# Low-luminosity GRBs as the sources of UHECR nuclei

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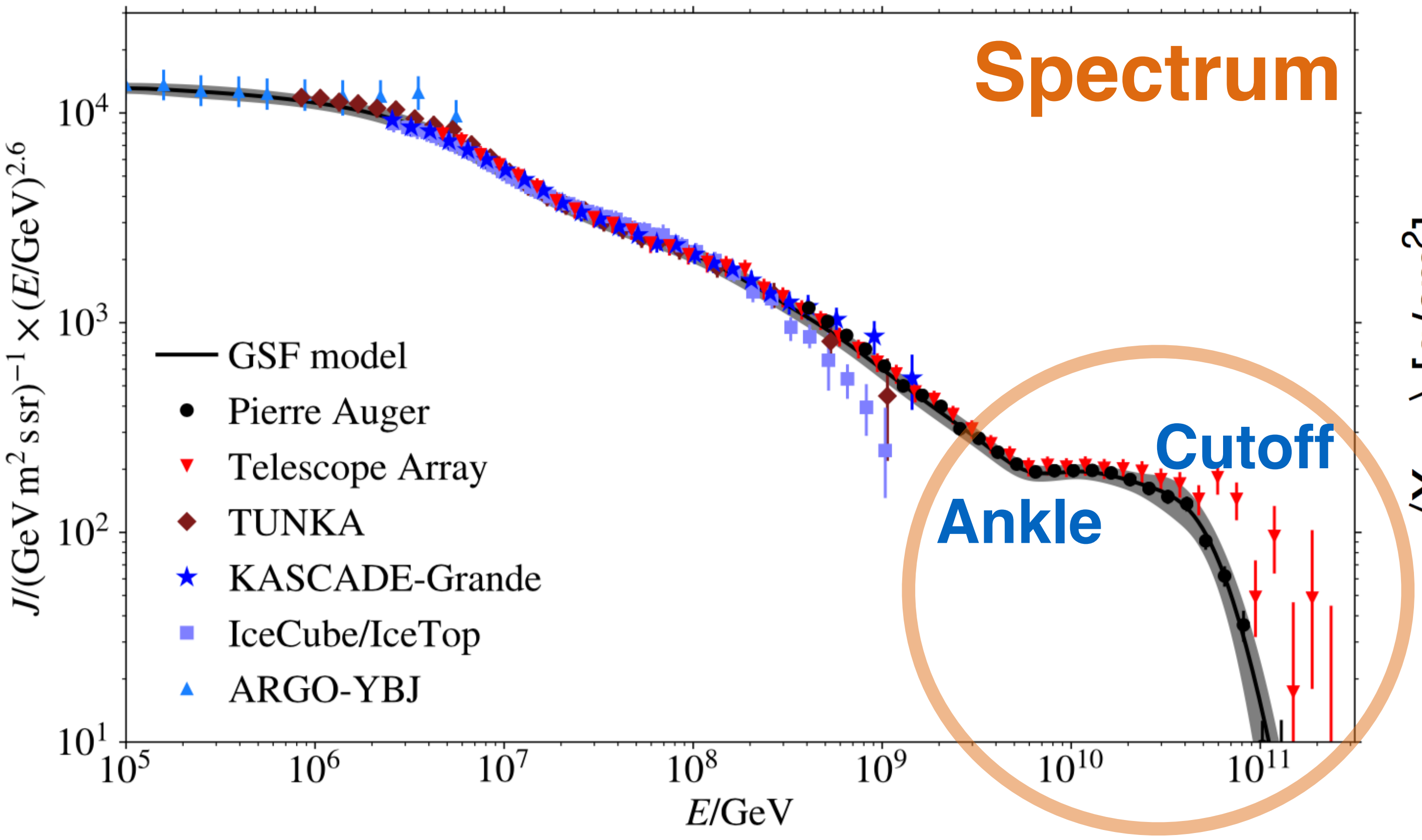
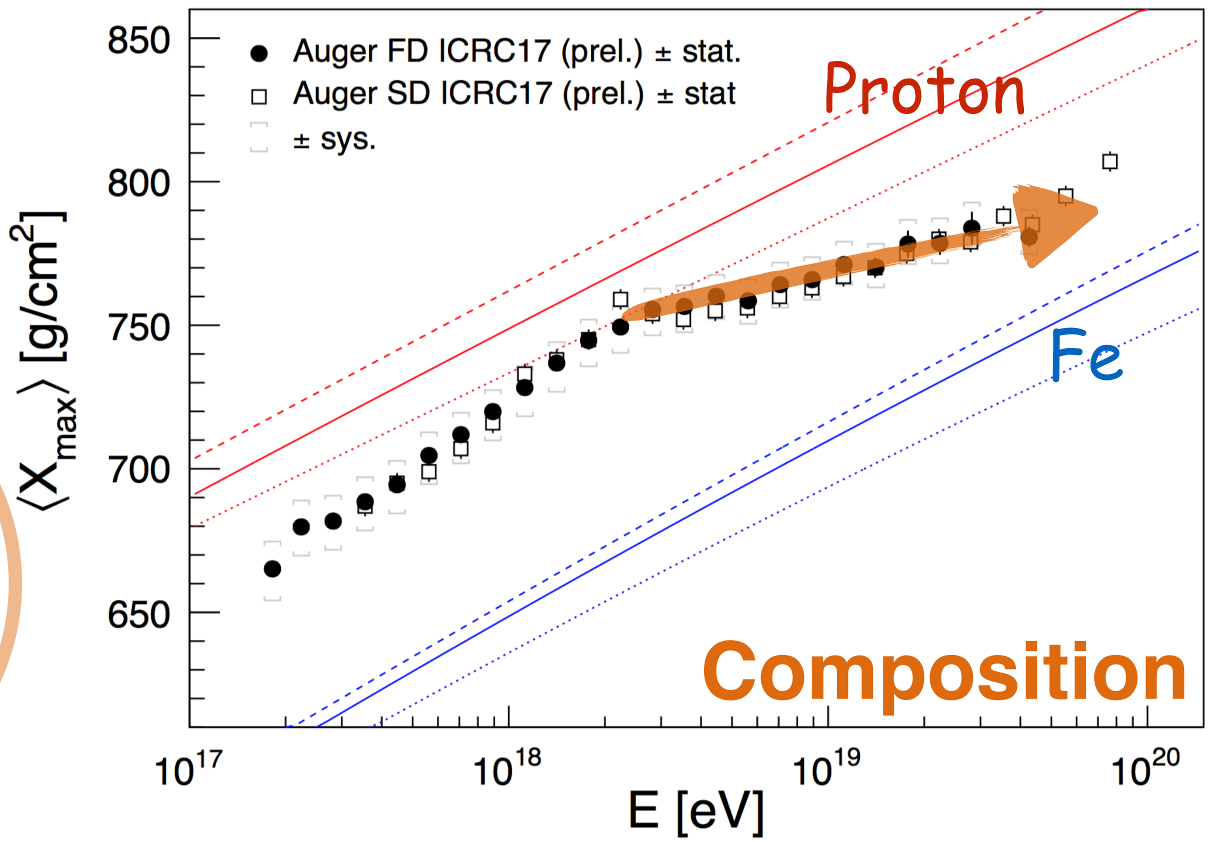
# The observation of UHECRs



Anchordoqui et al, 2018 (review) arXiv: 1807.09645



The Auger Collaboration, 2017 arXiv: 1708.06592

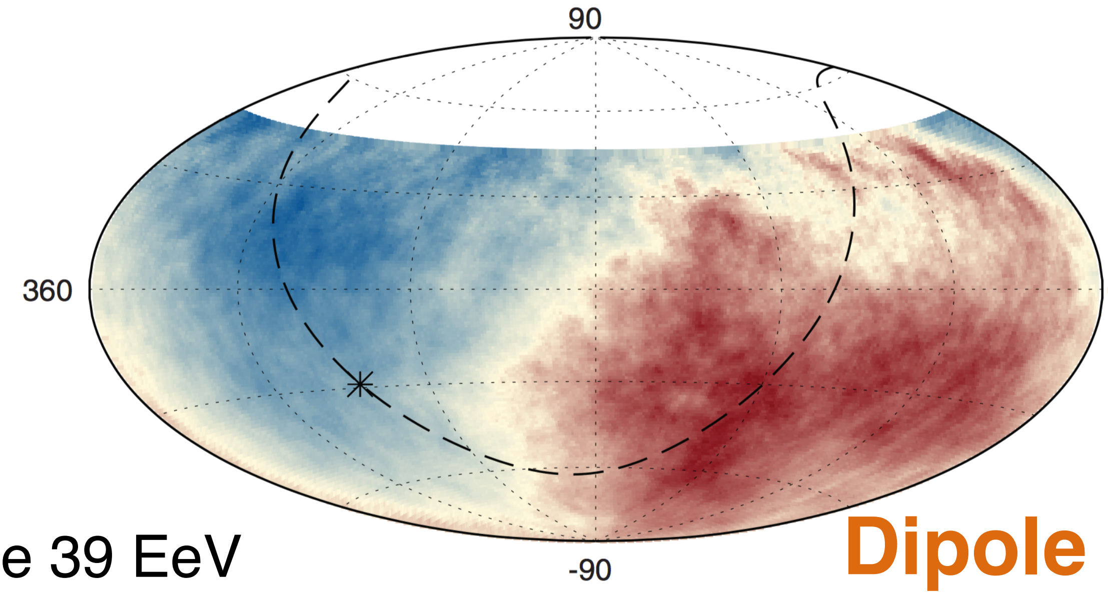
**Spectrum:** Ankle and GZK cutoff

**Composition:** A trend toward heavy nuclei

**Direction:** Large-scale anisotropy

Intermediate-scale anisotropy

—Starburst galaxies: 4.0 sigma above 39 EeV

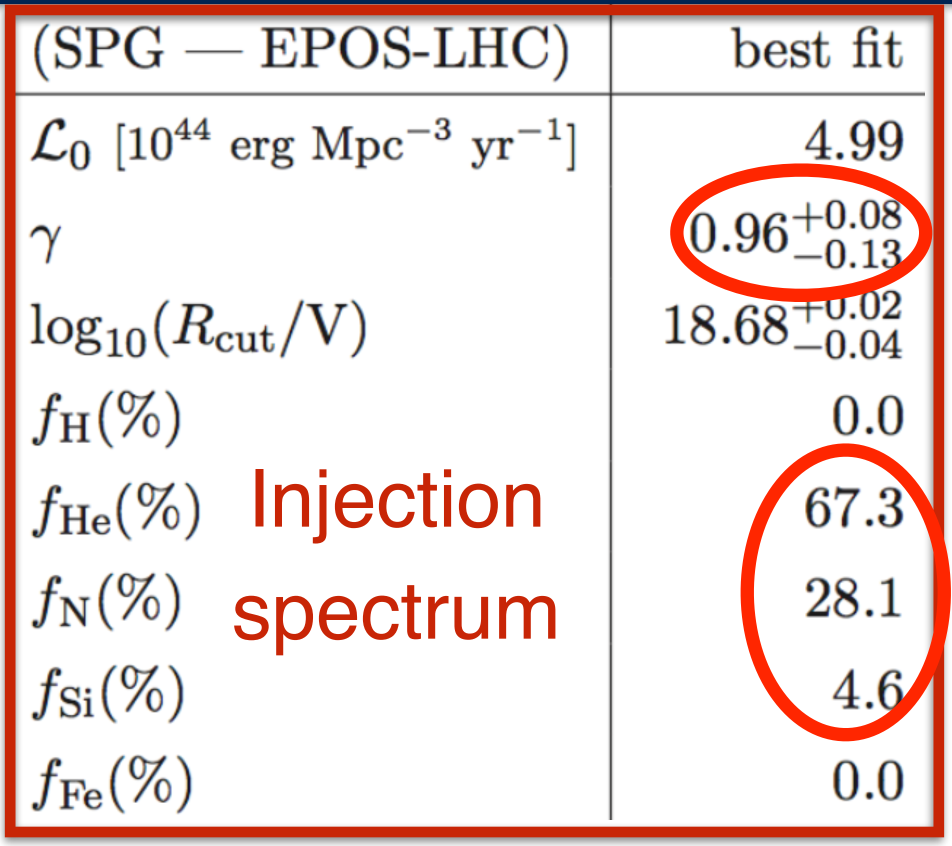


The Auger Collaboration, 2018 arXiv: 1801.06160 The Auger Collaboration, 2017 arXiv: 1709.07321

# Implications for the sources of UHECR nuclei

## Combined fit of UHECR spectrum and composition

The Auger Collaboration, 2017, JCAP, arXiv: 1612.07155



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

Injection spectrum

### Super-solar abundance

Intermediate mass nuclei: N, Si, …

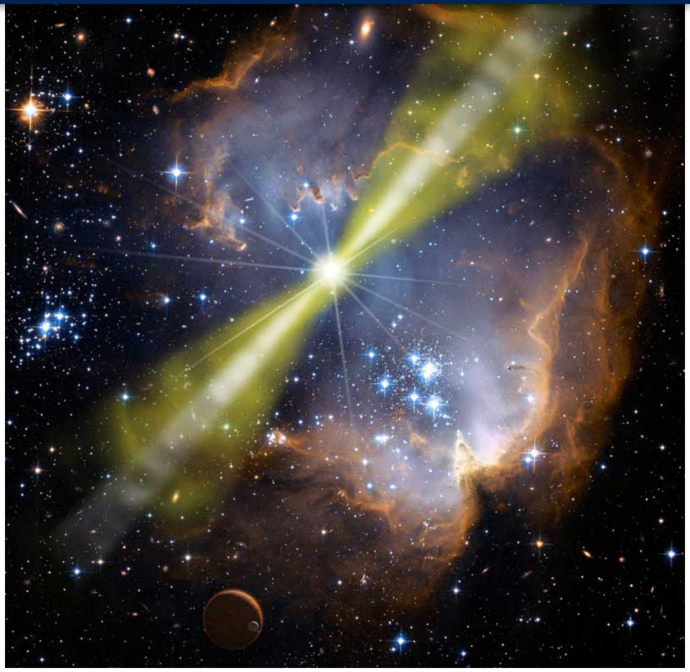
### Harder spectra

Spectral index ~ 1 or less

- The sources material should be rich in heavy nuclei
  - —Compact stars (WD and the atmosphere of NS) or the inner core of massive stars
- The sources environment should allow nuclei to survive
  - —Limits the ability of luminous objects
- Enough sources in the very nearby region within 10~100 Mpc
  - —Nuclei photodisintegrated into free nucleons before reaching Earth

