SFB 1258 Neutrinos Dark Matter Messengers

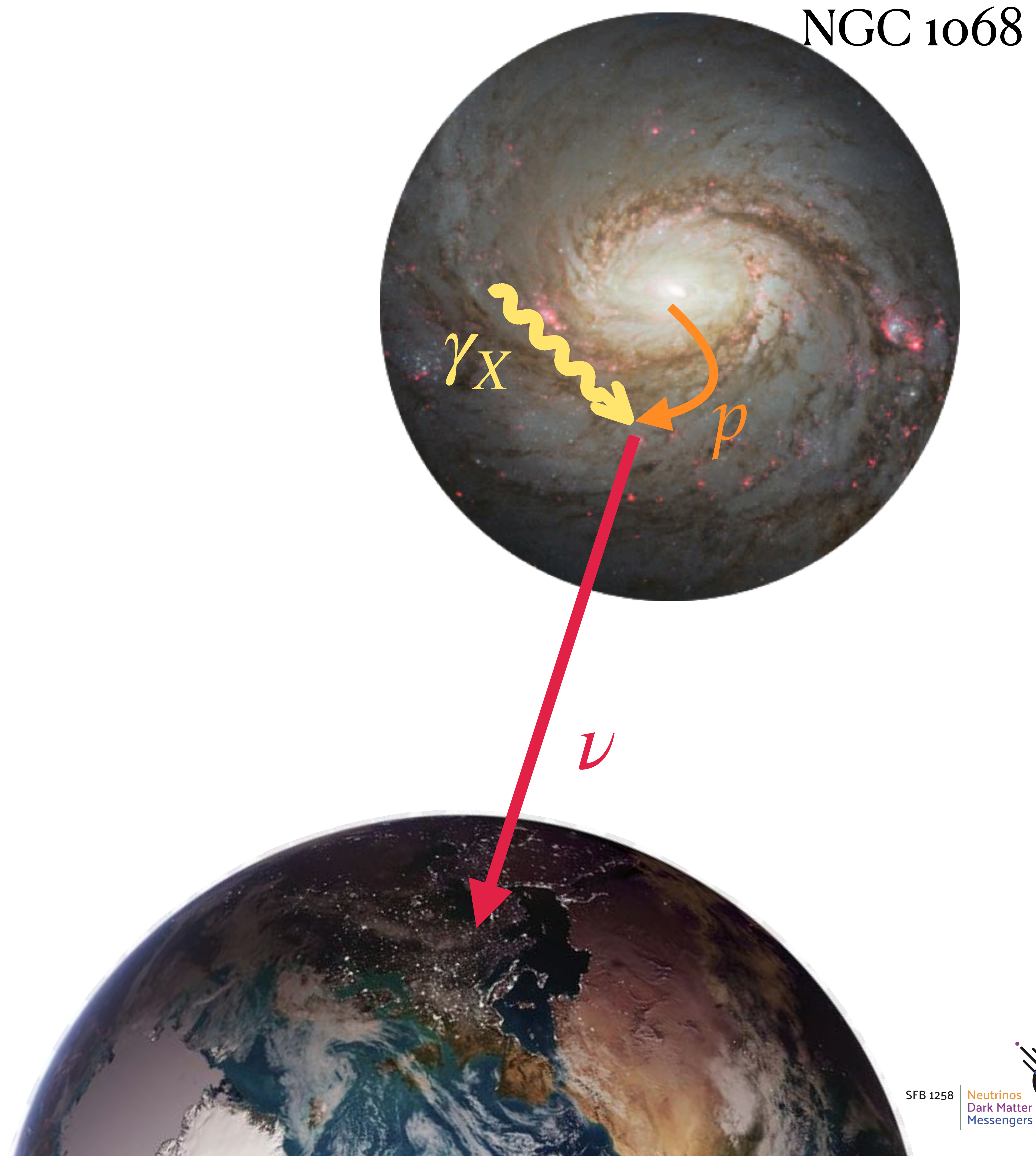
Exploring Cosmic Rays from Gravity-Limited Acceleration at Supermassive Black Holes

Elena Manao (elena.manao@tum.de)
Frank Rieger
Paolo Padovani
Gia Dvali
Elisa Resconi

Preprint out soon!

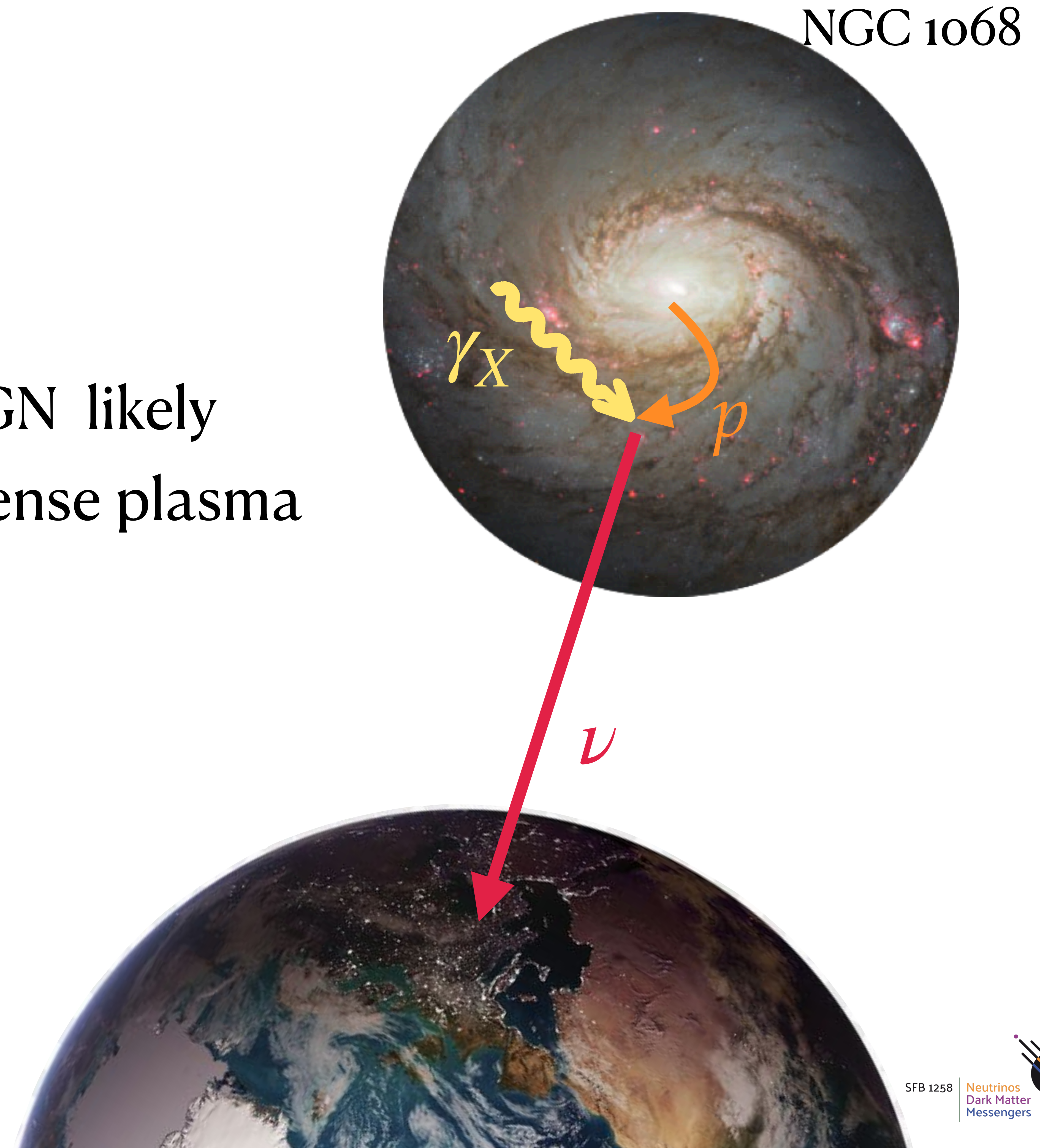
TeVPA 2026, Tendo (Japan) - Sept 1, 2026

UHECR — Neutrino (dis)connection



UHECR — Neutrino (dis)connection

- Consistently detected flux of UHECRs
- Origin still largely unknown
- From a neutrino perspective:
  - Neutrino flux from NGC 1068 and other X-ray bright AGN likely associated with $p\gamma$ interactions in the *corona* — a hot, dense plasma

