SUSY model for dark matter and muon g-2

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Evidences for physics beyond SM

Despite the phenomenological success, the Standard Model (SM) of particle physics has unsettled issues

- **No dark matter candidate**
- **Hierarchy problem (stability of the Higgs potential)**
- **Unification of the fundamental forces**
- **Muon g-2 anomaly**

etc …

Anomalous magnetic moment (g-2)

Fermion feels potential in the external magnetic field

$$H = -\vec{\mu}_l \cdot \vec{B} \qquad l = e, \mu, \tau$$

Magnetic moment $\vec{\mu}_l$ is proportional to the spin

$$\vec{\mu}_l = g_l \frac{e}{2m_l} \vec{S}_l$$

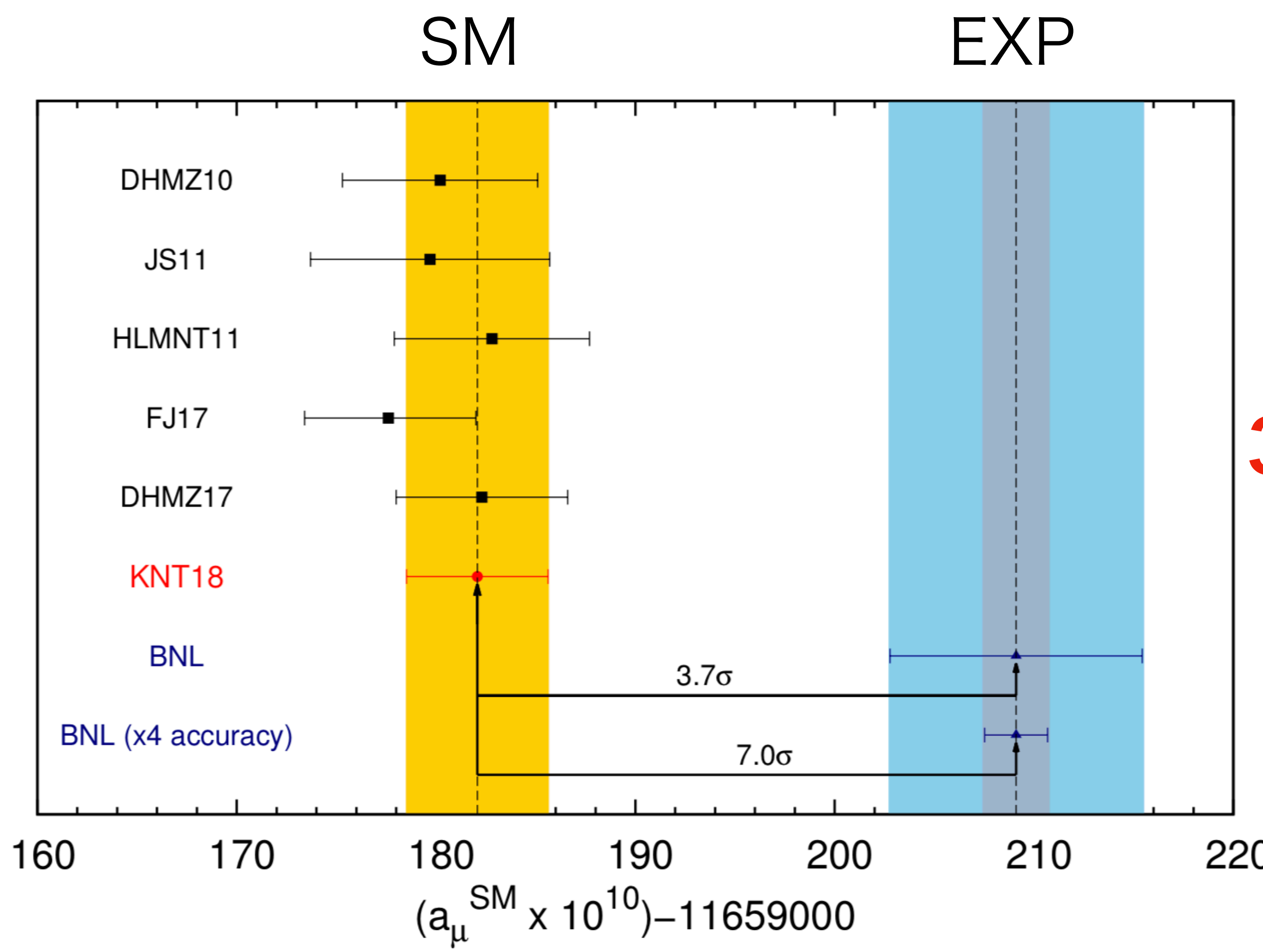
Radiative correction

$$g_l = 2(1 + a_l)$$

a_μ is very precisely measured at the E821 experiment (BNL)

Fermilab is expected to release the new result within this year!

Muon g-2 anomaly



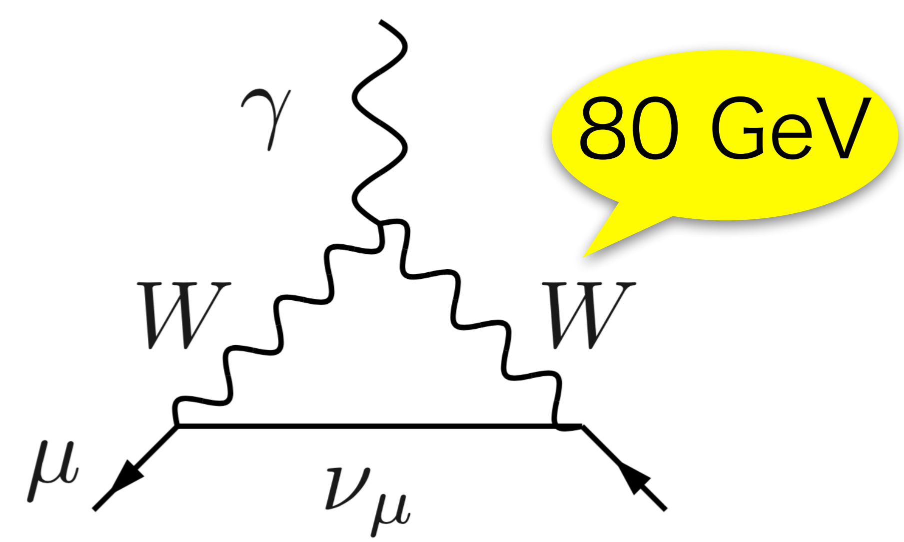
3.7σ deviation

[Keshavarzi, Nomura, Teubner, 2018]

$$\mathcal{L} = \frac{e}{4m_\mu}(a_\mu)\bar{\psi}_\mu \sigma_{\alpha\beta}\psi_\mu F^{\alpha\beta}$$

$(a_\mu)^{\rm NP} \approx 2 \times 10^{-9}$ is required

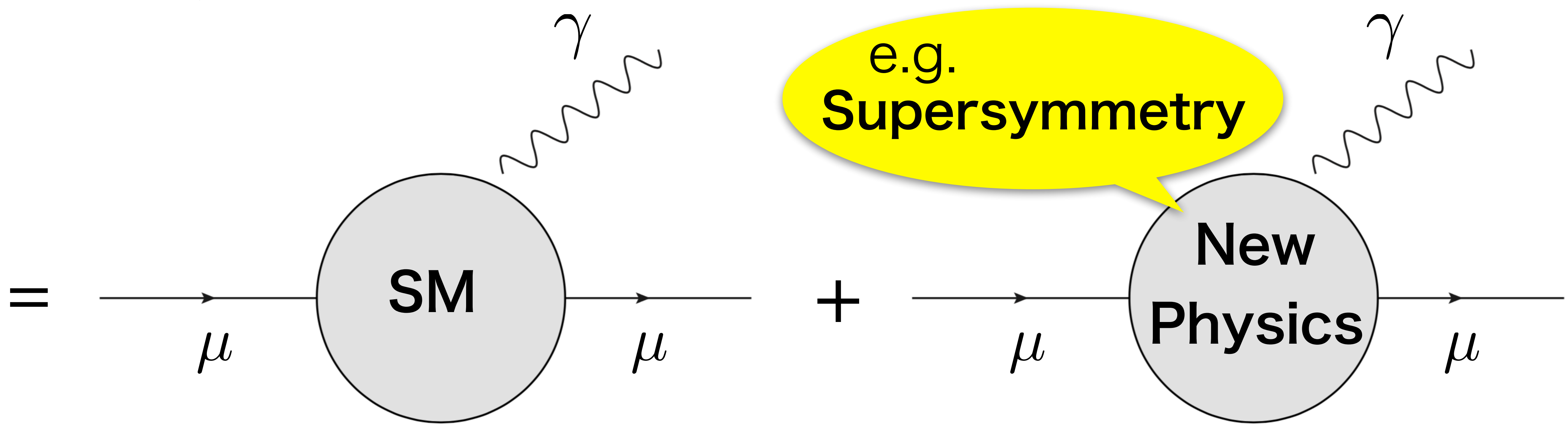
(similar to the size of W boson contribution)



$\approx 4 \times 10^{-9}$

Muon g-2 anomaly

$$\mathcal{L} = \frac{e}{4m_\mu}(a_\mu)\bar{\psi}_\mu \sigma_{\alpha\beta}\psi_\mu F^{\alpha\beta}$$

