UHECR from Dark Matter

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TEVPA 2019, Sydney, 2–6 Dec. 2019

Contents

Introduction

Everything can be explained by the Standard Model !

... but there should be more than one Standard Models

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

Dark Matter from a Parallel World

Our observable particles .... *very complex physics !!*
$G = SU(3) \times SU(2) \times U(1)$ (+ SUSY ? GUT ? Seesaw ?)
photon, electron, nucleons (quarks), neutrinos, gluons, $W^{\pm} - Z$, Higgs ...
long range EM forces, confinement scale $\Lambda_{\rm QCD}$, weak scale M_W
... matter *vs.* antimatter (B-L violation, CP ...)
... existence of nuclei, atoms, molecules .... life.... Homo Sapiens !
Best of the possible Worlds .... (Candid, Frank and Uncontrived)

Dark matter from parallel gauge sector ?
$G' = SU(3)' \times SU(2)' \times U(1)'$? (+ SUSY ? GUT '? Seesaw ?)
photon′, electron′, nucleons′ (quarks′), $W' - Z'$, gluons′ ?
... long range EM forces, confinement at $\Lambda'_{\rm QCD}$, weak scale M'_W ?
... asymmetric dark matter (B′-L′ violation, CP ...) ?
... existence of dark nuclei, atoms, molecules ... life ... Homo Aliens ?
Another Best of the possible Worlds? (Maybe Candide had a twin?)

Call it Yin-Yang (in chinise, dark-bright) duality

describes a philosophy how opposite forces are actually complementary, interconnected and interdependent in the natural world, and how they give rise to each other as they interrelate to one another.

$E_8 \times E'_8$

$SU(3)\times SU(2)\times U(1)$ vs. $SU(3)'\times SU(2)'\times U(1)'$

Two parities

Fermions and anti-fermions :

$$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad l_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}; \qquad u_R,\ d_R, \quad e_R$$

B=1/3 L=1 B=1/3 L=1

$$\bar q_R = \begin{pmatrix} \bar u_R \\ \bar d_R \end{pmatrix}, \quad \bar l_R = \begin{pmatrix} \bar\nu_R \\ \bar e_R \end{pmatrix}; \qquad \bar u_L,\ \bar d_L, \quad \bar e_L$$

B=-1/3 L=-1 B=-1/3 L=-1

Twin Fermions and anti-fermions :

$$q'_L = \begin{pmatrix} u'_L \\ d'_L \end{pmatrix}, \quad l'_L = \begin{pmatrix} \nu'_L \\ e'_L \end{pmatrix}; \qquad u'_R,\ d'_R, \quad e'_R$$

B′=1/3 L′=1 B′=1/3 L′=1

$$\bar q'_R = \begin{pmatrix} \bar u'_R \\ \bar d'_R \end{pmatrix}, \quad \bar l'_R = \begin{pmatrix} \bar\nu'_R \\ \bar e'_R \end{pmatrix}; \qquad \bar u'_L,\ \bar d'_L, \quad \bar e'_L$$

B′=-1/3 L′=-1 B′=-1/3 L′=-1

$$\mathcal{L}_{\rm Yuk} = \bar u_L Y_u q_L \bar\phi + \bar d_L Y_d q_L \phi + \bar e_L Y_e l_L \phi \quad + \quad \text{h.c.}$$
$$\mathcal{L}_{\rm Yuk} = \bar u'_L Y'_u q'_L \bar\phi' + \bar d'_L Y'_d q'_L \phi' + \bar e'_L Y'_e l'_L \phi' \quad + \quad \text{h.c.}$$

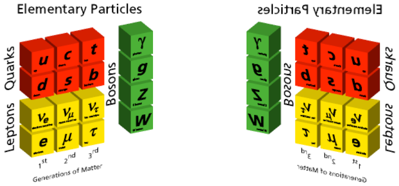
Z_2 symmetry $(L, R \to L, R)$: $\quad Y' = Y \qquad B - B' \to -(B - B')$

PZ_2 symmetry $(L, R \to R, L)$: $\quad Y' = Y^* \qquad B - B' \to B - B'$

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

$$G \times G'$$

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 :

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

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

Brief Cosmology of Mirror World

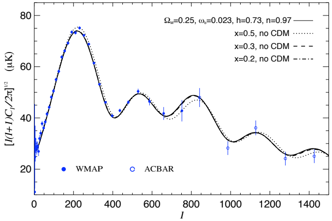
• CMB & (linear) structure formation epoch
Since $x = T'/T \ll 1$, mirror photons decouple before M-R equality:
$z'_{\rm dec} \simeq x^{-1} z_{\rm dec} \simeq 1100\,(T/T')$
After that (and before M–reionization) M matter behaves as collisionless CDM and $T'/T < 0.2$ is consistent with Planck, BAO, Ly-α etc.

• Cosmic dawn: M world is colder (and helium dominated), the first M star can be formed earlier and reionize M sector ($z'_{\rm r} \simeq 20$ or so vs $z_{\rm r} = 10 \div 6$). – EDGES 21 cm at $z \simeq 17$?
Heavy first M stars ($M \sim 10^3 M_\odot$) and formation of central BH – Quasars?

• Galaxy halos? if $\Omega'_B \simeq \Omega_B$, M matter makes ~ 20 % of DM, forming dark disk, while ~ 80 % may come from other type of CDM (WIMP?)
But perhaps 100 % ? if $\Omega'_B \simeq 5\Omega_B$: – M world is helium dominated, and the star formation and evolution can be much faster. Halos could be viewed as mirror elliptical galaxies dominated by BH and M stars, with our matter forming disks inside.
Maybe not always: Galaxies with missing DM, or too many DM, etc. ?