BTZ, Murase, Kimura, Horiuchi, Meszaros, 2018, PRD

# Low-luminosity GRBs as sources of UHECR nuclei



## GRBs are related to the deaths of massive stars

Nuclei can be extracted from the interior of massive stars

See, Horiuchi, Murase, Ioka, Meszaros, 2012, ApJ

Murase, Ioka, Nagataki, Nakamura, 2008, PRD

Wang, Razzaque, Meszaros, 2008, PRD

## High-luminosity GRBs Eg. Waxman, 1995, PRL

- The HL GRB - HE neutrinos connection are disfavored by IcuCube
- Nuclei are disintegrated at the engine for HL GRBs (such as, fireball model)

## Low-luminosity GRBs

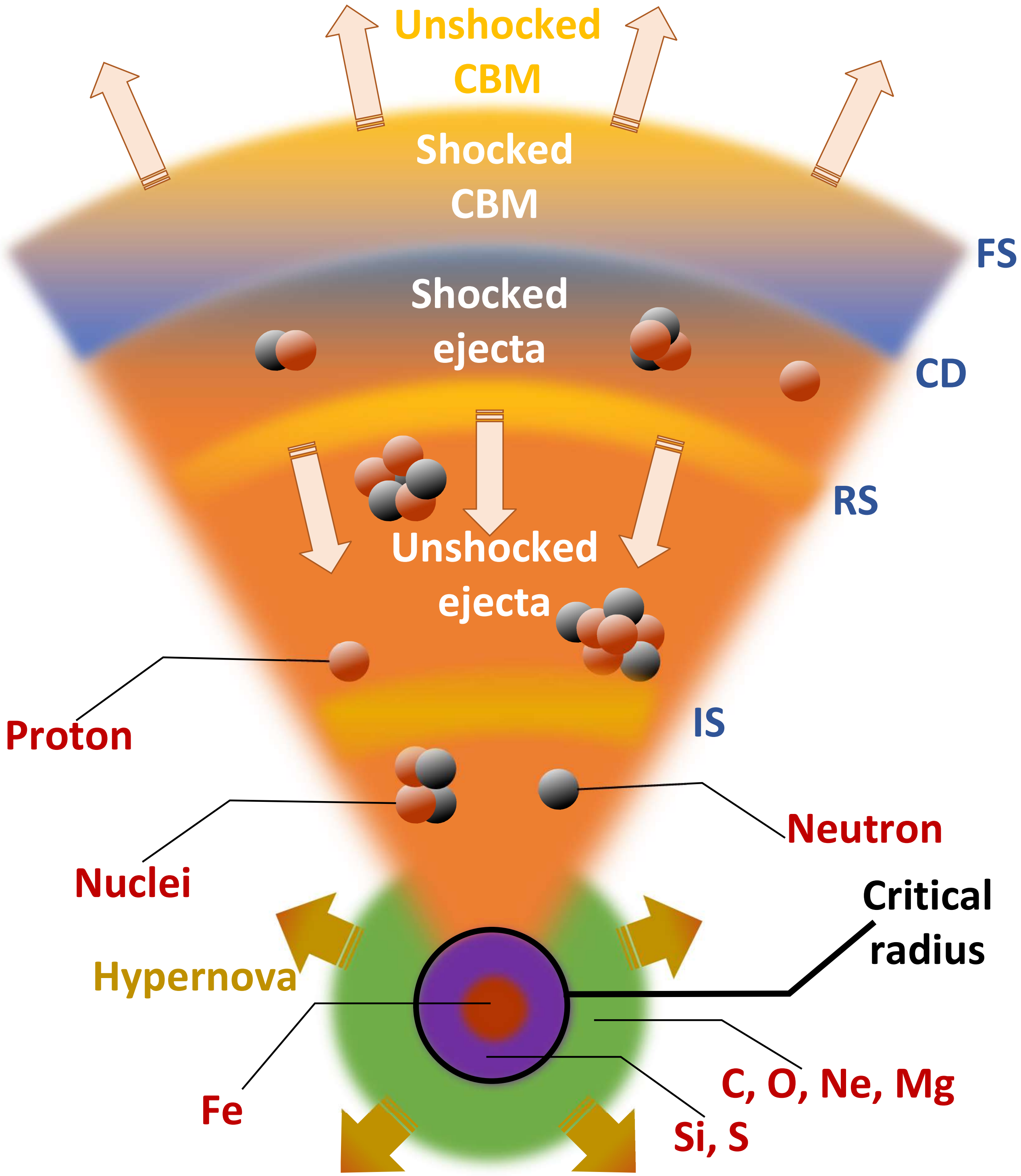
- Source rate much higher than HL GRBs
- The LL GRB - HE neutrinos connection are still possible
- Nuclei can survive at the engine for LL GRBs

Murase, Ioka, Nagataki, Nakamura, 2008, PRD    Liu, Wang, Dai, 2011, MNRAS

BTZ, Murase, Kimura, Horiuchi, Meszaros, 2018, PRD    Boncioli, Biehl, Winter, 2018

# The origin of UHECR nuclei from LL GRBs

## Low-luminosity GRBs



## The fate of nuclei

**The Earth**

Propagation

**Intergalactic space**

Escape

Acceleration

**Relativistic outflow**

Nuclei loading

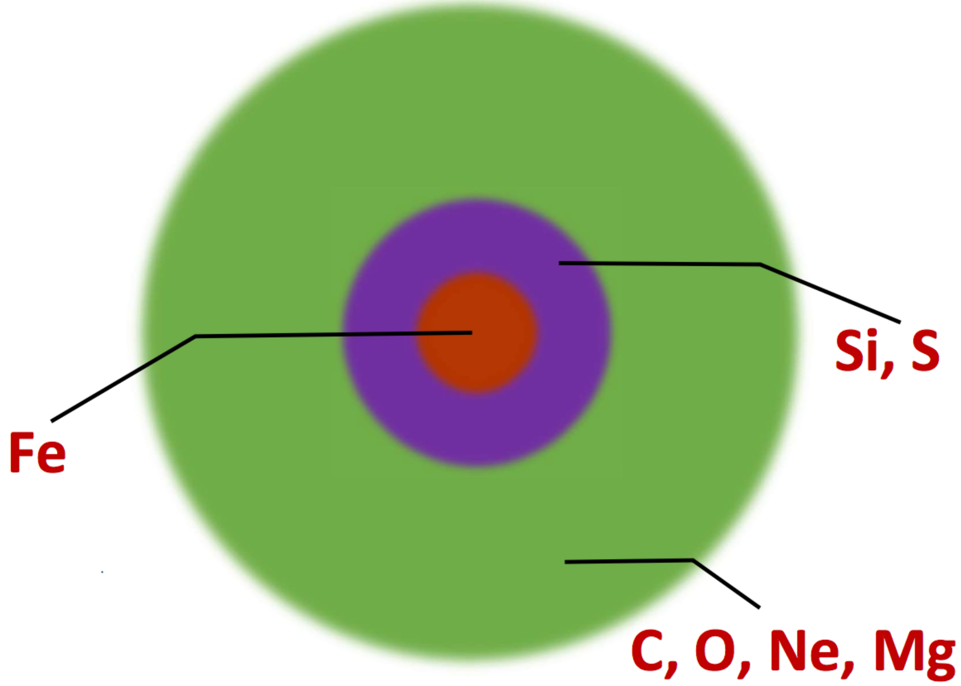
**Accretion disk**

Core collapse

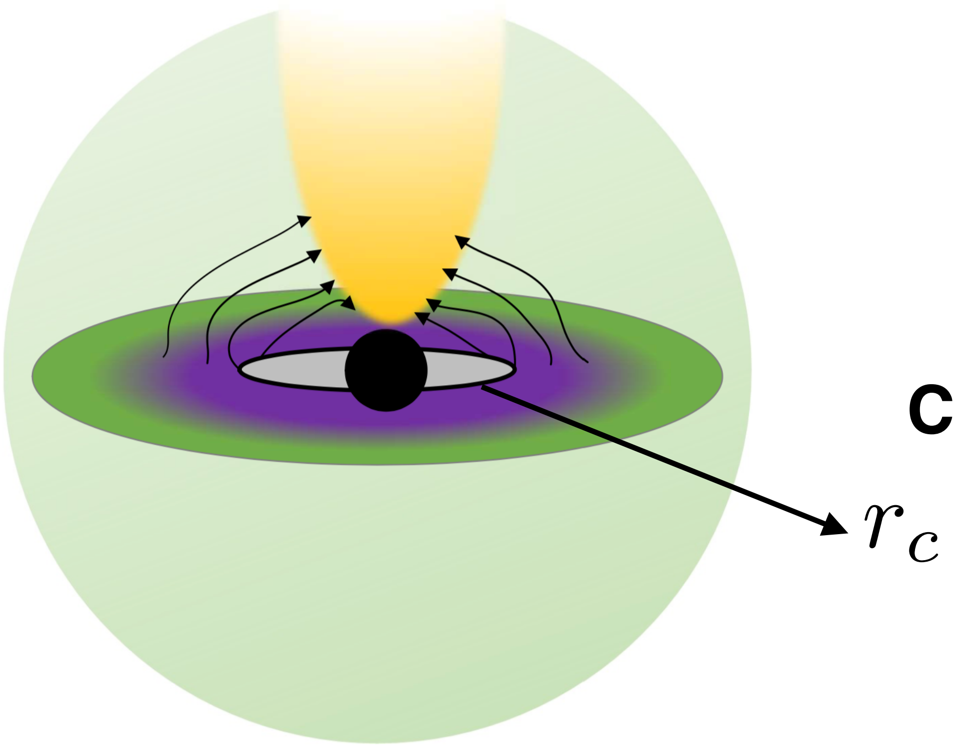
**Progenitor stars**

# Progenitor stars and nuclei loading

**Before core collapse**



**After core collapse**



**GRB progenitor stars:** (Woosley & Heger 2006, ApJ)

1. Wolf-Rayed stars stripped H/He envelop
2. “Onion-skin” structure at core collapse
3. Enough angular momentum

**Nuclei loading:** (Horiuchi, Murase, Ioka, Meszaros, 2012, ApJ)

A. Loading from accretion disk, “one-time” injection
B. Entrainment from hypernova ejecta
C. Entrainment from surrounding stellar material
D. Explosive nucleosynthesis in the jet

**Critical radius or inner stable circular orbit (ISCO)**

— Depend on the progenitors angular momentum

— Determine the composition of accretion disk !!!

