WKYC 2011 June 27 ~ July 1, KIAS

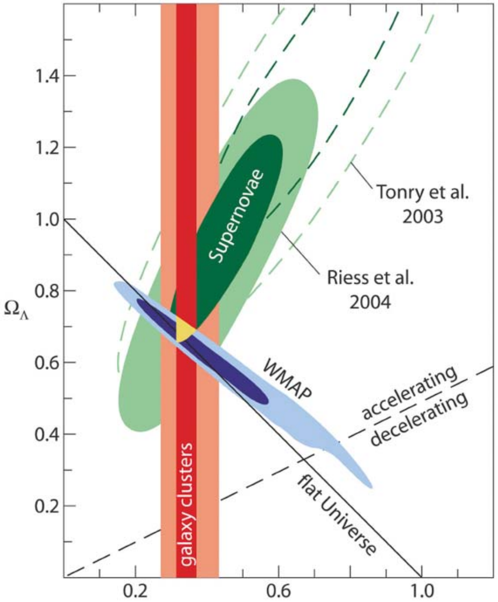
Future of Large Scale Structure Formation

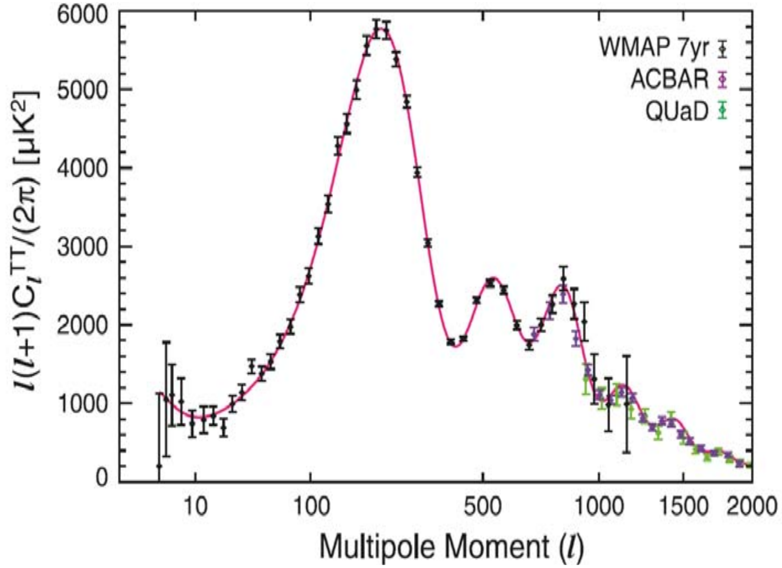
Dark Matter and Baryon Asymmetry

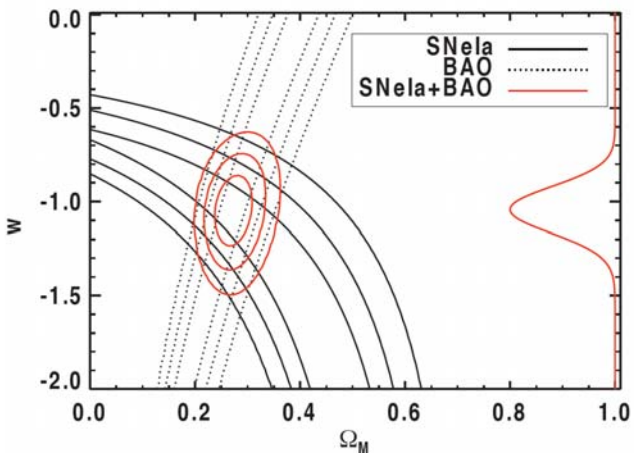
Korea Institute for Advanced Study

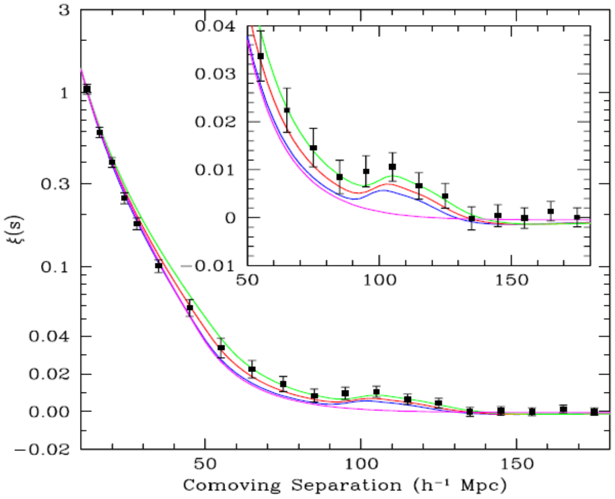
Eung Jin Chun

Astro/cosmo observations









The content of the Universe

- **$\Omega_{DE} h^2$ = 0.361 +/- 0.008**

  $\Omega_m h^2$ = 0.1349 +/- 0.004

  - $\Omega_B h^2$ = 0.0226 +/- 0.0008
  - $\Omega_\nu h^2$ = 0.0005 ~ 0.0047
  - $\Omega_{DM} h^2$ = 0.1123 +/- 0.0035

  $\Omega_r h^2 = 2.469\times10^{-5}$

WMAP7 + BAO + H_0
Komatsu et al. 2010

- Baryon asymmetry: $Y_B = (n_b - n_{\bar{b}})/s = 10^{-10}$

Particle Physics and Cosmology

- The history of the Universe is governed by the fundamental physical laws.
- Hot Big-Bang described by general relativity and thermodynamics.
- Big-Bang Nucleosynthesis: atomic abundance.
- Cosmological perturbation theory: CMBR anisotropy, structure formation.
- New physical laws beyond the Standard Model+gravity are required to answer:

What drives inflation?

What are the identities of dark energy and dark matter?
What happened to antiparticles?

Baryogenesis

Problem of matter-antimatter symmetry

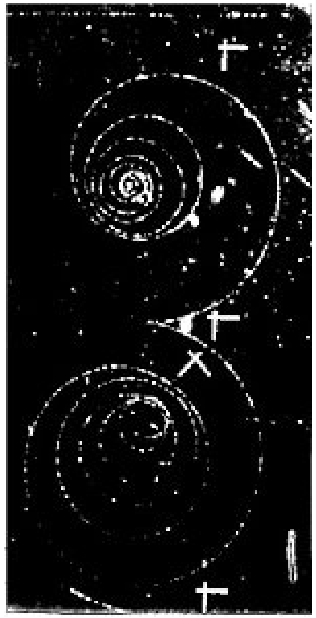
- Dirac predicts the existence of antiparticle (1927):

  phonton ⇔ particle + antiparticle

$$E^2 - p^2c^2 = m^2c^4$$

$$i\hbar(\partial^\mu + ieQA_\mu)\gamma_\mu\psi = mc\psi$$

$$\psi = (e^-_\uparrow, e^-_\downarrow, e^+_\uparrow, e^+_\downarrow)$$



- Why is the Universe asymmetric

  in the baryonic abundance?

Baryogenesis

- Was the baryon asymmetry set from the beginning?

$$\frac{n_b}{n_\gamma} = 1 + 10^{-10} \quad \text{vs.} \quad \frac{n_{\bar{b}}}{n_\gamma} = 1$$

- Was the baryon asymmetry generated dynamically from the initially symmetric universe?

