Neutron – Dark Matter Connection: astrophysical consequences

Symphonie fantastique en cinq parties

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Rêveries – Passions

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Visible vs. Dark matter: $\Omega_D/\Omega_B \sim 1$?

Visible matter from Baryogenesis

B $(B-L)$ & CP violation, Out-of-Equilibrium

$\rho_B = n_B m_B$, $m_B \simeq 1$ GeV, $\eta = n_B/n_\gamma \sim 10^{-9}$

η is model dependent on several factors:
coupling constants and CP-phases, particle degrees of freedom, mass scales and out-of-equilibrium conditions, etc.

- Sakharov 1967

Dark matter: $\rho_D = n_X m_X$, but $m_X = ?$, $n_X = ?$

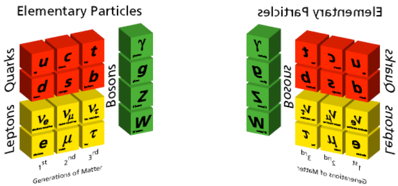
n_X is model dependent: DM particle mass and interaction strength (production and annihilation cross sections), freezing conditions, etc.

- Axion — $m_a \sim 10^{-5}$ eV $n_a \sim 10^4 n_\gamma$ - CDM
- Neutrinos — $m_\nu \sim 10^{-1}$ eV $n_\nu \sim n_\gamma$ - HDM $(\times)$
- Sterile ν' — $m_{\nu'} \sim 10$ keV $n_{\nu'} \sim 10^{-3} n_\nu$ - WDM
- Mirror baryons — $m_{B'} \sim 1$ GeV $n_{B'} \sim n_B$ - ???
- WIMP — $m_X \sim 1$ TeV $n_X \sim 10^{-3} n_B$ - CDM
- WimpZilla — $m_X \sim 10^{14}$ GeV $n_X \sim 10^{-14} n_B$ - CDM

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

$G \quad \times \quad G'$

Regular world — Mirror world



- Two identical gauge factors, e.g. $SU(5) \times SU(5)'$, with identical field contents and Lagrangians: $\mathcal{L}_{\rm tot} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{\rm mix}$
- Mirror sector ($\mathcal{L}'$) is dark – or perhaps grey? ($\mathcal{L}_{\rm mix} \;\to\;$ portals)
- MM is similar to standard matter, (asymmetric/dissipative/atomic) but realized in somewhat different cosmological conditions ($T'/T \ll 1$)
- $G \to G'$ symmetry (Z_2 or Z_2^{LR}): no new parameters in $\mathcal{L}'$ spont. broken?
- Cross-interactions between O & M particles
  $\mathcal{L}_{mix}$: new operators – new parameters! limited only by experiment!

Quick overview ...

Parallel/mirror sector of particles as a duplicate of our SM: SM $\times$ SM$'$
(or $SU(5) \times SU(5)'$ or $E_8 \times E_8'$ or parallel branes ... or more sectors)
– all our particles (e, p, n, ν, γ...) have dark M twins (e', p', n', ν', γ'...)
of exactly (or almost) the same masses

M matter is viable DM (asymmetric/baryonic/atomic/self-interacting/ dissipative etc. as ordinary (O) baryon matter) – but M sector must be colder than O sector: $T'/T < 0.2$ or so (BBN, CMB, LSS etc.)
– asymmetric reheating between the two sectors after inflation

– O matter mainly hydrogen (H 75%, ^{4}He 25%)
while M matter mostly helium (H$'$ 25%, ^{4}He$'$ 75%) – first M stars are formed earlier than O stars, are bigger, helium dominated and end up in heavy BH: $M \sim (10 \div 10^2)\, M_\odot$ (inferring $\sim 80\%$ of DM in galactic halo and for the rest of $\sim 20\%$ – M gas clouds, $\sim M_\odot$ stars etc.

There can exist interactions between O and M particles, e.g. photon kinetic mixing $\varepsilon F^{\mu\nu} F'_{\mu\nu}$, some common gauge bosons, etc.
Most interesting are the ones which violate baryon and lepton numbers between two sectors, and namely $B - L$ and $B' - L'$ which can co-generate baryon asymmetries in both sectors – and naturelly explain why the DM and baryon fractions are comparable, $\Omega_{B'}/\Omega_B \simeq 5$ or so

... Quick overview

These interactions can induce mixing of neutral particles between two sectors, e.g. $\nu - \nu'$ oscillations (M neutrinos = sterile neutrinos)

Oscillation $n \to n'$ can be very effective process, faster than the neutron decay. For certain parameters it can explain the neutron lifetime problem, 4.5σ discrepancy between the decay times measured by different experimental methods (bottle and beam), or anomalous neutron loses observed in some experiments and paradoxes in the UHECR detections

$n \to n'$ transition can have observable effects on neutron stars. It creates dark cores of M matter in the NS interiors, or eventually can transform them into maximally mixed stars with equal amounts of O and M neutrons

Such transitions in mirror NS create O matter cores. If baryon asymmetry in M sector has opposite sign, transitions $\bar{n}' \to \bar{n}$ create antimatter cores which can be seen by Fermi LAT and explain the origin of mirror nuclei in cosmic rays seen by AMS-2

If neutron has mixings both with M neutron and M antineutron, then the neutron can be promptly transformed into the antineutron via travelling in M world, $n \to n'/\bar{n}' \to \bar{n}$. This can be tested in oscillation experiments with magnetic fields. If discovered, the cheap and ecologically clean machines become possible producing energy (almost) for free

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

Two possible parities: with and without chirality change

fermions and anti-fermions :

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

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

$\updownarrow$ CP

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

B=–1/3 L=–1 B=–1/3 L=–1

Mirror fermions and antifermions :

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

B′=1/3 L′=1 B′=1/3 L′=1

$\updownarrow$ CP

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

B′=-1/3 L′=-1 B′=-1/3 L′=-1

$$\mathcal{L}_{\rm Yuk} = F_L Y \bar{F}_L \phi \ + \ \text{h.c.} \qquad \mathcal{L}'_{\rm Yuk} = F'_L Y' \bar{F}'_L \phi' \ + \ \text{h.c.}$$

Z_2: $L(R) \leftrightarrow L'(R')$: $Y'_{u,d,e} = Y_{u,d,e}$ B,L $\leftrightarrow$ B′,L′

Z_2^{LR}: $L(R) \leftrightarrow R'(L')$: $Y'_{u,d,e} = Y^*_{u,d,e}$ B,L $\leftrightarrow$ –B′,L′ $Z_2^{LR} = Z_2 \times$CP

– Sign of baryon asymmetries (BA)?

Ordinary BA is positive: $\mathcal{B} = \mathrm{sign}(n_b - n_{\bar{b}}) = 1$
– as produced by (unknown) baryogenesis a la Sakharov!

Sign of mirror BA, $\mathcal{B}' = \mathrm{sign}(n_{b'} - n_{\bar{b}'})$, is a priori unknown!

Imagine a baryogenesis mechanism *separately* acting in O and M sectors!
– without involving cross-interactions in $\mathcal{L}_{\rm mix}$
E.g. EW baryogenesis or leptogenesis $N \to \ell\phi$ and $N' \to \ell'\phi'$

Z_2: $\to$ $Y'_{u,d,e} = Y_{u,d,e}$ i.e. $\mathcal{B}' = 1$
– O and M sectors are CP-identical in same chiral basis! O=left, M=left

Z_2^{LR}: $\to$ $Y'_{u,d,e} = Y^*_{u,d,e}$ i.e. $\mathcal{B}' = -1$
– O sector in L-basis is identical to M sector in R-basis! O=left, M=right

In the absence of cross-interactions in $\mathcal{L}_{\rm mix}$ we cannot measure sign of BA (or chirality in weak interactions) in M sector – so all remains academic ...

But switching on cross-interactions, violating B and B′ – but conserving say B-B′ as neutron–mirror neutron mixing: $\epsilon n' n + \mathrm{h.c.}$
$\mathcal{B}' = -1$ $\to$ $\bar{n}' \to n$ M (anti)matter → O matter
$\mathcal{B}' = 1$ $\to$ $n' \to \bar{n}$ M matter → O antimatter

Movement II

Waltz in 3/8 – dolce e tenero

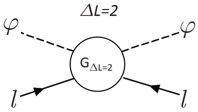
Un Bal

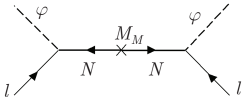
A Ball

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

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

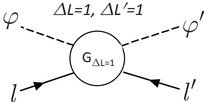
M is the (seesaw) scale of new physics beyond EW scale.





