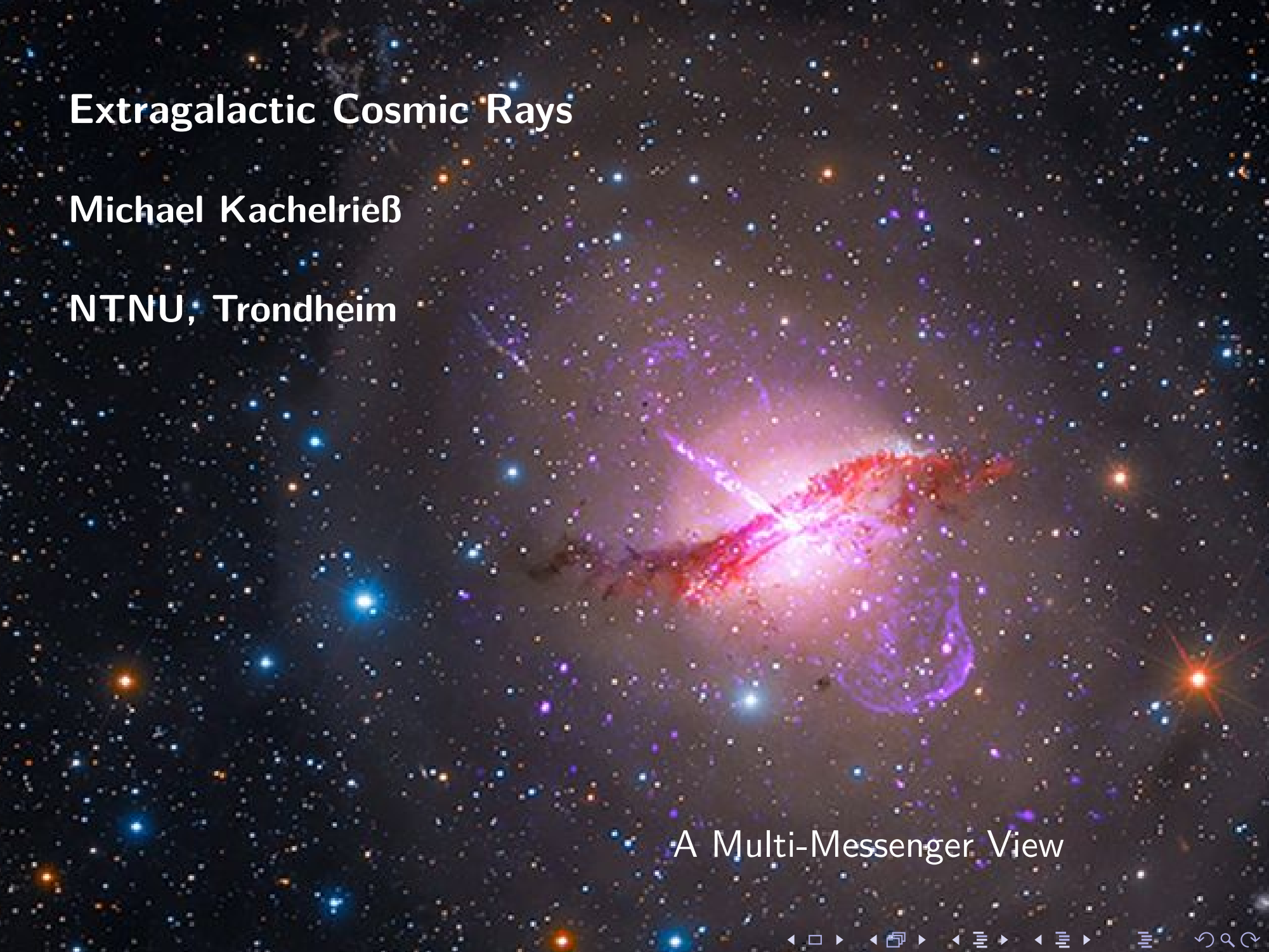
Extragalactic Cosmic Rays

Michael Kachelrieß

NTNU, Trondheim



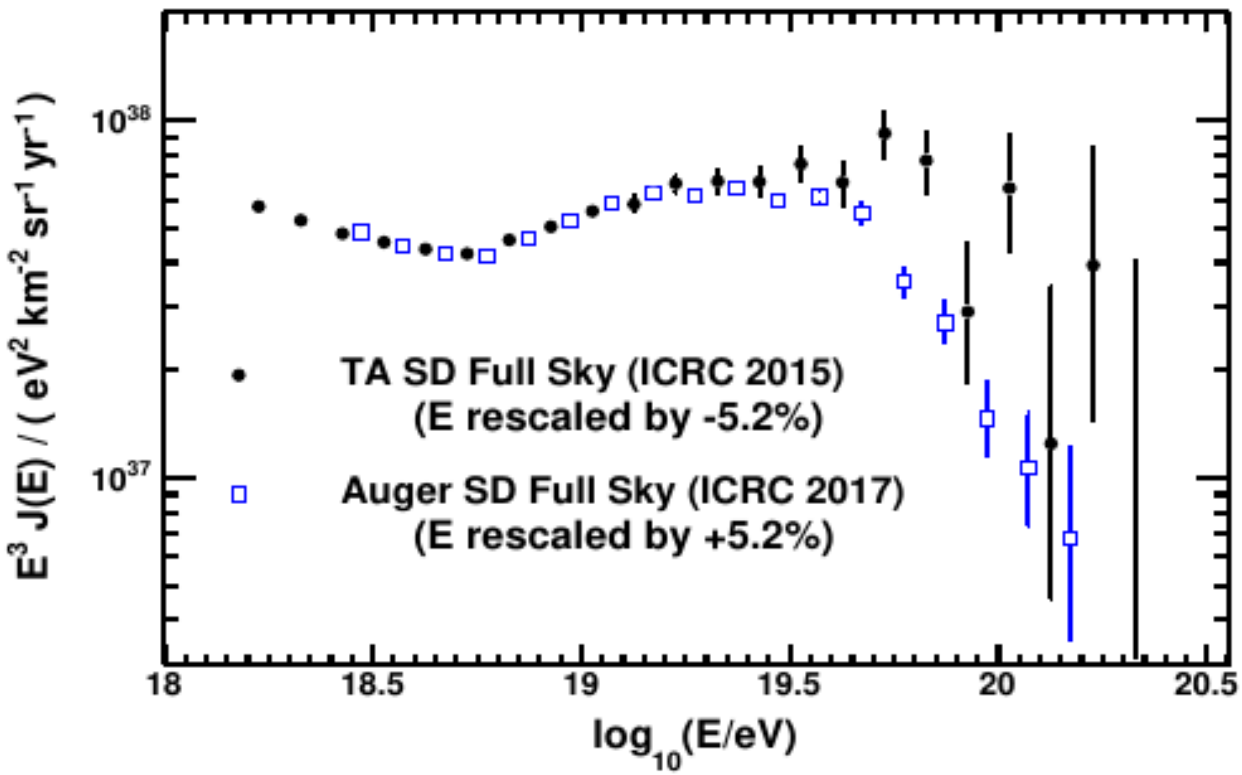
A Multi-Messenger View

Outline of the talk

1. Introduction $\Rightarrow$ HL talks Engel & Rubtsov
2. Observations and their interpretation:
   - Energy spectrum
   - CR composition $> 10^{17}$ eV
   - Anisotropies and correlations
   - EGRB, cascade limit and neutrinos

   $\Big\}\Rightarrow$ transition
3. Sources:
   - General constraints
   - Comment on EGMF
   - specific sources: starburst galaxies, GRBs, AGNe
4. Summary

Energy spectrum

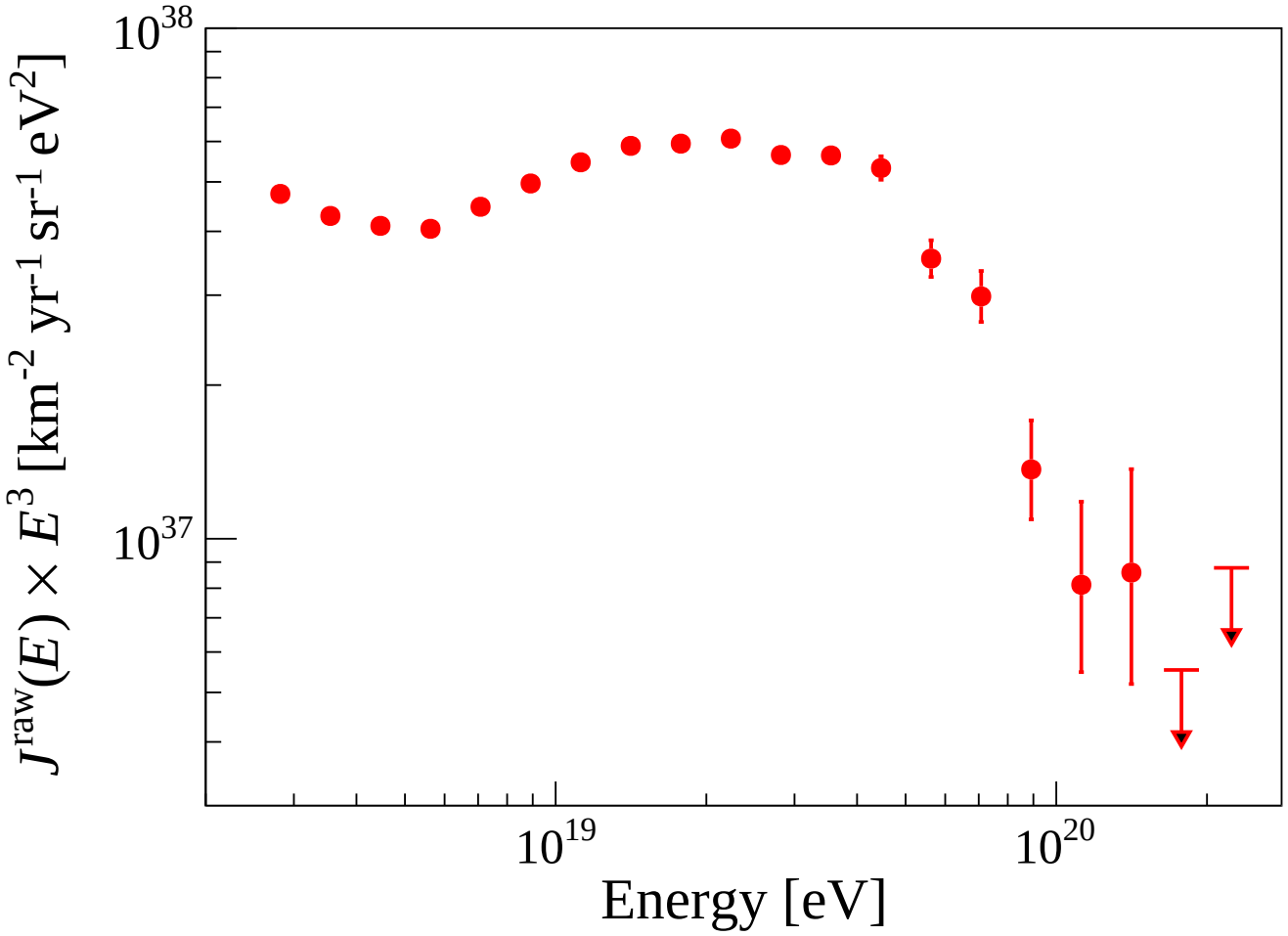


- traditionally: 6 parameter fit,
  - broken power-law, with ankle as break energy
  - "GZK suppression"

Instep: a new spectral feature?

[PAO '20]

- spectrum from raw data:



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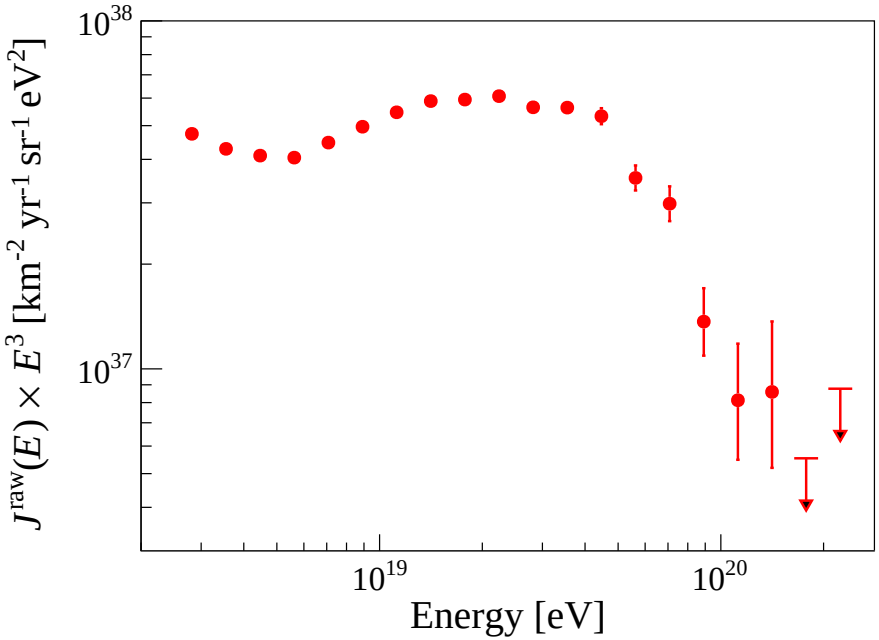
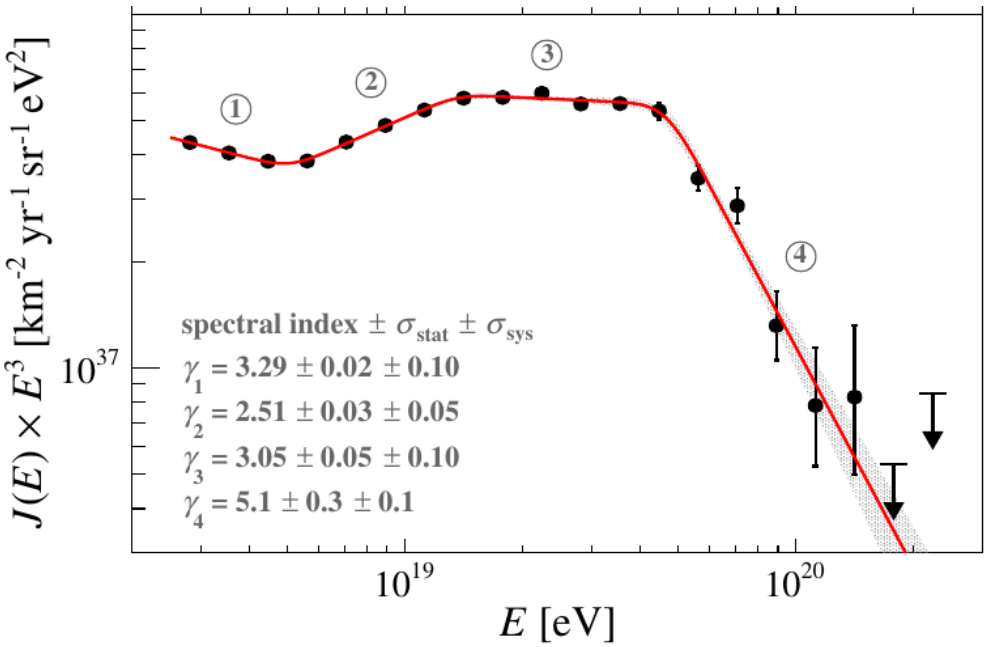


- 6 parameter: bad fit $\chi^2/\text{d.o.f.} = 35.6/14$

Instep: a new spectral feature?

[PAO '20]

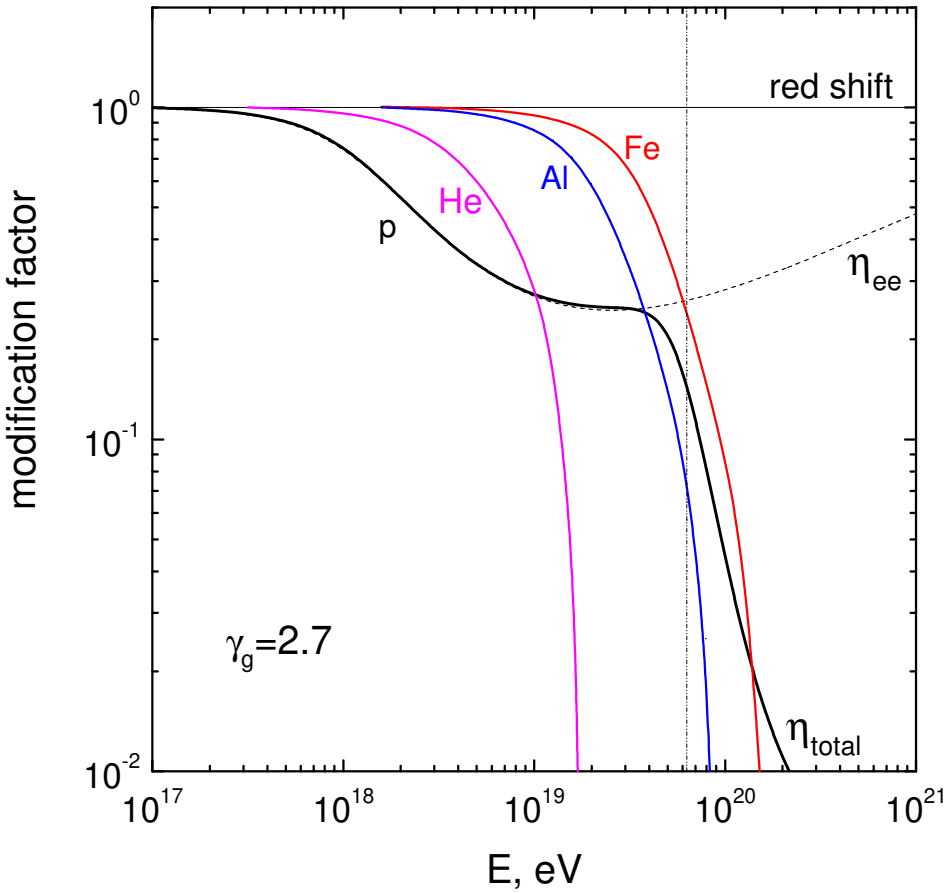
- spectrum from raw data:
- 6 parameter: bad fit $\chi^2/\text{d.o.f.} = 35.6/14$
- add one more break:



- new spectral feature?

Sequence of power-laws – good approximation?

