Extreme Energy Cosmic Rays and Dark Matter

Zurab Berezhiani

University of L'Aquila and LNGS

NOW 2024, Otranto, 2-8 Sept. 2024

Contents

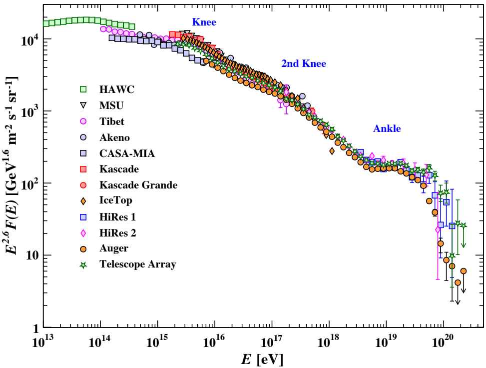
Chapter I

Extreme Energy Cosmic Rays:

Where do they all come from?

Cosmic Rays at highest energies

$E < 1$ TeV $= 10^{12}$ eV moderate energies
$E < 1$ PeV $= 10^{15}$ eV knee – galactic CR
$E > 1$ EeV $= 10^{18}$ eV UHECR: extragalactic
$E > 50$ EeV (GZK cutoff) $E > 100$ EeV $= 10^{20}$ eV EECR



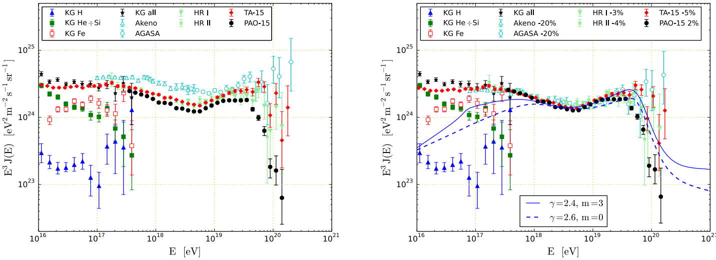
Cosmic Zevatrons exist in the Universe – but where is the End?

UHECR Observatories

Two giant detectors:

Pierre Auger Observatory (PAO) – South hemisphere
Telescope Array (TA) – North hemisphere

At $E < E_{\rm GZK}$ two spectra are perfectly coincident by relative energy shift $\approx 8 \div 10$ % – but become discrepant at $E > E_{\rm GZK}$



+ older detectors: AGASA, HiRes, etc. (all in north hemisphere)

Events with $E > 100$ EeV were observed

But also other problems are mounting ...

- Who are carriers of UHECR? (chemical content)

Chemical content: extragalactic UHECR are protons for $E = 1 \div 10$ EeV. But UHECR become gradually heavier nuclei above $E > 10$ EeV or so
Disappointing Model – or perhaps new physics?

- Different anistropies from North and South?

TA disfavors isotropic distribution at $E > 57$ EeV, observes hot spot for $E > E_{\rm GZK}$. PAO anisotropies not prominent: a spot around Cen A and warm spot at NGC 253 – are two skies really different?

- Arrival directions?

$E > 100$ EeV are expected from local supercluster (Virgo cluster etc.) and/or closeby structures. But they do not come from these directions. TA has small angle correlation for $E > 100$ EeV events (3 doublets) which may indicate towards strong sources – but no sources are associated
– where do they all come from?

- Who are cosmic Zevatrons?

Several candidates on Hillas Plot (AGN, HBL, SBG, GRB etc.)
– but no reliable acceleration mechanism

UHECR as protons and GZK cutoff

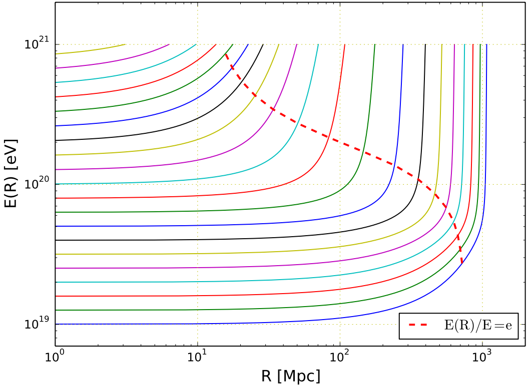
GZK cutoff:

Photo-pion production on the CMB if $E > E_{\rm GZK} \approx \frac{m_\pi m_p}{\varepsilon_{\rm CMB}} \approx 6 \times 10^{19}$ eV :