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

L and L' violation: $\frac{A}{M}(\ell\phi)(\ell\phi)$, $\frac{A}{M}(\ell'\phi')(\ell'\phi')$ and $\frac{B}{M}(\ell\phi)(l\ell'\phi')$



Mirror neutrinos naturally sterile neutrinos: $\langle\phi'\rangle/\langle\phi\rangle \sim 10 \div 10^2$

ZB and Mohapatra 95, ZB, Dolgov and Mohapatra 96

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

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

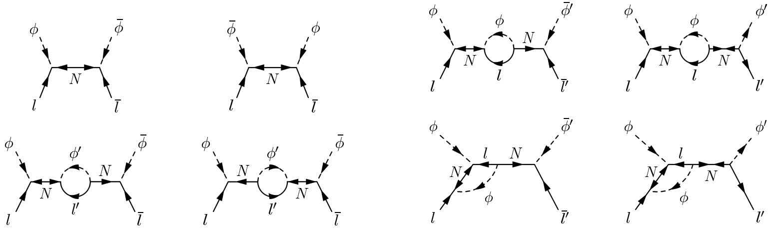
- These processes should be out-of-equilibrium
- Violate baryon numbers in both worlds, $B - L$ and $B' - L'$
- Violate also CP, given complex couplings

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 $\frac{1}{2}Mg_{jk}N_jN_k + \mathrm{h.c.}$



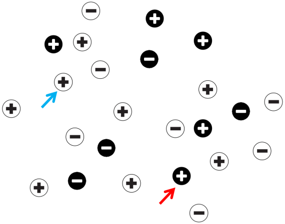
Complex Yukawa couplings $Y_{ij}l_iN_j\bar{\phi} + Y'_{ij}l'_iN_j\bar{\phi}' + \mathrm{h.c.}$

Z_2 (Xerox) symmetry $\rightarrow$ $Y' = Y$,
Z_2^{LR} (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 (Z_2^{LR}): $\quad Y' = Y^* \quad \to \quad \Delta\sigma' = -\Delta\sigma \quad \to \quad B > 0,\ B' > 0$

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 $\quad \to \quad n_{BL} = n'_{BL}$

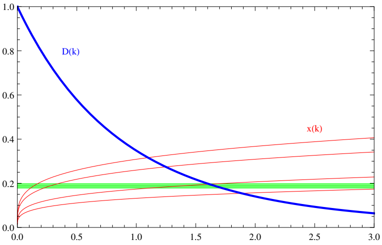
$$\Omega'_B = \Omega_B \simeq 10^3 \frac{J M_{Pl} T_R^3}{M^4} \simeq 10^3 J \left(\frac{T_R}{10^{11}\ {\rm GeV}}\right)^3 \left(\frac{10^{13}\ {\rm GeV}}{M}\right)^4$$

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

Movement III *Adagio in 6/8*

Scène aux champs ...

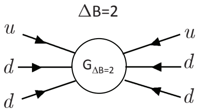
Scene in the country

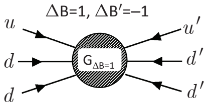
B violating operators between O and M particles in $\mathcal{L}_{\rm mix}$

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)

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

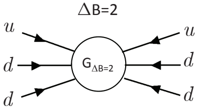




Oscillations $n \to \bar{n}$ $(\Delta B = 2)$
Oscillations $n \to \bar{n}'$ $(\Delta B = 1,\ \Delta B' = -1)$ $B + B'$ is conserved

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

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

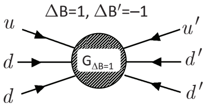
Key moment: *$n - \bar{n}$ oscillation destabilizes nuclei:*
$(A, Z) \to (A-1, \bar{n}, Z) \to (A-2, Z/Z-1) + \pi$'s

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 $\frac{1}{M^5}(udd)(u'd'd')$ $\rightarrow$ 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:*
$(A,Z) \rightarrow (A-1,Z) + n'(p'e'\bar{\nu}')$ *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 $n \rightarrow \bar{n}'$ and regeneration $n \rightarrow \bar{n}' \rightarrow n$
can be searched at small scale 'Table Top' experiments

Neutron – mirror neutron oscillation probability

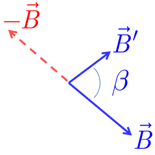
$$H = \begin{pmatrix} m + \mu\vec{B}\vec{\sigma} + V & \epsilon \\ \epsilon & m + \mu\vec{B}'\vec{\sigma} + V' \end{pmatrix}$$

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

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

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

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

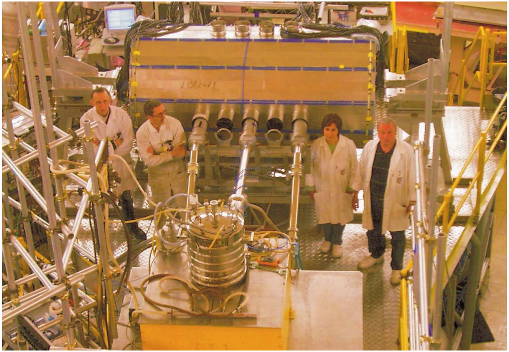


where $\omega = \frac{1}{2}\left|\mu B\right|$ and $\omega' = \frac{1}{2}\left|\mu B'\right|$; τ - oscillation time

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

Experiments

By now 8 experiments were done at ILL/PSI (one exp by myself +collaborators using the UCN Chamber of 200 ℓ volume)

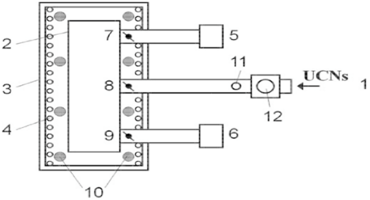


Several new experiments are underway at PSI, ILL and ORNL and can be projected at the ESS

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.

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

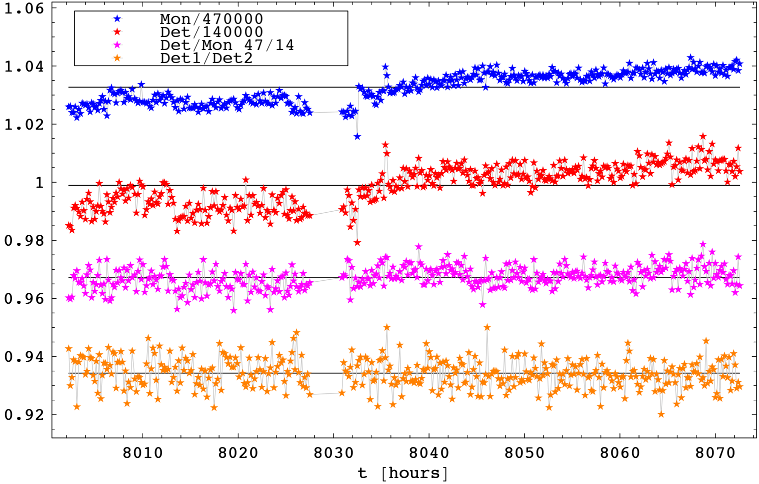
$$\frac{N_{B1}(T_S)}{N_{B2}(T_S)} = \exp\left[\left(\bar{\mathcal{P}}_{B2} - \bar{\mathcal{P}}_{B1}\right)\nu T_S\right]$$

So if we find that:

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

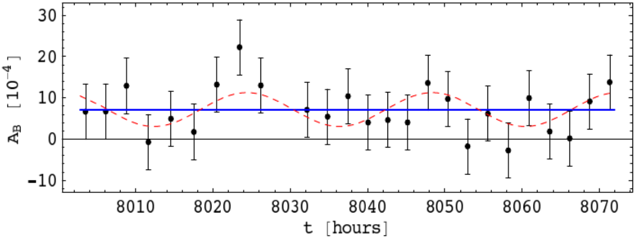
Serebrov III – Drifts of detector and monitor counts

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



measurements– magnetic field vertical

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



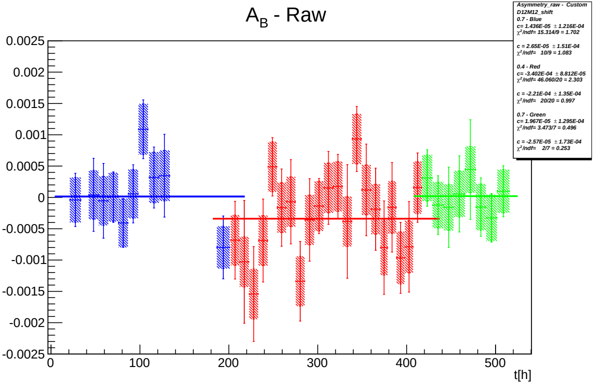
Analysis pointed out the presence of a signal:

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

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

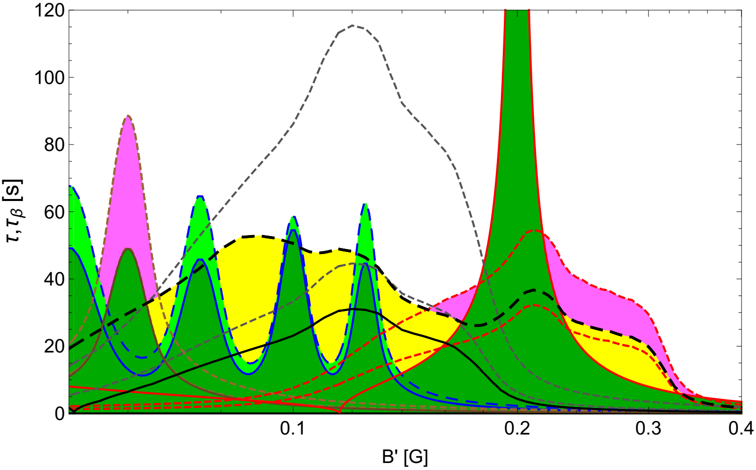
Z.B. and Nesti, 2012

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



$4\sigma \quad \rightarrow \quad 2.5\sigma$ 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 (experiments are looking for)
- In Cosmic Rays ($n - n'$ can reconcile TA and Auger experiments)
- During BBN epoch (fast $n' \to \bar{n}$ can solve Lithium problem)

