Dark Matter with Topological Defects in the Inert Doublet Model

arXiv:1311.1637
arXiv:1412.4821

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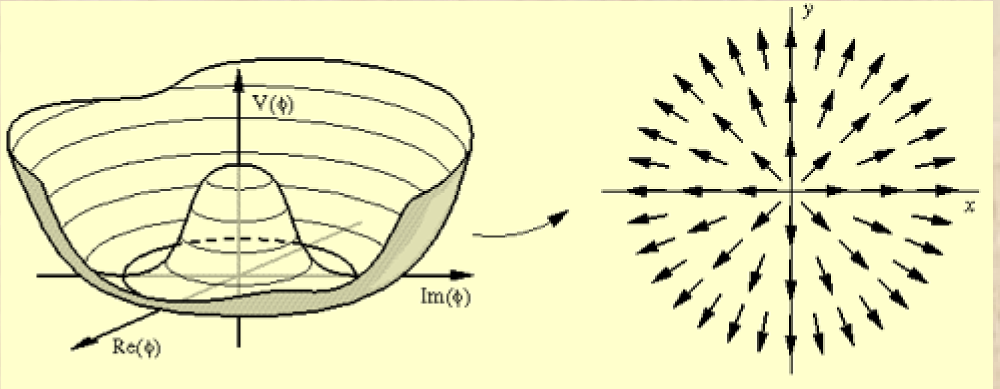

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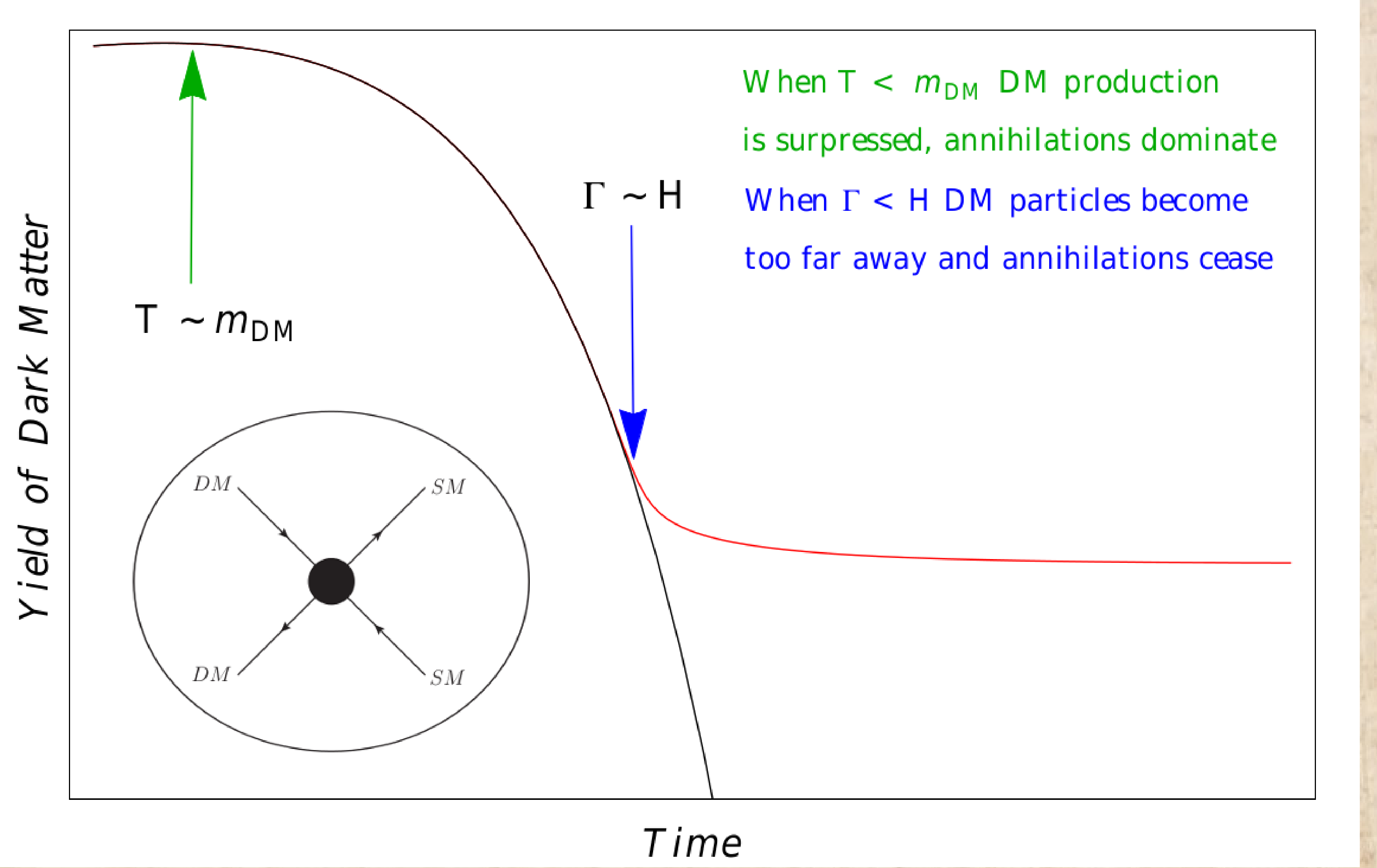
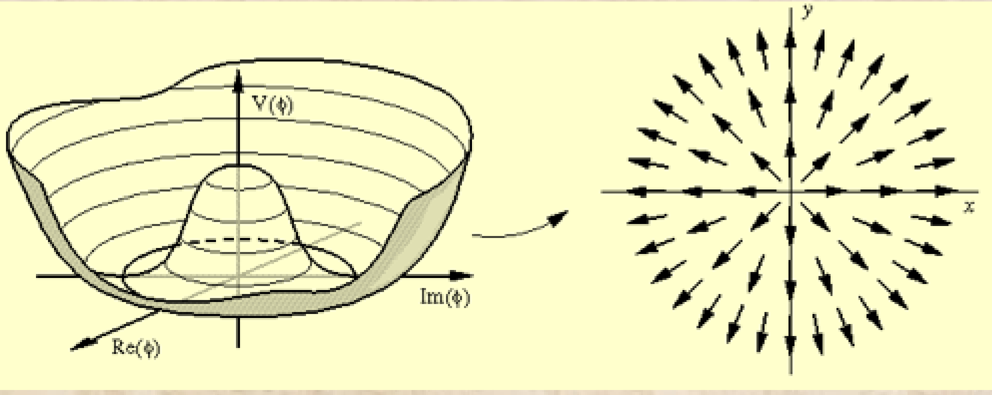
Freeze-Out

