Indirect constraints on the origins of UHECRs & VHE neutrinos

& possible indications of multiple sources

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springing from work with Michael Unger

(and earlier, Chen Ding and Noemie Globus)

What we know:

- No single (apparent) dominant source (or source class ???)
- Complex composition
- Highest energy Galactic CRs overlap the lowest energy extragalactic UHECRs

✦ Spectrum shaped by acceleration, propagation and interactions near source

  - Multi-messenger approach is essential

What we NEED TO know:

- Are sources weak and abundant or strong and rare?
- What are the principal source types?
  - Sources may not all be visible today (e.g., transients)
- What are the sources' spectra and composition?
  - Are UHECR sources (approximately) standardized?
- Better knowledge of magnetic fields
- Task seems hard…

In today's talk:

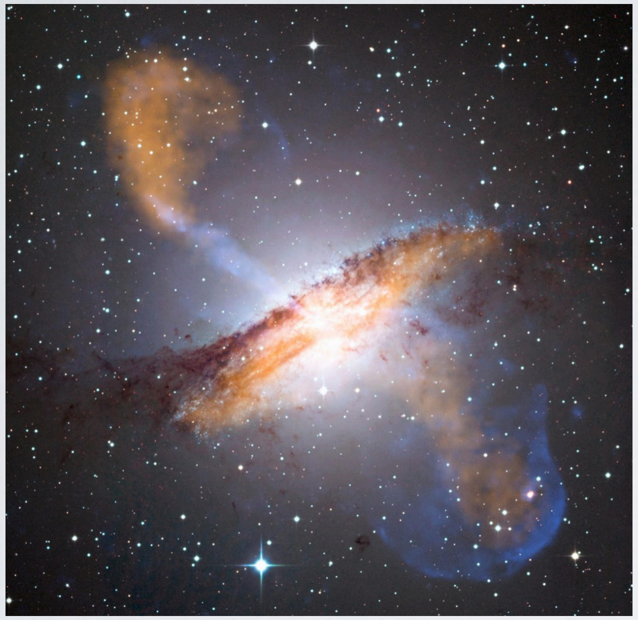
- Constrain *UHECR **source environments' T, B, L***
  - using spectrum, composition & neutrinos
  - ➡ **Data disfavors some candidate sources**

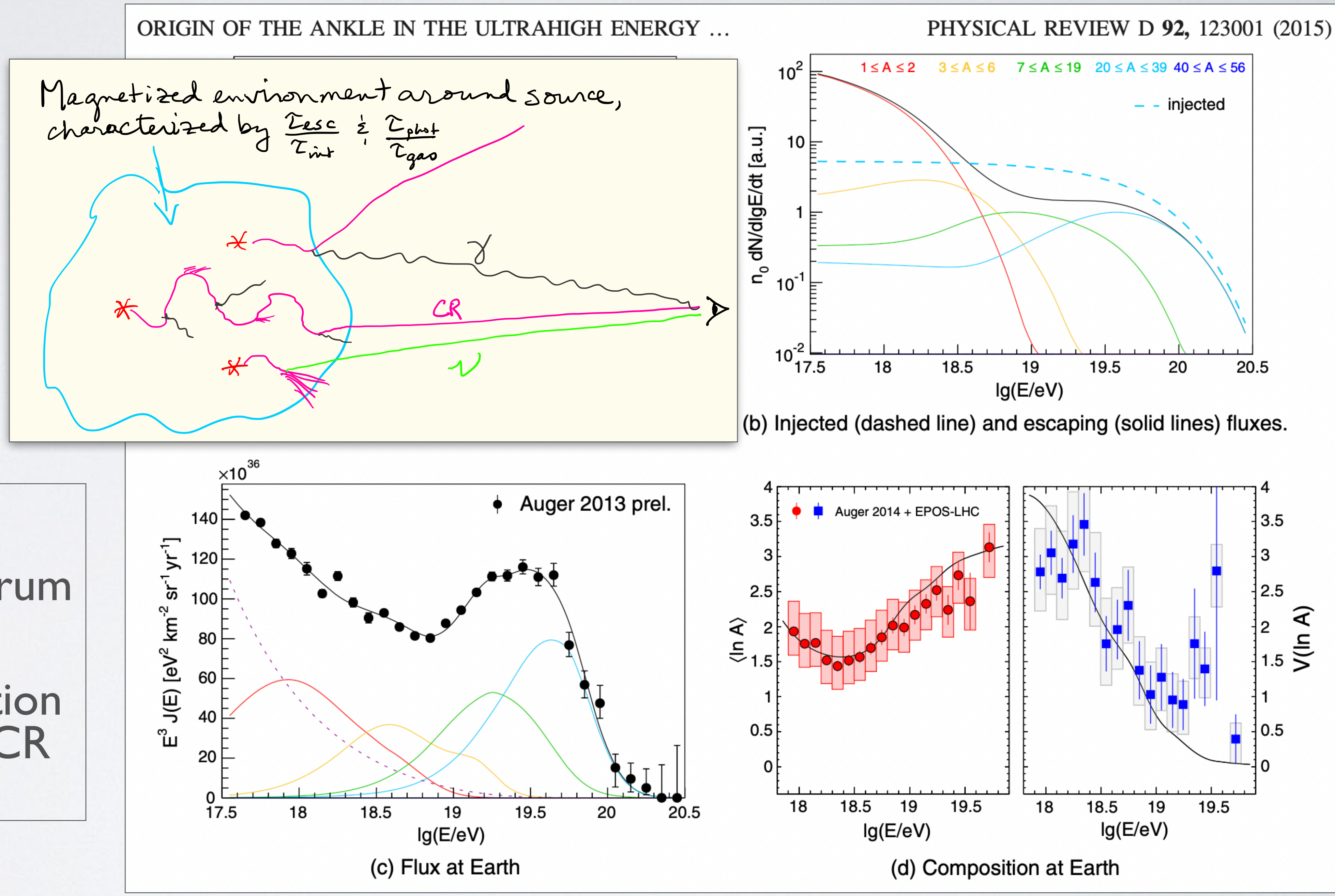
Also, anisotropy constraints (not today!):

- Dipole anisotropy ➜ natural baseline model   Ding, Globus, GRF ApJL'21 (see also Allard+ '21)
  - sources are abundant and weak
  - individually-distinct sources are few and nearby   (e.g., TA hotspot!)
  - SOURCE DISTRIBUTION KNOWN (LSS) ➜ refine GMF
- But maybe local radio galaxies are responsible!   Eichmann, Kachelreiss, Oikonomou 2022

Cosmic Rays are Accelerated, then fragmented

Unger, GF & Anchordoqui 2015





- Excellent fit to spectrum & composition
- Explains light population between between GCR & UHECR

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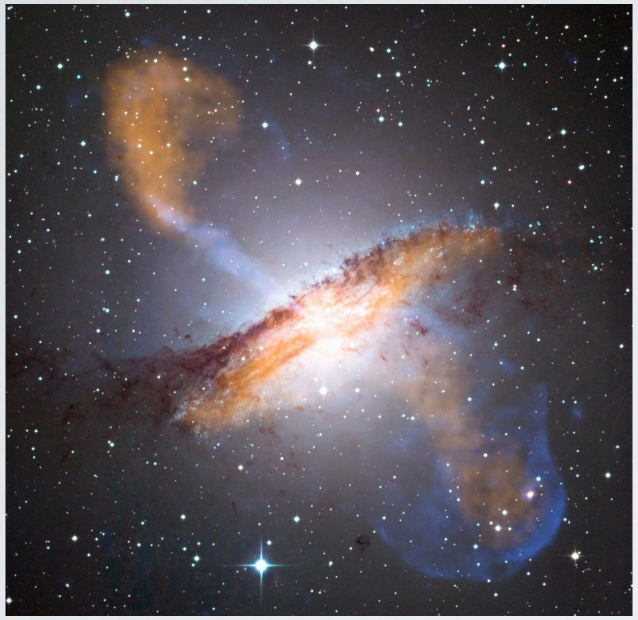
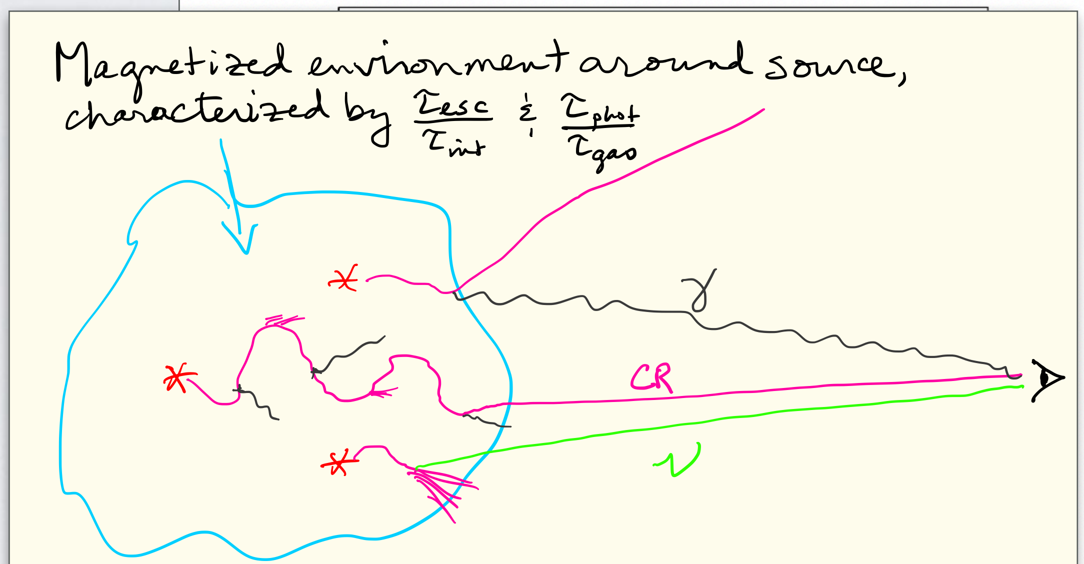
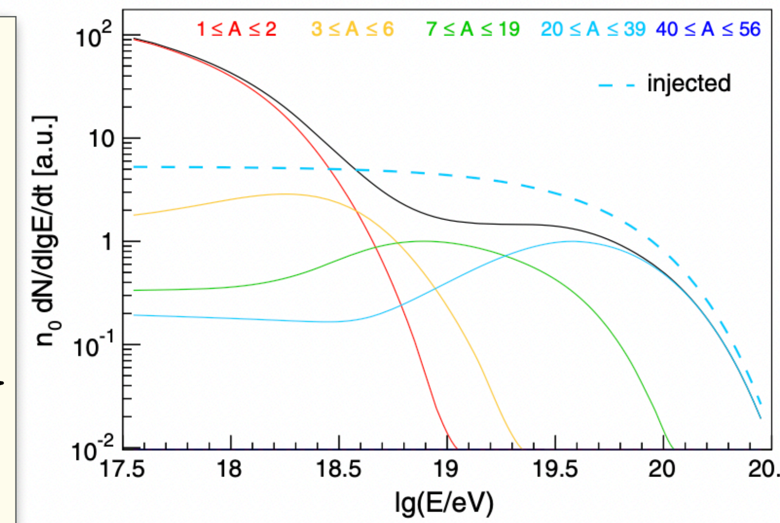
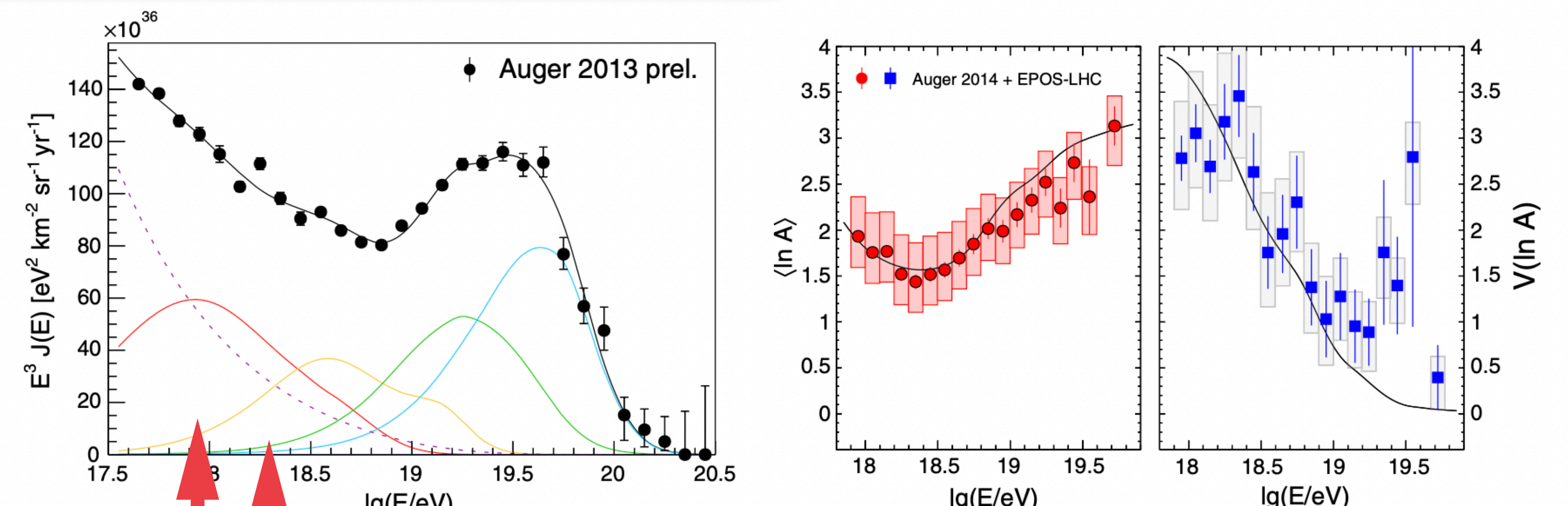