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

Movement IV

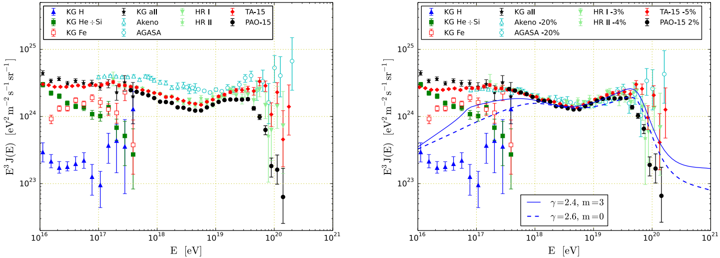
Marche au supplice ...

March to the scaffold ...

UHECR and GZK cutoff

Two giant detectors see UHECR spectra different at $E > E_{\rm GZK}$
$E > 100$ EeV events observed: Cosmic Zevatrons exist in the Universe

Pierre Auger Observatory (PAO) – South hemisphere
Telescope Array (TA) – North hemisphere
$+$ older detectors: AGASA, HiRes, etc. (all in north hemisphere)



At $E < 30$ EeV two spectra coincide (relative energy shift ≈ 8 %)
But at $E > 57$ EeV TA: 109 events PAO: 231 events
and at $E > 100$ EeV TA: 18 events PAO: 8 events (as by ICRC 2015)
Where is GZK cutoff? theoretically $E_{\rm GZK} \simeq 57$ EeV (for protons)
but $E_{\rm cut}^{\rm PAO} \simeq 25$ EeV and $E_{\rm cut}^{\rm TA} > 70$ EeV (??)

But also other discrepancies are mounting ...

- Who are carriers of UHECR ?

PAO and TA see different chemical content:
TA: protons for $E = 1 \div 30$ EeV + some light nuclei for $E > 30$ EeV
PAO: protons for $E = 1 \div 10$ EeV and heavier nuclei above $E > 10$ EeV
– 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 ?

- What are sources (BH in AGNs)? From where UHECR 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 and neutrinos ?

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

UHECR as protons and GZK cutoff

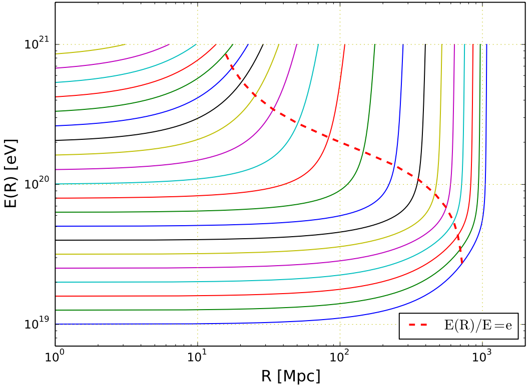
GZK cutoff:

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 :

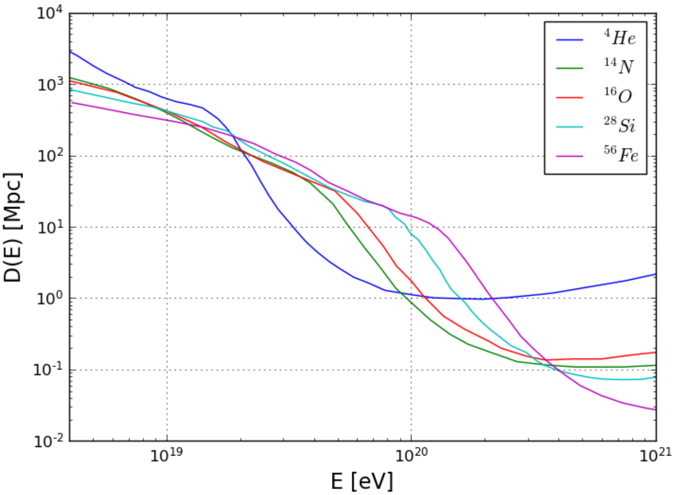
$p + \gamma \to p + \pi^0$ (or $n + \pi^+$), $l_{\rm mfp} \sim 5$ Mpc for $E > 10^{20}\ {\rm eV} = 100$ EeV

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

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

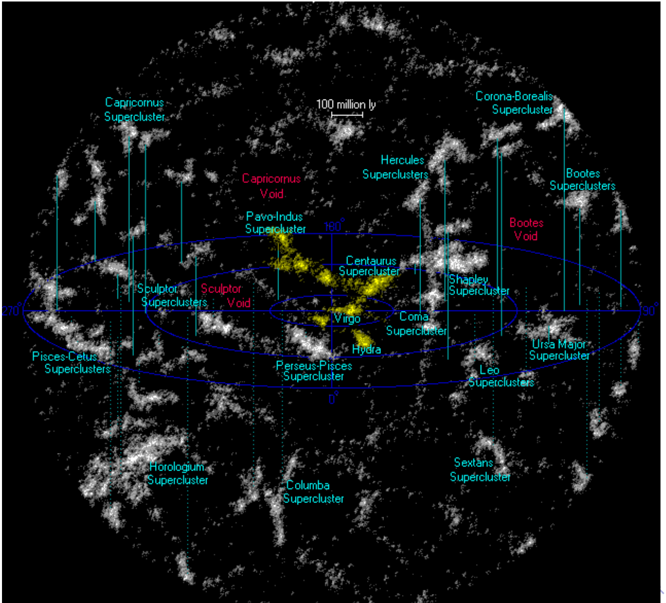


UHECR as nuclei



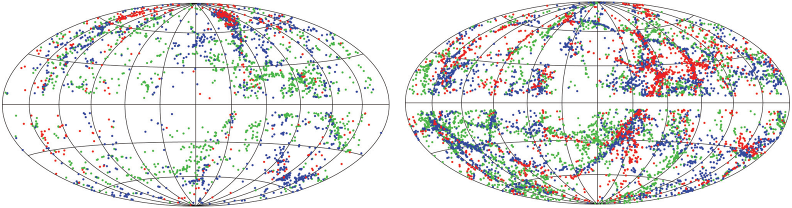
Swiss Cheese Structure of the Universe

R. Powell, https://commons.wikimedia.org/w/index.php?curid=54584281



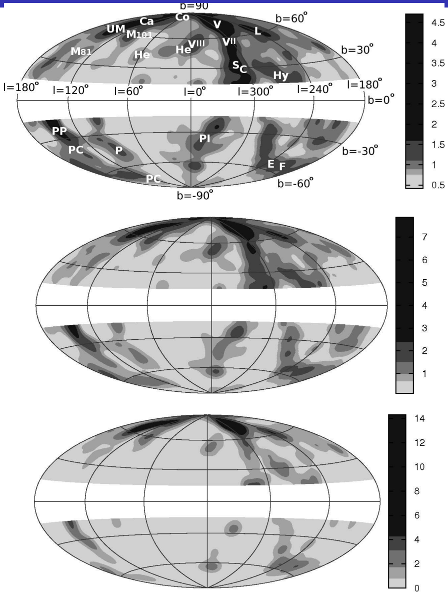
Local structure – 2Mass catalogue (J. Huchra et al.)

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

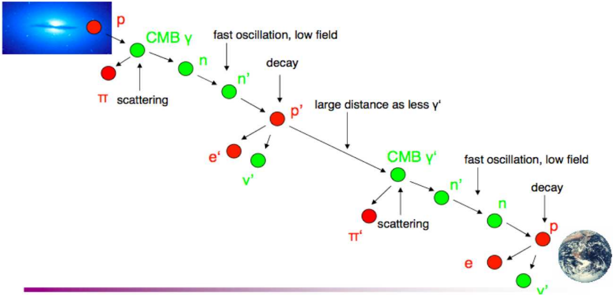


From where highest energy CR are expected ?

