Planck 2014

Paris

May 2014

Dark Matter from The Multiverse: SUSY and Axions

Lawrence Hall

University of California, Berkeley

BERKELEY CENTER FOR THEORETICAL PHYSICS

Two Surprises of Last 35 Years

- 1998 A Recent Cosmic Acceleration
- 2012 A Lonely Higgs Boson

Both are connected to fine-tuning

Both have a multiverse interpretation

Review the "Standard" Multiverse Interpretation

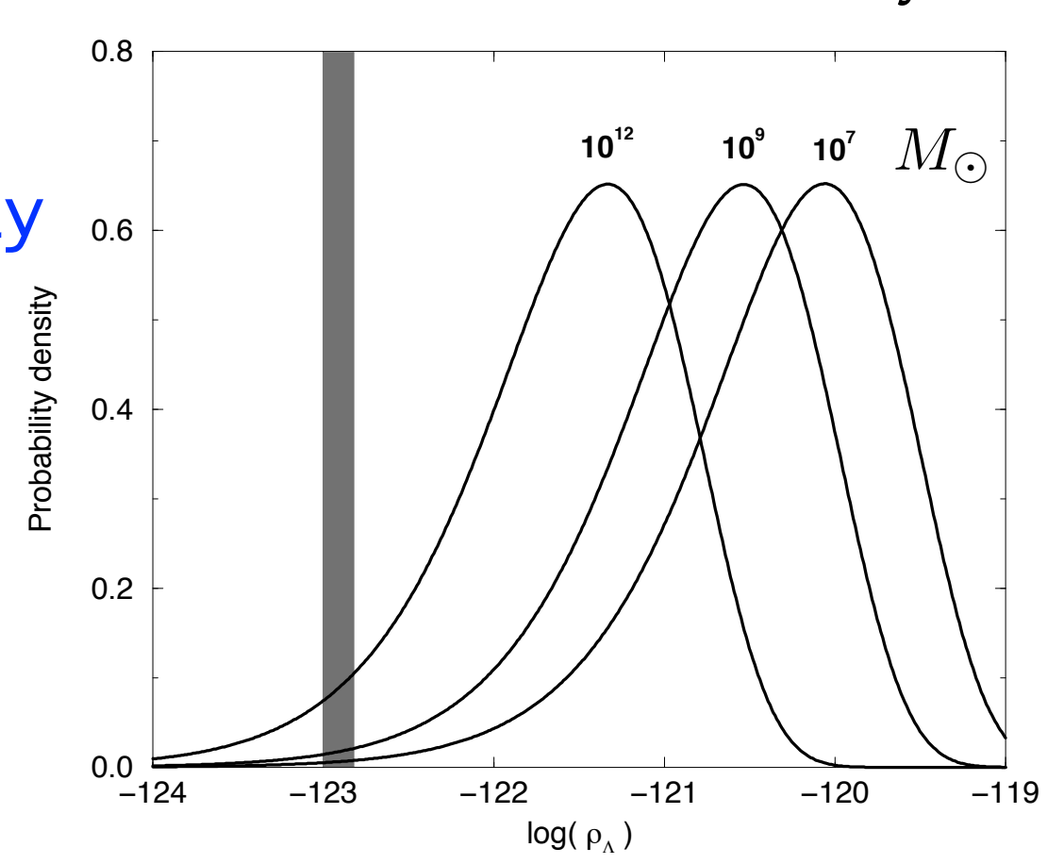
1. Dark Energy 1998

Predicted from multiverse view: Weinberg, 1987

Vary only the cosmological constant, Λ

Fraction of virialized baryons

Prob density



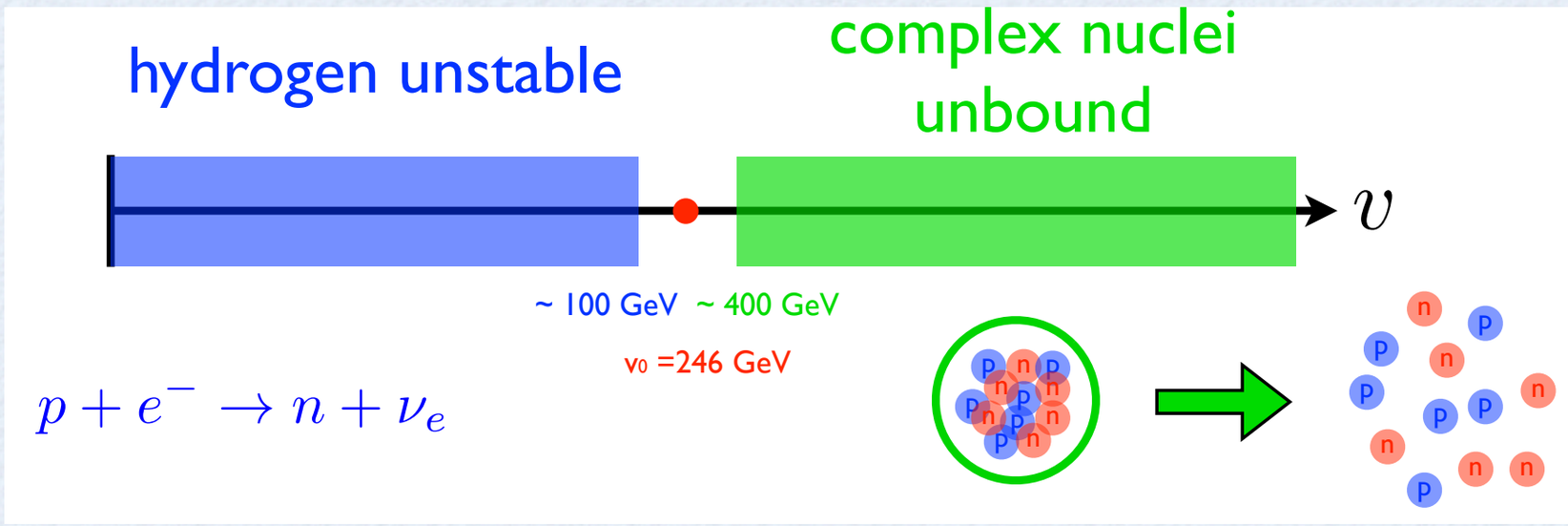
log Λ

Martell, Shapiro, Weinberg astro-ph/9701099

2. A Lonely Higgs Boson 2012

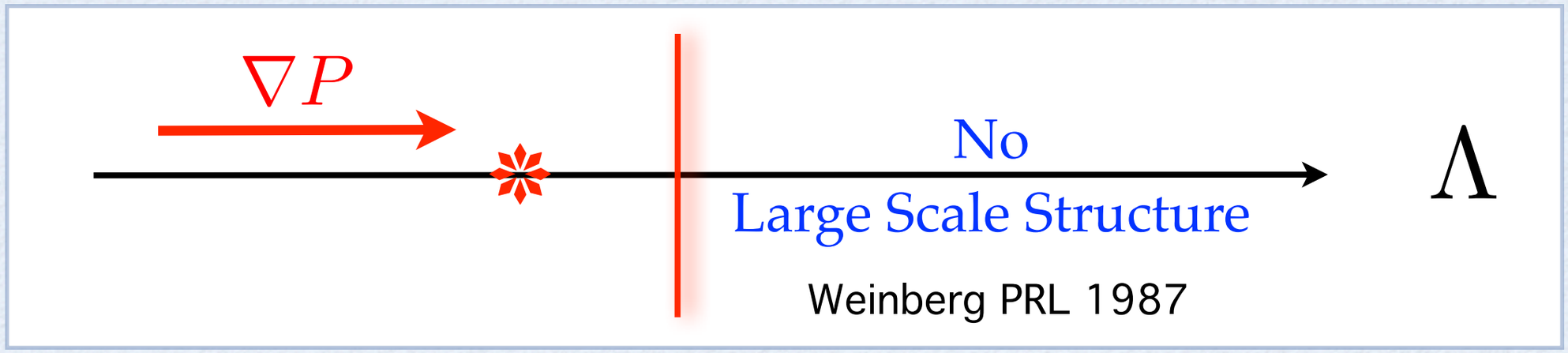
and nothing else for
EWSB at TeV scale ??

Predicted
Agrawal, Barr, Donoghue, Seckel hep-ph/9707380
Damour, Donoghue arXiv:0712.2968

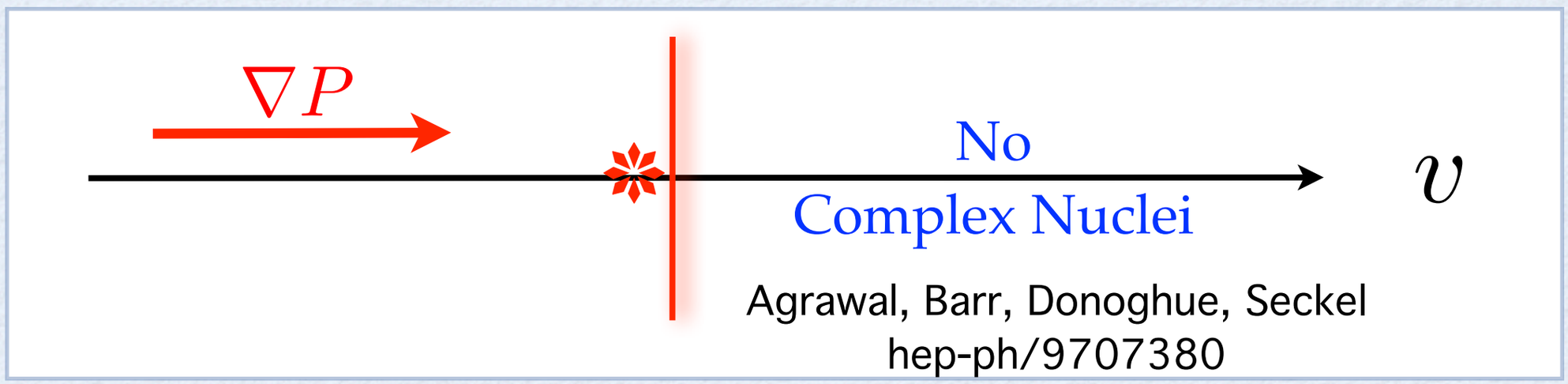


Multiverse for Λ and v

The two surprises have a common interpretation



Weinberg PRL 1987



Agrawal, Barr, Donoghue, Seckel
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Just Imagine ...

1. $\Omega_m = 0.99 \pm 0.02$

2. $\pi_T, \rho_T, \cdots$ at LEP, TeVatron, LHC

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1. $\Omega_m = 0.99 \pm 0.02$

2. $\pi_T, \rho_T, \cdots$ at LEP, TeVatron, LHC

- Data is telling us that Nature is fine-tuned
- The Multiverse provides a simple explanation

Outline

1. An Alternative Multiverse explanation for (Λ ,v)

2. Scanning the Dark Matter Abundance

3. Implications: Susy
   Axions

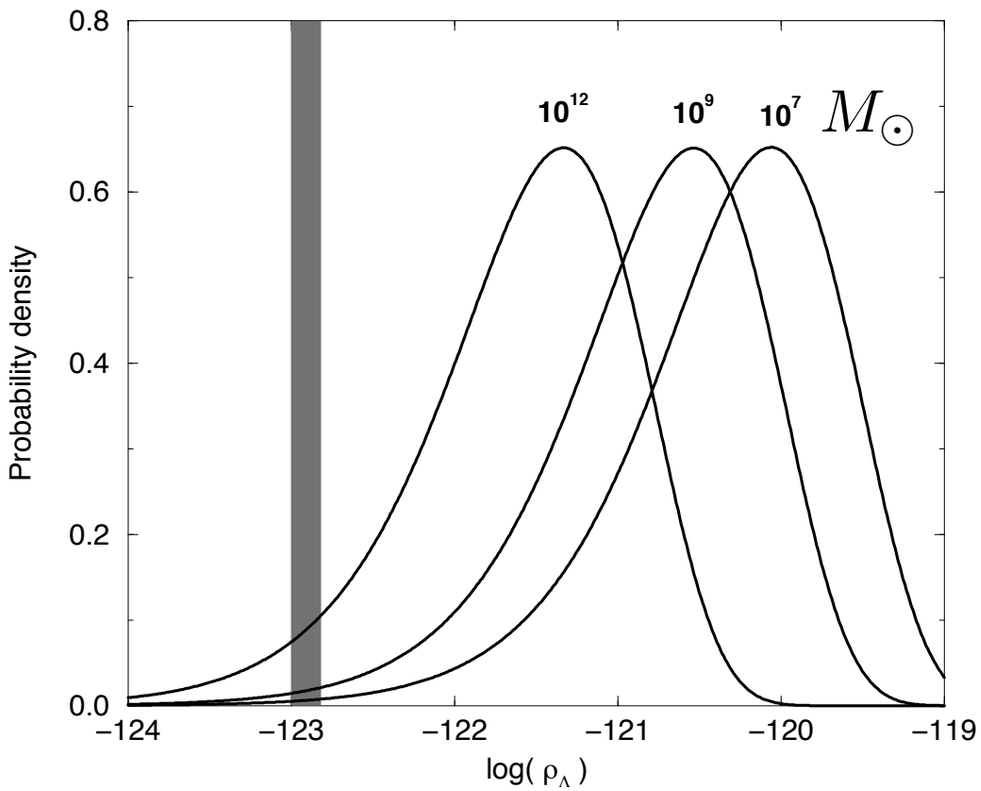
4. A Model for the Axion and Higgs Mass

(I)

An Alternative Explanation for $(\Lambda\,, v)$

Λ from the Measure

Fraction of virialized baryons

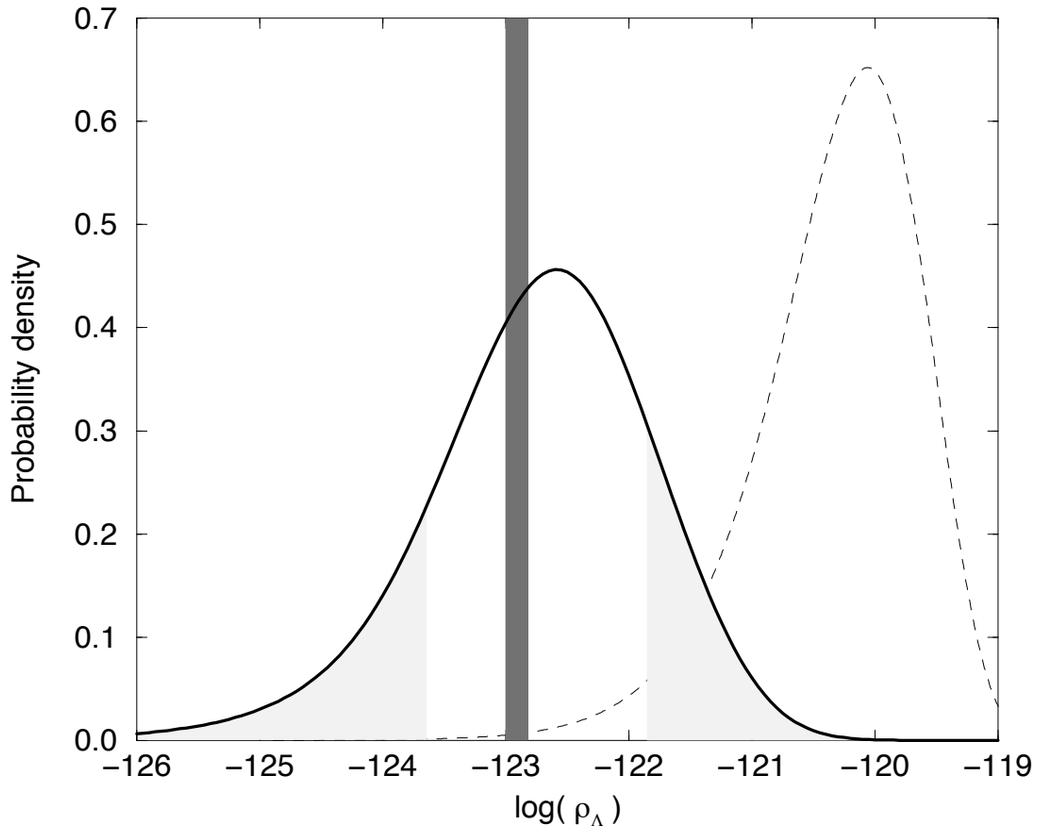


Martell, Shapiro, Weinberg astro-ph/9701099

Stars in the Causal Patch

$$t_\Lambda \sim t_{obs}$$

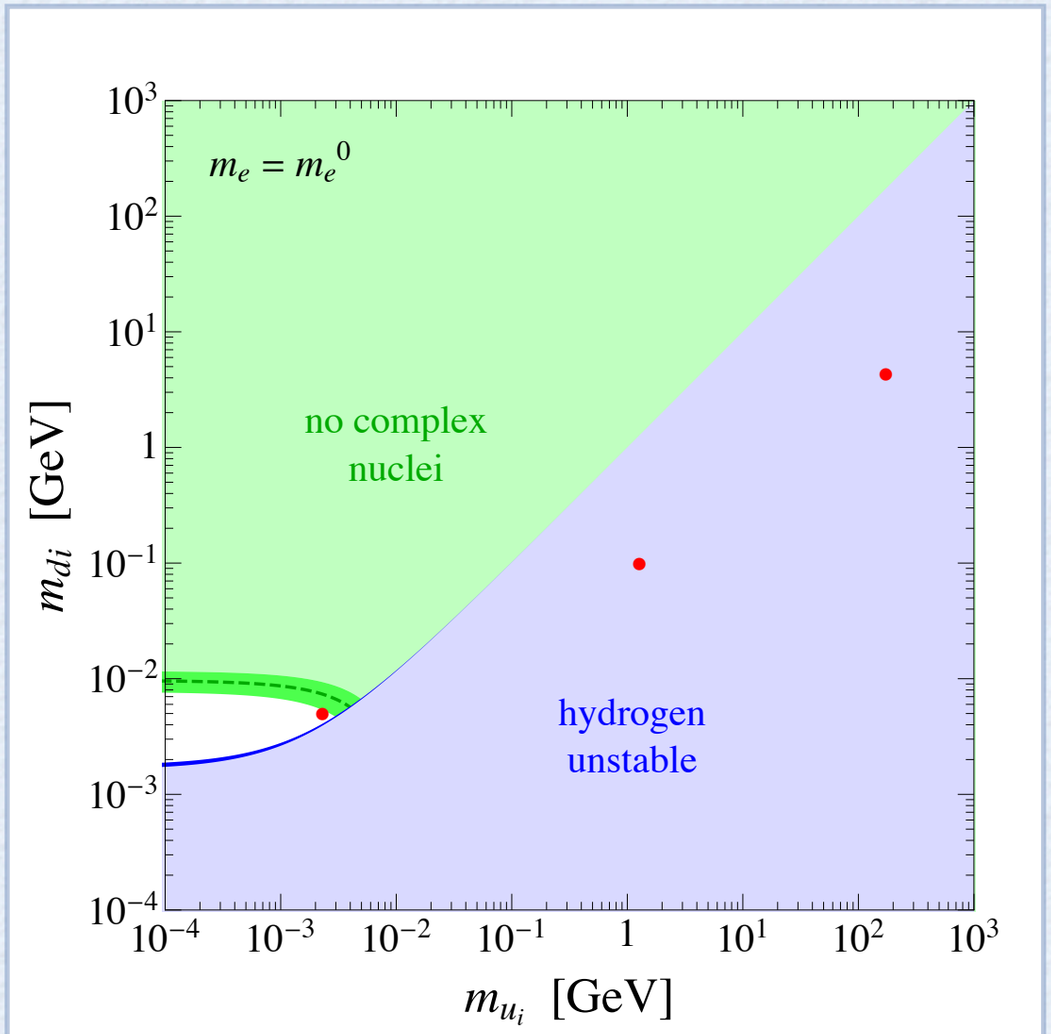
$$\Lambda \sim \frac{1}{G\, t_{obs}^2}$$



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

Nuclear Boundaries: Determine $m_{u,d}$

Hall, Pinner, Ruderman; to appear



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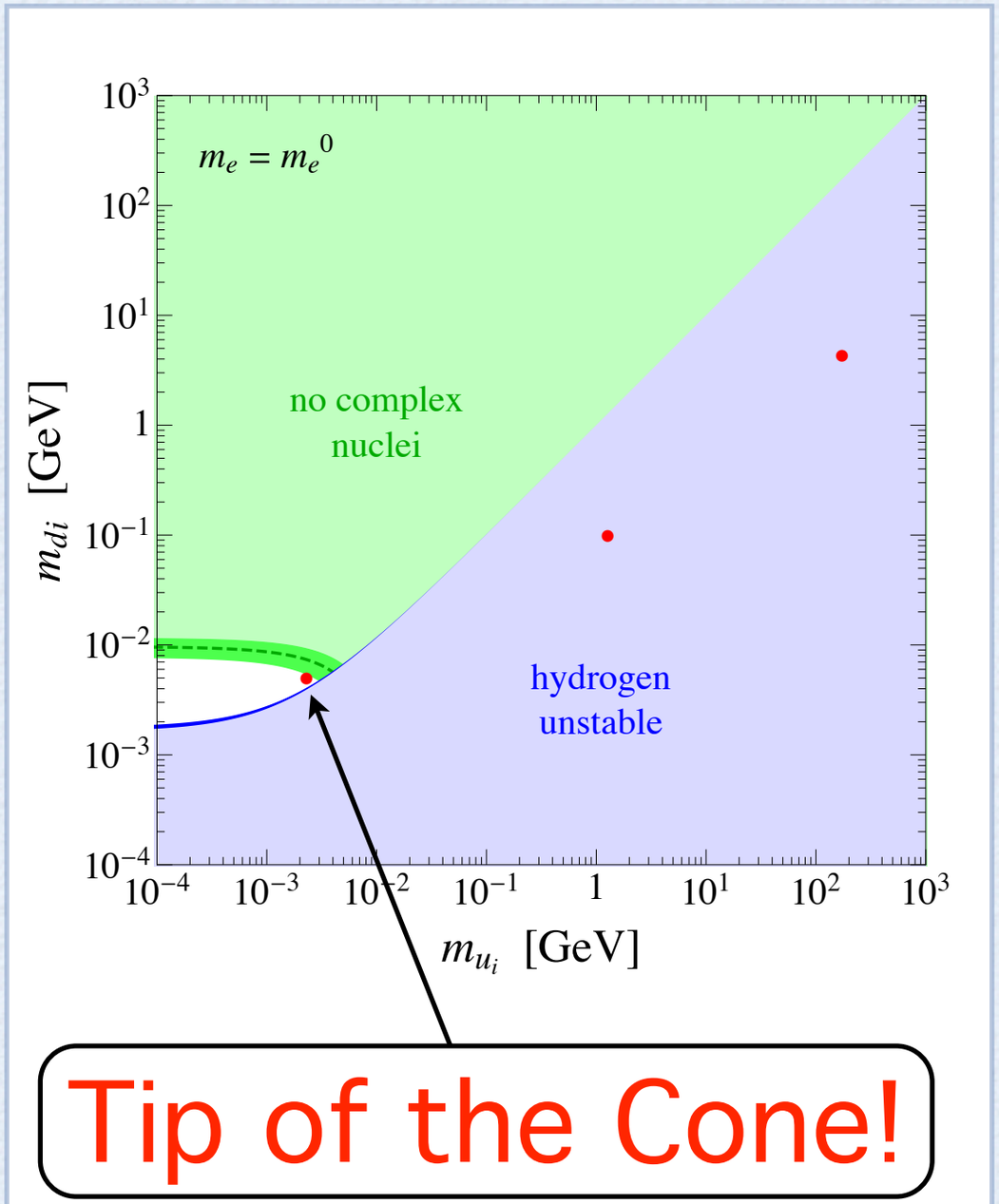

Tip of the Cone!

