Vacuum stability

So Chigusa @ Workshop for Tera-Scale Physics and Beyond (6/23)

EW vacuum stability

- Our electroweak (EW) vacuum is metastable in SM

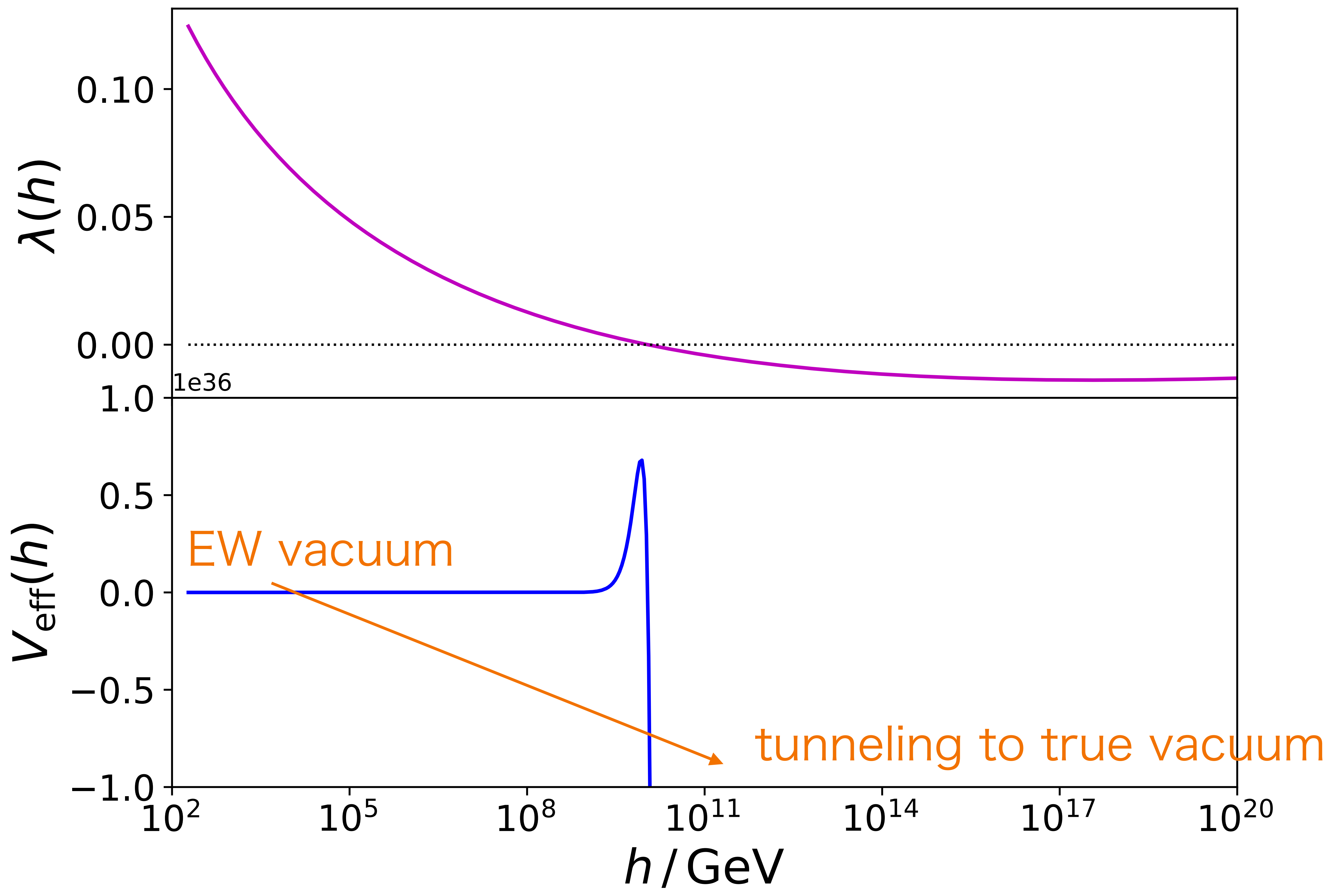
- Higgs potential

$$V(h) = \frac{1}{2}m^2h^2 + \frac{1}{4}\lambda\, h^4$$

- 1-loop effective potential at large h

$$V_{\rm eff}(h) \simeq \frac{1}{4}\lambda(h)\, h^4$$

- $\lambda(\mu) < 0$ for $\mu \gtrsim 10^{10}\,\mathrm{GeV}$ leads to metastability of EW vacuum $h = v$



SM phase diagram

$m_h = \sqrt{2\lambda}\,\langle\phi\rangle$; $v \simeq 246\,\mathrm{GeV}$

$$16\pi^2\beta_\lambda \simeq 12\lambda\left(2\lambda + y_t^2 - \frac{g_Y^2+g_2^2}{4} - \frac{g_2^2}{2}\right) - 6y_t^4 + 6\left(\frac{g_Y^2+g_2^2}{4}\right)^2 + 12\left(\frac{g_2^2}{4}\right)^2$$

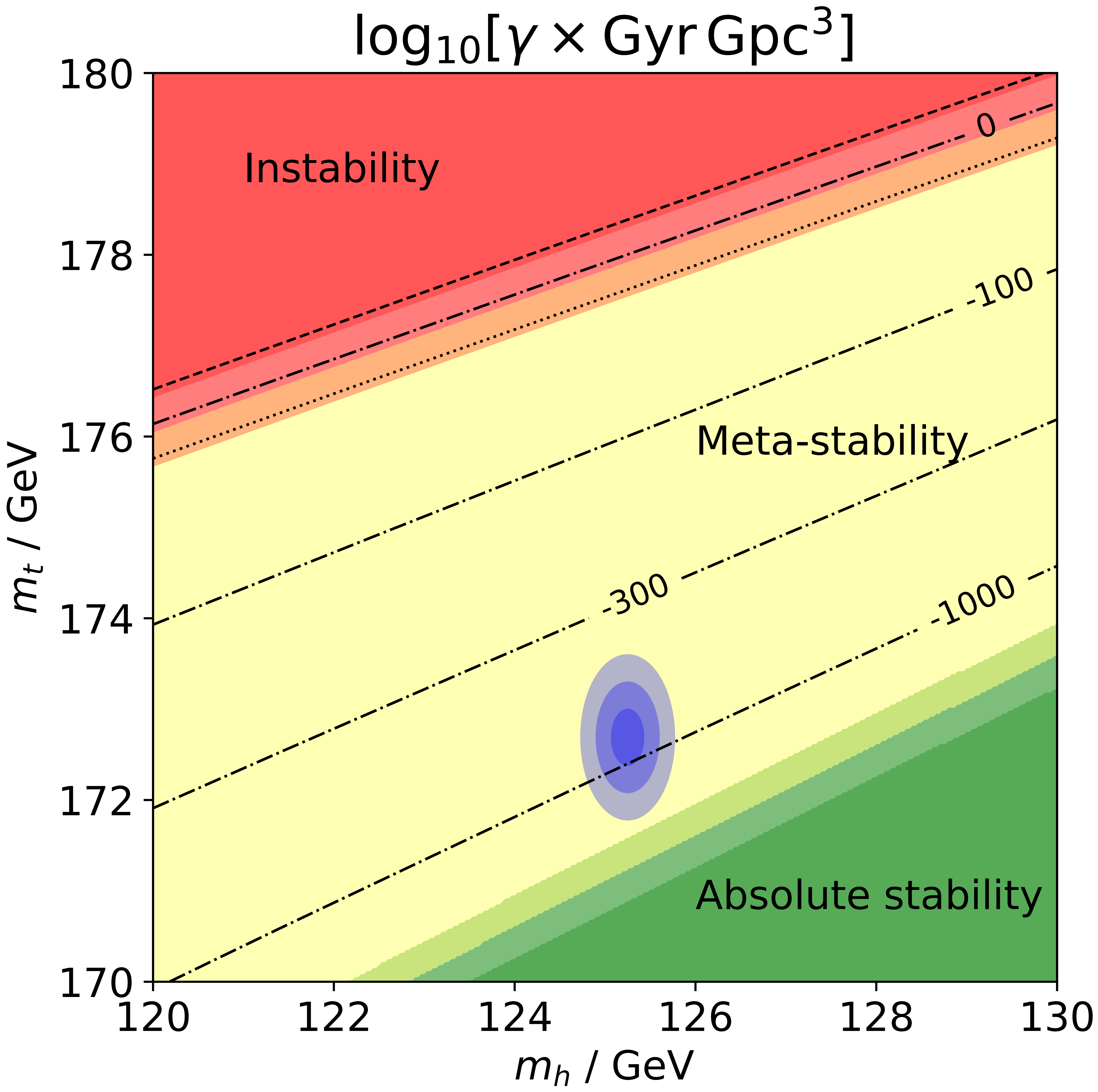
- Sensitive to Higgs/top mass
  - Larger Higgs mass, λ ➡ more stable
  - Larger top mass, y_t ➡ more unstable

