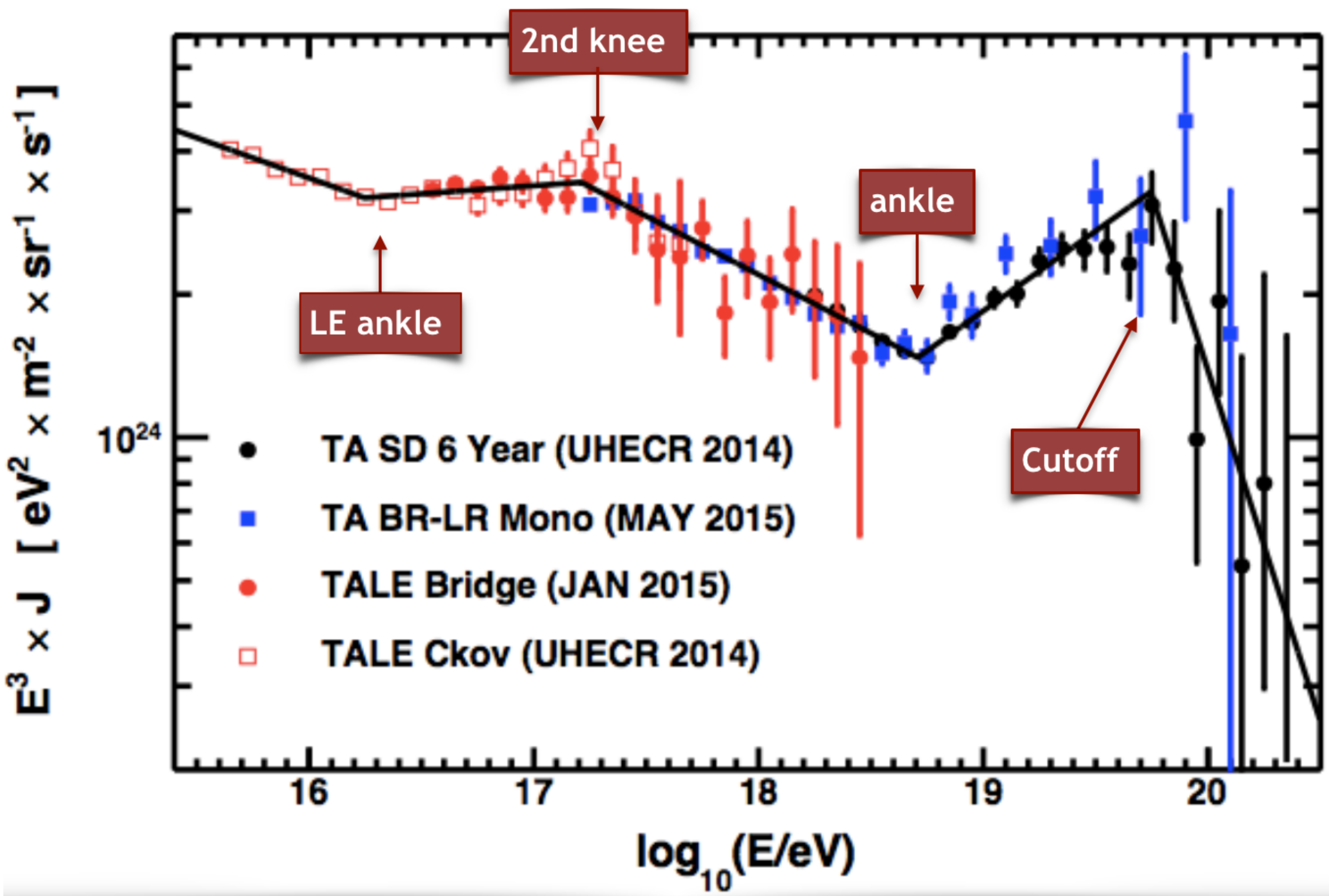
- features in agreement with KG experimental results
- agreement with TALE spectrum between 2 10^{17} and 10^{18} eV
- knee : p, He
- heavy knee at ~ 7 10^{16} eV
- EG light component growing above 4-5 10^{16} eV



The UHE region

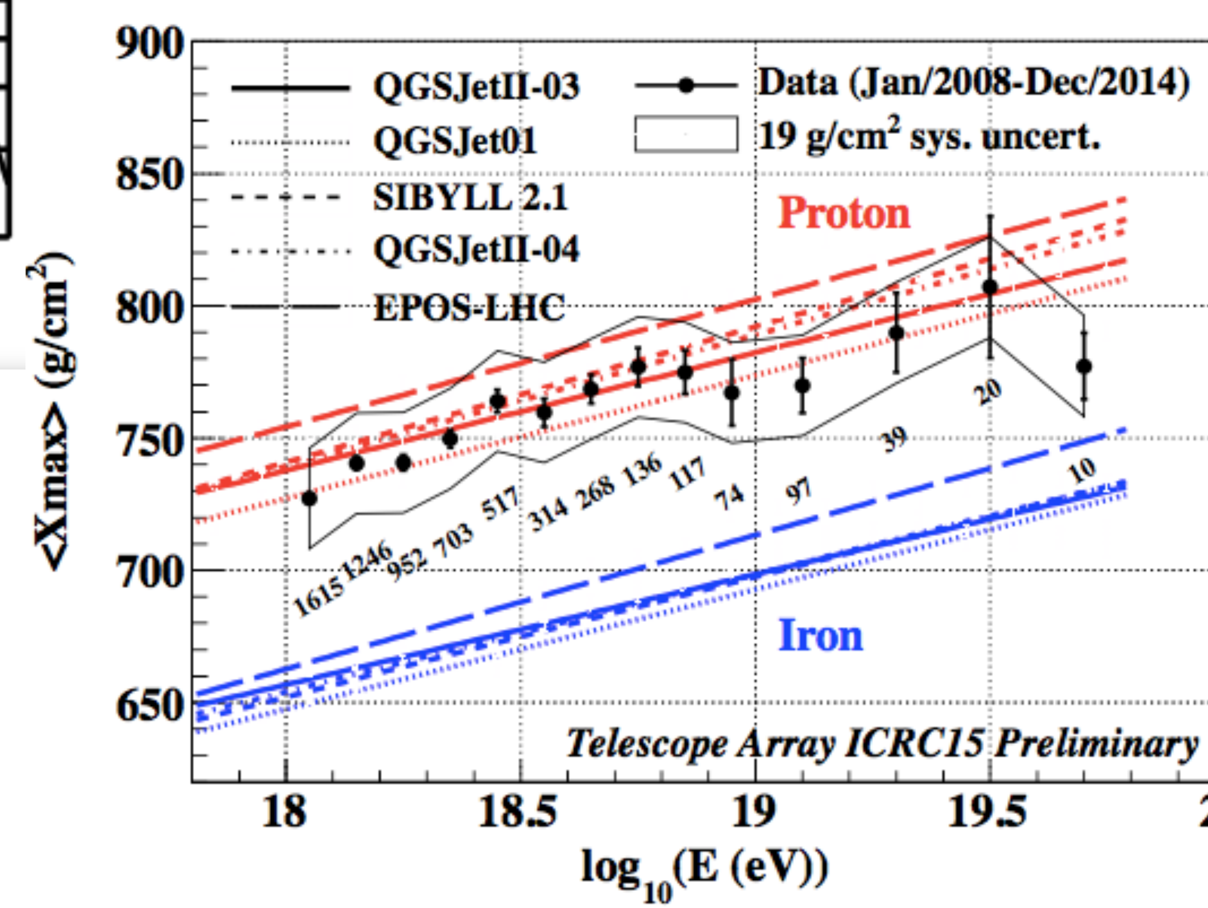
Telescope Array





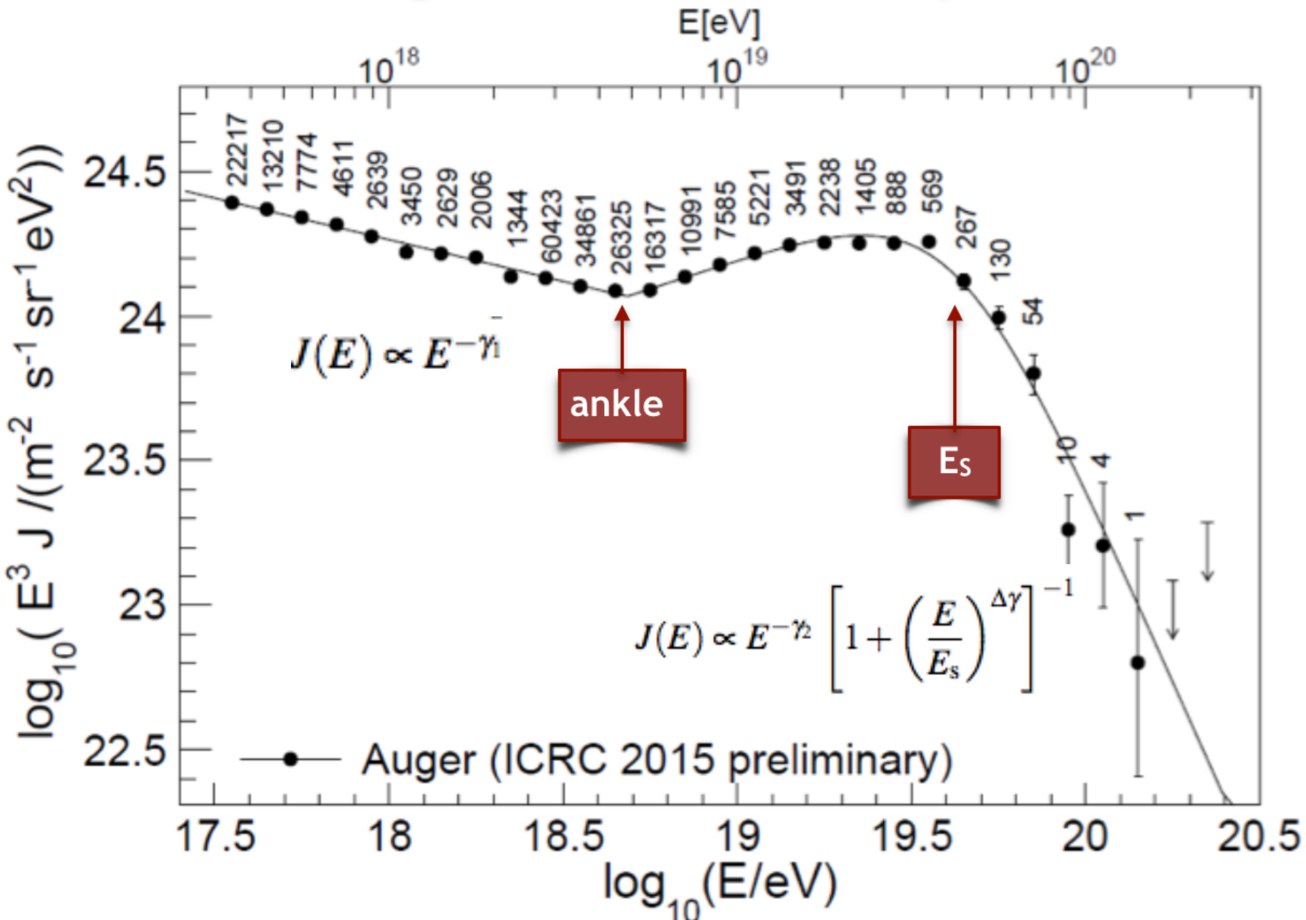
- 4.8 orders of magnitude spectrum, 4 spectral features
- thanks to TALE, a clear 2nd knee is visible at $10^{17.2}$ eV and a low energy ankle appears around $10^{16.25}$ eV

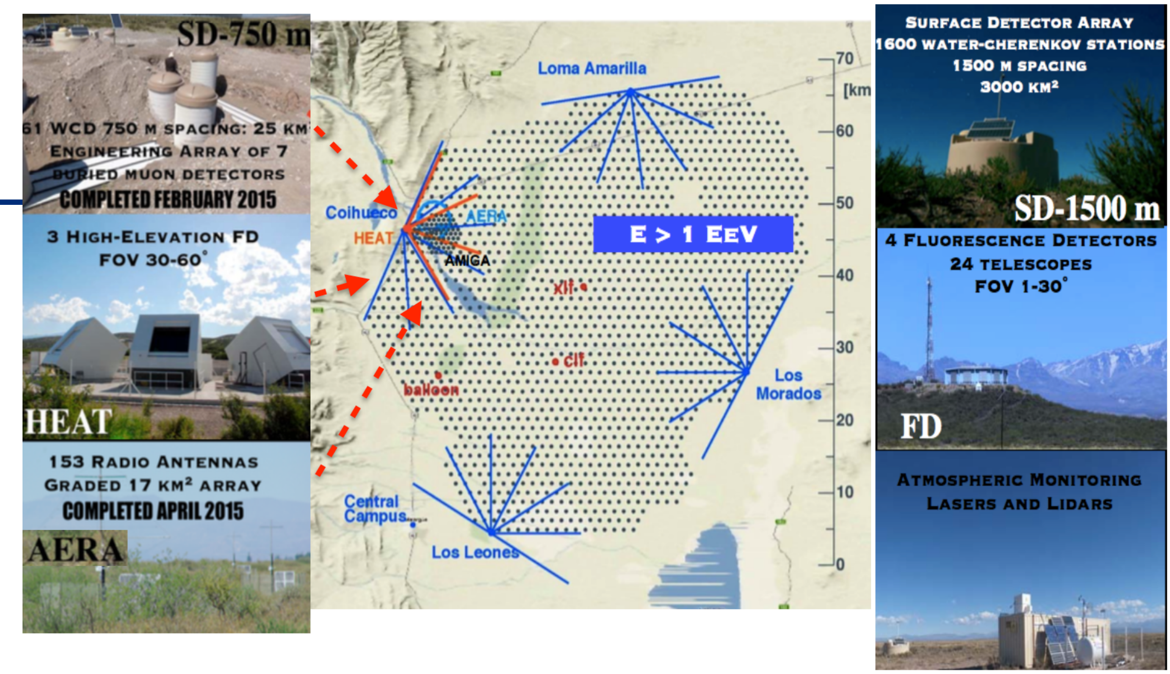
- knee for the heavy component ~7 10^{16} eV
- EG light component growing >4-5 10^{16} eV



