LEPTON PHOTON 2021 MAN

30th International Symposium on Lepton Photon Interactions at High Energies

Astroparticle Overview

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CNRS/IN2P3 – IJCLab Orsay

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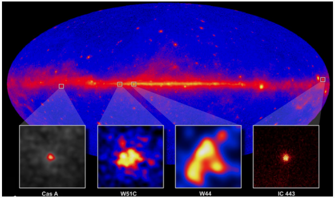
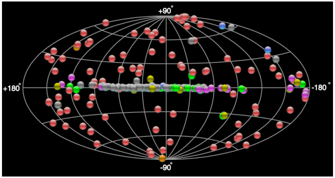
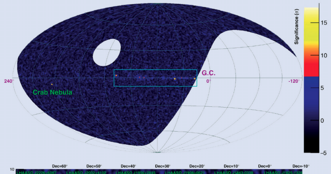
i. Introduction

From classical astronomy to high- and ultra-high energy photons

Classical astronomy: study of thermal emission and absorption processes in heated environments (black-body radiation of stars)



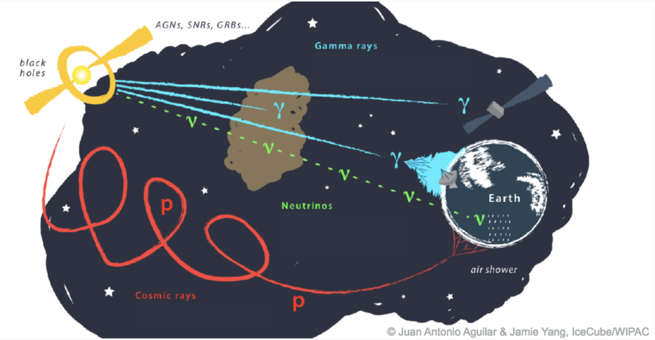




- GeV gamma rays – already too high energies to trace thermal processes
- TeV gamma rays uncovered by Cherenkov Telescopes (H.E.S.S., MAGIC, VERITAS)
- New: PeV gamma rays by high-altitude air shower arrays (TIBET, LHAASO)
- Large panoply of processes at the origin of these photons:
  - Tracing high energy particles
  - Locating cosmic particle accelerators

Astroparticle Physics

Probe of the "high-energy Universe", i.e. the extreme phenomena that generate and store high-energy particles in the Milky Way and beyond



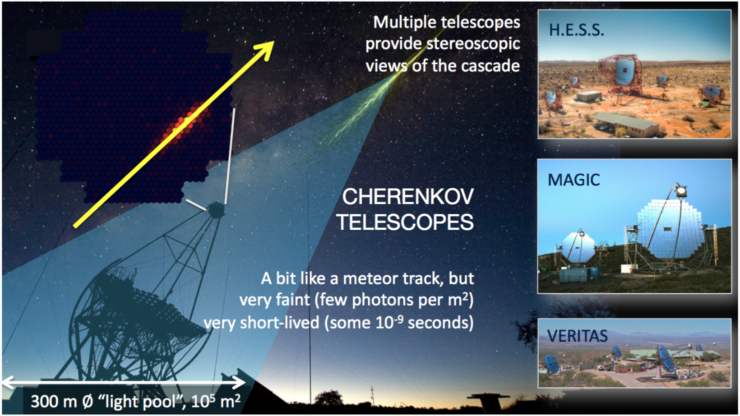
- Different messengers[1]: particles, namely cosmic rays, gamma rays and neutrinos[2], and gravitational waves[3]
- Access to processes that cannot be identified with photons only

1. cf. "Multi-messenger detection" talk at this conference (E. Cuoco)
2. cf. "Astrophysical and atmospheric neutrinos" talk at this conference (S. Klein)
3. cf. "Gravitational waves" talk at this conference (P. Schmidt)

Multi-messenger observatories

Extensive air showers

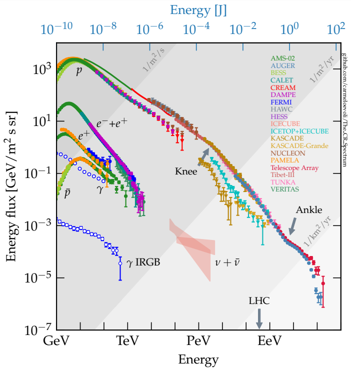
Credits: W. Hoffman



- Telescopes capturing the isotropic fluorescence emission at higher energies (de-excitation of nitrogen molecules excited by ionisation electrons left after the passage of the showers)
- Large surfaces of particle detectors at the ground level

