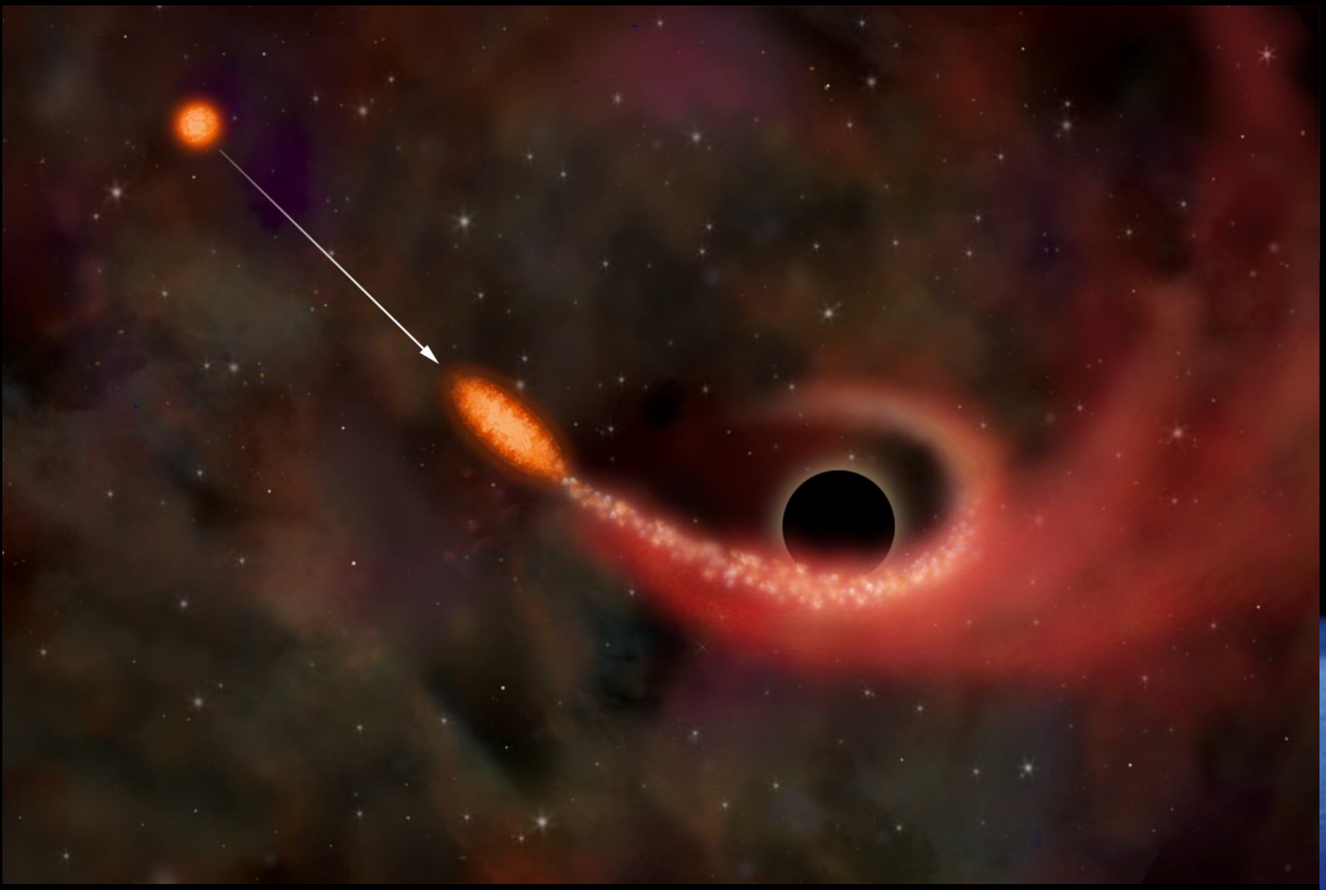
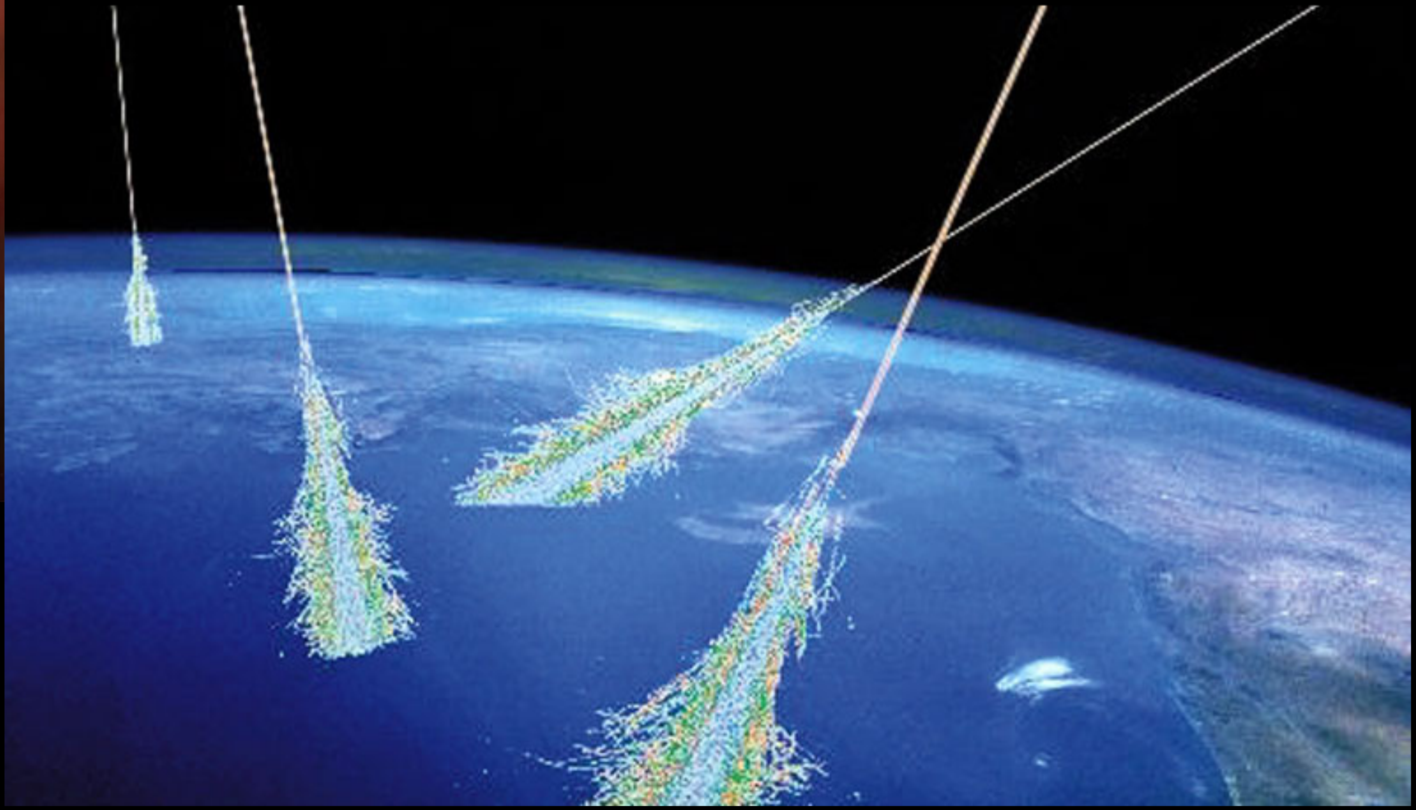
arXiv: 1706.00391 accepted by PRD

Ultrahigh Energy Cosmic Rays from Tidal Disruption Events: Origin, Survival, and Implications





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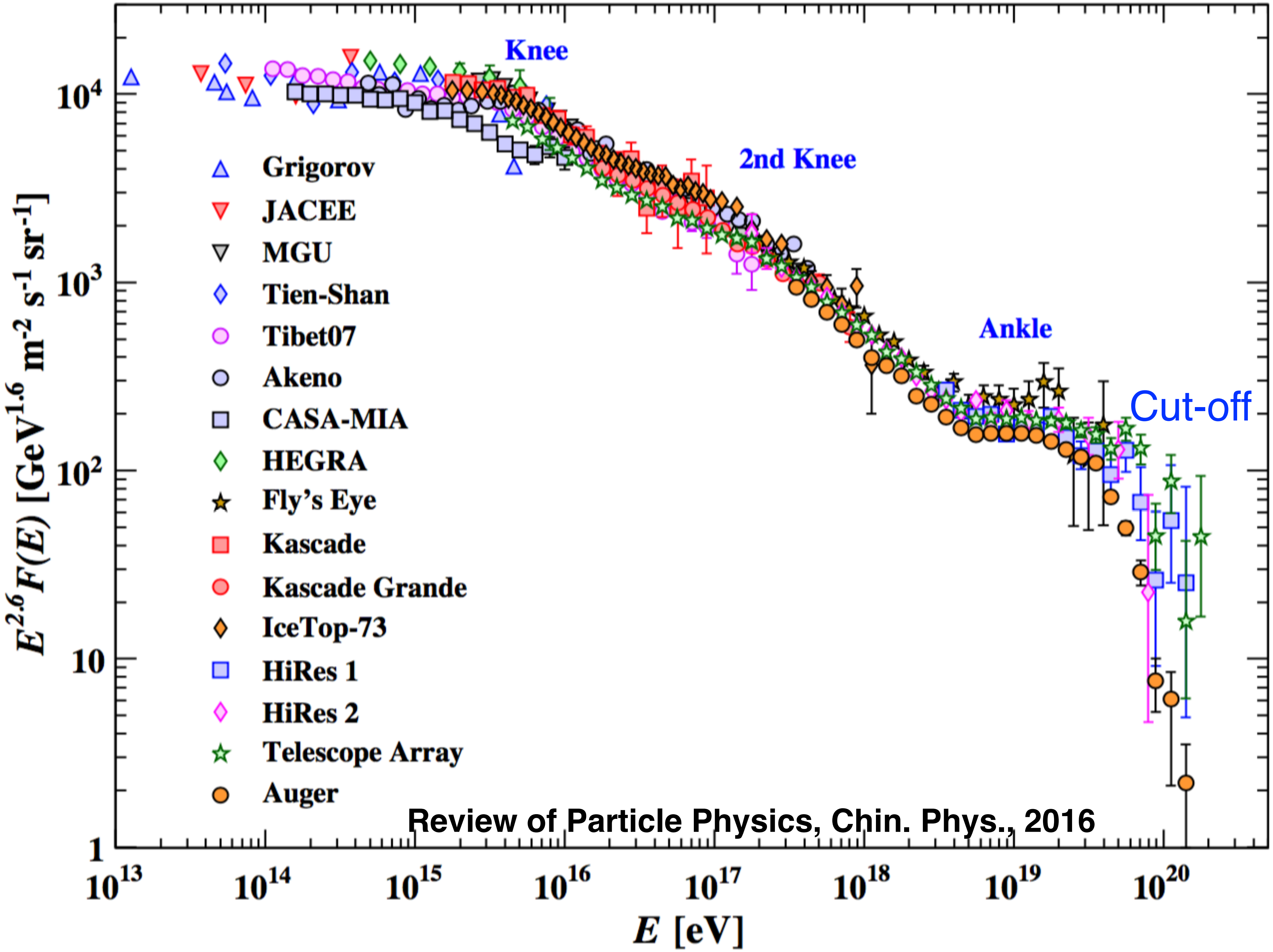
Collaborator: Kohta Murase, Foteini Oikonomou, Zhuo Li