# Jet nuclear composition models

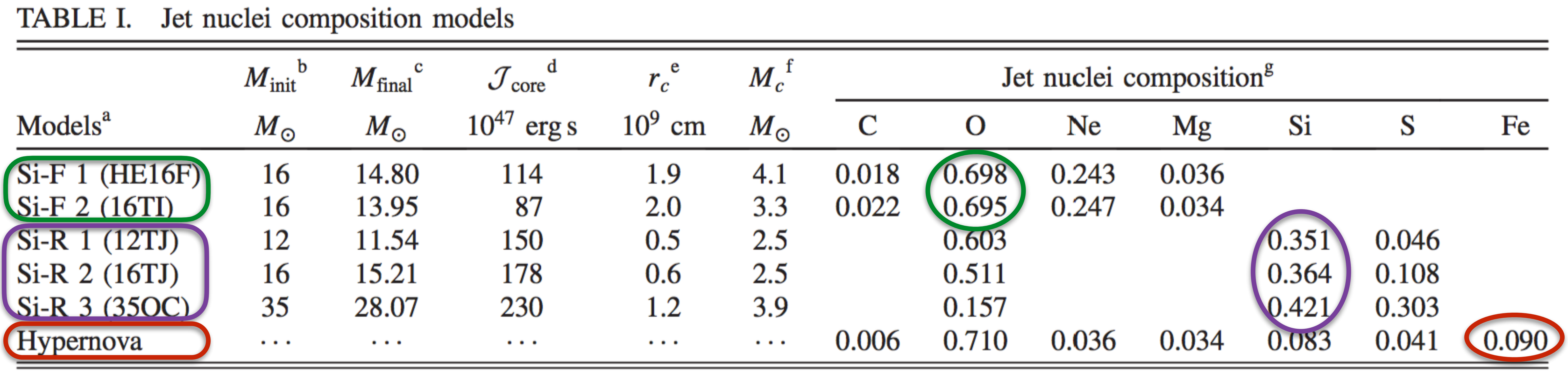
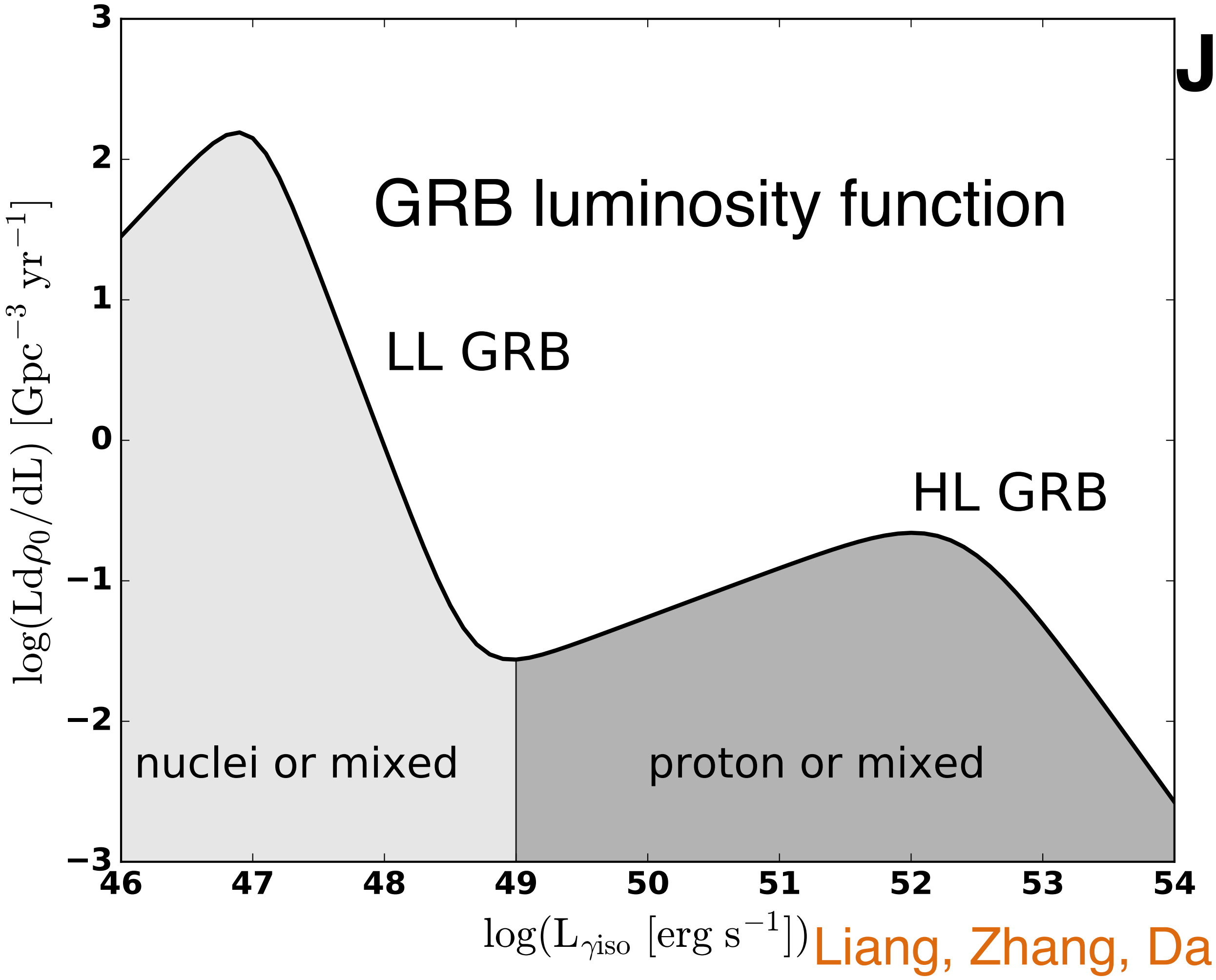


TABLE I. Jet nuclei composition models

| Models[a] | $M_{\rm init}$[b] | $M_{\rm final}$[c] | $\mathcal{J}_{\rm core}$[d] | $r_c$[e] | $M_c$[f] | Jet nuclei composition[g] | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $M_\odot$ | $M_\odot$ | $10^{47}$ erg s | $10^9$ cm | $M_\odot$ | 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 |



Liang, Zhang, Dai, 2007, ApJ

## Jet nuclear composition in LL GRBs:

1, Silicon-free:

— Dominated by Oxygen-group nuclei

2, Silicon-rich:

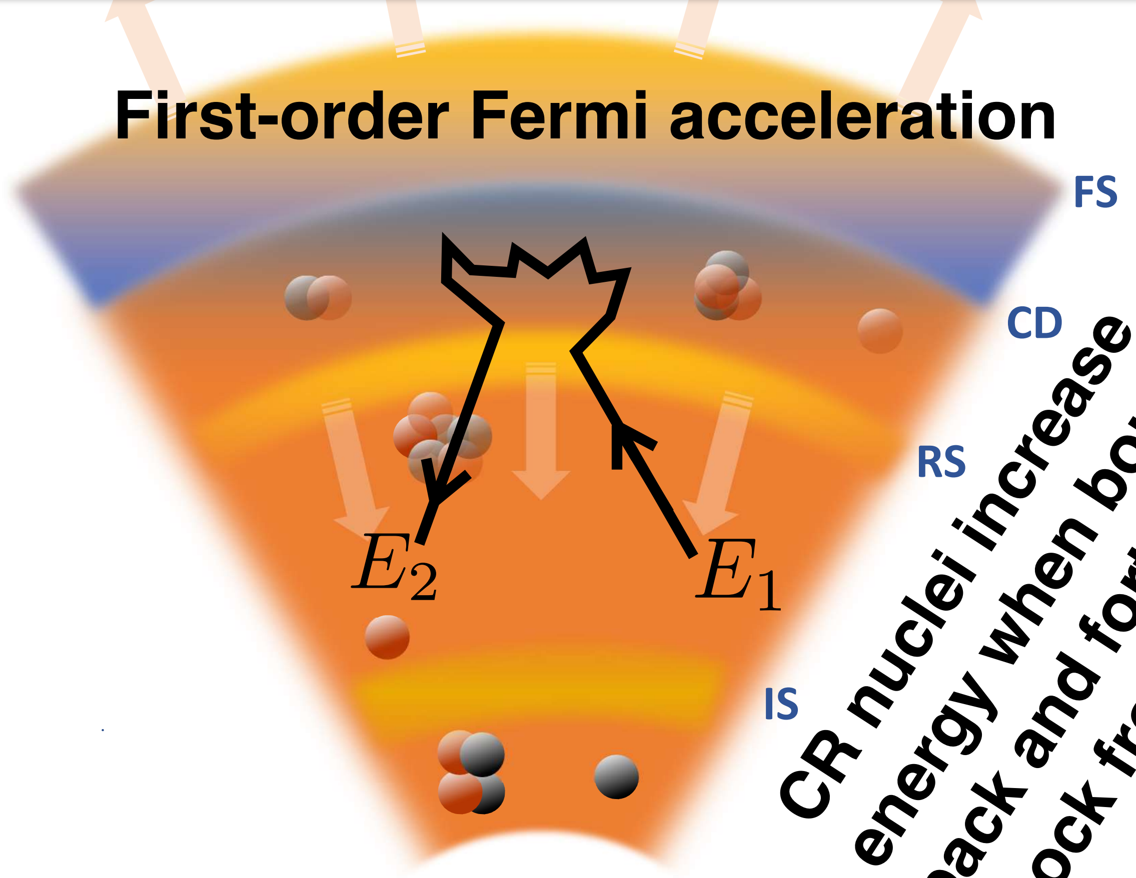
— Have Silicon-group nuclei

3, Hypernova:

— Synthesized in the ejecta, include Fe

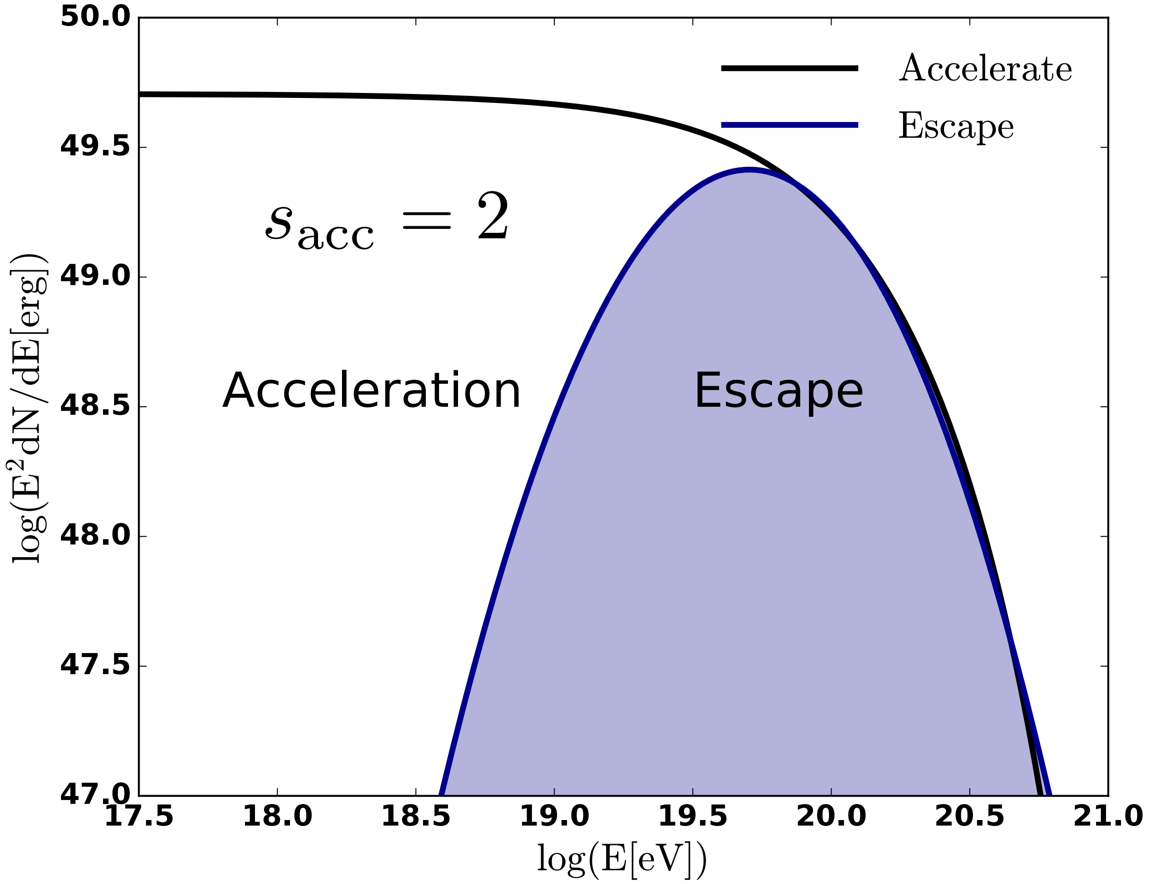
BTZ, Murase, Kimura, Horiuchi, Meszaros, 2018, PRD

# The acceleration and escape of UHECR nuclei



**First-order Fermi acceleration**

**CR nuclei increase energy when bouncing back and forth around shock front**



## Acceleration site:

**Internal shock:** Shocked GRB ejecta ✔

$$L_{\rm CRacc} \sim (100-200) L_{\gamma {\rm iso}}$$

**Reverse shock:** Shocked GRB ejecta ✔

$$\mathcal{E}_{\rm CRacc} \sim (0.1-1)\mathcal{E}_{\rm ej}$$

**Forward shock:** Shocked Interstellar medium ✘
Light composition dominated

**Maximum acceleration energy:**

$$t_{\rm acc} \leq \min(t_{\rm dyn}, t_{\rm esc}, t_{\rm cool})$$

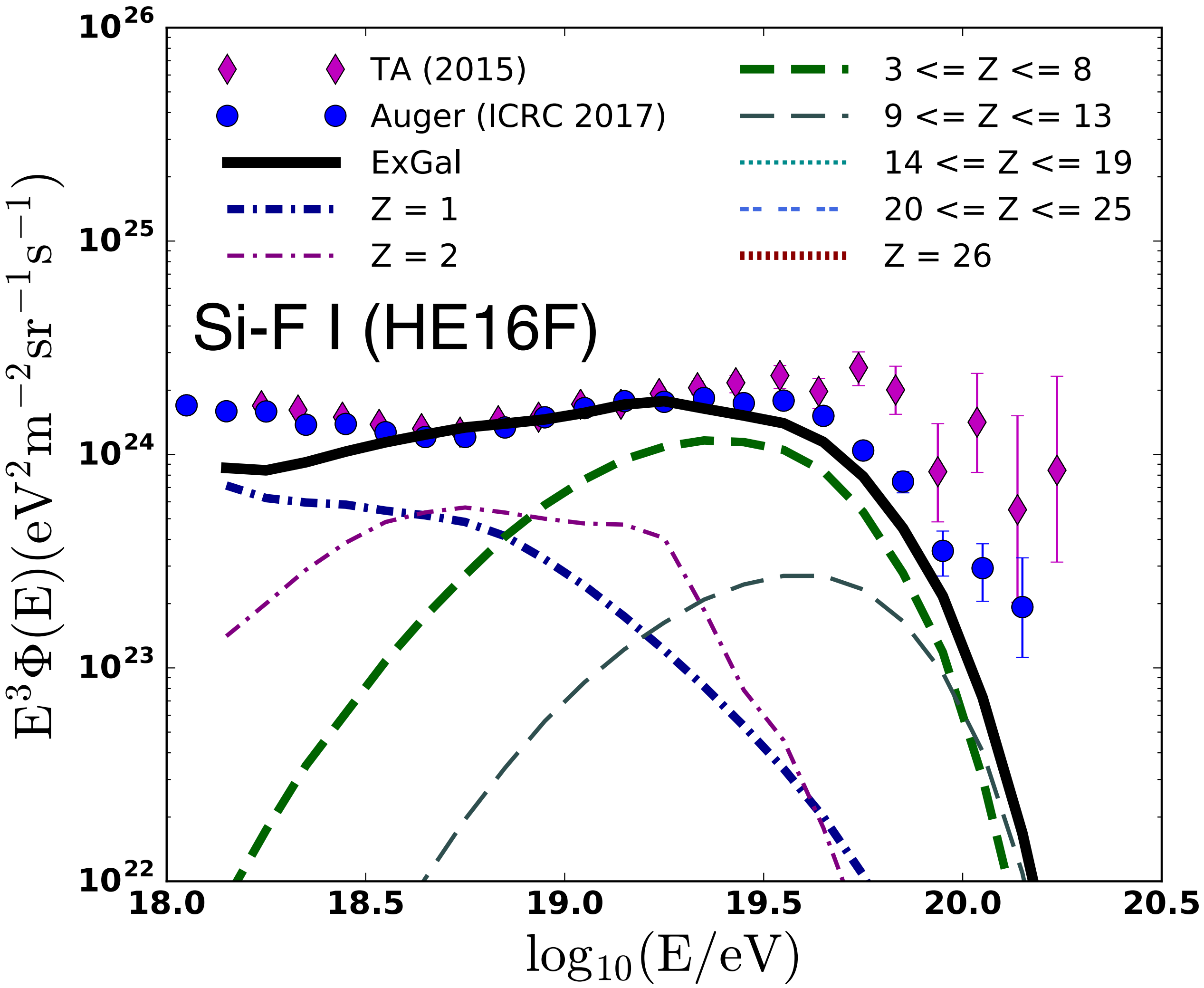
Hard spectrum of escaped CRs:

