17pSJ-3

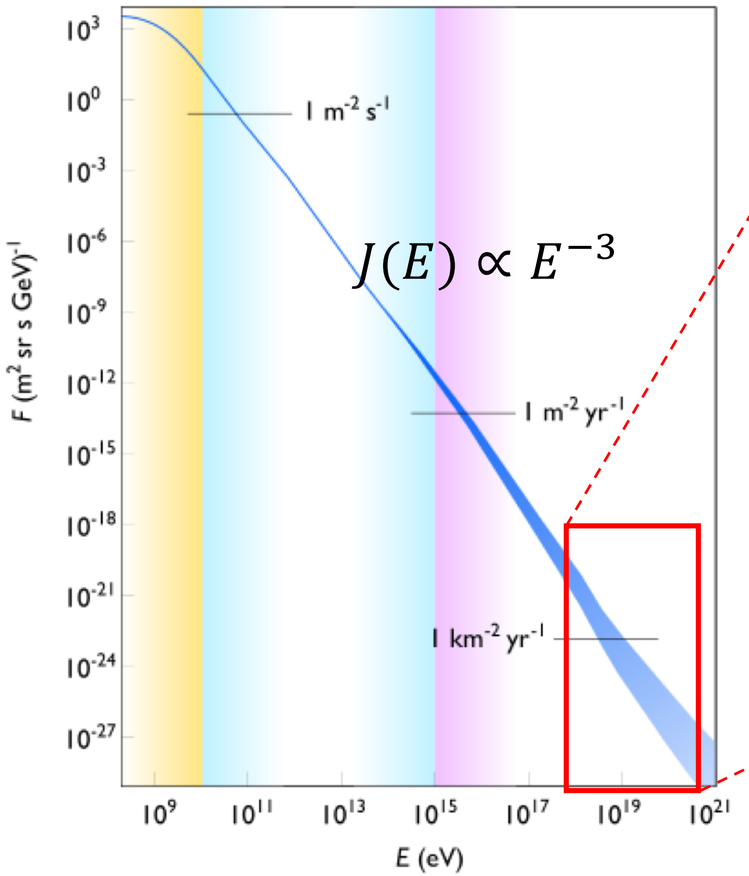
実験核物理学領域、理論核物理学領域、宇宙線・宇宙物理領域合同一般シンポジウム
「軽中重核の電弱励起・崩壊と宇宙物理」

テレスコープアレイ実験による超高エネルギー宇宙線原子核組成研究の進展

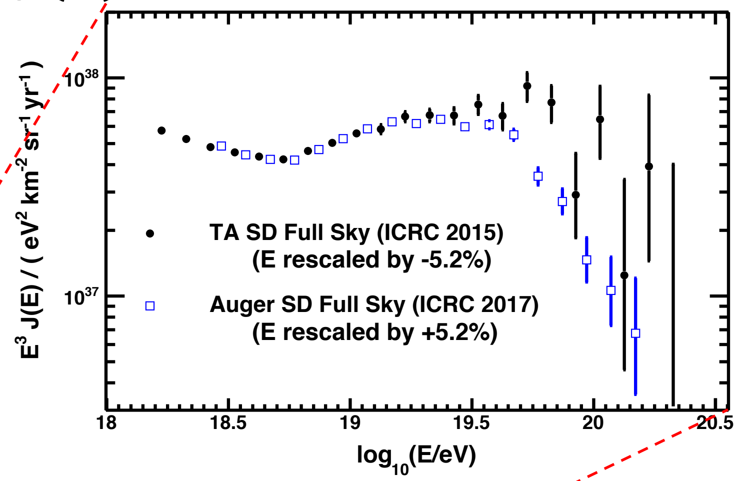
宇宙線観測と光核反応

塩さこ　隆志　　Takashi Sako
（東京大学宇宙線研究所, ICRR Univ. of Tokyo）

End of the CR energy spectrum



$E^3 J(E)$



Auger*, TA Collaborations, EPJ Web of Conferences **210**, 01002 (2019)

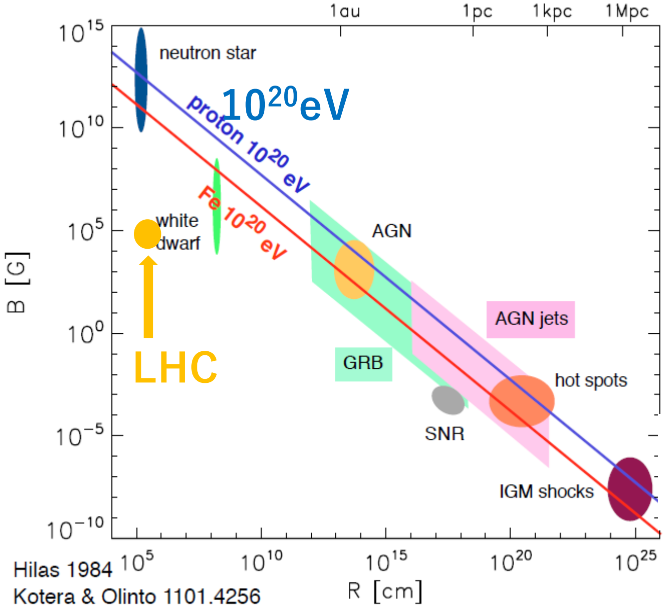
*Pierre Auger Observatory: 3000km^2 array operating in the Southern hemisphere

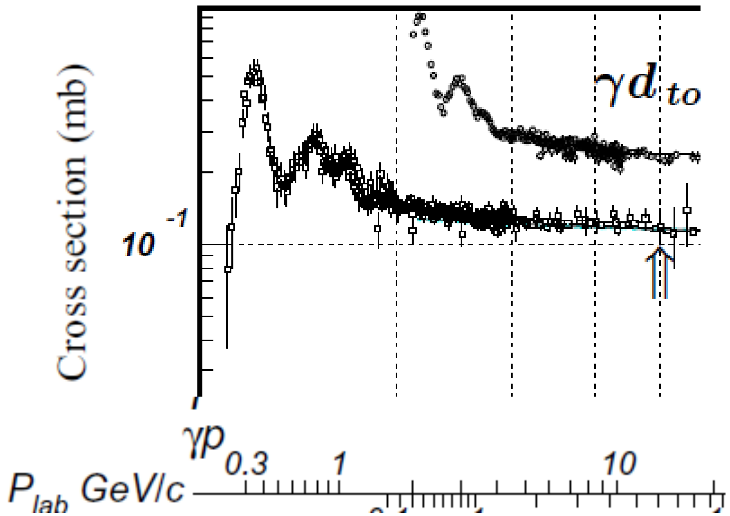
- Suppression (cutoff) at the highest energy is established by TA and Auger
  - Acceleration limit?
  - GZK cutoff by photo-pion production of proton CRs?
  - (GZK) cutoff by photo-disintegration of nuclear CRs?

What is the origin of suppression (cutoff)?

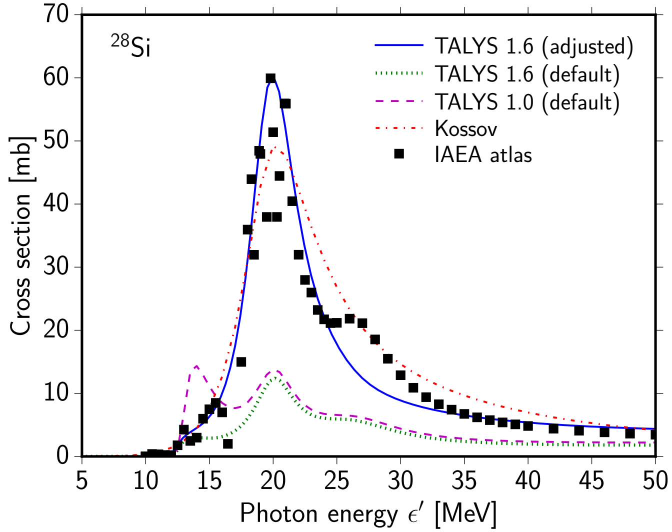
Three cutoff scenarios

Hilas plot





PDG



R.A. Vatista et al., JCAP05(2016)038

Confinement limit of cosmic storage ring for known objects suggests **10^{20}eV/Z** is the maximum energy

GZK cutoff (photopion production)

$p + \gamma \rightarrow p\ (n) + \pi^0\ (\pi^+)$ cross section opens at $E_p > 7\times10^{19}$eV with $E_{\gamma,CMB} \sim 2.4\times10^{-4}$eV ($\Gamma_{proton} > 7\times10^9$)

Photodisintegration

$A + \gamma \rightarrow (A\text{-}1) + p\ (n)$ cross section opens at $\Gamma_A \gtrsim 7\times10^8$

$E_A = \mathbf{A} \times m_p c^2 \Gamma_A$

- **All processes become effective at $E_{CR}\sim10^{20}$eV (E_{CR} is in total energy, but not in E/nucleon)**
- **Determination of CR mass composition is key and challenge in CR observations**

Long journey from the source(s) to our detectors

Source

object type
3D distribution/evolution
maximum energy (rigidity)
spectral index
mass composition
escape from environment

Propagation in photon field

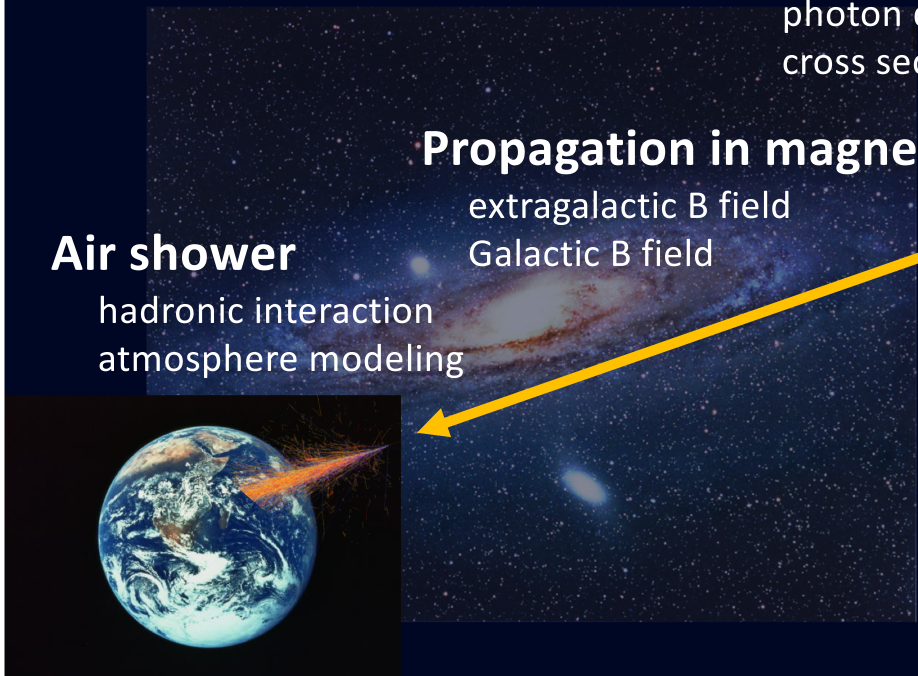
photon density (CMB/EBL)
cross section and particle production

