# ILC Physics Overview

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# Purpose

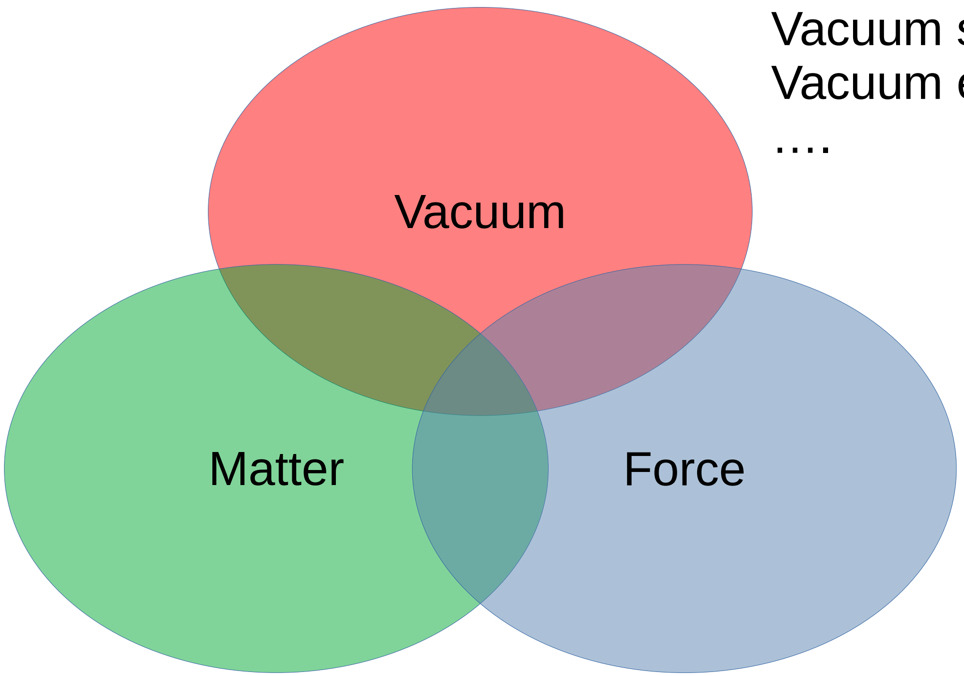
- In 2021, ILC-Japan (chair: Shoji Asai) starts to discuss physics and technology of future collider, including ILC.

(Physics side)

- Dark Matter, baryogenesis, cosmic ray, flavor, g-2 anomalies… and so on
- I will talk about brief summary of the discussion and my personal view.

# Physics target

Vacuum stability.
Vacuum energy.
….

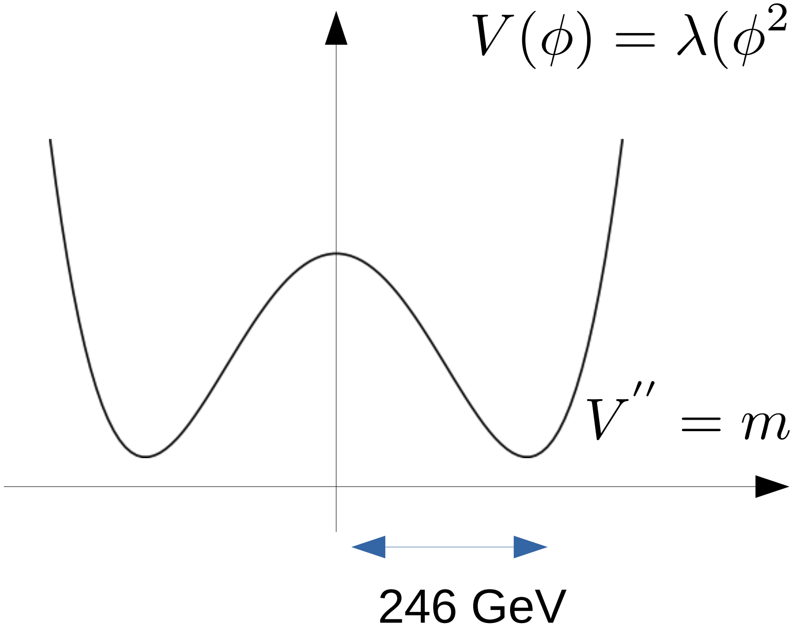



Origin of (dark) matter.
Three generation?
...

Grand unified theory.
Gravity.
...

# Higgs potential

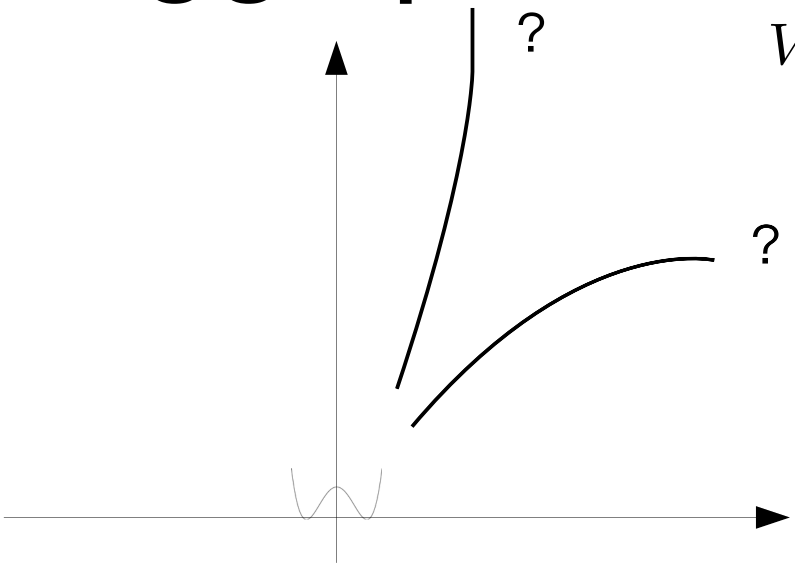
$$V(\phi) = \lambda(\phi^2 - v^2)^2$$




$$V^{''} = m_h^2 = (125\ \mathrm{GeV})^2$$

In Standard Model (SM), Higgs potential is now determined

# Higgs potential




$$V(\phi) = \lambda(\phi^2 - v^2)^{2?,\ 3?,\dots}$$

Theorist wants to know not only local but global structure of potential.