- EW vacuum decay rate

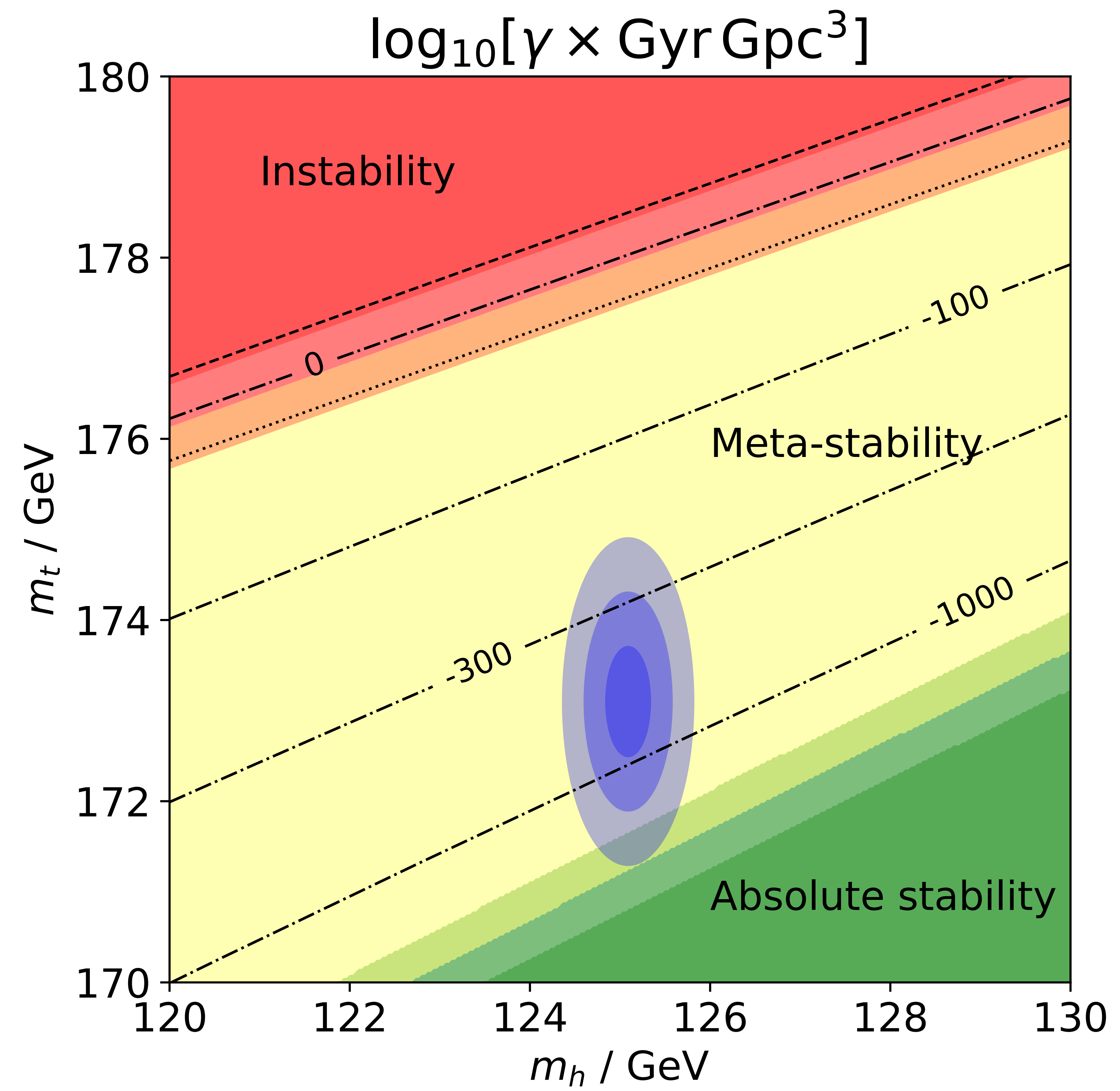
$$\log_{10}\left(\gamma \times \mathrm{Gyr\,Gpc}^3\right) = -785^{+45+155+181}_{-49-222-276}$$

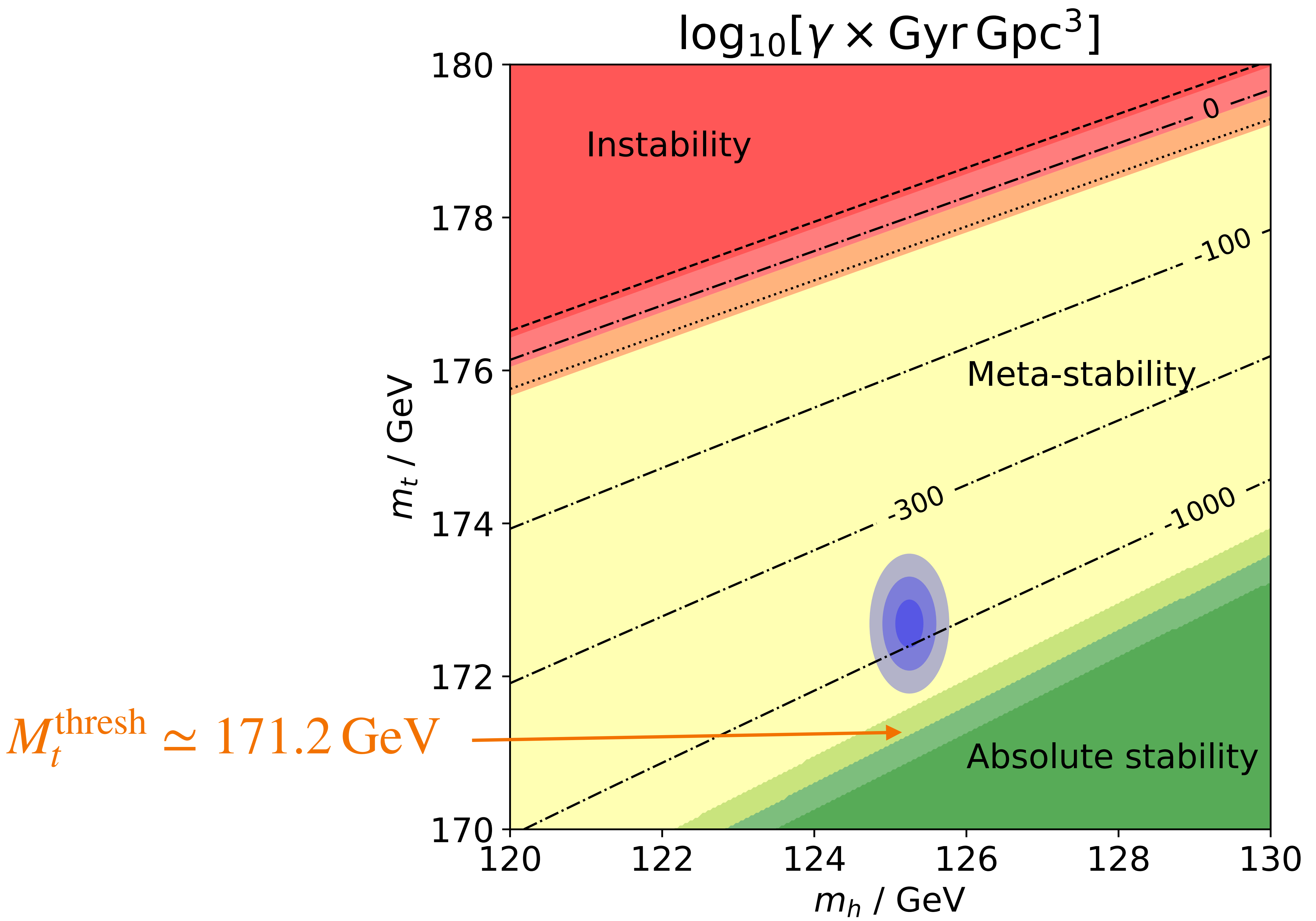
Δm_h Δm_t $\Delta \alpha_s$

  - Necessary condition: $\gamma < H_0^4 \simeq 10^{-3}\,\mathrm{Gyr}^{-1}\,\mathrm{Gpc}^{-3}$



Improvement over 5 years





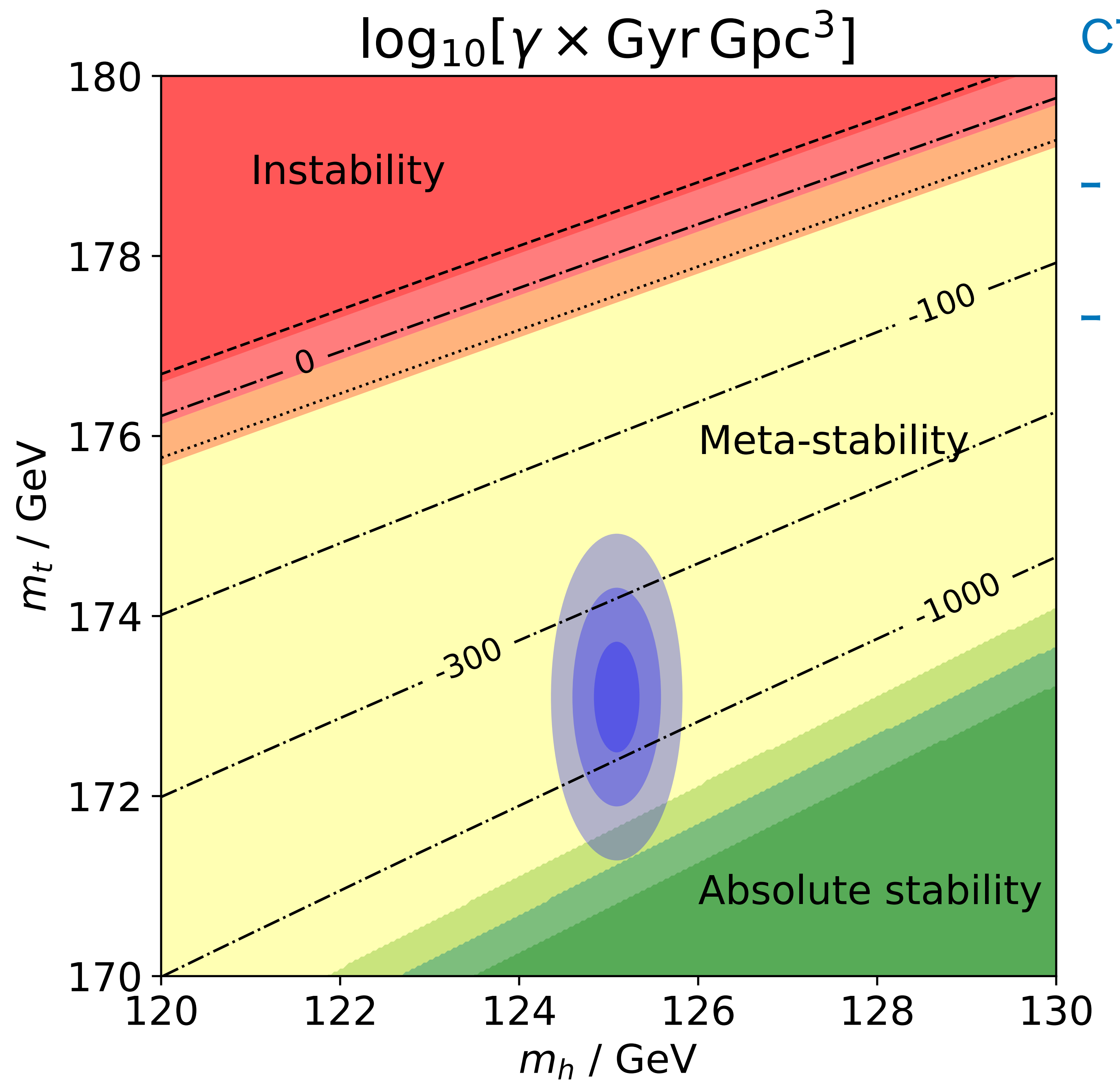
- $M_h = 125.09 \pm 0.24\,\mathrm{GeV}$
- $M_t = 173.1 \pm 0.6\,\mathrm{GeV}$
- $\alpha_s = 0.1181 \pm 0.0011$