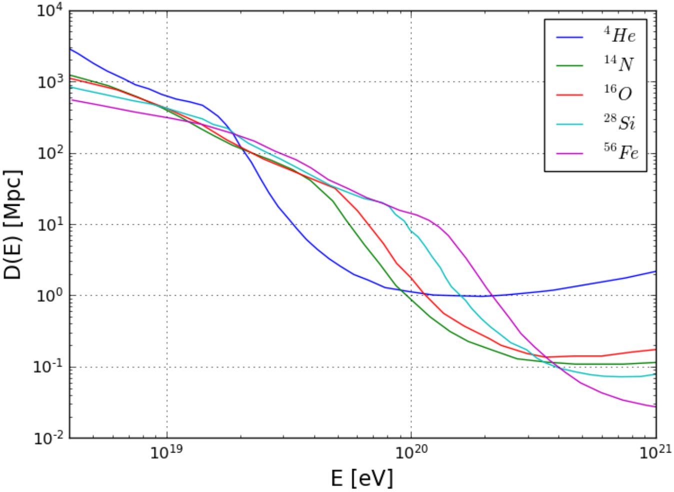
$p + \gamma \to p + \pi^0$ (or $n + \pi^+$), $\quad l_{\rm mfp} \sim 5$ Mpc for $E > 10^{20}$ eV $= 100$ EeV

Neutron decay: $n \to p + e + \bar{\nu}_e$, $\quad l_{\rm dec} = \left(\frac{E}{100\ {\rm EeV}}\right)$ Mpc

Neutron on CMB scattering: $n + \gamma \to n + \pi^0$ (or $p + \pi^-$)

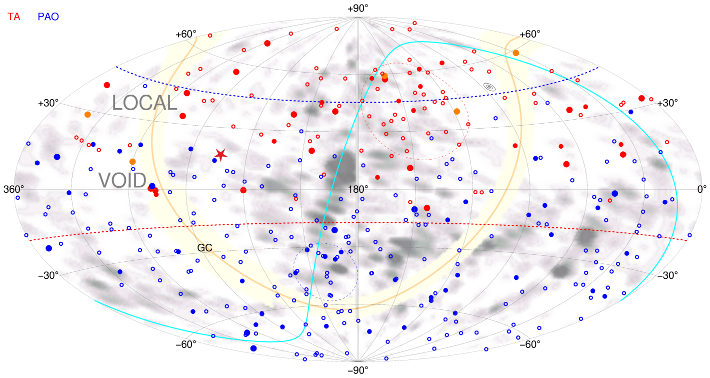


UHECR as nuclei – but still cutoff



UHECR $E > 100$ EeV (big circles) + all super GZK events $E > 60$ EeV

TA - 10 events, PAO - 8 events (data till 2015)



Eye: $E = 320$ EeV Fly'e Eye Monster Father McKenzie (FM)

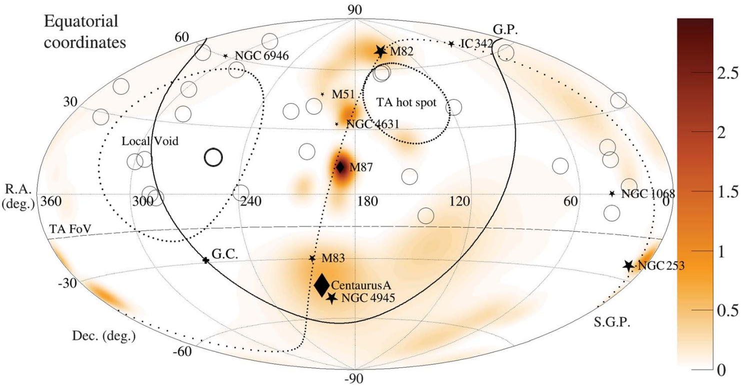
Star $E = 244$ EeV TA Energetic Record Eleanor Rigby (ER)

+ 2 AGASSA events $E > 200$ EeV + 2 PAO & 2 TA events $E > 165$ EeV

– Where do they all come from... and where do they all belong?

4 years after: Telescope Array, Science, Dec. 2023

$E > 244$ EeV (big circle) + 27 events $E > 100$ EeV (circles)

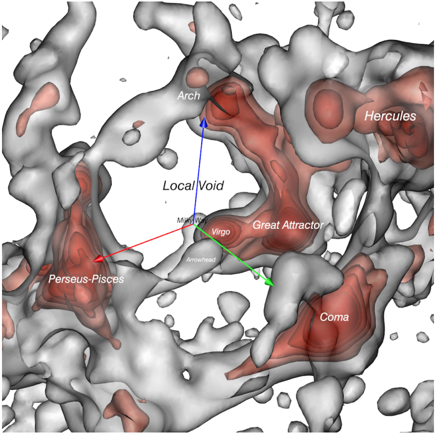


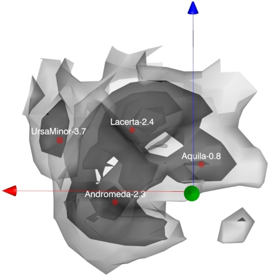
now PAO has published now 36 events with $E > 100$ EeV

Local Universe: Local Void and others around ...