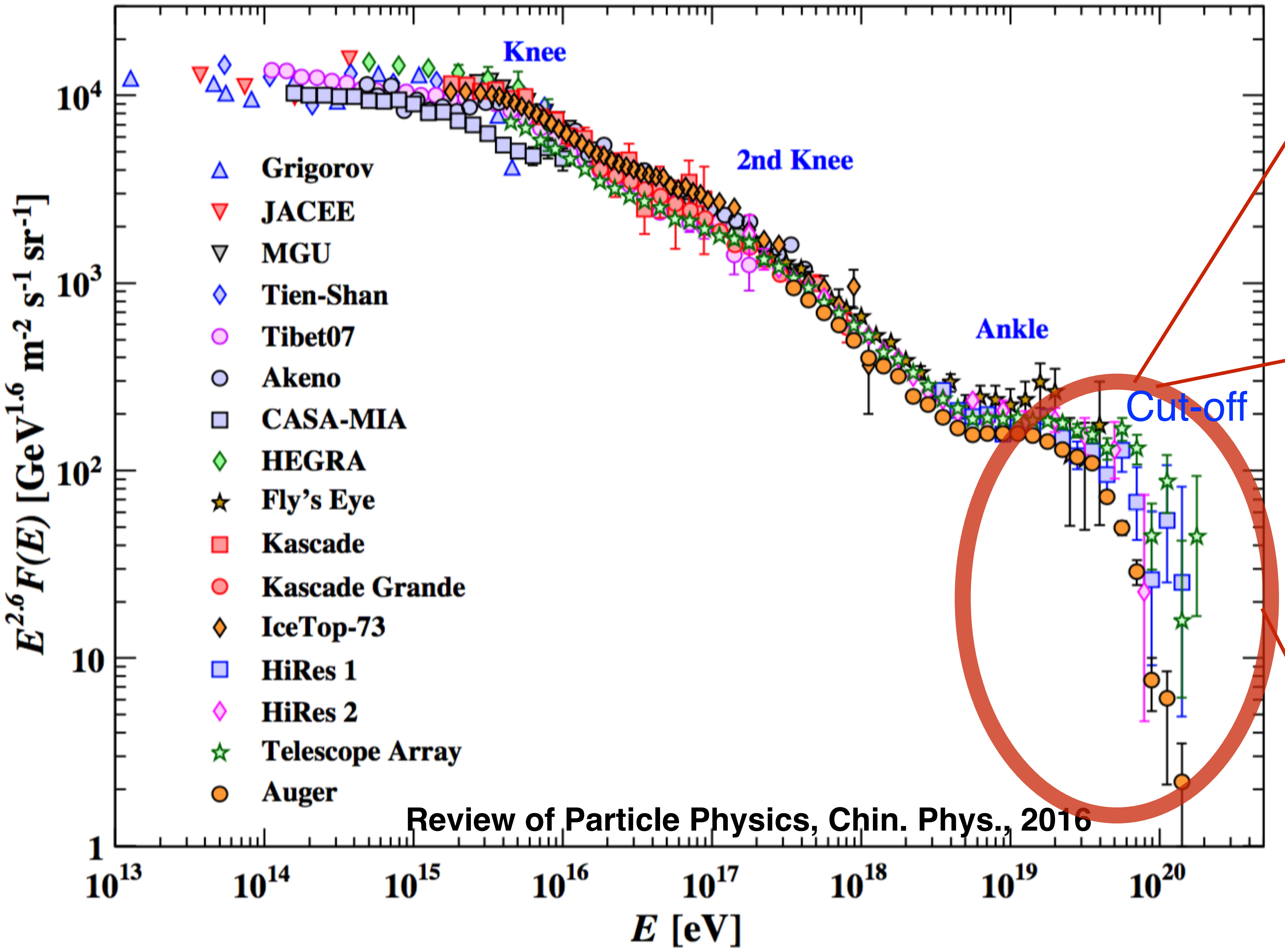
Ultrahigh-Energy Cosmic Rays - Spectrum



Review of Particle Physics, Chin. Phys., 2016

Ultrahigh-Energy Cosmic Rays - Spectrum

UHECRs: cosmic rays with energy larger than $\sim 10^{18}\ \mathrm{eV}$



Review of Particle Physics, Chin. Phys., 2016

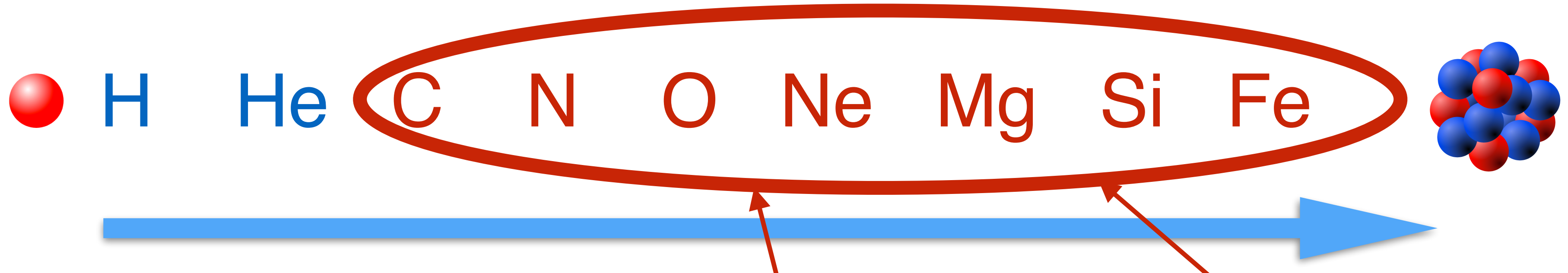
What is the composition?

Where are the sources?

How can they be accelerated to ultrahigh energy?

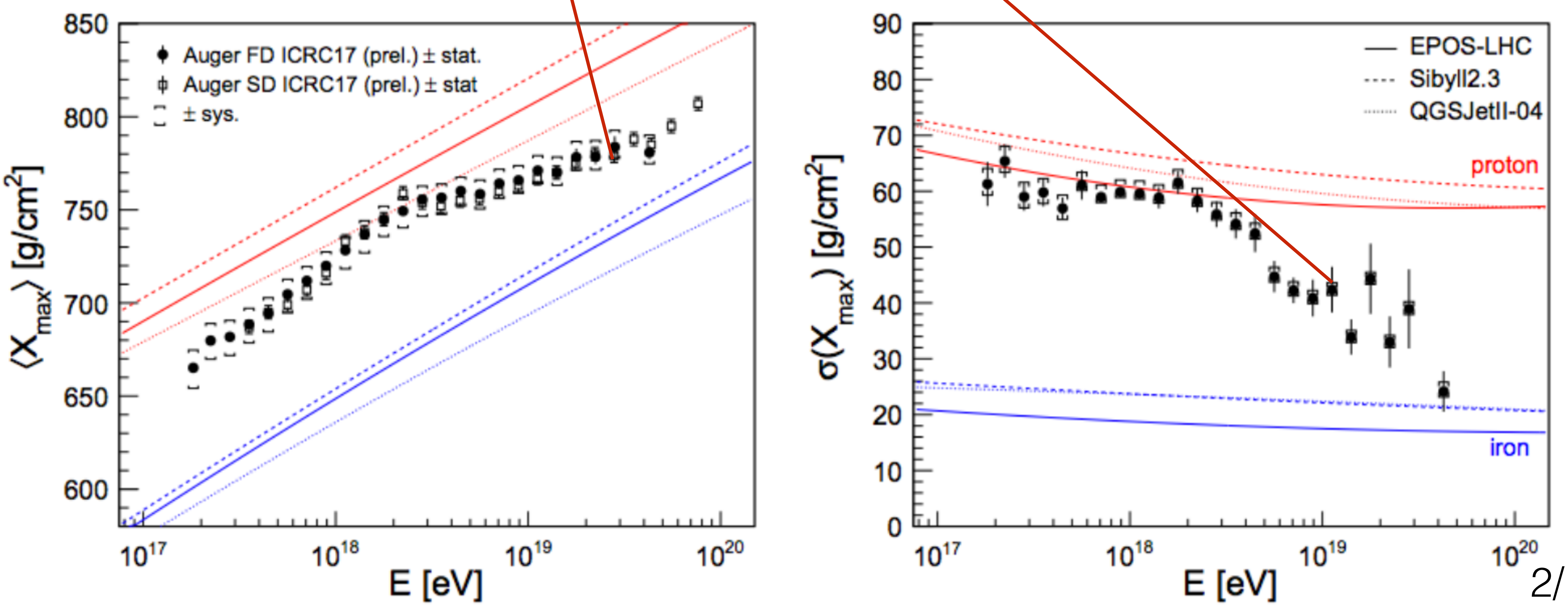
What is the composition?