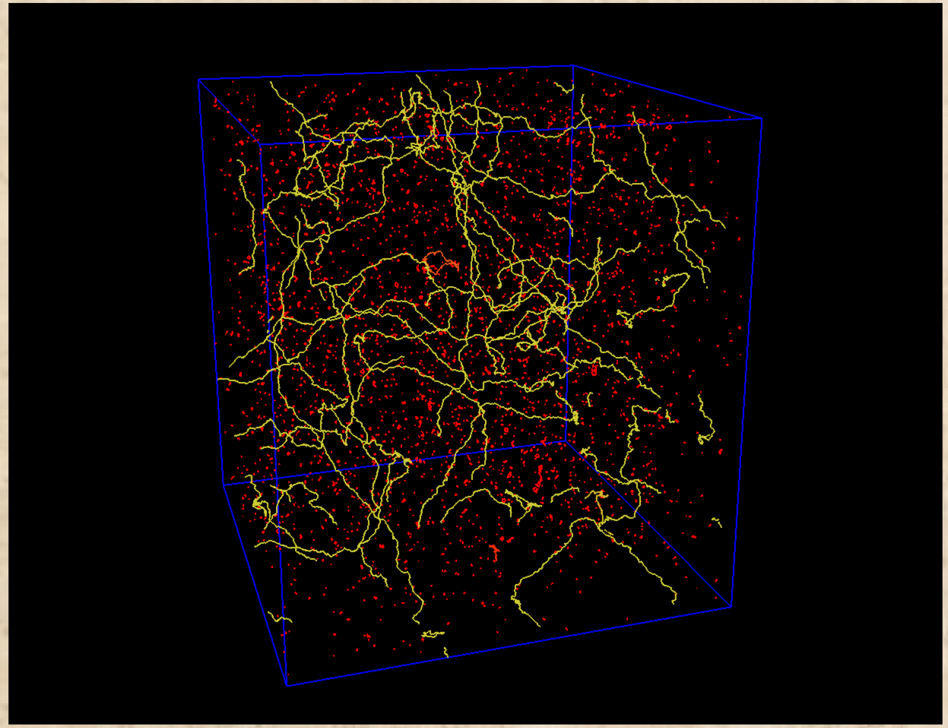


When T < m_{DM} DM production
is surpressed, annihilations dominate
When Γ < H DM particles become
too far away and annihilations cease
Γ ~ H
T ~ m_{DM}
DM
SM
DM
SM
Yield of Dark Matter
Time

Topological Defects

- Formed during a spontaneous symmetry breaking phase transition
- Choice of VEV "direction" is arbitrary
- Casually disconnected regions of space can have different VEV "directions"
- At the interface between these regions symmetry restoration can occur
- Thus n-D massive structures are formed

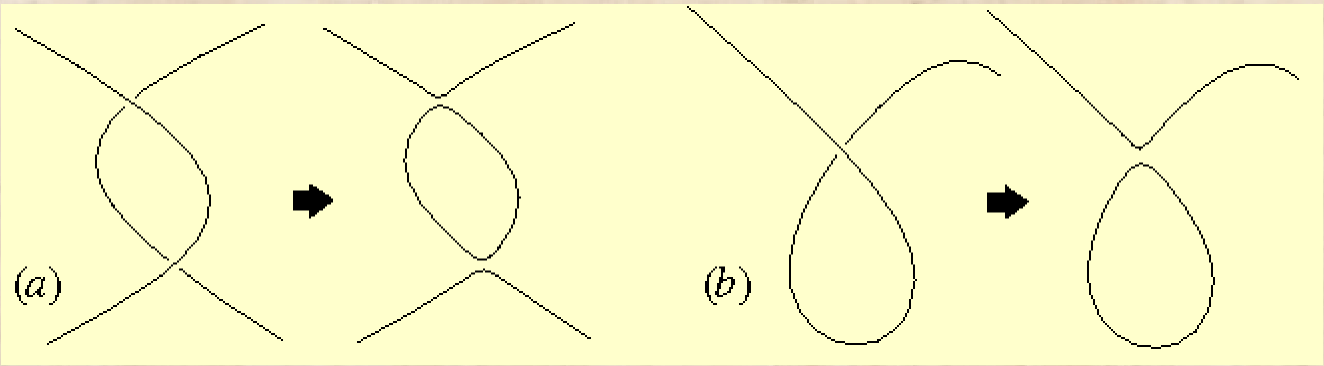




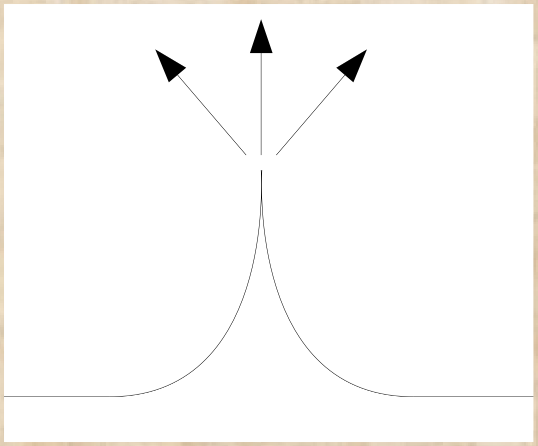
Images: http://www.damtp.cam.ac.uk/research/gr/public/cs_home.html

Defect Decays

1D defects (cosmic strings) evolve and intersect forming loops



These loops shrink and collapse, releasing energy into gravitational and particle radiation



Cusps form when the cosmic double backs on itself, they collapse releasing particle radiation

$$Q(t) = Q_\chi \left(\frac{t}{t_\chi}\right)^{p-4}$$

Defect Decays

Boltzmann Equation

$$\frac{dY}{dx} = -\frac{A(x)}{x^2}\left[Y^2 - (Y^{\mathrm{eq}})^2\right] + \frac{B}{x^{4-2p}}$$

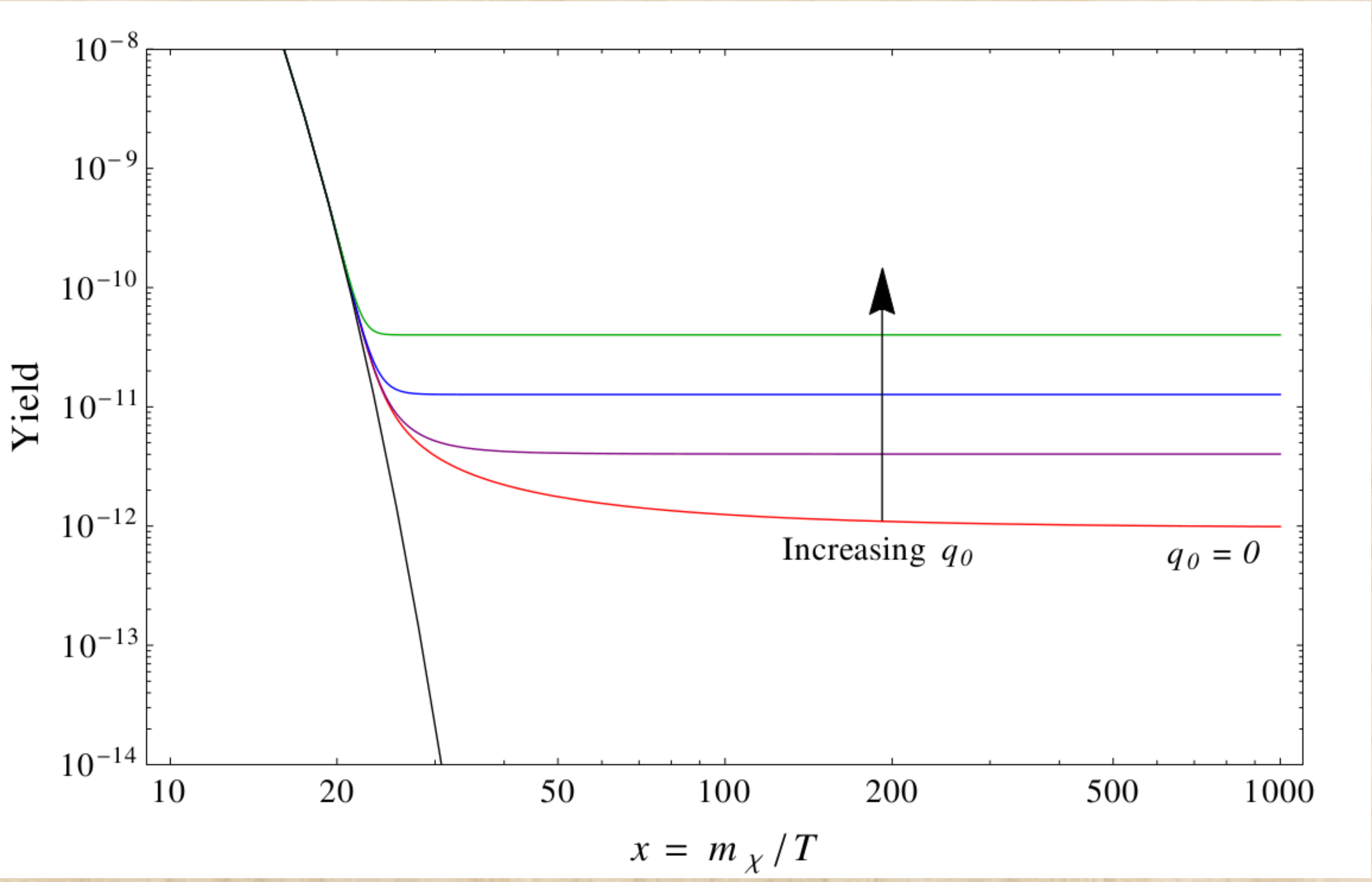
$$A(x) = \sqrt{\frac{\pi g_*}{45}} m_\chi M_{\mathrm{Pl}} \langle \sigma_{\mathrm{eff}} v \rangle (x) \qquad B = \frac{3}{4} r_0 q_0$$

