Quest to Physics Beyond the Standard Model: Some Astroparticle Topics

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Contents

Once upon a time .... in dark ages

Every epoch, starting from ancient times, had some fundamental(ist) "understanding" of the Universe – other ideas were coined as heres, heretics were ignored, some even killed

First Standard Model was based on flat Earth carried on shoulders by three elephants ...

The idea of round Earth was not sustainable: the antipodes would fall down

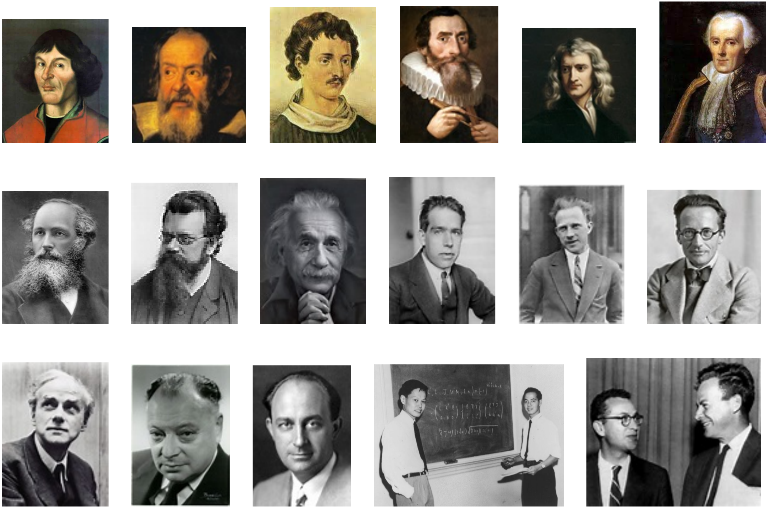
The Earth was at rest, sun and planets moving around it ...

The idea of moving Earth was not sustainable – there had to be ever blowing wind

Matter was a continuous medium ... four elements: Earth, Water, Air, Fire ... Phlogiston Theory of heat ... Aether

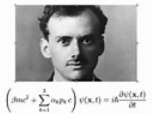
Someone courageously hypothesised existence of atoms ...
and even of multiverse

Some Beautiful Minds advanced the understanding of Cosmo and Microcosm



Epochal discoveries of new particles in 1930's

Anti-matter, 1930-32



Neutrino, 1930-34 ...



Neutron, 1932-33

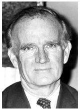


Dark Matter + Neutron Stars, 1933

in 50-60's: breaking tabu of "fundamental" symmetries ... and prophecy on the origin of matter

P Violation, 1956-57

CP Violation, 1964



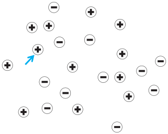
and a great vision ... 1967

Matter (Baryon asymmetry) in the early universe can be originated (from zero) by New Interactions which

- Violate B (now better $B - L$) and also CP
- and go out-of-equilibrium at some early epoch

$\sigma(bb \to \bar{b}\bar{b})/\sigma(\bar{b}\bar{b} \to bb) = 1 - \epsilon$

$\epsilon \sim 10^{-9}$: for every $\sim 10^9$ processes *one unit of B*
is left in the universe after the process is frozen



… and finally the Standard Model of all particles and interactions: $SU(3) \times SU(2) \times U(1)$




+ quarks and QCD (Gell-Mann et al.)

From Dynamit Prize in 1979
… to the publicity on T-shirts

$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
& + i \bar{\psi} \not{D} \psi + h.c. \\
& + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. \\
& + |D_\mu \phi|^2 - V(\phi)
\end{aligned}
$$

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

Matter and Antimatter

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

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

B=–1/3   L=–1   B=–1/3   L=–1

$\updownarrow$ CP

C and P are maximally broken in weak interactions
(not respected by gauge interactions)

but CP: $F_L \to F_R^c \equiv \bar{F}_R = C\overline{F_L}^T = C\gamma_0(F_L)^*$ is a nearly good symmetry
transforming Left-handed matter $\to$ Right-handed antimatter
– broken *only* by complex phases of Yukawa couplings to Higgs doublet ϕ

$$\mathcal{L}_{\rm Yuk} = Y_{ij}\overline{F_{Ri}}F_{Lj}\phi = Y_{ij}\bar{F}_{Li}F_{Lj}\phi \ + \ \text{h.c.} \qquad + \ \theta\text{-term in QCD}$$

B and L are automatically conserved in (renormalizable) couplings:
accidental global symmetries $U(1)_B$ and $U(1)_L$

B$-$L is conserved also by non-perturbative effects

B$-$L breaking needs New Physics

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

Bosons (= interactions): gauge fields + God's particle – Higgs

Fermions (= matter): quarks and leptons, *3 generations*

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

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

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm Gauge} + \mathcal{L}_{\rm Higgs} + \mathcal{L}_{\rm Yuk}$$

$P \; (\Psi_L \to \Psi_R)$ and $C \; (\Psi_L \to \tilde{\Psi}_L)$ broken by gauge interactions

