Neutrino masses, muon g-2, dark matter, lithium probelm, and leptogenesis at TeV-scale

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Outline

* Introduction
* The model of neutrino masses
* Side effects on anomalous muon g-2
* Inert doublet dark matter candidate of the model
* Catalyzed BBN as the solution to lithium problem
* Possibility of low energy leptogenesis
* Test the model
* Conclusion

Introduction

* SM describes the experimental data so well, but we already have some discoveries that are not comparable with it.
* Several deviations between theoretical predictions and experimental data appear both in Standard Model of Particle Physics and Cosmology due to precision measurement.
* Nentrino masses, anomalous μ magnetic moment,...
* Lithium problem, matter-antimatter asymmetry, dark matter dark energy, PAMALA/ATIC/FERMI .....
* Many scenarios beyond SM are proposed, including top-down and bottom-up approaches.

Neutrino oscillation experiments

$\nu_e + {}^{37}\mathrm{Cl} \mapsto {}^{37}\mathrm{Ar} + e^-$

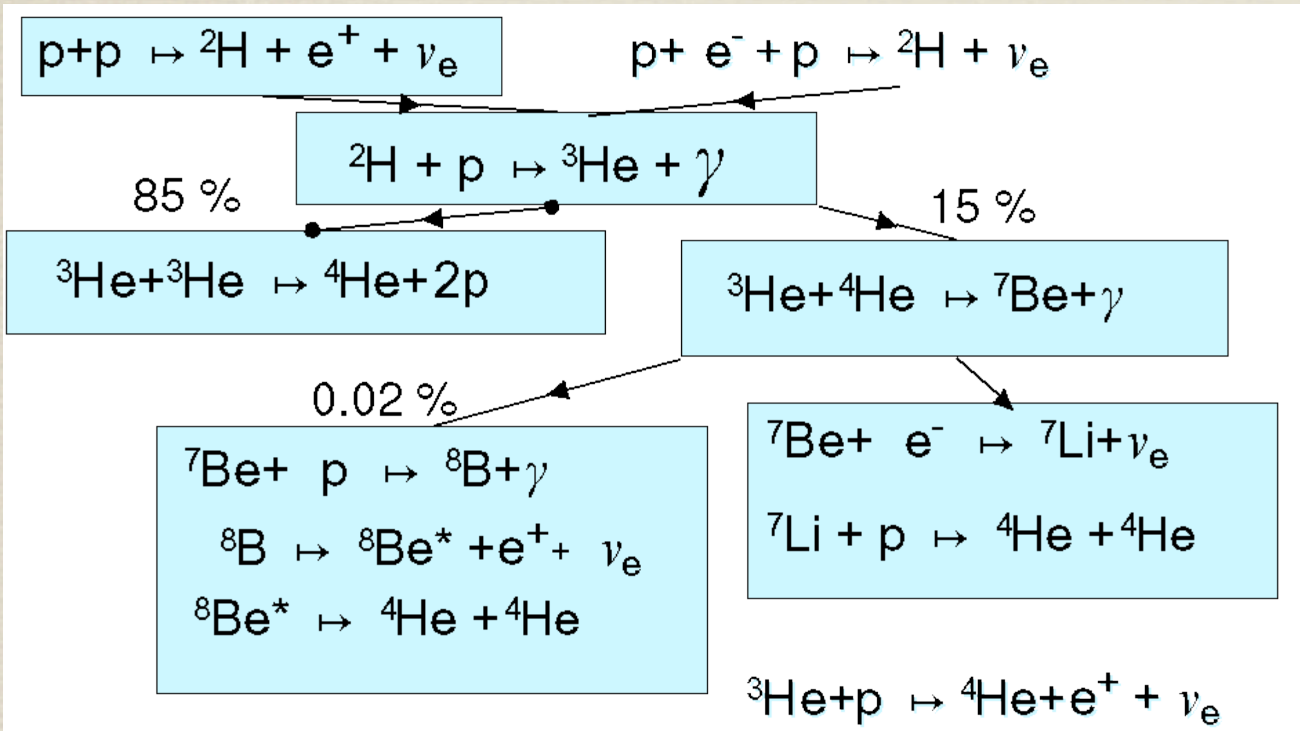
$\nu_e + {}^{71}\mathrm{Ga} \mapsto {}^{71}\mathrm{Ge} + e^-$

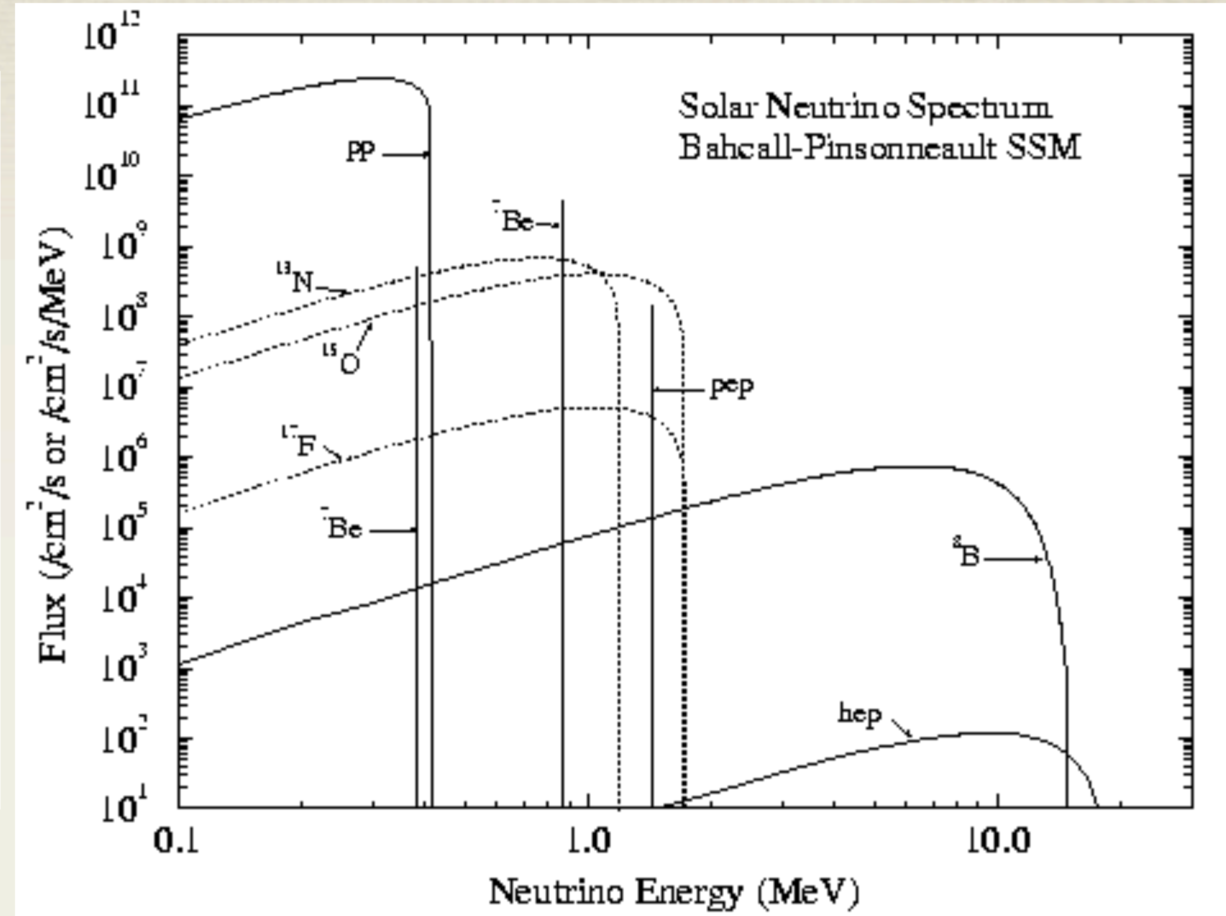
Experiment	measured flux	ratio exp/BP98	threshold energy	Years of running
Homestake	2.56 ± 0.16 ± 0.16	0.33 ± 0.03 ± 0.05	0.814 MeV	1970-1995
Kamiokande	2.80 ± 0.19 ± 0.33	$0.54 \pm 0.08\ ^{+0.10}_{-0.07}$	7.5 MeV	1986-1995
SAGE	75 ± 7 ± 3	0.58 ± 0.06 ± 0.03	0.233 MeV	1990-2006
Gallex	78 ± 6 ± 5	0.60 ± 0.06 ± 0.04	0.233 MeV	1991-1996
Super-Kamiokande	2.35 ± 0.02 ± 0.08	$0.465 \pm 0.005\ ^{+0.016}_{-0.015}$ (BP00)	5.5 (6.5) MeV	1996-
GNO	66 ± 10 ± 3	0.51 ± 0.08 ± 0.03	0.233 MeV	1998-
SNO	$1.68 \pm 0.06 \pm\ ^{+0.08}_{-0.09}$ (CC) 2.35 ± 0.22 ± 0.15 (ES) $4.94 \pm 0.21\ ^{+0.38}_{-0.34}$ (NC)		6.75 MeV	1999-

