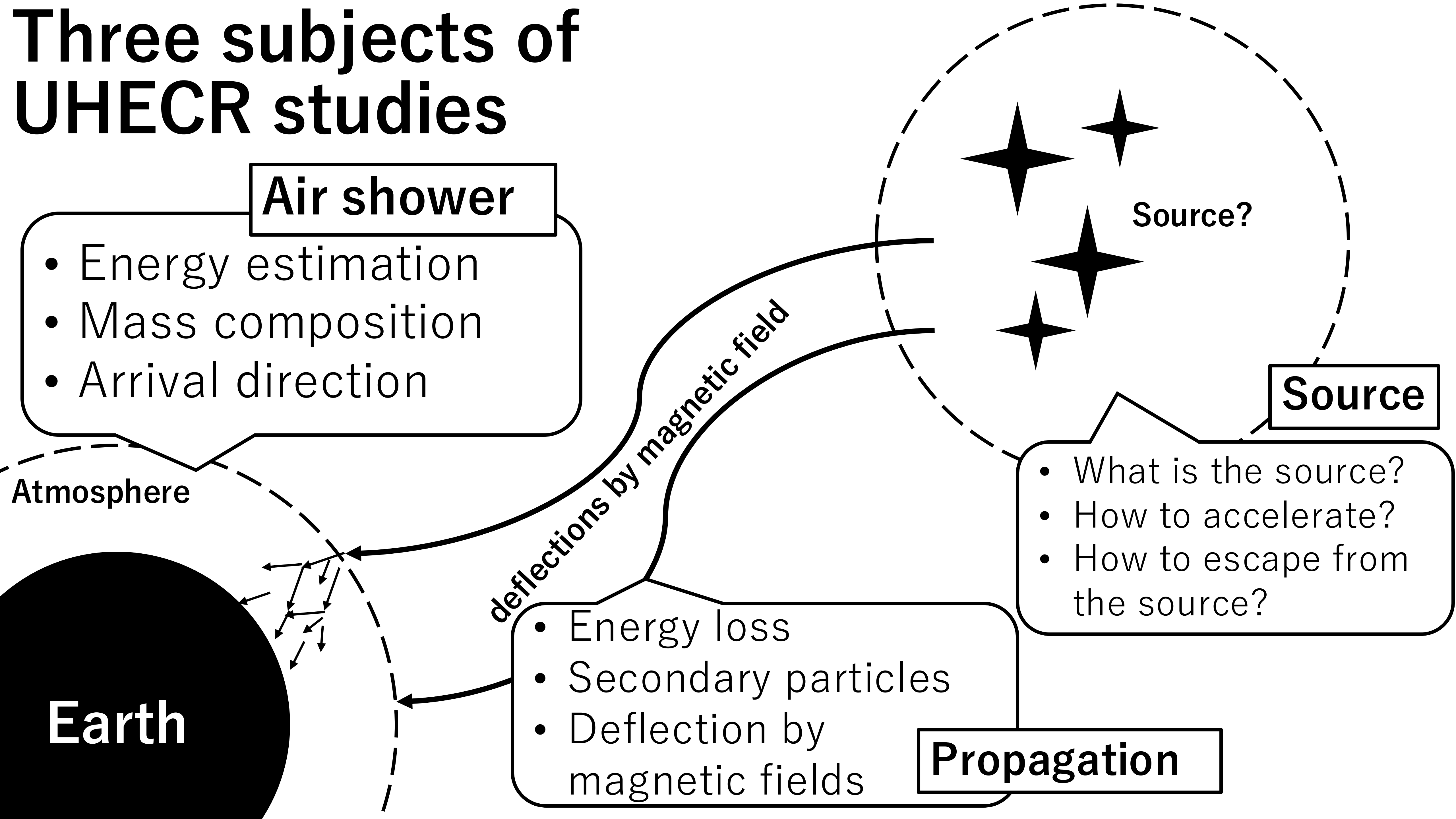
Constraints on super-heavy UHECR source model with a large-scale structure simulation

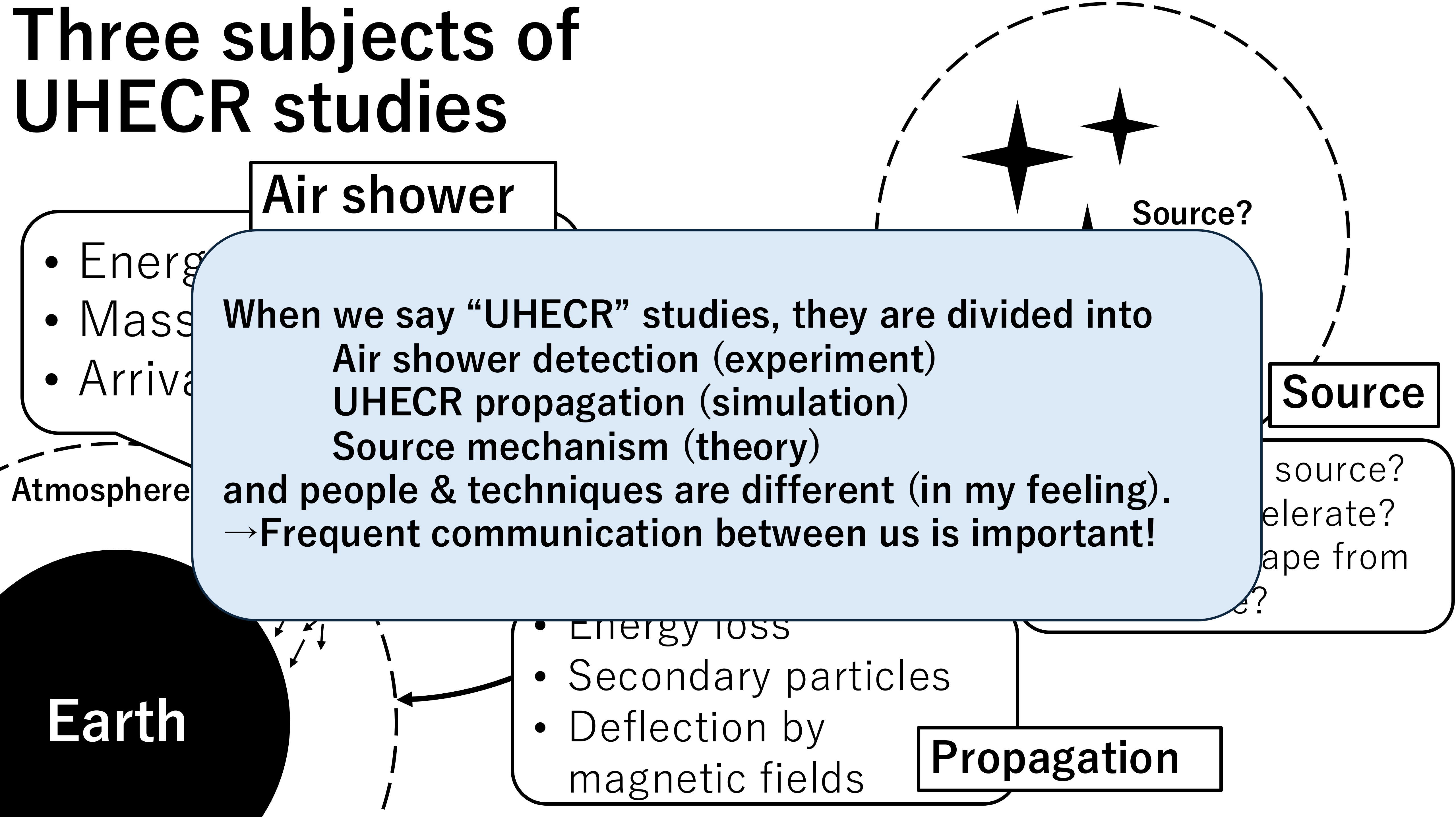
Ryo Higuchi (RIKEN)
with Eiji Kido
and Shigehiro Nagataki

based on Higuchi et al. in prep.

