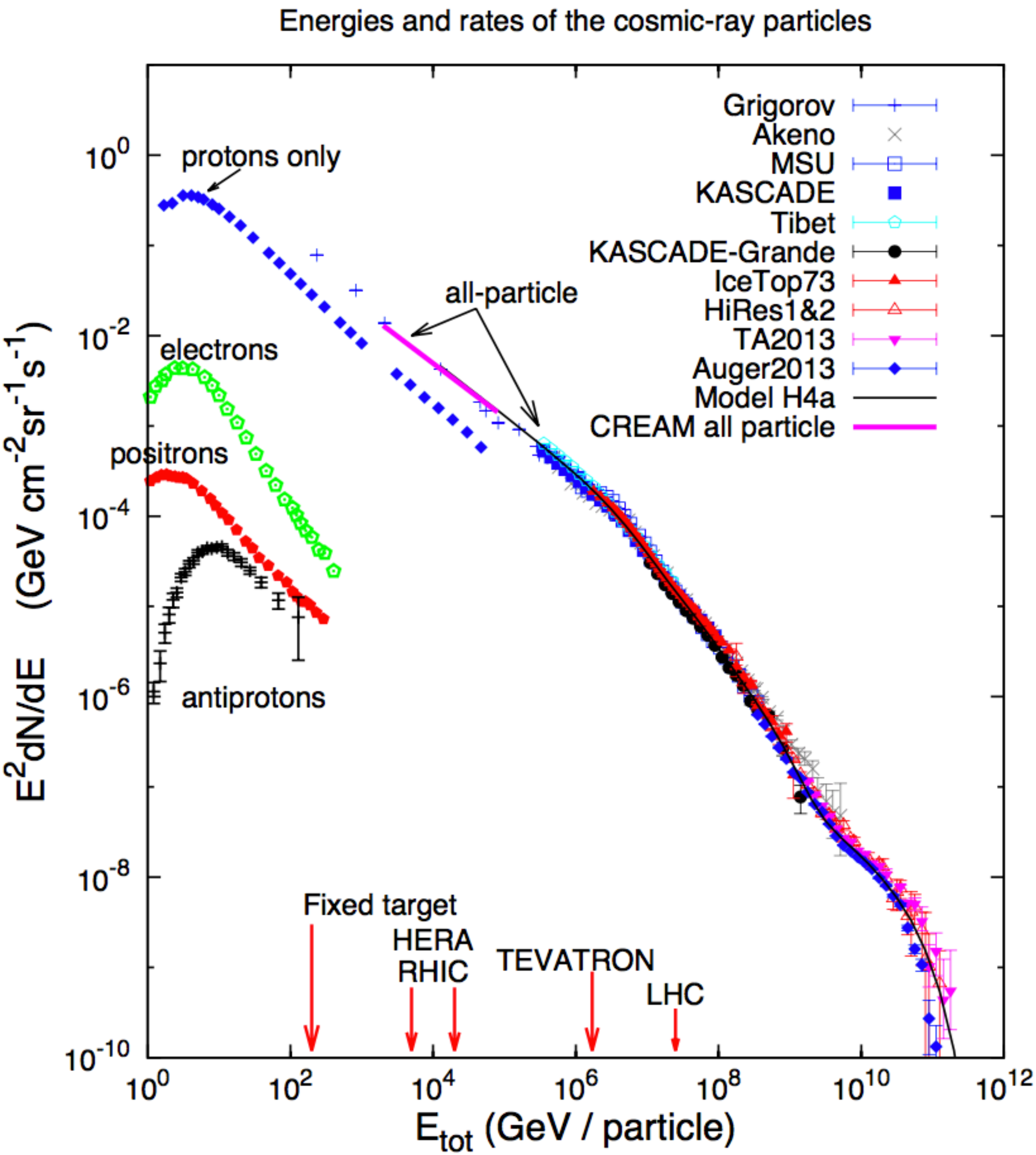
UHECR from LL GRBs

Peter Mészáros

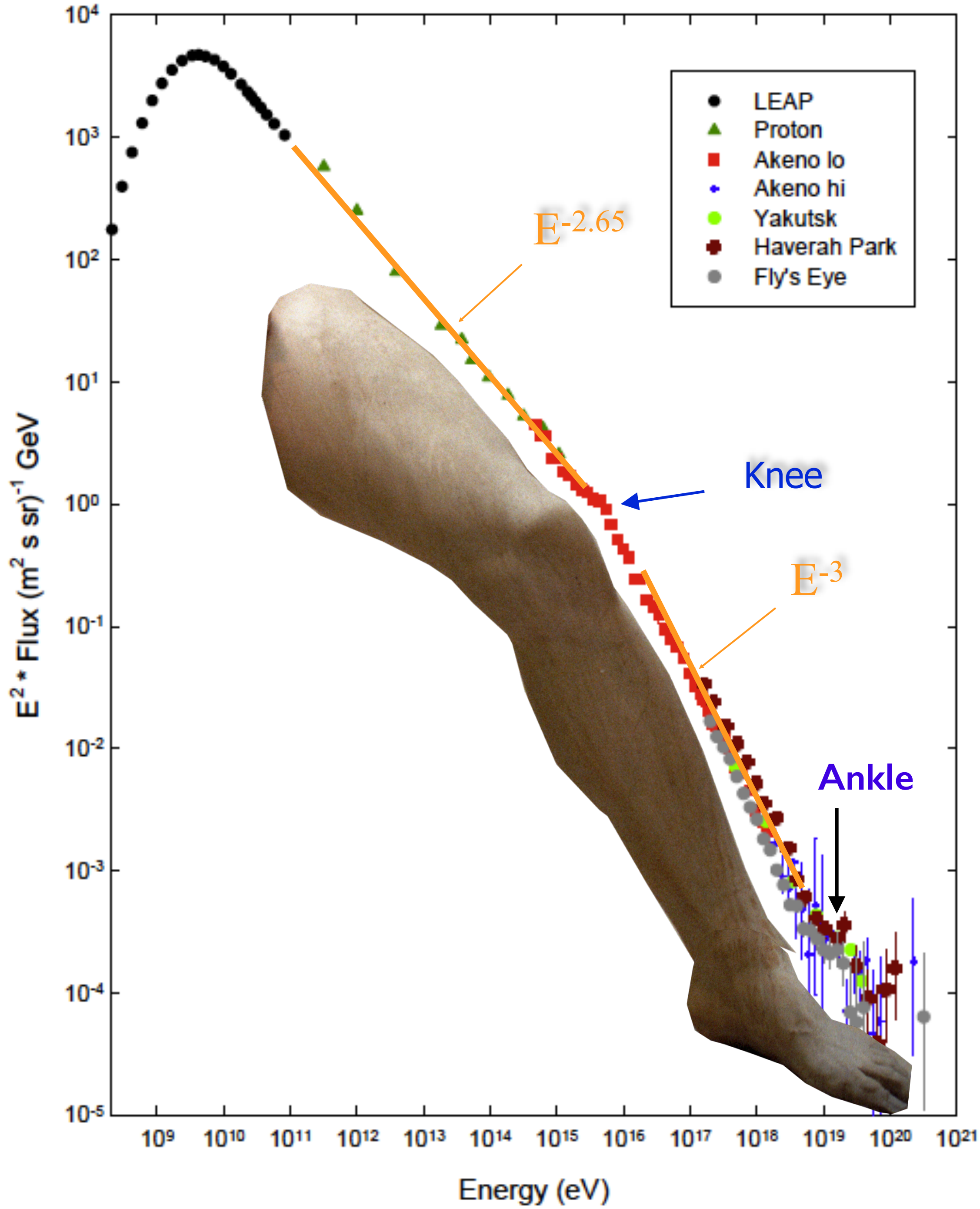
Pennsylvania State University

PKU, Beijing, March 2018

Collaborators: B.T. Zhang, K. Murase, S. Kimura, S. Horiuchi

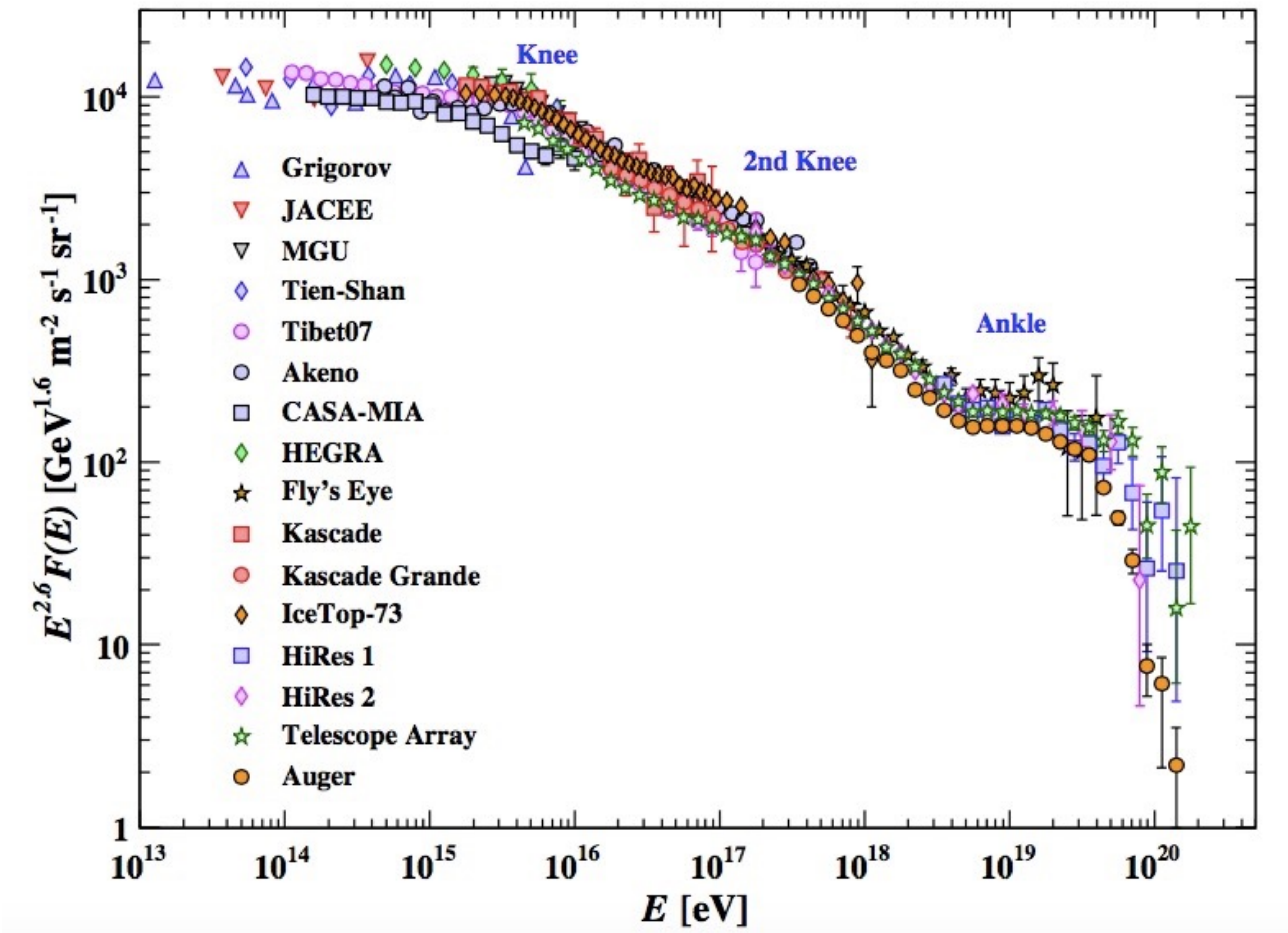


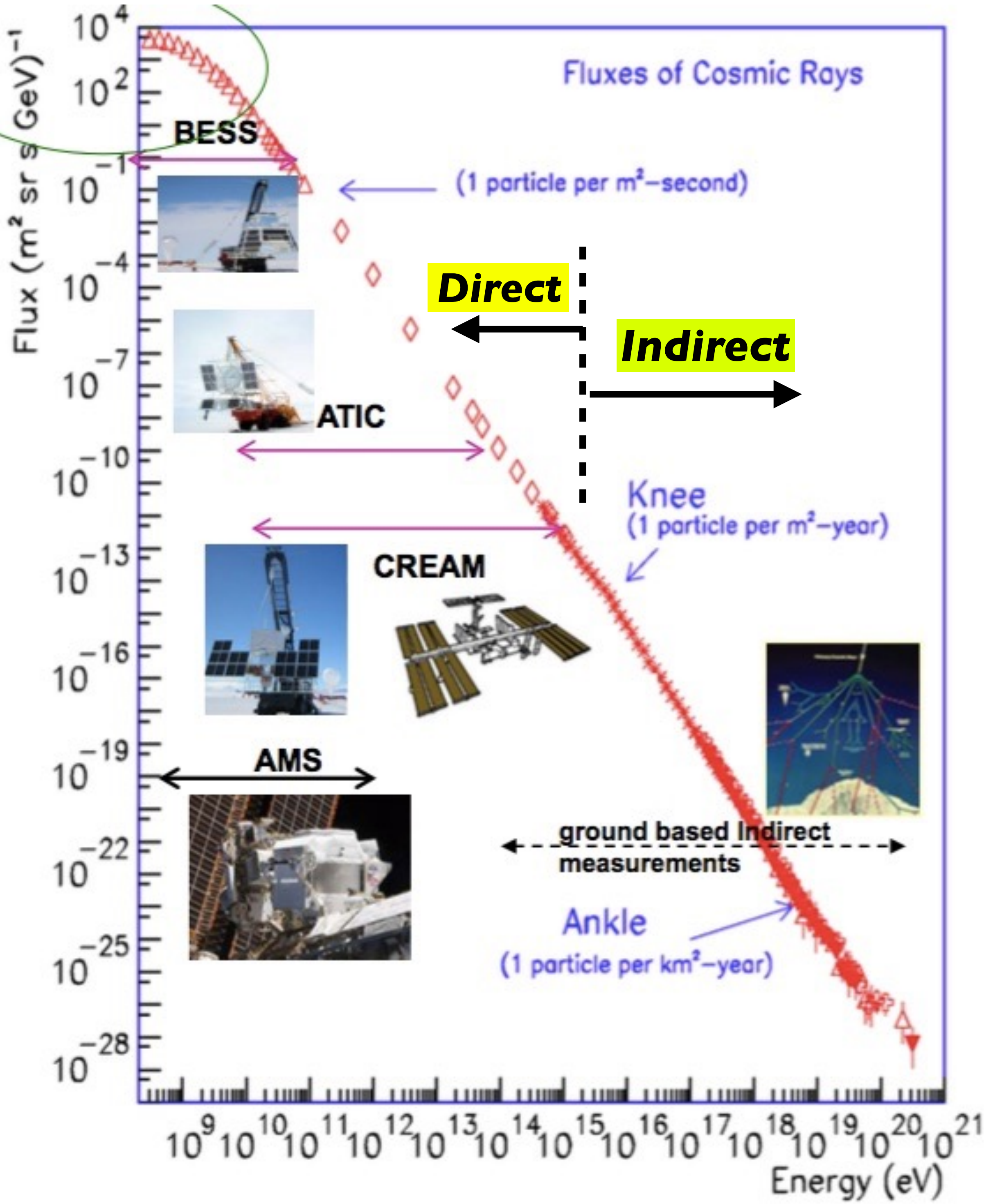
the whole CR spectrum



All-particle spectrum & simplified description

or in some more detail:





Measuring CR primaries

- Differential fluxes are low, and decrease with energy as $dN/dE \sim E^{-2.7}$
- At $E \lesssim 10^{12}$ eV ***balloon*** experiments can measure ***primary*** CRs
- Up to $\sim 10^{14}$ eV ***space*** experiments can measure ***primary*** CRs
- For $E \gtrsim 10^{14}$ eV, need measure from ***ground***

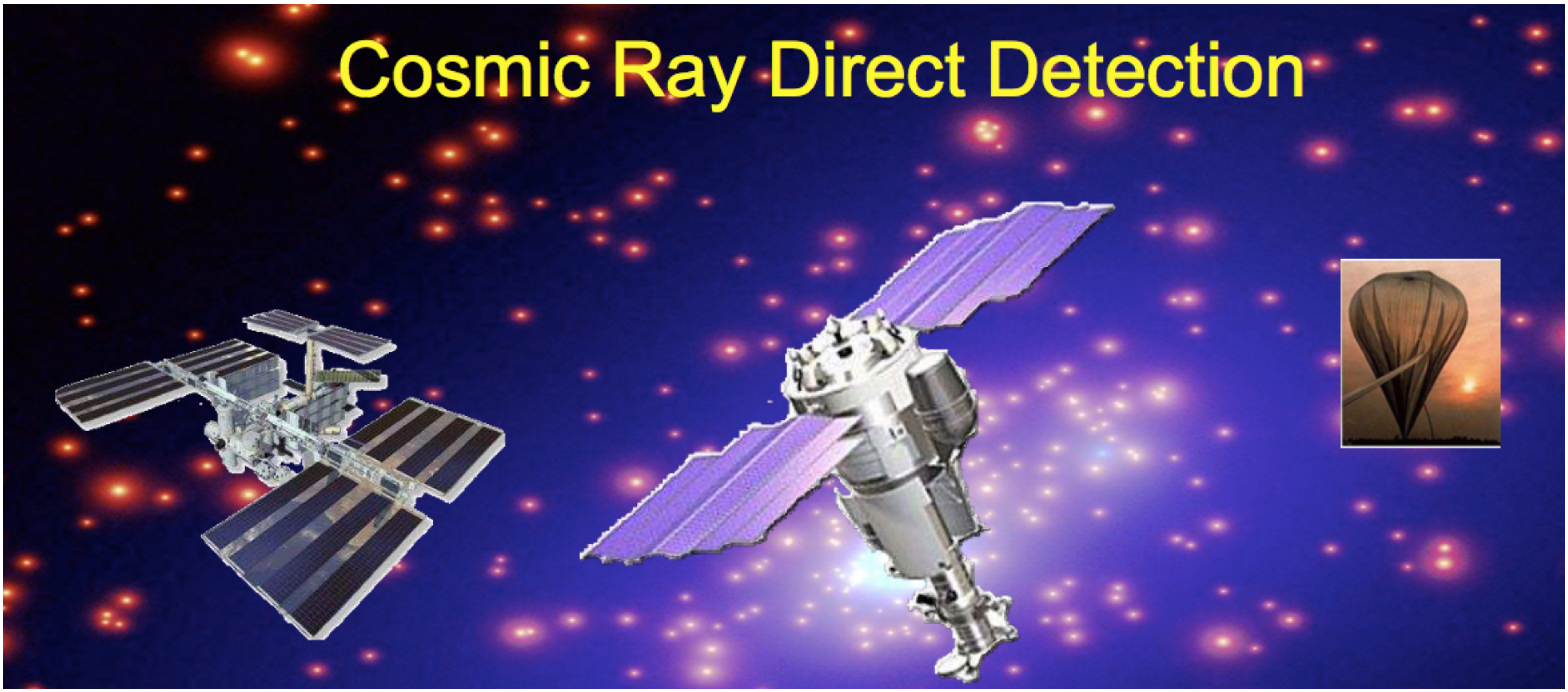
Direct: measure primary CRs ($\lesssim 10^{14}$ eV)

- Spectral index $\alpha = 2.7 \rightarrow$ even at 10^{12} eV = TeV, the flux is $\Phi(\text{TeV}) \sim 1\ \text{m}^{-2}\text{day}^{-1}$
- At primary energies $\epsilon \gtrsim 10^{15}$ eV, fluxes are $\Phi(\epsilon) \lesssim \text{m}^{-2}\text{yr}^{-1}$
- Space experiments: **weight, size & power** limited - although the Space Station (ISS) is somewhat better off than satellites

Indirect: measure CR secondaries ($\gtrsim 10^{14}$ eV)

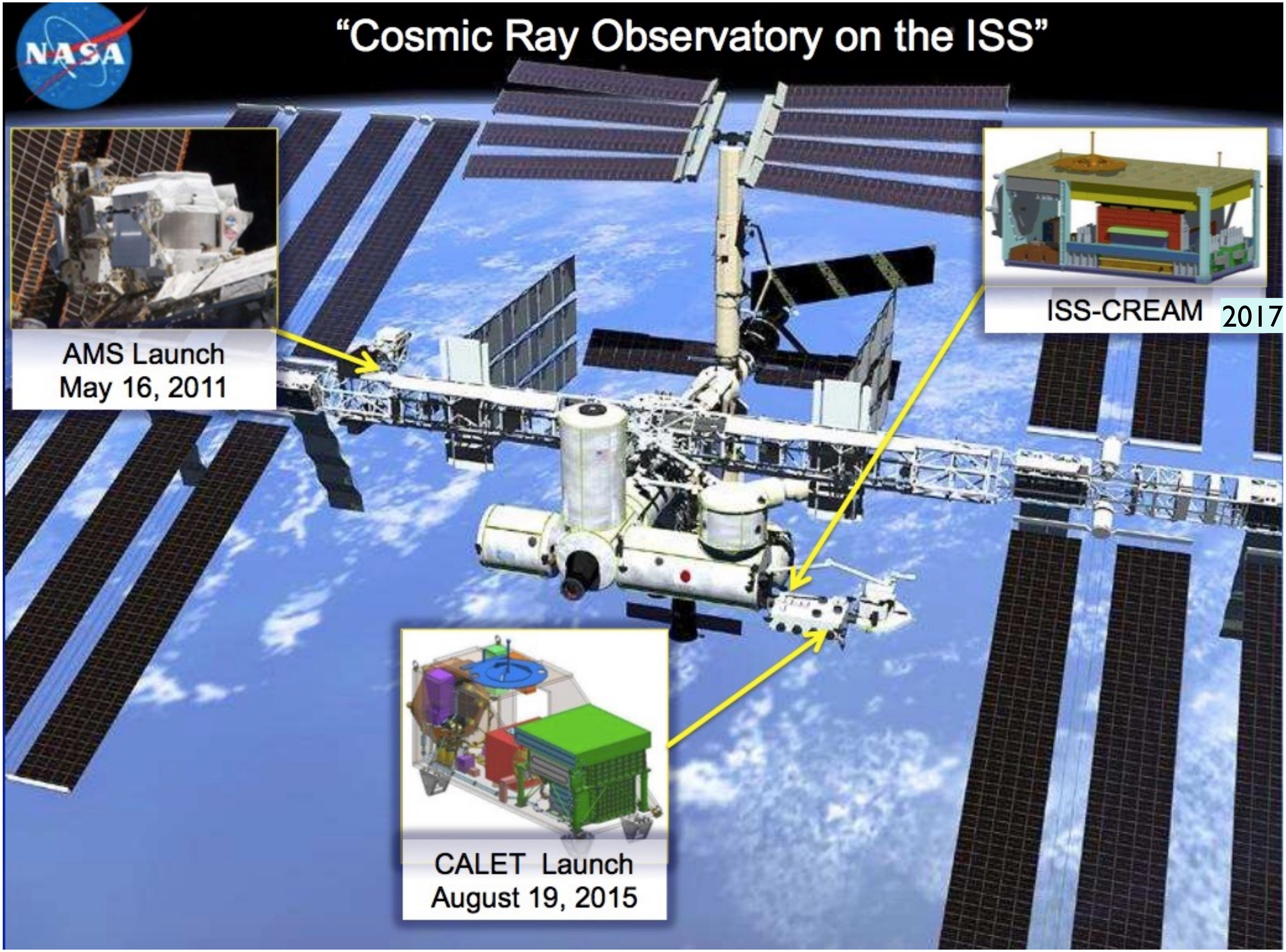
- **Good news**: secondary cascades can be measured from the **ground** $\rightarrow$ can build **very large** detector arrays, e.g.
  –KASCADE-Grande: 0.5 km^2 at $\sim$ PeV energies (knee);
  –Pierre Auger Observatory: 3,000 km^2 at EeV-ZeV (10^{18}–10^{21} eV).
- **Bad news**: inferring the primary CR energy and composition requires **complicated numerical modeling** of the cascade.

$$E_{primary} \lesssim 10^{14}\ \text{eV}$$



Space Station | Satellites | Balloons

e.g.