Propagation in magnetic field

extragalactic B field
Galactic B field

Air shower

hadronic interaction
atmosphere modeling



Long journey from the source(s) to our detectors

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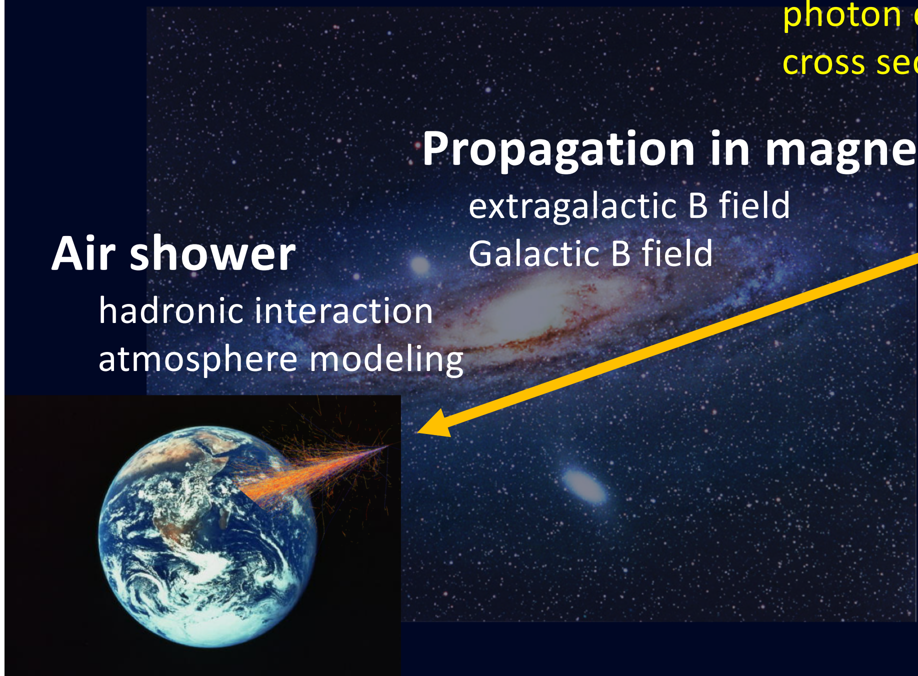


Propagation in magnetic field

extragalactic B field
Galactic B field

A -> (A-1) + N
E -> (A-1)/A x E + E/A

Air shower

hadronic interaction
atmosphere modeling

Long journey from the source(s) to our detectors

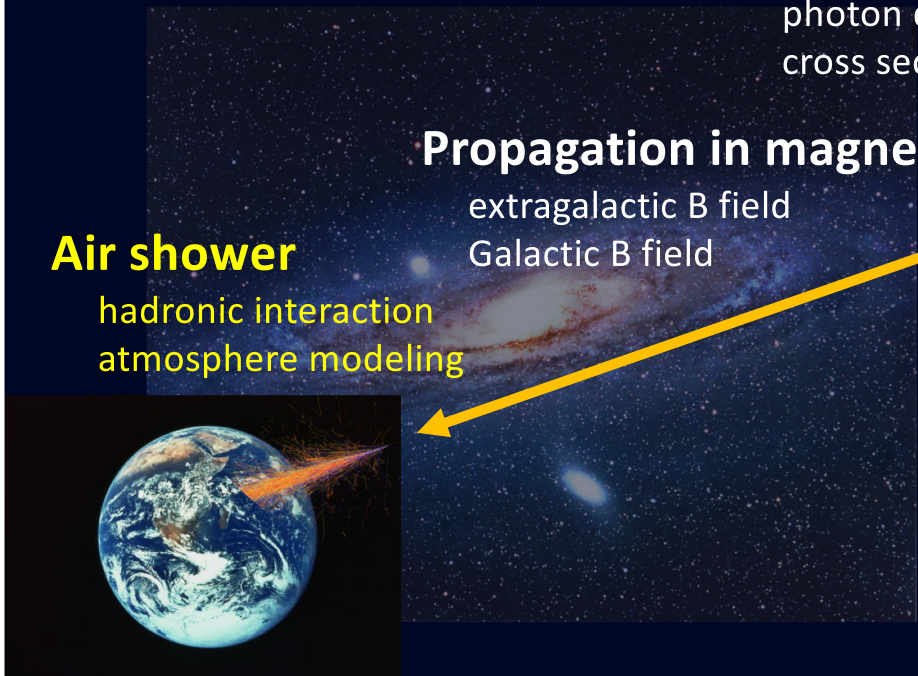
Source

object type
3D distribution/evolution
maximum energy (rigidity)
spectral index
mass composition
escape from environment

?

Propagation in photon field

photon density (CMB/EBL)
cross section and particle production



Propagation in magnetic field

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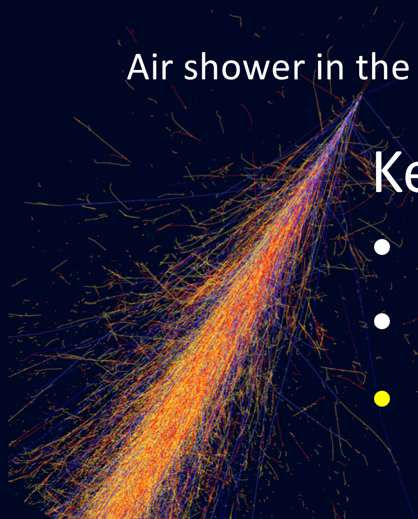
Galactic B field

Air shower

hadronic interaction
atmosphere modeling

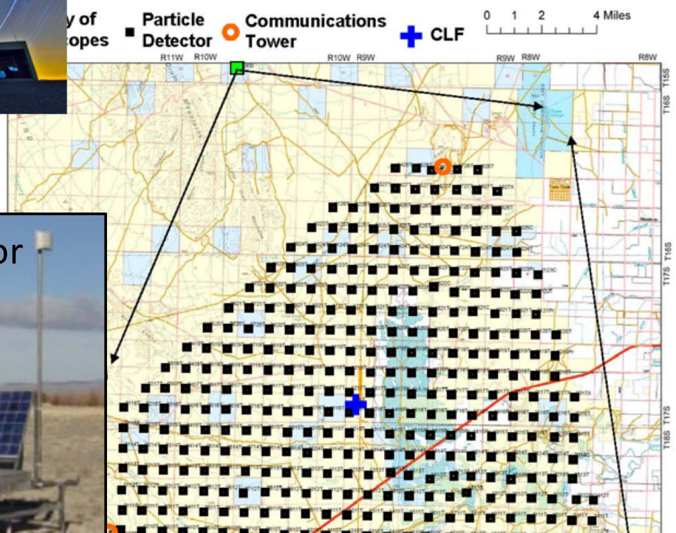


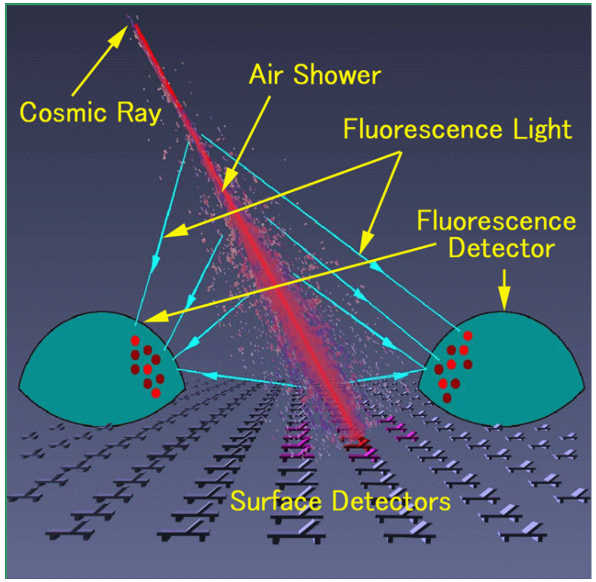
Air shower in the atmosphere

Key observables are

- $N_{ch} \propto E_{CR}$: energy
- θ, φ : arrival direction
- N_{ch}-N_{μ} , X_{max} : mass

Telescope Array is

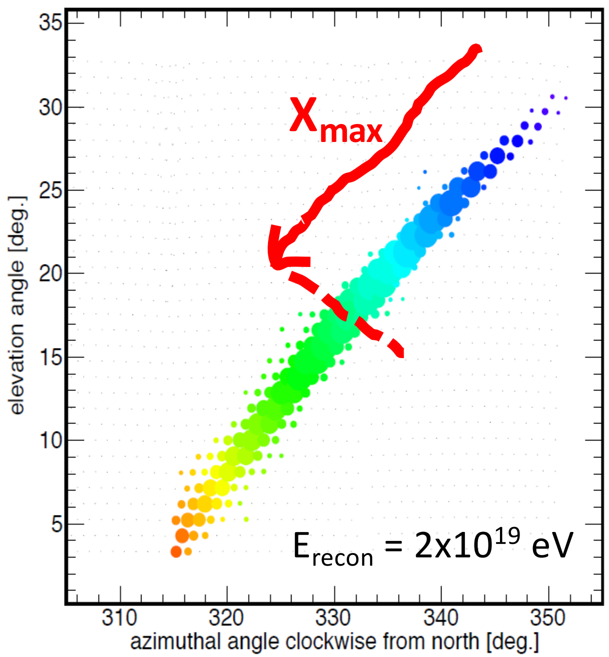




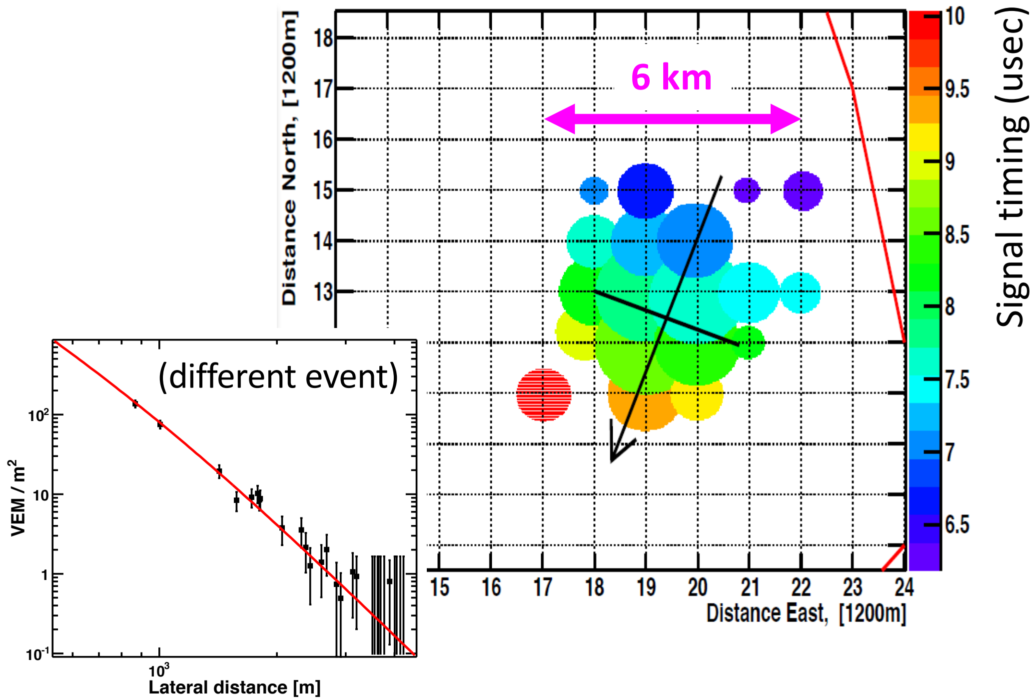
- Largest air shower experiment in Northern hemisphere, Utah in USA
- Since 2008
- Surface Detector (SD) array
  - $3m^2$ Scintillation Detector x 507
  - 1.2km spacing, total ~$700km^2$
- Fluorescence Detector (FD)
  - 3 stations, 38 telescopes

