Planck2010
CERN

A Finely-Predicted Higgs Mass from A Finely-Tuned Weak Scale

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arXiv:0910.2235

Outline

I. Environmental Selection of the Weak Scale

II. A Higgs Mass Prediction to 0.3%

III. Beyond the Basic Prediction

How can we understand the Weak Scale?

Two Conventional Options:

1. Strong Dynamics

2. Weak Scale Supersymmetry

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1. Strong Dynamics — "Stratus"
2. Weak Scale Supersymmetry — "Logos"

M. Luty

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Two Conventional Options:

1. Strong Dynamics — "Stratus"
2. Weak Scale Supersymmetry — "Logos"

M. Luty

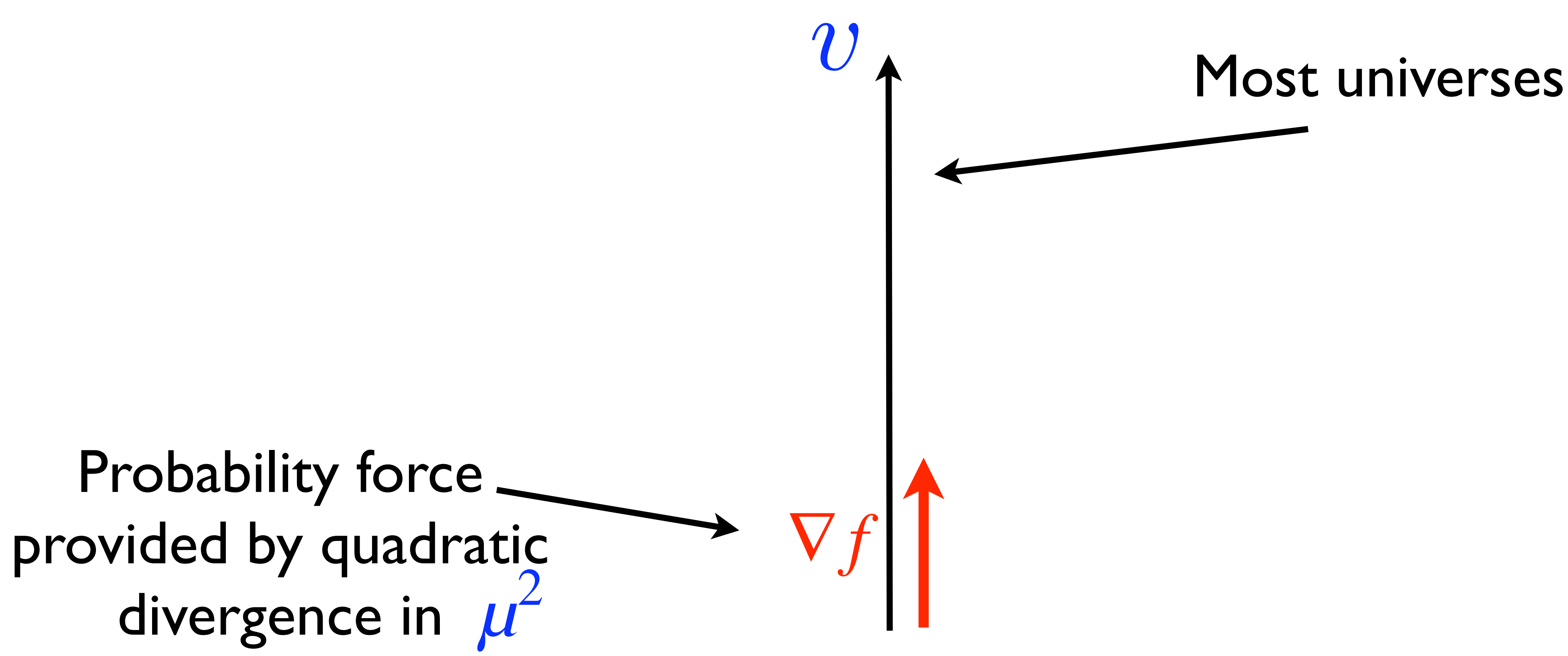
A third option

3. Environmental selection in a multiverse — "Chaos"

Cosmological constant problem, string landscape

Environment Selection of Weak Scale

- Our universe is part of a multiverse
- The SM Higgs mass parameter scans: $f(\mu^2)$
- Most universes have large v



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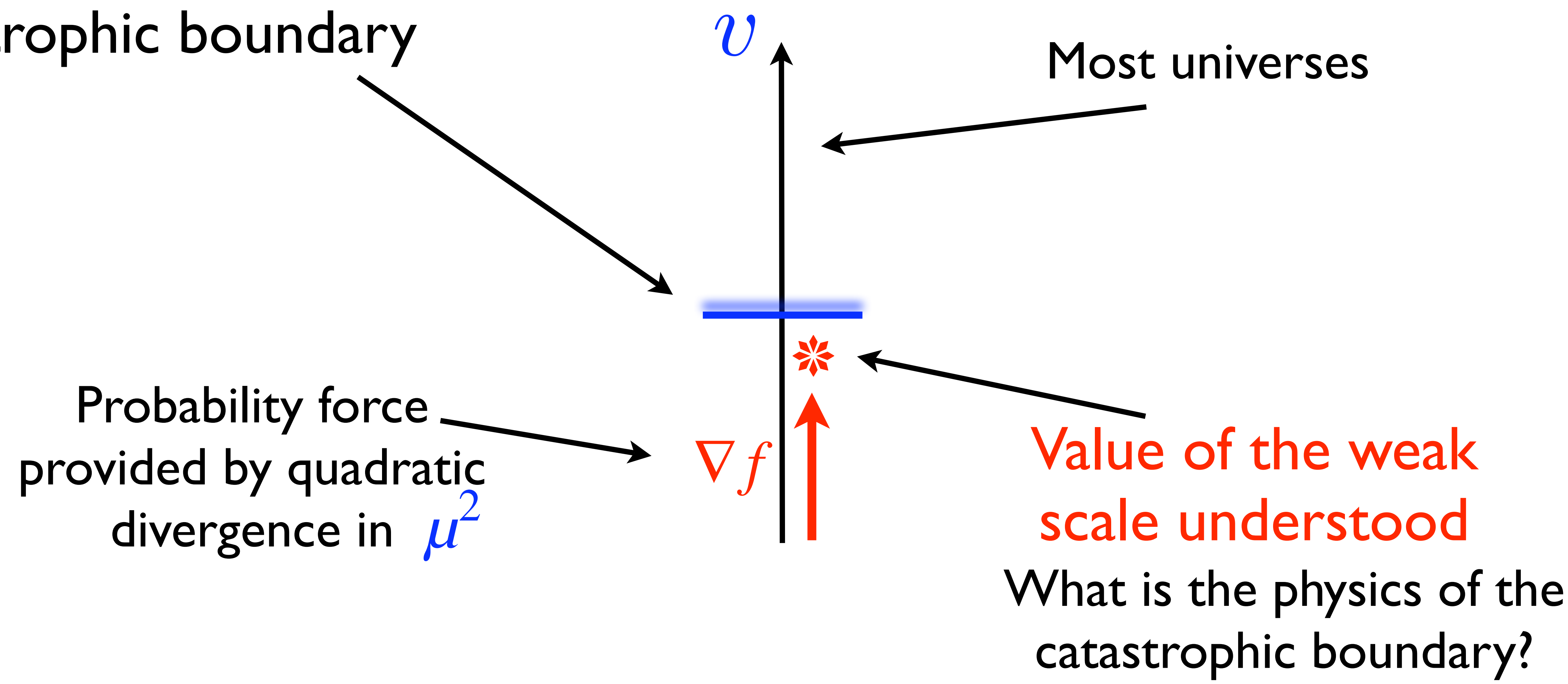

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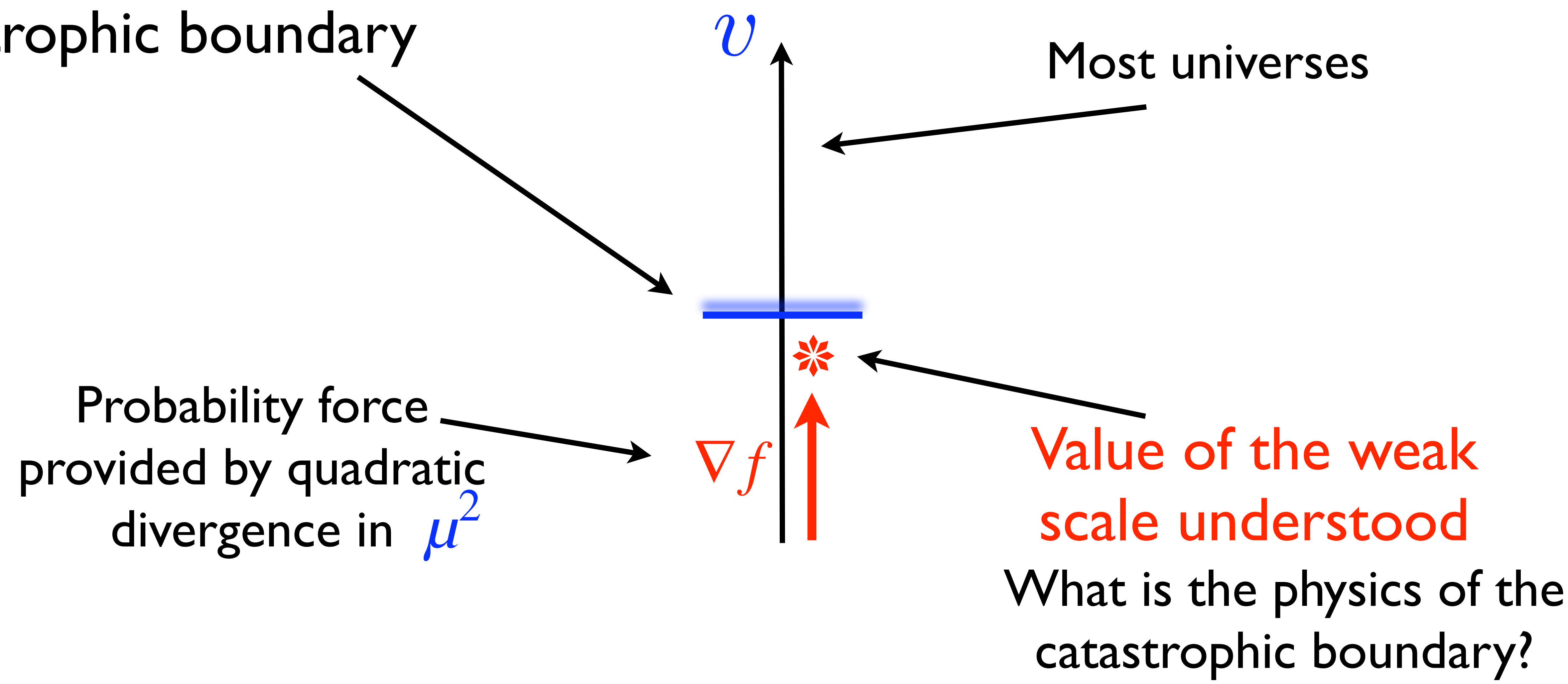


- The fine-tuning is <u>not</u> eliminated --- it is <u>evidence</u> for the multiverse

The Absence of Complex Nuclei

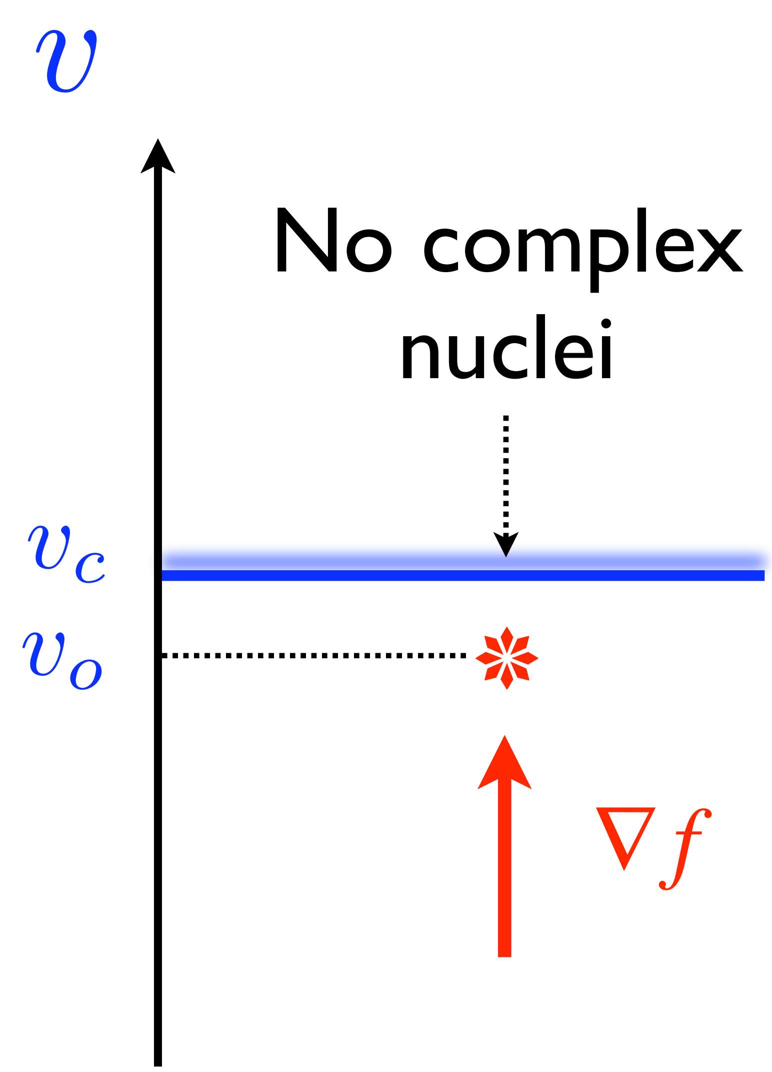
Agrawal, Barr, Donoghue, Seckel
hep/ph/9707380

- Increasing v leads to instability of heavy nuclei $d \to u \ldots$

- $v_c \simeq 2v_o$

- $v_c \simeq 1.6v_o$ Damour Donoghue arXiv:0712.2968

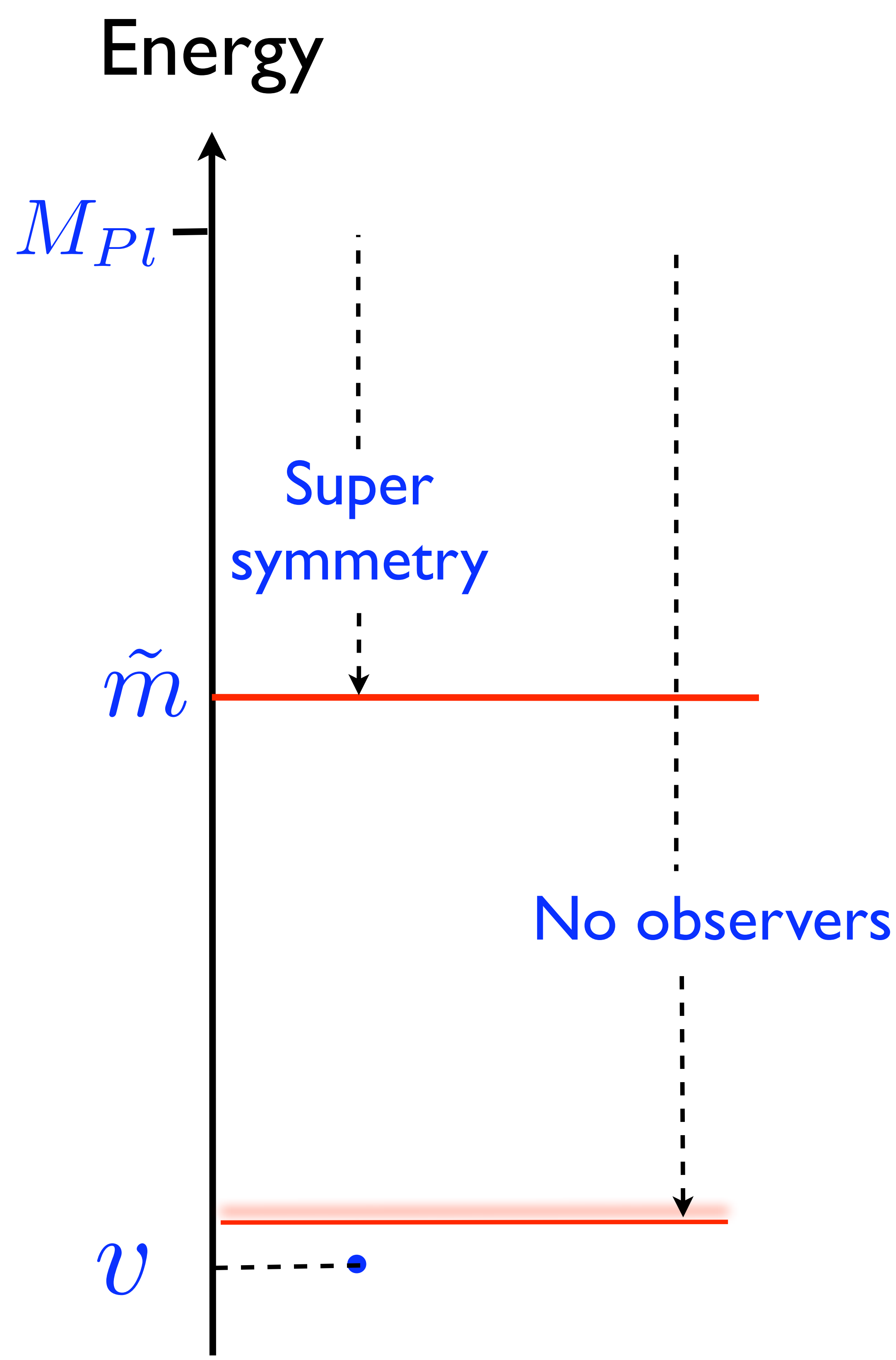
- Insufficient to select v if Yukawa couplings scan



Supersymmetry Breaking Scale?

- Environmental weak scale

→ $\tilde{m}$ decoupled from v



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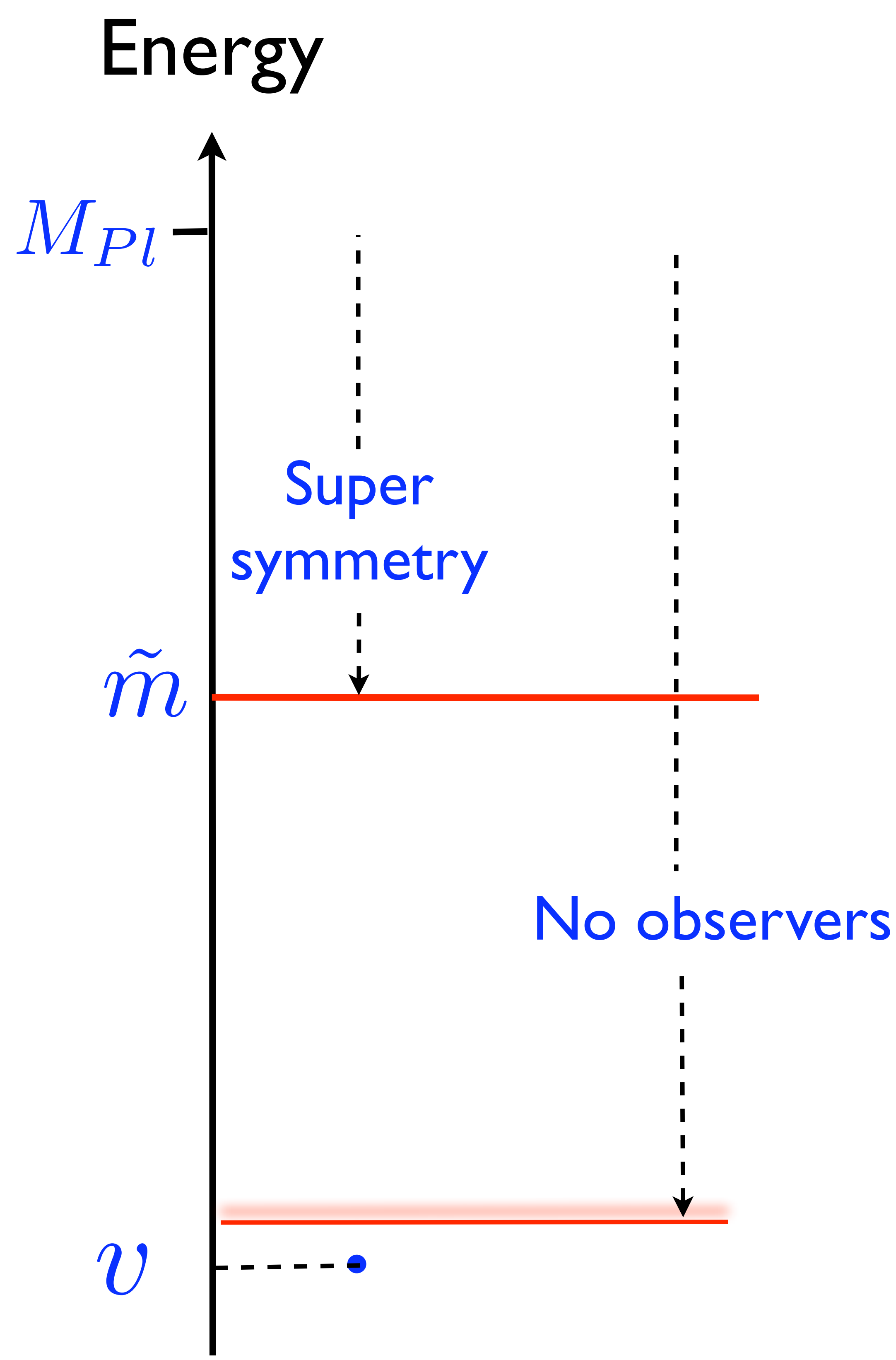

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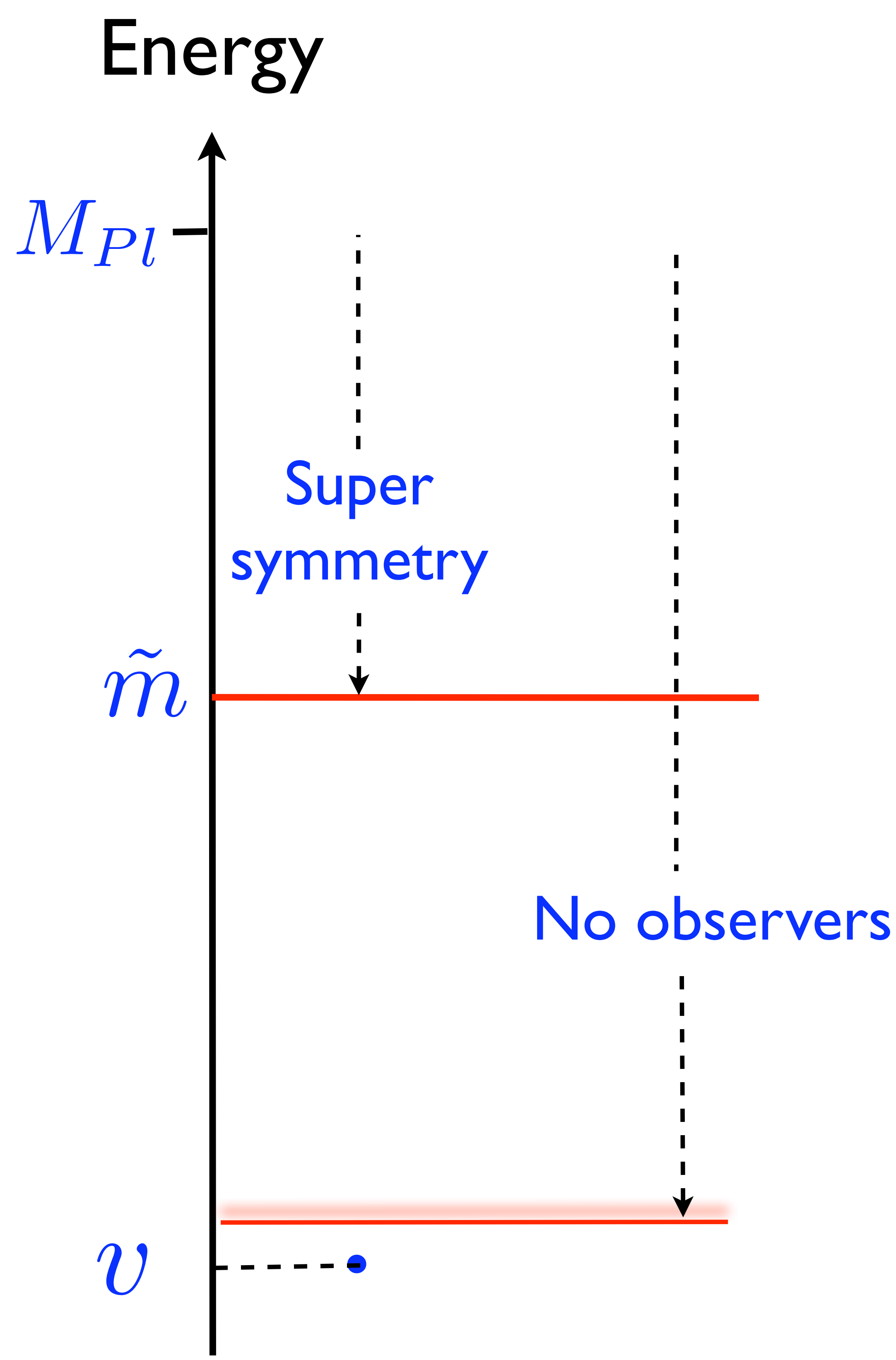
- If LHC does not discover supersymmetry, how will we learn $\tilde{m}$?