(b) Injected (dashed line) and escaping (solid lines) fluxes.



(c) Flux at Earth

(d) Composition at Earth

- Excellent fit to spectrum & composition
- Explains light population between between GCR & UHECR
- **Smoking gun for UFA mechanism:**

$E_p \sim E_{max} / A_{max}$ not E_{max} / Z_{max}

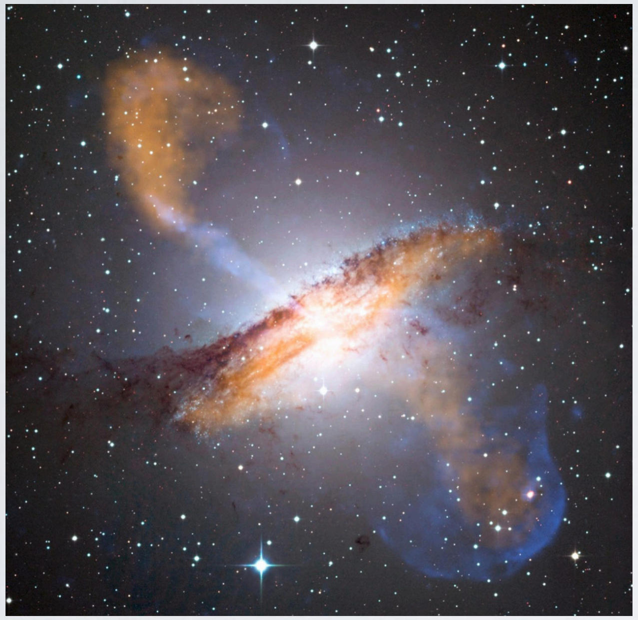
E_{max} / A_{max}

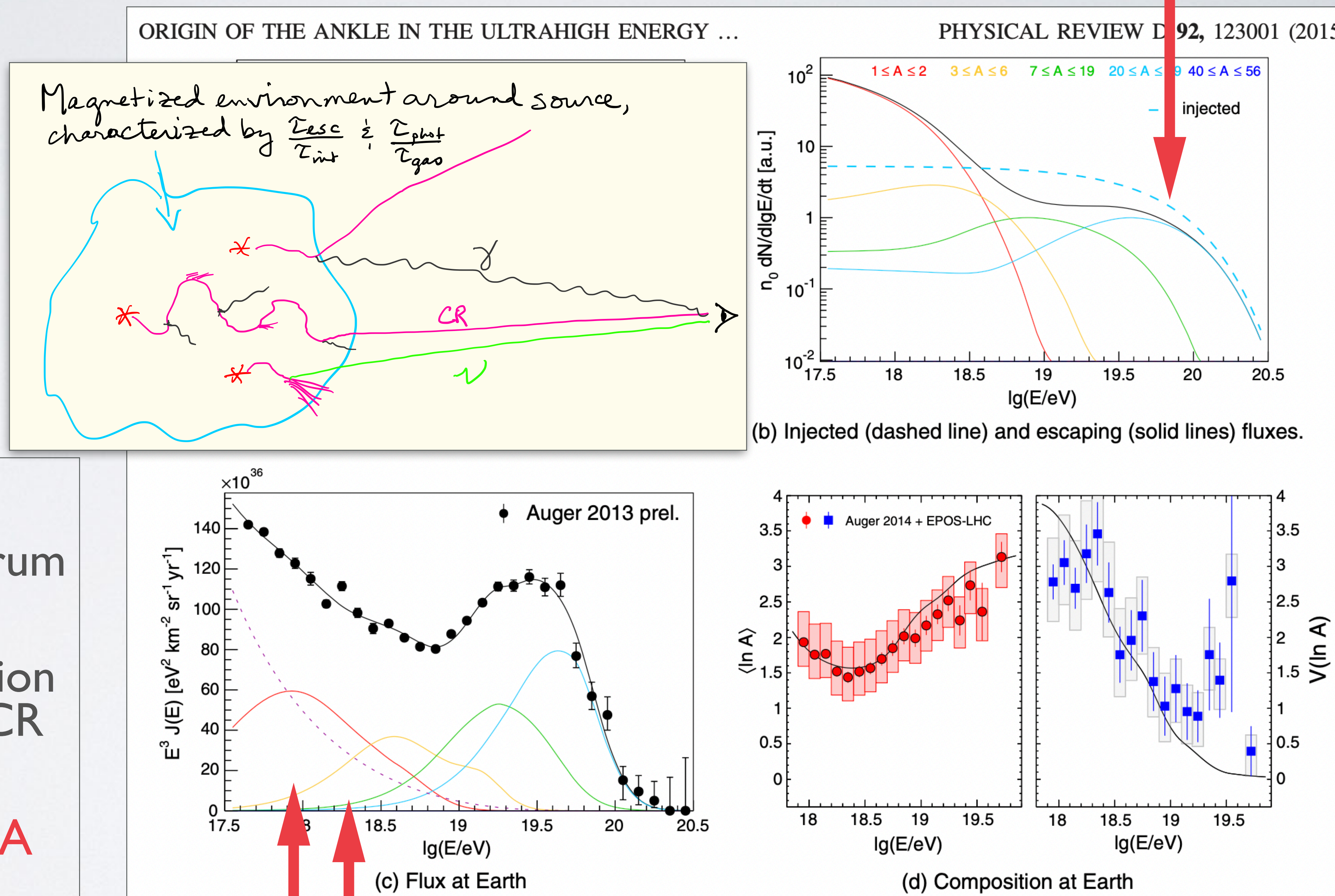
Peter's cycle protons would peak here

Cosmic Rays are Accelerated, then fragmented

Unger, GF & Anchordoqui 2015

Note large fraction of fragmented primaries





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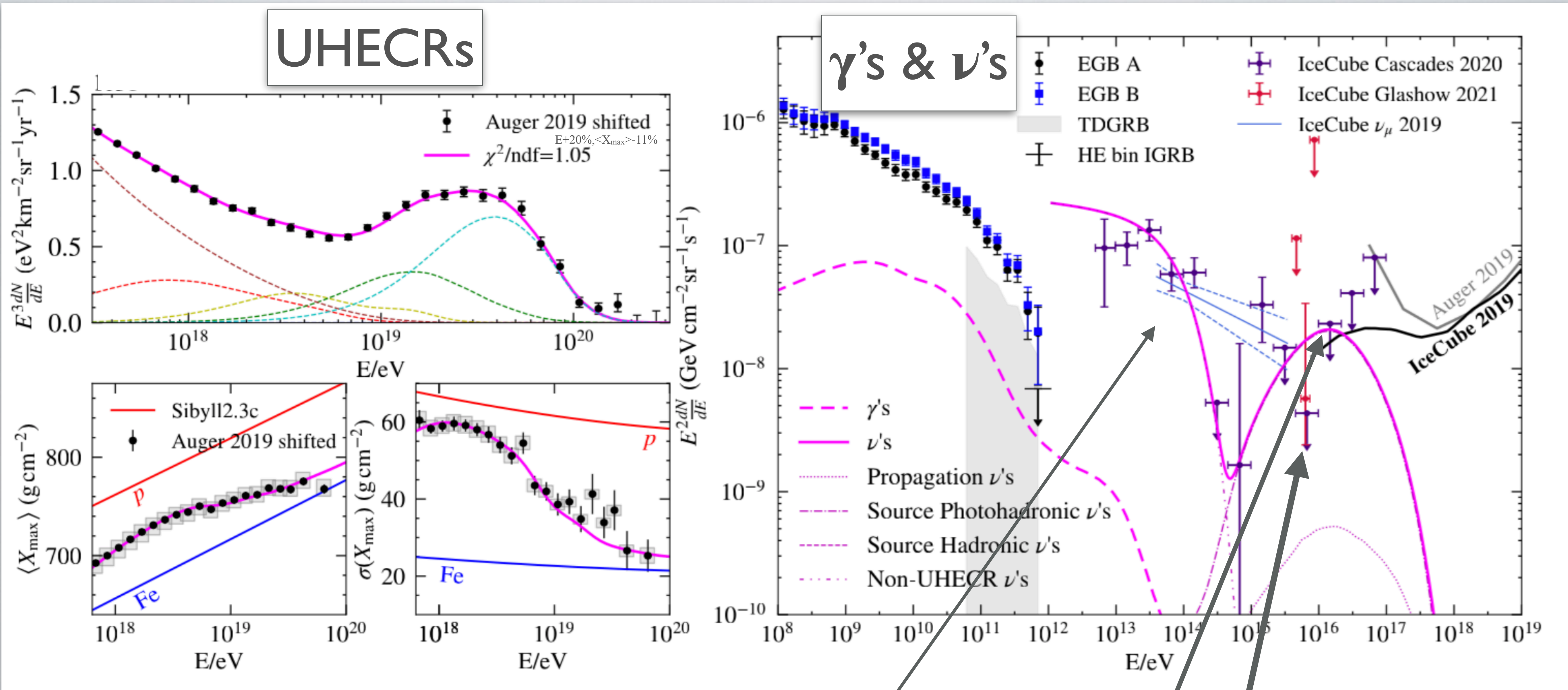
Refining & Extending the UFA mechanism

