Correlation studies between UHECR arrival directions and source candidates

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Outlines

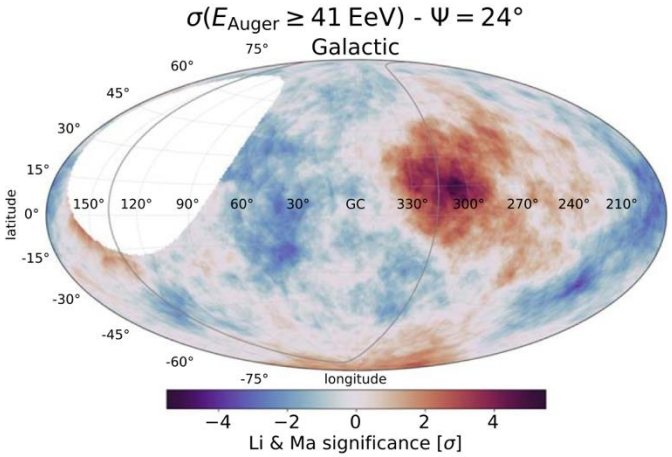
- **My work progress (TA SBG correlation)**
  - **Evaluation of each SBG contribution**
  - Analysis with GMF model
- What we can discuss in this workshop
  - ML application on anisotropy?
  - Wrap-up the TA anisotropy in 20yrs
  - Propose for TA anisotropy WG

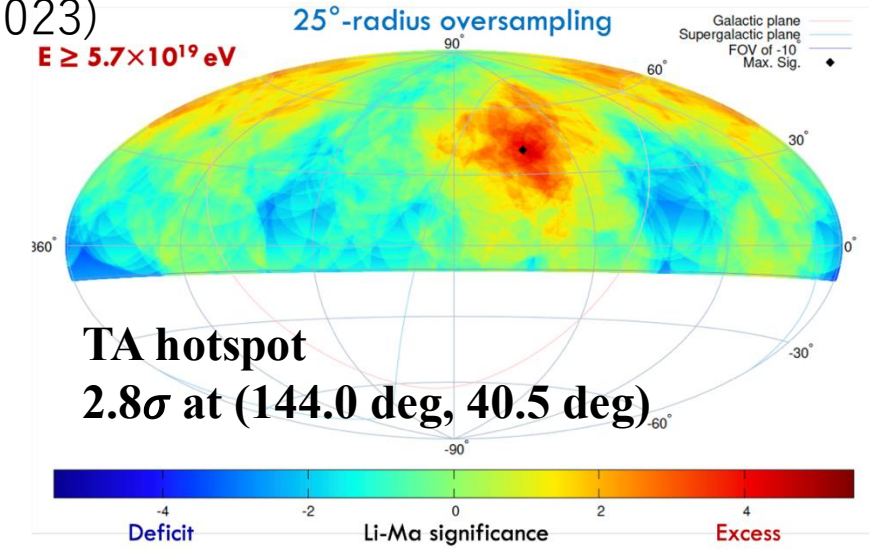
Analysis for intermediate-scale anisotropy

(ICRC2023)

- Blind search (Li-Ma significance)
  - We do not fix any source directions
  - TA hotspot
- Autocorrelation/crosscorelation search
  - I don't talk today
- **Maximum-likelihood Method**
  - Correlation studies with **known** nearby source candidates
  - I'm working on this!

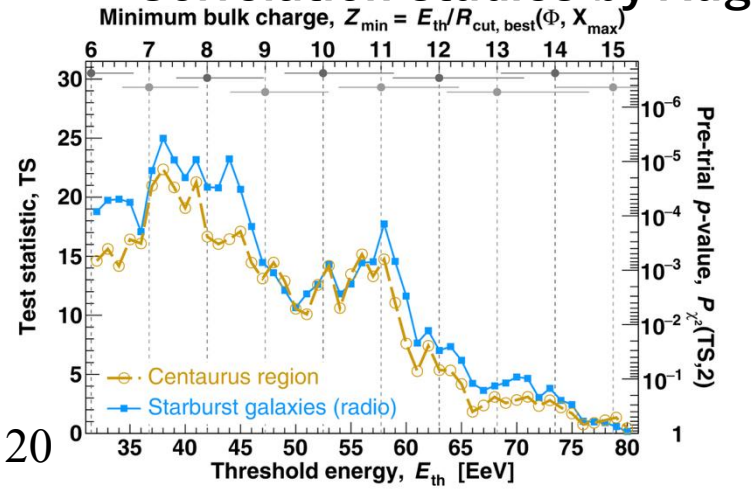
Blind search by Auger





Blind search by TA

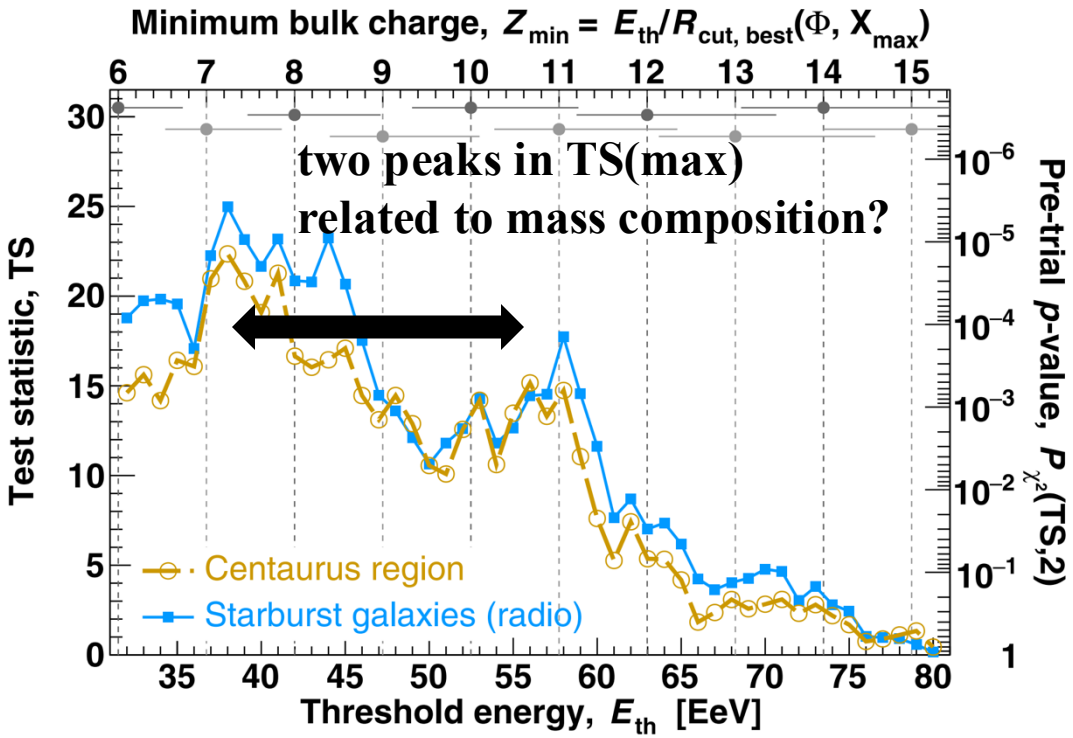
Correlation studies by Auger

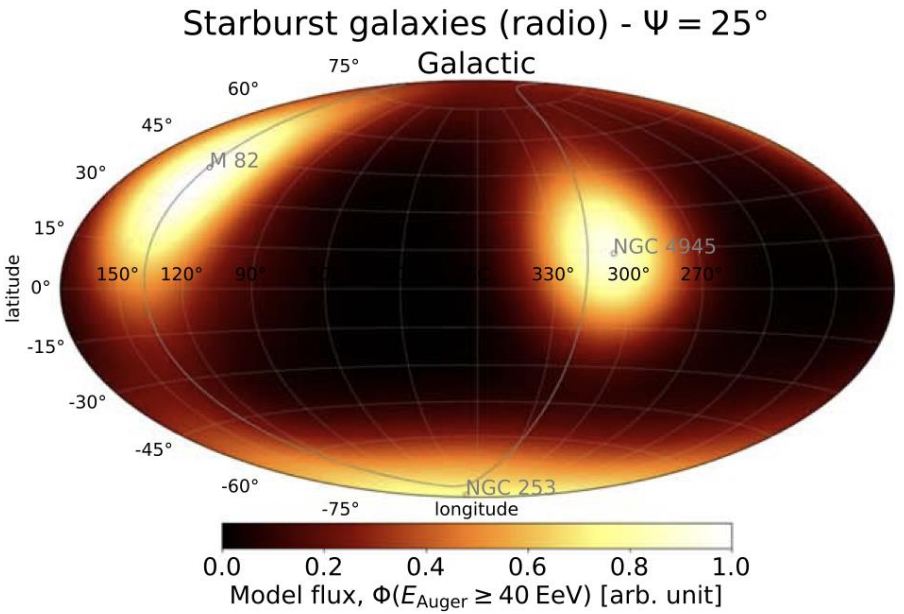


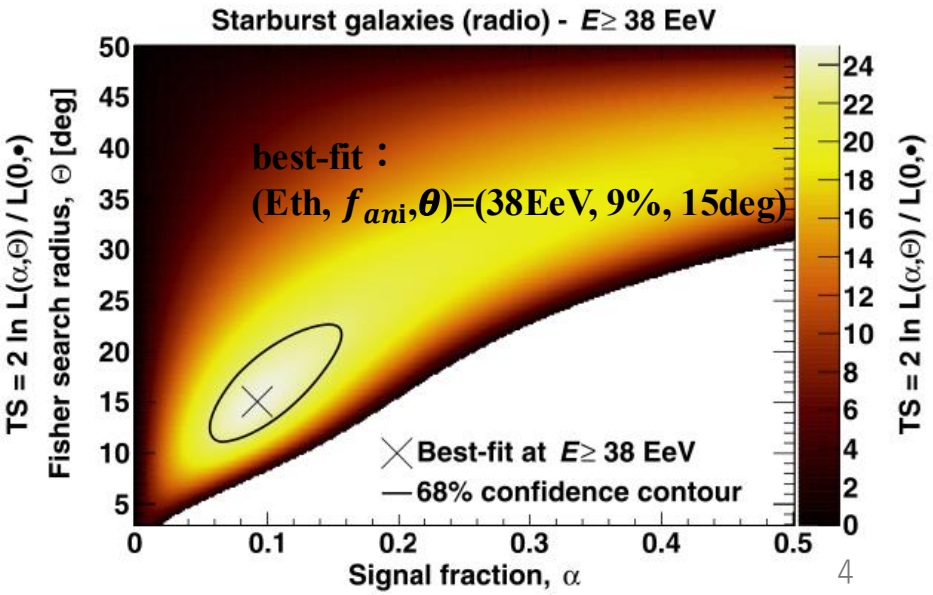
Auger collaboration, ApJ, 935:170(24pp),2022 August 20

SBG correlation? (Auger collaboration 2018/2022)

- Latest update with Auger Phase One datasets
  - nearby 44 SBGs × Auger 17yr UHECR events
  - best-fit：(Eth, f_{ani},$\boldsymbol{\theta}$)=(38EeV, 9%, 15deg)

