Session 02: Constraining UHECR Sources

Cosmic Ray Indirect

ONLINE ICRC 2021
THE ASTROPARTICLE PHYSICS CONFERENCE
Berlin | Germany

37th International
Cosmic Ray Conference
12–23 July 2021

13th July 2021 ICRC 2021

Constraining UHECR sources

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- Bister (Combined fit sensitivity) 2”
- Bakalova (Single source contribution at highest energies) 2”
- Farrar (Transient source of highest energy Galactic CRs) 2”
- Discussion 12”
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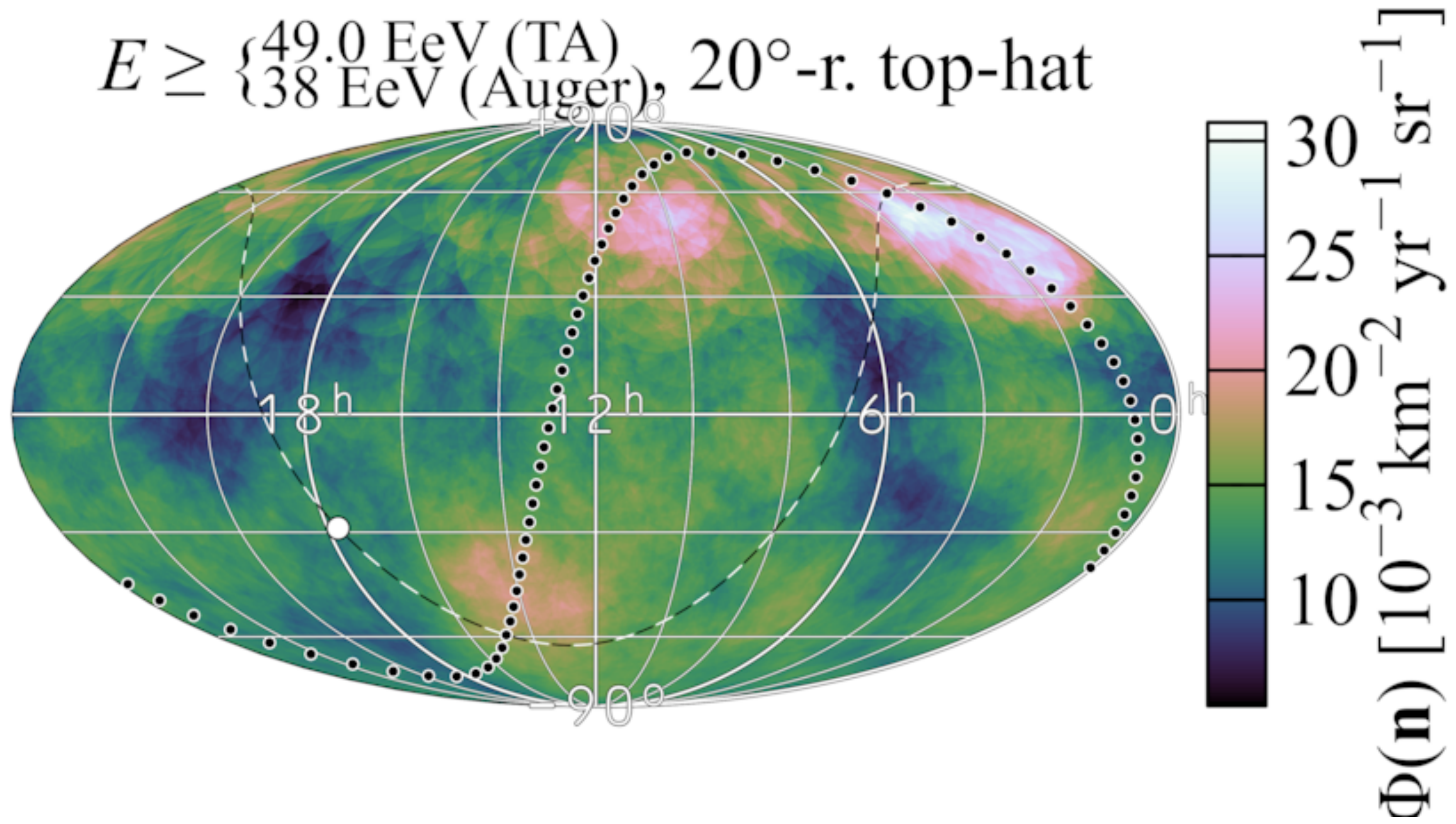
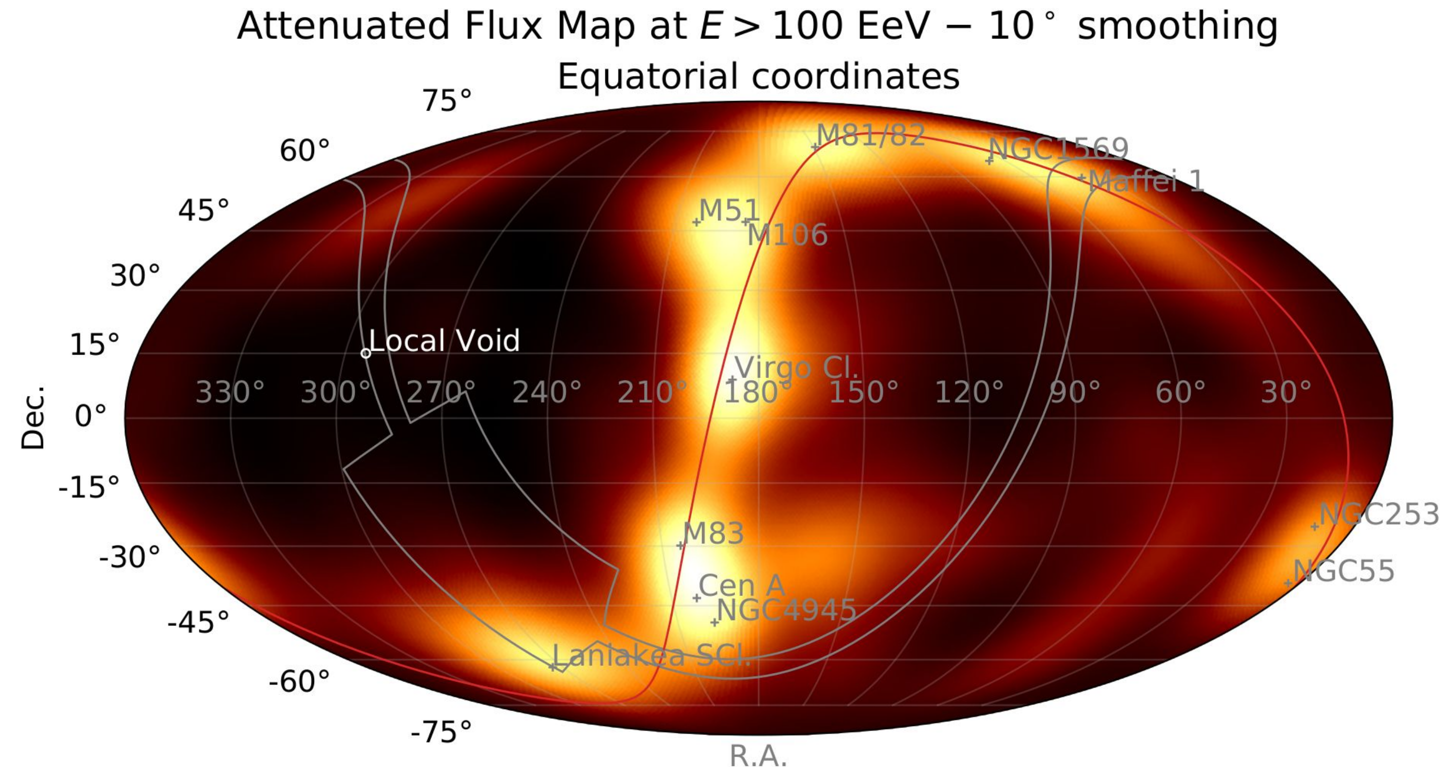
Topics

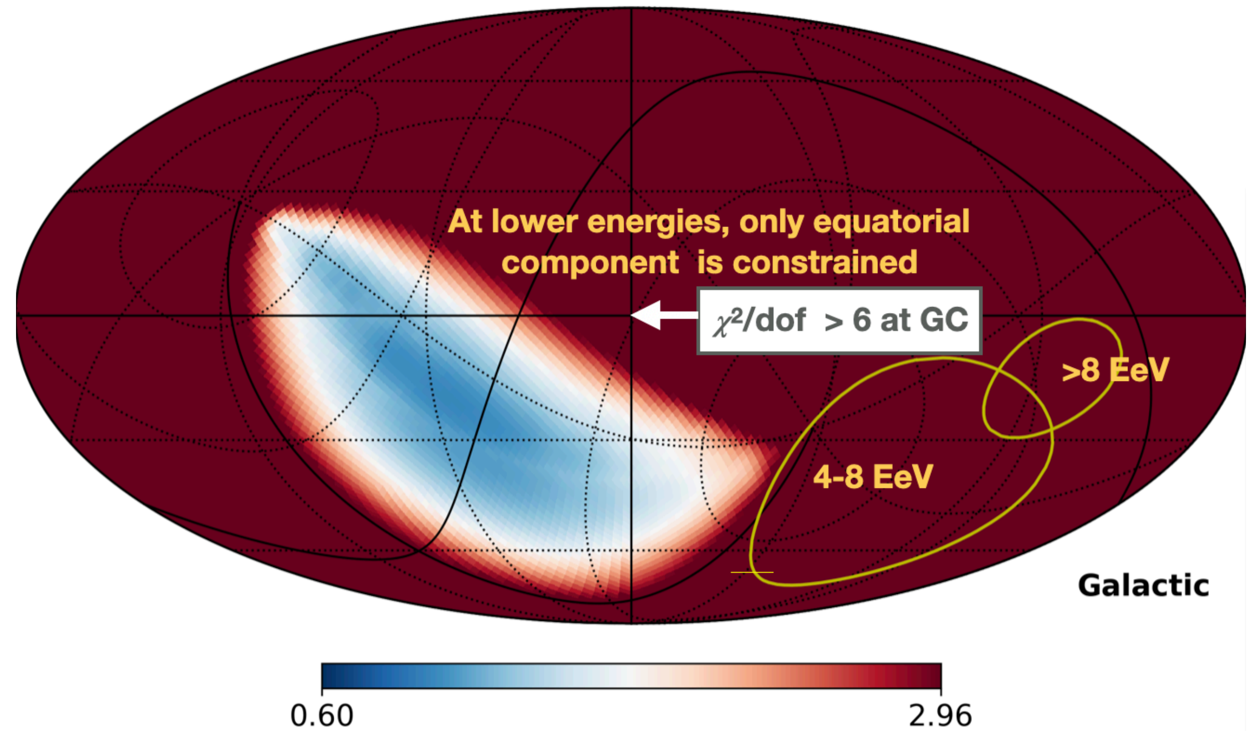
Arrival direction anisotropy: Status/Prospects





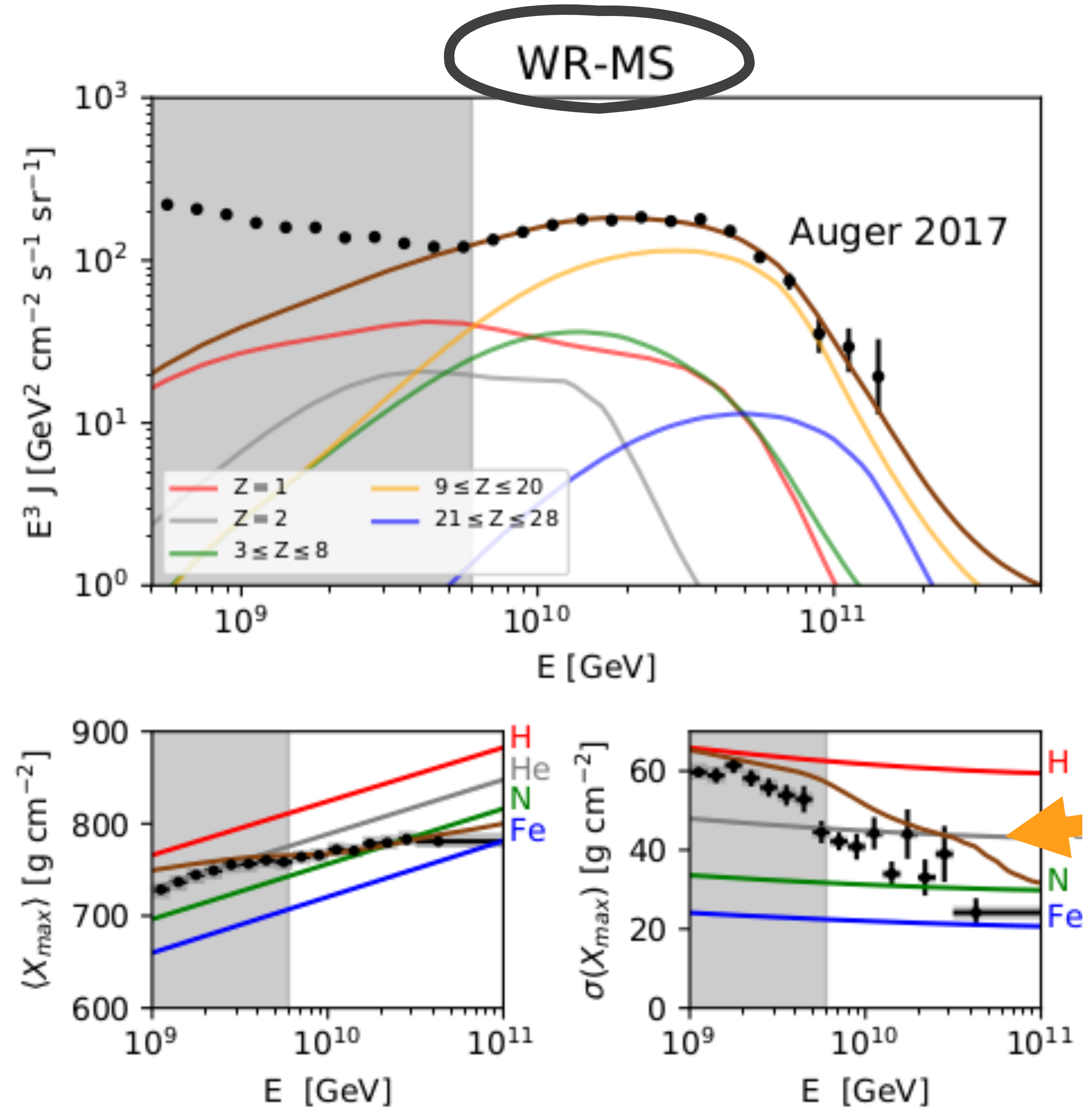
What can we learn from anisotropic arrival directions?
Can we understand the origin of the paucity of Virgo?