$\langle \sigma_{\mathrm{eff}} v \rangle$ controls *annihilation* rate from DM collisions

q_0 controls *production* rate from decaying defects

p in the FT scenario = 1, in the CE scenario = 7/6

Freeze-Out with Defects



Punchline: By considering DM production from defect decays, we can open up regions of a models parameter space which previously under-produced DM

The Inert Doublet Model

Extends the SM by adding a second Higgs doublet with the same gauge symmetries and charges

$$H_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG^0) \end{pmatrix} \qquad H_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H^0 + iA^0) \end{pmatrix}$$

This second doublet, H_2 is odd under an additional Z_2 symmetry,
making the lightest field stable, thus H^0 or A^0 can be a DM candidate

$$V = -\mu_1^2 |H_1|^2 + \mu_2^2 |H_2|^2 + \lambda_1 |H_1|^4 + \lambda_2 |H_2|^4 + \lambda_3 |H_1|^2 |H_2|^2$$
$$+\lambda_4 |H_1^\dagger H_2|^2 + \frac{\lambda_5}{2} \left\{ (H_1^\dagger H_2)^2 + h.c. \right\}$$

Parametrising...

$$m_{H^0}^2 = \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5)\, v^2$$

$$m_{A^0}^2 = \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4 - \lambda_5)\, v^2$$

$$m_{H^\pm}^2 = \mu_2^2 + \frac{1}{2}\lambda_3\, v^2$$

We choose H^0 as our DM candidate

Let $m_{A^0} = m_{H^\pm}$

Δm^2 affects
- co-annihilations

λ_L affects
- hH^0H^0 coupling

Free parameters...

$$m_{H^0}$$

$$\Delta m^2 \equiv m_{A^0}^2 - m_{H^0}^2$$

$$\lambda_L = \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5)$$

Defects in the IDM

$$\Delta V = \lambda_\phi |\phi|^4 + \tilde{\lambda}_1 |\phi|^2 |H_1|^2 + \tilde{\lambda}_2 |\phi|^2 |H_2|^2$$

Simple way: Add a scalar charged under a U(1)'

Scalar breaks the U(1)'...

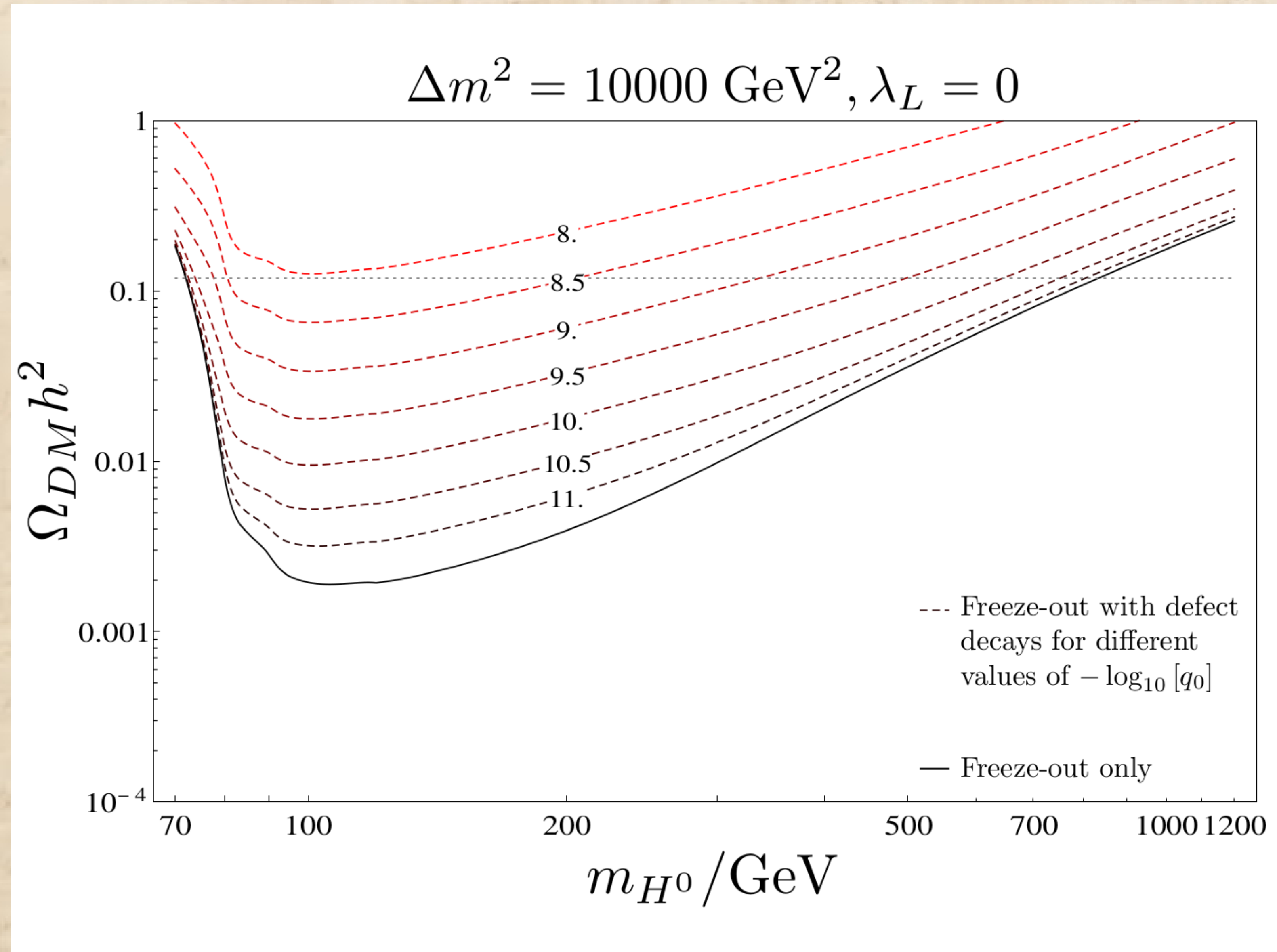
Leaves an additional Higgs and a massive gauge boson, whose masses are O(VEV)

Integrate out these new particles...