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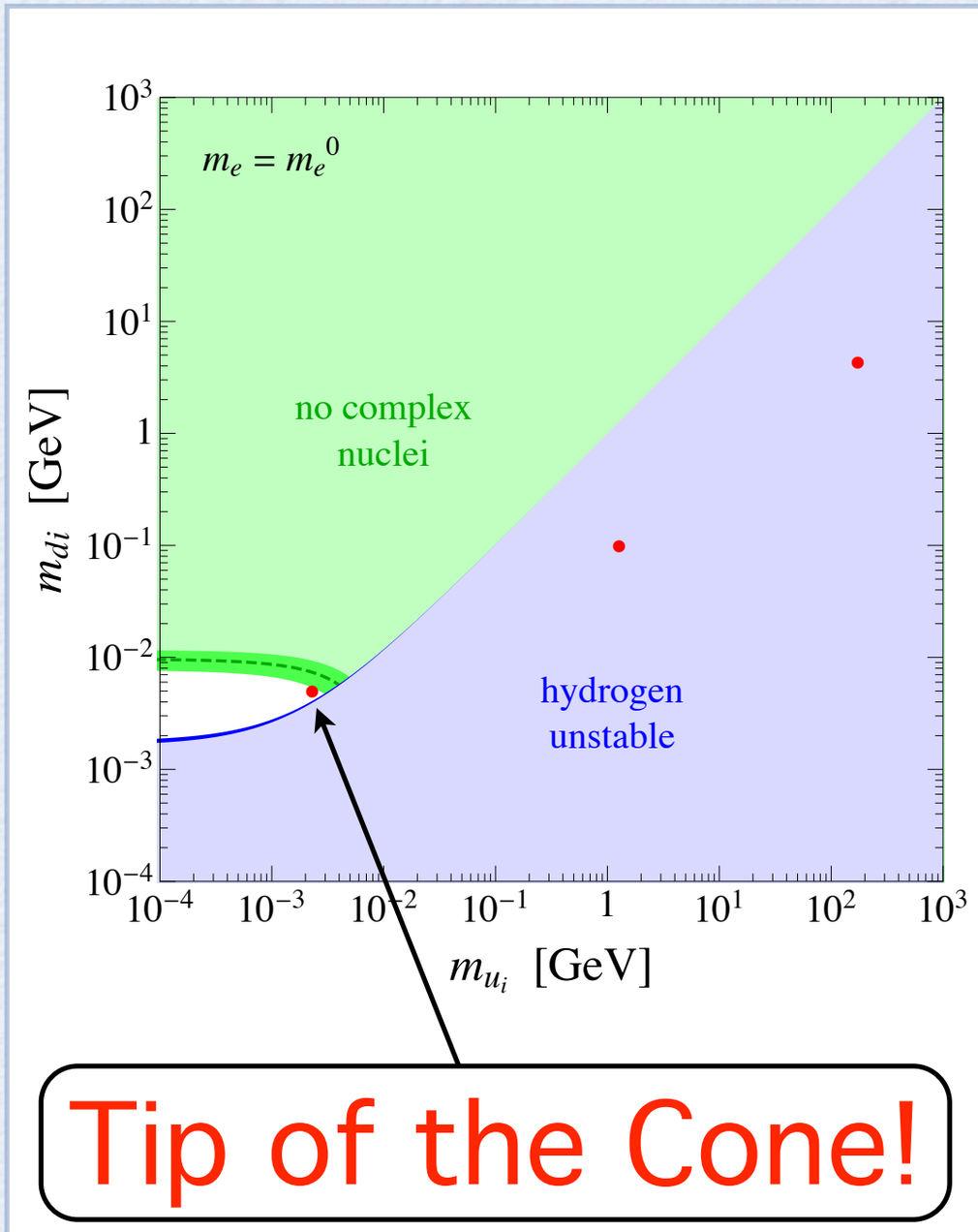

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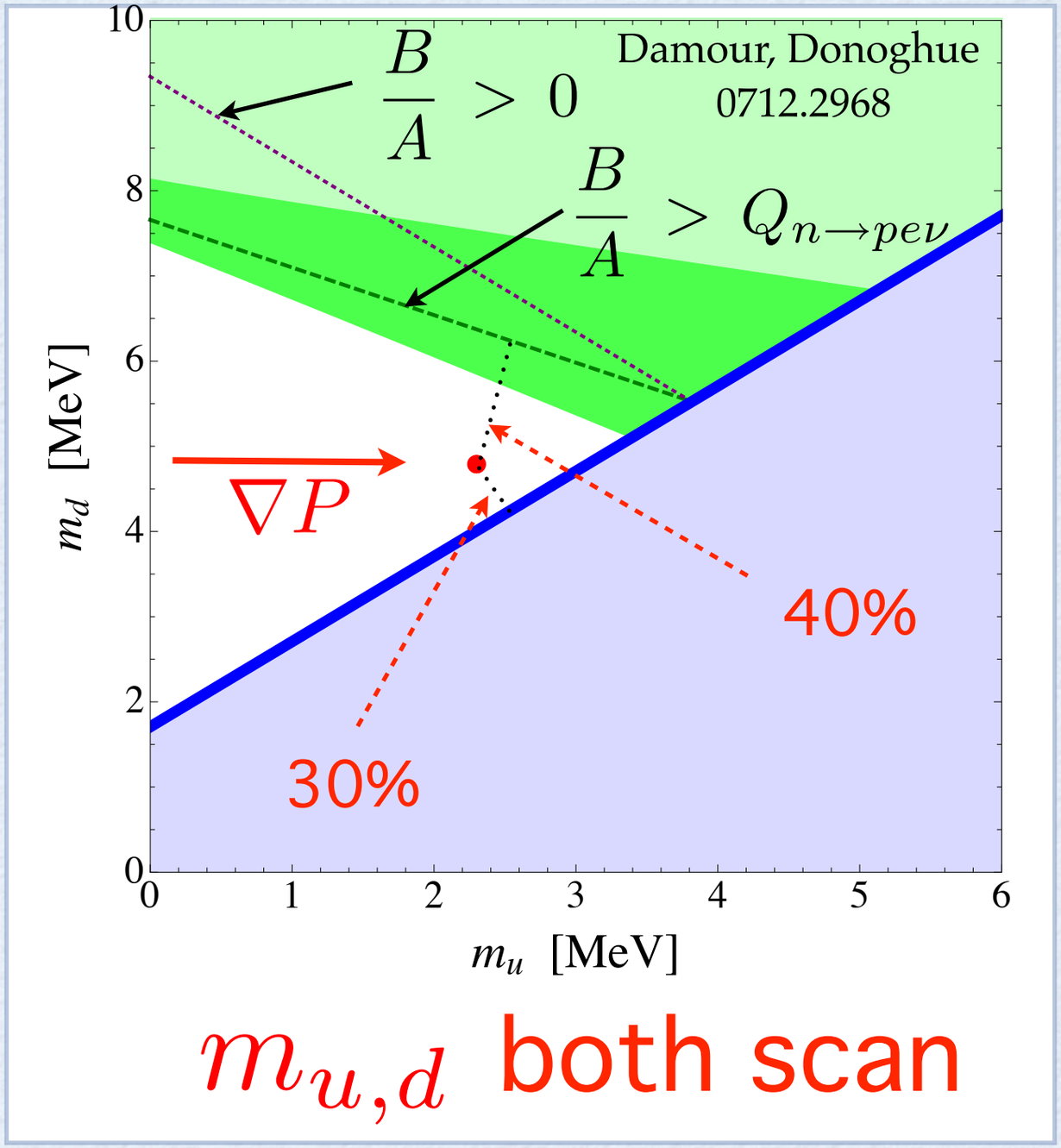

$m_{u,d}$ both scan

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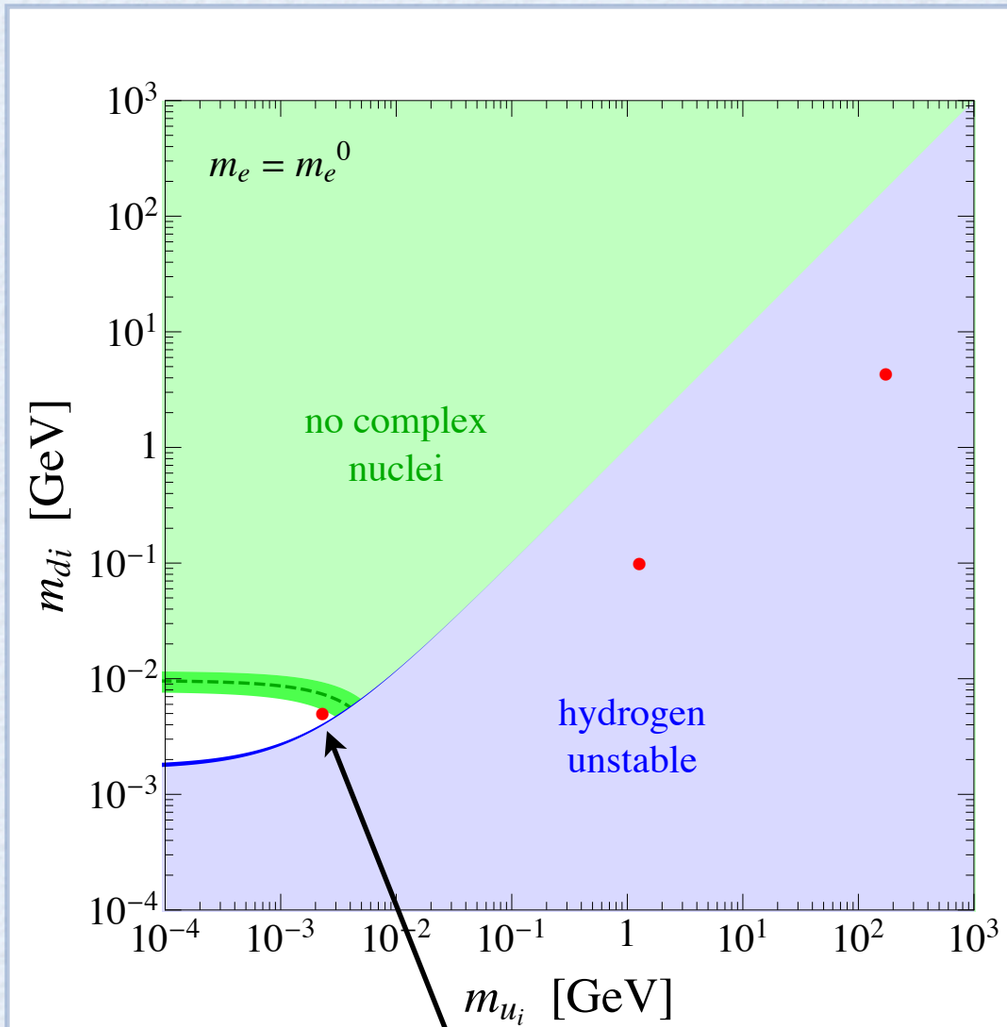

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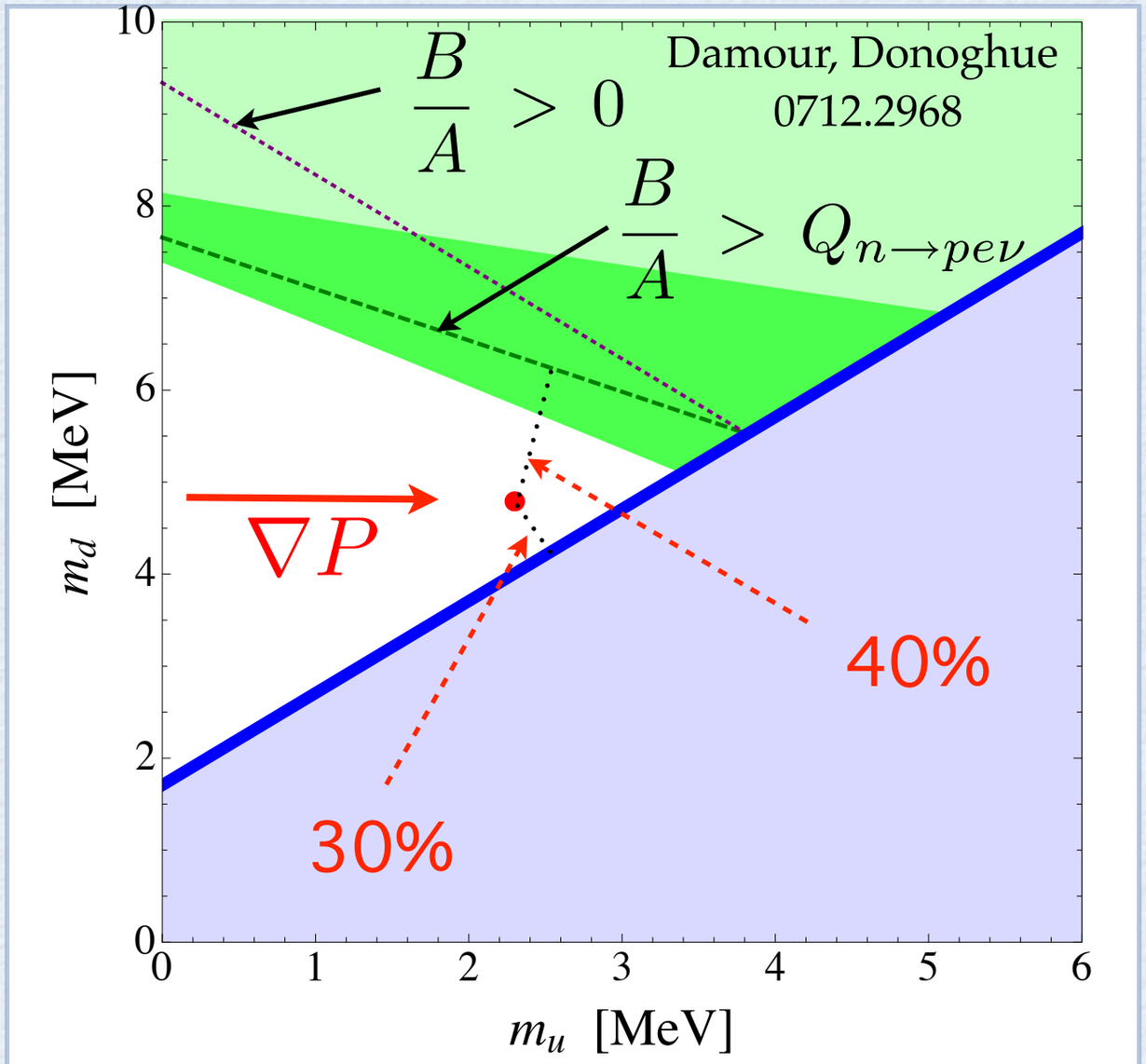

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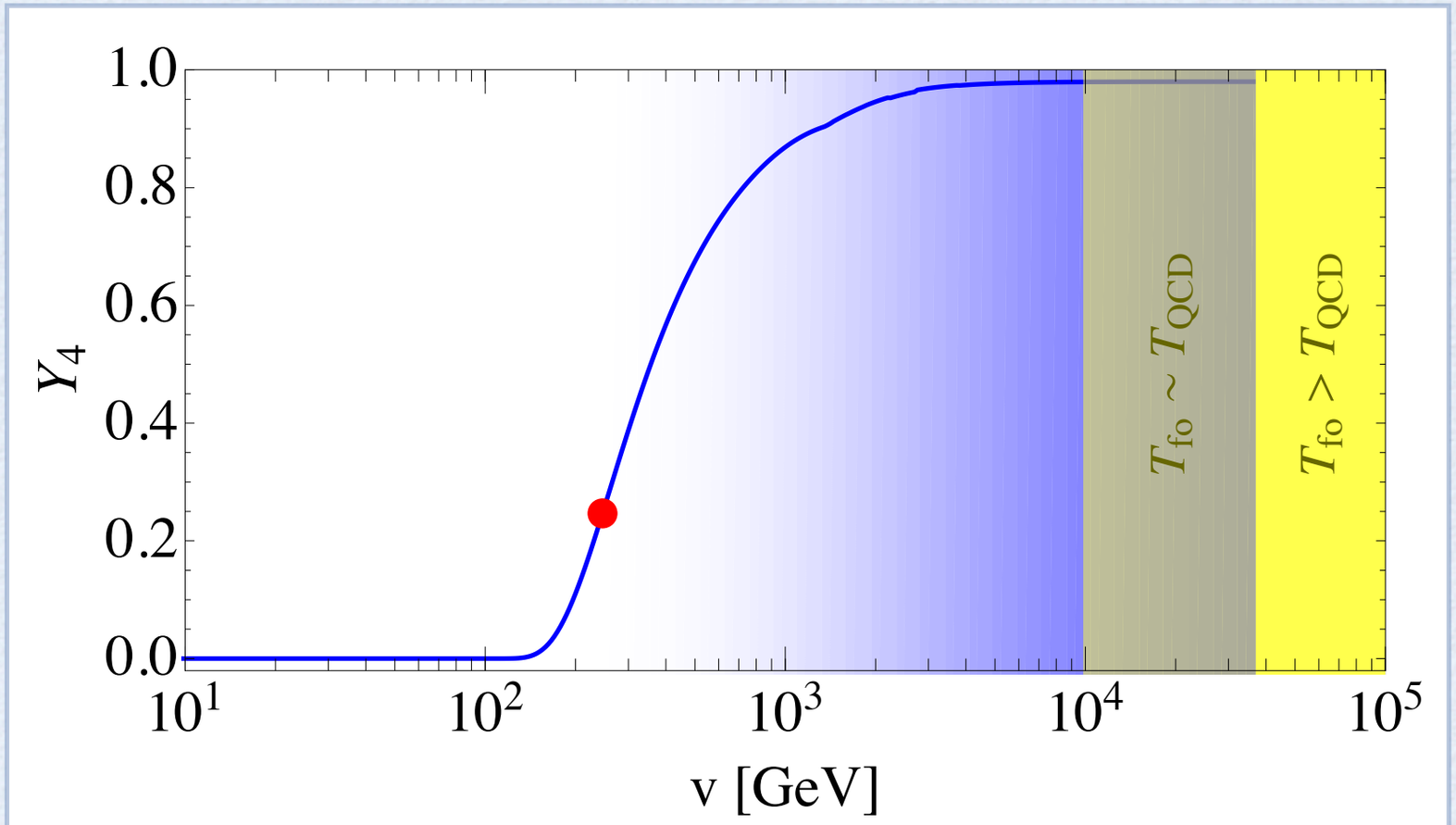
What determines v ?

v from the Helium Boundary

Hall, Pinner, Ruderman; to appear



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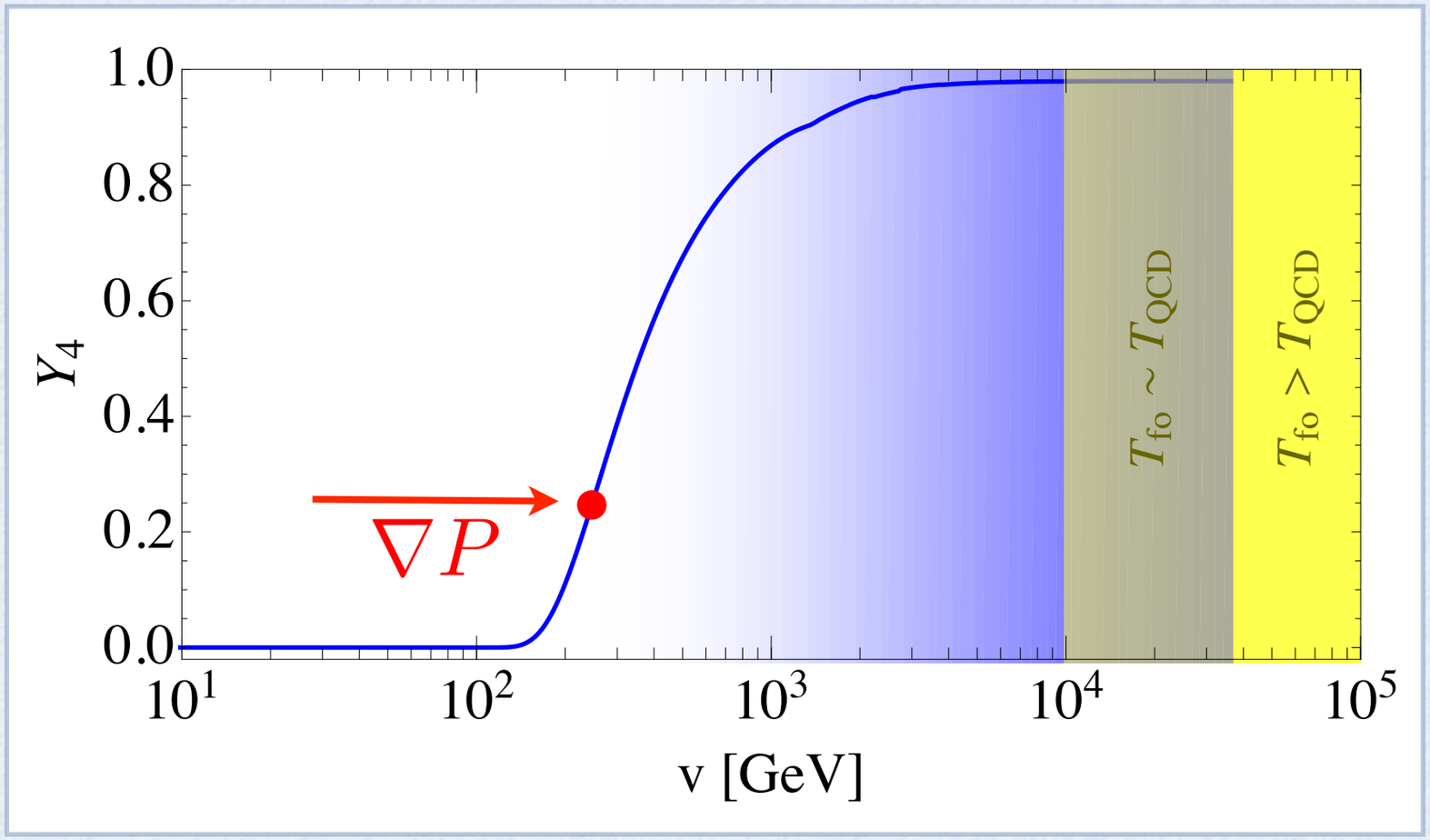