The UHE region

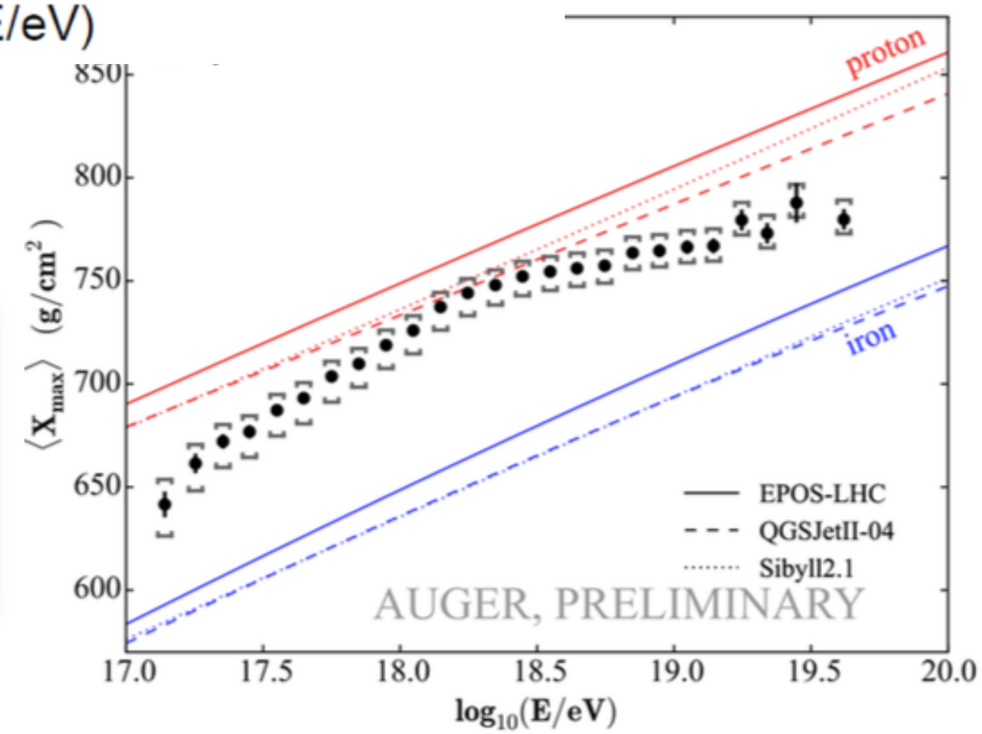
Pierre Auger Observatory

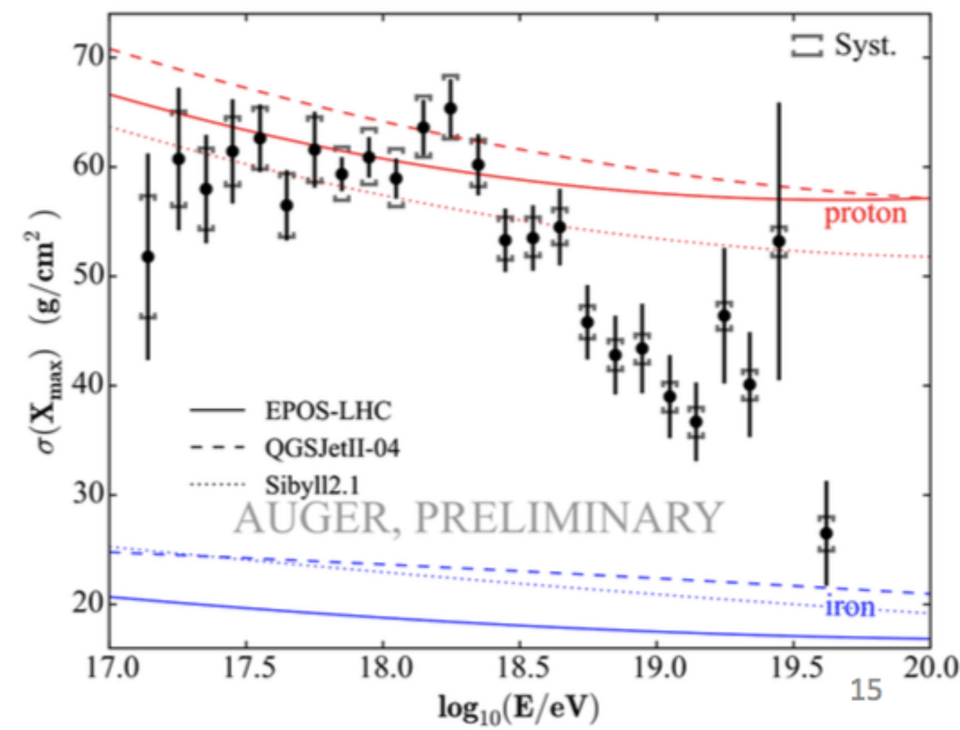




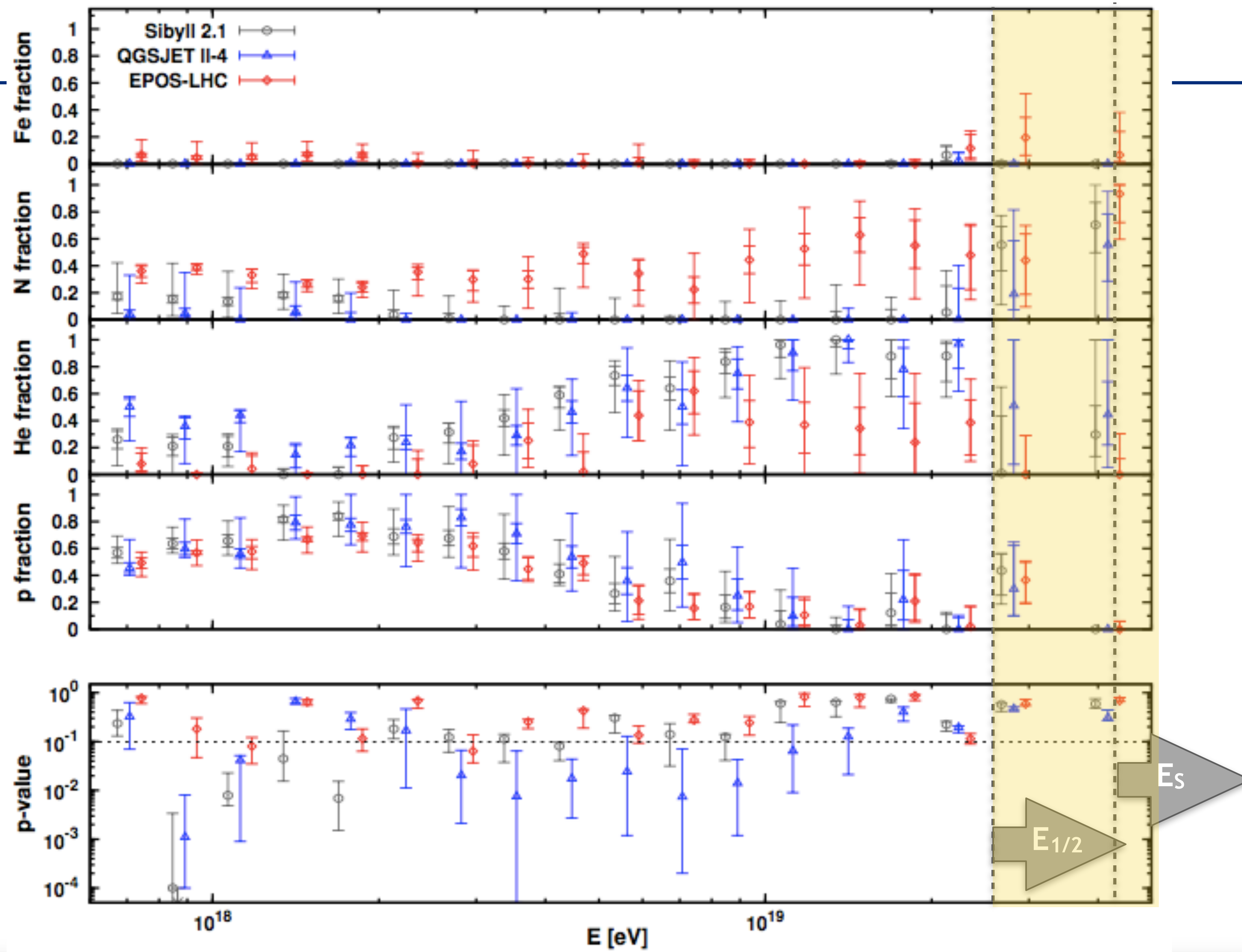
- ankle observed at E_{ankle}= **4.8 10^{18} eV**
- cut-off clearly observed (>20σ significance).
  $E_{1/2}$ = (2.48 ± 0.01)×10^{19} eV

- composition meas. extended to ~ 10^{17} eV thanks to HEAT
- **detector unfolded**





Pierre Auger



- **data better reproduced with a mixed composition**
- p fraction increases to >60% at the ankle, drops near 10^{19} eV, maybe rising again at higher energies —> but EG according to anisotropy limits !
- no significant contribution of Fe

The UHE region - interpretation

- Pure proton, E > $10^{18.2}$ eV
- Injection spectrum $E^{-\gamma}$, $E_{max} = 10^{21}$ eV
- Source density $(1 + z)^m$ (per comoving unit volume)
- Energy losses with CMB and IRB.
- Propagation code: TransportCR [checked by CRPropa]
- no magnetic fields

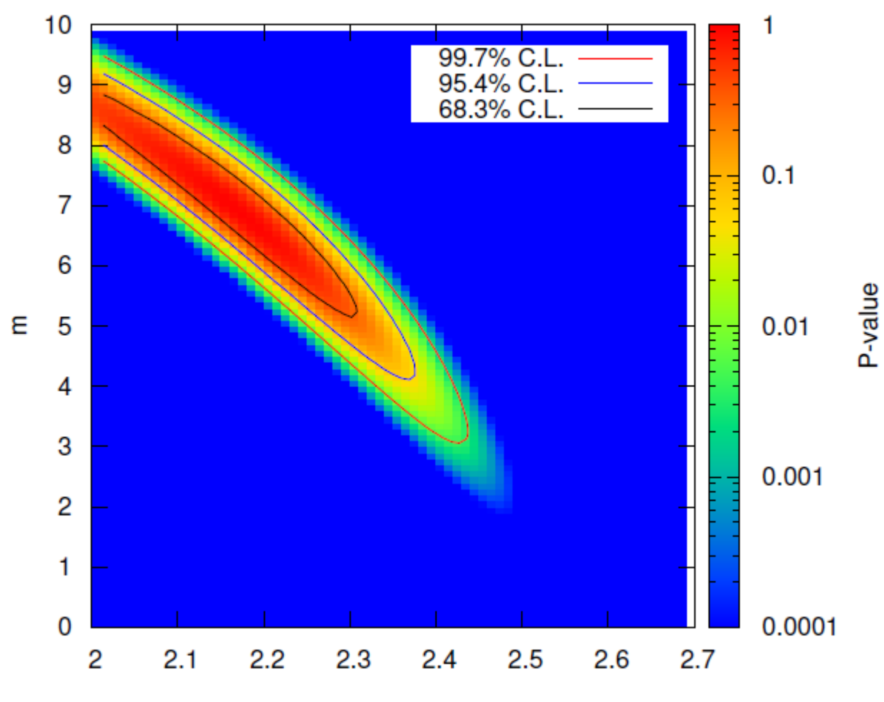
Telescope Array

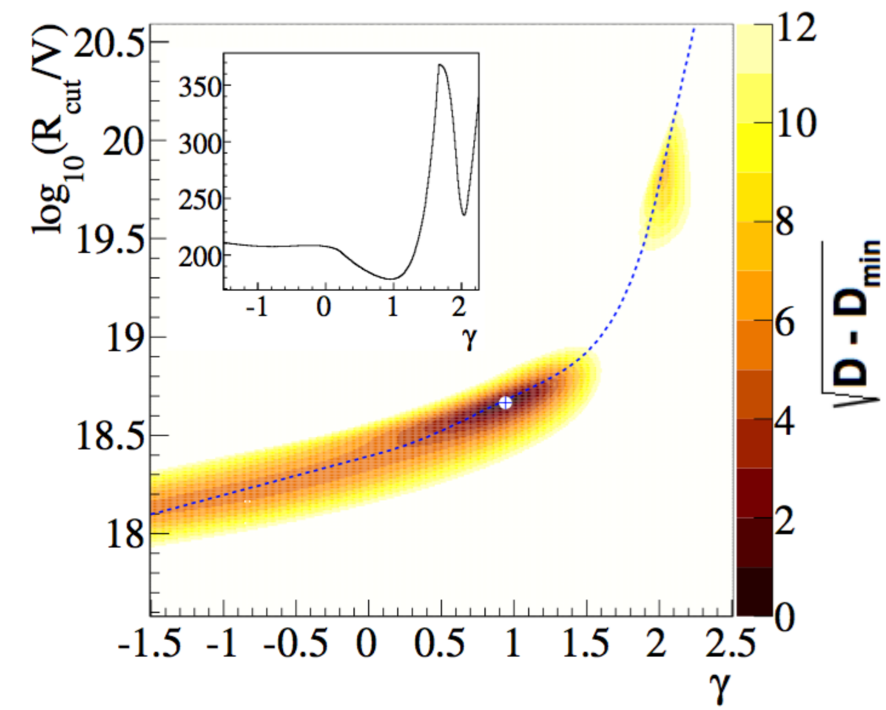
- identical sources homogeneously distributed
- Injection of H,He,N,Fe
- injection spectrum

$$\frac{dN_{inj,i}}{dE} = \begin{cases} J_0 p_i \left(\frac{E}{E_0}\right)^{-\gamma}, & E/Z_i < R_{cut} \\ J_0 p_i \left(\frac{E}{E_0}\right)^{-\gamma} \exp\left(1 - \frac{E}{Z_i R_{cut}}\right), & E/Z_i > R_{cut} \end{cases}$$

- Photodis.cross section + EBL (far IR)
- Propagation code: CRPropa,SimProp
- no magnetic fields

Pierre Auger Observatory

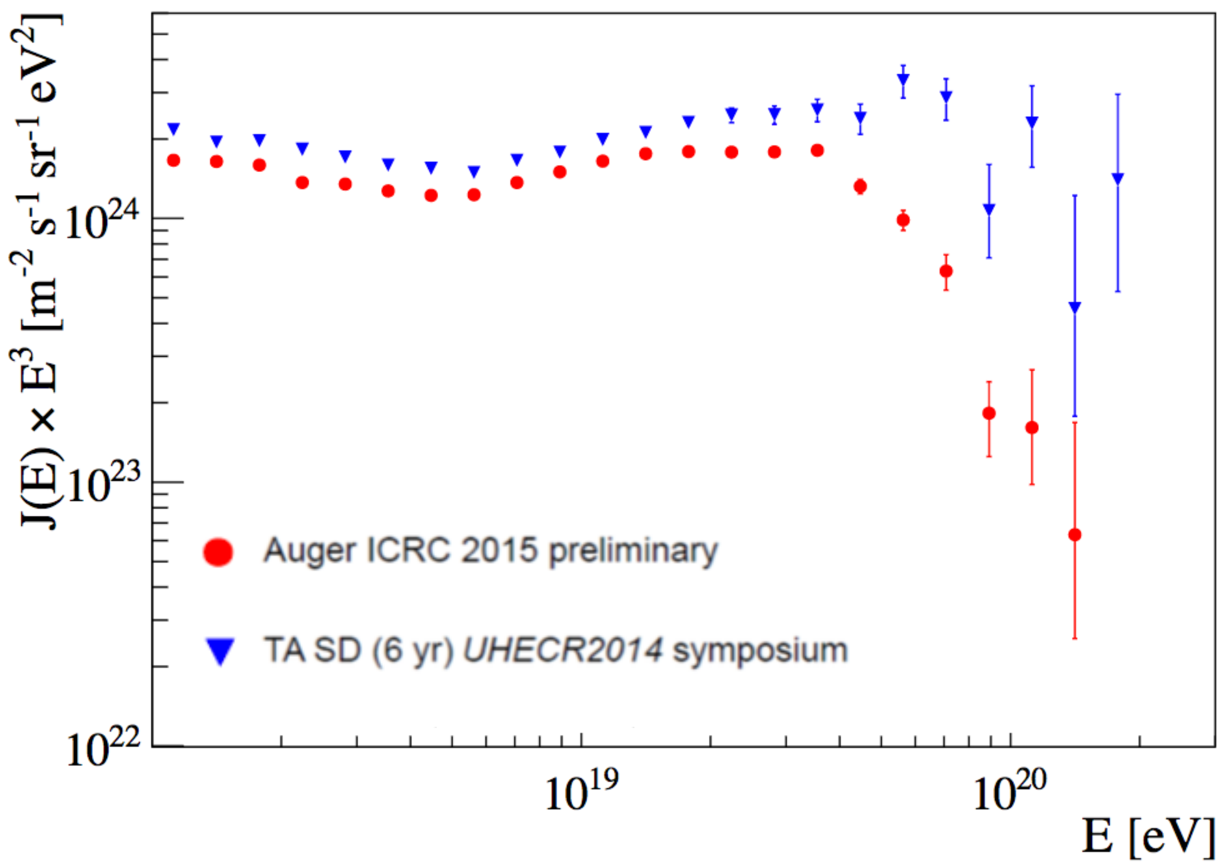




- data compatible with pure proton model
- γ= 2.18- 0.14 + 0.08 (stat.+sys.)
- suppression due to GZK cutoff

- hard injection (γ~1) and low cutoff (Rcut<$10^{18.7}$ eV) favoured
- γ~2 strongly disfavoured by X_{max} distribution width

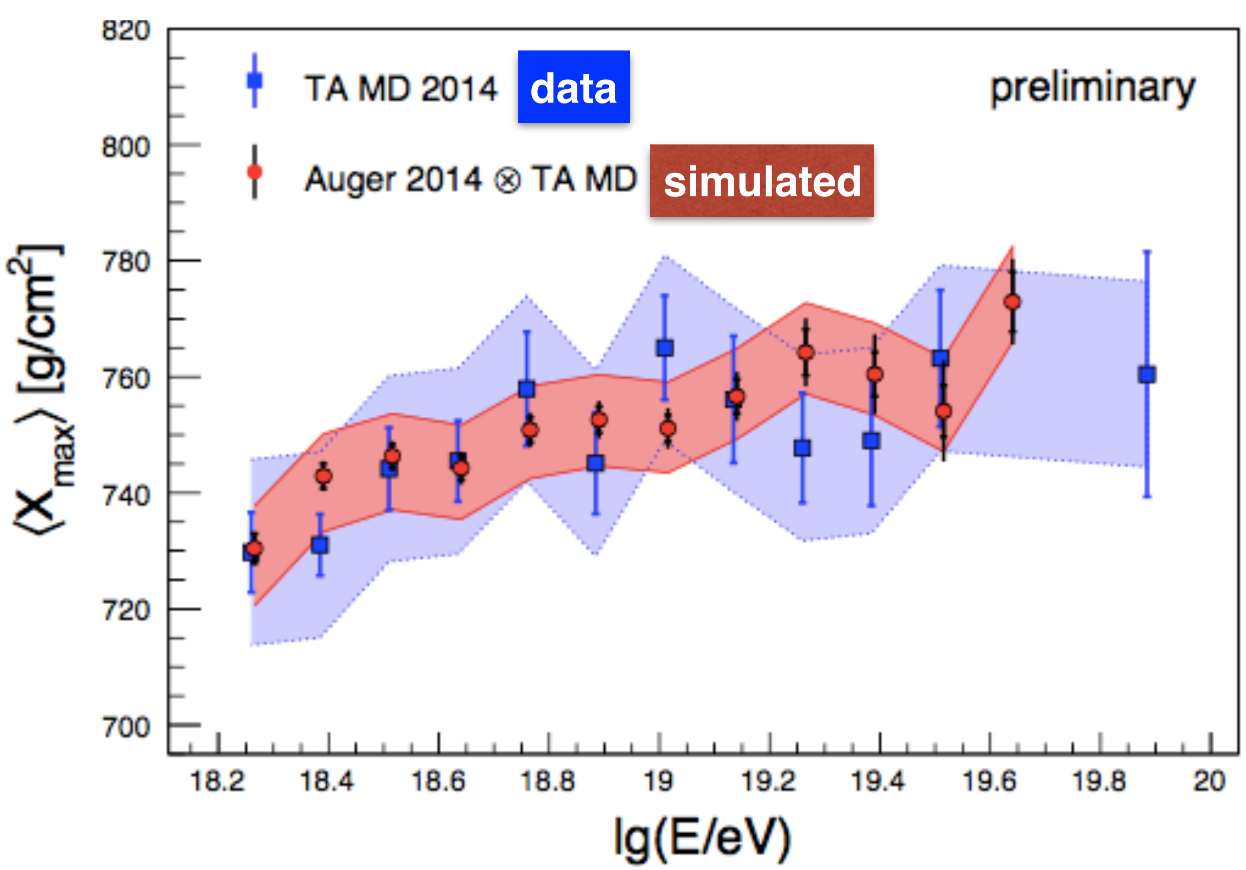
The UHE region - PAO and TA comparison



Energy spectrum

- very good agreement for E_{ankle}
- different interpretation for the suppression
- difference not due to different declination