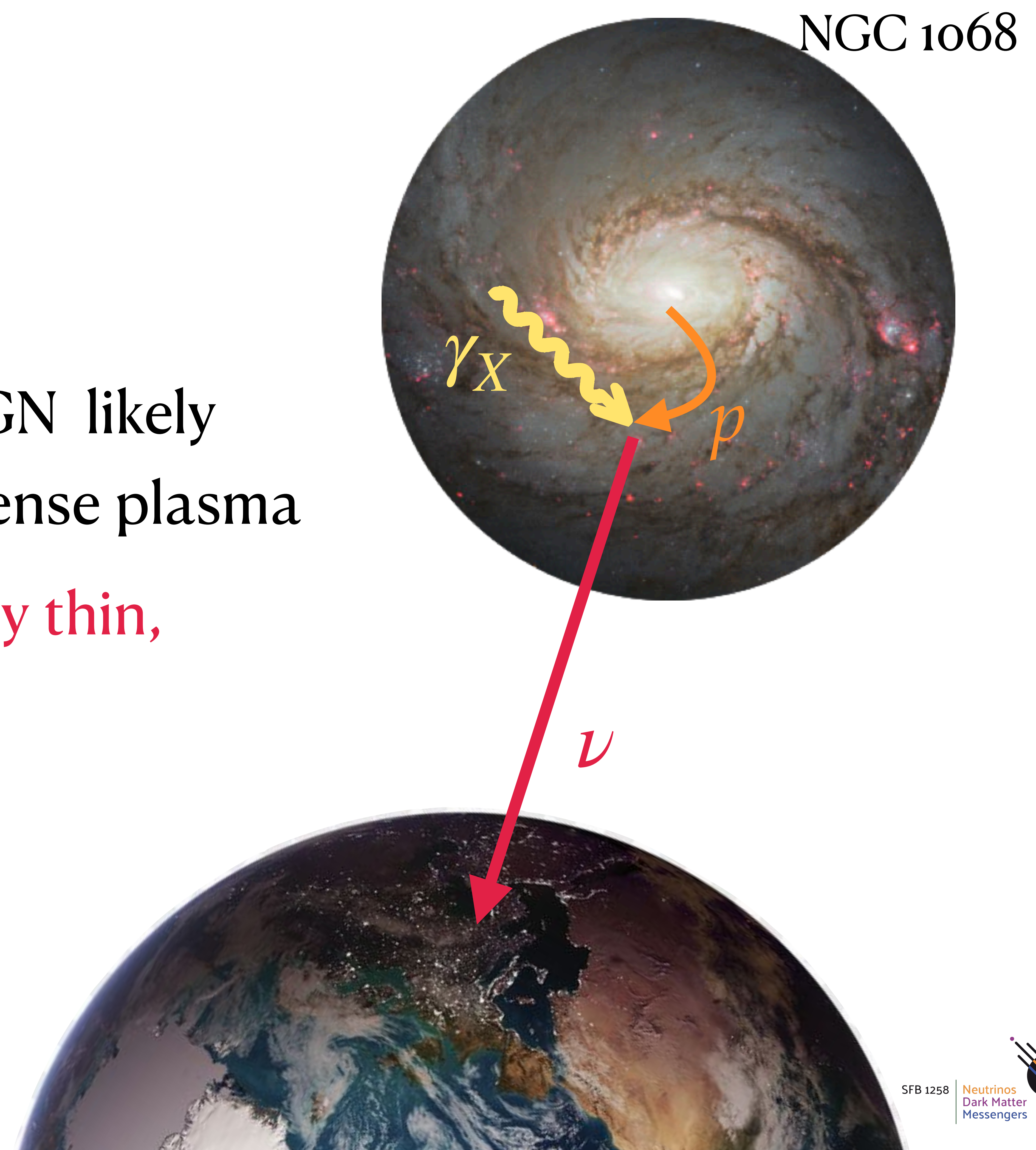


SFB 1258 Neutrinos Dark Matter Messengers

UHECR — Neutrino (dis)connection

- Consistently detected flux of UHECRs
- Origin still largely unknown
- From a neutrino perspective:
  - Neutrino flux from NGC 1068 and other X-ray bright AGN likely associated with $p\gamma$ interactions in the *corona* — a hot, dense plasma

➡UHECRs are more likely to survive and escape optically thin, 'diluted' environments

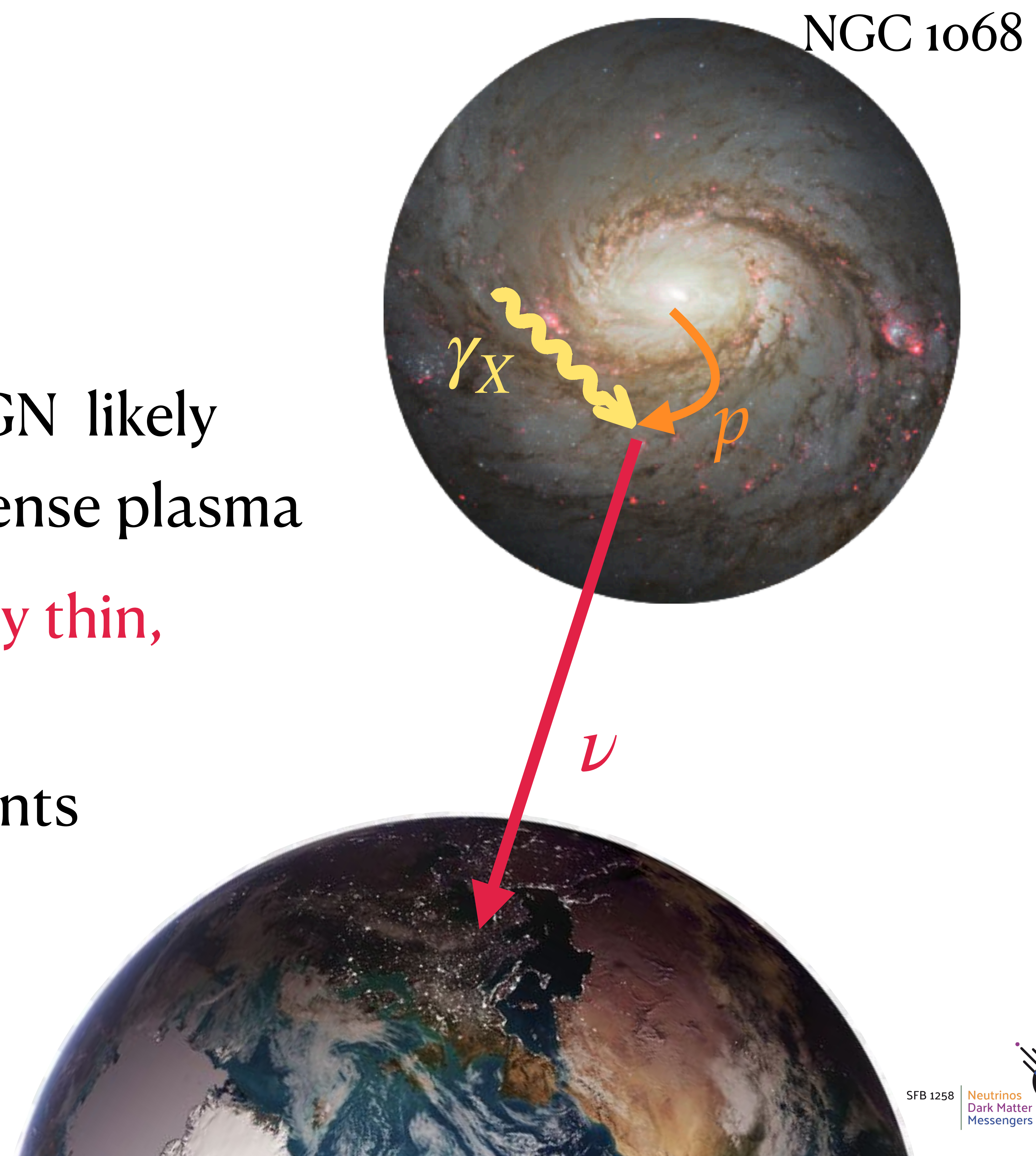


UHECR — Neutrino (dis)connection

- Consistently detected flux of UHECRs
- Origin still largely unknown
- From a neutrino perspective:
  - Neutrino flux from NGC 1068 and other X-ray bright AGN likely associated with $p\gamma$ interactions in the *corona* — a hot, dense plasma

➡UHECRs are more likely to survive and escape optically thin, 'diluted' environments

- These messengers being produced in different environments supported by lack of correlation in previous analyses



Where should we look for UHECR?

Where should we look for UHECR?

- **AGNs:** Optically thick, dense magnetospheres, highly accreting environments, jets

→ Heavy nuclei interact and don't escape; UHECRs are **unlikely unless there is a jet**, but jetted AGNs are rare in the nearby Universe

Where should we look for UHECR?

- **AGNs:** Optically thick, dense magnetospheres, highly accreting environments, jets

→ Heavy nuclei interact and don't escape; UHECRs are **unlikely unless there is a jet**, but jetted AGNs are rare in the nearby Universe

- **Low-Luminosity AGN:** Optically thin magnetospheres, radiatively inefficient accretion flows (RIAF)

→ Charge-starved regions (gaps) can form in the magnetosphere, particle acceleration and escape is **possible**

Where should we look for UHECR?

- **AGNs:** Optically thick, dense magnetospheres, highly accreting environments, jets

→ Heavy nuclei interact and don't escape; UHECRs are **unlikely unless there is a jet**, but jetted AGNs are rare in the nearby Universe

- **Low-Luminosity AGN:** Optically thin magnetospheres, radiatively inefficient accretion flows (RIAF)

→ Charge-starved regions (gaps) can form in the magnetosphere, particle acceleration and escape is **possible**

- **Quiescent Nuclei:**
very low accretion rates, lack of strong non-thermal radiation signatures

→ Magnetic fields are intrinsically generated by a SMBH, regardless of the specific environment or accretion.
New class of UHECR sources?

Gravity-Limited Magnetic Fields in SMBH

- The interplay between General Relativity and Electromagnetism results in:
  $$\frac{B^2}{8\pi} \lesssim \rho_{\rm grav} \sim \frac{GM^2}{R^4} \quad \longrightarrow \quad B_{\rm max} \sim \frac{c^4}{G^{3/2}M} \quad \text{assuming} \quad R \sim R_S = 2GM/c^2$$
- B intrinsically originated in the SMBH
  - Fundamental, model-independent limit.
- $B \approx 10^{10-13}$ G would not be sustained by a SMBH
  - Too large magnetic pressure
  - These objects would be more luminous than the brightest objects known to date (e.g., GRBs)

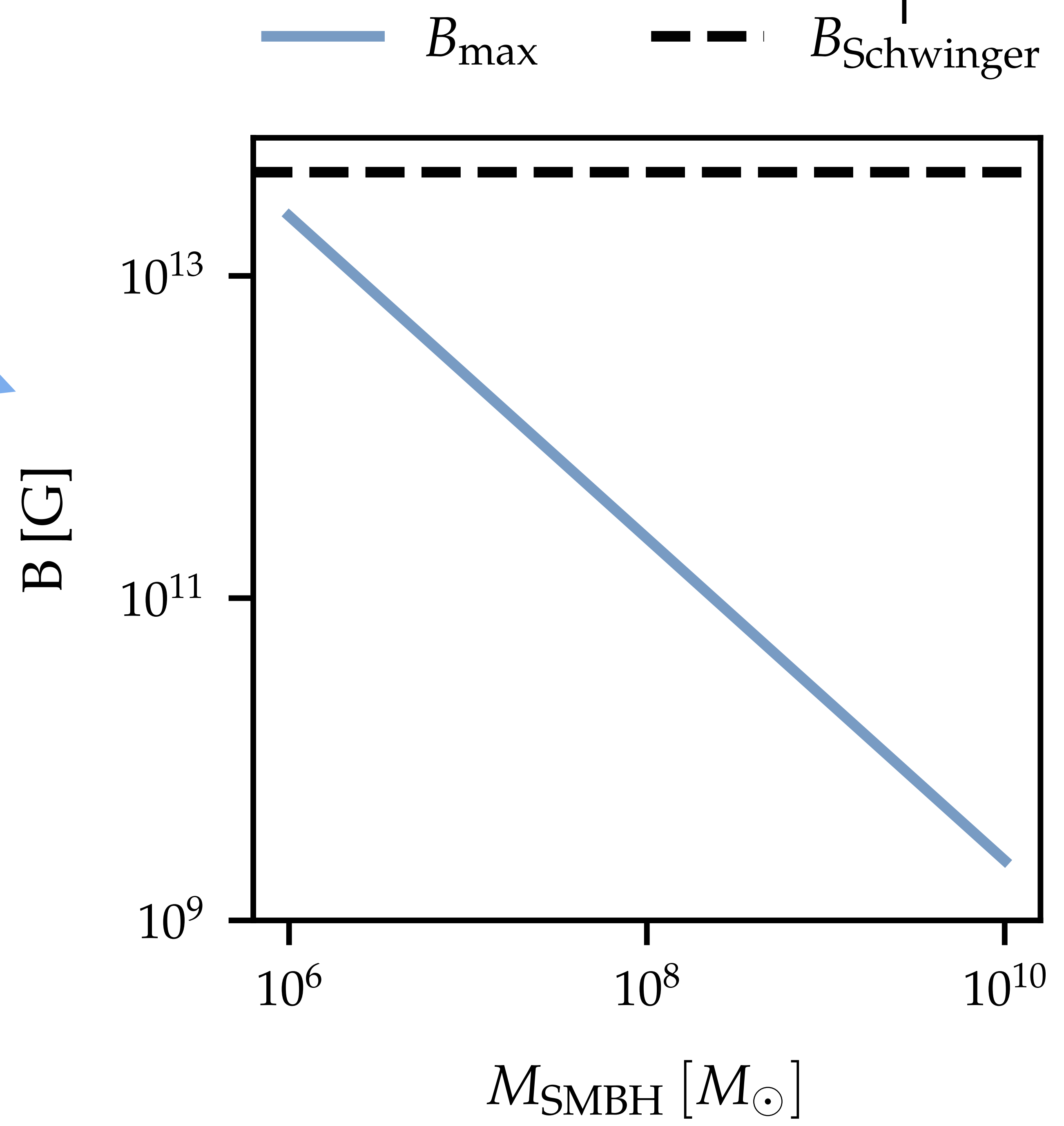
Gravity-Limited Magnetic Fields in SMBH

- The interplay between General Relativity and Electromagnetism results in:

$$\frac{B^2}{8\pi} \lesssim \rho_{\rm grav} \sim \frac{GM^2}{R^4} \longrightarrow \boxed{B_{\rm max} \sim \frac{c^4}{G^{3/2}M}} \text{ assuming } R \sim R_S = 2GM/c^2$$