A trend toward heavy nuclei




Air Shower

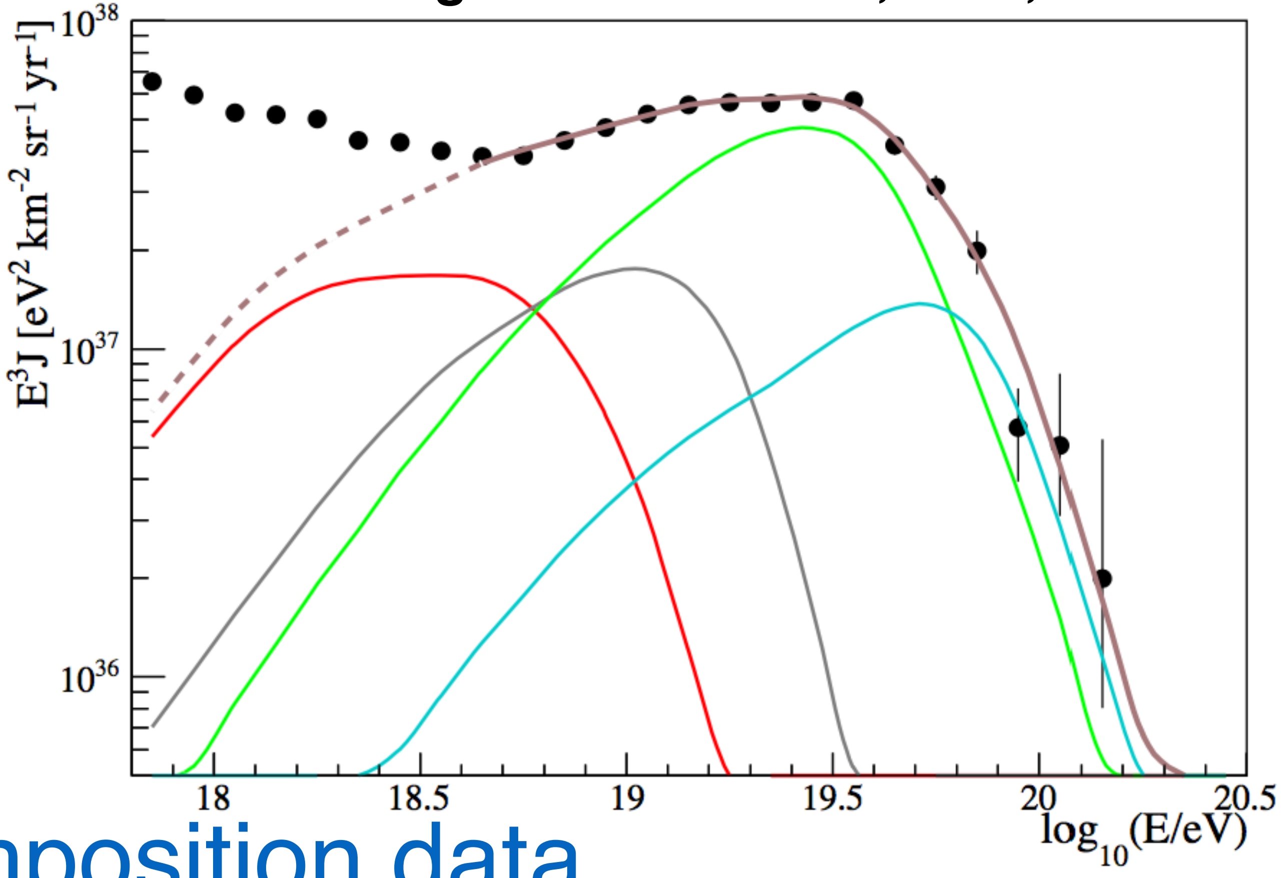
The Auger Collaboration, ICRC, 2017



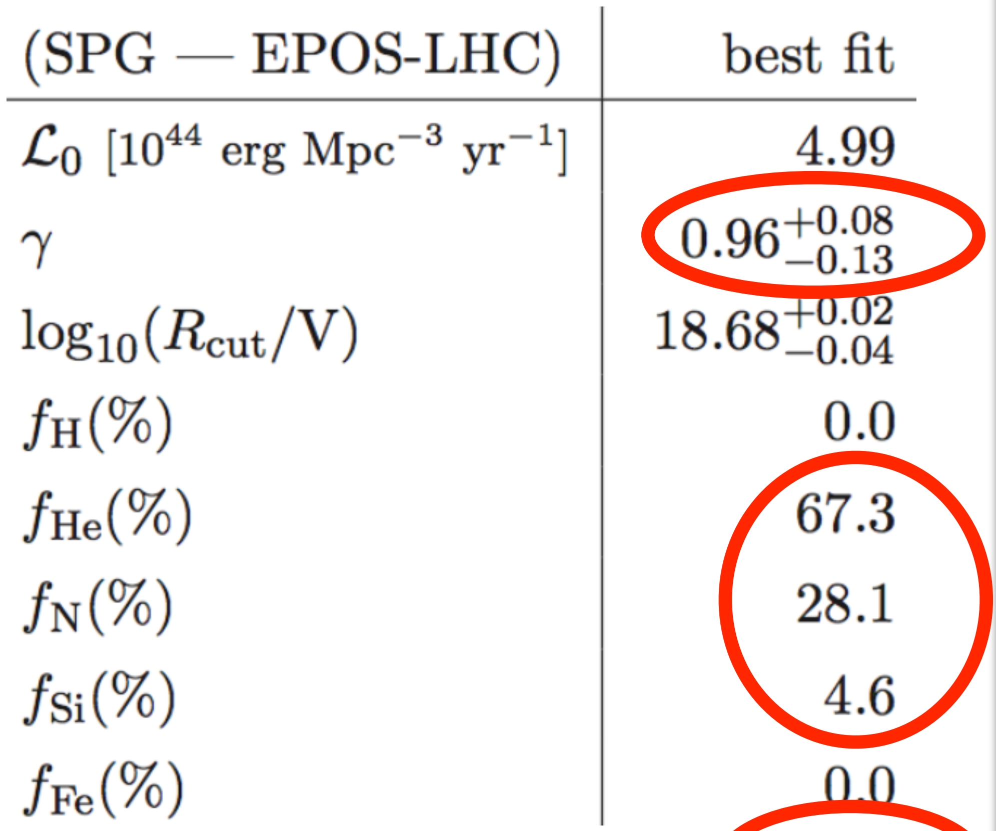
Combined fit spectrum and composition data

Spectrum

The Auger Collaboration, 2017, JCAP



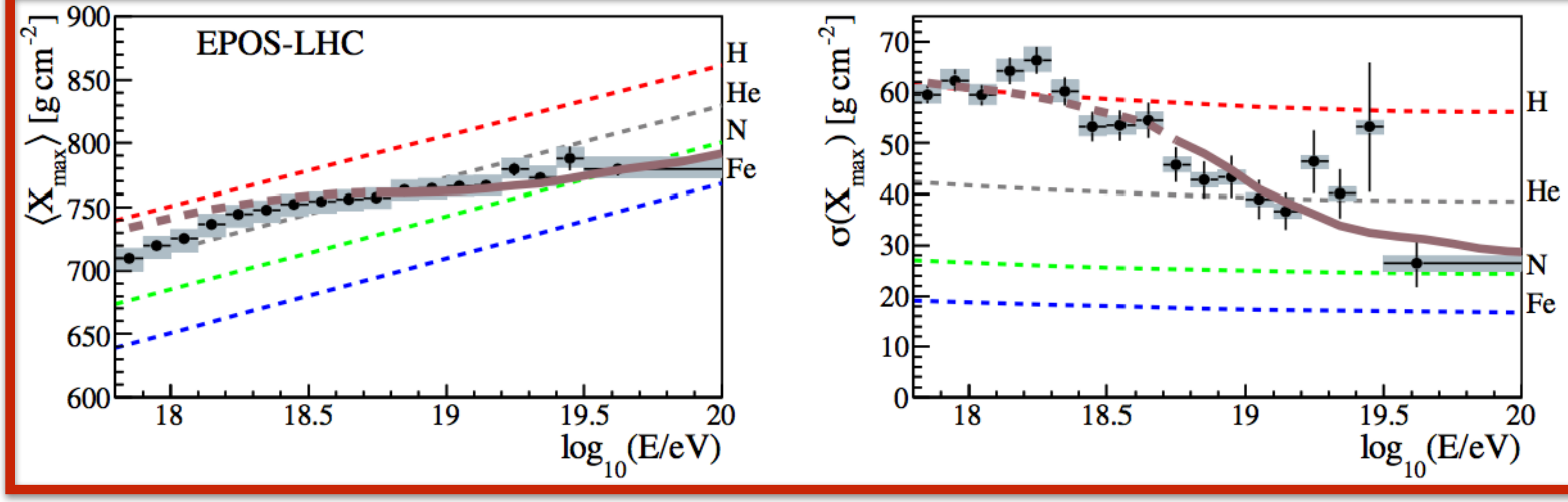
Injection spectrum



(SPG — EPOS-LHC)	best fit
$\mathcal{L}_0$ [10^{44} erg Mpc^{-3} yr^{-1}]	4.99
γ	$0.96^{+0.08}_{-0.13}$
$\log_{10}(R_{\rm cut}/{\rm V})$	$18.68^{+0.02}_{-0.04}$
$f_{\rm H}(\%)$	0.0
$f_{\rm He}(\%)$	67.3
$f_{\rm N}(\%)$	28.1
$f_{\rm Si}(\%)$	4.6
$f_{\rm Fe}(\%)$	0.0

Source evolution m = 0

Composition data

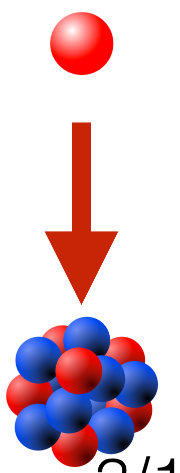


Proton

Helium

Nitrogen

Iron



Combined fit spectrum and composition data

Implications for the sources:

- heavy nuclei

  Intermediate mass, CNO, Ne, Mg, Si, …

- Hard spectra

  Spectral index less than 2

- Source evolution

  Prefer no evolution or negative evolution

Where are the sources ?

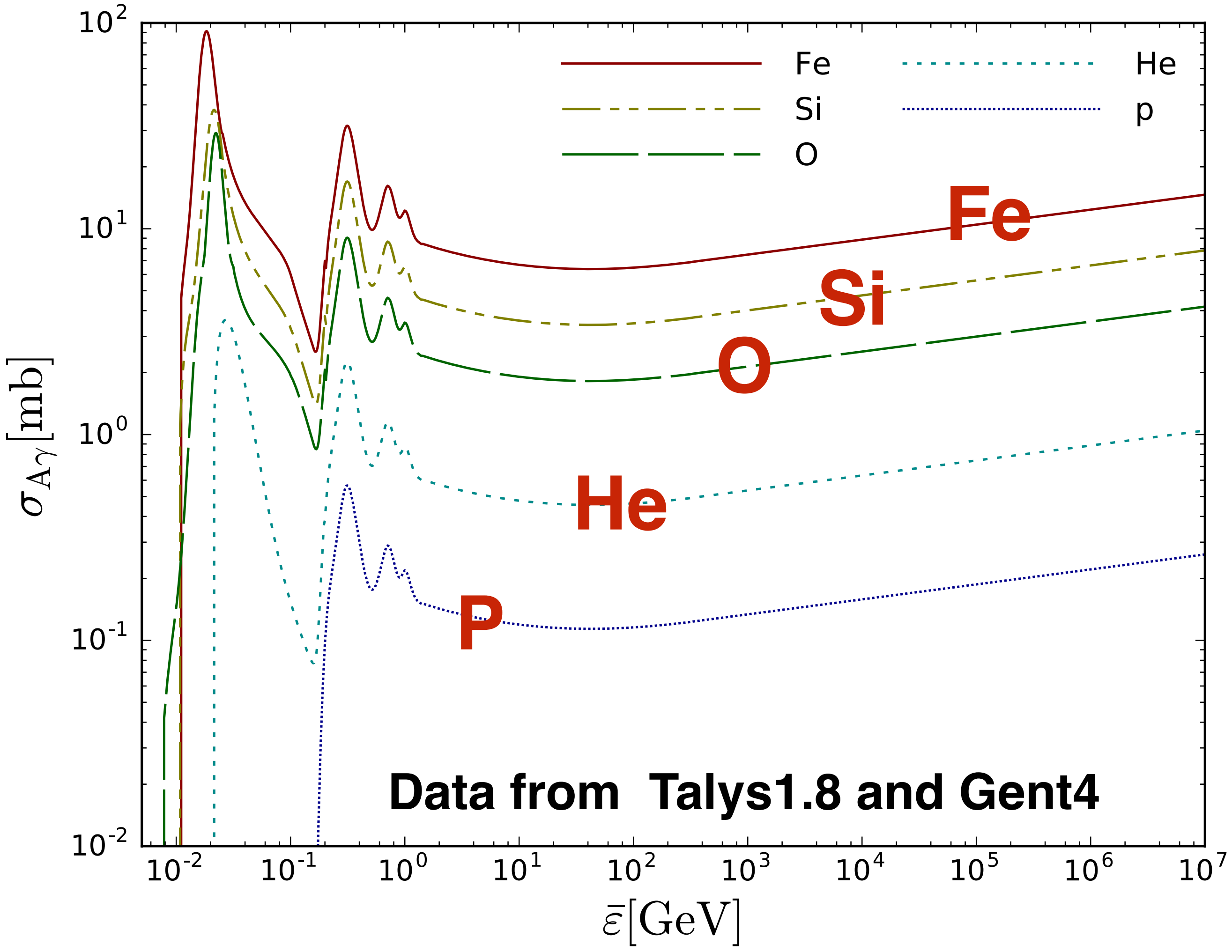
Gamma ray bursts

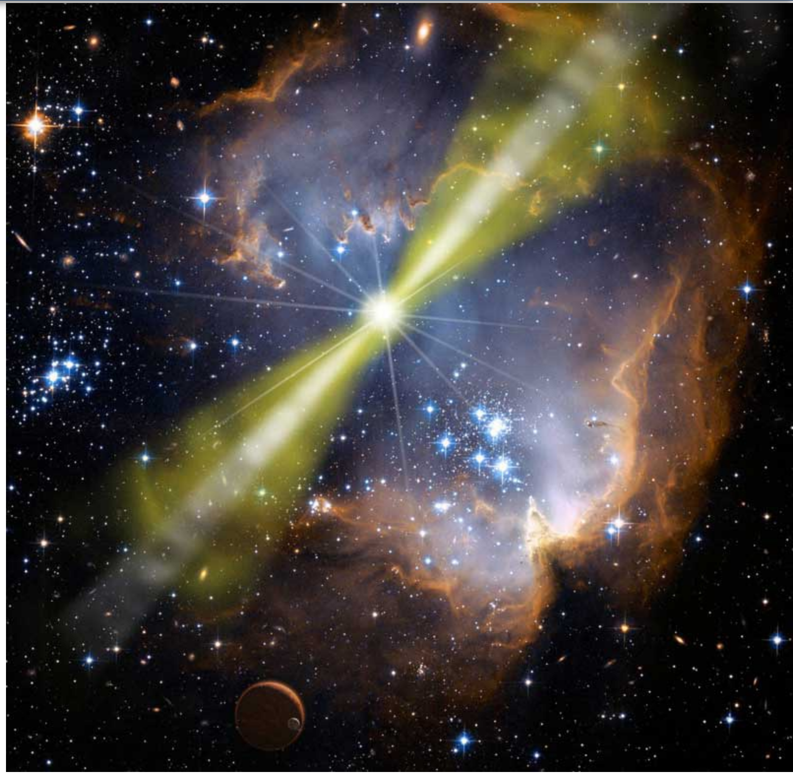
Heavy nuclei from the interior of progenitor stars