water Cerenkov detector ~elastic scattering

Heavy water Cerenkov detector ~ CC and NC

- The nuclear chain reactions in the Sun

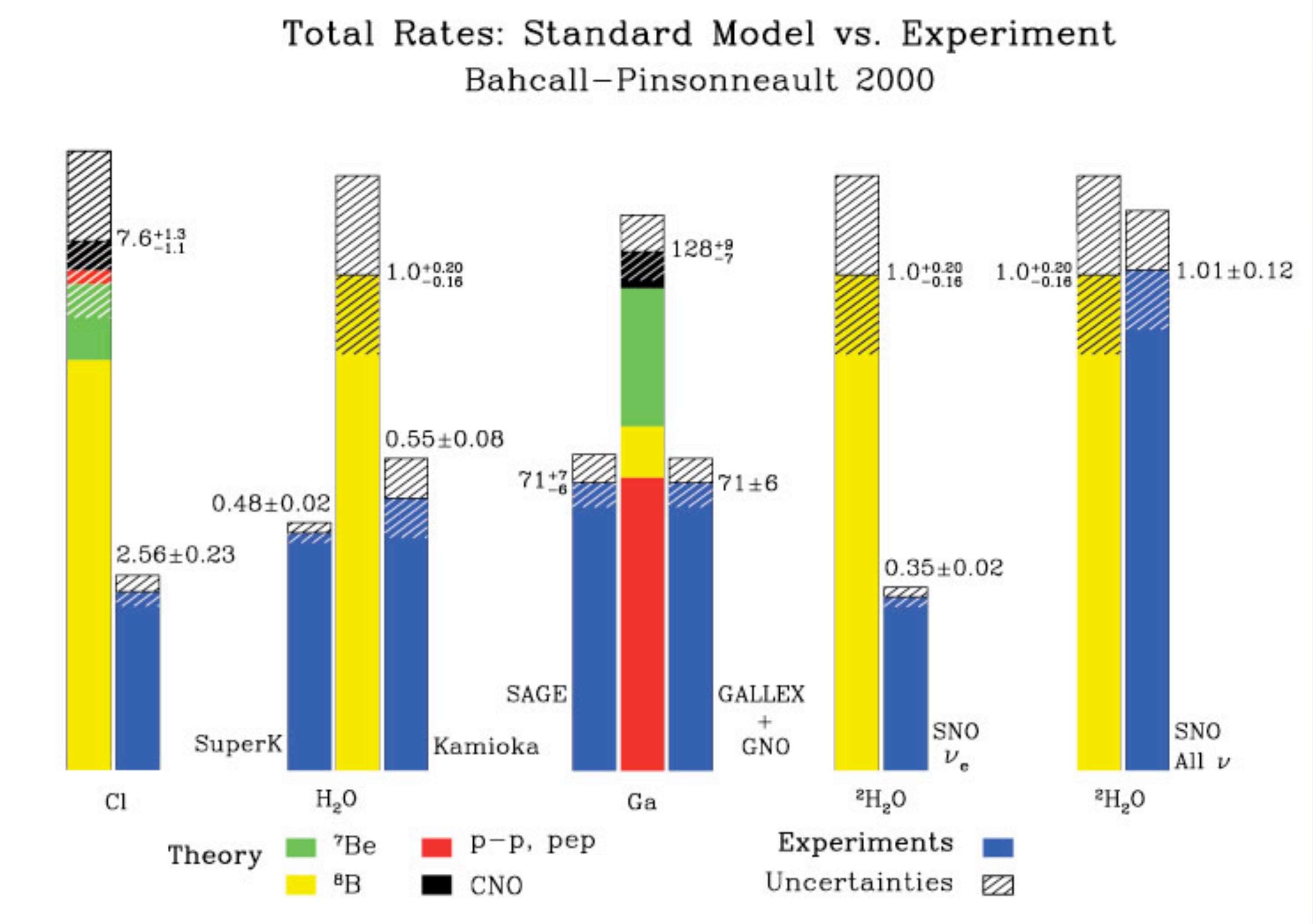




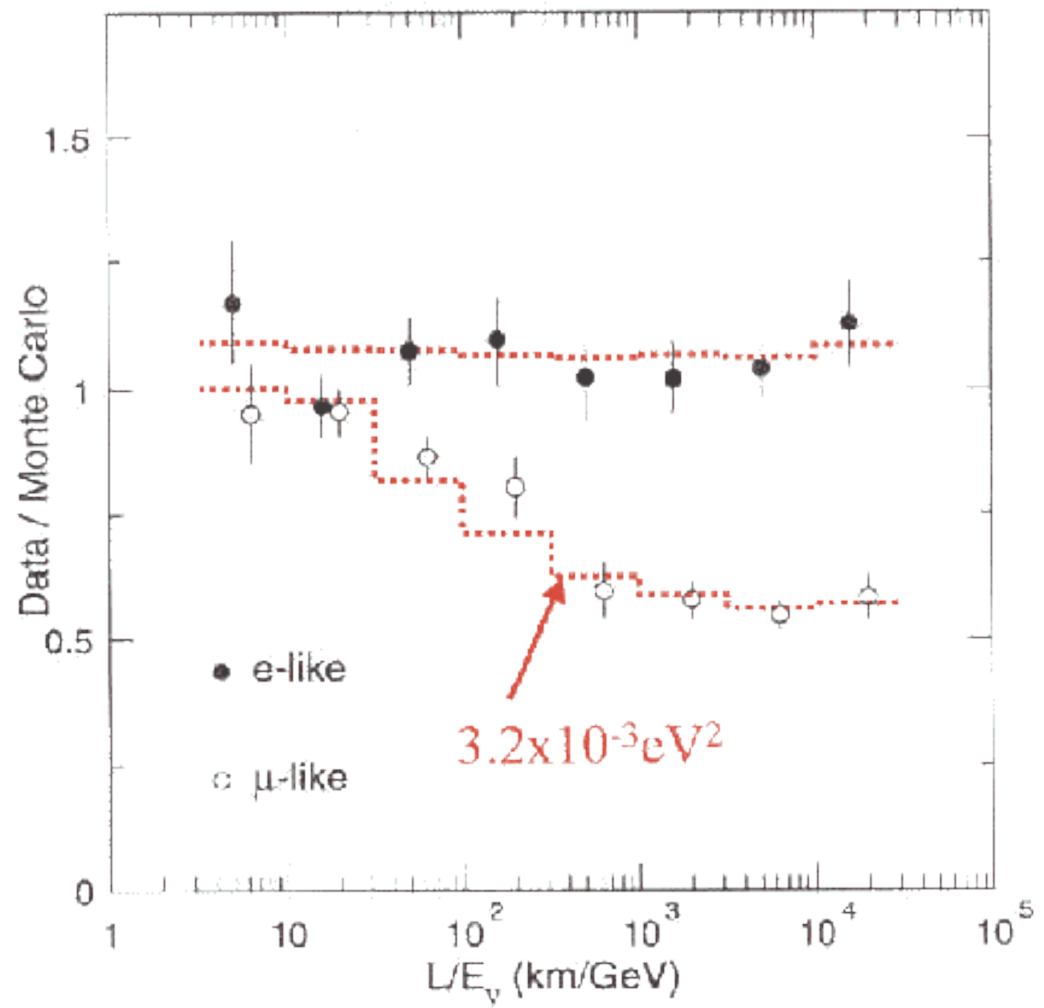
- The atmospheric neutrinos from cosmic rays

$$\pi^{\pm} \to \mu^{\pm} + \nu_\mu\,(\overline{\nu_\mu})$$
$$\searrow$$
$$e^{\pm} + \nu_e\,(\overline{\nu_e}) + \overline{\nu_\mu}\,(\nu_\mu)$$

$\nu_\mu : \nu_e = 2 : 1$



L/E plot of SuperKamiokande:



- Neutrino oscillation :

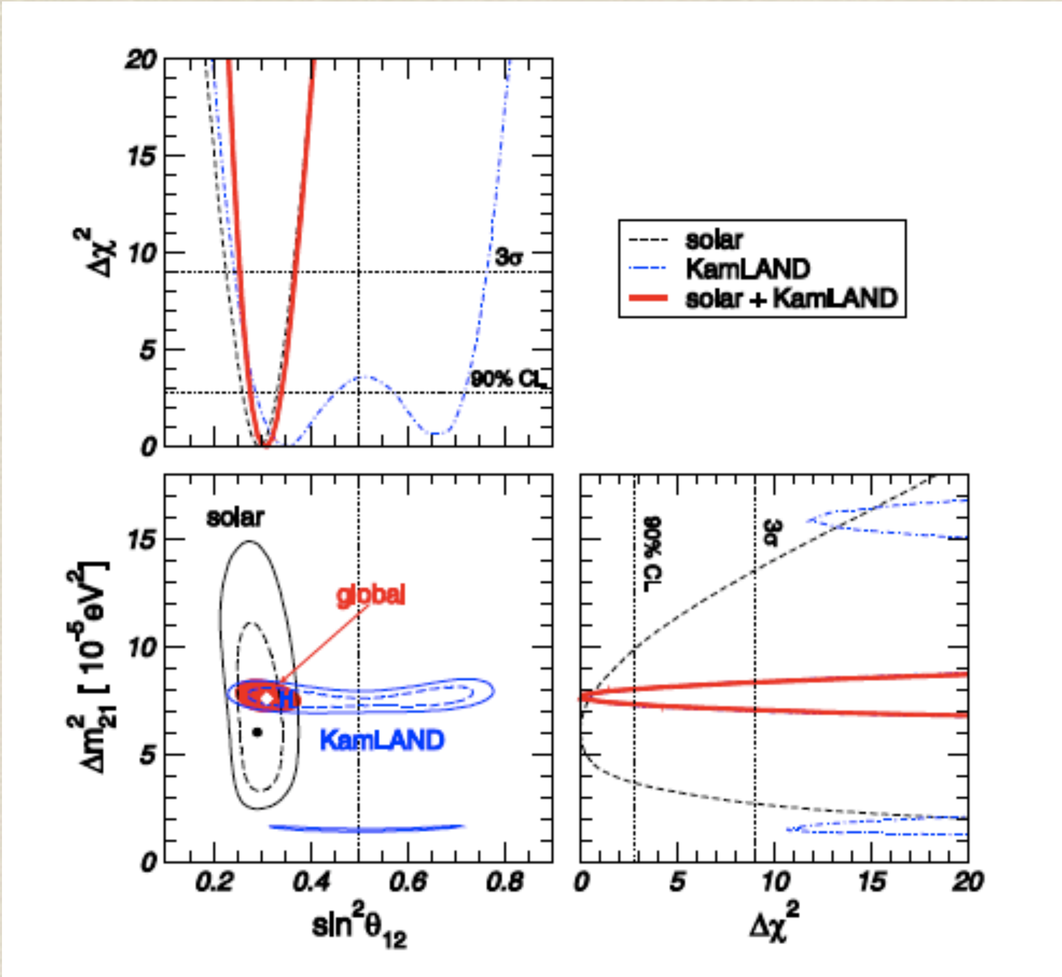
  Mass eigenstates and flavour eigenstates

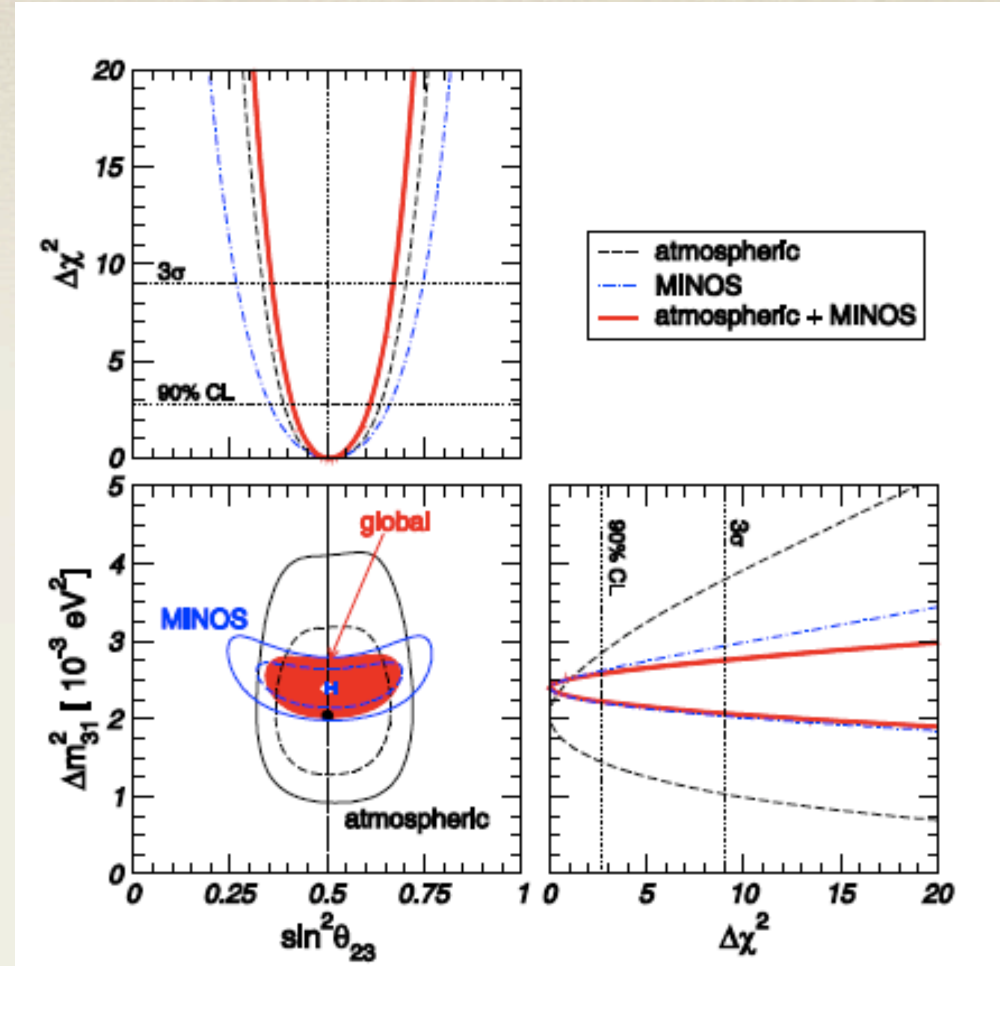
$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i}\nu_i$$

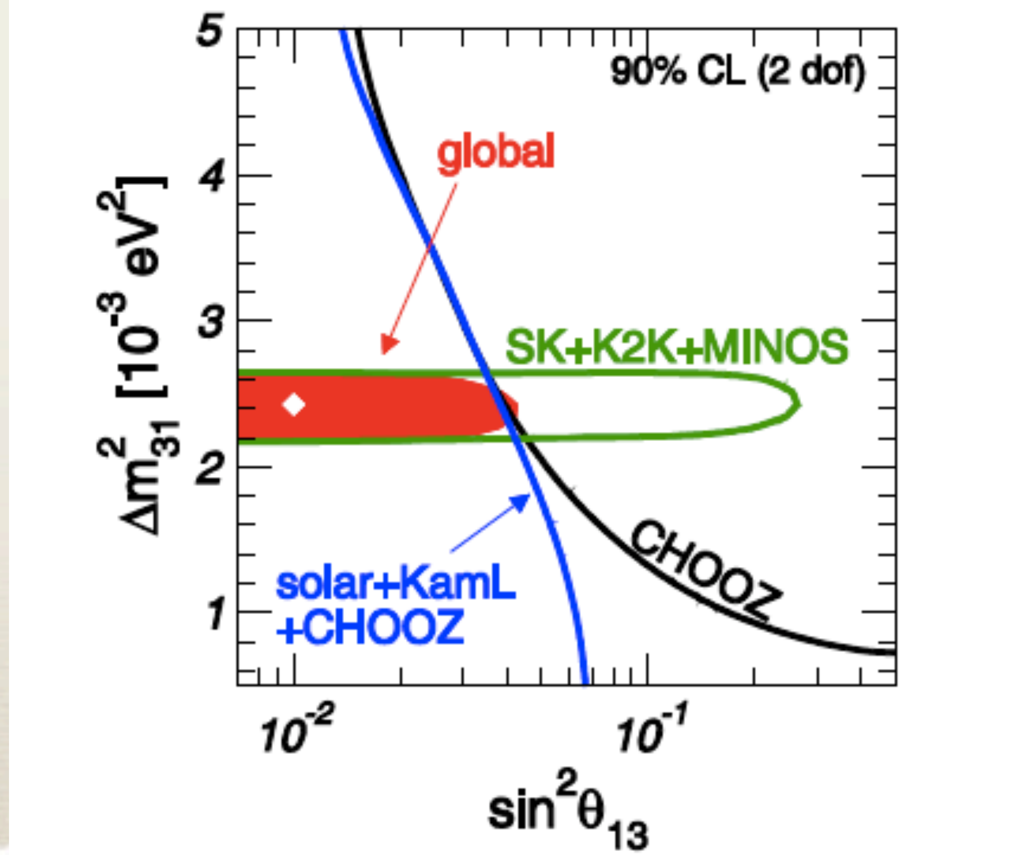
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\alpha} \\ 0 & 1 & 0 \\ -s_{13}e^{i\alpha} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\phi_1} & 0 \\ 0 & 0 & e^{i\phi_2} \end{pmatrix}$$

U : PMNS mixing matrix
Pontecorvo , Sov. Phys. JETP**6**,429(1958) , **33**, 549(1967)

• Current neutrino data







Parameter	Best fit	3 σ c.l.
$\Delta m^2_\odot$ (10^{-5} eV^2)	$7.65^{+0.23}_{-0.20}$	7.05 - 8.34
$\Delta m^2_{\rm Atm}$ (10^{-3} eV^2)	$2.40^{+0.12}_{-0.11}$	2.07 - 2.75
$\sin^2\theta_\odot$	$0.304^{+0.022}_{-0.016}$	0.25 - 0.37
$\sin^2\theta_{\rm Atm}$	$0.50^{+0.07}_{-0.06}$	0.36 - 0.67
$\sin^2\theta_{13}$	$0.01^{+0.016}_{-0.011}$	$\leq$ 0.056

$$\sin^2\theta_{12} = 0.304^{+0.022}_{-0.016} \qquad \sin^2\theta_{23} = 0.50^{+0.07}_{-0.06}$$

$$\Delta m^2_{21} = 7.65^{+0.23}_{-0.20} \times 10^{-5} \qquad |\Delta m^2_{31}| = 2.40^{+0.12}_{-0.11} \times 10^{-3}$$

Data from updated global fit:

Schwetz, Tortola & Valle, 2008

Hint for no-zero θ_{13} at 1.5 σ? - Fogli et al., 2008

* Neutrino angles

A very good first approximation :

"Tri-bimaximal" ansatz of neutrino mixing matrix

Harrison,Perkins & Scott, 2002

$$\mathcal{U}_\nu^{\mathrm{HPS}} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

Corresponding to

$$\tan^2\theta_{\mathrm{Atm}} = 1 \quad , \quad \tan^2\theta_{\odot} = \frac{1}{2} \quad , \quad \sin^2\theta_{\mathrm{R}} = 0$$

A4 symmetry : E. Ma ; G. Altarelli
T' symmetry : Frampton ......
μ-τ symmetry, S4 , Δ(54),......