- B intrinsically originated in the SMBH
  - Fundamental, model-independent limit.
- $B \approx 10^{10-13}$ G would not be sustained by a SMBH
  - Too large magnetic pressure
  - These objects would be more luminous than the brightest objects known to date (e.g., GRBs)

Limit at which non-linear QM effects start to emerge



SFB 1258 Neutrinos Dark Matter Messengers

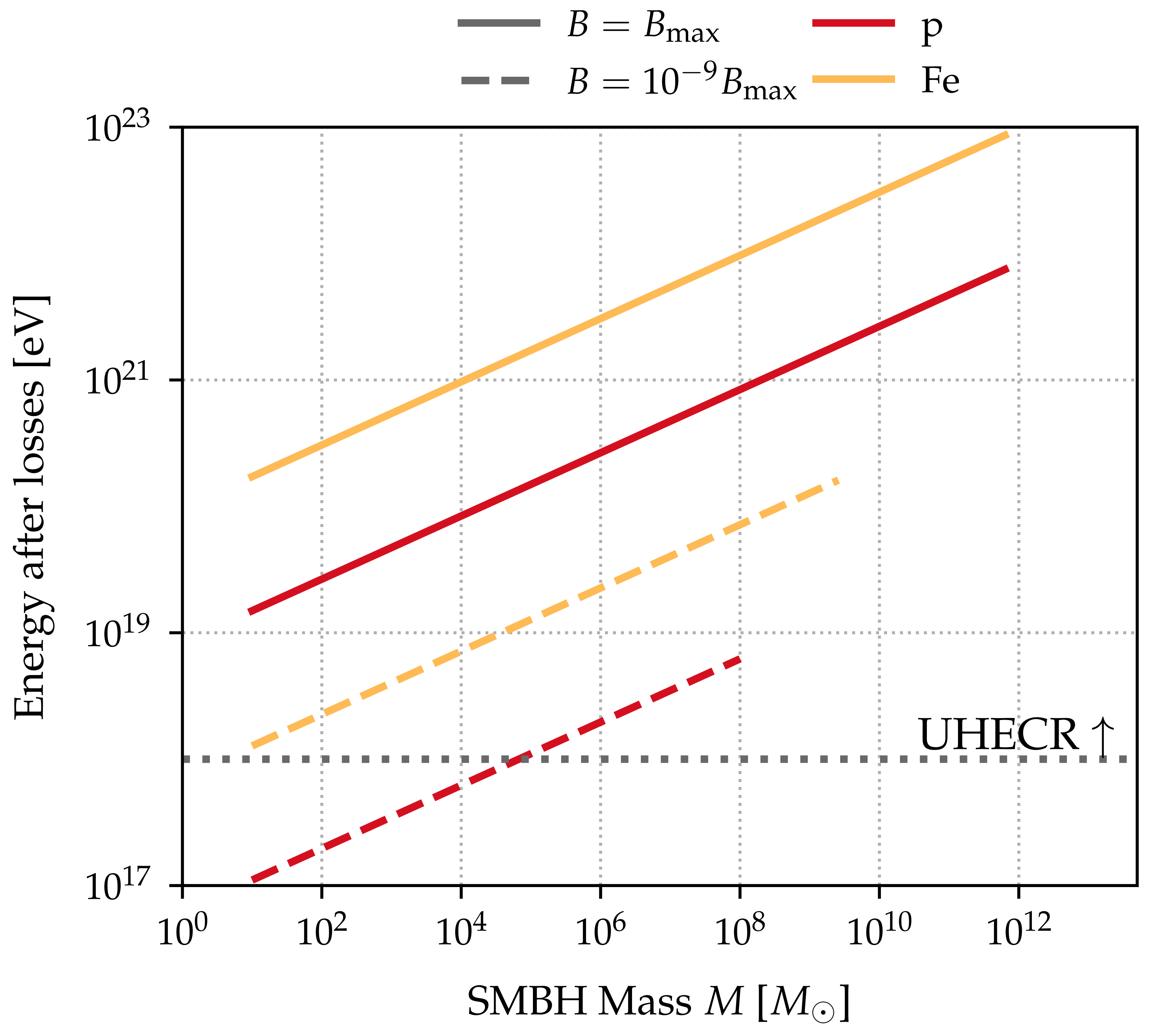
Scaling B_{max} to lower values

- B_{max} is an upper limit
  - Lower values of B can arise in the vicinity of SMBHs
- Focusing on **quiescent nuclei**, the requirements are:
  - **Luminosity**: $L \propto \dot{m}^2 L_{\mathrm{Edd}}$ → equivalent to RIAF regime, low-luminosity nucleus
  - **Magnetic Field**: $B \lesssim 10^5 \dot{m}^{1/2} (M/10^9 M_\odot)^{-1/2}\,\mathrm{G}$ → Equipartition Theorem for RIAF
  - **Gap width**: $w \sim \ell_{\mathrm{Photodisintegration}}$ → Nuclei must escape before being disintegrated

Can a B << B_{max} in a quiescent nucleus accelerate CR to the highest energies?

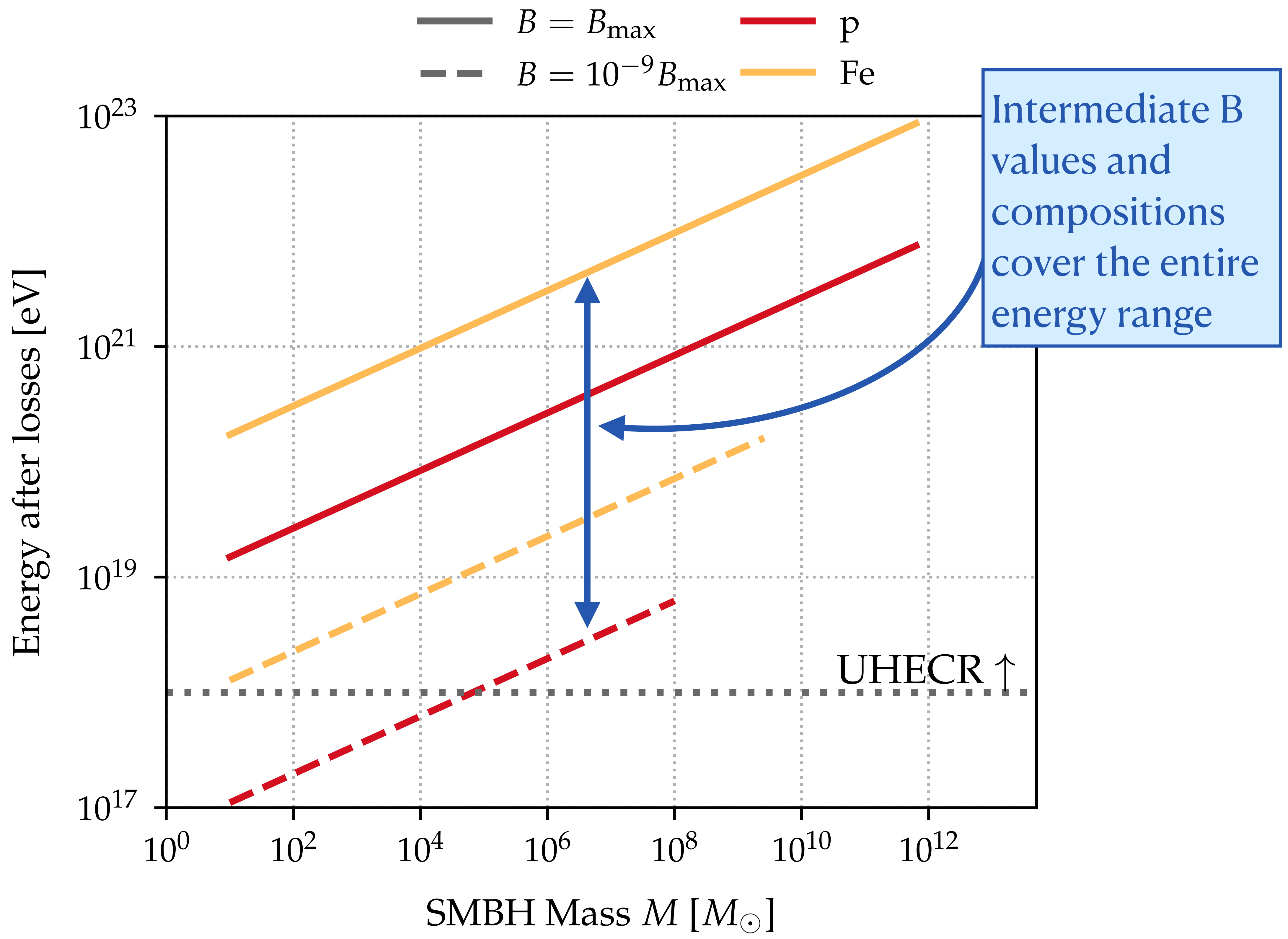
Energy Gain in the Gravity-Limited Scenario

- Geometric energy gain by acceleration along electric field lines:
  $E_{\mathrm{geom}} = aZeBR_S \xrightarrow{B=B_{\max}} E_{\mathrm{geom}} \approx O(10^{27})\,\mathrm{eV}$
- Including curvature energy losses and considering values of B comparable to those of known systems, $B \approx 10^{-9}B_{\max}$
- Final energies comparable to observed UHECR