- propagation effects vs. different populations, nuclear groups



- generally: reduce errors and/or energy resolution ⇒ more segments

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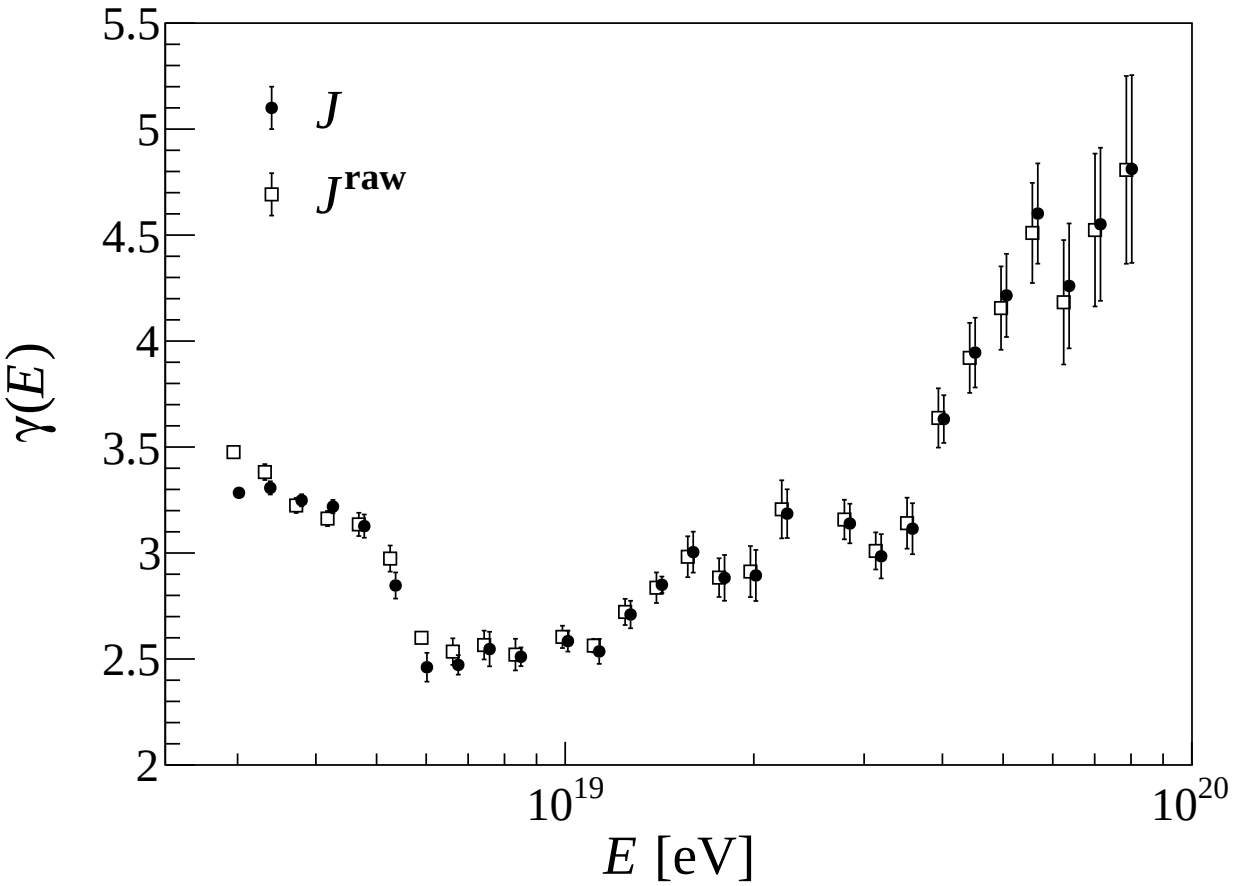

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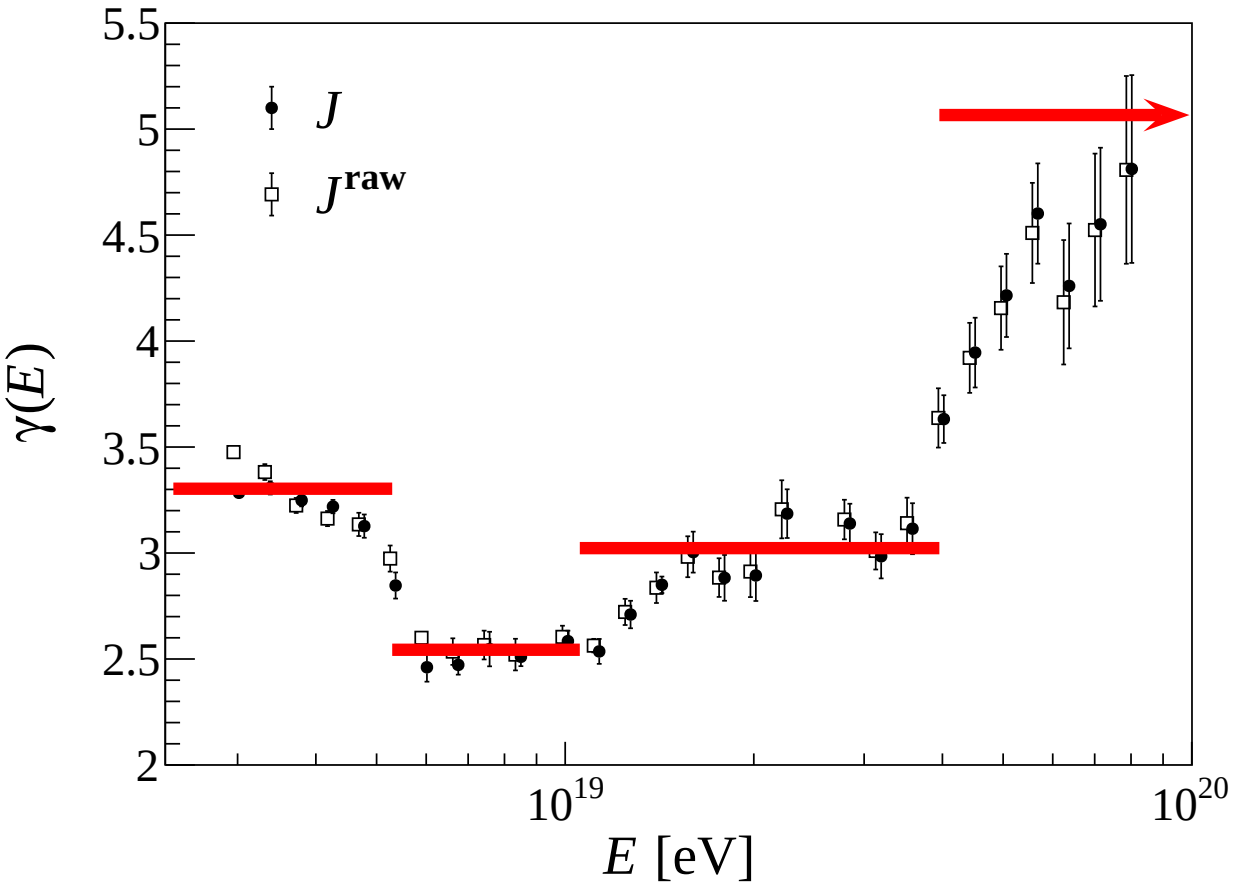
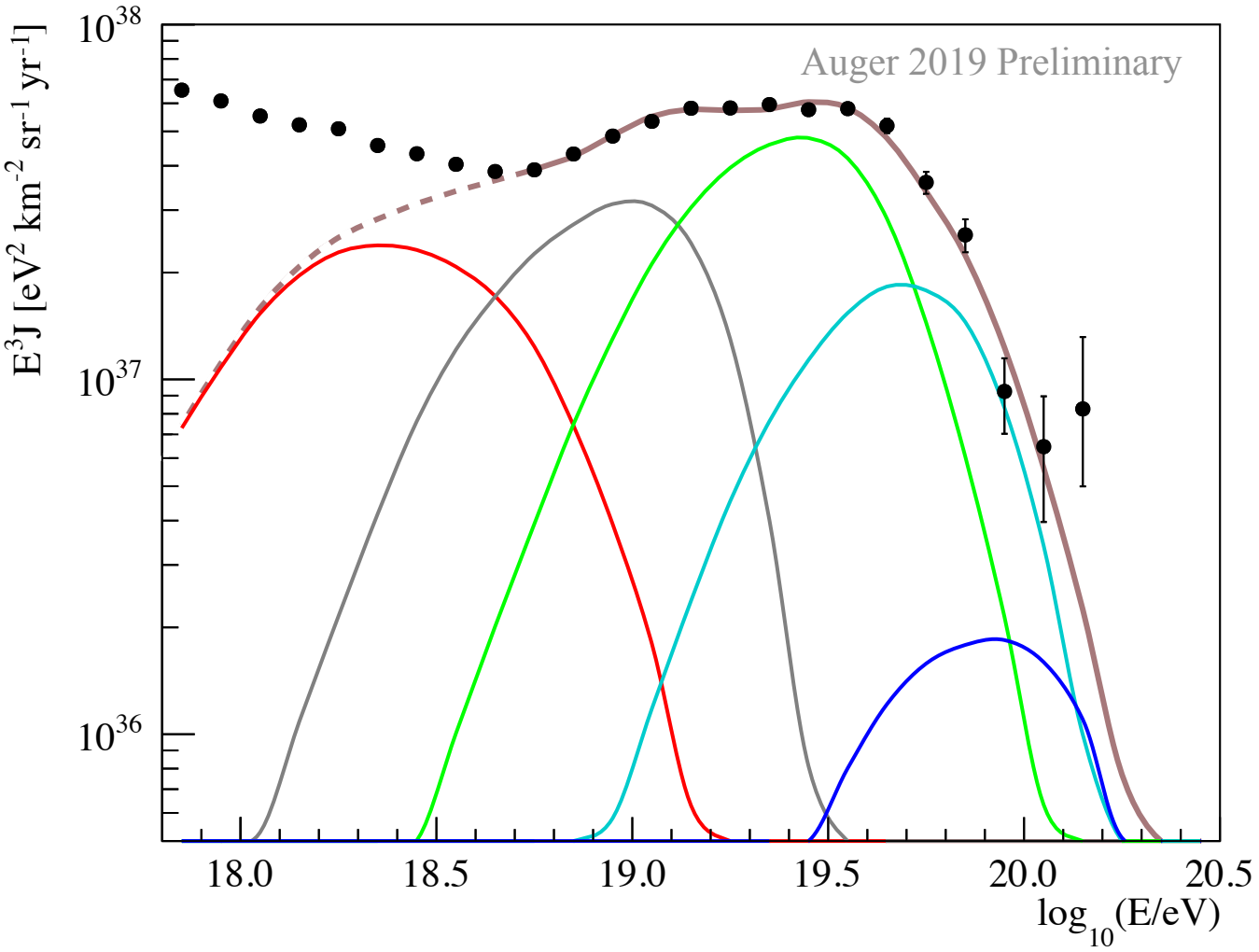


Interpretation

[PAO '20]

- single source: excluded by anisotropy
- transition between different nuclear groups:



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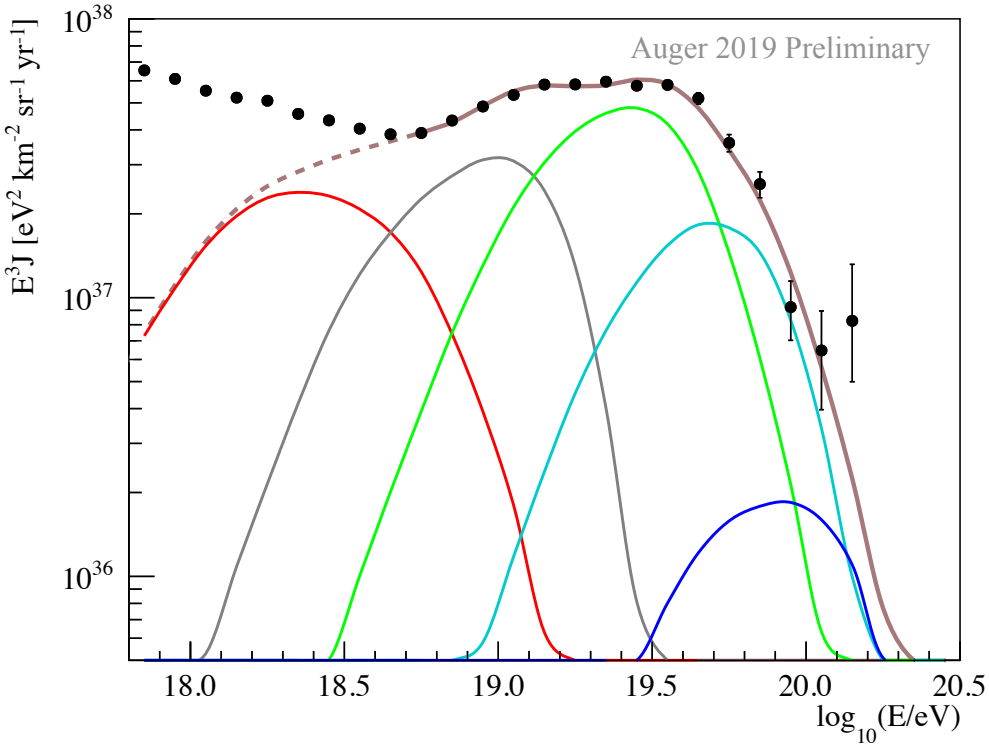

\+ good fit of spectrum and composition

– additional component below ankle needed

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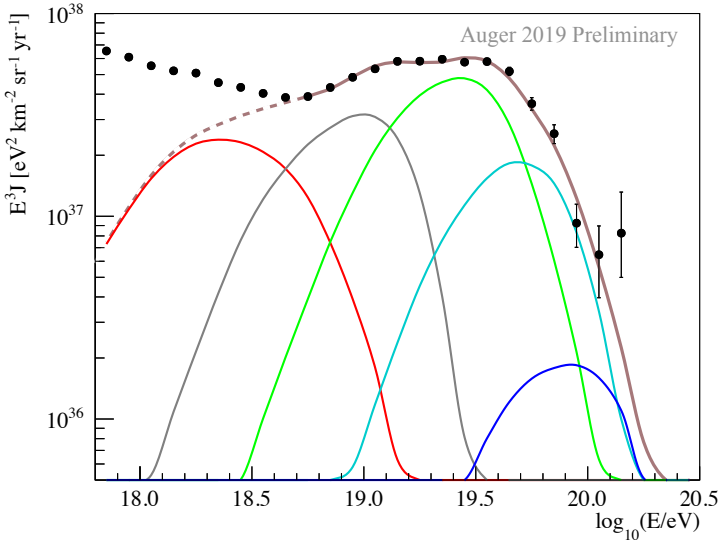

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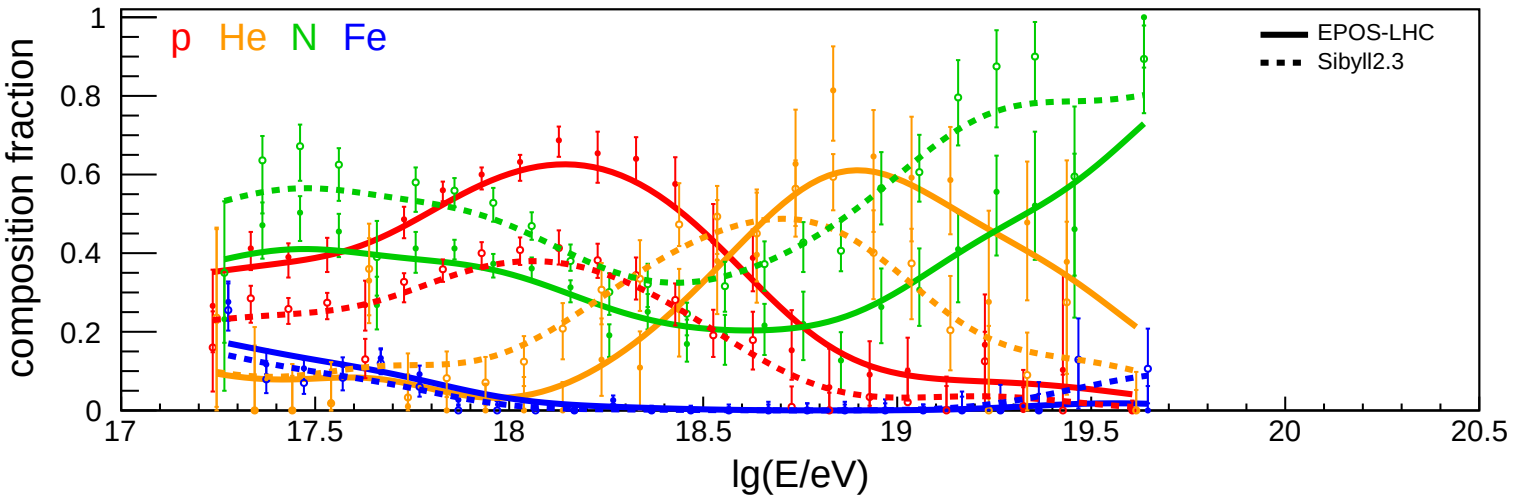
  - flat "average" spectra require even flatter single source spectra
- typical source $\Rightarrow$ population: RMS(X_{max}) becomes wider

Composition of CRs:

[*PAO '18*]



mixed composition:

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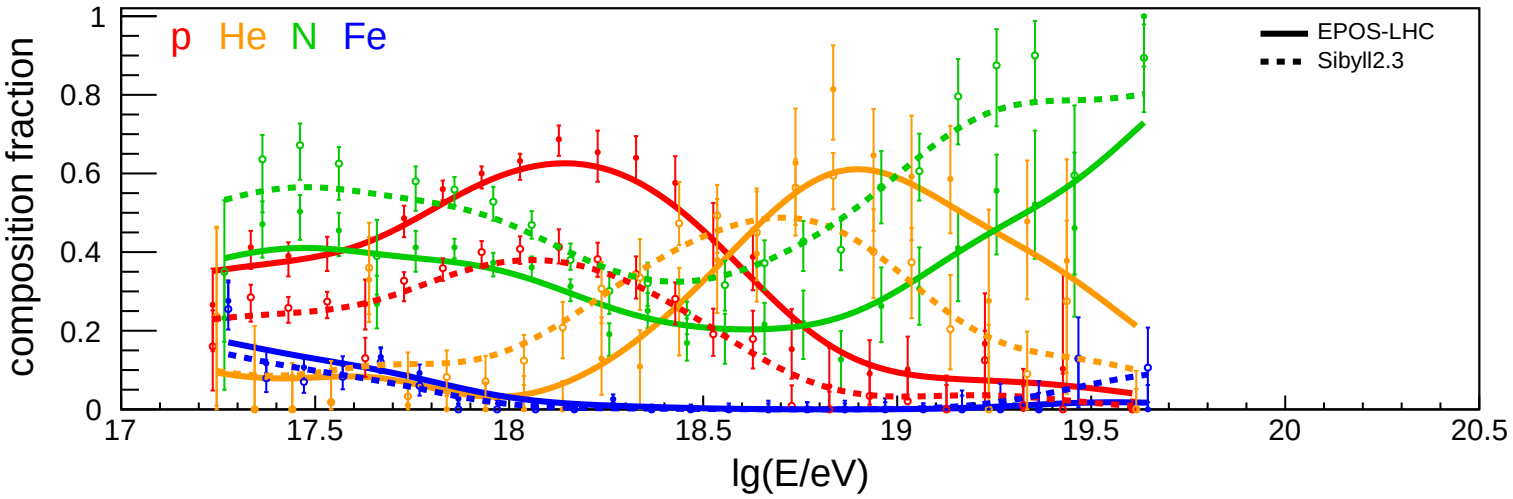

