Insights on super-heavy UHECRs scenario with large-scale structure simulation

(R. Higuchi, E. Kido, and S. Nagataki in preparation)

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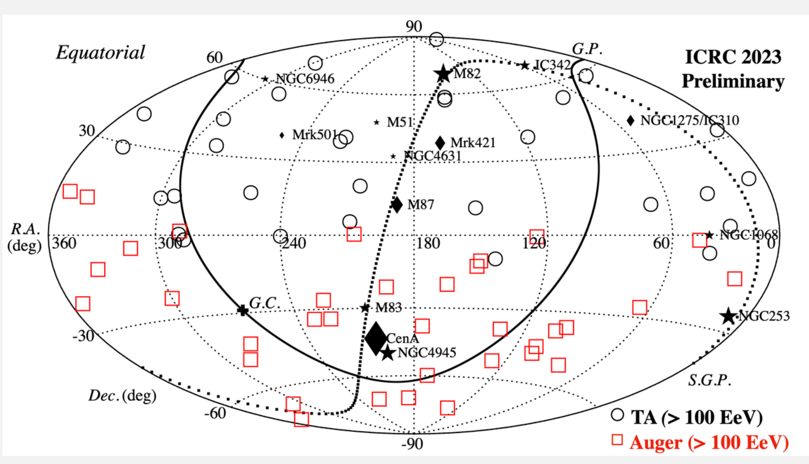
Current observations of arrival directions of ultra-high energy cosmic rays (UHECR) whose energies are above 100 EeV do not show significant anisotropy.
A heavier nucleus (ex. uranium) is known to have a longer propagation length than that of protons or irons. With a convolution of the longer propagation length and homogenous distribution of galaxies in longer distances, we can explain the current absence of UHECR anisotropy above 100 EeV.
Based on this idea, we conduct a mock observation of UHECR above 100 EeV for single-proton, iron, and uranium cases.
We predict the UHECR distribution from the Millenium Run semi-analytic galaxy catalog (Springel et al. 2005) and turbulent extra-galactic magnetic fields. Changing the parameters of UHECR source density and magnetic fields $\alpha = \left(\frac{\lambda}{1\,\mathrm{Mpc}}\right)^{1/2}\left(\frac{B}{1\,\mathrm{nG}}\right)$, we evaluate the anisotropy for each case.
With no magnetic fields, the isotropy excludes single-proton and iron cases. The single-uranium case can explain the current observation with turbulent magnetic fields when the source density is high ($\rho_{\mathrm{source}} = 10^{-3}\ \mathrm{Mpc}^{-3}$). When the turbulent field is strong, the single-iron and uranium cases are consistent with the observation. Any parameter sets (ρ_{source}, α)rejects the single-proton case.
In this study, we set the limit of UHECR source density $\rho_{\mathrm{source}} = 10^{-3}\ \mathrm{Mpc}^{-3}$ and the strength of magnetic fields α for each nucleus case and discuss the scenario of future UHECR observation.

Introduction

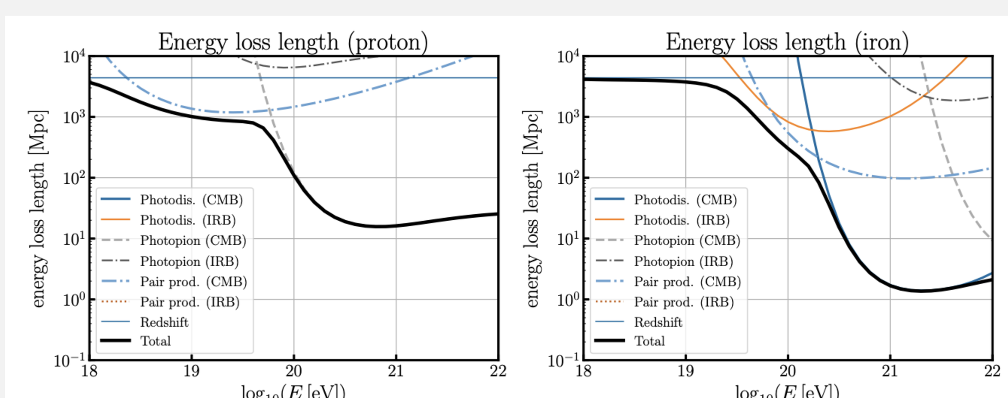
Q1. Anisotropy of UHECRs above 100 EeV?