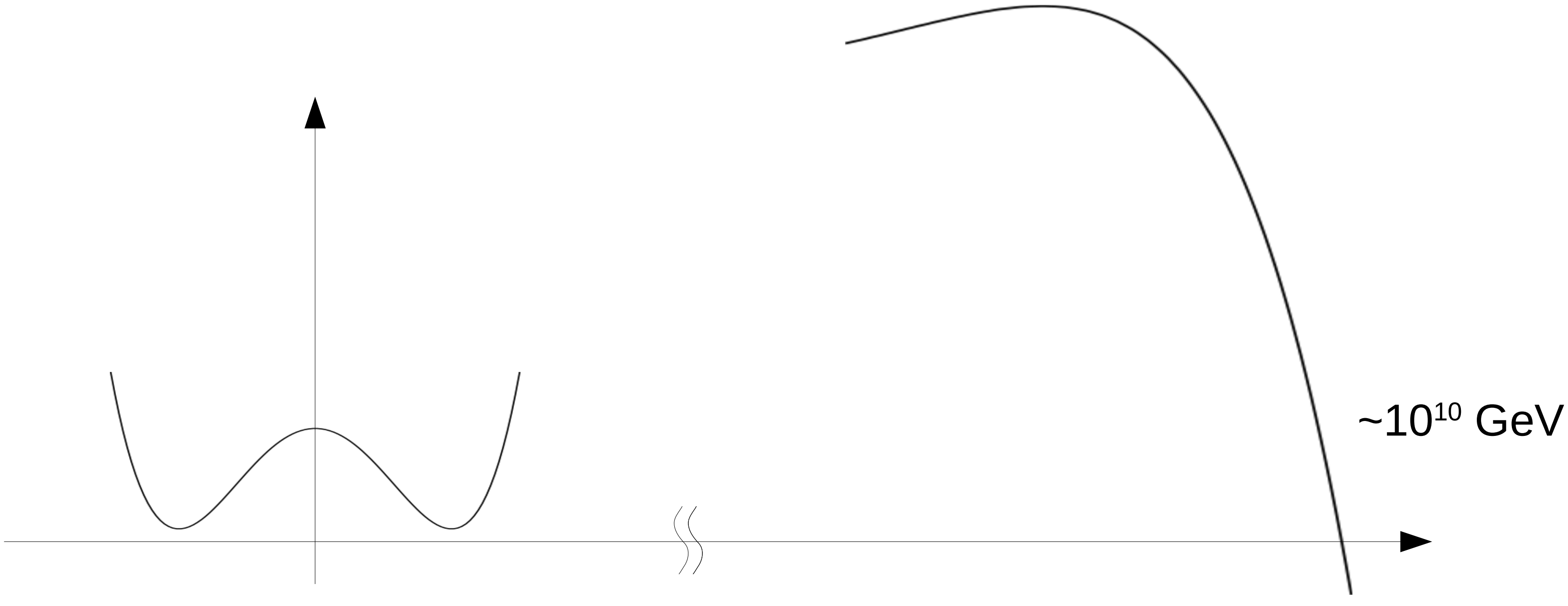
Measurement of Higgs self-coupling is crucial.

# Fate of Higgs

Current observation suggests our vacuum is not stable...

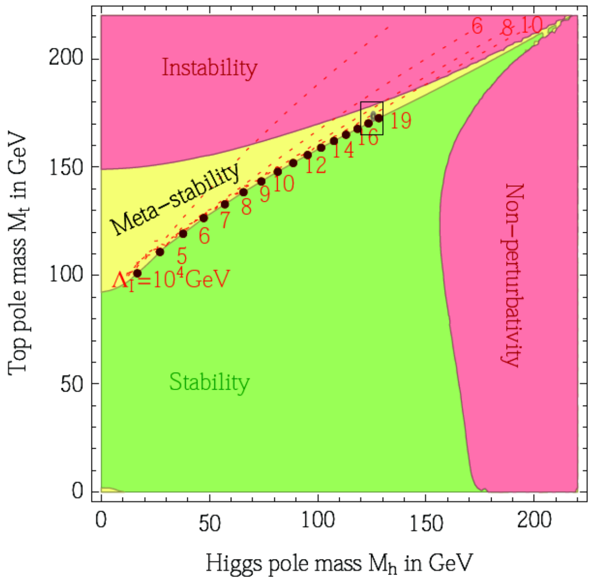
$$V(\phi) = \lambda(\phi)(\phi^2 - v^2)^2 \quad \lambda(\phi) = \lambda_0 + \frac{3y_t^2}{4\pi^2}\log(\phi/m_t)(2\lambda_0 - y_t^2) + \cdots$$

Top quark contribution

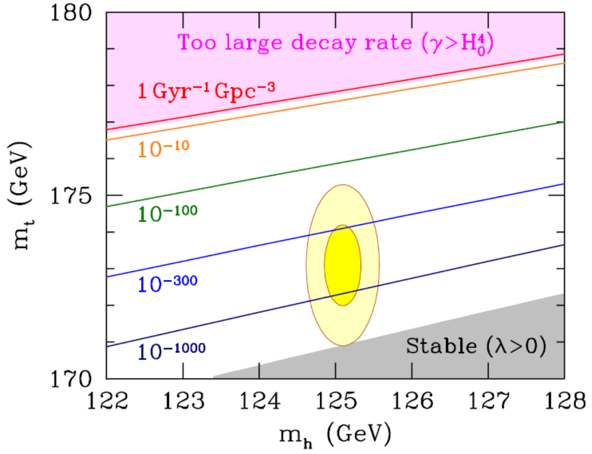


# Higgs and Top

[Buttazzo et.al, 2013]




[Chigusa,Moroi&Shoji 2017]




Does universe exist in parameters that are on the edge of metastable?