* Among the ways to measure the neutrino masses, three ways are sensitive to the absolute scale : 0νββ decay , tritium β-decay , and cosmology

Tritium decay end point searches:

$$m_\nu^\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2} \leq 2.2 \text{ eV}$$

Double beta decay: Majorana neutrino!

$$m_\nu^{\beta\beta} = \sum_i U_{ei}^2 m_i \leq (0.5 - 1.0) \text{ eV}$$

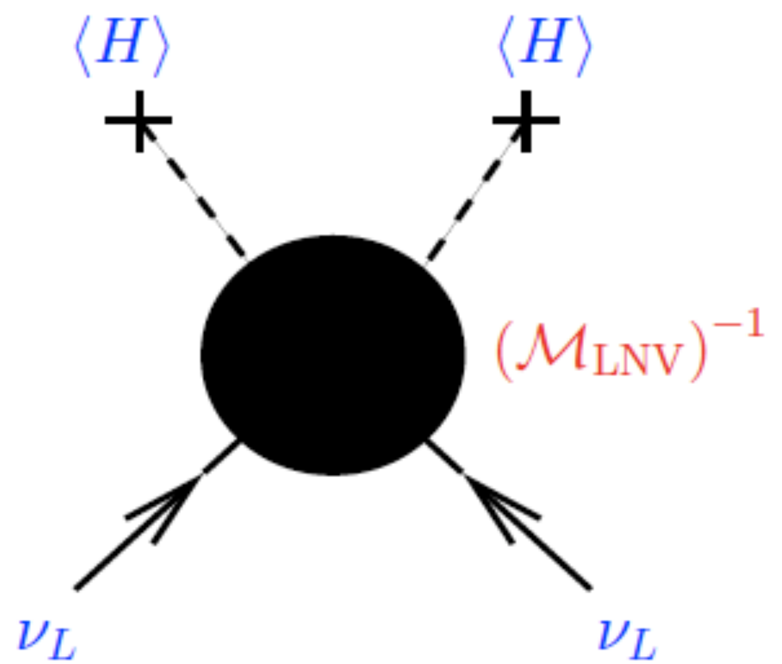
Cosmology (CMB + LSS + $\cdots$):

$$\sum_i m_{\nu_i} \leq (0.4 - 1.0) \text{ eV}$$

$$m_\beta = [c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2]^{1/2} \qquad m_{\beta\beta} = |c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}|$$

* Majorana Neutrino

If Lepton Number is Violated :



Weinberg, 1979

$$m_\nu = \frac{1}{\mathcal{M}_{LNV}}(LH)(LH)$$

$\langle H \rangle \sim 246$ GeV and $m_{\nu_3} \sim 0.05$ eV

Which scale?

$\mathcal{M}_{LNV} \simeq M_{GUT}$

or

$\mathcal{M}_{LNV} \simeq M_{EW}$

Many realiztion :

(1)Seesaw mechanism:TypeI,II,III

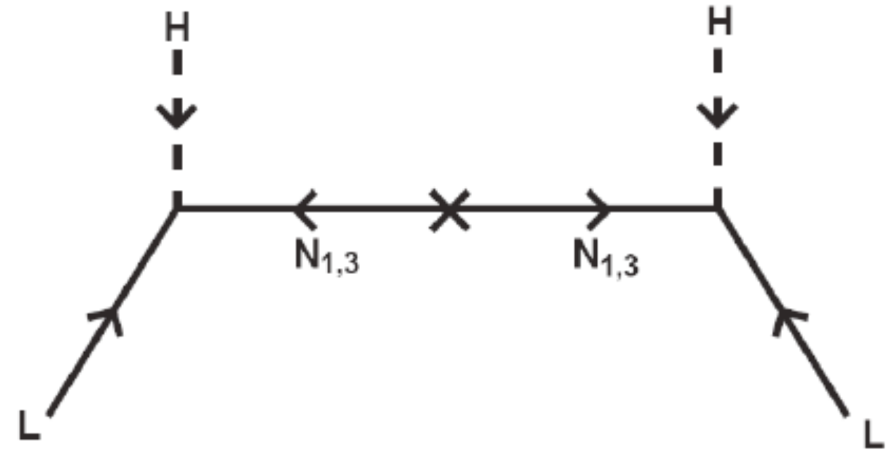
(2)Radiative models : Zee, Babu,LQs,C.S. Chen,..

(3)SUSY neutrino masses : R-parity violation

....

✳ Seesaw mechanism (Type I,III seesaw)

Type (I,III) seesaw



$N_1 : (1,1,0)$

$N_3 : (1,3,0)$

Type-I: SM + 3 right-handed Majorana ν's
(Minkowski 77; Yanagida 79; Glashow 79; Gell-Mann, Ramond, Slanski 79; Mohapatra, Senjanovic 79)

Type-III: SM + 3 triplet fermions (Foot, Lew, He, Joshi 89)

In the basis of (ν_L, ν_R) with mass matrix

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D & M_M \end{pmatrix}$$

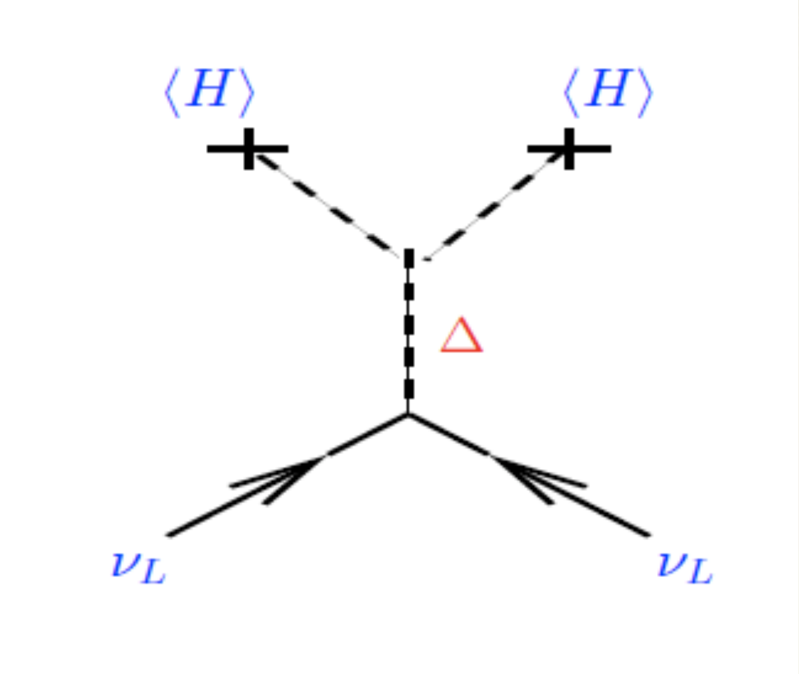
If $m_D \ll M_M$:

$$m_{1/2} \simeq \left(-\frac{m_D^2}{M_M}, M_M\right)$$

Replaced ν_R by $\mathbf{\Sigma} = (\Sigma^+, \Sigma^0, \Sigma^-)$

✳ Seesaw mechanism (Type II seesaw)

Schechter & Valle, 1980, 1982
Cheng & Li, 1980
Mohapatra, Senjanovic, 1981
...



Δ : (1,3,2)

$$\mathcal{V} = -\mu^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2 + \frac{1}{2} M_\Delta^2 \mathrm{Tr}\left(\Delta^\dagger \Delta\right) - \left[\lambda_\Delta M_\Delta H^T i\sigma_2 \Delta H + \mathrm{h.c.}\right]$$

$$\mathcal{M}_\nu = \begin{pmatrix} m_M & 0 \\ 0 & 0 \end{pmatrix}$$

$$m_M \simeq Y^\nu \langle \Delta_L^0 \rangle$$

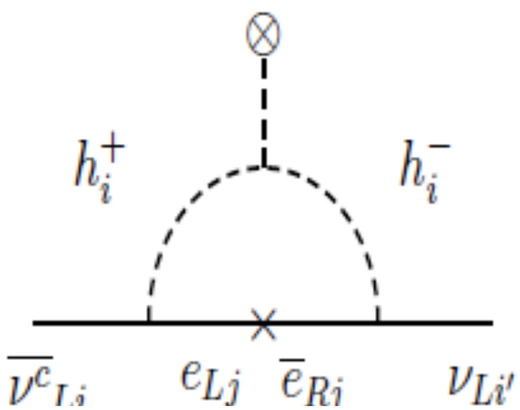
$$Y_\Delta v_\Delta \approx \lambda_\Delta Y_\Delta \frac{v^2}{M_\Delta}$$

✳ Radiative models

Zee, 1981:

2 Higgs doublets

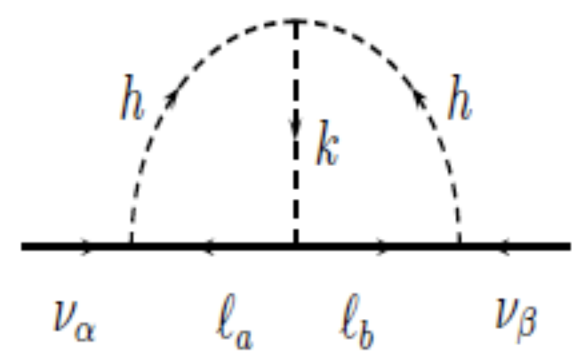
+ 1 charged singlet



Cheng & Li, 1980; Zee, 1985; Babu, 1988:

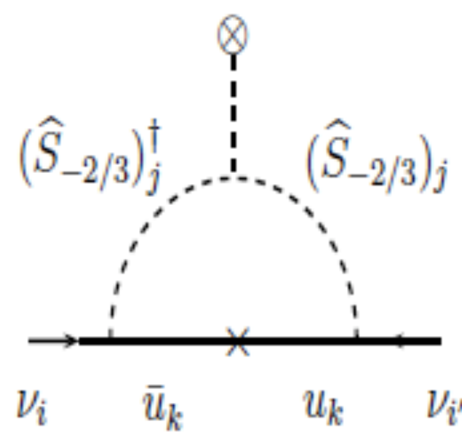
1 singly charged singlet

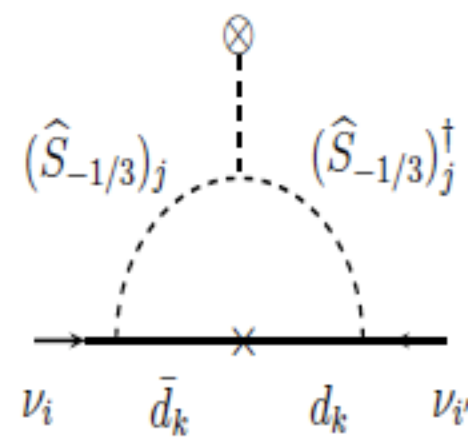
+ 1 doubly charged singlet



Hirsch et al. 1996, Aristizabal et al. 2008

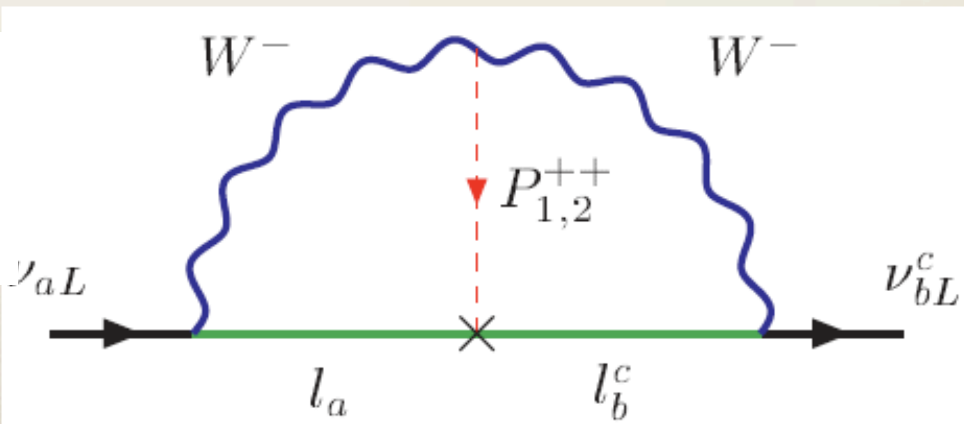
Leptoquarks





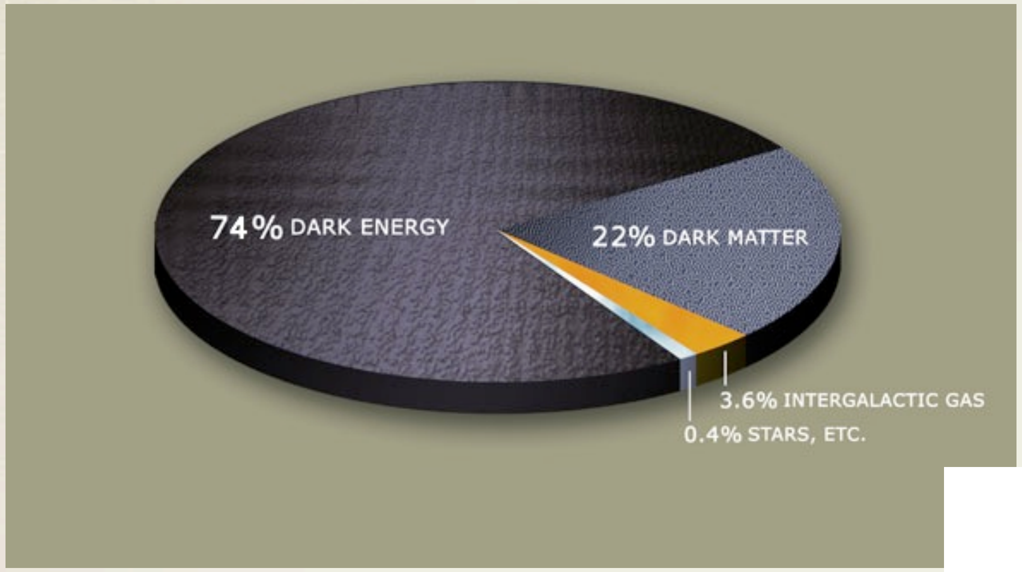
Geng, Ng, Chen 2007

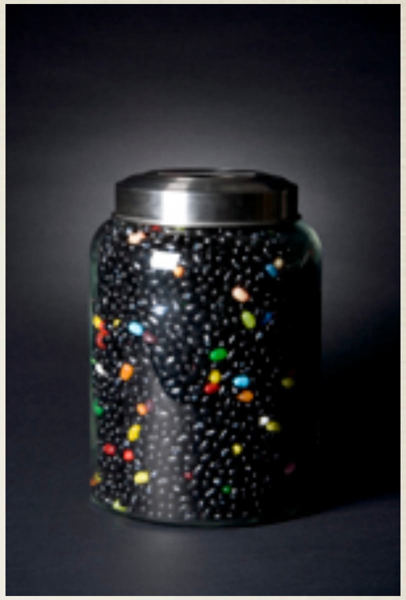
Triplet Higgs + 1 doubly charged singlet