[Sakharov, 1967]

Baryon number violation

C & CP violation

Out of equilibrium

Baryogenesis and neutrinos

- Neutrinos are massless in the Standard Model:

$$\mathcal{L}_{SM} = y_u Q H_u u^c + y_d Q H_d d^c + y_e L H_d e^c + h.c.$$

$$m_f = y_f \langle H_f \rangle$$

Note) $m_e = 5 \times 10^{-4}\mathrm{GeV}$

$m_t = 172\ \mathrm{GeV}$

$$\mathcal{L}_{mass} = m_u\, uu^c + m_d\, dd^c + m_e\, ee^c + h.c.$$

- Massive Dirac neutrinos (L-conserving):

$$\mathcal{L}_{\nu-mass} = y_\nu L H_u N + h.c \quad \Rightarrow m_\nu \nu N + h.c$$

- Massive Majorana neutrinos (L-violating):

$$\mathcal{L}_{seesaw} = y_\nu L H_u N + \frac{1}{2} M N N + h.c. \Rightarrow m_\nu^D \nu N + \frac{1}{2} M N N + h.c.$$

$$\sim \frac{1}{2} m_\nu \nu\nu + \frac{1}{2} M \nu^c \nu^c + h.c. \qquad m_\nu \approx -\frac{(m_\nu^D)^2}{M}$$

Seesaw Mechanism : $M = 10^{14}\mathrm{GeV}, m_\nu^D = 10^2\mathrm{GeV} \Rightarrow m_\nu = 0.1\mathrm{eV}$

Neutrino mass and mixing

Neutrino mass matrix : $m^{\nu}_{\alpha\beta} = U_{\alpha i} U_{\beta i} m_i$

$$
\begin{aligned}
|\nu_e\rangle &= U_{e1}|\nu_1\rangle + U_{e2}|\nu_2\rangle + U_{e3}|\nu_3\rangle \\
|\nu_\mu\rangle &= U_{\mu 1}|\nu_1\rangle + U_{\mu 2}|\nu_2\rangle + U_{\mu 3}|\nu_3\rangle \\
|\nu_\tau\rangle &= U_{\tau 1}|\nu_1\rangle + U_{\tau 2}|\nu_2\rangle + U_{\tau 3}|\nu_3\rangle
\end{aligned}
$$

$$
U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{\theta_{23}} & s_{\theta_{23}} \\ 0 & -s_{\theta_{23}} & c_{\theta_{23}} \end{pmatrix}
\begin{pmatrix} c_{\theta_{13}} & 0 & s_{\theta_{13}} e^{i\delta} \\ 0 & 1 & 0 \\ -s_{\theta_{13}} e^{-i\delta} & 0 & c_{\theta_{13}} \end{pmatrix}
\begin{pmatrix} c_{\theta_{12}} & s_{\theta_{12}} & 0 \\ -s_{\theta_{12}} & c_{\theta_{12}} & 0 \\ 0 & 0 & 1 \end{pmatrix}
\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\phi_2} & 0 \\ 0 & 0 & e^{i\phi_3} \end{pmatrix}
$$

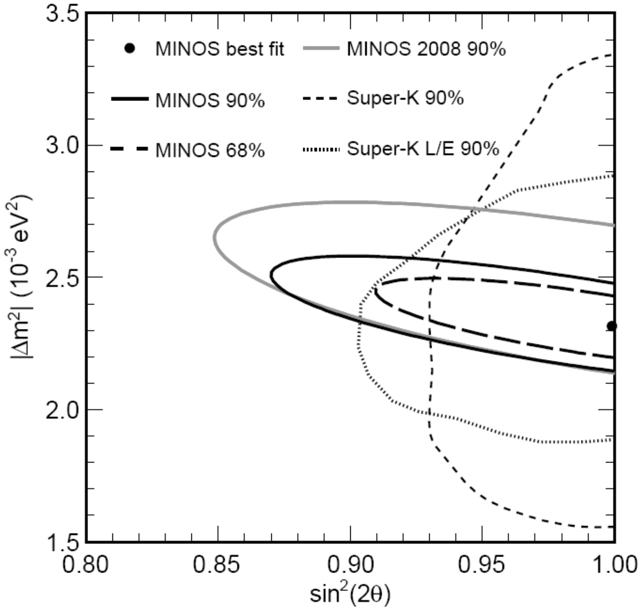
atmoshperic reactor solar Majorana

Three mixing angles : [illegible]

Neutrino oscillation : $P_{\alpha\beta} = \sin^2 2\theta \sin^2(\Delta m^2 L/4E)$

Recent oscillation data

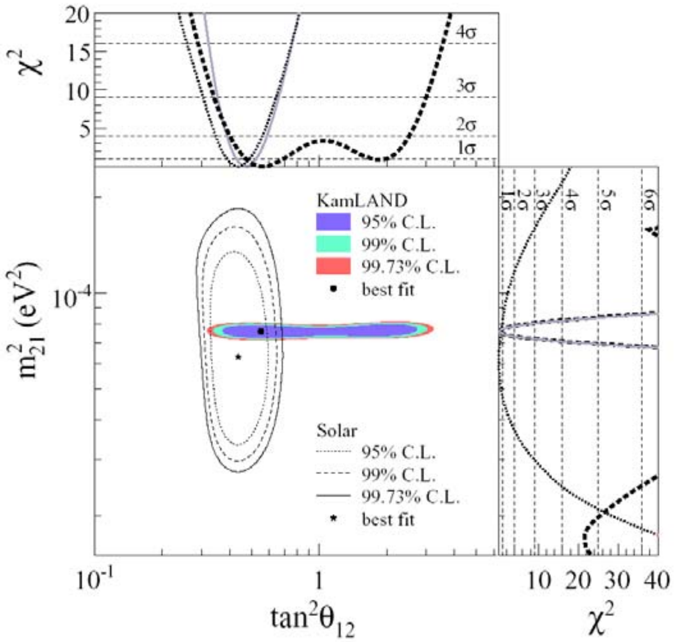
MINOS (11)



$$|\Delta m^2_{31}| = 2.32^{+0.12}_{-0.08} \times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2 2\theta_{23} > 0.90$$

KAMLAND (Jan. 08)



$$\Delta m^2_{21} = 7.59^{+0.21}_{-0.21} \times 10^{-5}\ \mathrm{eV}^2$$

$$\tan^2\theta_{12} = 0.47^{+0.06}_{-0.05}$$

Baryogenesis through Leptogenesis

- Seesaw mechanism realizes the Sakharov conditions of

  Lepton number violation

  C & CP violation

  Out of equilibrium

- It generates a lepton asymmetry which is transformed to a baryon asymmetry through the B+L violating anomalous $SU(2)_L$ process.