- Current Telescope Array/Auger UHECR datasets does not show clear anisotropy above 100 EeV? [1].
- **If UHECRs are truly isotropic:**
  - **larger source density?**
  - **heavier mass composition?**
  - **stronger magnetic fields?**

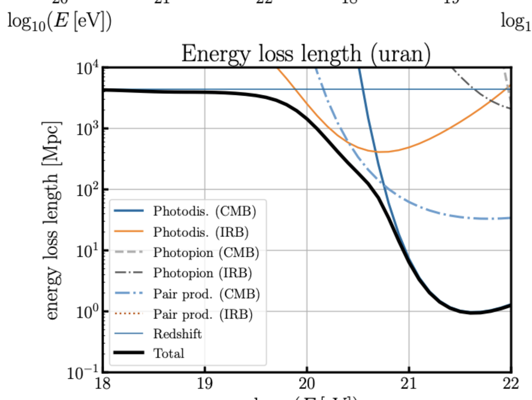
Q2. Super-heavy UHECRs? [2][3]

- Ideas about "super-heavy" UHECRs, whose mass is heavier than iron [2][3].
- r-process nuclei from binary neutron star (BNS) mergers?



Q3. How to constrain?

- Detection completeness of galaxy catalog is a problem, when we assume far sources.
- →Establish a simple method with large-scale structure simulation!



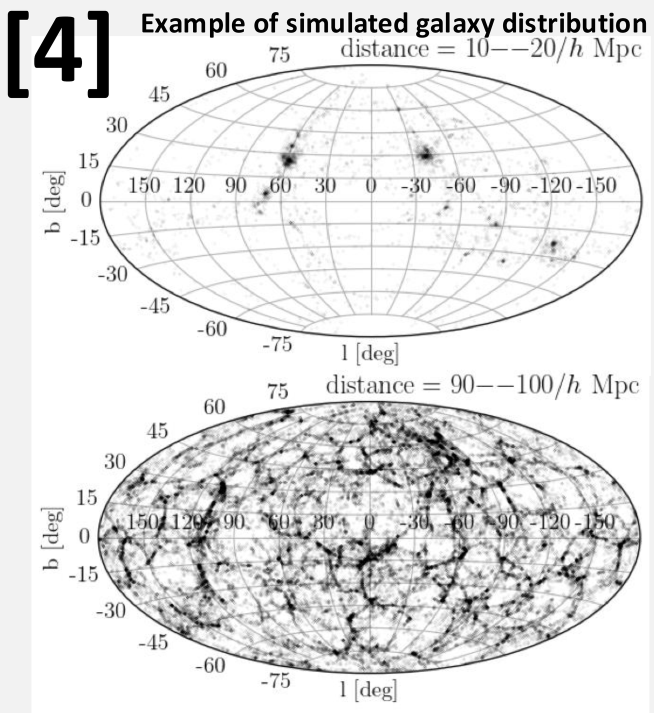
Today's goal:
Establish a method with a large-scale structure simulation, which include super-heavy UHECR scenario, to constrain source & magnetic field parameters.

Models

Millenium Run simulation [4]