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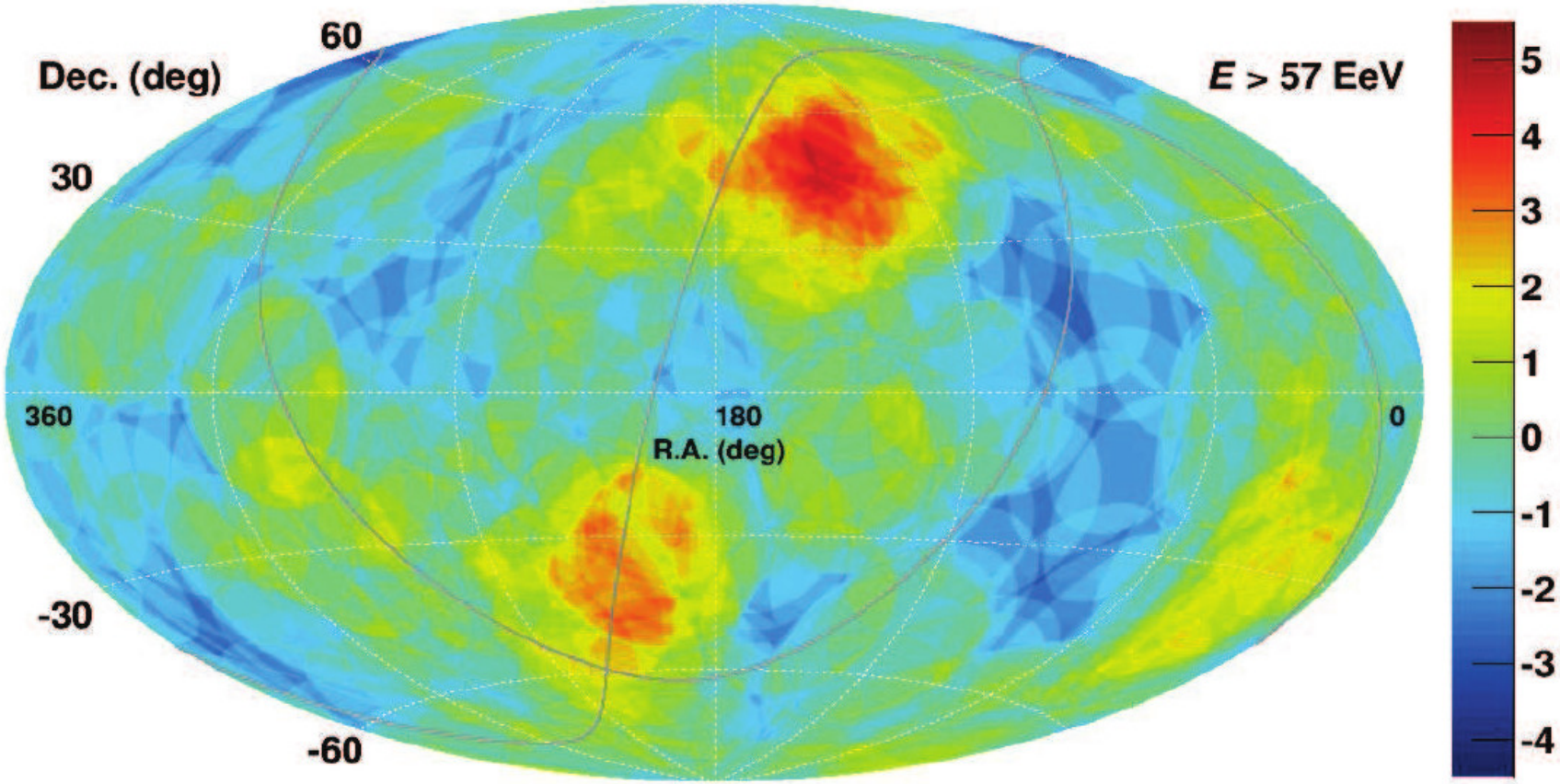
TA analysis '21:

- mainly proton+He

Potential anisotropies:



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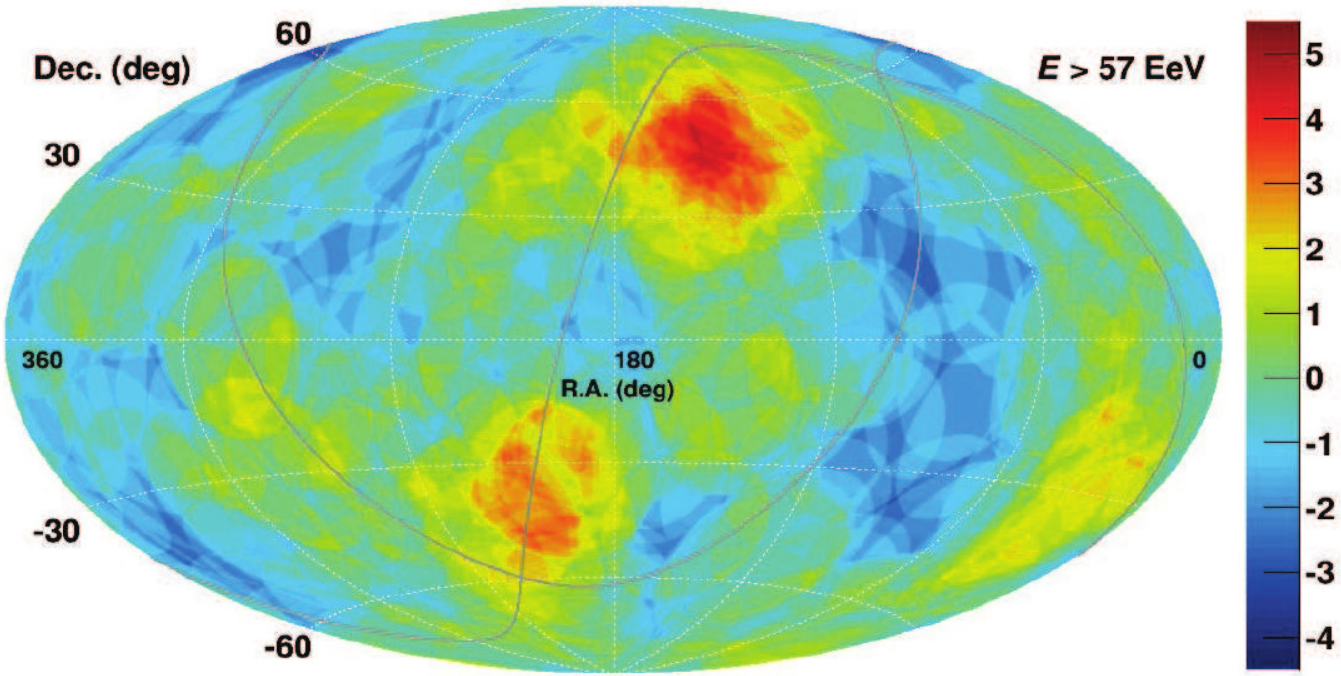


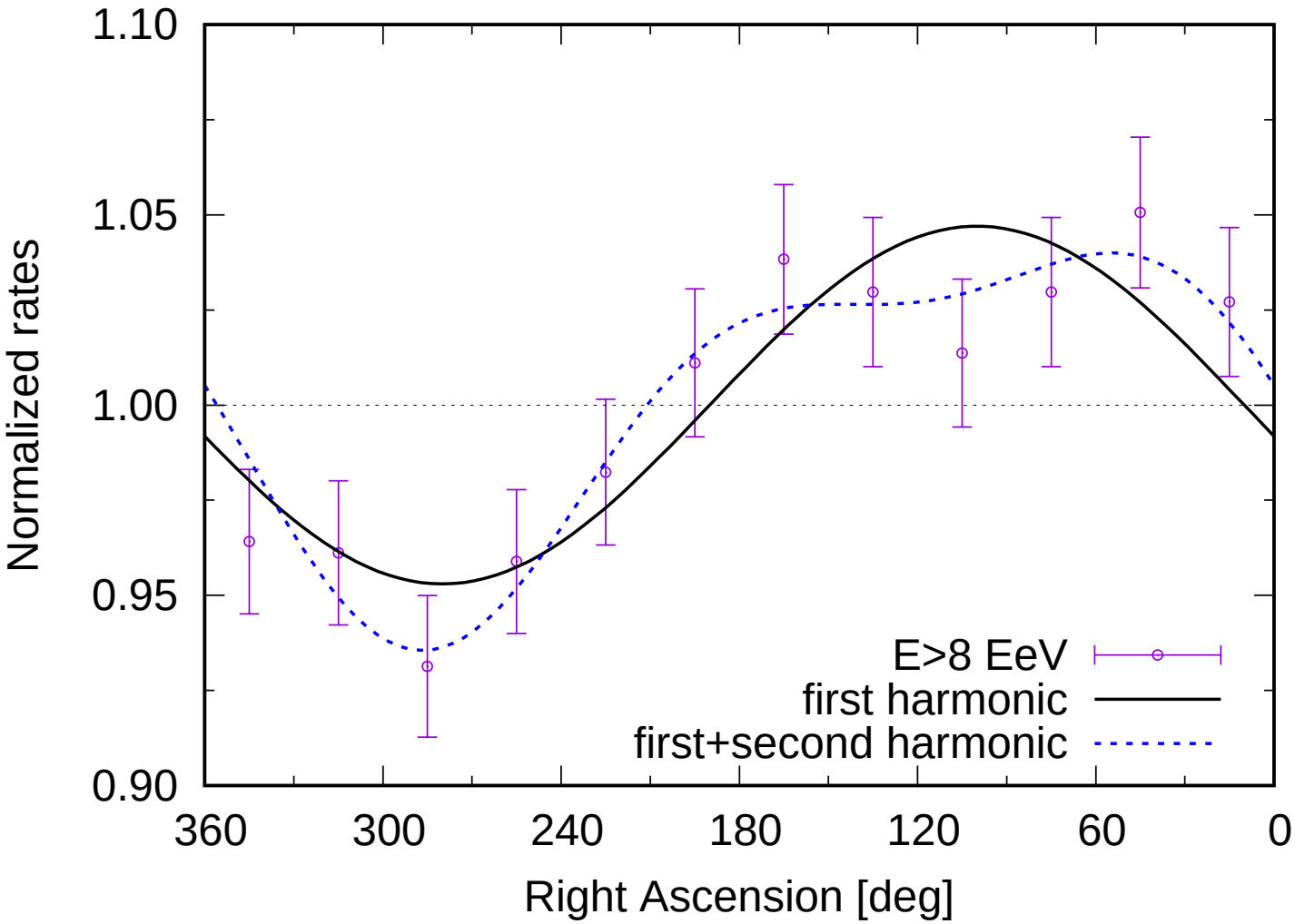
Various signatures for deviations from isotropy:

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

Observation of dipole

[*PAO '17, '18*]

- $E > 8\,\text{EeV}$: dipole observed with $A \simeq 6.5\%$ and $\text{R.A.} \simeq 120^\circ$



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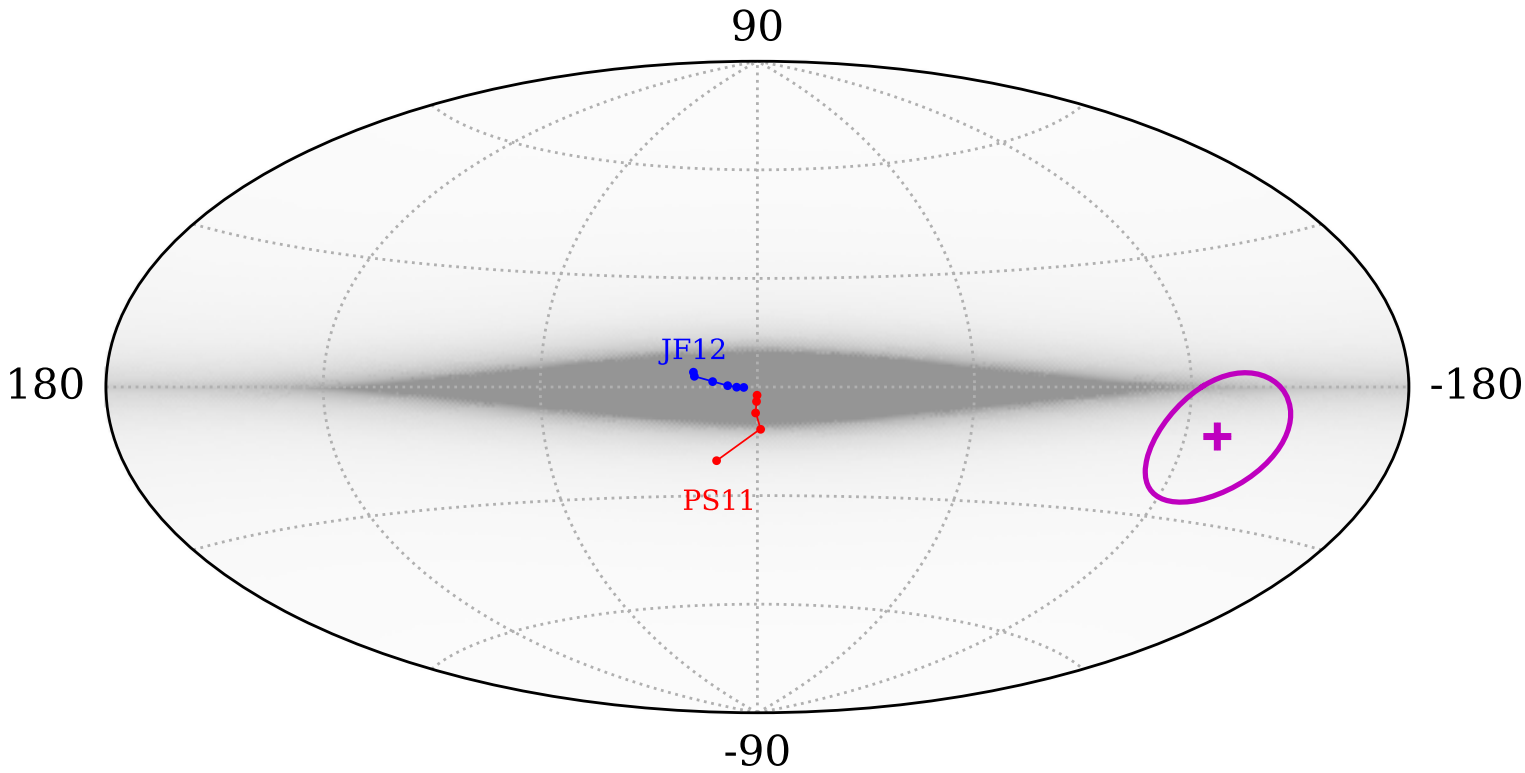


- direction consistent with extragalactic mass distribution

Dipole: interpretations

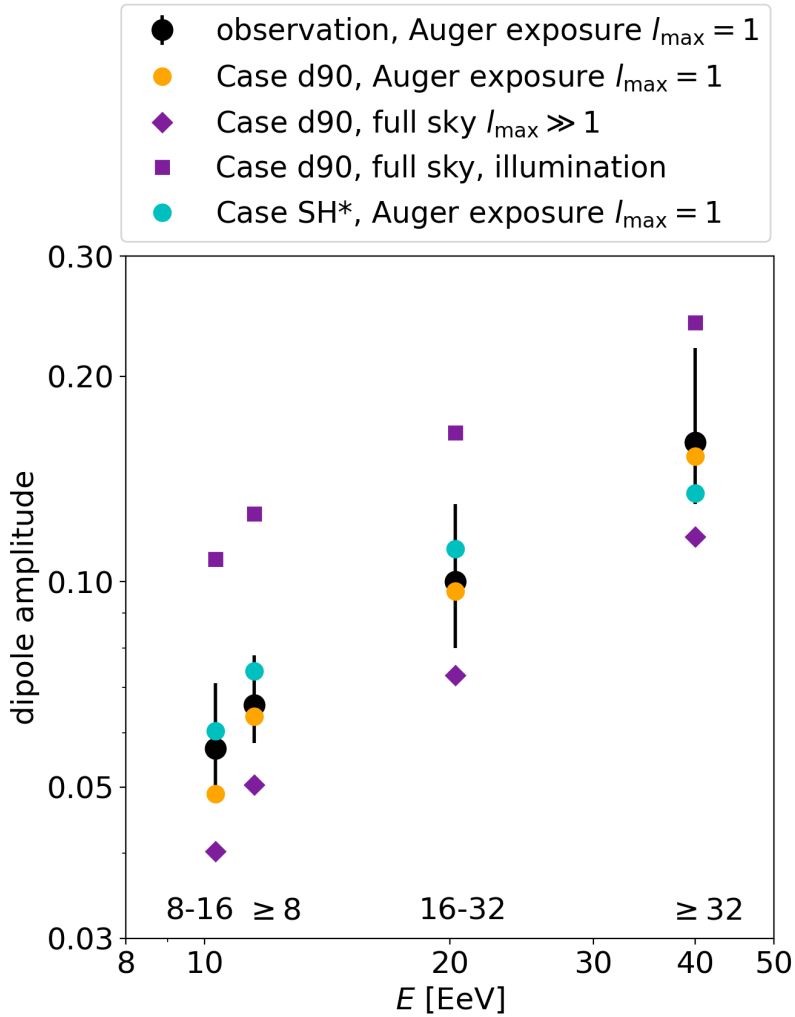
- open questions:

[*ICRC Lang # 1387, Ding # 1415*]

  - few nearby sources vs. LSS
  - EGMF: magnetic horizon limiting λ_{CR}?
  - GMF: shift of dipole direction

Dipole: interpretations

- energy dependence of amplitude and phase can be reproduced



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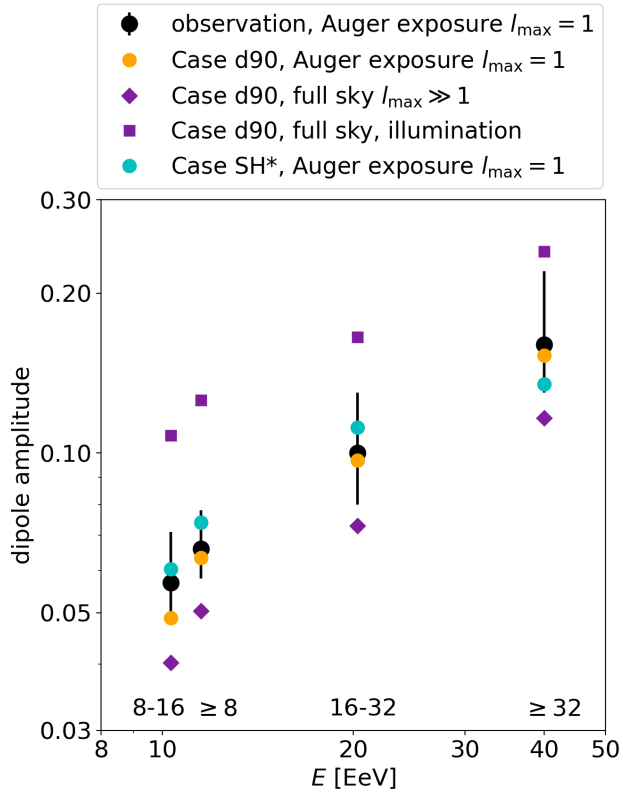
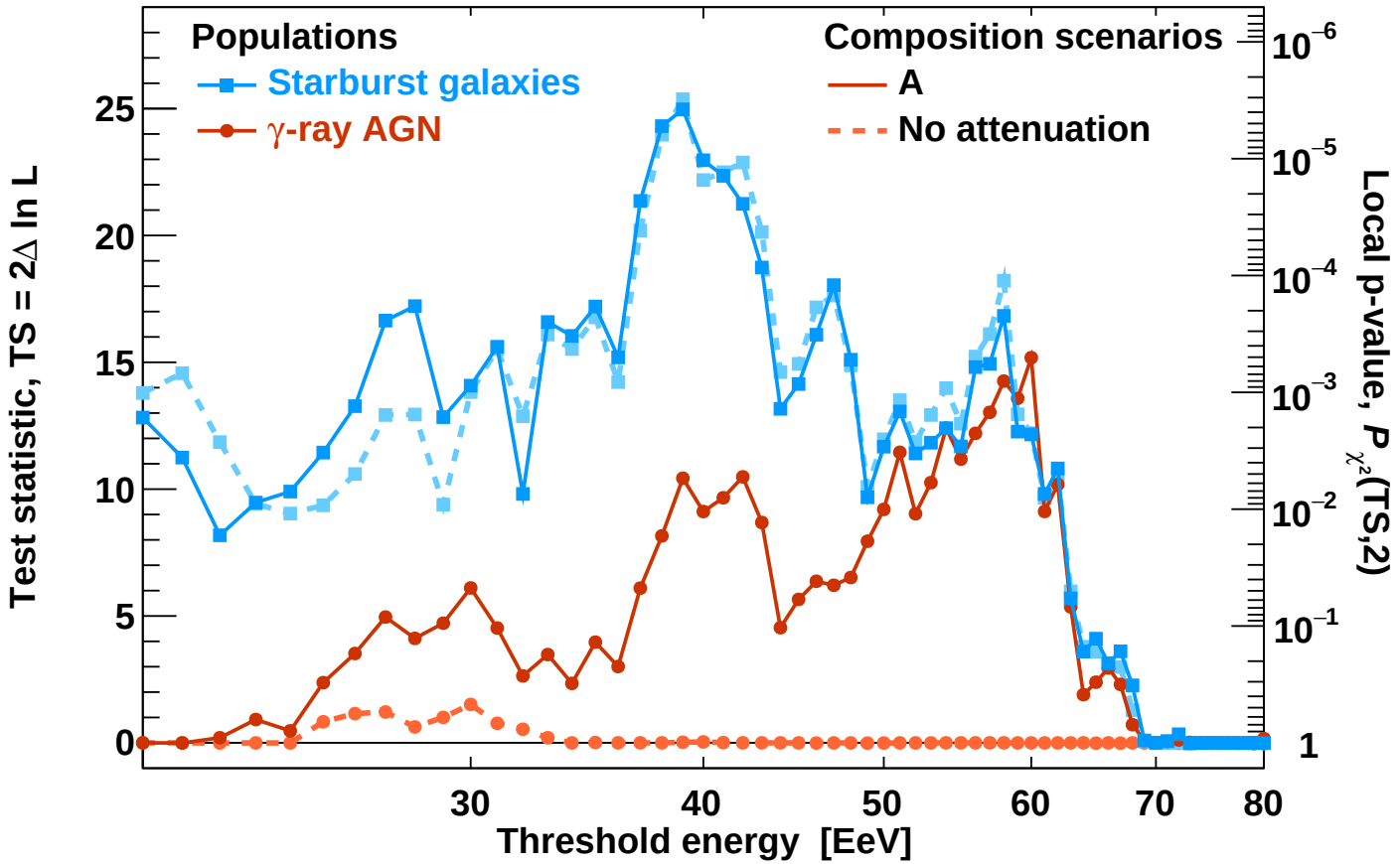


[*ICRC Ding # 1415*]

- use CosmicFlows-2 catalogue of peculiar velocities ⇒ LSS effect
- TA hot spot less pronounced ⇒ caused by local sources?

