Ultra-high energy Inverse Compton emission from Galactic electron accelerators

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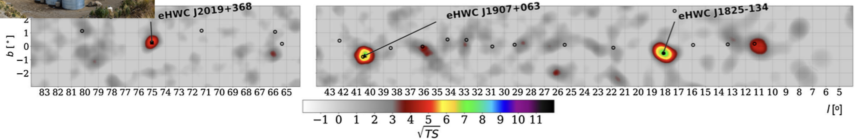
Based on Breuhaus et al. 2021 ApJL vol. 908, Breuhaus et al. 2022 A&A vol. 660

What is the origin of UHE γ-ray sources?



Credits: HAWC collaboration 2020

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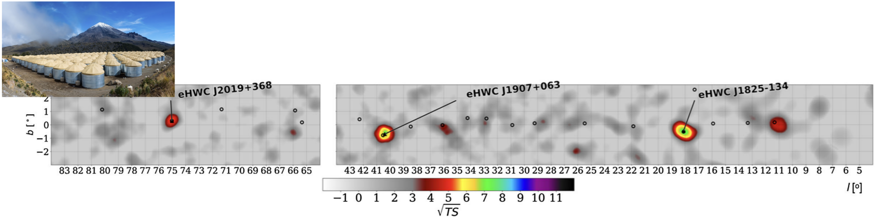

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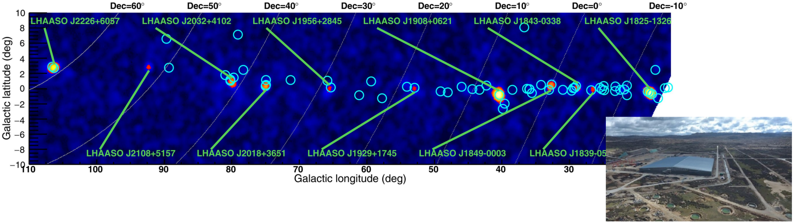
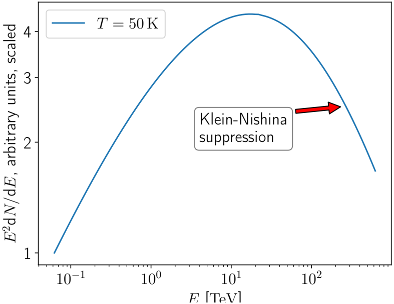


Credits: LHAASO collaboration 2021

How to get hard IC spectra at 100 TeV?

- Problem: Klein-Nishina suppression at high energies



IC SED of $\propto E^{-2}$ distributed electrons and a 50 K radiation field

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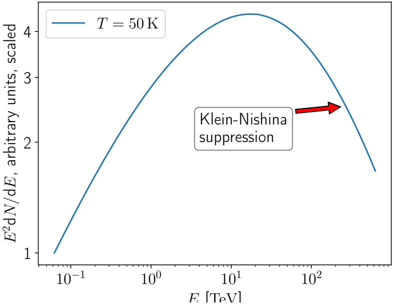

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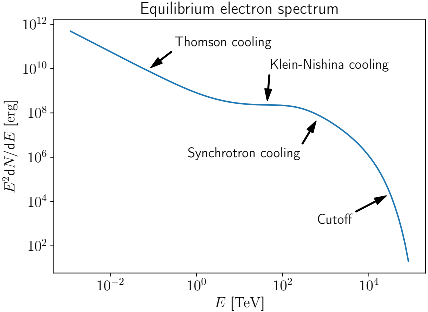
- Solution: Equilibrium spectra in radiation dominated environments



How to get hard IC spectra at 100 TeV?

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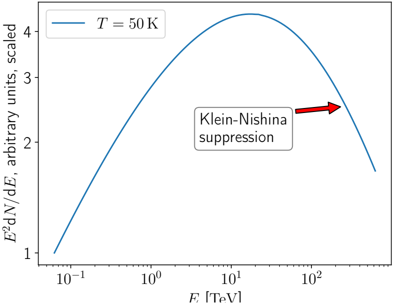