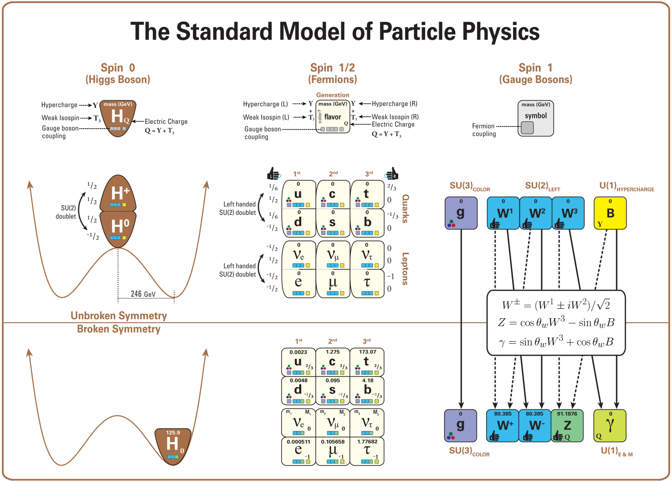
$CP \; (\Psi_L \to \tilde{\Psi}_R)$ broken in Yukawa sector $\mathcal{L}_{\rm Yuk} = \mathcal{W} + \mathcal{W}^\dagger$

$$\mathcal{W} = \tilde{\Psi}_L Y \Psi_L \phi \equiv \bar{u}_L Y_u q_L \phi_u + \bar{d}_L Y_d q_L \phi_d + \bar{e}_L Y_e l_L \phi_d$$
$$\mathcal{W}^\dagger = \Psi_R Y^* \tilde{\Psi}_R \tilde{\phi} \equiv u_R Y_u^* \bar{q}_R \tilde{\phi}_u + d_R Y_d^* \bar{q}_R \tilde{\phi}_d + e_R Y_e^* \bar{l}_R \tilde{\phi}_d$$

complex Yukawas $\quad Y = Y_{ij}^{u,d,e}, \quad i,j = 1,2,3 \quad (\phi = \phi_d \sim \phi_u^*)$

CPT is OK (Lagrangian formulation)

Standard Model: Two Phases



Standard Model after breaking .... $\langle \phi^0 \rangle = \frac{v+\eta}{\sqrt{2}}$

$$\mathcal{L}_{GWS} = \sum_f (\bar\Psi_f (i\gamma^\mu \partial\mu - m_f)\Psi_f - eQ_f \bar\Psi_f \gamma^\mu \Psi_f A_\mu) +$$

$$+\frac{g}{\sqrt{2}} \sum_i (\bar a^i_L \gamma^\mu b^i_L W^+_\mu + \bar b^i_L \gamma^\mu a^i_L W^-_\mu) + \frac{g}{2c_w} \sum_f \bar\Psi_f \gamma^\mu (I^3_f - 2s^2_w Q_f - I^3_f \gamma_5)\Psi_f Z_\mu +$$

$$-\frac{1}{4}|\partial_\mu A_\nu - \partial_\nu A_\mu - ie(W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 - \frac{1}{2}|\partial_\mu W^+_\nu - \partial_\nu W^+_\mu +$$

$$-ie(W^+_\mu A_\nu - W^+_\nu A_\mu) + ig' c_w (W^+_\mu Z_\nu - W^+_\nu Z_\mu|^2 +$$

$$-\frac{1}{4}|\partial_\mu Z_\nu - \partial_\nu Z_\mu + ig' c_w (W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 +$$

$$-\frac{1}{2} M^2_\eta \eta^2 - \frac{g M^2_\eta}{8 M_W} \eta^3 - \frac{g'^2 M^2_\eta}{32 M_W} \eta^4 + |M_W W^+_\mu + \frac{g}{2} \eta W^+_\mu|^2 +$$

$$+\frac{1}{2}|\partial_\mu \eta + i M_Z Z_\mu + \frac{ig}{2c_w} \eta Z_\mu|^2 - \sum_f \frac{g}{2} \frac{m_f}{M_W} \bar\Psi_f \Psi_f \eta$$

Standard Model is very natural/economic

- Renormalizability (one can control radiative corrections)

- Origin of Mass I: spont. breaking of electroweak $SU(2) \times U(1)$ – Weak Bosons W, Z and Quarks & Leptons ($f = u, d, e$) all get (elementary) masses $v_{\rm EW} \simeq 100$ GeV

- Origin of Mass II: dimensional transmutation of color $SU(3)$, asymptotic freedom and confinement & chiral symmetry breaking baryons (p, n, Λ) and vector mesons (ρ, ω etc.) get (composite) masses $\Lambda_{\rm QCD} \simeq 100$ MeV

- CKM mixing $V_{\rm CKM} = V_u^\dagger V_d$ + CP violation

- Natural flavor conservation in neutral transitions (flavor is violated only in GIM suppressed radiative corrections)

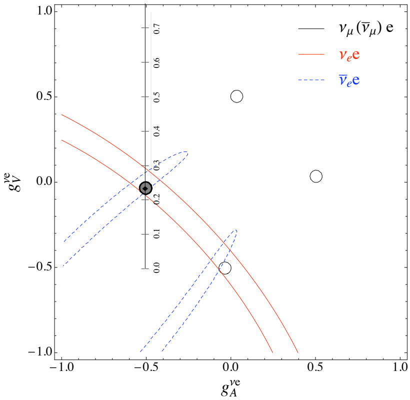
- Natural baryon and lepton conservation (accidental global $U(1)_B$ & $U(1)_B$ in renormalizable Yukawas)