	TA [16]	Auger [21]
E_{ankle} (EeV)	5.2 ± 0.2	$4.8 \pm 0.1 \pm 0.8$ (syst)
$E_{1/2}$ (EeV)	60 ± 7	$24.7 \pm 0.1\ ^{+8.2}_{-3.4}$ (syst)
$\Delta E/E$	21%	14%



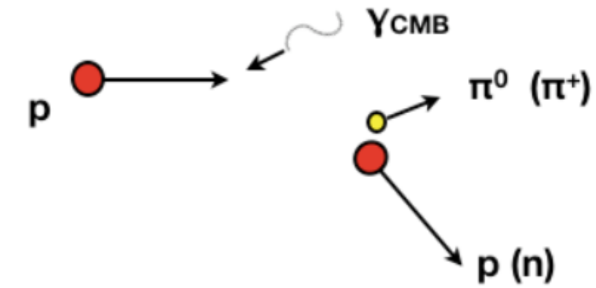
PAO Composition in TA reconstruction chain:

- TA reconstruction of events simulated according to PAO Xmax distribution
- average X_{max} agrees within uncertainties

TA cannot distinguish between "proton" or "Auger mixed" composition with the current level of uncertainties

Multimessengers

From primary p and heavy nuclei production, acceleration and propagation, we can expect neutral primaries

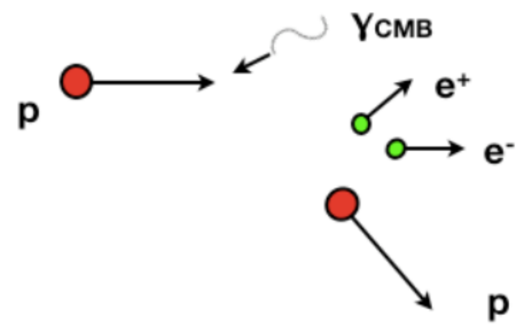


γ

- p pair production
- pion photo production ($E\gamma$ ~0.1E_p)
- neutron decay
- top-down models
- in EM cascades by pair production, inverse Compton scattering

Travel distance ~ 4.5/EeV Mpc

Galactic + EG



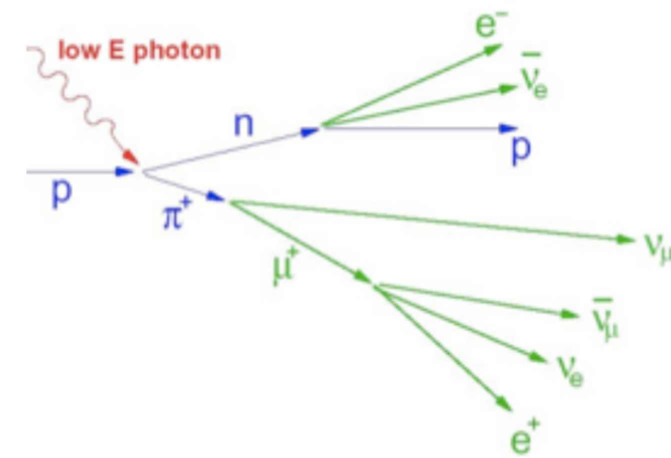
n

- pp interaction near the source
- pion photo production ($E\gamma$ ~0.8E_p)
- neutron decay
- neutron decay

τ~886 s

Travel distance ~ 9.2/EeV kpc

Galactic sources only

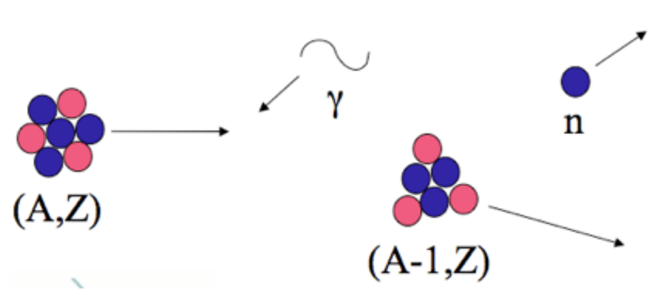


ν

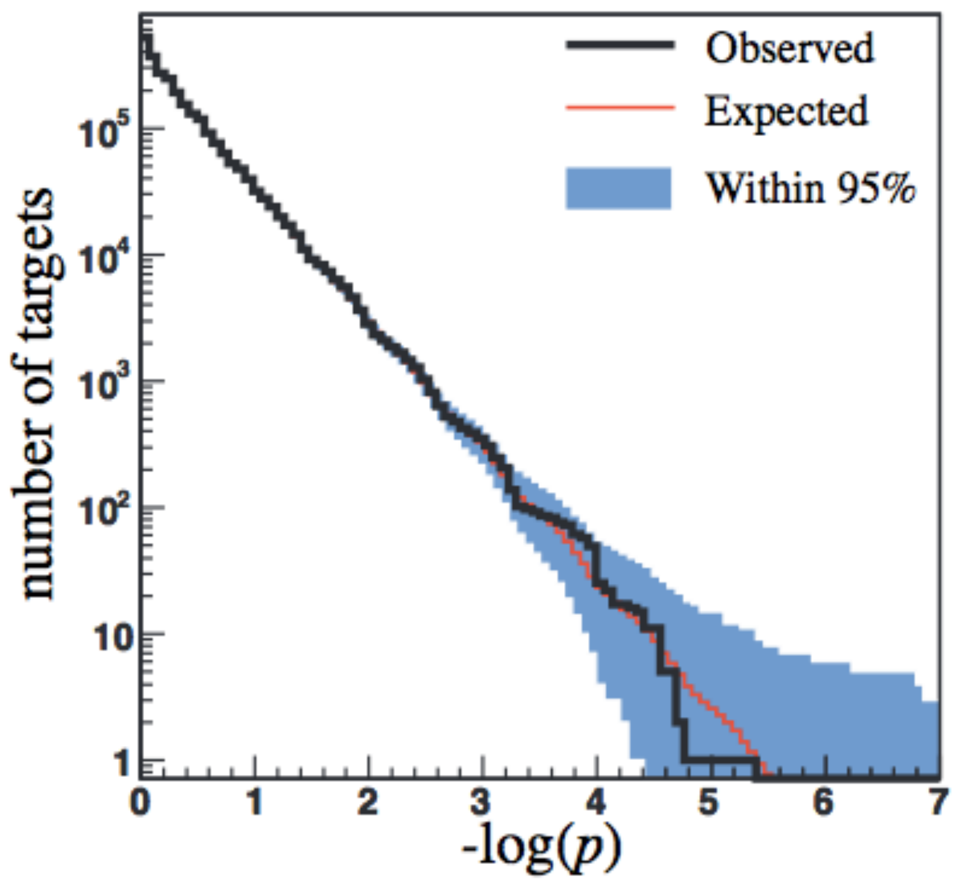
- pion photo production (UHE) ($E\nu$ ~0.05E_p)
- interactions within the sources (PeV)
- interaction with relic ν (Z-burst)
- top-down mechanisms

unattenuated

Up to cosmological distances



EeV γ and n point sources



Photon point sources

- Protons near the ankle produce photons ~ 1 EeV : can we find them?
- as the energy flux in TeV γ rays exceeds 1 eV cm^{-2} s^{-1} for some sources (CenA, GC) with this energy spectrum, we expect similar flux at EeV (as sources with spectrum ~ E^{-2} put the same energy flux/decade)

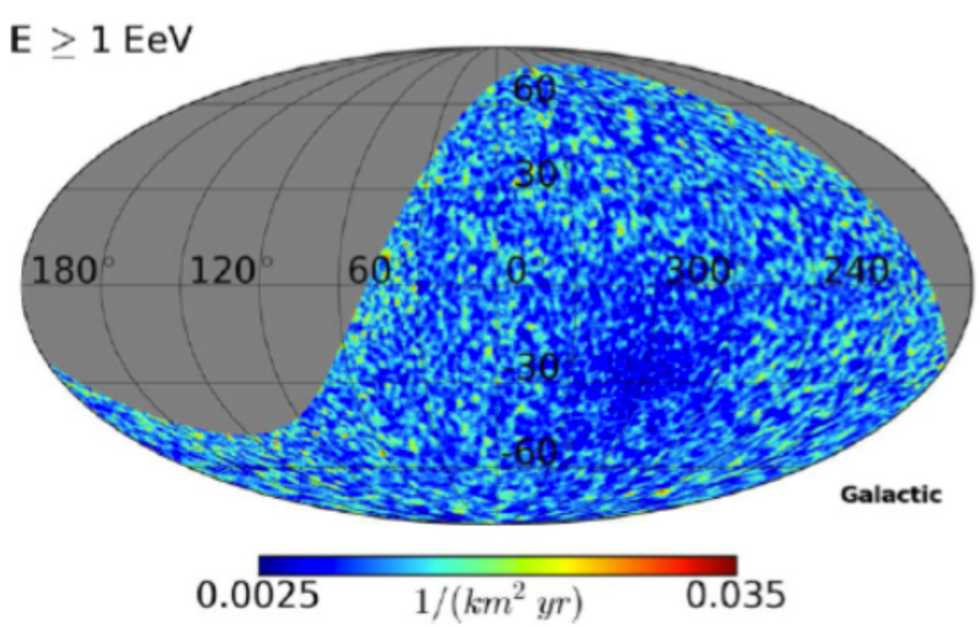
No point sources of EeV photons is found.
For $d\phi/dE \sim E^{-2}$

$\phi_\gamma < 0.25$ eV cm^{-2} s^{-1}

well below expectations

No Galactic sources of protons IF
—> they are not transient
—> they do not emit in jets towards Earth
—> they are too faint

[Aab et al., ApJ 789 (2014) 160]



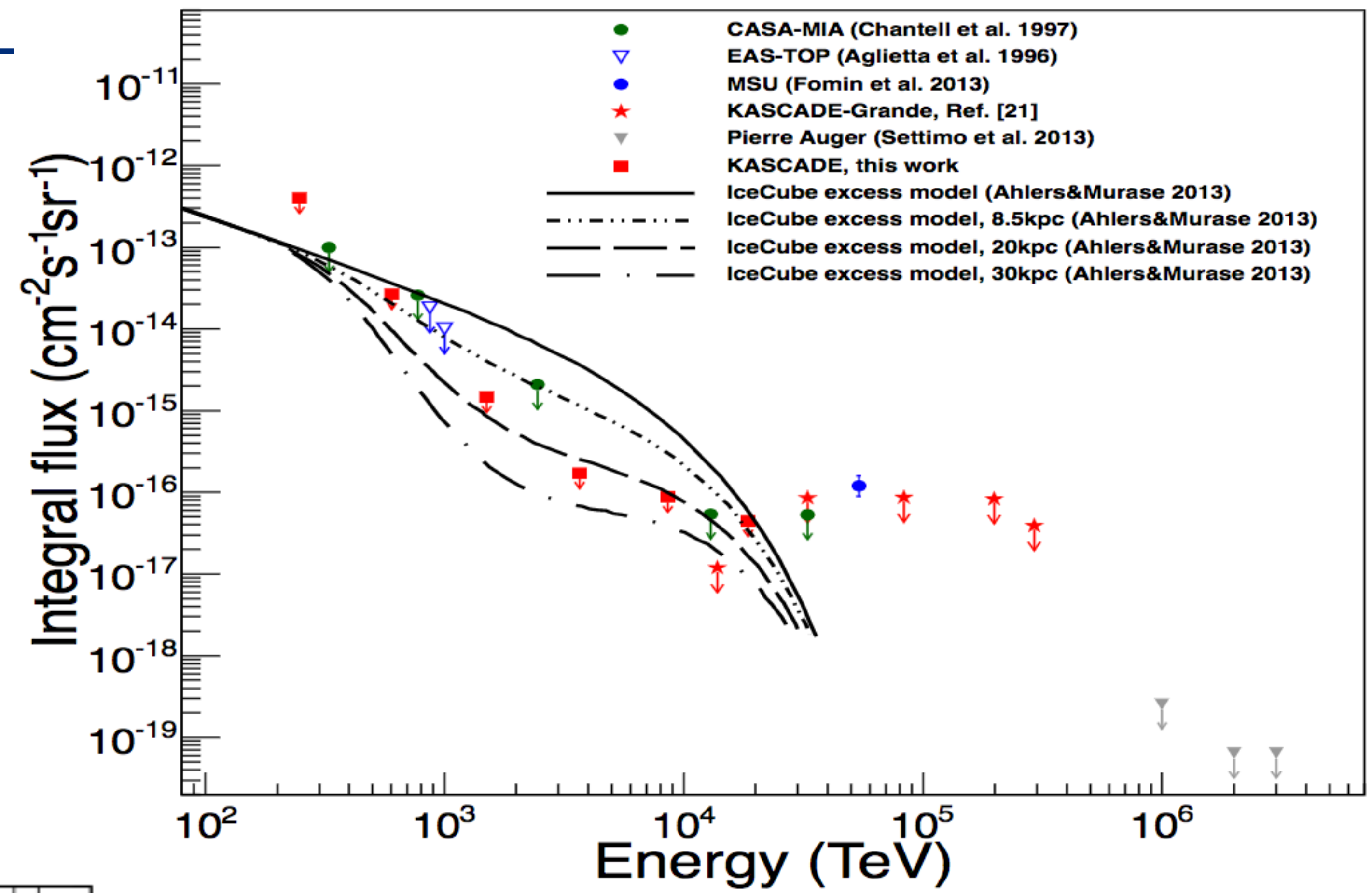
Neutron point sources

No candidates found:
For an E^{-2} neutron spectrum
0.083 eV cm^{-2} s^{-1}

Sources could be extragalactic transient emitting in jets too weak or too thin ….

[Aab et al., ApJL 789 (2014) L34]

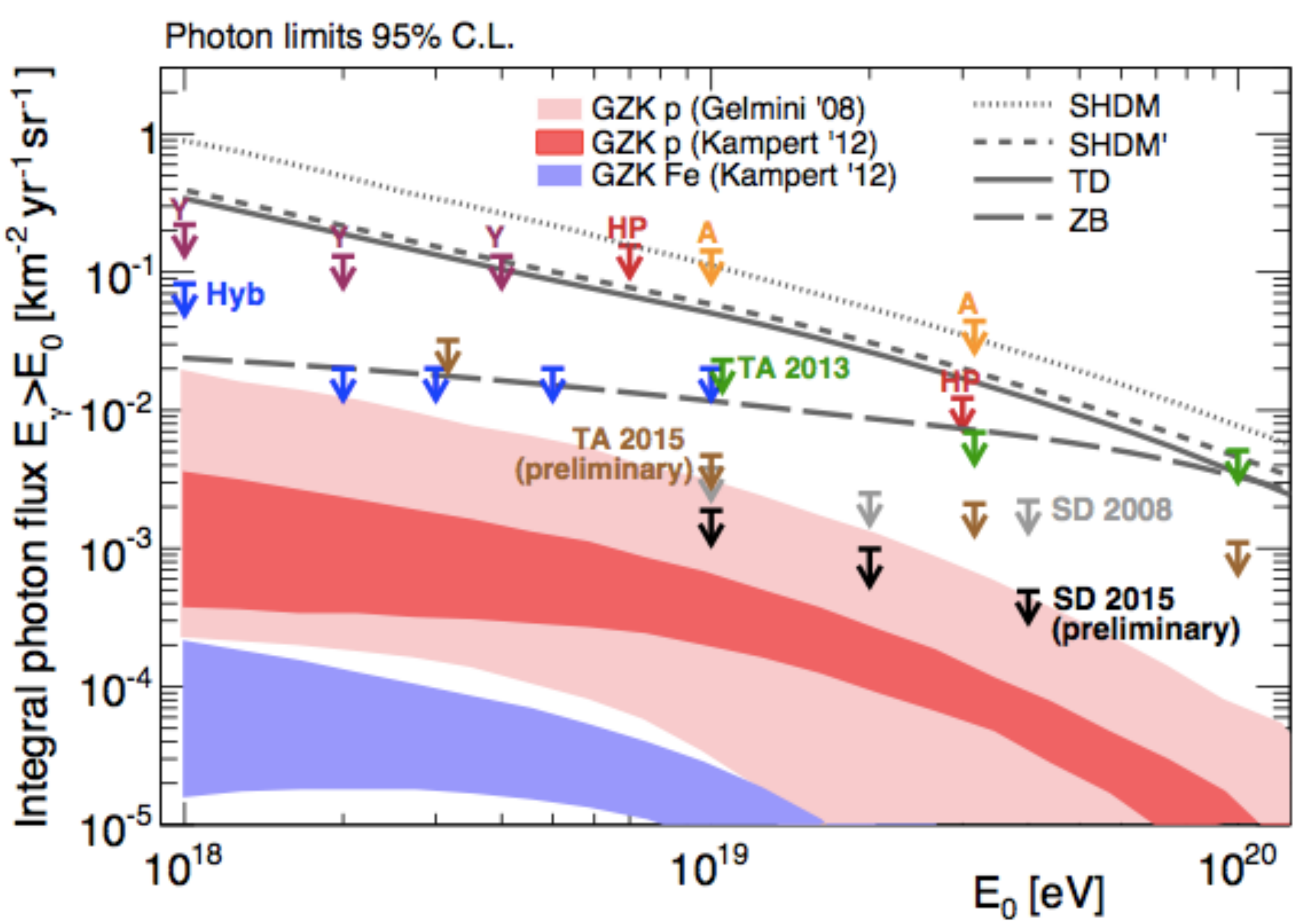
Photon flux



VHE

- new upper limits from Kascade-Grande
- the limits on TeV to PeV diffuse γ-ray flux can set constraints on the galactic or EG origin of the IceCube excess

