Galileo Galilei Institute
Beyond the SM after LHC 8
July 2013

TeV-Scale Superpartners with an Unnatural Weak Scale

Lawrence Hall
University of California, Berkeley

OR

Multiverse SUSY

Outline

1. High Scale SUSY

   Hall, Nomura 0910.2235

2. Spread SUSY

   Hall, Nomura 1111.4519

3. TeV SUSY with

   $\rho_D \sim \rho_B$

   Bousso, Hall 1304.6407

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(multi)-TeV superpartners

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(multi)-TeV superpartners

All three have a fine-tuned weak scale

Agnostic

Multiverse

Simplest Interpretation of LHC 8

125 GeV Higgs

v is fine tuned (to some degree)

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A Simple Interpretation:

Λ_{CC} : tuning and size understood

v : in the multiverse.

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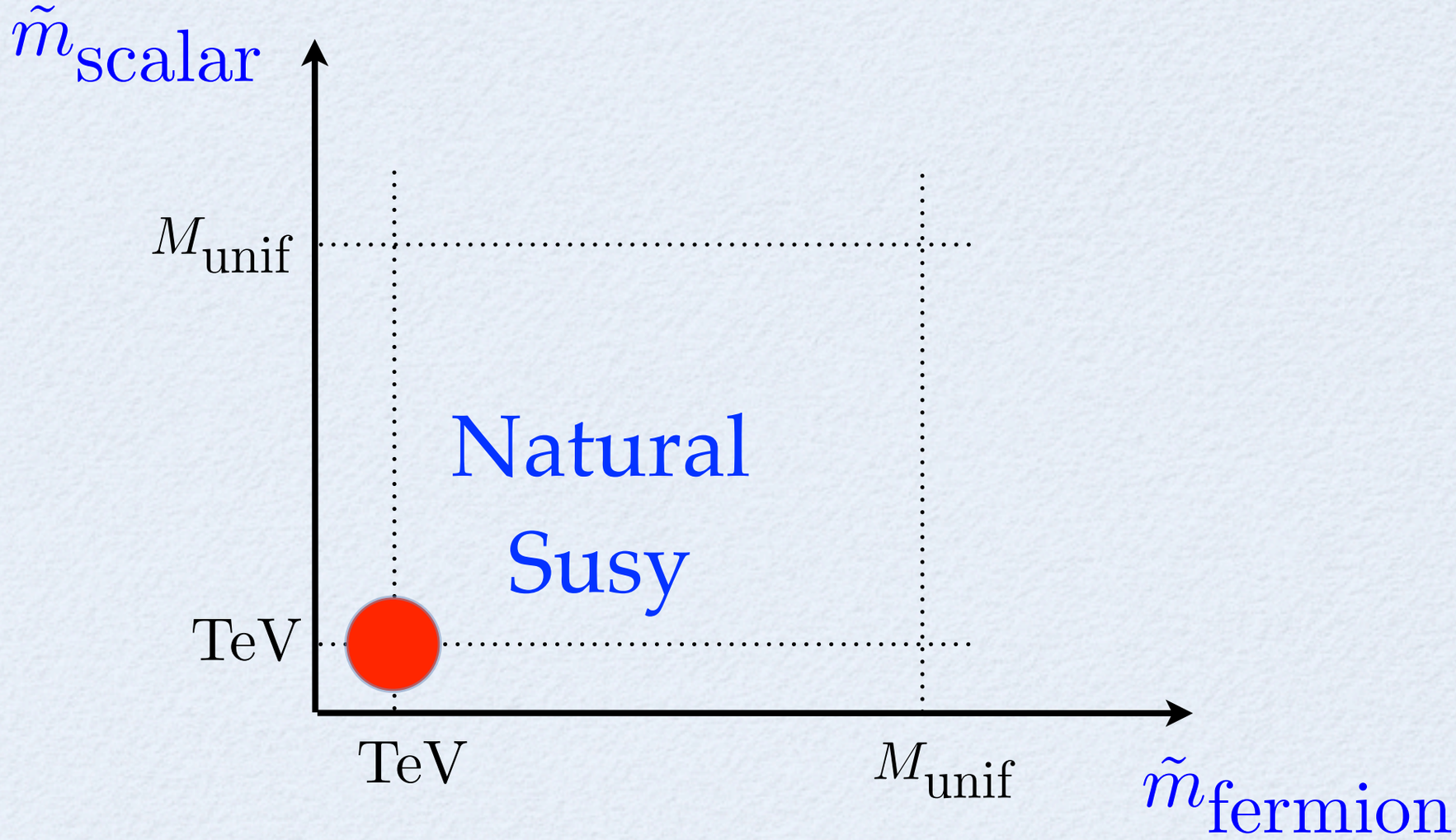
$\tilde{m}$

Multiverse arguments for the scale of superpartners?

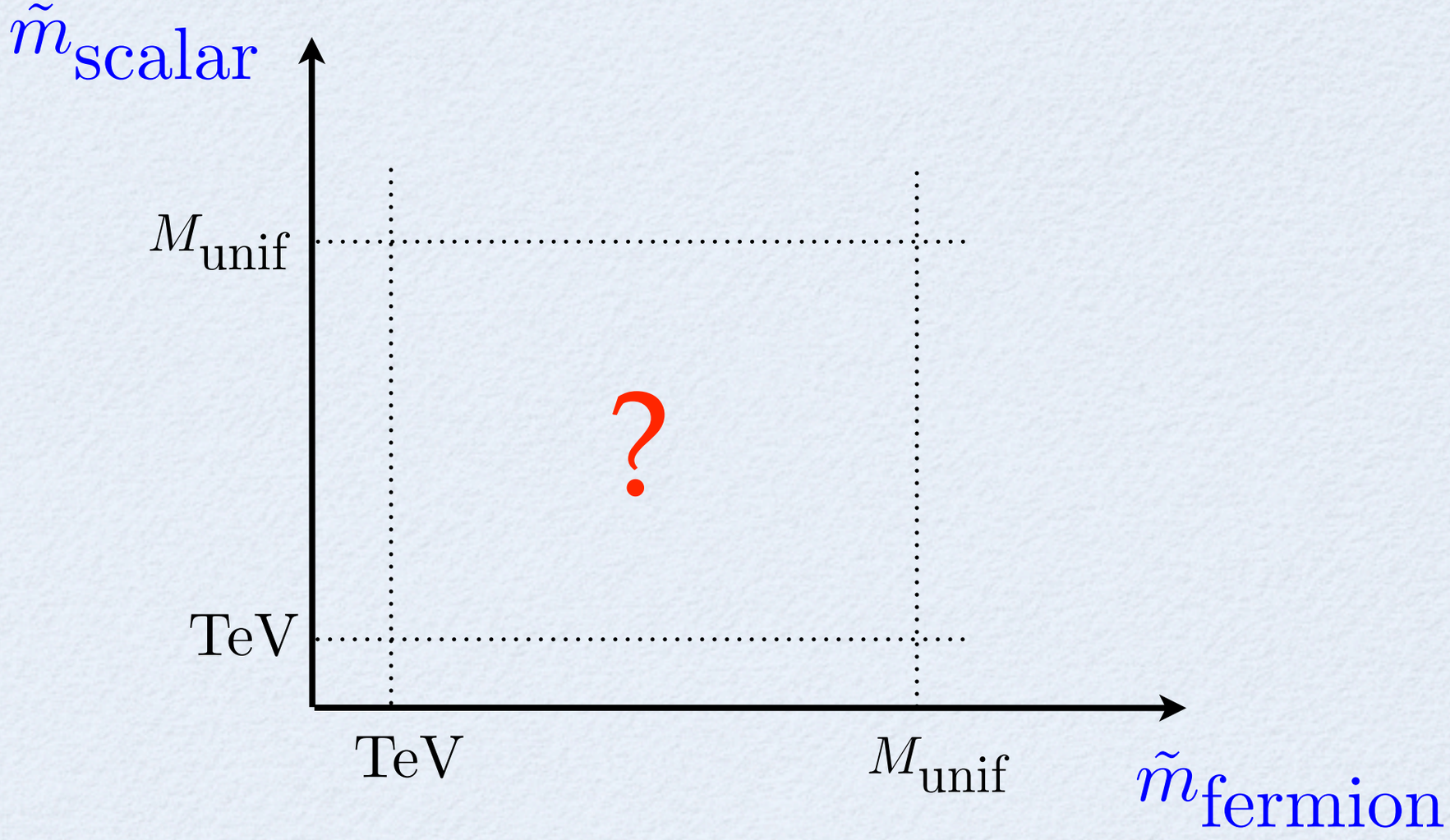
Where are the Superpartners?



Cornered after 30+ years

-- of course, we need to be sure

Without Naturalness

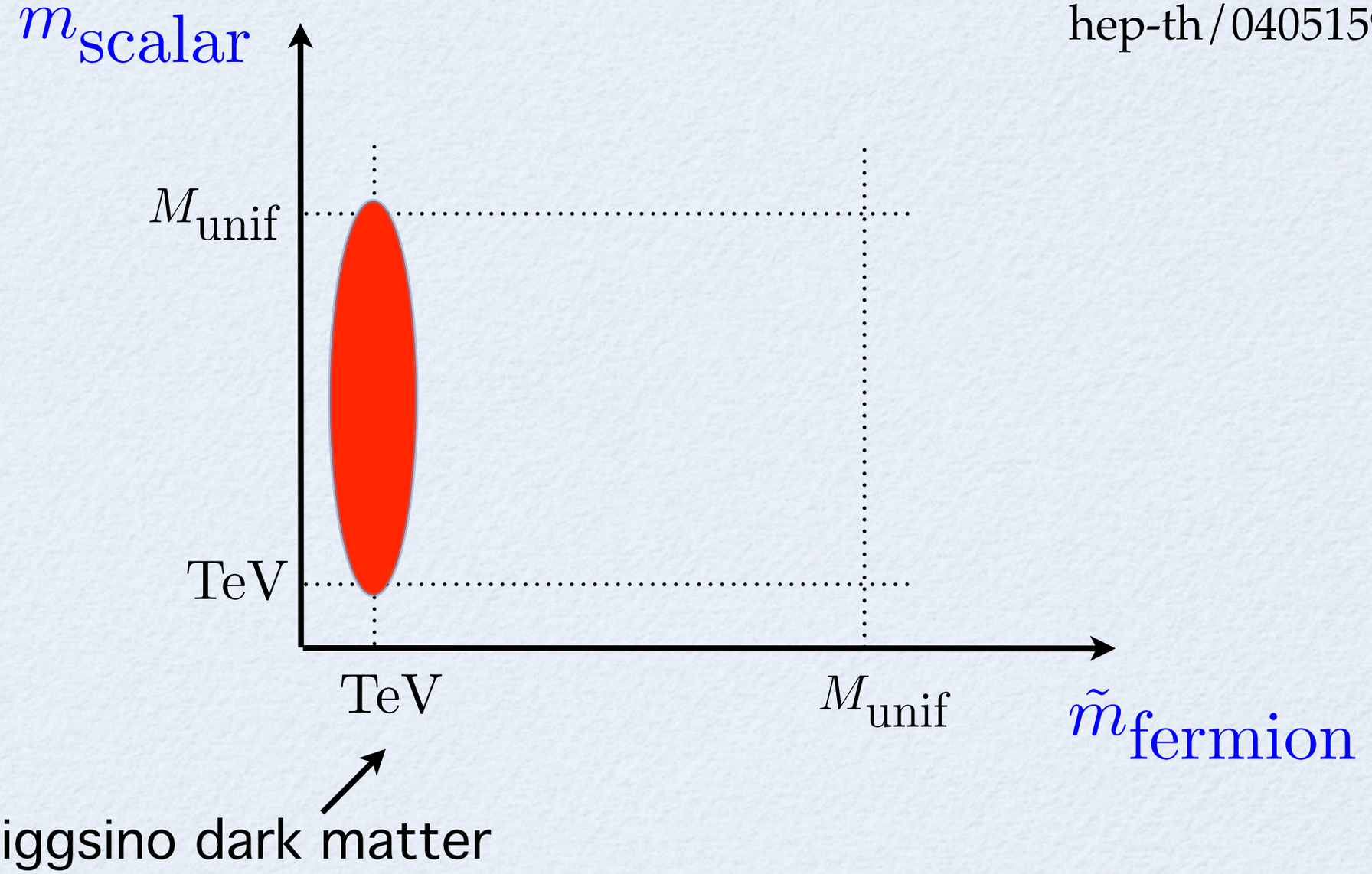


Where are the Superpartners?

Split SUSY

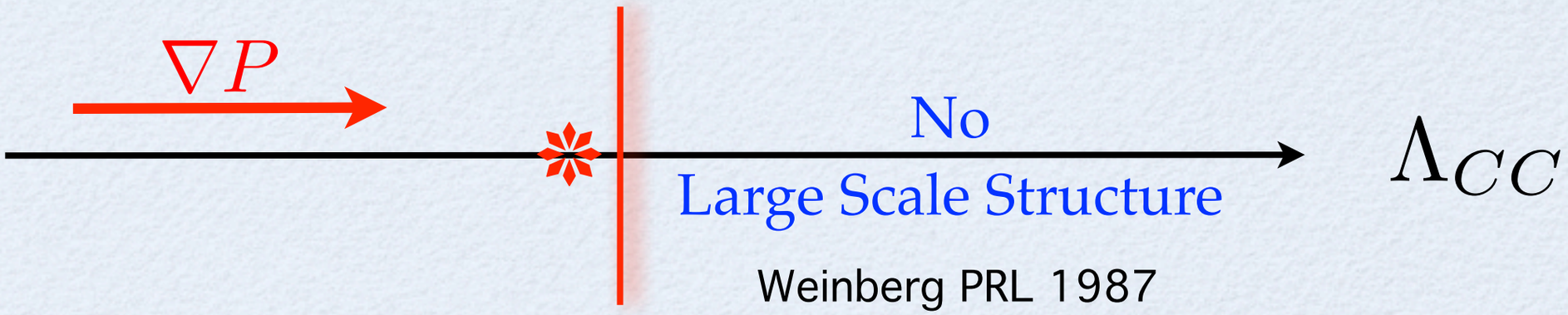
Pioneered multiverse reasoning in BSM particle physics

Arkani-Hamed, Dimopoulos
hep-th/0405159



Measurements could imply huge fine-tuning of weak scale

Anthropics for Λ_{CC}



Weinberg PRL 1987

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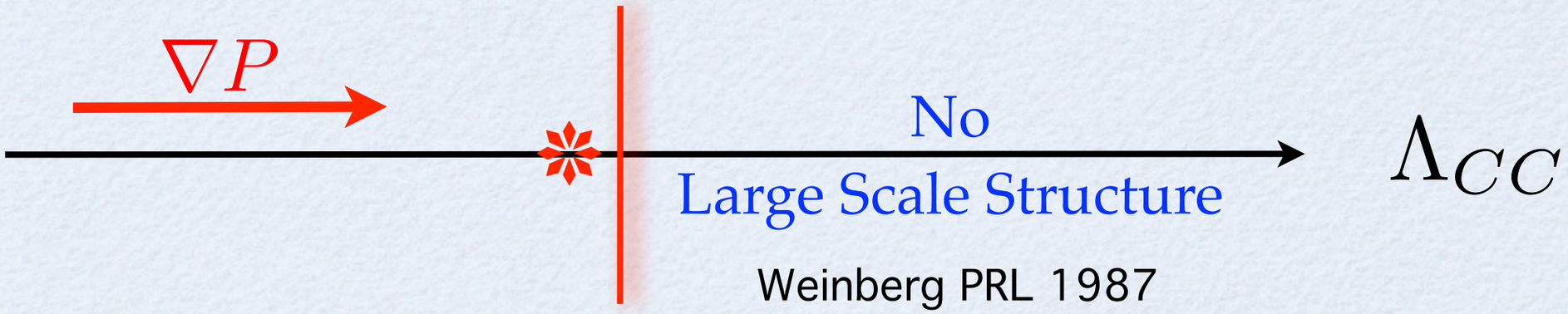
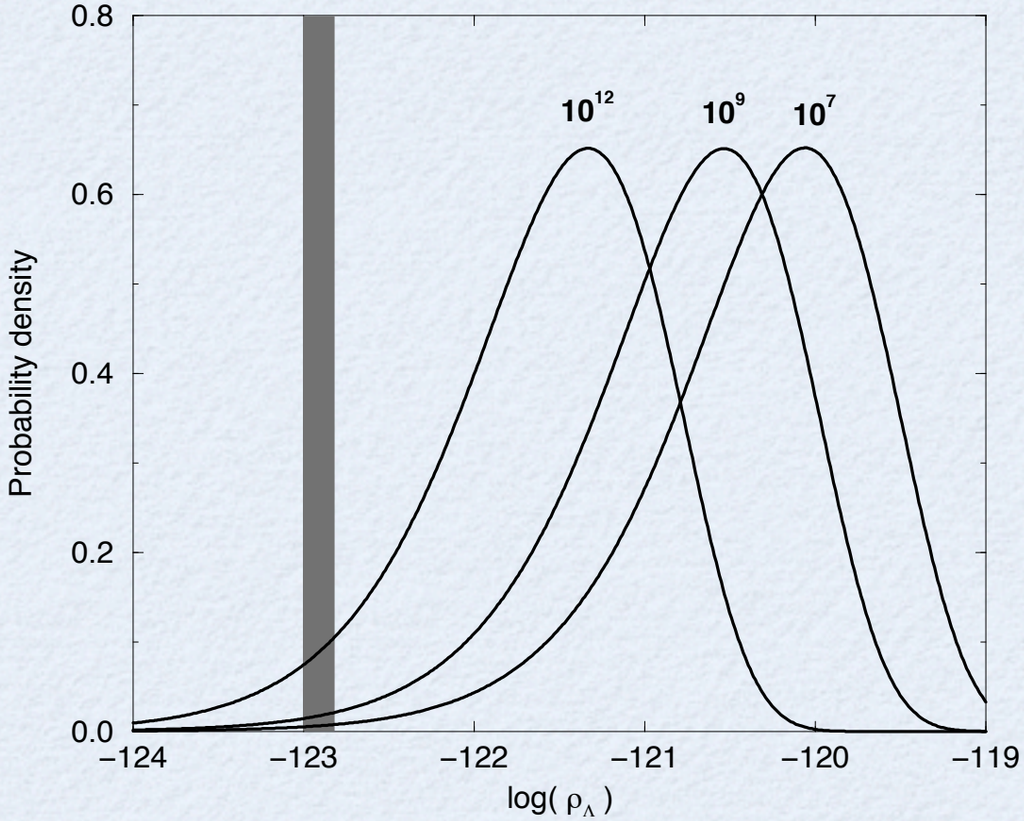