CR energy spectrum

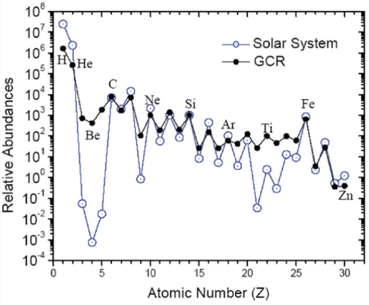
Compilation: C. Evoli, 10.5281/zenodo.4396125



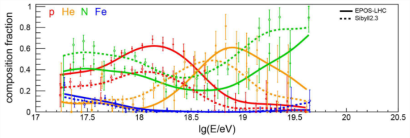
- Nearly a power law, with spectral features
- Heliosphere “bubble” shielding <GeV energies (confirmed by Voyager)
- Contribution of light elements dominant at GeV energies and important up to the “knee” (3×10^{15} eV), after which heavier elements gradually take over up to a few 10^{17} eV – Calls for a rigidity-dependent acceleration:
  - Most abundant element in the interstellar medium: hydrogen
  - Heavier elements accelerated to higher energies for two decades above the knee
- No Galactic confinement/anisotropies above the ankle (5×10^{18} eV): extragalactic origin
- Electrons/positrons from local sources? **[e.g. P. Mertsch & S. Sarkar, PRD 90 (2014) 061301]** Background important to understand for indirect searches of dark-matter

cf. “Dark matter astrophysics” talk at this conference (K. Perez)

CR composition



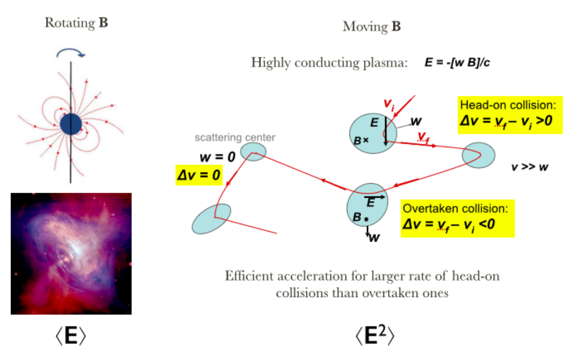
Auger Collaboration, 2017



- Galactic CR composition similar to that of ISM, except:
  - Li, Be, B, F, Sc-Mn produced by spallation of heavier primaries
  - Overabundance of ^{22}Ne/^{20}Ne
  - Mass-dependent enrichment of volatiles w.r.t. H
  - Constant overabundance ($\times$20) of refractories w.r.t. H
- Extragalactic composition: highly non-solar metallicities [Auger Collaboration, PRL 104 (2010) 091101]
- Elements getting heavier at UHE from all contemporary observatories [A.A. Watson, JHEAp 33 (2022) 14]

ii. Production of Galactic cosmic rays and gamma rays

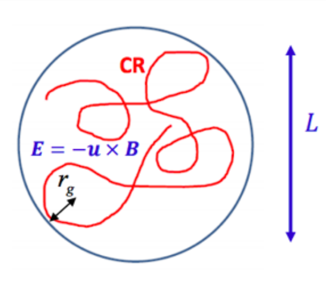
Acceleration of charged particles → Electric fields (not expected in space plasma)



- Non-MHD flows: $\mathbf{E} \cdot \mathbf{B} \neq 0$, $\mathbf{E}^2 - \mathbf{B}^2 > 0$
- Gaps in magnetospheres (pulsars...)
- Magnetic reconnection
- Ideal Ohm's law in highly conducting plasma
- Fermi-type scenarios: magnetized turbulence, shear flows, shock waves

Maximum acceleration energy? Hillas criterium

Necessary condition but not sufficient (losses, ages, etc.) **[A.M. Hillas, 1984]**

