Is SUSY Alive and Well?

Madrid, September 2016

Dark Matter:
Implications of a Saxion Condensate

Lawrence Hall

University of California, Berkeley

BERKELEY CENTER FOR THEORETICAL PHYSICS

(I)

Where are We?

After 43 Years of BSM Theory

No Experimental BSM Discovery

Without data, no aspect of BSM is healthy

We don't know what is going on;
Everything is open for discussion

Where are we with SUSY?

We have discovered a highly perturbative Higgs: $\lambda = 0.13$

$m_h = 125\,\mathrm{GeV}$

SUSY is very much alive

But:

Higgs mass needs boost of 40%: $\tilde{m} \gg v$?

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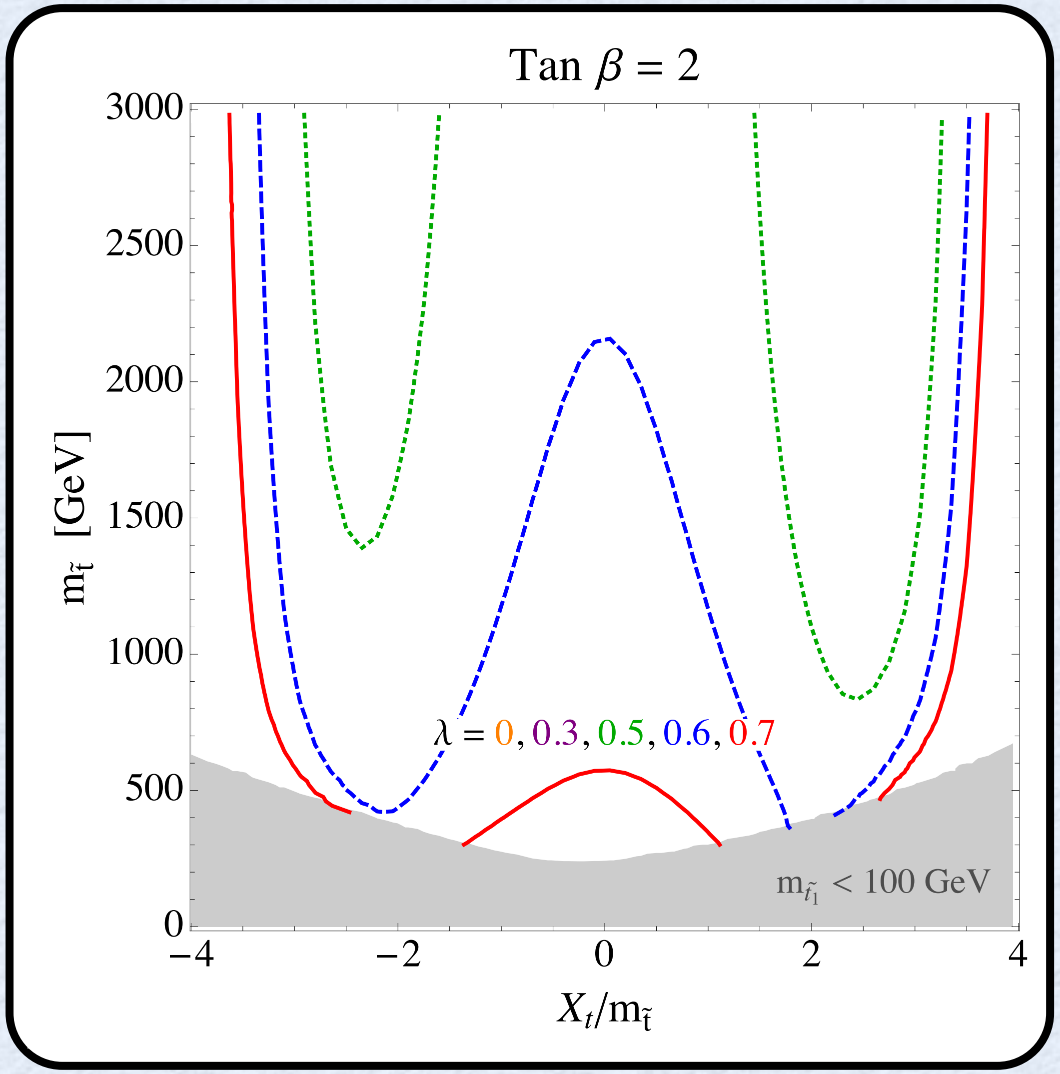
EWSB is fine-tuned: Anthropics?

$m_h = 125\,\mathrm{GeV}$ & Gauge unification

Keeps me motivated

Higgs Mass: Some Favorite Possibilities

NMSSM



Hall, Ruderman, Pinner
arXiv:1112.2703

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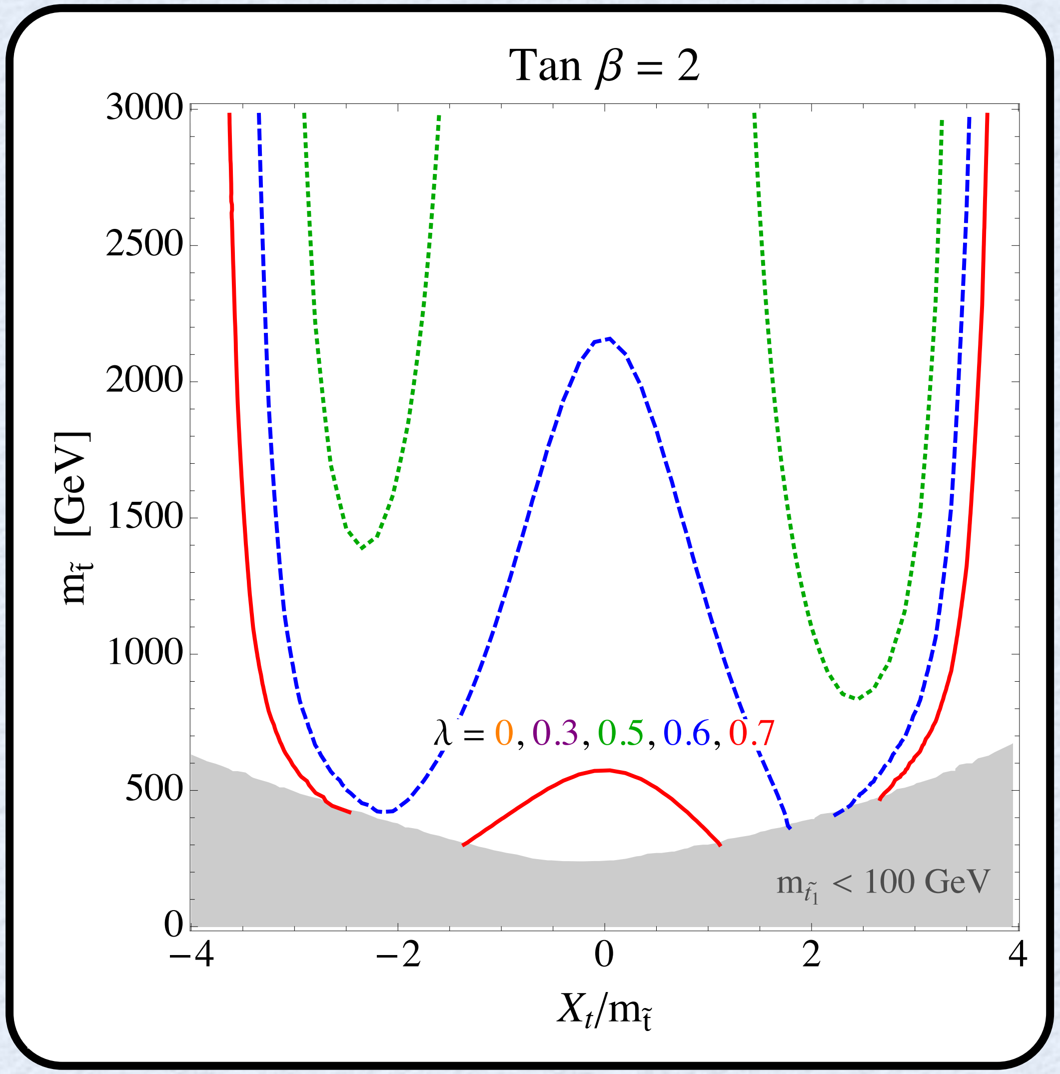

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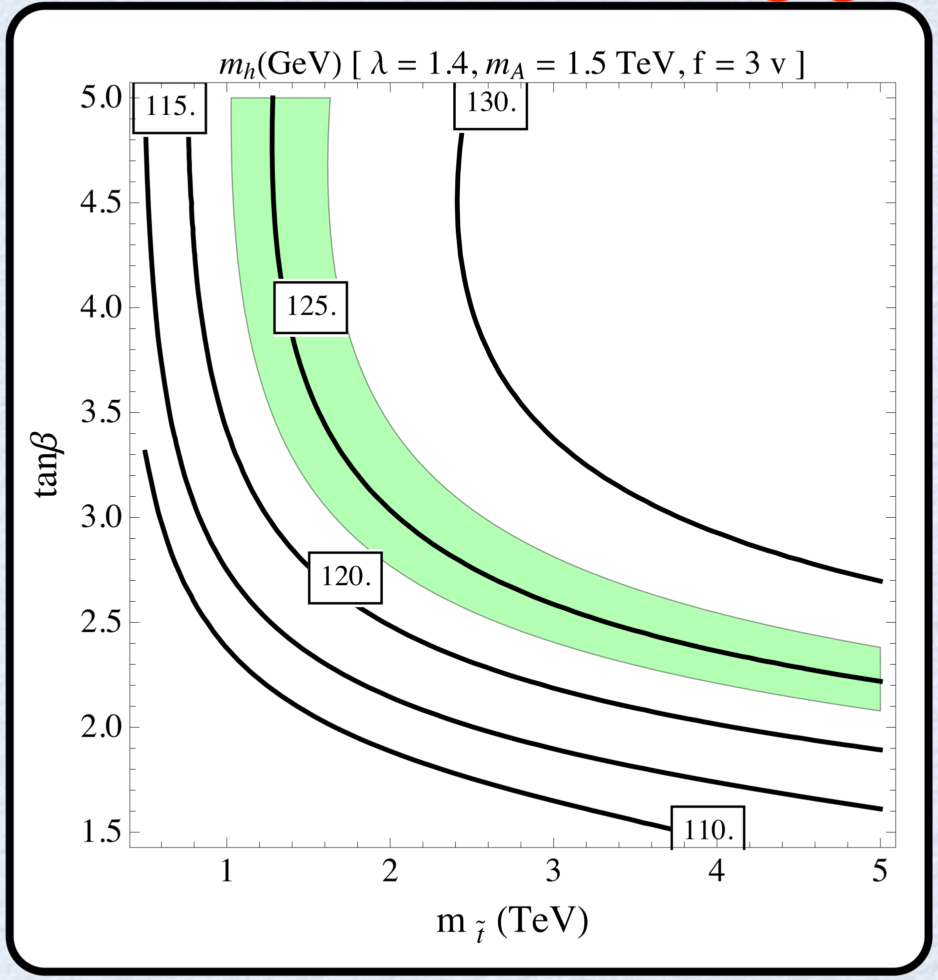
SUSY Twin Higgs



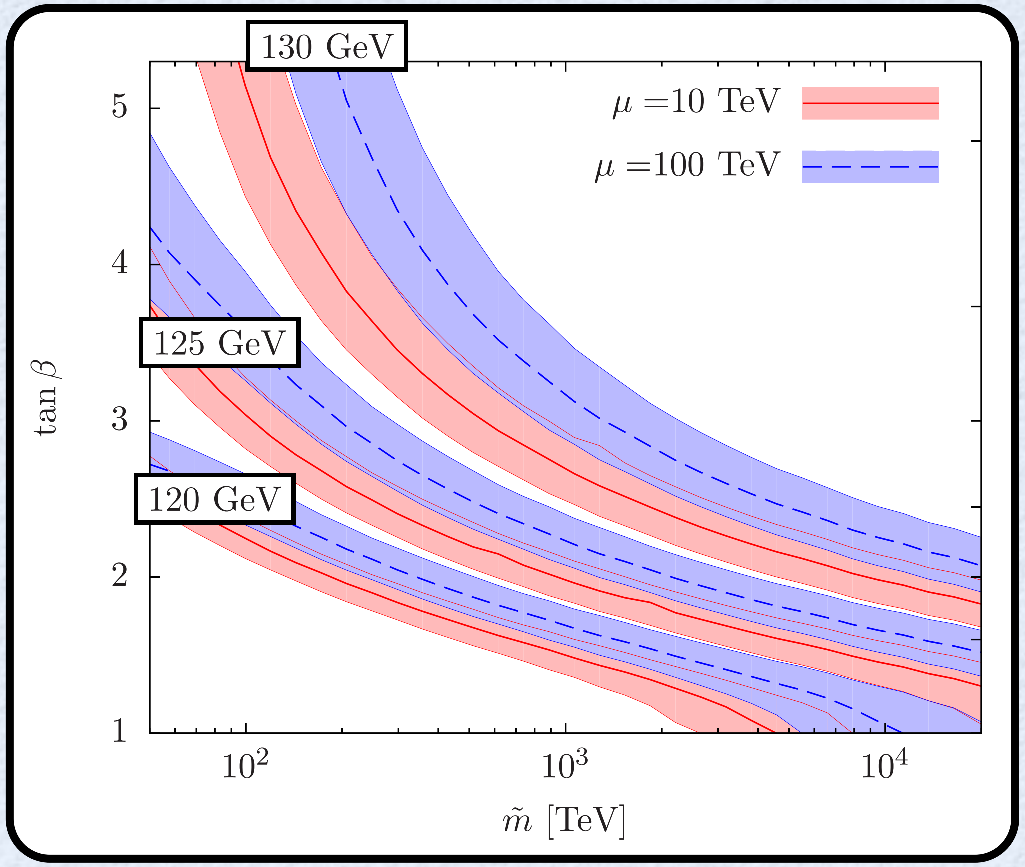
Craig, Howe
arXiv:1311.1341

$$\tilde{m} \sim (1-5)\ \mathrm{TeV}$$

$$m_\phi^2 = (m_Z^2 \cos^2 2\beta + 4\delta\lambda_u v^2 \sin^4\beta)\left(2 - \frac{2v^2}{f^2}\right)$$

Higgs Mass: My Favorite Possibilities

"Mini-Split" or "Spread SUSY"



Hall, Nomura, Shirai arXiv:1210.2395

$$\tilde{m} \sim (10^2 - 10^4)\ \mathrm{TeV}$$

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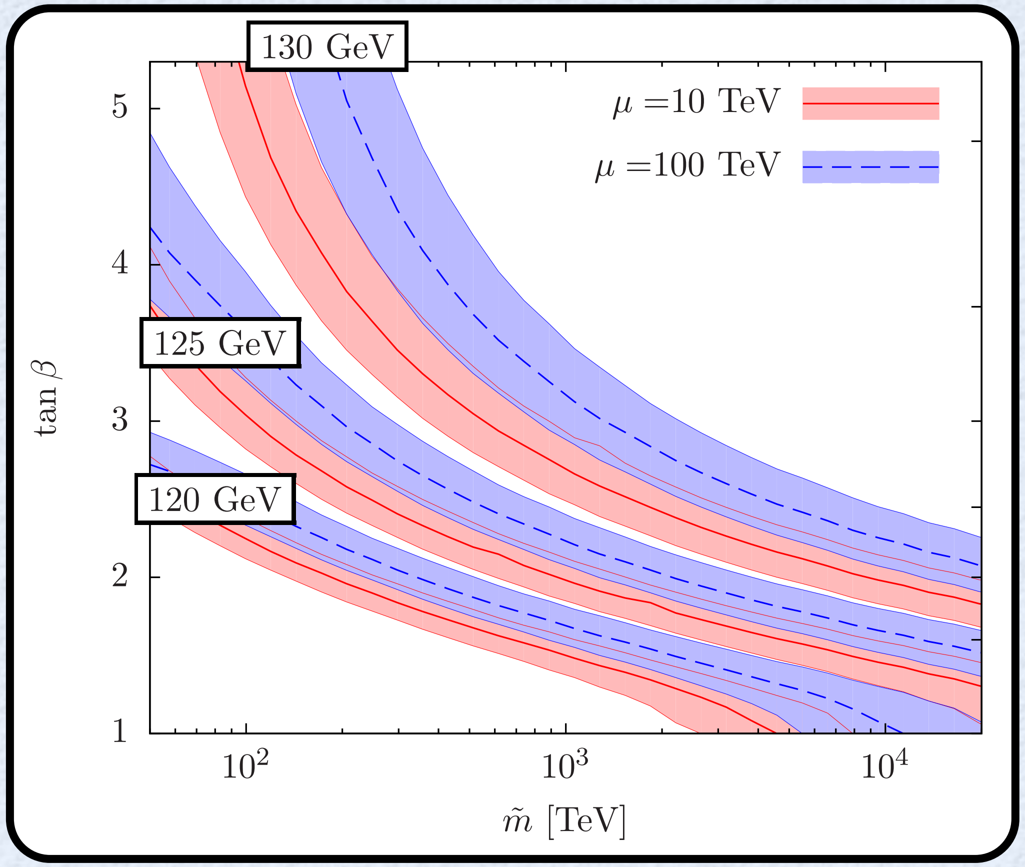

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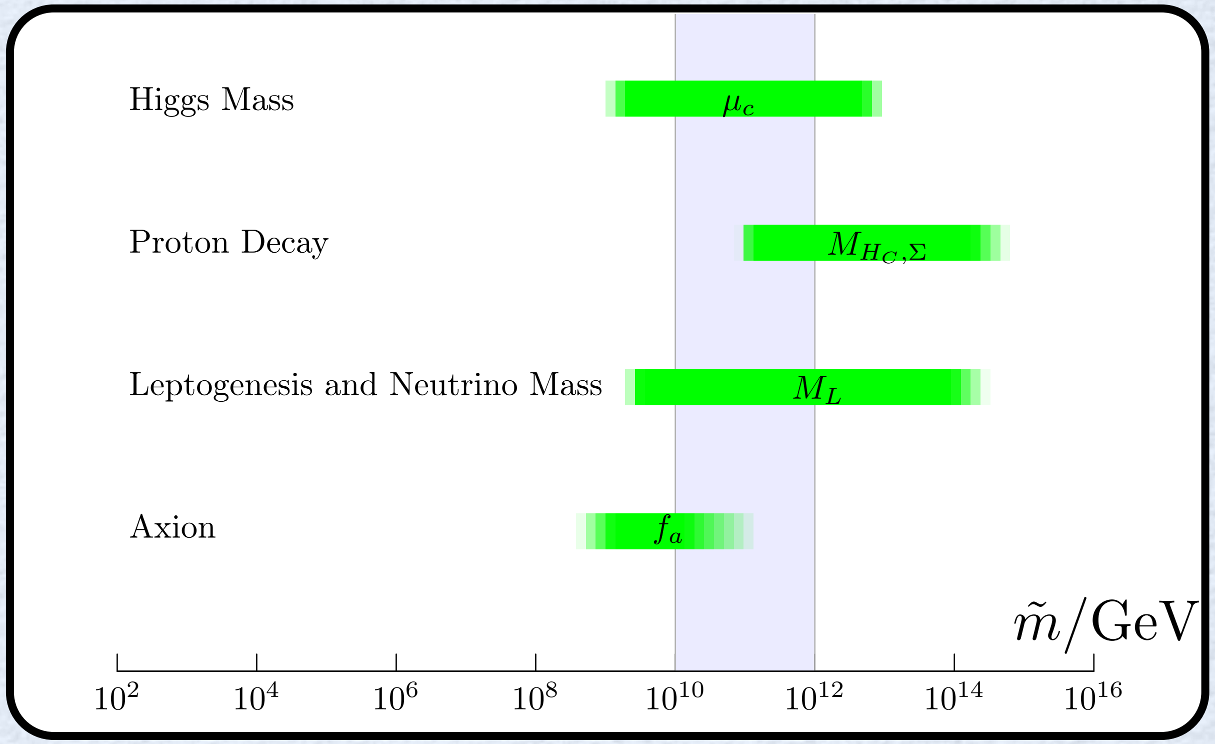
"Intermediate Scale" SUSY



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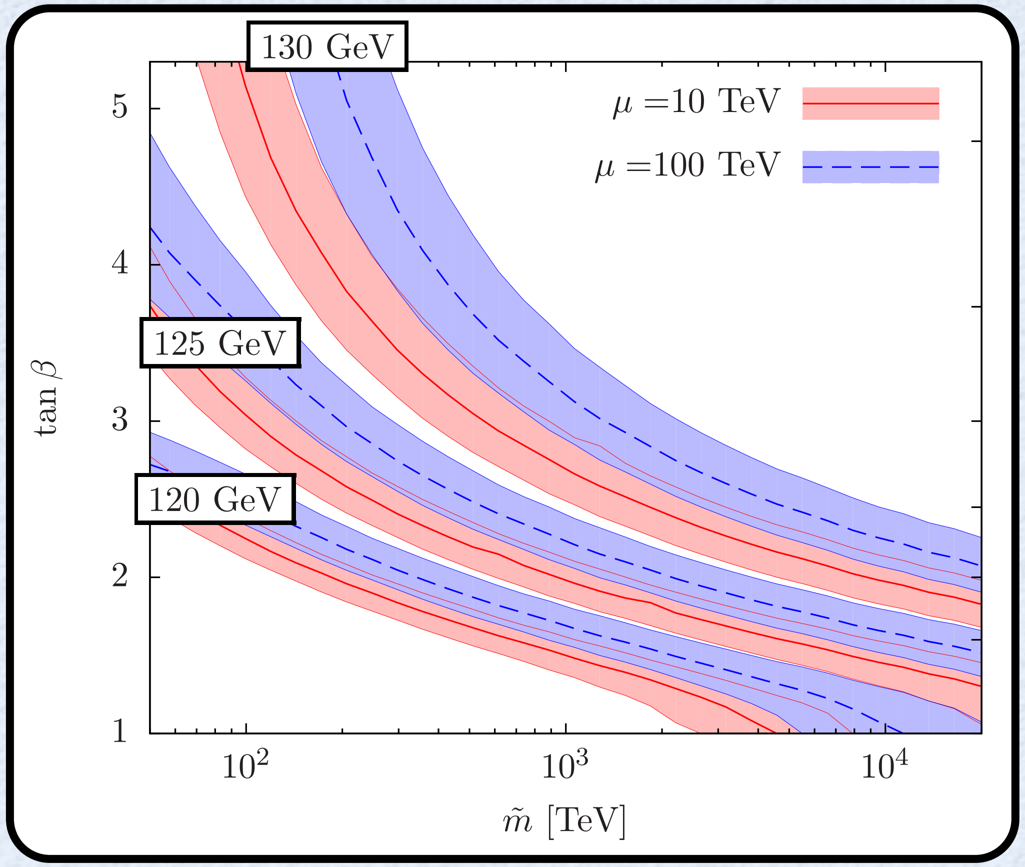

