since 1887

Beyond the SM

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Summer Camp on ILC 2019@Itako 04.09.2019

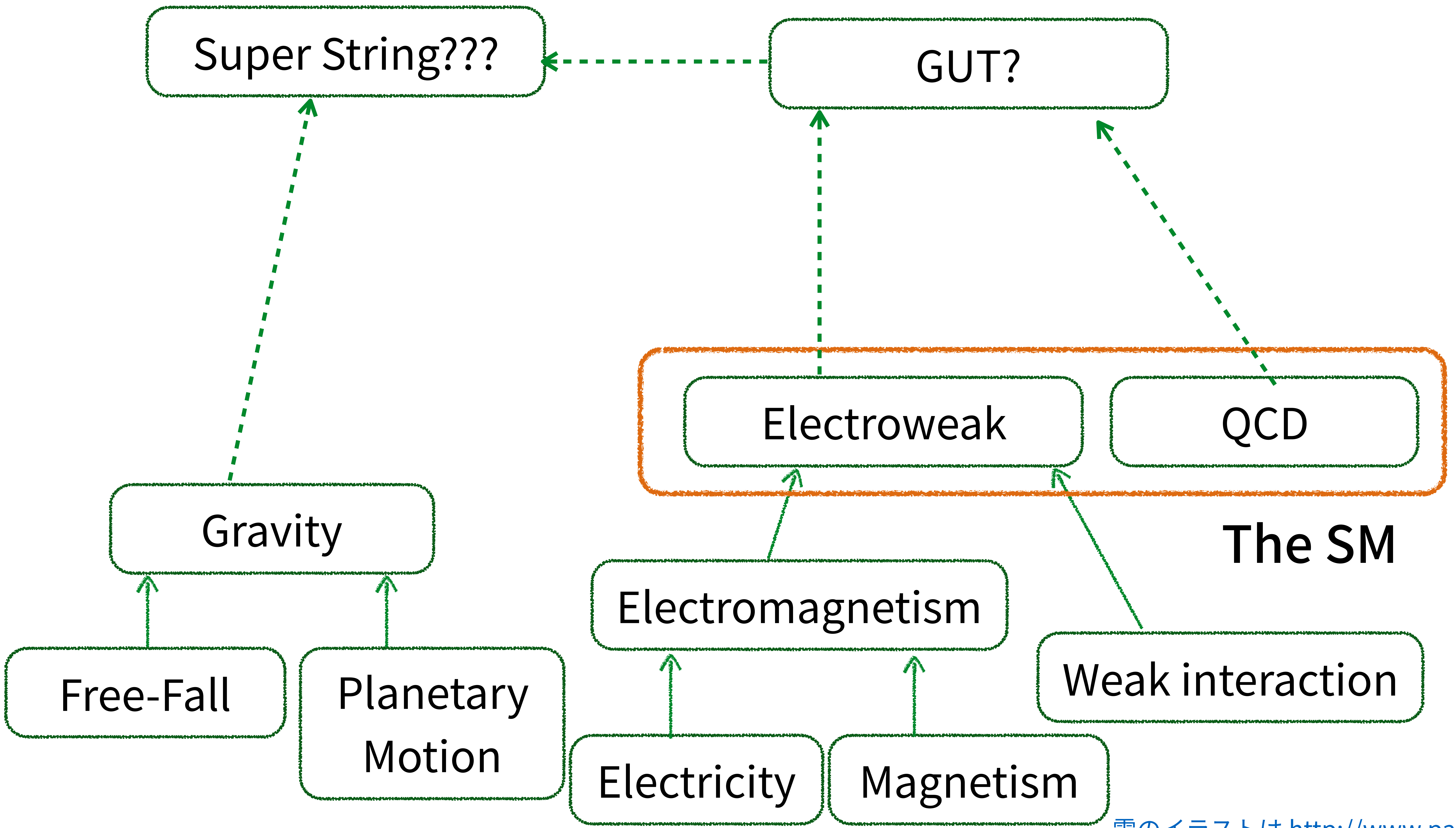
The SM is established

- The SM is quite successful theory of the particle physics
- All the particles are already discovered : The last one is the Higgs boson
- Most of the experimental data are consistent with the SM predictions
- However we still consider that there should be new physics beyond the SM somewhere
  - Unfortunately there is few of hints for the scale of BSM…
- In this talk, we will see some motivations for the BSM

Theoretical Issues

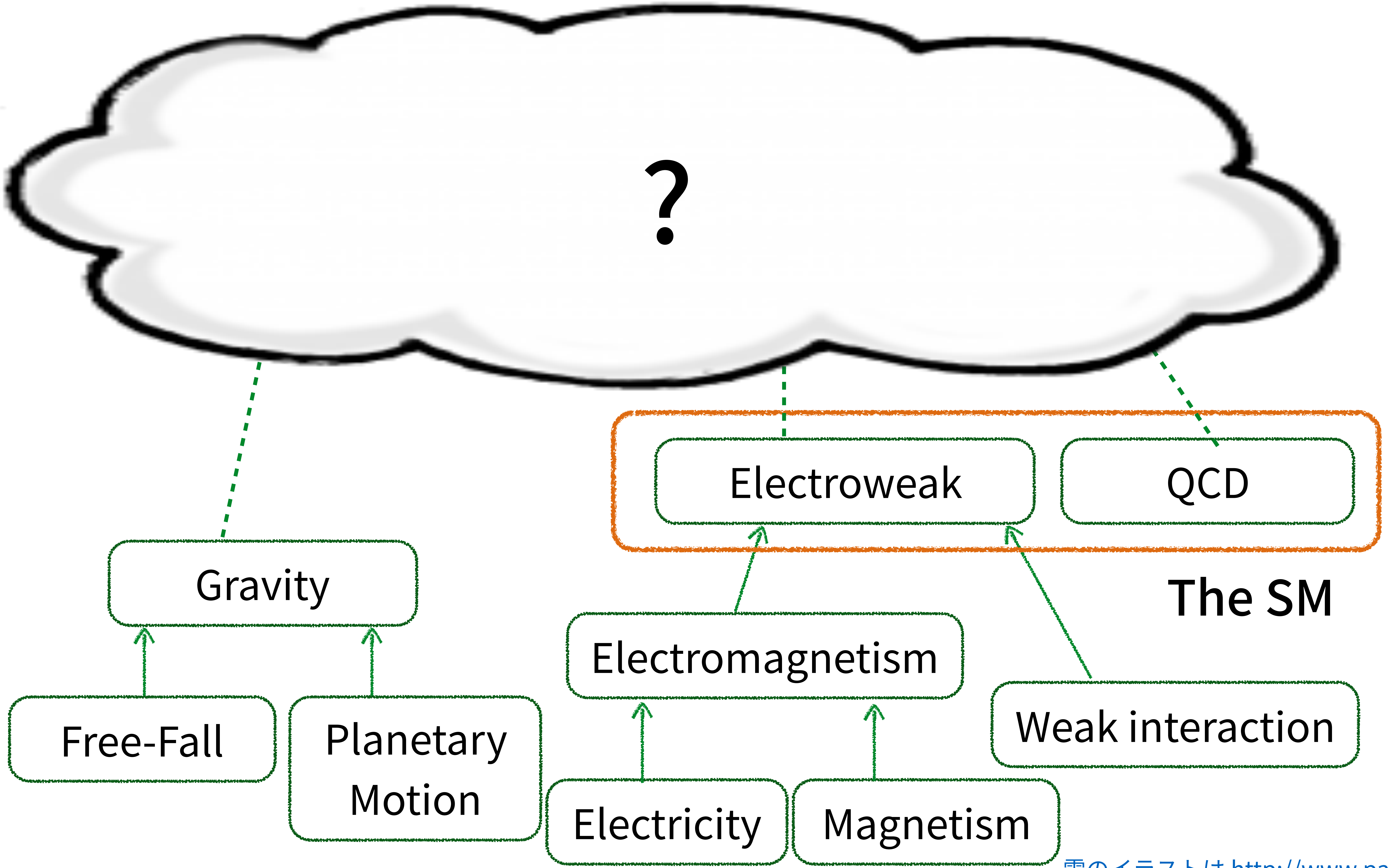
- Grand Unified Theory?
- Gauge Hierarchy problem and scalar mass?
- Origin of generations?
- …

Unification of Interactions



雲のイラストは http://www.pancos-sozai.com/ より

Unification of Interactions



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Desire for Unification

- History of Physics $\simeq$ Unification of Interactions

- A puzzle for charge quantization : $|Q_e + Q_p| < 1 \times 10^{-21} e$

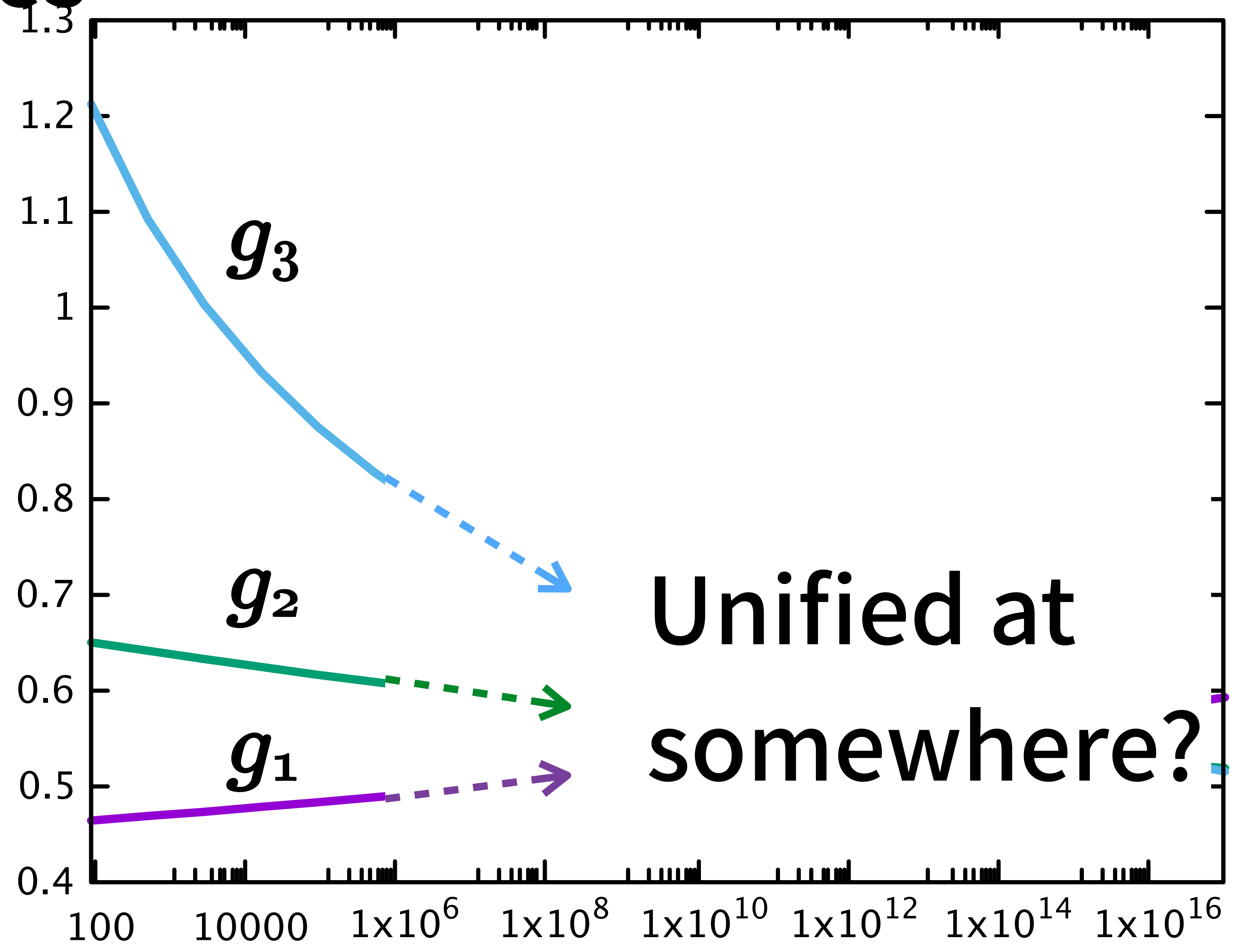
  $\rightarrow$ Unification of matters

- We expect some unification at high energy scales

  - Electroweak + QCD + Gravity

    Grand Unified Theory?

$$g_1 = \sqrt{\frac{5}{3}} g'$$



SU(5) GUT:The simplest realization

- The simplest one is SU(5) GUT

  G_{SM}: rank 4 $\leftrightarrow$ rank 4 simple group: SU(5), O(8), O(9), Sp(8), F_4

Georgi&Glashow,...

q_L can be embedded

- At the GUT scale, the theory predicts $g_3 = g_2 = g_1 (= \sqrt{\frac{5}{3}} g')$

$$\mathrm{SU}(5) \underset{\langle \Sigma_{24} \rangle}{\rightarrow} \mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1) \underset{\langle H_5 \rangle}{\rightarrow} \mathrm{SU}(3) \times \mathrm{U}(1)_{\mathrm{em}}$$

- Unification of matter:

  Quarks and leptons are embedded into $\bar{5}$ and 10 representations

$$\bar{5} = \begin{pmatrix} d_R^c \\ d_R^c \\ d_R^c \\ e_L \\ -\nu_L \end{pmatrix} \qquad 10 = \begin{pmatrix} 0 & u_R^c & -u_R^c & u_L & d_L \\ -u_R^c & 0 & u_R^c & u_L & d_L \\ u_R^c & -u_R^c & 0 & u_L & d_L \\ -u_L & -u_L & -u_L & 0 & e_R^c \\ -d_L & -d_L & -d_L & -e_R^c & 0 \end{pmatrix}$$

Charge quantization is realized.

SU(5) GUT:The simplest realization

The idea of SU(5) GUT is simple and beautiful but …

☆ Doublet triplet splitting: $H_5 = \begin{pmatrix} (H_{5C})^a \\ \boxed{(H_5)^\alpha} \end{pmatrix}$ ← Color triplet ← SU(2) doublet with $Y = \frac{1}{2}$

=

Why the color triplet is very heavy, while doublet Higgs is light?