Local Universe within 150 Mpc (SG coordinates X, Y, Z)

Local Void – $\Delta X \times \Delta Y \times \Delta Z \simeq 70 \times 50 \times 60 \simeq 2 \times 10^5$ Mpc^3





Sculptor Void - $\Delta X \times \Delta Y \times \Delta Z \simeq 190 \times 90 \times 140 \simeq 2 \times 10^6$ Mpc^3.

Chapter II

Dark Matter from a Parallel World

Bright & Dark Sides of our Universe

- $\Omega_B \simeq 0.05$ observable matter: electron, proton, neutron !
- $\Omega_D \simeq 0.25$ dark matter: WIMP? axion? sterile ν? ...
- $\Omega_\Lambda \simeq 0.70$ dark energy: Λ-term? Quintessence? ....
- $\Omega_R < 10^{-3}$ relativistic fraction: relic photons and neutrinos

Matter – dark energy *coincidence:* $\Omega_M/\Omega_\Lambda \simeq 0.45$, $(\Omega_M = \Omega_D + \Omega_B)$
$\rho_\Lambda \sim$ Const., $\rho_M \sim a^{-3}$; *why* $\rho_M/\rho_\Lambda \sim 1$ – *just Today?*
Antrophic explanation: if not *Today*, then *Yesterday* or *Tomorrow*.

Baryon and dark matter *Fine Tuning:* $\Omega_B/\Omega_D \simeq 0.2$
$\rho_B \sim a^{-3}$, $\rho_D \sim a^{-3}$: *why* $\rho_B/\rho_D \sim 1$ - *Yesterday Today & Tomorrow?*

Baryogenesis requires BSM Physics: (GUT-B, Lepto-B, AD-B, EW-B ...)

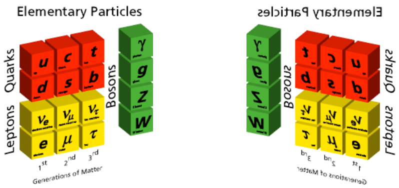
Dark matter requires BSM Physics: (Wimp, Wimpzilla, sterile ν, axion, ...)

Different physics for B-genesis and DM?
Not very appealing: looks as Fine Tuning

$SU(3) \times SU(2) \times U(1) \quad + \quad SU(3)' \times SU(2)' \times U(1)'$

$$G \times G'$$

Regular world — Mirror world



- Two identical gauge factors, e.g. $SU(5) \times SU(5)'$, with identical field contents and Lagrangians: $\mathcal{L}_{\rm tot} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{\rm mix}$
- Exact parity $G \to G'$: no new parameters in dark Lagrangian $\mathcal{L}'$
- MM is dark (for us) and has the same gravity
- MM is identical to standard matter, (asymmetric/dissipative/atomic) but realized in somewhat different cosmological conditions: $T'/T \ll 1$.
- New interactions between O & M particles $\quad \mathcal{L}_{mix}$

– All you need is ... M world colder than ours !

For a long time M matter was not considered as a real candidate for DM: naively assuming that exactly identical microphysics of O & M worlds implies also their cosmologies are exactly identical :

- $T' = T, \quad g'_* = g_* \quad \to \quad \Delta N_\nu^{\rm eff} = 6.15$ vs. $\Delta N_\nu^{\rm eff} < 0.5$ (BBN)
- $n'_B/n'_\gamma = n_B/n_\gamma \ (\eta' = \eta) \quad \to \quad \Omega'_B = \Omega_B$ vs. $\Omega'_B/\Omega_B \simeq 5$ (DM)

But all is OK if : Z.B., Dolgov, Mohapatra, 1995 *(broken PZ_2)*
Z.B., Comelli, Villante, 2000 *(exact PZ_2)*

A. after inflation M world was born colder than O world, $T'_R < T_R$
B. any interactions between M and O particles are feeble and cannot bring two sectors into equilibrium in later epochs
C. two systems evolve adiabatically (no entropy production): $T'/T \simeq$const

$T'/T < 0.5$ from BBN, but cosmological limits $T'/T < 0.2$ or so.