Lepton asymmetry from RHN decay

- Seesaw with heavy right-handed neutrinos:

$$\mathcal{L} = yLH_2N + \frac{1}{2}MNN \qquad \boxed{M^\nu_{ij} = y_{ik}y_{jk}\frac{\langle H_2\rangle^2}{M_k}}$$

- N decay: C/CP violation (CP phase in y)

  Out of equilibrium (Γ< H)

- L asymmetry from N decay:

$$\epsilon_1 = \frac{\Gamma(N_1\to LH_2)-\Gamma(N_1\to\bar{L}\bar{H}_2)}{\Gamma(N_1\to LH_2)+\Gamma(N_1\to\bar{L}\bar{H}_2)} = \frac{3}{8\pi}\frac{\sum_i \mathrm{Im}\left([(yy^\dagger)_{1i}]^2\right)}{(yy^\dagger)_{11}}\frac{M_1}{M_i}$$

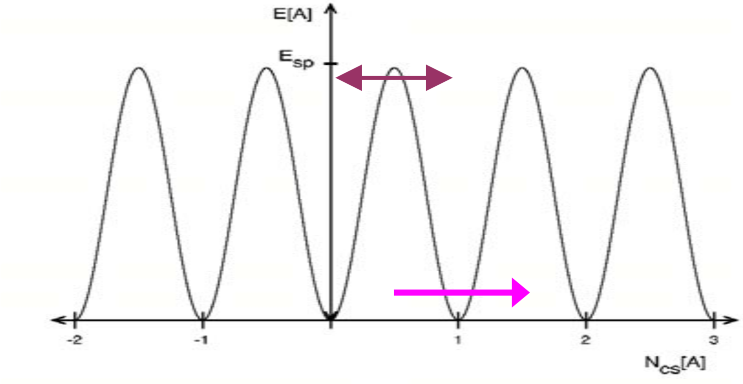
$$\epsilon_1 \leq \frac{M_1 m_{\nu_3}}{\langle H_2\rangle^2} \simeq 2\times 10^{-7}\left(\frac{M_1}{10^9\ \mathrm{GeV}}\right)\left(\frac{m_{\nu_3}}{0.05\ \mathrm{eV}}\right)$$

Standard Model violates B+L

- B+L is anomalous :

$$\partial^\mu J^B_\mu = \partial^\mu J^L_\mu = \frac{N_f}{32\pi^2} g^2 W^{\mu\nu}\tilde{W}_{\mu\nu}$$
$$= \partial^\mu K^{CS}_\mu$$

$$B = L = N_f N_{CS}$$



$$\Delta(B+L) = 2N_f$$
$$\Delta(B-L) = 0$$

- Active B+L violation at finite temperaure :

$$\Gamma_{sp} \sim \alpha_W^4 T^4 e^{-E_{sp}(T)/T} \qquad \frac{\Gamma_{sp}}{T^3} > H \Rightarrow T < \alpha_W^4 \frac{M_P}{\sqrt{g_*}} \sim \boxed{10^{12}\ \text{GeV}}$$

Leptogenesis origin of baryons

- Standard interactions in thermal equilibrium:

$$\begin{array}{ccll} S & \leftrightarrow & 3q+\ell & \text{B+L=0} \\ \phi & \leftrightarrow & q+\bar{u} & \\ \bar{\phi} & \leftrightarrow & q+\bar{d} & \\ \bar{\phi} & \leftrightarrow & \ell+\bar{e} & \end{array}
\left.\begin{array}{c} \\ \\ \\ \end{array}\right\} \text{B-L=0}$$

$(B-L)_i = -L_i \neq 0$

$\rightarrow (B-L)_f \neq 0$

L asymmetry converted to B asymmetry: $n_B = c_{SP} L_i$ (c_{SP}=28/79)

- Origin of (asymmetric) baryon abundance:

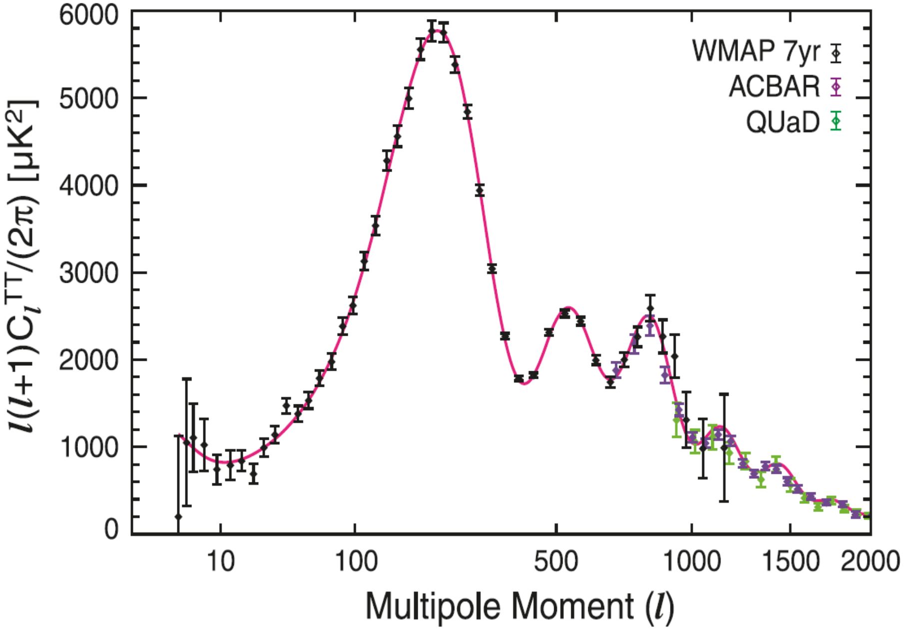
$$\boxed{Y_B \equiv c_{sp}\frac{n_L - n_{\bar{L}}}{s} = c_{sp}\frac{n_N^{eq}}{s}\epsilon\eta \approx 0.1\frac{1}{g_*}\epsilon_1\eta \sim 10^{-10}}$$

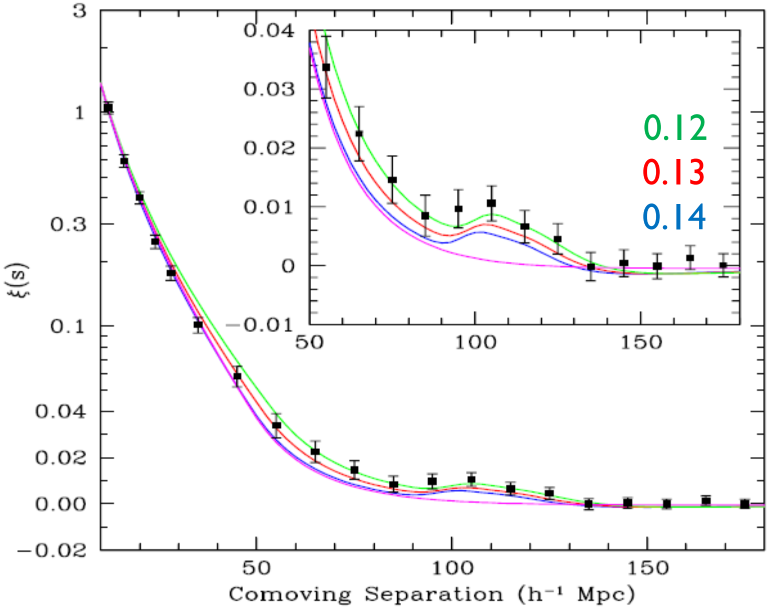
$g_* \sim 100$, $\eta < 1$, $\varepsilon > 10^{-7}$ (M > 10^9 GeV)

Dark Matter

More on DM: K.Y. Choi and J.C. Park in this workshop.