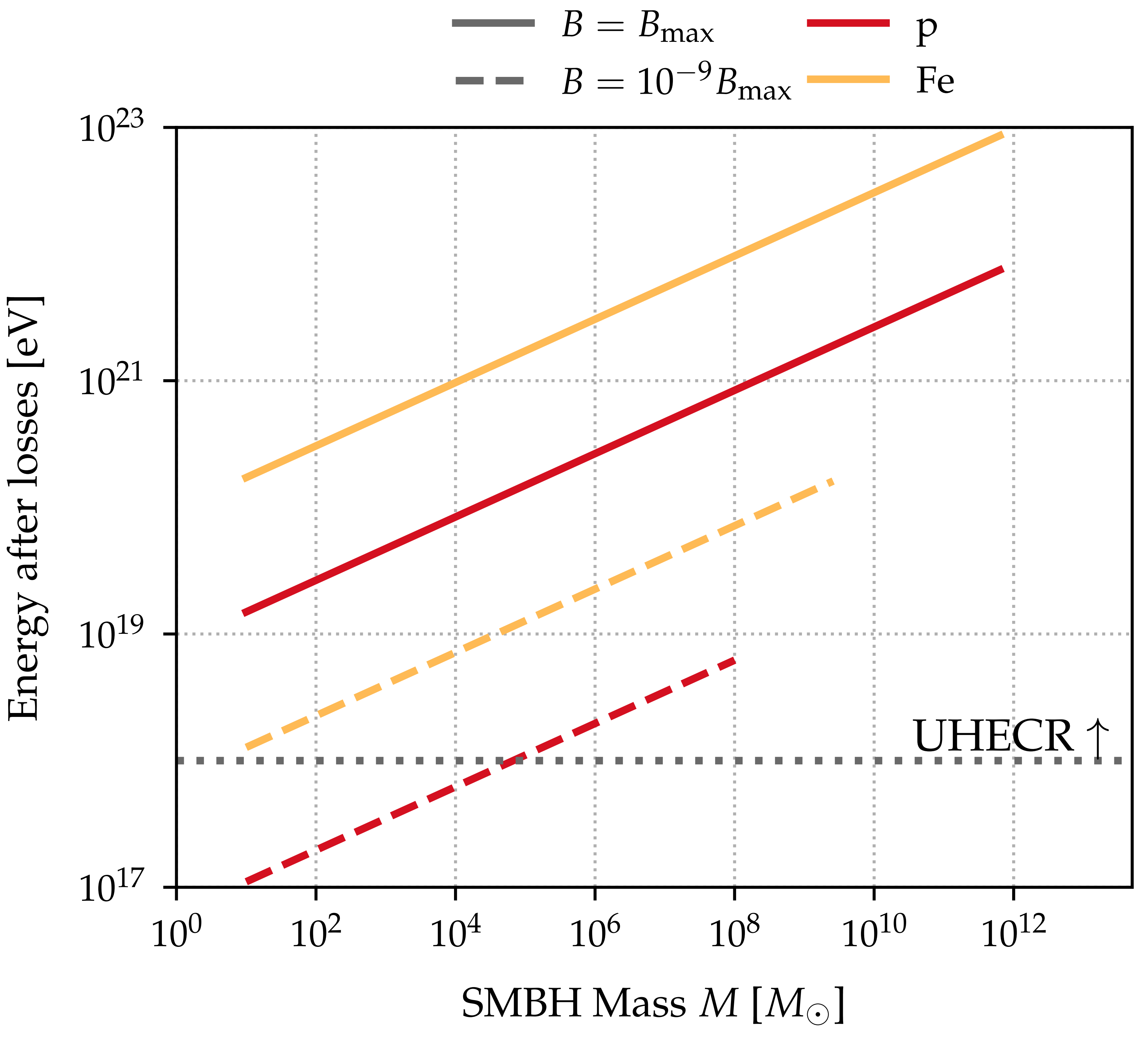
Energy Gain in the Gravity-Limited Scenario

- Geometric energy gain by acceleration along electric field lines:
$E_{\rm geom} = aZeBR_S \xrightarrow{B=B_{\rm max}} E_{\rm geom} \approx O(10^{27})\,{\rm eV}$
- Including curvature energy losses and considering values of B comparable to those of known systems, $B \approx 10^{-9} B_{\rm max}$
- Final energies comparable to observed UHECR



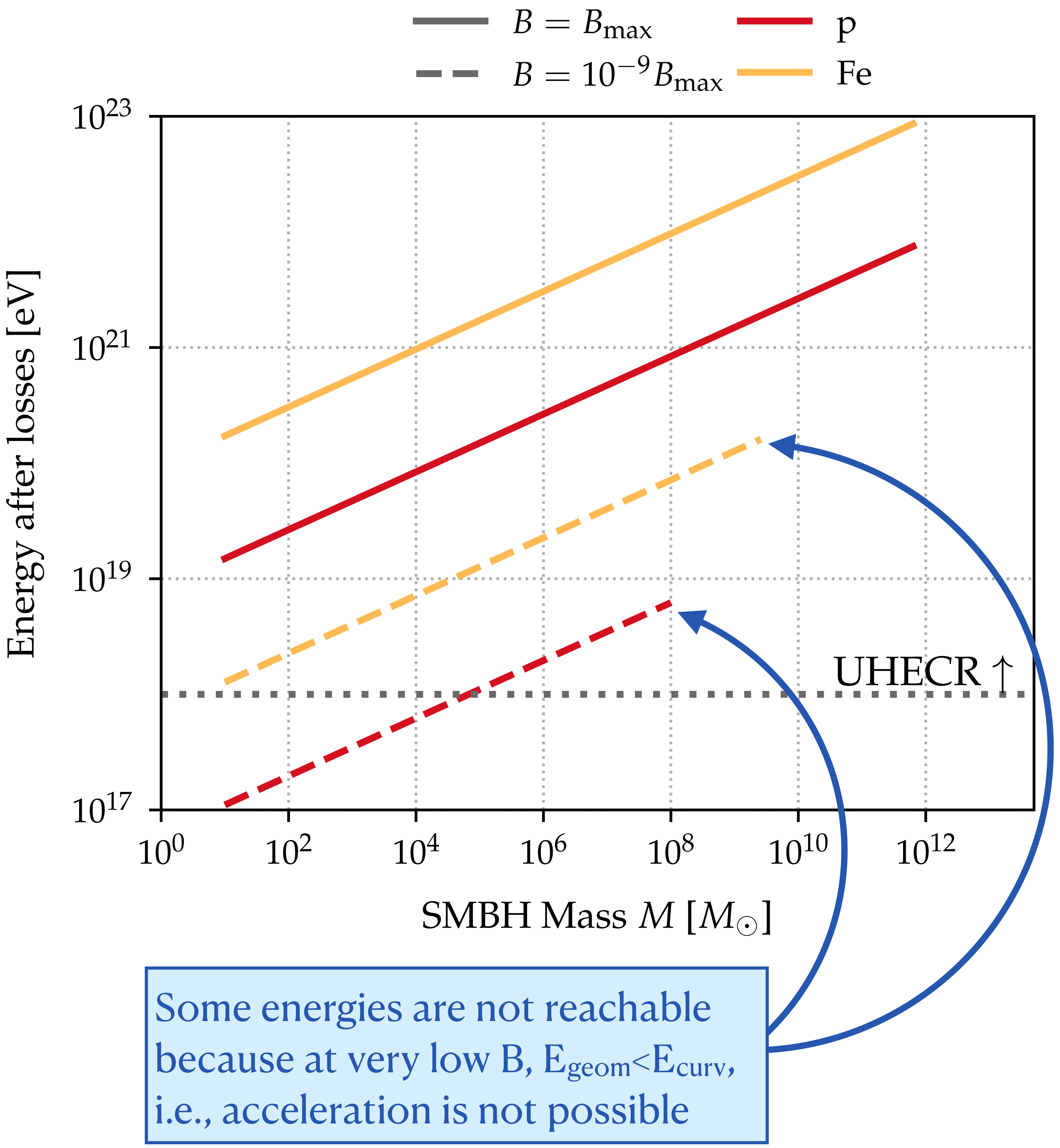
Energy Gain in the Gravity-Limited Scenario

- Geometric energy gain by acceleration along electric field lines:
$E_{\mathrm{geom}} = aZeBR_S \xrightarrow{B=B_{\mathrm{max}}} E_{\mathrm{geom}} \approx O(10^{27})\,\mathrm{eV}$
- Including curvature energy losses and considering values of B comparable to those of known systems, $B \approx 10^{-9} B_{\mathrm{max}}$
- Final energies comparable to observed UHECR



Energy Gain in the Gravity-Limited Scenario

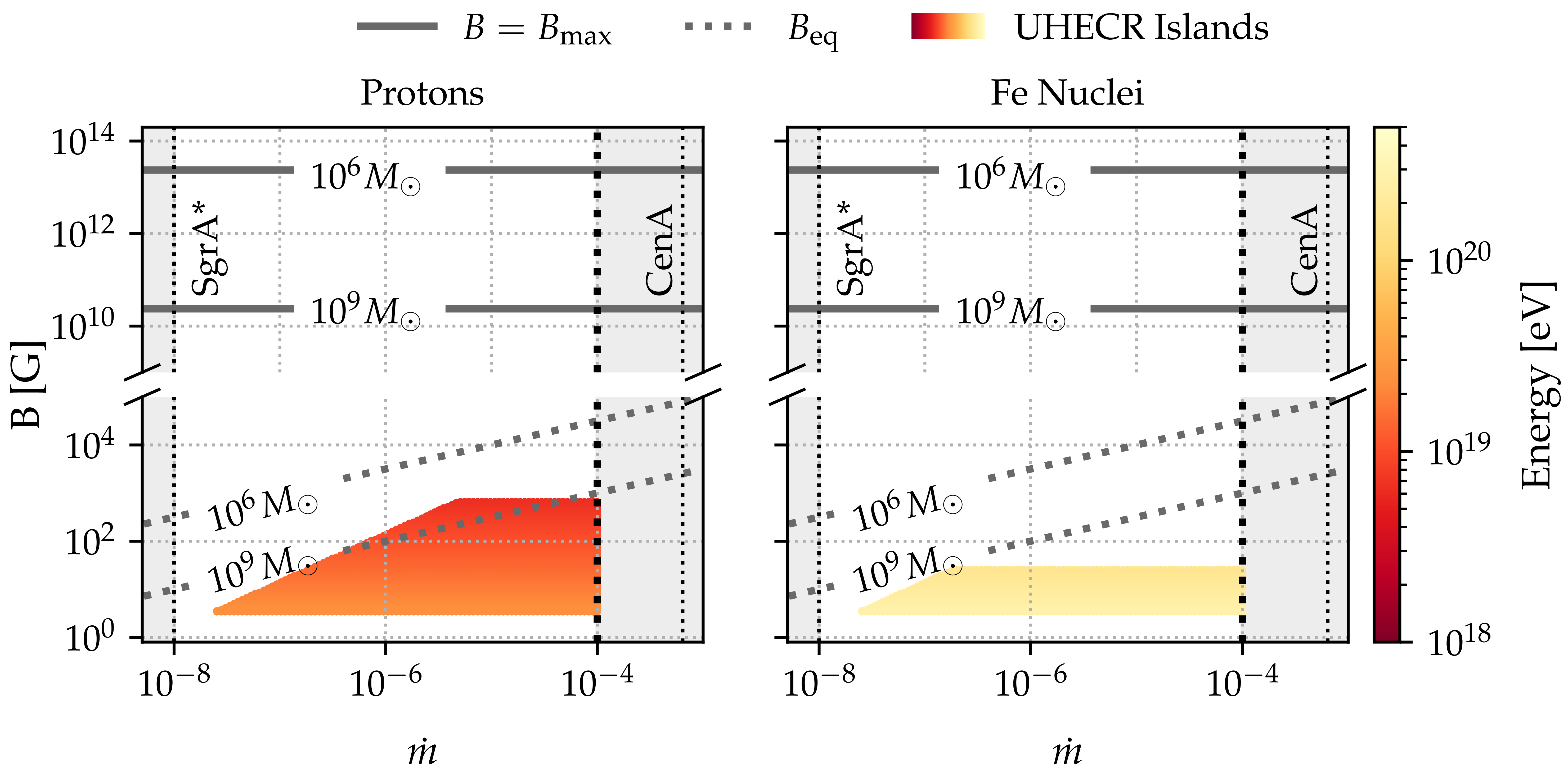
- Geometric energy gain by acceleration along electric field lines:
  $E_{\mathrm{geom}} = aZeBR_S \xrightarrow{B=B_{\mathrm{max}}} E_{\mathrm{geom}} \approx O(10^{27})\,\mathrm{eV}$
- Including curvature energy losses and considering values of B comparable to those of known systems, $B \approx 10^{-9}B_{\mathrm{max}}$
- Final energies comparable to observed UHECR