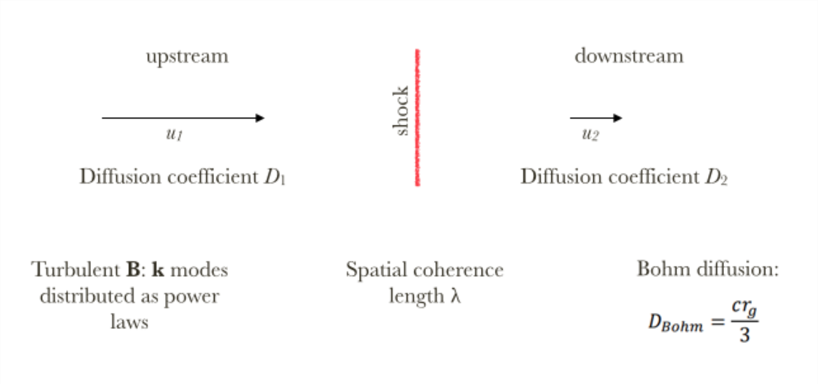


- Spatial confinement: gyration radius $r_g (= E/cB) <$ plasma size $\implies E < cBL$
- Acceleration by electric field $\mathbf{E} = -\mathbf{u} \times \mathbf{B}$
- Max. gain: $L \times \max(\mathbf{E}) \implies E < uBL$
- Max. energy: $E_{\max} = \left(\frac{u}{c}\right)\left(\frac{B}{1\ \mu\mathrm{G}}\right)\left(\frac{L}{1\ \mathrm{pc}}\right)$ PeV

- Moving **B**: at the shocks and in shear flows
- Efficiency to convert the kinetic energy of large scale supersonic plasma motion into the population of high energy particles?

Diffusive shock acceleration

How to reach $E_{\max}$? [A. Bell, MNRAS 182 (1978) 147, 182 (1978) 443]



- Max. energy: $E = \frac{3}{4}\left(\frac{D_1}{D_{\text{Bohm}}}\right)^{-1} u_1 BL \leftrightarrow E_{\max} = \frac{1}{4}\left(\frac{\lambda}{r_{\text{g}}}\right)^{-1} u_1 BL$
- Production of power-law energy spectra ($\simeq E^{-2}$), possibly modified by non-linear effects

SNR paradigm

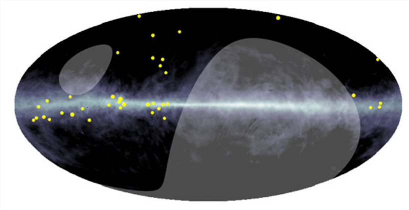
- Hillas criterium:
  $u = 5000$ km s^{-1}, $L = 1$ pc
  $\Longrightarrow \quad E_{\rm max} \simeq 30 \left(\frac{B}{1\ \mu{\rm G}}\right)$ TeV (e.g. P. Lagage & C. Cesarsky, A&A 125 (1983) 249)
- Magnetic field amplification by accelerated CRs $\Longrightarrow$ increase of $E_{\rm max}$ [S. Lucek & A. Bell, MNRAS 314 (2000) 65]
- Modification of the shock structure due to CR pressure gradient: possible deviations from power law [E. Berezhko, JETP 82 (1996) 1]

- Energy density of GCRs:
  1 eV cm^{-3} $\simeq 10^{-12}$ erg cm^{-3}
- Galactic confinement volume:
  $\pi(20$ kpc$)^2$ 100 pc $\simeq 3\ 10^{67}$ cm^3
- CR residence time: $3\ 10^7$ yr
- Required power to fuel the observed energy density:
  $3\ 10^{40}$ erg s^{-1}
- Energy input from SNRs:
  10^{42} erg s^{-1}
- Energy in CRs $\simeq$ Energy in γs! [W. Baade & F. Zwicky, Proc Natl Acad Sci USA 20(5):254Ð259]

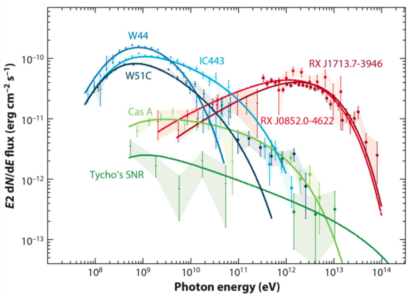
- Highly non-linear problem: accelerated particles feed back on the electromagnetic environment...