Three subjects of UHECR studies



Three subjects of UHECR studies



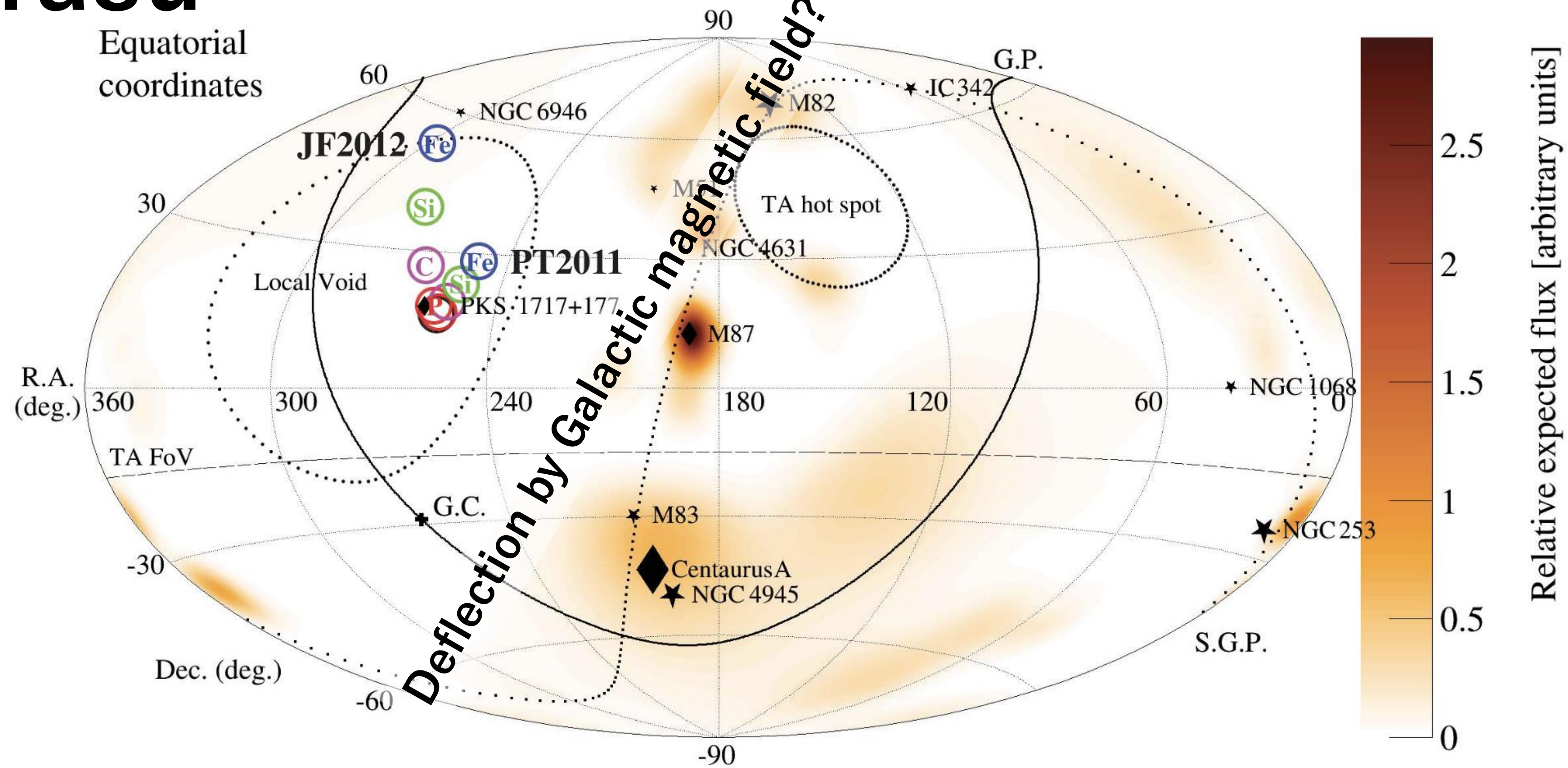
When we say "UHECR" studies, they are divided into

Air shower detection (experiment)
UHECR propagation (simulation)
Source mechanism (theory)

and people & techniques are different (in my feeling).
→Frequent communication between us is important!

Highest energy particle in TA experiment "Amaterasu"

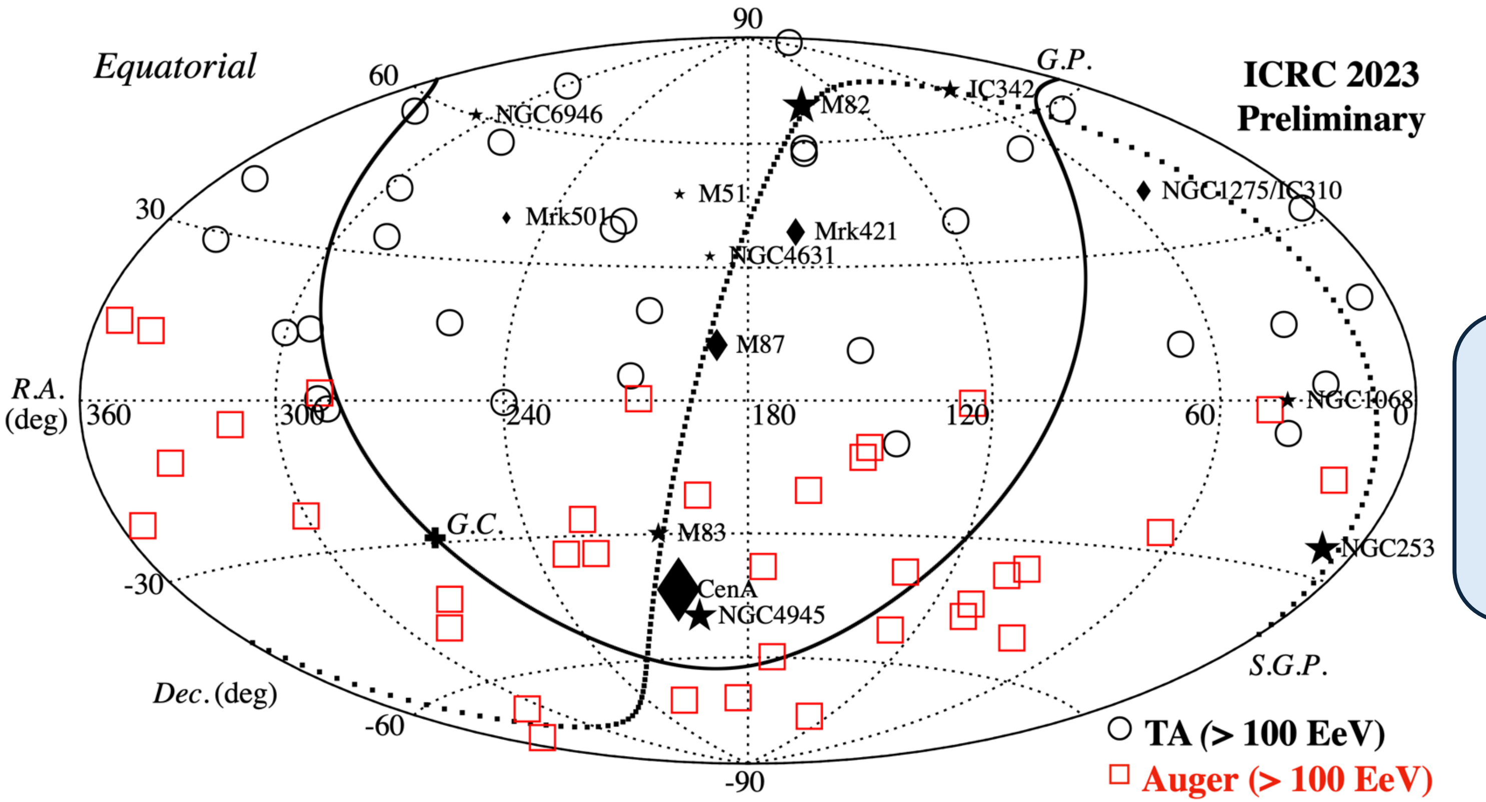
TA collaboration, Science, Volume 382, Issue 6673, pp. 903-907 (2023)



- Highest energy UHECR in TA experiment arrived on May 27th, in 2021(244 EeV, second highest to "Oh-My-God" particle).
- Where does it come from?
  - Lack of mass information & large uncertainty between GMF models.
- **UHECR above 100 EeV is an interesting topic today!**

Arrival directions of UHECRs above 100EeV

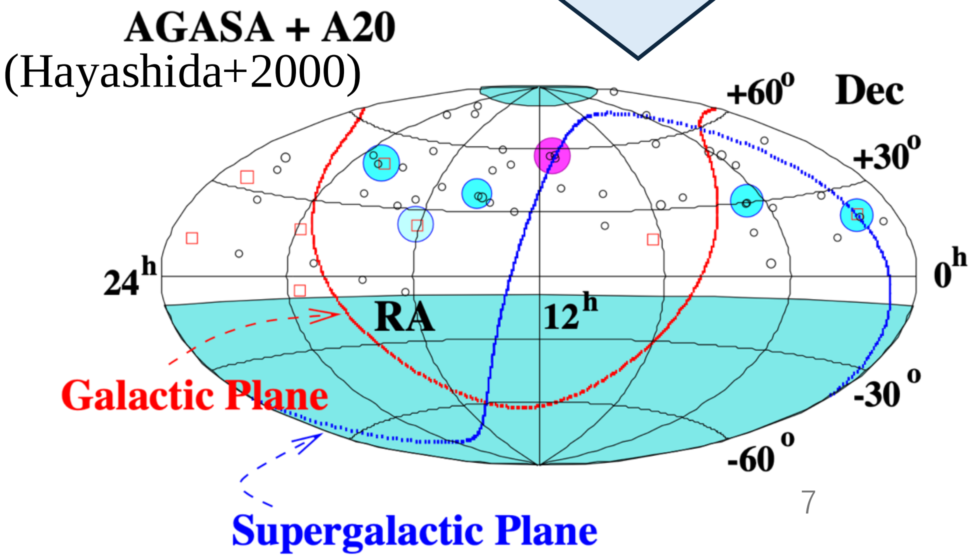
The correlation with source was expected for higher energy…



T. Fujii 2024 (ICRC2023)

- (Currently)no significant anisotropy
- **Doublet/triplet** exist, but consistent with isotropy.

