

TeV Supersymmetry with Dynamical Axion Decay Constant

Raymond Co, UC Berkeley

23rd SUSY Conference

August 24th 2015



Advisor:

Collaborators:

Prof. Lawrence Hall

Dr. Francesco D'Eramo

Dr. Duccio Pappudopulo

Table of Content

- Motivation
- Model
- Mass Spectrum
- Analysis
- Work in Progress
- Conclusion

Table of Content

- Motivation
- Model
- Mass Spectrum
- Analysis
- Work in Progress
- Conclusion

Motivation

Slide 2/22

1. Strong CP Problem
2. Proton Stability Problem
3. μ Problem
4. Seesaw Mechanism
5. Dark Matter Abundance
6. Collider Signals

Motivation

Slide 2/22

1. Strong CP Problem

$$\mathcal{L} \supset \bar{\theta} \frac{g_s^2}{32\pi^2} G_b^{\mu\nu} \tilde{G}_{b\mu\nu} + \xi \frac{a}{f_a} \frac{g_s^2}{32\pi^2} G_b^{\mu\nu} \tilde{G}_{b\mu\nu}$$

2. Proton Stability Problem

3. μ Problem

4. Seesaw Mechanism

5. Dark Matter Abundance

6. Collider Signals

Motivation

Slide 2/22

1. Strong CP Problem

$$\mathcal{L} \supset \bar{\theta} \frac{g_s^2}{32\pi^2} G_b^{\mu\nu} \tilde{G}_{b\mu\nu} + \xi \frac{a}{f_a} \frac{g_s^2}{32\pi^2} G_b^{\mu\nu} \tilde{G}_{b\mu\nu}$$

2. Proton Stability Problem

$$W_R \supset \lambda' L Q D + \lambda'' U D D$$

3. μ Problem

4. Seesaw Mechanism

5. Dark Matter Abundance

6. Collider Signals

Motivation

Slide 2/22

1. Strong CP Problem

$$\mathcal{L} \supset \bar{\theta} \frac{g_s^2}{32\pi^2} G_b^{\mu\nu} \tilde{G}_{b\mu\nu} + \xi \frac{a}{f_a} \frac{g_s^2}{32\pi^2} G_b^{\mu\nu} \tilde{G}_{b\mu\nu}$$

2. Proton Stability Problem

$$W_R \supset \lambda' L Q D + \lambda'' U D D$$

3. μ Problem

$$W_{\text{MSSN}} \supset \mu H_u H_d$$

4. Seesaw Mechanism

5. Dark Matter Abundance

6. Collider Signals

Motivation

1. Strong CP Problem

$$\mathcal{L} \supset \bar{\theta} \frac{g_s^2}{32\pi^2} G_b^{\mu\nu} \tilde{G}_{b\mu\nu} + \xi \frac{a}{f_a} \frac{g_s^2}{32\pi^2} G_b^{\mu\nu} \tilde{G}_{b\mu\nu}$$

2. Proton Stability Problem

$$W_R \supset \cancel{Y' L Q D} + \cancel{Y'' U D D}$$

Forbidden by PQ Symmetry

3. μ Problem

$$W_{\text{MSSM}} \supset \cancel{\mu H_u H_d} \Rightarrow \frac{S^2}{M} H_u H_d$$

4. Seesaw Mechanism

5. Dark Matter Abundance

6. Collider Signals

Motivation

1. Strong CP Problem

$$\mathcal{L} \supset \bar{\theta} \frac{g_s^2}{32\pi^2} G_b^{\mu\nu} \tilde{G}_{b\mu\nu} + \xi \frac{a}{f_a} \frac{g_s^2}{32\pi^2} G_b^{\mu\nu} \tilde{G}_{b\mu\nu}$$

2. Proton Stability Problem

$$W_R \supset \cancel{N' L Q D} + \cancel{N'' U D D}$$

Forbidden by PQ Symmetry

3. μ Problem

$$W_{\text{MSSM}} \supset \cancel{\mu H_u H_d} \Rightarrow \frac{S^2}{M} H_u H_d$$

4. Seesaw Mechanism

$$W \supset \frac{y_N}{2} S N N$$

5. Dark Matter Abundance

6. Collider Signals

Motivation

Slide 2/22

1. Strong CP Problem

$$\mathcal{L} \supset \bar{\theta} \frac{g_s^2}{32\pi^2} G_b^{\mu\nu} \tilde{G}_{b\mu\nu} + \xi \frac{a}{f_a} \frac{g_s^2}{32\pi^2} G_b^{\mu\nu} \tilde{G}_{b\mu\nu}$$

2. Proton Stability Problem

$W_R \supset \cancel{N' L Q D} + \cancel{N'' U D D}$
Forbidden by PQ Symmetry

3. μ Problem

$$W_{\text{MSSM}} \supset \cancel{\mu H_u H_d} \Rightarrow \frac{S^2}{M} H_u H_d$$

4. Seesaw Mechanism

$$W \supset \frac{y_N}{2} S N N$$

5. Dark Matter Abundance

Axino Freeze-In

6. Collider Signals

Motivation

Slide 2/22

1. Strong CP Problem

$$\mathcal{L} \supset \bar{\theta} \frac{g_s^2}{32\pi^2} G_b^{\mu\nu} \tilde{G}_{b\mu\nu} + \xi \frac{a}{f_a} \frac{g_s^2}{32\pi^2} G_b^{\mu\nu} \tilde{G}_{b\mu\nu}$$

2. Proton Stability Problem

$W_R \supset \cancel{N' L Q D} + \cancel{N'' U D D}$
Forbidden by PQ Symmetry

3. μ Problem

$$W_{\text{MSSM}} \supset \cancel{\mu H_u H_d} \Rightarrow \frac{S^2}{M} H_u H_d$$

4. Seesaw Mechanism

$$W \supset \frac{y_N}{2} S N N$$

5. Dark Matter Abundance

Axino Freeze-In

6. Collider Signals

Displaced Vertices

Table of Content

- Motivation
- Model
- Mass Spectrum
- Analysis
- Work in Progress
- Conclusion

Table of Content

- Motivation
- Model
- Mass Spectrum
- Analysis
- Work in Progress
- Conclusion

Peccei-Quinn Symmetry

slide 3/22

	Q	U	D	L	E	N	H_u	H_d	S
PQ Charge	1	1	1	3	-1	-1	-2	-2	2

$$W_{\text{MSSM}-\mu+N} = \lambda_U Q U H_u + \lambda_D Q D H_d + \lambda_E L E H_d + \lambda_N L N H_u$$

$$\quad \quad \quad +1 \quad +1 \quad -2 \quad \quad \quad +1 \quad +1 \quad -2 \quad \quad \quad +3 \quad -1 \quad -2 \quad \quad \quad +3 \quad -1 \quad -2$$

$$W_S = \frac{S^2}{M} H_u H_d + \frac{y_N}{2} S N N$$

$$W \not\supset \cancel{\lambda' L Q D} + \cancel{\lambda'' U D D} + \cancel{\mu H_u H_d}$$

$$\quad \quad \quad +3 \quad +1 \quad -1 \quad \quad \quad -1 \quad -1 \quad -1 \quad \quad \quad -2 \quad -2$$

Our Axion Model

slide 4/22

$$\mathcal{L}_{\text{fermion mass}} = -\frac{S^2}{M} \tilde{H}_u \tilde{H}_d - \frac{y_N}{2} S N^\dagger N$$

