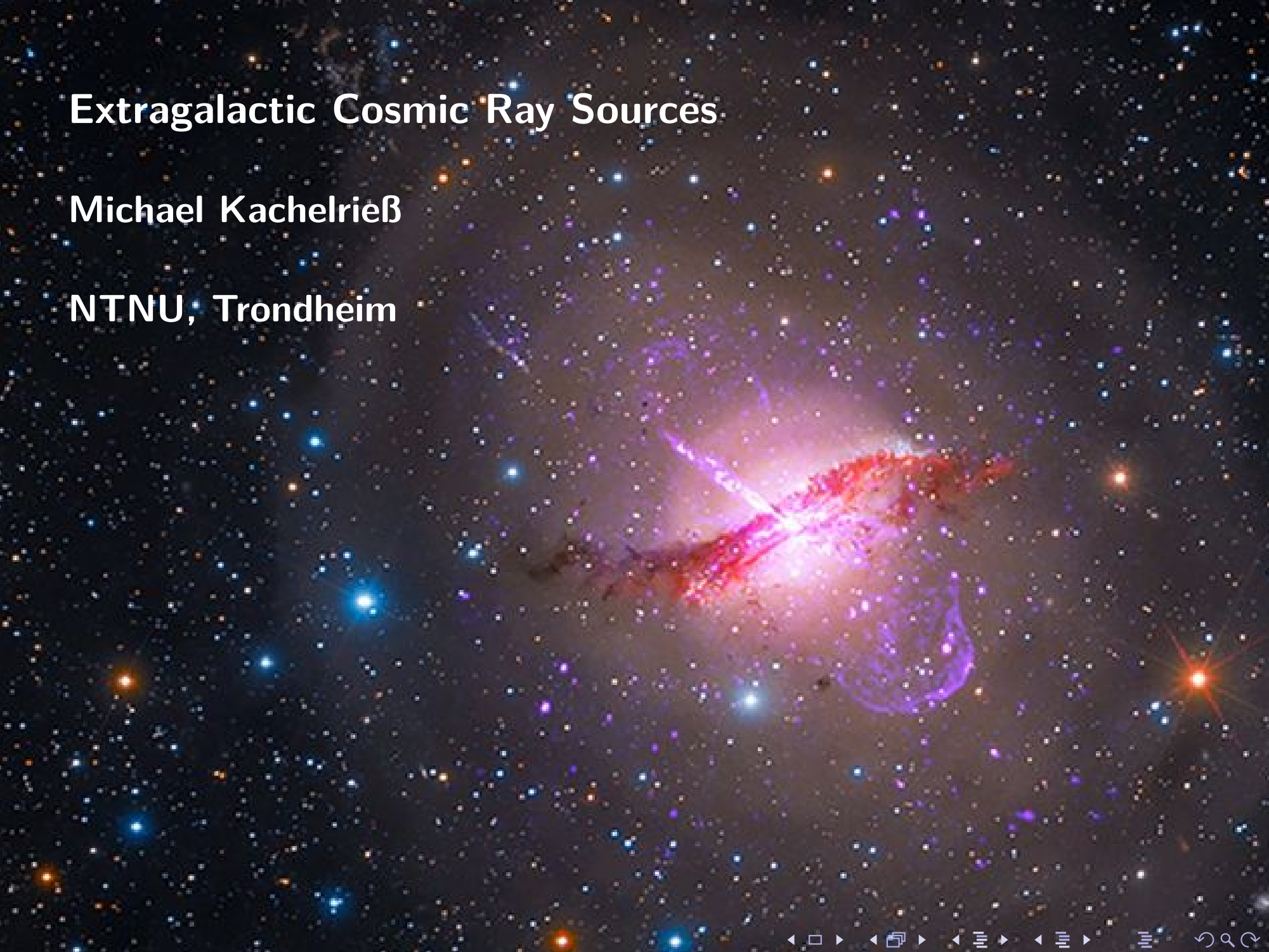
Extragalactic Cosmic Ray Sources

Michael Kachelrieß

NTNU, Trondheim



Outline of the talk

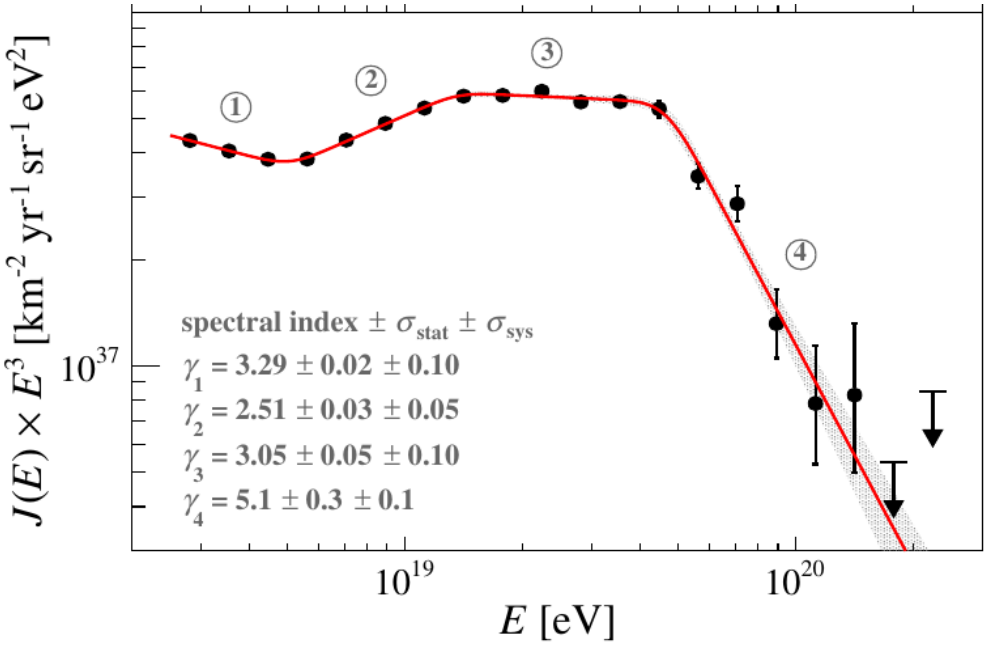
1. Introduction
2. Observations and their interpretation:
   - Energy spectrum
   - CR composition $> 10^{17}$ eV
   - Anisotropies and correlations
   - EGRB, cascade limit and neutrinos
3. Sources:
   - General constraints
   - Comment on EGMF
   - specific sources: radio galaxies
4. Summary

Outline of the talk

1. Introduction ⇒ talk by M. Unger
2. Observations and their (my) interpretation: ⇒ talk by M. Unger
   - Energy spectrum
   - CR composition $> 10^{17}$ eV
   - Anisotropies and correlations
   - EGRB, cascade limit and neutrinos
3. Sources:
   - General constraints
   - Comment on EGMF
   - specific sources: radio galaxies
4. Summary

Observations I: Energy spectrum

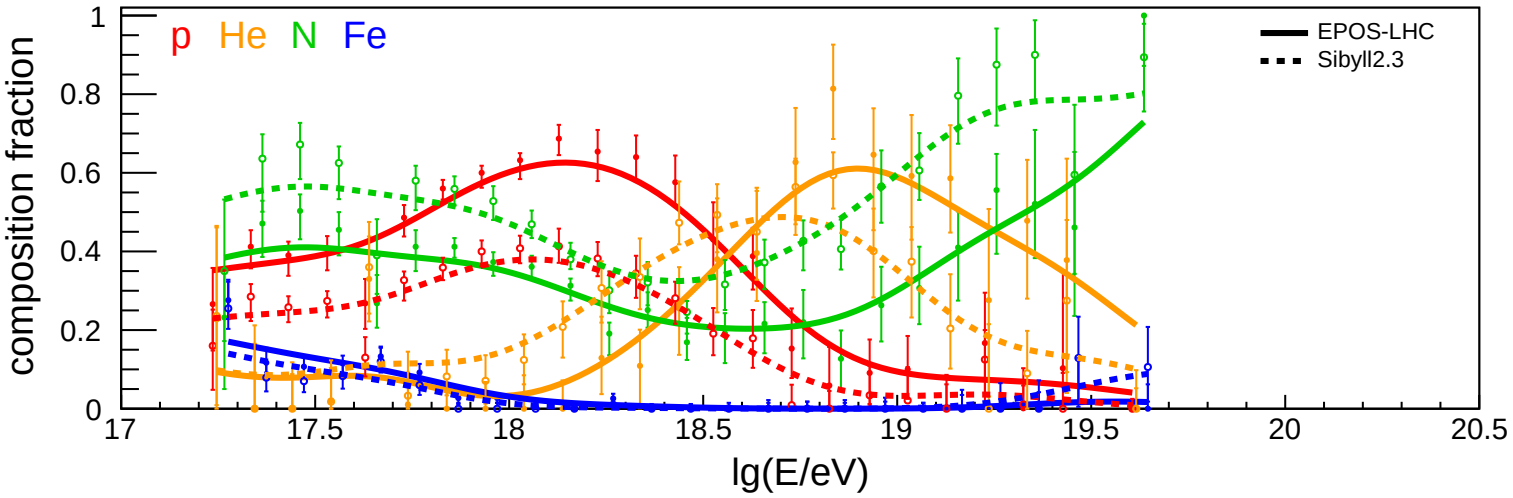
- precision increases ⇒ more features



[*PAO '20*]

Observations I: Composition

- precision increases ⇒ more features
- clearly separated groups of elements:

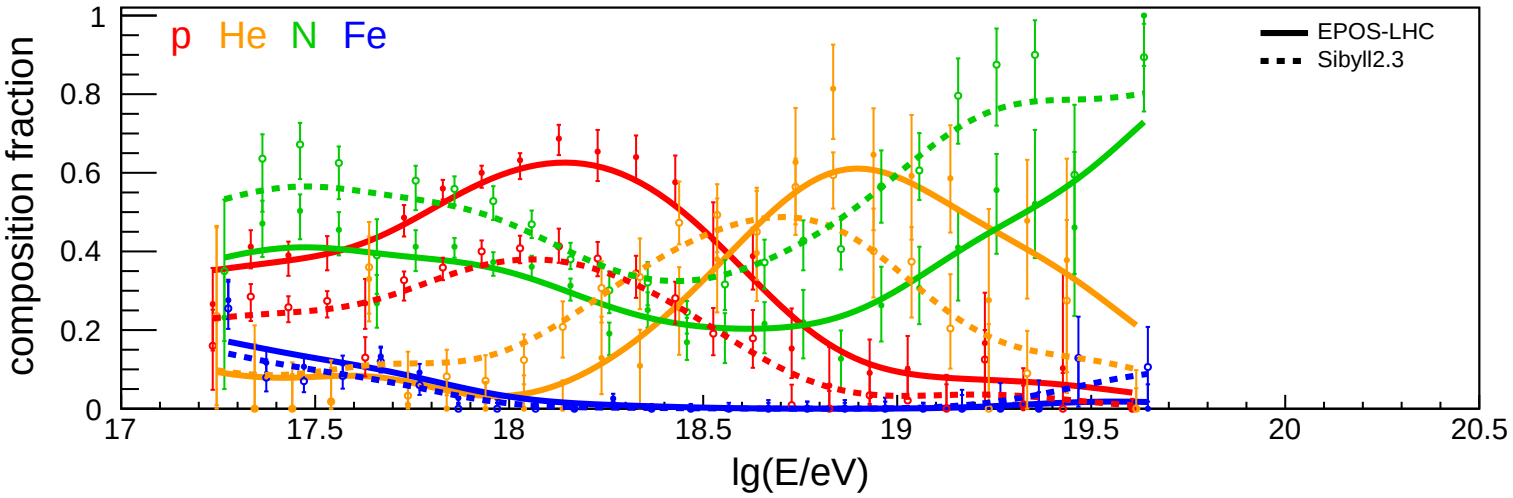


mixed composition:

- indicates Peter's cycle
- p+He$\sim 50\%$, plus intermediate nuclei; (Galactic) iron: $< 20\%$

Observations I:

- precision increases ⇒ more features
- clearly separated groups of elements:



mixed composition:

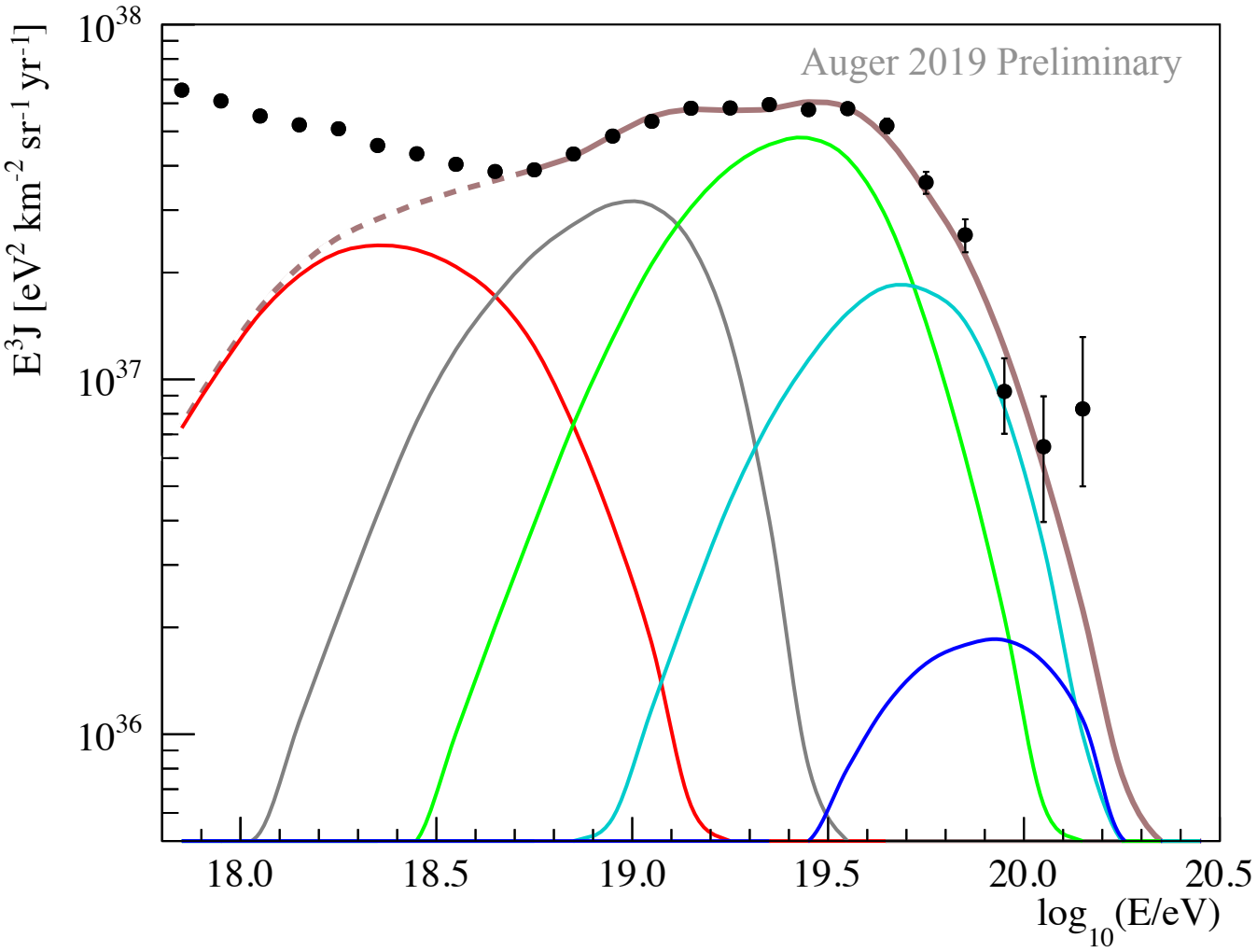
- indicates Peter's cycle
- p+He$\sim 50\%$, plus intermediate nuclei; (Galactic) iron: $< 20\%$

⇒ early transition from Galactic to extragalactic CRs

Interpretation

[PAO '20]