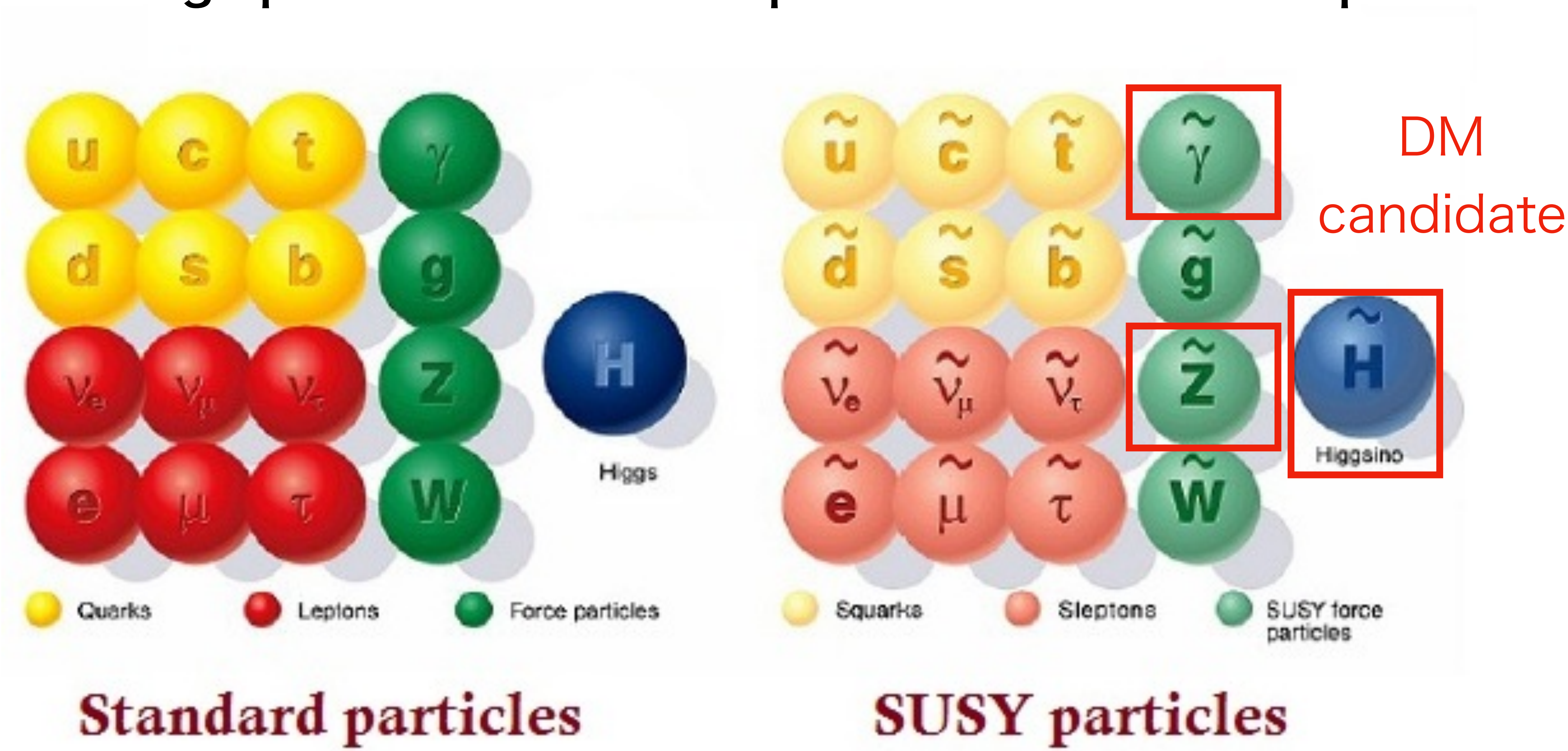


Muon g-2 anomaly indicates the existence of new particles of O(100) GeV,

within the reach of LHC and future collider experiments

Supersymmetry

Introducing sparticles with half-spin differences to SM particles

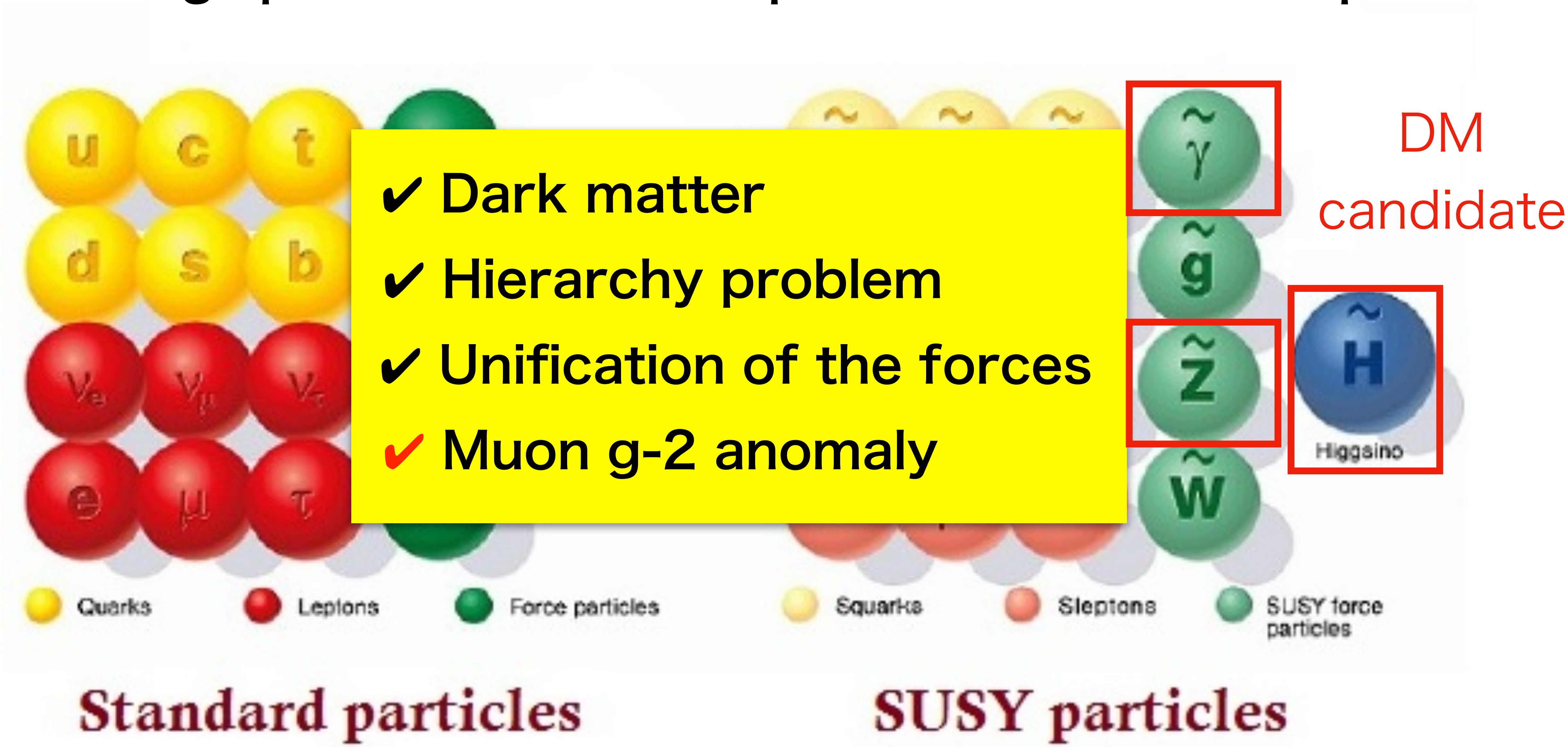


[CERN & IES de SAR]

Minimal supersymmetric standard model (MSSM)

Supersymmetry

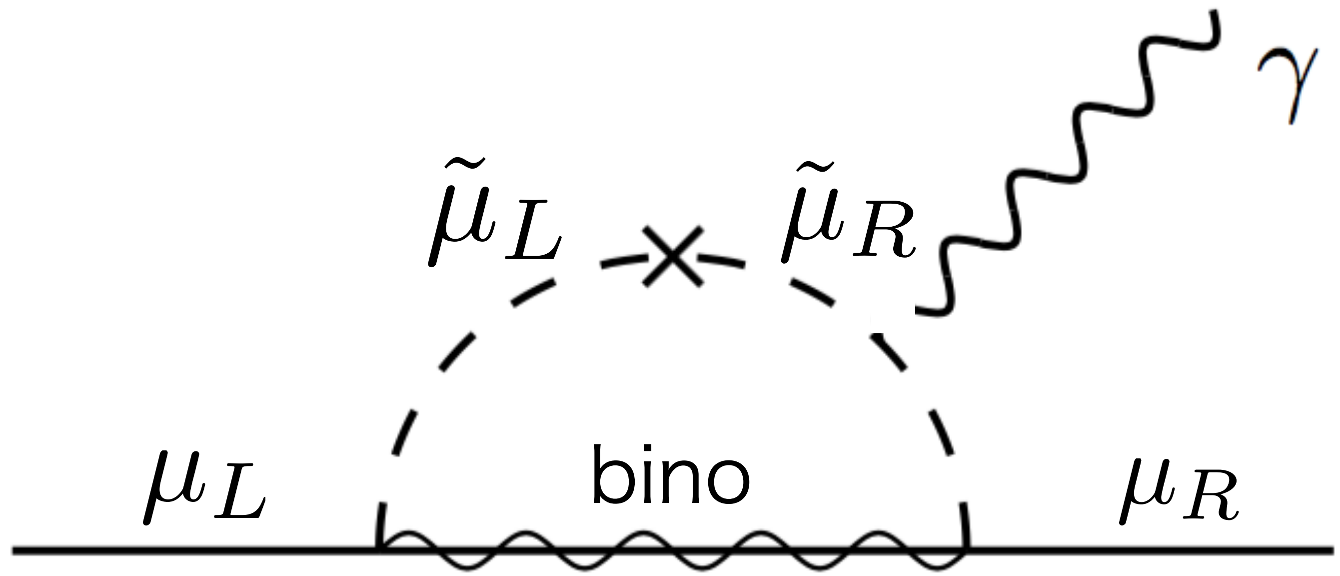
Introducing sparticles with half-spin differences to SM particles