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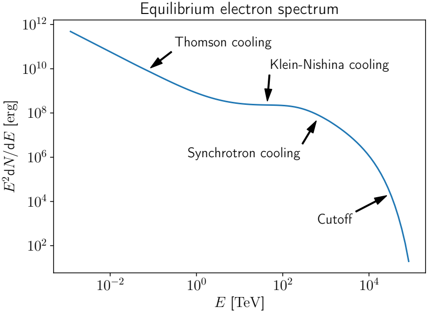
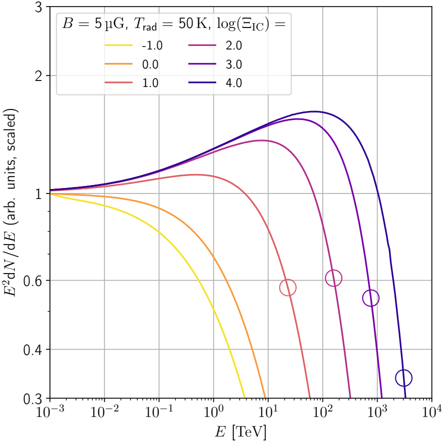


- From now on: $\Xi_{\mathrm{IC}} := \frac{U_{\mathrm{rad}}}{U_{\mathrm{B}}}$

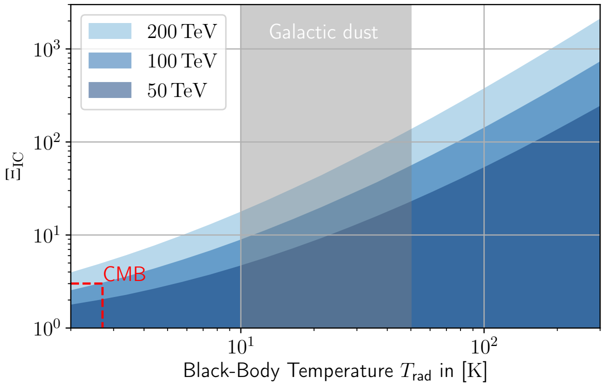
Equilibrium spectra in radiation dominated environments



γ-ray spectra in different environments, *Breuhaus et al. 2021*

- Low energy losses $\Rightarrow$ hard e^- spectra in KN-regime $\Rightarrow$ hard γ-rays
- Need to be dominated by radiation losses until energies above 100 TeV

Temperature influence

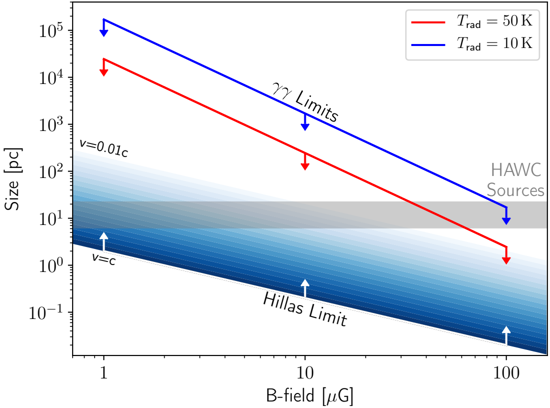


Excluded parameter space for hard UHE IC spectra, *Breuhaus et al. 2021*

- Lower temperature $\Rightarrow$ KN-transition at higher energies $\Rightarrow$ smaller Ξ_{IC}
- For CMB: Radiation dominance at 100 TeV for $B < 1.8\,\mu G$

System constraints

- Acceleration and confinement ⇒ Hillas limit
- Pulsars: possible accelerators
- Absorption by strong FIR field ⇒ upper limit on size
- Absorption by interstellar galactic FIR fields at 100 TeV < 0.5



Size limits for confinement and absorption, *Breuhaus et al. 2021*

Galactic Environments

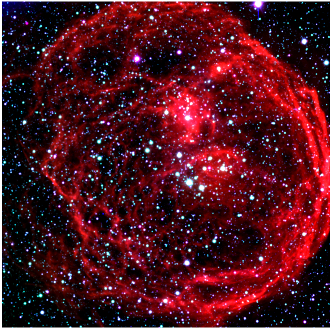
- Need special local regions with high intensity radiation fields and/or low B-field