SC, Moroi & Shoji [1803.03902]

- $M_h = 125.25 \pm 0.17\,\mathrm{GeV}$
- $M_t = 172.69 \pm 0.30\,\mathrm{GeV}$
- $\alpha_s = 0.1179 \pm 0.0009$

PDG 2023

Top mass subtlety

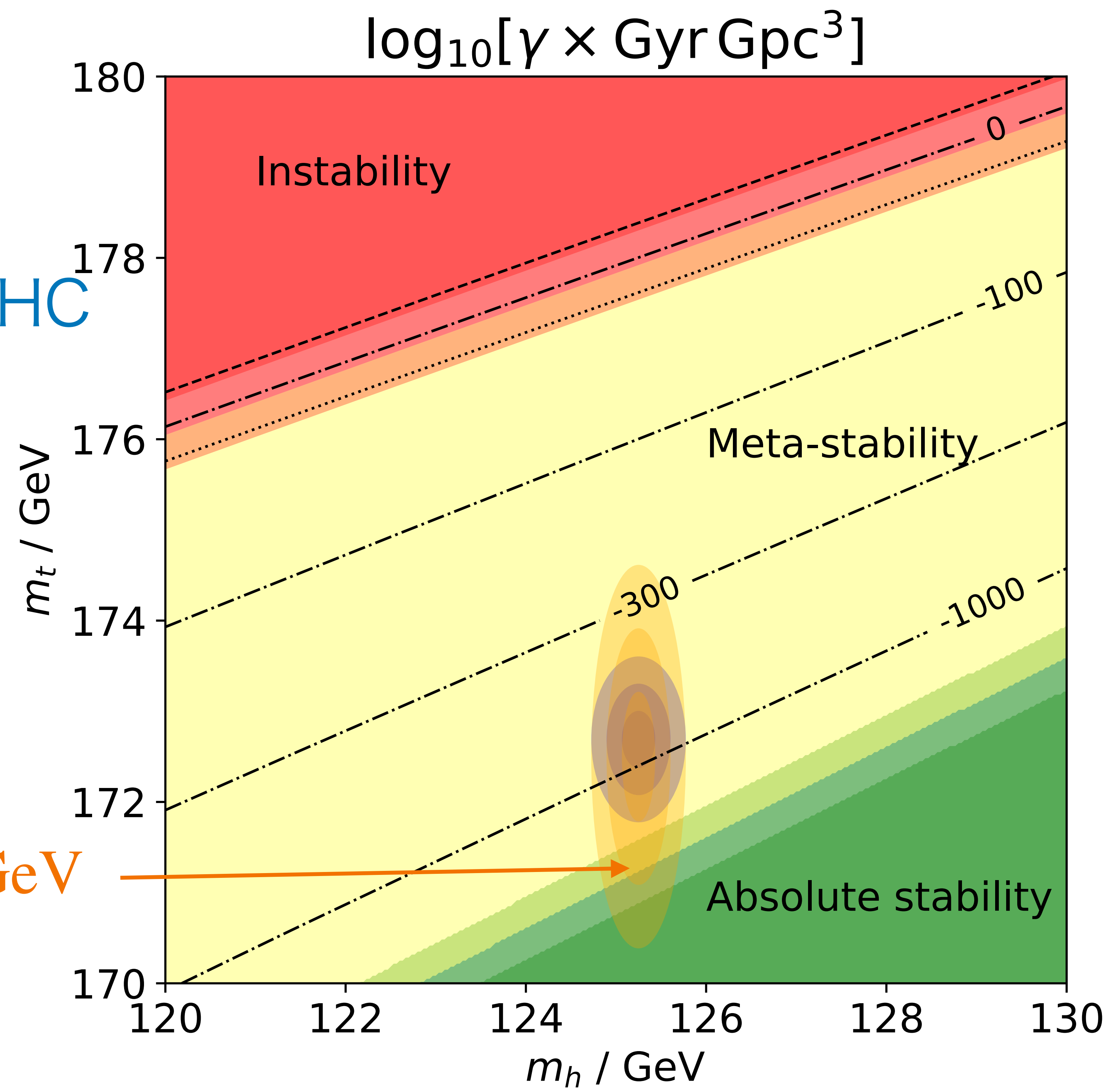


cf.

- $\left| m_t^{\mathrm{MC}} - m_t^{\mathrm{pole}} \right| \lesssim 1\,\mathrm{GeV}$
- $\Delta m_t \sim 0.2\,\mathrm{GeV}$ @ HL-LHC

Hoang [2004.12915]

$M_t^{\mathrm{thresh}} \simeq 171.2\,\mathrm{GeV}$



- $m_h = 125.09 \pm 0.24\,\mathrm{GeV}$
- $m_t = 173.1 \pm 0.6\,\mathrm{GeV}$ (MC mass)
- $\alpha_s = 0.1181 \pm 0.0011$

SC, Moroi & Shoji [1803.03902]

- $m_h = 125.25 \pm 0.17\,\mathrm{GeV}$
- $m_t = 172.5 \pm 0.7\,\mathrm{GeV}$ (Pole from cross-section)
- $\alpha_s = 0.1179 \pm 0.0009$

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"Small" new physics effect

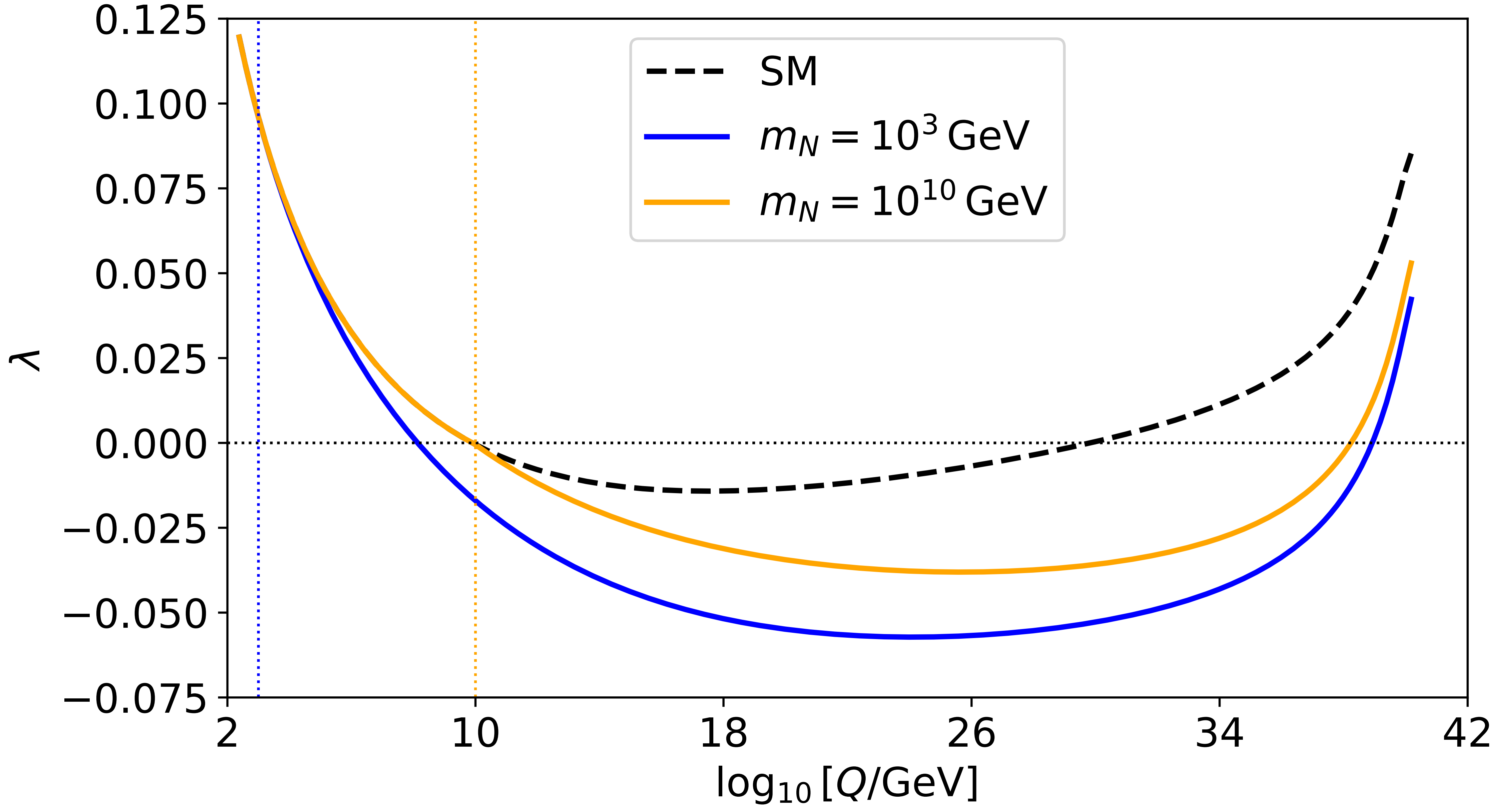
- "Non-decoupling" behavior e.g., Branchina+ [1507.08812], Patel+ [1704.00775]
  - New physics at high energy scale affects the EW vacuum stability