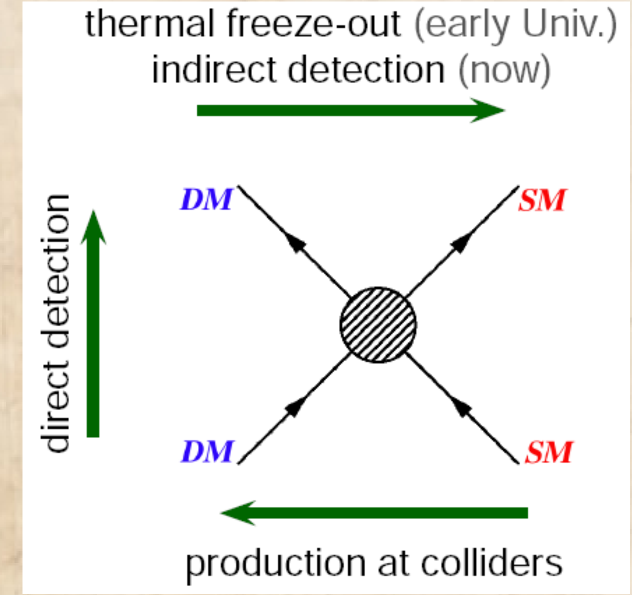
The effective theory is *identical* to the IDM at the EW scale

Proviso: Fine-tuning required for EW scale H^0, A^0 & H^+ masses

The Mechanism at Work



Constraining the IDM...



Direct Detection

- H0 can scatter off nuclei via SM higgs exchange
- Signal disappears if $\lambda_L = 0$
- Limits taken using 85.3 live days of LUX data

Indirect Detection

- Cosmic DM annihilations can contribute to the gamma ray sky
- Limits were taken from a combined analysis of several dSphs using Fermi-LAT data in the 1 – 100 GeV range.

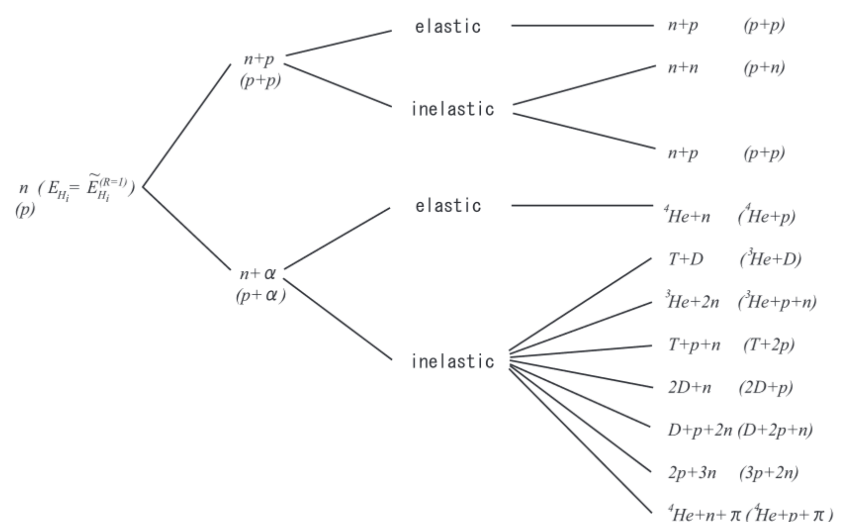
Collider Bounds

- Monojet limits taken from an analysis of simplified models using 8 TeV LHC data, signal disappears as λ_L goes to zero. Limit comes at smaller DM mass than we are considering.
- $H^{\pm}$ loops contribute to the SM higgs diphoton decay rate. Within our phase space these contributions are minute enough to be consistent with ATLAS and CMS values.

Constraining cosmic strings...

Big Bang Nucleosynthesis (BBN)

- The injection of high energy particles during BBN can affect the light nuclei abundances
- Alters p-n ratio early on or influences hadrodissociation later
- Limits q_0 and leads the string constraints in the CE scenario

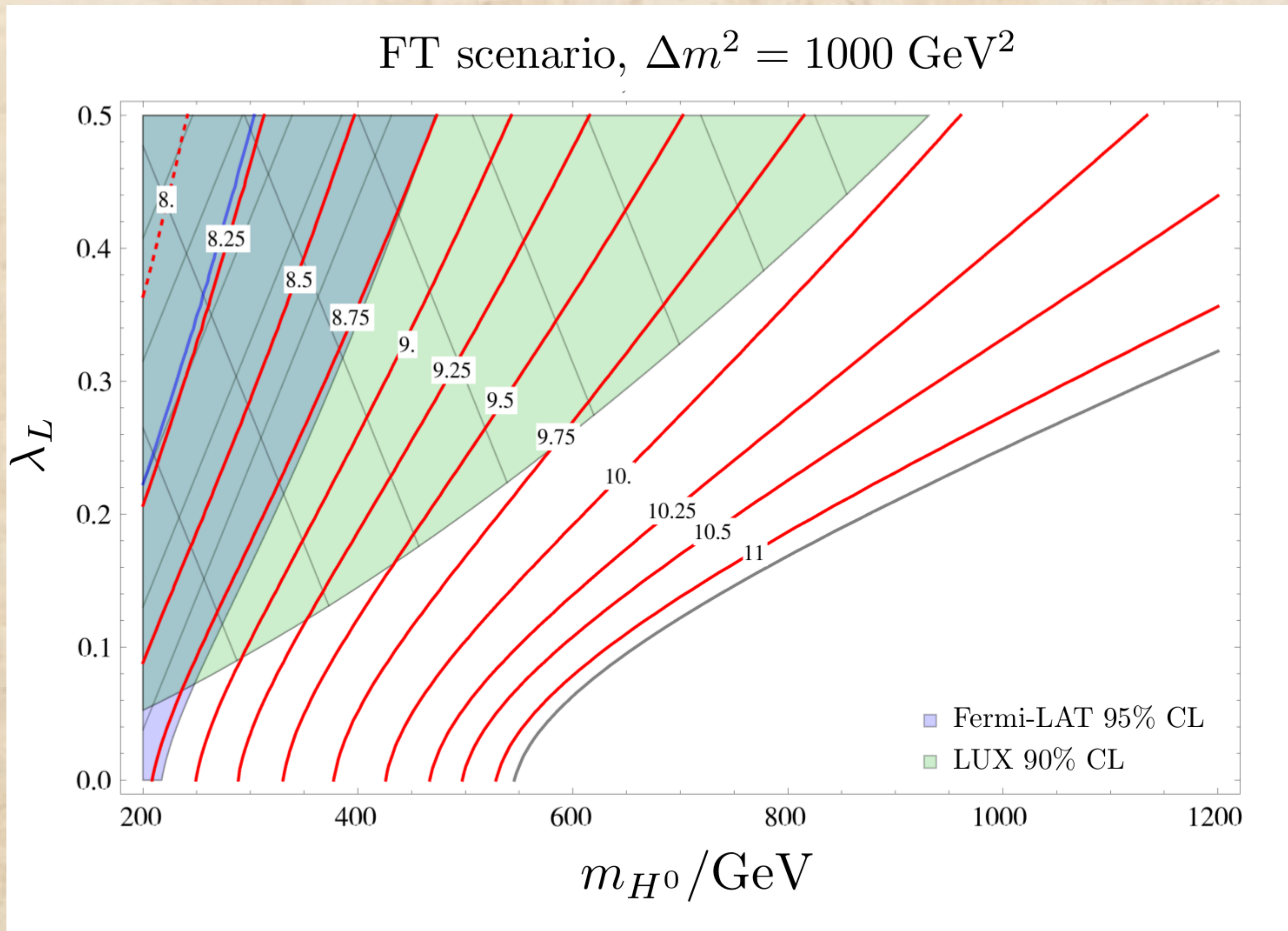


arXiv:astro-ph/0408426

Diffuse Gamma-Ray Background (DGRB)