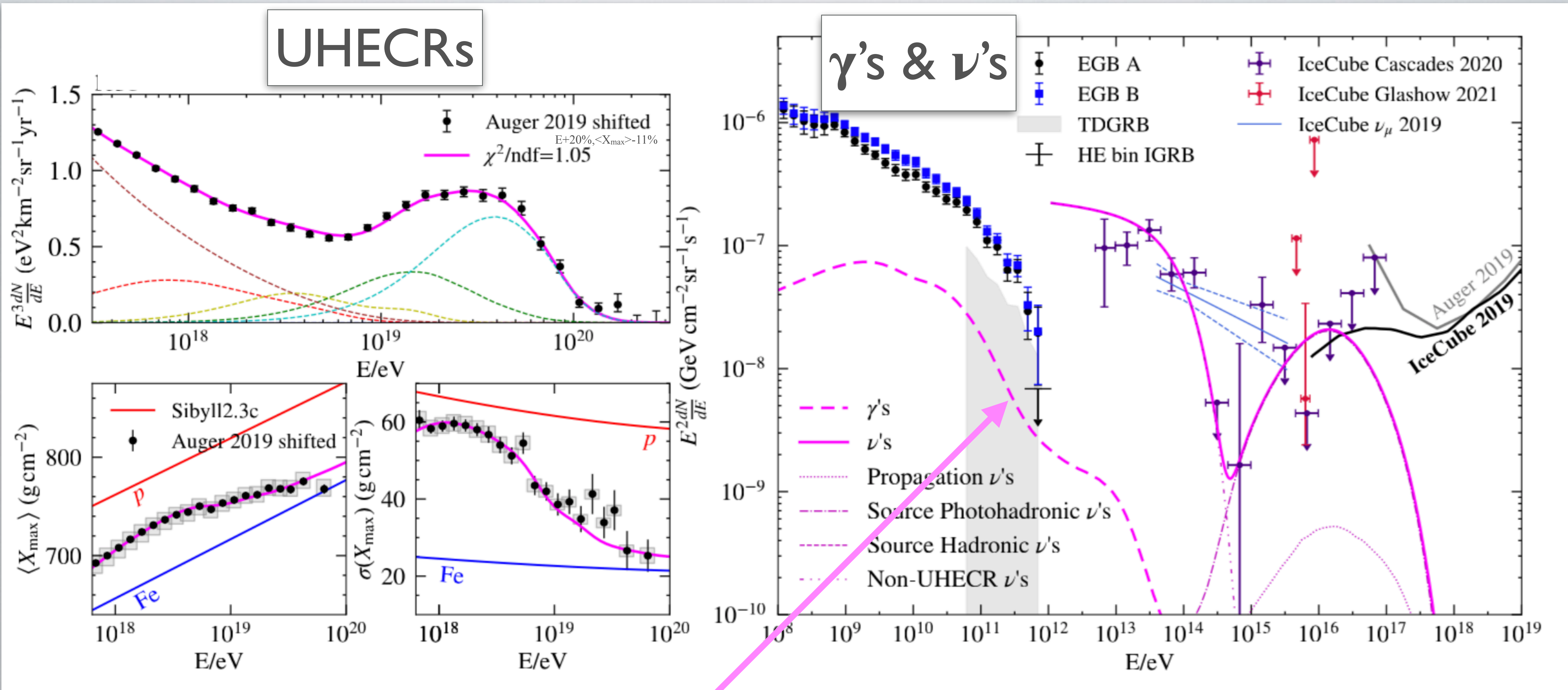
Muzio, Unger, GF 2019



- Galactic-sourced ν's cutting off ≈ 0.1 PeV
- **UHECR-sourced ν's *predicted from UHECRs;* peak ≈ 10 PeV**
- **Abundant $\bar{\nu}_e$ expected from n ➜ p e⁻ $\bar{\nu}_e$** *Glashow event predicted*
- UHECR-originated TeV-PeV gammas below other sources

Refining & Extending the UFA mechanism

Muzio, Unger, GF 2019, Muzio, GF, Unger 2022



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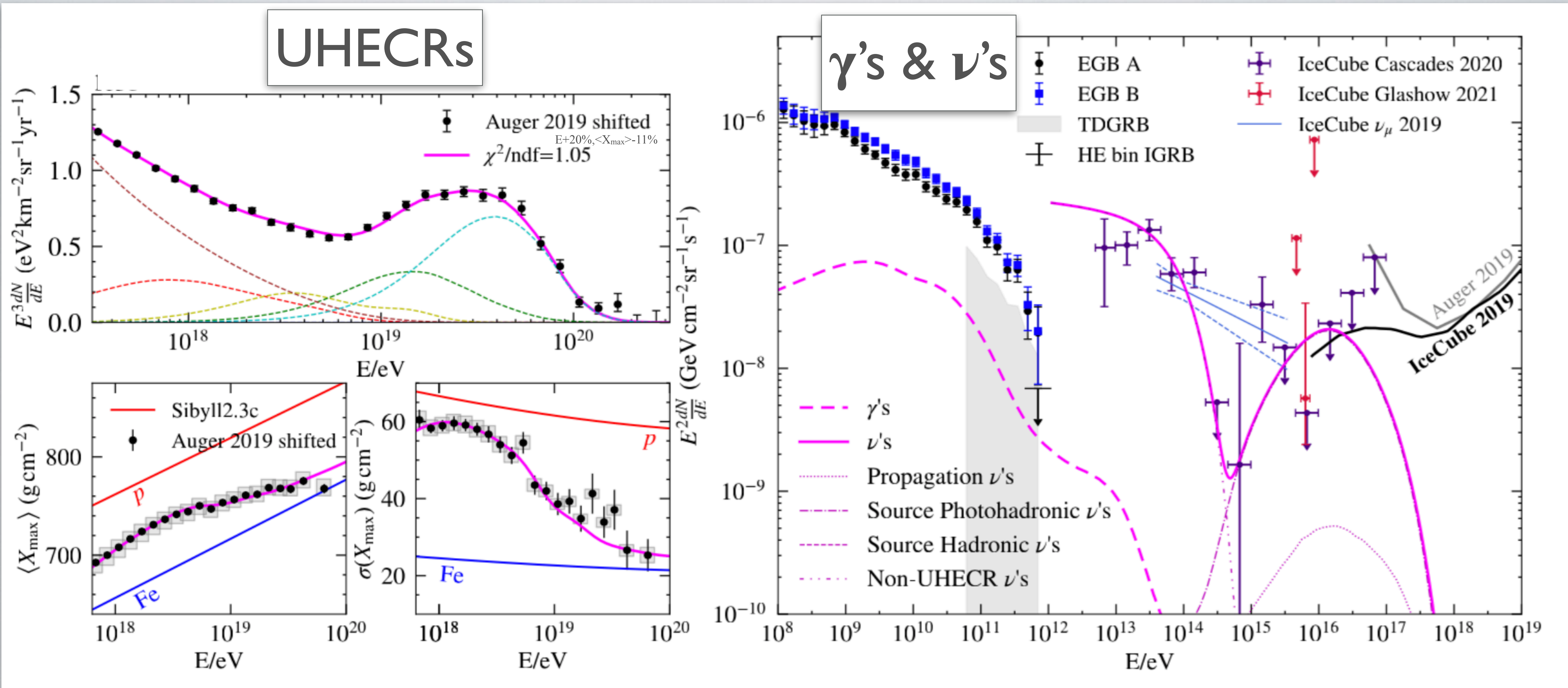
Today: exploiting the UFA mechanism

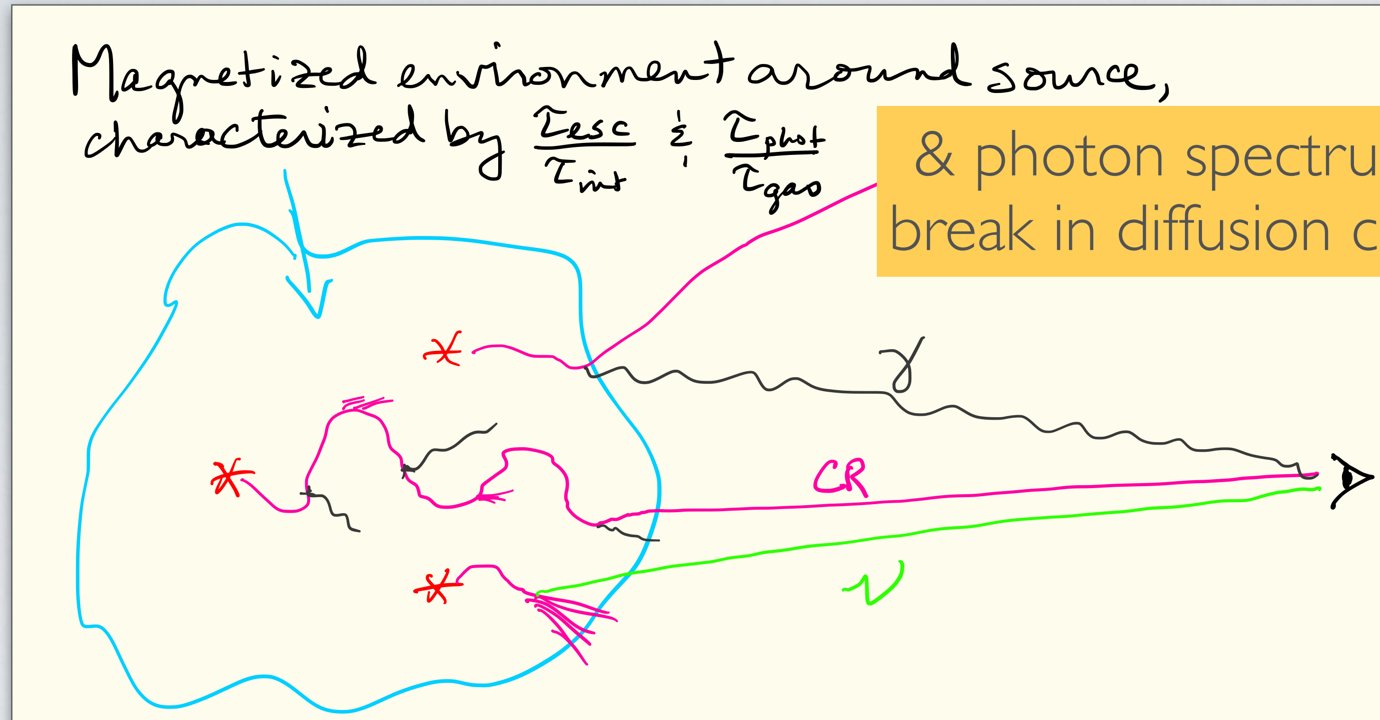
Muzio & GF arXiv:2209.08068



MODEL FIT PARAMETERS ⇔ ratio of escape & interaction times; break in diffusion coefficient