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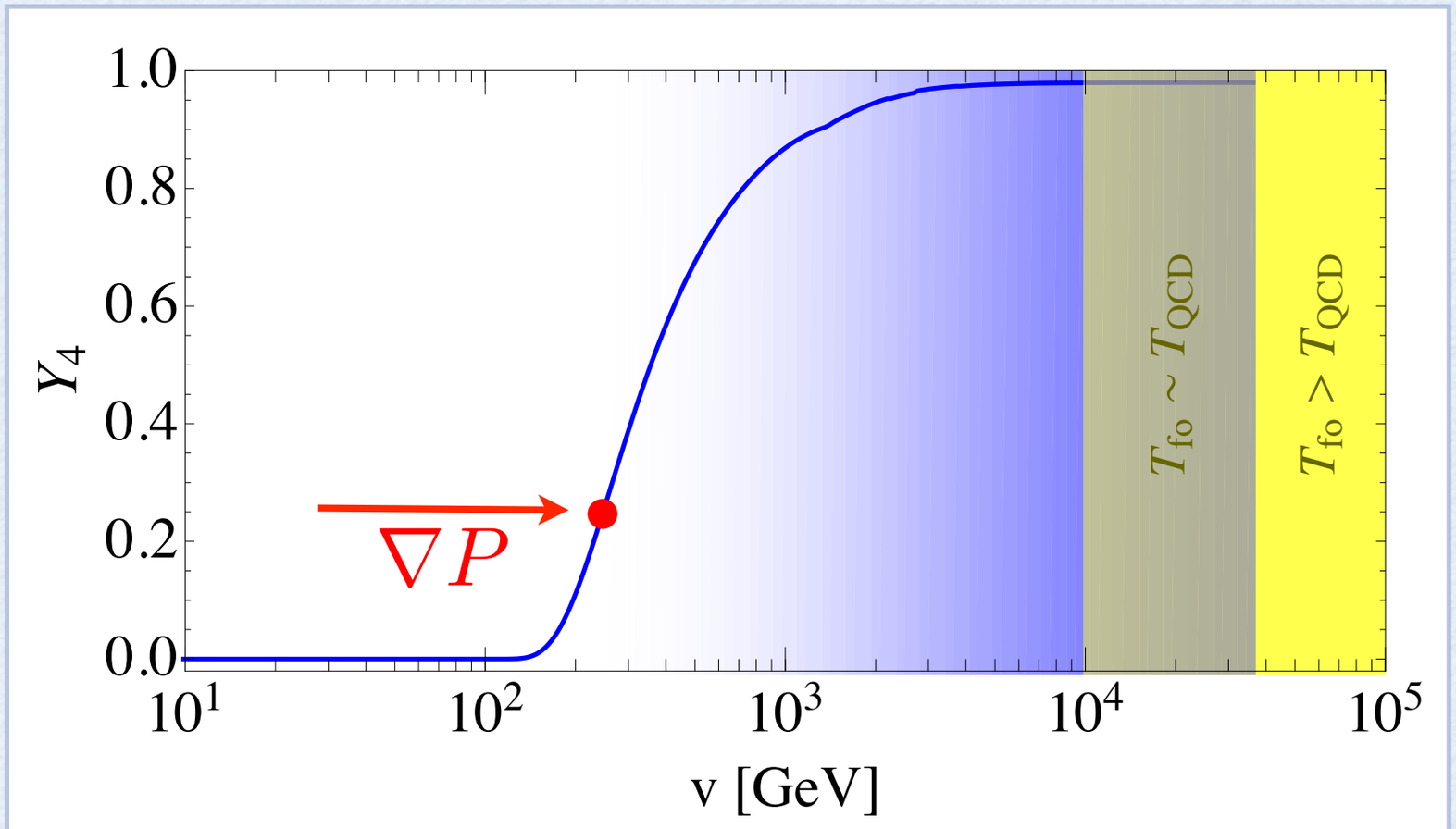

$$\left(\frac{n}{p}\right)_f \sim e^{-(m_n - m_p)/T_{np}}$$

$$\frac{v^{4/3}}{M_{Pl}^{1/3}}$$

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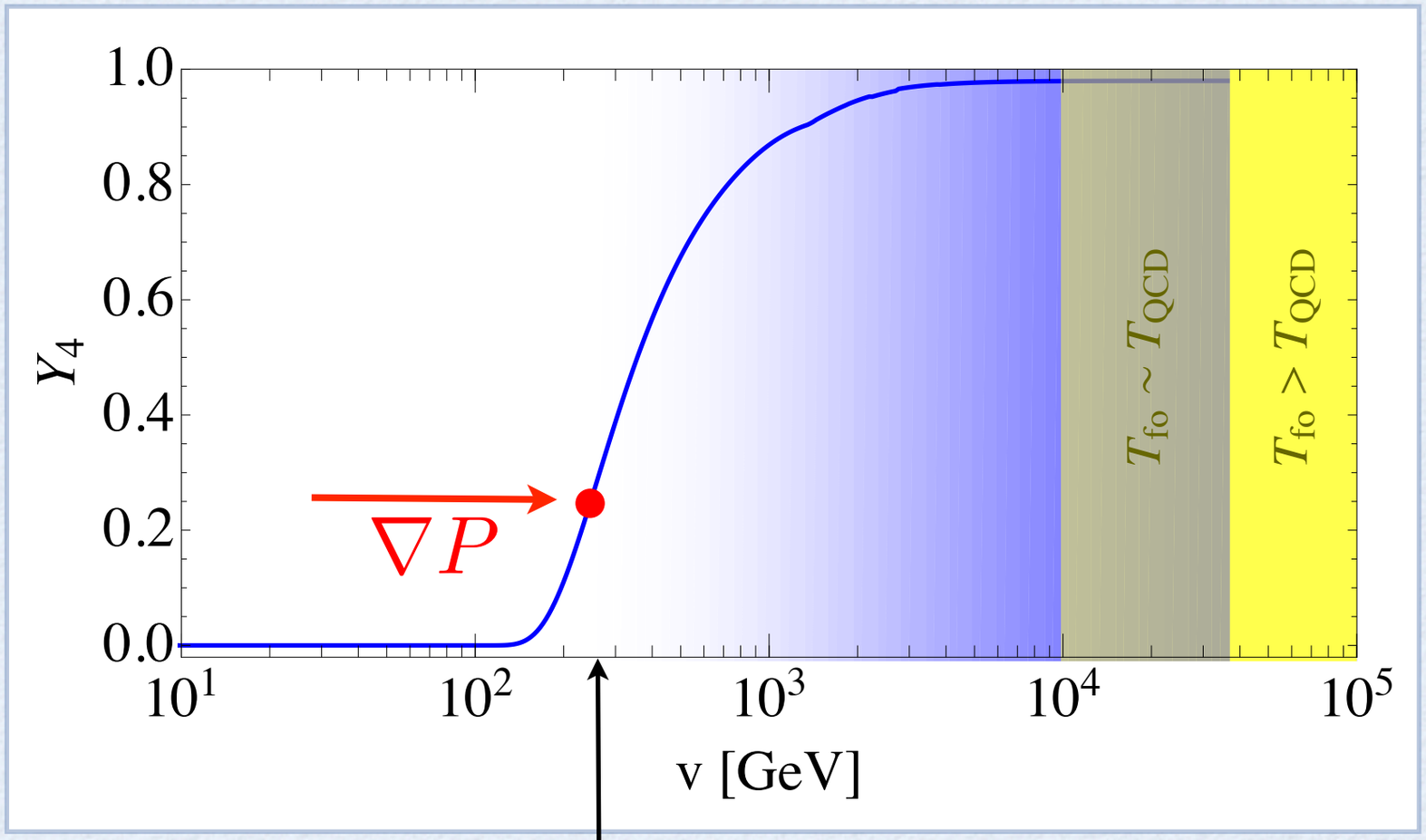

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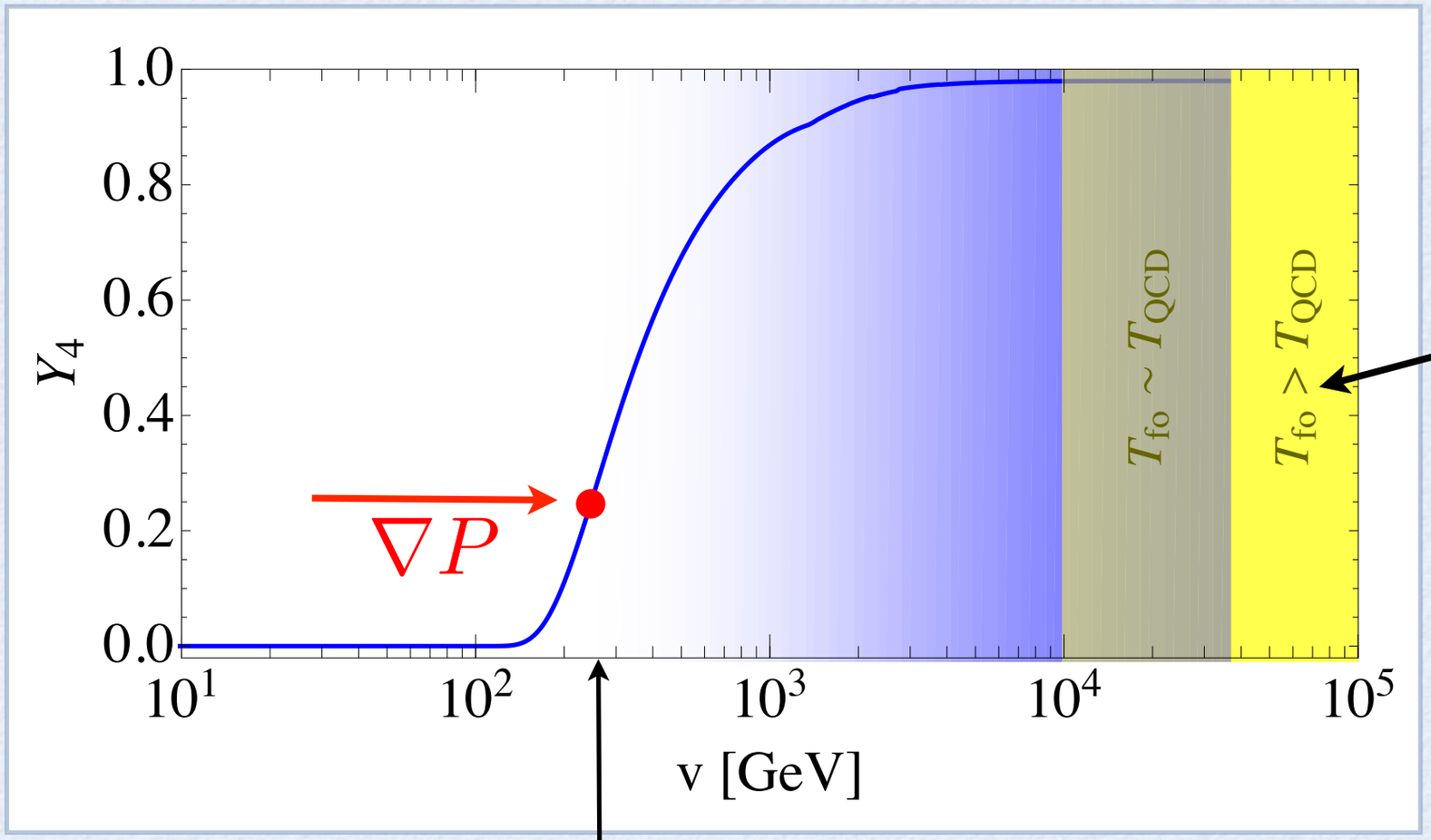

???

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(II)

Scanning the Dark Matter Abundance

Francesco D'Eramo, Lawrence Hall, Duccio Pappadopulo

to appear

Large Scale Structure: Varying DM

$$\rho \sim T^4 + (\xi_D + \xi_B) T^3 + \Lambda$$

$$\delta(\lambda) \sim \frac{T_e}{T_\Lambda} \left(\frac{\xi_D}{\xi_D + \xi_B} + \frac{\xi_B}{\xi_D + \xi_B} \, e^{-(\lambda_S/\lambda)^{1.4}} \right) Q_0$$

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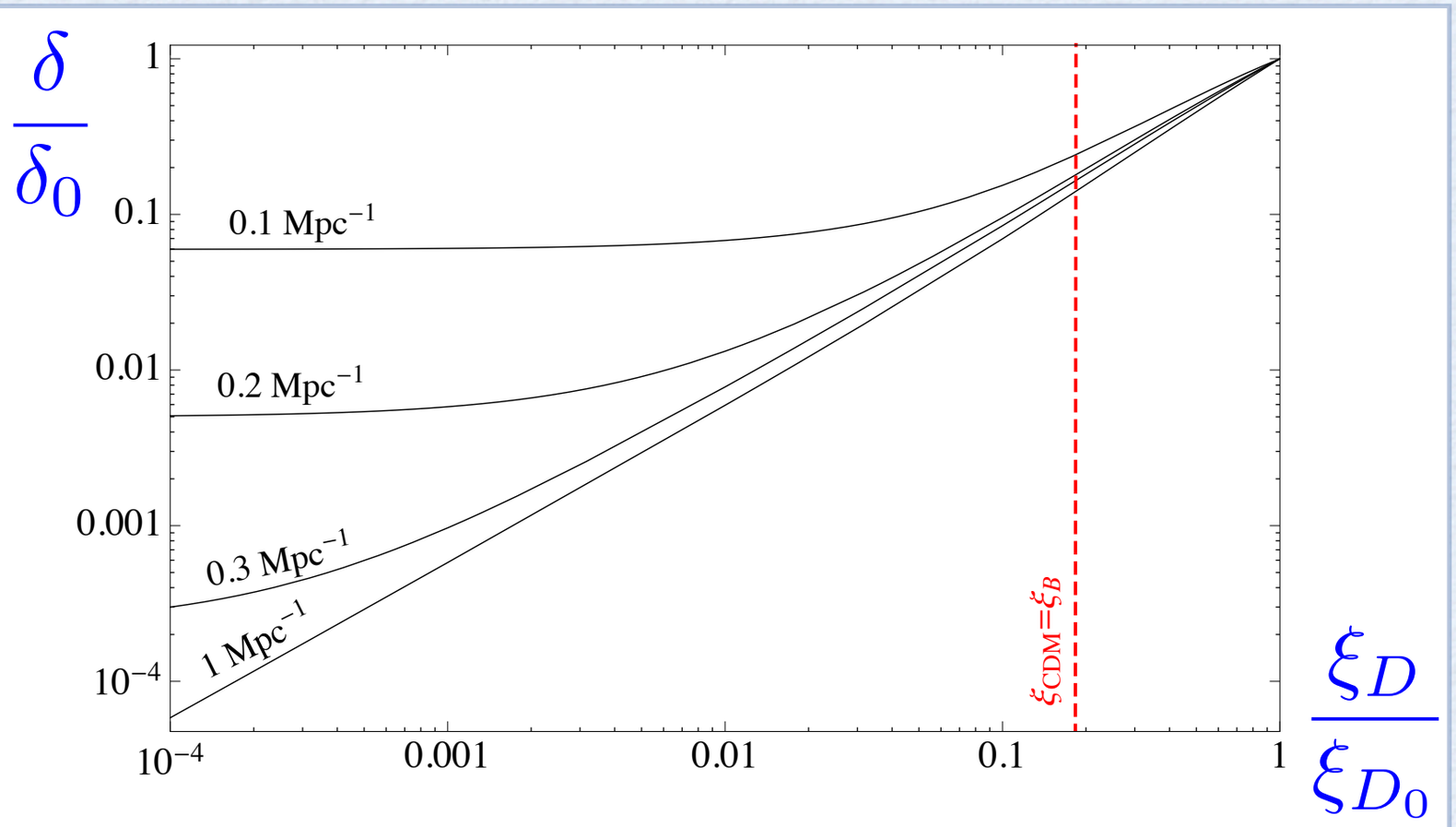

All relevant scales are Silk damped

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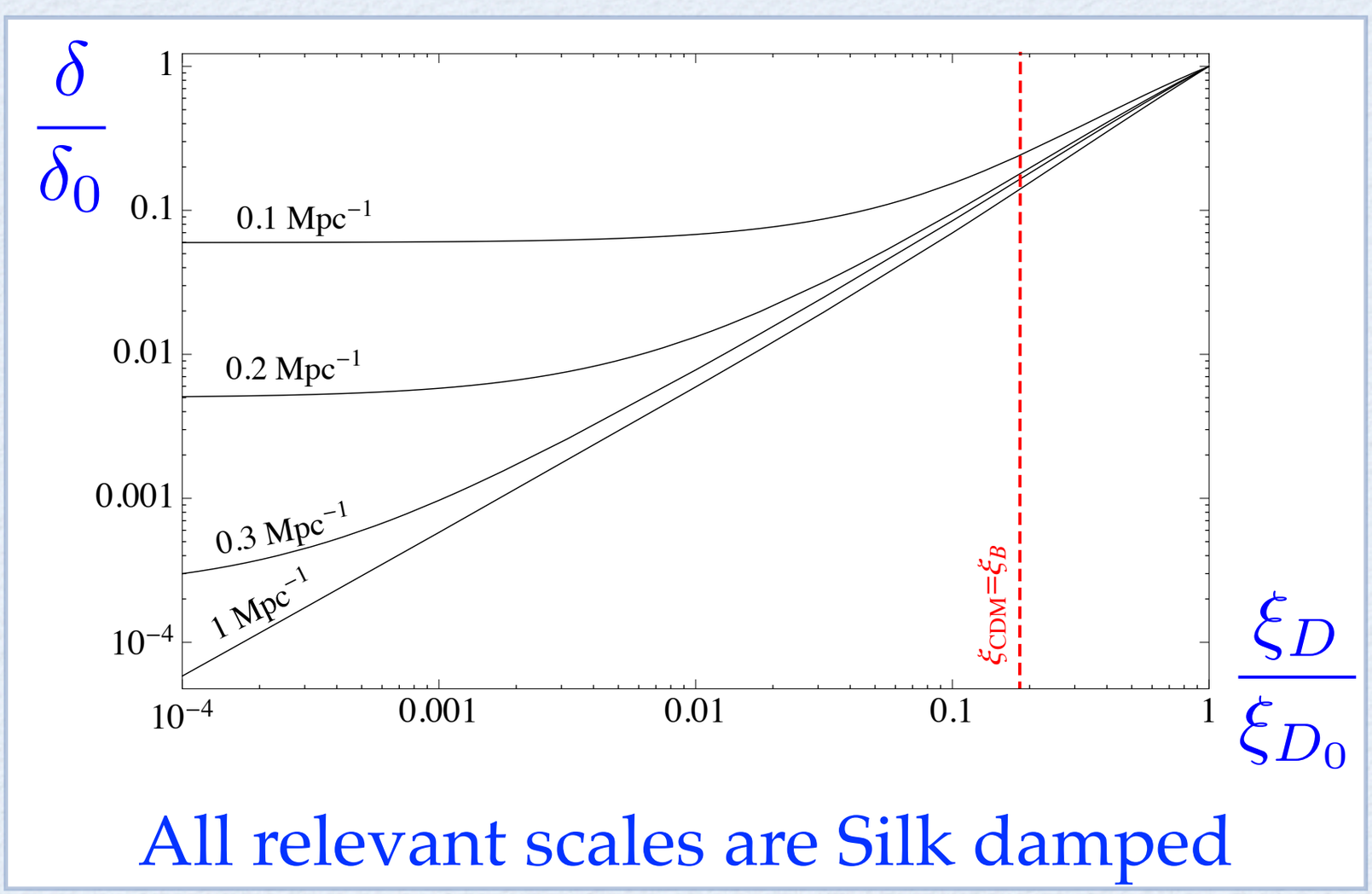

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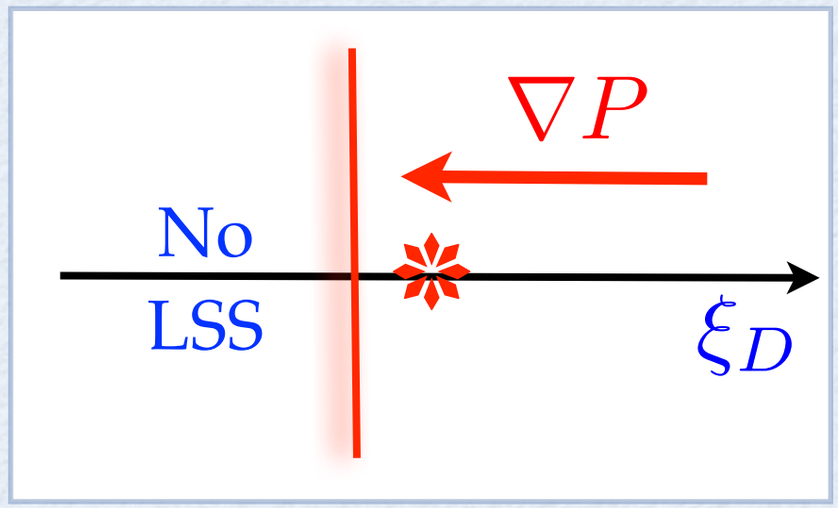

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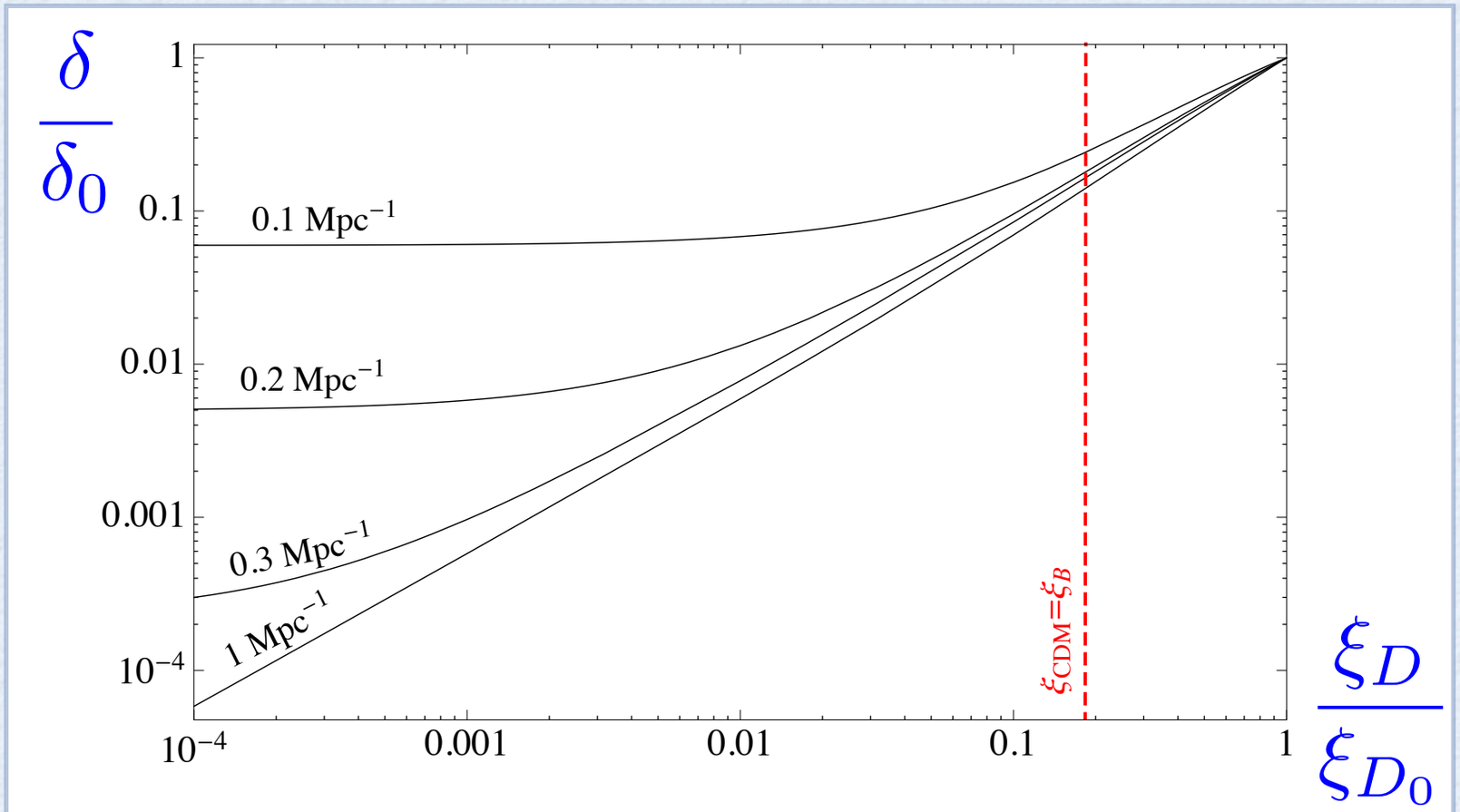