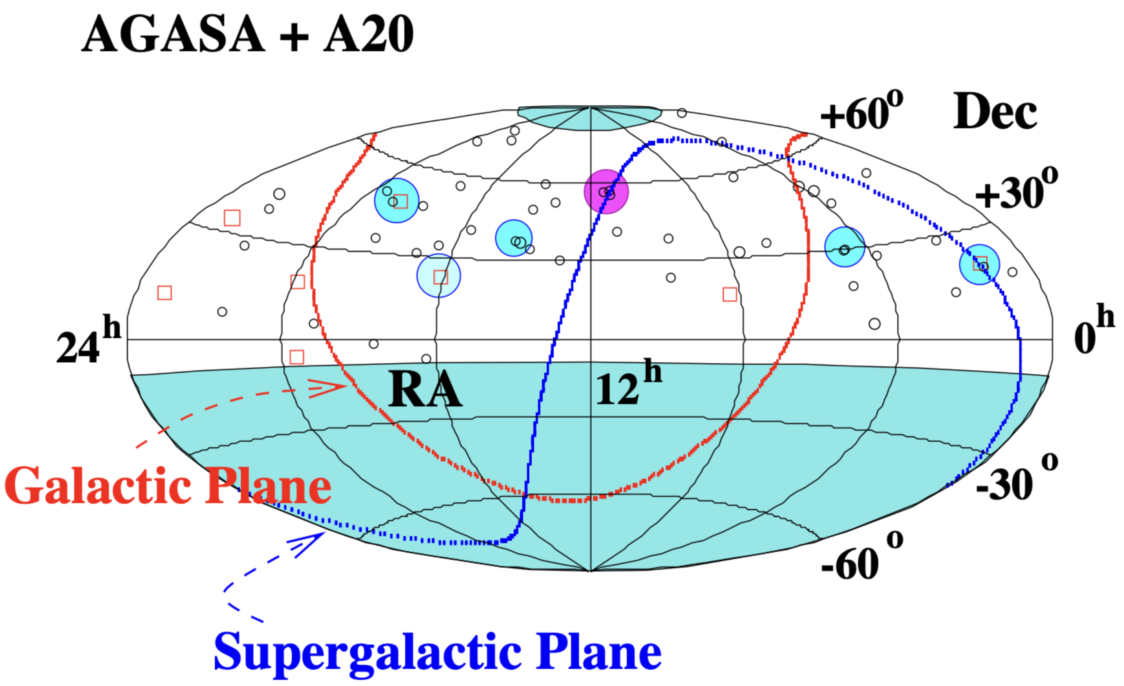
The situation looks the same as 20yrs ago, but **energy is ×10 higher** & we know UHECRs seems **not only protons**!



- Interpretation：
  - ① **higher source density**
  - ② **stronger magnetic field**
  - ③ **heavier mass composition**
- …How to separate the scenario?

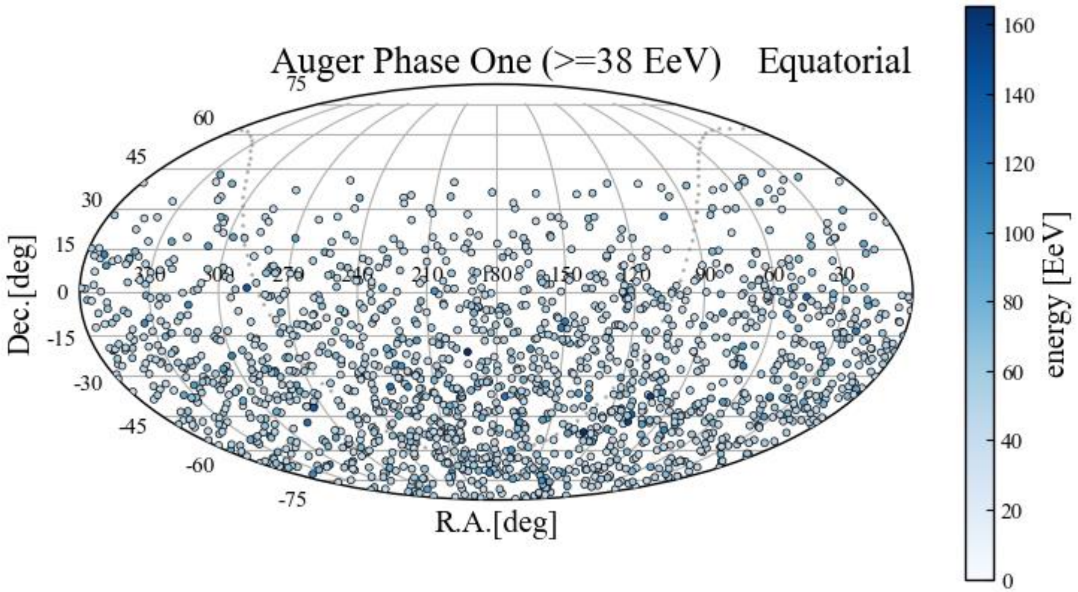
Small-scale anisotropy

- Before TA & Auger experiment, there was an expectation to detect a **small-scale anisotropy (multiplet)**
  - Higher-energy UHECRs are less deflected by magnetic field, and concentrates around a point-source
  - **The situation is totally different!**
- Still works as a test for anisotropy?
  - Today we adapt **a number of multiplets** as a test parameter.

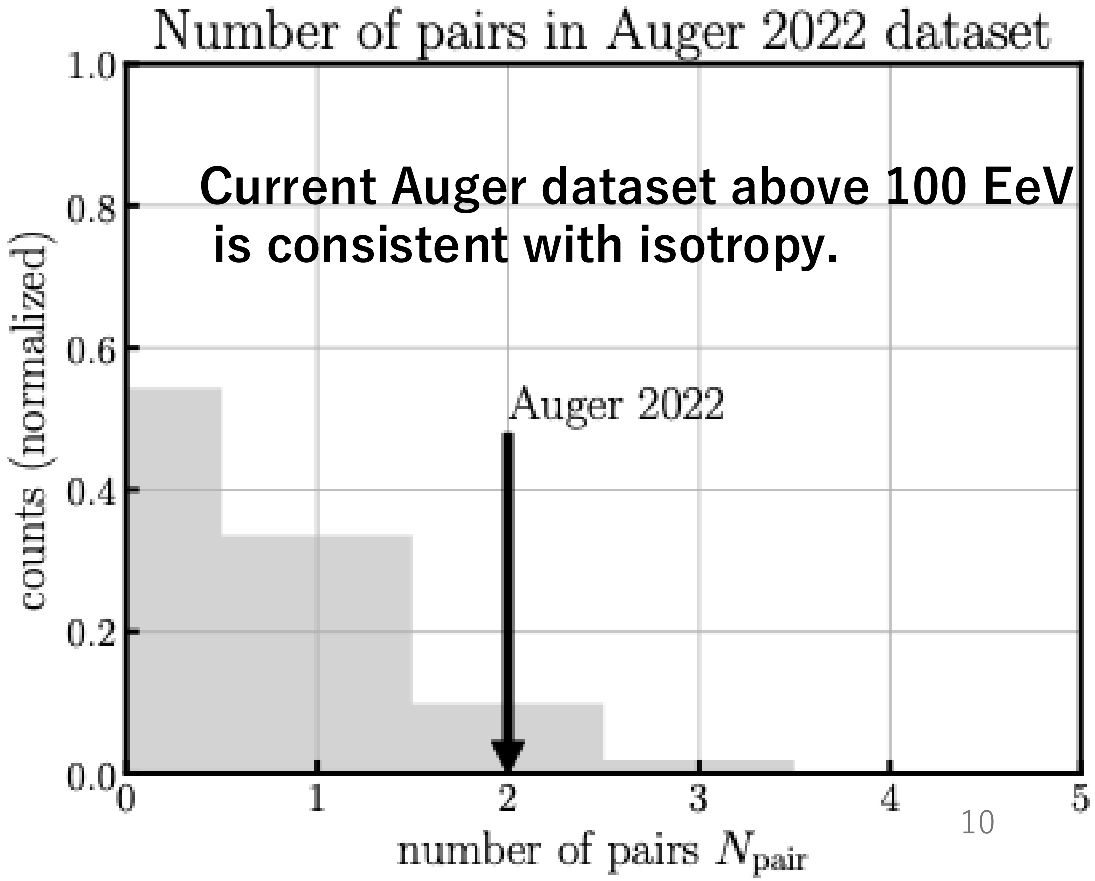


(Hayashida+2000)

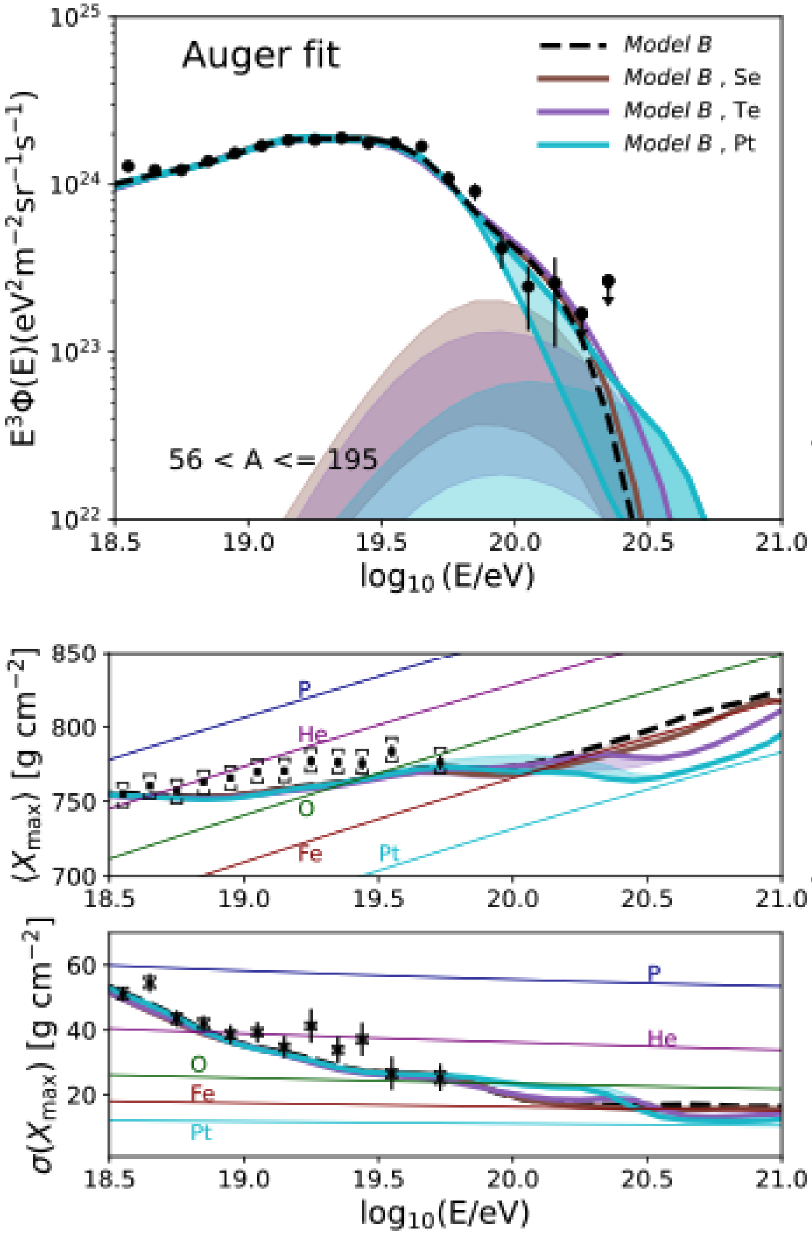
How isotropic the distribution of UHECR above 100 EeV be?



