Summary

Mirror Matter: general questions

Chapter I: *ordinary – mirror particle mixings*

Chapter II: *neutron – mirror neutron mixing*

Chapter III: $n - n'$ and UHECR

Mirror Matter as Dark Matter ...

... and ordinary – mirror particle mixings

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Particle Physics with Neutrons at the ESS,
Nordita, 10-14 Dec. 2018

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Introduction

Mirror Matter: generalities

Bright & Dark Sides of our Universe

Todays Universe: flat $\Omega_{\rm tot} \approx 1$ *(inflation)* ... and multi-component:

- $\Omega_B \simeq 0.05$ 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

B-genesis and DM require new physics: but which ?
Why $\Omega_D/\Omega_B \sim 1$?

Visible matter from Baryogenesis (*Sakharov*)

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

$\rho_B = m_B n_B$, $m_B \simeq 1$ 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.

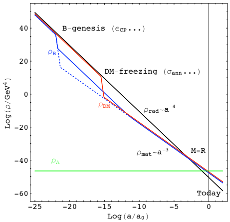
Dark matter: $\rho_D = m_X n_X$, but $m_X = ?$, $n_X = ?$
and why $m_X n_X = 5 m_B n_B$?

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

Axion	$m_a \sim$ meV	$n_a \sim 10^4 n_\gamma$	– CDM
Neutrinos	$m_\nu \sim$ eV	$n_\nu \sim n_\gamma$	– HDM (×)
Sterile ν'	$m_{\nu'} \sim$ keV	$n_{\nu'} \sim 10^{-3} n_\nu$	– WDM
WIMP	$m_X \sim$ TeV	$n_X \sim 10^{-3} n_B$	– CDM
WimpZilla	$m_X \sim$ ZeV	$n_X \sim 10^{-12} n_B$	– CDM

How these Fine Tunings look ...

B-genesis + WIMP



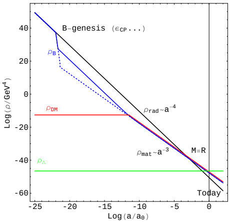
$m_X n_X \sim m_B n_B$

$m_X \sim 10^3 m_B$

$n_X \sim 10^{-3} n_B$

Fine Tuning?

B-genesis + axion



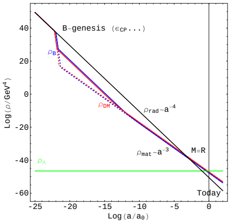
$m_a n_a \sim m_B n_B$

$m_a \sim 10^{-13} m_B$

$n_a \sim 10^{13} n_B$

Fine Tuning?

B-cogenesis



$m_{B'} n_{B'} \sim m_B n_B$

$m_{B'} \sim m_B$

$n_{B'} \sim n_B$

Natural ?

Two different New Physics for B-genesis and DM ?

Or co-genesis by the same Physics explaining why $\Omega_{DM} \sim \Omega_B$?

Dark sector ... similar to our luminous sector?

"Imagination is more important than knowledge." *Albert*

For 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 !

If dark matter comes from extra gauge sector ... it is as *complex*:
$G' = SU(3)' \times SU(2)' \times U(1)'$? (+ 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 ?

Let us call it Yin-Yang Theory

in chinise, Yin-Yang means dark-bright duality

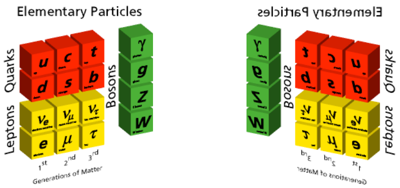
describes a philosophy how opposite forces are actually complementary, interconnected and interdependent in the natural world, and how they give rise to each other as they interrelate to one another.

$E_8 \times E'_8$

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

$$G \times G'$$

Regular world | Mirror world



• Two identical gauge factors, e.g. $SU(5) \times SU(5)'$, with identical field contents and Lagrangians: $\mathcal{L}_{\rm tot} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{\rm mix}$

• Exact parity $G \to G'$: no new parameters in dark Lagrangian $\mathcal{L}'$

• MM is dark (for us) and has the same gravity

• MM is identical to standard matter, (asymmetric/dissipative/atomic) but realized in somewhat different cosmological conditions: $T'/T \ll 1$.

• New interactions between O & M particles $\quad \mathcal{L}_{mix}$

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

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

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

But M World is OK if : Z.B., Comelli, Villante, 2001

(A) after inflation M world was born colder than O world

(B) all particle interactions between M and O sectors are so feeble that cannot bring them into equilibrium in later epochs

(C) two systems evolve adiabatically when the universe expands (no entropy production) and their temperature ratio T'/T remains nearly constant.