Fraction of virialized baryons



Martell, Shapiro, Weinberg astro-ph/9701099

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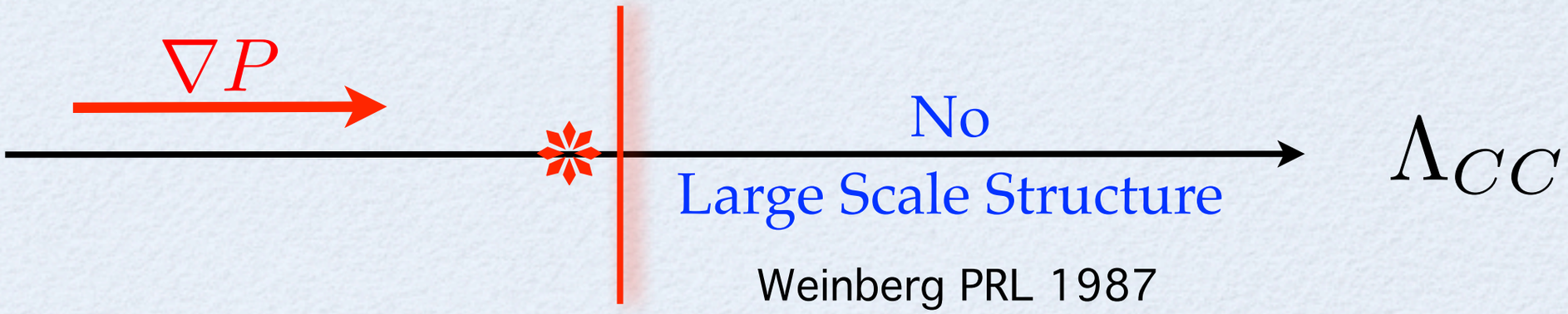

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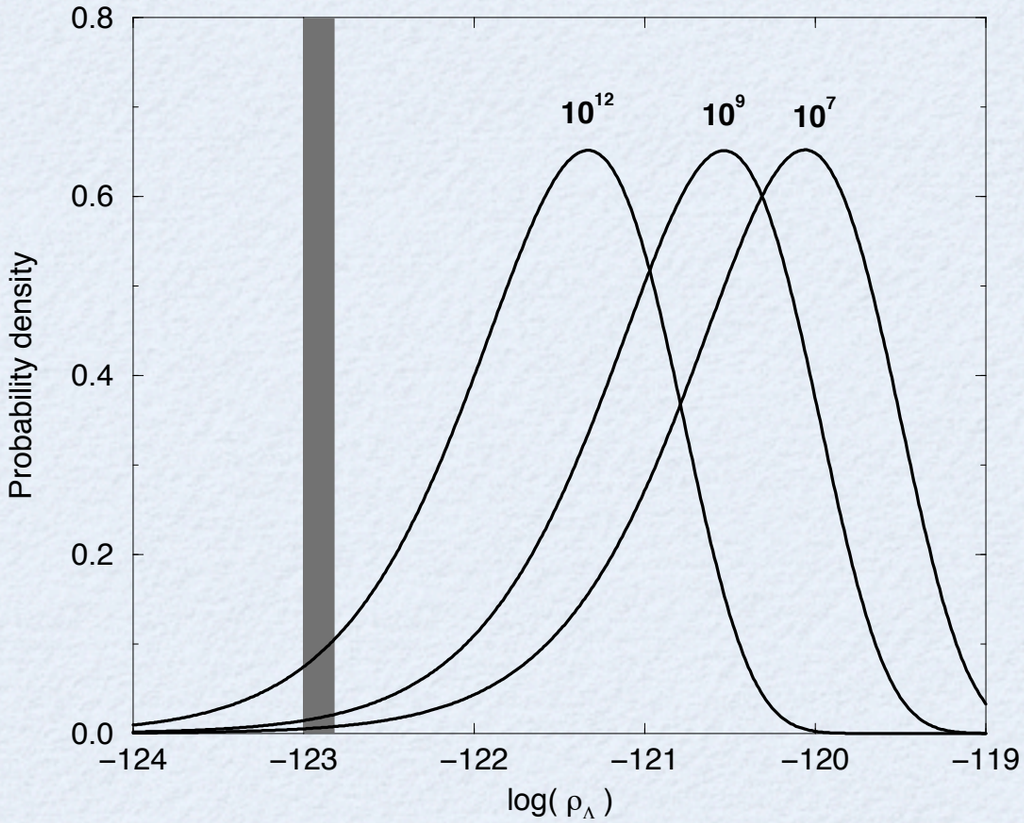
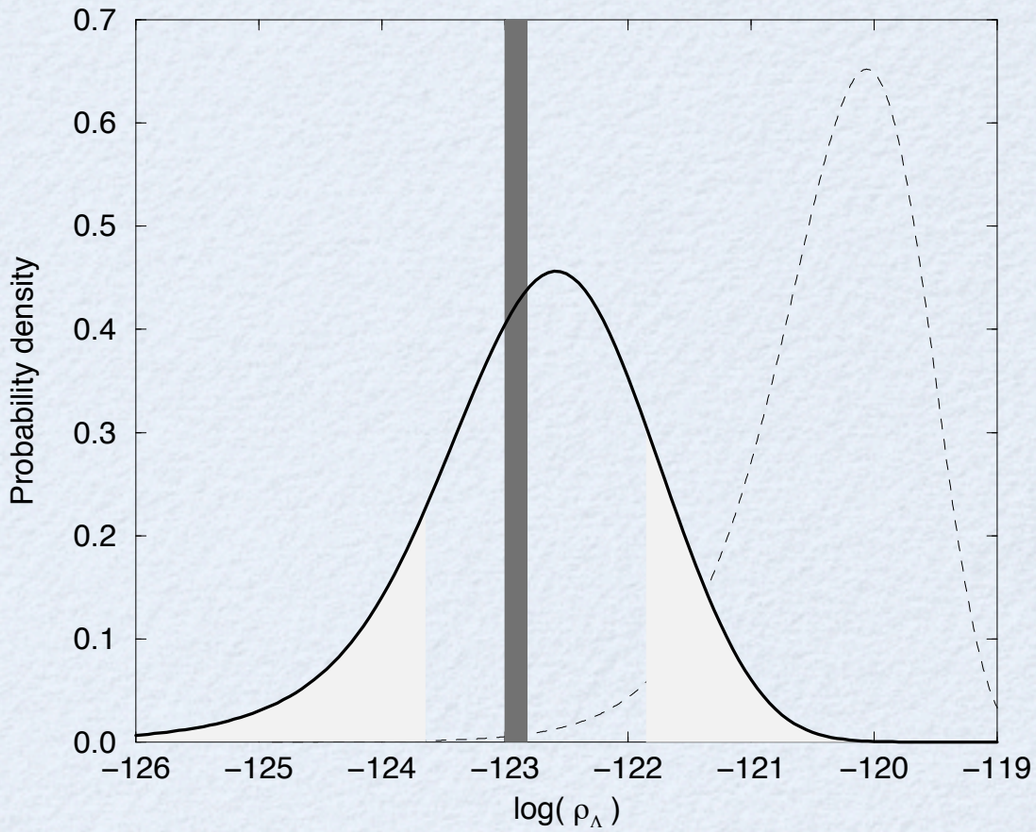


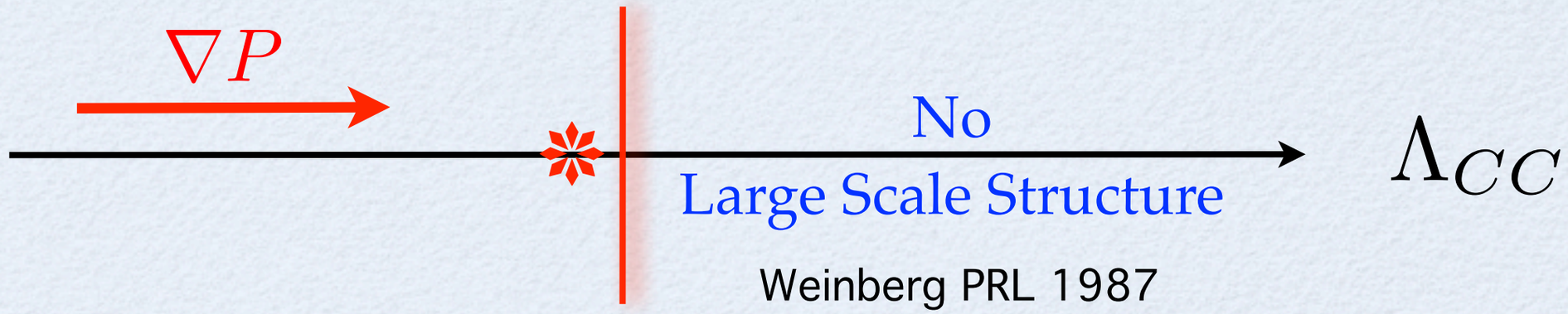
Martell, Shapiro, Weinberg astro-ph/9701099

Causal patch measure

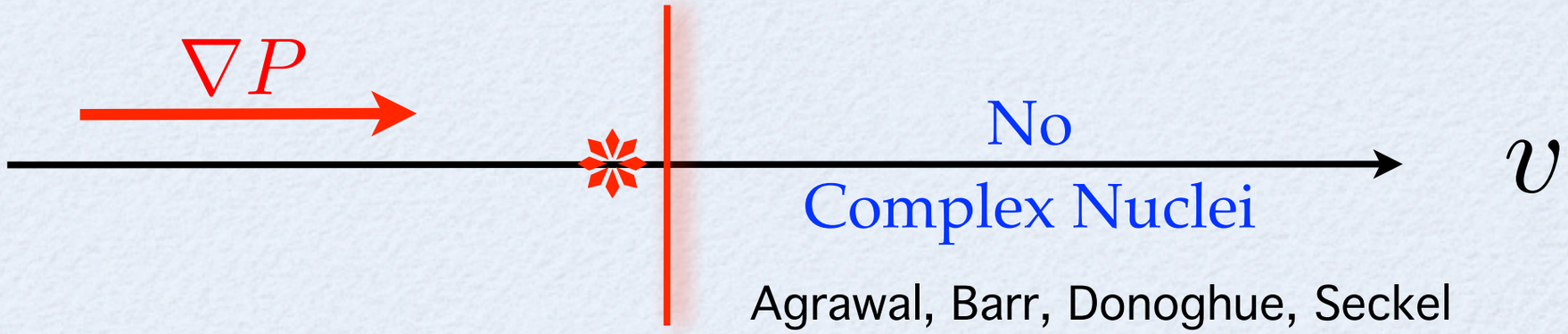


Bousso, Harnik, Kribs,Perez hep-th/0702115

Anthropics for v and Λ_{CC}



Weinberg PRL 1987



Agrawal, Barr, Donoghue, Seckel
ph/9707380

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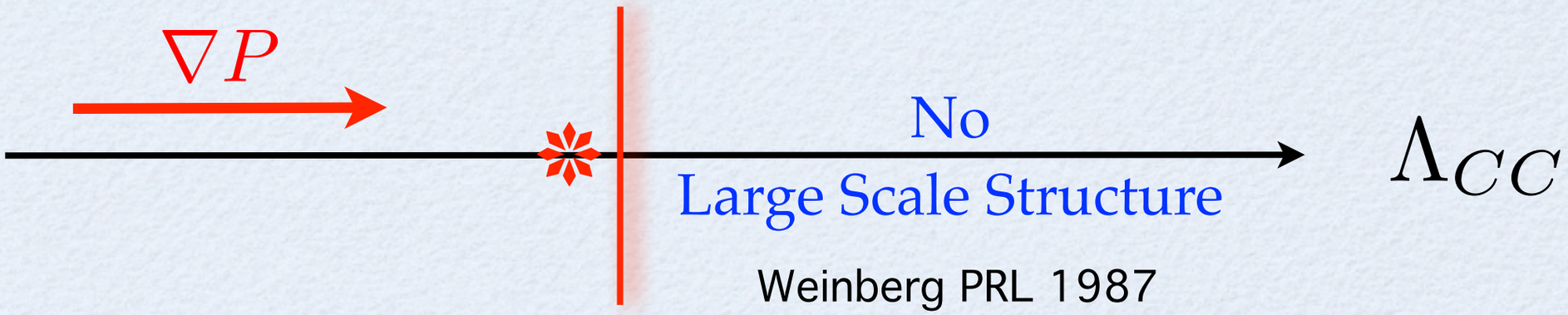

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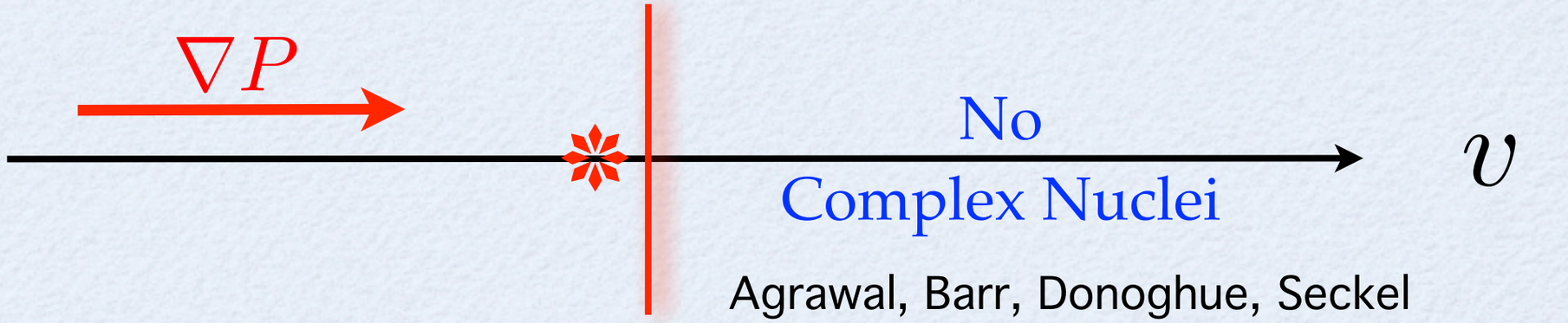

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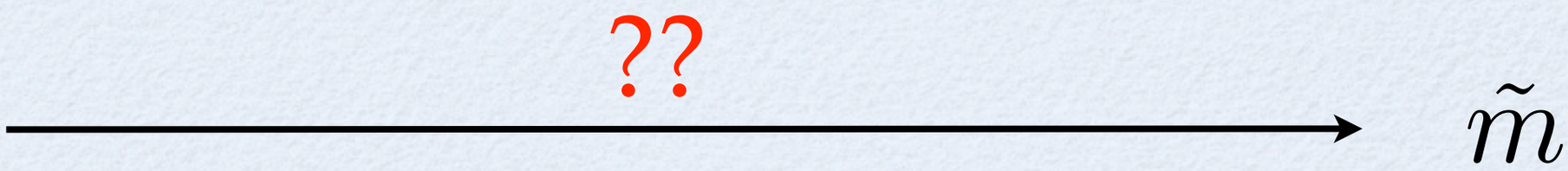