- Public dataset of Auger experiment (Auger collaboration 2022)
- Evaluation with:
  - **number of multiplets** (within 3 deg):
  - Comparison with isotropic MC datasets



“Super-heavy” UHECR ? (Farrar 24,Zhang+24)



(Zhang+24, arXiv:2405.17409)

- UHECRs include r-process nuclei heavier than iron?
  - Much larger deflection by magnetic field!
  - +longer propagation distance
  - source: BNS merger?
- Observational side:
  - We cannot constrain from current statistics…
  - Especially, **we don’t have mass information above 100 EeV**
  - Just one of the theoretical possibility!

Our work

Questions:

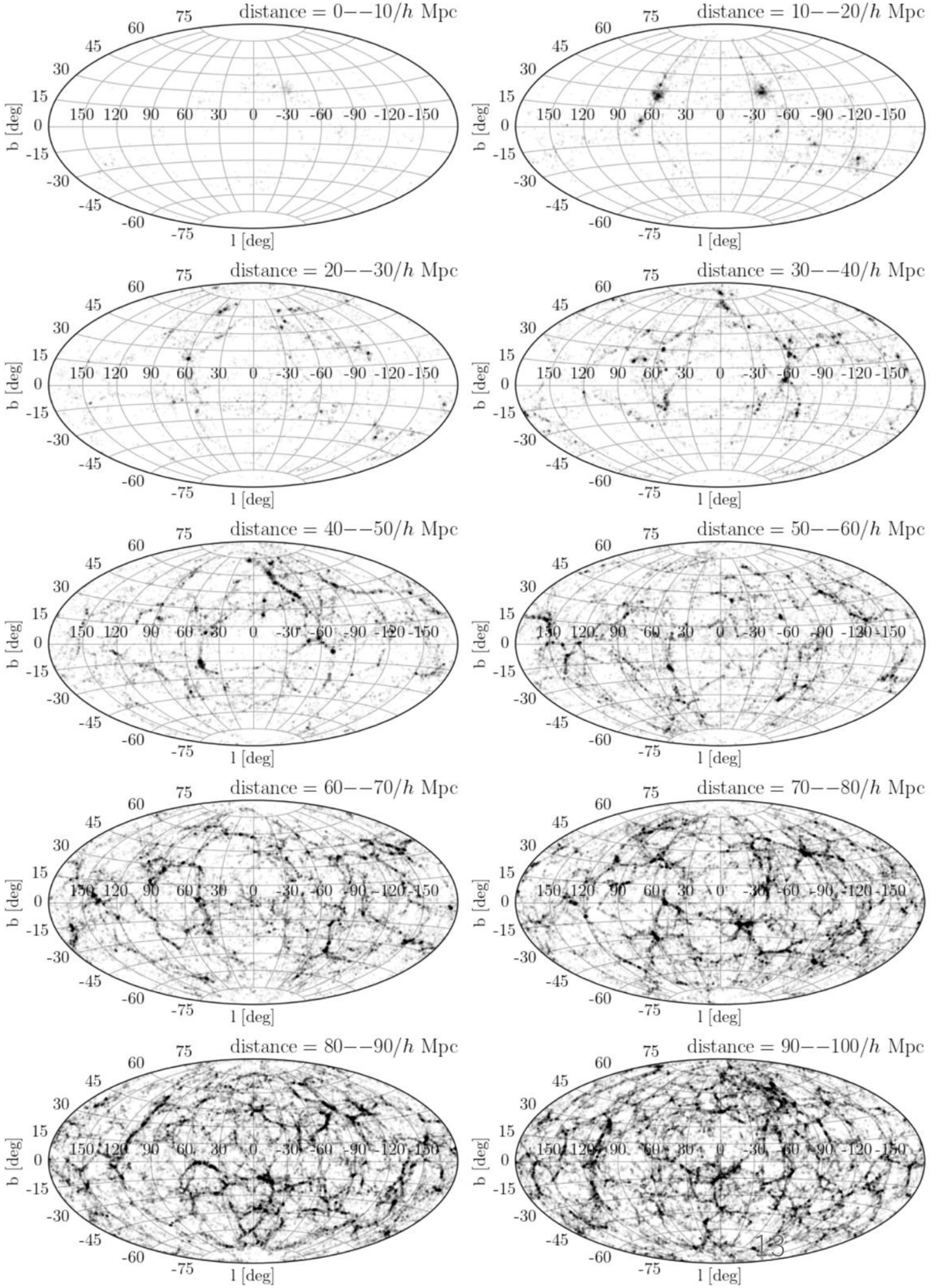
- How to explain **non-anisotropic UHECR distribution** above 100EeV?
- How to test the **super-heavy UHECR scenario**?
  - Detection completeness of galaxy catalog is a problem, when we assume distant sources.

Goal:

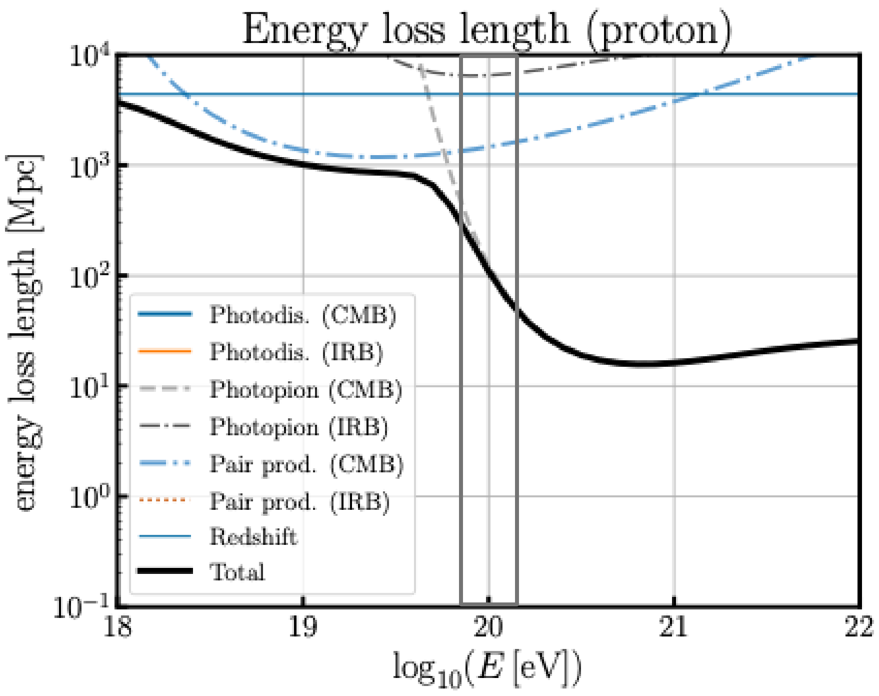
- Establish a simple method
  - **with a large-scale structure simulation,**
  - **which include super-heavy UHECR scenario,**
  - **to constrain source & magnetic field parameters.**

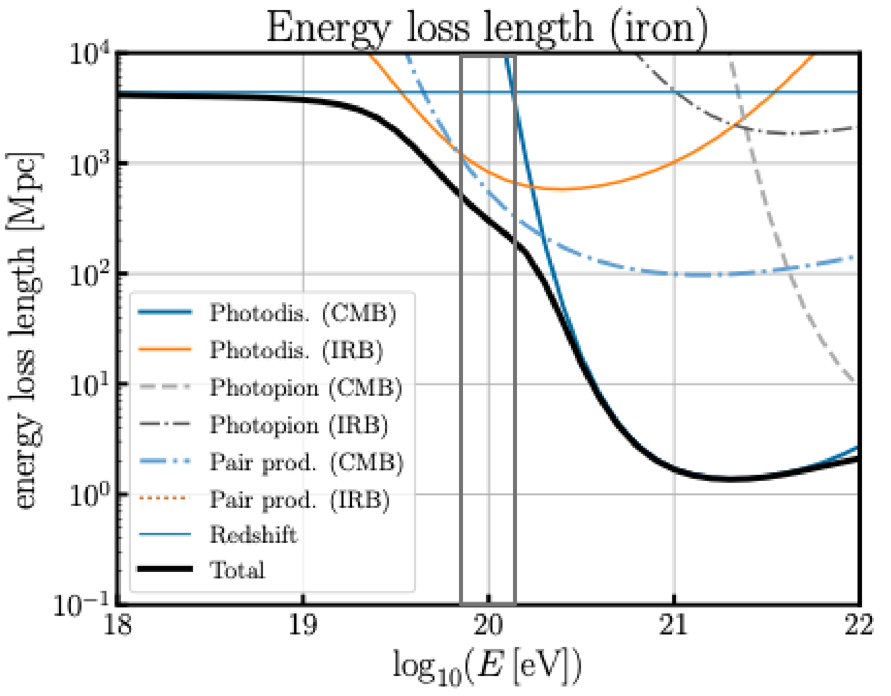
Catalog: Millenium Run

- Today, we focus on a simple (and less-model dependent) discussion based on **simulated galaxy catalog:**
  - **Millenium Run** (Springel et al. 2005)
  - Semi-analytical galaxy model
  - Large-scale structure inside the cube (500 Mpc/h)^3
- The cluster can be seen around 10-20 Mpc.
- The distribution of more distance galaxies becomes more isotropic.