Star forming regions

Credits: Hubble space telescope

FIR densities $\sim 100\,\mathrm{eV\,cm^{-3}}$ for tens of pc

Superbubbles

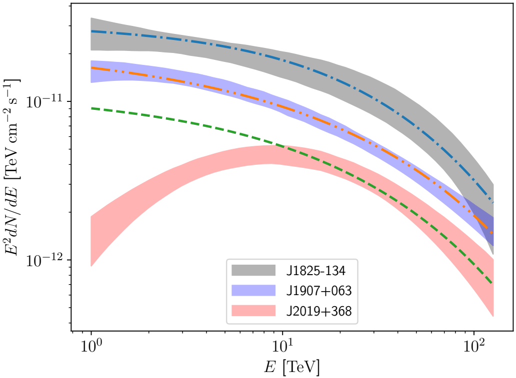


Credits: ESO

Low values of $B \lesssim 3\,\mu\mathrm{G}$

Equilibrium models for the UHE HAWC sources

- Plausibly associated pulsars: $\dot{E}_{36} = 2.8$ to 3.4
- Emission region sizes of 6 pc to 22 pc $\Rightarrow$ fulfilment of size constraints
- Models: FIR/UV radiation from Popescu et al. 2017 enhanced by η + CMB
- All η compatible with data from IRAS survey



Breuhaus et al. 2021

J1825-134: $\eta = 3/5$, $E_{\text{cut}} = 350$ TeV

J1907+063: $\eta = 1$, $E_{\text{cut}} = 480$ TeV

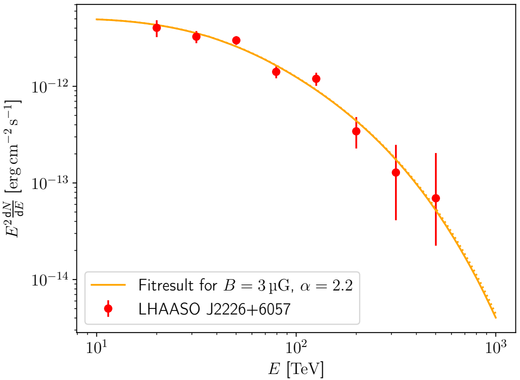
J2019+368: $\eta = 2$, $E_{\text{cut}} = 400$ TeV

All models: $B = 3\,\mu$G, $\alpha = 2$

Finite age model: LHAASO J2226+6057

Injection spectrum: $\frac{\mathrm{d}N}{\mathrm{d}E} = N_0 \cdot \left(\frac{E}{1\,\mathrm{erg}}\right)^{-\alpha} \cdot \exp\left(-\frac{E}{E_{\mathrm{cut}}}\right)$

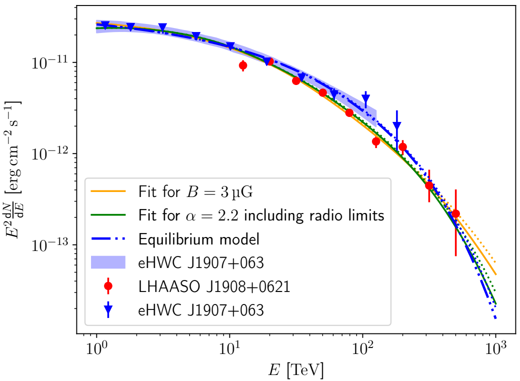
- PSR J2229+6114: $L_{\mathrm{SD}} = 2.2 \times 10^{37}\,\mathrm{erg\,s^{-1}}$, dist. of 0.8 kpc, age 10.0 kyr



Breuhaus et al. 2022
$B = 3\,\mu\mathrm{G}$, $\alpha = 2.2$ (fixed),
$N_0 = (9 \pm 2) \times 10^{33}\,\mathrm{erg^{-1}\,s^{-1}}$,
$E_{\mathrm{cut}} = 420^{+210}_{-130}$ TeV

LHAASO J1908+0621 and eHWC J1907+063

- PSR 1907+0602: $L_{\mathrm{SD}} = 2.8 \times 10^{36}\,\mathrm{erg\,s^{-1}}$, dist. of 2.4 kpc, age 19.5 kyr



Breuhaus et al. 2022
Orange: $\dot{N}_0 = (10 \pm 2) \times 10^{35}\,\mathrm{erg^{-1}\,s^{-1}}$,
$\alpha = 2.66 \pm 0.03$, $E_{\mathrm{cut}} > 1.4\,\mathrm{PeV}$