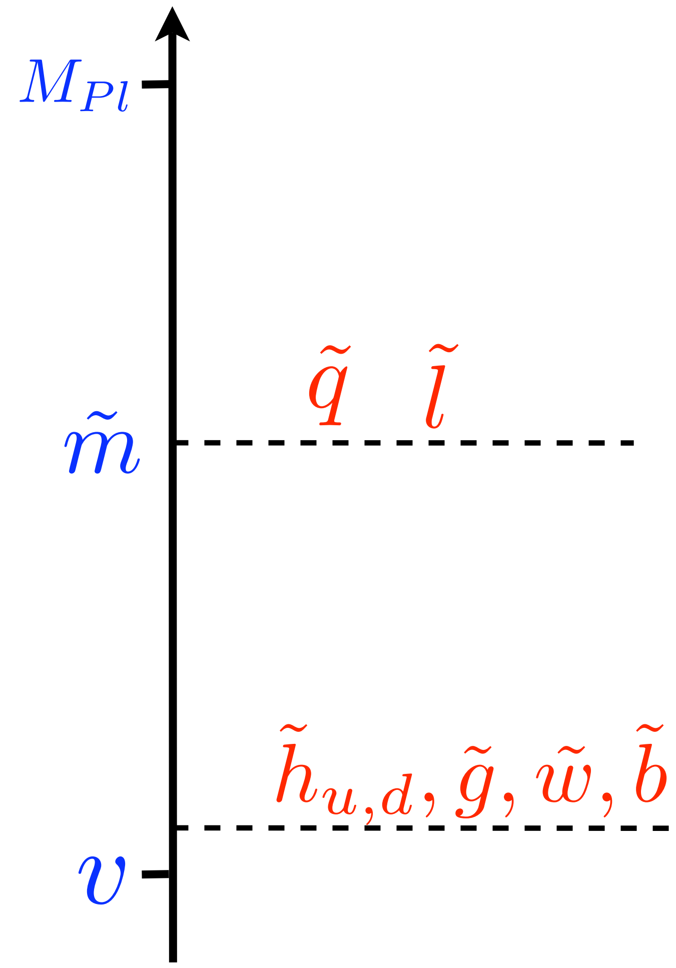


Split Supersymmetry

Arkani-Hamed, Dimopoulos, hep-th/0405159

- susy broken at a very high scale

- fermionic superpartners provide WIMP dark matter



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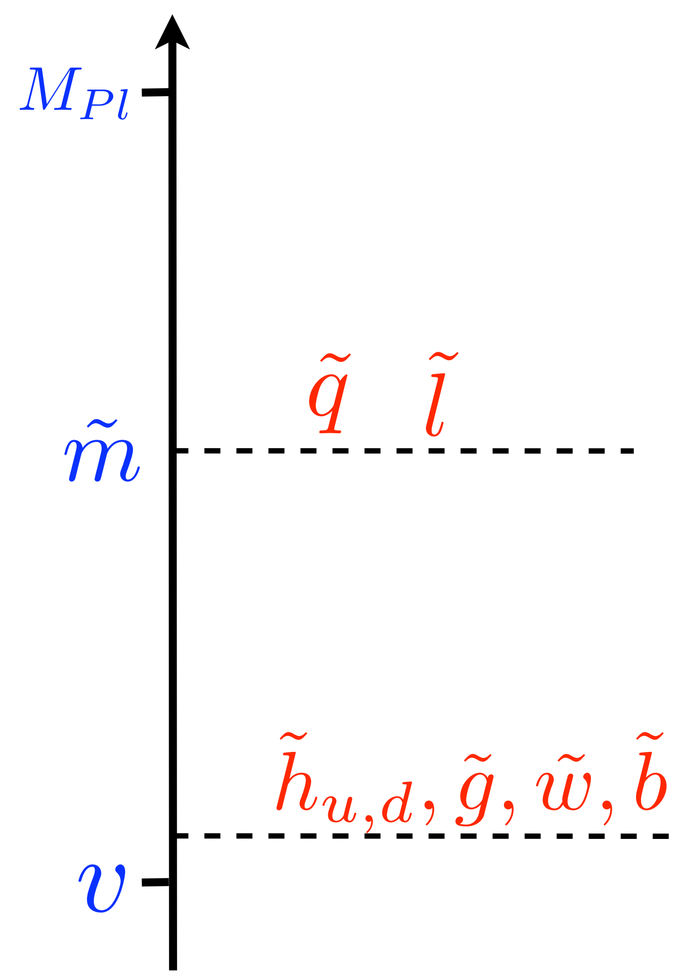

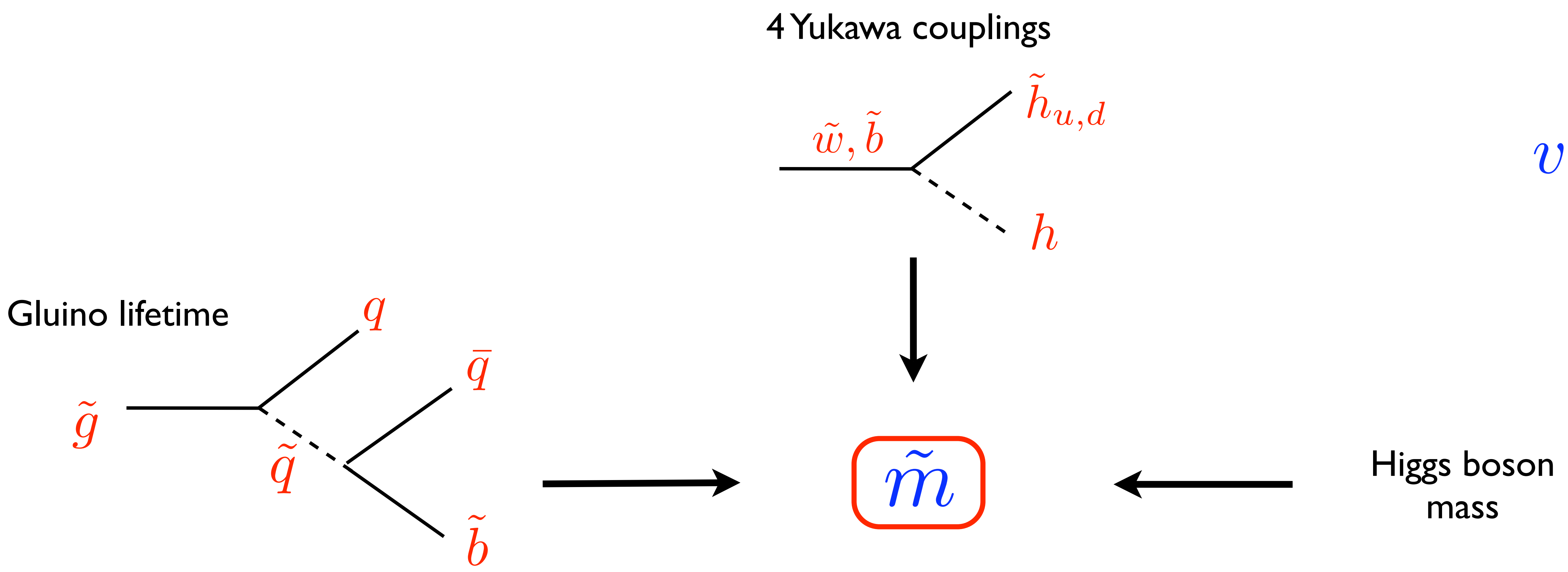

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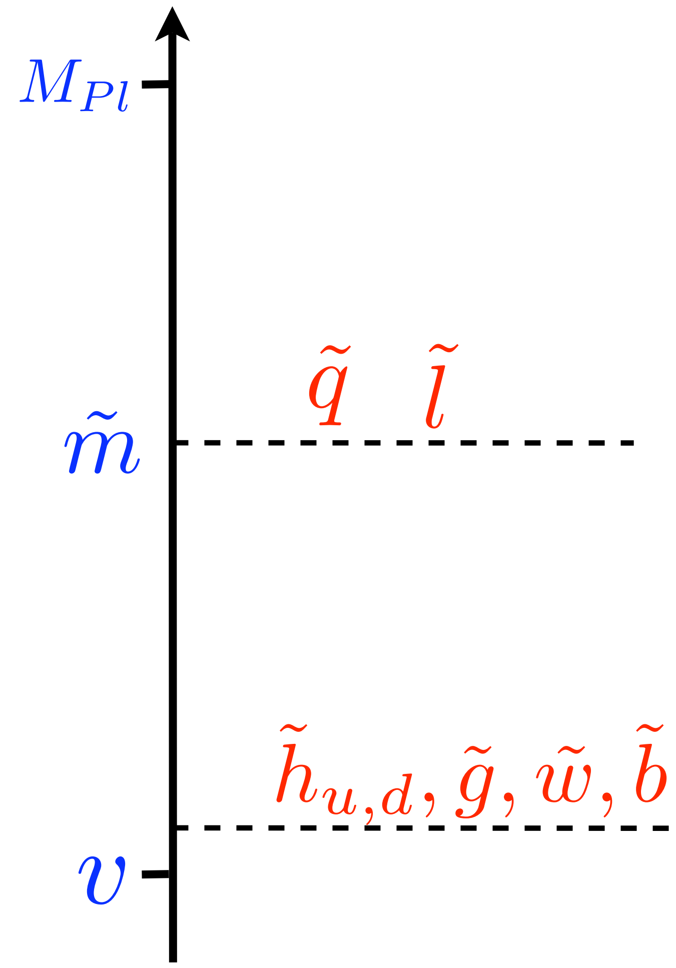

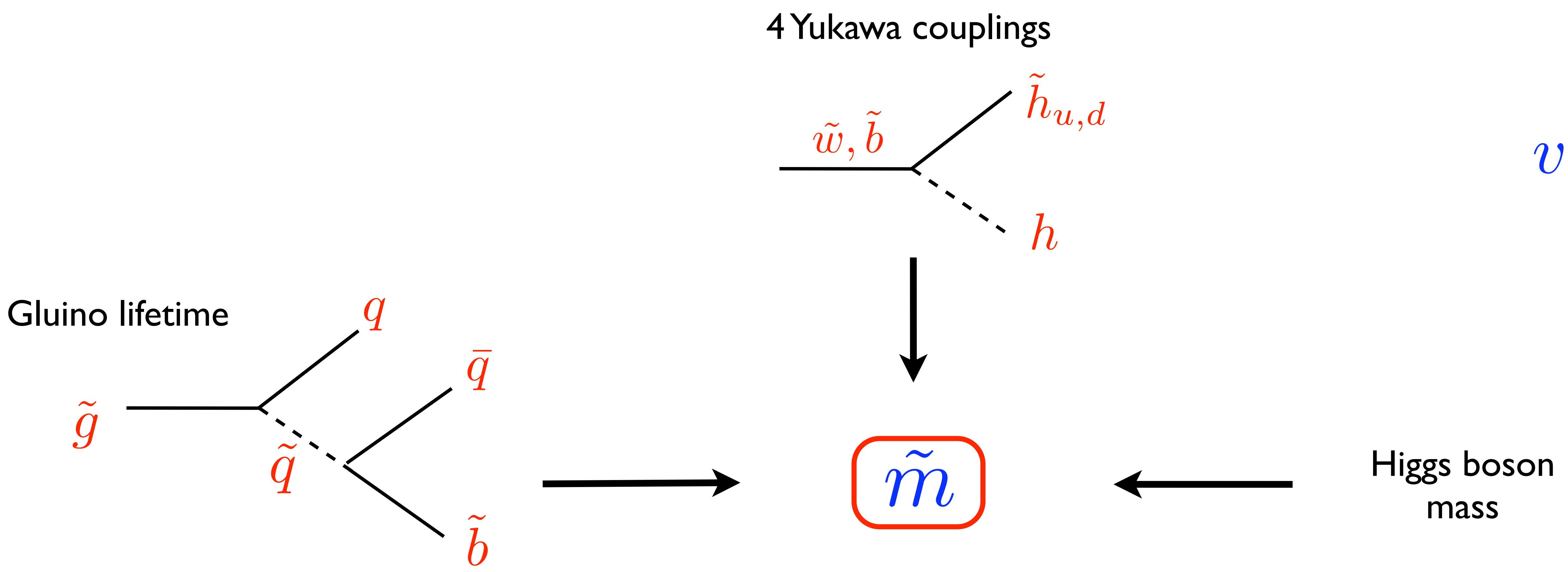

- Convincing evidence for an elementary Higgs between v and $\tilde{m}$ with

fine tuning of 1 in $\dfrac{\tilde{m}^2}{v^2}$

II

A Higgs Mass Prediction

The Simplest Model

- Environmental v $\longrightarrow$ $\tilde{m}$ decoupled from v
- $\tilde{m}$ scans with some distribution $f(\tilde{m})$
- Observations do not favor low $\tilde{m}$

Susy flavor problem, susy CP problem, gravitino problem, moduli problem, mu problem, B/muB problem, proton decay problem, *Little susy hierarchy problem*

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  Susy flavor problem, susy CP problem, gravitino problem, moduli problem, mu problem, B/muB problem, proton decay problem, *Little susy hierarchy problem*

- Assume $f(\tilde{m})$ prefers large $\tilde{m}$

  $\tilde{m} \rightarrow M_*$

- No superpartners light -- the "nightmare" scenario

  SM + GR

Too Far?

- Gauge Coupling Unification

  is significantly improved
  by weak scale susy

- Dark Matter

  ?

- Experimental Tests

  Nothing to measure!

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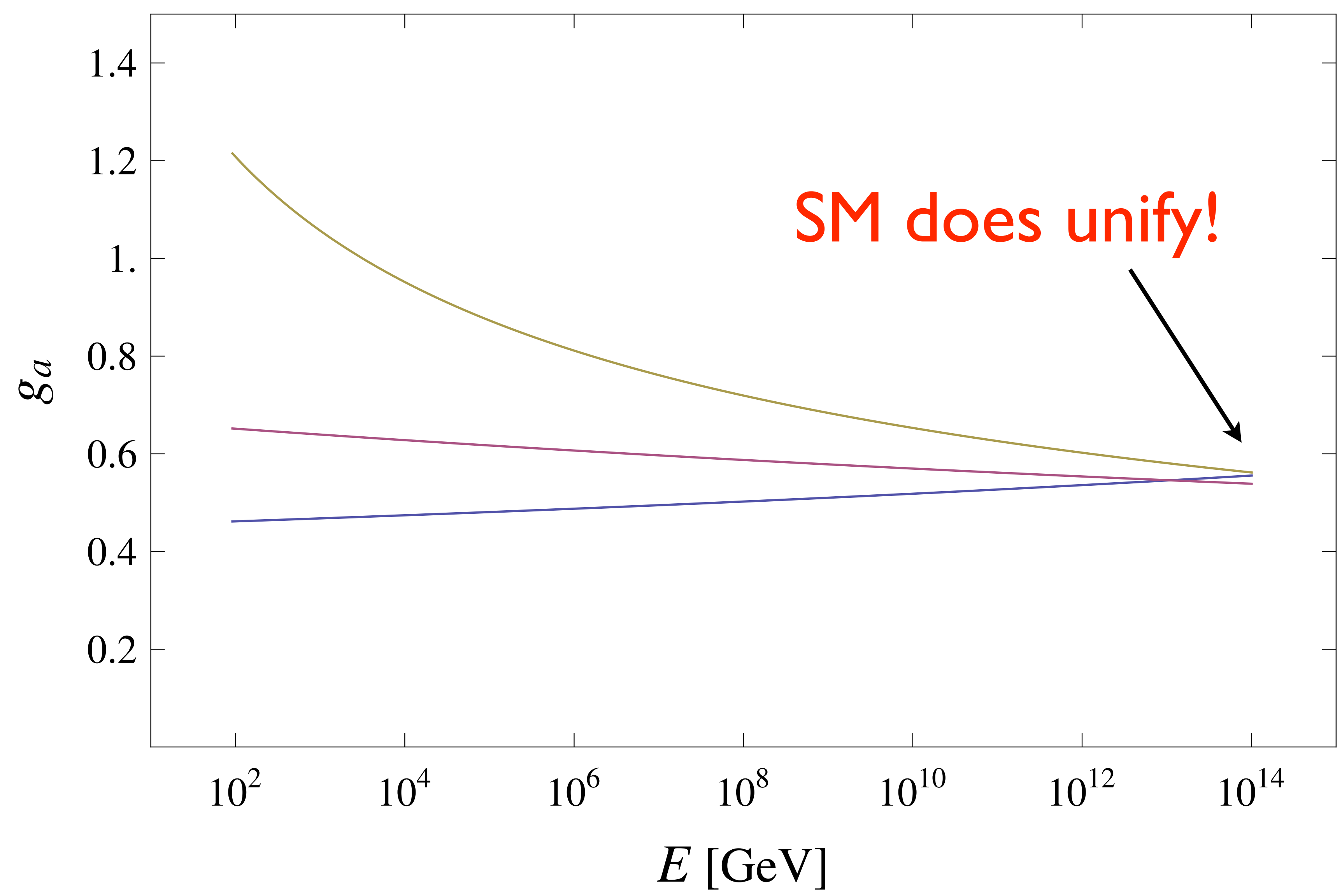

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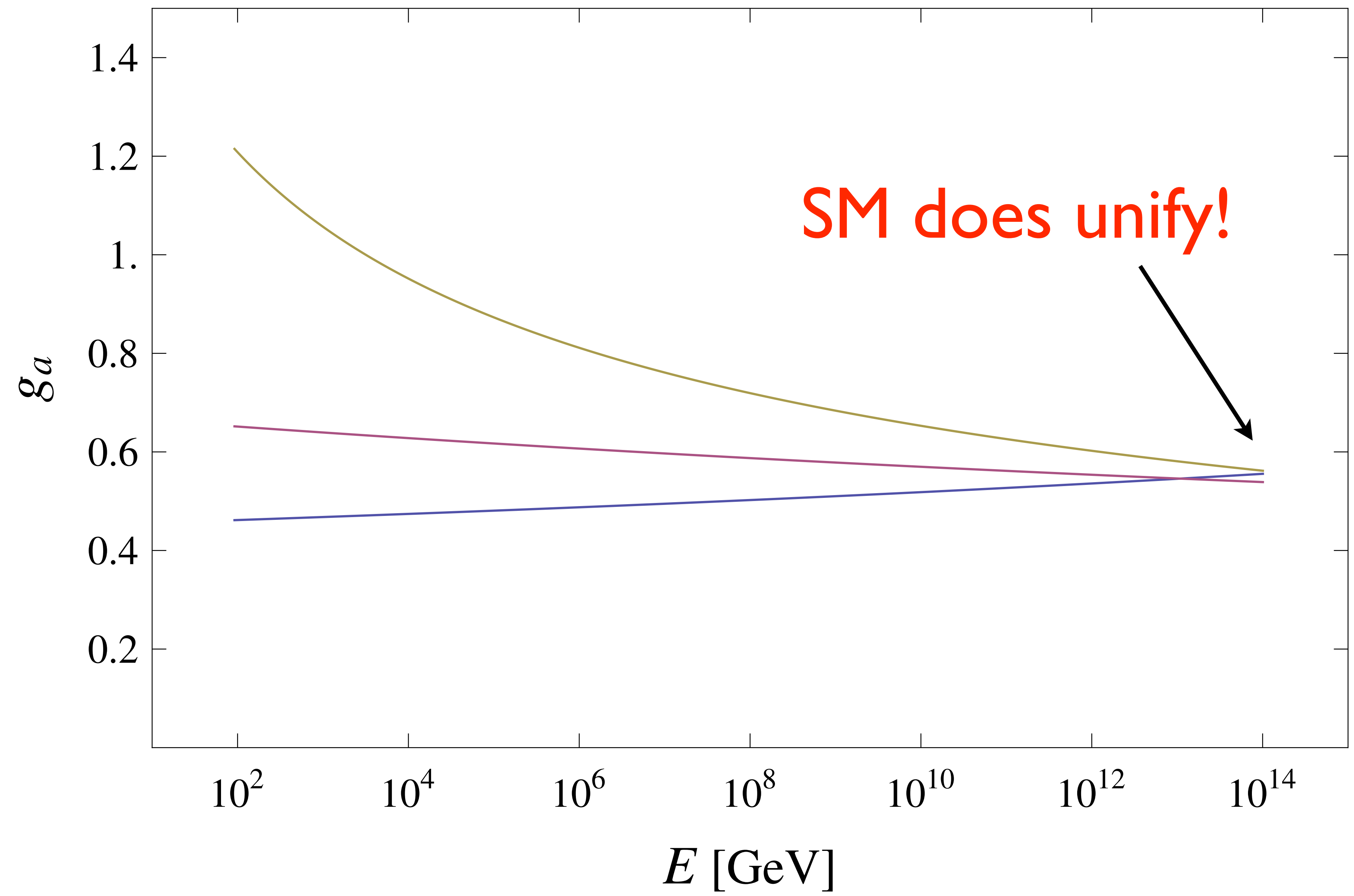

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Axion

- Needed to solve strong CP problem
- Expected in string theory with $f_a \sim M_*$
- θ_{mis} selected to be small

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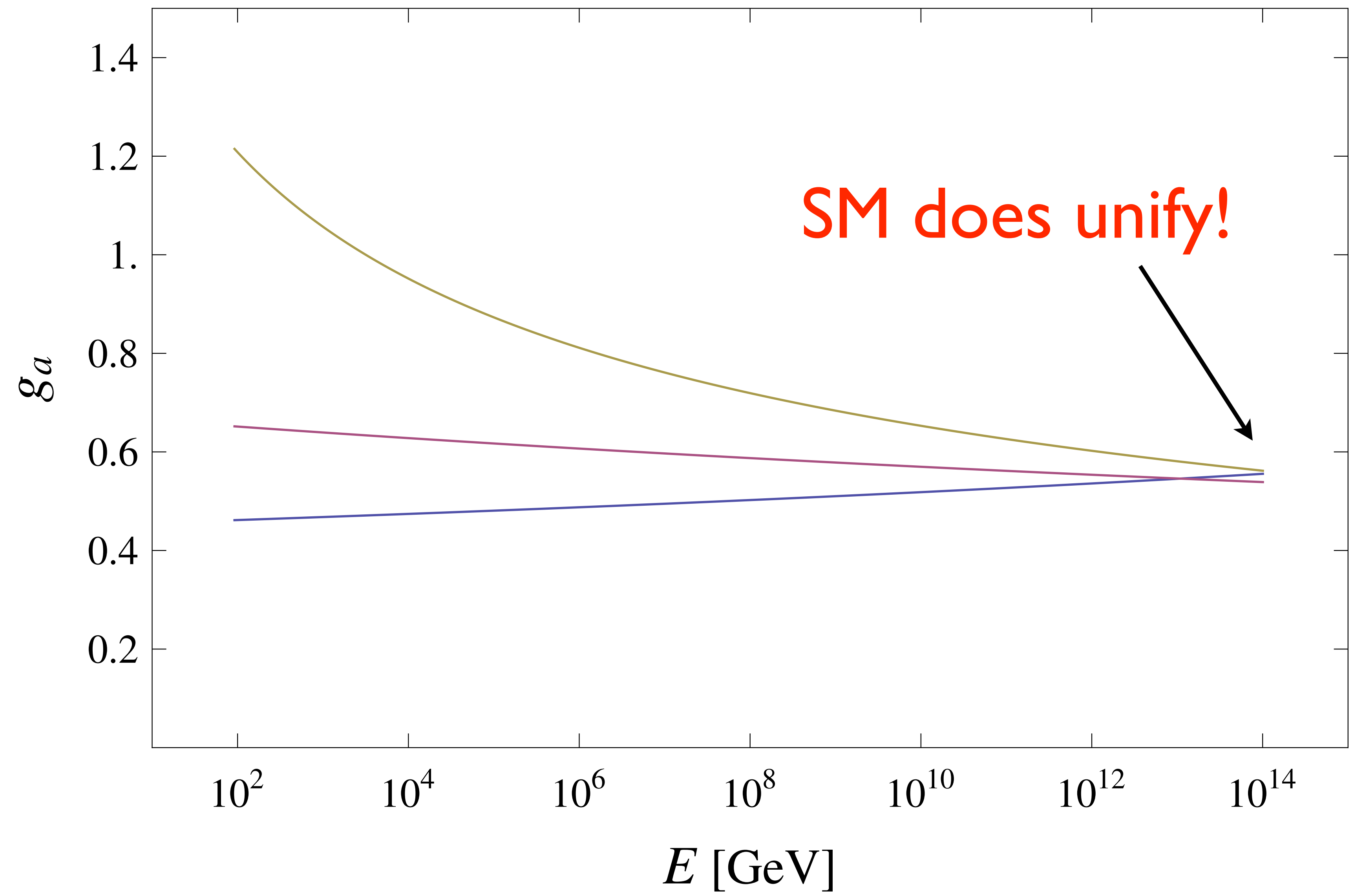

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❊ Experimental Tests

** Are we sure? **

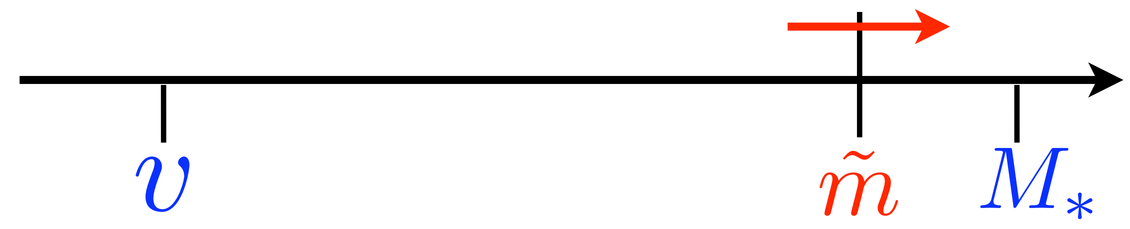
Nothing to measure!

A Supersymmetric Boundary Condition

- At $\tilde{m}$ we expect a susy boundary condition on the Higgs quartic

$$\lambda(\tilde{m}) = \frac{g^2(\tilde{m}) + g'^2(\tilde{m})}{8} \cos^2 2\beta$$

- If $\tilde{m}$ slides to M_* could this be destroyed?