Neutrino Interactions on electron

$$\mathcal{L} = \frac{G_F}{\sqrt{2}} \overline{\nu}\gamma^\mu(1-\gamma_5)\nu\, \overline{e}\gamma_\mu(g_V - g_A\gamma_5)e$$

In SM, $g_A = -\frac{1}{2}$ and $g_V = s_W^2 - \frac{1}{4}$,

$$s_W^2 = \frac{g'^2}{g^2+g'^2} = 1 - c_W^2 \qquad c_W^2 = \cos^2\theta_W = \frac{g^2}{g^2+g'^2} = \frac{M_W^2}{M_Z^2}$$

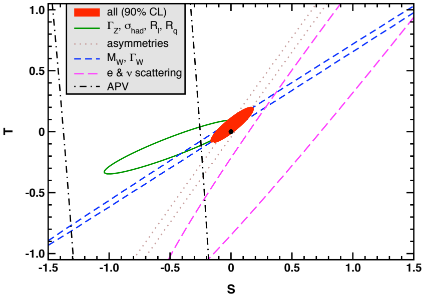


New Physics and S,T,U parameters

$$M_Z^2 = M_{Z0}^2 \frac{1-\widehat{\alpha}(M_Z)T}{1-G_F M_{Z0}^2 S/2\sqrt{2}\pi} ,$$

$$M_W^2 = M_{W0}^2 \frac{1}{1-G_F M_{W0}^2 (S+U)/2\sqrt{2}\pi} ,$$

$$S = \frac{C}{3\pi} \sum_i \Big(t_{3L}(i) - t_{3R}(i) \Big)^2 ,$$



Fourth (chiral) family is excluded at about 7σ level ....

Standard Model is very natural/economic

- Renormalizability (i.e. one can control radiative corrections)
- Origin of Mass: $\langle\phi^0\rangle = \frac{1}{\sqrt{2}}(v+\eta)$

God's condensate ($v = 246$ GeV) and Higgs particle ($\eta \sim H$)

Weak Bosons: $M_W = \frac{1}{2}gv$, $M_Z = \frac{1}{2}\bar{g}v$ ($\bar{g} = \left(g^2 + g\prime 2\right)^{1/2}$)

$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2} = \frac{1}{2v^2}$

Quarks & Leptons ($f = u,d,e$): $M_{ij}^f = \frac{v}{\sqrt{2}}Y_{ij}^f$, $\tilde{V}_f^\dagger M^f V_f = M_{\rm diag}^f$

mass eigenstates (m_e, m_u, m_d etc.) are all $\propto v \sim 100$ GeV

- CKM mixing $V_{\rm CKM} = V_u^\dagger V_d$ + *CP* violation
- Natural flavor conservation in neutral currents (Z, H)
- CP-violation: complex Yukawas $Y = Y_{ij}^{u,d,e}$, $i,j = 1,2,3$

$$\mathcal{W} = \tilde{\Psi}_L Y \Psi_L \phi \equiv \bar{u}_L Y_u q_L \phi_u + \bar{d}_L Y_d q_L \phi_d + \bar{e}_L Y_e l_L \phi_d$$
$$\mathcal{W}^\dagger = \Psi_R Y^* \tilde{\Psi}_R \tilde{\phi} \equiv u_R Y_u^* \bar{q}_R \tilde{\phi}_u + d_R Y_d^* \bar{q}_R \tilde{\phi}_d + e_R Y_e^* \bar{l}_R \tilde{\phi}_d$$

CPT is OK (Lagrangian formulation)

CKM mixing

$$\frac{-g}{\sqrt{2}}(\overline{u_L},\, \overline{c_L},\, \overline{t_L})\gamma^\mu W_\mu^+ V_{\rm CKM} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + {\rm h.c.}, \qquad V_{\rm CKM} \equiv V_L^u V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Standard parametrization (3 angles and CP-phase)

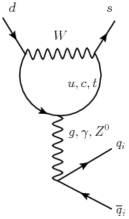
$$V_{\rm CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

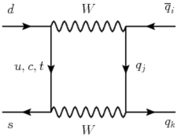
or

$$V_{\rm CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

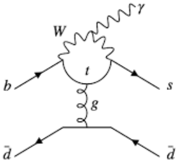
Flavor and CP violation

$K^0 - \tilde{K}^0$ system

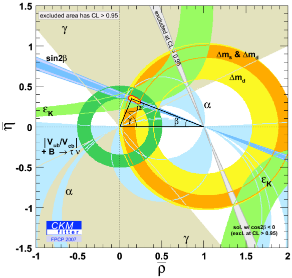


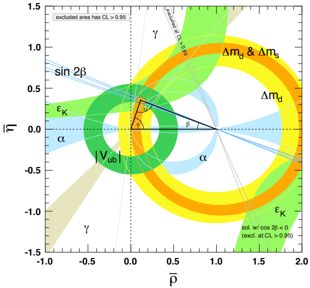


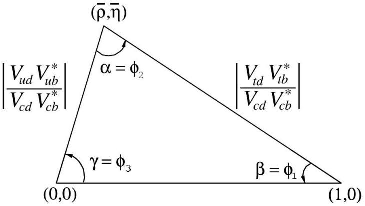
or B-mesons (e.g. $b \to s\gamma$)



Unitarity Triangle: $V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$







SM: Yes, No ... and I don't know
or *The Good, The Bad and ... The Ugly*



Good ! strongly and honestly passes all precision tests ...