PAO correlation analysis:

[*PAO '18*]



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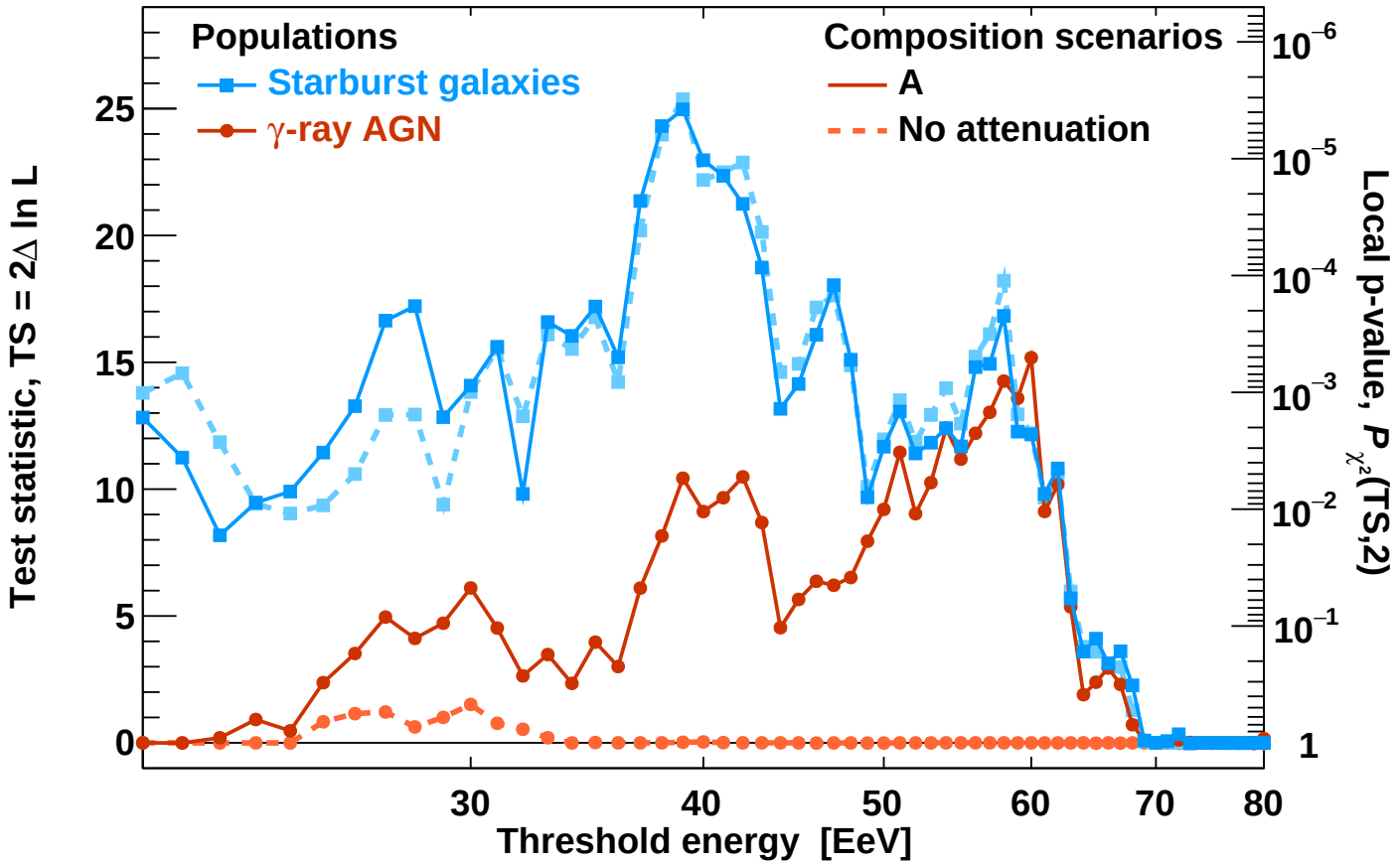

$\sim 4\sigma$ significance relative isotropy: reduced at ICRC '21

- best-fit values: SBG fraction 10%, search radius $\delta = 13^\circ$

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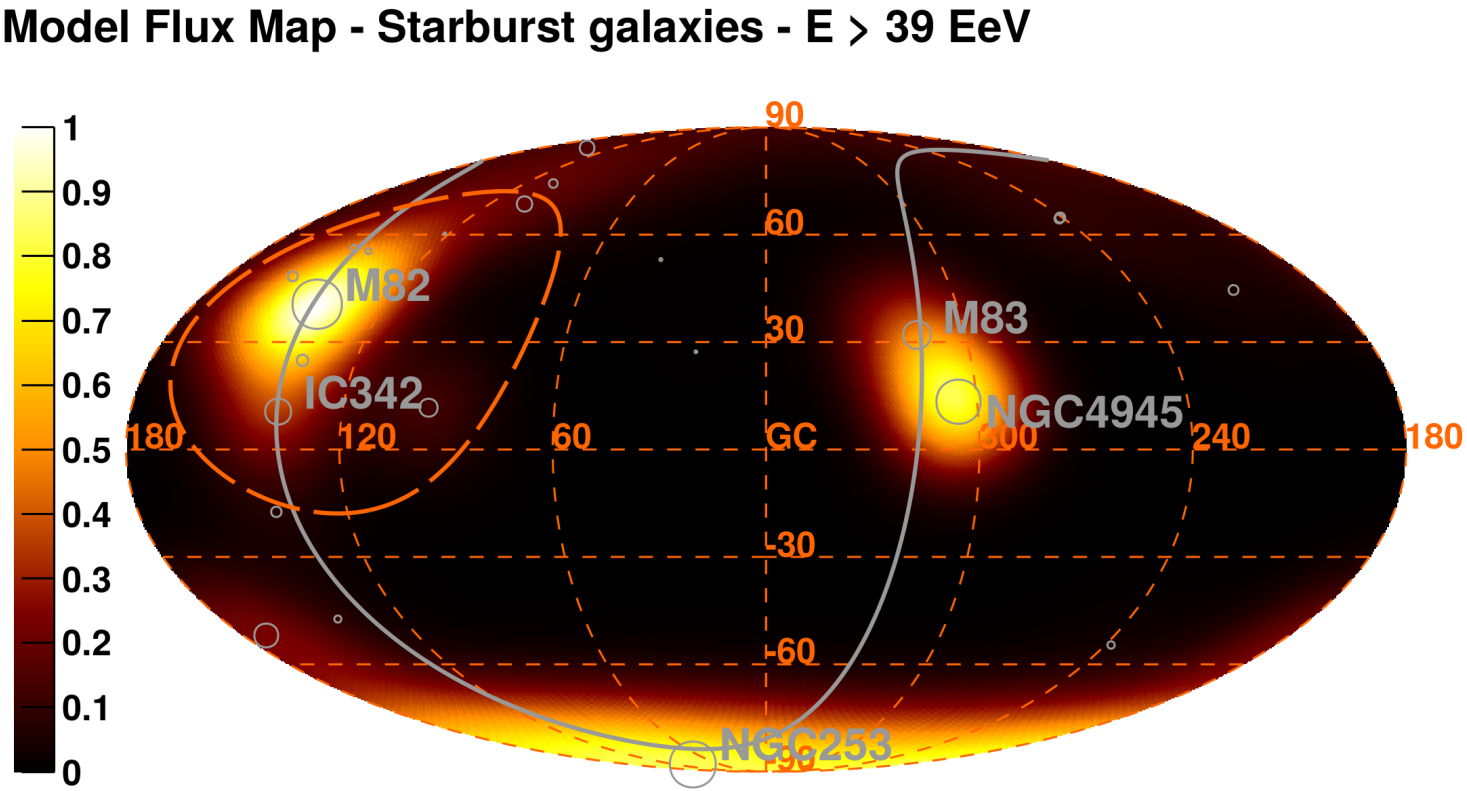

for uniform exposure from starburst galaxies:

- main contribution: M82 (TA HS), M83, NGC4985, NGC253

PAO correlation analysis:

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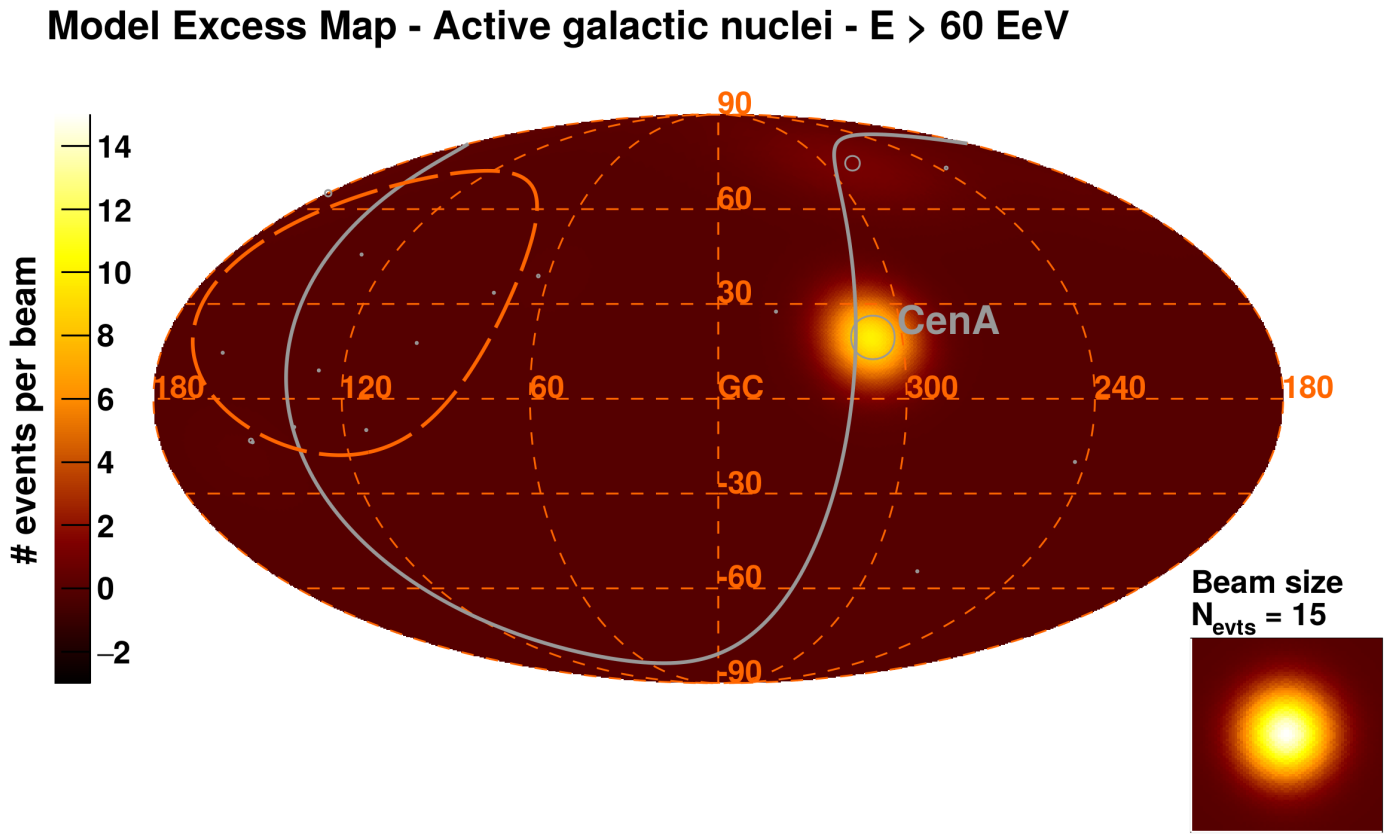

for uniform exposure from AGN

- main contribution: Cen A

PAO correlation analysis:

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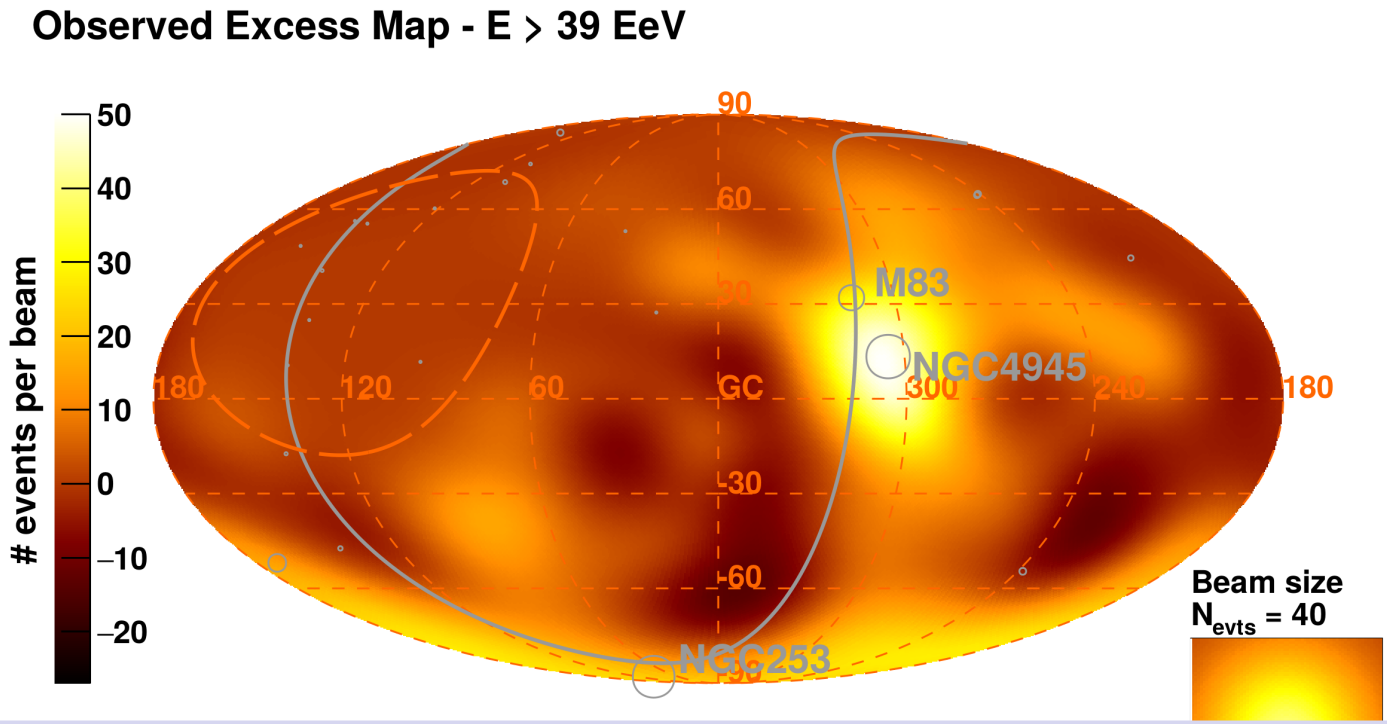

Comments:

- unknown penalty for searches in multiple catalogues...
- source confusion:
  - \+ nearby LSS contributes
  - − but which source type? $\Rightarrow$ need to reduce δ $\Rightarrow$ proton rich events

Transition to extragalactic CRs

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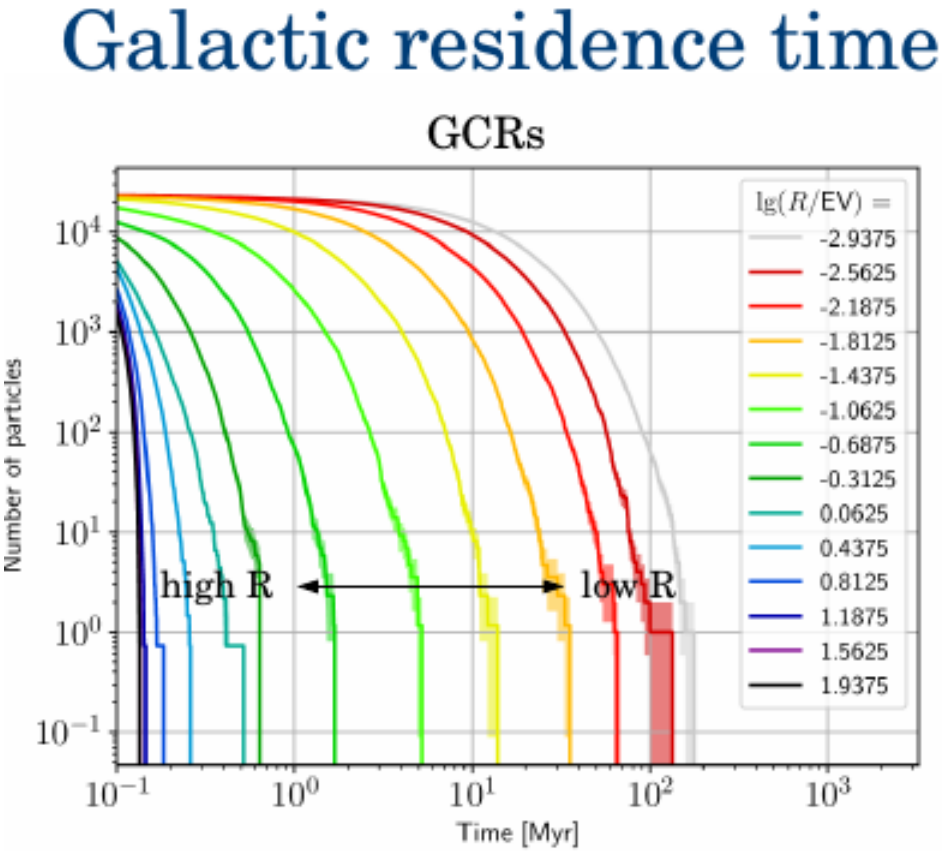