"Cosmic Ray Observatory on the ISS"
AMS Launch
May 16, 2011
ISS-CREAM
2017
CALET Launch
August 19, 2015

- **Principle of PRIMARY measurement technique**

- magnet
- tracker
- time of flight

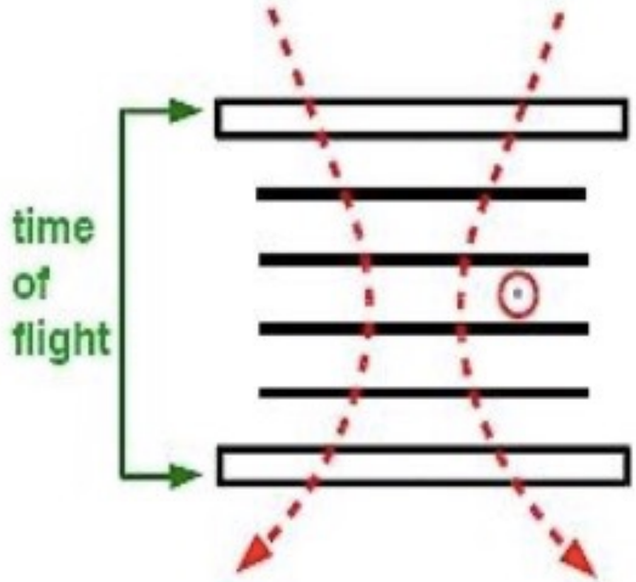


Figure 1.19: Schematic of a generic primary CR time-of-flight magnetic tracker detector. Magnetic field points into the picture.

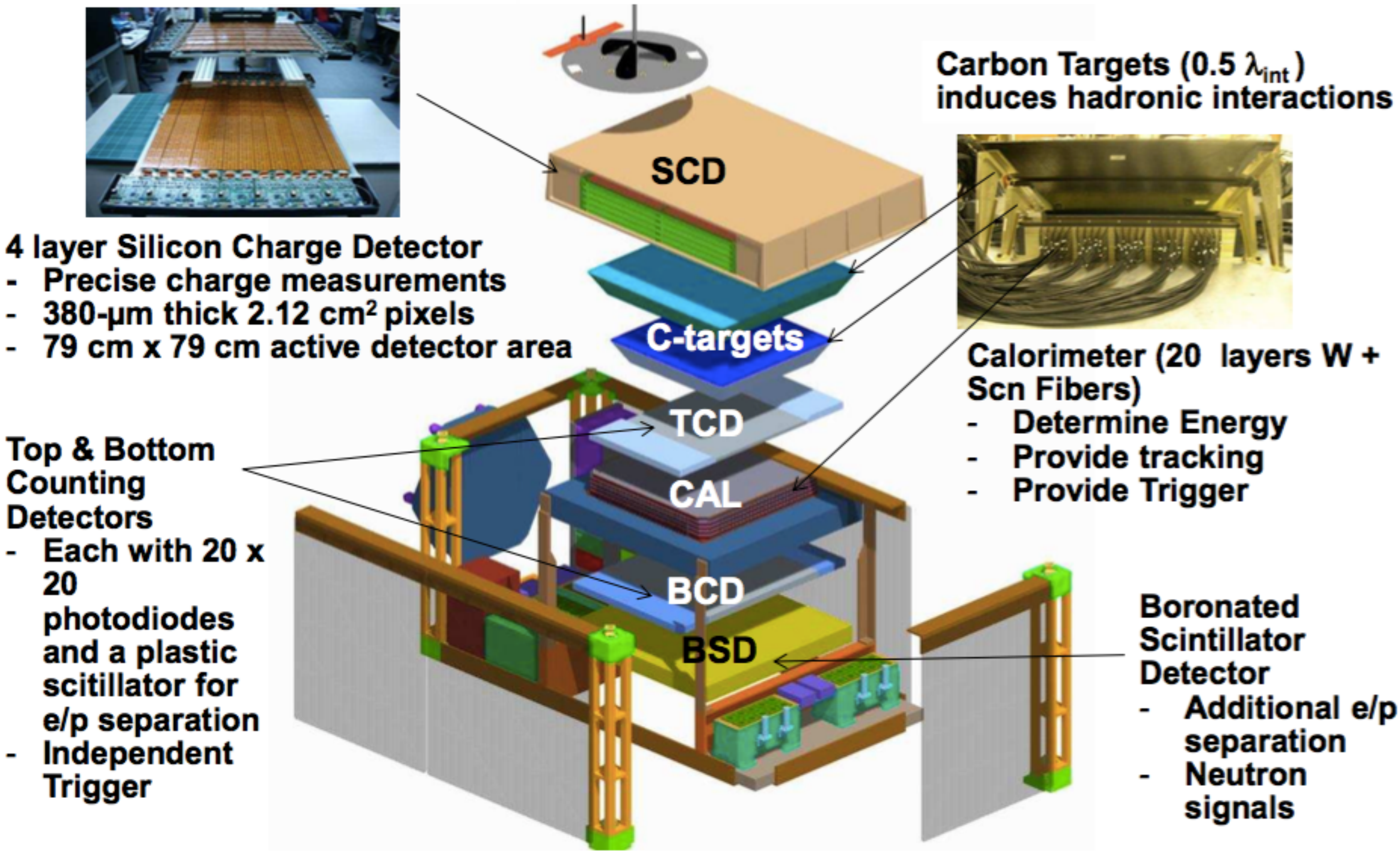
- p = γmv from curvature
- v from time of flight
- q magnitude from energy loss
- q sign from direction of curvature

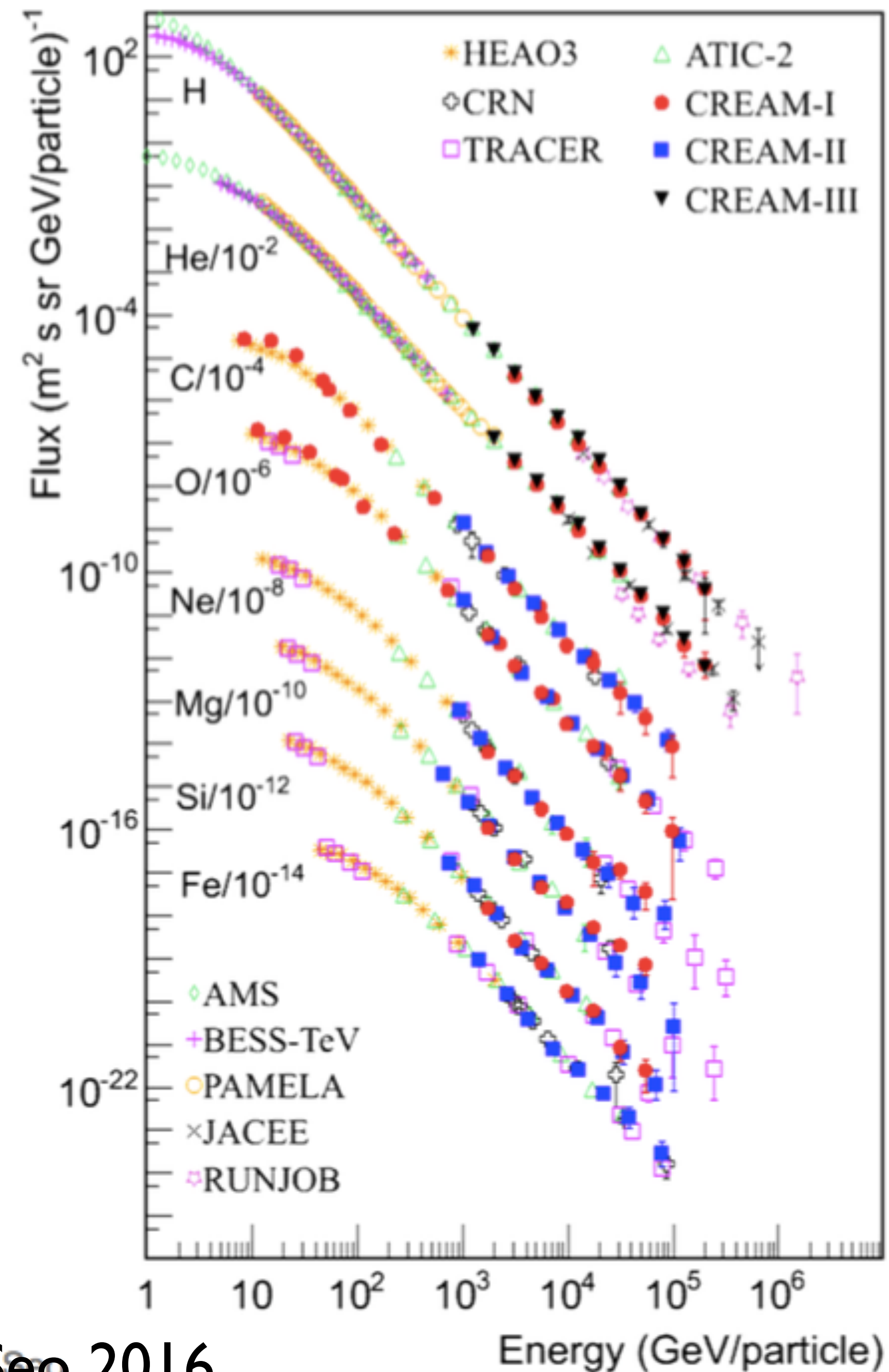
m,q identifies particle

e.g. →

on ISS:

ISS-CREAM Instrument





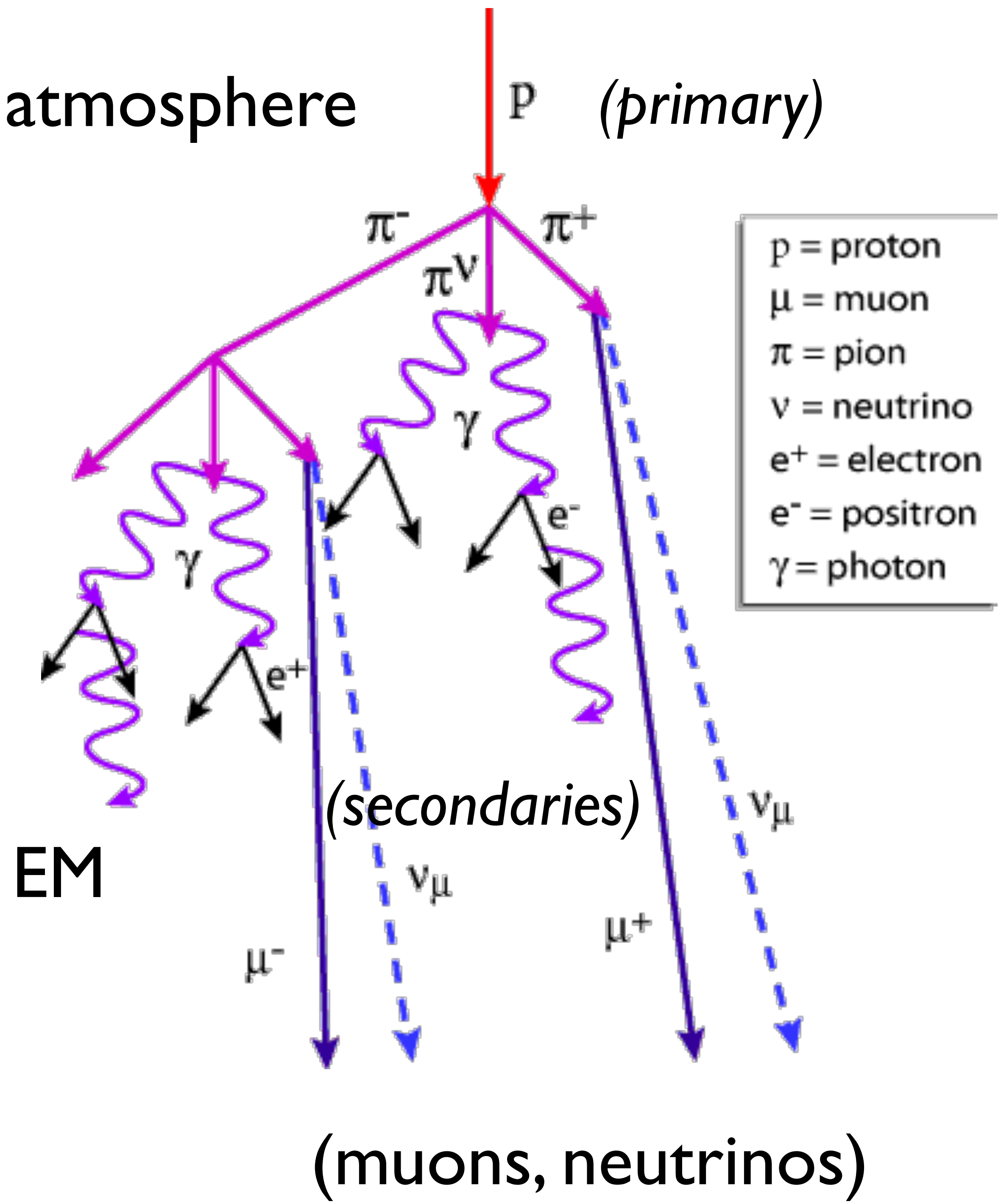
Seo 2016

Below the knee results:

- The spectrum is roughly $\sim E^{-2.7}$
- Composition is mainly protons, heavy elements less abundant

But, above ~10^{14} eV:

- Size/Cost forces detectors to the ***ground***
- This is,under 10 Km of Earth ***atmosphere*** (until we can put detectors on the Moon)
- But relativistic CR ***collides*** with nuclei of atmospheric N, O → makes ***secondary*** particles, to whom it loses its energy

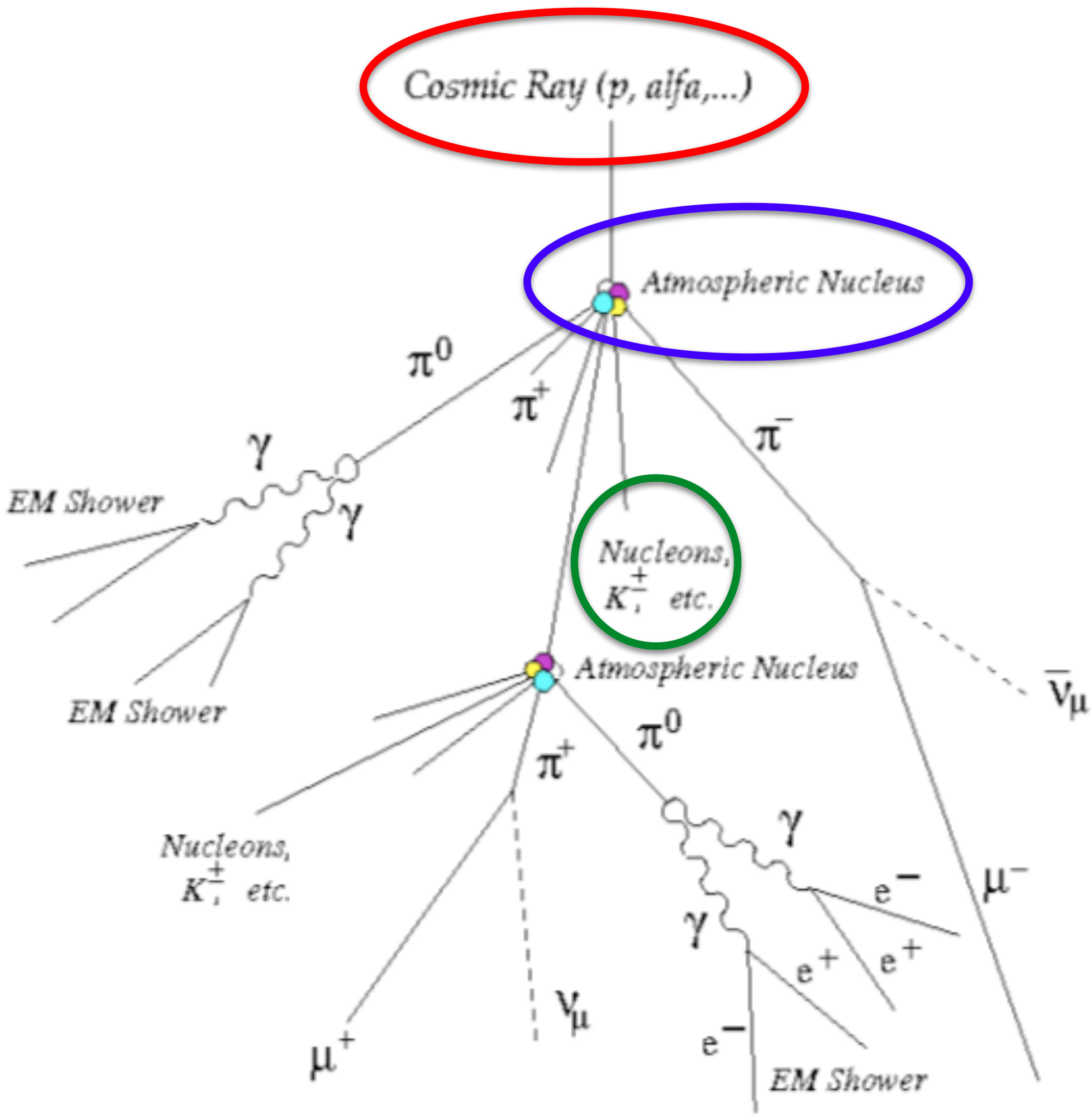


Cosmic ray air shower

(in Earth atmosphere)

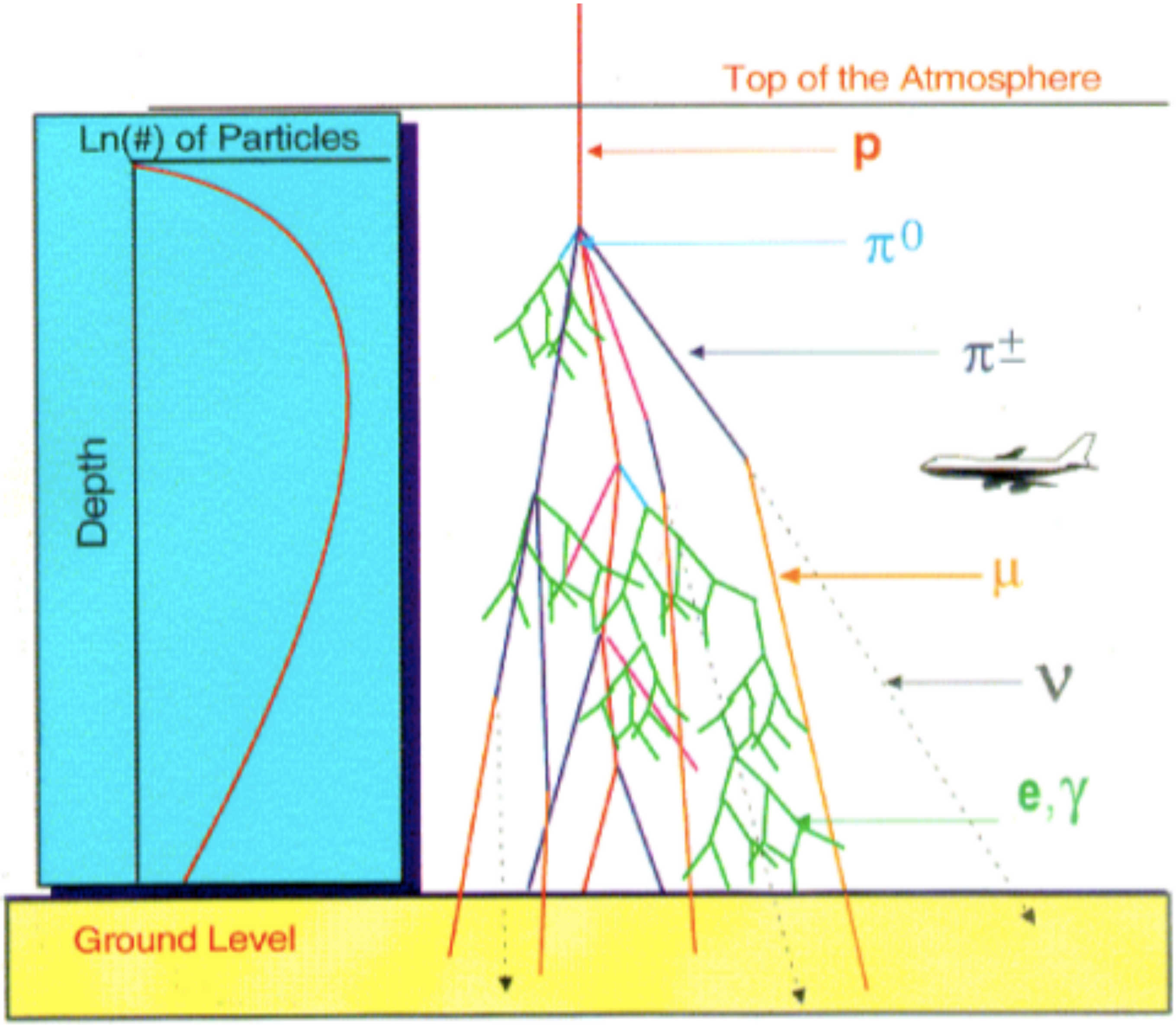
- Two components: -***EM*** ($e^{\pm}$, γ), and -***hadronic*** ($\pi^{\pm} \rightarrow \mu^{\pm}$)
- ***EM***: exhausted in upper atmosphere → fluoresc. light
- ***Hadronic: muons*** are harder, they can reach the ground (and the ν_μ reach ground)