FD-SD Hybrid observation and analysis

Fluorescence image



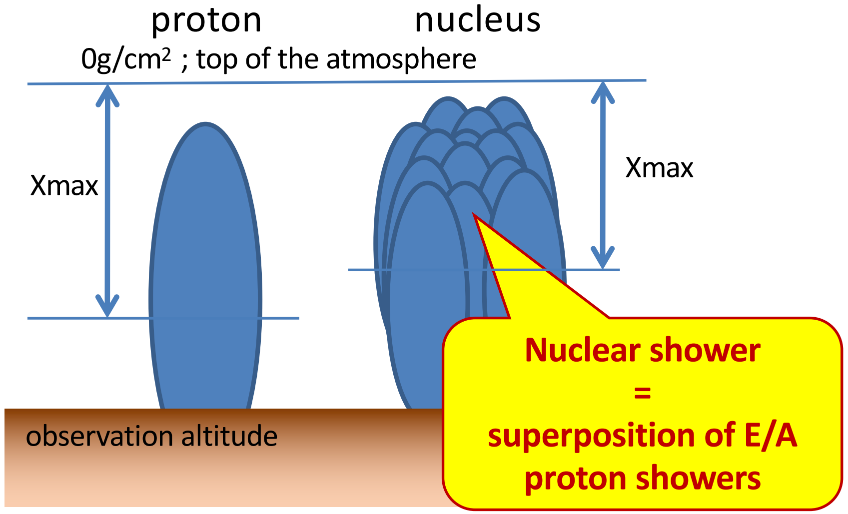
Footprint by Surface scintillators

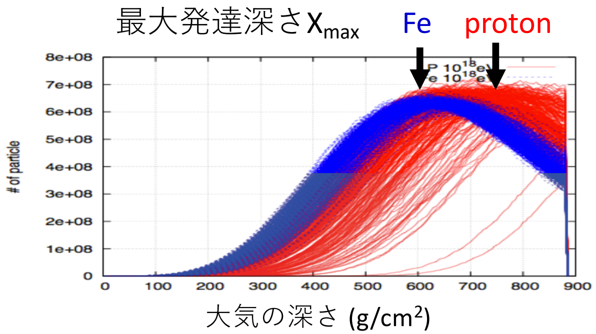


- Calorimetric energy determination => E
- Longitudinal profile => X_{max} : depth of the maximum from the top of the atmosphere (g/cm^2)

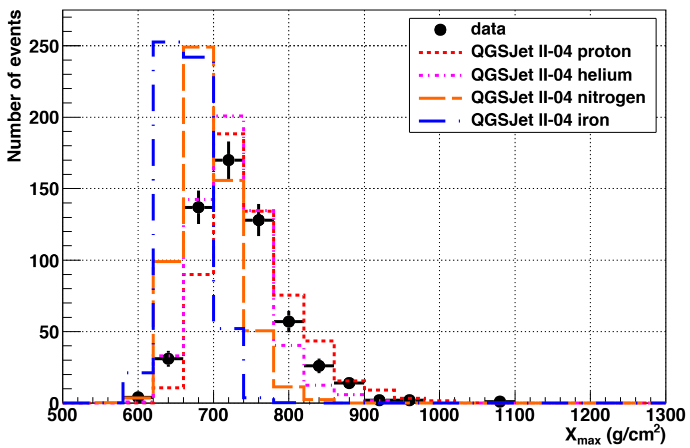
- Normalization of lateral fit => E

FD/SD hybrid analysis for mass composition

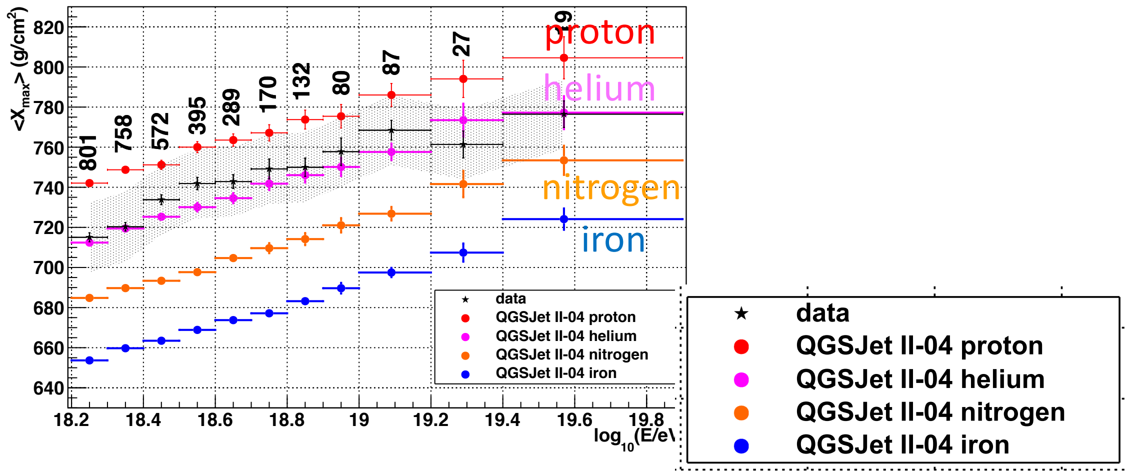




Telescope Array, ApJ, 858:76 (2018)

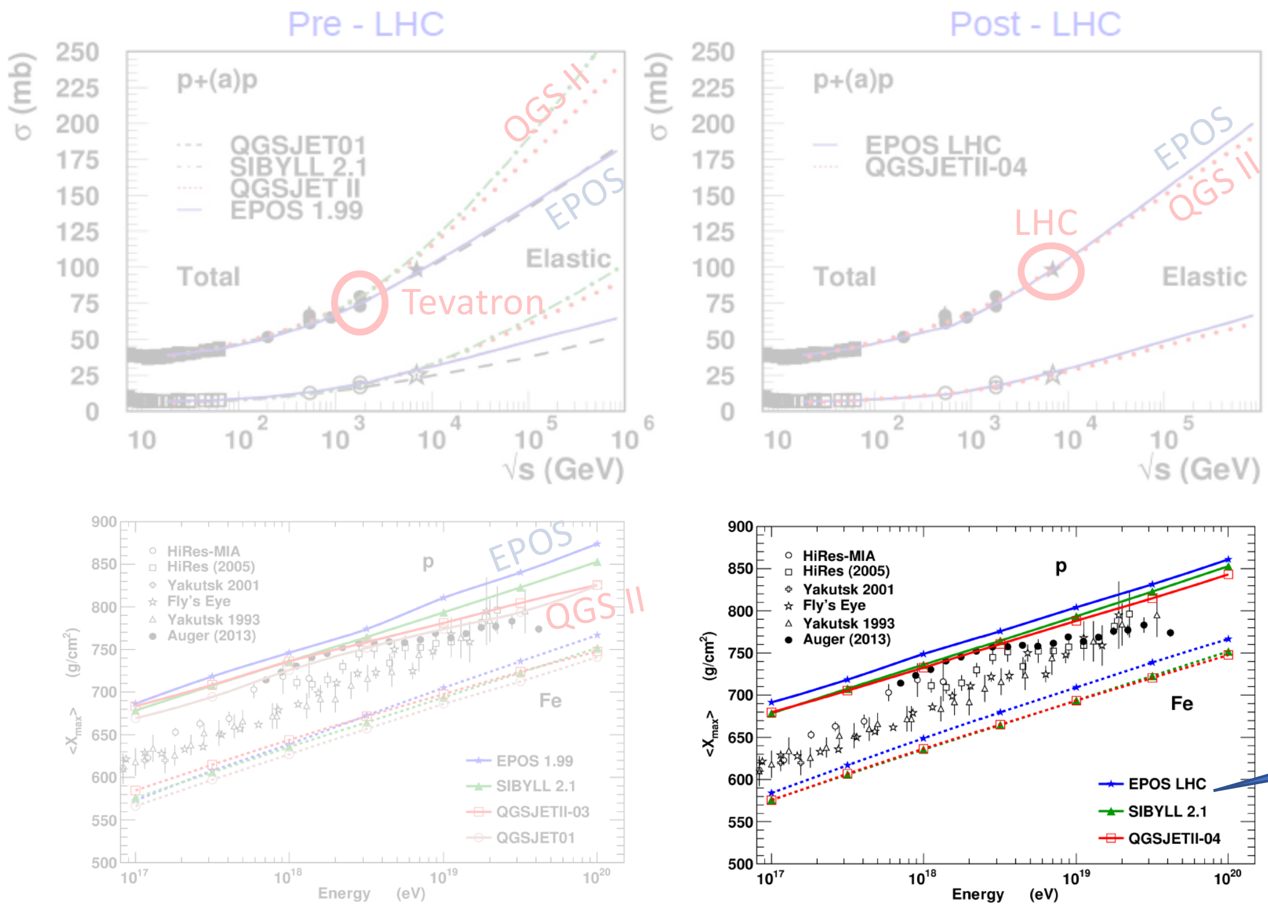


(c) $18.4 \leq \log_{10}(E/\mathrm{eV}) < 18.5$



- Light composition up to $10^{19.6}$eV
- What is QGSJET II-04?