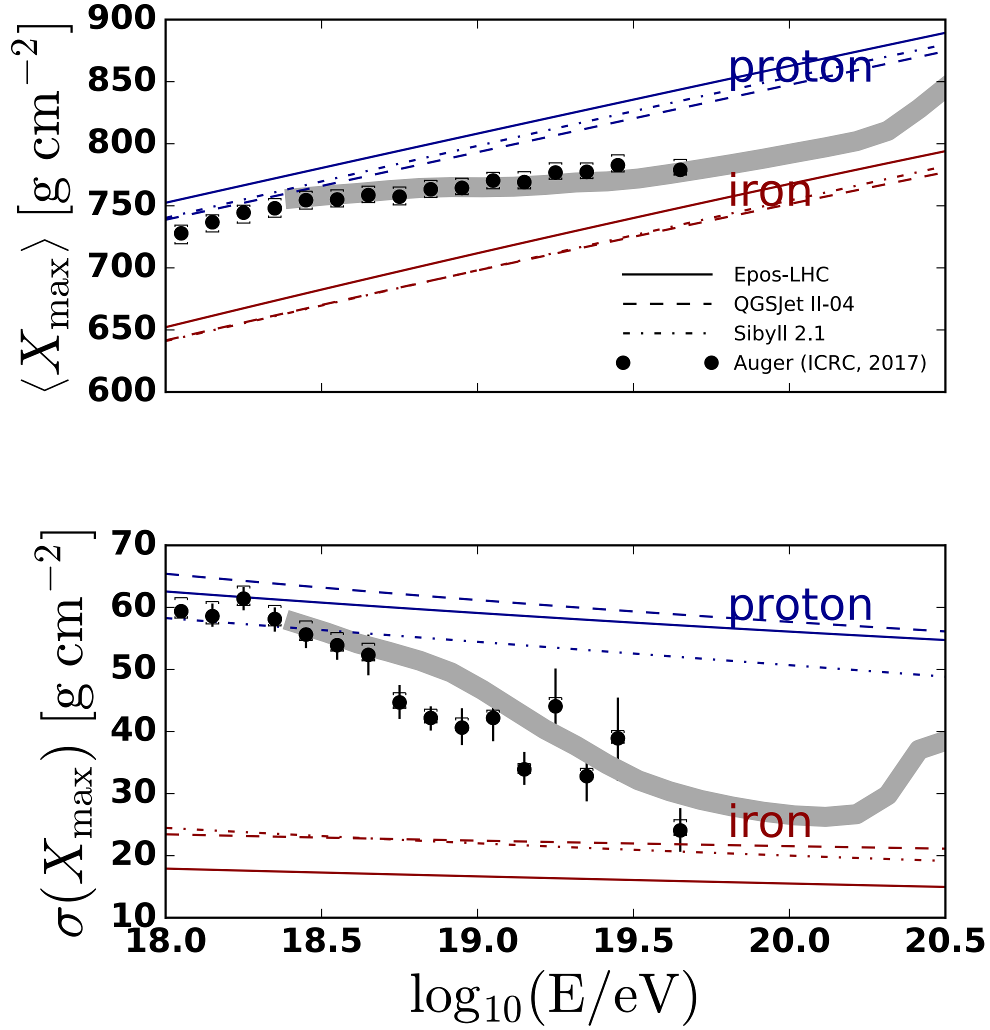
$$\frac{dN_A}{dE} = f_A N_{\rm esc} \exp\left[-\ln^2\left(\frac{E}{ZE_{p,\max}^{\rm esc}}\right)\right]$$

CRs around maximum acceleration energy can escape efficiently

Ohira, Murase & Yazamaki, 2010, A&A

# Compared with Auger data - Silicon-free model





Silicon-free composition

O: ~ 70% Ne: ~ 30%

CRPropa 3

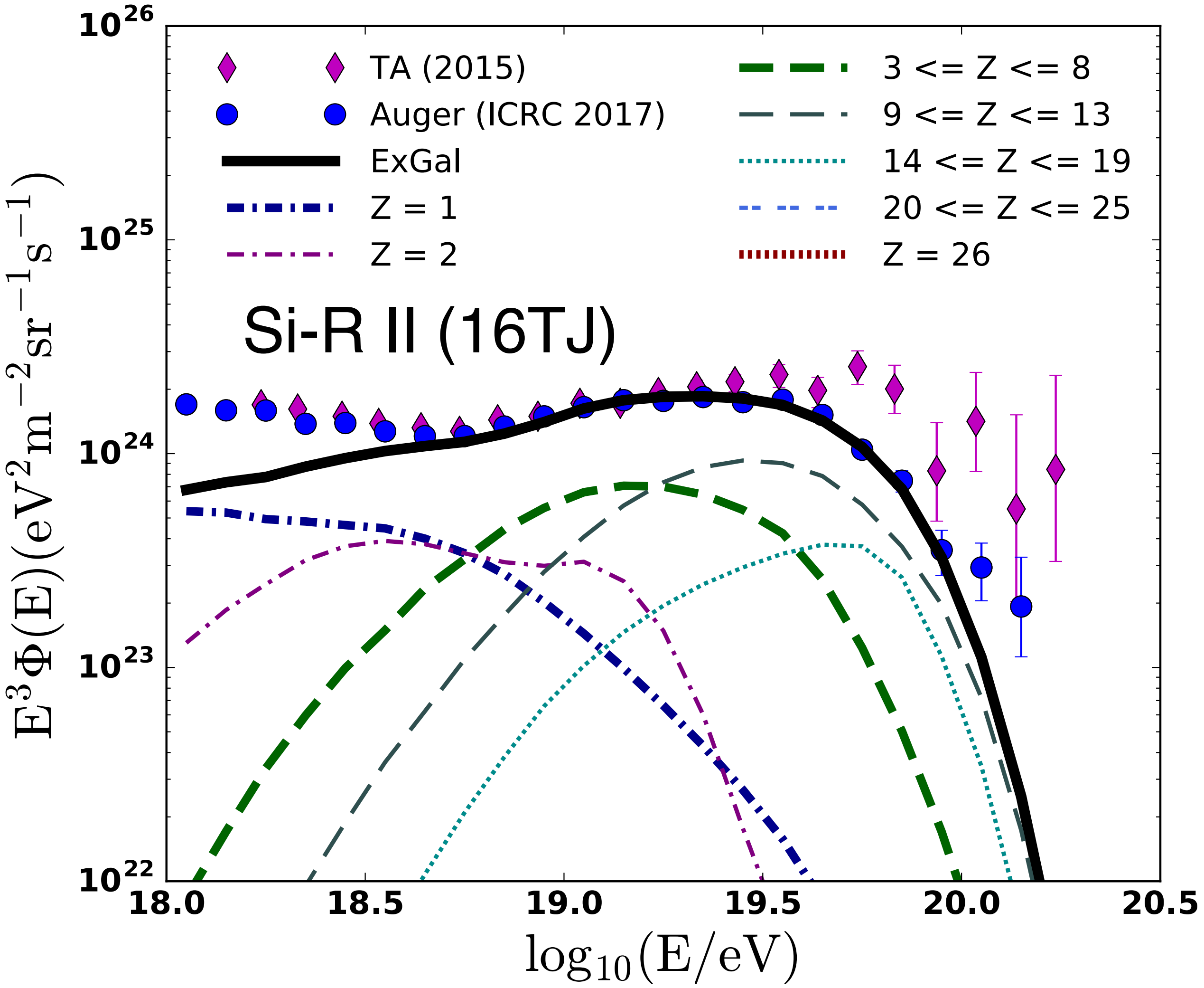
$$E_{A,\mathrm{esc}} \simeq 10^{18.2}(\eta/15)^{-1} Z\xi_B^{1/2} x_{\mathrm{esc},-0.5} L_{\gamma\mathrm{iso},47}^{1/2}\Gamma_1^{-2}\ \mathrm{eV}$$

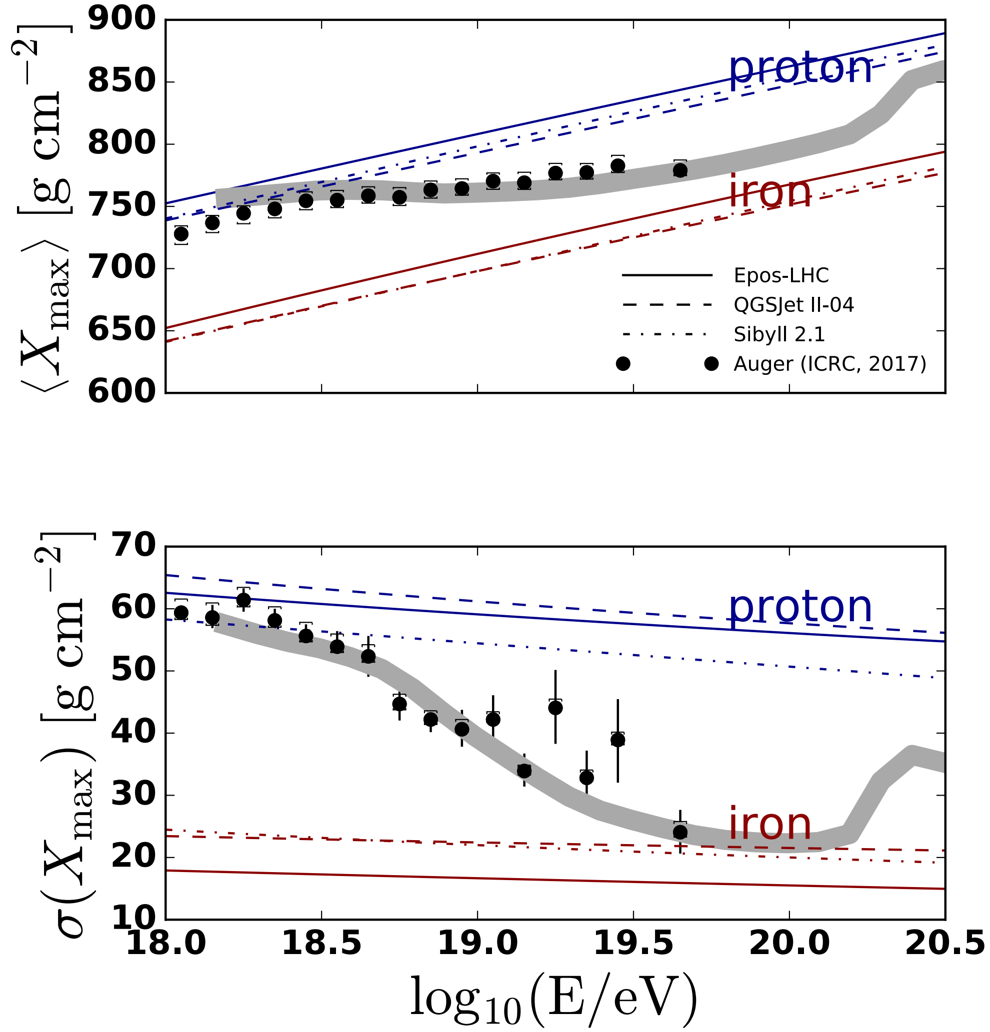
Have difficulty in fitting the spectrum! (deficiency at the highest energy)