# Higgs and top

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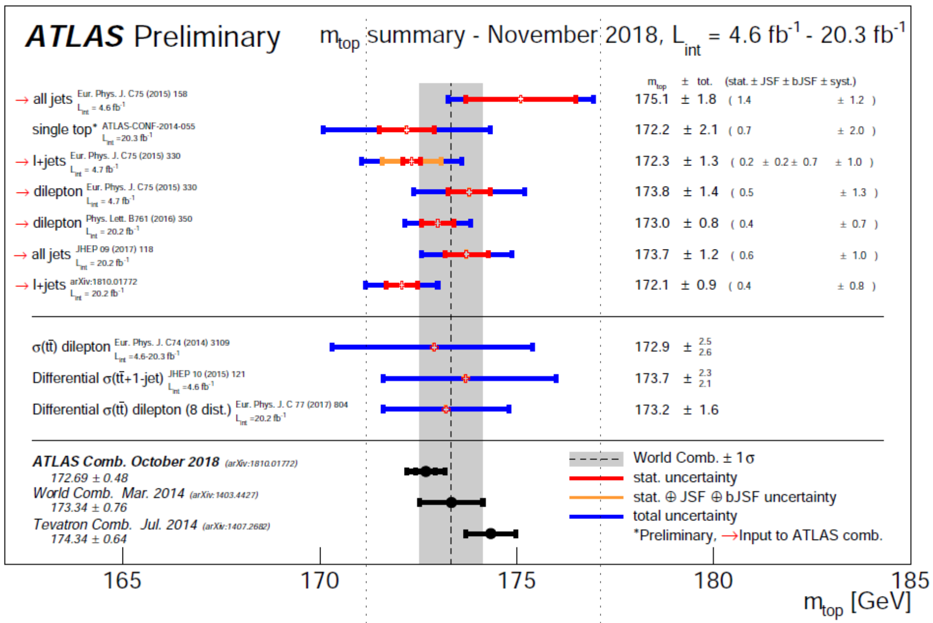


Stable

Unstable

171.0

177.8

# Higgs and top

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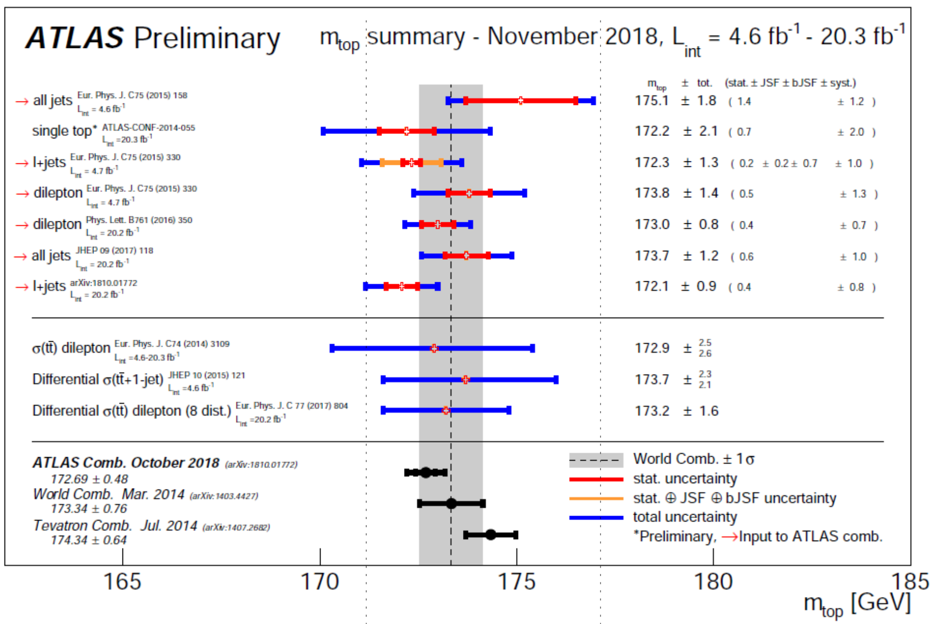



| Stable | Unstable |
|---|---|

171.0 177.8

top Yukawa

Top uncertainty

MC mass ↔ Pole mass ↔ $\overline{\text{MS}}$

Higher order: 300 MeV

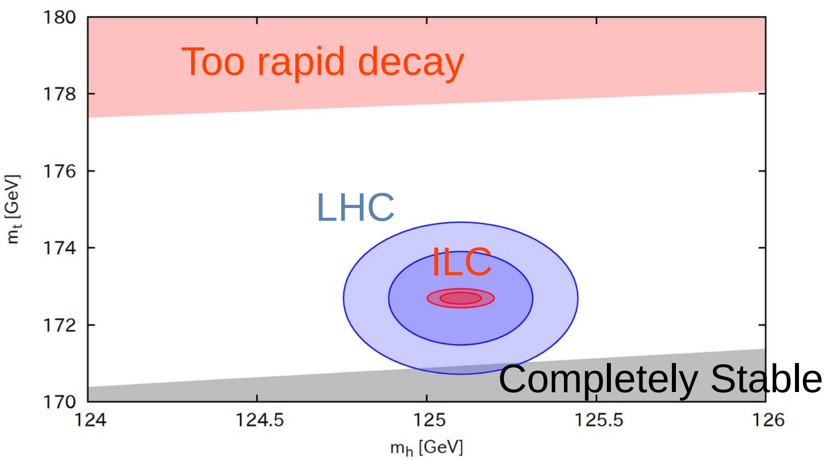
[Beneke,Marquard,Nason&Steinhauser 2016]

Renormalon: $\Lambda_{QCD}$ ?