If $x = T'/T \ll 1$, BBN is OK

M world in Winter

Z.B., Comelli, Villante, 2000

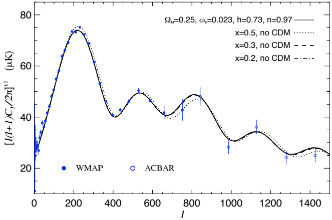
$T'/T < 0.5$ is enough to concord with the BBN limits and do not affect standard primordial mass fractions: 75% H + 25% ^{4}He.
(Cosmological limits are more severe, requiring $T'/T < 0.2$ os so.)
In turn, for M world this implies helium domination: 25% H$'$ + 75% ^{4}He$'$.

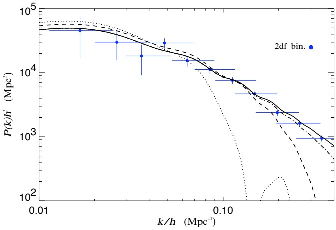
Because of $T' < T$, in mirror photons decouple much earlier than ordinary photons, and after that M matter behaves for the structure formation and CMB anisotropies essentially as CDM. This concords M matter with WMAP/Planck, BAO, Ly-α etc. if $T'/T < 0.25$ or so.

Halo problem – 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, with our matter inside forming disks.

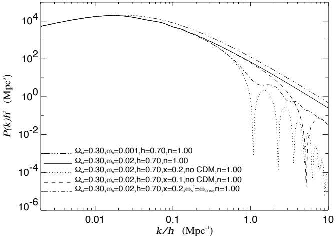
Because of $T' < T$, the situation $\Omega'_B > \Omega_B$ becomes plausible in baryogenesis. So, M matter can be dark matter (as we show below)

CMB and LSS power spectra





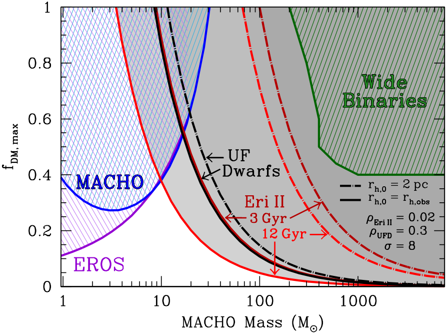
Z.B., Ciarcelluti, Comelli, Villante, 2003



Acoustic oscillations and Silk damping at short scales: $x = T'/T < 0.2$

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 $M = 20 - 200\ M_\odot$ but see Brandt '05



GW events without any optical counterpart

point towards massive BH compact binaries, $M \sim 10 - 30\ M_\odot$ and radius $R \sim 10 R_\odot$

How such objects can be formed ?

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 ?

Experimental and observational manifestations of mirror matter

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.

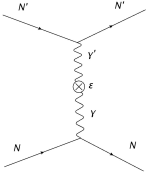
C. *Oscillation phenomena between ordinary and mirror particles.*
The most interesting interaction terms in $\mathcal{L}_{\rm mix}$ are the ones which violate B and L of both sectors. Neutral particles, elementary (as e.g. neutrino) or composite (as the neutron or hydrogen atom) can mix with their mass 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 $\Omega'_B/\Omega_B = 1 \div 5$.

Discussing $\mathcal{L}_{\rm mix}$: possible portal between O and M particles

- Photon-mirror photon kinetic mixing $\epsilon F^{\mu\nu} F'_{\mu\nu}$

Experimental limit $\epsilon < 4 \times 10^{-7}$
Cosmological limit $\epsilon < 5 \times 10^{-9}$

Makes mirror matter nanocharged ($q \sim \epsilon$)
A promising portal for DM direct detection Foot, 2003

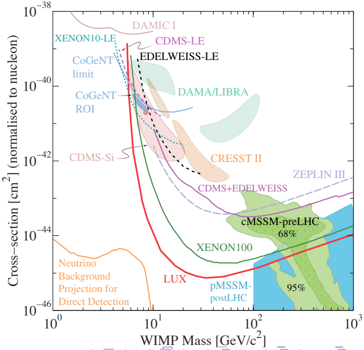


Mirror atoms: He' – 75 %, C',N',O' etc. few %
Rutherford-like scattering

$$\frac{d\sigma_{AA'}}{d\Omega} = \frac{(\epsilon\alpha Z Z')^2}{4\mu^2_{AA'} v^4 \sin^4(\theta/2)}$$

or

$$\frac{d\sigma_{AA'}}{dE_R} = \frac{2\pi(\epsilon\alpha Z Z')^2}{M_A v^2 E_R^2}$$



