SUSY 2013
ICTP Trieste
August 2013

TeV-Scale Superpartners from the Multiverse

Lawrence Hall
University of California, Berkeley

BERKELEY CENTER FOR THEORETICAL PHYSICS

Results and Implications of LHC 8

A Surprise:

125 GeV Higgs

No BSM Discovery

v is fine tuned (to some degree)

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Almost Natural Physics will show up soon

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Multiverse

Λ_{CC}, v : tuning and size understood

$\tilde{m}$:

Multiverse arguments for the scale of superpartners?

Outline

1. High Scale SUSY

2. Spread SUSY

3. TeV SUSY with

$$\rho_D \sim \rho_B$$

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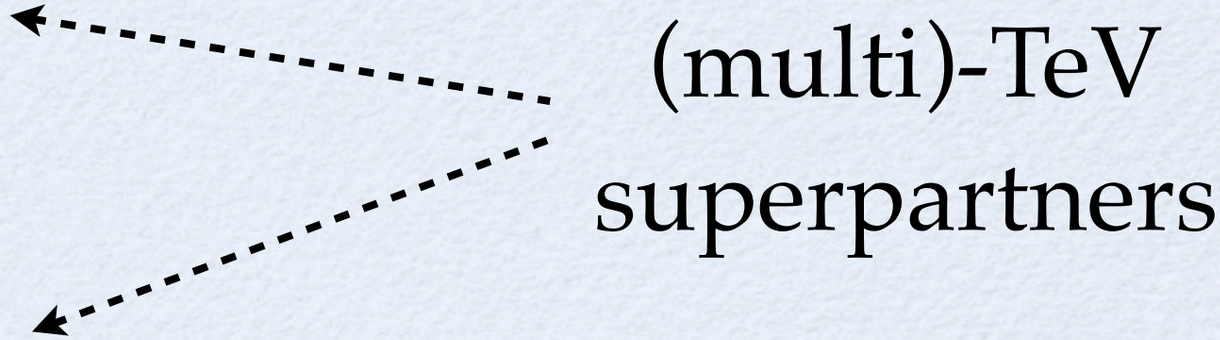
3. TeV SUSY with $\rho_D \sim \rho_B$



Outline

1. High Scale SUSY

2. Spread SUSY

3. TeV SUSY with $\rho_D \sim \rho_B$

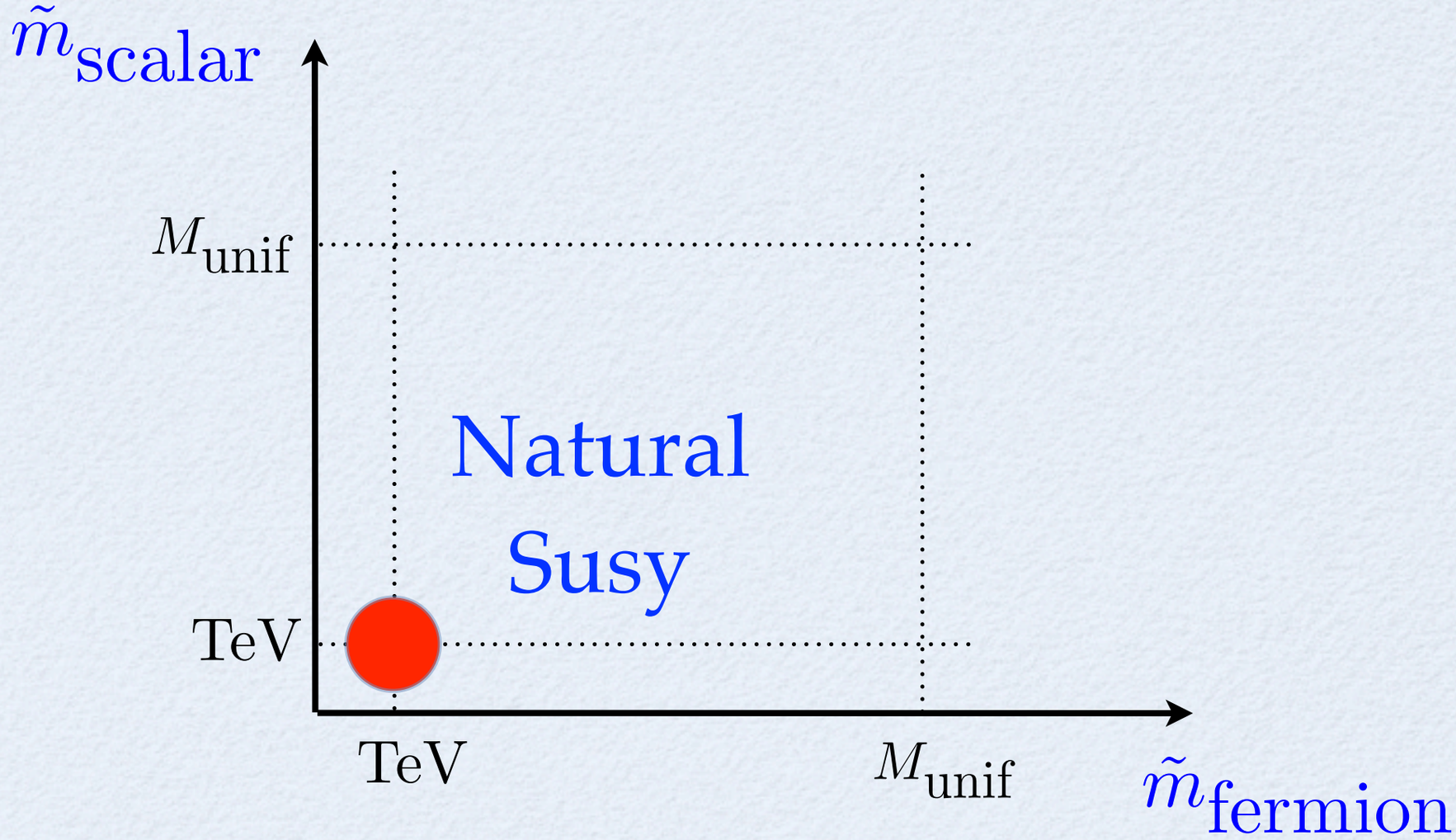
(multi)-TeV superpartners

All three have a fine-tuned weak scale

Agnostic

Multiverse

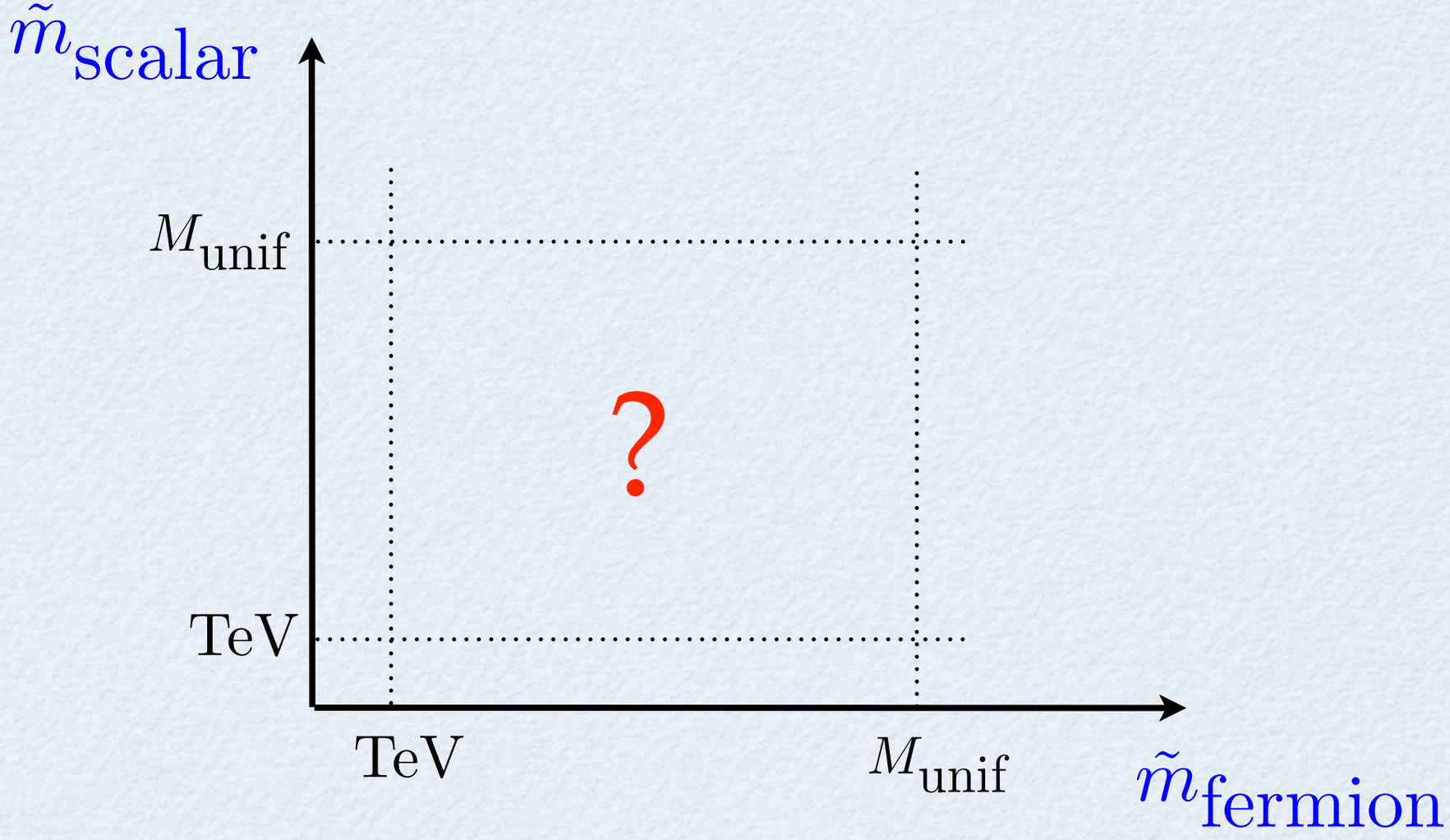
Where are the Superpartners?



Cornered after 30+ years

-- of course, we need to be sure

Without Naturalness

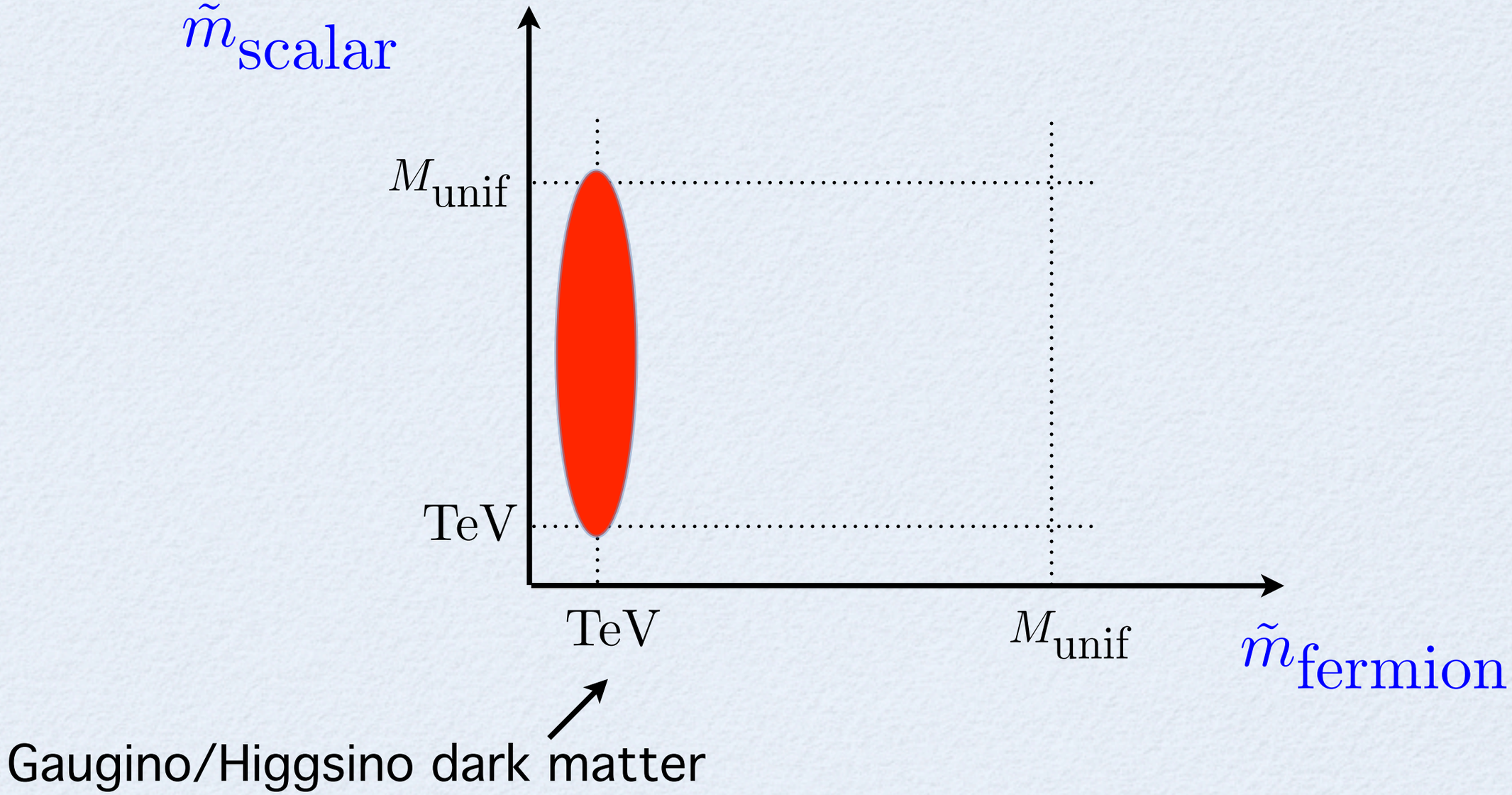


Where are the Superpartners?

Split SUSY

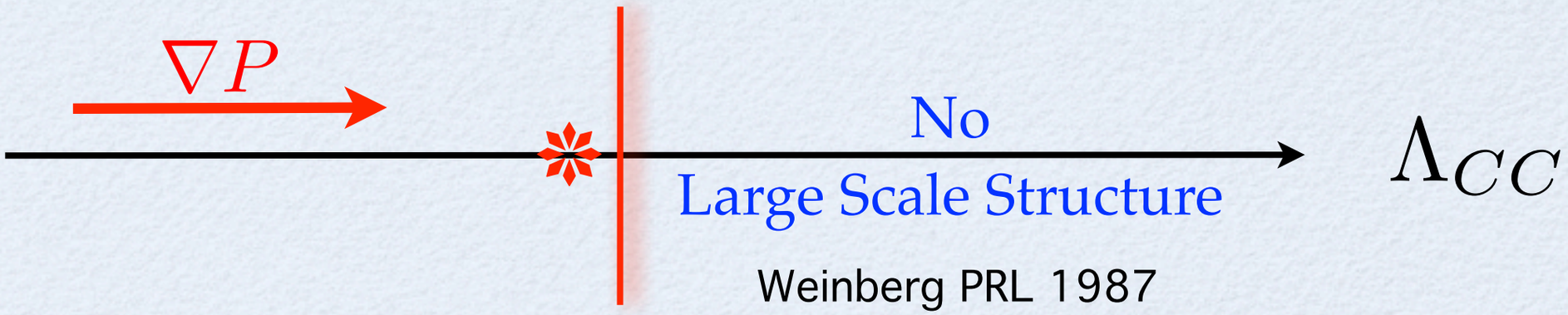
Arkani-Hamed, Dimopoulos
hep-th/0405159

Pioneered multiverse reasoning in BSM particle physics



Measurements could imply huge fine-tuning of weak scale

Λ_{CC} from the Multiverse



Weinberg PRL 1987

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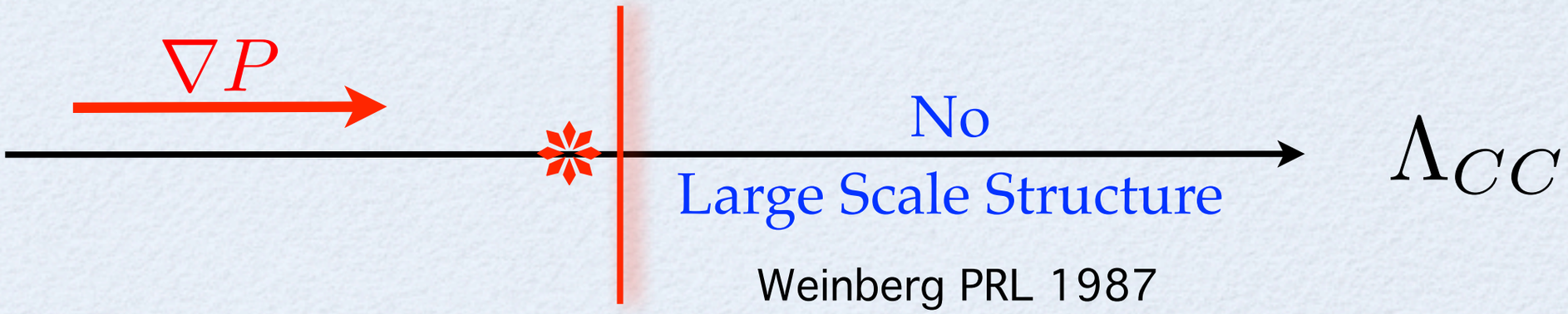
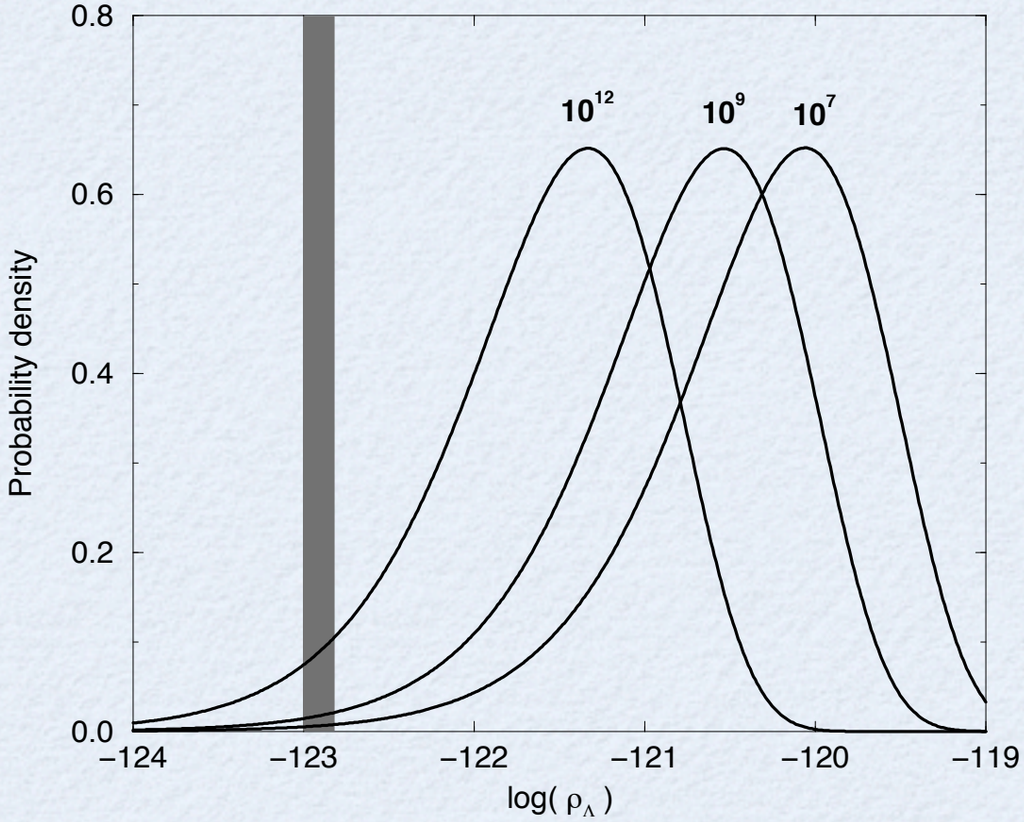


Weinberg PRL 1987

Fraction of virialized baryons



Martell, Shapiro, Weinberg astro-ph/9701099

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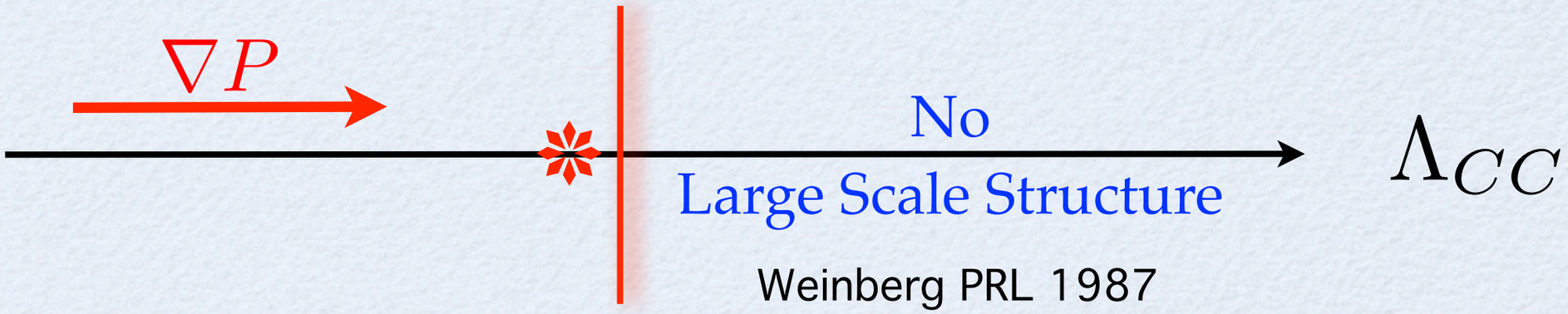