CR air shower cascade



- **Primary** CR (p, He,...heavies) **interact** at top of atmosphere
- Produce **cascade** of **secondary**, lighter particles
- Both ***EM*** ($e^{\pm}$,γ) and ***hadronic*** (N, K, π, μ, ν..) cascades
- ***Secondaries*** are detected in ***air*** or at ***ground*** level

Extensive air showers



e.g. at ≳ the knee energies,

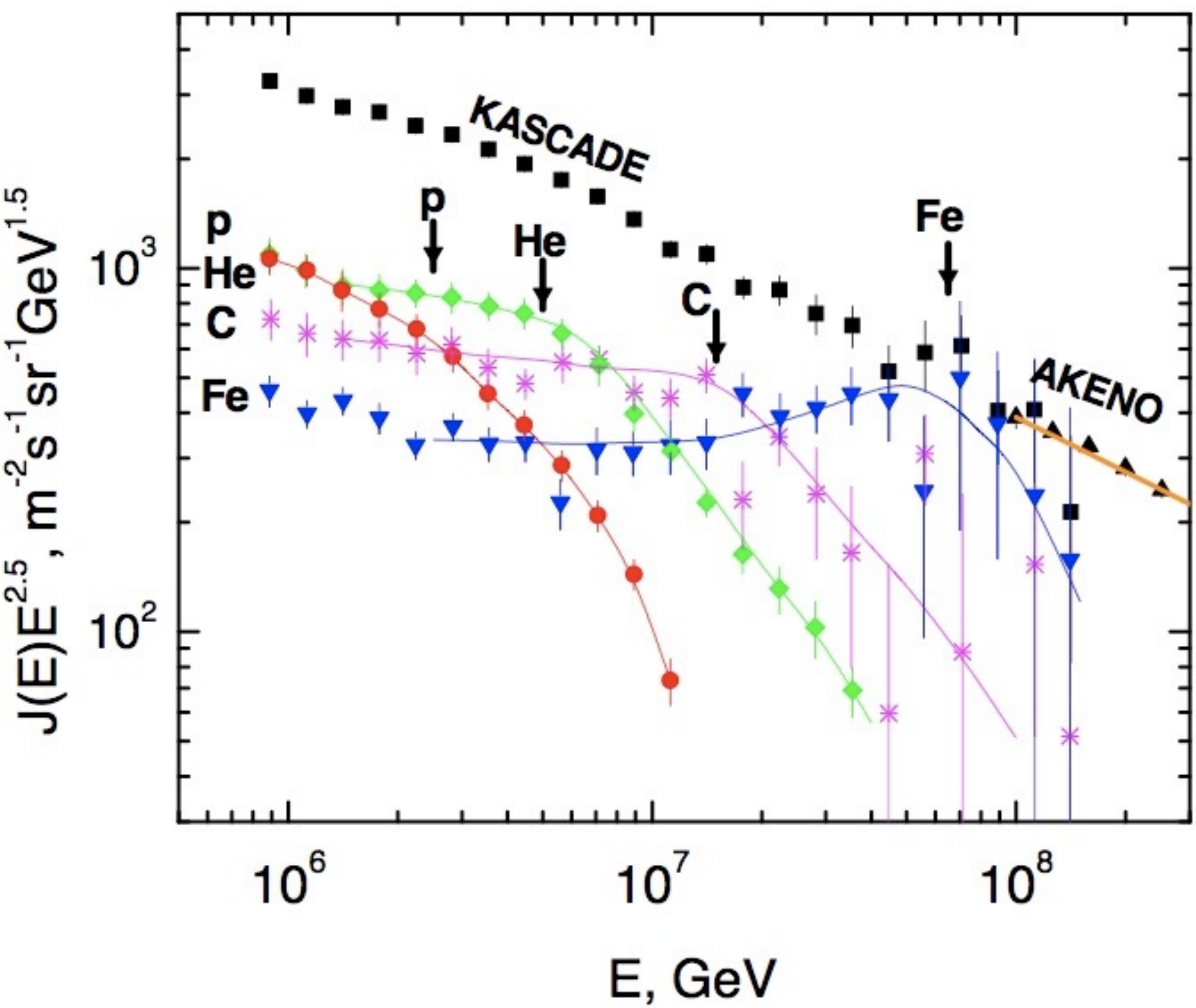
KASCADE-Grande *(Indirect)*

K**A**rlsruhe **S**hower **C**ore **A**rray **DE**tector - Grande

Located in Karlsruhe, Germany: (Charlemagne's burial place)

- ***Indirect*** detection of the primary CRs (10^{16}-10^{18} eV) via their ***secondaries***
- Monte Carlo simulations allow determination of ***chemical composition*** of primary CRs
- Beyond $\mathbf{10^{15}}$ eV, composition increasingly weighted towards ***heavy elements***, He, .., C, O, ..Fe

CR spectrum @ E < 10^{17} eV



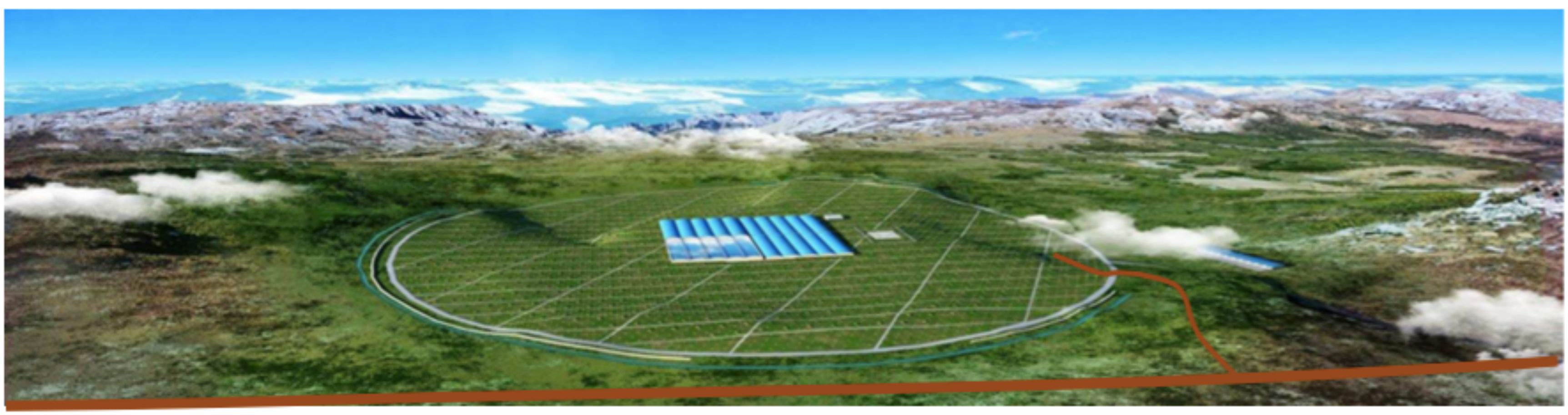
- Spectrum steepens in a "***knee***"
- Knee energy depends on ***charge*** Z
- For ***p***, knee @ 10^{15} eV
- For ***Fe***, knee @ 10^{17} eV

E_{max}~βcZeBL ✔

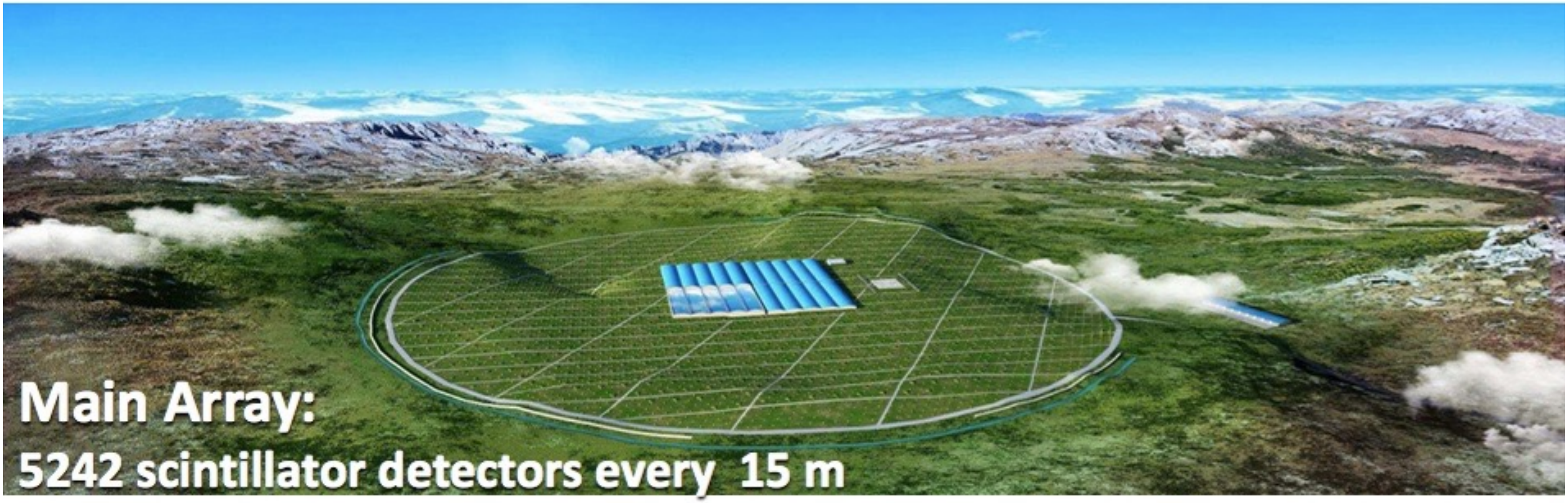
Newest major project 2018, Dao Cheng plateau, Sichuan:

LHAASO at Mt. Haizi, Sichuan, China

N29°21’27.6”, E100 ° 08’19.6”, 4400 m a.s.l.



LHAASO Layout



LHAASO:

Zhen Cao summary slide from 2016 (Vulcano)

- Absolute Energy Scale at 10TeV could be established by using moon shadow technique
- Great opportunity for cross-calibration with space-borne Measurements
- Separation between species can be done at energy of 0.1-10 PeV
- The Knees at 0.7, 1.4, ~3 PeV ... and 18 PeV are expected to be fixed on the individual spectra
- The schedule is fixed:
  - Civil construction is finished by April, 2017
  - Construction of No.1 pool & tanks: start around April, 2017
  - Detector installation starts by the end of 2017
  - Physics data taking in 2018 with ¼ LHAASO array

Next:

Ultra-High Energy CRs: (***UHECR***s)

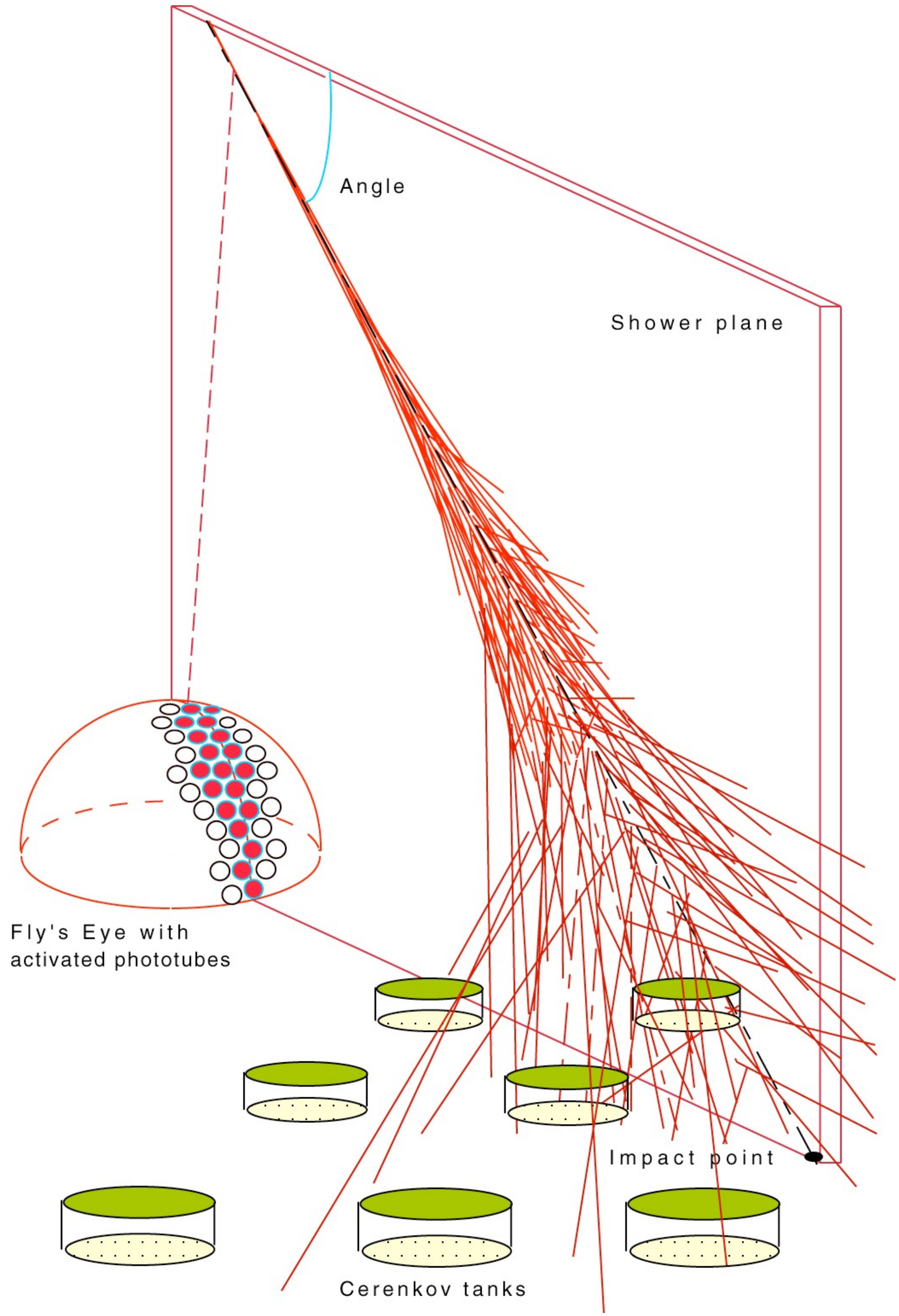
- UHECRs : roughly if ***$E>10^{18}$ eV*** (EeV)
- Measurement technique: only ***indirect,*** via their EM and hadronic cascades
- (1) Can image effects of ***EM cascade*** in the upper ***atmosphere***
- (2) Can measure ***hadronic cascade*** that reaches ***ground***

Pierre Auger Observatory

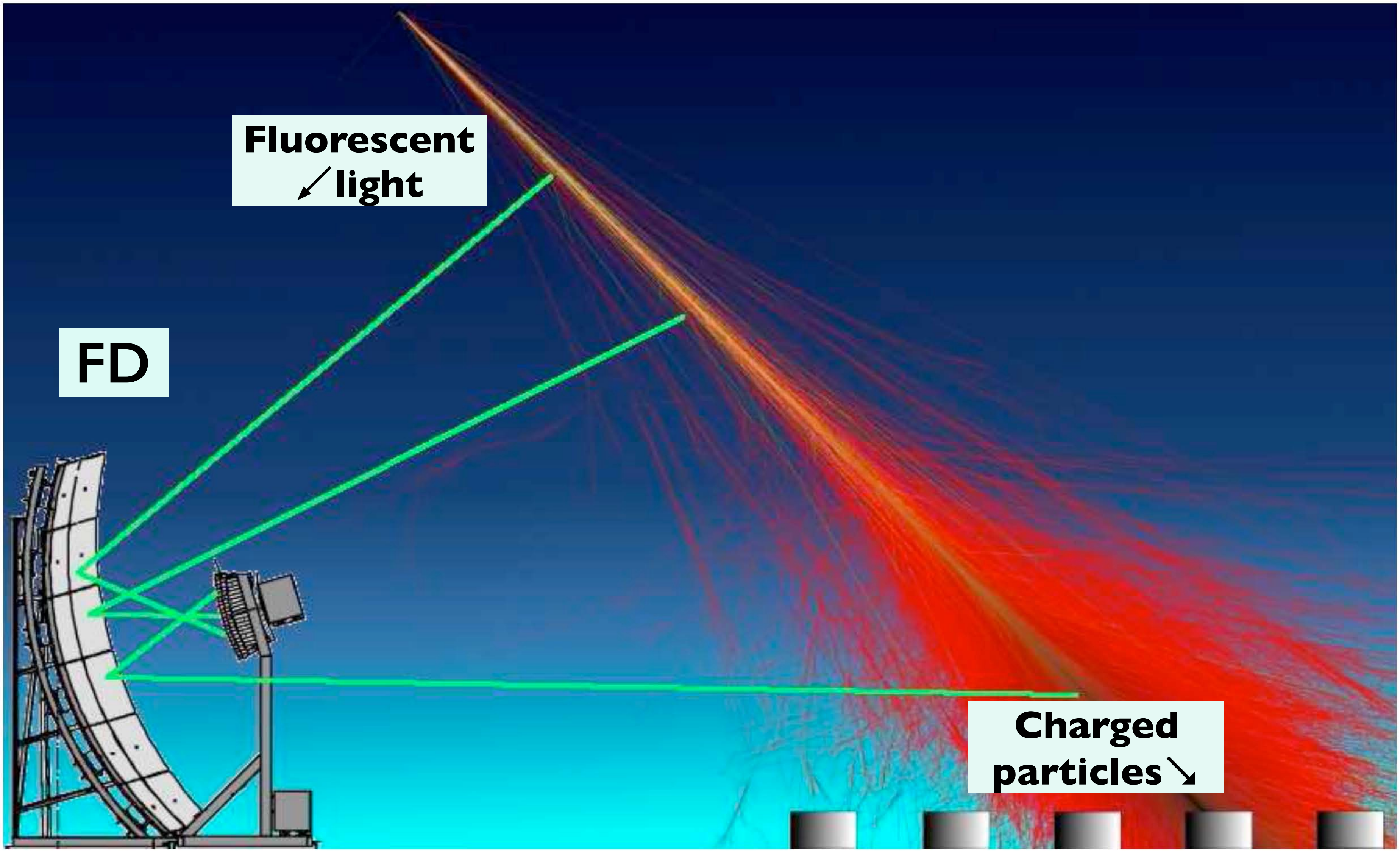
Uses two techniques for detecting CR shower:

- detect air fluorescence photons (light) produced by shower particles with telescopes (FD)

- detect shower particles (muons) on the surface detectors via Cherenkov radiation (SD)