OM-MM interactions in the Early Universe after recombination

After recombination fractions $\sim 10^{-4}$ of OM and $\sim 10^{-3}$ of MM remains ionized. $\gamma - \gamma'$ kinetic mixing $\rightarrow$ Rutherford scatterings $ep' \rightarrow ep'$, $ee' \rightarrow ee'$ etc

Relative motion (rotation) of O and M matter drags electrons but not protons/ions which are much heavier. So circular electric currents emerge which can generate magnetic field. MHD equations with the source (drag) term induces magnetic seeds $B, B' \sim 10^{-15}$ G in galaxies/clusters then amplified by dynamo. So magnetic fields $\sim \mu$G can be formed in very young galaxies Z.B., Dolgov, Tkachev, 2013

MM capture by Earth can induce mirror magnetic field in the Earth, even bigger than ordinary 0.5 G.

New EDGES measurements of 21 cm emission (T-S hydrogen) indicates that at redshift $z \sim 17$ baryons were factor 2 cooler than predicted: if true, it can be beautiful implication of OM matter cooling (momentum transfer) via their Rutherford collisions with (cooler) MM

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Chapter I

Ordinary – mirror particle mixings

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

Two parities

Fermions and anti-fermions :

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

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

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

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

Twin Fermions and anti-fermions :

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

B′=1/3 L′=1 B′=1/3 L′=1

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

B′=-1/3 L′=-1 B′=-1/3 L′=-1

$$(\bar{u}_L Y_u q_L \bar{\phi} + \bar{d}_L Y_d q_L \phi + \bar{e}_L Y_e l_L \phi) + (u_R Y_u^* \bar{q}_R \phi + d_R Y_d^* \bar{q}_R \bar{\phi} + e_R Y_e^* \bar{l}_R \bar{\phi})$$

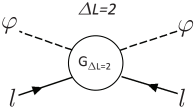
$$(\bar{u}'_L Y'_u q'_L \bar{\phi}' + \bar{d}'_L Y'_d q'_L \phi' + \bar{e}'_L Y'_e l'_L \phi') + (u'_R Y'^*_u \bar{q}'_R \phi' + d'_R Y'^*_d \bar{q}'_R \bar{\phi}' + e'_R Y'^*_e \bar{l}'_R \bar{\phi}')$$

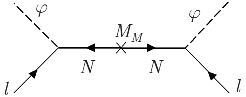
Z_2 symmetry $(L, R \to L, R)$: $Y' = Y$ $\quad B - B' \to -(B - B')$

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

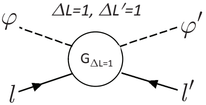
B-L violation in O and M sectors: Active-sterile neutrino mixing

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





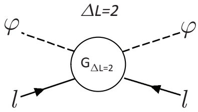
- Neutrino -mirror neutrino mixing – (active - sterile mixing)
L and L' violation: $\frac{1}{M}(l\bar{\phi})(l\bar{\phi})$, $\frac{1}{M}(l'\bar{\phi}')(l'\bar{\phi}')$ and $\frac{1}{M}(l\bar{\phi})(l'\bar{\phi}')$

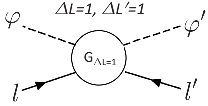


Mirror neutrinos are natural candidates for sterile neutrinos

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

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





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

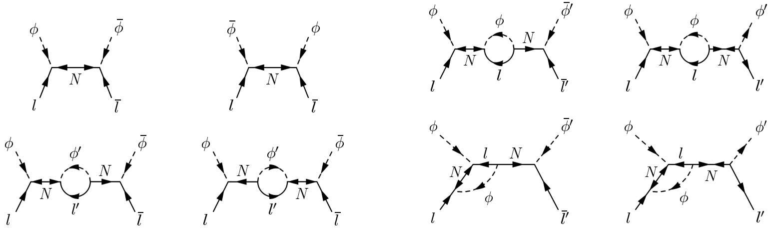
- These processes should be out-of-equilibrium
- Violate baryon numbers in both worlds, $B - L$ and $B' - L'$
- Violate also CP, given complex couplings