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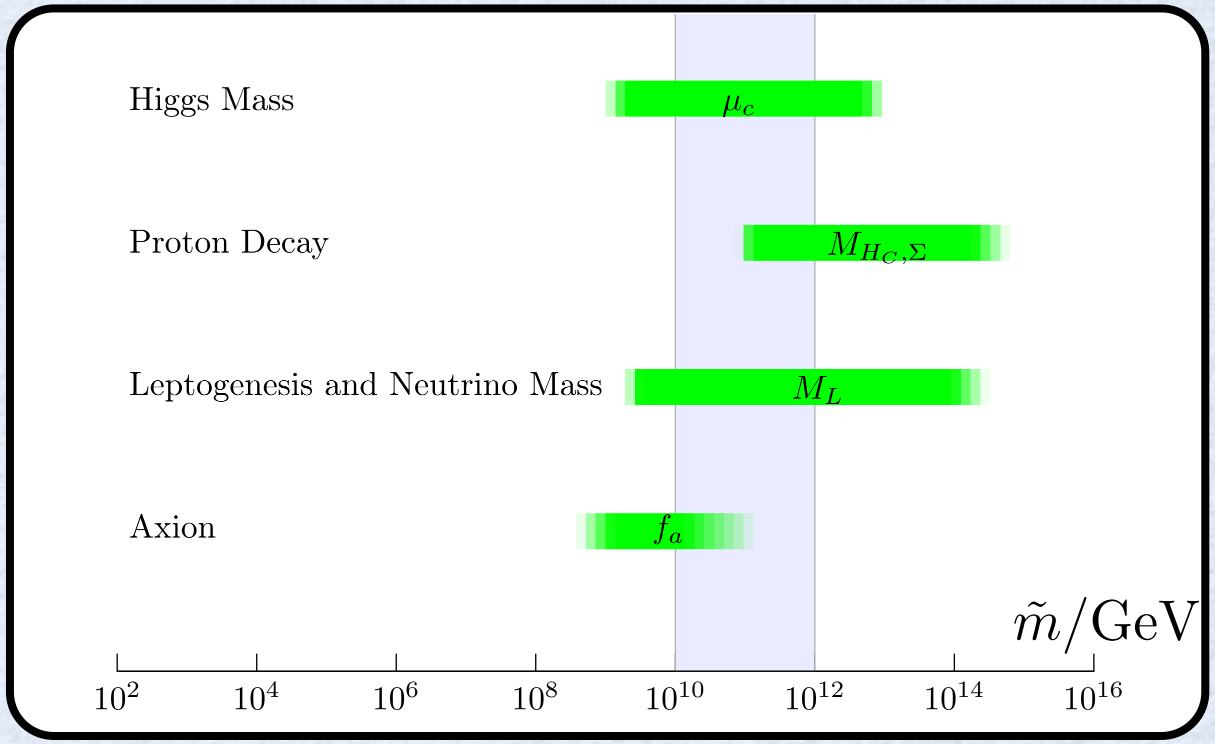


Hall, Nomura arXiv:1210.2395

$$\tilde{m} \sim (10^{10} - 10^{12})\,\mathrm{GeV}$$

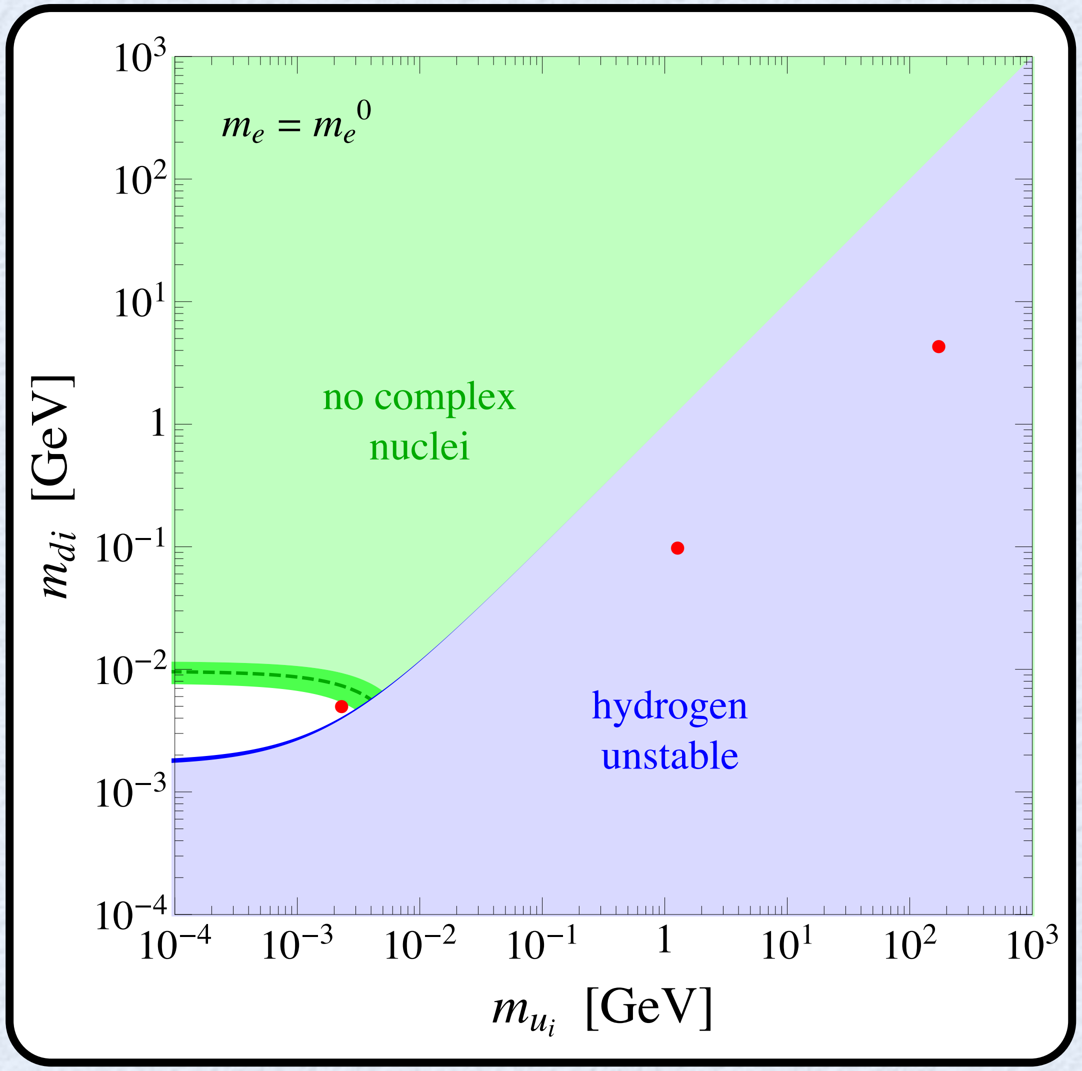
Without naturalness

$m_h = 125\,\mathrm{GeV}$ & Gauge unification

insufficient to determine $\tilde{m}$

An Anthropic Weak Scale?

Atomic Boundaries



$m_{u,d}$ both scan

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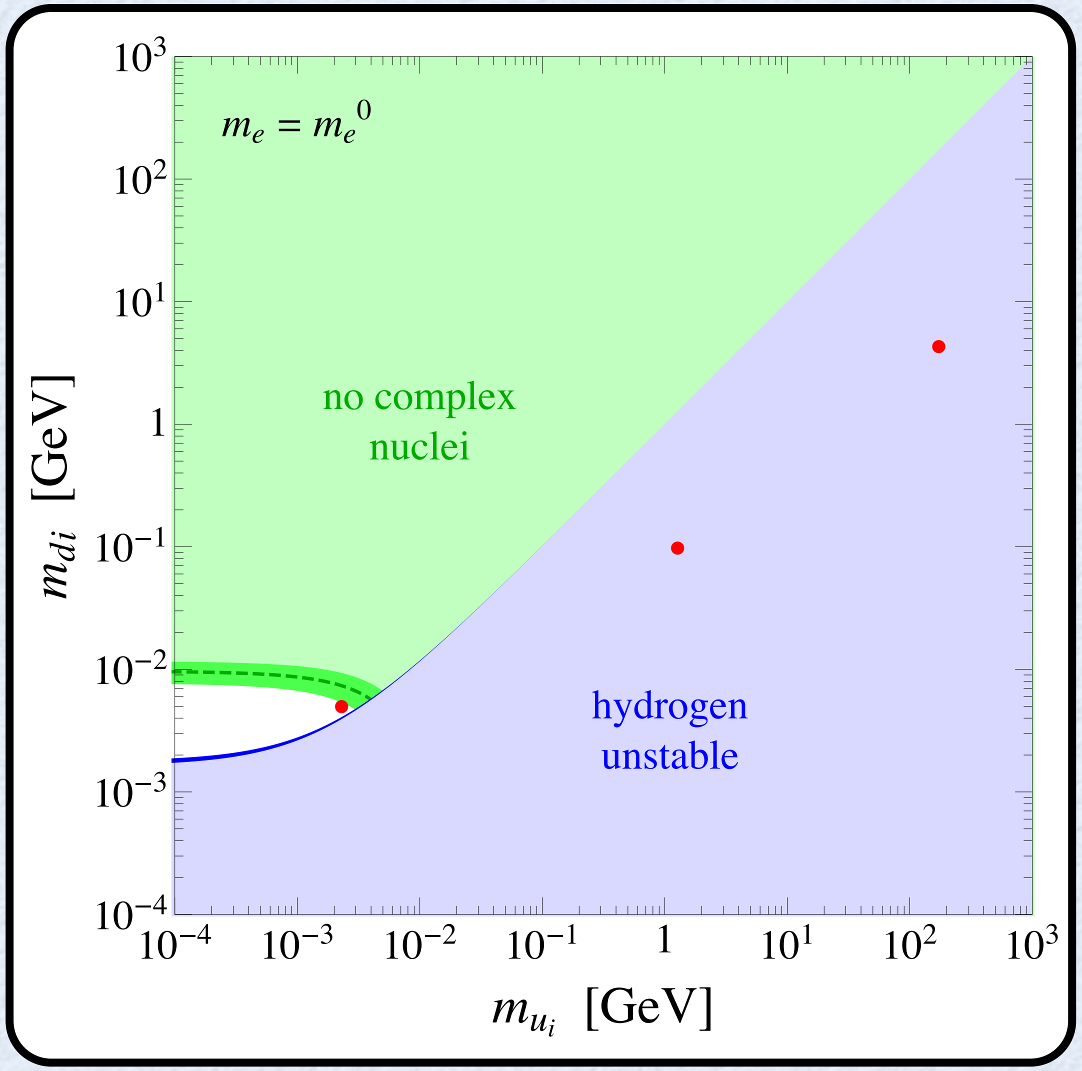
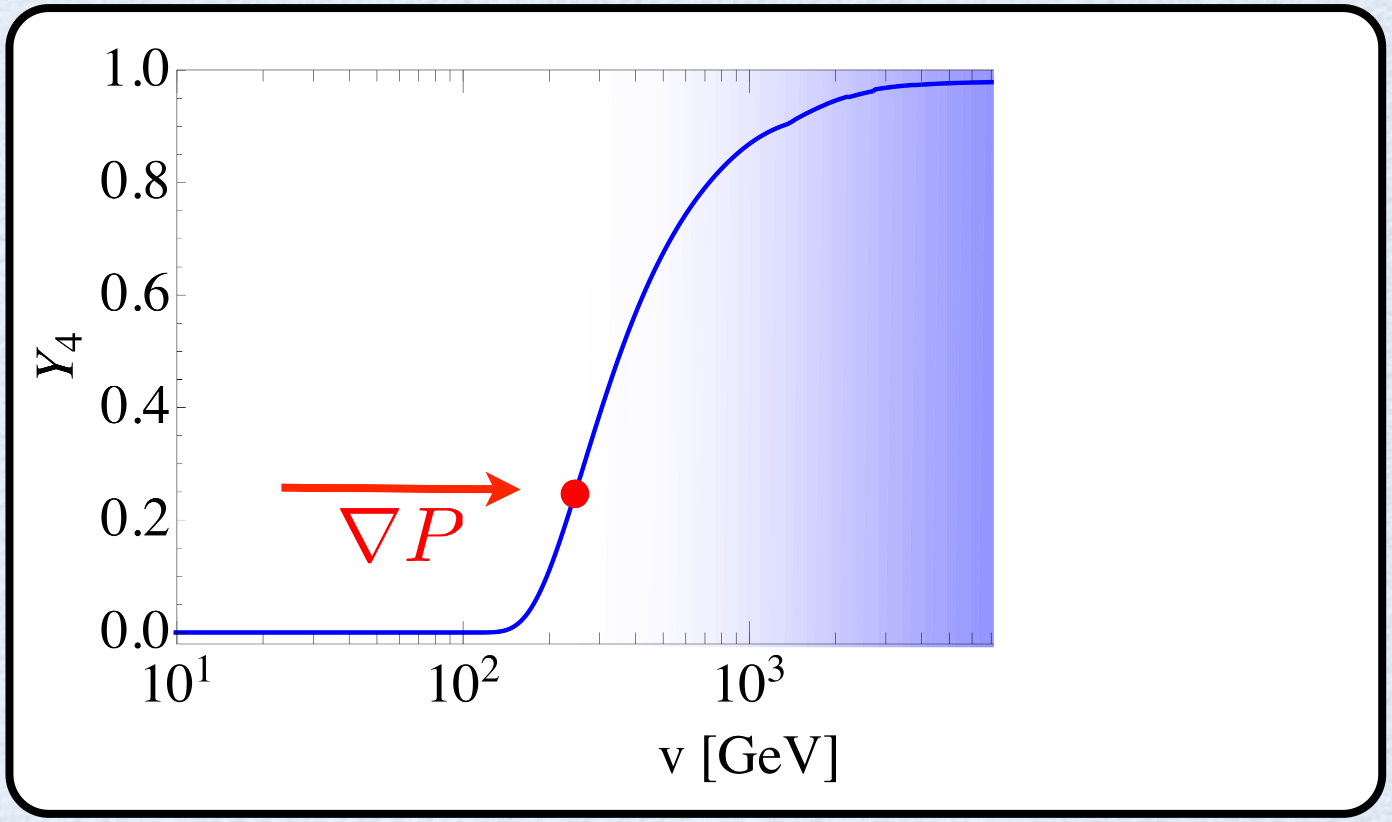


He-4 BBN Boundary



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arXiv:1409.0551

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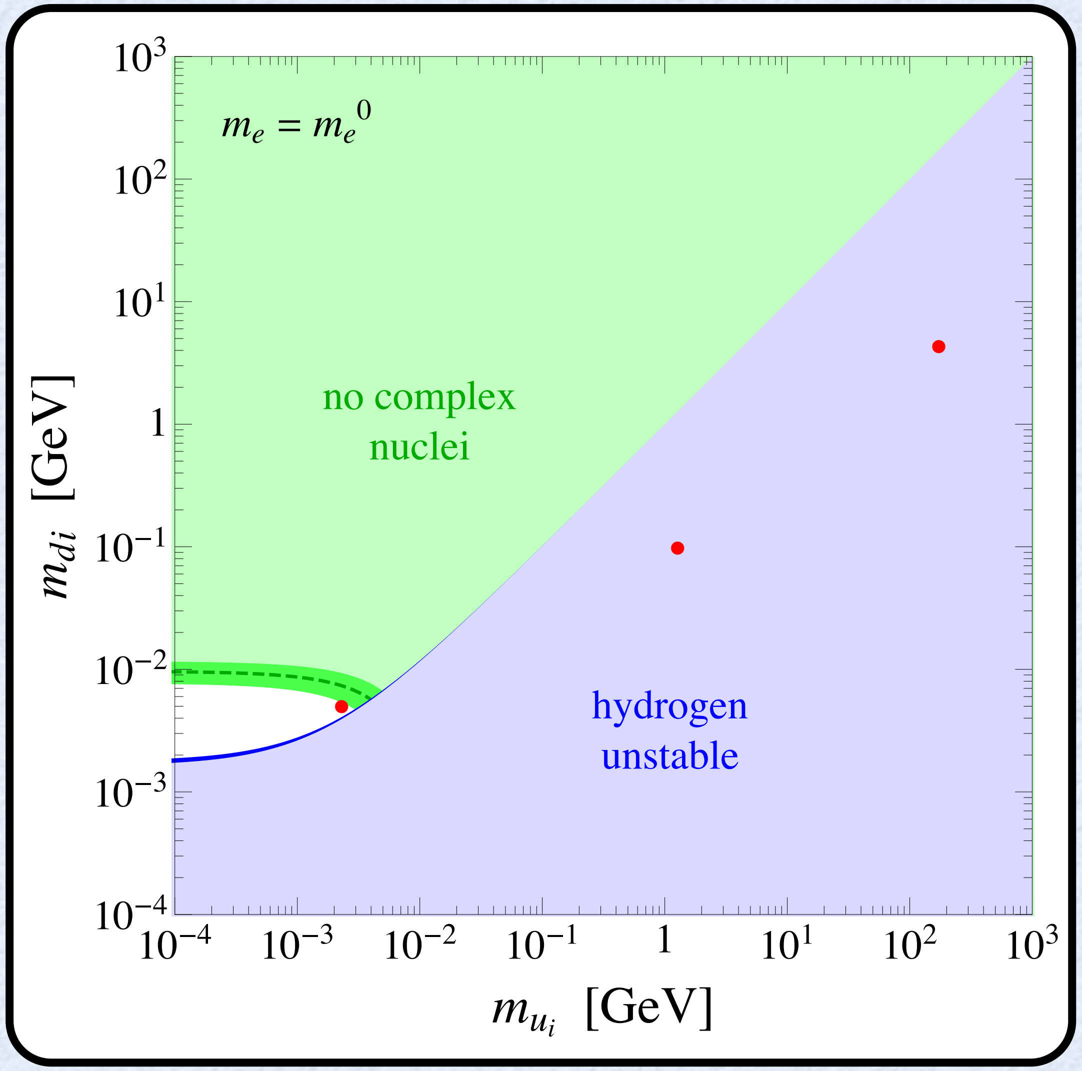

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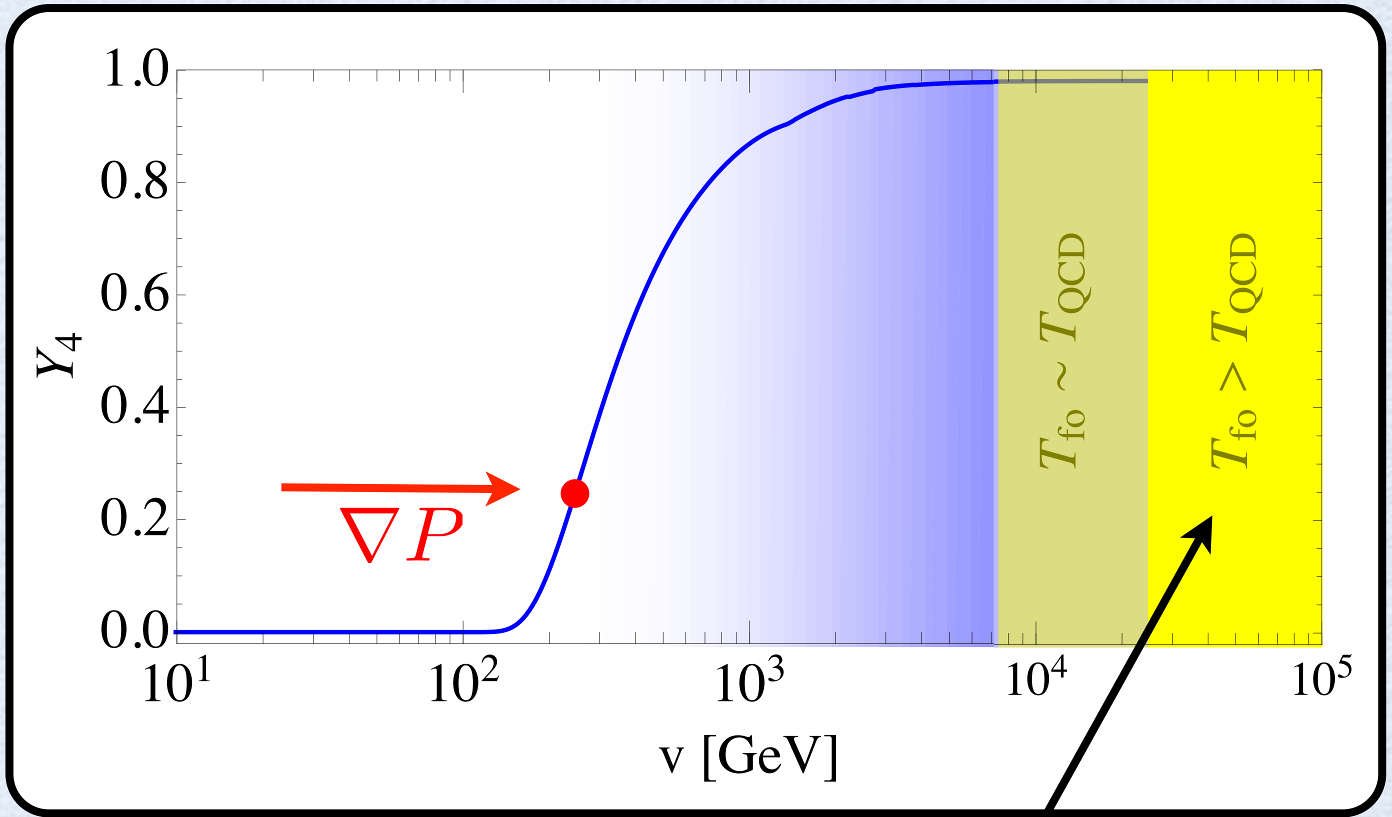

He-4 depends on asymmetries, not v

Hall, Pinner, Ruderman

arXiv:1409.0551

My View

Without data, no aspect of BSM is healthy

We don't know what is going on;
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(II)

Dark Matter in (SUSY + PQ)

Raymond Co, Francesco D’Eramo, Lawrence Hall

1603.04439, 1610.xxxxx

Two Favorite DM Candidates

- $\boxed{\text{Axion (a)}}$

$$f_a \sim 10^{12}\,\mathrm{GeV} \qquad \theta_{mis} \sim 1$$

$$f_a \sim 10^{16-18}\,\mathrm{GeV} \qquad \theta_{mis} \ll 1 \qquad \text{“anthropic window”}$$

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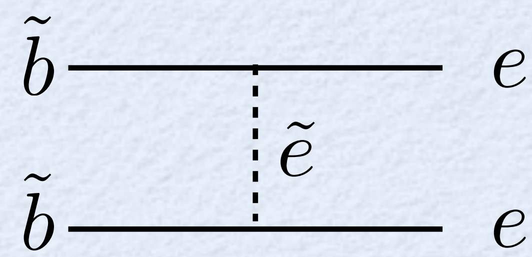
- $\boxed{\text{LSP}(\tilde{b}, \tilde{h}, \ldots \tilde{G}_{3/2})}$

- Freeze-Out



Excluded; but there are others

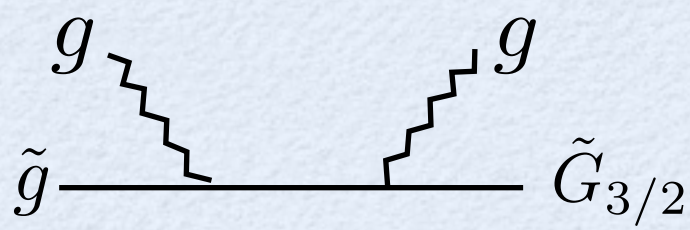
- Gravitino Problem

Abundance

Late Decays

TeV-scale SUSY: Gravitino Problem

- Abundance:



UV $\tilde{G}_{3/2}$

$$T_{RI} < 10^9\ \mathrm{GeV}\left(\frac{m_{3/2}}{\mathrm{TeV}}\right)$$

severe for
Low Scale Mediation

TeV-scale SUSY: Gravitino Problem

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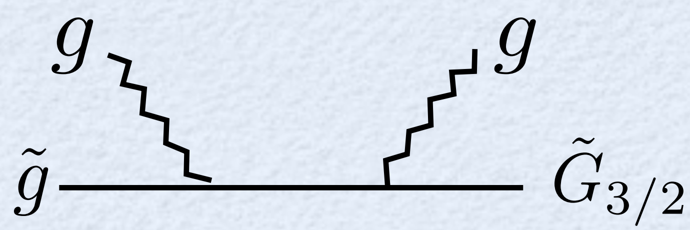