Because of $T' < T$, the situation $\Omega'_B \simeq 5\Omega_B$ becomes plausible in baryogenesis. So, M matter can be dark matter (as we show below)

CMB and LSS power spectra

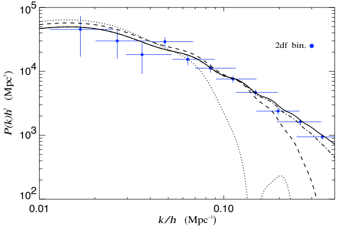


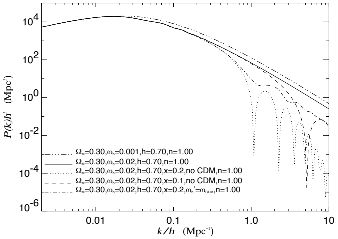
ZB, Ciarcelluti, Comelli, Villante, 2003

$$z'_{\rm dec} \simeq x^{-1} z_{\rm dec} \simeq 1100\,(T/T')$$

⟵ imprint of $\Delta N_{\rm eff}$

imprint of M-baryon oscillations



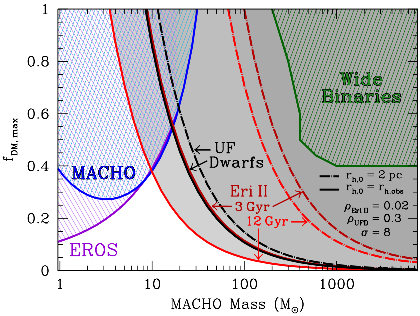


Acoustic oscillations and Silk damping scales: $x = 0.5,\ 0.3,\ 0.2$

$x < 0.2$: Galaxies with $M < 10^{8\div 9} M_\odot$ will be damped

Can Mirror stars be progenitors of gravitational Wave bursts GW150914 etc. ?

Picture of Galactic halos as mirror ellipticals (Einasto density profile?), O matter disk inside (M stars = Machos)
Microlensing limits: $f \sim 20 - 40$ % for $M = 1 - 10\ M_\odot$,
$f \sim 100$ % is allowed for $M = 20 - 200\ M_\odot$



GW events without any optical counterpart

Massive BH compact binaries, $M \sim 10 - 100\ M_\odot$

Can such objects be formed from MM?

M matter: 25 % Hydrogen vs 75 % Helium: M stars more compact, less opaque, less mass loses by stellar wind and evolving much faster.
Appropriate for forming such BH binaries ? And perhaps large seeds for central BH in overdense regions?

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 $\Omega'_B/\Omega_B = 1 \div 5$.

Possible portals to Mirror World: $\mathcal{L}_{\rm mix}$

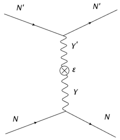
these terms can be limited (only) by experiment/cosmology !

- Kinetic mixing of photons $\epsilon F^{\mu\nu} F'_{\mu\nu}$

Makes mirror matter nanocharged ($q \sim \epsilon$)

$\epsilon < 3 \times 10^{-7}$ (EXP) $\quad \epsilon < 5 \times 10^{-9}$ (COSM)

GUT: $\frac{1}{M^2} (\Sigma G^{\mu\nu})(\Sigma' G'_{\mu\nu}) \quad \epsilon \sim \left(\frac{M_{GUT}}{M}\right)^2$



Can induce galactic magnetic fields Z.B., Dolgov, Tkachev, 2013

- Higgs-Higgs′ coupling $\lambda(\phi^\dagger \phi)(\phi'^\dagger \phi')$

$\lambda < 10^{-7}$ (COSM)

SUSY: $\frac{1}{M}(\phi_1\phi_2)(\phi'_1\phi'_2)$

$\lambda \sim M_{\rm SUSY}/M$

or NMSSM (Twin Higgs)

$\lambda S(\phi_1\phi_2 + \phi'_1\phi'_2) + \Lambda S + \ldots$

- Neutrino-neutrino′ (active-sterile) mixing – discussed later

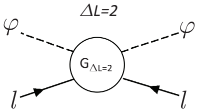
- Neutron-neutron′ mixing – discussed later

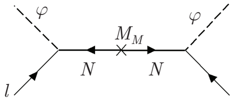
Chapter I

Neutrino – mirror neutrino mixings

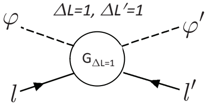
B-L violation in O and M sectors: Active-sterile mixing

- $\frac{1}{M}(l\bar{\phi})(l\bar{\phi})$ $(\Delta L = 2)$ – neutrino (seesaw) masses $m_\nu \sim v^2/M$
M is the (seesaw) scale of new physics beyond EW scale.



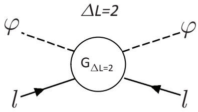


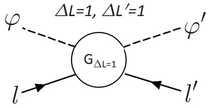
- Neutrino -mirror neutrino mixing – (active - sterile mixing)
L and L' violation: $\frac{1}{M}(l\bar{\phi})(l\bar{\phi})$, $\frac{1}{M}(l'\bar{\phi}')(l'\bar{\phi}')$ and $\frac{1}{M}(l\bar{\phi})(l'\bar{\phi}')$



Mirror neutrinos are natural candidates for sterile neutrinos

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 $l\phi \to \bar{l}'\bar{\phi}'$ $(\Delta L = 1, \Delta L' = 1)$





After inflation, our world is heated and mirror world is empty: but ordinary particle scatterings transform them into mirror particles, heating also mirror world.

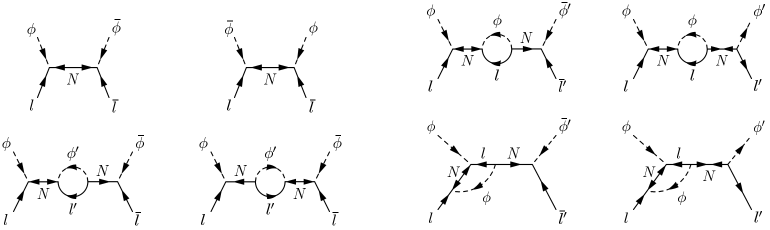
- These processes should be out-of-equilibrium
- Violate baryon numbers in both worlds, $B - L$ and $B' - L'$
- Violate also CP, given complex couplings

Green light to celebrated conditions of Sakharov

Co-leptogenesis:

Z.B. and Bento, PRL 87, 231304 (2001)

Operators $\frac{1}{M}(l\bar{\phi})(l\bar{\phi})$ and $\frac{1}{M}(l\bar{\phi})(l'\bar{\phi}')$ via seesaw mechanism –
heavy RH neutrinos N_j with
Majorana masses $\frac{1}{2}Mg_{jk}N_jN_k + \mathrm{h.c.}$



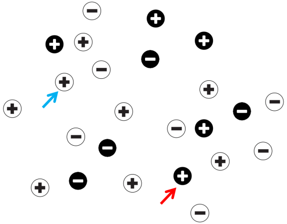
Complex Yukawa couplings $Y_{ij}l_iN_j\bar{\phi} + Y'_{ij}l'_iN_j\bar{\phi}' + \mathrm{h.c.}$

Z_2 (Xerox) symmetry $\rightarrow Y' = Y$,
PZ_2 (Mirror) symmetry $\rightarrow Y' = Y^*$