UHECR contribution of single sources



Galactic Component B transient origin? Single source contribution at highest energies? Cen A?

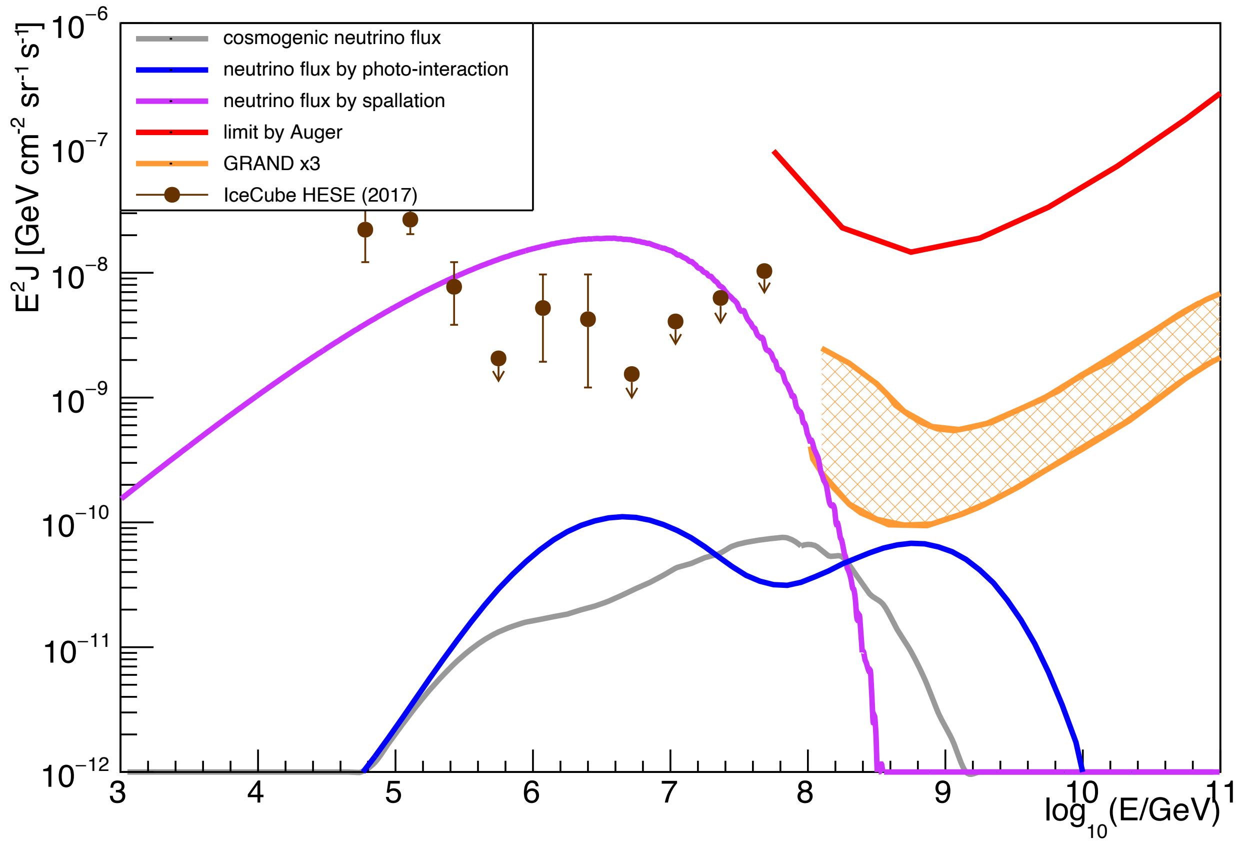
Composition

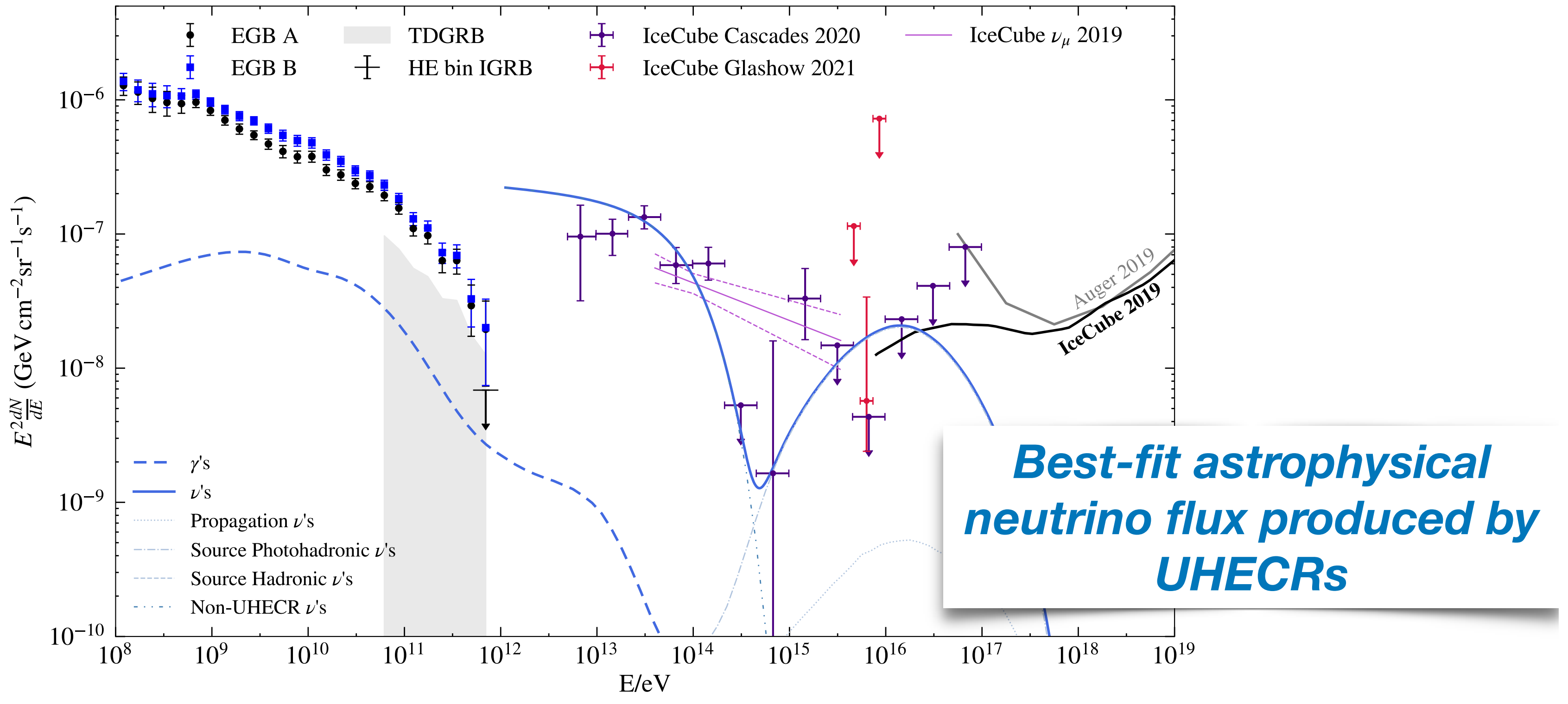


Models challenged by composition data
What can we learn from this?
Inferring non-thermal elemental abundances

Topics

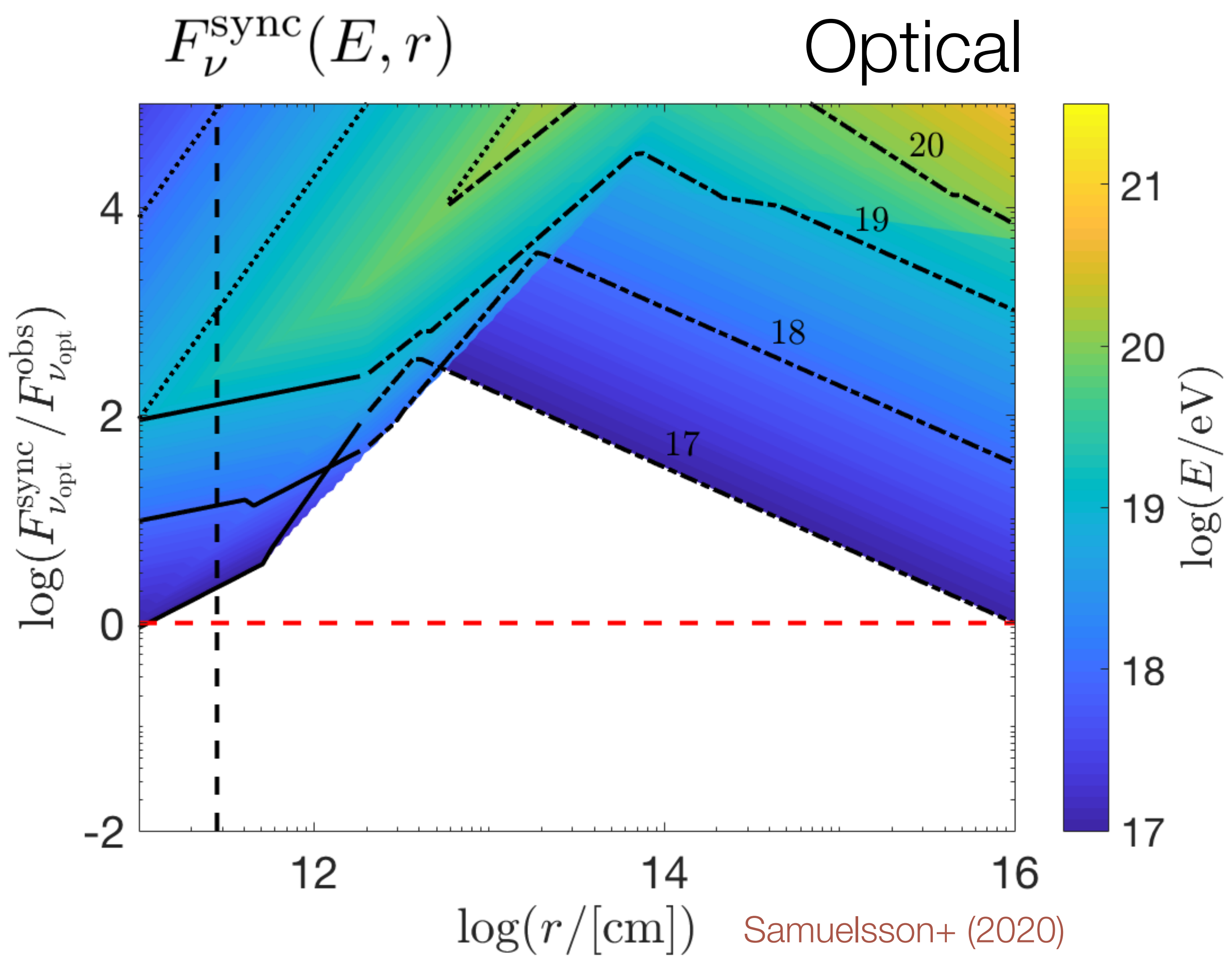
Cosmic-ray reservoirs





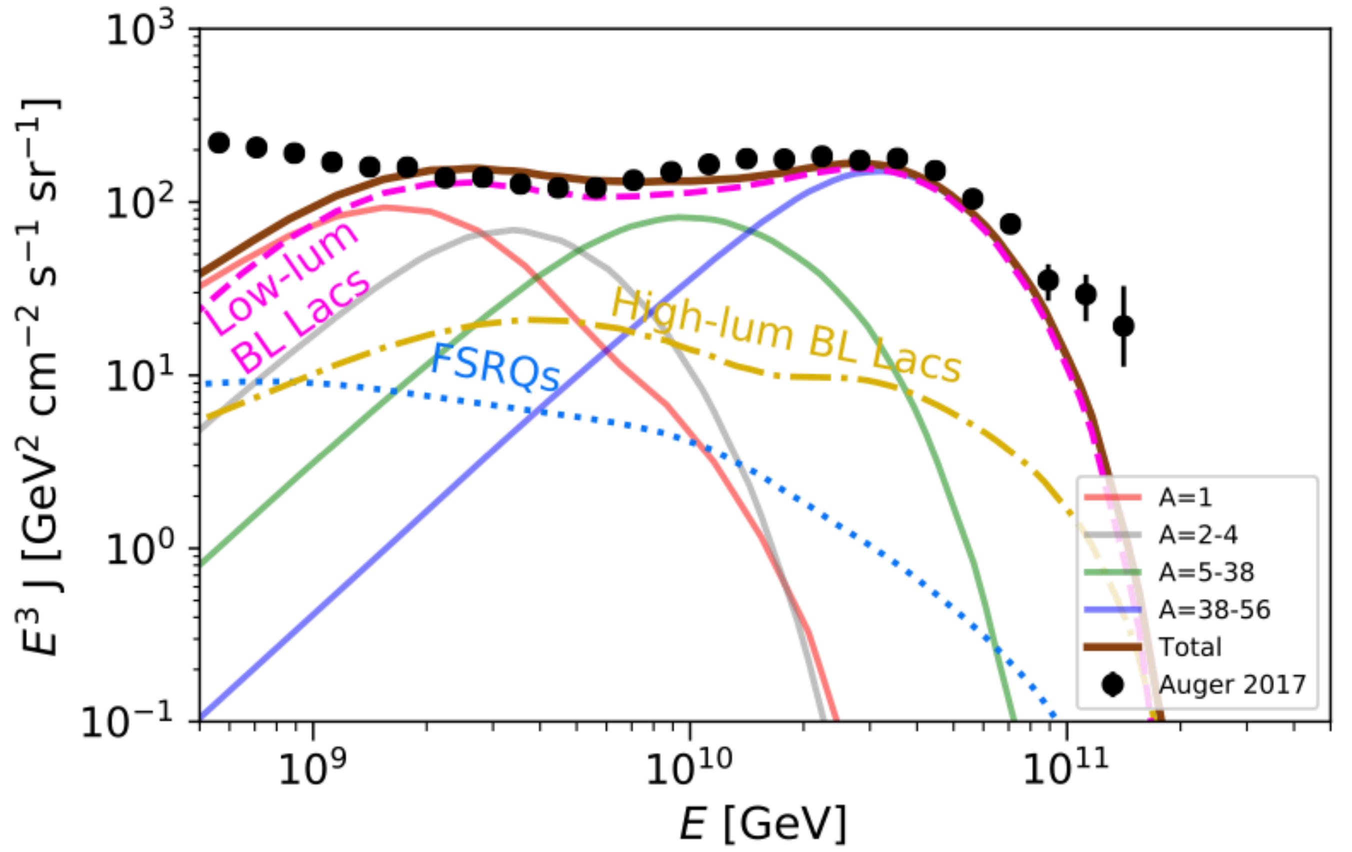
Is the hard neutrino index unavoidable?
Do the UHECR data challenge the reservoir model?
Sensitivity of combined fit?