$x = T'/T \ll 1 \quad \Longrightarrow \quad$ in O sector 75% H + 25% ^{4}He
$\Longrightarrow \quad$ in M world 25% H$'$ + 75% ^{4}He$'$

For broken PZ_2, DM can be compact H' atoms or n' with $m \simeq 5$ GeV or (sterile) mirror neutrinos $m \sim$ few keV Z.B., Dolgov, Mohapatra, 1995

Experimental and observational manifestations

A. *Cosmological implications.* $T'/T < 0.2$ or so, $\Omega'_B/\Omega_B = 1 \div 5$.
Mass fraction: H' – 25%, He' – 75%, and few % of heavier C', N', O' etc.
• Mirror baryons as asymmetric/collisional/dissipative/atomic dark matter: M hydrogen recombination and M baryon acoustic oscillations?
• Easier formation and faster evolution of stars: Dark matter disk? Galaxy halo as mirror elliptical galaxy? Microlensing ? Neutron stars? Black Holes? Binary Black Holes? Central Black Holes?

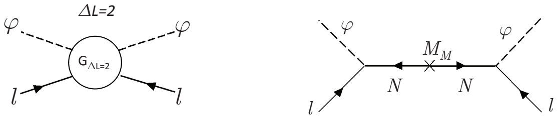
B. *Direct detection.* M matter can interact with ordinary matter e.g. via kinetic mixing $\epsilon F^{\mu\nu} F'_{\mu\nu}$, etc. Mirror helium as most abundant mirror matter particles (the region of DM masses below 5 GeV is practically unexplored). Possible signals from heavier nuclei C,N,O etc.

C. *Oscillation phenomena between ordinary and mirror particles.*
The most interesting interaction terms in $\mathcal{L}_{\rm mix}$ are the ones which violate B and L of both sectors. Neutral particles, elementary (as e.g. neutrino) or composite (as the neutron or hydrogen atom) can mix with their mass degenerate (sterile) twins: matter disappearance (or appearance) phenomena can be observable in laboratories.
In the Early Universe, these B and/or L violating interactions can give primordial baryogenesis and dark matter genesis, with $\Omega'_B/\Omega_B = 1 \div 5$.

B-L violation in O and M sectors: Active-sterile mixing

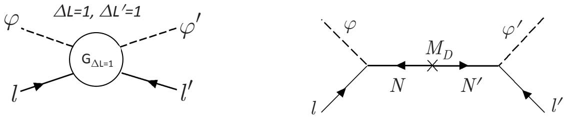
- $\frac{1}{M}(l\bar{\phi})(l\bar{\phi})$ $(\Delta L = 2)$ – neutrino (seesaw) masses $m_\nu \sim v^2/M$

M is the (seesaw) scale of new physics beyond EW scale.



- Neutrino -mirror neutrino mixing – (active - sterile mixing)

L and L' violation: $\frac{1}{M}(l\bar{\phi})(l\bar{\phi})$, $\frac{1}{M}(l'\bar{\phi}')(l'\bar{\phi}')$ and $\frac{1}{M}(l\bar{\phi})(l'\bar{\phi}')$



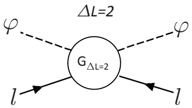
Mirror neutrinos are natural candidates for sterile neutrinos

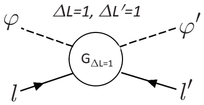
Akhmedov, Z.B. and Senjanovic, 1992,

Foot and Volkas, Z.B. and Mohapatra, 1995

Co-leptogenesis: B-L violating interactions between O and M worlds

L and L' violating operators $\frac{1}{M}(l\bar{\phi})(l\bar{\phi})$ and $\frac{1}{M}(l\bar{\phi})(l'\bar{\phi}')$ lead to processes $l\phi \to \bar{l}\bar{\phi}$ $(\Delta L = 2)$ and $l\phi \to \bar{l}'\bar{\phi}'$ $(\Delta L = 1,\ \Delta L' = 1)$





Asymmetric reheating: our world is heated and mirror is empty: but $l\phi \to \bar{l}'\bar{\phi}'$ heat also mirror world (but with $T' < T$)

- These processes should be out-of-equilibrium
- Violate baryon numbers in both worlds, $B-L$ and $B'-L'$
- Violate also CP, given complex couplings