MC ↔ "Pole": ~400 MeV

[ATL-PHYS-PUB-2021-034]

# Top quark at ILC

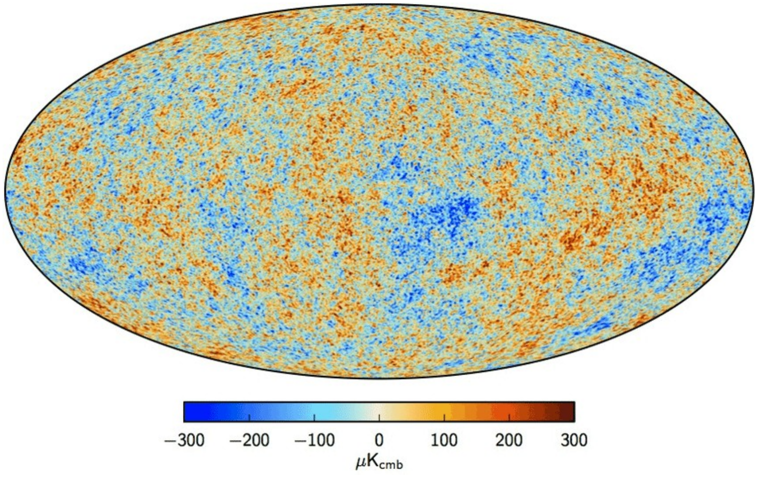


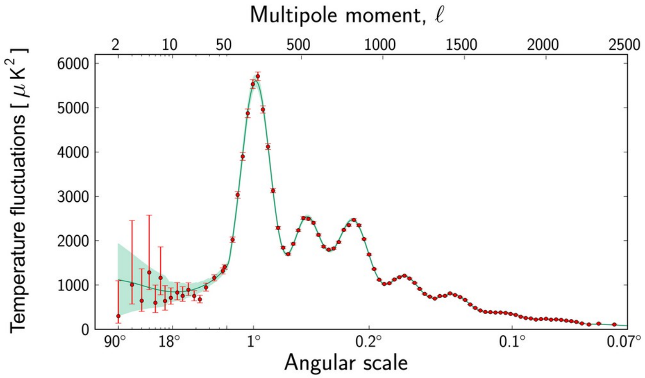

Precise top mass measurement

- Higgs stability.
- Important for electroweak precision.
- Higgs mass prediction in SUSY.

# Origin of Matter

As inflation paradigm is established, this problem should be solved.



# Baryogenesis

| Sakharov conditions | SM |
|---|---|
| Baryon number B violation | OK |
| C and CP-symmetry violation | Not enough |
| Out of thermal equilibrium | No |

Needs of New Physics

# Many Models

[Shaposhnikov Discrete'08]

1. GUT baryogenesis2. 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

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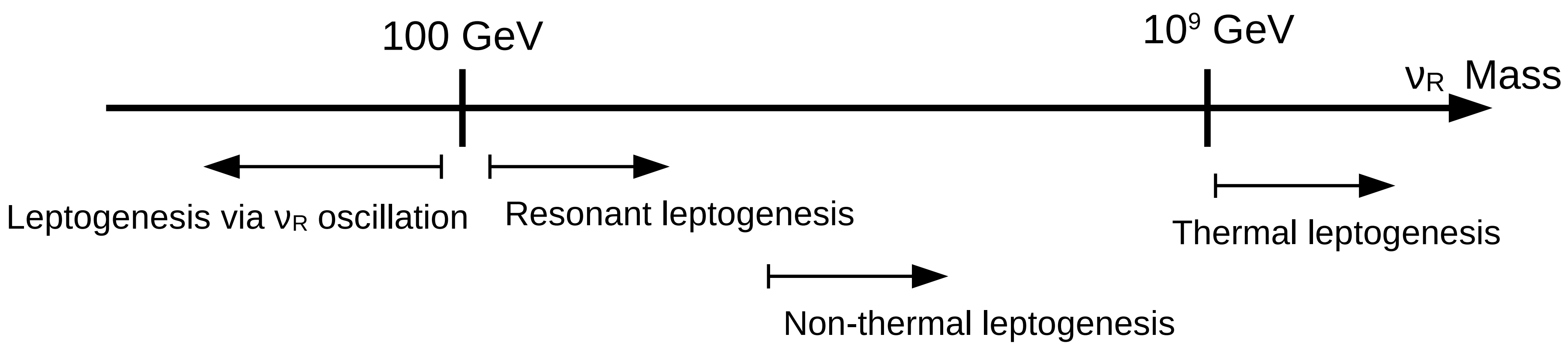
# Leptogenesis

[Fukugita, Yanagida 1986]

In SM, neutrinos should be massless, but...

neutrino oscillation ⇒ neutrino mass ⇒ right-handed neutrinos $\nu_R$

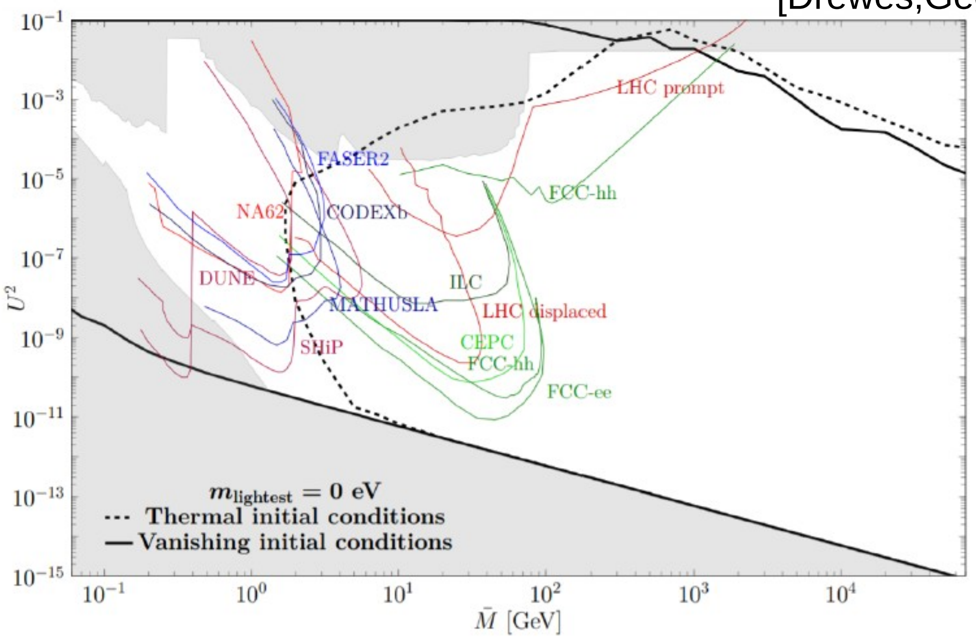
Leptogenesis: right-handed neutrinos generate lepton and baryon numbers



# Leptogenesis and Collider

- Resonant and/or $N_R$ oscillation is OK for low-scale leptogenesis.
- Heavy neutrino can couple to weak bosons.
- Right-handed neutrinos can be either long-lived or short-lived.
  - Beam dump, B-factory, LHC,...