- The injection of high energy particles after recombination initiates electromagnetic cascades, contributing to the diffuse gamma-ray background
- Limits q_0 and leads the string constraints in the FT scenario
- Used an analysis of Fermi-LAT data

Constraining parameter space



Summary of results

$(\lambda_L, \Delta m^2/\text{GeV}^2)$	m_{H^0}/GeV		q_0	
	FT	CE	FT	CE
$(0, 1000)$	$220 - 550$	$380 - 550$	$\lesssim 2 \times 10^{-9}$	$\lesssim 3 \times 10^{-11}$
$(0.1, 1000)$	$310 - 660$	$440 - 660$	$\lesssim 9 \times 10^{-10}$	$\lesssim 2 \times 10^{-11}$
$(0, 10000)$	$260 - 830$	$580 - 830$	$\lesssim 2 \times 10^{-9}$	$\lesssim 2 \times 10^{-11}$
$(0.1, 10000)$	$320 - 1040$	$690 - 1040$	$\lesssim 2 \times 10^{-9}$	$\lesssim 2 \times 10^{-11}$

Allowed ranges of DM masses and the maximum q_0 values required

$(\lambda_L, \Delta m^2/\text{GeV}^2)$	$G\mu$	
	FT	CE
$(0, 1000)$	$\lesssim 6 \times 10^{-12} P_{\text{FT}}^{-1}$	$\lesssim 1 \times 10^{-15} P_{\text{CE}}^{-1}$
$(0.1, 1000)$	$\lesssim 3 \times 10^{-12} P_{\text{FT}}^{-1}$	$\lesssim 1 \times 10^{-15} P_{\text{CE}}^{-1}$
$(0, 10000)$	$\lesssim 7 \times 10^{-12} P_{\text{FT}}^{-1}$	$\lesssim 1 \times 10^{-15} P_{\text{CE}}^{-1}$
$(0.1, 10000)$	$\lesssim 7 \times 10^{-12} P_{\text{FT}}^{-1}$	$\lesssim 1 \times 10^{-15} P_{\text{CE}}^{-1}$

Maximum Gμ values required

Summary

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- Dark matter models can be *heavily constrained* by relic density bounds
- These problems can be relieved by introducing a new source of dark matter in the early universe in the form of topological defects
- Now regions previously under producing dark matter can now meet the relic density requirement
- In the IDM we can introduce defects while *keeping the theory the same* at the EW scale
- The inclusion allows for *lighter DM states* consistent with observational evidence

Appendix: Alternate Model

Charge the inert doublet under the additional U(1)' local symmetry

- Forbids a λ_5 term

  Thus it must be generated using higher order operators

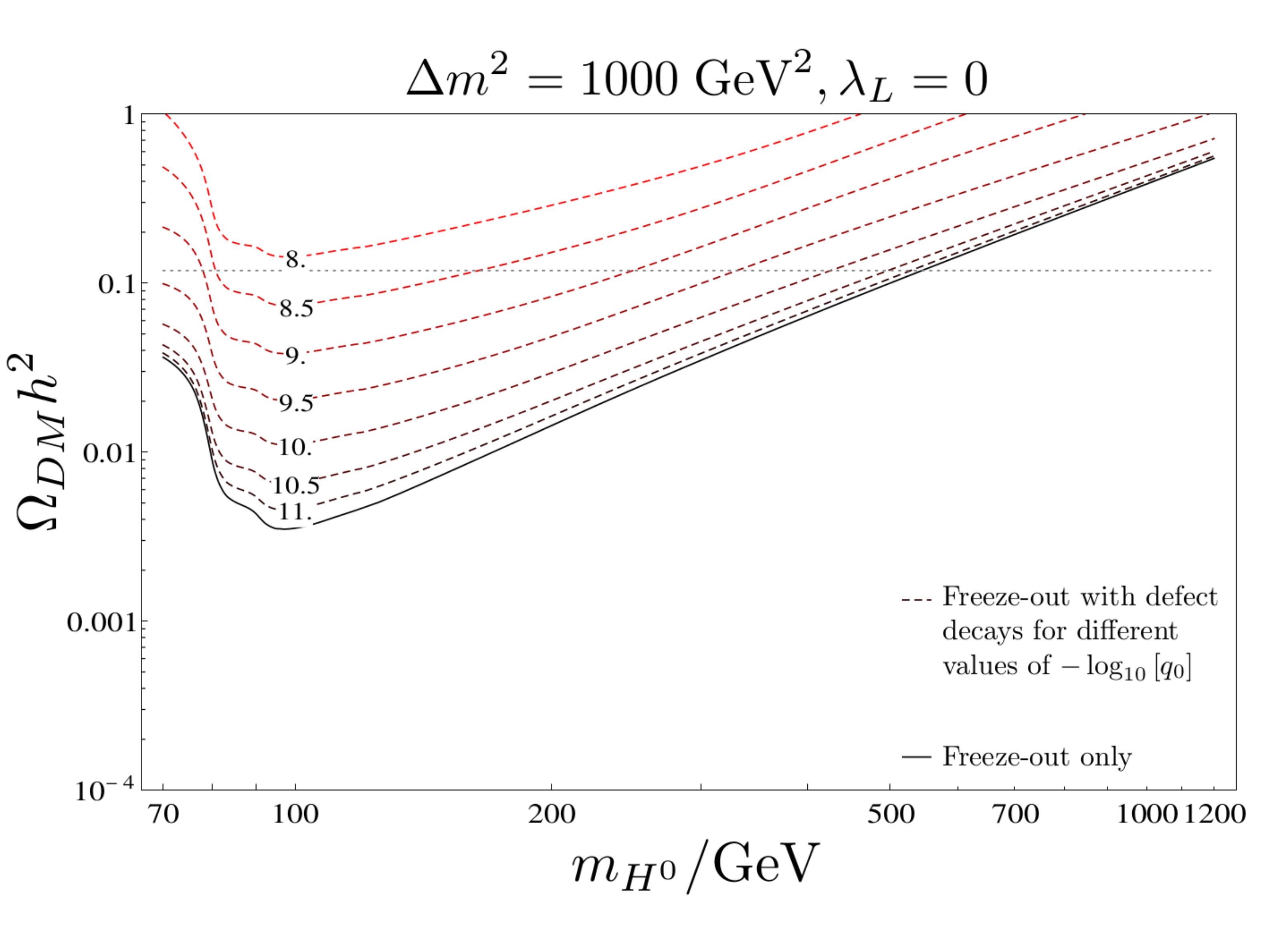
- Generates the Z_2 stabilising

  Thus we don't need to impose an arbitrary Z_2 symmetry, it is generated dynamically

This model has studied before (arXiv:1406.1952) with the U(1)' gauge symmetry breaking at the TeV scale, where it was shown to allow lighter DM states by increasing the annihilation cross-section (as additional Z' final states are now possible).

Here since we are considering near GUT scale SSB, the effective theory at EW scale is the IDM again.