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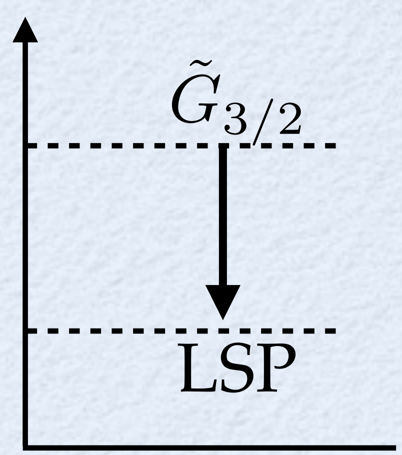

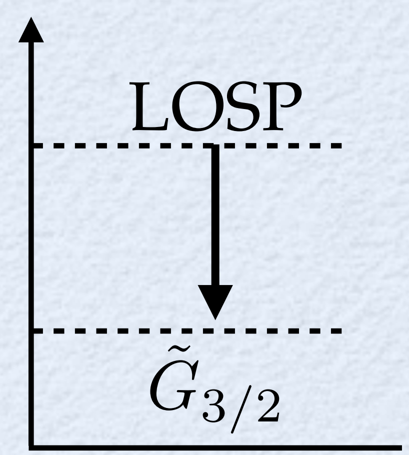

$$\tau_{3/2} \sim 10^6\mathrm{s}\left(\frac{\mathrm{TeV}}{m_{3/2}}\right)^3$$

$$\tau_{LOSP} \sim 10^4\mathrm{s}\left(\frac{\mathrm{TeV}}{m_{LOSP}}\right)^5\left(\frac{m_{3/2}}{100\mathrm{GeV}}\right)^2$$

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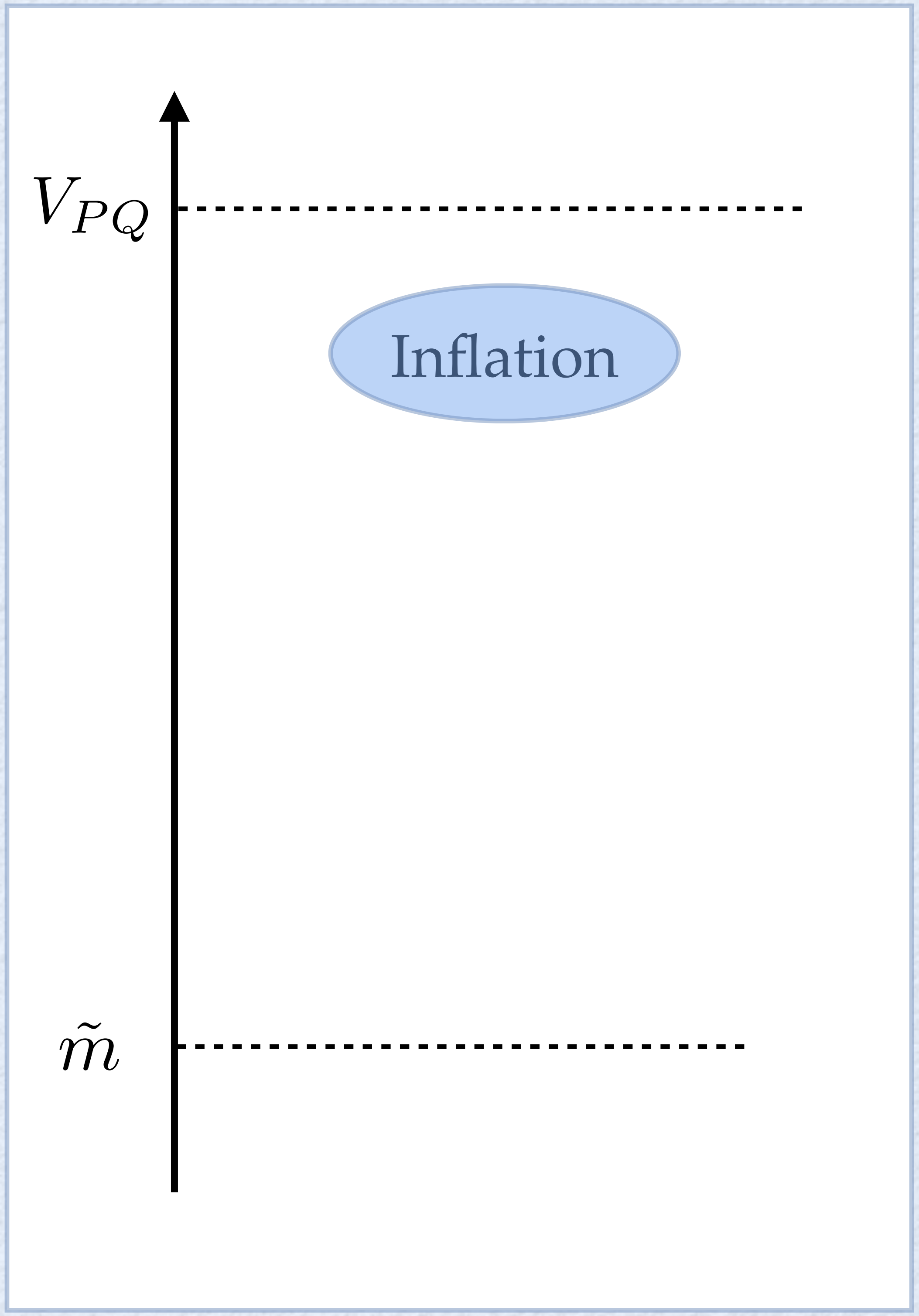
High Scale Mediation

Dark Matter in (SUSY + PQ)

- Everything changes!!
- $$V_{PQ} = \frac{N_{DW}}{\sqrt{2}} f_a$$



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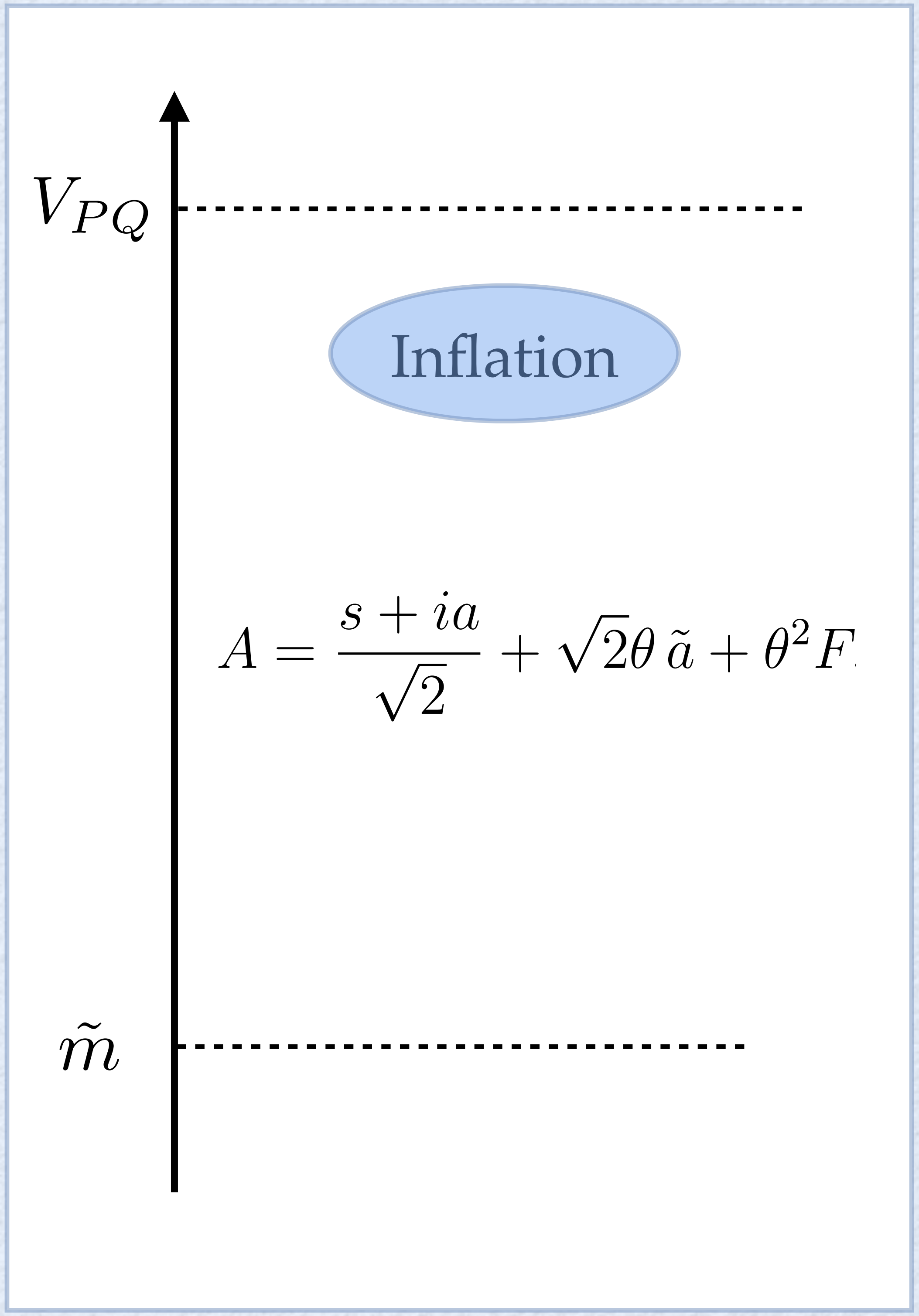

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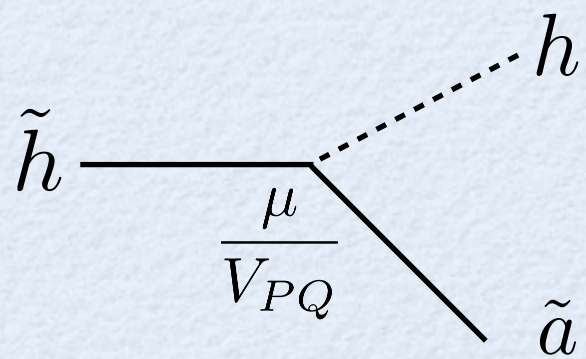
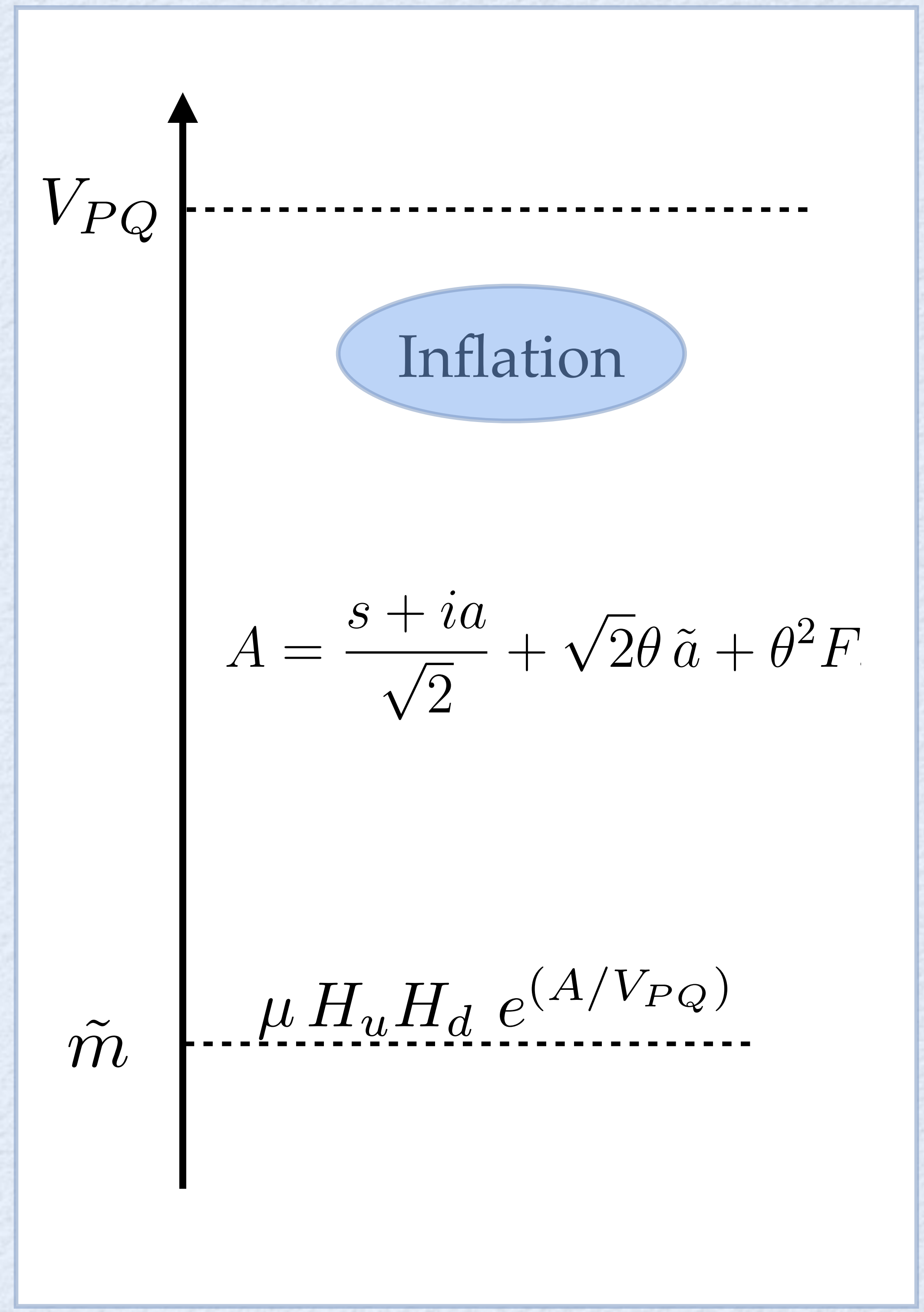
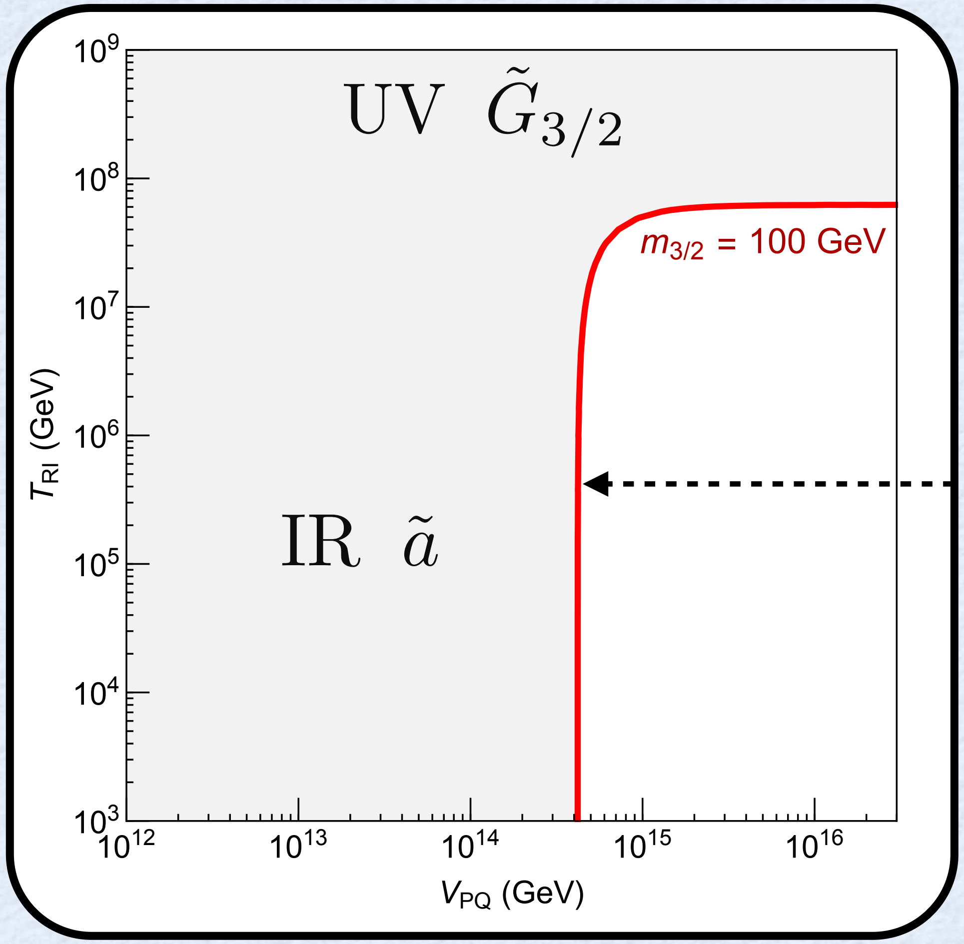


IR $\tilde{a}$



Axino - Gravitino Problem

High Scale Mediation



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$$m_{3/2} < m_{\tilde{a}} \lesssim 1\,\mathrm{TeV}$$

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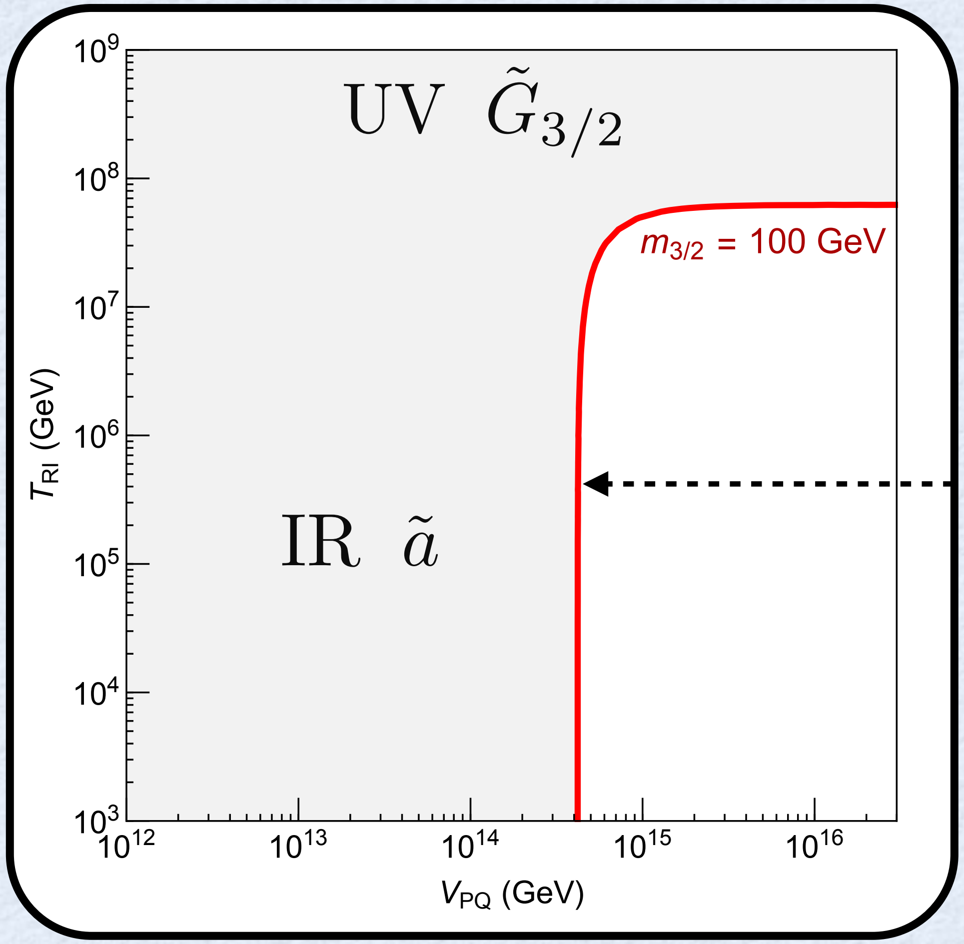

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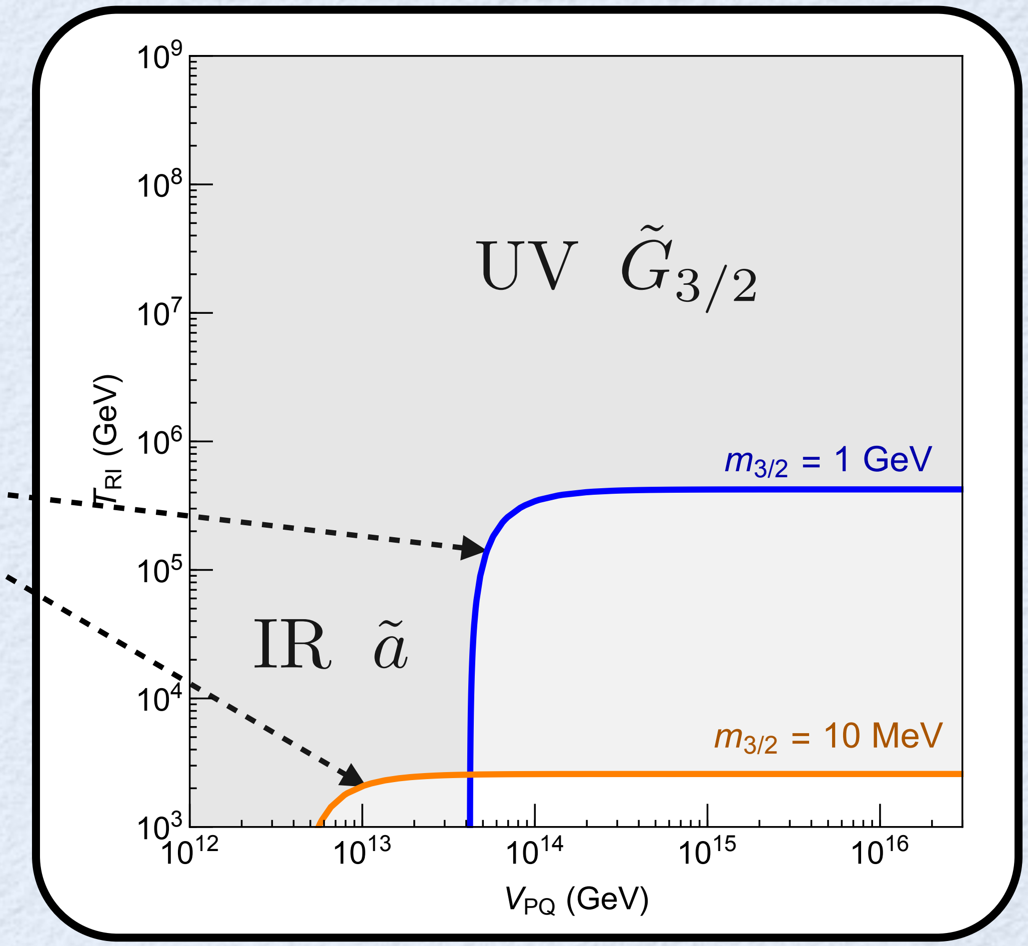