Gamma-ray bursts



Consensus that LL GRBs cannot reach the highest energies?

Active Galactic Nuclei



Are we seeing hints of paucity of HL AGN or model assumptions? Role of LL jetted AGN/FR0s?Hints from TeV gamma-rays?

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UHECR arrival directions in the latest data from the original Auger and TA surface detectors and nearby galaxies

Executive Summary

Armando di Matteo[a], Luis Anchordoqui, Teresa Bister, Jonathan Biteau, Lorenzo Caccianiga, Rogério de Almeida, Olivier Deligny, Ugo Giaccari, Diego Harari, Jihyun Kim, Mikhail Kuznetsov, Ioana Mariș, Grigory Rubtsov, Peter Tinyakov, Sergey Troitsky and Federico Urban on behalf of the Pierre Auger[b] and Telescope Array[c] Collaborations

[a] INFN Sezione di Torino, Via Pietro Giuria 1, 10125 Torino, Italy

[b] Observatorio Pierre Auger, Av. San Martín Norte 304, 5613 Malargüe, Argentina

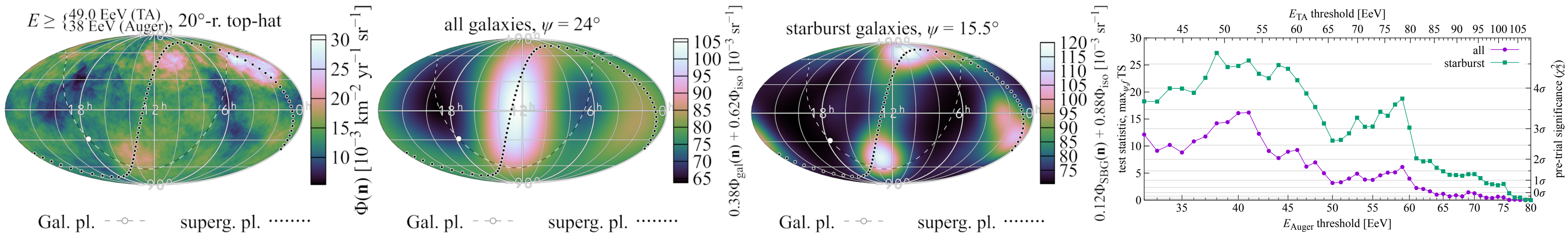
[c] Telescope Array Project, 201 James Fletcher Bldg, 115 S. 1400 East, Salt Lake City, UT 84112-0830, USA

What is this contribution about?

A search for medium-scale anisotropies in the distribution of UHECR arrival directions detected using the Pierre Auger Observatory and Telescope Array surface detector arrays

Why is it relevant/interesting?

The origins of UHECRs is still not known, but at the highest energies they are not expected to be able to freely travel for cosmological distances, so their sources must be in nearby galaxies and we would like to eventually identify them. Several hints have already been reported (Pierre Auger coll., *ApJL* **853** (2018) L29; Telescope Array coll., *ApJ* **899** (2020) 86).



What has been done?

We searched for correlations with a catalog of galaxies of all types (1 Mpc $\leq D <$ 250 Mpc) and one of starburst galaxies (1 Mpc $\leq D <$ 130 Mpc) using a log-likelihood-ratio test.

What is the result?

Correlation with starburst galaxies ($\psi = 15.5°^{+5.3°}_{-3.2°}$ scale, $f = 11.8\%^{+5.0\%}_{-3.1\%}$ signal fraction; 4.2σ post-trial significance) and with all galaxies ($\psi = 24°^{+13°}_{-8°}$, $f = 38\%^{+28\%}_{-14\%}$; 2.9σ post-trial)

A combined fit of energy spectrum, shower depth distribution and arrival directions to constrain astrophysical models of UHECR sources

Executive Summary

PIERRE AUGER OBSERVATORY

Teresa Bister[a] for the Pierre Auger Collaboration[b]

[a] Physics Institute IIIA, RWTH Aachen University, Otto-Blumenthal-Str., 52074 Aachen, Germany

[b] Observatorio Pierre Auger, Av. San Martín Norte 304, 5613 Malargüe, Argentina

What is this contribution about?

We present a method to describe the UHECR **energy spectrum, shower depth distribution and arrival directions** all in one model.
For that, we use **catalogs of starburst galaxies (SBGs)** & **active galactic nuclei (AGNs)**.

Why is it relevant/interesting?

- **First** presentation of a combined fit using all three UHECR observables as complementary information
- Can determine source emission spectrum & composition, energy-dependent **signal fraction** & **size of the rigidity-dependent turbulent magnetic field smearing**

What has been done?

Construction of a universe model, presentation of benchmark simulation resembling Auger data, likelihood fit with MCMC sampler, parameter estimation, significance determination

What is the result?

- Sensitivity of the fit to **discriminate between the different source catalogs** increases significantly compared to an analysis using only the arrival directions *(on benchmark simulation)*
- Significance driven by **energy-dependent arrival directions**
  → arrival patterns depend on source catalog, injection spectrum & composition, propagation effects

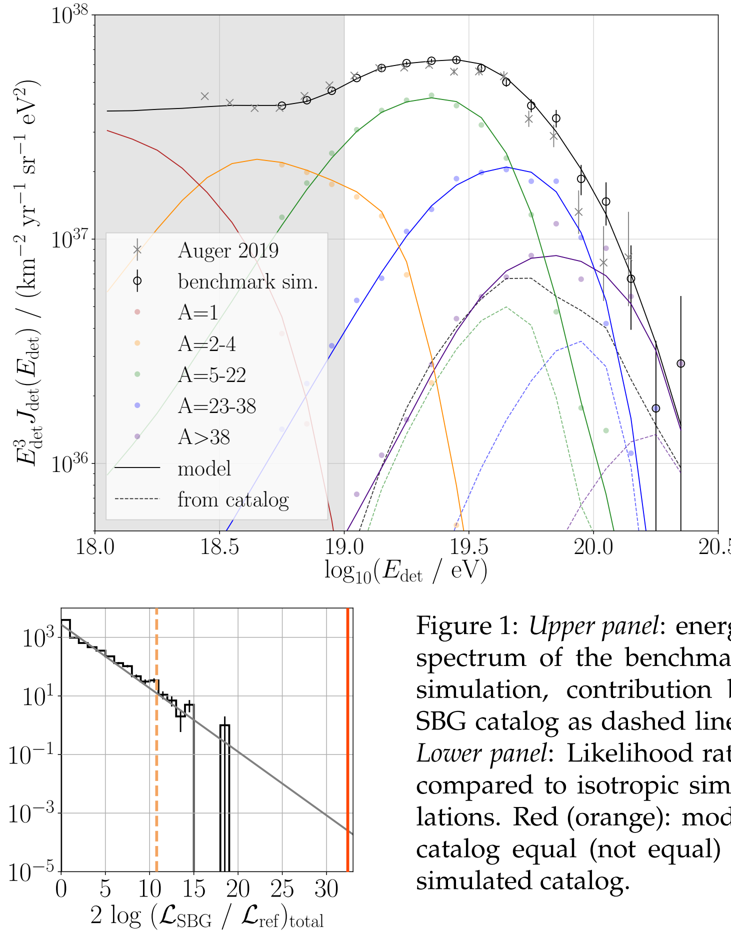


Figure 1: *Upper panel*: energy spectrum of the benchmark simulation, contribution by SBG catalog as dashed lines. *Lower panel*: Likelihood ratio compared to isotropic simulations. Red (orange): model catalog equal (not equal) to simulated catalog.

Features of a single source describing the very end of the energy spectrum of cosmic rays

Alena Bakalová, Jakub Vícha, Petr Trávníček

ICRC 2021, June 13th Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic

FZU Institute of Physics of the Czech Academy of Sciences

What is this contribution about?

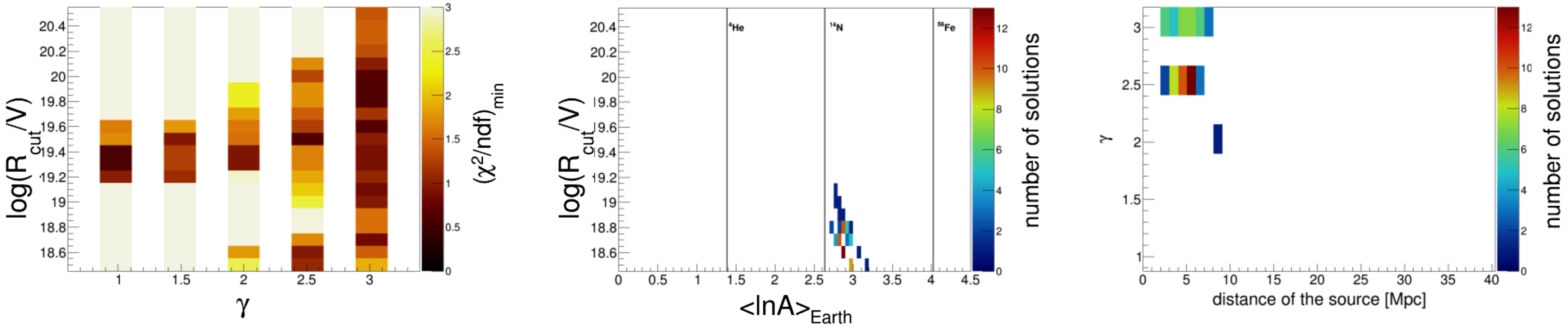
- We investigate if the energy spectrum of cosmic rays (CRs) measured by the Pierre Auger Observatory above $\log_{10}(E/V) = 19.5$ can be explained by a single dominant source.

Why is it relevant / interesting?

- The Pierre Auger Observatory and Telescope Array observe different suppression of the flux of CRs at the highest energies and this might be explained by the ability to observe different sources in the Northern and Southern hemispheres.

What have we done?

- We investigate different characteristics of sources and compare the energy spectrum and mass composition of CRs after their propagation simulated in CRPropa 3 with available measurements.



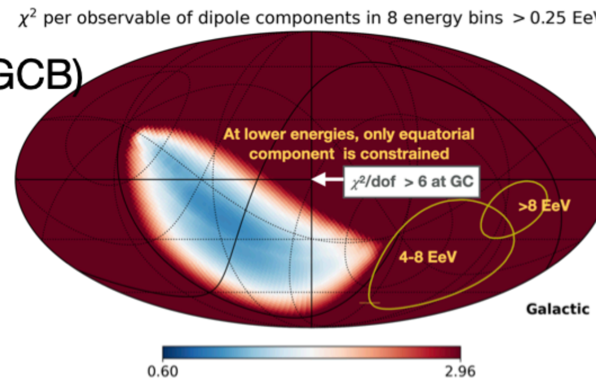
What is the result?

- A source distant within 10 Mpc from the Earth with spectral index $\gamma \gtrsim 2.0$ and $\log_{10}(R_{\mathrm{cut}}/V) < 19.2$ can produce energy spectrum and mass composition on the Earth compatible with Auger measurements.

Transient Source for the Highest Energy Galactic CRs

Glennys Farrar and Chen Ding, NYU

CONCLUSIONS



- We have measured the dipole anisotropy of the highest energy Galactic CRs (GCB)
  - < Rigidity > ≈ 0.15 EV, A up to ≈ 15
  - Dipole anisotropy **α** ≈ 0.05, towards B ≈ 0° (from theory), L ≈ 70° ±~15° (from data)
    - **dipole toward GC excluded at > 6 σ**
  - **Dipole anisotropy not toward GC:**
    - Galactic wind termination shock disfavored
    - ***favors transient source***
- Observed GCB Anisotropy strength and direction ➜ SNR G65.3+5.7 / PSR1931+30 (?)
  - 0.8 kpc away, 20+2.4 kyr ago excellent agreement with **α** (≈ r/2ct) ≈ 0.05
  - ≲ 10^{45} erg in CRs with E>100 PeV energy budget very comfortable (~10^{54} erg available)
- Proposed system:
  - core-collapse SN in massive binary ➜ converging shock flow: SN ejecta-Wolf-Rayet wind
  - population statistics: O(1) probability of seeing anisotropy and flux level observed

X

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Cosmographic model of the astroparticle skies

400,000 galaxies within 1 Gyr to constrain the astroparticle skies (arXiv:2105.11345, Biteau+ 2021 ApJS in press)

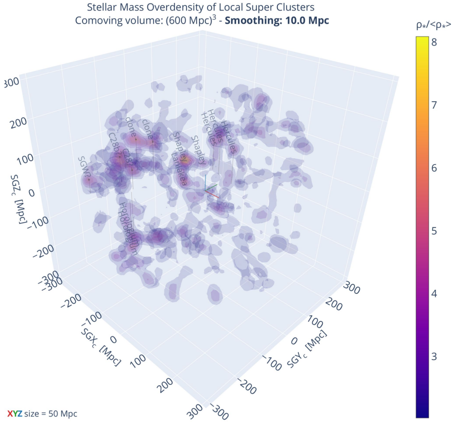
Expands on near-infrared catalogs proposed gravitational-wave (GW) community: **improved distance & completeness estimates**