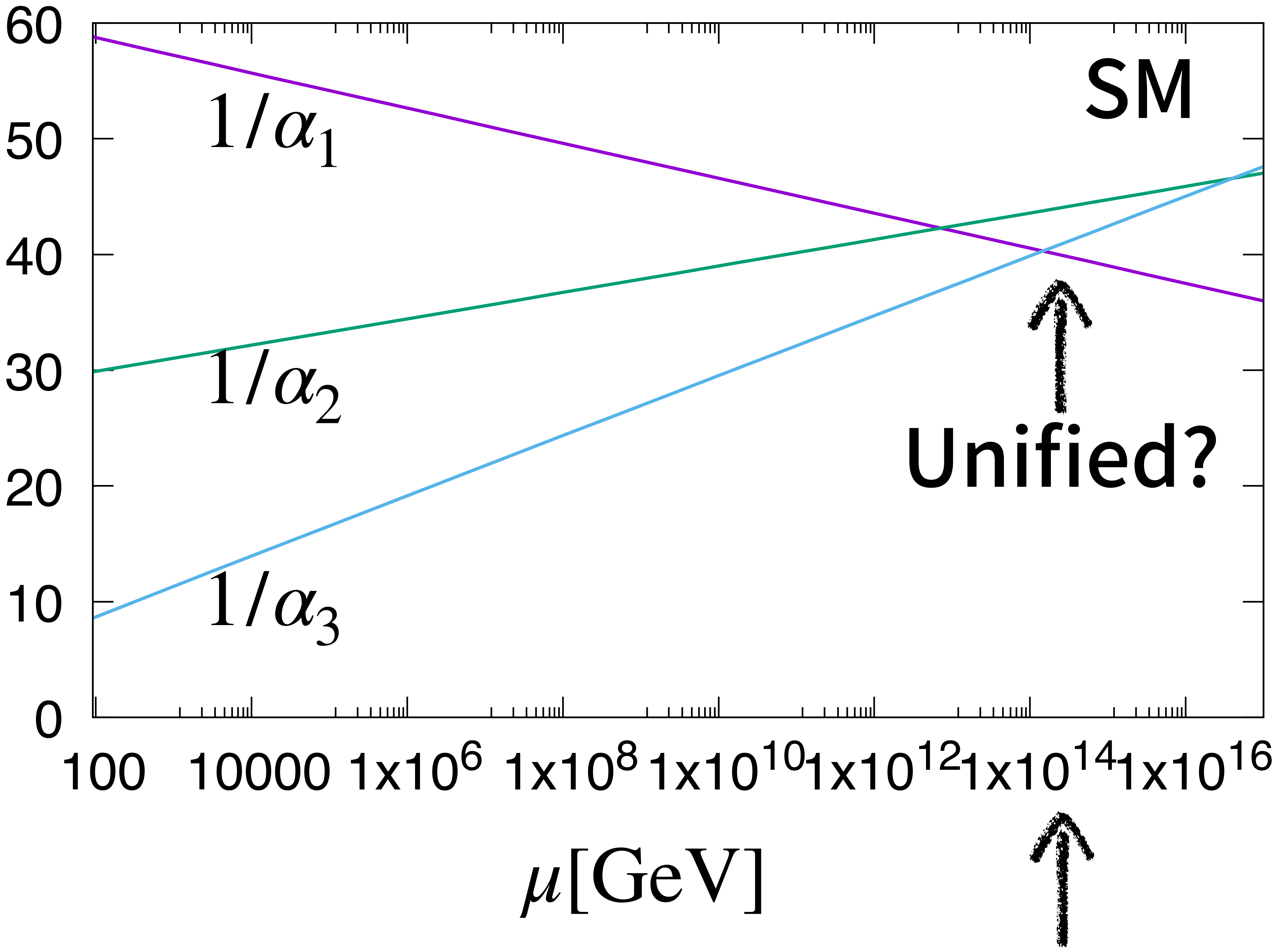
☆ Bad Yukawa relation: $Y_d^T = Y_E = Y_5$

☆ Gauge coupling unification may fail

☆ Unification scale ~ 10^{15}GeV → Too fast proton decay

SU(5) GUT:The simplest realization

Let’s approach some of these problems.

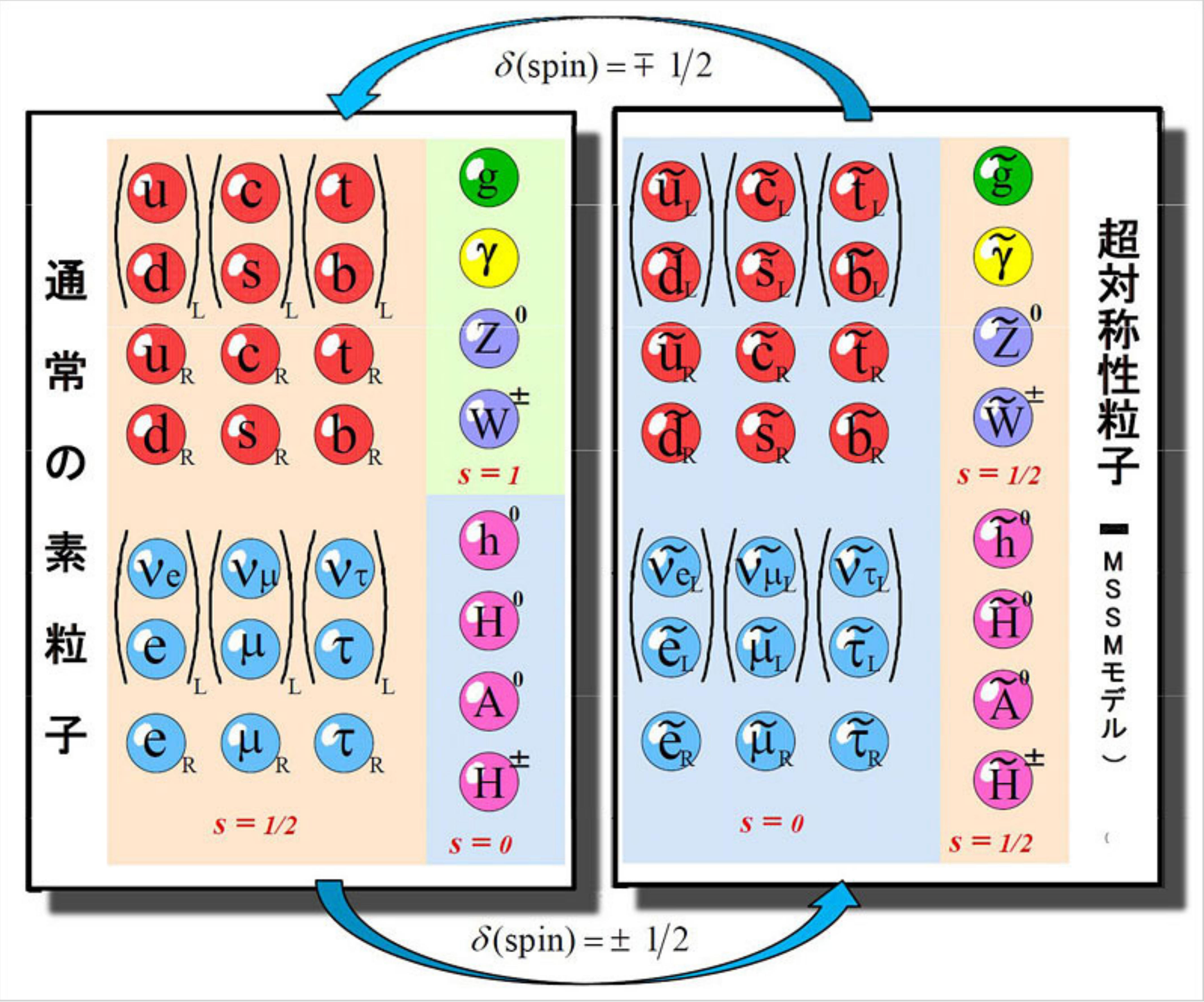


The unification will be restored by adding new particles in the low energy scale

The scale is 10^{12}-10^{15} GeV

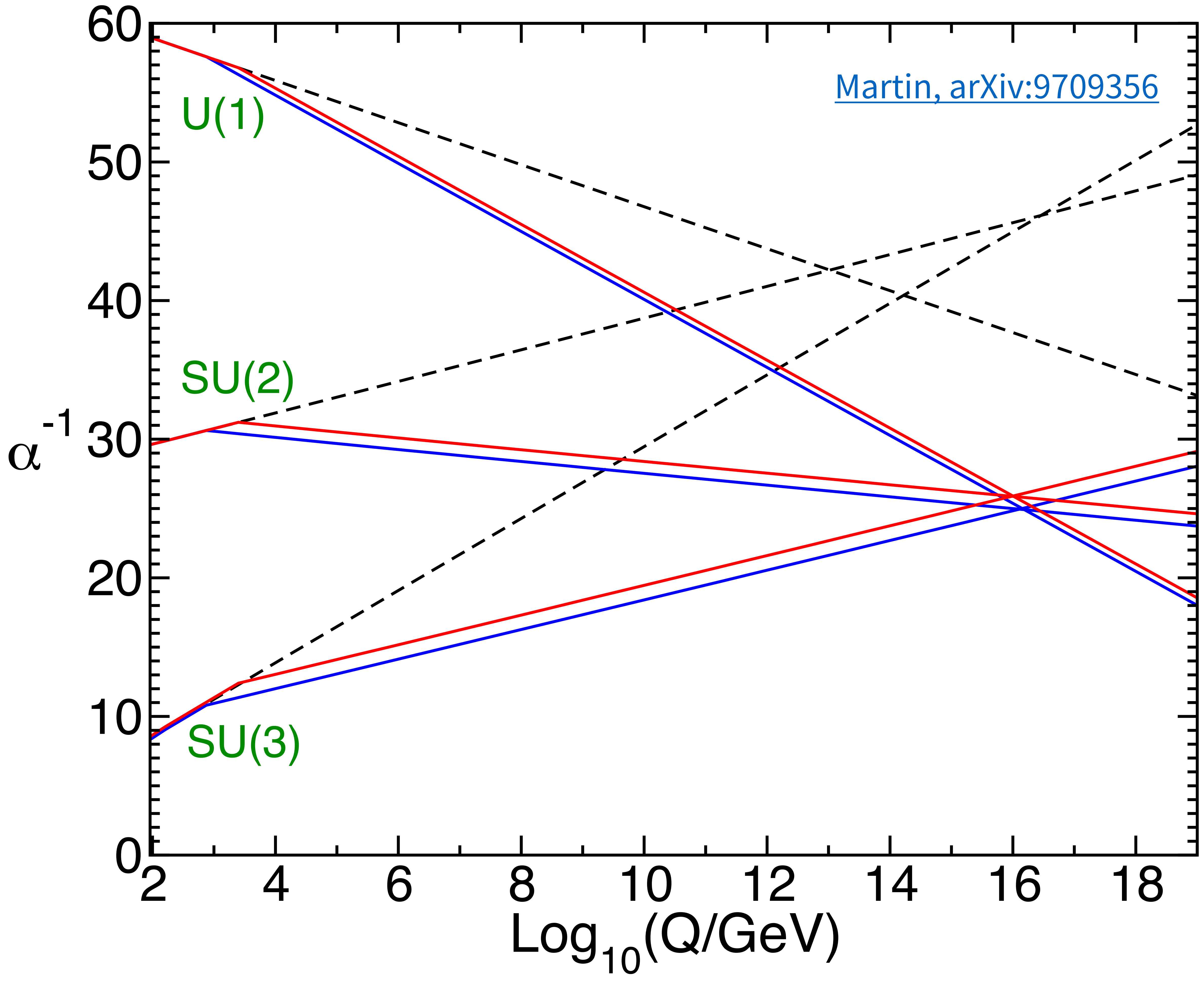
Minimal SUSY SM

- SUSY: Boson ↔Fermion
- Many new particles (super partners)
- Quadratic divergence in scalar sector cancels (later)
- If R-parity is conserved, a DM candidate is provided
- But no super partners are found …



[https://natgeo.nikkeibp.co.jp/ (KEK)](https://natgeo.nikkeibp.co.jp/)

SUSY SU(5) GUT



m_S=750GeV and 2.5TeV

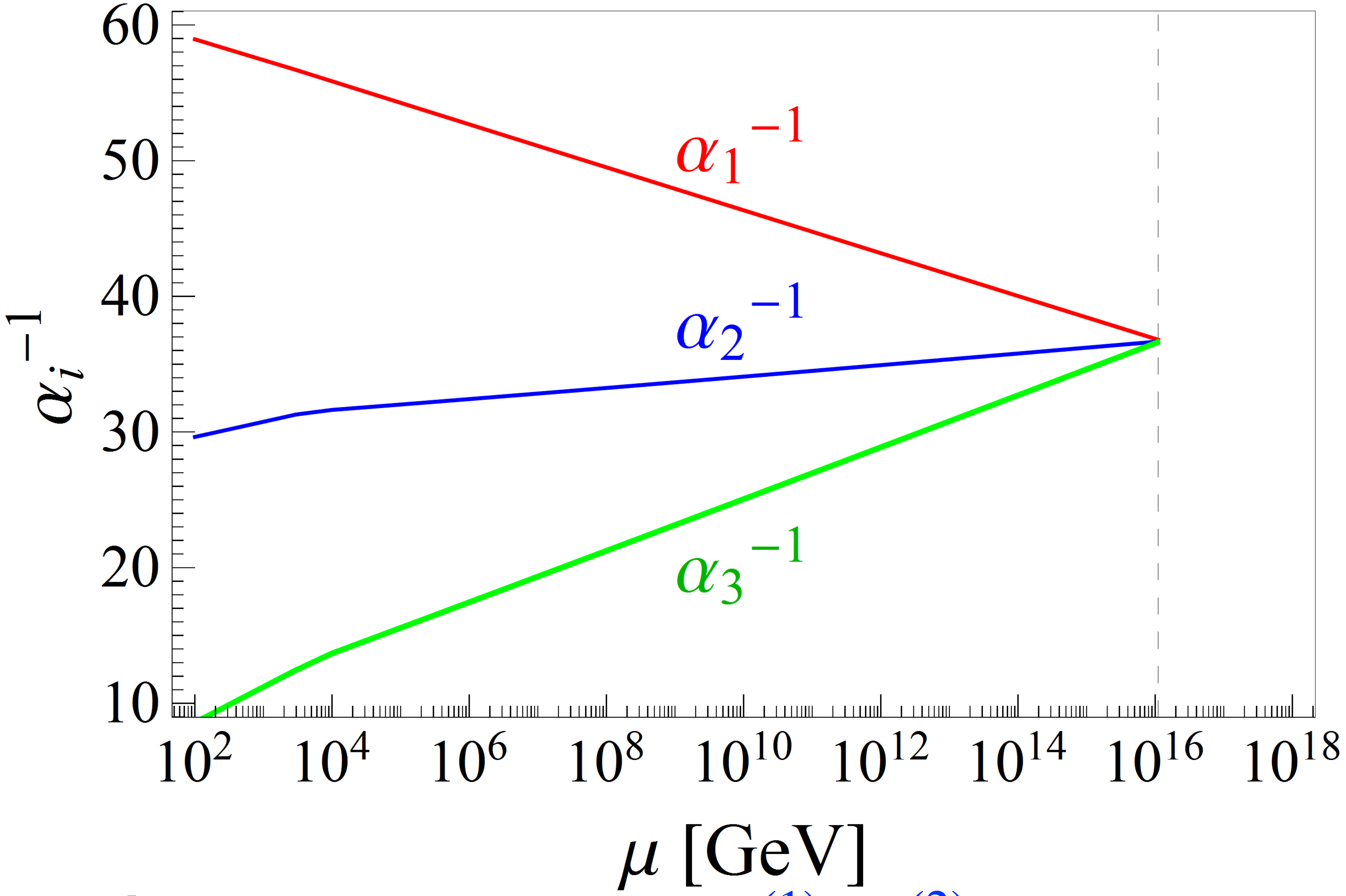
- With additional particles, the coefficients b_i increase:

$$\frac{dg_i}{d\log\mu} = \frac{b_i}{(4\pi)^2} g_i^3 + \cdots$$

- In order to make GUT scale high enough, additional colored particle is necessary
  - In SUSY, gluino contribution is important!