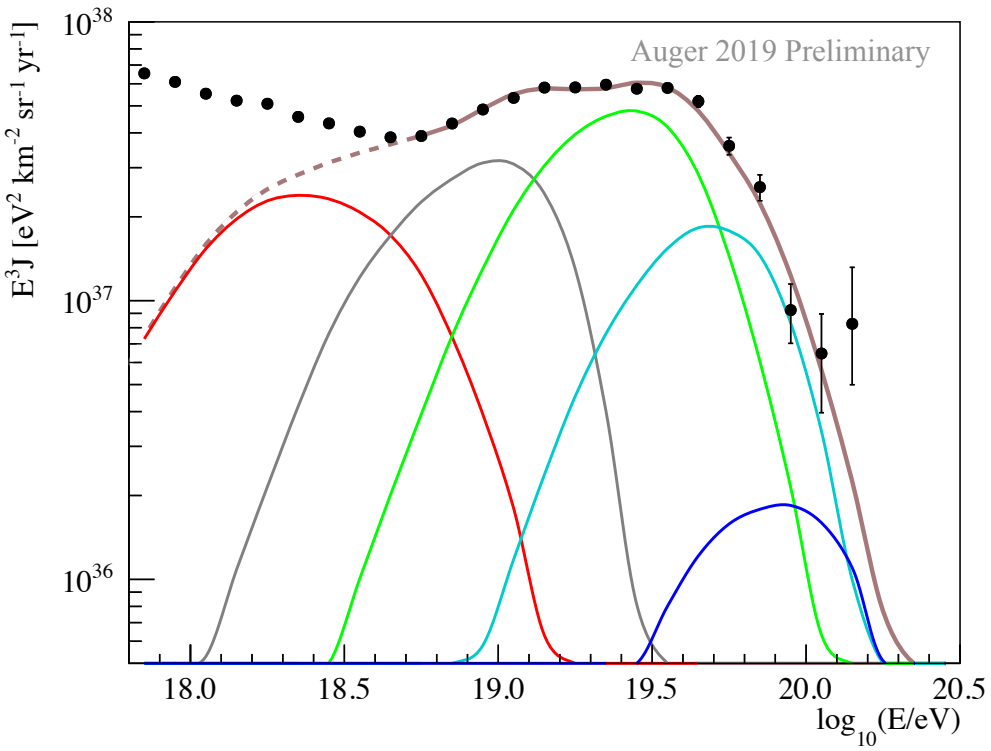
- single source: excluded by anisotropy: – few sources possible?
- transition between different nuclear groups, from uniform sources:



Interpretation

[PAO '20]

- single source: excluded by anisotropy: – few sources possible?
- transition between different nuclear groups, from uniform sources:



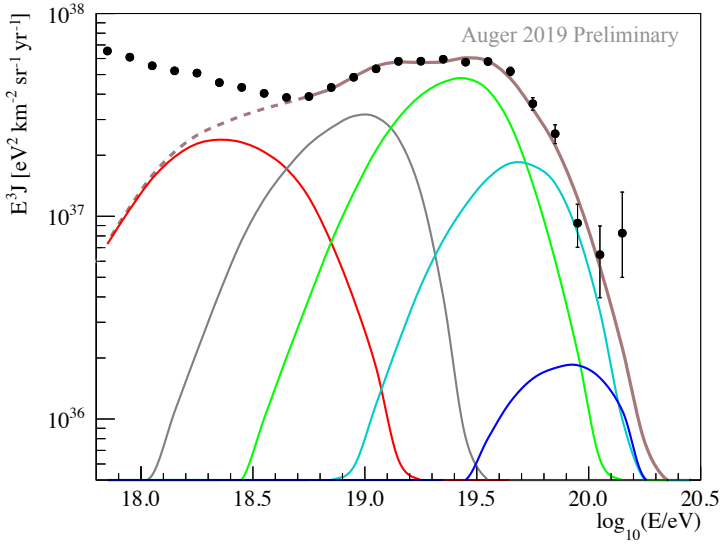
+ good fit of spectrum and composition
– extremly flat spectra $dN/dE \propto 1/E - E$

Identical sources vs. population

- most analyses use average or typical sources
- what changes using full population?

Identical sources vs. population

- most analyses use average or typical sources
- what changes using full population?
- previous fit:



  - Ex.: effective spectra for source population $\mathrm{d}n_s/\mathrm{d}E_{\mathrm{max}} \sim E_{\mathrm{max}}^{-\beta}$ with $\mathrm{d}N_{\mathrm{inj}}/\mathrm{d}E \sim E^{-\alpha}$

Identical sources vs. population

- most analyses use average or typical sources
- what changes using full population?
- previous fit:
  - Ex.: effective spectra for source population $\mathrm{d}n_s/\mathrm{d}E_{\mathrm{max}} \sim E_{\mathrm{max}}^{-\beta}$ with $\mathrm{d}N_{\mathrm{inj}}/\mathrm{d}E \sim E^{-\alpha}$

$\Rightarrow$ observed spectrum $\mathrm{d}N_{CR}/\mathrm{d}E \sim E^{-\alpha-\beta+1}$

  - flat "average" spectra require even flatter single source spectra

Identical sources vs. population

- most analyses use average or typical sources
- what changes using full population?
- previous fit:
  - Ex.: effective spectra for source population $\mathrm{d}n_s/\mathrm{d}E_{\mathrm{max}} \sim E_{\mathrm{max}}^{-\beta}$ with $\mathrm{d}N_{\mathrm{inj}}/\mathrm{d}E \sim E^{-\alpha}$

  $\Rightarrow$ observed spectrum $\mathrm{d}N_{CR}/\mathrm{d}E \sim E^{-\alpha-\beta+1}$
  - flat "average" spectra require even flatter single source spectra
- typical source $\Rightarrow$ population: RMS(X_{max}) becomes wider

  $\Rightarrow$ only small variation allowed

Identical sources vs. population

- most analyses use average or typical sources
- what changes using full population?
- previous fit:
  - Ex.: effective spectra for source population $\mathrm{d}n_s/\mathrm{d}E_{\mathrm{max}} \sim E_{\mathrm{max}}^{-\beta}$ with $\mathrm{d}N_{\mathrm{inj}}/\mathrm{d}E \sim E^{-\alpha}$

  $\Rightarrow$ observed spectrum $\mathrm{d}N_{CR}/\mathrm{d}E \sim E^{-\alpha-\beta+1}$
  - flat "average" spectra require even flatter single source spectra
- typical source $\Rightarrow$ population: RMS(X_{max}) becomes wider

  $\Rightarrow$ only small variation allowed
  - are UHECR sources standard candles?? [*Ehlert, Oikinomou, Unger '22*]

Identical sources vs. population

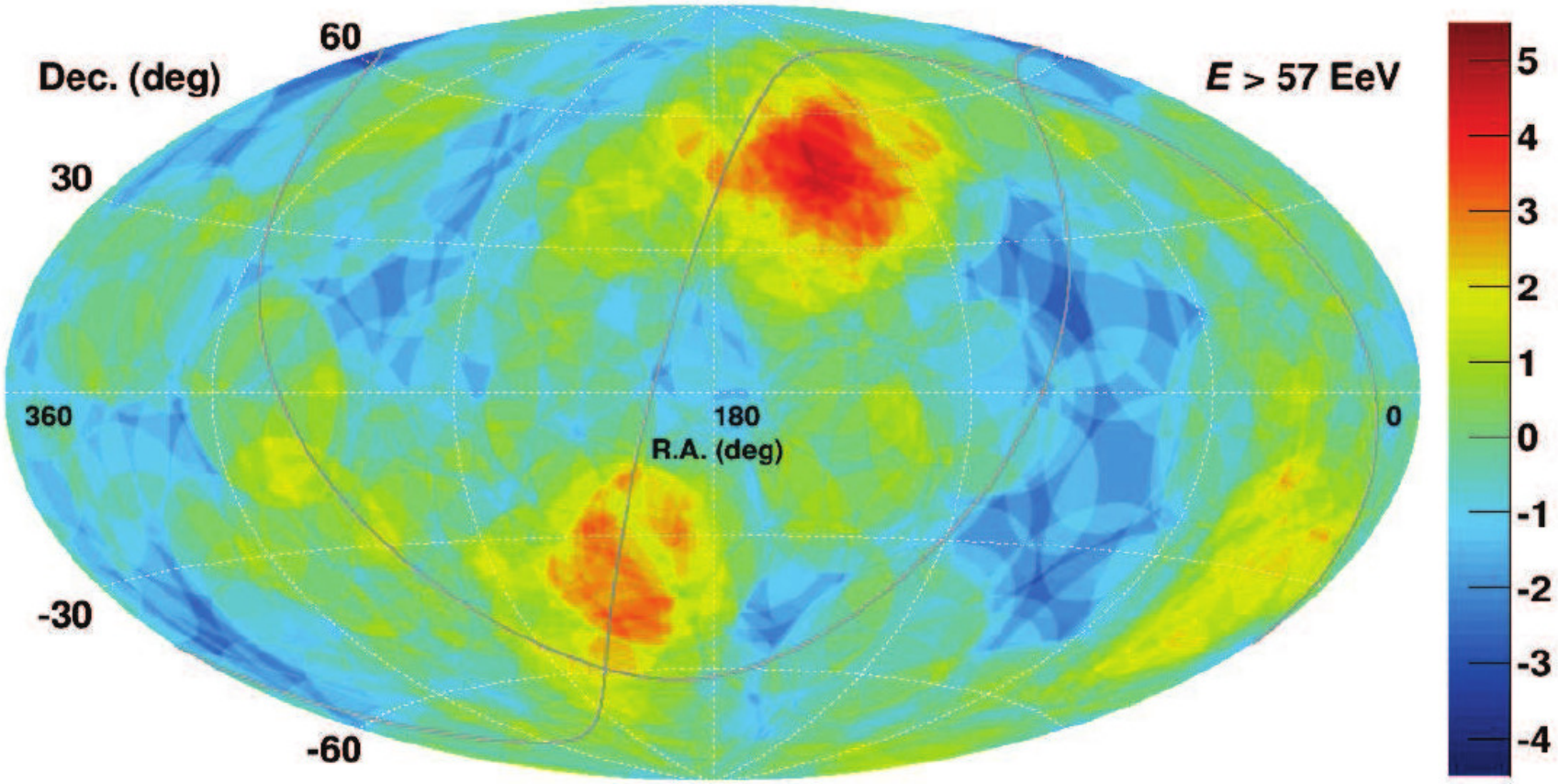
- most analyses use average or typical sources
- what changes using full population?
- previous fit:
  - Ex.: effective spectra for source population $\mathrm{d}n_s/\mathrm{d}E_{\mathrm{max}} \sim E_{\mathrm{max}}^{-\beta}$ with $\mathrm{d}N_{\mathrm{inj}}/\mathrm{d}E \sim E^{-\alpha}$

  $\Rightarrow$ observed spectrum $\mathrm{d}N_{CR}/\mathrm{d}E \sim E^{-\alpha-\beta+1}$
  - flat "average" spectra require even flatter single source spectra
- typical source $\Rightarrow$ population: RMS(X_{max}) becomes wider

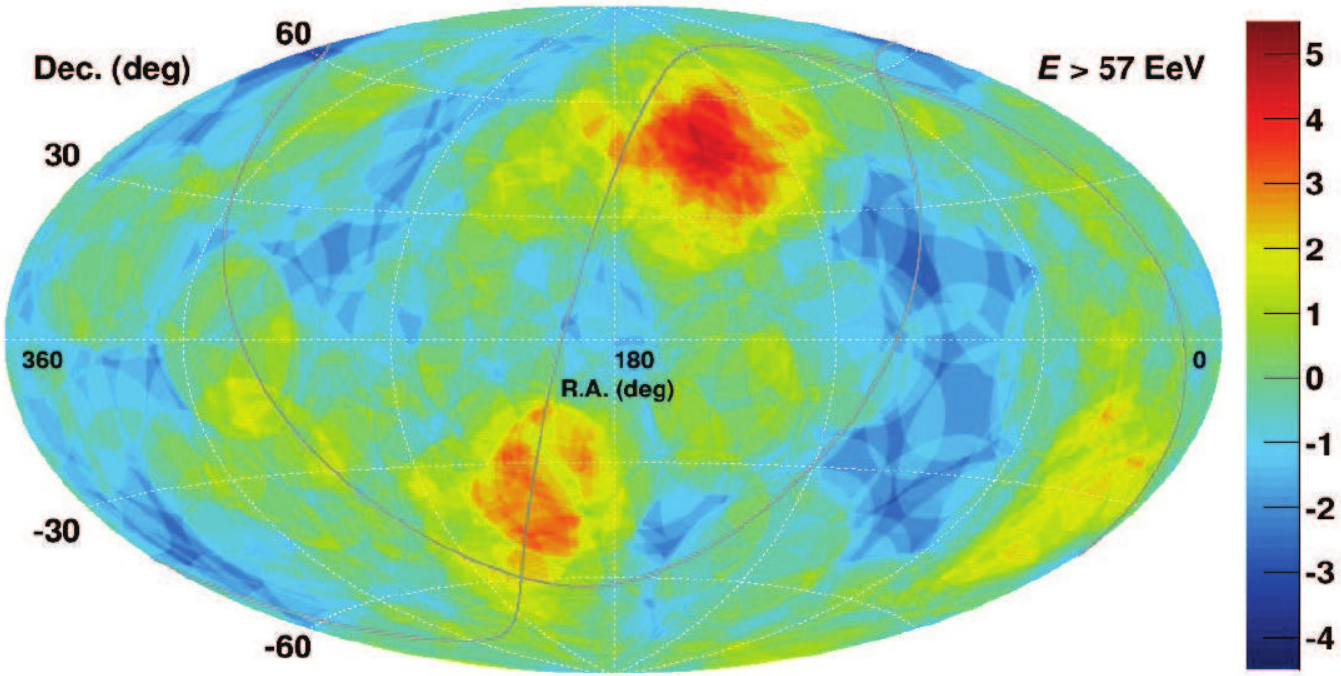
  $\Rightarrow$ only small variation allowed
  - are UHECR sources standard candles?? [*Ehlert, Oikinomou, Unger '22*]

  or few UHECR sources dominate flux?