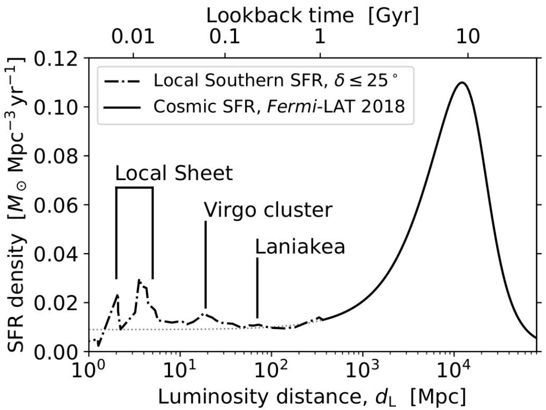
Provides **stellar mass and star formation rate (SFR) estimate for each galaxy**, with resolution & bias X-checked against deep fields

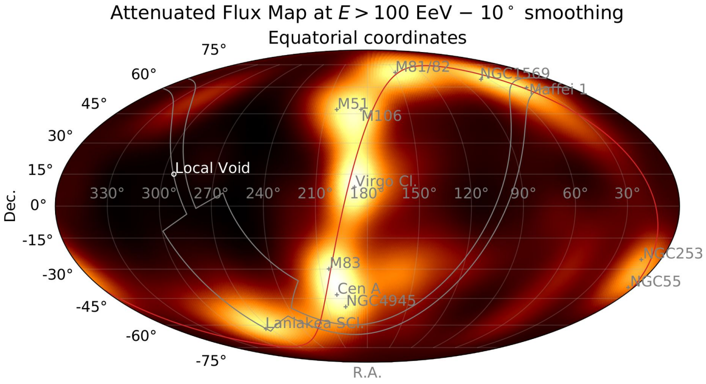
Of interest to ν, ɣ-ray, GW and UHECR wide field-of-view searches: latter explored in this ICRC contribution

Local overdensity impact on **UHECR spectrum, composition, and flux maps**, in a transient UHECR scenario (production ∝ SFR)

Constraints on transient rate: **promising match with UHECR data**. Skymap discrepancies: likely **confinement on cluster scales.**







Constraining the origin of UHECRs and astrophysical neutrinos

Executive Summary

Marco Muzio* (NYU), Glennys Farrar (NYU), Michael Unger (KIT)

NYU

Karlsruher Institut für Technologie

What is the contribution about?

A multimessenger analysis into properties of ultrahigh energy cosmic ray (UHECR) sources, their ability to explain astrophysical neutrinos, & to infer preferred candidate source types.

Why is it relevant/interesting?

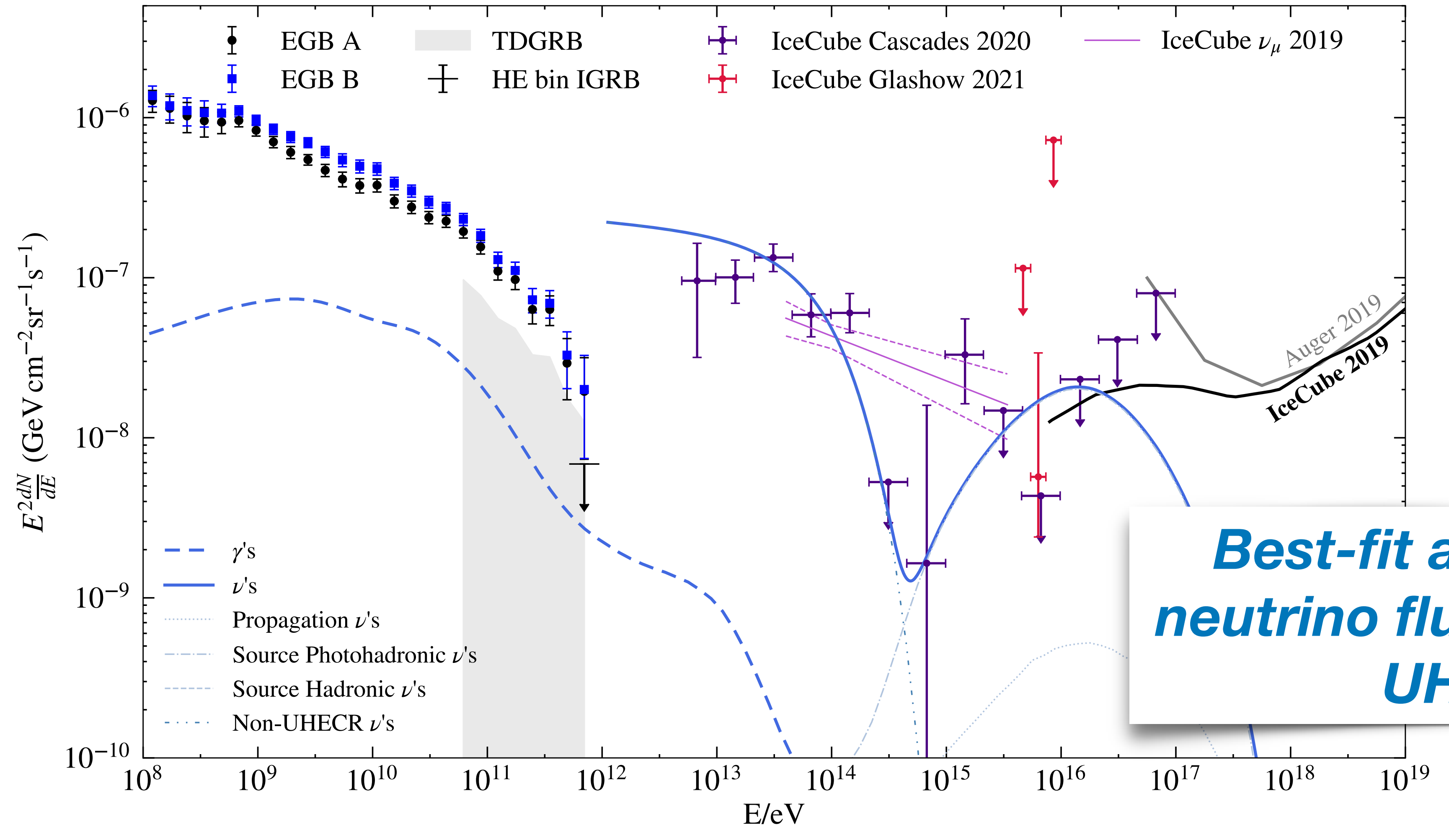
The origin of UHECRs is a longstanding problem but here we make new progress, while also probing astrophysical & particle physics processes.

What has been done?

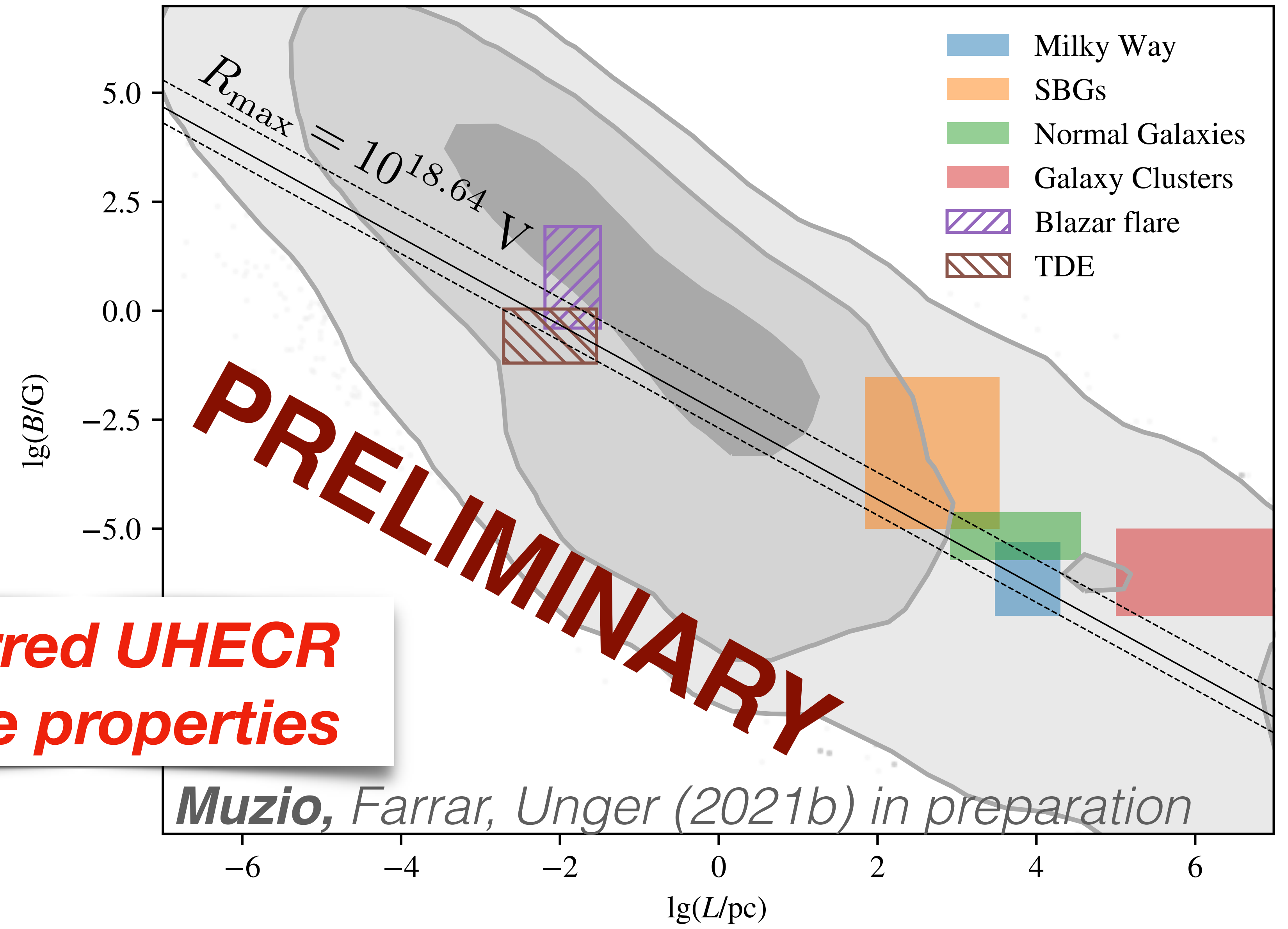
We have conducted a fully consistent multimessenger analysis using a newly elaborated phenomenological UHECR source model to infer constraints and determine preferred astrophysical properties with an MCMC.

What is the result?

- UHECR data can be explained by both gas- and photon-dominated source environments, but **gas-dominated sources are in tension with neutrino bounds**
- **~10 PeV neutrinos will determine the viability of** conventional acceleration mechanisms producing soft spectral indices, like **diffusive shock acceleration**
- Only astrophysical neutrinos above ~1 PeV can be explained by UHECR sources
- Data prefers small (< 10 pc) sources with strong (>1 mG) magnetic fields, similar to TDEs & AGN



Muzio, *Farrar, Unger (2021a) in preparation*

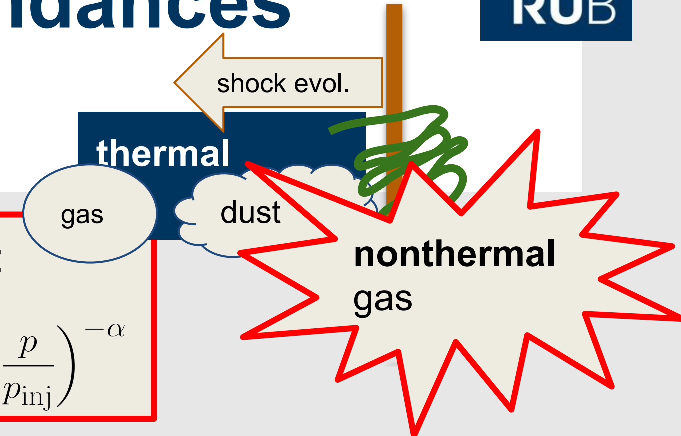


Muzio, *Farrar, Unger (2021b) in preparation*

RUHR-UNIVERSITÄT BOCHUM

Thermal-to-nonthermal element abundances in different Galactic environments

Björn Eichmann | Jörg P. Rachen

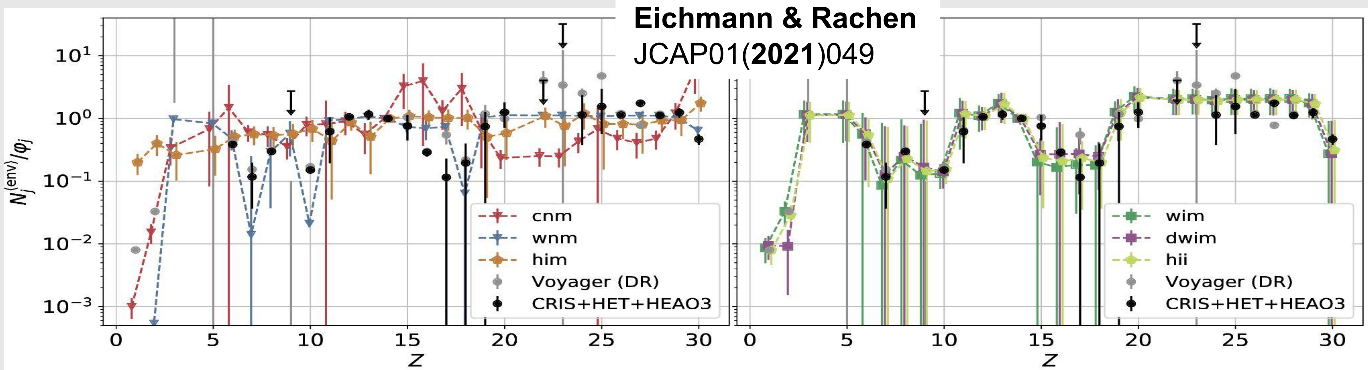


Overall differential (LE)CR number at the end (t_f) of the SNR evolution:

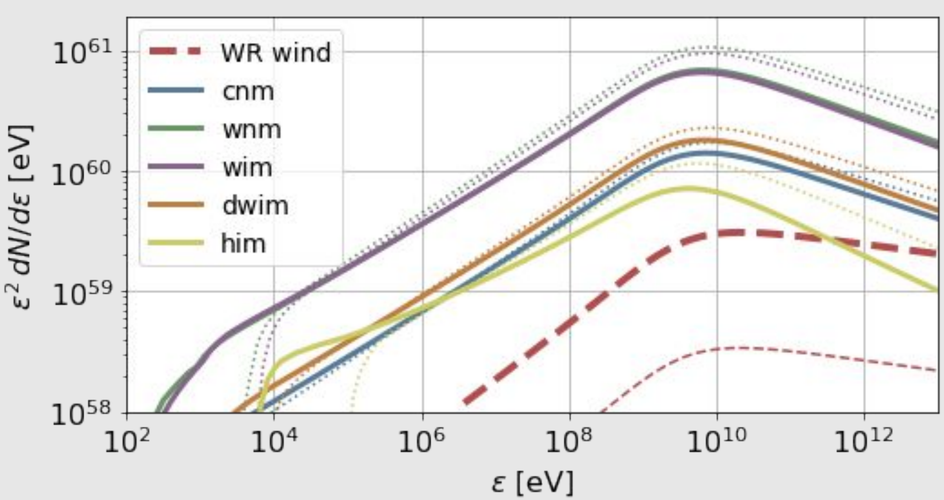
$$N(p,t_\mathrm{f}) = \int_0^{t_\mathrm{f}} dt\; n(p,t)\, A_\mathrm{sh}(t)\, \beta_\mathrm{sh}(t) c\, \Lambda_\mathrm{ad}(t,t_\mathrm{f}) \quad \text{with} \quad n(p,t) = \frac{(\alpha-1)\,\tilde{n}_j^{\langle\mathrm{env}\rangle}}{p_\mathrm{inj}} \left(\frac{p}{p_\mathrm{inj}}\right)^{-\alpha}$$

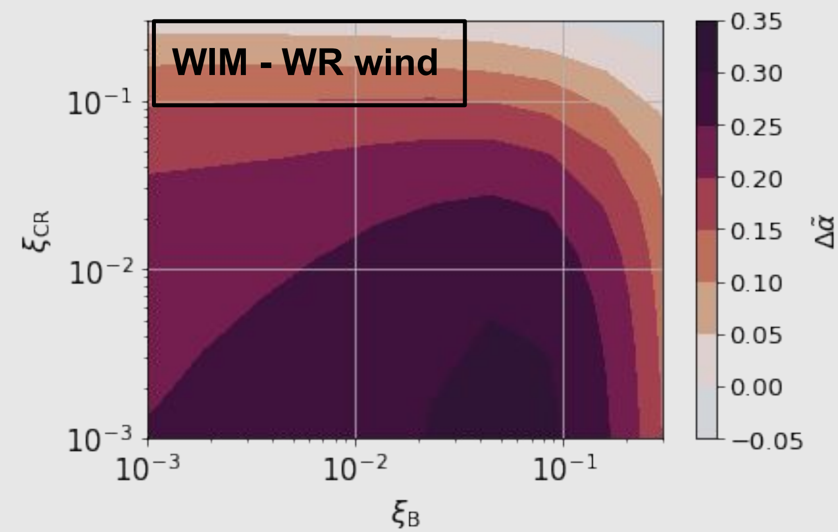
❖ Comparing different uniform ISM phases *at the same kinetic energy per momentum*:

Eichmann & Rachen
JCAP01(**2021**)049



❖ Comparing *the spectral behavior* of uniform ISM and WR wind environments:





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UHECR from High- and Low-Luminosity GRBs

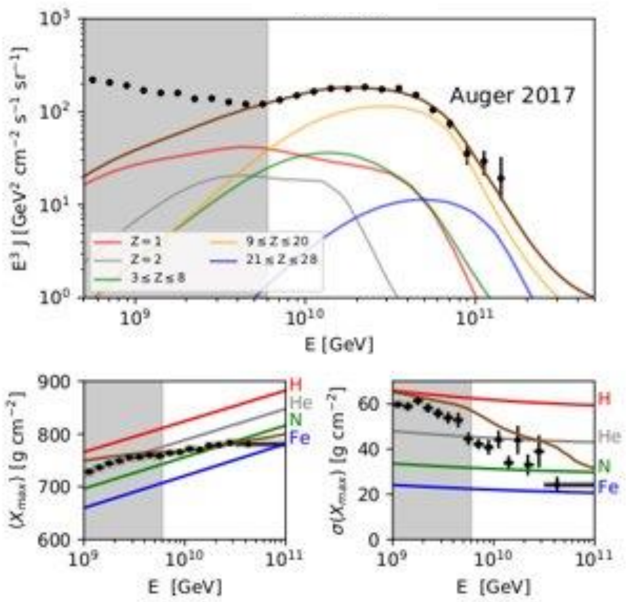
A. Rudolph, J. Heinze, D. Biehl, D. Boncioli, A. Fedynitch, Z. Bosnjak, I. Sadeh, A. Palladino, W. Winter

Can GRBs still be UHECR sources, despite neutrino limits (IceCube)?
Two scenarios within a multi-collision internal shock model:

(1) Fit to UHECR spectrum and $\langle X_{max} \rangle$: parameter scan over engine realisations

- *Fit parameters:* injection composition & baryonic loading
- *Results:*
  - broad fit range
  - large engine kinetic energy required
  - neutrinos within sensitivity of IceCube Gen2
  - stochasticity of engine /light curve limited by $\sigma(X_{max})$

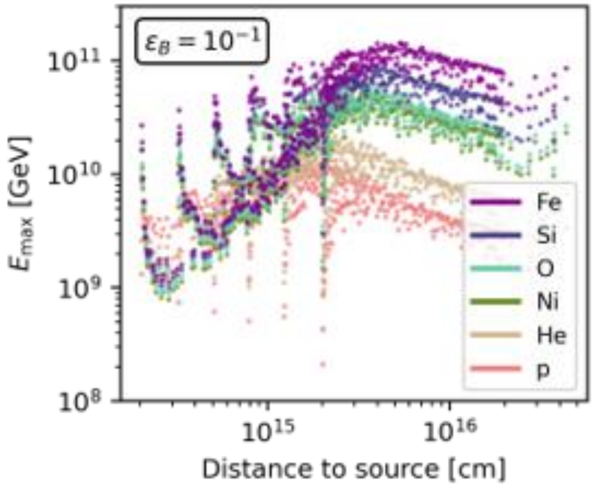
Best fit



(2) LL-GRBs as potential sources of VHE radiation/ UHECR

- *Methods:* Leptonic radiation modeling for prototype GRBs with properties similar to real events.
  Vary magnetic field via ε_B
  Calculate maximal cosmic-ray energies
- *Results:*
  - low ε_B: high VHE fluxes
  - high ε_B: high maximal cosmic-ray energies
  - decoupling of particle production regions (gamma-rays, UHECR)

GRB 100316D- like GRB



MNRAS 498 (2020) arxiv 2006.1430

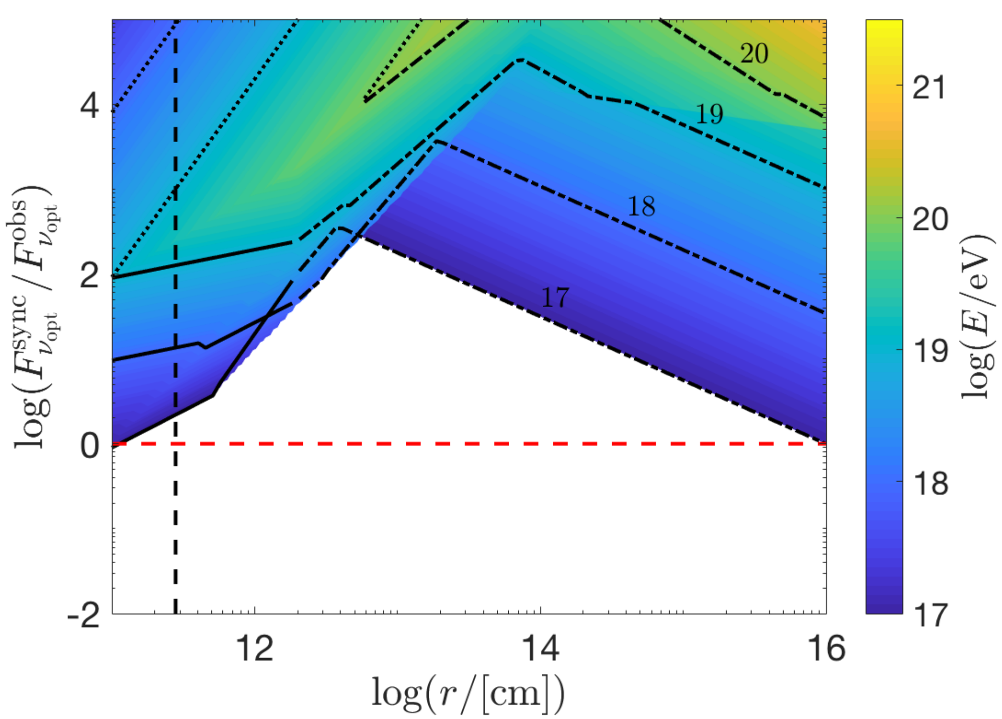
Problematic connection between UHECRs and LLGRBs

Filip Samuelsson, Damien Bégué, Felix Ryde, Asaf Pe'er, Kohta Murase

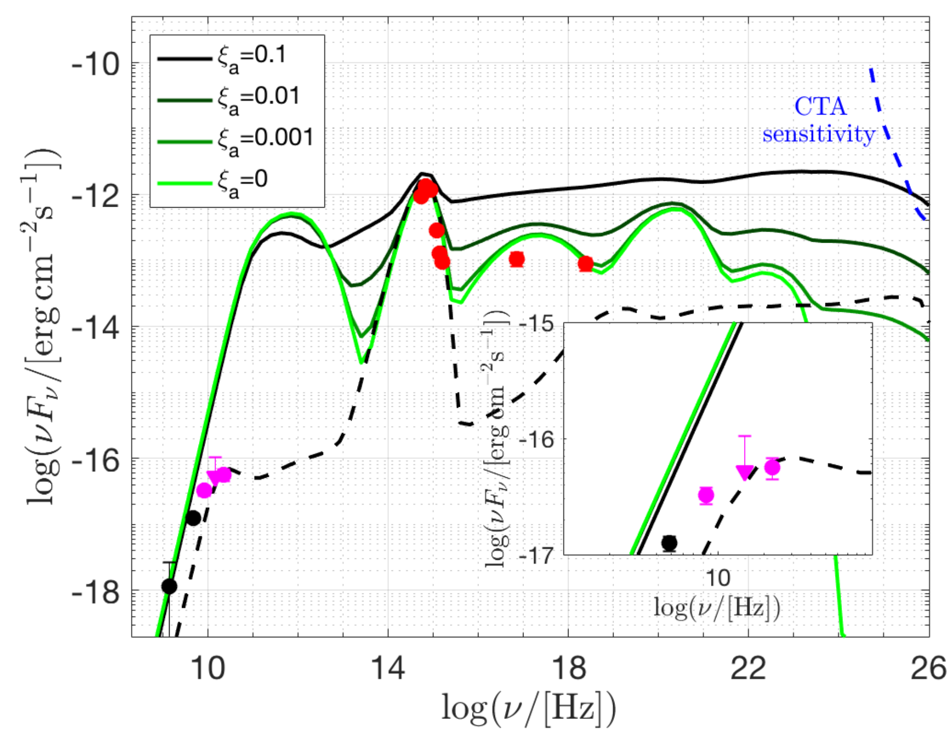
Samuelsson et al. (2019) ApJ, 876:93, Samuelsson et al. (2020) ApJ, 902:148

Idea: Use the synchrotron emission from the primary electrons as an additional messenger and compare the emission with observations of GRB 060218.

Results prompt phase:
The high magnetic field required for UHECR acceleration lead to immense optical emission from the electrons



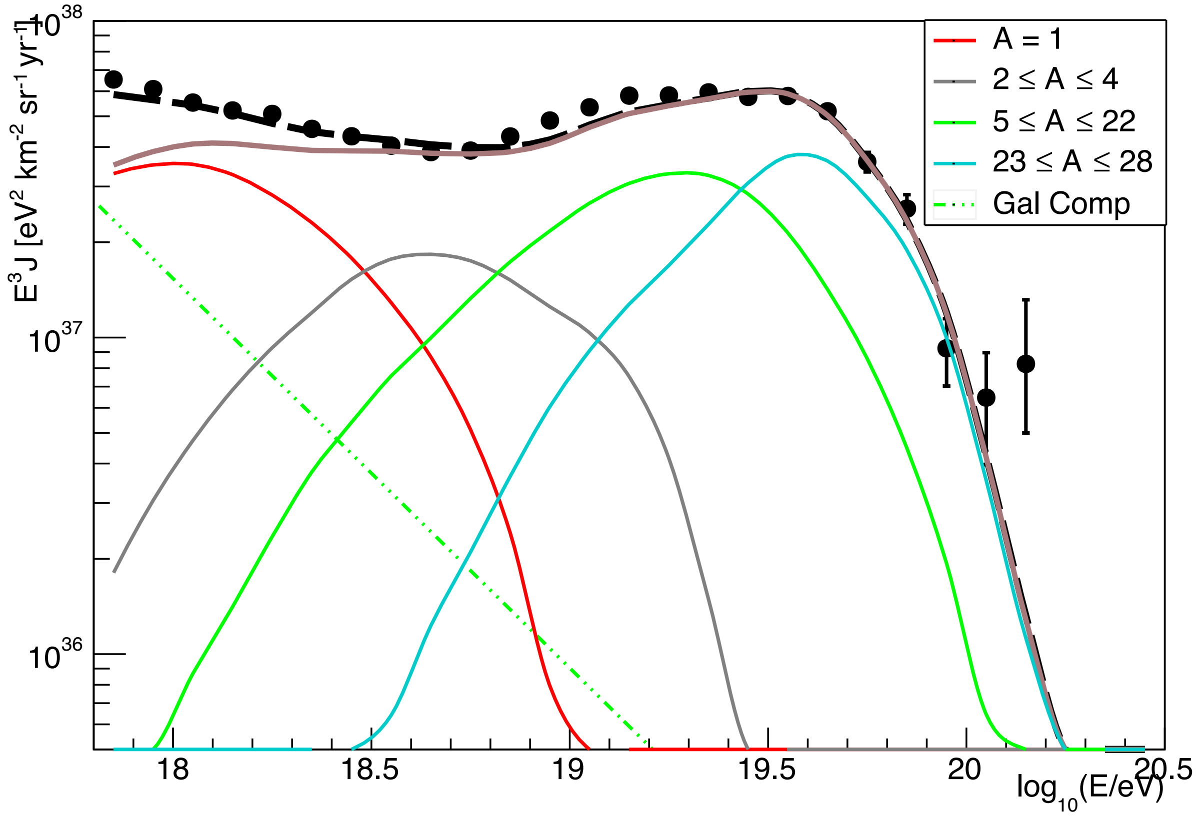
Results afterglow phase:
The high energy budget required for observed UHECR flux lead to immense radio emission from the electrons