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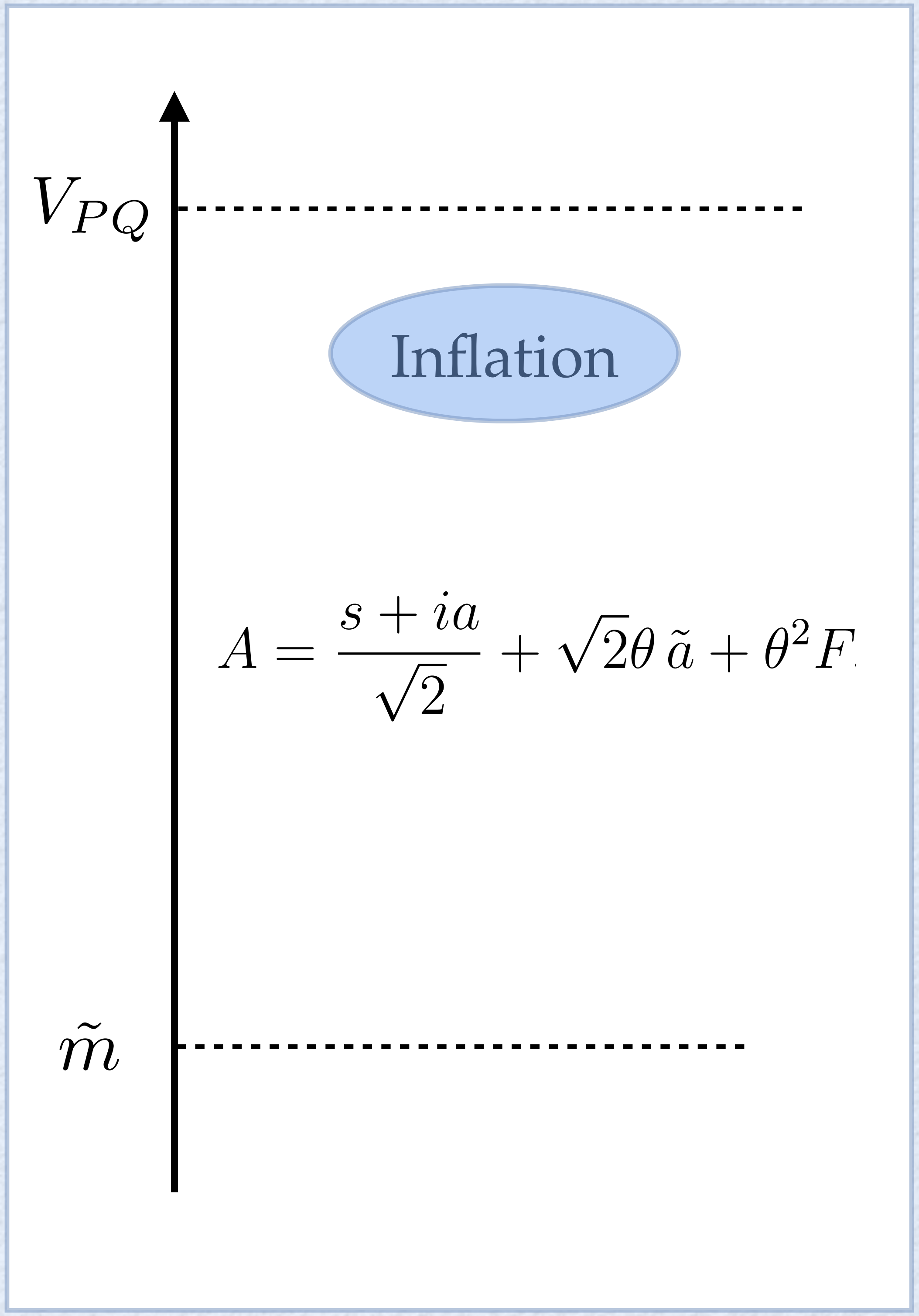
The Saxion Condensate

- Forms during inflation

$$\sigma_i \sim V_{PQ},\, M_*$$



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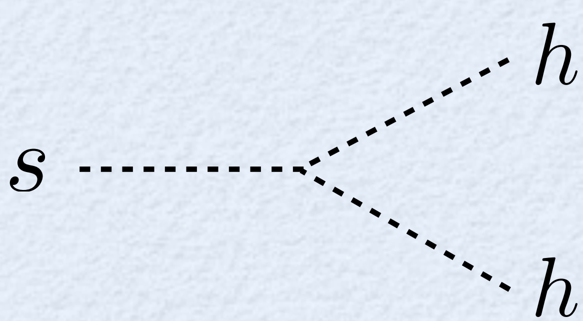
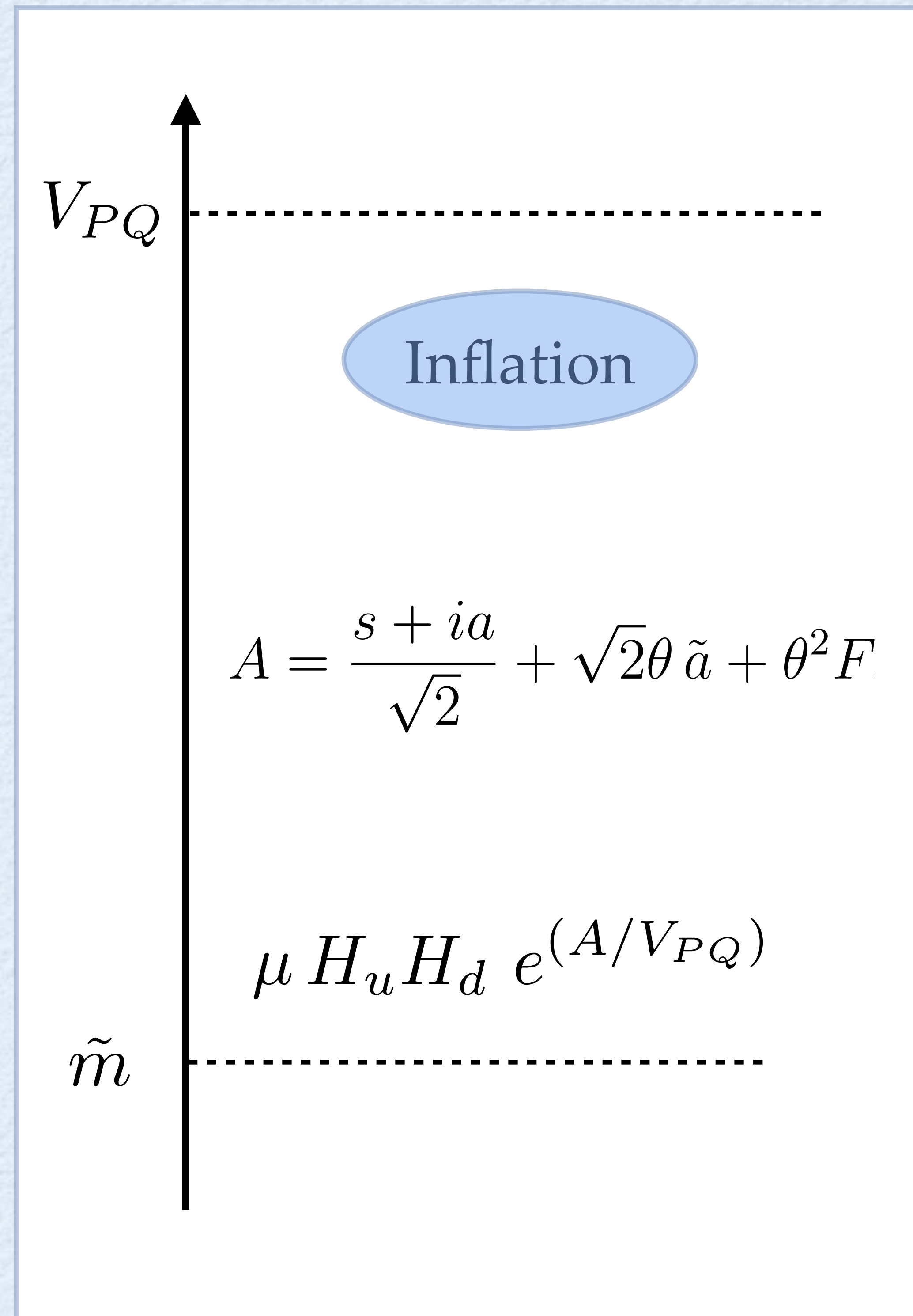


$$\frac{\mu^2}{V_{PQ}}$$

$$(s \nrightarrow \tilde{h}\tilde{h})$$



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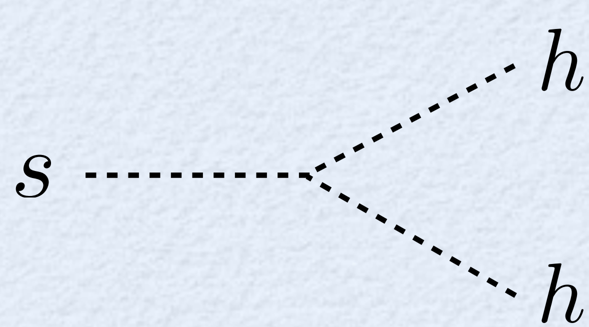

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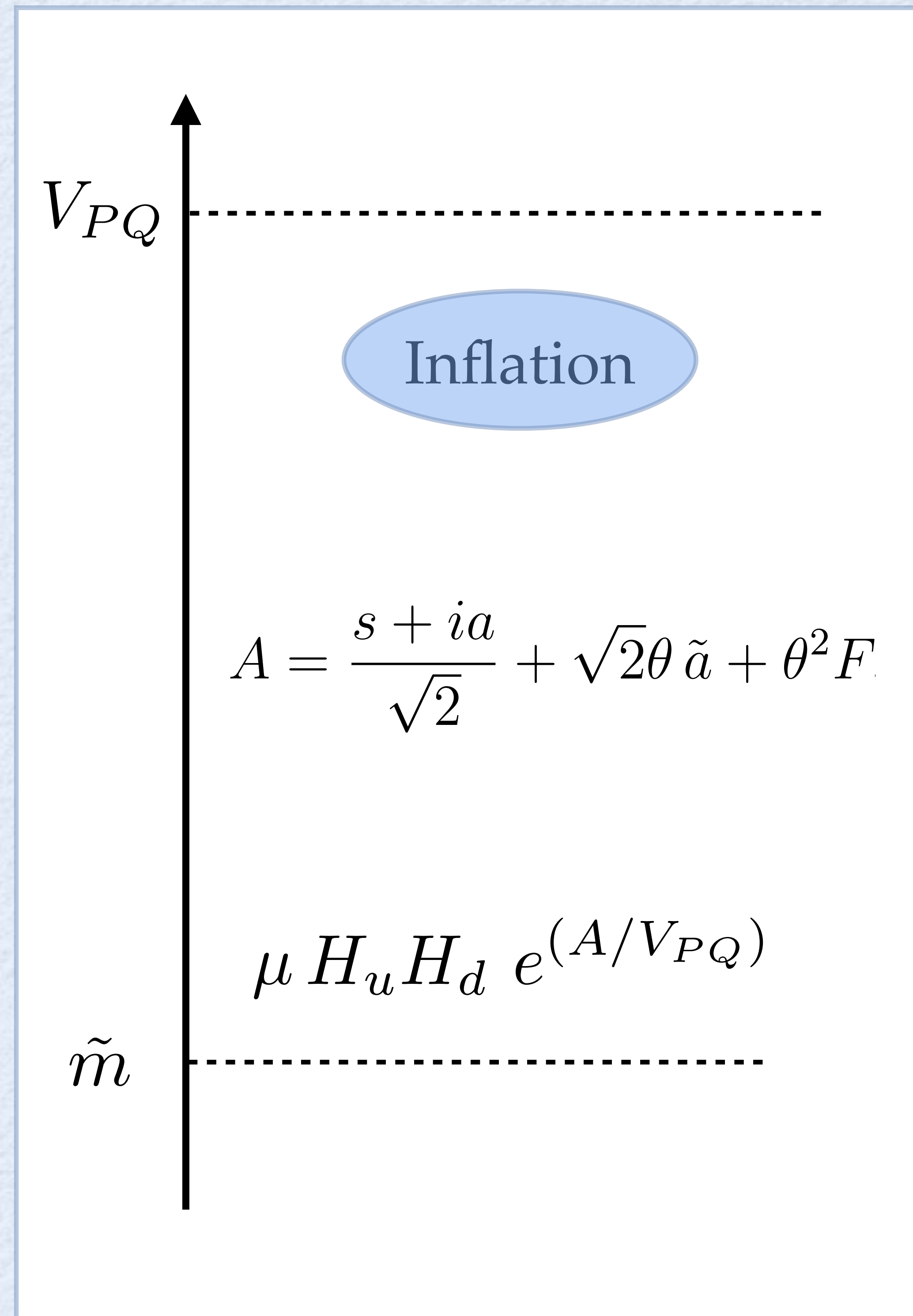

Warnings

- Saxion Condensate is Not New!

Hashimoto, Izawa, Yamaguchi, Yanagida hep-ph/9803263

...

Kawasaki, Nakayama arXiv:0802.2487

...

Baer, Lessa, Sreethawong arXiv:1110.2491

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Under-appreciated; Complex; Much still to do

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- Suppressed Parameters!

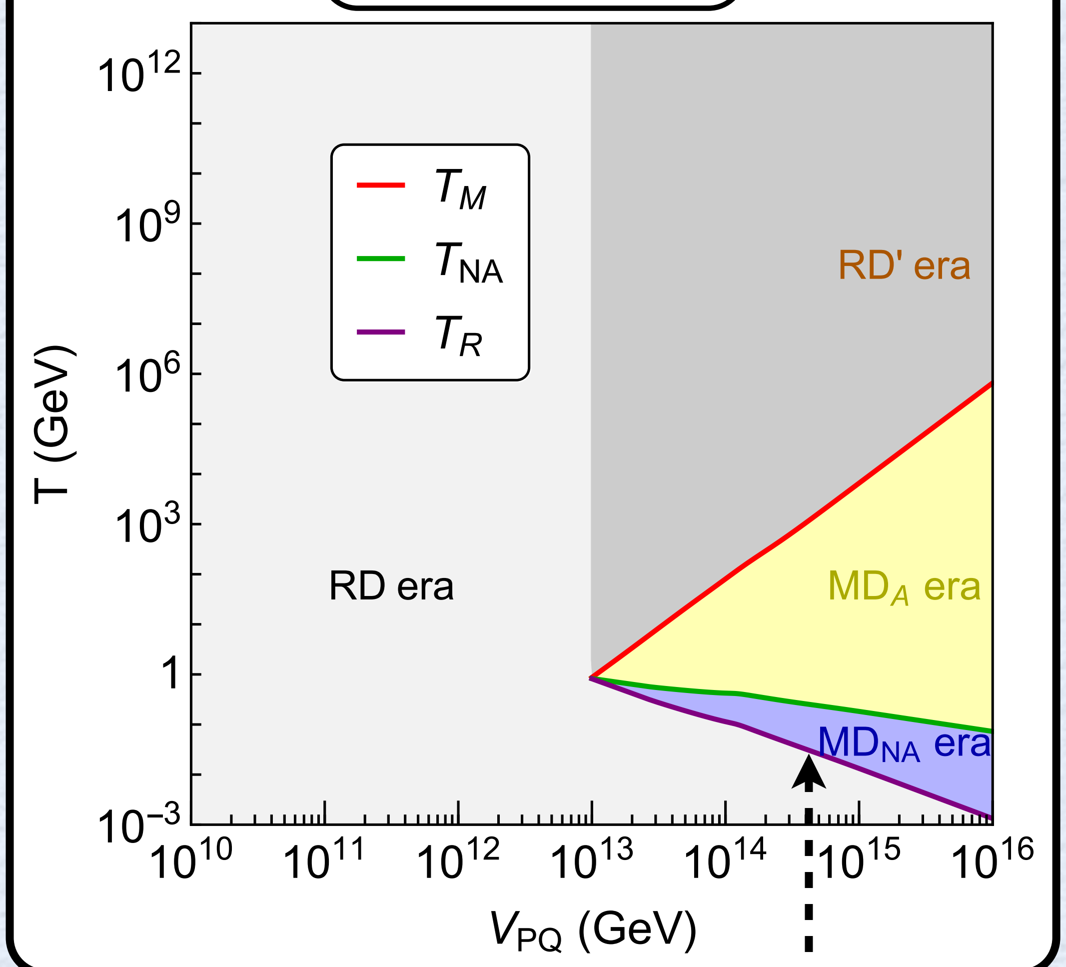
$$\mu, M_i, m_s \sim \mathcal{O}(\mathrm{TeV})$$

$$N_{DW} \sim \mathcal{O}(10)$$

$$q_\mu \sim \mathcal{O}(1)$$

A Saxion Matter Dominated Era

$\sigma_i = V_{PQ}$



DFSZ: $s \to hh$

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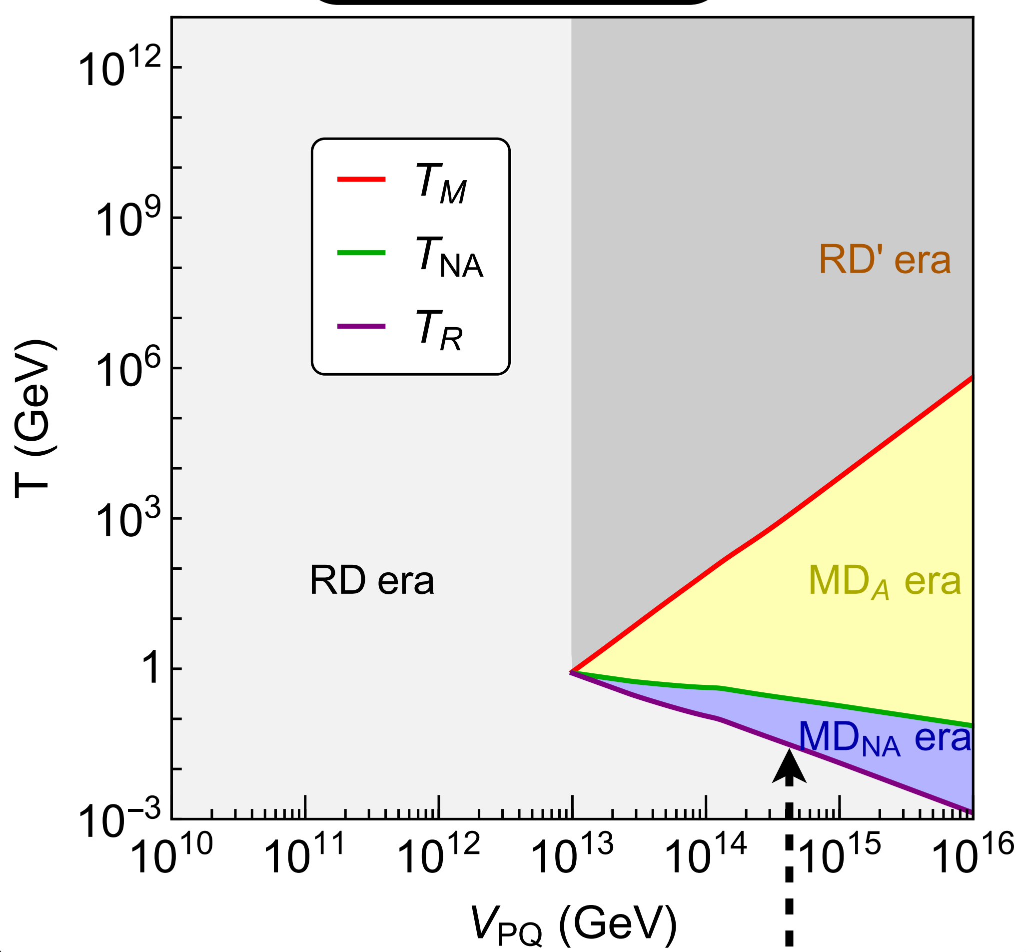
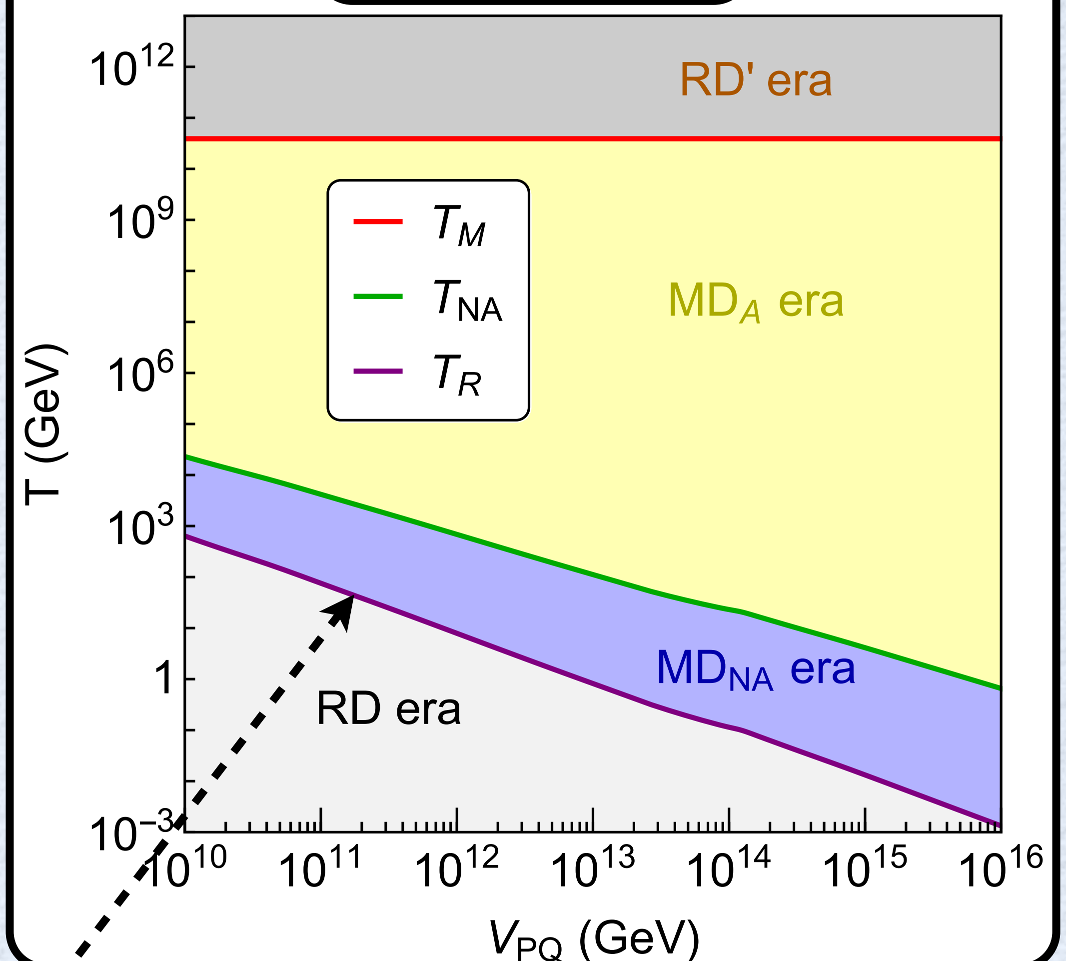


