Summary

Fisica Astroparticellare

Dark Matter

Supersymmetry and WIMPs

Mirror Matter

Mirror Matter, B-violation and Cogenesis

Conclusions

Dark Matter

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IAPS, LNGS, L'Aquila, 7 May 2015

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2. Dark Matter
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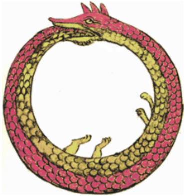
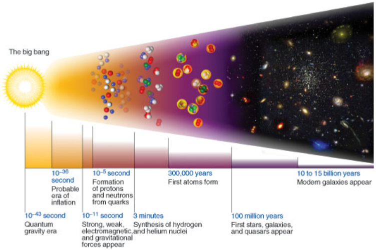
Fisica Astroparticellare: Uroboros





Physics of Particles and Fundamental Interactions $\rightarrow$ smallest distances ($\mathrm{TeV}^{-1} \sim 10^{-16}$ cm today)

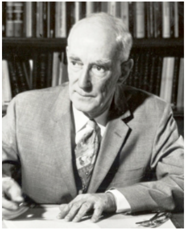
Cosmology $\rightarrow$ largest distances (Gpc $\sim 10^{27}$ cm today)

... Universe is expanding ... Early Universe was small and hot – and it tests particle physics at small distances/high energies

Intuiting *Dunkle Materie*

Existence of invisible (dark) matter in the galaxies and in the Universe was hypothetized long time ago ... *(e.g. Zwicky applied Virial to Coma cluster and noted the deficit of mass ...)*

• Jan Oort 1932 • Fritz Zwicky 1933 • Vera Rubin 1970



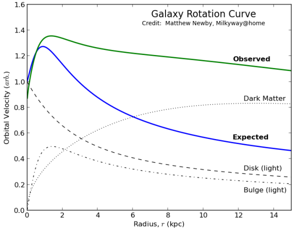
That time, in principle, this dark matter could be more conservatively interpreted as invisible baryonic matter in the form of dim stars *... Zwicky also hypothesized, after discovery of the neutron, existence of neutron stars*

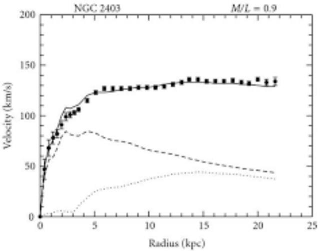
Rubin: *Galactic rotation velocities*

In disc galaxies (differential) rotation velocities, as a function of the distance from the center, indicate flat behaviour $v \simeq$ Const. instead of Keplerian Fall $(v \propto r^{-1/2})$

Grav. force = Centr. force $\quad m\frac{v^2}{r} = m\frac{GM(r)}{r^2} \quad \rightarrow \quad v \simeq \sqrt{GM(r)/r}$

Instead .... flat rotational curves were observed





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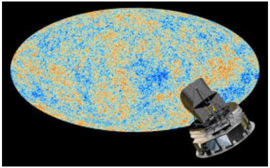
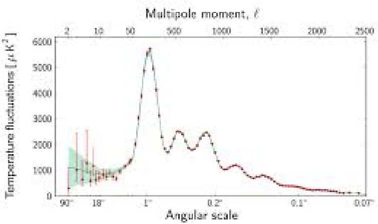
Precision Cosmology *CMB, LSS, lensing ....*



Planck measurements of CMB anisotropies



$\theta_* = (1.0415 \pm 0.0006) \times 10^{-2}$

$H_0 = (67.3 \pm 0.6)\ \mathrm{km/s \cdot Mpc^{-1}}$, inflation $n_s = 0.960 \pm 0.005$

$\Omega_B = 0.0487 \pm 0.0006$, $\Omega_D = 0.2647 \pm 0.0060$ $\Omega_{\rm tot} \approx 1$

$\Omega_M = \Omega_B + \Omega_D \simeq 0.31$ $\longrightarrow$ $\Omega_\Lambda \approx 0.69$

Dark Side of the Universe

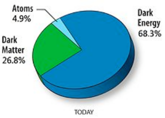
Todays Universe: flat $\Omega_{\rm tot} \approx 1$ *(inflation)* and multi-component:

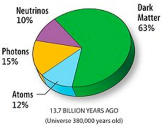
- $\Omega_B \simeq 0.05$ observable matter: electron, proton, neutron
- $\Omega_D \simeq 0.25$ dark matter: WIMP? axion? sterile ν? ...
- $\Omega_\Lambda \simeq 0.70$ dark energy: Λ-term? Quintessence? ....