$$16\pi^2\beta_\lambda \simeq 12\lambda\left(2\lambda + y_t^2 - \frac{g_Y^2+g_2^2}{4} - \frac{g_2^2}{2}\right) - 6y_t^4 + 6\left(\frac{g_Y^2+g_2^2}{4}\right)^2 + 12\left(\frac{g_2^2}{4}\right)^2$$

$$+\frac{1}{2}\lambda_{hs}^2 - 2Y^4 + \cdots$$

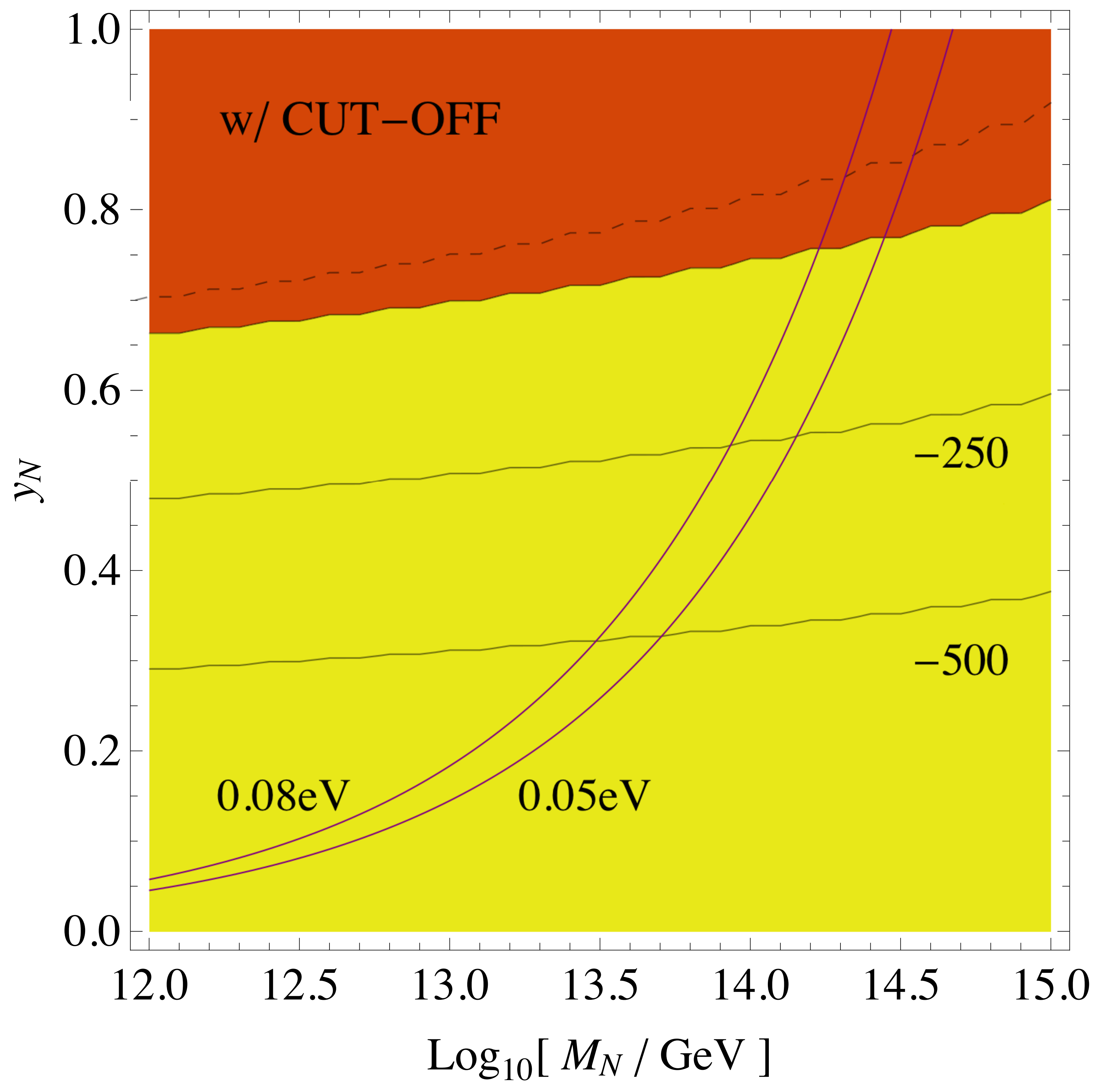
- As a general rule
  - Portal coupling λ_{hs} with a new scalar
    ➡ more stable
  - Yukawa coupling Y with a new fermion
    ➡ more unstable

- Right-handed neutrino with Yukawa coupling

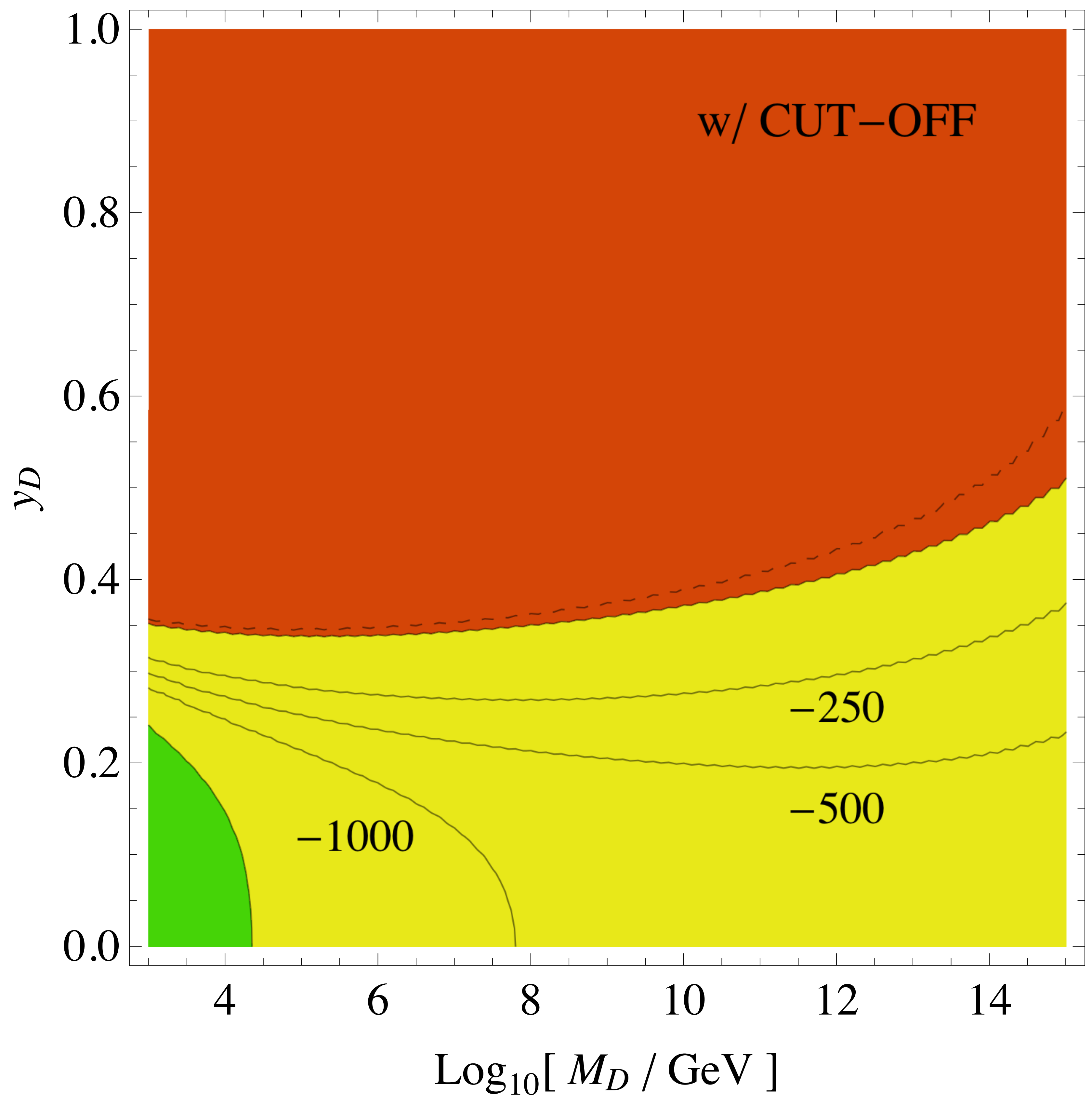


Constraints on new Yukawa couplings

- Right-handed neutrino



- Vector-like quarks



SC, Moroi & Shoji [1803.03902]