Uncertainty in the air shower interpretation



Interaction model EPOS, QGS, SIBYLL

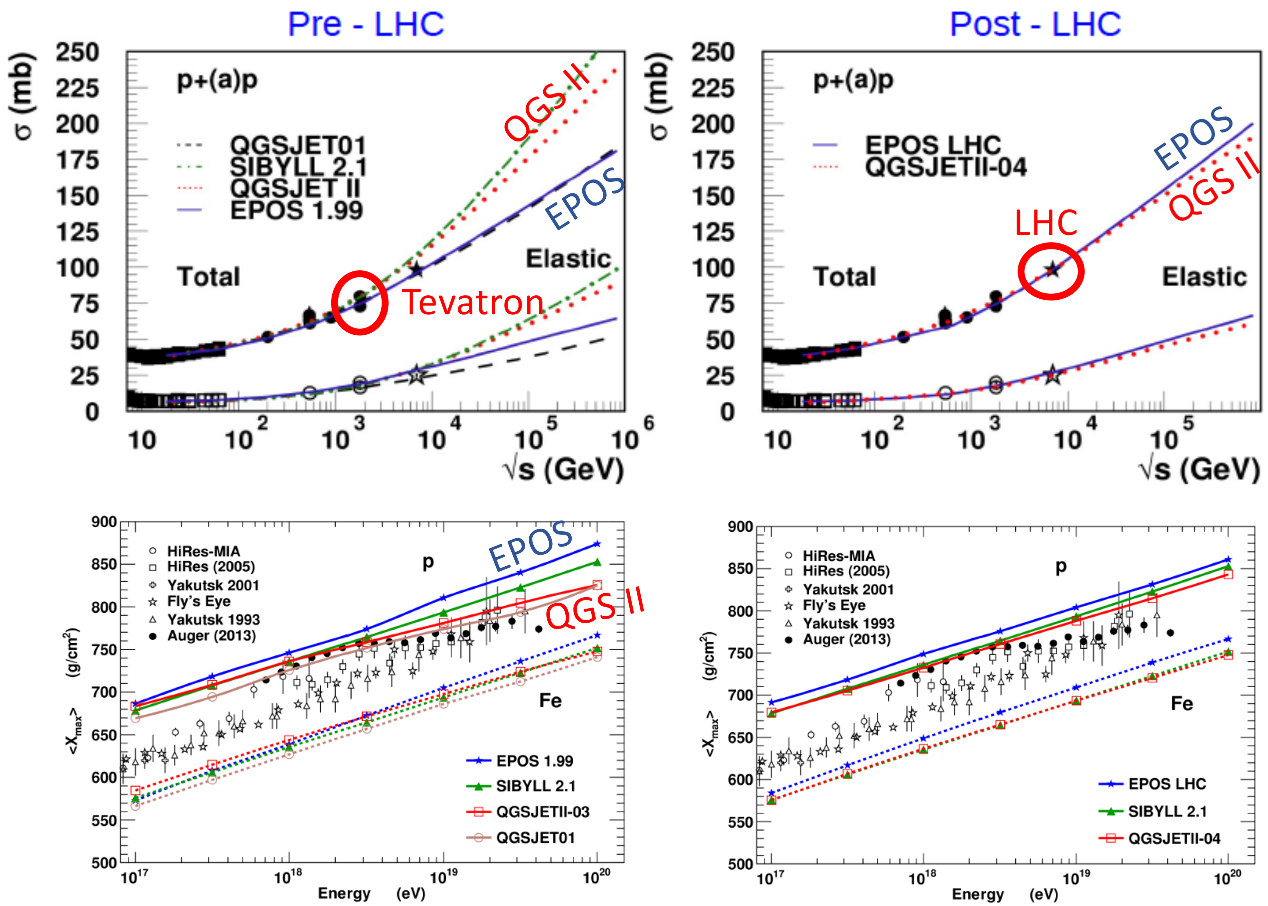
Plots by T. Pierog

- MC predictions depend on the choice of hadronic interaction model

Uncertainty in the air shower interpretation

Before/after LHC

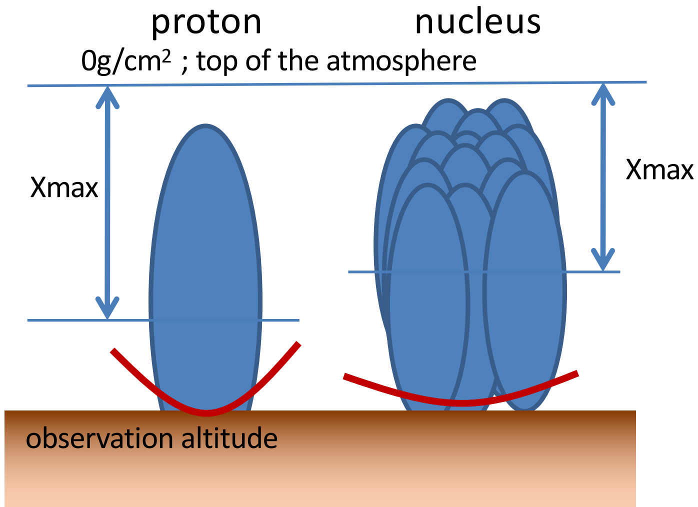
σ_{ine} @ LHC



Plots by T. Pierog

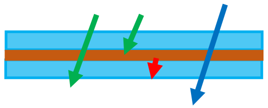
- MC predictions depend on the choice of hadronic interaction model
- Difference becomes smaller in the LHC era, and intensively studies on going

Mass estimation using SD

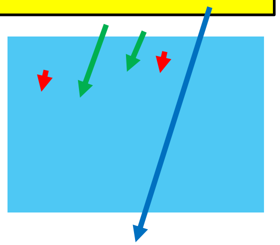


Deep shower => curved front

$$N_\mu = A\left(\frac{E}{A}\right)^{0.8-0.9} = A^{0.1-0.2}E^{0.8-0.9}$$



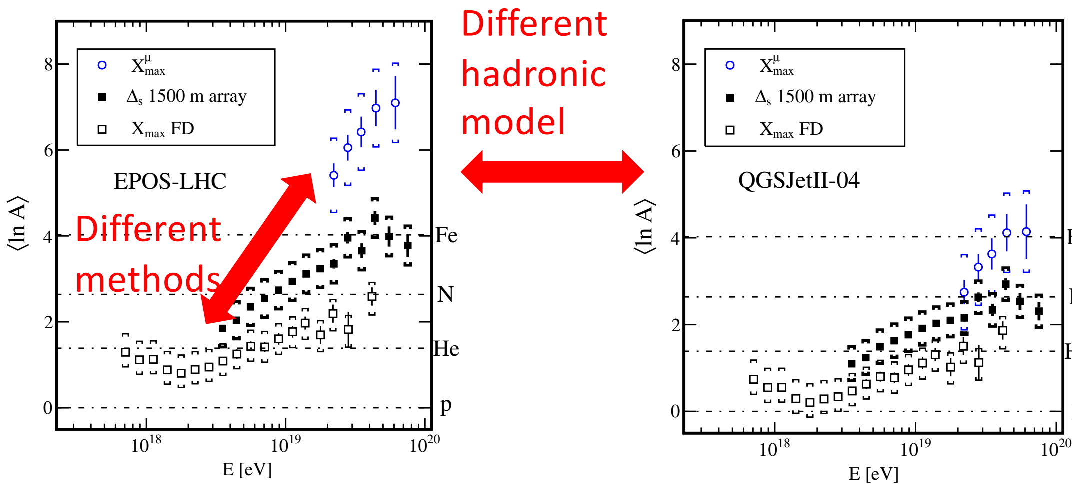
Thin scintillators (TA type)



Thick water Cherenkov detector (Auger type)

- FD observation is limited in duty time O(10%)
- Muon sensitive analyses (Auger*) and machine learning (TA) to use SD in progress

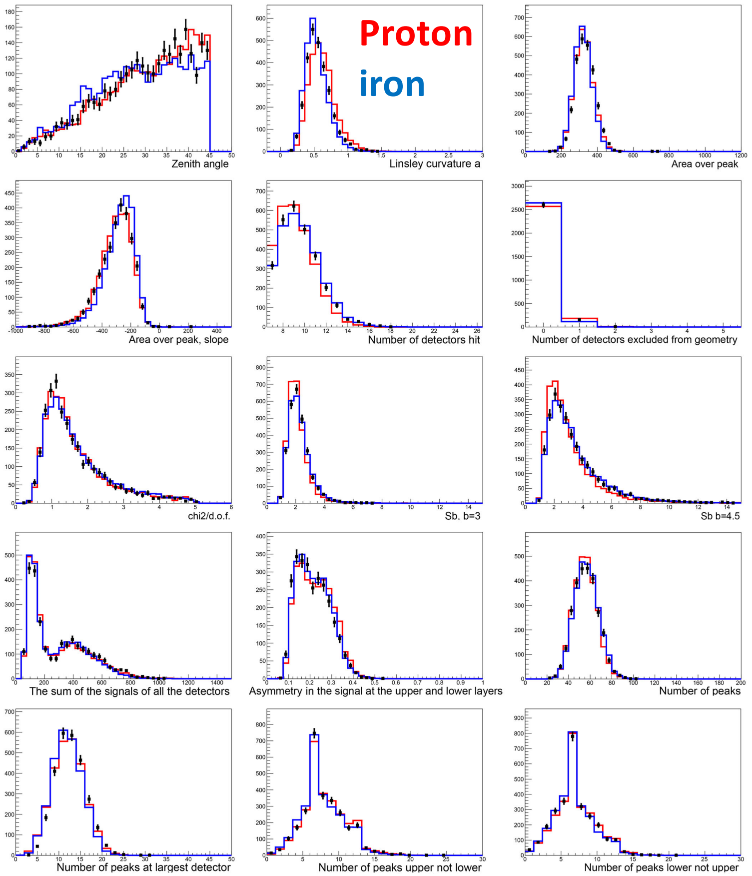
Auger, PRD 96, 122003 (2017)



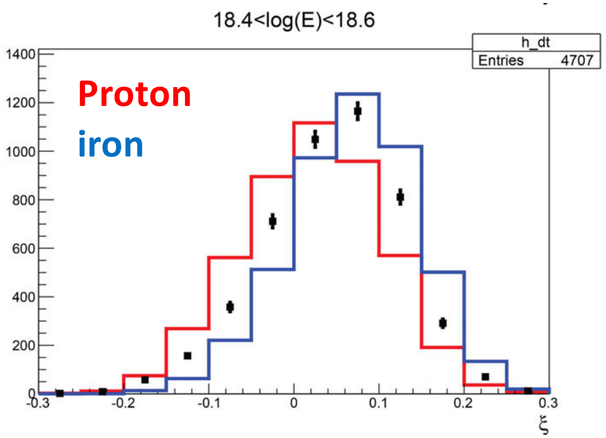
- Auger: different <lnA> with different analyses, different models,…
- Unnatural ‘heavier than Fe’ using muon data

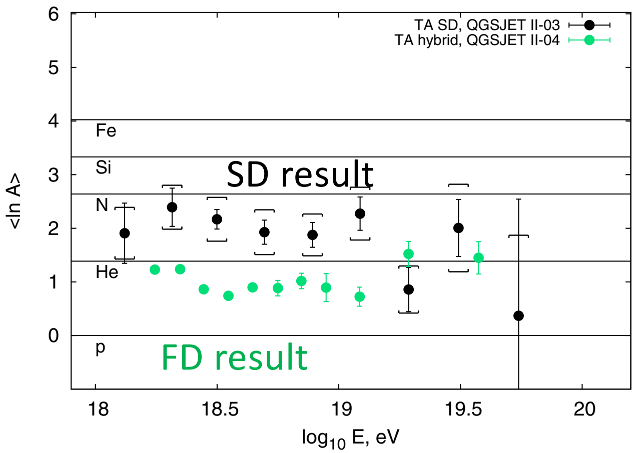
Mass estimation using SD

Telescope Array, PRD 99, 022002 (2019)



16 reconstructed parameters to train BDT classifier, ξ





- Mass (<lnA>) determination suffers from the shower modeling and is hot topic of improvement

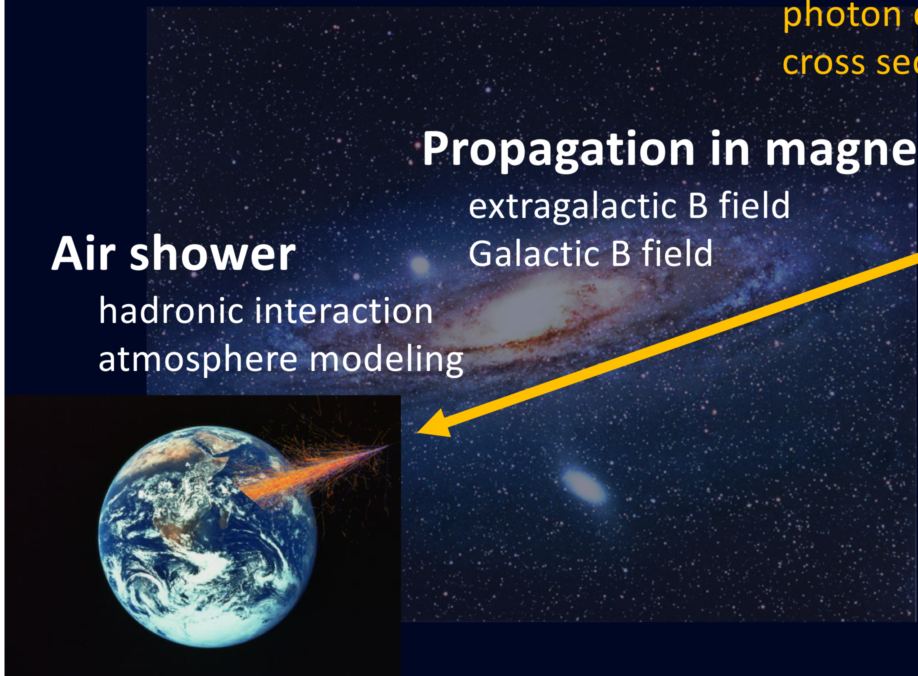
Let us interpret the observations

Source

object type
3D distribution/evolution
maximum energy (rigidity)
spectral index
mass composition
escape from environment