Searching for PeVatrons with γ rays

M. Amenomori et al., PRL 126 (2021) 141101



S. Funk, Ann. Rev. Nuc. Part. (2015)

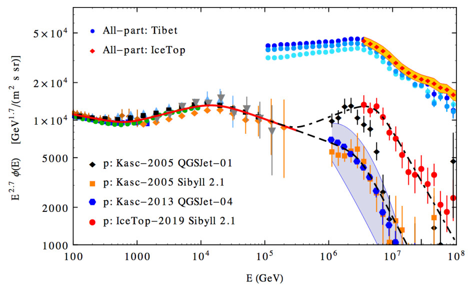


- Diffuse PeV flux from the Galactic disk, p gas $\rightarrow$ nπ^0 $\rightarrow \gamma\gamma$
- A dozen of unidentified sources up to a few 100s of TeV **[Z. Cao et al., Nature 594 (2021) 33]**
- Protons accelerated to knee energies in the Galaxy
- Typical spectra for several of the most prominent SNRs
- Hard spectra in the GeV-TeV
- $\simeq$ 10 TeV cutoffs
- No smoking-gun of CR PeVatrons, yet

Interpretations and alternative to SNRs?

Small variations on top of power-law shape revealed by precision measurements of mass-discriminated spectra

P. Lipari & S. Vernetto, Astropart. Phys. 120 (2020)



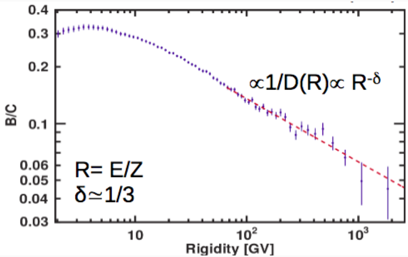
- Hardening and softening established in the proton spectrum
- Same hardening established for He and other nuclei
- Hardening origin in terms of source properties or propagation effects? (e.g. R. Aloisio & P. Blasi, JCAP 07 (2013) 001)

- Softening origin? Injected spectra from sources (SNRs? SNRs+others?) with a large variety of shapes, combining to form an average spectrum that has a nearly power law form
- Reaching the knee energy? Pulsar wind nebulae? (e.g. E. Amato, Paris-Saclay Astroparticle Symposium 2021) Winds in star clusters? (e.g. G. Morlino, Paris-Saclay Astroparticle Symposium 2021) Starburst-driven superbubbles? (e.g. Z. Zhang et al., MNRAS 492 (2020) 2250)
- Need to bridge mass-discriminated direct and indirect measurements...

iii. Propagation of cosmic rays in the Galaxy

Diffusion in the Galaxy

AMS, PRL 117 (2016) 231102

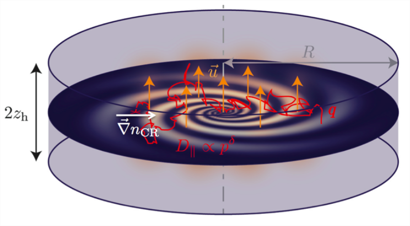


- "Leaky box" model:
  - Free streaming of CRs inside the confinement volume
  - Constant densities and escape times $\tau(E)$ of CRs
- Boron and Beryllium isotopes: secondaries from spallation of C,N,O primaries with H targets

- Combination of $N_{\mathrm{B}}(E)/N_{\mathrm{CNO}}(E)$ and unstable/stable $N_{^{10}\mathrm{Be}}(E)/N_{^{9}\mathrm{Be}}(E)$: measurements of $\tau(E)$ and n_{H}
  - $\tau(E) \simeq 30$ Myr ($\gg$ time flight to GC)
  - $n_{\mathrm{H}} \simeq 0.1 - 0.3\ \mathrm{cm}^{-3}$ ($<$ disk density)

$\Longrightarrow$ Diffusion of CRs in the Galaxy with substantial part of life time in low-density regions

The diffusion/advection problem



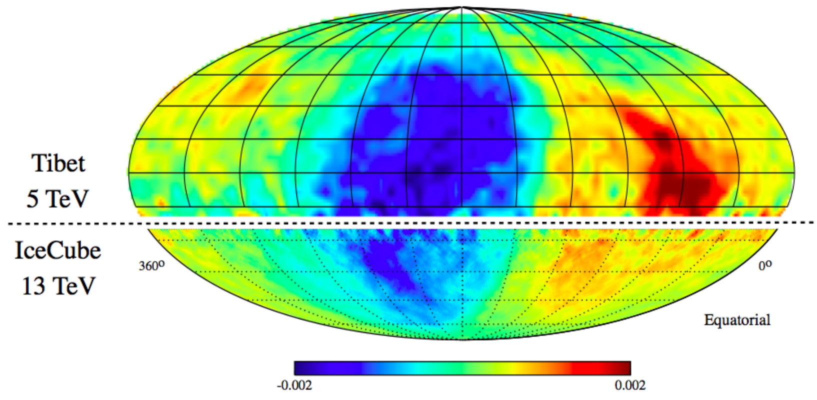
- Beyond leaky box model, transport governed by CR scattering off magnetic turbulence
- Fluctuating **B** acting as an effective source of collisions [cf. J. Jokipii, ApJ 172 (1972) 319]