Co-leptogenesis: Mirror Matter as Dark Anti-Matter

Z.B., arXiv:1602.08599

Hot O World $\longrightarrow$ *Cold M World*



$$\frac{dn_{\rm BL}}{dt} + (3H+\Gamma)n_{\rm BL} = \Delta\sigma\, n_{\rm eq}^2$$

$$\frac{dn'_{\rm BL}}{dt} + (3H+\Gamma')n'_{\rm BL} = -\Delta\sigma'\, n_{\rm eq}^2$$

$$\sigma(l\phi \to \bar{l}\bar{\phi}) - \sigma(\bar{l}\,\bar{\phi} \to l\phi) = \Delta\sigma$$

$$\sigma(l\phi \to \bar{l}'\bar{\phi}') - \sigma(\bar{l}\,\bar{\phi} \to l'\phi') = -(\Delta\sigma + \Delta\sigma')/2 \quad \to \quad 0 \quad (\Delta\sigma = 0)$$

$$\sigma(l\phi \to l'\phi') - \sigma(\bar{l}\,\bar{\phi} \to \bar{l}'\bar{\phi}') = -(\Delta\sigma - \Delta\sigma')/2 \quad \to \quad \Delta\sigma \quad (0)$$

$$\Delta\sigma = {\rm Im\,Tr}[g^{-1}(Y^\dagger Y)^* g^{-1}(Y'^\dagger Y')g^{-2}(Y^\dagger Y)] \times T^2/M^4$$

$$\Delta\sigma' = \Delta\sigma(Y \to Y')$$

Mirror (PZ_2): $\quad Y' = Y^* \quad \to \quad \Delta\sigma' = -\Delta\sigma \quad \to \quad B, B' > 0$

Xerox (Z_2): $\quad Y' = Y \quad \to \quad \Delta\sigma' = \Delta\sigma = 0 \quad \to \quad B, B' = 0$

If $k = \left(\frac{\Gamma}{H}\right)_{T=T_R} \ll 1$, neglecting Γ in eqs $\quad \to \quad n_{BL} = n'_{BL}$

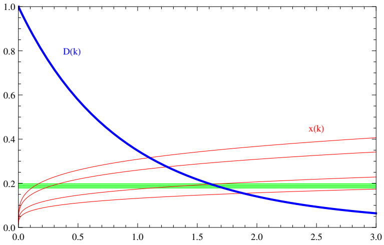
$$\Omega'_B = \Omega_B \simeq 10^3 \frac{J M_{Pl} T_R^3}{M^4} \simeq 10^3 J \left(\frac{T_R}{10^{11}\ {\rm GeV}}\right)^3 \left(\frac{10^{13}\ {\rm GeV}}{M}\right)^4$$

Cogenesis: $\Omega'_B \simeq 5\Omega_B$ Z.B. 2003

If $k = \left(\frac{\Gamma_2}{H}\right)_{T=T_R} \sim 1$, Boltzmann Eqs.

$$\frac{dn_{\rm BL}}{dt} + (3H+\Gamma)n_{\rm BL} = \Delta\sigma\, n_{\rm eq}^2 \qquad \frac{dn'_{\rm BL}}{dt} + (3H+\Gamma')n'_{\rm BL} = \Delta\sigma\, n_{\rm eq}^2$$

should be solved with Γ:



$D(k) = \Omega_B/\Omega'_B$, $\quad x(k) = T'/T$ for different $g_*(T_R)$ and Γ_1/Γ_2.

So we obtain $\Omega'_B = 5\Omega_B$ when $m'_B = m_B$ but $n'_B = 5n_B$

– the reason: mirror world is colder

Chapter II

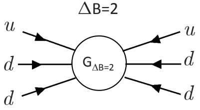
Neutron – mirror neutron mixing

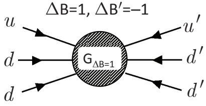
B violating operators between O and M particles in $\mathcal{L}_{\rm mix}$

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)

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

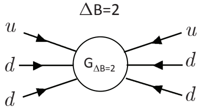




Oscillations $n \to \bar{n}$ $(\Delta B = 2)$
Oscillations $n \to \bar{n}'$ $(\Delta B = 1,\ \Delta B' = -1)$ $B + B'$ is conserved

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 $\tau = \epsilon^{-1}$

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

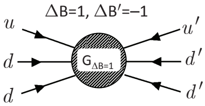
Key moment: *$n - \bar{n}$ oscillation destabilizes nuclei:*
$(A,Z) \to (A-1,\bar{n},Z) \to (A-2,Z/Z-1) + \pi's$

Present bounds on ϵ from nuclear stability

$\varepsilon < 1.2 \times 10^{-24}$ eV	$\to$	$\tau > 1.3 \times 10^{8}$ s	Fe, Soudan 2002
$\varepsilon < 2.5 \times 10^{-24}$ eV	$\to$	$\tau > 2.7 \times 10^{8}$ s	O, SK 2015
$\varepsilon < 7.5 \times 10^{-24}$ eV	$\to$	$\tau > 0.9 \times 10^{8}$ s	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 $\quad B - B'$



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

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

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

Neutron – mirror neutron oscillation probability

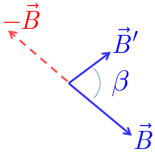
$$H = \begin{pmatrix} m_n + \mu_n \mathbf{B}\sigma & \epsilon \\ \epsilon & m_n + \mu_n \mathbf{B}'\sigma \end{pmatrix}$$

The probability of n-n' transition depends on the relative orientation of magnetic and mirror-magnetic fields. The latter can exist if mirror matter is captured by the Earth

$$P_B(t) = p_B(t) + d_B(t) \cdot \cos\beta$$

$$p(t) = \frac{\sin^2\left[(\omega-\omega')t\right]}{2\tau^2(\omega-\omega')^2} + \frac{\sin^2\left[(\omega+\omega')t\right]}{2\tau^2(\omega+\omega')^2}$$

$$d(t) = \frac{\sin^2\left[(\omega-\omega')t\right]}{2\tau^2(\omega-\omega')^2} - \frac{\sin^2\left[(\omega+\omega')t\right]}{2\tau^2(\omega+\omega')^2}$$