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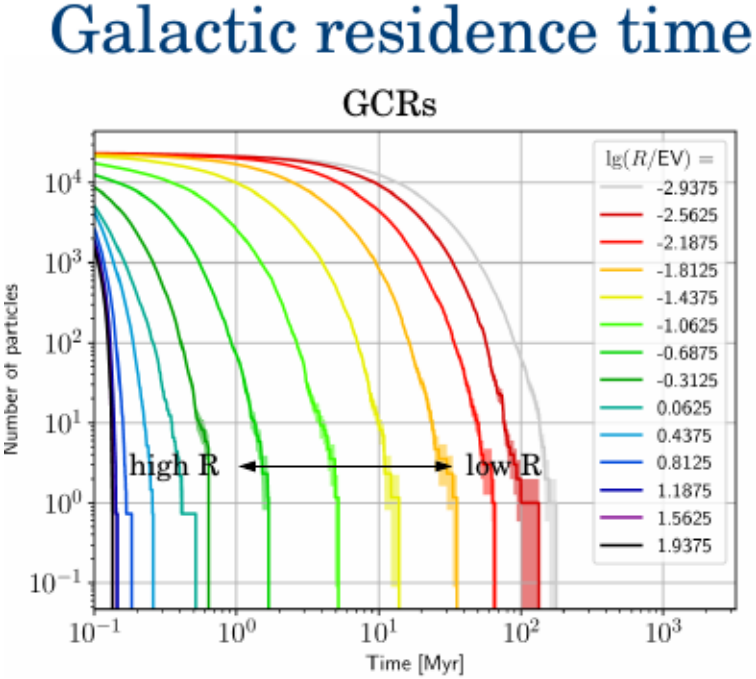

- $\tau_{\rm esc} \sim 10\,{\rm Myr}$ @ PeV $\Rightarrow \tau_{\rm esc} \sim E^{1/3} \Rightarrow \tau_{\rm esc} \sim 500\,{\rm Myr}$ @ 10 GeV
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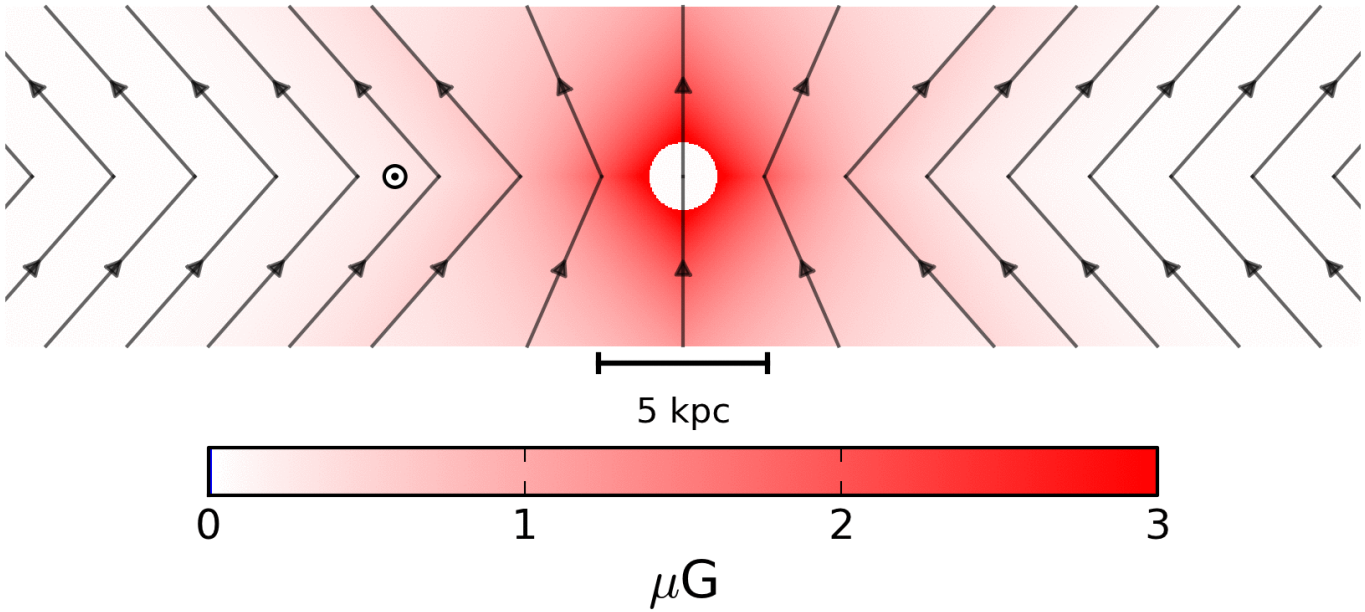
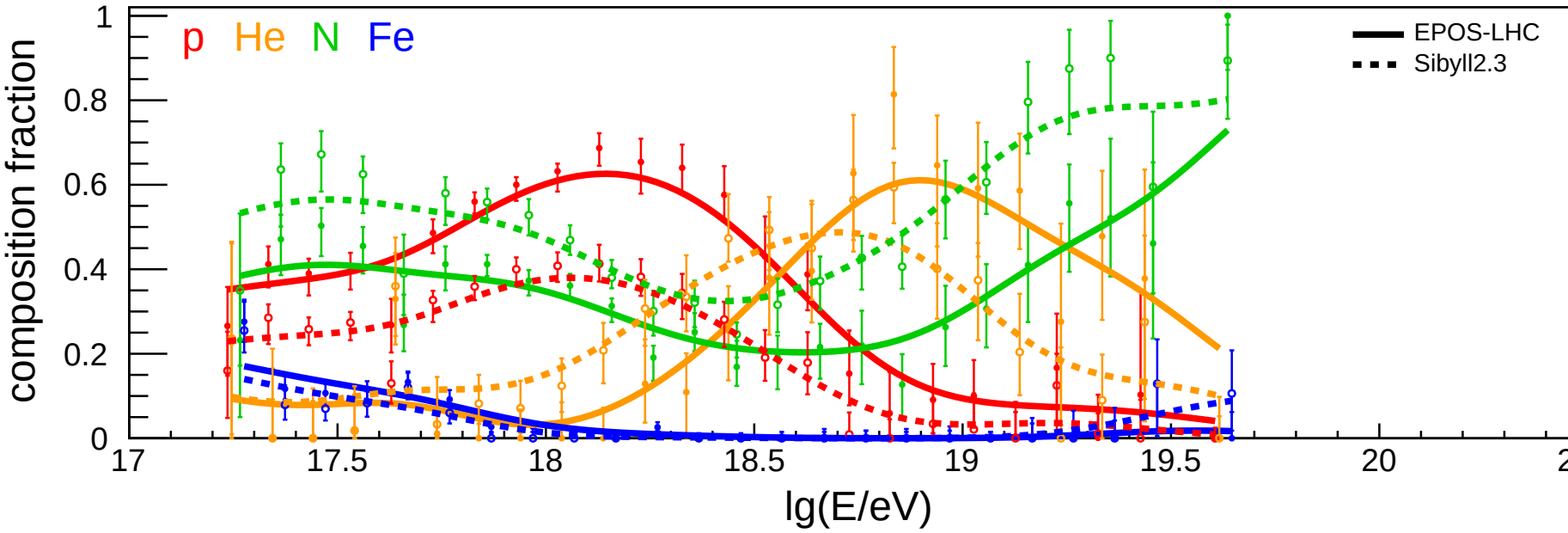
- one option: anisotropic diffusion [*Giacinti, MK, Semikoz '14, '15, '18*]



Early transition



Both TA & PAO: composition $6 \times 10^{17} - 5 \times 10^{18}$ eV consistent with

- $< 20\%$Fe, large fraction of p/HE

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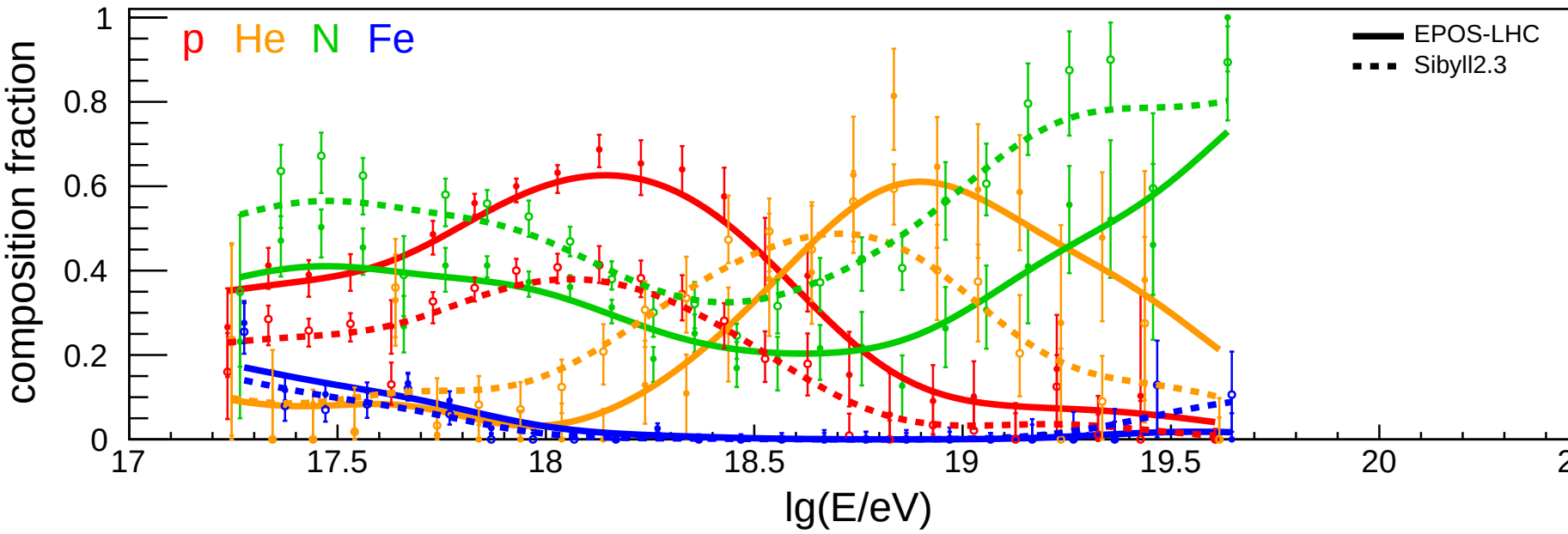

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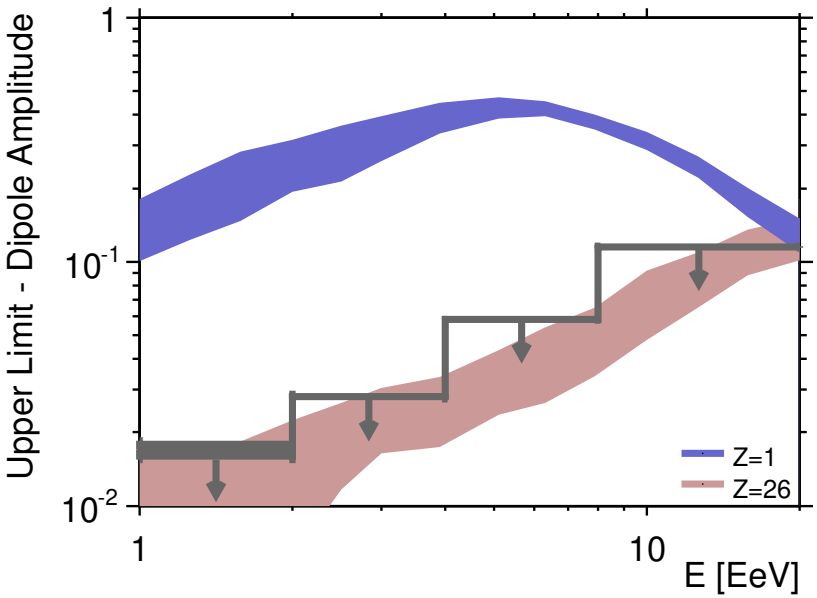
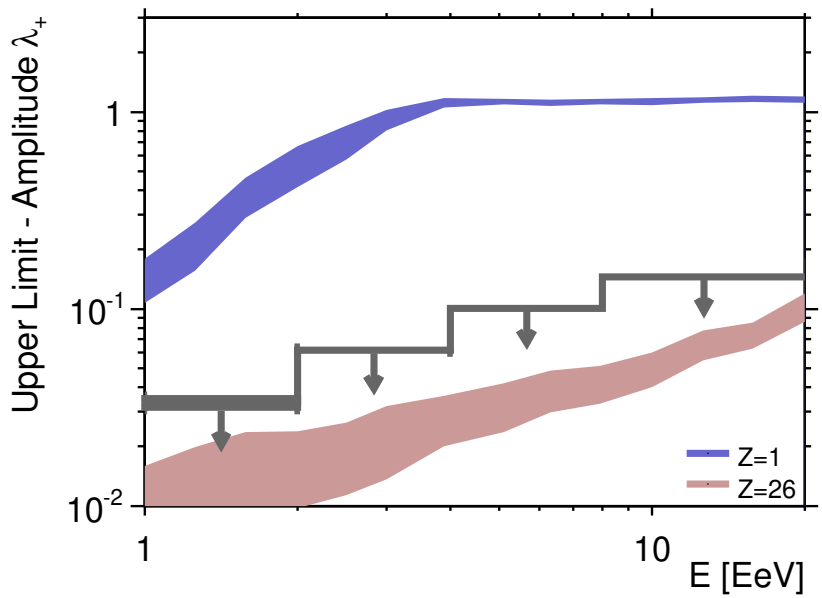
$\Rightarrow$ early transition from Galactic to extragalactic CRs

Transition to extragalactic CRs – anisotropy limits

dipole



quadrupole



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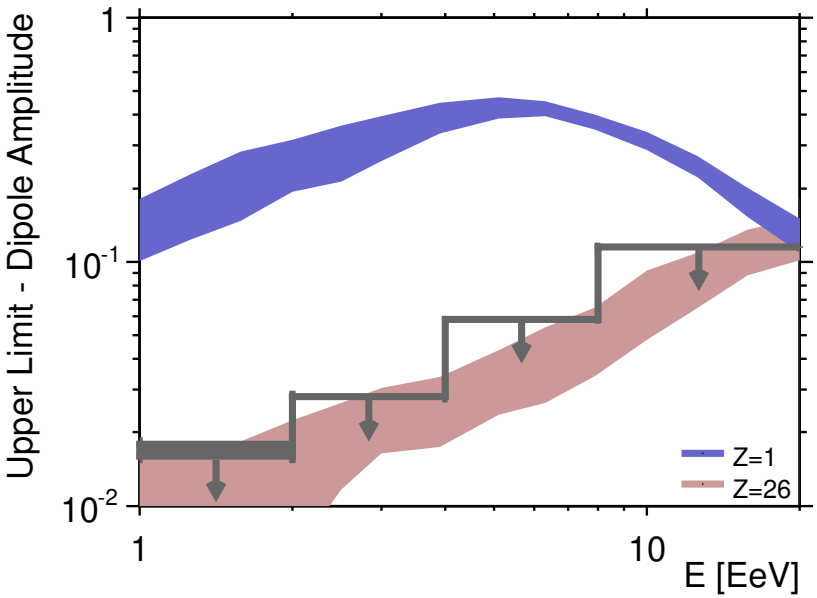

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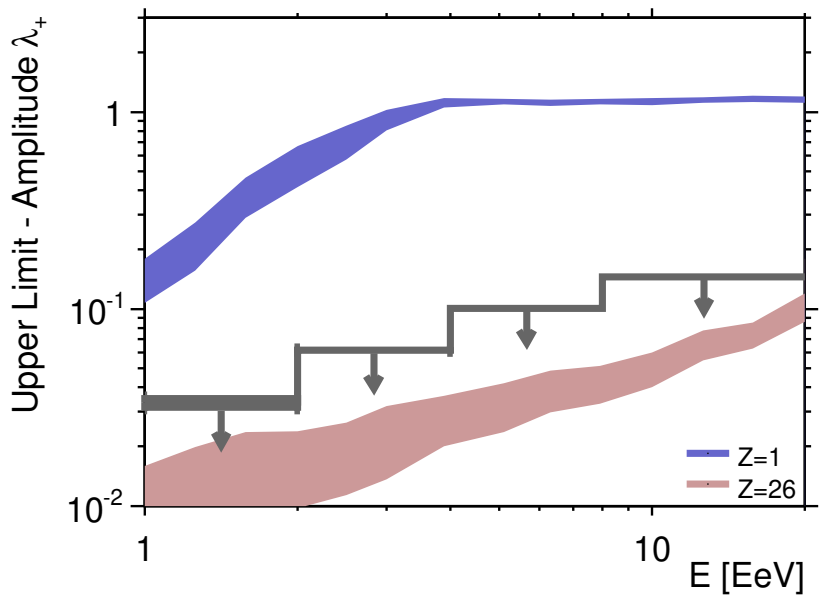
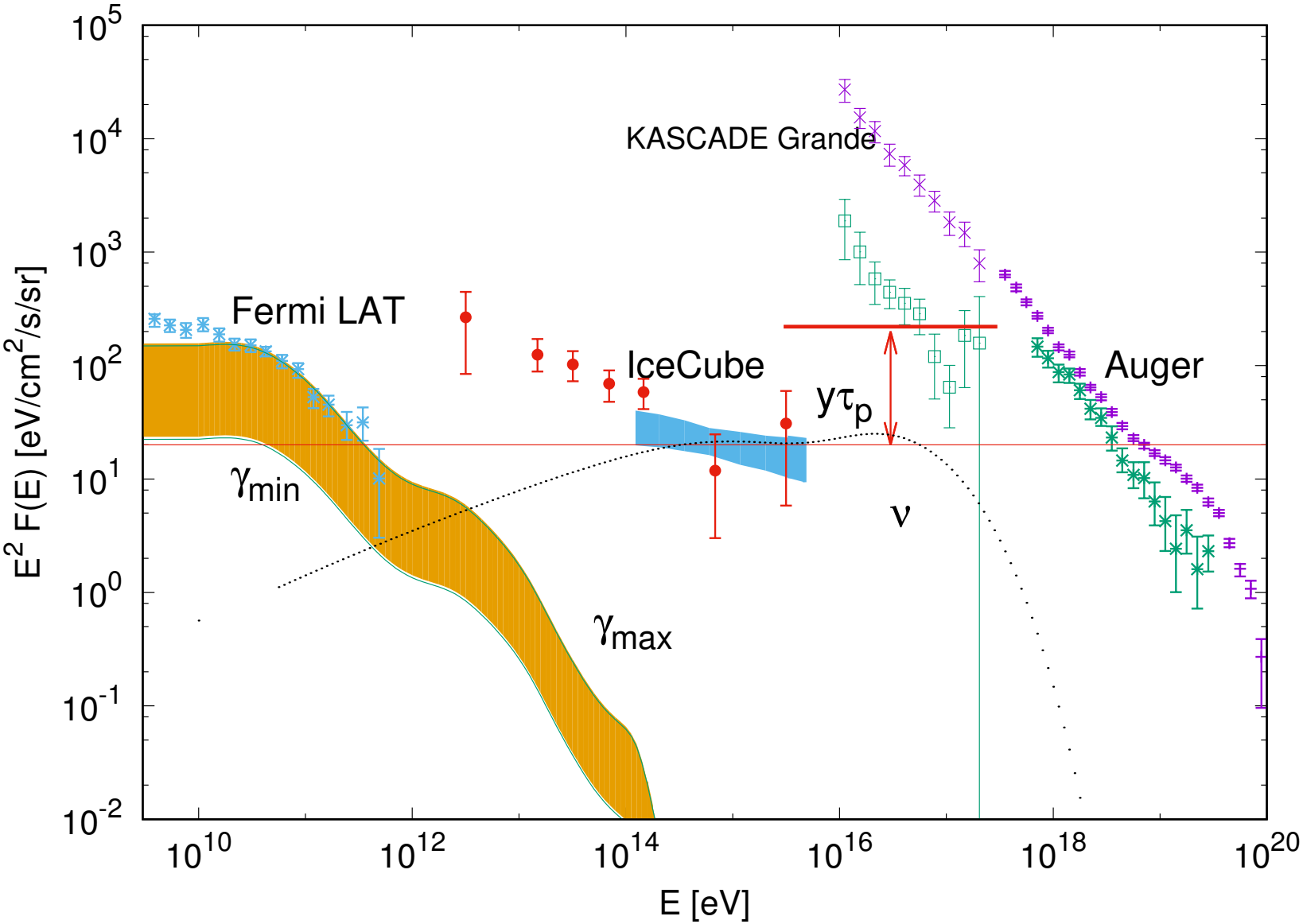


