Sources models of Ultrahigh Energy Cosmic Rays

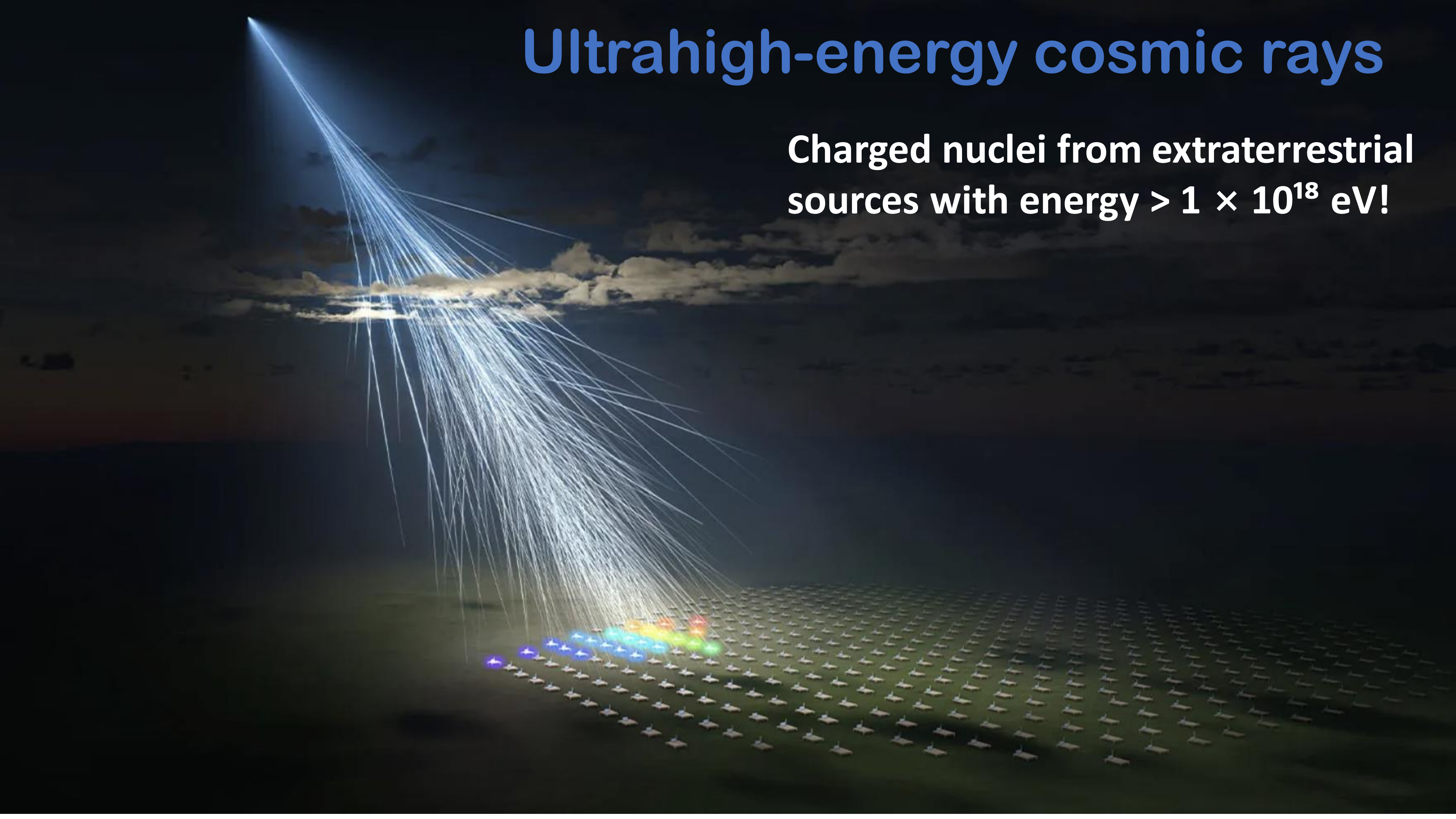
Bing Theodore Zhang

Institute of High Energy Physics, Chinese Academy of Science

2024/11/18

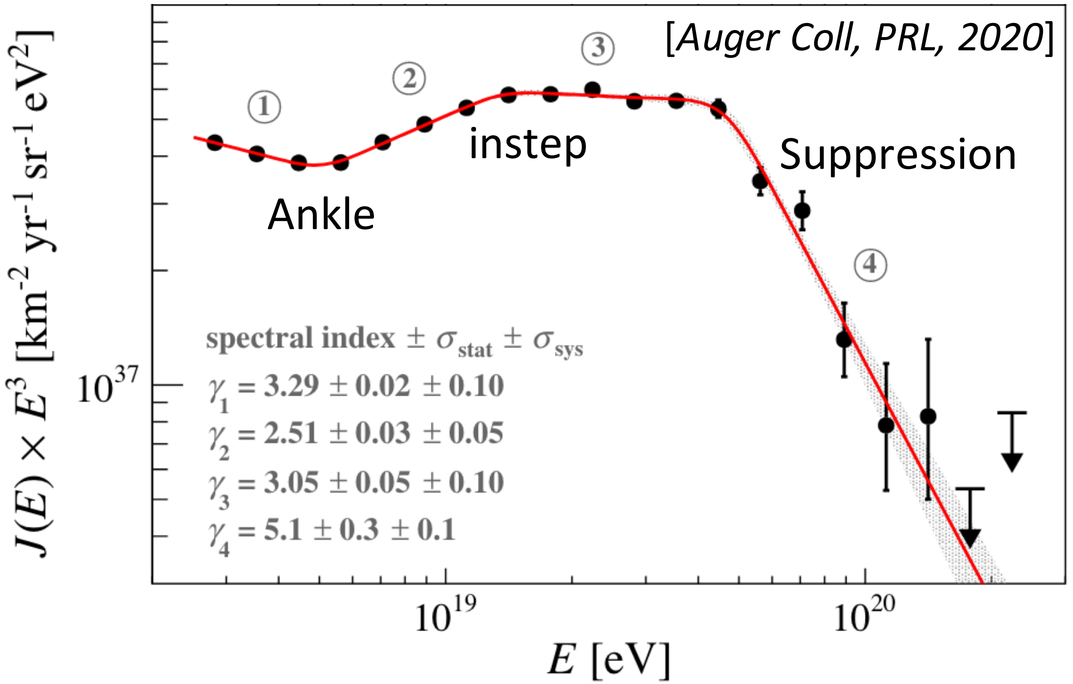
Ultrahigh-energy cosmic rays

Charged nuclei from extraterrestrial sources with energy > 1×10^{18} eV!



Spectrum of UHECRs

Well measured by not understand



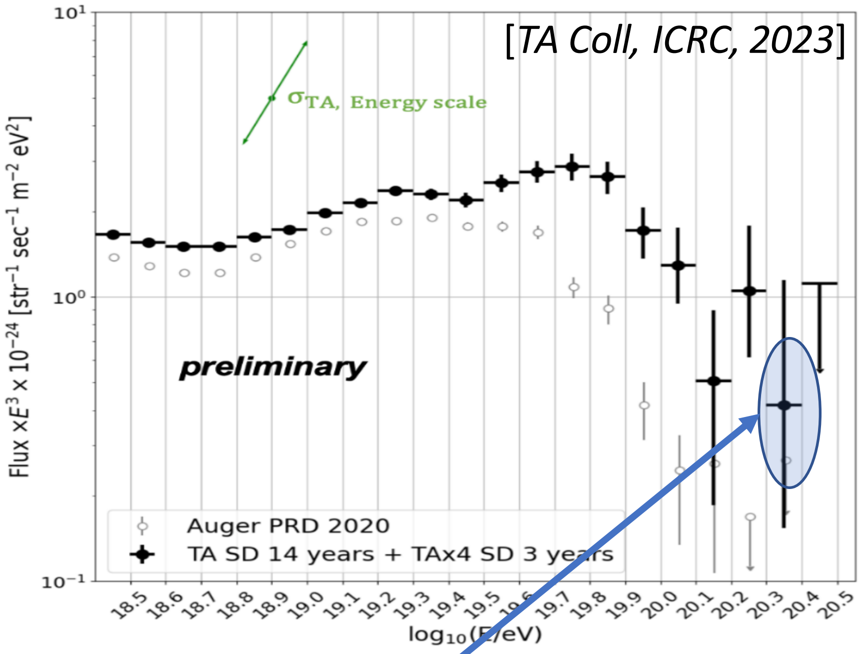
Ankle: Transition from Galactic to Extragalactic ?

Instep: Related to composition transition ?

Suppression: Interaction with CMB/EBL photons

Maximum acceleration energy at sources ?

More > 100 EeV cosmic rays ?



Energy range including Amaterasu particle

Observation of Amaterasu particle, ~240 EeV!

[TA Coll, Science, 2023]

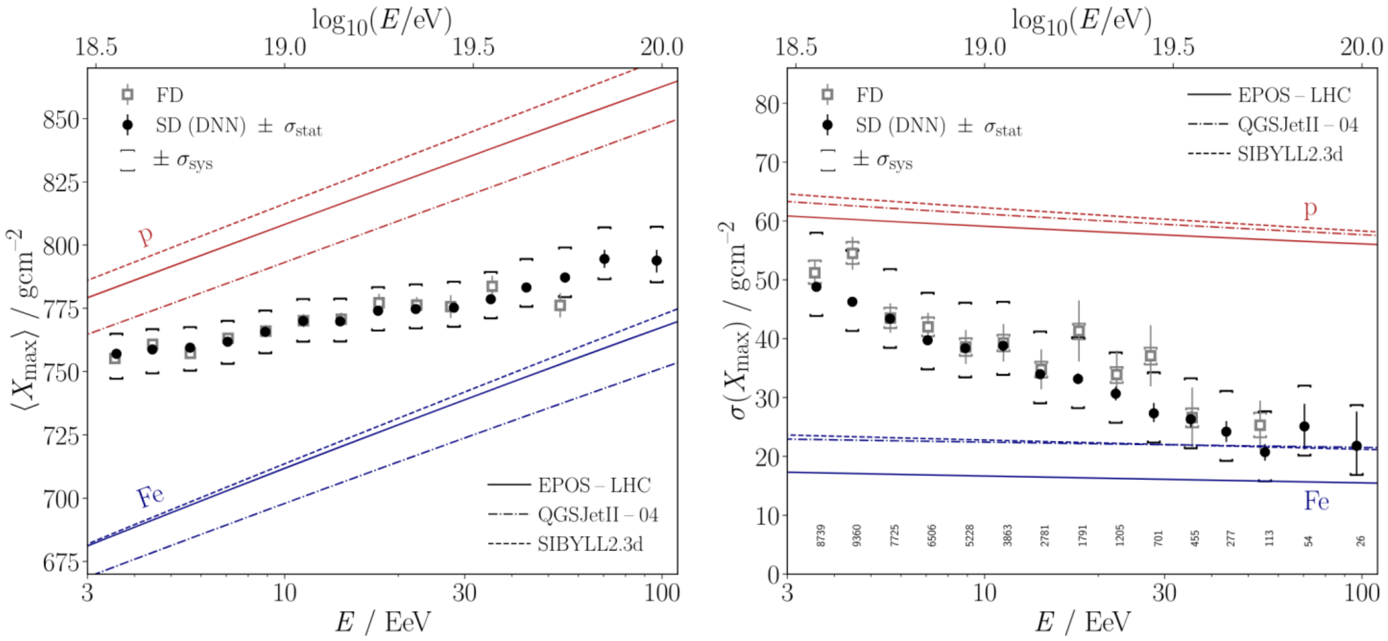
Detection of 320 EeV by the Fly's Eye air shower detector in 1991!

[Bird+, ApJ, 1995]

Composition of UHECRs

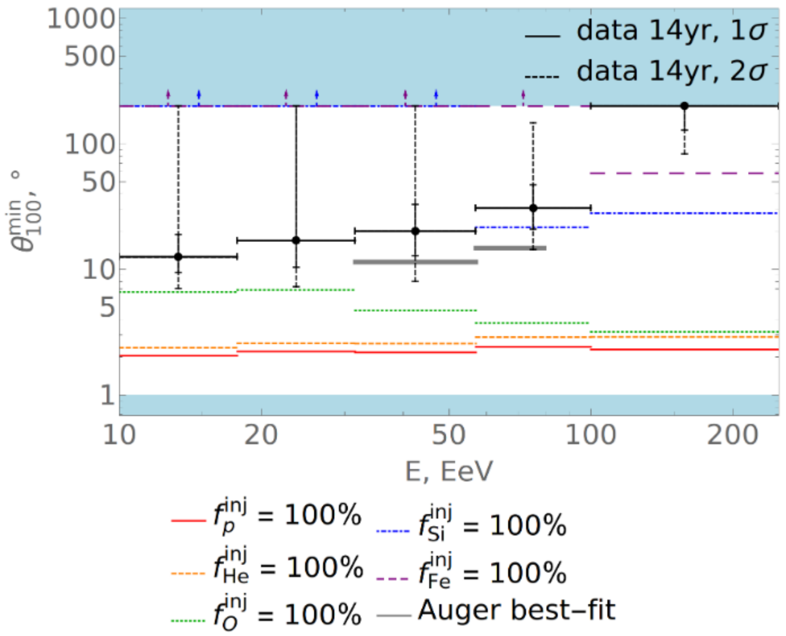
Big progress on the determination of UHECR composition !