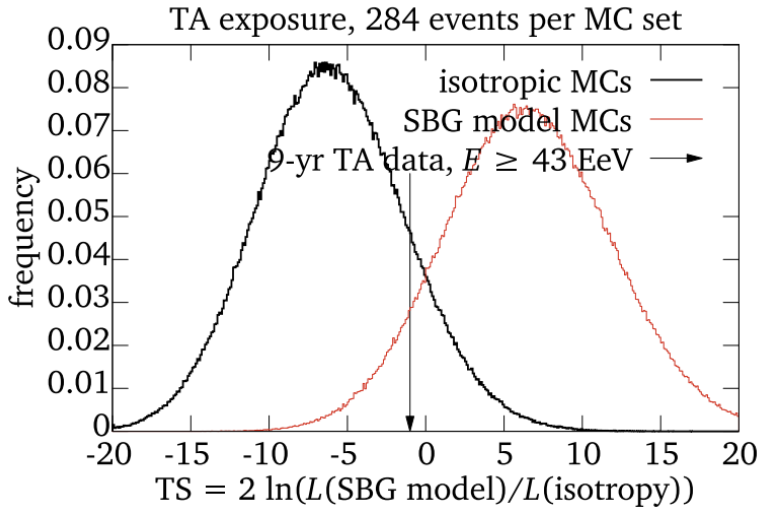




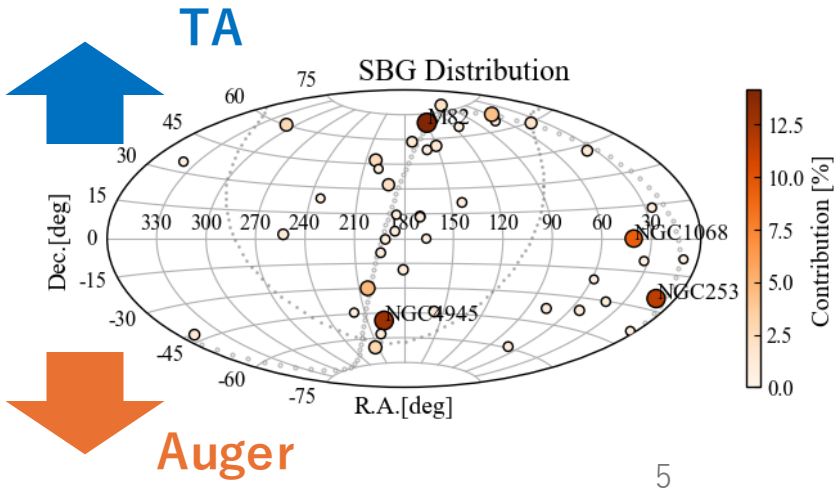


Questions on “SBG correlation”

- **How about TA?**
  - TA reported a test in 2018, but only for the best-fit parameter set from Auger
  - Now we have larger sample!
- **When we say “SBG correlations”, what we actually see?**
  - Clearly Cen A dominates the SBG correlations for Auger dataset
  - What about TA?
    - M82 should dominate the correlation → Let’s check
- **How to reconcile coherent deflection by magnetic fields?**
  - If turbulent >> coherent field, the original analysis should work
  - If coherent is strong, the analysis shows the discrepancy between TA/Auger.
  - Convolution of GMF model

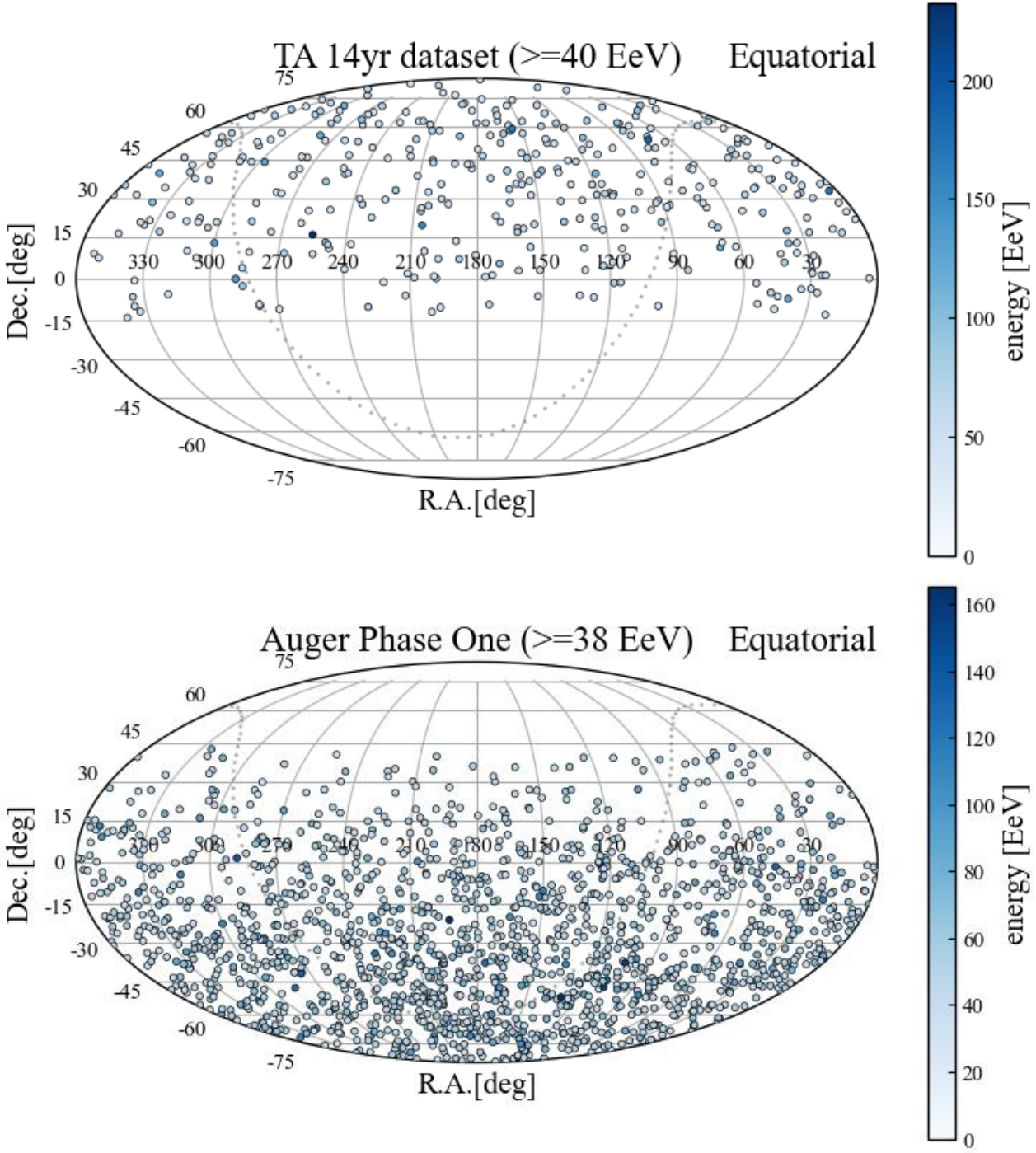


(TA collaboration 2018)



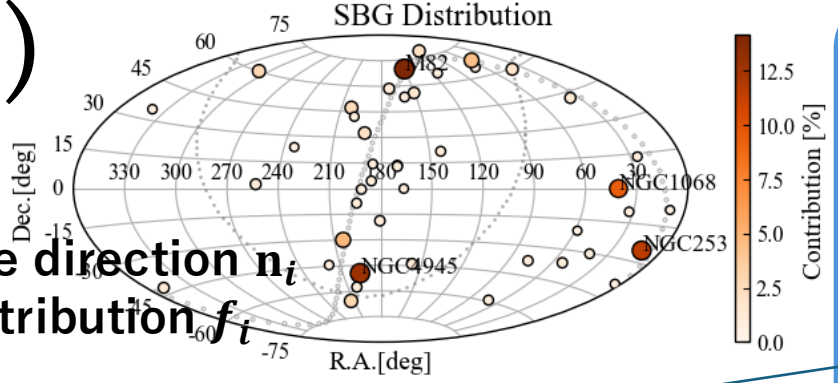
Datasets

- **TA 14yr dataset:**
  - May. 2008~May. 2022
  - 541 events over ~32EeV
- **Auger Phase One:**
  - Jan. 2004~Dec. 2020
  - ~2600 events over 32 EeV
- Energy scaling:
  - +4.5% for Auger
  - -4.5% for TA
  - energy threshold scan Eth = 34-100EeV



Method(Auger 2022)

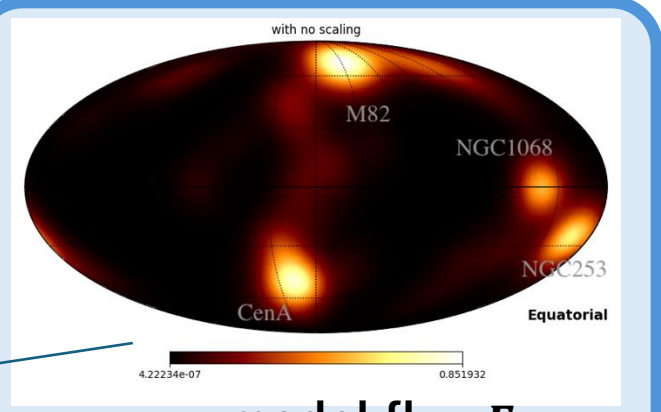
- Parameters:
  - **anisotropic fraction[%] (f_{ani})**
  - **angular scale [deg](θ)**



source direction $\mathbf{n}_i$ & contribution f_i

(from the table in Lunardini 2019)

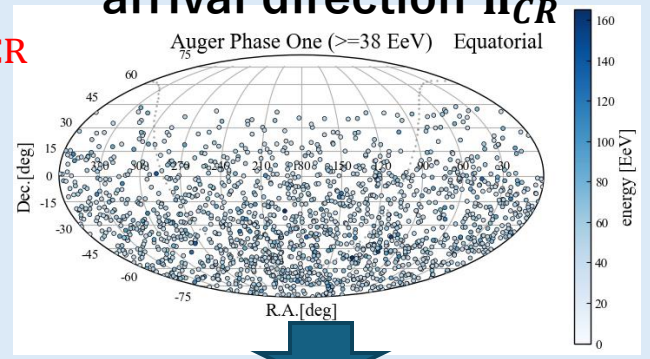
- CR flux calculation from source list
  - $F(\mathbf{n_{pixel}}) = \sum_i w_i f_i(\mathbf{n_{pixel}})$ CR flux calculation at each pixel $\mathbf{n_{pixel}}$
  - $f_i(\kappa, \mathbf{n}) = \kappa \exp(\kappa \cos \mathbf{n_i} \cdot \mathbf{n}) / (4\pi \sinh \kappa),\ \kappa = \frac{1}{2(1-\cos(\theta))}$
- **likelihood calclation:** CR flux calculation at each arrival direction $\mathbf{n_{CR}}$
  - **SBG model:** $H_1(\mathbf{n_{CR}}) = \frac{(1-\alpha)\cdot F_{\mathrm{iso}}\cdot\omega(\mathbf{n_{CR}})+\alpha\cdot F(\mathbf{n_{CR}})\cdot\omega(\mathbf{n_{CR}})}{\sum_{\mathrm{pixel}}[(1-\alpha)\cdot F_{\mathrm{iso}}\cdot\omega(\mathbf{n_{pixel}})+\alpha\cdot F(\mathbf{n_{pixel}})\cdot\omega(\mathbf{n_{pixel}})]}$
  - **isotropic model:** $H_0(\mathbf{n_{CR}}) = F_{\mathrm{iso}} \frac{\omega(\mathbf{n_{CR}})}{\sum_{\mathrm{pixel}} \omega(\mathbf{n_{pixel}})}$
- **Test statistics：** $TS = 2 \times \sum_{\mathrm{CR}} \ln\{(H_1(\mathbf{n_{CR}})/H_0(\mathbf{n_{CR}}))$
  - **Hypothesis：SBG source model**
  - **null hypothesis：isotropic model**
- Find the best-fit parameter set **(Eth,f_{ani},θ)** which maximize TS
  - We follow Auger coll. (2022), and confirmed reproductivity
  - Consistency check with both TA/Auger FoV （reproduction of Higuchi et al. 2023)
    - We fixed a part of equations