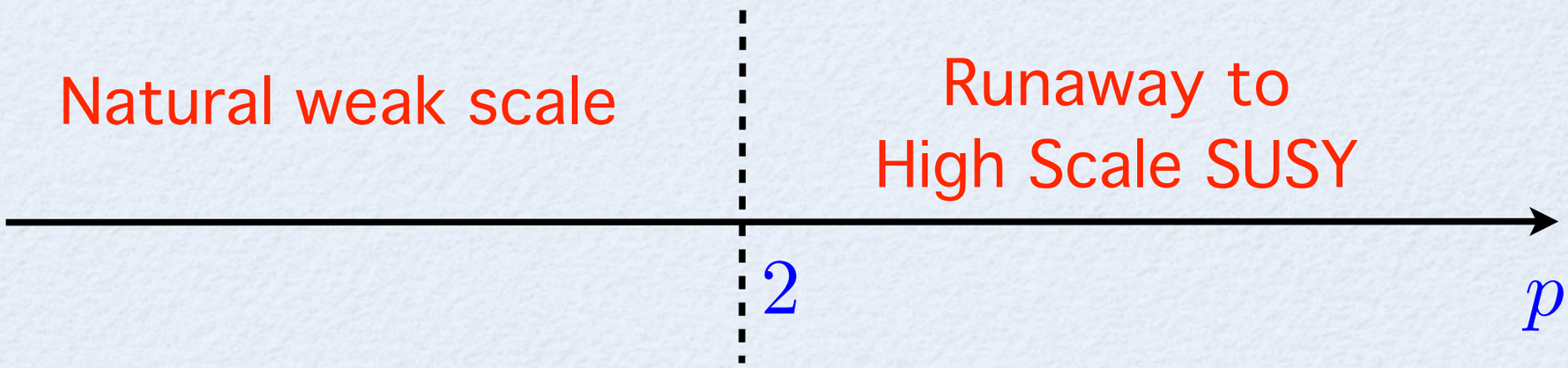
Scanning SUSY Breaking

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

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

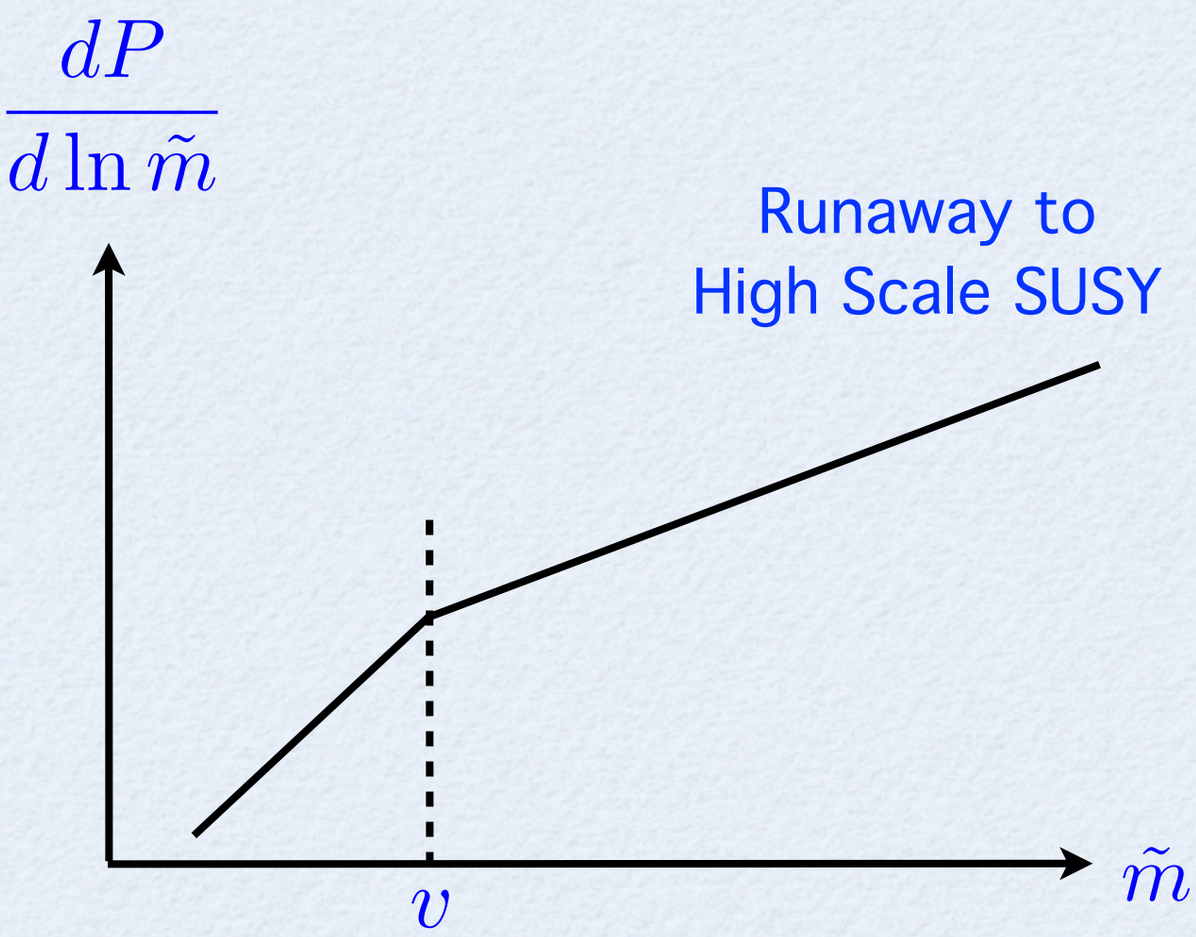


1. High Scale SUSY

Hall, Nomura 0910.2235

Runaway to High Scale SUSY

$$p > 2$$



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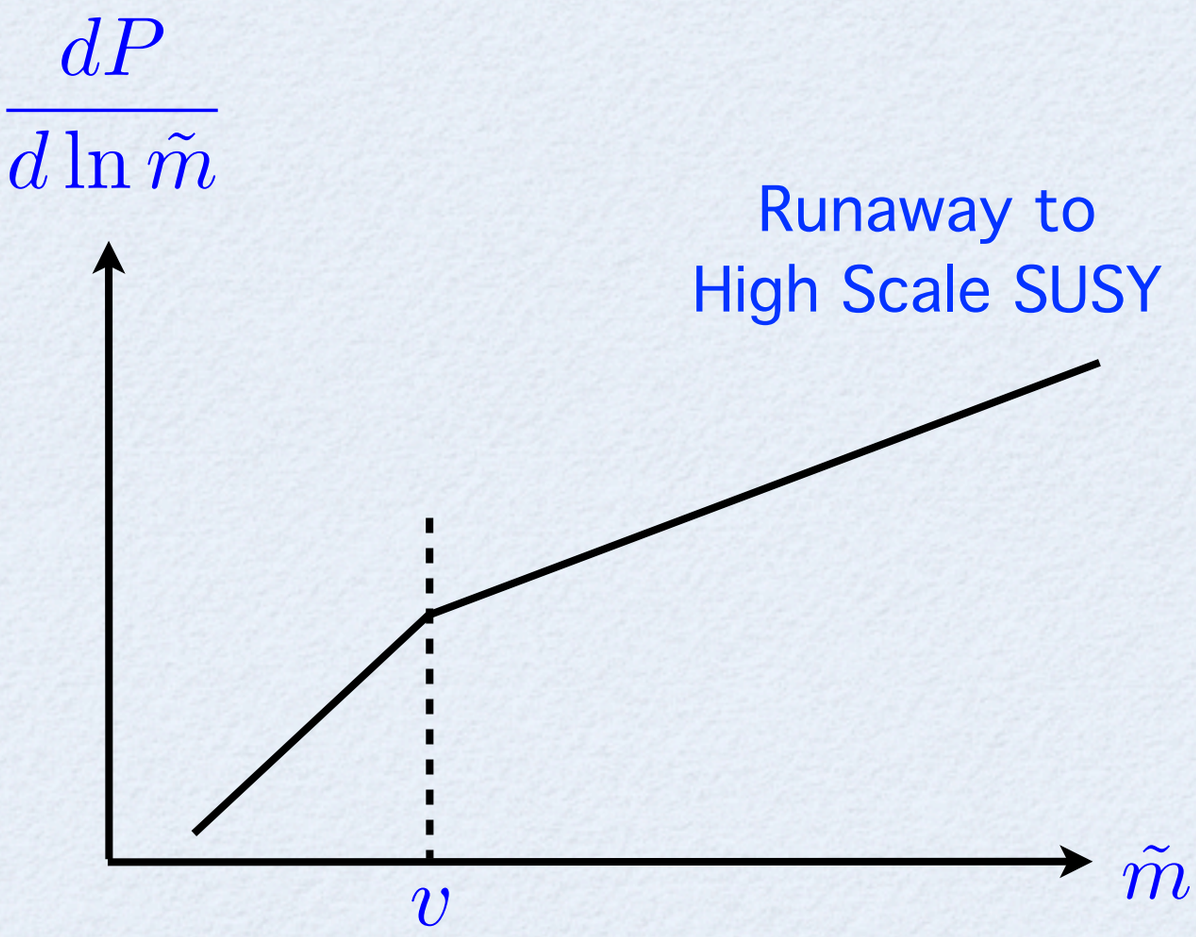
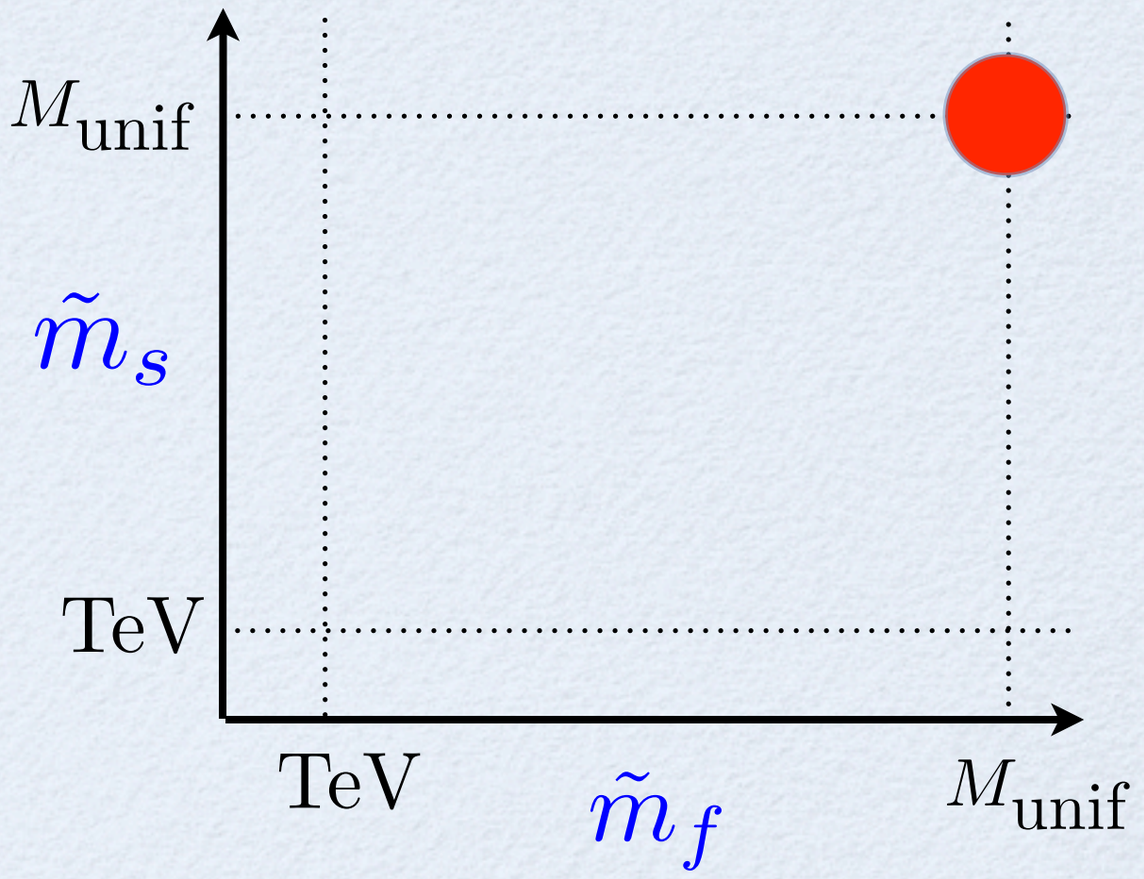
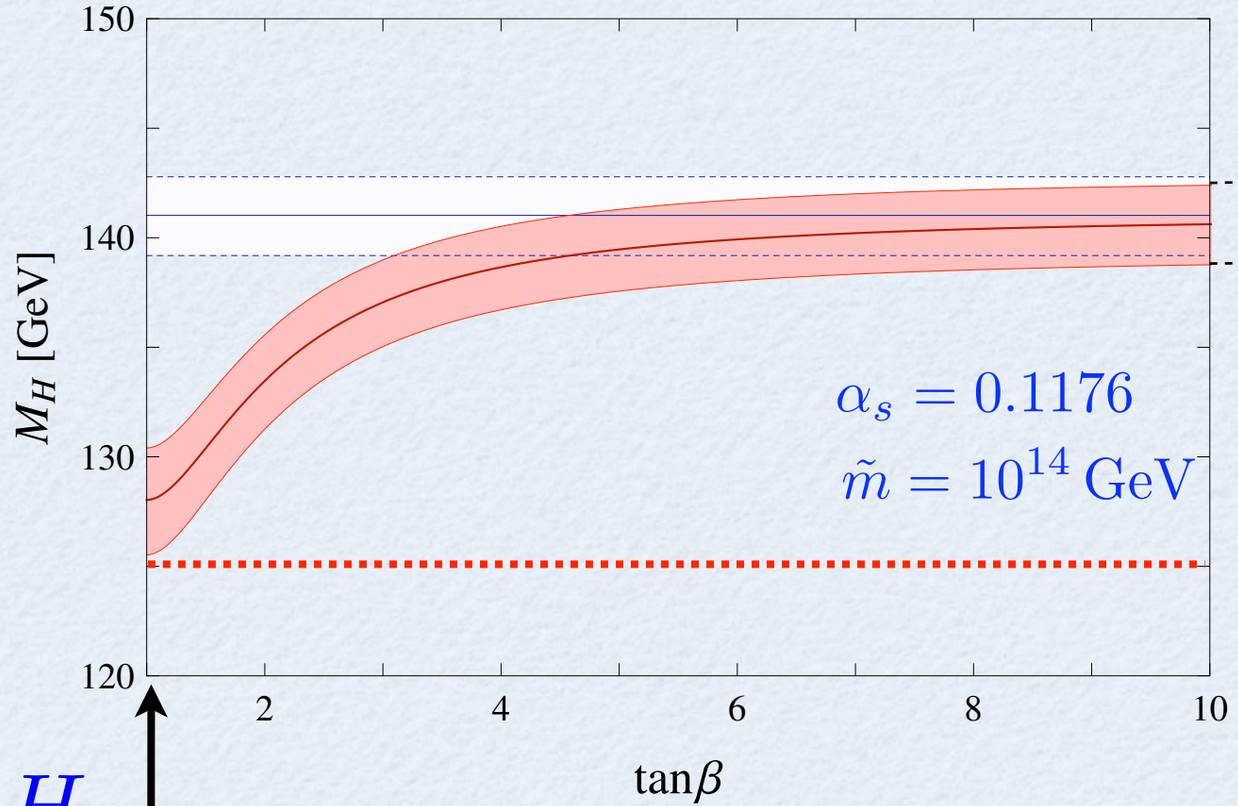