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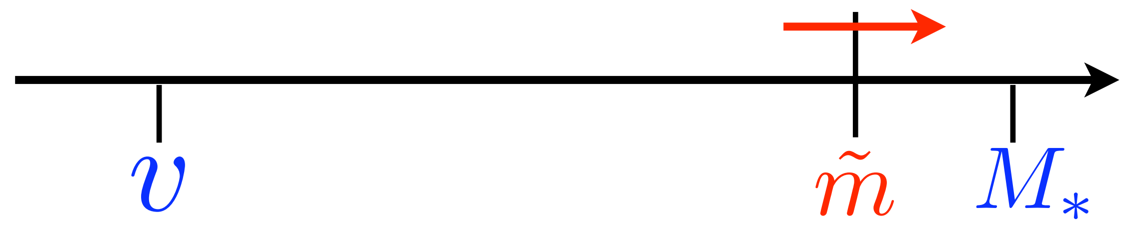
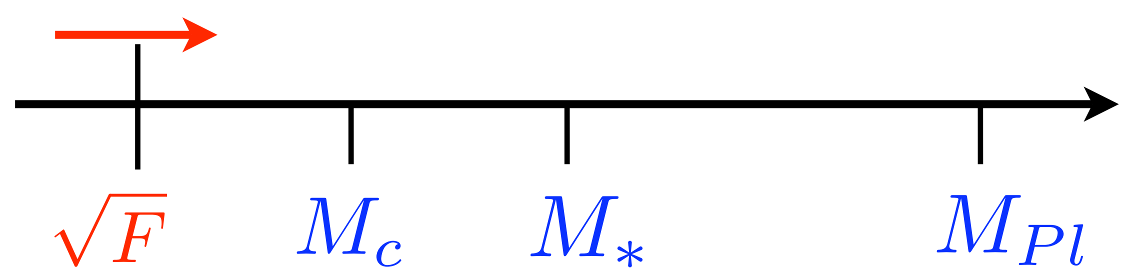
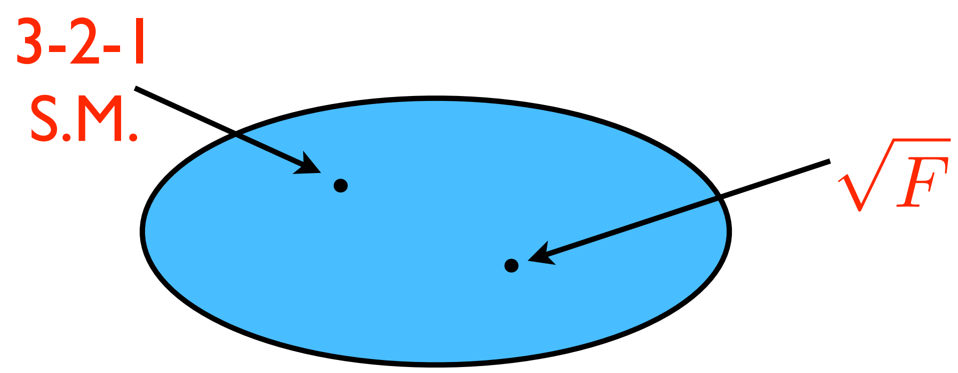


- We expect to encounter extra dimensions



- Susy breaking can be anywhere in a huge bulk extra dimensions



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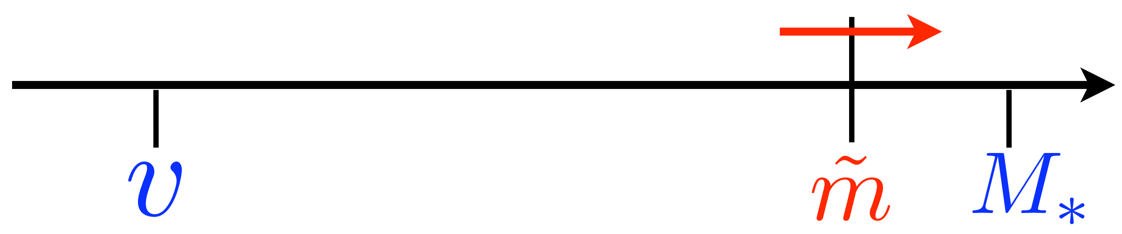

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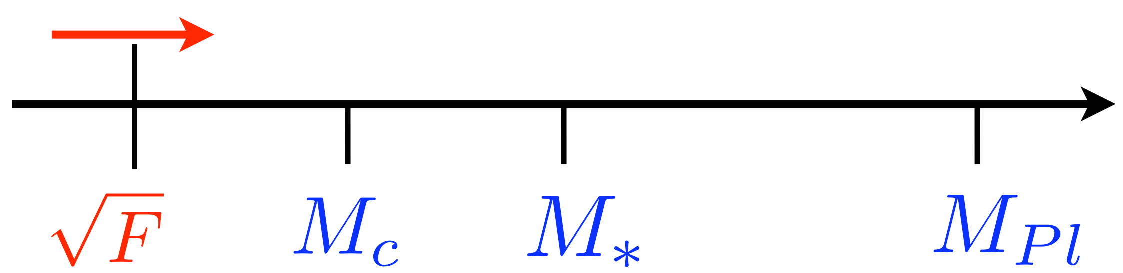

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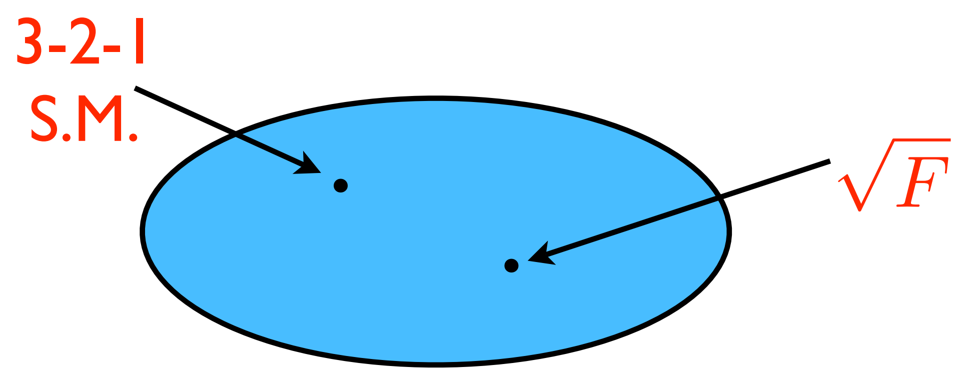


- Suppressed mediation

$\leq \dfrac{1}{(M_* R)^p}$ Non-grav.

$\dfrac{M_*^2}{M_{Pl}^2}$ Grav.

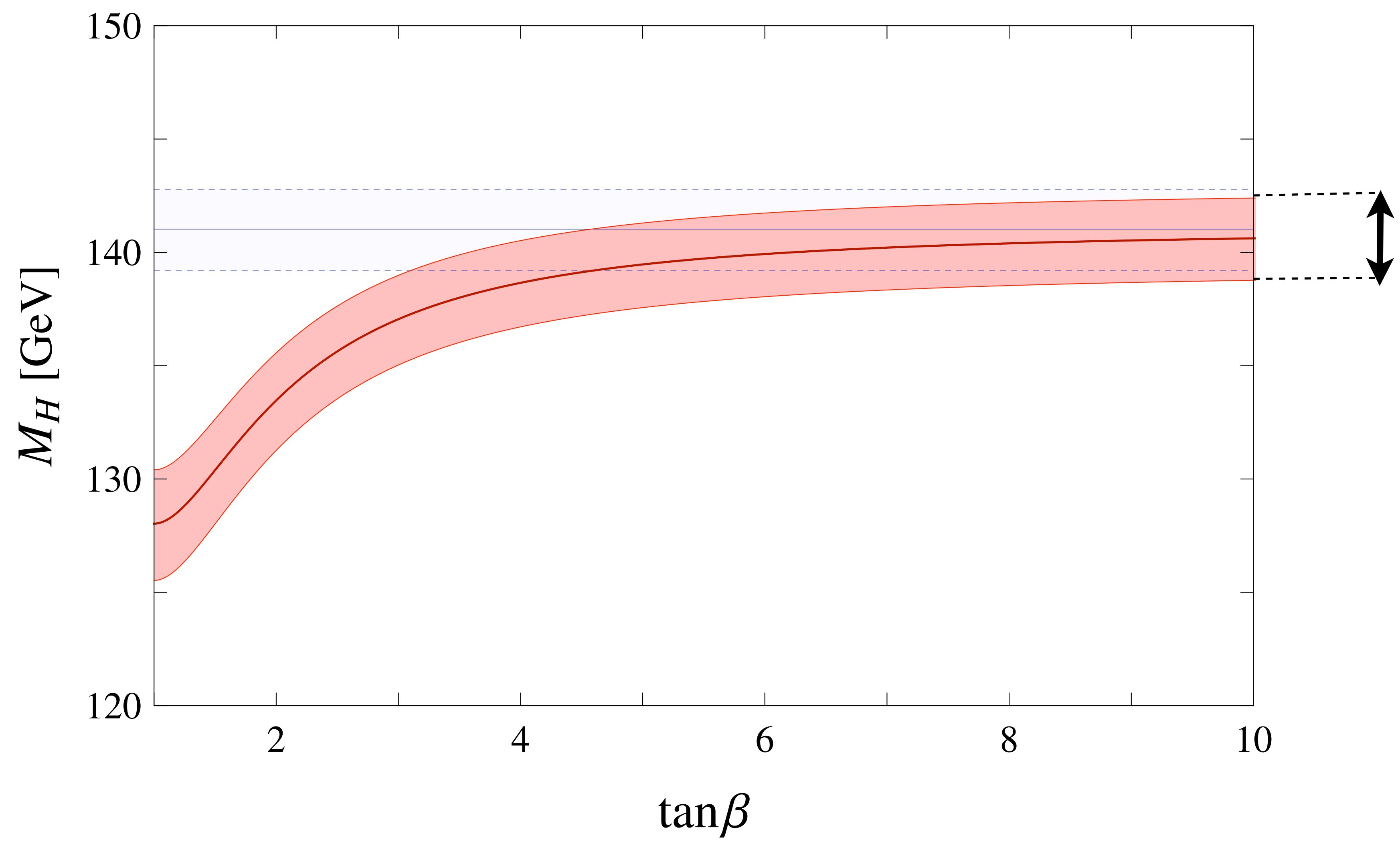
(Same if susy breaking non-local)

Destruction of boundary condition requires special situation

The Higgs Mass Range

- SM up to $\tilde{m} = 10^{14}\,\text{GeV}\,(\sim M_u)$ $\qquad \lambda(\tilde{m}) = \frac{g^2(\tilde{m}) + g'^2(\tilde{m})}{8}\cos^2 2\beta$

- Scale λ to weak scale: introduces a dependence on m_t and α_s



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$\alpha_s = 0.1176$

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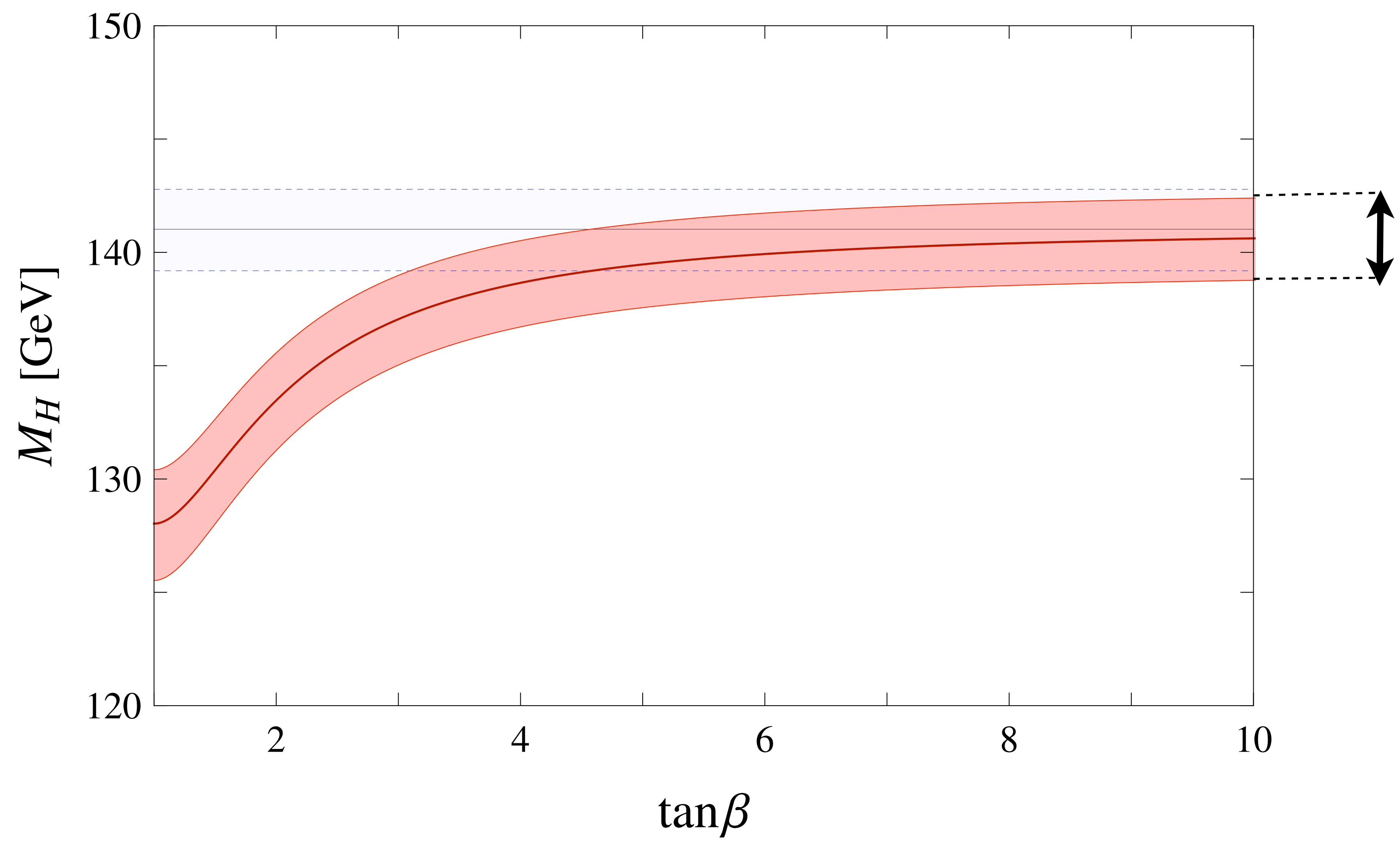

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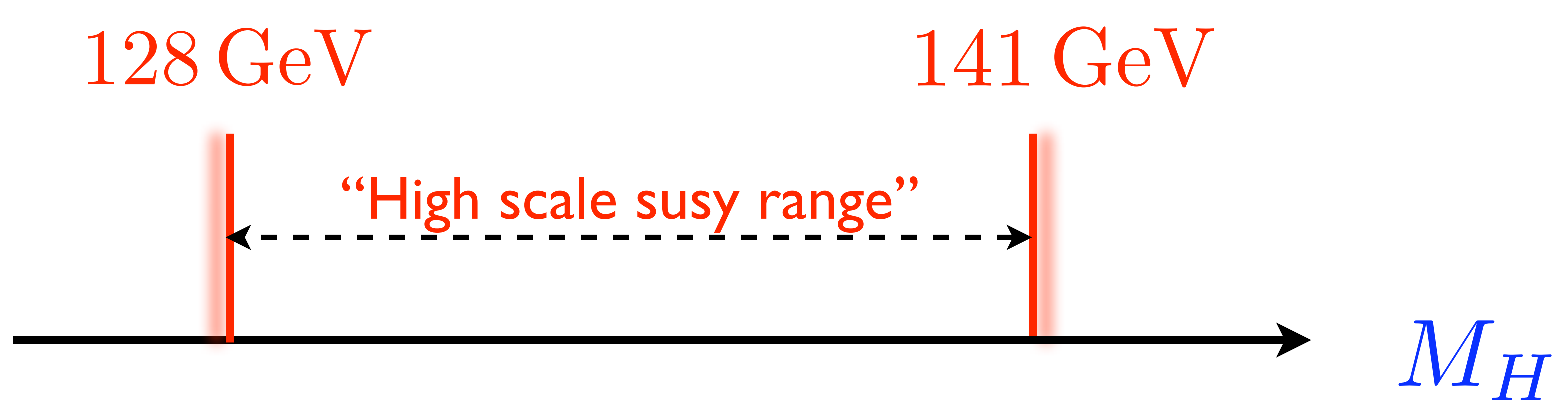
- 

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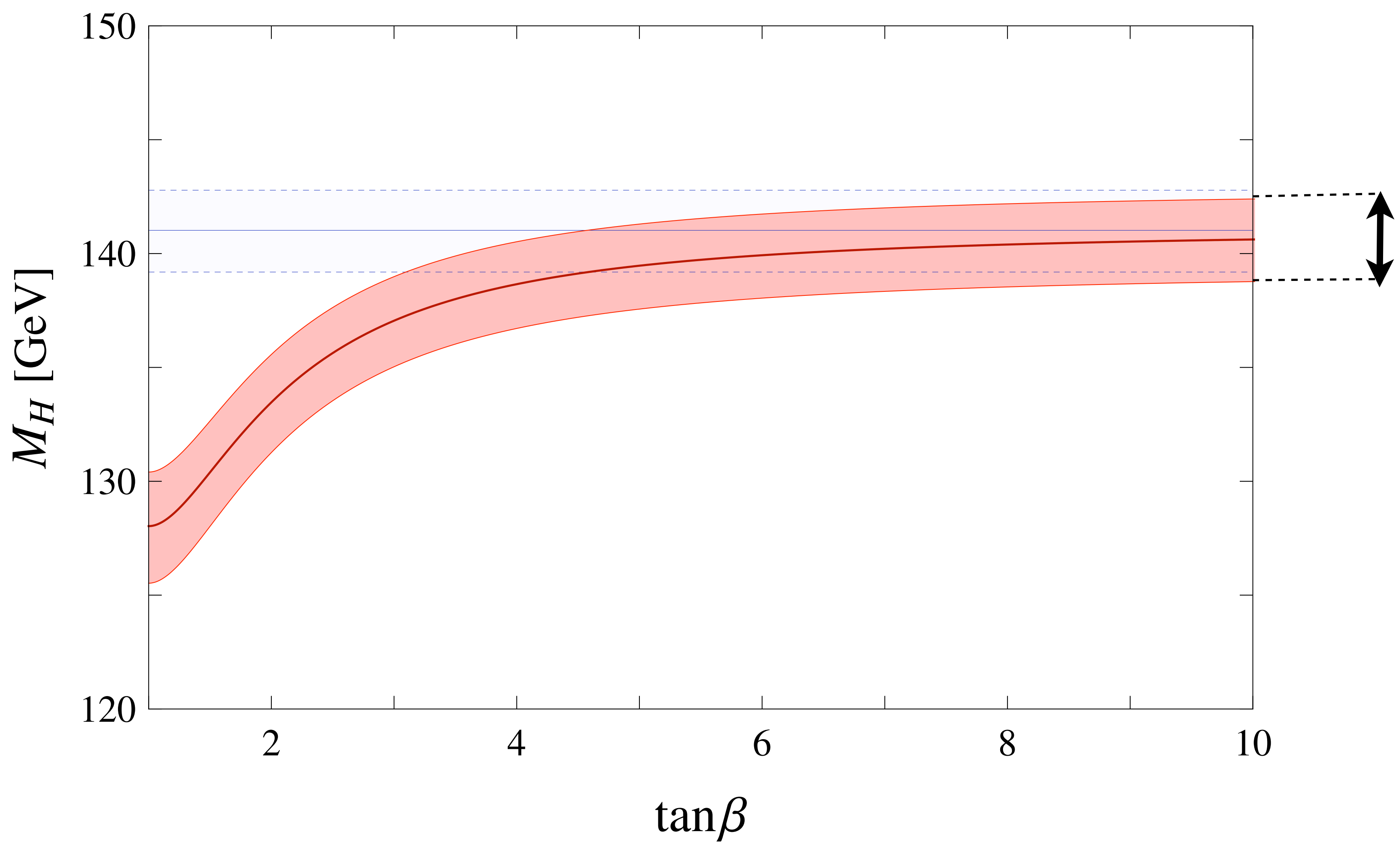

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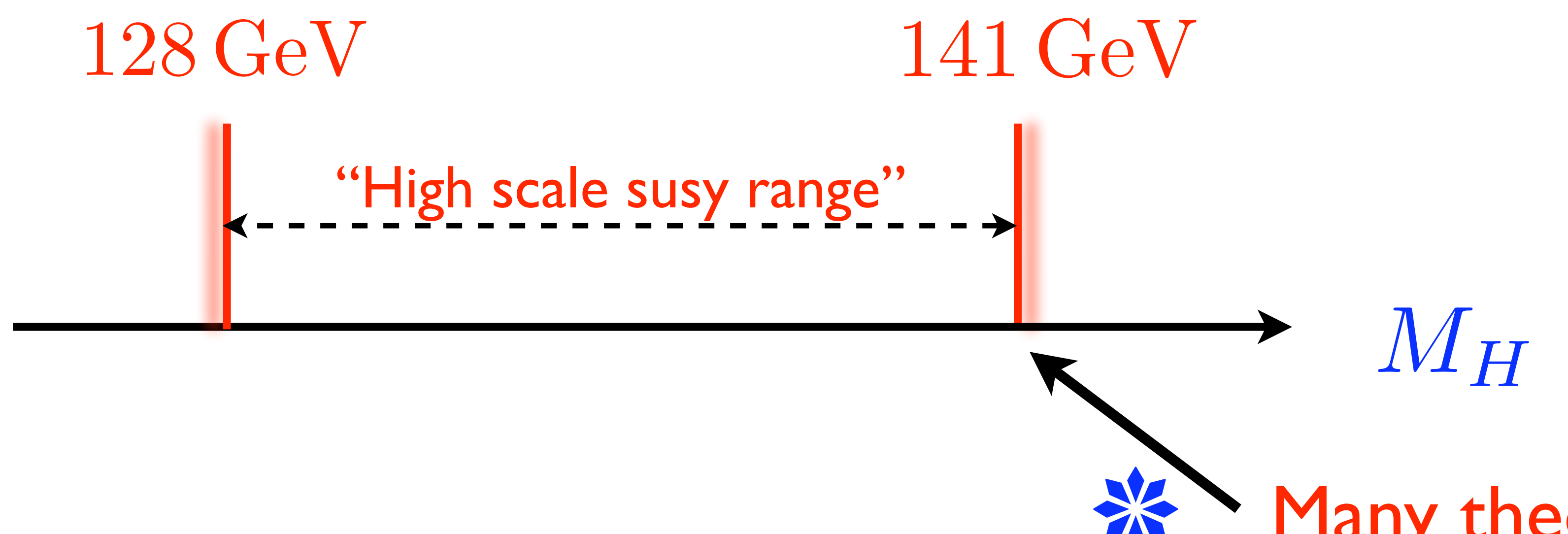
- 

- Many theories lead to this edge

Many Theories lead to the Upper Edge

- $SU(2)_R$ $> 4d$ at $\tilde{m}$ If H lies *predominantly in a single supermultiplet*

  upper edge results from $SU(2)_R$ invariant gauge interactions

- $U(1)_{PQ}$ $4d$ at $\tilde{m}$ approximate symmetry on h_u, h_d

  $> 4d$ at $\tilde{m}$ from profiles of h_u, h_d

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$SU(2)_R$
$U(1)_{PQ}$ $\longrightarrow$ $\lambda(\tilde{m}) = \frac{g^2(\tilde{m}) + g'^2(\tilde{m})}{8}$ $\longrightarrow$ $M_H \simeq 141\,\text{GeV}$

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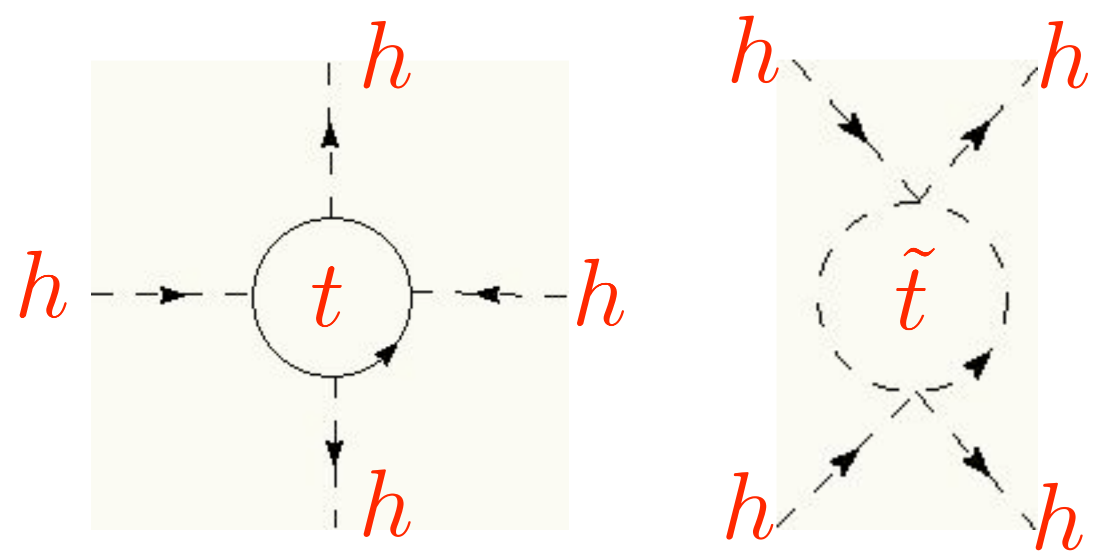
❇ What is the theoretical uncertainty? $\delta M_H = \pm\,?$

Threshold Corrections

- Study the boundary condition $\lambda(\tilde{m}) = \frac{g^2(\tilde{m}) + g'^2(\tilde{m})}{8}(1 + \delta(\tilde{m}))$

- δ has contributions from superpartner loops

  From MSSM we are familiar with large stop corrections giving δM_H of up to 40%!!