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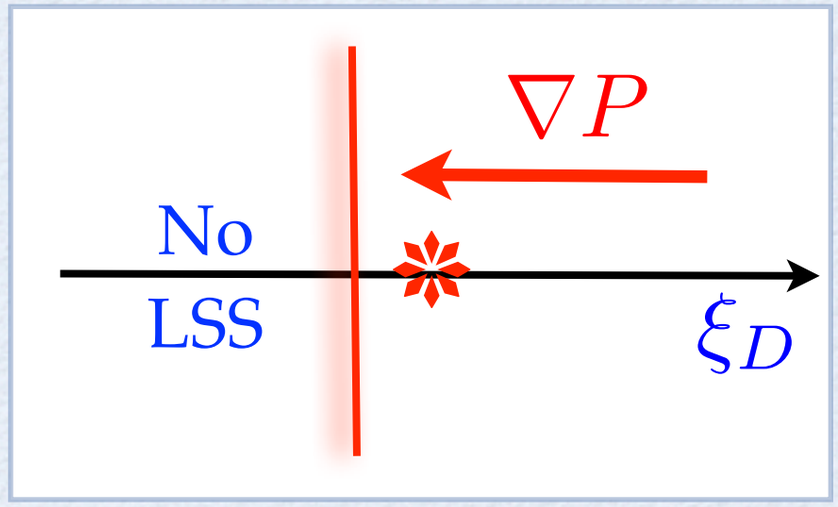


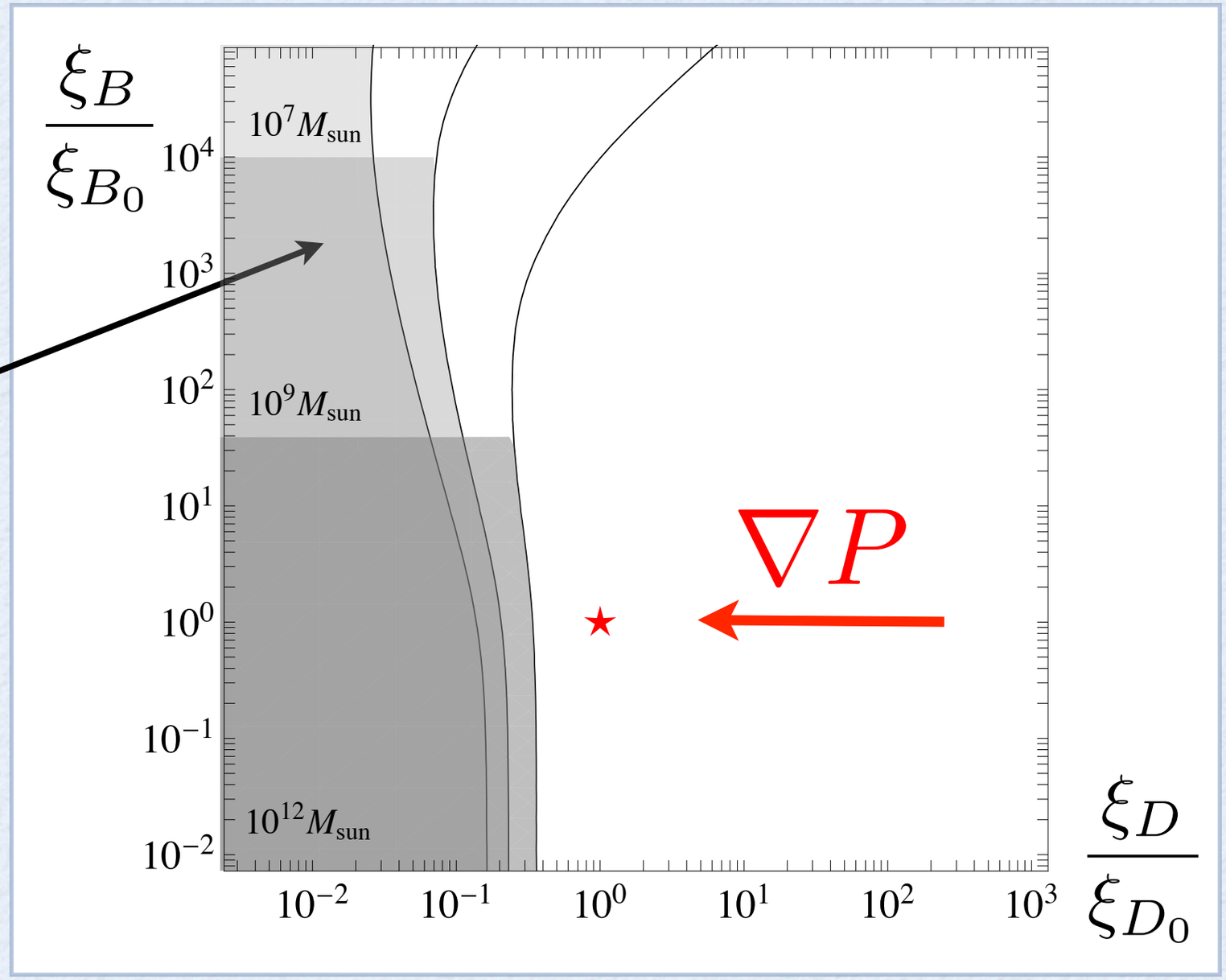
$$\frac{\xi_D^4}{\Lambda}$$

$10^2 - 10^3$ in Λ

$3 - 5$ in ξ_D

Varying Baryons and Dark Matter

Could we live here?



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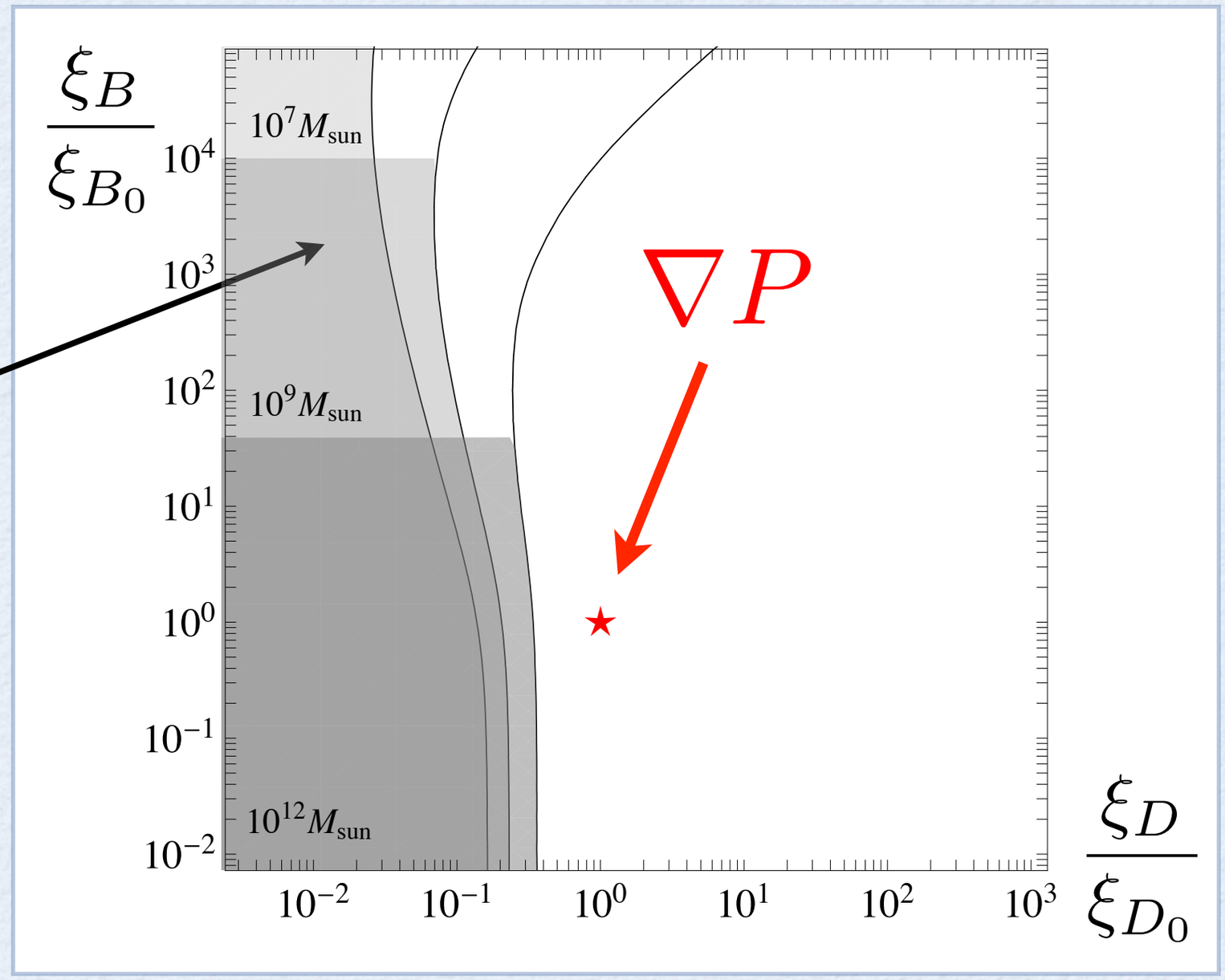

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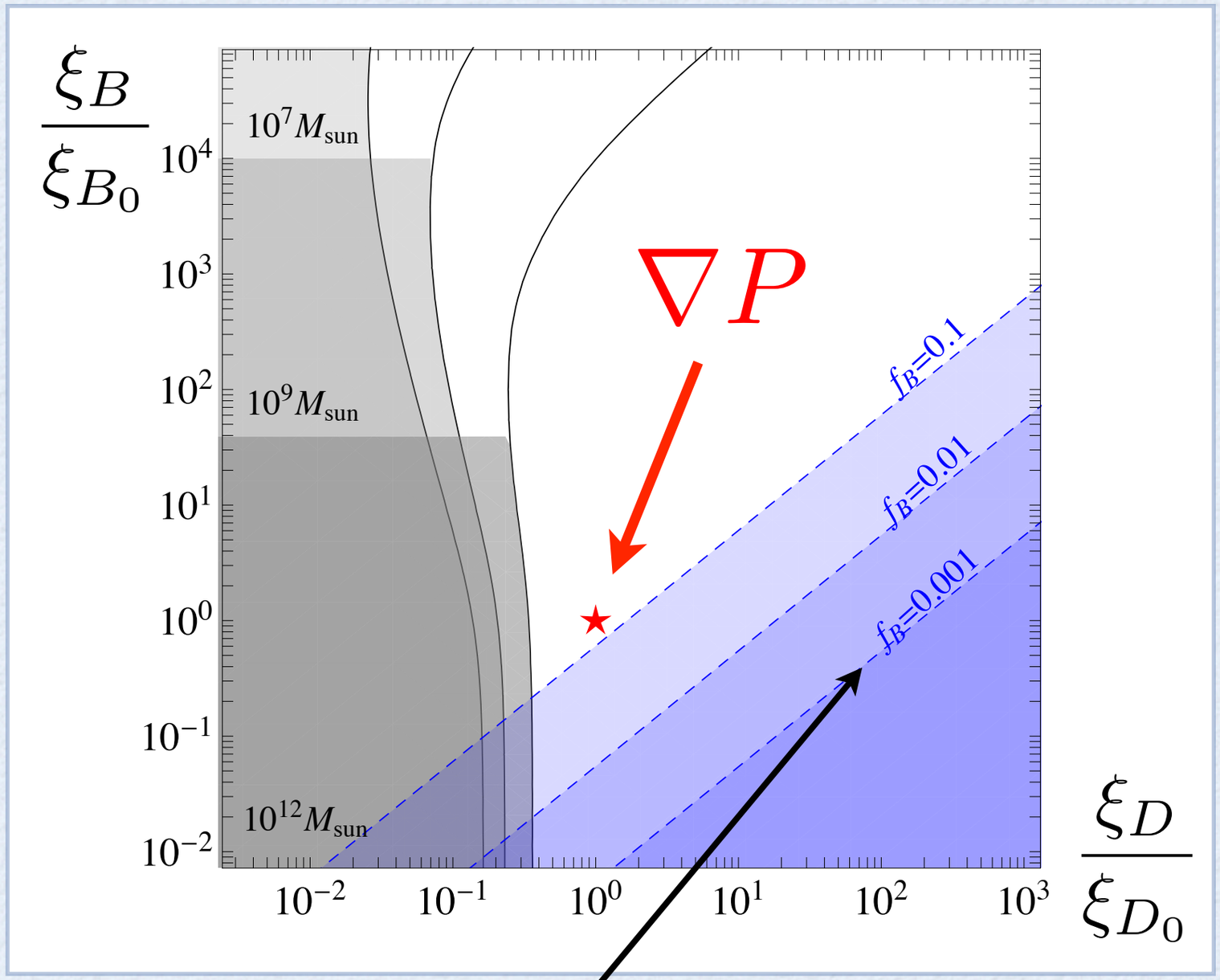


Probability cost from the measure

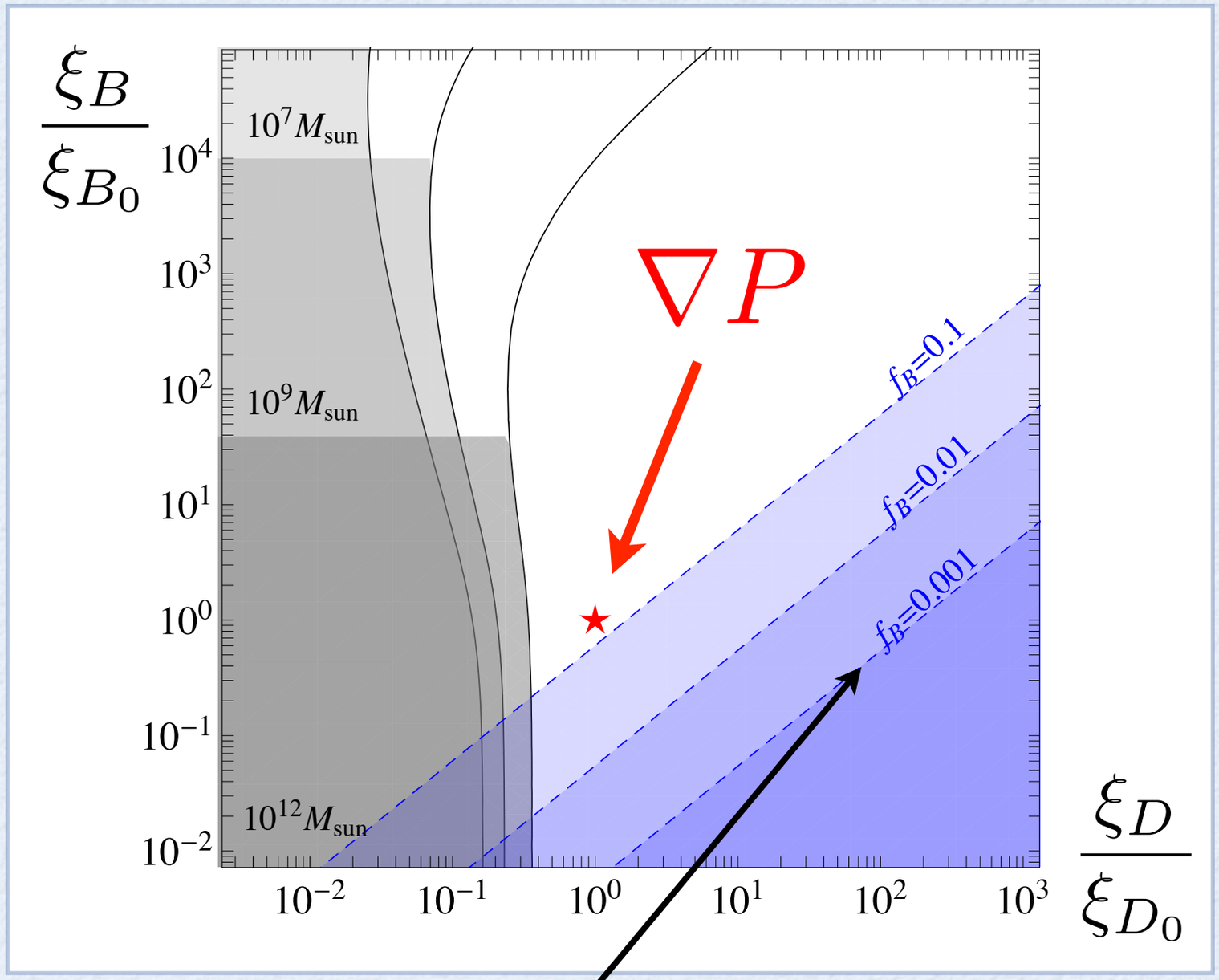
$$f_B = \frac{\xi_B}{\xi_D + \xi_B}$$

Freivogel 0810.0703
Bousso, Hall 1304.6407

Varying Baryons and Dark Matter

Explain both

ξ_D, ξ_B



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Towards a Larger Picture

Observable	**Physical Origin**
Λ	Observer dilution
v	Avoid ^{4}He universe
$m_{u,d,e}$	H, complex nuclei
ξ_D	Large Scale Structure
ξ_B	Observer dilution

- Tentative
- A beginning -- just “scatching the surface”
- Implications for Symmetries are Immense

(III)

Implications: SUSY

D'Eramo, Hall, Pappadopulo; to appear

SUSY LSP Freeze-Out

Suppose the overall scale of SUSY breaking scans:

$$\xi_D \propto \frac{1}{\sigma_A} \propto \tilde{m}^2$$

$$dP \sim \tilde{m}^n \left(\frac{v^2}{\tilde{m}^2}\right) d\ln\tilde{m}$$

EWSB fine-tuning

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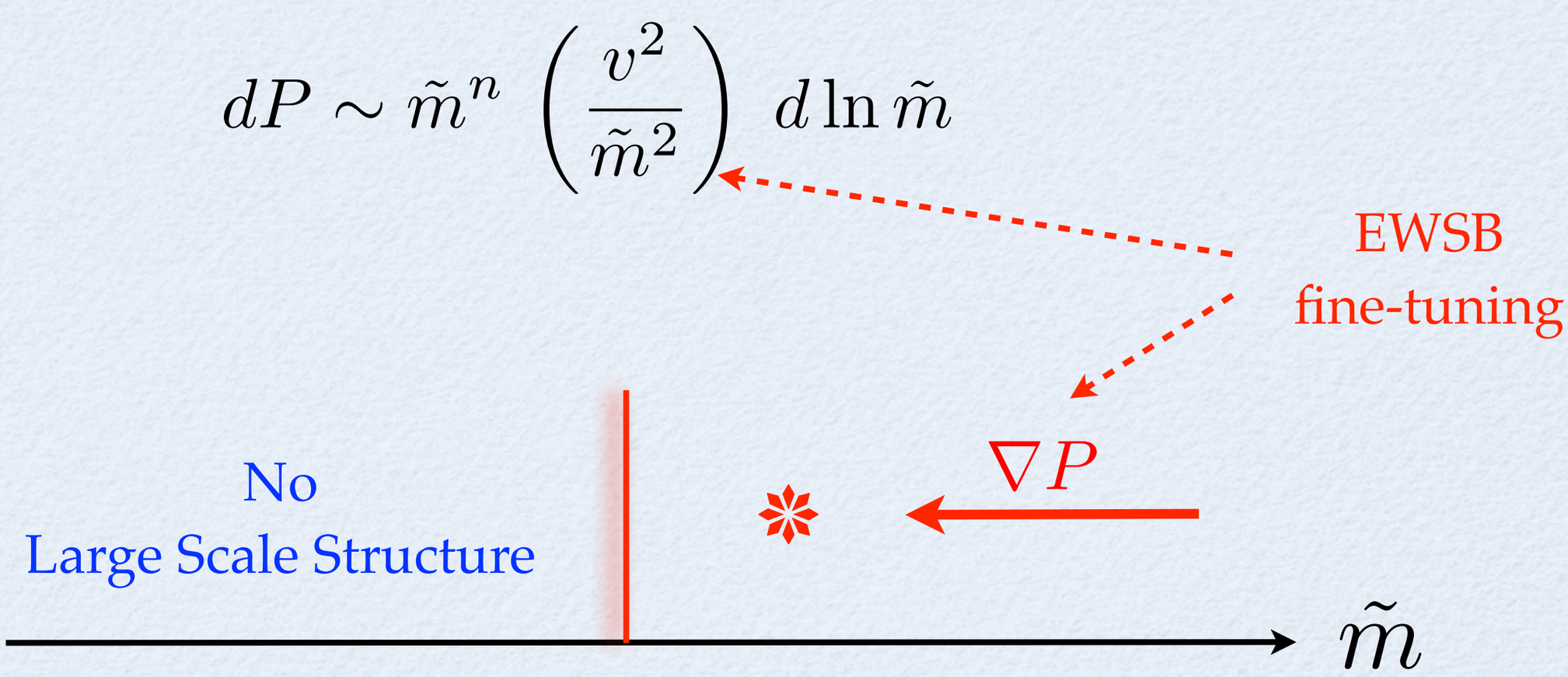