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



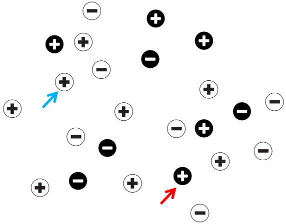
Complex Yukawa couplings $Y_{ij}l_iN_j\bar{\phi} + Y'_{ij}l'_iN_j\bar{\phi}' + \text{h.c.}$

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

Co-leptogenesis: Mirror Matter as hidden 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 $\quad \to \quad n_{BL} = n'_{BL}$

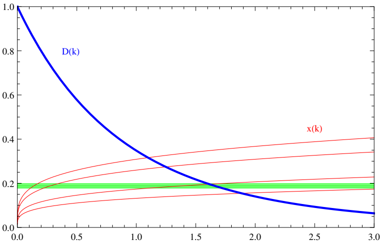
$$\Omega'_B = \Omega_B \simeq 10^3 \frac{J M_{Pl} T_R^3}{M^4} \simeq 10^3 J \left(\frac{T_R}{10^{11}\ {\rm GeV}}\right)^3 \left(\frac{10^{13}\ {\rm GeV}}{M}\right)^4$$

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:



$D(k) = \Omega_B/\Omega'_B$, $x(k) = T'/T$ 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

Free Energy from DM for the future generations ?

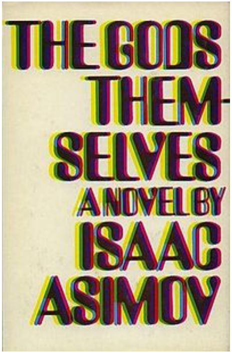
$n' \to \bar{n}$ produces our antimatter from mirror DM

Encounter of matter and antimatter leads to immediate (uncontrollable) annihilation which can be destructive

Annihilation can take place also between our matter and dark matter, but controllable by tuning of vacuum and magnetic conditions. Dark neutrons can be transformed into our antineutrons ....

Two civilisations can agree to built scientific reactors and exchange neutrons ... and turn the energy produced by each reactor in 1000 times more energy for parallel world .. and all live happy and healthy ...

Isaak Asimov



First Part: Against Stupidity ...

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

Third Part: ... Contend in Vain?

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

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Chapter I

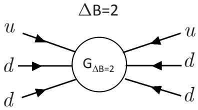
Neutron – mirror neutron mixing

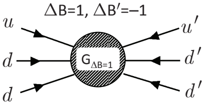
B violating operators between O and M particles in $\mathcal{L}_{\rm mix}$

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)

$$\frac{1}{M^5}(udd)(udd) \text{ and } \frac{1}{M^5}(udd)(u'd'd') \qquad (+\text{ h.c.})$$



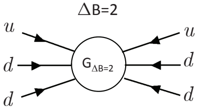


Oscillations $n(udd) \leftrightarrow \bar n(\bar u \bar d \bar d)$ $(\Delta B = 2)$
$n(udd) \to \bar n'(\bar u' \bar d' \bar d')$, $n'(udd) \to \bar n(\bar u \bar d \bar d)$ $(\Delta B = 1,\ \Delta B' = -1)$

Can co-generate Baryon asymmetries in both worlds
of the same sign, $B, B' > 0$, with $\Omega'_B \simeq 5\,\Omega_B$

Neutron– antineutron oscillation

Majorana mass of neutron $\epsilon(n^T Cn + \bar{n}^T C\bar{n})$ 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

Free neutron– antineutron oscillation

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

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

Oscillation probability $P_{n\bar{n}}(t) = \frac{\varepsilon^2}{\omega_B^2} \sin^2(\omega_B t)$, $\quad \omega_B = \mu_n B$

If $\omega_B t \gg 1$, then $P_{n\bar{n}}(t) = \frac{1}{2}(\varepsilon/\omega_B)^2 = \frac{(\varepsilon t)^2}{(\omega_B t)^2}$

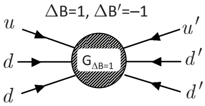
If $\omega_B t < 1$, then $P_{n\bar{n}}(t) = (t/\tau)^2 = (\varepsilon t)^2$

"Quasi-free" regime: for a given free flight time t, magnetic field should be properly suppressed to achieve $\omega_B t < 1$.
More suppression makes no sense !