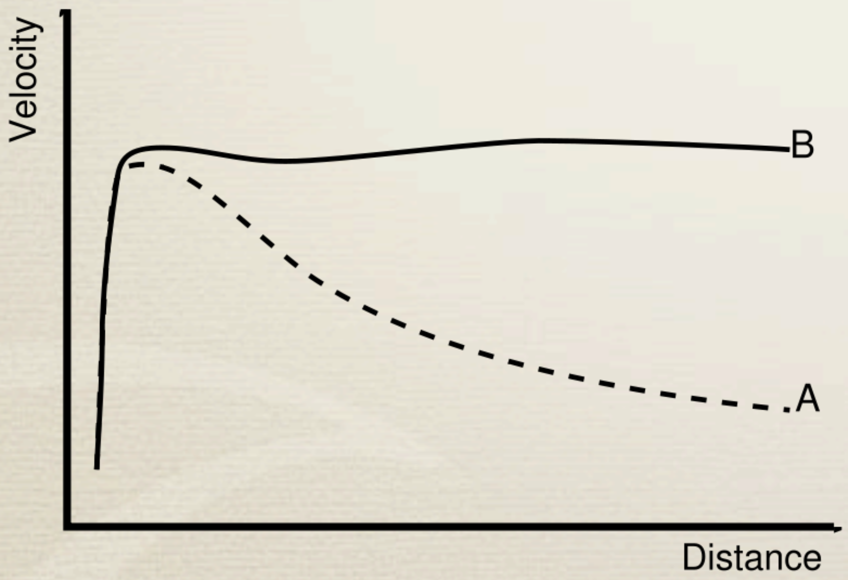
And many others ....

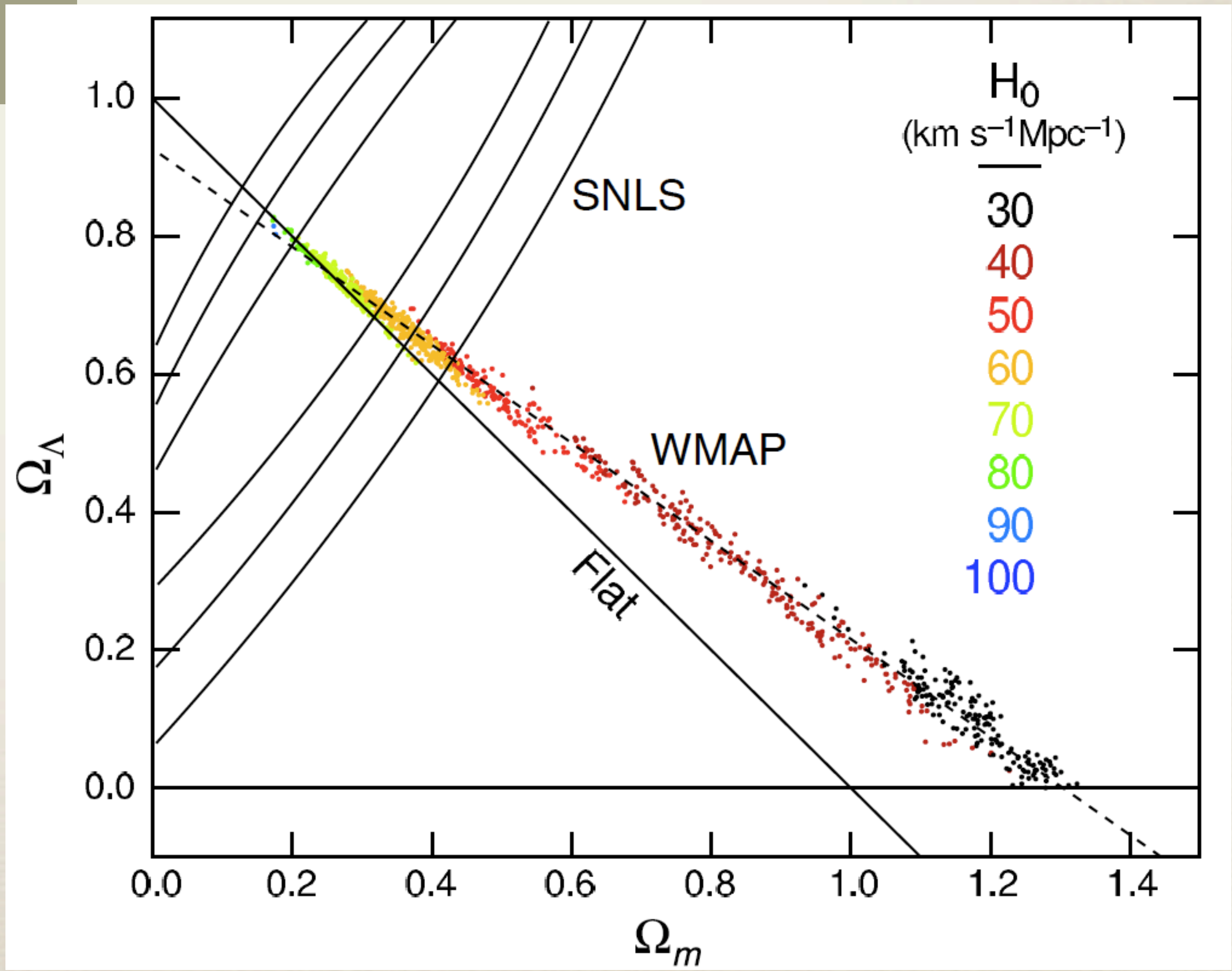
* Anomalous muon g-2 : the deviation between SM calculations and the experimental result is 3.2σ
* The existence of dark matter in our universe





DarkMatterPie





- Lithium problem states the discrepancy between SBBN and the abundance of $Li^{6,7}$ we observed.
- This problem has loomed for the past decade, with a persistent discrepancy for a factor of 2-3 in Li^7/H.
- Recently developments have sharpened this problem from

(1) the reduction of error to 7.4% in nuclear reaction for

$$^{3}He(\alpha, \gamma)^{7}Be$$

(2) the WMAP 5-year data set now yields a cosmic baryon density with an uncertainty reduced to 2.7%

(3) Observations of metal-poor stars have tested for systematic effects

* BBN + WMAP shift the central value up to

$$^7Li/H = (5.24^{+0.71}_{-0.67}) \times 10^{-10}$$

⟶ Discrepancy 2.4 or 4.2 σ to 4.3 or 5.3 σ

Too much ^{7}Li and too less ^{6}Li are predicted theoretically
3 times ^{7}Li larger / 1000 times ^{6}Li smaller than the observation

* The universe appears to be populated exclusively with matter rather than antimatter, the amount of asymmetry is around

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 10^{-10}$$

Many scenarios are proposed :

1. GUT thermal baryogenesis,
2. Leptogenesis,
3. Affleck-Dine mechanism,
4. CPT violation
5. ......

The model

- The evidence of dark matter $\longrightarrow$ Z_2 symmetry
- All the new particles besides SM sectors are Z_2 odd

Field	l_L	l_R	ϕ_1	L_L	E_R	ϕ_2	S
SM	$(2,-1)$	$(1,-2)$	$(2,-1)$	$(2,-1)$	$(1,-2)$	$(2,-1)$	$(1,2)$
Z_2	$+$	$+$	$+$	$-$	$-$	$-$	$-$

The masses of all new particles are around TeV scale

- New Yukawa couplings

$$\begin{aligned} L_Y &= f_{\alpha i} l_{L\alpha}^T C^{-1} L_{Li} S^+ + y_{\alpha i} \bar{L}_{Li} \tilde{\phi}_2 l_{R\alpha} + g_{\alpha i} \bar{l}_{L\alpha} \tilde{\phi}_2 E_{Ri}^- + h.c. \\ &= f_{\alpha i}(\bar{\nu}_\alpha E_i^- + l_\alpha^- N_i^c) S^+ + y_{\alpha i}(N_i \phi_2^+ l_{R\alpha}^- - E_i^+ \phi_2^{0*} l_{R\alpha}^-) \\ &\quad + g_{\alpha i}(\bar{\nu} \phi_2^+ E_{Ri}^- - \bar{l}_\alpha \phi_2^{0*} E_{Ri}^-) + h.c. \end{aligned}$$

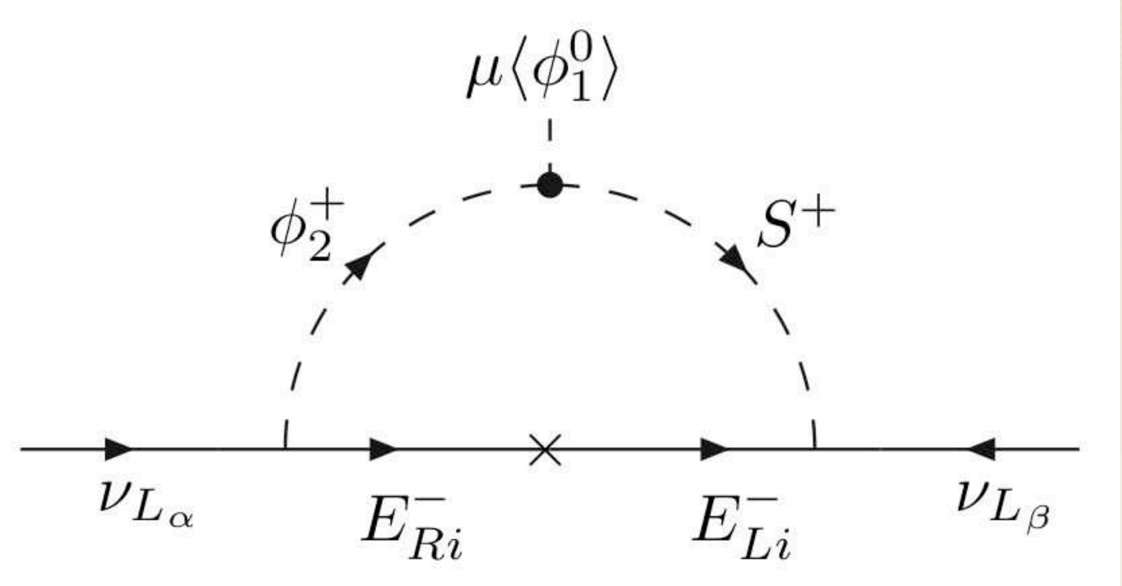
✳ Potential

$$
\begin{aligned}
V(\phi_1,\phi_2,S^-) &= -\mu_1^2|\phi_1|^2+\lambda_1|\phi_1|^4+m_2^2|\phi_2|^2+\lambda_2|\phi_2|^4+\lambda_3|\phi_1|^2|\phi_2|^2 \\
&+ \lambda_4|\phi_1^\dagger\phi_2|^2+\frac{\lambda_5}{2}\left[(\phi_1^\dagger\phi_2)^2+h.c.\right]+m_s^2|S|^2+\lambda_s|S|^4 \\
&+ \mu\left[(\phi_1^{0*}\phi_2^- - \phi_1^-\phi_2^0)S^+ + h.c.\right].
\end{aligned}
$$

$$
\begin{pmatrix} \phi_2^+ & S^+ \end{pmatrix}
\begin{pmatrix} \mu_2^2+\frac{\lambda_3 v^2}{2} & \frac{\mu v}{\sqrt{2}} \\ \frac{\mu v}{\sqrt{2}} & m_s^2 \end{pmatrix}
\begin{pmatrix} \phi_2^- \\ S^- \end{pmatrix}
$$