Alternative Scenarios

Cox, Kusenko, Sumensari, Yanagida, JHEP1703, 035

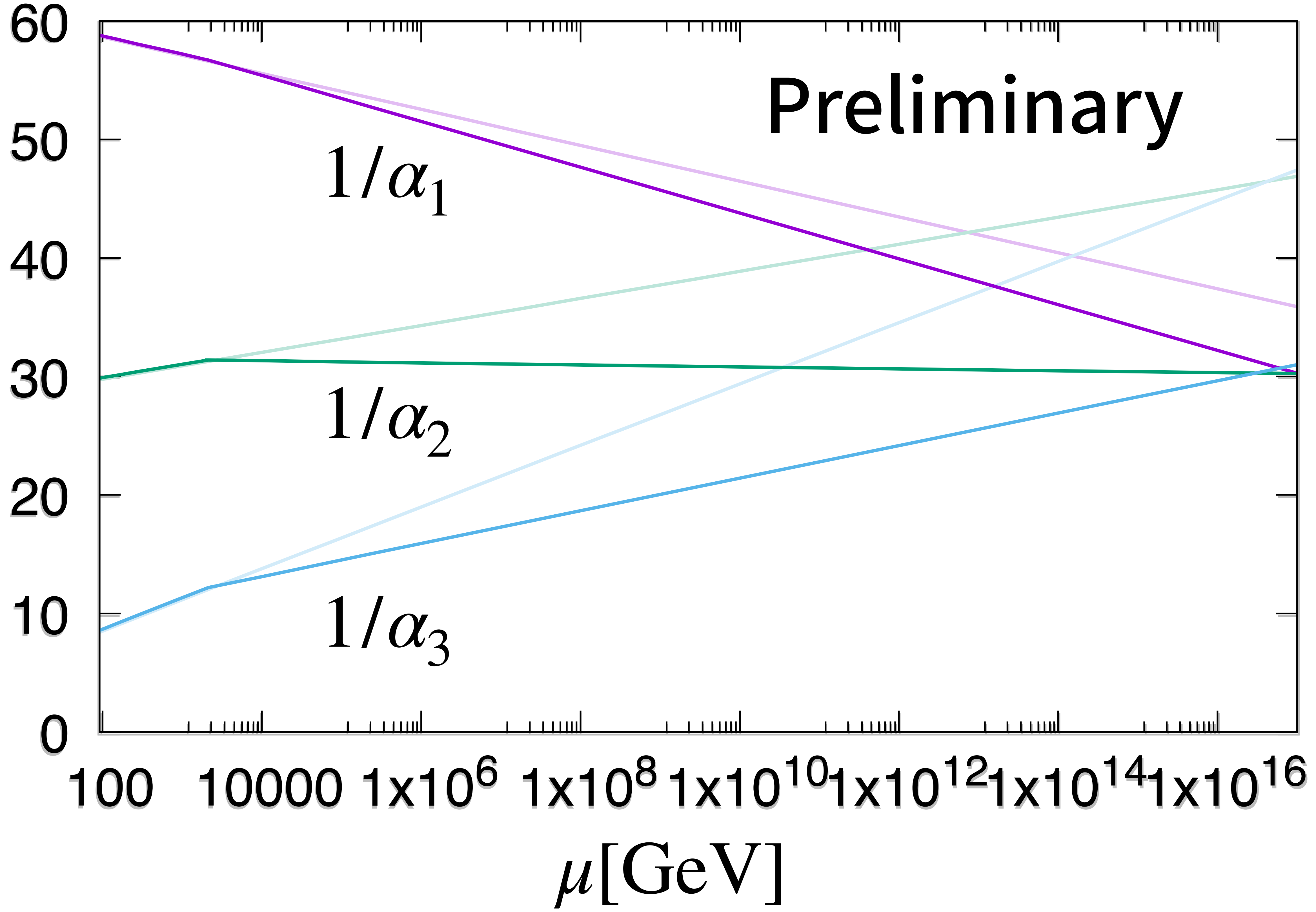


Scalar sector: $H_5, H_{\bar{5}}, H_{10}^{(1)}, H_{10}^{(2)}, \Sigma_{24}$

2(1,2,1/2) + 2(3,2,1/6)+(8,1,0)+(1,3,0)

$m_H = m_{\Delta_{1,2}} = 3$TeV, $m_{38} = 10$TeV

Goto, Mishima, T.S., work in progress



Scalar sector: H_5, H_{45}, Σ_{24} w/o $\Psi_{10}\Psi_{10}H_{45}$

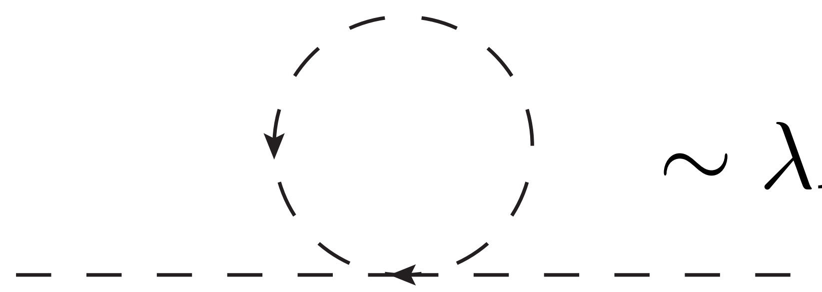
(1,2,1/2) + (3,3,-1/3)+(6,1,1/3)+(8,2,1/2)

$m_{S_3} = 2$TeV, $m_{6,8} = 8$TeV

Gauge Hierarchy Problem

It strongly suggests BSM physics at around TeV scale!

- No symmetry can prohibit the scalar mass term
  - ~~Fermion mass~~ Chiral symmetry
  - ~~Vector boson mass~~ Gauge symmetry
- Naive mass scale can be a typical scale of the theory
  - Planc? GUT? Much much larger than electroweak scale!
- Quadratic divergence from loop contributions



$\sim \lambda\Lambda^2$

Attempts to gauge hierarchy problem

- How to approximately forbid scalar mass term?
- How to avoid quadratic divergence via radiative correction

☆ SUSY

- ☆ Quadratic divergence cancels between scalar loop and fermion loop
- ☆ Higgs mass comes from $W \ni \mu H_1 \cdot H_2$ & SUSY breaking $\rightarrow \mu$-problem

☆ Higgs as a pseudo Nambu-Goldstone boson

☆ Gauge Higgs Unification

- ☆ Higgs boson = extra component of gauge field in extra dimension

LHC gives a stringent bound on all these scenarios…

Three Generations?

- We don't know why there are three generation fermions
  - Only the difference is their mass!
- In the SM, fermion mass is generated via Yukawa interactions!
  - What is the origin of Yukawa interactions?
    e.g. $Y_U^{ij}\bar{u}_{Ri}\tilde{\Phi}q_{Lj} \to M_U^{ij}\bar{u}_{Ri}u_{Li}$
  - Why the interactions are different?
    while the quantum charges are the same.

There is no good explanation of it in the SM.

Higgs Sector?

- The gauge sector of the SM is very beautiful
  - Gauge principle controls everything
  - There are only three parameters
- The Higgs sector is not.
  - There seems to be no principle to control the Higgs sector.
  - Negative mass squared? Complexity of Yukawa interactions, …

Is there some principle to control the Higgs sector? If yes, what is it?

Phenomenological Motivations

There are some phenomena which the SM does not explain

- Neutrino oscillation
- Existence of the DM
- Baryon asymmetry of the Universe

Relevant to Cosmology

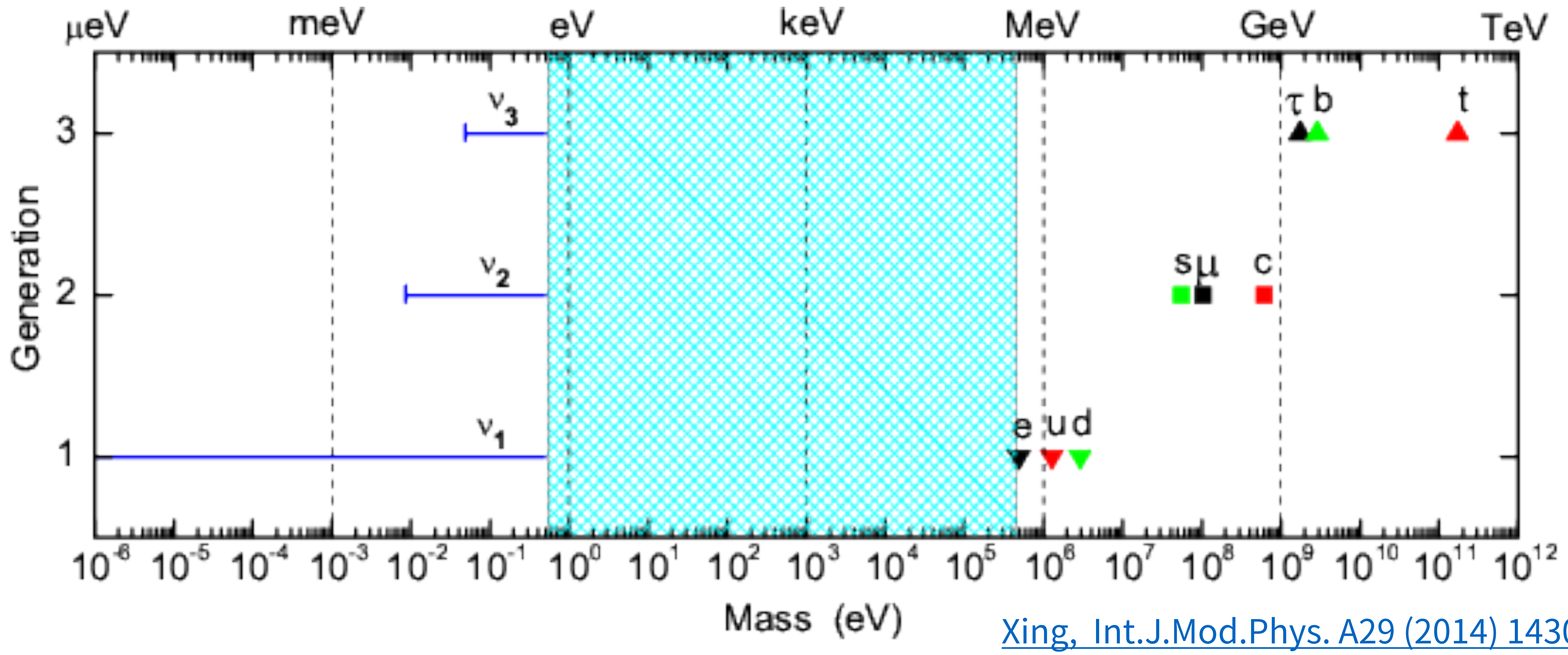
- Muon g-2 ?
- Lepton non-universality ?

Excess?

- …

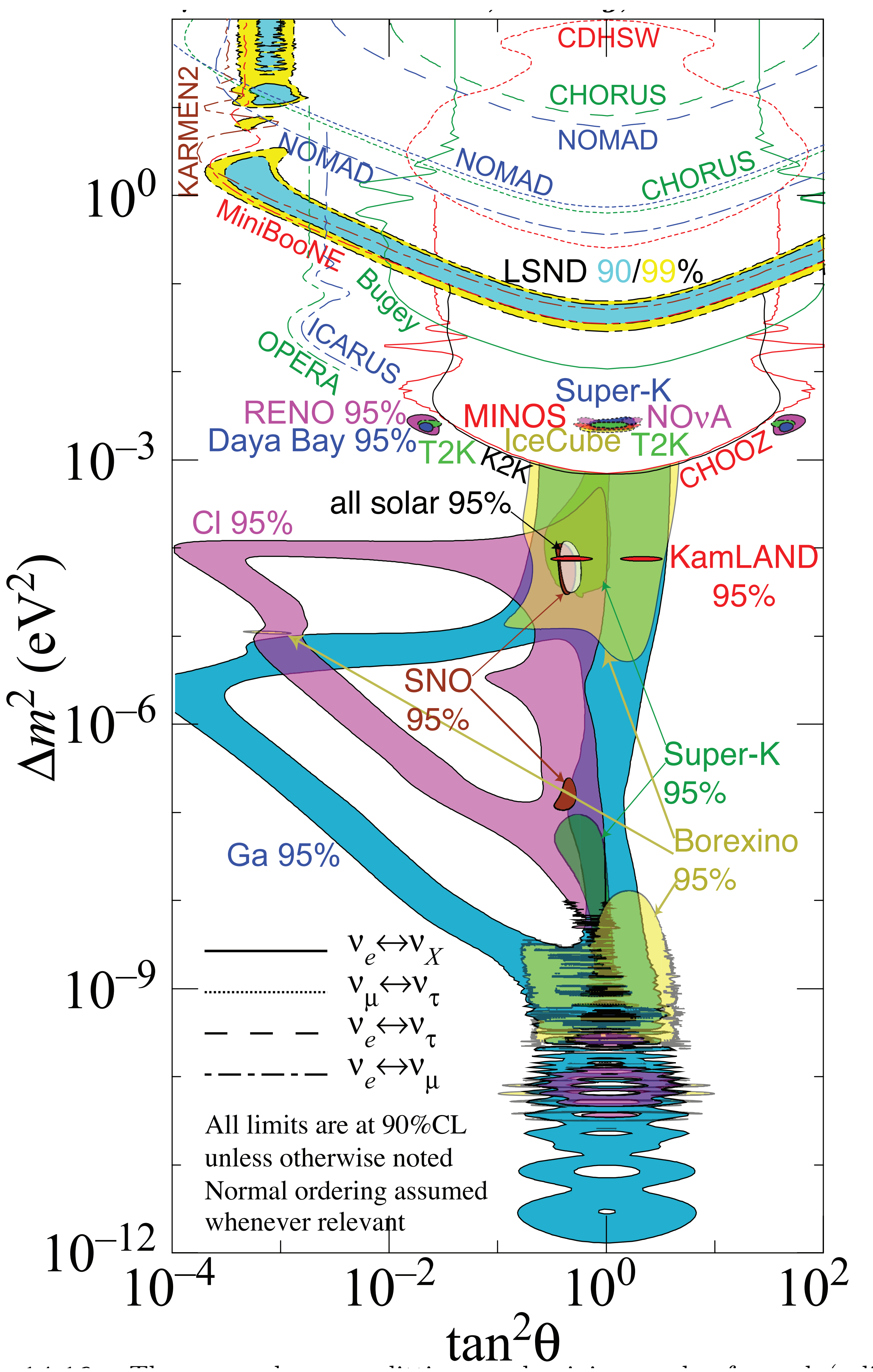
Neutrino Oscillation

- Neutrino oscillation → Mass differences
- Tritium beta decay experiment → $m_\nu < 2$ eV
- Neutrinos are not massless but have TINY mass



Xing, Int.J.Mod.Phys. A29 (2014) 1430067

PDG2018



Tiny neutrino mass

- In the SM, the neutrinos are massless
  - We need to consider the origin of neutrino masses
- Two possible type of neutrino mass $\leftarrow$ Neutrinos have no em charge

TINY Yukawa

  - Dirac neutrino: $\mathscr{L}_m = m_\nu \bar{\nu}_R \nu_L \longleftarrow \mathscr{L}_y = y_\nu \bar{\nu}_R \Phi \ell_L$

Right-handed neutrino is introduced

  - Majorana neutrino: $\mathscr{L}_m = m_\nu \bar{\nu}_L^c \nu_L \longleftarrow \mathscr{L}_\nu = \frac{c}{M} (\bar{\ell}_L^c \Phi)(\ell_L \Phi)$

Dimension five operator is introduced

Tiny neutrino masses

Natural suppression for Majorana mass

$$\frac{c_{ij}}{M}(\bar{\ell}^c_L\Phi)(\ell_L\Phi)$$

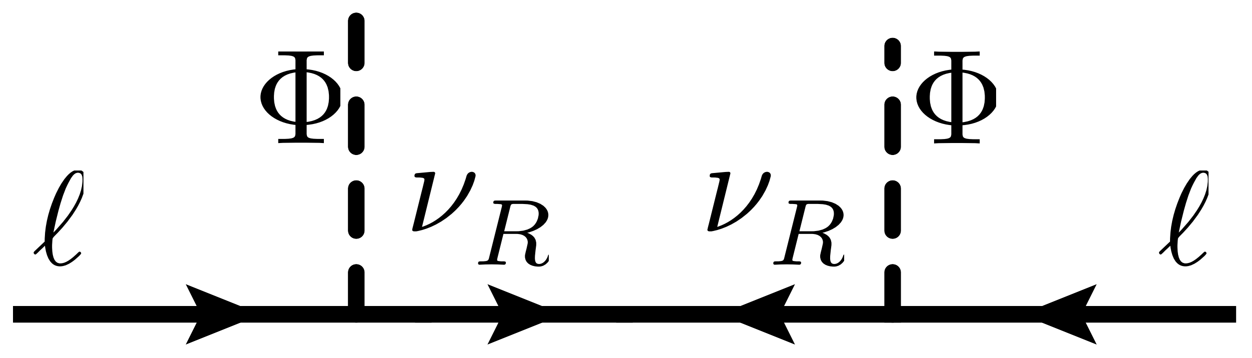
For tiny neutrino mass,
- Large M

  or

- Small c_{ij}

is necessary

Seesaw model (SM+RN) $\quad \dfrac{c_{ij}}{M} = (y_N^T M^{-1} y_N)_{ij}^{\ell}$



Heavy RN mass M gives strong suppression

$c_{ij} \sim 0.01^2$ & $M \sim 10^{10}$ GeV $\longrightarrow$ $m_\nu \sim 0.1$ eV

Loop induced case

n-loop contribution: $c_{ij} = \mathcal{O}\left(\dfrac{f^{2n}}{(16\pi^2)^n}\right)$

$f \sim 0.01$ & $M \sim 1$ TeV & $n = 2$ $\longrightarrow$ $m_\nu \sim 0.1$ eV

Testable at Collider!