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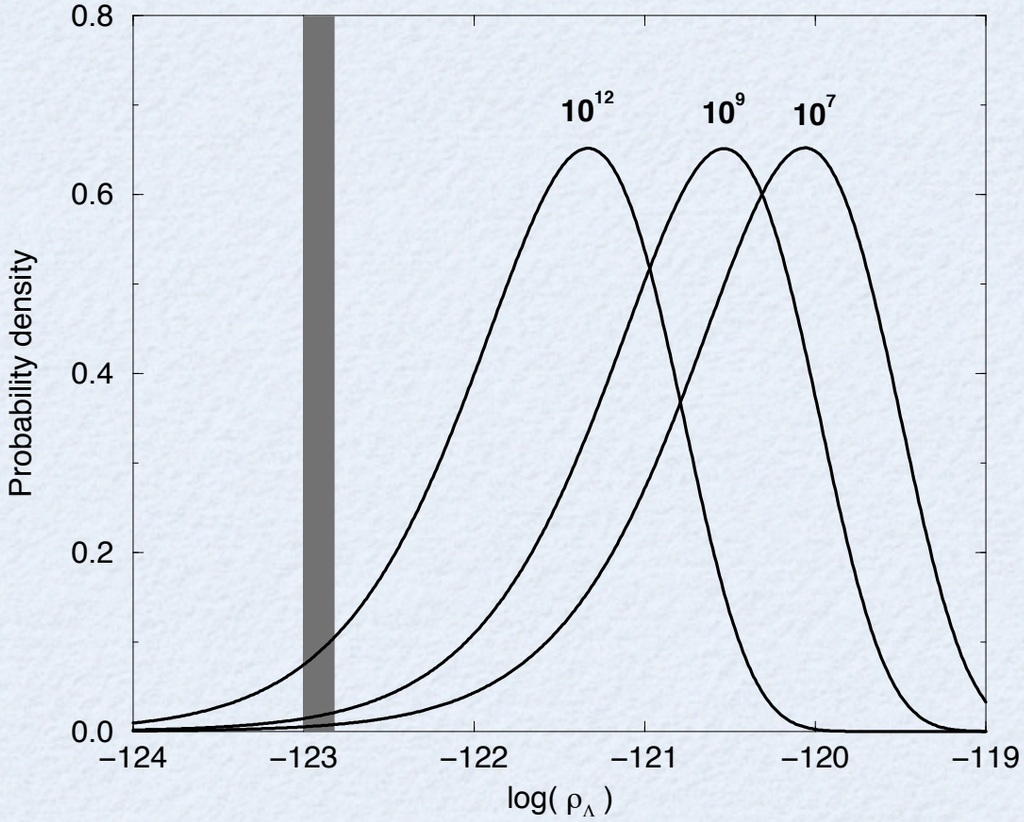

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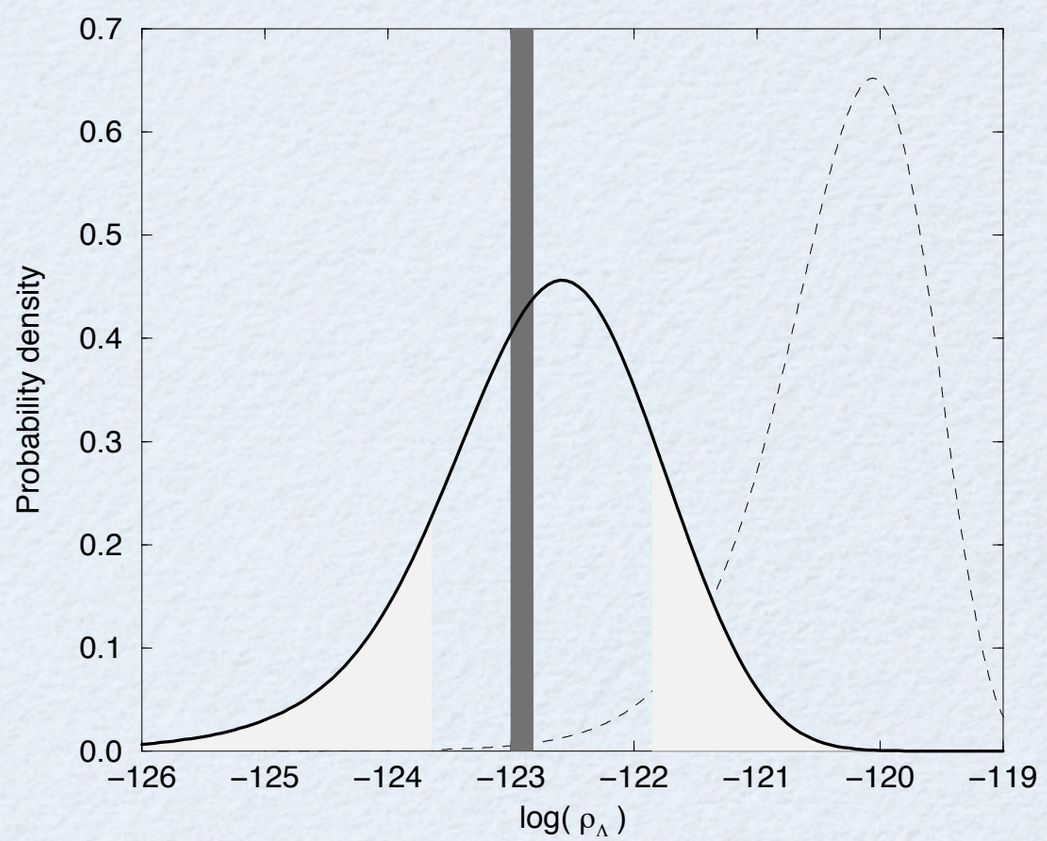
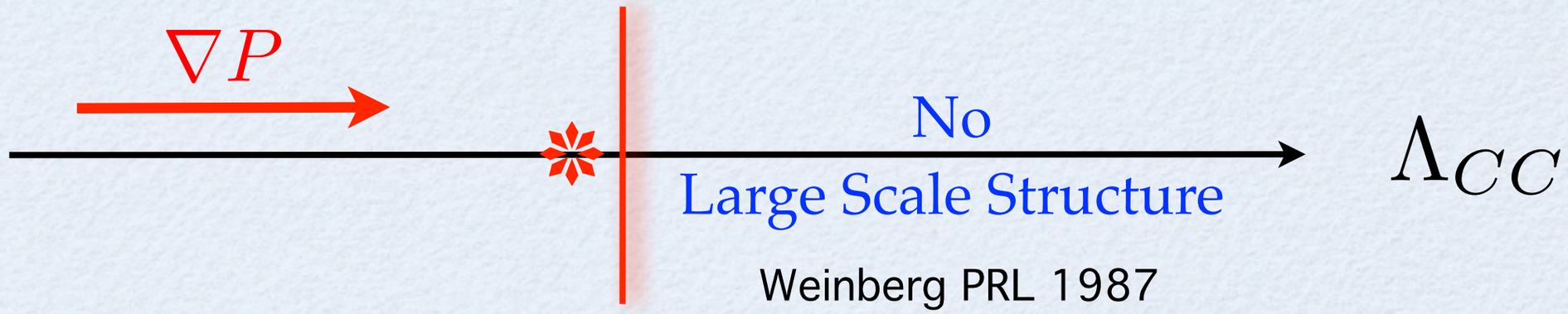
Stars in the Causal Patch

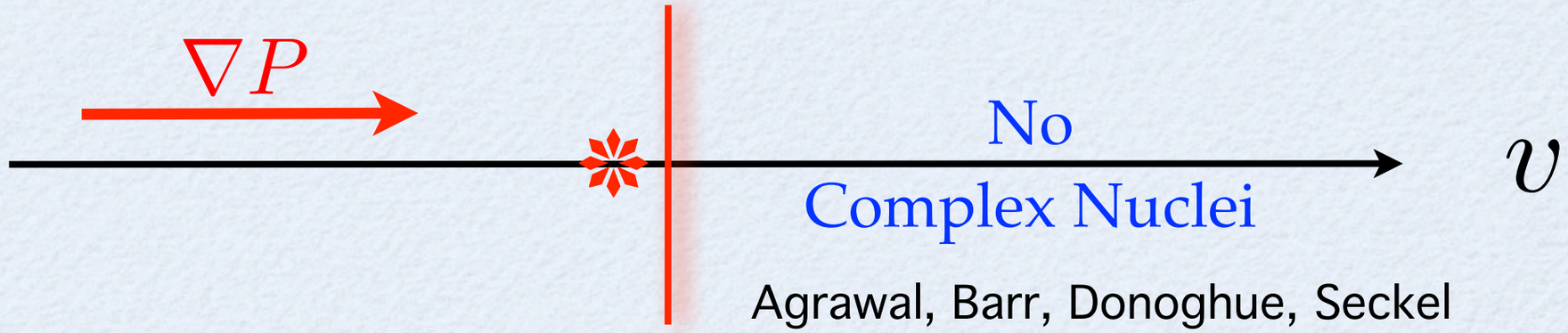


Bousso, Harnik, Kribs,Perez hep-th/0702115

Multiverse for v and Λ_{CC}



Weinberg PRL 1987



Agrawal, Barr, Donoghue, Seckel
ph/9707380

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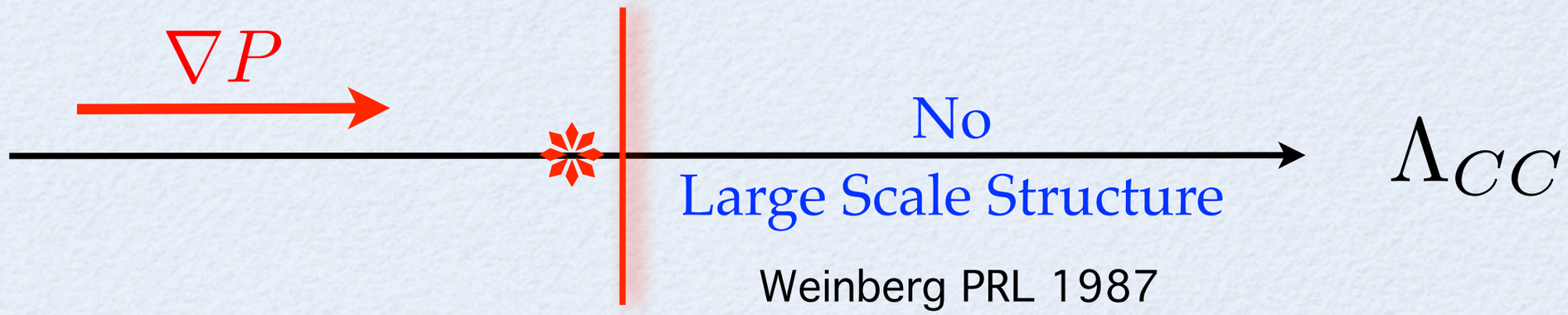

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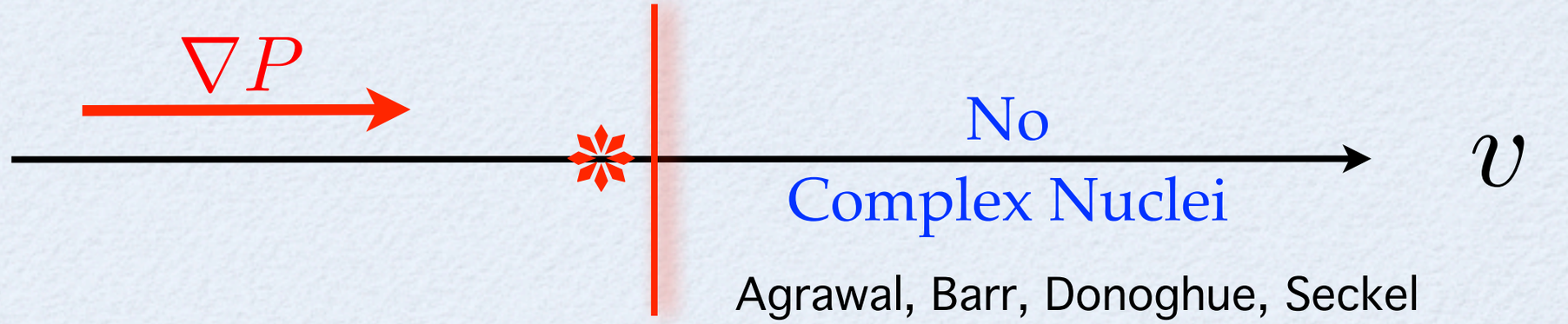

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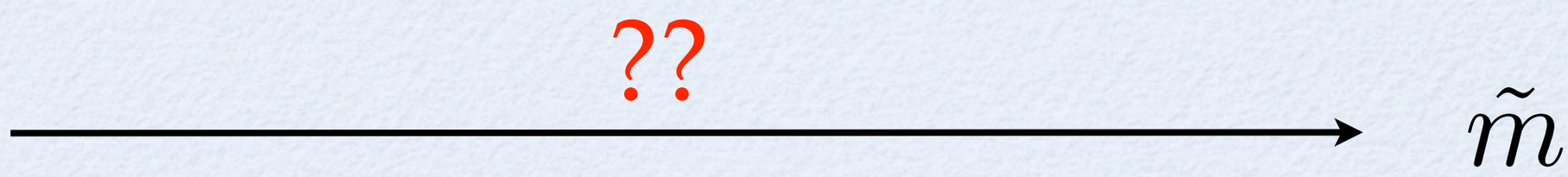


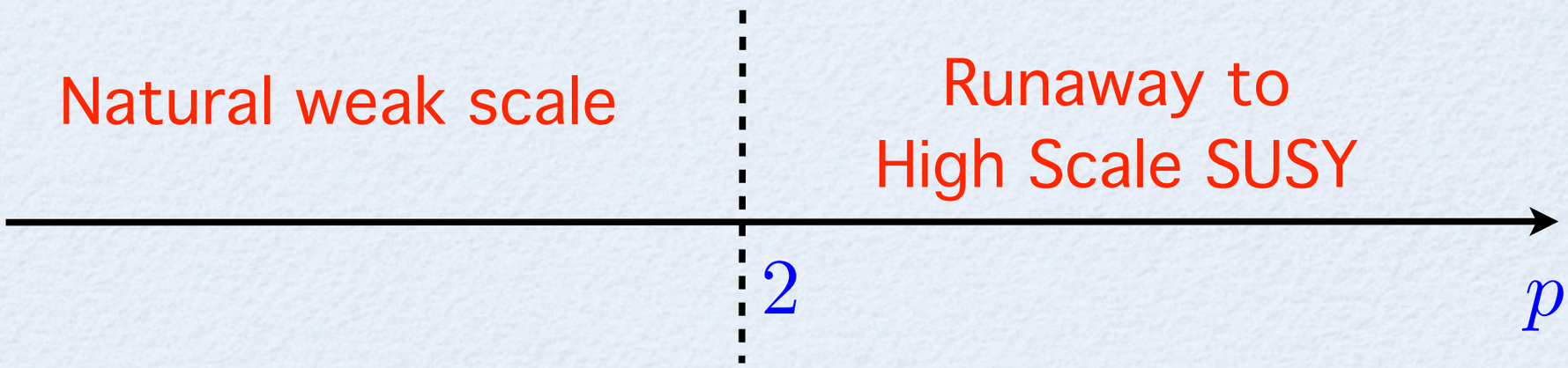
Scanning SUSY Breaking

Consider a power law distribution for $\tilde{m}$ in multiverse

$$dP \propto \tilde{m}^p \;\; d\ln\tilde{m}$$

For $\tilde{m} \geq v$ include a factor for fine tuning of weak scale

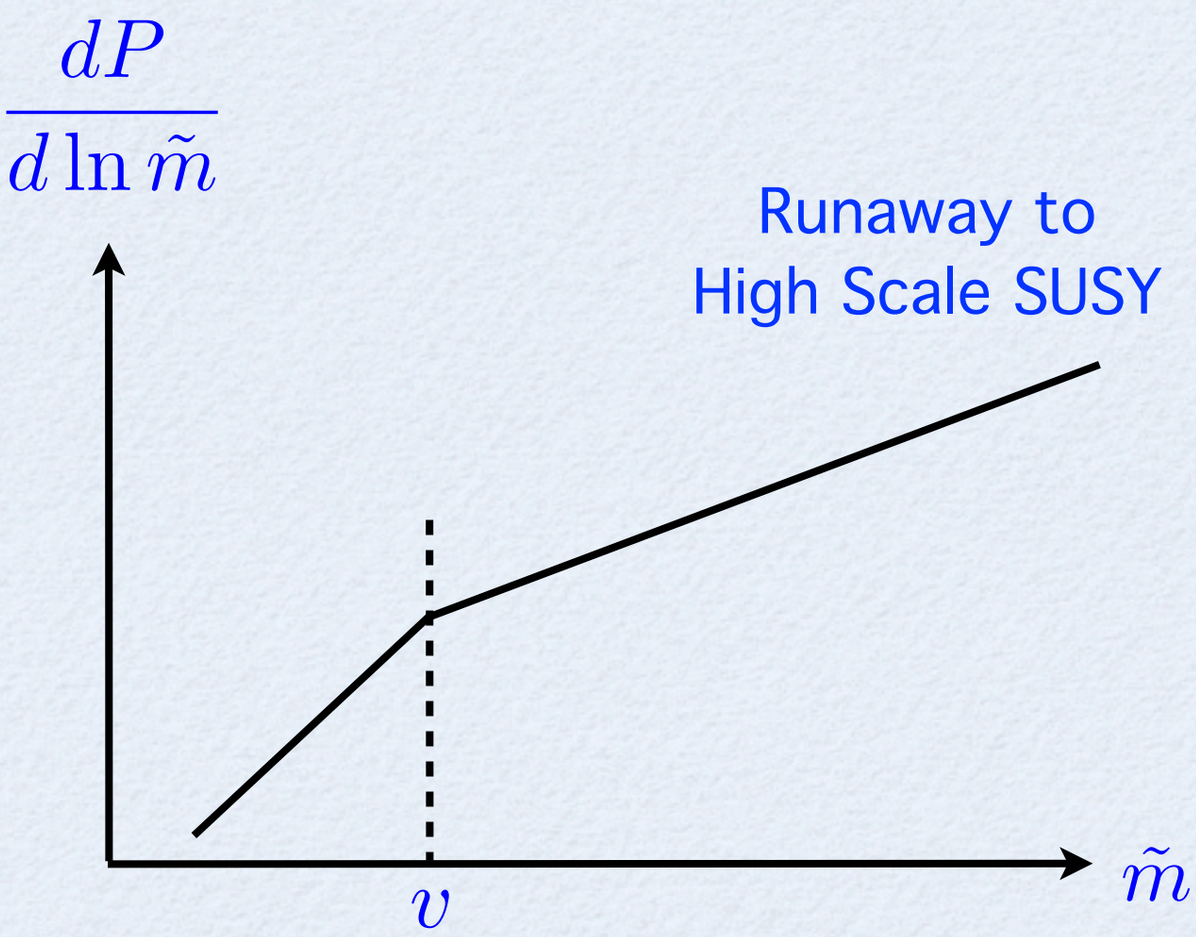
$$dP \propto \left(\frac{v}{\tilde{m}}\right)^2 \;\; \tilde{m}^p \;\; d\ln\tilde{m}$$



1. High Scale SUSY

Runaway to High Scale SUSY

$$p > 2$$



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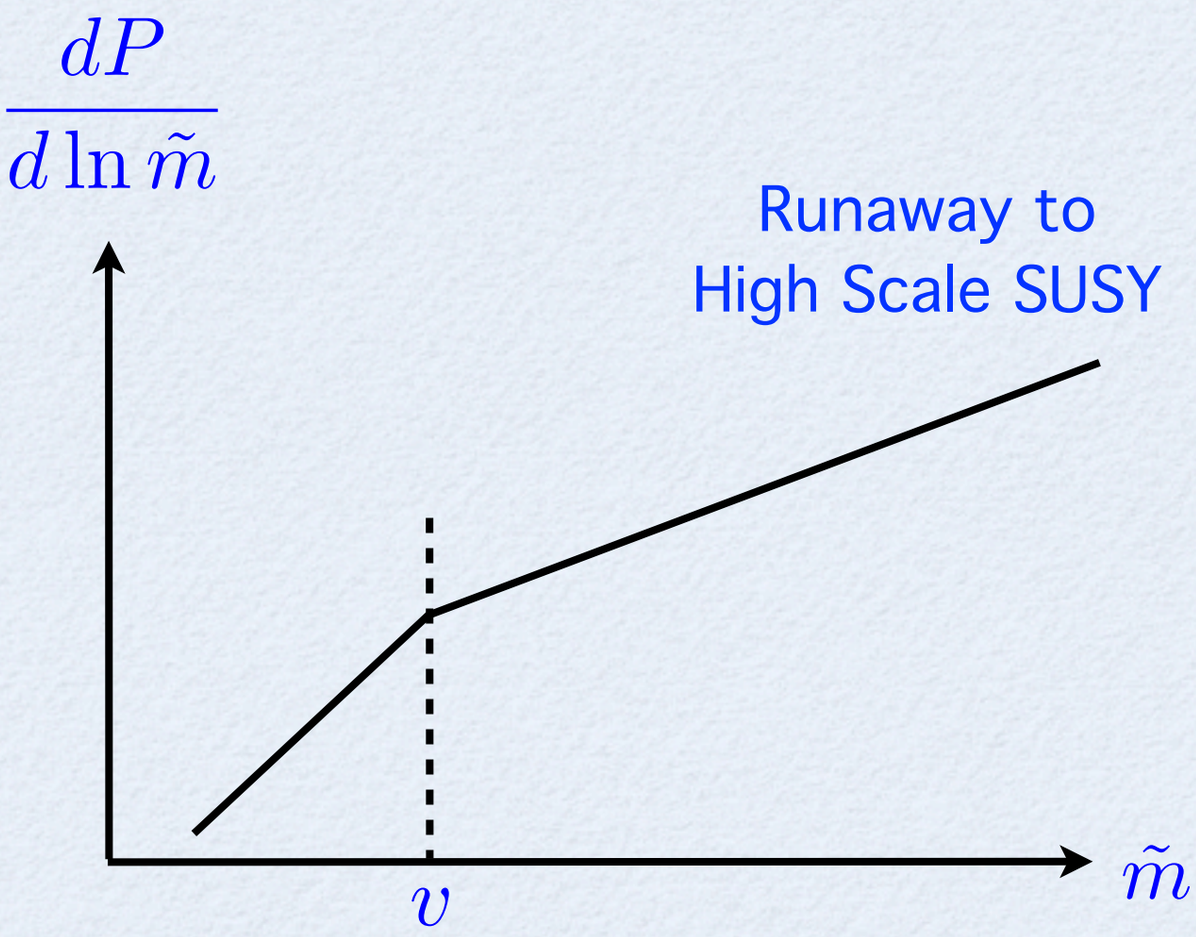