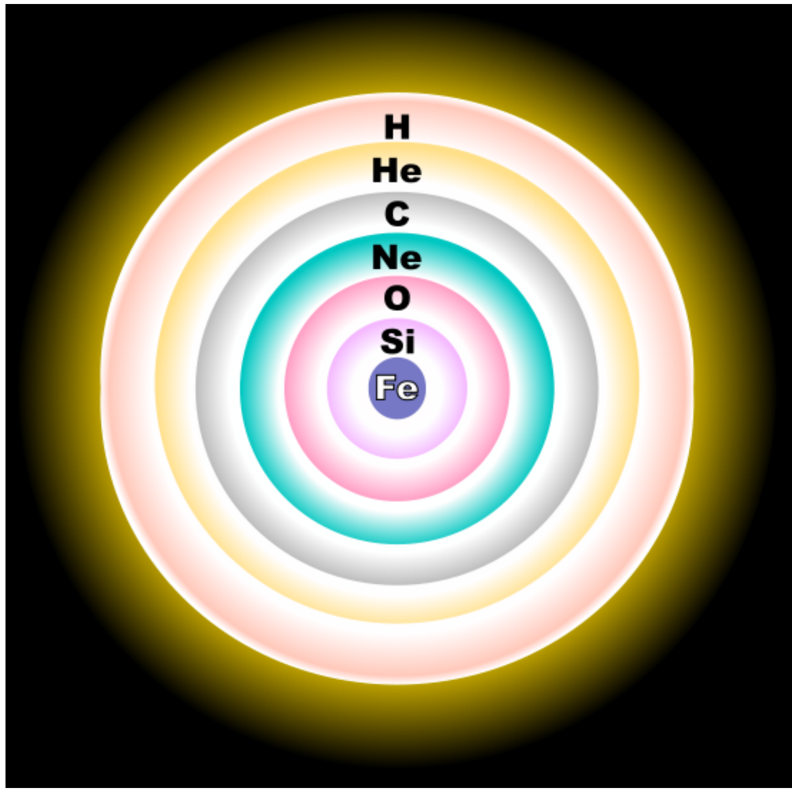
Survival of nuclei :

For GRBs, it is difficult in high-luminosity GRBs but easy in low-luminosity GRBs.

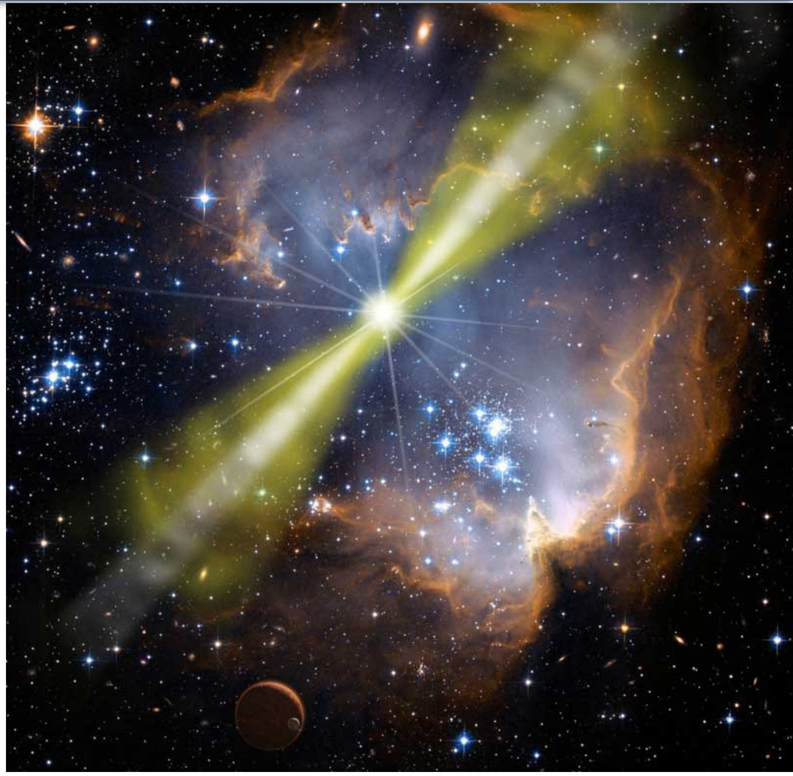
Murase et al, 2006; Murase et al, 2008; Wang et al, 2007; Chakraborti et al, 2010; Liu et al, 2011; Horiuchi et al, 2012; Globus et al, 2014; Biehl et al, 2017







Where are the sources ?



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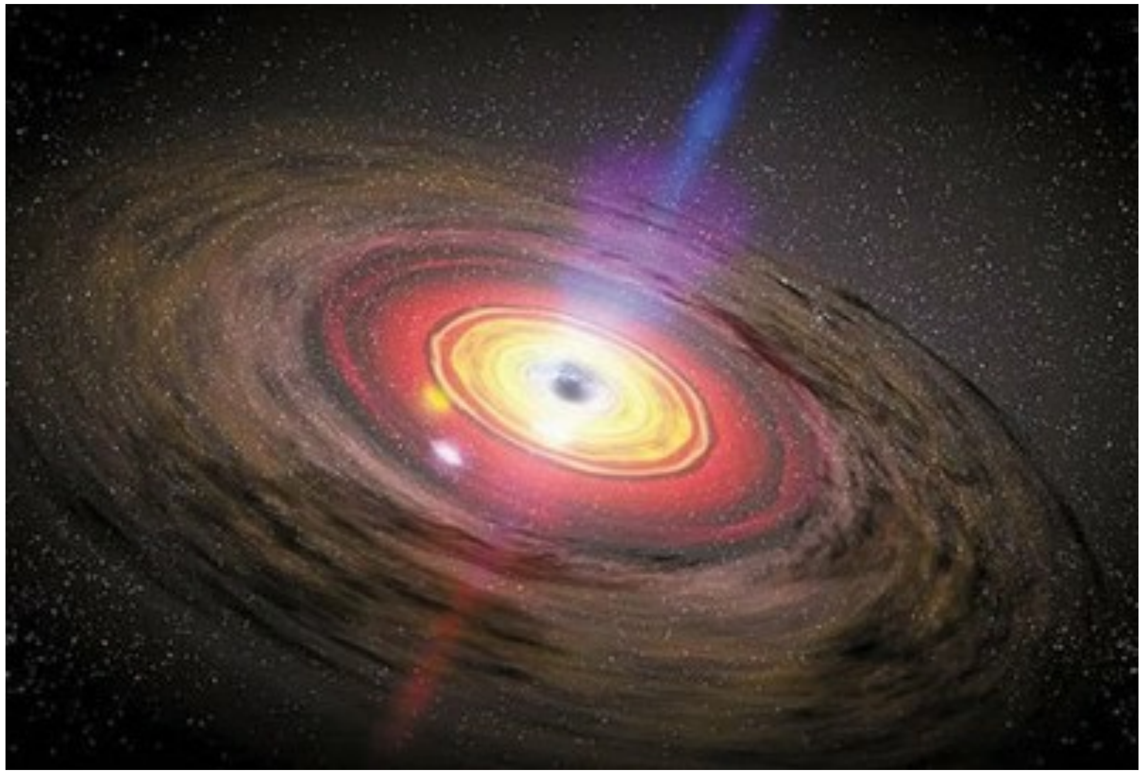


Active galactic nuclei

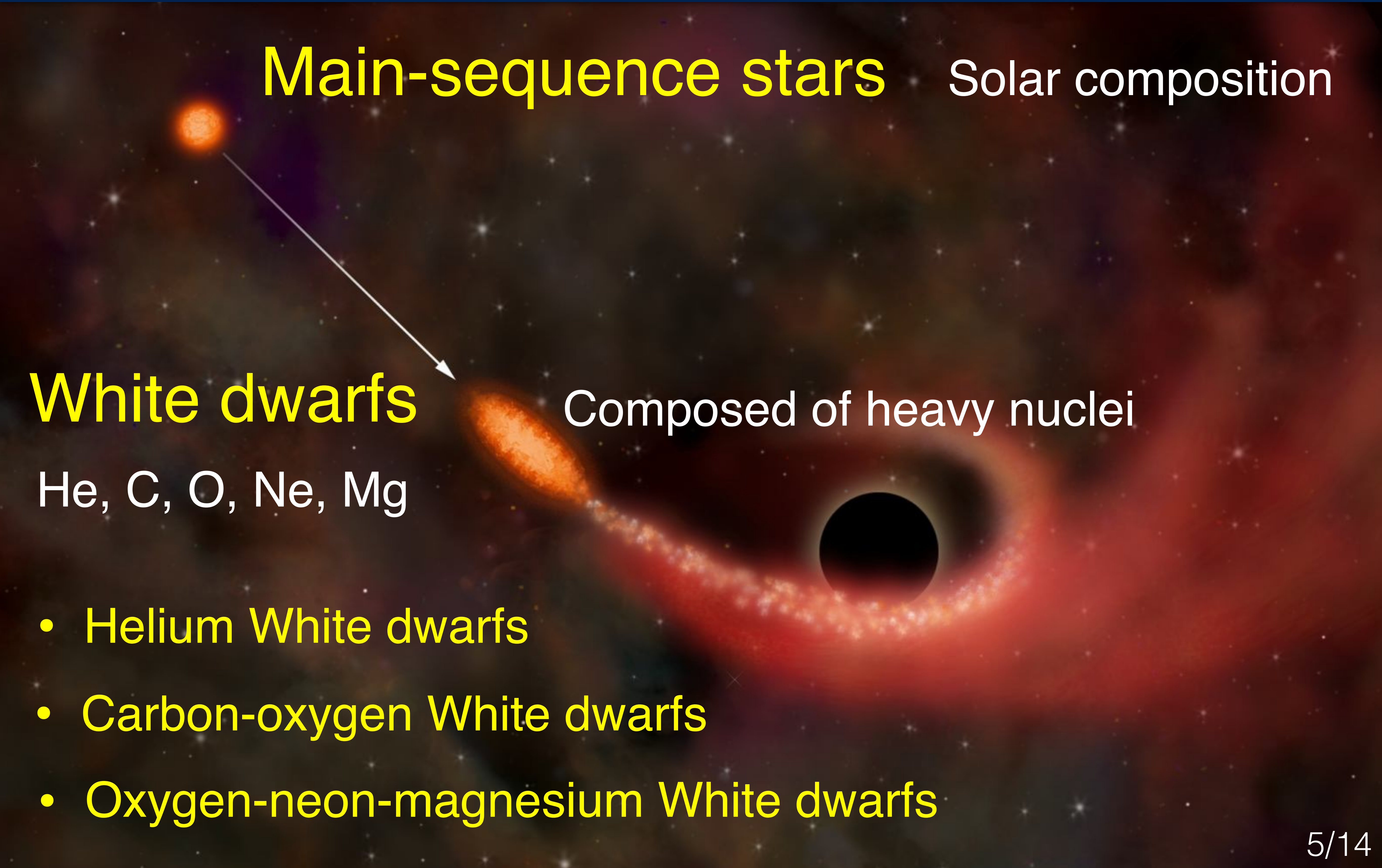
Heavy nuclei from the interstellar medium