Examples of Radiative models

with Right-handed neutrinos

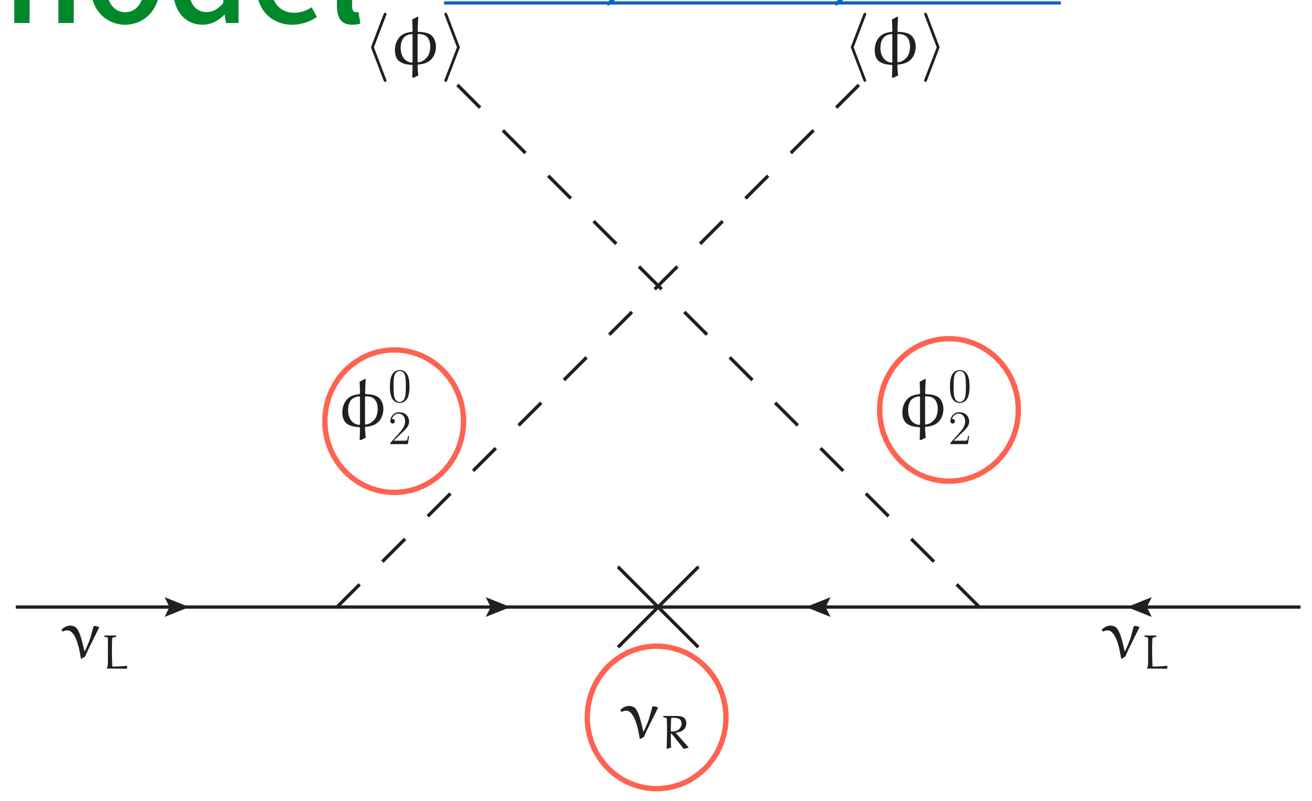
Z_2-parity is introduced to forbid tree contributions

The lightest Z_2-odd particle is stable

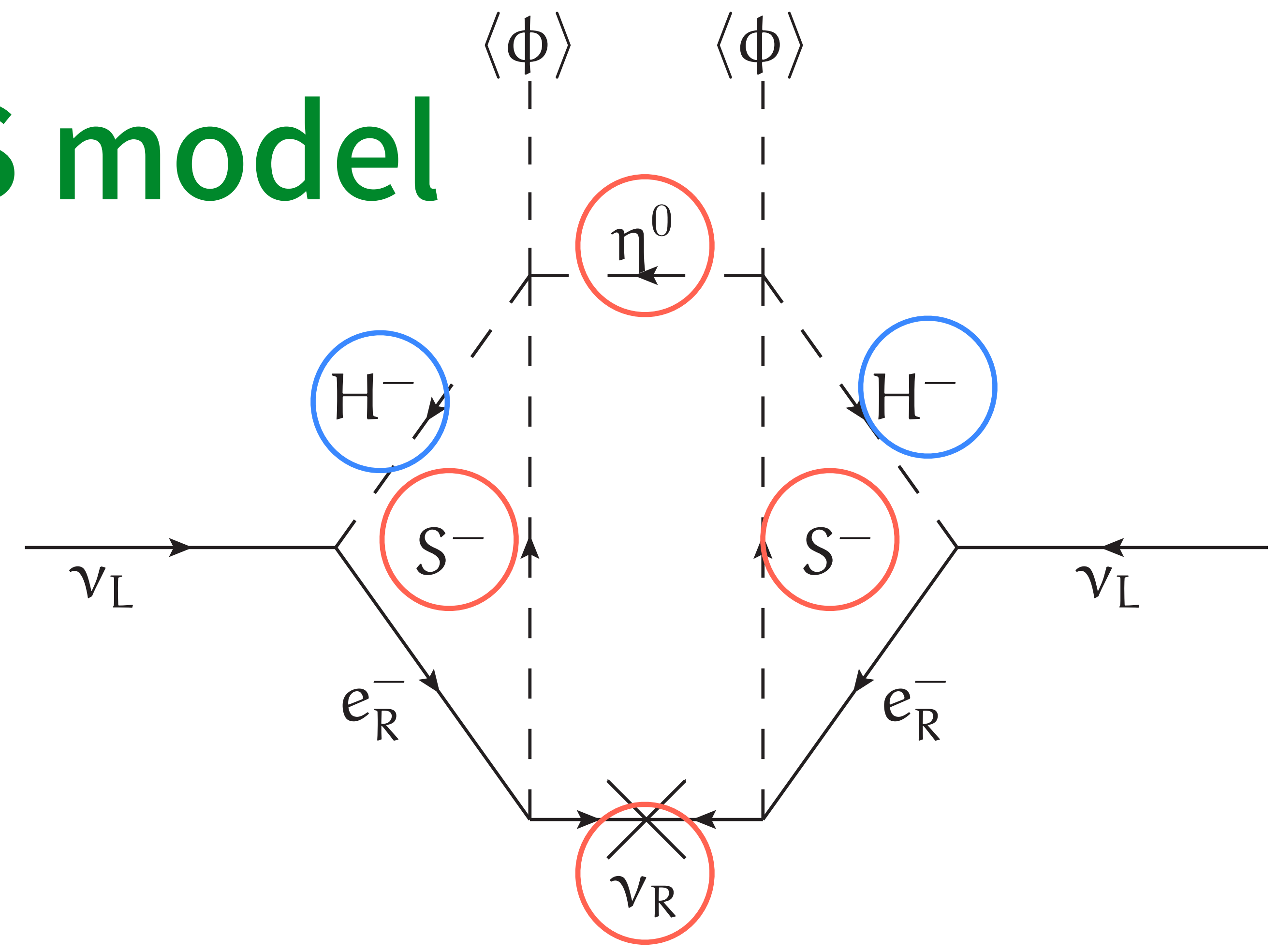
Candidate of DM

Ma model

E. Ma, PRD73,077301

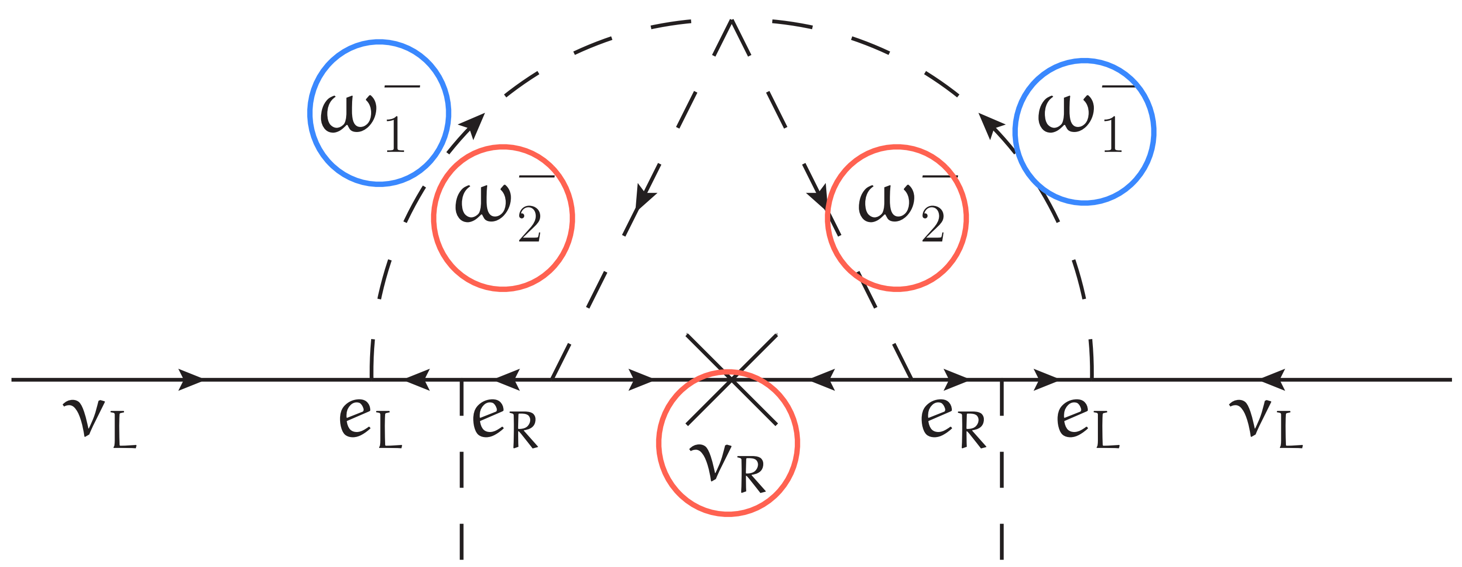


AKS model



M.Aoki, S. Kanemura, O. Seto, PRL102,051805

KNT model



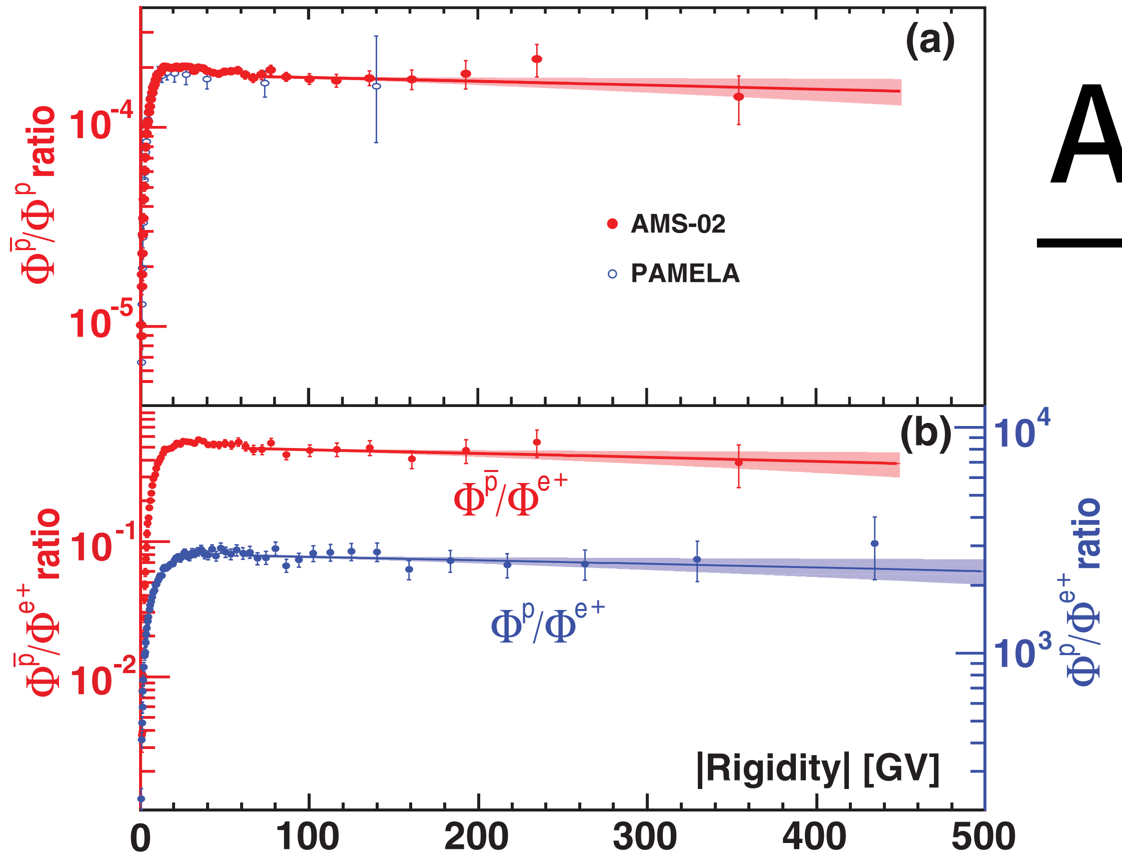
L.M.Krauss,S.Nasri,M.Trodden, PRD67,085002

Additional scalars are introduced!