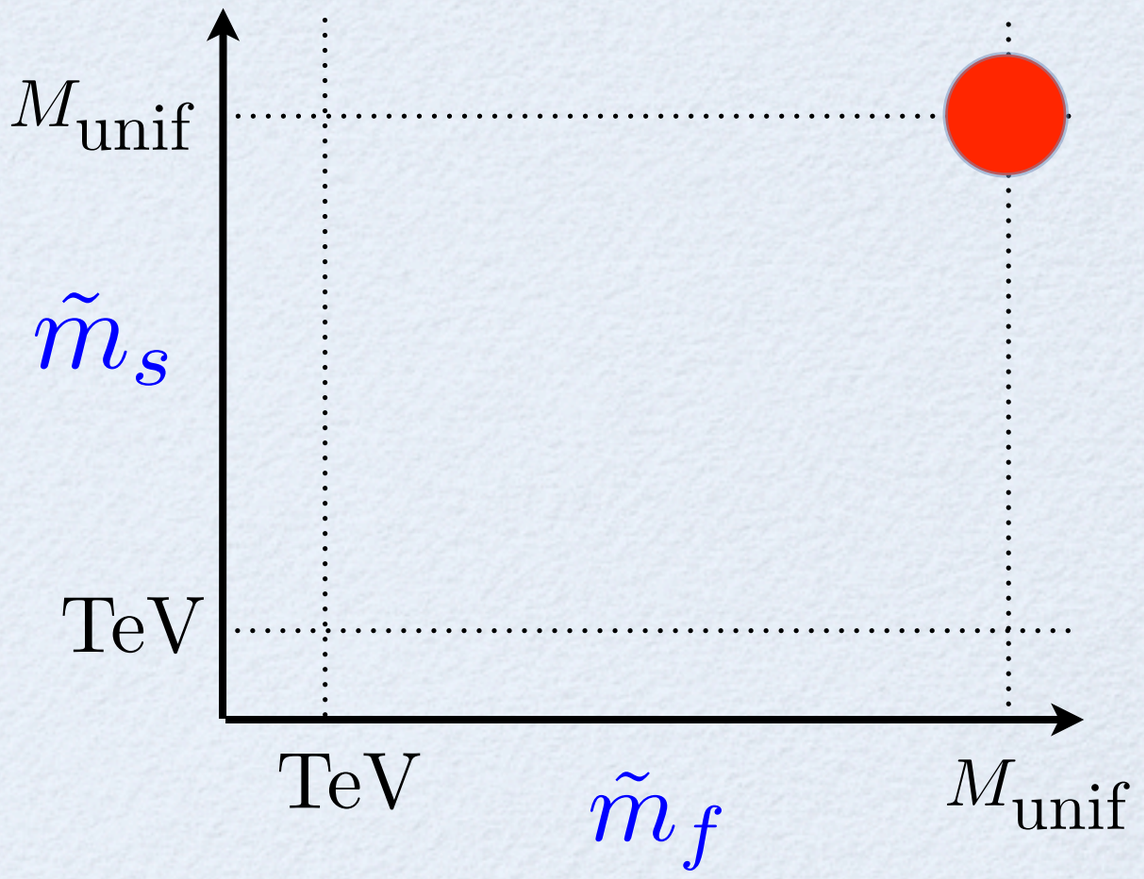

Higgs Mass Prediction

1. From Approximate Symmetry

Hall, Nomura 0910.2235

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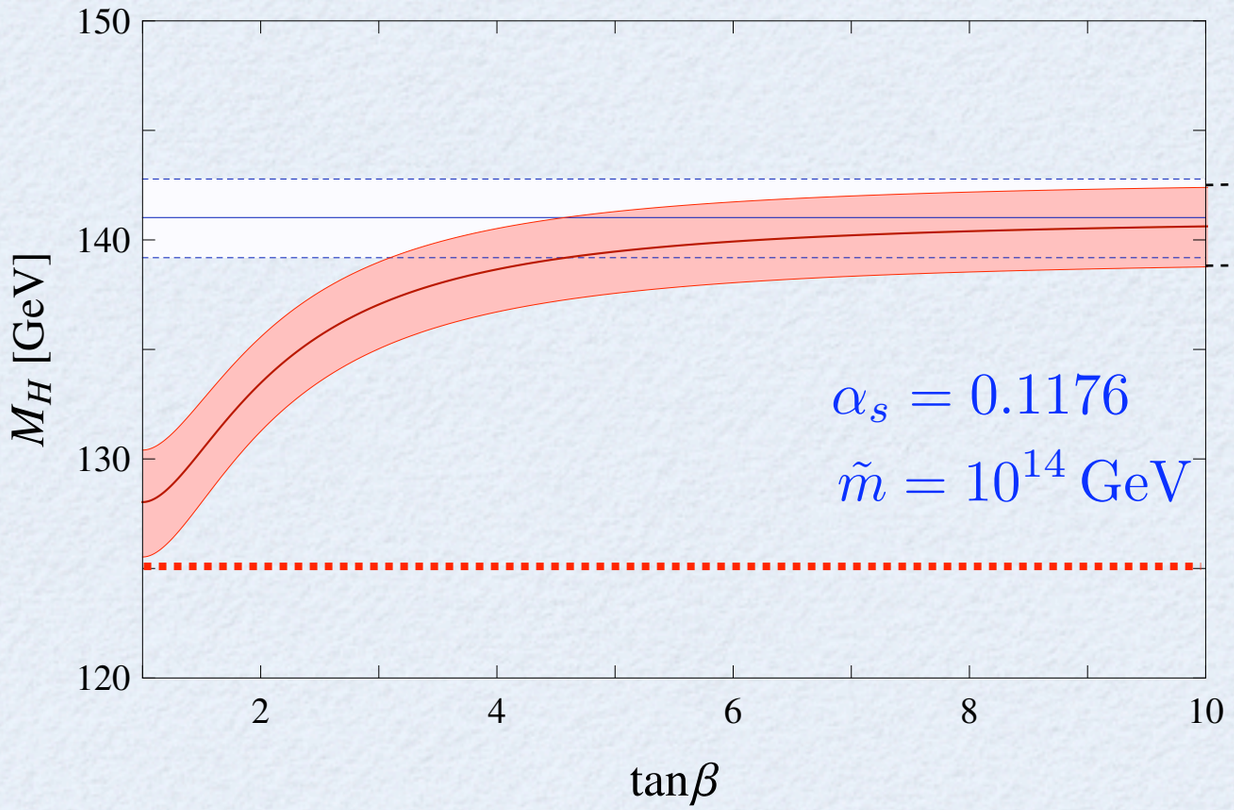

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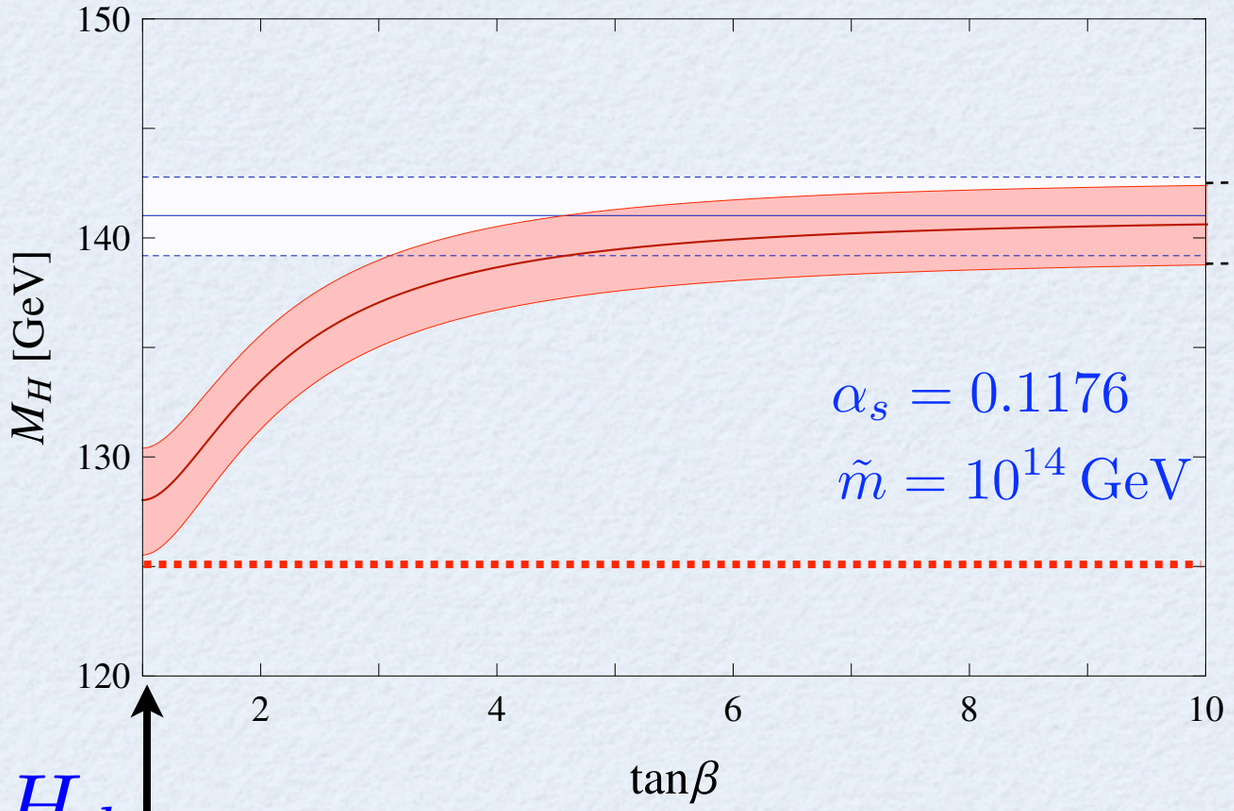

$H_u \leftrightarrow H_d$

$m_h = (128 \pm 3 \pm 0.6 \pm 1.0)\ \mathrm{GeV}$

m_t, α_s $\quad$ $\tilde{t}$ loop $\quad$ $\tilde{m} = 10^{14\pm2}\ \mathrm{GeV}$

Axion
Dark Matter

Higgs Mass Prediction

2. From Multiverse Argument

Feldstein, Hall, Watari
hep-ph/0608121

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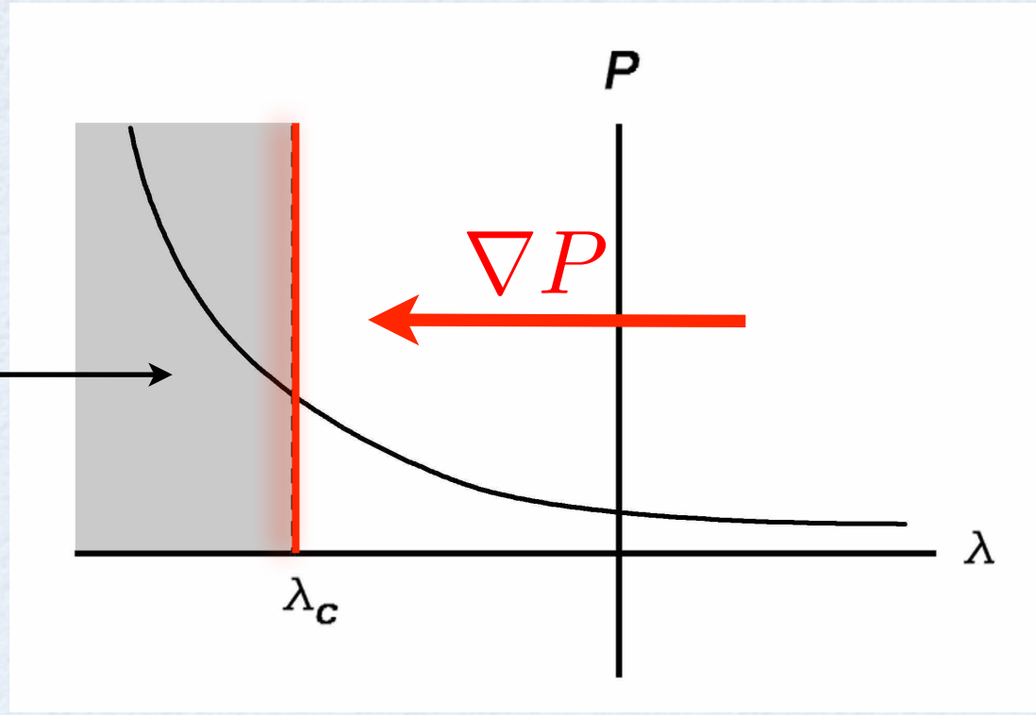
Electroweak vacuum
highly unstable



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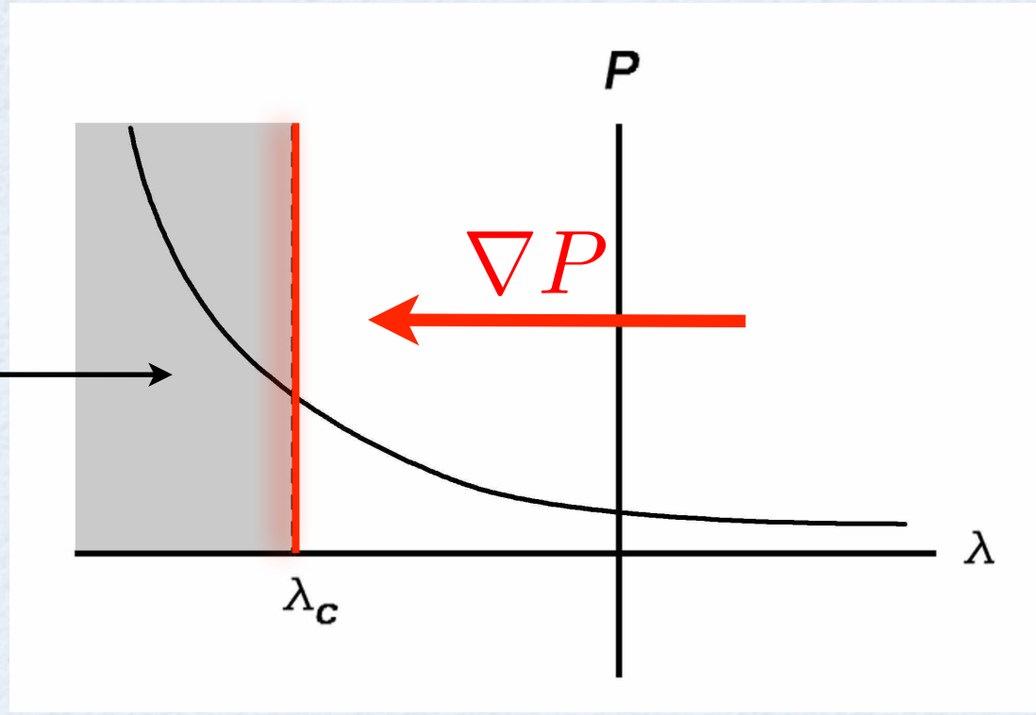


$$m_H = \left[112 + 6\left(\frac{m_t - 173\,\mathrm{GeV}}{2\,\mathrm{GeV}}\right) - 2.6\left(\frac{\alpha_s - 0.1176}{0.002}\right) \pm 6 + \frac{25}{q}\right]\,\mathrm{GeV}$$

2 loop running

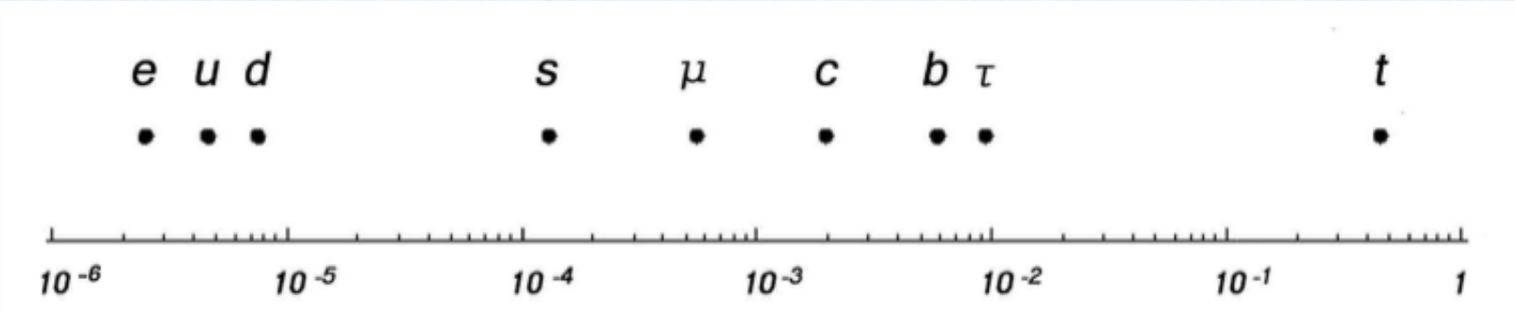
Top and QCD contributions to running

running to pole

Strength of probability distribution

Both Schemes Require a Heavy Quark

Feldstein, Hall, Watari
hep-ph/0608121



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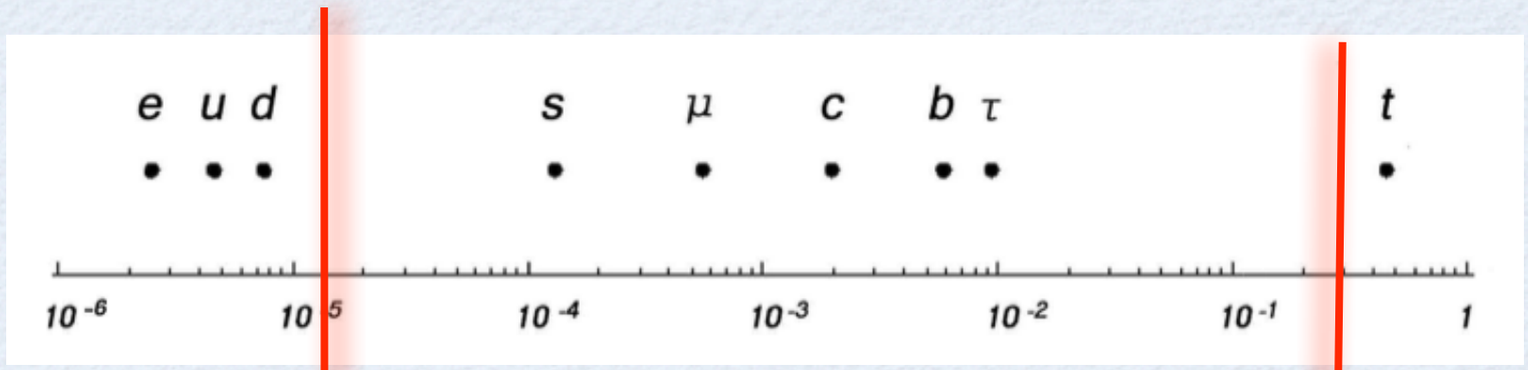
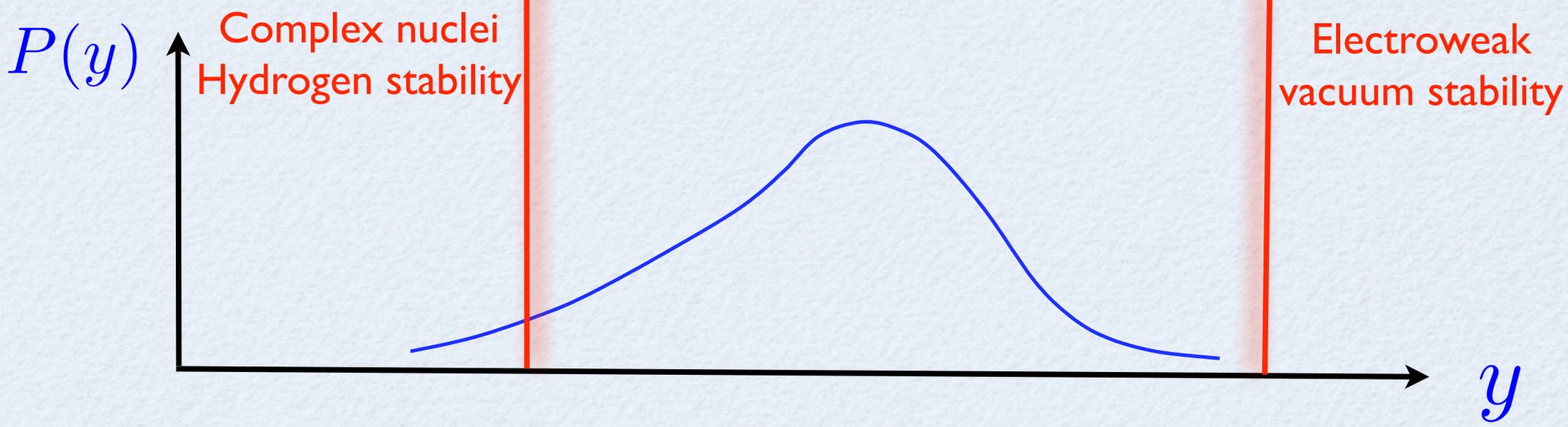