Observations II: Potential anisotropies



Observations II: Potential anisotropies



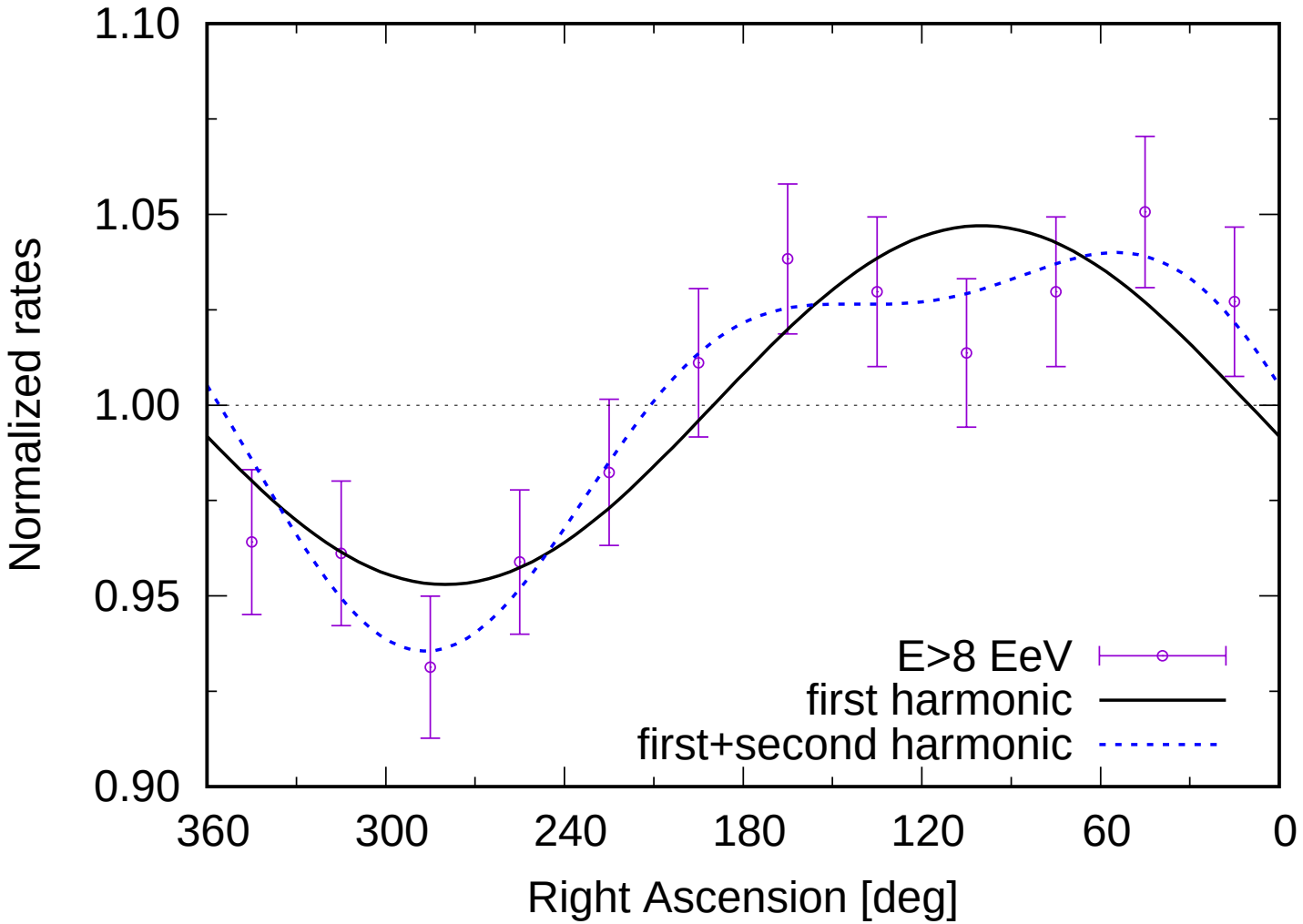
Various signatures for deviations from isotropy:

- small-scale anisotropies or multiplets: absent
- medium-scale anisotropies, hot and cold spots: evidence
- dipole anisotropy: detected
- cross-correlations UHECR and source catalogues: evidence

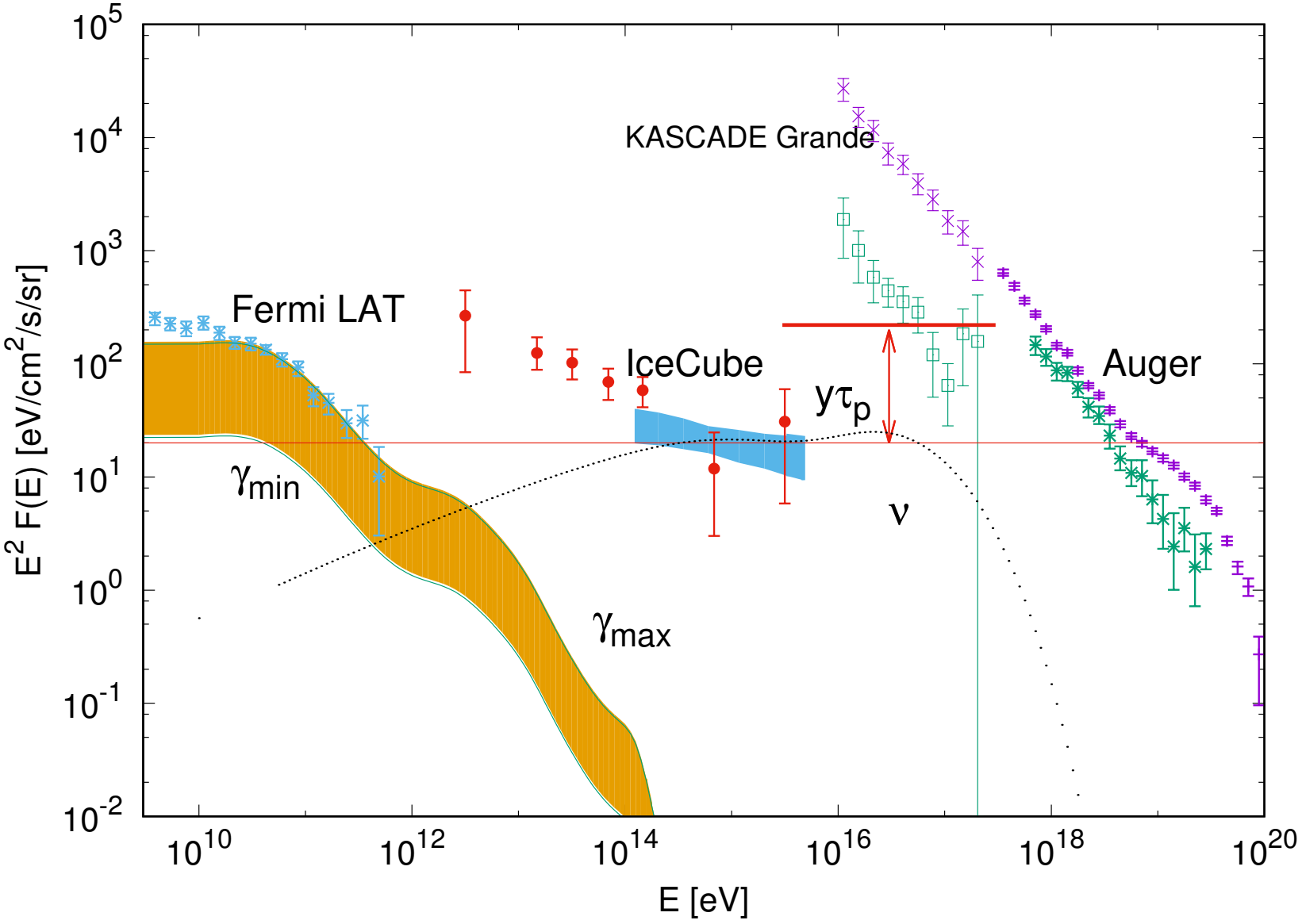
Observations II: dipole

[PAO '17, '18]

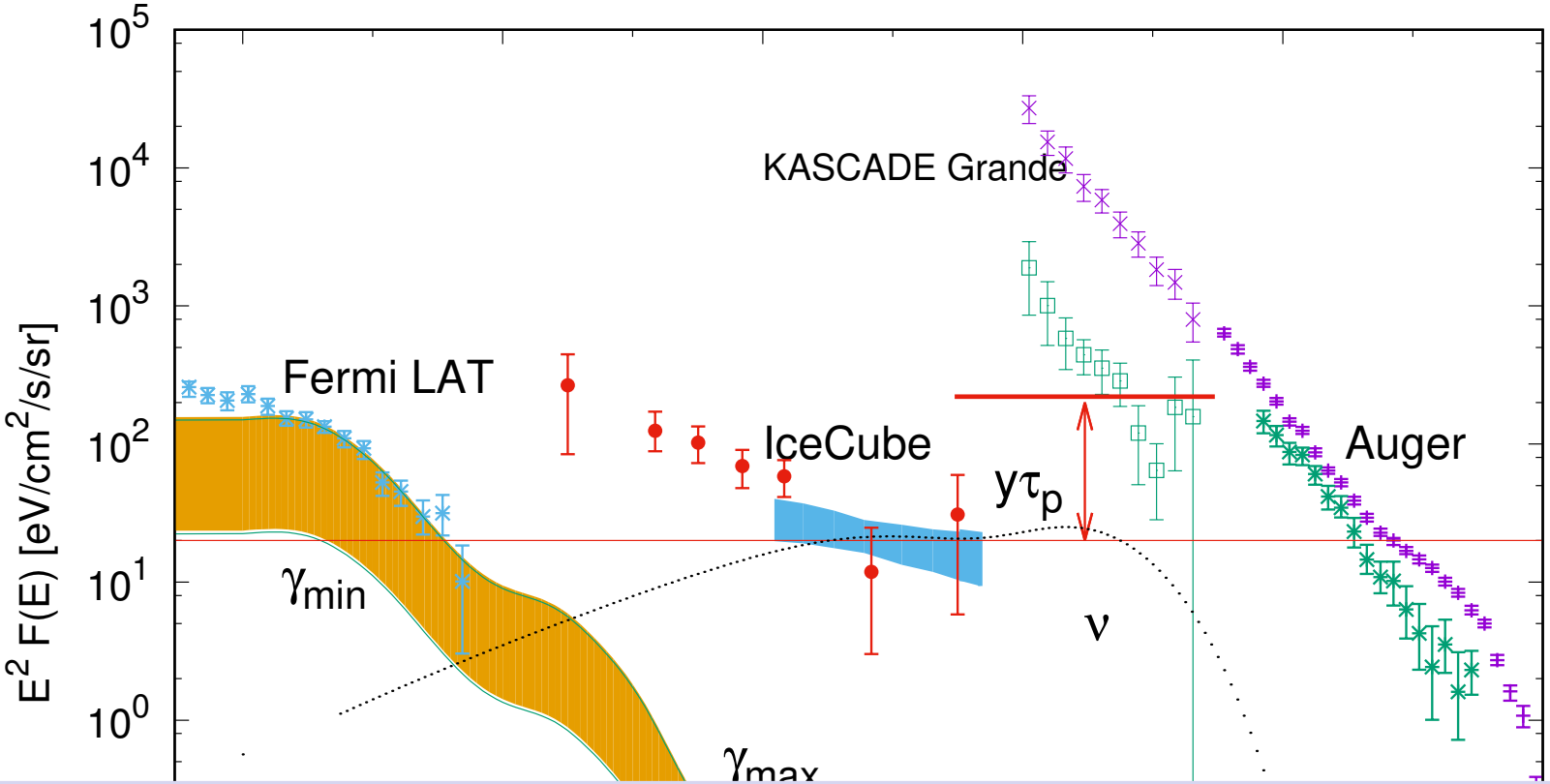
- $E > 8$ EeV: dipole observed with $A \simeq 6.5\%$ and $\mathrm{R.A.} \simeq 120°$



Multi-messenger picture



Multi-messenger picture

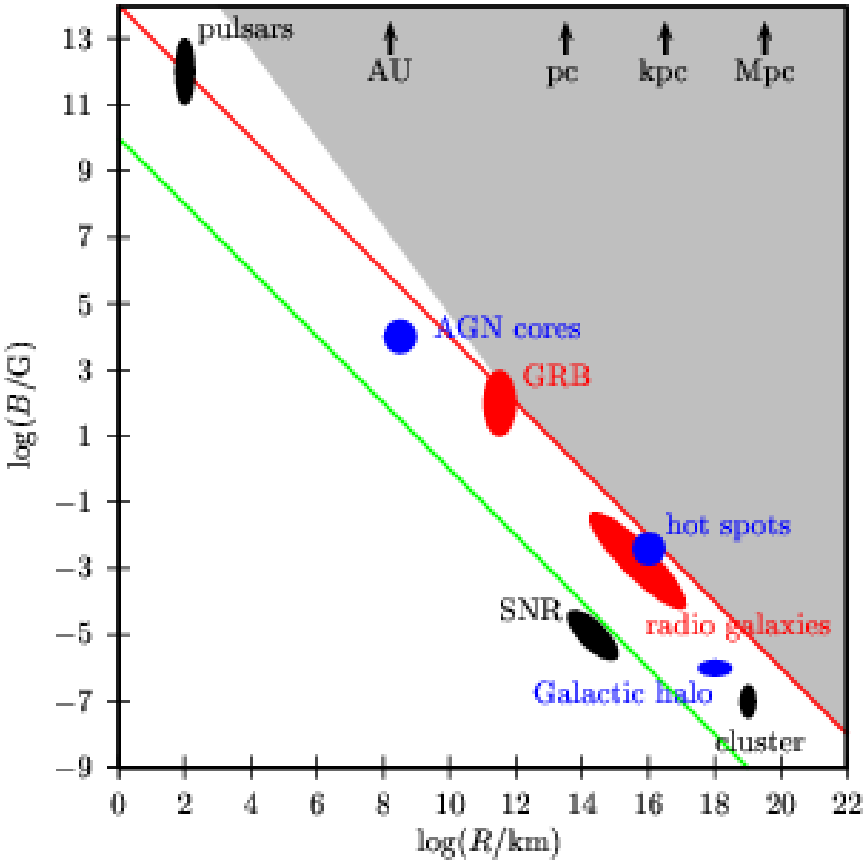


Constraints for a possible ν-γ-UHECR connection:

- $\tau_p \sim 1$ required
- EGRB: $(86 \pm 15)\%$ from unresolved blazars [*Fermi-LAT '15*]
- IceCube ν: $< 17\%$ from blazars

General constraints on UHECR sources:

- Hillas criterium: $R_L = cp/ZeB \leq R_s$ or $E_{\max} \lesssim \Gamma ZeBR_s$



and $t_{\rm acc} \leq t_{\rm act}, t_{\rm loss}$

General constraints on UHECR sources:

- Hillas criterium: $R_L = cp/ZeB \leq R_s$ or $E_{\max} \lesssim \Gamma ZeBR_s$
- Blandford criterium: $L_{\min} = U^2/R$ or

$$L_{\min} \sim 3 \times 10^{42} \mathrm{erg/s} \left(\frac{E/Z}{5 \times 10^{18} \mathrm{eV}} \right)^2 (\Gamma^2/\beta)$$

General constraints on UHECR sources:

- Hillas criterium: $R_L = cp/ZeB \leq R_s$ or $E_{\max} \lesssim \Gamma ZeBR_s$
- Blandford criterium: $L_{\min} = U^2/R$ or

$$L_{\min} \sim 3 \times 10^{42} \mathrm{erg/s} \left(\frac{E/Z}{5 \times 10^{18} \mathrm{eV}} \right)^2 (\Gamma^2/\beta)$$

- UHECR emissivity $Q \sim 10^{45}$ erg/Mpc^3/yr

General constraints on UHECR sources:

- Hillas criterium: $R_L = cp/ZeB \leq R_s$ or $E_{\max} \lesssim \Gamma ZeBR_s$
- Blandford criterium: $L_{\min} = U^2/R$ or

$$L_{\min} \sim 3 \times 10^{42}\mathrm{erg/s} \left(\frac{E/Z}{5 \times 10^{18}\mathrm{eV}} \right)^2 (\Gamma^2/\beta)$$

- UHECR emissivity $Q \sim 10^{45}$ erg/Mpc^3/yr
- source density for stationary sources:
  - sufficiently luminuous: $n_s \lesssim Q/L_{\min} \sim 10^{-5}/\mathrm{Mpc}^3$
  - avoid multiplets: $n_s \gtrsim 10^{-5}/\mathrm{Mpc}^3$ (for weak EGMF)

General constraints on UHECR sources:

- Hillas criterium: $R_L = cp/ZeB \leq R_s$ or $E_{\max} \lesssim \Gamma ZeBR_s$
- Blandford criterium: $L_{\min} = U^2/R$ or

$$L_{\min} \sim 3 \times 10^{42} \mathrm{erg/s} \left(\frac{E/Z}{5 \times 10^{18} \mathrm{eV}} \right)^2 (\Gamma^2/\beta)$$

- UHECR emissivity $Q \sim 10^{45}$ erg/Mpc^3/yr
- source density for bursting sources: $n_s \simeq 3R\tau/5$
  - sufficiently luminuous: $R \lesssim Q/(\tau L_{\min}) \sim 10^{-8}$/Mpc^3/yr (for $\tau \sim 10^3$ yr)
  - avoid multiplets: $R \sim n_s/\tau \gtrsim 10^{-8}$/Mpc^3/yr

General constraints on UHECR sources:

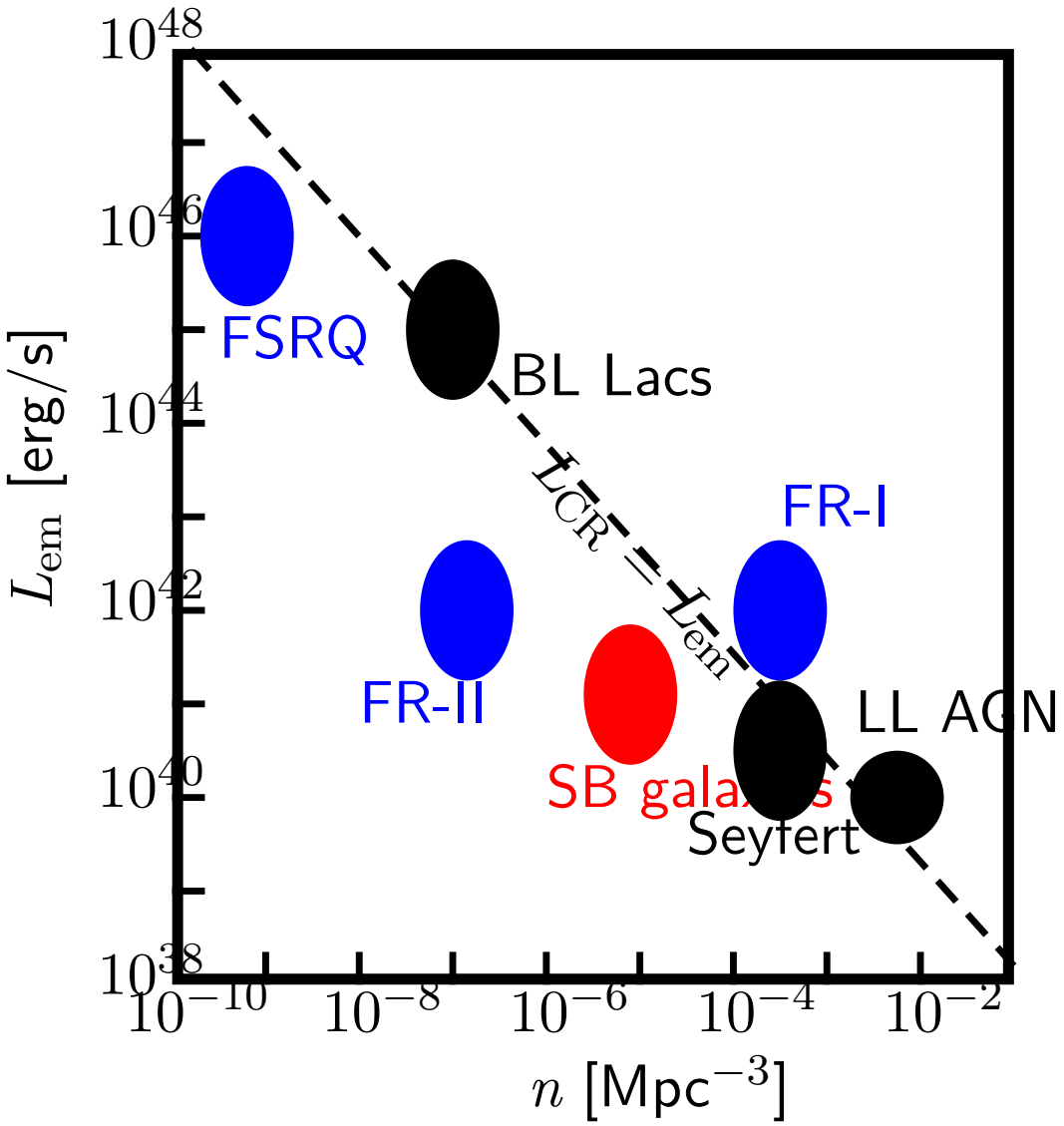
- Hillas criterium: $R_L = cp/ZeB \leq R_s$ or $E_{\max} \lesssim \Gamma ZeBR_s$
- Blandford criterium: $L_{\min} = U^2/R$ or

$$L_{\min} \sim 3 \times 10^{42} \mathrm{erg/s} \left(\frac{E/Z}{5 \times 10^{18} \mathrm{eV}} \right)^2 (\Gamma^2/\beta)$$

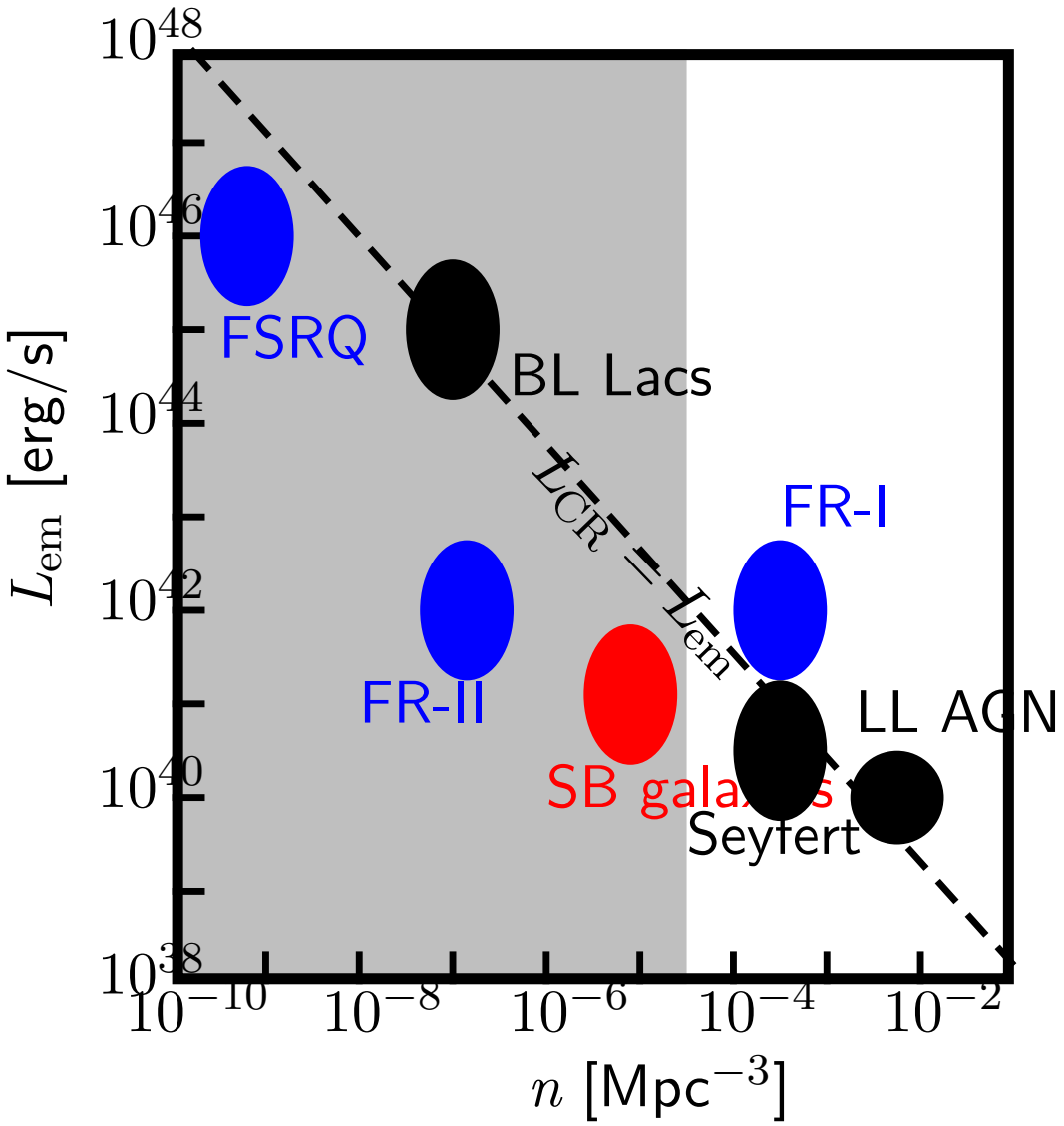
- UHECR emissivity $Q \sim 10^{45}$ erg/Mpc^3/yr

$\Rightarrow$ source density/rate tightly constrained

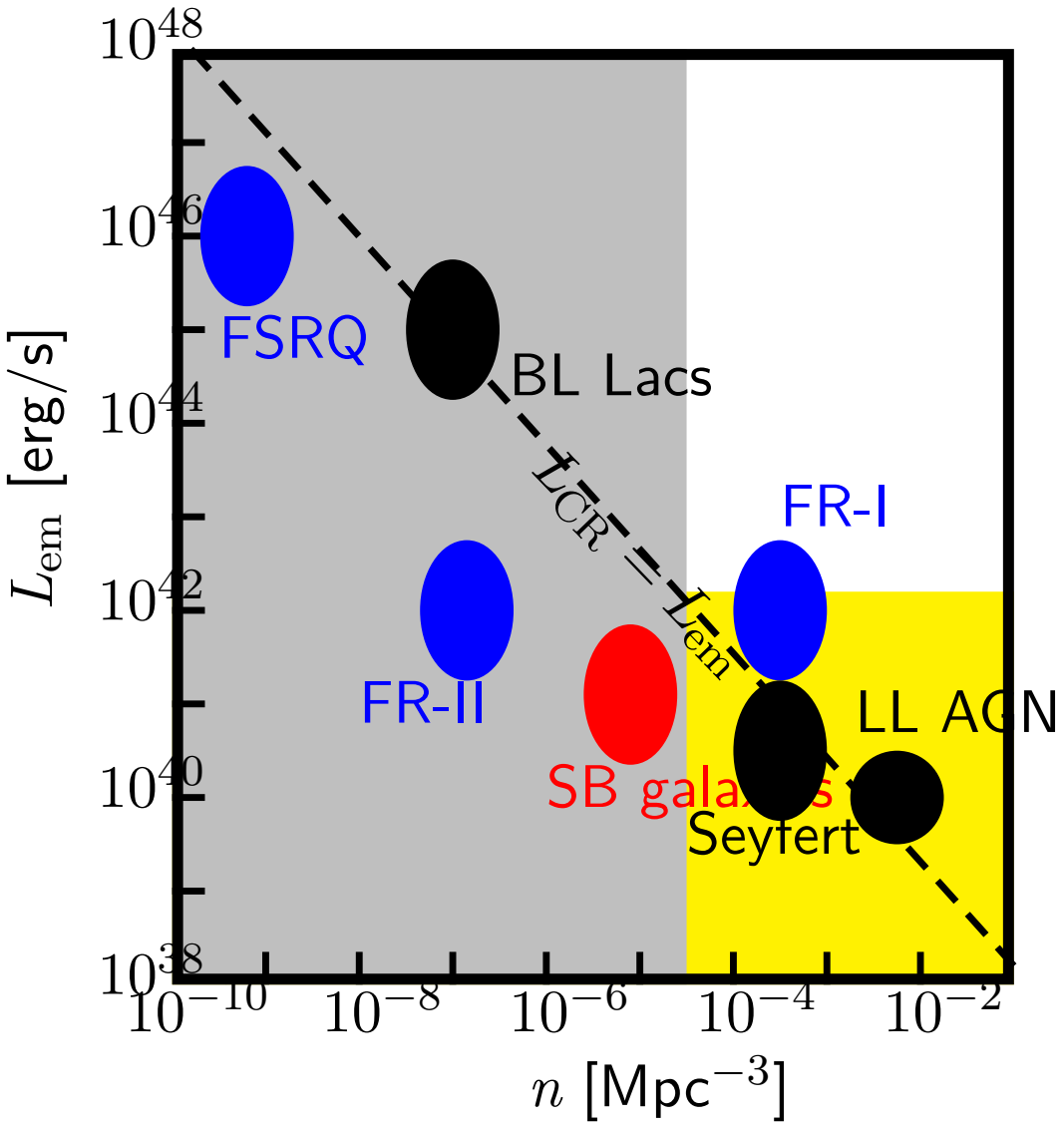
Density vs. luminosity for stationary sources



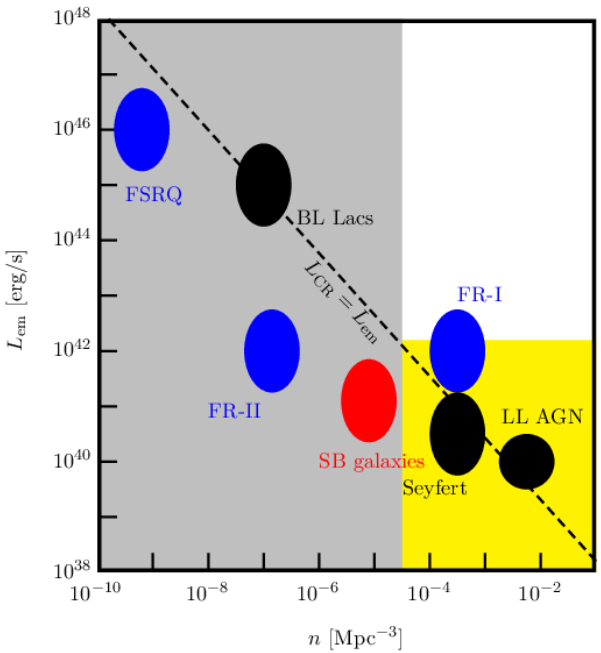
Density vs. luminosity for stationary sources



Density vs. luminosity for stationary sources



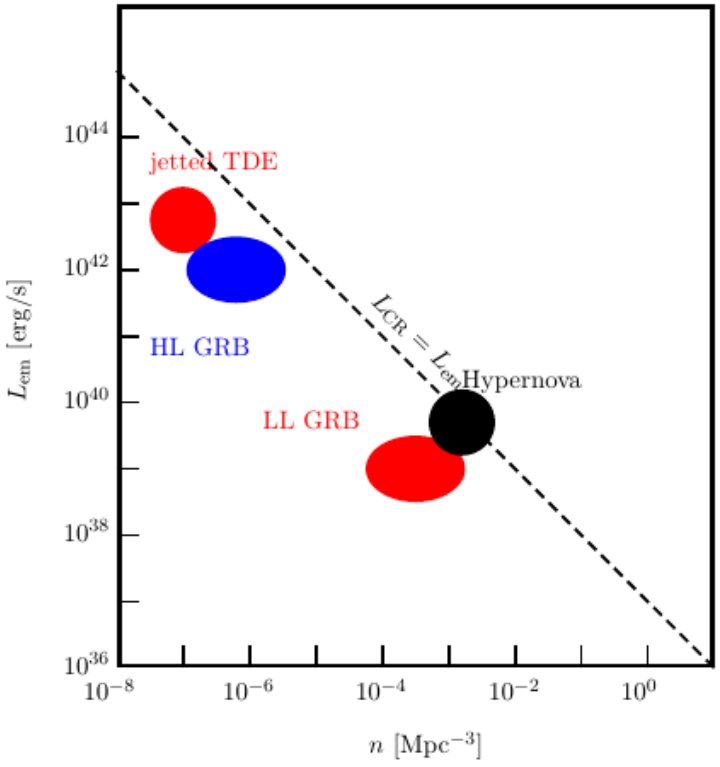
Density vs. luminosity for stationary sources



how to relax constraints?

