

Enabling forbidden dark matter from a first-order phase transition

arXiv: 2601.12319 [hep-ph]

in collaboration with S. Mahapatra and N. Sahu

Partha Kumar Paul

Department of Physics

Indian Institute of Technology Hyderabad

May 12, 2026

Phenomenology Symposium 2026 @ University of Pittsburgh



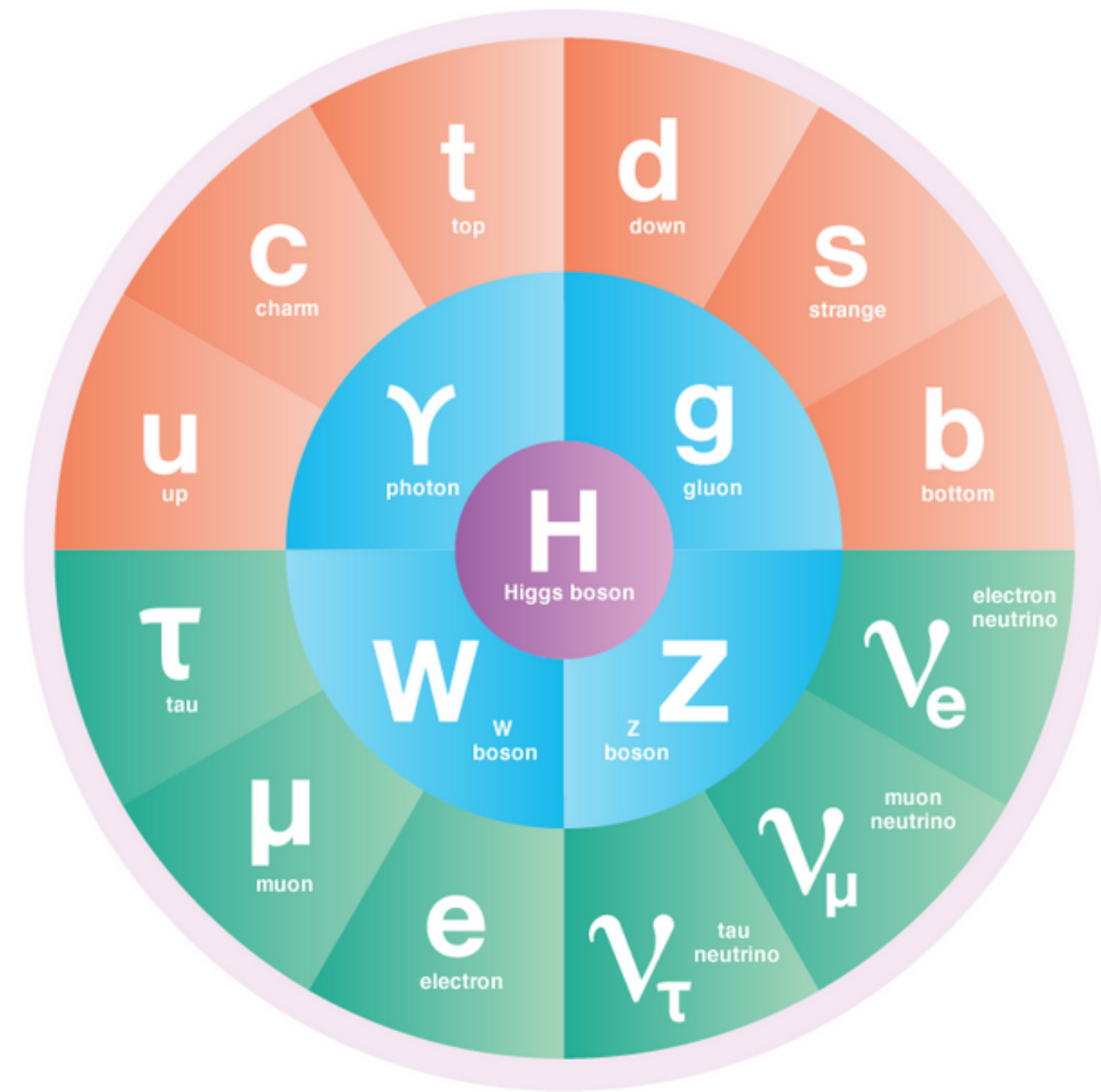
सत्यमेव जयते

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MINISTRY OF
EDUCATION



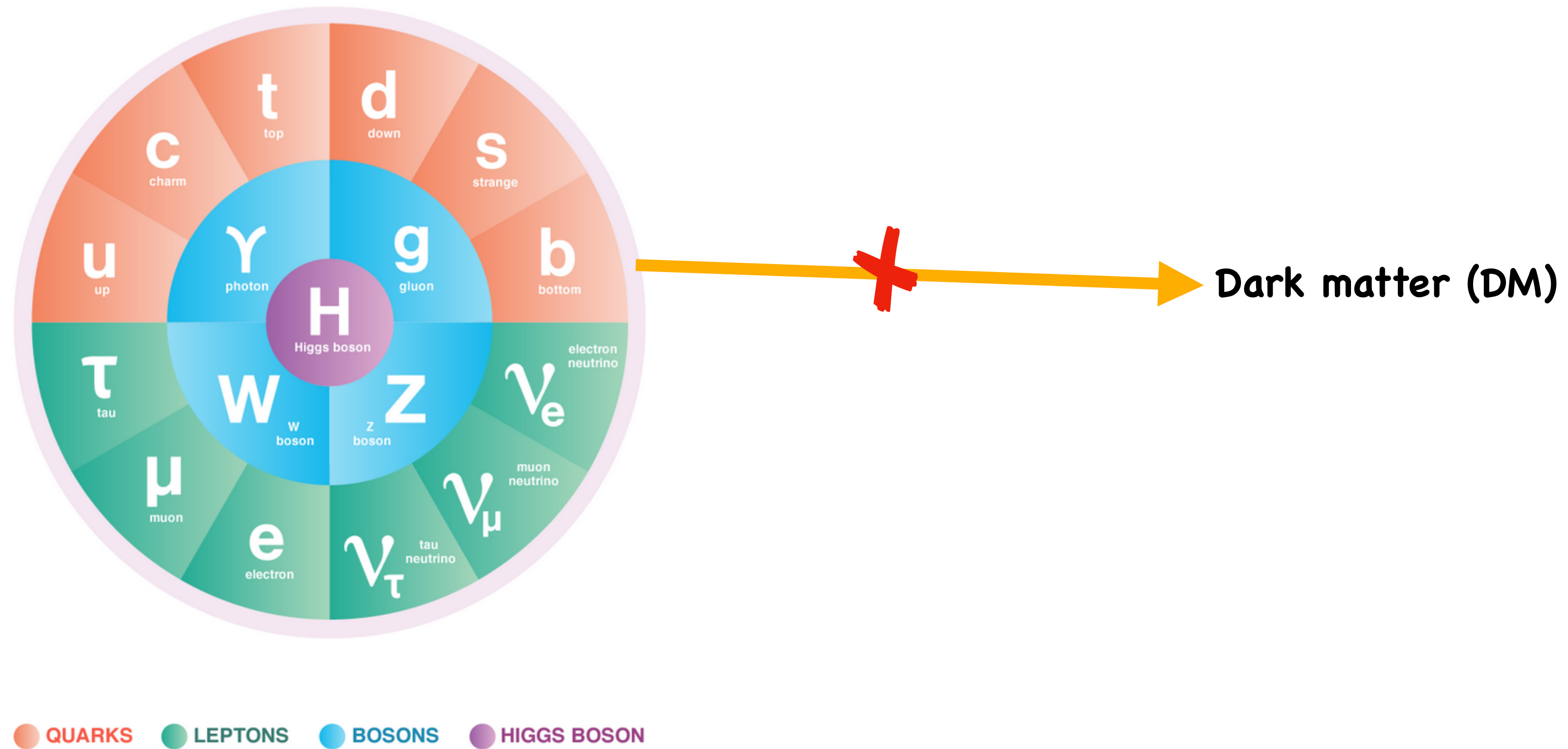
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भारतीय प्रौद्योगिकी संस्थान हैदराबाद
Indian Institute of Technology Hyderabad

The Standard Model and dark matter

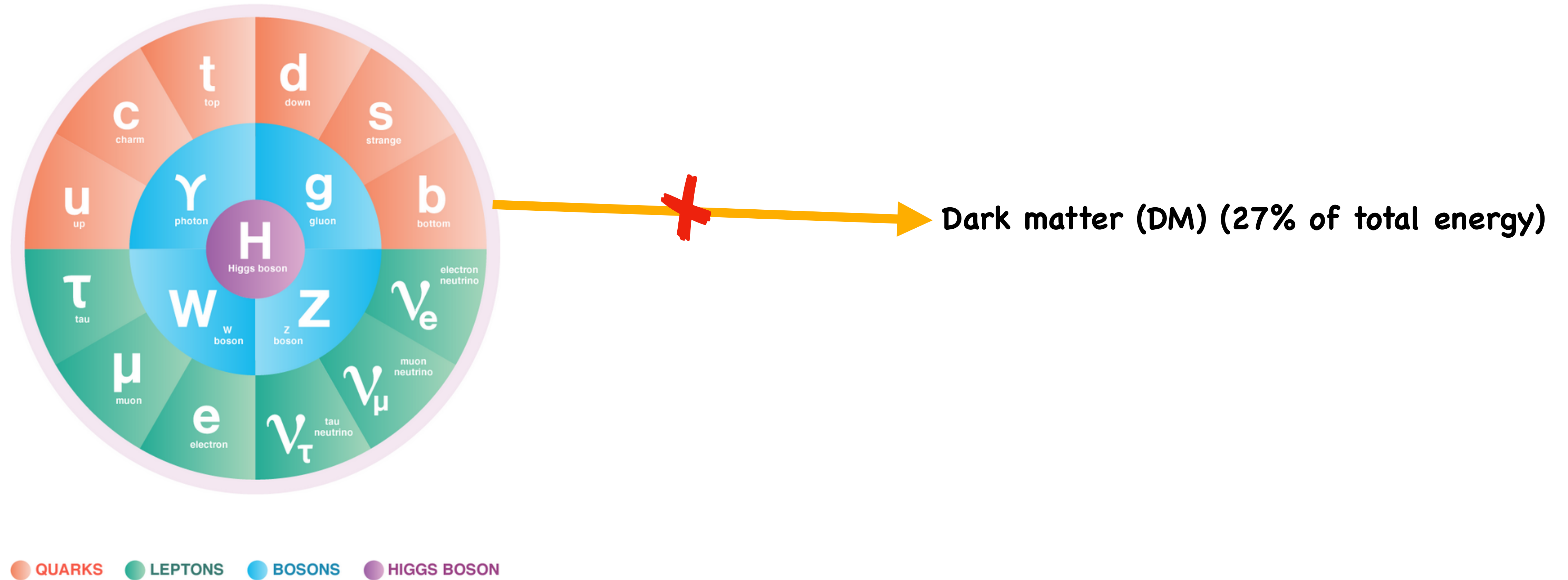


● QUARKS ● LEPTONS ● BOSONS ● HIGGS BOSON

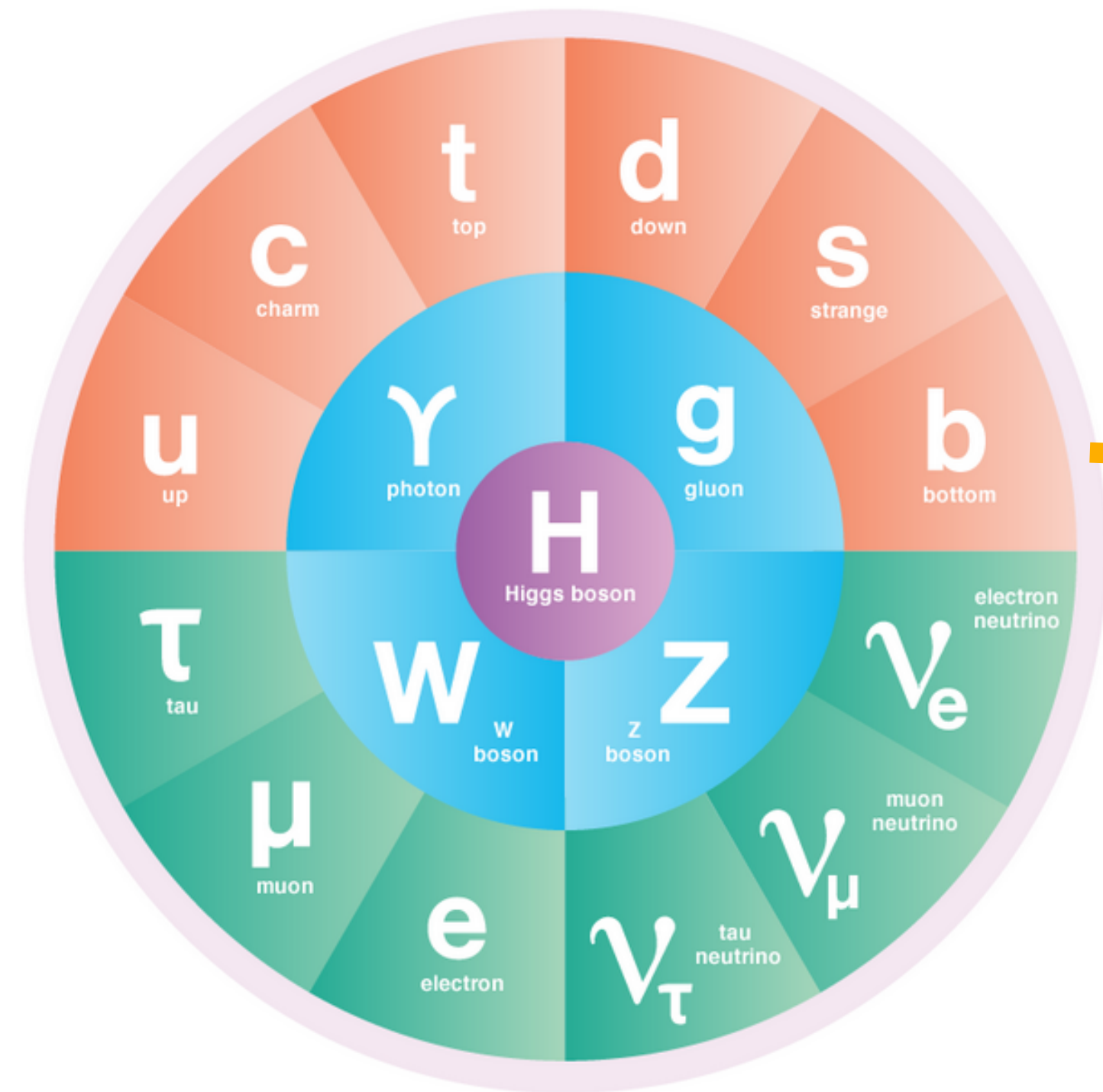
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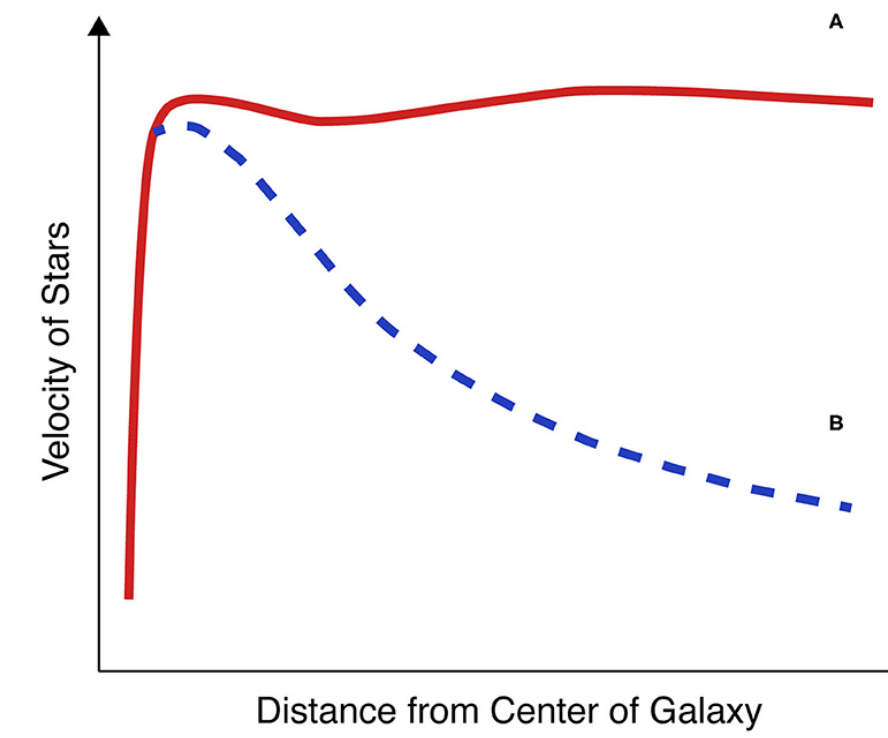
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Galaxy rotation curve