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?*





– How Baryogenesis could know about Dark Matter? popular models for primordial Baryogenesis (GUT-B, Lepto-B, Affleck-Dine B, EW B ...) have no relation to popular DM candidates (Wimp, Wimpzilla, sterile ν, axion, gravitino ...)

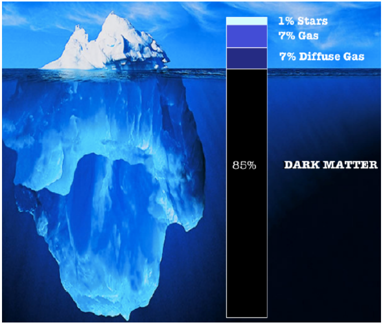
– Anthropic? Another Fine Tuning in Particle Physics and Cosmology?

Dark matter is everywhere in the Universe ...

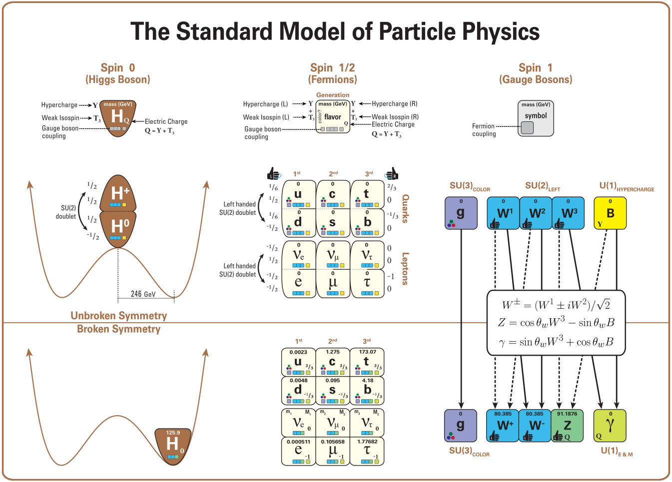
Evidence for the existence of an dark matter in the Universe comes from several independent observations at different length scales ...
and now we are certain that that dark matter is not baryonic !
... but unfortunately we do not know who is dark matter !

Experimental Hints:

- Rotation Curves
- Clusters of Galaxies
- CMB and LSS
- Supernovae 1a
- Gravitational Lensing



Standard Model $SU(3) \times SU(2) \times U(1)$



$W^{\pm} = (W^1 \pm iW^2)/\sqrt{2}$
$Z = \cos\theta_w W^3 - \sin\theta_w B$
$\gamma = \sin\theta_w W^3 + \cos\theta_w B$

Dark Matter Candidates

In the Standard Model $SU(3) \times SU(2) \times U(1)$ we do not have a candidate particle for dark matter ... *massive neutrino (~ 20 eV) was a natural "standard" candidate of dark matter (HDM) forming cosmological structures (Zeldovich's Pencakes) – but it was excluded by astrophysical observations in 80's – and later on by the neutrino physics itself*

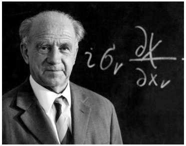
In about the same period the BBN limits excluded dark matter in the form of invisible baryons (dim stars, etc.)

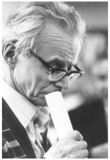
In 80's a new *Strada Maestra* was opened – $\mathcal{SUSY}$ – well-motivated theoretical concept promising to be a highway for solving a vast amount of fundamental problems, brought to a natural *almost "Standard"* candidate for dark matter – LSP or WIMP

* *Another interesting candidate, Axion, emerged from Peccei-Quinn anomalous global $U(1)$ for solving strong CP problem:* dark matter as a condensate of very light scalar bosons, $m \sim 10^{-4}$ eV

SUSY

Heisenberg 1965 — Volkov Akulov 1973 — Golfand Likhtman 1971





Supersymmetry between fermions and bosons
– extension of the Poincare symmetry:
space $\rightarrow$ superspace, fields $\rightarrow$ superfields
spontaneously (softly) broken at weak scale
– medicine for the Higgs health (origin of the weak scale)
+ gauge coupling unification etc.