Bad ! pragmatically tolerates many fundamental problems, and does not address others at all ...

One, two, three, four, five, and six. Six, the perfect number.
– I thought three was the perfect number ?
I've got six more bullets in my gun ...

Ugly ! does not leave any traces to New Physics at all ...

But if you miss you had better miss very well. Whoever double-crosses me and leaves me alive, he understands nothing about me. Nothing!

... and motivates a desperate *anthropic* way of thinking
If you work for a living, why do you kill yourself working?

Standard Model $SU(3) \times SU(2) \times U(1)$ vs. P, C and CP parities & baryon number violation

Fermions:

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

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

Anti-Fermions:

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

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

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm Gauge} + \mathcal{L}_{\rm Higgs} + \mathcal{L}_{\rm Yuk}$$

CPT is OK (Local Lagrangian)

P $(\Psi_L \to \Psi_R)$ & C $(\Psi_L \to \bar{\Psi}_L)$ broken by gauge interactions

CP $(\Psi_L \to \bar{\Psi}_R)$ broken by complex Yukawas $Y = Y_{ij}^{u,d,e}$

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

There are no renormalizable interactions which can break B and L !

Good for our stability but Bad for experimental search ... and Ugly for baryogenesis – So, one had to believe in New Physics beyond SM

Baryon & Lepton violation

- B & L can be violated only in higher order (non-renormalizable) terms

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

$\frac{1}{M^2} qqql$ etc. $(\Delta L = 1,\ \Delta B = 1\ )$ – proton decay $p \to \pi^0 e^+$, $p \to \pi^+ \nu$ etc.

$\frac{1}{M^5} qqqqqq$ etc. $(\Delta B = 2,\ \Delta B = 1\ )$ – neutron-antineutron oscillation $n(udd) \to \tilde{n}(\bar{u}\bar{d}\bar{d})$

coming from new physics related to scale $M \gg v_{\rm EW}$

- B & L can be (non-perturbatively) violated only in (very) higher order terms due to $U(1)_B$ and $U(1)_B$ anomalies ('t Hooft) but $B - L$ must be conserved !

Standard Model and Problems

- Hierarchy problem: origin of electroweak (Higgs) mass scale $M_H \sim 100$ GeV (N.B. no problem with QCD scale $\Lambda_{\rm QCD} \sim 100$ MeV)

- Family problems: Why 3 fermion families? Why hierarchy of fermion masses and CKM mixing? CP-violation ?

- Strong CP-problem: Where ends up beautiful effect of CP-violation due to term $\theta G_{\mu\nu} \tilde{G}^{\mu\nu}$ in non-perturbative QCD vacuum $\theta \sim 1$ expected vs. $\theta < 10^{-10}$ – exp. DEMON (EDM of neutron)

- Neutrino masses: Why they are so small? .... (and why they have large mixing?)

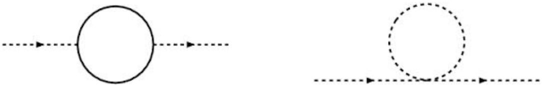
- Lepton and Baryon numbers: why are conserved ? and why are violated ? (deep connection to the origin of matter in the Universe)

- Dark matter: from where it comes ? can it be detectable ? (can it have interactions to normal matter or self-interactions ?)

- Scalar fields in cosmology: Inflaton? Quintessence ? (is dark energy just cosmological constant or something (time-variable) else ? related: can be then also fundamental constants time variable ?)

Hierarchy Problem

- Origin of electroweak (Higgs) mass scale and quadratic divergency:



Consitutes a hierarchy problem – 34 orders of magnitude – between $M^2_{\rm Higgs} \sim (100 \ {\rm GeV})^2$ and $M^2_{Pl} \sim (10^{19} \ {\rm GeV})^2$

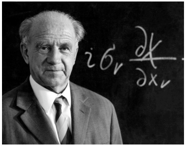
Possible cures: SUSY, technocolor, composite Higgs ....

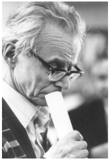
But SM precision tests exclude existence of all these up to scales of few TeV .... and LHC did not discover anything below TeV scale ...

New Physics (SUSY) can exist at $E > 1$ TeV – but there will remain a *little* hierarchy problem – 2 orders of magnitude – between $M^2_{\rm Higgs} \sim (10^2 \ {\rm GeV})^2$ and $M^2_{\rm SUSY} \sim (10^3 \ {\rm GeV})^2$

SUSY

Heisenberg 1965 | Volkov Akulov 1972 | Golfand Likhtman 1971





Supersymmetry between fermions and bosons – extension of the Poincare symmetry: $x^\mu \to x^\mu + a^\mu$

space $(x_\mu) \to$ superspace $(x_\mu, \theta_\alpha, \bar{\theta}_{\dot{\alpha}})$, $\quad \bar{\theta}_{\dot{1},\dot{2}} = (\theta_{1,2})^*$

fields $\Phi(x) \to$ superfields $\Phi(x, \theta, \bar{\theta})$

$$\Phi(x,\theta,\bar{\theta}) = \phi(x) + \theta\psi(x) + \bar{\theta}\bar{\psi}(x) + \ldots + \theta^2\bar{\theta}^2 D(x)$$

$$\theta^2 = \epsilon^{\alpha\beta}\theta_\alpha\theta_\beta = \theta_1\theta_2 - \theta_2\theta_1 = 2\theta_1\theta_2$$

fermion coordinates anticommuting (Grassmann) numbers:

$\theta_\alpha\theta_\beta = -\theta_\beta\theta_\alpha$ (and so $\theta_\alpha^2 = 0$)

$\theta_\alpha \to \theta_\alpha + \epsilon_\alpha \quad \to \quad x^\mu \to x^\mu + \bar{\epsilon}\sigma^\mu\epsilon$

SUSY, soft SUSY breaking and R-parity

SM $\to$ MSSM: fields $\to$ 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 $M_S \sim 1$ TeV, 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

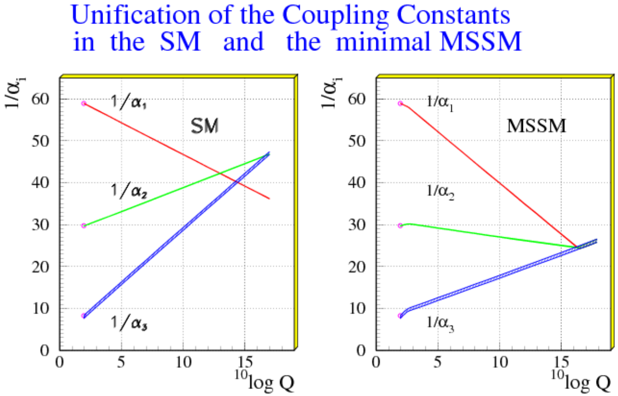
$R = (-1)^{3B+L+2s}$ (+ for SM particles, $-$ for superpartners)

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

makes lightest SUSY partner (LSP) stable !

Charge quantization and gauge coupling unification

- GUT: $SU(3) \times SU(2) \times U(1) \to SU(5)$



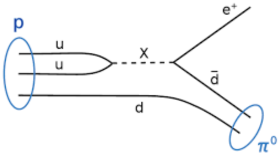
SUSY + GUT = LOVE (coupling crossing $\to M_{\mathrm{SUSY}} < 10$ TeV)

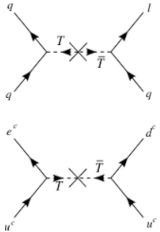
Hierarchy (and doublet-triplet splitting) problems – 28 orders – between $M^2_{\mathrm{Higgs}} \sim (100\ \mathrm{GeV})^2$ and $M^2_{GUT} \sim (10^{16}\ \mathrm{GeV})^2$

Proton decay in $SU(5) \to SU(3) \times SU(2) \times U(1)$

Proton decay: $p \to \pi^0 e^+$, $p \to K^+ \nu$ etc.

- gauge mediated $D = 6$: new gauge bosons X, Y violating baryon and lepton numbers – $\frac{1}{M_X^2} \bar{q}\gamma_\mu \tilde{u} \bar{l} \gamma^\mu \tilde{d}$, etc.
- Higgs mediated $D = 6$: color scalar triplets (leptoquarks) T, brothers of SM Higgs doublet ϕ, – $\frac{1}{M_T^2} qqql$, etc.
- Higgsino mediated $(D = 5)$: fermion superpartners of T, – $\frac{1}{M_T} qq\tilde{q}\tilde{l}$





proton stability limits $\tau_p > 10^{34}$ yr require $M_X, M_T > 10^{16}$ GeV.

D-T splitting: $m_\phi \sim 100$ GeV , $M_T > 10^{16}$ GeV – 14 orders!

N.B. this B-violation not good for baryogenesis in the universe

SUSY + GUT = SU(6)

SUSY can provide *technical solution* to the D-T in $SU(5)$

Good solution (GIFT) with larger symmetry:
$SU(3) \times SU(2) \times U(1) \to SU(5) \to SU(6) \qquad (SU(6) \to E_6\ ?)$

Pseudo-Goldstone mechanism: gauge $SU(6)$ breaking in 2 channels

$SU(6) \to SU(5)$: fundamental reps $H, \bar{H} \sim 6, \bar{6}$ $(5, \bar{5}$ in $SU(5))$
$SU(6) \to SU(4) \times SU(2) \times U(1)$: - adjoint $\Sigma \sim 35$ (24 in $SU(5)$)

while superpotential has double global symmetry $SU(6)_H \times SU(6)_\Sigma$

Higgs (super)fields remain as Goldstone modes not eaten by gauge (super)fields due to accidental global symmetry $SU(6)_H \times SU(6)_\Sigma$ (just kill the term $H\Sigma\bar{H}$ by discrete symmetry)

It gets mass $\sim M_{\rm SUSY} \sim 1$ TeV after SUSY breaking

and makes clear also many other problems (μ-problem, why top quark mass ~ 100 GeV and other fermions are light, etc.)