Exp. Baldo-Ceolin et al, 1994 (ILL, Grenoble) : $t \simeq 0.1$ s, $\quad B < 100$ nT
$\tau > 2.7 \times 10^8 \quad \to \quad \varepsilon < 7.7 \times 10^{-24}$ eV
At ESS 2 orders of magnitude better sensitivity can be achieved, down to $\varepsilon \sim 10^{-25}$ eV

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 $\quad B - B'$



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

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

Even if $m_n = m_{n'}$, $n - \bar{n}'$ oscillation can be as fast as $\epsilon^{-1} = \tau_{n\bar{n}'} \sim 1$ s, without contradicting experimental and astrophysical limits.
(c.f. $\tau_{n\bar{n}'} > 2.5 \times 10^8$ s 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 mixing

The Mass Mixing $\epsilon(nCn' + \mathrm{h.c.})$ comes from six-fermions effective operator $\frac{1}{M^5}(udd)(u'd'd')$, M is the scale of new physics violating B and B' – but conserving $B - B'$

$$\epsilon = \langle n|(udd)(u'd'd')|n'\rangle \sim \frac{\Lambda^6_{\rm QCD}}{M^5} \sim \left(\frac{10\ \mathrm{TeV}}{M}\right)^5 \times 10^{-15}\ \mathrm{eV}$$

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

Surprisingly, $n - \bar n'$ oscillation can be as fast as $\epsilon^{-1} = \tau_{nn'} \sim 1$ s, without contradicting any experimental and astrophysical limits.
(c.f. $\tau_{n\bar n} > 2.5 \times 10^8$ s for neutron – antineutron oscillation)
Disappearance $n \to \bar n'$ (regeneration $n \to \bar n' \to n$) can be searched at small scale 'Table Top' experiments

Neutron – mirror neutron oscillation probability

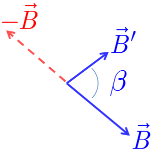
$$H = \begin{pmatrix} m_n + \mu_n \mathbf{B}\sigma & \epsilon \\ \epsilon & m_n + \mu_n \mathbf{B}'\sigma \end{pmatrix}$$

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

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

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

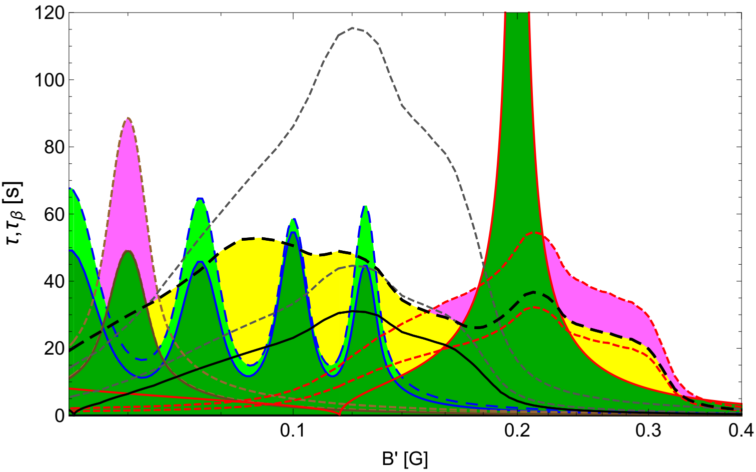
$$d(t) = \frac{\sin^2\left[(\omega - \omega')t\right]}{2\tau^2(\omega-\omega')^2} - \frac{\sin^2\left[(\omega + \omega')t\right]}{2\tau^2(\omega+\omega')^2}$$



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

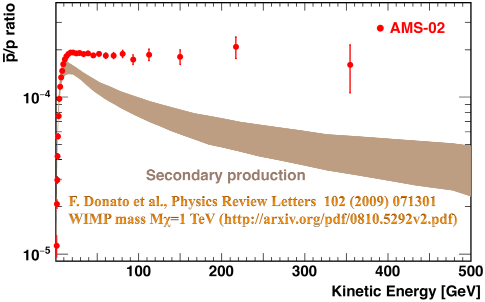
$$A_B^{\rm det}(t) = \frac{N_{-B}(t) - N_B(t)}{N_{-B}(t) + N_B(t)} = N_{collis} d_B(t) \cdot \cos\beta \leftarrow \text{ assymetry}$$

Experimental limits on $n - n'$ oscillation time



Mirror matter is a hidden antimatter: antimatter in the cosmos?

In mirror cosmic rays, disintegration of mirror nuclei by galactic UV background or in scatterings with mirror gas, frees out mirror neutrons which the oscillate into our antineutron, $n' \to \bar{n}$, which then decays as $\bar{n} \to \bar{p} + \bar{e} + \nu_e$.
so we get antiprotons (positrons), with spectral index similar to that of protons in our cosmic rays ?