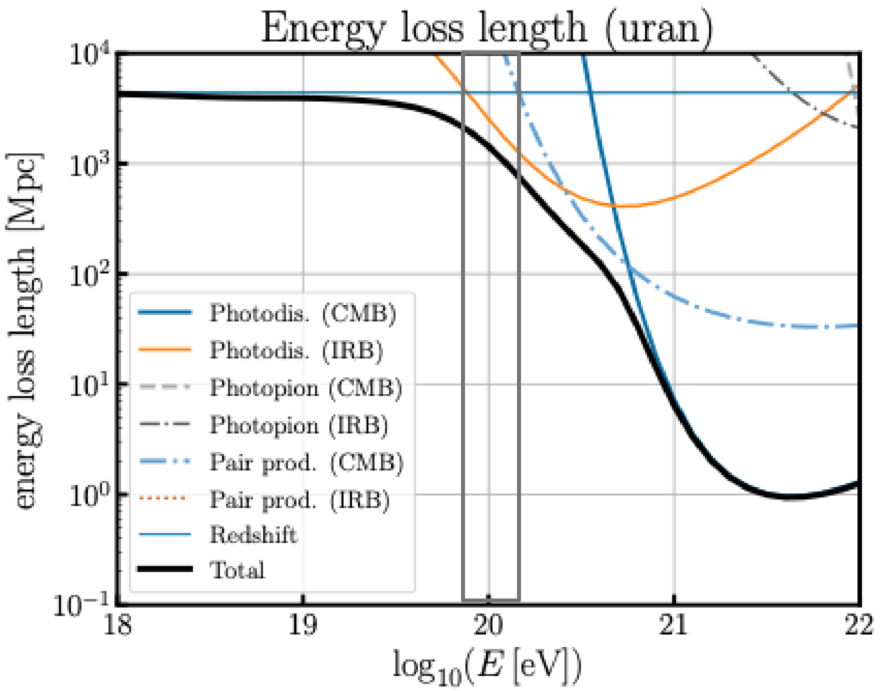


Energy loss length

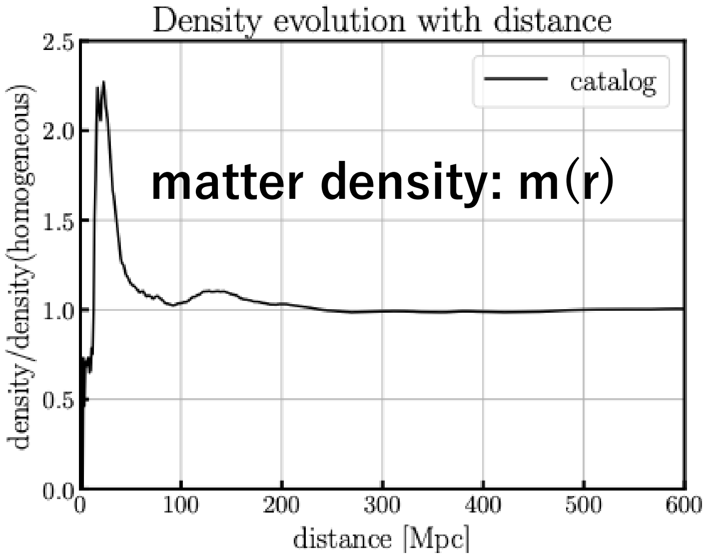




- Evaluation of energy loss length
  - propagation code: CRPropa
  - calculation of uran's cross-section: TALYS-2.0
- The energy-loss length of uranium is 1 magnitude larger !
- We calculate a distribution of source distance r : $\rho(r)$



Source distribution



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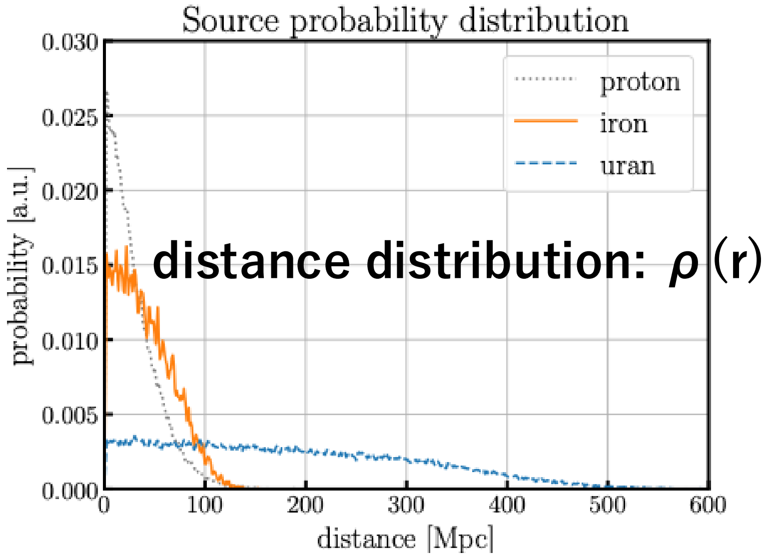

- Calculation of source density distribution $m(r) \times \rho(r)$
- The nearby matter density peak dominate proton/iron source distribution.
- Uranium can reach the Earth over 100 Mpc scale!

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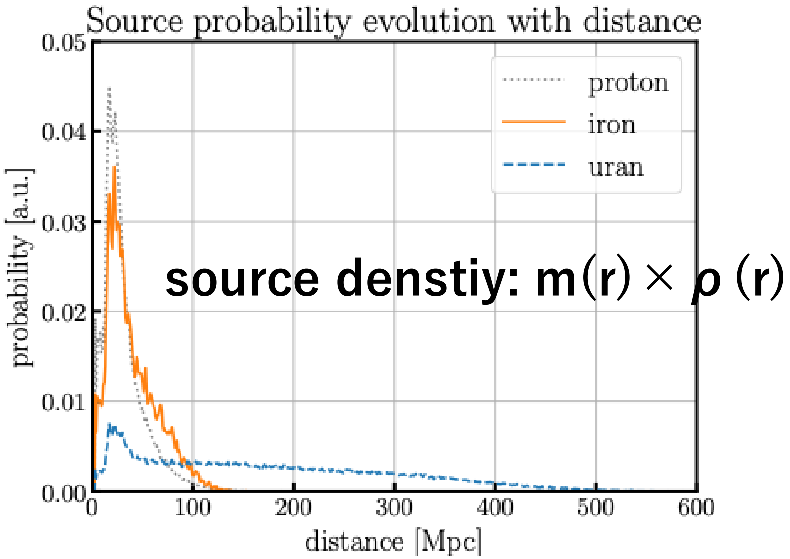
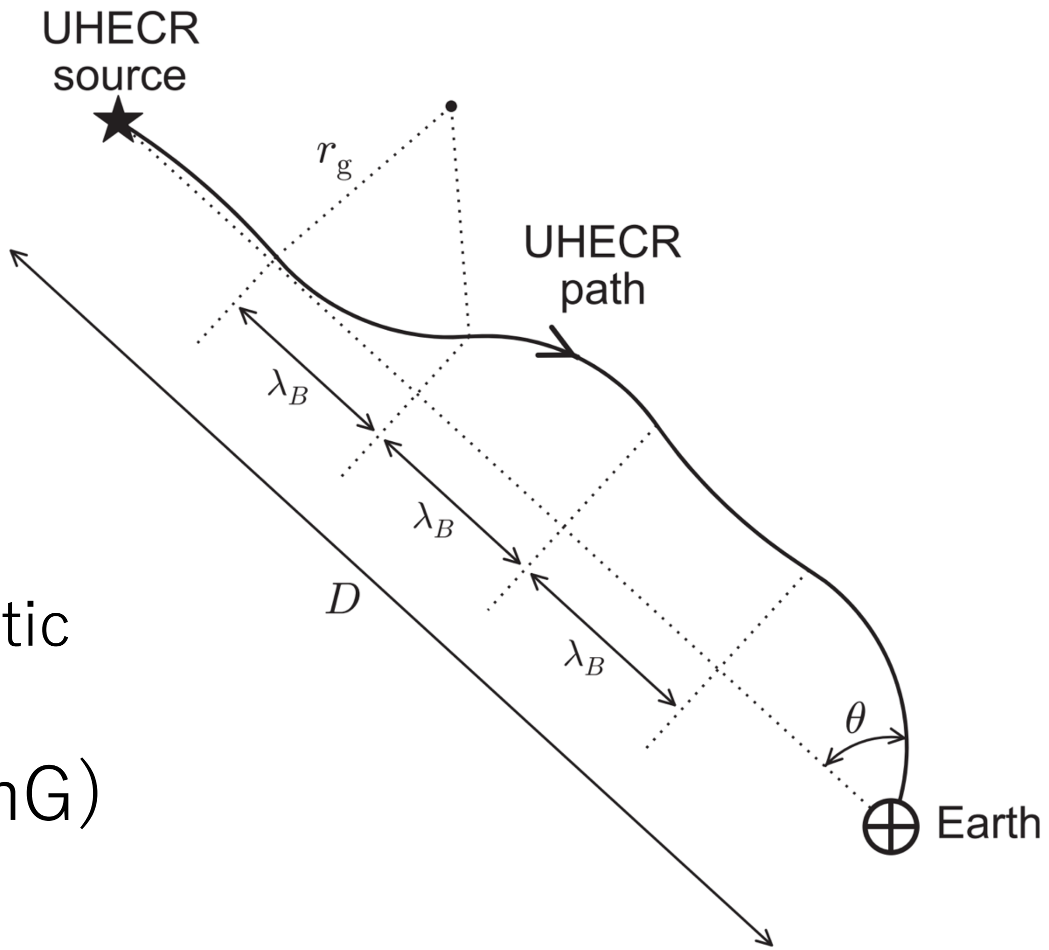