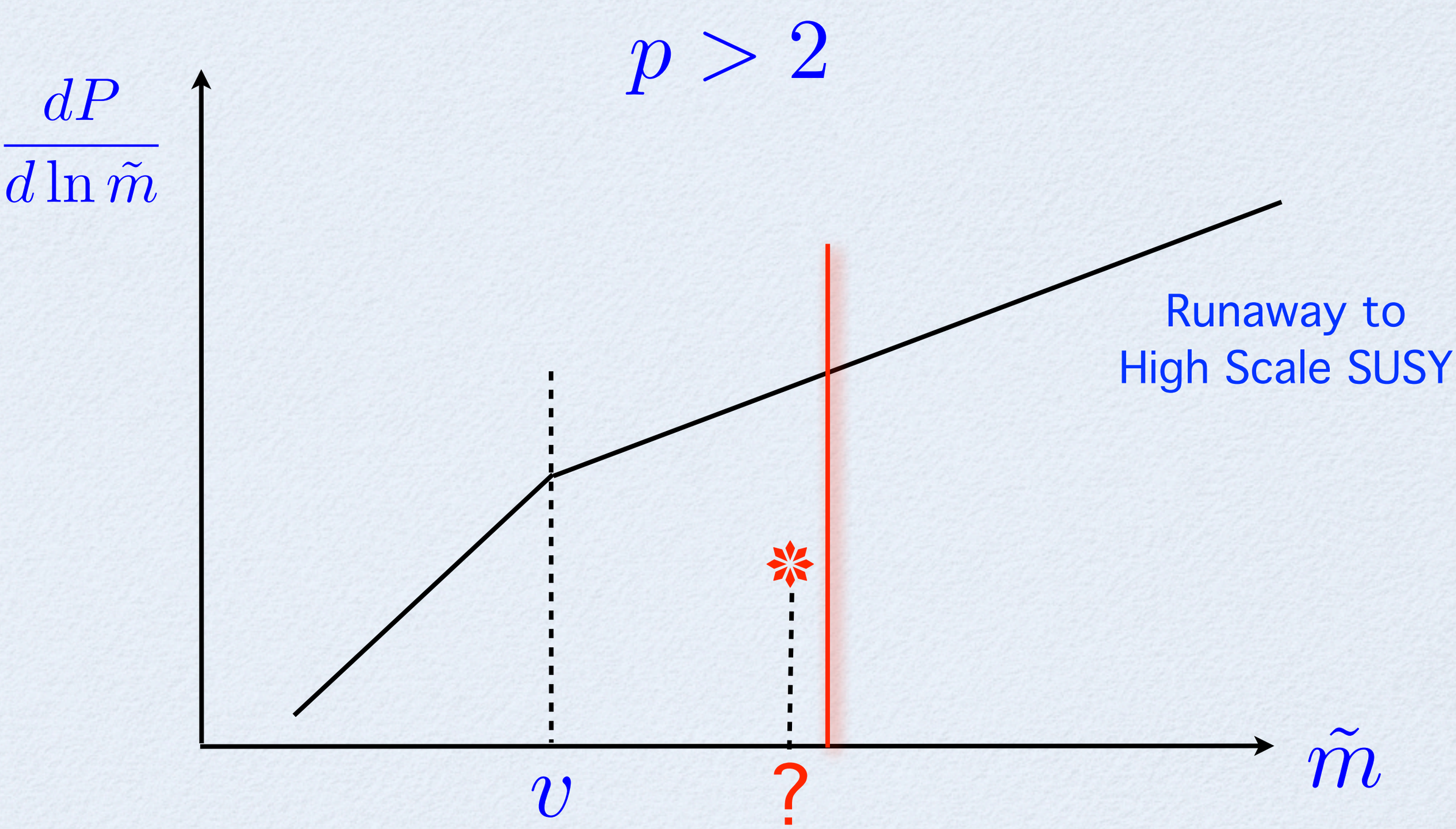


A universal Yukawa distribution peaked around 10^{-3}

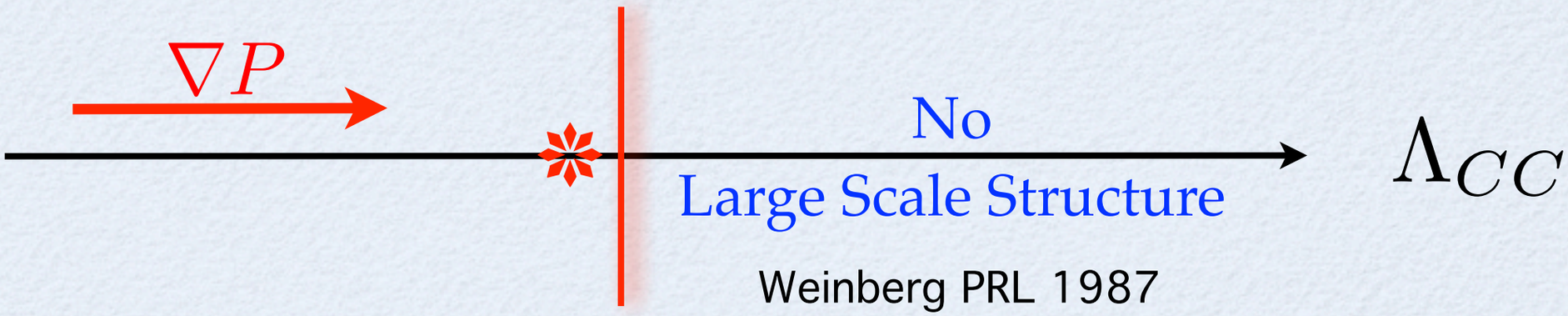
2. Spread SUSY

Hall, Nomura 1111.4519

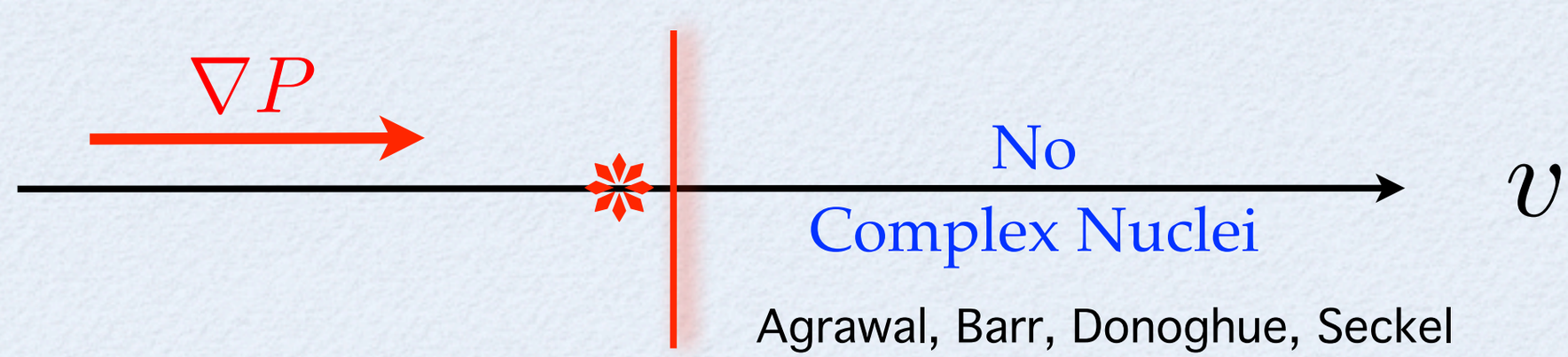
Stabilizing SUSY Breaking at Multi-TeV



Multiverse for v, Λ_{CC}, and $\tilde{m}$



Weinberg PRL 1987



Agrawal, Barr, Donoghue, Seckel
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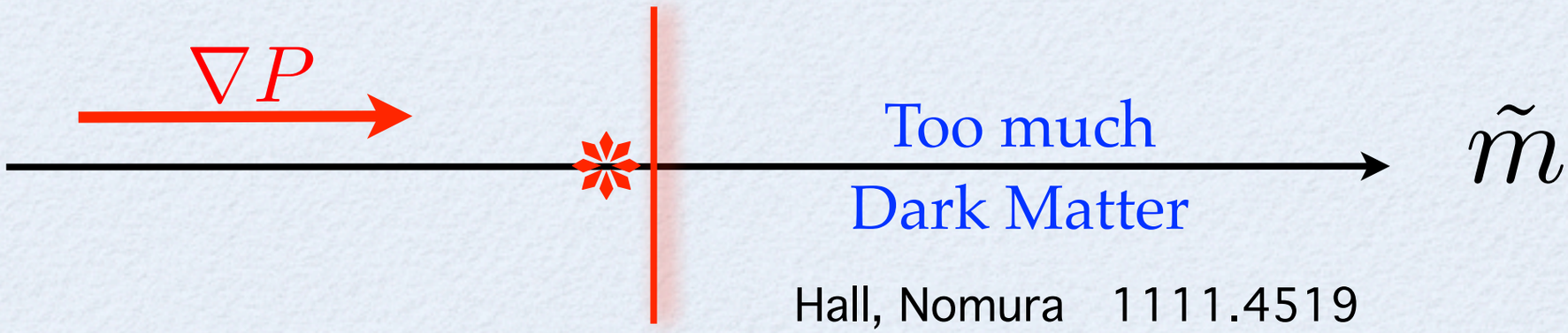

Hall, Nomura 1111.4519

A Boundary from LSP Freeze-Out

Assumptions:

1. The LSP is cosmologically stable
2. $T_R \geq \tilde{m}$
3. No Dilution

The result:

$$\Omega h^2 \propto \frac{1}{\langle \sigma_A v \rangle} \propto m_{LSP}^2 \propto \tilde{m}^2$$

$$\rho_D < \rho_c \quad \Rightarrow \quad \tilde{m} < \tilde{m}_c$$

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Tegmark, Aguirre, Rees, Wilczek astro-ph/0511774 { Galactic disks don't fragment; Close stellar encounters disrupt planets

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$m_{LSP} \sim \alpha_{\rm eff} \sqrt{T_{\rm eq} M_{\rm P}} \approx \left(\frac{\alpha_{\rm eff}}{0.01}\right) 1\,{\rm TeV}$ ⇒ Unnatural Multi-TeV SUSY

Two Cases

Scalar Masses $\quad \dfrac{X^\dagger X}{M^2}(Q^\dagger Q + \dots)$ $\qquad \tilde{m} \sim \dfrac{F_X}{M} \sim m_{3/2}$

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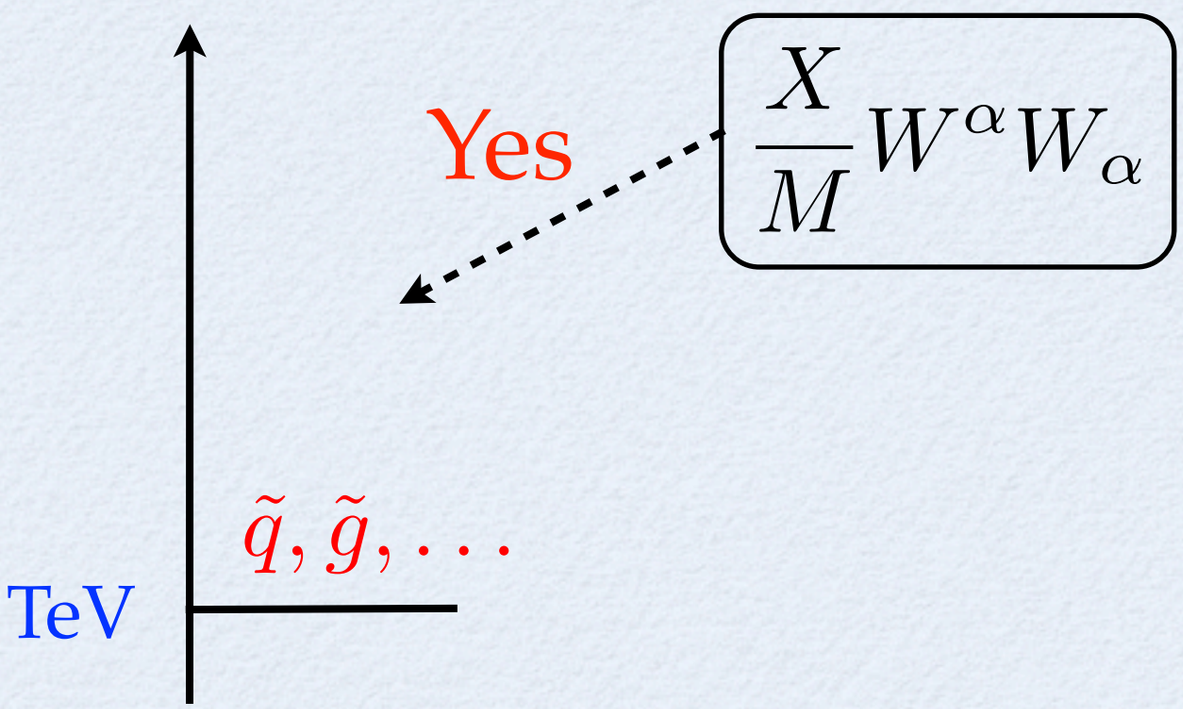

Multiverse MSSM

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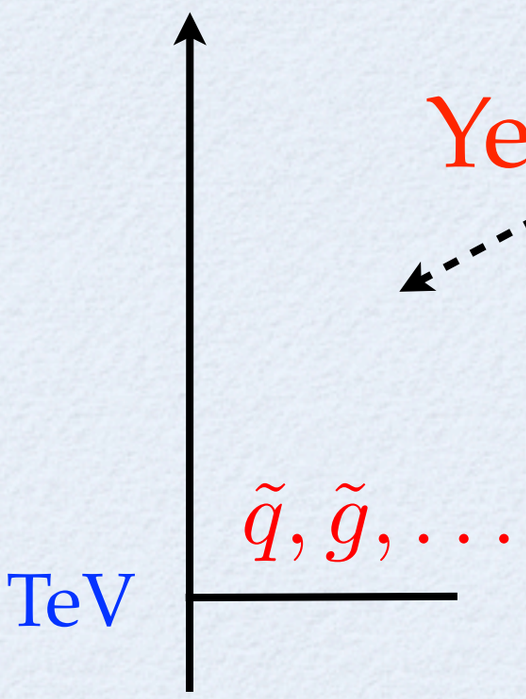
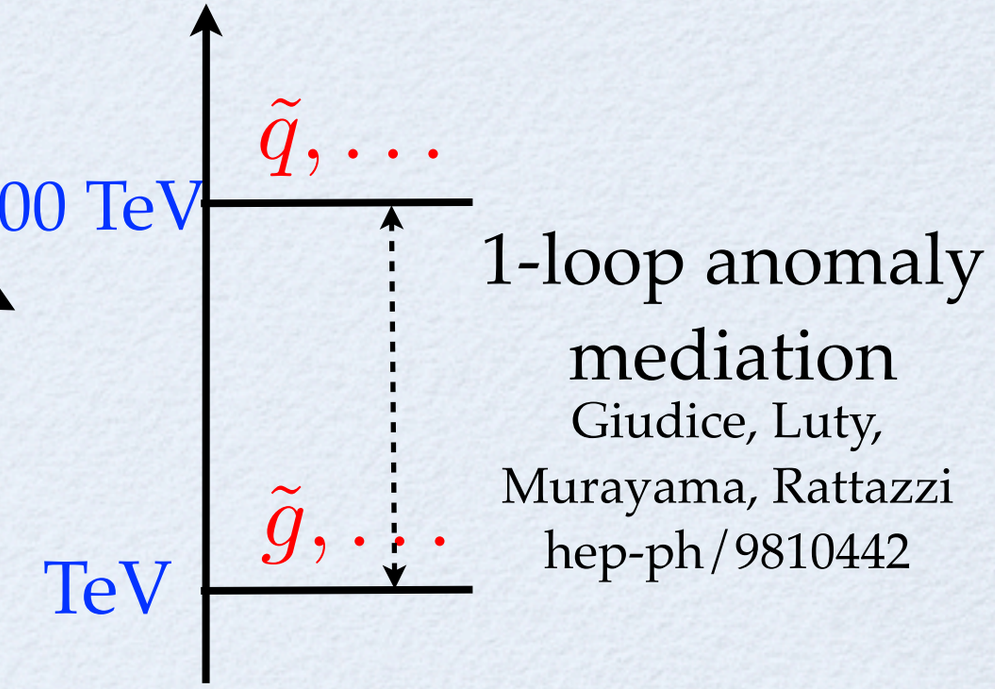
Yes



Multiverse MSSM

No



Spread SUSY

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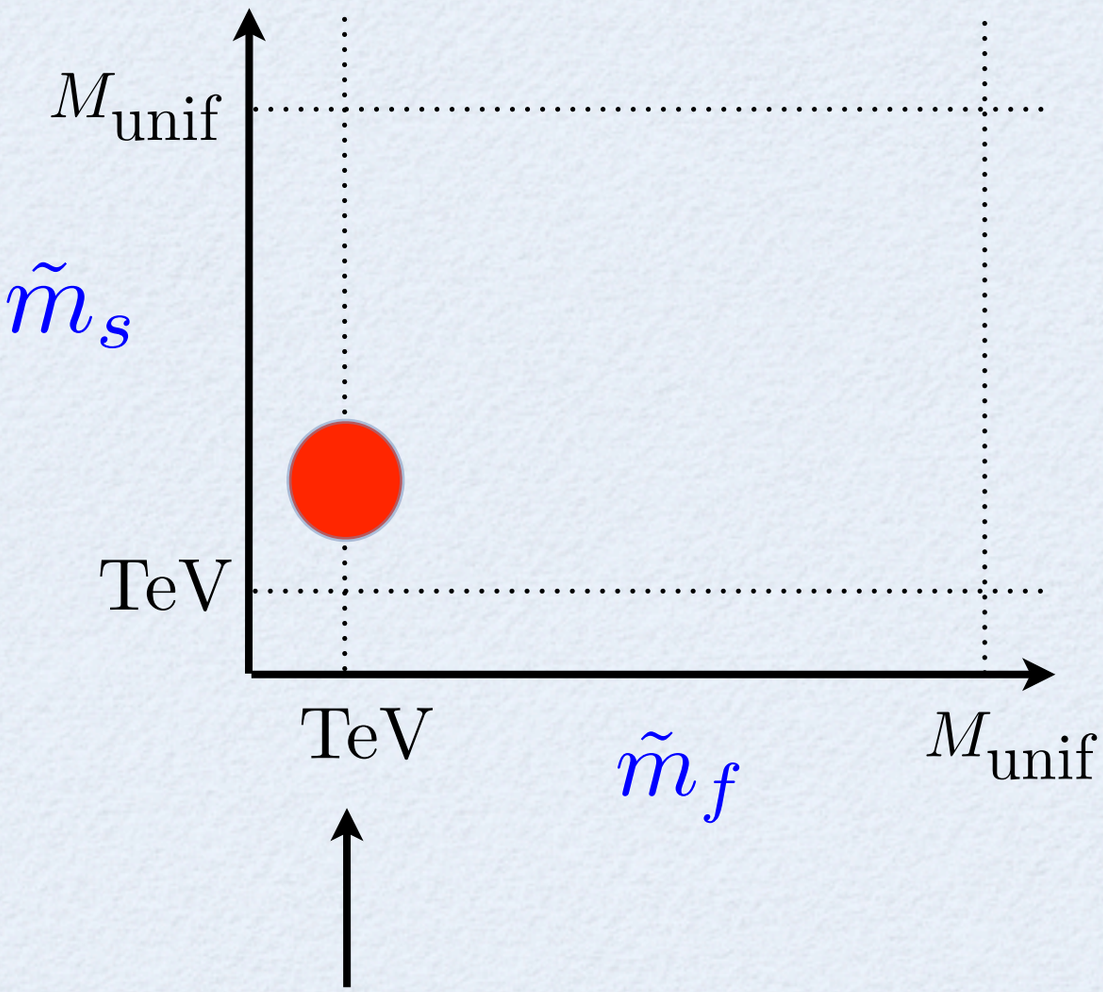
$M_{\rm unif}$
$\tilde{m}_s$
TeV
TeV
$\tilde{m}_f$
$M_{\rm unif}$
Gaugino dark matter

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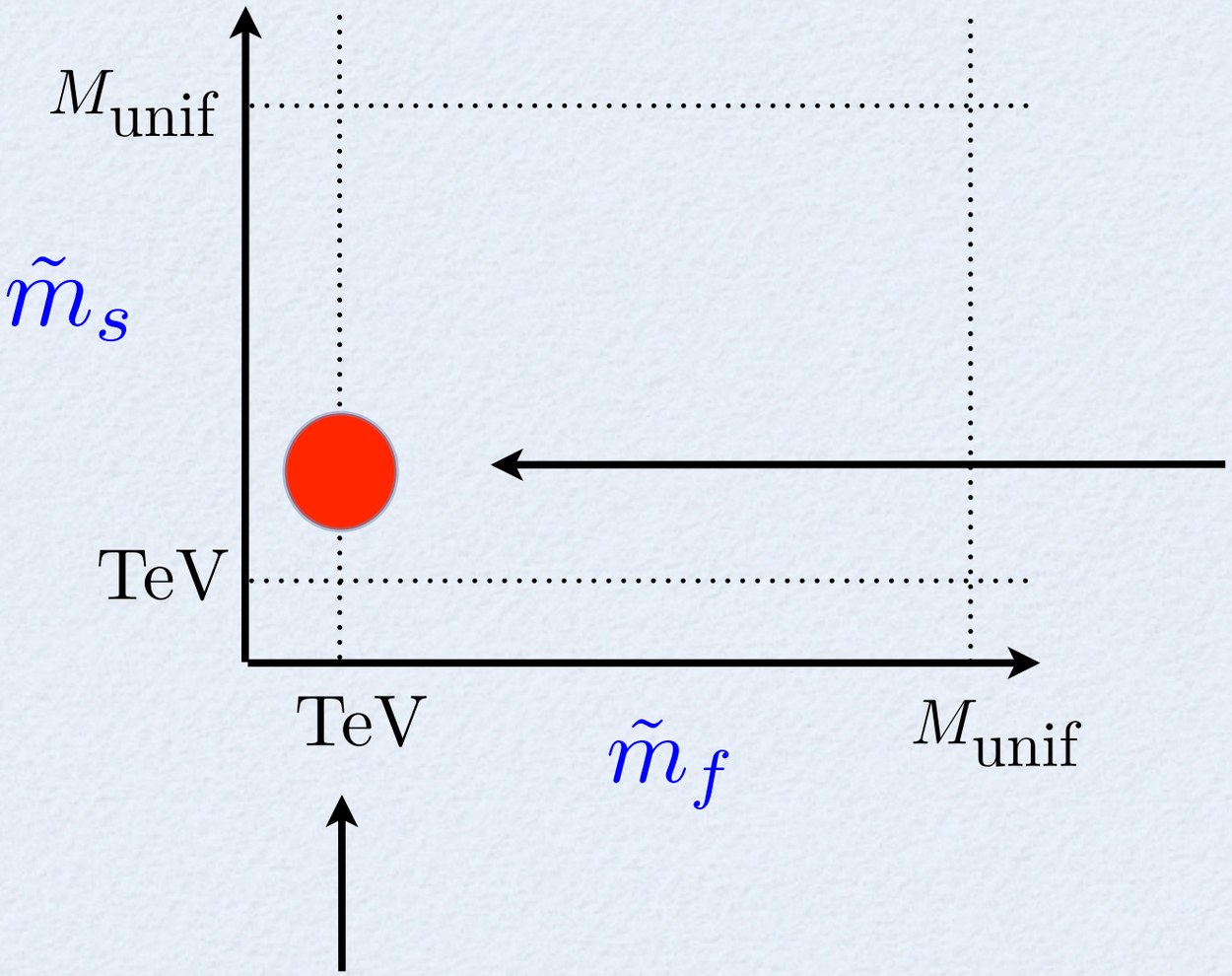
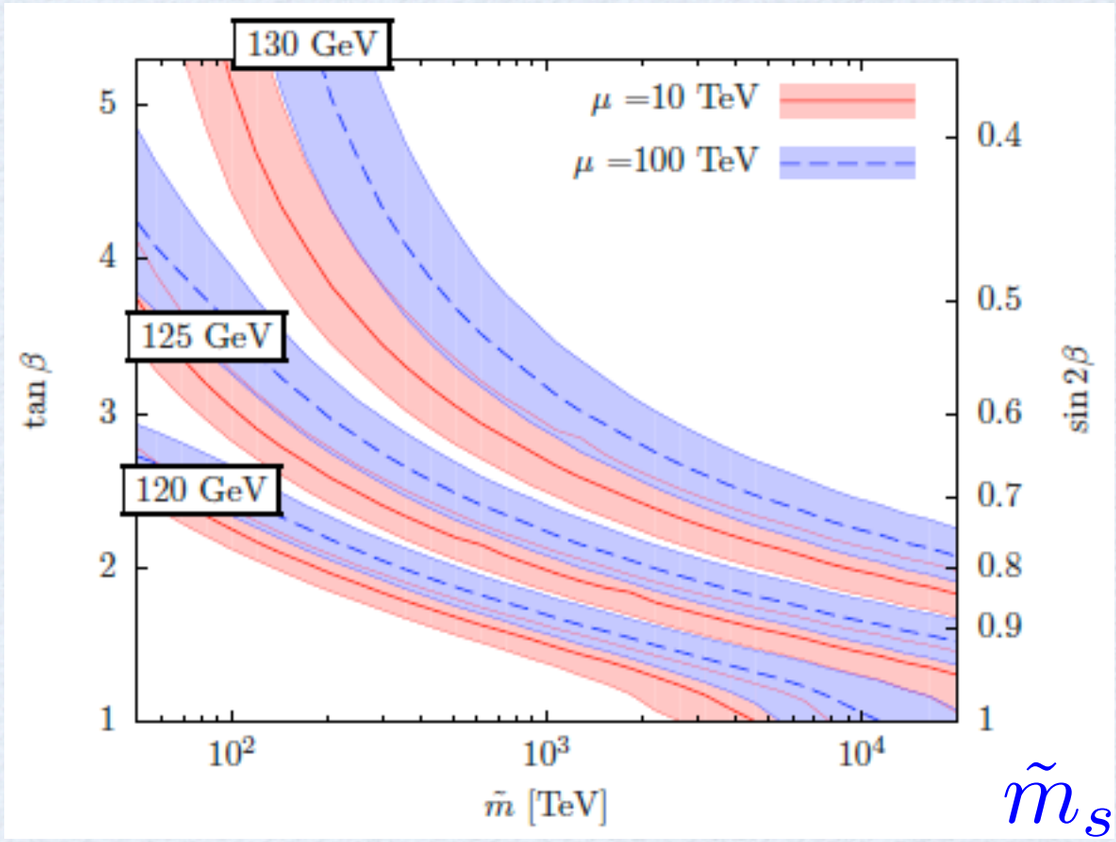