Also for other Si-F model

BTZ, Murase, Kimura, Horiuchi, Meszaros, 2018, PRD

# Compared with Auger data - Silicon-rich model





Silicon-rich composition

O: ~ 50%   Si: ~ 40%   S: ~ 10%

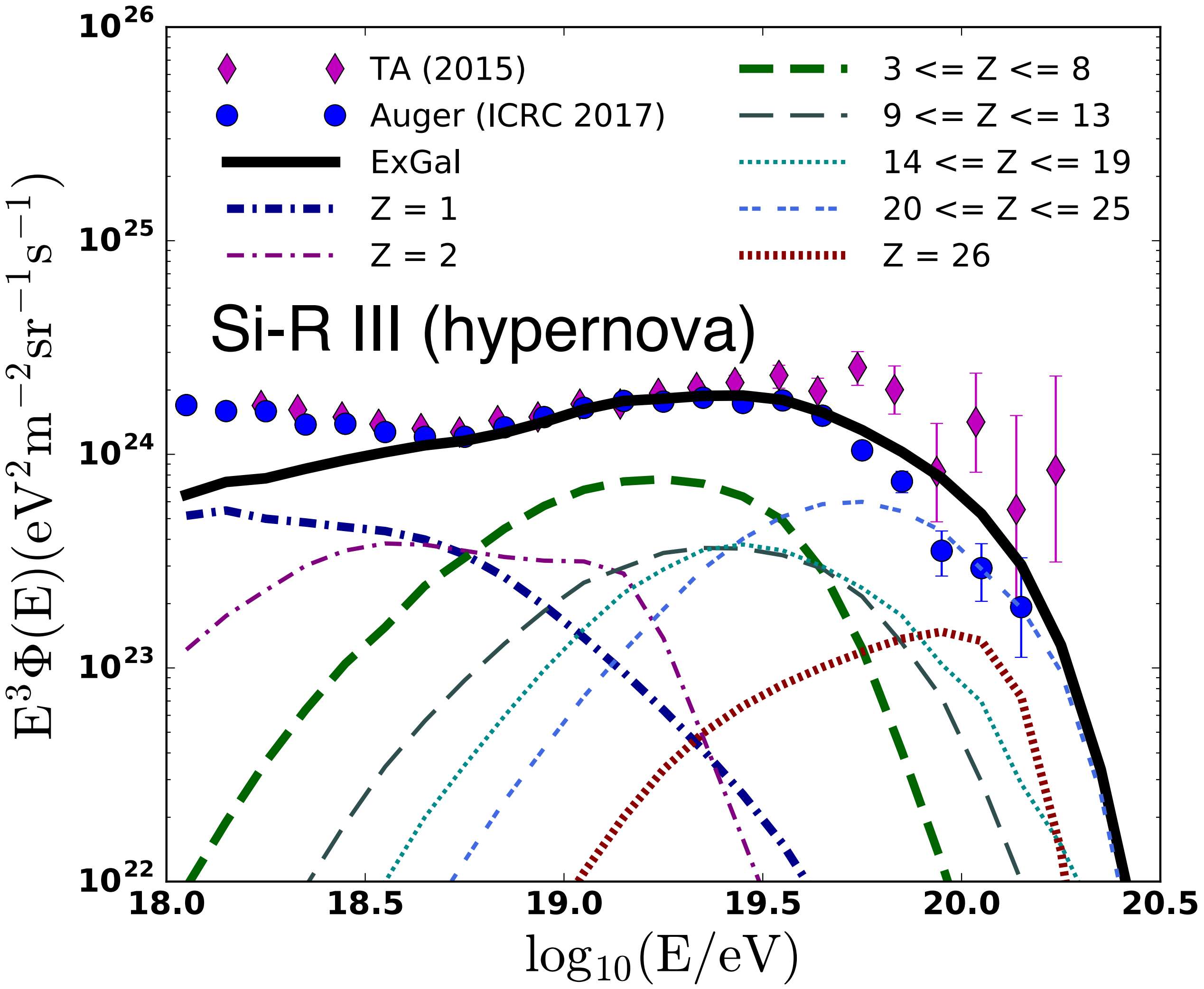
The fitting now looks better!

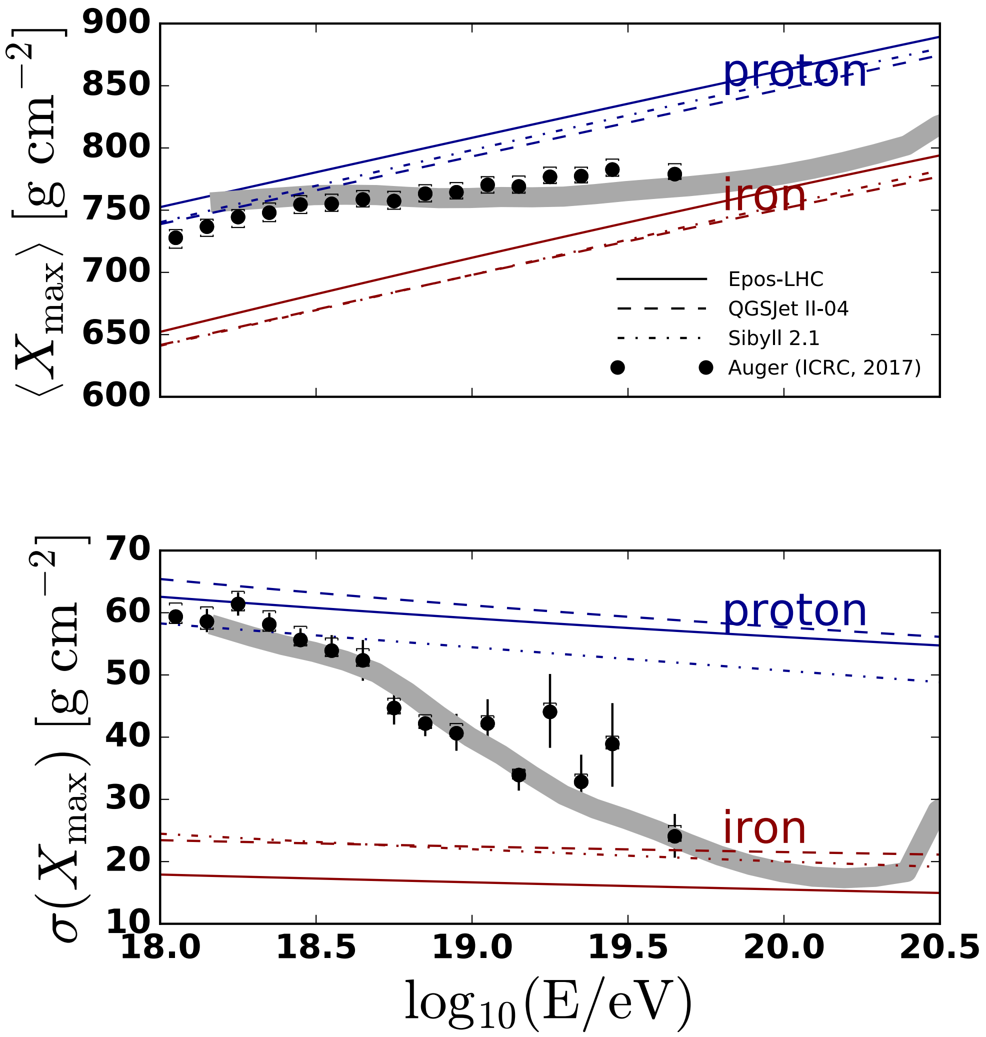
Match the Auger data very well

Also for other Si-R model

BTZ, Murase, Kimura, Horiuchi, Meszaros, 2018, PRD

# Compared with Auger data - hypernova model





Hypernova ejecta composition

O: ~ 70% Si: ~ 10% Fe: ~ 10%

The fitting is similarly good!

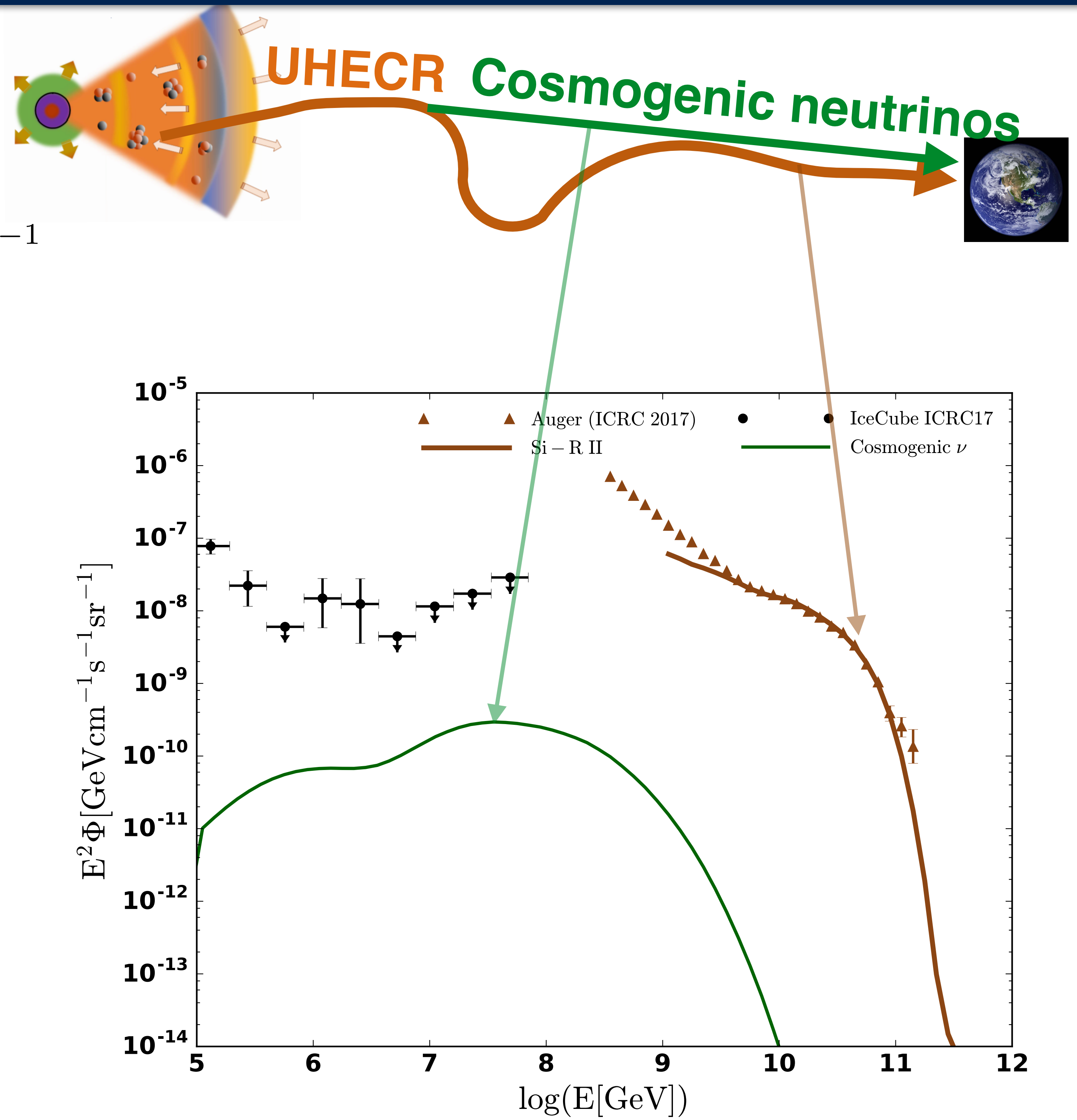
BTZ, Murase, Kimura, Horiuchi, Meszaros, 2018, PRD

# Cosmogenic neutrinos and diffuse source neutrinos

## Cosmogenic neutrinos

*Produced in the intergalactic space*

*Peak flux:* $E_\nu^2\Phi \sim 2\times10^{-10}\ \mathrm{GeV\ cm^{-1}\ s^{-1}\ sr^{-1}}$



Combined spectrum of UHECRs and neutrinos

BTZ & Murase 2018b, to be submitted

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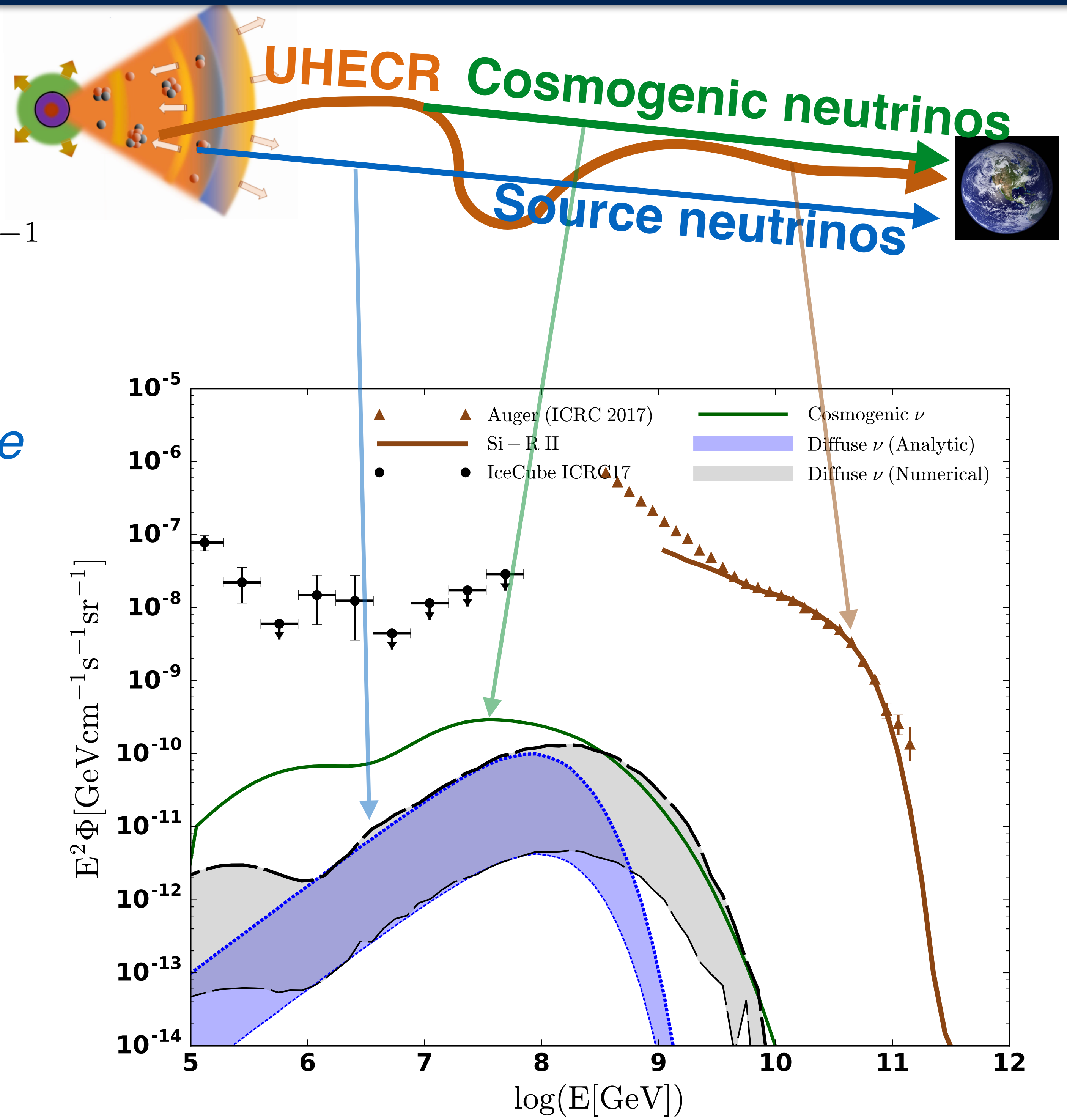
## Source neutrinos