Green light to celebrated conditions of Sakharov

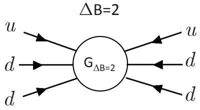
Co-leptogenesis in both sectors Z.B. and Bento, PRL 87, 231304 (2001)
naturally explaining $\Omega'_B \simeq 5\,\Omega_B$ Z.B., IJMP A19, 3775 (2004)

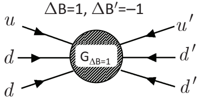
B violating operators between O and M particles in $\mathcal{L}_{\rm mix}$

Ordinary quarks u, d (antiquarks $\bar{u}$, $\bar{d}$)
Mirror quarks u', d' (antiquarks $\bar{u}'$, $\bar{d}'$)

- Neutron -mirror neutron mixing – (Active - sterile neutrons)

$$\frac{1}{M^5}(udd)(udd) \qquad \& \qquad \frac{1}{M^5}(udd)(u'd'd')$$

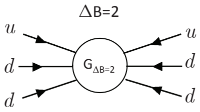




Oscillations $n \to \bar{n}$ $(\Delta B = 2)$
Oscillations $n \to \bar{n}'$ $(\Delta B = 1,\ \Delta B' = -1)$ $B - B'$ is conserved

Neutron– antineutron mixing

Majorana mass of neutron $\epsilon(n^T C n + \bar{n}^T C \bar{n})$ violating B by two units comes from six-fermions effective operator $\frac{1}{M^5}(udd)(udd)$



It causes transition $n(udd) \to \bar{n}(\bar{u}\bar{d}\bar{d})$, with oscillation time $\tau = \epsilon^{-1}$

$$\varepsilon = \langle n|(udd)(udd)|\bar{n}\rangle \sim \frac{\Lambda^6_{\rm QCD}}{M^5} \sim \left(\frac{100\ \rm TeV}{M}\right)^5 \times 10^{-25}\ \rm eV$$

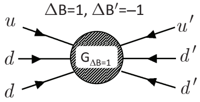
Key moment: *$n - \bar{n}$ oscillation destabilizes nuclei:*
$(A, Z) \to (A-1, \bar{n}, Z) \to (A-2, Z/Z-1) + \pi$'s

Present bounds on ϵ from nuclear stability

$\varepsilon < 2.5 \times 10^{-24}$ eV $\quad\to\quad$ $\tau > 2.7 \times 10^8$ s $\qquad$ O, SK 2015
$\varepsilon < 7.5 \times 10^{-24}$ eV $\quad\to\quad$ $\tau > 0.9 \times 10^8$ s $\qquad$ direct limit free n

Neutron – mirror neutron mixing

Effective operator $\frac{1}{M^5}(udd)(u'd'd') \quad \to \quad$ mass mixing $\epsilon n C n' + \mathrm{h.c.}$
violating B and B' – but conserving $B - B'$



$$\epsilon = \langle n|(udd)(u'd'd')|\bar{n}'\rangle \sim \frac{\Lambda^6_{\rm QCD}}{M^5} \sim \left(\frac{1\ \mathrm{TeV}}{M}\right)^5 \times 10^{-10}\ \mathrm{eV}$$

Key observation: *$n - \bar{n}'$ oscillation cannot destabilise nuclei:*
$(A, Z) \to (A-1, Z) + n'(p'e'\bar{\nu}')$ forbidden by energy conservation

For $m_n = m_{n'}$, $n - \bar{n}'$ oscillation can be as fast as $\epsilon^{-1} = \tau_{n\bar{n}'} \sim 1$ s without contradicting experimental and astrophysical limits.
(c.f. $\tau > 10$ yr for neutron – antineutron oscillation)

Neutron disappearance $n \to \bar{n}'$ and regeneration $n \to \bar{n}' \to n$ can be searched at small scale 'Table Top' experiments

Z.B. and Bento, PRL 96, 081801 (2006)

Free Neutrons: Where to find Them ?

Neutrons are making 1/7 fraction of baryon mass in the Universe.

But most of neutrons are bound in nuclei ....

$n \to \bar{n}'$ or $n' \to \bar{n}$ conversions are effective only for free neutrons.