[Drewes,Geori&Klarić 2021]

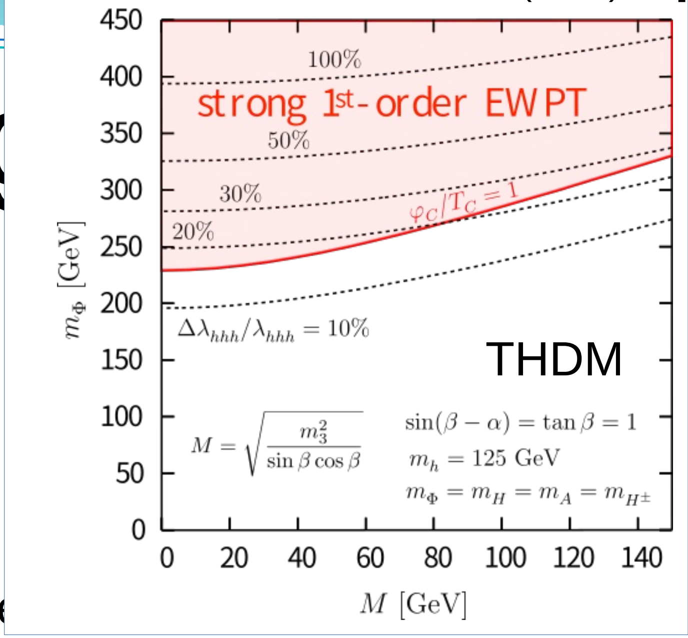


# Electroweak baryogenesis

- New particle coupling with Higgs.
  - Strong 1$^{st}$ order phase transition.
  - Large CP violation.
  - e.g., singlet scalar, electroweak-charged particles.
- Many models. Generally, new particle lighter than 1 TeV.
  - Higgs Coupling should be large.
- Direct search of new particles.
  - Production via Higgs and gauge bosons.
- Precise measurement of modification of Higgs potential.
  - Self-interaction, and so on.

# Electroweak baryog

[Kanemura, Okada, Senaha, PLB606,(2005)361]

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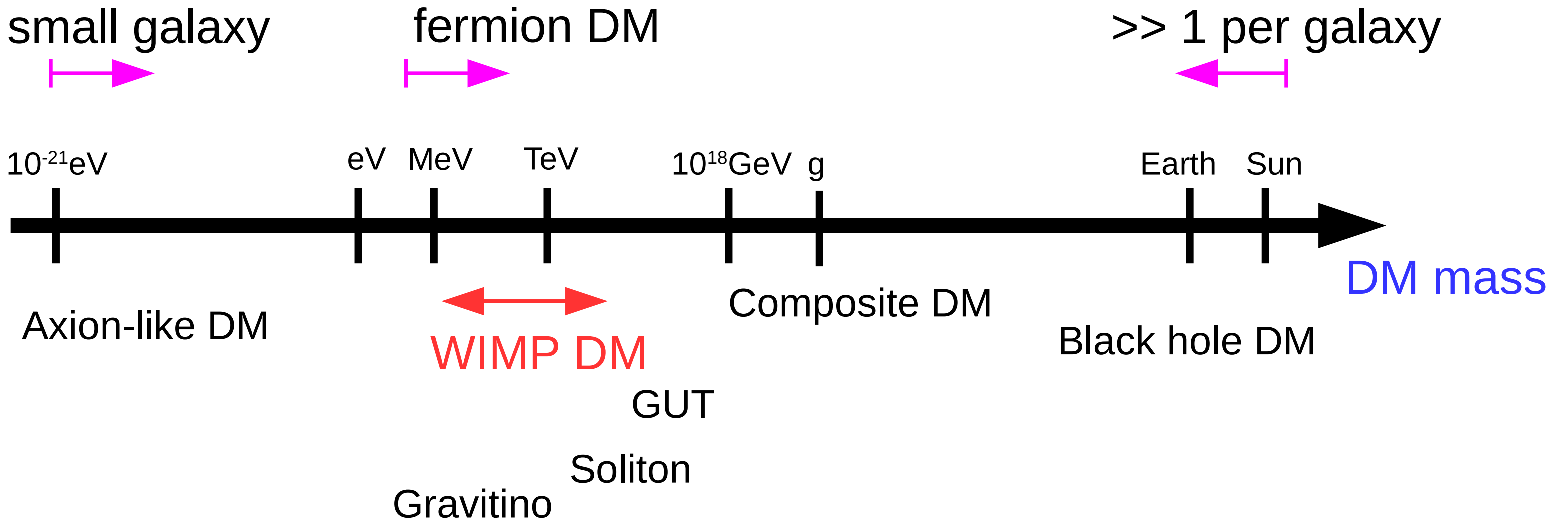
# DM Landscape




- Very wide mass range for DM
- Collider accessible region looks small...
  - Small mass region: too small to produce at collider.
    - Beam dump?
  - High mass region: beam energy is not enough.

# WIMP Example

Ambitious model that tries to solve many problems, such as SUSY

- 3 TeV Wino dark matter
  - Well motivated.
  - How robust constraint from H.E.S.S./MAGIC.
  - $\sqrt{s} = 2m_{\rm wino} + \epsilon$ lepton collider for direct search.
    - Mono-photon BG?
    - Use of disappearing charged track?
  - $\sqrt{s} \sim 80\% \times 2m_{\rm wino}$ lepton collider for indirect search.
    - How robust estimation of SM BG?
  - $\sim$ 2030, both direct detection and cosmic ray experiments can t
    3 TeV Wino.
    - If confirmed, strong motivation for collider search.
- 1 TeV Higgsino
  - Similar collider signature as Wino.
  - Weaker signature of direct detection and cosmic ray experiment
    compared to Wino case.
- SUSY DM with muon $g - 2$
  - Slepton and chargino searches.
    - Mass range of chargino and slepton for $\Omega h^2 = 0.12$ and $a_\mu$ consistent with Fermilab and Brookhaven?
    - How much compressed spectrum for slepton and LSP system?

# Various Hints

Origin of
(dark) matter

Should be solved!