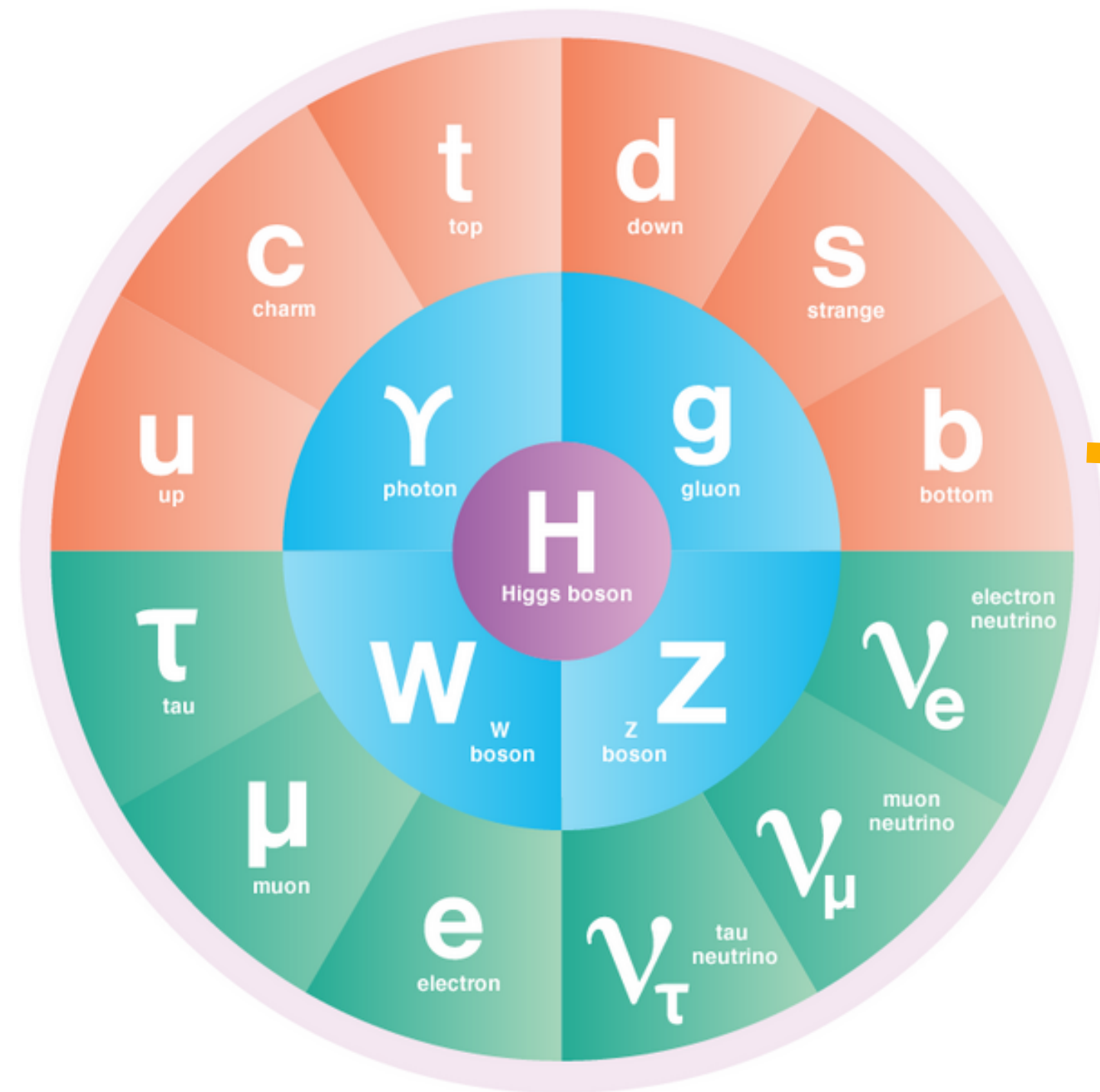


Bullet cluster

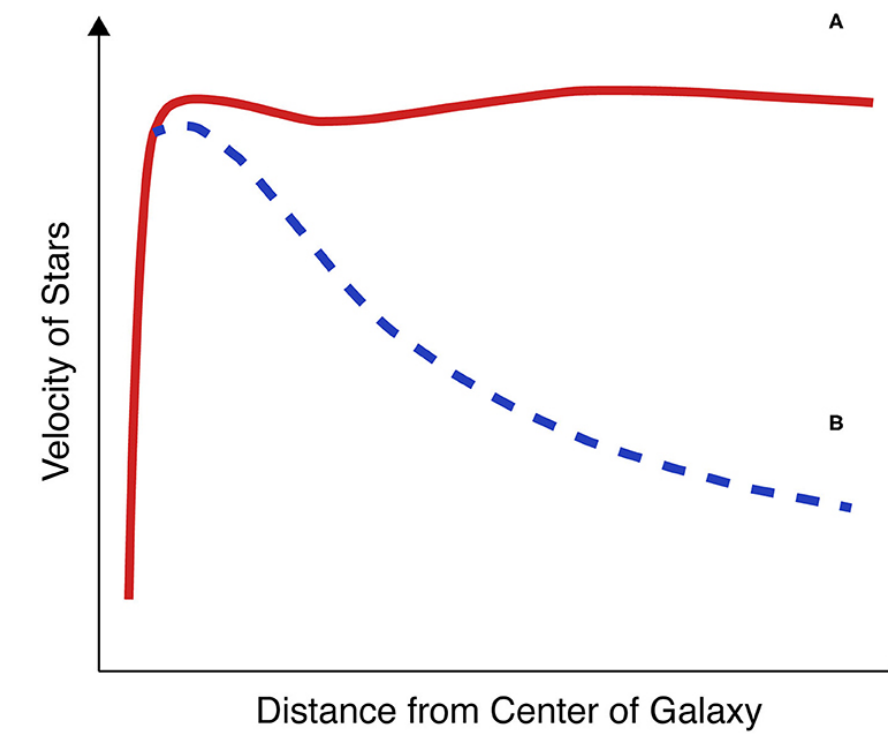
etc...

 Dark matter (DM) (27% of total energy)

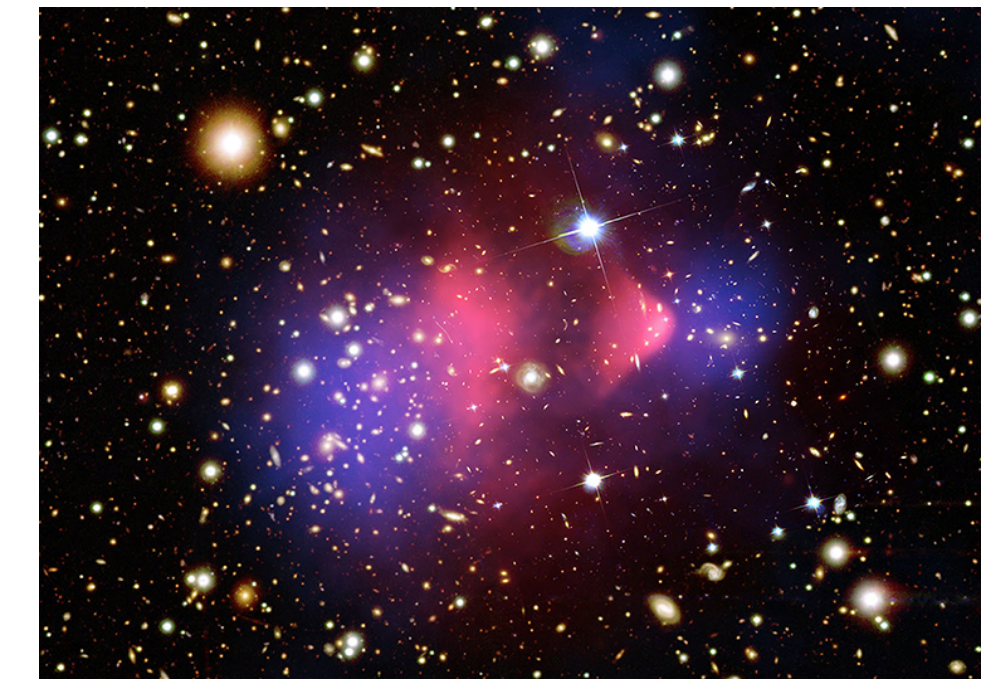
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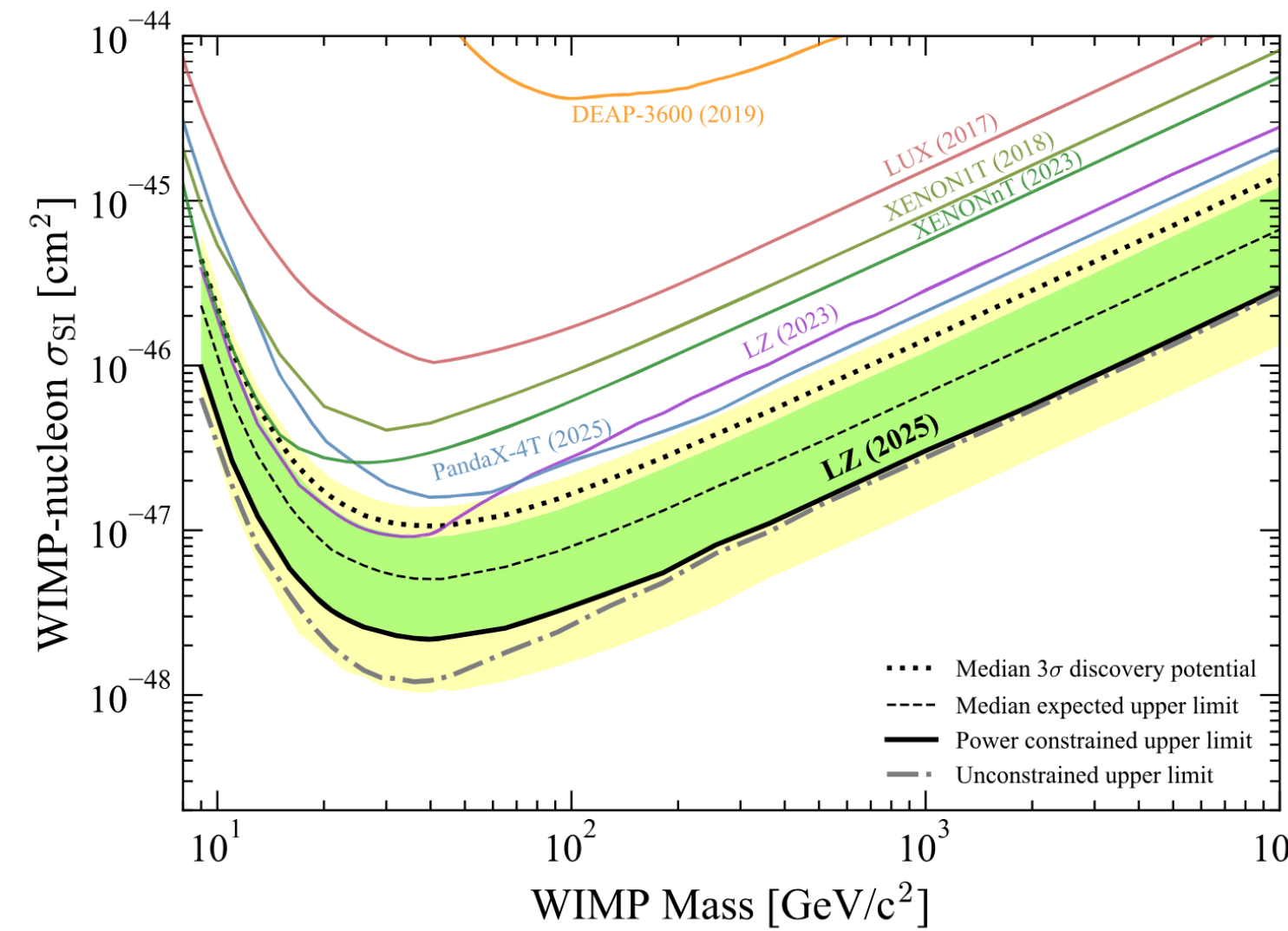
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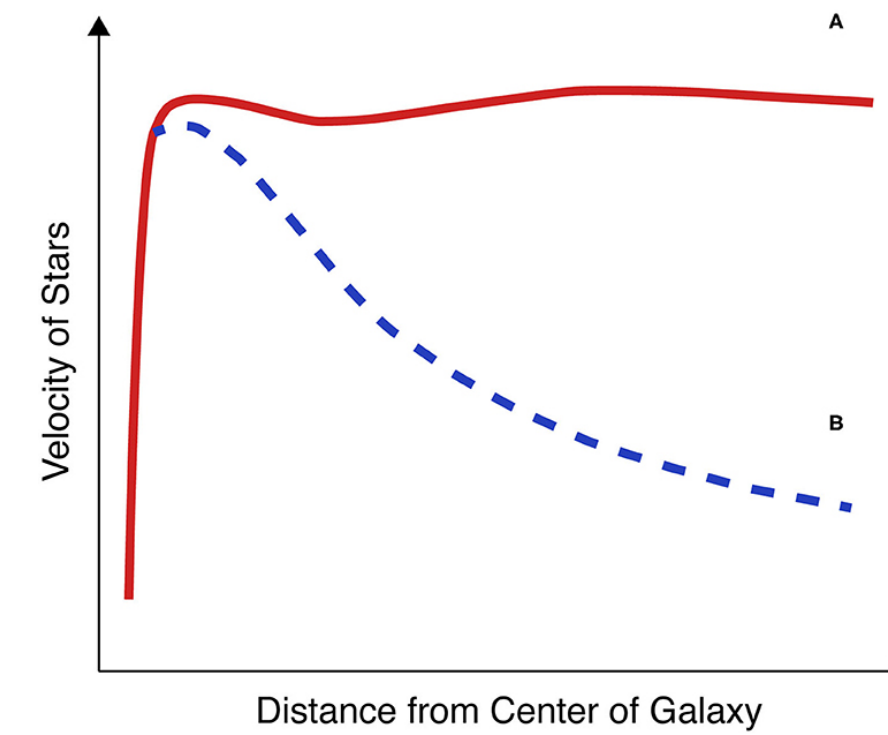
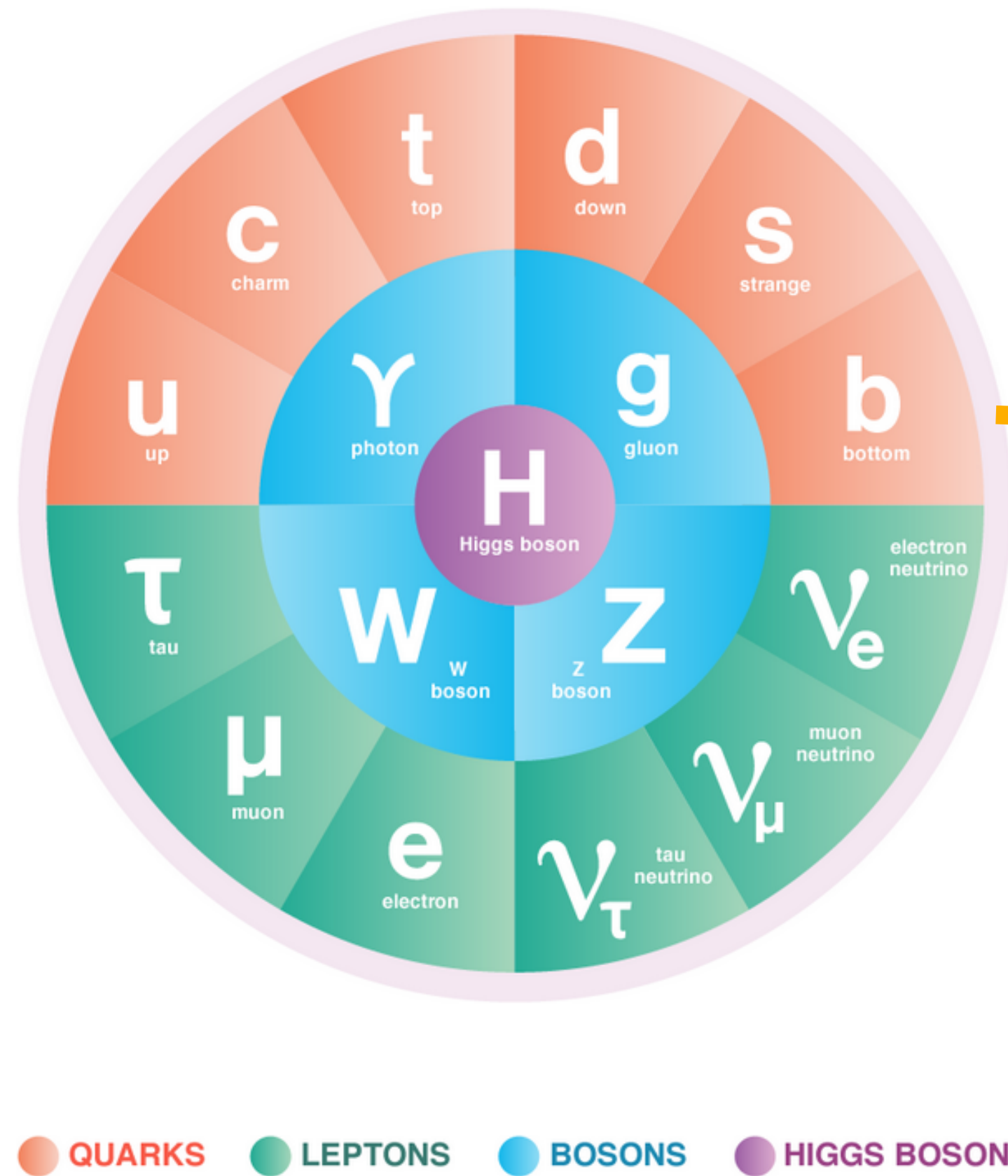
~~Standard Model~~ → Dark matter (DM) (27% of total energy)