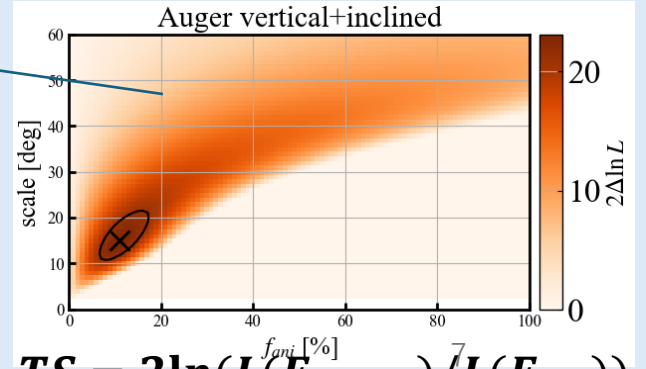


model flux F_{model}

×

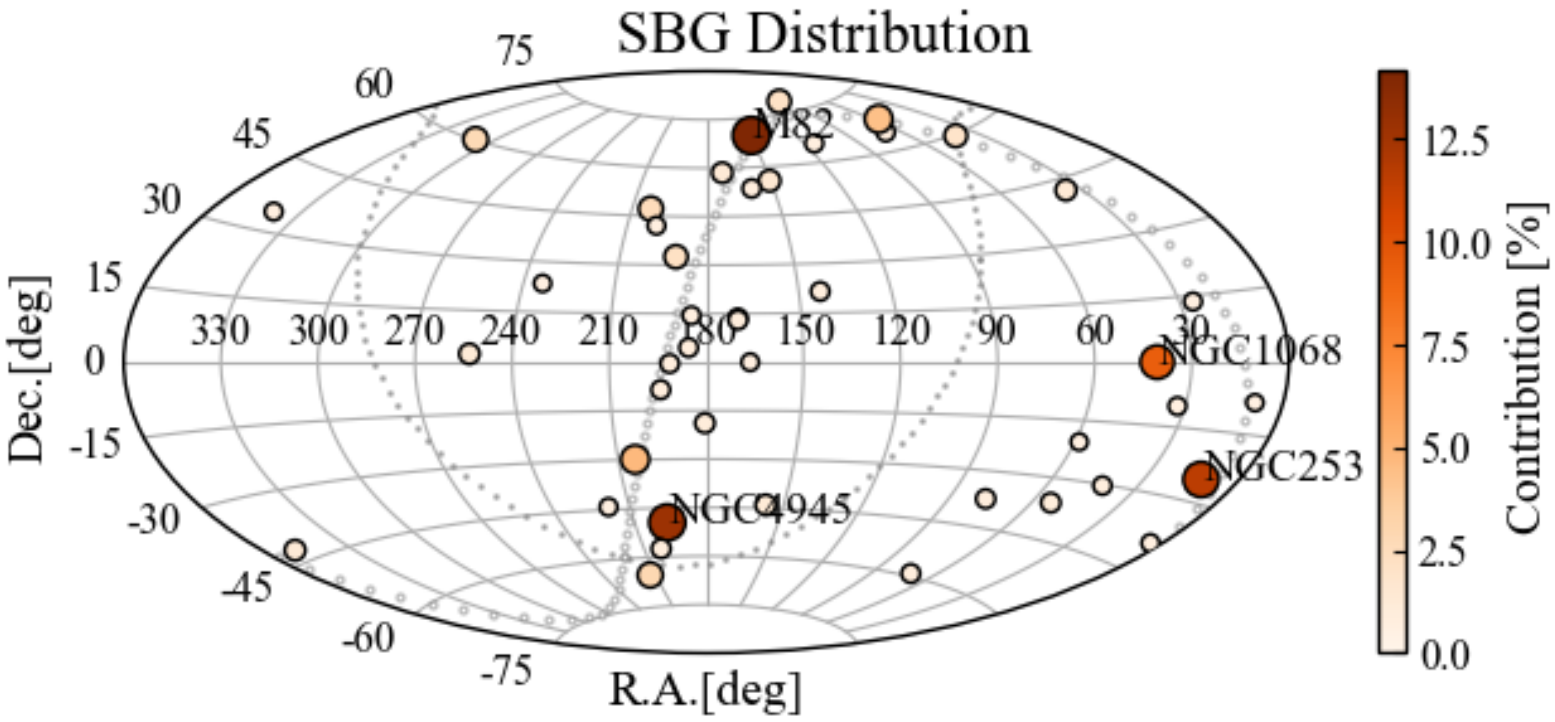
arrival direction $\mathbf{n}_{CR}$





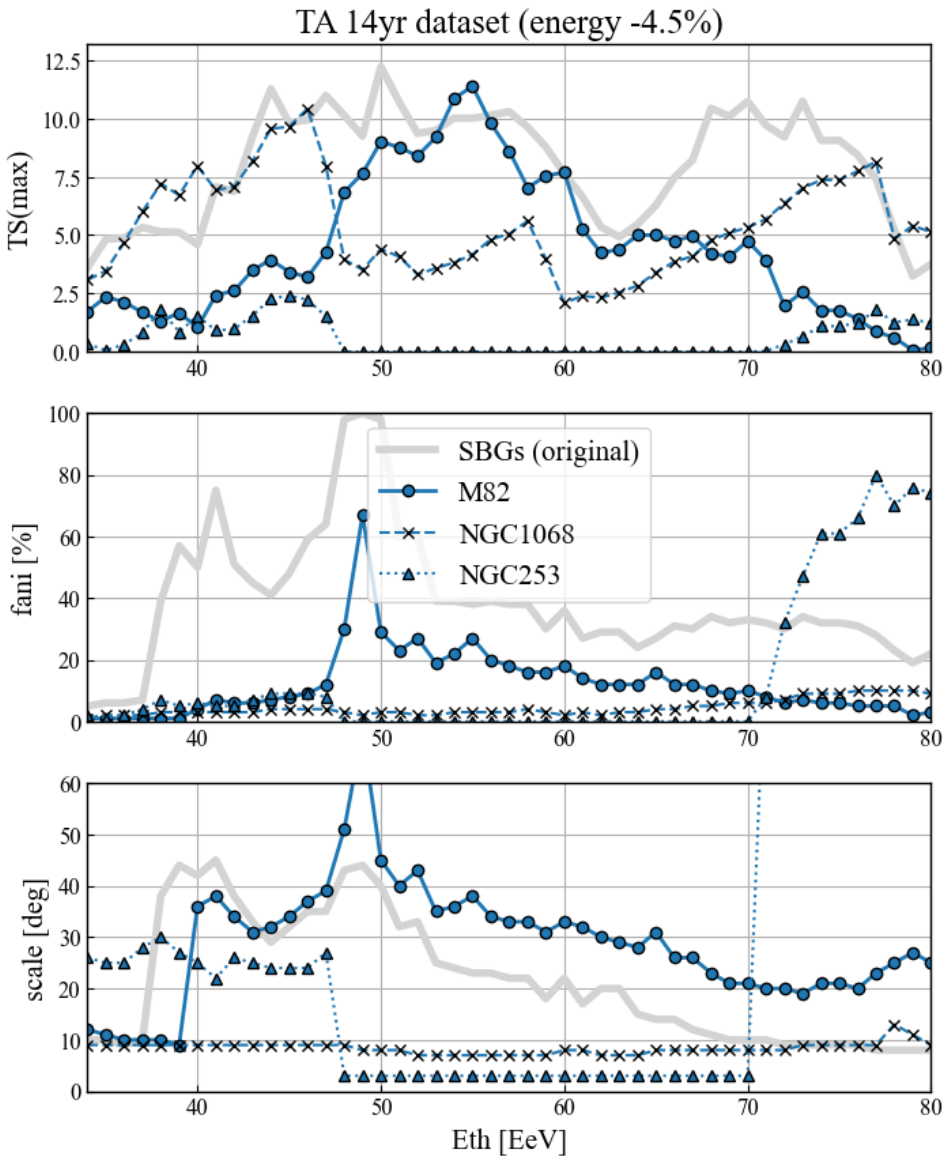
$TS = 2\ln(L(F_{\mathrm{model}})/L(F_{iso}))$

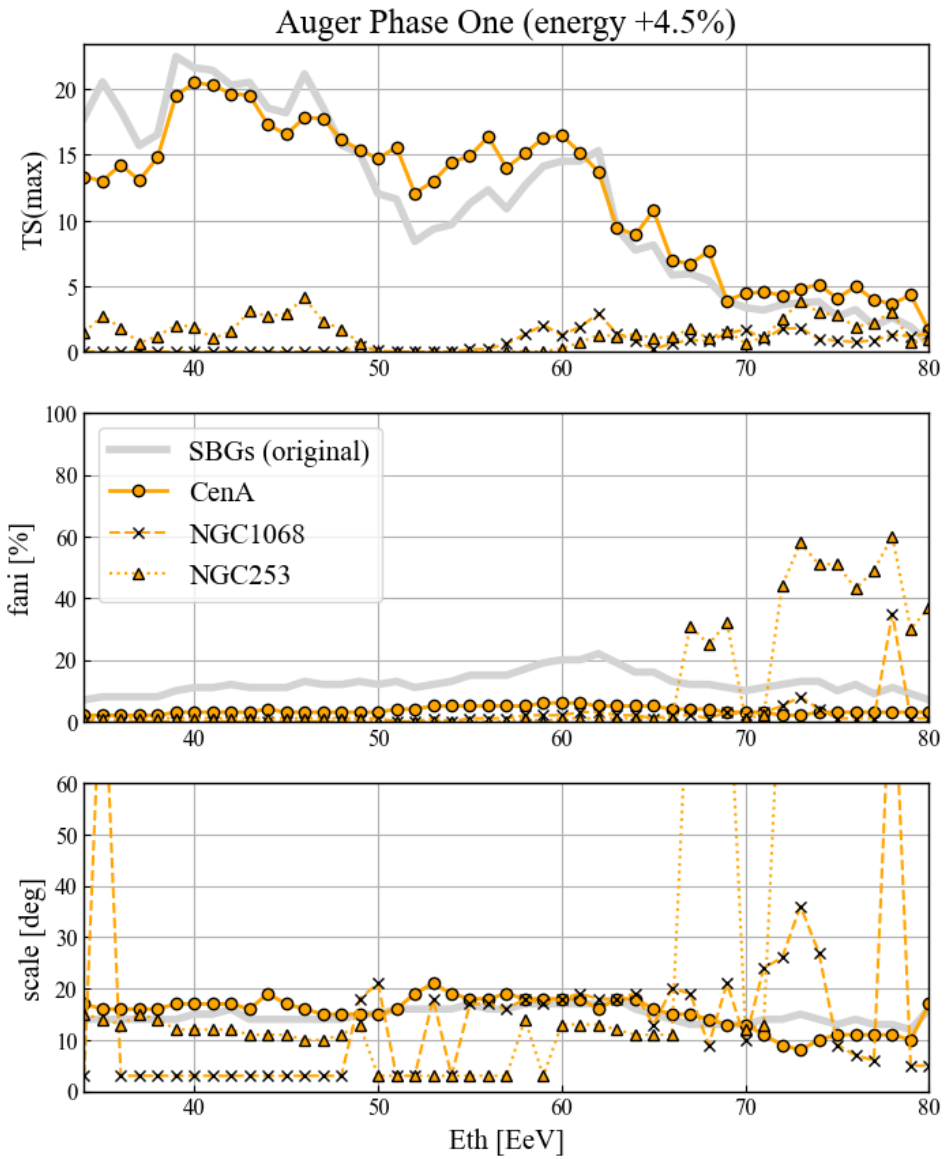
Single-source contribution



- The top-4 contribution in SBG model are **M82, CenA(NGC4945), NGC253, NGC1068.**
- In TA exposure (when θ =15deg)
  - **M82: 30%**
  - **NGC1068: 7.9%**
  - **NGC253: 2%**
  - CenA: 0.3%
- In Auger exposure
  - **CenA: 24%**
  - **NGC253: 19%**
  - **NGC1068: 11%**
  - M82: 0.2%