The fraction of heavy nuclei is too low

Re-acceleration (galactic CRs) model

Kimura, Murase, BTZ, 2017

Heavy nuclei in Tidal disruption events



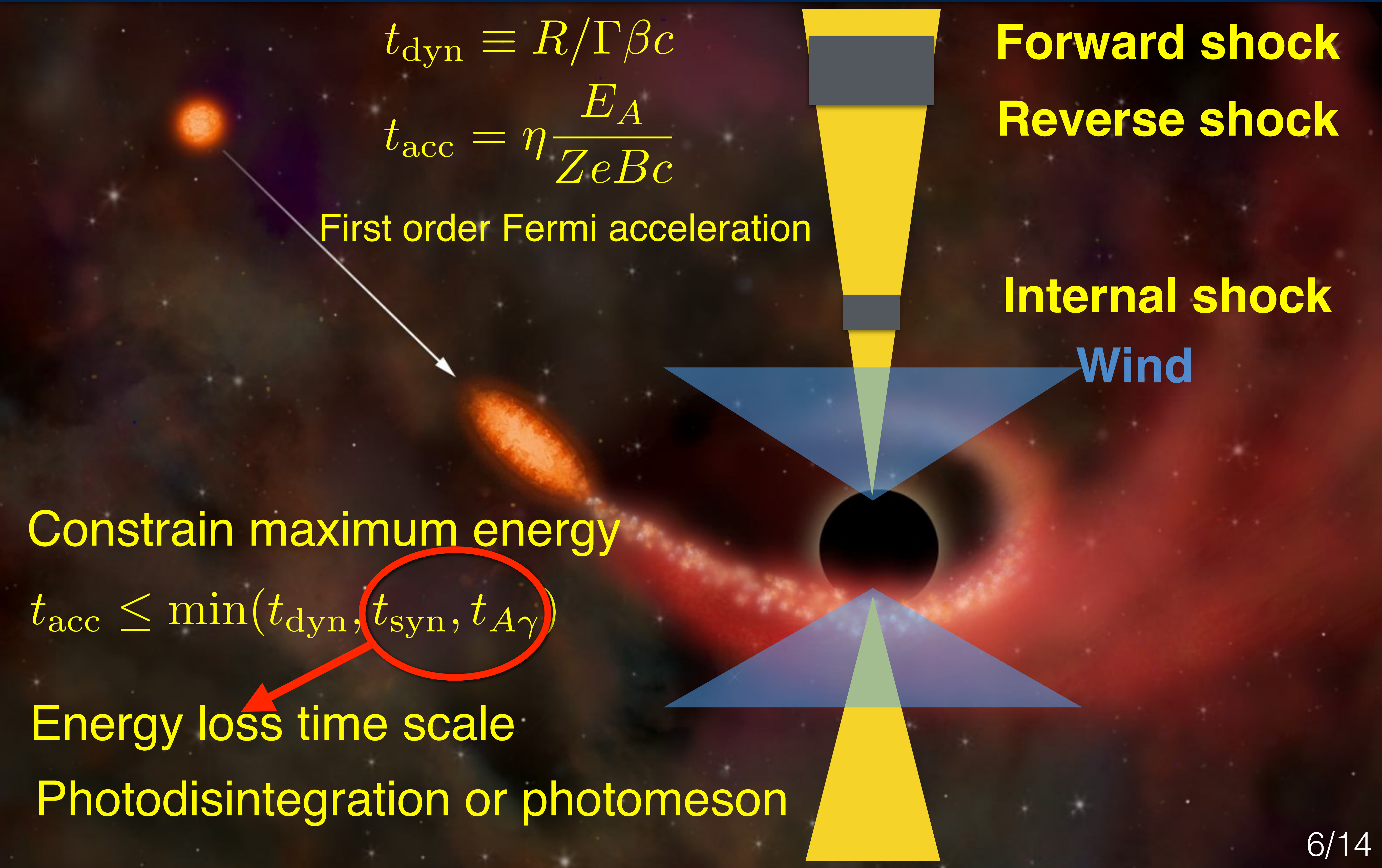
Main-sequence stars Solar composition

White dwarfs Composed of heavy nuclei

He, C, O, Ne, Mg

- Helium White dwarfs
- Carbon-oxygen White dwarfs
- Oxygen-neon-magnesium White dwarfs

CR acceleration in jetted TDEs



$$t_{\mathrm{dyn}} \equiv R/\Gamma\beta c$$

$$t_{\mathrm{acc}} = \eta \frac{E_A}{ZeBc}$$

First order Fermi acceleration

Constrain maximum energy

$$t_{\mathrm{acc}} \leq \min(t_{\mathrm{dyn}}, \boxed{t_{\mathrm{syn}}, t_{A\gamma}})$$

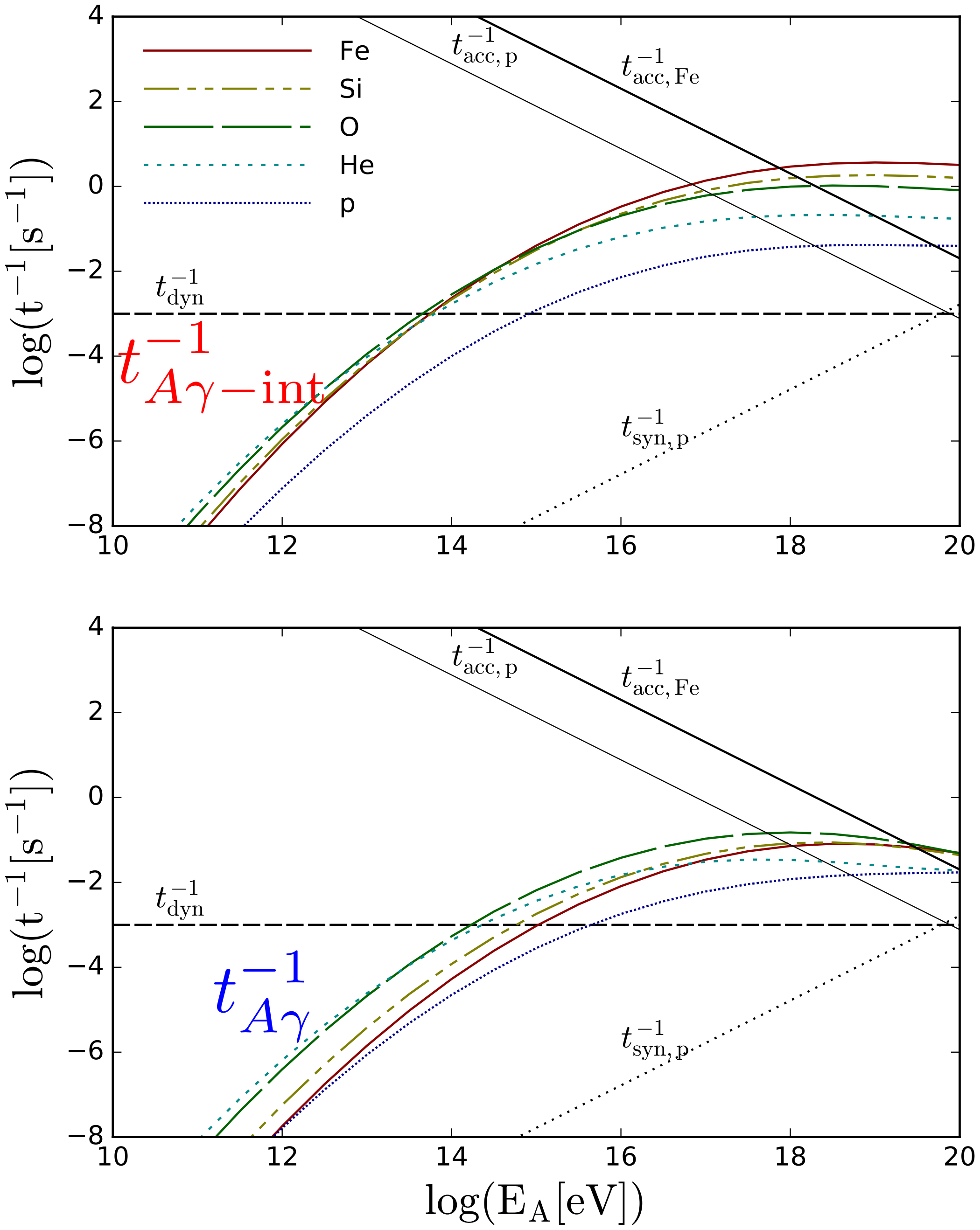
Energy loss time scale

Photodisintegration or photomeson

Internal shock model

CRs can be accelerated to ultrahigh energy

Difficult for UHECR nuclei to survive in luminous TDE jets such as Swift J1644+57



UHECR nuclei mainly lose one nucleon in each interaction

Inelasticity $\kappa_{A\gamma}(\bar{\varepsilon}) \equiv \frac{\Delta E}{E} = \frac{\Delta N}{N}$

Interaction time scale

$$t^{-1}_{A\gamma-\mathrm{int}} \propto \sigma_{A\gamma}(\bar{\varepsilon})$$

Energy loss time scale

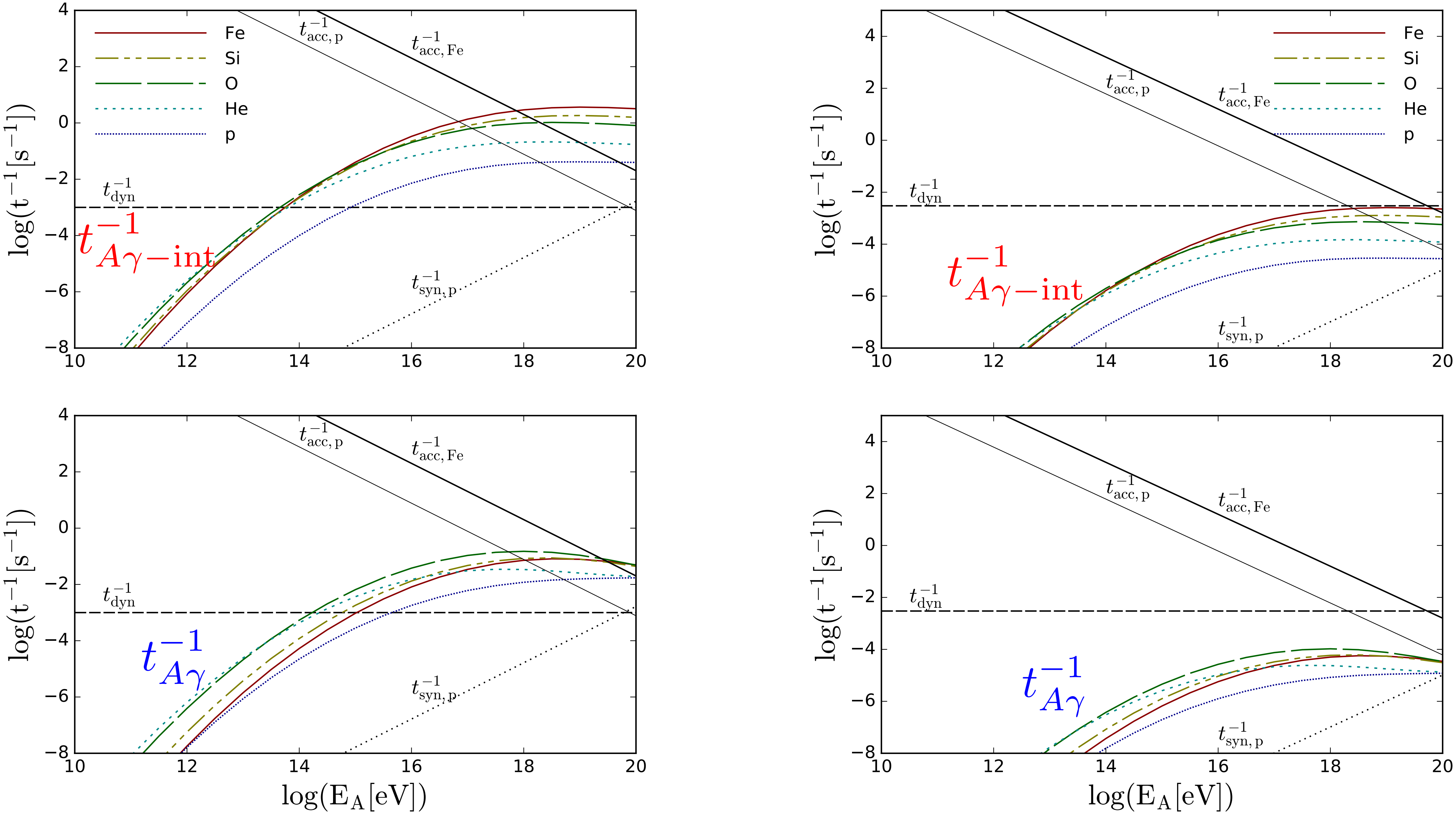
$$t^{-1}_{A\gamma} \propto \sigma_{A\gamma}(\bar{\varepsilon})\kappa_{A\gamma}(\bar{\varepsilon})$$