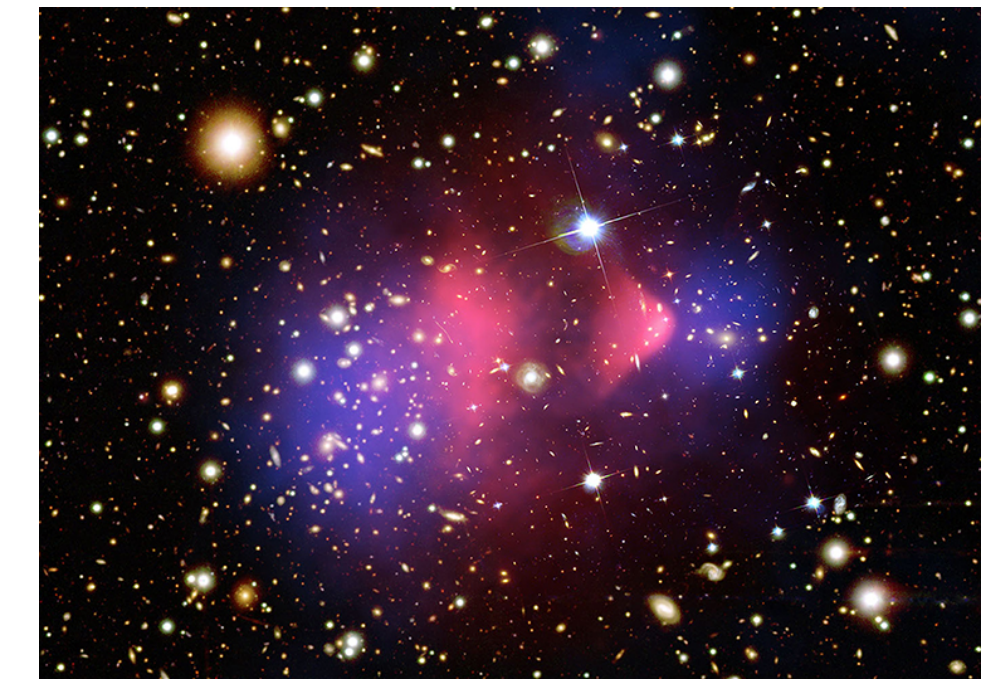
PRL 135, 011802 (2025)

zero direct detection signal confirmed!