Remains *Little* hierarchy problem – 2 orders Fine Tuning – between $M^2_{\rm Higgs} \sim (100\ {\rm GeV})^2$ and $M^2_{\rm SUSY} \sim (1\ {\rm TeV})^2$

LHC: can SUSY be just around the corner?

So called Natural SUSY (2 Higgses with $m \sim 100$ GeV + Higgsinos) is dead ! *One* Higgs discovered by LHC perfectly fits the SM Higgs ...

but already at LEP epoch many theorists understood (felt) that $M_{SUSY} < 1$ TeV was problematic

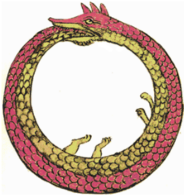
- SUSY induced proton decays ($D = 5$) require $M_{SUSY} > 1$ TeV or so
- SUSY induced CP-violation: electron EDM, $M_{SUSY} > 1$ TeV or so
- But gauge coupling crossing requires $M_{SUSY} < 10$ TeV or so

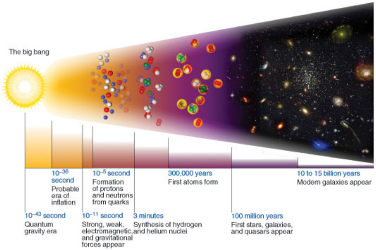
- Generically, SUSY flavor limits in $K - \bar{K}$ mixing, $\mu \to e\gamma$ etc. require $M_{SUSY} > 100$ TeV or so

But can be quark-squark mass allignment: universal relations like $\tilde{m}_d^2 = m_0^2 + m_1^2(Y_d^\dagger Y_d) + m_2^2(Y_d^\dagger Y_d)^2$, etc.
assuming the gauge symmetry $SU(3)$ between 3 fermion families – coined as Minimal Flavor Violation (MFV)

SUSY at scale of few TeV is still the best choice for BSM physics: maybe SUSY is indeed just around the corner? Remains *Little* hierarchy problem – 2 orders Fine Tuning – between $M^2_{\rm Higgs} \sim (100~{\rm GeV})^2$ and $M^2_{\rm SUSY} \sim (1~{\rm TeV})^2$

Uroboros: Standard Model and Cosmology





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)

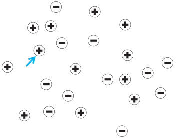
... Universe is expanding ... Early Universe was small and hot – and it tests particle physics at small distances/high energies

Origin of matter: matter over antimatter

Andrei Sakharov, 1966

Matter (Baryon asymmetry) in the early universe can be originated (from zero) by processes that

- Violate B (better $B - L$)
- Violate CP
- and go out-of-equilibrium at some early epoch



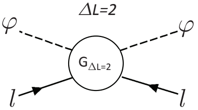
$\sigma(B_+ B_+ \to B_- B_-)/\sigma(B_- B_- \to B_+ B_+) = 1 - \epsilon$

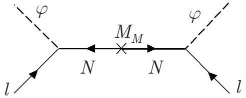
$\epsilon \sim 10^{-9}$: for every $N \sim 10^9$ processes *one unit of B_+* is left in the universe after the process is frozen

Baryogenesis requires new physics:

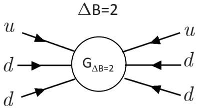
B & L can be violated only in higher order (non-renormalizable) terms

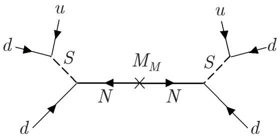
- $\frac{1}{M}(l\bar{\phi})(l\bar{\phi})$ $(\Delta L = 2)$ – neutrino (seesaw) masses $m_\nu \sim v^2/M$





- $\frac{1}{M^5}(udd)(udd)$ $(\Delta B = 2)$ – neutron-antineutron oscillation $n \to \bar{n}$



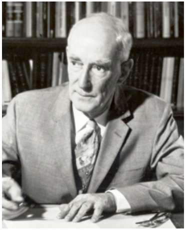


can originate from new physics related to scale $M \gg v_{\rm EW}$ via seesaw

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*

Zwicky – citation evolution

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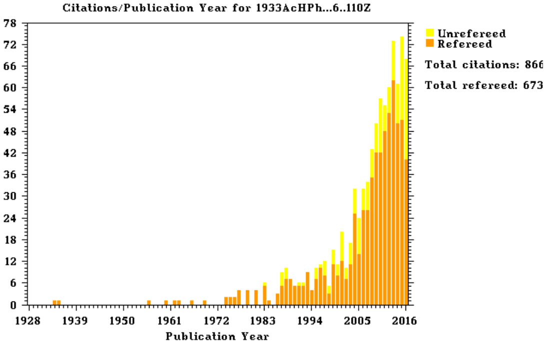

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Quest to Physics Beyond the Standard Model: Some Astroparticle Topics

Zurab Berezhiani

Summary

Standard Model and its problems

Supersymmetry

Baryon asymmetry and dark matter

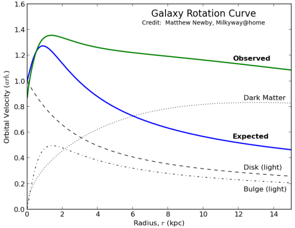
Dark matter candidates

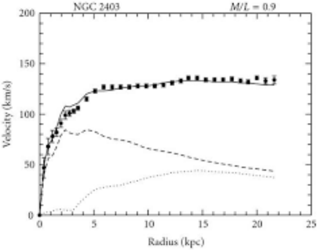
Galactic rotation velocities

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 $\quad m\frac{v^2}{r} = m\frac{GM(r)}{r^2} \quad \to \quad v \simeq \sqrt{GM(r)/r}$