Baryogenesis

We mainly observe matter (not antimatter)

- ☆ Earth, Sun, Solar system, …
- ☆ Cosmic ray from our galaxy

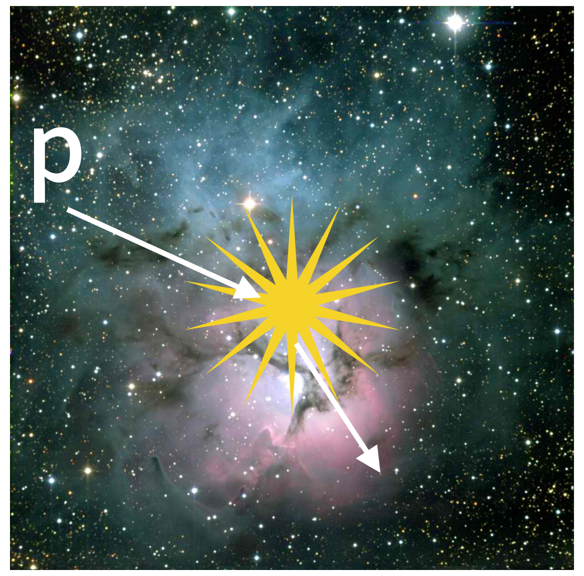


AMS(2016)

$$\frac{\text{Anti-Proton}}{\text{Proton}} \sim 10^{-4} \longrightarrow$$

Consistent with secondary production

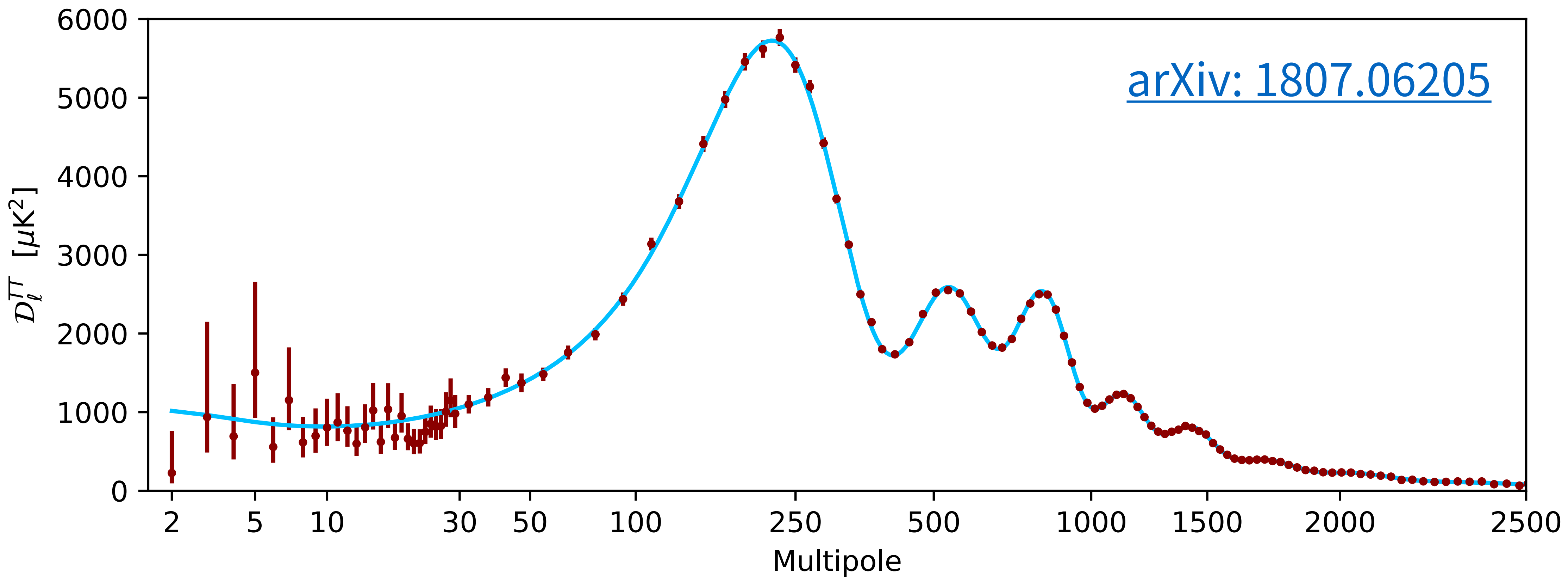
$$p + p \to p + p + p + p + \bar{p}$$



ISM

Baryogenesis

CMB also tells us that our Universe is Baryonic



Temperature fluctuations

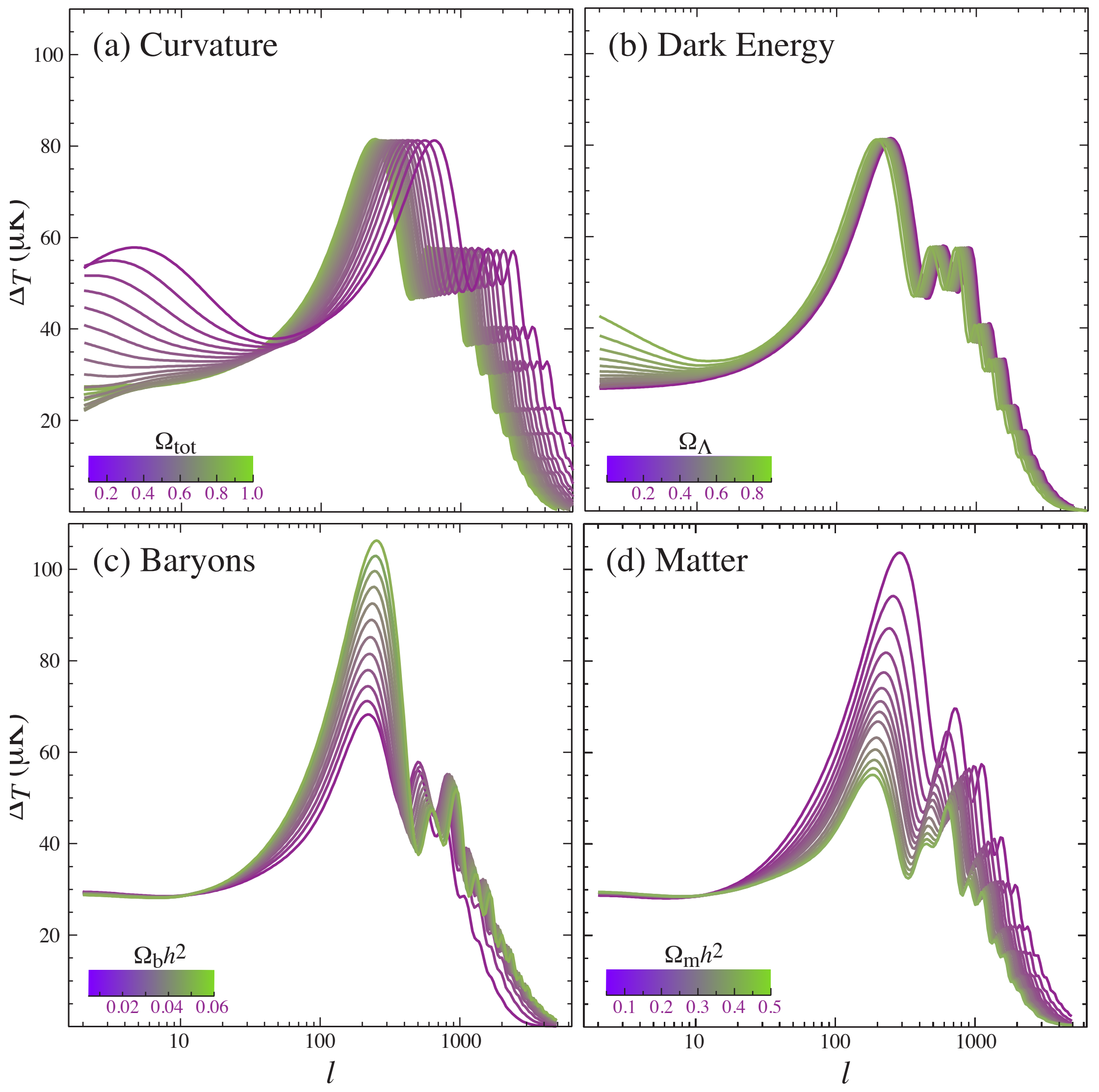
↓

$$\text{Correlation} \left\langle \frac{\delta T(x)}{T} \frac{\delta T(y)}{T} \right\rangle$$

↓ Fourier trf

$$D_\ell^{TT} = \frac{\ell(\ell+1)C_\ell}{2\pi}$$

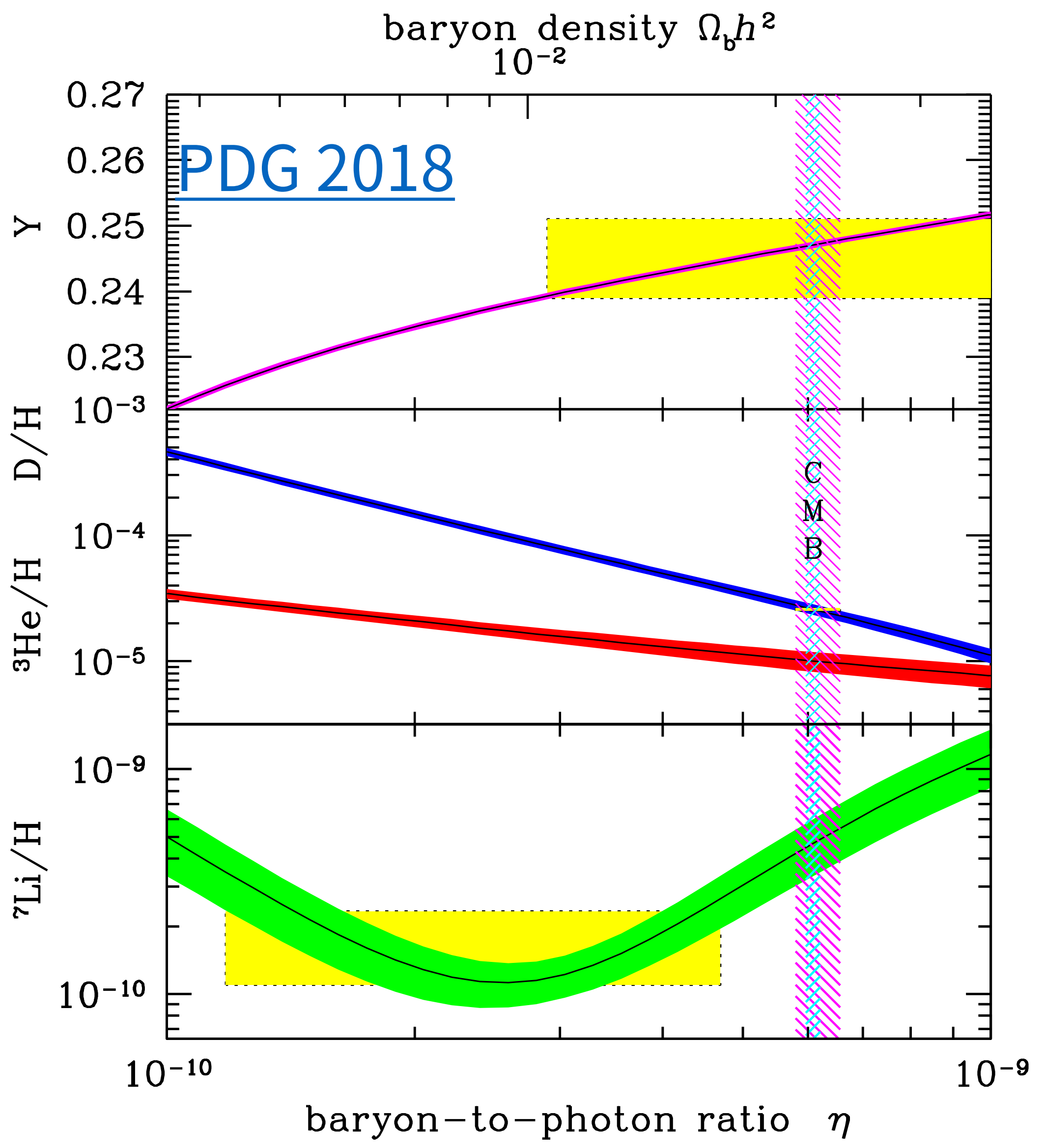
It depends on cosmological parameters



$$\Omega_B h^2 = 0.0224 \pm 0.0001$$

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 6.14 \times 10^{-10}$$

Consistent with BBN



W. Hu and S. Dodelson, astro-ph/0110414

Baryogenesis

$$\boxed{\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 6.14 \times 10^{-10}}$$

The observations (CMB, BBN) strongly suggest baryon asymmetric Universe

Baryogenesis

How can we produce the appropriate amount of asymmetry in baryon symmetric Universe?

One comment: In inflation scenario, primordial baryon number is diluted by reheating of Universe

Baryogenesis should occur after inflation!

Baryogenesis

In order to produce BAU, the following three conditions should be satisfied.

Sakharov's conditions

- ☆ Baryon number is violated
- ☆ Both C and CP are violated
- ☆ There is an interaction outside of thermal equilibrium

Note that they are not sufficient conditions but necessary conditions

Baryogenesis

The conditions might be satisfied in the framework of the SM

Sakharov's conditions

☆ Baryon number is violated	⟶	Sphaleron
☆ Both C and CP are violated	⟶	Kobayashi-Maskawa phase
☆ There is an interaction outside of thermal equilibrium	⟶	1st order PT

Sphaleron: Non-perturbative saddle point solution @ high temperature

- B+L number is violated (in Left-handed Q&L), while B-L is conserved
- The process is relevant when T=100 GeV-10^{12} GeV

Baryogenesis

But, it is known that the mechanism cannot work in the SM

Sakharov's conditions

- ☆ Baryon number is violated ⟶ Sphaleron
- ☆ Both C and CP are violated ⟶ Kobayashi-Maskawa phase
- ☆ There is an interaction outside of thermal equilibrium ⟶ 1st order PT

- The electroweak phase transition is NOT 1st order for m_h=125GeV
- Even if EWPT were 1st order, KM phase (J_{CP}) is too small to produce enough Baryon asymmetry.

New physics is necessary!!!

Scenarios of Baryogenesis

Very many scenarios are considered in literatures

Shaposhnikov, J.Phys.Conf.Ser.171:012005,2009.

1. GUT baryogenesis. 2. GUT baryogenesis after preheating. 3. Baryogenesis from primordial black holes. 4. String scale baryogenesis. 5. Affleck-Dine (AD) baryogenesis. 6. Hybridized AD baryogenesis. 7. No-scale AD baryogenesis. 8. Single field baryogenesis. 9. Electroweak (EW) baryogenesis. 10. Local EW baryogenesis. 11. Non-local EW baryogenesis. 12. EW baryogenesis at preheating. 13. SUSY EW baryogenesis. 14. String mediated EW baryogenesis. 15. Baryogenesis via leptogenesis. 16. Inflationary baryogenesis. 17. Resonant leptogenesis. 18. Spontaneous baryogenesis. 19. Coherent baryogenesis. 20. Gravitational baryogenesis. 21. Defect mediated baryogenesis. 22. Baryogenesis from long cosmic strings. 23. Baryogenesis from short cosmic strings. 24. Baryogenesis from collapsing loops. 25. Baryogenesis through collapse of vortons. 26. Baryogenesis through axion domain walls. 27. Baryogenesis through QCD domain walls. 28. Baryogenesis through unstable domain walls. 29. Baryogenesis from classical force. 30. Baryogenesis from electrogenesis. 31. B-ball baryogenesis. 32. Baryogenesis from CPT breaking. 33. Baryogenesis through quantum gravity. 34. Baryogenesis via neutrino oscillations. 35. Monopole baryogenesis. 36. Axino induced baryogenesis. 37. Gravitino induced baryogenesis. 38. Radion induced baryogenesis. 39. Baryogenesis in large extra dimensions. 40. Baryogenesis by brane collision. 41. Baryogenesis via density fluctuations. 42. Baryogenesis from hadronic jets. 43. Thermal leptogenesis. 44. Nonthermal leptogenesis.