Neutrino mass generation

* No tree level seesaw due to Z_2 symmetry, neutrino masses are generated in one-loop level



$$
\begin{aligned}
(m_\nu)_{\alpha\beta} &= -i g_{\alpha i} f_{\beta i} M_{E_i} \mu \langle \phi_1^0 \rangle \\
&\times \int \frac{d^4 q}{(2\pi)^4} \frac{1}{(q^2 - M_s^2)} \frac{1}{(q^2 - M_{\phi_2}^2)} \frac{1}{(q^2 - M_{E_i}^2)} \\
&= \frac{g_{\alpha i} f_{\beta i} \mu v M_{E_i}}{16\sqrt{2}\pi^2 (M_{E_i}^2 - M_{\phi_2}^2)} \left[F(M_{E_i}^2) - F(M_{\phi_2}^2) \right],
\end{aligned}
$$

$$F(M^2) = \frac{M^2}{(M^2 - M_s^2)} \ln \frac{M^2}{M_s^2}$$

Assuming $M_{E_i} \gtrsim M_s \gtrsim M_{\phi_2^-}$ →

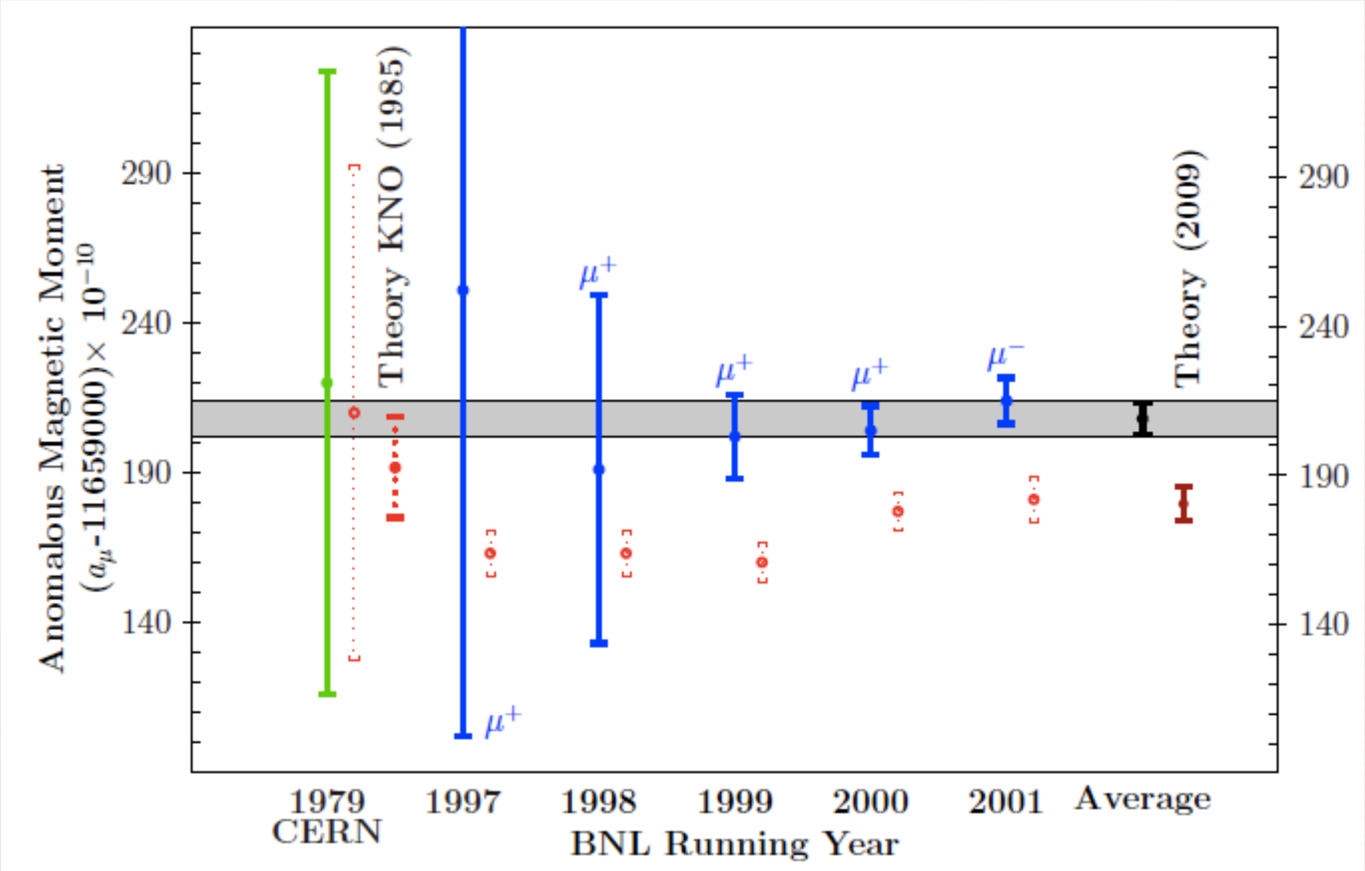
$$
\begin{aligned}
(m_\nu)_{\alpha\beta} &\approx \frac{g_{\alpha i} f_{\beta i}}{16\sqrt{2}\pi^2} \frac{\mu v}{M_{E_i}} \\
&\approx 10^{-3} g_{\alpha i} f_{\beta i} \mu \sim 10^{-2} \mathrm{eV},
\end{aligned}
$$

Eq. (1)

Muon g-2

- μ anomalous magnetic moment is one of the most precisely measured quantities in particle physics.
- A recent experiment at Brookhaven it has been measured with a remarkable 14-fold improvement of the previous CERN result.

Contribution	Value	Error
QED incl. 4-loops+LO 5-loops	116 584 718.1	0.2
Leading hadronic vacuum polarization	6 903.0	52.6
Subleading hadronic vacuum polarization	-100.3	1.1
Hadronic light–by–light	116.0	39.0
Weak incl. 2-loops	153.2	1.8
Theory	116 591 790.0	64.6
Experiment	116 592 080.0	63.0
Exp. - The. 3.2 standard deviations	290.0	90.3

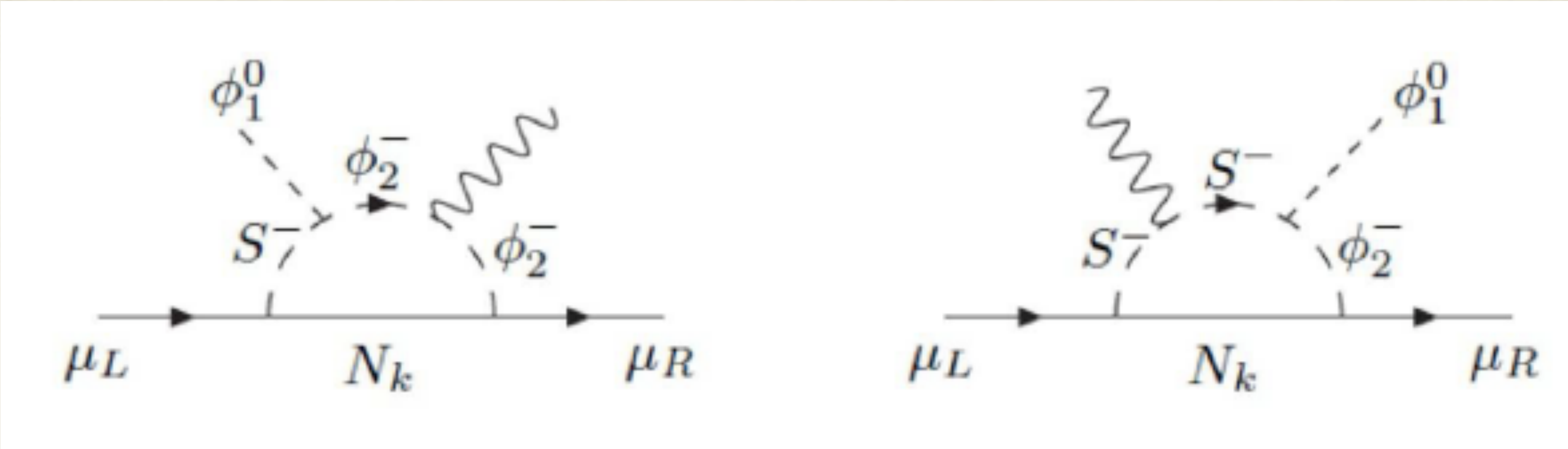


3.2σ

Neutrino masses and μ g-2

$$\Delta a_\mu = (290 \pm 90) \times 10^{-11}$$

* A similar mechanism



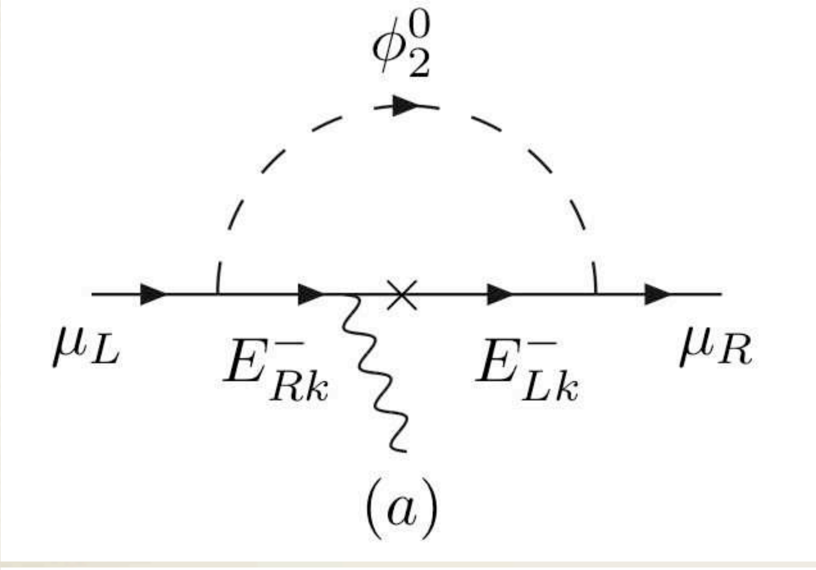
$$\begin{aligned}\Delta a^{NP}_{\mu(N_k)} &= -\frac{\sin\delta\cos\delta}{16\pi^2}(f_{\mu k} y_{\mu k})\frac{m_\mu}{M_k}\left[F(x_{P_1}) - F(x_{P_2})\right] \\ &\approx -\sin\delta\cos\delta(f_{\mu k} y_{\mu k}) \times 10^{-5\sim-6}\end{aligned}$$

Eq. (2)

$$\begin{pmatrix} P_1^- \\ P_2^- \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{pmatrix}\begin{pmatrix} \phi_2^- \\ S^- \end{pmatrix} \quad \sin\delta\cos\delta = \frac{\mu v}{\sqrt{2}(m^2_{P_1} - m^2_{P_2})}$$

$$F(x) = \frac{1}{(1-x)^3}\left[1 - x^2 + 2x\ln x\right] \qquad x_{P_i} = m^2_{P_i}/M_k^2$$

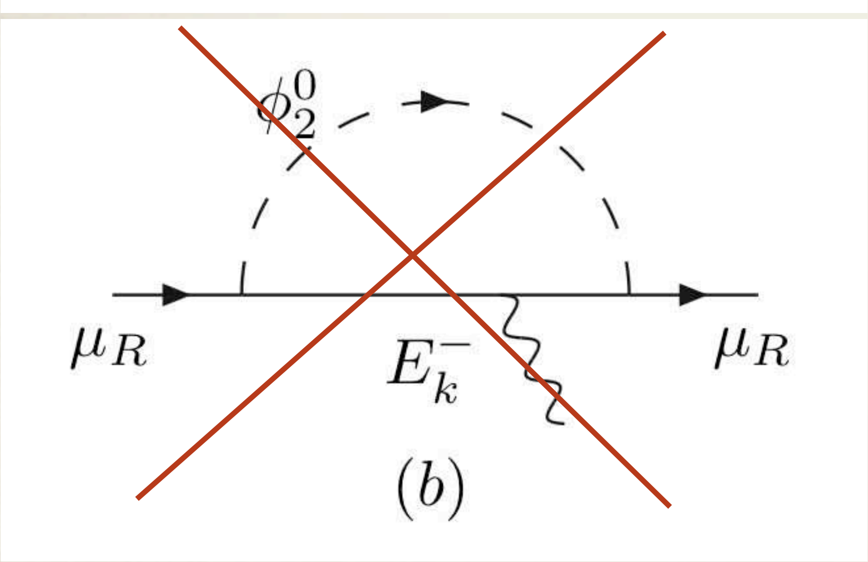
✳ And



$$\Delta a^{NP}_{\mu(E_k^-,(a))} = \frac{g_{\mu k} y_{\mu k}}{12\pi^2} \frac{m_\mu}{M_k} G(x_{\phi_2^0}) \approx g_{\mu k} y_{\mu k} \times 10^{-5},$$

Eq. (3)

$$G(x) = -\frac{3}{2(1-x)^3}\left[3 - 4x + x^2 + 2\ln x\right] \quad x_{\phi_2^0} = M_k^2/m^2_{\phi_2^0}$$



$$\Delta a^{NP}_{\mu(E_k^-,(b))} \approx \frac{y^2_{\mu k}}{48\pi^2} \frac{m^2_\mu}{M^2_{\phi_2^0}} \approx y^2_{\mu k} \times 10^{-11}$$

Dark matter

* A dark matter can be realized in the inert scalar doublet ϕ_2^0
* The lightest Z_2 odd component is determined by the sign of quartic coupling λ_5

$$m^2_{\phi_{2(R,I)}} = \frac{m_2^2}{2} + \frac{1}{2}(\lambda_3 + \lambda_4 \pm \lambda_5)v^2.$$

* The relic abundance of DM in our universe $\Omega_{CDM} h^2 = 0.106 \pm 0.008,$
* Numerically a WIMP will freeze out at temperature $T_f \sim m_{\phi_2^0}/25$
* The relation of final abundance and the (co)annihilations rate can be well approximated as

$$\Omega_{\phi_2^0} h^2 \approx \frac{3 \times 10^{-27} cm^3 s^{-1}}{\langle \sigma_{ijA} v_{ij} \rangle}. \qquad \text{with} \qquad v_{ij} = \frac{\sqrt{(p_i \cdot p_j)^2 - m_i^2 m_j^2}}{E_i E_j}$$

During the freeze out temperature $v_{ij} \sim 0.3$

* The dominant annihilation channel of DM is into gauge bosons $\phi_2^0 \phi_2^0 \rightarrow AA$