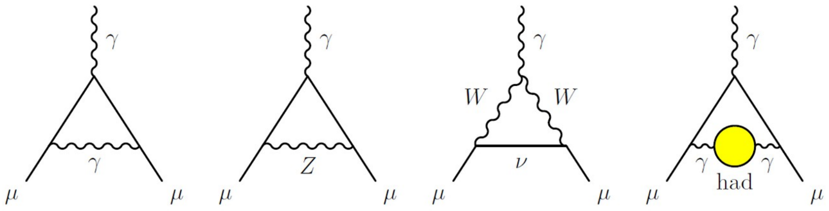
Vacuum structure

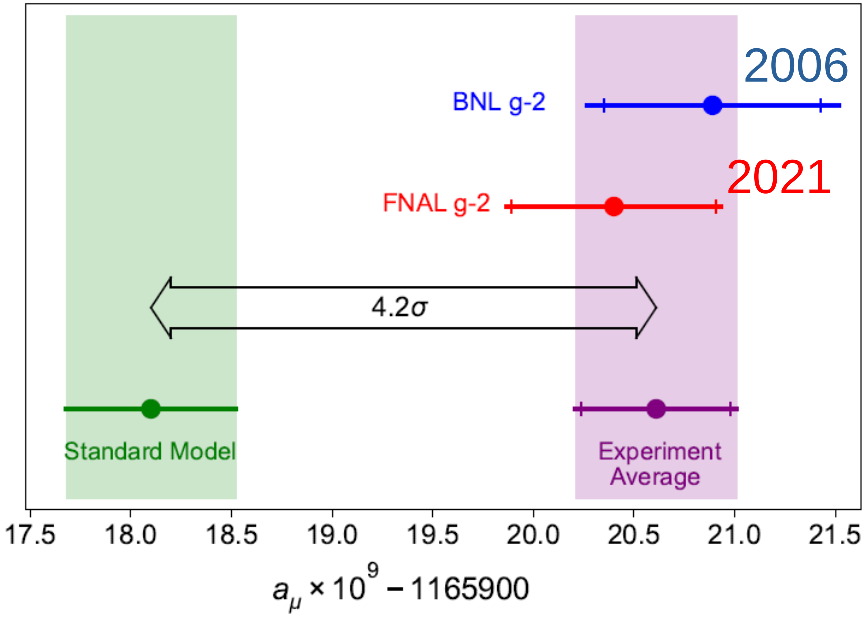
More conceptual issues?

muon g-2
flavor anomaly
cosmic ray
W boson mass
…

Current experimental anomalies.
It could be a problem to be solved.

# Muon g-2




Experimental error?

SM estimation?

New physics?

# New physics and Muon g-2

Effective field theory

$$\mathcal{L}_{\text{eff}} = a_\mu \frac{e}{4m_\mu} \bar{\psi} \sigma^{\mu\nu} \psi F_{\mu\nu}$$

$$a_\mu \sim \frac{m_\mu^2}{\Lambda_{\text{NP}}^2} \ (\text{tree}) \qquad \Lambda_{\text{NP}} \sim 3 \text{ TeV}$$

$$a_\mu \sim \frac{1}{16\pi^2} \frac{m_\mu^2}{\Lambda_{\text{NP}}^2} \ (\text{loop}) \qquad \Lambda_{\text{NP}} \sim 200 \text{ GeV}$$

new physics up-to TeV scale?

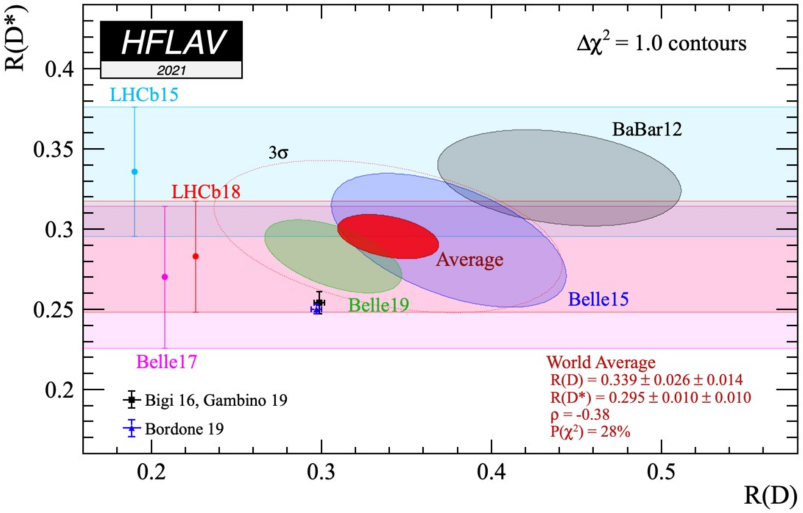
Examples:

| New physics | Mass scale | Collider |
|---|---|---|
| Leptoquark | $m_{LQ} \lesssim$ 5-10 TeV | $\delta\Gamma(h \to \mu^+\mu^-) \sim 10\%$ |
| Vector-like lepton | $m_L \lesssim$ 5-10 TeV | $\delta\Gamma(h \to \mu^+\mu^-) \sim 100$ |
| SUSY: light wino/Higgsino | $\mathrm{m}_{\tilde{l},\tilde{\chi}} \lesssim$ 600 GeV | Direct SUSY search |
| SUSY: pure wino | $\mathrm{m}_{\tilde{l},\tilde{\chi}} \lesssim$ 300 GeV | Direct SUSY search |
| Leptophilic scalar | $\mathrm{m}_\phi \sim$ 10 GeV | Direct search |
| ... | | |

# Flavor anomalies

E.g., lepton universality

$$R_{X^{(*)}} = \frac{\Gamma(\bar{B} \to X^{(*)}\ell')}{\Gamma(\bar{B} \to X^{(*)}\ell)}$$