Propagation in photon field

photon density (CMB/EBL)
cross section and particle production



Propagation in magnetic field

extragalactic B field
Galactic B field

Air shower

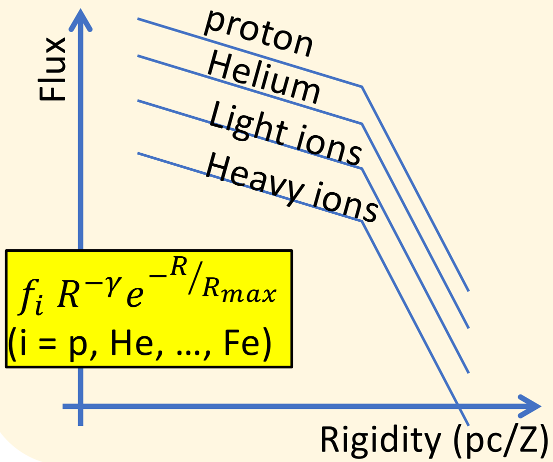
hadronic interaction
atmosphere modeling

References for contents from here

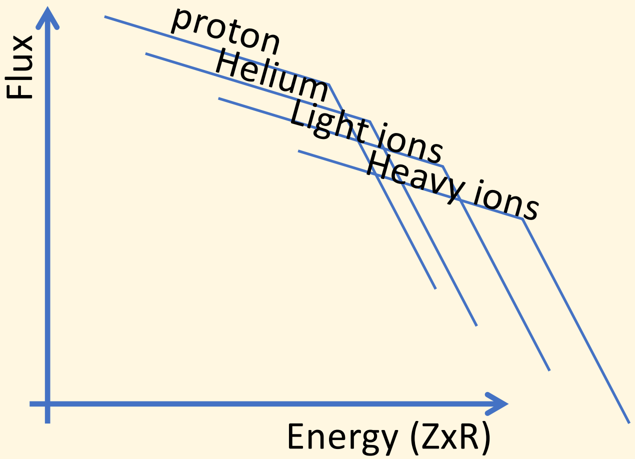
R.A. Vatista et al., JCAP05(2016)038
R.A. Vatista et al., JCAP10(2015)063
K. Kotera and A. V. Olinto,Annu. Rev. Astron. Astrophys. 2011. 49:119–53
J. Heinze et al., ApJ, 873:88, 2019
TA Collaboration, PoS (ICRC2019) 190

Forward-folding analysis : Source model

METHOD: Assume source and propagation physics and fit to the air shower observations



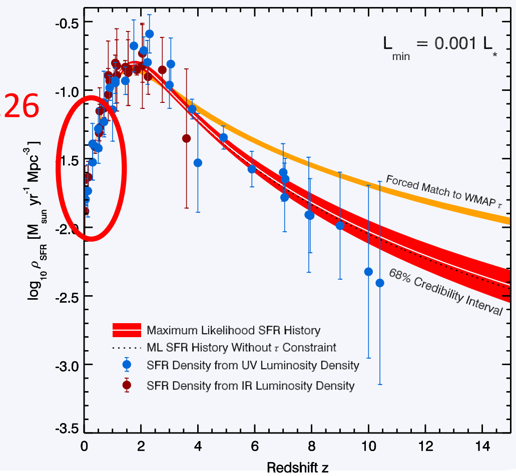
$f_i \, R^{-\gamma} e^{-R/R_{max}}$
(i = p, He, …, Fe)



- Parameters at source
  - Power index : γ
  - Rigidity limit : R_{max}
  - Abundance : f_p, f_{He}, …, f_{Fe}

- Source distribution
  - $\rho \propto (1+z)^m$

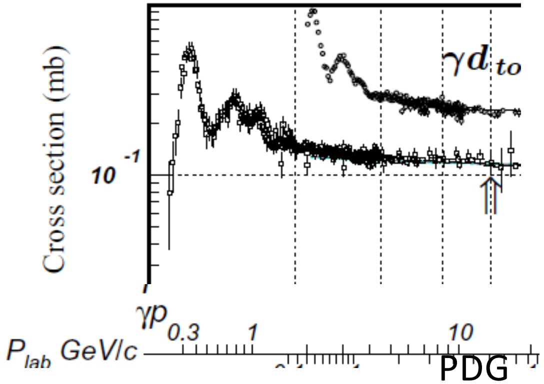
$(1+z)^{3.26}$

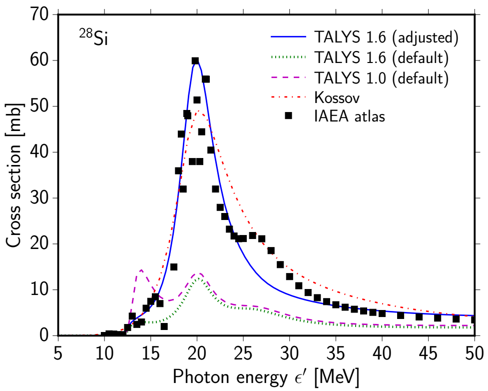


Ex) Star formation rate (SFR)
B. E. Robertson, et al. ApJ. Lett., 802:L19 (5pp), 2015

Forward-folding analysis : Propagation

Cross sections as input
- TALYS
- PSB
- Kossov



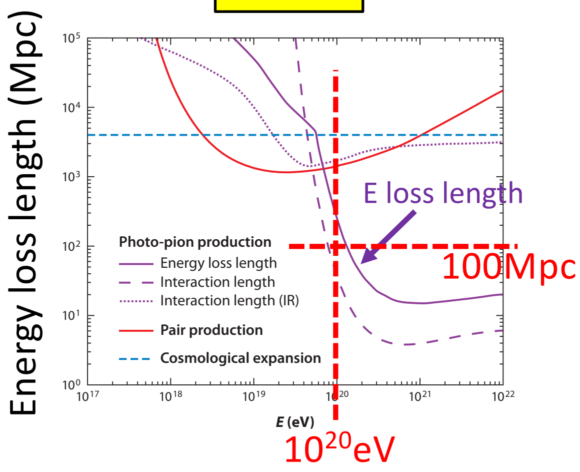


R.A. Vatista et al., JCAP05(2016)038

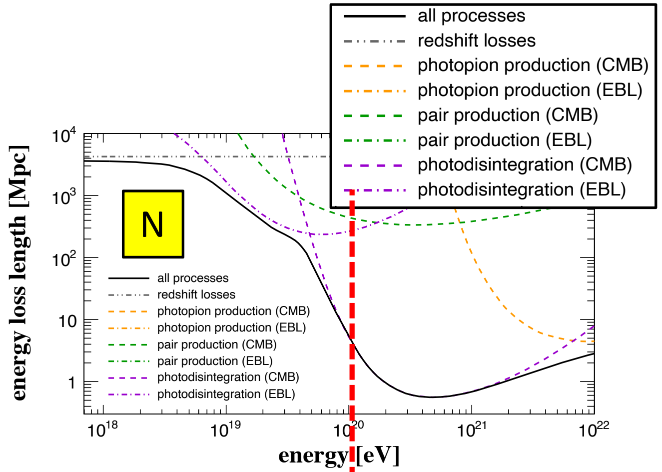
Photon density
- CMB
- EBL

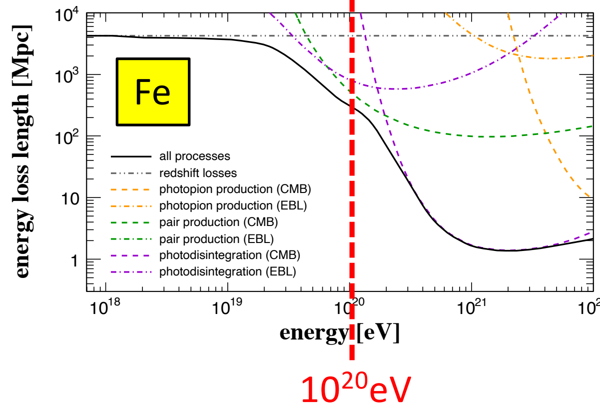
Propagation tool such as
- CRPropa
- SimProp
- PRINCE

proton



K. Kotera and A. V. Olinto,Annu. Rev. Astron. Astrophys. 2011. 49:119–53





R.A. Vatista et al., JCAP10(2015)063

- Strong energy loss above 10^{20}eV
- Heavy nuclei (smaller Lorentz factor) exhibit less attenuation

Forward-folding analysis : Propagation, model dependence

Calculated spectrum at the earth

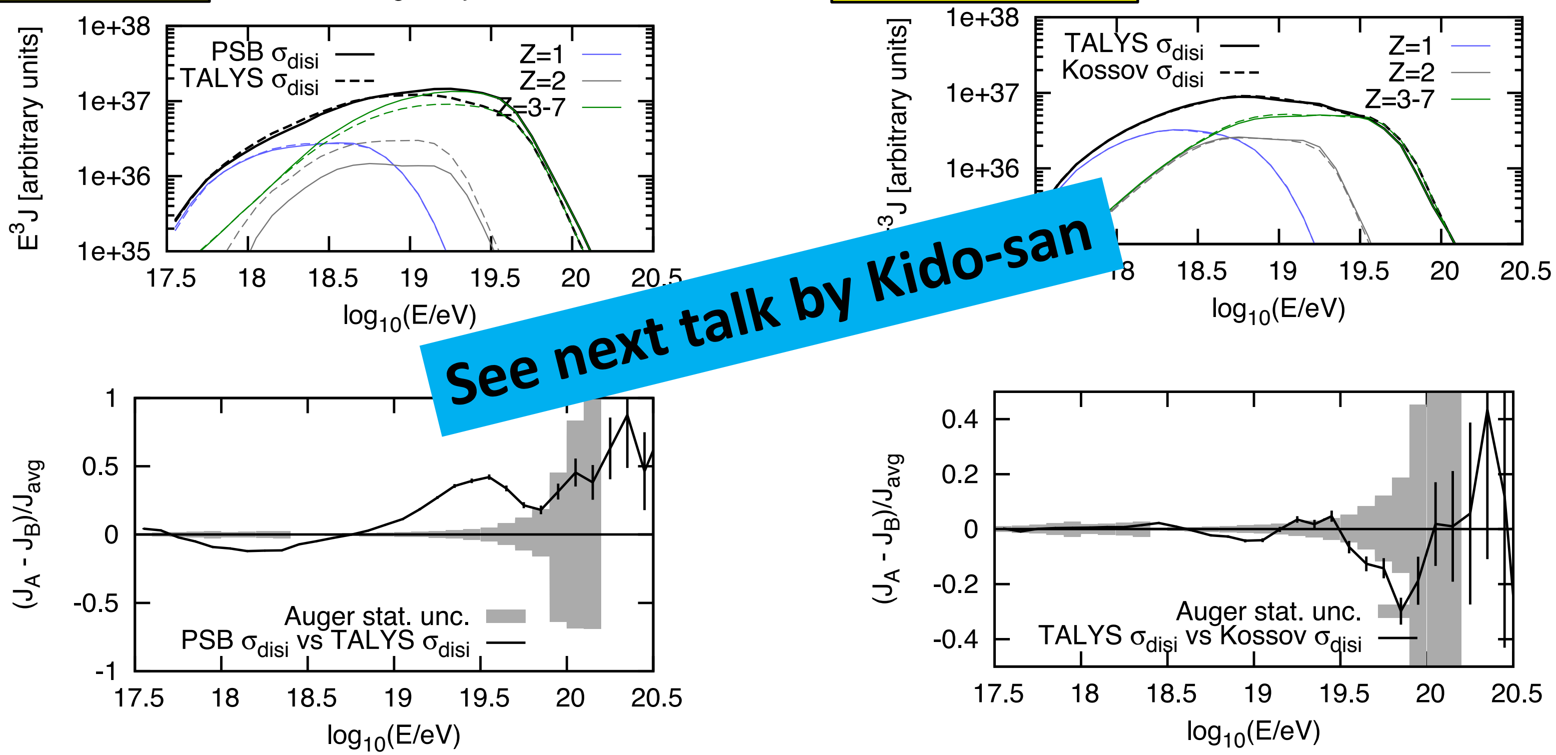
R.A. Vatista et al., JCAP10(2015)063

PSB vs. TALYS

hard nitrogen injection

TALYS vs. Kossov

hard nitrogen injection



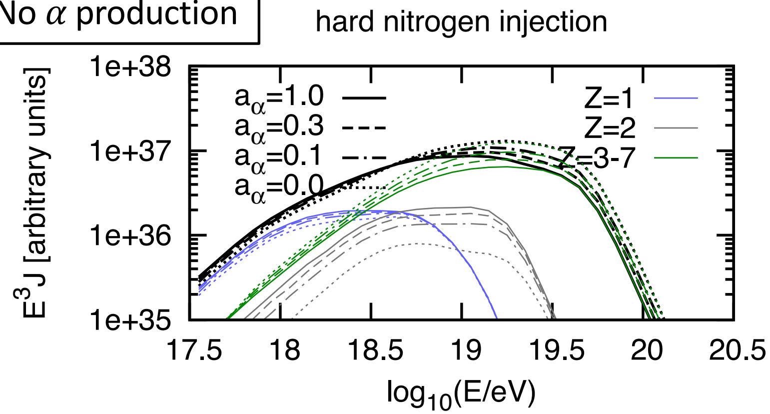
- TALYS models α production while PSB does not
- 50% difference at the highest energy