Internal shock model

CRs can be accelerated to ultrahigh energy

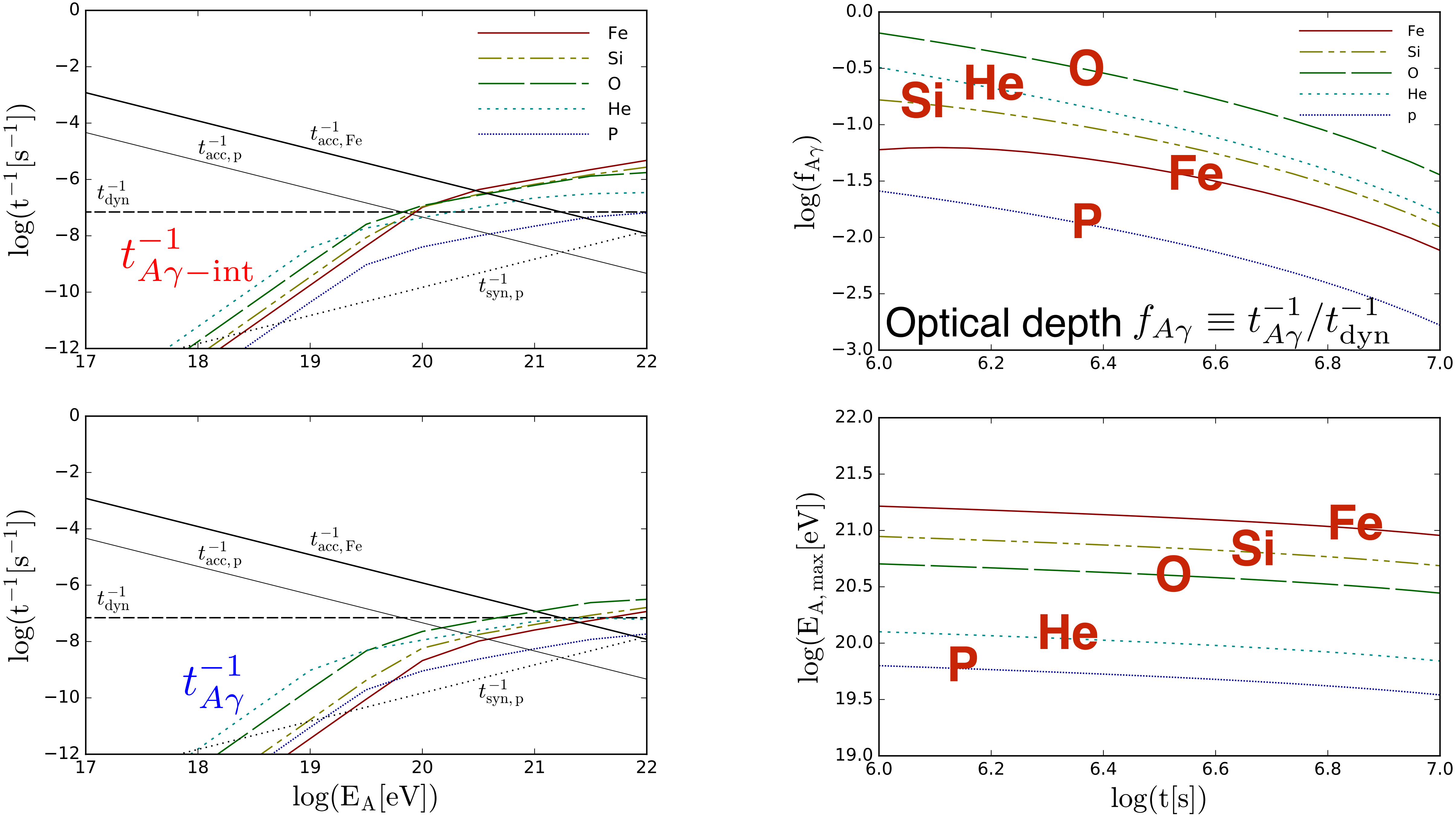
Difficult for UHECR nuclei to survive in luminous TDE jets such as Swift J1644+57

The survival is allowed for less powerful TDE jets



Forward shock model

UHECR nuclei can survive at forward shock such as Swift J1644+57



Reverse shock: CRs can be accelerated to ultrahigh energy and survive

Non relativistic wind: CRs cannot be accelerated to ultrahigh energy

Cosmic rays escaping from sources

Acceleration spectral index $s_{\rm acc}$ $\neq$ $s_{\rm esc}$ Escape spectral index

CRs can be confined and lose their energies during diffusive escape

A harder spectrum $s_{\rm esc} < s_{\rm acc} = 2$

- Direct escape of CRs in internal shock **Baerwald, Bustamante and Winter, 2013**
- Escape from a relativistic decelerating blast wave

Katz, Meszaros and Waxman, 2010

Two assumptions:

The number of ejected CRs is similar to the number of particles at radius R

$$\varepsilon N_{\rm esc}(\varepsilon) \sim \varepsilon N(\varepsilon, R|_{\varepsilon_{\rm max}=\varepsilon})$$

The minimum, maximum and total cosmic ray energies are power low functions of the radius

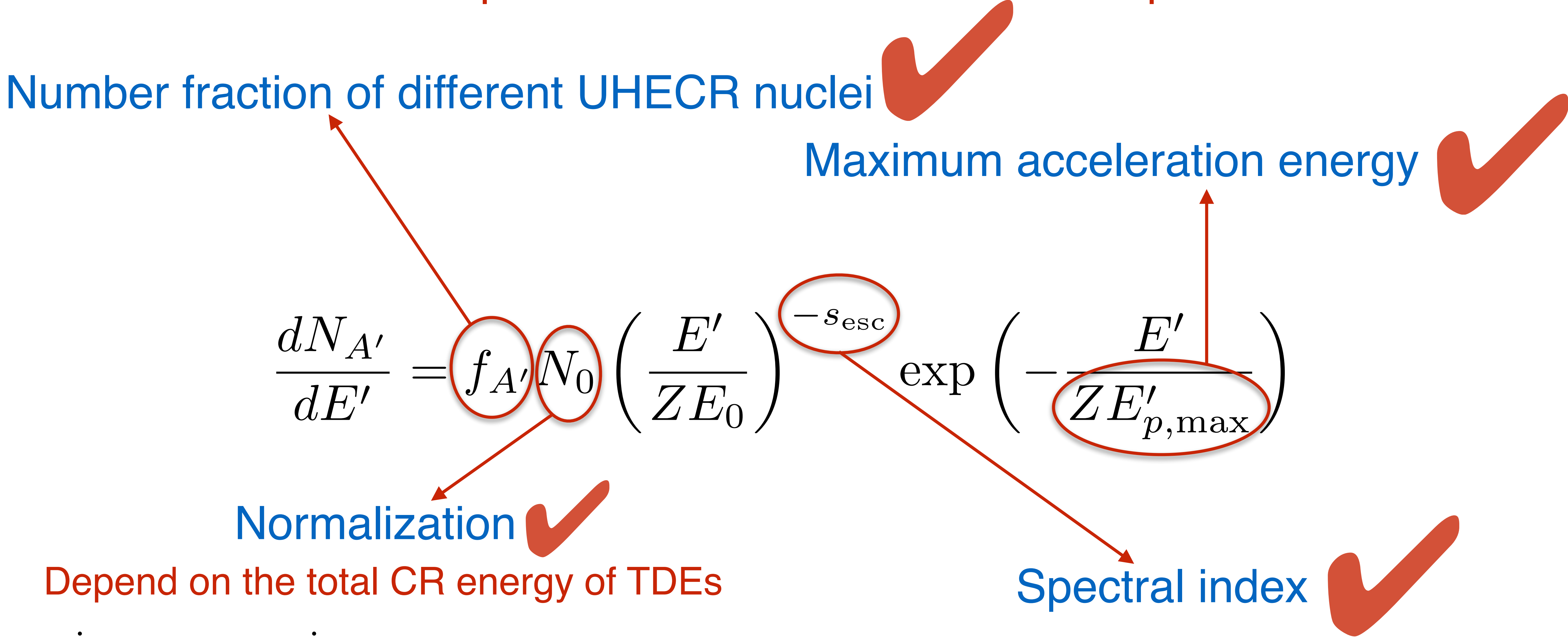
$$E_{A,\rm min} \simeq \Gamma^2 A m_p c^2 \propto r^{-\alpha_{\rm min}} \quad E_{A,\rm max} \simeq ZeBr \propto r^{-\alpha_{\rm max}} \quad \mathcal{E}_{\rm CR} \propto r^{-\alpha_{\mathcal{E}}}$$

The spectral index of escaped particles:

$$s_{\rm esc} = s_{\rm acc} - (\alpha_{\rm min}(s_{\rm acc} - 2) + \alpha_{\mathcal{E}})/\alpha_{\rm max}$$

UHECR nuclei injection spectrum

UHECR nuclei follow a power-law distribution with an exponential cutoff



Number fraction of different UHECR nuclei ✓

Maximum acceleration energy ✓

$$\frac{dN_{A'}}{dE'} = f_{A'} N_0 \left(\frac{E'}{ZE_0}\right)^{-s_{\rm esc}} \exp\left(-\frac{E'}{ZE'_{p,\rm max}}\right)$$

Normalization ✓

Spectral index ✓

Depend on the total CR energy of TDEs

$$\mathcal{E}_{\rm CR}^{\rm iso} = \xi_{\rm CR}\mathcal{E}_{\rm rad}^{\rm iso} \quad \xi_{\rm CR} \sim 100$$