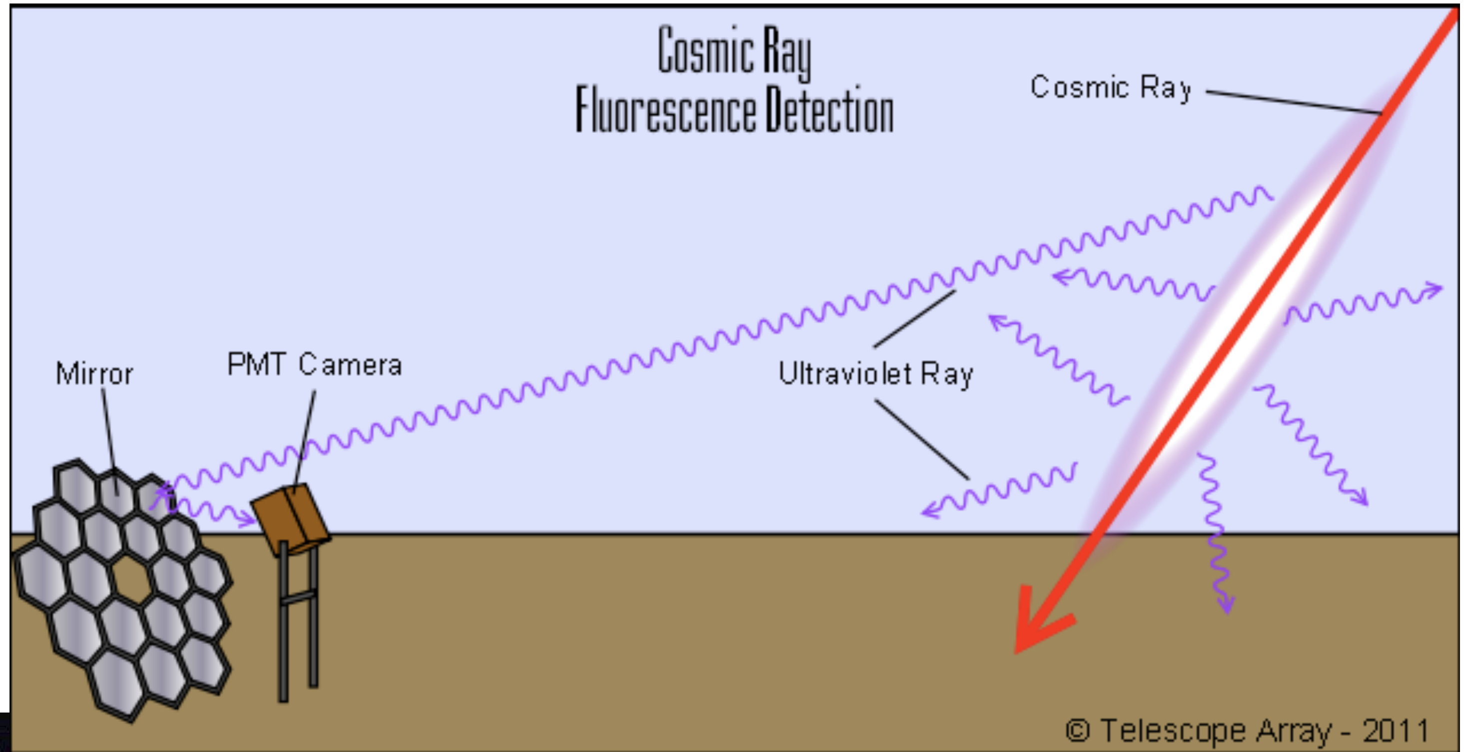


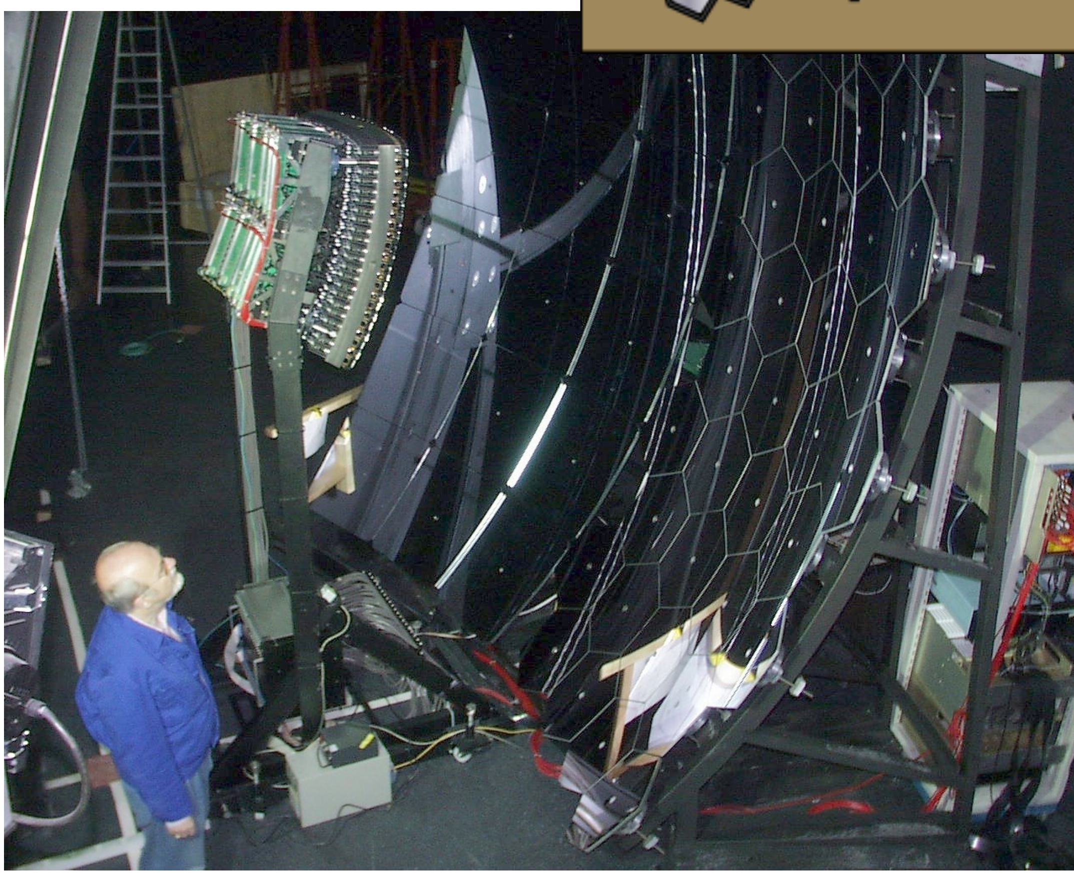
Hybrid FD and SD technique



SD

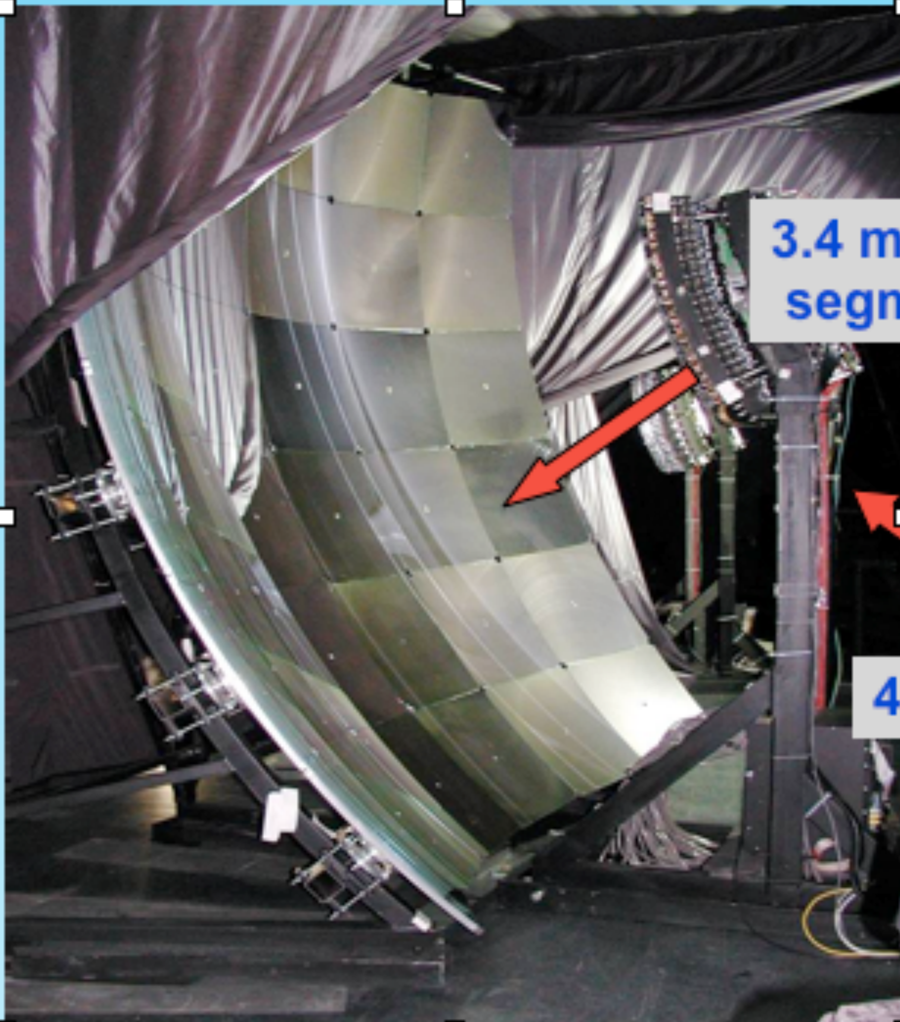
FD → schematic



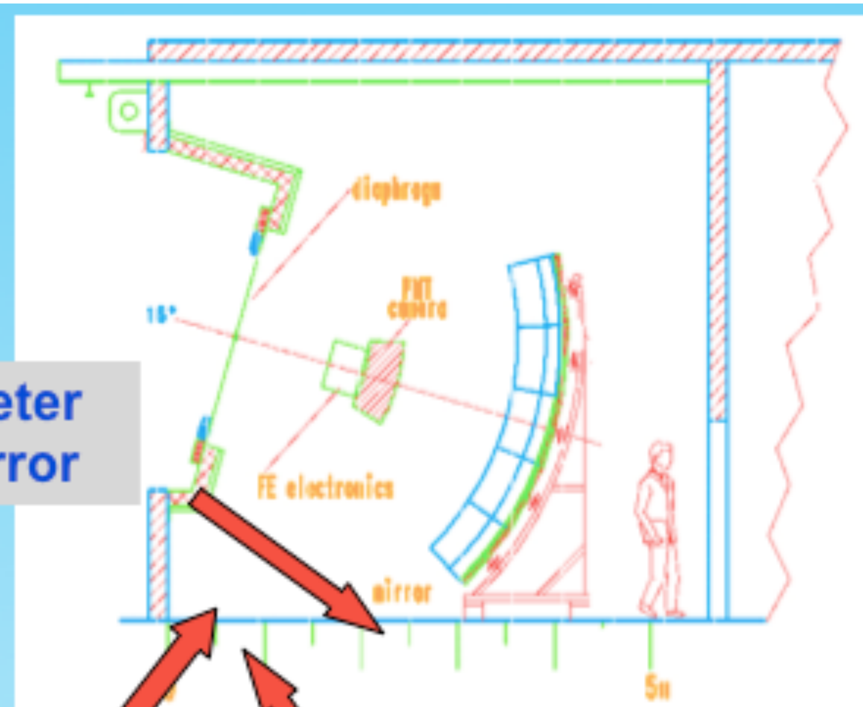


← ***FD*** mirrors & prime focus

Fluorescence detector (FD)

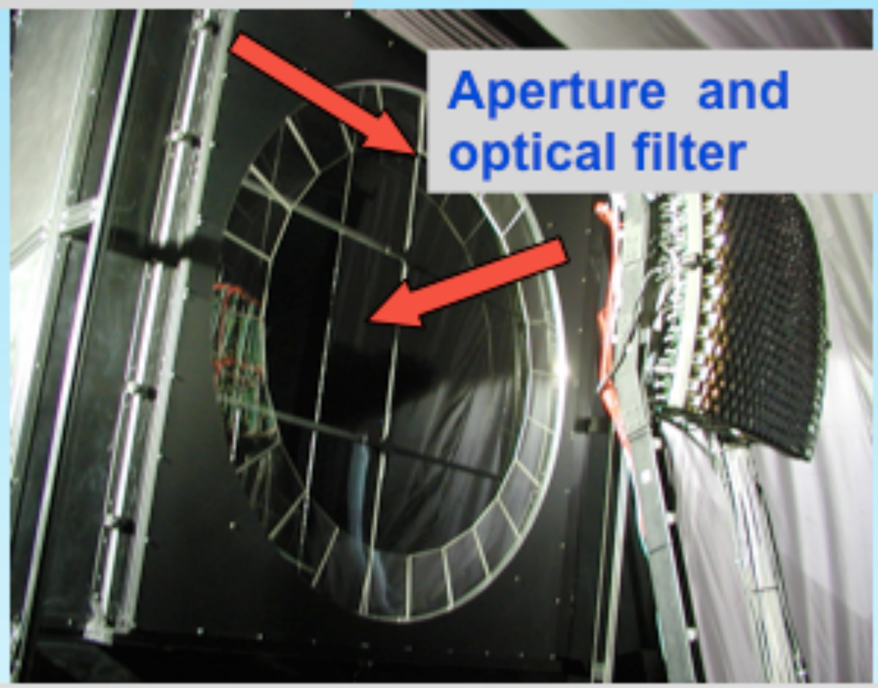


3.4 meter diameter segmented mirror



440 pixel camera

Aperture and optical filter

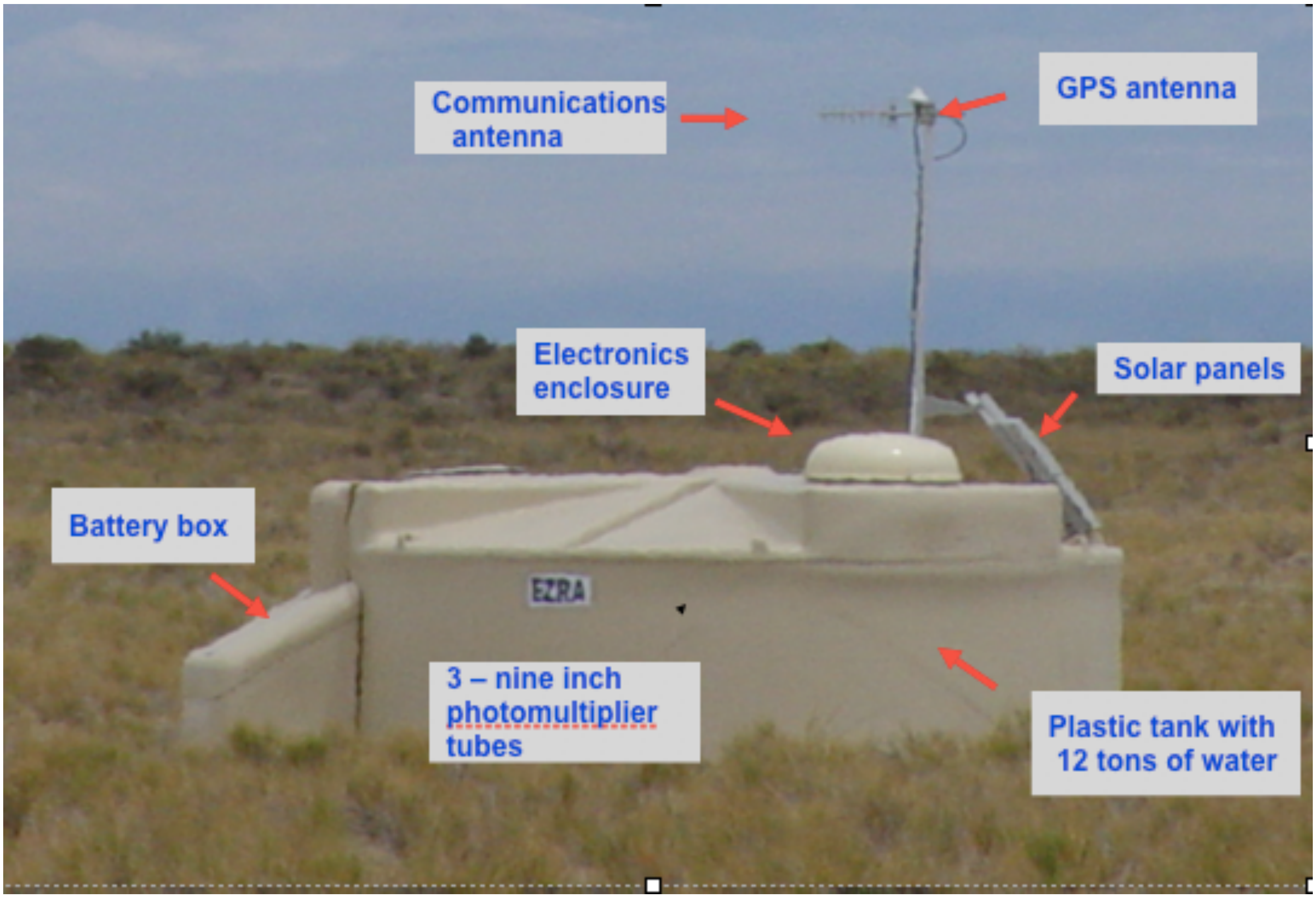


e± impact on N_2 molecules →
fluorescence light observed by FD

SD

surface detector

Measure Cherenkov light from charged particles (muons) entering water tanks



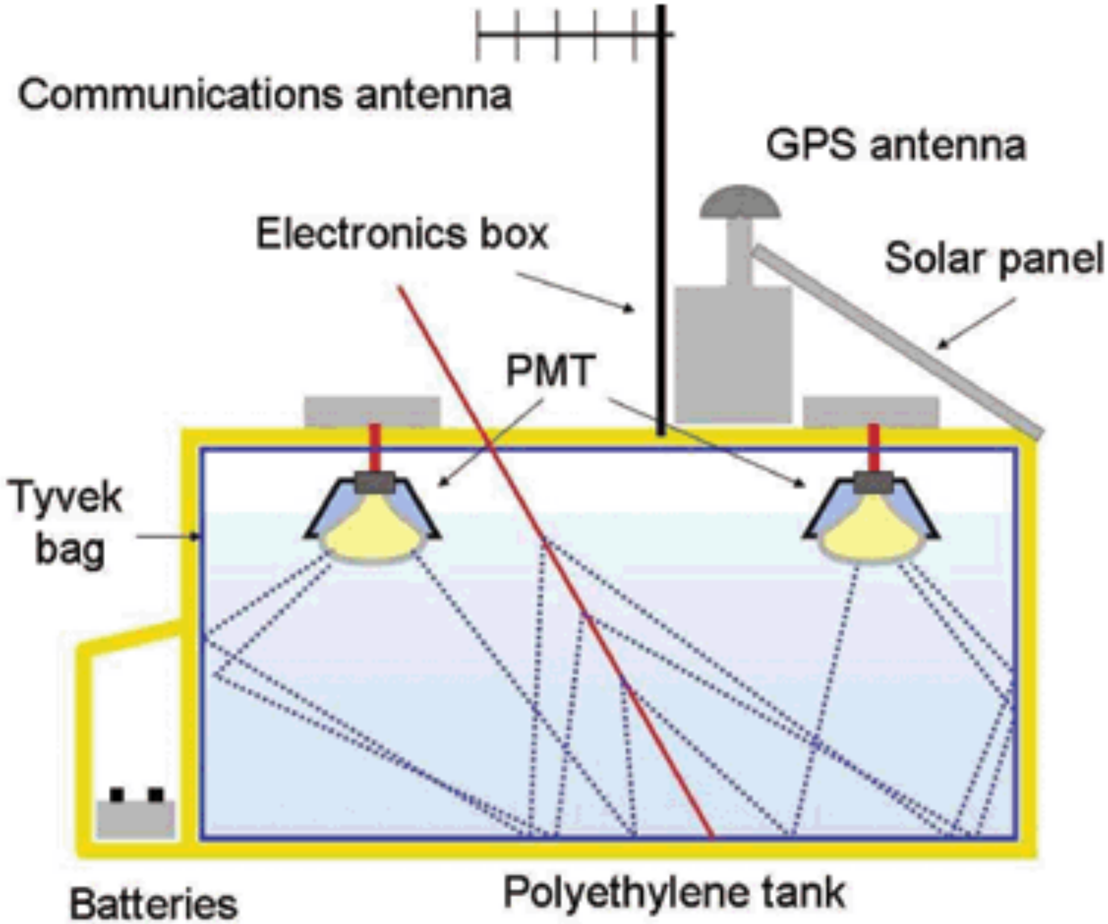
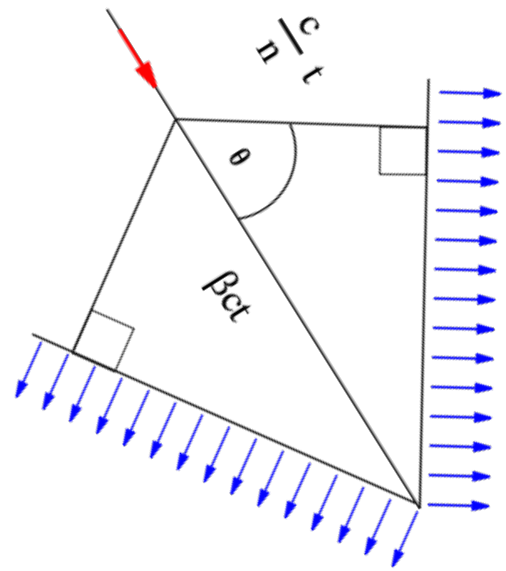


FIG. 2: A schematic view of the Cherenkov water tanks, with the components indicated in the figure.