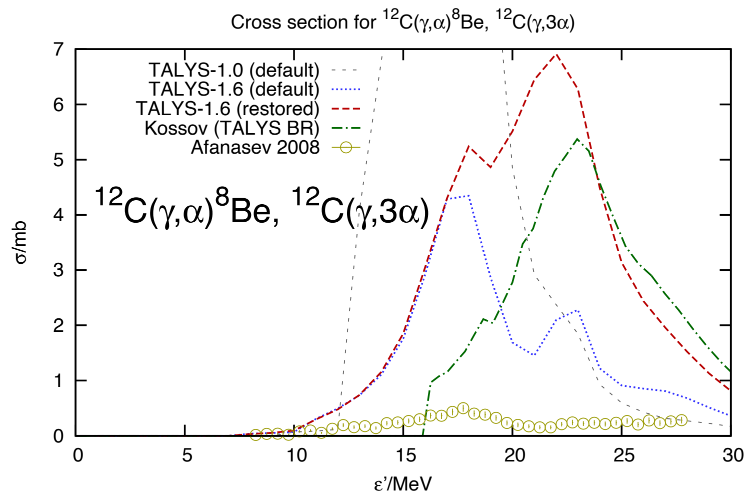
- TALYS and Kossov: different in inclusive cross section, but common in partial cross section
- +/-20% difference at the highest energy

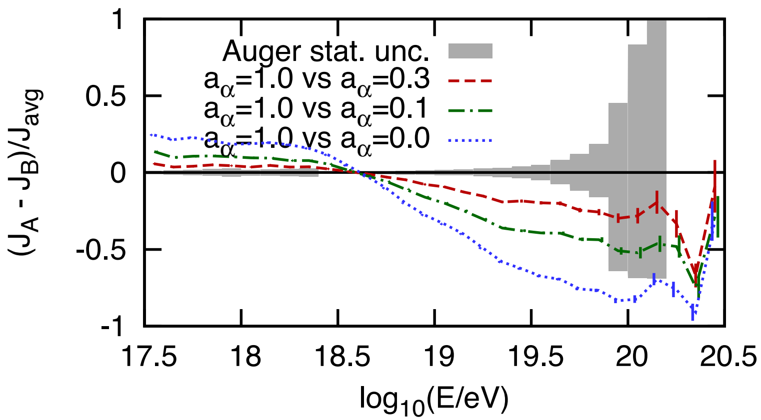
Forward-folding analysis : Propagation, model dependence

R.A. Vatista et al., JCAP10(2015)063

a_α = 1.0 : TALYS original
a_α = 0.0 : No α production



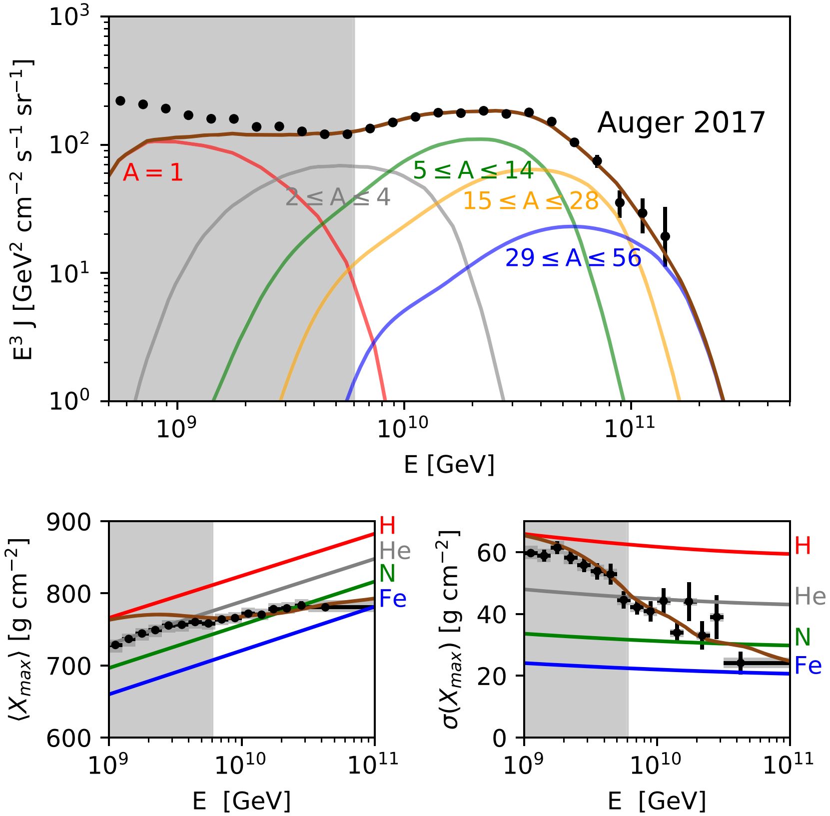


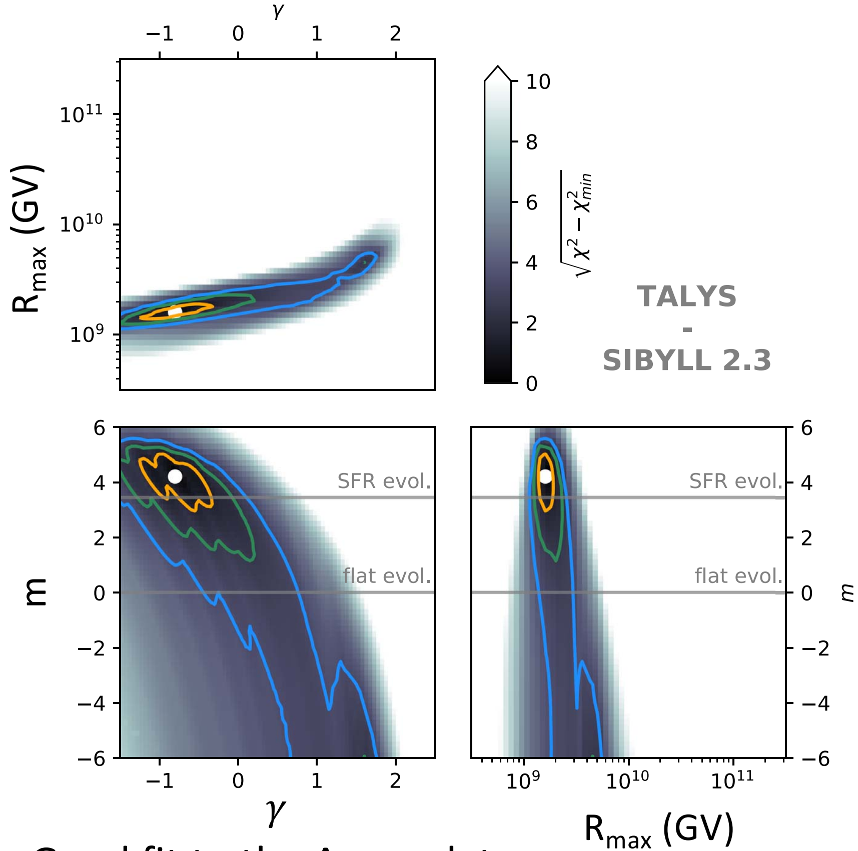


- >50% effect of ***α* production rate**, which is poorly constrained by the laboratory experiments, or poorly modeled for existing data (plot above)

Forward-folding analysis : fitting to the Auger results

J. Heinze et al., ApJ, 873:88, 2019



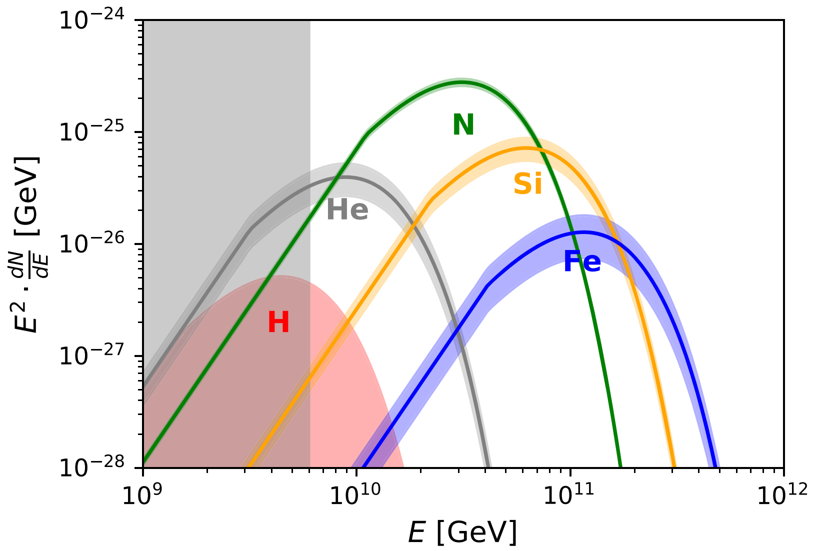


- Good fit to the Auger data
- R_{max} = 1.6x10^{18} V
- m~4 supports star formation evolution
- γ=-1 means very hard spectrum