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SUSY and R-parity

SM $\rightarrow$ MSSM: fields $\rightarrow$ superfields: $G = (g, \tilde{g})$, $Q = (q, \tilde{q})$ ...

$$\mathcal{L}_{\rm SUSY} = \mathcal{L}_{\rm gauge} + \mathcal{L}_{\rm matter} = \int d^2\theta G^2 + \int d^4\theta \Phi^\dagger e^V \Phi + \int d^2\theta W_{\rm matter}$$

$$W_{\rm matter} = QU^c H_2 + QD^c H_1 + LE^c H_1 + \mu H_1 H_2$$

$\sim \mathcal{L}_{\rm Yuk} + \mu^2 H^\dagger H$ in SM

$$\mathcal{L}_{\rm SSB} = \mathcal{L}^{\rm mass}_{\rm gaugino} + \mathcal{L}^{\rm mass}_{\rm scalars} + \mathcal{L}^{\rm trilinear}_{\rm scalars} =$$
$$\int d^2\eta\theta G^2 + \int d^4\theta\eta\bar{\eta}\Phi^\dagger e^V \Phi + \int \eta d^2\theta W_{\rm matter}$$

All superpartners get masses $M_S \sim 100$ GeV, from $\eta = M_S \theta^2$

.... $W_{\rm R-viol} = QD^c L + U^c D^c D^c + E^c LL + \mu' L H_2$

problems for proton stability

$R = (-1)^{3B+L+2s}$ (+ for SM particles, $-$ for superpartners)

or matter parity Z_2: $F \rightarrow -F$, $H \rightarrow H$

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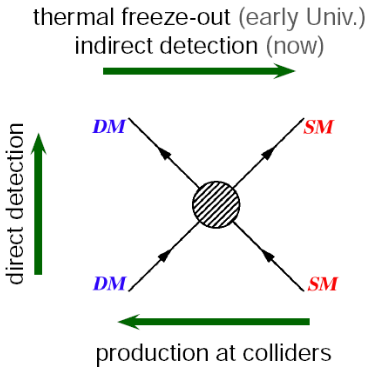
WIMP detection modes

Weak scale MSSM + R-parity: lightest spartner (LSP) is stable !
A perfect candidate for CDM with mass $M_X \sim 100$ GeV



LHC

Direct Detection @ LNGS: DAMA, CRESST, XENON, DARKSIDE

WIMP miracle and optimism for direct detection

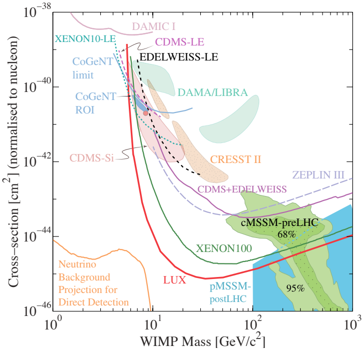
WIMP/LSP with mass $M_X \sim 100$ GeV – perfect candidate for CDM

$$\Omega_D h^2 \simeq \frac{0.02 x_f}{g_f^{1/2}} \left(\frac{1 \text{ pb}}{v\sigma_{\text{ann}}} \right) \qquad v\sigma_{\text{ann}} \sim 1 \text{ pb} \quad \to \quad \Omega_D h^2 \sim 0.1$$

$$\text{WIMP Miracle: } v\sigma_{\text{ann}} \sim \frac{\pi\alpha^2}{M_S^2} \sim \left(\frac{100 \text{ GeV}}{M_X} \right)^2 \times 10^{-36} \text{ cm}^2$$

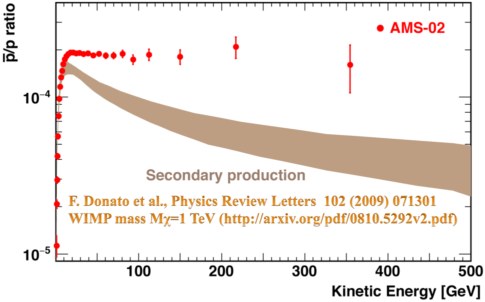
But for elastic scattering $X + N \to X + N$ one expects $\sigma_{\text{scat}} \sim \sigma_{\text{ann}}$ which is important for direct detection