[K.Feng et al., ICRC2015]

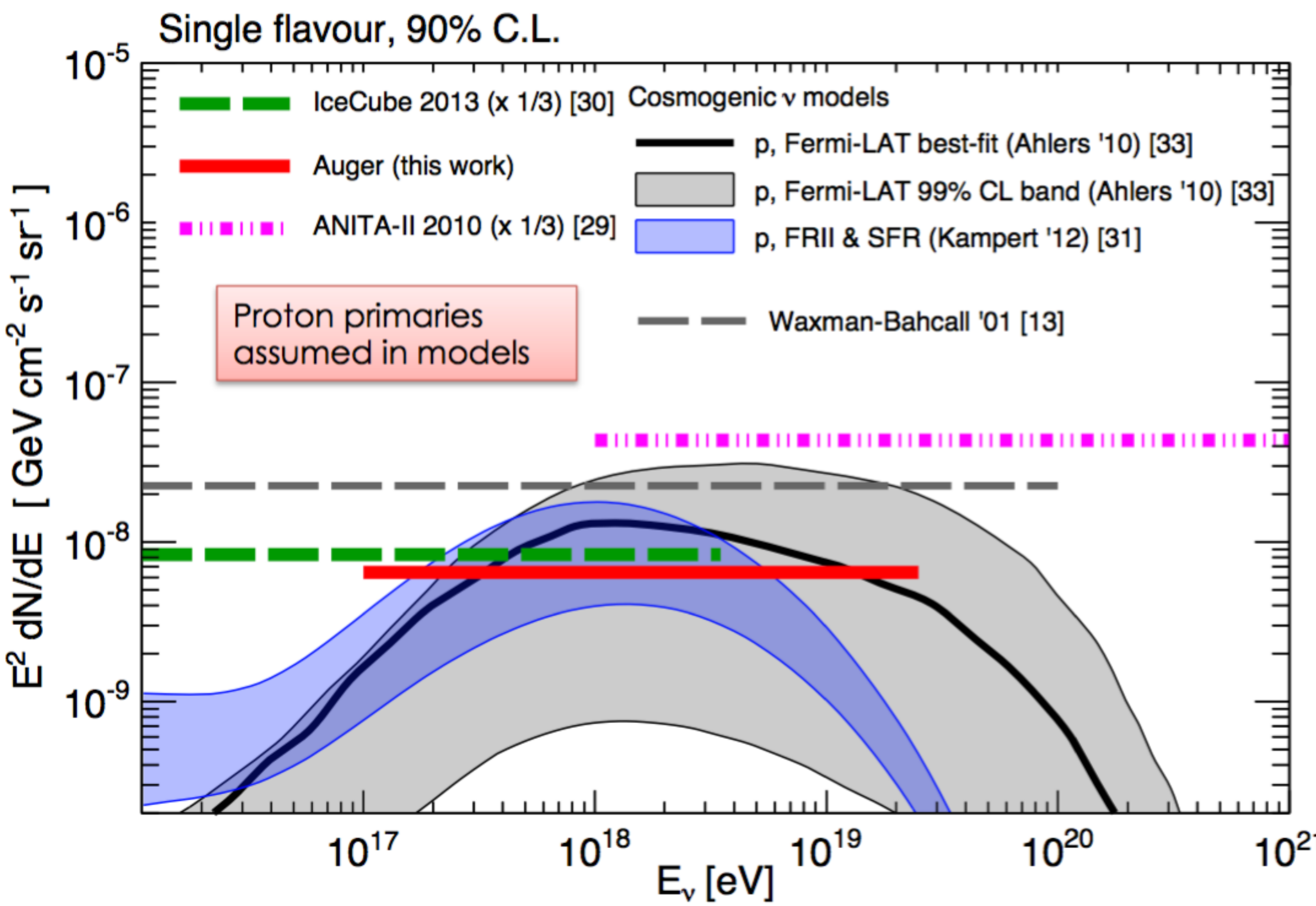


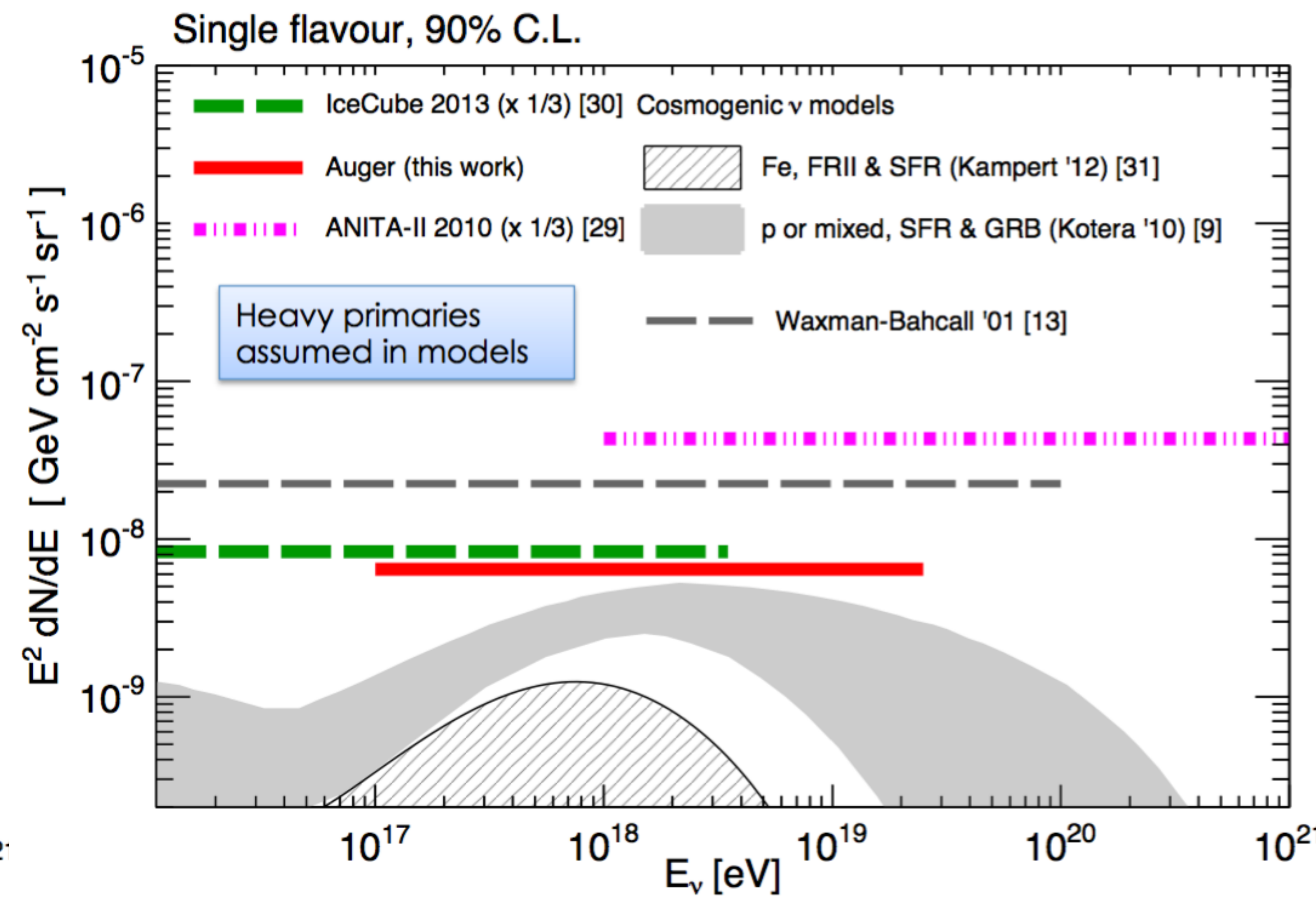
UHE

- top-down models highly disfavoured
- first constraints to the most optimistic predictions for cosmogenic photon fluxes
- 4 times lower or 2 order of magnitude fluxes are predicted for p or Fe primaries if γ_{inj}~-2 and Emax~10^{21} eV at the sources
- observations cover both hemispheres

[C.Bleve et al., arXiv:1509.03732]

ν detection in EAS arrays





- maximum sensitivity where cosmogenic ν flux peaks
- first EAS detector reaching factor ~4 below WB
- strong constraints to models with proton primaries and strong evolution with redshift

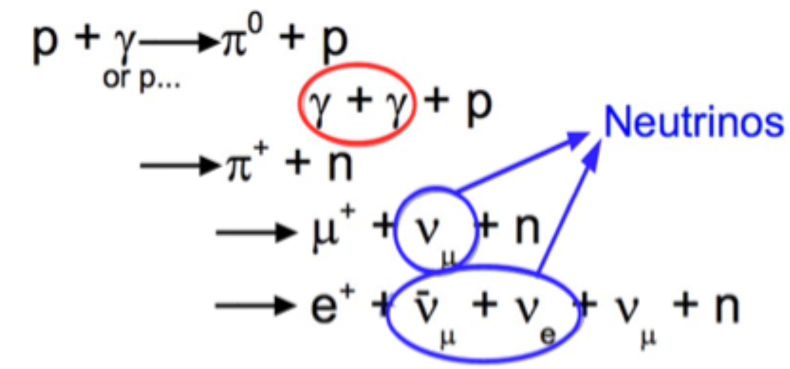
Auger data do not yet constrain neutrinos from heavy primaries

- search limited by exposure

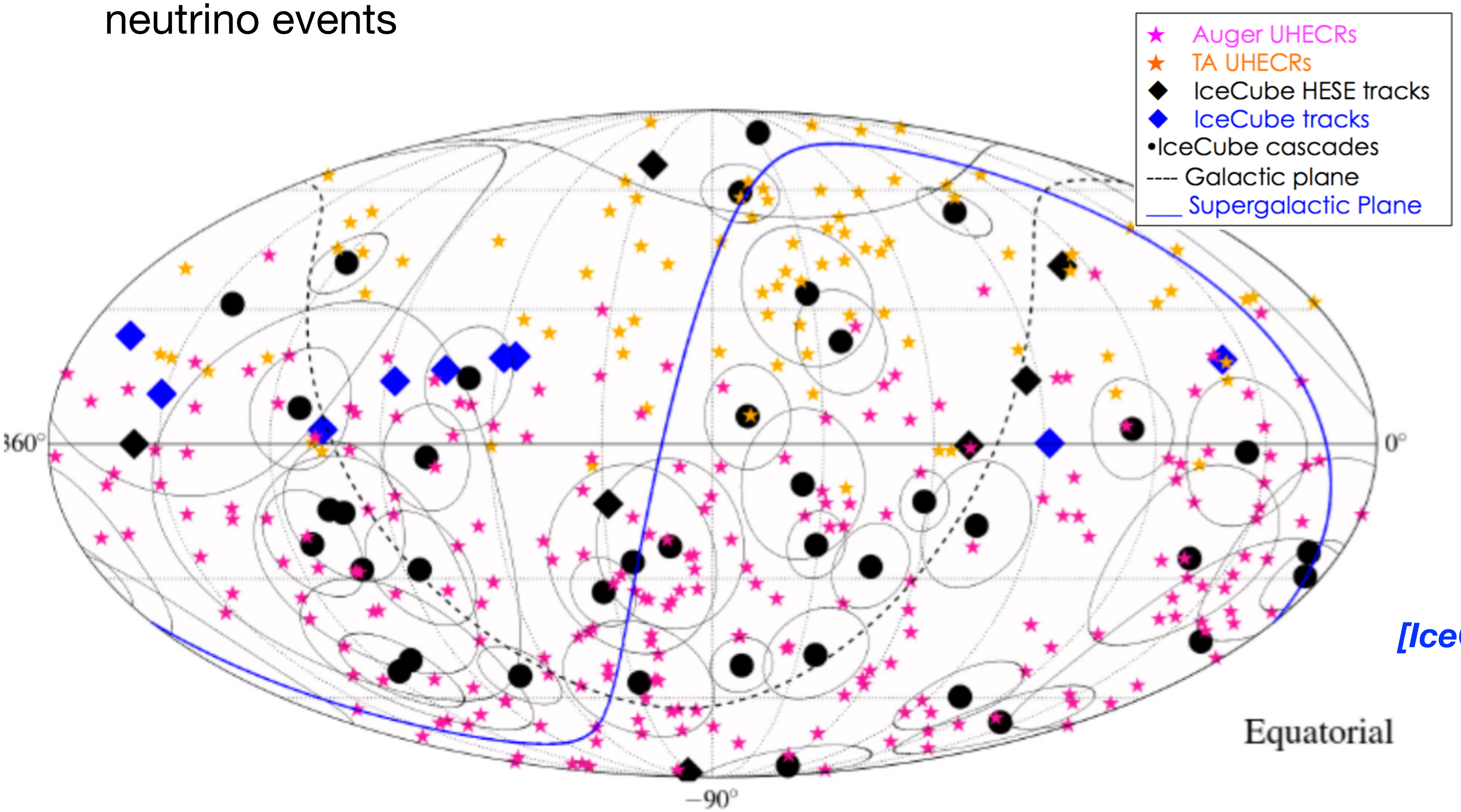
[A.Aab et al., PRD91 (2015) 092008]

Neutrinos and UHECRs

- HE extraGal. neutrinos can be produced by protons of 10^{15}-10^{17} eV
- sources of UHECRs >50 EeV can produce also lower energy CRs



Different analyses are employed to investigate the possible correlations between 318 UHECRs in Auger+TA with IceCube neutrino events



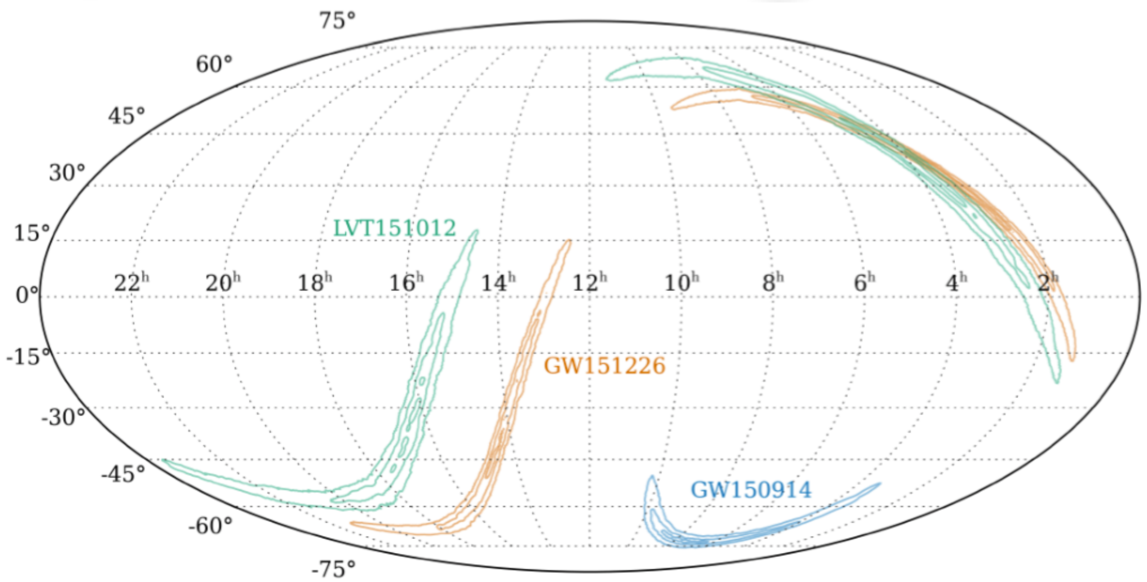
- ***all results below 3.3σ***
- *with IC cascades: correlation analysis: p 5×10^{-4}, at angular scale $\sim22^0$*
- *higher correlations in the region of TA hot spot an close to the Supergalactic Plane (PAO warm spot)*

[IceCube, TA, Auger Coll., JCAP 01 (2016) 037]

But

- if suppression of UHECRs flux due to GZK, maybe just a % fraction of HE neutrinos come from the same (nearby) sources producing UHECRs
- if burst-like sources, neutrinos arrive long before UHECRs, correlation not feasible
- sources producing HE neutrinos could be unable to produce UHECRs