$\sigma_i = M_{Pl}$



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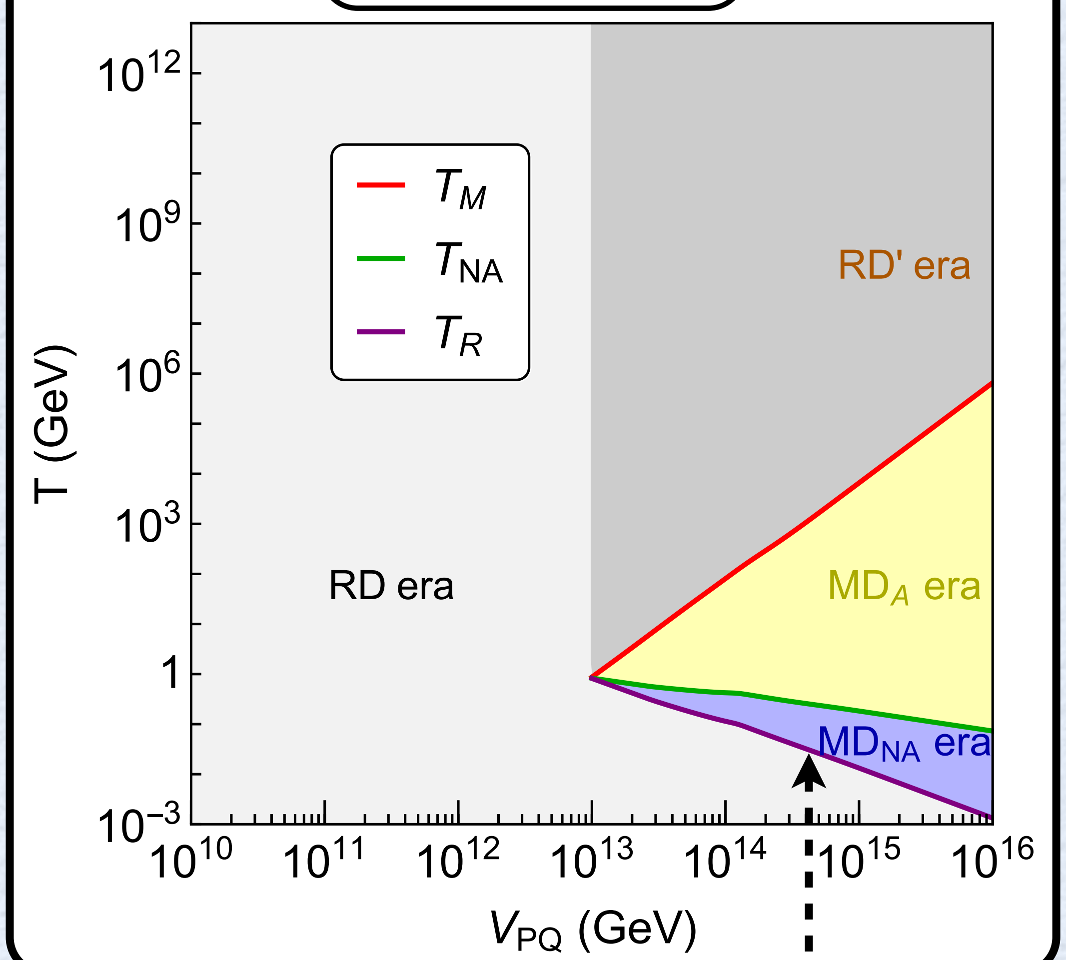

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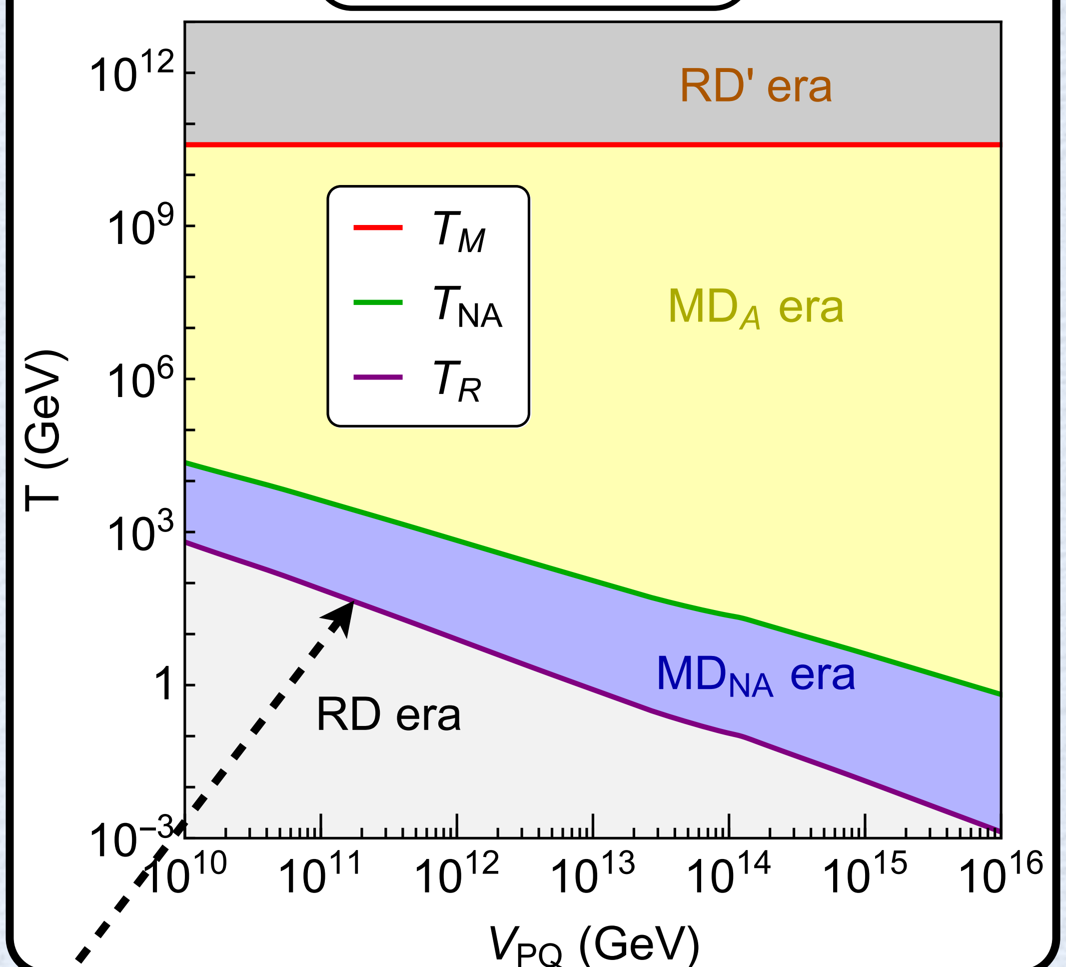


DFSZ: $s \to hh$

$$T_R \simeq 10\,\mathrm{MeV}\; q_\mu \left(\frac{10.75}{g_*(T_R)}\right)^{\frac{1}{4}} \left(\frac{\mathcal{D}}{4}\right)^{\frac{1}{2}} \left(\frac{\mu}{1\ \mathrm{TeV}}\right)^{\frac{3}{2}} \left(\frac{\mu}{m_s}\right)^{\frac{1}{2}} \left(\frac{10^{15}\ \mathrm{GeV}}{V_{PQ}}\right)$$

Gravitino Problem Solved

$$Y_{3/2}^{UV} = 6.11 \times 10^{-12} \frac{T_{RI}}{10^{10}\ \mathrm{GeV}} \sum_i \gamma_i(T_{RI}) \left(1 + \frac{m_i^2}{3m_{3/2}^2}\right)$$

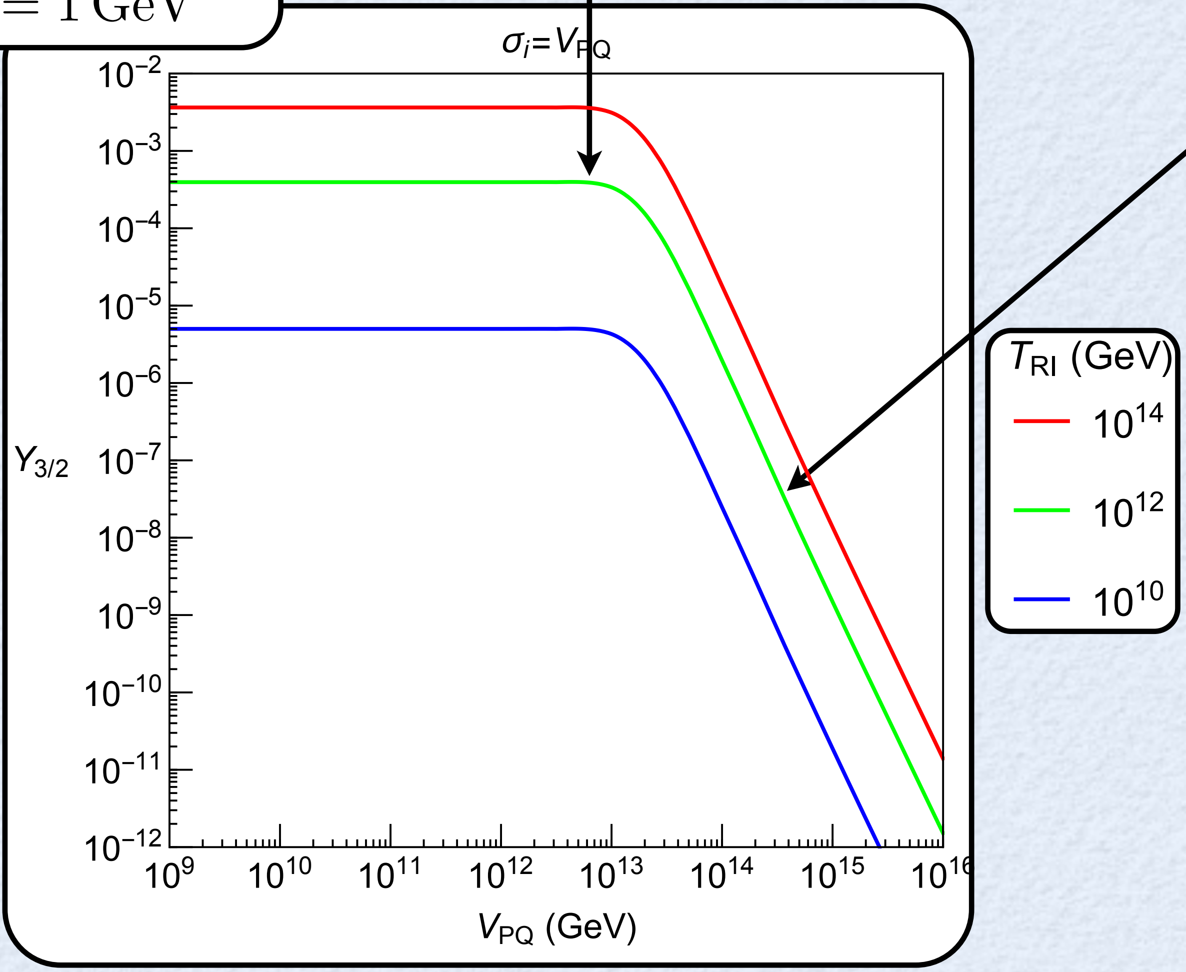
Large Dilution

$D \propto \sigma_i^2 V_{PQ}$

No Dilution

$\sigma_i = V_{PQ}$

$m_{3/2} = 1\,\mathrm{GeV}$



$$Y_{3/2} \propto \frac{1}{m_{3/2}^2}$$

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Large Dilution

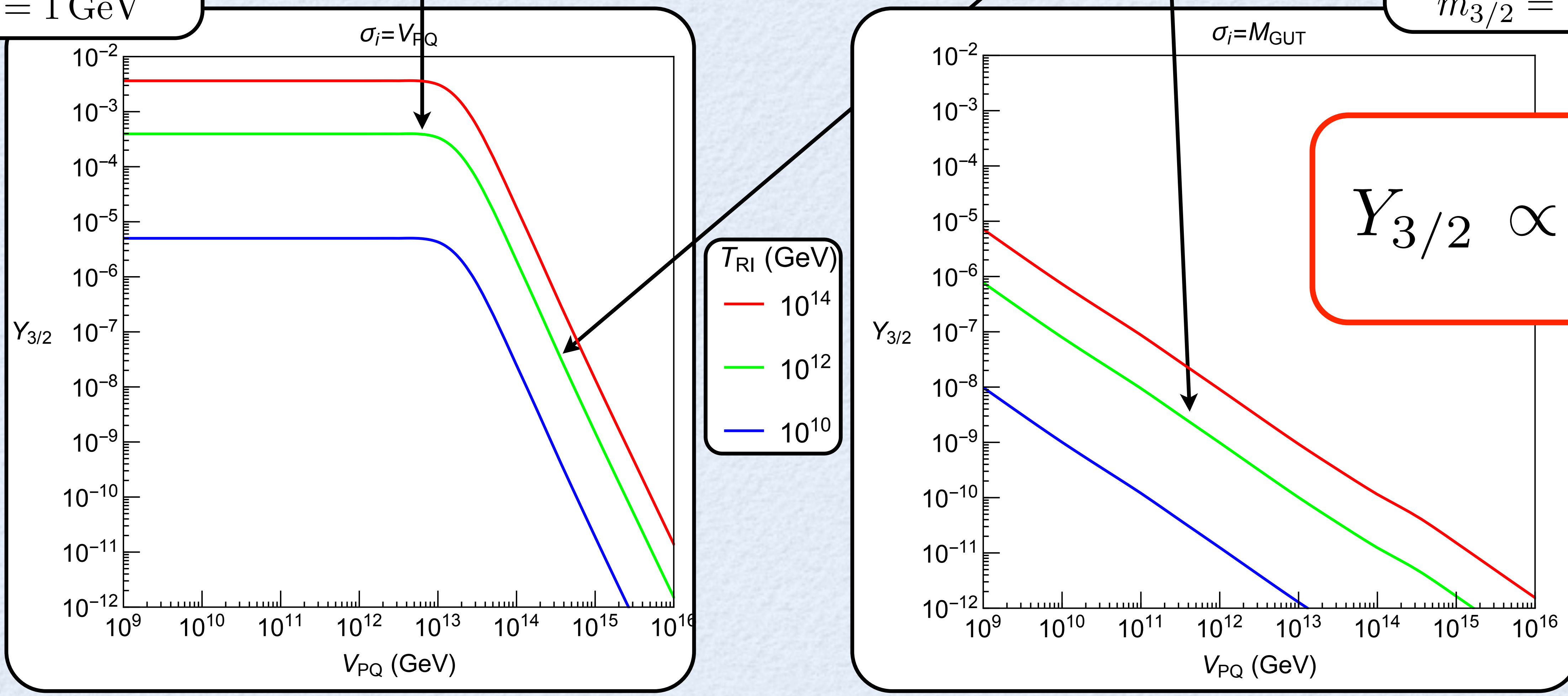
$D \propto \sigma_i^2 V_{PQ}$

$\sigma_i = V_{PQ}$

$m_{3/2} = 1\,\mathrm{GeV}$

$\sigma_i = M_{GUT}$

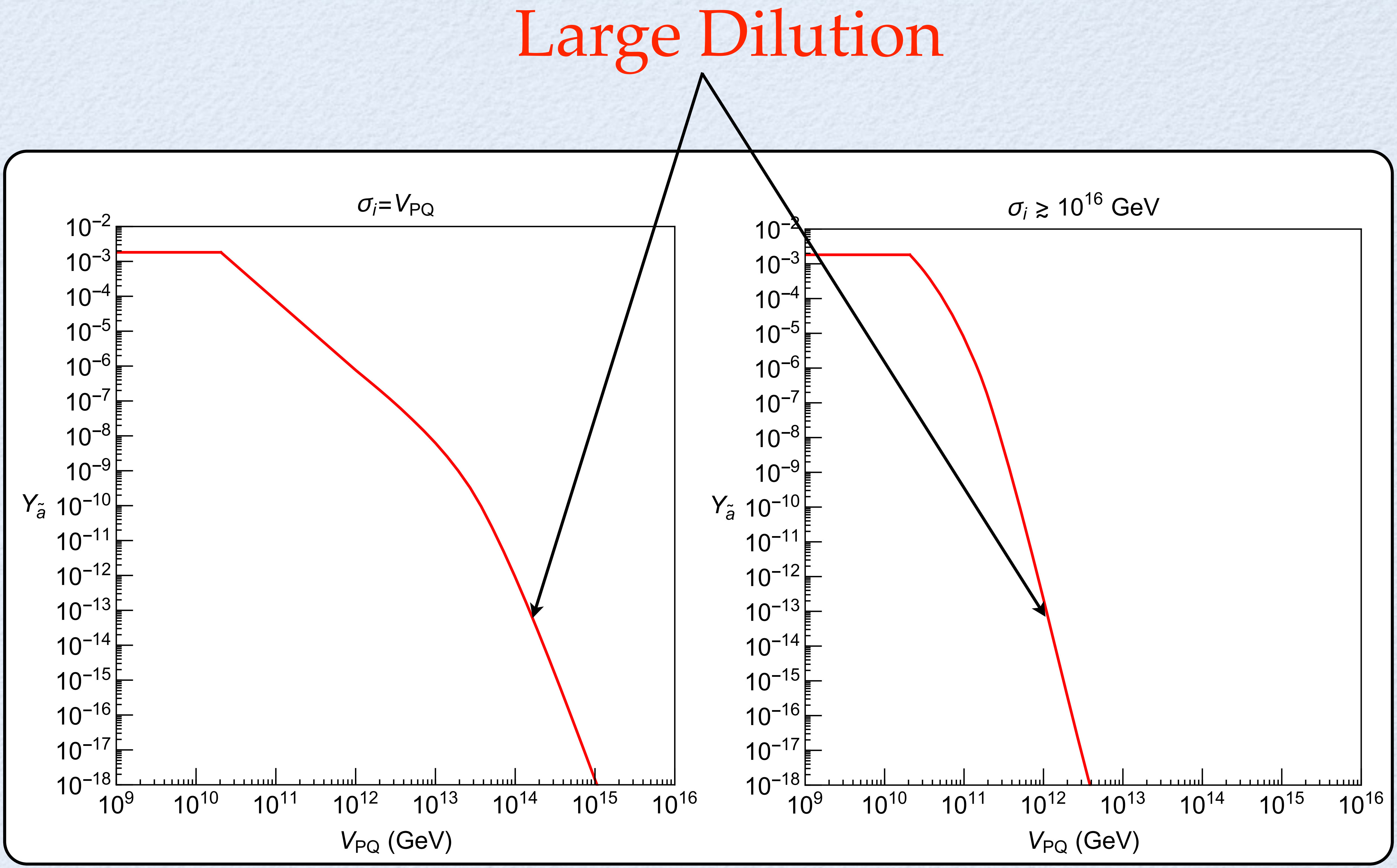
$m_{3/2} = 1\,\mathrm{GeV}$



$$Y_{3/2} \propto \frac{1}{m_{3/2}^2}$$

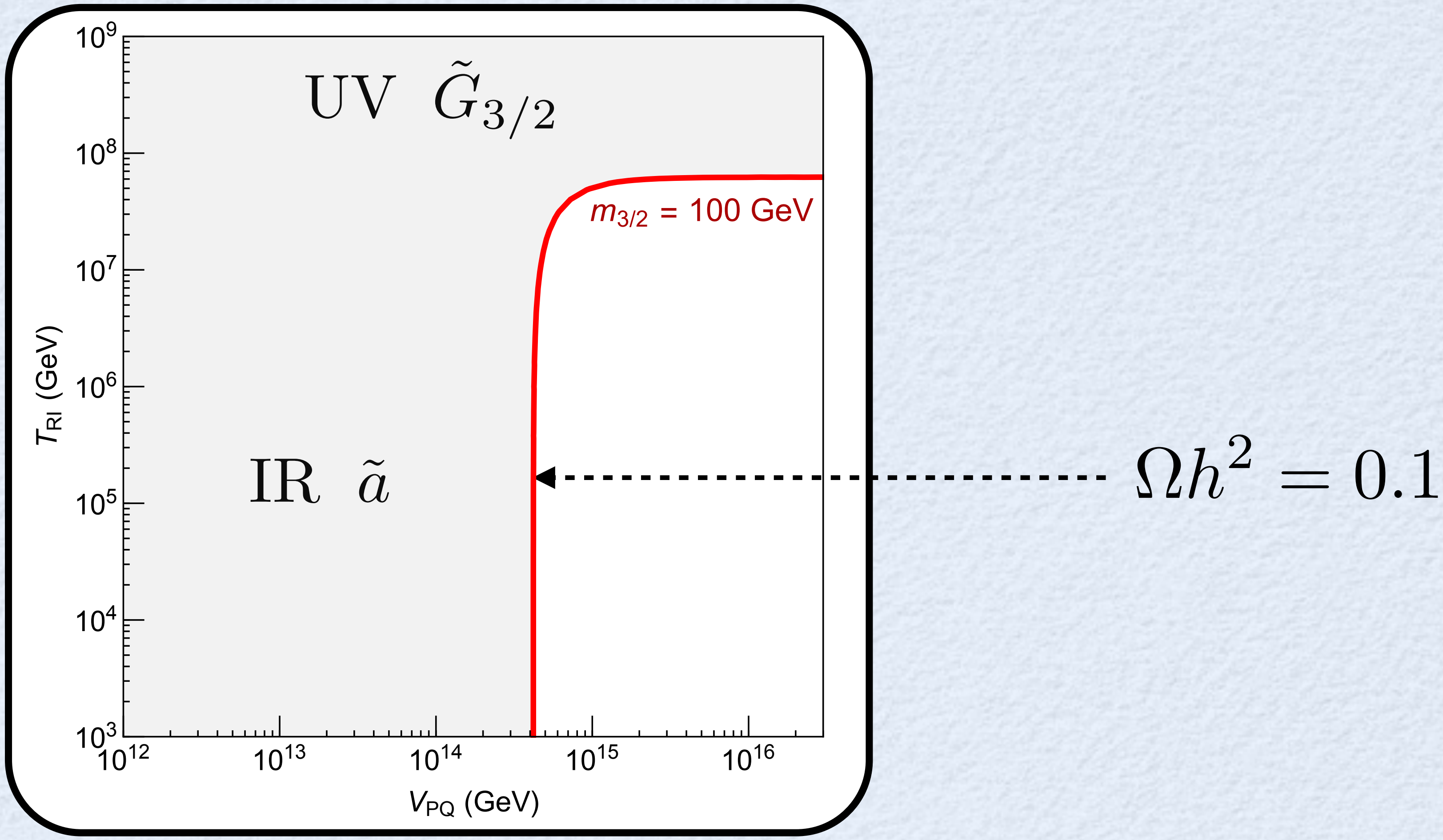
Earlier work: Kawasaki, Nakayama arXiv:0802.2487