⇔ magnetic field strength and coherence length; source size; photon spectrum and gas density…

The surroundings of UHECR Accelerators are constrained by MFU fit



& photon spectrum, break in diffusion coef

Parameter	Sibyll2.3c	EPOS-LHC
$\gamma_{\rm inj}$	$-1.45^{+1.26}_{-1.21}$	$-1.31^{+1.23}_{-1.17}$
$\log_{10}(R_{\max}/\mathrm{V})$	$18.63^{+0.81}_{-0.38}$	$18.65^{+0.78}_{-0.37}$
$\log_{10} r_{\rm esc}$	$2.32^{+1.16}_{-0.92}$	$2.01^{+1.49}_{-0.78}$
f_g frac. (ref) hadronic ints	$0.17^{+0.6}_{-0.17}$	$0.29^{+0.56}_{-0.29}$
$\log_{10}(R_{\rm diff}/\mathrm{V})$	$17.65^{+0.85}_{-1.7}$	$17.7^{+1.01}_{-1.65}$
$\tanh(\log_{10} r_{\rm size})$	$0.81^{+0.18}_{-1.07}$	$0.74^{+0.25}_{-1.02}$
$f_{\rm gal}$	$0.71^{+0.16}_{-0.47}$	$0.76^{+0.08}_{-0.49}$
$\gamma_{\rm gal}$	$-3.4^{+0.74}_{-0.21}$	$-3.46^{+0.74}_{-0.23}$
$\log_{10}(E^{\rm galFe}_{\max}/\mathrm{eV})$	$18.86^{+1.35}_{-0.63}$	$18.66^{+1.45}_{-0.47}$
$\log_{10}(T/\mathrm{K})$	$2.41^{+0.85}_{-0.6}$	$2.21^{+1.05}_{-0.39}$
$A_{\rm inj}$	$28.83^{+18.78}_{-18.83}$	$28.62^{+18.93}_{-18.71}$
$A_{\rm gal}$	$28.78^{+18.77}_{-18.8}$	$28.7^{+18.8}_{-18.72}$
$\log_{10}(B\lambda_c/\mu\mathrm{G}\cdot\mathrm{kpc})$	$0.49^{+0.85}_{-1.7}$	$0.54^{+1.01}_{-1.65}$
$\log_{10}(Ln_\gamma/(10\ \mathrm{kpc}\cdot\mathrm{cm}^{-3}))$	$3.96^{+3.09}_{-1.51}$	$4.15^{+2.65}_{-1.48}$
$\log_{10}(n_\gamma/n_g)$	$3.17^{+1.7}_{-1.18}$	$3.05^{+2.06}_{-1.22}$
$\log_{10}(L/10\ \mathrm{kpc})_{\rm BB}$	$-4.7^{+2.75}_{-2.4}$	$-4.12^{+1.87}_{-2.56}$
$\log_{10}(\lambda_c/\mathrm{kpc})_{\rm BB}$	$-4.71^{+3.91}_{-4.0}$	$-4.23^{+3.11}_{-3.2}$
$\log_{10}(n_g/\mathrm{cm}^{-3})_{\rm BB}$	$5.52^{+2.25}_{-2.17}$	$5.08^{+3.2}_{-2.24}$
$\log_{10}(B/\mu\mathrm{G})_{\rm BB}$	$5.19^{+4.33}_{-4.97}$	$4.64^{+3.77}_{-4.02}$

Key parameters:

$$r_{\rm esc} \equiv \tau^{\rm ref}_{\rm esc}/\tau^{\rm ref}_{\rm int} = \langle N^{\rm ref}_{\rm int}\rangle$$

reference: ^{56}Fe at 10 EeV.

$$n_\gamma = n_0 I_{\rm BB}(T) \qquad r_{\rm size} \equiv L/\lambda_{\rm c}$$

$$\tau_{\rm esc}(R) = \frac{L^2}{6D(R)} + \frac{L}{c}.$$

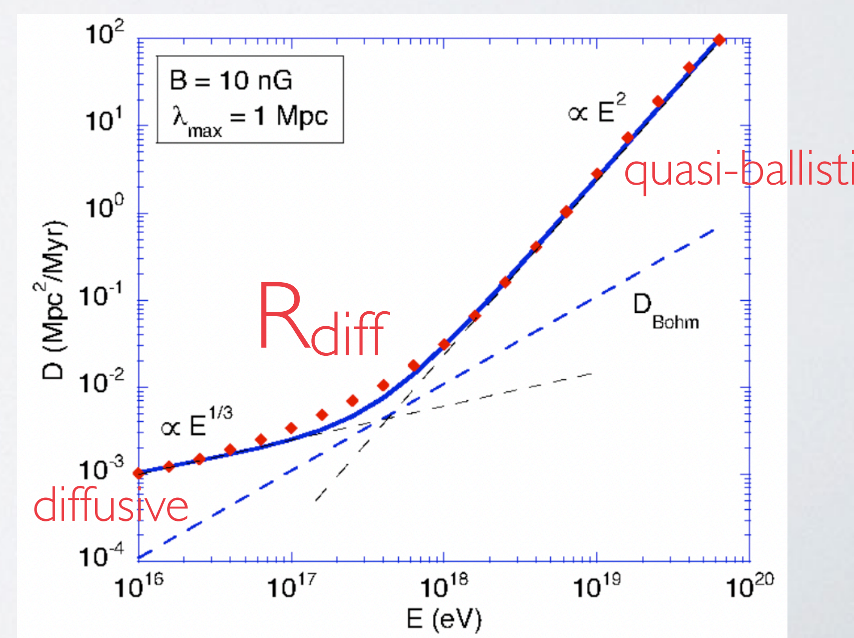
$$D(R) \equiv c\lambda_{\rm c} d(R)/6\pi, \qquad 2\pi r_{\rm L}(R_{\rm diff}) \equiv \lambda_{\rm c}.$$

$$d(R) = \left(\frac{R}{R_{\rm diff}}\right)^{1/3} + \frac{1}{2}\left(\frac{R}{R_{\rm diff}}\right) + \frac{2}{3}\left(\frac{R}{R_{\rm diff}}\right)^2$$

$$n_0\, L = \frac{c\,\tau^{\rm ref}_{{\rm BB},\gamma}\, r_{\rm esc}\, r_{g\gamma}}{(\pi\, r_{\rm size}/d(R^{\rm ref}) + 1)\,(1 + r_{g\gamma})}$$