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

$n - n'$ 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:

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

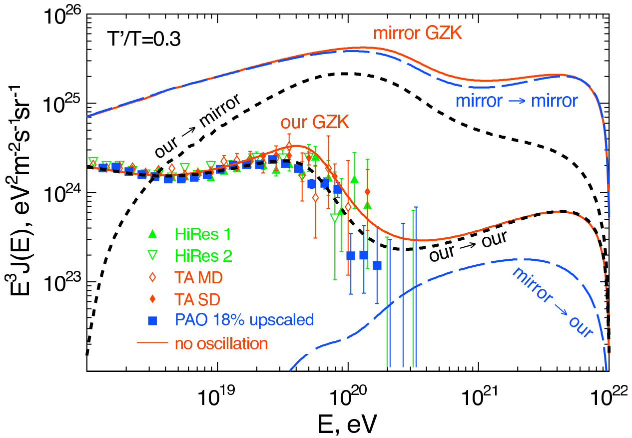
$$Q = (\gamma\Delta B/2\epsilon)^2 \approx 0.5\left(\frac{\tau_{nn'}}{1\ \rm s}\right)^2\left(\frac{\Delta B}{1\ \rm fG}\right)^2\left(\frac{E}{100\ \rm EeV}\right)^2 \qquad \Delta B = |B_{\rm tr} - B'_{\rm tr}|$$

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

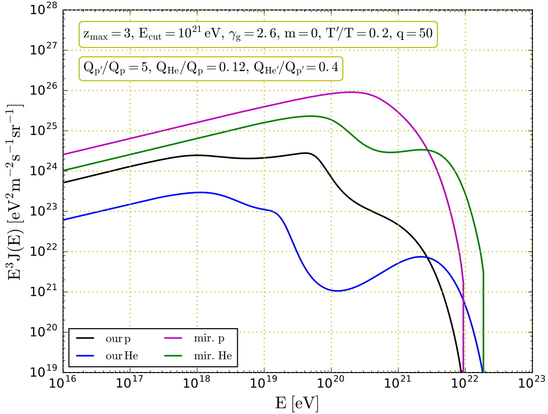
Z.B. and Gazizov, Neutron Oscillations to Parallel World: Earlier End to the Cosmic Ray Spectrum? Eur. Phys. J. C 72, 2111 (2012)

Baryon number is not conserved in propagation of the UHECR



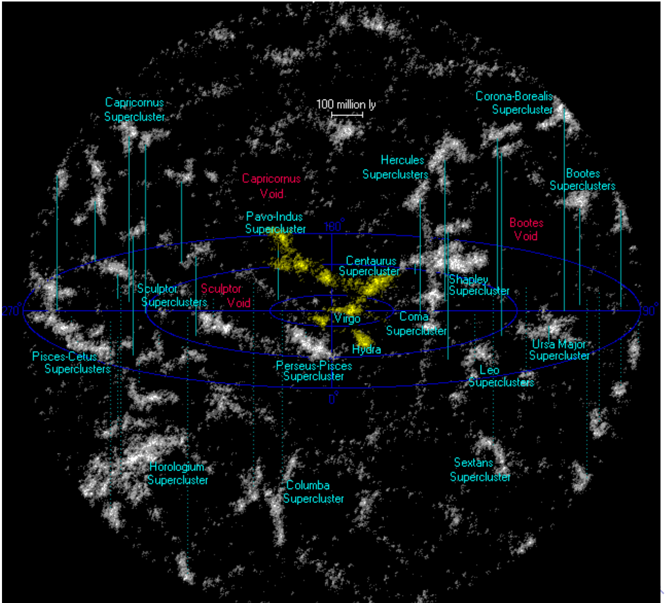
Ordinary and Mirror UHECR

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



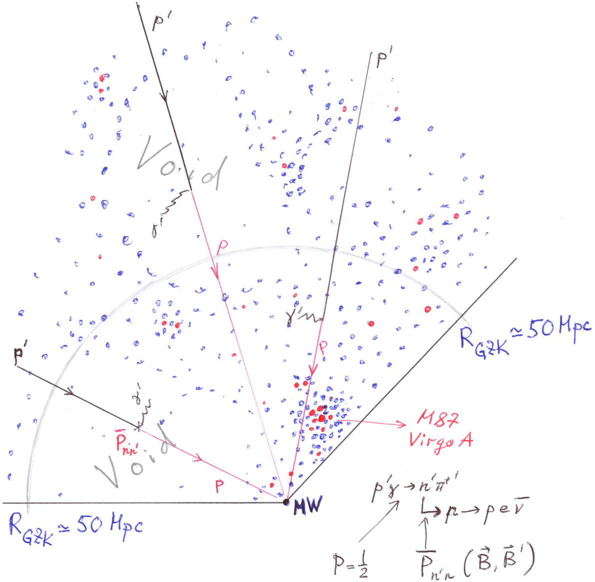
Swiss Cheese Structure of the Universe

R. Powell, https://commons.wikimedia.org/w/index.php?curid=54584281



Swiss Cheese Model: Mirror CRs transform into our CR in Voids.

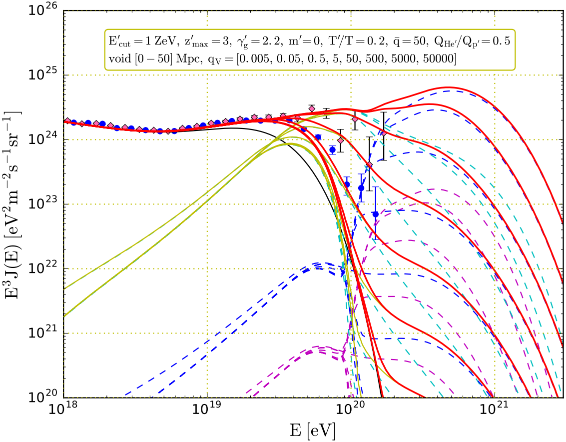
Z.B., Biondi, Gazizov



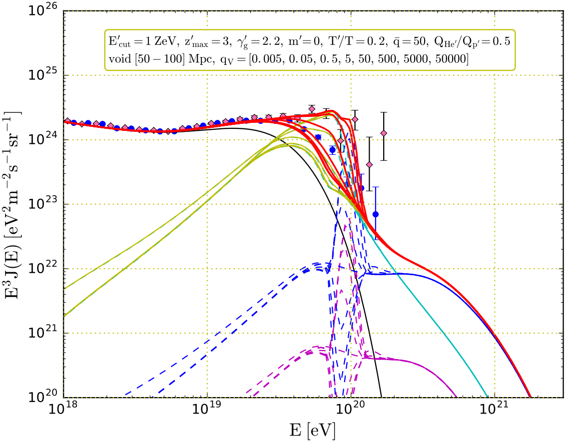
Swiss Cheese Model: Mirror CRs are transformed into ordinaries in nearby Voids. Z.B., Biondi, Gazizov

$$P_{nn'} \simeq \frac{1}{2}\,\frac{1}{1+q_B\,(E/100\,\mathrm{EeV})^2}$$

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

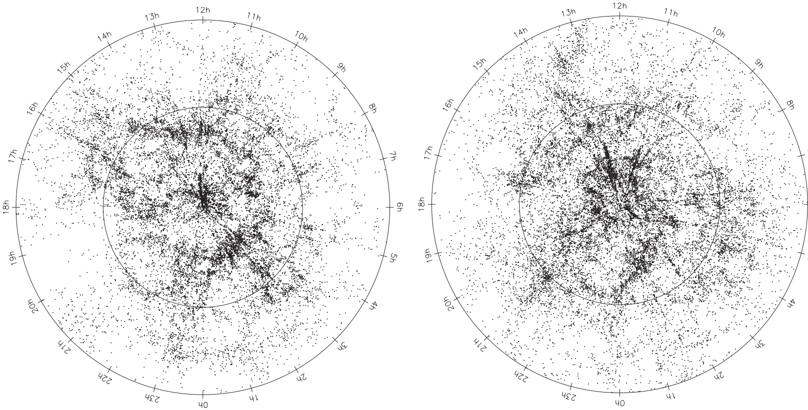


Swiss cheese: More distant Void (50–100 Mpc)



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

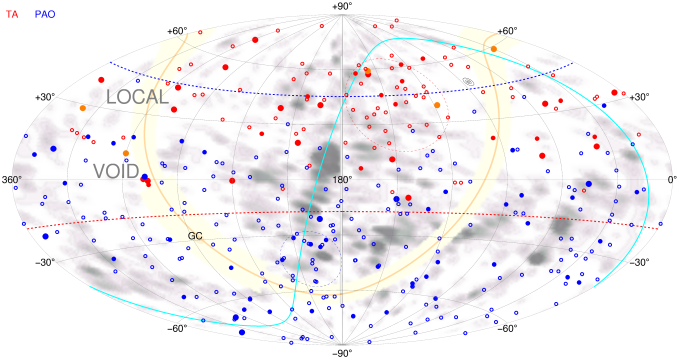
Are North Sky and South Sky different ?