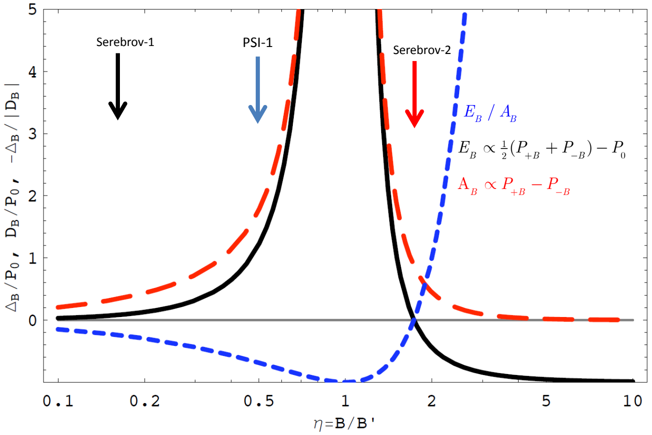


where $\omega = \frac{1}{2}\left|\mu B\right|$ and $\omega' = \frac{1}{2}\left|\mu B'\right|$; τ - oscillation time

$$A_B^{\rm det}(t) = \frac{N_{-B}(t) - N_B(t)}{N_{-B}(t) + N_B(t)} = N_{collis} d_B(t) \cdot \cos\beta \leftarrow \text{ assymetry}$$

A and E are expected to depend on magnetic field

E.g. assume B'=0.12 Gauss



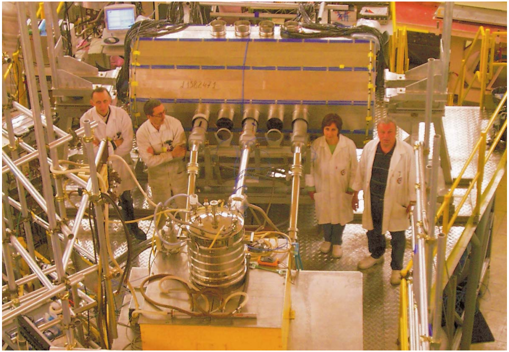
Earth mirror magnetic field via the electron drag mechanism

Earth can accumulate some, even tiny amount of mirror matter due to Rutherford-like scattering of mirror matter due to photon-mirror photon kinetic mixing.
Rotation of the Earth drags mirror electrons but not mirror protons (ions) since the latter are much heavier.
Circular electric currents emerge which can generate magnetic field.
Modifying mirror Maxwell equations by the source (drag) term, one gets $B' \sim \epsilon^2 \times 10^{15}$ G before dynamo, and even larger after dynamo.

Such mechanism can also induce cosmological magnetic fields
Z.B., Dolgov, Tkachev, 2013

Experiments

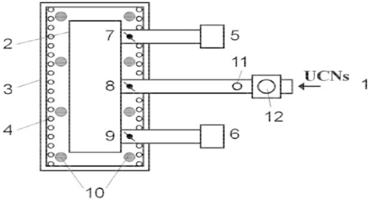
Several experiment were done, 3 by PSI group, most sensitive by the Serebrov's group at ILL, with 190 l beryllium plated trap for UCN



Experimental Strategy

To store neutrons and to measure if the amount of the survived ones depends on the magnetic field applied.

- Fill the Trap with the UCN
- Close the valve
- Wait for T_S (300 s ...)
- Open the valve
- Count the survived Neutrons



Repeat this for different orientation and values of Magnetic field.

$$N_B(T_S) = N(0)\exp\left[-\left(\Gamma + R + \bar{\mathcal{P}}_B \nu\right) T_S\right]$$

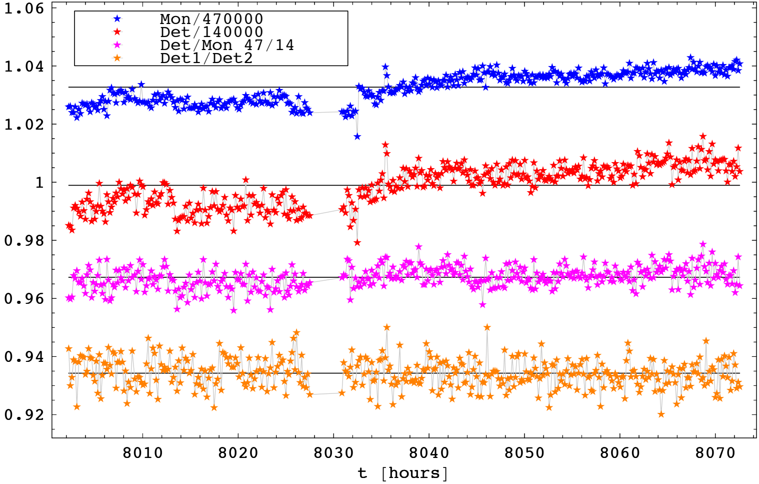
$$\frac{N_{B1}(T_S)}{N_{B2}(T_S)} = \exp\left[\left(\bar{\mathcal{P}}_{B2} - \bar{\mathcal{P}}_{B1}\right) \nu T_S\right]$$

So if we find that:

$$A(B, T_S) = \frac{N_B(T_S) - N_{-B}(T_S)}{N_B(T_S) + N_{-B}(T_S)} \neq 0 \qquad E(B, b, T_S) = \frac{N_B(T_S)}{N_b(T_S)} - 1 \neq 0$$

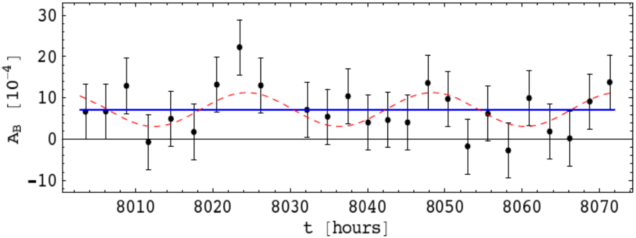
Serebrov III – Drifts of detector and monitor counts