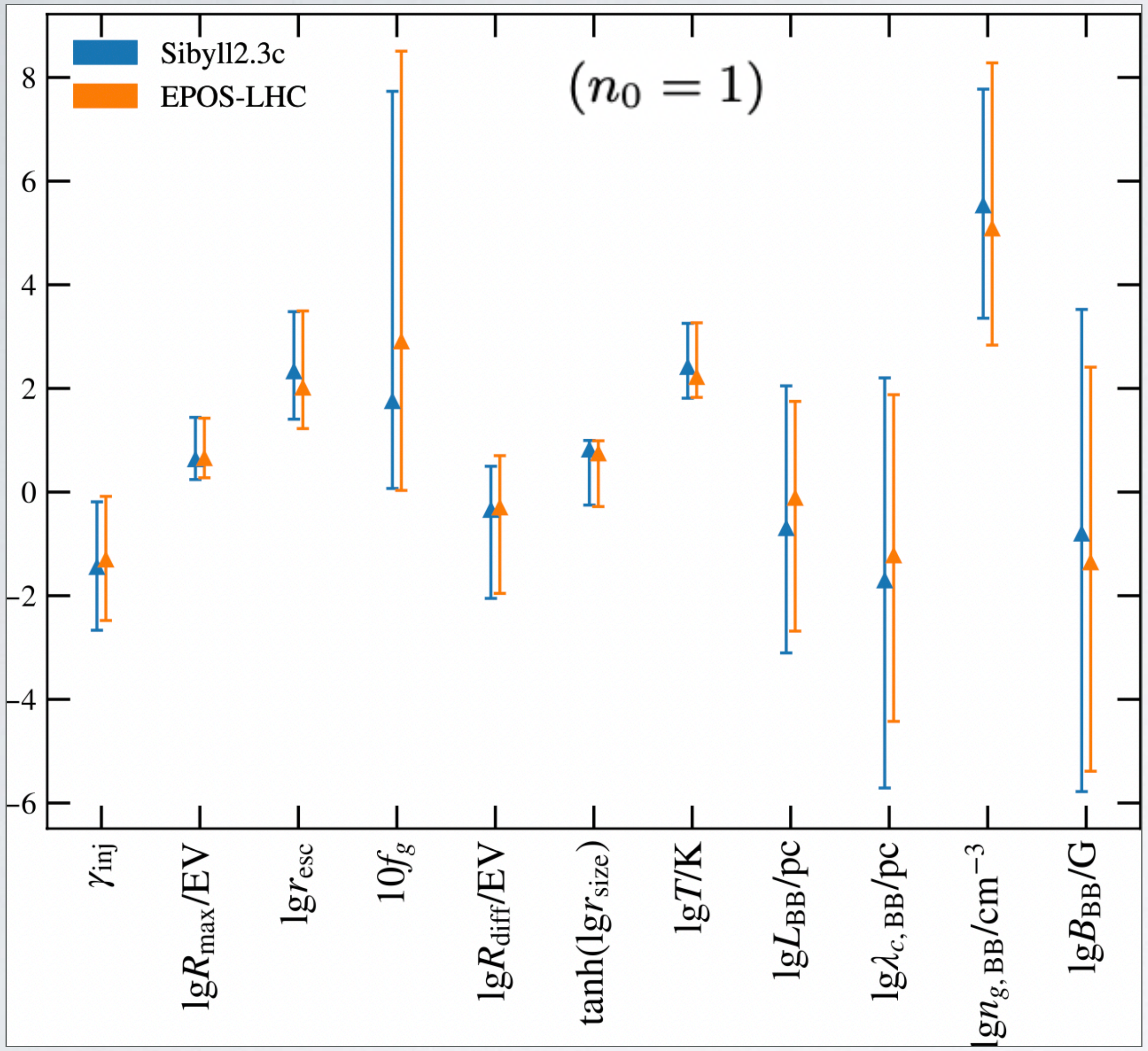
T: $\sigma_\gamma A(E_{\rm CR})$

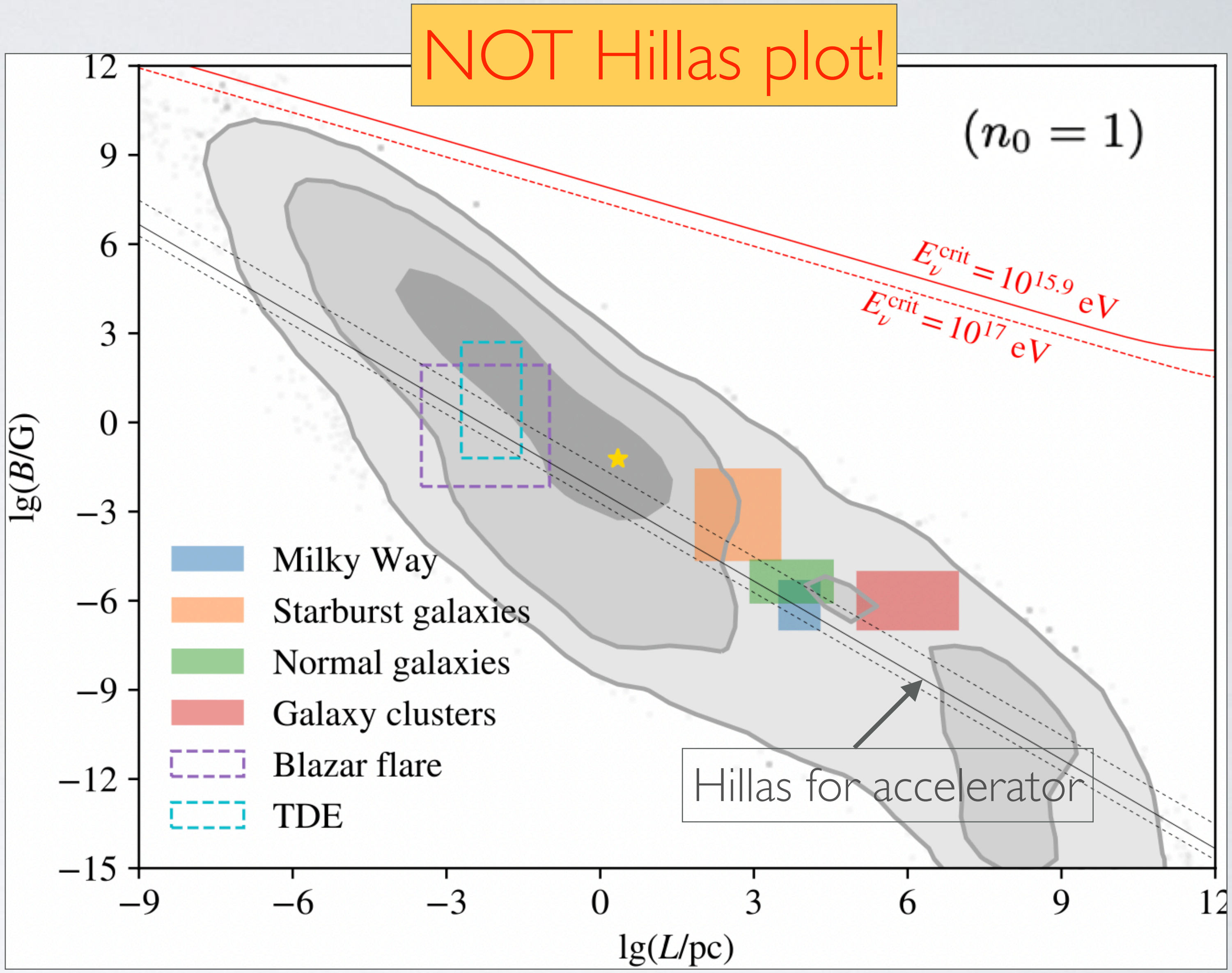
$R_{\rm diff}$, $\tau_{\rm esc}$: B, L, $\lambda_{\rm c}$



Globus, Allard Parizot 08

Surroundings of UHECR Accelerators





btw: $\gamma_{\rm inj} = -1.45^{+1.25}_{-1.15}$ ➜ Diffusive Shock Accel. OK *(accelerator ≠ source)*

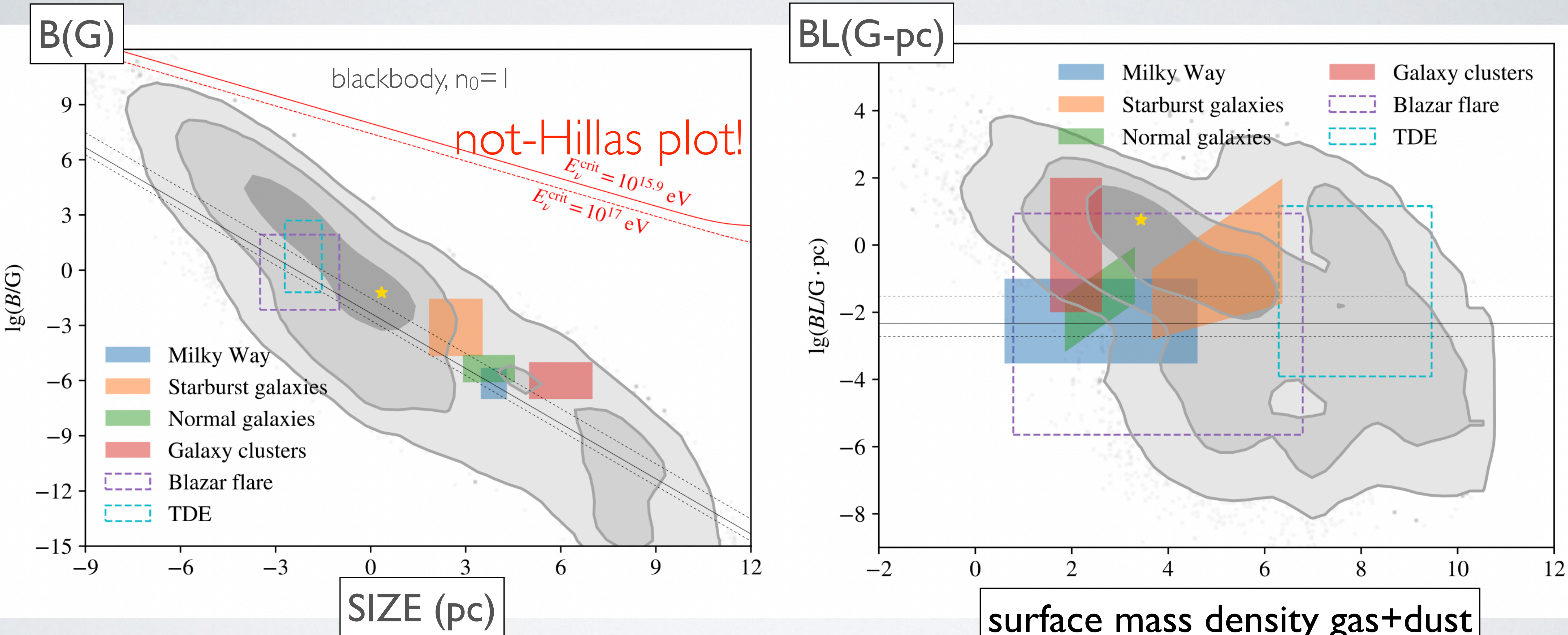
$T_{\rm surround}$ = 60 - 2000 K

$\{B_{\rm rms}, L\}$ — ***of source, not accelerator*** — is constrained

black-body case $n_0 = 1$; the conversion for other n_0 values is $L = L_{\rm BB}/n_0$, $B = n_0 B_{\rm BB}$, $\lambda_{\rm c} = \lambda_{\rm c,BB}/n_0$, and $n_{\rm g} = n_0\, n_{g,{\rm BB}}$.

Muzio&GF arXiv:2209.08068

Magnetic Field, Size, baryon density & photon field of source are constrained ➜ (dis)allowed candidates