Mirror Matter as Dark Matter ...
... and ordinary – mirror particle mixings
Zurab Berezhiani
Summary
Mirror Matter: general questions
Chapter I: *ordinary – mirror particle mixings*
Chapter II: *neutron – mirror neutron mixing*
Chapter III: $n - n'$ and UHECR

Chapter III

$n - n'$ and UHECR

UHECR and GZK cutoff

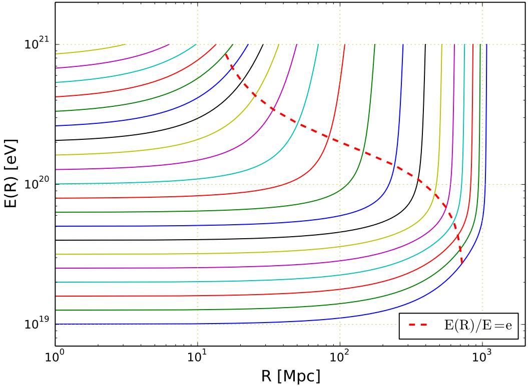
GZK cutoff:

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

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

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

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

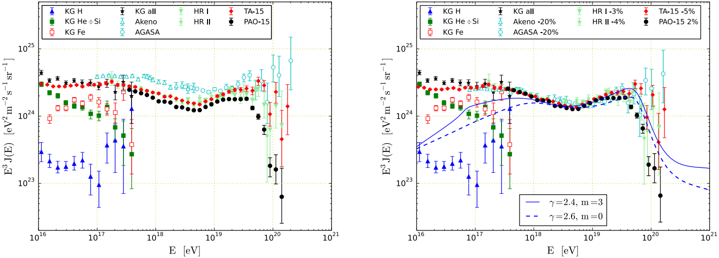


UHECR and GZK cutoff

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 at all energies, 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 cold for $E < E_{\rm GZK}$) . PAO anisotropies not so prominent: warm spot around Cen A, but observe dipole for $E > 10$ EeV – are two skies realy different ?

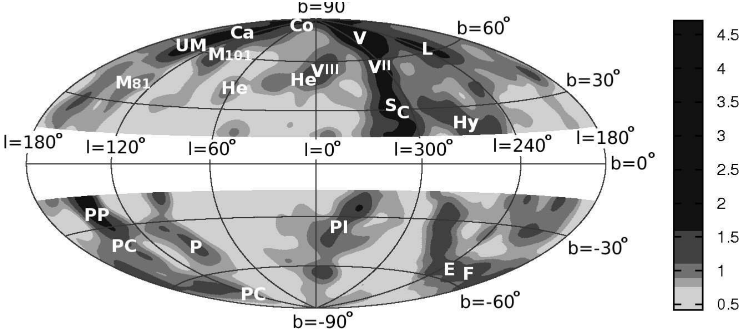
- From where highest energy events do come ?

$E > 100$ EeV are expected from local supercluster (Virgo, 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?

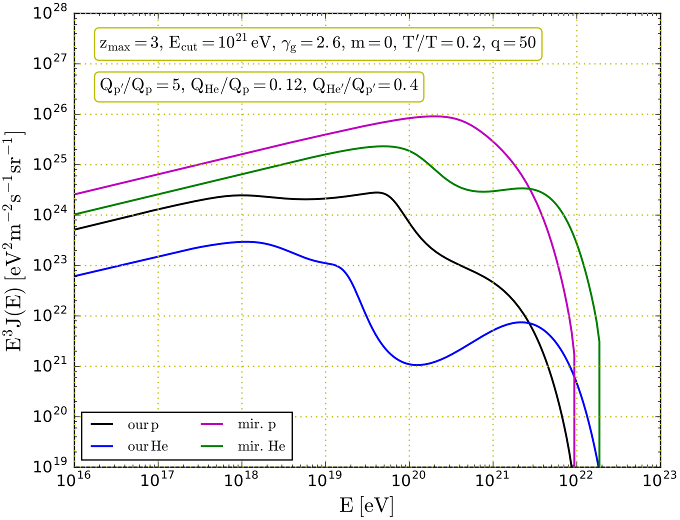
- Excess of cosmogenic photons ?