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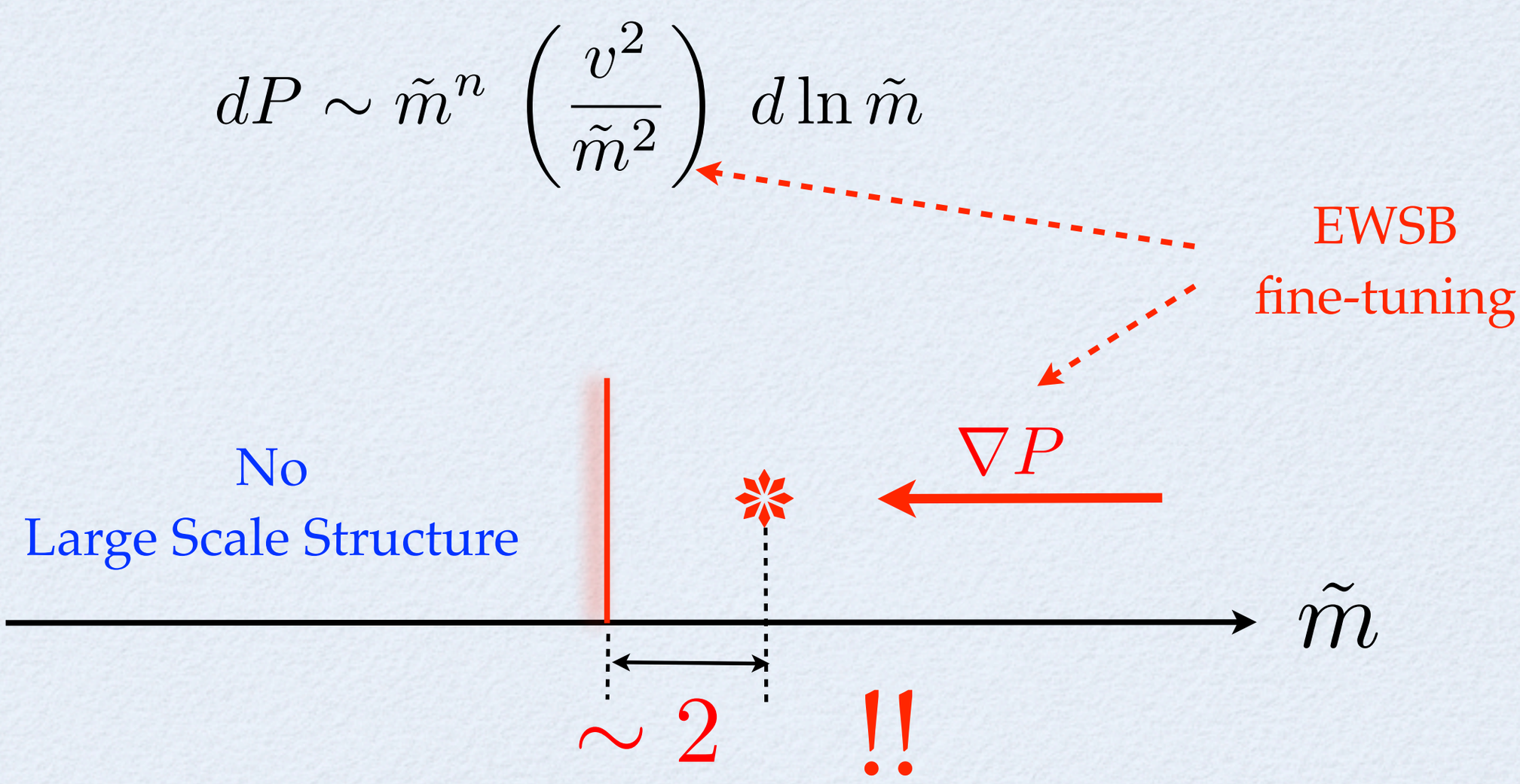
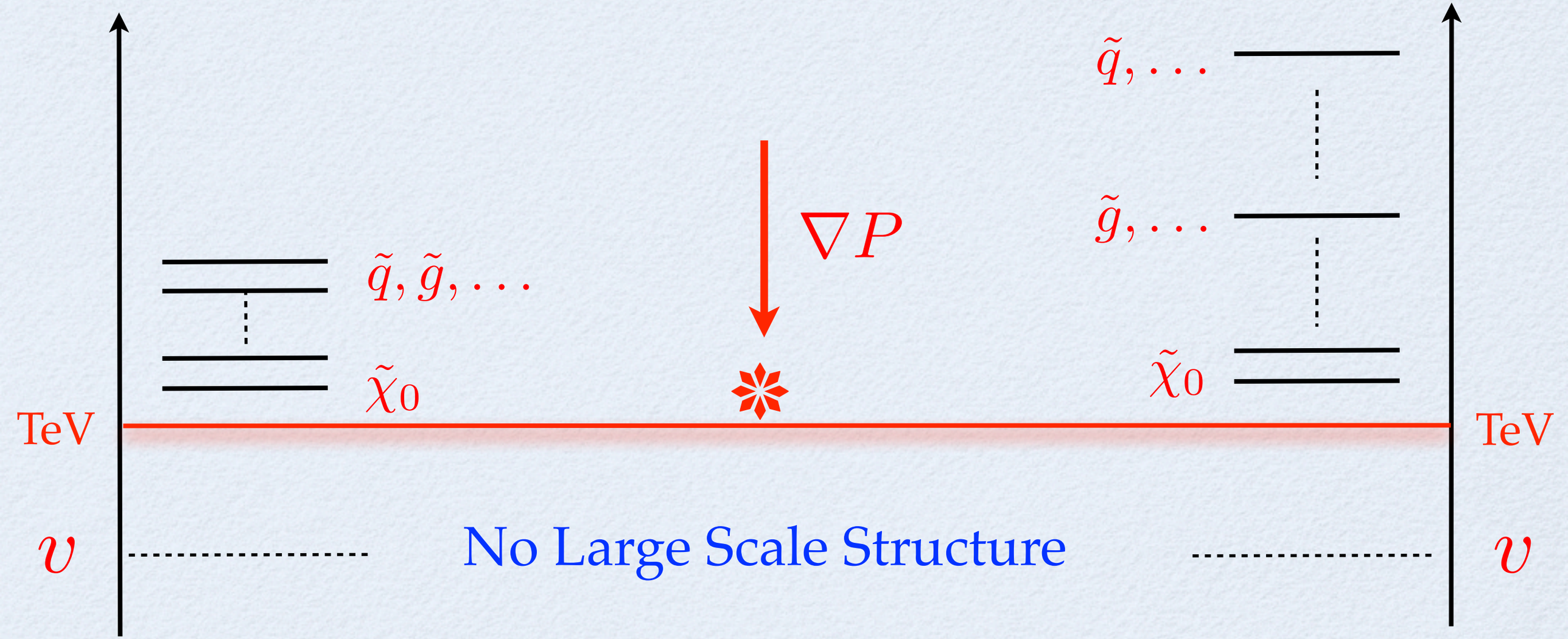


A Little SUSY Hierarchy

The SUSY spectrum may be the most natural consistent with Large Scale Structure

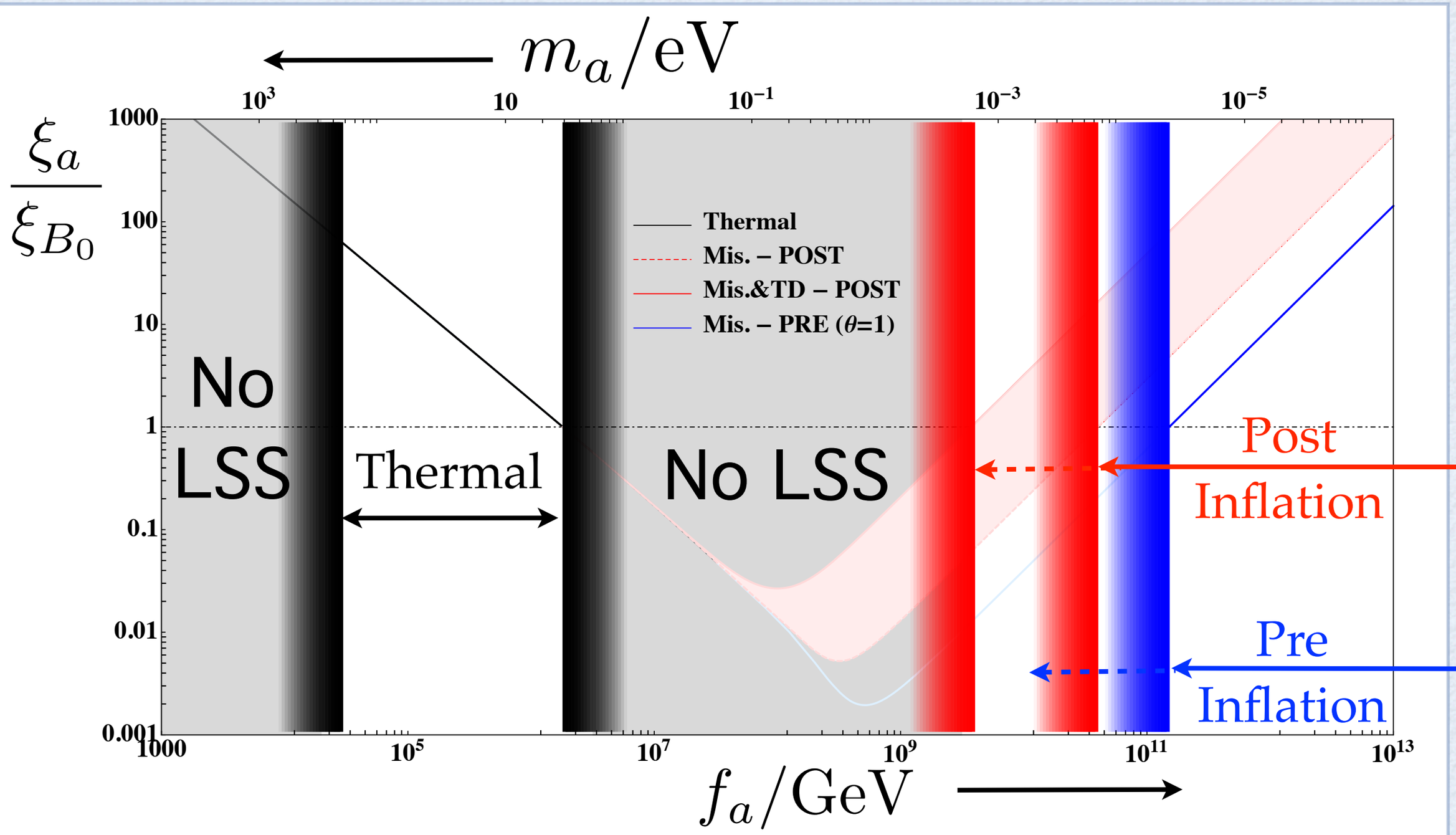


(III)

Implications:
Axion with Low f

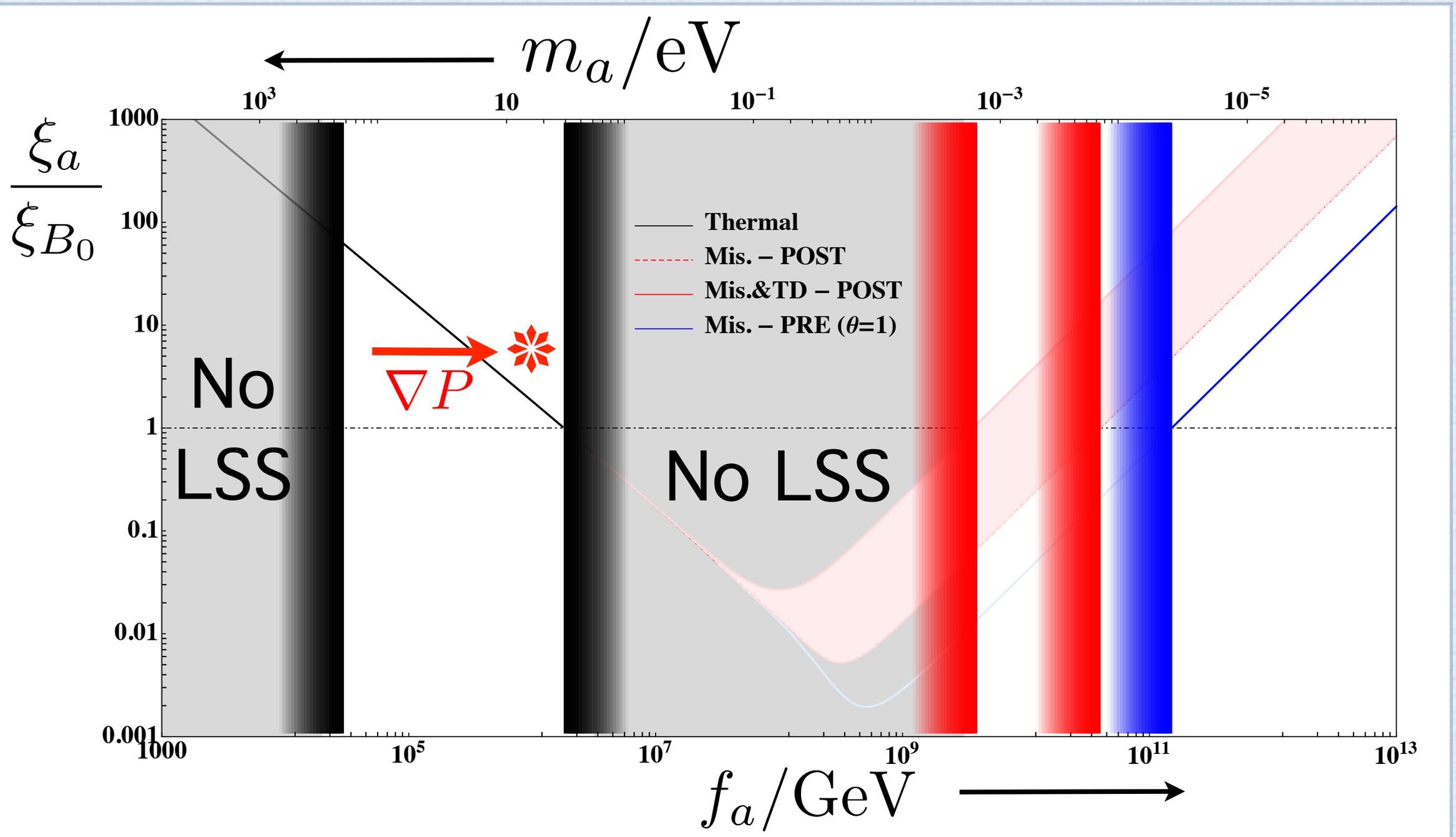
D'Eramo, Hall, Pappadopulo; to appear

Axions and the LSS Boundary



(using results from: Bae, Huh, Kim 0806.0497; Kawasaki, Nakayama 1301.1123)

Axions with High f



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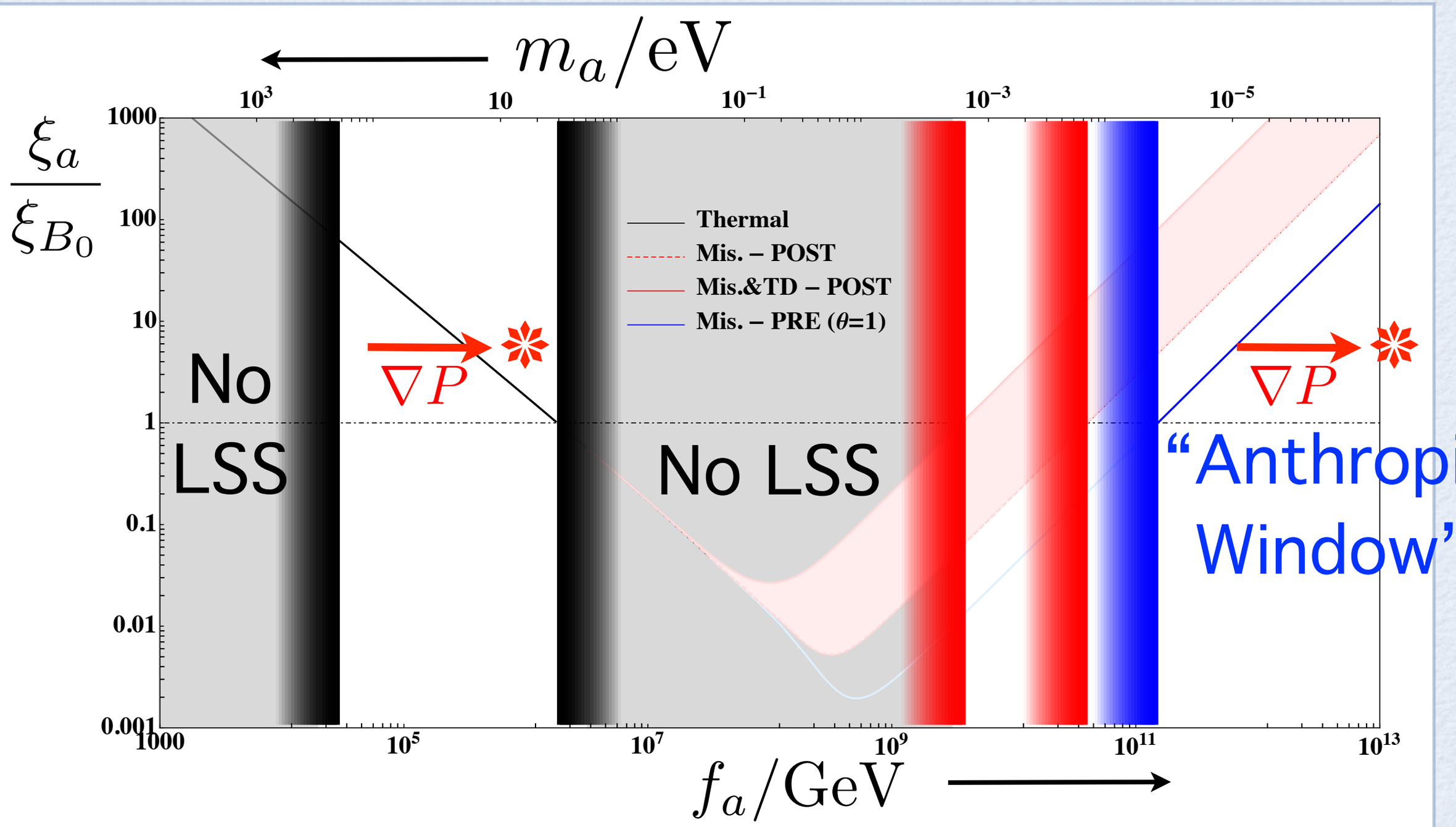

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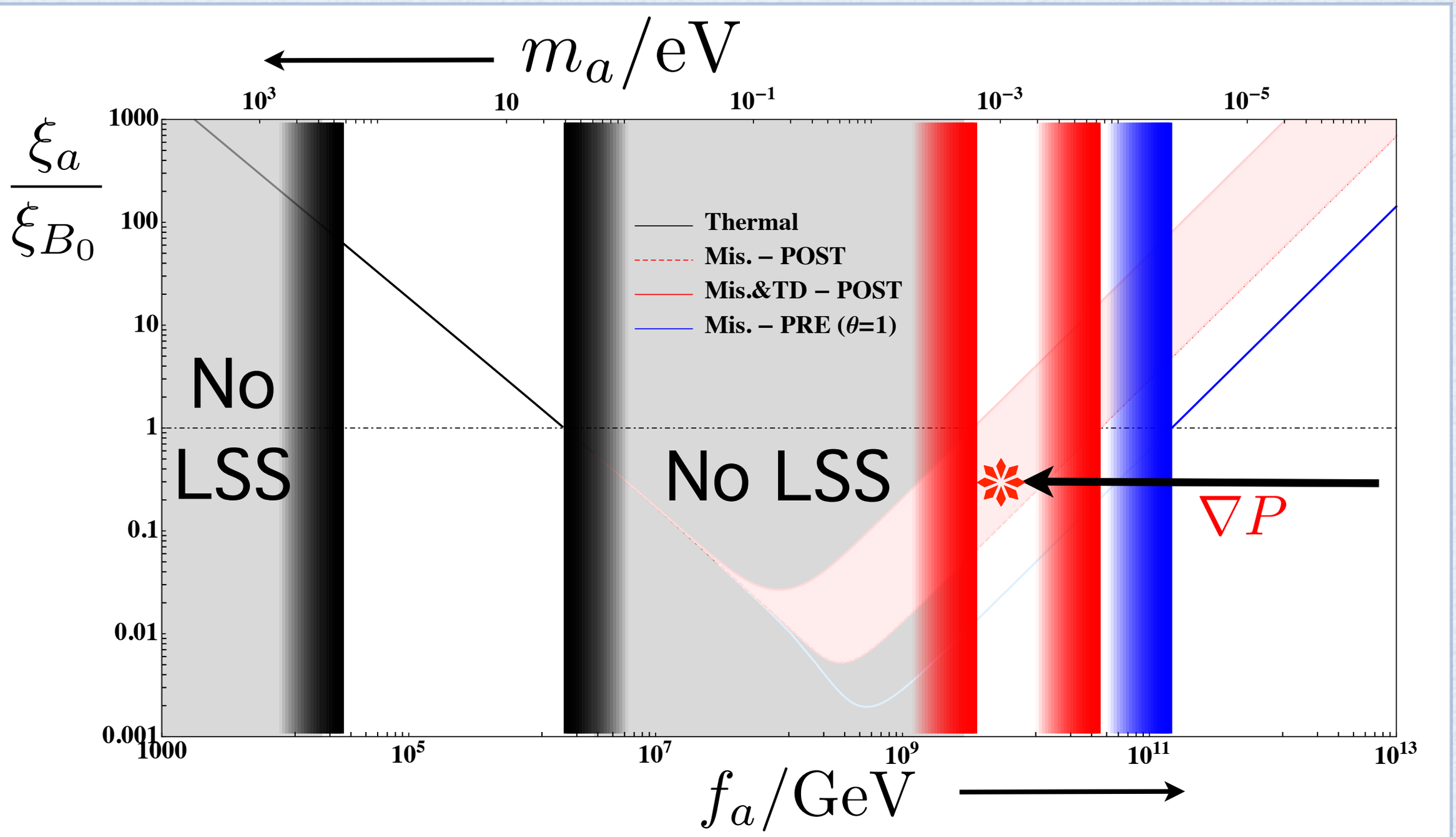