Free neutrons are present only in

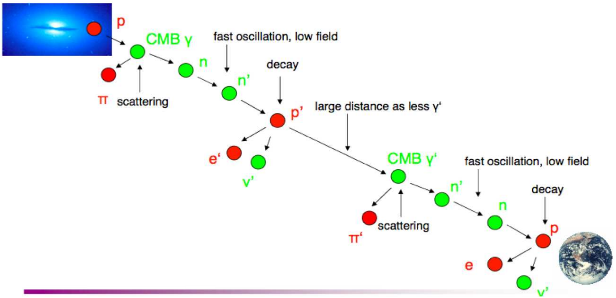
- Reactors & Spallation Facilities (challenge $\tau_{n\bar{n}'} < \tau_{dec} \simeq 10^3$ s)
- UHE Cosmic Rays: $p + \gamma \to n + \pi^+$, $N_A + \gamma \to N_{A-1} + n$

$-$ $n \to \bar{n}'$ can take place in Neutron Stars (gravitationally bound)
– conversion of NS into mixed ordinary/mirror NS

Chapter III

$n - n'$ and UHECR

$n - n'$ oscillation and UHECR propagation



Z. Berezhiani, L. Bento, Fast neutron – Mirror neutron oscillation and ultra high energy cosmic rays, Phys. Lett. B 635, 253 (2006).

A. $p + \gamma \to p + \pi^0$ or $p + \gamma \to n + \pi^+$ $\quad P_{pp,pn} \approx 0.5 \quad l_{\rm mfp} \sim 5$ Mpc

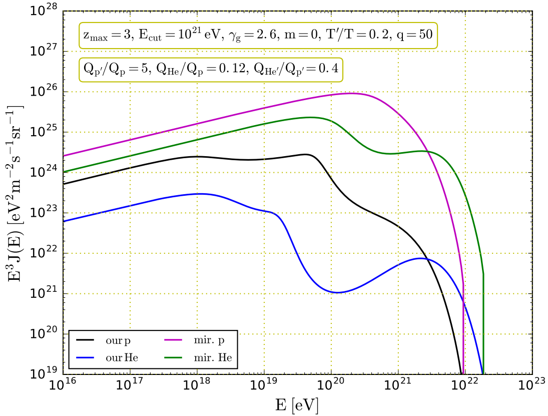
B. $n \to n' \quad P_{nn'} \simeq 0.5 \quad l_{\rm osc} \sim \left(\frac{E}{100~\rm EeV}\right)$ kpc

C. $n' \to p' + e' + \bar{\nu}'_e \quad l_{\rm dec} \approx \left(\frac{E}{100~\rm EeV}\right)$ Mpc

D. $p' + \gamma' \to p' + \pi'^0$ or $p' + \gamma' \to n' + \pi'^+ \quad l'_{\rm mfp} \sim (T/T')^3\, l_{\rm mfp} \gg 5$ Mpc

Ordinary and Mirror UHECR

$$\frac{n'_{\rm CMB}}{n_{\rm CMB}} = \left(\frac{T'}{T}\right)^3 \ll 1 \quad \longrightarrow \quad \frac{\ell'_{\rm mfp}}{\ell_{\rm mfp}} \simeq \left(\frac{T}{T'}\right)^3 \gg 1$$



$n - n'$ oscillation in the UHECR propagation

Baryon number is not conserved in propagation of the UHECR

$$H = \begin{pmatrix} \mu_n \mathbf{B}\sigma & \epsilon \\ \epsilon & \mu_n \mathbf{B}'\sigma \end{pmatrix} \times (\gamma = E/m_n)$$

In the intergalactic space magnetic fields are extremely small ... but

for relativistic neutrons transverse component of B is enhanced by Lorentz factor: $B_{\rm tr} = \gamma B$ $(\gamma \sim 10^{11}$ for $E \sim 100$ EeV)

Average oscillation probability:

$$P_{nn'} = \sin^2 2\theta_{nn'} \sin^2(\ell/\ell_{\rm osc}) \simeq \frac{1}{2}\left[1 + Q(E)\right]^{-1} \qquad \tan 2\theta_{nn'} = \frac{2\epsilon}{\gamma \mu_n \Delta B}$$

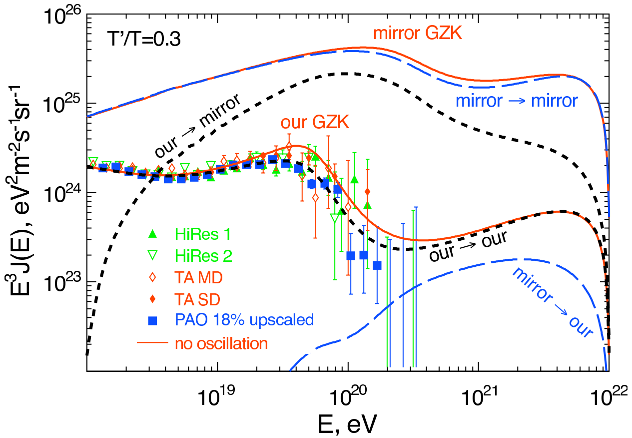
$$Q = (\gamma \Delta B/2\epsilon)^2 \approx 0.5 \left(\frac{\tau_{nn'}}{1~\rm s}\right)^2 \left(\frac{\Delta B}{1~\rm fG}\right)^2 \left(\frac{E}{100~\rm EeV}\right)^2 \qquad \Delta B = |B_{\rm tr} - B'_{\rm tr}|$$