$T_{surround}$ = 60 - 2000 K

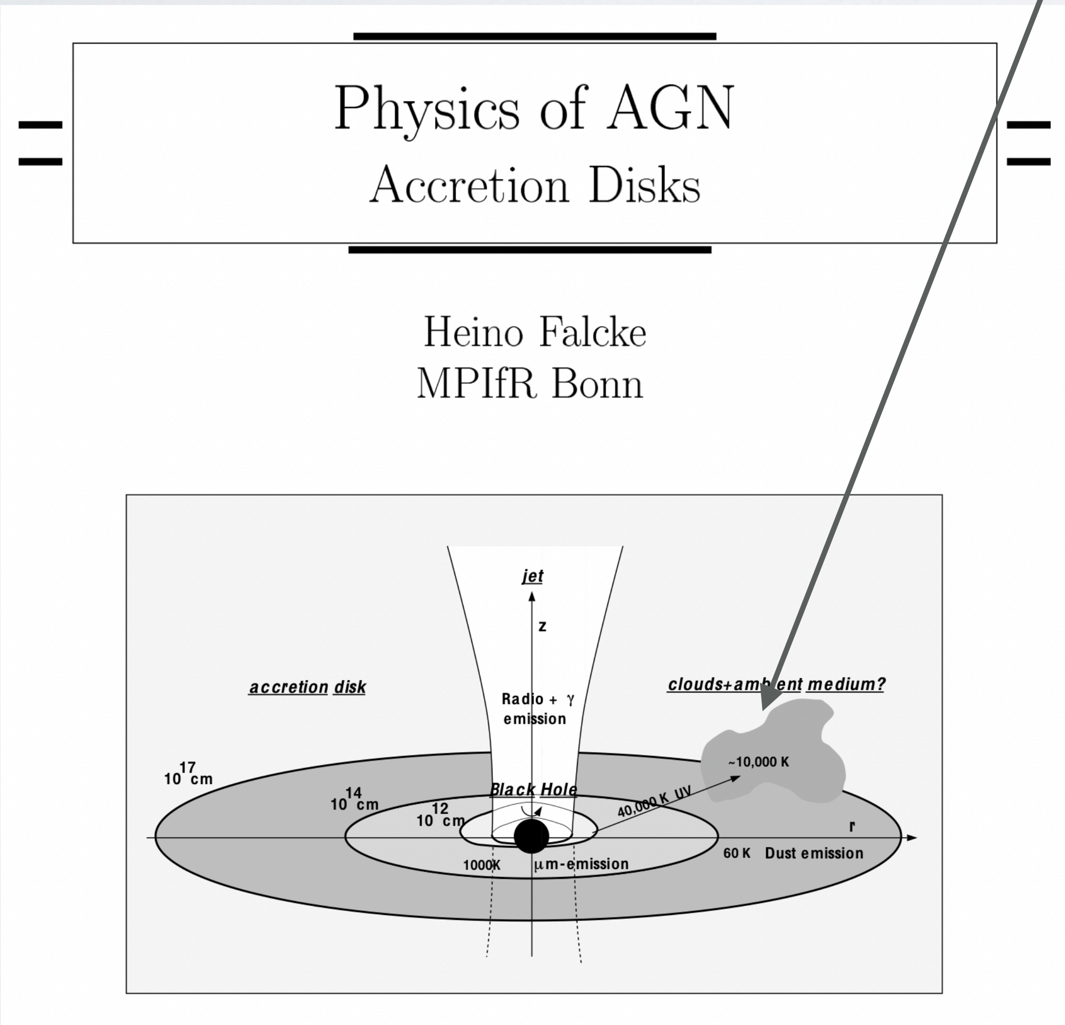
Muzio&GF arXiv:2209.08068

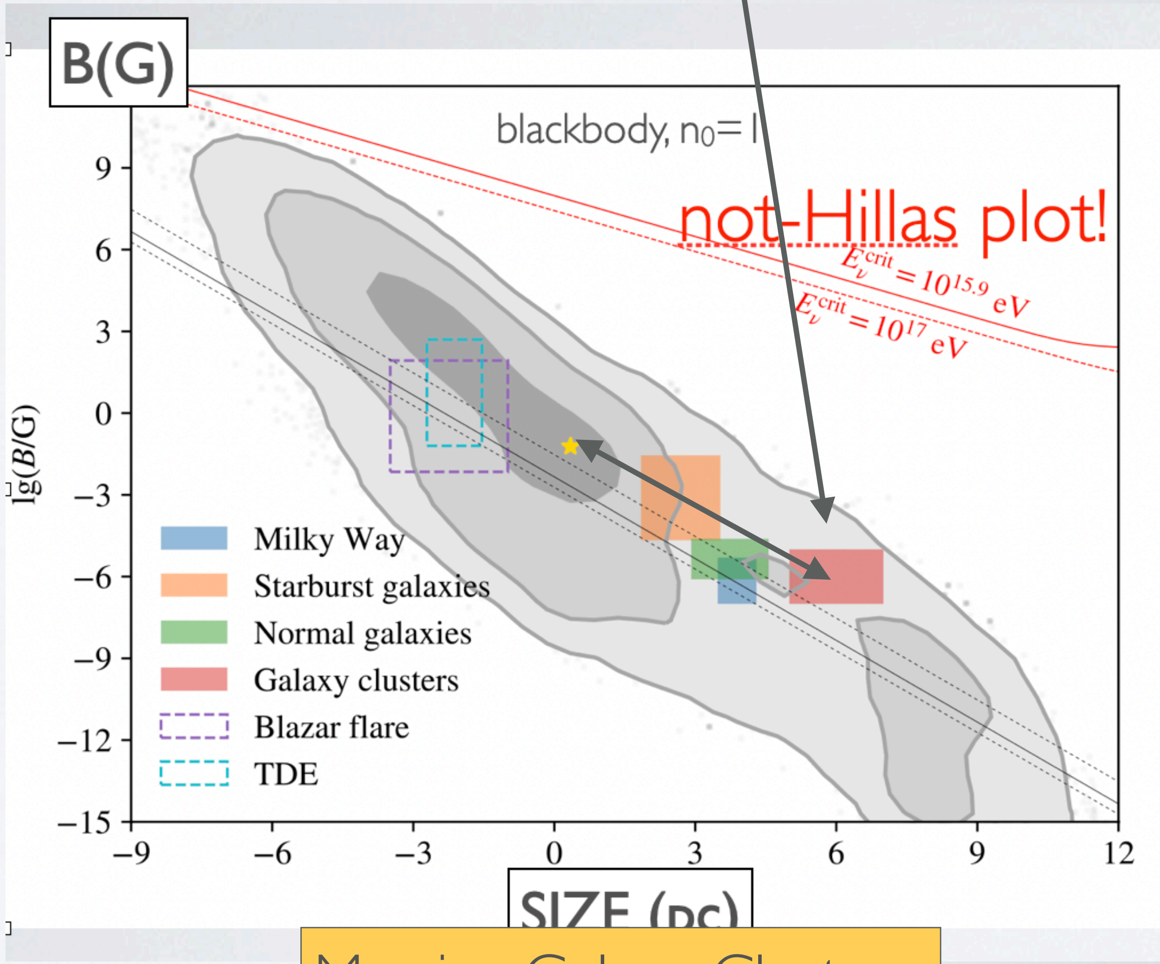
$T_{surround}$ = 60 - 2000 K excludes many candidate acceleration regions

~~Massive Galaxy Clusters~~ (2 x disfavored: T = $10^{7\text{-}8}$ K; n_0 = 1)

AGN:

- ~~radio lobes~~ (T ≈ few keV)
- ?internal shocks in jet? likely problematic; must also account for boost
- inner AGN disk: maybe ok (T=60-1000 K)
  - but nearby dangerous regions & must account boost

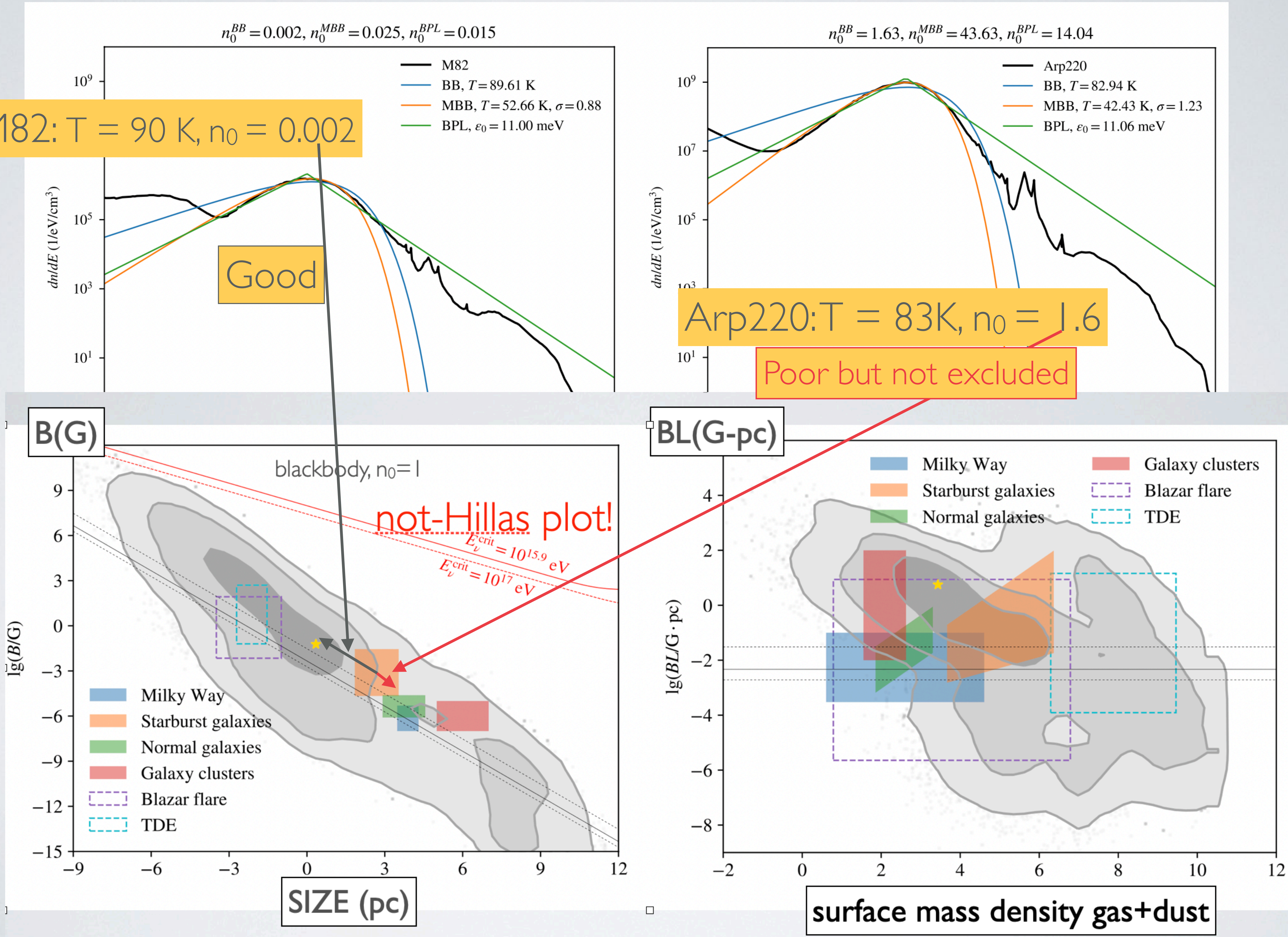




Massive Galaxy Clusters: poor fit to UHECRs

Typical Starburst Galaxies are viable: both T and B & L

Muzio&GF arXiv:2209.08068. See also Condorelli+arXiv:2209.08593

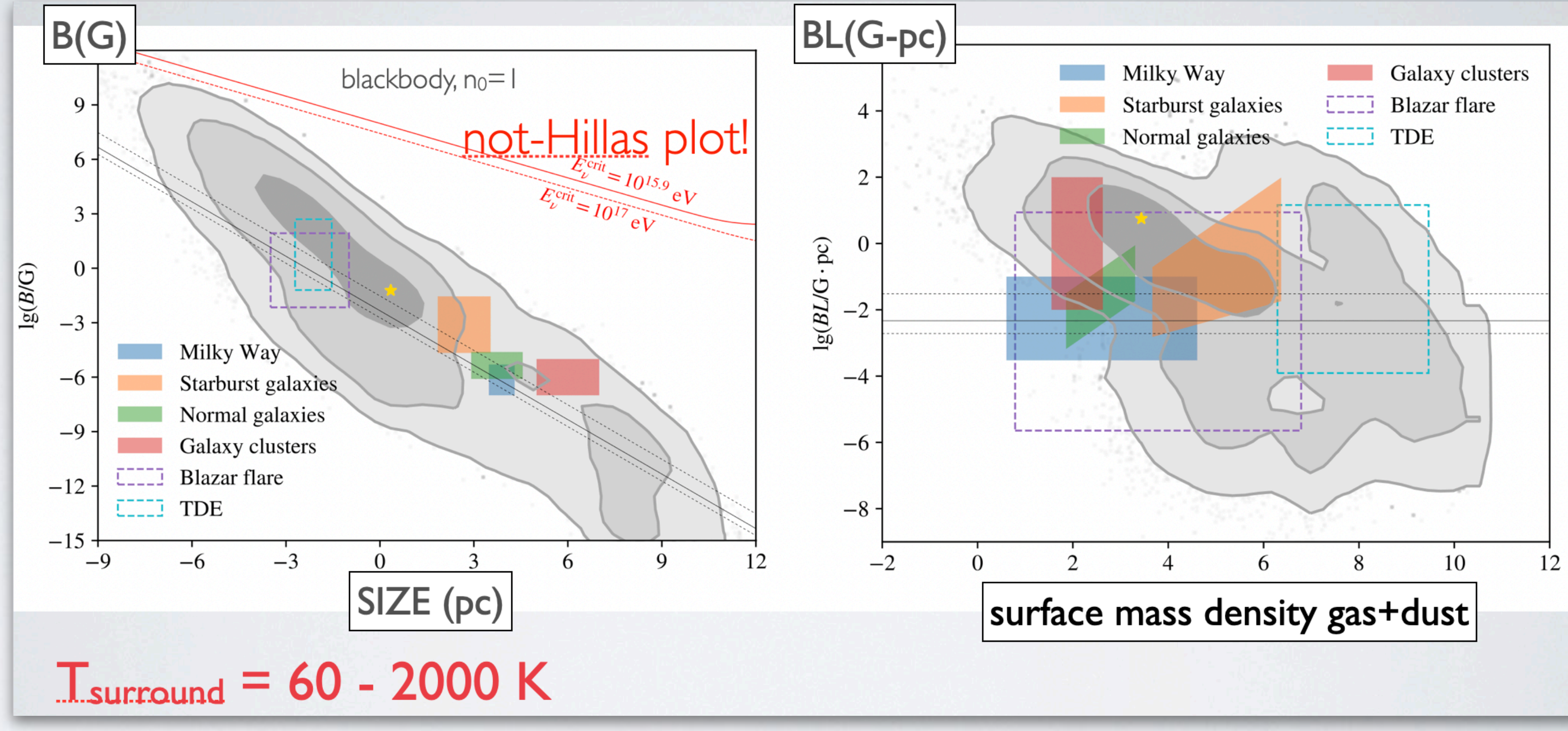


What if you don't believe UFA picture?