Mass composition of UHECRs from the mean depth and the fluctuations of shower maximum



Auger: UHECR composition toward heavier nuclei

Mass composition of UHECRs from distribution of their arrival directions



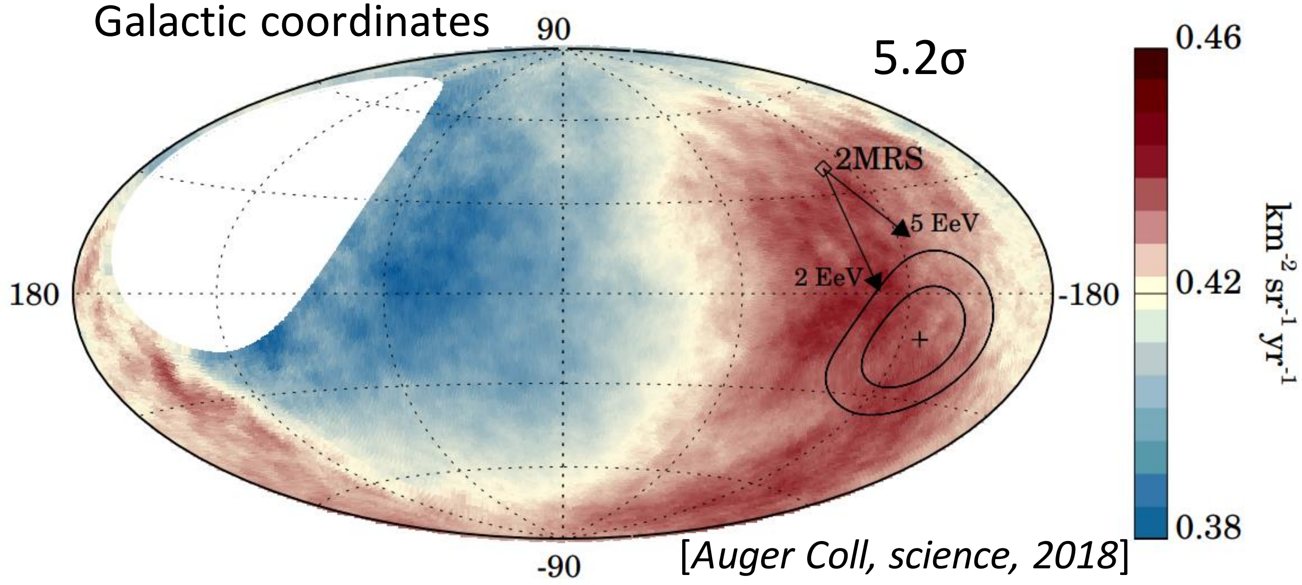
TA: Heavy UHECRs are supported

[*Auger Coll, PRD, 2014, 2024*]

[*TA Coll, PRL, 2024*]

Anisotropy of UHECRs

Large-Scale Anisotropy - Dipole



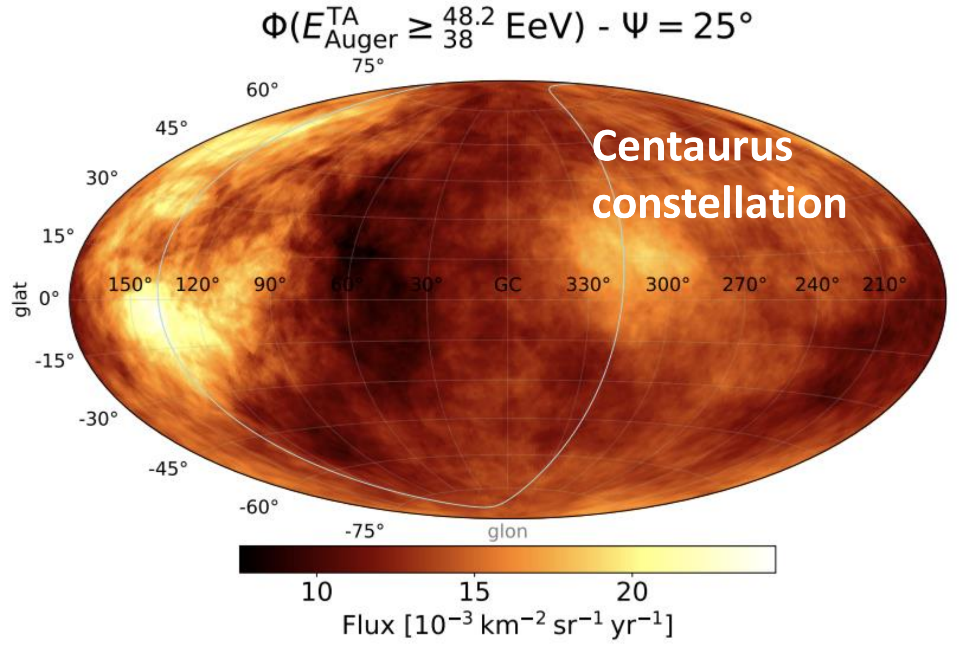
[*Auger Coll, science, 2018*]

Now, 6.8σ above 8 EeV [*Auger Coll 2024*]

Implications:

- Supporting extragalactic origin of UHECRs
- UHECR sources correlate with local matter distribution

Intermediate scale anisotropy



[*Caccianiga+, ICRC, 2023*]

- Hot spot at Centaurus region 4.0σ for E > 38 EeV
- Correlation with SBGs, 4.7σ
- TA hotspot, 3.2σ [*Kim+ 2023*]
- Excess at Perseus-Pisces supercluster, 3.2σ

The candidate sources of UHECRs - Hillas condition

$$L_{\mathrm{bol,min}} > \frac{1}{2}\Gamma^2 c\beta \left(\frac{E}{Ze\beta}\right)^2 \sim 10^{45}\ \mathrm{erg\ s^{-1}}\Gamma^2\beta^{-1}\left(\frac{E}{Z10^{20}\ \mathrm{eV}}\right)^2$$

[*LoveLace 1966; Waxmann 1995; Blandford 2000*]

e.g. [*Blasi+ 2000, Arons 2003, Murase+ 2009, Fang+ 2012*]

Energetic transients in star-forming galaxies $L_{\gamma\mathrm{iso}} \sim 10^{52}\ \mathrm{erg\ s^{-1}}$

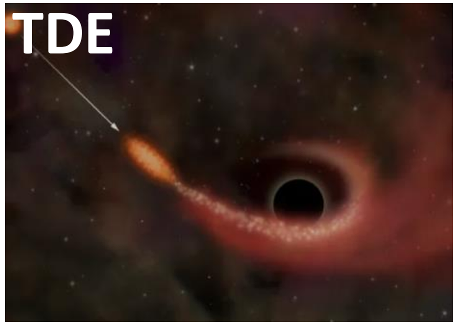
e.g. [*Murase+ 2006 2008, Wang+ 2007, Chakraborty 2009*]

e.g. [*Waxman 1995, Vietri 1995, BTZ+ 2024*]

e.g. [*Takami+ 2013, Kimura+ 2018, Rodrigues+ 2019*]

e.g. [*Jokipii & Morfill 1985, Anchordoqui+ 2001, Bertone+ 2002*]

Supermassive black holes



e.g. [*Farrar&Gruzinov 2009; Farrar&Piran 2014; BTZ+ 2017*]

e.g. [*Gintzburg & Syrovatskii 1964, Takahara 1990, Rachen & Biermann 1993, Murase+ 2012*]

Merger shocks

e.g. [*Norman+ 1995, Kang+ 1996; Inoue+ 2007, Murase+ 2008*]

The candidate sources of UHECRs - Energetics of UHECRs

Total energy generation density above ~3 EeV:

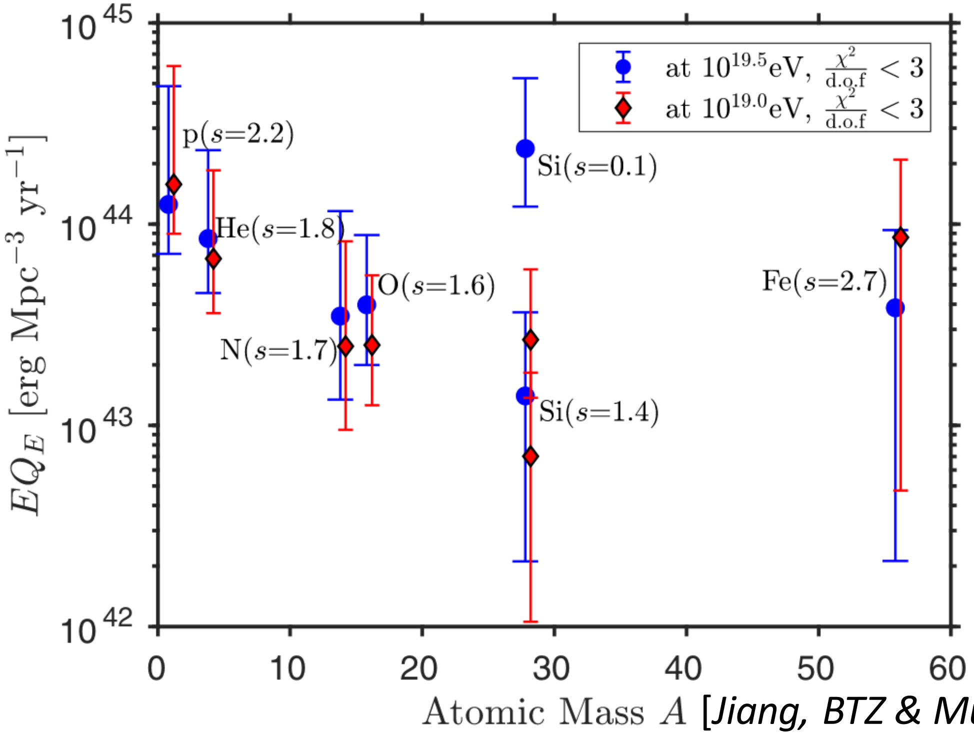
$$Q_{\rm inj} \sim 6 \times 10^{44}\ {\rm erg\ Mpc^{-3}\ yr^{-1}}$$

[*Auger Coll, PRL, 2020*]

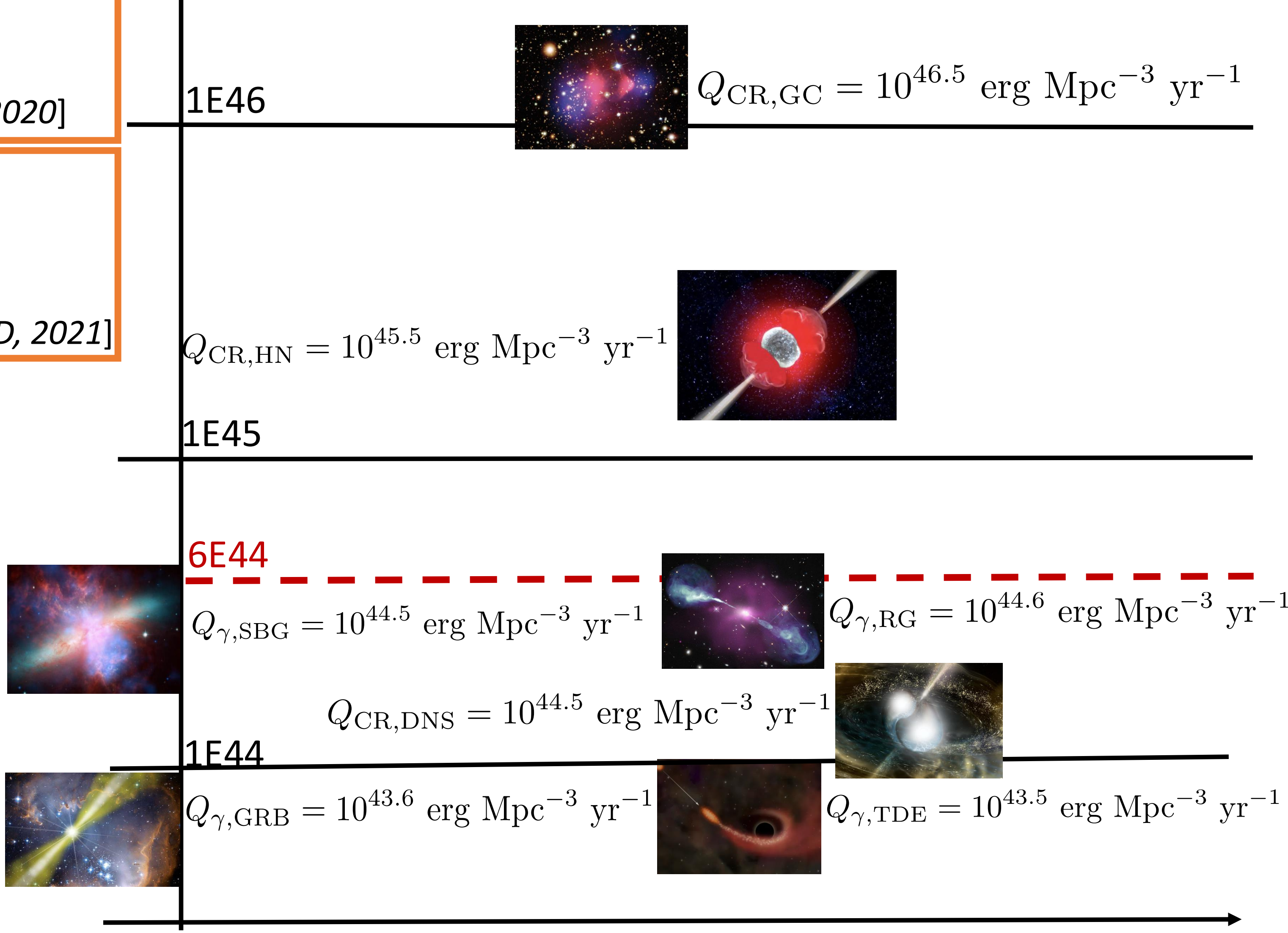
Differential energy generation rate density for different species

$$EQ_E^{19.5} \approx (0.4\text{–}1.5) \times 10^{44}\ {\rm erg\ Mpc^{-3}\ yr^{-1}}\ \text{ for } s \gtrsim 1.5$$

[*Jiang, BTZ & Murase, PRD, 2021*]



See also. [*Waxman 1995; Boza+ 2009; Murase & Fukugita 2019*]



UHECR composition at the sources in Auger/TA era

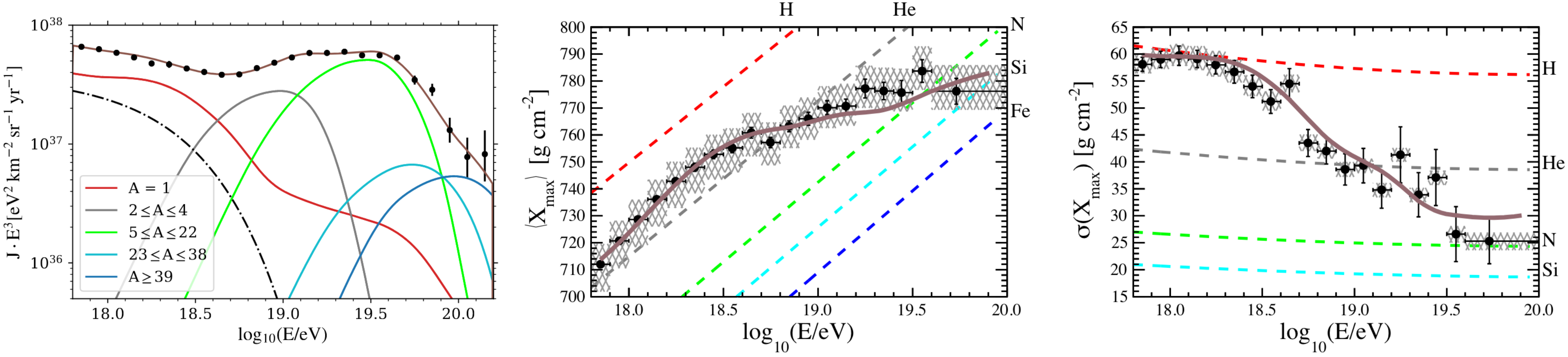
Composition is the key to identify the sources of UHECRs

Mixed composition at the sources from combined fit to UHECR spectrum and composition

[*Auger Coll, JCAP, 2017;2024*]

Best-fit results for injection: f_H : f_He : f_N : f_Si : F_Fe = 0 : 24.5% : 68.1% : 4.9% : 2.5%

[*Auger Coll, JCAP, 2024*]



[*Auger Coll, JCAP, 2024*]

UHECR composition at the sources in Auger/TA era

Composition is the key to identify the sources of UHECRs

Solar composition does not work !