Higgs Mass Prediction

Hall, Nomura 0910.2235



$H_u \leftrightarrow H_d$

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

m_t, α_s

$\tilde{t}$ loop

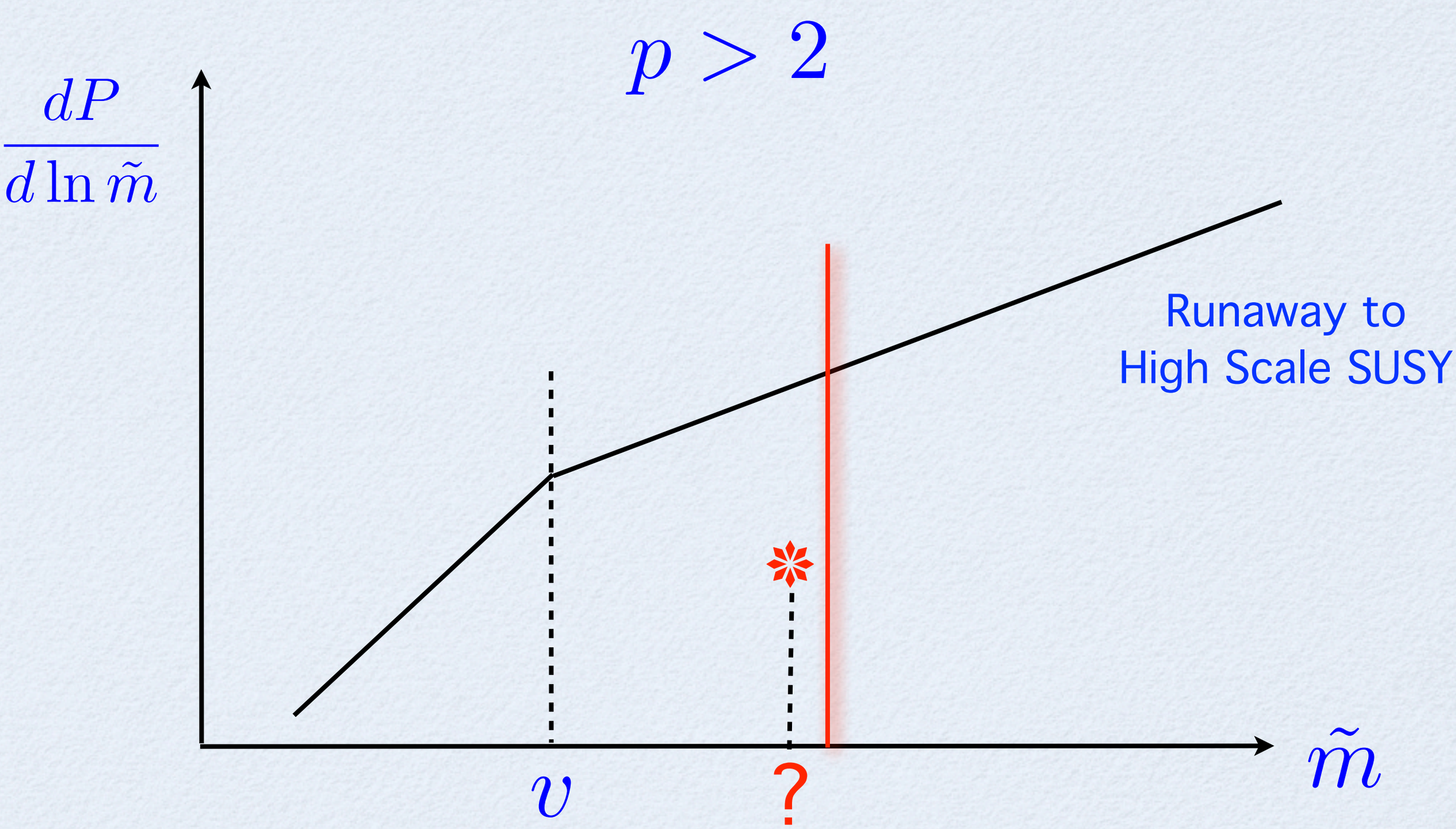
$\tilde{m} = 10^{14\pm2}$ GeV

Axion
Dark Matter

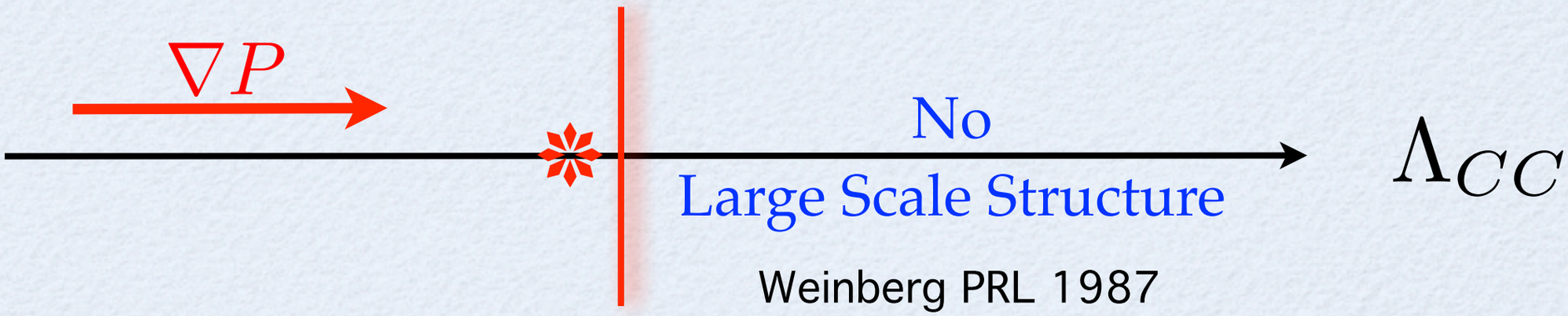
2. Spread SUSY

Hall, Nomura 1111.4519

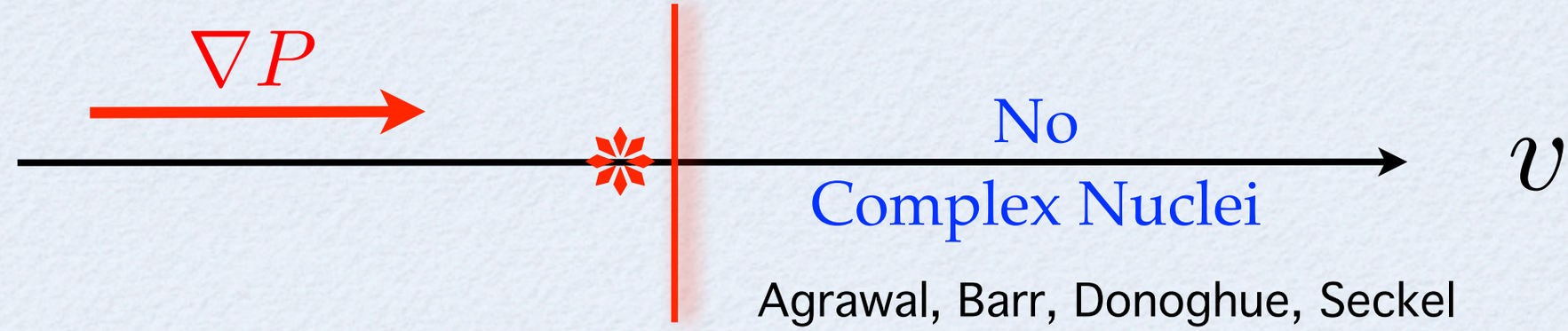
Stabilizing SUSY Breaking at Multi-TeV



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



Weinberg PRL 1987



Agrawal, Barr, Donoghue, Seckel
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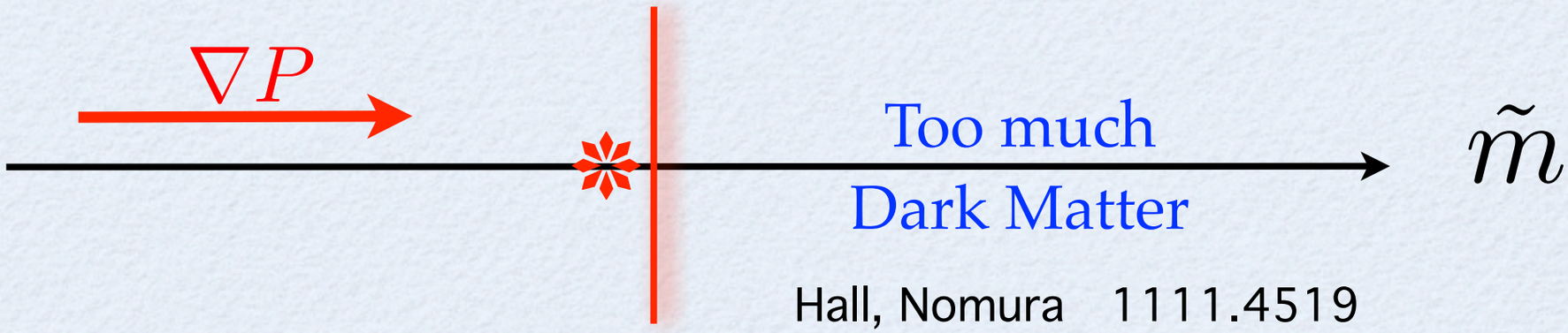

Hall, Nomura 1111.4519

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 { Disks don't fragment
Close encounters

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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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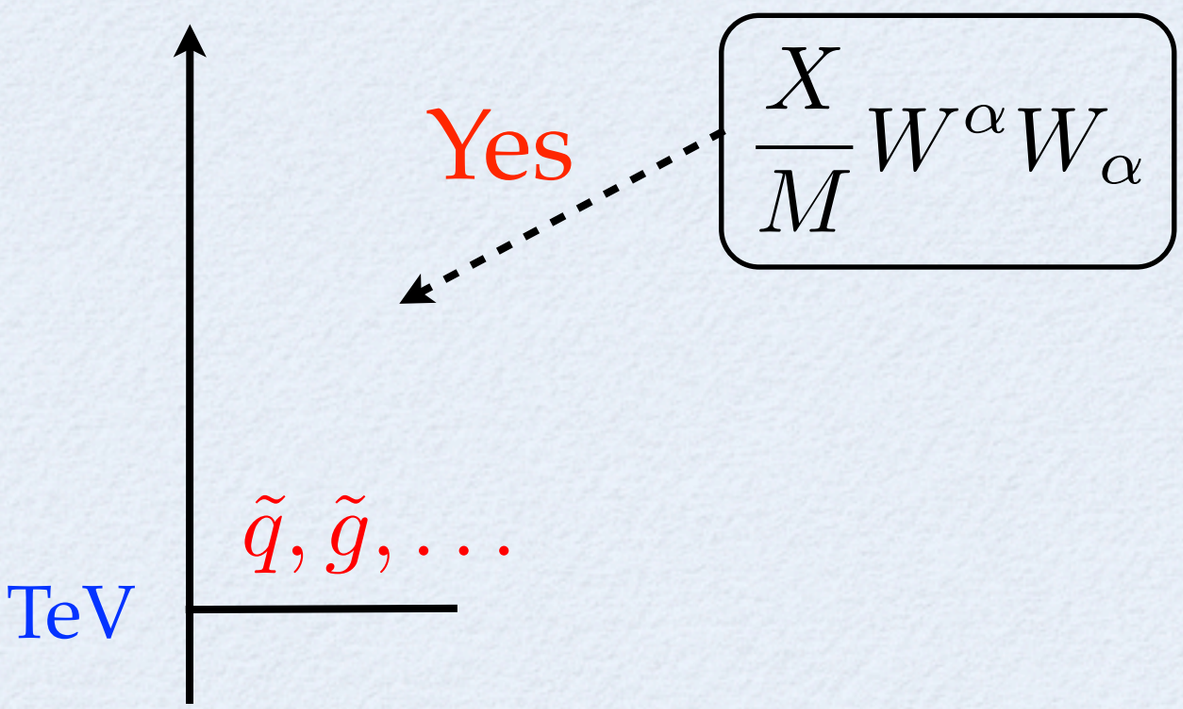

Multiverse MSSM

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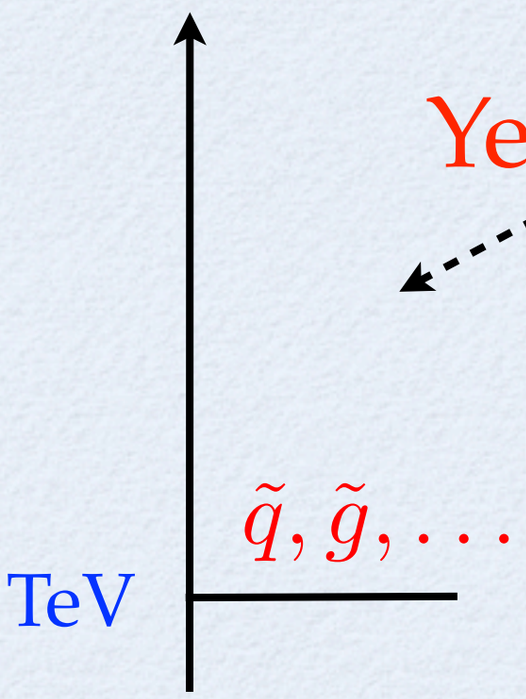
??

$\dfrac{X}{M} W^\alpha W_\alpha$

Yes



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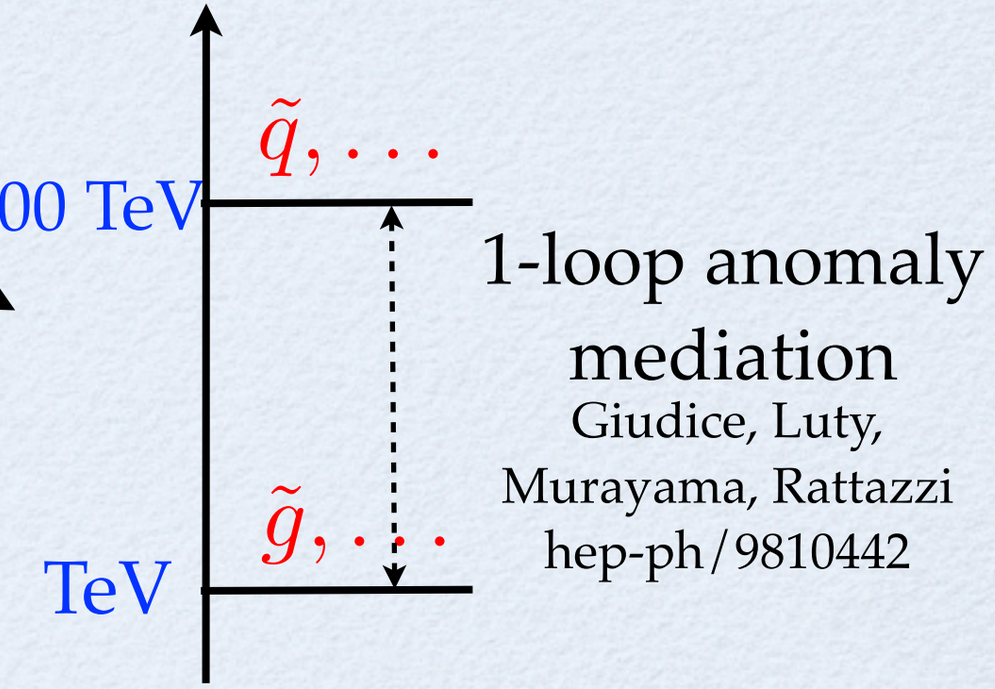

Spread SUSY

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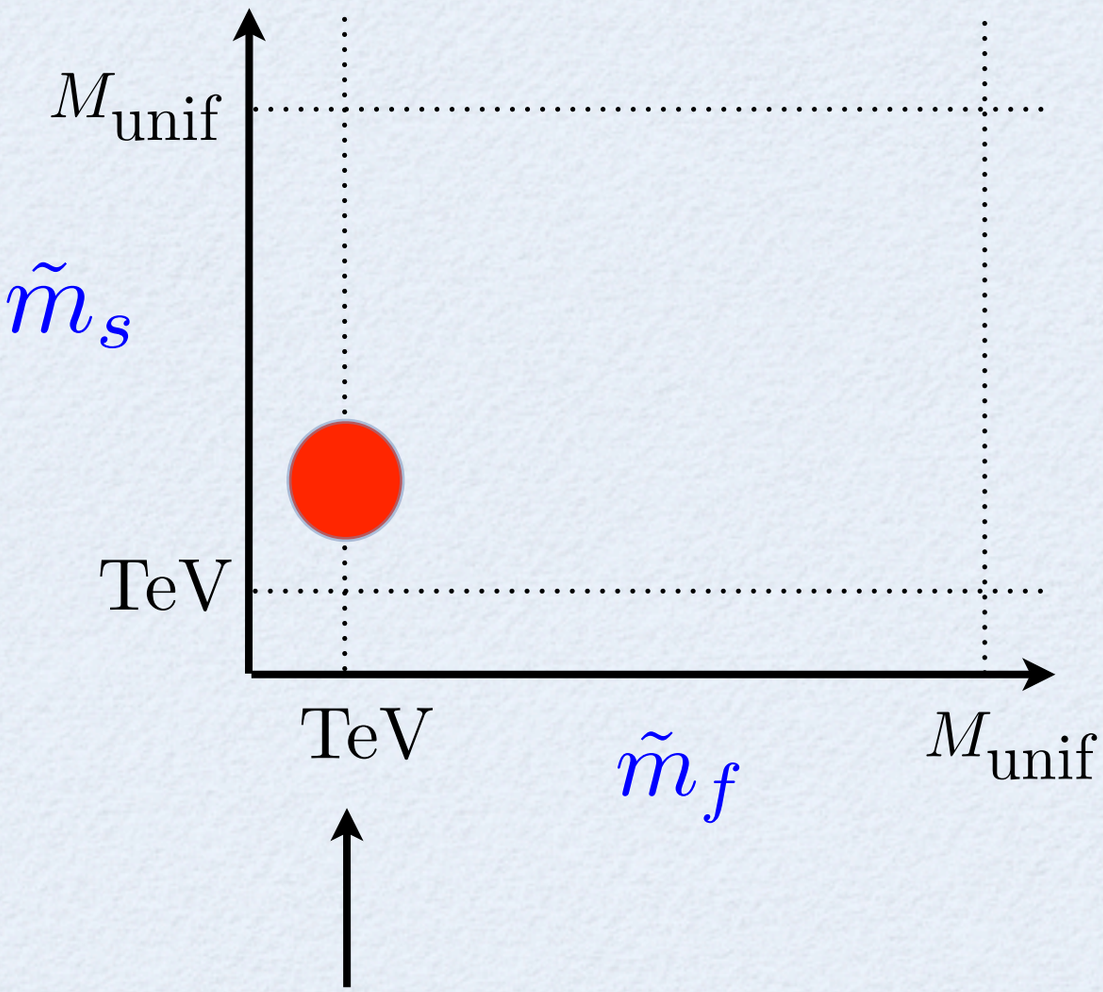
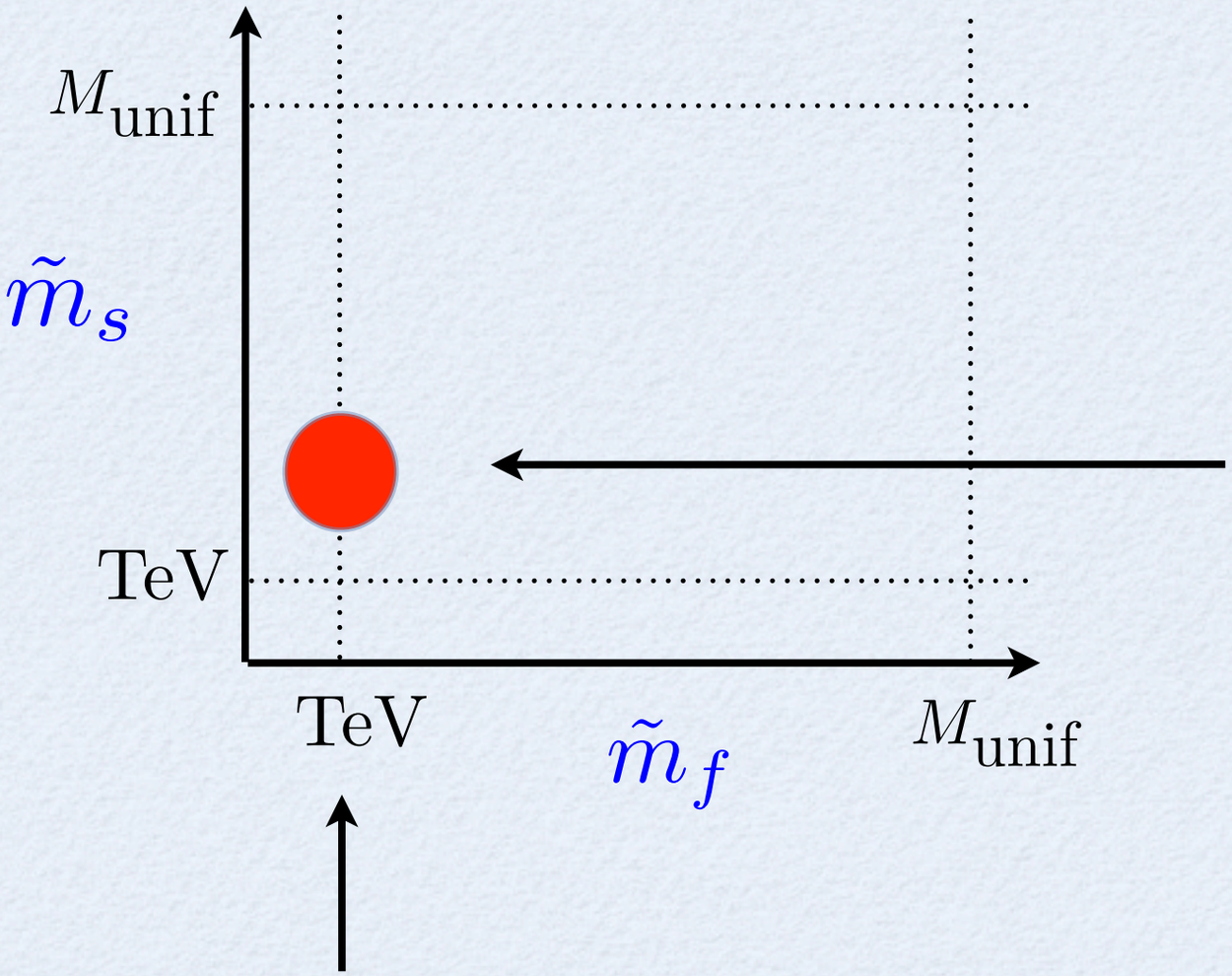

$M_{\rm unif}$
$\tilde{m}_s$
TeV
TeV
$\tilde{m}_f$
$M_{\rm unif}$
Gaugino dark matter