$\Rightarrow$ dominant light Galactic composition around $E = 10^{18}$ eV excluded

$\Rightarrow$ transition is below the ankle

[Giacinti, MK, Semikoz, Sigl '12, PAO '13]

Multi-messenger picture



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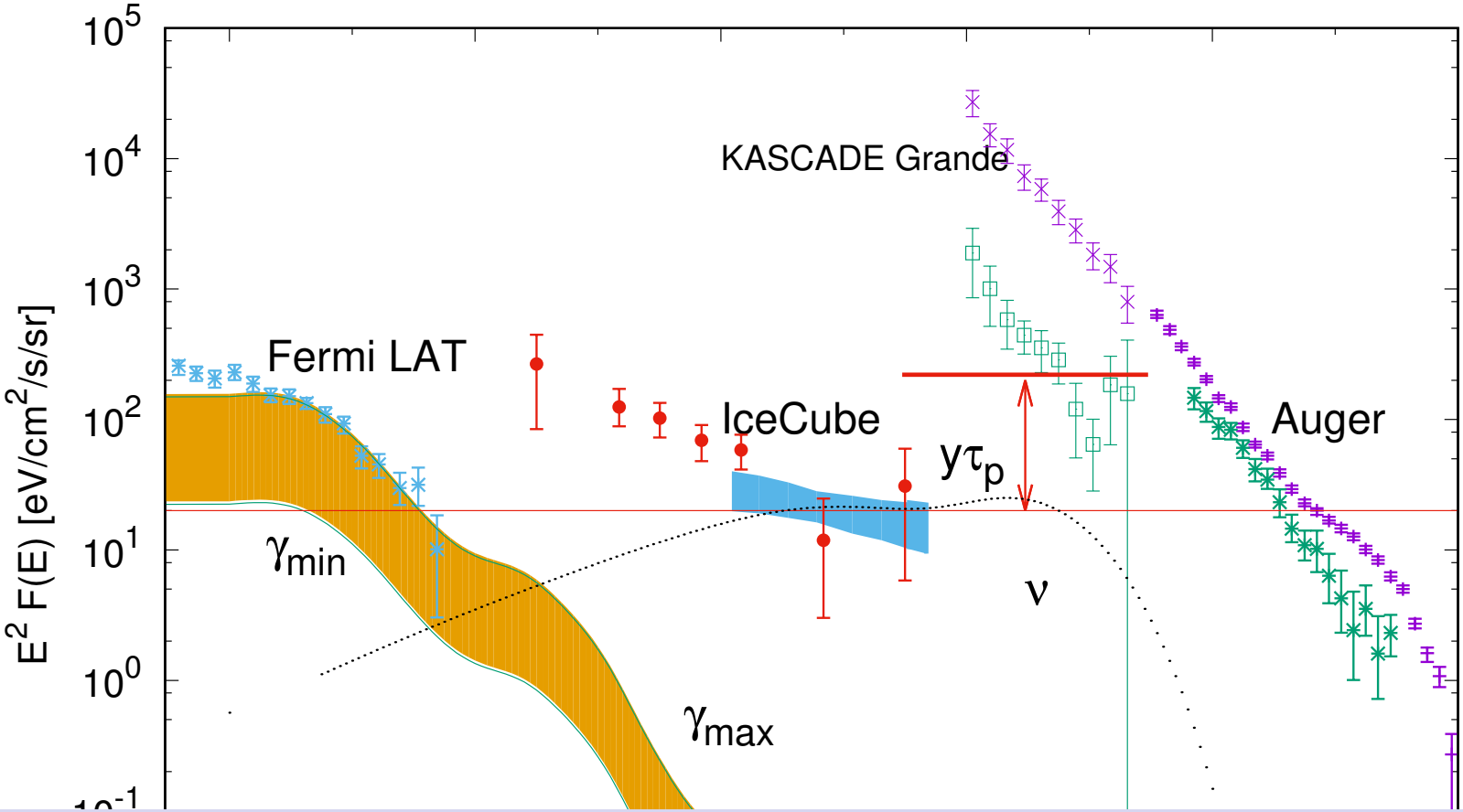
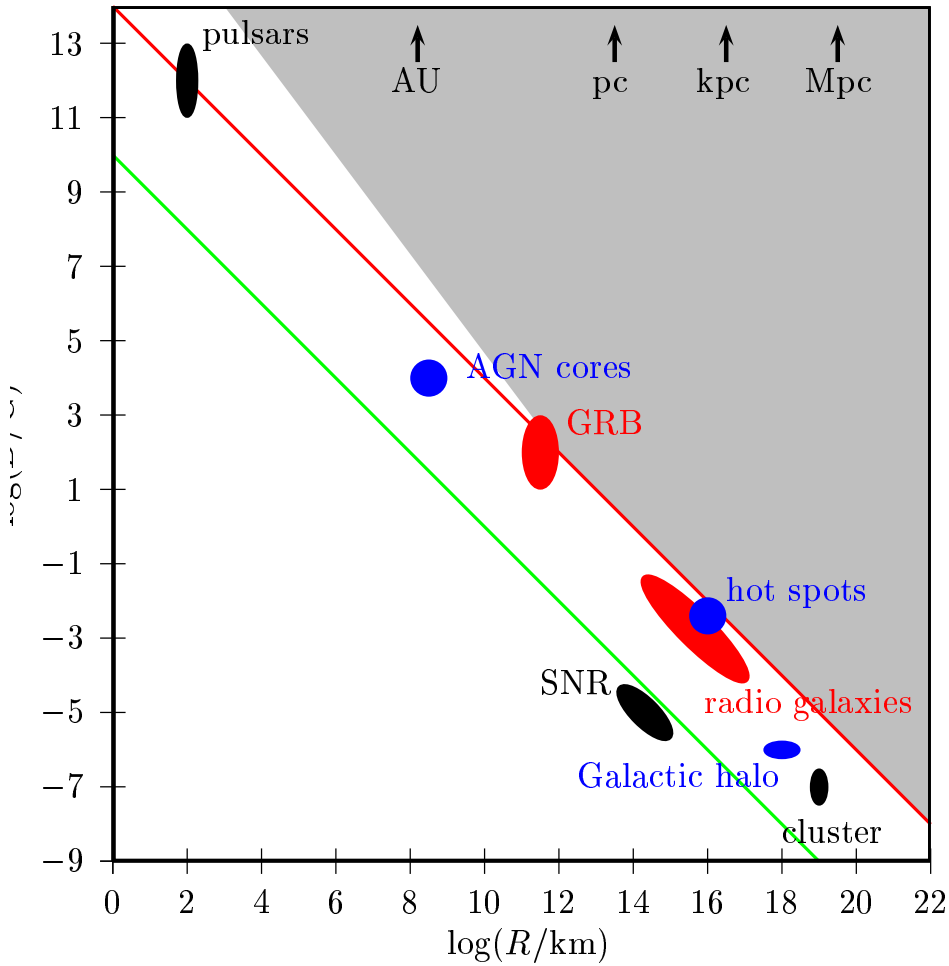


Constraints for a possible ν-γ-UHECR connection:

- 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 $E_{\rm max} \lesssim \Gamma ZeBR_s$



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

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

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

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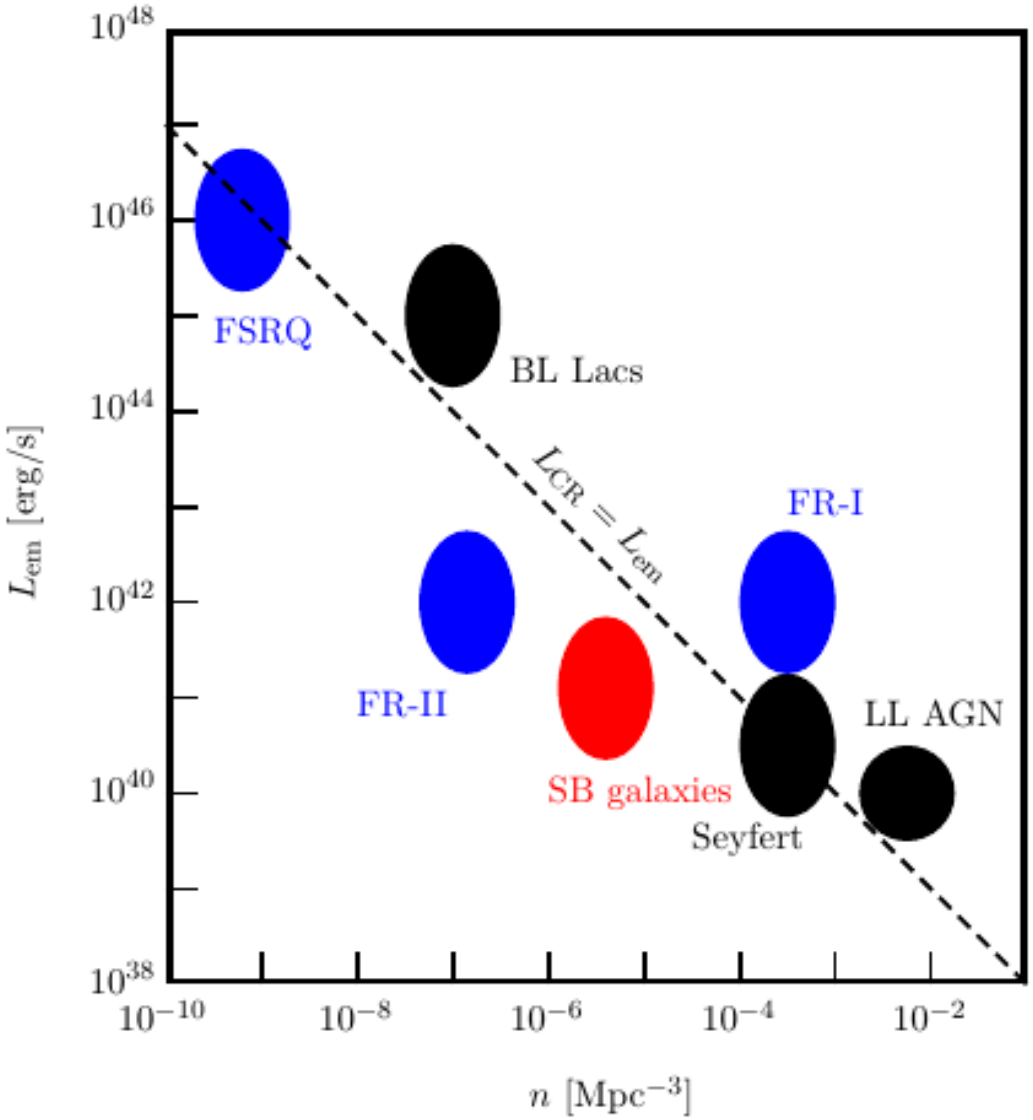
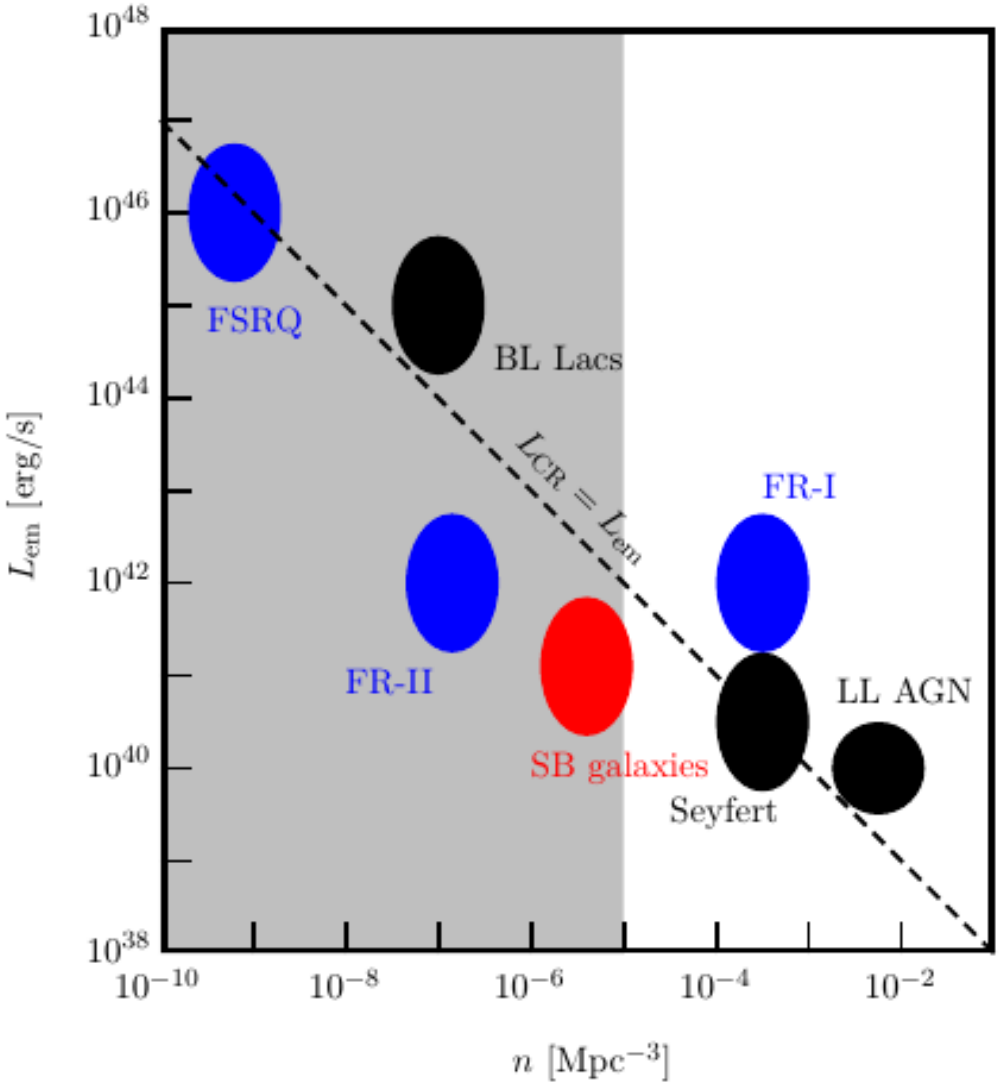
$\Rightarrow$ source density/rate tightly constrained

Density vs. luminosity for stationary sources



Density vs. luminosity for stationary sources



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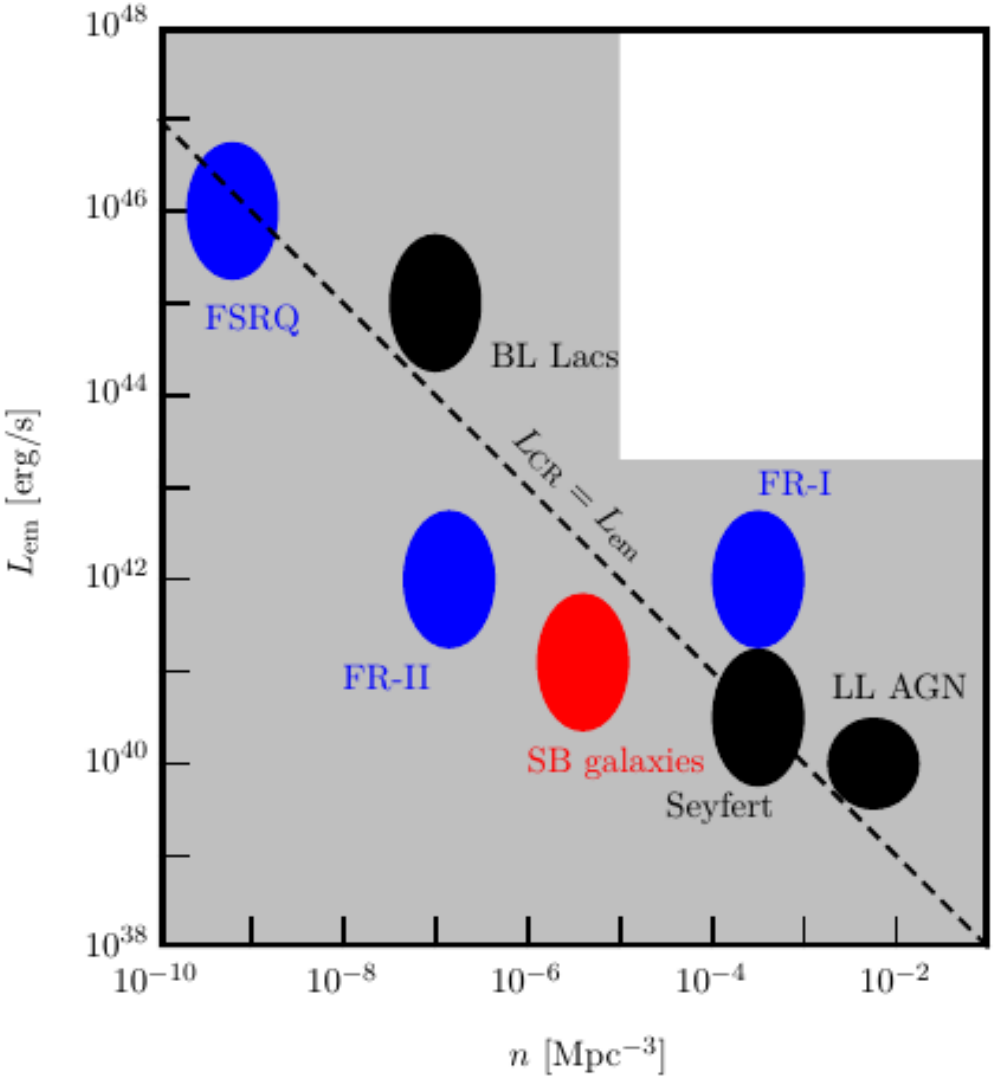