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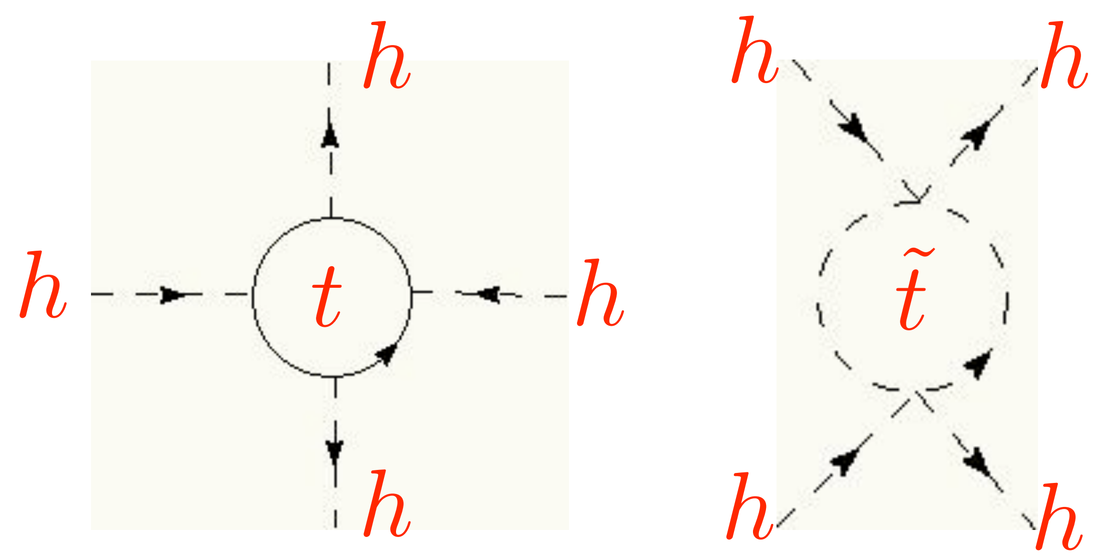

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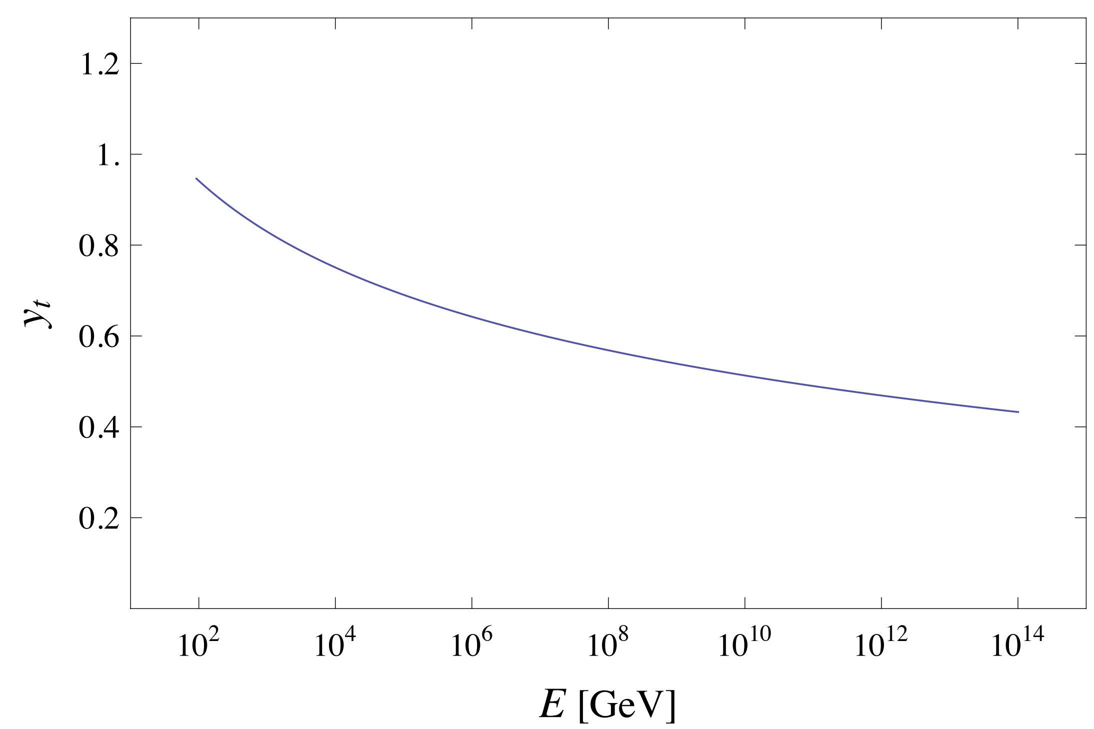
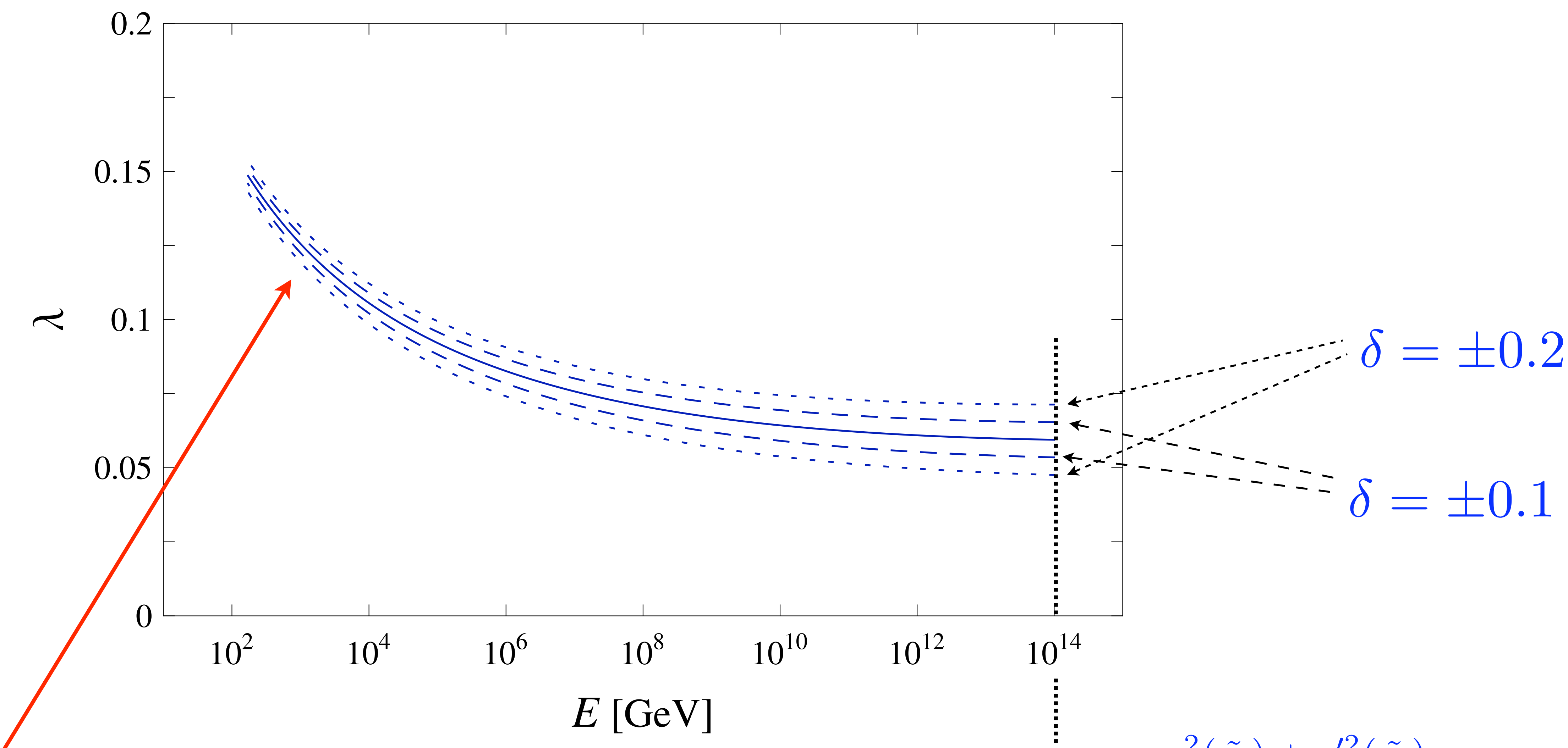
- We are extremely lucky:



y_t^4 ↓ factor of 20

IR Convergence

- RG scale to low energies



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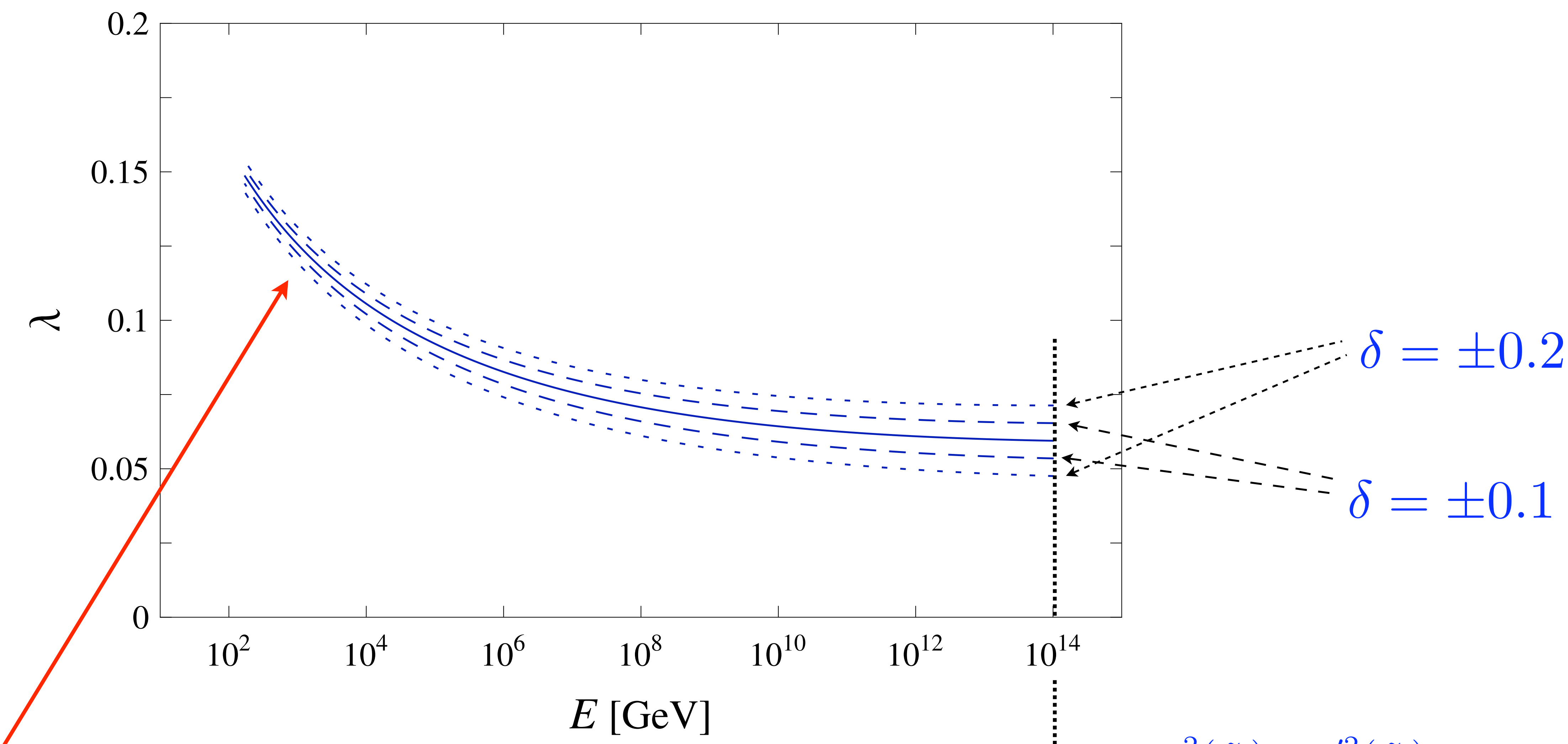

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- Guess that $\tilde{t}$ threshold corrections to Higgs mass reduced compared to MSSM: 40% $\xrightarrow{y_t}$ 2% $\xrightarrow{IR}$ 0.3% !!

The Prediction

- Compute complete 1 loop leading log threshold corrections at $\tilde{m}$

  They vanish if we choose to match at $\tilde{m} \simeq \frac{m_\lambda^{1.6}}{m_{\tilde{t}}^{0.6}}$

- The leading finite correction is $\delta_s = \frac{3y_t^4}{32\pi^2\lambda}\left(\frac{2A_t^2}{m_{\tilde{t}}^2} - \frac{A_t^4}{6m_{\tilde{t}}^4}\right) \simeq 0.007\left(\frac{2A_t^2}{m_{\tilde{t}}^2} - \frac{A_t^4}{6m_{\tilde{t}}^4}\right)$

  ie $\delta_s \simeq 0.01$ for $A_t = m_{\tilde{t}}$

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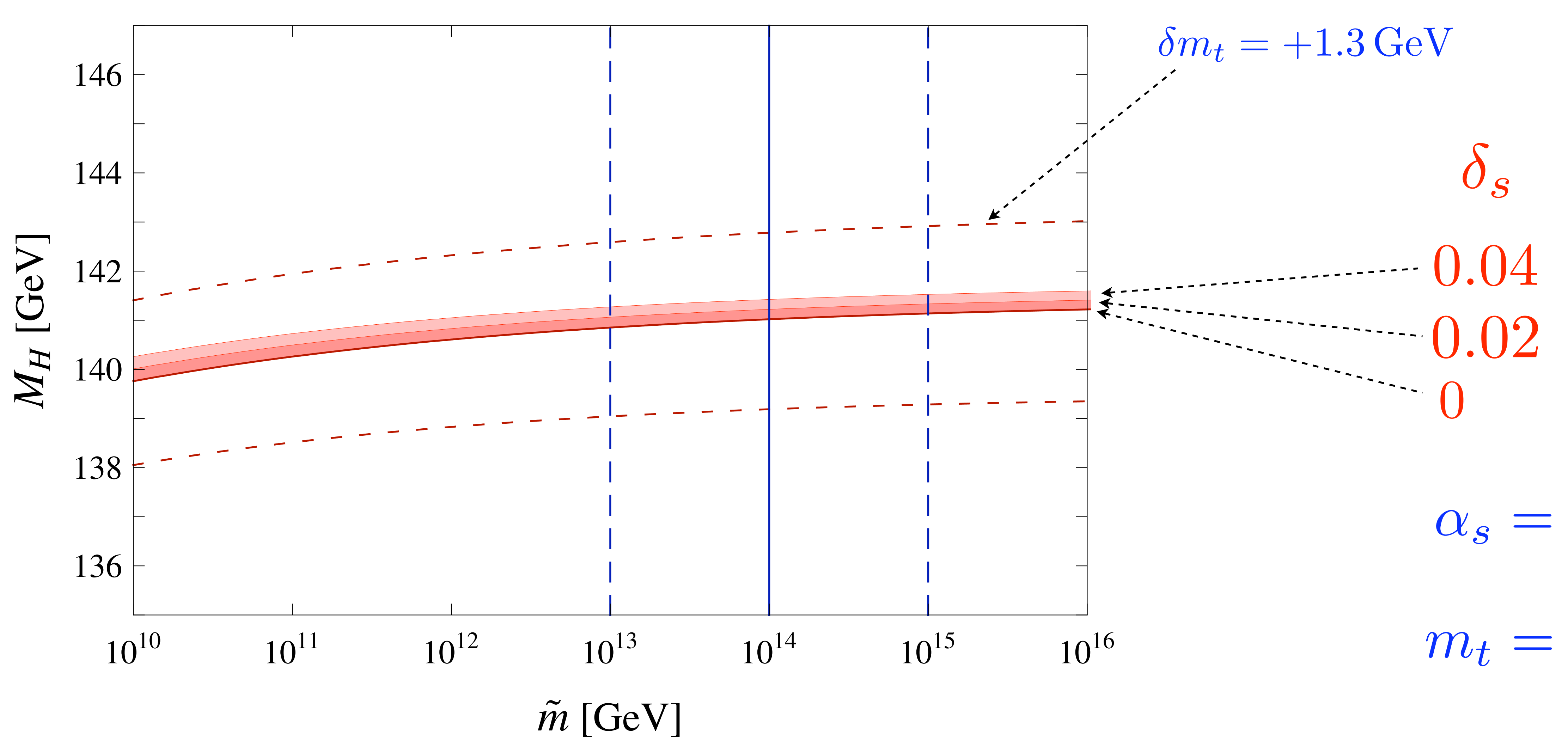
- 

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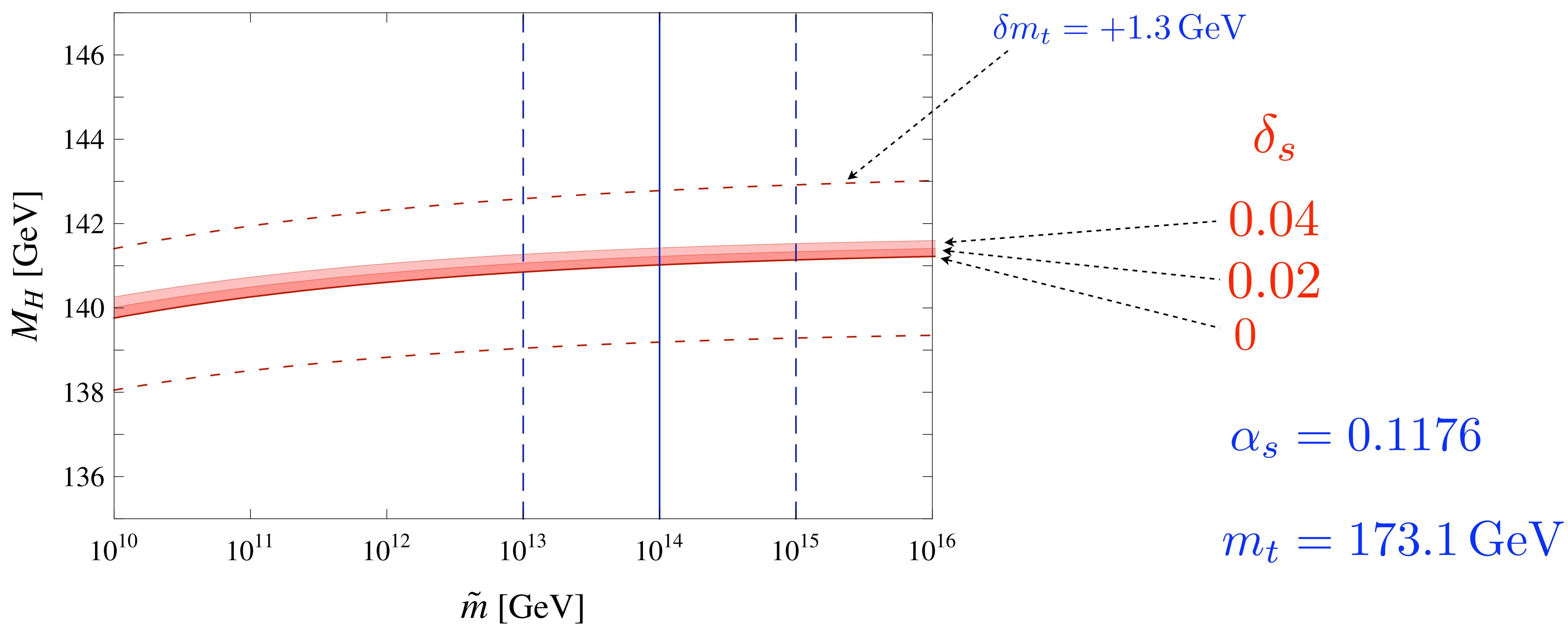
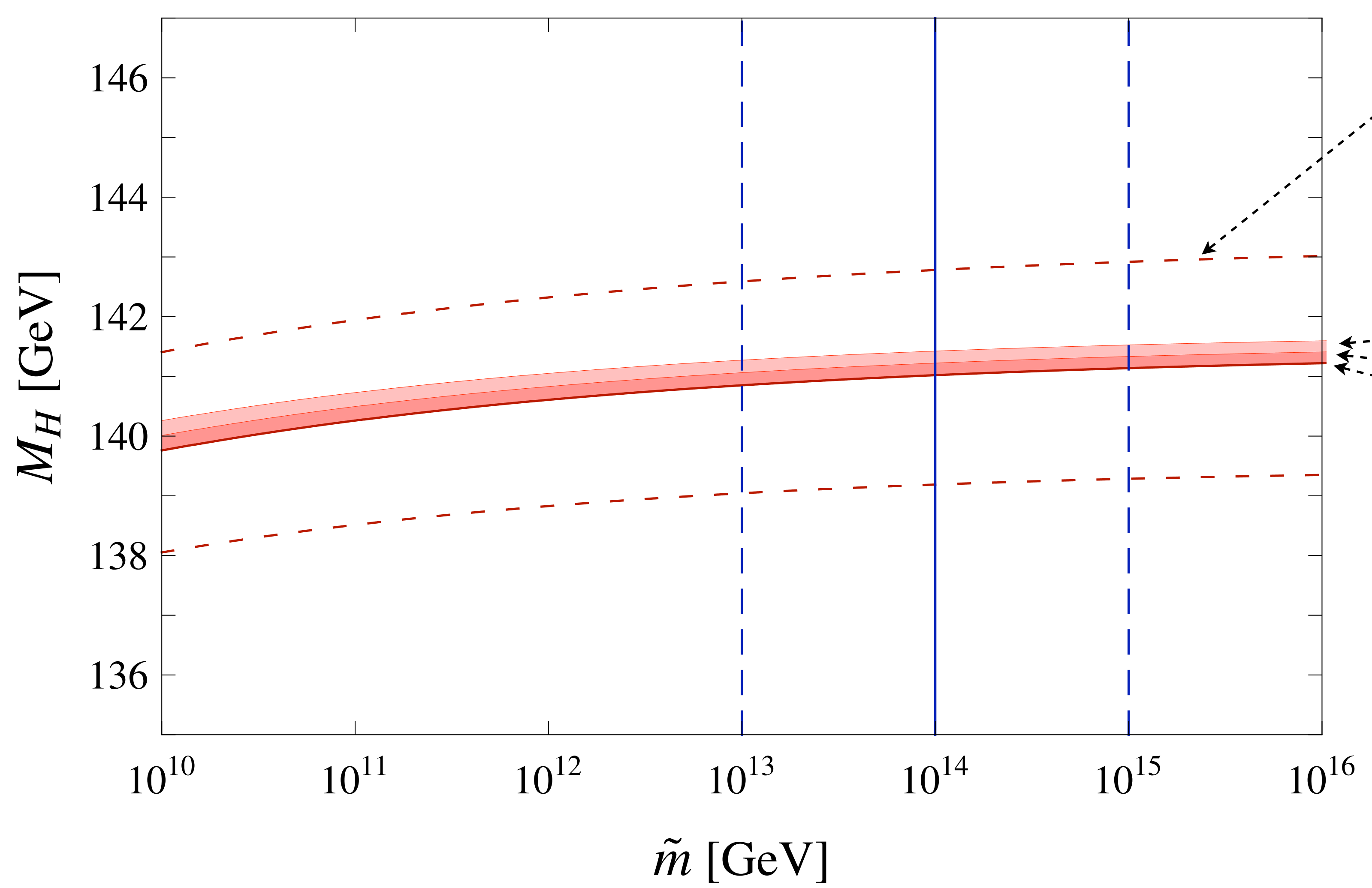


$$M_H = 141.0\text{ GeV} + 1.8\text{ GeV}\left(\frac{m_t - 173.1\text{ GeV}}{1.3\text{ GeV}}\right) - 1.0\text{ GeV}\left(\frac{\alpha_s(M_Z) - 0.1176}{0.002}\right)$$
$$+\,0.14\text{ GeV}\left(\log_{10}\frac{\tilde{m}}{10^{14}\text{ GeV}}\right) + 0.10\text{ GeV}\left(\frac{\delta}{0.01}\right) \pm 0.5\text{ GeV},$$

The Prediction



❋

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❋ Allowing $\tilde{m} = 10^{14\pm2}\,\mathrm{GeV}$, $\delta \approx O(0.01 - 0.03)$ the theoretical uncertainties from the high scale are $\delta M_H \sim \pm 0.4\,\mathrm{GeV}$

0.3% !!

III

Beyond (SM+GR)

New Physics Near $\tilde{m}$

Change to Higgs mass prediction

- SU(5): small
- SO(10): $\delta M_H = +2.4\,\mathrm{GeV}$
- High scale see-saw for neutrino masses:

Typically negligible

Except in special regions,
e.g. $\tilde{m} > M_R \approx 10^{15}\,\mathrm{GeV}$ $\delta M_H \approx +1\,\mathrm{GeV}$

New Physics Below $\tilde{m}$

Higgs mass prediction *rapidly destroyed*

- Additions to gauge group

- New interactions of Higgs or top quark

- New contributions to 3-2-1 beta functions

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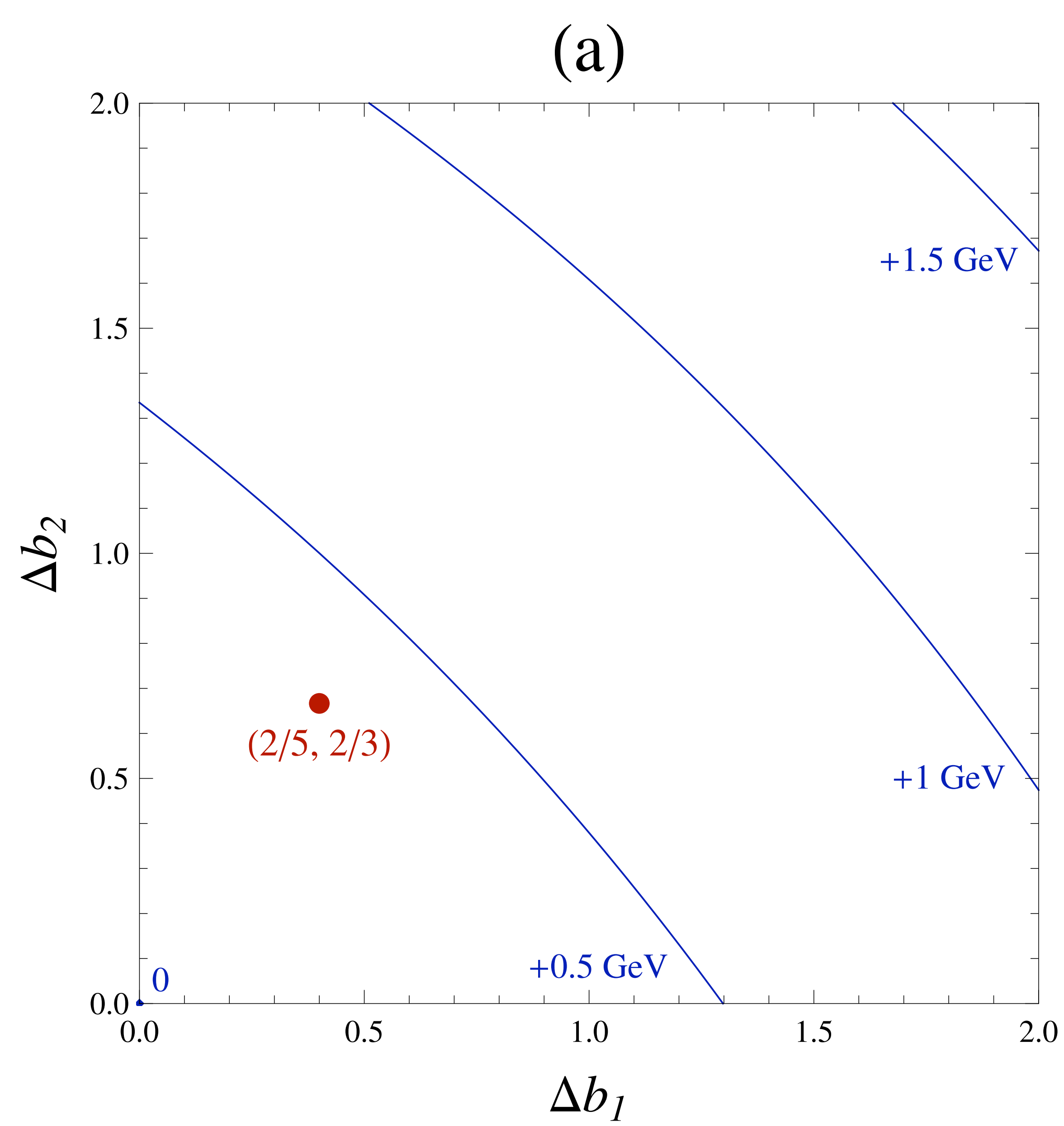