Exp. sequence: $\{B_-, B_+, B_+, B_-, B_+, B_-, B_-, B_+\}$, $B = 0.2$ G



Serebrov III – magnetic field vertical

Exp. sequence: $\{B_-, B_+, B_+, B_-, B_+, B_-, B_-, B_+\}$, $B = 0.2$ G



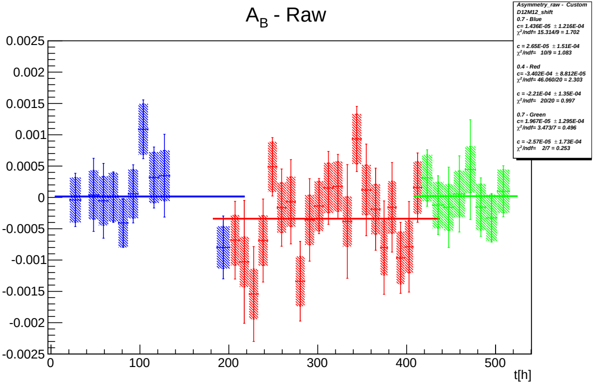
Analysis pointed out the presence of a signal:

$$A(B) = (7.0 \pm 1.3) \times 10^{-4} \qquad \chi^2_{/dof} = 0.9 \longrightarrow 5.2\sigma$$

interpretable by $n \to n'$ with $\tau_{nn'} \sim 2 - 10s$‘ and $B' \sim 0.1G$

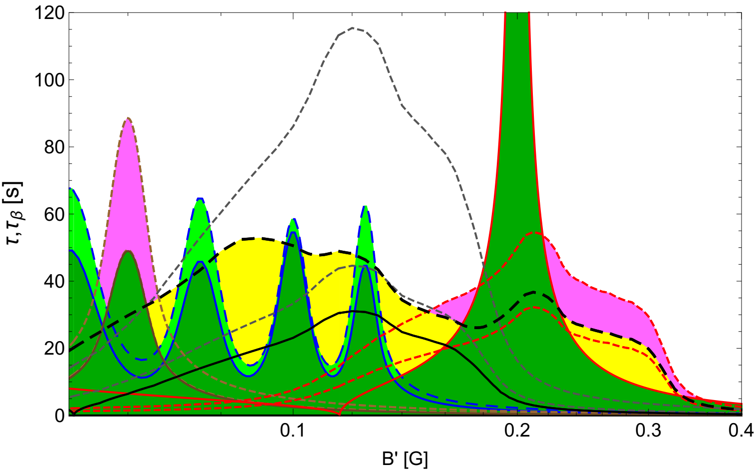
Z.B. and Nesti, 2012

My own experiment at ILL – Z.B., Biondi, Geltenbort et al. 2018



$4\sigma \quad \rightarrow \quad 2.5\sigma \quad$ effect

Exp. limits on $n - n'$ oscillation time – ZB et al, Eur. Phys. J. C. 2018



Free Neutrons: Where to find Them ?

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

But most of neutrons bound in nuclei ....

$n \to \bar{n}'$ or $n' \to \bar{n}$ conversions can be seen only with free neutrons.

Free neutrons are present only in

- Reactors and Spallation Facilities
- In Cosmic Rays
- During BBN epoch (fast $n' \to \bar{n}$ can solve Lithium problem)

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

Chapter III

$n - n'$ and UHECR

Z.B., Biondi, Gazizov

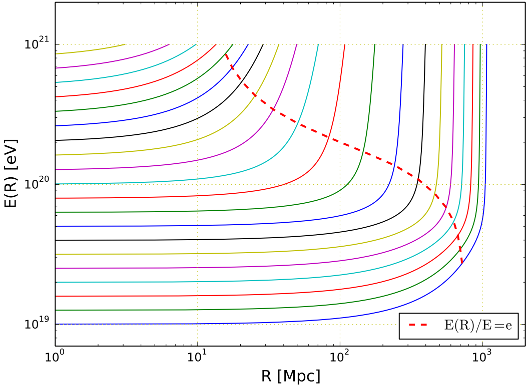
GZK cutoff:

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 :

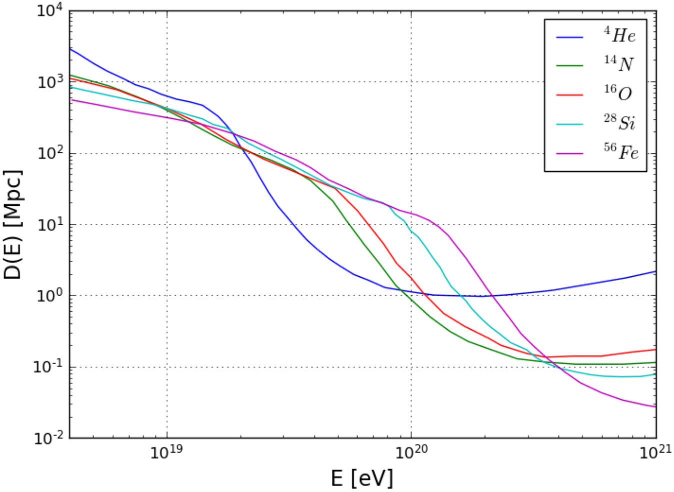
$p + \gamma \to p + \pi^0$ (or $n + \pi^+$), $\quad l_{\rm mfp} \sim 5$ Mpc for $E > 10^{20}$ eV $= 100$ EeV

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

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



UHECR as nuclei

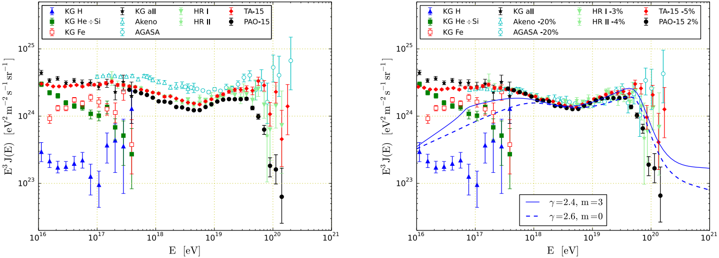


UHECR and GZK cutoff

Two giant detectors see UHECR spectra different at $E > E_{\rm GZK}$

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 ≈ 8 %



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

Events with $E > 100$ EeV were observed
Cosmic Zevatrons exist in the Universe – but where is GZK cutoff?

But also other discrepancies are mounting ...

- Who are carriers of UHECR ?

PAO and TA see different chemical content: TA is compatible with protons below 10 EeV, PAO insists UHECR become heavier nuclei above $E > 10$ EeV or so – perhaps new physics ?

- Different anistropies from North and South ?

TA excludes isotropic distribution at $E > 57$ EeV, observes hot spot for events $E > E_{\rm GZK}$ (which spot is colder for $E < E_{\rm GZK}$) . PAO anisotropies not prominent: warm spot around Cen A, and small dipole for $E > 10$ EeV – are two skies realy different ?

- From where highest energy events do come ?