"Large" new physics effect

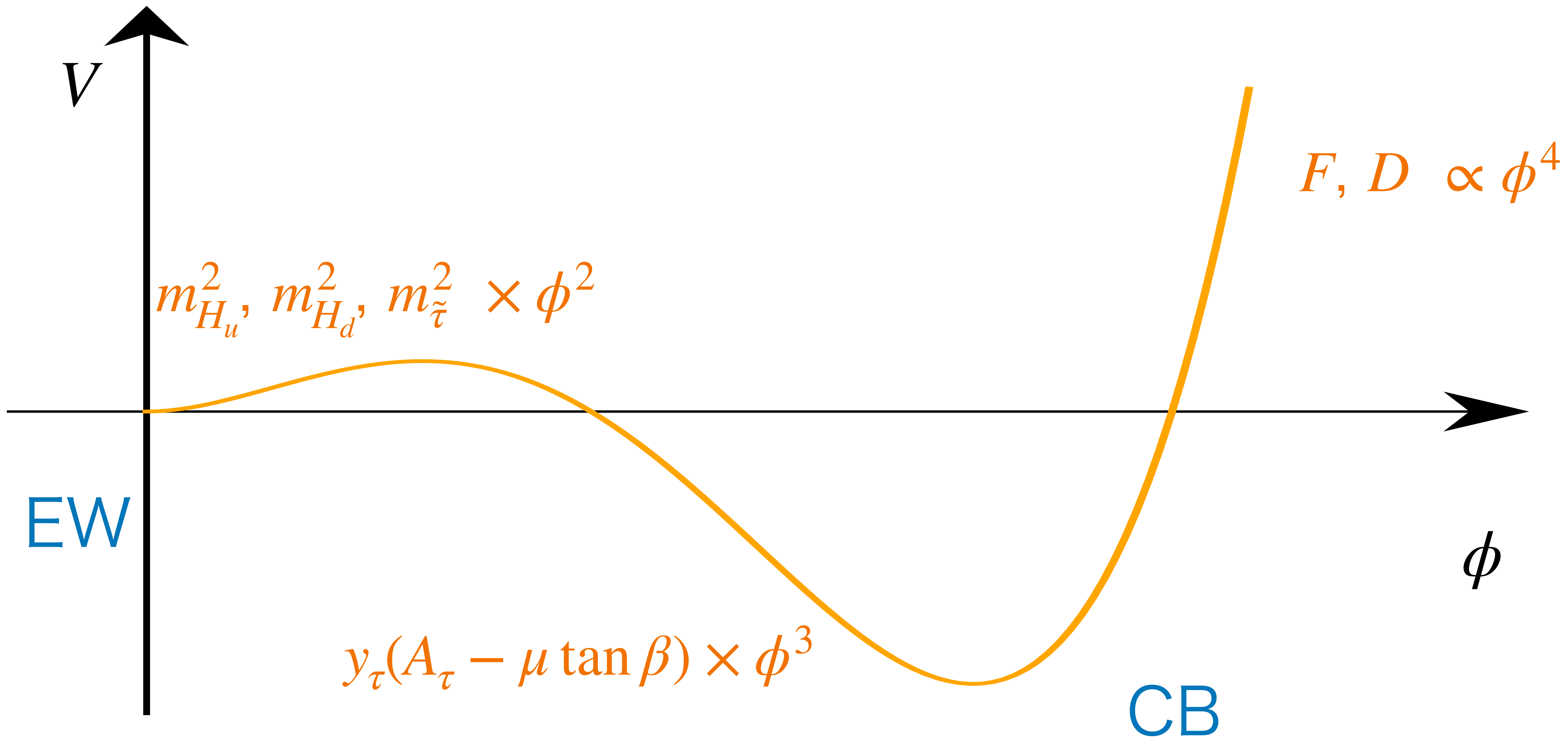
- New scalar fields also get VEV, generating new directions of vacuum

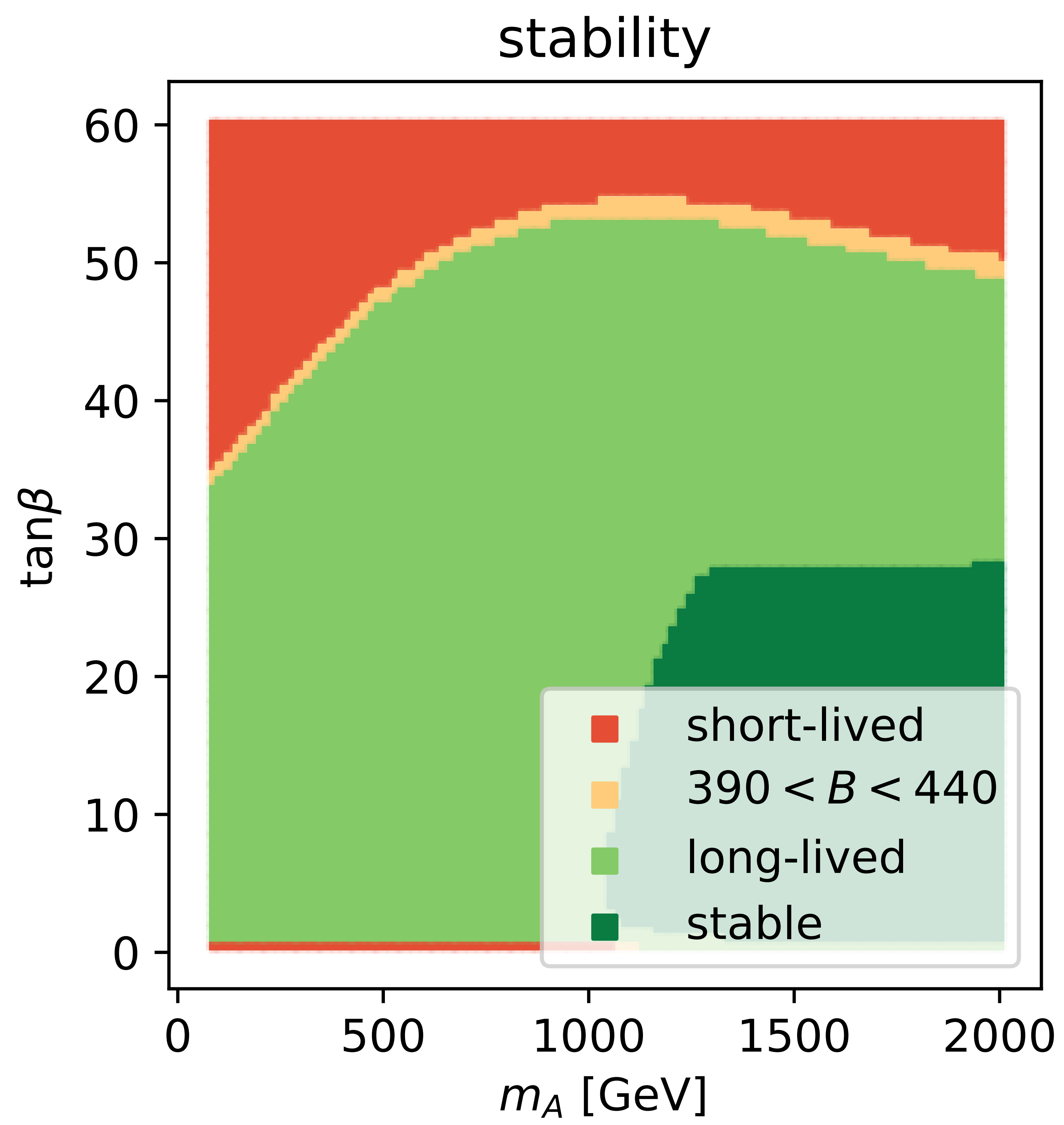
- MSSM benchmark scenario $M_h^{125}(\tilde{\tau})$ Bagnaschi+ [1808.07542]

$$M_{Q_3} = M_{U_3} = M_{D_3} = 1.5 \text{ TeV}, \quad M_{L_3} = M_{E_3} = 350 \text{ GeV},$$

$$\mu = 1 \text{ TeV}, \quad M_1 = 180 \text{ GeV}, \quad M_2 = 300 \text{ GeV}, \quad M_3 = 2.5 \text{ TeV},$$

$$X_t = 2.8 \text{ TeV}, \quad A_b = A_t, \quad A_\tau = 800 \text{ GeV}.$$





Hollik+ [1812.04644]