Cosmic structures require CDM

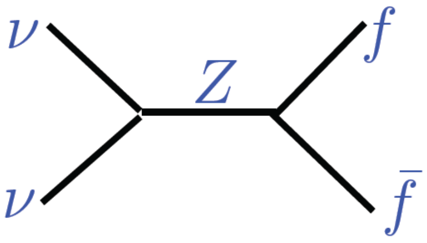




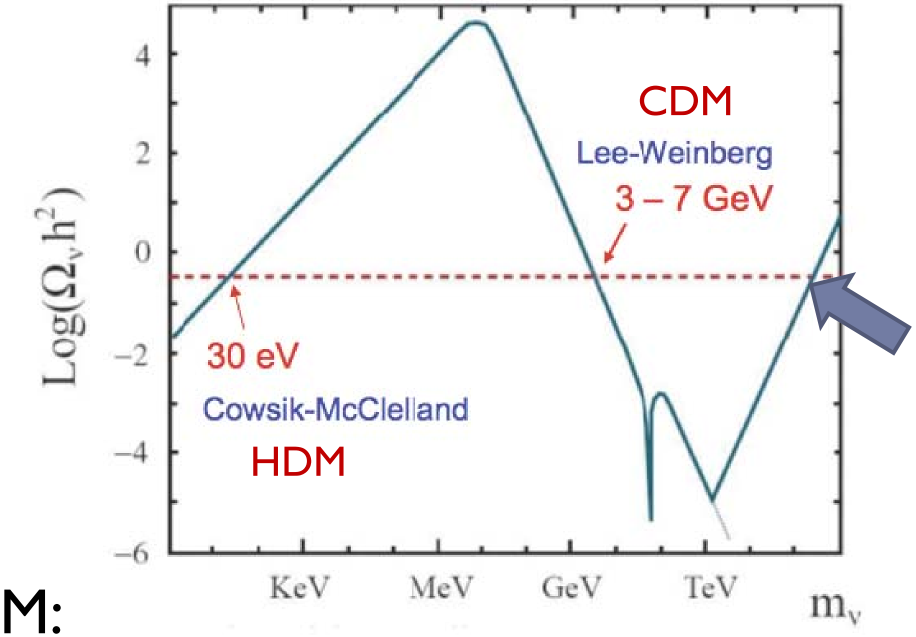
Postulated heavy neutrino as CDM

- The standard weak interaction of a 10 GeV neutrino:

[Lee-Weinberg, 1977]



$$\langle \sigma v \rangle \sim \frac{\alpha_w^2 m_{\nu_H}^2}{m_Z^4} \sim \frac{10^{-9}}{\mathrm{GeV}^2}$$



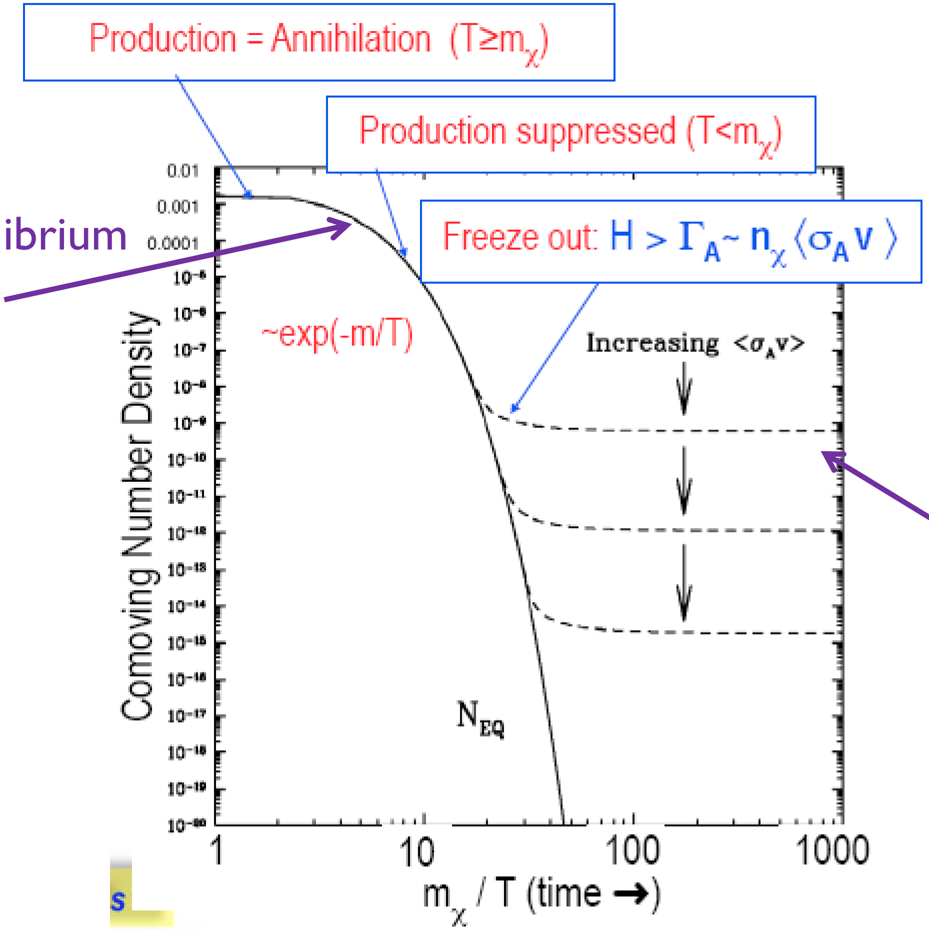
- Ordinary neutrinos are HDM:

$$\Omega_\nu h^2 = 3 \times \frac{3}{4} \times \left(\frac{T_\nu}{T_\gamma} \right)^3 n_\gamma m_\nu / \rho_c \approx \frac{m_\nu}{30\ \mathrm{eV}} \approx 0.003$$

DM abundance: thermal freeze-out

In thermal equilibrium

Out of equilibrium when relativistic (HDM)



Production = Annihilation ($T \geq m_\chi$)

Production suppressed ($T < m_\chi$)

Freeze out: $H > \Gamma_A \sim n_\chi \langle \sigma_A v \rangle$

Out of equilibrium when non-relativistic (CDM)

WIMP miracle

- CDM from New Physics at TeV scale:

$$\langle\sigma v\rangle \sim \frac{\alpha_w^2}{\tilde{m}^2} \sim \frac{10^{-9}}{\mathrm{GeV}^2} \text{ for } \tilde{m} \sim 1\mathrm{TeV}$$

- Non-relativistic freeze-out:

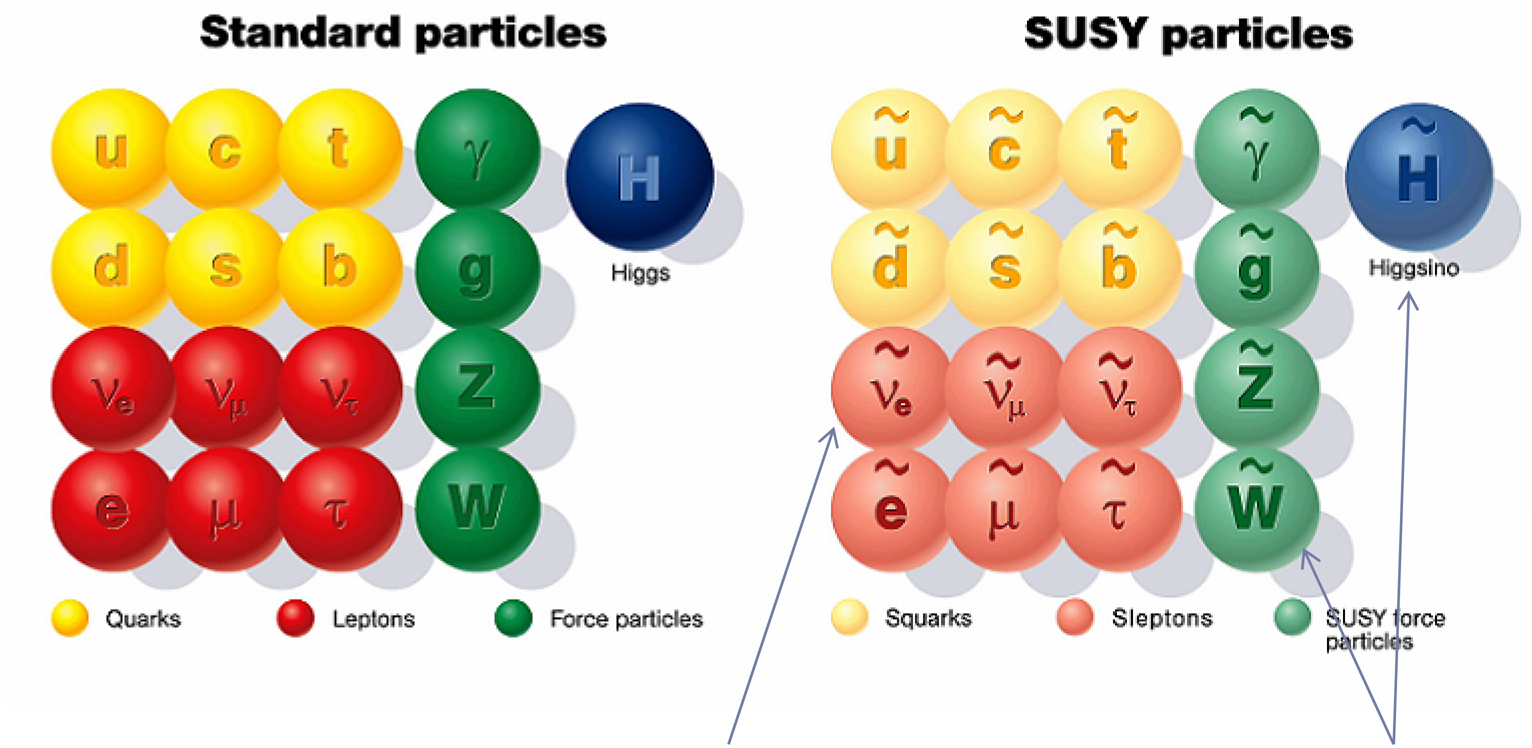
$$\Gamma_A = H\Big|_{T_f} \qquad n_f\langle\sigma v\rangle \approx 0.6\sqrt{g_*}\frac{T_f^2}{M_P}$$

$$n_f = g\left(\frac{mT_f}{2\pi}\right)^{3/2}\exp\left(-\frac{m}{T_f}\right)$$

$$\frac{m}{T_f} \sim \log\langle\sigma v\rangle \sim 20 \qquad Y_{DM} = \frac{n_f}{s_f} \sim \frac{1}{T_f M_P\langle\sigma v\rangle}$$

$$\Omega_{DM}h^2 = \frac{\rho_{DM}}{\rho_c} = \frac{m_{DM}Y_{DM}s_0}{\rho_c} \qquad \Omega_{DM}h^2 \sim 0.1\frac{2\times10^{-9}\ \mathrm{GeV}^{-2}}{\langle\sigma v\rangle}$$

SUSY DM



Large Z^0 interaction excluded by direct detection
(Same for a heavy neutrino)

Good DM candidate

Minimal Dark Matter

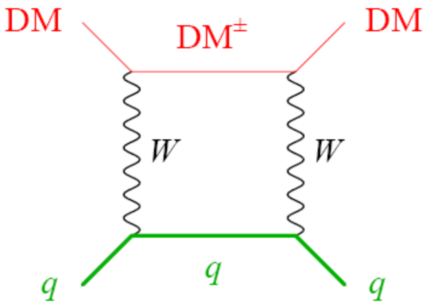
Cirelli, et.al., 0512090

- An $SU(2)_L$ multiplet with Y=0: DM component (T_3=Y=0).
- A large gauge annihilation: multi-TeV mass for the thermal freeze-out relic density.
- Nucleonic scattering at one-loop: $\sigma_{SI} \sim 10^{-45}$ cm^2.
- Radiative mass splitting between the charged and neutral components

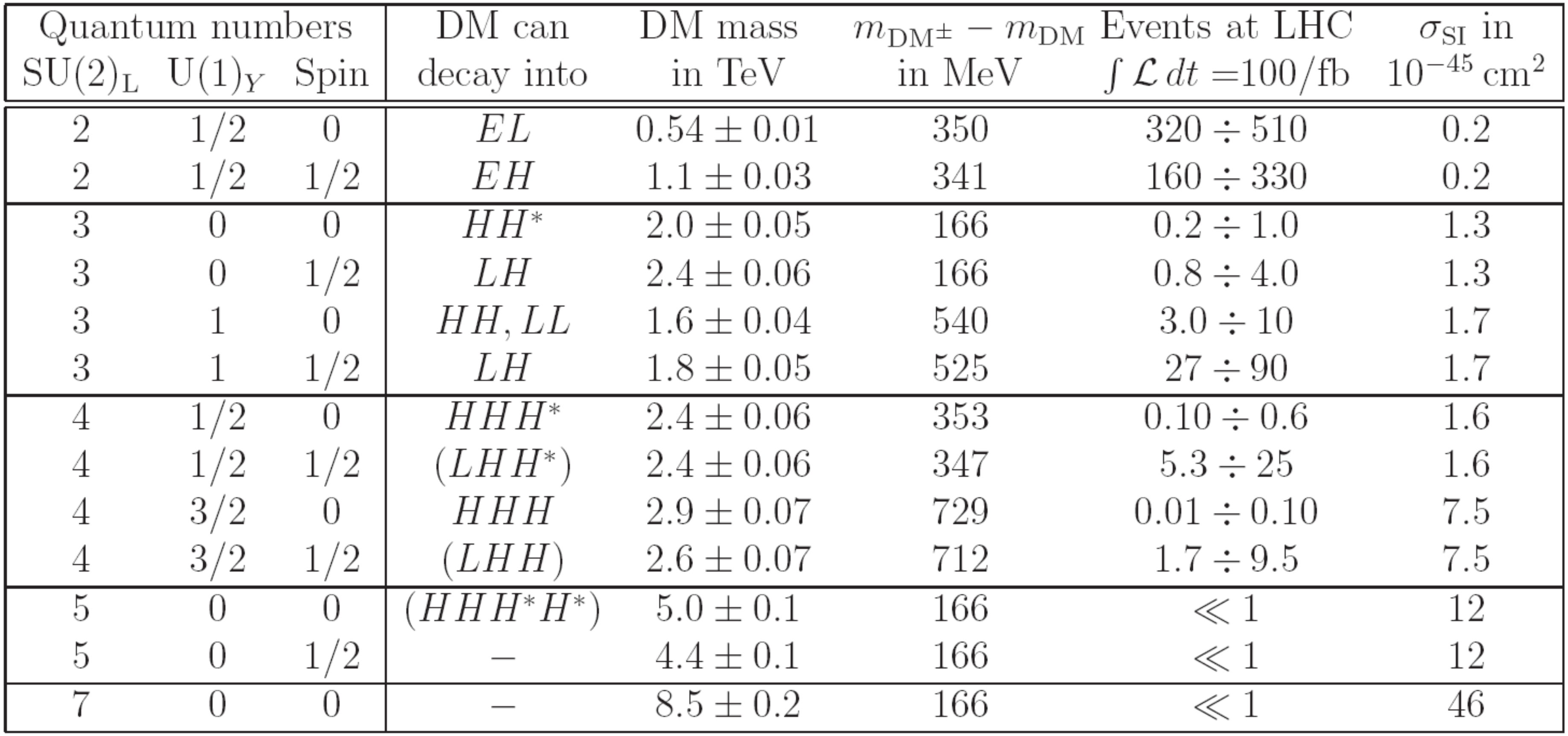
  ~ 0.1 GeV.
- Disappearing charged tracks at LHC.