UHECR islands

Parameter space in $\dot{m}$ and B that satisfies:

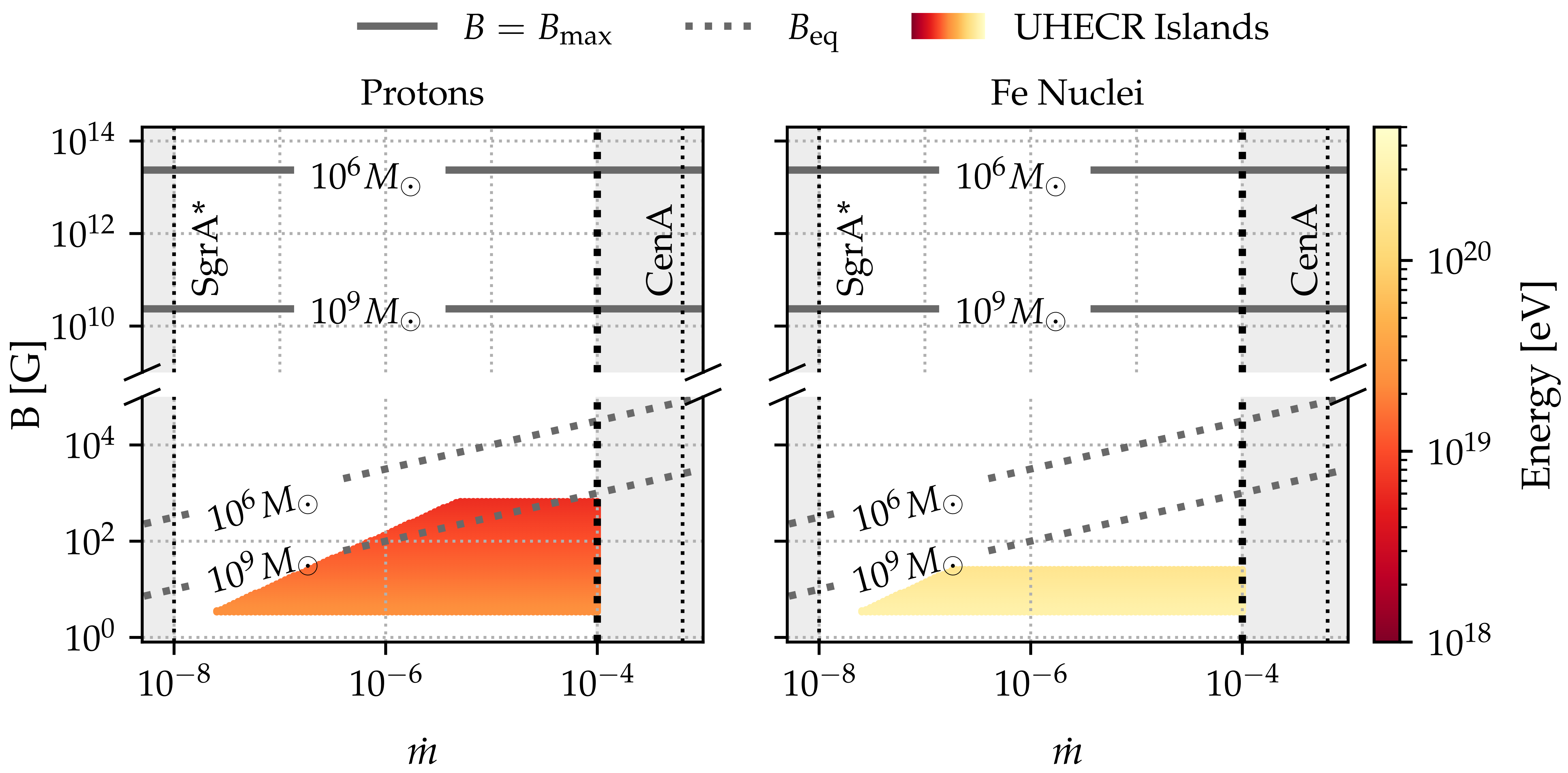
- $\dot{m} < 10^{-4}$: quiescent nuclei
- $10^{-9} B_{\rm max}(M) < B_{\rm eq}(\dot{m}, M)$: B fields comparable to those of known systems
- $E_{\rm curv}(M, B) > 10^{18}\,\mathrm{eV} \rightarrow$ UHECR
- SMBH masses $10^6 M_\odot \leq M \leq 10^{10} M_\odot$



UHECR islands

Parameter space in $\dot{m}$ and B that satisfies:

- $\dot{m} < 10^{-4}$: quiescent nuclei
- $10^{-9} B_{\rm max}(M) < B_{\rm eq}(\dot{m}, M)$: B fields comparable to those of known systems
- $E_{\rm curv}(M, B) > 10^{18}\,\mathrm{eV} \rightarrow$ UHECR
- SMBH masses $10^6 M_\odot \leq M \leq 10^{10} M_\odot$

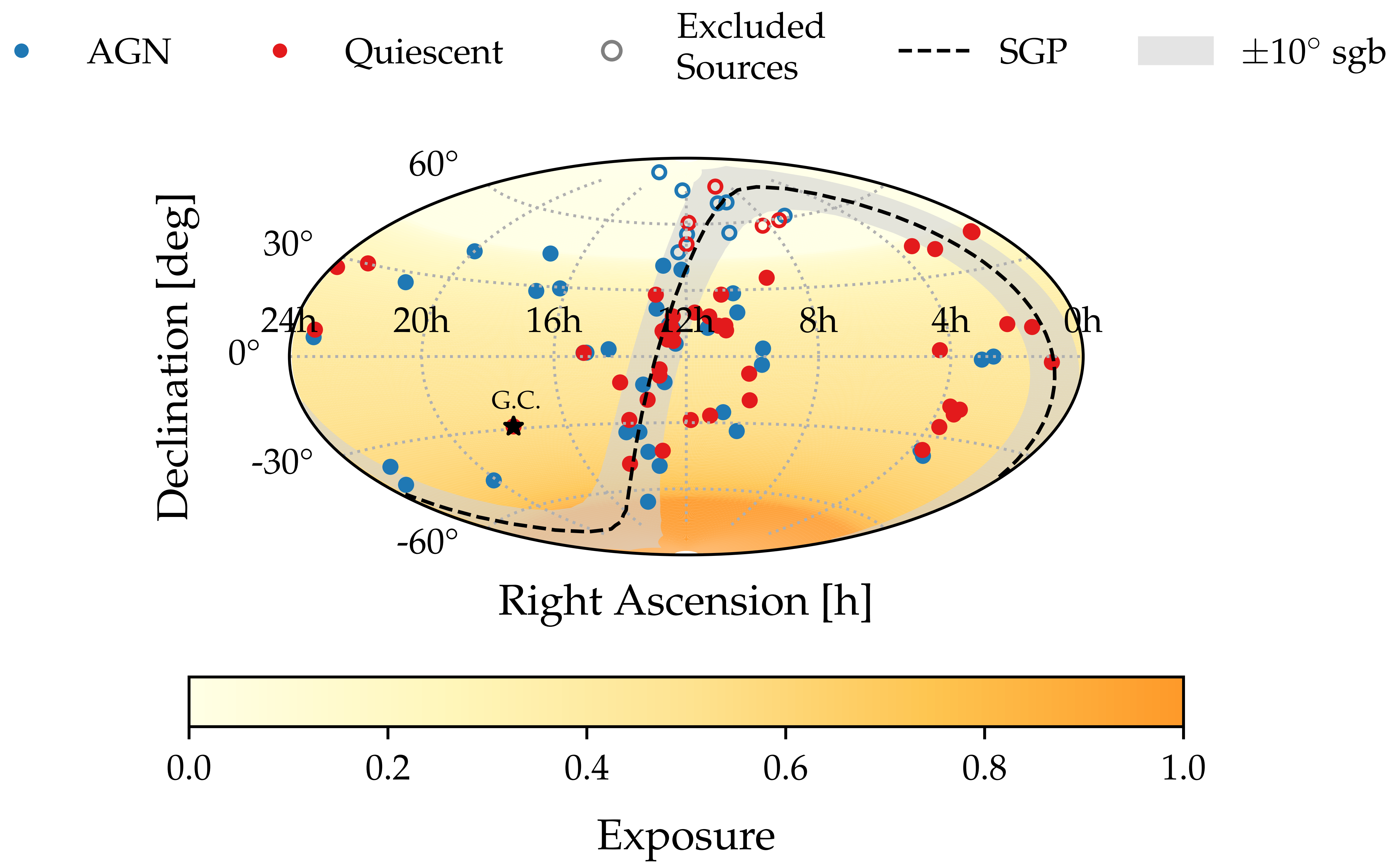


UHECR energies are also reachable in environments with very low accretion rates

Testing the scenario on UHECR data

Correlating quiescent nuclei with UHECR from the Pierre Auger Observatory

(2022 data release by PAO)