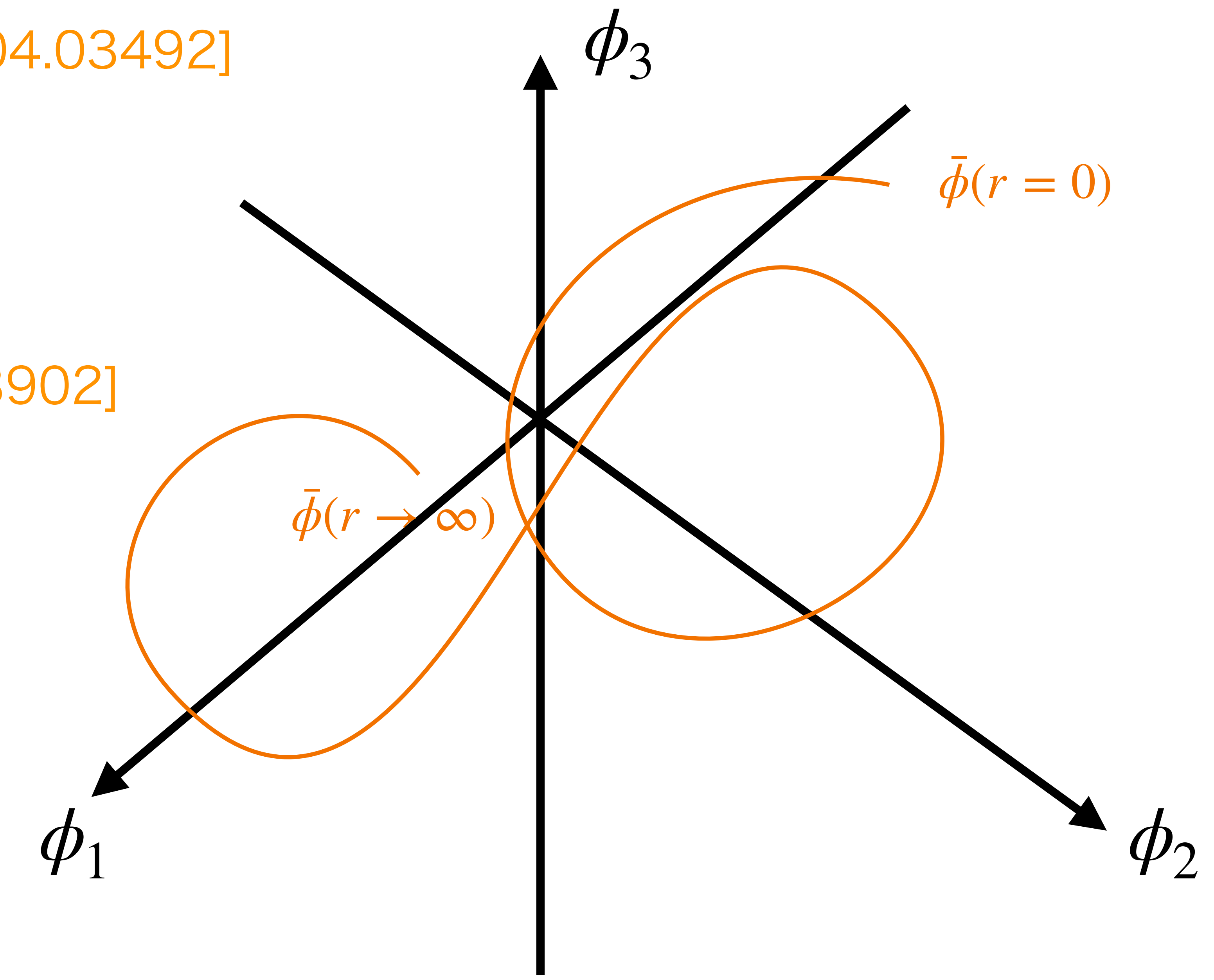
Improvements on decay rate calculation

$$\gamma = \mathscr{A} e^{-\mathscr{B}}$$

NLO part → $\mathscr{A}$

Bounce action (LO part) → $\mathscr{B}$

- First formulation Coleman '77, Callan & Coleman '77, Coleman '85
- Semi-analytic expression Endo, Moroi, Nojiri & Shoji [1703.09304][1704.03492]
- SM (single scalar)
  - Tentative estimate Isidori, Ridolfi & Strumia [hep-ph/0104016]
  - Analytic expression Andreassen+ [1707.08124], SC+ [1707.09301][1803.03902]
- Multi-field bounce
  - Semi-analytic expression SC+ [2007.14124]
  - Applications to MSSM motivated by $(g-2)_\mu$



MSSM motivated by $(g-2)_\mu$

- Muon $g-2$ anomaly status
  - $\Delta a_\mu \equiv a_\mu^{\rm BNL+FNAL} - a_\mu^{\rm SM} = (25.1 \pm 5.9) \times 10^{-10}$

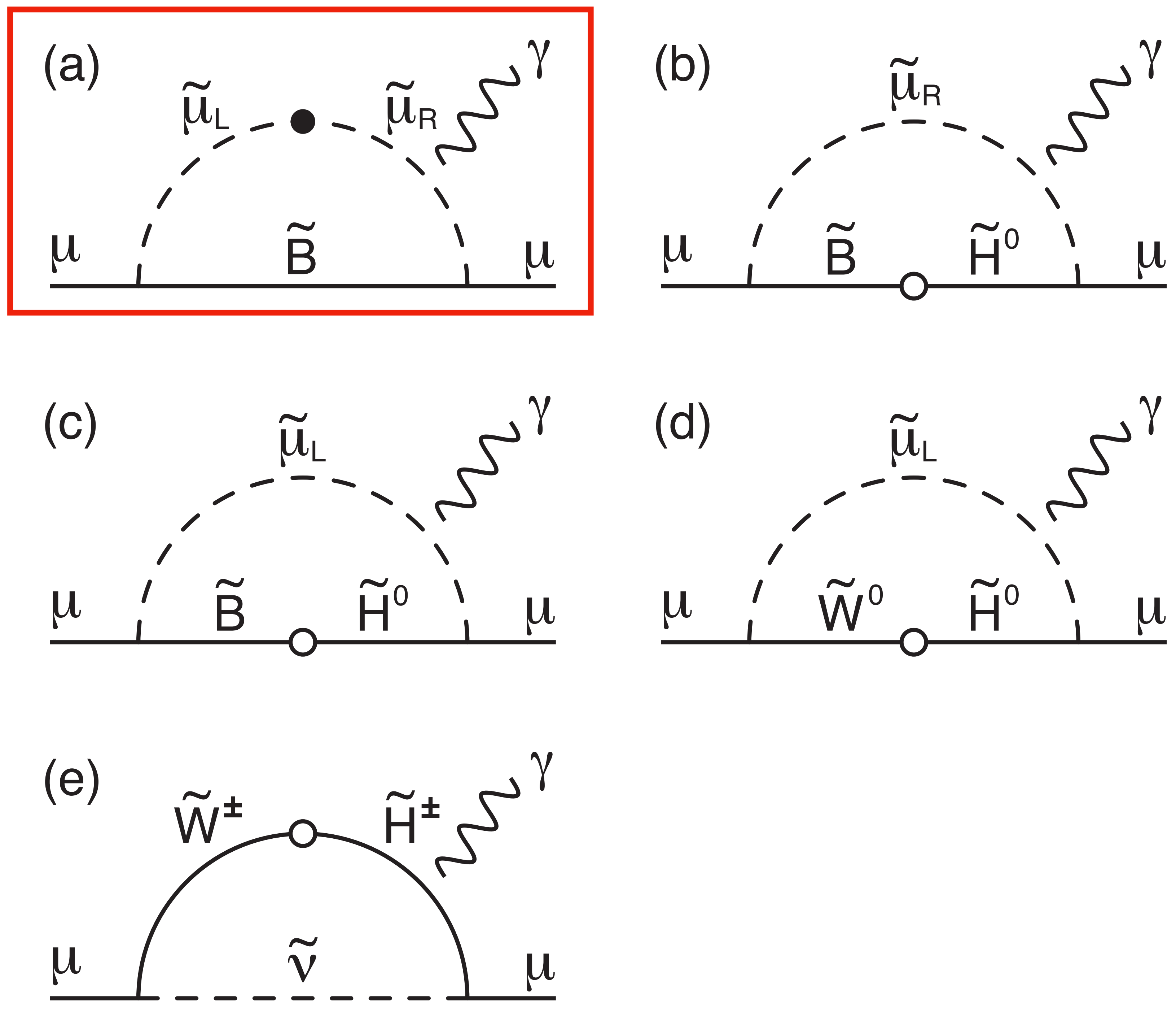
Experiment
Muon $g-2$ collaboration [2104.03281]

Theory
T. Aoyama [2006.04822]

- (Recent updates)
  - lattice HVP calculation $\Delta a_\mu^{\rm SM,BMW} = 14.4 \times 10^{-10}$ Borsanyi+ [2002.12347]
  - $\pi^+\pi^-$ cross-section measurement $\Delta a_\mu^{{\rm SM},\pi\pi,{\rm CMD3}} = 10.5 \times 10^{-10}$
    CMD-3 collaboration [2302.08834]

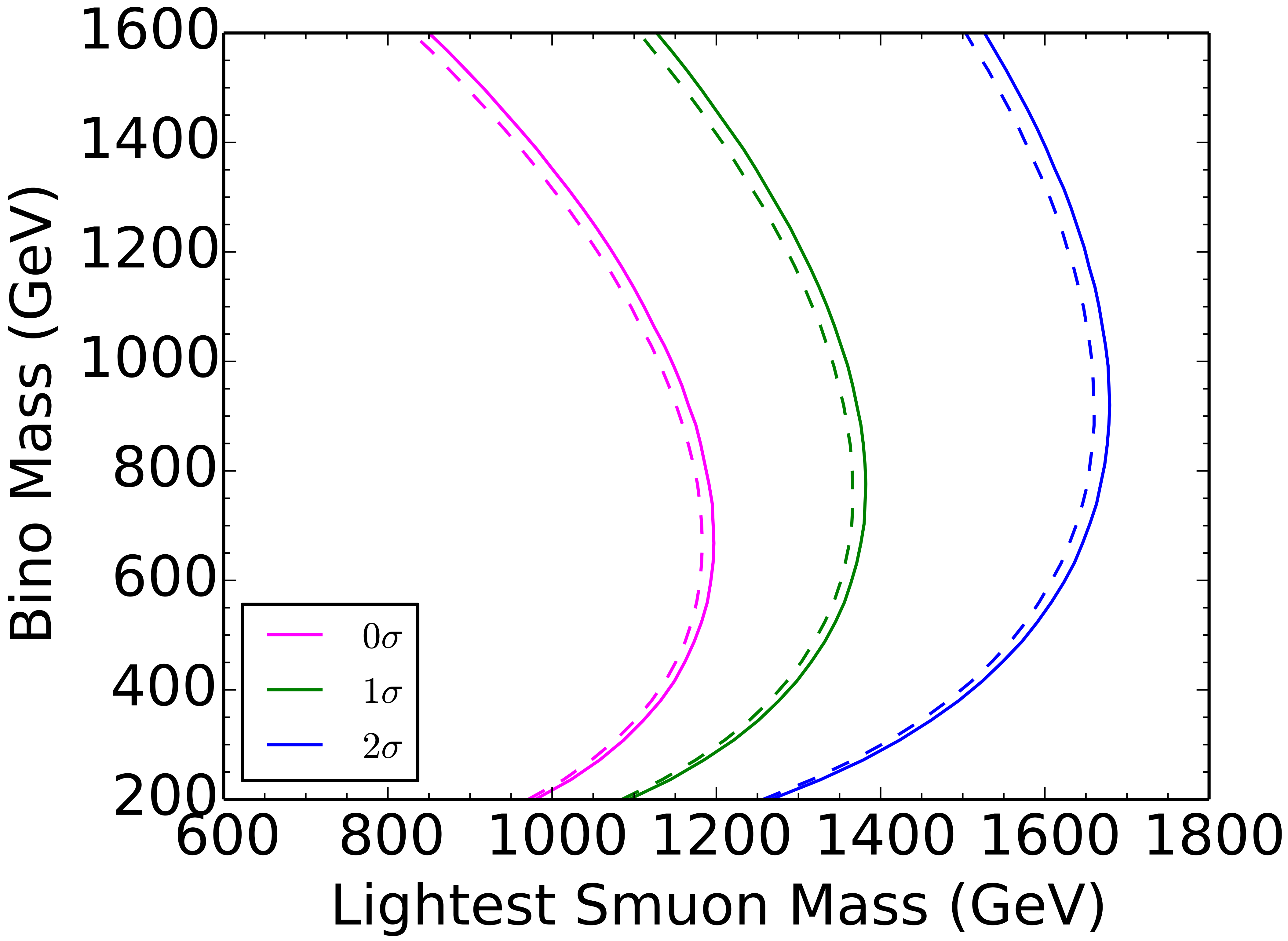
- MSSM contribution can be as large as Δa_μ with
  e.g., Endo+ [2104.03217]
  - Light sleptons
  - Light EWinos
  - Sizable $\tan\beta$
- Larger contribution from (a) requires larger μ