However ... no evidence at LHC and no evidence from DM direct search + many problems to natural SUSY



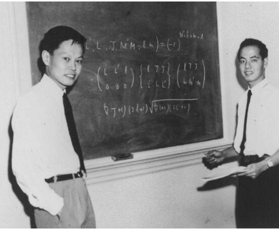
Indirect detection: antimatter in the cosmos?

WIMP + WIMP annihilation into proton + antiproton ?
(electron + positron?) $M_X \sim$ few hundred GeV



Parity Violation & Mirror Fermions – *Lee and Yang, 1956*

The conservation of parity is usually accepted without questions concerning its possible limit of validity being asked. The is actually no *a priori* reason why its violation is undesirable. Its violation implies the existence of right-left asymmetry and we have shown in the above some possible experimental tests os this asymmetry.



If such asymmetry is indeed found, *the question could still be raised whether there could not exist corresponding elementary particles exhibiting opposite asymmetry such that in the broader sense there will still be over-all right-left symmetry. If this is the case, there must exist two kinds of protons p_R and p_L, the right-handed one and the left-handed one.* At the present time the protons in the laboratory must be predominantly of one kind to produce the supposedly observed asymmetry. *This means that the free oscillation period between them must be longer than the age of the Universe. They could therefore both be regarded as stable particles. The numbers of p_R and p_L must be separately conserved.* Both p_R and p_L could interact with the same E-M field and perhaps the same pion field ...

Mirror Fermions as parallel sector – *Kobzarev, Okun, Pomeranchuk, 1966*



In connection with the discovery of CP violation, we discuss the possibility that "mirror" (R) particles exist in addition to the ordinary (L) particles. The introduction of these particles reestablishes the equivalence of left and right. It is shown that *mirror particles cannot interact with ordinary particles strongly, semistrongly or electromagnetically.* Weak interactions between L and R particles are possible owing to the exchange of neutrinos. *L and R particles must have the same gravitational interactions. The possibility of existence and detection of macroscopic bodies (stars) made up of R-matter is discussed.*

Alice @ Mirror World – "Through the Looking-Glass" (1871)

I'll tell you all my ideas about Looking-glass House. *The room you can see through the glass – that's just the same as our room ... the books there are something like our books, only the words go the wrong way ...* I can see all of it – all but the bit just behind the fireplace. *I want so to know whether they've a fire*: you never can tell, you know, unless *our fire smokes, and then smoke comes up in that room too ...* Oh, how nice it would be if we could get through into Looking-glass House! Let's pretend there's a way of getting through into it, somehow ... *It'll be easy enough to get through I declare!'*

Lewis Carroll

Parallel hidden sector vs. observable sector ?

For observable particles .... *very complex physics !!*
Gauge $G = SU(3) \times SU(2) \times U(1)$ (+ SUSY ? GUT ? RH neutrinos ?)
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-conserviolation, C/CP ... Sakharov)
... existence of nuclei, atoms, molecules .... life.... Homo Sapiens !

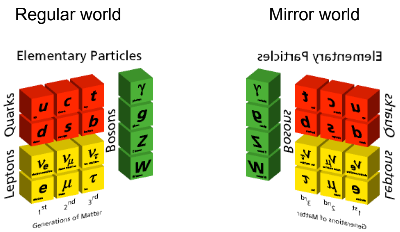
What if dark matter comes from extra gauge sector ... which is as *complex* as the observable one?
Parallel gauge sector: – $G' = SU(3)' \times SU(2)' \times U(1)'$?
photon′, electron′, nucleons′ (quarks′), $W' - Z'$, gluons′ ?
... long range EM forces, confinement at $\Lambda'_{\rm QCD}$, weak scale M'_W ?
... asymmetric dark matter (B′-conserviolation, C/CP ... Sakharov′) ?
... existence of dark nuclei, atoms, molecules ... life ... twin Homo Sapiens?