Significant enhancement of nuclei is needed

Solar composition

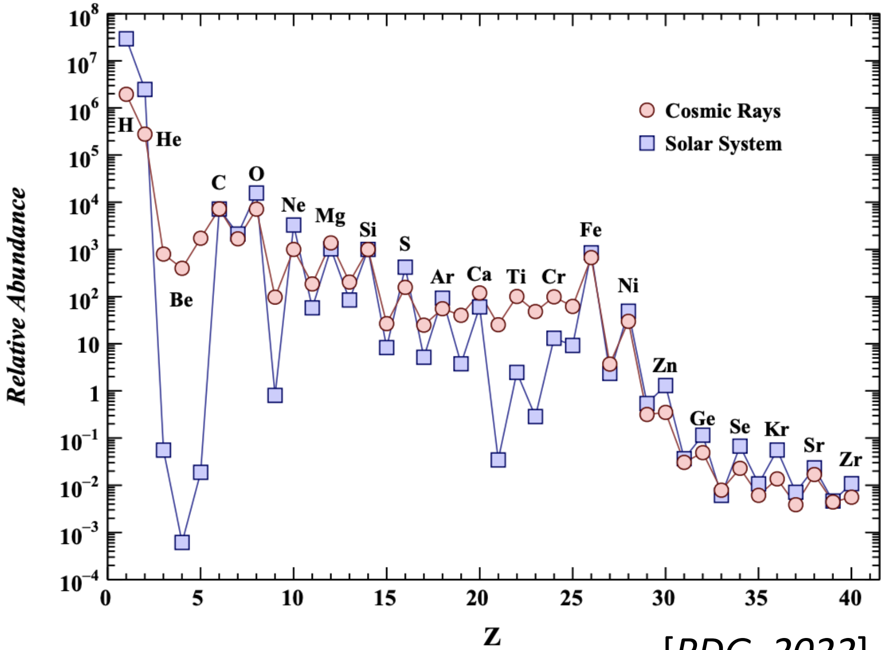
$$ZE_{p,\max} = Z\ 2\times10^{19}\ \mathrm{eV}$$

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

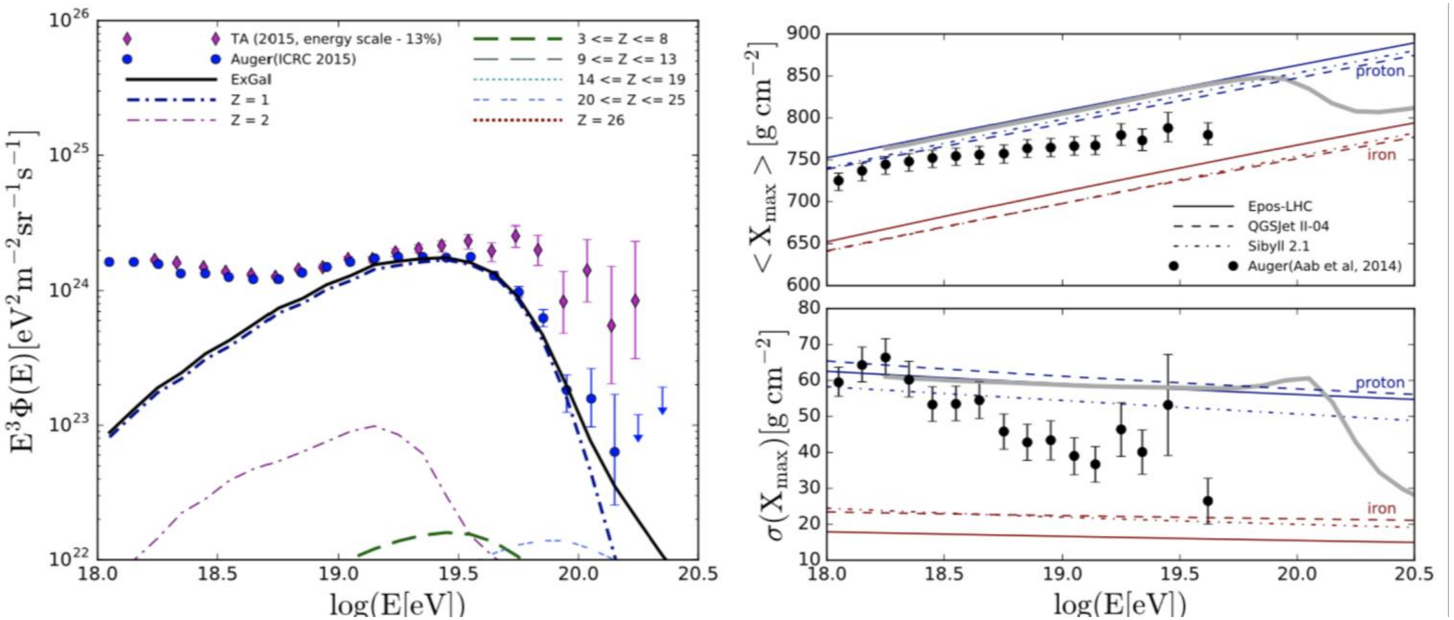
$$\xi_{\rm CR} \sim 100\ Q_{{\rm CR},44.6}\,\rho_{0}{}_{-10.5}^{-1}\ \mathcal{E}_{{\rm rad},53}^{-1}$$

Propagate with CRPropa 3 - 1D
EBL: Gilmore 12

Proton dominated in nearly all the energy range



[PDG, 2022]



[BTZ+, PRD, 2017]

Origin of intermediate mass and heavy nuclei

1, Ejecta and/or wind? (Yes) See Ref. [*BTZ+, PRD, 2018; BTZ & Murase, PRD, 2019*]

- Sources related to deaths of massive stars or compact stars

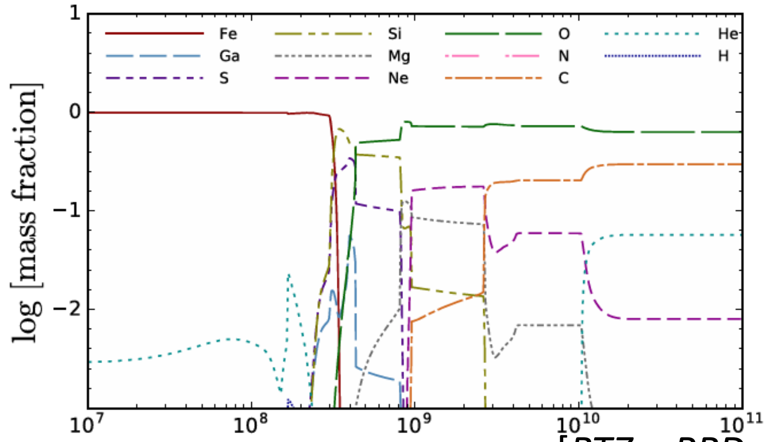
  A. Loading from stellar ejecta through accretion disk, "one-time" injection

  B. Entrainment from stellar ejecta through mixing

  C. Explosive nucleosynthesis in the jet

- Strong constrains on the luminosity and emission region of the sources

Dominated by intermediate mass nuclei !



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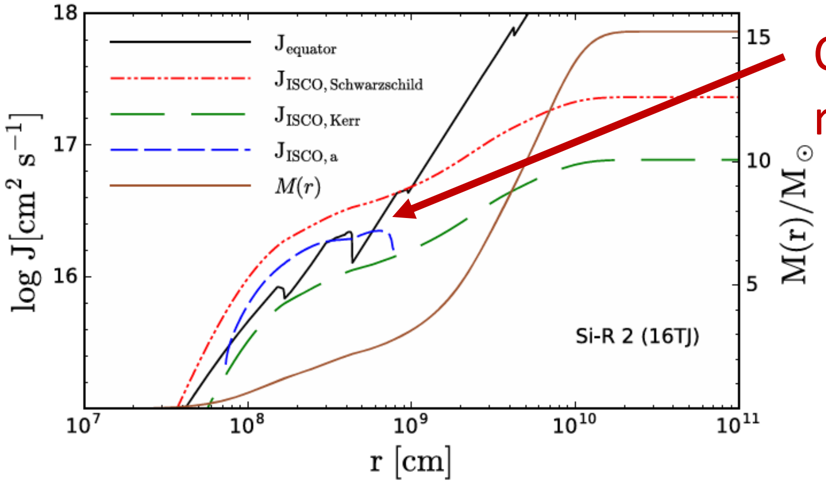

Critical radius

The distribution of the nuclear mass fraction (upper panel) and the specific angular momentum (lower panel)

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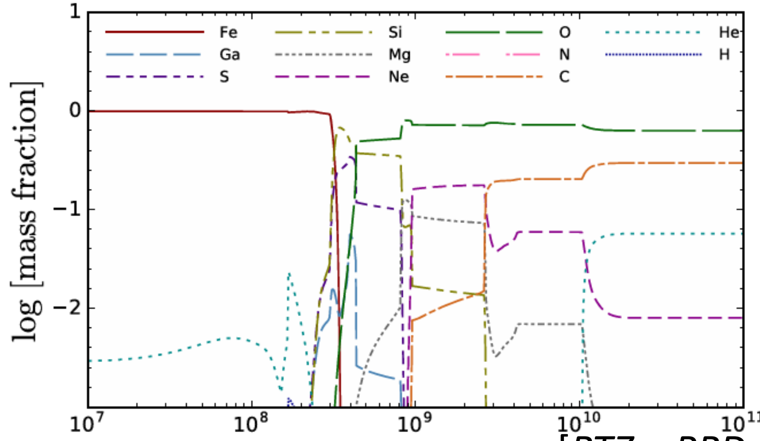
2, Reacceleration of low-energy CRs?

See Ref. [*Caprioli, ApJL 2015, Kimura, Murase & BTZ, PRD, 2018*]

- Injection at same energy (e.g., at TeV)?
- Additional heavy nuclei enhancement may be needed

Dominated by intermediate mass nuclei !



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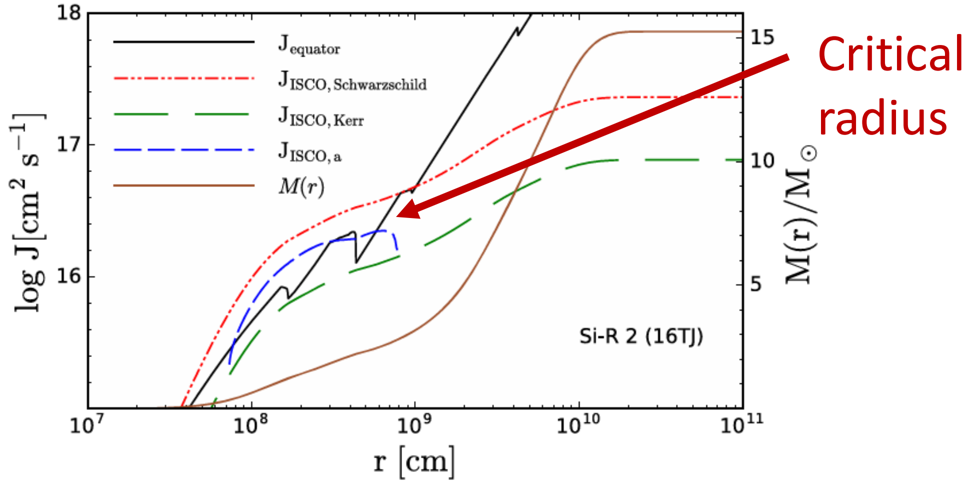

The distribution of the nuclear mass fraction (upper panel) and the specific angular momentum (lower panel)

Transients as UHECR sources

Absense of small scale anisotropy

- Constraints on the effective source number density

  $N_s > 10^{-5} - 10^{-4}\ \mathrm{Mpc}^{-3}$

- Challenging for "rare" steady sources

  [*Auger 2013 ApJ; Takami+, ApJ, 2016;*]

- Transients are good [*Murase & Takami2009, Takami & Murase 2012*]

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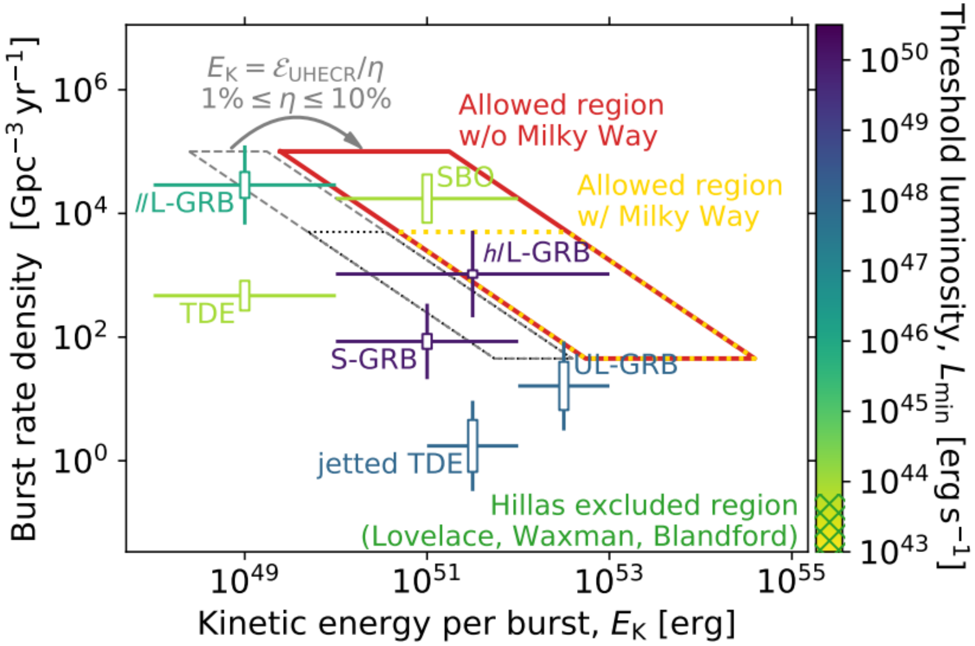

[*Marafico+ 2024*]

Anisotropy correlated with galaxies in the Local Sheet

- Transient sources in star-froming galaxies (or dwrafs)

  See Ref. [*Marafico+ 2024*]

- Constraints of UHECRs: $50\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1} < \rho_\mathrm{s} < 30000\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$