Isotropic scattering by turbulent magnetic field

$$\theta_{\rm rms} \approx \frac{\sqrt{D\ \lambda_B}}{2}\ \frac{ZecB_\perp}{E} \quad (6)$$

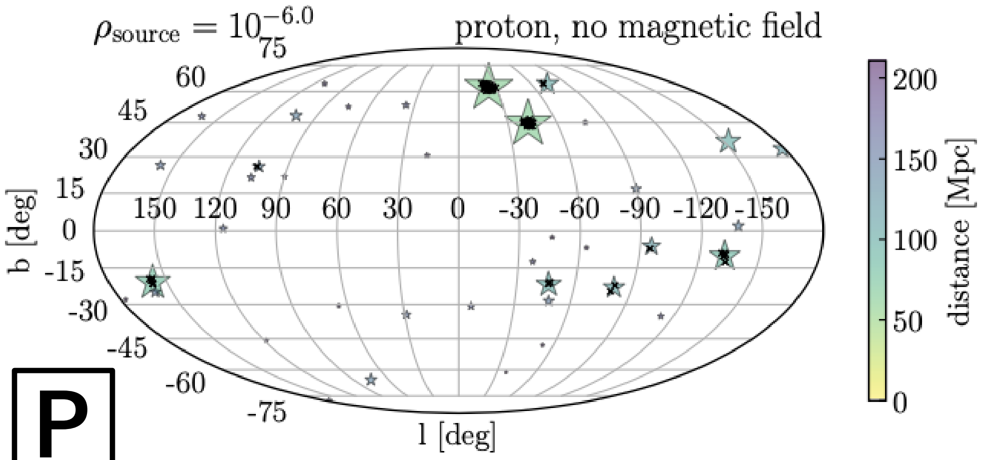
$$\approx 0\overset{\circ}{.}84 Z \left(\frac{D}{10\ \mathrm{Mpc}}\right)^{\frac{1}{2}} \left(\frac{\lambda_B}{1\ \mathrm{Mpc}}\right)^{\frac{1}{2}} \times \left(\frac{B_\perp}{10^{-9}\ \mathrm{G}}\right) \left(\frac{E}{10^{20}\ \mathrm{eV}}\right)^{-1}. \quad (7)$$

- For simplicity, we assume only isotropic random magnetic field.
  - coherent deflection by Galactic/extra-Galactic magnetic field is a next topic
- scale factor $\alpha = (\lambda/1\mathrm{Mpc})^{1/2} \times (B/1\mathrm{nG})$



(Bray & Scaife 2018, ApJ, 861,3)

Simulated UHECR distribution above 100 EeV



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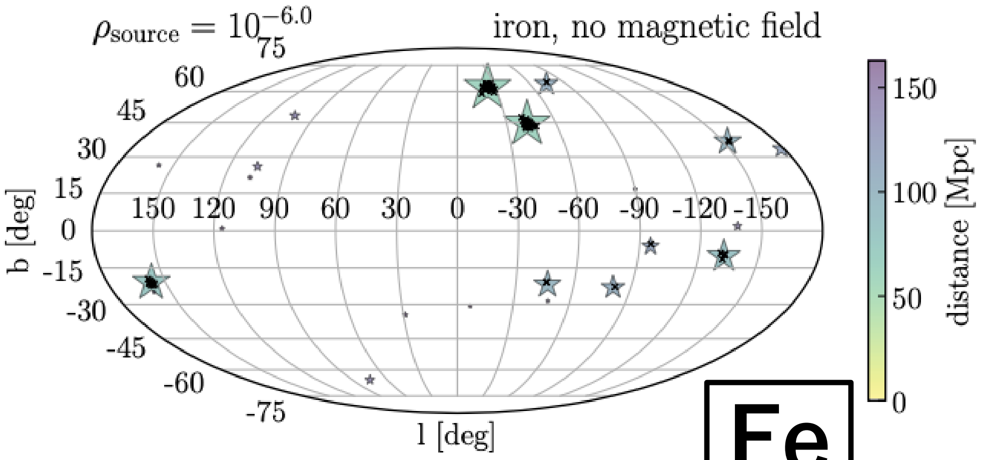

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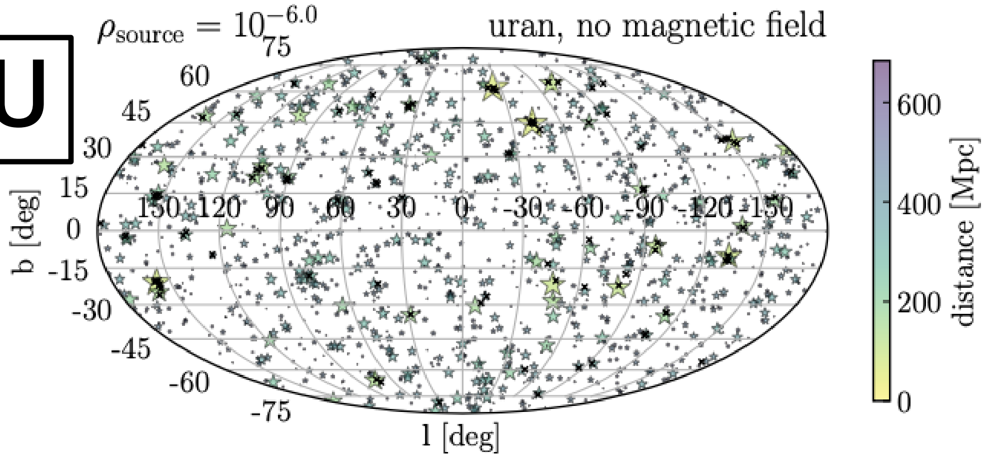
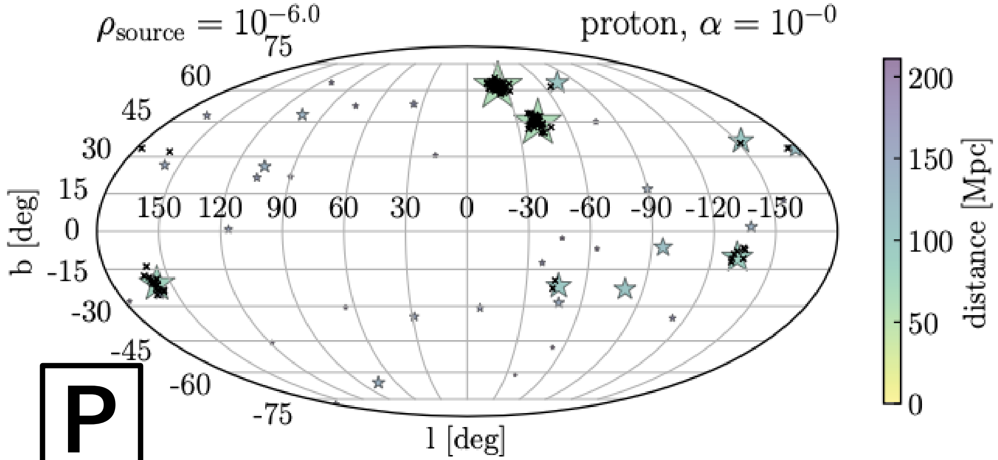


without magnetic field

★ source
× event

- 100 events over the sky × 1000 datasets
- Even without magnetic fields, uranium reflects isotropic distribution of distant sources.