$$\langle \sigma_A v \rangle \approx \frac{4\pi\alpha_2^2}{m_{DM}^2}$$

$$\Omega_{\rm SDM} h^2 \sim 0.1 \left(\frac{2{\rm TeV}}{m_{DM}} \right)^2$$



$$\mathrm{DM}^{\pm} \to \mathrm{DM}^0 \pi^{\pm}$$



Quantum numbers			DM can	DM mass	$m_{\mathrm{DM}^\pm} - m_{\mathrm{DM}}$	Events at LHC	σ_{SI} in
$\mathrm{SU}(2)_\mathrm{L}$	$\mathrm{U}(1)_Y$	Spin	decay into	in TeV	in MeV	$\int \mathcal{L}\, dt$ =100/fb	$10^{-45}\ \mathrm{cm}^2$
2	1/2	0	EL	0.54 ± 0.01	350	$320 \div 510$	0.2
2	1/2	1/2	EH	1.1 ± 0.03	341	$160 \div 330$	0.2
3	0	0	HH^*	2.0 ± 0.05	166	$0.2 \div 1.0$	1.3
3	0	1/2	LH	2.4 ± 0.06	166	$0.8 \div 4.0$	1.3
3	1	0	HH, LL	1.6 ± 0.04	540	$3.0 \div 10$	1.7
3	1	1/2	LH	1.8 ± 0.05	525	$27 \div 90$	1.7
4	1/2	0	HHH^*	2.4 ± 0.06	353	$0.10 \div 0.6$	1.6
4	1/2	1/2	(LHH^*)	2.4 ± 0.06	347	$5.3 \div 25$	1.6
4	3/2	0	HHH	2.9 ± 0.07	729	$0.01 \div 0.10$	7.5
4	3/2	1/2	(LHH)	2.6 ± 0.07	712	$1.7 \div 9.5$	7.5
5	0	0	(HHH^*H^*)	5.0 ± 0.1	166	$\ll 1$	12
5	0	1/2	–	4.4 ± 0.1	166	$\ll 1$	12
7	0	0	–	8.5 ± 0.2	166	$\ll 1$	46

Co-genesis of dark matter & baryon

Baryon and Dark Matter Asymmetry

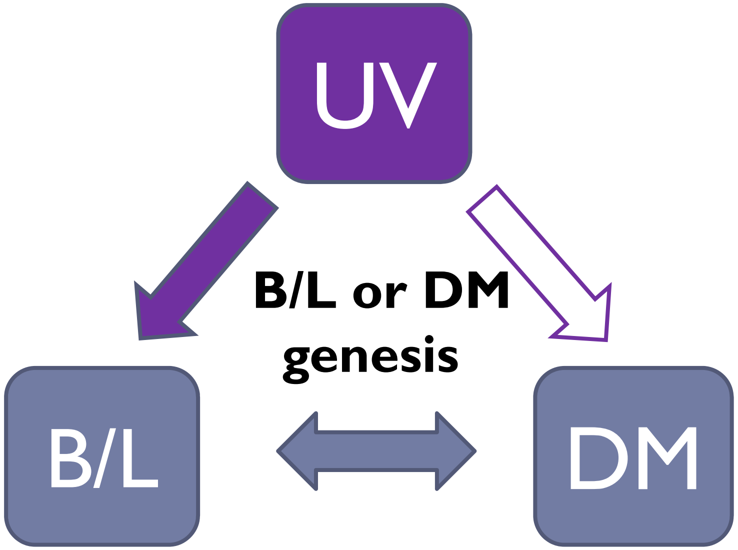
- $\Omega_{DM}/\Omega_B = 5$: coincidence?
- Postulate the same origin for matter-antimatter asymmetry & dark matter population.

$$\Omega_{DM}/\Omega_B = m_{DM}Y_{DM}/m_B Y_B$$

i) $Y_{DM} \sim Y_B$, $m_{DM} \sim 5$ GeV (for COGENT/DAMA)

ii) $Y_{DM} \sim 0.05 Y_B$, $m_{DM} \sim 100$ GeV

Scenarios



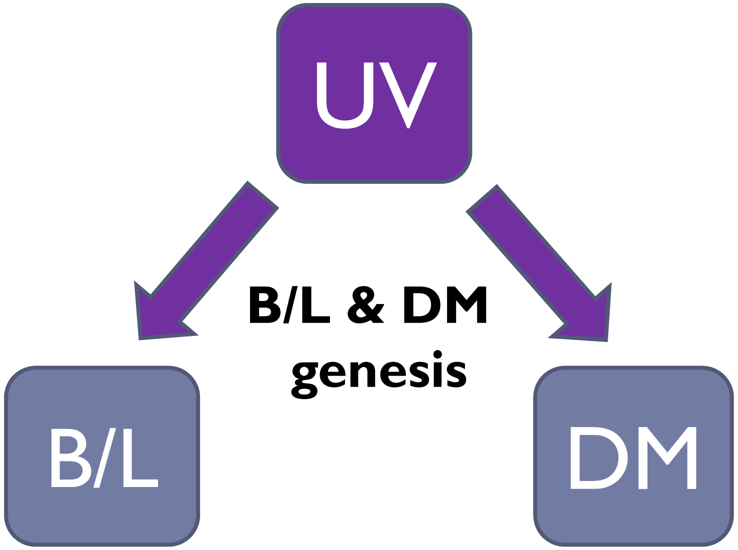
UV

B/L or DM genesis

B/L

DM

Equilibration



UV

B/L & DM genesis

B/L

DM

Techni-baryons

Nussinov, PLB, 1985

- Consider a GUT group containing both the baryon sector ($SU(3)_c$) and the techni-baryon sector ($SU(n)_{TC}$).
- Asymmetries in both sectors can be assumed to arise from a heavy GUT particle decay: $Y_B = Y_{TB}$.

$$\rho_B = Y_B\, m_B, \quad \rho_{TB} = Y_{TB}\, m_{TB} = \rho_{DM}$$

$$\Omega_{DM}/\Omega_B = m_{TB}/m_B = 5 \text{ if } \Lambda_{TB}/\Lambda_B = 5$$

- The techni-baryon sector is really "dark" (only gravitational)…

Equilibration of B-L & DM

- Assume an initial B-L (or DM) asymmetry
- Add an interaction which equilibrate the dark matter asymmetry and the initial B-L asymmetry
- A conserved quanturm number: B-L+DM/2

L H ⇔ X X

Kaplan, et.al., 0911.4117

Equilibration interaction

$$W = \frac{1}{M} L H_u X X + m_X X X^c$$

Interaction rate > Expansion rate

$$\Gamma \sim \frac{T^3}{8\pi M^2} > H \sim \frac{3T^2}{M_P}$$

Chemical equilibrium relation

$$X = -\frac{11}{79}(B-L), \ B = 0.3(B-L)$$

$$\frac{\Omega_{DM}}{\Omega_B} = \frac{m_X X}{m_B B} \Rightarrow m_X = 12\mathrm{GeV}$$

Equilibration of B-L & DM

- Need to suppress the symmetric component

→ Annihilation rate of DM much lager than the standard value for the thermal freeze-out relic density.