[CERN & IES de SAR]

Minimal supersymmetric standard model (MSSM)

Muon g-2 anomaly in MSSM



(bino: superpartner of $U(1)_Y$ gauge boson)

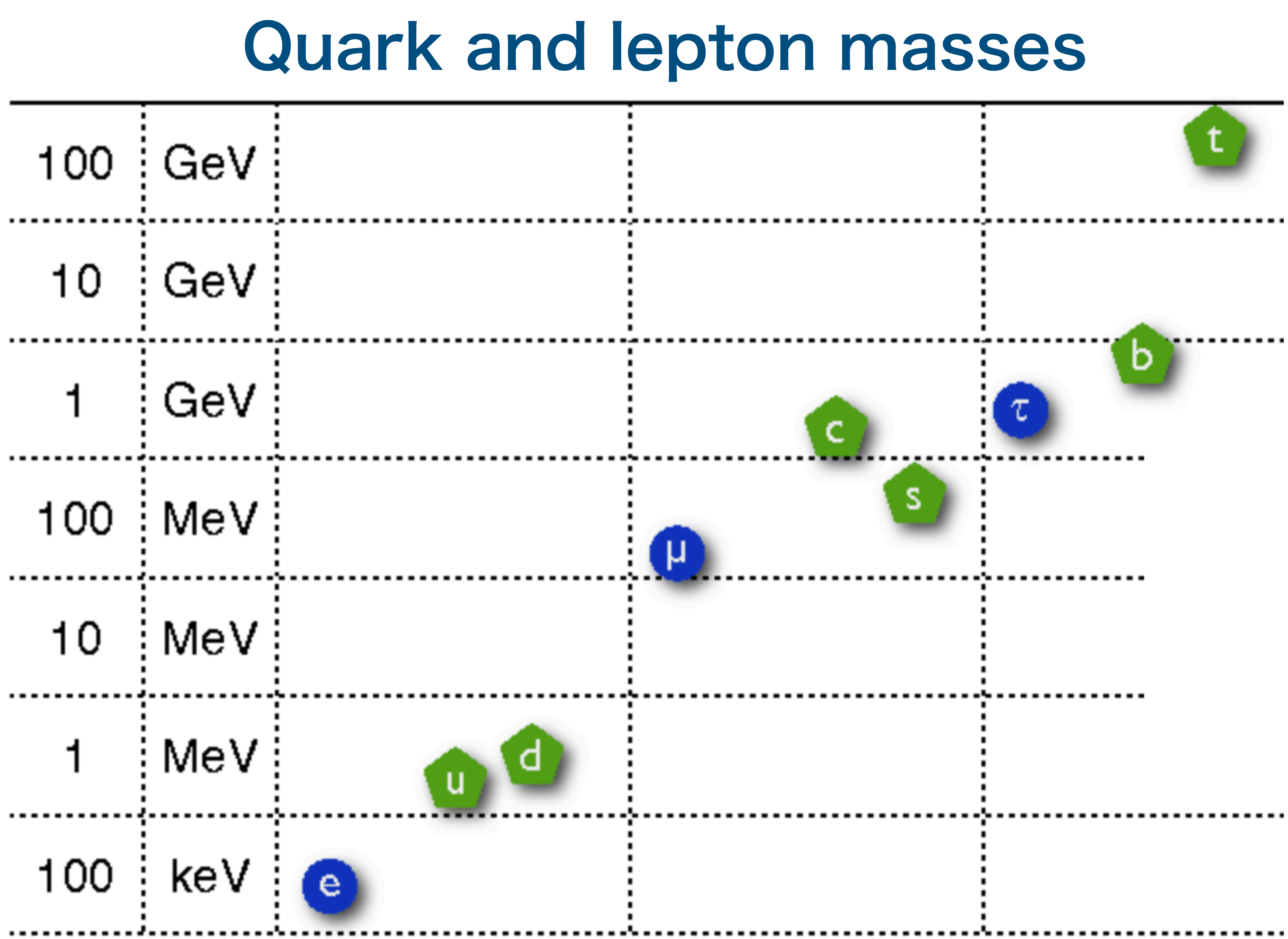
Muon g-2 anomaly suggests smuons and bino of O(100)GeV within the reach of LHC

[Lopez, Nanopoulos and Wang, 1994; Chattopadhyay and Nath, 1996; Moroi, 1996]

However, the LHC data excludes squarks and gluino lighter than ~3000 GeV, suggesting heavy SUSY particles

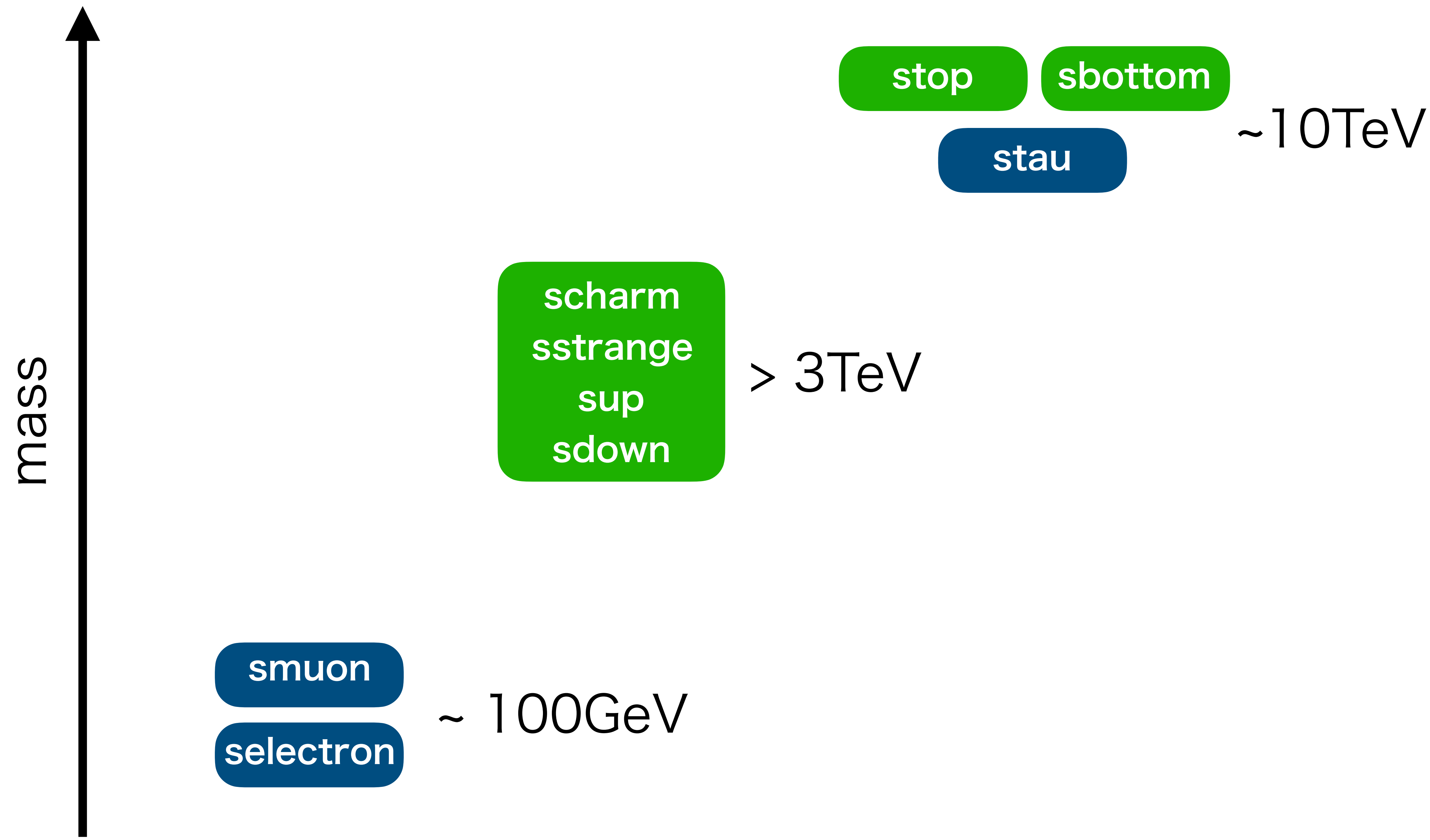
How can we explain the muon g-2 anomaly?