If $q = 0.5 \left(\frac{\tau_{nn'}}{1~\rm s}\right)^2 \left(\frac{\Delta B}{1~\rm fG}\right)^2 < 1$,
$n - n'$ oscillation becomes effective for $E = 100$ EeV

Earlier (than GZK) cutoff in cosmic rays

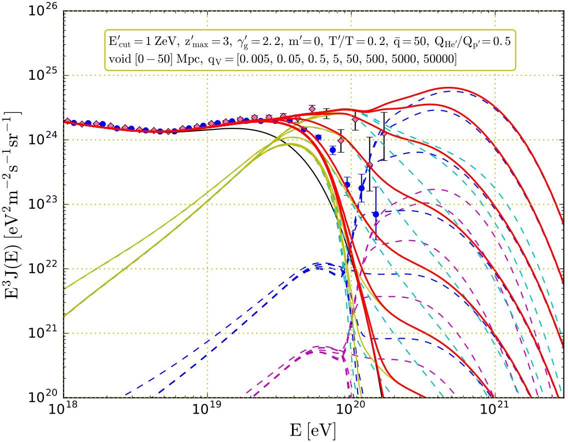
Z.B. and Gazizov, Neutron Oscillations to Parallel World: Earlier End to the Cosmic Ray Spectrum? Eur. Phys. J. C 72, 2111 (2012)

Baryon number is not conserved in propagation of the UHECR

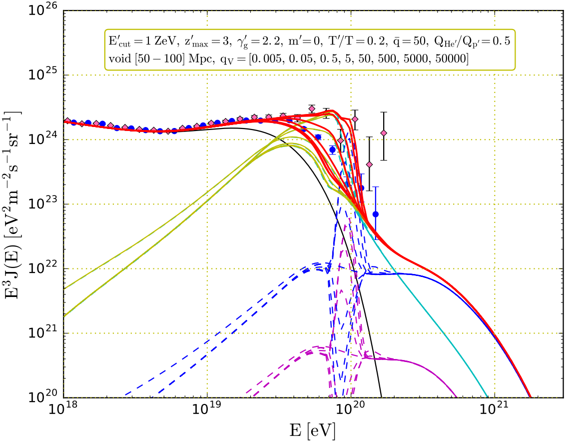


Swiss Cheese Model: Mirror CRs are transformed into ordinaries in nearby Voids. Z.B., Biondi, Gazizov, 2019

Adjacent Void (0–50 Mpc) $\quad q = 0.5 \times \left(\frac{\tau_{nn'}}{1\ \mathrm{s}}\right)^2 \left(\frac{B_{\rm tr} - B'_{\rm tr}}{1\ \mathrm{fG}}\right)^2$



Swiss cheese: More distant Void (50–100 Mpc)



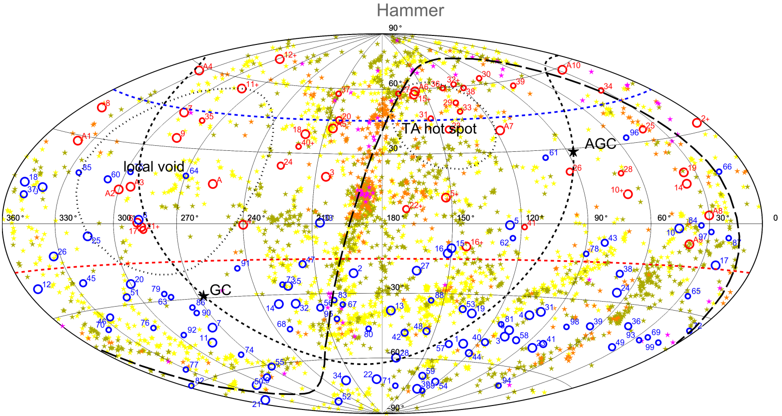
Is northern sky (TA) is more "voidy" than the Southern sky (PAO) ?

Interestingly, some 20–30% admixture of protons above the GZK energies improves the "chemical" fit also for PAO data Muzio et al. 2019

Razzaque, this conference

Today's situation ...