Instead .... flat rotational curves were observed



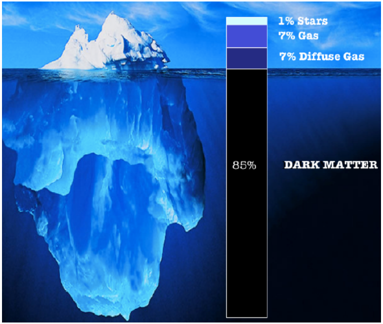


Dark matter is everywhere in the Universe ...

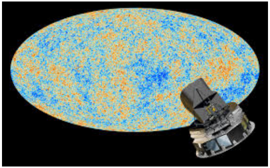
Evidence for the existence of an dark matter in the Universe comes from several independent observations at different length scales ...
and now we are certain that that dark matter is not baryonic !
... but unfortunately we do not know who is dark matter !

Experimental Hints:

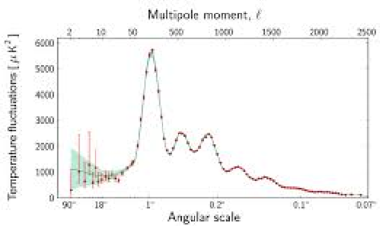
- Rotation Curves
- Clusters of Galaxies
- CMB and LSS
- Supernovae 1a
- Gravitational Lensing



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 $n_s = 0.960 \pm 0.005$

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

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

Hubble tension

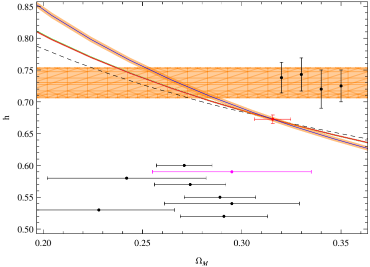


FIG. 1: The vertical error bars correspond to the results for h taken from Refs. [4], [5], [6] and [7] while the orange shaded area corresponds to the result $h = 0.73 \pm 0.024$ of Ref. [8]. The (thin orange) strip indicates the relation between the Ω_m and h for angular distance scale given by the *Planck* measurements of θ^*. **Dashed line is for $\Omega_m h^3$ determination by *Planck* which is only a good approximation (To be removed from last version of paper)**. The *Planck* best fit values for h and Ω_m are indicated by red cross. The horizontal error bars indicate results of astronomical measurements

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.)

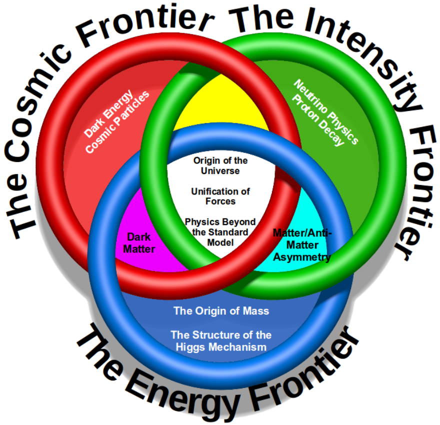
In 80's a new *Strada Maestra* was opened – *SUSY*
– well-motivated theoretical concept promising to be a highway for solving a vast amount of fundamental problems, brought to a natural *almost "Standard"* candidate for dark matter – LSP or WIMP

* *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

Questions to Dark Matter

- Is it neutral ? Or it can have some electric charges ?
- Is it cold (or warm) ? Or it can be self-interacting and dissipative ?
- Is it stable ? Or it can be decaying with $t \sim 10$ Gyr ?
- Is it consistent with BBN, CMB and LSS tests ?
- Is it consistent with astrophysical constraints ? Galaxy structure, stellar evolution, etc.
- does it match the appropriate relic density ($\Omega_{DM} \simeq 0.25$) ?
- Can it explain why $\Omega_{DM} \simeq 5\Omega_B$?
- Can it be probed experimentally, via direct detection by dark matter detectors?
- Can it be probed by indirect signals, as gamma astronomy, cosmic rays, UHE neutrinos ?
- Can it be produced experimentally, at the LHC or reactors ?
- Is its physics related to other fundamental problems ?

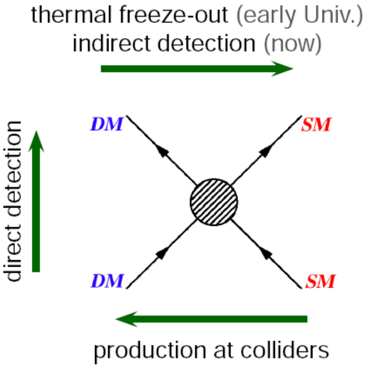
Research Frontiers



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

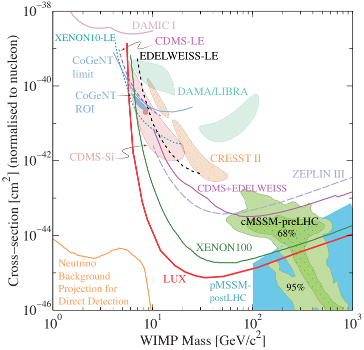
WIMP/LSP with mass $M_X \sim 100$ GeV – perfect candidate for CDM