  Consistent w. long-duration GRBs or transrelativistic SNe/hypernovae

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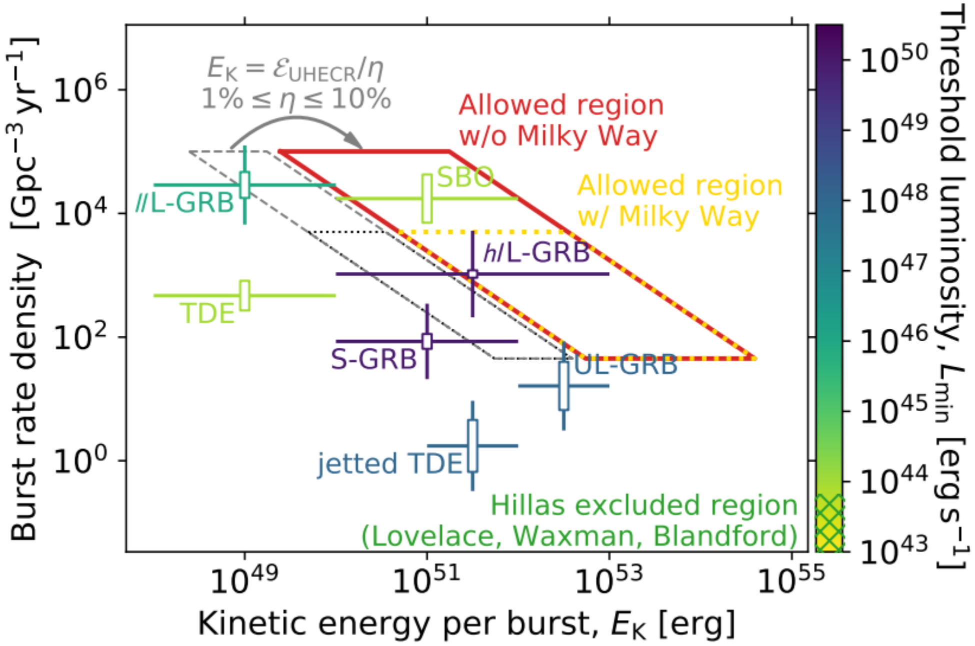

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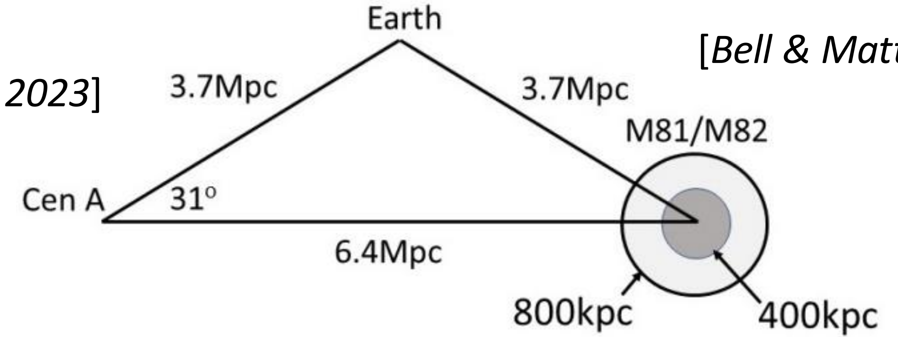
Echo of a past burst of Cen A? [*Bell & Matthews 2022, Taylor+ 2023*]

- Sensitive to the magnitude and structure of the magnetic field in the outer parts of starburst haloes

[*Bell & Matthew 2022*]



Narrow Rigidity of UHECR sources ?

Narrow rigidity, nearly identity sources ?

Maximum energy depends on luminosity

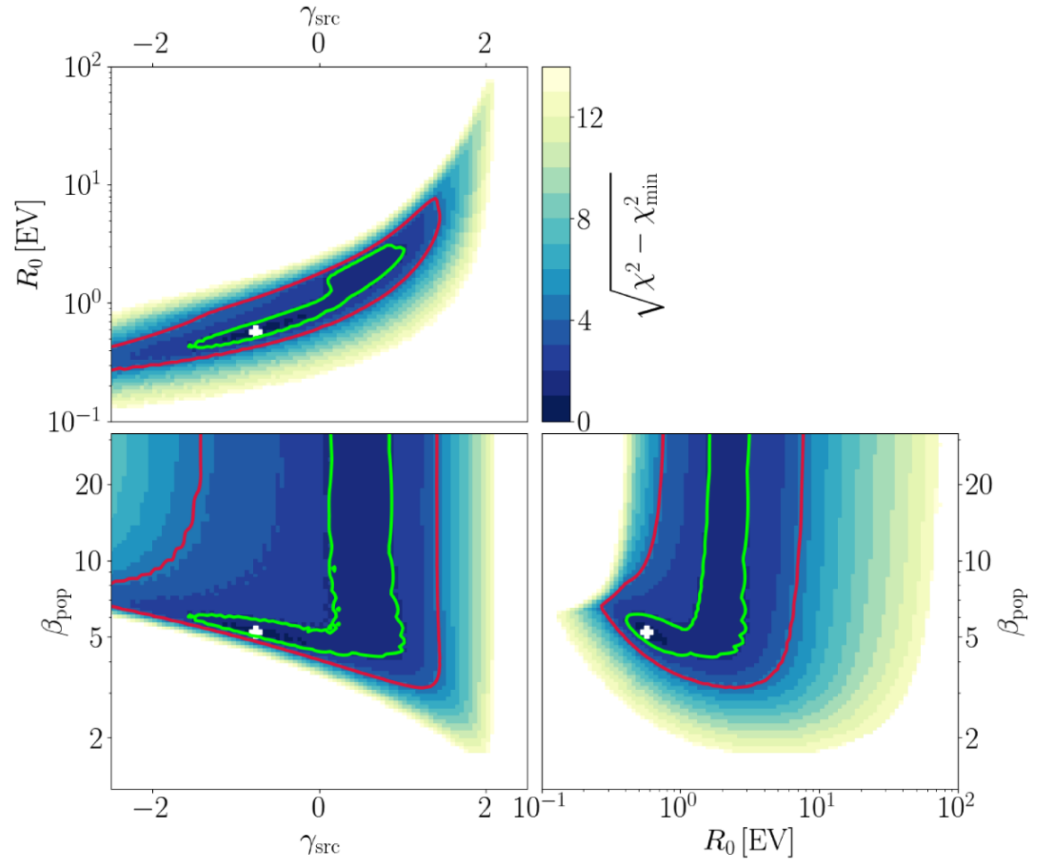
$$R_{\max} \sim R_0 \beta^{1/2} \left(\frac{L}{L_0}\right)^{1/2}$$

Powerlaw distribution of rigidity $p(R_{\max}) \propto R_{\max}^{-\beta_{\rm pop}}$

If Auger spectrum and composition are considered, a finite value of β_{pop} ~ 5 are preferred, dispersion in maximum rigidity by a factor of 2 !!!

However, acceleration mechanisms may not reflect the luminosity function

Such conclusion depends on source models – where and how the acceleration occurs !



[*Ehlert, Oikonomou, Unger, PRD, 2023*]

Candidates sources: 1, Massive stellar deaths

Transient sources related to massive stellar deaths

High-luminosity GRB

[*Waxman, PRL, 1995, Viertri, ApJ, 1995*]

Low-luminosity GRB

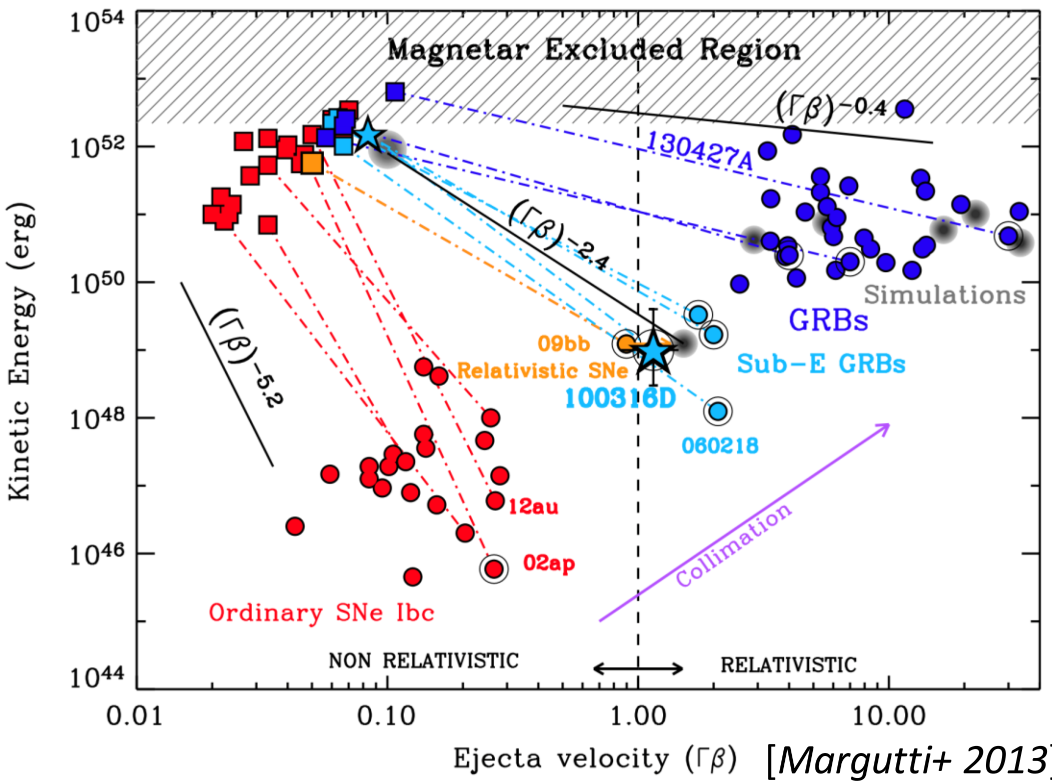
[*Murase+, PRD, 2008, Liu+, MNRAS, 2011, BTZ+, PRD, 2018, Boncioli+ 2018*]

Engine-driven supernova / hypernova

[Wang+, PRD, 2018, *BTZ & Murase, PRD, 2019*]

Pulsar/magnetar-driven transients [*Arons+ ApJ 2003, Murase+, PRD 2009, Fang+, ApJ, 2012, Fang+, ApJ, 2019*]

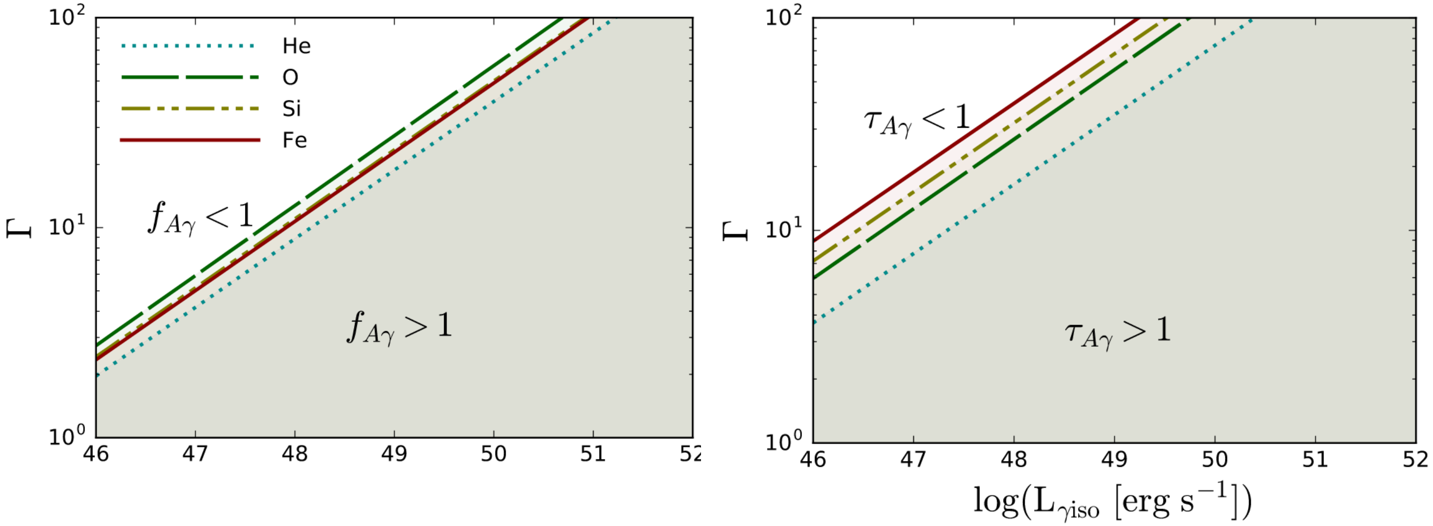
The diversity of the explosive phenomenon



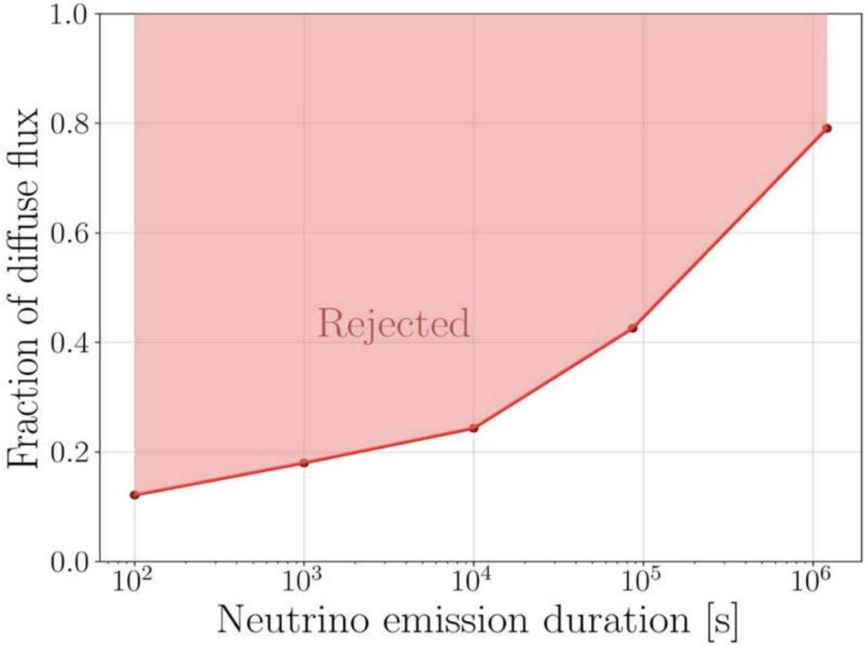
[*Margutti+ 2013*]

High-luminosity GRBs

Issues: bayon loading and "survival" of nuclei



Diffuse neutrinos from HL GRBs



Prompt emission phase:

Only low-luminosity is allowed to survive

Afterglow phase:

Nuclei survival is allowed

See [*Murase+, PRD, 2008, Wang+, ApJ, 2008*] for earliest studies

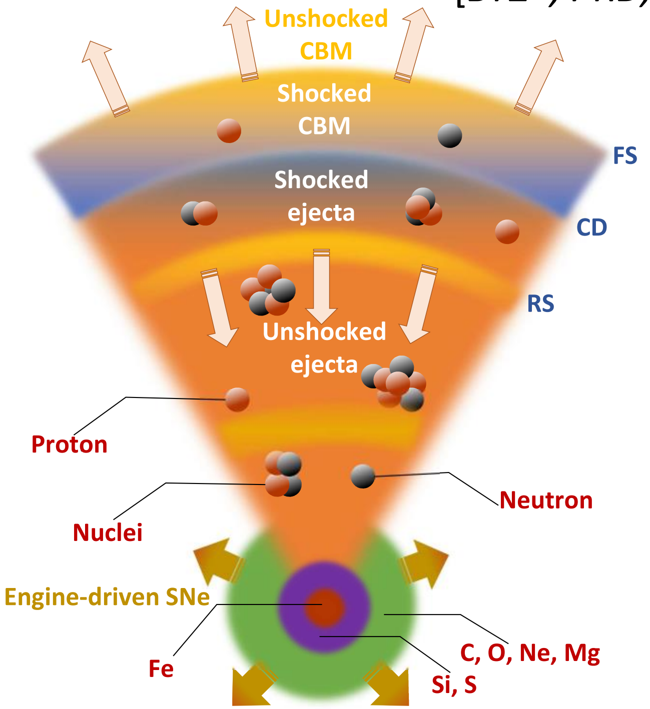
Strong constrains by high-energy neutrino observations

[*IceCube Coll, ApJ, 2022*]

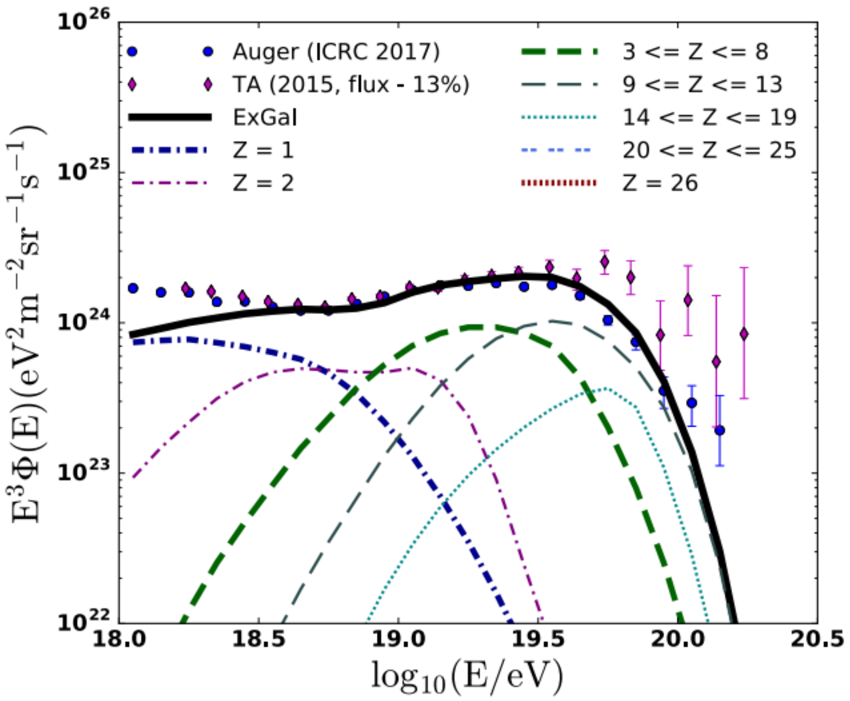
Note: true for prompt emission only !

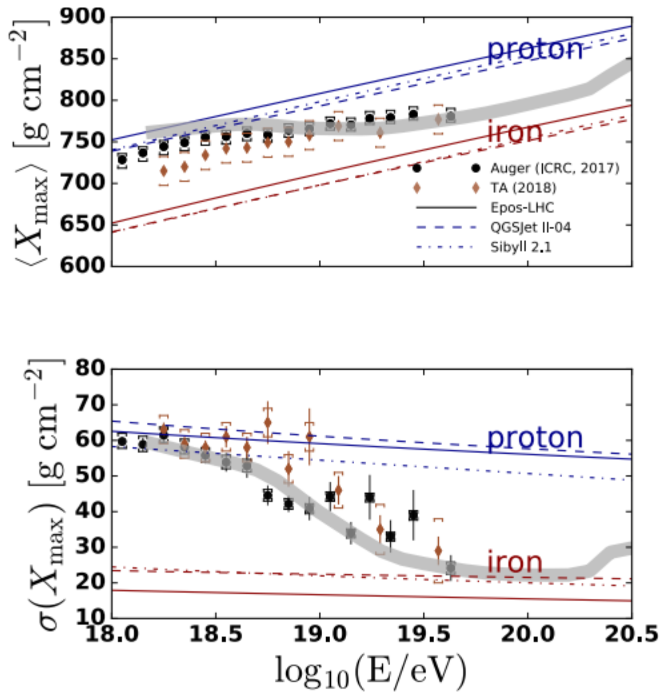
Low-luminosity GRBs and engine-driven supernova

[*BTZ+, PRD, 2018, BTZ & Murase, PRD, 2019*]



Silicon-rich composition $O :\sim 60\%$ $Si :\sim 35\%$ $S :\sim 5\%$





See Ref. [*Murase+, ApJL, 2006, Wang+, PRD, 2007, Murase+, PRD, 2008, Chakraborty 2009, Budnik+ 2009; Liu+, MNRAS, 2011, BTZ+, PRD, 2018, Boncioli+ 2018, BTZ & Murase, PRD, 2019*]

- We just use the results of massive stellar evolution
- The narrow rigidity problem could be solved if the external shock accelerates cosmic rays?
- They are transients and the source number can be very large

Candidate sources: 2, Compact binary mergers

Compact binary mergers (BNS / NSBH)

GRB shocks:

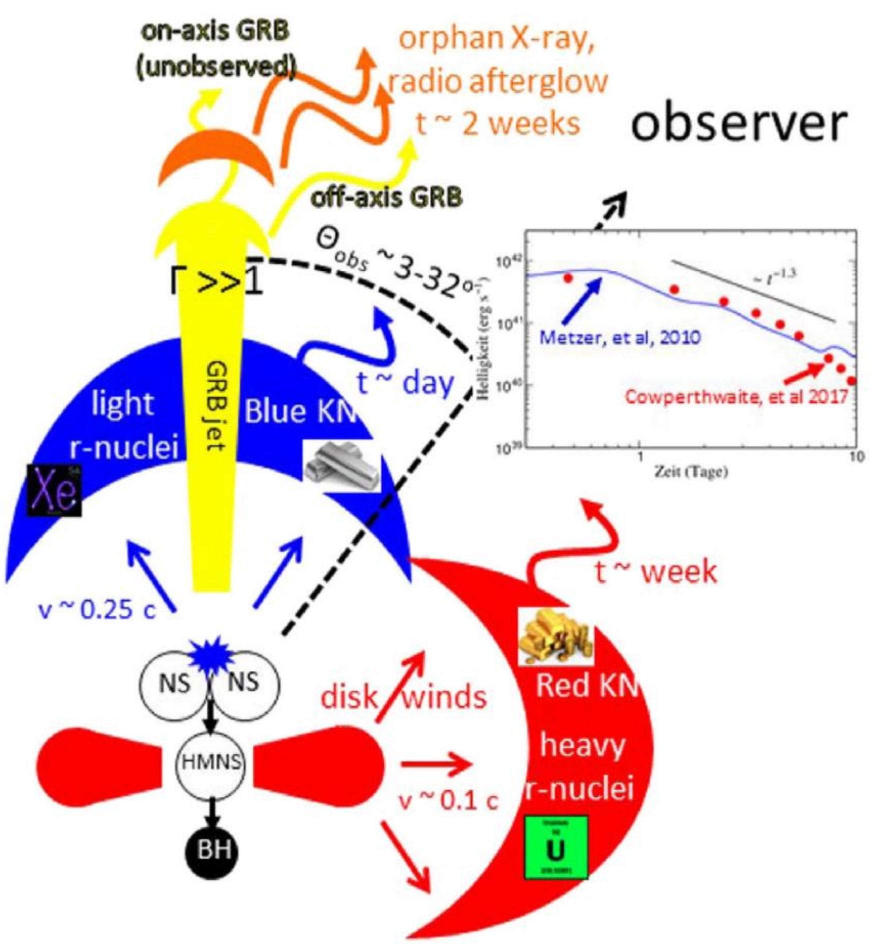
Short GRBs

Acceleration is efficient

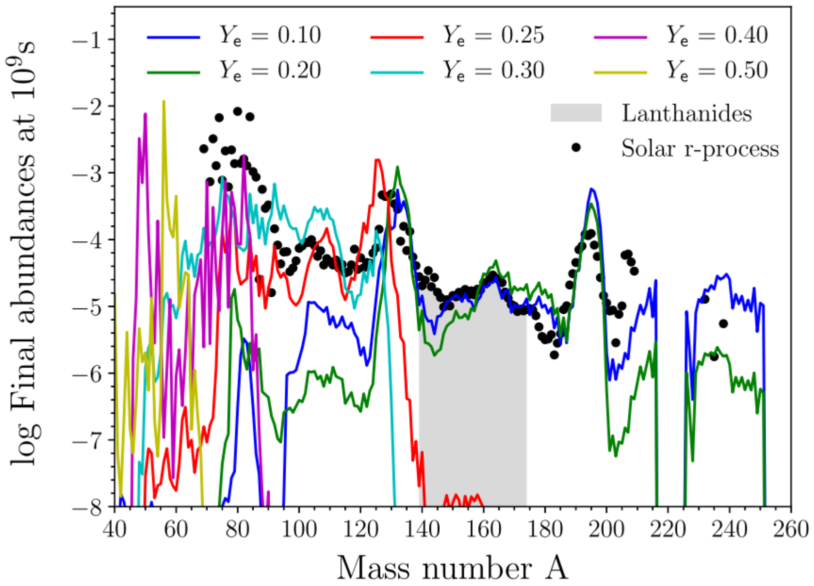
Merger shocks:

Acceleration is unefficient, unless it is Ultraheavy UHECR nuclei

[*Takami+2013, Kimura+ 2018, Murase & Fukugita 2019, Rodrigues+ 2019, BTZ+ 2024; Farrar+2024*]



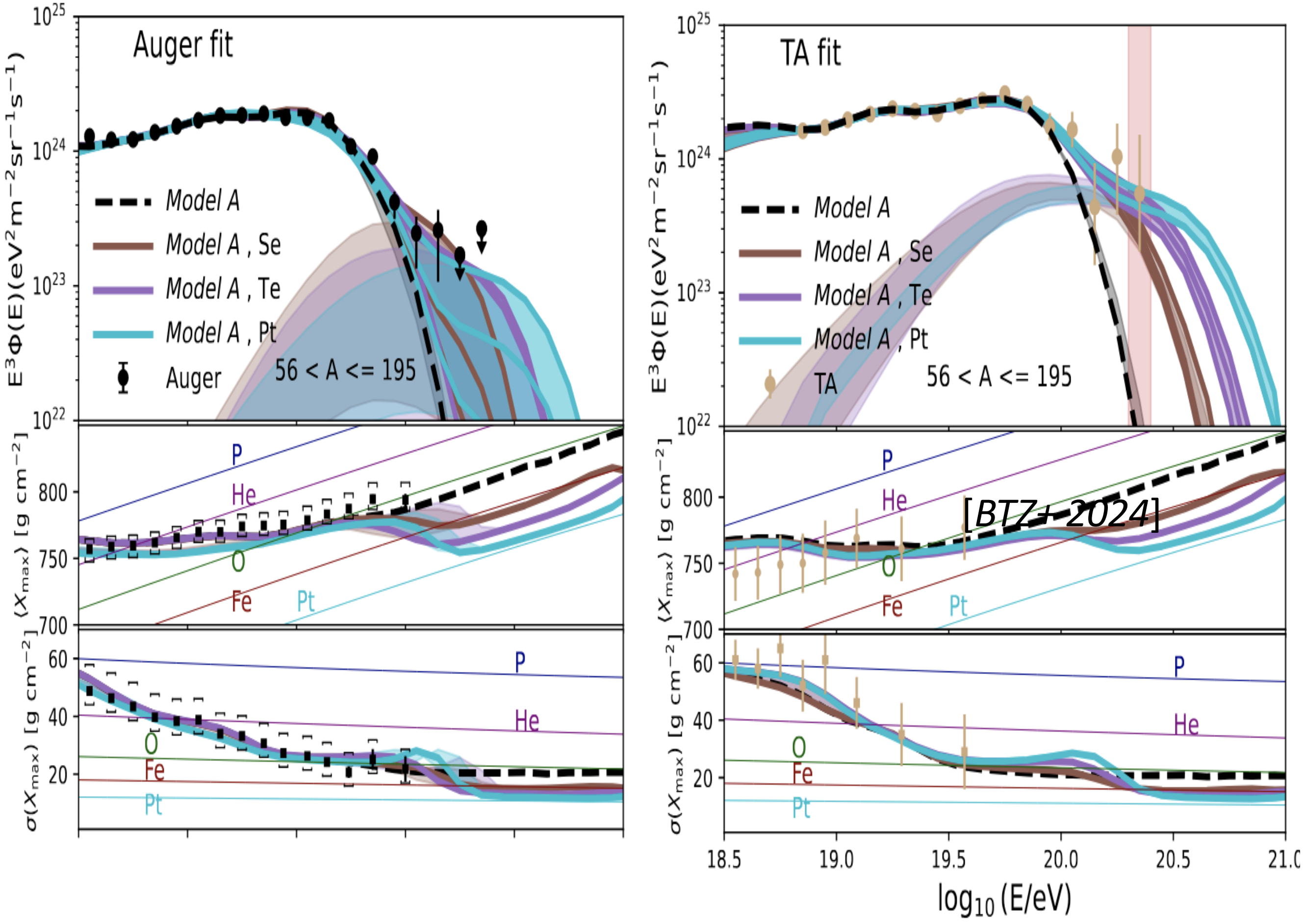
[Arcones&Thielemann 2022, *Metzger 2017*]



- Synthesized due to the r-process occurring inside neutron-rich environments
- 3rd peak material exists in equatorial plane (dynamical ejecta)

[*Lippuner & Roberts 2017; Perego+ 2021*]

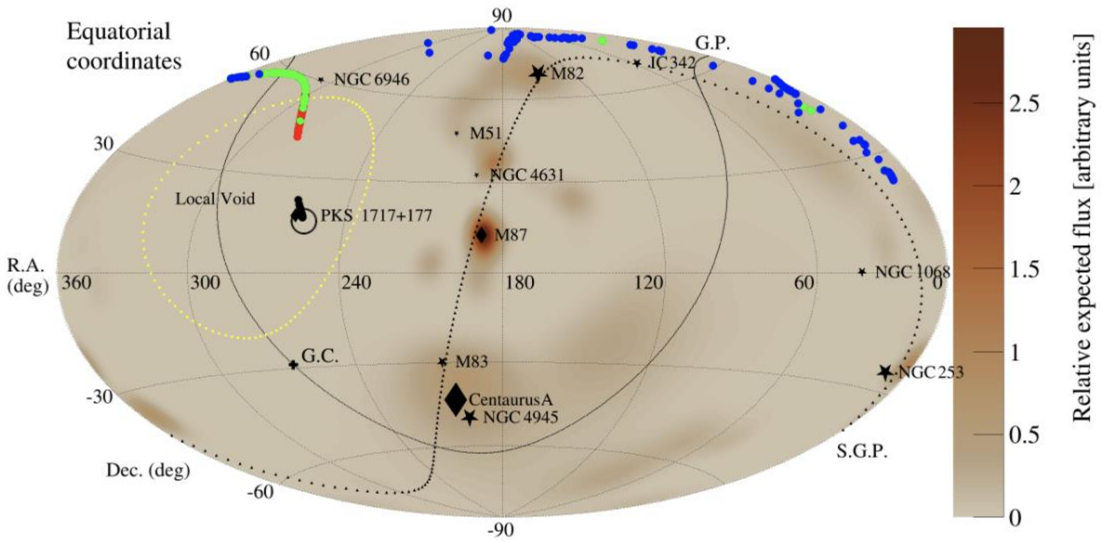
Origin of Amaterasu particle – UH-UHECR nuclei?