*Produced inside the sources at the same acceleration site of UHECR nuclei*

(reverse shock model)



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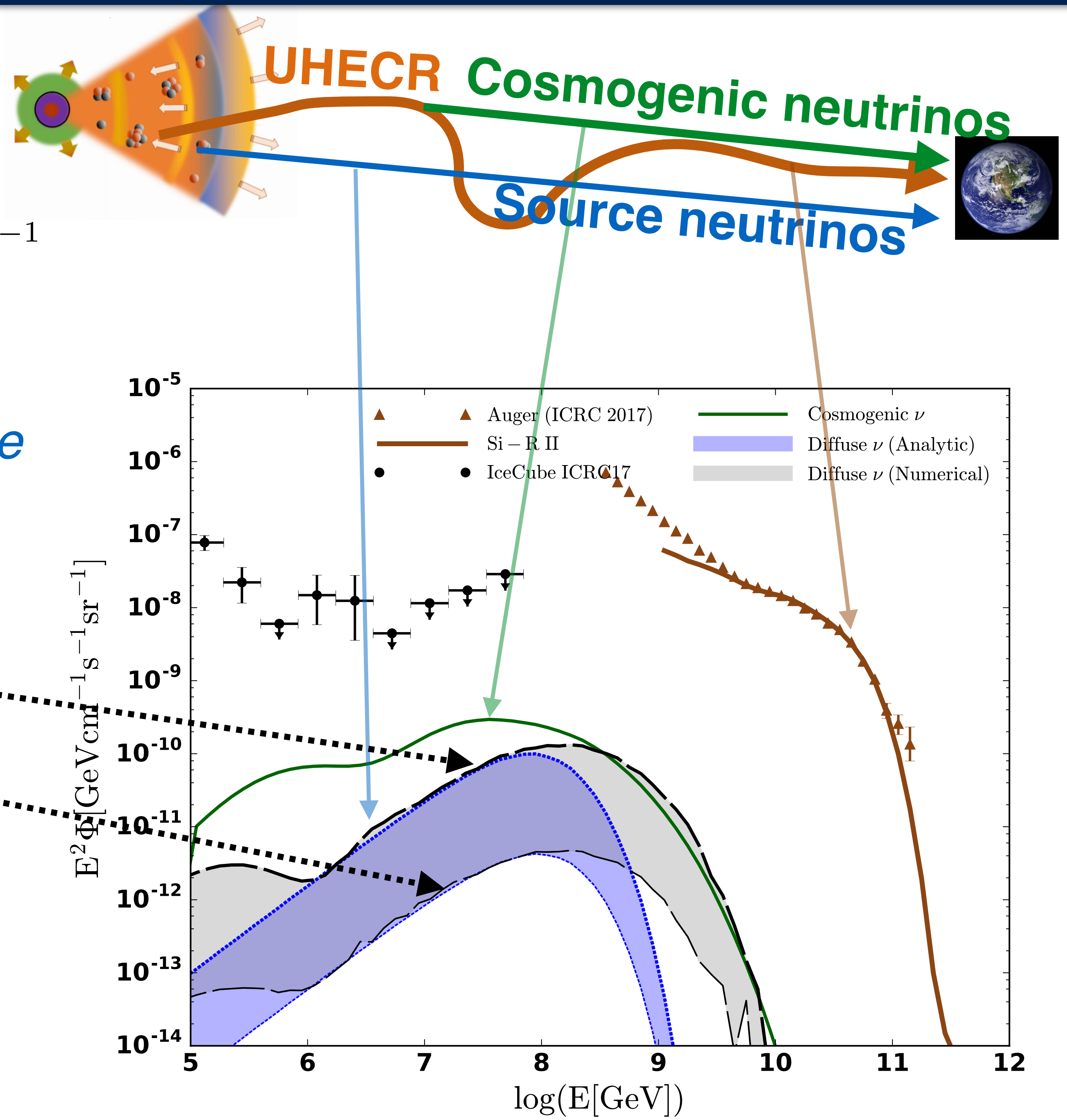
## Source neutrinos

*Produced inside the sources at the same acceleration site of UHECR nuclei* (reverse shock model)

— **Partial survival regime**

— **Completely survival regime**



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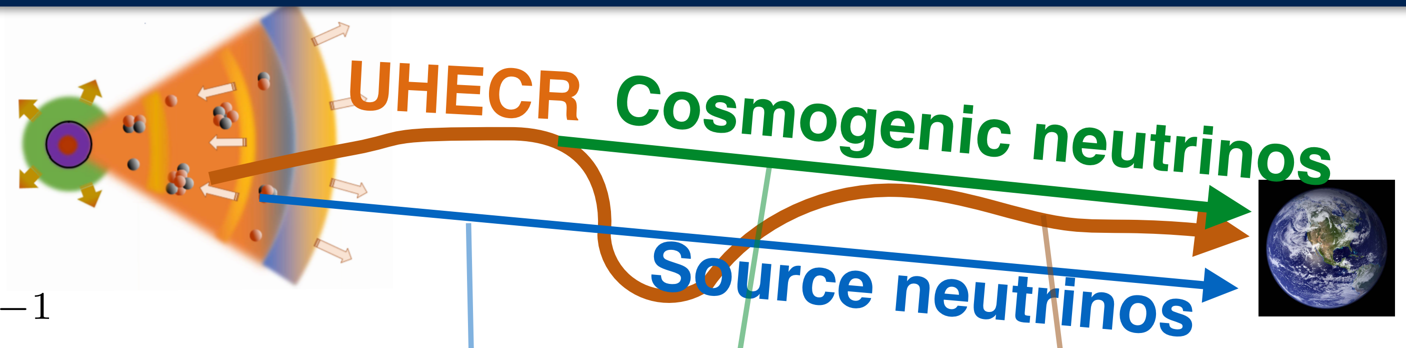

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*Peak flux:* $E_\nu^2\Phi \sim 2 \times 10^{-10}\ \mathrm{GeV\ cm^{-1}\ s^{-1}\ sr^{-1}}$

## Source neutrinos

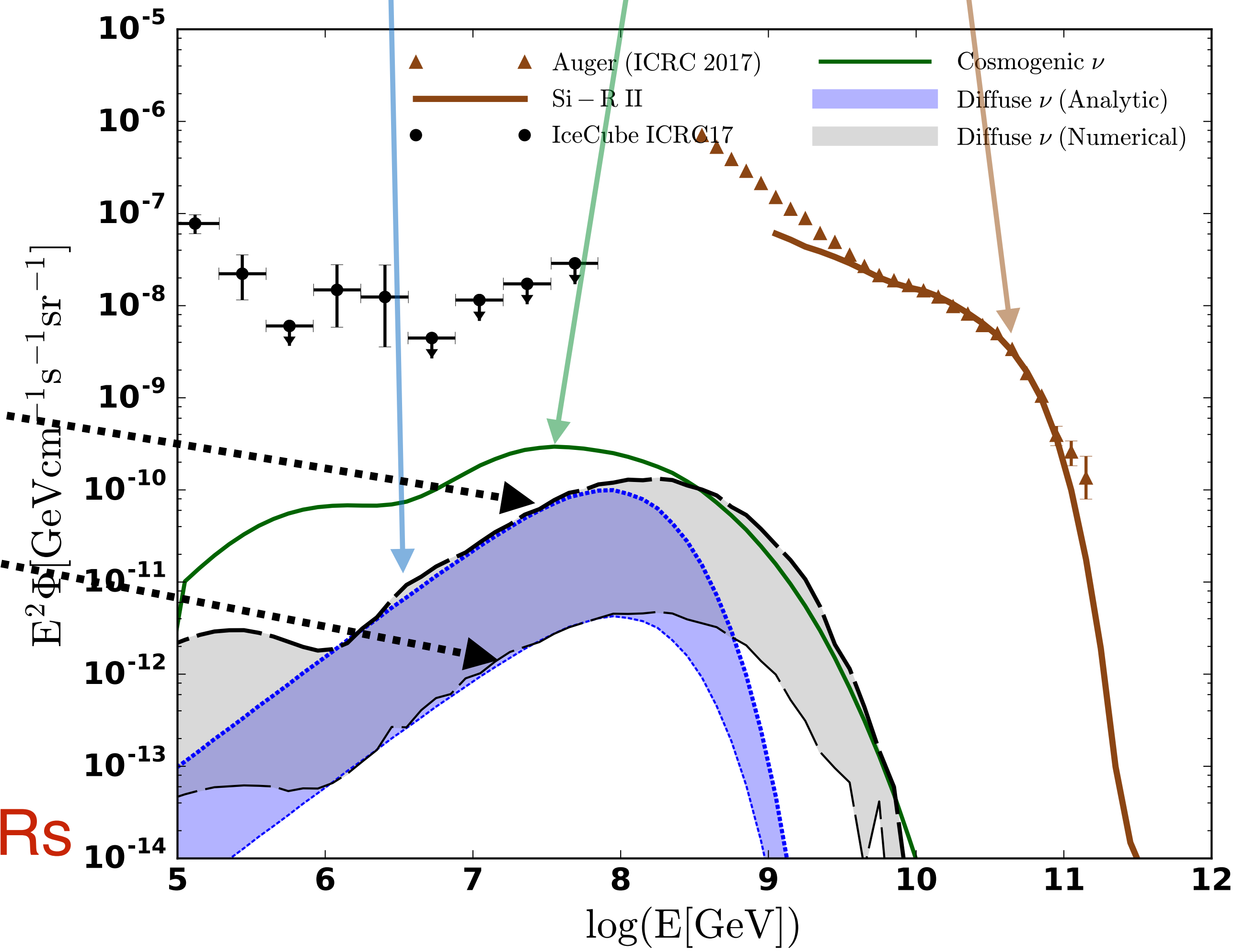
*Produced inside the sources at the same acceleration site of UHECR nuclei* (reverse shock model)

- **Partial survival regime**
  $$f_{A\gamma} < 1 < \tau_{A\gamma}$$
- **Completely survival regime**
  $$\tau_{A\gamma} < 1$$