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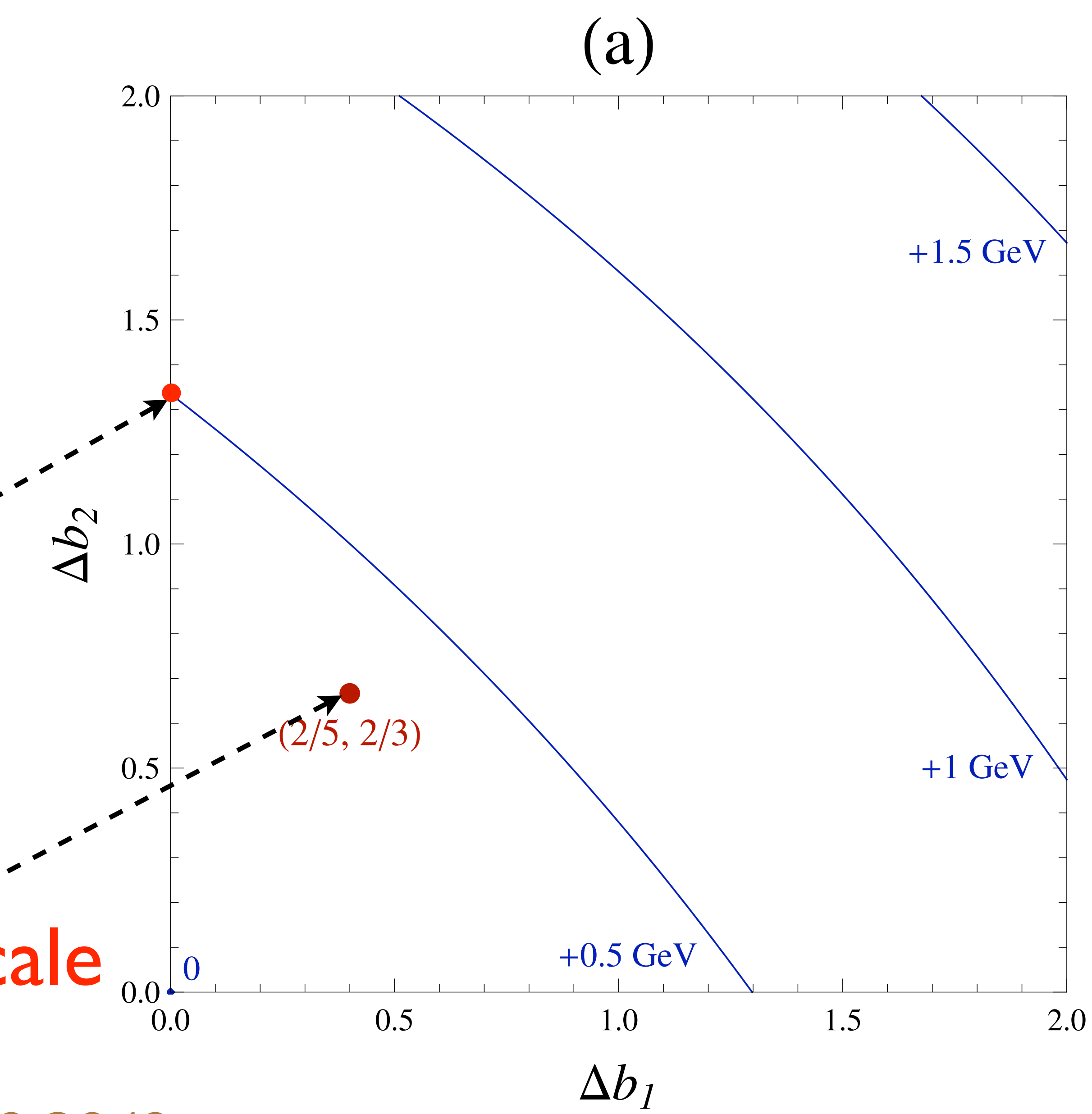
$\mathrm{SM} + \tilde{w}$: Wino at weak scale

$\mathrm{SM} + \tilde{h}/\tilde{s}$: Higgsinos and Singlino at weak scale



Elor, Goh, Hall, Kumar, Nomura 0912.3942

Environmental Selection of Dark Matter

Elor, Goh, Kumar, Hall, Nomura 0912.3942

- Axion $f_a \sim M_*$ with θ_{mis} selected to be small

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- **Five theories with states at $\tilde{m}$ of MSSM + singlets**

	I	II	III	IV	V
States at TeV scale	SM	(SM + $\tilde{w}$)	(SM + $\tilde{h}/\tilde{s}$)	(SM + $\tilde{g}, \tilde{w}, \tilde{b}, \tilde{h}$)	MSSM
Dark Matter	QCD axion	WIMP LSP	WIMP LSP	WIMP LSP	WIMP LSP
DM selection acts on	θ_{mis}	$m_{\tilde{w}}$	ϵ	ϵ_R	$\tilde{m}$
New parameters	f_a, θ_{mis}	$m_{\tilde{w}}$	μ, m, y	$m_{\tilde{g}}, m_{\tilde{w}}, m_{\tilde{b}}, \mu, \tan\beta$	MSSM set
Gauge coupling unif.	SM	$\approx$ SM	$\approx$ MSSM	$\approx$ MSSM	$\approx$ MSSM
Higgs mass	141 GeV	142 GeV	(141-210) GeV	(114-154) GeV	(114-125?) GeV

Conclusions

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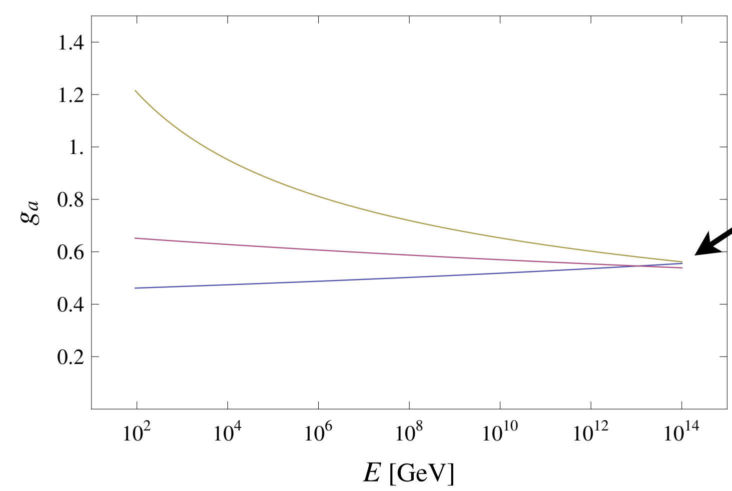

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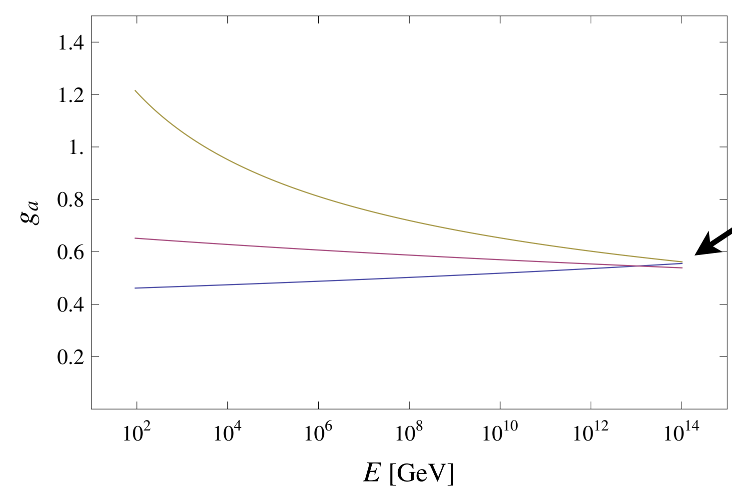

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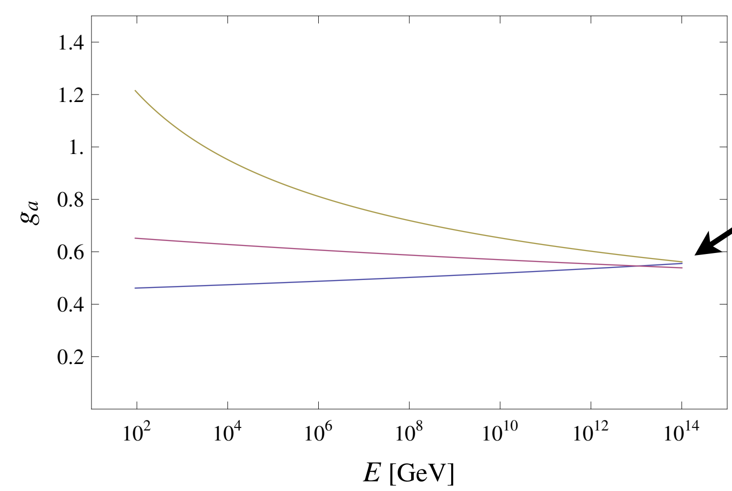

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- Axion DM is strongly motivated -- but Higgsino and wino WIMPs possible

Strong Evidence for the Multiverse

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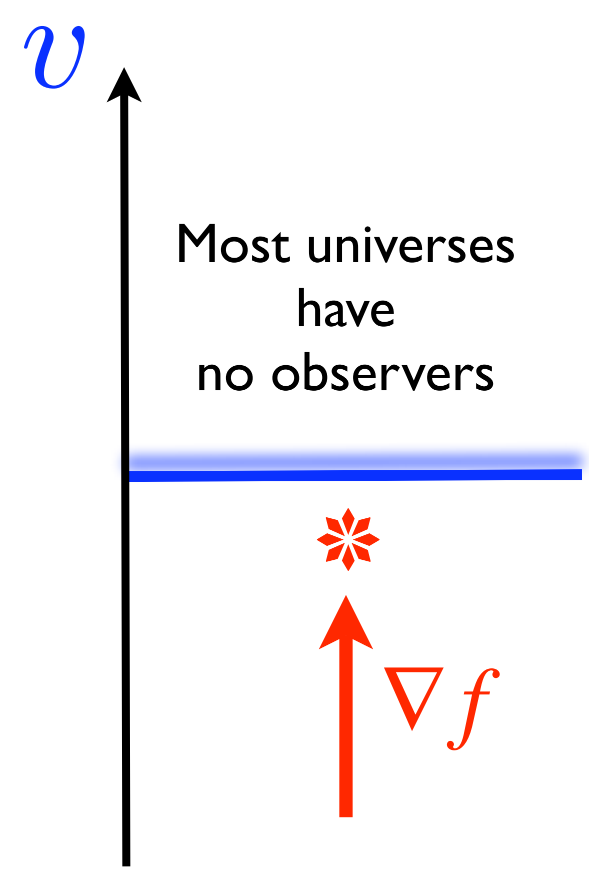

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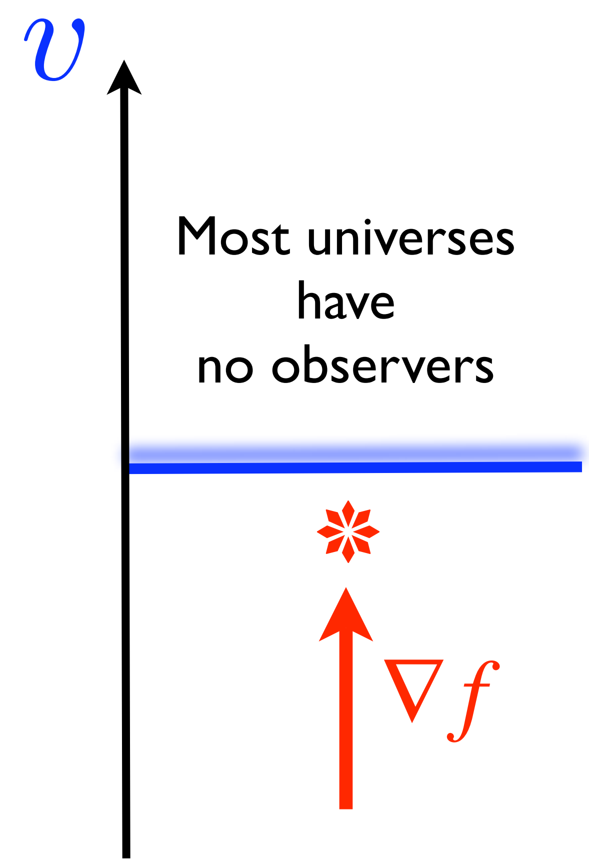

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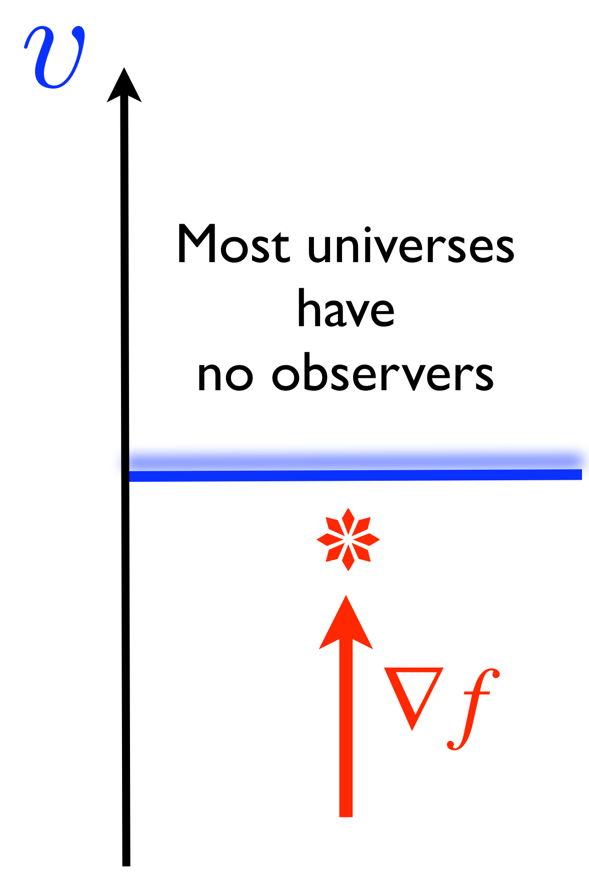

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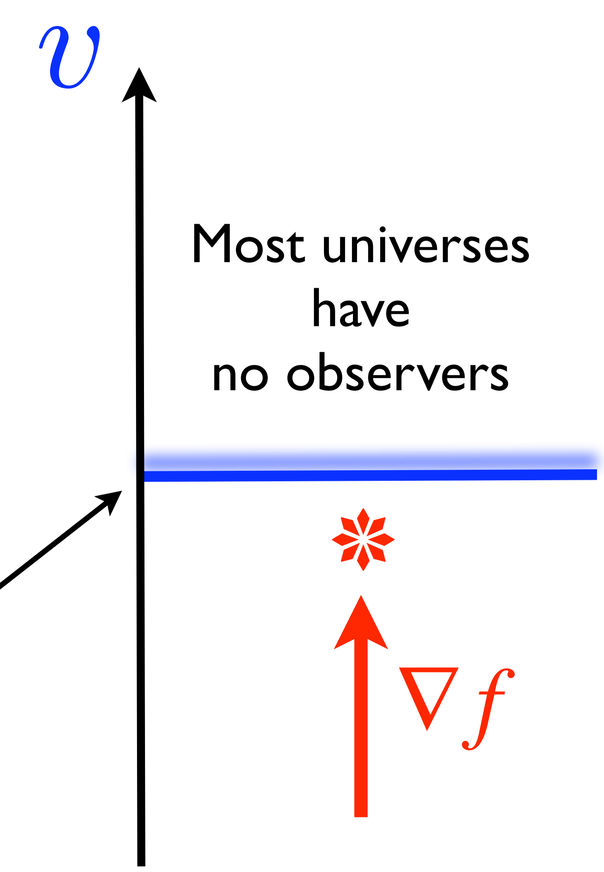

Only ways out:

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❉ Need better understanding of the physics of the catastrophic boundary

❉ Search for more boundaries!

The Excitement of the LHC

New strong dynamics — Stratus

Weak scale supersymmetry — Logos

Multiverse — Chaos

Do you know which one is correct?
I don't!

Future Confrontation between Theory and Experiment

Future Linear Collider

$$\delta m_t = \pm 0.1\,\mathrm{GeV} \qquad \delta M_H = 0.14\,\mathrm{GeV}$$

$$\delta \alpha_s = 0.0012 \qquad \delta M_H = 0.6\,\mathrm{GeV}$$

$$\delta M_{H_{exp}} = \pm 0.1\,\mathrm{GeV}$$

Giga Z

$$\delta \alpha_s = 0.0005 \qquad \delta M_H = 0.25\,\mathrm{GeV}$$

Three loop QCD running $\qquad \delta M_H = -0.2\,\mathrm{GeV}$

Three loop y_t running $\qquad \delta M_H \approx \pm 0.2\,\mathrm{GeV}$

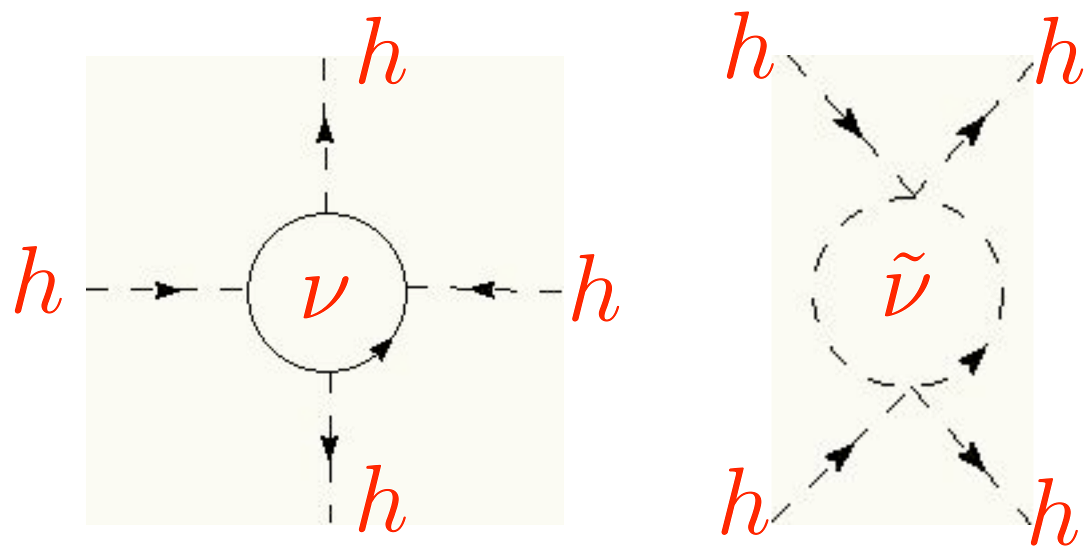
Four loop QCD for top mass $\qquad \delta M_H \approx \pm 0.2\,\mathrm{GeV}$

$$M_H = (141.0 + \Delta)\ \mathrm{GeV} + 0.14\ \mathrm{GeV}\left(\frac{m_t - 173.1\ \mathrm{GeV}}{0.1\ \mathrm{GeV}}\right) - 0.25\ \mathrm{GeV}\left(\frac{\alpha_s(M_Z) - 0.1176}{0.0005}\right)$$
$$+ 0.14\ \mathrm{GeV}\left(\log_{10}\frac{\tilde{m}}{10^{14}\ \mathrm{GeV}}\right) + 0.10\ \mathrm{GeV}\left(\frac{\delta}{0.01}\right)$$

Neutrino Masses

- See-saw neutrino masses $$\mathcal{L}_\nu = y_\nu \, l \nu_R h + \frac{M_R}{2} \nu_R \nu_R + h.c.$$

- λ radiatively corrected by ν_R



$\propto \, y_\nu^4$

- For $M_R \ll \tilde{m}$ $$\delta\lambda = \frac{y_\nu^4}{2\pi^2} \ln \frac{\tilde{m}}{M_R}$$

- But $m_\nu \simeq 0.05 \, \mathrm{eV} \, y_\nu^2 \, \frac{10^{15} \, \mathrm{GeV}}{M_R}$

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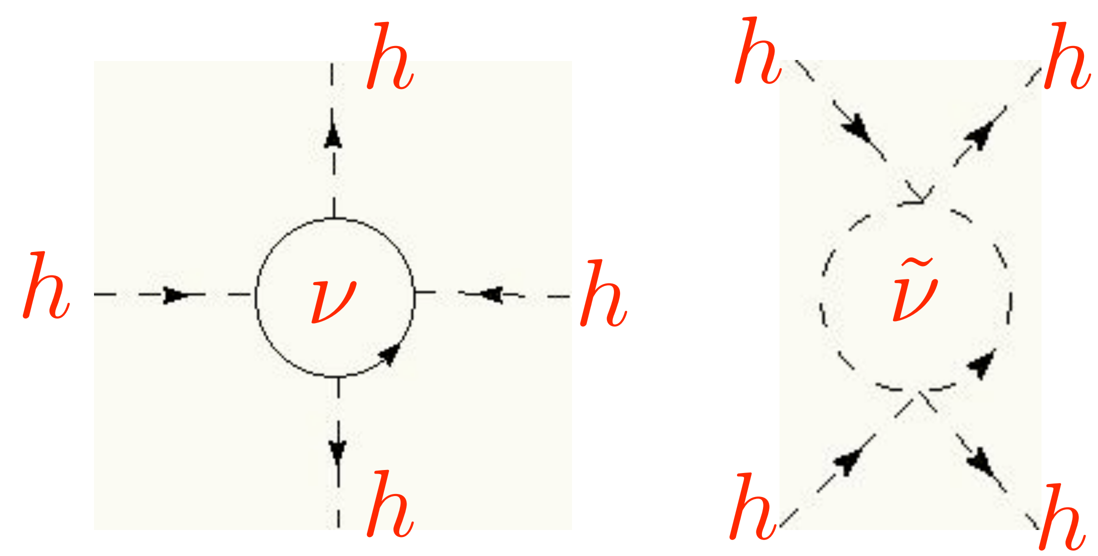

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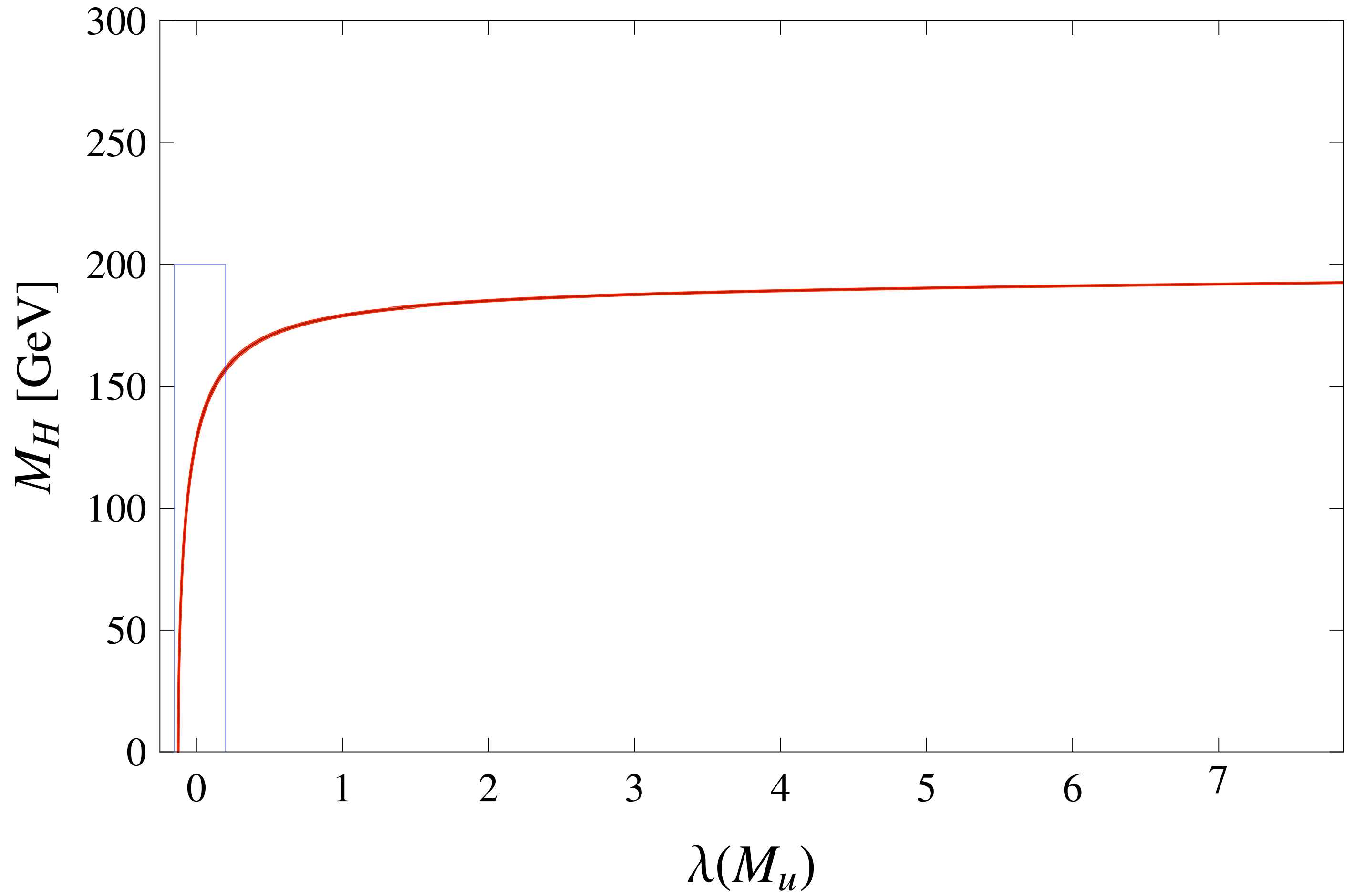
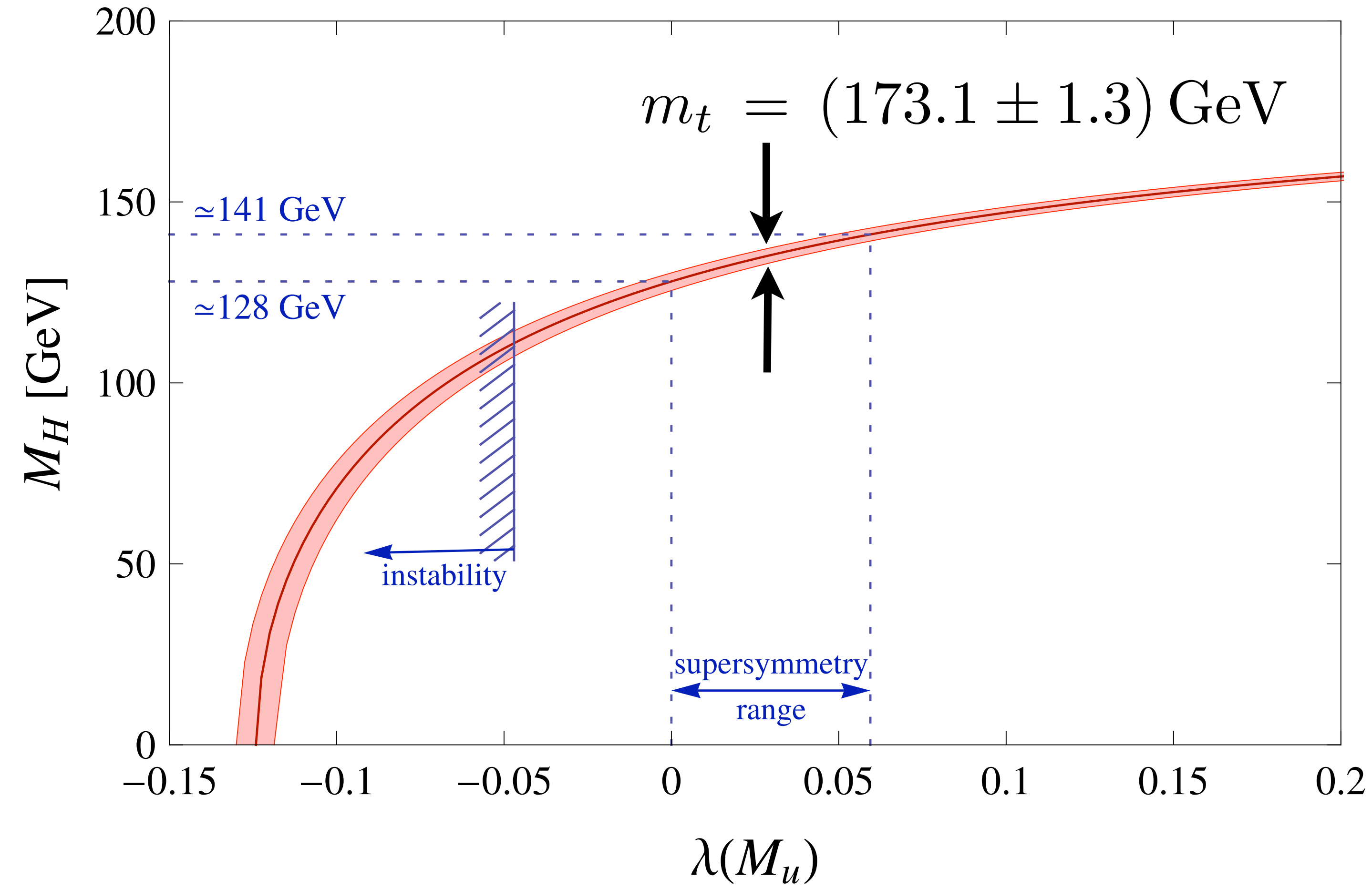
Neutrino corrections typically negligable

- Except in special regions, e.g.