Model A: P, He, O, Si   Model B: P, He, O, Si, Fe

Auger: Model A gives the best-fit of the observed spectrum

TA: Model A + Te (A = 130) / Pt (A = 195) gives the best-fit of the observed spectrum



Backtracked directions: Proton(26, black), Iron(red), Zr(40, green) and Pt (78, blue)

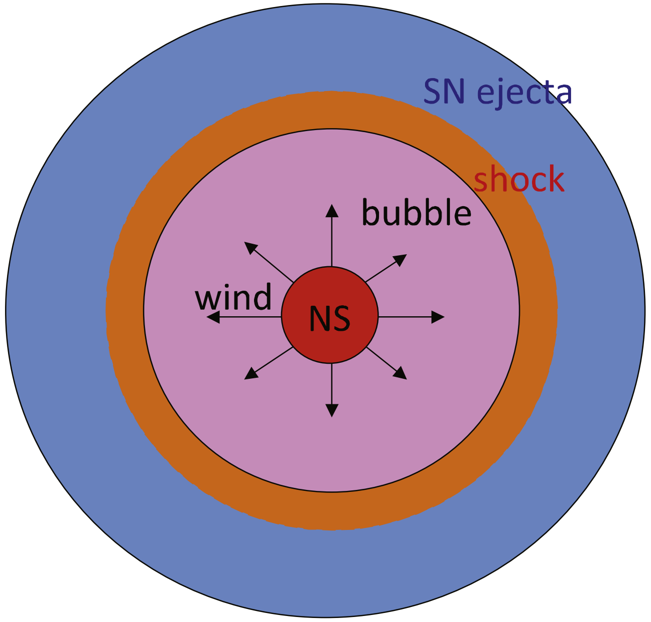
A robust bound of energy injection rate of UH-UHECR nuclei

$$Q^{\rm Auger}_{\rm UH-UHECR} \lesssim (0.1 - 15) \times 10^{42}\ {\rm erg\ Mpc^{-3}\ yr^{-1}},$$

$$Q^{\rm TA}_{\rm UH-UHECR} \lesssim (1.4 - 5.6) \times 10^{43}\ {\rm erg\ Mpc^{-3}\ yr^{-1}},$$

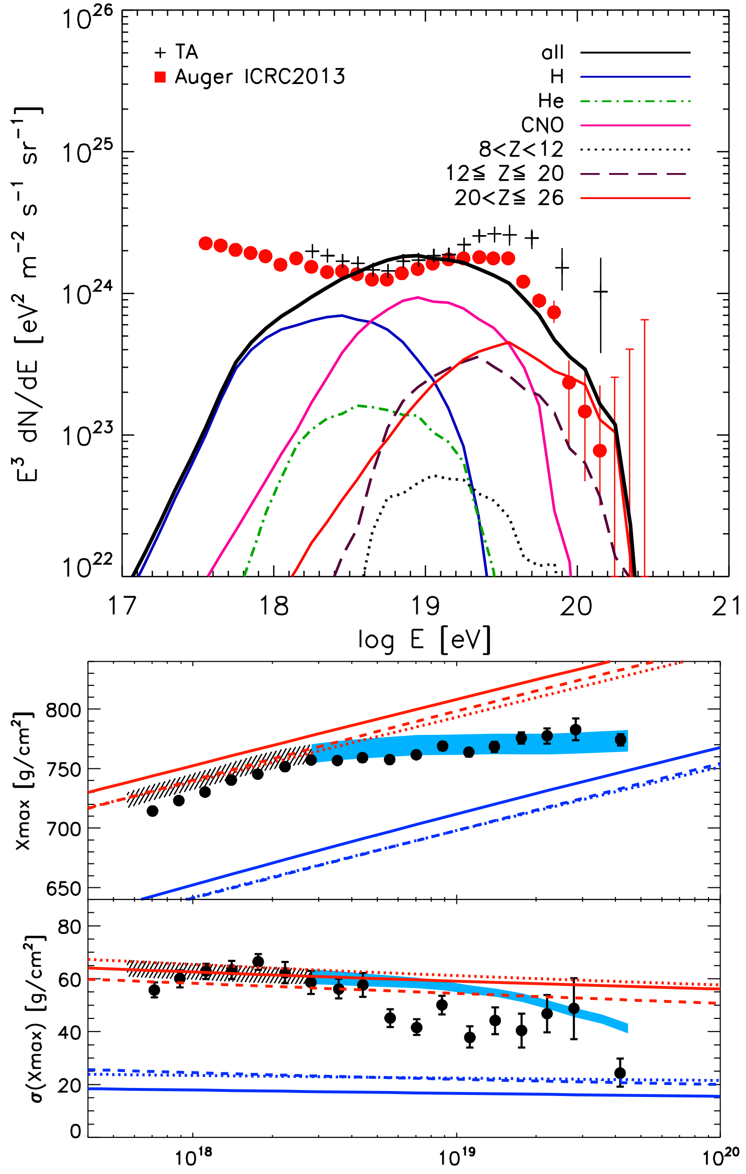
Candidate sources: 2.5, New-born pulsars / magnetars

New-born pulsars and magnetars
- massive stellar collapse
- low-mass NS merger remnant



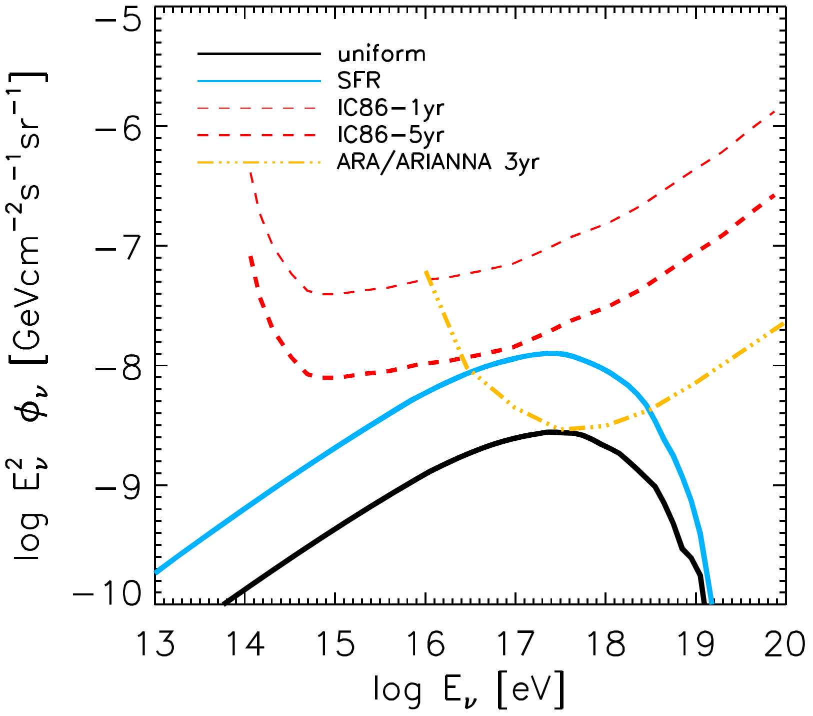
Heavy nuclei may come from neutron star surface

See Refs. [*Blasi+, ApJ, 2000, Arons, ApJ, 2003, Murase+, PRD, 2009, Fang+, ApJ, 2012, Fang+ 2014; Piro+ 2016*]



Current limits from Auger and IceCube started to constrain the relevant parameter space

[*Fang+, PRD, 2014*]



Candidate sources: 3, Tidal disruption events

A star disrupted by SMBH in the galactic center

TDEs as UHECR nuclei

[*BTZ+, PRD, 2017; Guepin+ 2018; Piran+ 2023; Plotko, 2024;*]

Acceleration is possible inside relativistic jets

Prompt emission region: nuclei cannot survive

Low-luminosity TDEs or reverse shock acceleration is possible

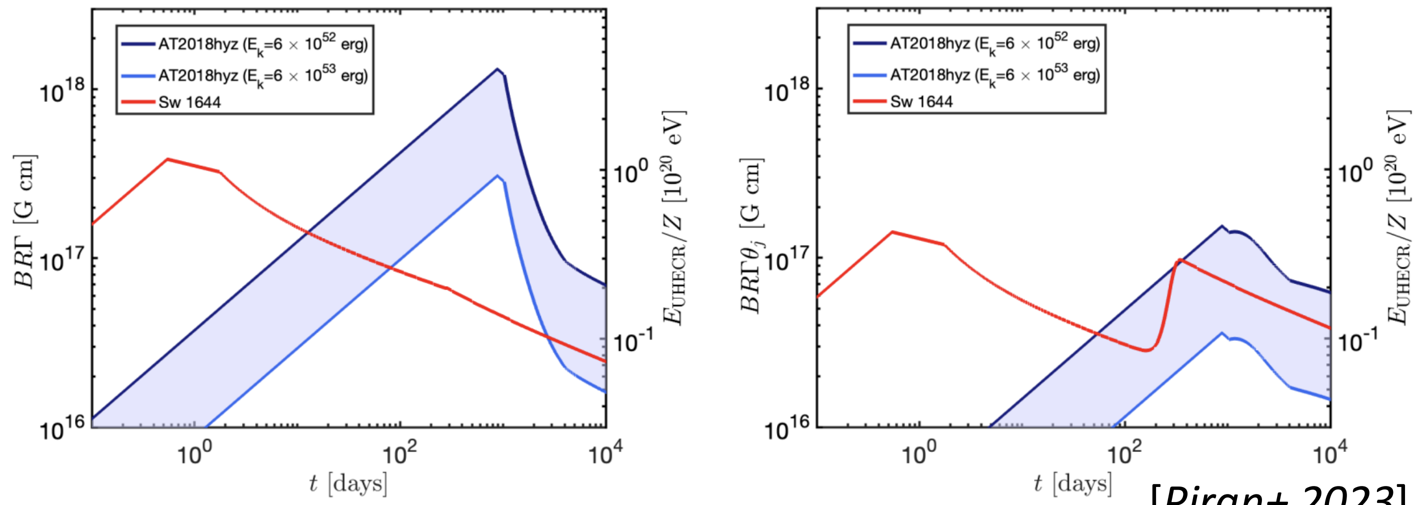
Composition is related to the disrupted stars

Main-sequence star, unlikely

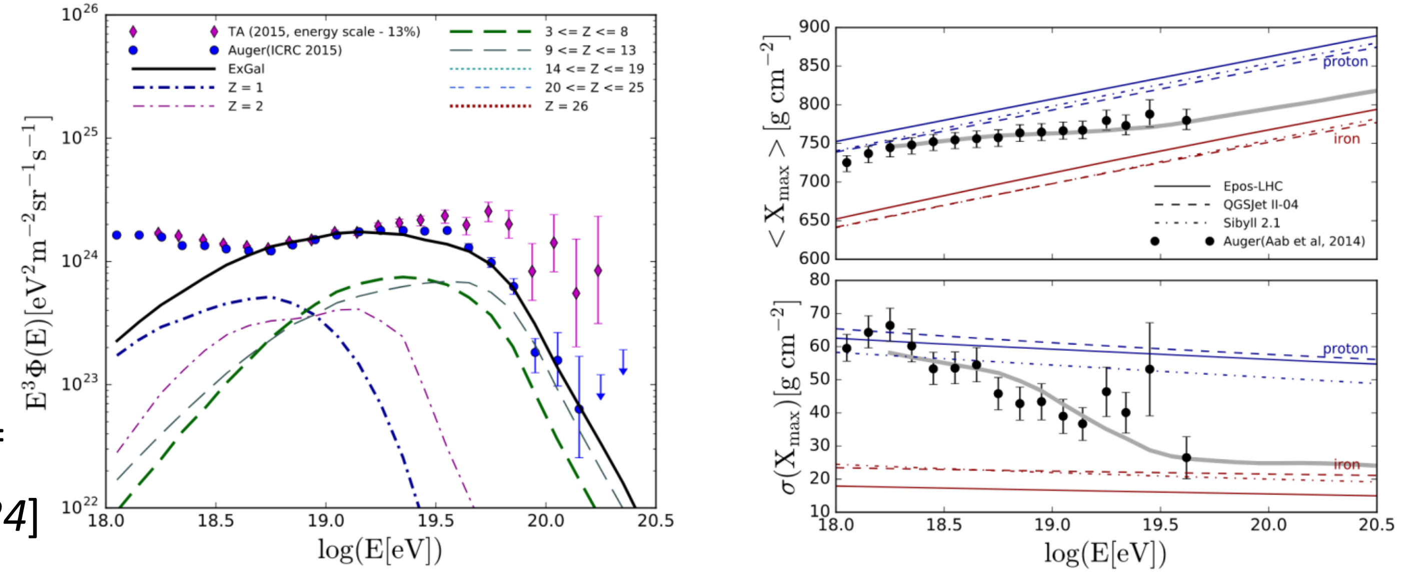
ONeMg-WDs with an initial mass composition f_O = 0.12, f_Ne = 0.76, f_Mg = 0.12