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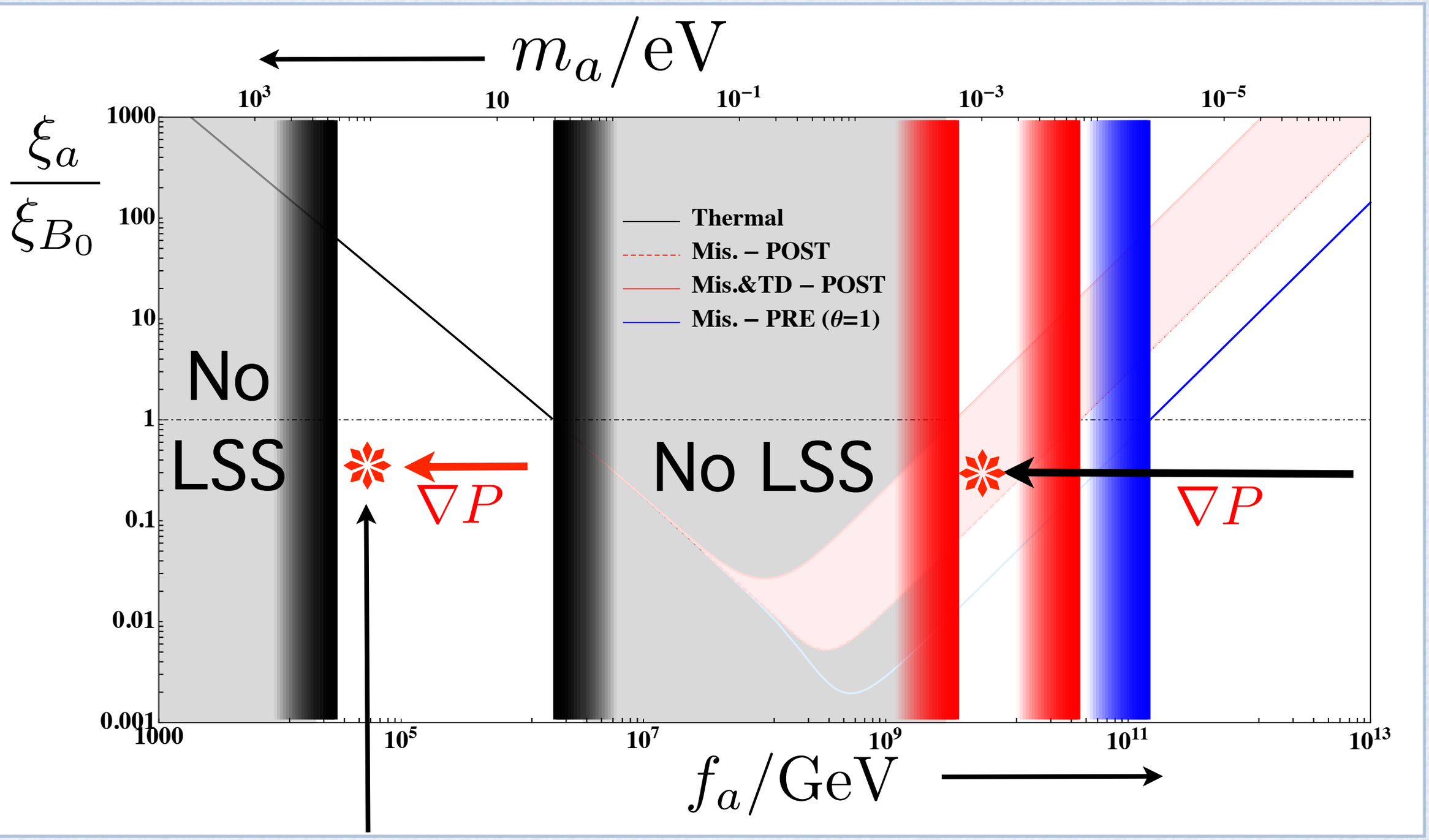

Likely Excluded: free streaming, decays, stars

Axion Dark Matter Searches

LSS boundary predicts single component dark matter

From observed abundance we can predict f_a

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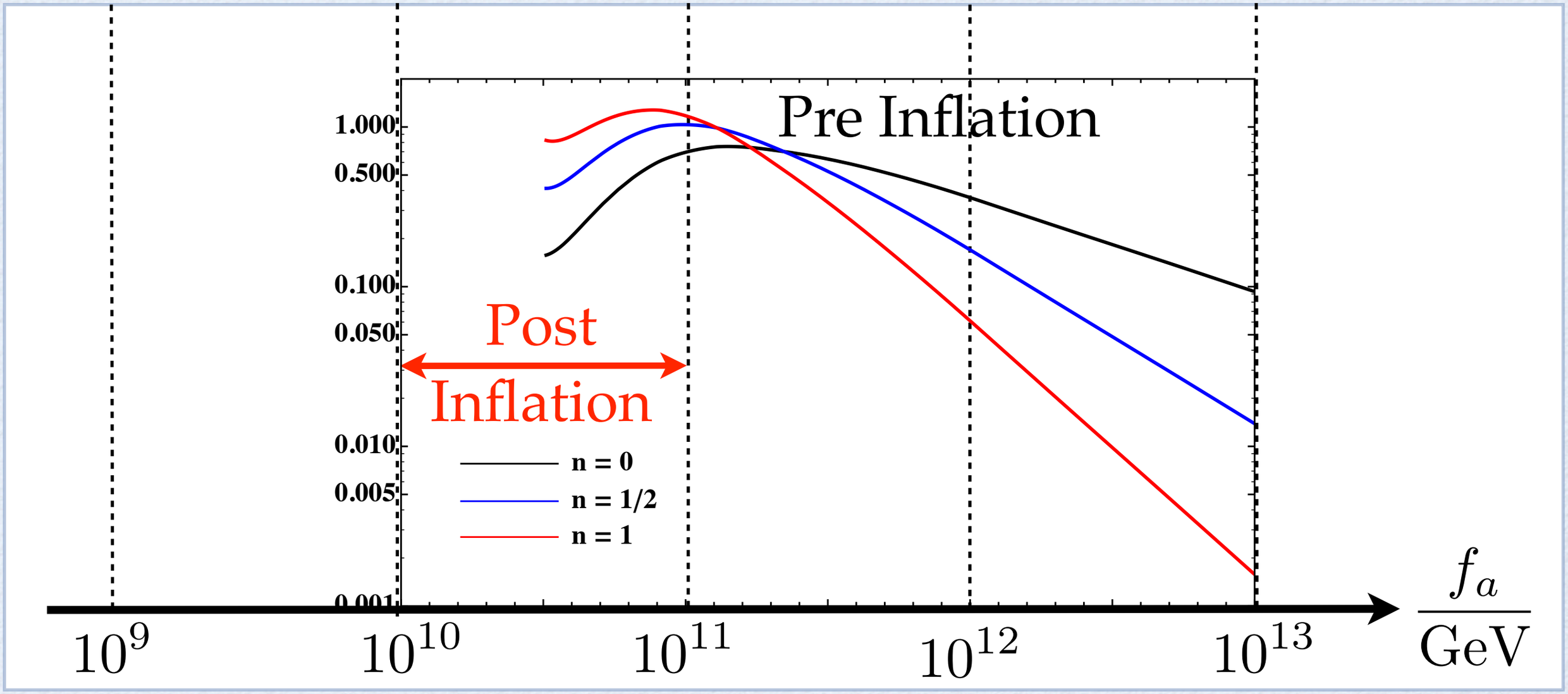

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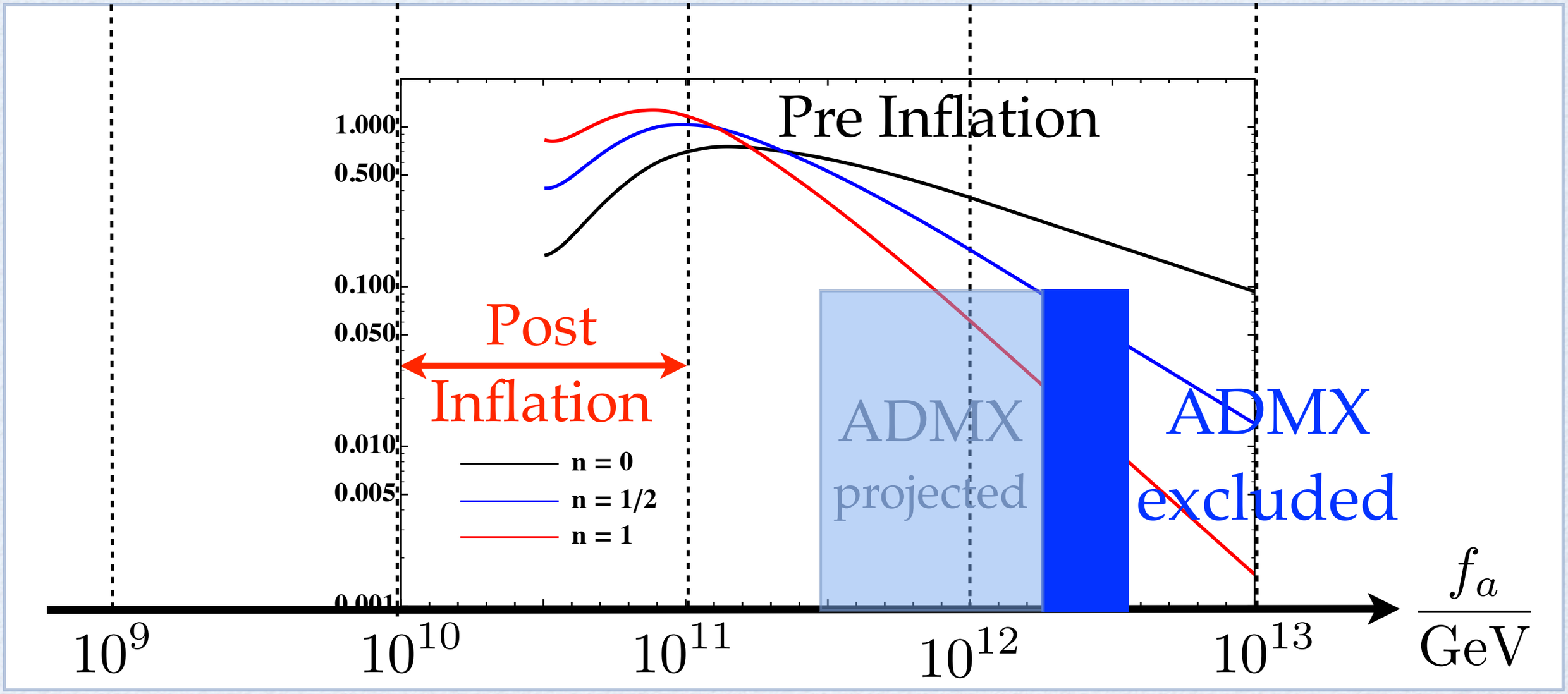

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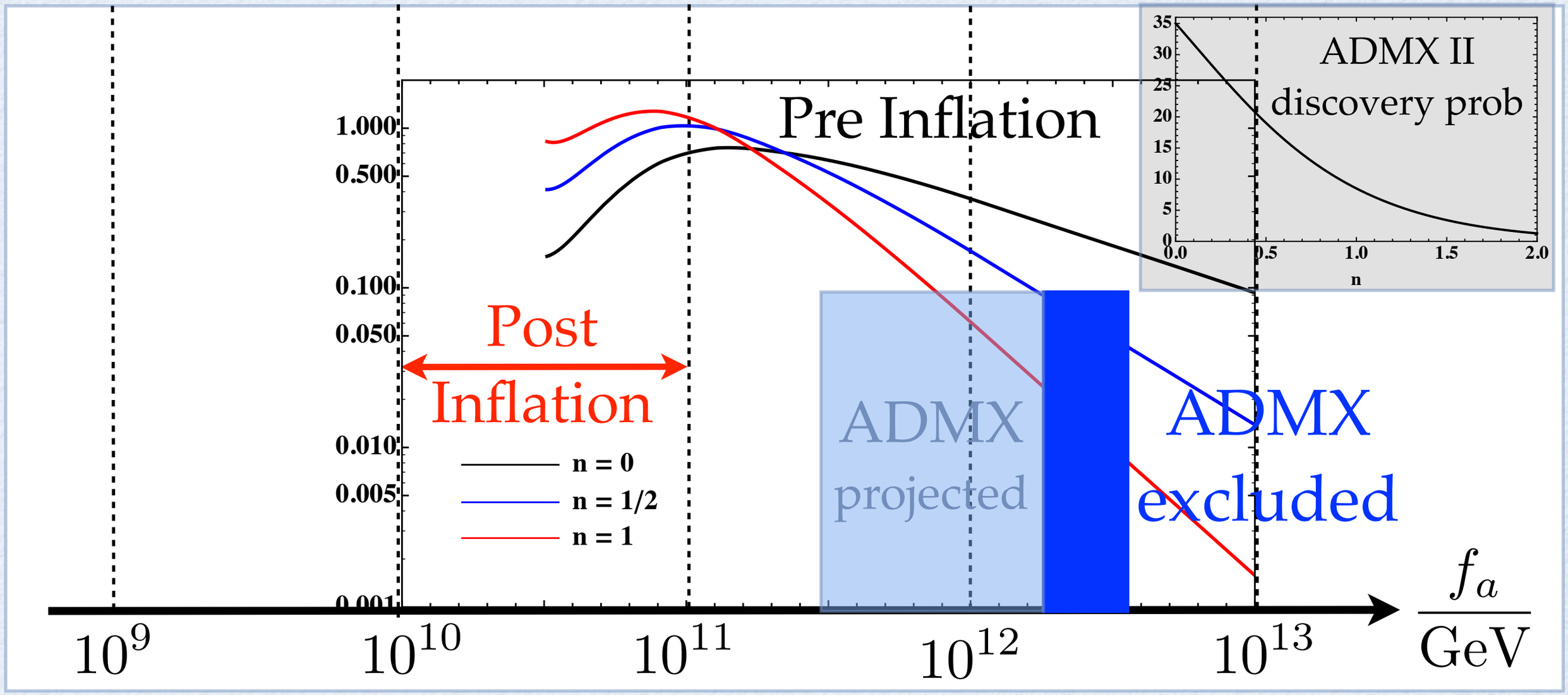

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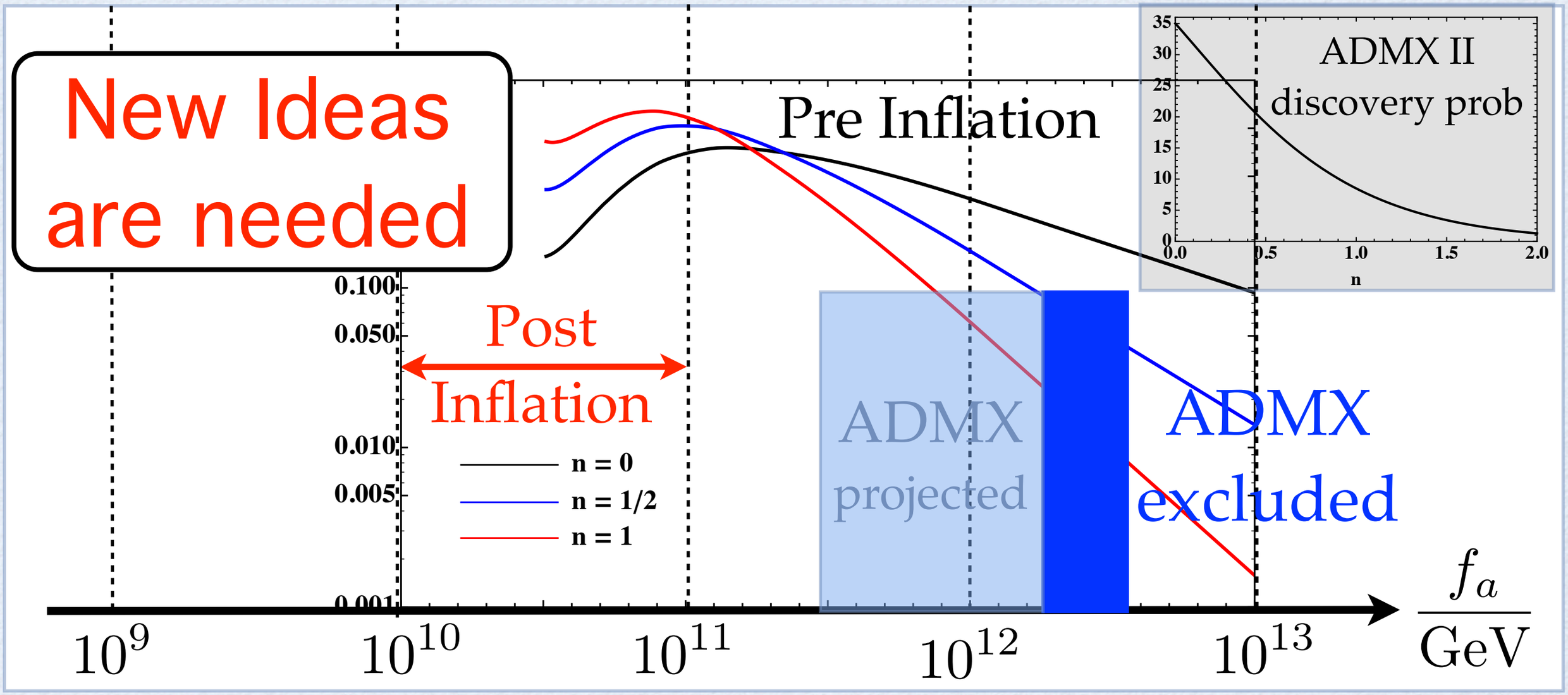

(IV)

A Model for the Multiverse Axion and the Higgs Mass

D'Eramo, Hall, Pappadopulo; to appear

Minimal Supersymmetric PQ

- MSSM: $W = \mu H_u H_d$ Radiative EWSB
- MSPQ: $W = \xi S H_u H_d$ Radiative PQB

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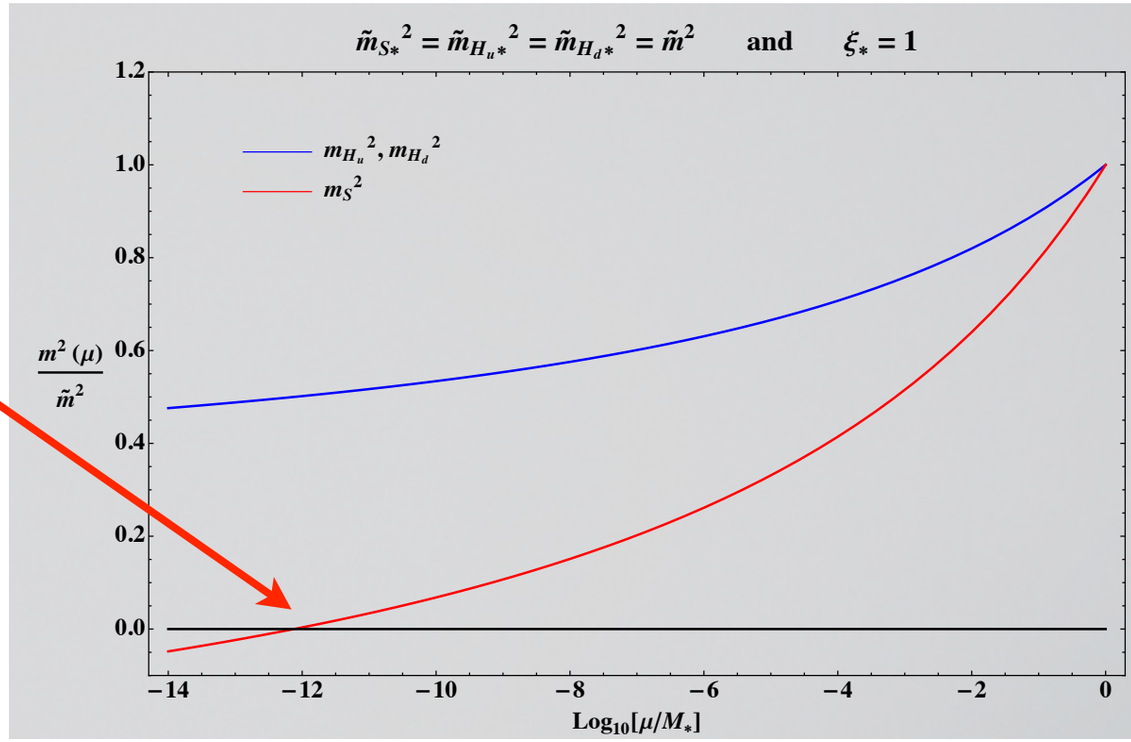
Dimensional Transmutation

$$f \sim e^{-\frac{16\pi^2}{\xi^2}} M_*$$



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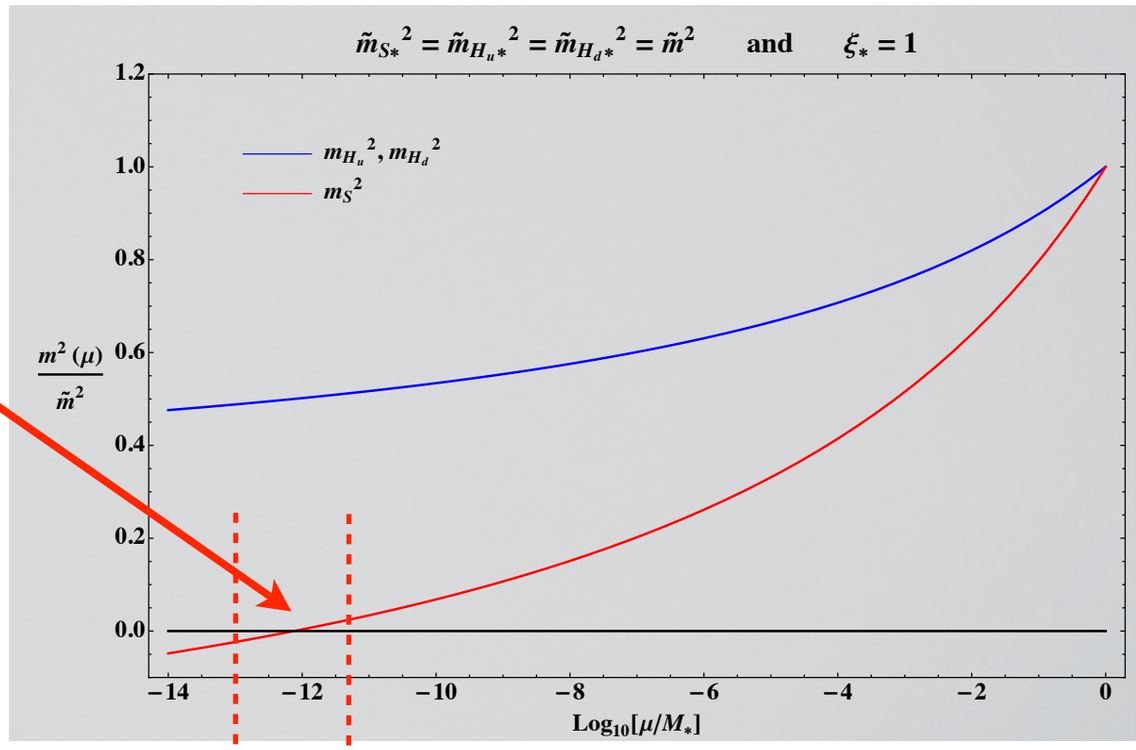
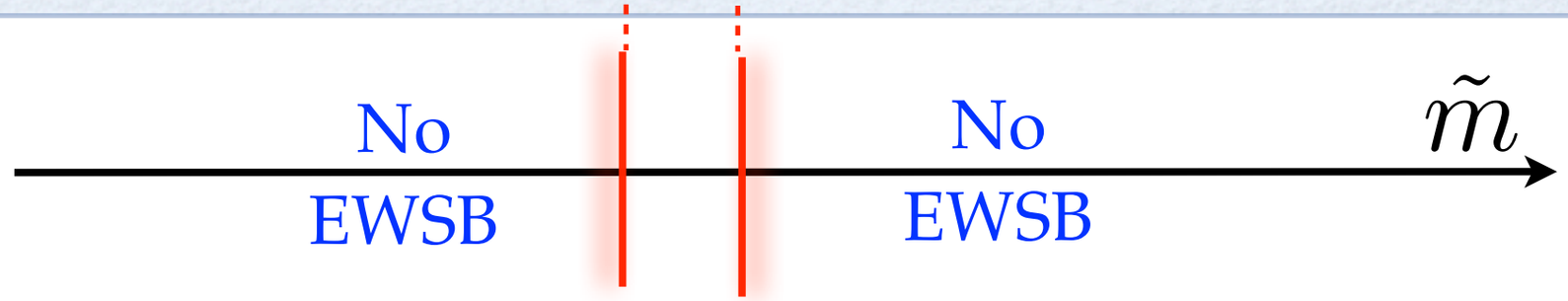
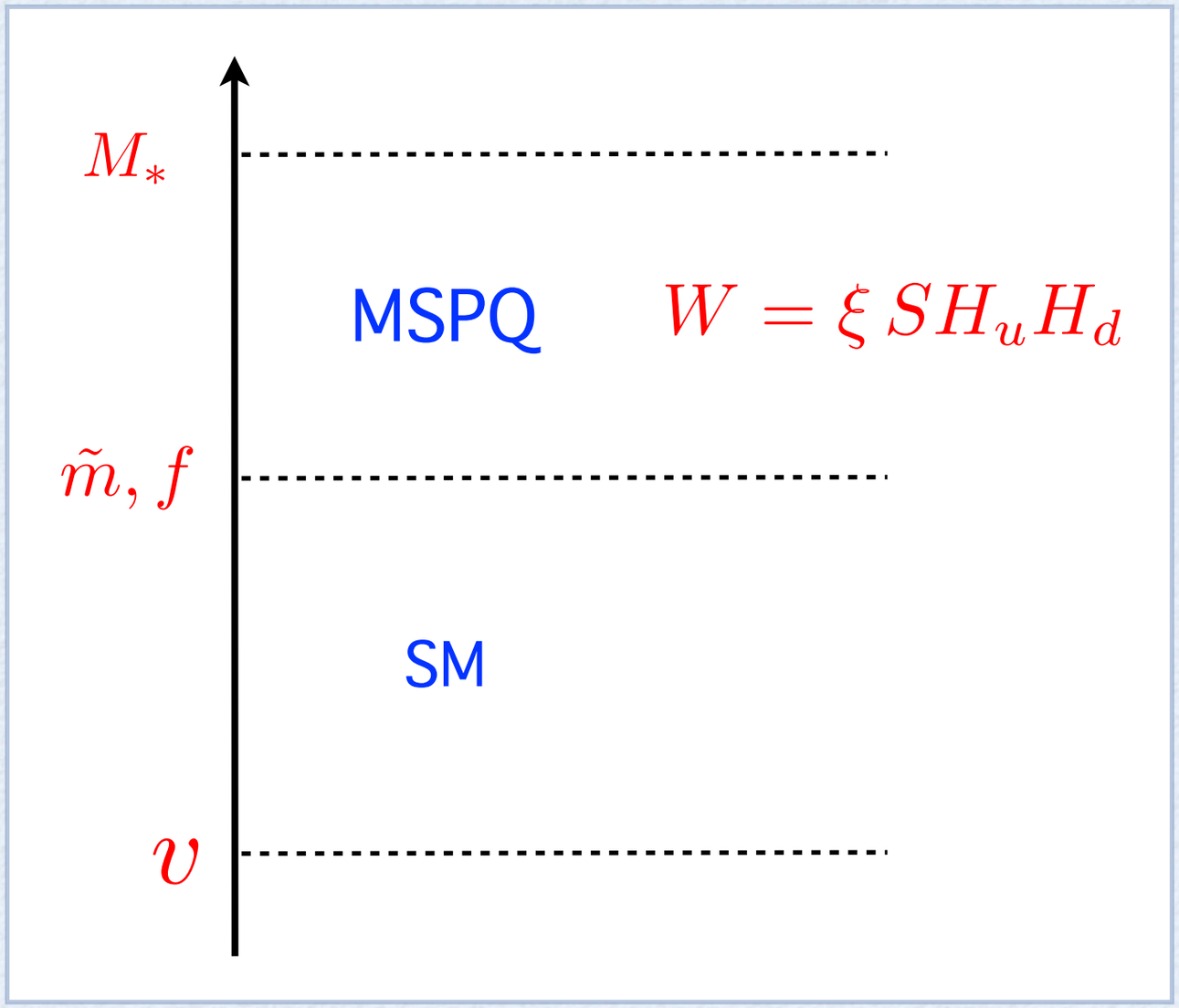