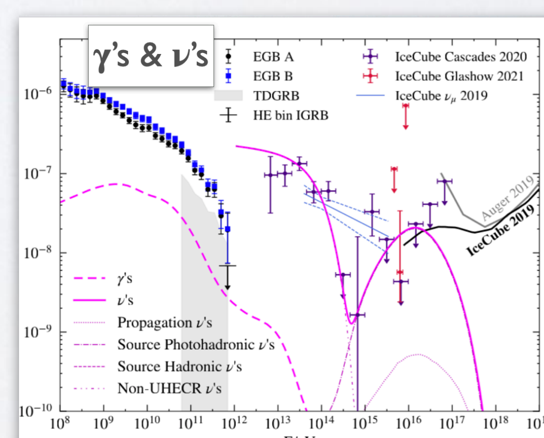
(disintegration ⇒ sub-ankle EGCRs)

- Need to invent explanation for magnitude of spectrum below ankle.
- Need to explain regularity of $E_p \sim 1/4\ E_{He}$ (common accel: $1/2\ E_{He}$).
- SOURCE ENVIRONMENT WILL (in general) STILL disintegrate UHECRs;
  - high T environment is especially dangerous
  - problem must be studied

Summary



- **Composition & Spectrum of UHECRs + VHE ν** (upper limits) **constrain source environment:** $\mathbf{B_{rms}}$ **, size , T , …** MF22
  - disfavors massive Galaxy Clusters and radio lobes of AGN
  - inner AGN disk maybe ok (n.b., boost); internal shocks in jets problematic(?)
  - typical starburst galaxies ok
  - to do: TDE's, GRBs, magnetars, … (please make suggestions, lend ideas & wisdom!)
- **Accelerator spectral index is compatible with Diffusive Shock Accel.** MFU22, MF22
- **Multi-messenger:** MFU22
  - ✓ Predicted HE ν's from UHECRs (> few PeV) fit data
  - ✓ GeV-TeV γ's from UHECRs << observed
  - VHE ν spectrum important for constraining sources



BACKUP SLIDES

"Imprint of Large scale structure on THE UHECR SKY"

Chen Ding, Noemie Globus, Glennys Farrar
New York University

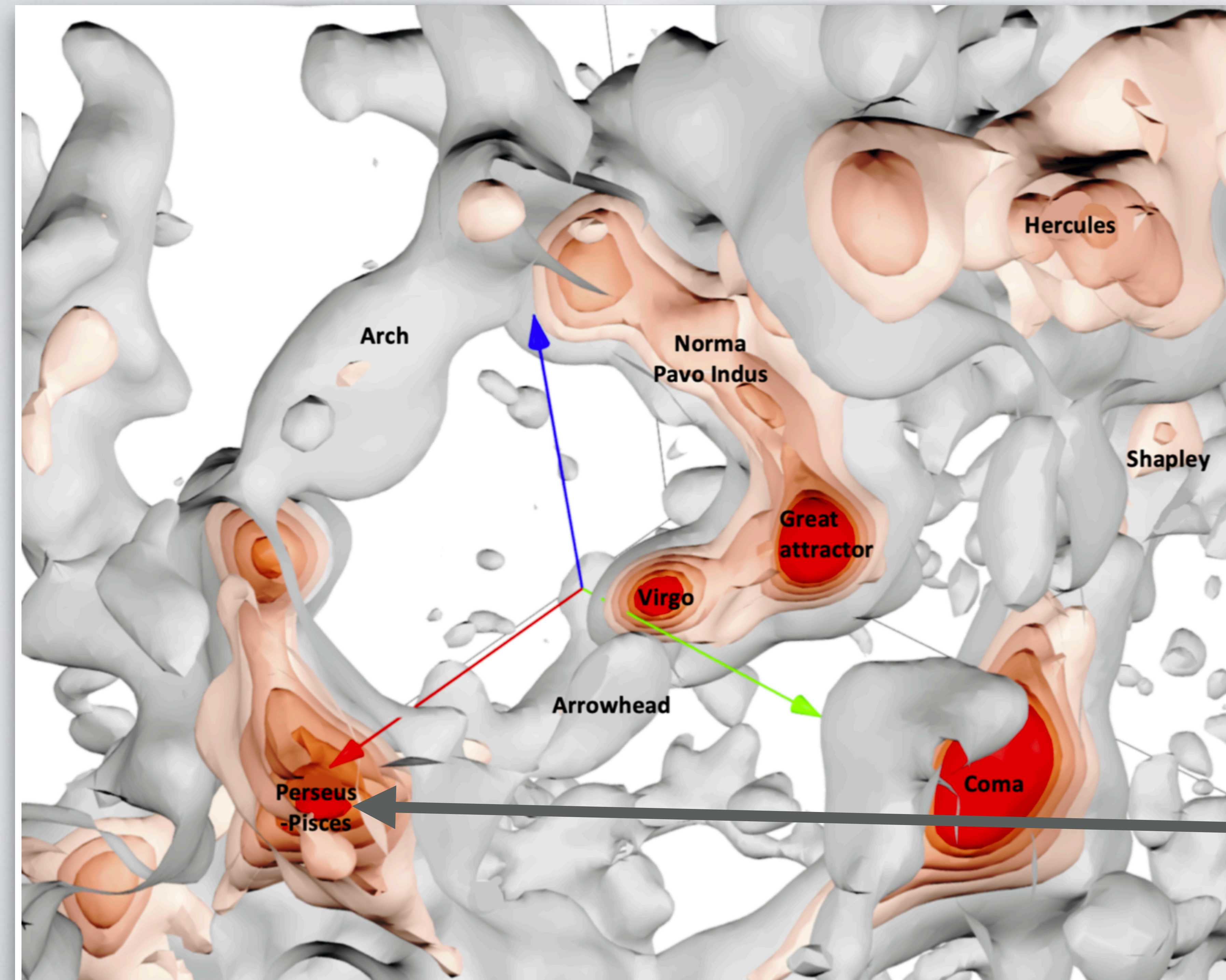
ApJ Letters 2021; arXiv 2101.04564 [astro-ph.HE]

DGF21 CONCLUSIONS

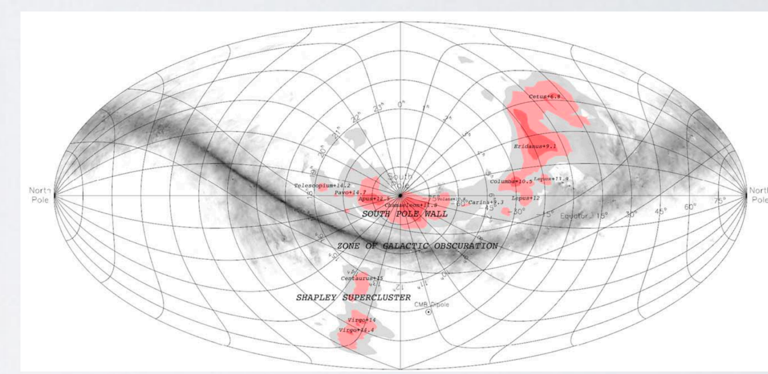
- Assumption that UHECR injection follows the large scale matter distribution explains Auger anisotropy measurements above 8 EeV.
  - *Rather than few prominent sources, there appear to be many weak ones.*
- Individual sources:
  - Auger hotspot may be from LSS (conclusion very sensitive to composition)
  - TA hotspot ⇔ nearby (e.g., transient) source like a TDE (in M82?)
- *Pure proton composition can be ruled out on anisotropy grounds alone.*
- EGMF has insignificant effect
- Composition inhomogeneities from LSS small ⇒ composition will help isolate individual sources

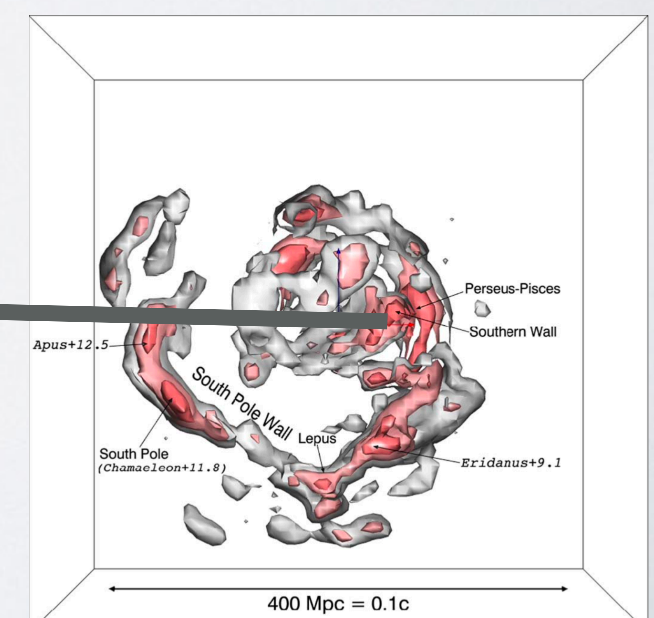
Source distribution ⇔ local matter distribution