SD

surface detector



- Left : SD collecting in its PMTs the Cherenkov light emitted by muon
- Right: Geometry of Cherenkov light cone emission y relativistic particle in a medium

Surface detector (SD)

Muons from shower ⟶ Cherenkov light in water tank, detected by phototubes

Pierre Auger Observatory: Malargue, Mendoza, Argentina: ***$E \sim 10^{17} - 10^{21}$ eV***

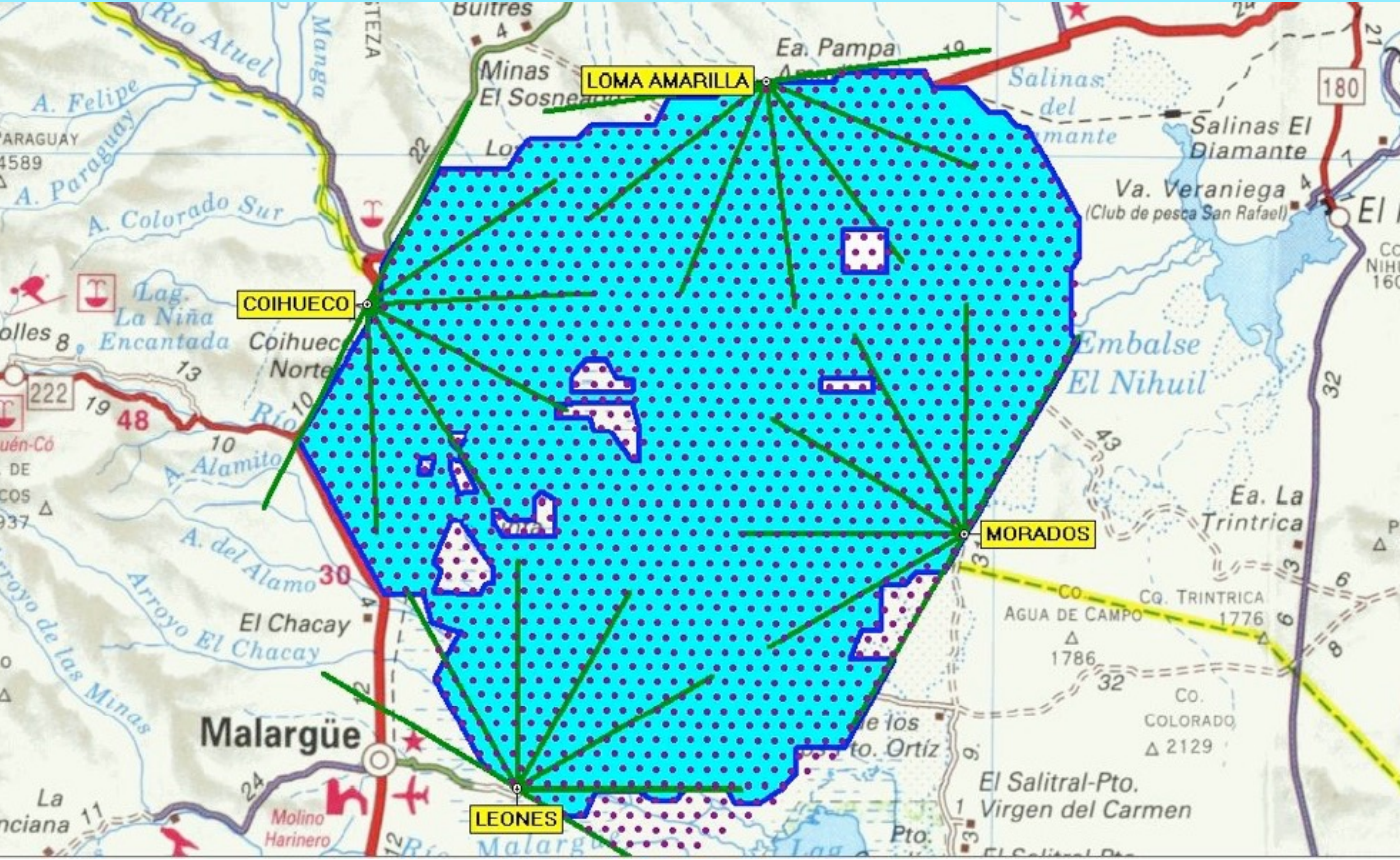
-***1600 surface detectors***: water Cherenkov tanks, 11 kliters ea., 1.5 km apart

-***32 air fluoresence telescopes***, 4x8 arrays of 30x30 deg. sky coverage

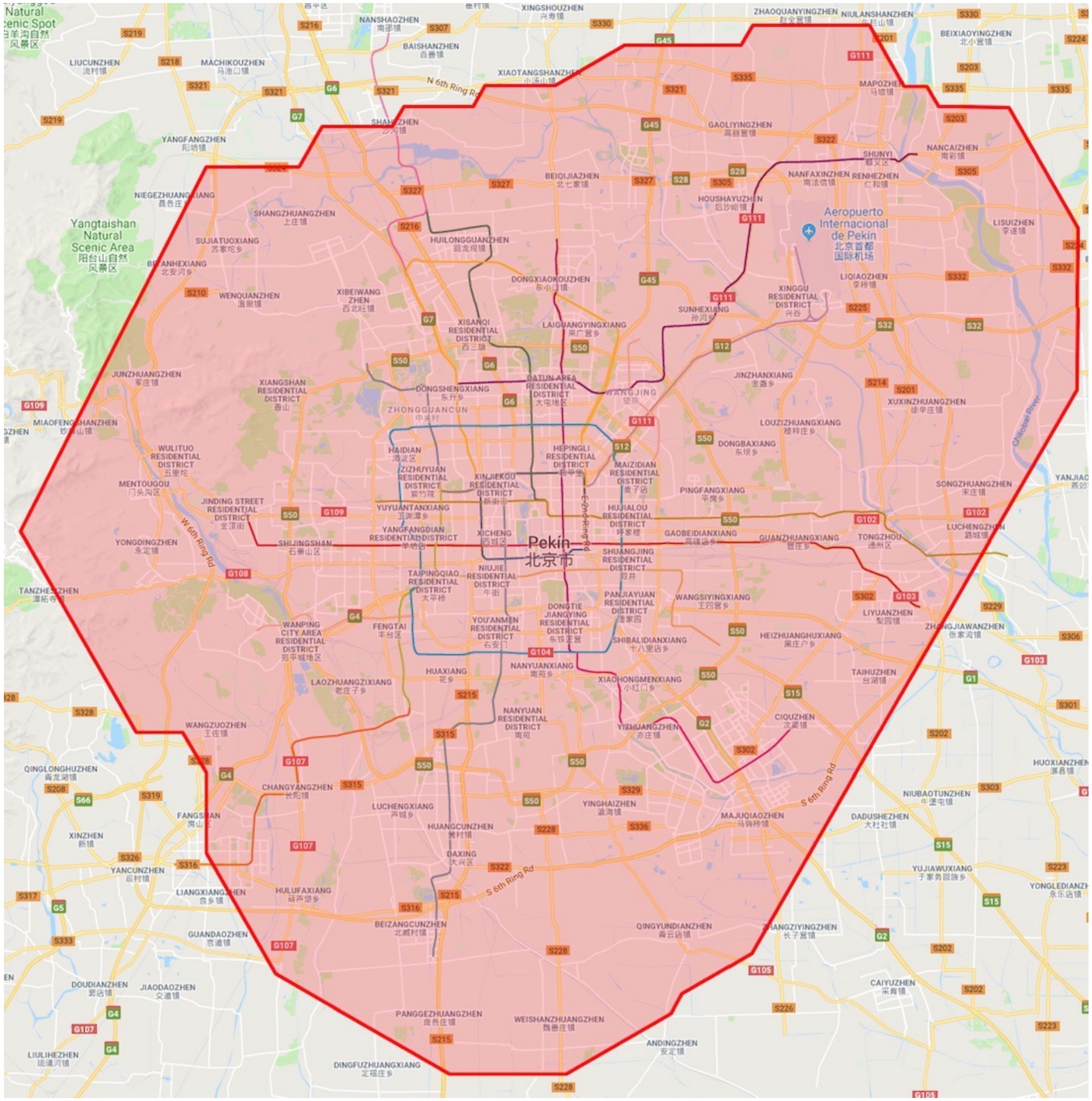
-Also: ***tau-nu*** (horiz.l shower capability: Earth-skimming & through Andes)

Auger Obs. - 3000 km^2 ***UHECR*** detector

Mendoza, Argentina

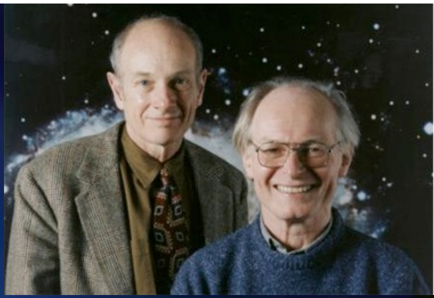


Surface areas of Auger and Beijing



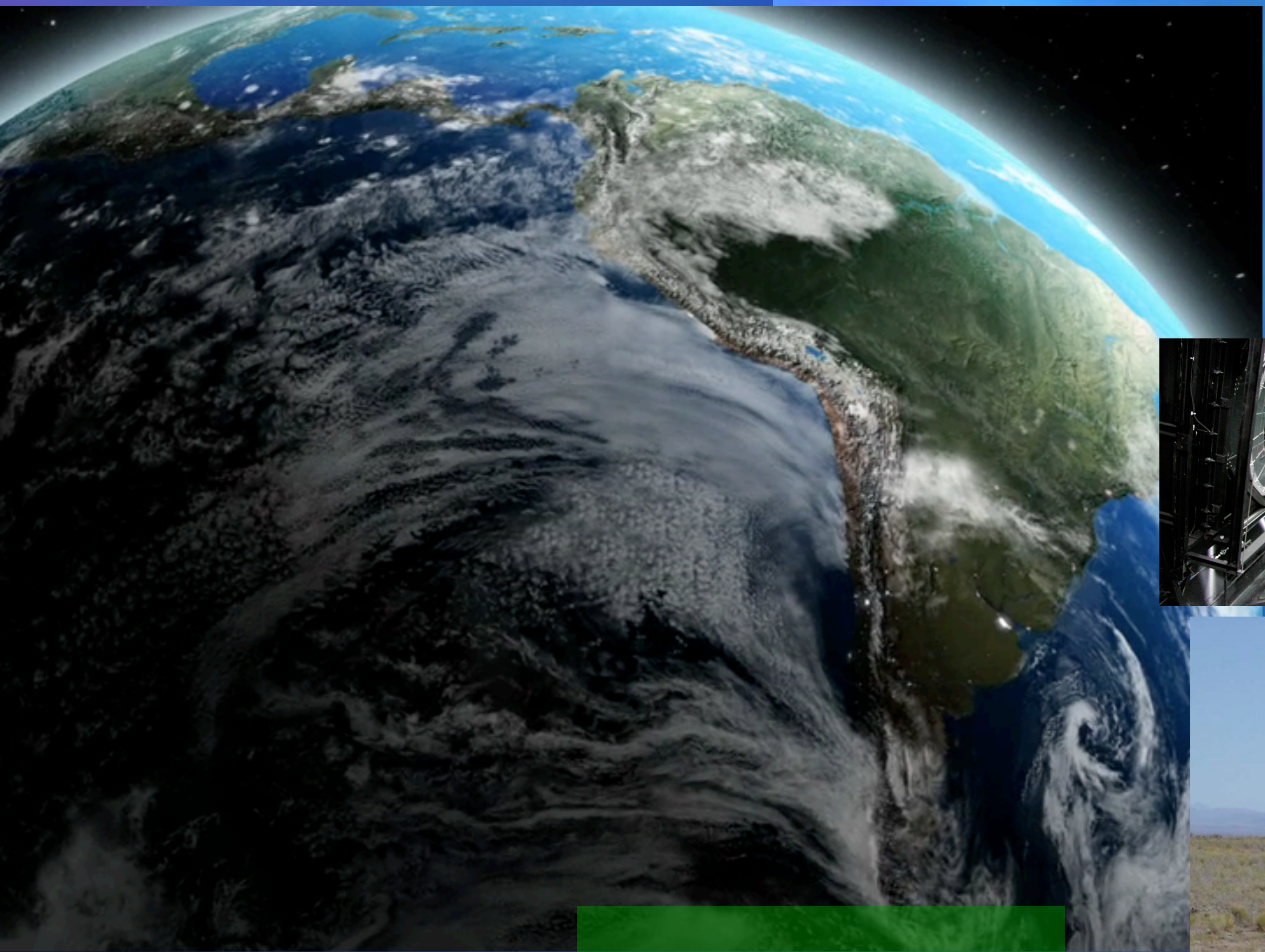
The Pierre Auger Observatory

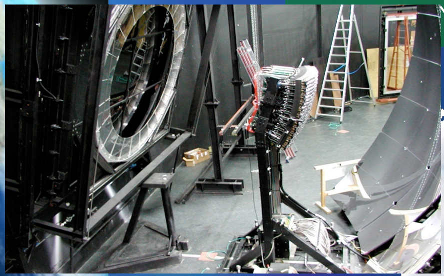
(in Argentina, Malargue, Prov. Mendoza)



Jim Cronin
Alan Watson

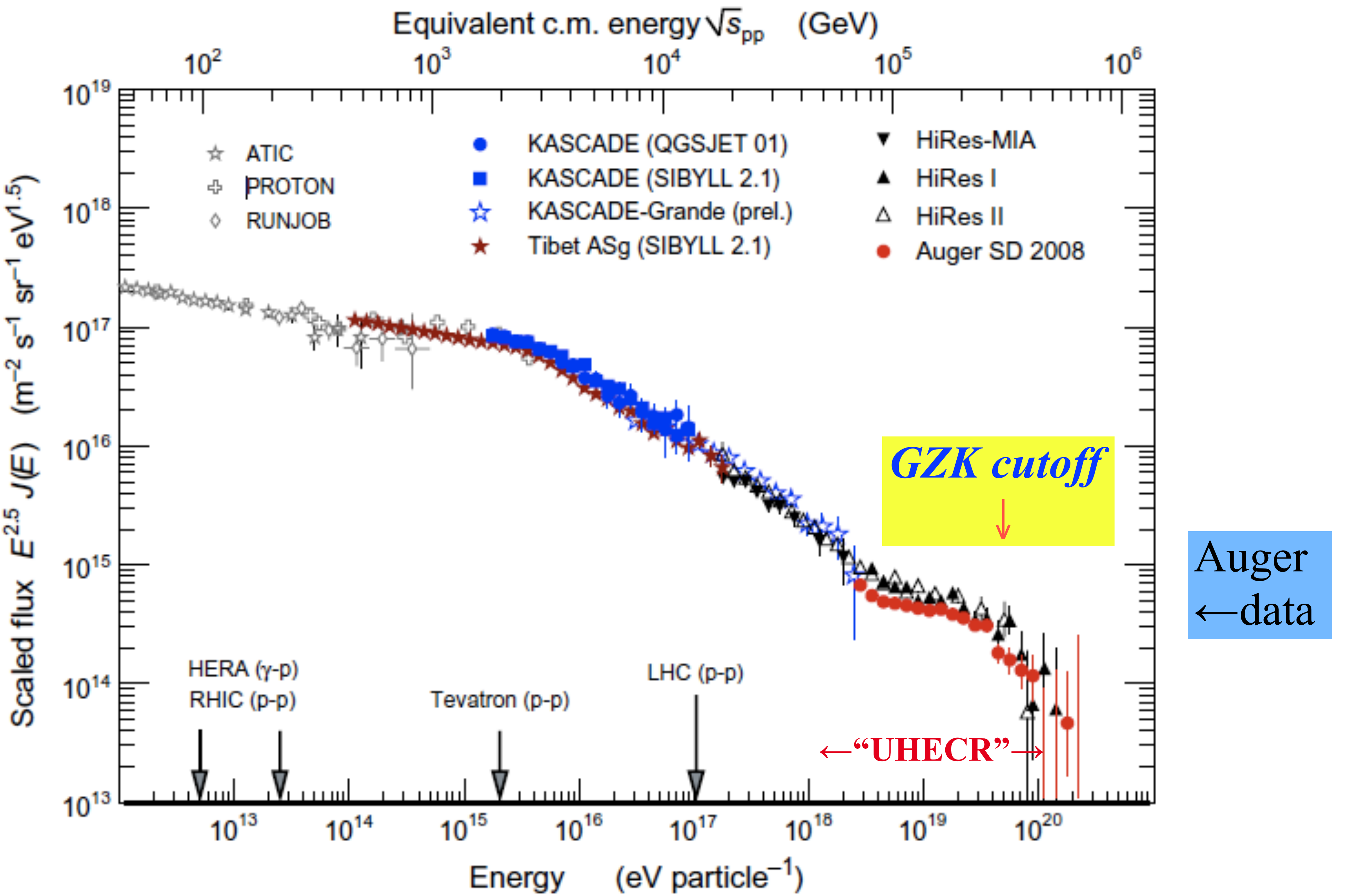
Fluorescence Detectors
4 Telescope enclosures
6 Telescopes per enclosure
24 (+3) Telescopes total





Surface Array
1663 detector stations
1.5 km spacing
3000 km²

Cosmic ray spectrum (2008)



GZK cut-off

- ***"GZK"*** = Greisen-Zatsepin-Kuz'min (1967)
- ***"UHECR"*** = ultra-high energy cosmic ray, roughly 10^{18}-10^{21} eV = 10^{-2} -10 E_{GZK}
- ***E_{GZK}*** ~ 10^{20} eV ≡ 100 EeV (Exa-electron-Volt) ≈ 1.6×10^{8} erg ≈ 16 Joule ≈ 4 calories
- E_{GZK} ≈ fast-serve ***tennis ball*** (~ 130 km/h), or ~ 1/10 the energy of a ***bullet*** (7.65 mm, .32 cal)
- Significance: $E \gtrsim E_{GZK}$ protons encountering a ~10^{-3} eV cosmic microwave background photon undergo ***photo-hadronic*** losses, $p+\gamma \rightarrow \pi+n$

Major UHECR features expected

- GZK **cut-off** expected @ $10^{19.5}$ eV (CMB)
- Below $\sim 10^{18.5}$ eV CRs may be **galactic** origin (Larmor radius r_L in B~μG ≲ size of galaxy)
- At $\gtrsim 10^{18.5}$ eV CRs must be ***extragalactic*** origin ($r_L > R_{gal}$), could have ≠ ***spectrum***
- Depth of maximum atmospheric penetration $\mathbf{X_{max}}$ is expected to be **shallower** for **heavy** nuclei (and with less variance) than for protons

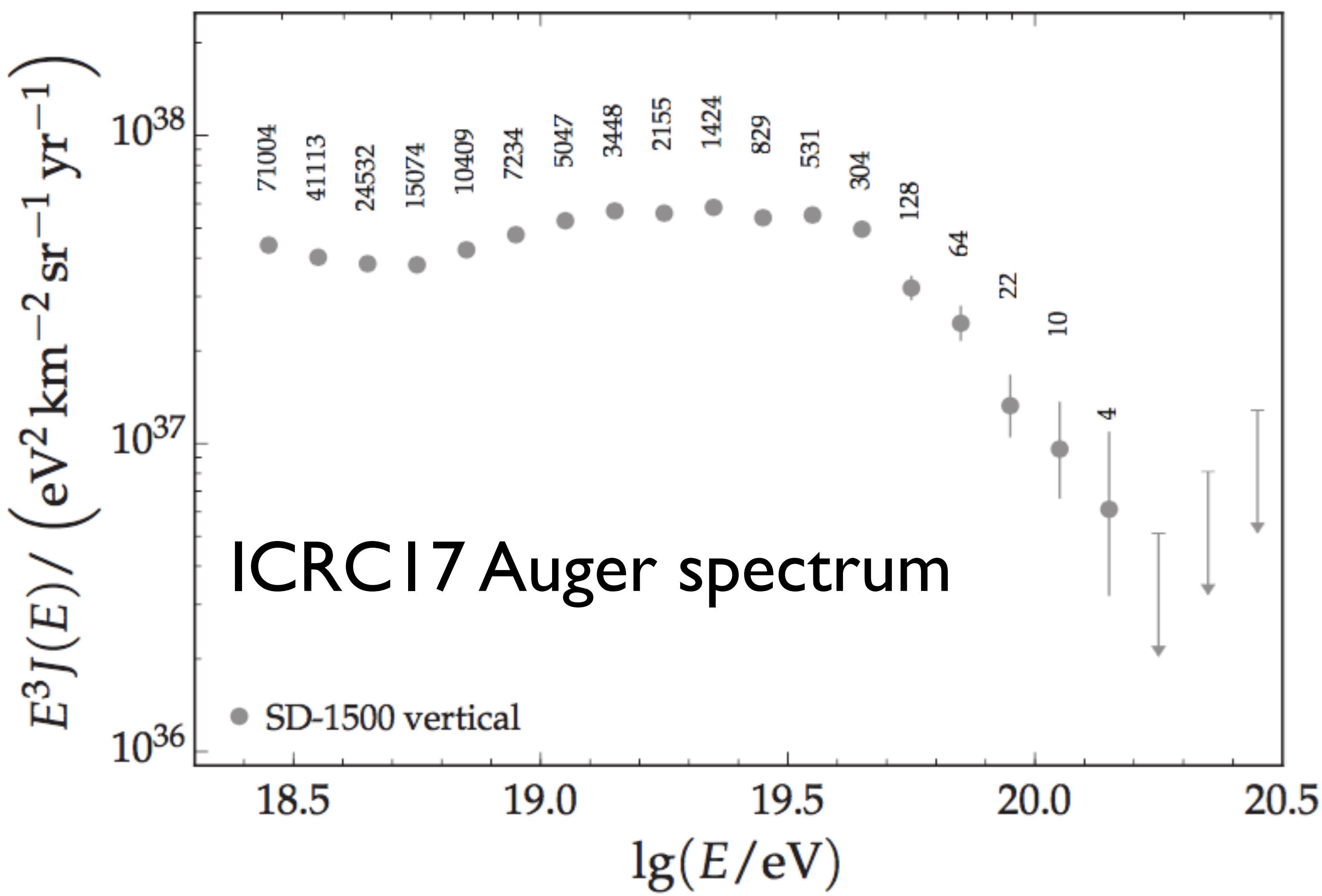
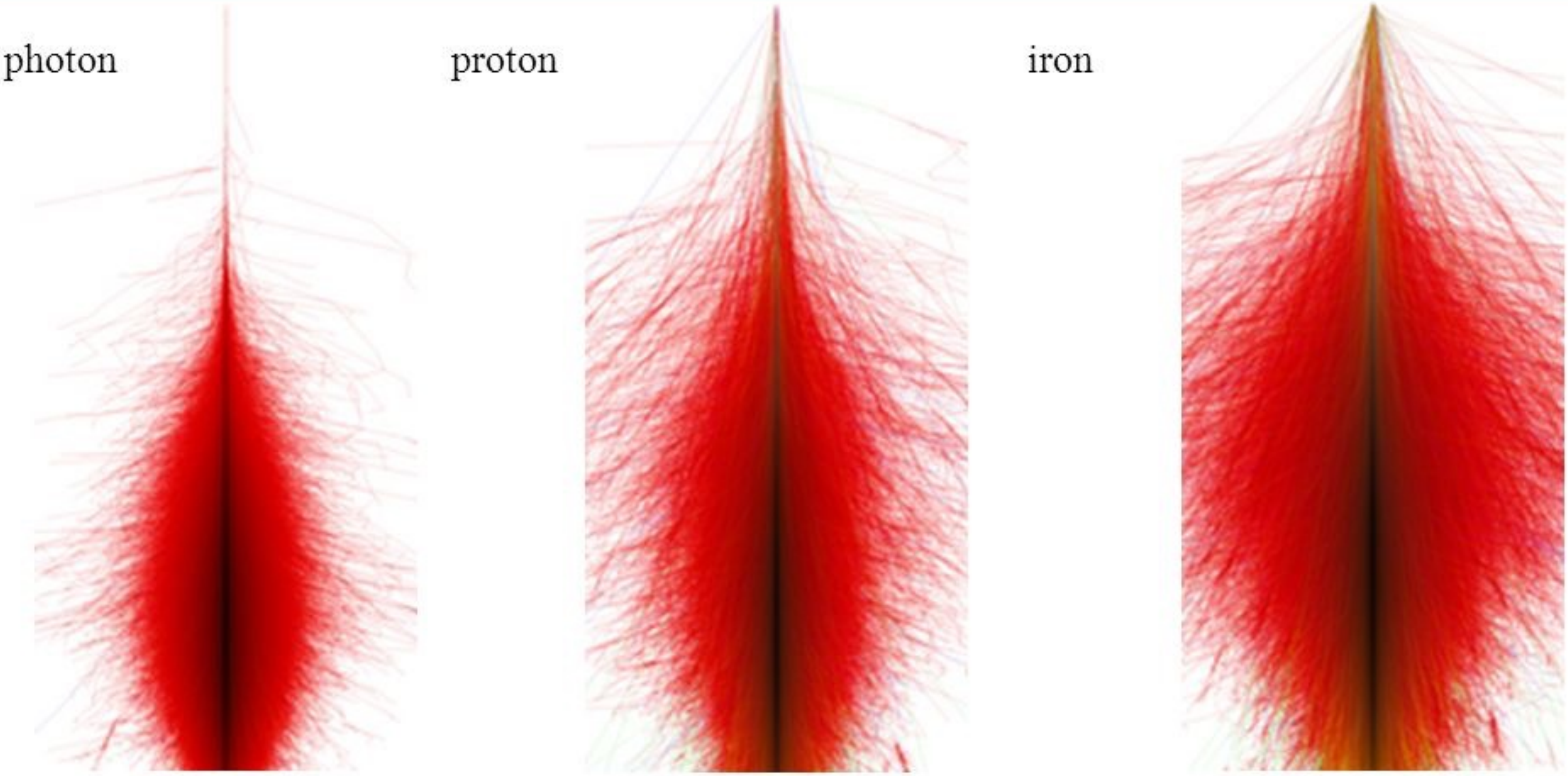


Figure 2: The unfolded spectrum for the SD 1500 vertical sample. The number of events is shown for each bin. The error bars represent statistical uncertainties. The upper limits correspond to the 84% C.L.