- Approximation of the collision term by a relaxation one → CR flux related to gradient density through diffusion tensor:

$$D_{ij} = D_{\perp}\delta_{ij} + \left(D_{\parallel} - D_{\perp}\right) b_i b_j + D_A \epsilon_{ijk} b_k$$

- $D_i(E)$ coefficients related to turbulence properties, high-energy regime [I. Plotnikov et al., A&A 532 (2011) A68], gyro-resonant regime [OD, ApJ 920 (2021) 87], Monte-Carlo otherwise

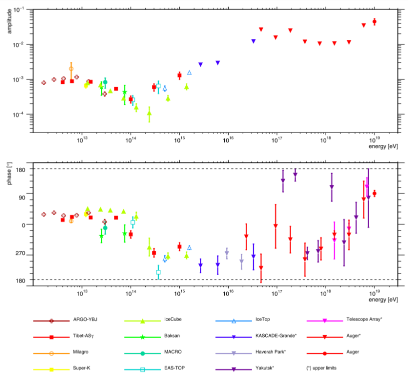
Clues with dipole anisotropies



- Dipolar anisotropies up to the level of one-per-mille at various energies (Super-Kamiokande, Milagro, ARGO-YBJ, EAS-TOP, Tibet AS-γ, IceCube, HAWC)
- Diffusion: source=dipole ($\delta = \frac{3D}{c}\frac{\nabla n}{n}$)

Clues with dipole anisotropies

Compilation: OD, Astropart. Phys. 104 (2019) 13

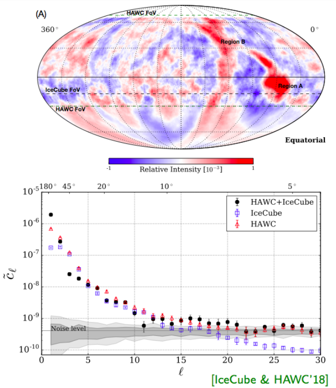


- Amplitude decreasing at $\simeq$ 100 TeV, with change of phase
- PeV-EeV: upper limits only
- Strong regular **B** in the local environment $\Longrightarrow$ Diffusion tensor reducing to projector **[e.g. P. Mertsch & S. Funk, XX (2014) XX]**
- $D_{ij} \simeq D_{\|} b_i b_j$: projection of gradient density onto $\pm$**B**

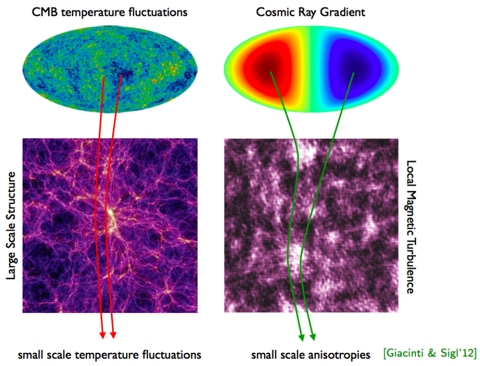
- TeV-PeV dipole data consistent with **B** direction inferred from IBEX data **[McComas et al., Review of Geophysics 52 (2014) 118]**
- Energy of flip of phase similar to that of the softening of protons – transition between dominating sources...

Small-sale anisotropies

Significant TeV small-scale anisotropies down to angular scales of $\mathcal{O}(10^\circ)$!