single-source contribution



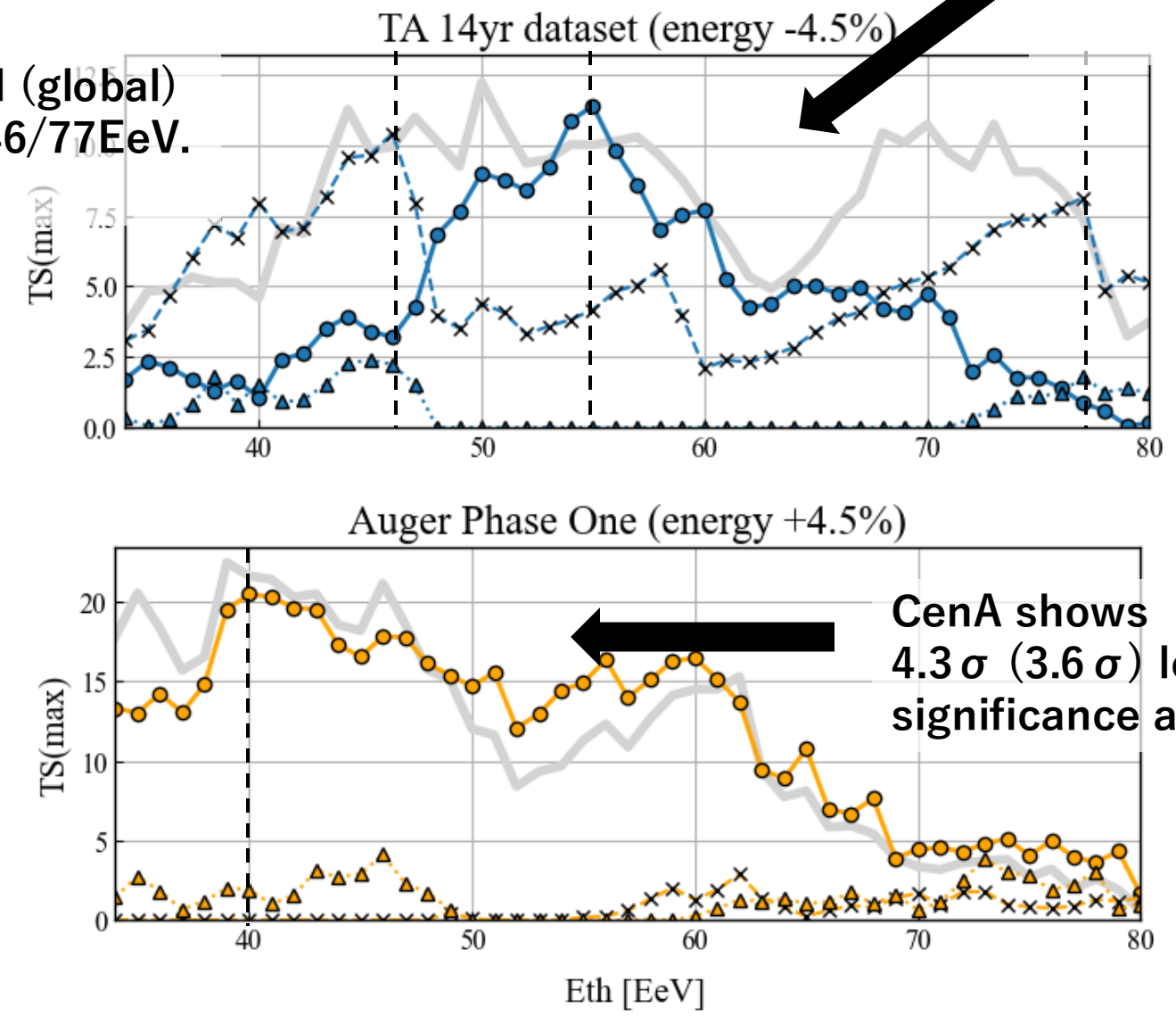


- Calculation with top-4 sources (M82,CenA,NGC1068/253)
- In Auger case
  - We are seeing correlation with **Cen A**!
  - As reported in Auger publication.
- In TA case
  - **M82 & NGC1068** has some contribution to TS distribution

single-source contribution

M82 shows 3.2 σ (1.6 σ) local (global) significance at Eth = 54 EeV.

NGC1068 shows 2.9/2.8 σ (1.5 σ) local (global) significance at Eth=46/77EeV.



CenA shows 4.3 σ (3.6 σ) local (global) significance at Eth=40EeV.

Interpretations

- **Diversity of acceleration for each source?**
  - If we follow the Auger collaboration's discussion, Eth at TS maximum indicates Rcut parameter:
    - 39 EeV for CenA, 54 EeV for M82 → seeing a fluctuation of acceleration limit for individual sources?
  - →In this case, how can we interpret NGC1068 peaks?
- **NGC1068 correlation/non-correlation?**
  - Why doesn't Auger dataset show NGC1068 correlation?
  - We need to check global significance of NGC1068-Auger correlation.
    - HOKUSAI starts today, so I can show the result this week.

- These are the case with turbulent>>coherent deflections by magnetic fields
  - What happens when coherent >> turbulent?
  - Next topic

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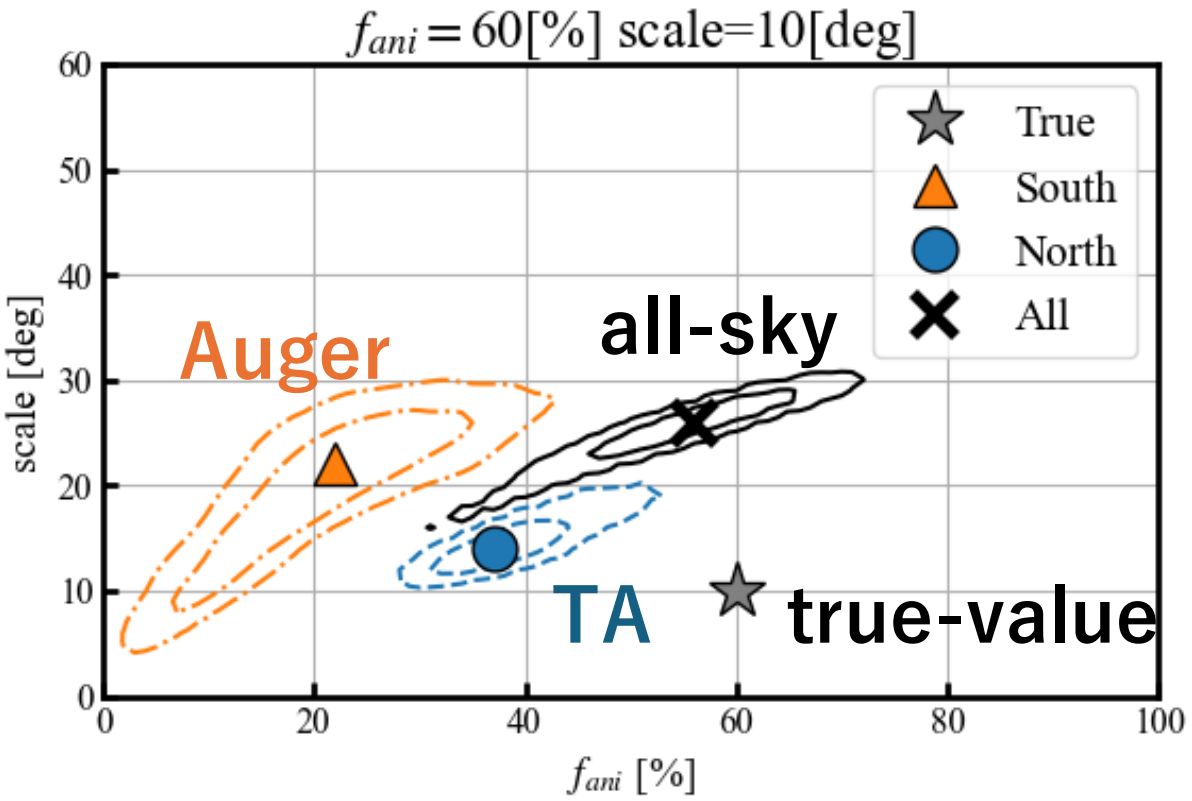
GMF effect (my previous work)

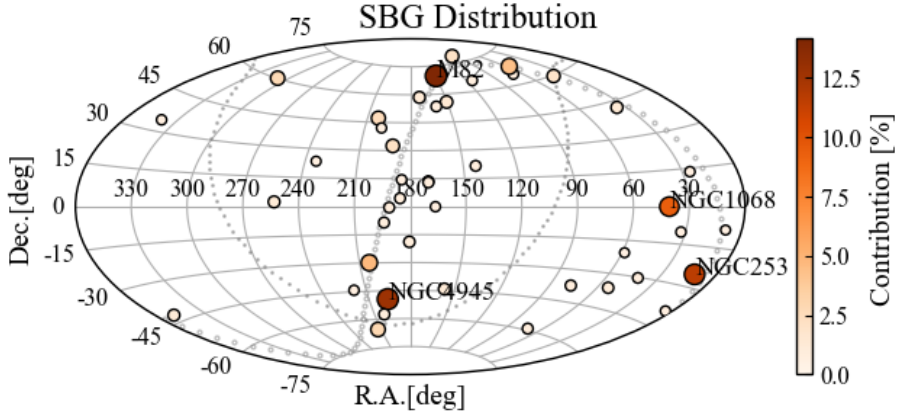


(Reproduction of Higuchi et al. 2023)

- How a Galactic magnetic field (GMF) affect the source catalog correlation?
- If we assume coherent deflection, the catalog correlation analysis does not work.
  - We need to analyze with magnetic field model

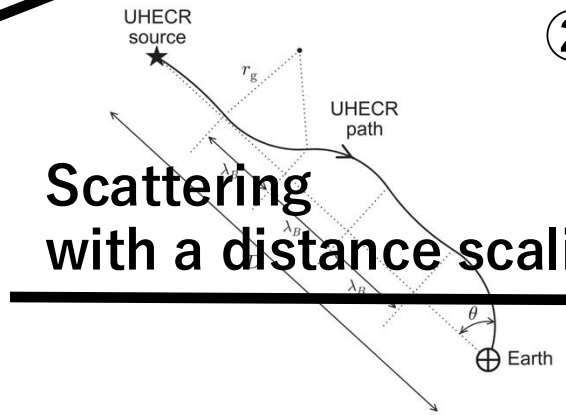
CR flux model with magnetic field assumptions

Source model (fixed)