Assume a “strong” interaction:

$$W = \lambda_X S X X^c + \lambda_H S H_u H_d + \lambda_S S^3$$

$$X\bar{X} \leftrightarrow H_u H_d$$

$$\Omega_{X+\bar{X}} h^2 \approx 0.1 \frac{3 \times 10^{-9}\mathrm{GeV}^{-2}}{\langle \sigma_A v \rangle}$$

Baryons and DM via Leptogenesis

- A simple model relating the origins of tiny neutrino masses, and the asymmetric baryon and DM densities.
- Realize asymmetric MDM with sub-TeV mass.
- Naturally suppressed symmetric density. $\Omega_{\rm SDM} h^2 \sim 0.1 \left(\frac{2{\rm TeV}}{m_{DM}}\right)^2$
- Copious production at the LHC.
- Clean signals of disappearing charged tracks & stable charged tracks.

An, et.al., 0911.4463
EJC, 1009.0983
Falkowski, et.al., 1101.4936
Haba, et.al., 1101.5679

The Model

EJC, 1102.3455

- Introduce a vector-like SU(2)$_L$ multiplet:

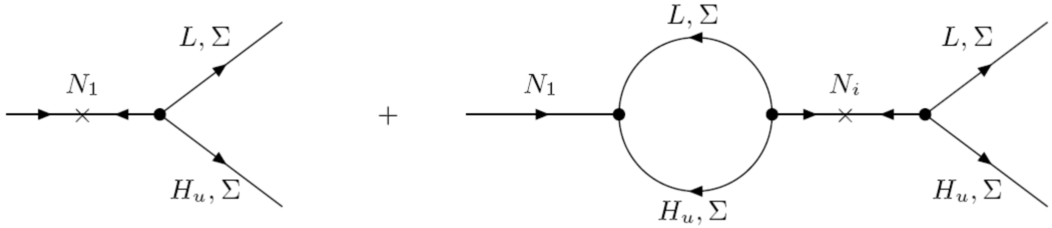
$$\Sigma, \Sigma^c \text{ with } Y = 0 \text{ and } T = 1, 2, 3, \cdots$$

$$W = y_i N_i L H_u + \frac{1}{2} h_i N_i \Sigma\Sigma + m_\Sigma \Sigma\Sigma^c + \frac{1}{2} M_i N_i N_i$$

  - “Extended B-L” broken by M:

superfields	L	N	Σ	Σ^c	M
$B-L$	-1	1	$-\frac{1}{2}$	$\frac{1}{2}$	-2

- Asymmetries from N decay:



$$\varepsilon_L \approx \frac{1}{4\pi} \frac{\sum_i \mathrm{Im}[y_i y_1^* (y_i y_1^* + h_i h_1^*)]}{|y_1|^2 + \frac{3}{4}|h_1|^2} \frac{M_1}{M_i},$$

$$\varepsilon_{DM} \approx \frac{2}{4\pi} \frac{\sum_i \mathrm{Im}[h_i h_1^* (y_i y_1^* + h_i h_1^*)]}{|y_1|^2 + \frac{3}{4}|h_1|^2} \frac{M_1}{M_i},$$

$$\Rightarrow \quad Y_{L,DM} = \frac{315\zeta(3)}{4\pi^4 g_*} \varepsilon_{L,DM}\, \eta_{L,DM}$$

Boltzmann Equations

$$\begin{aligned} Y'_{N_1} &= -zK(\gamma_D+\gamma_S)[Y_{N_1}-Y^{\rm eq}_{N_1}]\,, \\ Y'_L &= zK\gamma_D[\varepsilon_L(Y_{N_1}-Y^{\rm eq}_{N_1})-B_L\frac{Y^{\rm eq}_{N_1}}{2Y^{\rm eq}_l}Y_L]\,, \\ Y'_{\rm DM} &= zK\gamma_D[\varepsilon_{\rm DM}(Y_{N_1}-Y^{\rm eq}_{N_1})-B_{\rm DM}\frac{Y^{\rm eq}_{N_1}}{2Y^{\rm eq}_{\Sigma}}Y_{\rm DM}]\,, \end{aligned}$$

$$K = \frac{\Gamma_{N_1}}{H(T=M_{N_1})} \sim \frac{\tilde{m}_\nu}{10^{-3}\,{\rm eV}}$$

$$\gamma_S = \gamma^{\rm L}_{s,t}+\gamma^{\rm DM}_{s,t} \approx \gamma^{\rm L}_{s,t} \text{ for } B_{\rm DM} \ll B_{\rm L}$$

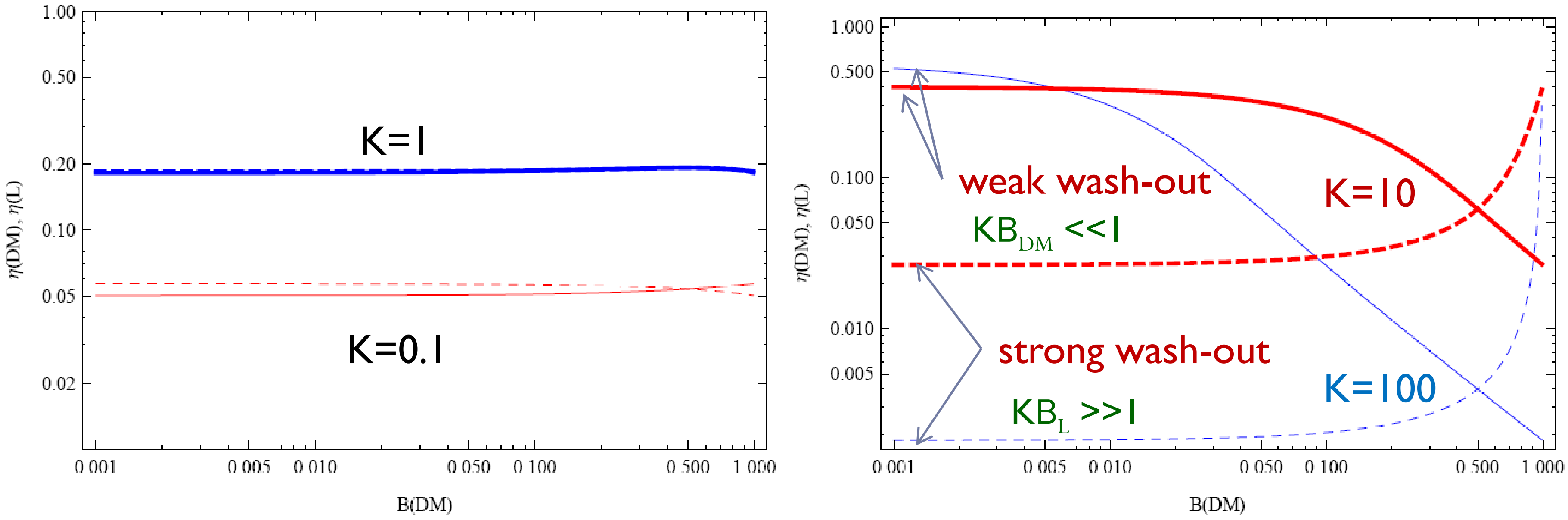
ΔL=1 scattering through gauge boson/Higgs exchange

$$\gamma_D+\gamma_S \approx \frac{9}{8\pi^2}\left[1+\ln\left(\frac{M_1}{M_h}\right)z^2\ln\left(1+\frac{a}{z}\right)\right]$$