## Higher source neutrino fluxes ?

- Produced at different region from UHECRs

  Eg. Neutrinos are produced in the inner denser region or in the host galaxy

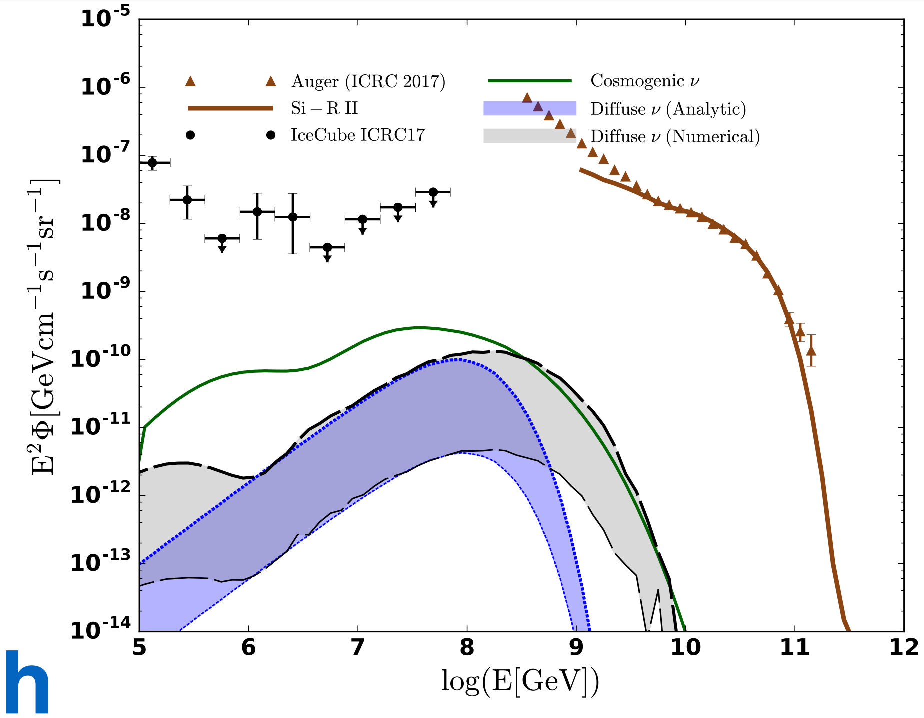


Combined spectrum of UHECRs and neutrinos

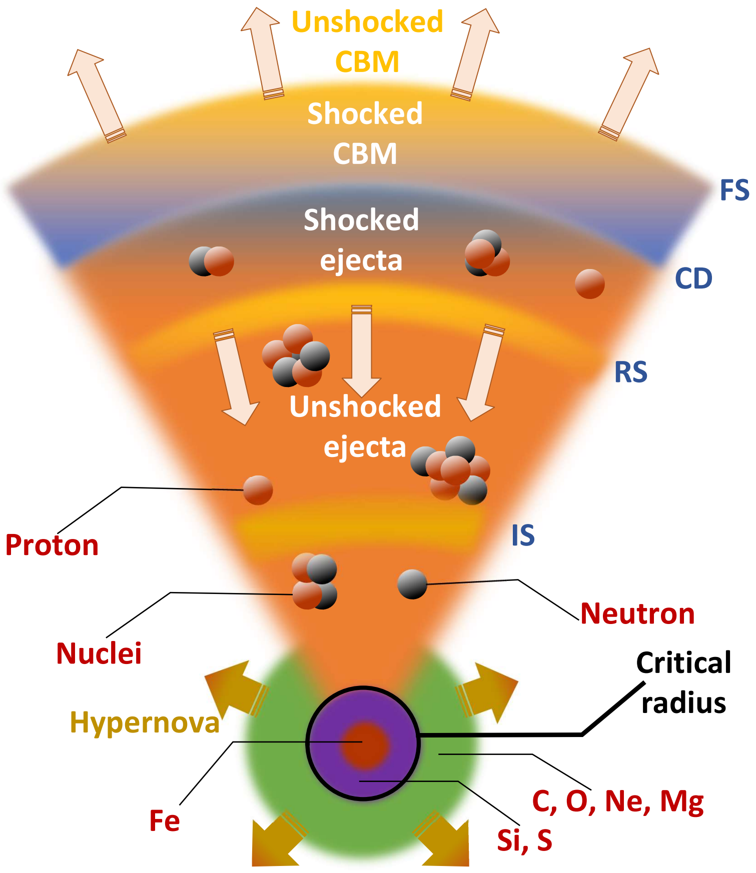
BTZ & Murase 2018b, to be submitted

# Conclusion and Summary

1, The **intrajet nuclei composition** from **LL GRBs** are dominated by **intermediate mass nuclei: O, Si, …**



2, UHECR nuclei from LL GRBs can **match the Auger data** (including spectrum and composition)



3, The **cosmogenic neutrinos** and **source neutrinos** can constrain the origin of UHECR nuclei

Detected by **GRAND, ARA, ARIANNA**

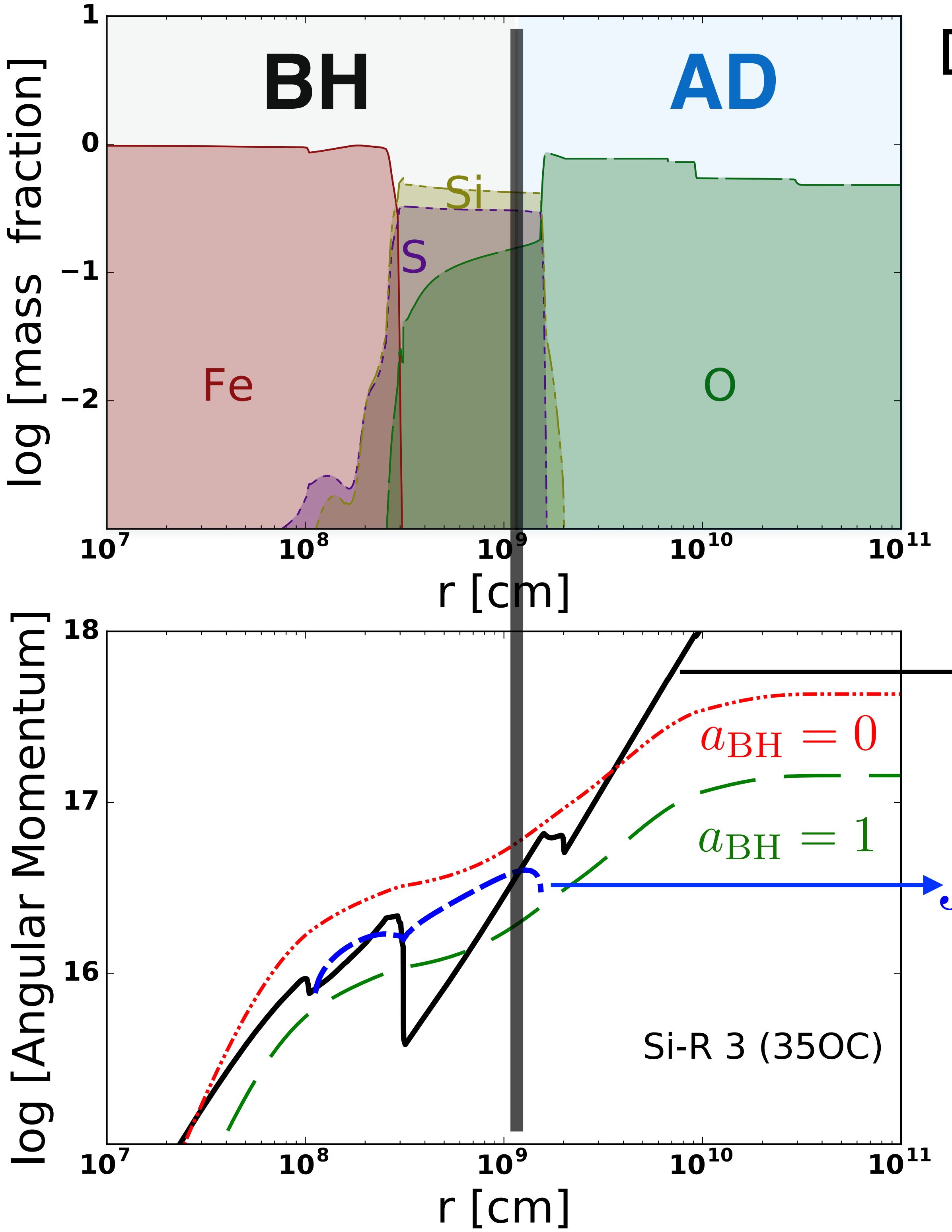
# Supplementary material

## Backup slide

# The composition of accretion disk

**Nuclear mass fraction distribution**

(Woosley & Heger 2006, ApJ)



Determine the Critical radius:

$$J_{\mathrm{ISCO},a_{\mathrm{BH}}} = \mathcal{J}(r)$$

$$r_c \sim 1.2 \times 10^9 \ \mathrm{cm}$$

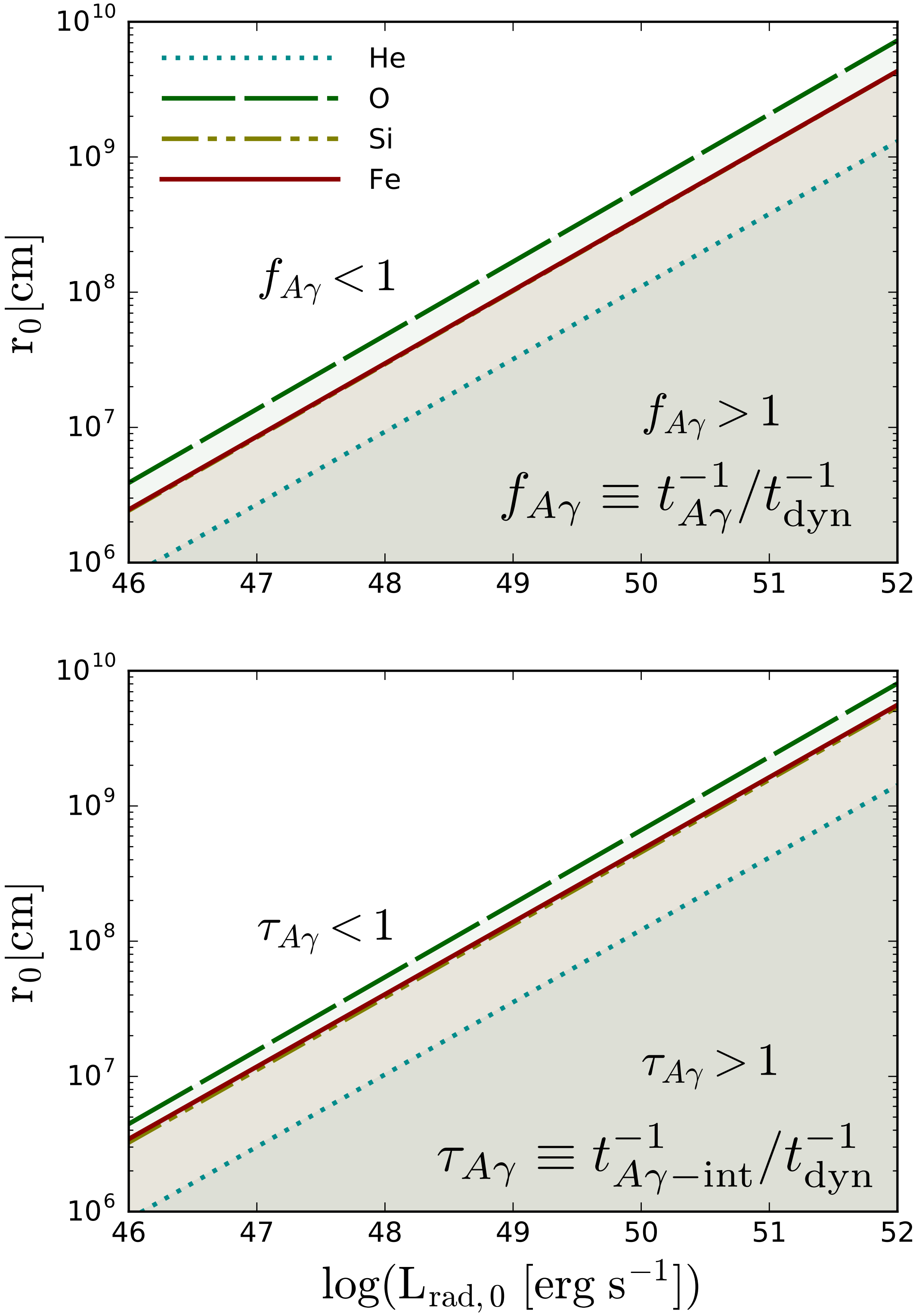
$\mathcal{J}(r)$ Enclosed angular momentum in the progenitor stars at core collapse

$J_{\mathrm{ISCO},a_{\mathrm{BH}}}$ Angular momentum at the inner stable circular orbit (ISCO)

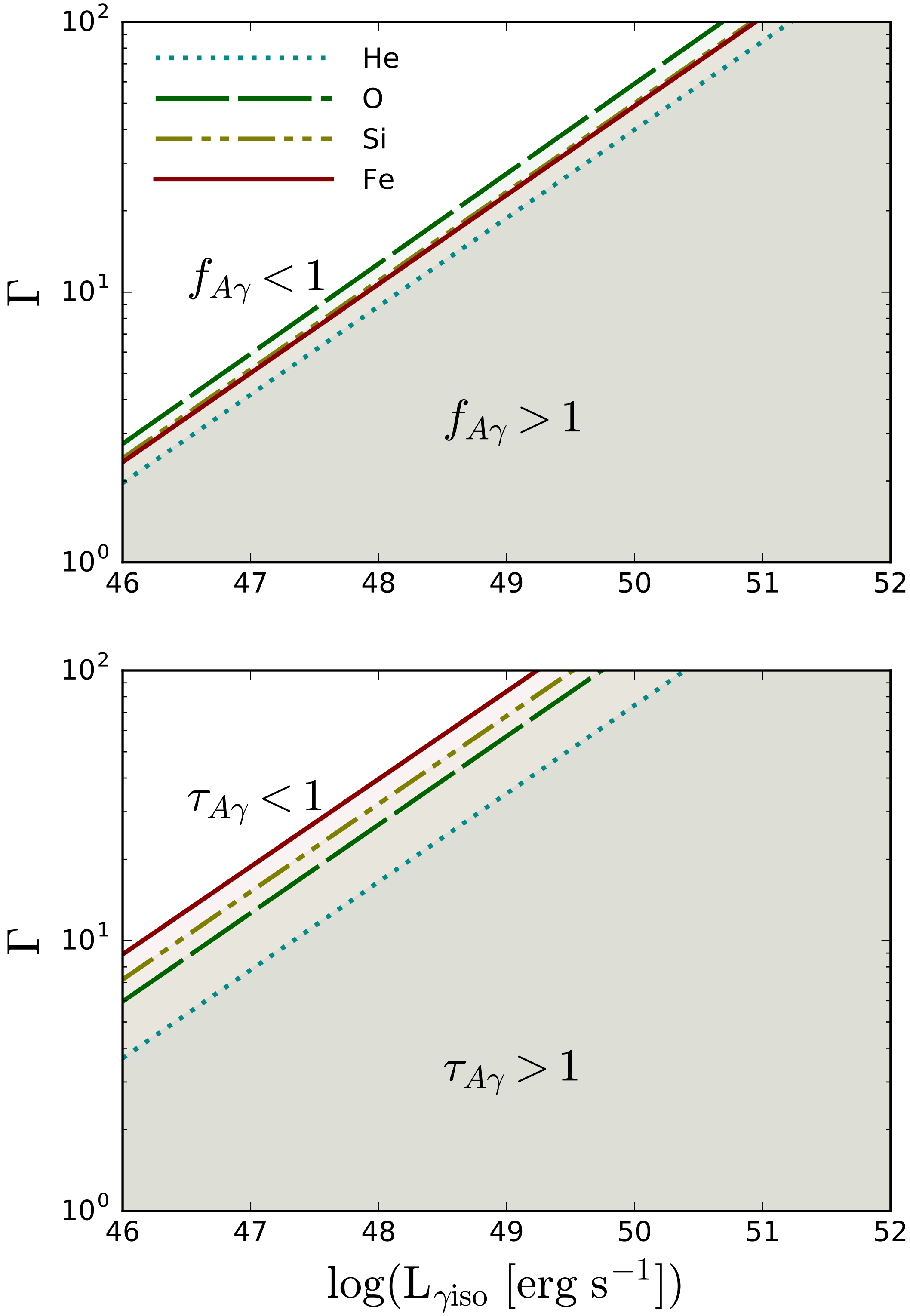
$$a_{\mathrm{BH}} = \frac{c\mathcal{J}_{\mathrm{BH}}}{GM_{\mathrm{BH}}^2} \sim \frac{c\mathcal{J}(r)}{GM(r)^2}$$