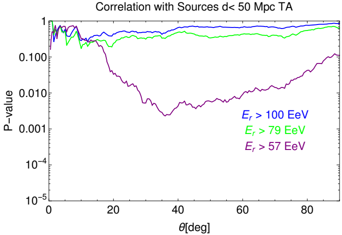
The northern sky is well structured, dominated by LSC at the center, and the Great Wall and Pisces-Perseus ... The southern hemisphere is more amorphous. There is a Cetus Wall, southern part of LSC at the center, Hydra-Centaurus region but also a large and diffuse overdensity between 19 and 22 h ...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

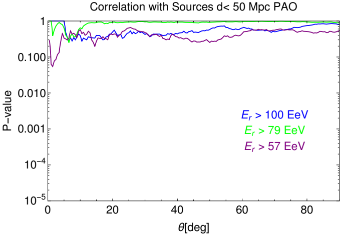
Arrival directions TA and PAO events of $E > 100$ EeV

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

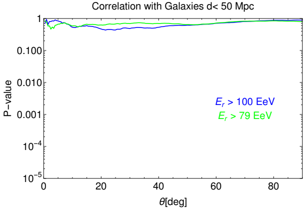


TA & PAO events: correlations with sources (AGN & radiogalaxies) and mass





Transient sources (GRB?)



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

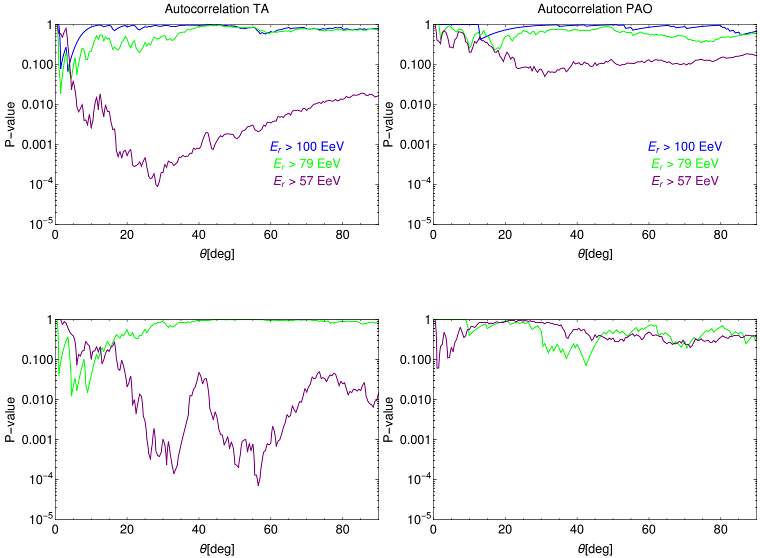
TA & PAO events: autocorrelations & with tracers

Neutron – Dark Matter Connection: astrophysical consequences

Symphonie fanta-stique en cinq parties

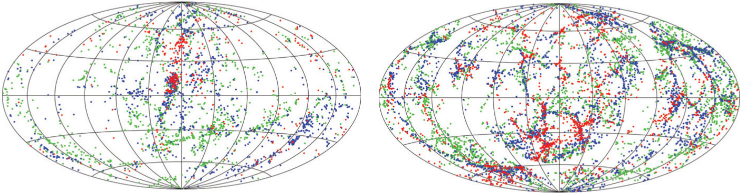
Zurab Berezhiani

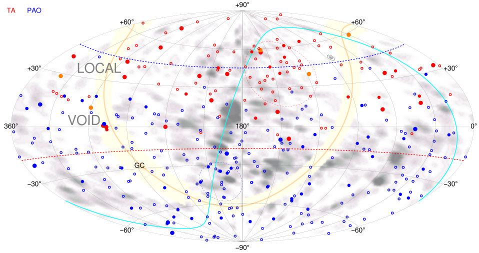
Summary



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 $h_{\max}$ 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.

Movement V *Allegro in 6/8 ft. Dies Irae*

Songe d'une nuit du sabbat

Dreaming the Sabbath of witches

Neutron Stars: $n - n'$ conversion

Two states, n and n'

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

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

Fermi degenerate neutron liquid $p_F \simeq (n_b/0.3\,\mathrm{fm}^{-3})^{2/3} \times 400$ MeV

$nn \to nn'$ with rate $\Gamma = 2\theta^2 \eta \langle \sigma v \rangle n_b$

$\frac{dN}{dt} = -\Gamma N \quad \frac{dN'}{dt} = \Gamma N \qquad N + N' = N_0$ remains Const.

$\tau_\epsilon = \Gamma^{-1} = \epsilon_{15}^{-2} \left(\frac{M}{1.5\, M_\odot}\right)^{2/3} \times 10^{15}$ yr $\quad N'/N_0 = t/\tau_\epsilon$

for $t = 10$ Gyr, $\tau_\epsilon = 10^{15}$ yr gives M fraction 10^{-5} – few Earth mass

$\dot{\mathcal{E}} = \frac{E_F N}{\tau_\epsilon} = \left(\frac{10^{15}\,\mathrm{yr}}{\tau_\epsilon}\right) \left(\frac{M}{1.5\, M_\odot}\right) \times 10^{31}$ erg/s $\quad$ NS heating – surface T

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

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

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

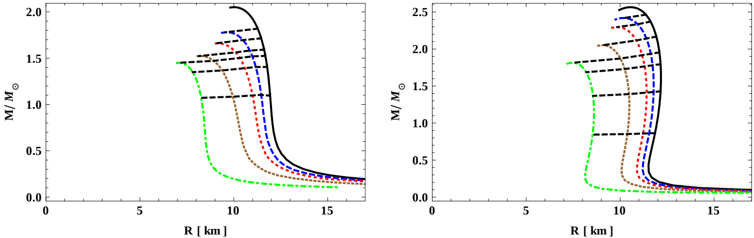
$$\rho = \rho_1 + \rho_2 \ \& \ p = p_1 + p_2, \qquad p_\alpha = F(\rho_\alpha)$$

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

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

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

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

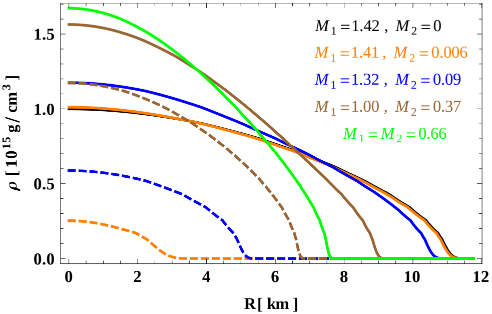


$\sqrt{2}$ rule: $\quad M^{\rm max}_{\rm mix} = \frac{1}{\sqrt{2}} M^{\rm max}_{\rm NS} \qquad R_{\rm mix}(M) = \frac{1}{\sqrt{2}} R_{\rm NS}(M)$

Neutron Star transformation

$\frac{dN}{dt} = -\Gamma N \qquad \frac{dN'}{dt} = \Gamma \qquad N + N' = N_0$ remains Const.

Initial state $N = N_0,\ N' = 0$ final state $N = N' = \frac{1}{2} N_0$



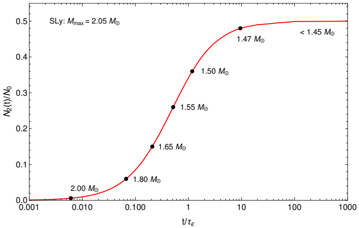
Quark stars: in strange quark matter (color-superconducting phase) transition is not energetically farored. So Quark stars (which perhaps are heavy pulsars with $M \simeq 2\, M_\odot$ or so) are insensitive to $n \to n'$.

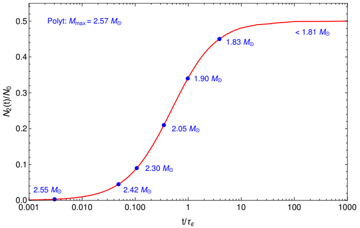
Neutron Stars Evolution to mixed star

$\tau_\epsilon = (10^{-15}\,\mathrm{eV}/\epsilon)^2 \times 10^{15}$ yr   Two regimes are allowed :

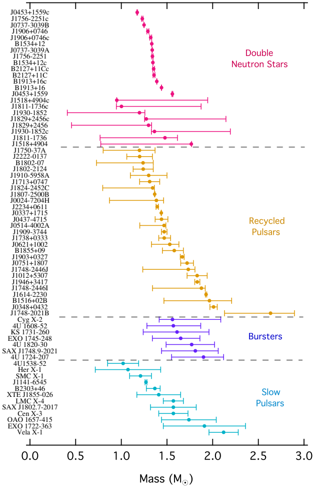
1. slow transformation ($\tau_\varepsilon \gg 14$ Gyr age of universe)
then limit from pulsar heating tells $\tau_\epsilon > 10^{15}$ yr $\longrightarrow$ $\epsilon < 10^{-15}$ eV or so
matches exp. limits for exactly degenerate $n - n'$

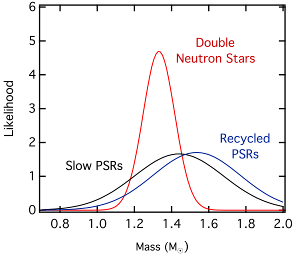
2. fast transformation $\tau_\epsilon < 10^5$ yr or so $\longrightarrow$ $\epsilon > 10^{-10}$ eV or so
– then old pulsars all should be transformed into maximally mixed stars
matches explanation of neutron lifetime anomaly, non-degenerate $n - n'$