➡ EW vacuum destabilized with slepton CB minimum!



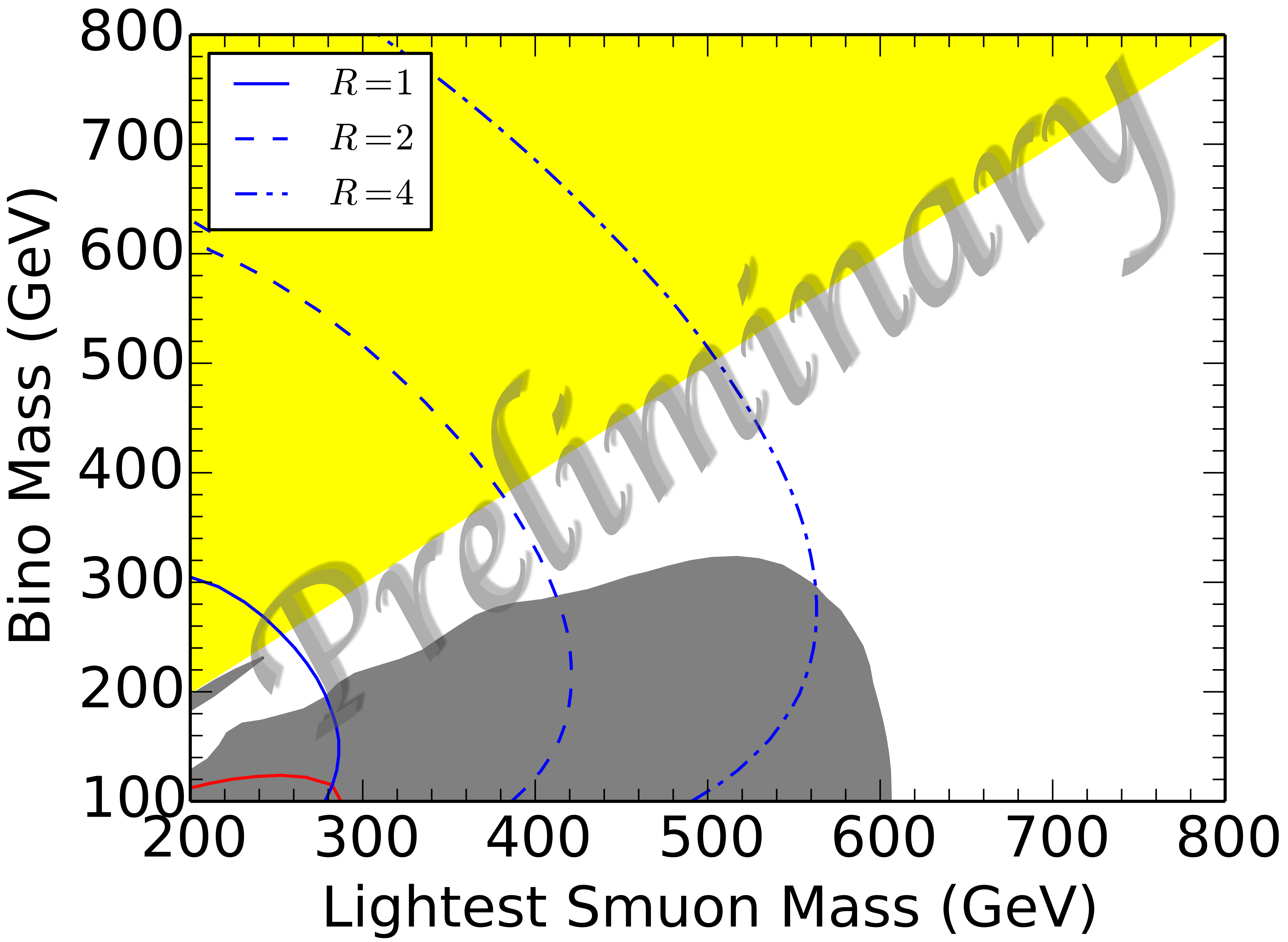
Constraints on $(g-2)_\mu$ MSSM explanation

- light $\tilde{B}$, $\tilde{\mu}$
  - CB minimum with $\langle \tilde{\mu} \rangle \neq 0$



SC, Moroi & Shoji [2203.08062]

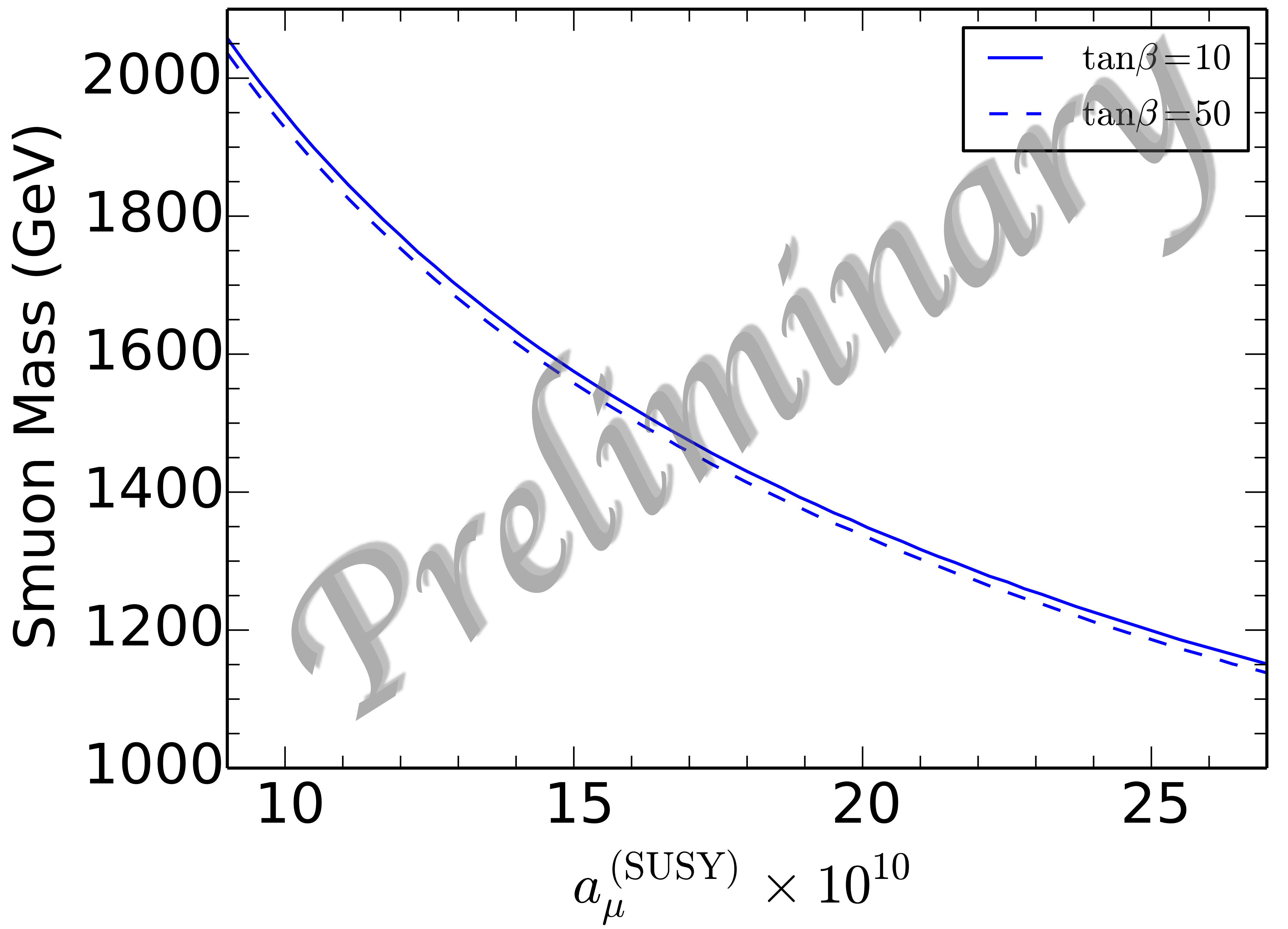
- light $\tilde{B}$, sleptons $m_{\tilde{\tau}} = R(m_{\tilde{\mu}} = m_{\tilde{e}})$
  - CB minimum with $\langle \tilde{\tau} \rangle \neq 0$