UHEν follow-up of GW events



GW150914 & GW151226

- merger of binary black holes
- 3 and 1 M⊙ released in GW
- D_{GW} ~ 410 and 440 Mpc
- position few 100 deg^2

[LIGO & Virgo Coll., PRL116 (2016) 061102 and 241103]

Em counterpart improbable, but
- Fermi GBM: transient source at 50 keV, 0.4s delay wrt GW150914 [V.Connaughton, arXiv:1602.07352]
- different models predict UHE neutrino production

Auger neutrino selection
- evt +/- 500 s around GW evt
- evt +1 day after GW evt (GRB afterglow in UHE ν)

No UHE neutrino candidate found

Limits on radiated energy in UHEν (declination dependent) at E>10^{17} eV

- *< (0.5, 3) M⊙ released from both GW150914 and GW151126*
- *first limit in EAS*

[Auger Coll., arXiv:1608.07378, subm.PRD]

Example:

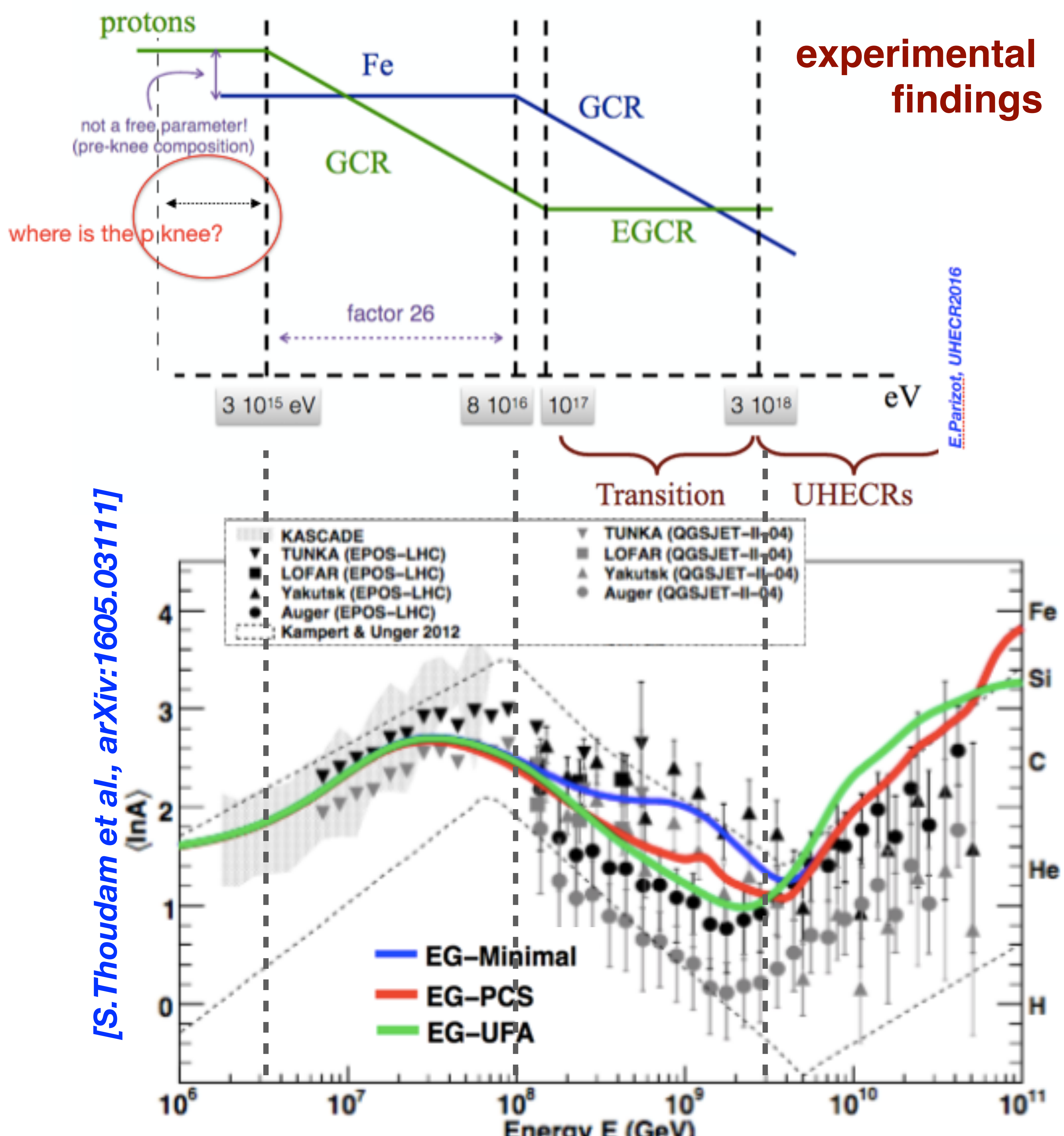
UHECRs and neutrinos from BH-mergers
[K.Kotera & Silk, ApJL823 (2016) L29]

Transient sources can provide an environment for production and acceleration of UHECRs,

- ✓ rare transients (~ 1 Gpc^{-3} yr^{-1}) could be enough to produce a dense population
- ✓ BH mergers should be surrounded by metal-rich debris and able to accelerate heavy nuclei

Constraints from Pierre Auger:
- limit on source number density **[P.Abreu et al., JCAP 1305 (2013) 009]**
- heavier composition at UHE **[A.Aab et al., PRD90 (2014) 122006]**

The current view



Conclusion

Galactic Cosmic Rays

✓ all experiments see the *all-particle knee ~3-4 PeV*
✓ *ARGO, Tibet: proton knee at ~700 TeV*
✓ *Kascade-Grande, Tunka : E_{knee}(p) ~3 10^{15} eV and E_{knee}(Fe)=26 x E_{knee}(p)~80 PeV*

but

- analysis based on indirect extraction of information from EAS: strong dependence on models of hadronic interactions
- different definition of elemental groups
- difficult evaluation of systematic uncertainties

Open issues

Revision of ideas about particle acceleration up to PeV?
Is there an additional component of GCRs?

Transition region and above

✓ *Kascade Grande: E_{knee}(Fe)~8 10^{16} eV, light hardening ~10^{17} eV*
✓ *IceTop measurements up to ~10^{17} eV: too large fraction of iron*
✓ *constraints on elemental fractions from Auger >6 10^{17} eV*
✓ *PAO, TA good agreement in the ankle region,* ***different interpretation of suppression***
✓ *PAO, TA* ***different conclusion on composition,*** *but agreement within systematics*
✓ *constraints from Auger LSA UL*

- **proton dip, ankle, mixed composition models are the main alternatives**

Open issues

can we dismiss the dip model ?
is the suppression due to propagation or source effects?

multimessengers needed

Example : the dip model

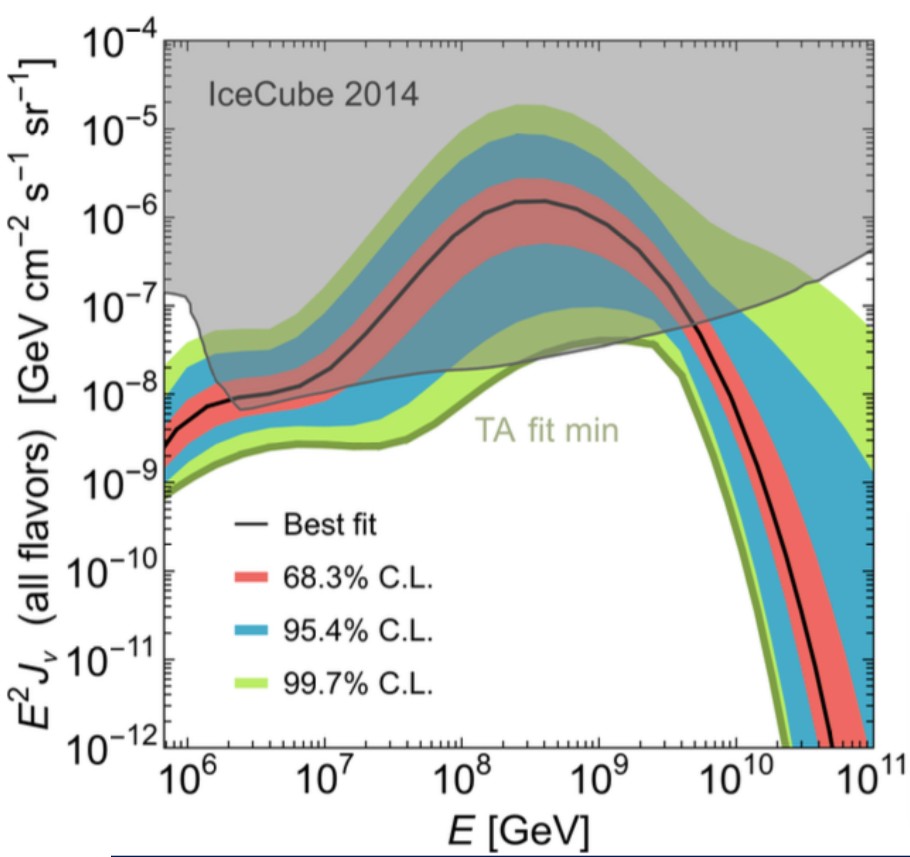
Signatures

- ✓ proton composition
- ✓ ankle and $E_{1/2}$
- ✓ measure of the cosmogenic ν flux
- ✓ measure of the diffuse γ flux

Serious problems

- ✓ Auger composition (~40% p below ankle)
- ✓ hard spectra and low cutoff suggested by Auger spectrum+comp
- ✓ measure of the cosmogenic ν flux (IceCube)
- ✓ measure of the diffuse γ flux ***[(Fermi-LAT, ApJ799 (2015) 86]*** *but see also arXiv:1606.09293)*

Multi-messenger approach to break the degeneracy wrt models of the spectrum alone and to reach conclusion independent of composition



UHECR spectrum from TA + IceCube limit on cosmogenic neutrinos

[J.Heinze et al., arXiv:1512:05988]

Test of dip model : UHECRs $>10^{19}$ eV are EG protons with a **3D parameter space scan**

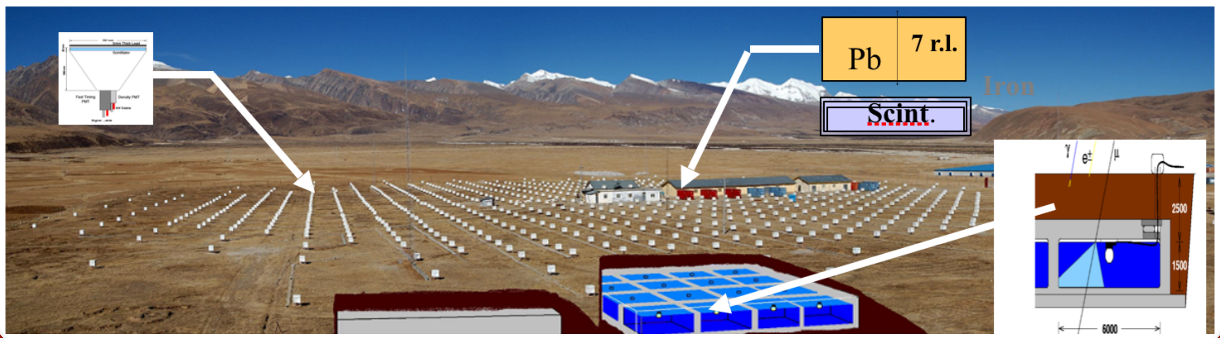
[$\gamma_{injection}$, E_{max}(p), source evolution parameter m]

- the minimum "TA allowed" cosmogenic ν flux is in tension with IceCube upper limit at more than 95% CL
- hard spectra, strong source evolution and low Emax(p) are favored wrt the GZK scenario
- the proton dip model is strongly challenged

Future - 1

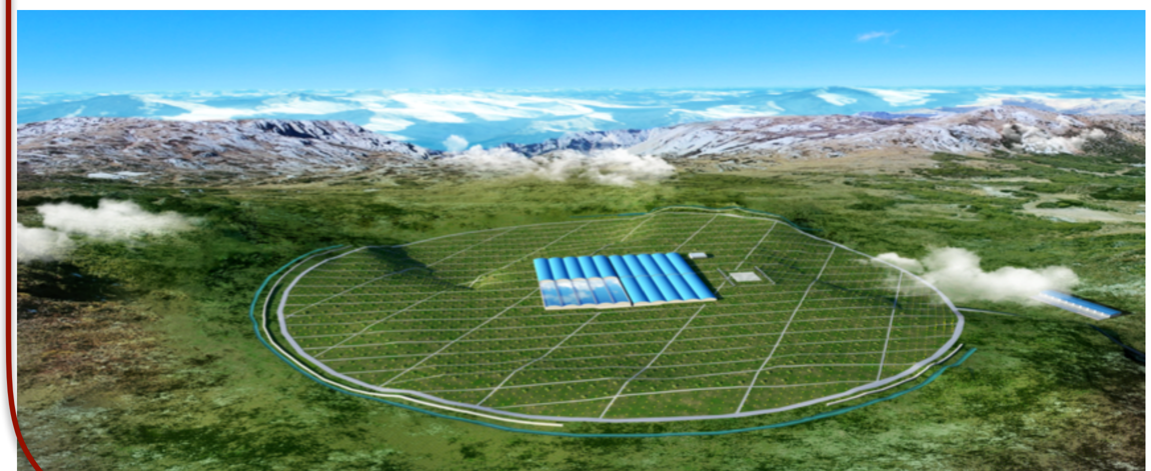
hybrid Tibet experiment

- high accuracy in the light spectrum determination between 50 TeV and 10 PeV accurately..
- energy resolution at 1 PeV better than 12%
- expected systematics on the flux ~30% (mostly from hadr.int.model dependence)



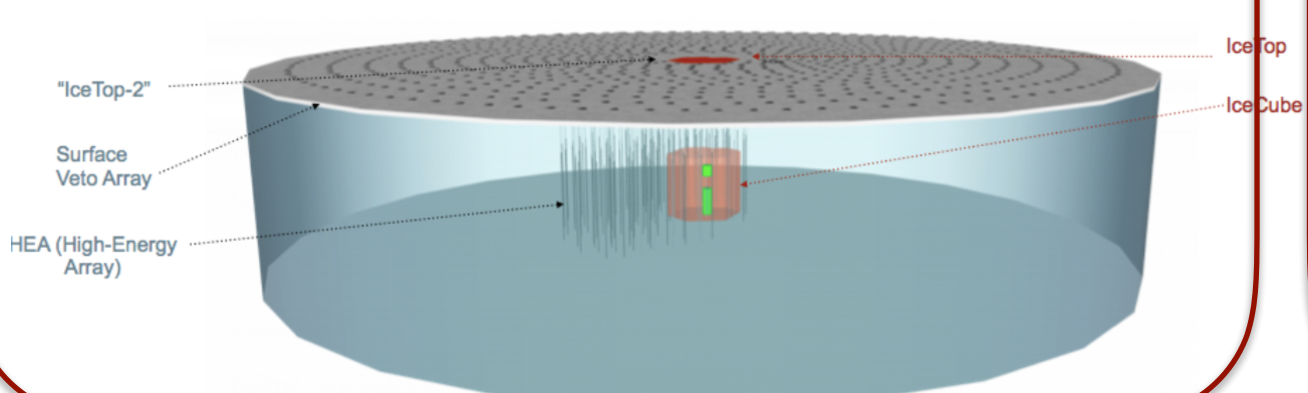
LLHASO

- 1 km2 hybrid array at 4410 m asl
- gamma ray astronomy
- cosmic rays from 300 GeV to 1 PeV
- Cherenkov+fluorescence telescopes



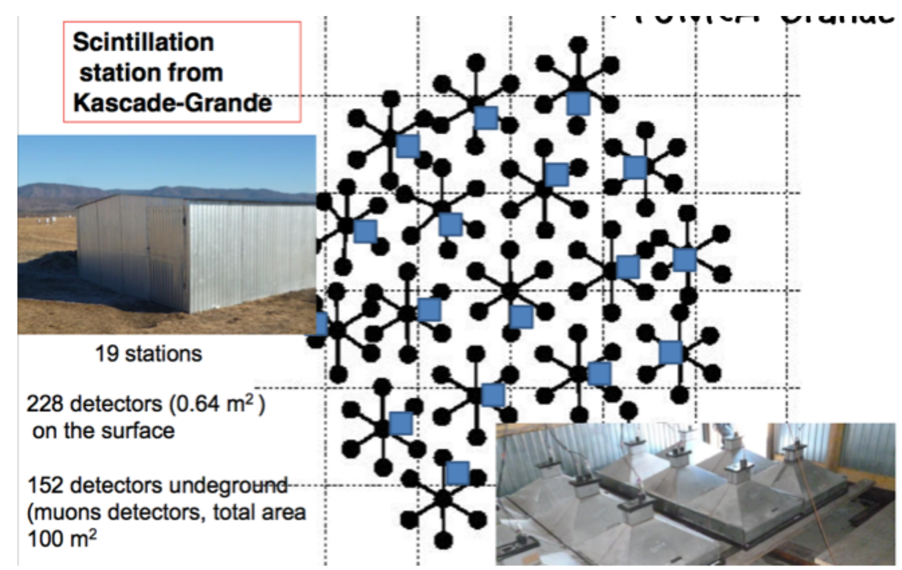
IceTop-2

- 10 km^3 in-ice array with 10 km^2 IceTop-2 on top
- energy range increased by a factor 3
- coincident events increased by factor 50
- 100 km2 veto EAS array (muon LDF)