Neutron Stars: mass distribution





Neutron Stars: observational $M - R$

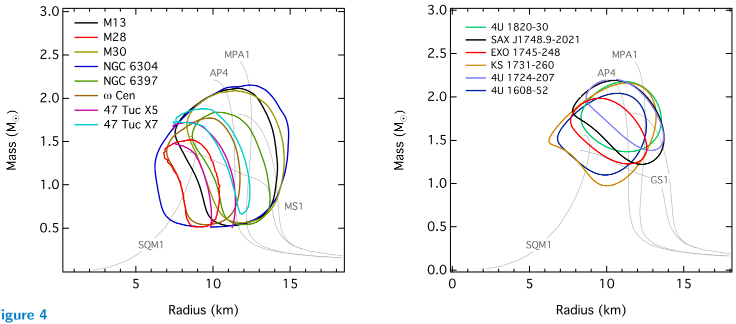


Figure 4

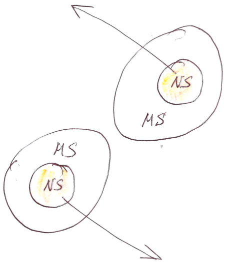
The combined constraints at the 68% confidence level over the neutron star mass and radius obtained from (Left) all neutron stars in low-mass X-ray binaries during quiescence (Right) all neutron stars with thermonuclear bursts. The light grey lines show mass-relations corresponding to a few representative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

Neutron Star Mergers

NS-NS merger and kilonova (GW170817 ?)
r-processes can give heavy *trans-Iron* elements

Mirror NS-NS merger is invisible (GW190425 ? $M_{\rm tot} = 3.4 M_\odot$)

But not completely ... if during the evolution they developed small core of our antimatter (depends on the mirror BA sign)
– their mergers can be origin of antinuclei for AMS-2



Antimatter Cores in Mirror Neutron stars

DUPOURQUÉ, TIBALDO, and VON BALLMOOS PHYS. REV. D **103**, 083016 (2021)

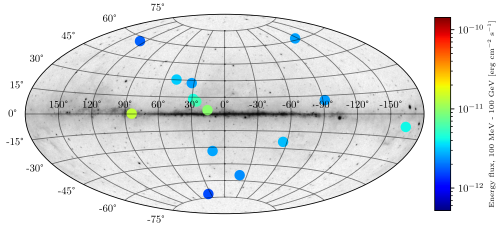


FIG. 1. Positions and energy flux in the 100 MeV–100 GeV range of antistar candidates selected in 4FGL-DR2. Galactic coordinates. The background image shows the *Fermi* 5-year all-sky photon counts above 1 GeV (image credit: NASA/DOE/Fermi LAT Collaboration).

Antimatter production rate: $\dot{N}_{\bar{b}} = \frac{N_0}{\tau_\epsilon} \simeq \epsilon_{15}^2 \left(\frac{M}{M_\odot}\right)^{2/3} \times 3 \cdot 10^{34}\ \mathrm{s}^{-1}$

ISM accretion rate: $\dot{N}_b \simeq \frac{(2GM)^2 n_{\rm is}}{v^3} \simeq \frac{10^{32}}{v_{100}^3} \times \left(\frac{n_{\rm is}}{1/\mathrm{cm}^3}\right) \left(\frac{M}{M_\odot}\right)^2 \mathrm{s}^{-1}$

Annihilation γ-flux from the mirror NS as seen at the Earth:

$J \simeq \frac{10^{-12}}{v_{100}^3} \left(\frac{n_{\rm is}}{1/\mathrm{cm}^3}\right) \left(\frac{M}{1.5\, M_\odot}\right)^2 \left(\frac{50\ \mathrm{pc}}{d}\right)^2 \frac{\mathrm{erg}}{\mathrm{cm}^2\mathrm{s}}$ d – distance to source

Alternative: Antistars – Dolgov & Co. but some difference:

– the surface redshift s expected $\sim 15 \div 30$ % for the NS

– which should be absent for antistars (weak gravity)

Getting Energy from Dark Parallel World

I argued that in O and M worlds baryon asymmetries can have same signs: $B > 0$ and $B' > 0$. Since $B - B'$ is conserved, our neutrons have transition $n \to \bar{n}'$ (which is the antiparticle for M observer)
while n' (of M matter) oscillates $n' \to \bar{n}$ into our antineutron

Neutrons can be transformed into antineutrons, but (happily) with low efficiency: $\tau_{n\bar{n}} > 10^8$ s

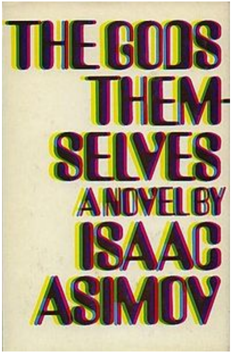
dark neutrons, before they decay, can be effectively transformed into our antineutrons in controllable way, by tuning vacuum and magnetic fields, if $\tau_{n\bar{n}'} < 10^3$ s

$E = 2m_nc^2 = 3 \times 10^{-3}$ erg
per every $\bar{n}$ annihilation

Two civilisations can agree to built scientific reactors and exchange neutrons ... ... we could get plenty of energy out of dark matter !

E.g. source with 3×10^{17} n/s (PSI) $\longrightarrow$ power $= 100$ MW

Asimov Machine: the "Pump"



First Part: Against Stupidity ...

Second Part: ...The Gods Themselves ...

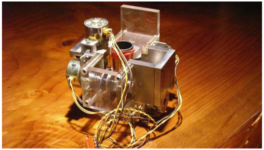
Third Part: ... Contend in Vain?

"Mit der Dummheit kämpfen Götter selbst vergebens!" – Friedrich Schiller

Radiochemist Hallam constructs the "Pump": a cheap, clean, and apparently endless source of energy functioning by the matter exchange between our universe and a parallel universe ....
His "discovery" was inspired by beings of "parallel" universe where stars were old and became too cold – they had no more energy resources ...

Che cretini! Hanno scoperto il protone neutro e non se ne accorgono!

La fisica è su una strada sbagliata. Siamo tutti su una strada sbagliata...



La fantomatica macchina forse teorizzata da Ettore Majorana! Nella sua formulazione attuale violerebbe un'infinità di principi scientifici, producendo enormi quantità di energia a costo zero. Non può affatto esistere ...

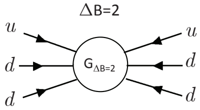
Backup

Some auxiliary slides

Neutron–antineutron oscillation

Neutron is a Dirac particle: $m\,\overline{n}\,n$ conserves B

Majorana mass of neutron $\frac{\epsilon}{2}(n^T C n + \bar{n}^T C \bar{n})$ $\Delta B = 2$
comes from six-fermions effective operator $\frac{1}{M^5}(udd)(udd)$



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

$\epsilon \sim \frac{\Lambda^6_{\rm QCD}}{M^5} \sim \left(\frac{1\ {\rm PeV}}{M}\right)^5 \times 10^{-25}$ eV $\tau_{n\bar{n}} \sim 10^9$ s

ILL experiment: $\tau_{n\bar{n}} > 0.86 \times 10^8$ s $\longrightarrow \epsilon < 7.7 \times 10^{-24}$ 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

Nuclear stability bounds: Oxygen$\to 2\pi$ – $\tau_{\rm nucl} > 10^{32}$ yr (SK)
$\epsilon < 2.5 \times 10^{-24}$ eV $\to$ $\tau > 2.7 \times 10^8$ s

$n - \bar{n}$ oscillation: Free (or bound)

Two states, n and $\bar{n}$

$$H = \begin{pmatrix} m + \mu\vec{B}\vec{\sigma} - V_n & \epsilon \\ \epsilon & m - \mu\vec{B}\vec{\sigma} - V_{\bar{n}} \end{pmatrix}$$

Free oscillation probability $P_{n\bar{n}}(t) = \frac{\epsilon^2}{\omega_B^2} \sin^2(\omega_B t)$, $\quad \omega_B = \mu B$

$\omega_B t < 1 \;\rightarrow\; P_{n\bar{n}}(t) = (\epsilon t)^2 = (t/\tau_{n\bar{n}})^2$

$\omega_B t \gg 1 \;\rightarrow\; P_{n\bar{n}}(t) = \frac{1}{2}(\epsilon/\omega_B)^2 < \frac{(\epsilon t)^2}{(\omega_B t)^2}$

for a given free flight time t, magn. field should be properly suppressed to achieve "quasi-free" regime: $\omega_B t < 1$

Baldo-Ceolin et al, 1994 (ILL, Grenoble) : $t \simeq 0.1$ s, $\quad B < 1$ mG

$P_{n\bar{n}}(t) = (t/\tau_{n\bar{n}})^2 < 10^{-18} \quad \longrightarrow \quad \epsilon < 7.7 \times 10^{-24}$ eV

Neutrons in nuclei: $\omega_B \rightarrow V_{\bar{n}} - V_n \sim 100$ MeV

Can neutron be transformed into antineutron ... more effectively?