Our Axion Model

$$\mathcal{L}_{\text{fermion mass}} = -\frac{S^2}{M} \tilde{H}_u \tilde{H}_d - \frac{y_N}{2} S N^\dagger N$$

$$V_F = \sum_i \left| \frac{\partial W}{\partial \phi_i} \right|^2$$

$$= \frac{4S^\dagger S}{M} (H_u H_d) (H_u H_d)^\dagger + \left(2y_N \frac{S}{M} (H_u H_d) (N^\dagger N^\dagger) + \text{h.c.} \right) + \frac{y_N^2}{4} (N^\dagger N)^2$$

$$+ y_N^2 (S^\dagger S) (N^\dagger N) + \frac{(S^\dagger S)^2}{M^2} \left(H_u^\dagger H_u + H_d^\dagger H_d \right)$$

$$V_{\text{soft}} = m_S^2 S^\dagger S + m_N^2 N^\dagger N + \tilde{m}_{H_u}^2 H_u^\dagger H_u + \tilde{m}_{H_d}^2 H_d^\dagger H_d + \left[A_M \frac{S^2}{M} H_u H_d + \text{h.c.} \right] + \left[A_y \frac{y_N}{2} S N N + \text{h.c.} \right]$$

Table of Content

- Motivation
- Model
- Mass Spectrum
- Analysis
- Work in Progress
- Conclusion

Table of Content

- Motivation
- Model
- Mass Spectrum
- Analysis
- Work in Progress
- Conclusion

Mass Spectrum

slide 5/22

$$m_{Higgsino}^2 = \left| \frac{S^2}{M} \right|^2 \quad m_{N_R}^2 = y_N^2 S^\dagger S$$

$$m_{H_1^\pm, H_2^\pm}^2 = m_{H,h}^2 = \frac{\tilde{m}_{H_u}^2 + \tilde{m}_{H_d}^2 + 2\left(\frac{S^\dagger S}{M}\right)^2 \pm \sqrt{\left(\tilde{m}_{H_u}^2 - \tilde{m}_{H_d}^2\right)^2 + 4|A_M|^2\left(\frac{S^\dagger S}{M}\right)^2}}{2}$$

$$m_{\tilde{N}_R}^2 = m_N^2 + y_N^2 S^\dagger S \pm |A_y y_N S|$$

Table of Content

- Motivation
- Model
- Mass Spectrum
- Analysis
- Work in Progress
- Conclusion

Table of Content

- Motivation
- Model
- Mass Spectrum
- Analysis
- Work in Progress
- Conclusion

S-Dependent Scalar Potential

slide 6/22

$$V(S) = \Lambda(\mu) + V^{(0)}(S, \mu) + V^{(1)}(S, \mu)$$

$$V^{(0)}(S, \mu) = m_S^2(\mu) S(\mu)^2$$

Coleman-Weinberg Potential

slide 6/22

$$V(S) = \Lambda(\mu) + V^{(0)}(S, \mu) + V^{(1)}(S, \mu)$$

$$V^{(1)}(S, \mu) = \sum_i (-1)^{2s_i} (2s_i + 1) \frac{m_i^4(S)}{64\pi^2} \left[\log \left(\frac{m_i^2(S)}{\mu^2} \right) - \frac{3}{2} \right]$$

Coleman-Weinberg Potential

slide 6/22

$$V(S) = \Lambda(\mu) + V^{(0)}(S, \mu) + V^{(1)}(S, \mu)$$

$$V^{(1)}(S, \mu) = \sum_i (-1)^{2s_i} (2s_i + 1) \frac{m_i^4(S)}{64\pi^2} \left[\log \left(\frac{m_i^2(S)}{\mu^2} \right) - \frac{3}{2} \right]$$

$$m_{\tilde{N}_R}^2 = m_N^2 + y_N^2 S^\dagger S \pm |A_y y_N S| \quad m_{N_R}^2 = y_N^2 S^\dagger S$$

S-Dependent Scalar Potential

slide 6/22

$$V(S) = \Lambda(\mu) + V^{(0)}(S, \mu) + V^{(1)}(S, \mu)$$

$$V^{(0)}(S, \mu) = m_S^2(\mu) S(\mu)^2$$

$$V^{(1)}(S, \mu) = \sum_i (-1)^{2s_i} (2s_i + 1) \frac{m_i^4(S)}{64\pi^2} \left[\log \left(\frac{m_i^2(S)}{\mu^2} \right) - \frac{3}{2} \right]$$

$$m_{\tilde{N}_R}^2 = m_N^2 + y_N^2 S^\dagger S \pm |A_y y_N S| \quad m_{N_R}^2 = y_N^2 S^\dagger S$$

Dimension Transmutation

slide 7/22

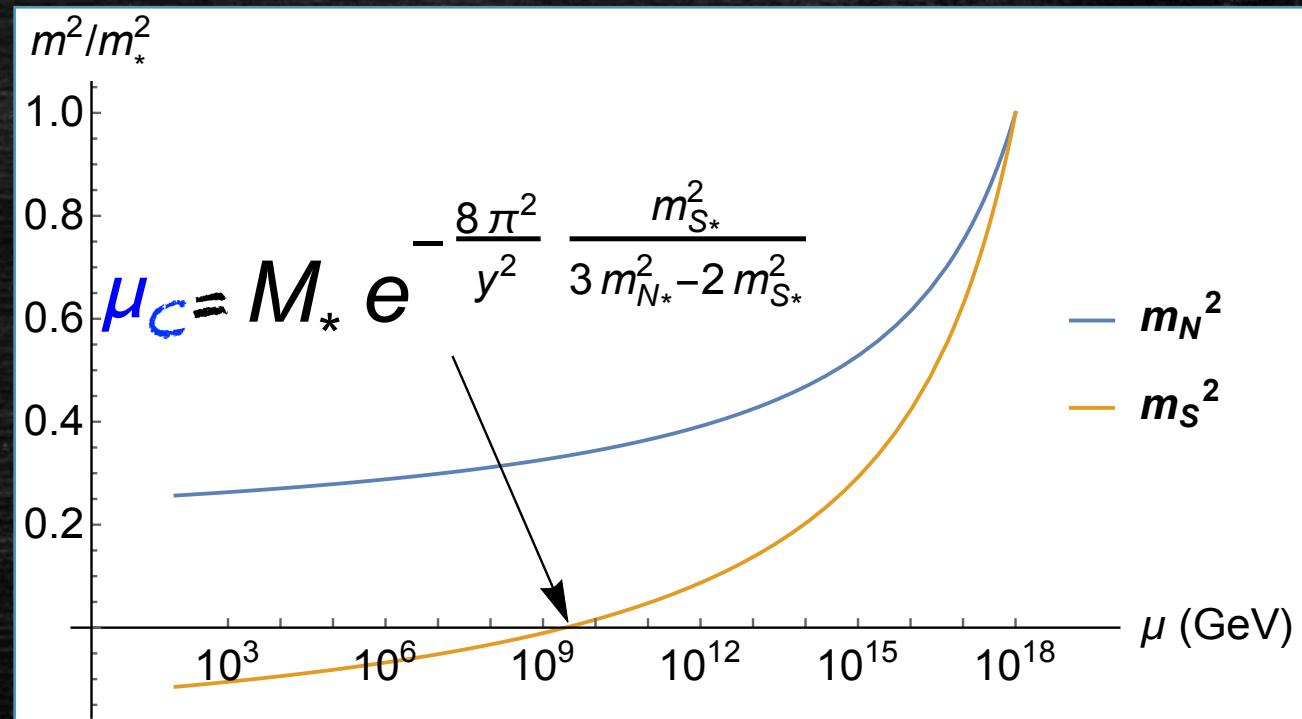
RG Equations

$$\frac{dy_N}{d \log \mu} = \frac{5 y_N^3}{32\pi^2}$$

$$\frac{dA_y}{d \log \mu} = \frac{25y_N^2 A_y}{32\pi^2}$$

$$\frac{dm_S^2}{d \log \mu} = \frac{N_N y_N^2}{16\pi^2} (m_S^2 + 2m_N^2 + A_y^2)$$