Tunka-Grande

- Tunka-133 + 228 detectors of Kascade-Grande + 152 underground muon detectors



Future -2

AugerPrime *[arXiv:1604.03637]*

- ✓ Origin of the flux suppression and mass composition at UHE
- ✓ proton contribution >10% above $6x10^{19}$ eV, particle astronomy?
- ✓ explore particle physics beyond the reach of LHC

by

- ✓ extension of the composition measurements into the extreme energy range above 5×10^{19} eV
- ✓ increase of data quality (timing, dynamic range…)
- ✓ extension of FD on-time

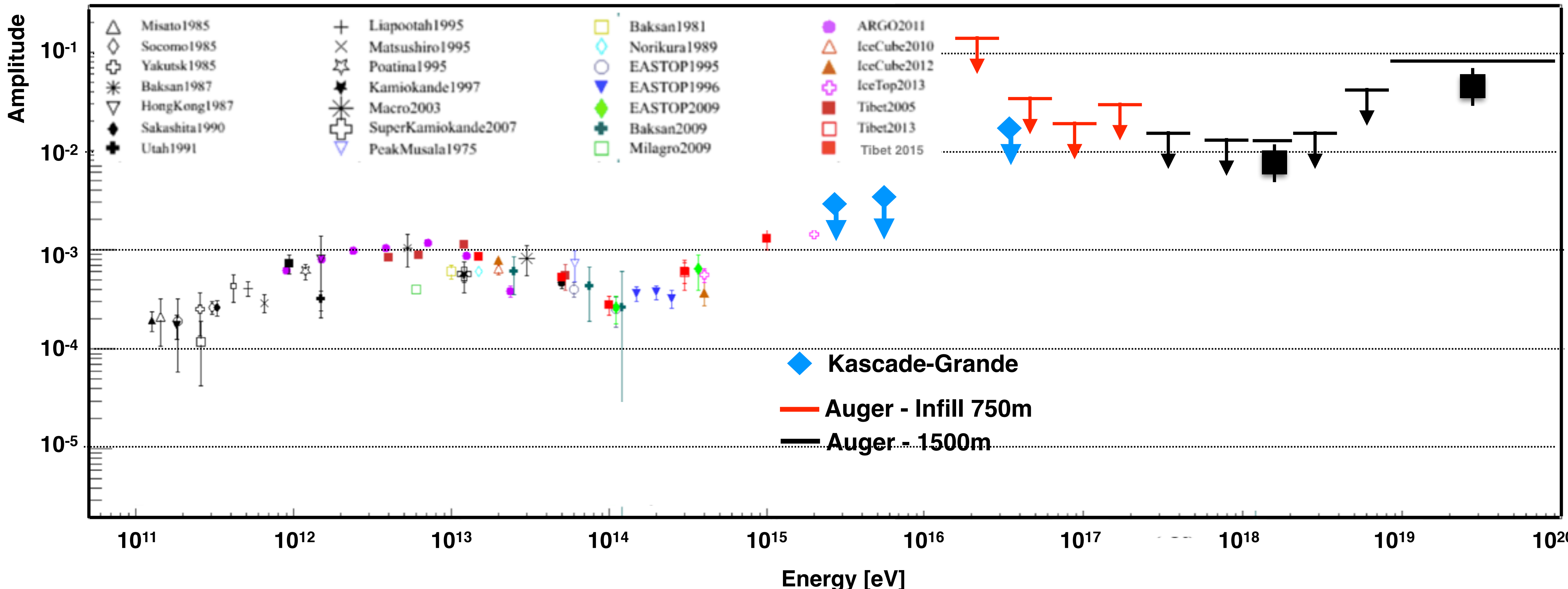
TAx4 *[E.Kido, UHECR2016]*

- ✓ Origin of the flux suppression and mass composition at UHE
- ✓ confirm the hot spot with >5σ significance
- ✓ search for point sources
- ✓ extension of statistics for composition at UHE
- ✓ flux limits on UHE γ and ν

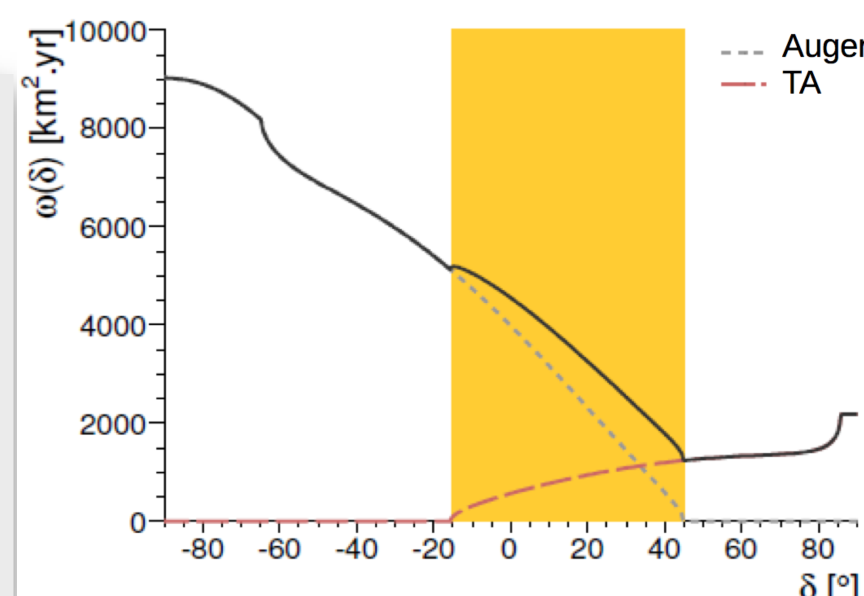
500 additional scintillato counters, 2.08 km spacing + 2 new FD
~3000 km^2 area

BACKUP SLIDES

Large Scale Anisotropy



- low amplitudes over a wide range of energy: hint for a crossover between GCRs and EGCRs;
- around 1 EeV, the isotropy hints to an extragalactic origin of CRs
- indication for LSA
  - ✓ at E>8 EeV from Auger : dipole amplitude 7.3±1.5% pointing to (a,d)=(95°±13°,-39°±13°)
  - ✓ in a joint analysis Auger-TA at E>10 EeV : 6.5±1.9% with (a,d)=(93°±24°,-46°±18°)



Small Scale Anisotropy

Auger

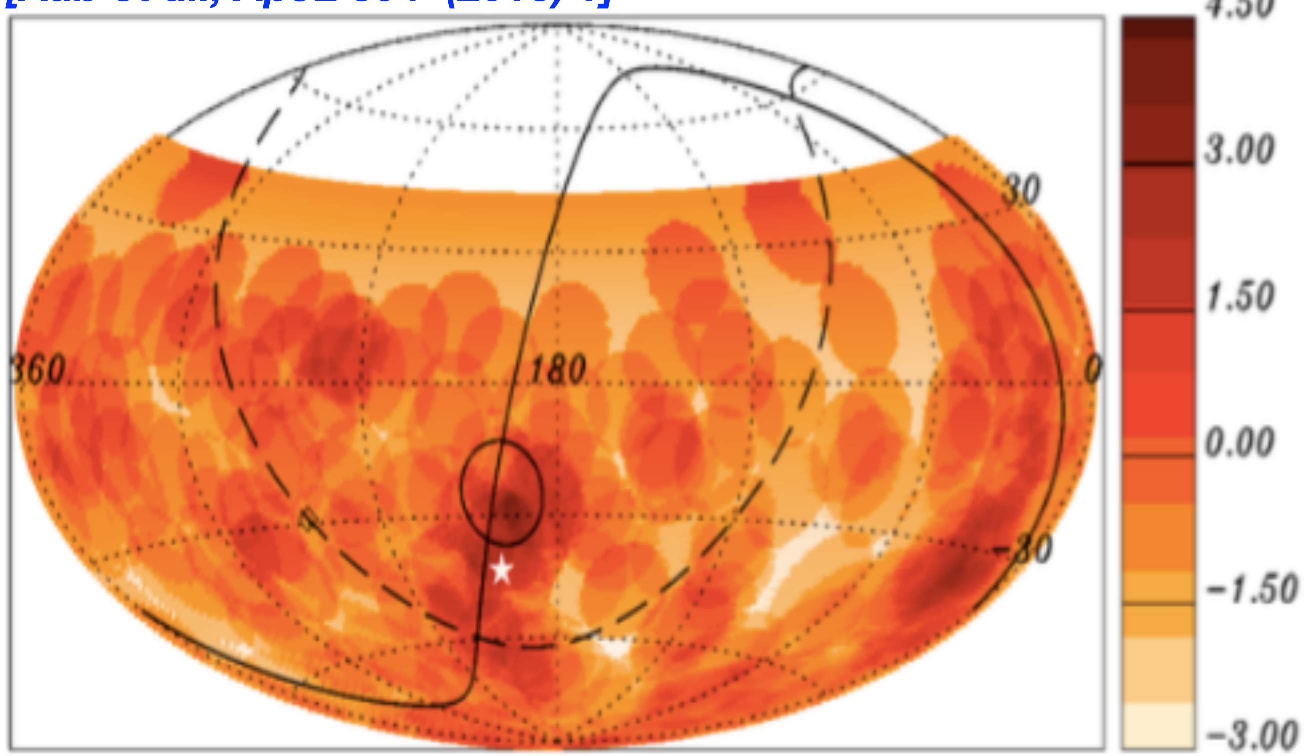
- $r = 1^o - 30^o$, $\Delta r = 1^o$
- $E = 40 - 80$ EeV, $\Delta E = 1$ EeV

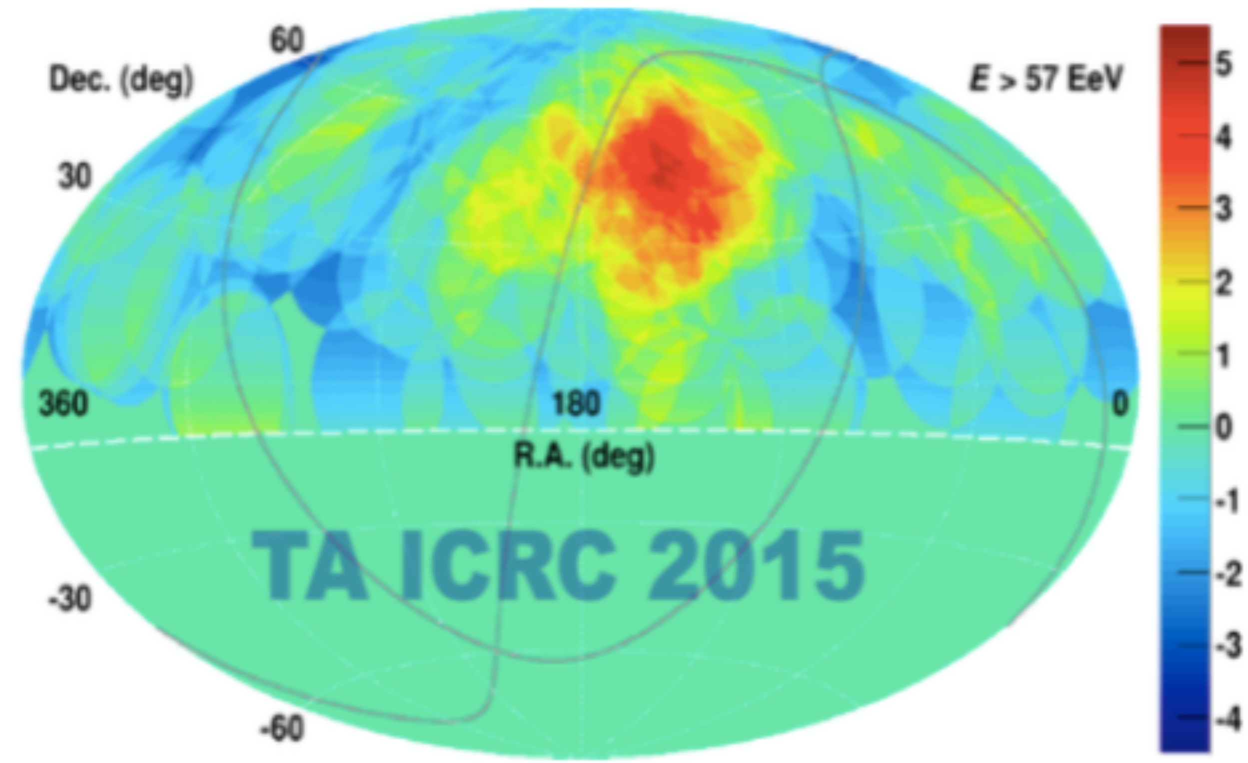
scan parameters

TA

- $r = 15^o - 35^o$, $\Delta r = 5^o$
- $E = 57$ EeV

[Aab et al., ApJL 804 (2015) 1]





[K.Kawata et al., POS (ICRC2015) 276]

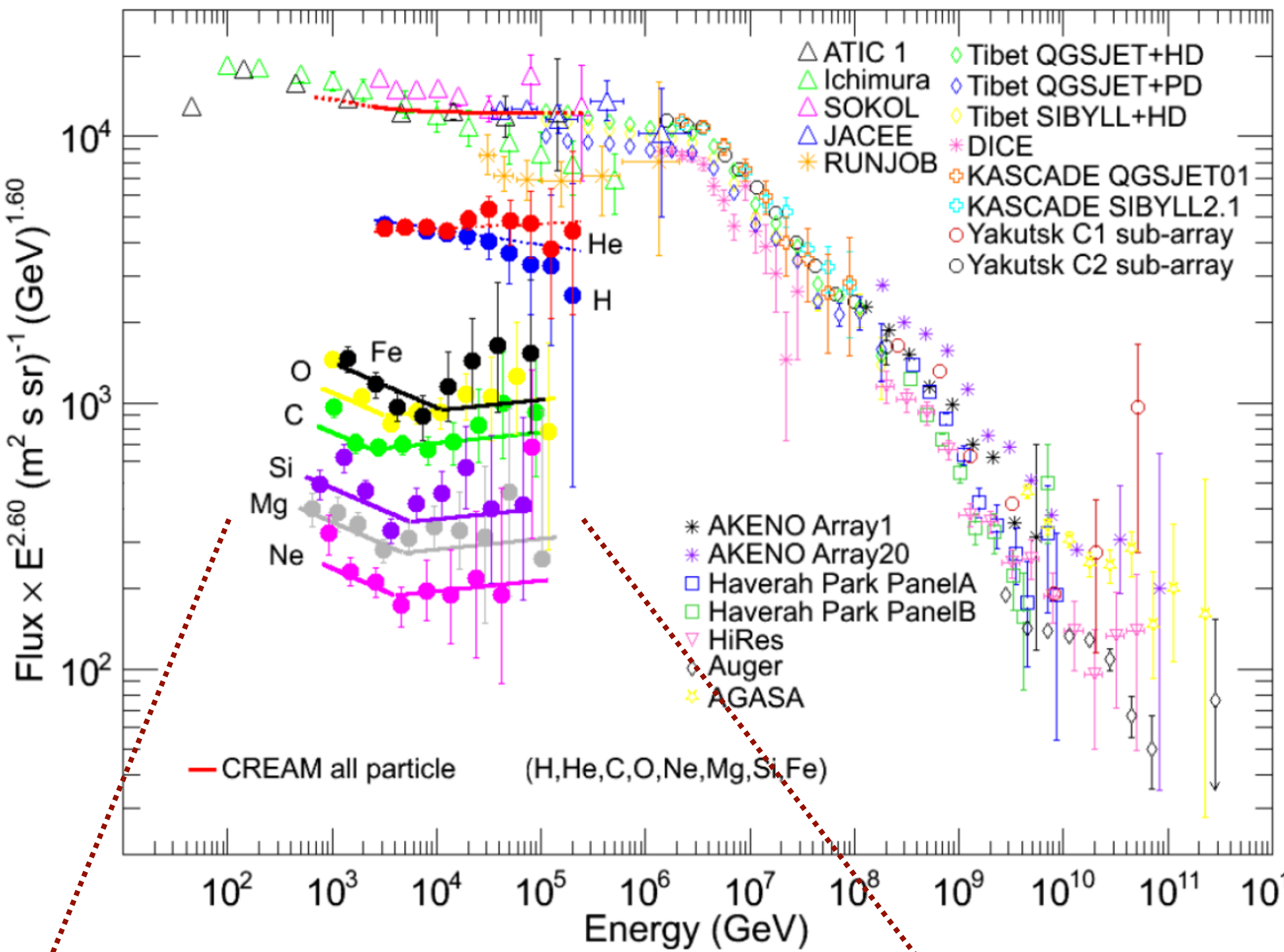
- $r = 12^o$, $E = 54$ EeV
- $n_{obs}/n_{exp} = 14/3.23$
- pre-trial → 4.3 σ
- post-trial P = 69%