Mass hierarchy in SM



Standard model particles have a broad mass spectrum due to Yukawa couplings

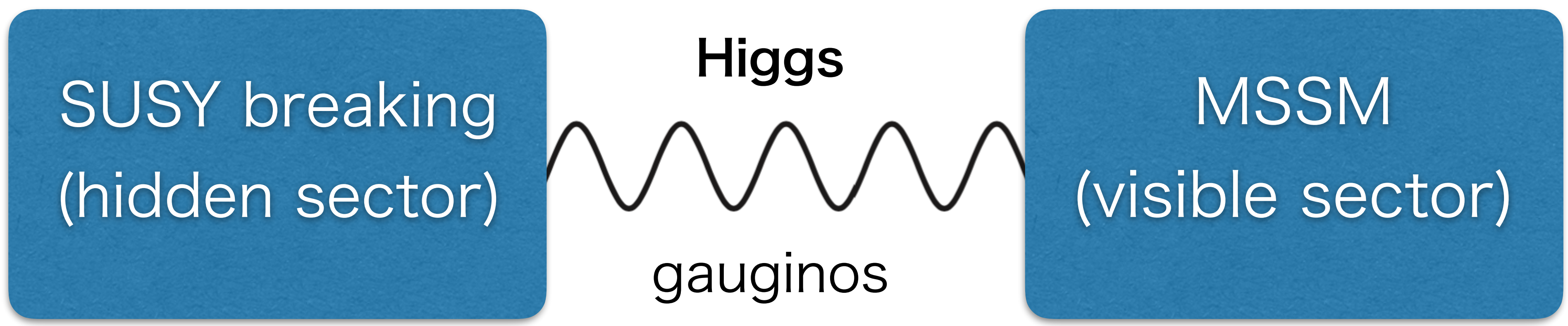
Mass hierarchy in MSSM



SUSY particles can also have hierarchical masses rather than common mass, due to the Yukawa couplings

SUSY breaking

It determines the masses of SUSY particles

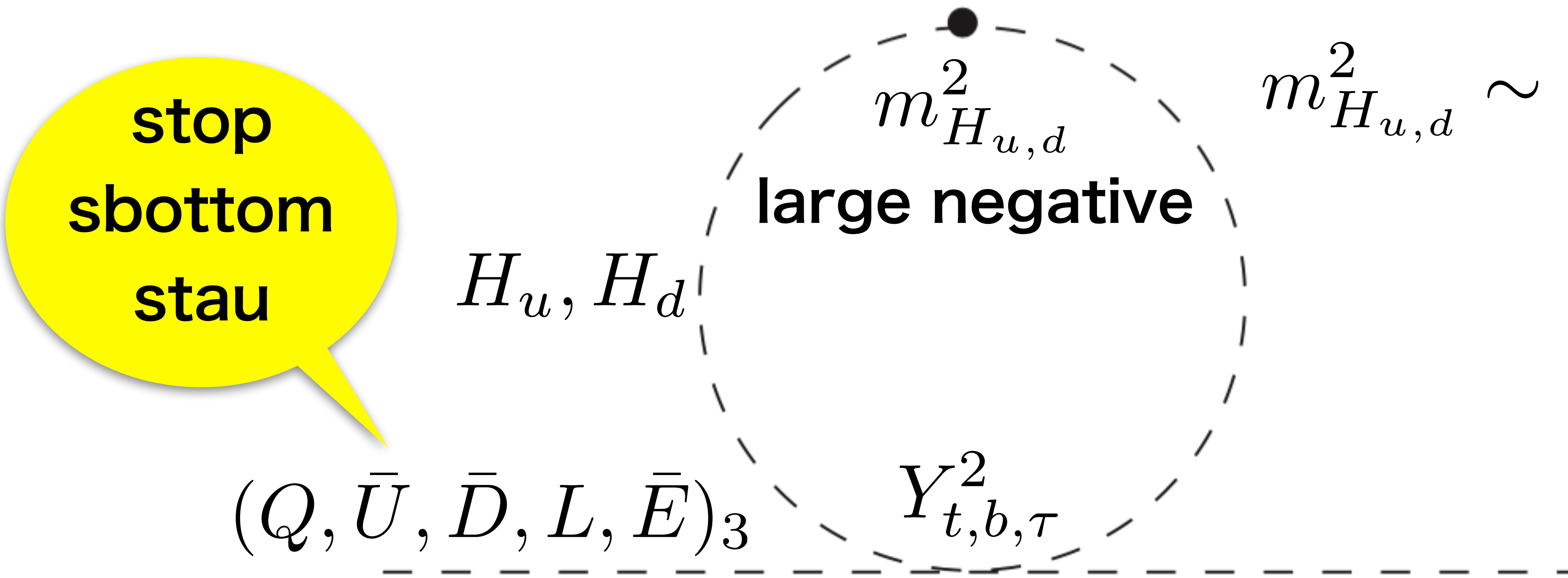


- Higgs doublets obtain large tachyonic SUSY breaking masses
- Squarks and sleptons are massless at the tree-level, avoiding the SUSY flavor problem
- Higgs loop effects induce the mass hierarchy of SUSY particles
  -> Higgs mediation

[Yin, NY, 2016]

[Cox, Han, Yanagida, NY, 2018]

3rd gen. >> 1st/2nd gen.



$m^2_{H_{u,d}} \sim (10\,\mathrm{TeV})^2$

One-loop diagrams induce large positive squared masses for the third generation squarks and sleptons

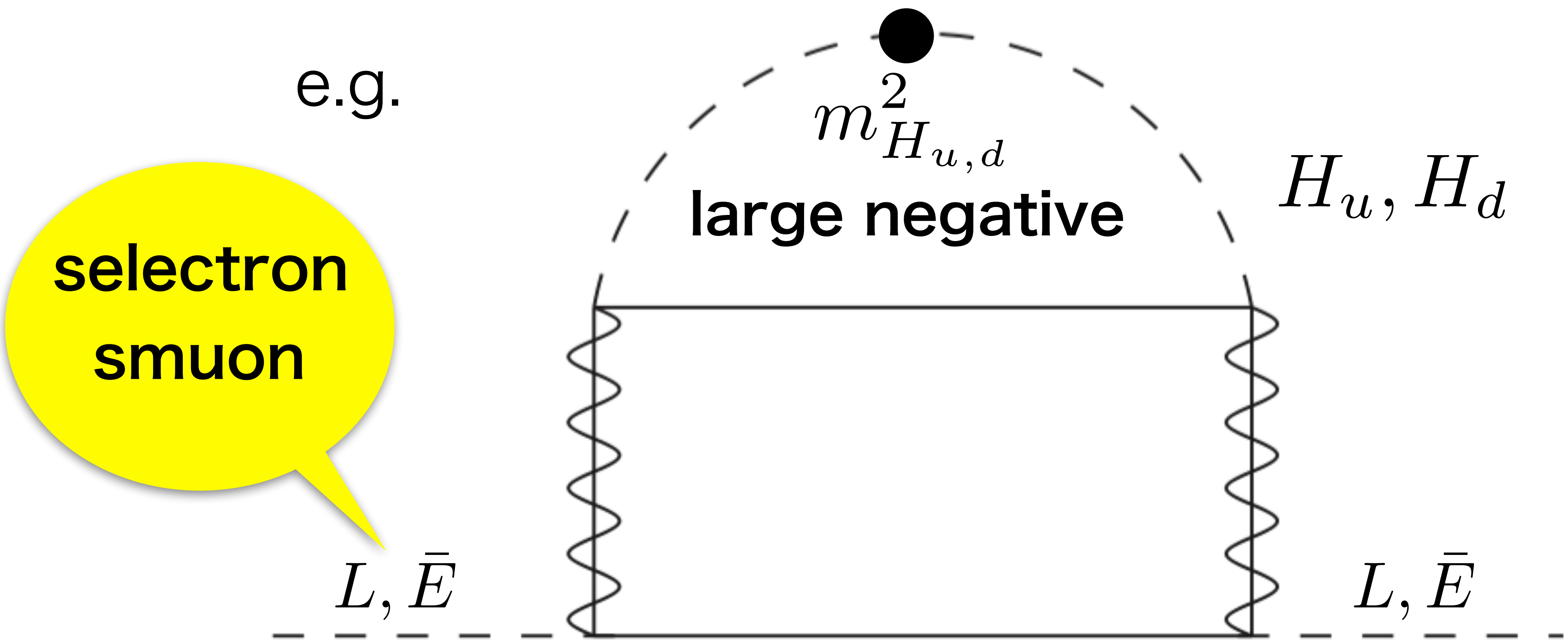
Third generation sfermions are as heavy as ~10TeV

Consistent with the Higgs boson mass of 125 GeV

Avoiding the instability of the stau-Higgs potential

3rd gen. >> 1st/2nd gen.