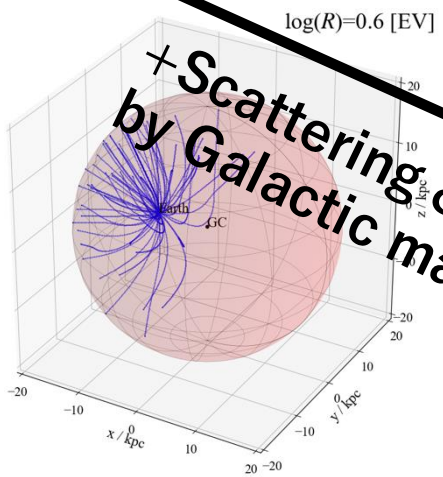
Scattering with a same angular scale

① original



Scattering with a distance scaling

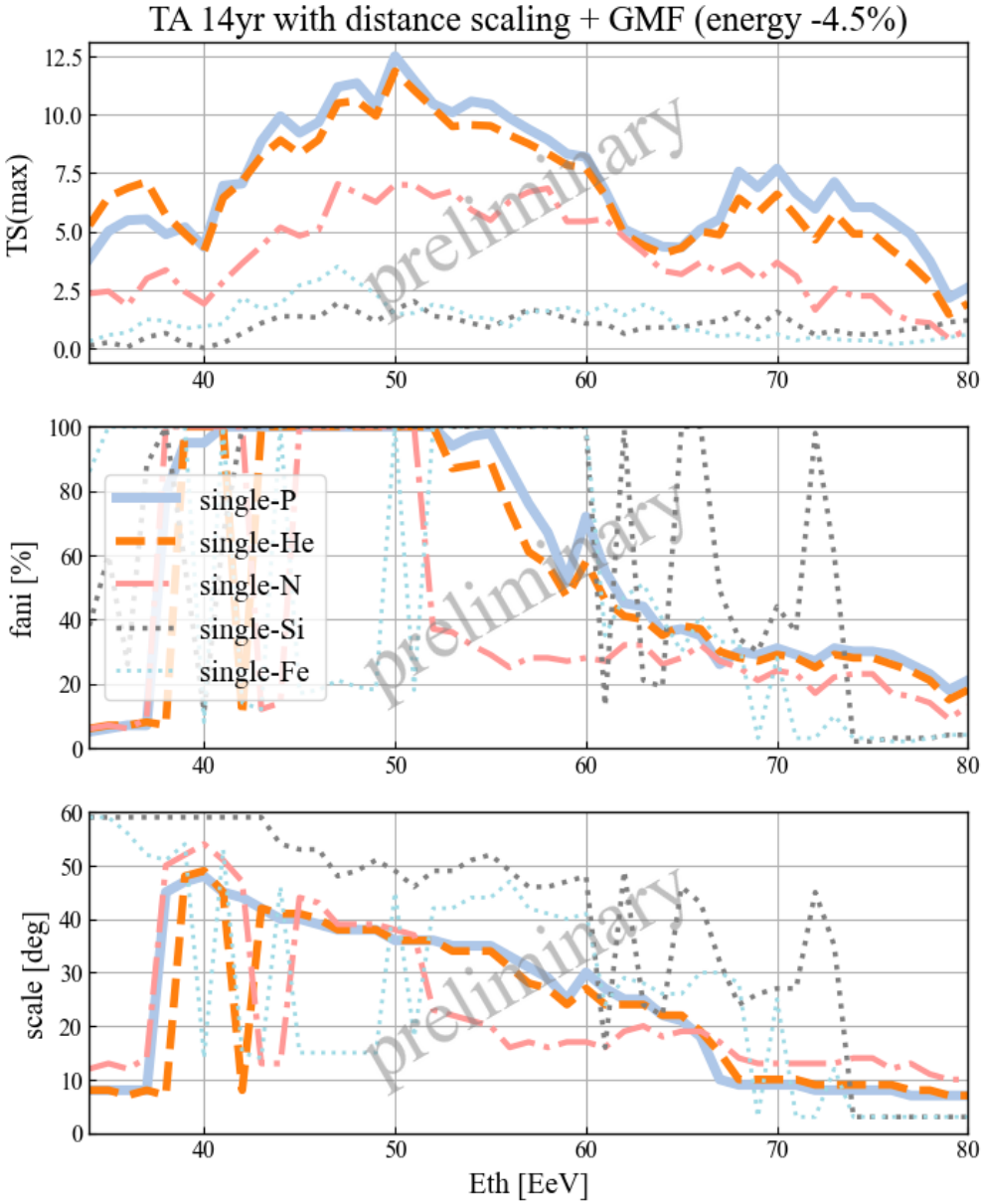
② with scaling

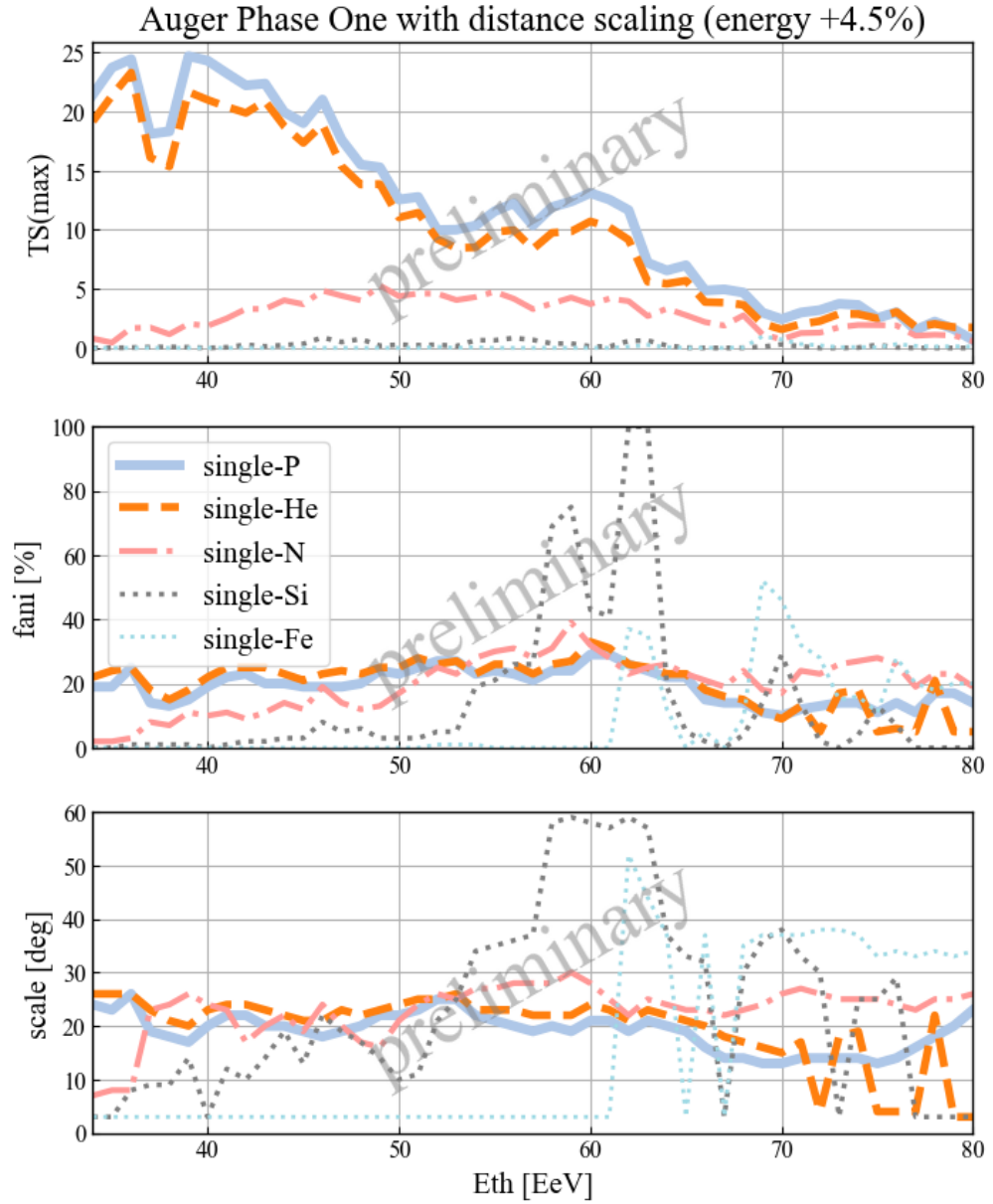


+Scattering & deflection by Galactic magnetic field

③ with GMF lens

GMF with single charge number





- We include GMF(JF12)model in the analysis
- TS decreases for heavier composition
- Best-fit parameter (fani, θ)fluctuates
  - We need some evaluation of uncertainty
  - Still working on.

To do next & questions

- Clearly **GMF+likelihood analysis has a sensitivity to mass composition model** (not only to GMF model)
  - Latest global-spline fit (Fujisue in prep.) is one of the answer
  - Before we apply, I need to **understand behavior with single charge number**.
  - I check single-source+GMF analysis in the next step
- **Mass composition assumption**
  - I tested GSF, but uncertainty of mass composition at each energy-bin is not included.
  - How to reconcile the un-uniformity of mass number?
- **Evaluation of GMF uncertainty itself**
  - Update of GMF models (UF23, KST24…)
    - We can expect improvement of GMF models after SKA!
  - However, **“How can we trust the GMF model?”** will be always a serious problem.

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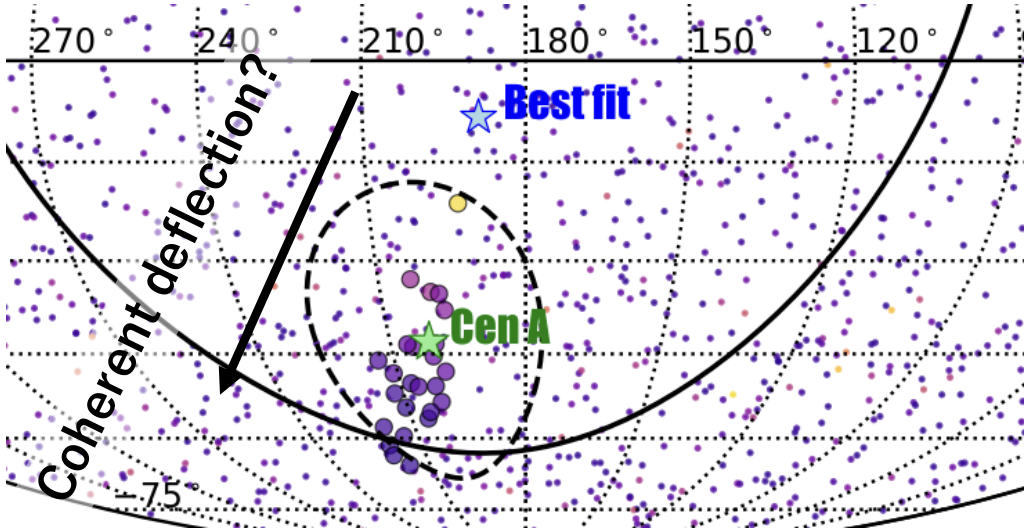
What can we do with TA-ML?

- Of course, **event-by-event mass** information from TA-ML is mandatory.
  - How to include the mass uncertainty in the analysis?
  - I need to learn about the outputs.
- Statistical feature of mass composition
  - In many analysis, **uniformity of mass** should be a problem
    - ex. He et al. 2016/2024 assume single-mass composition
  - **Mass-dependent anisotropy** is still a problem?
    - at least, we should check
- Any idea is helpful!

(He & Kido et al., arXiv: 2412.11966)



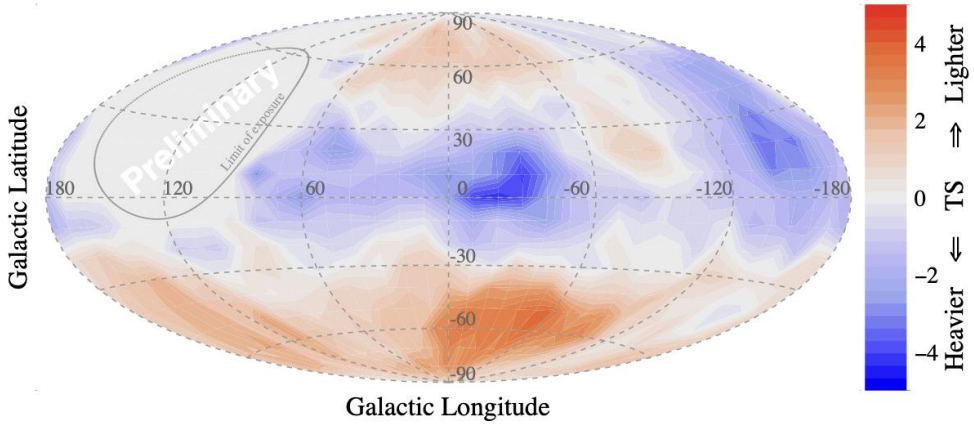
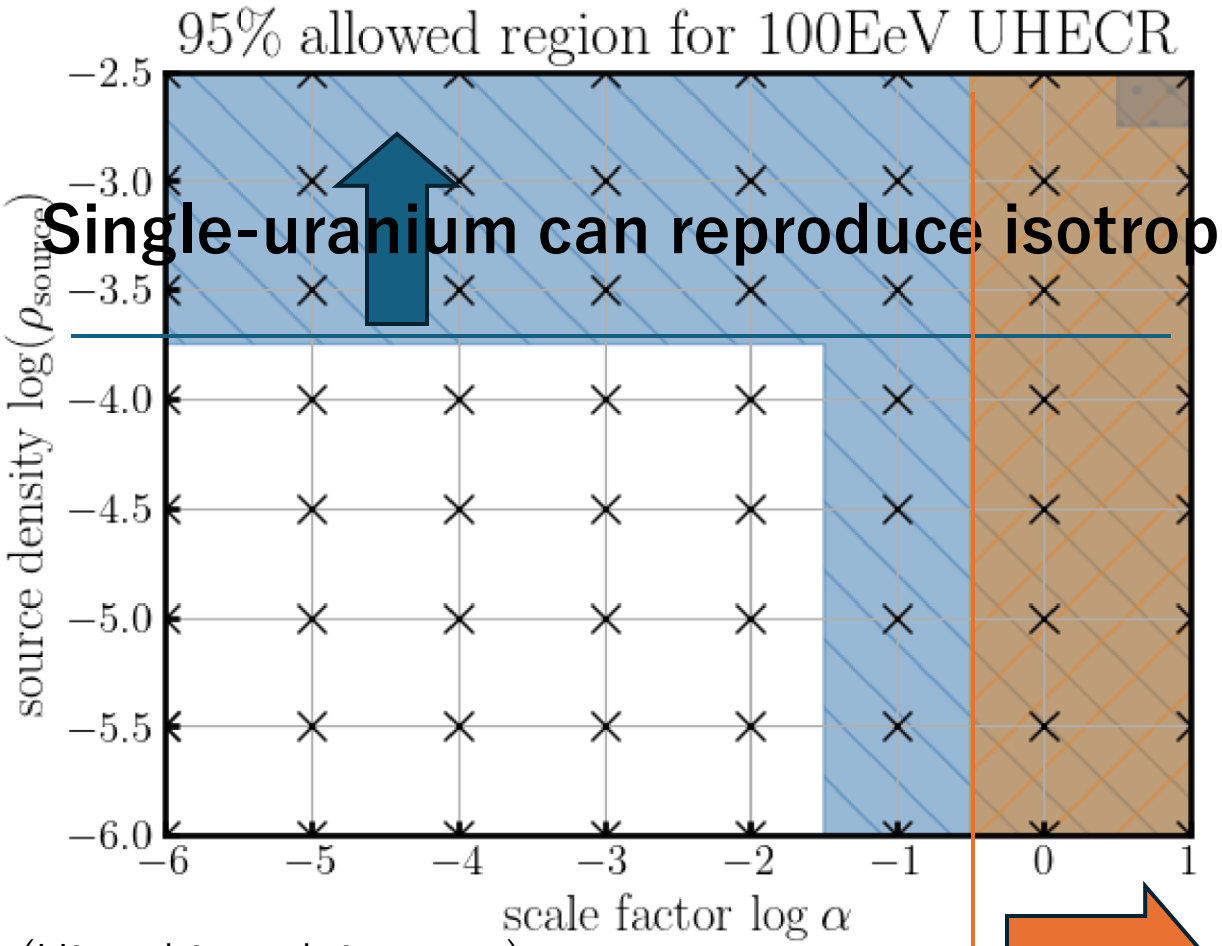