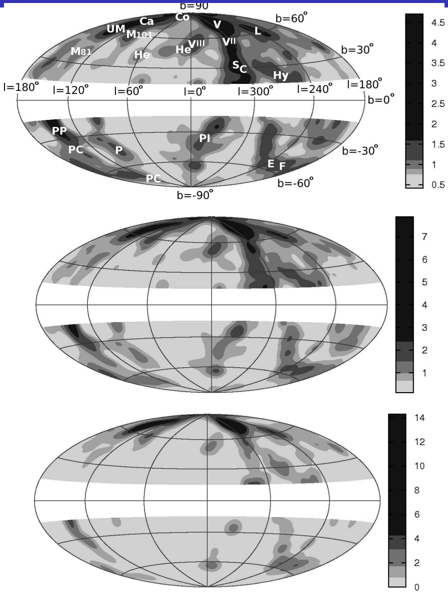
$E > 100$ EeV are expected from local supercluster (Virgo, Fornax, UM, PP etc.) and closeby structures. But they do not come from these directions. TA observes small angle correlation for $E > 100$ EeV events (2 doublets), which may indicate towards strong source – from where they come?

- Excess of cosmogenic photons ?

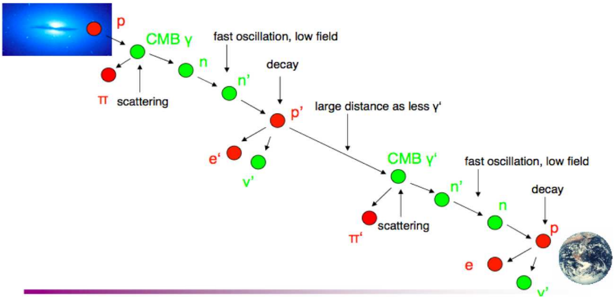
Standard GZK mechanism of UHECR produces too much cascades – contradicts to Fermi-LAT photon spectrum at $E \sim 1$ TeV – local Fog ?

From where highest energy CR are expected ?

For protons with $E > 40, 60$ and 100 EeV (Plots by Tynyakov)



$n - n'$ 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

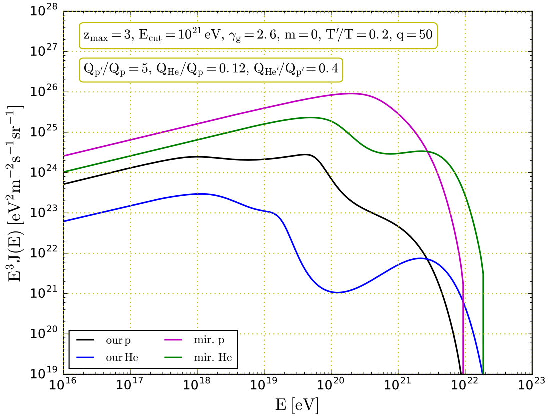
B. $n \to n' \quad P_{nn'} \simeq 0.5 \quad l_{\rm osc} \sim \left(\frac{E}{100\ {\rm EeV}}\right)$ kpc

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: $B_{\rm tr} = \gamma B \quad (\gamma \sim 10^{11}$ for $E \sim 100$ EeV)

Average oscillation probability:

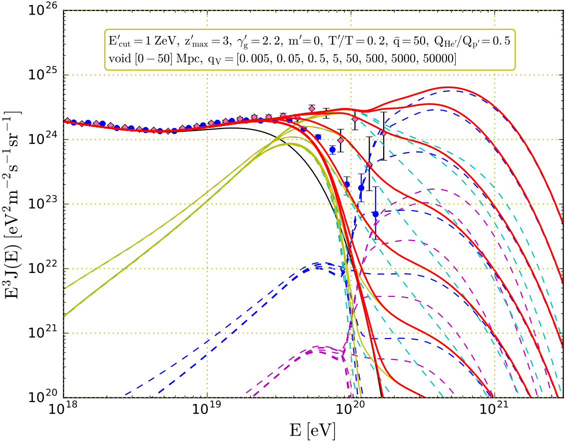
$$P_{nn'} = \sin^2 2\theta_{nn'} \sin^2(\ell/\ell_{\rm osc}) \simeq \frac{1}{2}\left[1 + Q(E)\right]^{-1} \qquad \tan 2\theta_{nn'} = \frac{2\epsilon}{\gamma\mu_n\Delta B}$$

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

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

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

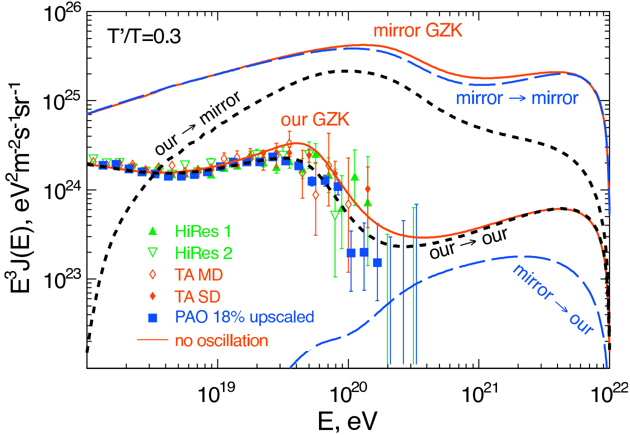
Adjacent Void (0–50 Mpc) $\quad q = 0.5 \times \left(\frac{\tau_{nn'}}{1\ \mathrm{s}}\right)^2 \left(\frac{B_{\rm tr} - B'_{\rm tr}}{1\ \mathrm{fG}}\right)^2$



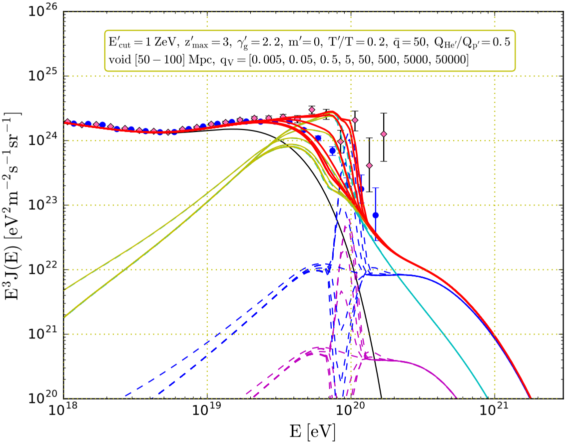
Earlier (than GZK) cutoff in cosmic rays

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: More distant Void (50–100 Mpc)

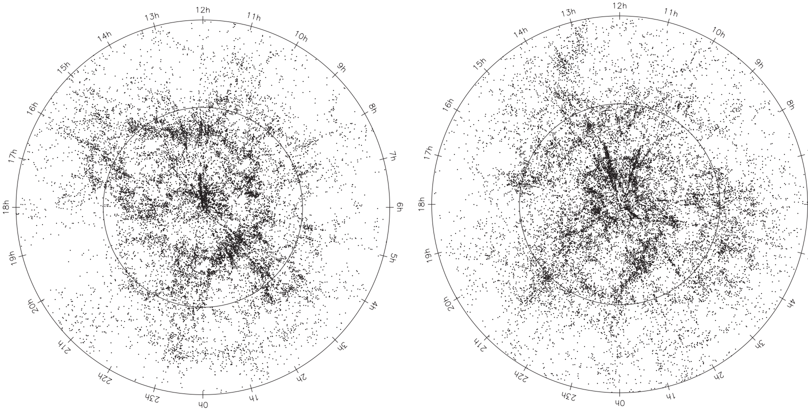


Is northern sky (TA) is more "voidy" than the Southern sky (PAO) ?