Spread SUSY



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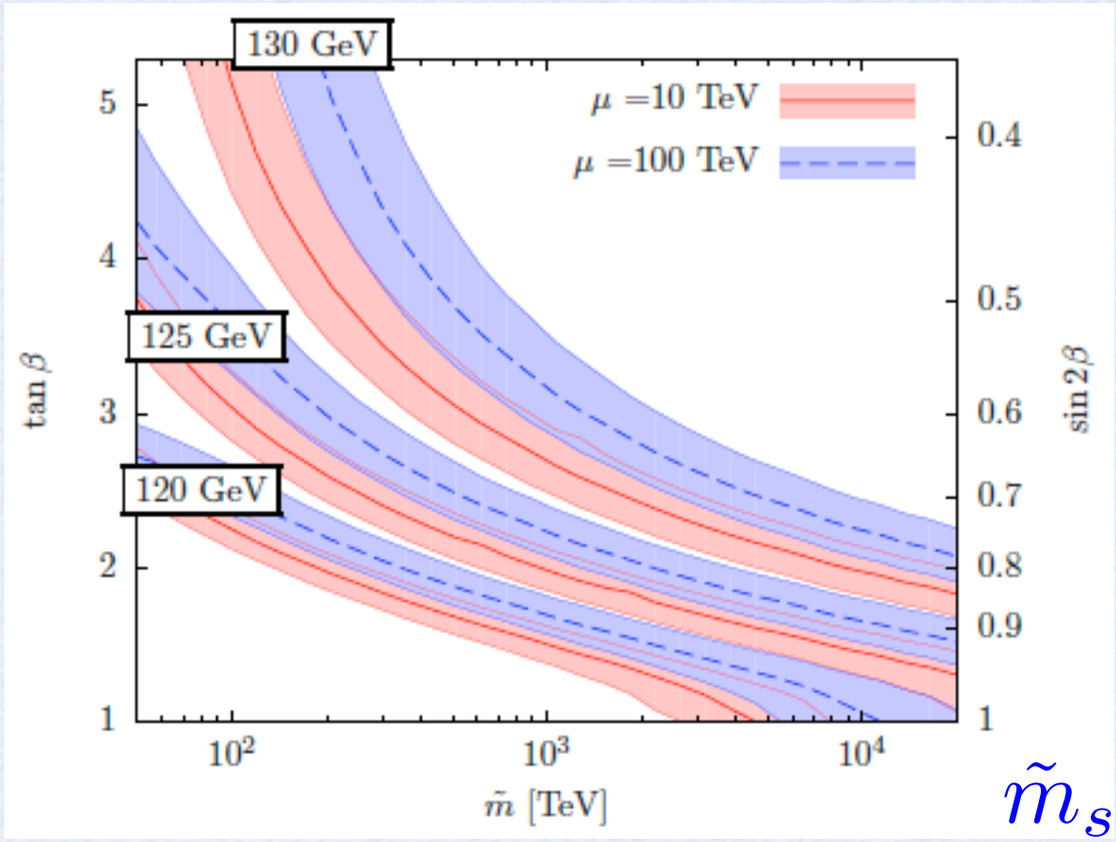
125 GeV Scalar is "effortless"



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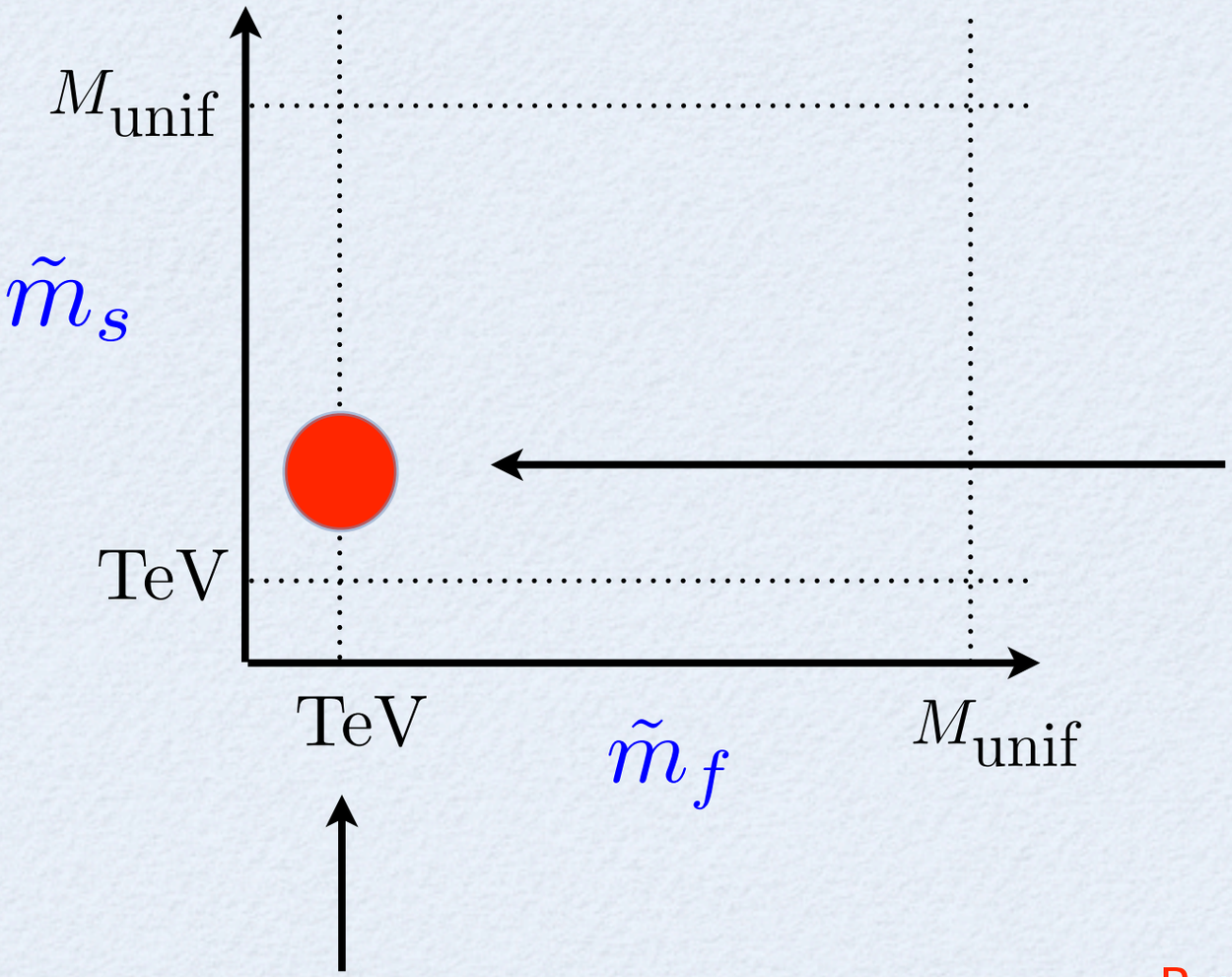

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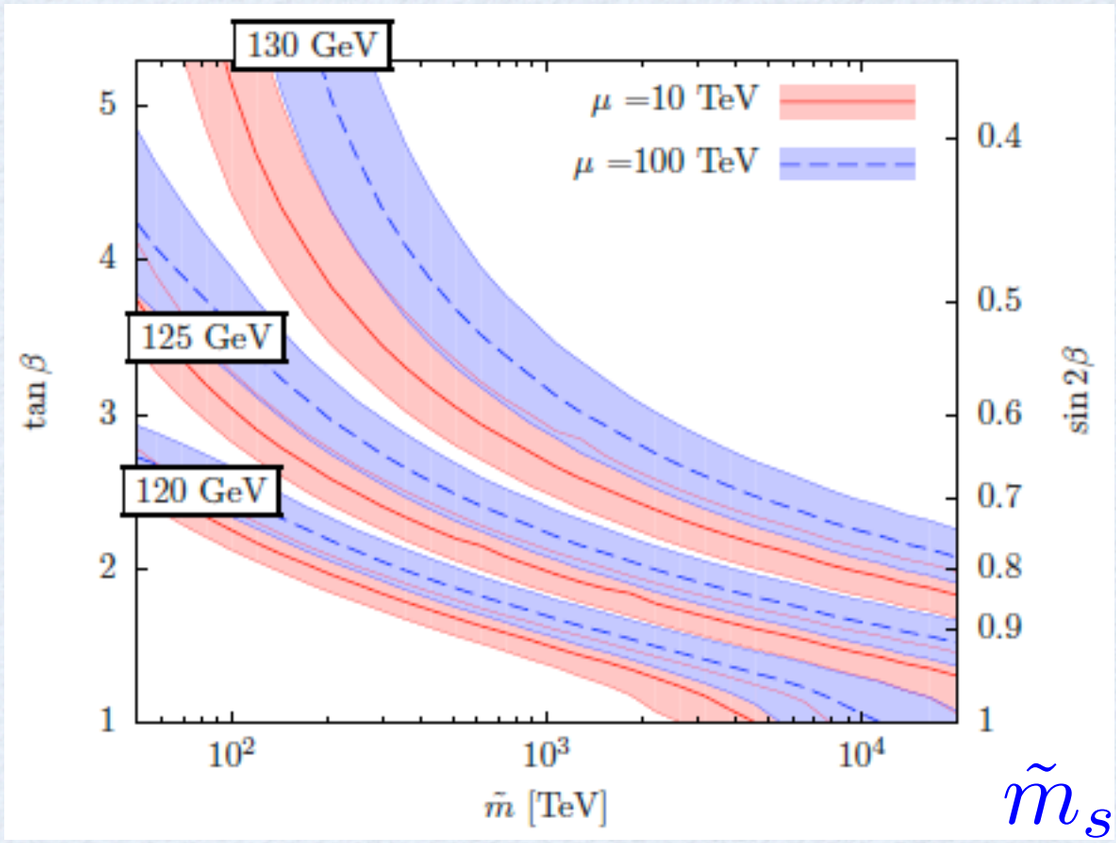
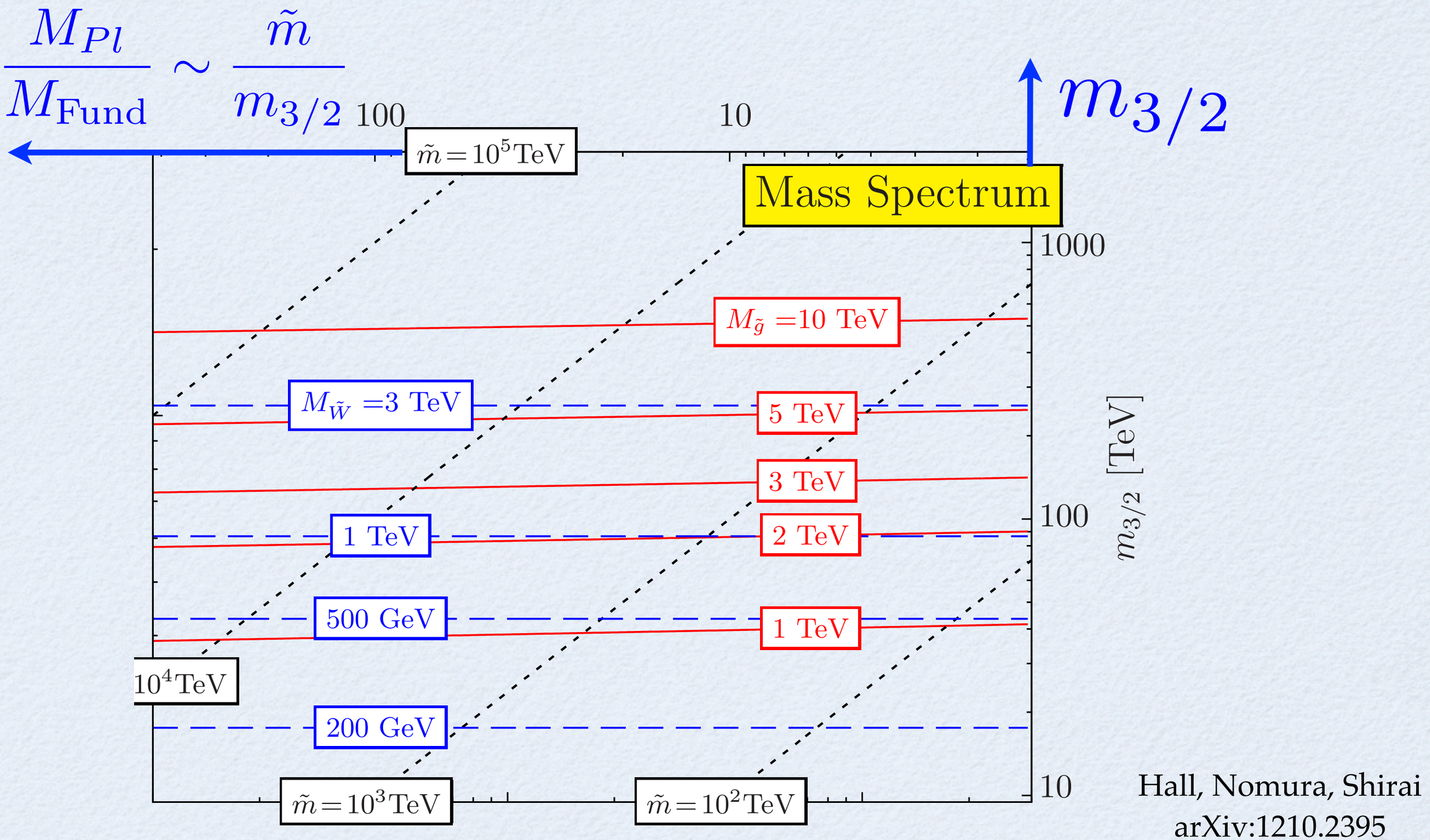


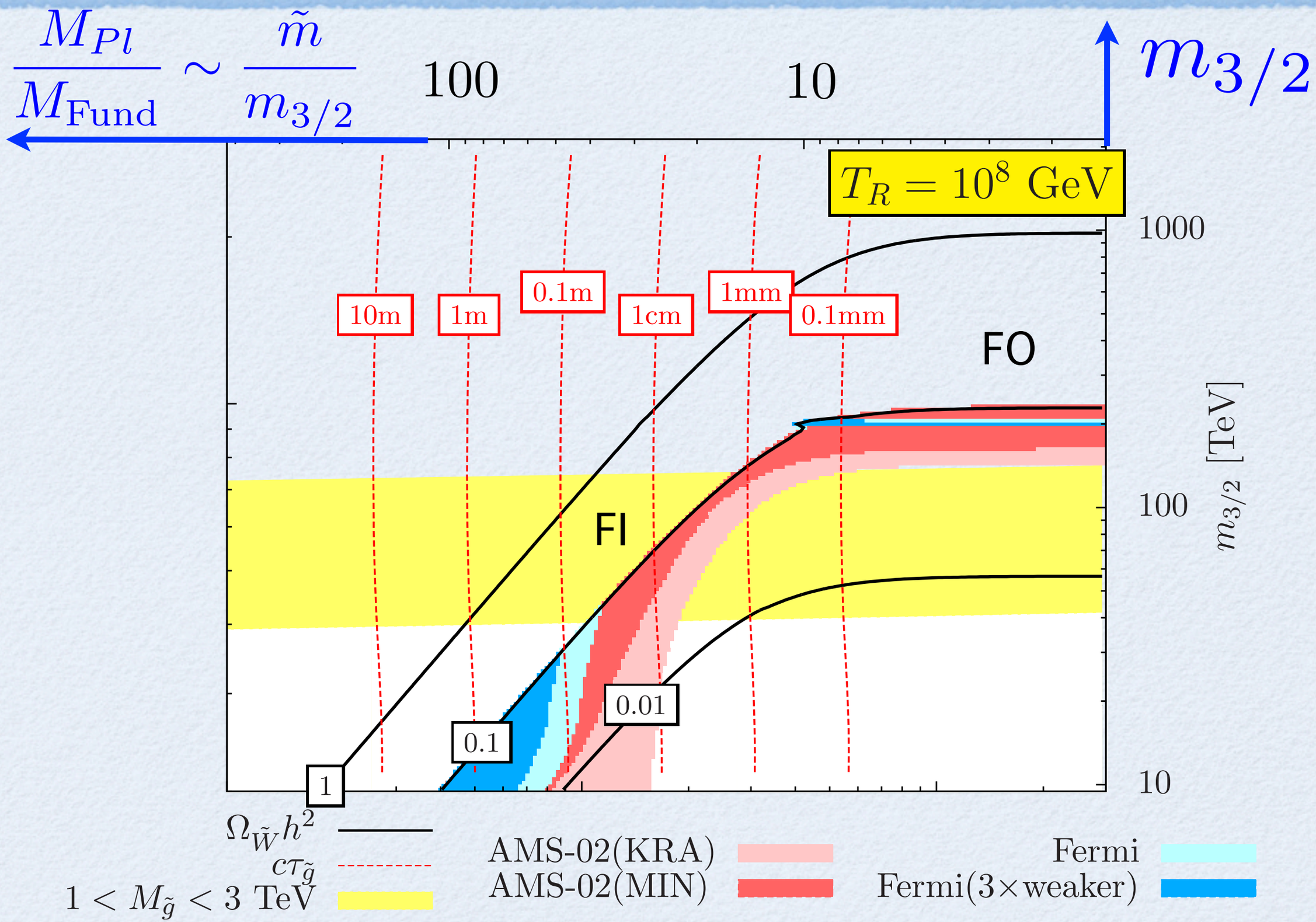
Spread	Hall, Nomura arXiv:1111.4519
Pure Gravity Mediation	Ibe, Yanagida arXiv:1112.2462
Mini-Split	Arvanitaki, Craig, Dimopoulos, Villadoro arXiv:1210.0555
Simply Unnatural	Arkani-Hamed, Gupta, Kaplan, Weiner, Zorawski arXiv:1212.6971