- density limit relaxed by strong EGMF
- $L_{\rm em} \gg L_X$?
- $L_{\rm em}$ relaxed by two-step acceleration
- missing subclasses

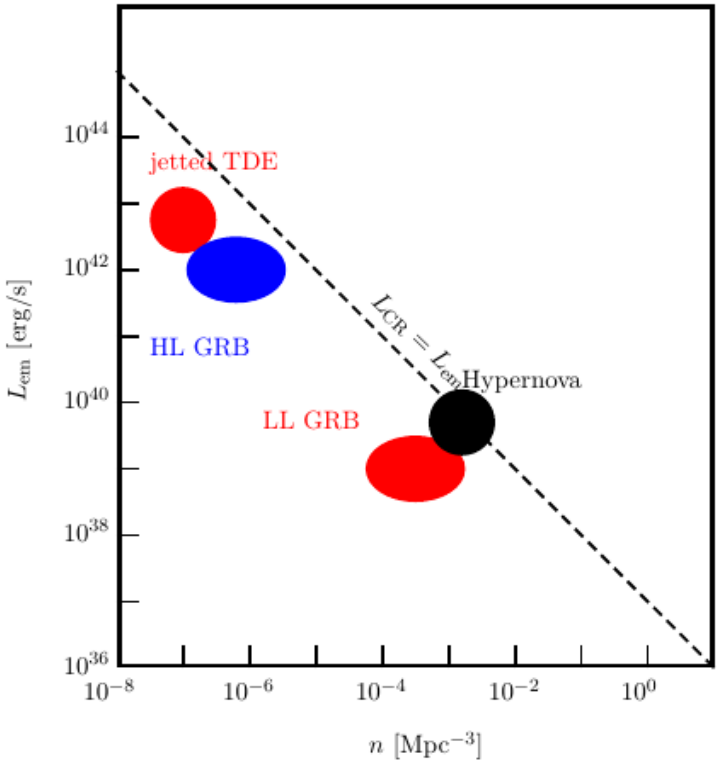
Density vs. luminosity for bursting sources



- time-delay τ in turbulent EGMF

$$\tau \simeq 10^3 \mathrm{yr} \left(\frac{3\times 10^{19}\mathrm{eV}}{E/Z}\right)^2 \left(\frac{d}{100\,\mathrm{Mpc}}\right) \left(\frac{l_c}{1\,\mathrm{Mpc}}\right) \left(\frac{B}{10^{-10}\mathrm{G}}\right)^2$$

Density vs. luminosity for bursting sources



- time-delay τ in turbulent EGMF
- $L > L_{\rm min}$ typically no problem, since $\tau_0 \ll \tau$
- but emissivity too smalll

$\Rightarrow$

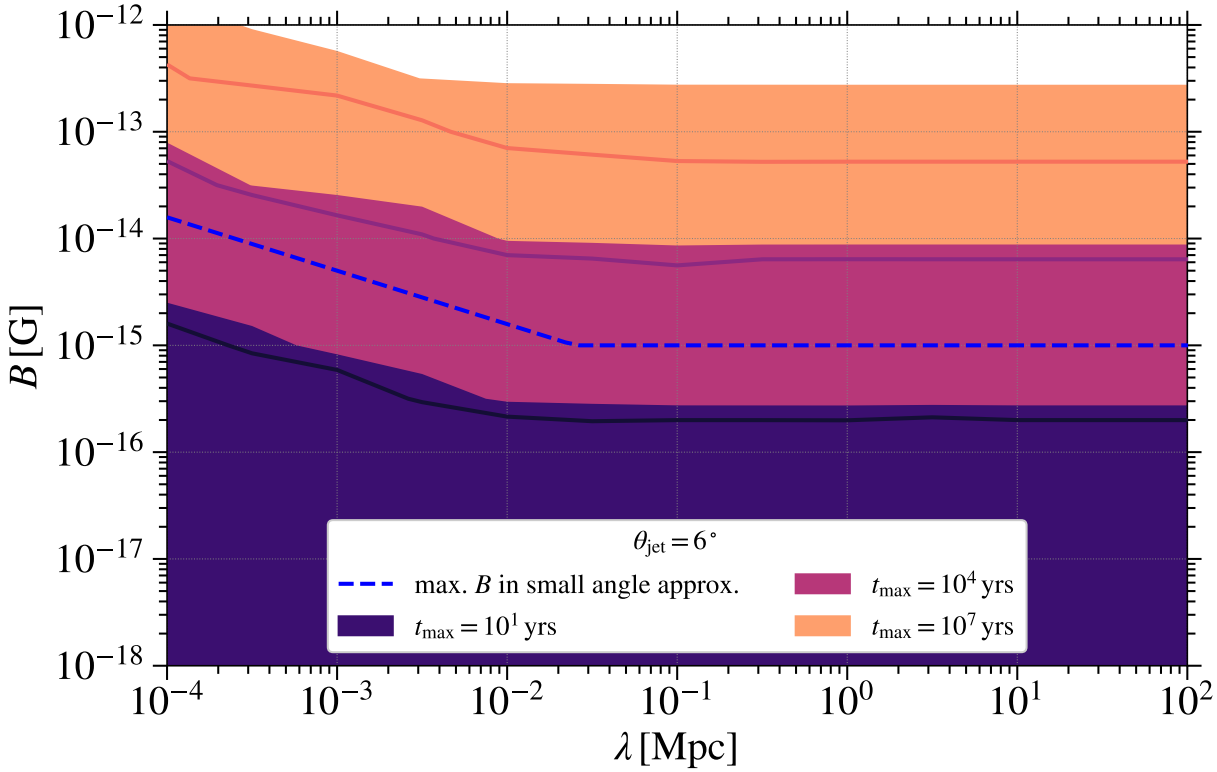
Constraints on the EGMF

- strong EGMF required for large deflections of UHECRs

$$\vartheta_{\rm rms} \simeq 0.8^\circ \left(\frac{3\times 10^{19}{\rm eV}}{E/Z}\right)\left(\frac{d}{100\,{\rm Mpc}}\right)^{1/2}\left(\frac{l_c}{1\,{\rm Mpc}}\right)^{1/2}\left(\frac{B}{10^{-10}{\rm G}}\right)$$

Constraints on the EGMF

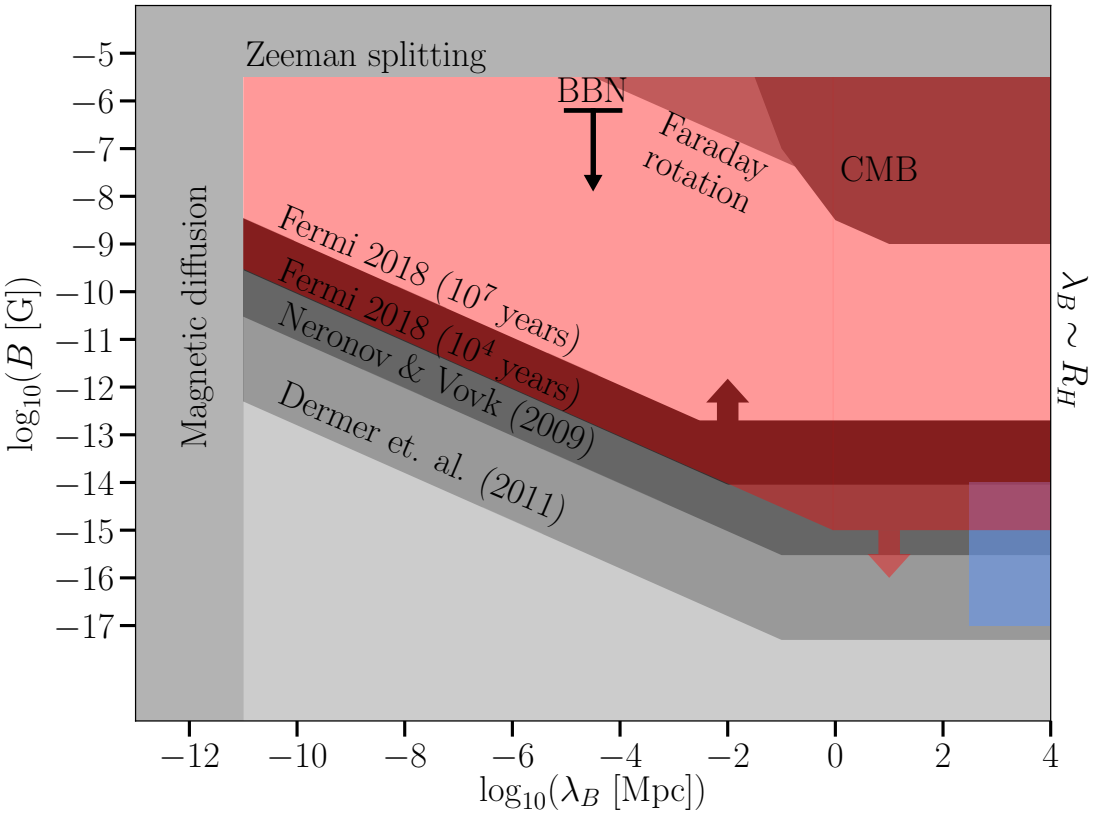
- strong EGMF required for large deflections of UHECRs
- larger effect on TeV cascade electrons ⇒ lower limits:



[*Fermi-LAT & Biteau'18*]

Constraints on the EGMF

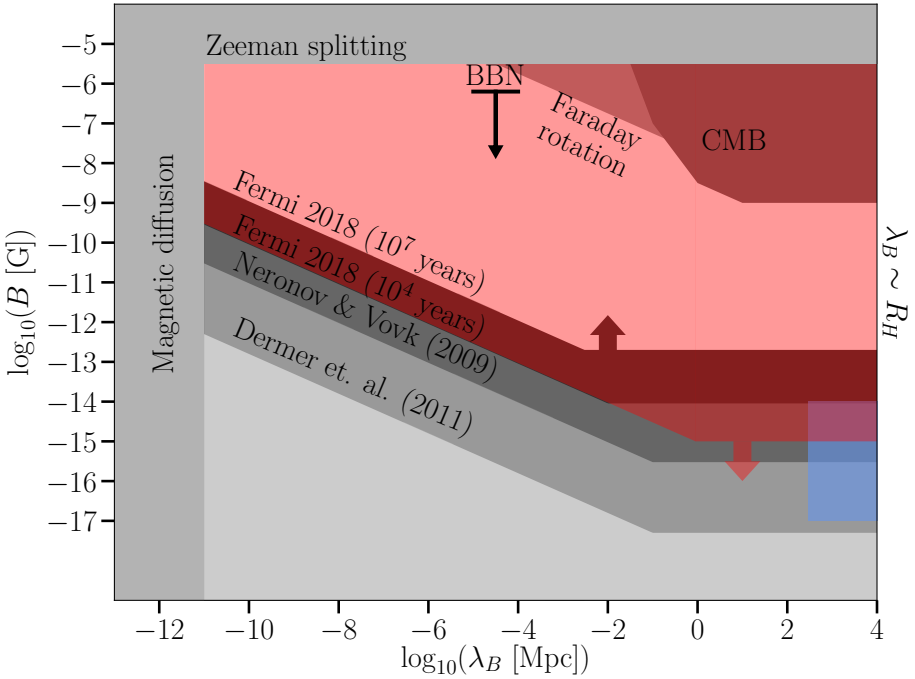
- strong EGMF required for large deflections of UHECRs
- larger effect on TeV cascade electrons ⇒ lower limits
- absence of halos ⇒ upper limit ⇒ overlap except for $t < 10^4$ yr



[Broderick et. al '18]

Constraints on the EGMF

- strong EGMF required for large deflections of UHECRs
- larger effect on TeV cascade electrons ⇒ lower limits
- absence of halos ⇒ upper limit ⇒ overlap except for $t < 10^4$ yr



[*Broderick et. al '18*]

- importance of plasma instability?

[*Broderick et. al '12*]

Radio galaxies

[*Eichmann, MK, Oikonomou '22*]

- longstanding UHECR sources
  - FR-I or low-luminosity radio galaxies
  - FR-II or high-luminosity radio galaxies

Radio galaxies

[*Eichmann, MK, Oikonomou '22*]

- longstanding UHECR sources
  - FR-I or low-luminosity radio galaxies
  - FR-II or high-luminosity radio galaxies
- rather detailed information about local sources
- but indirect:
  - CR luminosity

$$L_{151} \Rightarrow Q_{\rm jet} \Rightarrow L_{\rm CR}$$

  - maximal rigidity

$$Q_{\rm jet} \Rightarrow \mathcal{R}_{\rm max}$$

Radio galaxies

[*Eichmann, MK, Oikonomou '22*]

- longstanding UHECR sources
  - FR-I or low-luminosity radio galaxies
  - FR-II or high-luminosity radio galaxies
- rather detailed information about local sources
- but indirect:
  - CR luminosity

$$L_{151} \Rightarrow Q_{\rm jet} \Rightarrow L_{\rm CR}$$

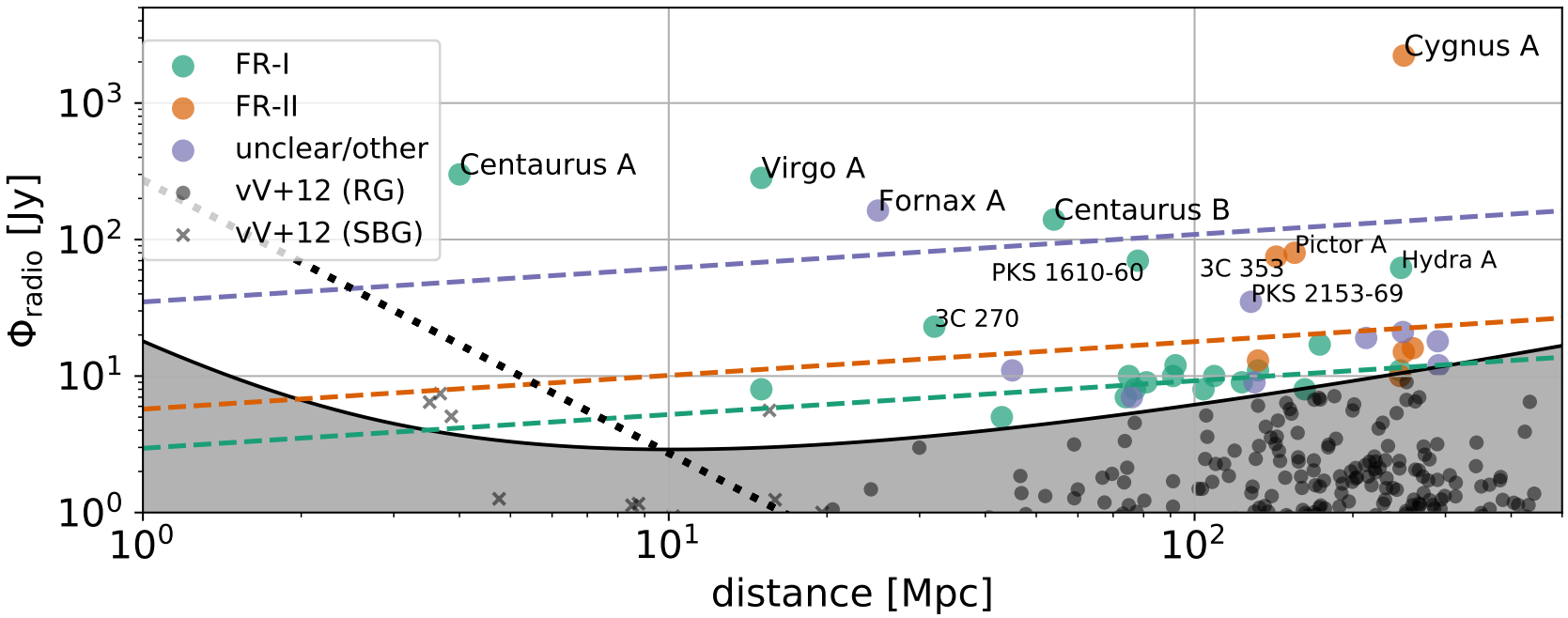
  - maximal rigidity

$$Q_{\rm jet} \Rightarrow \mathcal{R}_{\rm max}$$

$\Rightarrow$ model local sources individually: $t_{\rm acc}, \ldots$

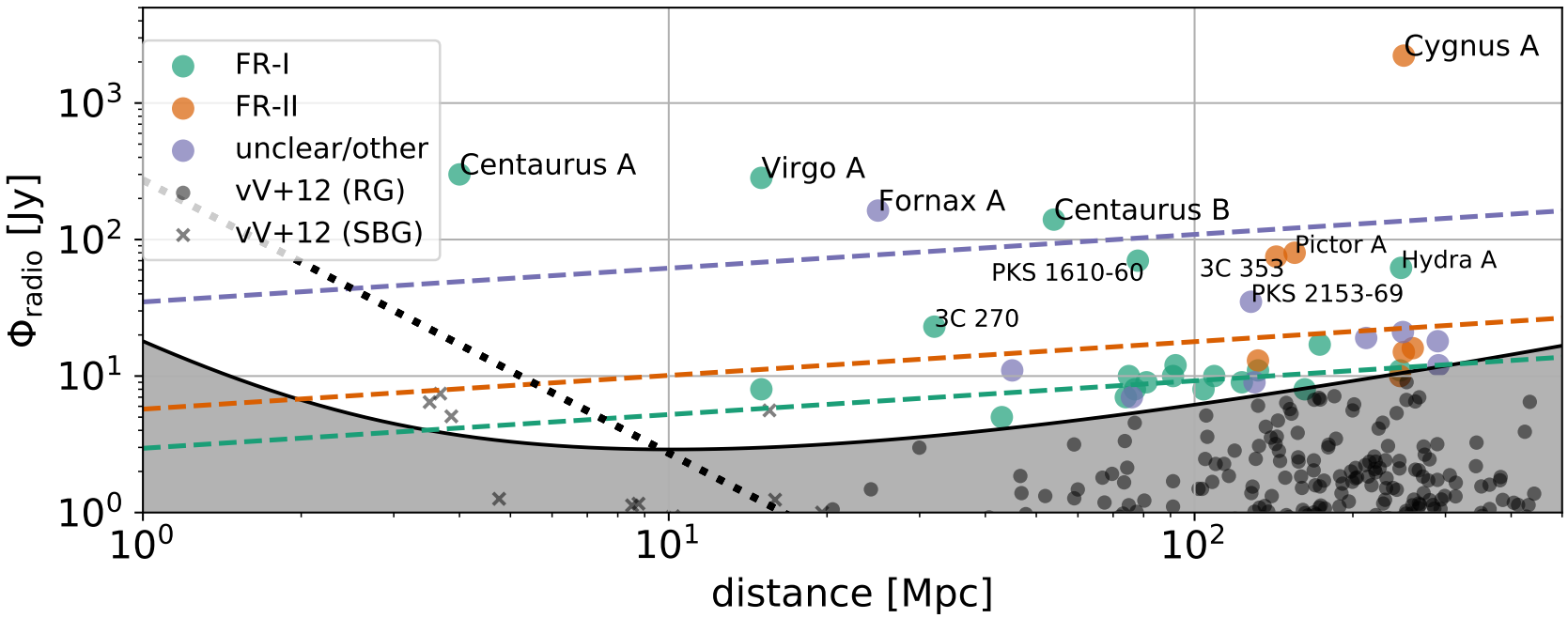
- add continuous source function for $d > 200\,\mathrm{Mpc}$