Simulated UHECR distribution above 100 EeV



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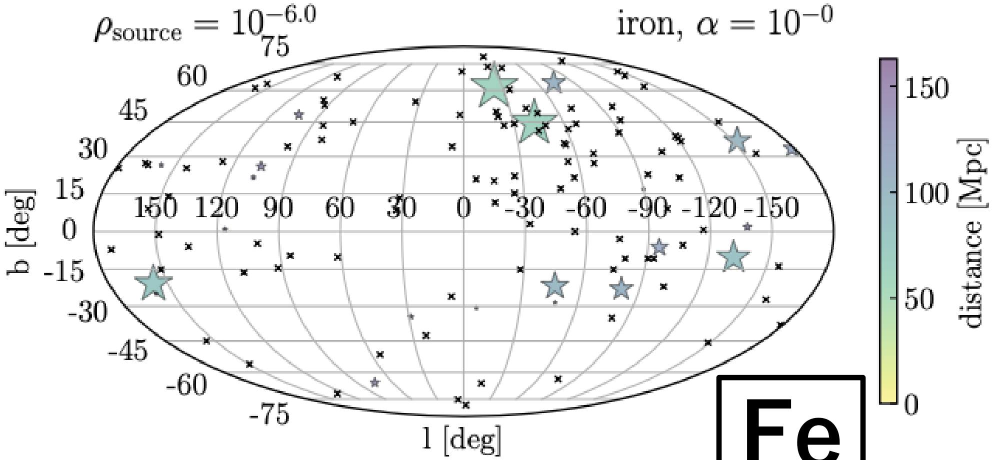

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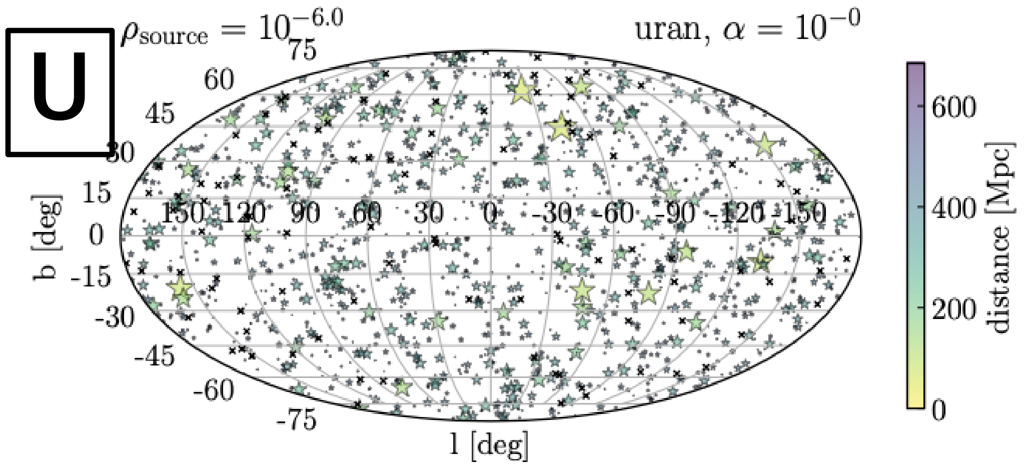

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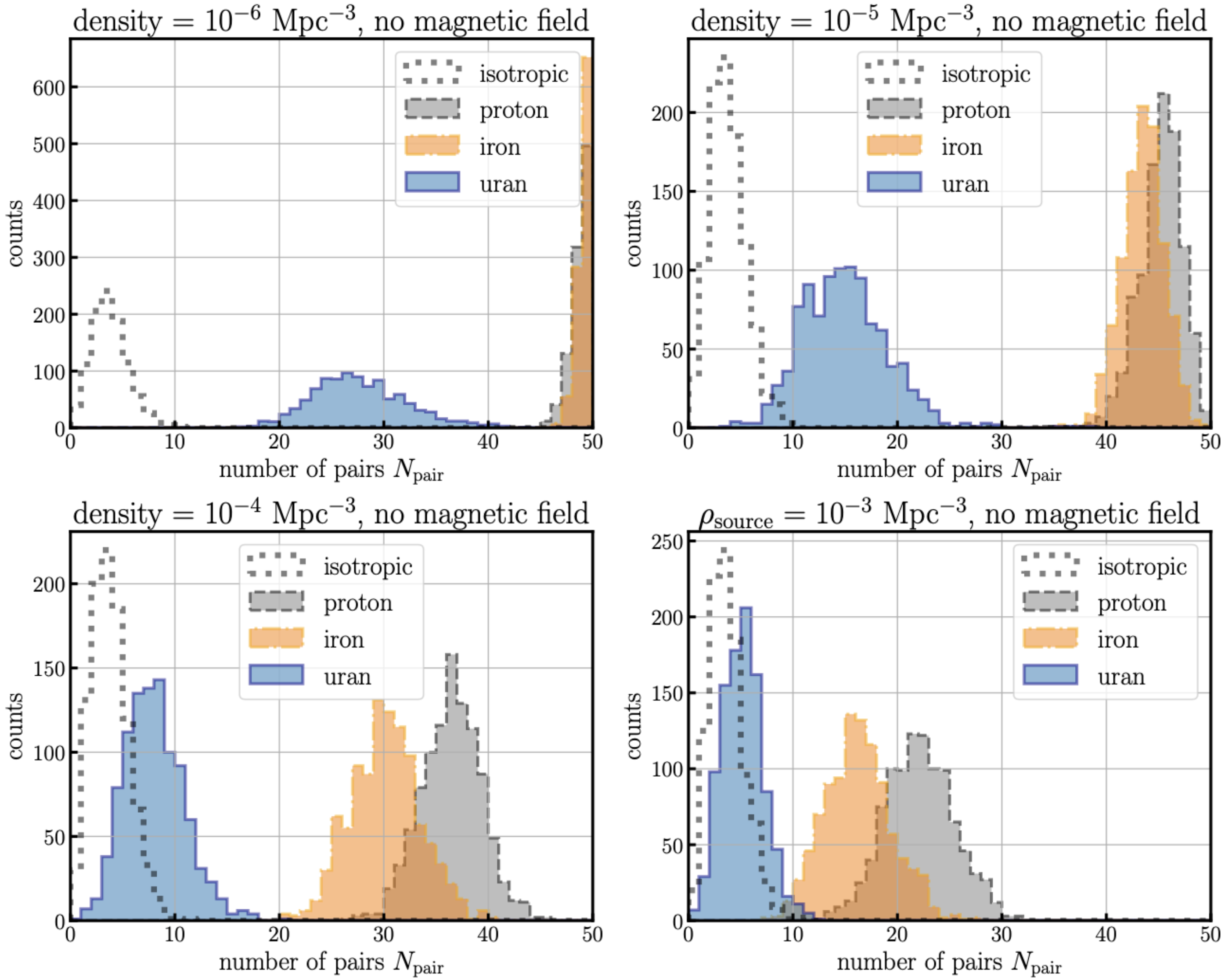
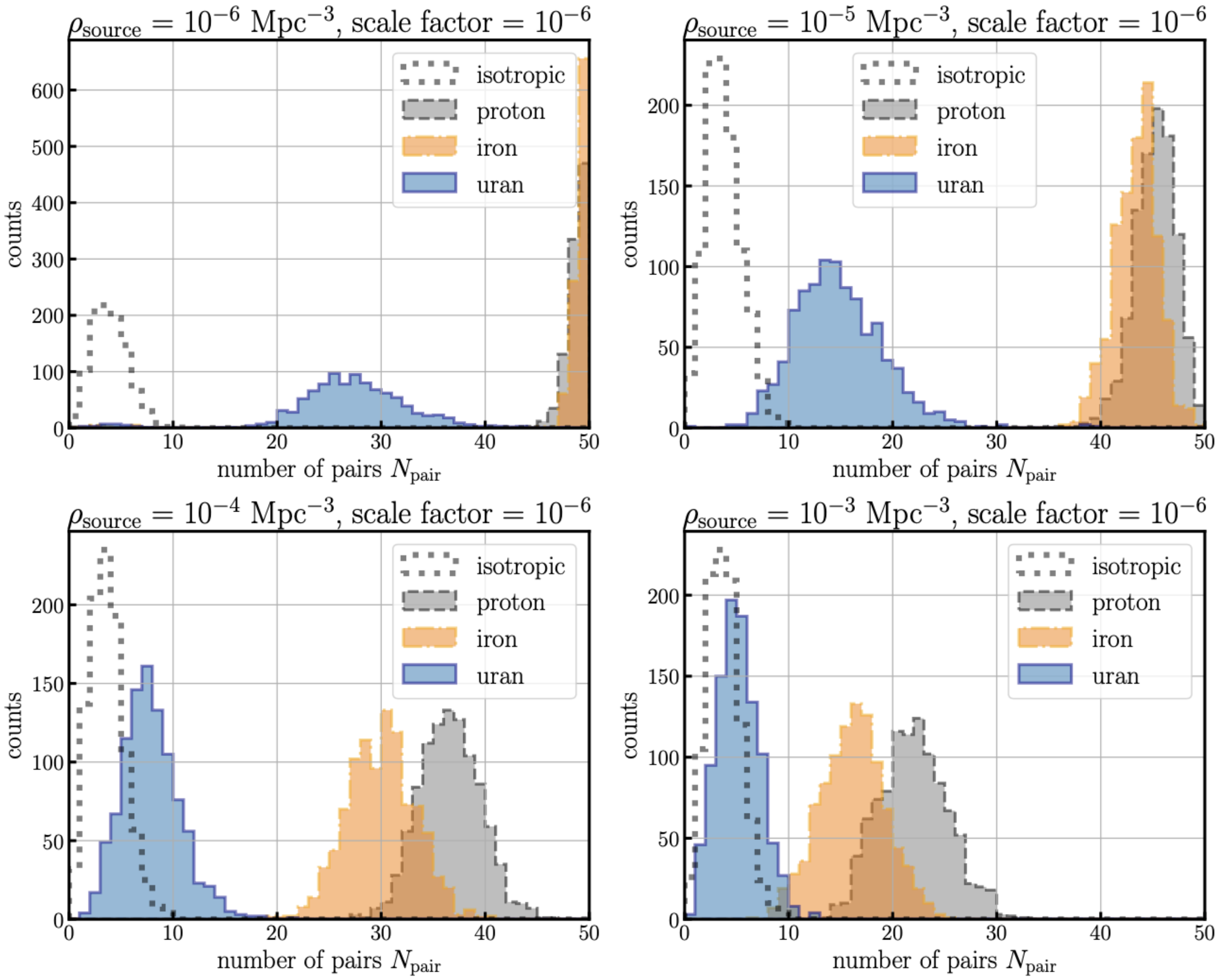
Result: number of multiplets

- no magnetic field case:
    - single-proton is rejected
    - single-iron is rejected
- for higher source density, only single-uran case can reproduce isotropy.