$$\frac{dm_N^2}{d \log \mu} = \frac{2y_N^2}{16\pi^2} (m_S^2 + 2m_N^2 + A_y^2)$$



After S Gets a VEV = f_A

slide 8/22

$$\mathcal{L} \supset \frac{S^2}{M} H_u H_d \Rightarrow \frac{f_A^2}{M} H_u H_d \quad \mu = \frac{f_A^2}{M}$$

$$m_{\tilde{N}_R}^2 = m_N^2 + y_N^2 f_A^2 \pm |A_y y_N f_A|$$

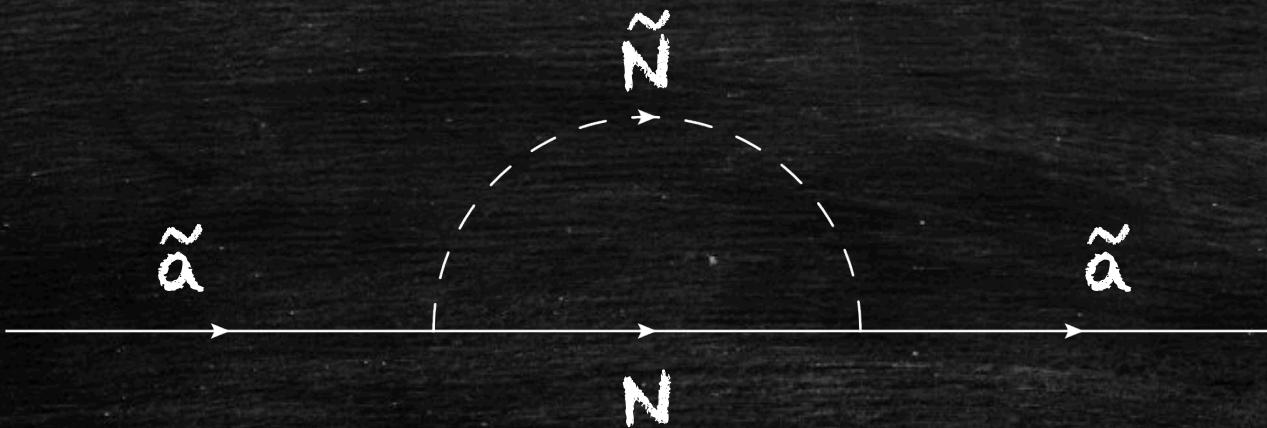
$$m_{Higgsino}^2 = |\frac{f_A^2}{M}|^2 \quad m_{N_R}^2 = y_N^2 f_A^2$$

$$\mathcal{L} \supset -\frac{f_A}{M} \tilde{S} \tilde{H} H$$

Axino LSP

Slide 9/22

$$\mathcal{L} \supset -y_N \tilde{S} \tilde{N} N + \text{h.c.}$$



$$m_{\tilde{a}} = \frac{y_N^2 A_y}{16\pi^2}$$

Dark Matter Abundance

slide 10/22

1. Axion Dark Matter

- Misalignment Mechanism

2. Axino Dark Matter

- Freeze-In Production

Dark Matter Abundance

slide 11/22

1. Axion Dark Matter

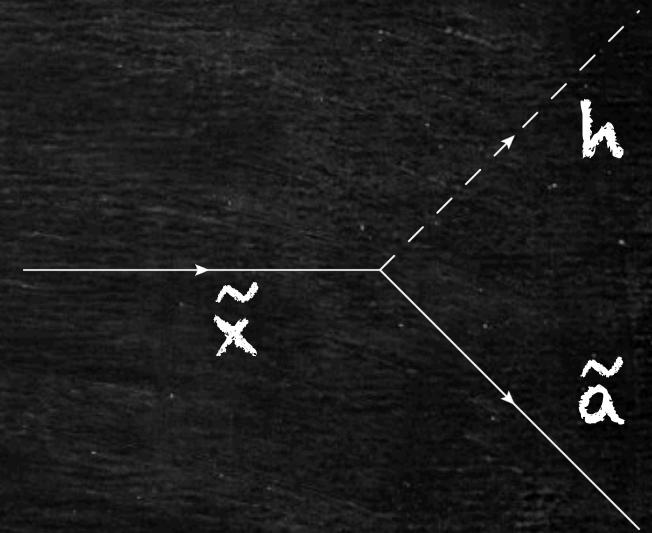
- Misalignment Mechanism

$$\Omega_A h^2 \approx 0.11 \left(\frac{f_A}{5 \times 10^{11} \text{ GeV}} \right)^{1.184} F \bar{\Theta}_i^2$$