The Standard Model and dark matter



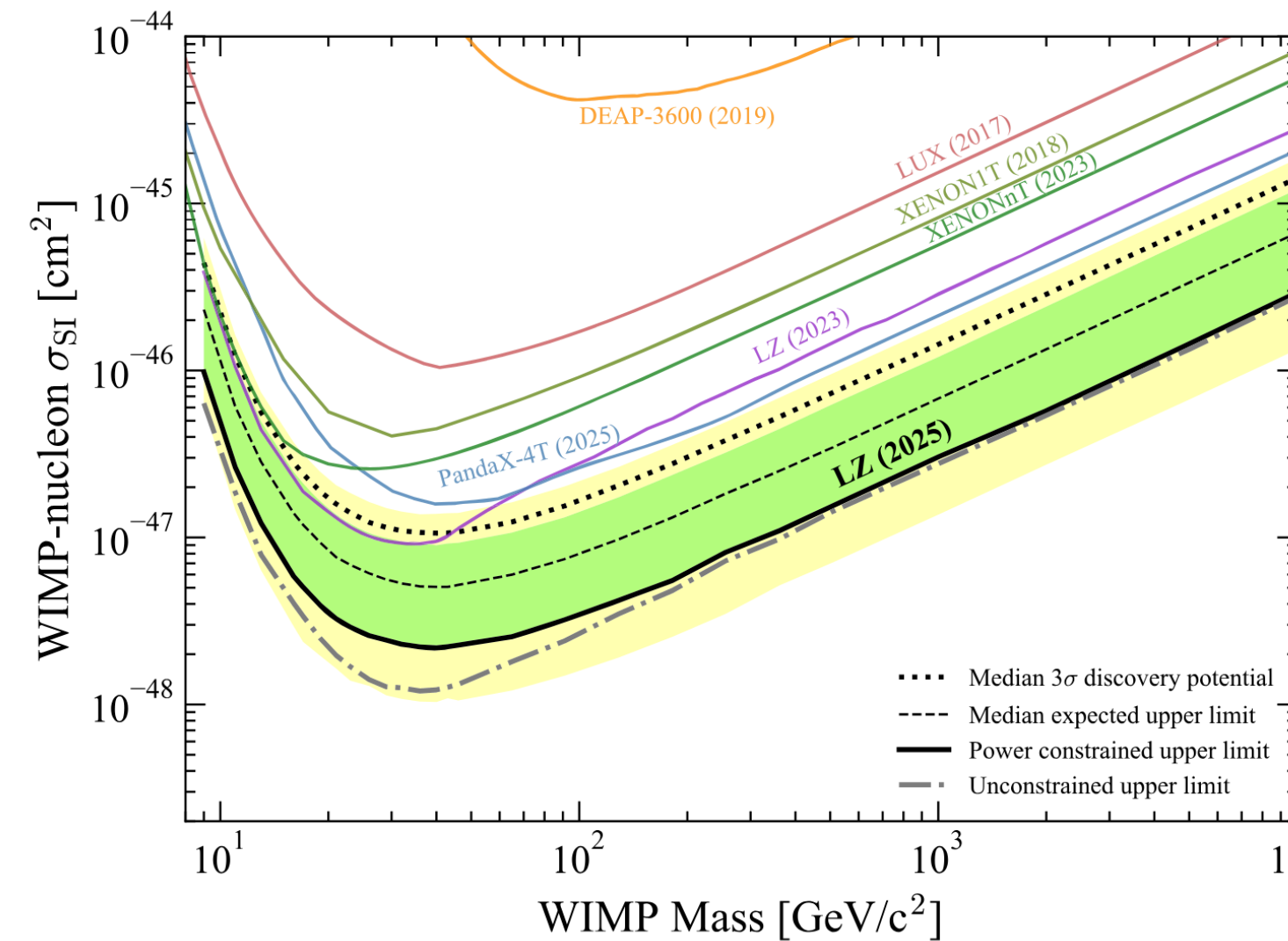
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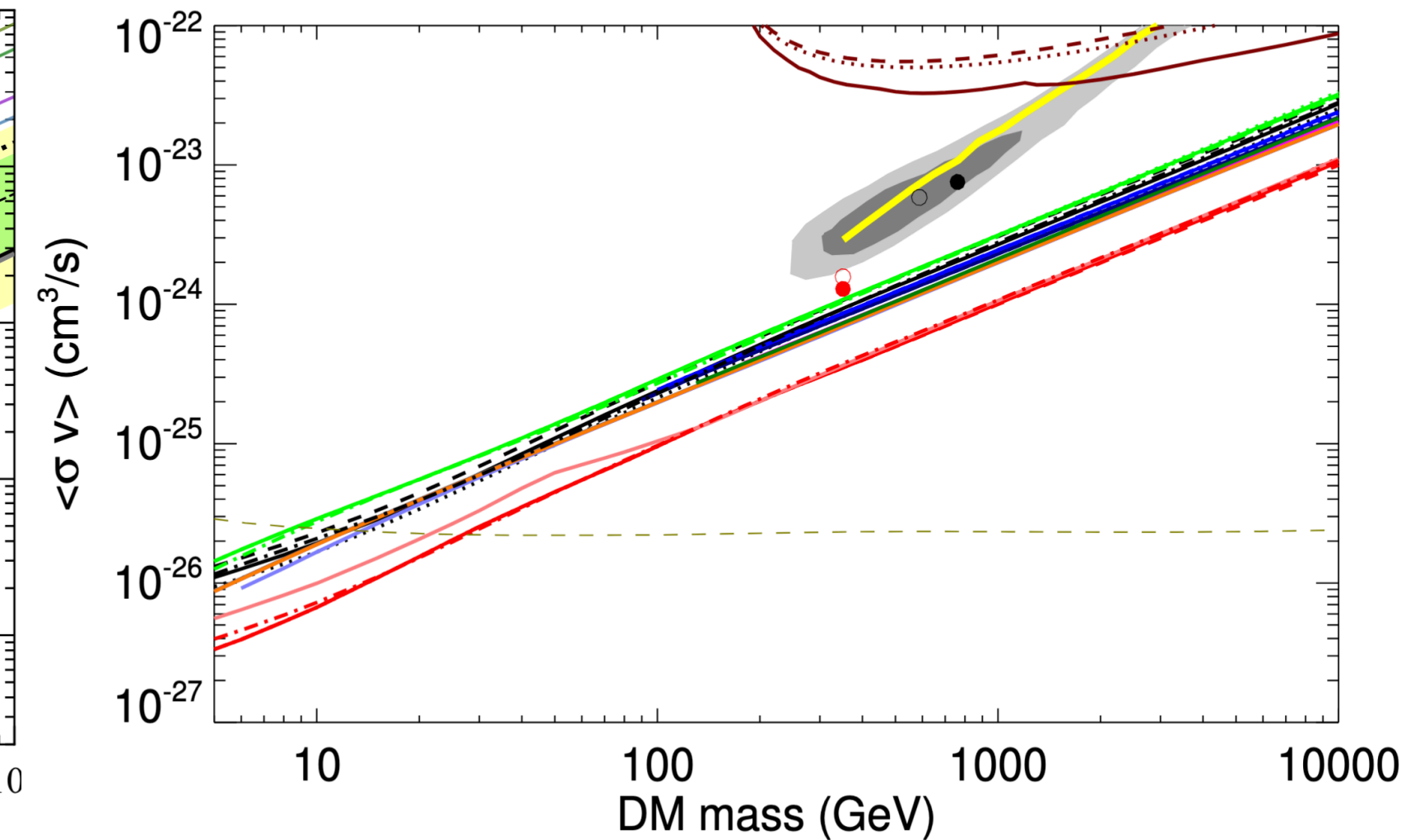
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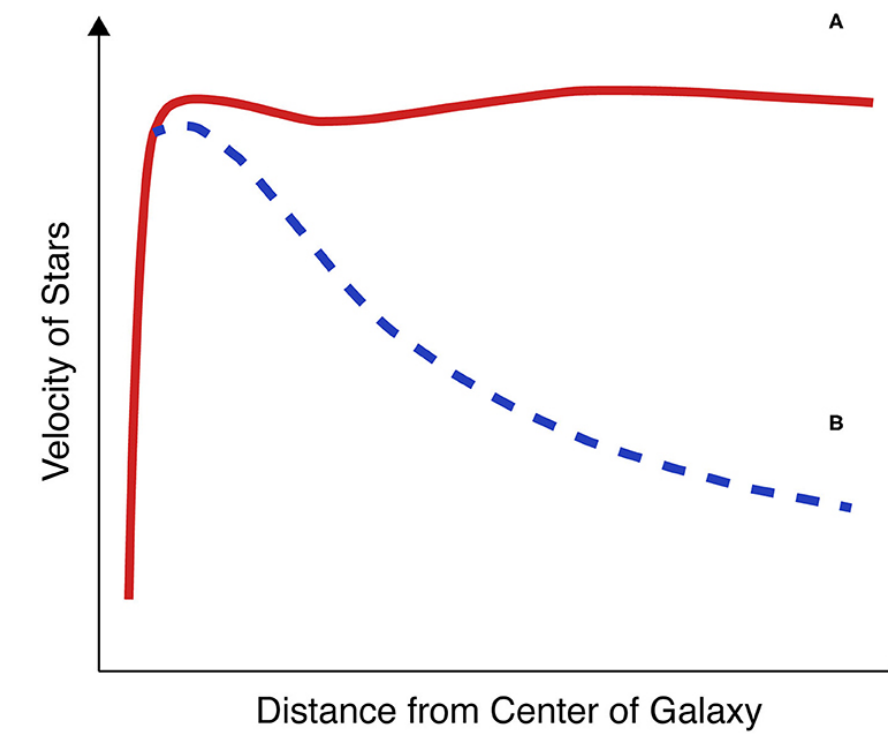
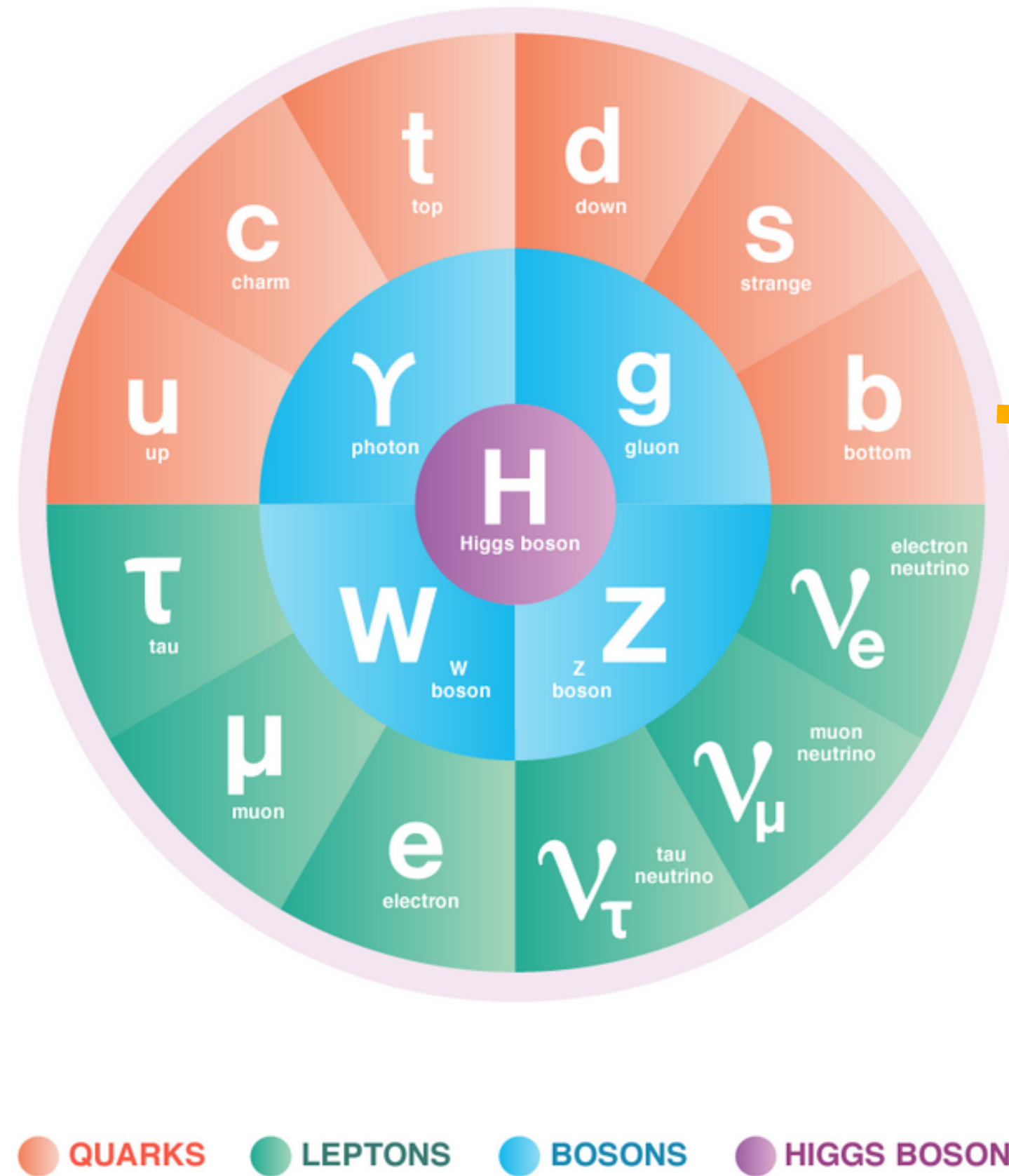
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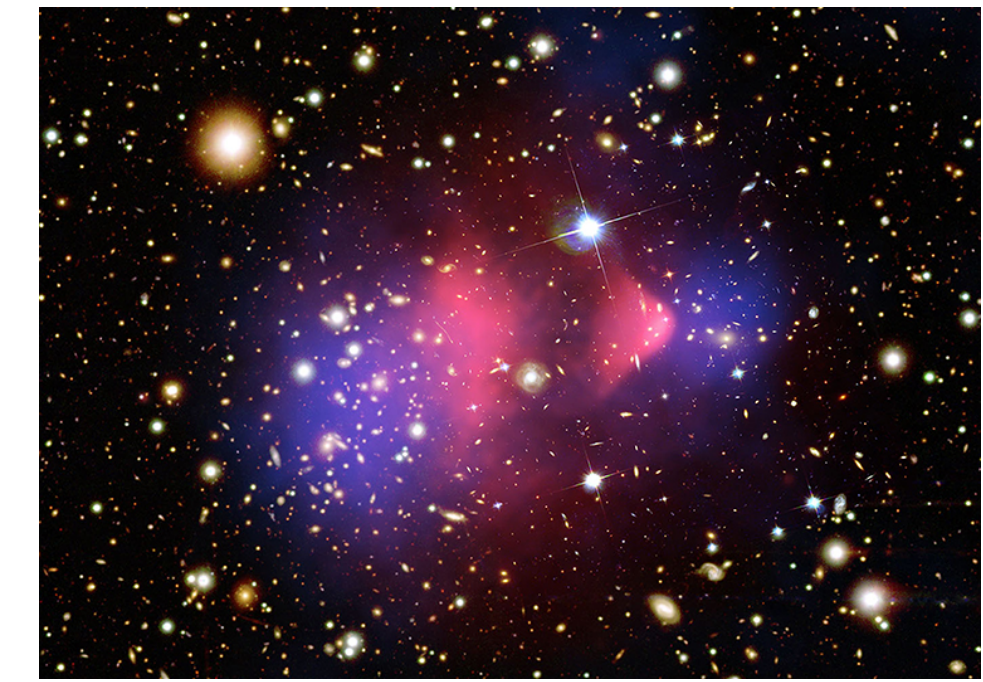
PRD 93, 023527 (2016)

Standard WIMP $m_{DM} \lesssim 20$ GeV is ruled out from CMB and indirect detection!

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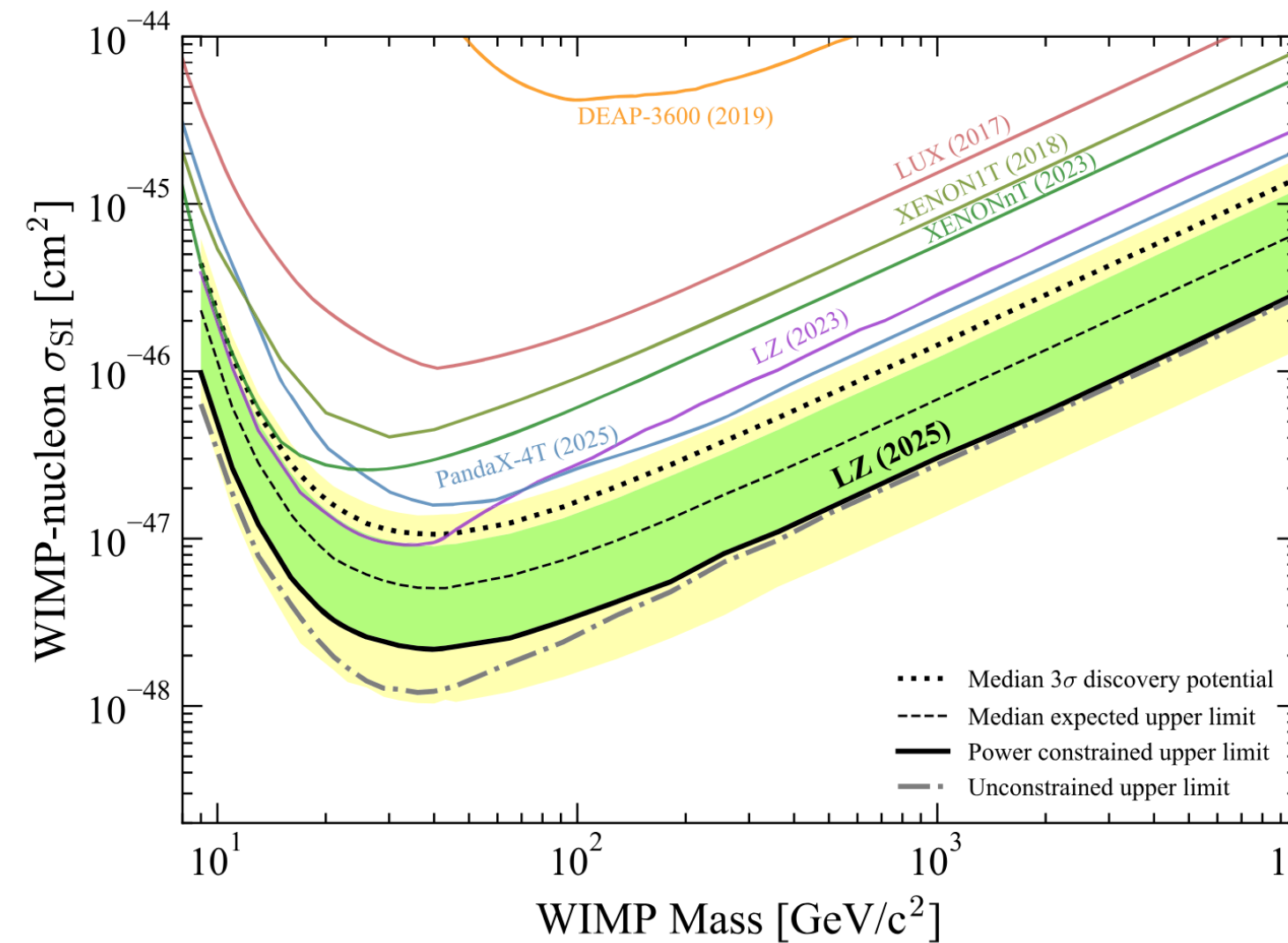
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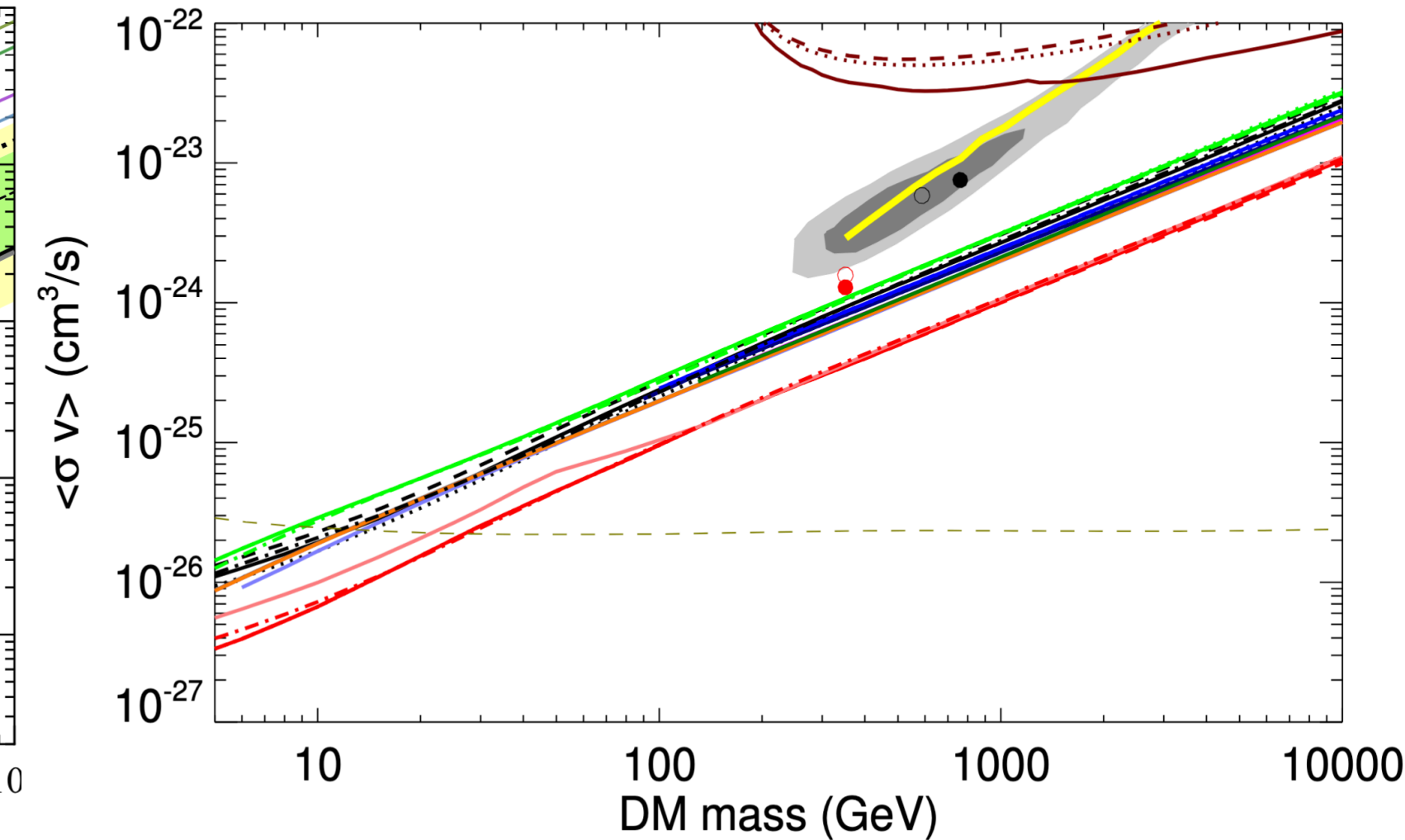
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Motivates to explore non-standard mechanisms