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

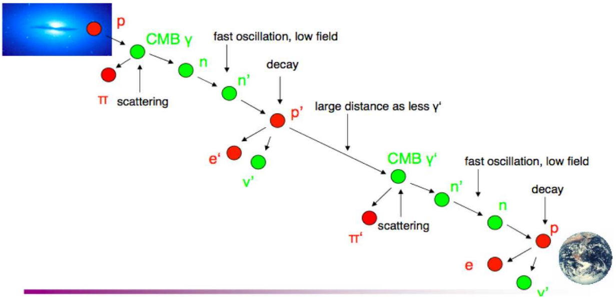
From where highest energy CR are expected ?



Ordinary and Mirror UHECR



$n - n'$ oscillation and UHECR propagation



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

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

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

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

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

$n - n'$ oscillation in the UHECR propagation

Baryon number is not conserved in propagation of the UHECR

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

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: $P_{nn'} = \frac{1}{1+q(E)}$

$$q = 0.45 \times \left(\frac{\tau_{nn'}}{1\ \rm s}\right)^2 \times \left(\frac{B_{\rm tr} - B'_{\rm tr}}{1\ \rm fG}\right)^2 \times \left(\frac{E}{100\ \rm EeV}\right)^2$$

If $q(E) < 1$, $\quad n - n'$ oscillation becomes effective

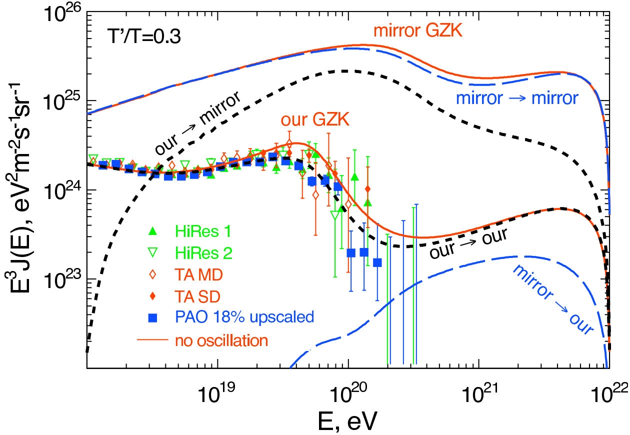
$$\frac{n'_{\rm CMB}}{n_{\rm CMB}} = \left(\frac{T'}{T}\right)^3 \ll 1 \qquad \frac{n'_{\rm EBL}}{n_{\rm EBL}} \sim 1$$

M-star formation & evolution

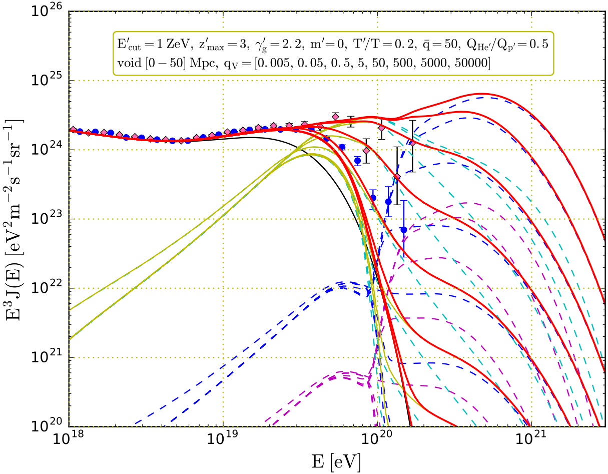
Earlier (than GZK) cutoff in cosmic rays

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

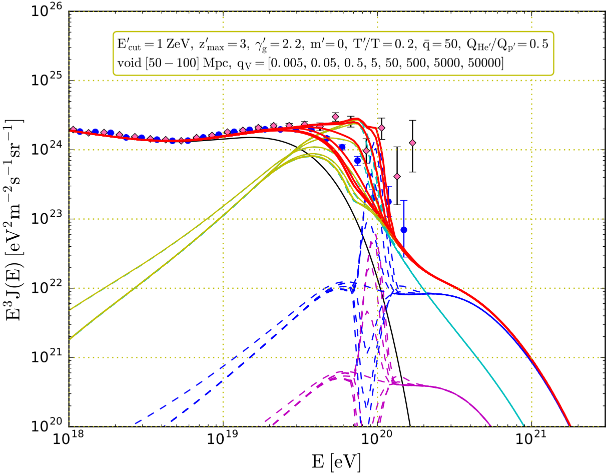
Baryon number is not conserved in propagation of the UHECR