Cosmic ray loading factor

Results of MS - SMBH tidal disruptions

Solar composition

$$ZE_{p,\max} = Z\ 2 \times 10^{19}\ \mathrm{eV}$$

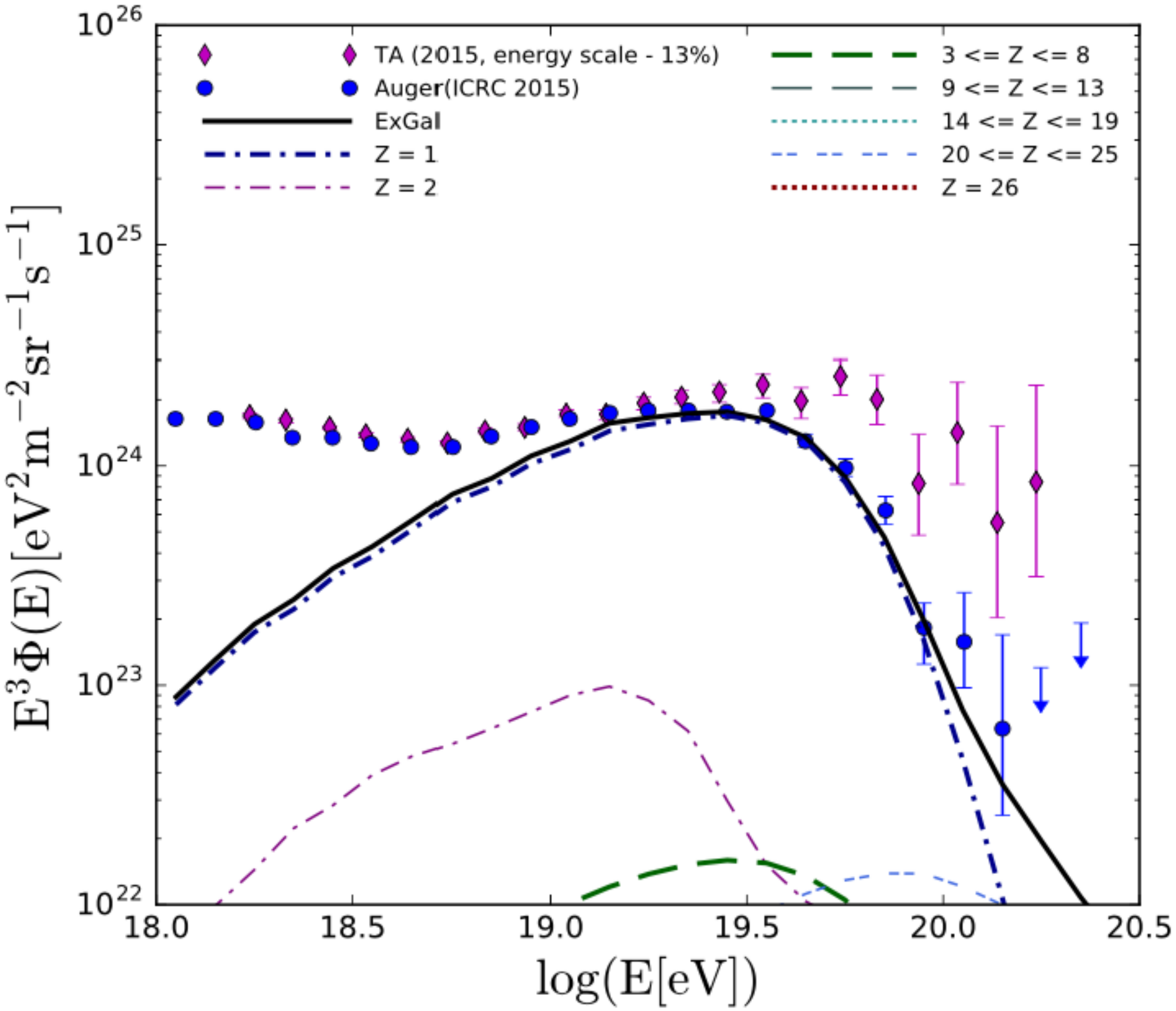
$$s_{\rm esc} = 1$$

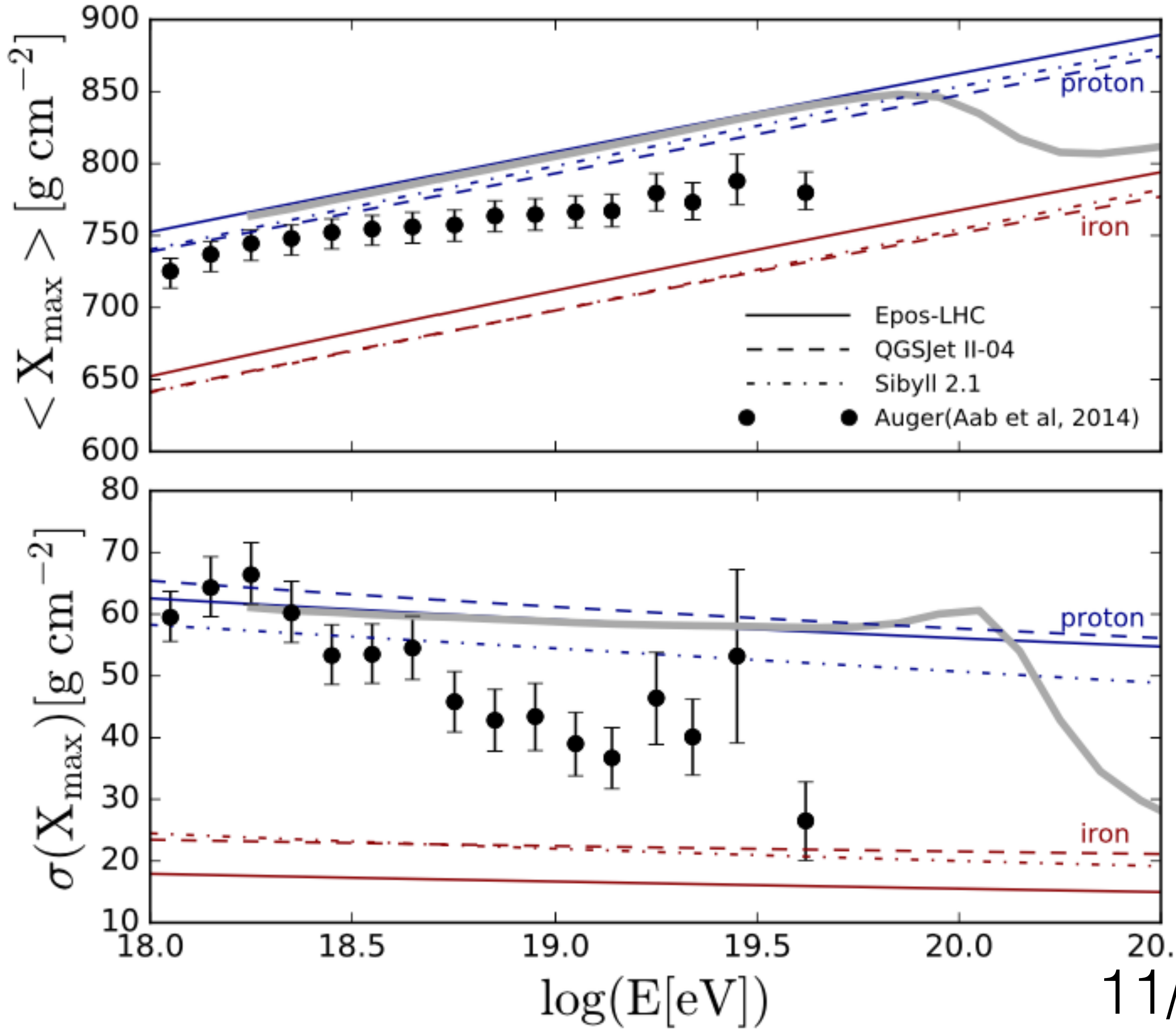
$$\xi_{\rm CR} \sim 100\ Q_{{\rm CR},44.6}\rho 0^{-1}_{-10.5}\ \mathcal{E}^{-1}_{{\rm rad},53}$$