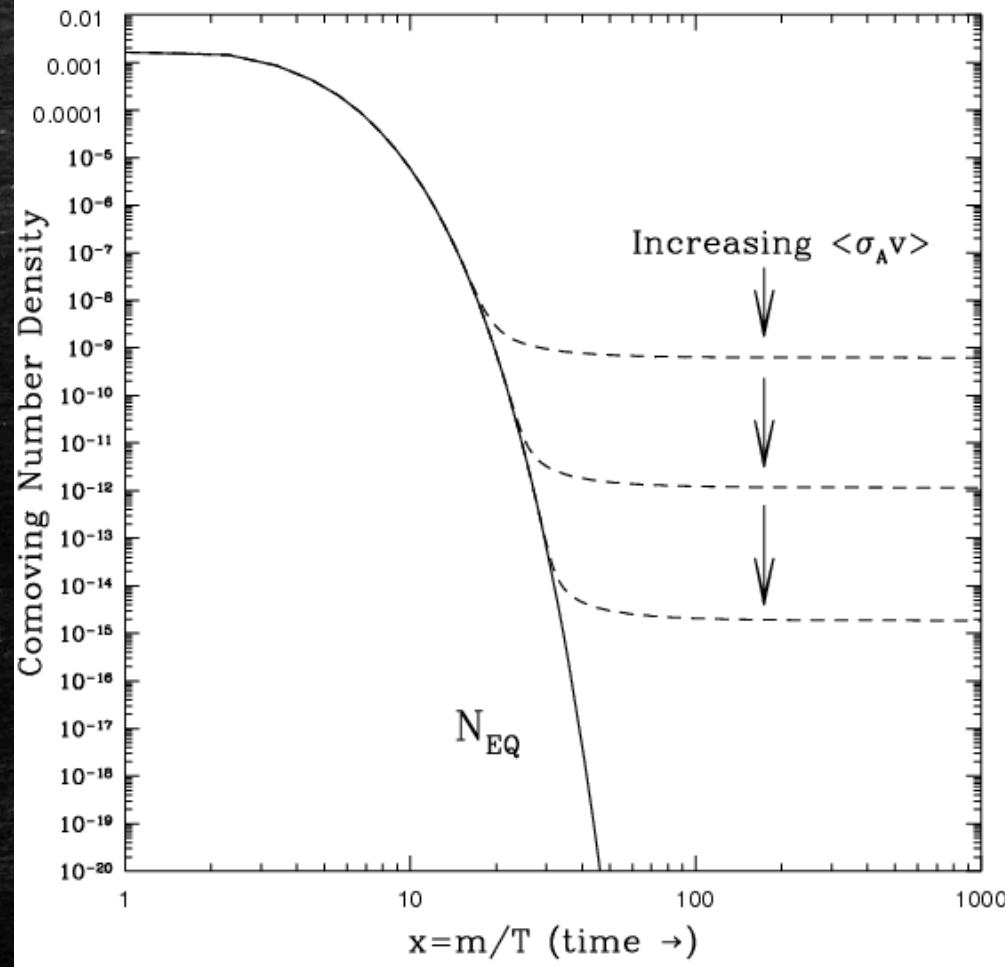
Dark Matter Abundance

slide 12/22

- 2. Axino Dark Matter
 - Not from Freeze-Out



Freeze-Out



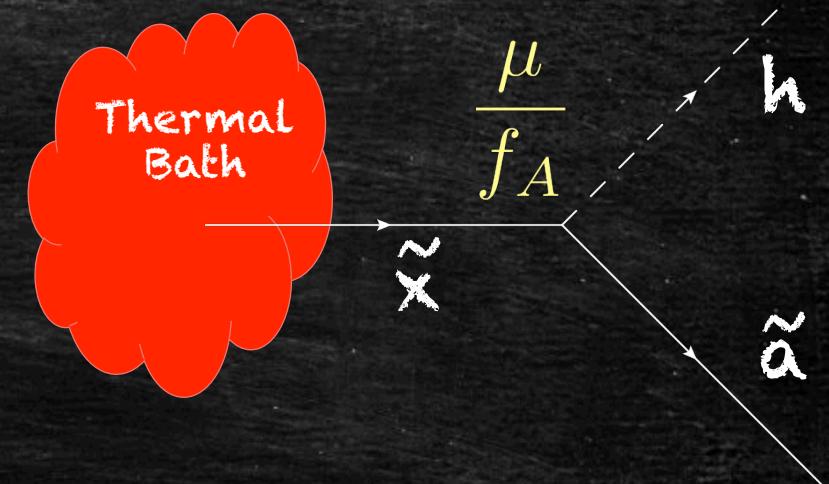
Dark Matter Abundance

slide 14/22

$$\mathcal{L} \supset -\frac{f_A}{M} \tilde{S} \tilde{H} H = -\frac{f_A}{M} \frac{k}{\sqrt{2}} \tilde{S} \tilde{\chi}_1 h^0$$

2. Axino Dark Matter $\mu = \frac{f_A^2}{M}$

➤ Freeze-In Production



Dark Matter Abundance

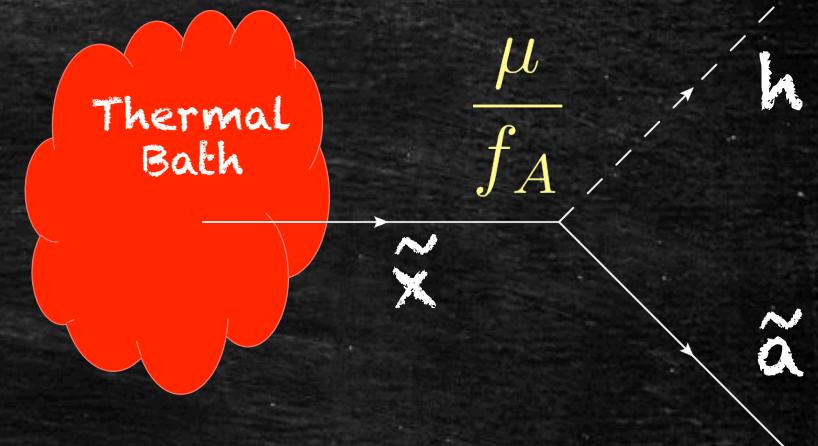
slide 14/22

$$\mathcal{L} \supset -\frac{f_A}{M} \tilde{S} \tilde{H} H = -\frac{f_A}{M} \frac{k}{\sqrt{2}} \tilde{S} \tilde{\chi}_1 h^0$$

2. Axino Dark Matter $\mu = \frac{f_A^2}{M}$

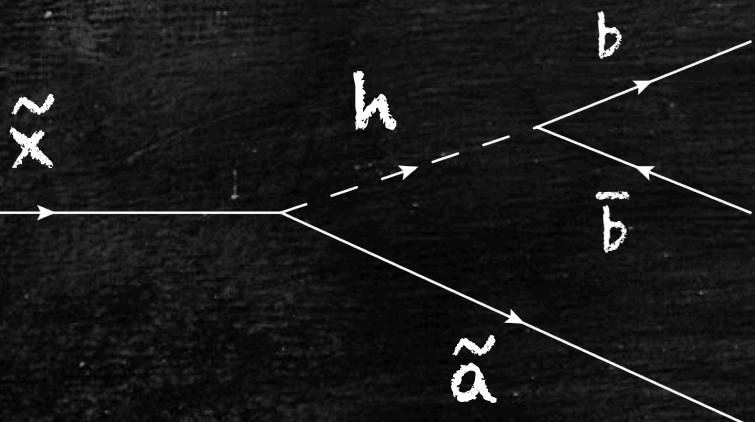
➤ Freeze-In Production

$$f_A \geq 2 \times 10^{14} \text{ GeV} \left(\frac{k}{\sqrt{2}} \right) \left(\frac{\mu}{10^3 \text{ GeV}} \right) \left(\frac{m_{axino}}{25 \text{ GeV}} \right)^{1/2} \left(\frac{300 \text{ GeV}}{m_{\tilde{\chi}_1}} \right)^{1/2} \left(\frac{10^2}{g_*(m_{B_1})} \right)^{3/4}$$