See also [*Plotko, 2024*]

However, ONeMg-WDs are rare (~1/30 CO-WDs)

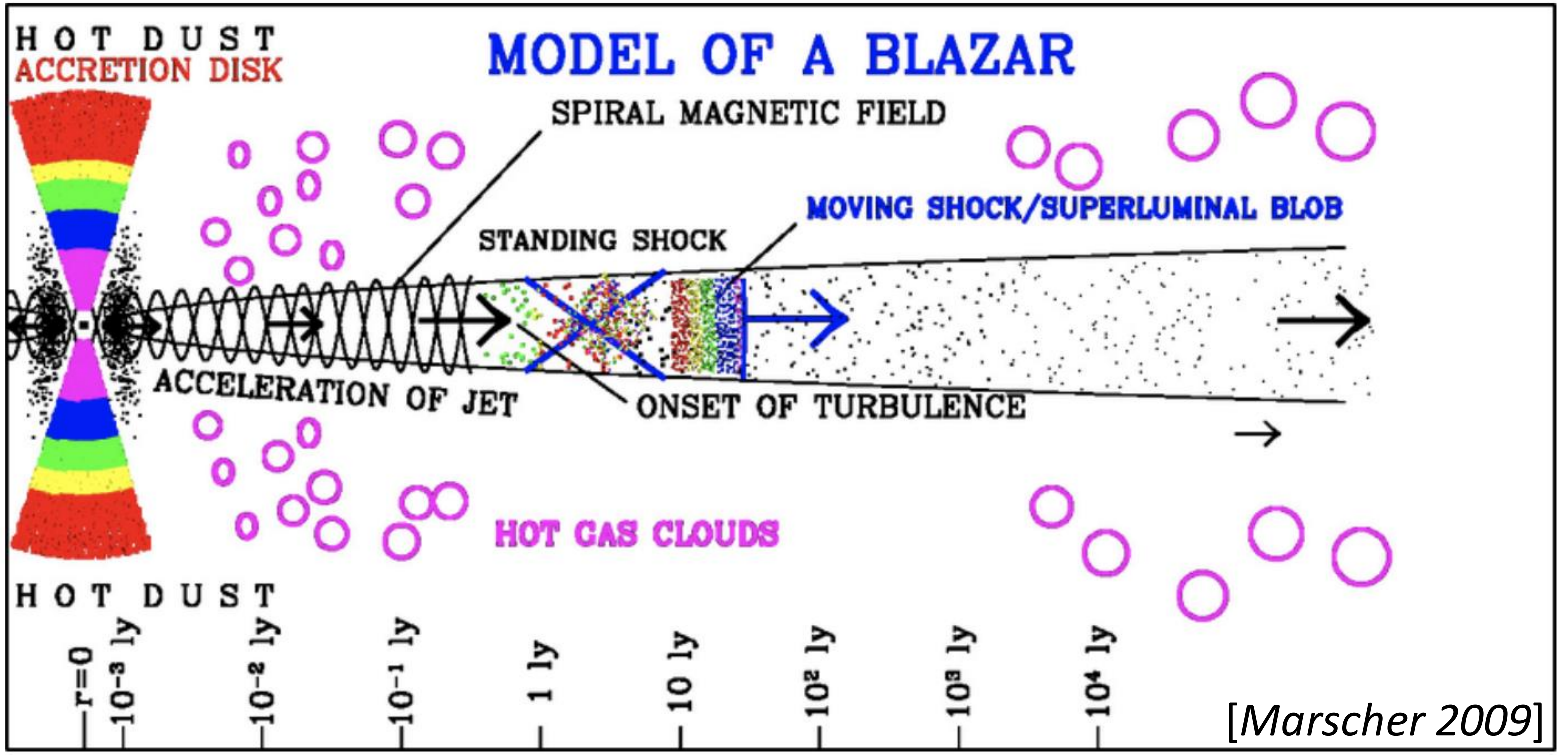


[*Piran+ 2023*]

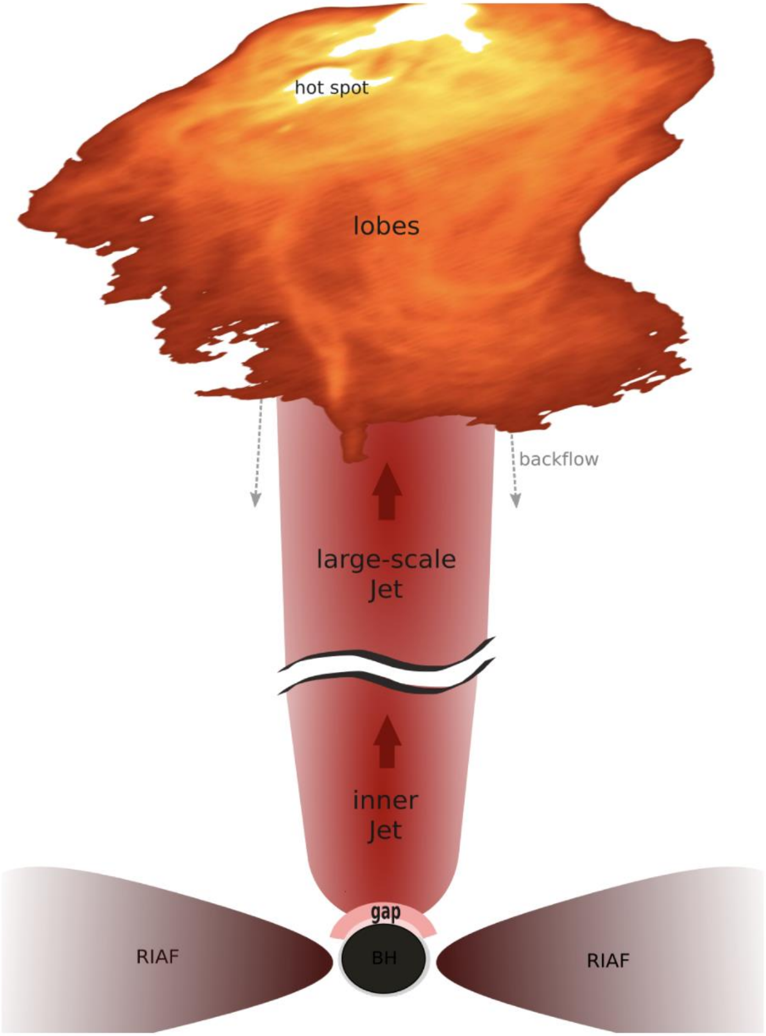


[*BTZ+, PRD, 2017*]

Candidate sources: 4, Active galactic nuclei



[*Marscher 2009*]



Black-hole vicinity	Inner jet (Blazar blob)	Kpc-scale jet	Jet lobes and hot-spot
Γ~1	Γ~10	Γ~ a few	Γ~1

Γ: Lorentz factor

Refs. [Rieger *2021*]

Blazars as UHECR sources

Extremly powerful high-energy sources

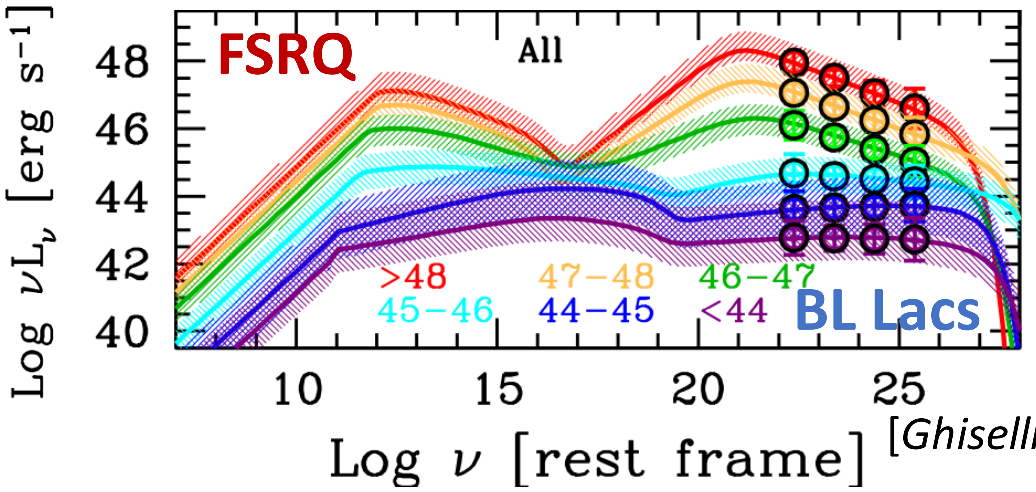
Could accelerate "nuclei" to ultrahigh energies
[*Murase+ 2012, Murase+ 2014, Rodrigues+2019*]

UHECR nuclei are accelerated in BL Lacs, but they are disintegrated in FSRQs

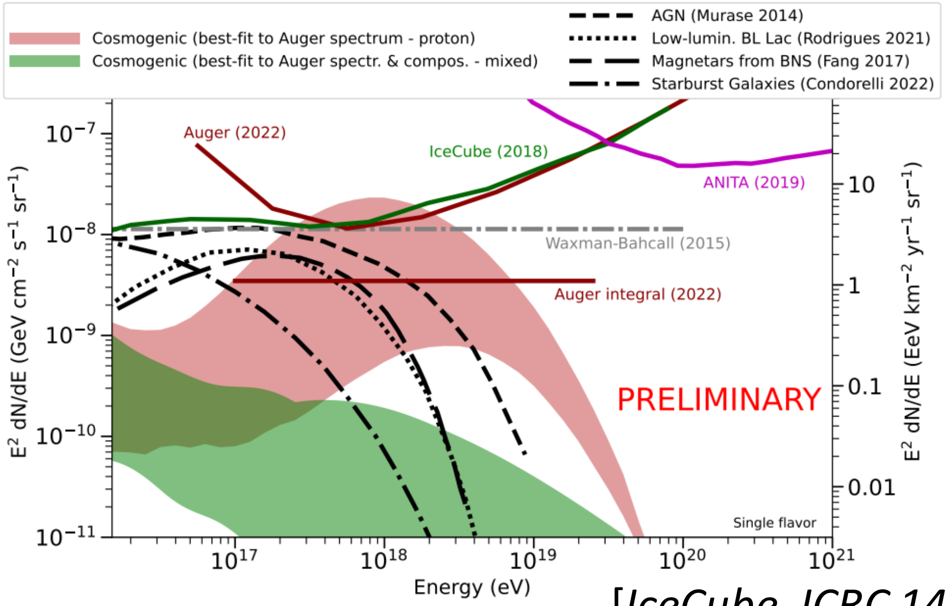
FSRQs are very promising sources of UHE neutrinos

High-energy neutrinos from blazars are constrained by Auger for optimistic models (e.g., s = 2.3)

(model dependence due to spectral indices etc.)

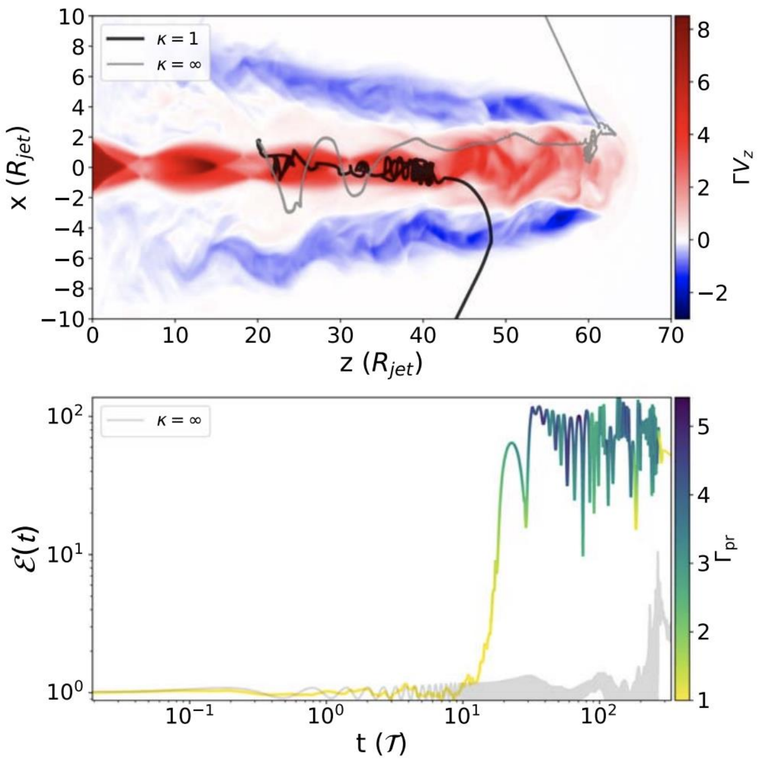


[*Ghisellini+ 2017*]

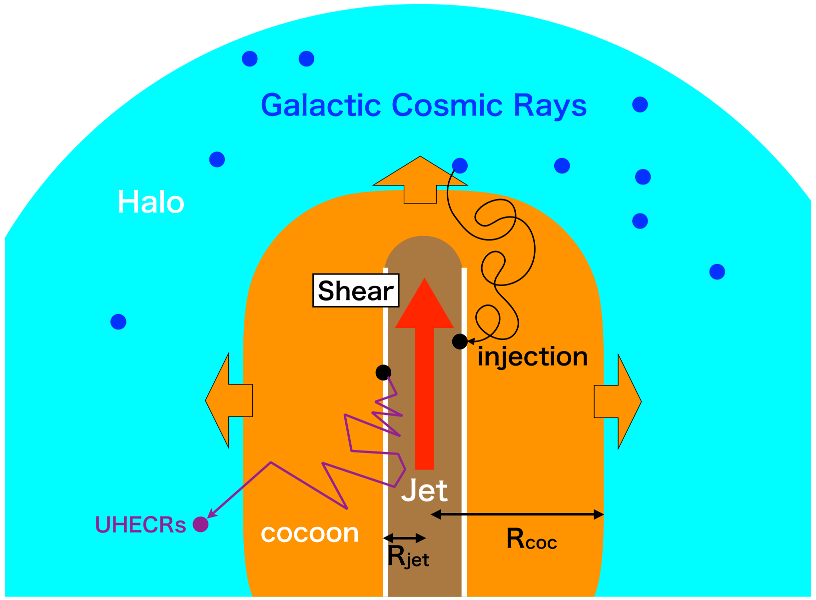


[*IceCube, ICRC 1488, 2023*]