Gaugino dark matter

125 GeV Scalar is "effortless"



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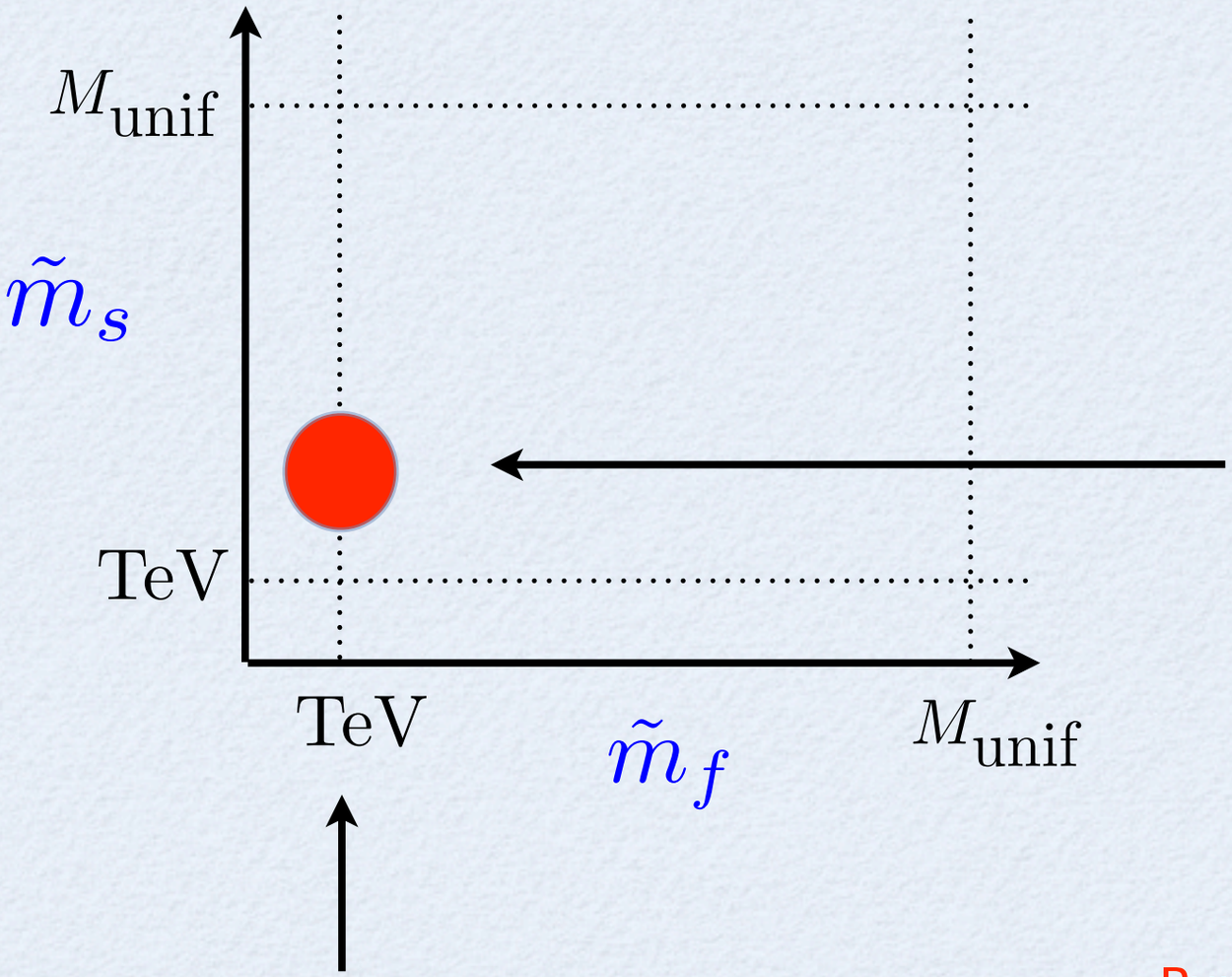

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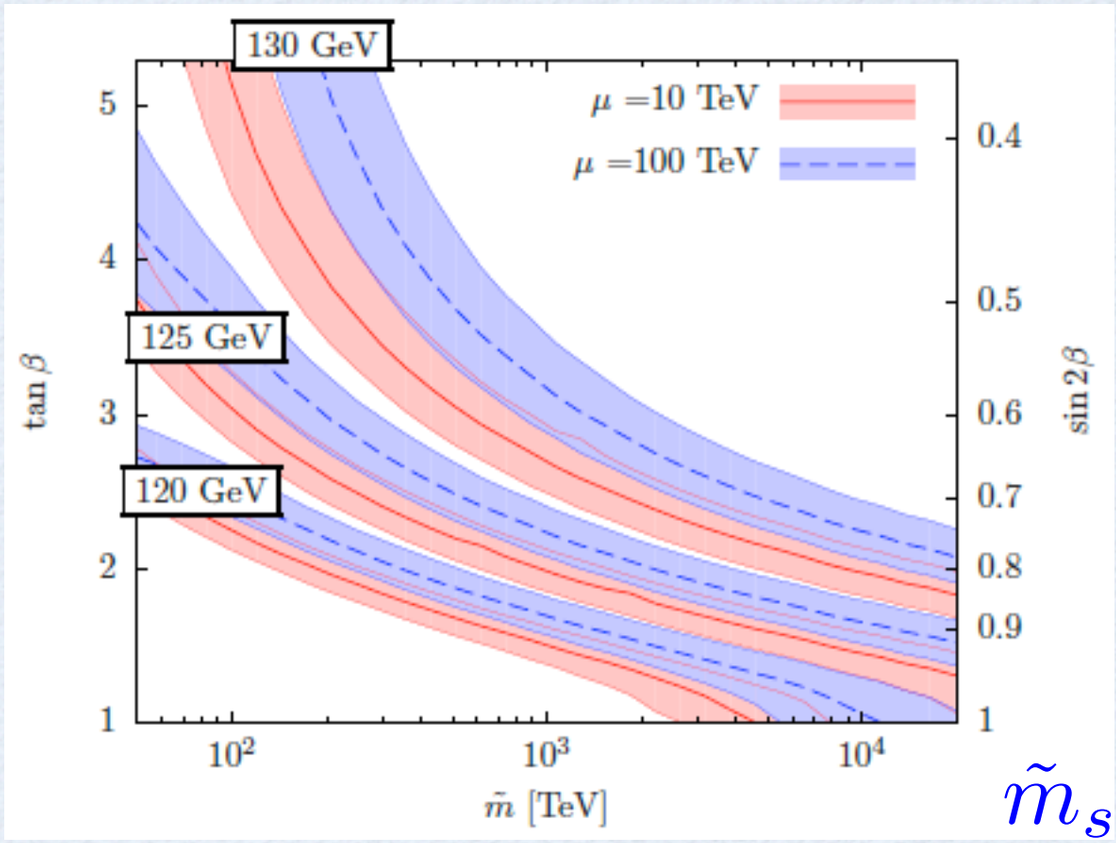
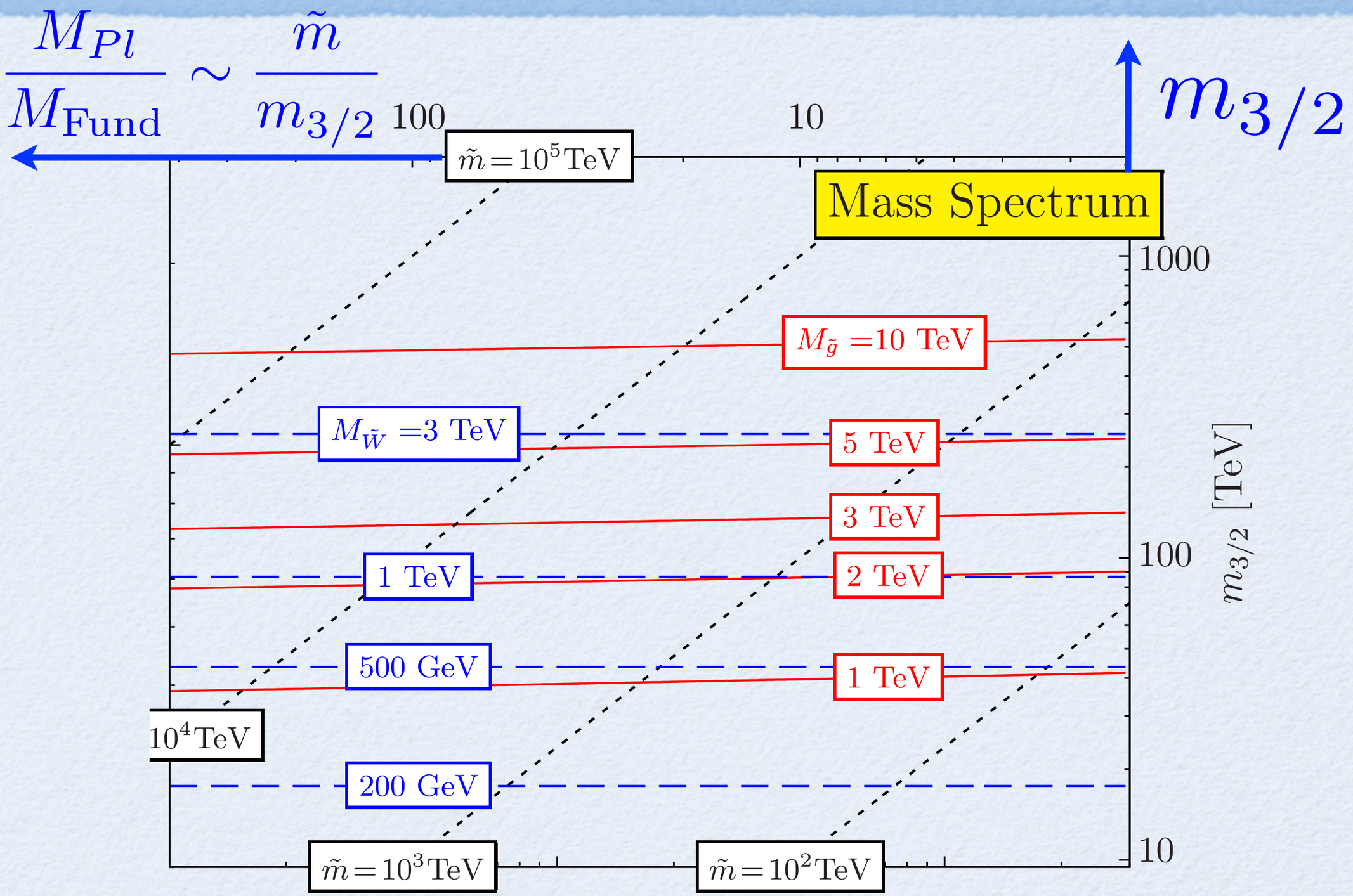


Spread	Hall, Nomura arXiv:1111.4519
Pure Gravity Mediation	Ibe, Yanagida arXiv:1112.2462
Mini-Split	Arvanitaki, Craig, Dimopoulos, Villadoro arXiv:1210.0555
Simply Unnatural	Arkani-Hamed, Gupta, Kaplan, Weiner, Zorawski arXiv:1212.6971

Susy Spectrum



Hall, Nomura, Shirai
arXiv:1210.2395

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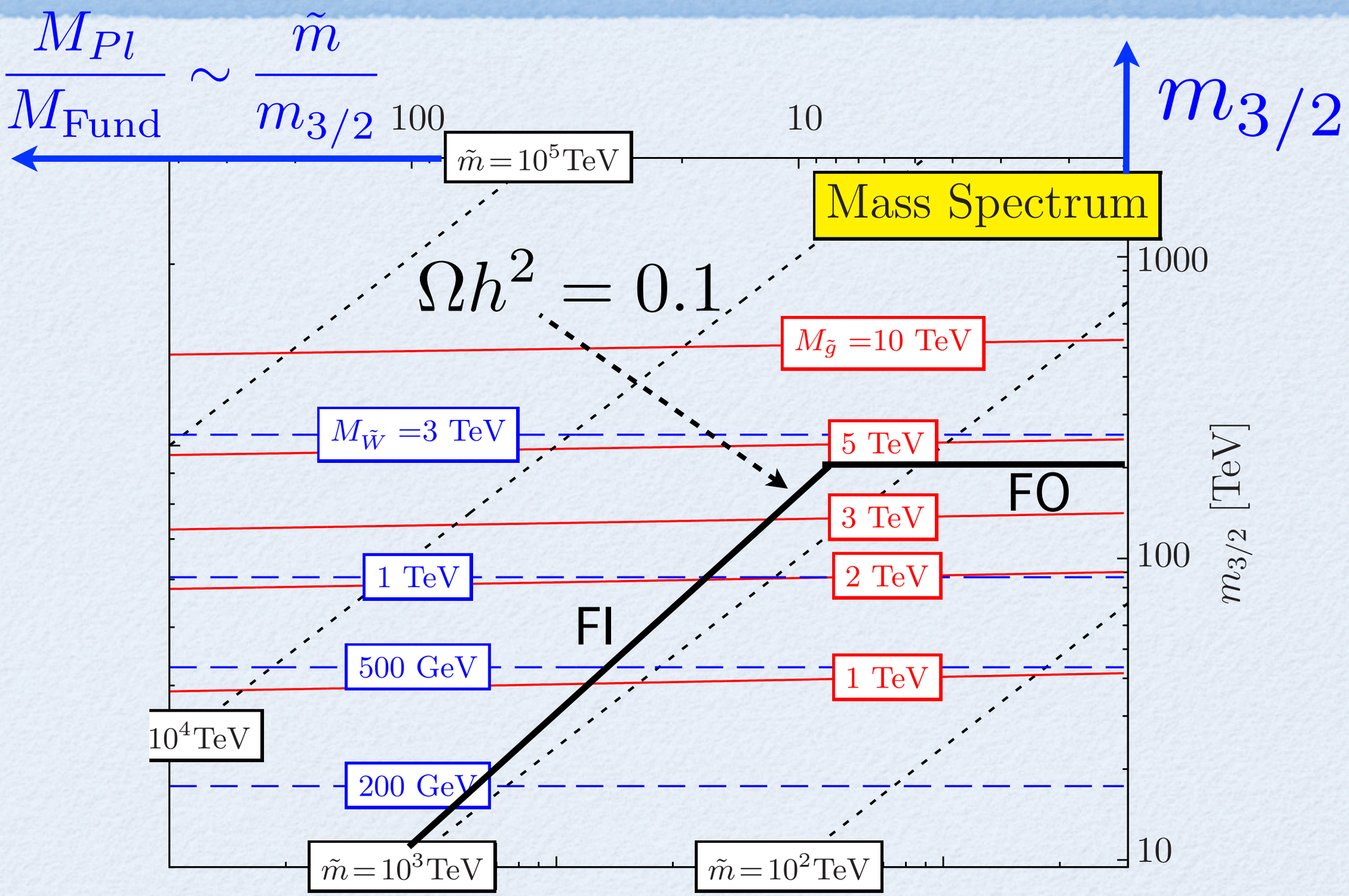

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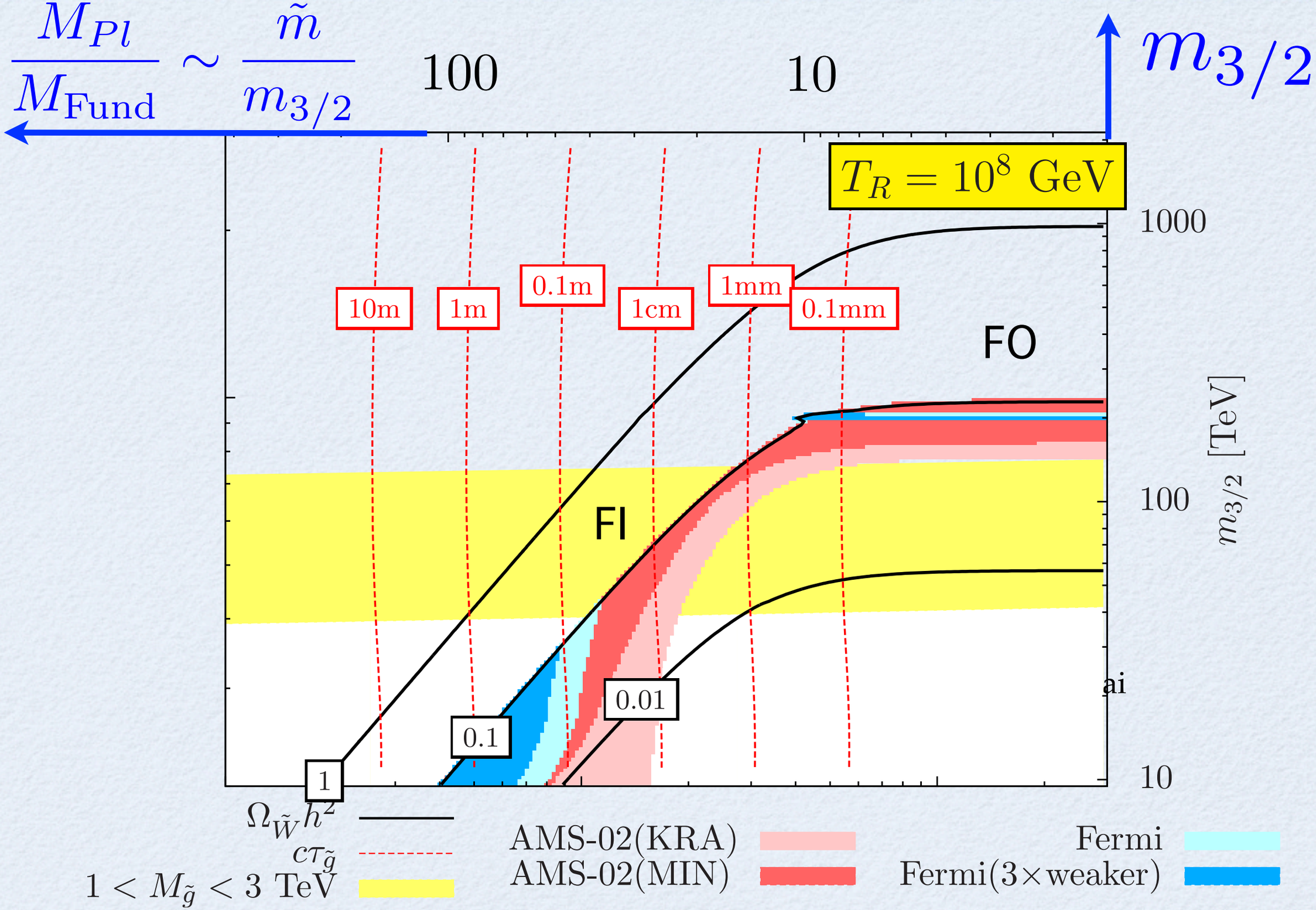
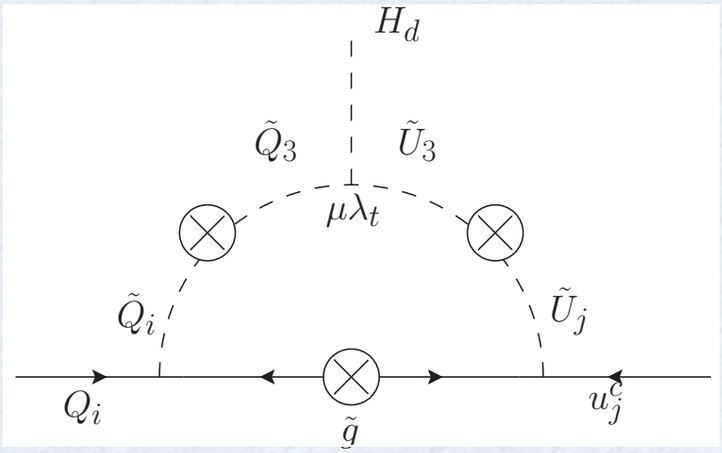
Dark Matter Abundance