Swiss Cheese Model: UHECR from Voids – adjacent Void



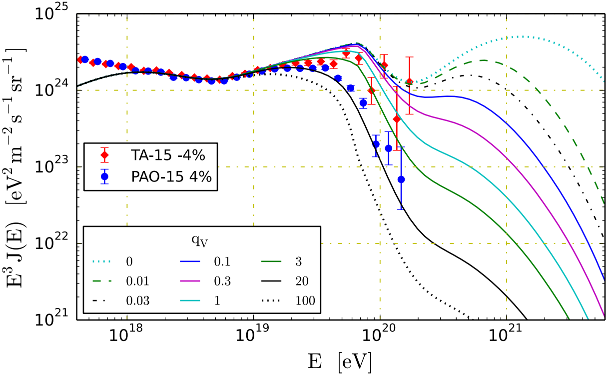
More distant Void



Swiss Cheese Model

Z.B., Biondi, Gazizov, 2018

Mirror CRs are transformed into ordinaries in nearby Voids. $n - n'$ oscillation probability depends on the magnetic fields in the Voids.



Are North Sky and South Sky different ?

Mirror Matter as Dark Matter ...

... and ordinary – mirror particle mixings

Zurab Berezhiani

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The Astrophysical Journal Supplement Series, 199:26 (22pp), 2012 April Huchra et al.

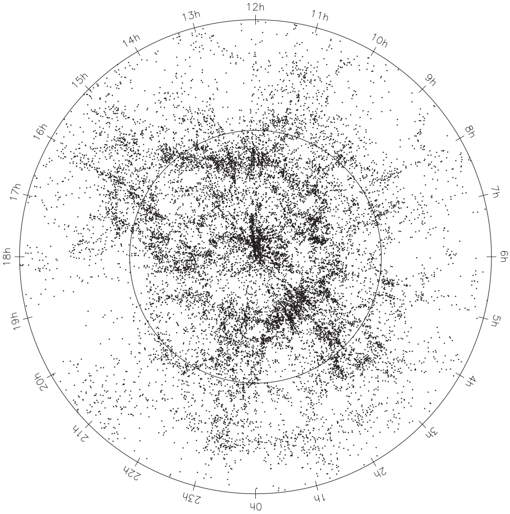

Figure 7. Hockey Puck plot—a full cylinder section—of 2MRS in the north celestial cap. The view is looking downward from the NCP, the thickness of the "puck" is 8000 km s^{-1}, and its radius is 15,000 km s^{-1}.

Are South Sky and North Sky different ?

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THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 199:26 (22pp), 2012 April HUCHRA ET AL.

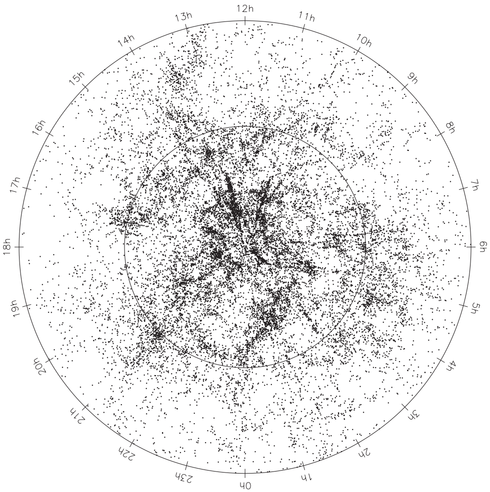
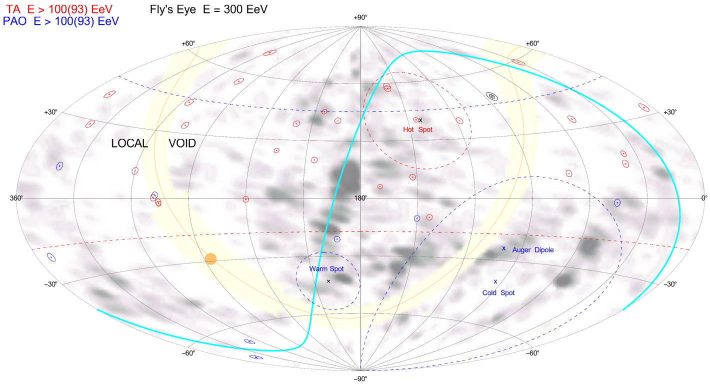


Figure 8. Same as Figure 7 but for the south celestial cap.

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



Arrival directions of $E > 80$ EeV events