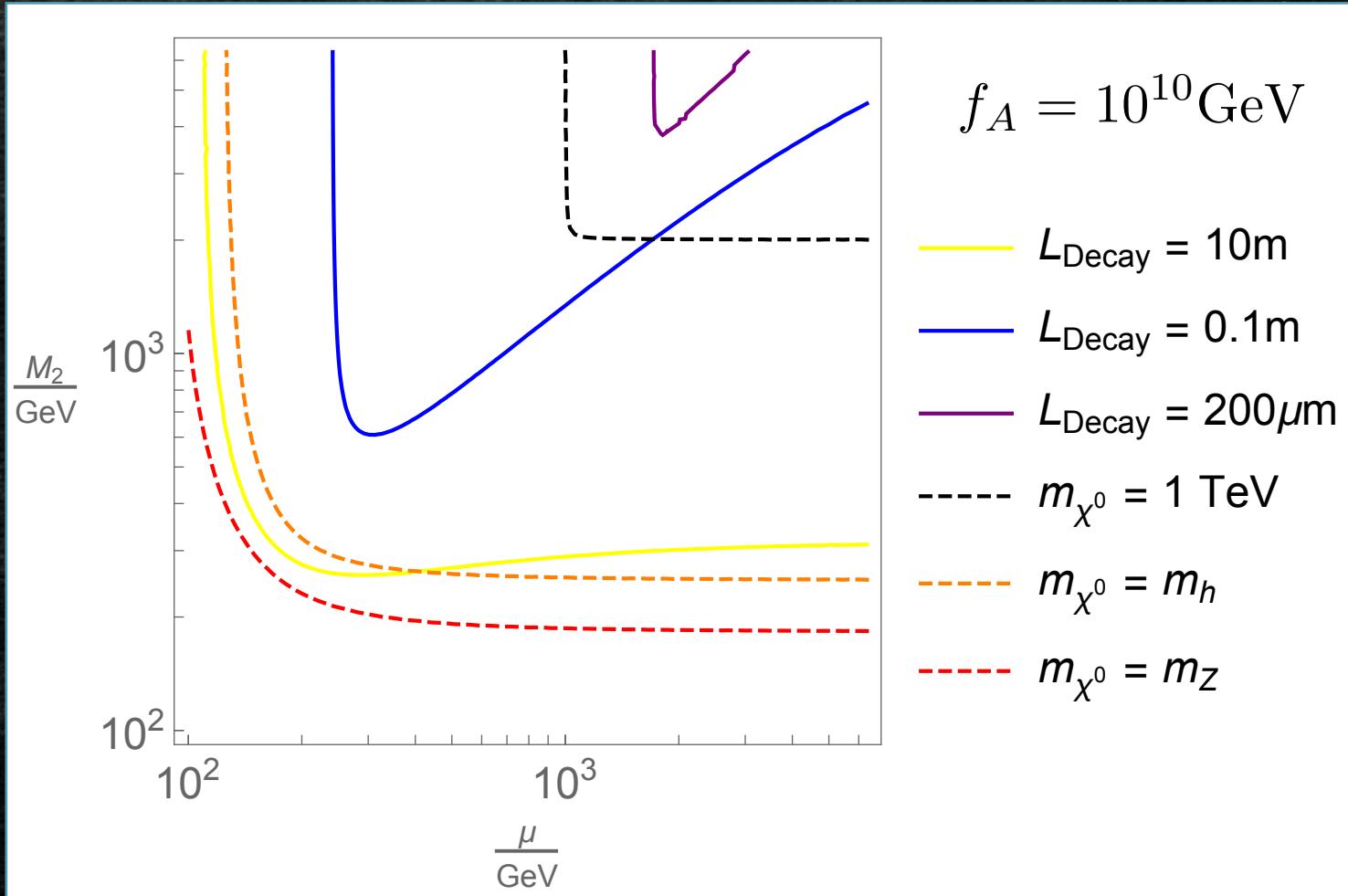


LHC Signals

Neutralino Decay
to Axino and Higgs

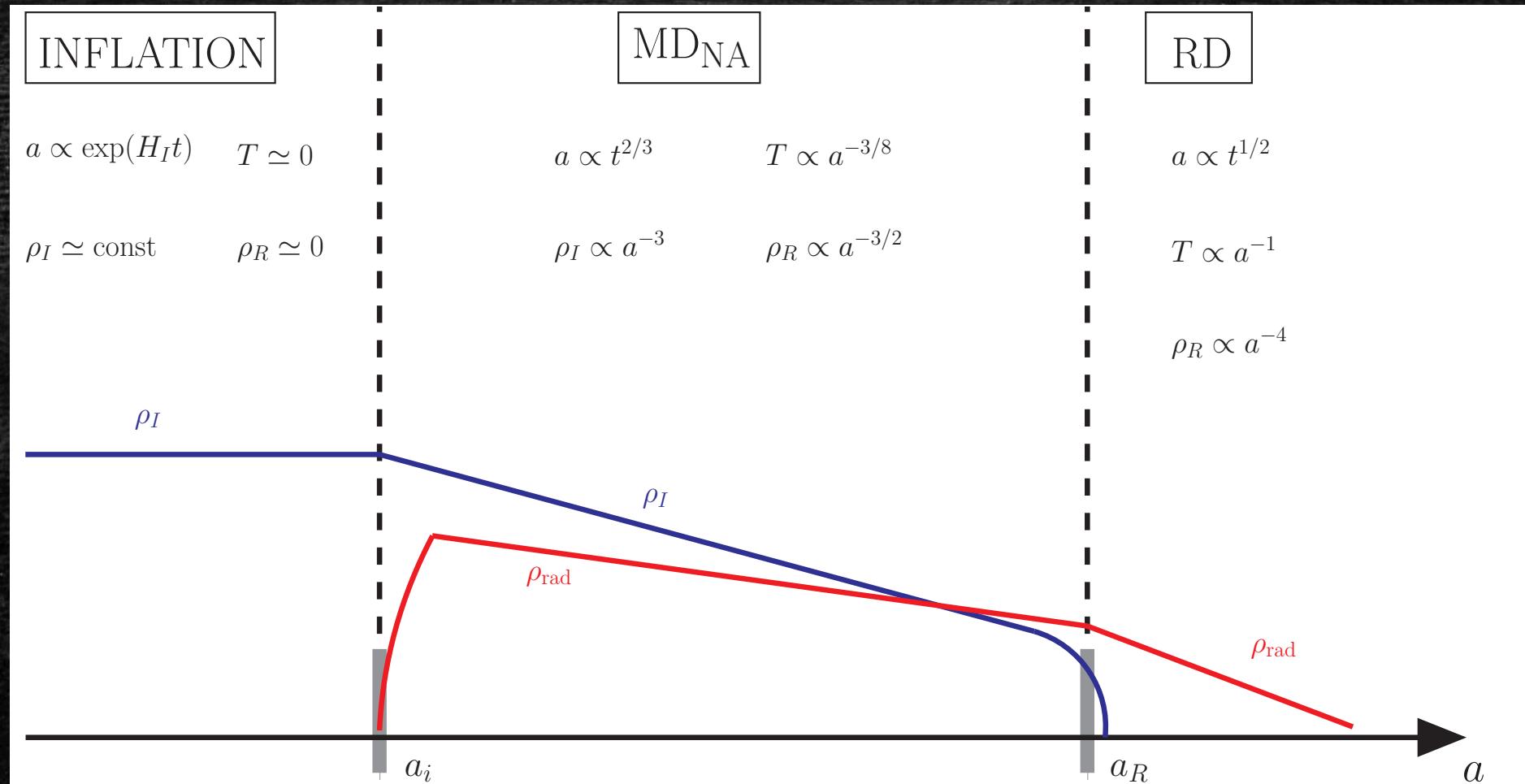


$$\Gamma_\chi \approx \left(\frac{\mu}{f_A} \frac{k}{\sqrt{2}} \right)^2 \frac{m_\chi}{8\pi}$$