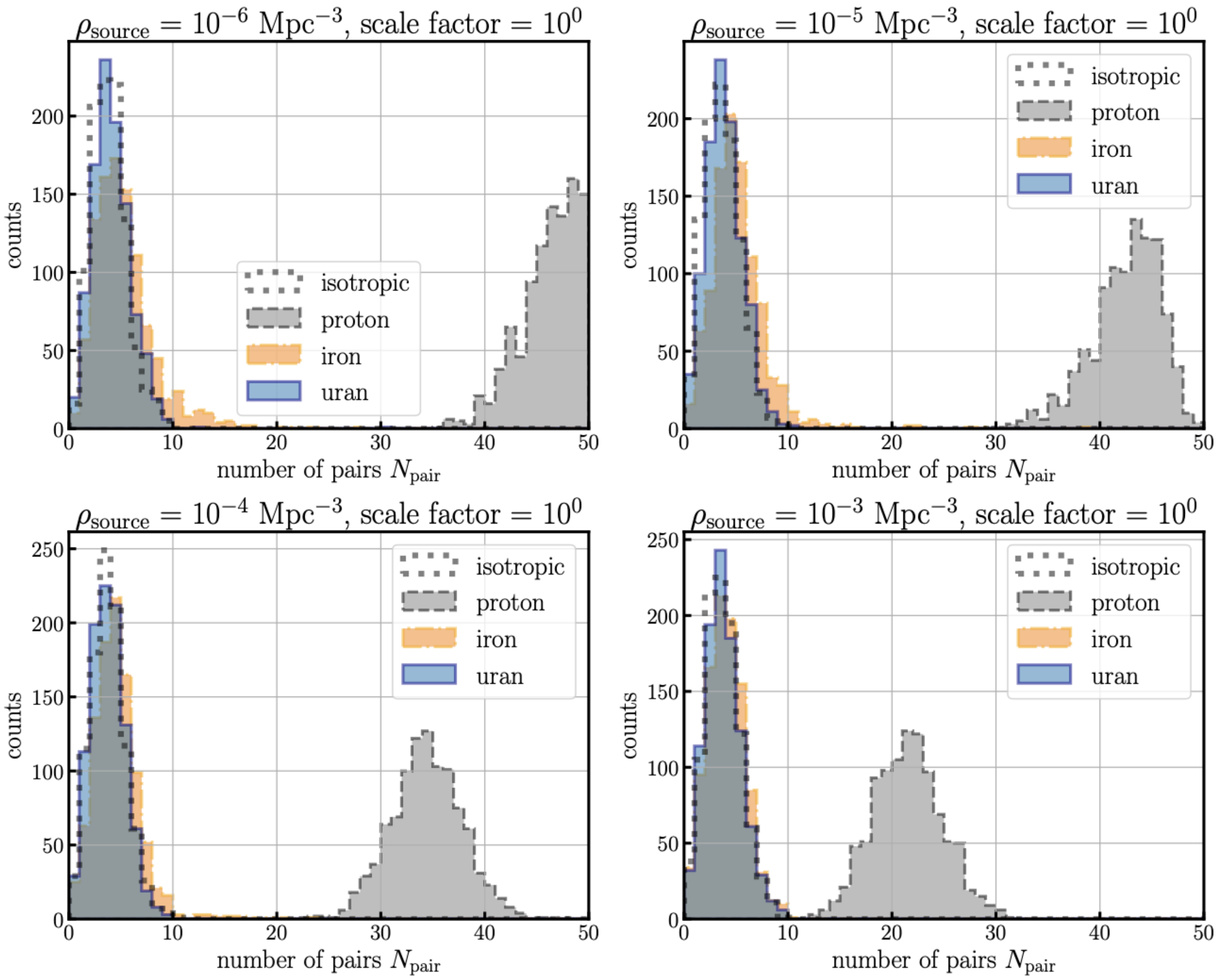
Result: number of multiplets

- Weak magnetic field:
  - single-proton is rejected
  - single-iron is rejected
- for higher source density, only single-uranium case can reproduce isotropy.

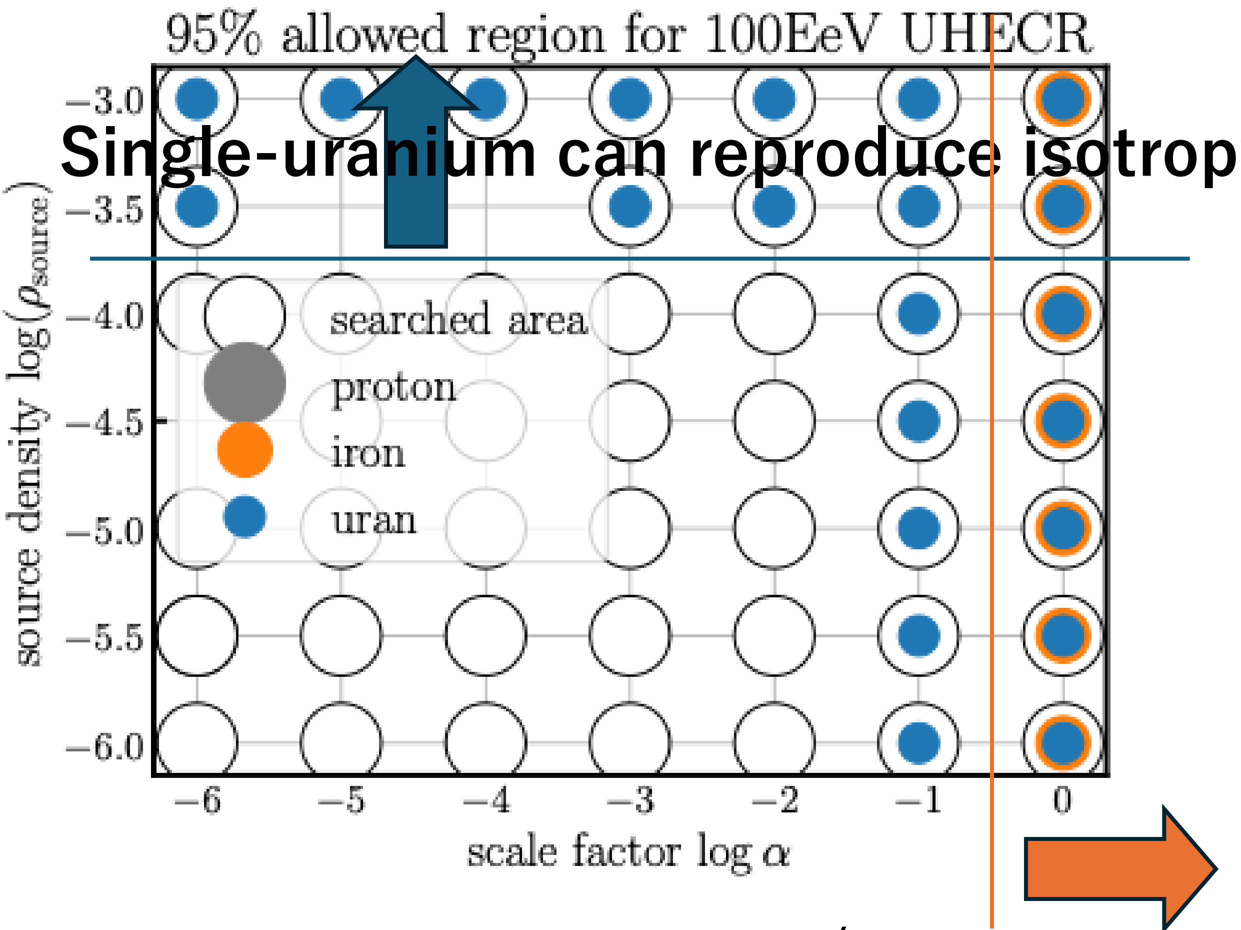


Result: number of multiplets

- strong magnetic field:
  - single-proton is rejected
- single-iron/uranium can produce the isotropy



Result: allowed region for isotropy



Single-iron/uranium can reproduce when magnetic field is strong.

- Single-proton is rejected for all parameters
- Single-iron case can reproduce isotropy, only when turbulent EGMF is strong (α >0.1).
- Single-uranium can reproduce isotropy when the source density is high （ ρ >10^-3/Mpc^3)

Summary & future

- **Single-proton can be rejected** above 100 EeV?
- When the EGMF turned to be weak, **super-heavy UHECR model & high-source density** may explain the non-anisotropic distribution.

- The simple multiplet counts still works!
  - Lower limits of **source density** and **magnetic field**
  - We cannot distinguish heavy/super-heavy UHECR, when the magnetic filed is strong.
  - The intermediate & large-scale anisotropy should be able to distinguish them (next goal)

What can we do next