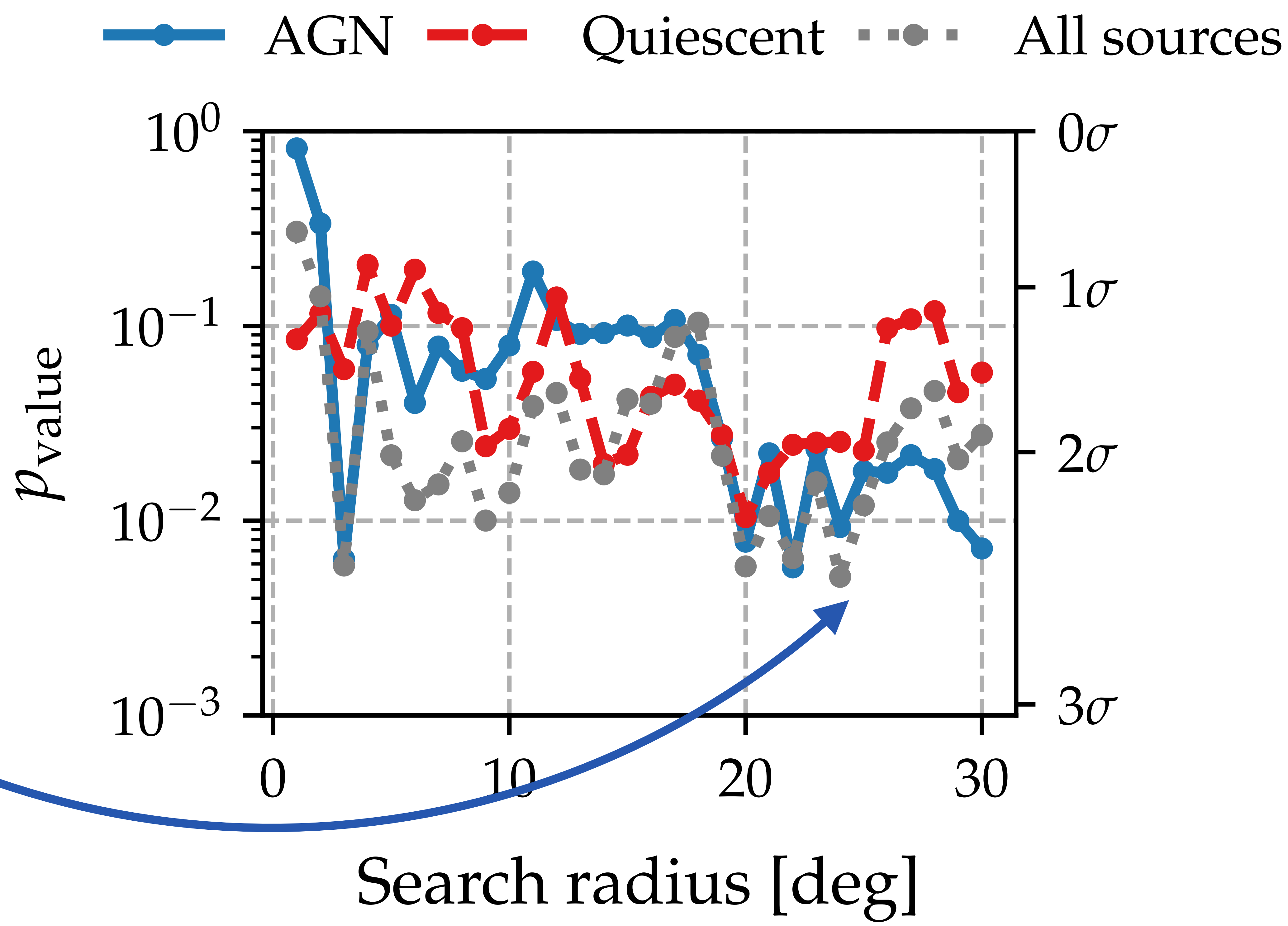
- Count events that fall in the vicinity of a source, testing angular distances $\theta = 1^\circ, \ldots, 30^\circ$ at steps of 1°
- Estimate the fraction of associated events $\boldsymbol{f}$ for each angular distance θ and compare it with the outcome of background simulations

Correlation Results

3 tested cases

- AGN only
- Quiescent only
- All the sources

- Best result:
  - All the sources for a search radius of 24°
  - Local p_{value} of ~2.8σ, compatible with background after correcting for look-elsewhere effect
  - The analysis is not sensitive enough to identify signal from these sources



SFB 1258 Neutrinos Dark Matter Messengers

Conclusions

Preprint out soon!

- **B fields emerging from gravity-limited constraints can produce Cosmic Rays with energies above 10^{18} eV**
- Such energies are attainable with minimal requirements on the environment surrounding the SMBH
  - **Not needed**: efficient accretion flow, jet, corona,
  - **Needed**: gap in the magnetosphere with width $w \sim R_S \sim \ell_{\mathrm{Photodisintegration}}$, $B \sim B_{eq}$
- In this scenario, quiescent galaxies satisfy the requirements to be UHECR sources
- Correlation analysis between nearby SMBHs and UHECR doesn't show significant results, but it is also <u>not powerful enough to exclude such a scenario</u>

Outlook

- **Analysis side:** need for more sophisticated searches for UHECRs in quiescent nuclei
    - Larger datasets and improved knowledge of UHECR composition
- **Theoretical side:** more precise quantification of gap formation, field topology, and cosmic-ray injection in quiescent nuclei is needed

Thank you for your attention!
Questions?

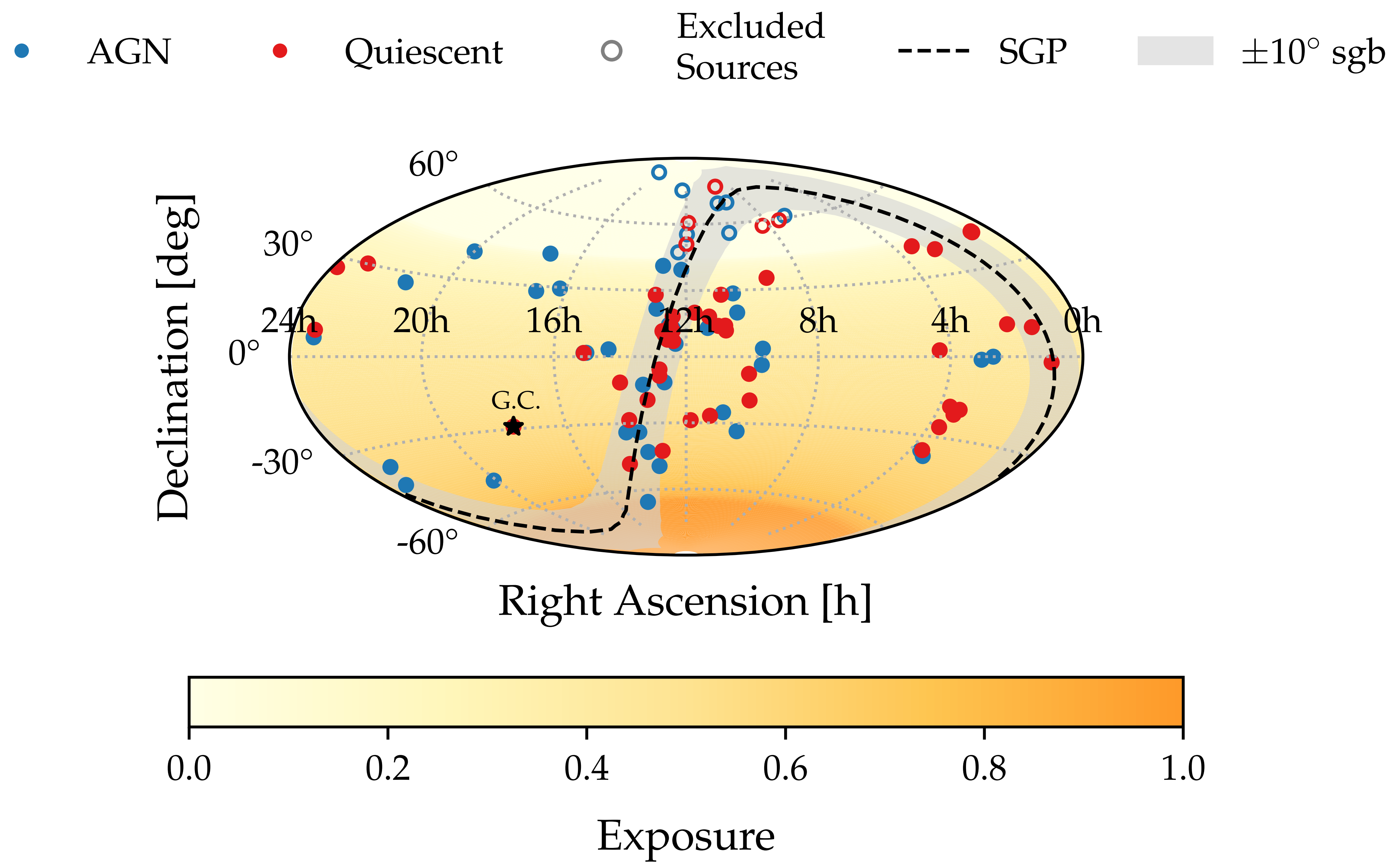
Backup Slides

Curvature losses

- The final energy of the particle after accounting for curvature energy losses is calculated as follows:
  - Equating the geometric energy gain and the curvature energy loss
  $$\left(\frac{dE}{dt}\right)_{\text{gain}} = Ze\, a_s\, B\, c \;=\; \left(\frac{dE}{dt}\right)_{\text{loss}} = \frac{2}{3}\frac{(Ze)^2 c\, \gamma^4}{R_c^2}$$
  - Substituting $\gamma = E/(mc^2)$
  - The final energy results in: $E_{\text{curv}} = \left(\dfrac{3\, a_s\, m^4 c^8\, B\, R_c^2}{2\, Ze}\right)^{1/4}$
  - Assuming $R_c \sim R_S$ and $B \propto B_{\max}$ one finds: $E_{\text{curv}} \propto \left(B_{\max} R_S^2\right)^{1/4} \propto M^{1/4}$
  - The final energy of the particle has a slight dependence on the SMBH mass