Forbidden Dark Matter (FDM)

PRL 115, 061301(2015)

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We explored the possibility of FDM naturally arising from
a first-order phase transition (FOPT) in dark sector

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$$U(1)_D : \chi \sim +1, \phi \sim -1$$

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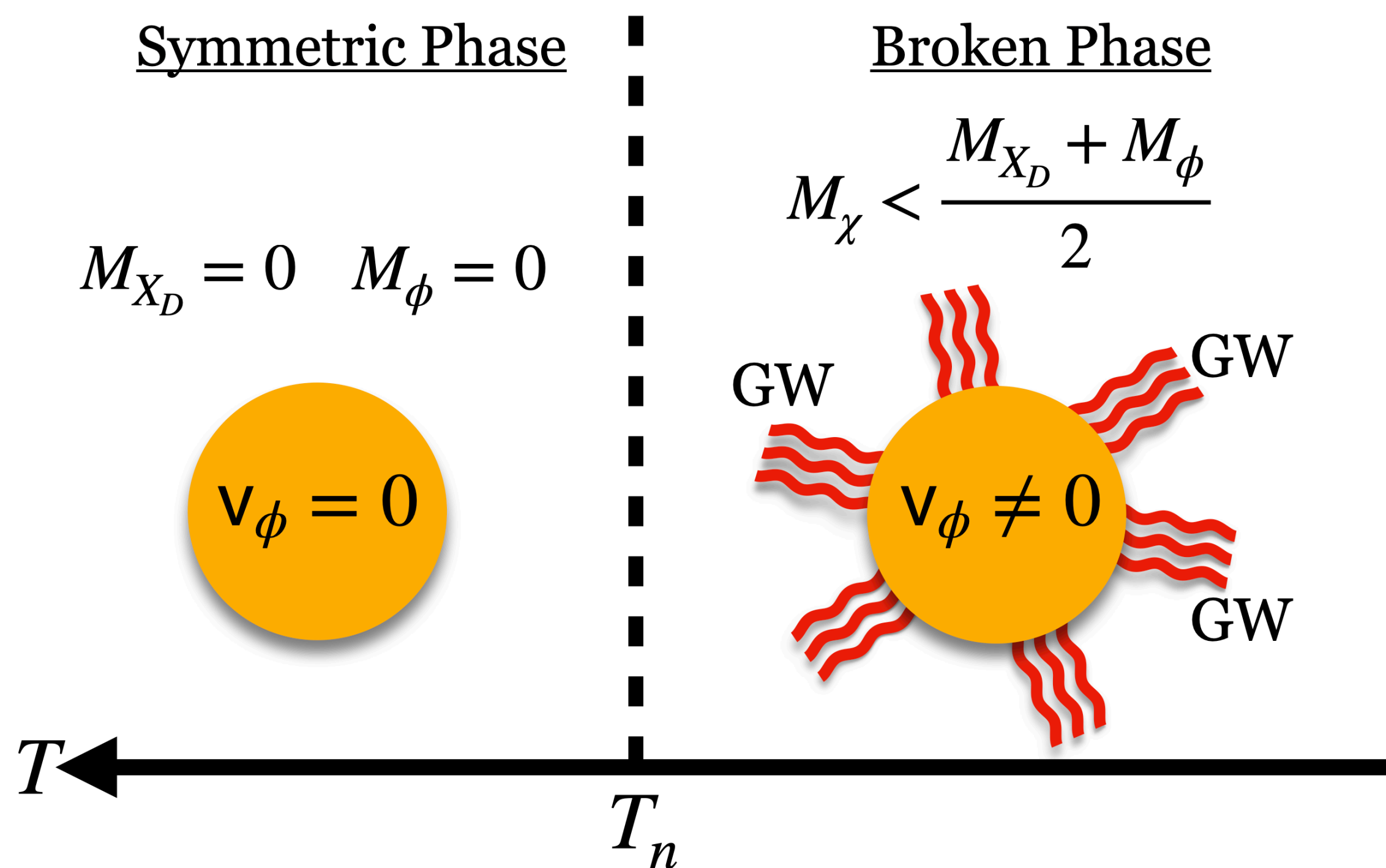
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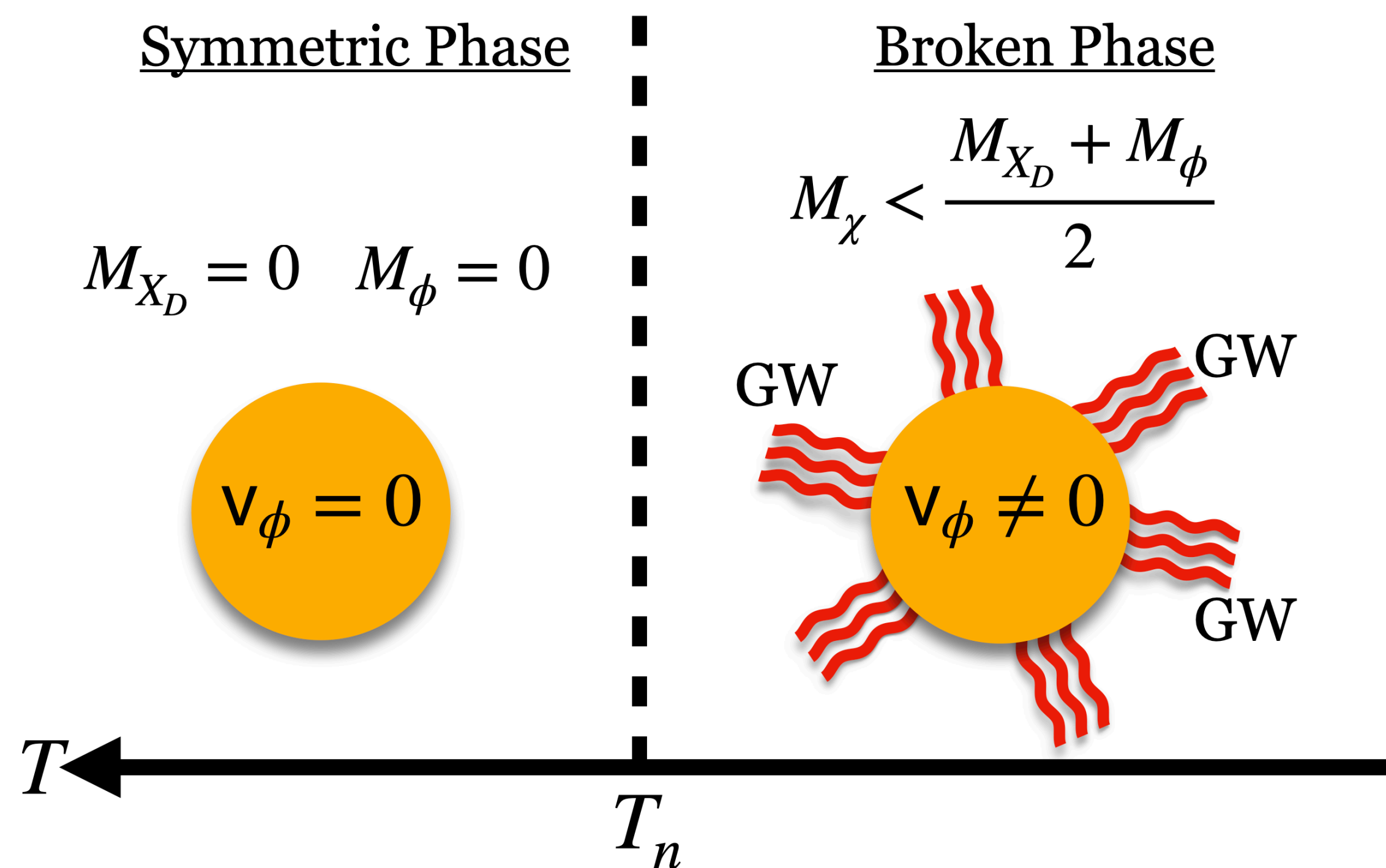


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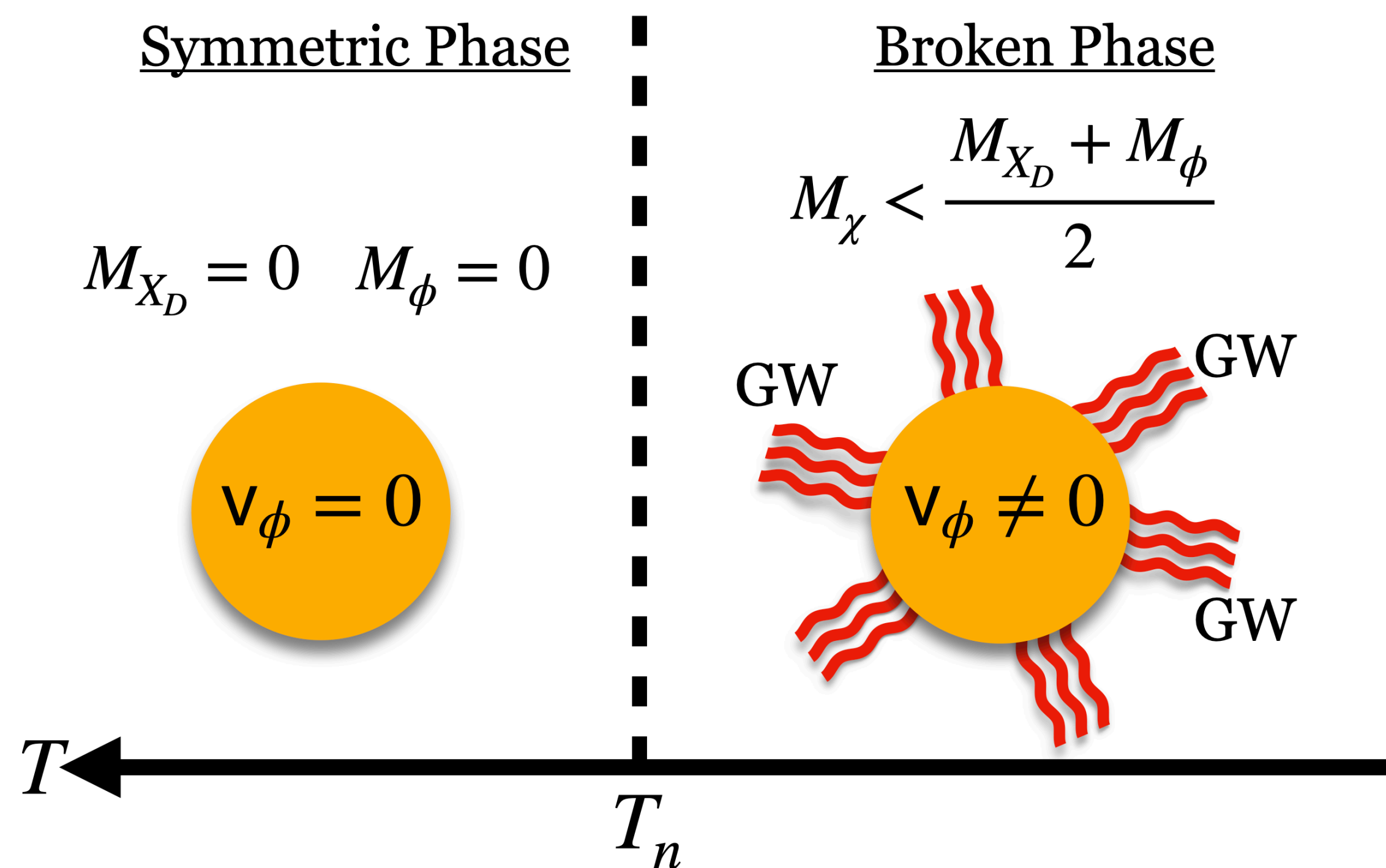
$$M_{X_D} = g_D v_\phi, \quad M_\phi = \sqrt{2\lambda_\Phi} v_\phi$$