Forward-folding analysis :

fitting to the Auger, source parameters

J. Heinze et al., ApJ, 873:88, 2019

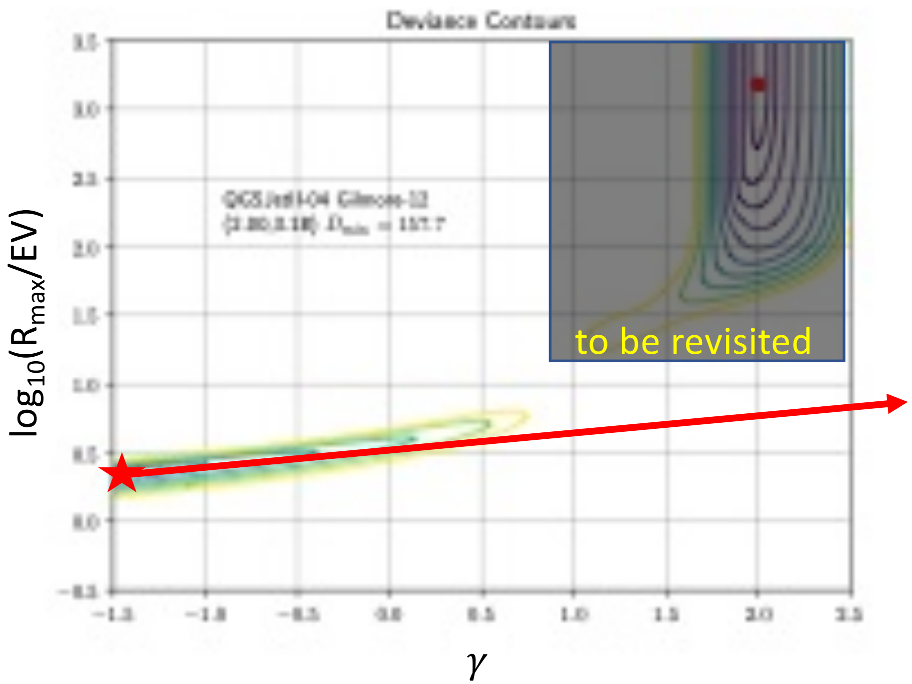


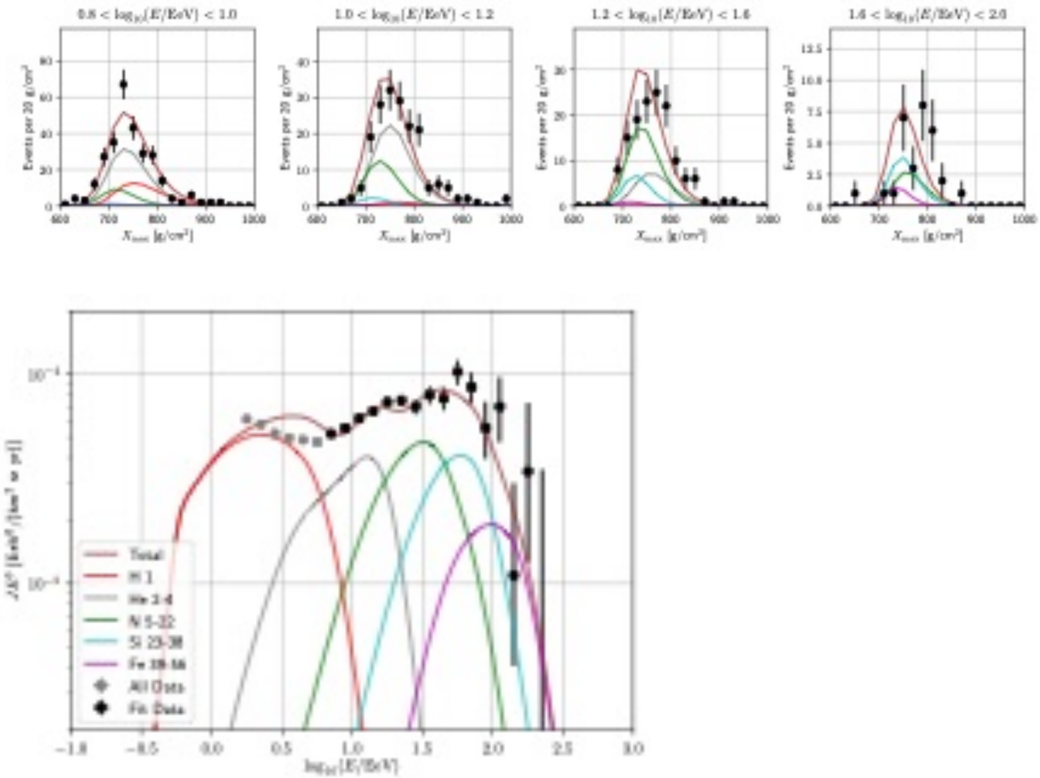
		TALYS–SIBYLL 2.3	
γ		$-0.80^{+0.27}_{-0.23}$	
$R_{\max}$ (GV)		$(1.6 \pm 0.2) \cdot 10^9$	
m		$4.2^{+0.4}_{-0.6}$	
δ_E		$0.14^{+0.00}_{-0.03}$	
f_A (%)	H	He	N
	$0.0^{+42.6}_{-0.0}$	$82.0^{+3.8}_{-6.4}$	$17.3^{+1.0}_{-1.1}$
	Si	Fe	
	0.6 ± 0.1	$(2.0 \pm 0.8) \cdot 10^{-2}$	
I_A^9(%)	H	He	N
	$0.0^{+1.2}_{-0.0}$	$9.8^{+2.8}_{-2.9}$	$69.2^{+1.5}_{-1.6}$
	Si	Fe	
	$17.9^{+3.2}_{-3.5}$	$3.2^{+1.2}_{-1.3}$	
χ^2/dof			27.0/21

- Very hard spectrum suggests effect of confinement and escape
- m = 4.3 supports star formation evolution
- No proton! But with a large uncertainty

Forward-folding analysis : fitting to the TA data

TA Collaboration, PoS (ICRC2019) 190

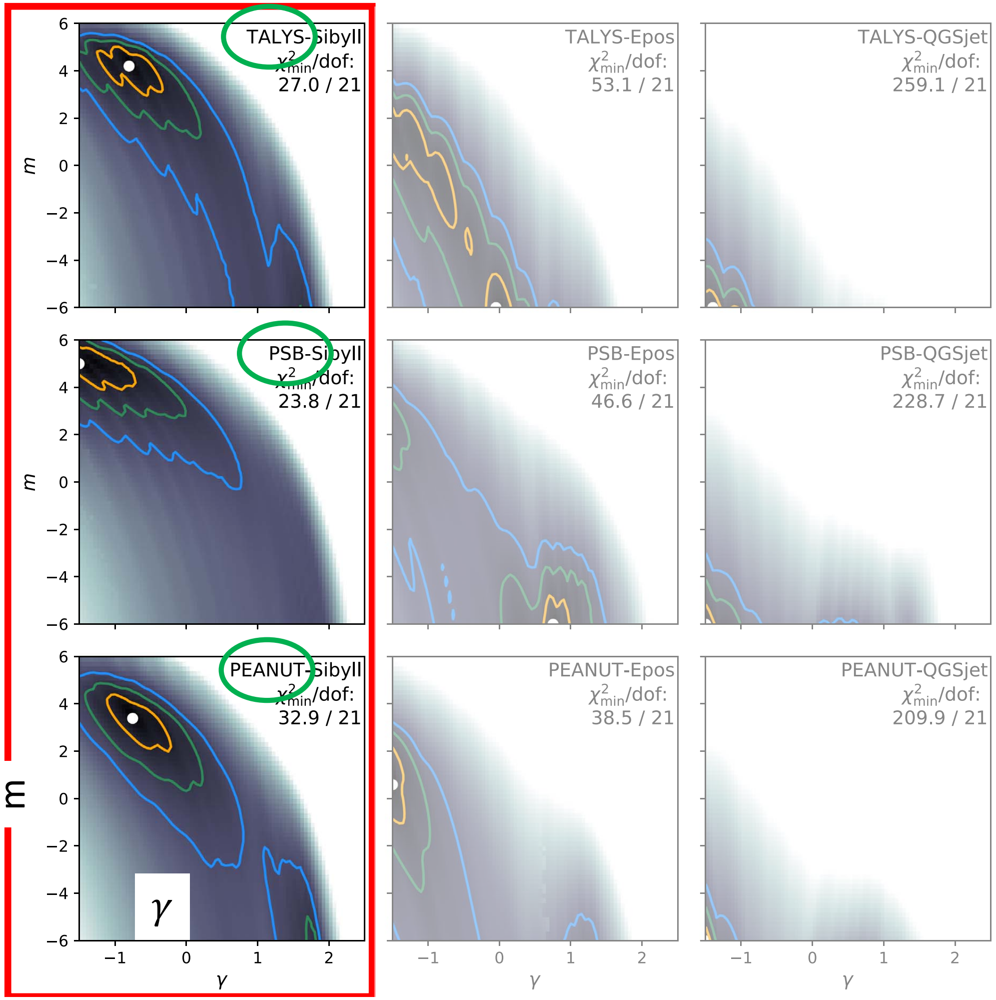




- γ = -1.5, R_{max} = 2.2 EV, f_p:f_{He}:f_N:f_{Si}:f_{Fe} = 61.0%:37.4%, 1.5%, 0.1%, 0.003%
- Similar to the Auger fitting, but with a large proton fraction
- Not very good fit for high energy Xmax…

Forward-folding analysis :

Fitting to Auger, impact of photo-dis. uncertainty

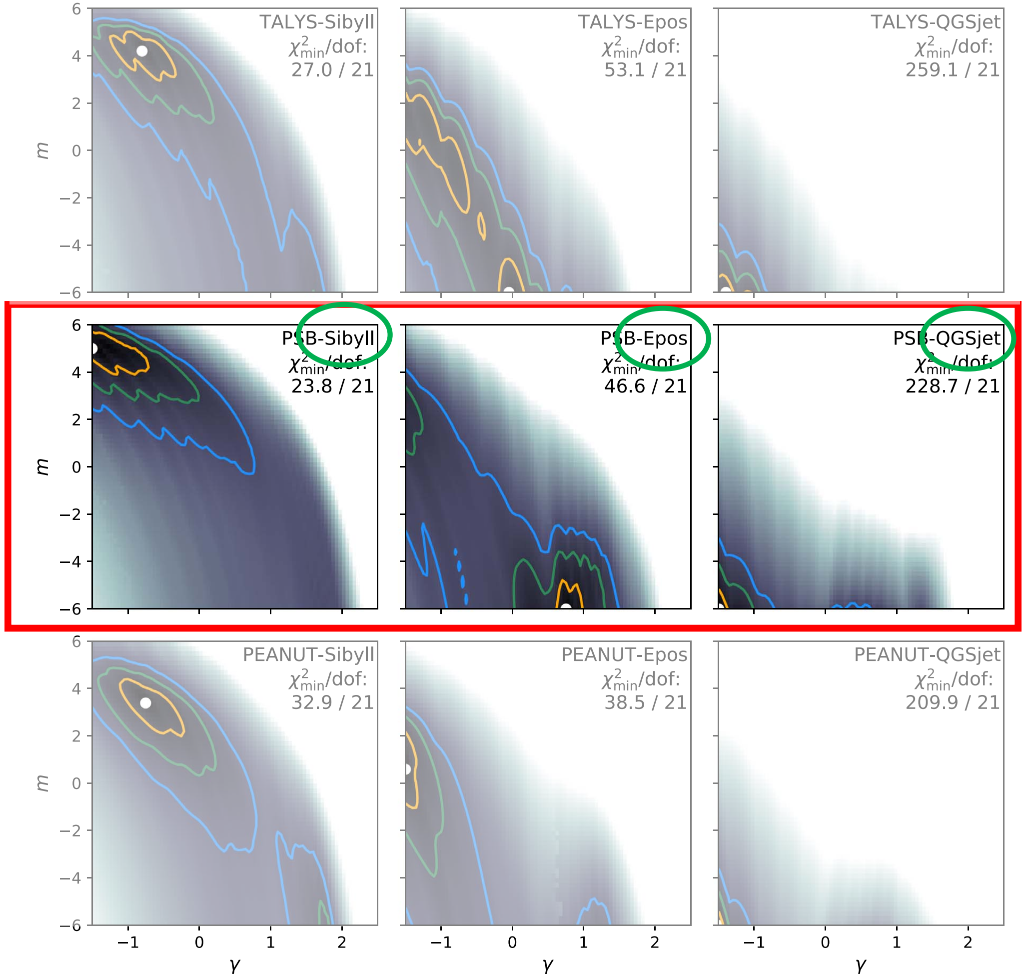


J. Heinze et al., ApJ, 873:88, 2019

- Impact of photodisintegration model on the source parameters estimation
- $\Delta\gamma \sim 1$
- $\Delta m \sim 2$