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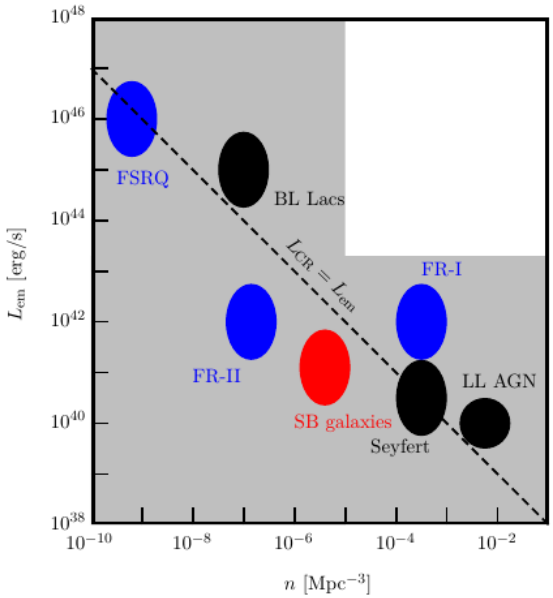
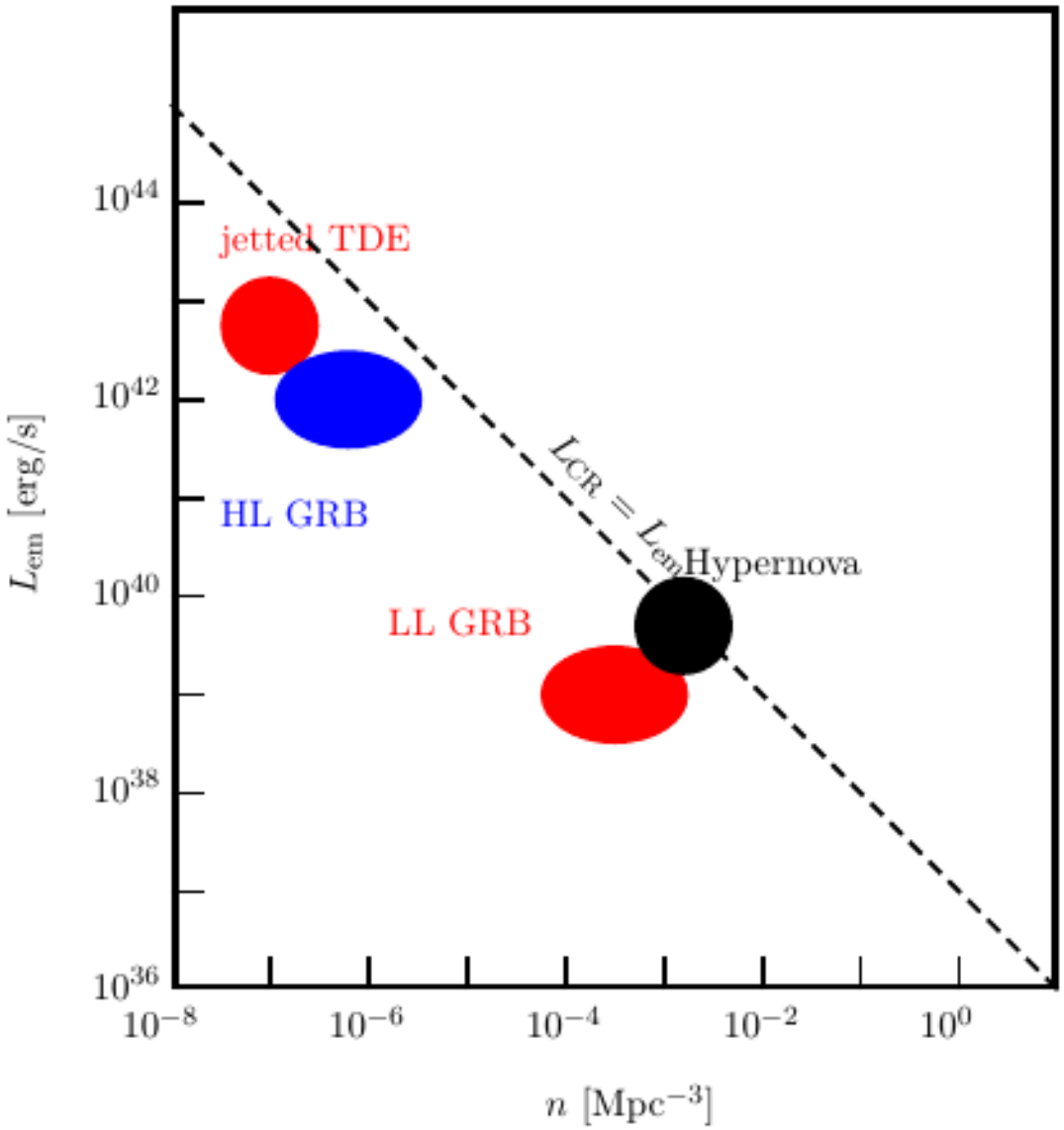


what goes wrong?

- 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



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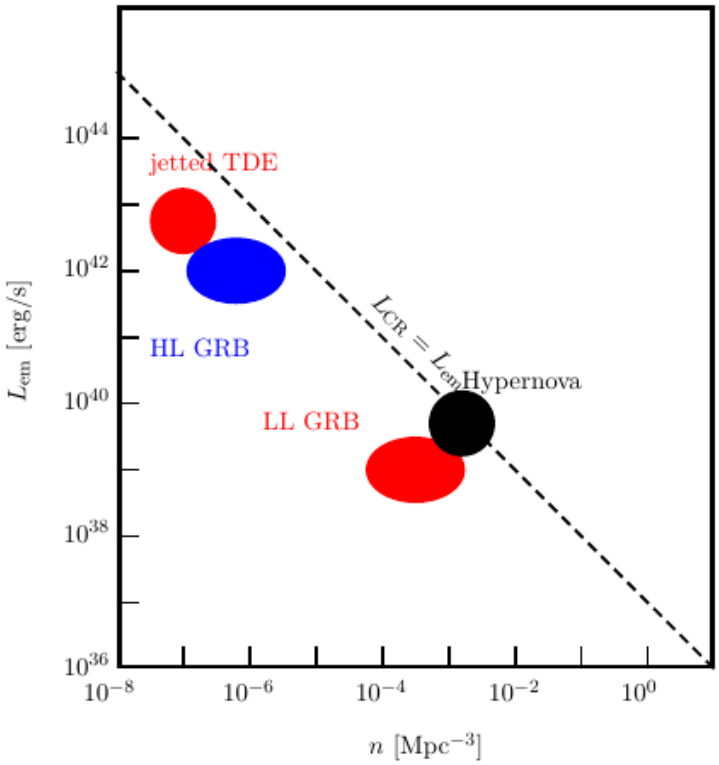

- time-delay τ in turbulent EGMF

$$\tau \simeq 10^3 \mathrm{yr} \left(\frac{3\times10^{19}\mathrm{eV}}{E/Z}\right)^2 \left(\frac{d}{100\,\mathrm{Mpc}}\right) \left(\frac{l_c}{1\,\mathrm{Mpc}}\right) \left(\frac{B}{10^{-10}\mathrm{G}}\right)^2$$

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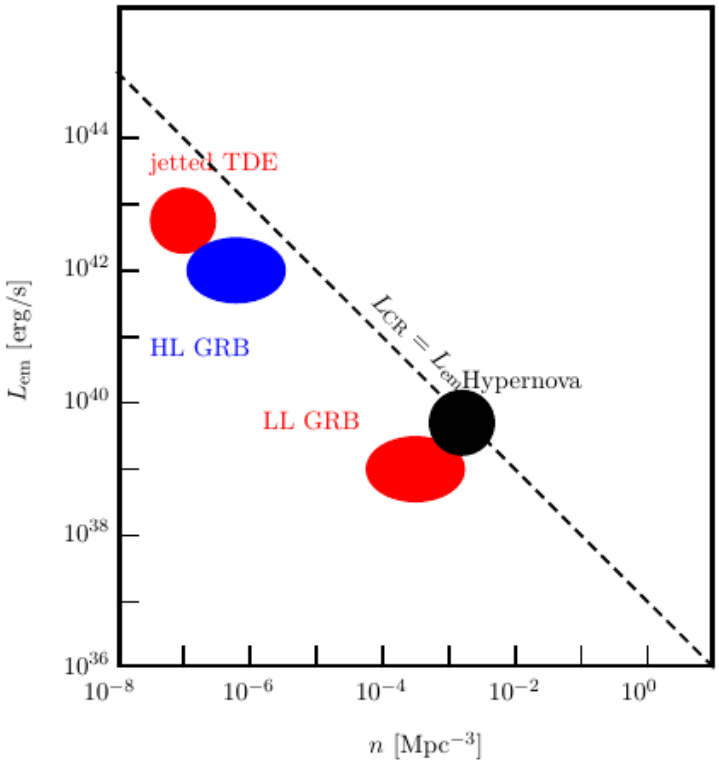

- time-delay τ in turbulent EGMF
- $L > L_{\rm min}$ typically no problem, since $\tau_0 \ll \tau$

Constraints on the EGMF

- strong EGMF required for large deflections of UHECRs

$$\vartheta_{\rm rms} \simeq 0.8^\circ \left(\frac{3\times10^{19}{\rm eV}}{E/Z}\right)\left(\frac{d}{100\,{\rm Mpc}}\right)^{1/2}\left(\frac{l_c}{1\,{\rm Mpc}}\right)^{1/2}\left(\frac{B}{10^{-10}{\rm G}}\right)$$

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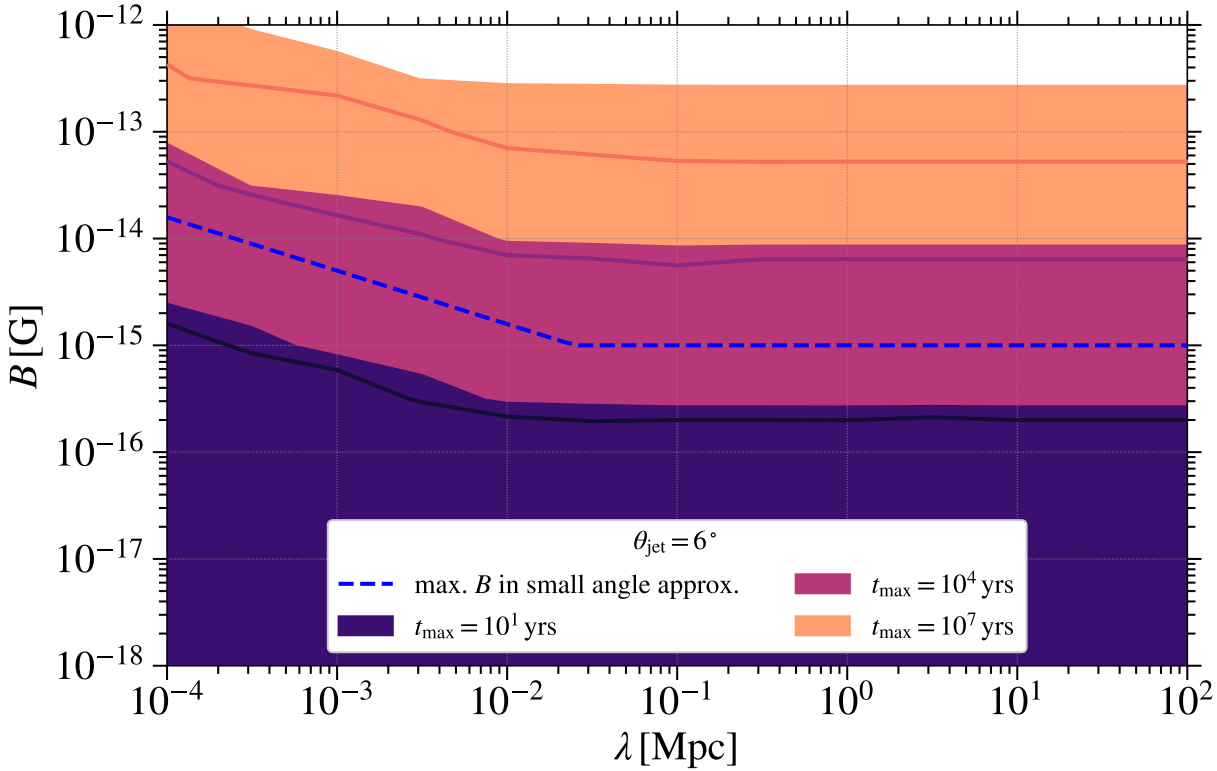

[*Fermi-LAT & Biteau'18*]

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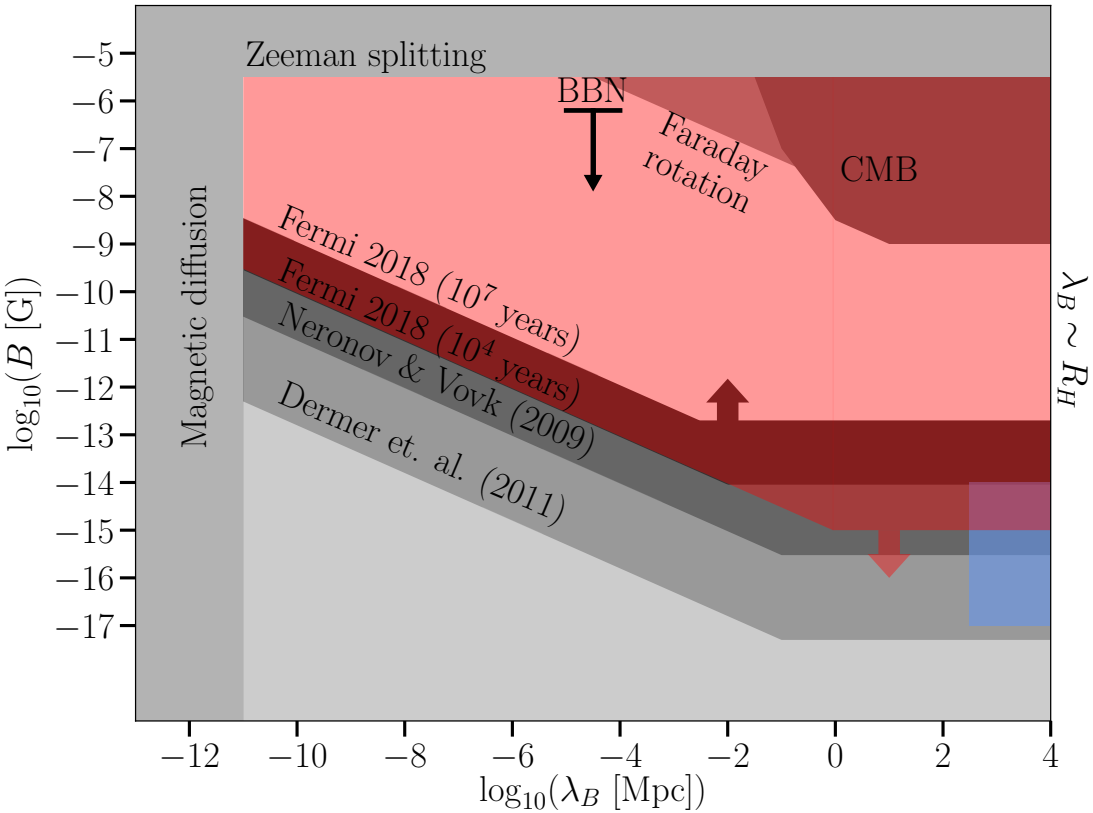

[*Broderick et. al '18*]

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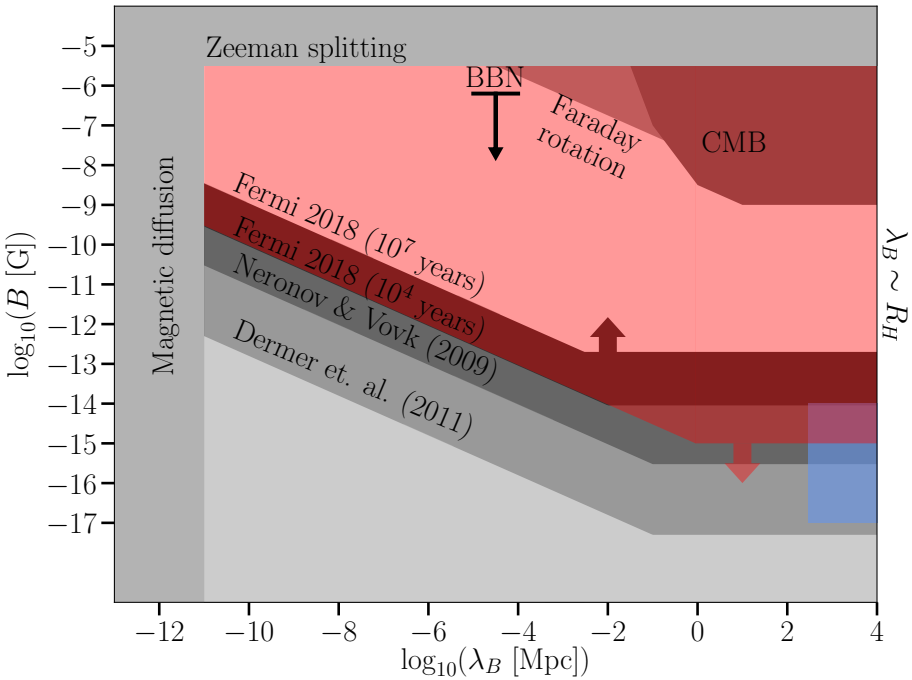

[*Broderick et. al '18*]

- importance of plasma instability?