Much To Explore: (1) Flavor/CP

Radiative quark and lepton masses

Arkani-Hamed, Gupta, Kaplan,
Weiner, Zorawski arXiv:1210.0555



Flavor/CP

Altmanshofer, Harnik, Zupan
arXiv:1308.3653

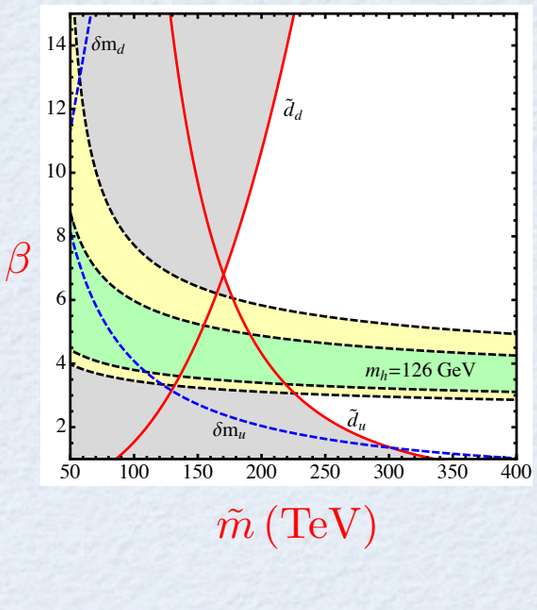
LFV/CP

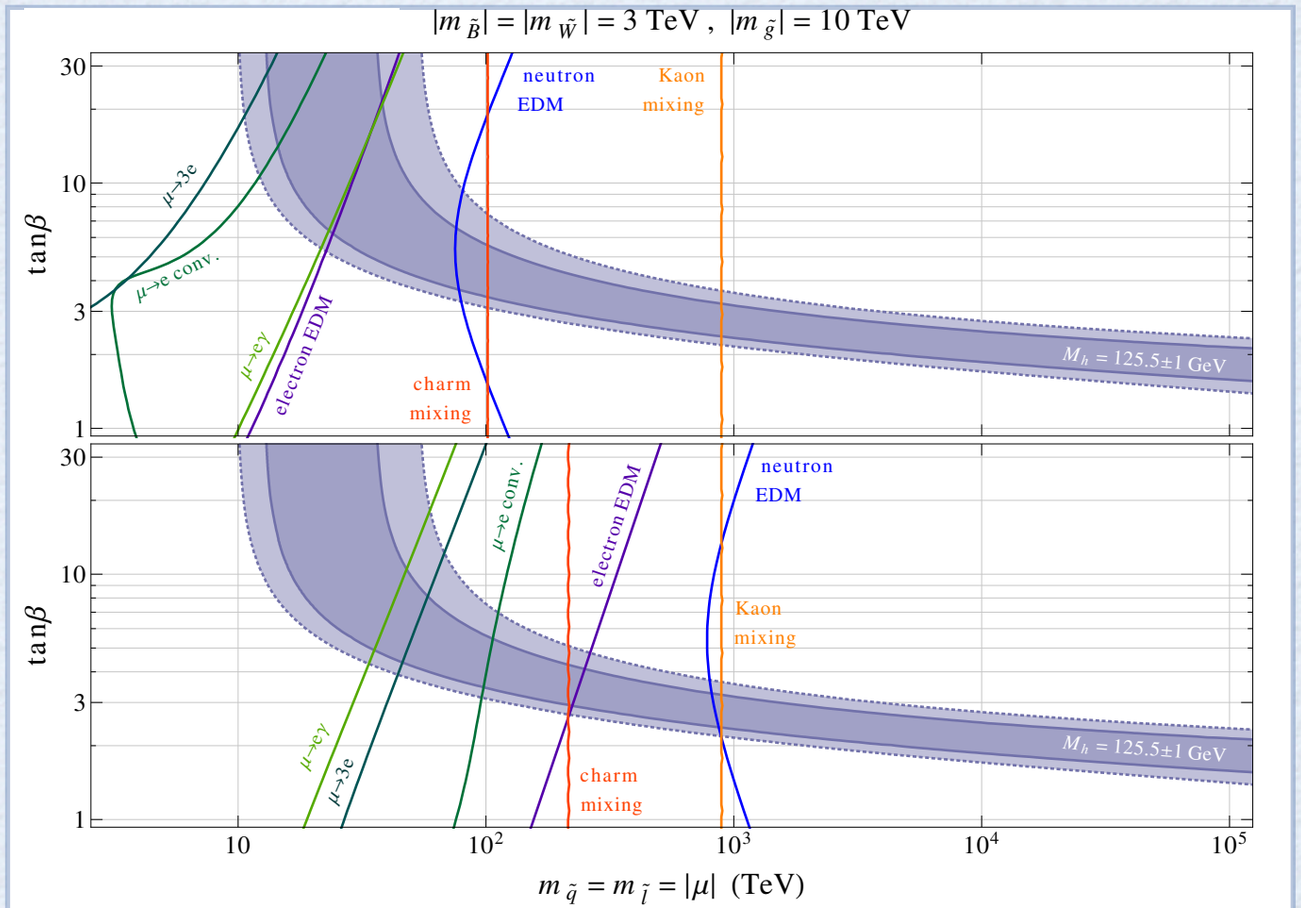
Moroi, Nagai arXiv:1303.0668

Moroi, Nagai Yanagida arXiv:1305.7357

Nuclear EDMs

McKeen, Pospelov, Ritz
arXiv:1303.1172

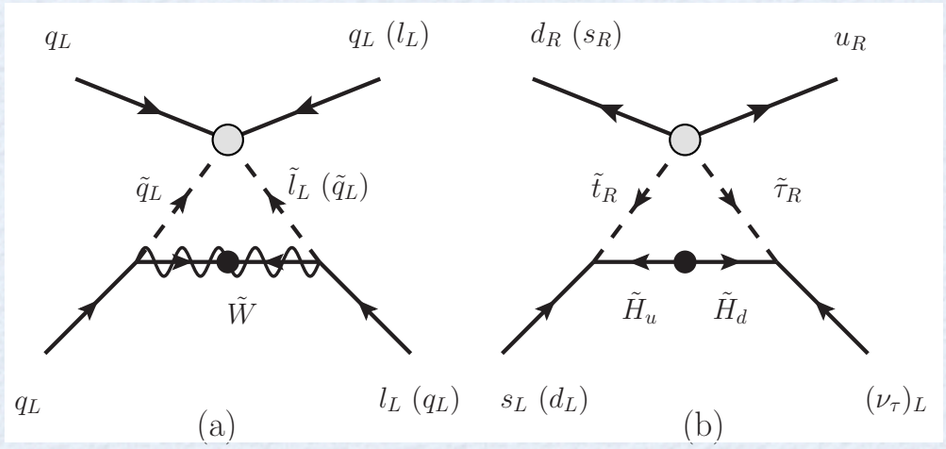




Much To Explore: (2) Proton Decay

Minimal Susy SU(5) alive

Hisano, Kobayashi, Kuwahara, Nagata
arXiv:1304.3651



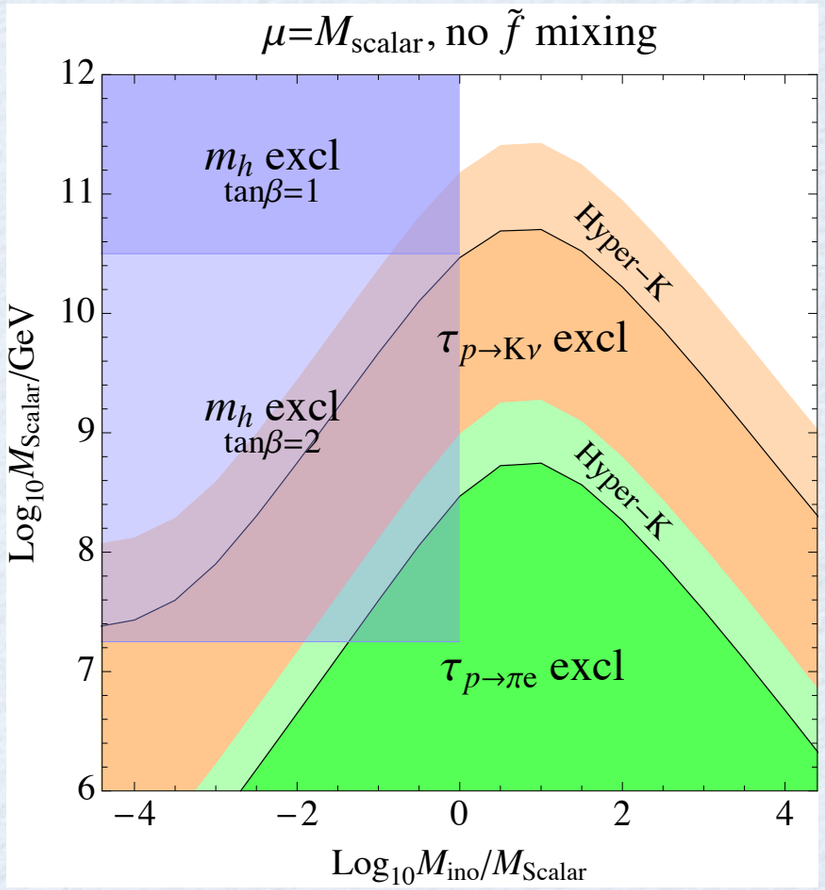
d=6 Gauge exchange enhanced

Hall, Nomura arXiv:1111.4519

$$\tau_{p\to e^+\pi^0} \simeq (0.8-5)\times 10^{34}\ \text{years}$$

d=5 from Planck scales needs to be controlled

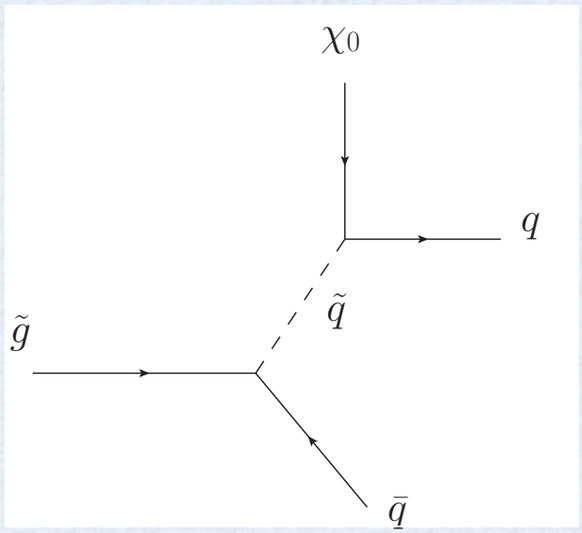
Dine, Draper, Shepherd
arXiv 1308.0274



Gluino cascades at LHC

Gluino decays

Arkani-Hamed, Gupta, Kaplan,
Weiner, Zorawski arXiv:1210.0555

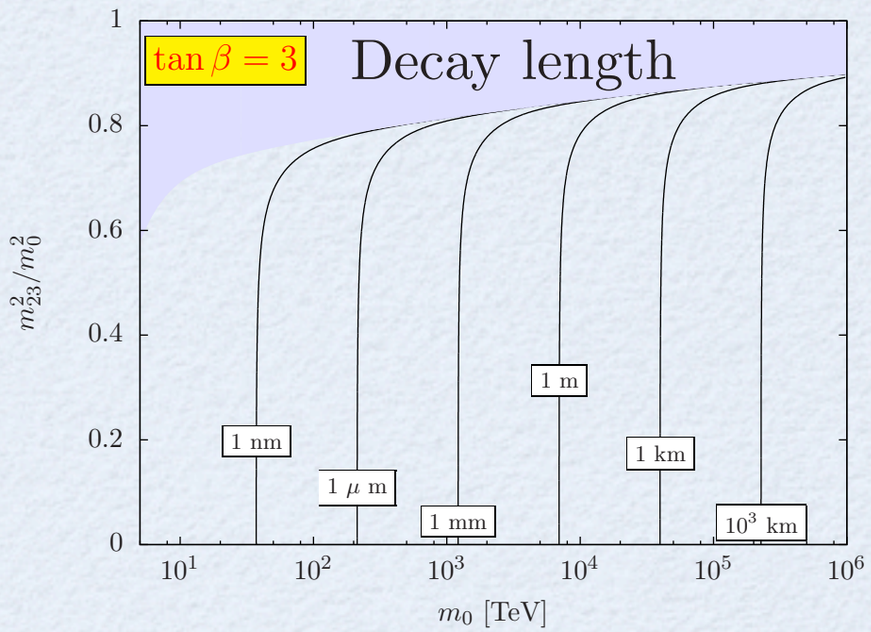


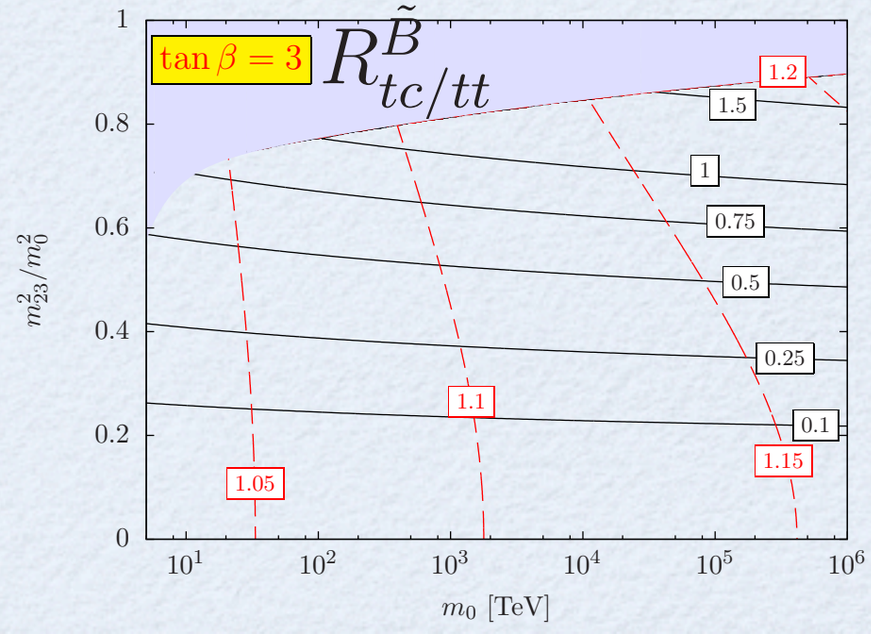
$$\tilde{g} \to \bar{t}t\tilde{W}^0$$
$$\tilde{g} \to \bar{b}b\tilde{W}^0$$
$$\tilde{g} \to \bar{t}b\tilde{W}^+$$
$$\tilde{g} \to \bar{t}t\tilde{B}^0$$
$$\tilde{g} \to \bar{b}b\tilde{B}^0$$

only UV 3 params
(comb. $\tilde{q}, \tilde{u}, \tilde{d}$ masses)

Gluino decays

Sato, Shirai, Tobioka
arXiv:1307.7144



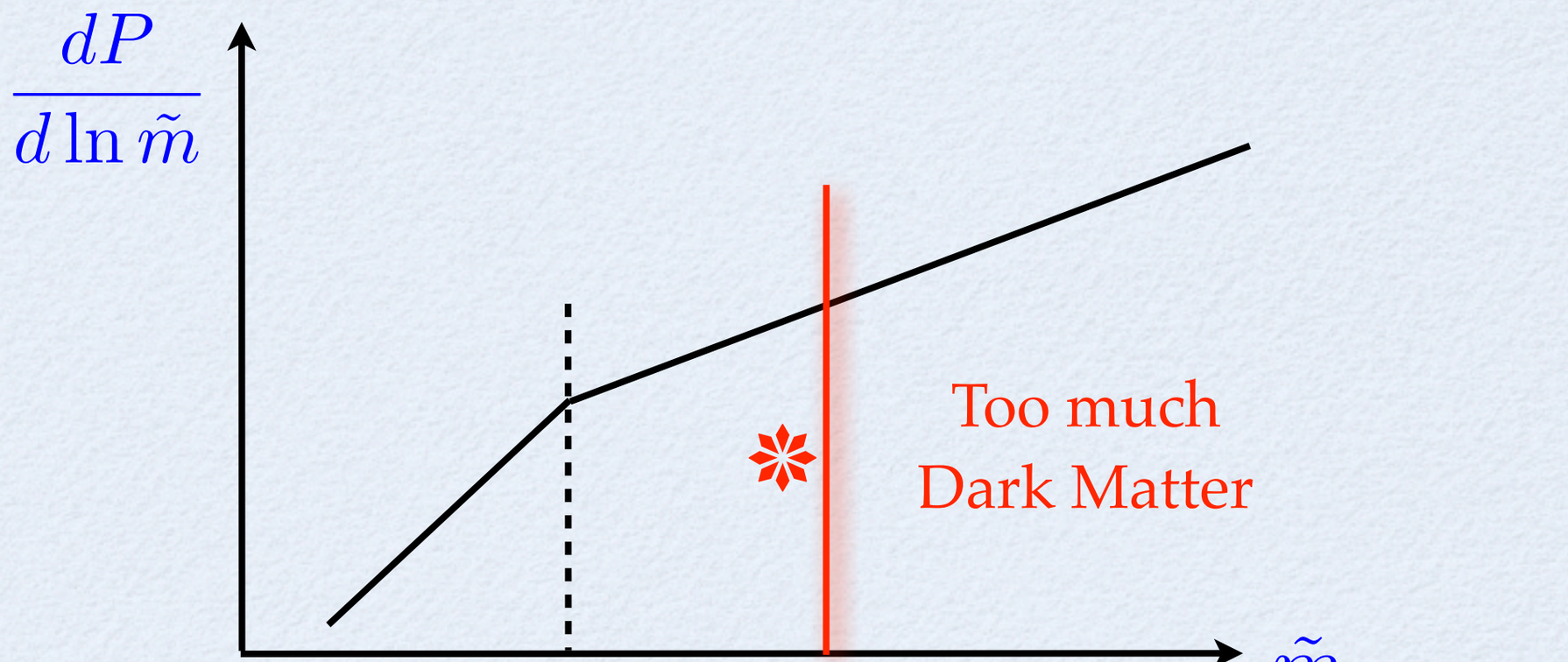


3. TeV Scale Superpartners with

$$\rho_D \sim \rho_B$$

Bousso, Hall 1304.6407

No Catastrophic Boundary for Dark Matter



If this boundary does not exist,
or is far from our universe,
are we forced to High Scale SUSY?