Credits: M. Ahlers



MC-based studies to infer properties of local turbulence by reproducing the C_ℓ

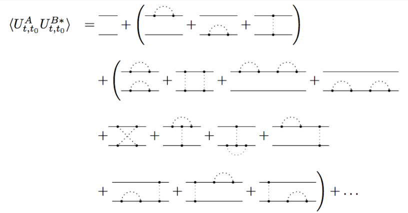
Small-sale anisotropies

- Phase-space distribution function $f(\mathbf{p})$ governed by a Vlasov equation

$$\frac{\partial f}{\partial t} + \mathcal{L} f + \delta \mathcal{L} f = 0, \ \mathcal{L}, \delta\mathcal{L} : \text{ Liouville operator}$$

- Standard diffusion, $C_\ell = \frac{1}{4\pi} \iint \mathrm{d}\mathbf{p}_1 \mathrm{d}\mathbf{p}_2 \, P_\ell(\mathbf{p}_1 \cdot \mathbf{p}_2) \langle f(\mathbf{p}_1) \rangle \langle f(\mathbf{p}_2) \rangle$
- Individual realisation of $\delta\mathbf{B}$: $C_\ell = \frac{1}{4\pi} \iint \mathrm{d}\mathbf{p}_1 \mathrm{d}\mathbf{p}_2 \, P_\ell(\mathbf{p}_1 \cdot \mathbf{p}_2) \langle f(\mathbf{p}_1) f(\mathbf{p}_2) \rangle$
- Formal solution of Vlasov equation: $f(\mathbf{p}, t) = U(t, t_0) f(\mathbf{p}, t_0)$ with "propagator" $U(t, t_0) = \mathcal{T} \exp \left(- \int_{t_0}^{t} \mathrm{d}t' (\mathcal{L} + \delta\mathcal{L}(t')) \right)$
- Expansion of $U(t, t_0)$ as a Dyson series $\rightarrow$ stat. properties of turbulence
- $\langle f(\mathbf{p}_1) f(\mathbf{p}_2) \rangle \implies \langle U^A(t, t_0) U^B(t, t_0) \rangle$: "intensity" operator

[M. Ahlers & P. Mertsch, JCAP 11(2019)048]

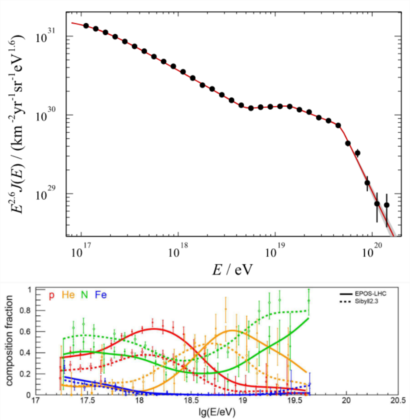


- No perturbation theory...
- Partial summation schemes needed
- Promising developments to characterise CR propagation

iv. Ultra-high energy cosmic rays

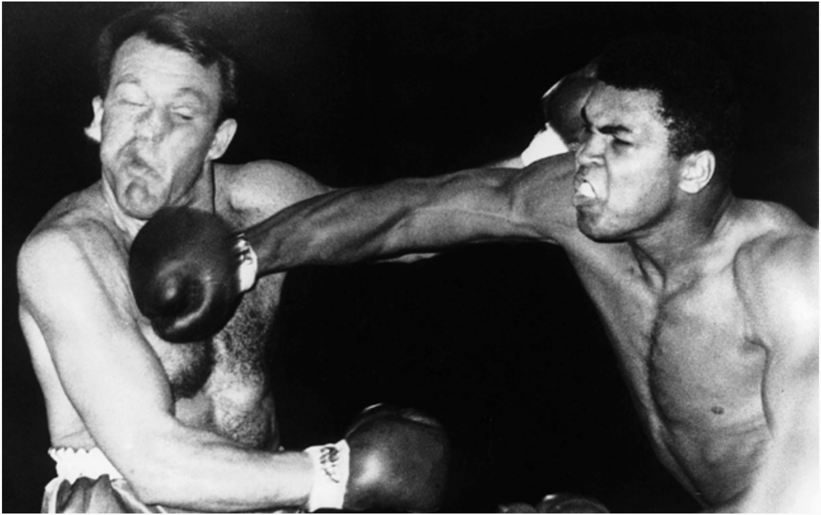
UHECRs

Auger Collaboration, EPJC 81 (2021) 966



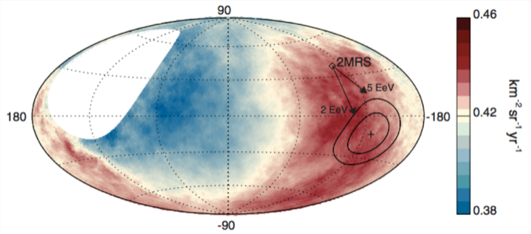
- Extragalactic origin above the ankle energy?
- Steepening at UHE expected from energy losses (GZK cutoff)...
- ...but unexpected “instep” steepening at $\simeq 10^{19}$ eV **[Auger Collaboration, PRD 102 (2020) 062005]**
- Composition getting heavier with E, with little mixing...
- ...cutoff at the sources?
- Second knee-to-ankle region: complex intertwining of phenomena hid beneath the featureless all-particle flux

10^{20} eV!