DGF 21 uses Hoffmann+18 *Cosmicflows-2*



Pomerede+20 discovered
South Pole Wall @~160 Mpc
Cosmicflows-3
under development



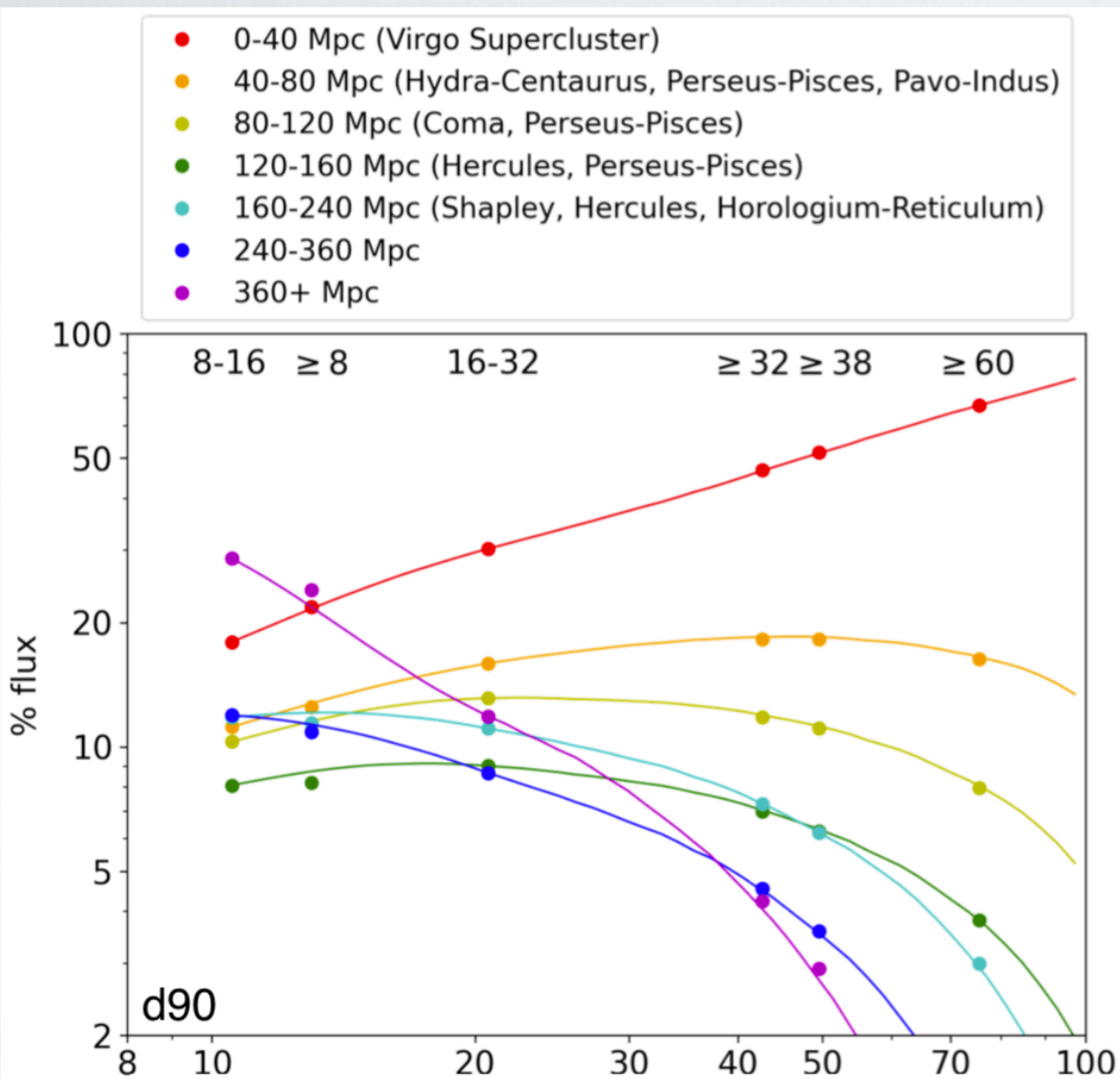


DGF: “Continuum” model

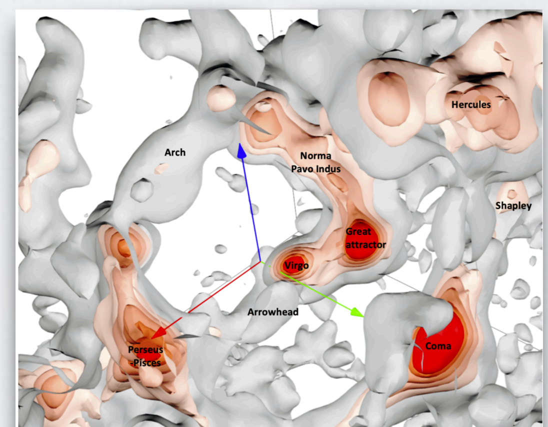
- Source distribution ⇔ matter distribution
- Extragalactic propagation: energy losses, possible magnetic diffusion (EGMF turns out to have negligible impact)
- Galactic propagation: JF12 field model with adjustable coherence length (1.8B GF-Sutherland trajectories)

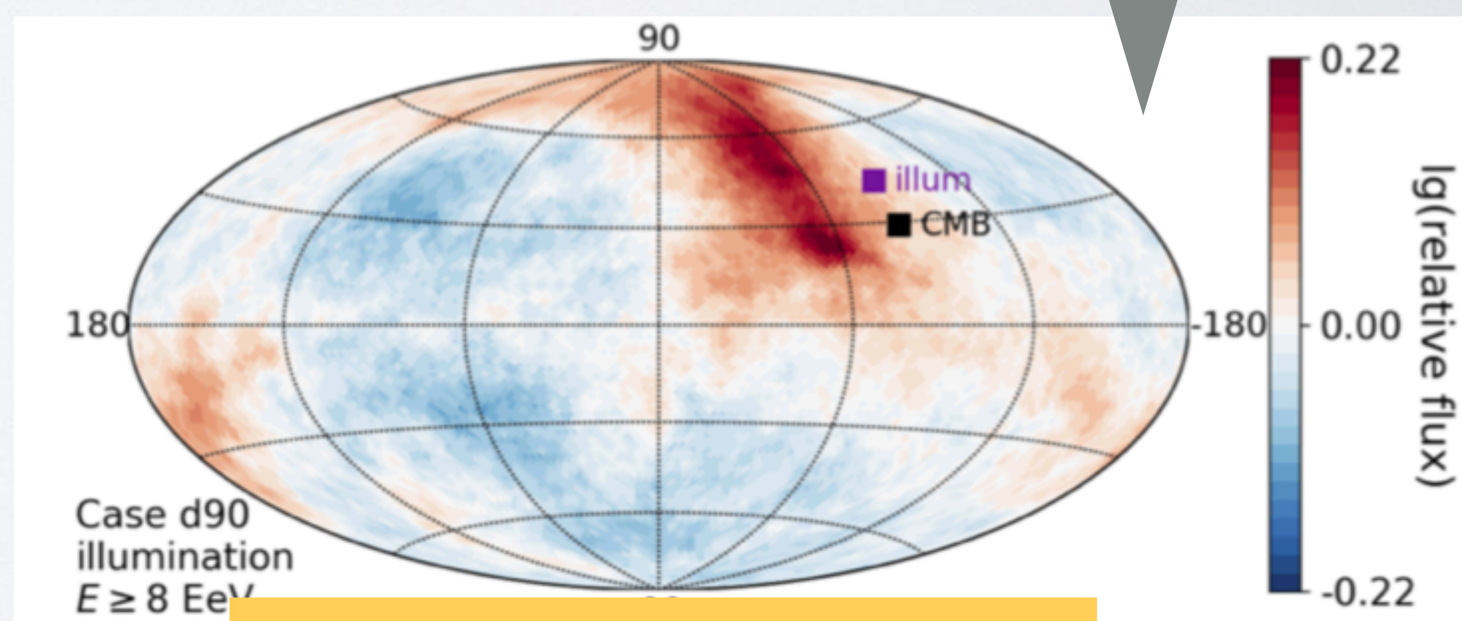
ILLUMINATION MAP

(EGMF diffusion is insignificant. Fit result: B_{EG} = 0.3-0.5 nG)



E (EeV)



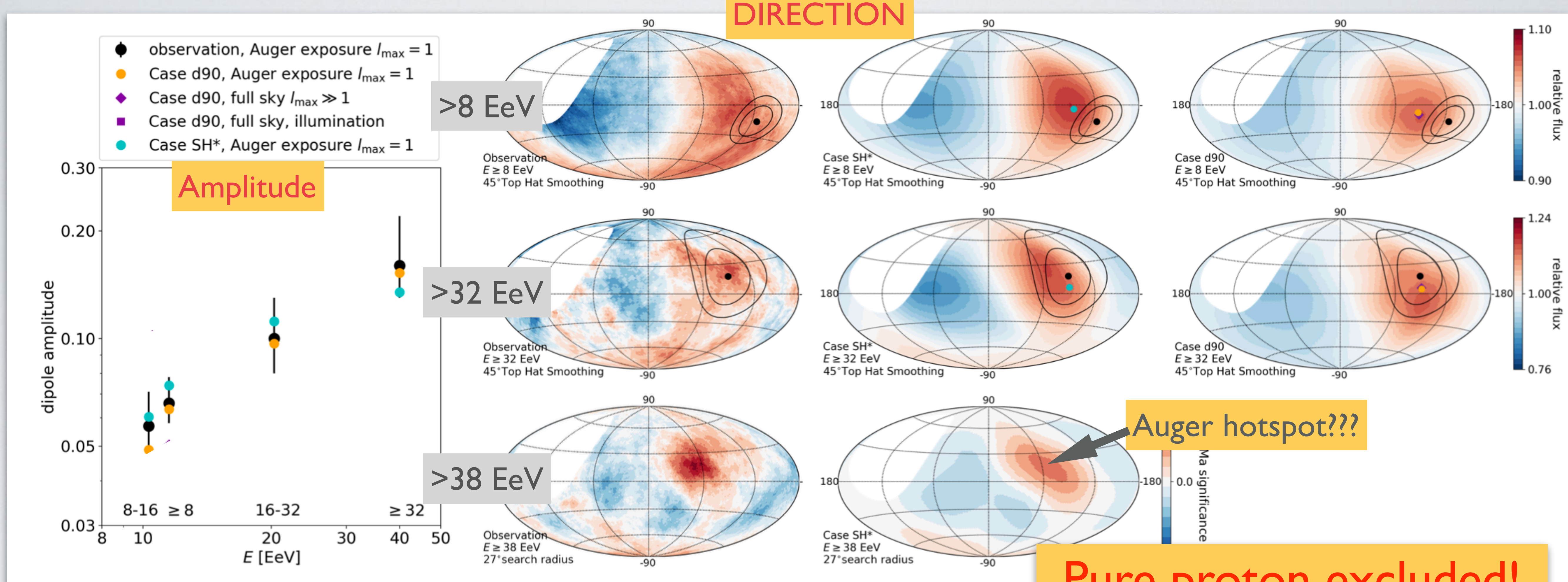


ILLUMINATION MAP

★ ★ Dipole Amplitude & Energy dependence

★ Dipole Direction

? Auger's hotspot



Pure proton excluded!
wrong direction & amp

GOOD FIT TO COMPOSITION