Small Majorana mass of neutron $\frac{\epsilon}{2}\left(n^T C n + \overline{n} C \overline{n}^T\right) = \frac{\epsilon}{2}\left(\overline{n_c}\, n + \overline{n}\, n_c\right)$
$\equiv \quad n - \bar{n}$ oscillation $\;(\Delta B = 2)$

Oscillation probability for free flight time t
$P_{n\bar{n}}(t) = (\epsilon\, t)^2 = (t/\tau_{n\bar{n}})^2$ in quasi-free regime $\omega_B t < 1$

Present bounds on oscillation time $\tau_{n\bar{n}} = \epsilon^{-1}$ are severe:
$\tau_{n\bar{n}} > 0.86 \times 10^8$ s direct limit (free n) ILL, 1994
$\tau_{n\bar{n}} > 2.7 \times 10^8$ s nuclear stability (bound n) SK, 2020 (this conf.)

$$P_{n\bar{n}}(t) = \frac{t^2}{\tau_{n\bar{n}}^2} = \left(\frac{10^8\ \mathrm{s}}{\tau_{n\bar{n}}}\right)^2 \left(\frac{t}{0.1\ \mathrm{s}}\right)^2 \times 10^{-18}$$

Shortcult through mirror world: $n \to n' \to \bar{n}$:
Experimental search to be tuned against (dark) environmental conditions

$$P_{n\bar{n}}(t) = P_{nn'}(t) P_{n\bar{n}'}(t) = \frac{t^4}{\tau_{nn'}^2 \tau_{n\bar{n}'}^2} = \left(\frac{1\ \mathrm{s}^2}{\tau_{nn'}\tau_{n\bar{n}'}}\right)^2 \left(\frac{t}{0.1\ \mathrm{s}}\right)^4 \times 10^{-4}$$

No danger for nuclear stability !

If discovered, a potential source of enormous free energy !

$2 \times 2 = 4$!

Z.B., Eur.Phys.J C81:33 (2021), arXiv:2002.05609

4 states: $n,\ \bar{n}\ :\ n',\ \bar{n}'$ and mixing combinations:

$n \longleftrightarrow \bar{n}$ $(\Delta B = 2)$ & $n' \longleftrightarrow \bar{n}'$ $(\Delta B' = 2)$

$n \longleftrightarrow n'$ + $\bar{n}' \longleftrightarrow \bar{n}$ $\Delta(B - B') = 0$

$n \longleftrightarrow \bar{n}'$ + $n' \longleftrightarrow \bar{n}$ $\Delta(B + B') = 0$

Full Hamiltonian is 8×8:

$$\begin{pmatrix} m_n + \mu\vec{B}\vec{\sigma} & \epsilon_{n\bar{n}} & \epsilon_{nn'} & \epsilon_{n\bar{n}'} \\ \epsilon_{n\bar{n}} & m_n - \mu\vec{B}\vec{\sigma} & \epsilon_{n\bar{n}'} & \epsilon_{nn'} \\ \epsilon_{nn'} & \epsilon_{n\bar{n}'} & m'_n + V'_n + \mu'\vec{B}'\vec{\sigma} & \epsilon_{n\bar{n}} \\ \epsilon_{n\bar{n}'} & \epsilon_{nn'} & \epsilon_{n\bar{n}} & m'_n + V'_n - \mu'\vec{B}'\vec{\sigma} \end{pmatrix}$$

Present bounds on oscillation time $\tau_{n\bar{n}} = \epsilon^{-1}$:

$\tau_{n\bar{n}} > 0.86 \times 10^8$ s (free n), $\tau_{n\bar{n}} > 4.7 \times 10^8$ s (bound n)

$$P_{n\bar{n}}(t) = \frac{t^2}{\tau_{n\bar{n}}^2} = \left(\frac{10^8\ \mathrm{s}}{\tau_{n\bar{n}}}\right)^2 \left(\frac{t}{0.1\ \mathrm{s}}\right)^2 \times 10^{-18}$$

Shortcut for $n \to \bar{n}$ via $n \to n' \to \bar{n}$

Consider case when direct $n - \bar{n}$ mixing simply absent: $\epsilon_{n\bar{n}} = 0$

Anyway, $n \to \bar{n}$ emerges as second order effect via $n \to n' \bar{n}' \to \bar{n}$

$$\overline{P}_{n\bar{n}} = \overline{P}_{nn'} \overline{P}_{n\bar{n}'}$$

$$\overline{P}_{nn'} = \frac{2\epsilon^2_{nn'} \cos^2(\beta/2)}{(\Omega-\Omega')^2} + \frac{2\epsilon^2_{nn'} \sin^2(\beta/2)}{(\Omega+\Omega')^2}, \quad \overline{P}_{n\bar{n}'} = \frac{2\epsilon^2_{n\bar{n}'} \sin^2(\beta/2)}{(\Omega-\Omega')^2} + \frac{2\epsilon^2_{n\bar{n}'} \cos^2(\beta/2)}{(\Omega+\Omega')^2}$$

where β is the (unknown) angle between the vectors $\vec{B}$ and $\vec{B}'$

Disappearance experiments measure the sum $P_{nn'} + P_{n\bar{n}'} \propto \epsilon^2_{nn'} + \epsilon^2_{n\bar{n}'}$

$n - \bar{n}$ transition measures the product $P_{n\bar{n}} = P_{nn'} P_{n\bar{n}'} \propto \epsilon^2_{nn'} \epsilon^2_{n\bar{n}'}$
From the ILL'94 limit $P_{n\bar{n}} < 10^{-18}$ (measured at $B = 0$) we get

$$\tau_{nn'}\, \tau_{n\bar{n}'} > \frac{2 \times 10^9}{\Omega'^2} \approx \left(\frac{0.5\,\mathrm{G}}{B'}\right)^2 \times 100\ \mathrm{s}^2$$

E.g. $\tau_{nn'}\, \tau_{n\bar{n}'} \sim 1$ second is possible if $B' \sim 5$ G
Limits become even weaker if $\Delta m > 0.1$ neV

How good the shortcut can be?

Assuming e.g. $\tau_{nn'}\,\tau_{n\bar{n}'} = 100$ s and $B' = 0.5$ G, we see that ILL94-like measurement at $B = 0.45$ G (or $B = 0.49$ G) would give $P_{n\bar{n}} \simeq \sin^2\beta \times 10^{-15}$ (or $P_{n\bar{n}} \simeq \sin^2\beta \times 10^{-12}$)

To maximalize $n - \bar{n}$ probability, one has to match resonance with about 1 mG precision: we get

$$P_{nn'}(t) = \left(\frac{t}{\tau_{nn'}}\right)^2 \cos^2\frac{\beta}{2}, \qquad P_{n\bar{n}'}(t) = \left(\frac{t}{\tau_{n\bar{n}'}}\right)^2 \sin^2\frac{\beta}{2}$$

and

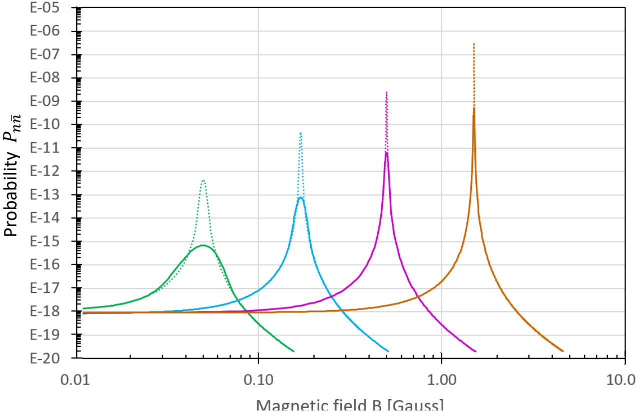
$$P_{n\bar{n}}(t) = P_{nn'}(t)P_{n\bar{n}'}(t) = \frac{\sin^2\beta}{4}\left(\frac{t}{0.1\ \mathrm{s}}\right)^4\left(\frac{100\ \mathrm{s}^2}{\tau_{nn'}\tau_{n\bar{n}'}}\right)^2 \times 10^{-8}$$

Practically no limit from nuclear stability

E.g. ^{16}O decay time predicted $\sim 10^{60}$ yr vs. present limit $\sim 10^{32}$ yr !

How effective $n \to \bar{n}$ can be?

simulations for $n - \bar{n}$ experiment with
$t = 0.1$ s ($\ell = 100$ m as ILL) and $t = 0.02$ s ($\ell = 20$ m)



– and perhaps a chance for free energy ?

Anthrophic

Is the Universe Anthropic? multiverse...

or Anthropomorphic? has basic instincts ...

or Anthrophilic? has sapience and purposes ...