Susy Spectrum



Hall, Nomura, Shirai
arXiv:1210.2395

Dark Matter Abundance

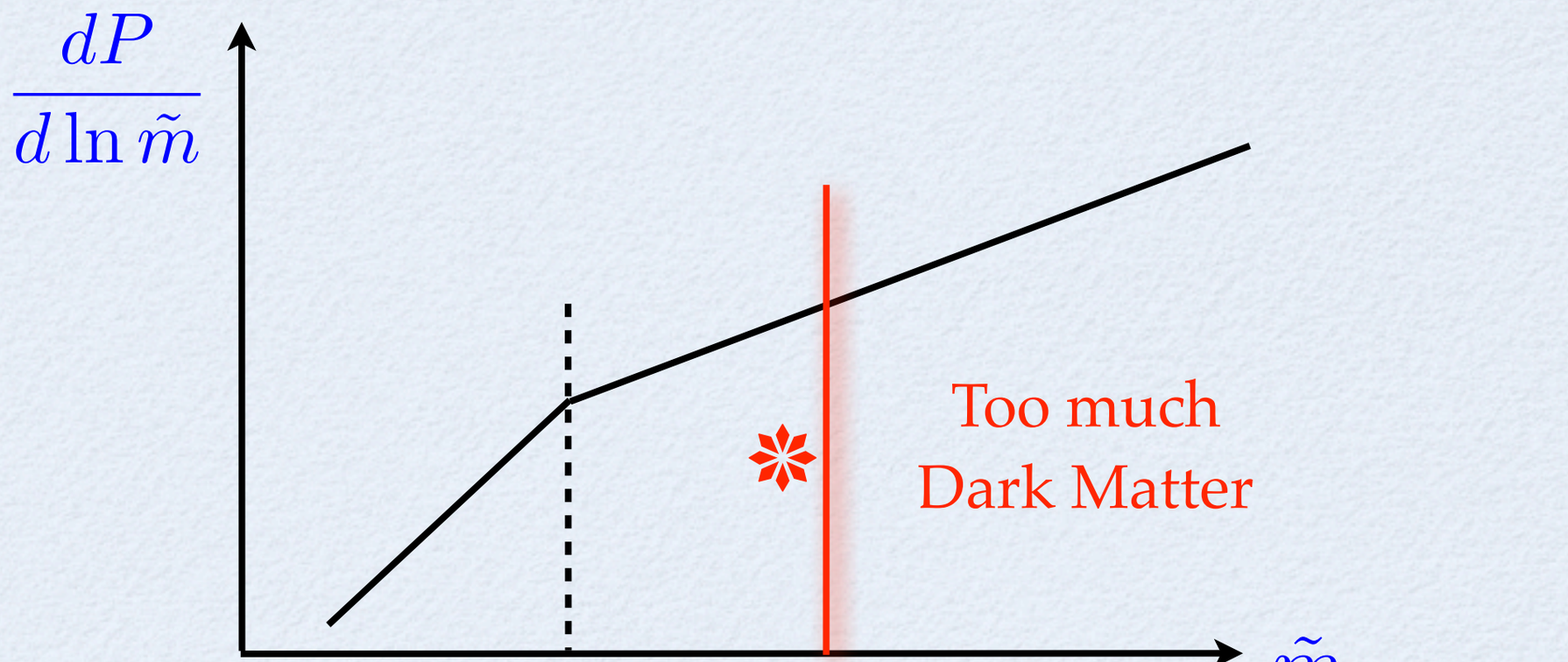


3. TeV Scale Superpartners with

$$\rho_D \sim \rho_B$$

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

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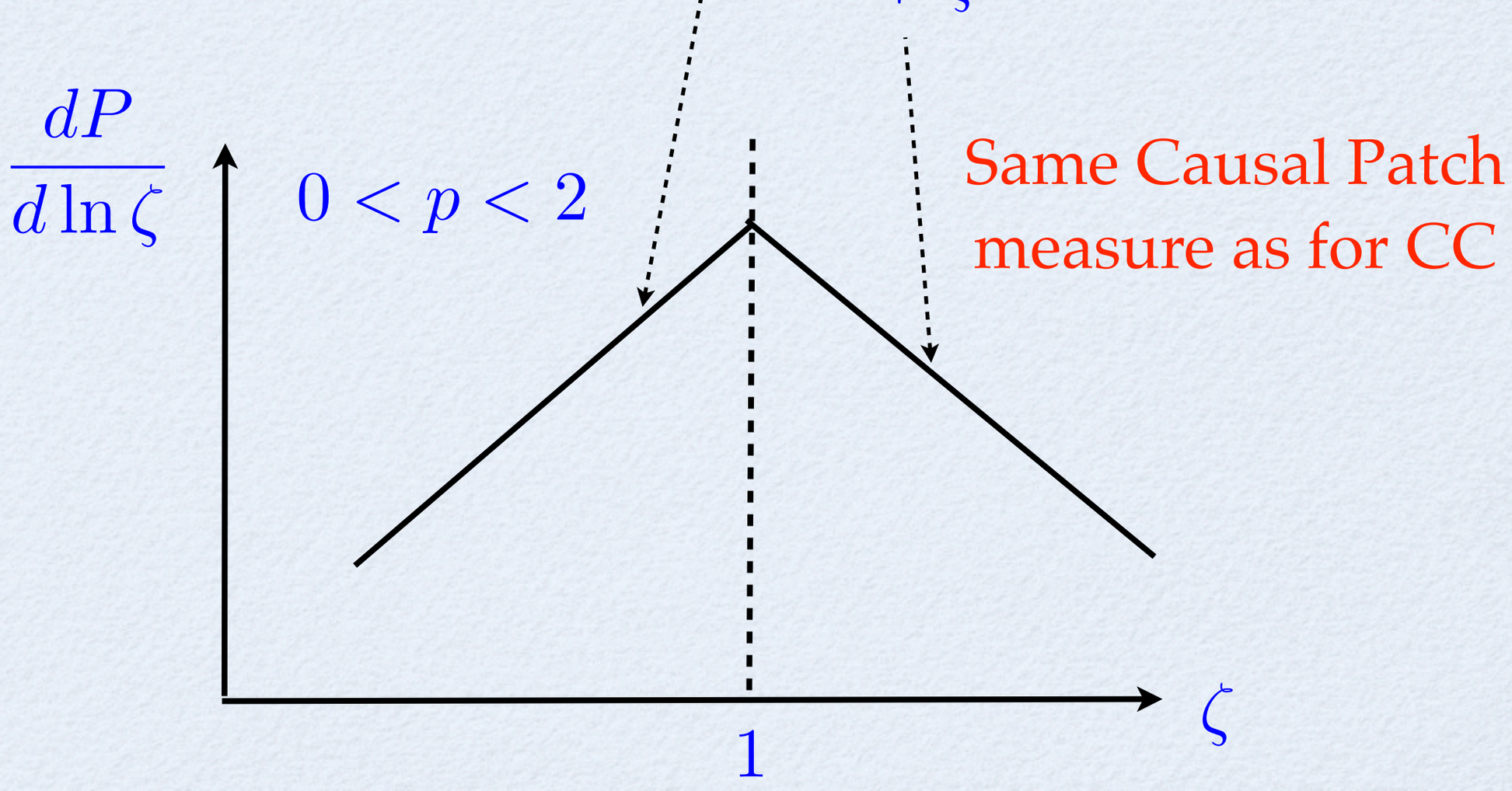
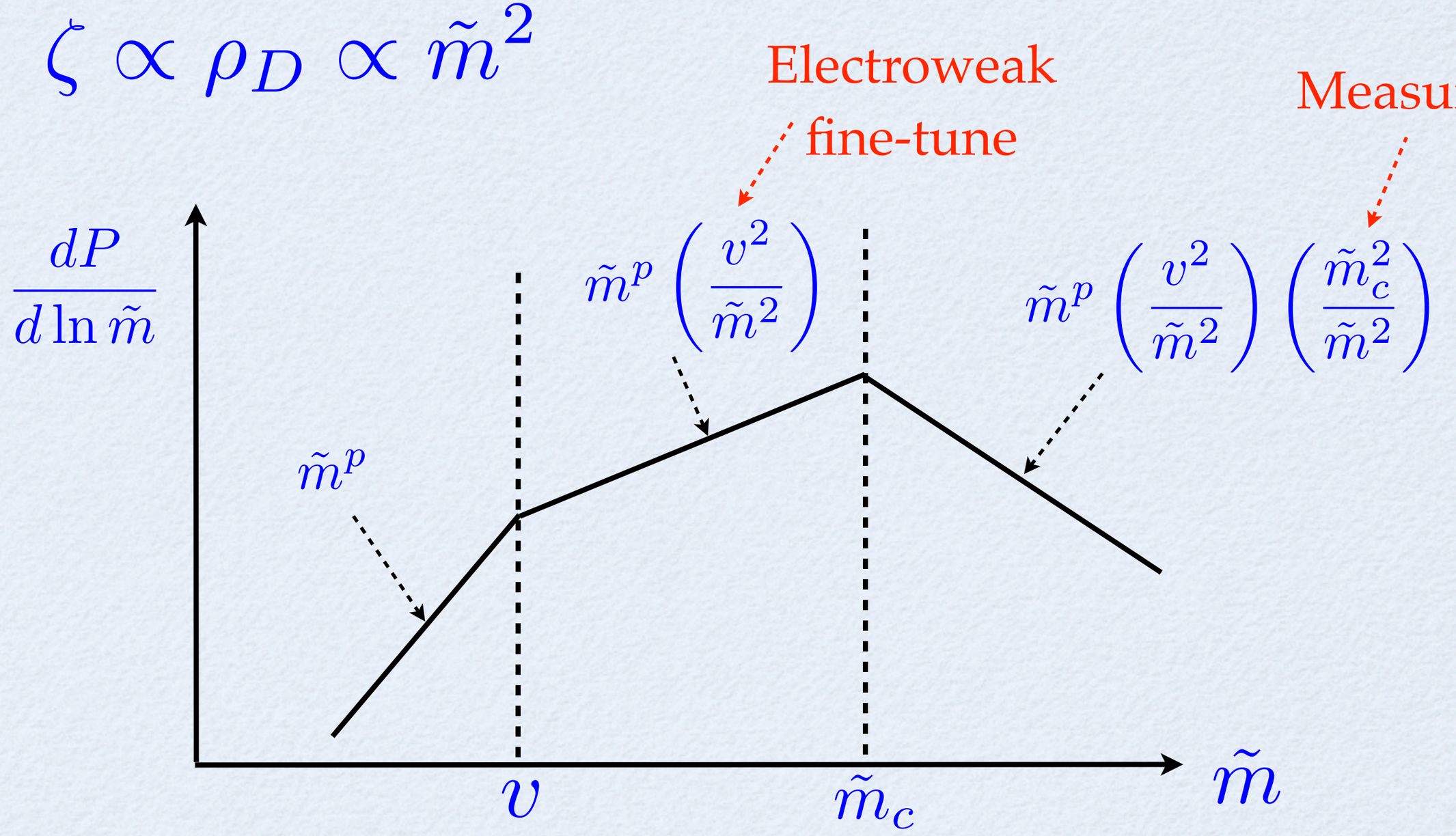
A multiverse explanation: $\quad dP \sim \zeta^{p/2} \dfrac{1}{1+\zeta} d\ln\zeta$



LSP Dark Matter from Freeze-Out

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



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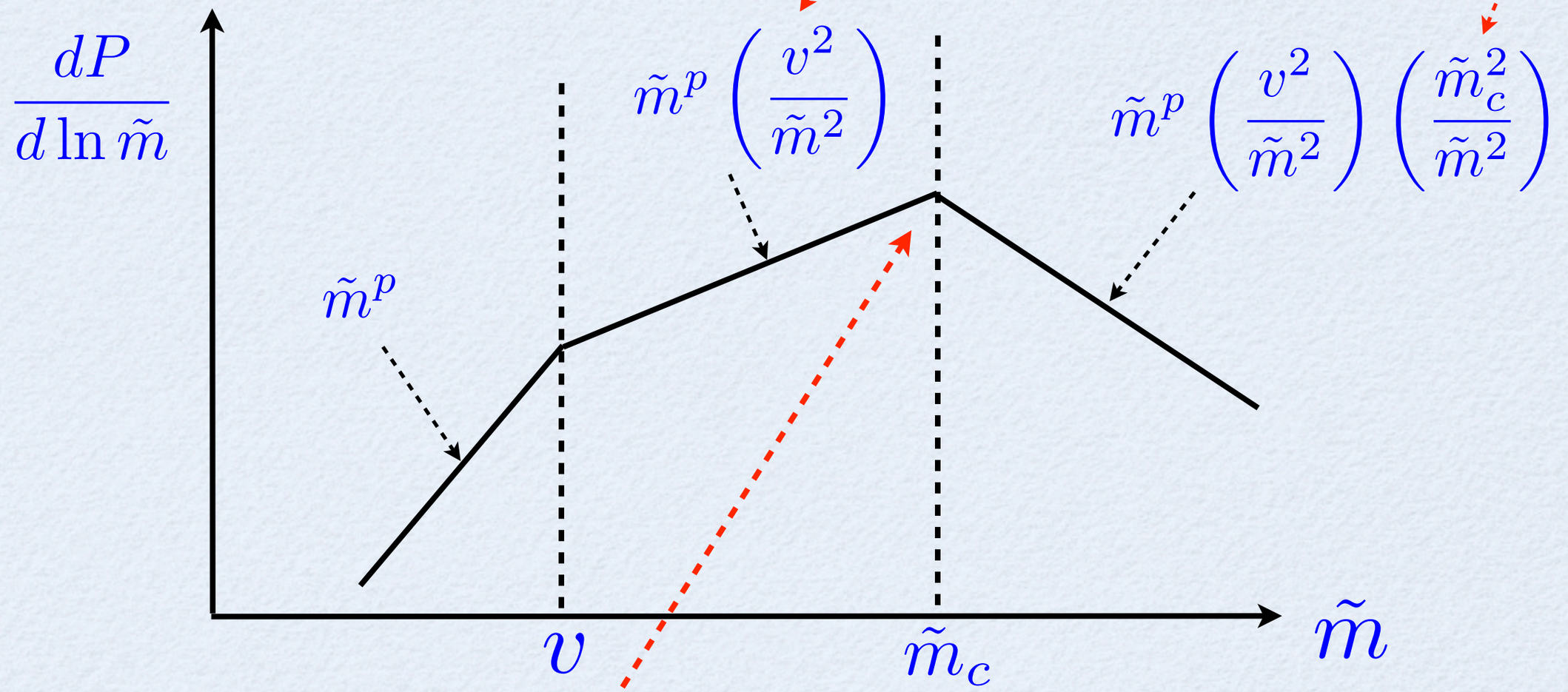

$$2 < p < 4$$

Little SUSY Hierarchy

LSP Dark Matter from Freeze-Out

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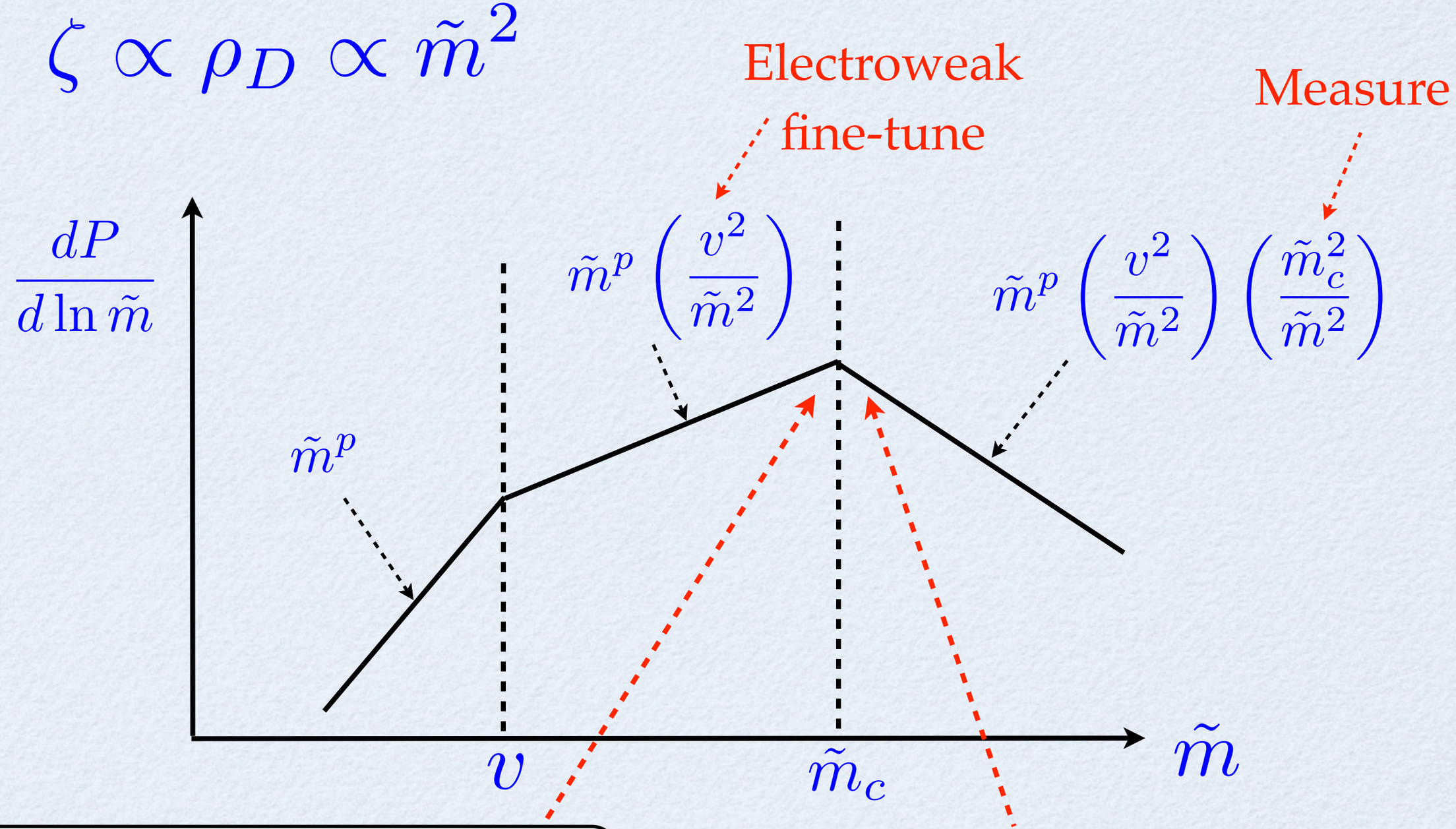


$2 < p < 4$

Little SUSY Hierarchy

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

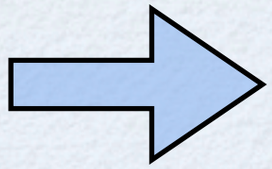
4. Gravitino LSP

Hall, Ruderman, Volansky 1302.2620

TeV scale superpartners in unnatural theories rest on LSP freeze-out DM (multiverse or not)

What if LSP does not reach Thermal Equilibrium?

$$m_{3/2} \sim \frac{F}{M_{Pl}}$$



Gravitino is often the LSP

Large Loop-hole?