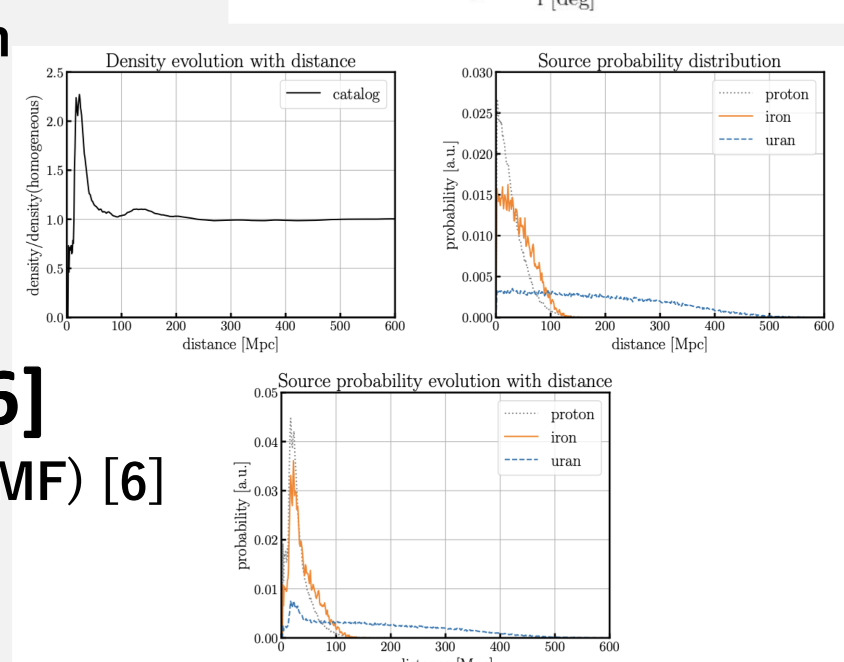
- a simulated galaxy catalog based on the semi-analytical model
- ΛCDM simulation in a cube with 500h−1 Mpc size
- To enlarge the volume of the simulation, we connect 2^3 boxes

Example of simulated galaxy distribution



UHECR Propagation [5]

- Calculation for energy loss length with CRPropa 3.2 [5]
- Source distribution with single-proton/iron/uranium case(right figure)



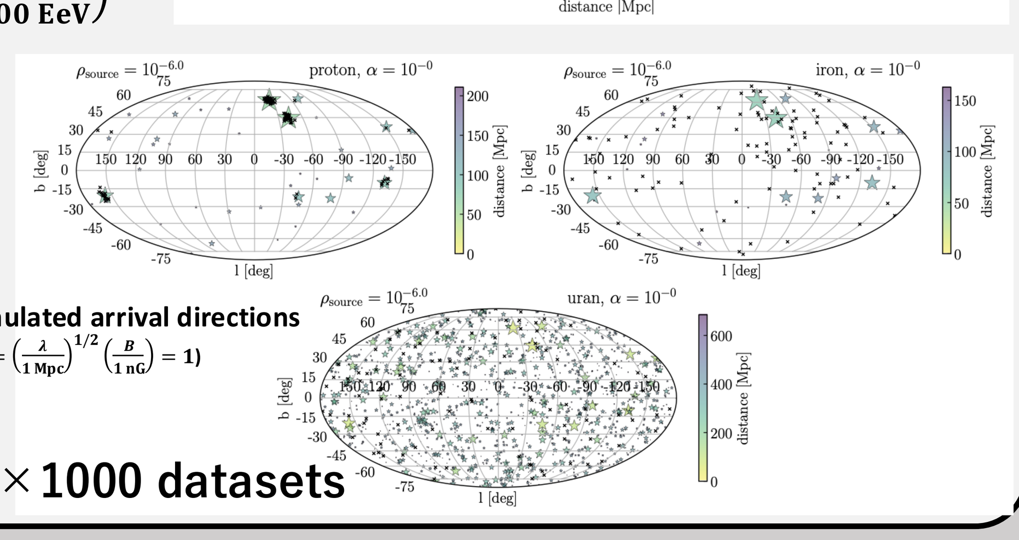
Turbulent magnetic field [6]

- Isotropic turbulent magnetic fields (MF) [6]
- Scattering angle:
  - $\theta \propto Z\left(\frac{r}{10\,\mathrm{Mpc}}\right)^{1/2}\left(\frac{\lambda}{1\,\mathrm{Mpc}}\right)^{1/2}\left(\frac{B}{1\,\mathrm{nG}}\right)\left(\frac{E}{100\,\mathrm{EeV}}\right)^{-1}$