Appendix: Relic Abundance



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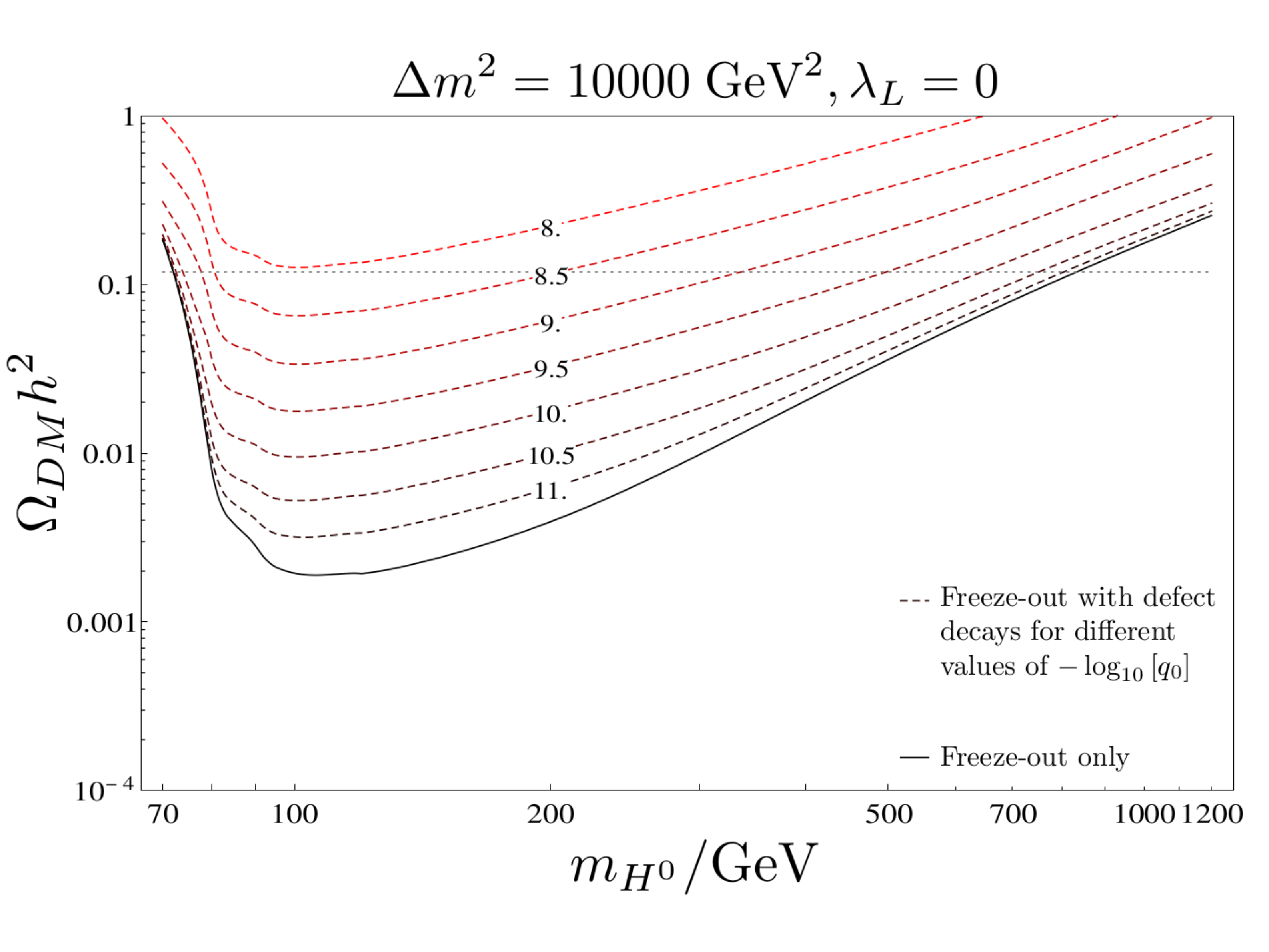

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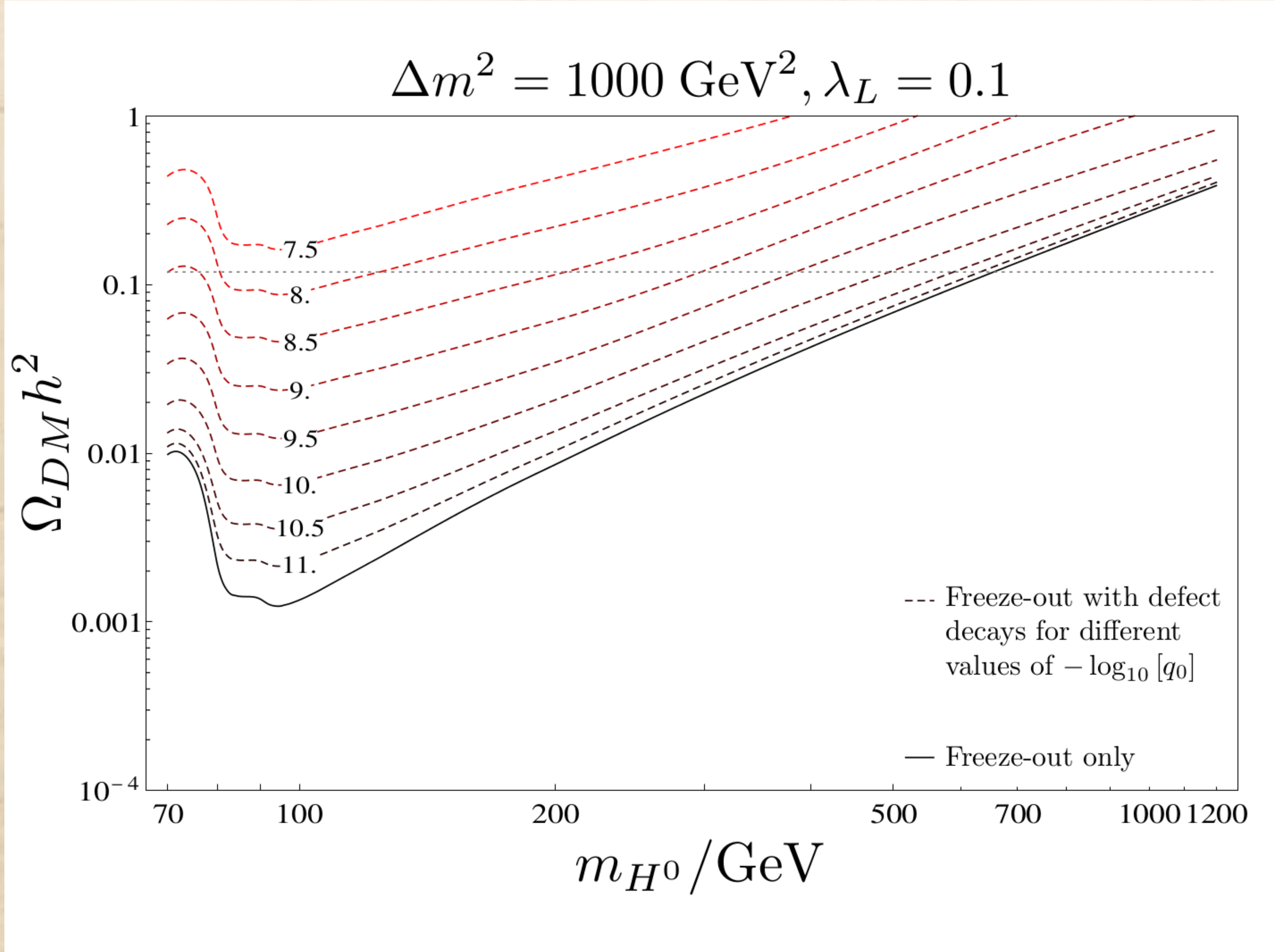