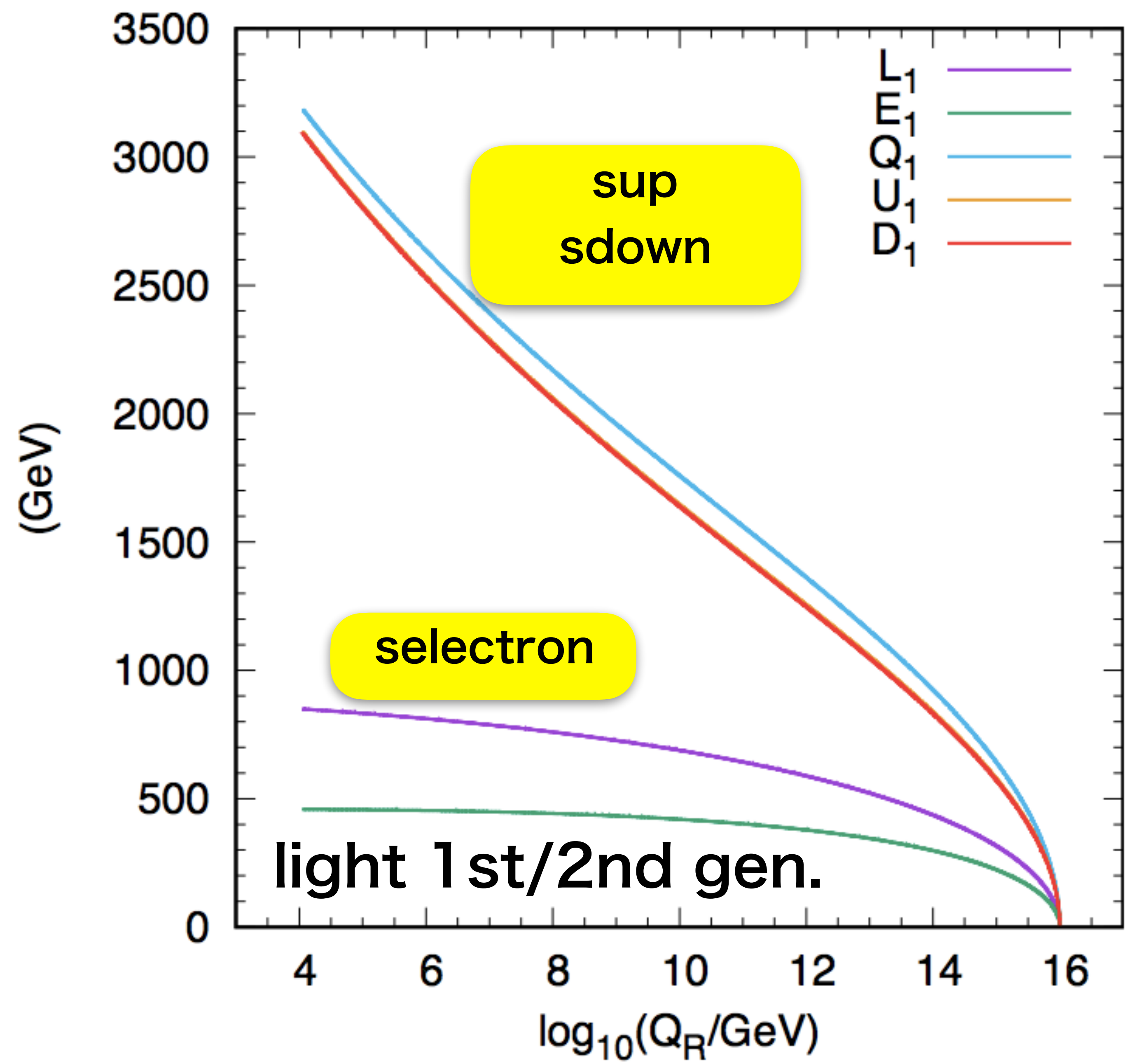
e.g.



Two-loop diagrams induce positive smuon/selecton squared masses of O((100 GeV)²)

Consistent with the muon g-2 experiment

3rd gen. >> 1st/2nd gen.



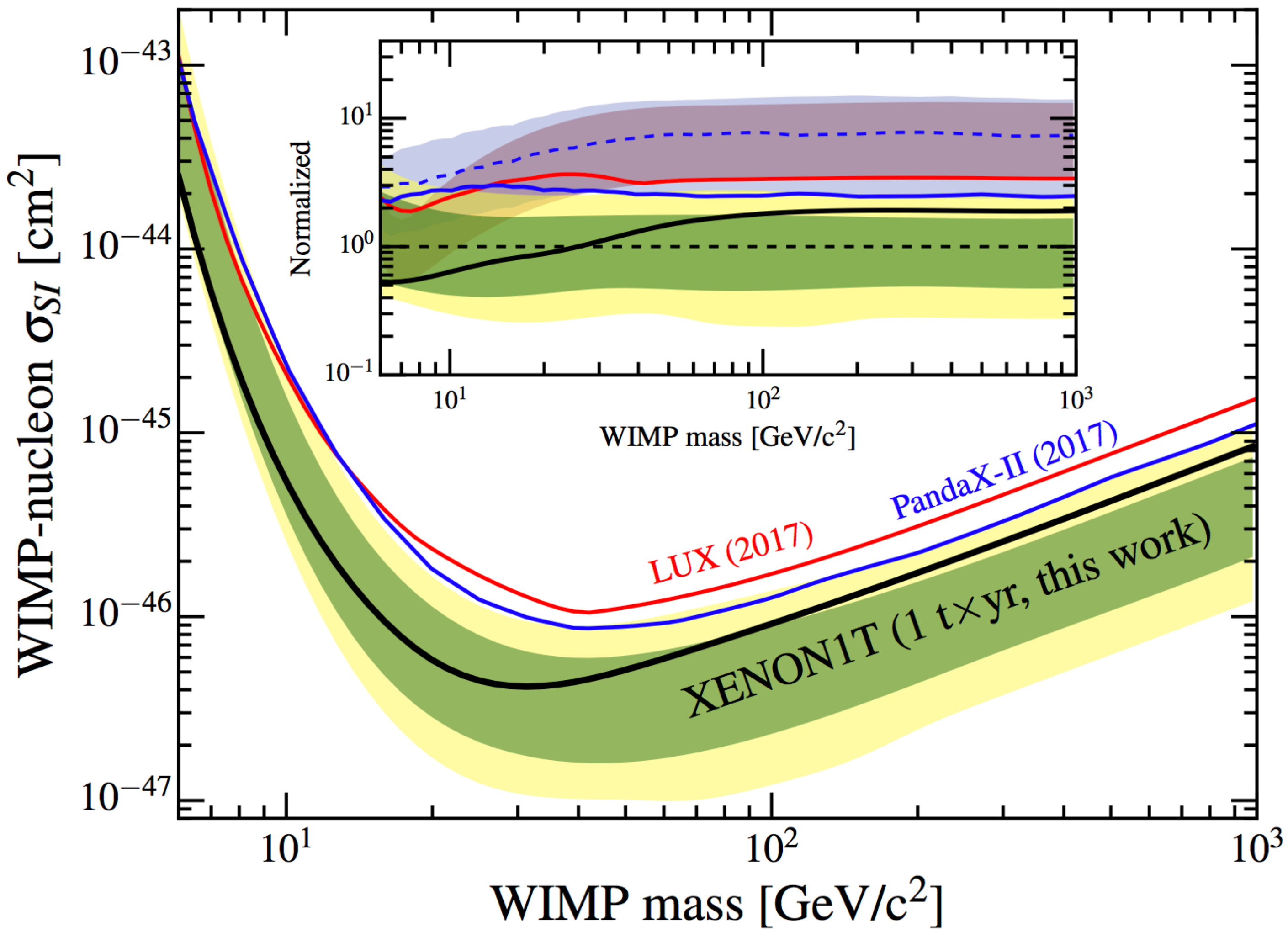
$$M_1 = 440\,\mathrm{GeV}, M_2 = 220\,\mathrm{GeV}, M_3 = -2000\,\mathrm{GeV}, m_{H_u}^2 = -7 \times 10^8\,\mathrm{GeV}^2, \tan\beta = 40$$

[Cox, Han, Yanagida, NY, 2018]

With this mass spectrum, we can explain the muon g-2 anomaly while avoiding all the existing constraints

Dark matter in MSSM

SUSY dark matter is searched in various experiments such as LUX, PandaX and XENON



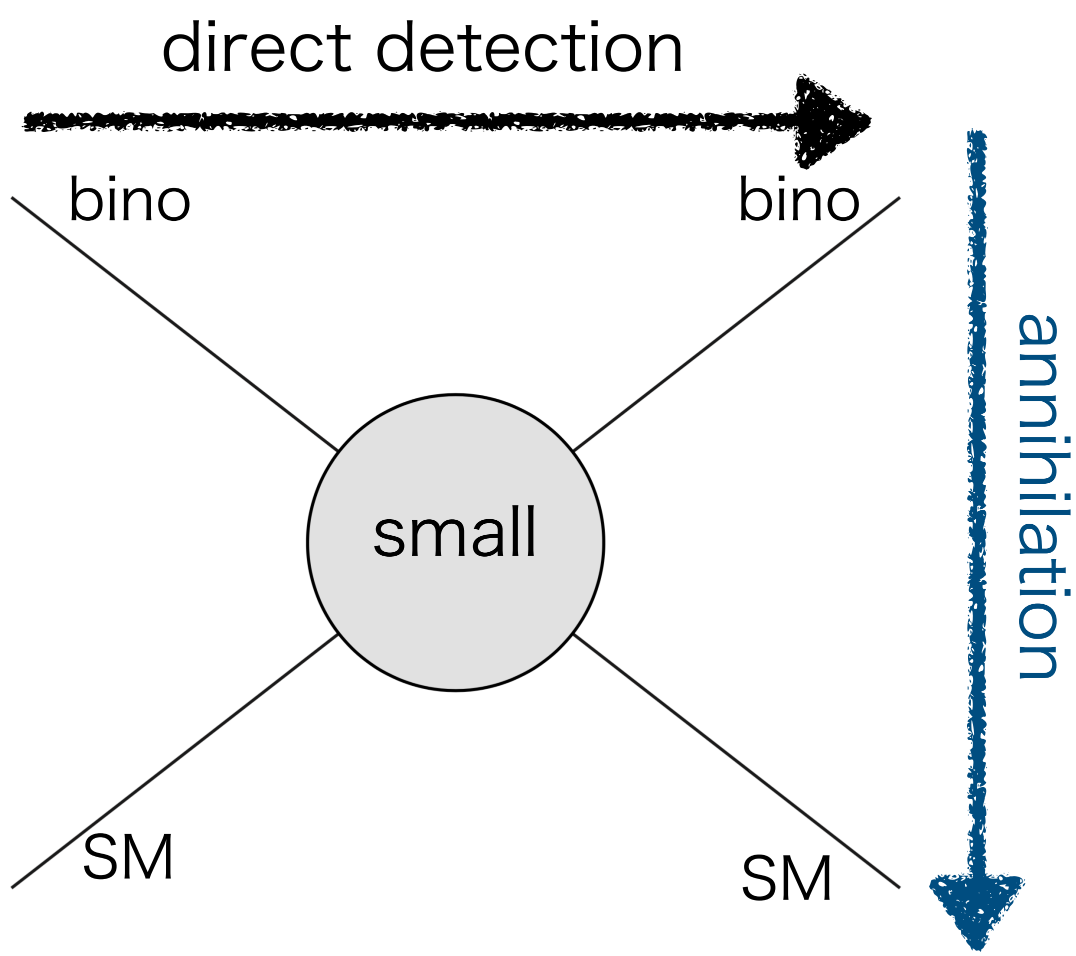
[Phys.Rev.Lett. 121 (2018) no.11, 111302]