Figure 13: Sky map of comic ray composition for $E \geq 10^{18.7}$ eV

(Mayotte et al. UHECR2022)

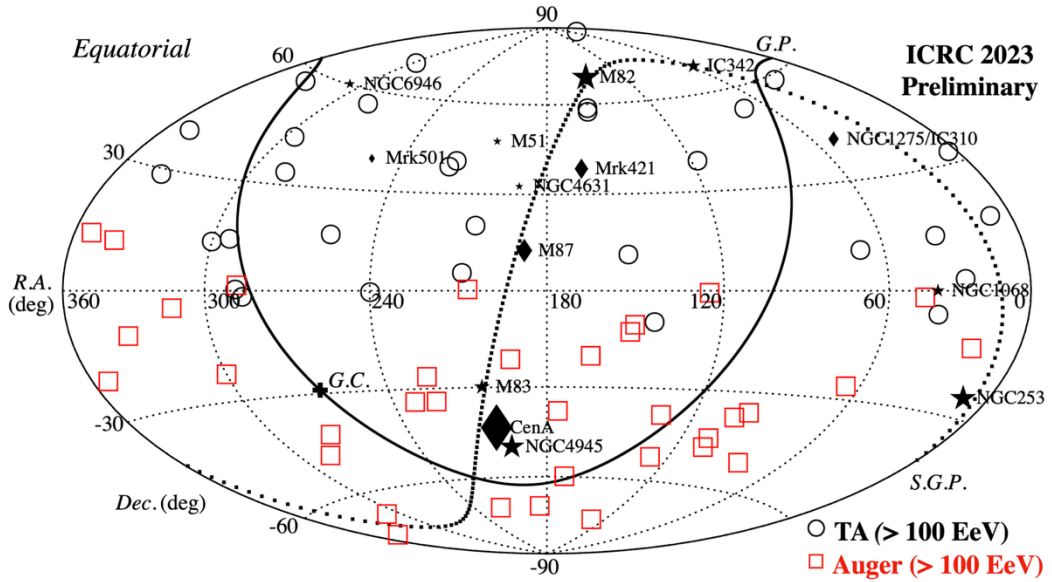
Conservative limits from non-detection of anisotropy



Single-uranium can reproduce isotropy!

(Higuchi et al. in prep.)

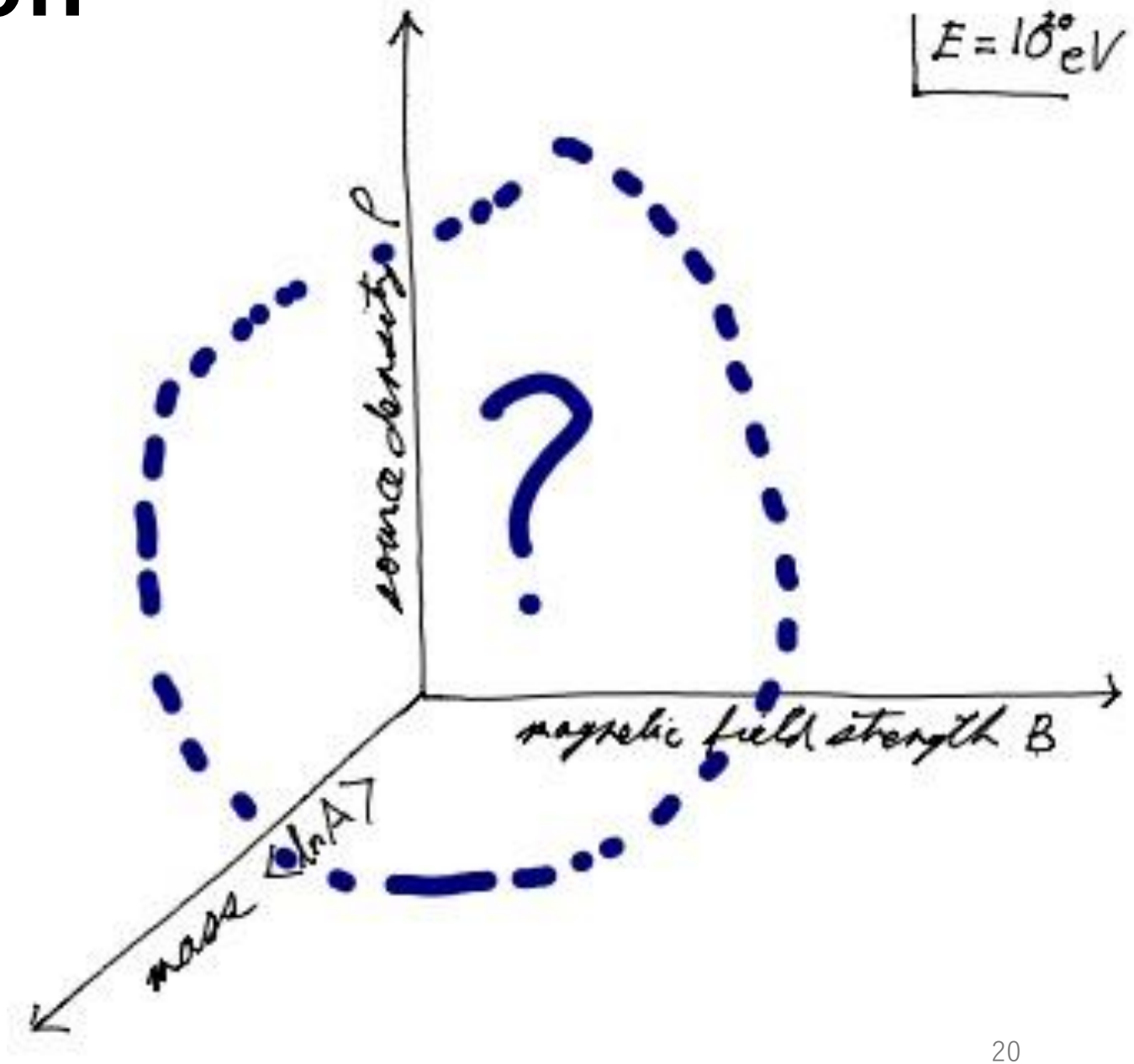
Single-iron/uranium can reproduce when magnetic field is strong.



- **Current highest energy events in TA/Auger do not show clear anisotropy**
- Non-detection of (small—scale) anisotropy can set lower limits
  - source density
  - magnetic fields strength
  - mass composition

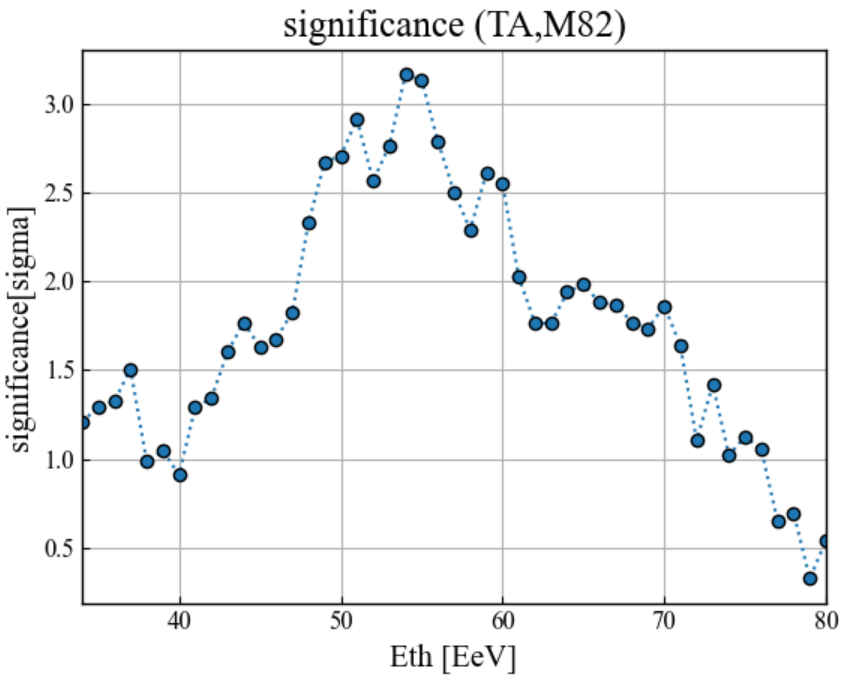
Future & my question

- Can we constrain conservative lower limits on
  - source density?
  - mass composition?
  - magnetic field strength?
- **How much did we “mine out” with the best effort of 20yr TA datasets?**
- **TA約20年間の観測で、どこまでパラメータ空間を掘り尽くしたのか？**
  - Auger comparison is also nice