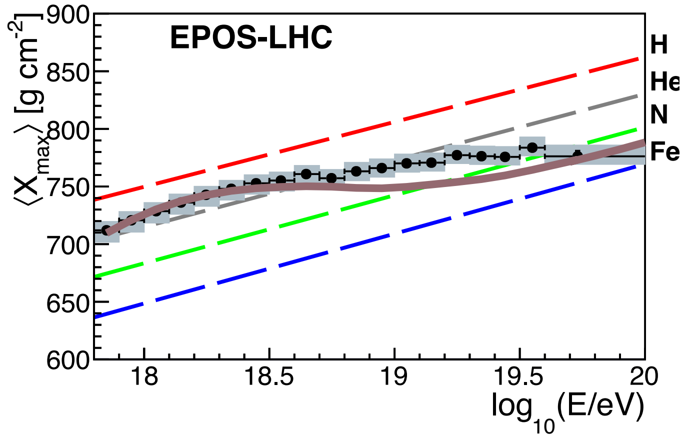


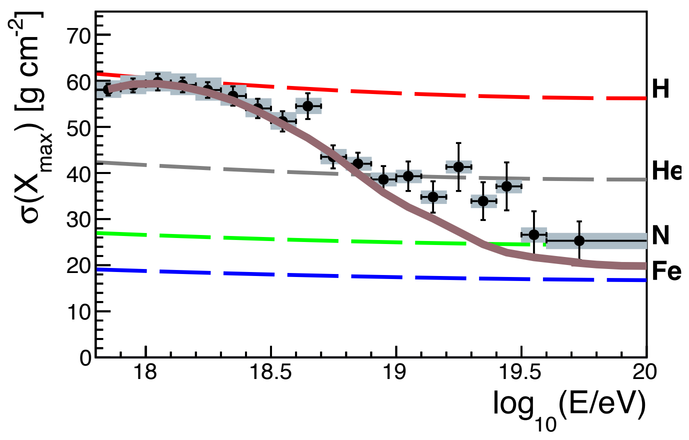
Conclusions: Emission from electrons is a powerful additional tool in UHECR multi-messenger studies. Mildly relativistic outflows of LLGRBs unlikely to be the main sources of UHECRs.

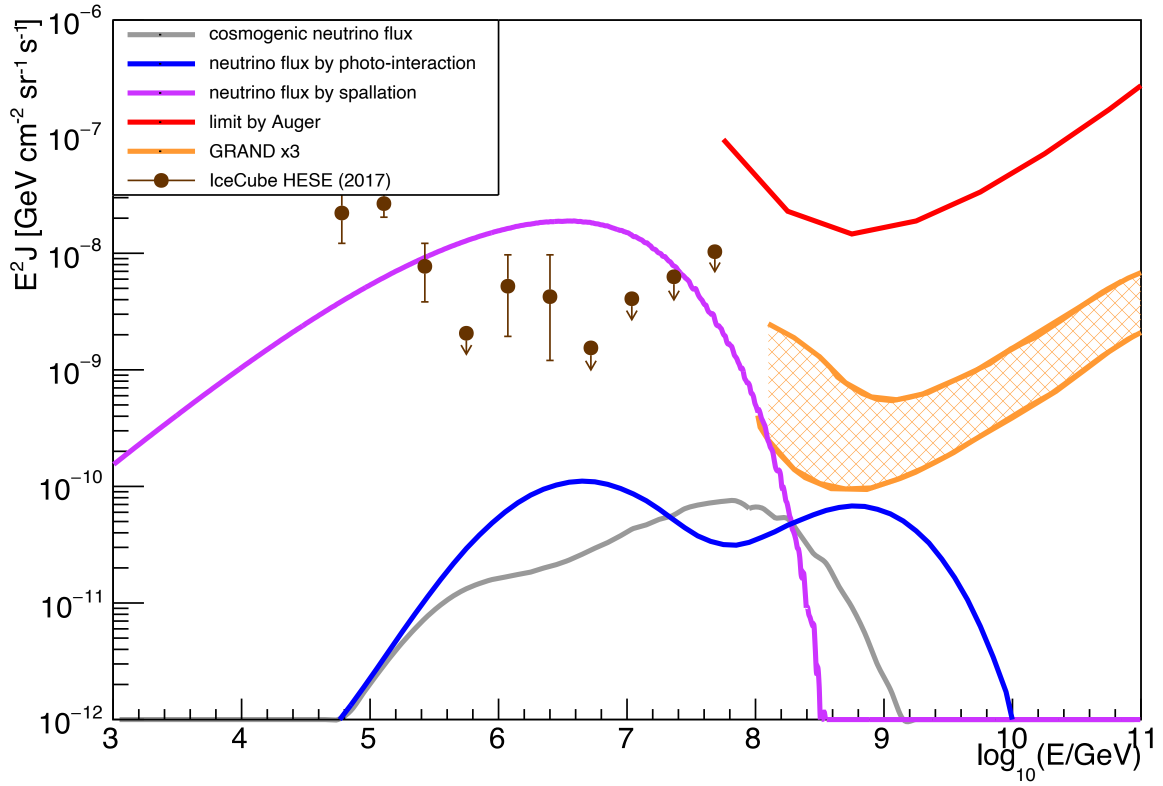
Starburst Galaxies as possible sources of UHECRs and neutrinos

- Study of the UHECRs interactions in the environment surrounding the sources, applied to Starburst Galaxies (SBG).
- Connection between the features of the UHECR spectrum and composition at Earth to the SBG parameters.
- Using a SBG prototype, a diffuse flux from sources uniformly distributed is propagated and then compared to the measurements at Earth.
- Outcomes in cosmic ray and neutrino fluxes can constrain the parameter space.









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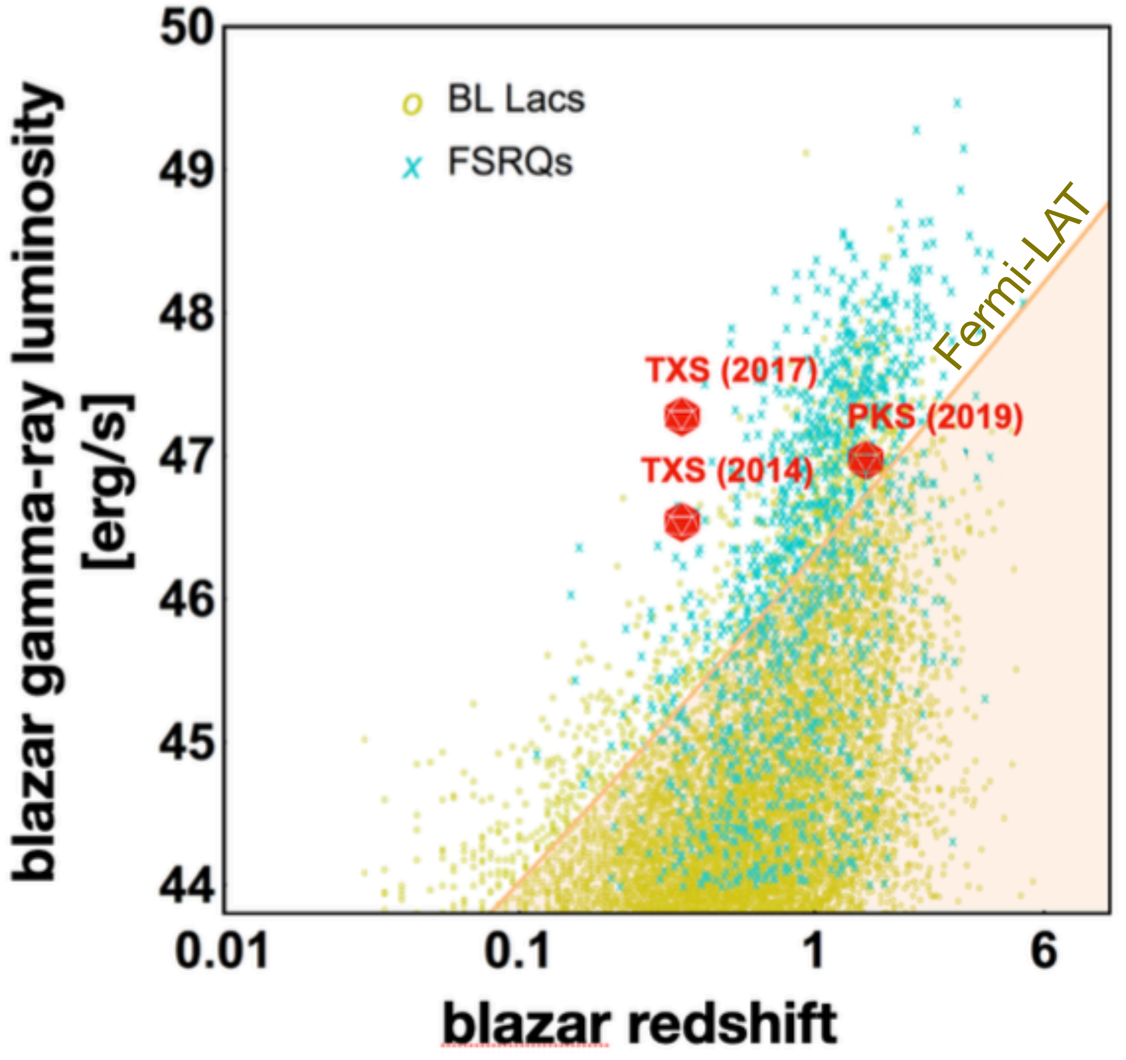
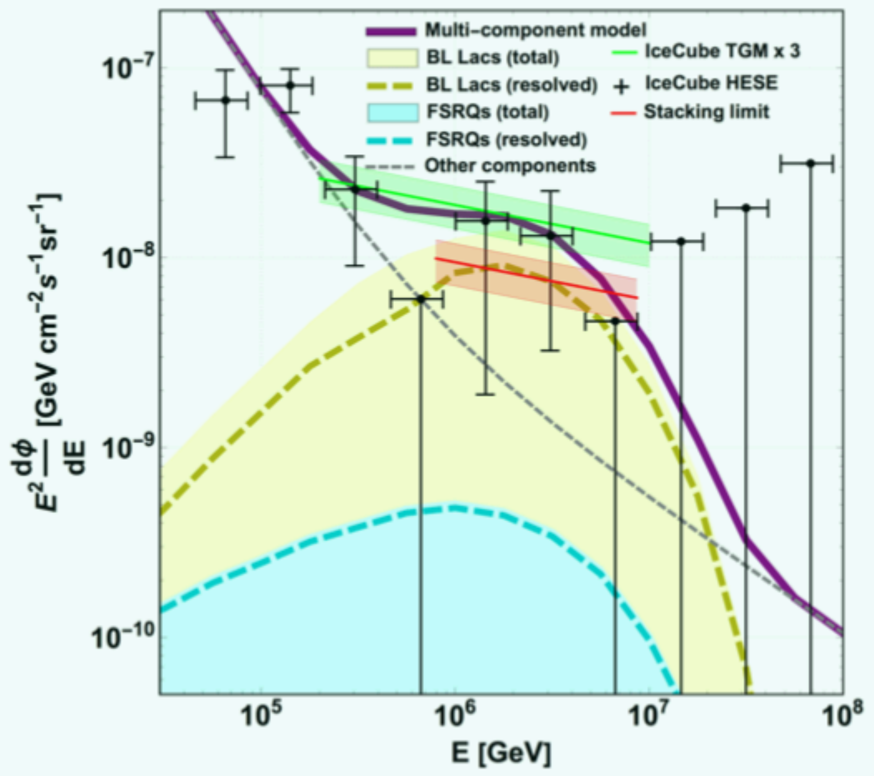
- Farrar (Transient source of highest energy Galactic CRs) 2”
- Discussion 12”
- **12:25 General tools and multimessenger constraints** **15”**
- Biteau (source catalogue/UHECR arrival direction application) 2”
- Muzio (fit to multimessenger data) 2”
- Eichmann(thermal to non-thermal elemental abundances) 2”
- Discussion 9”
- **12:40 Gamma-ray Bursts and Starburst Galaxies** **15”**
- Rudolph (GRB/LL GRB models and UHECR combined fit) 2”
- Samuelsson (GRB/LL GRB maximum UHECR energy) 2”
- Condorelli (starburst galaxy combined fit) 2”
- Discussion 9”
- **12:55 Active Galactic Nuclei** **20”**
- Rodrigues (jetted AGN combined fit and blazar modelling) 2”
- Merten (FR0 galaxies) 2”
- Das (UHECRs from TeV gamma-ray emitting BL Lacs) 2”
- Morejon (Cen A as source of UHECRs) 2”
- Discussion 12”
- **General Discussion/Closing Remarks** **15”**