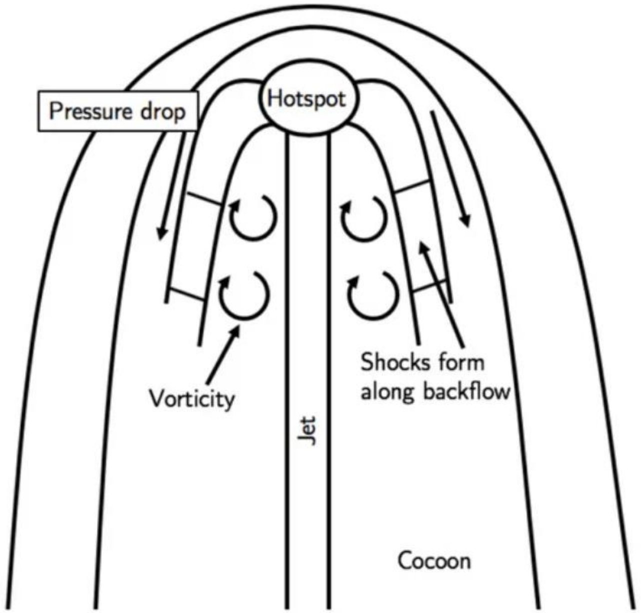
AGN: Acceleration at Kpc-scale jets



[Caprioli 2016, Mbarek&Caprioli, 2021]



[Kimura, Muarse & BTZ, PRD, 2018]



[Bell+ 2019; Matthews+ 2019; Mathhew & Taylar 2023]

Fermi acceleration at the jet-cocoon boundary

Fermi acceleration in backflows in cocoons

One-shot (Espresso) Acceleration

Shear acceleration

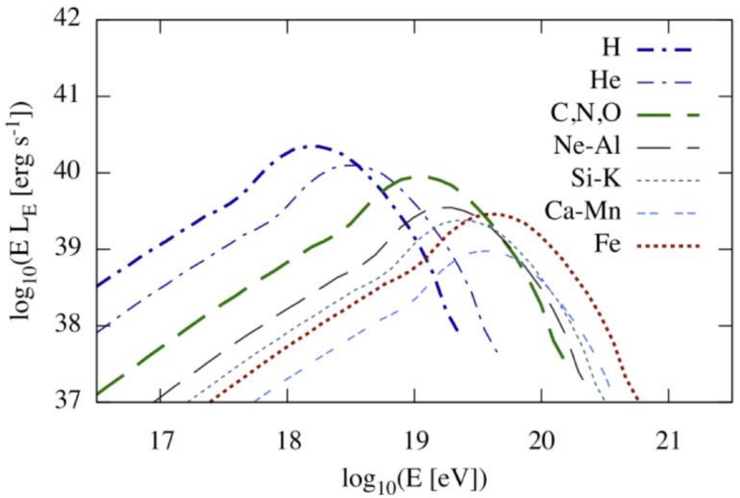
Relativistic jet

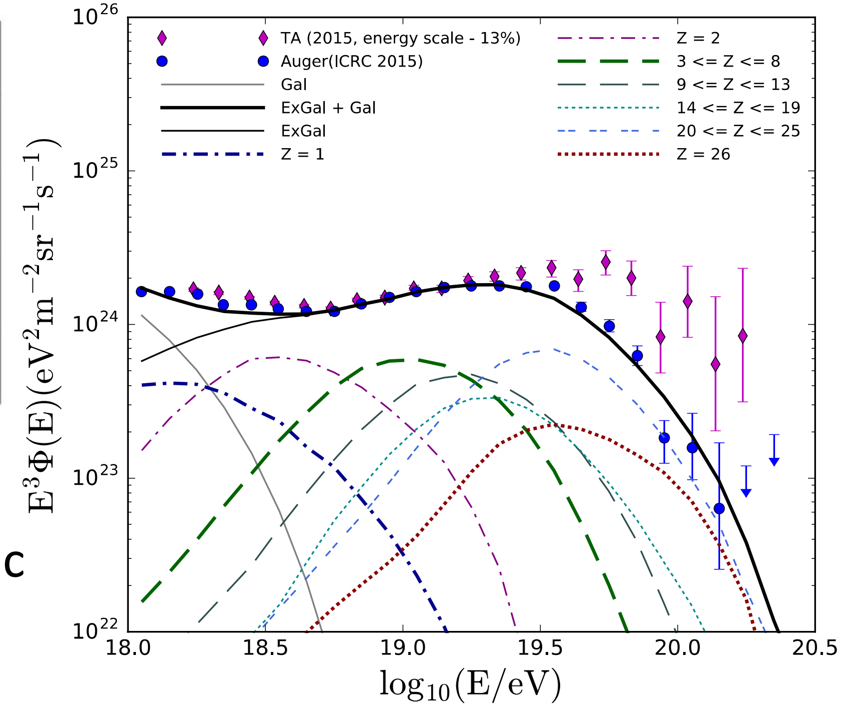
"subrelativistic" jet

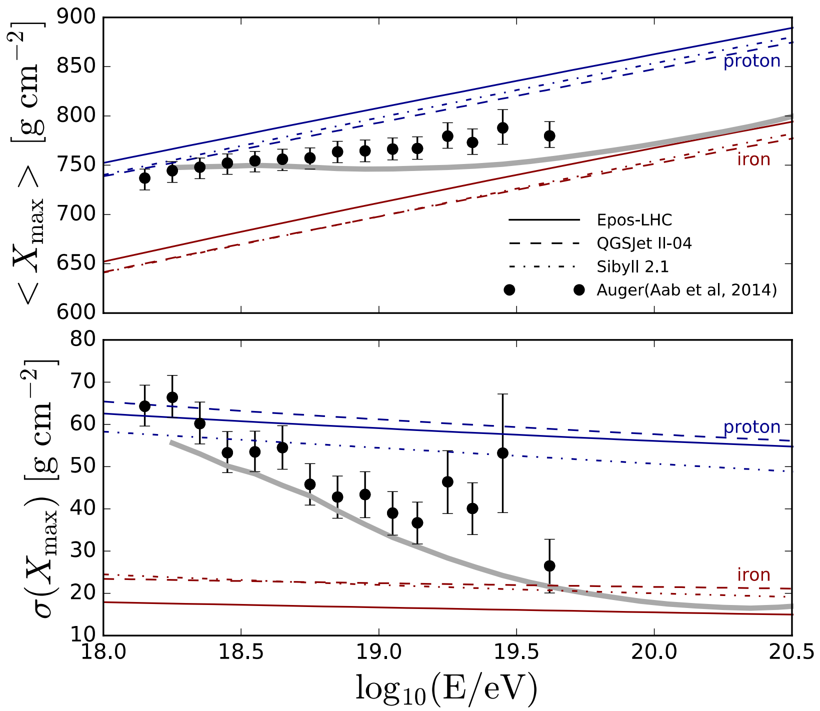
Non-relativistic

See [*Mbarek & Capriolii 2021, Seo+, APJ, 2023*] for both relativistic and nonrelativistic cases

AGN: UHECR composition and spectrum







Reacceleration of Galactic cosmic rays

[*Kimura, Murase & BTZ, PRD, 2018*]

Reacceleration at the same energy, not the same rigidity !!!

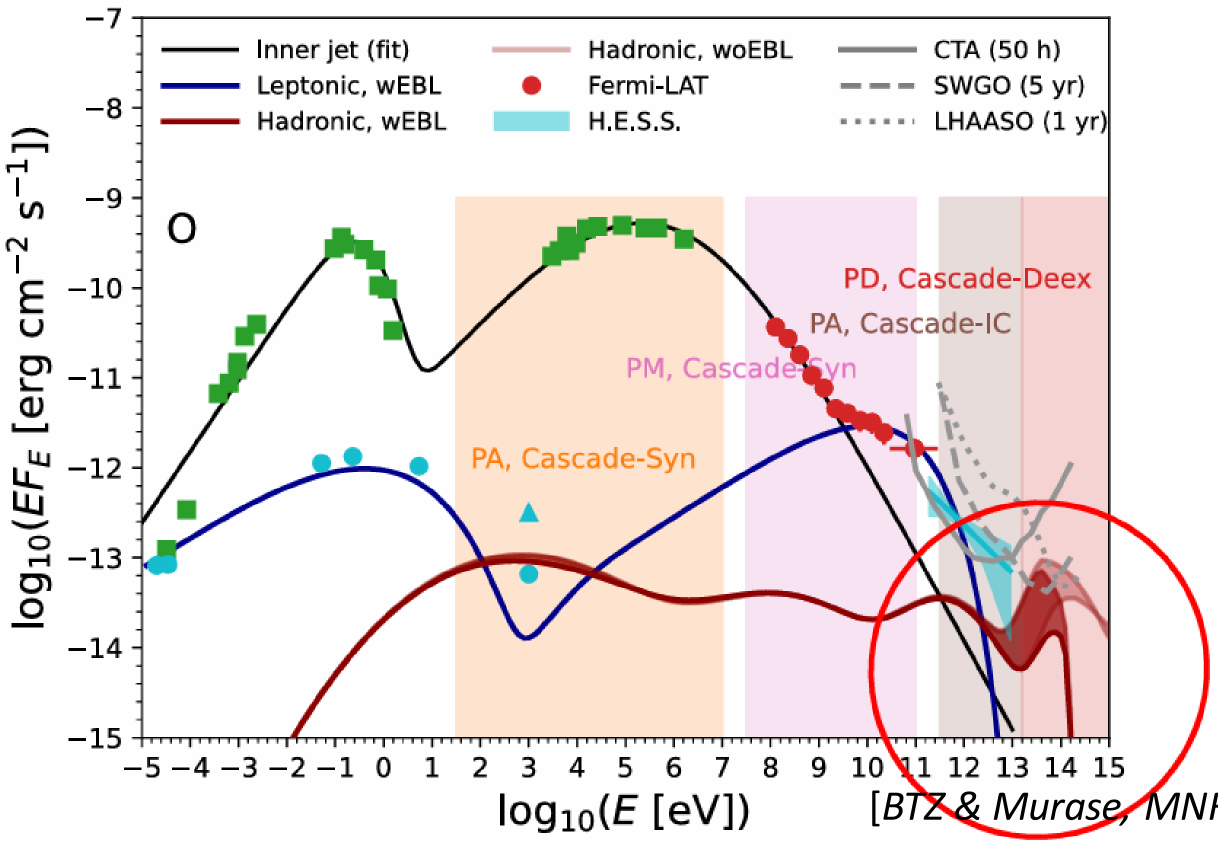
K_H, K_He, K_CNO, K_MgAlSi, K_Fe = 1 : 0.65 : 0.33 : 0.14 : 0.23

Intermediate and heavy nuclei fraction enhanced by a factor of 3

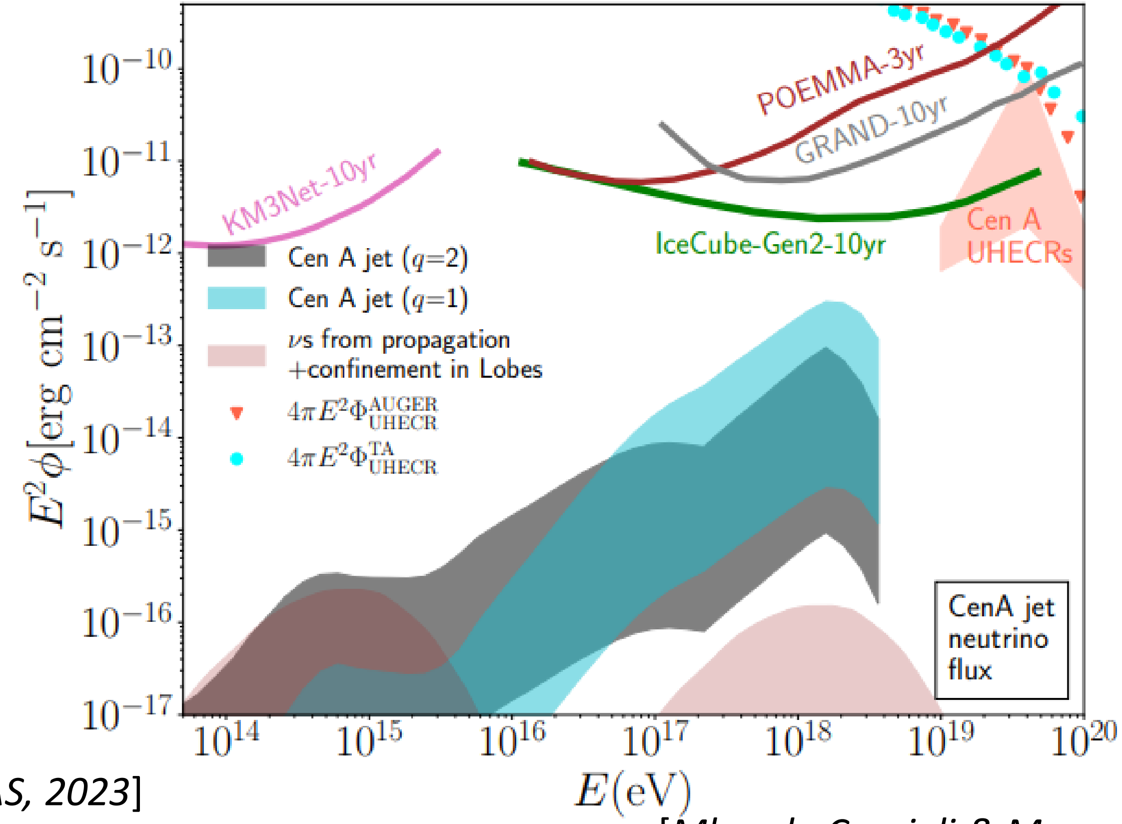
Note: AGN may have a metal enhancement, but some fine tuning is still needed

Multimessenger constraints: Cen A example

Secondary gamma-ray and neutrinos produced inside UHECR sources



[*BTZ & Murase, MNRAS, 2023*]



[*Mbarek, Caprioli & Murase 2024*]

Centaurus A: De-excitation gamma-rays and Bethe-Heitler pairs induced gamma-rays -> CTA south?

Prediction of espresso-shear acceleration, the survival of nuclei keeps the neutrino flux very low, requiring next-generation neutrino detectors!

Summary and perspective

Traditionally, there are two basic requirements of UHECR accelerators

- Energetics
- Accelerate to maximum energy (Hillas condition)

New clues for the sources of UHECRs in the Auger/TA era:

Compostion   Anisotropy   Rigidity distribution   Multimessenger

- Massive stellar deaths: HL-GRBs (Constrained by ν, nuclei "survival"), LL GRBs/engine-driven SNe (Intermediate and heavy mass composition)
- Compact binary mergers: BNS (sources of UH-UHECR nuclei?)
- Magnetars (Testable by UHE ν, heavy composition)
- Tidal disruption events : MS+SMBH(Composition?) CO/ONeMg(rare) WD + IMBH
- Active galactic nuclei: Blazar (FSRQ (Strong ν emitter), BL Lac ("nuclei" could survive)), radio galaxies (Re-acceleration at Kpc-scale jet?)