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Free parameters

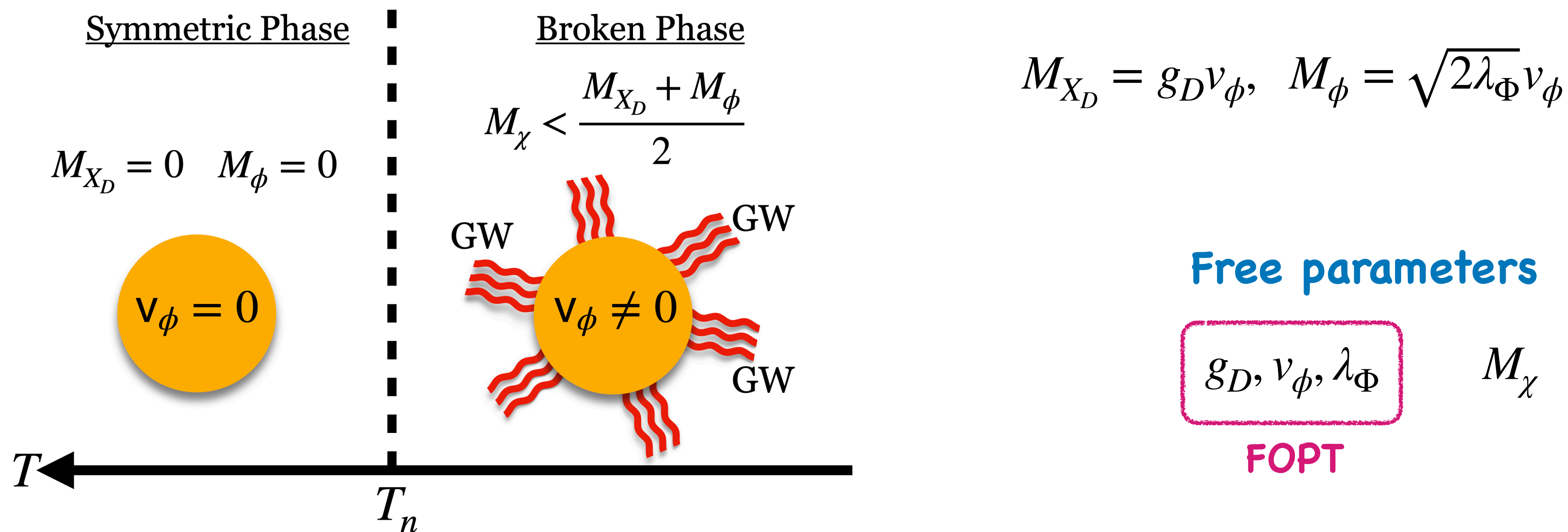
$$g_D, v_\phi, \lambda_\Phi \quad M_\chi$$

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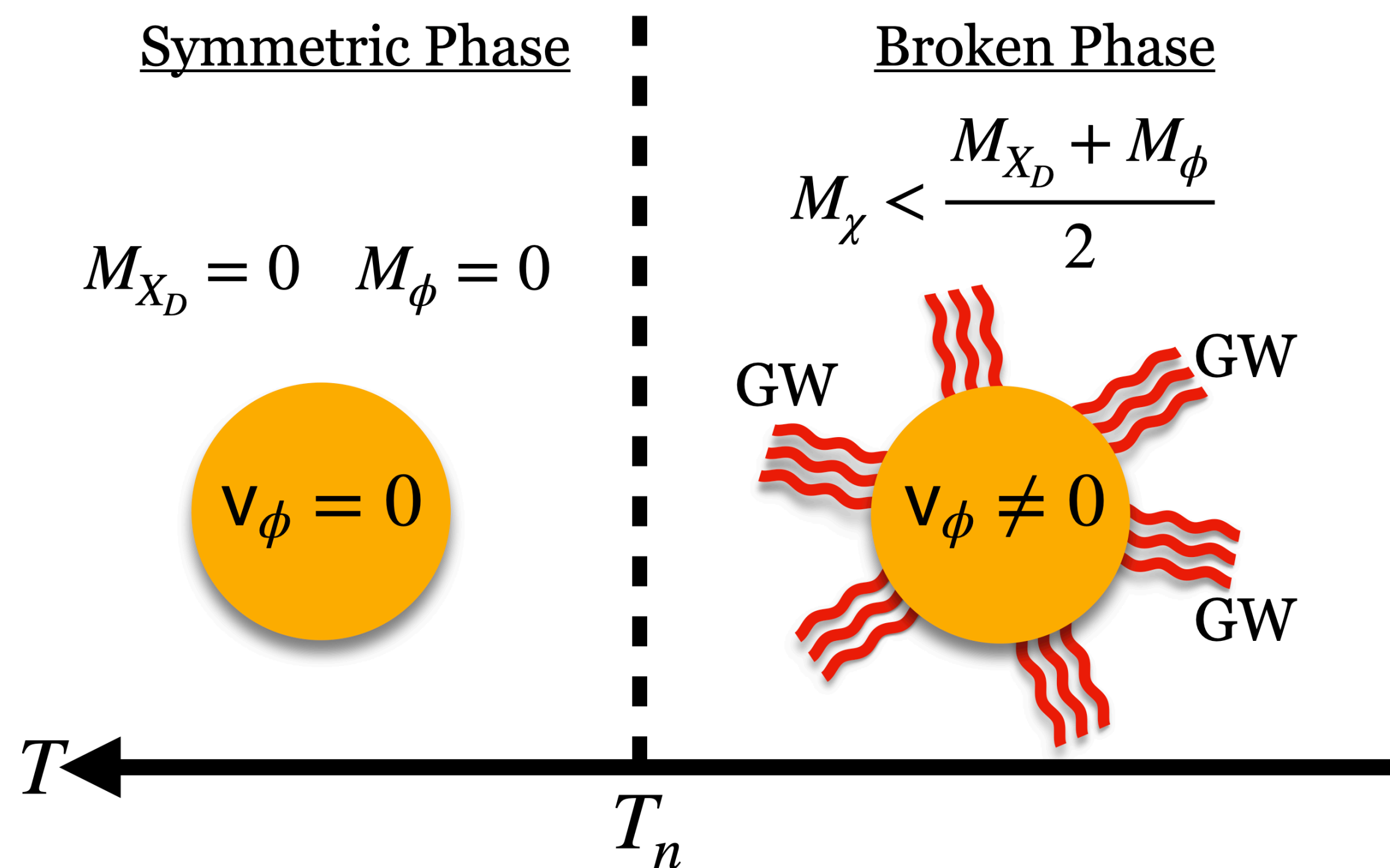


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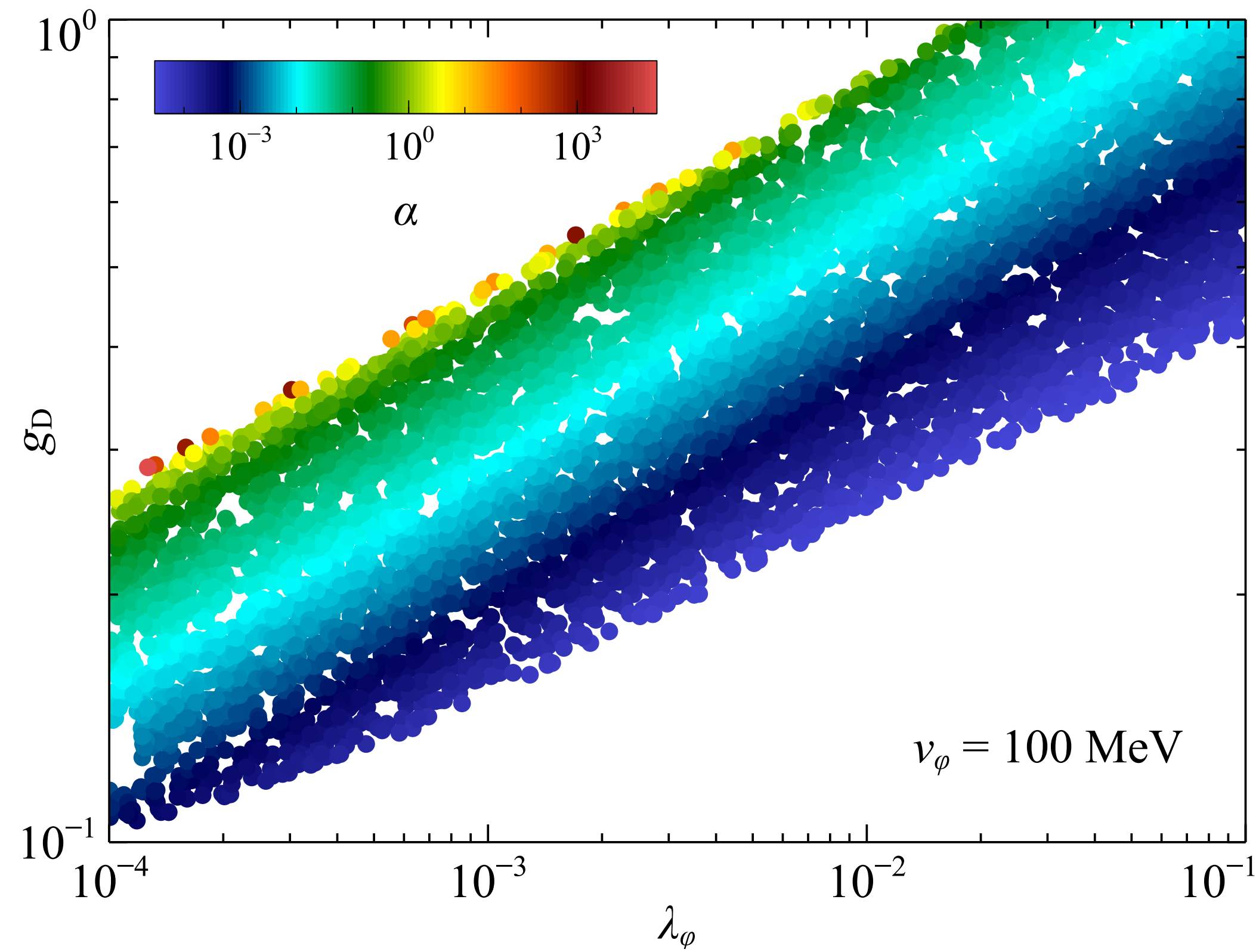
$$M_\chi$$