AGN as neutrino sources in the PeV and EeV regimes

Xavier Rodrigues

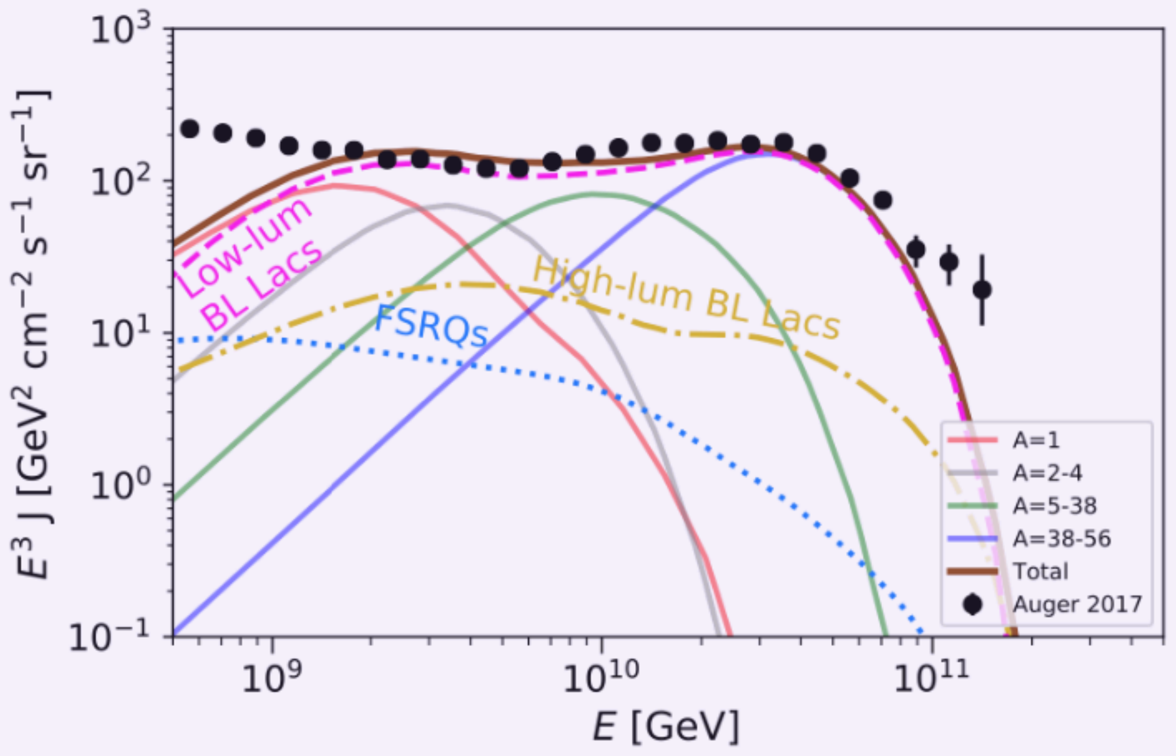


Scenario 1: AGN accelerate CRs up to max 10 PeV

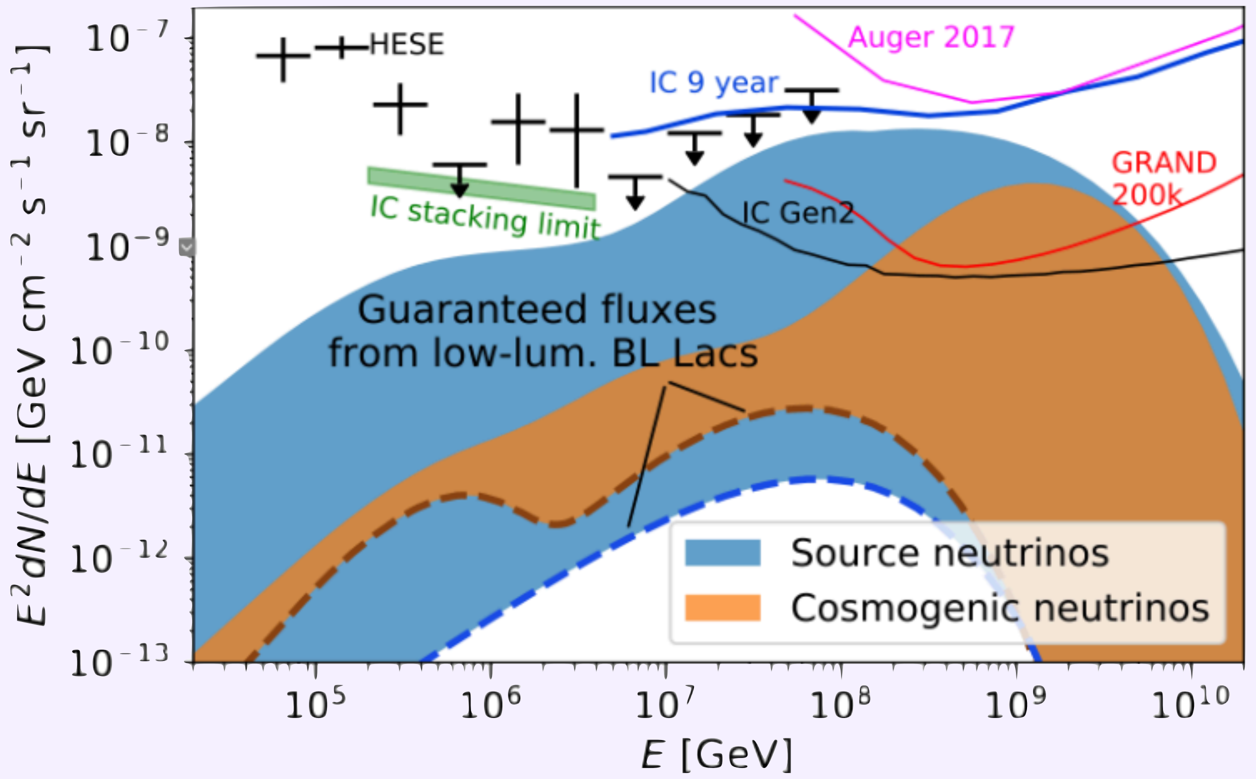


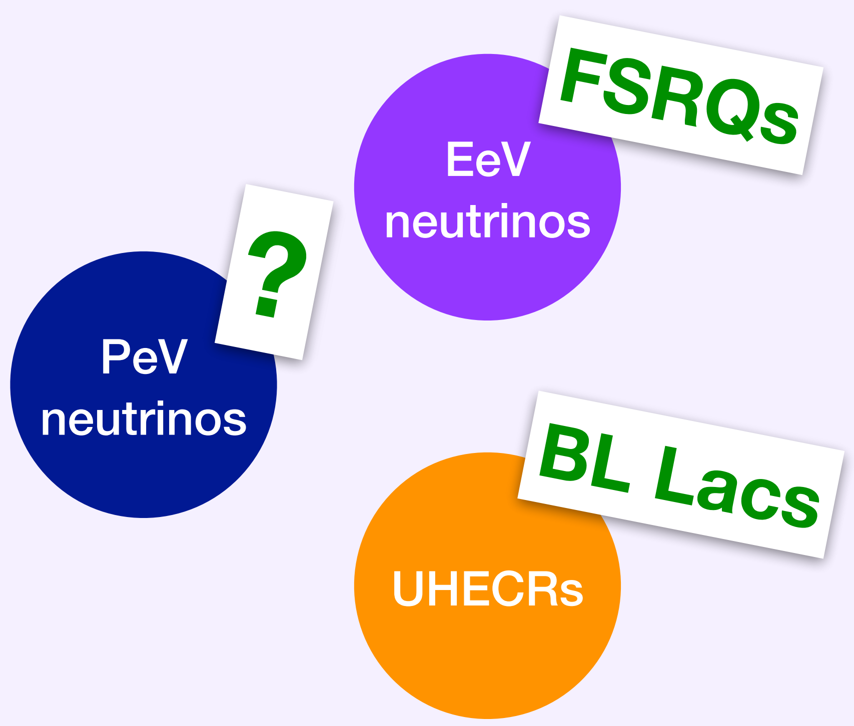
Palladino, XR, Gao & Winter, ApJ 871 (2019)

Scenario 2: AGN accelerate CRs up to ~EeV



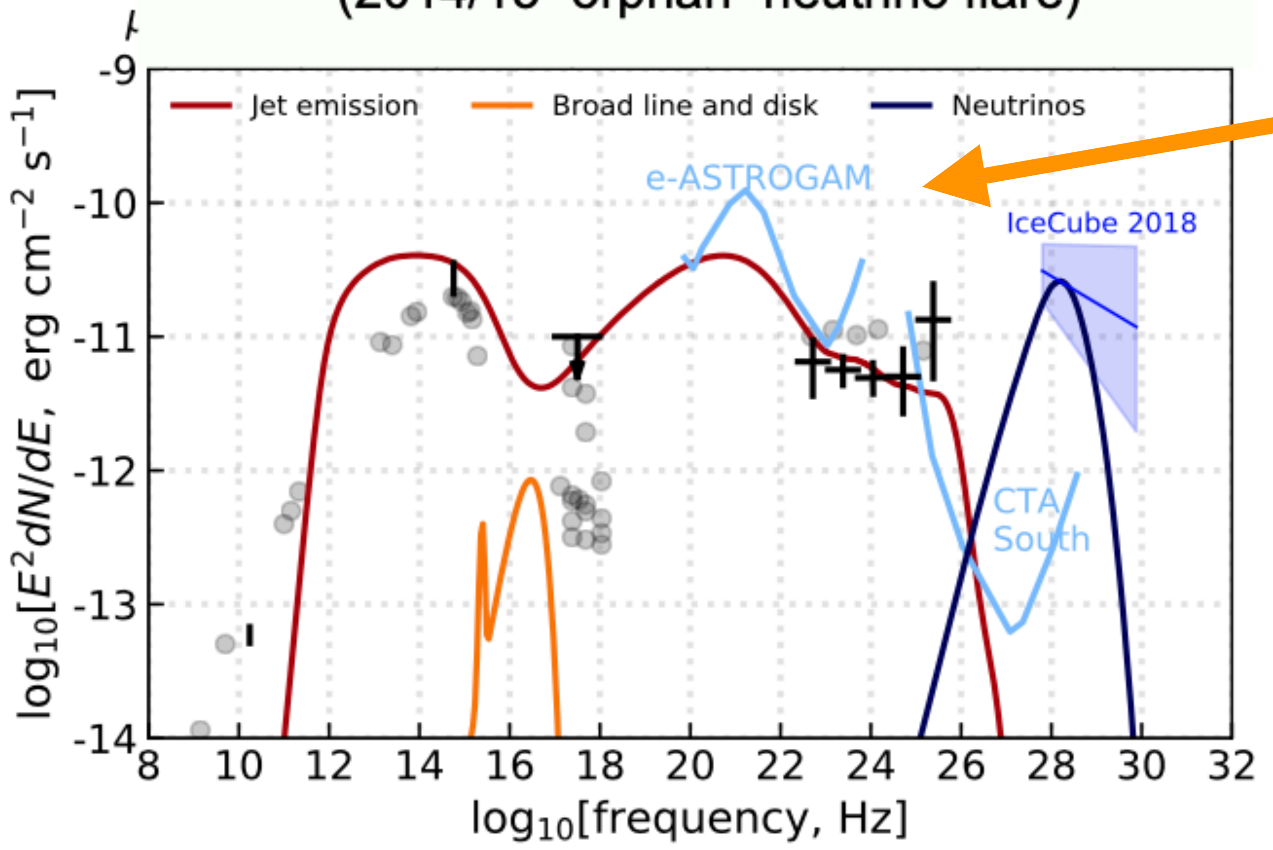
XR, Heinze, Palladino, van Vliet, Winter, PRL 126 (2021)





Dedicated modelling shows us that each source is a source

Blazar TXS 0506+056
(2014/15 “orphan” neutrino flare)

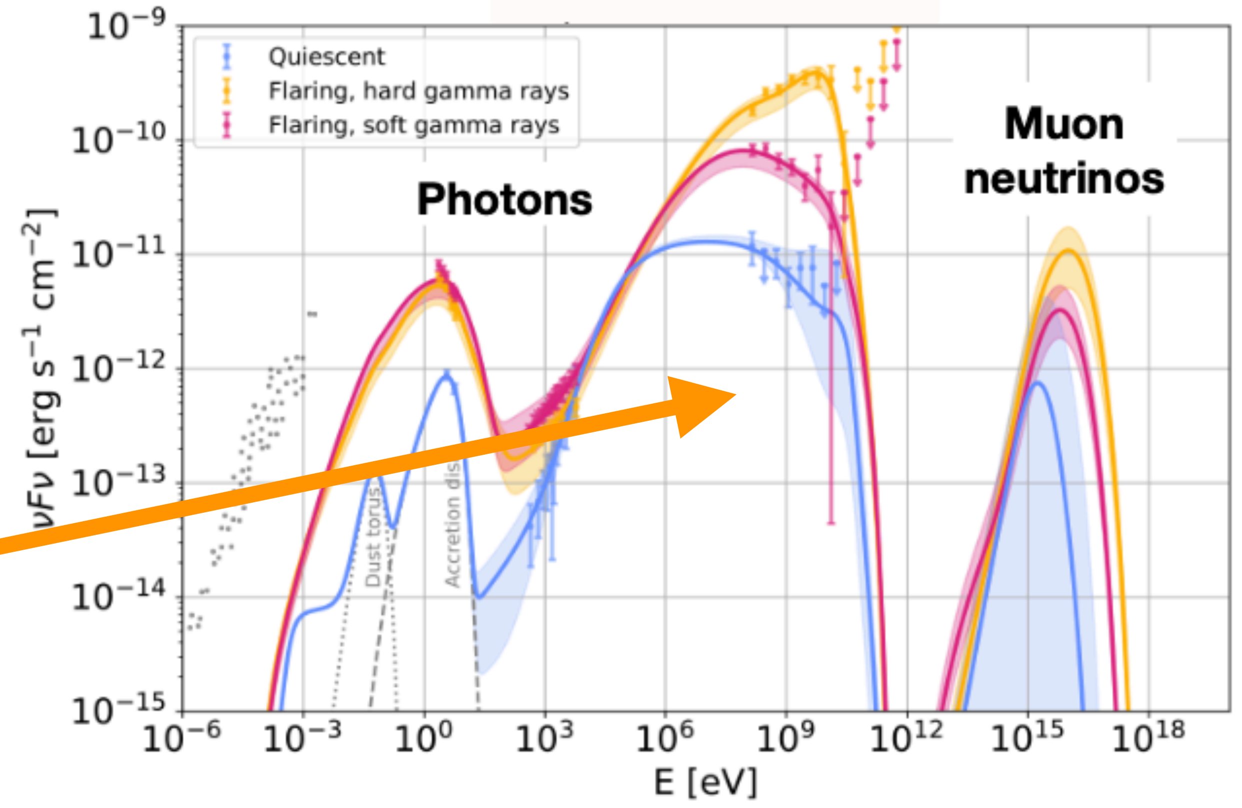


XR, Gao, Fedynitch, Palladino, Winter, ApJ L874 (2019)