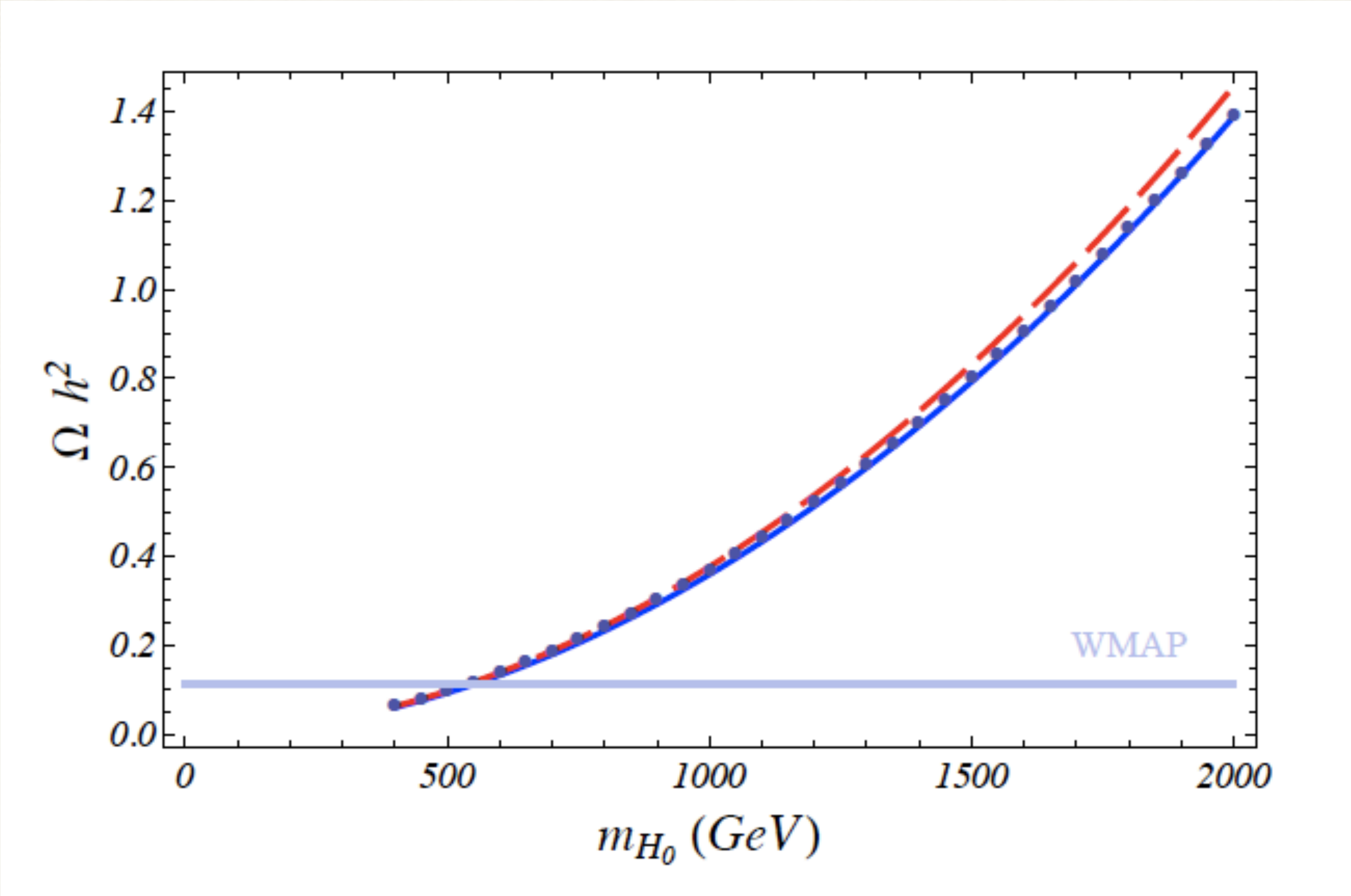
$$\langle \sigma_A v \rangle \simeq \frac{3g_2^4 + g_Y^4 + 6g_2^2 g_Y^2}{256\pi M_{\phi_2^0}^2}$$

* DM can (co)annihilate into or through SM Higgs by trilinear and quartic couplings of the scalars

$$\sigma_\lambda^{ij} = \frac{\lambda^{ij}}{32\pi m_{\phi_2^0}^2}, \qquad i,j = \{0,1,2,3,4\} = \{\phi_{2R}^0, \phi_{2I}^0, \phi_2^+, \phi_2^-, S^\pm\}$$

$$\begin{aligned}
\lambda^{00} = \lambda^{11} &= \frac{5}{2}\lambda_3^2 + 2\lambda_4^2 + 4\lambda_3\lambda_4 + 2\lambda_5^2 \\
\lambda^{22} = \lambda^{33} = 2\lambda^{01} &= 8\lambda_5^2 \\
\lambda^{02} = \lambda^{03} = \lambda^{12} &= \lambda^{13} = 2(\lambda_3/2 + \lambda_4)^2 + 2\lambda_5^2 \\
\lambda^{23} &= 4(\lambda_3 + \lambda_4)^2 + \lambda_3^2 \\
\lambda^{24} = \lambda^{34} &= 4(\lambda_3 + \lambda_4)^2 + (\mu/v)^2.
\end{aligned}$$

$$\begin{aligned}
V_{3,4} = {} & \lambda_1 v h^3 + \frac{\lambda_1}{4} h^4 + \lambda_2 |\phi_2|^4 + \lambda_3 v h |\phi_2|^2 + \frac{\lambda_3}{2} h^2 |\phi_2|^2 \\
& + \lambda_4 v h |\phi_2^0|^2 + \frac{\lambda_4}{2} h^2 |\phi_2^0|^2 + \lambda_5 v h ({\phi^0}_{2R}^2 - {\phi^0}_{2I}^2) \\
& + \frac{\lambda_5}{2} h^2 ({\phi^0}_{2R}^2 - {\phi^0}_{2I}^2) + \lambda_s |S|^4 + \left[\frac{\mu}{2} h \phi_2^- S^+ + h.c.\right]
\end{aligned}$$



T.Hambye el. (09)

In pure gauge interaction limit, the lower bound of DM mass is 530 GeV

Lithium problem

* Big-bang nucleosynthesis (BBN) offers the deepest reliable probe of the early universe, being based on Standard Model physics.

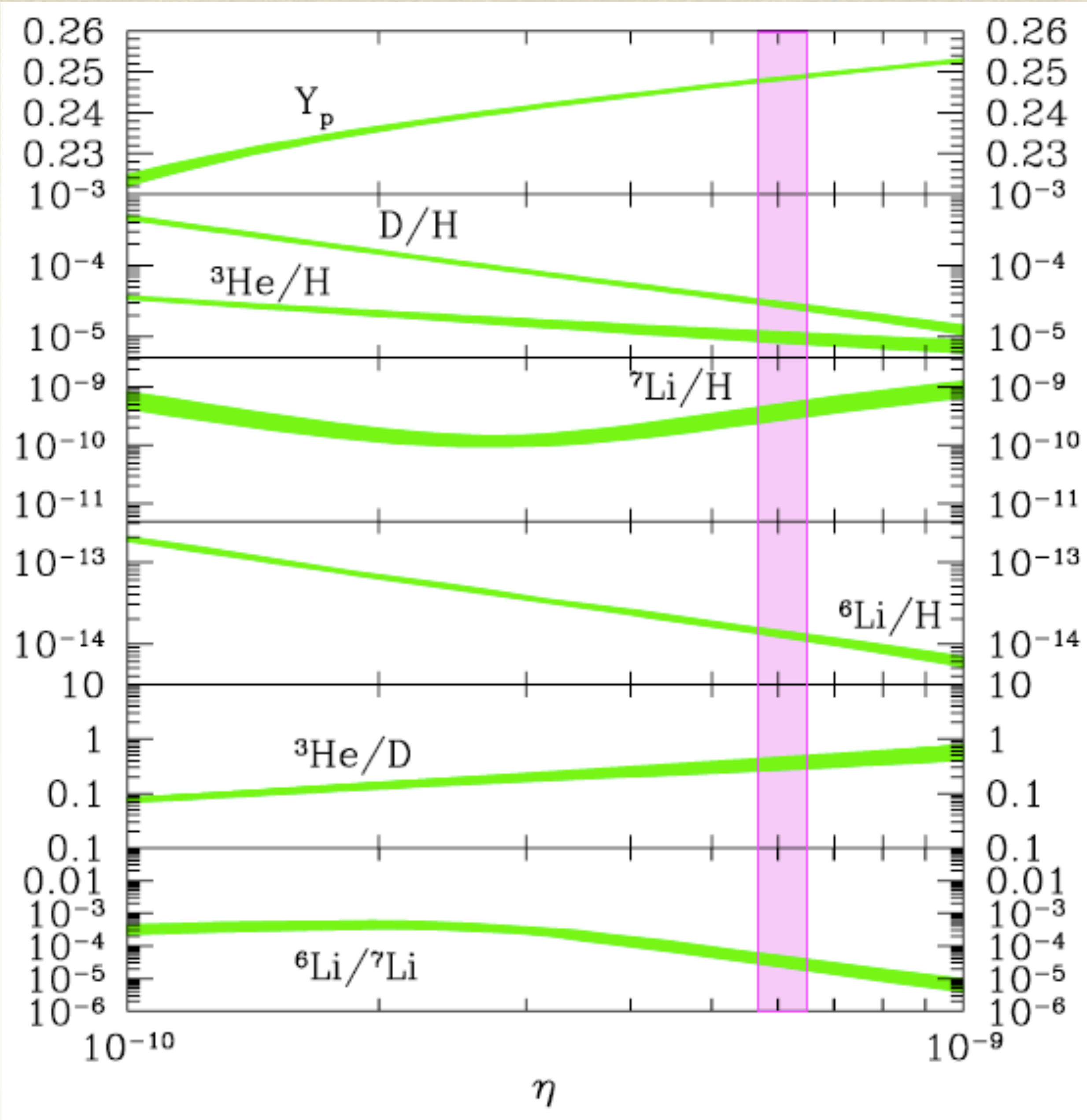
* Predictions of the abundances of the light elements, D, ^3He, ^4He, and ^7Li, synthesized at the end of the "first 3 minutes."

* A good overall agreement with the primordial abundances with the observational data $\longrightarrow$ span 9 orders of magnitude from

$$^4He/H \sim 0.08 \quad \text{down to} \quad ^7Li/H \sim 10^{-10}$$

* BBN was generally taken to be a three-parameter theory

Baryon density	Neutron mean-life	Number of neutrino flavors
η_{10}(WMAP2008)=6.23±0.17	T_n=878.5±0.8 s	3



* SBBN predict the ratio of Lithium and Helium is about

$$^7Li/H = (5.24^{+0.71}_{-0.62}) \times 10^{-10}$$

and ^{6}Li to ^{7}Li component is small

$$^6Li/^7Li \sim 3.3 \times 10^{-5}$$

* Metal-poor halo stars --- $Li/H = (1.23 \pm 0.06) \times 10^{-10}$

  Galactic cosmic rays --- primordial value $Li/H = (1 \sim 2) \times 10^{-10}$

  Measurement from clusters (NGC 6397) --- $Li/H = (2.19 \pm 0.28) \times 10^{-10}$

* Recent high-precision measurements are sensitive to the tiny isotopic shift in Li absorption and indicate

$$^6Li/^7Li \leq 0.15$$

* Lithium problem : The SBBN predicts primordial ^{6}Li abundance about 1000 times smaller than the observed abundance level and ^{7}Li abundance a factor of 2-3 larger than when one adopts a value of η inferred from the WMAP data.

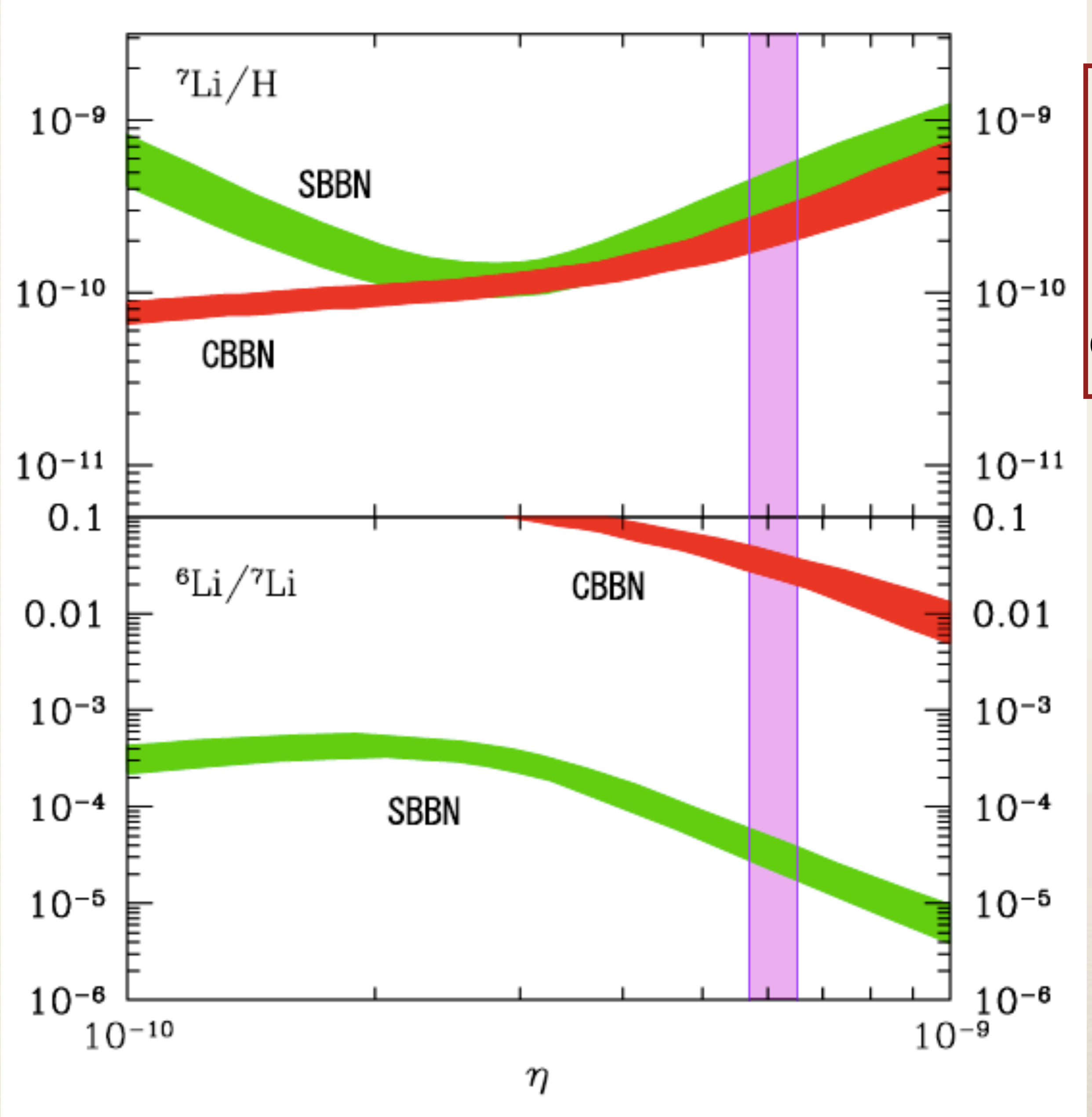
* Catalyzed BBN (CBBN) may provide the solution S^-.