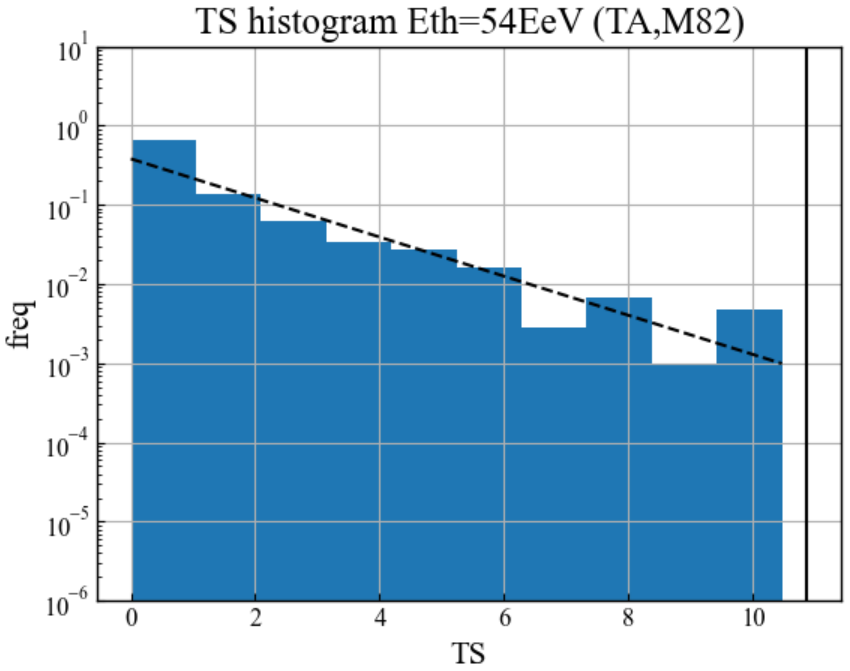


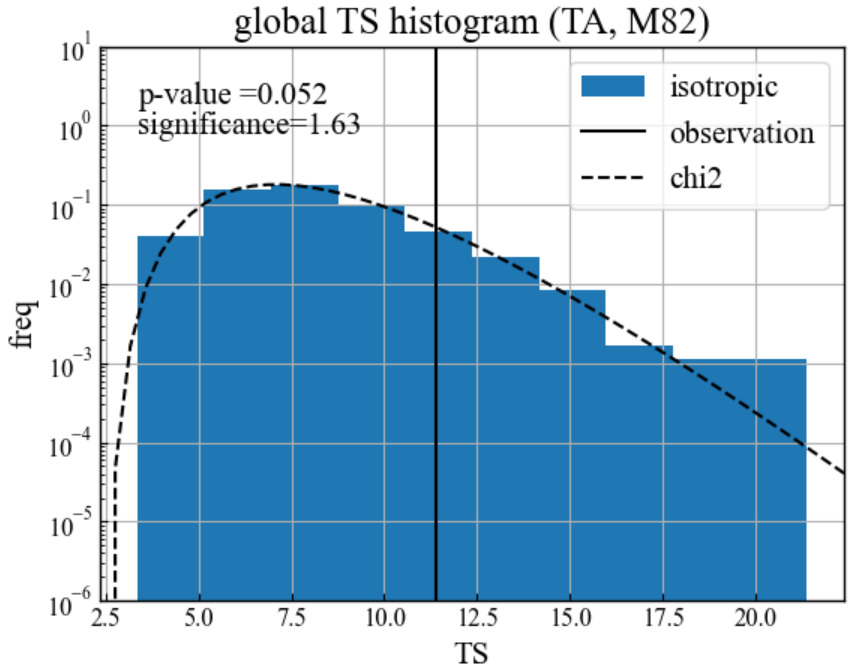
Appendix

M82 & TA dataset

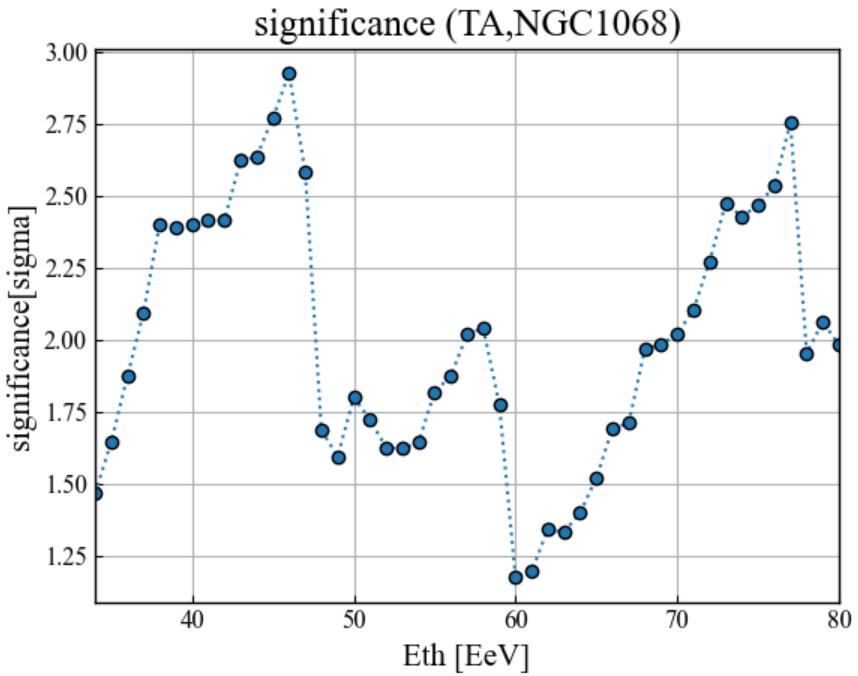


- local significance
  - 3.2 σ peak at Eth=54 EeV
- global significance
  - 1.6 σ

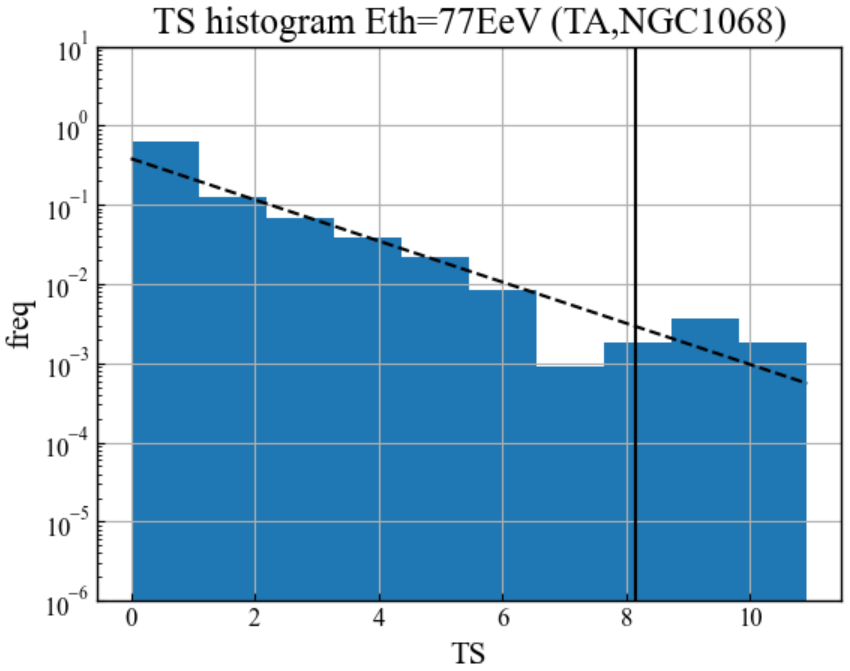


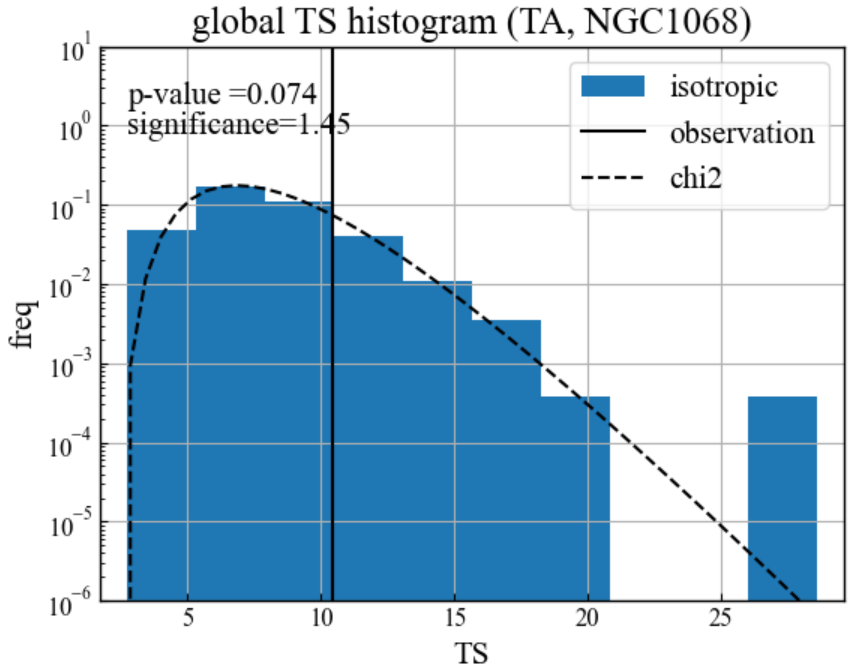


NGC1068 & TA dataset



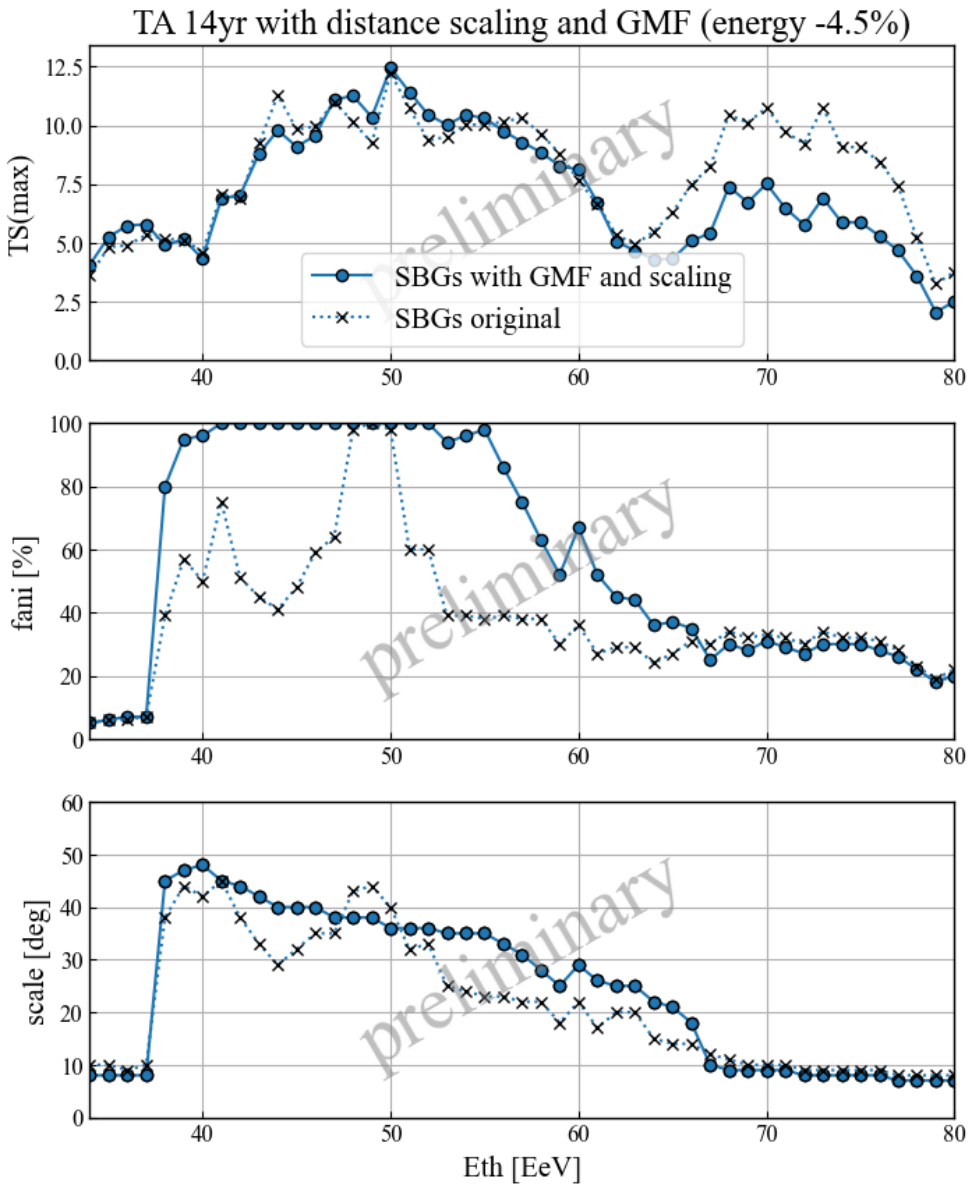
- local significance
  - 2.9 σ peak at Eth=46 EeV
  - 2.8 σ peak at Eth=77 EeV
- global significance
  - 1.5 σ