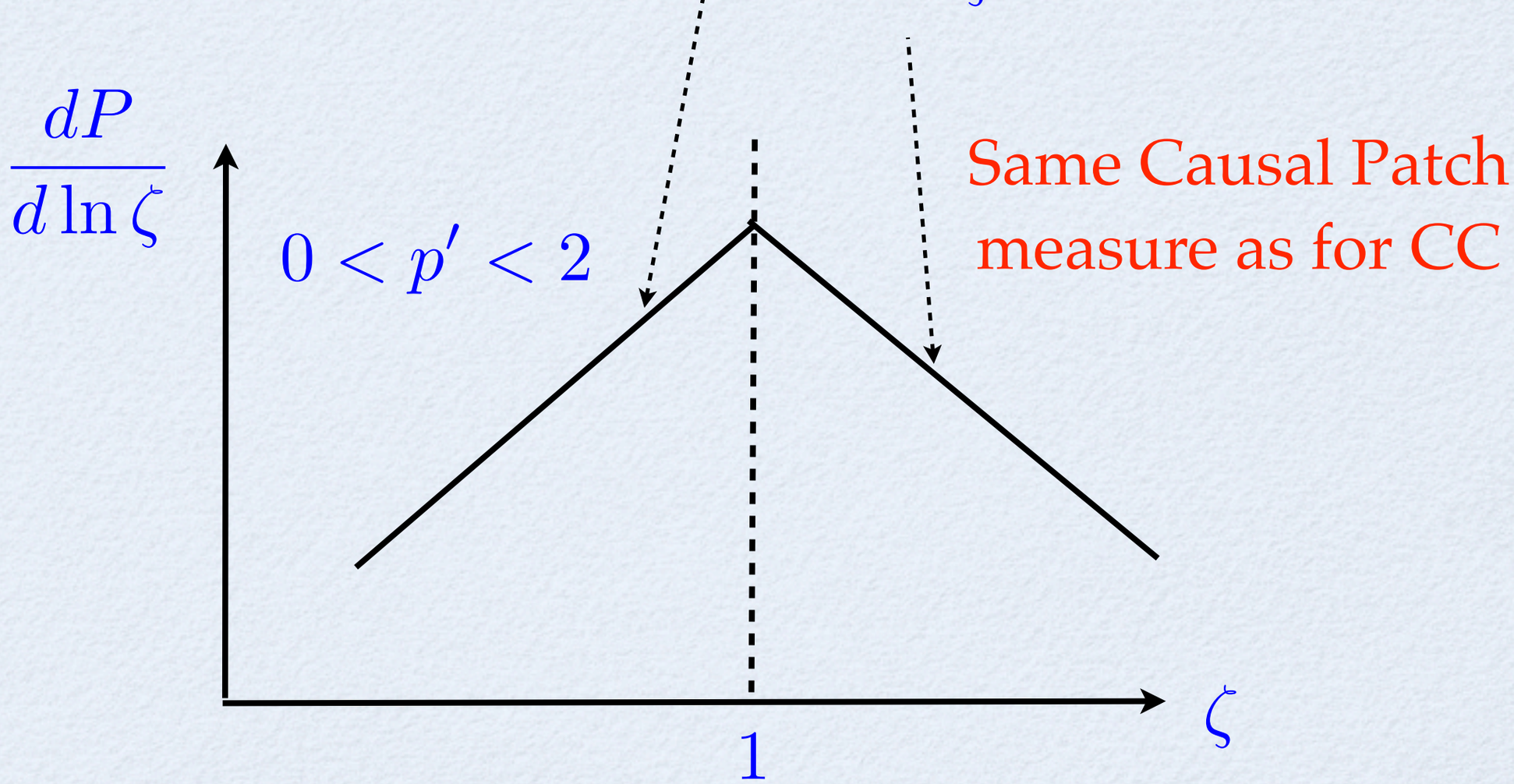
The Dark to Baryon Ratio

$$\text{Why is } \zeta = \frac{\rho_D}{\rho_B} \sim 1\,?$$

The Dark to Baryon Ratio

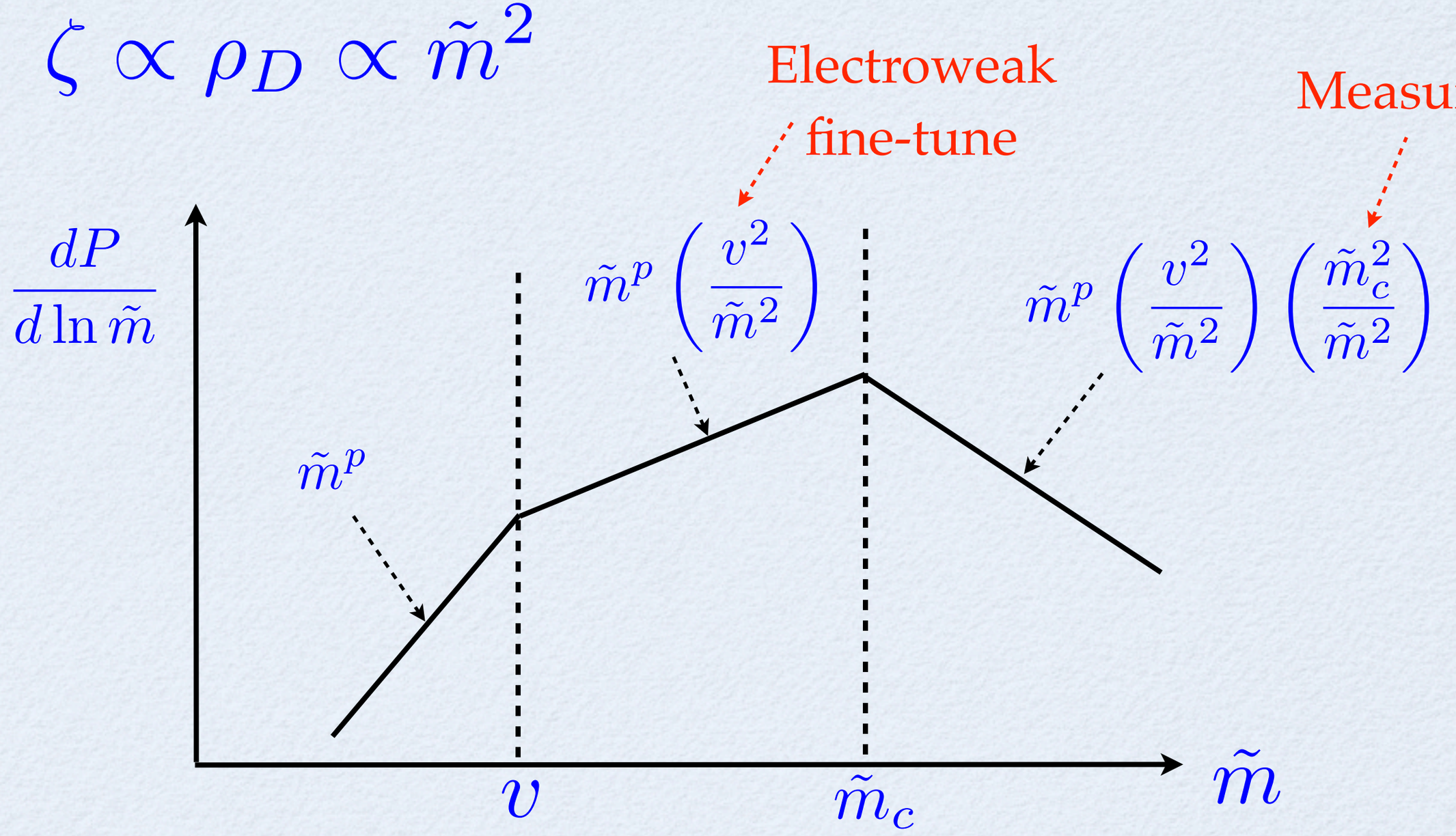
Why is $\zeta = \dfrac{\rho_D}{\rho_B} \sim 1$?

A multiverse explanation: $dP \sim \zeta^{p'/2} \dfrac{1}{1+\zeta}\, d\ln\zeta$



LSP Dark Matter from Freeze-Out

$$\zeta \propto \rho_D \propto \tilde{m}^2$$



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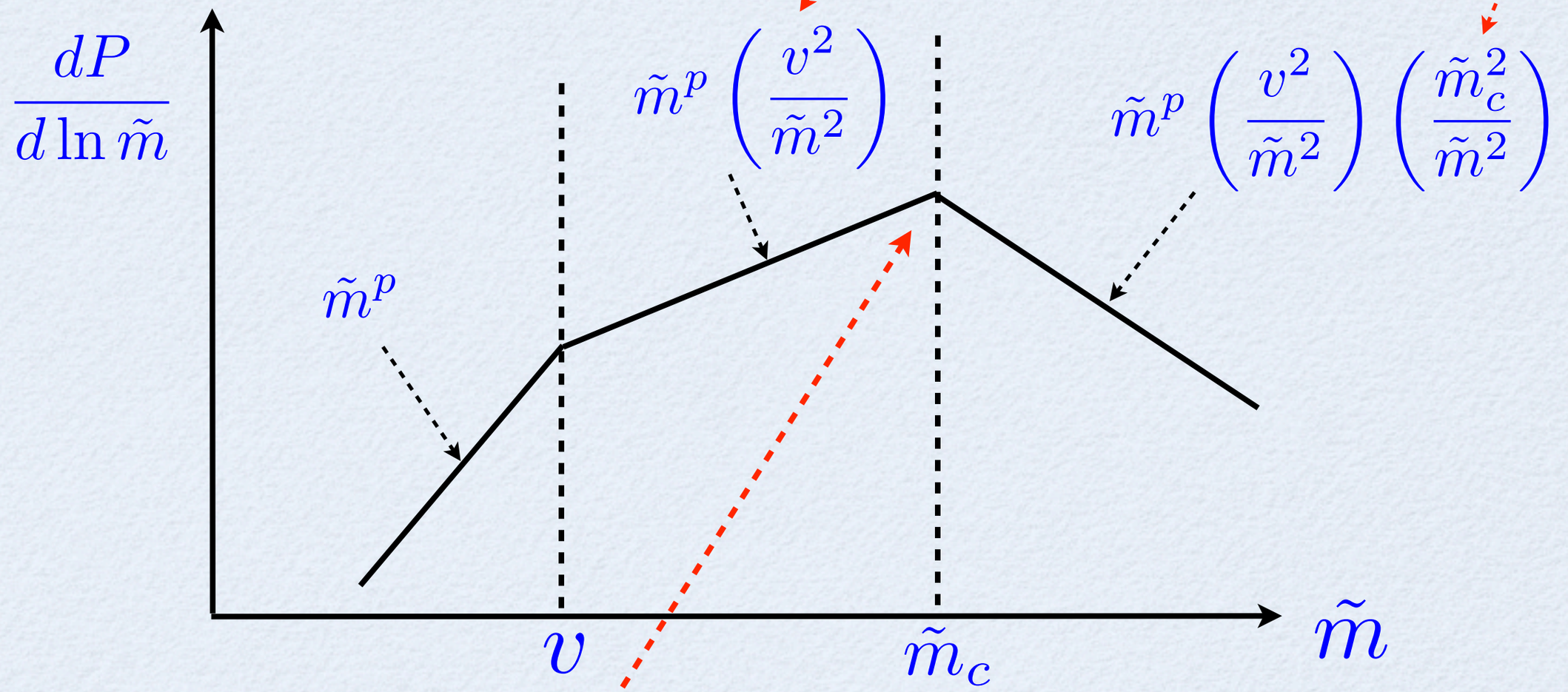
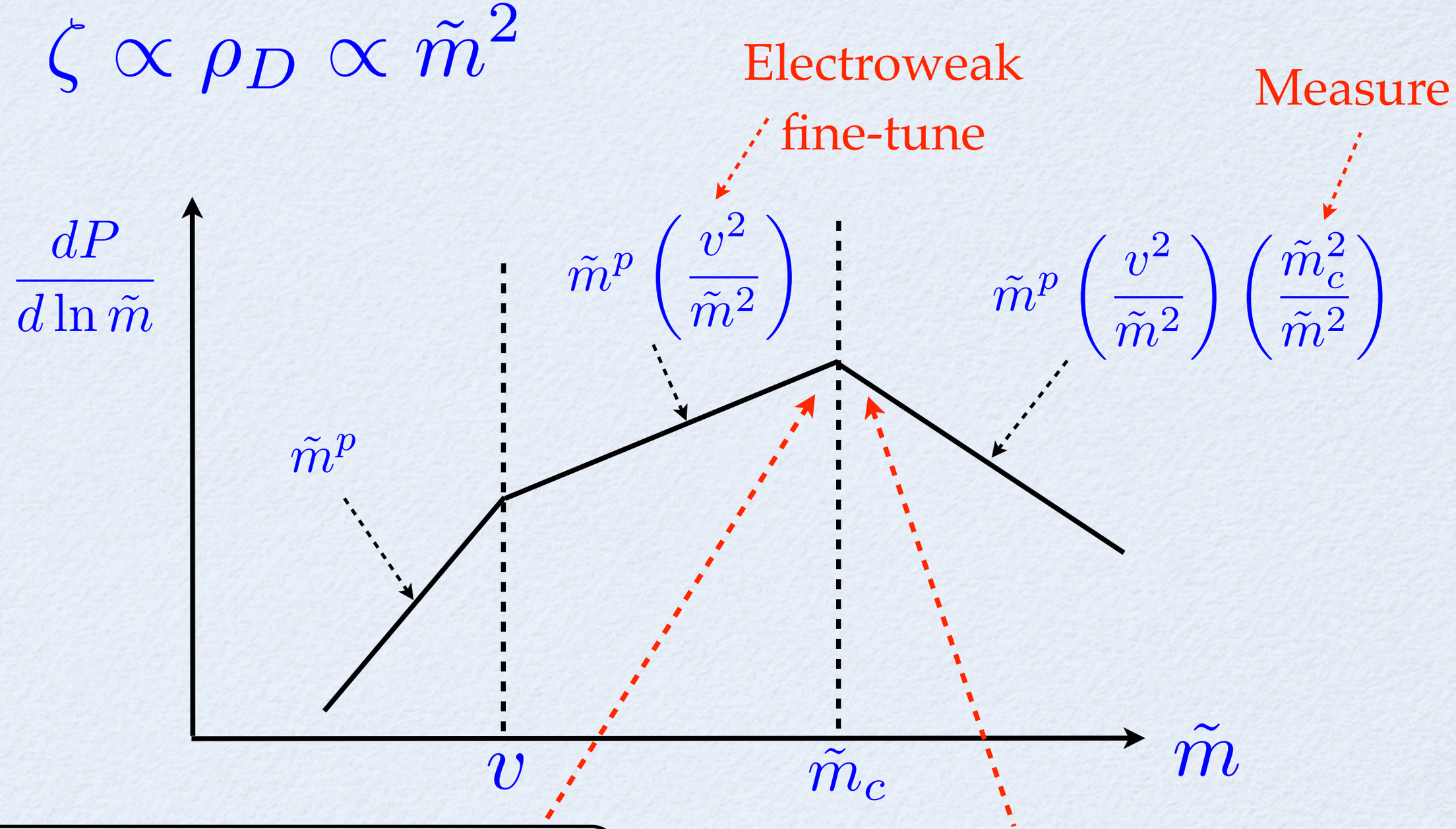


$$2 < p < 4$$

Little SUSY Hierarchy

LSP Dark Matter from Freeze-Out

$$\zeta \propto \rho_D \propto \tilde{m}^2$$



$2 < p < 4$

Little SUSY Hierarchy

Bonus: $\frac{\rho_D}{\rho_B} \sim 1$

Summary:

SUSY in the Multiverse

A Remarkable Situation

1973-2013: 40 years without BSM discovery

1998: $$\Lambda_{CC} \sim \frac{1}{G_N\, t_{obs}^2}$$

2013: SM Higgs, apparently tuned

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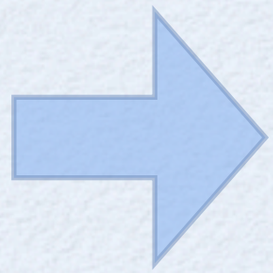

A New Framework

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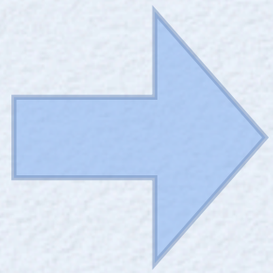


A New Framework

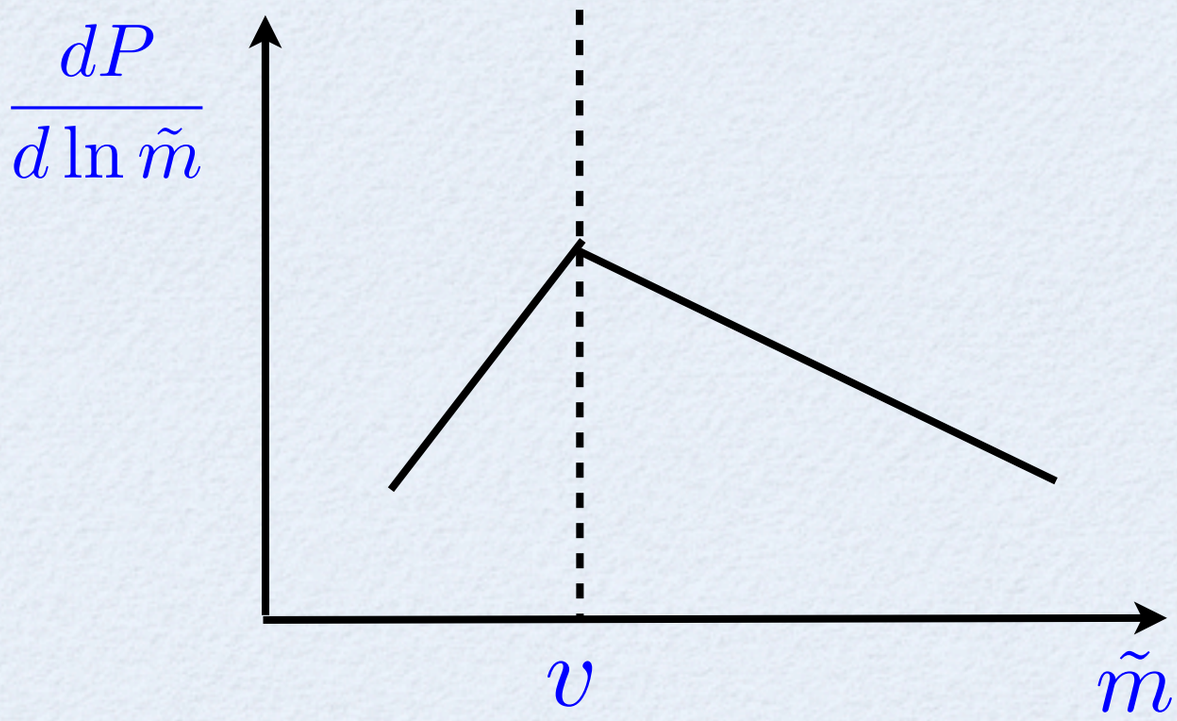
A Multiverse

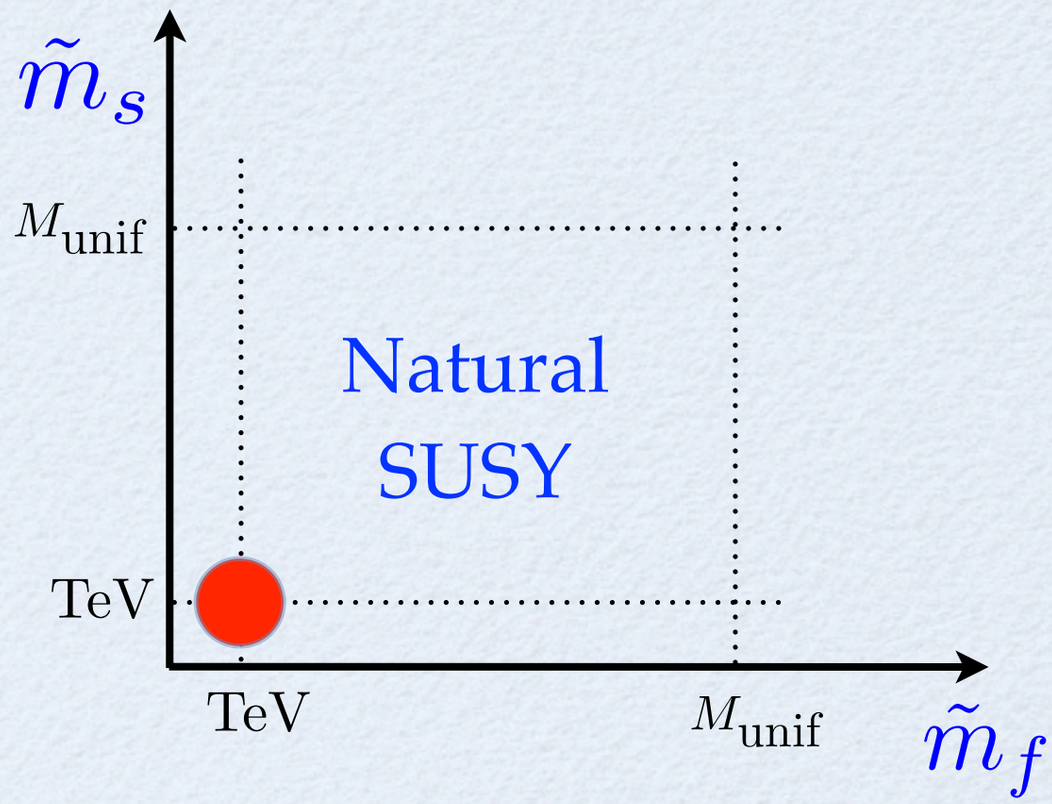
scanning mass scales: $\Lambda_{CC}, v, ...$

investigate $dP \propto \tilde{m}^p \;\; d\ln\tilde{m}$

Natural SUSY

$$0 < p < 2$$

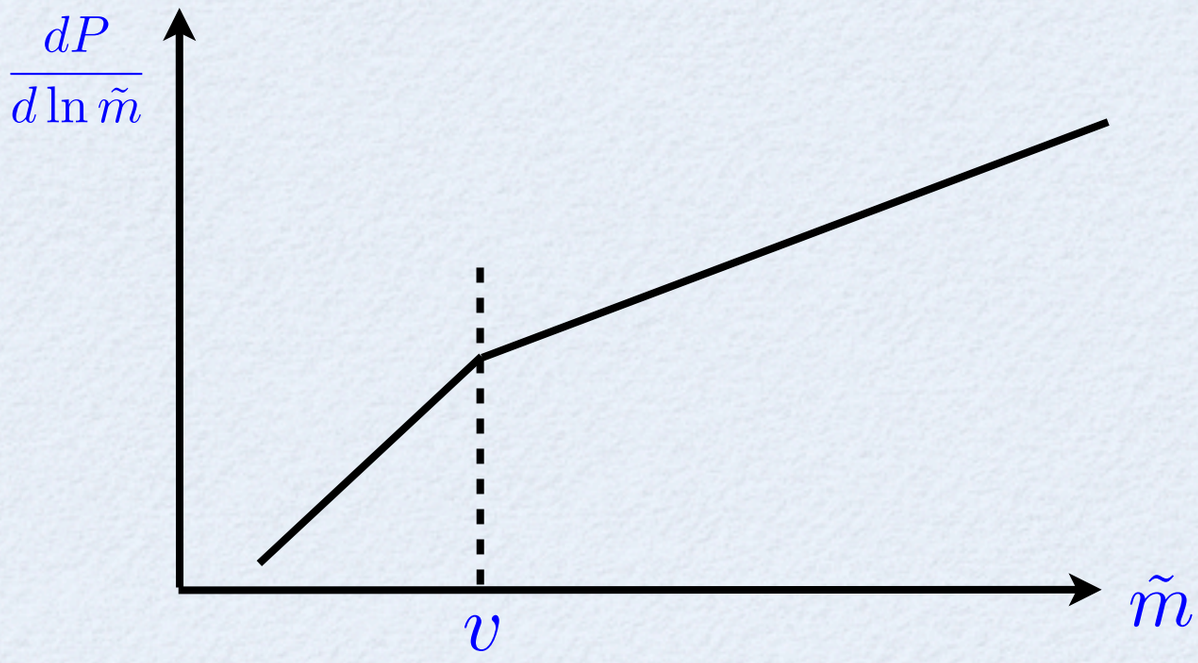


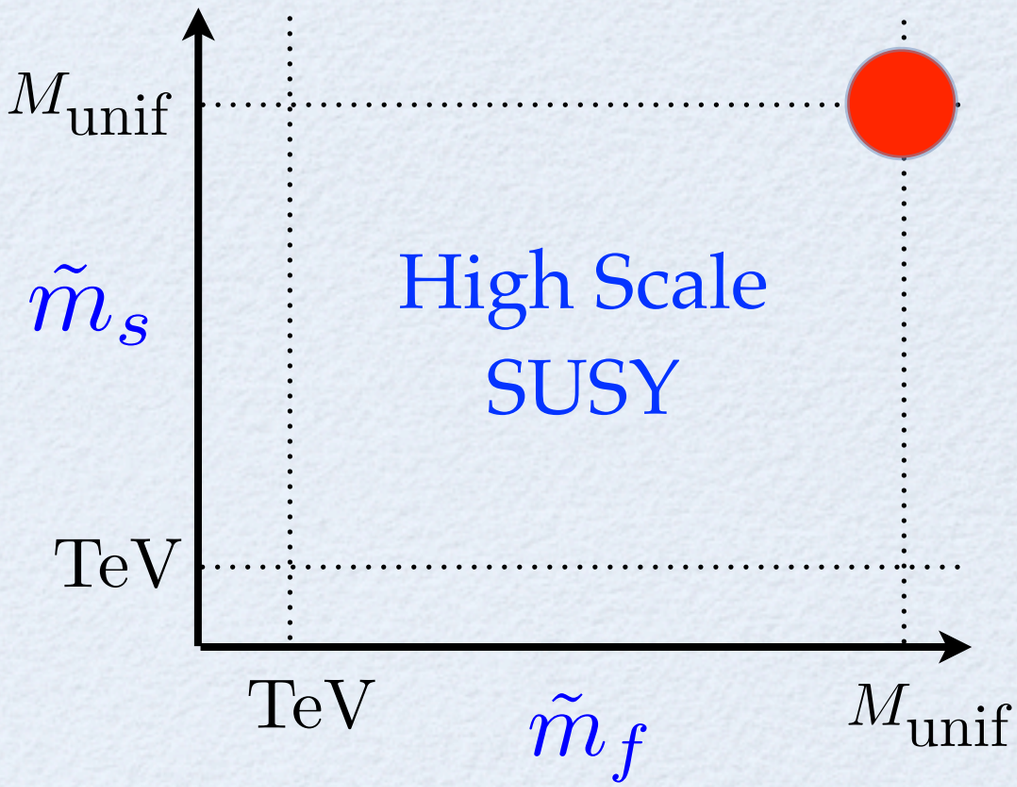


Cornered after 30+ years -- we need to be sure

Runaway to High Scale SUSY

$$p > 2$$





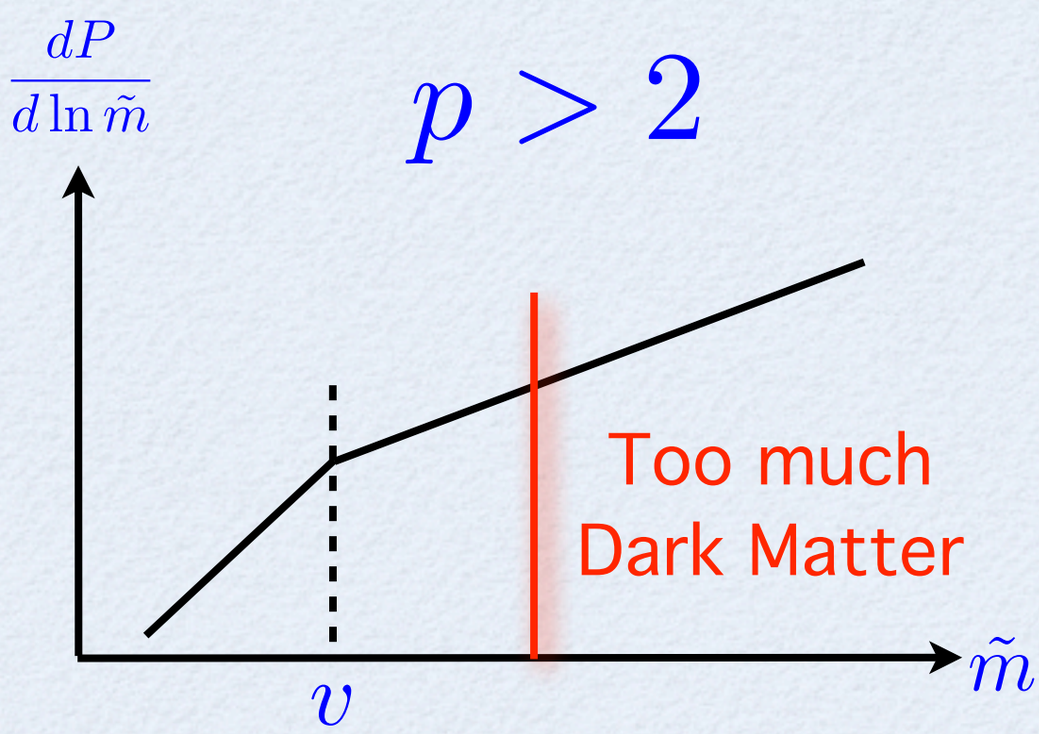
$H_u \leftrightarrow H_d$ ⇒ $m_h = (128 \pm 3 \pm 0.6 \pm 1.0)$ GeV