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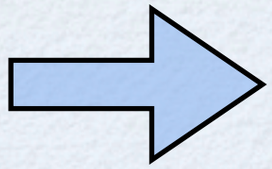

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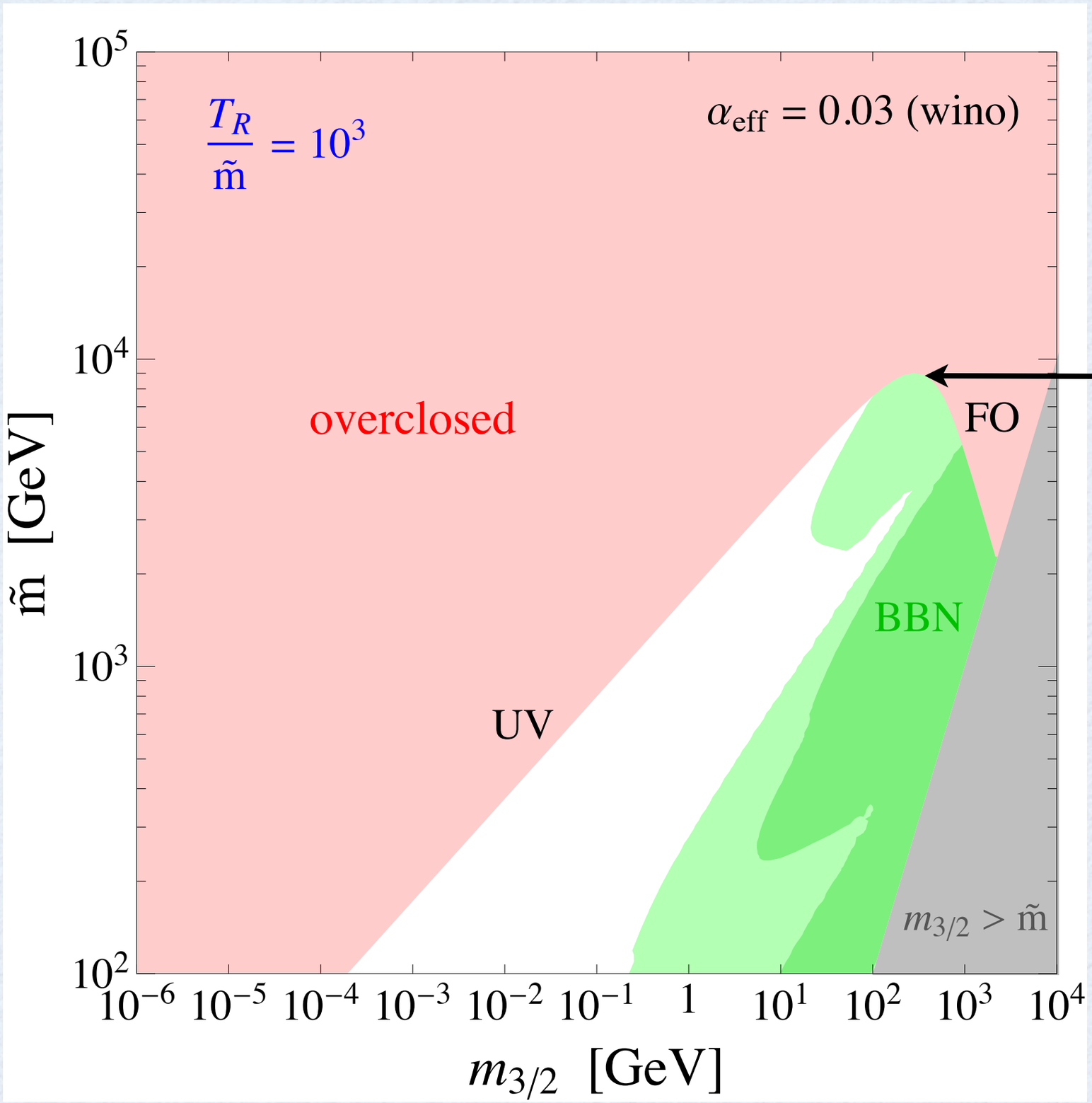
Large Loop-hole?

Josh's talk: No!

Must include all production mechanisms

$\tilde{m}$: TeV ⟶ multi-TeV



$$\frac{T_R}{\tilde{m}} = 10^3$$

$$\tilde{m} \lesssim 9 \text{ TeV}$$

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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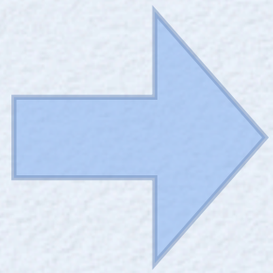
2013: SM Higgs, apparently tuned

Naturalness/Symmetry may be in trouble



A New Framework

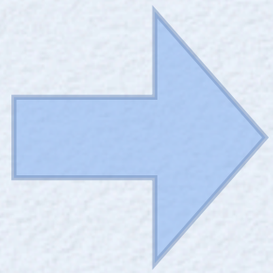
A Remarkable Situation

1973-2013: 40 years without BSM discovery

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

2013: SM Higgs, apparently tuned

Naturalness/Symmetry may be in trouble



A New Framework

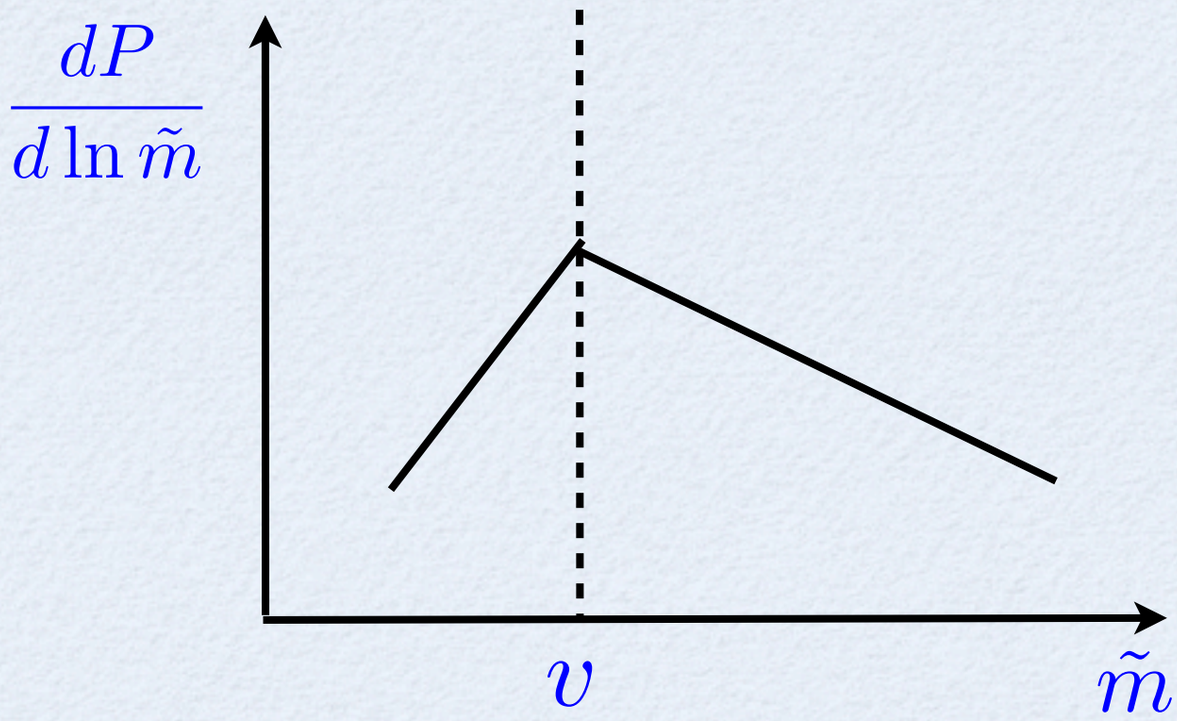
A Multiverse

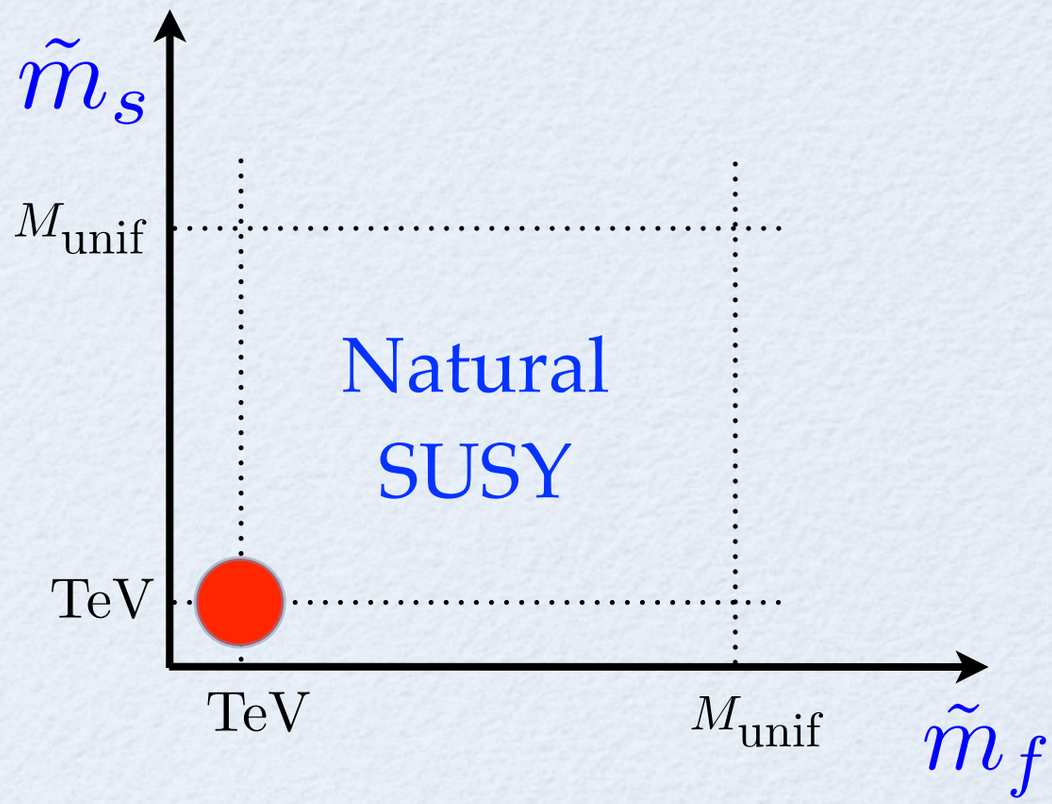
scanning mass scales: $\Lambda_{CC}, v, ...$