Extragalactic origin above the ankle energy

Auger Collaboration, Science 357 (2017) 1266



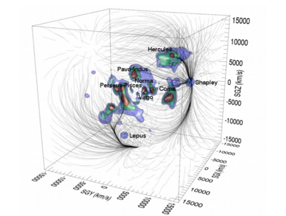


Fig. ED 1. — Structure within a cube extending 16,000 km s^{-1} (~200 Mpc)

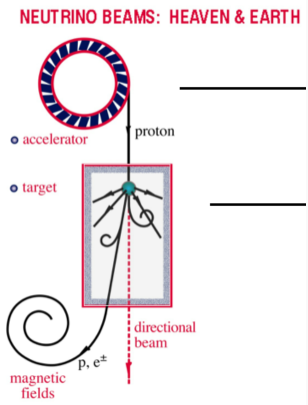
Tully, Courtois, Hoffman, Pomarède, Nature 2014

- No fingerprint of Milky Way > 8 EeV
- Mapping of local matter (Laniakea): overdensities and void within 70 Mpc
- Deficit aligned with void direction with $> 5\sigma$
- Correlation with nearby starburst galaxies at higher energies (4σ) **Auger Collaboration, ApJL 853 (2018) L29**

Energy content of messengers

Particle fluxes extremely different... Energetics is the key

Credits: F. Halzen

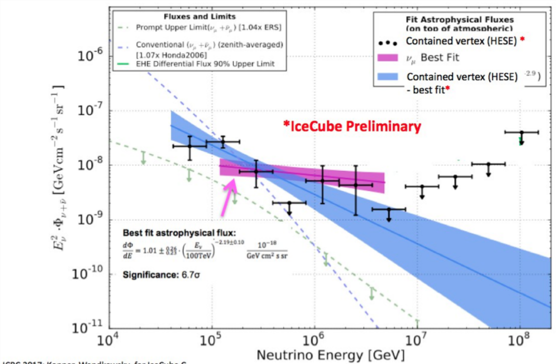


- $p\gamma \rightarrow n\pi^0 \rightarrow$ CRs+γs
- $p\gamma \rightarrow n\pi^+ \rightarrow$ CRs+νs

- Carbon copy of SNRs energetics in the case of GCRs
- Energy density: 3×10^{-19} erg cm^{-3}
- Accumulation time: 10^9 yr
- Required energy production rate: 10^{44} erg Mpc^{-3} yr^{-1}
- Luminosity of active galaxies: 3×10^{44} erg s^{-1}
- Energy released by gamma ray burst: 2×10^{51} erg

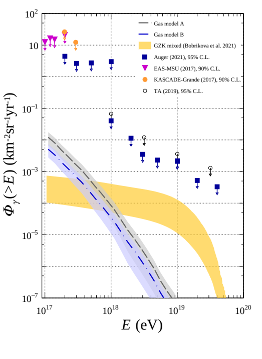
$\Longrightarrow$ Energy in CRs $\simeq$ Energy in γs $\simeq$ Energy in νs!

Towards multi-messenger astronomy...



ICRC 2017: Kopper, Wandkowsky for IceCube C.
ICRC 2017: Haack for IceCube C.

Z. Torrès et al., 2022, submitted to ApJ



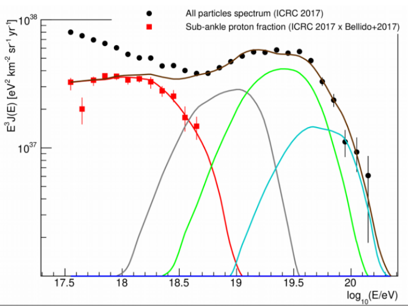
- Diffuse flux of astrophysical νs – several possible origins – but confirmation of similar energy content in $\simeq$ EeV CRs and νs!
- At present only limits on ν point sources **[IceCube, PRL 124 (2020) 051103]**
- No cross-correlation between ν and UHECR arrival directions (not unexpected given the different horizons) **[Auger/TA/IceCube/ANTARES, ICRC2021, in preparation]**
- At present only limits on $>$ PeV photons