M.Pospelov(07,08), K.Kohri,el(07), J.Ellis,K.A.Olive(03), M.Kaplinghat,el(06), T.T.Yanagida(07).....

*
$$SBBN : {}^4He + D \rightarrow {}^6Li + \gamma$$

$$CBBN : \quad S^- \rightarrow ({}^4HeS^-) \rightarrow {}^6Li \quad \text{and} \quad S^- \rightarrow ({}^4HeS^-) \rightarrow ({}^8BeX^-) \rightarrow {}^9Be.$$

$$({}^4HeS^-) + D \rightarrow {}^6Li + S^- \quad \text{and} \quad ({}^8BeS^-) + n \rightarrow {}^9Be + S^-.$$



The most significant difference is seen in the ^{6}Li production

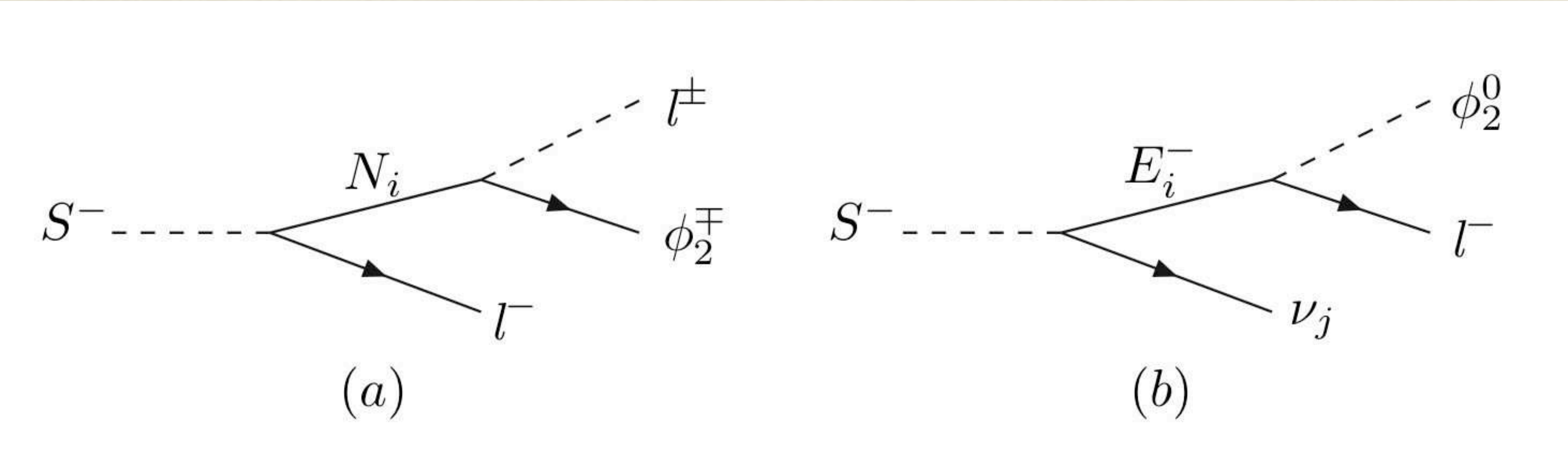
SBBN : ${}^4He + D \rightarrow {}^6Li + \gamma$; Q = 1.47MeV

CBBN : $({}^4HeS^-) + D \rightarrow {}^6Li + S^-$; Q $\simeq$ 1.13MeV

The existence of a long-lived singly charged particle ~ 1000s to catalyze the chain reactions

K.Kohri and F.Takayama (07)

* A long-lived S^+ is needed ~ 1000 sec



* (a),(b) :

$$\Gamma_s|_{\alpha\beta(N_i)} \approx \frac{(f_{\alpha i} y_{i\beta})^2}{30\pi^3 M_{N_i}^4} \times (\delta m)^5 (1 - \frac{5m_l^2}{\delta m^2})$$

$$\delta m = M_s - M_{\phi_2}$$

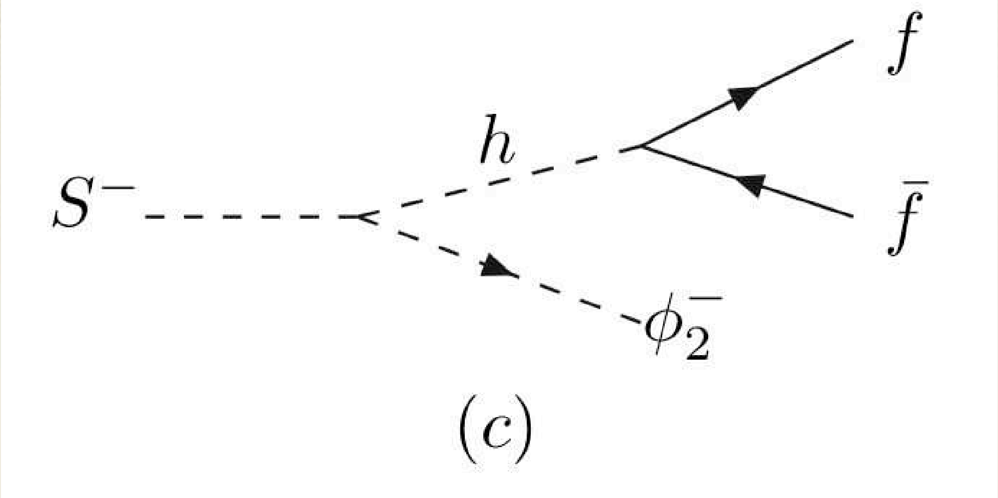
$$\approx f_{\alpha i}^2 y_{i\beta}^2 \times 10^{-15} (\frac{\delta m}{GeV})^5 \text{GeV},$$

$$\tau_{\alpha\beta} \approx 6.6 \times f_{\alpha i}^{-2} y_{i\beta}^{-2} \times (\frac{\delta m}{GeV})^{-5} \times 10^{-10} sec,$$

We have the constraint $f_{\alpha i}^2 y_{\beta i}^2 \approx 10^{-12} \times (\frac{\delta m}{GeV})^{-5}.$

Eq. (4)

* The second kind of diagram decay through SM Higgs



$$\Gamma_{s(h)} = \frac{10^{-6}\mu^2}{4\times 96(2\pi)^3}\frac{m_s}{m_h^4}(\delta m)^2$$

$$\approx 10^{-16}\times(\frac{\mu}{GeV})^2(\frac{\delta m}{GeV})^2\text{GeV},$$

We obtain $(\frac{\mu}{GeV})^2(\frac{\delta m}{GeV})^2 \approx 10^{-11}.$ Eq. (5)

The usual matter (light elements) and dark matter are formed at the same period !!

* We put all constraints to find a consistent solutions

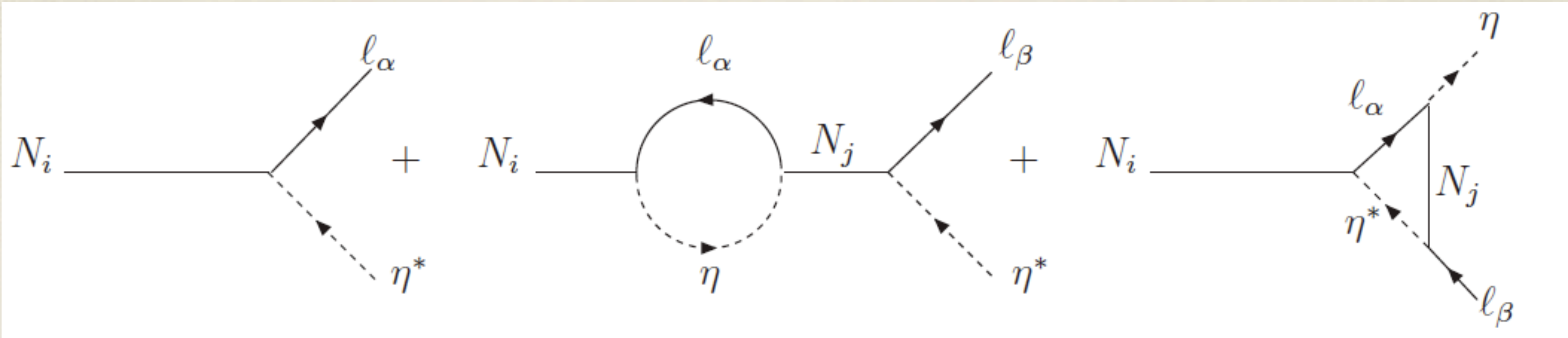
$$
\begin{aligned}
fg(\frac{\mu}{GeV}) &\sim 10^{-8}, && \leftarrow \text{Neutrino masses} \\
fy &\sim 10^{-4}, \\
gy &\sim 10^{-5}, && \leftarrow \text{Anomalous muon g-2} \\
f^2y^2(\frac{\delta m}{GeV})^5 &\sim 10^{-12}, \\
(\frac{\mu}{GeV})^2(\frac{\delta m}{GeV})^2 &\sim 10^{-11}. && \leftarrow \text{Lithium problem}
\end{aligned}
$$

$$\mu \sim 10^{-5} GeV,\ \delta m \lesssim 1 GeV,$$

$$f \sim 10^{-1},\ y \sim 10^{-3},\ \text{and}\ g \sim 10^{-2}$$

Leptogenesis

- The difficulties to have a simple leptogenesis at the TeV-scale



1. The out-of-equilibrium condition

$$\Gamma_{N_i} \equiv \sum_\alpha [\Gamma(N_i \to \ell_\alpha \eta) + \Gamma(N_i \to \overline{\ell}_\alpha \eta^\dagger)] = \frac{1}{8\pi}(\tilde{Y}_\nu^\dagger \tilde{Y}_\nu)_{ii} M_i \delta^2_{N_i\eta}$$

$$\Gamma_{N_k} < H(T = M_{N_k}) = \sqrt{\frac{4\pi^3 g_*}{45}} \frac{T^2}{M_{Planck}}\Big|_{T=M_{N_k}}$$

One can define a wash-out factor

$$K_i = \frac{\Gamma_i}{H(M_i)} \simeq 3 \times 10^{16} g_\nu^2 (\frac{GeV}{M_i}) \delta^2_{N\eta}$$

On the other hand

2. CP asymmetry

$$\varepsilon_i^\alpha = \frac{\Gamma(N_i \to \ell_\alpha \eta) - \Gamma(N_i \to \overline{\ell}_\alpha \eta^\dagger)}{\sum_\alpha [\Gamma(N_i \to \ell_\alpha \eta) + \Gamma(N_i \to \overline{\ell}_\alpha \eta^\dagger)]}$$
$$= \frac{1}{8\pi(\tilde{Y}_\nu^\dagger \tilde{Y}_\nu)_{ii}} \sum_{j \neq i} \mathrm{Im}\left\{ (\tilde{Y}_\nu^\dagger \tilde{Y}_\nu)_{ij} (\tilde{Y}_\nu)^*_{\alpha i} (\tilde{Y}_\nu)_{\alpha j} \right\} g\left(\frac{M_j^2}{M_i^2}\right)$$

with function $g(x) = \sqrt{x}\left[\frac{1}{1-x} + 1 - (1+x)\ln\frac{1+x}{x}\right]$

The amount of matter-antimatter asymmetry leads

$$Y_{B-L} \simeq -Y_L = -\frac{n_L - n_{\overline{L}}}{s} = -\kappa \frac{\varepsilon_1}{g_*}$$

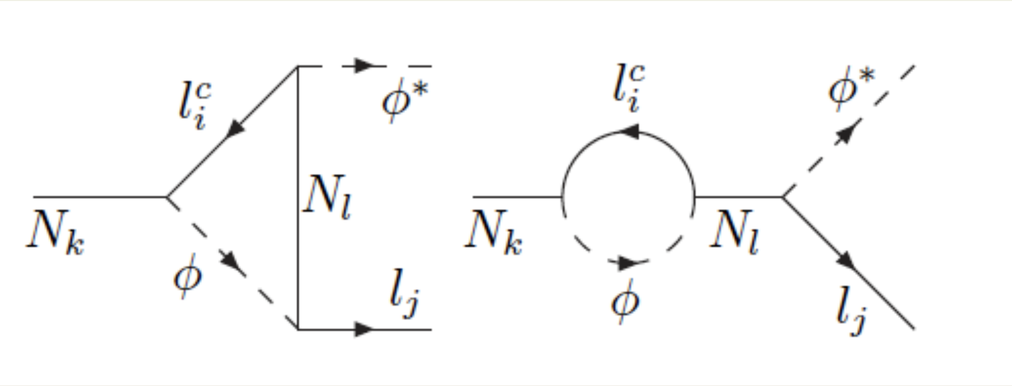
Usually $\kappa = \frac{1}{K}$

Three possibilities enhancement mechanisms

1. Mass degeneracy : CP asymmetry induced by self-energy diagram display an interesting resonant behavior when the masses of the decaying particles are nearly degenerate.

$$(m_{Ni} - m_{Nj})/(m_{Ni} + m_{Nj}) \sim 10^{-7}$$

2. Hierarchy of couplings : Assuming two particles (A,B) decaying into the same decay products. The lighter one A with the suppressed coupling g_A to reach the out-of-equilibrium condition while the heavier one B with unsuppressed coupling g_B will produce large CP asymmetry through one-loop.