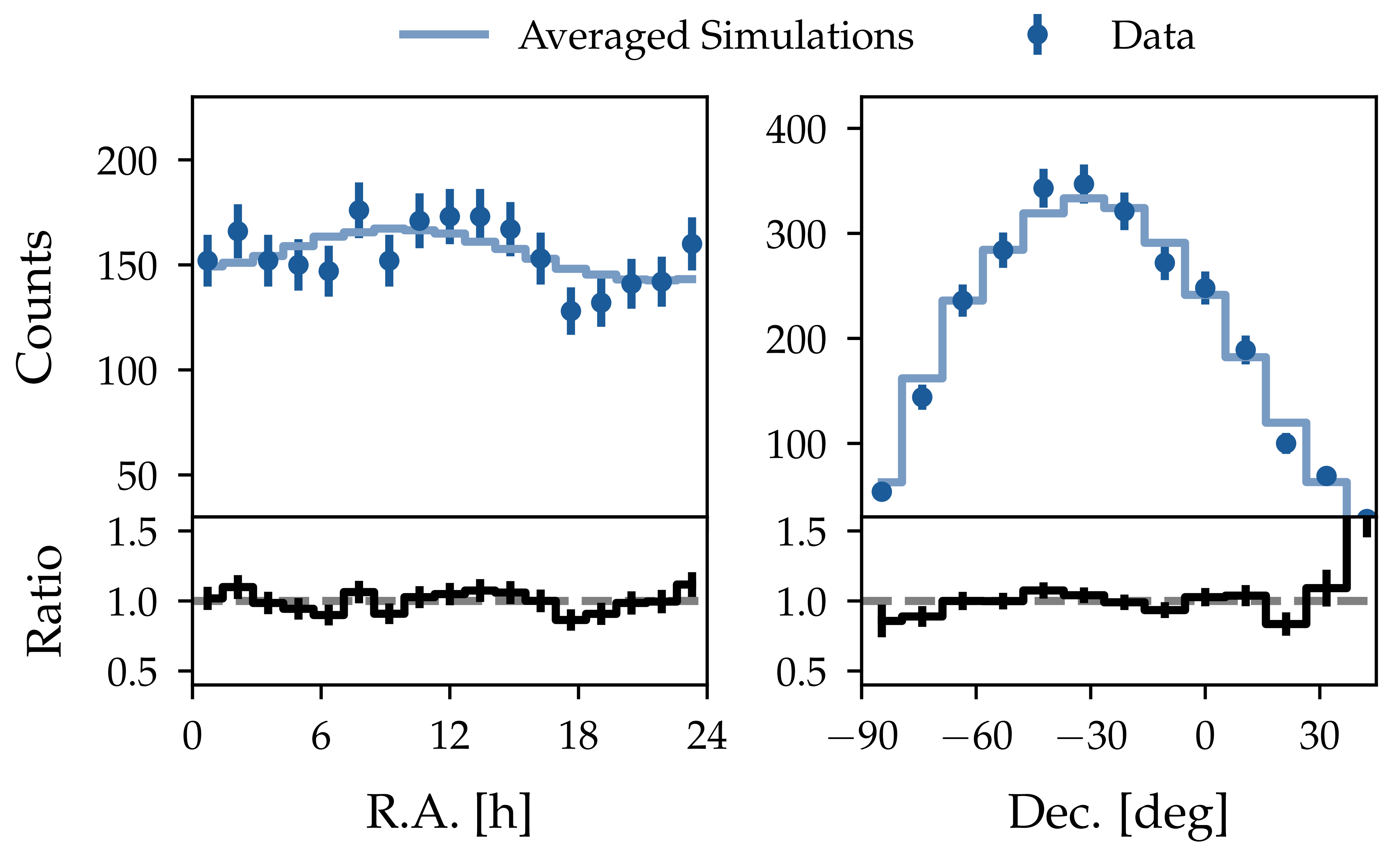
Source Selection Details

- The sources are mostly nearby, with distances between 0.77 and 242 Mpc
- No distance cut imposed, upper bound reflects angular resolution limit of current instrumentation
- Strongly anisotropic distribution, most of the sources aligned with Supergalactic Plane (SGP)
- Classification criterion:
  - AGN: presence of a jet, hard X-ray signatures, gamma-ray observations
  - Quiescent: no report of high-energy non-thermal activity



Simulation and Analysis details

- Simulation performed according to the convolution of dipole and PAO exposure PDFs
- Include both inclined and vertical events
- Good agreement in the whole coordinate range
- Correlation analysis performed on a large set of simulations, the outcome of the analysis on the data was compared to the simulations to assess the significance

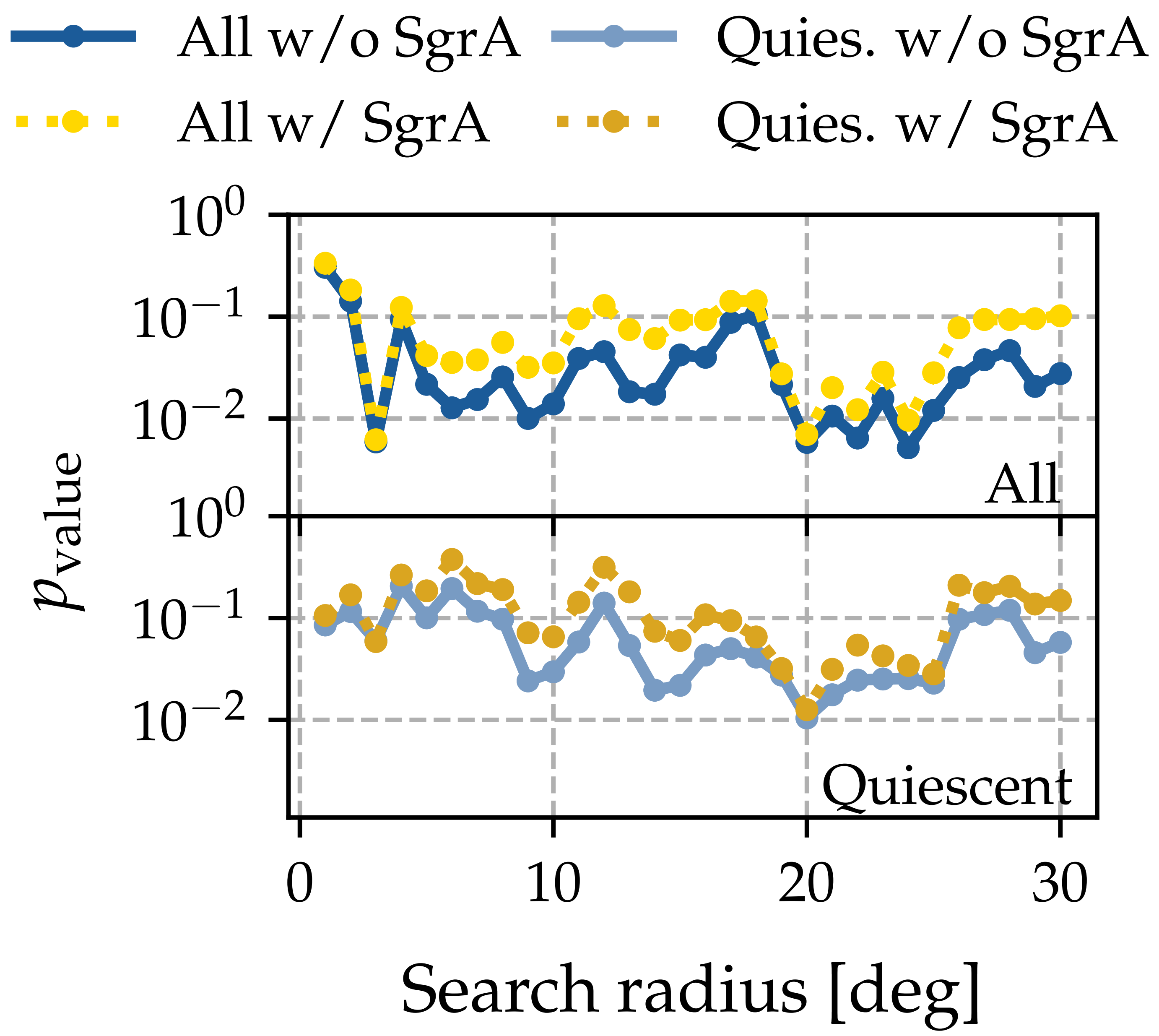


SFB 1258 Neutrinos Dark Matter Messengers

Results including Sgr A*

- SgrA* excluded due to its extremely diluted surrounding environment ($\dot{m} \approx 10^{-8}$) and the lack of previous evidence of UHECR emission
- When included, the results only change slightly
- Most significant excess now at 3° with very similar significance

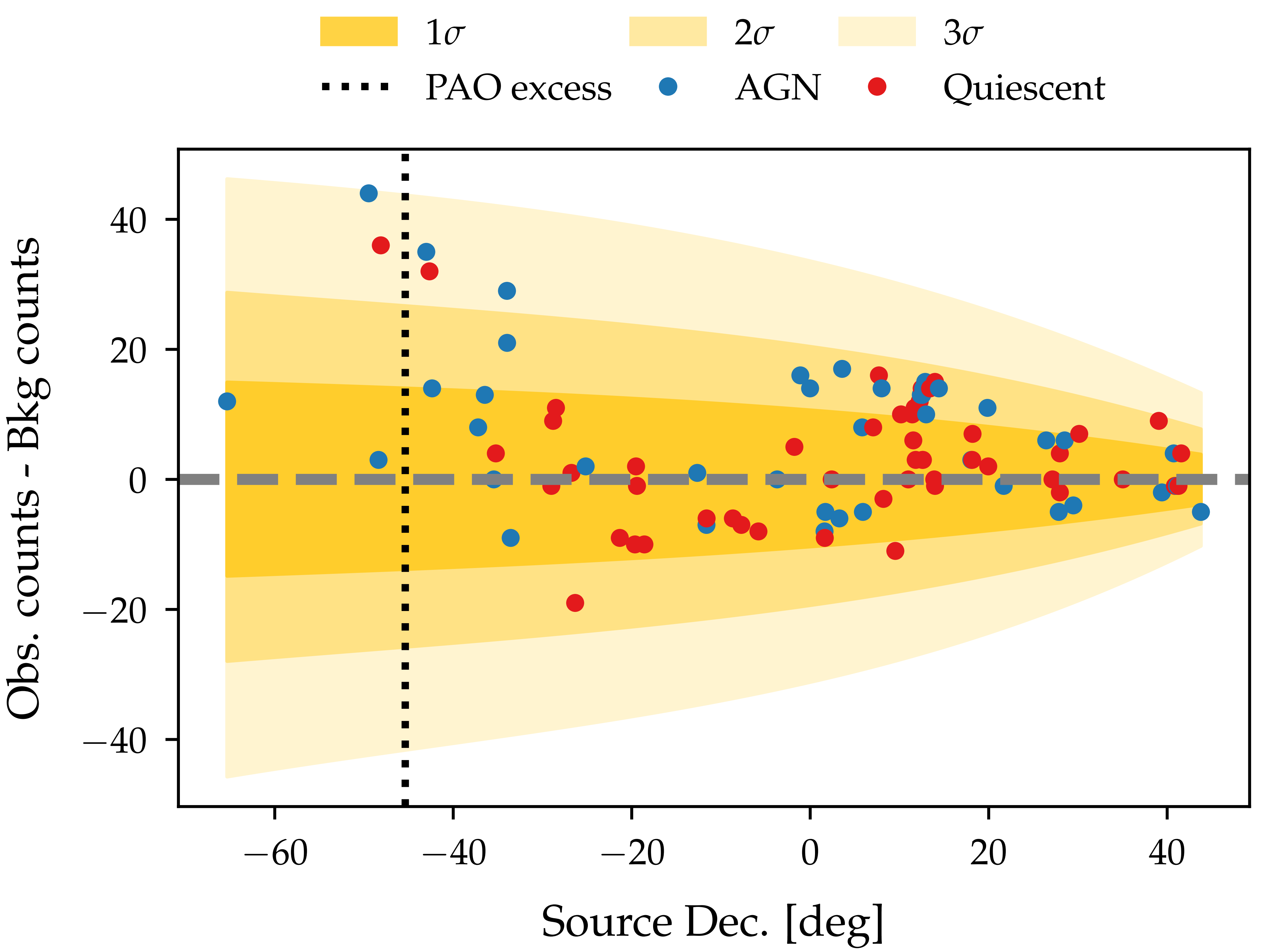
Source Class	With Sgr A*		Without Sgr A*	
	ψ [deg]	p_{value}	ψ [deg]	p_{value}
AGN	22°	0.0058 (2.76σ)	22°	0.0058 (2.76σ)
Quiescent Galaxies	20°	0.012 (2.50σ)	20°	0.010 (2.56σ)
All Sources	3°	0.006 (2.73σ)	24°	0.0051 (2.79σ)