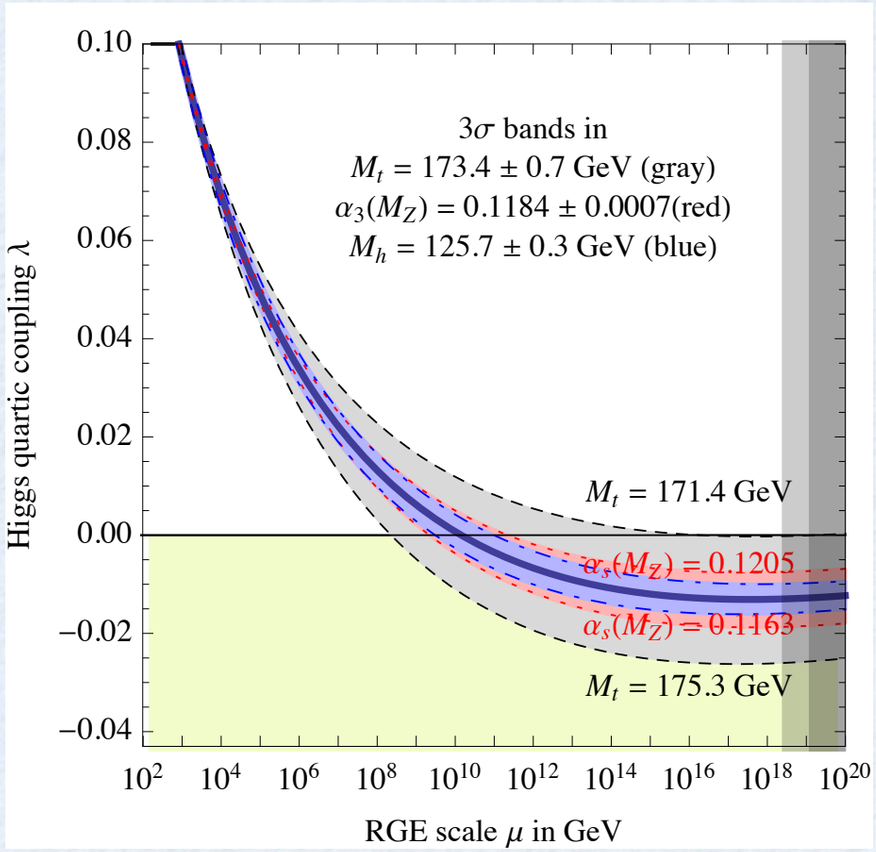


Mass Scales



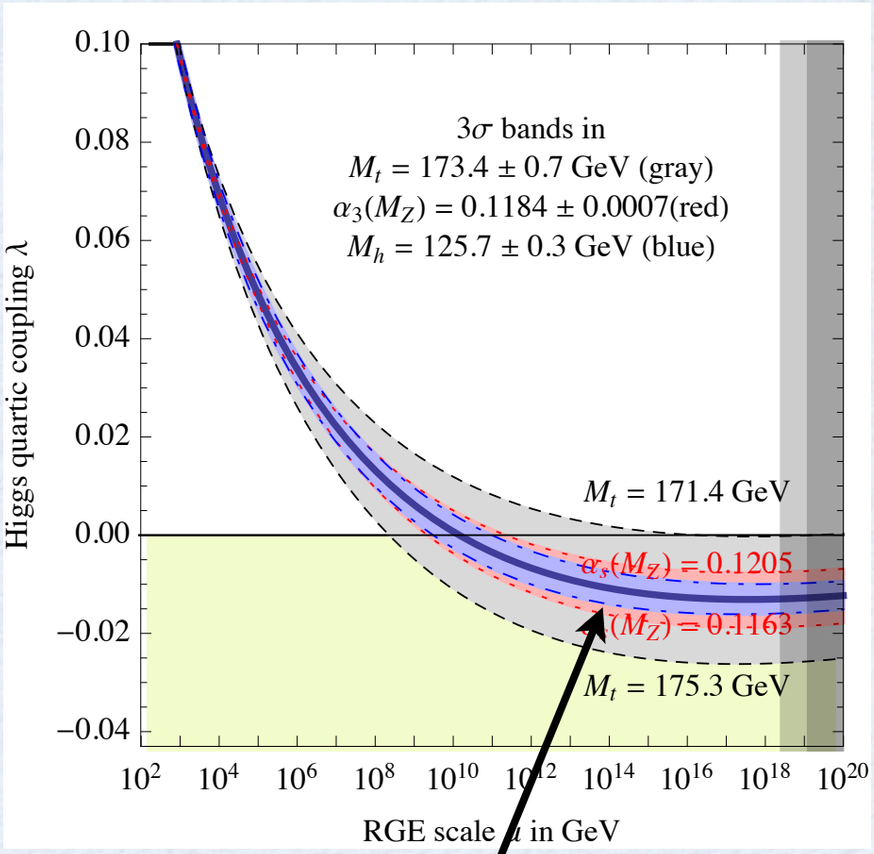
- The Multiverse allows a new Minimal SUSY
- It solves strong CP, and gives axion DM

Higgs Mass From Vacuum Stability



Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia
1307.3536

Higgs Mass From Vacuum Stability



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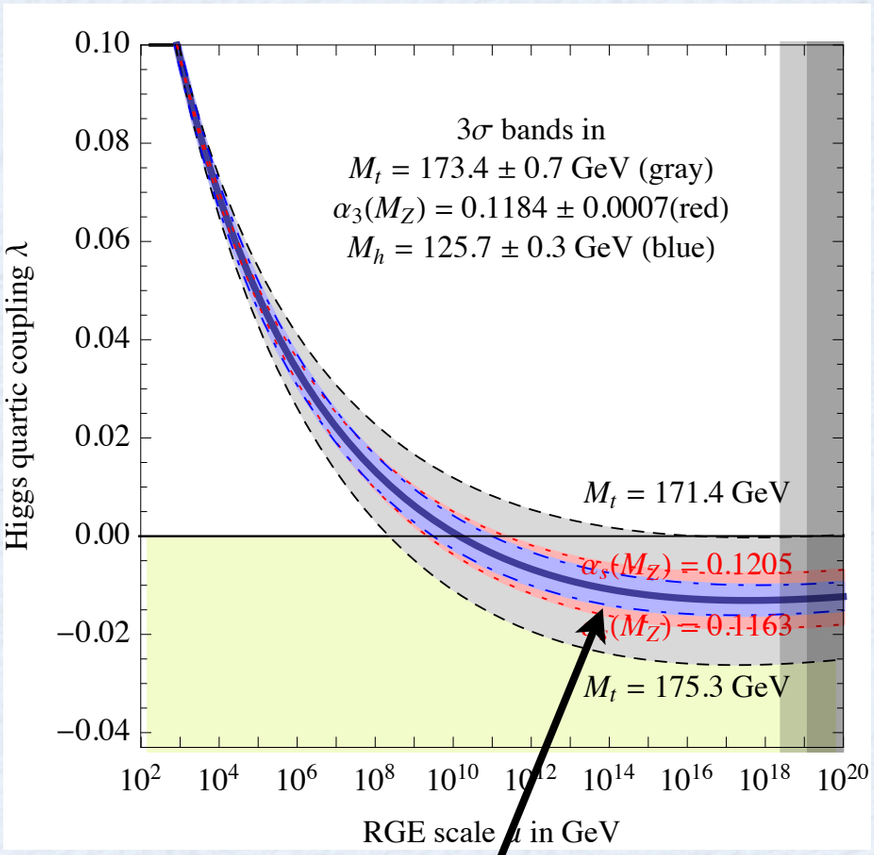
Why is quartic so small?

Higgs Mass From Vacuum Stability



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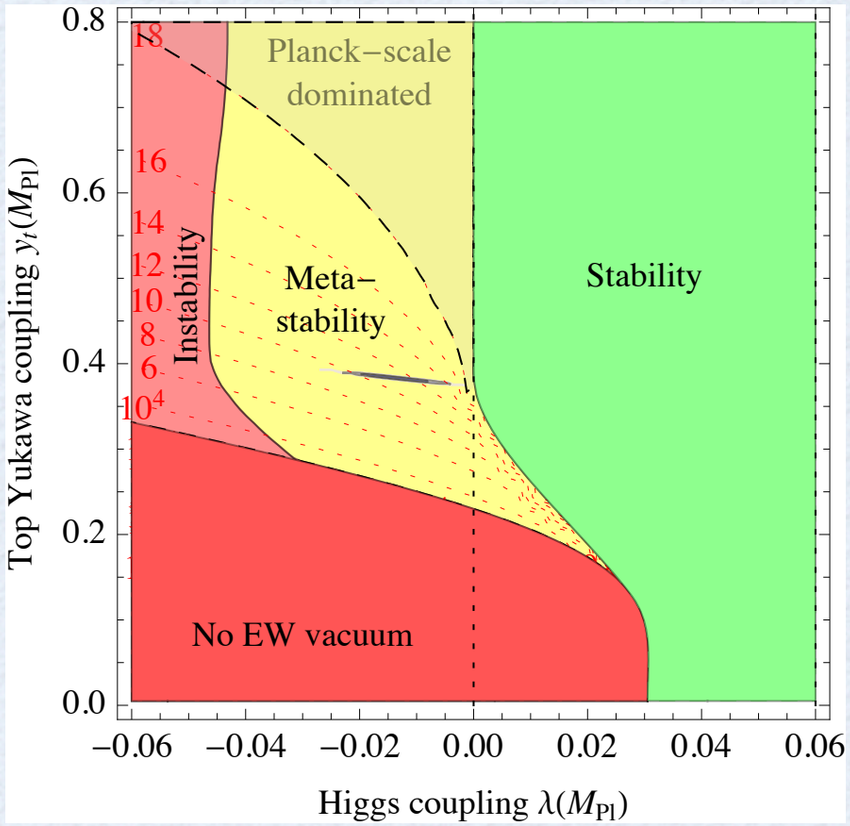

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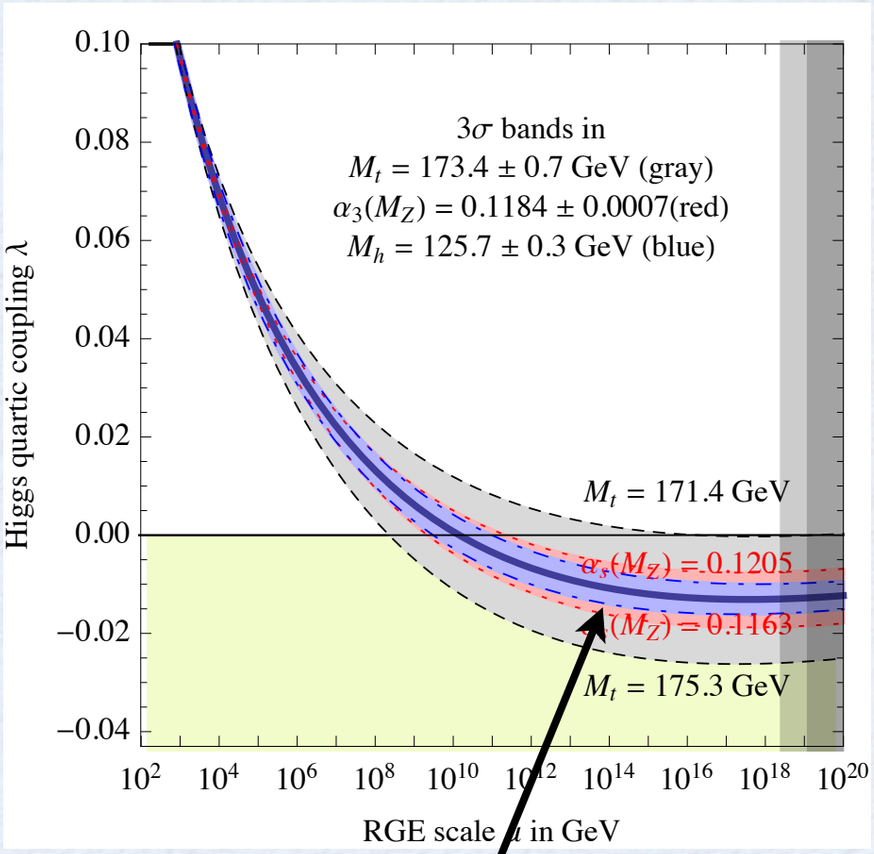

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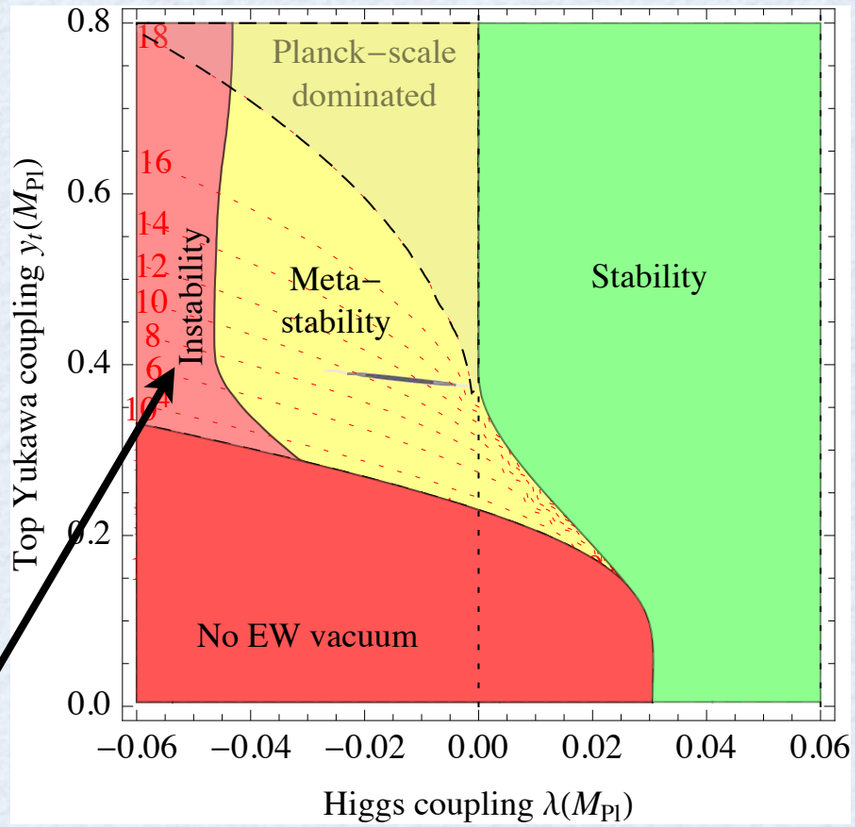
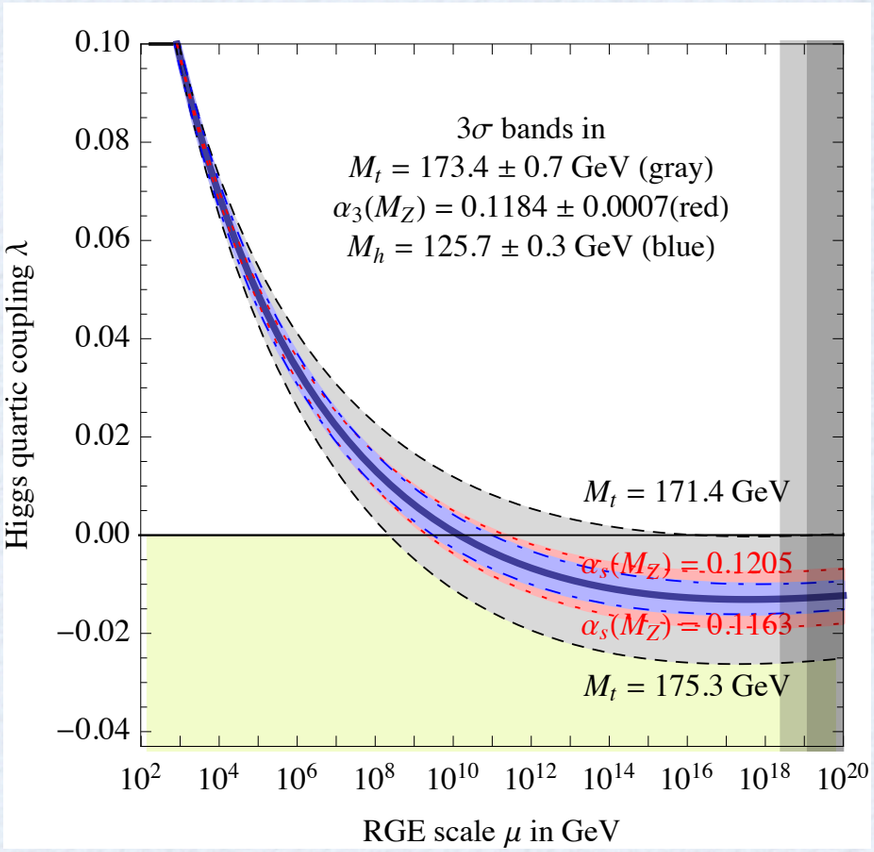


Why is quartic so small?

Close to vacuum instability!