Propagate with CRPropa 3 - 1D

EBL: Gilmore 12

Proton dominated in nearly all the energy range





Results of CO WD - IMBH tidal disruptions

$$X_{\mathrm{C}} = 0.5, X_{\mathrm{O}} = 0.5$$

$$ZE_{p,\mathrm{max}} = 6.3 \times 10^{18} Z \quad \mathrm{eV}$$

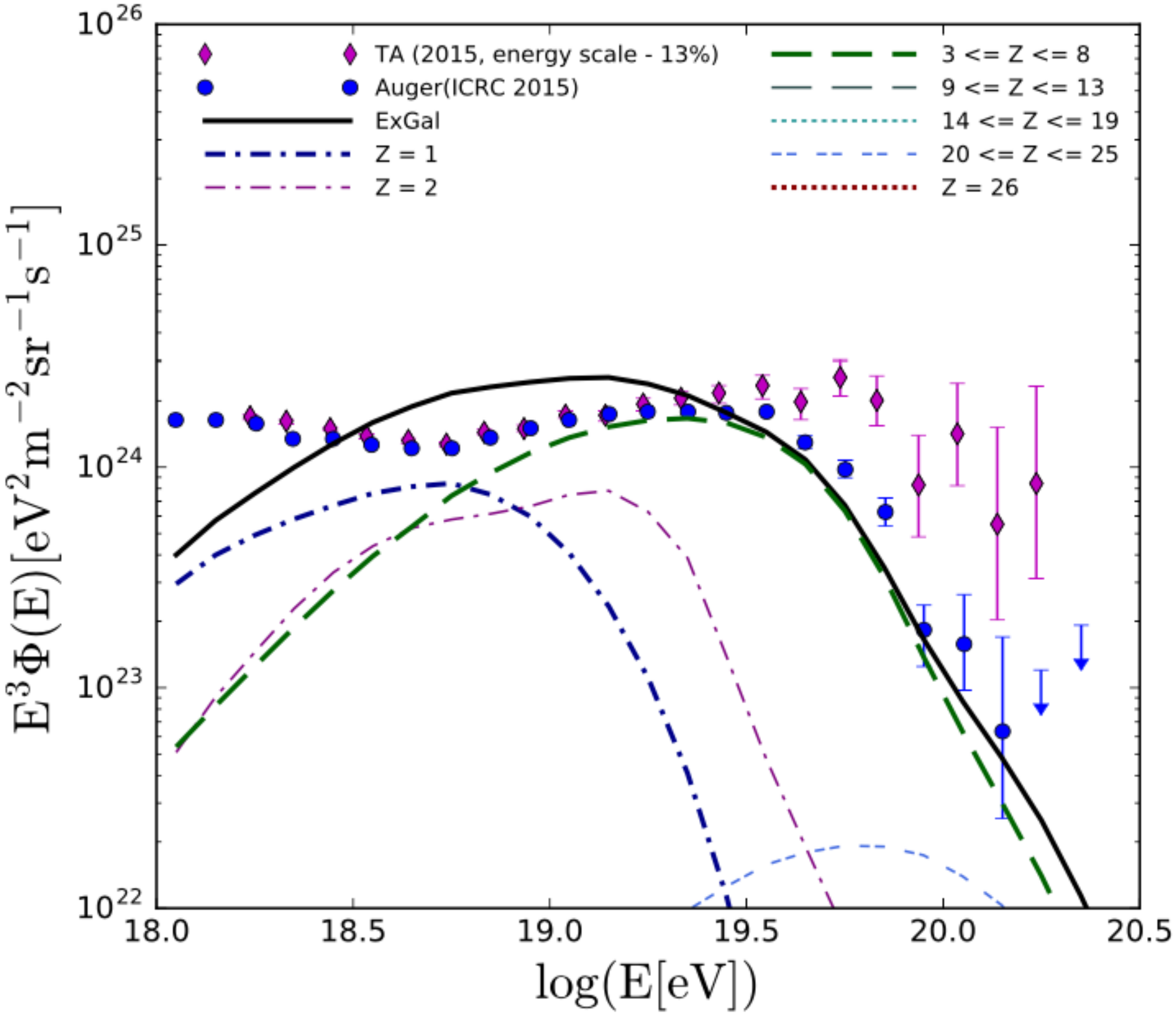
$$s_{\mathrm{esc}} = 1$$

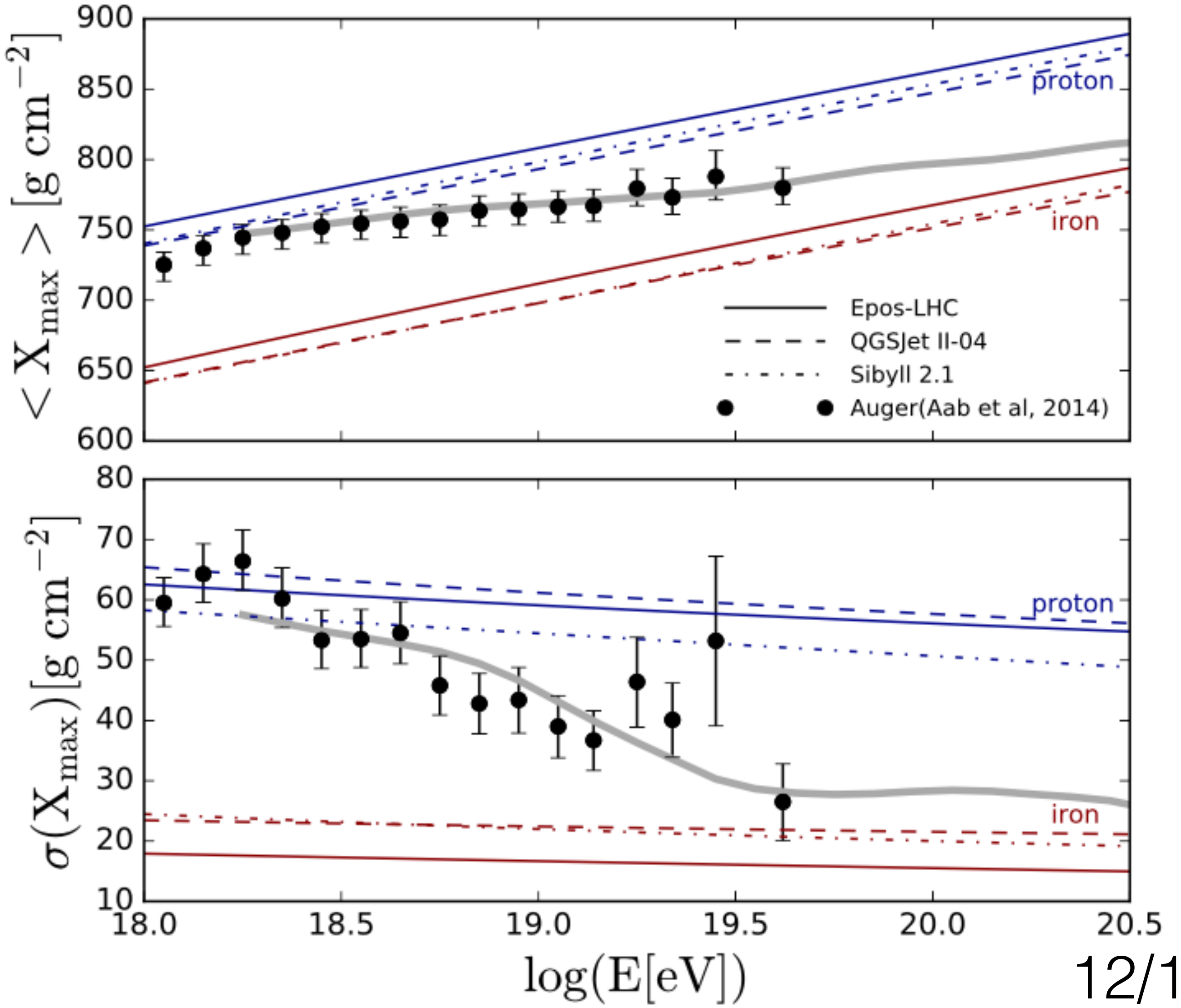
$$\xi_{\mathrm{CR}} \sim 100 \; Q_{\mathrm{CR},44.6} \rho_{0\,-10.2}^{-1} \; \mathcal{E}_{\mathrm{rad},53}^{-1}$$

Propagate with CRPropa 3 - 1D

EBL: Gilmore 12

Poor fit to the UHECR spectrum





Results of ONeMg WD - IMBH tidal disruptions

$X_{\rm O} = 0.12, X_{\rm Ne} = 0.76, X_{\rm Mg} = 0.12$

$ZE_{p,\rm max} = 6.3 \times 10^{18} Z \quad {\rm eV}$

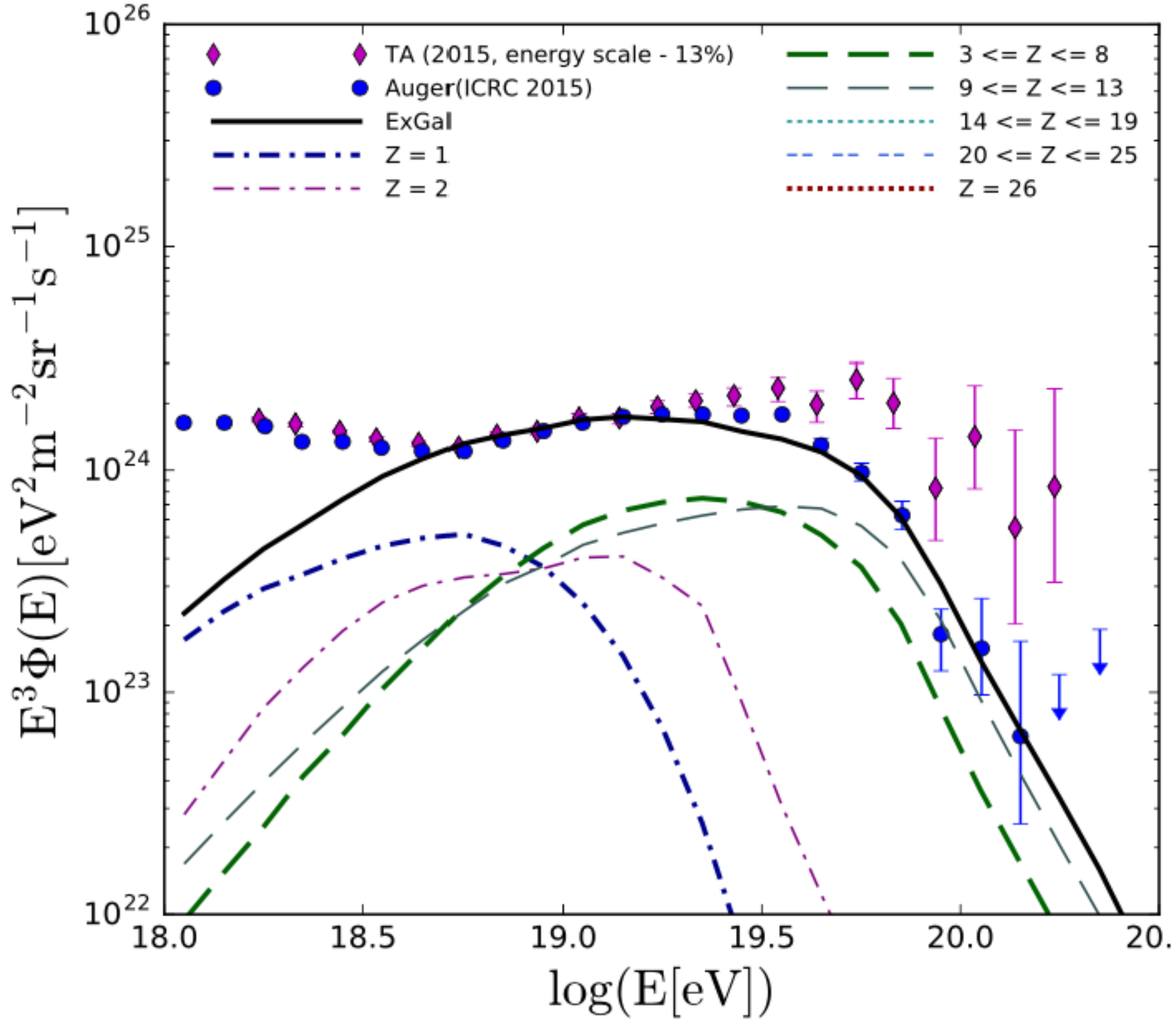
$s_{\rm esc} = 1$

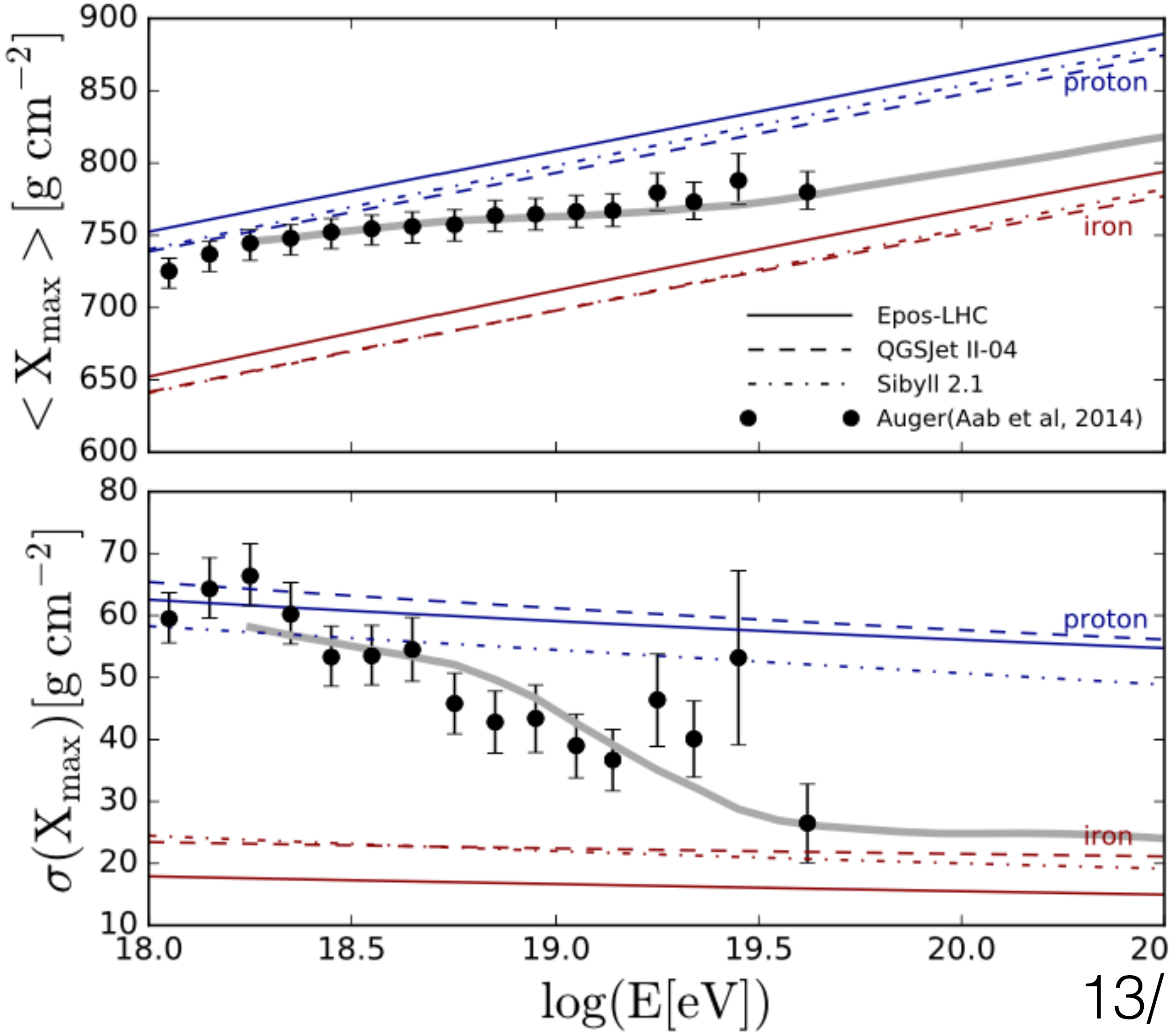
$\xi_{\rm CR} \sim 1000 \ Q_{{\rm CR},44.6}\rho_{0-11.7}^{-1} \ \mathcal{E}_{{\rm rad},53}^{-1}$

Propagate with CRPropa 3 - 1D

EBL: Gilmore 12

Consistent with Auger data





Summary, conclusion and implications

The production of UHECRs in TDEs accompanied by relativistic jets

- Internal shock The survival is allowed for less powerful TDEs
- Forward shock Production and survival of UHECRs
- Reverse shock Production and survival of UHECRs
- Non-relativistic wind CRs can only be accelerated to ~ PeV

Examine different composition models for TDEs

- MS-SMBH Proton dominate in nearly all the energy range
- CO-IMBH Poor fit to the spectrum
- ONeMg-IMBH The number density of ONeMg WDs is lower than CO WDs ~ 1/30 CO WDs
- WD-IMBH with ignition Difficult to reconcile Auger data Simulation resolution

Secondary gamma rays and neutrinos signals are of interest to test the model

- Cosmogenic neutrinos flux $E_\nu^2\Phi_\nu \sim 10^{-10}\ \mathrm{GeV\ cm^{-2}\ sr^{-1} s^{-1}}$
- High energy gamma rays Gamma rays can escape from sources

Neutron pion decay, photodeexcitation, Bethe-Heitler process