Dilution from Inflaton Decays

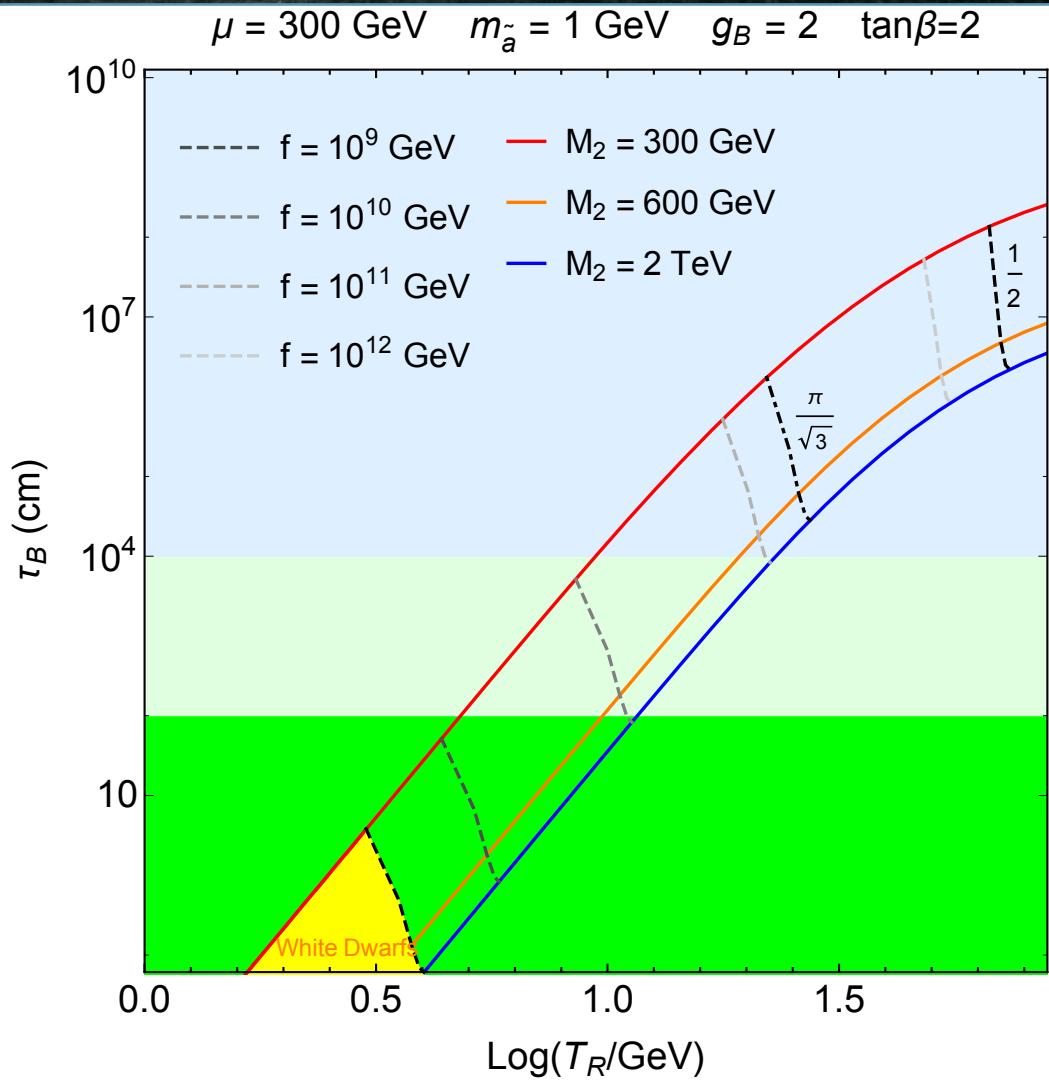
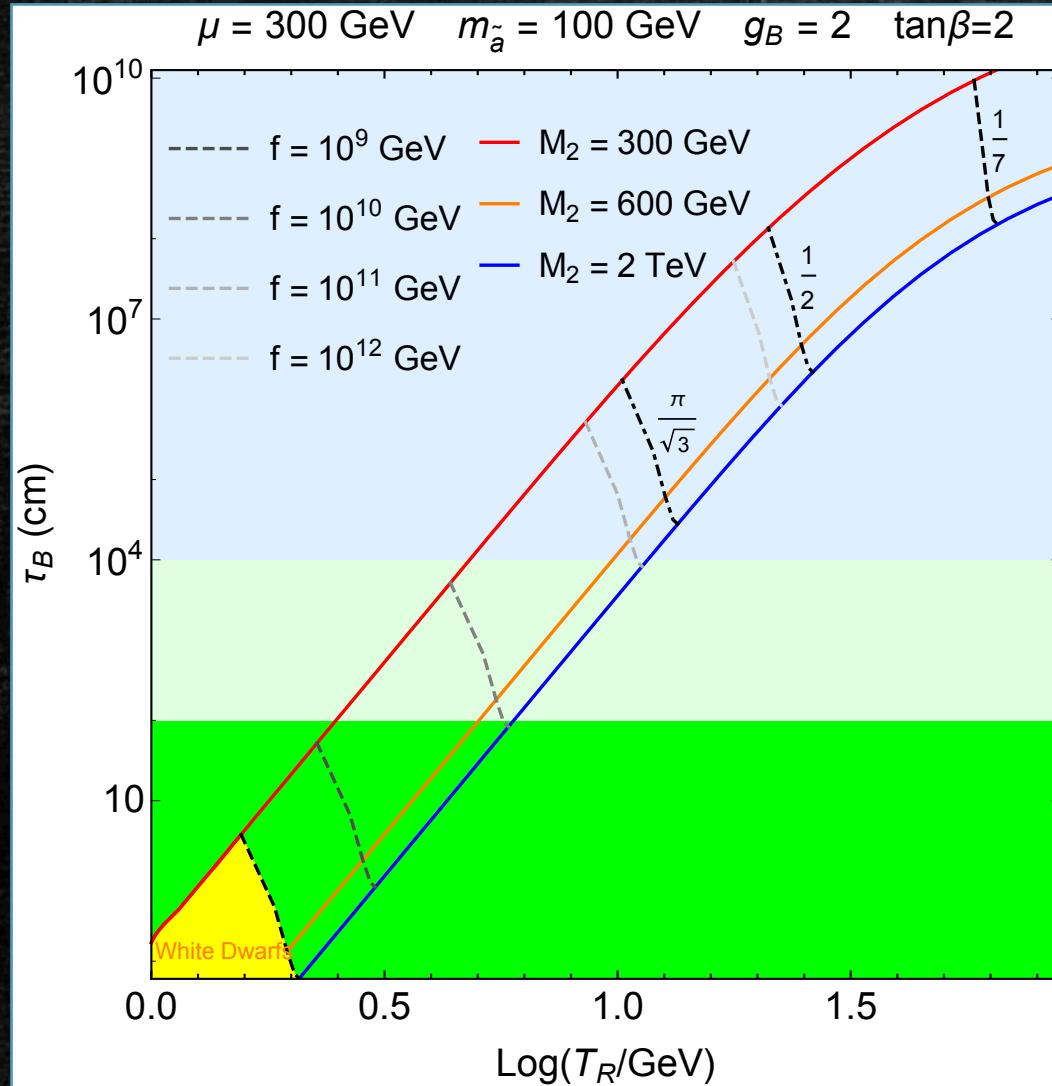
slide 16/22



Collider Signals

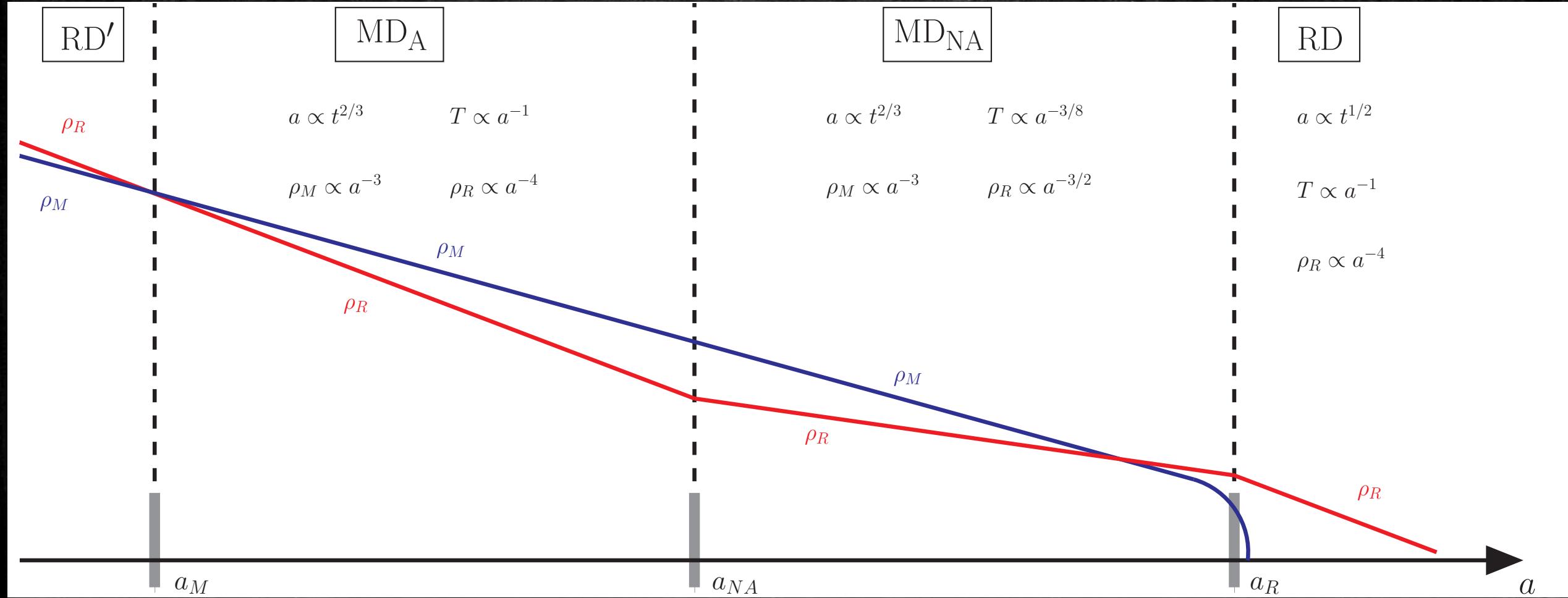
Shaded region	Decay length	Signature from LOSP	Neutral	Charged
Dark green	$10^{-2}\text{cm} < \tau_B < 10^2\text{cm}$	Displaced vertices	✓	✓
Light green	$10^2\text{cm} < \tau_B < 10^4\text{cm}$	Displaced jets/leptons	✓	✓
Light blue	$10^4\text{cm} < \tau_B$	Stopped particle decays	X	✓