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

Natural SUSY

$$0 < p < 2$$

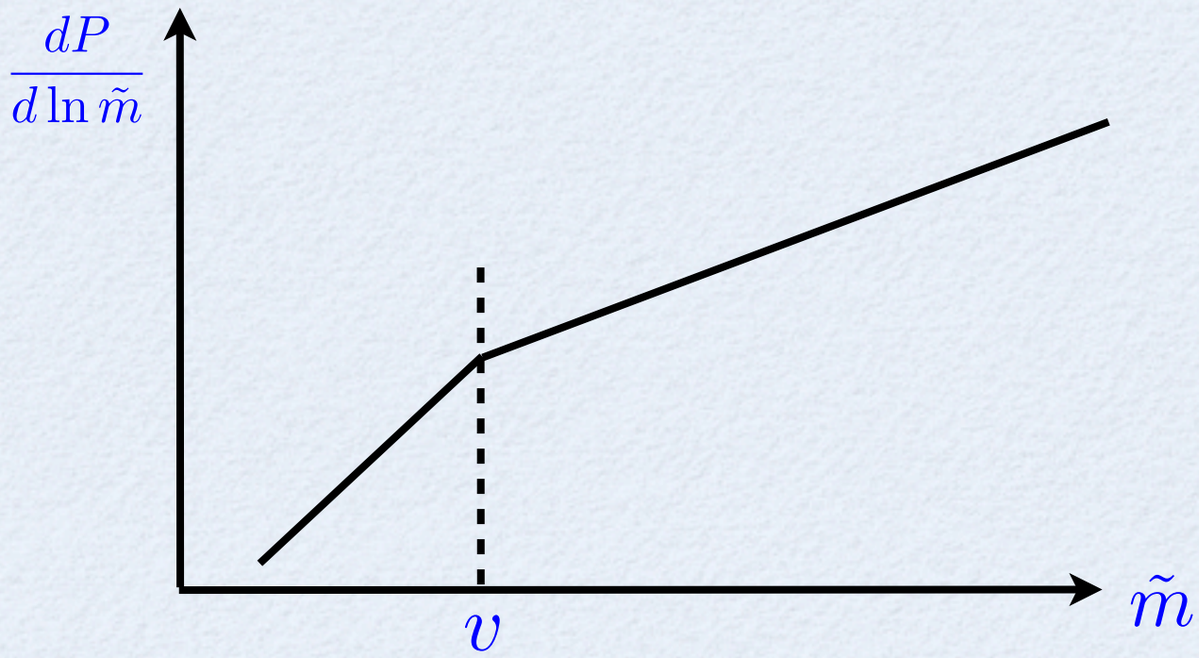


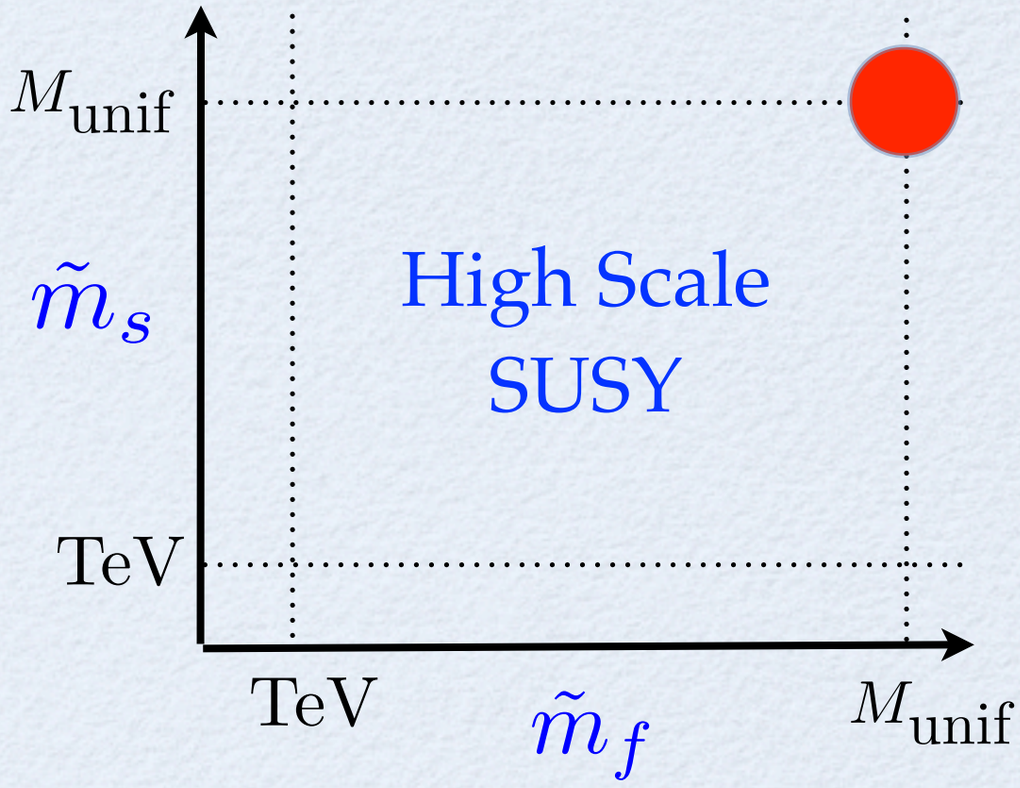


Cornered after 30+ years -- we need to be sure

Runaway to High Scale SUSY

$$p > 2$$



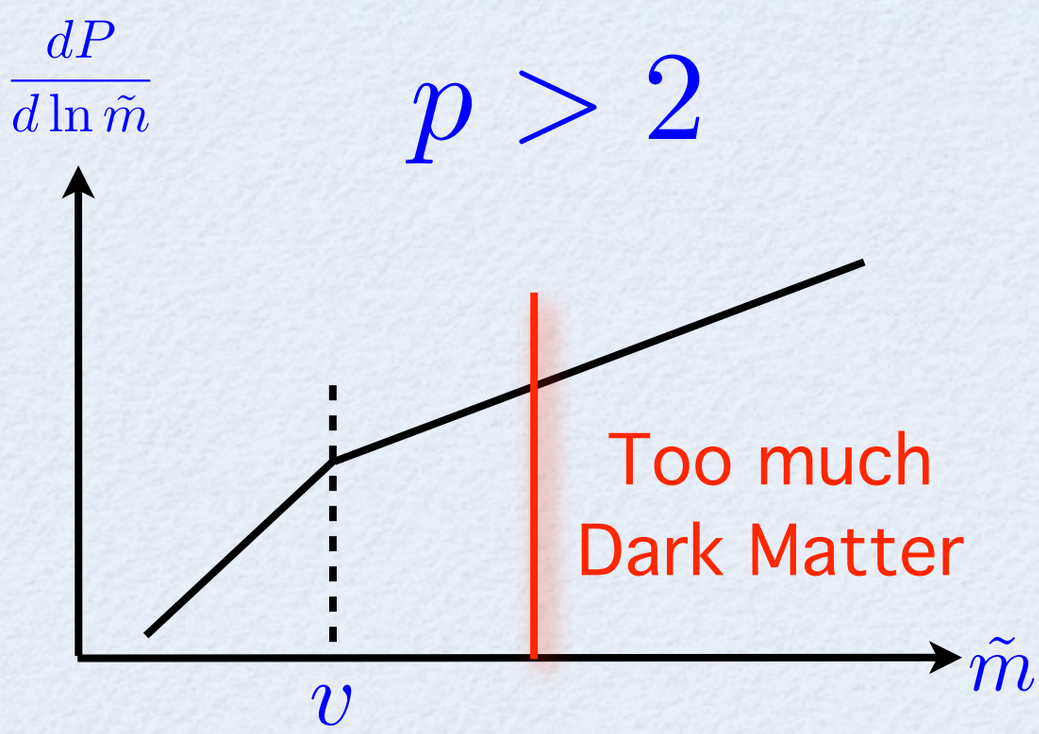


$H_u \leftrightarrow H_d$

$$m_h = (128.0 \pm 0.6 \pm 1.0)\ \text{GeV}$$

Axion Dark Matter

Stabilizing SUSY Breaking at Multi-TeV



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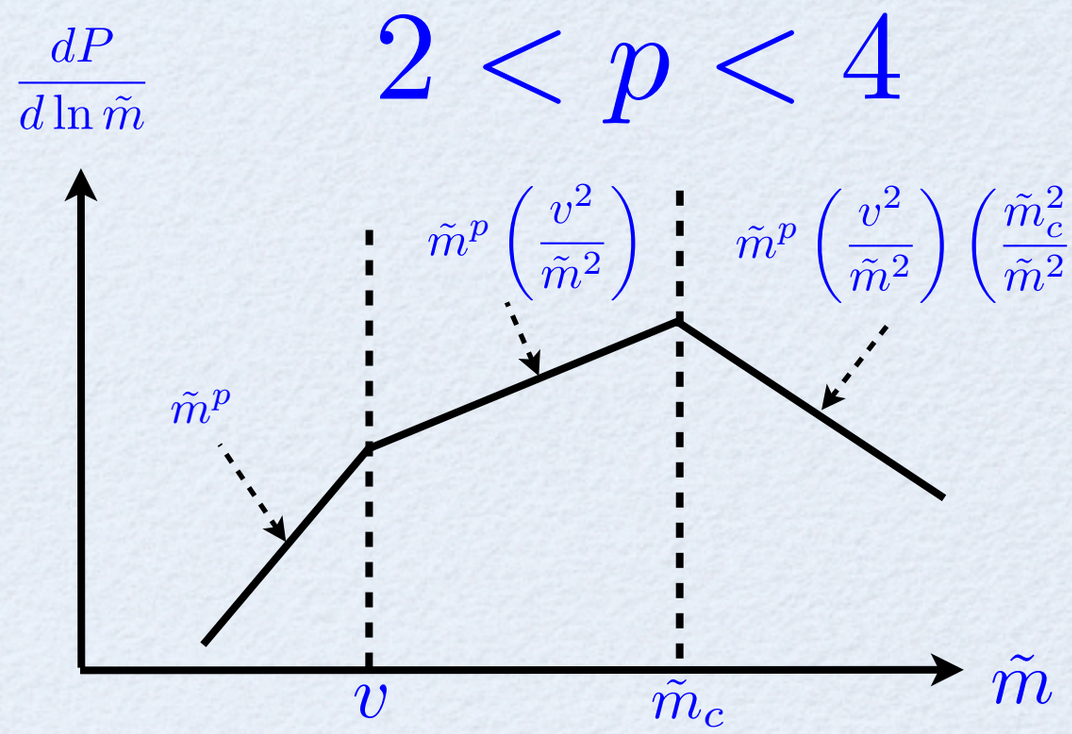
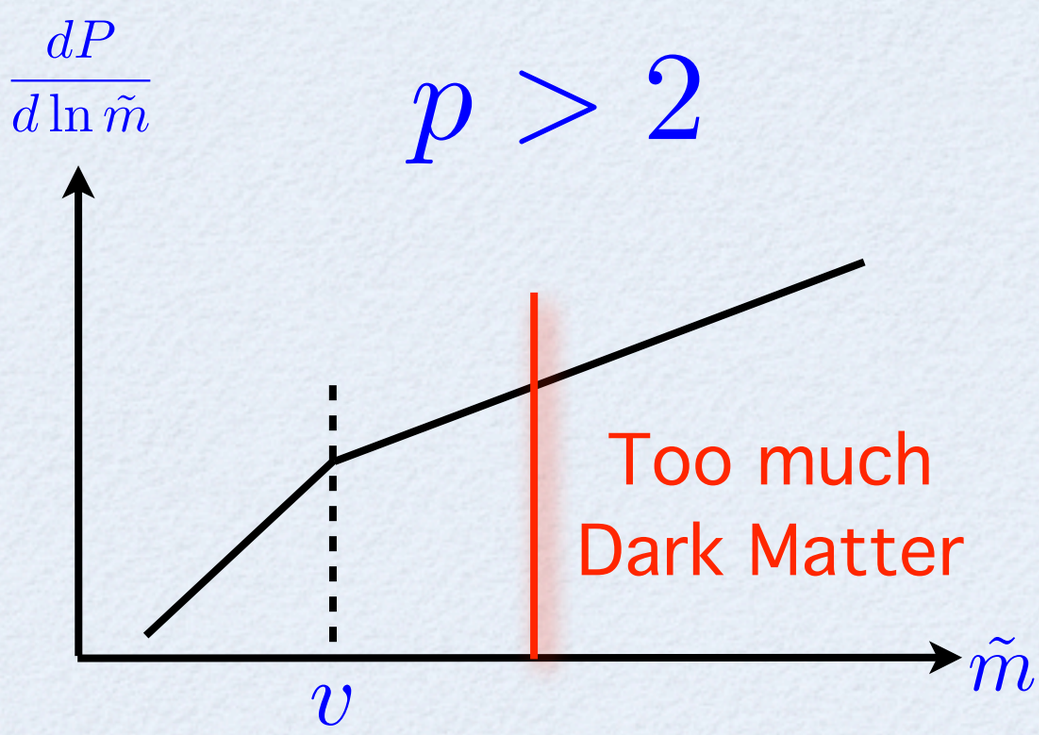


Stabilizing SUSY Breaking at Multi-TeV



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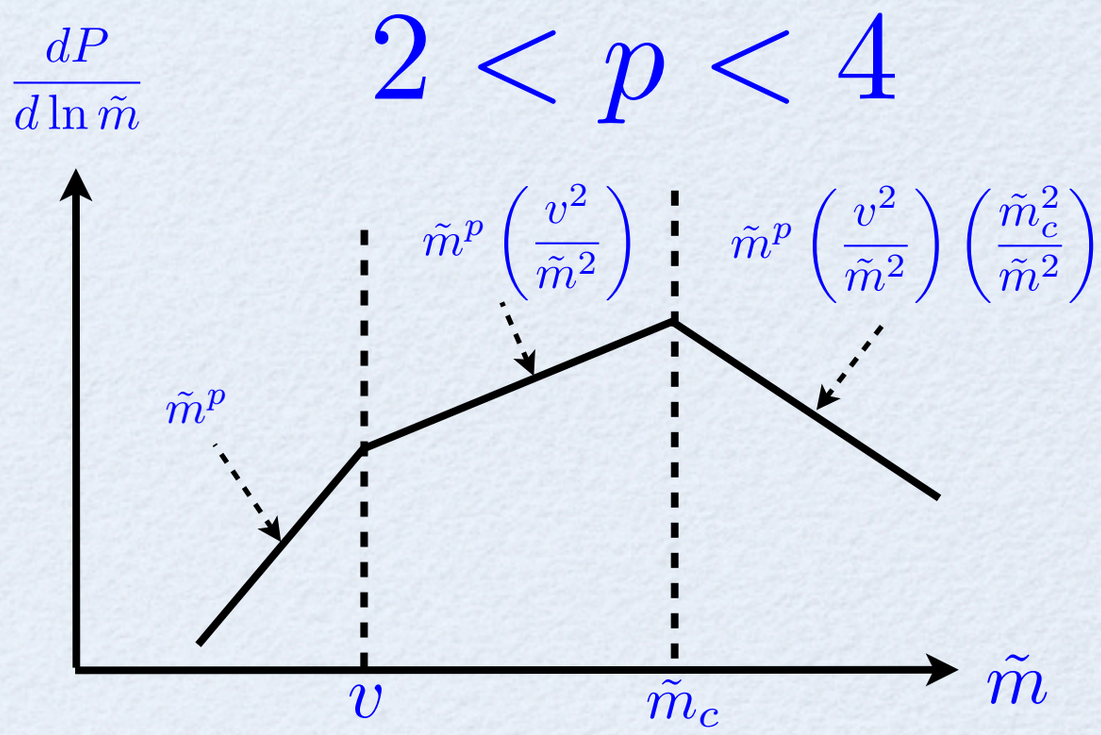
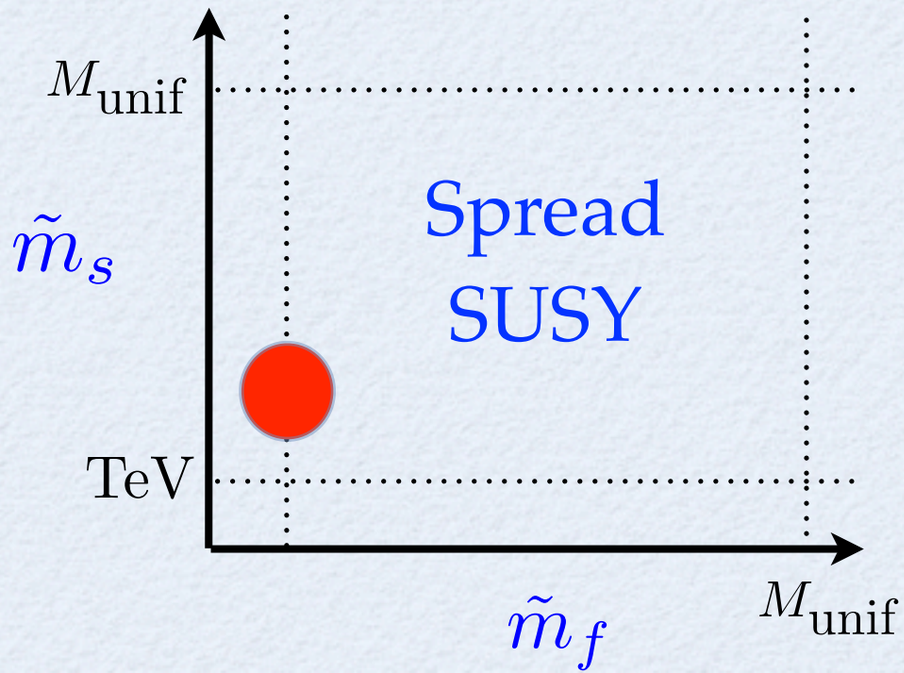
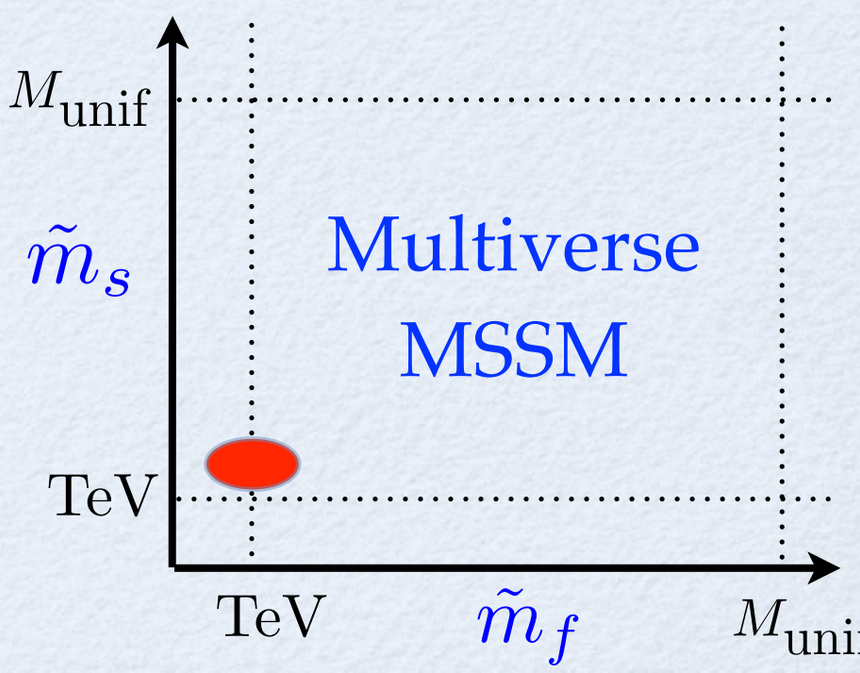
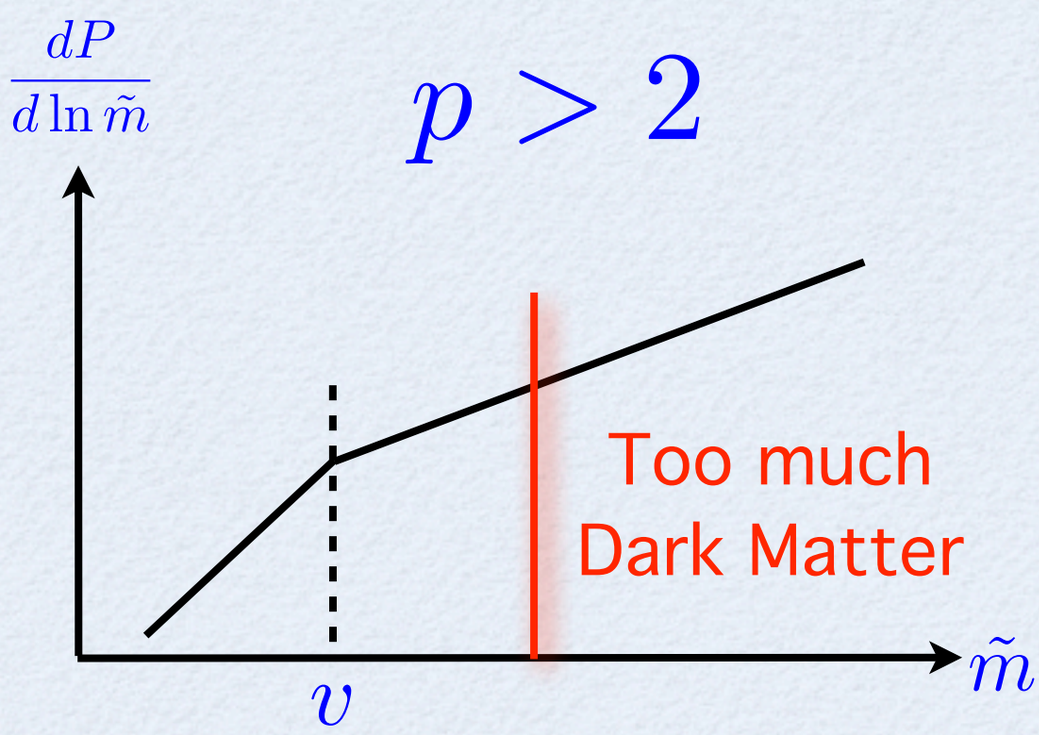






Stabilizing SUSY Breaking at Multi-TeV



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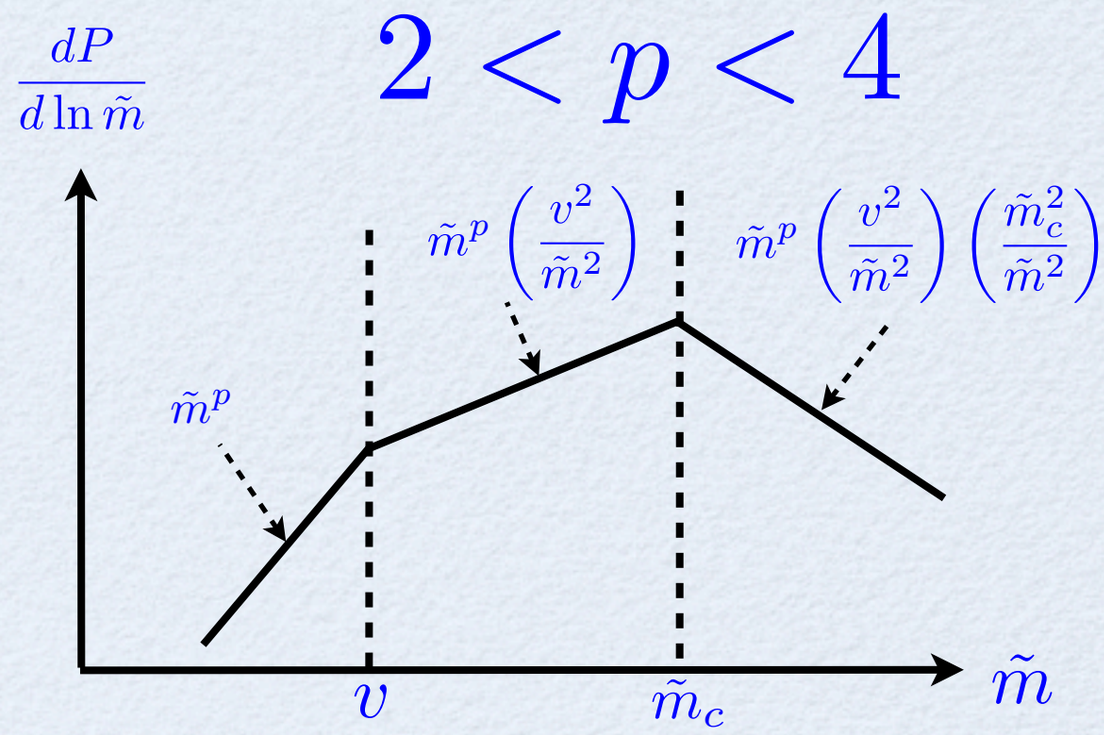

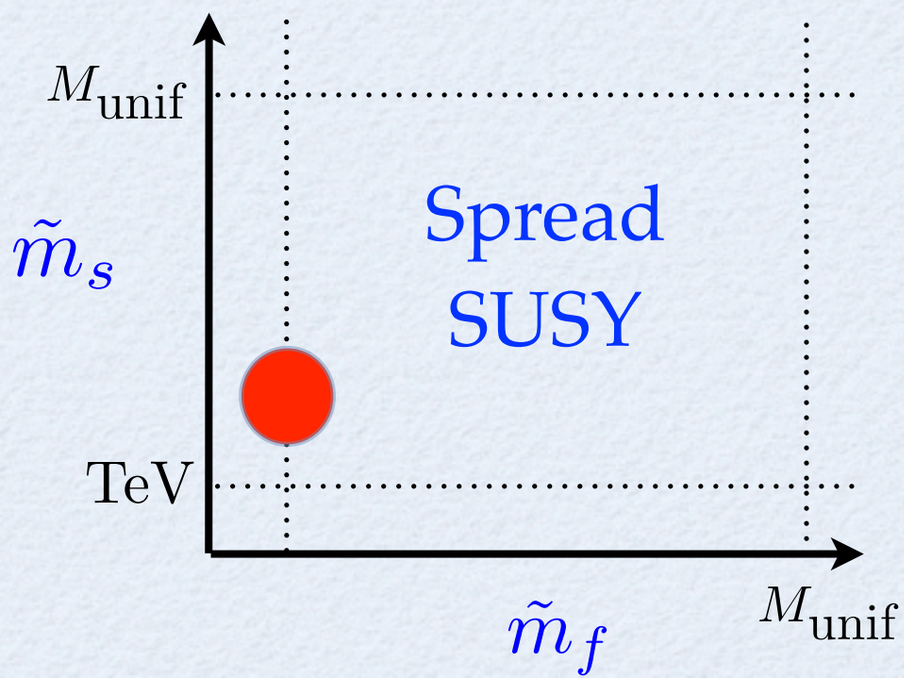

1-20 TeV

May need
100 TeV
Collider