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

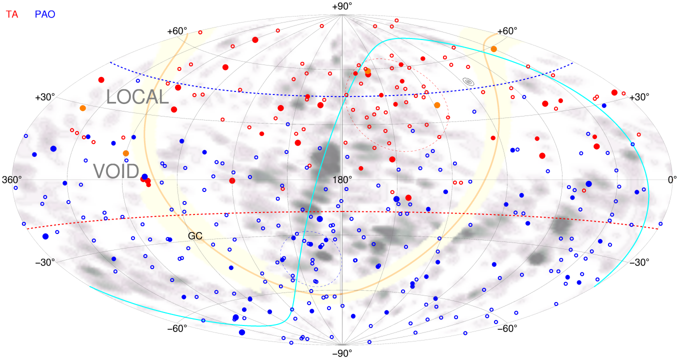
Are North Sky and South Sky different ?



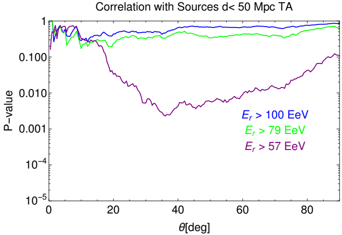
The northern sky is well structured, dominated by LSC at the center, and the Great Wall and Pisces-Perseus ... The southern hemisphere is more amorphous. There is a Cetus Wall, southern part of LSC at the center, Hydra-Centaurus region but also a large and diffuse overdensity between 19 and 22 h ... "Hockey Puck" diagrams from Huchra et al., 2Mass

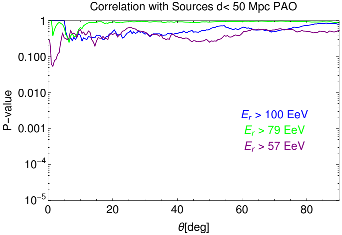
Arrival directions TA and PAO events of $E > 100$ EeV

TA 2008-14 ● $E > 100$ EeV, ● $79 \div 100$ EeV, ○ $57 \div 79$ EeV
PAO 2004-14 .... the same for $E_r = 1.1 \times E$

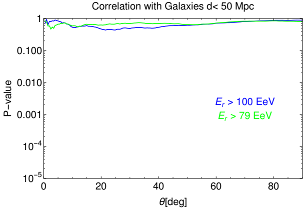


TA & PAO events: correlations with sources (AGN & radiogalaxies) and mass



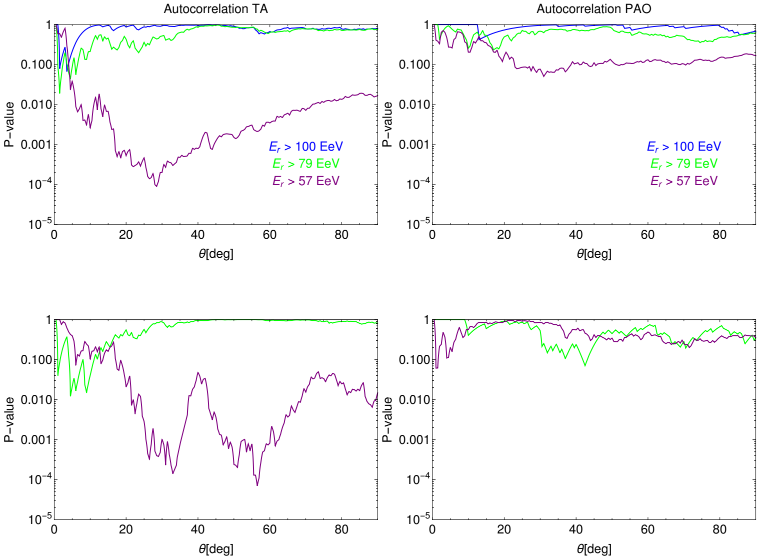


Transient sources (GRB?)



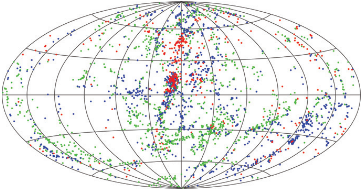
$$E_r = E \text{ (TA)}, \qquad E_r = 1.1.\, E \text{ (PAO)}$$

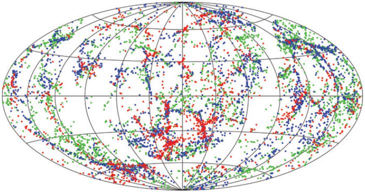
TA & PAO events: autocorrelations & with tracers

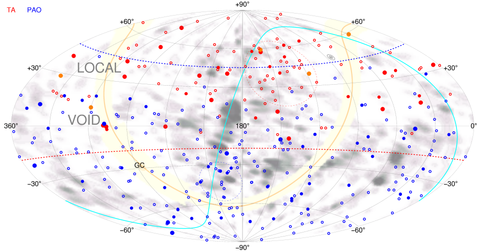


Local structure – Mass2 catalogue

● 0-15 ● 15-30 ● 30-45 (d [Mpc]) ● 45-60 ● 60-75 ● 75-90







Summary

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 inbetween S-sky is more amorphous with diffused galaxies ...

It is unlikely that PAO–TA discrepancy is due to different power of sources within the GZK radius (no correlation with the mass distribution at highest energies $E > 79$ EeV, no event from the Virgo or Fornax clusters, etc.)

But it can be explained in "Swiss Cheese" model: the highest energy UHECR are born from mirror UHECR in nearby holes within the GZK radius (Voids = small magnetic fileld) via $n' - n$ conversion

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 while the PAO data show non ... Interestingly, the TA/PAO spectra are concordant in the common sky ...

Our hypothesis is testable by analyzing the new data of TA/PAO at higher statistics (e.g. studying the average $h_{\rm max}$ and its RMS in the common sky)

Summary

$n - n'$ 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 $\sqrt{2}$ smaller 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.