Dark gauge sector ... similar to our particle sector? ... or exactly the same?
.... two (or more) parallel branes in extra dimensions? $E_8 \times E'_8$?
..... let us imagine !

"Imagination is more important than knowledge..." A. Einstein

Ordinary and Mirror Worlds

$$G \times G'$$



- 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 $G \to G'$: Mirror matter is dark (for us), but its particle physics we know – no new parameters!

- Naturally in string theory: O & M matters localized on two parallel branes and gravity propagating in bulk: e.g. $E_8 \times E_8'$

Mirror vs. ordinary matter

Particle physics will is described by a symmetric Lagrangian:

$$\mathcal{L}_{tot} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{mix}$$

- Invariant under two identical gauge groups: $G \times G'$
- Identical field contents
- Mirror Parity $P(G \leftrightarrow G')$ (no new parameters in $\mathcal{L}'$)

Gravity *is not* the only common force between two sectors!
Other interactions are possible $\mathcal{L}_{mix}$

- Mirror Matter is a natural candidate for dark matter.
- If after Inflation $T' < T/2$ or so $\rightarrow$ consistent with BBN

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Mirror Particle Physics

For Ordinary particles we have the **Standard Model**:

- Gauge Symmetry: $G = SU(3) \times SU(2) \times U(1)$
- Particles: quarks, leptons, photon, gluons, $W^{\pm}$, Z, Higgs.
- Interactions: long-range EM forces, Strong interaction confinement ($\Lambda_{\rm QCD}$), Weak scale M_W

In the Mirror Sector we have the same:

- Gauge Symmetry: $G' = SU(3)' \times SU(2)' \times U(1)'$
- Particles: quarks′, leptons′, photon′, gluons′, W', Z', Higgs′.
- Interactions: long-range EM forces, Strong interaction confinement ($\Lambda'_{\rm QCD}$), Weak scale M'_W

$\mathcal{L}_{mix} \longrightarrow$ possible interactions (also $B-L$ violating as $\frac{1}{M} LHL'H'$)
as Lepton + Higgs → Lepton′ + Higgs′ scattering: $\Delta L = 1$, $\Delta L' = 1$

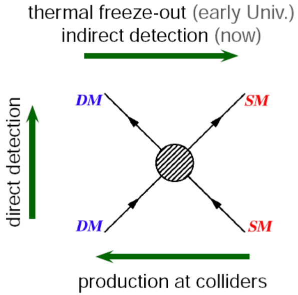
O-M particle mixing (only for neutral particles)
$\nu - \nu'$ mixing, photon-photon′ kinetic mixing, etc.

Mirror Matter Detection Modes

A candidate for self-interacting DM with mass $M_X \sim$ few GeV

The lightest baryon′ is stable (B-conservation) ! Asymmetric Dark Matter: Baryon′ asymmetry of the Universe (excess of baryons over antibaryons) due to $B-L$ and CP violating processes out-of-equilibrium

E.g. $LH \to L'H'$, $UDD \to U'D'D'$ in Early Universe $\frac{1}{M}LHL'H'$



Neutral DM particles (mirror neutrinos, neutron, hydrogen atom) can mix our neutral particles (ordinary neutrinos, neutron and hydrogen atom)

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

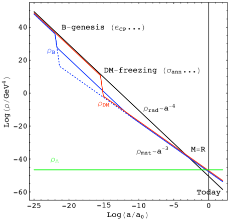
Dark matter: $\rho_D = n_X m_X$, but $m_X = ?$, $n_X = ?$

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

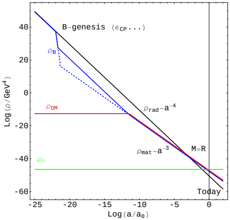
Axion	$m_a \sim 10^{-5}$ eV $n_a \sim 10^4 n_\gamma$ - CDM
Neutrinos	$m_\nu \sim 10^{-1}$ eV $n_\nu \sim n_\gamma$ - HDM $(\times)$
Sterile ν'	$m_{\nu'} \sim 10$ keV $n_{\nu'} \sim 10^{-3} n_\nu$ - WDM
Mirror baryons	$m_{B'} \simeq 1$ GeV $n_{B'} \sim n_B$ - ???
WIMP	$m_X \sim 1$ TeV $n_X \sim 10^{-3}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