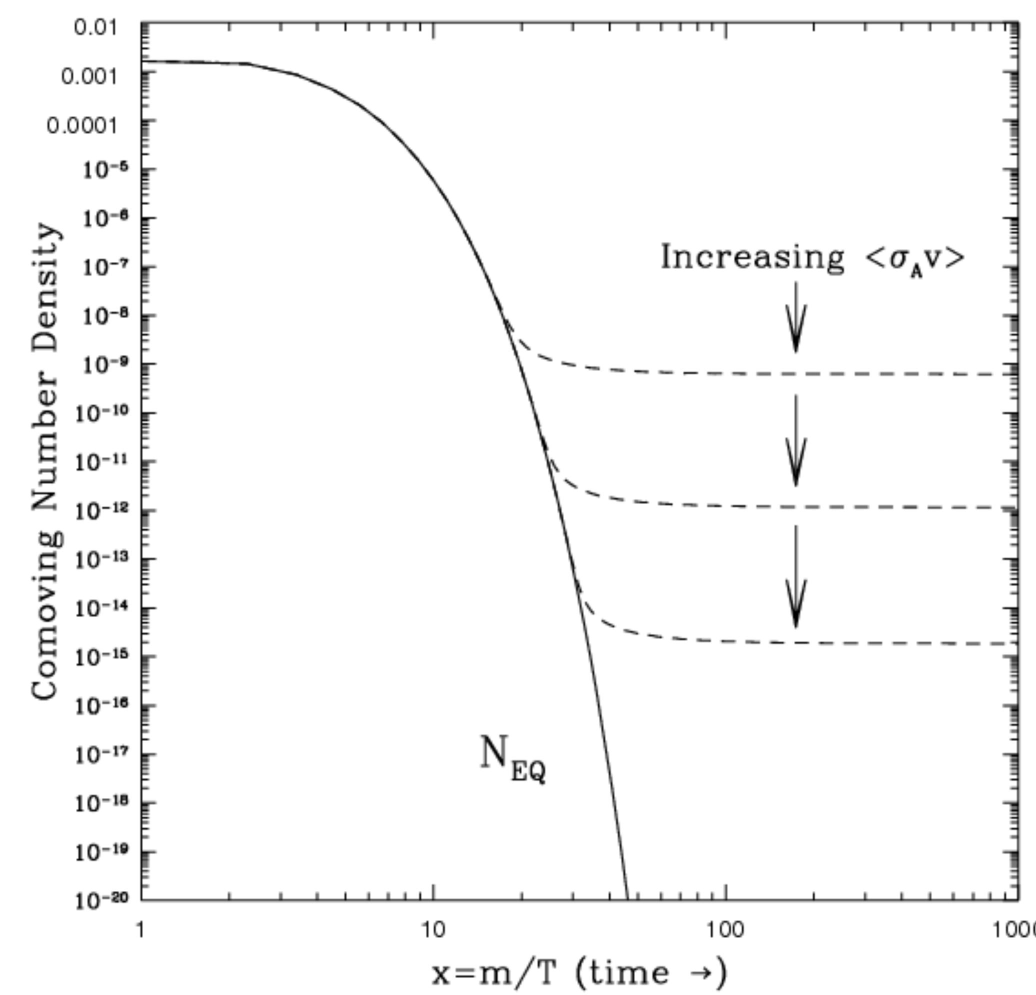
However, there is no signal so far

The fact excludes a conventional SUSY dark matter scenario

Dark matter in MSSM

Because of the severe constraints, we consider the bino dark matter





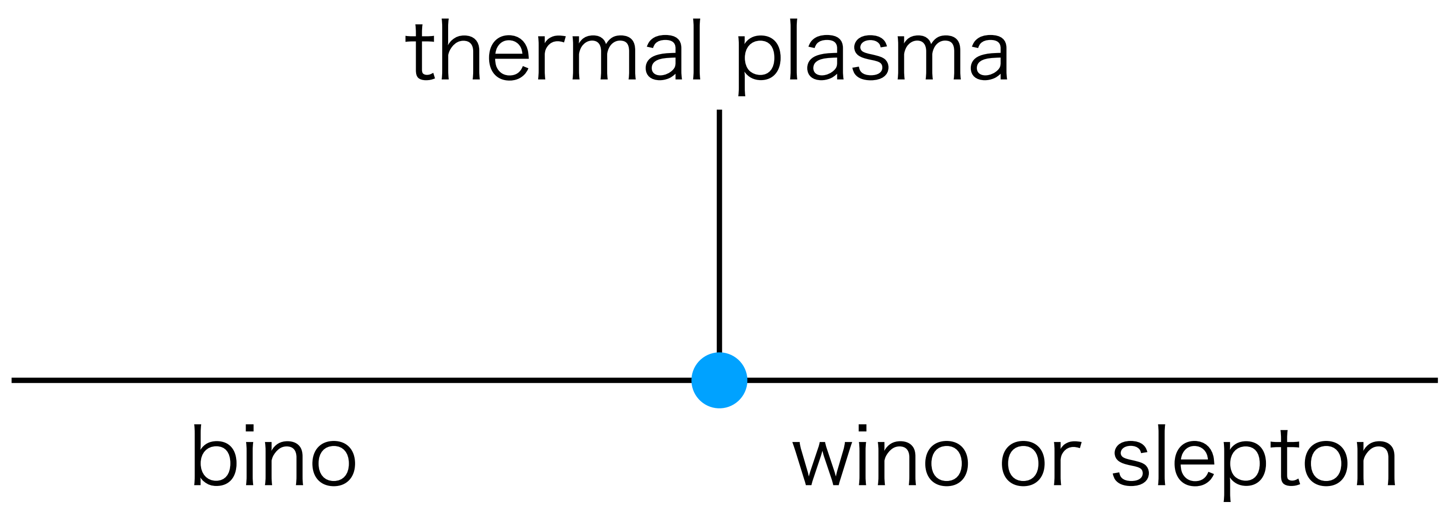
[Dan Hooper, 2019]

How can we obtain the correct relic abundance?

Coannihilation

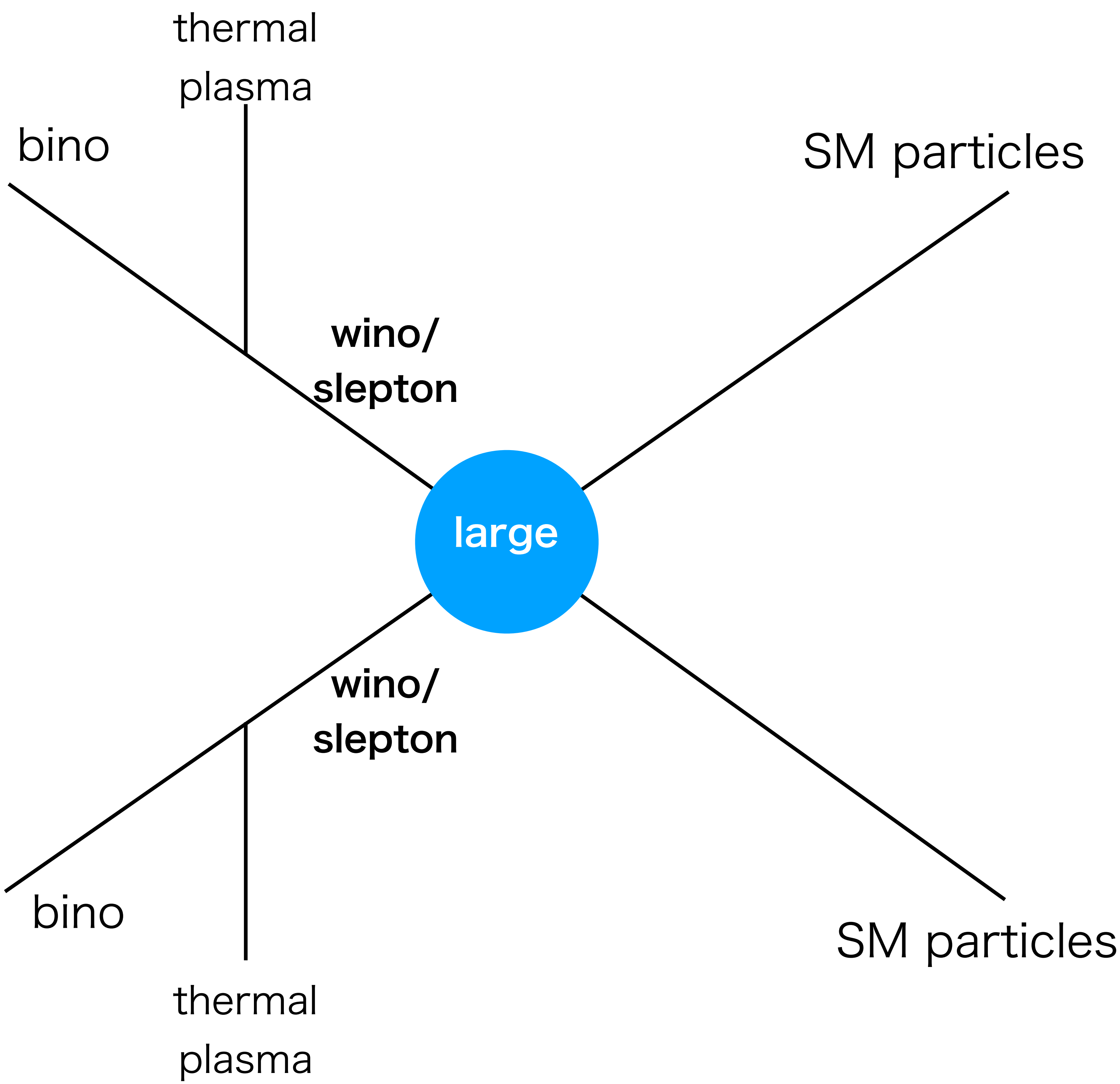
In early universe, transition between bino and wino or slepton is rapid