Hall, Nomura 0910.2235

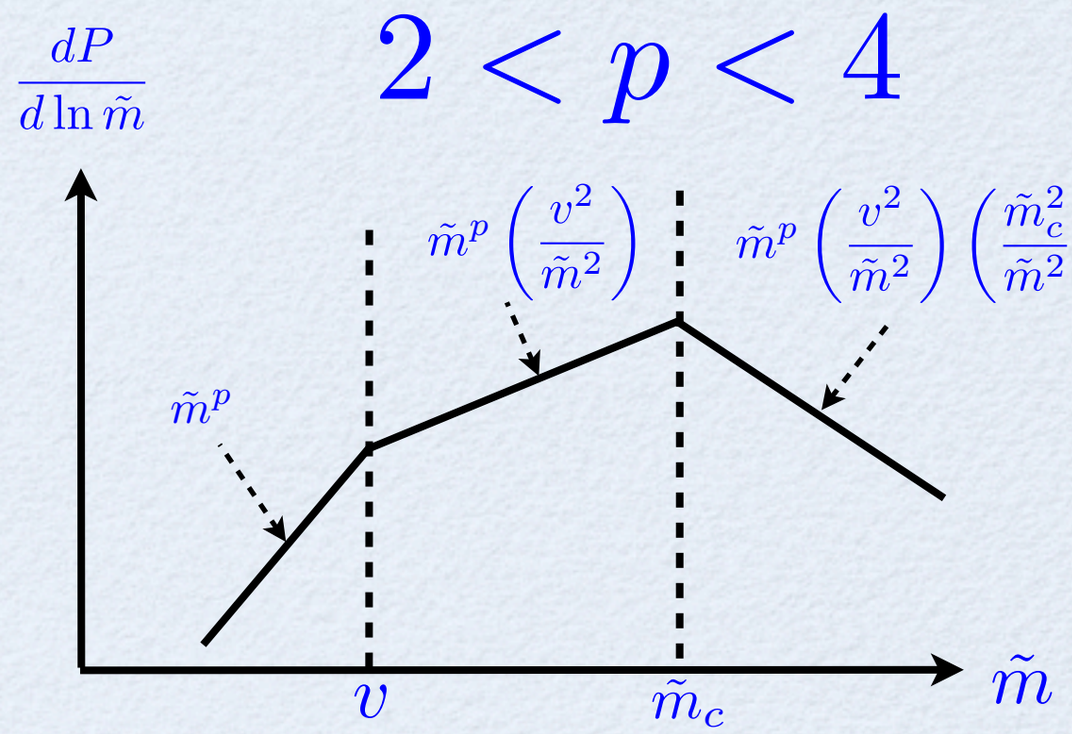
Scanning λ ⇒ $m_h = (112 \pm 8 + 25/q)$ GeV

Feldstein, Hall, Watari hep-ph/0608121

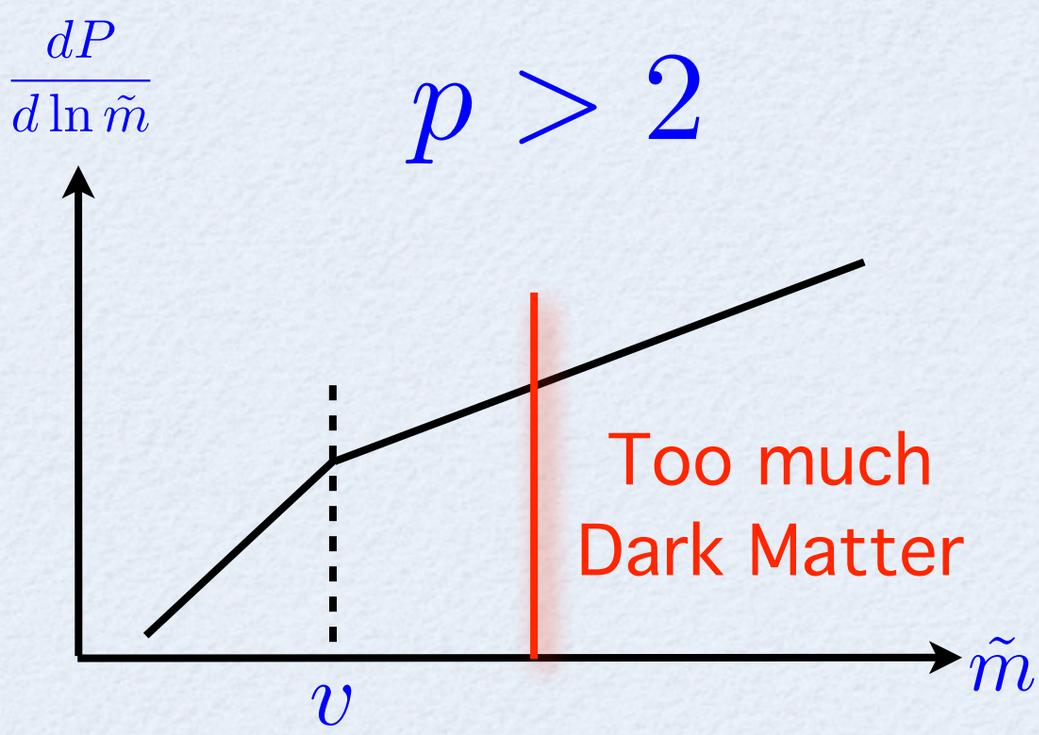
Stabilizing SUSY Breaking at Multi-TeV



OR



Stabilizing SUSY Breaking at Multi-TeV



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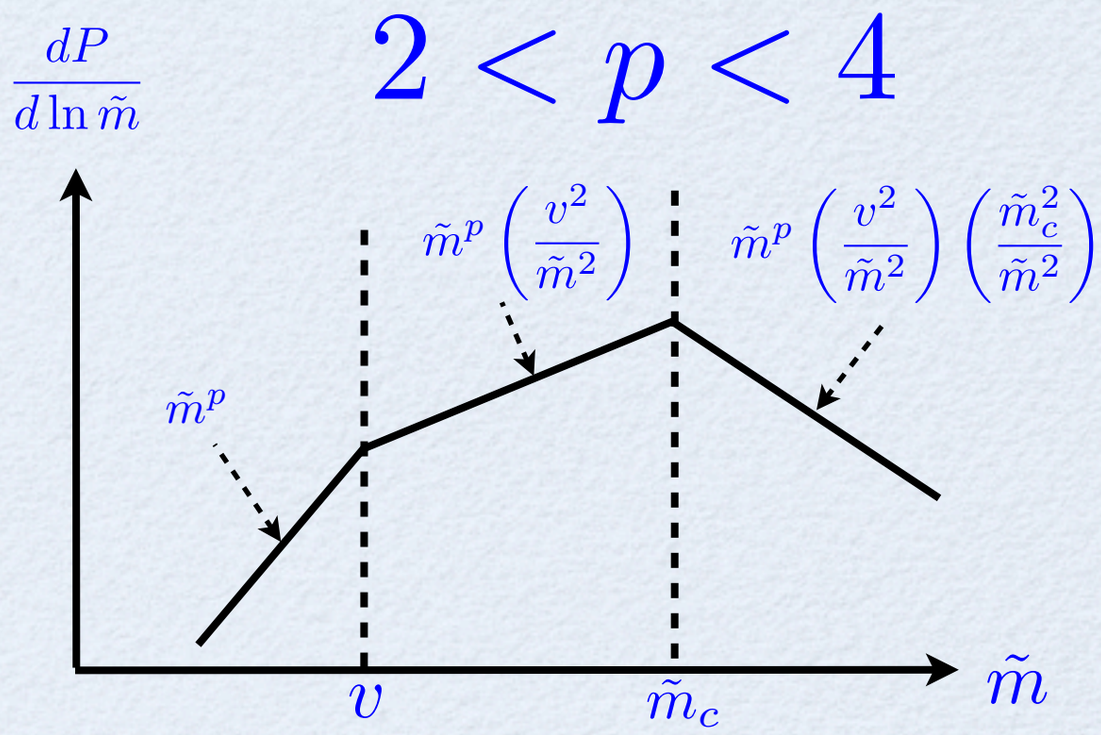
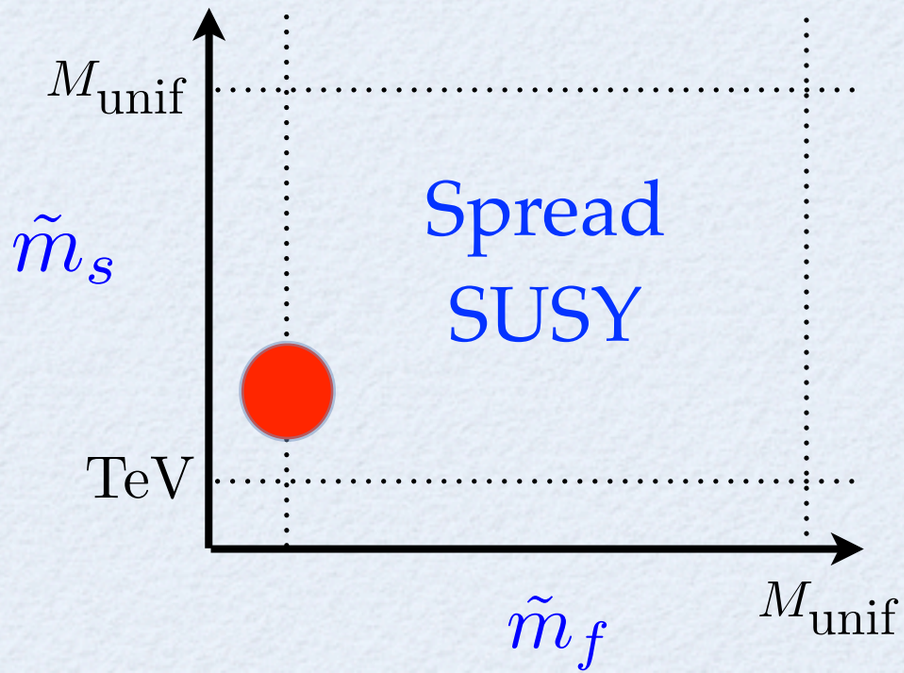
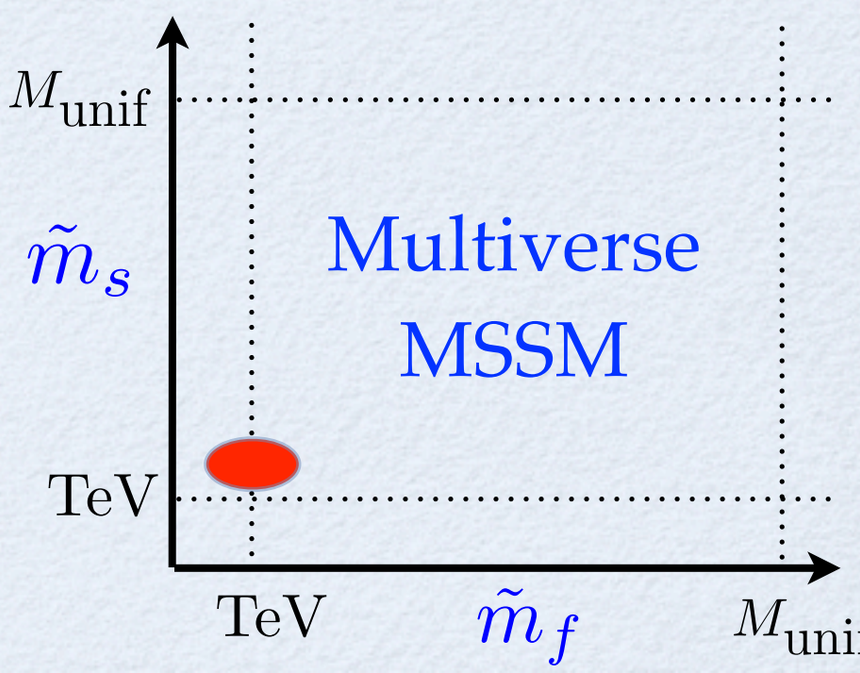
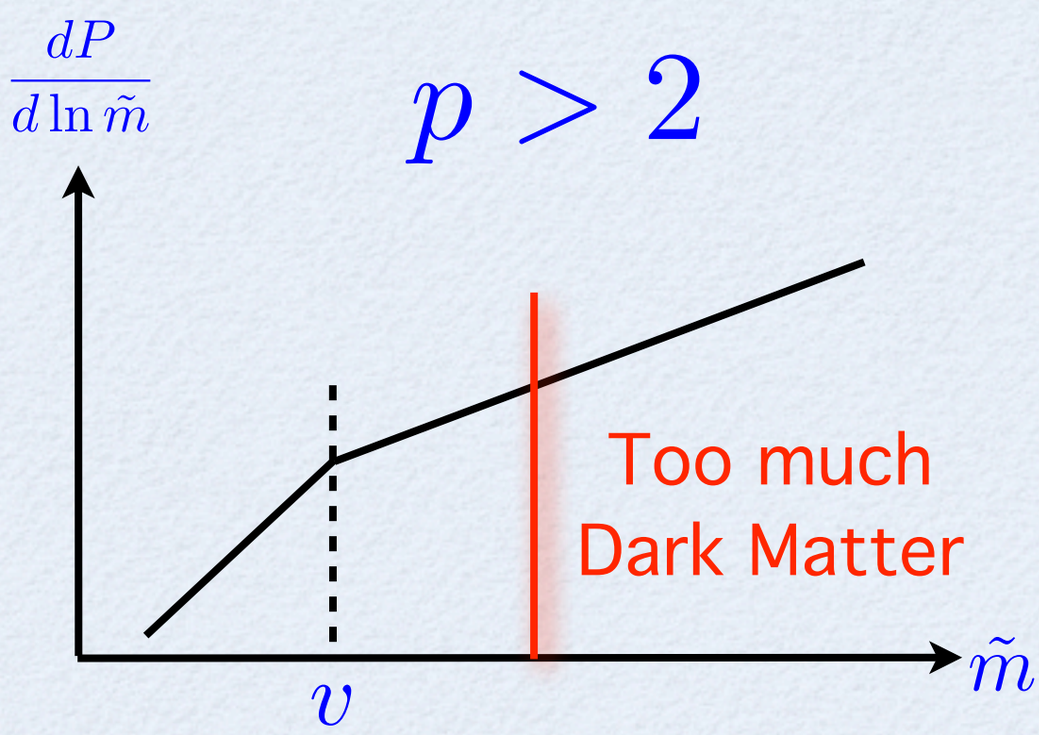






Stabilizing SUSY Breaking at Multi-TeV



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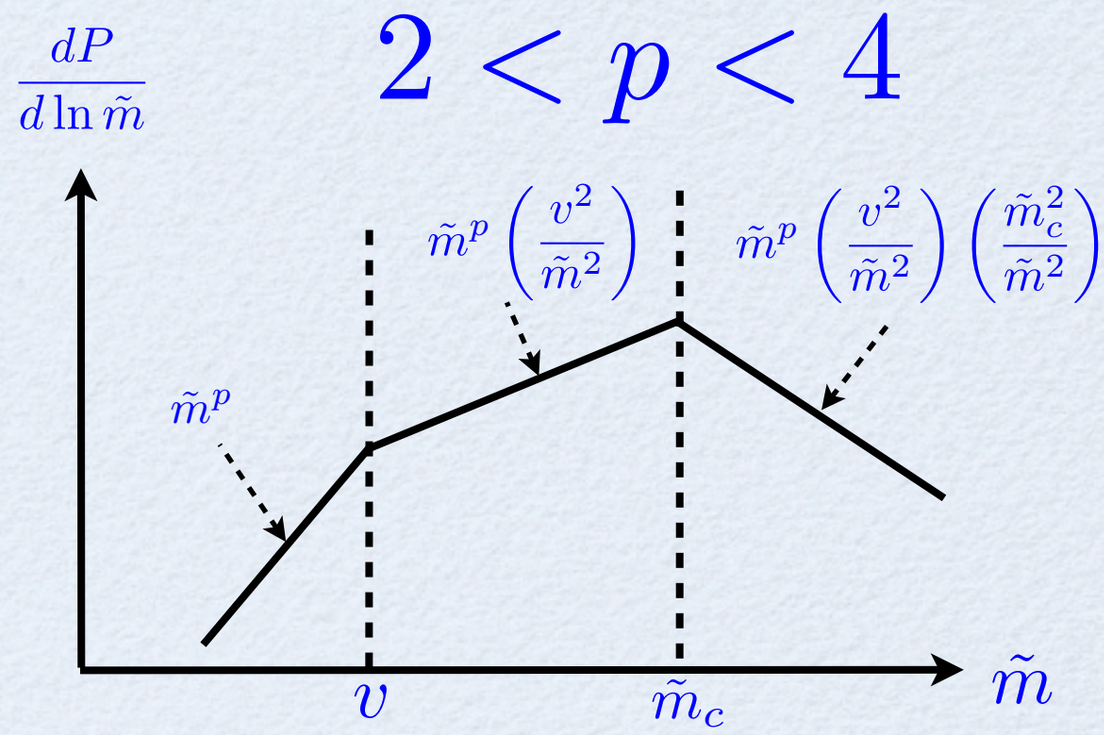

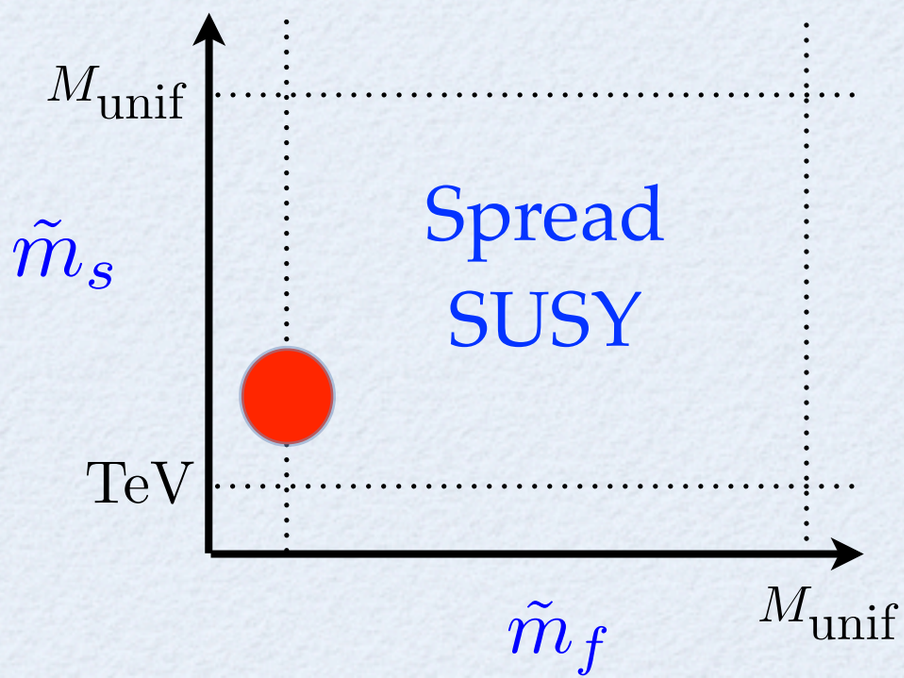

1-20 TeV

May need
100 TeV
Collider