Cosmological evolution: B vs. D

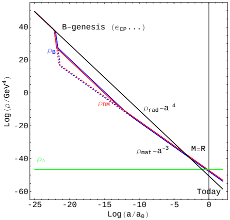
B-genesis + WIMP



B-genesis + axion



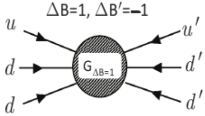
B-cogenesis



B-genesis + WIMP	B-genesis + axion	B-cogenesis
$m_X n_X \sim m_B n_B$	$m_a n_a \sim m_B n_B$	$m_{B'} n_{B'} \sim m_B n_B$
$m_X \sim 10^3 m_B$	$m_a \sim 10^{-13} m_B$	$m_{B'} \sim m_B$
$n_X \sim 10^{-3} n_B$	$n_a \sim 10^{13} n_B$	$n_{B'} \sim n_B$
Fine Tuning?	Fine Tuning?	Natural ?

Neutron – mirror neutron oscillation

The Mass Mixing $\epsilon(\bar{n}n' + \bar{n}'n)$ comes from a B and B' violating six-fermions effective operator: $\frac{1}{M^5}(udd)(u'd'd')$



M is the scale of new physics beyond EW scale.

$m_n = m_{n'} \longrightarrow \tau_{nn'} \sim \epsilon^{-1} \sim (M/10\,TeV)^5 \times 1s$

All the experimental limits on this transition become invalid in the presence of a mirror magnetic field:

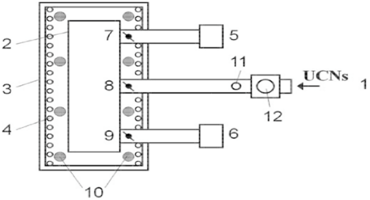
$$H = \begin{pmatrix} \mu\mathbf{B}\sigma & \epsilon \\ \epsilon & \mu\mathbf{B}'\sigma \end{pmatrix}$$

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

Experimental Strategy

We need to store neutron 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 ($75s$, $150s$, ...)
- Open the valve
- Count the survived Neutrons



Repeat this for different orientation and values of Magnetic field.

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

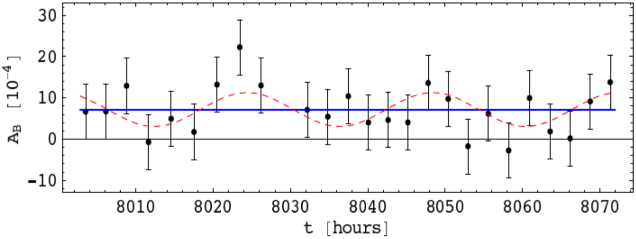
$$\frac{N_{B1}(T_S)}{N_{B2}(T_S)} = \exp\left[\left(\bar{\mathcal{P}}_{B2} - \bar{\mathcal{P}}_{B1}\right)\nu T_S\right]$$

So if we find that:

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

ILL Serebrov 2007

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



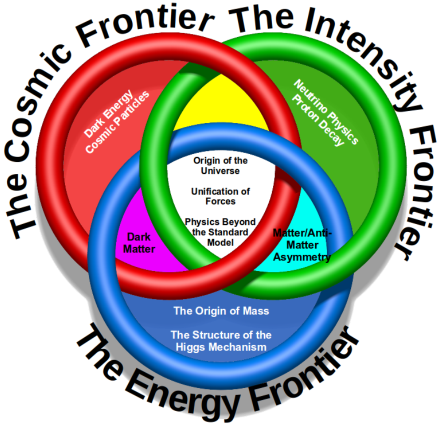
Analysis[1] pointed out the presence of a signal:

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

so that: $\tau_{nn'} \sim 2 - 10s$' and $B' \sim 0.1G$

[1]Z.Berezhiani, F. Nesti, Eur. Phys. J. 72, 1974 (2012)

Research Frontiers



Conclusions

Most interesting is still ahead!

Identity of Dark Matter is still unknown !

Plenty of perspectives for important discoveries

You have all chances to make it ...
but hard work (and imagination) are needed !