Axino Freeze-In Problem Solved



High Scale Mediation

Gravitino/Axino DM



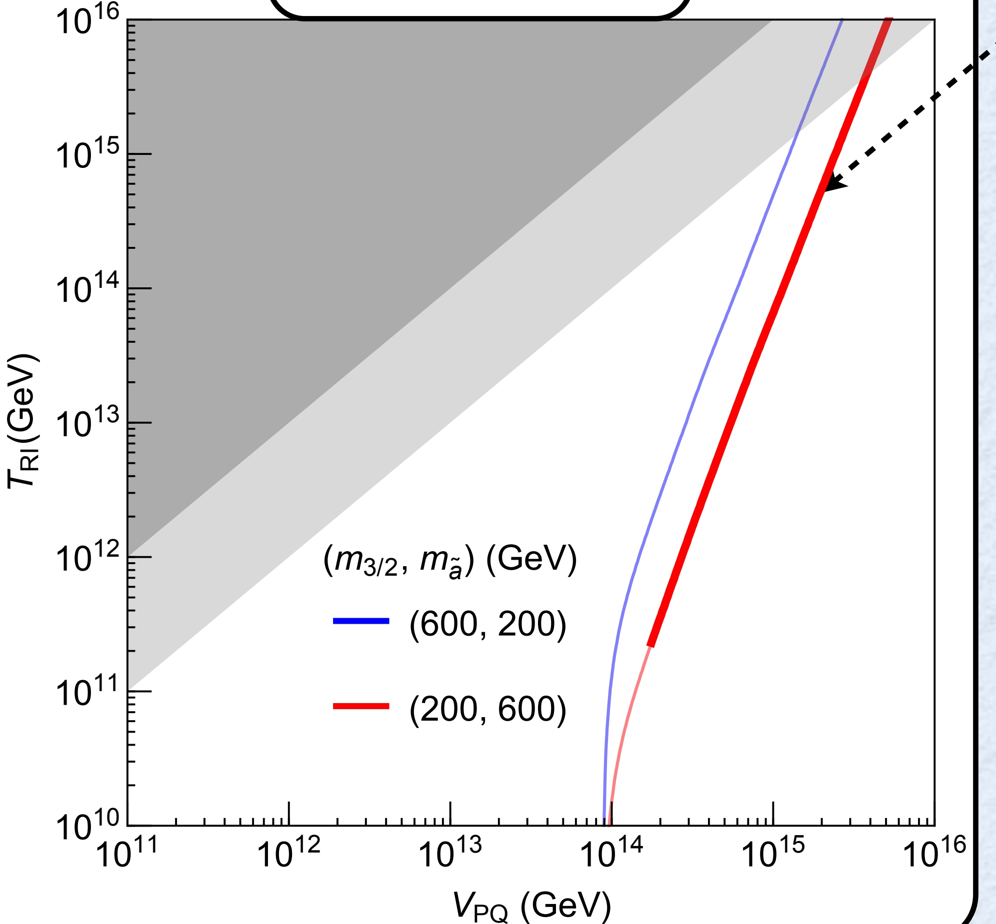
Expect saxion condensate

opens up high T_{RI}

High Scale Mediation

Gravitino DM from UV scattering

$\sigma_i = V_{PQ}$



High Scale Mediation

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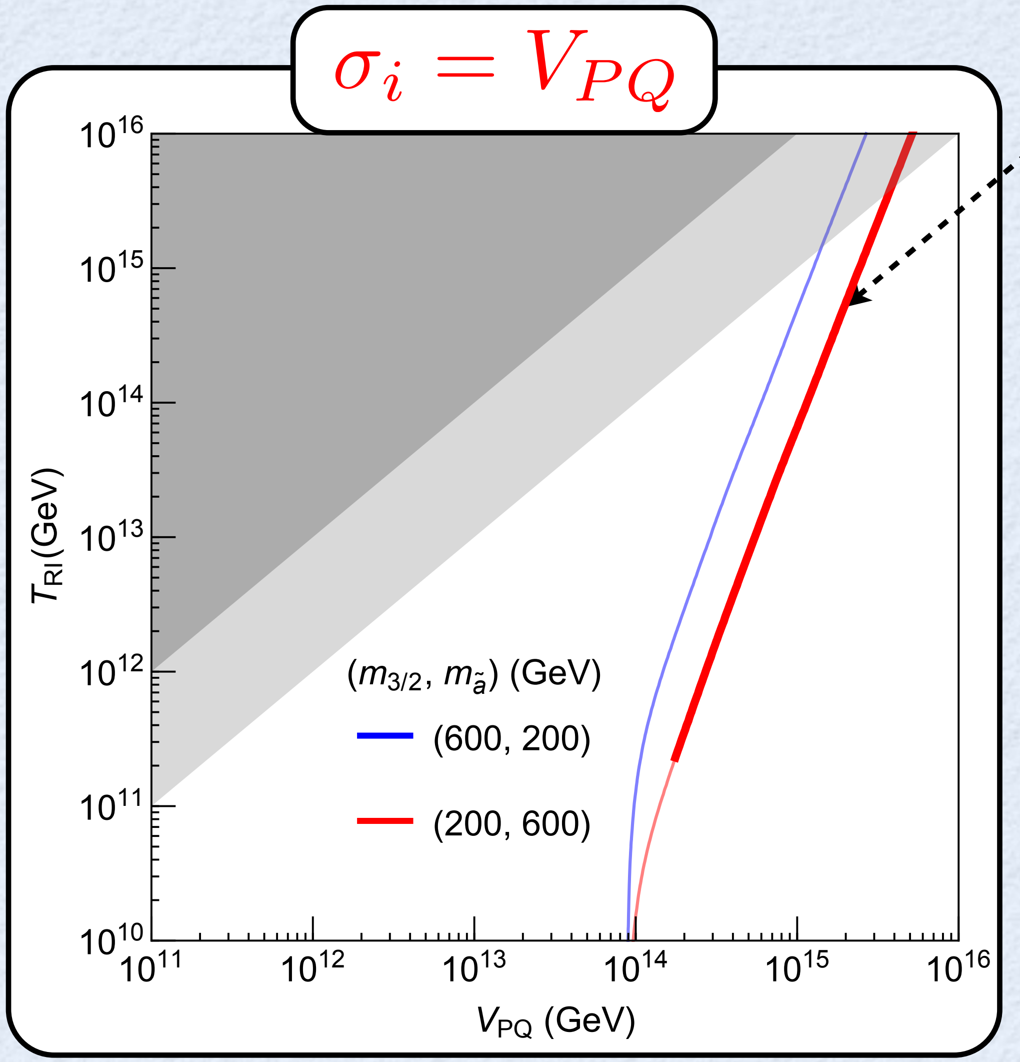

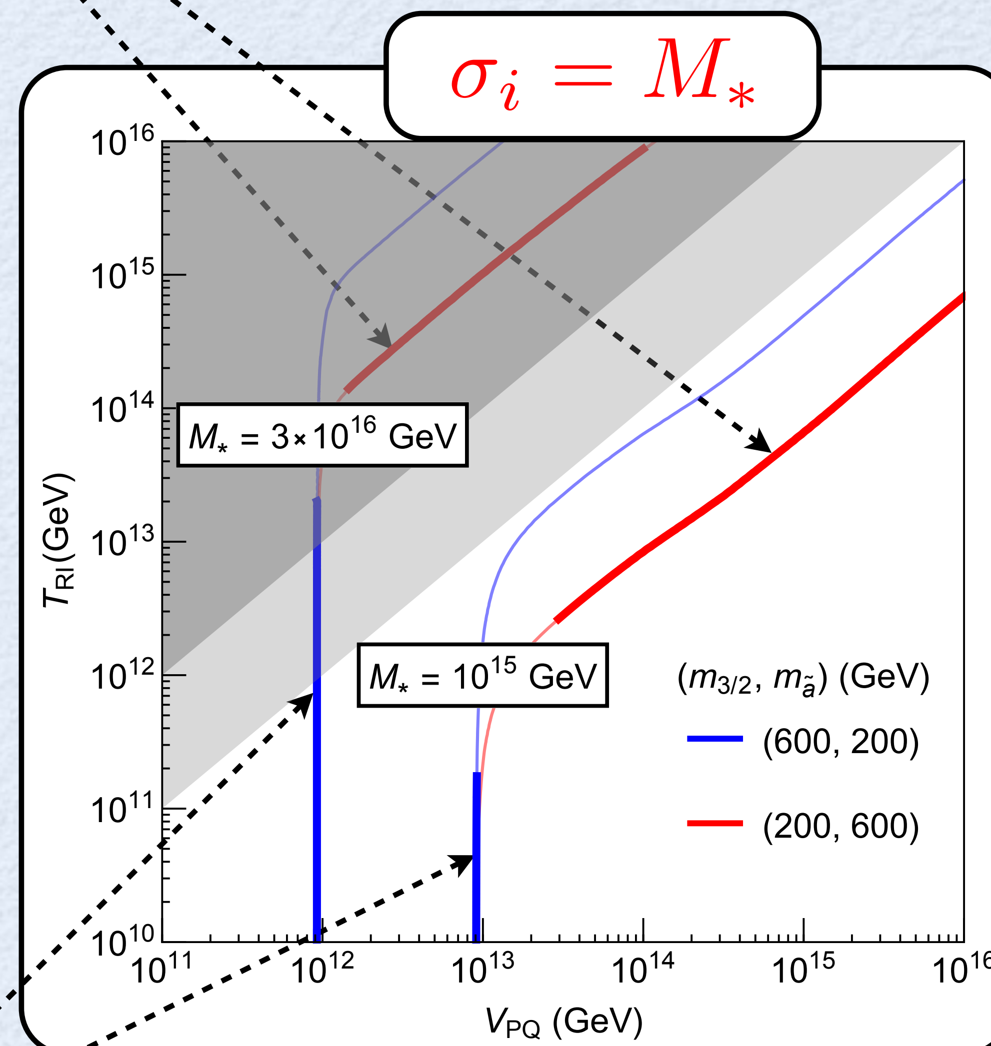

Axino DM from Freeze-In

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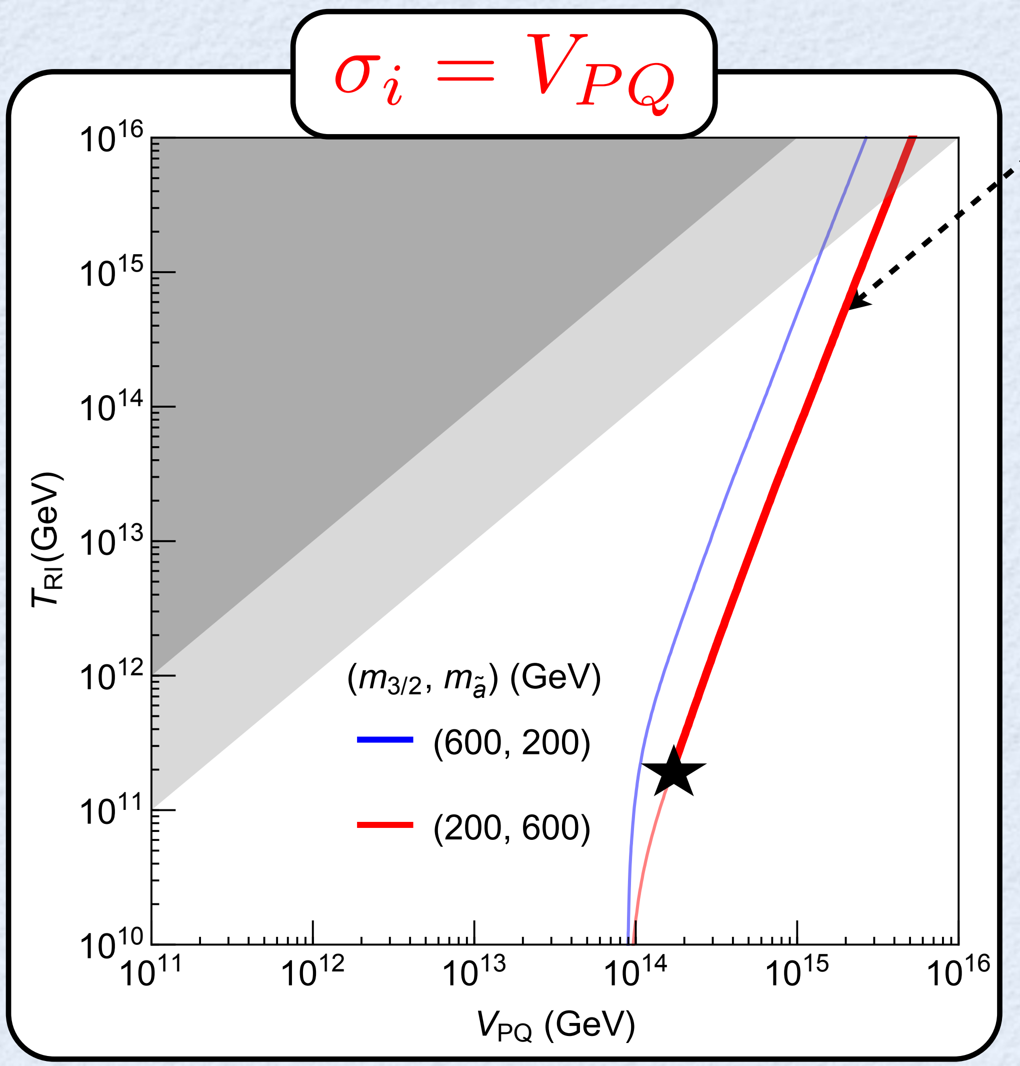

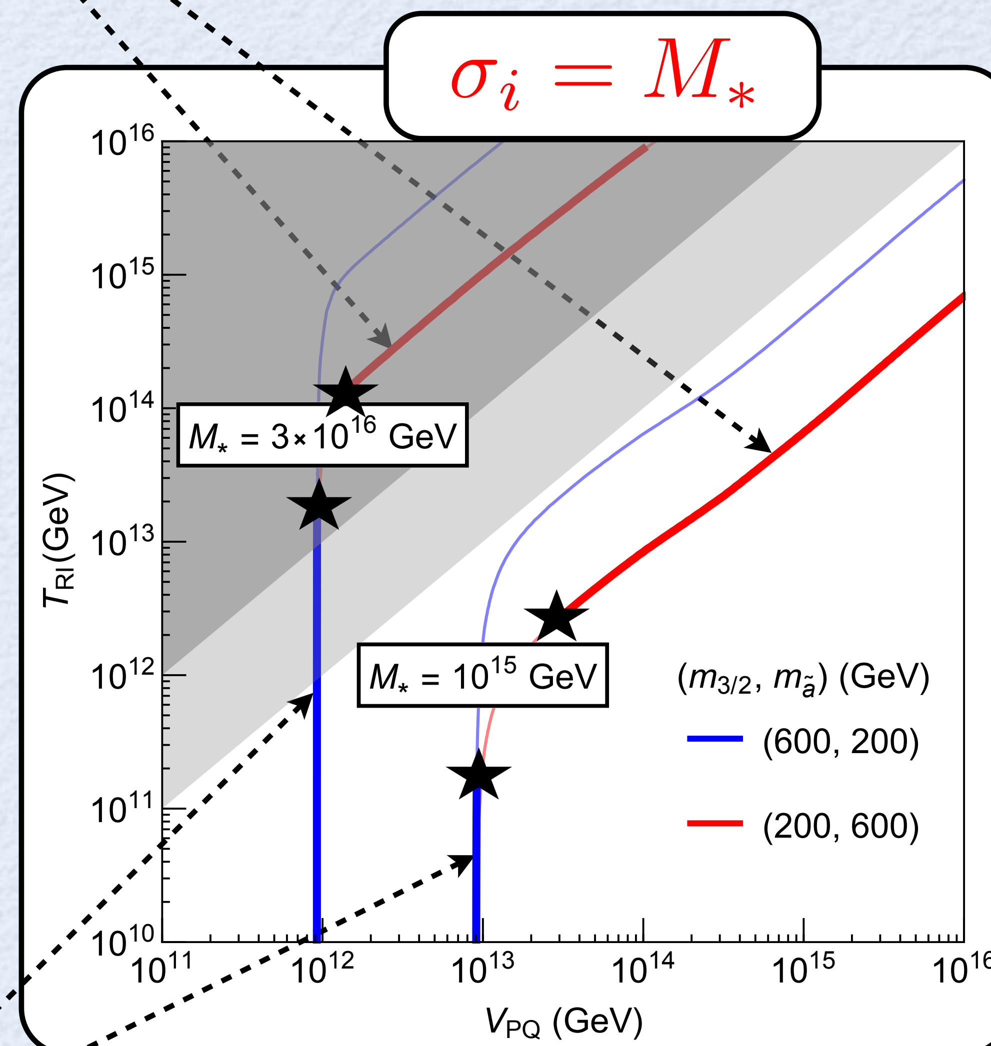

Axino DM from Freeze-In

★ A warm sub-dominant component

Displaced Vertices at Colliders

High Scale Mediation

Axino DM from Freeze-In

Neutralino LOSP

$$\boxed{\tilde{\chi} \to \tilde{a} + (h/Z)}$$

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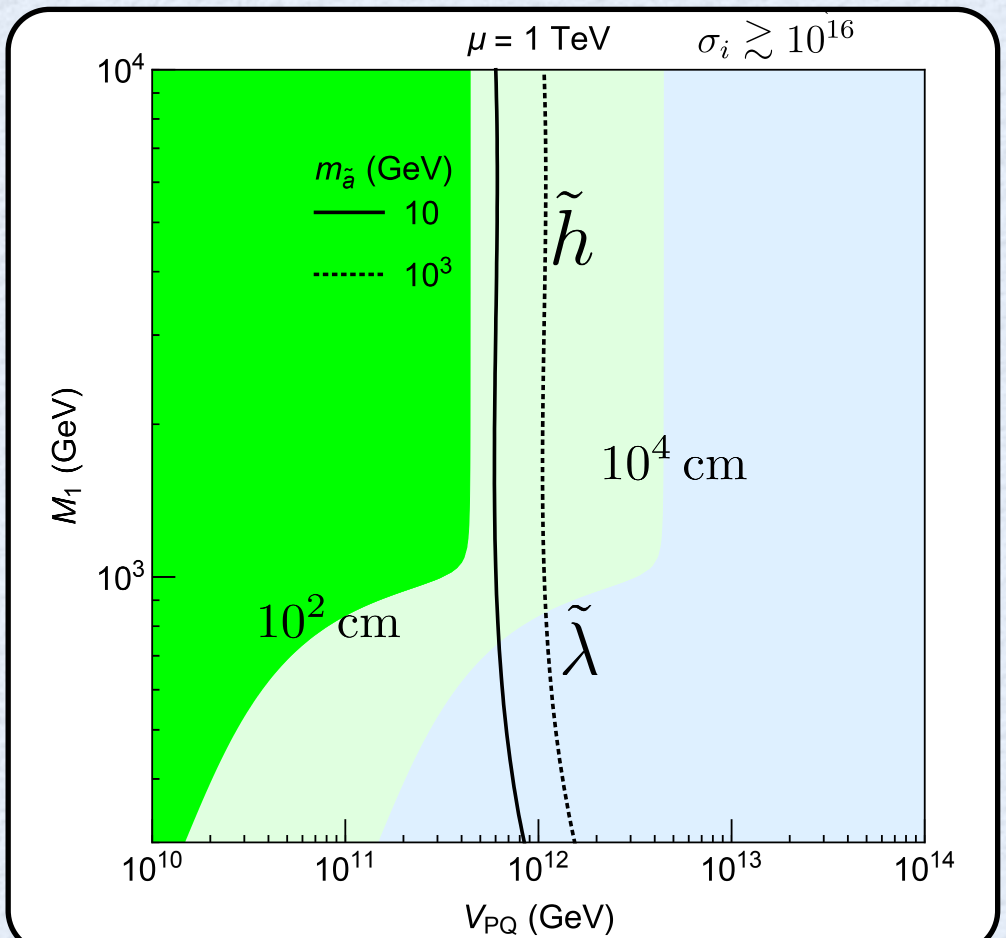
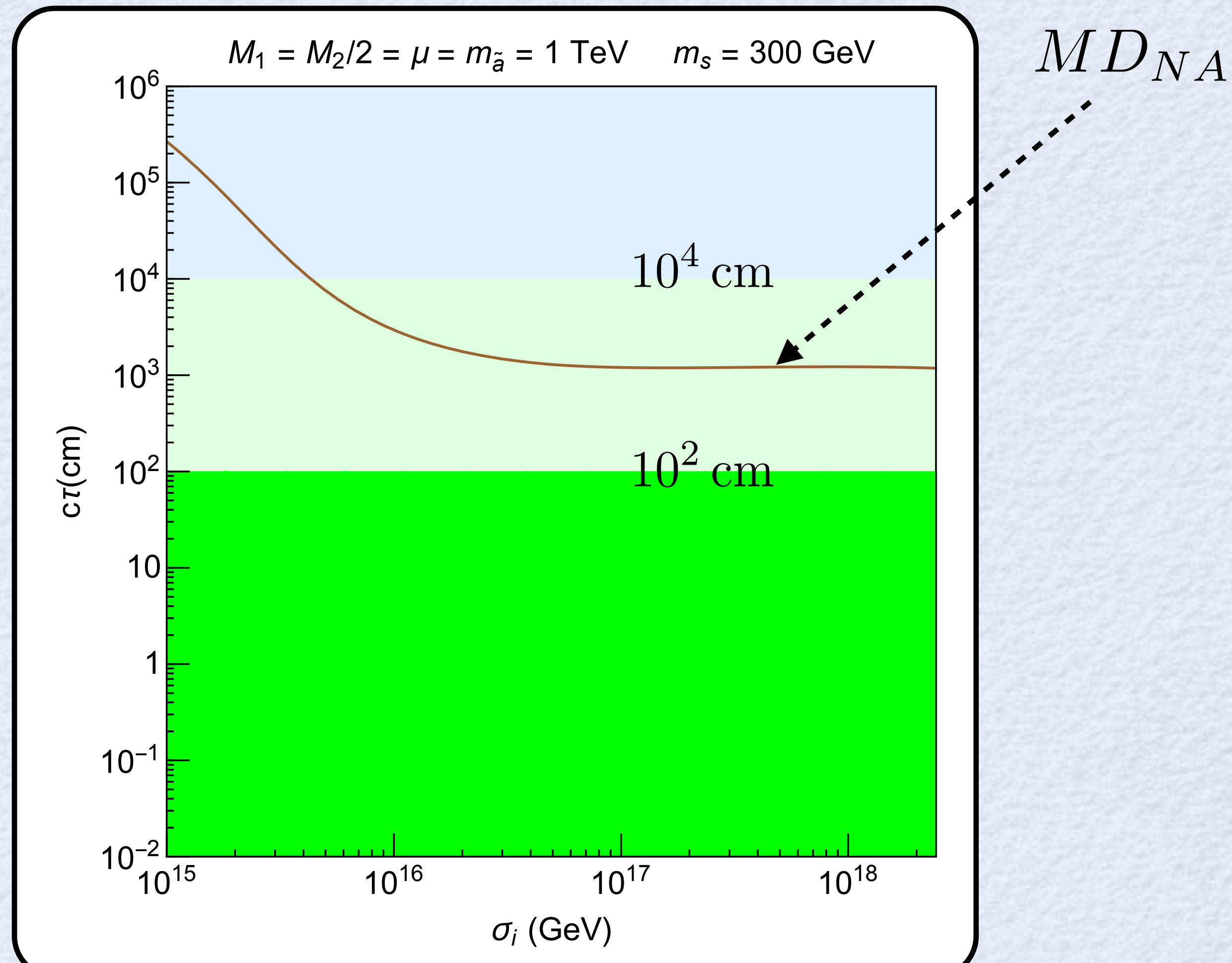
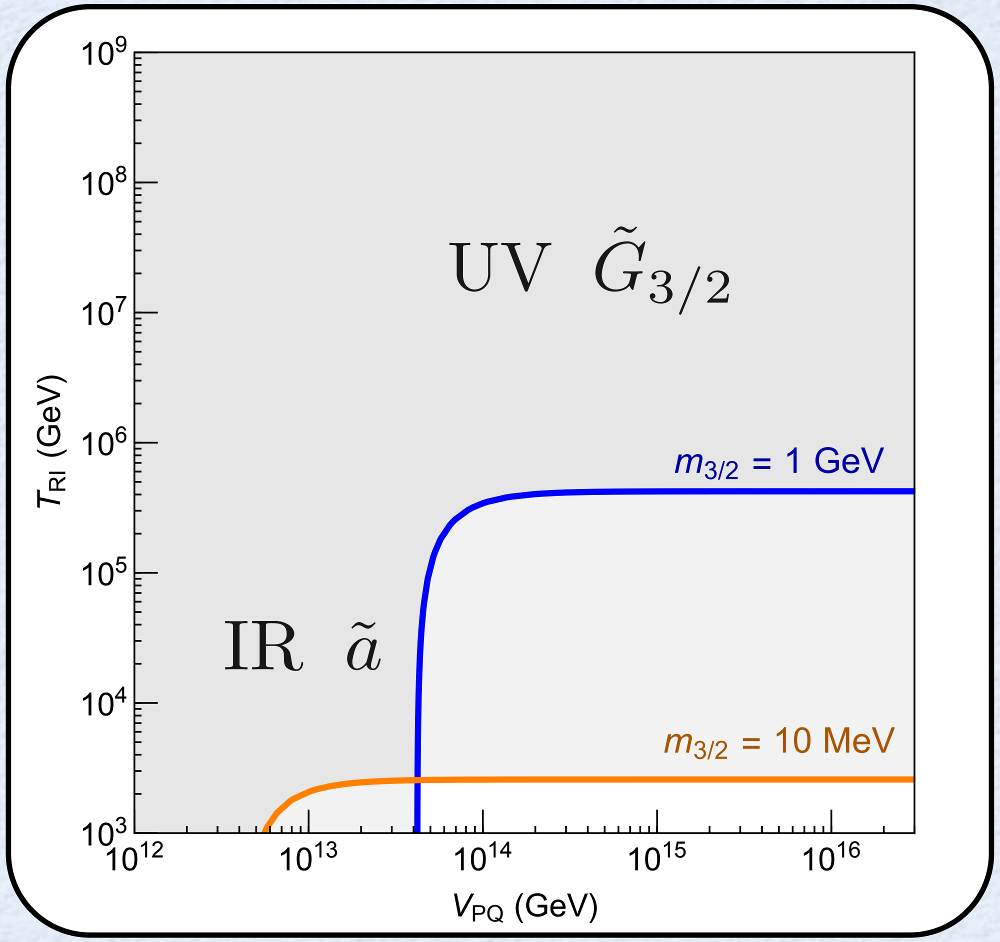