Now even more…

Baryogenesis

There are two possible cases of Baryogenesis

1. B is produced by the 1st order electroweak phase transition just before the sphaleron decoupling.

2. B-L is produced before the sphaleron decoupling era.

Typical example of 1 is electroweak baryogenesis, and that of 2 is leptogenesis

For Electroweak Baryogenesis

Strong 1st order EWPT requires extension of the SM

Extra boson loop can contribute

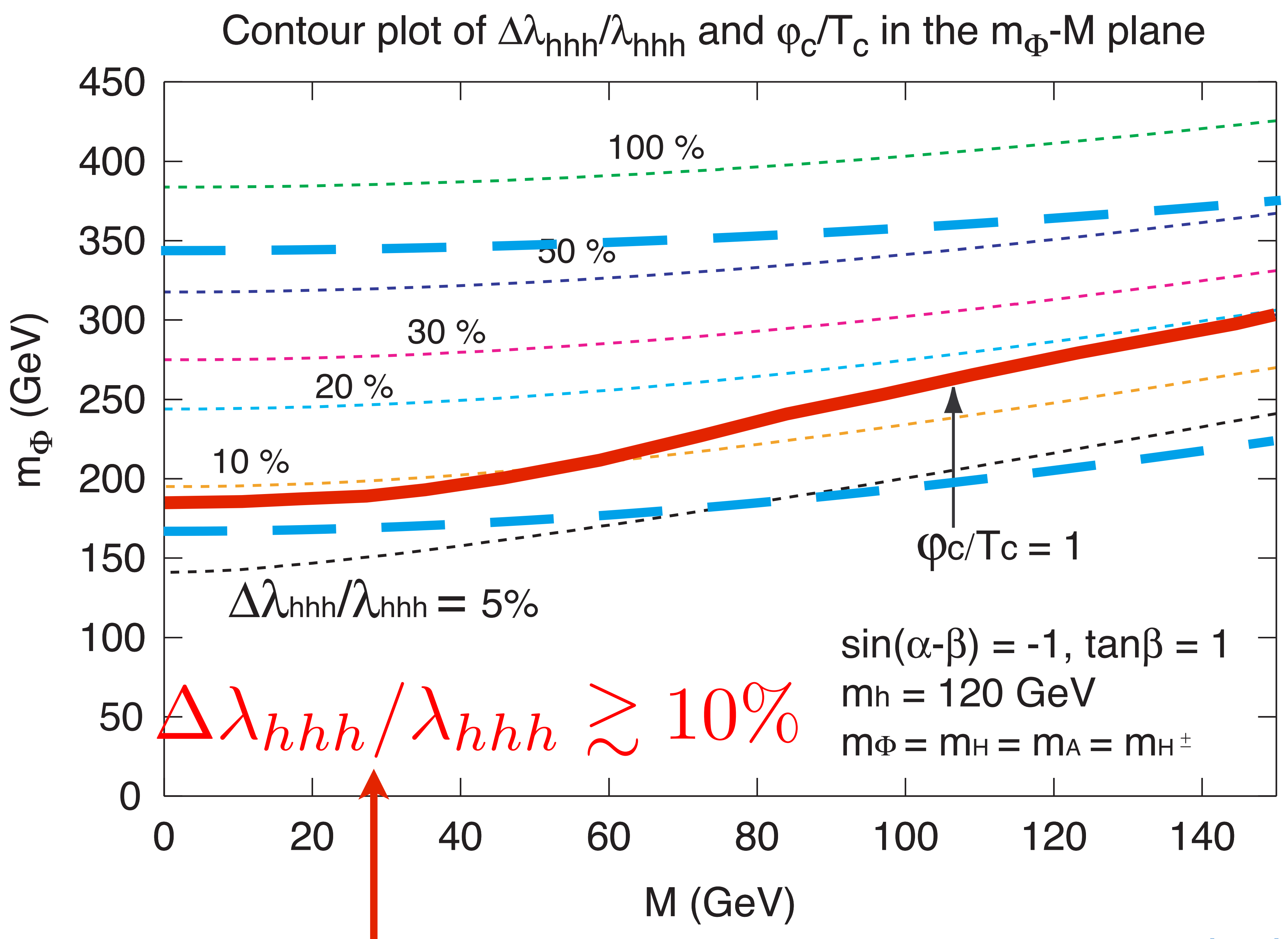
↓

Extended Higgs sector!

e.g. 2HDM

$$\mathcal{L} = \frac{\lambda_i}{2} h^2 |\Phi_i|^2$$

$$m_\Phi^2(\varphi) = M^2 + \lambda_i \varphi^2$$



Kanemura, Okada, Senaha,PLB606,361

Extra Higgs bosons as H,A $H^\pm$ Testable@Collider exp.

In an extended Higgs sector, new CP phases can be introduced

↕

EDM

Thermal Leptogenesis

M. Fukugida&T. Yanagida, PLB174,45;
W. Buchmüller, P. Di Bari, and M. Plümacher, Annals. Phys. 315,305;
G. F. Giudice et al, NPB685,89 ....

#L is produced by heavy right-handed neutrino decay

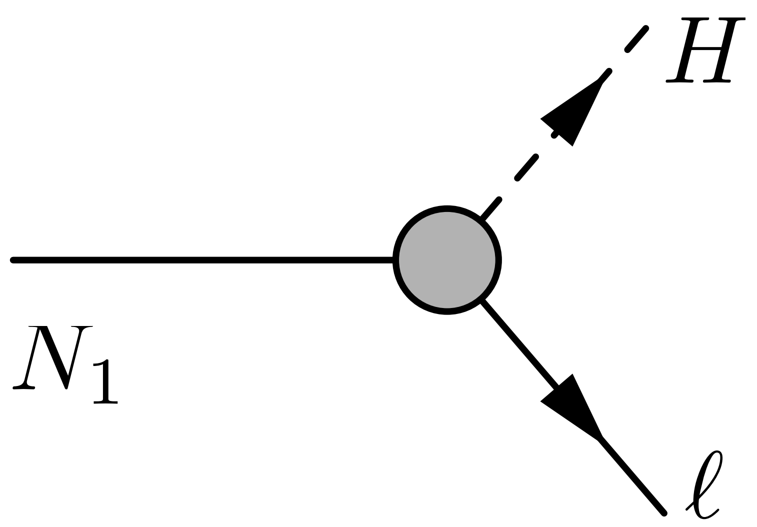
↓

Converted to #B via sphaleron

- ☆ Baryon number is violated → Sphaleron
- ☆ Both C and CP are violated → CP violating RN decay
- ☆ There is an interaction outside of thermal equilibrium → Decoupling of RN decay

Thermal Leptogenesis

CP-violation



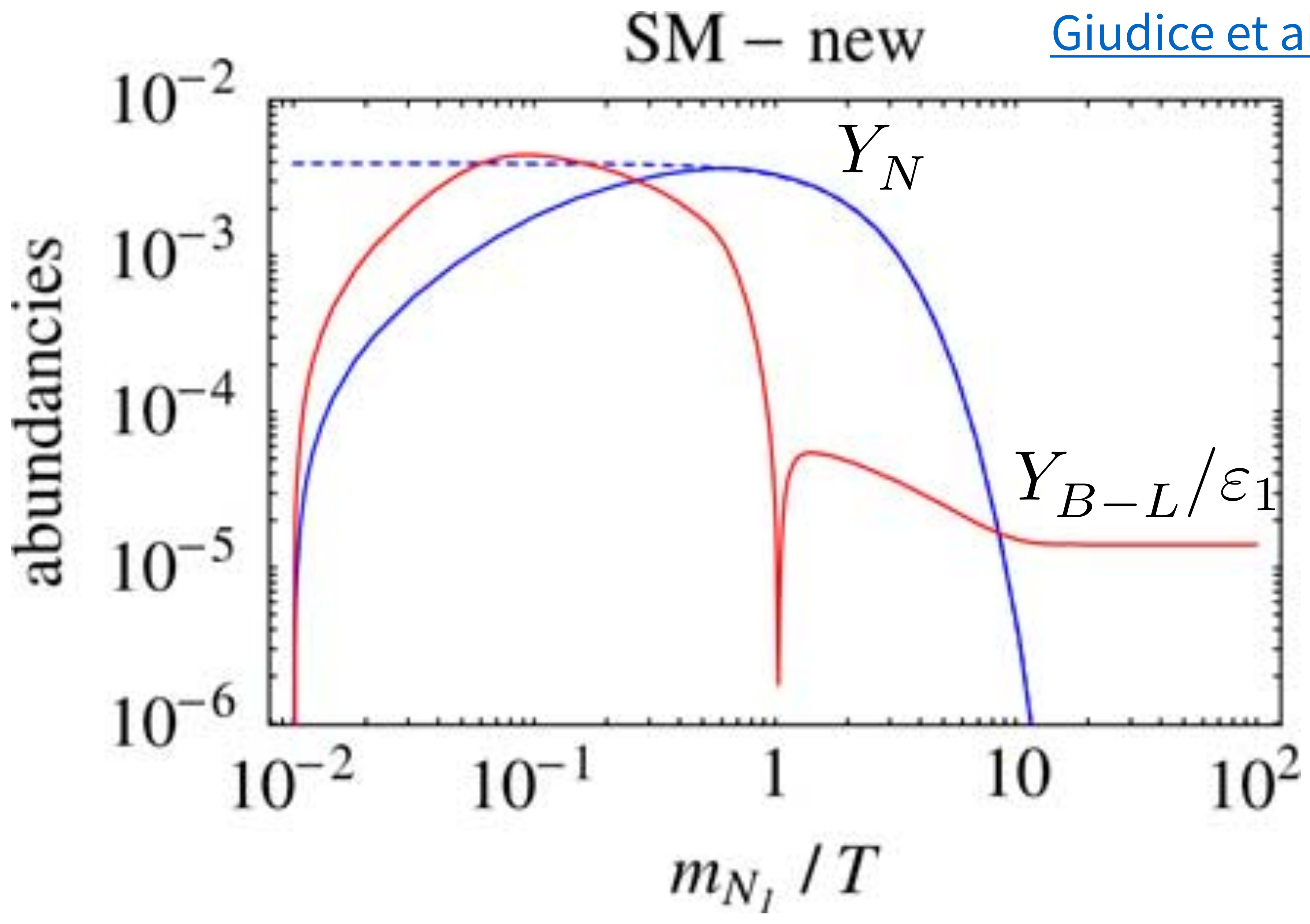
$$\varepsilon_1 = \frac{\Gamma(N_1 \to \ell H) - \Gamma(N_1 \to \ell^c H^*)}{\Gamma(N_1 \to \ell H) + \Gamma(N_1 \to \ell^c H^*)}$$

Naively

Large enough CPV → $M_1 > 10^{10}$GeV

Out of equilibrium

[Giudice et al., NPB685, 89(2004)]



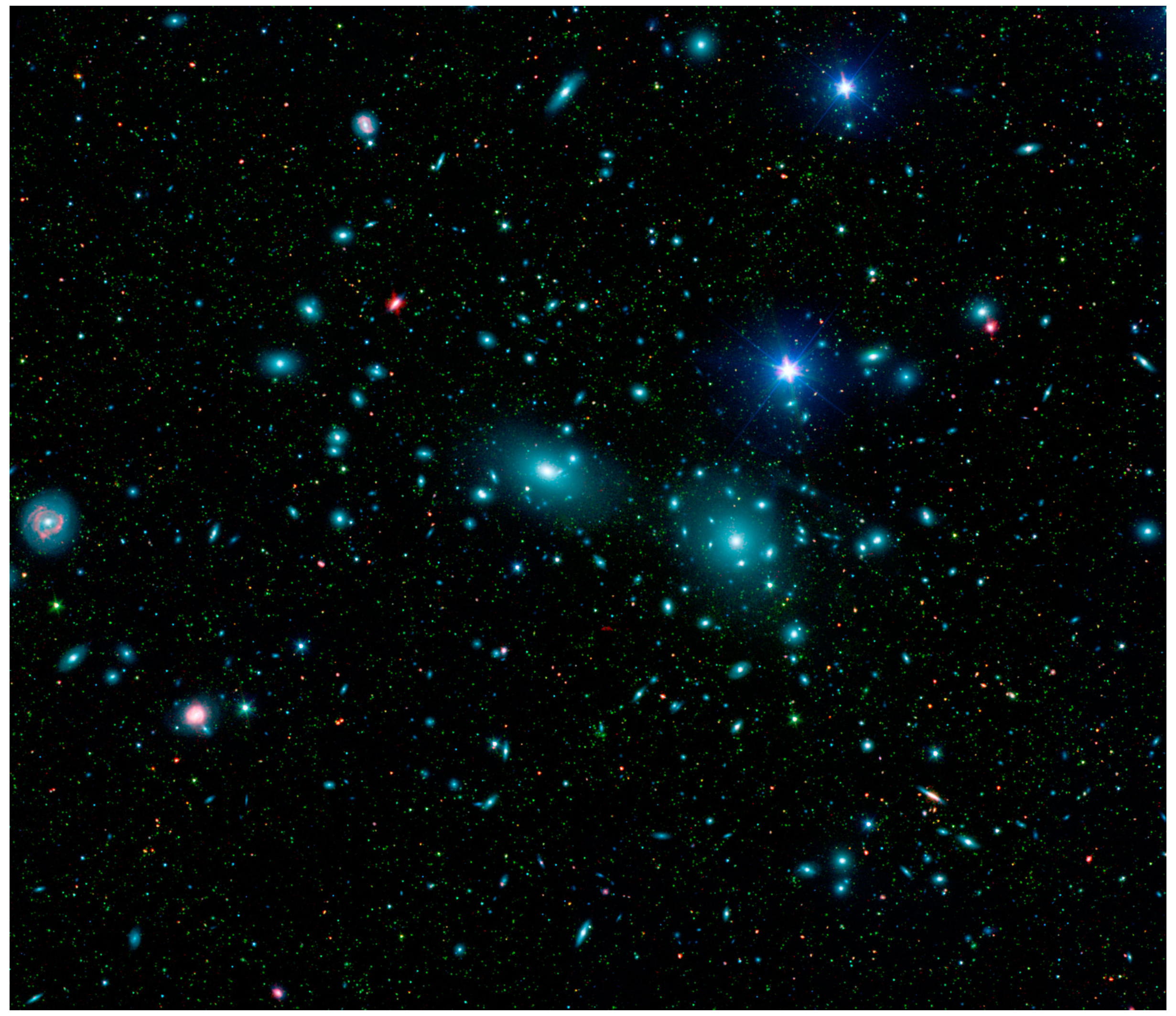
$\tilde{m}_1 = 0.06$ eV $\quad M_{N_1} = 10^{10}$ GeV

B-L is frozen out

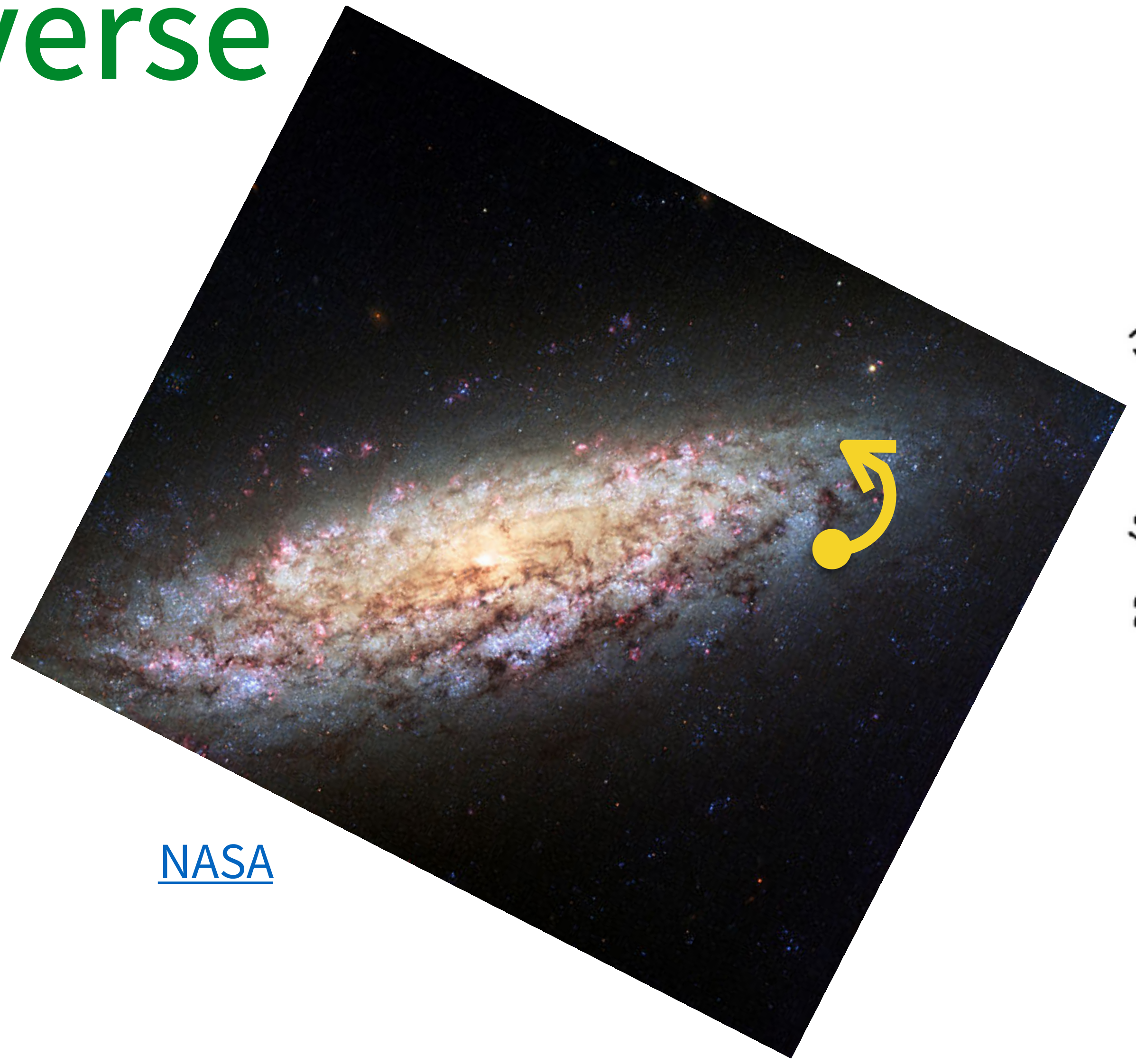
Unfortunately, it is very hard to probe this scenario ☹️