Inferring accelerator properties

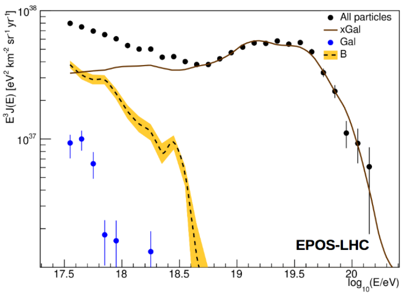
Inferring properties of the acceleration processes and source environments

e.g. R. Aloisio et al., JCAP 10(2014)020, A. Taylor et al., PRD 92(2015)063011, Auger Collab., JCAP 04(2017)038, ... above $10^{18.7}$ eV

Q. Luce et al., Paris-Saclay Astroparticle Symposium 2021



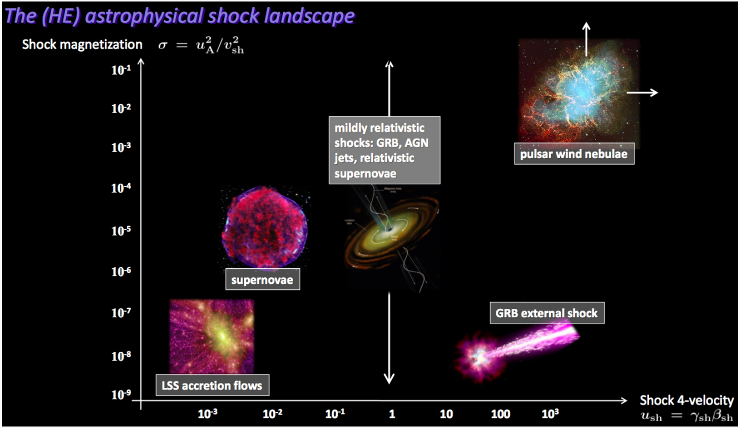
Q. Luce et al., Paris-Saclay Astroparticle Symposium 2021



- Abundance dominated by intermediate elements at the sources
- In-source interactions shaping ejection spectra of protons differently from nuclei **(e.g. Unger et al., PRD 92 (2005) 123001, Biehl et al., A&A 611 (2018) A101)**
- Upper end of GCRs not reaching the ankle energy
- “B component”? **[A.M. Hillas, J. Phys. G 31 (2005) R95]**

The UHE landscape

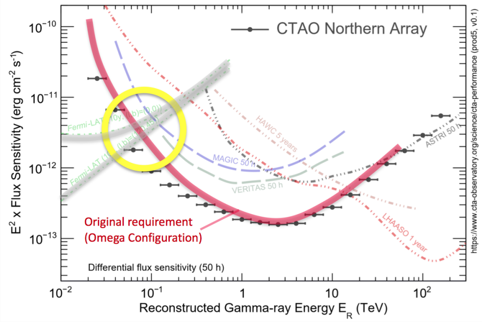
Credits: M. Lemoine, Paris-Saclay Astroparticle Symposium 2021

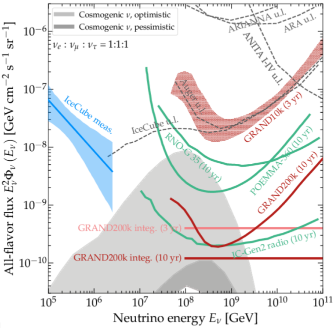


- Most promising regime for efficient acceleration: mildly magnetized, mildly relativistic shocks
- Along the lines of several observations (e.g. in-source interactions shaping spectra, correlation with starburst galaxies)

v. What's next

What's next





- UHECRs next: Auger upgraded, TA upgraded
- UHECRs future: space observatories (POEMMA, JEM-EUSO), ground observatories (GRAND, GCOS)?

Outlook

- Origin of Galactic CRs still uncovered 110 years after discovery
  - Probes of acceleration processes in the Galaxy
  - Recent observations calling into question the perception of GCRs
  - Complex intertwining of several phenomena to reach the knee energies
  - Anisotropies: local environment
- Origin of extragalactic CRs and astrophysical νs?
  - Data-driven understandings
  - Some benchmark scenarios preferred
  - Need of even larger exposures...
- Data-driven quests benefiting from theoretical advances
- Challenging but exciting field at the “frontiers” in science to understand the “high-energy” Universe