More generally: Co, D'Eramo, Hall, Pappadopulo arXiv:1506.07532

Low Scale Mediation

No Dilution



Low Scale Mediation

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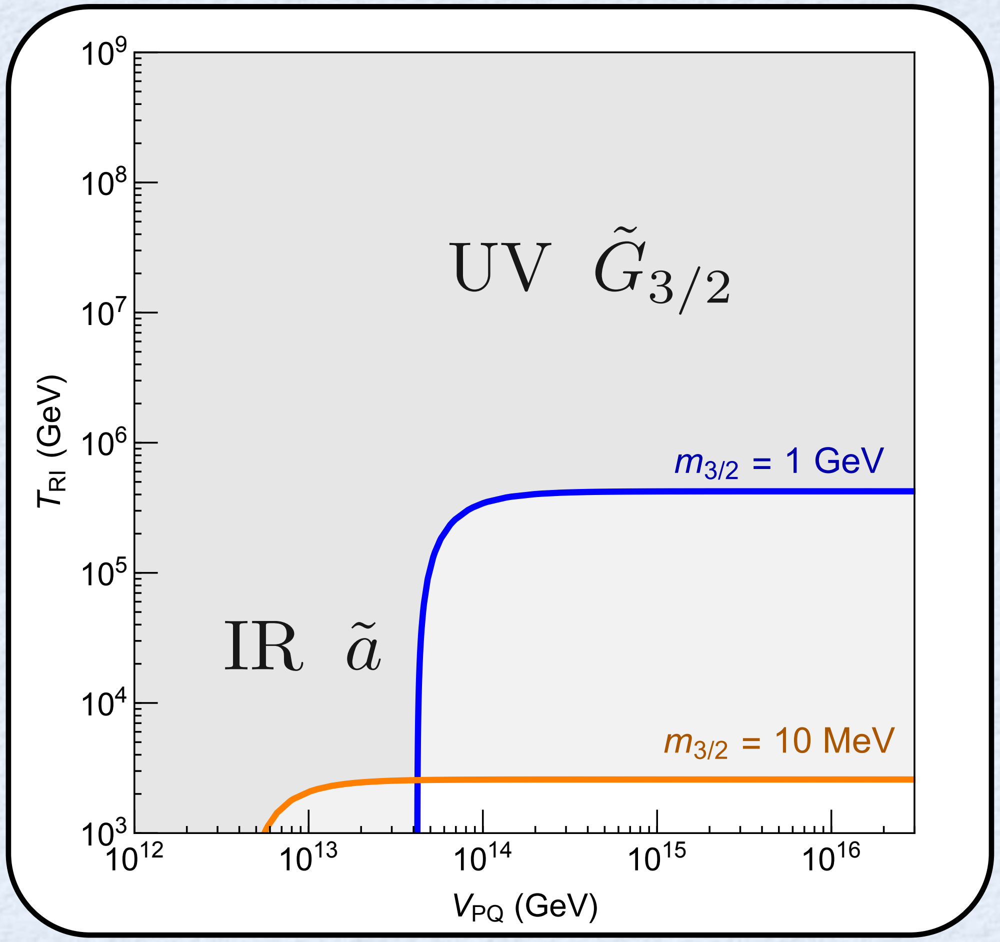

Conventional displaced vertex signal

$$\text{LOSP} \to \tilde{G}_{3/2}$$

requires $m_{3/2} \leq \text{MeV}$

What is the cosmology?

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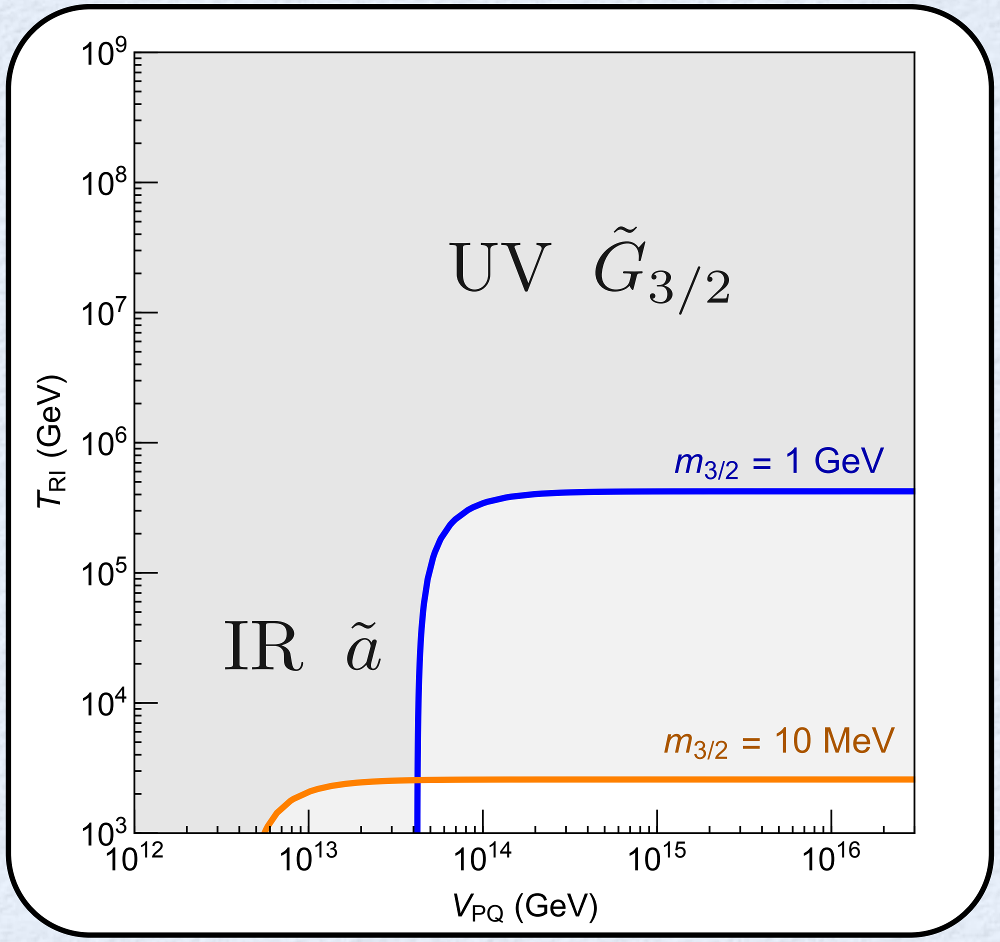

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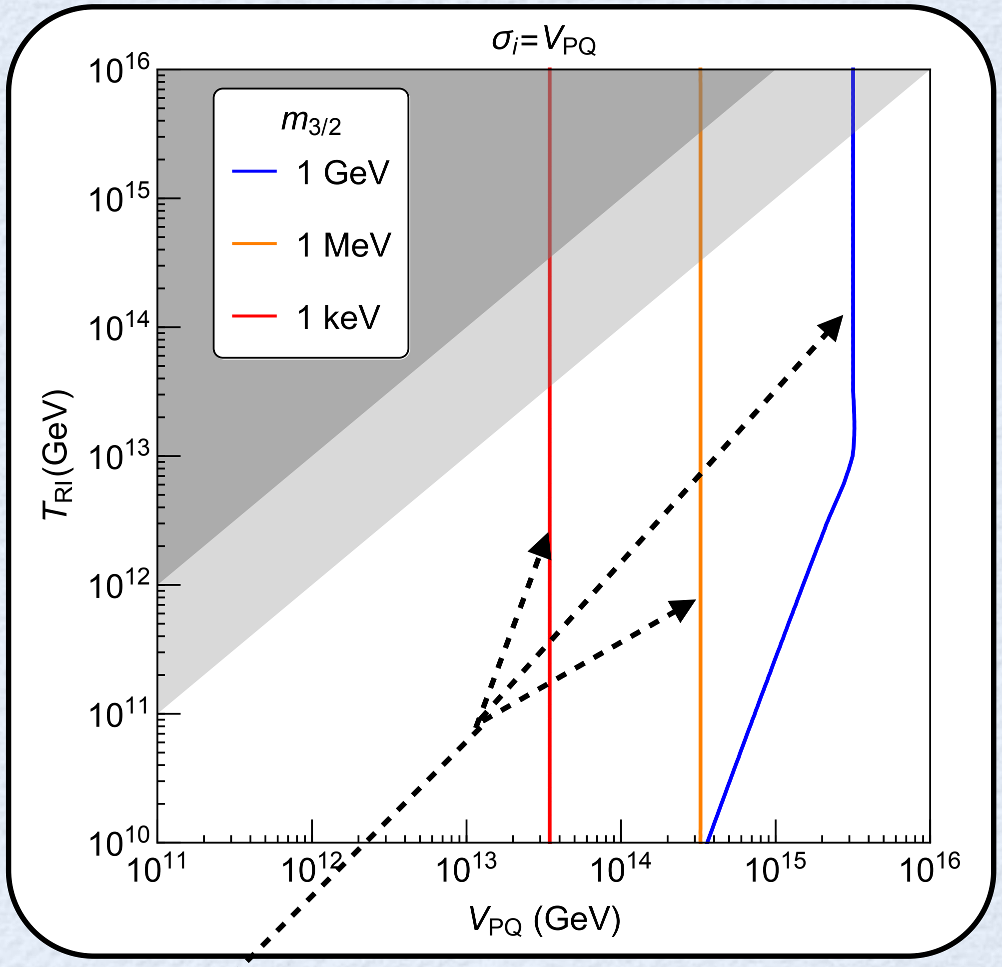
Saxion Condensate



UV $\tilde{G}_{3/2}$ thermalize

Dilution gives:
$V_{PQ} \sim 10^{14}$ GeV

IR $\tilde{a}$ negligible

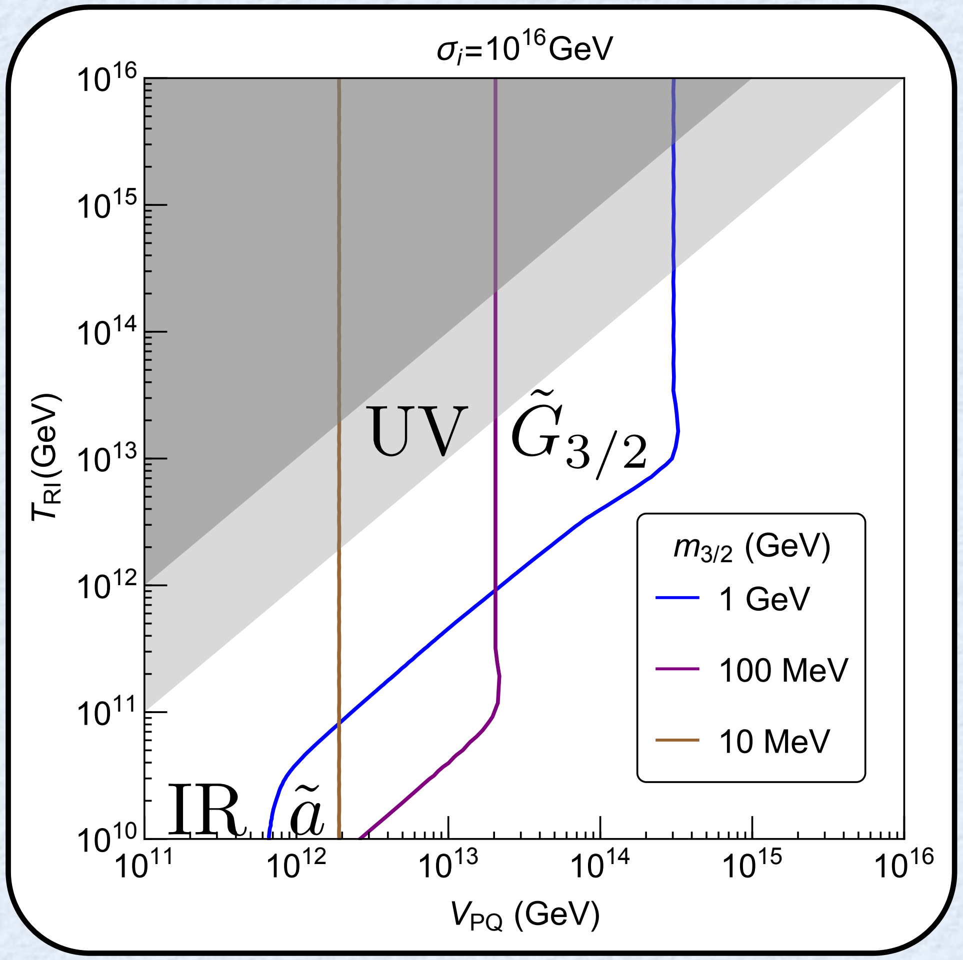
$\text{LOSP} \to \tilde{G}_{3/2}$

$T_{RI} \leq 10^{14}$ GeV

Low Scale Mediation

Larger Saxion Condensate

$\longrightarrow$ Lower V_{PQ}



Lower V_{PQ} $\longrightarrow$ LOSP $\to \tilde{a}$

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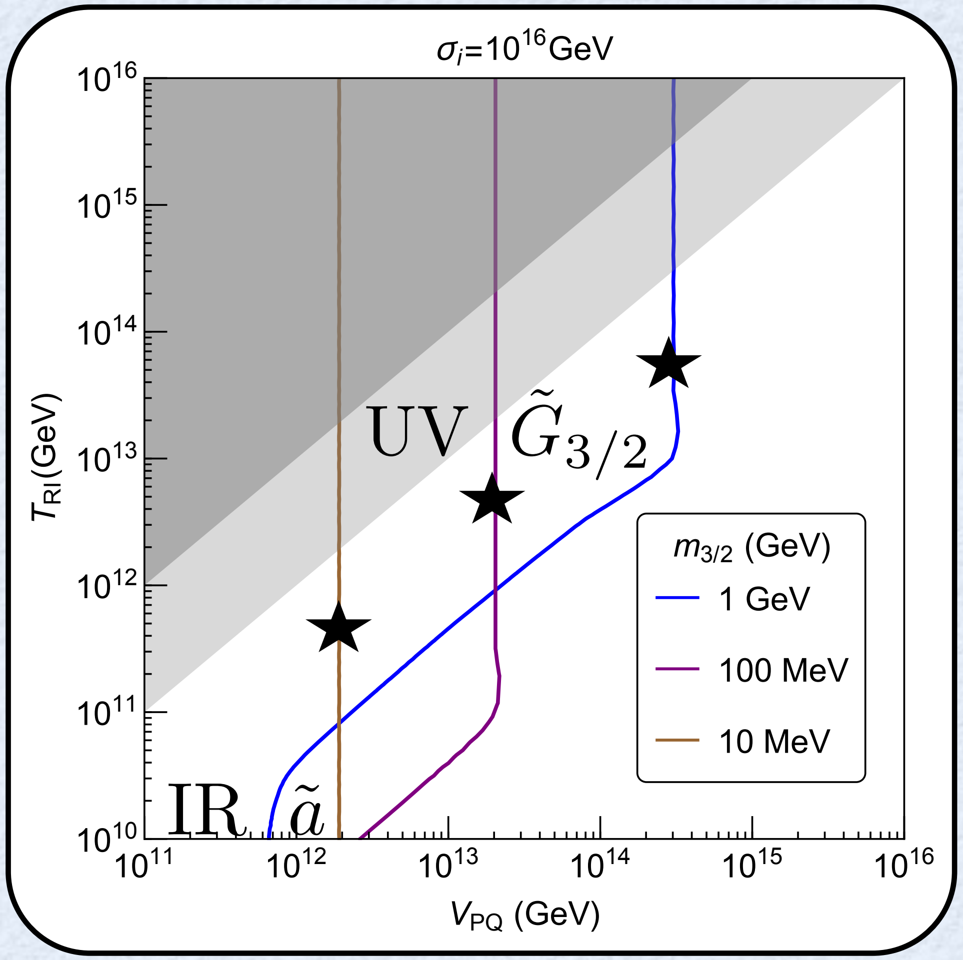

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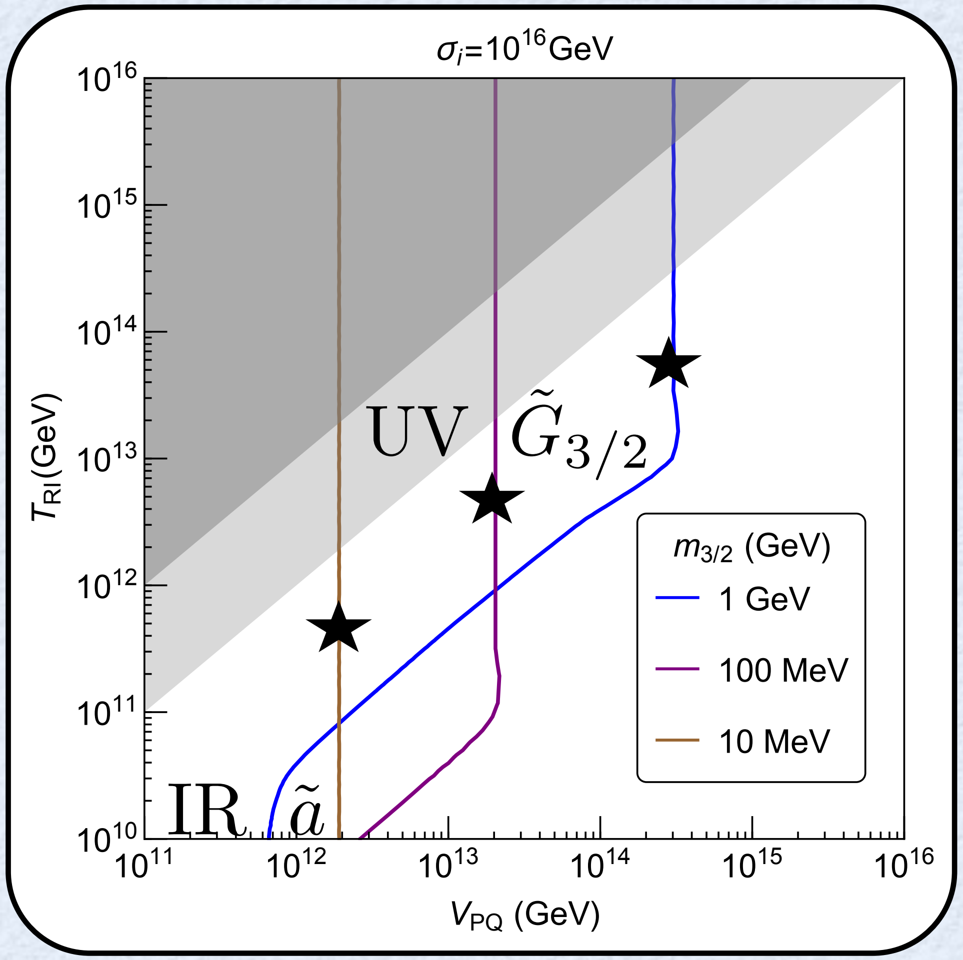

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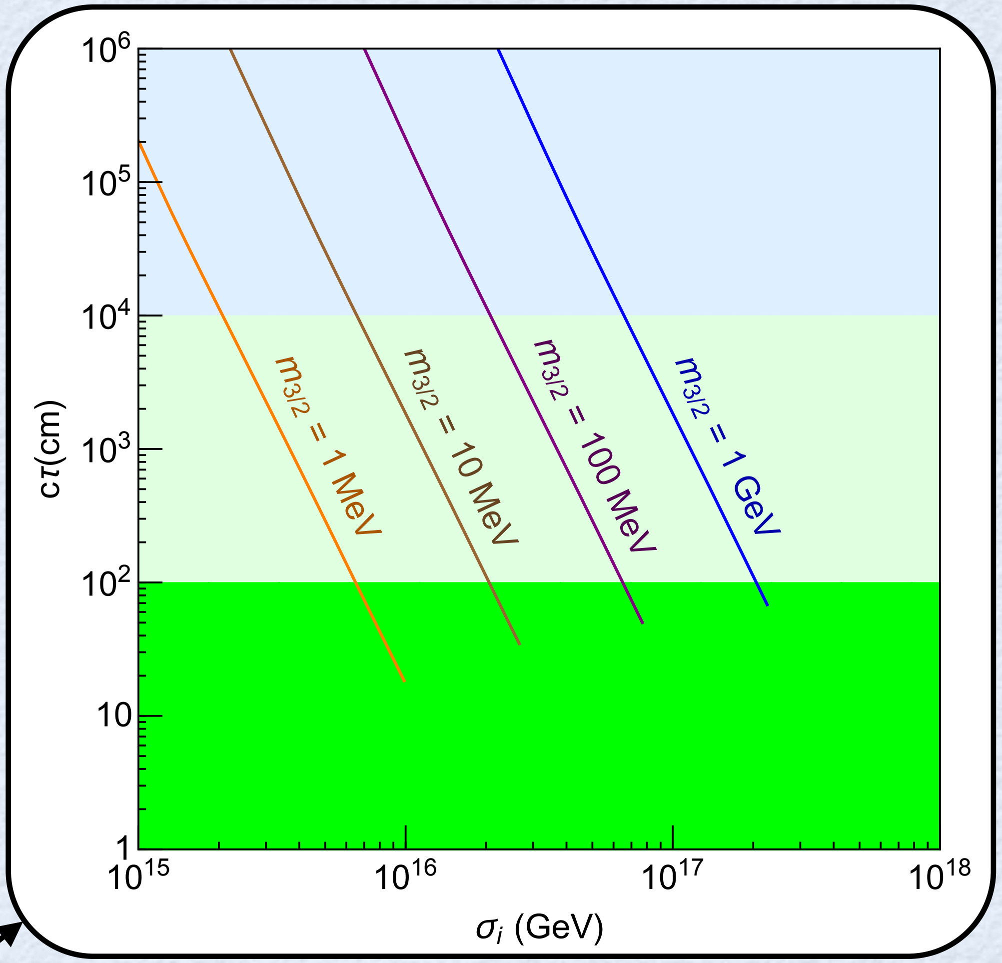
Higgsino-like LOSP lifetime



Even smaller lifetimes for lower T_{RI} where $\tilde{G}_{3/2}$ not thermalized

LSP Neutralino Dark Matter

Two production mechanisms:

- $\tilde{a}$ Freeze-In and Decay to LSP

typically over-produce

- LSP Freeze-Out

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$\boxed{\text{+ Saxion Dilution}}$