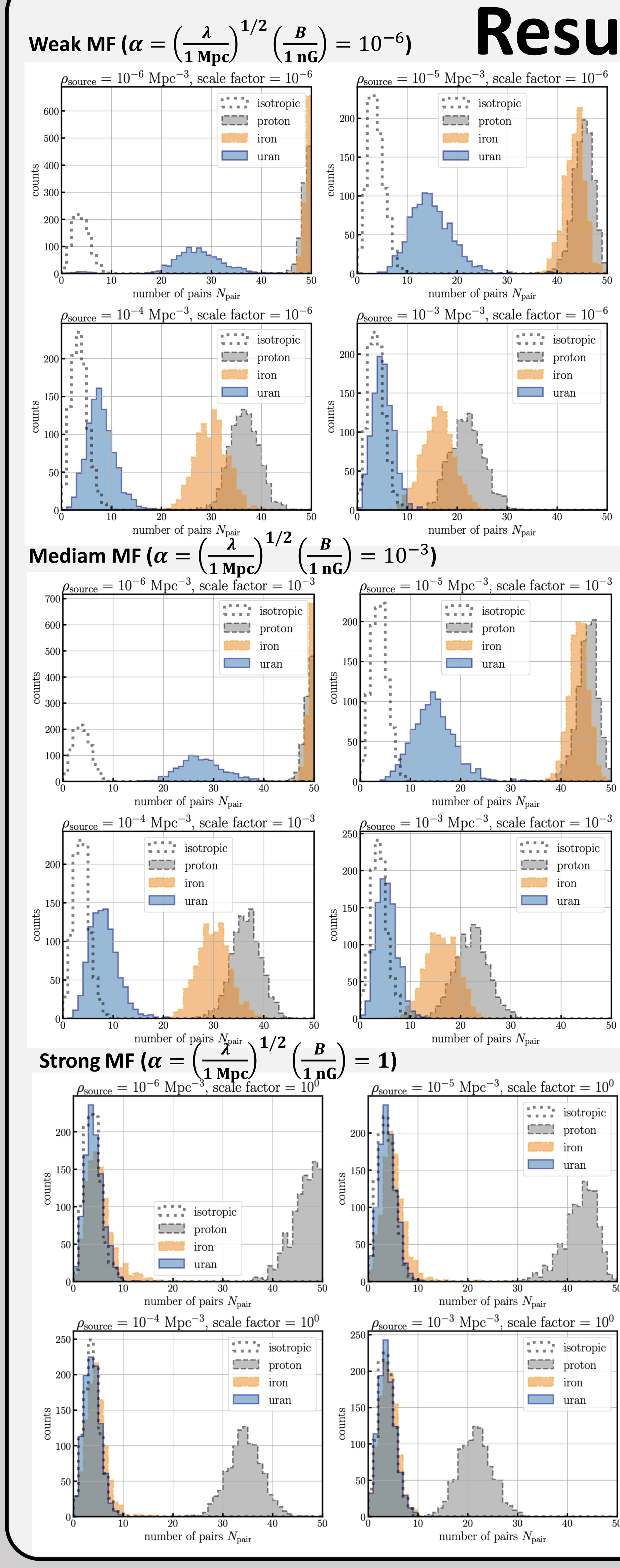
Simulated events

- Input parameters:
  - Source density: ρ_{source}
  - Strength of magnetic field:
    - $\alpha = \left(\frac{\lambda}{1\,\mathrm{Mpc}}\right)^{1/2}\left(\frac{B}{1\,\mathrm{nG}}\right)$
- 100 UHECR events over full-sky ×1000 datasets

Simulated arrival directions ($\alpha = \left(\frac{\lambda}{1\,\mathrm{Mpc}}\right)^{1/2}\left(\frac{B}{1\,\mathrm{nG}}\right) = 1$)



Results



Evaluation of anisotropy

- We count the number of multiplets N_{pair} for each dataset.