$\tilde{m} > M_R \approx 10^{15}\,\mathrm{GeV}$ giving $\delta M_H \approx +1\,\mathrm{GeV}$

Special Higgs Masses of (SM+GR)





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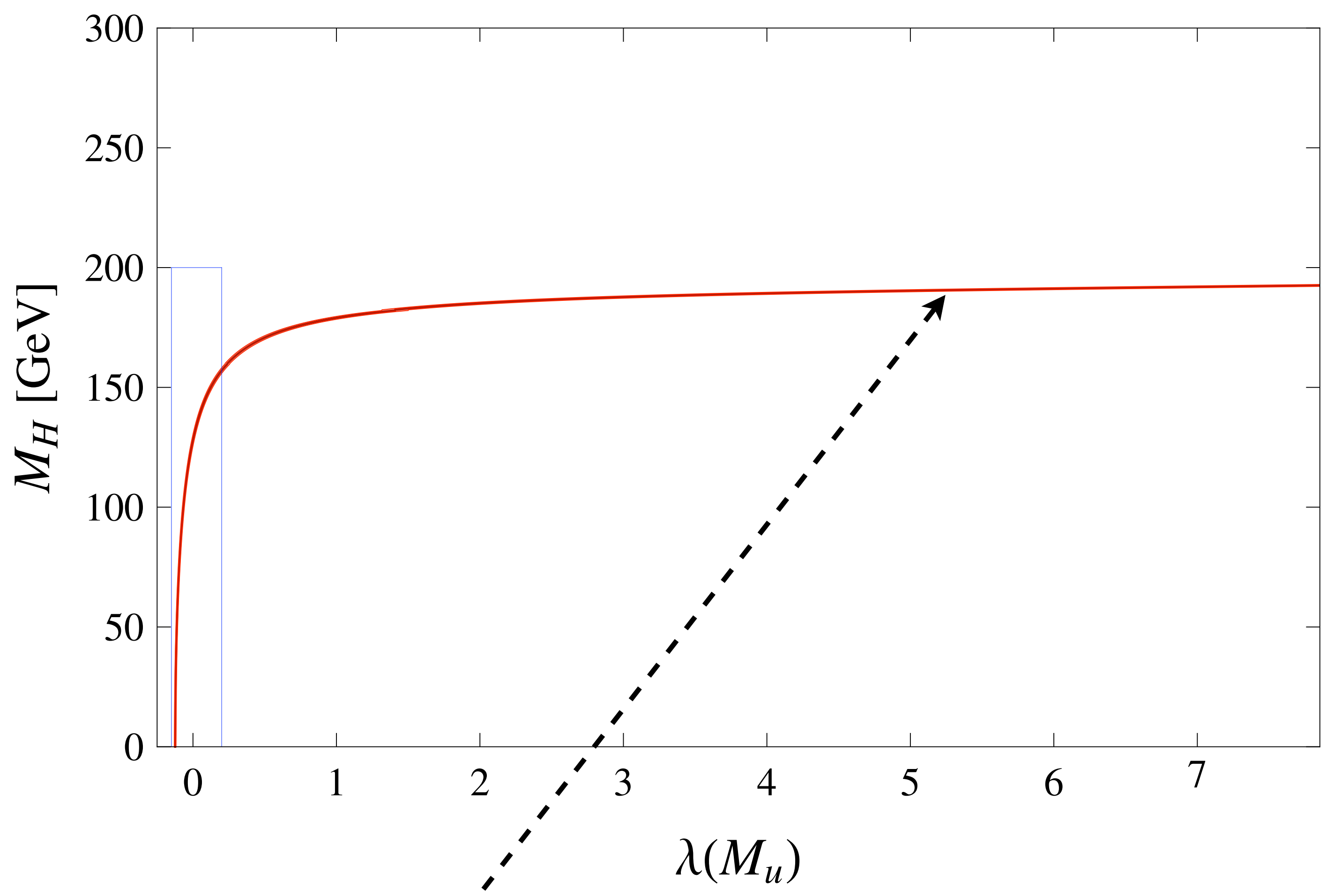

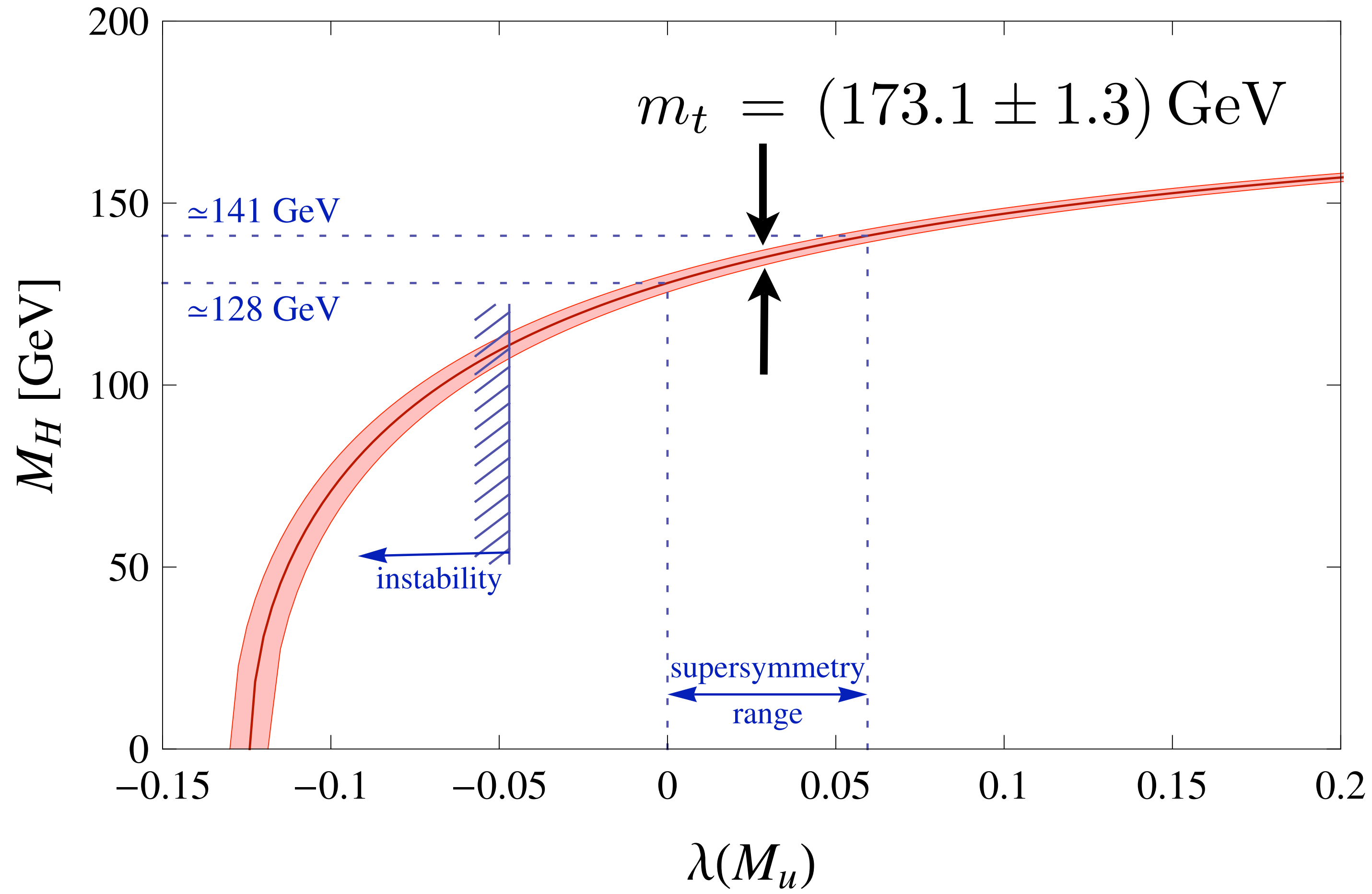

$$M_H \sim 190\,\mathrm{GeV}$$

$$\lambda(M_u) > 2$$

but $\pm 10\,\mathrm{GeV}$

for $M_u = 10^{14\pm 2}\,\mathrm{GeV}$

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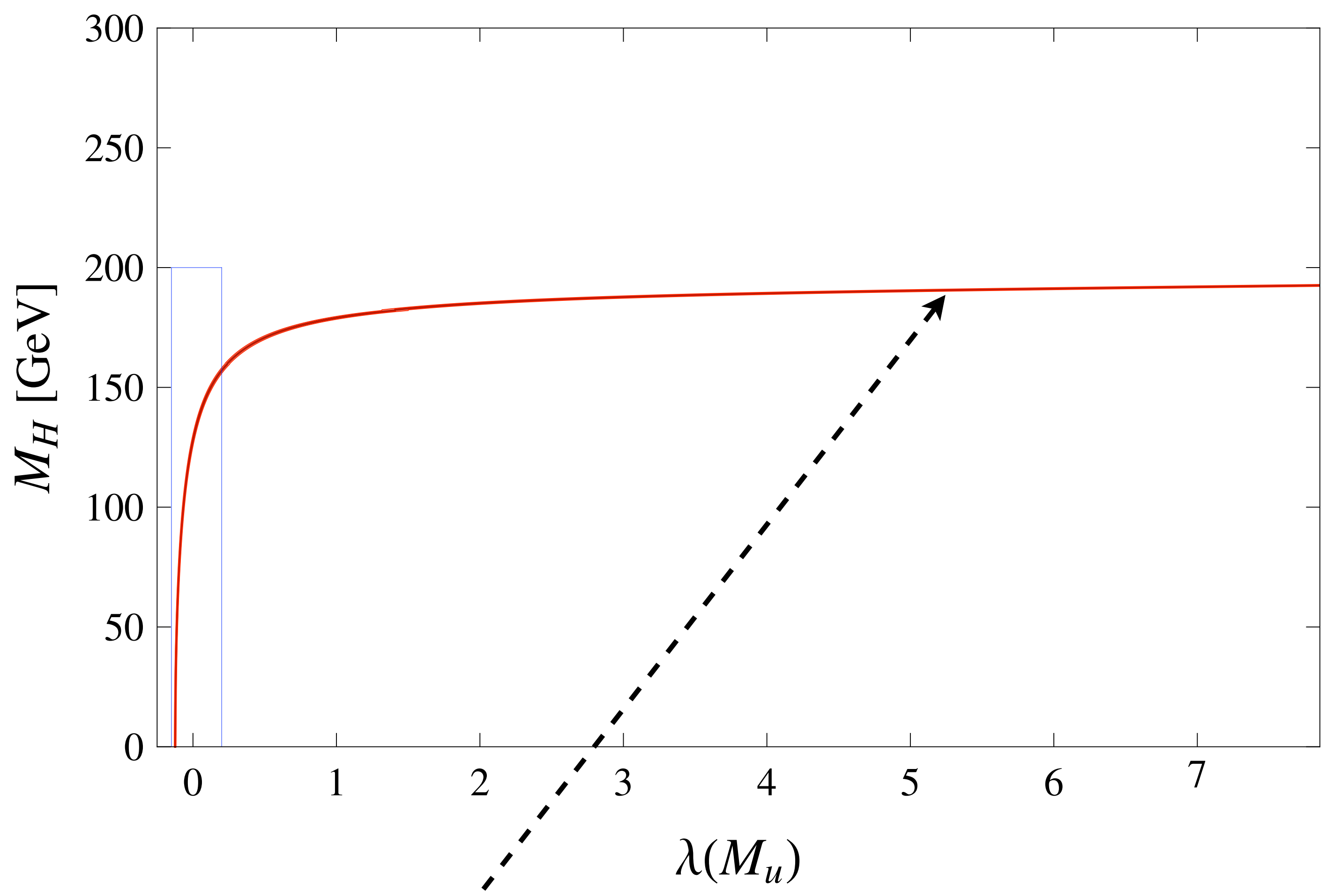

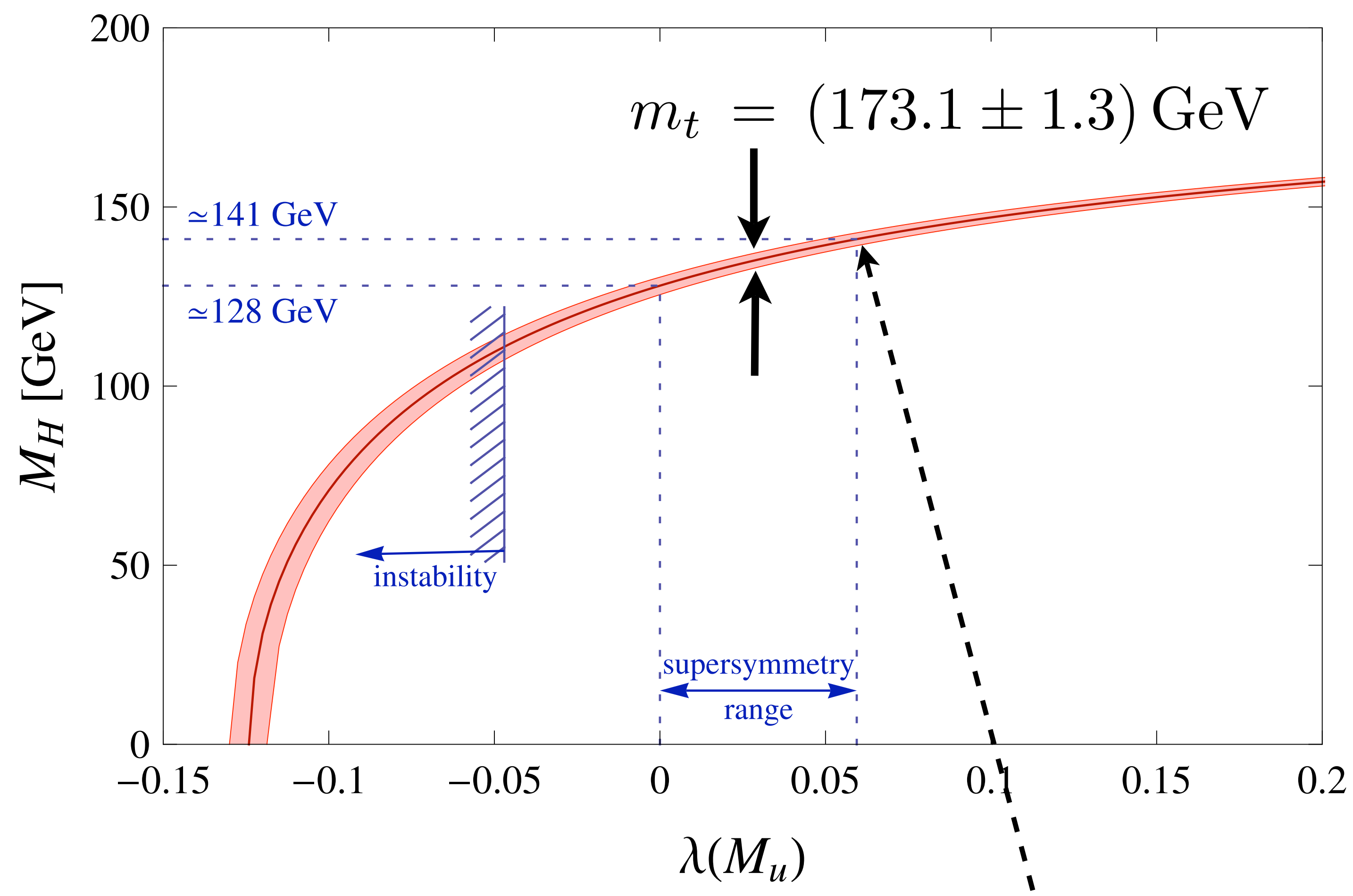

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Higgs in single supermultiplet

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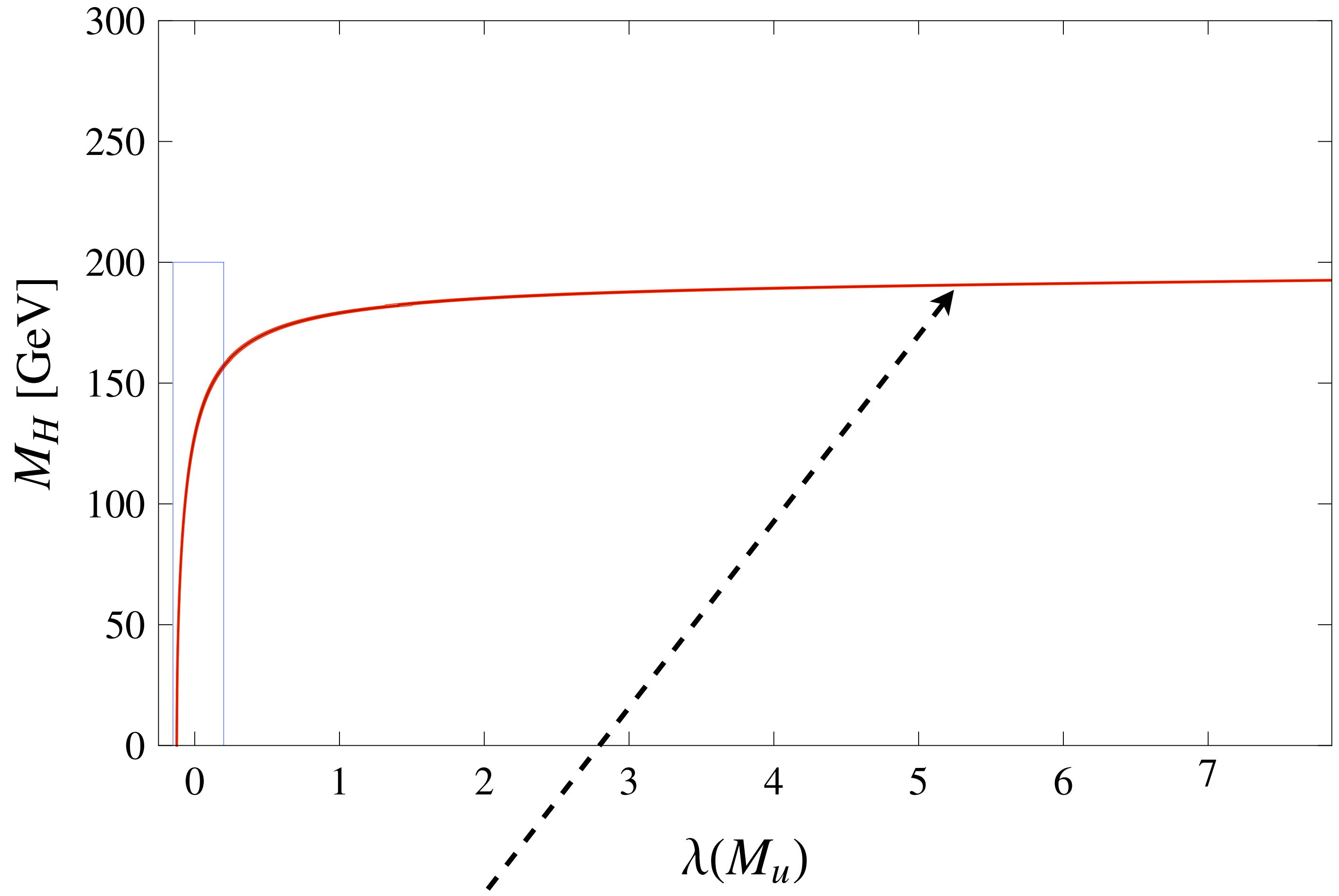

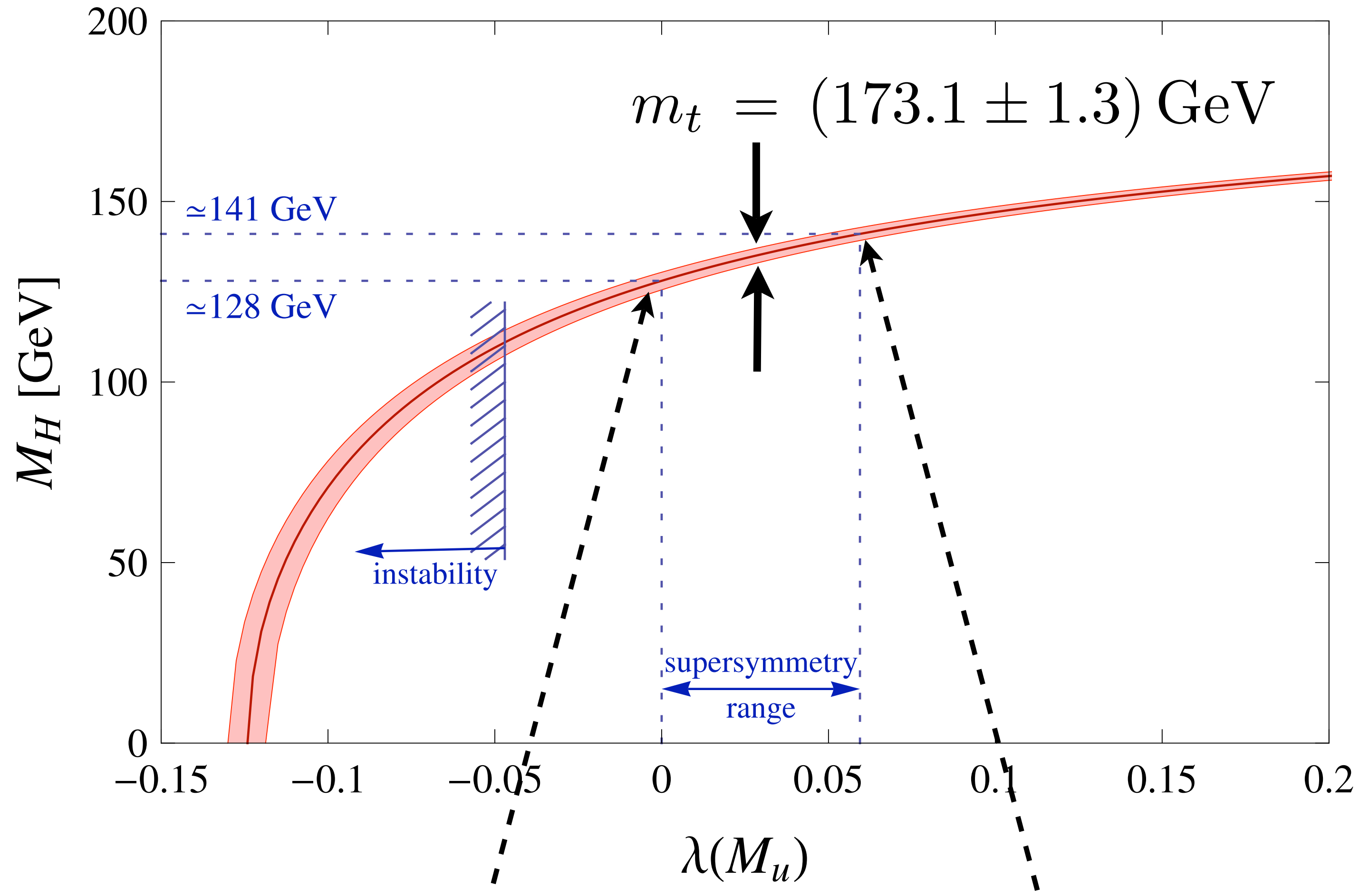

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eg PGB Higgs

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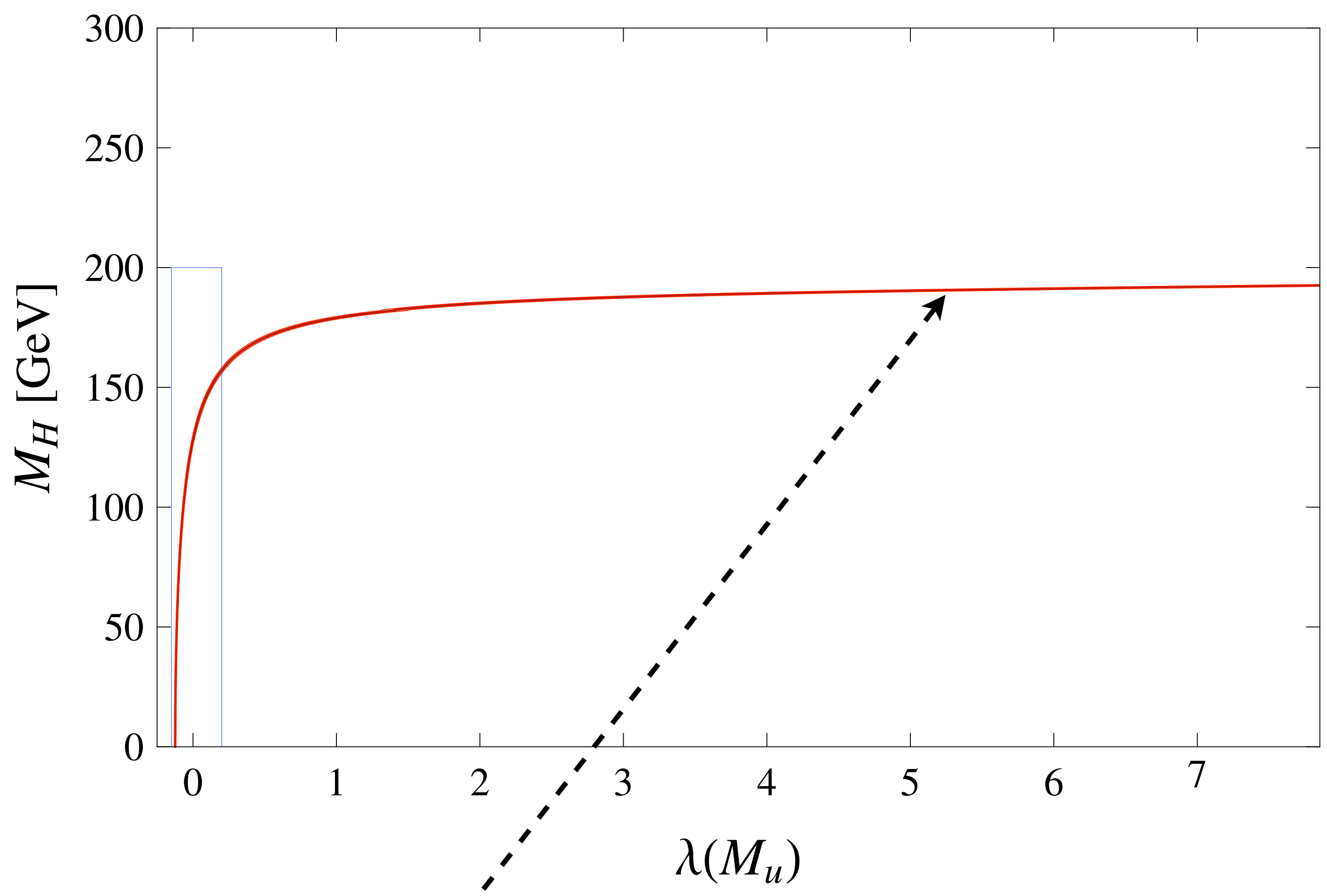