The Dark Matter

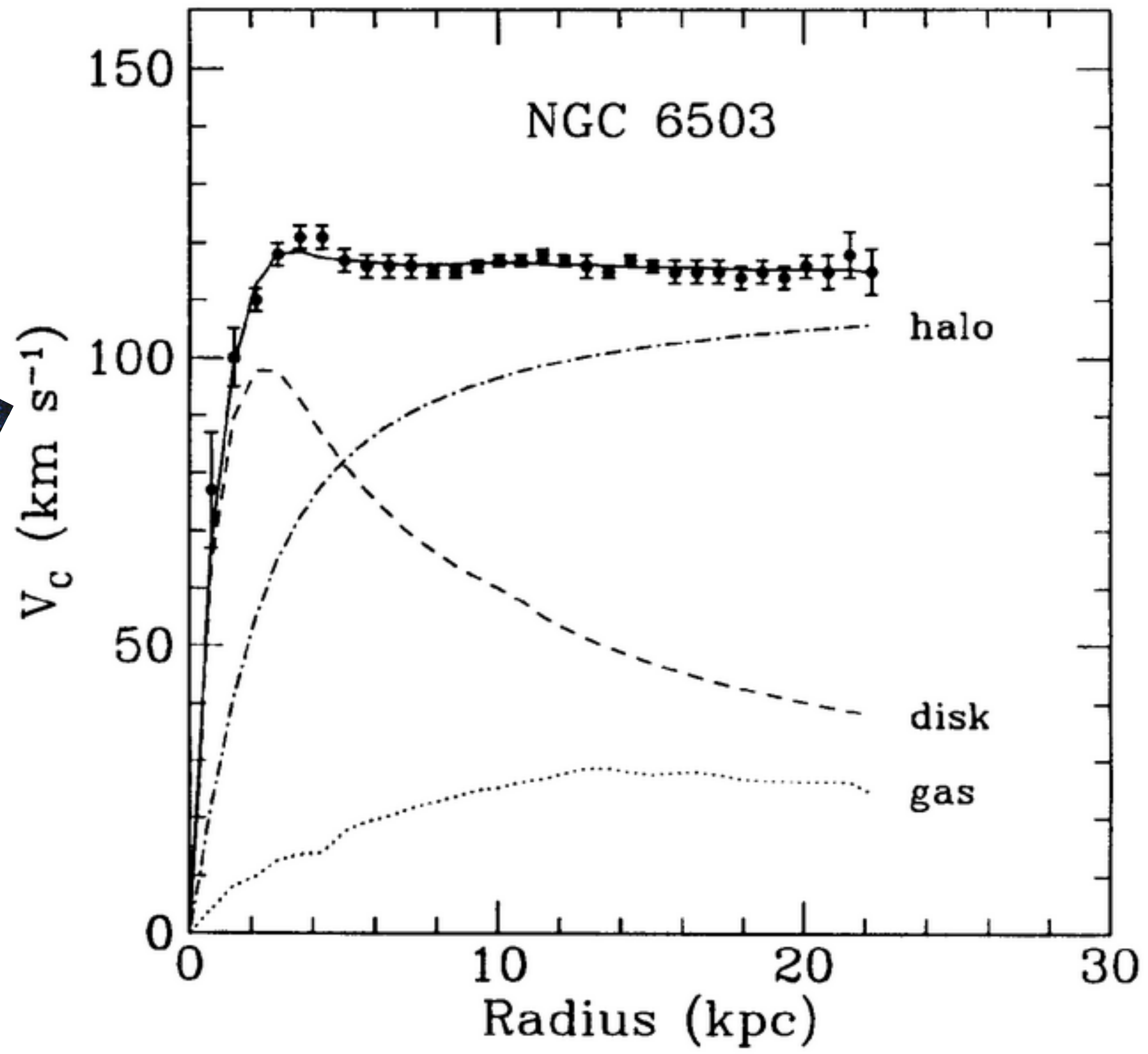
There should be Dark Matter in the Universe



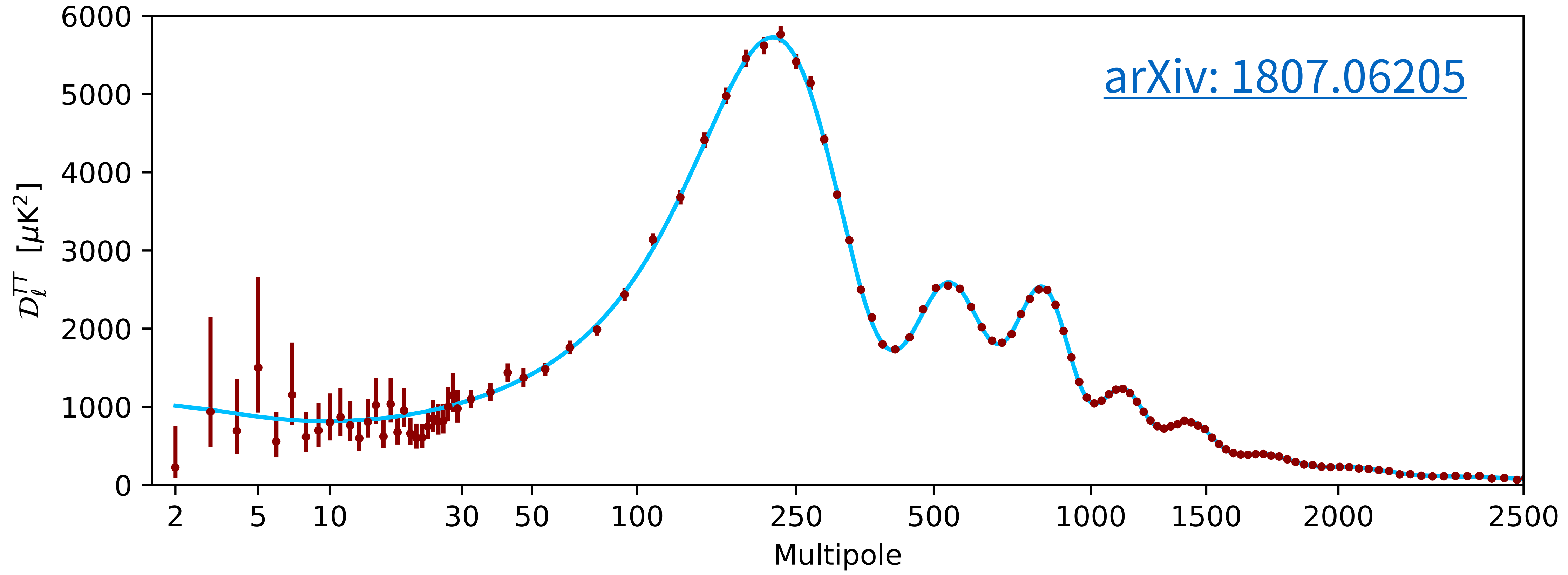
NASA



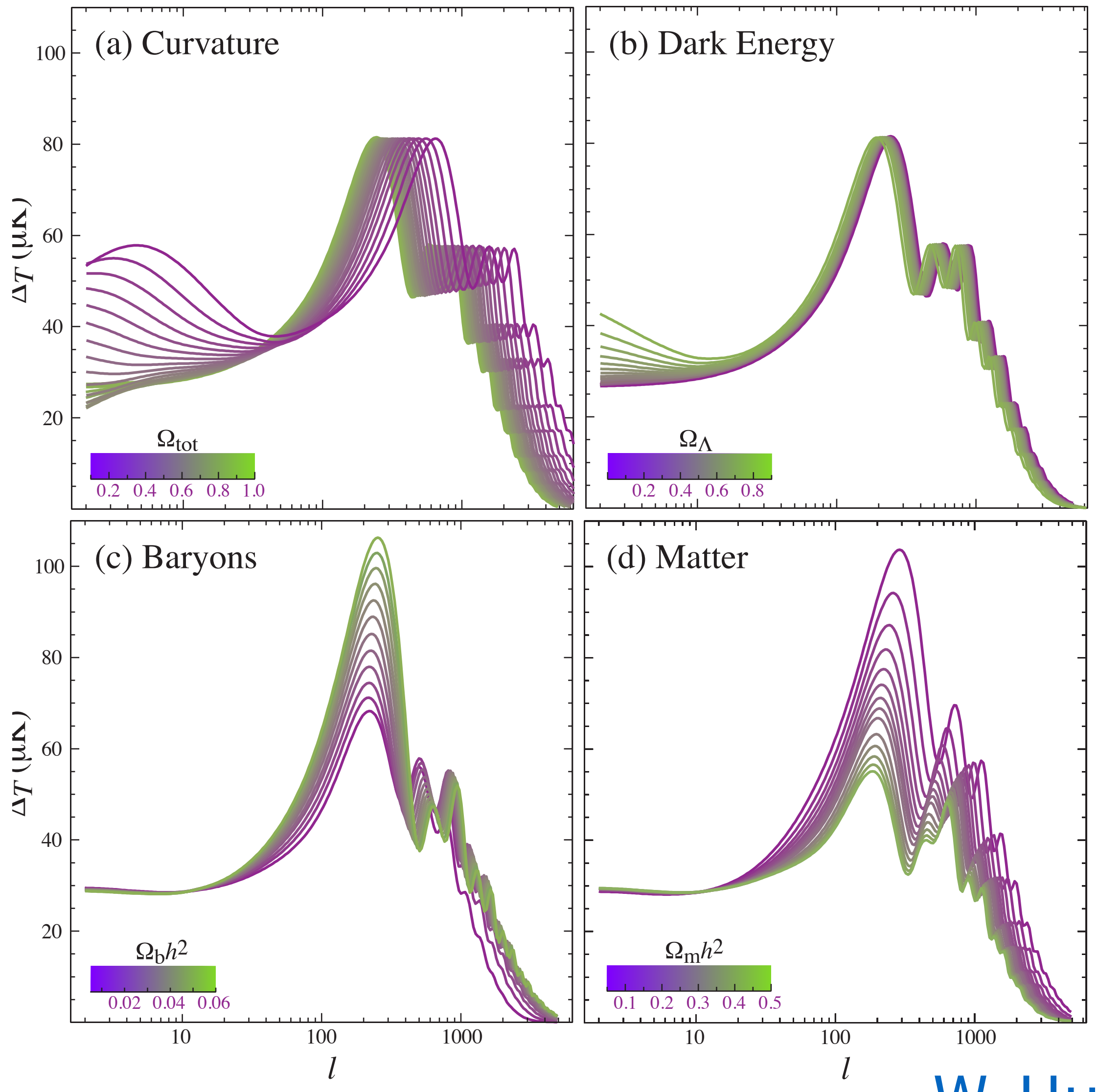
NASA

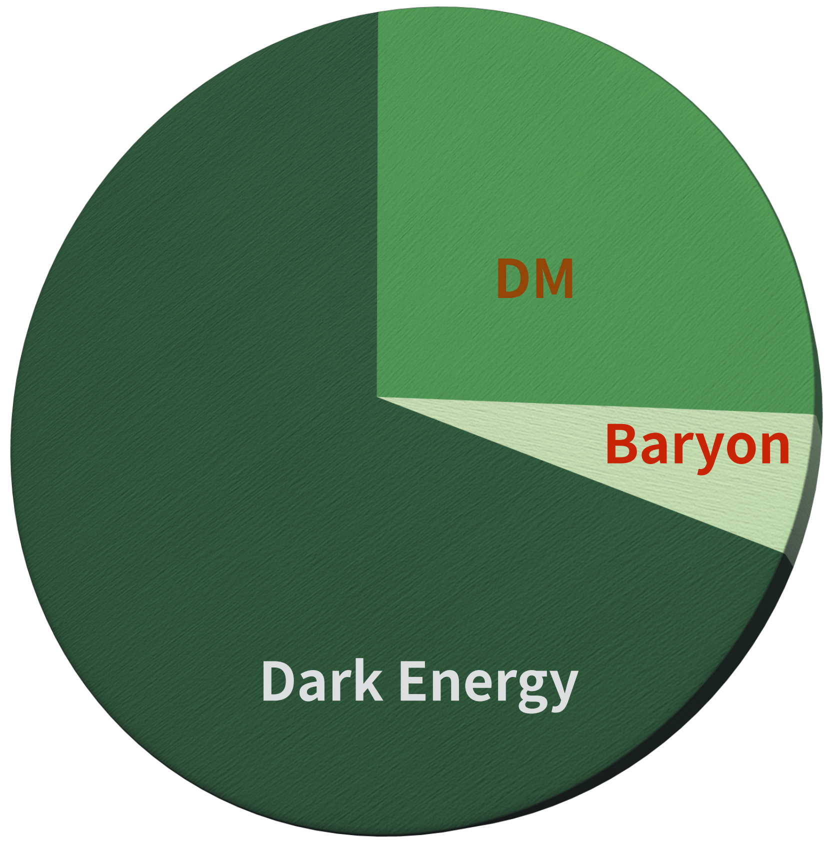


K. Freese, EAS Publ. Ser. 36, 113



arXiv: 1807.06205





W. Hu and S. Dodelson, astro-ph/0110414

Dark Matter

- Particle DM or primordial Black hole

  It may not be likely (recently shown by Subaru)