SFB 1258 Neutrinos Dark Matter Messengers

More results

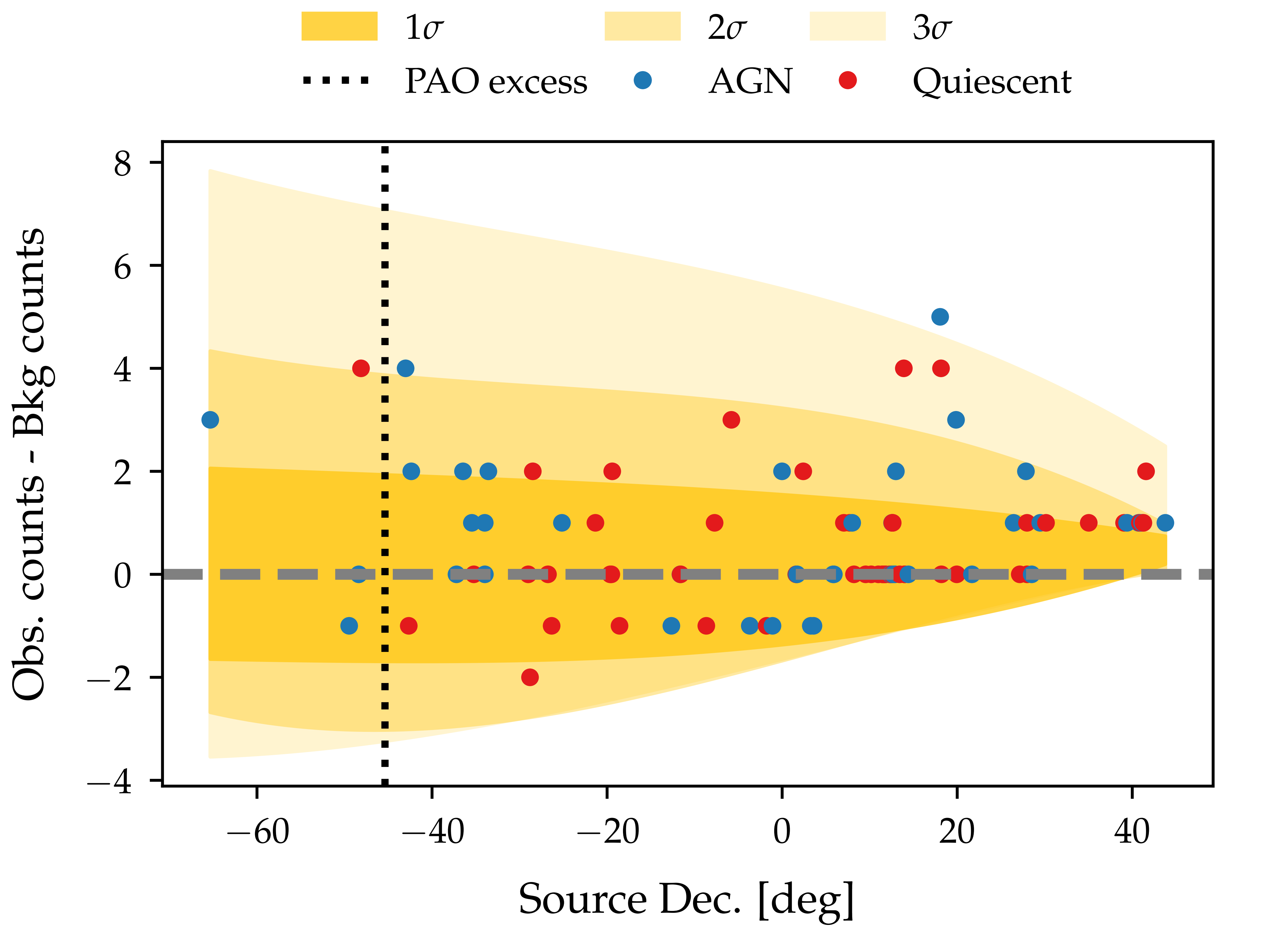
- Largest deviations from background observed in the same region as the PAO hotspot ($\delta = -45.4°$)
- Sources with local excesses above 2σ:
  - **AGN**: NGC 4945 ($\delta = -49.5°$), Cen A ($\delta = -43.0°$), NGC 5419 ($\delta = -34.0°$)
  - **Quiescent**: NGC 5516 ($\delta = -48.1°$), NGC 4751 ($\delta = -42.6°$)



SFB 1258 Neutrinos Dark Matter Messengers

Is there an excess also at 3 deg?

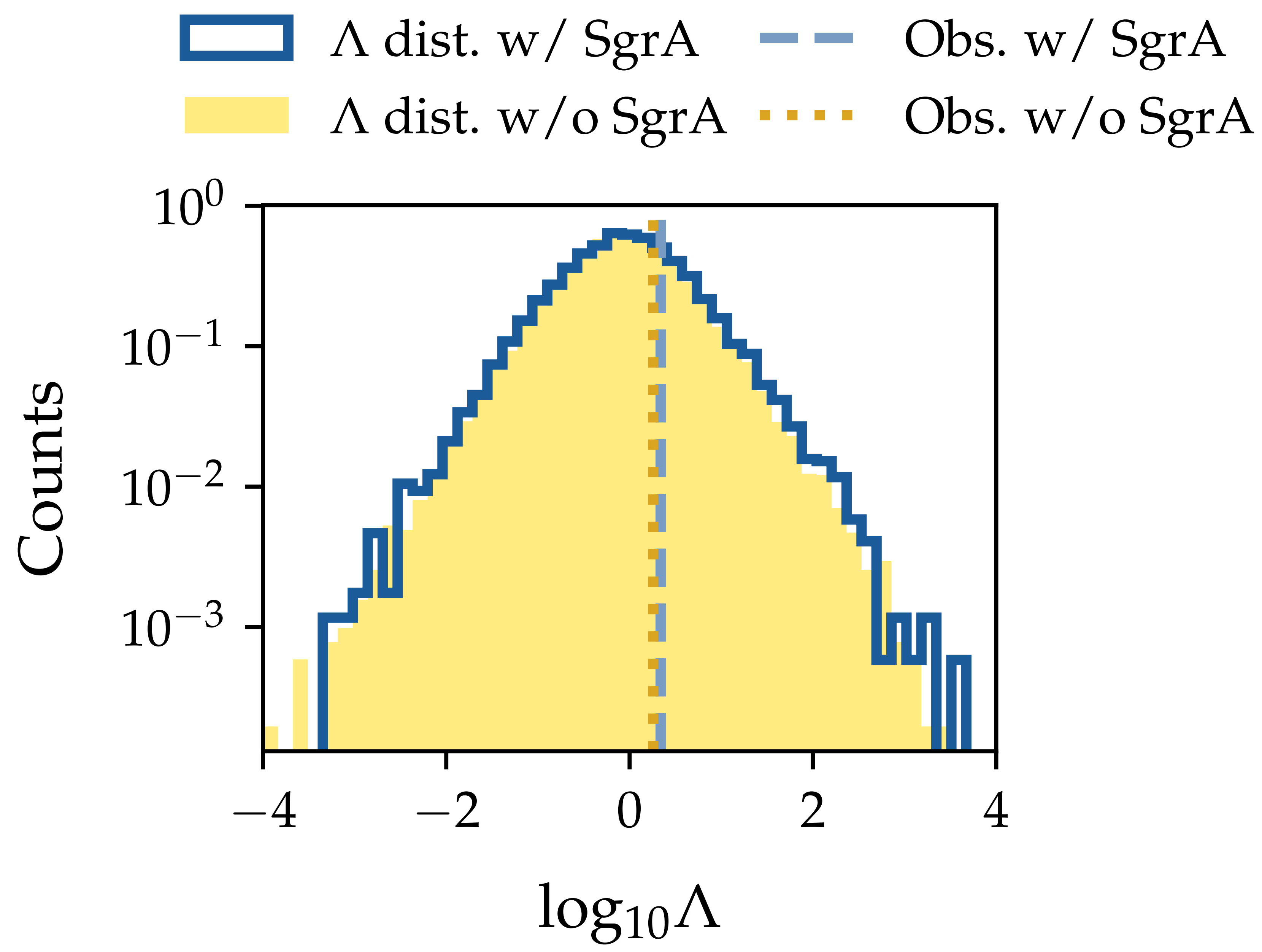
- Yes, also at 3 deg we observe an excess of similar significance to the one around 20-24 degrees.
- Quiescent galaxy NGC 5516 ($\delta = -48.1°$) and the AGN NGC 5128 ($\delta = -43.02°\circ$), which present mild excesses, are located in the Centaurus region
- Additionally, three other sources, the quiescent galaxies NGC 3489 ($\delta = 13.9°$) and NGC 3608 ($\delta = 18.15°$), and the active galaxy NGC 3607 ($\delta = 18.05°$), emerge from the background more significantly



Likelihood ratio test

- Test to assess whether the **data prefers the AGN or non-AGN**
- The test statistic Λ is defined as

$$\Lambda = \frac{\min\limits_{\theta}(p_{\mathrm{AGN}})}{\min\limits_{\theta}(p_{\mathrm{Quiesc.}})} \rightarrow \begin{cases} \Lambda > 1 \rightarrow \text{AGN preferred} \\ \Lambda < 1 \rightarrow \text{Quiescent preferred} \end{cases}$$



- Observed value:

  $\Lambda = 1.81$ when SgrA* is excluded

  $\Lambda = 2.18$ when SgrA* is included

- Both cases **fully consistent with background median** ($\Lambda = 1$)