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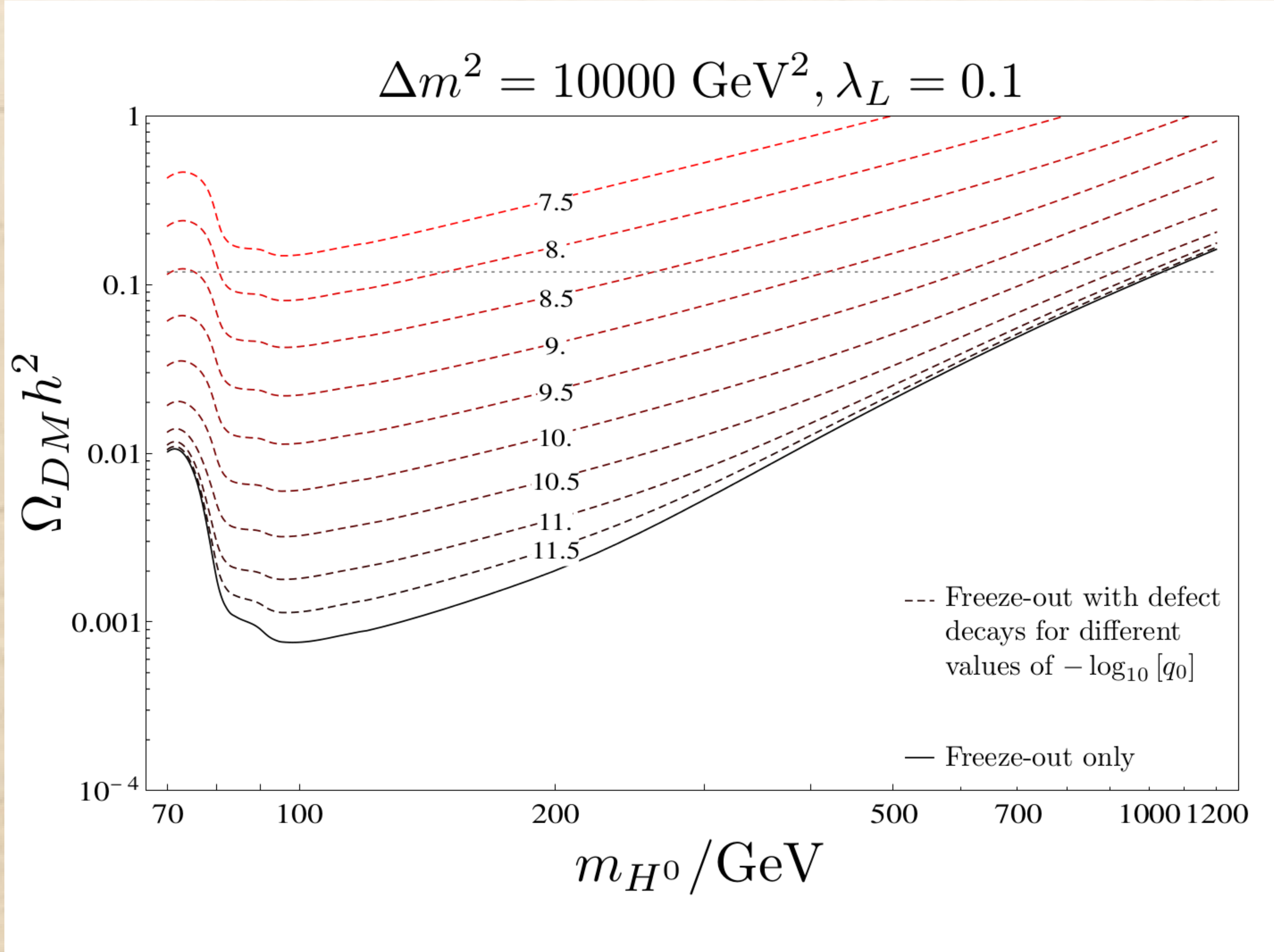
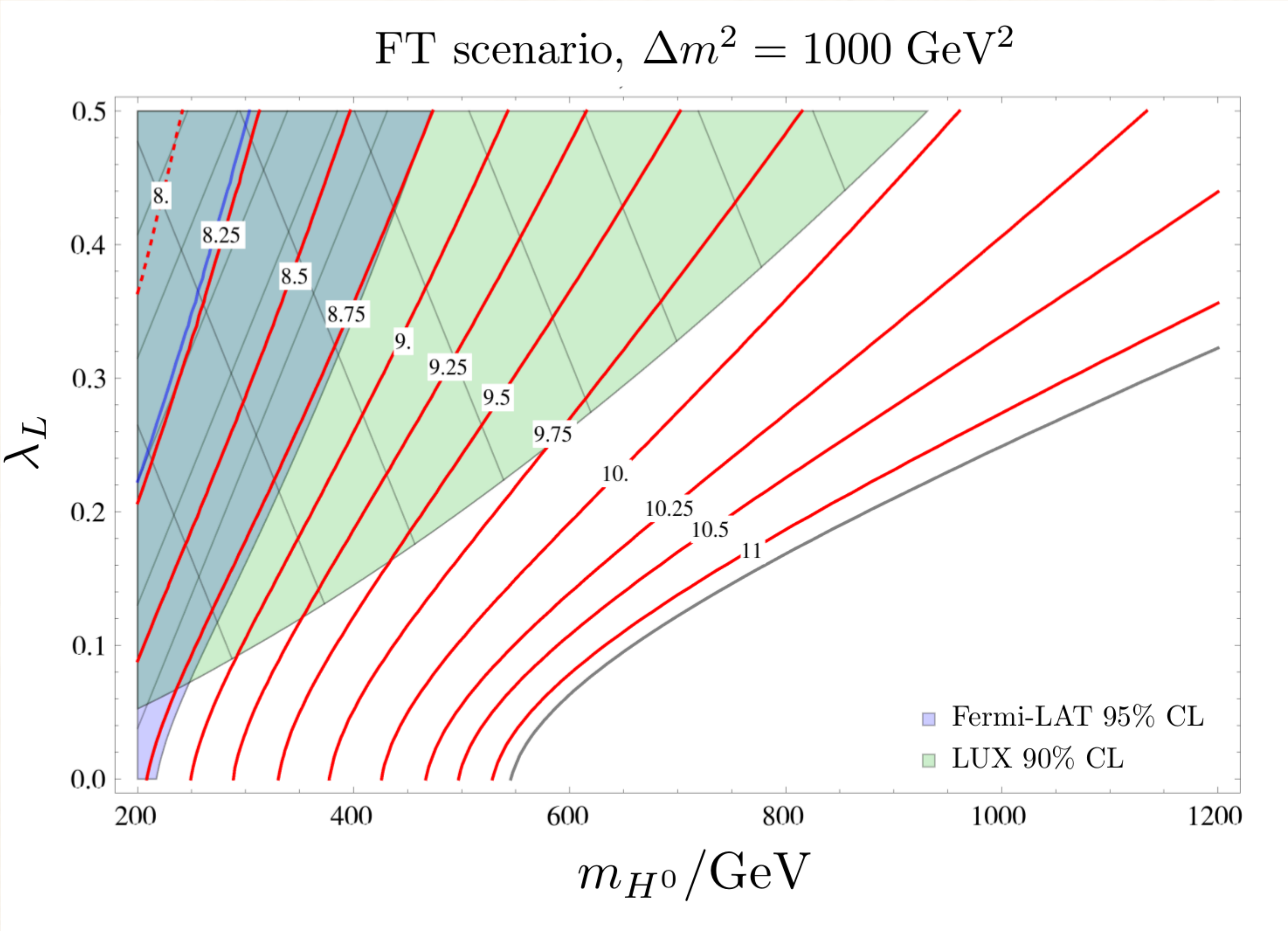