Backup

Chapter IV

$n - n'$ and Neutron Stars

Z.B., Biondi, Mannarelli, Tonelli

Neutron Stars: $n - n'$ conversion

Two states, n and n'

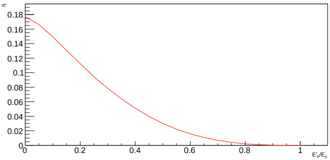
$$H = \begin{pmatrix} m_n + V_n + \mu_n \mathbf{B}\sigma & \varepsilon \\ \varepsilon & m'_n + V'_n - \mu_n \mathbf{B}'\sigma \end{pmatrix}$$

$$n_1 = \cos\theta n + \sin\theta n', \quad n_2 = \sin\theta n - \cos\theta n', \quad \theta \simeq \frac{\epsilon}{V_n - V'_n}$$

$$nn \to nn' \text{ with probability } P_{nn'} = \frac{1}{2}\sin^2 2\theta_{nn'} = 2\left(\frac{\epsilon}{E_F - E'_F}\right)^2$$

$$E_F \simeq (n/n_s)^{2/3} \times 60 \text{ MeV}, \quad n_s = 0.16 \text{ fm}^{-3} \quad E'_F = ...n'$$

$$\Gamma_0 = \langle \sigma v_F \rangle n \eta_0 P_{nn'}(0) \simeq \left(\frac{a}{1\,\mathrm{fm}}\right)^2 \left(\frac{\varepsilon}{10^{-14}\,\mathrm{eV}}\right)^2 \times 10^{-13}\ \mathrm{yr}^{-1}$$



$$\frac{dN_1(t)}{dt} = -\Gamma N_1 \qquad \frac{dN_2(t)}{dt} = \Gamma N_1 \qquad N_1 + N_2 = \text{Const.}$$

Mixed Neutron Stars: TOV and $M - R$ relations

$$g_{\mu\nu} = \mathrm{diag}(-g_{tt}, g_{rr}, r^2, r^2 \sin^2\theta) \qquad g_{tt} = e^{2\phi},\ g_{rr} = \frac{1}{1-2m/r}$$

$$T_{\mu\nu} = T^1_{\mu\nu} + T^2_{\mu\nu} = \mathrm{diag}(\rho g_{tt}, p g_{rr}, p r^2, p r^2 \sin^2\theta)$$

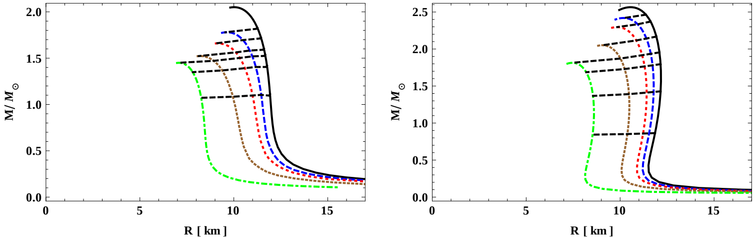
$$\rho = \rho_1 + \rho_2 \ \&\ p = p_1 + p_2, \qquad p_\alpha = F(\rho_\alpha)$$

$$\frac{dm}{dr} = 4\pi r^2 \rho \ \rightarrow \ \frac{dm_{1,2}}{dr} = 4\pi r^2 \rho_{1,2} \qquad m = m_1 + m_2$$

$$\frac{d\phi}{dr} = -\frac{1}{\rho + p}\frac{dp}{dr} \ \rightarrow \ \frac{dp_1/dr}{\rho_1 + p_1} = \frac{dp_2/dr}{\rho_2 + p_2}$$

$$\frac{dp}{dr} = (\rho + p)\frac{m + 4\pi p r^3}{2mr - r^2}$$

$$(m_1 \neq 0, m_2 = 0)_{\rm in} \rightarrow (m_1 = m_2)_{\rm fin} \qquad r \rightarrow \frac{r}{\sqrt{2}}, \quad m_\alpha \rightarrow \frac{m_\alpha}{2\sqrt{2}}$$



$\sqrt{2}$ rule: $\quad M^{\rm max}_{\rm mix} = \frac{1}{\sqrt{2}} M^{\rm max}_{\rm NS} \qquad R_{\rm mix}(M) = \frac{1}{\sqrt{2}} R_{\rm NS}(M)$

Neutron Stars: observational $M - R$

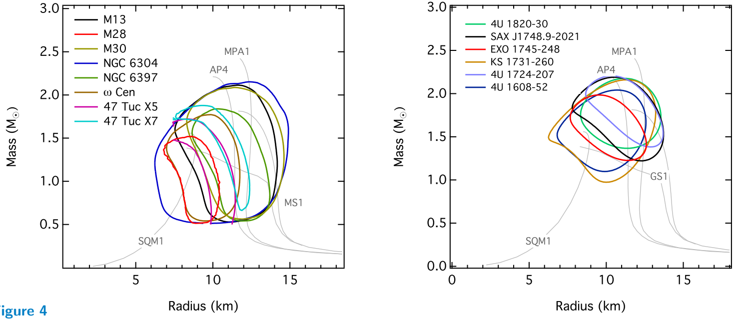


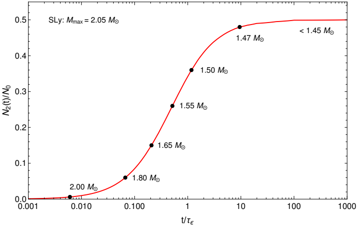
Figure 4

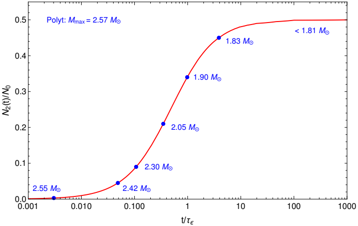
The combined constraints at the 68% confidence level over the neutron star mass and radius obtained from (Left) all neutron stars in low-mass X-ray binaries during quiescence (Right) all neutron stars with thermonuclear bursts. The light grey lines show mass-relations corresponding to a few representative equations of state (see Section 4.1 and Fig. 7 for detailed descriptions.)

Neutron Stars: Evolution to mixed star

$$\frac{dN_1(t)}{dt} = -\Gamma N_1 \qquad \frac{dN_2(t)}{dt} = \Gamma N_1 \qquad N_1 + N_2 = \text{Const.}$$

Initial state $N_1 = N_0,\ N_2 = 0$ final state $N_1 = N_2 = N_0/2$





NS-NS merger: can be at the origin of heavy *trans-Iron* elements

Neutron Stars: mass distribution