- There is no candidate in the SM

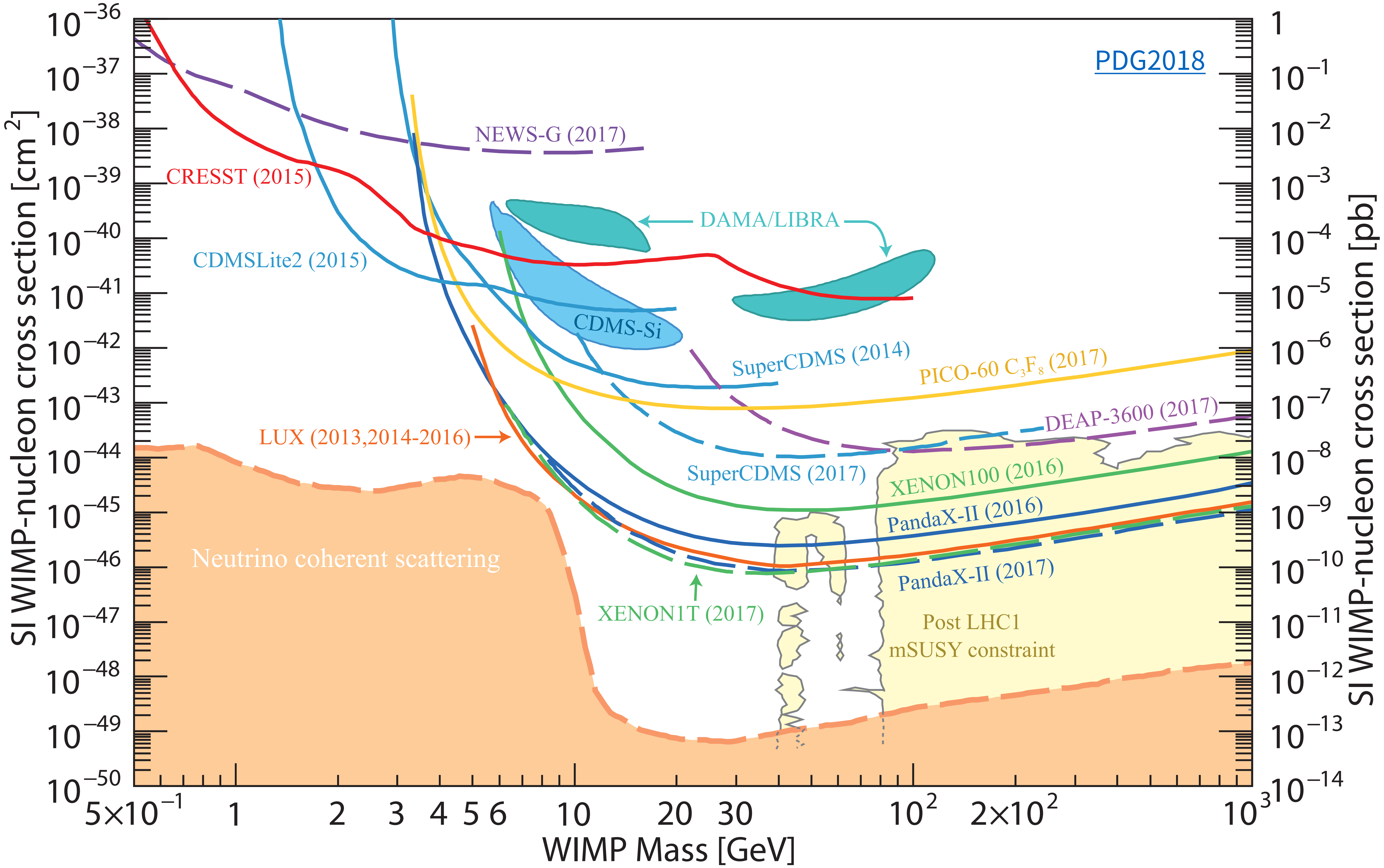
  - Neutrino is a candidate of hot DM but it is inconsistent with large scale structure of the Universe

- New particle is necessary

  - Electrically neutral

  - Stable enough $\leftarrow$ Some symmetry as R_p, Z_2, Z_3, …

Direct search of DM



Direct detection of DM provides stringent bound on many DM models

Summary

- There are several motivations for BSM
  - Theoretical issues such as Unification, hierarchy problem, …
  - There are also phenomenological problems
- But we don't know anything about the scale of BSM…
  maybe just above the EW scale, maybe much higher than EW scale
  It is important to test this case!
  - Some BSM models predict extension of scalar sector at rather low scale.
  - Since the Higgs sector of the SM is not well-understood, exploring it will be the most important task

Backup

Current anomaly in SM

B,L currents are anomalous in the SM

$$\partial_\mu j_B^\mu = \partial_\mu j_L^\mu = \frac{N_f}{32\pi^2}\left[g^2 \mathrm{tr}(W^a_{\mu\nu}\tilde{W}^{a\mu\nu}) - g'^2 B_{\mu\nu}\tilde{B}^{\mu\nu}\right]$$

$$\downarrow$$

B-L is conserved $\quad \partial_\mu j^\mu_{B-L} = 0$

B+L is violated due to the vacuum structure

$$\partial_\mu j^\mu_{B+L} = 2N_f \partial_\mu K^\mu$$

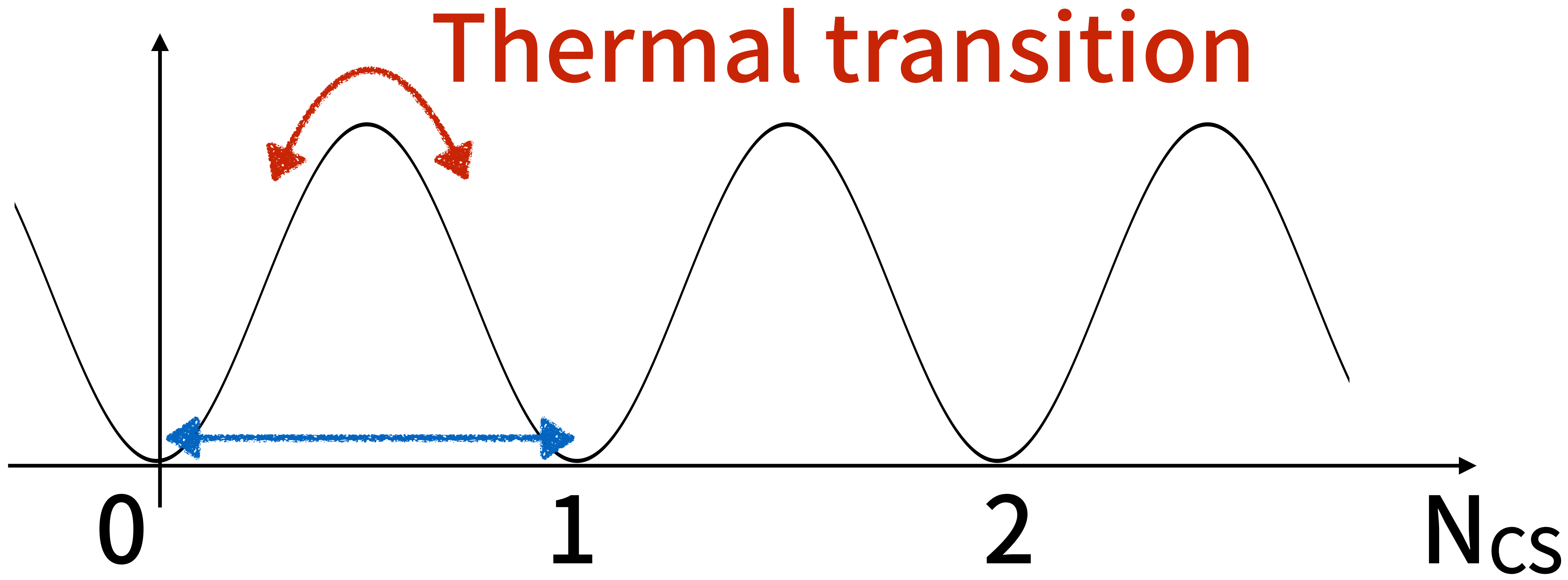
$$B(t_f) - B(t_i) = \int_{t_i}^{t_f} dt \int d^3x \partial^\mu j_{B\mu} = N_f\left[N_{cs}(t_f) - N_{cs}(t_i)\right]$$

$$N_{cs}(t) = \frac{g^3}{96\pi^2}\int d^3x \epsilon_{ijk}\epsilon^{IJK} W^{Ii} W^{Jj} W^{Kk}$$

Chern-Simons number $\quad \Delta N_{cs} = \pm 1, \pm 2, \cdots$

Vacuum structure

Classical vacuum of the SU(2) gauge system



$$W_\mu = iU^{-1}\partial_\mu U$$

$$U \in \mathrm{SU}(2) \simeq S^3$$

$$\pi_3(S^3) = Z$$

Tunneling effect The vacuum is characterized by Ncs

Tunnelling rate $\sim e^{-2S_{\mathrm{instanton}}} = e^{-8\pi^2/g^2} \simeq e^{-164} \ll 1$

Thermal transition rate

- symmetric phase $\Gamma \simeq T^4 e^{-E_{\mathrm{sph}}/T}$
- broken phase $\Gamma \simeq \kappa(\alpha_W T)^4$

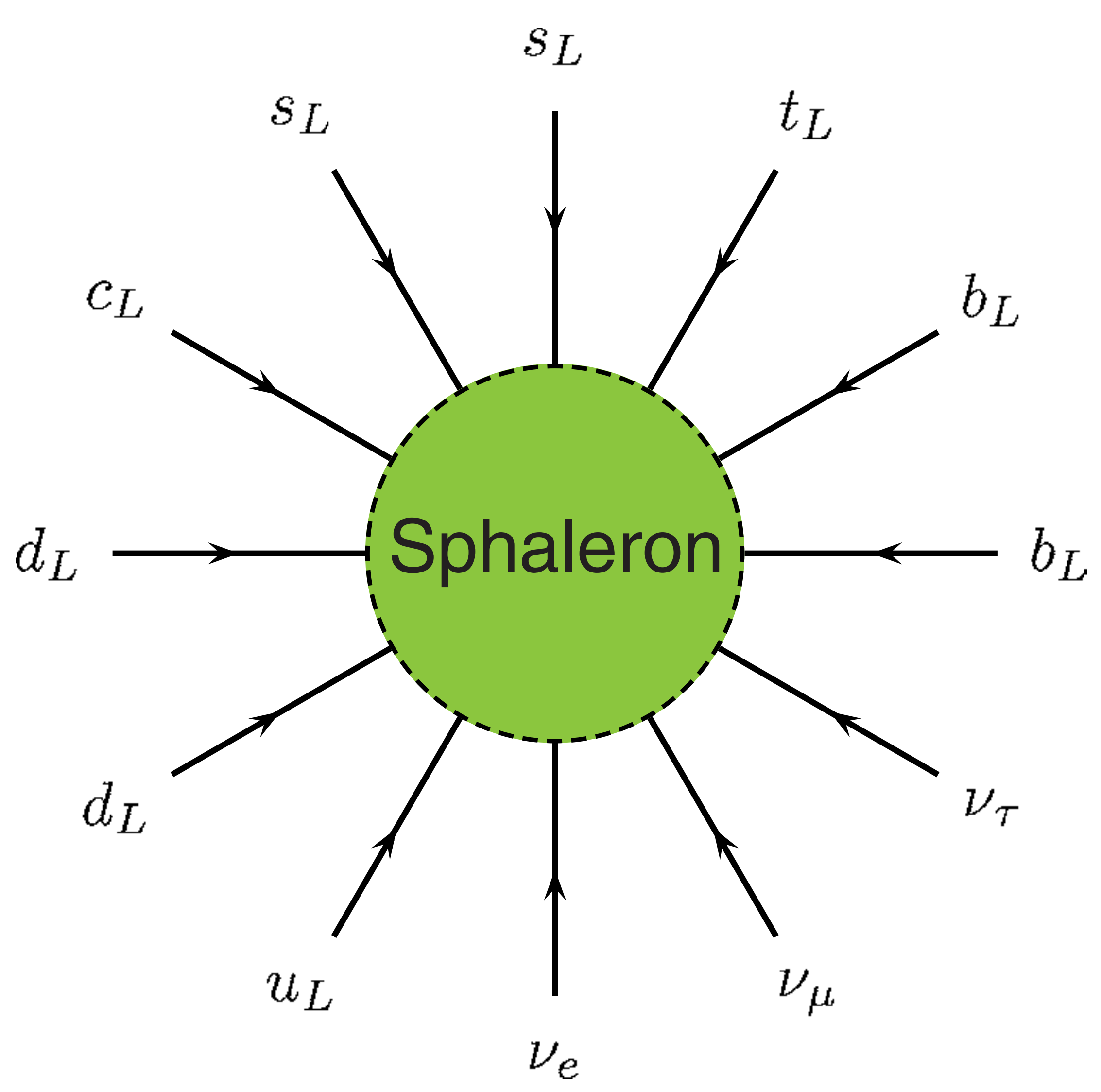
It is significant at finite temperature

Sphaleron

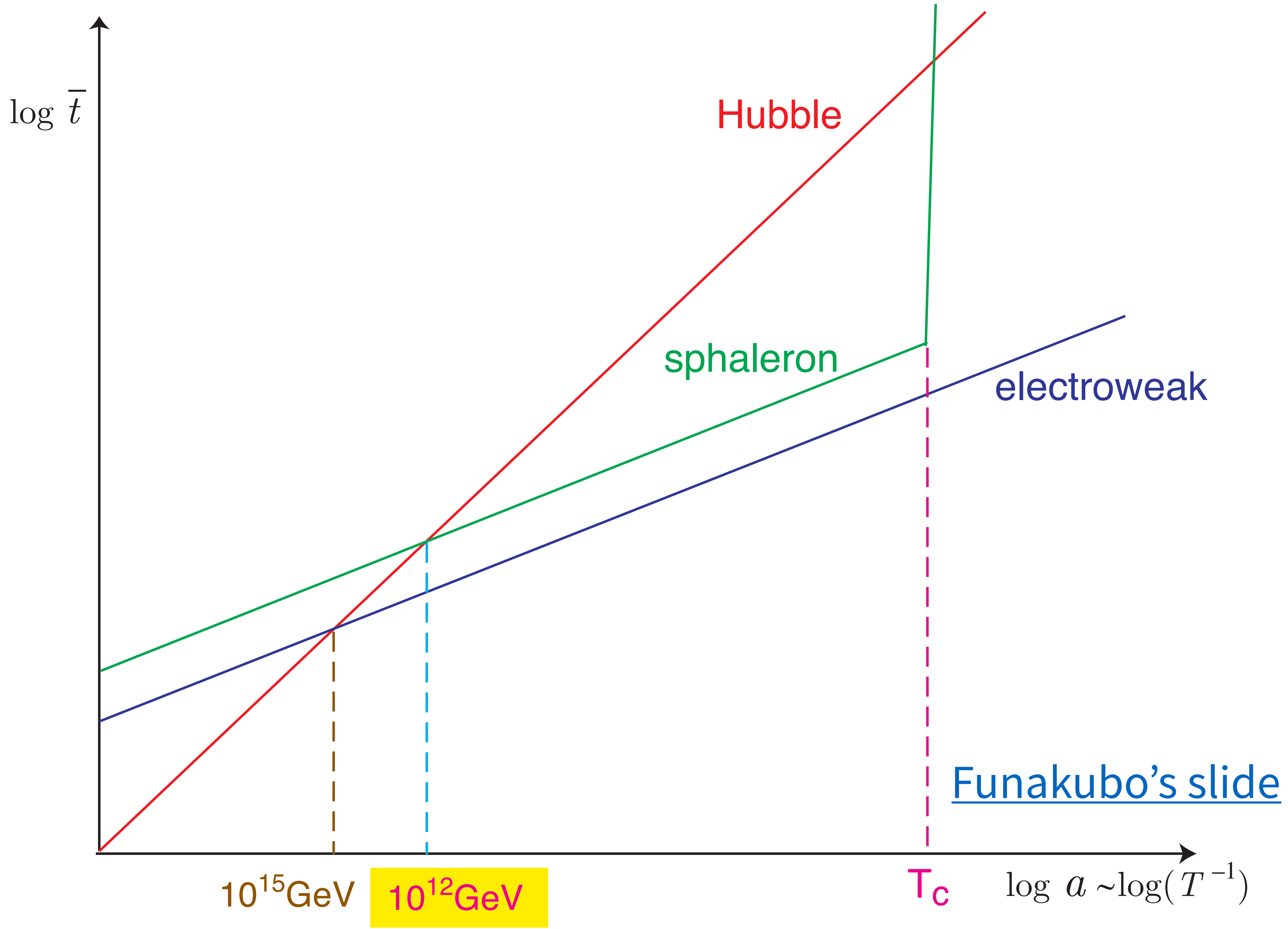
"Sphaleron process" leads to the effective operator

$$O_{B+L} = \Pi_i (q_{Li} q_{Li} q_{Li} \ell_{Li})$$

All left handed!



Taken from hep-ph/0406014



Funakubo's slide

The process is in the thermal bath at

$$100 \text{ Gev} \leq T \leq 10^{12} \text{ GeV}$$

Sphaleron

- ☆ B+L is violated (only in the left-hand fermions)
- ☆ B-L is conserved
- ☆ The process is relevant when T=100GeV-10^{12}GeV

Because of the sphaleron, all the baryogenesis scenarios are classified into two cases

- B-L is produced before the sphaleron decoupling era.
- B is produced by the 1st order electroweak phase transition just before the sphaleron decoupling.