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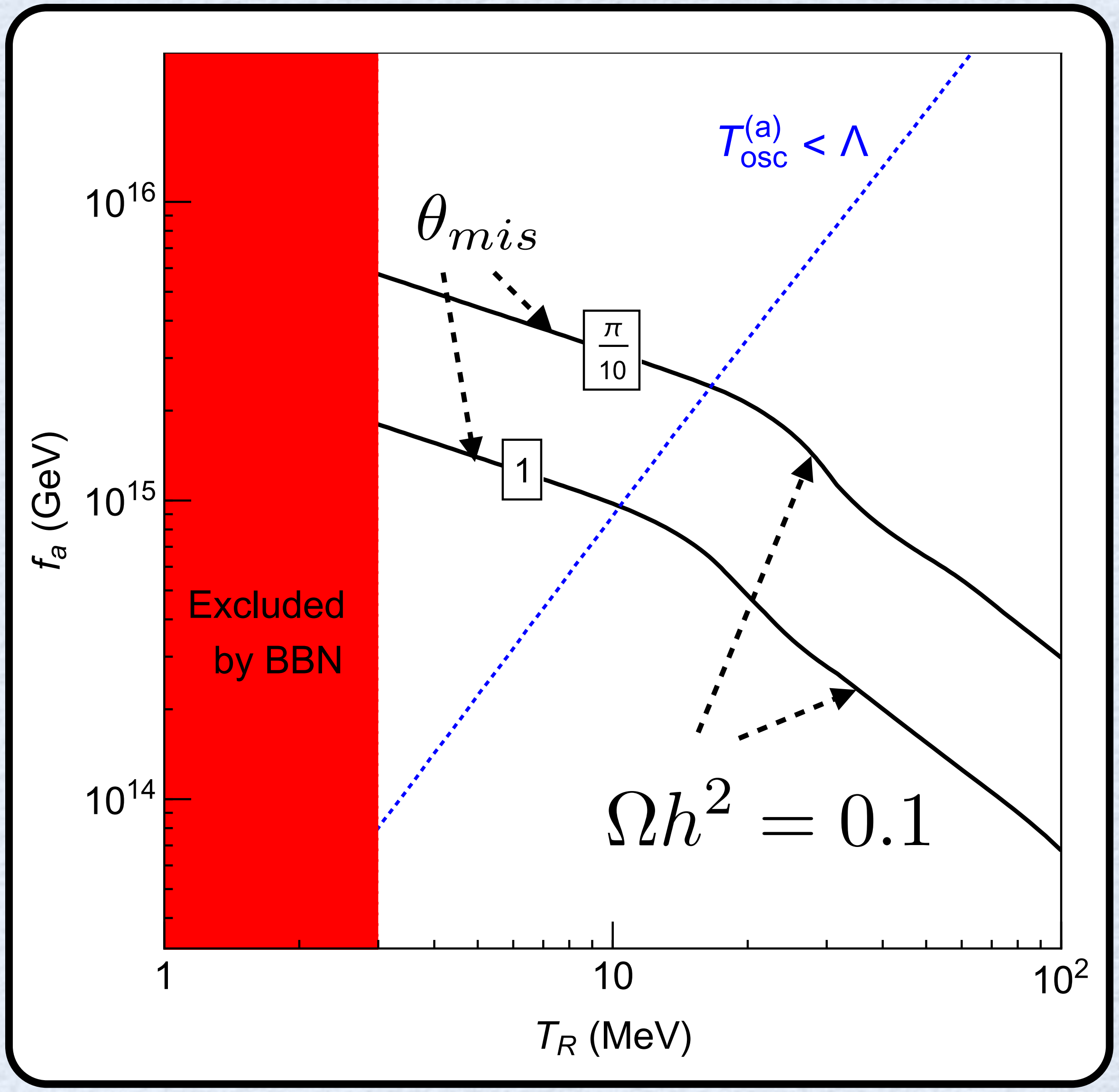

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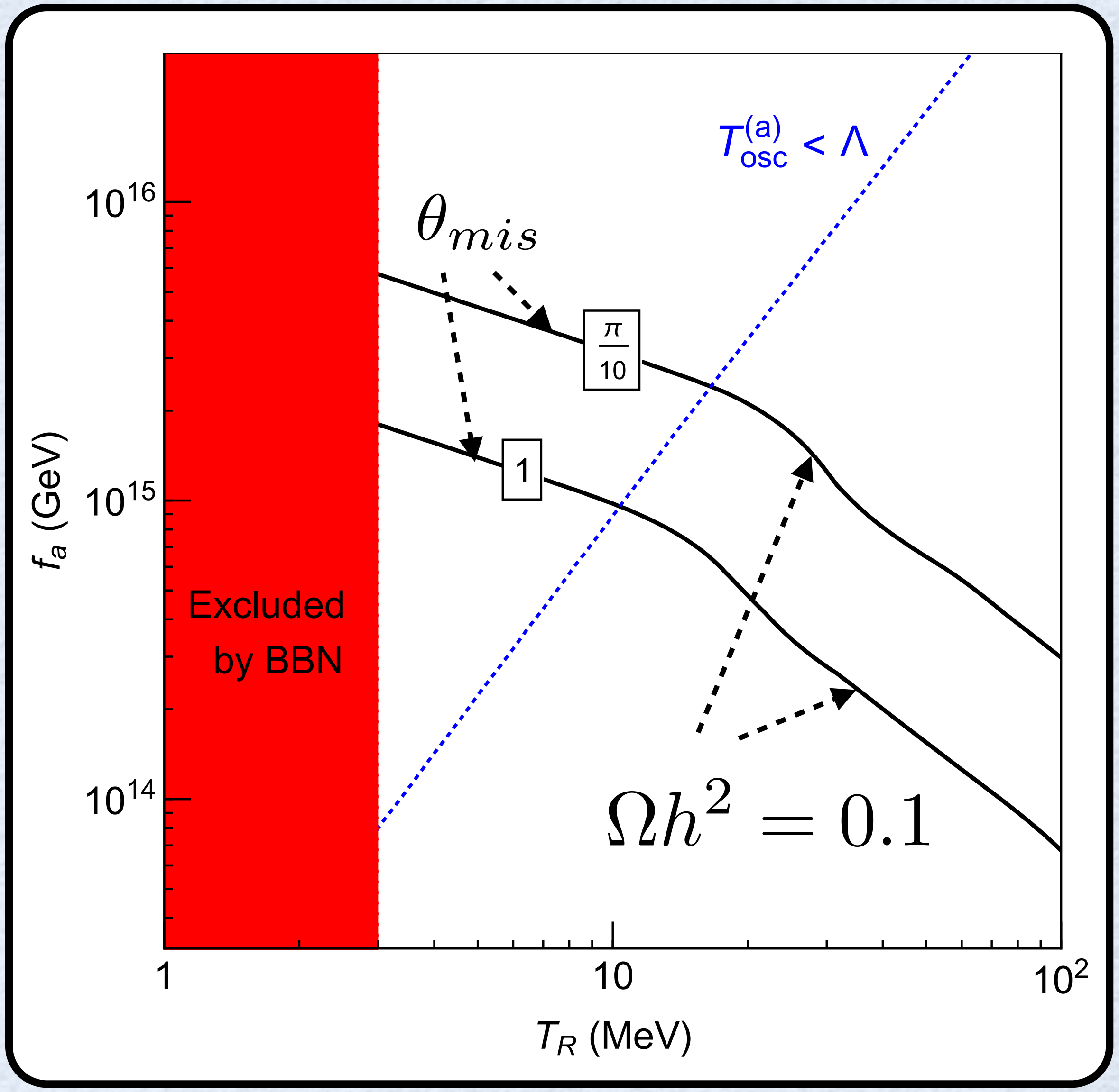
$$\boxed{V_{PQ} \sim V_{GUT}}$$

"SaxiGUTs"

Raymond Co, Francesco D'Eramo, LH 1603.04439



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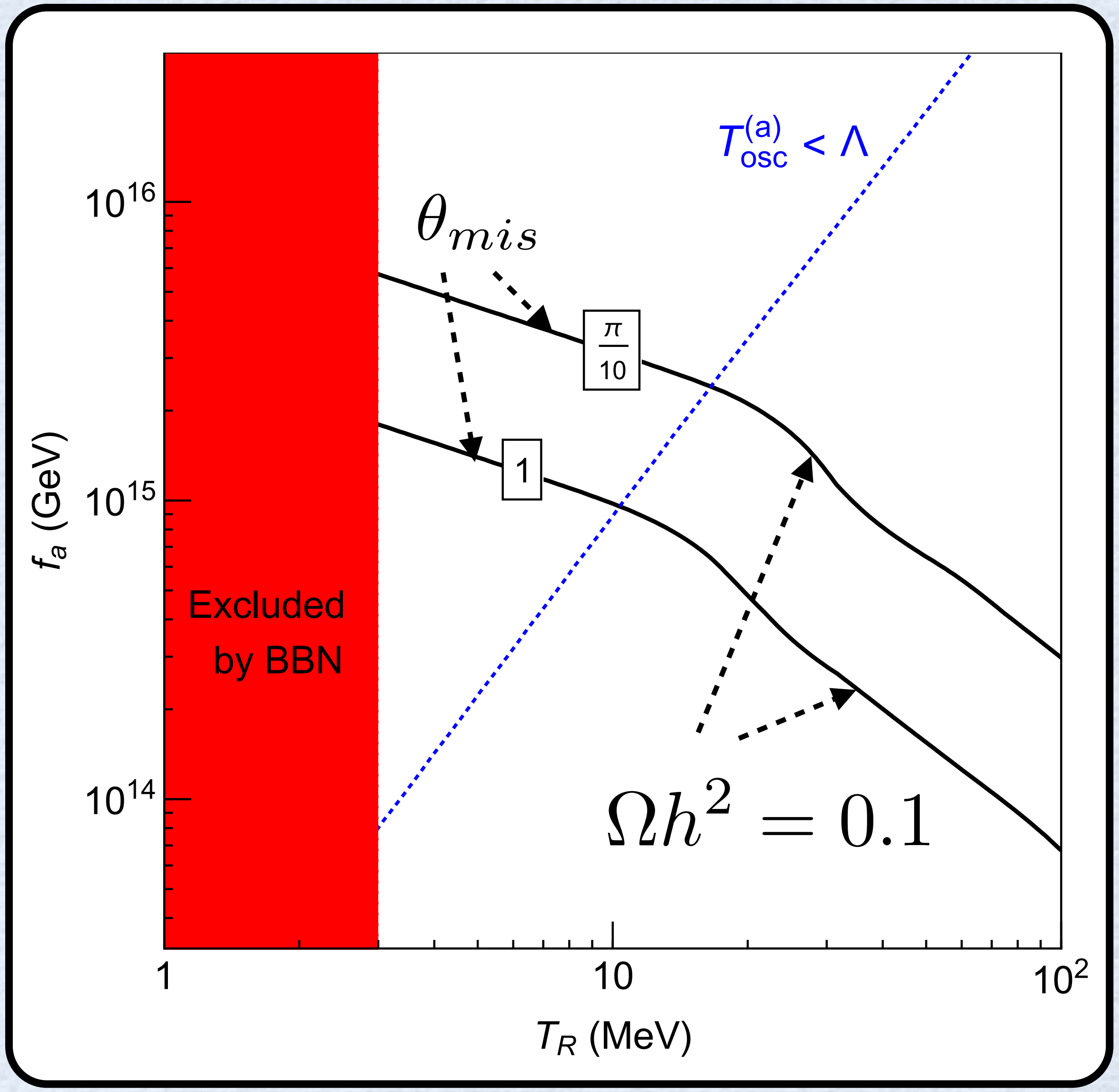

Earlier work: Hashimoto, Izawa, Yamaguchi, Yanagida hep-ph/9803263

Dark Radiation from $s \to aa$

$$\boxed{\boldsymbol{K} = \sum_i v_i^2 \exp\left[q_i \left(\frac{\boldsymbol{A}+\boldsymbol{A}^\dagger}{V_{PQ}}\right)\right] = \boldsymbol{A}^\dagger \boldsymbol{A} + \frac{1}{2}\sum_i \frac{q_i^3 v_i^2}{V_{PQ}^3}\boldsymbol{A}^\dagger \boldsymbol{A}\left(\boldsymbol{A}+\boldsymbol{A}^\dagger\right) + \dots\ .}$$

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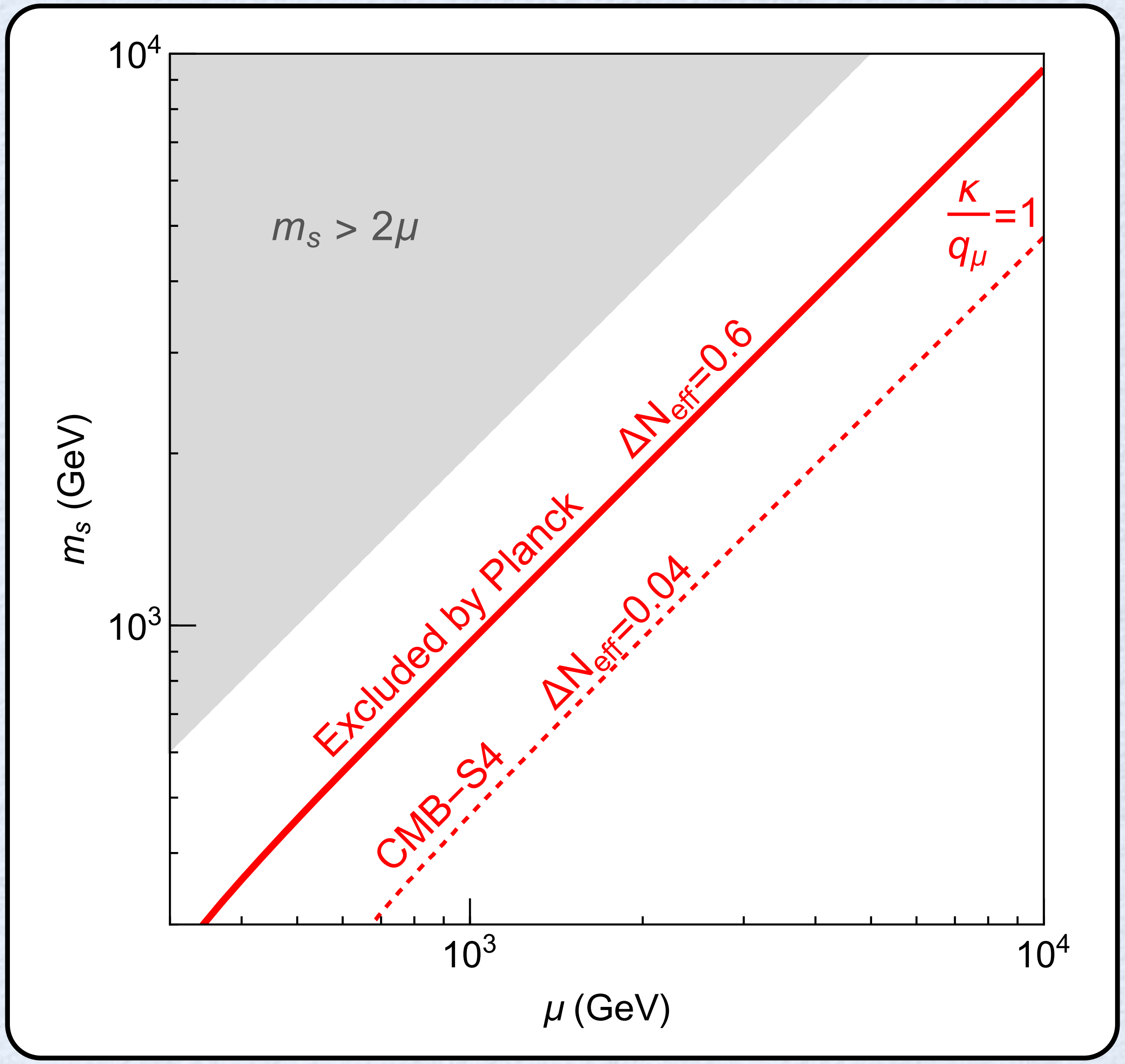

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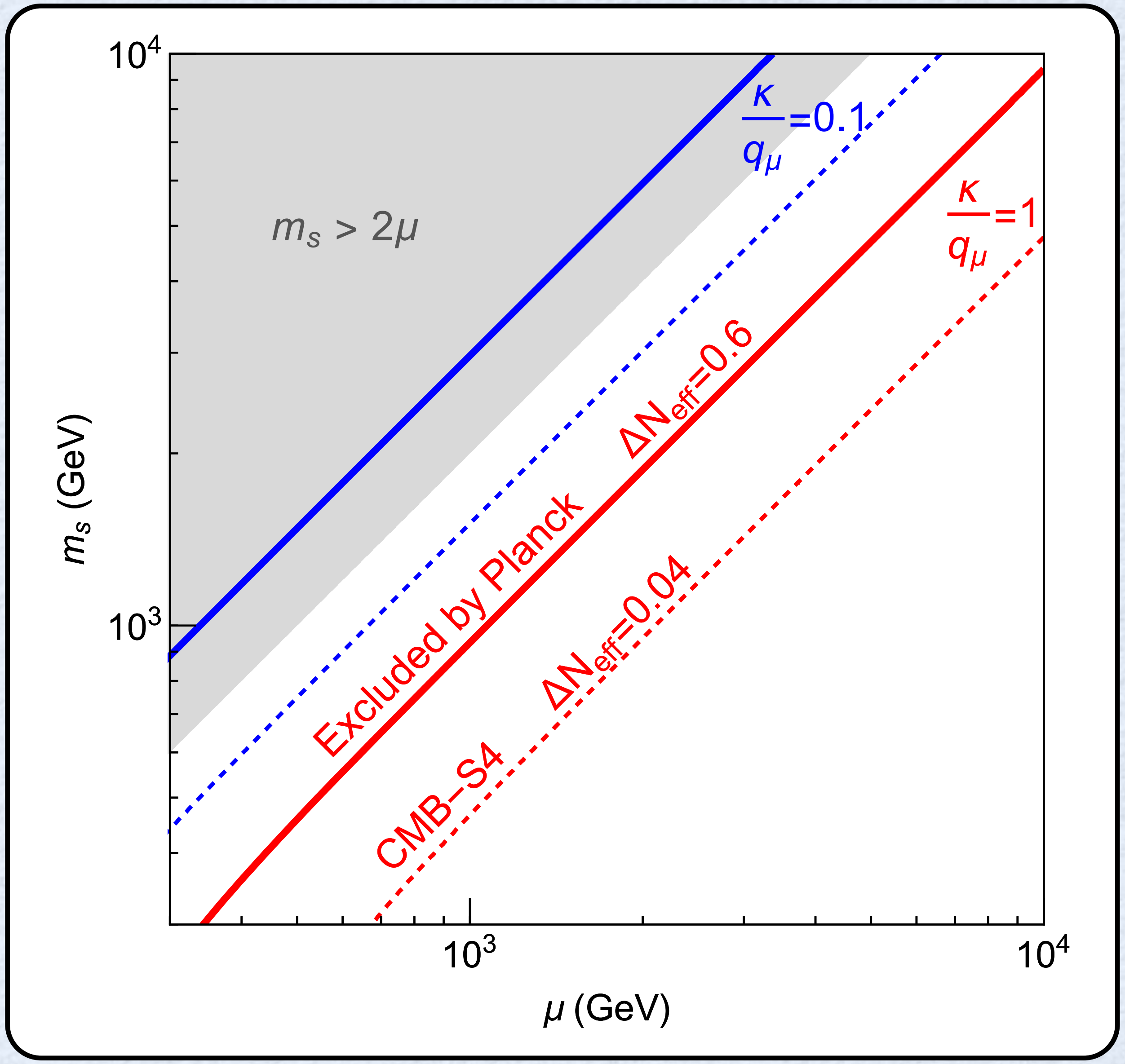

Conclusions

- SUSY + PQ $\quad T_{RI} > V_{PQ}$ Domain Wall Problem

  $T_{RI} < V_{PQ}$ Saxion Condensate

- DFSZ $\quad s \rightarrow hh$

- New Plausible Schemes for LSP / Axion Dark Matter

Conclusions

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  - $T_{RI} > V_{PQ}$ Domain Wall Problem
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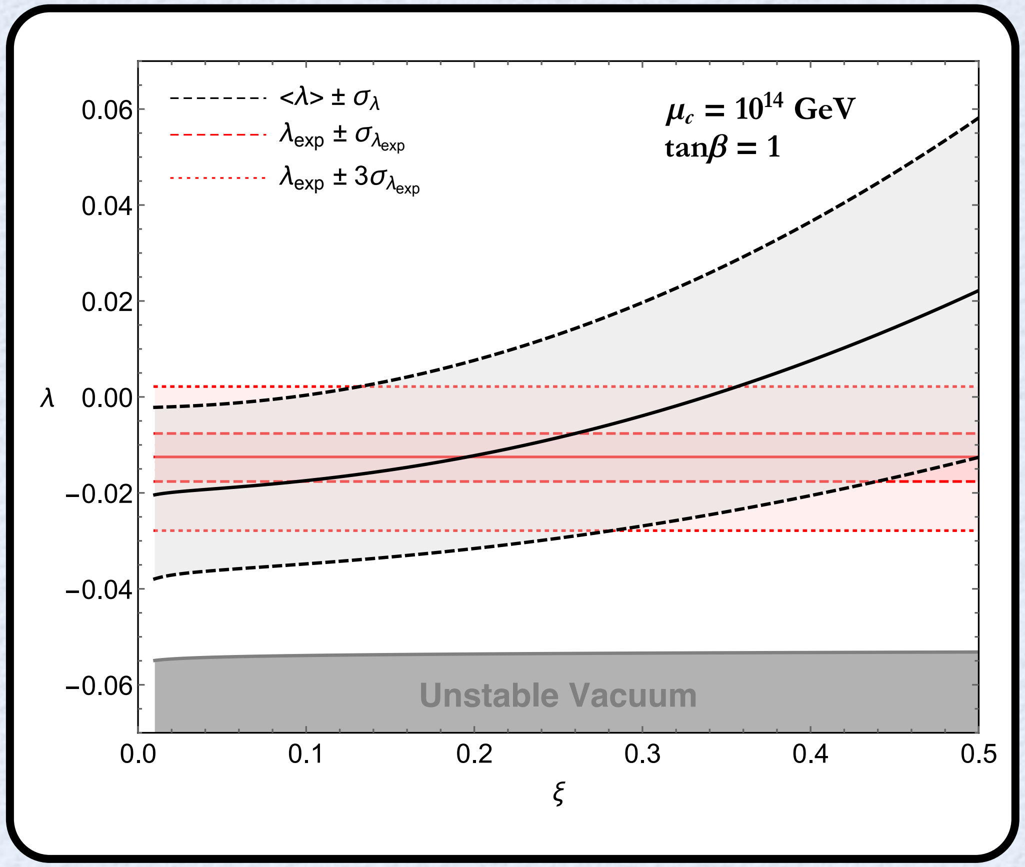
- DFSZ $s \to hh$
- New Plausible Schemes for LSP / Axion Dark Matter

Examples

- UV Scattering $\tilde{G}_{3/2}$ Independent of T_{RI} $T_{RI} \sim 10^{15}$ GeV
- IR Freeze-In $\tilde{a}$ $10^{11}\,\text{GeV} < V_{PQ} < 10^{15}\,\text{GeV}$ Displaced Vertices
- Misalignment a $\theta_{mis} \sim 1$ and $V_{PQ} \sim V_{GUT}$

Higgs Mass: My Favorite Possibilities

High Scale SUSY + PQ



D'Eramo, Hall, Pappadopulo arXiv:1502.06963

$$\tilde{m} > 10^{10}\,\mathrm{GeV}$$