Appendix: Phase Space



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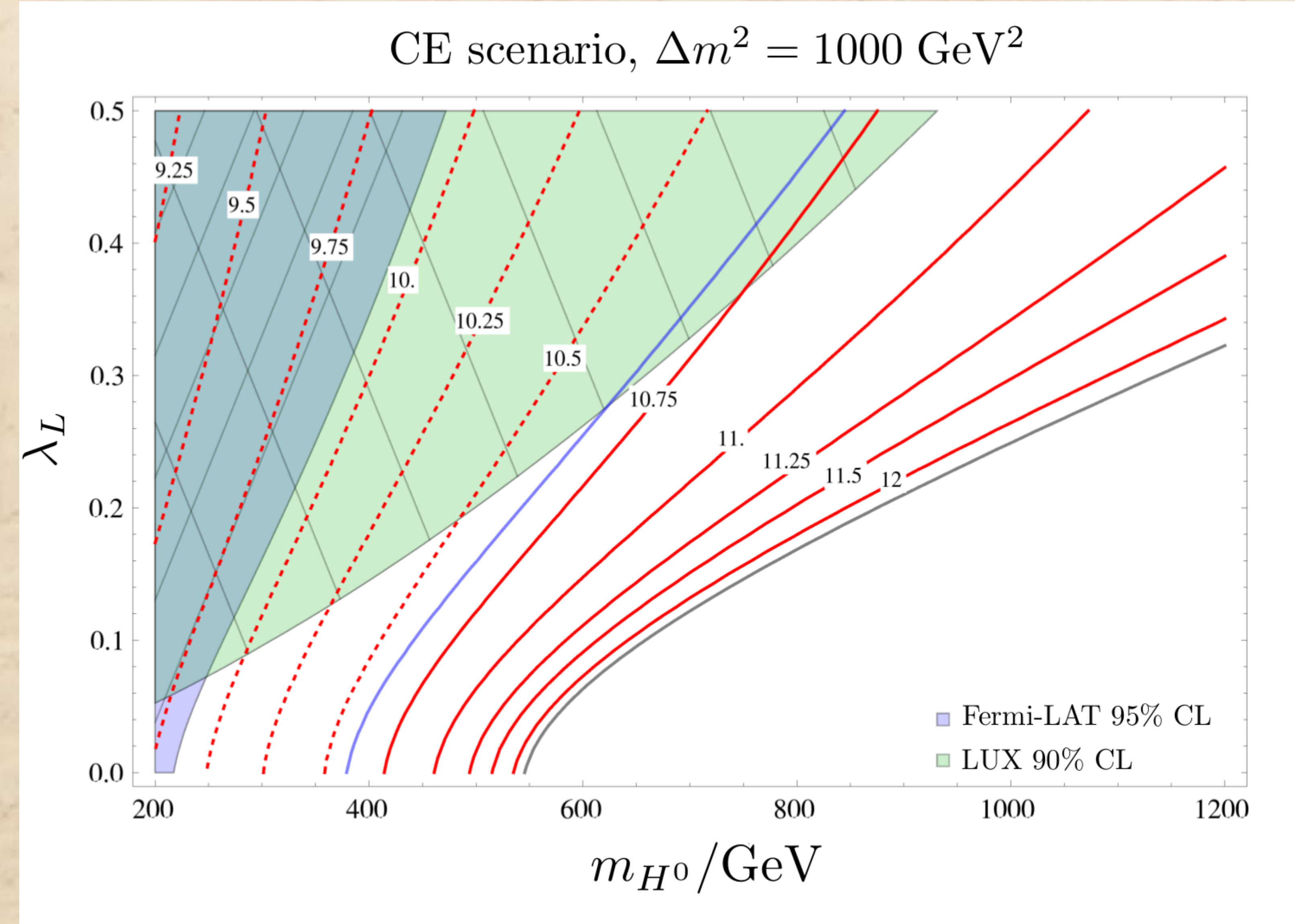

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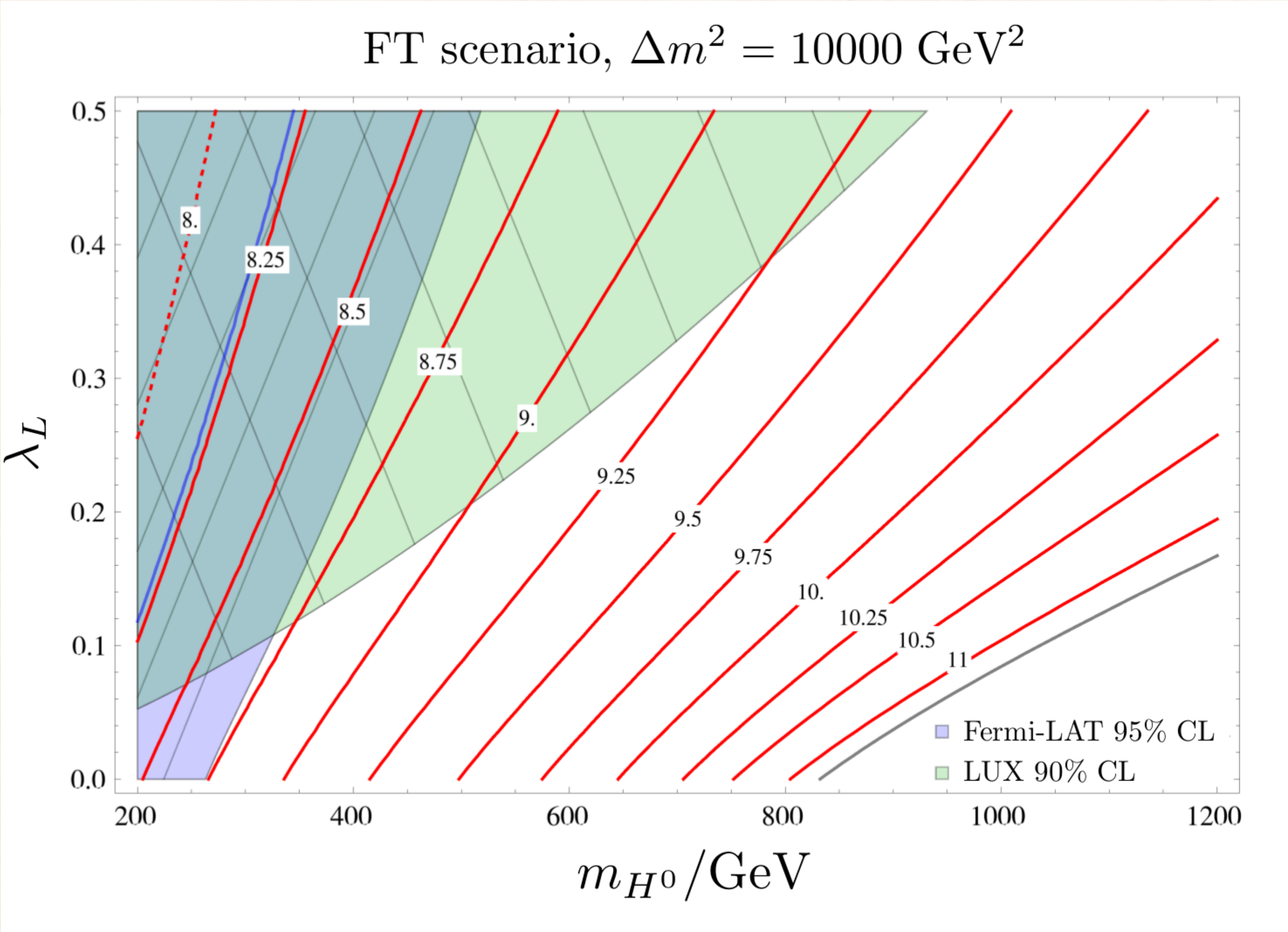

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