(wino: superpartner of $SU(2)_L$ gauge boson)

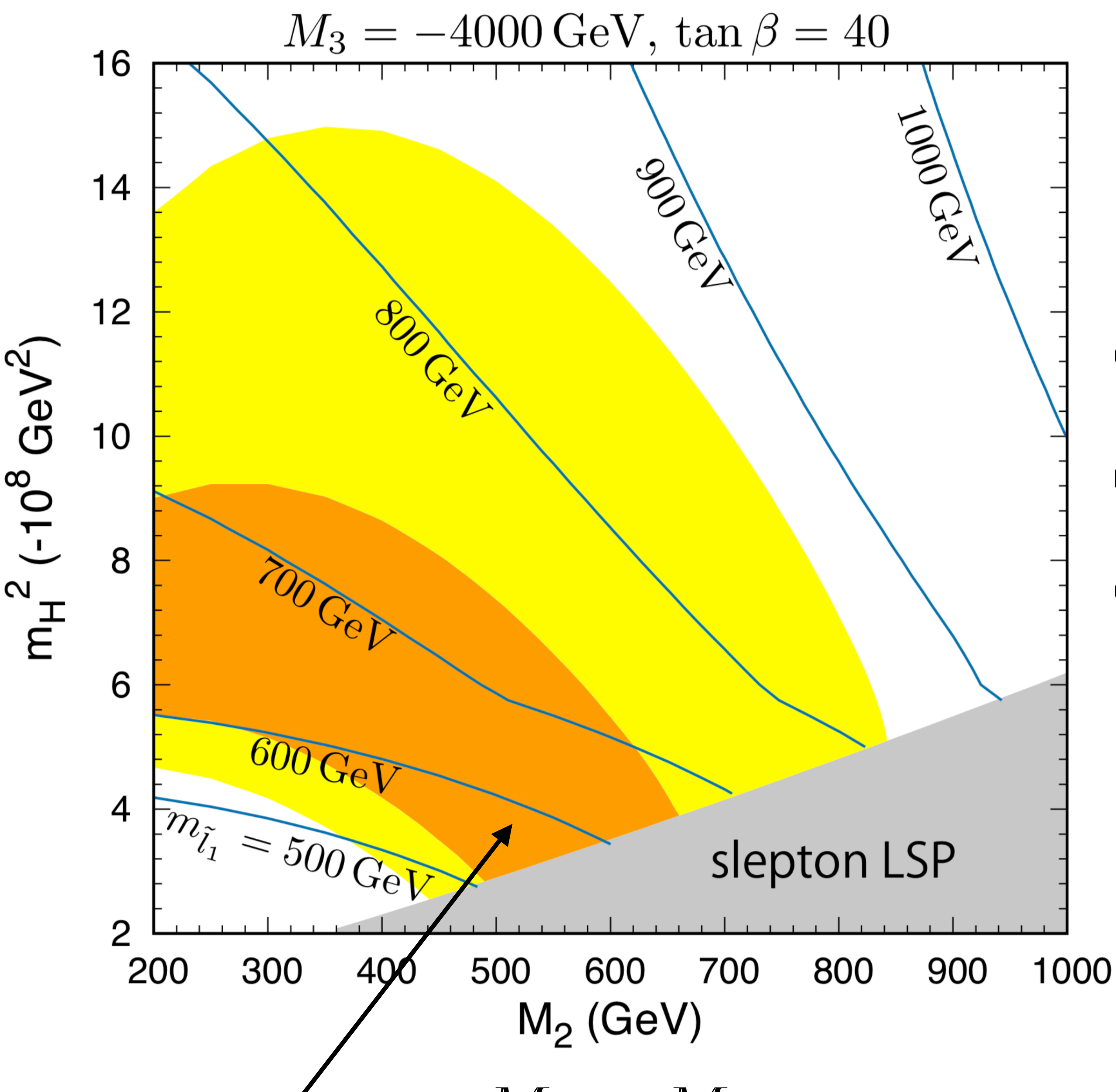


In order to have a large enough transition rate when the bino freezes out, the masses of bino and wino or slepton should be nearly degenerated

Coannihilation



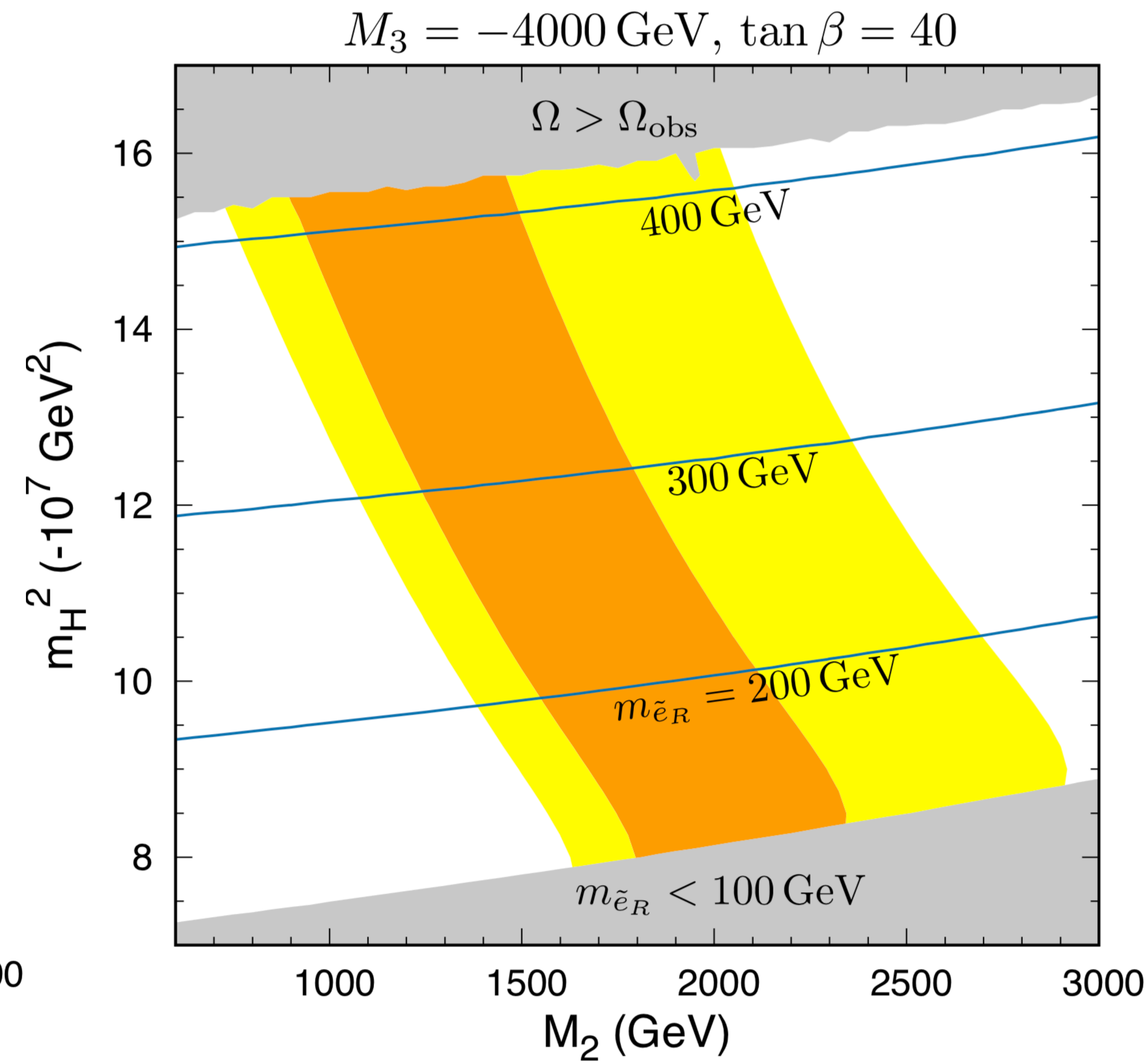
The relic abundance of bino dark matter is efficiently reduced bino-wino coannihilation