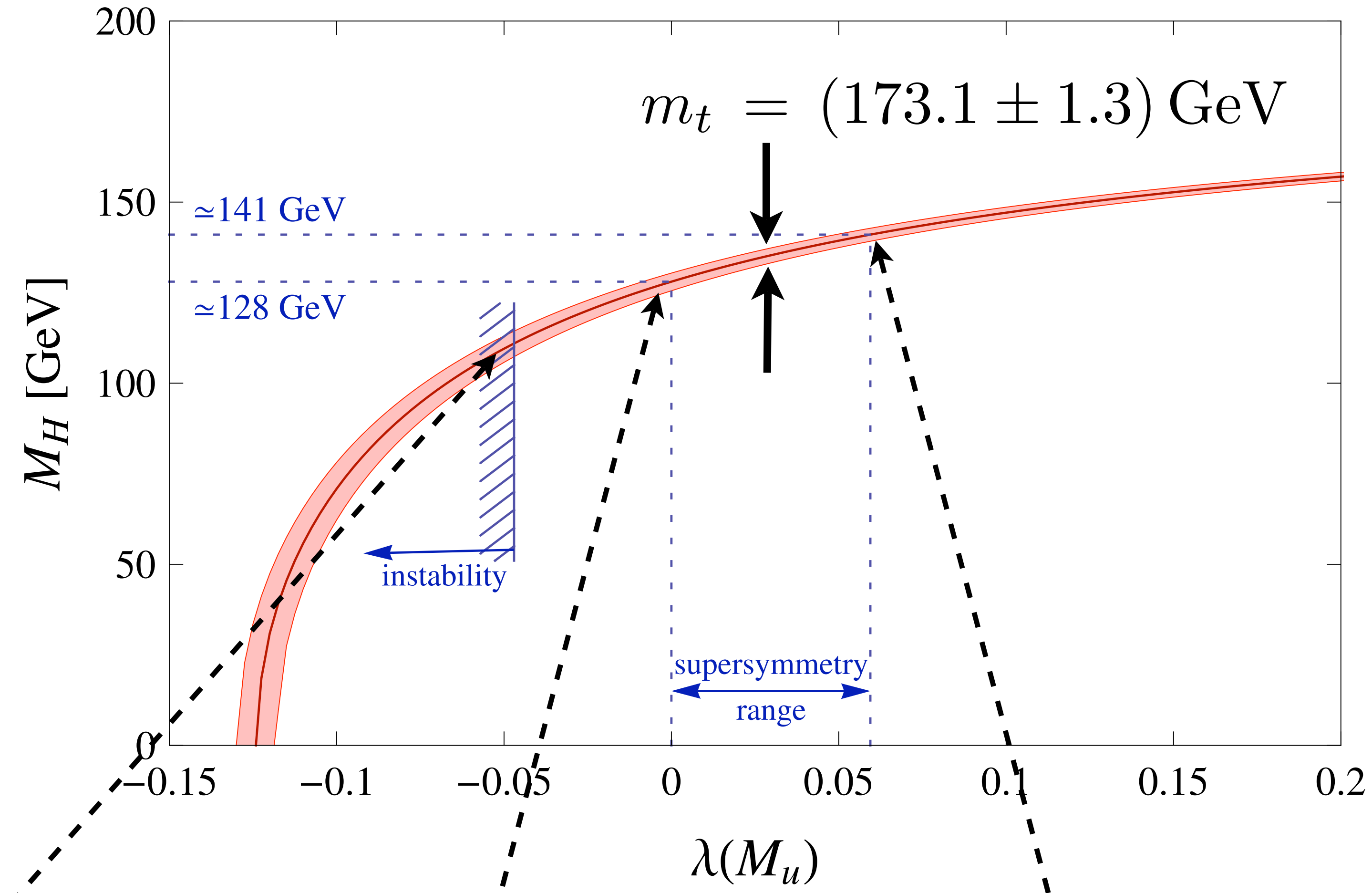

$M_H \sim 190\,\mathrm{GeV}$

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$M_H \sim 112\,\mathrm{GeV}$

Electroweak phase unstable

Feldstein, Hall, Watari
hep-ph/0608121

$M_H \sim 128\,\mathrm{GeV}$

$\lambda(M_u) = 0$

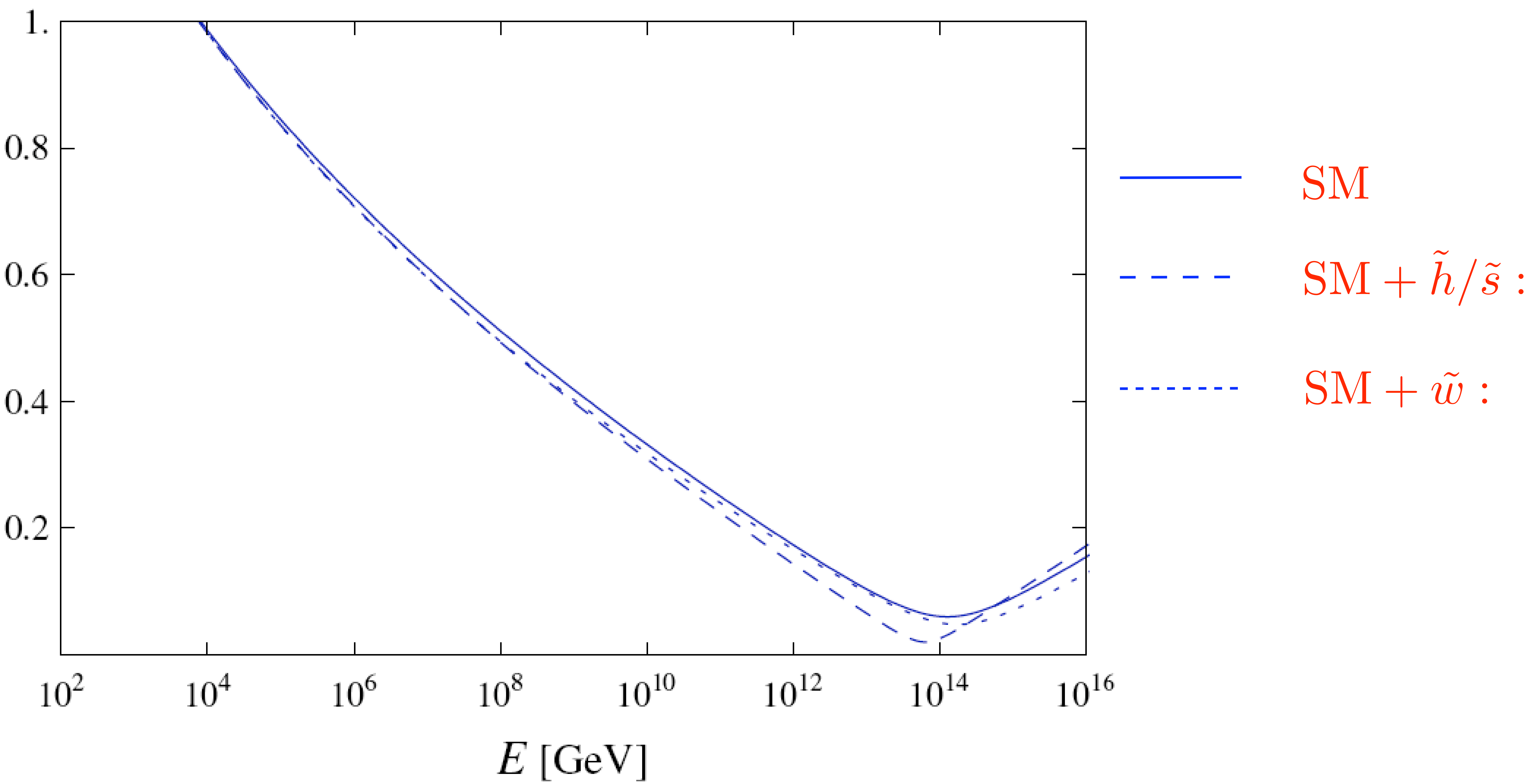
eg PGB Higgs

$M_H \sim 141\,\mathrm{GeV}$

Higgs in single supermultiplet

Gauge Coupling Unification

$$\delta \equiv \sqrt{(g_1^2 - \bar{g}^2)^2 + (g_2^2 - \bar{g}^2)^2 + (g_3^2 - \bar{g}^2)^2}/\bar{g}^2$$

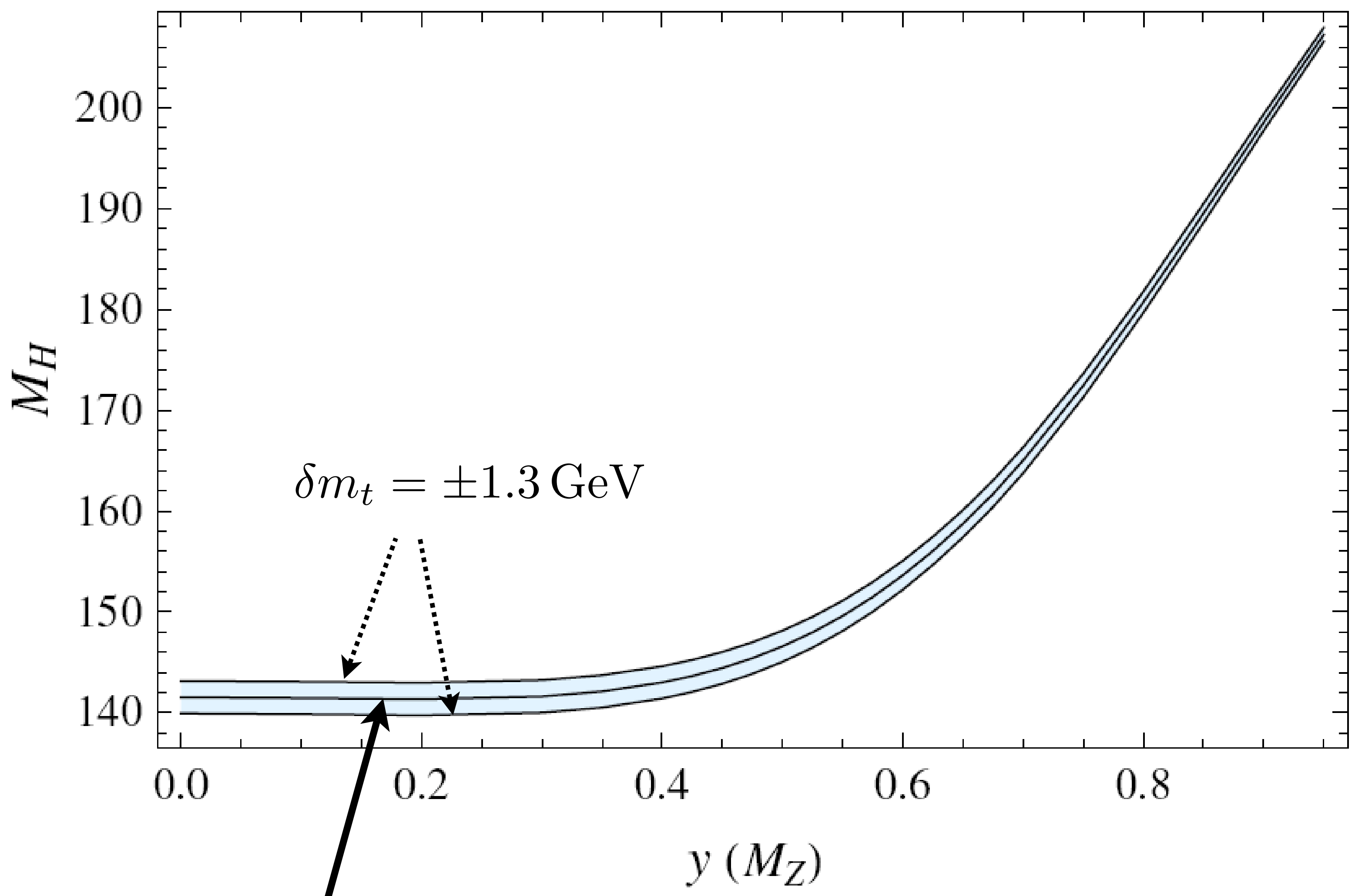


Higgs Mass Prediction $\mathrm{SM} + \tilde{h}/\tilde{s}$

- Three new parameters

$$\mathcal{L}_{\mathrm{SM}}(q,u,d,l,e,h) + \left\{ \mu \tilde{h}_u \tilde{h}_d + \frac{m}{2}\tilde{s}^2 + y \tilde{h}_d \tilde{s} h + \mathrm{h.c.} \right\}$$

- Supersymmetric boundary condition $\lambda(\tilde{m}) = \frac{g^2(\tilde{m}) + g'^2(\tilde{m})}{8}(1+\delta(\tilde{m}))$



0.35 GeV above SM

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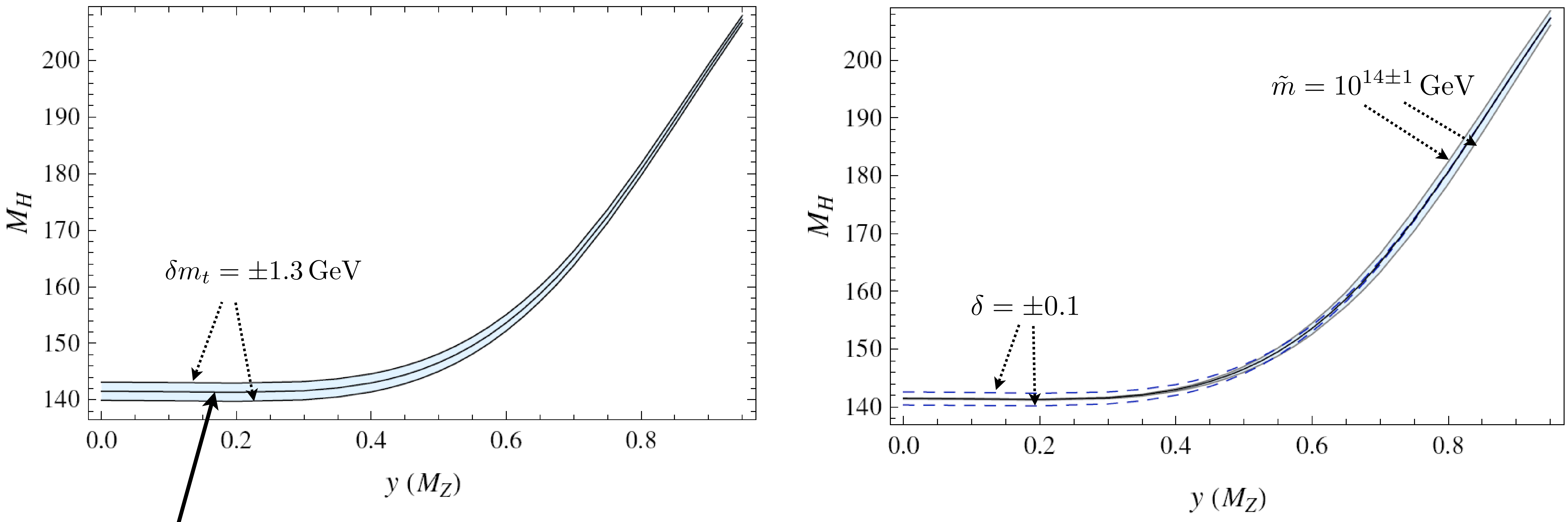

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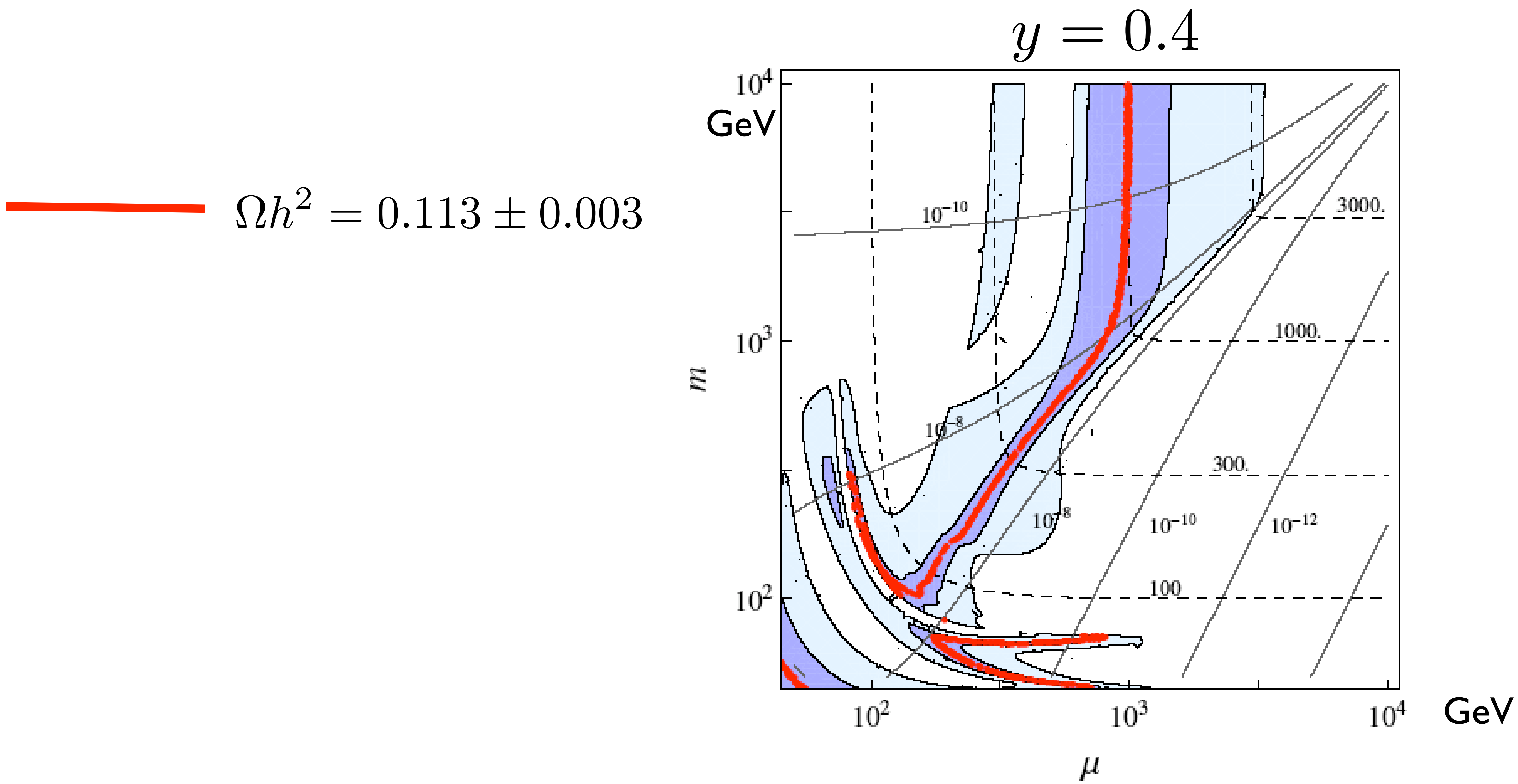
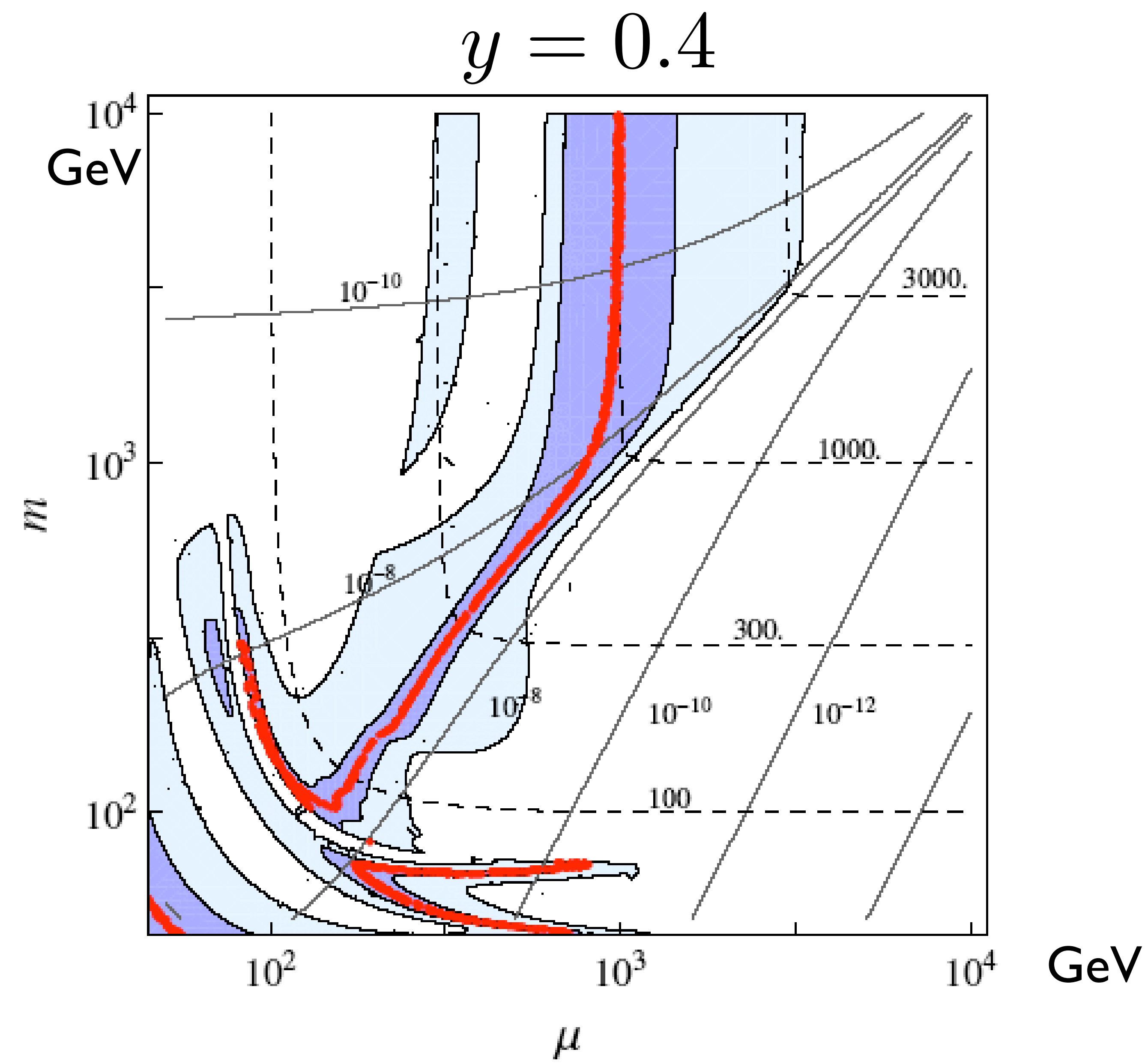
Dark Matter: $\mathrm{SM} + \tilde{h}/\tilde{s}$