Slide 17/22



Dilution from “Modulus” Decays

slide 18/22



Collider Signals

Shaded region	Decay length	Signature from LOSP	Neutral	Charged
Dark green	$10^{-2}\text{cm} < \tau_B < 10^2\text{cm}$	Displaced vertices	✓	✓
Light green	$10^2\text{cm} < \tau_B < 10^4\text{cm}$	Displaced jets/leptons	✓	✓
Light blue	$10^4\text{cm} < \tau_B$	Stopped particle decays	✗	✓

Slide 19/22

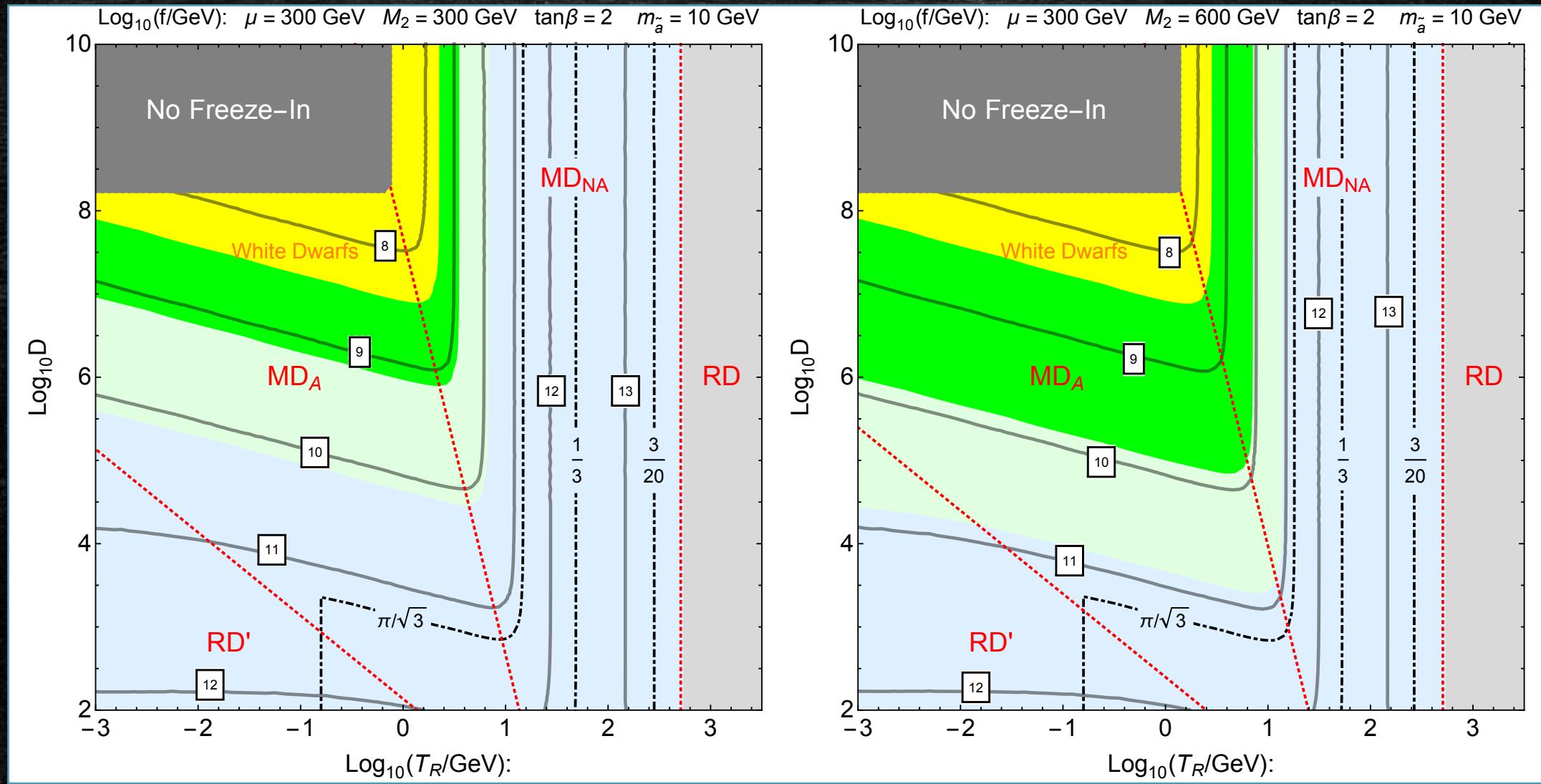


Table of Content

- Motivation
- Model
- Mass Spectrum
- Analysis
- Work in Progress
- Conclusion

Table of Content

- Motivation
- Model
- Mass Spectrum
- Analysis
- Work in Progress
- Conclusion

Saxion Cosmology

- Can saxion decays provide the necessary dilution?
- Will saxion decays overproduce axion dark matter?

Table of Content

- Motivation
- Model
- Mass Spectrum
- Analysis
- Work in Progress
- Conclusion

Table of Content

- Motivation
- Model
- Mass Spectrum
- Analysis
- Work in Progress
- Conclusion

Conclusion

Slide 21/22

- Strong CP Problem- Axion decay constant from dimension transmutation.
- R-Parity- a direct consequence of PQ charges.
- μ Problem- generated from S vev.
- Neutrino mass- using see-saw mechanism.
- Dark matter abundance- axino Freeze-In.
- LHC displaced vertices- neutralino decays.

References

- Similar axion models: (1) Murayama et al Phys.Lett. B291 (1992)
(2) Stewart et al hep-ph/9603324
(3) Choi et al [hep-ph/9608222]
- Freeze-Out during MD: (1) J. McDonald Phys. Rev. D 43, 1063 (1991)
(2) Chung et al [hep-ph/9809453]
(3) Giudice (2001) [hep-ph/0005123]
- Axino FI during MD: (1) L. Covi et al [hep-ph/0101009]
(2) E. J. Chun et al [arXiv:1104.2219]

THANK YOU!

Appendix: RG Running

$$y_N(\mu) = \frac{y_{N^*}}{\left(1 + \frac{5y_{N^*}^2}{16\pi^2} \log \frac{M_*}{\mu}\right)^{\frac{1}{2}}}$$