UHECR events with $E > 100$ EeV: TA – 28 events (red circles) – 15 from LV, others mostly under dense regions PAO = 36 events (blue circles) – 5 from LV, many from Sculptor, Eridanus and Puppis



Sculptor Void - $\Delta X \times \Delta Y \times \Delta Z \simeq 190 \times 90 \times 140 \simeq 2 \times 10^6$ Mpc^3.

Summary (From my talk at TEVPA 2019)

The UHECR spectra observed by TA and PAO are perfectly concordant (after 10% rescaling) at energies up to 10 EeV ... but become increasingly discordant at higher energies, very strongly above the GZK cutoff (60 EeV)

The discrepancy can be due to difference between the N- and S-skies! N-sky is well structured, with prominent overdensities and large voids ... S-sky is more amorphous with diffuse galaxies ...

It is unlikely that PAO–TA discrepancy is due to different power of sources within the GZK radius (no correlation with the galaxy distribution at $E > 80$ EeV, no event from the Virgo or Fornax clusters, etc.)

But it can be explained in "Swiss Cheese" model: UHECR above $80 - 100$ EeV are born from mirror UHECR via $n' - n$ conversion in nearby voids within the radius $\sim 50 - 100$ Mpc (Voids = small magnetic fields)

The TA signal at super-GZK energies is boosted by prominent Voids in N-hemisphere. This can also explain intermediate scale anisotropies (20-30 degrees) in the TA arrival directions Interestingly, the TA/PAO spectra are concordant in the common sky ...

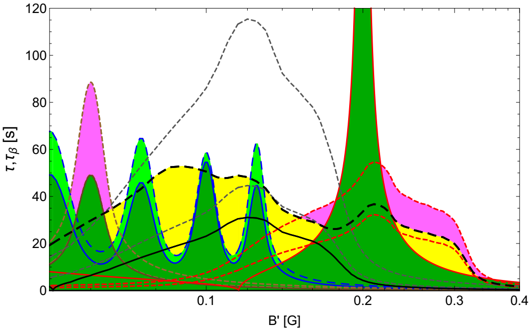
My hypothesis is testable with the new data of TA/PAO at higher statistics on $E > 100$ EeV events for which typical "voidity" radius is ~ 50 Mpc

Summary (Continued)

Implication for cosmogenic neutrinos. Mirror Sector is Helium dominated, and in mirror UHECR $^4He'$ can be more than p'. So neutrons can be produced also by $^4He' + \gamma' \to ^3 He' + n'$. Subsequent decay $n' \to p'e'\bar{\nu}'$ and (sterile-active) oscillation $\nu' \to \nu$ can produce large flux of cosmogenic neutrinos which may explain astrophysical neutrino flux of IceCube above 100 TeV at higher redshifts

$n - n'$ conversion also has interesting implications for the neutron stars (gradual conversion of the neutron stars into mixed ordinary-mirror stars till achieving "fifty-fifty" mixed twin star configuration with $\sqrt{2}$ times smaller radius and maximal mass ...

Remarkably, it can be tested in laboratories via looking for anomalous (magnetic field dependent) disappearance of the neutrons (for which there already exist some experimental indications, most remarkable at the 5.2σ level) due to $n \to n'$ conversion and and "walking through the wall" experiments ($n \to n' \to n$ regeneration). $n - n'$ oscillation can be also related to the neutron lifetime puzzle.



$q = 0.5 \left(\frac{\tau_{nn'}}{1\ \mathrm{s}}\right)^2 \left(\frac{\Delta B}{1\ \mathrm{fG}}\right)^2 \geq 1$ implies $\Delta B \leq 1$ fG for $\tau_{nn'} \simeq 1$ s
In turn, $\Delta B > 10^{-17}$ G implies $\tau_{nn'} < 100$ s

limits from the Neutron Star surface heating: $\tau_{nn'} > 1 - 10$ s
Z.B., Biondi, Mannarelli and Tonelli, Eur. Phys. J. C 81, 1036 (2021)

Optimism for $n - n'$ search in new experiments at PSI, ILL and ESS targeting $\tau_{nn'} \sim 100 - 200$ s
N. Ayres et al. [PSI collaboration] , 2021

Thanks

Many Thanks for Listening

The talk of Z.B. was supported in part by the research grant No. 2022E2J4RK "PANTHEON: Perspectives in Astroparticle and Neutrino THEory with Old and New messengers" under the program PRIN 2022 funded by the Italian Ministero dell'Universitá e della Ricerca (MUR) and by the European Union – Next Generation EU.