Neutron, proton, electron mass conspiracy: $m_e < m_n - m_p$ etc.
– free neutron decays but it becomes stable when bound in nuclei

Taken Standard Model with all coupling constants fixed in UV, sort of "explanation" why $M_W \sim 10^2$ GeV

$M_W < 10$ GeV $\longrightarrow m_e > m_n - m_p$ hydrogen atom decays $pe \to n\nu$

$M_W > 10^3$ GeV $\longrightarrow m_n > m_p + m_e + E_b$ only hydrogen, no nuclei

Anthropic limit on $n - \bar{n}$ mixing

Nuclear instability against
$(A,Z) \to (A-1, \bar{n}, Z) \to (A-2, Z/Z-1) + \pi$'s scales as
Scale of new physics unknown – but $\tau_{\rm nucl} \propto \epsilon^2 \propto 1/M^{10}$ $(\epsilon \propto 1/M^5)$

Present limit $\tau_{\rm nucl} > 10^{32}$ yr implies
$\epsilon < 2.5 \times 10^{-24}$ eV $\longrightarrow$ $M > 500$ TeV or so

$M \to M/3$ (just 3 times less) would give $\tau_{\rm nucl} \to \tau_{\rm nucl}/3^{10} \approx 10^{27}$ yr

$\bar{n}n$ $(\bar{n}p)$ annihilation releases energy $E_{\rm ann} = 2m_n c^2 \approx 3 \times 10^{-10}$ J

Then the Earth power $= E_{\rm ann} N_\oplus / \tau_{\rm nucl} \simeq 10$ TW
.. the Earth radioactivity turns dangerous for the Life!

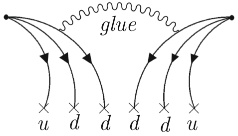
And (happily) the neutron is not elementary particle
– in which case it could have unsuppressed Majorana mass $\varepsilon n^T C n$
It is composite $n = (udd)$ of three quarks – Majorana mass
can be induced only by D=9 operator $\frac{1}{M^5}(udd)^2$
Life is permitted due to the structure of the SM

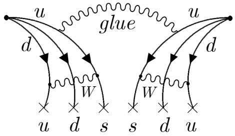
Anthropic θ-term in QCD (a provocation)

Z.B., EPJ C 76, 705 (2016), arXiv:1507.05478

QCD forms quark condensate $\langle \overline{q}q \rangle \sim \Lambda^3_{\rm QCD}$ breaking chiral symmetry (and probably 4-quark condensates $\langle \overline{q}q\overline{q}q \rangle$ not reducible to $\langle \overline{q}q \rangle^2$)

Can six-quark condensates $\langle qqqqqq \rangle$ be formed? B-violating namely $\langle (udd)^2 \rangle$ or $\langle (uds)^2 \rangle$ causing $n - \bar{n}$, $\Lambda - \overline{\Lambda}$ mixings



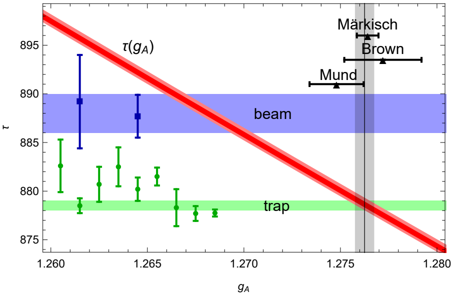


Vafa-Witten theorem: QCD cannot break vector symmetries ...
.. the prove relies on the absence of θ-term (i.e. valid for $\theta = 0$)
Imagine world $\theta \sim 1$ where $\langle qqqqqq \rangle \sim \Lambda^9_{\rm QCD}$ – bad for Life
– large $n - \bar{n}$, Goldstone β inducing $n \to \bar{n} + \beta$ in nuclei ...

Let us assume $\langle qqqqqq \rangle_\theta \sim F(\theta)\, \Lambda^9_{\rm QCD}$ with
$F(\theta)$ smooth periodic even function: $F(\theta) \simeq \cos\theta \simeq \theta^2 + \ldots$
Then for $\theta \sim 10^{-10}$, $\langle qqqqqq \rangle_\theta = \theta^2 \Lambda^9_{\rm QCD} \sim (1\ {\rm MeV})^9$
– can such a fuzzy condensate be OK? Maybe in dense matter?

Back to trap-beam problem: τ_n vs. β-asymmetry

Updated Fig.7 from Belfatto, Beradze and Z.B, EPJ C 80, 149 (2020)



$$g_A = 1.27625(50)$$

$$\tau_{\rm beam} = 888.0 \pm 2.0 \text{ s}$$

$$\tau_{\rm trap} = 878.5 \pm 0.5 \text{ s}$$

Free neutron decay:

$$G_V^2 = \frac{K/\ln 2}{\mathcal{F}_n \tau_n (1+3g_A^2)(1+\Delta_R)}$$

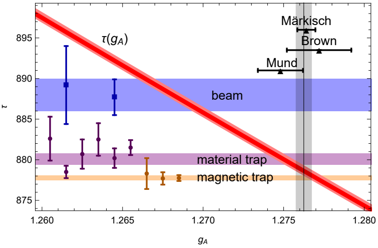
$0^+ - 0^+$ decays:

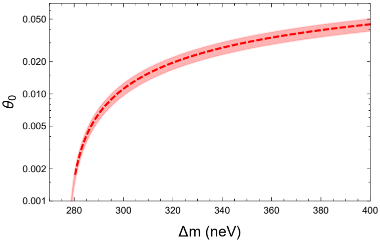
$$G_V^2 = \frac{K}{2\mathcal{F}t\,(1+\Delta_R)}$$

$$\tau_n = \frac{2\mathcal{F}t}{\mathcal{F}_n(1+3g_A^2)} = \frac{5172.1(1.1 \to 2.8)}{1+3g_A^2} \text{ s}$$ Czarnecki et al. 2018

G_V and Δ_R cancel out even in BSM $G_V \neq G_F|V_{ud}|$: $g_A = -G_A/G_V$

$$g_A = 1.27625(50) \longrightarrow \tau_n^{\rm theor} = 878.7 \pm (0.6 \to 1.5) \text{ s} \approx \tau_{\rm trap}$$





$\tau_n^{\rm theor} = 878.7 \pm 1.5$ s $\quad \tau_{\rm trap} = 878.5 \pm 0.5$ s (compatible)

$\tau_{\rm beam} = 888.0 \pm 2.0$ s $\quad (4.5\sigma)$

$\tau_{\rm mat} = 880.1 \pm 0.7$ s $\quad \tau_{\rm magn} = 877.8 \pm 0.3$ s $\quad (3.3\sigma$ discrepancy)

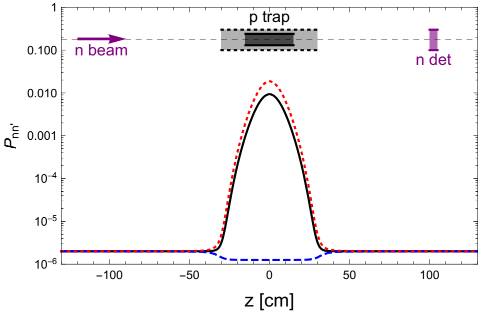
So experimentally we have $\quad \tau_{\rm magn} < \tau_{n\to p}^{\rm theor} < \tau_{\rm mat} < \tau_{\rm beam}$

which is possible in $n - n'$ oscillation scenario $\quad$ So far so Good!

Dark matter Factory ?

If my hypothesis is correct, a simple solenoid (magn. field $\sim$ Tesla) can be an effective machine transforming neutrons into DM neutrons

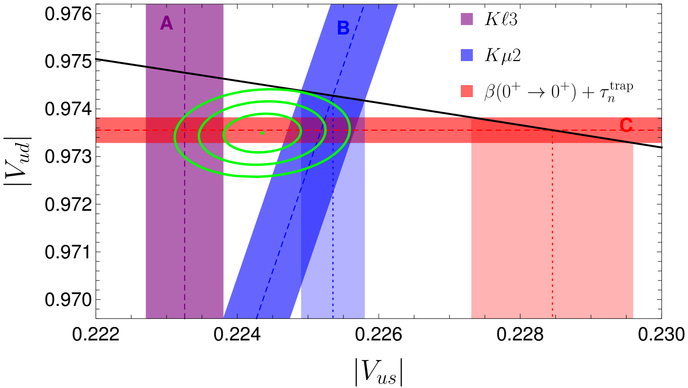
With good adiabatic conditions 50 % transformation can be achieved



$$P^{\rm tr}_{nn'} \approx \frac{\pi}{4}\xi \simeq 10^{-2}\left(\frac{2\ {\rm km/s}}{v}\right)\left(\frac{P^0_{nn'}}{10^{-6}}\right)\left(\frac{B_{\rm res}}{1\ {\rm T}}\right)\left(\frac{R_{\rm res}}{10\ {\rm cm}}\right)$$

ORNL experiment via $n \to n' \to n$ in strong magn. fields

Cabibbo Angle Anomaly



If CKM unitarity is assumed – strong discrepancy between

A: $|V_{us}| = \sin\theta_C$

B: $|V_{us}/V_{ud}| = \tan\theta_C$ Unitarity excluded at $> 3\sigma$

C: $|V_{ud}| = \cos\theta_C$

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Oldies ... but Goldies – Psychedelia or Serendipities of Artist?

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