Range of parameters:

- Change the parameter sets:
  - source density
    - $\rho_{\mathrm{source}} = 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3}$
  - Strength of magnetic field:
    - $\alpha = \left(\frac{\lambda}{1\,\mathrm{Mpc}}\right)^{1/2}\left(\frac{B}{1\,\mathrm{nG}}\right) = 10^{-6}, 10^{-3}, 1$

Result 1: Mass composition

- Single-proton case cannot reproduce isotropy in any case.
- Single-uran case can reproduce isotropy with wider area of parameter space.
- single-iron case can reproduce isotropy, only when turbulent MF is strong.

Result 2: Source density

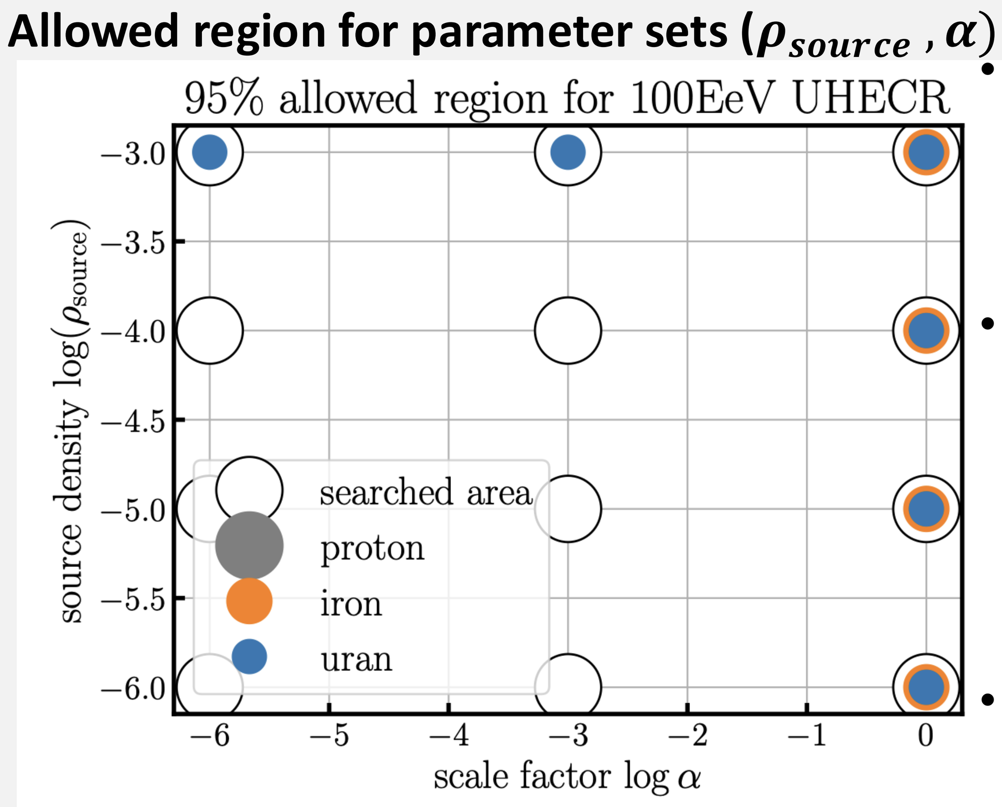
- High-source density case ($\rho_{\mathrm{source}} = 10^{-3}\ \mathrm{Mpc}^{-3}$) can explain the isotropy, when MF is weak and single-uran case.
- When MF is strong, single-iron/uran cases can survive independent on source density.

Result 3: Magnetic Fields

- MF should be strong, if we assume lighter mass composition.
- In this study, we cannot distinguish single-iron/uran cases when MF is strong.

Summary & To do next

Allowed region for parameter sets (ρ_{source}, α)



Summary

- We conduct the self-consistent simulation for light/heavy/super-heavy nuclei to explain the distribution of UHECRs above 100 EeV.
- super-heavy UHECR can reproduce the isotropy, due to the large scattering angle by magnetic fields & longer propagation distance.

To do next

- Consistency check with [2]Farrar 2024 & [3]B.Zhang+2024
- How to distinguish heavy/super-heavy nuclei?
- Discussions on GMF structure & harmonic analysis

References
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[6] Bray, J. D., & Scaife, A. M. M. 2018, The Astrophysical Journal, 861, 3