Higgs Mass From Vacuum Stability



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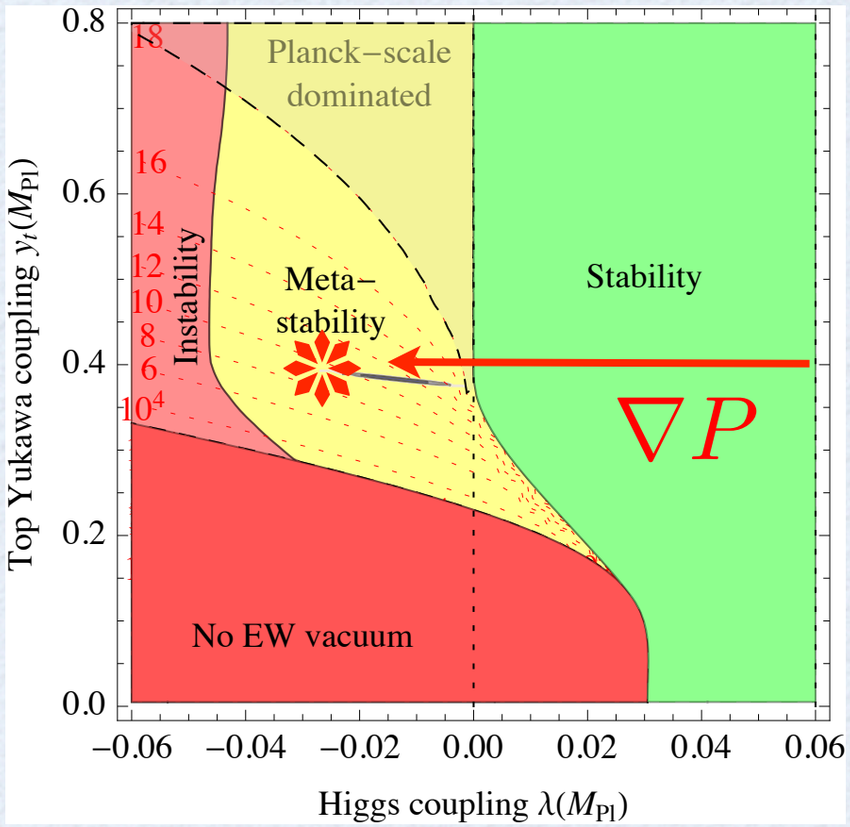
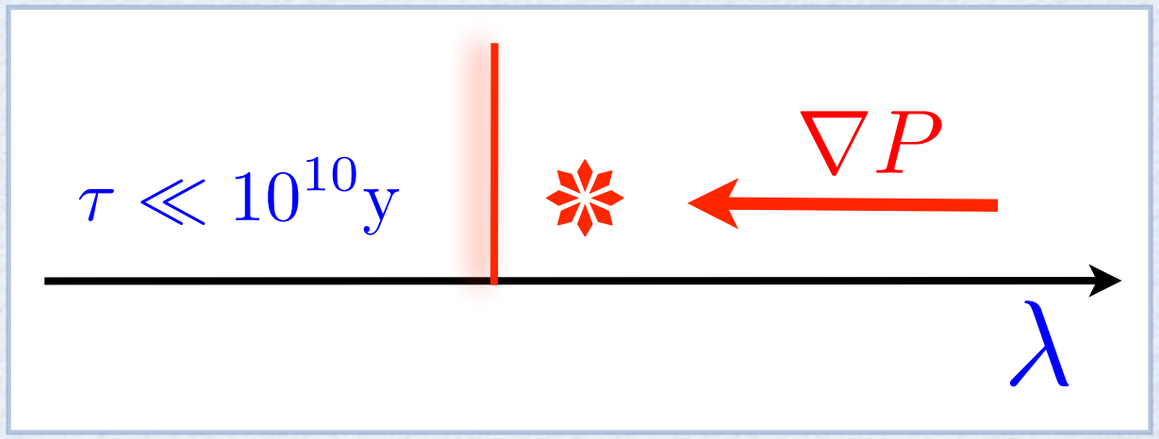
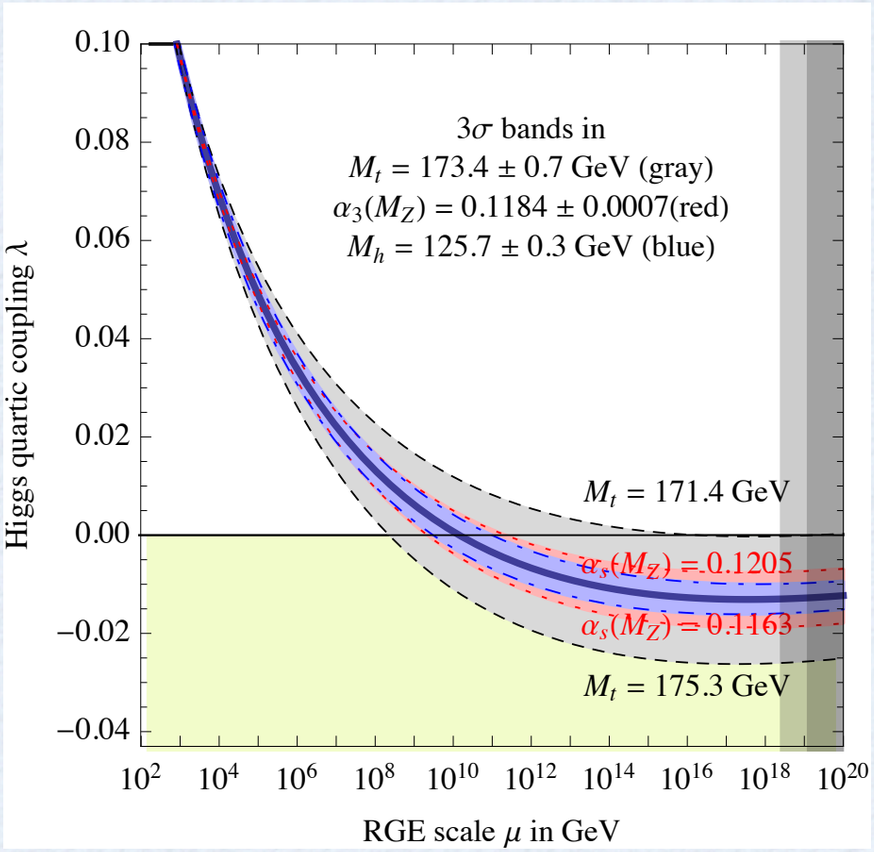


$$m_h = (112 \pm 8 + 25/n)\ \text{GeV}$$

Feldstein, Hall, Watari
hep-ph/0608121



Higgs Mass in MSPQ



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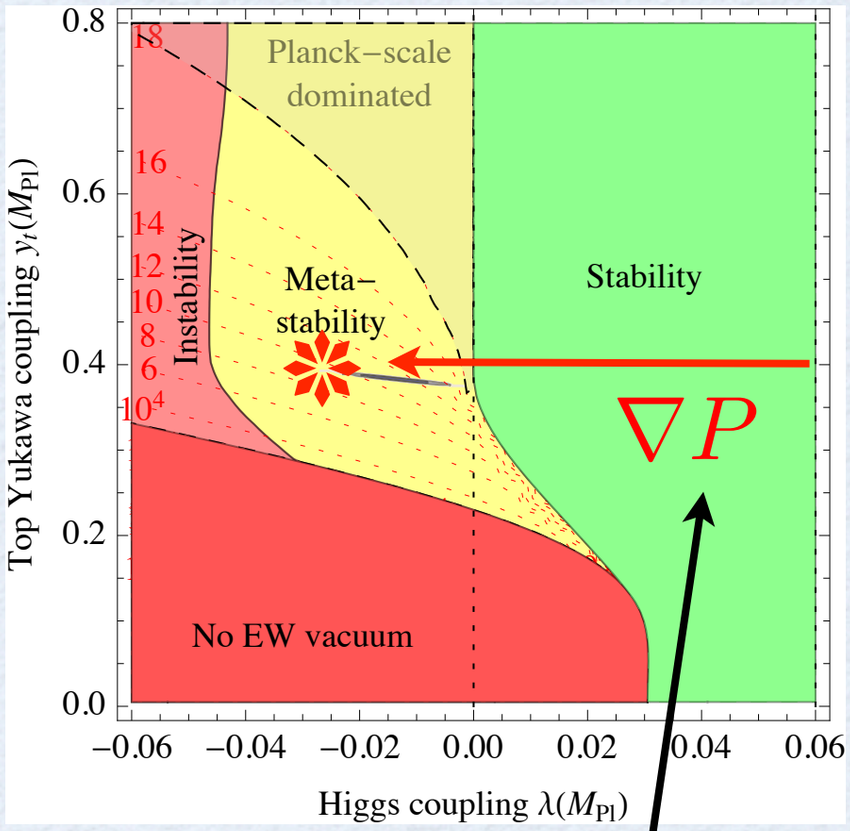
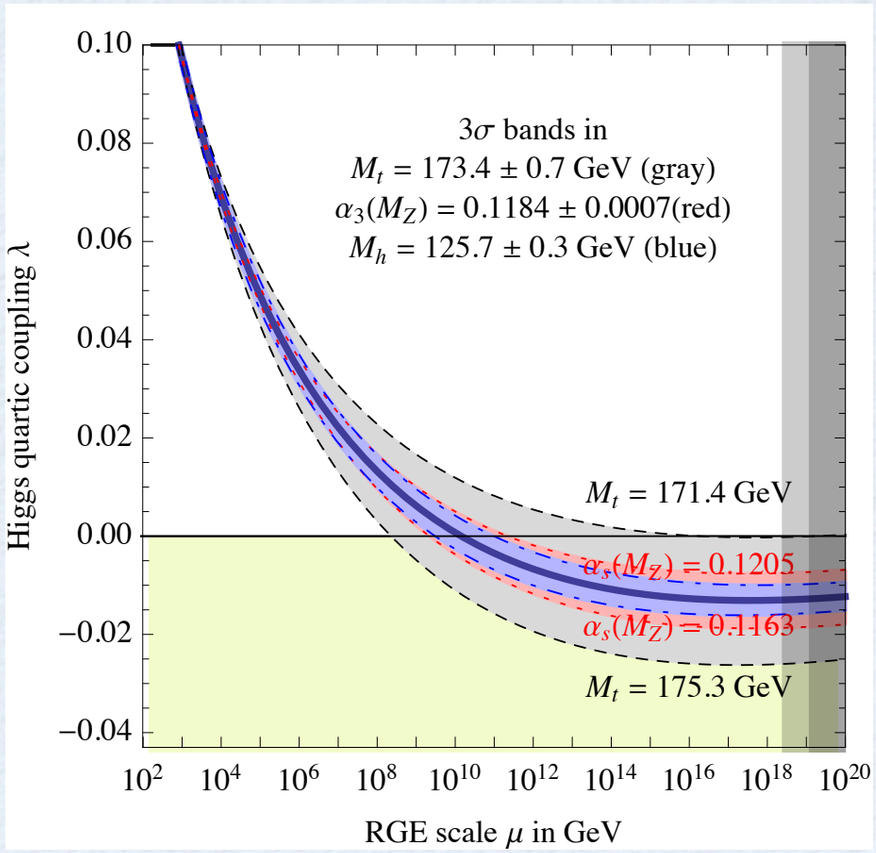


∇P

Origin?

Higgs Mass in MSPQ



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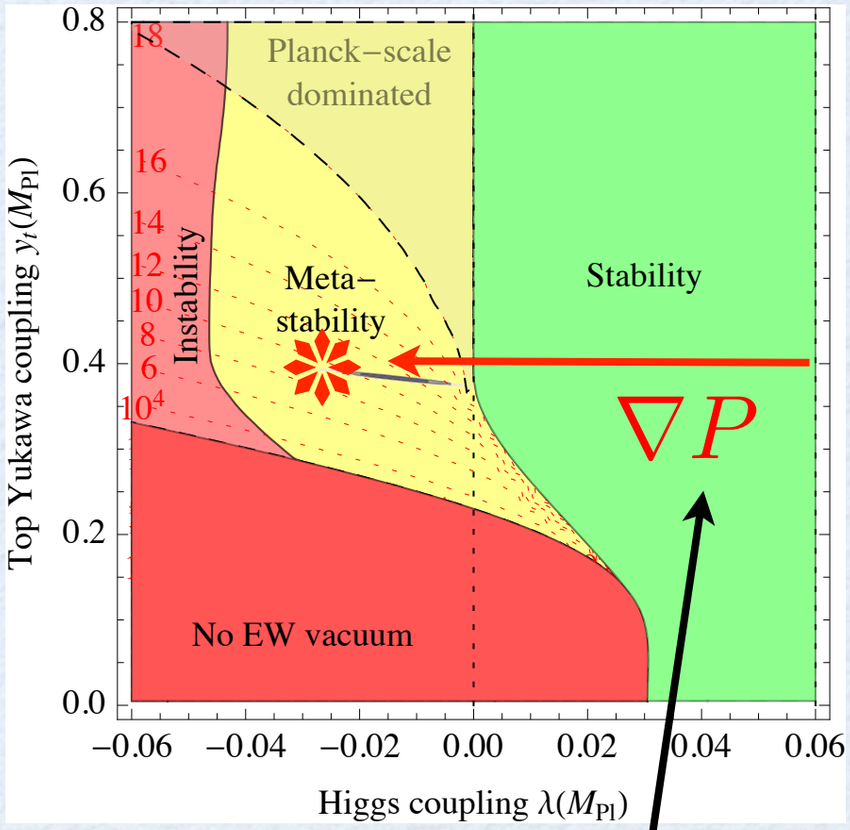
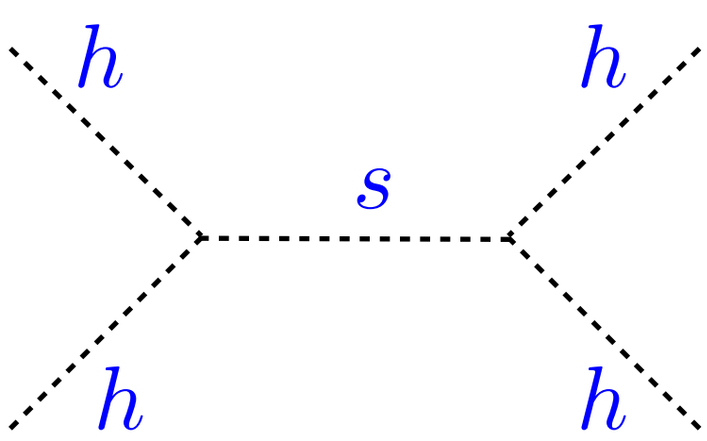


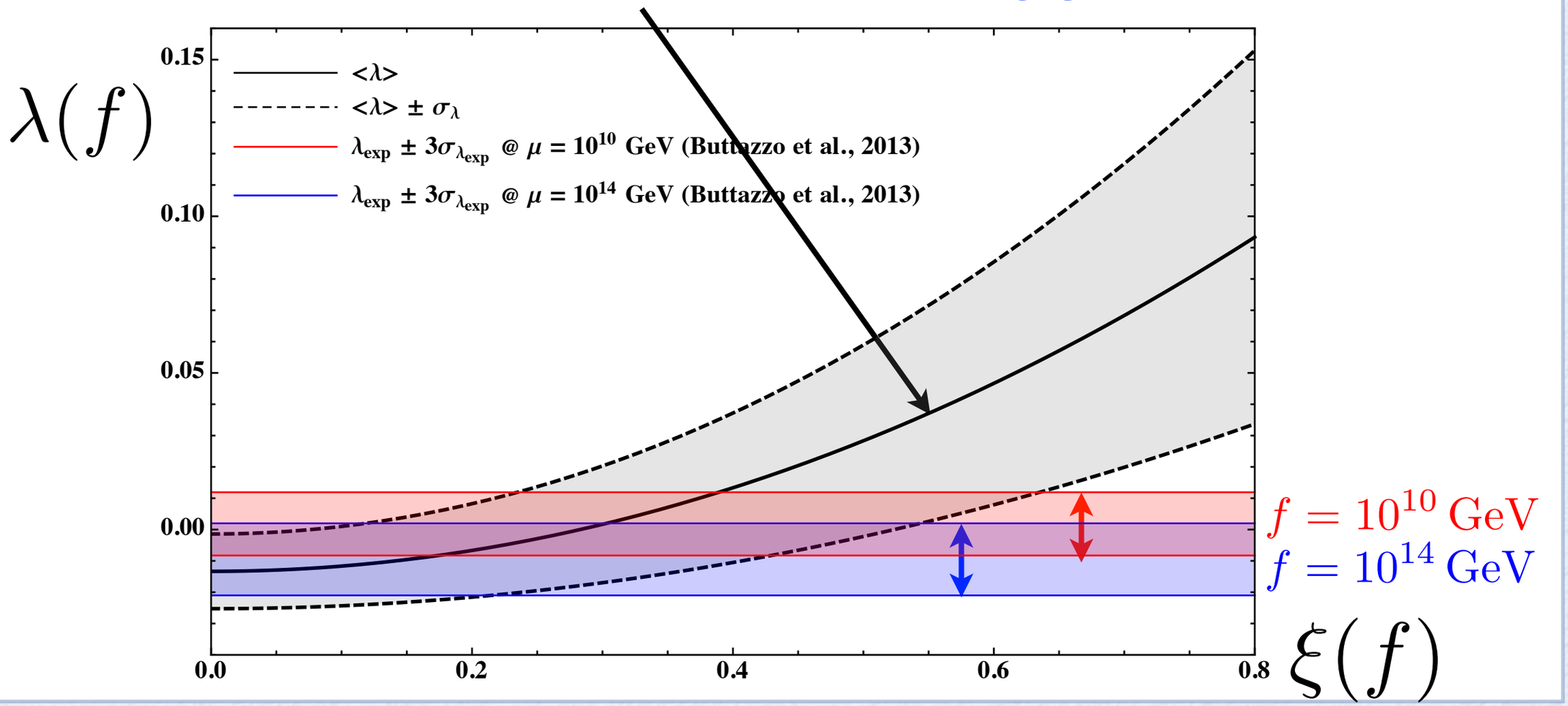


$$\Delta\lambda = -16\pi^2\,(\ldots\ldots)$$

Origin?

MSPQ: $W = \xi S H_u H_d$

- Statistical prediction of Higgs mass



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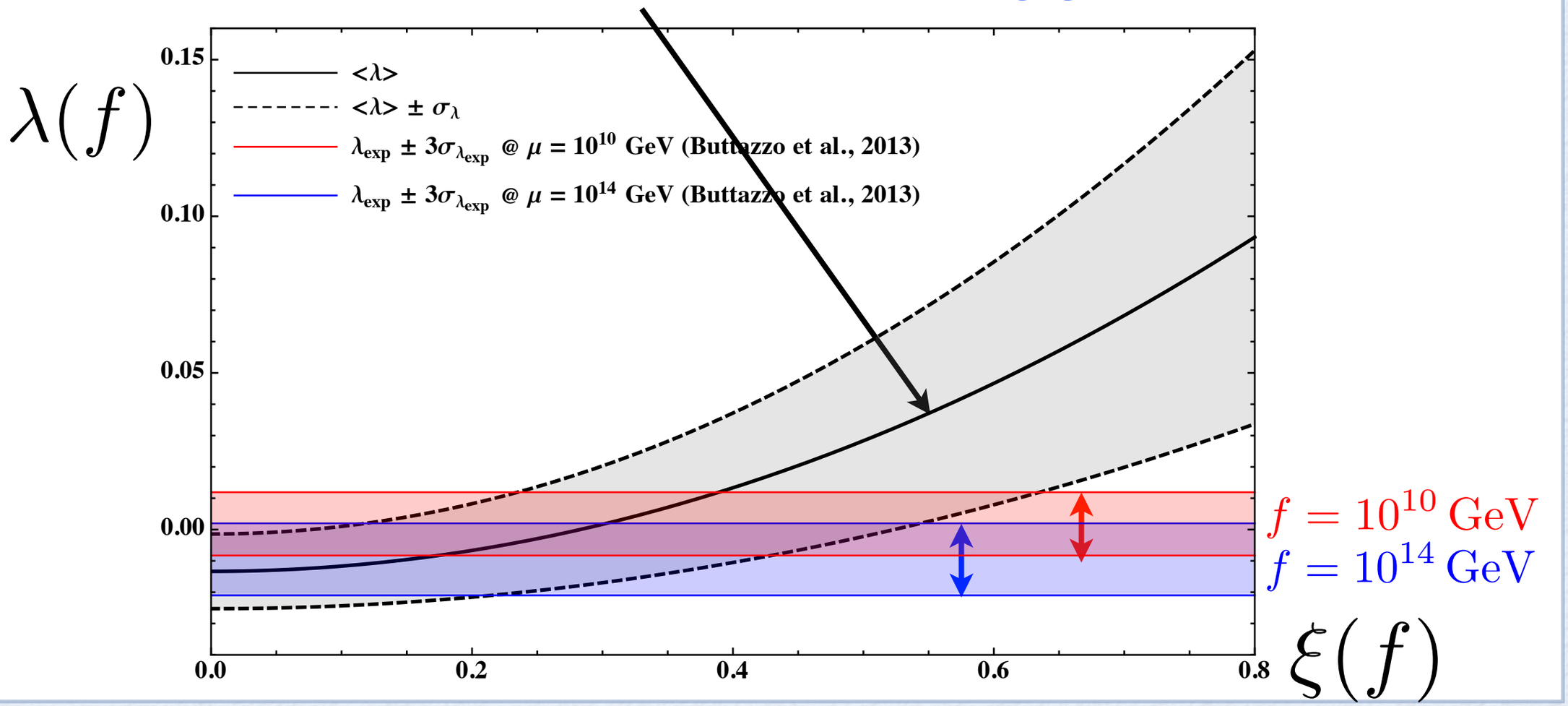

- Radiative PQB: f from dim. trans.
- Environmental selection: $v \ll \tilde{m} \sim f$
- DM and Strong CP: Axions

Conclude: A Multiverse View

Two surprises → | ← Non standard

Observable	**Physical Origin**
Λ	Observer dilution
v	Avoid ^{4}He universe
$m_{u,d,e}$	H, complex nuclei
ξ_D	Large Scale Structure
ξ_B	Observer dilution
m_H	EW vacuum stability

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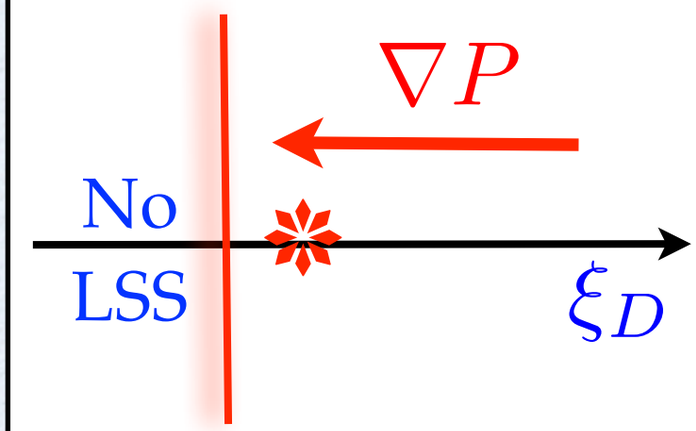

Little SUSY hierarchy

or

Axion with $f \sim 10^{10-11}$ GeV

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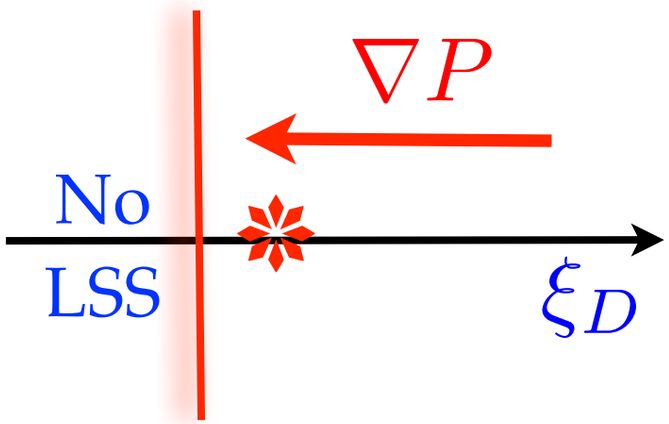

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MSPQ

$W = \xi S H_u H_d$

The Troubling Question

$\Lambda,\ m_{u,d,e},\ v,\ \xi_D,\ \xi_B, \ldots$

could all be
anthropically determined

How will we ever be sure?

The Troubling Question

Λ, $m_{u,d,e}$, v, ξ_D, ξ_B, ...

could all be
anthropically determined

How will we ever be sure?

- We may never have a high level of certainty
- The situation is similar to other great ideas
  (inflation, grand unification, string theory; seesaw neutrinos/leptogenesis)
- I aim not to convince you, but to challenge you
- We should seek evidence wherever we can

The MeV Scale

Several aspects of our Universe
-- some of which seem to be prerequisites for the evolution of any form of life--
depend rather delicately on apparent coincidences among the physical constants

Carr, Rees
Nature (1979)

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m_e $(m_n - m_p)_{EM}$ $(m_n - m_p)_q$ $T_{n \leftrightarrow p}$

$y_e\, v$ $\alpha\, \Lambda_{QCD}$ $(y_d - y_u)v$ $\dfrac{v^{4/3}}{M_{Pl}^{1/3}}$

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All four are within a factor 2 of 1 MeV