# The fate of nuclei

## Jet base

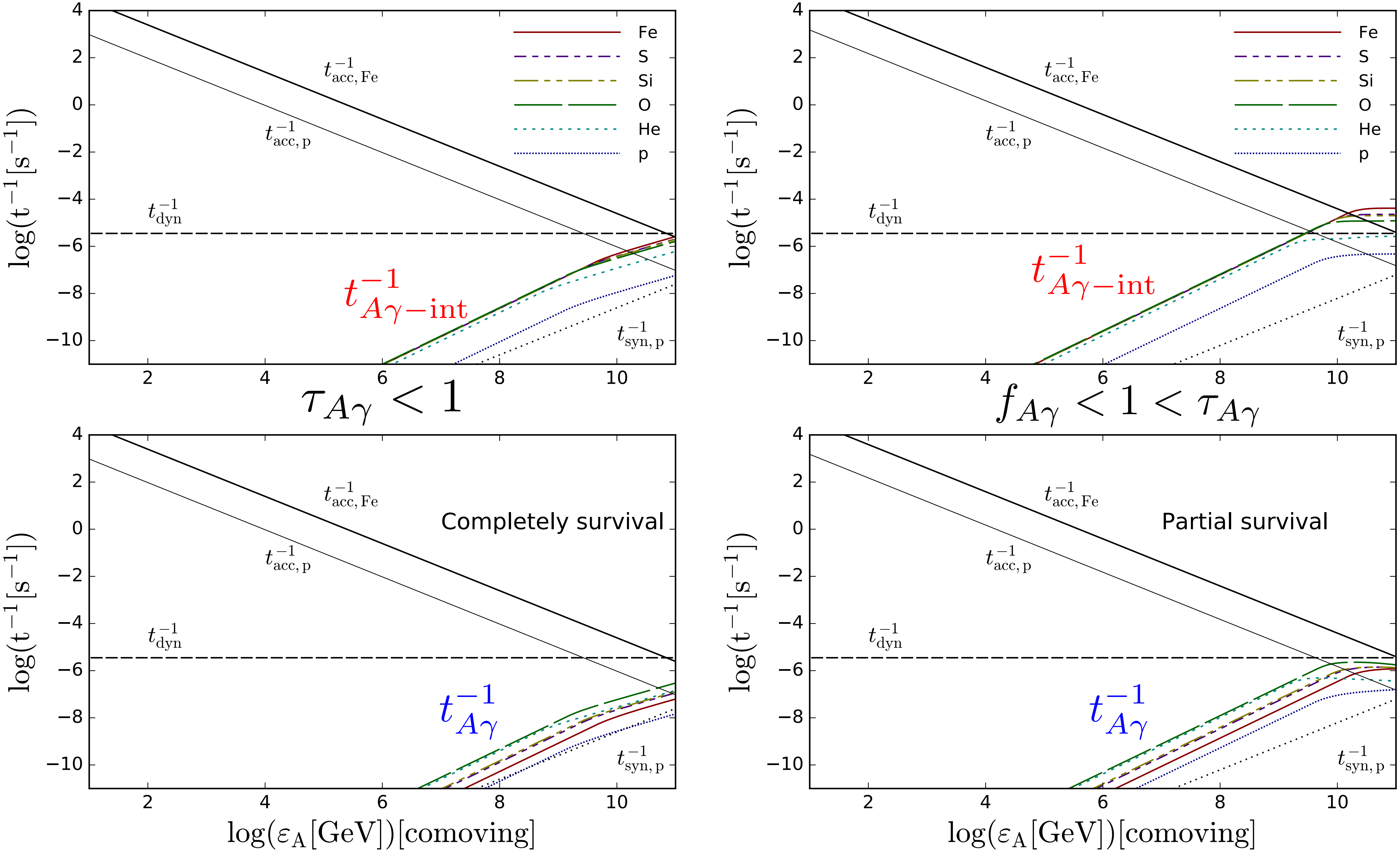


## Internal shock



# The survival of UHECR nuclei

## Reverse shock model



$\tau_{A\gamma} < 1$

$f_{A\gamma} < 1 < \tau_{A\gamma}$

# Secondary neutrinos from UHECR nuclei

Neutrinos originated from UHECR nuclei can be divided into two parts:

Murase & Beacom 2010, arXiv: 1003.4959;
BTZ & Murase 2018b, to be submitted

1, Direct neutrinos: $A + \gamma \rightarrow \nu$

Photopion interaction on nuclei directly

$$\varepsilon_\nu^2 \frac{dN_\nu}{d\varepsilon_\nu} = \frac{3}{8} f_{\rm sup} f_{\rm mes}(\varepsilon_A) \boxed{(1 - f_{A\gamma}(\varepsilon_A))} \varepsilon_A^2 \frac{dN_A}{d\varepsilon_A}$$

2, Indirect neutrinos: $p/n + \gamma \rightarrow \nu$

Photopion interaction on secondary nucleons

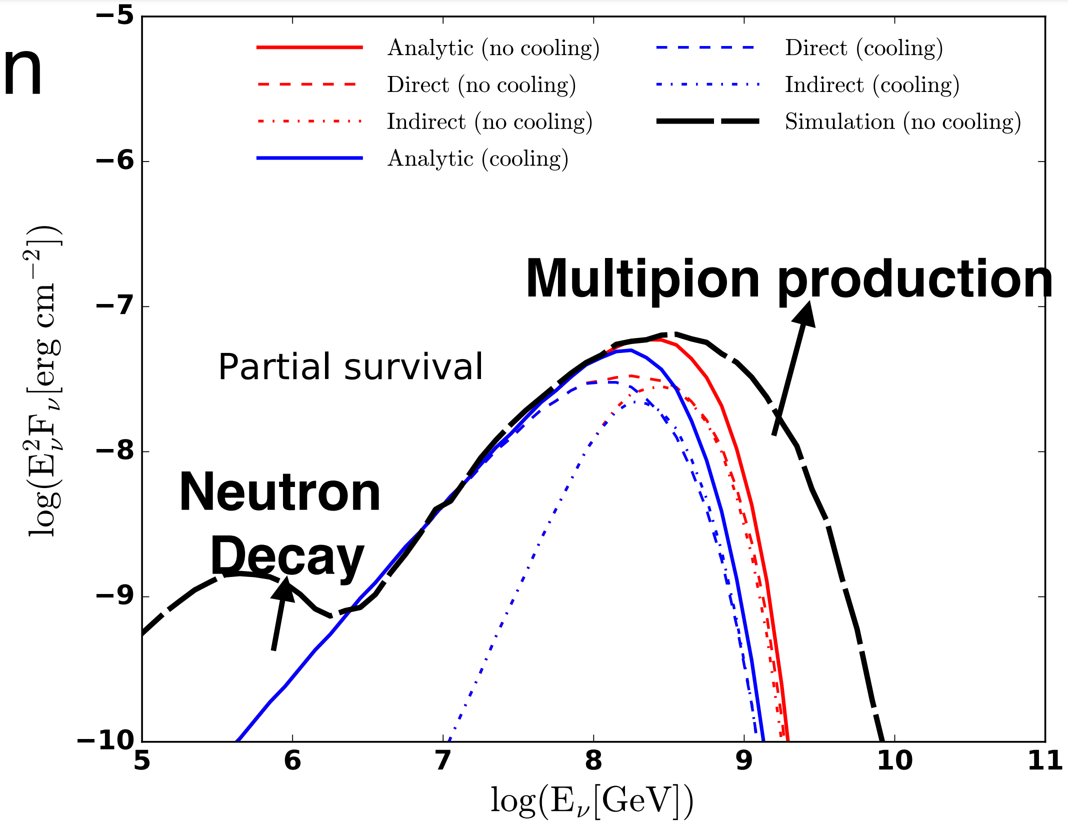
$$\varepsilon_\nu^2 \frac{dN_\nu}{d\varepsilon_\nu} = \frac{3}{8} f_{\rm sup} f_{p\gamma}(\varepsilon_p) \boxed{f_{A\gamma}(\varepsilon_A)} \varepsilon_A^2 \frac{dN_A}{d\varepsilon_A}$$

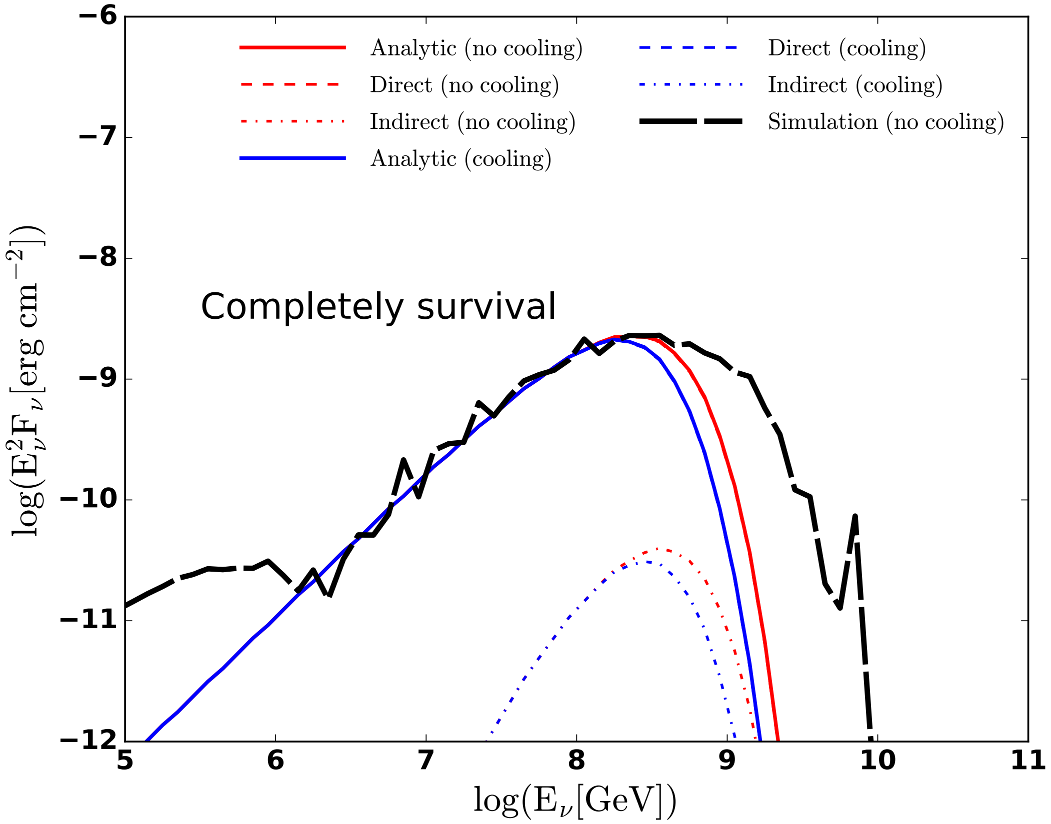
**Partial survival regime:**

Indirect neutrinos dominate high energy part

**Completely survival regime:**

Direct neutrinos dominate the whole spectrum





# 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:

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

# Escape-limited model

CRs whose energy is close to the maximum acceleration energy can escape from the escape boundary for instantaneous sources

Ohira et al. 2010;

Number fraction of different UHECR nuclei ✓

$$\frac{dN_{A'}}{dE'} = f_{A'} J_0 \exp\left[-\ln^2\left(\frac{E'}{Z E'_{p,\mathrm{max}}}\right)\right]$$

Normalization ✓

Maximum acceleration energy ✓

$$Q_{\mathrm{UHECR}} = \xi_{\mathrm{CResc}} \mathcal{E}_{\gamma \mathrm{iso}} \rho_0^{\mathrm{LL}}$$

$$\xi_{\mathrm{CResc}} \sim (10 - 20)\ \mathcal{E}_{\gamma \mathrm{iso},50}$$

$$\xi_{\mathrm{CRacc}} \sim 100 - 200$$

$$E_{A,\mathrm{dyn}} \simeq 10^{18.7} (\eta/15)^{-1} Z \xi_B^{1/2} L_{\gamma \mathrm{iso},47}^{1/2} \Gamma_1^{-2}\ \mathrm{eV}$$

$$l_{\mathrm{esc}} \approx x_{\mathrm{esc}} (R/\Gamma)$$

$$E_{A,\mathrm{esc}} \simeq 10^{18.2} (\eta/15)^{-1} Z \xi_B^{1/2} x_{\mathrm{esc},-0.5} L_{\gamma \mathrm{iso},47}^{1/2} \Gamma_1^{-2}\ \mathrm{eV}$$