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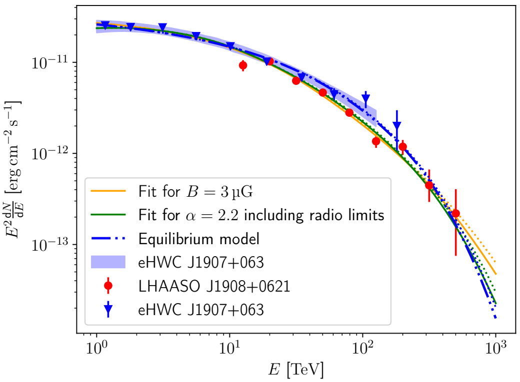

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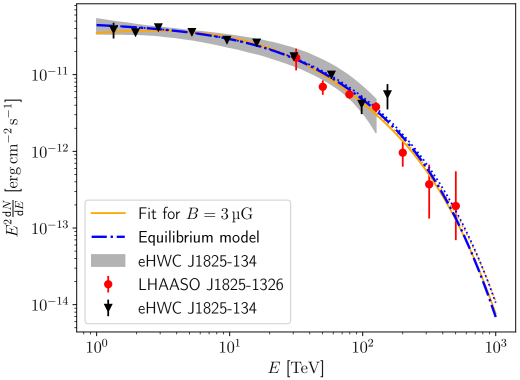
$\alpha = 2.66 \pm 0.03$, $E_{\rm cut} > 1.4\,\mathrm{PeV}$
Green: $B = (5.7 \pm 0.3)\,\mu\mathrm{G}$,
$\dot{N}_0 = (2.8 \pm 0.2) \times 10^{35}\,\mathrm{erg^{-1}\,s^{-1}}$,
$E_{\rm cut} = 830^{+360}_{-220}$ TeV

LHAASO J1825-1326 and eHWC J1825-134

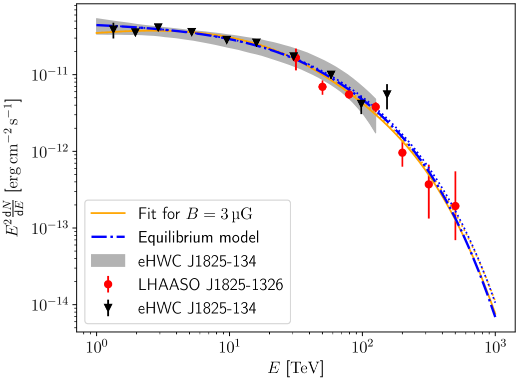
- PSR J1826-1334: $L_{\mathrm{SD}} = 2.8 \times 10^{36}\,\mathrm{erg\,s^{-1}}$, dist. of 3.1 kpc, age 21.4 kyr



Breuhaus et al. 2022
PSR J1826-1334: $\dot{N}_0 = (5 \pm 2) \times 10^{35}\,\mathrm{erg^{-1}\,s^{-1}}$, $\alpha = 2.23 \pm 0.09$, $E_{\mathrm{cut}} = 390^{+340}_{-150}$ TeV

LHAASO J1825-1326 and eHWC J1825-134

- PSR J1826-1334: $L_{\rm SD} = 2.8 \times 10^{36}\,\mathrm{erg\,s^{-1}}$, dist. of 3.1 kpc, age 21.4 kyr
- PSR J1826-1256: $L_{\rm SD} = 3.6 \times 10^{36}\,\mathrm{erg\,s^{-1}}$, dist. of 1.6 kpc, age 14.4 kyr



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PSR J1826-1256: $\dot{N}_0 = (4 \pm 2) \times 10^{35}\,\mathrm{erg^{-1}\,s^{-1}}$, $\alpha = 2.39 \pm 0.09$, $E_{\rm cut} = 410^{+380}_{-160}$ TeV

Conclusion

- 100 TeV hard IC spectra possible if IC losses dominate up to high energies $\Rightarrow U_{\text{rad}}/U_{\text{B}} > 1$
- High power pulsars coincident with star forming regions and superbubbles are ideal candidates
- HAWC and LHAASO sources can be explained with reasonable leptonic scenarios
- Redundancy in many model parameters $\Rightarrow$ Environmental conditions and multiwavelength data crucial to distinguish between leptonic and hadronic sources
- IC sources are likely an important contributor to the γ-ray sky $>$100 TeV