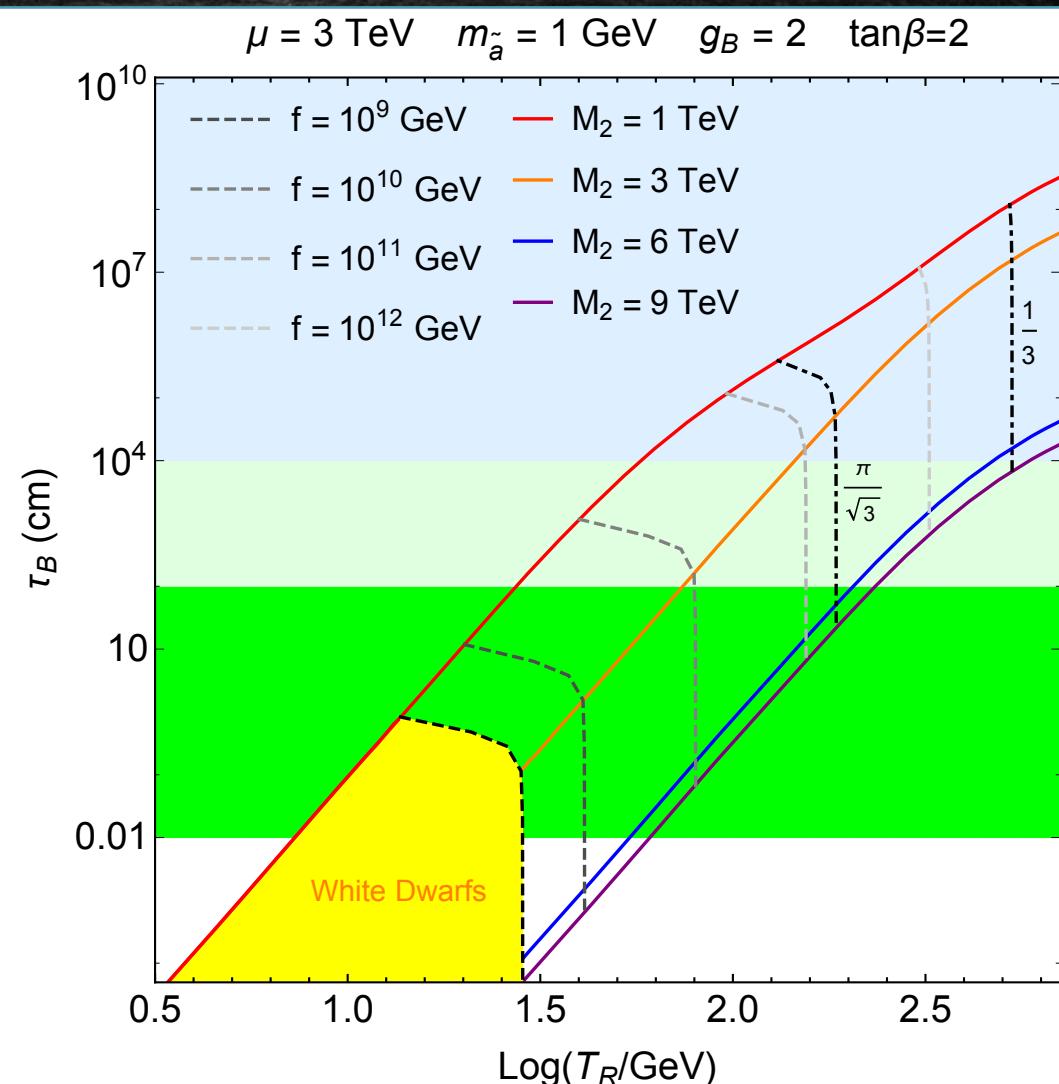
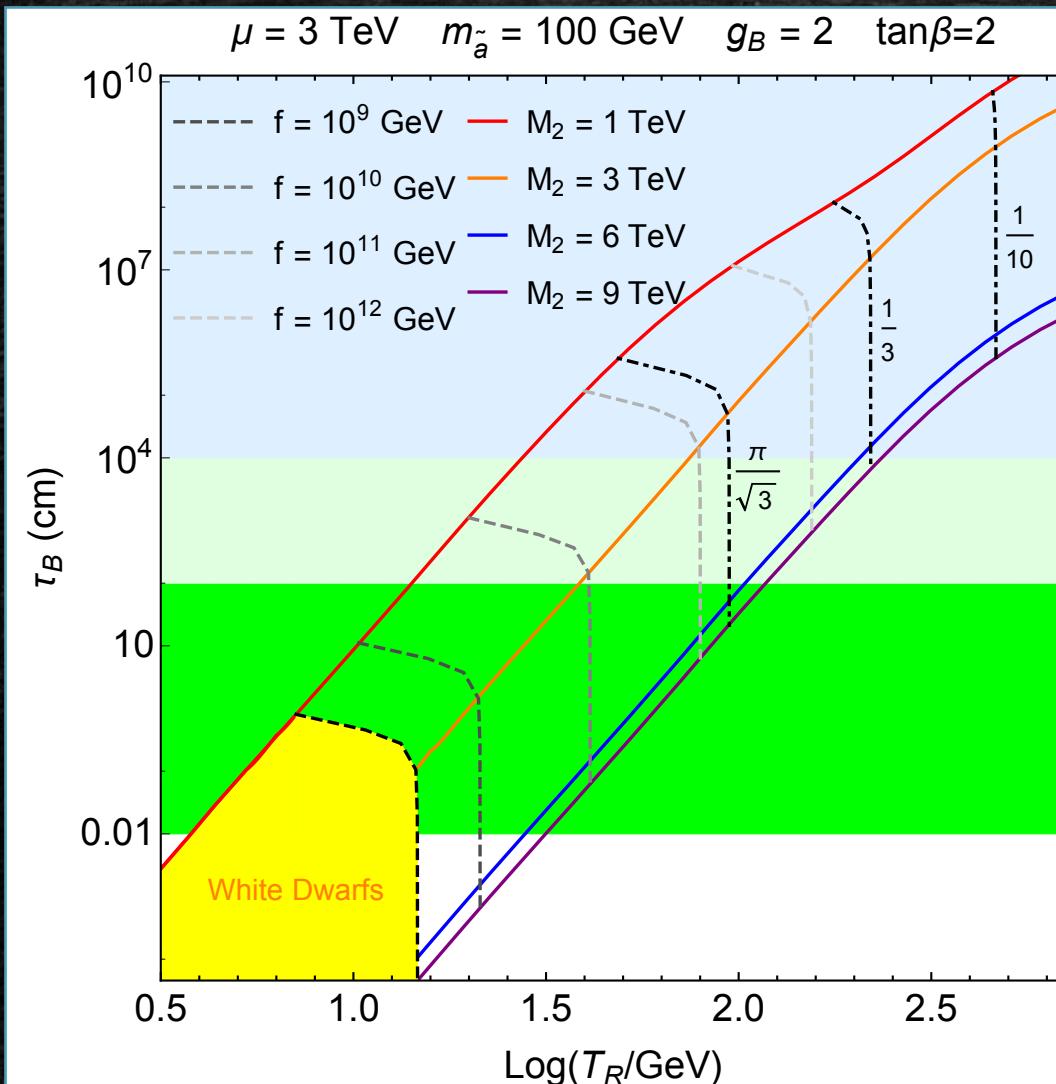
$$A_y(\mu) = \frac{A_{y^*}}{\left(1 + \frac{5y_{N^*}^2}{16\pi^2} \log \frac{M_*}{\mu}\right)^{\frac{5}{2}}}$$

$$m_S^2(\mu) = \frac{1}{20} \left(8(2m_{S^*}^2 - m_{N^*}^2) + \frac{4(m_{S^*}^2 + 2m_{N^*}^2) - A_{y^*}^2}{\left(1 + \frac{5y_{N^*}^2}{16\pi^2} \log \frac{M_*}{\mu}\right)} + \frac{A_{y^*}^2}{\left(1 + \frac{5y_{N^*}^2}{16\pi^2} \log \frac{M_*}{\mu}\right)^5} \right)$$

$$m_N^2(\mu) = \frac{1}{10} \left(2(m_{N^*}^2 - 2m_{S^*}^2) + \frac{4(m_{S^*}^2 + m_{N^*}^2) - A_{y^*}^2}{\left(1 + \frac{5y_{N^*}^2}{16\pi^2} \log \frac{M_*}{\mu}\right)} + \frac{A_{y^*}^2}{\left(1 + \frac{5y_{N^*}^2}{16\pi^2} \log \frac{M_*}{\mu}\right)^5} \right)$$

Appendix: Collider Signals

Shaded region	Decay length	Signature from LOSP	Neutral	Charged
Dark green	$10^{-2}\text{cm} < \tau_B < 10^2\text{cm}$	Displaced vertices	✓	✓
Light green	$10^2\text{cm} < \tau_B < 10^4\text{cm}$	Displaced jets/leptons	✓	✓
Light blue	$10^4\text{cm} < \tau_B$	Stopped particle decays	X	✓



Appendix: Collider Signals

Shaded region	Decay length	Signature from LOSP	Neutral	Charged
Dark green	$10^{-2}\text{cm} < \tau_B < 10^2\text{cm}$	Displaced vertices	✓	✓
Light green	$10^2\text{cm} < \tau_B < 10^4\text{cm}$	Displaced jets/leptons	✓	✓
Light blue	$10^4\text{cm} < \tau_B$	Stopped particle decays	✗	✓