Radio flux vs. distance



- sources above (black dotted) accelerate $\mathcal{R} \gtrsim 1\,\mathrm{EV}$
- few sources contribute at least $> 5\%$ of Cen A flux (orange)

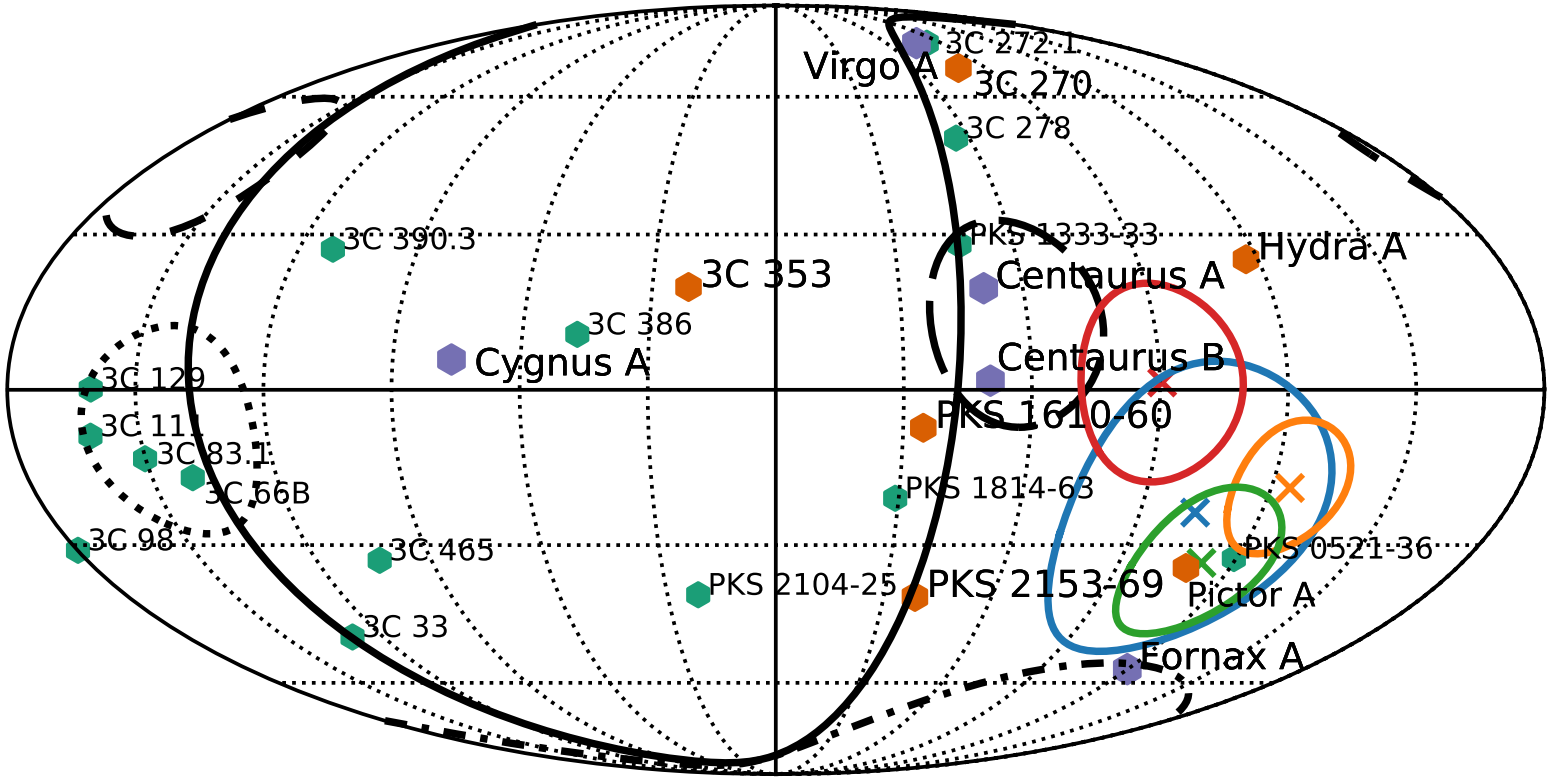
Radio flux vs. distance



- sources above (black dotted) accelerate $\mathcal{R} \gtrsim 1\,\mathrm{EV}$
- few sources contribute at least $> 5\%$ of Cen A flux (orange)
- can such small a sample explain dipole data?

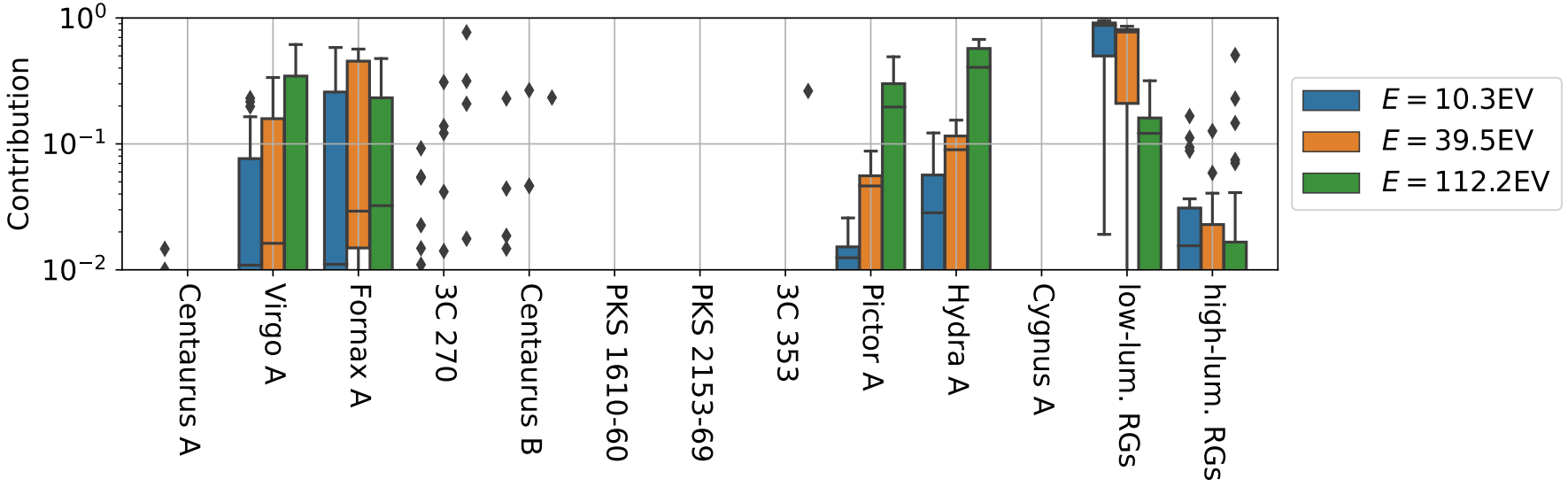
Sky map of local radio galaxies

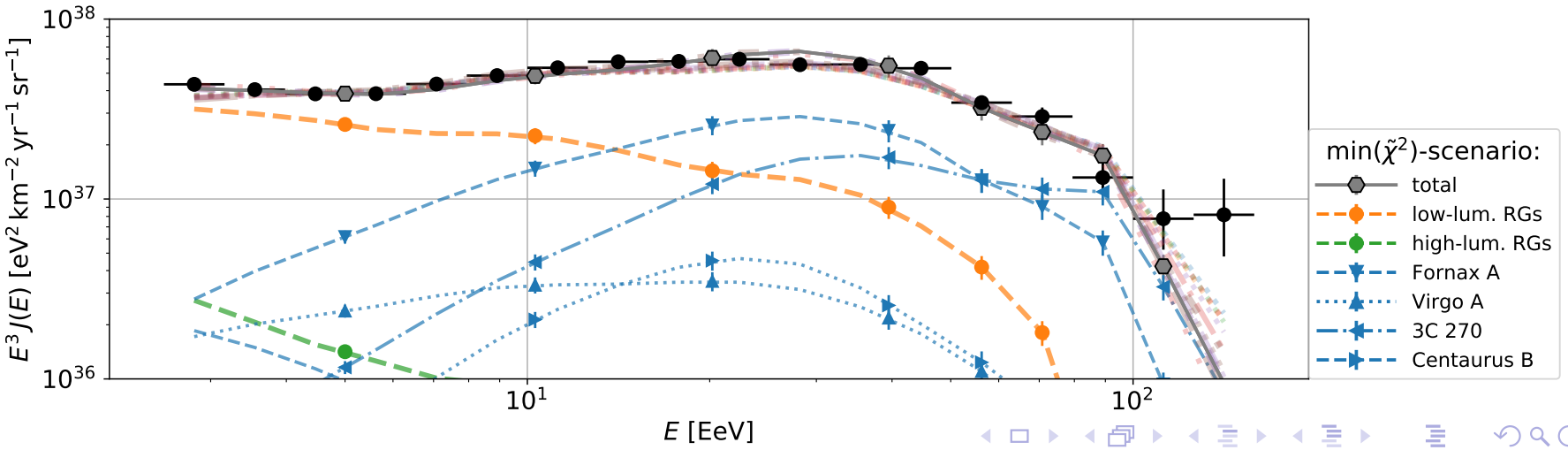
Galactic coordinates



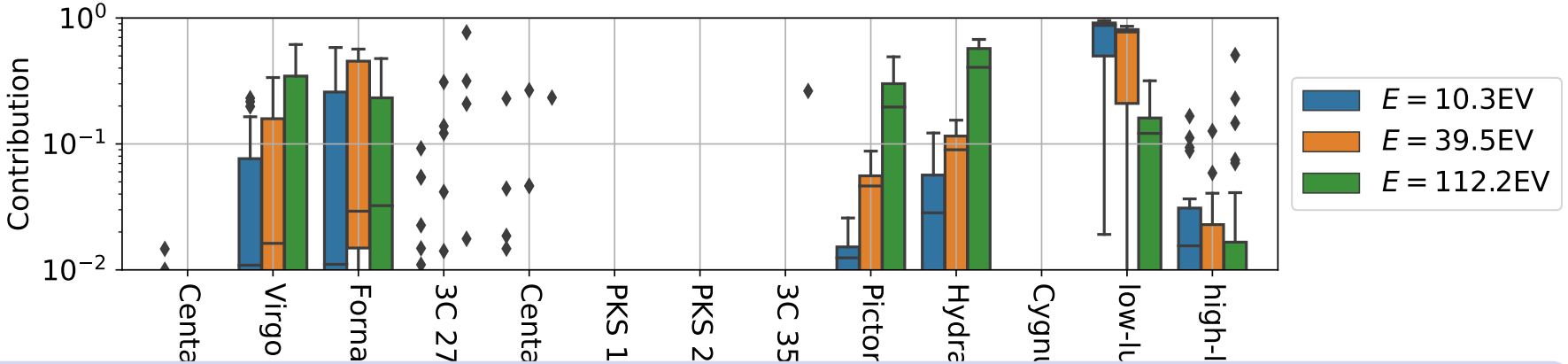
- non-uniform distribution:
  - concentrated towards SG plane
  - dipole structure present
  - "close" to observed UHECR dipole

Relative contributions and spectrum:



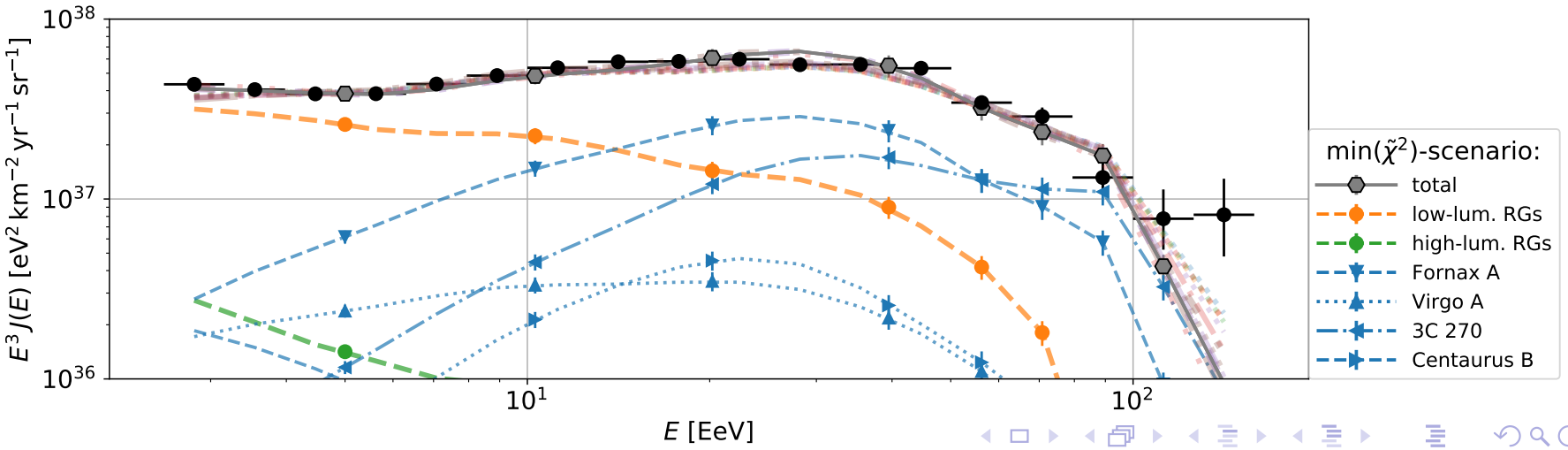


Relative contributions and spectrum:

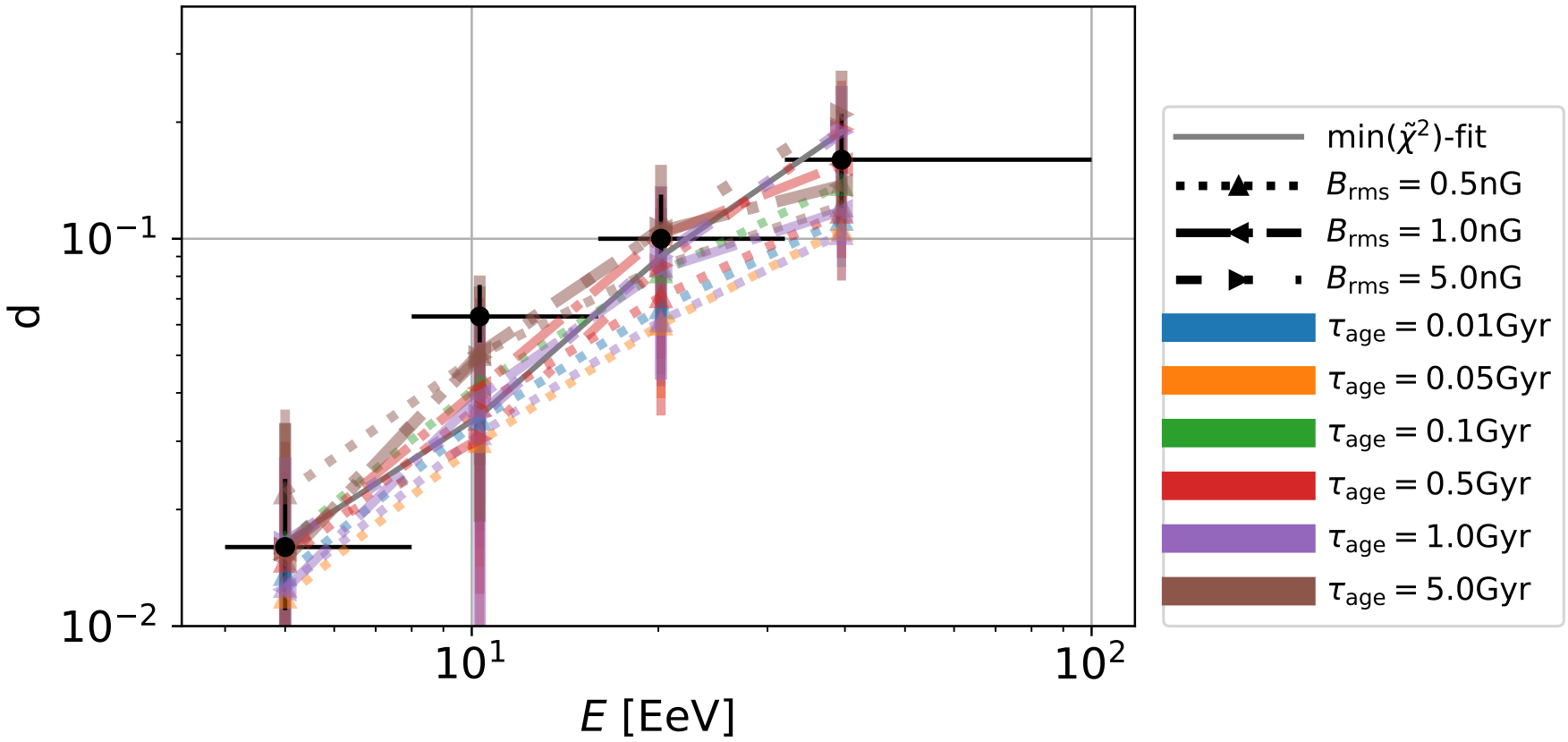


few sources:

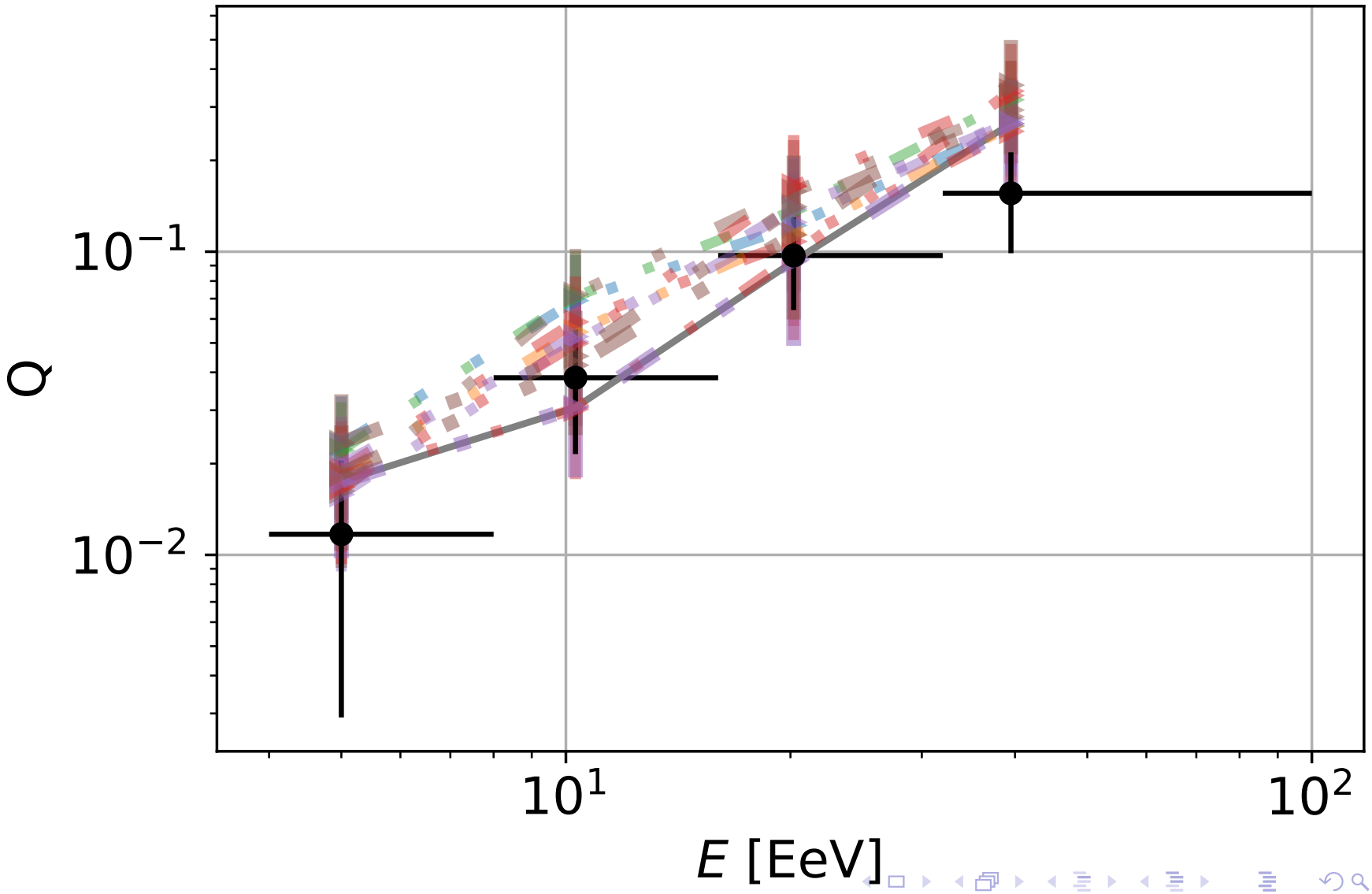
- features like instep & ankle expected



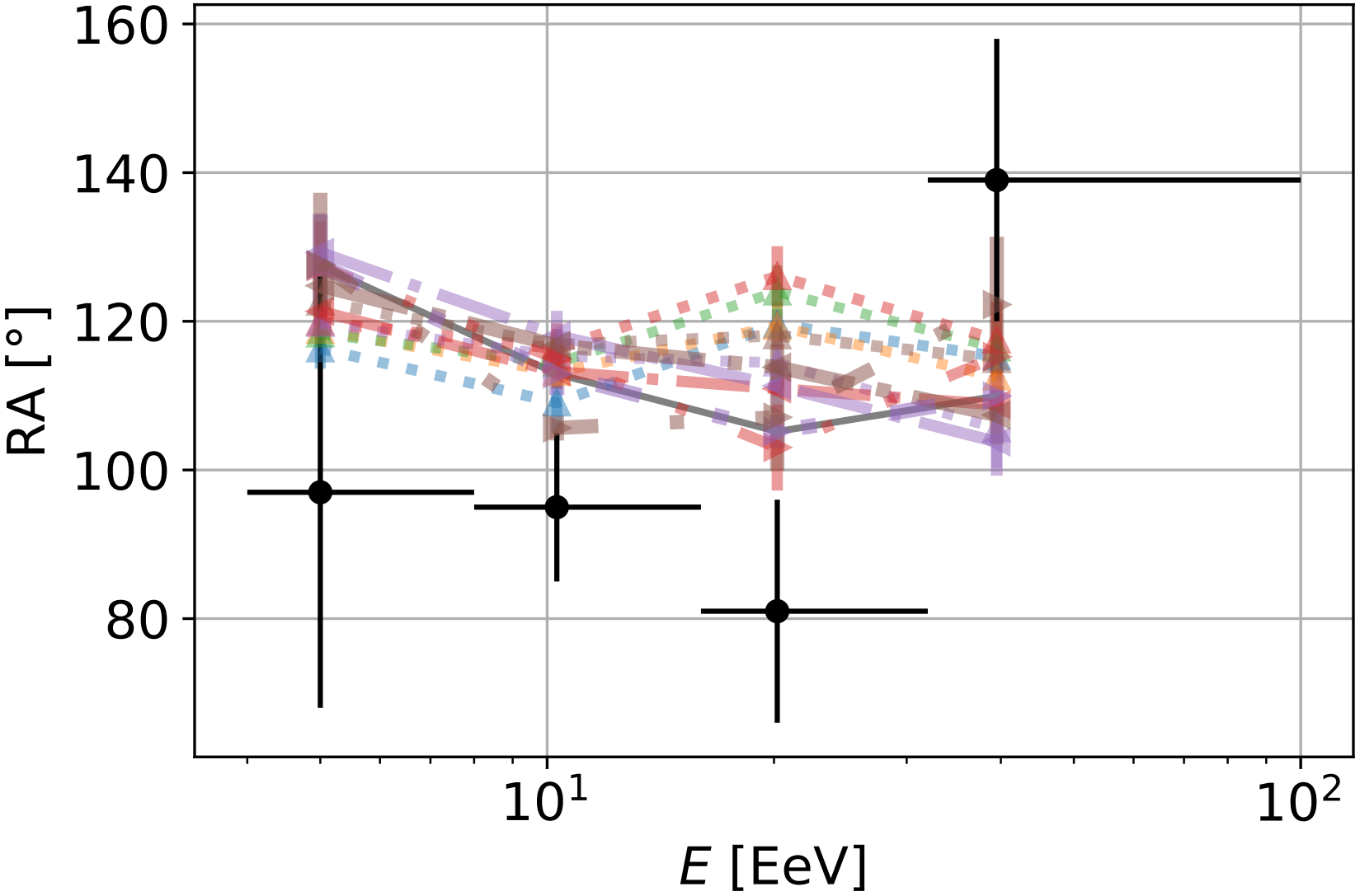
Dipole and quadrupole strength:



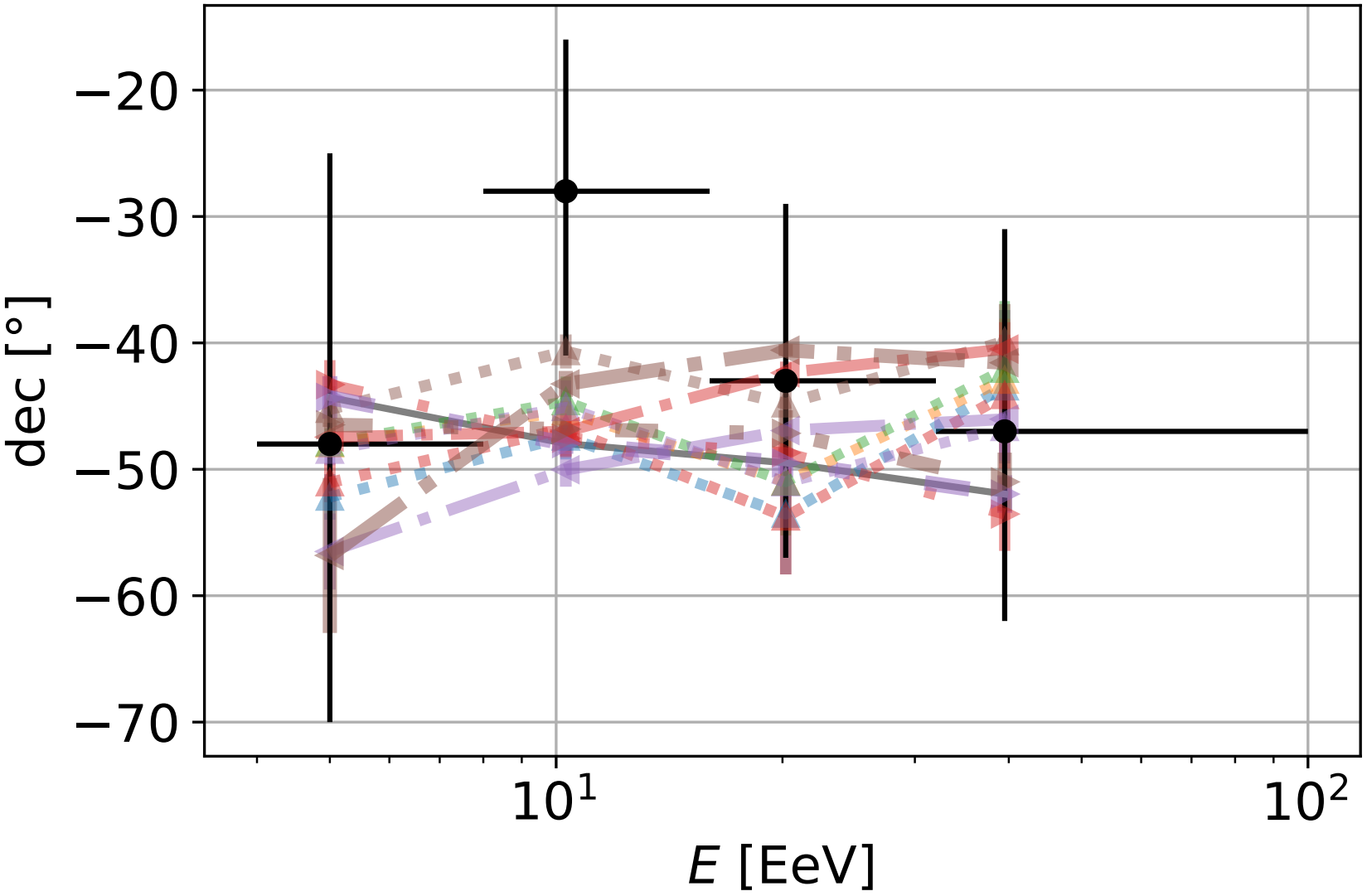
Dipole and quadrupole strength:



Dipole direction:



Dipole direction:

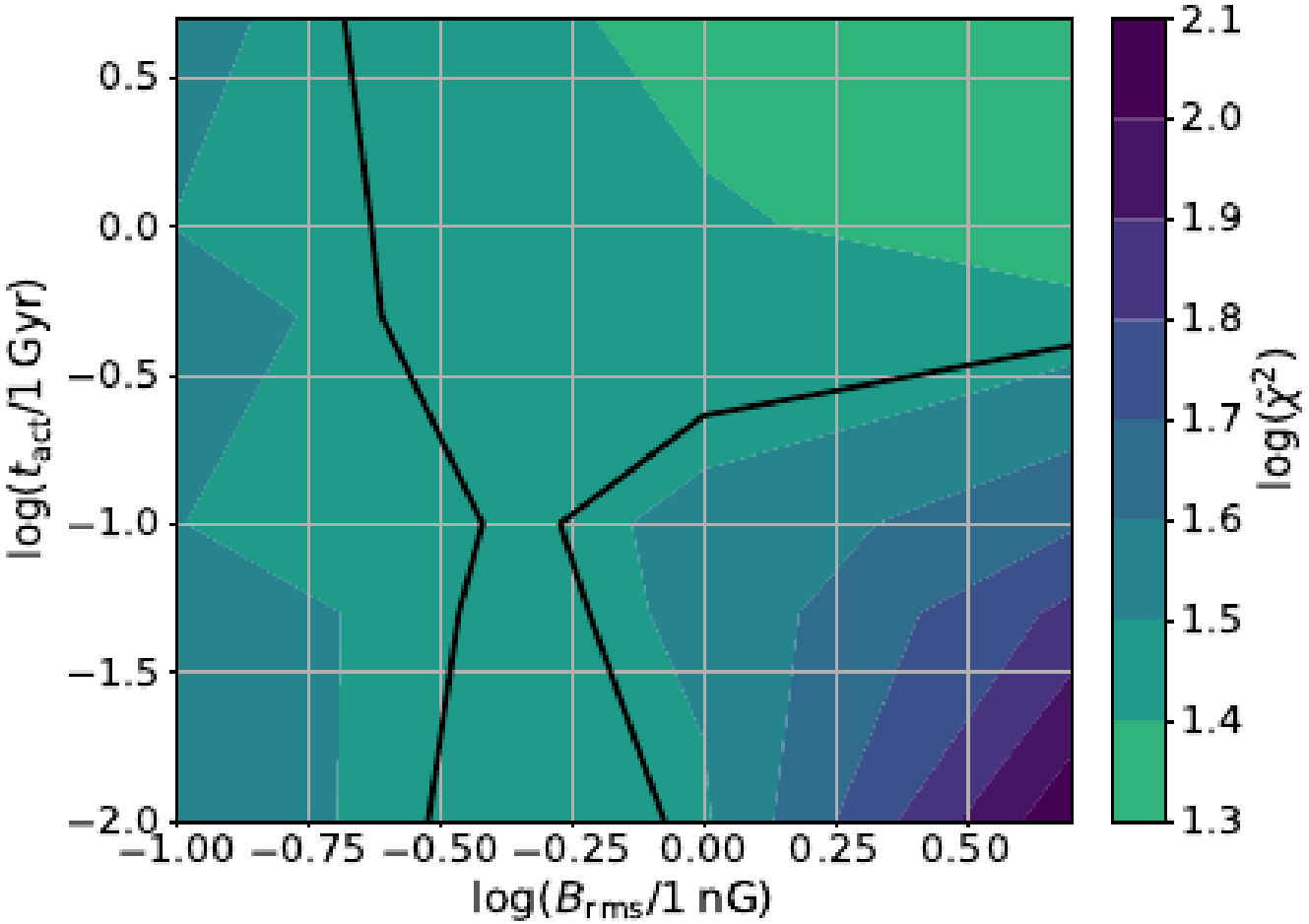


Constraints on EGMF and source life-time:

- Five sources:
  - \+ good fits using only Fornax A, Virgo A and/or 3C270
  - \+ knee: transition local, LL radio galaxies
  - \- requires $B \sim 1$nG $\Rightarrow$ large $t_{\rm act} \sim 1\,$Gyr

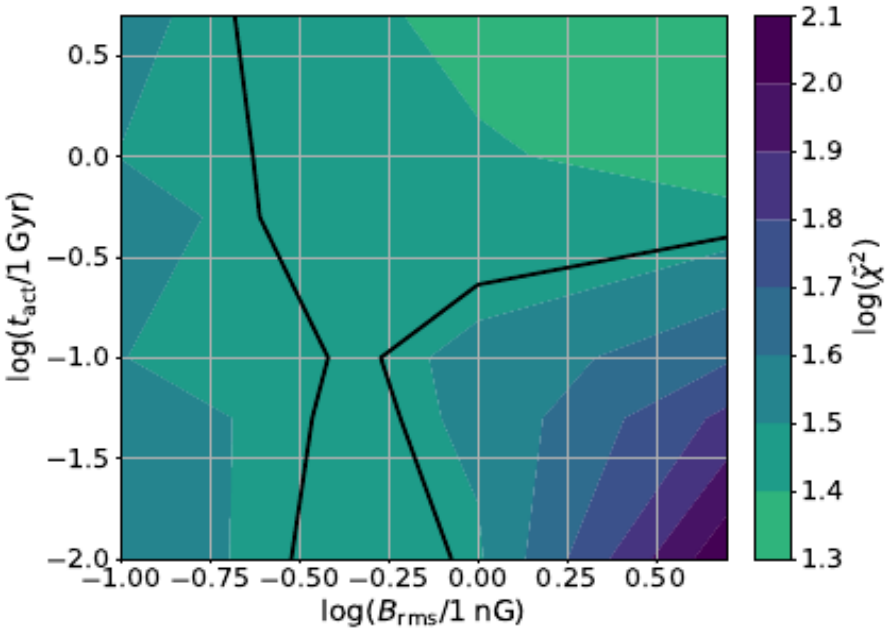
Constraints on EGMF and source life-time:

- Five sources:
- Eleven sources: many more scenarios
  - + allows to reduce B and t_{act}:



Constraints on EGMF and source life-time:

- Five sources:
- Eleven sources: many more scenarios
  - + allows to reduce B and $t_{\rm act}$:



  - - some sources are generically suppressed:
    - ★ Cygnus A: too short $t_{\rm act}$
    - ★ Cen A: too strong anisotropy

Effect of finite life-time:

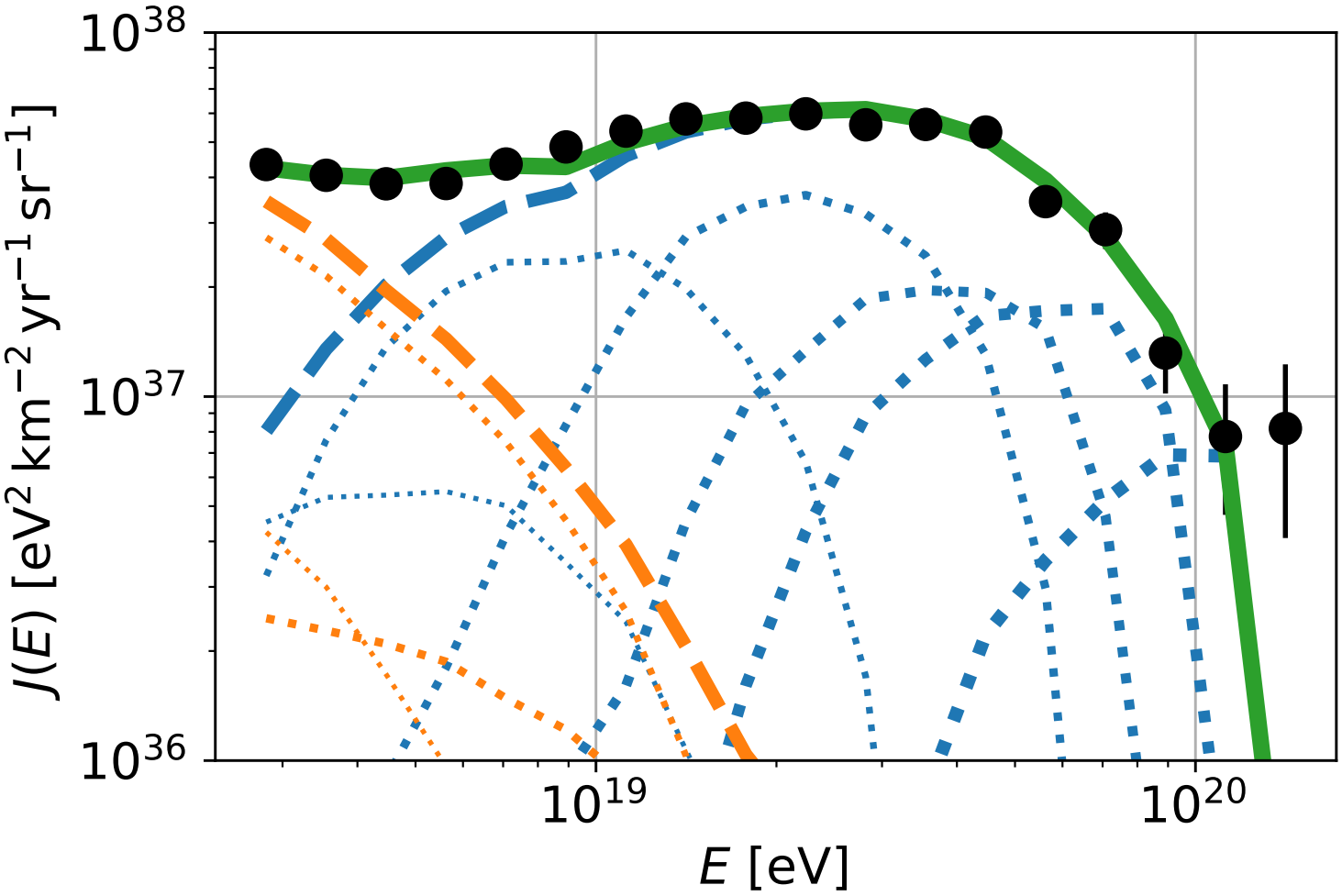
[*Eichmann, MK '22*]

- magnetic horizon suppresses low-rigidity CRs [*Parizot '04, Berezinsky, Gazizov '05*]

Effect of finite life-time:

[Eichmann, MK '22]

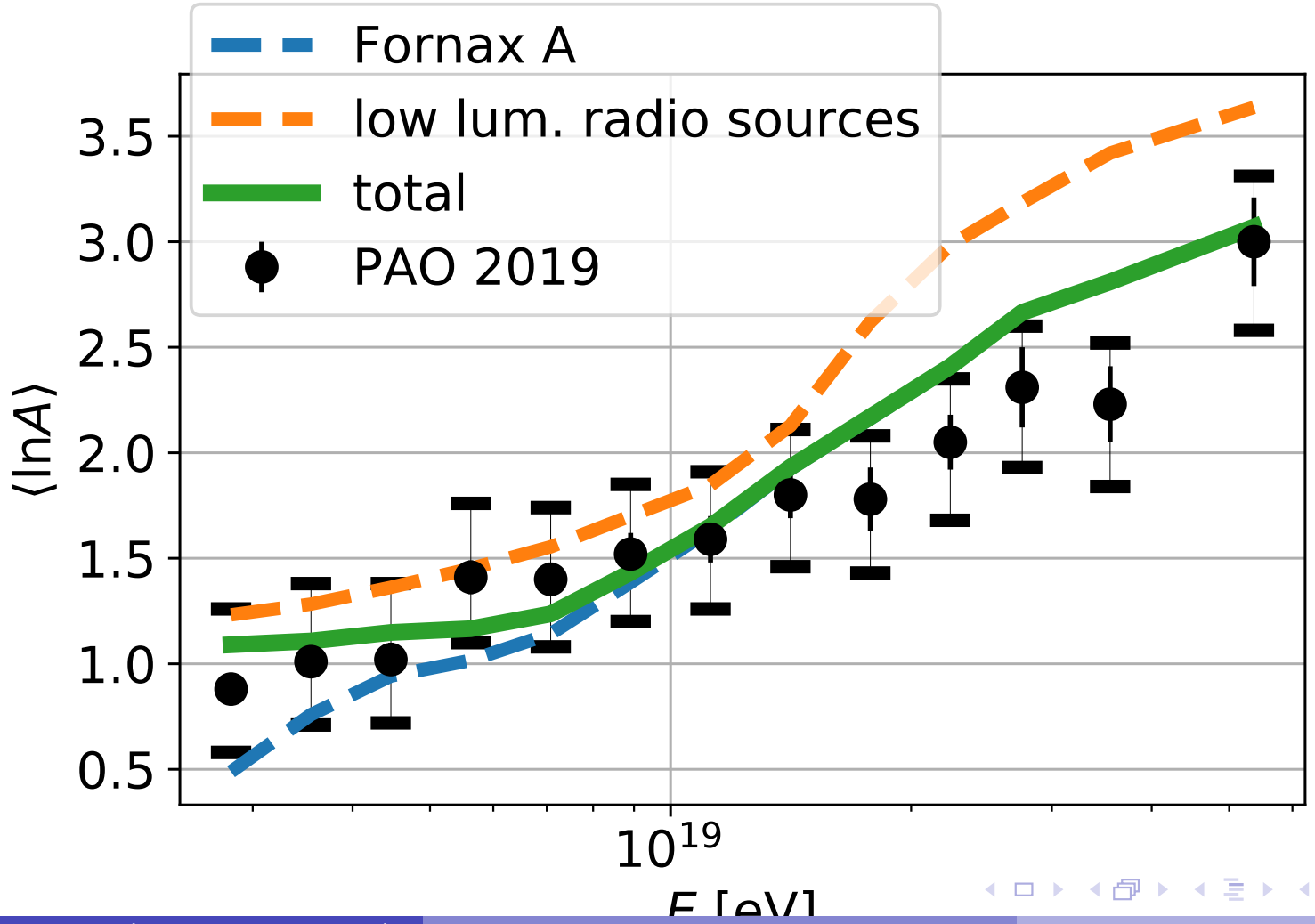
- magnetic horizon suppresses low-rigidity CRs [Parizot '04, Berezinsky, Gazizov '05]
- $1/E^2$ spectrum, finite life-time & dominance of one source:



Effect of finite life-time:

[Eichmann, MK '22]

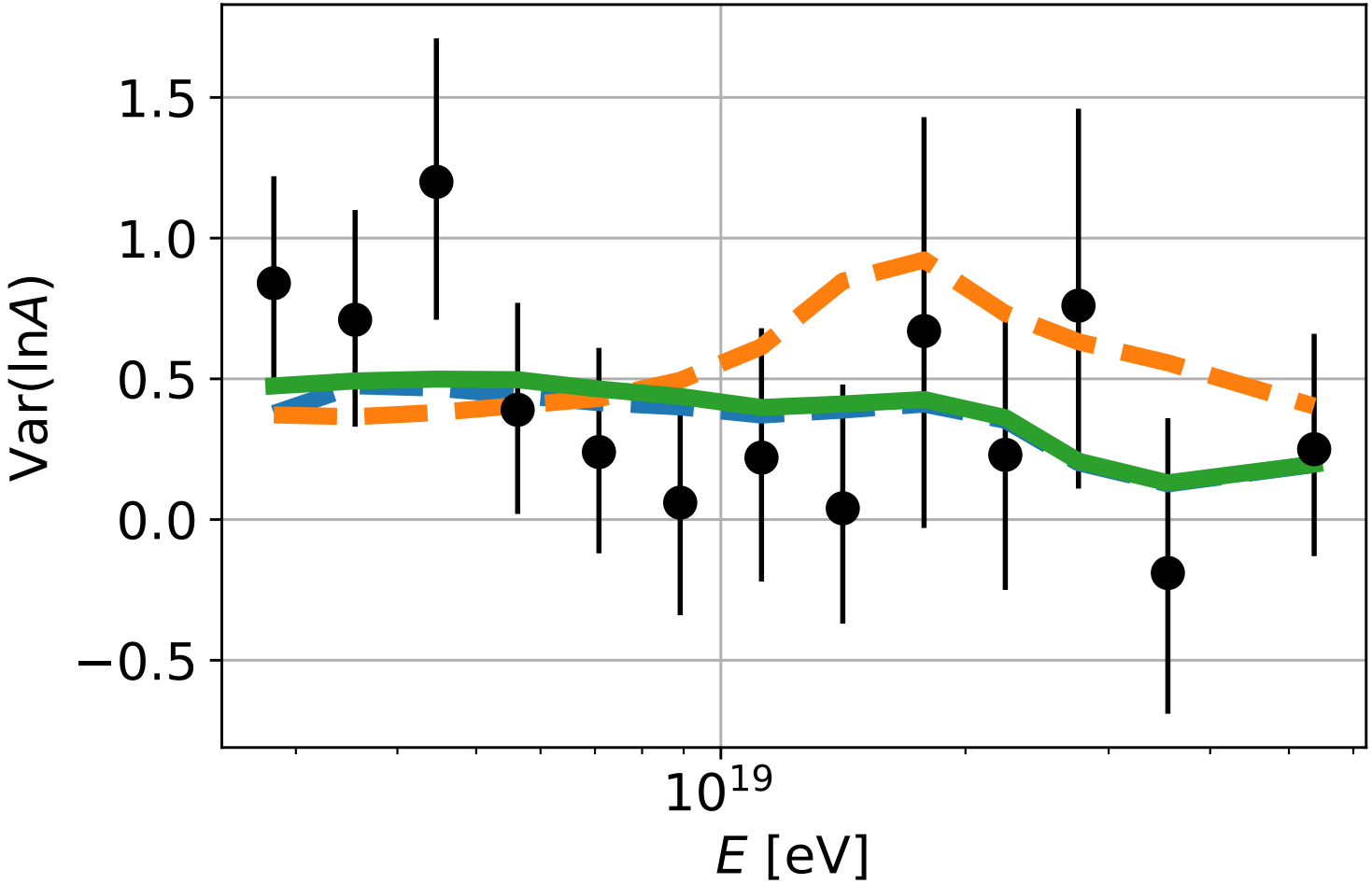
- magnetic horizon suppresses low-rigidity CRs [Parizot '04, Berezinsky, Gazizov '05]
- $1/E^2$ spectrum, finite life-time & dominance of one source:



Effect of finite life-time:

[Eichmann, MK '22]

- magnetic horizon suppresses low-rigidity CRs [Parizot '04, Berezinsky, Gazizov '05]
- $1/E^2$ spectrum, finite life-time & dominance of one source:



Summary

1. considerable experimental progress:
   - spectrum and dipole
   - composition: agreement PAO vs. TA?
   - progress of correlation analyses needs proton rich event samples
2. theoretical studies:
   - include all info: spectrum, composition & anisotropies
   - abandon average sources
   - impose finite activity time of sources
3. promising UHECR sources:
   - several candidates as GRBs are already disfavoured
   - (subclasses of) AGNs remain attractive option
   - probably only few dominating sources
4. common source class for UHECRs and neutrinos: unlikely?