FOPT

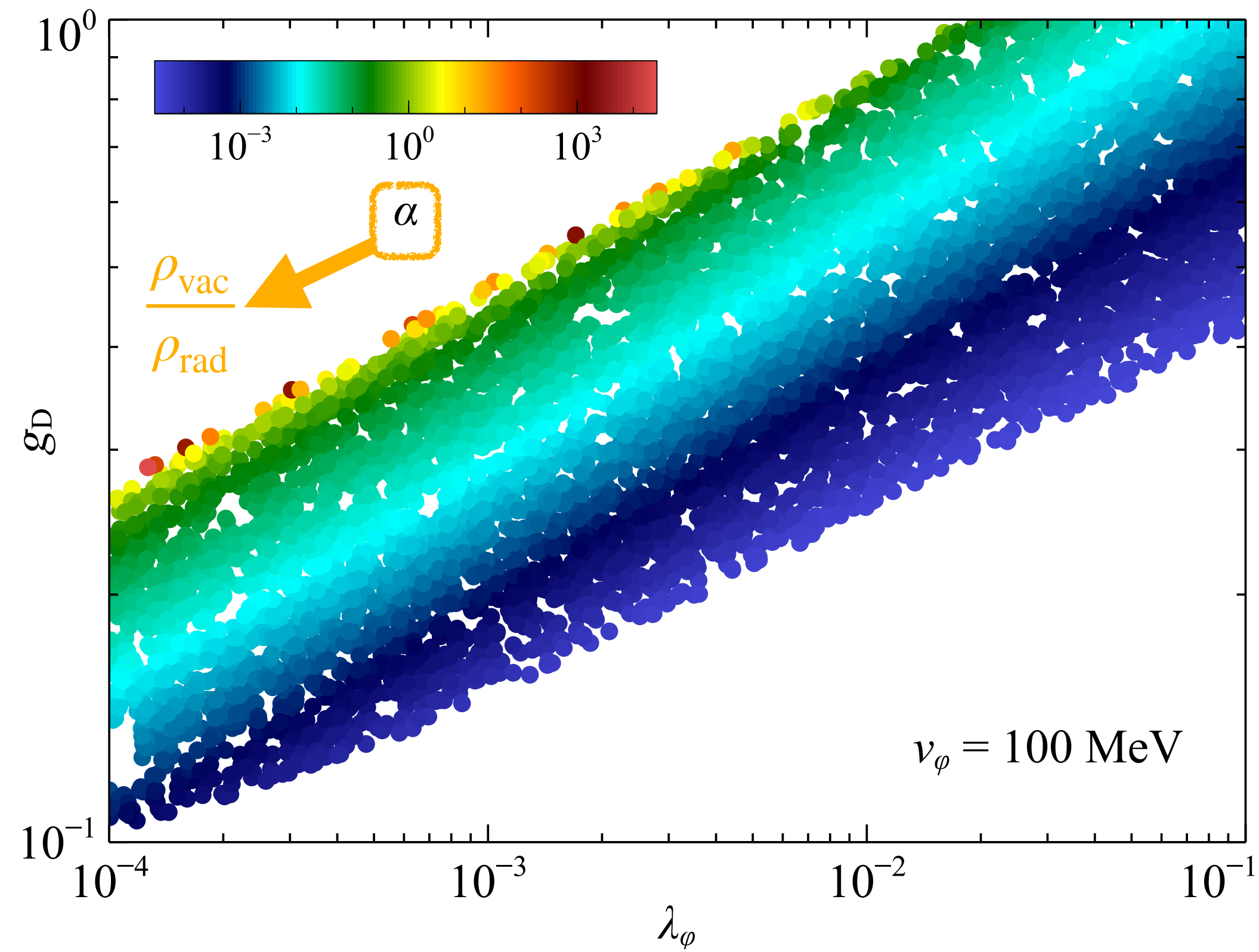
DM relic

A first-order phase transition in dark sector

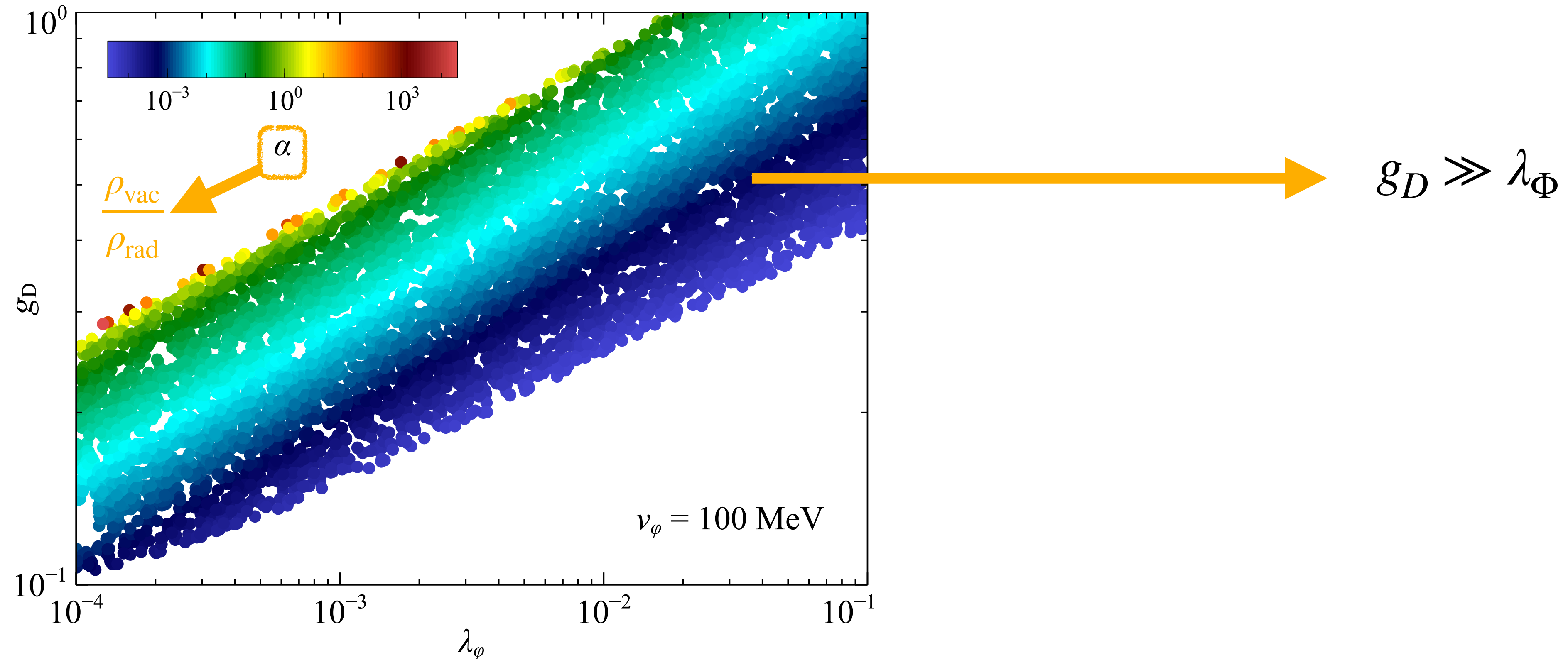
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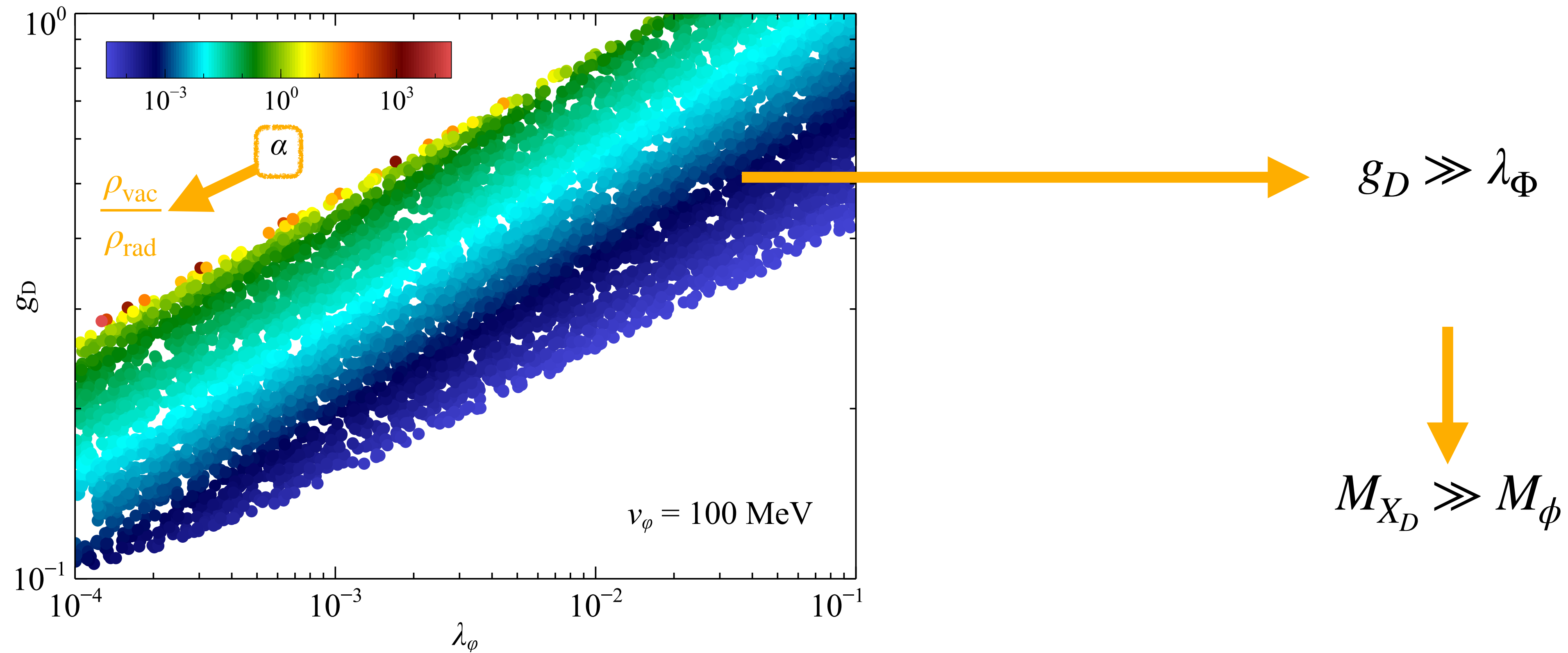
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Forbidden DM from FOPT

$$\bar{\chi}\chi \rightarrow X_D X_D, \bar{\chi}\chi \rightarrow X_D \phi, \bar{\chi}\chi \rightarrow \phi\phi, \bar{\chi}\chi \rightarrow \bar{f}f$$

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very suppressed compared
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$$2M_\chi < M_{X_D} + M_\phi$$

channel is forbidden

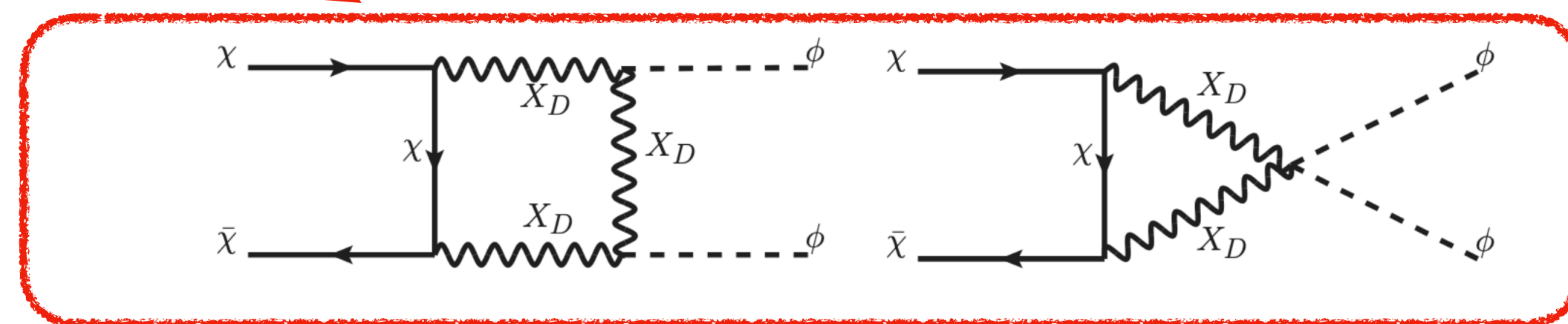
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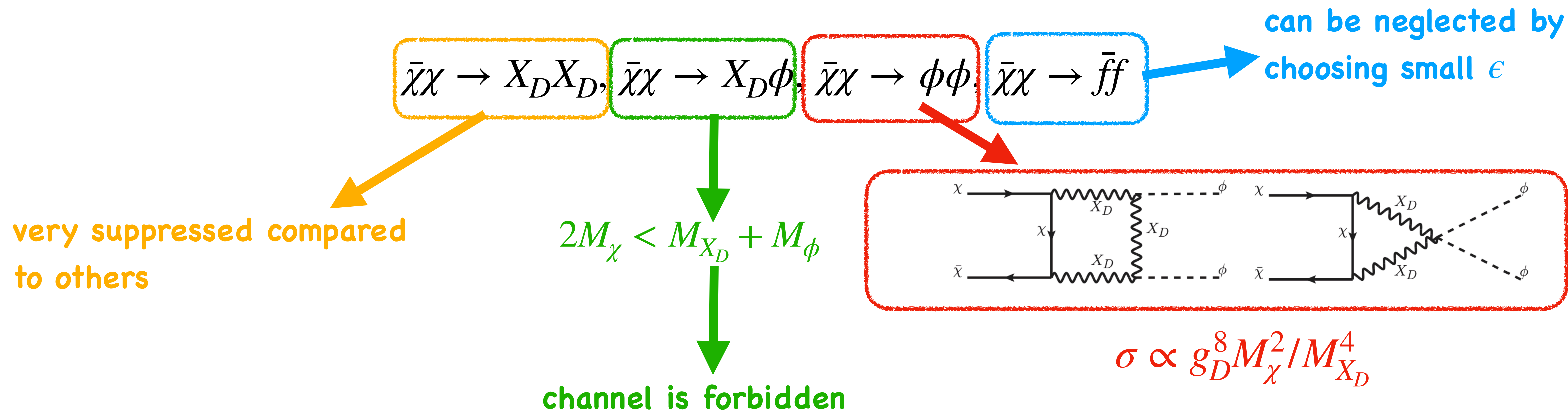
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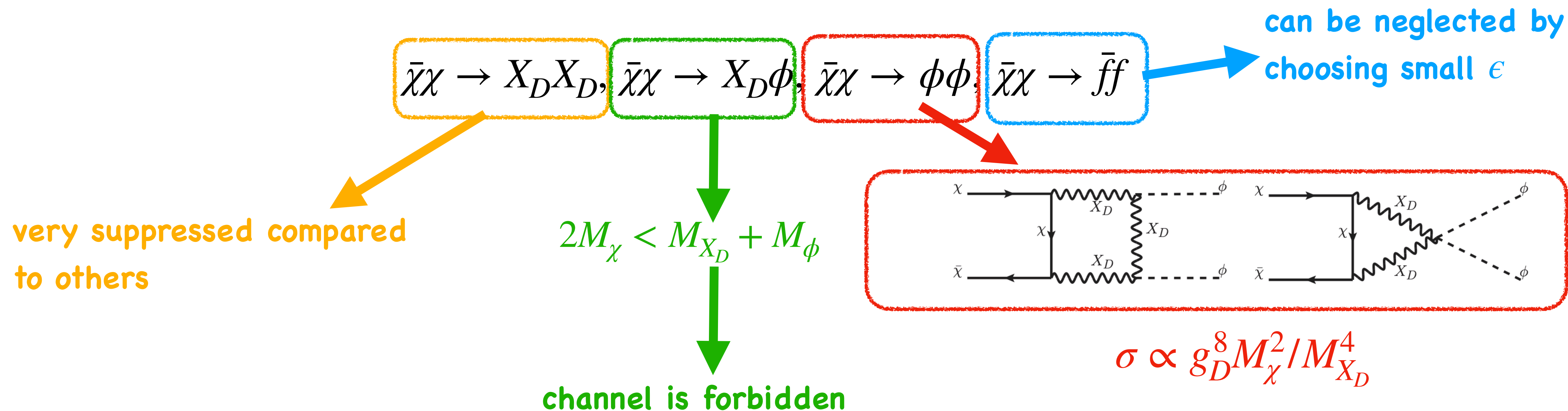


$$\sigma \propto g_D^8 M_\chi^2 / M_{X_D}^4$$

Forbidden DM from FOPT

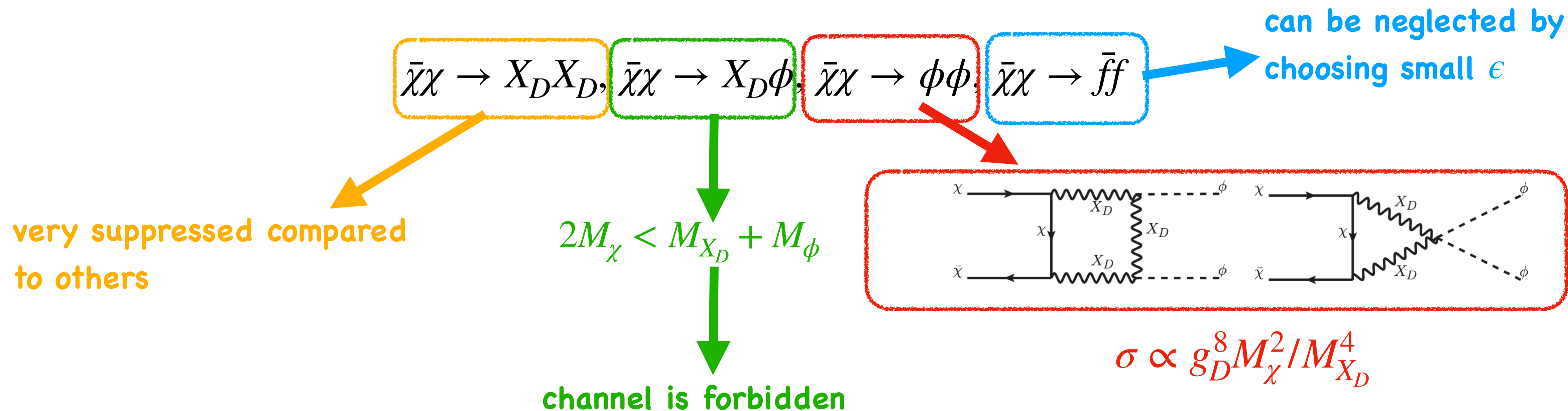


Forbidden DM from FOPT



Case-1: $\bar{\chi}\chi \rightarrow X_D \phi$ is forbidden $\bar{\chi}\chi \rightarrow \phi\phi$ is allowed