scan minima

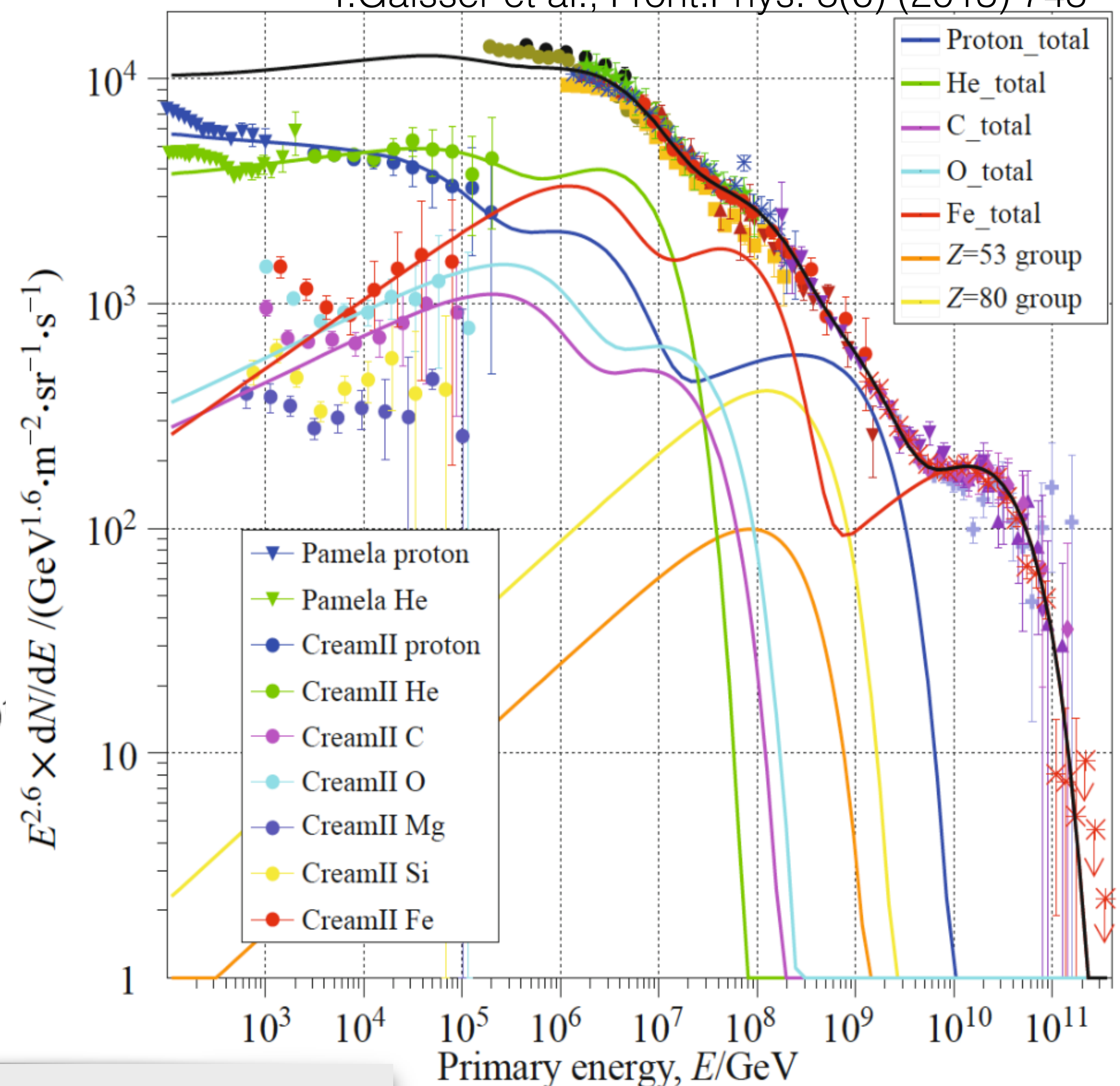
- $r = 20^o$, $E = 57$ EeV
- $n_{obs}/n_{exp} = 24/6.88$
- pre-trial → 5.1 σ
- post-trial → 3.4 σ

detectable with Jem-Euso and Klipve at 5σ with >300 events [D.Semikoz, arXiv:1601.06363]

Direct + indirect measurements



T.Gaisser et al., Front.Phys. 8(6) (2013) 748



From CREAM, ATIC, PAMELA, AMS :

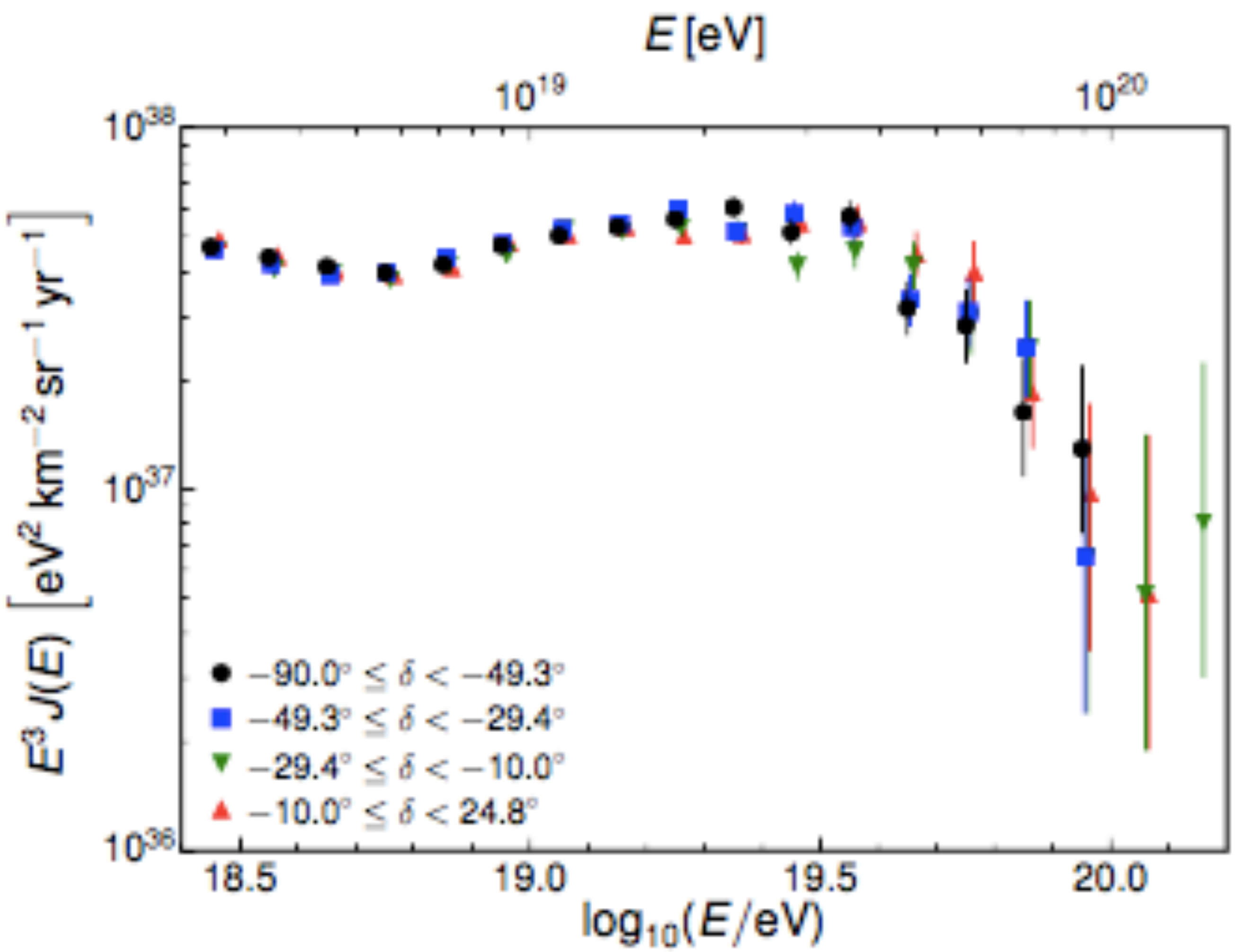
Spectral index for p different from other nuclei

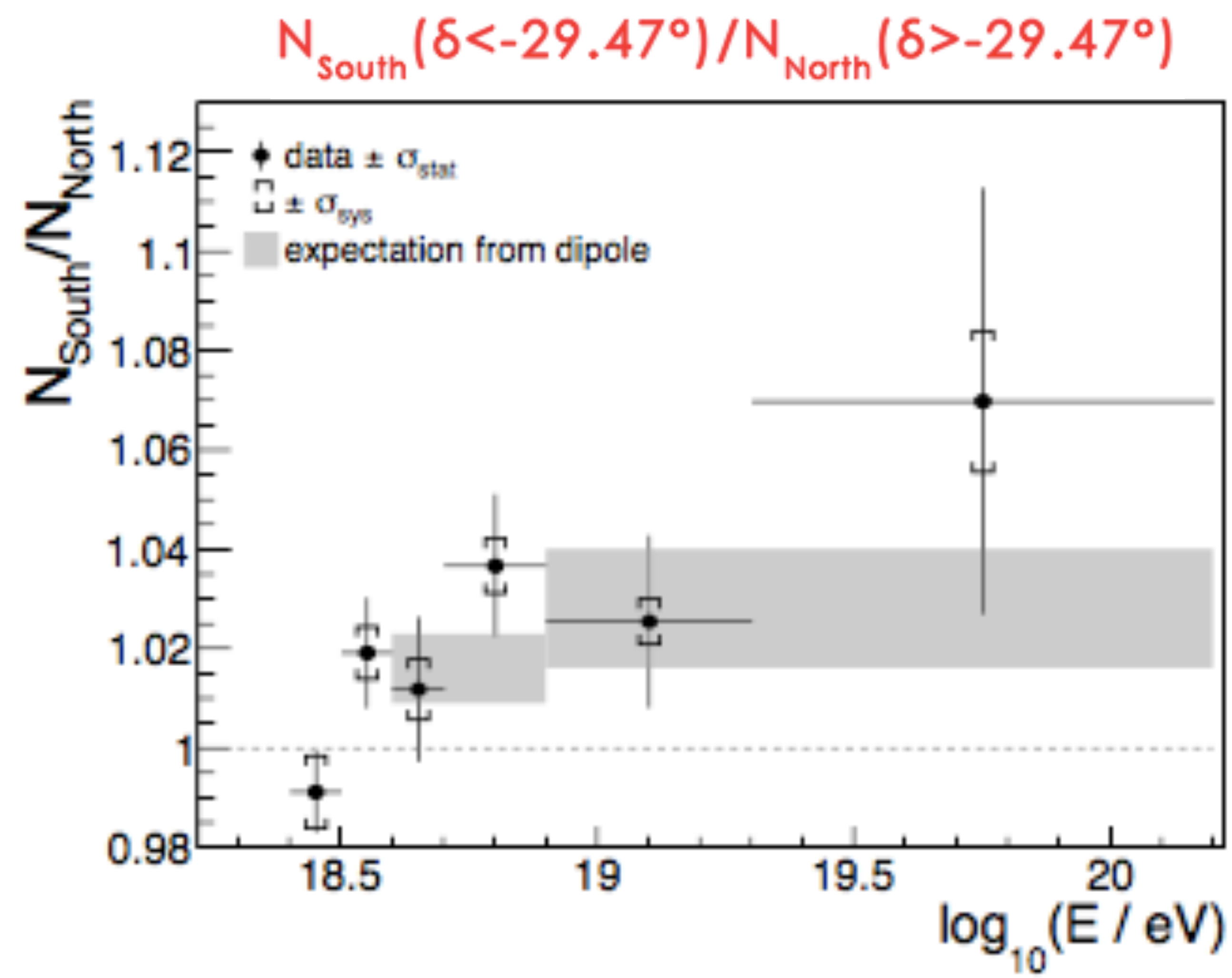
Spectra at >TeV harder than at lower energy

models for composition

exploit the normalisation to direct measurements

Auger : declination dependence of energy flux





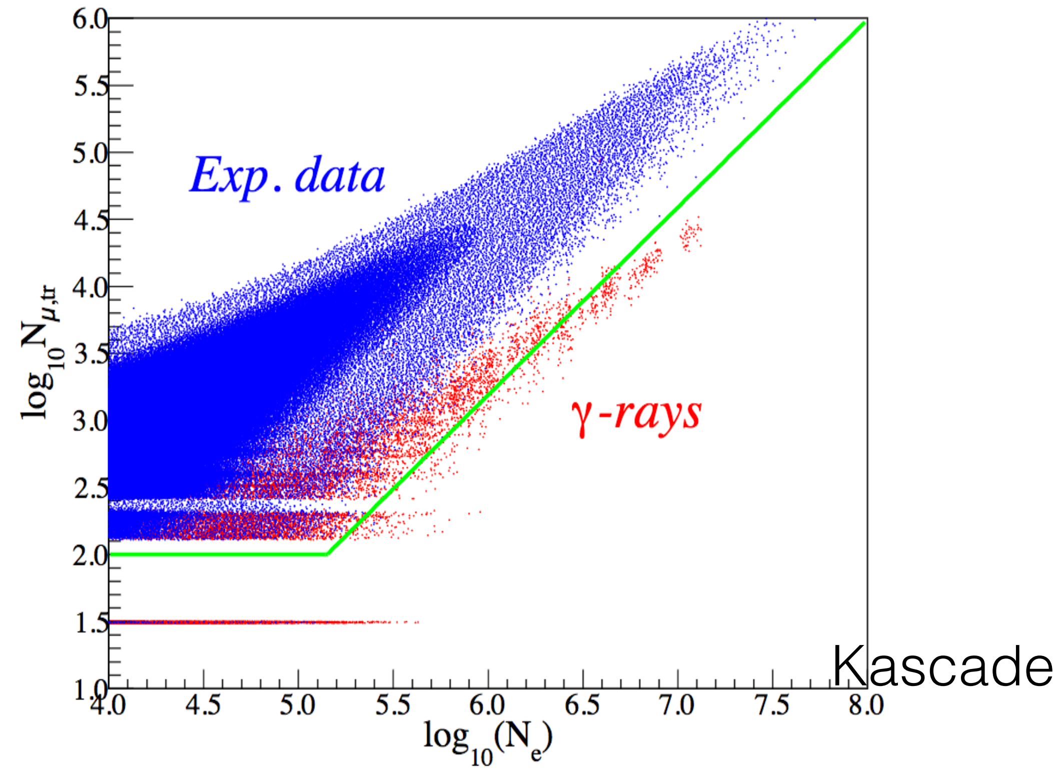
- no indication of a declination-dependent flux
- differencies between Auger and TA in the suppression region not explained
- the differences found between the measurements in two separate declination bands are compatible with the variations expected from a dipolar modulation of the flux.

γ detection in EAS arrays

VHE

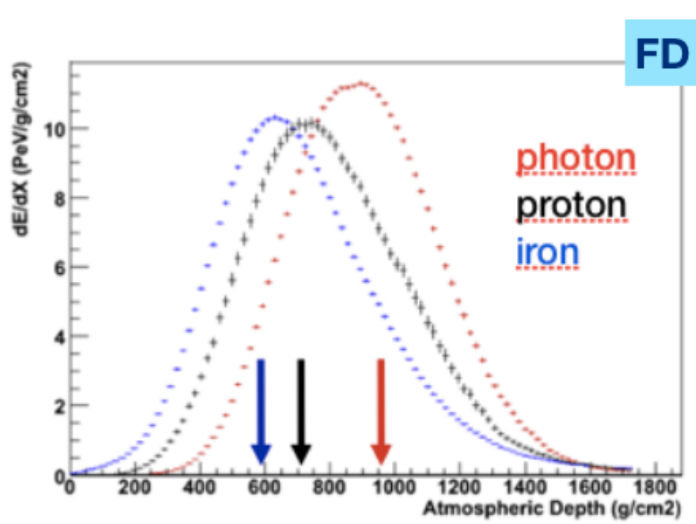
Muon-poor shower selection

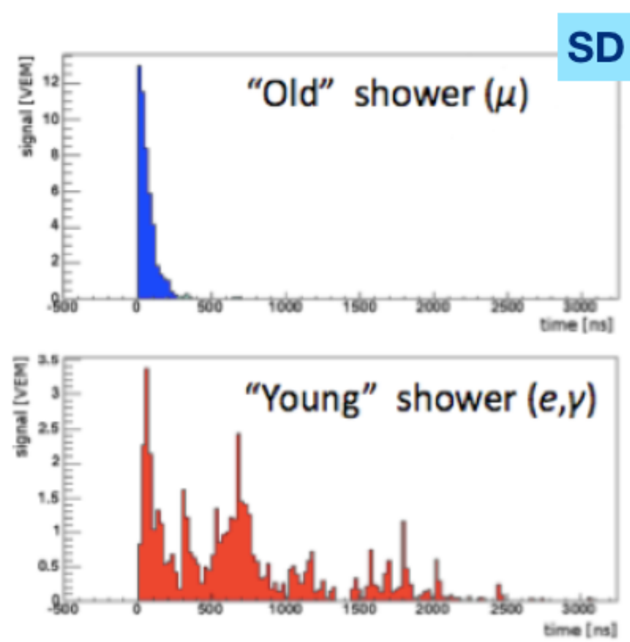
Observatory	Position	$[\delta_{min}, \delta_{max}]$	Zenith
KASCADE	49.0°N, 8.4°E	[14°, 84°]	< 35°
EAS-TOP	42.5°N, 13.5°E	[7°, 78°]	< 35°
GAMMA	40.5°N, 44.2°E	[10°, 71°]	< 30°
UMC	40.2°N, 112.8°W	[0°, 80°]	< 40°
CASA-MIA	40.2°N, 112.8°W	[−20°, 90°]	< 60°
Milagro	35.9°N, 106.7°W	[−14°, 86°]	< 50°
Tibet	30.1°N, 90.5°E	[−20°, 80°]	< 50°
HEGRA	28.7°N, 17.9°W	[−6°, 64°]	< 35°
GRAPES-3	11.4°N, 76.7°E	[−14°, 36°]	< 25°
IceCube	South Pole	[−90°, −60°]	< 30°