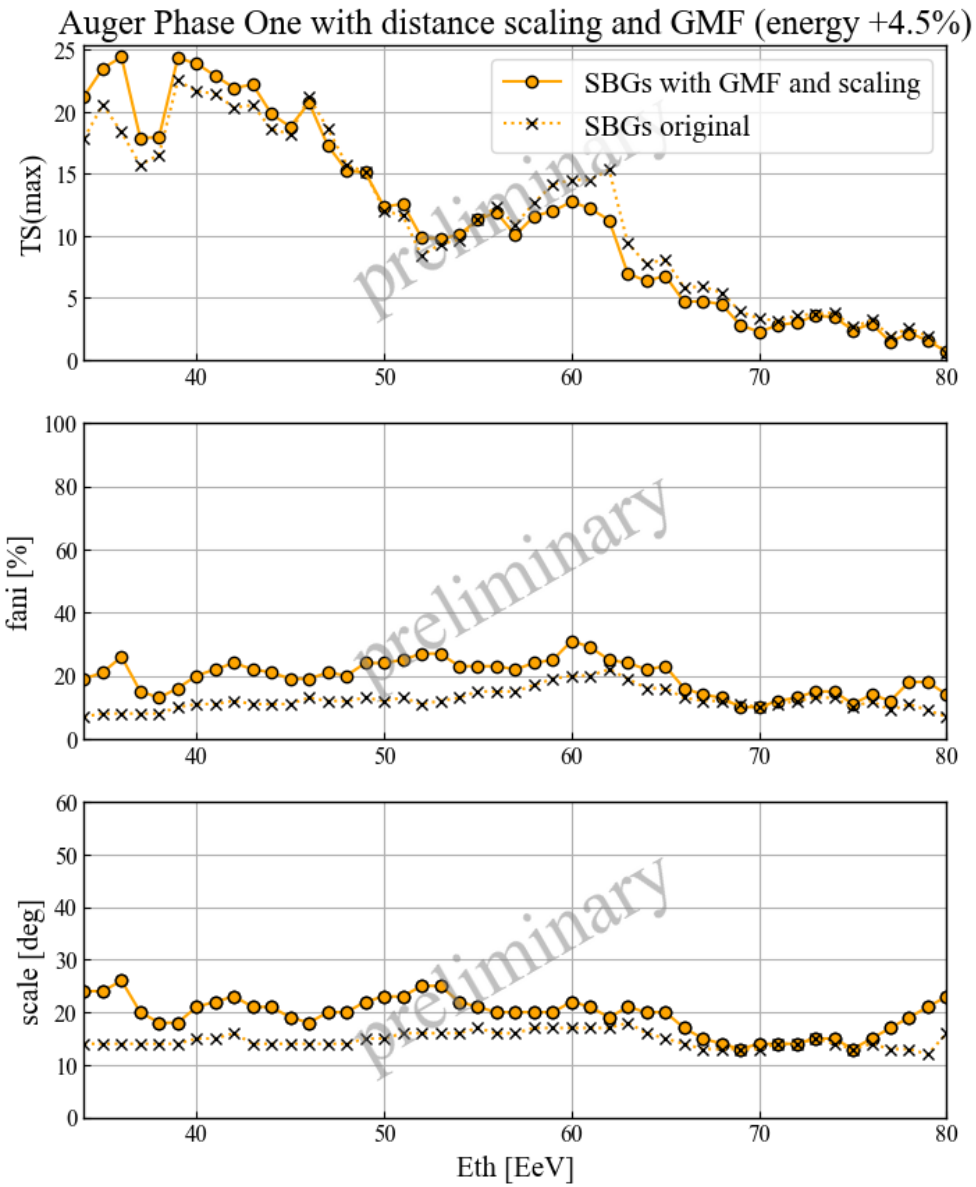




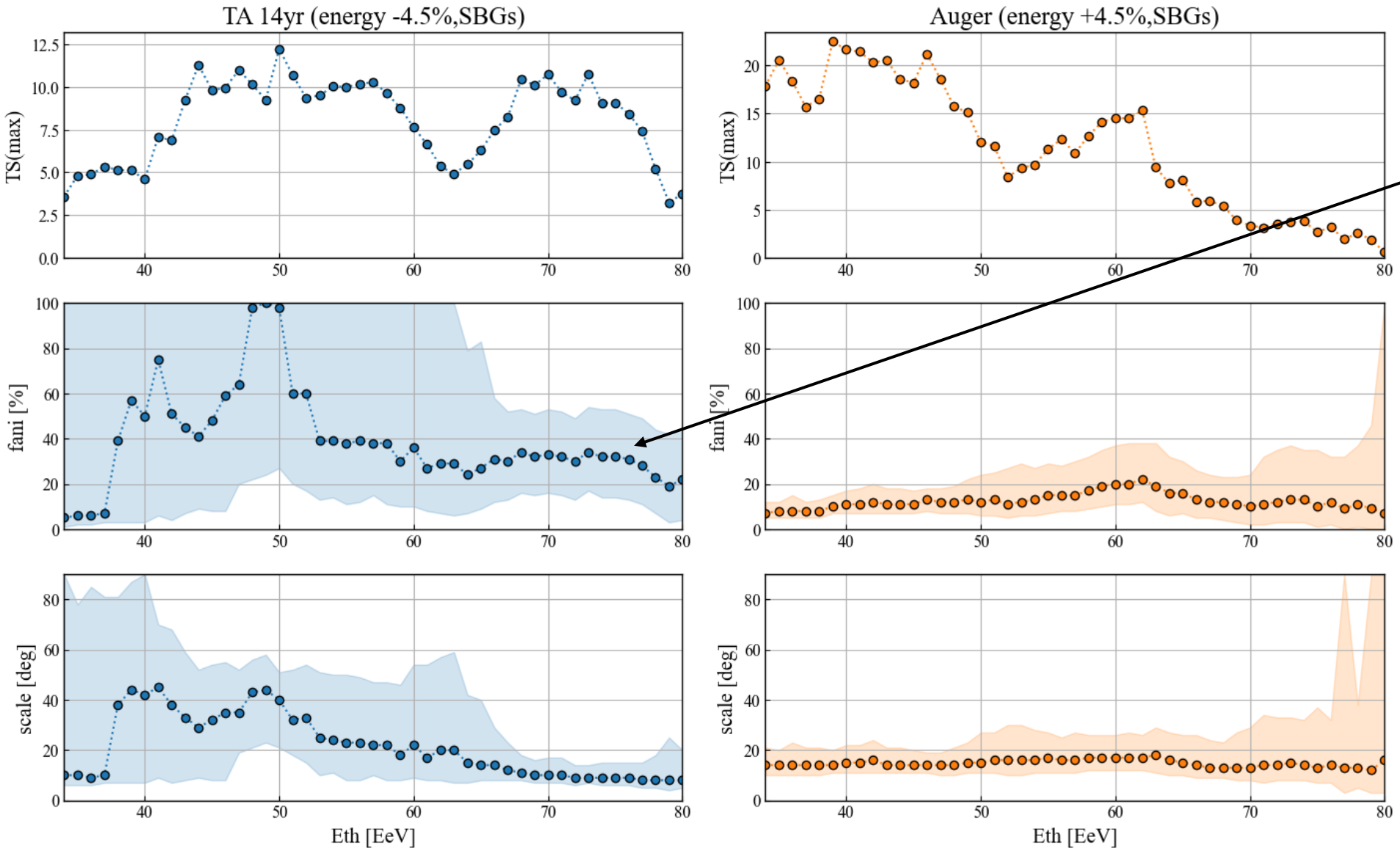
with GMF & GSF

- GMF



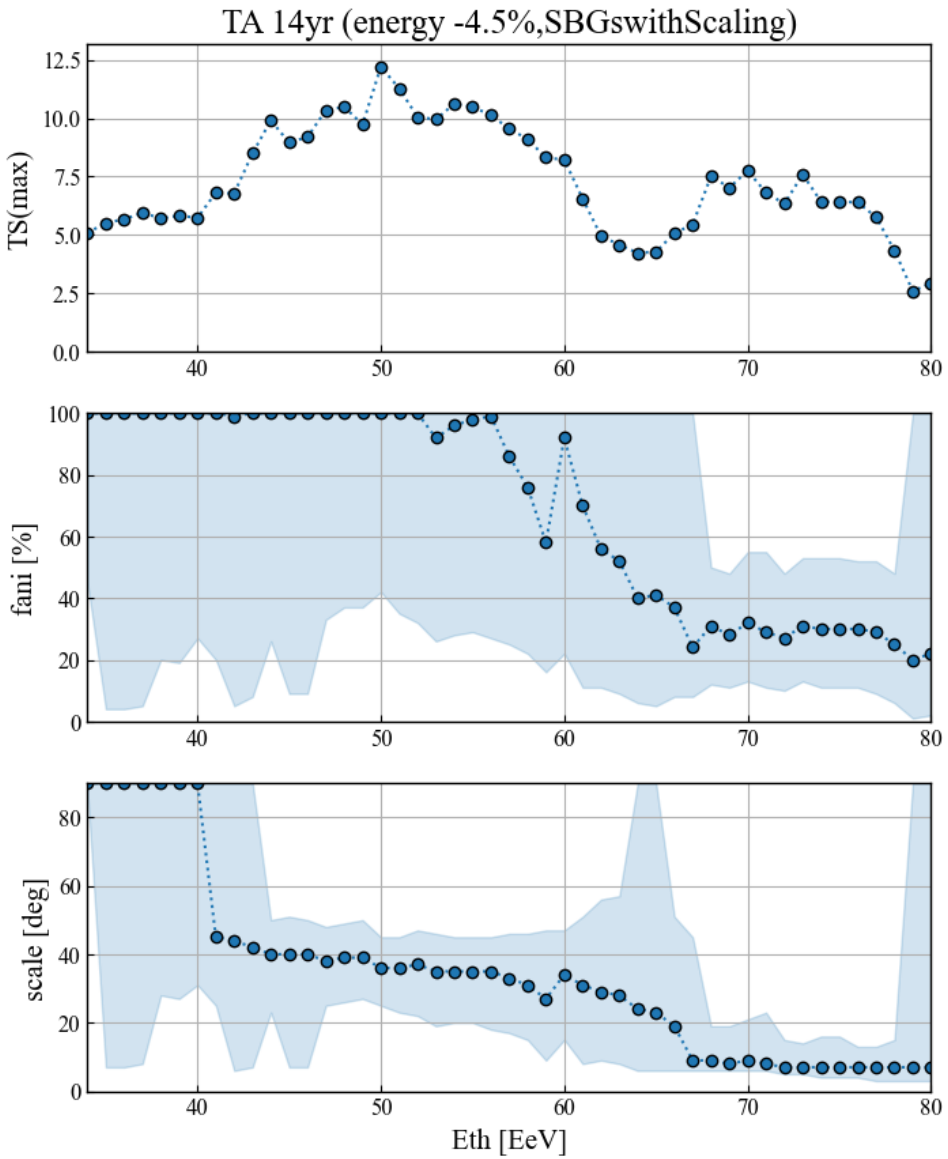


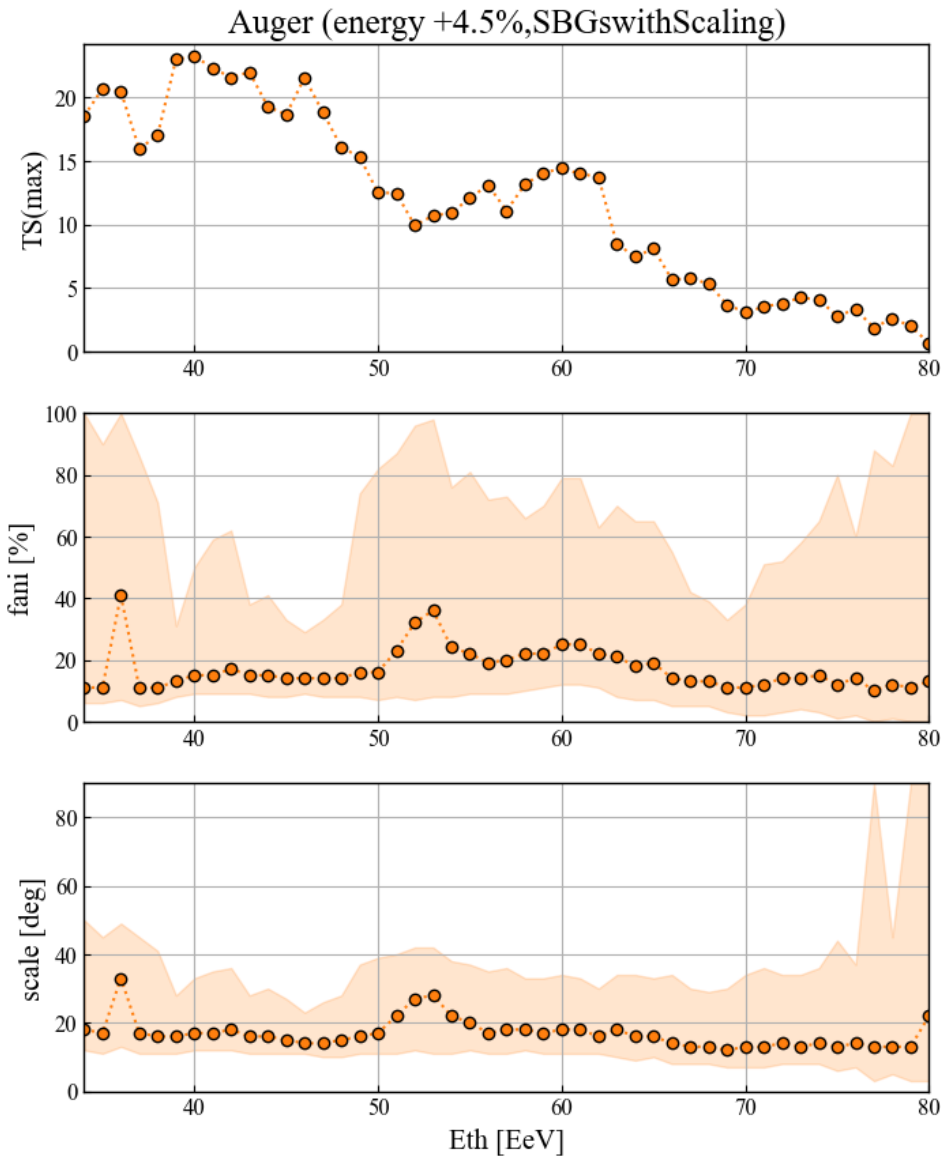
①Original analysis



- Uncertainty above 70EeV in TA is somehow gets smaller
  - I discuss about this later.

②with distance scaling





③with distance scaling & GMF lens (JF12)