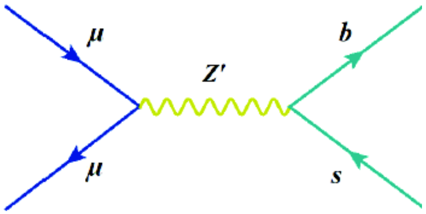

$R_{D^{(*)}}$: $\sim 3\sigma$ deviation

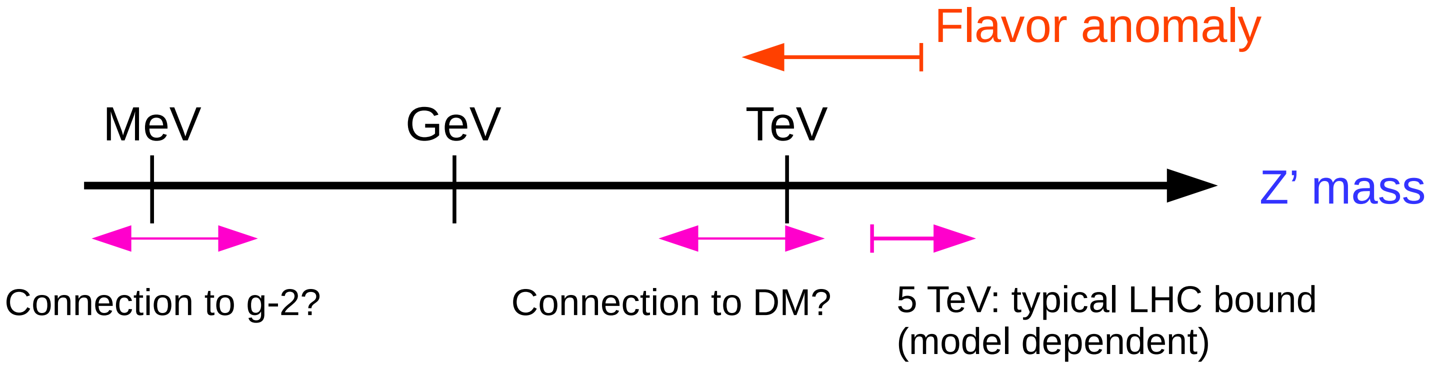
$R_{K^{(*)}}$: $\gtrsim 5\sigma$ deviation

# Flavor and New Physics

Tree level NP contribution with $M_{\rm NP} < 10$ TeV

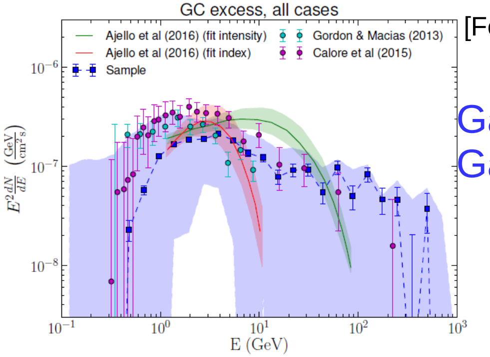
Z' model



# Cosmic Ray Anomalies

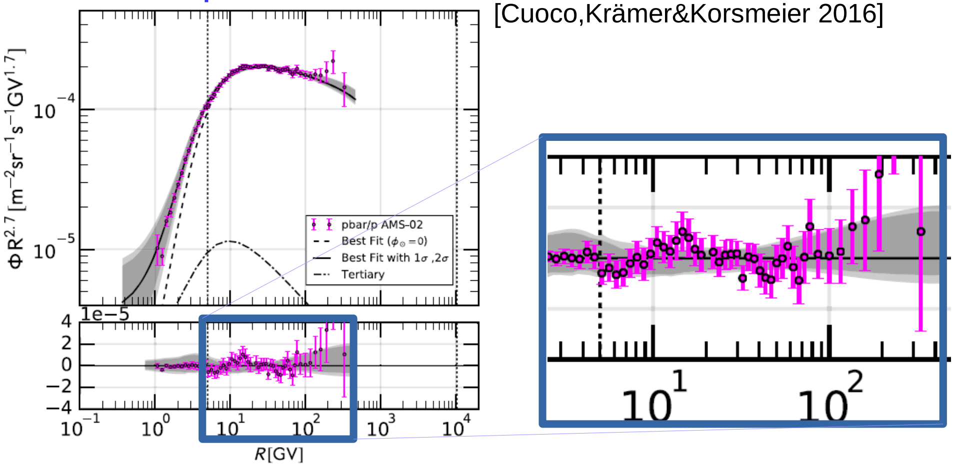
- GC Gamma-ray excess
- Andromeda excess
- 130 GeV Gamma-ray line
- 511 keV excess
- 3.5 keV X-ray line
- WMAP excess
- Isotropic radio excess
- Positron excess
- Anti-proton excess




[Fermi -LAT collaboration 2017]

Gamma-ray excess at Galactic center.

Anti-proton excess

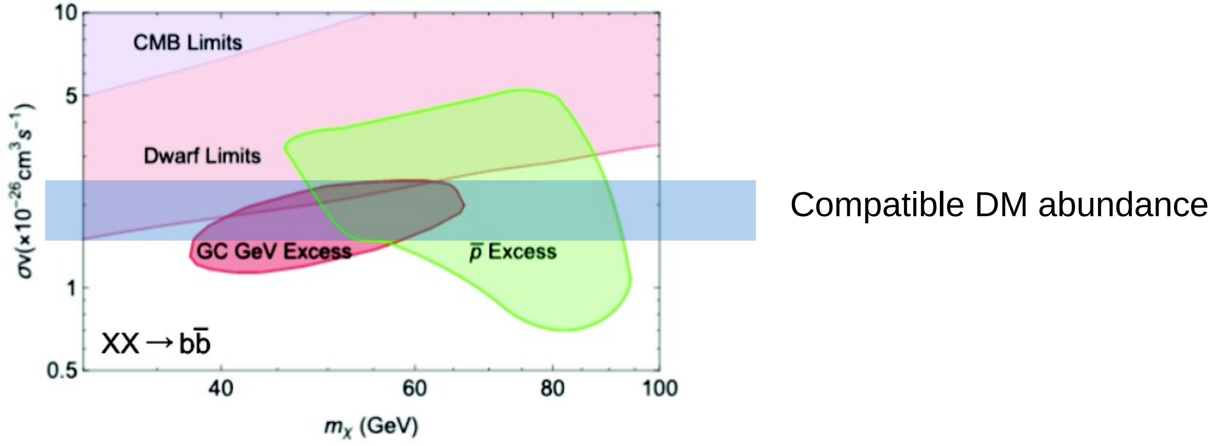



[Cuoco,Krämer&Korsmeier 2016]

DM? Astrophysics? Systematics?