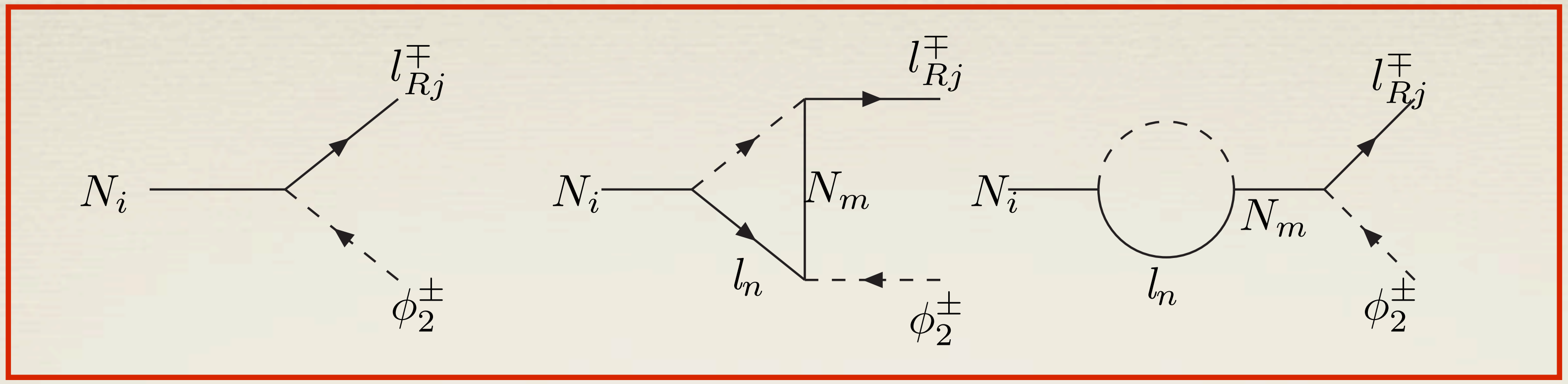


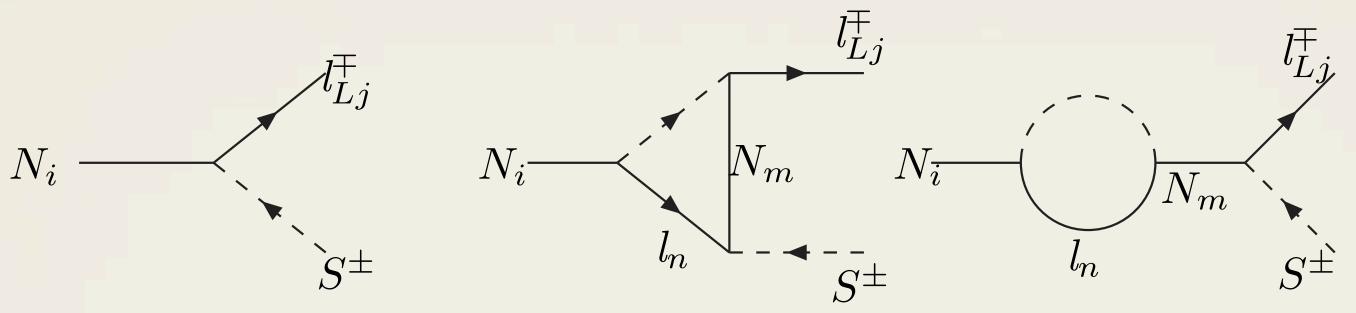
3. Phase space suppression : Instead of tuning down the Yukawa couplings, one can simply use the phase space to suppress the wash-out factor while at the same time keep a large Yukawa couplings.

Leptogensis

Fikugita, Yanagita(86)

* Two contributions





$$\Gamma_{N_1} = \frac{\sum_\alpha (y_{1\alpha})^2}{16\pi} M_{N_1} \quad \text{and} \quad \Gamma_{N_1} = \frac{(f^\dagger f)_{11}}{8\pi} M_{N_1}$$

The right-handed sector is not constrained by neutrino masses

$$L_Y = f_{\alpha i} l^T_{L\alpha} C^{-1} L_{Li} S^+ + y_{\alpha i} \bar{L}_{Li} \tilde{\phi}_2 l_{R\alpha} + g_{\alpha i} \bar{l}_{L\alpha} \tilde{\phi}_2 E^-_{Ri} + h.c.$$

$$(m_\nu)_{\alpha\beta} \approx \frac{f_{\alpha i} g_{\beta i}}{16\sqrt{2}\pi^2} \frac{\mu v}{M_{E_i}}$$

$$\epsilon_1 = \frac{\Gamma(N_1 \to l\phi_2^+) - \Gamma(N_1 \to \bar{l}\phi_2^-)}{\Gamma(N_1 \to l\phi_2^+) + \Gamma(N_1 \to \bar{l}\phi_2^-)} = \frac{1}{8\pi} \sum_{m\neq 1} \frac{Im[(y^\dagger y)^2_{1m}]}{\sum_\alpha (y^\dagger y)_{1\alpha}} \{f_v(\frac{M_m^2}{M_1^2}) + f_s(\frac{M_m^2}{M_1^2})\}$$

$$= \frac{3}{16\pi} \sum_{m\neq 1} \frac{Im[(y^\dagger y)^2_{1m}]}{\sum_\alpha (y^\dagger y)_{1\alpha}} \frac{M_1}{M_m}, \qquad (26)$$

If $y^{(2)} = \sqrt{\frac{Im[(y_{1\alpha})(y^*_{2\alpha})]^2}{\sum_\alpha (y_{1\alpha})(y^*_{1\alpha})}} \geq 1.05 \times 10^{-3} \sqrt{\frac{M_{N_2}}{M_{N_1}}},$

One has $\frac{n_B}{s} = -\frac{28}{79}\frac{n_L}{s} = -1.36 \times 10^{-3} \epsilon_1 \eta = 9 \times 10^{-11},$

Out of equilibrium condition $\Gamma_{N_1} < H(T) = \sqrt{\frac{4\pi^3 g_*}{45}} \frac{T^2}{M_{pl}} |_{T=M_{N_1}}.$

We have $y^{(1)} = \sqrt{\sum_i |y_{1i}|^2} < 3 \times 10^{-4} \sqrt{\frac{M_{N_1}}{10^9 GeV}}.$

Hierarchy couplings : $\frac{y^{(1)}}{y^{(2)}} < 0.28 \times \sqrt{\frac{M_{N_1}}{M_{N_2}} \frac{M_{N_1}}{10^9 GeV}}.$

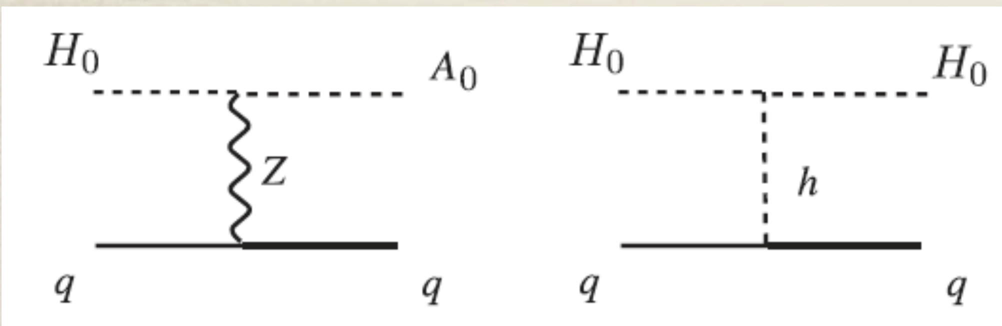
Consistent with the previous constraints

$$M_{N_1} = 1TeV,\ M_{N_2} = 5TeV,\ y^{(2)} \simeq 2.3 \times 10^{-3},\ \text{and}\ y^{(1)} \simeq 3 \times 10^{-7}.$$

Test of the model

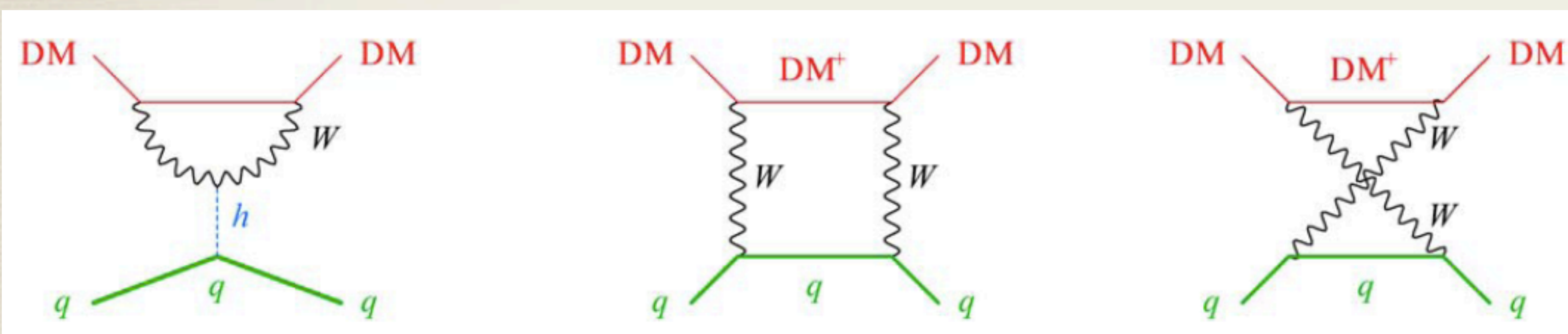
LHC search see M. Hirsch,K.S. Babu

* Direct detection



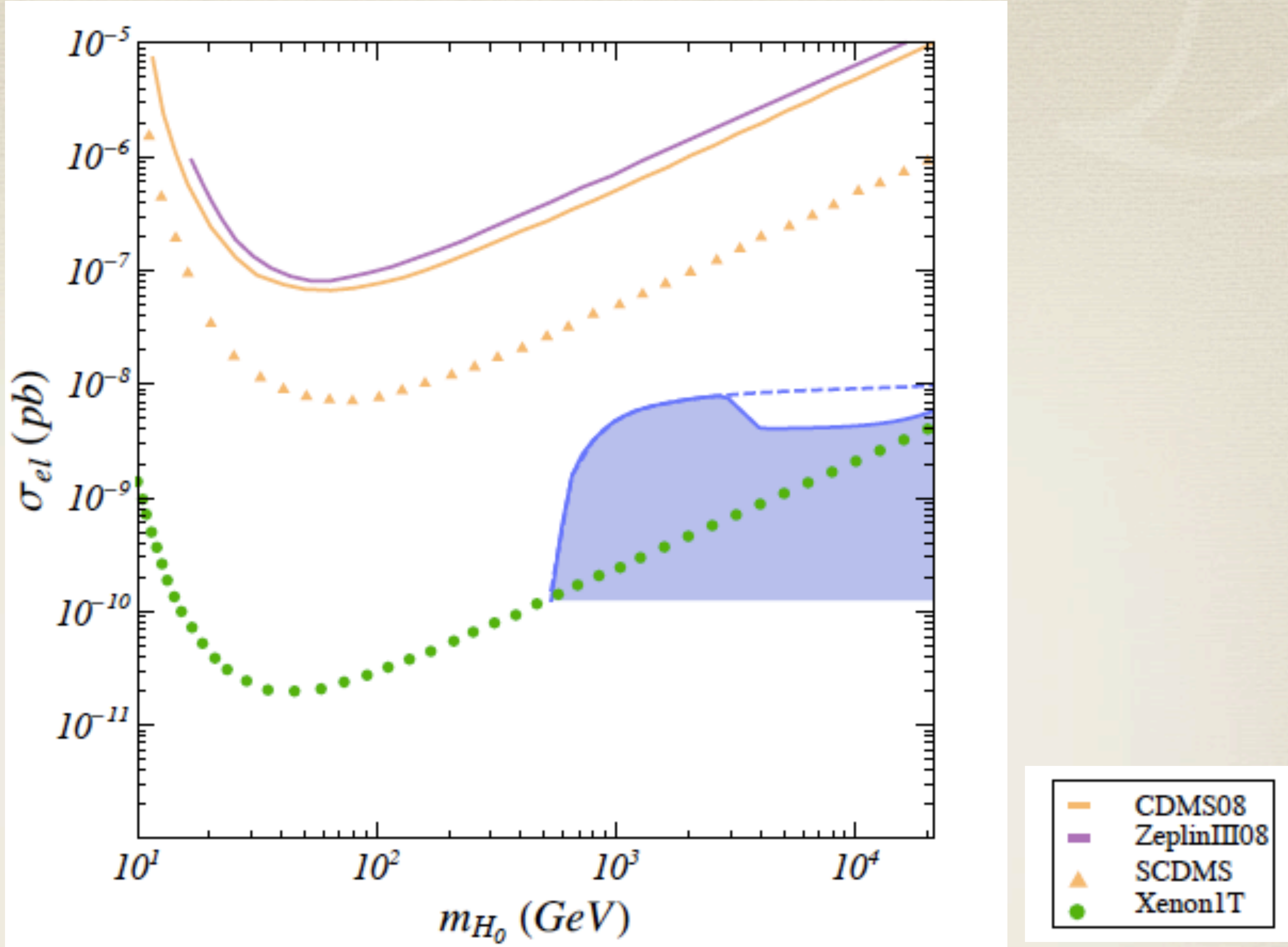
Experimental limit on Z exchange --
$M_{H^0} - M_{A^0} \sim (10^2)$keV

$$\sigma^h_{DM-N} \approx \frac{f_N^2 \lambda^2_{\phi_2^0}}{4\pi} \left(\frac{m_N^2}{m_{DM} m_h^2}\right)^2.$$



$$\sigma_{1-loop} = \frac{9 f_N^2 \pi \alpha_2^4 m_N^4}{64 M_W^2} \left(\frac{1}{M_W^2} + \frac{1}{m_h^2}\right)^2.$$

Independent of DM mass



T.Hambye, el(09)

$\rho_0 = 0.3 GeV/cm^3$ m_h = 120 GeV

Next generation experiment

Conclusions

* The neutrino masses generated through the radiative seesaw mechanism with GIM suppression from singly charged Higgs mixing is presented.
* Anomalous muon magnetic moment is given through the mechanism similar to neutrino masses generation.
* Dark matter candidate is realized in inert doublet scalar, and a direct measurement is possible in next-generation experiments.
* Lithium problem can be solved by a long-lived singly charged scalar S^- to by Catalyzed BBN method.
* DM is produced during the period of BBN.
* TeV-scale leptogenesis utilizing right-handed lepton sector as well as left-handed is presented.
* The model can be tested in near future at collider.