[*Broderick et. al '12, ICRC Al-Awashra # 76*]

Gamma-Ray Bursts

Long-standing candidate as UHECR and neutrino source [*Waxmann '95, Vietri '95*]

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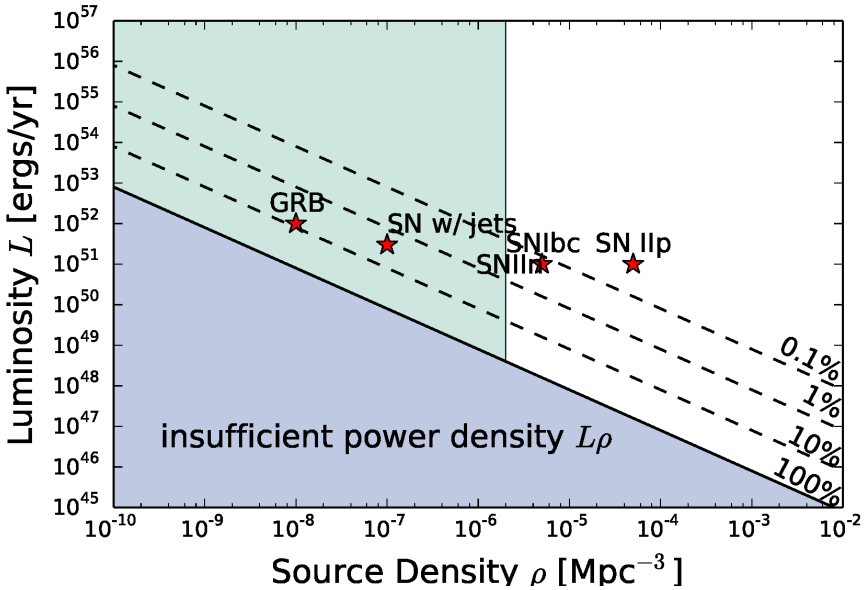

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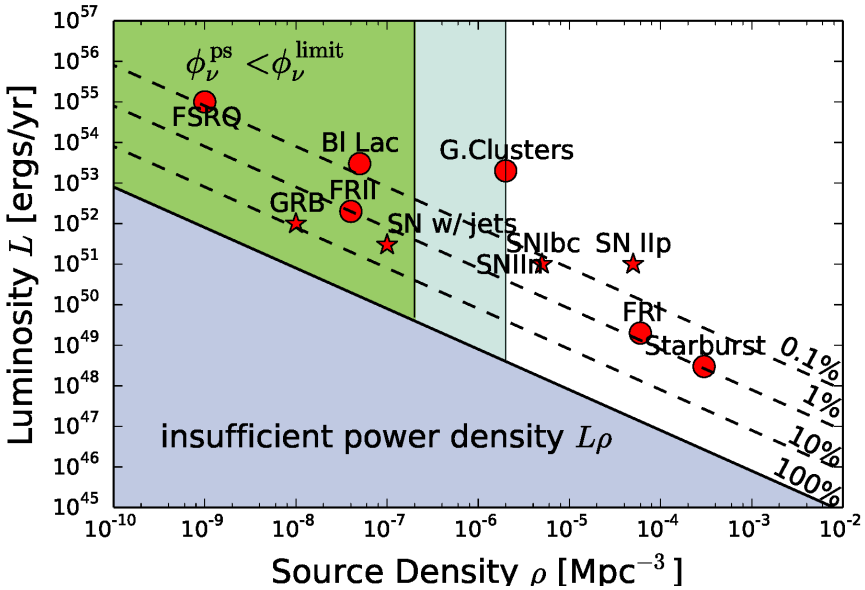

Gamma-Ray Bursts

Two classes: High- and low-luminosity GRBs

- HL GRBs, constraints from IceCube require either
  - low $E_{\rm max}$ or
  - small baryon load

  $\Rightarrow$ excluded as main UHECR source

Gamma-Ray Bursts

Two classes: High- and low-luminosity GRBs

- HL GRBs
- LL GRBs: $L \sim 10^{46} - 10^{49}$erg/s), what is $E_{\rm max}$?
  - GRB 060218: effective acceleration of e^- excluded both prompt & afterglow phase

[ICRC Samuelsson # 637]

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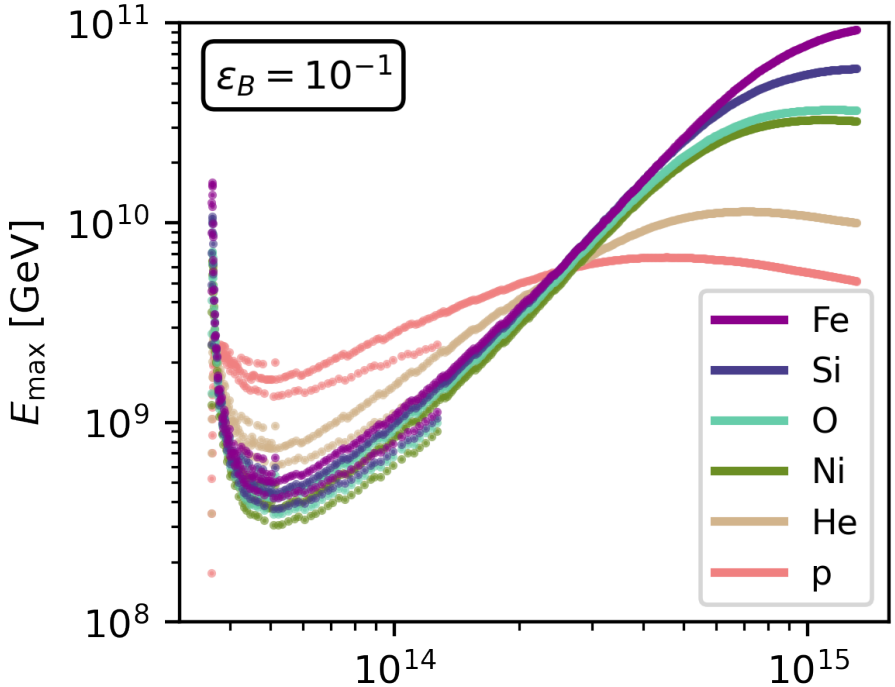

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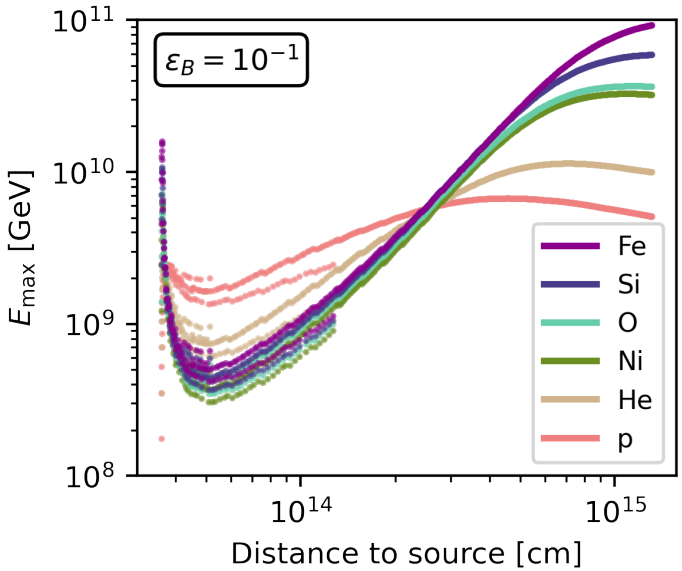

  - too small emissivity

Starburst galaxies as UHECR sources

Acceleration:

- termination shock of galactic wind:
  - $E_{\rm max} \simeq 10^{17}{\rm eV}(t_{\rm acc}/10^9{\rm yr})(B/0.3\mu{\rm G})(v_{\rm sh}/1000\,{\rm km/s})$

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  - $1/E^{2.2}$ spectrum $\Leftrightarrow$ composition?
- LL GRBs, hypernova, pulsars, ...
  - superposition of single sources (?)
- neutrino source

[*Condorelli ICRC #899, Marinelli # 1205*]

Active Galactic Nuclei

- FR-0 galaxies [*ICRC Merten # 43, # 59 Lundquist*]
- NGC 1068 [*ICRC Anchordoqui #187 , Eichmann # 601, Inoue # 1177*]
- UHECR acceleration in AGN [*ICRC Gouveia Dal Pino # 220, Mbarek # 1325, O'Sullivan # 1433*]
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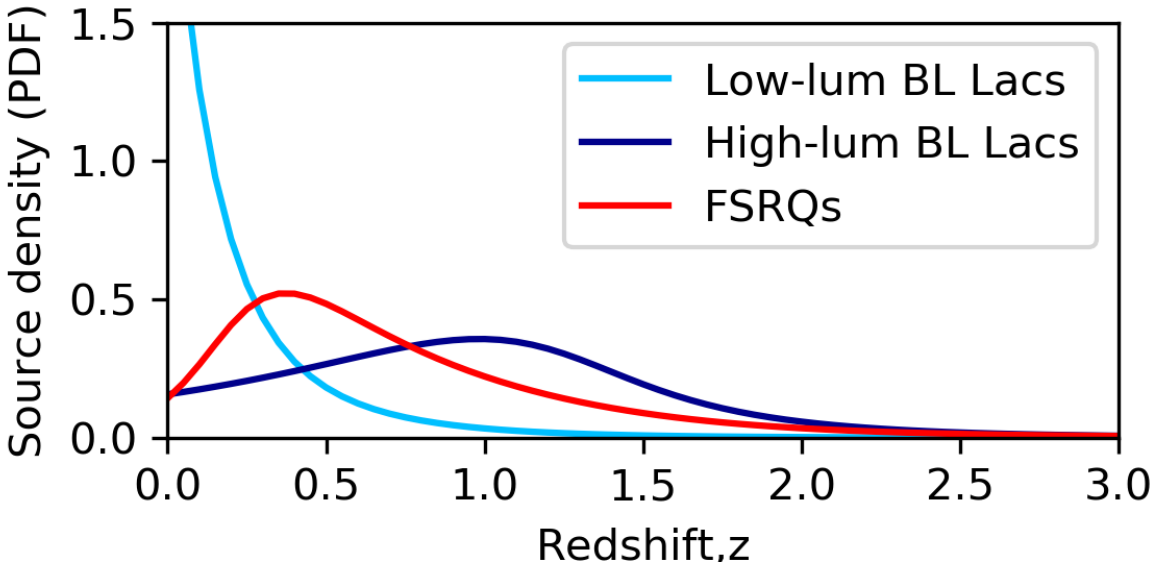
  - FSRQ, LL + HL BL Lacs



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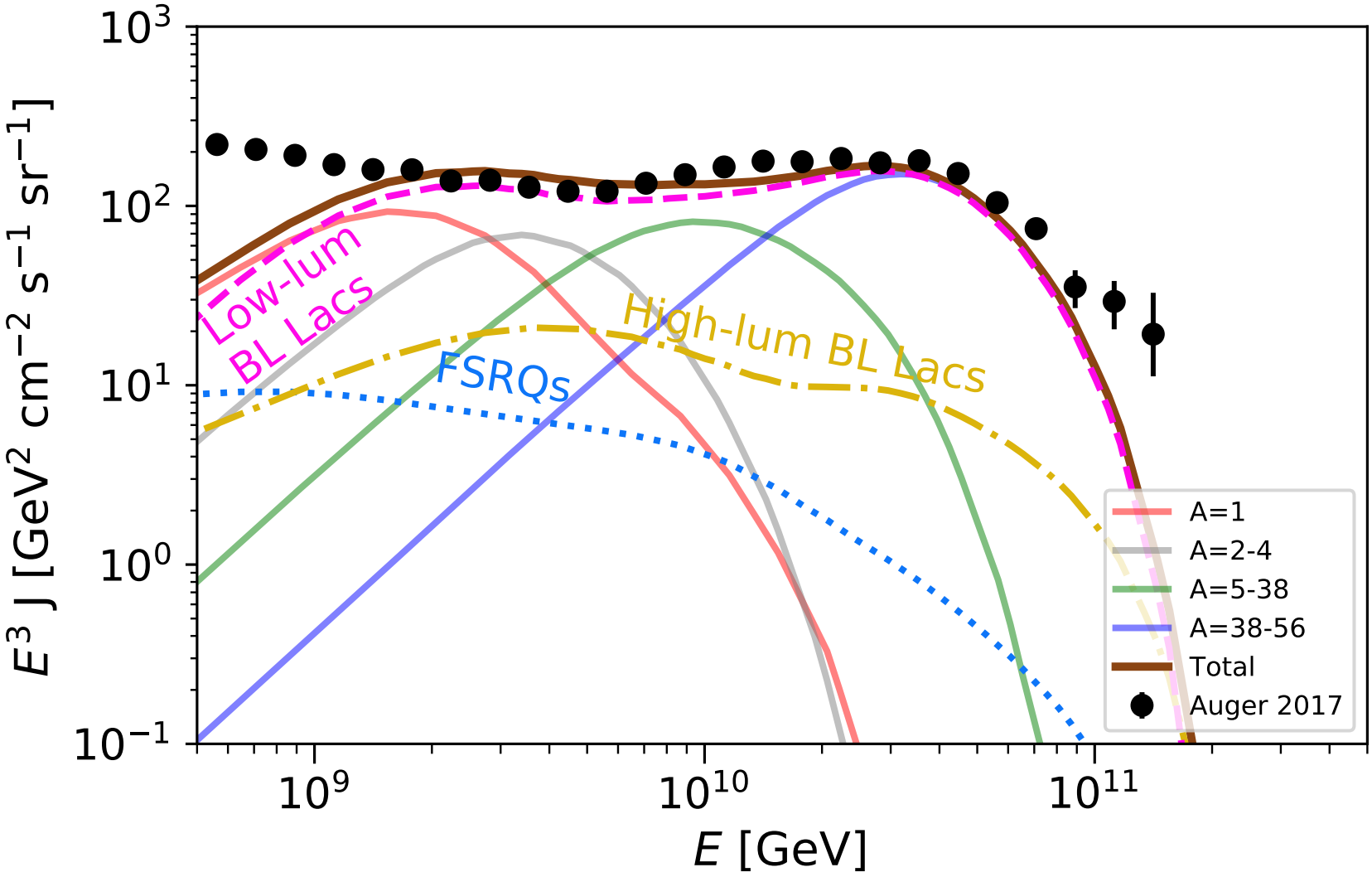

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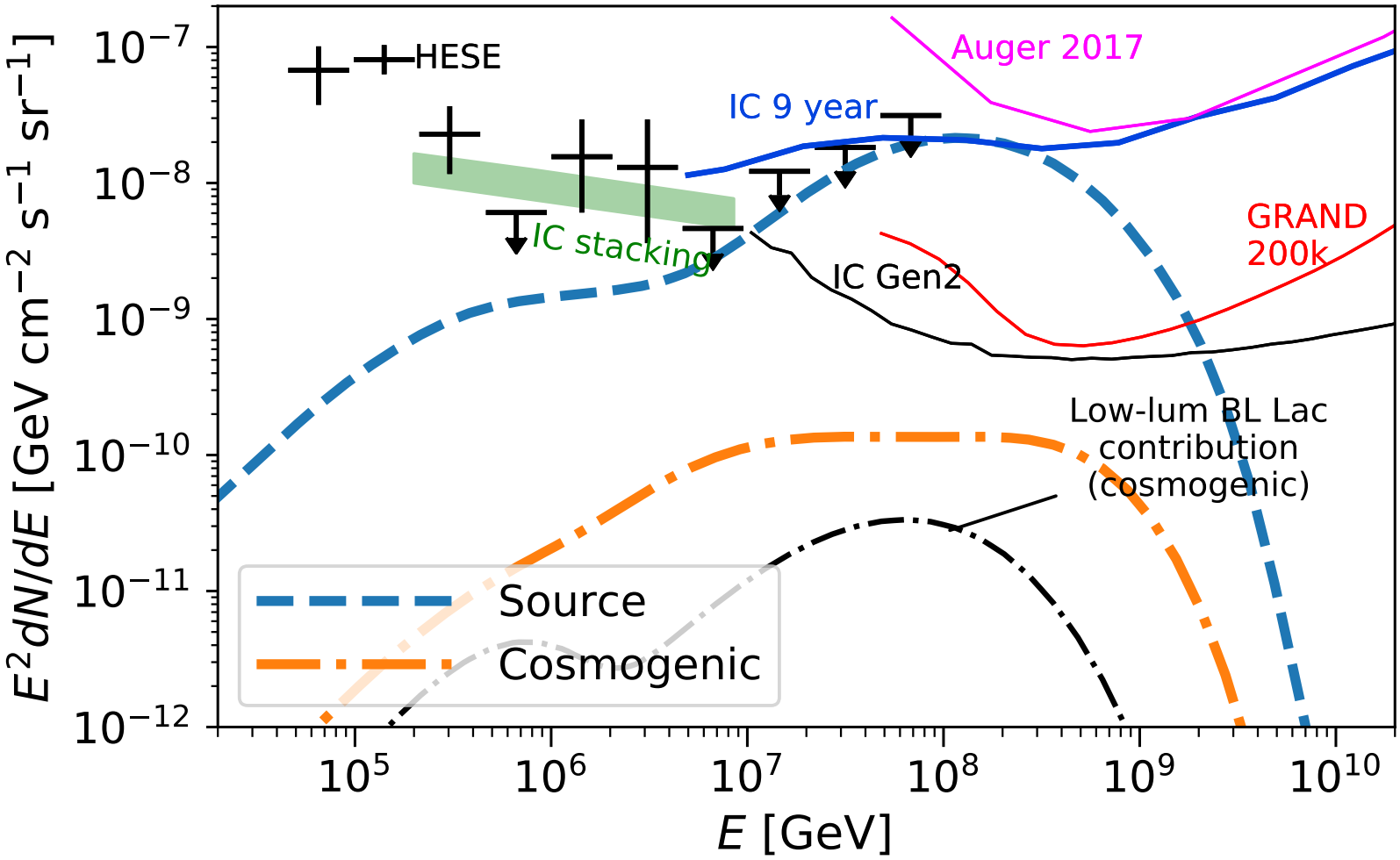

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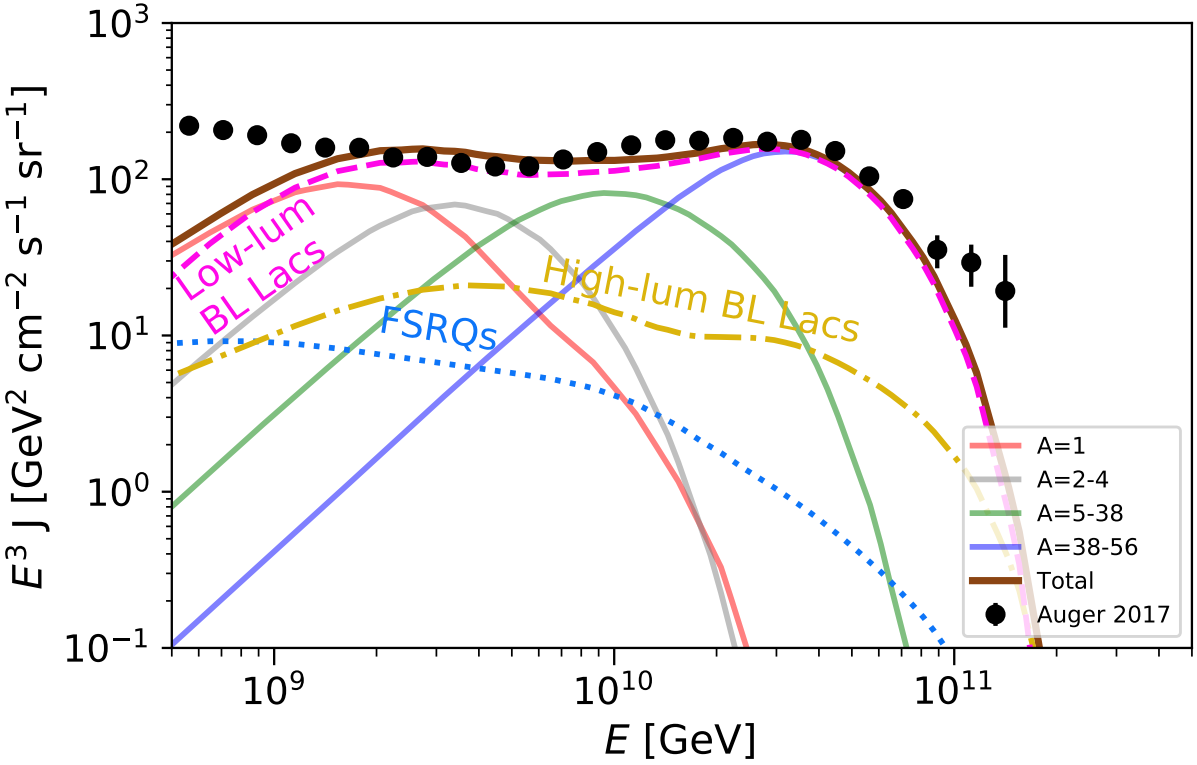

approach using

- various source populations
- observed luminosity functions

Summary

1. great experimental progress:
   - spectrum, dipole, correlation anlyses
   - composition: discrepancy PAO vs. TA?
   - progress of correlation analyses need proton rich event samples
2. common source class for UHECRs and neutrinos?
   - several candidates as GRBs are already disfavoured
   - (subclasses of) AGNs remain attractive option
   - large neutrino flux at "low" energies favours Ap interactions
   - EGRB is a strong constraint
3. theoretical studies:
   - abandon average source – and a single population?