# Cosmic Ray Anomalies

[Cholis,Linden&Hooper 2019]




- If DM,  DM lighter than 100 GeV and interaction is sizable.
    - e.g., Higgs portal DM.
    - Best game for lepton collider .

- Astrophysical background is non-trivial. Several studies show that astrophysical template functions can fit the anomaly.

# Summary

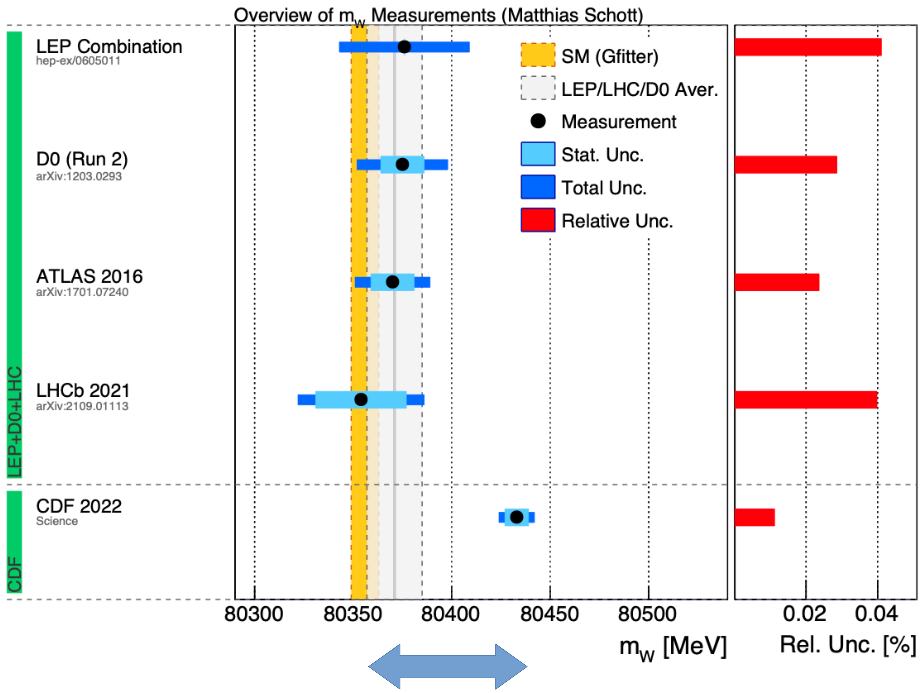
- As for new physics in general, accelerator experiments are not a panacea.
  - Theorists can make up any models which include super-massive particles and tiny interactions.

- Not so many model is well-motivated to solve many models.
  - “Older models" that have withstood various tests are still strong.
  - In many cases, TeV is prime target.

- Synergy with other experiments is important.
  - Flavor and g-2 may be clues, but they don't convince everyone, such as systematic errors.
  - Cosmic ray is extremely useful for  WIMP DM
    - con: Large astrophysical uncertainties.

- ILC can cover blind spots of LHC.
  - Compressed mass spectra. Less QCD uncertainties.

# W Boson Mass

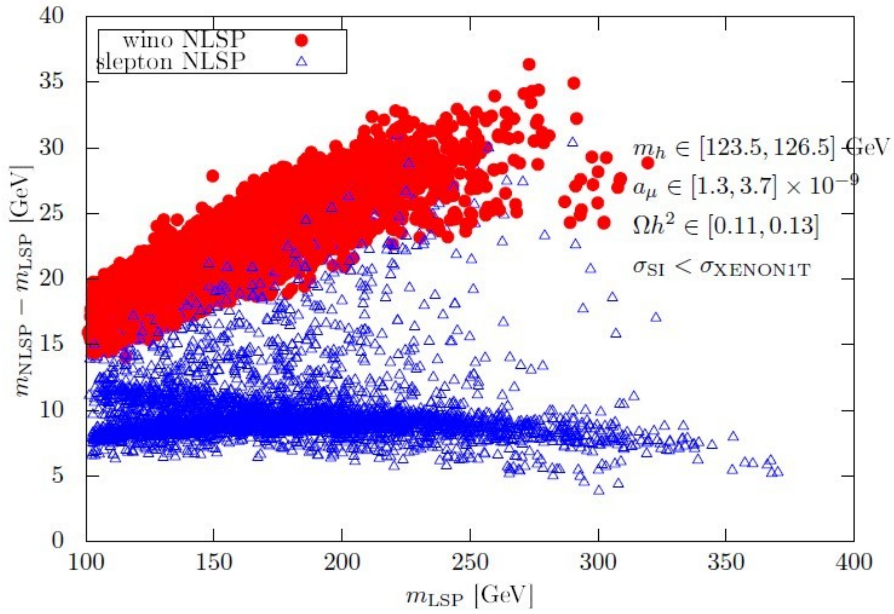



~90 MeV

$$\delta m_W|_{\mathrm{ILC}} \sim 5 \text{ MeV}$$

# Muon g-2 and SUSY

SUSY model with good muon g-2 and DM natures



# Vacuum

Naive estimation of vacuum energy.

$$\Lambda_{\mathrm{c.c.}}^{\mathrm{naive}} = (O(100)\ \mathrm{GeV})^2 - (O(10^{18})\ \mathrm{GeV})^2$$

Observed value is;

$$\Lambda_{\mathrm{c.c.}}^{\mathrm{obs}} \sim 10^{-84}\ \mathrm{GeV}^2$$

Why non-zero but small value?

- Hidden symmetry or dynamics?
- Simply parameter tuning?
- Anthropic?

UV theory indication?

- de Sitter conjecture: [Obied, Ooguri, Spodyneiko&Vafa, 2018]
  No (local) minimum of vacua with positive energy.
- Trans-Planckian censorship conjecture: [Bedroya&Vafa, 2019]
  No stable vacua
- Multiple Point Principle: [Froggatt&Nielsen, 1995]
  Multiple degenerated vacua.

# Flavor and New Physics

Tree level NP contribution with $M_{\rm NP} < 10$ TeV

Leptoquark model