Monte Carlo simulations of

Photon, Proton and Iron Induced Air Showers

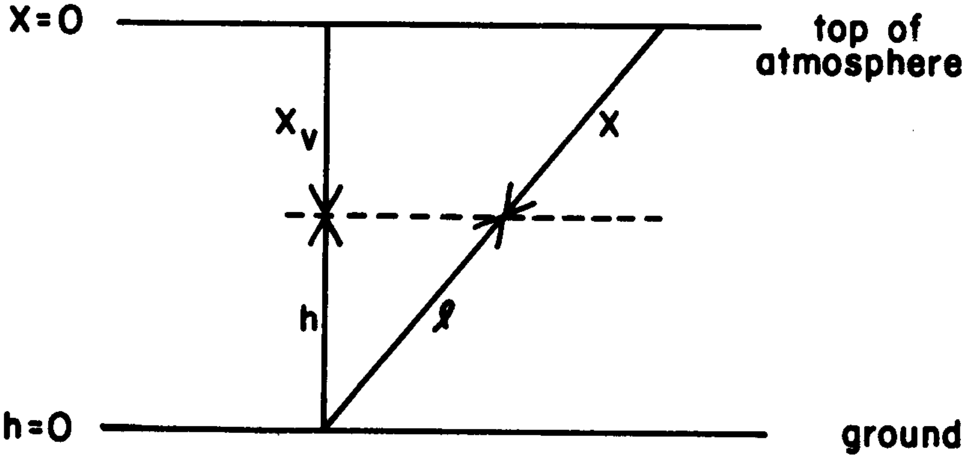


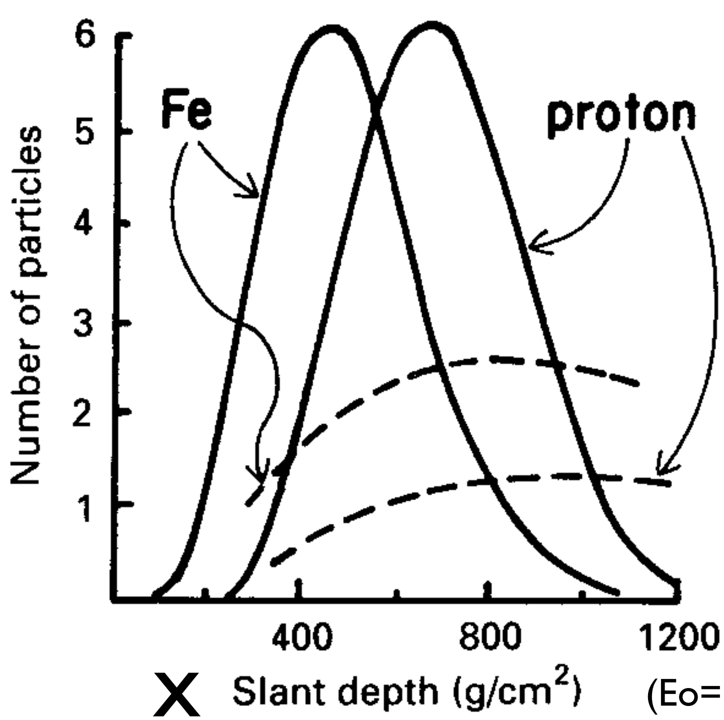
Vertical (z-) axis range is 30 km. First interaction at a height of 30 km. The shower is projected onto the x-z plane. Horizontal (x-) axis range is +/- 5 km around the shower core. Energy: 100 TeV. Vertical injection of the cosmic ray particle. Colors: e+,e-,photons (red) / muons (green) / hadrons (blue) (red+green -> yellow)

(www.ast.leeds.ac.uk/~fs/showerimages.html)

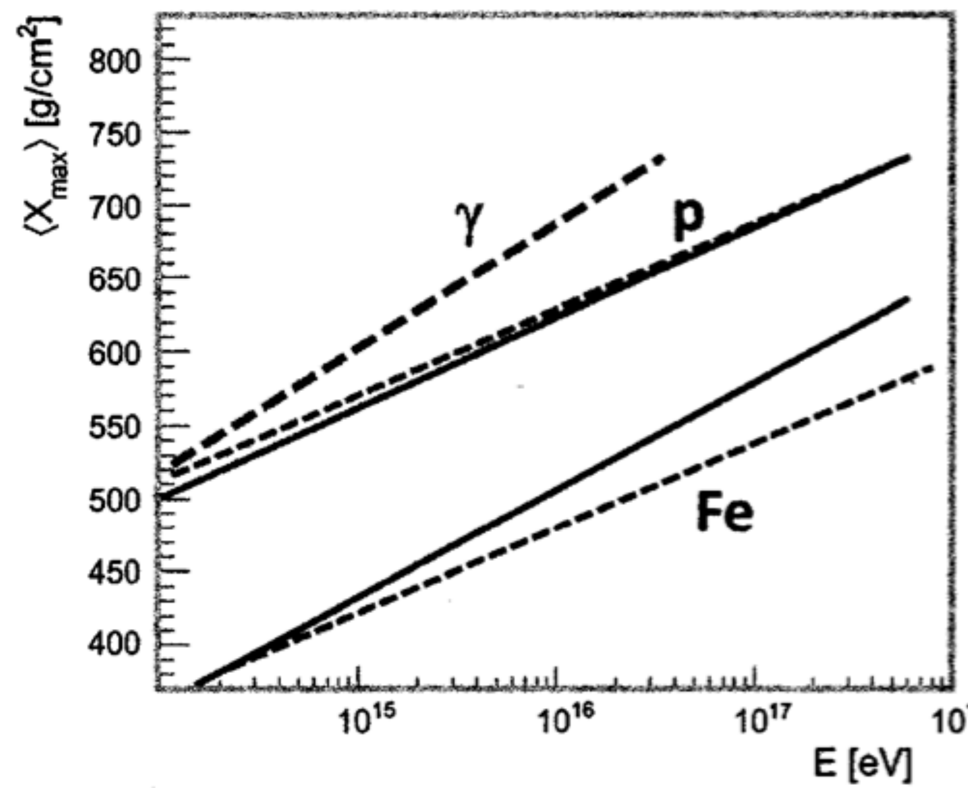
Shower development

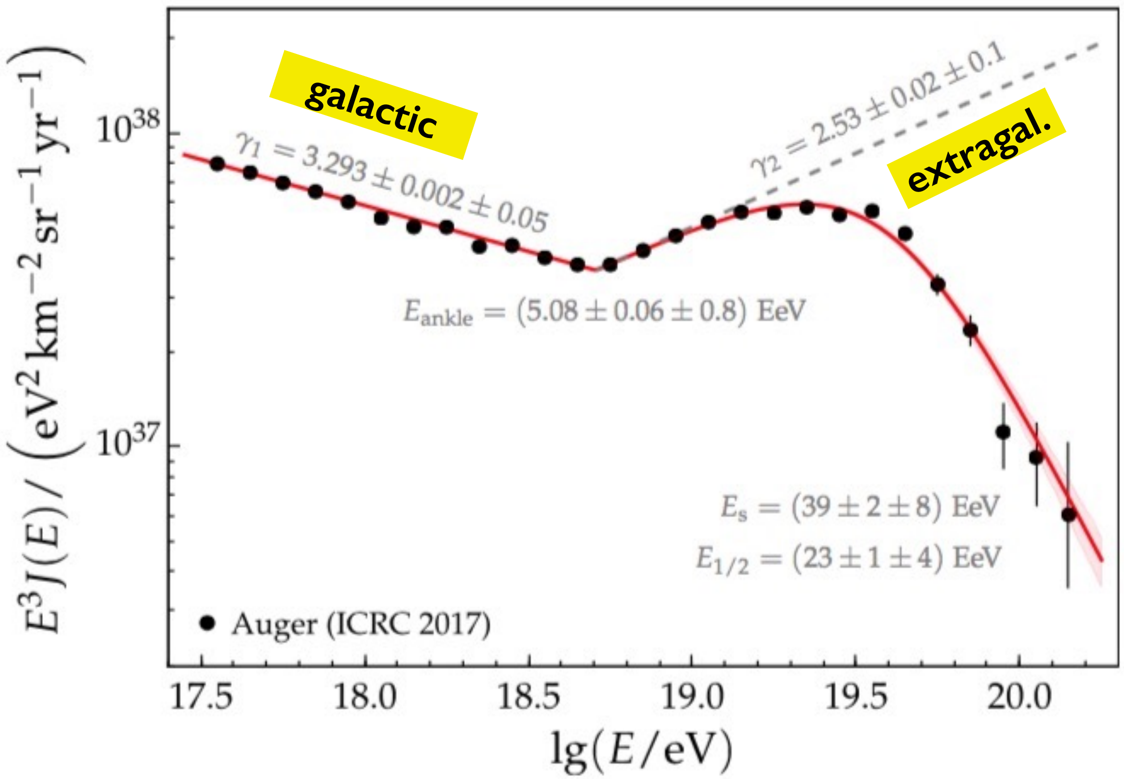
- ←Vertical depth X_v slant depth X
- ↙Fe and p shower maximum vs. X
- ↓ Xmax vs. energy for γ, p and Fe





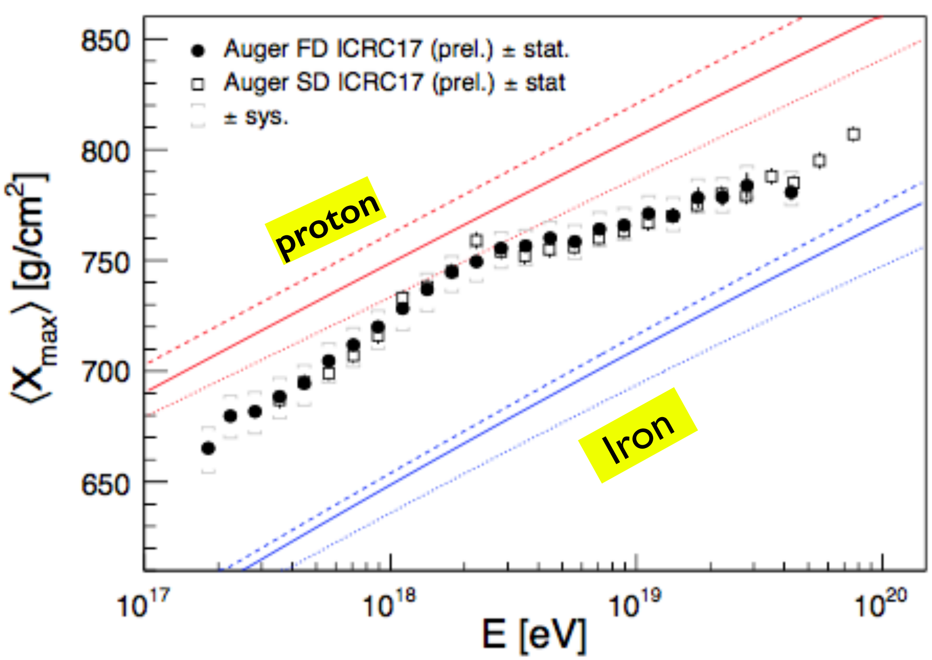
(Eo=10^7 GeV)

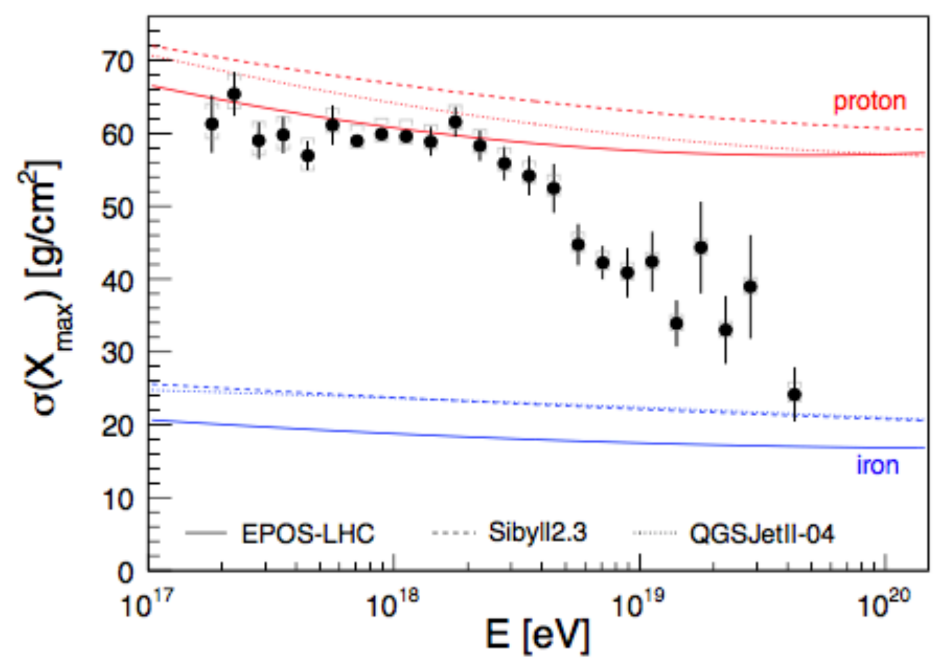




Auger ICRC 17

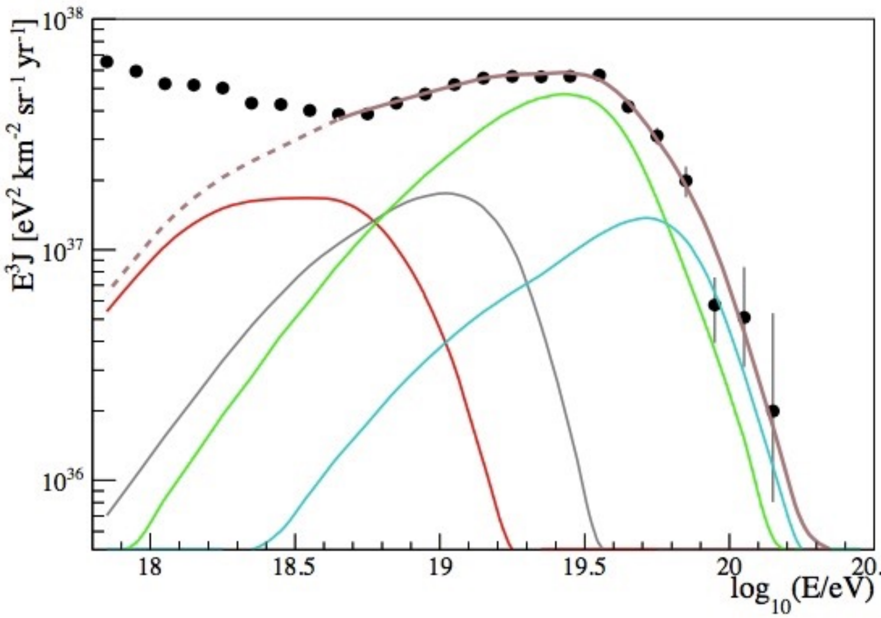
Spectrum & composition, $[X_{max}, Var(X_{max})]$



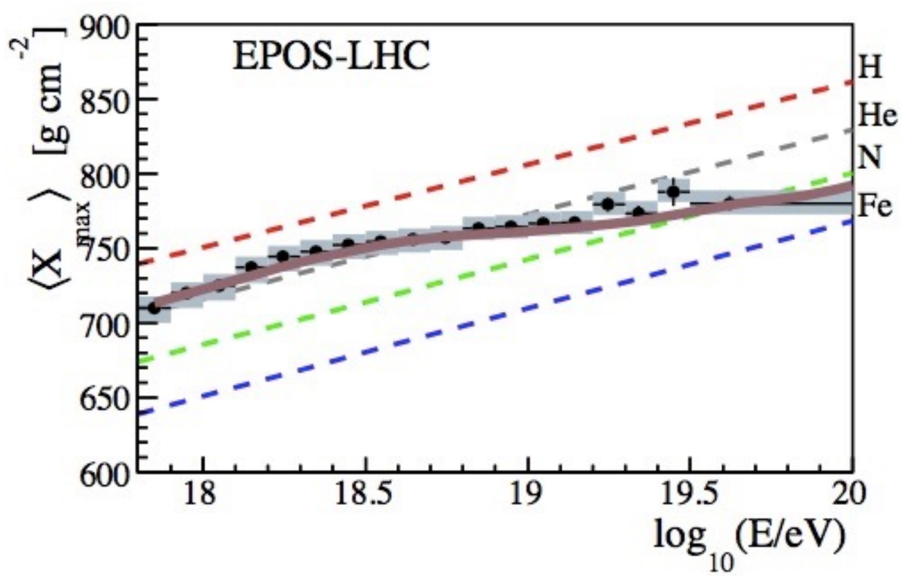


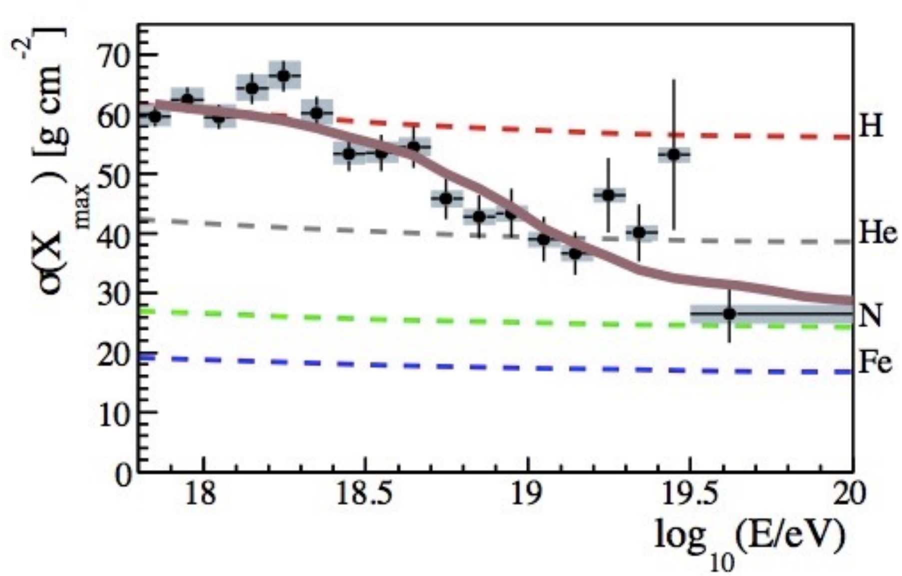
Phenomenological fit to Auger data

An ***ad-hoc spectral and composition*** best-fit using EPOS-LHC hadronic model (Mollerach & Roulet 2017) where atomic numbers A :



A=1:	red
A=2-4:	grey
A=5-22:	green
A=23-38:	cyan





Raw interpretation of Auger data phenom. fit:

- Transition gal-extragal @ $10^{18.7}$ eV ***favored***
- Injection spectral slope ***s~ -1 favored*** above ankle (hard slope!)
- ***s~-2*** strongly ***disfavored*** by X_{max} distribution
- X_{max} and $\sigma(X_{max})$ ***favor*** significant fractions of ***medium-high A*** (heavy) elements
- EPOS-LHC favored over Sybill2.1 , QGSJet04

But:

Can interpret a spectrum+composition fit with physically motivated sources?