Low gamma-ray fluxes; MeV bump

Gammas ~ neutrinos

Blazar PKS 1502+106
(coincident with event IC-170922)



XR, Garrappa, Gao, Paliya, Franckowiak & Winter, ApJ 912 (2021)

Merten et al. *Astropart. Phys.* (2021) **128** 102564

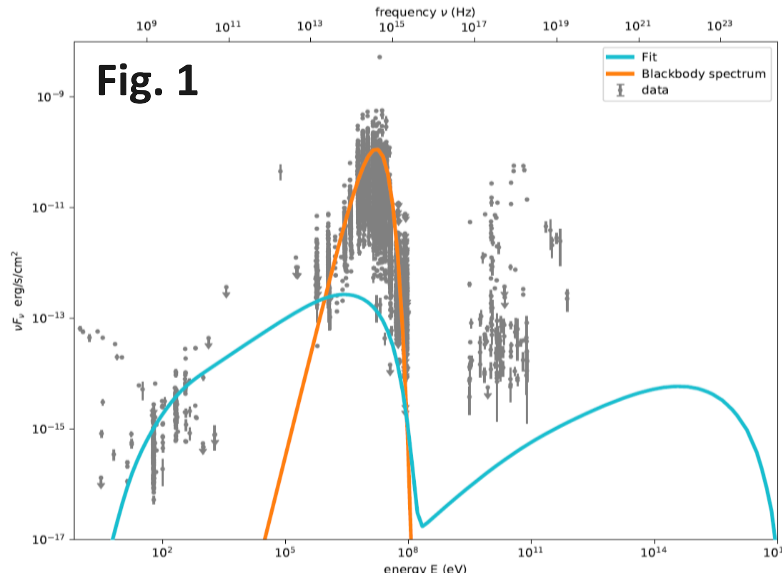
UHECRs from FR-0 radio galaxies

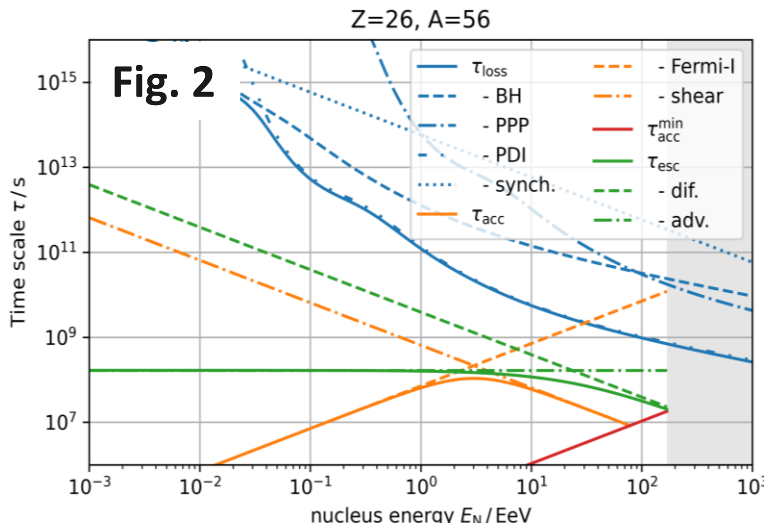
FR-0s are **less luminous** but **more numerous** than known accelerators FR-1/2 galaxies → good candidate class for **isotropic UHECR flux contribution**

Can FR-0s accelerate up to the highest energies?

- Estimate **source environment** parameters: photon target field (Fig. 1), magn. field, size, Doppler factor
- Calculate **relevant time scales** (Fig. 2): **acceleration** (Fermi-1 and gradual shear), **escape** (diffusion and advection) **losses** (nuclei-photons)
- Derive **maximal energies**

$\langle \log(R/\mathrm{V}) \rangle$	Fermi-1	Fermi-1+ grad. shear
Bohm Dif.	16.91±0.03	18.82±0.03
Kolmog. Dif.	14.08±0.02	18.82±0.03





UHECR Interactions As The Origin of Very High-Energy γ-rays From BL Lacs

Saikat Das[a] · Nayantara Gupta[a] · Soebur Razzaque[b]

[a] Astronomy & Astrophysics Group, Raman Research Institute, Bangalore 560080, India
[b] Centre for Astro-Particle Physics (CAPP) and Department of Physics, University of Johannesburg, P.O. Box 524, Auckland Park 2006, South Africa

1. Motivation:

- **Unattenuated TeV γ-ray spectrum** in some blazars is inconsistent with the $\gamma\gamma$ absorption inside/outside the relativistic jet
- In addition, the efficiency of **IC emission is suppressed** at such high energies, leading to a decrease in flux at higher energies

2. Model:

- Accelerated inside the blazar jets, **UHECRs (E $\gtrsim 10^{17}$ eV) can escape from HBLs** and interact with the cosmic background photons
- The resultant $e^{\pm}$ and γ-rays can induce electromagnetic cascade resulting in a **photon spectrum peaking at ~ 1 TeV energies**

3. Timescales & EGMF:

- We find that the **energy loss rate is lower than escape rate** for protons via $p\gamma$ processes inside the jet up to $E_{p,\max} = 10^{19}$ eV.
- A **random turbulent EGMF with $B_{\rm rms} \approx 10^{-5}$ nG** is taken to constrain the survival fraction of UHECRs along the observer's line of sight.

4. Our Method:

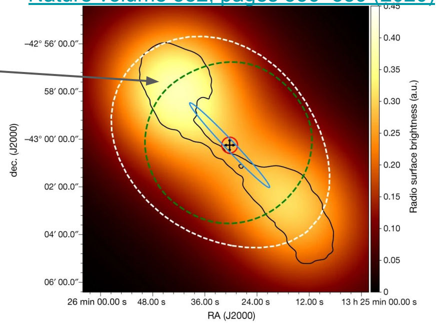
- **One-zone leptonic model** is used to calculate the source parameters (B, Γ, δ, R, $E_{e,\max}$) from fitting the synchrotron spectrum
- Higher energy peak is explained using a combination of SSC and **line-of-sight UHECR interactions**

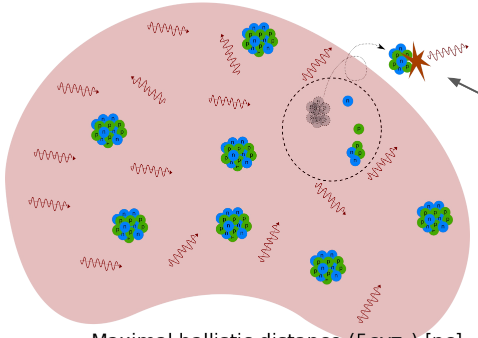
5. Multi-messenger Implications:

- *The neutrino flux from individual BL Lacs obtained is too low to be detected by currently operating and upcoming future detectors*
- *For $E_{p,\max} = 10$ EeV and deflections in the EGMF and GMF, identifying UHECRs coming from individual BL Lacs will be difficult*

Nature volume 582, pages 356–359 (2020)

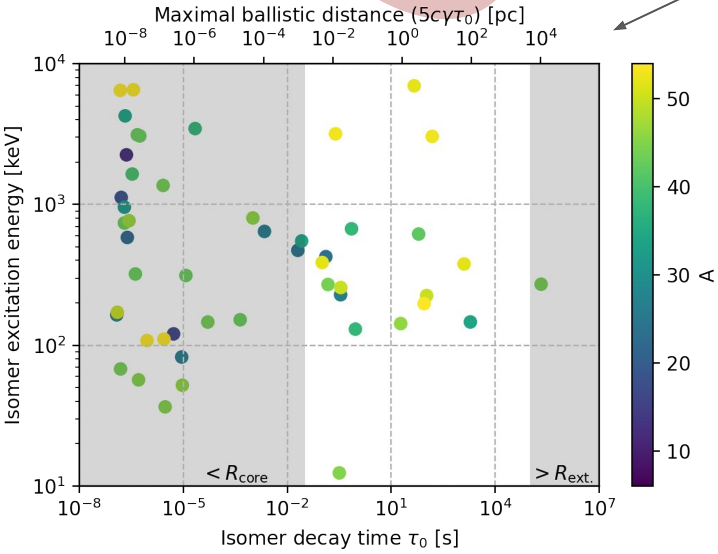
Isomers and VHE emission from Cen A

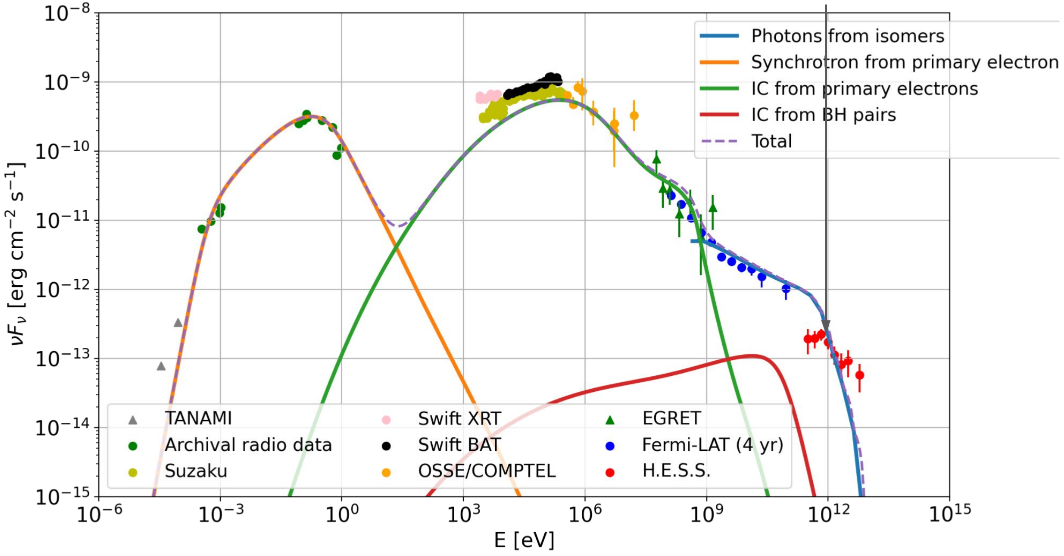




Disintegration products in the core of Cen A may be isomer states.

Isomer decays after escape may explain VHE photons





From Armando Di Matteo:
@Jonathan: What's the minimum distance included in your catalog? 1 Mpc? Also, what composition was assumed to compute the attenuation?
From Jonathan Biteau:
@Armando: Yes. We will discuss this point in an upcoming paper: bottom line in a transient scenario, bursts from nearby dwarf galaxies would be missed of the time, so that the SFR in the Local Group does not really matter.For the composition we used a fit of the public Auger spectrum, ln A, sigma(ln A), assuming Sybill. The results are very similar to those obtained in the Auger combined fit paper as far as Rmax and the index are concerned.

From Markus Roth:
@Jonathan: How do you ensure completeness you had mentioned in your talk?
From Jonathan Biteau:
@Markus: With an empirical approach as a function of Galactic latitude (modelling of the drop in number counts when you get closer to the Galactic plane). As a function of distance, I use the luminosity function reconstructed in the near-infrared. Given a set flux limit, you can determine how much stellar mass you miss when looking farther away.

From Kevin Almeida Cheminant :
@Marco: did you assume a pure proton composition for the gas? Did you try any other composition?
From Marco Muzio:
@Kevin: Yes, for this first work with gas we used a pure proton composition. We hope to explore other compositions in the future.

From Luis Anchordoqui:
@Glennys: Hi Glennys, nice talk! I was wondering what is the typical and maximum energy of Galactic cosmic rays used in your analysis, and whether this local SN you mentioned has some particularity that allows acceleration of particles to these high (if typical $E > 100$ PeV) energies.
From Glennys Farrar:
@Luis — Most massive stars are in binaries with another massive star, so what seems most reasonable to me is the colliding shock flow model of Bykov, Ellison et al, but where the core collapse SN of one produces the csf into the Wolf-Rayet wind of the binary partner. The energetics work nicely. (Bykov+ proposed a star-forming region produce the winds needed, but there is no star-forming region where needed to produce the

GCB anisotropy.

From Noemie Globus:
@Filip: What is the rate of LL-GRBs that is assumed here?
From Walter Winter:
@Noemie: The rate is not needed to compute the maximal energies. If you want to understand the UHECR energy budget, you need it of course. A typical number is around 300-400 Gpc-3 yr-1
From Filip Samuelsson:
@Noemie: The rate we use is conservative. We use a rate of 10^3 Gpc^-3 year^-1

From Susumu Inoue:
@Filip: Depends on the nature of “LL-GRBs”, whose origin is not clearly understood…
From Filip Samuelsson:
@Susumu: The origin of the prompt emission is not really important in our analysis. As long as UHECRs are accelerated, electrons are as well and there emission can be calculated
From Susumu Inoue:
@Filip: yes, I meant that it’s important to clarify what is assumed for the physical conditions of the UHECR acceleration site, which can depend on what you consider to be a “LL-GRB”
From Walter Winter:
@Filip: it is nevertheless an implied assumption that the prompt emission and UHECR acceleration happen in the same region in your model, as far as I understand. It is known (also for high-luminosity GRBs) that the dissipation radius is in all realistic cases distributed, and the region creating the junk of the prompt emission may have properties than the region optimal for UHECR acceleration ...
From Filip Samuelsson:
@Walter: Yes, I agree
From Annika Rudolph:
@Filip: also, the optical fluxes in your model were determined assuming a synchrotron spectrum. I would assume this to be different in a shock breakout scenario?
From Filip Samuelsson:
@Walter: That is not true. We only consider the emission in the UHECR acceleration, which may be different from the prompt emission site, and we state this several times.
@Annika: Yes, but again we do not try to explain the prompt emission.

We only want to be consistent with the observations, regardless of what caused the prompt emission. The electrons existing in the UHECR acceleration region will be in a strong magnetic field and will therefore emit synchrotron emission

From Matteo Cerruti:
@Saikat Das: [following comment by Jonathan that a purely leptonic interpretation is also viable for these extreme BL Lacs, albeit with extreme parameters]: You can also the VERITAS paper of 2014 (aliu et al. 2014) in which we did a scan of the SSC parameter space. It works (as Jonathan said with some extreme values though).