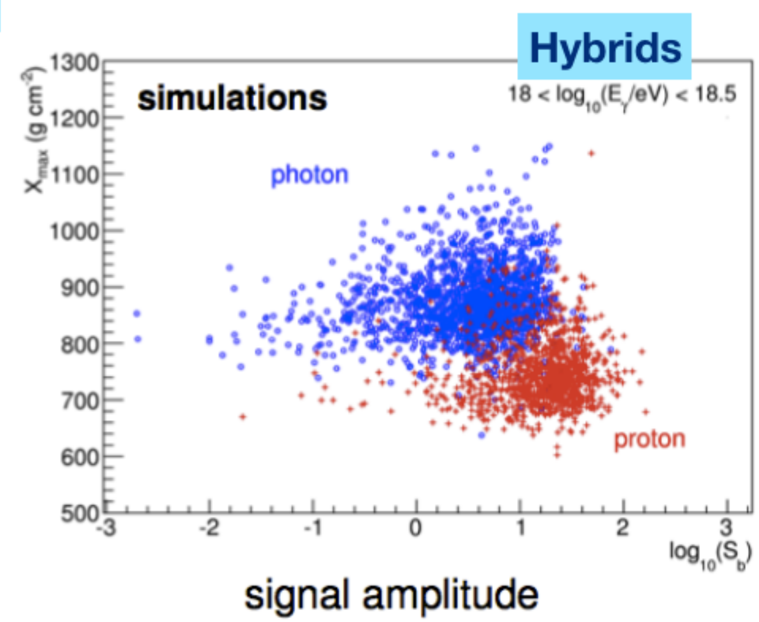


UHE

Exploit observable differencies between γ and hadrons
- γ EAS develop deeper in atmosphere: larger Xmax
- γ EAS look young: larger rise time, smaller radius of curvature

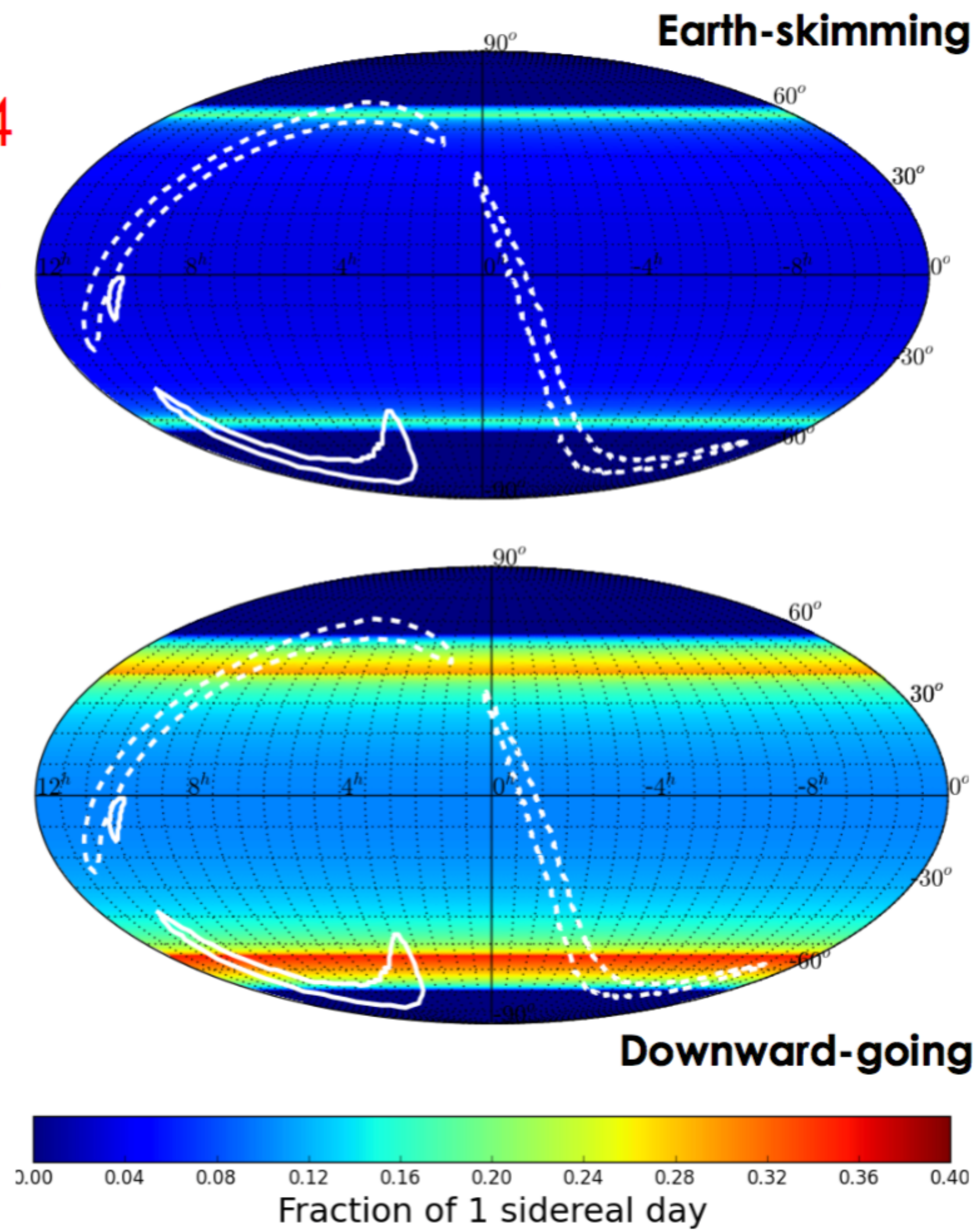






Fraction of time in one day GW150914 & GW15126 are visible in the Earth-skimming & Downward-going channels

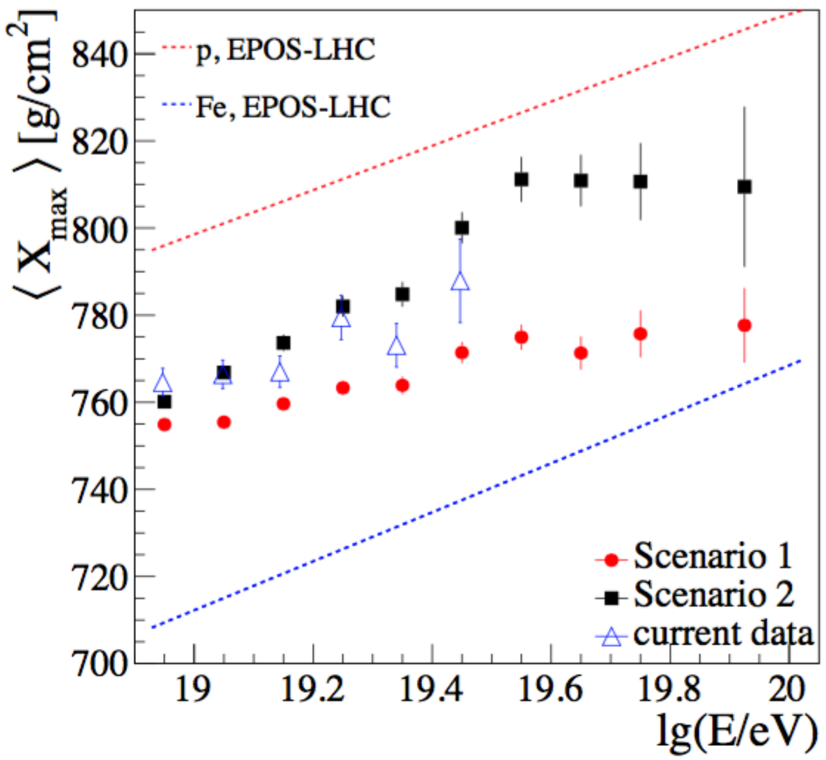
Constraints are declination-dependent

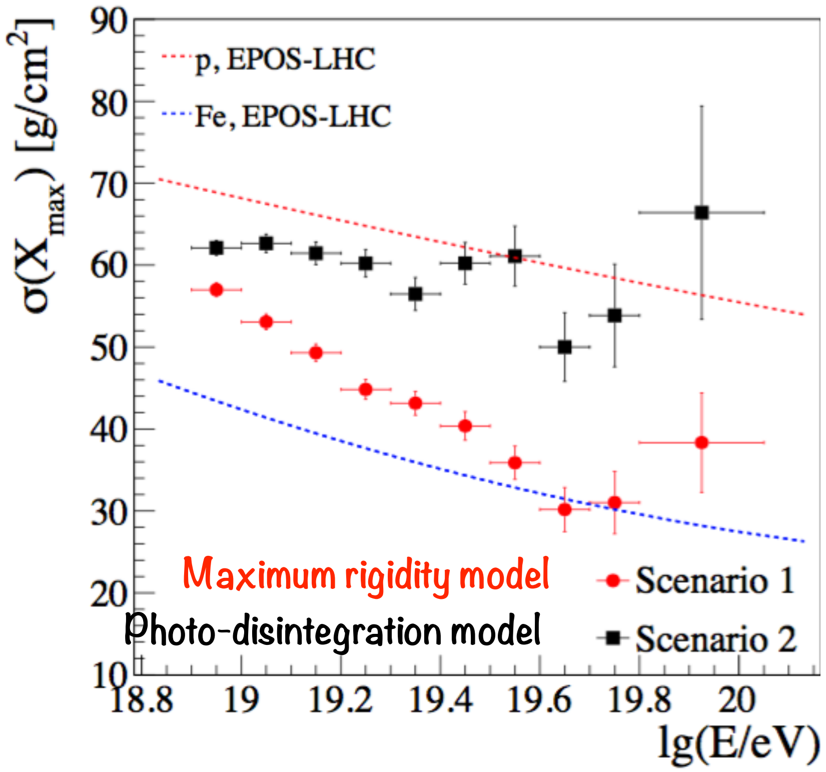


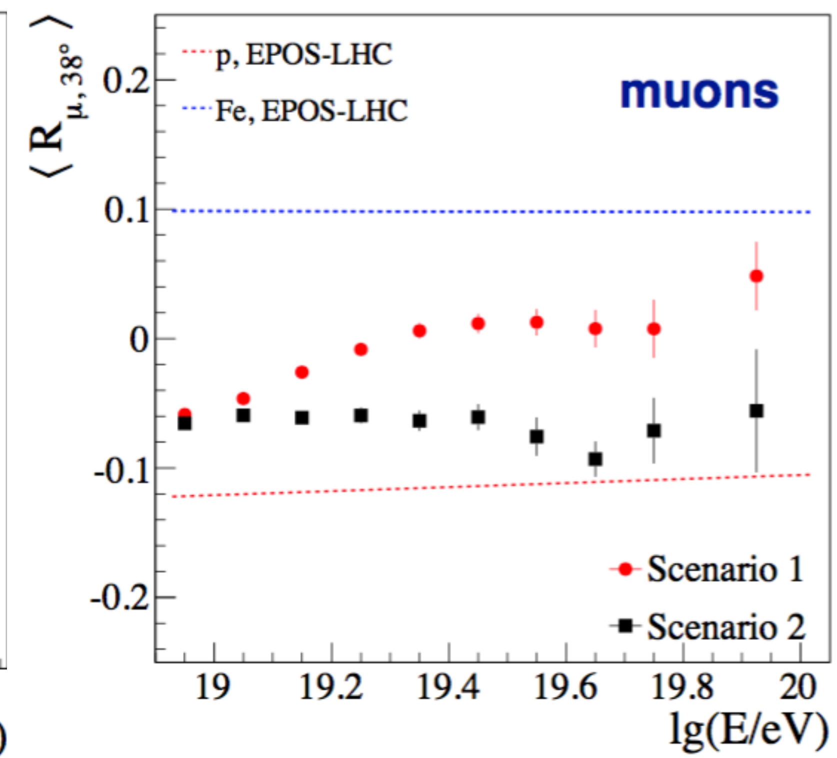
Pierre Auger Collaboration, arXiv:1608.07378 [astro-ph]

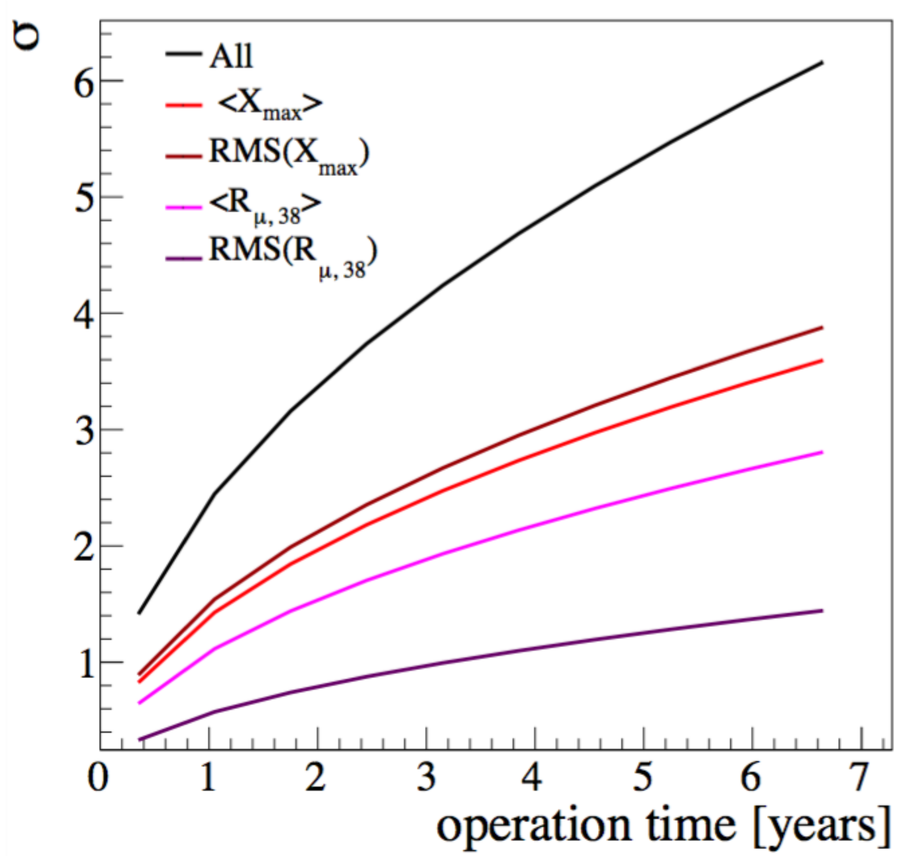
Physics goals of AugerPrime

Origin of the suppression









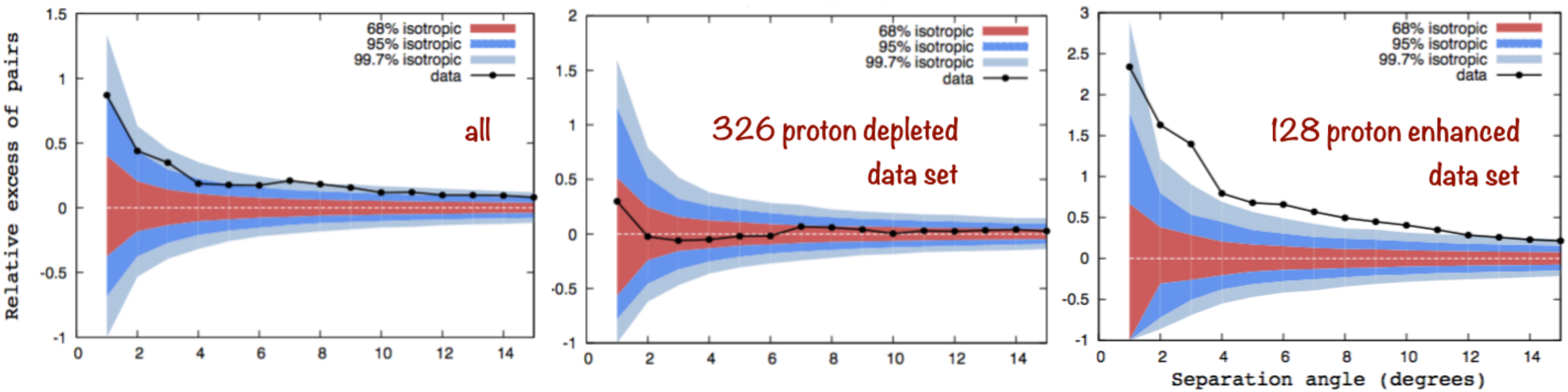
scenario 1 : maximum rigidity model
scenario 2 : GZK suppression

Sensitivity to proton fraction

significance of tagging scenarios with and without 10% protons (ref. scenario 1, no uncertainties due to hadronic interaction models included)

Physics goals of AugerPrime

Set of 454 Auger data : E> 4 x 10^{19} eV, random Xmax according to scenario 1.
10% protons added, ½ coming from AGNs within 3^0



ν and γ

Improvement in

- exposure
- low energy trigger
- hadronic bckg rejection