- Most previous arguments considered **HL GRB**s, i.e. the "classical", high-luminosity GRBs

- In favor of this: HL GRBS have shock accelerators, right energies, source numbers (Waxman'95, …)
- Against: for HL GRBs one expects a HENU-UHECR connection : **IceCube** say that HLGRB/HENU are ***not*** correlated, providing limits on UHECR contribution
- However: this is GRB model-dependent, to resolve issue need more data (Waxman, He+, Hummer+)

Other ***variations*** on the ***HL*** GRB theme :

- HL GRBS: High $\tau_{p\gamma}$ makes HENU but kills CRs, while low $\tau_{p\gamma}$ allows CR escape without HENU (Rachen+, Bustamante+, etc)
- HL GRBs: High photon (high $\tau_{p\gamma}$) regions could be $\neq$ shocks where CR accelerated (Asano+PM)

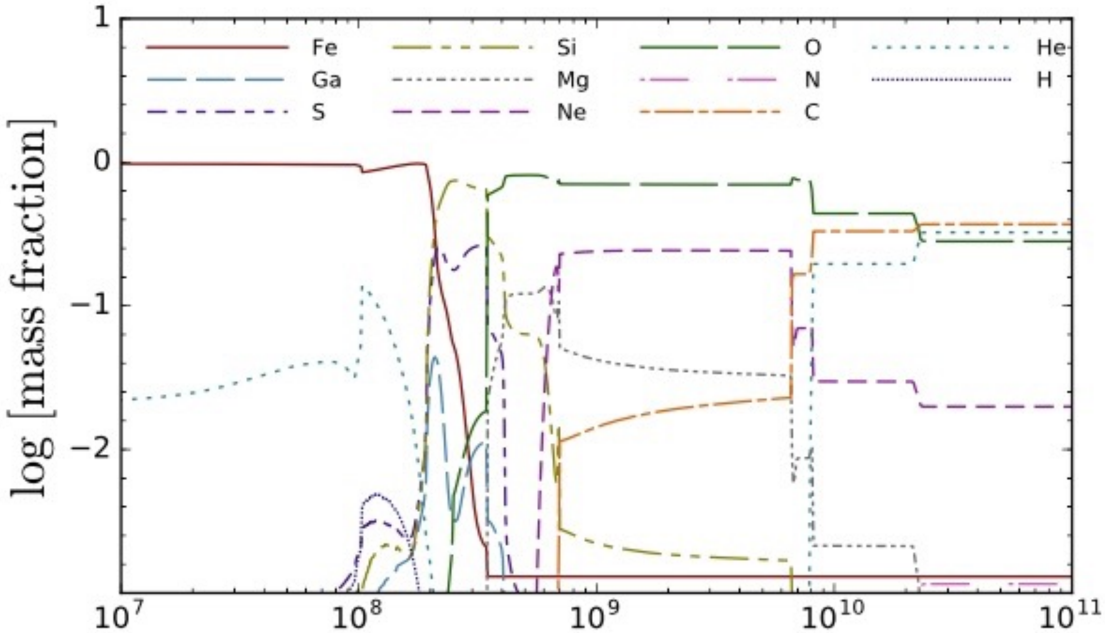
Or, a different alternative ?

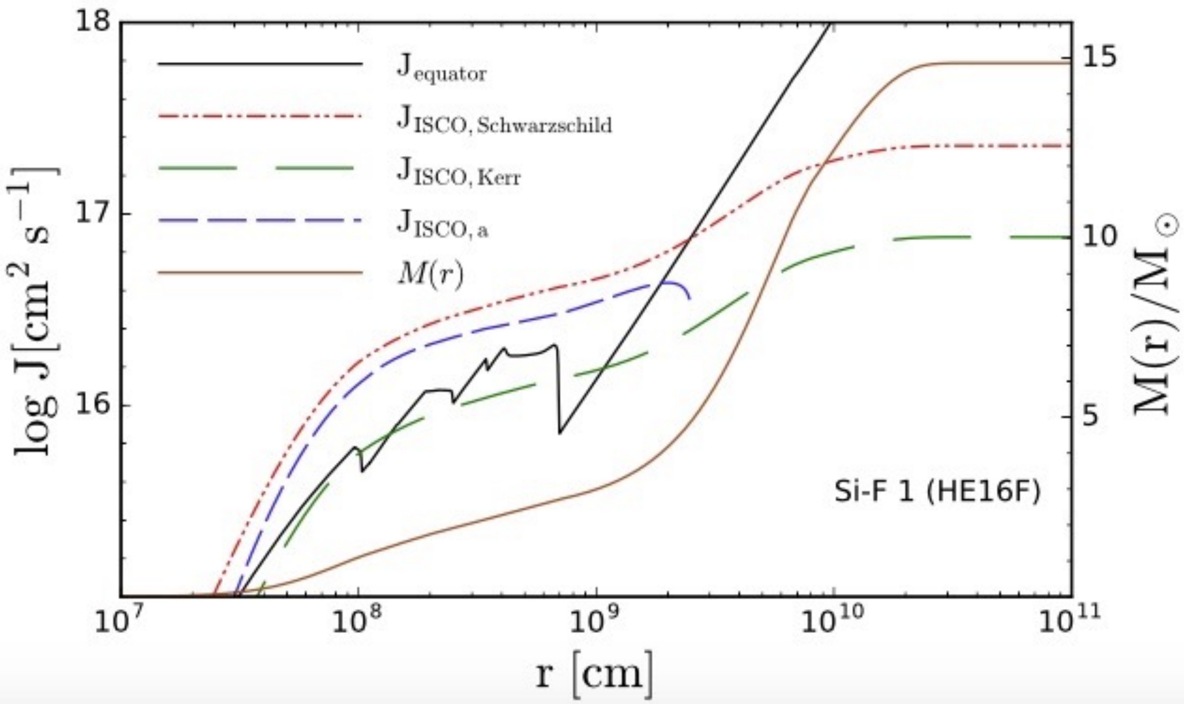
- **LL GRB**s (instead of LL GRBs) could produce UHECR and/or νs (B. Zhang, Murase,…)
- Source rate much higher than for HLGRBs
- energetics, $\tau_{p\gamma}$ appear to be adequate
- They are a γ-faint (EM detection difficult)

consider

Low-luminosity GRBs as the sources of UHECR nuclei (heavies too)

B.T. Zhang, K. Murase, S. Kimura, S. Horiuchi, P. Mészáros, PRD'18, in press, 1712.09984





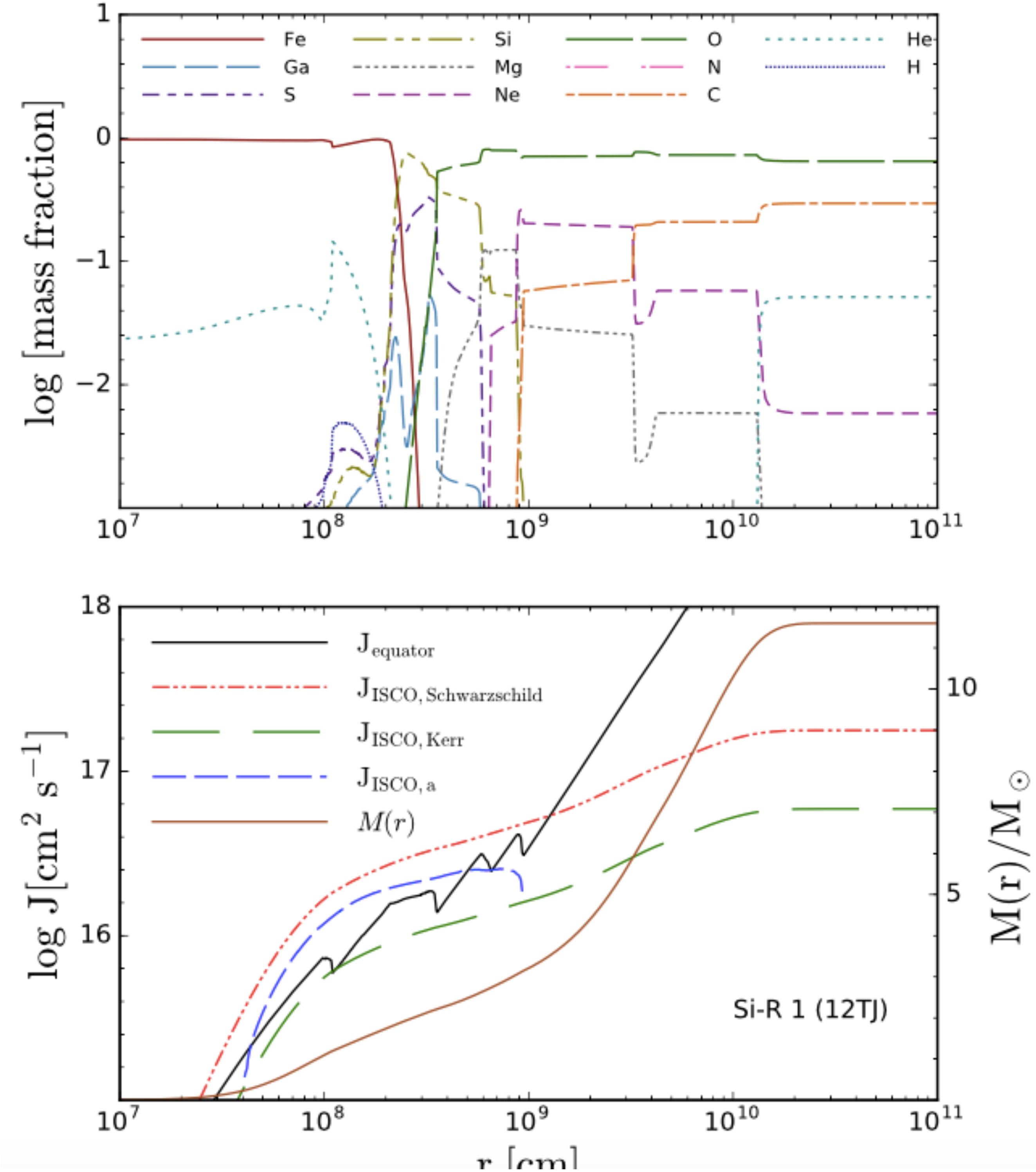
GRB progenitor stellar models

(Woosley & Heger'06)

Several fast-rotating pre-supernova WR *, ≠initial chem. comp. ←e.g. a Si-poor one

Top: chemical comp. vs. radius
Bot: specific ang. momentum J_{ISCO} at ISCO vs. radius

$$J_{\rm ISCO} = \frac{2GM_{\rm BH}}{3^{3/2}c}\left[1 + 2\left(3\frac{r_{\rm ISCO}}{r_g} - 2\right)^{1/2}\right]$$



But:

- ≠ progenitor models lead to ≠ chemical (A) distribution vs. radius, and
- also $\neq J_{ISCO}$ vs. radius distrib.
- ←e.g. , Si-rich model Si-R-1

Jet chemical composition is characterized by that of the progenitor star at ~ r_{ISCO}

$$J_{\rm ISCO} = \frac{2GM_{\rm BH}}{3^{3/2}c}\left[1 + 2\left(3\frac{r_{\rm ISCO}}{r_g} - 2\right)^{1/2}\right]$$

where $r_g = GM_{\rm BH}/c^2$ and

$$r_{\rm ISCO} = \frac{GM_{\rm BH}}{c^2}\{3 + z_2 - [(3 - z_1)(3 + z_1 + 2z_2]^{1/2}\},$$

with

$$z_1 = 1 + (1 - a_{\rm BH}^2)^{1/3}[(1 + a_{\rm BH})^{1/3} + (1 - a_{\rm BH})^{1/3}],$$

and

$$z_2 = (3a_{\rm BH}^2 + z_1^2)^{1/2}.$$

- J_{ISCO} = spec. mom. of last inner stable circular orbit, occurs at **r_{ISCO}**
- Inside **r_{ISCO}** matter falls in
- Jet launched from **r >r_{ISCO}**
- **Chem**ical comp. of jet is that. of star at r > **r_{ISCO}**

GRB Pre-SN models used

TABLE I. Jet nuclei composition models

Models[a]	M_{init}[b] $M_\odot$	M_{final}[c] $M_\odot$	$\mathcal{J}_{core}$[d] 10^{47} erg s	r_c[e] 10^9 cm	M_c[f] $M_\odot$	Jet nuclei composition[g] C	O	Ne	Mg	Si	S	Fe
Si-F 1 (HE16F)	16	14.80	114	1.9	4.1	0.018	0.698	0.243	0.036			
Si-F 2 (16TI)	16	13.95	87	2.0	3.3	0.022	0.695	0.247	0.034			
Si-R 1 (12TJ)	12	11.54	150	0.5	2.5		0.603			0.351	0.046	
Si-R 2 (16TJ)	16	15.21	178	0.6	2.5		0.511			0.364	0.108	
Si-R 3 (35OC)	35	28.07	230	1.2	3.9		0.157			0.421	0.303	
Hypernova	–	–	–	–	–	0.006	0.710	0.036	0.034	0.083	0.041	0.090

[a] Presupernova models calculated in Ref. [67].
[b] The initial mass of GRBs progenitors.
[c] The final mass of GRBs progenitors at the onset of core collapse.
[d] The angular momentum of the iron core at core collapse.
[e] Critical radius in the progenitors where accreting material starts to form the accretion disk.
[f] Enclosed mass within the critical radius r_c.
[g] Jet nuclear composition. The blank space means that nuclei have mass fraction less than 0.01. The last row represents the hypernova ejecta composition.

Si-F indicates the Si-poor initial stellar models
Si-R indicate Si-rich (by comparison to above)

Another possibility for jet composition:

Jet through Hypernova

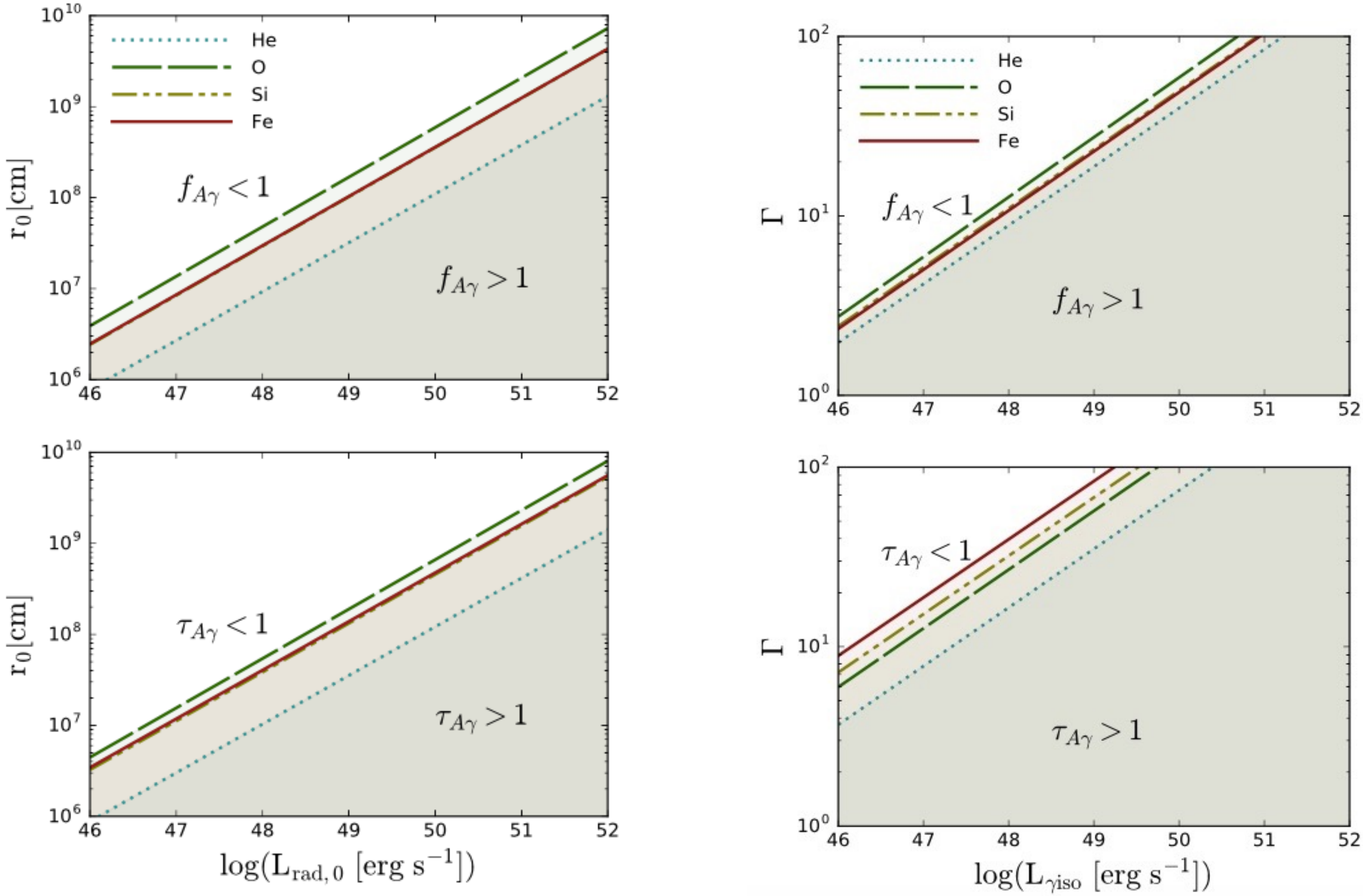
- In hypernovae heavy nuclei may be synthesized in the semi-relativistic shocked ejecta
- if semi-relativistic ejecta is launched before the jet goes through it, jet will entrain a nuclear mass fraction similar to that of the ejecta
- Used ejecta model CO138E50 (Nakamura+ '01) which reproduces light curve of SN1988bw

Heavy nuclei acceleration & survival in jet

- Assume usual internal shock Fermi acceleration of protons and nuclei of atomic weight A
- Jet photon luminosity $L_{\gamma,iso}$ determines survival of nuclei A against photodesintegration and photomeson
- Broken power law (Band) photon spectrum

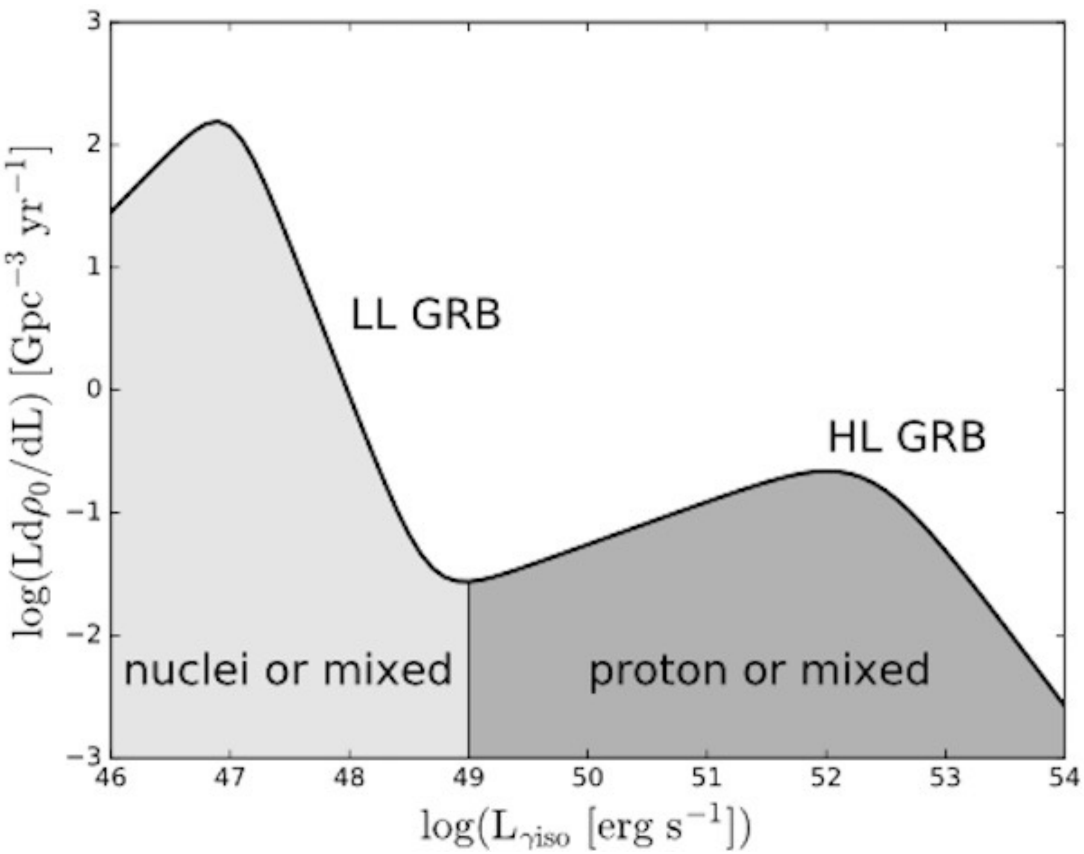
$$\frac{dn}{d\varepsilon} = \frac{(L_{\gamma iso}/5)e^{-\varepsilon/\varepsilon_{max}}}{4\pi r^2\Gamma^2 c\varepsilon_b{}^2}\begin{cases}(\varepsilon/\varepsilon_b)^{-1} & (\varepsilon_{min} \le \varepsilon < \varepsilon_b)\\(\varepsilon/\varepsilon_b)^{-2.2} & (\varepsilon_b \le \varepsilon \le \varepsilon_{max})\end{cases}$$