Forward-folding analysis :

Fitting to Auger, hadron int. uncertainty



J. Heinze et al., ApJ, 873:88, 2019

- Impact of photodisintegration model on the source parameters estimation
- $\Delta\gamma \sim 1$
- $\Delta m \sim 2$

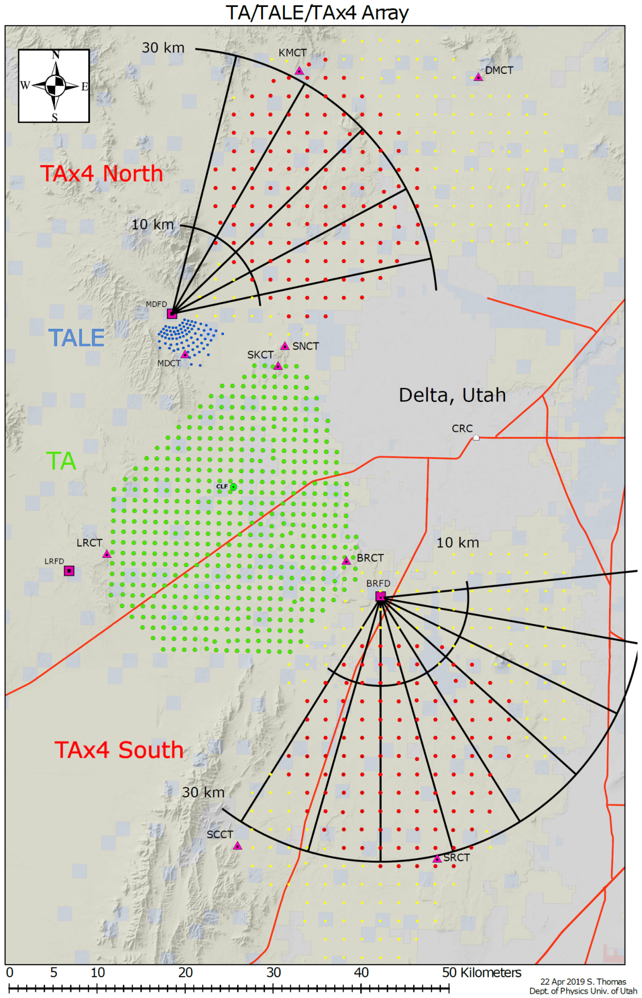
- Impact of hadronic interaction model on the source parameters estimation
- Too large…

Summary

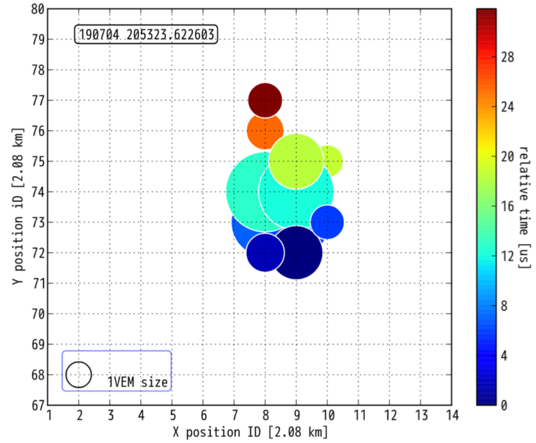
- A (mass) and Z (charge) dependence everywhere in CR physics
  - Source : $E_{max} = Z \times R_{max}$
  - Interaction with photon : $\Gamma = {}^{E_{CR}}/_{A \times m_p c^2}$
  - Magnetic deflection : $\theta \propto {}^{BL}/_{R} = {}^{ZBL}/_{E_{CR}}$
  - Air shower : 'A' superposition of ${}^{E_{CR}}/_{A}$ proton showers
- Currently mass estimation from air shower analyses suffers from uncertainty of ***hadronic interaction*** => hot topic with LHC
- Uncertainty of ***photodisintegration*** modeling also shows sizable effects in the mass composition at the earth
  - α production is not well constrained and has impact on the CR propagation

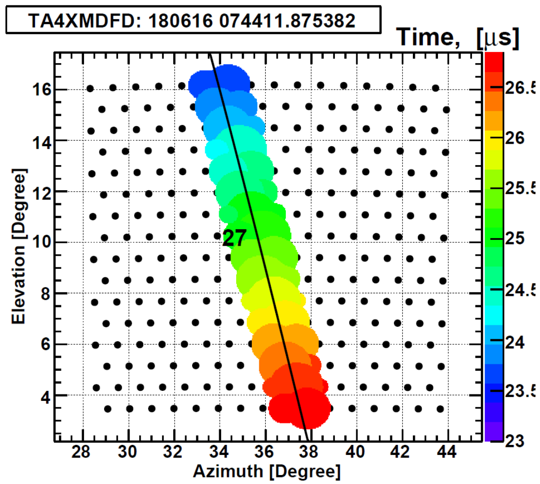
Few more slides…

Future



- More events with a larger area
  => TAx4 (partially) started





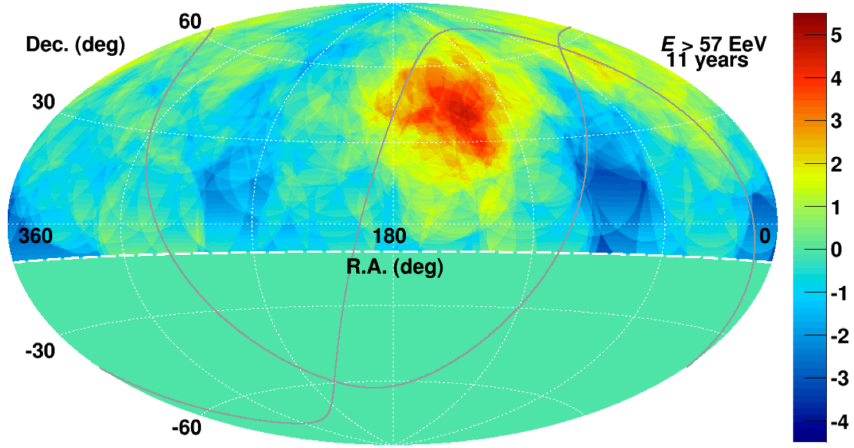
- More improvements on hadronic interaction
  => Measurements at LHC, Oxygen collisions in Run3?

Future

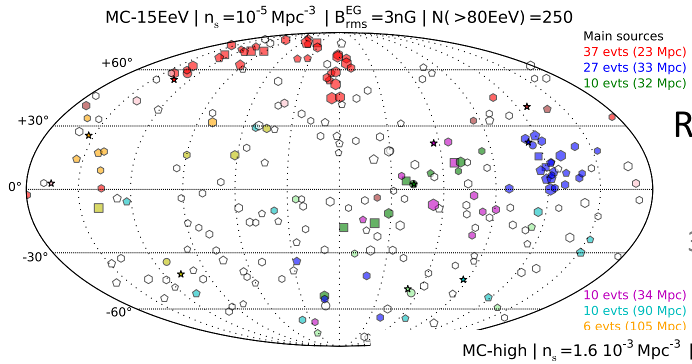
- More and more events
  - SD with better mass sensitivity
  - FD with a huge coverage area (to compensate duty time)
- Analysis for **individual source**, or sky area
  - **Magnetic deflection** becomes important

B. R. d'Orfeuil et al., A&A 567, A81 (2014)

TA 11 years

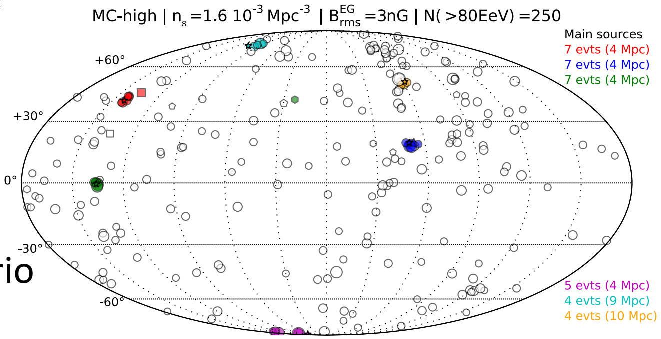


K. Kawata, ICRC2019



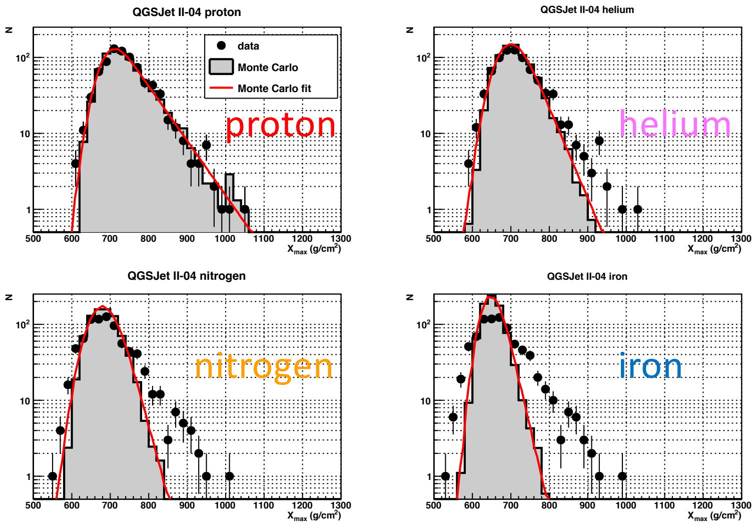
R_{max}=15EV mix scenario

300,000 km^2 sr yr
= (300,000/pi/700) = 136 TA yrs

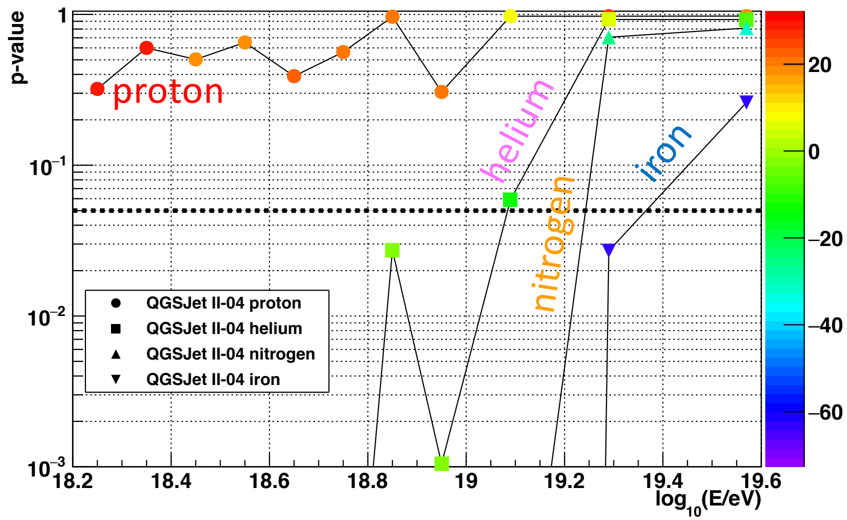


Proton dominant scenario
w/ high source density

BR, LR大気蛍光望遠鏡と地表検出器ハイブリッド観測による化学組成解析



$18.2 \leq \log_{10}(E/\mathrm{eV}) < 18.3$



Telescope Array, ApJ, 858:76 (2018)

- ✓ X_{max}の分布を実験とモデルで比較
- ✓ X_{max}+定数、を許して比較