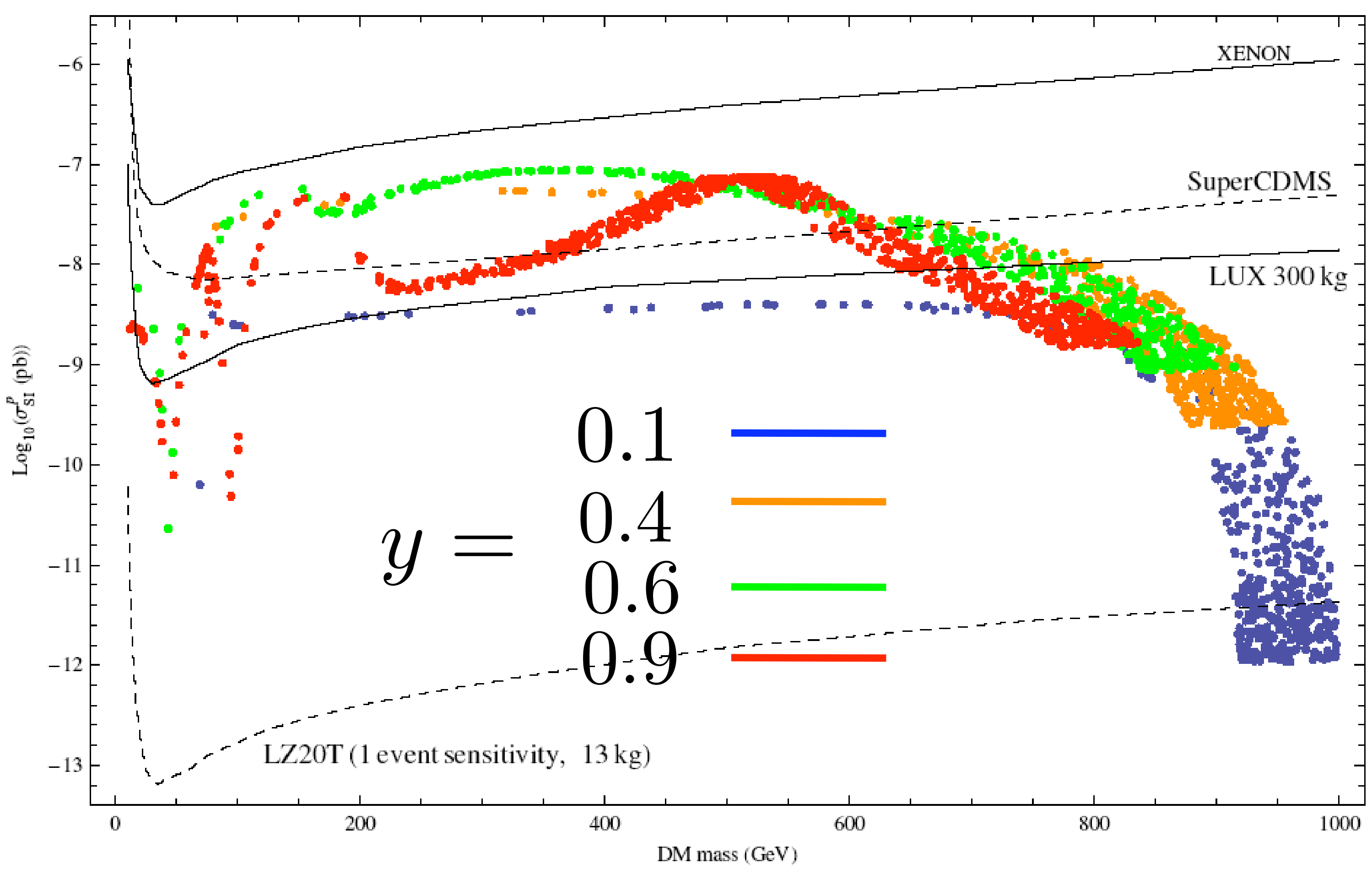


Dark Matter: $\mathrm{SM} + \tilde{h}/\tilde{s}$

$\Omega h^2 = 0.113 \pm 0.003$

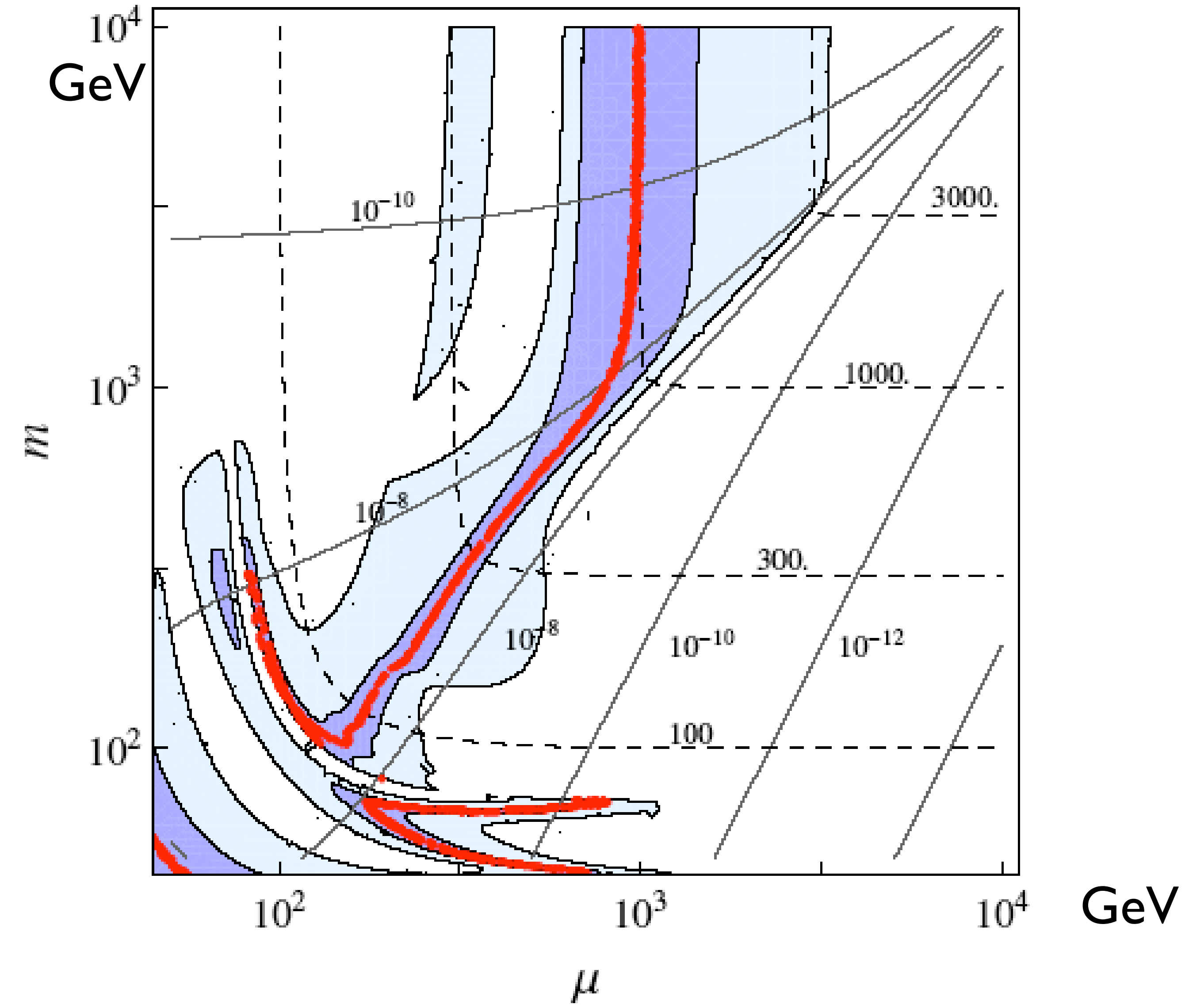


Direct detection



Dark Matter: $\mathrm{SM} + \tilde{h}/\tilde{s}$

$y = 0.4$



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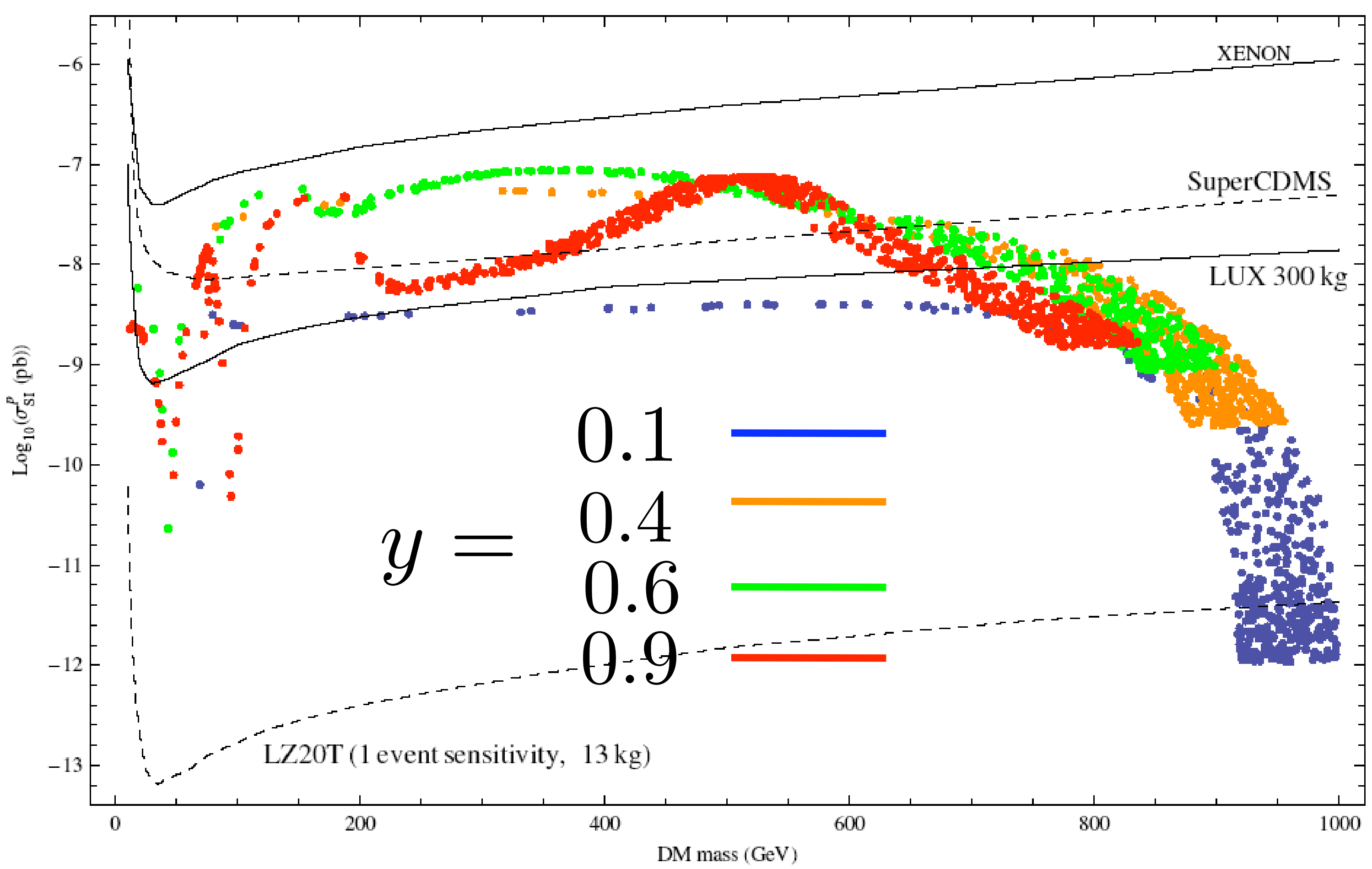
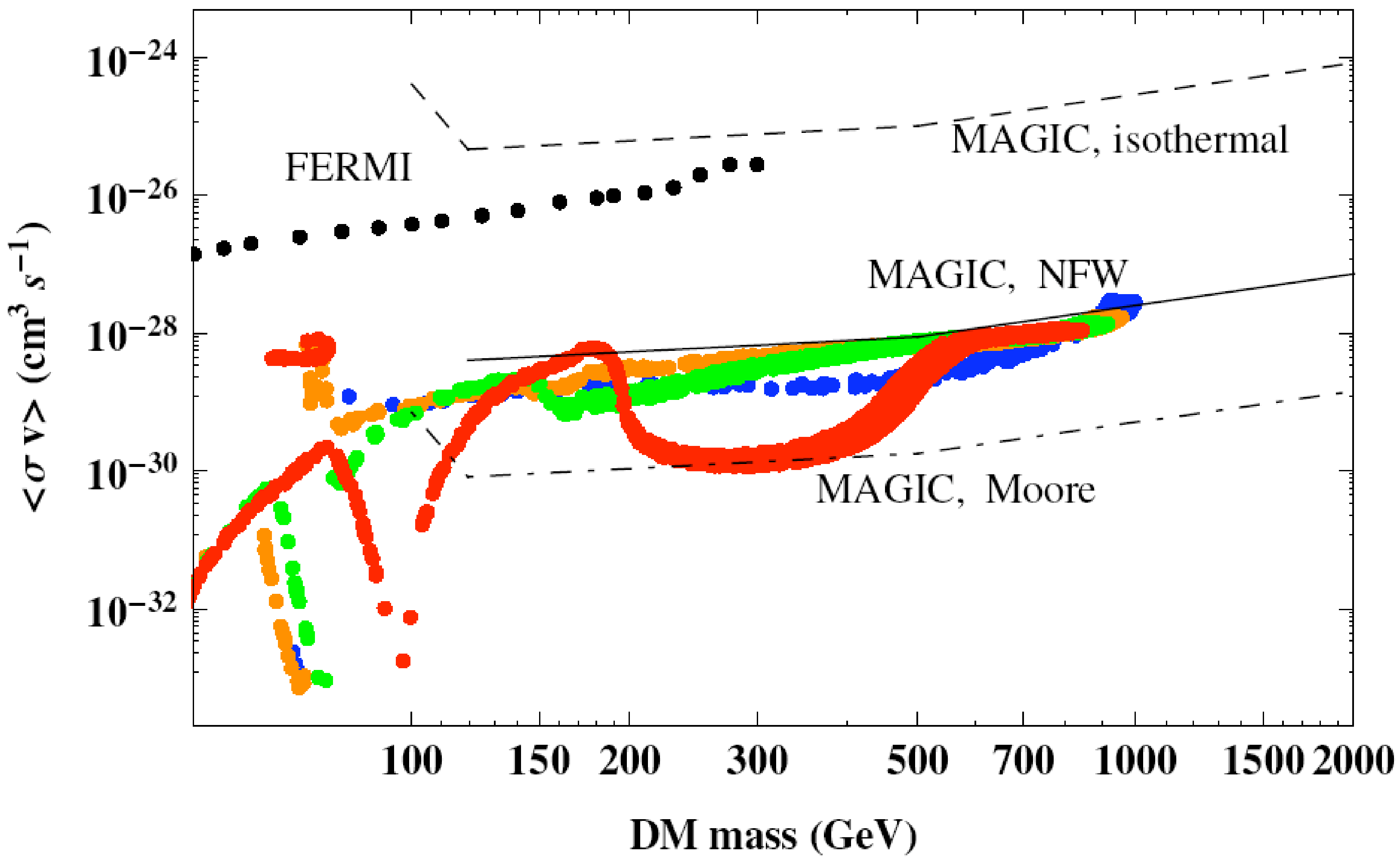


$\tilde{\chi}\tilde{\chi} \to \gamma\gamma$ from the galactic center



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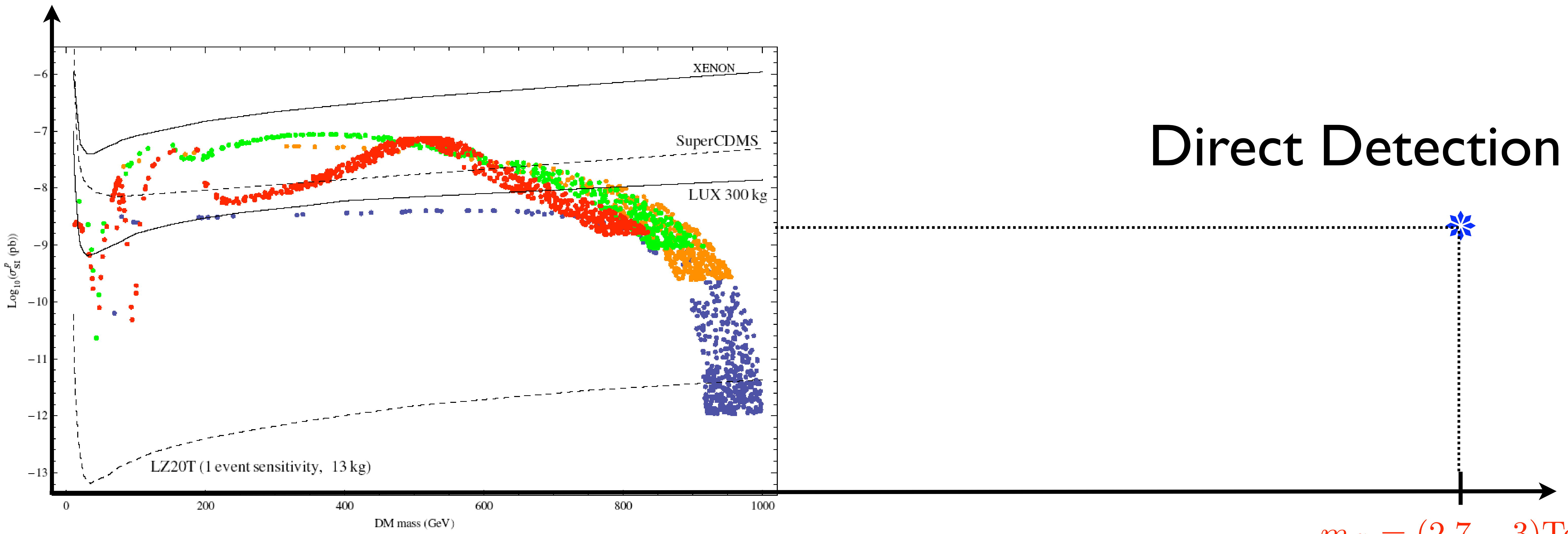
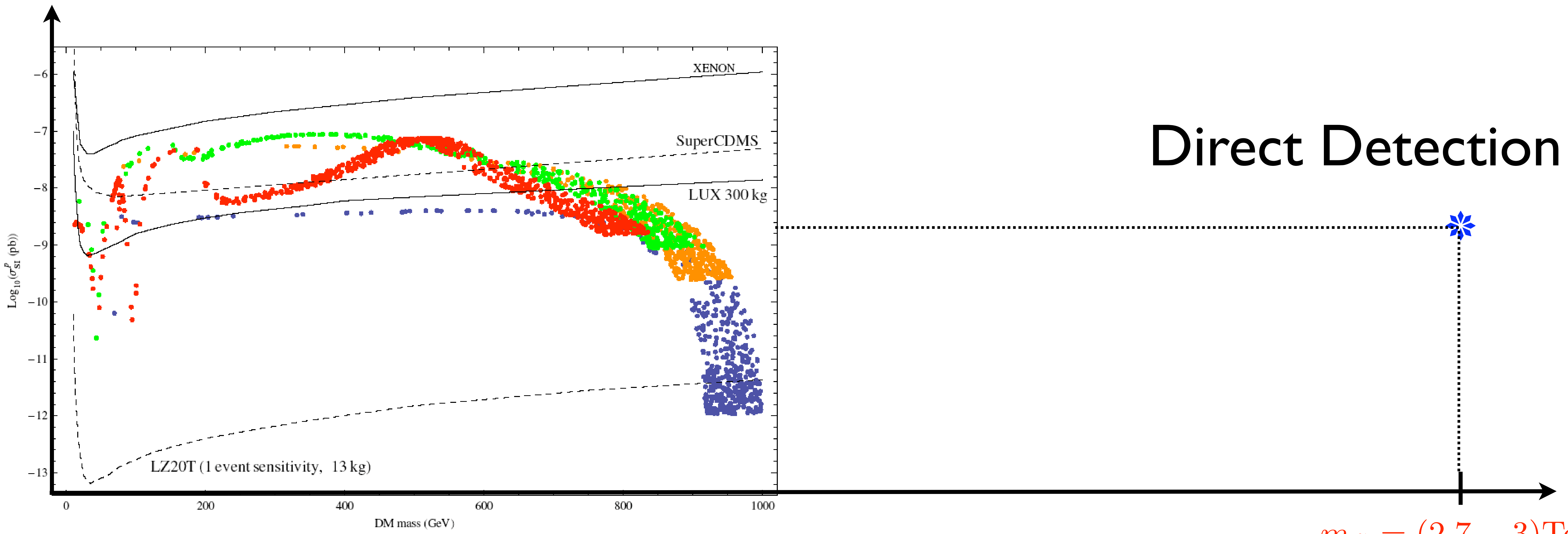


Direct Detection

$m_{\tilde{w}} = (2.7 - 3)\mathrm{TeV}$

Dark Matter: $\mathrm{SM} + \tilde{w}$:

Direct Detection



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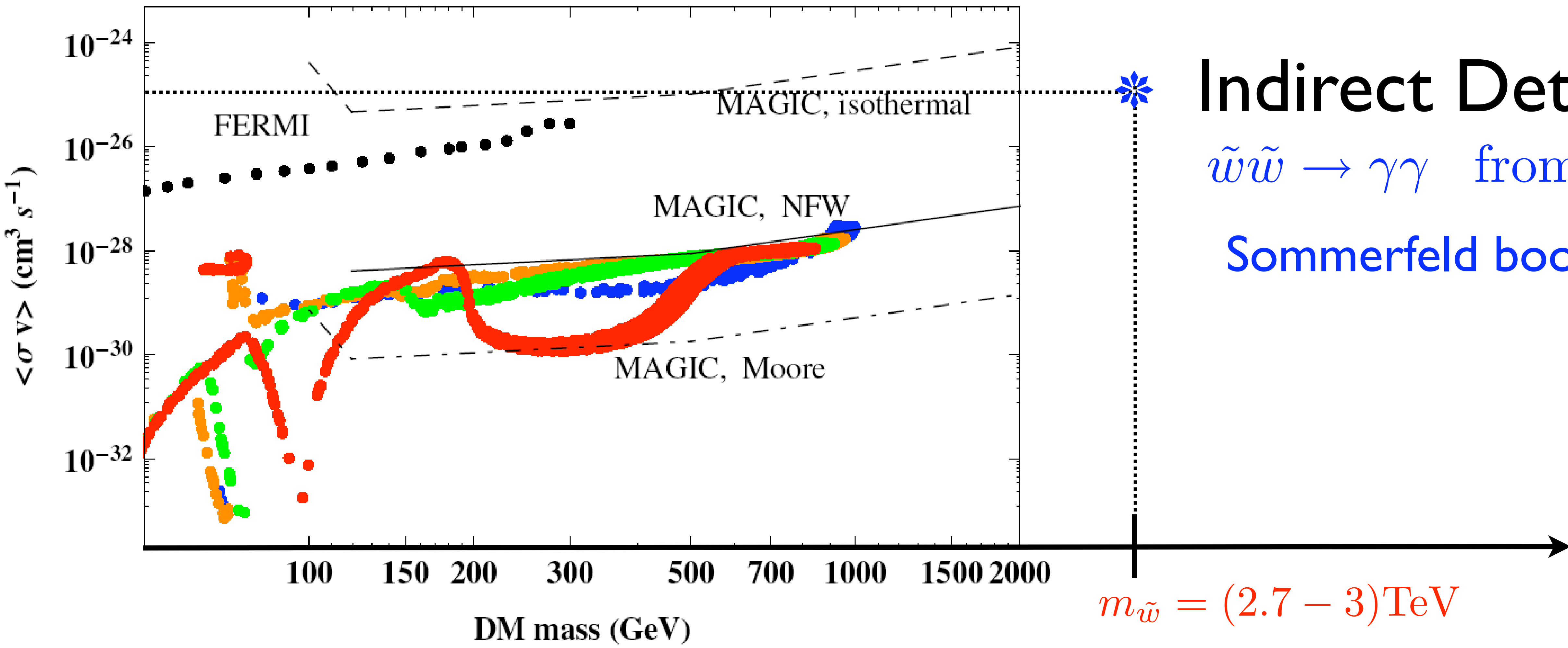
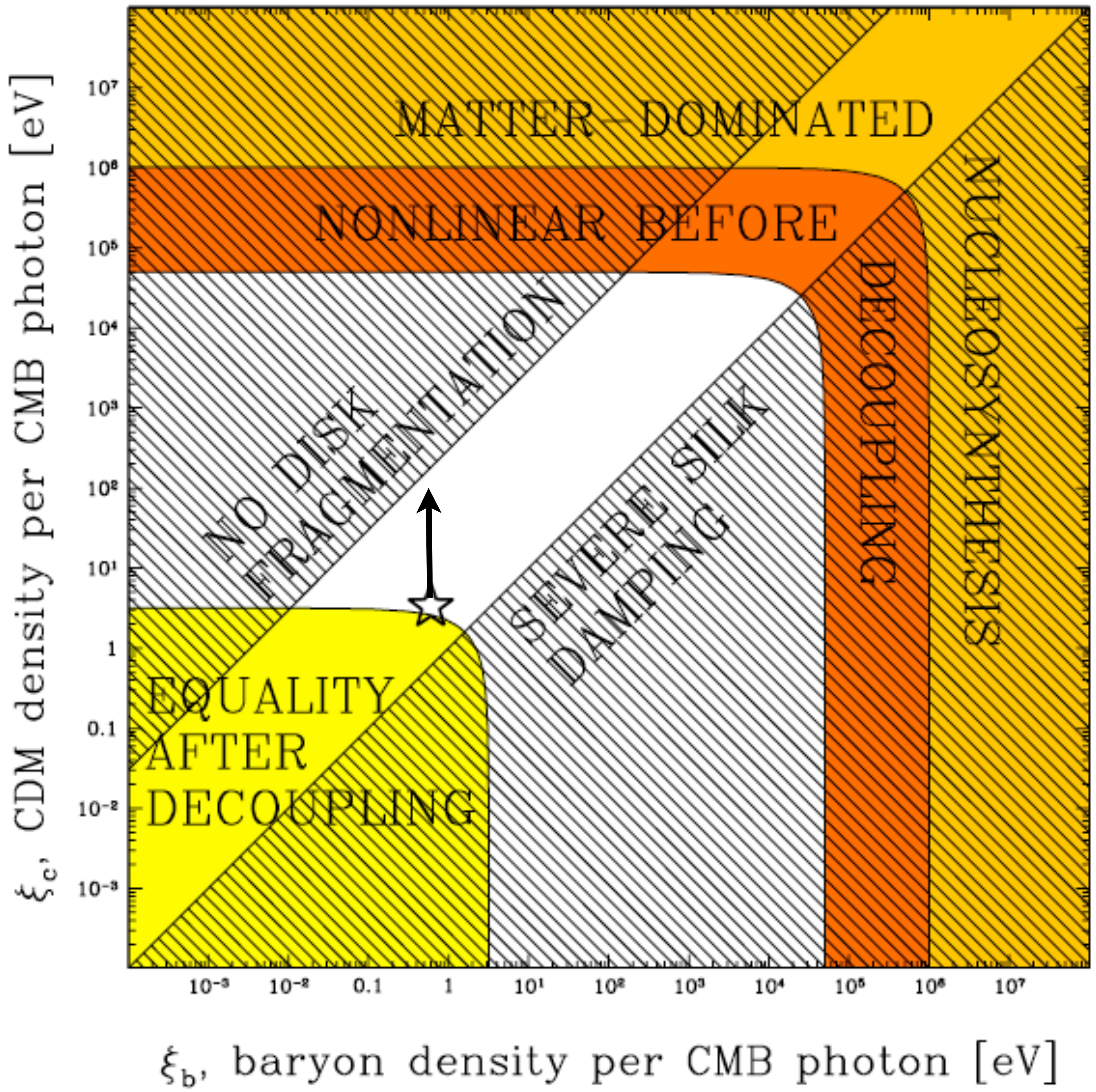
Indirect Detection

$\tilde{w}\tilde{w} \to \gamma\gamma$ from the galactic center

Sommerfeld boost $\approx 10^2$



Selection of Dark Matter



Tegmark, Aguirre, Rees, Wilczek
astro-ph/0511774

- As DM mass increases we hit boundary where galactic disks do not fragment
- In absence of DM galactic size perturbations removed by Silk damping
- Multi-parameter scan: unknown