Constraint on initial $L_{\gamma,iso}$



$\tau_{A\gamma}$ = opt. depth (interaction efficiency); $f_{A\gamma}$ = energy loss efficiency; r_0 = base of jet

Luminosity function: LL and HL



$$\frac{d\rho_0}{dL} = A_0 \left[\left(\frac{L}{L_b} \right)^{\alpha_1} + \left(\frac{L}{L_b} \right)^{\alpha_2} \right]^{-1}$$

- LL GRB: $L_{\gamma,iso} \leq 10^{49}$ erg/s
- LF for LLGRB + HLGRB ←(Liang, Zhang, Dai '07)
- Contribution is dominated by LL GRB, but HL GRB can also contribute
- Nuclei destruction dep. on $L_{\gamma,iso}$, Γ and r_0 (r_{ISCO})

CR injection & escape spectrum

- Max. energy $ZE'_{p,max} \sim 10^{18.2}\, Z L_{\gamma,iso}^{1/2}$ eV
- Fermi I : ***injection spectrum*** is typically power law $dN'_A/dE' \sim E'^{s}$ with $s \sim 2$ (but for large angle scatt. or magnetic reconnection; may have $s \sim 1.5$)
- ***Escape spectrum*** may be ≠ than injection
- I) assume only CRs of max. energy escape
- II) or, assume escape spectrum ~ injected

CR Propagation & flux at Earth

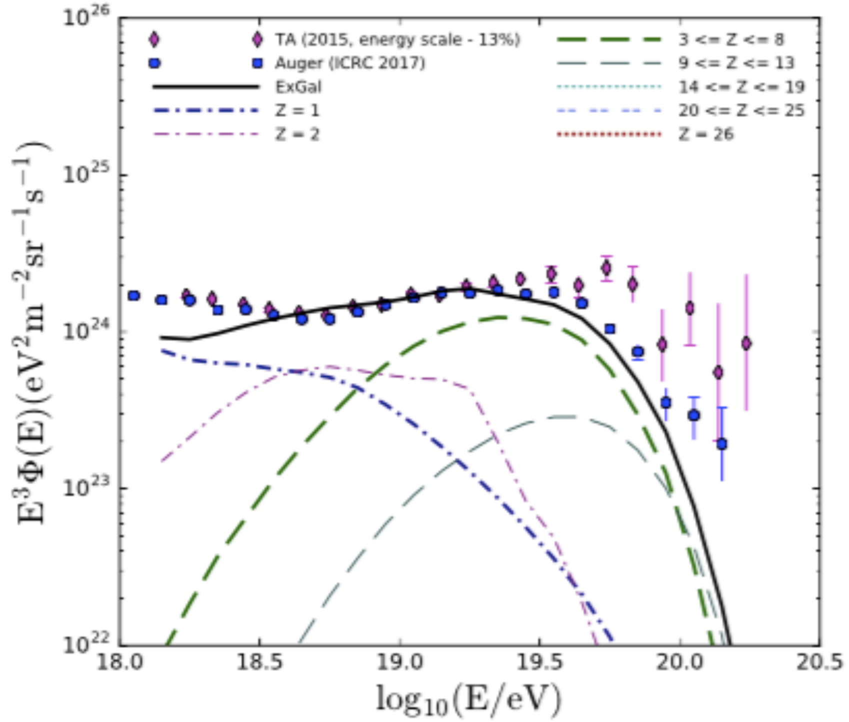
- CRPropa 3 Monte Carlo propagation of nuclei A
- The CMB and EBL fields as function of z lead to photodesintegration, Bethe-Heitler, photomeson
- Flux of nuclei A at Earth given by

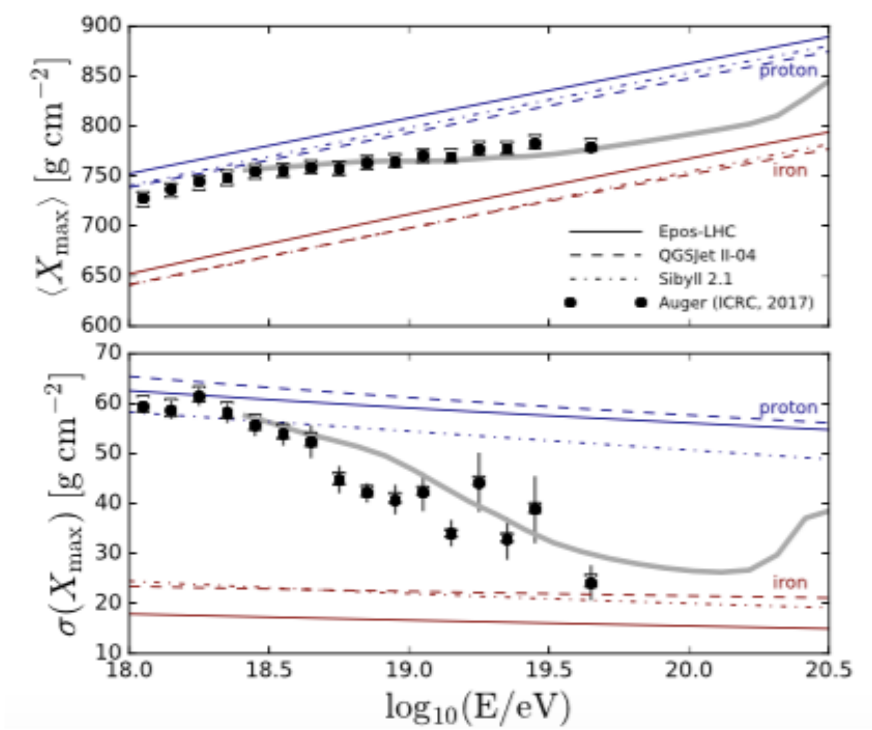
$$\Phi_A(E) = \sum_{A'} \frac{c}{4\pi} \int_{z_{\rm min}}^{z_{\rm max}} dz \left| \frac{dt}{dz} \right| F_{\rm GRB}(z) \times \int_{L_{\rm min}}^{L_{\rm max}} \frac{d\rho_0}{dL} \int_{E'_{\rm min}}^{E'_{\rm max}} dE' \frac{dN_{A'}}{dE'} \frac{d\eta_{AA'}(E, E', z)}{dE}$$

where $F_{\rm GRB}(z)$ is the redshift distribution parameter of long GRBs which trace the star formation history (SFH) [37], ρ_0 is the local event rate of GRBs, $d\rho_0/dL$ is the GRB luminosity function in the local universe [35], and $\eta_{AA'}(E, E', z)$ is the fraction of generated cosmic rays of mass A and energy E from parent particles of mass A' and energy E' [28]. The redshift range is from $z_{\rm min} = 0.0005$ to $z_{\rm max} = 2$. We use the same method as in Ref. [28] to calculate the final spectrum and the distribution of $\langle X_{\rm max} \rangle$ and $\sigma(X_{\rm max})$ [7]. In this work,

Results :

B.T. Zhang, K. Murase, S. Kimura, S. Horiuchi, P. Mészáros,
PRD'18, in press, 1712.09984

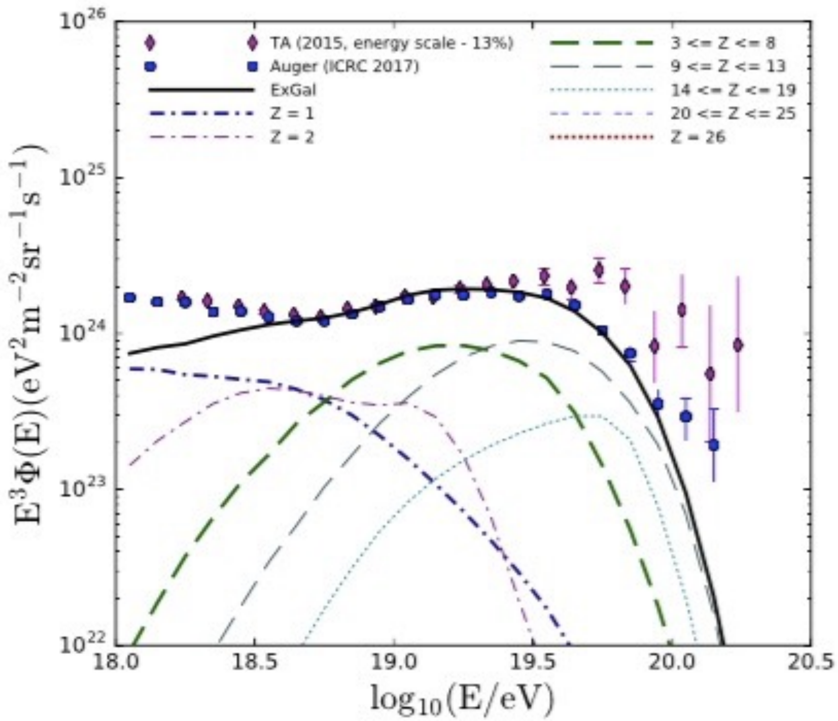




Spectrum, X_{max}, $\sigma(X^{max})$

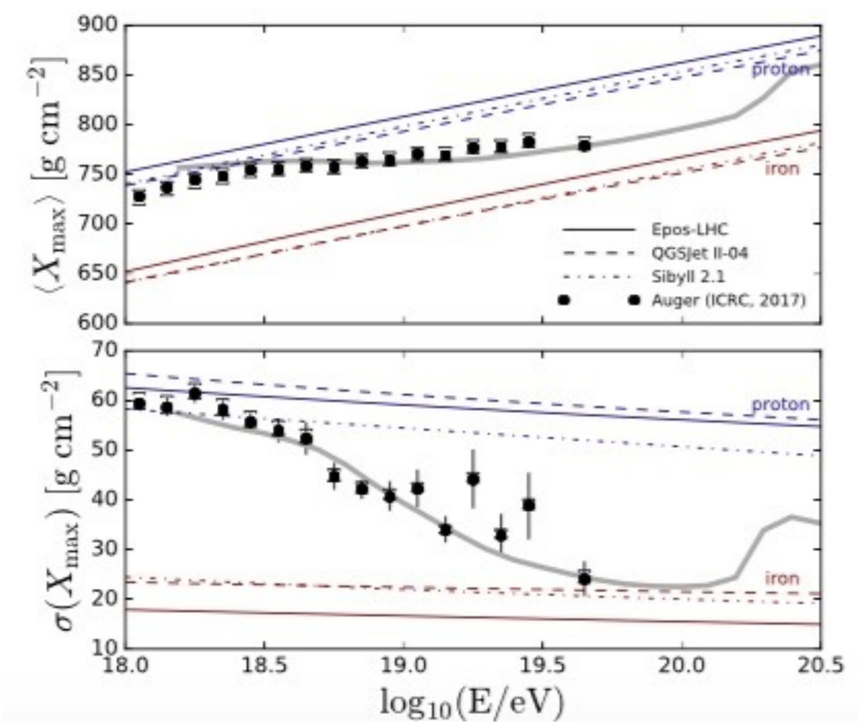
from Silicon-poor E_{max} escape models

- Si-F-1 Si-poor model
- Blue data points: Auger, magenta data pts : TA
- $ZE'_{p,max} \sim 10^{18.2}\, ZL_{\gamma,iso}^{1/2}$ eV
- Fit $\chi 2$ not good (same for other for Si-poor models)

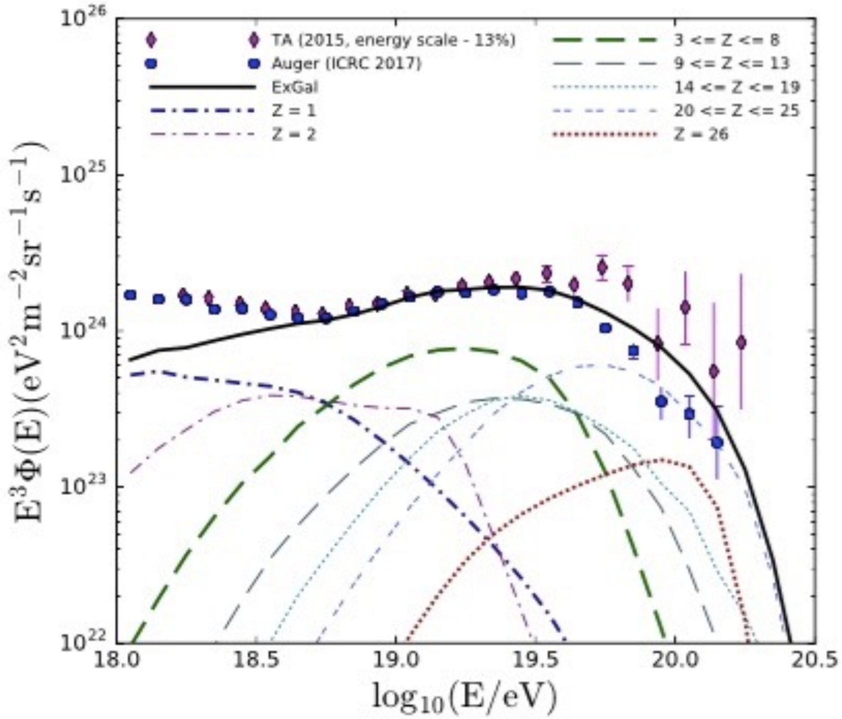


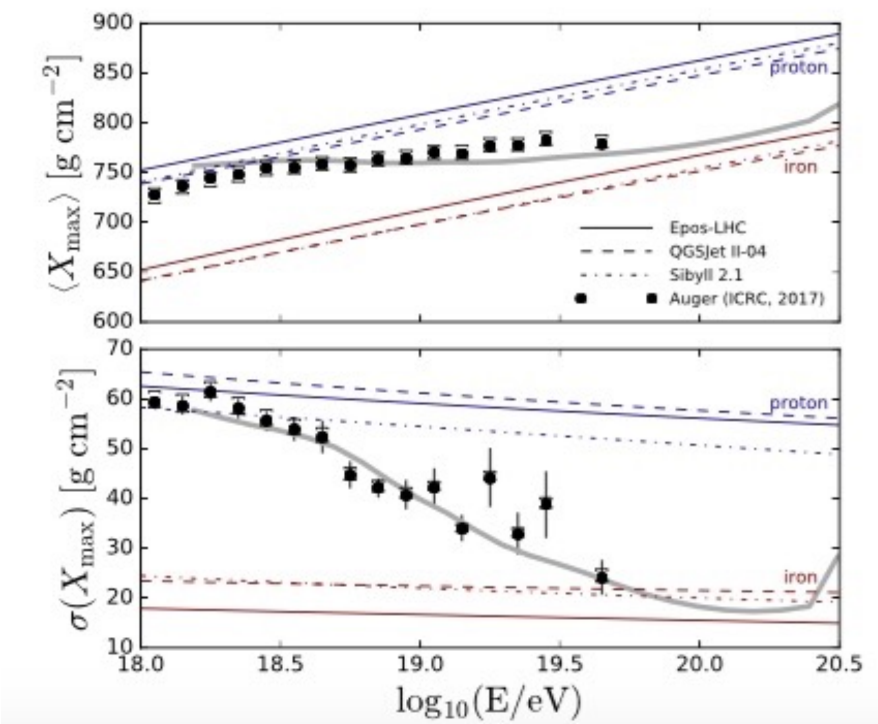
Spectrum, X_{max}, $\sigma(X^{max})$

from Silicon rich
E_{max} escape models



- Si-R-1 Si-rich model
- Blue data points: Auger, magenta data pts : TA
- Fit $\chi 2$ is now better
- Also better for Si-R2, 3



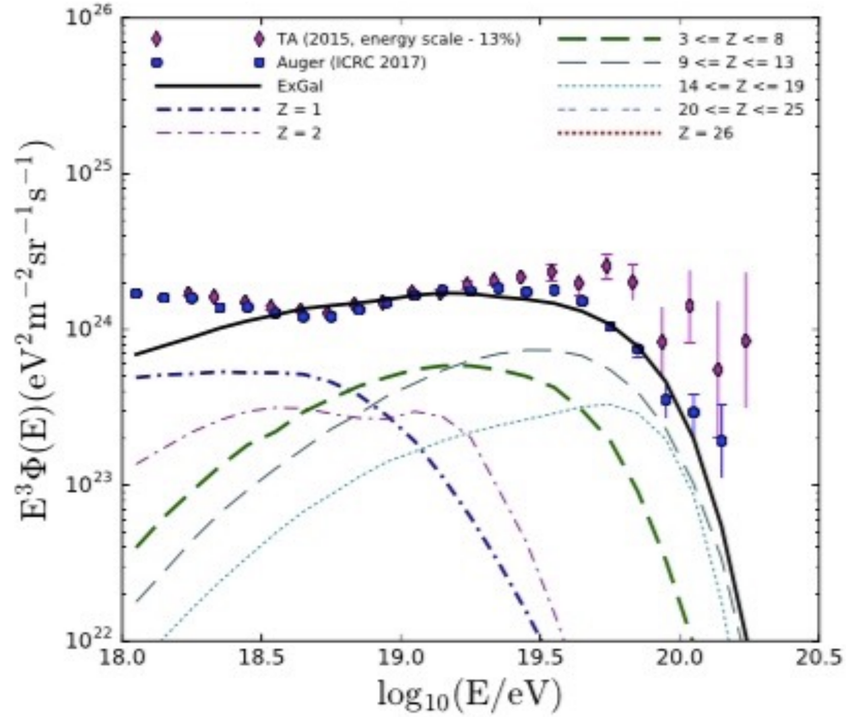


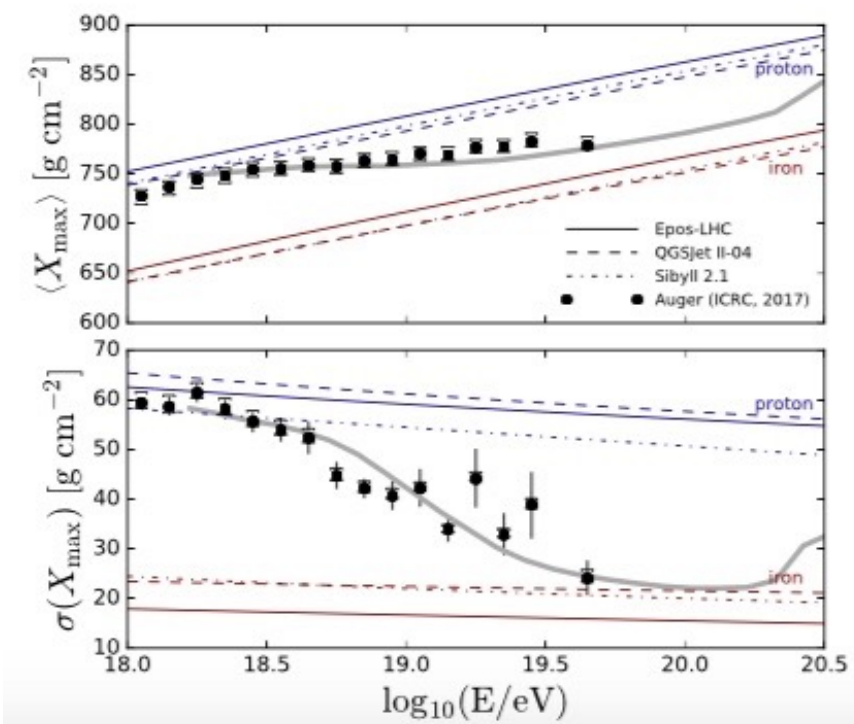
Spectrum, X_{max}, $\sigma(X^{max})$

Si-rich Hypernova
E_{max} escape models

- Si-R-2 Hypernova model
- Blue data points: Auger, magenta data pts : TA
- Fit $\chi 2$ is similarly good

Spectrum, X_{max}, $\sigma(X^{max})$





Si-rich PL spectrum escape model:

- Si-R-2 Si-rich model but with escape power law spectrum index s_{esc}=0.5 (injection s_{inj} =1/5)
- Blue data points: Auger, magenta data pts : TA
- Fit $\chi 2$ is also OK

summary of ***RESULTS*** for ***UHECR***

- LL GRBs from ***Si-R*** progenitors, or from ***hypernova*** models can explain the Auger spectrum and composition: X_{max}, $\sigma(X_{max})$,
- Either in E_{max} escape model, or hard PL model, favor having a hard $\boldsymbol{s_{inj} < 1.5}$.

(B.T. Zhang, K. Murase, S. Kimura, S. Horiuchi, P. Mészáros, PRD'18, in press, 1712.09984)

What about neutrinos?

- Intra-source **pγ** neutrinos can be estimated from

$$E_\nu^2\Phi_\nu \approx \frac{c}{4\pi H_0}\frac{3}{8}\xi_z f_{\rm sup}\min[1, f_{p\gamma}(E_A/A) f_{A\gamma}(E_A) + f_{\rm mes}(E_A)(1 - f_{A\gamma}(E_A))] E_A^2 \frac{dN_A}{dE_A}\rho_0^{\rm LL}$$
$$\sim 2\times 10^{-8}\ {\rm GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}\min[1, f_{p\gamma}] f_{\rm sup} \times \left(\frac{\xi_{\rm CR}/\mathcal{R}}{1}\right)\left(\frac{\xi_z}{3}\right)\left(\frac{\mathcal{E}_{\rm rad}^{\rm iso}}{10^{50}\ {\rm erg}}\right)\left(\frac{\rho_0^{\rm LL}}{200\ {\rm Gpc^{-3}\ yr^{-1}}}\right)$$

- If f_{mes}~$f_{p\gamma}$, this ***could*** give the IceCube observed flux ***if*** have $f_{p\gamma}$~1, i.e., if all nuclei are destroyed (no CRs)
- But two-zone model where νs come from inner radii and UHECR from outer radii ***might*** explain both

Thanks!