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

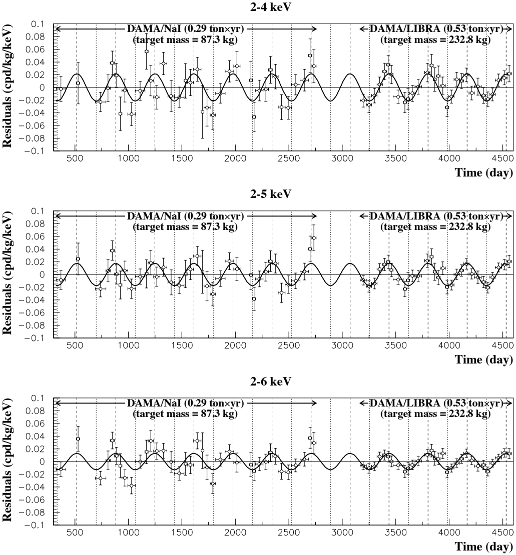
$$\text{WIMP Miracle:} \;\; v\sigma_{\rm ann} \sim \frac{\pi\alpha^2}{M_S^2} \sim \left(\frac{100 \text{ GeV}}{M_X} \right)^2 \times 10^{-36} \text{ cm}^2$$

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

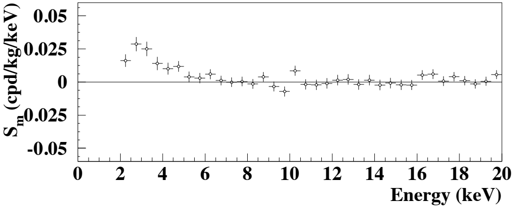
However ... no evidence at LHC and no evidence from DM direct search + many problems to natural SUSY

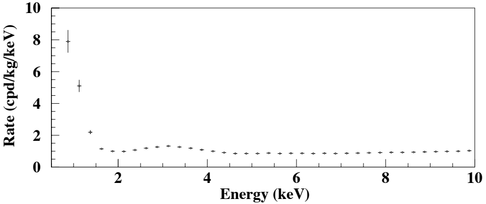


DAMA-LIBRA: seasonal variations



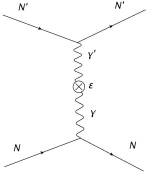
DAMA-LIBRA: modulation spectrum





Discussing $\mathcal{L}_{\text{mix}}$: 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 ($q \sim \epsilon$) and is a promising interaction for dark matter direct detection

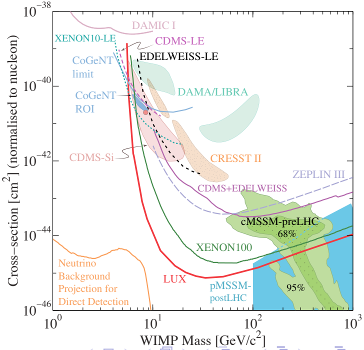
Mirror atoms: He' – 75 %, C',N',O' etc. few %

Rutherford-like scattering

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

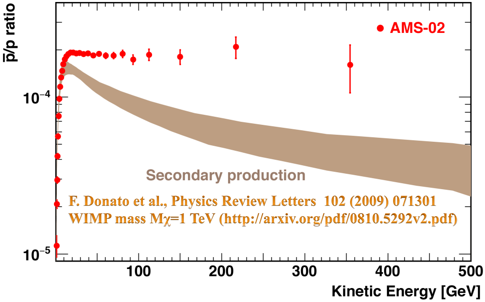
or

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



Indirect detection: antimatter in the cosmos?

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



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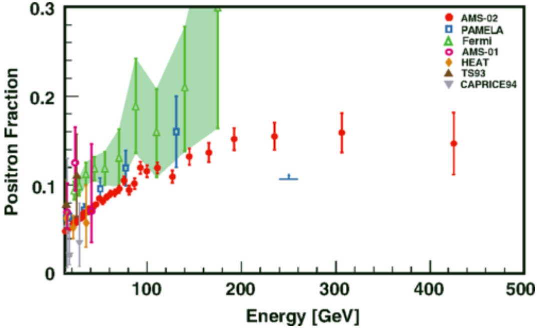


Dark Side of the Universe

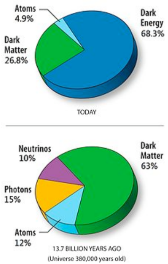
Todays Universe: flat $\Omega_{\rm tot} \approx 1$ *(inflation)* and multi-component:

- $\Omega_B \simeq 0.05$ 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?

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.

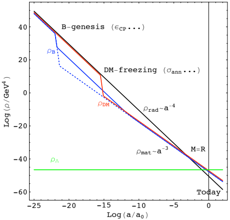
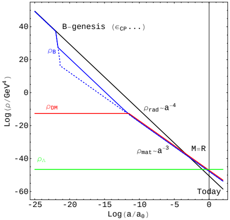
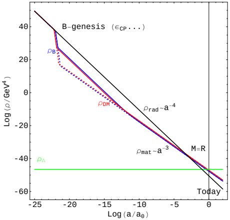
- Sakharov 1967

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