SC, Moroi & Shoji [2306.xxxxx]

Possible Δa_μ update and upper bound

- Light $\tilde{B}$, $\tilde{\mu}$



SC, Moroi & Shoji [2306.xxxxx]

Conclusion

- Vacuum stability is a useful tool to constrain models

- Sensitive to SM parameters and new physics effects
  - Precise determination of m_t is crucial Also, Horii-san's talk
  - Can constrain new particles even if they are considerably heavier than TeV

- Semi-analytic expression for a general gauge theory is available
  - Application to the MSSM parameter space motivated by $(g-2)_\mu$

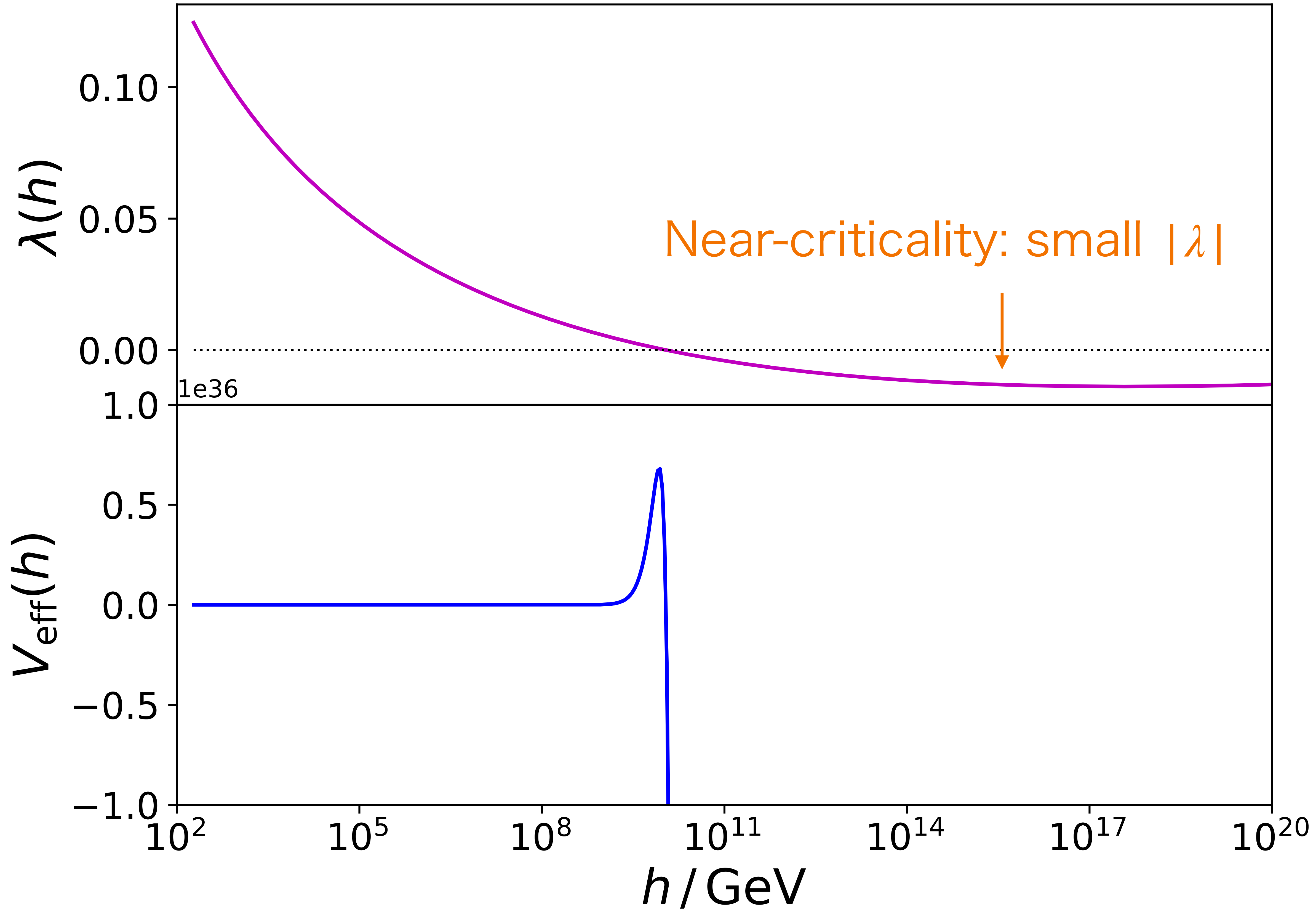
Backup slides

Vacuum stability as theoretical tools

- Prior to Higgs discovery, EW vacuum stability set lower bound on m_h

e.g., Isidori+ [hep-ph/0104016]

- Together with other SM parameters, can constrain new physics models



- Near-criticality requires precision
  - full 2-loop + partial 3-loop RGE available

    Buttazzo+ [1307.3536]
  - Sensitive to measurement errors
  - Sensitive to new physics

Higgs portal coupling

- Vacuum stability during cosmological history
  - during inflation
  - during post-inflationary reheating
  - during thermal history
    e.g., Lebedev [2104.03342]

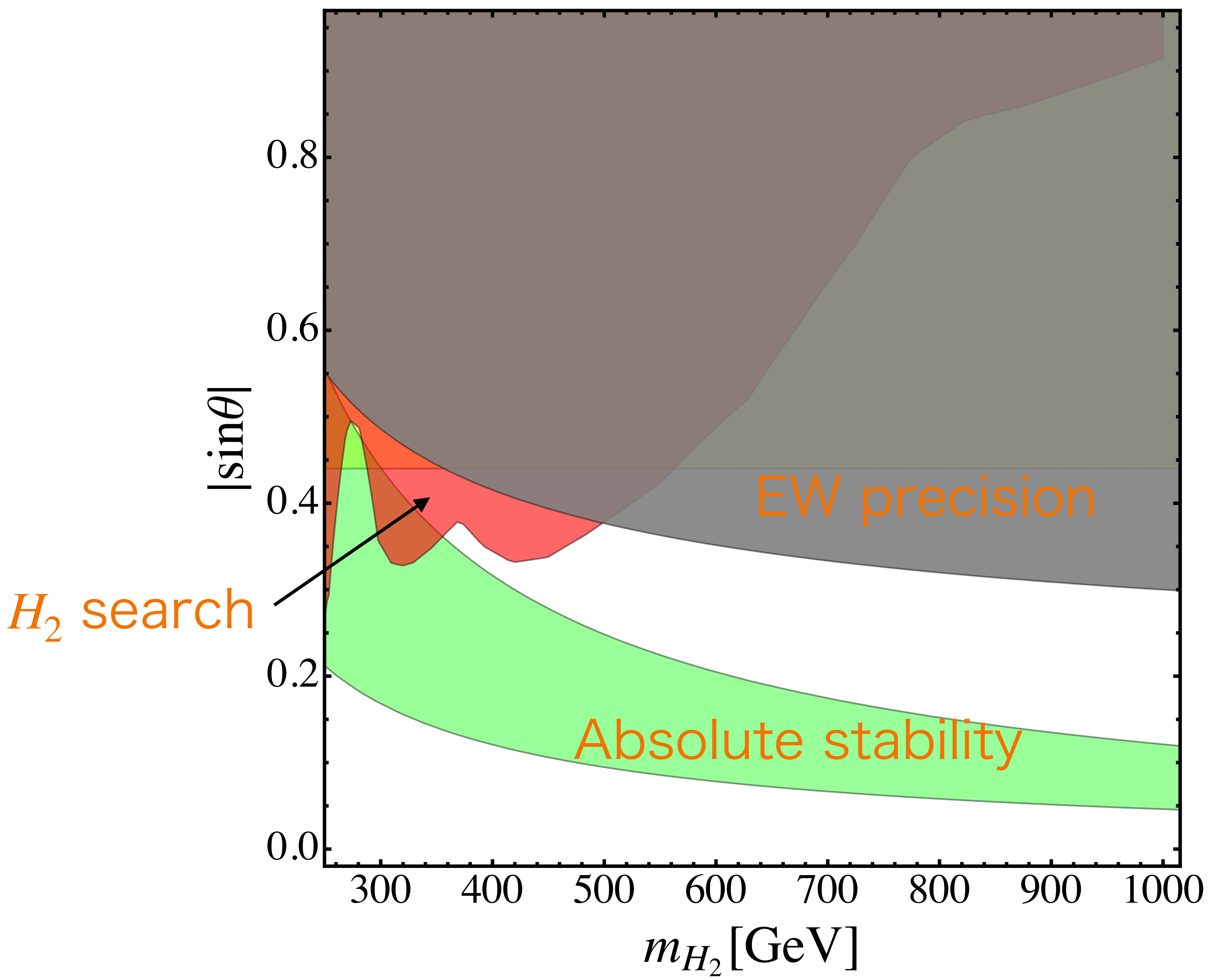
- Absolute stability is the simplest solution

- Model

$$\Delta V = \frac{1}{2}\mu^2 s^2 + \frac{\lambda_s}{4}s^4 + \frac{\lambda_{hs}}{4}h^2 s^2$$

$$\Delta\beta_\lambda = \frac{1}{2}\lambda_{hs}^2$$

- Absolute stability with $\lambda_{hs} = 0.01$



Falkowski+ [1502.01361], Péli+ [2204.07100]