Buchmuller, et.al., 0401240

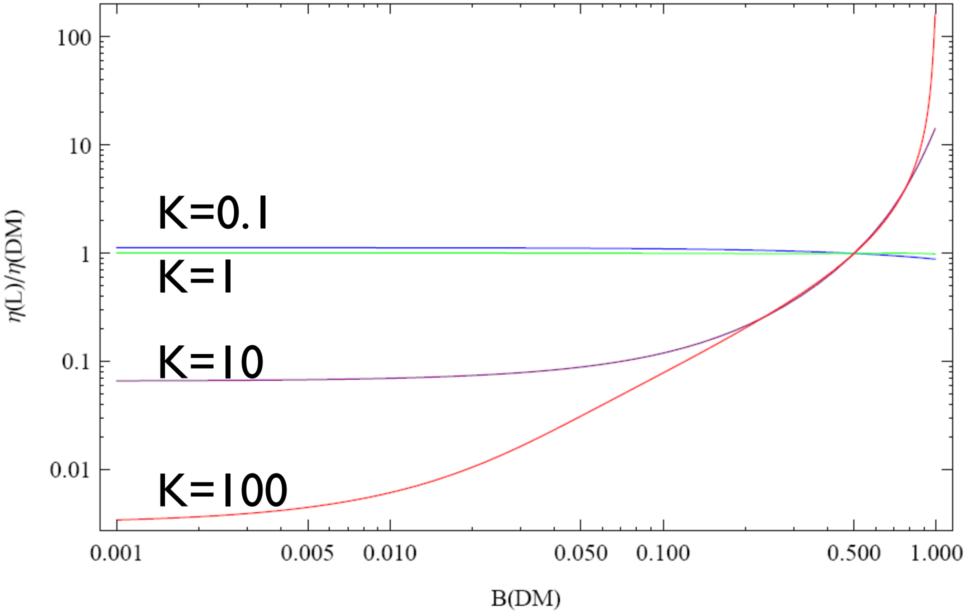
$$\frac{\Omega_{DM}}{\Omega_B} = \frac{m_{DM}Y_{DM}}{m_B Y_B} \approx \frac{31}{10}\frac{\varepsilon_{DM}}{\varepsilon_L}\frac{\eta_{DM}}{\eta_L}\frac{m_{DM}}{1\,{\rm GeV}}$$

Solutions



$\eta_{\rm DM}$: solid lines, $\eta_{\rm L}$: dotted lines

$\eta_{\rm L}/\eta_{\rm DM}$



$$\frac{\varepsilon_{\rm DM}}{\varepsilon_{\rm L}} \approx 10^{-2}\,\frac{\eta_{\rm L}}{\eta_{\rm DM}}\,\frac{200\ {\rm GeV}}{m_{\rm DM}}$$

$$\frac{\Omega_{DM}}{\Omega_B} = \frac{m_{DM}Y_{DM}}{m_B Y_B} \approx \frac{31}{10}\,\frac{\varepsilon_{DM}}{\varepsilon_L}\,\frac{\eta_{DM}}{\eta_L}\,\frac{m_{DM}}{1\,{\rm GeV}}$$

Mass spectra of DM multiplet for T=1

- Fermion: $\Sigma^{\pm}$ $\qquad \tilde{\Sigma} = (\tilde{\Sigma}^{+}, \tilde{\Sigma}^{0}, \tilde{\Sigma}^{-})$

  Scalar: $\tilde{\Sigma}^{\pm}$ $\qquad \tilde{\Sigma}^{c} = (\tilde{\Sigma}^{c+}, \tilde{\Sigma}^{c0}, \bar{\tilde{\Sigma}}^{c-})$

- Mass eigenstates of scalar DM components: $\lambda = \pm, 0$

$$\mathcal{M}^2 = \begin{bmatrix} m_\Sigma^2 + \tilde{m}^2 + \lambda m_Z^2 c_W^2 c_{2\beta} & B m_\Sigma \\ B m_\Sigma & m_\Sigma^2 + \tilde{m}^2 - \lambda m_Z^2 c_W^2 c_{2\beta} \end{bmatrix}$$

$$m_{\tilde{\Sigma}_1^0} - m_{\tilde{\Sigma}_1^\pm} \approx m_Z^4 c_W^4 c_{2\beta}^2 / 4 B m_\Sigma m_{\tilde{\Sigma}_1^0}$$

- Mass splittings: $m_{\tilde{\Sigma}_1^0} - m_{\tilde{\Sigma}_1^\pm} \sim 1 \text{ GeV}$

  $m_{\Sigma^\pm} - m_{\Sigma^0} \sim 0.1 \text{ GeV}$

- An interesting hierarchy: $\boxed{m_{\tilde{\Sigma}_1^0} > m_{\tilde{\Sigma}_1^\pm} > m_{\Sigma^\pm} > m_{\Sigma^0}}$

LHC Signatures

- Effective interaction below M:

$$\mathcal{L}_{eff} = \xi \nu \Sigma^{\pm} \tilde{\Sigma}^{\mp} \;\Leftarrow\; W_{eff} = \frac{yh}{2M} L H_u \Sigma \Sigma$$

$$\xi = \frac{yh\langle H_u^0 \rangle}{2M} \sim \frac{m_\nu}{\langle H_u^0 \rangle} \sim 10^{-12} \;\; \text{for} \;\; m_\nu = 0.1\text{eV}$$

- Two kinds of long-lived charged particle tracks:

$$\tilde{\Sigma}^{\pm} \rightarrow \nu \Sigma^{\pm}$$

$$\Gamma_{\tilde{\Sigma}^{\pm}} = \frac{\xi^2}{8\pi} m_{\tilde{\Sigma}^{\pm}}$$

$$\tau_{\tilde{\Sigma}^{\pm}} \sim 10^{-2}\text{sec}$$

Stable charged track

$$\Sigma^{\pm} \rightarrow \pi^{\pm} \Sigma^{0}$$

$$\Gamma_{\Sigma^{\pm}} = \frac{T(T+1)}{\pi} G_F^2 V_{ud}^2 \Delta m^3 f_\pi^3 \sqrt{1 - \frac{m_{\pi^{\pm}}^2}{\Delta m^2}}$$

$$\tau_{\tilde{\Sigma}^{\pm}} \approx 106\text{cm}$$

Disappearing charged tracks

- Multiply charged tracks for T=3,2:

$$\tilde{\Sigma}^{\pm\pm\pm}, \; \tilde{\Sigma}^{\pm\pm} \qquad \Sigma^{\pm\pm\pm} \xrightarrow{35\text{cm}} \pi^{\pm} \Sigma^{\pm\pm} \xrightarrow{18\text{cm}} \pi^{\pm} \Sigma^{\pm}$$

Conclusion

- Three important puzzles waiting to be solved.

  Why neutrino masses are so small?

  What happened to the antimatter in the universe?

  What is the identity of dark matter?

- Seesaw mechanism realizing leptogenesis connects them.
- DM may be the neutral component of a "light" extra MSSM multiplet whose population is asymmetric.
- It can be tested by the direct DM detection signal as well as by observing a stable and disappearing (multiply) charged particle tracks at the LHC.
- But, no indirect signals through co-annihilation.