g-2 1 σ

$M_1 \sim M_2$ @low-energy

bino-slepton coannihilation

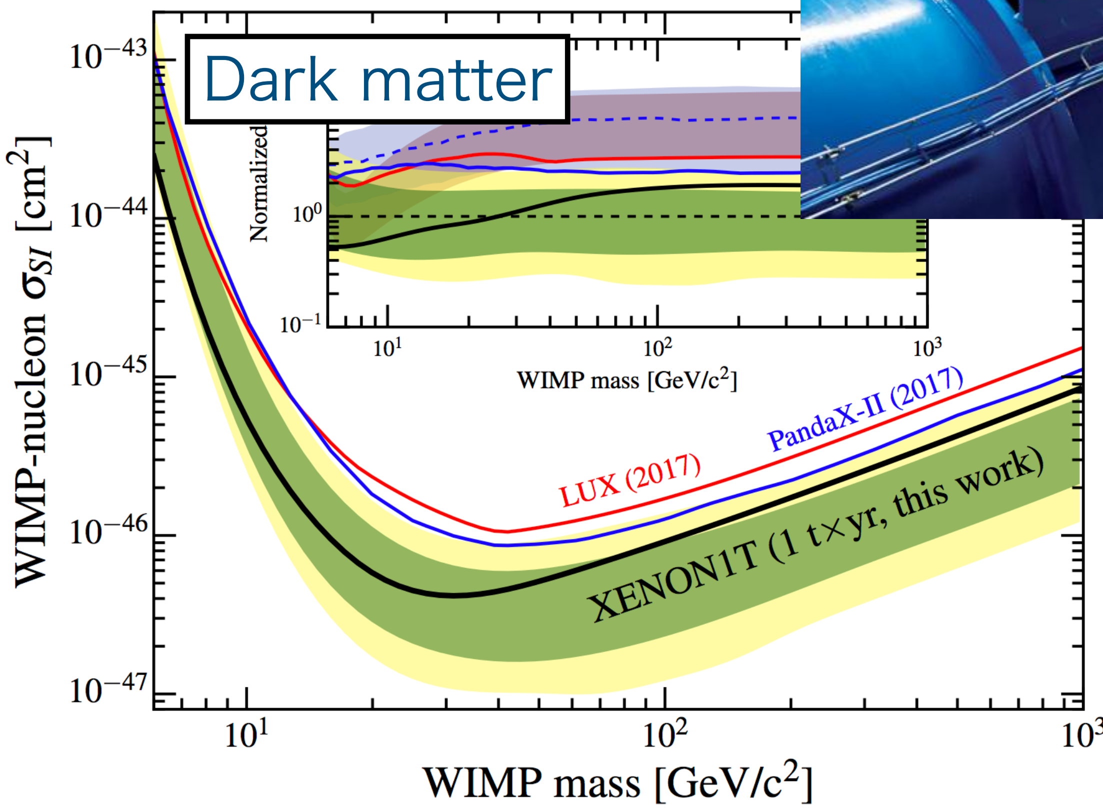


$M_1 \sim m_{\tilde{e}_R}$

[Cox, Han, Yanagida, NY, 2018]

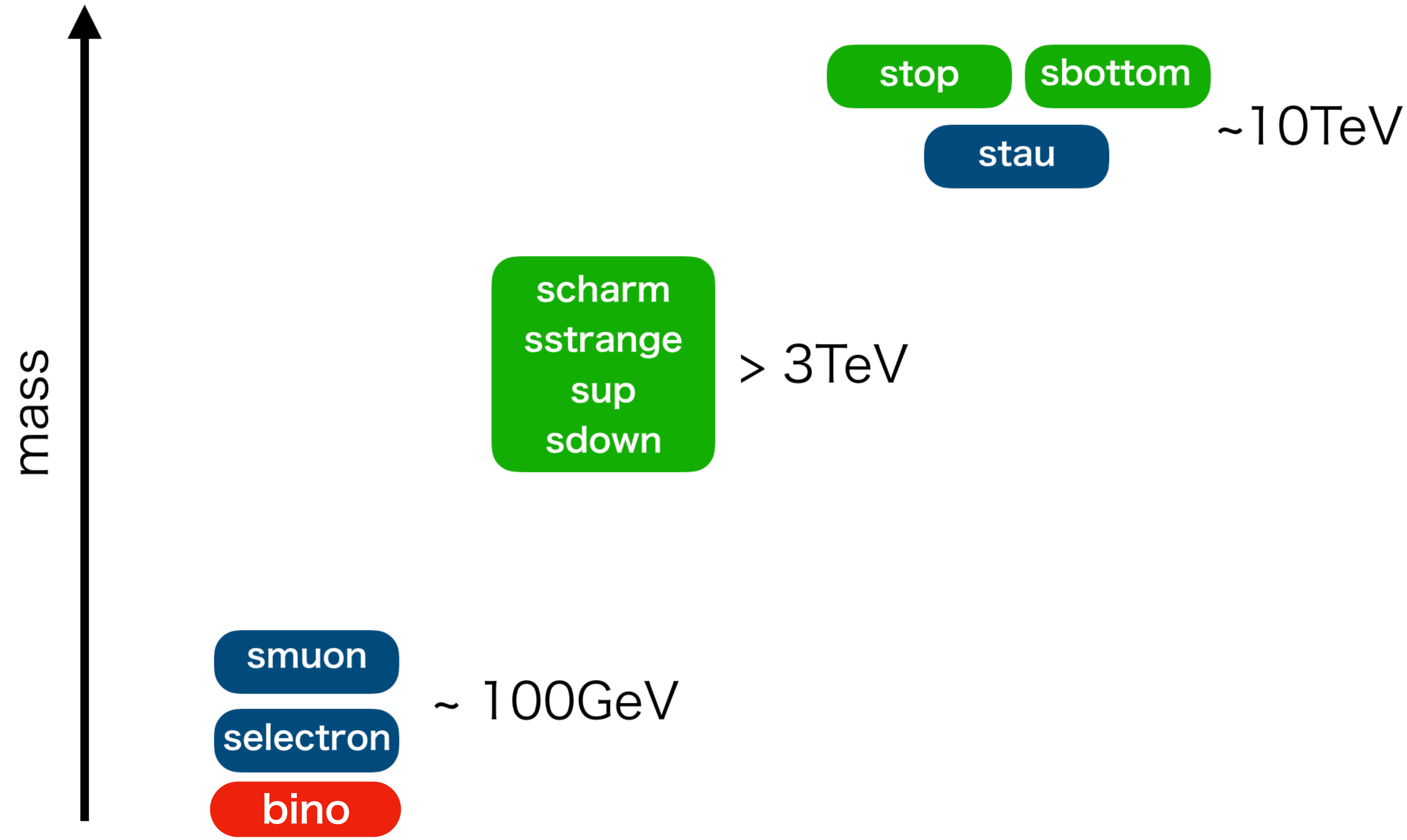
Whole viable regions are consistent with dark matter and LHC constraints

Summary



We are led to Higgs mediation

Summary



Higgs mediation predicts a unique SUSY mass spectrum

Smuons and selectrons can be checked at the LHC

Bino dark matter is a perfect dark matter candidate

with the help of coannihilation

Backup slides

Non-universal gaugino masses from product group unification

- In SUSY GUT models, there exists a serious fine-tuning problem: doublet-triplet splitting problem

- $SU(5) \times SU(3)_H \times U(1)_H$ model solves this problem elegantly

  [Yanagida, 1995; Hotta, Izawa, Yanagida, 1996]

- Non-universal gaugino masses naturally arise in this GUT model

- Gauge couplings (approximately) unify for large hidden gauge couplings

$U(1)_Y$: $$g_1^{-2} = g_5^{-2} + \mathcal{N}^{-1} g_{1H}^{-2} \,,$$

$SU(2)_L$: $$g_2^{-2} = g_5^{-2} \,,$$

$SU(3)_C$: $$g_3^{-2} = g_5^{-2} + g_{3H}^{-2} \,,$$

The corrections can be small

For the gaugino masses, the relevant Lagrangian is

$$\mathcal{L} = \int d^2\theta \left(\frac{1}{4g_5^2} - \frac{k_5}{2M_P} Z \right) W_5 W_5 + h.c.$$
$$+ \int d^2\theta \left(\frac{1}{4g_{3H}^2} - \frac{k_{3H}}{2M_P} Z \right) W_{3H} W_{3H} + h.c.$$
$$+ \int d^2\theta \left(\frac{1}{4g_{1H}^2} - \frac{k_{1H}}{2M_P} Z \right) W_{1H} W_{1H} + h.c.\,,$$

$\simeq g_5^2/\mathcal{N}$

bino: $$M_1 = (k_5 \mathcal{N} + k_{1H}) \frac{g_5^2 g_{1H}^2}{g_5^2 + \mathcal{N} g_{1H}^2} \frac{F_Z}{M_P}\,,$$

wino: $$M_2 = k_5 g_5^2 \frac{F_Z}{M_P}\,,$$

$\simeq g_5^2$

gluino: $$M_3 = (k_5 + k_{3H}) \frac{g_5^2 g_{3H}^2}{g_5^2 + g_{3H}^2} \frac{F_Z}{M_P}\,,$$