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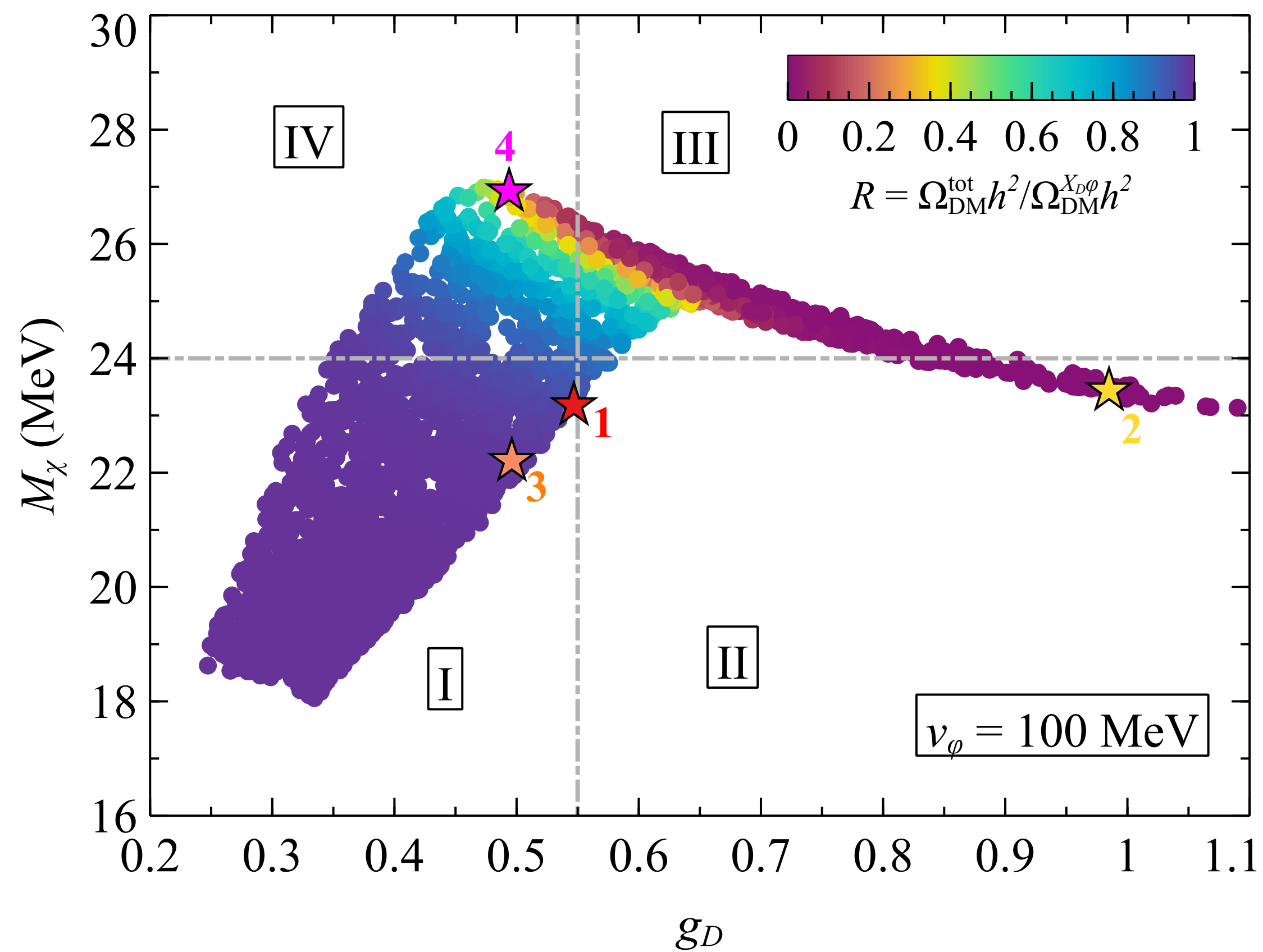
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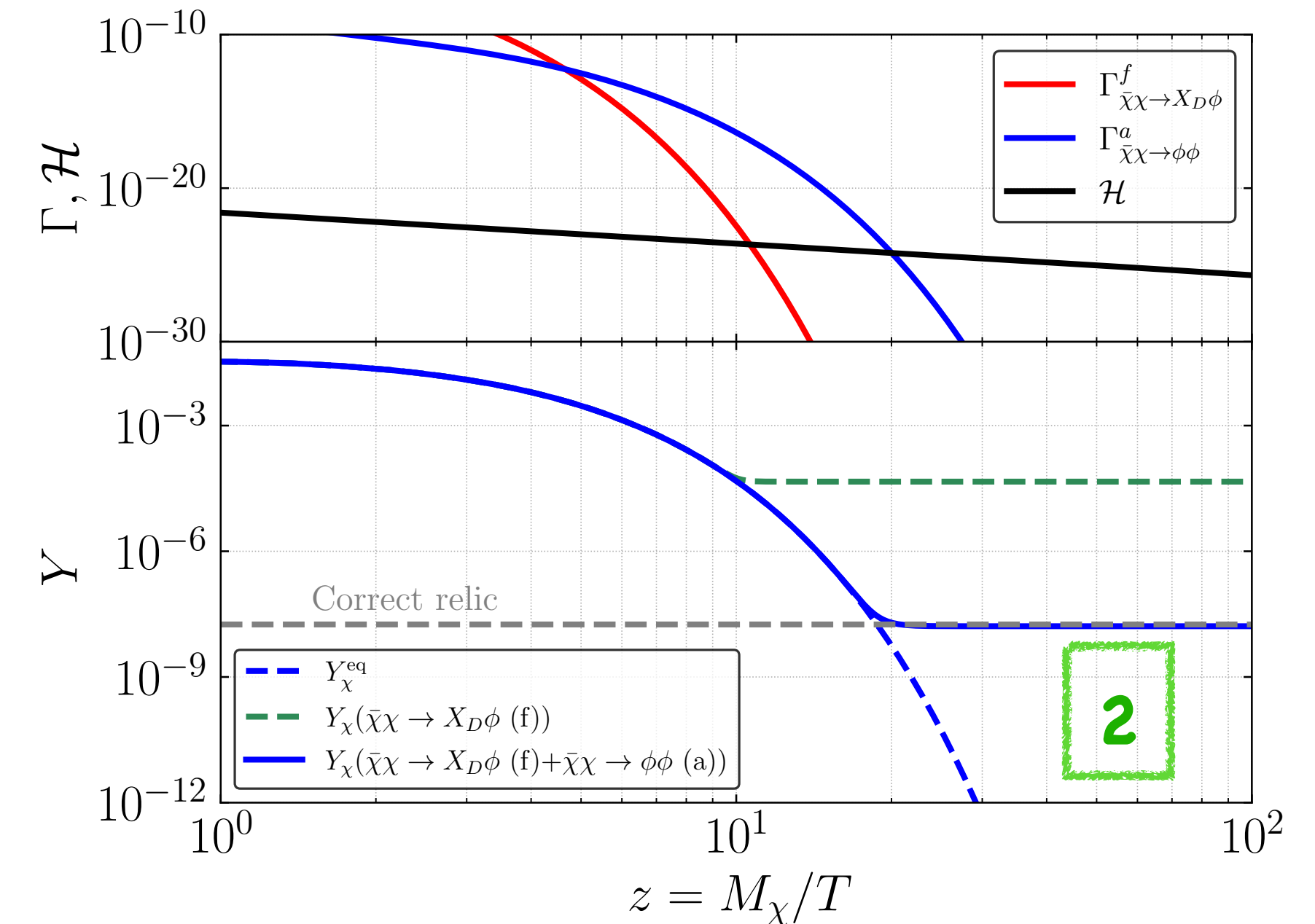
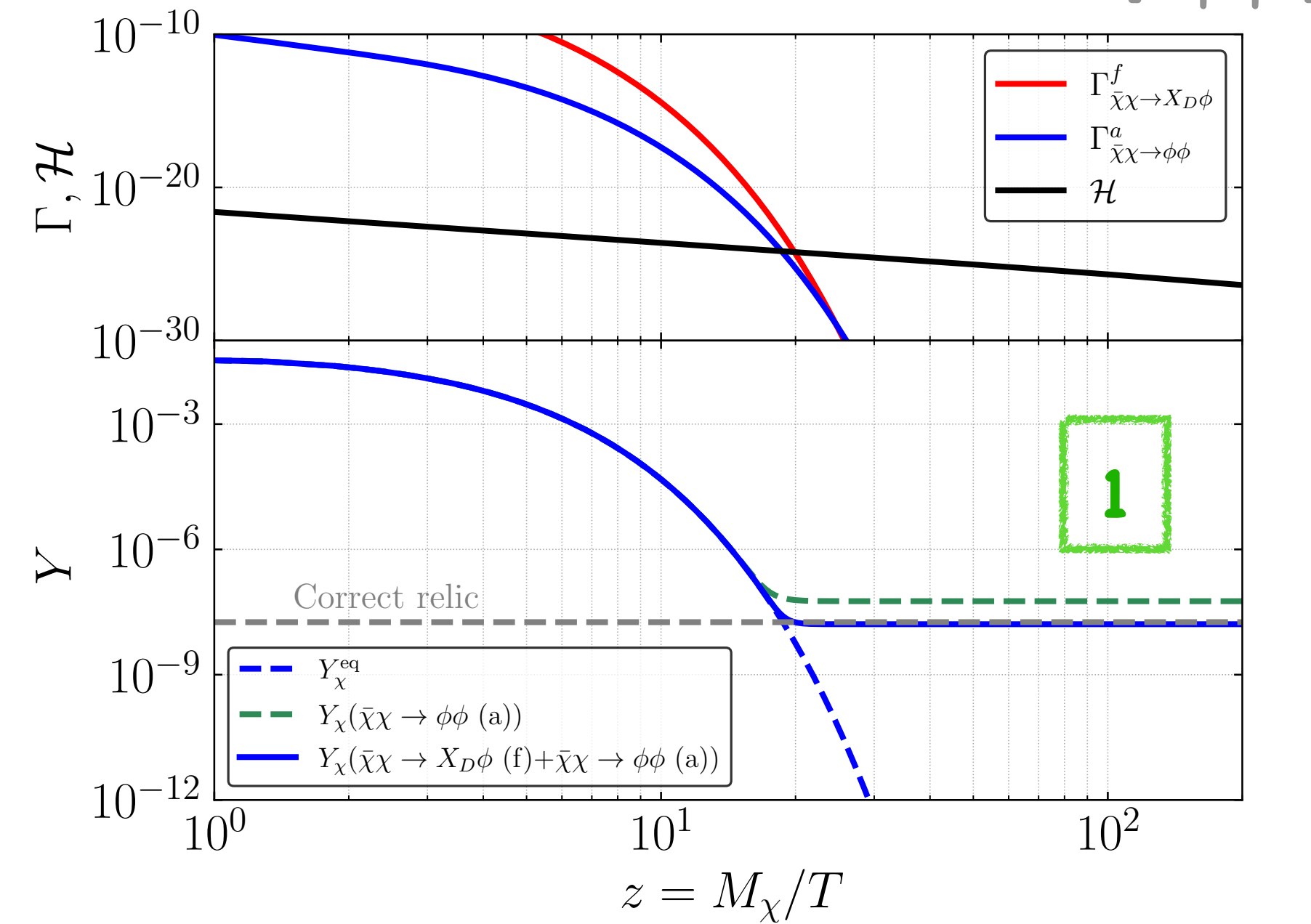
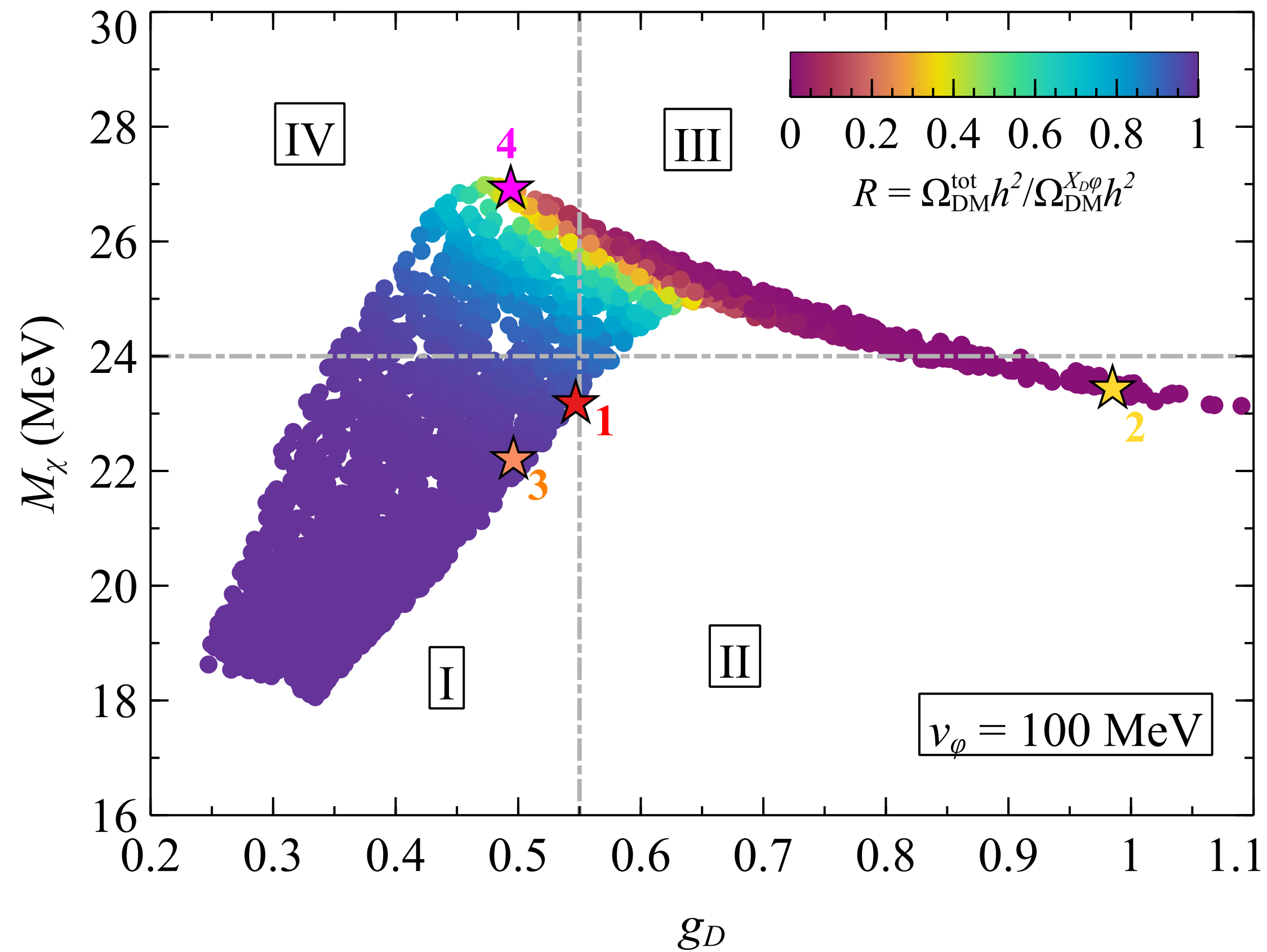
$\frac{n_\chi}{s}$ (green arrow pointing to dY_χ)
 $\frac{M_\chi}{T}$ (blue arrow pointing to dz)



Case-1: $\bar{\chi}\chi \rightarrow X_D\phi$ is forbidden $\bar{\chi}\chi \rightarrow \phi\phi$ is allowed

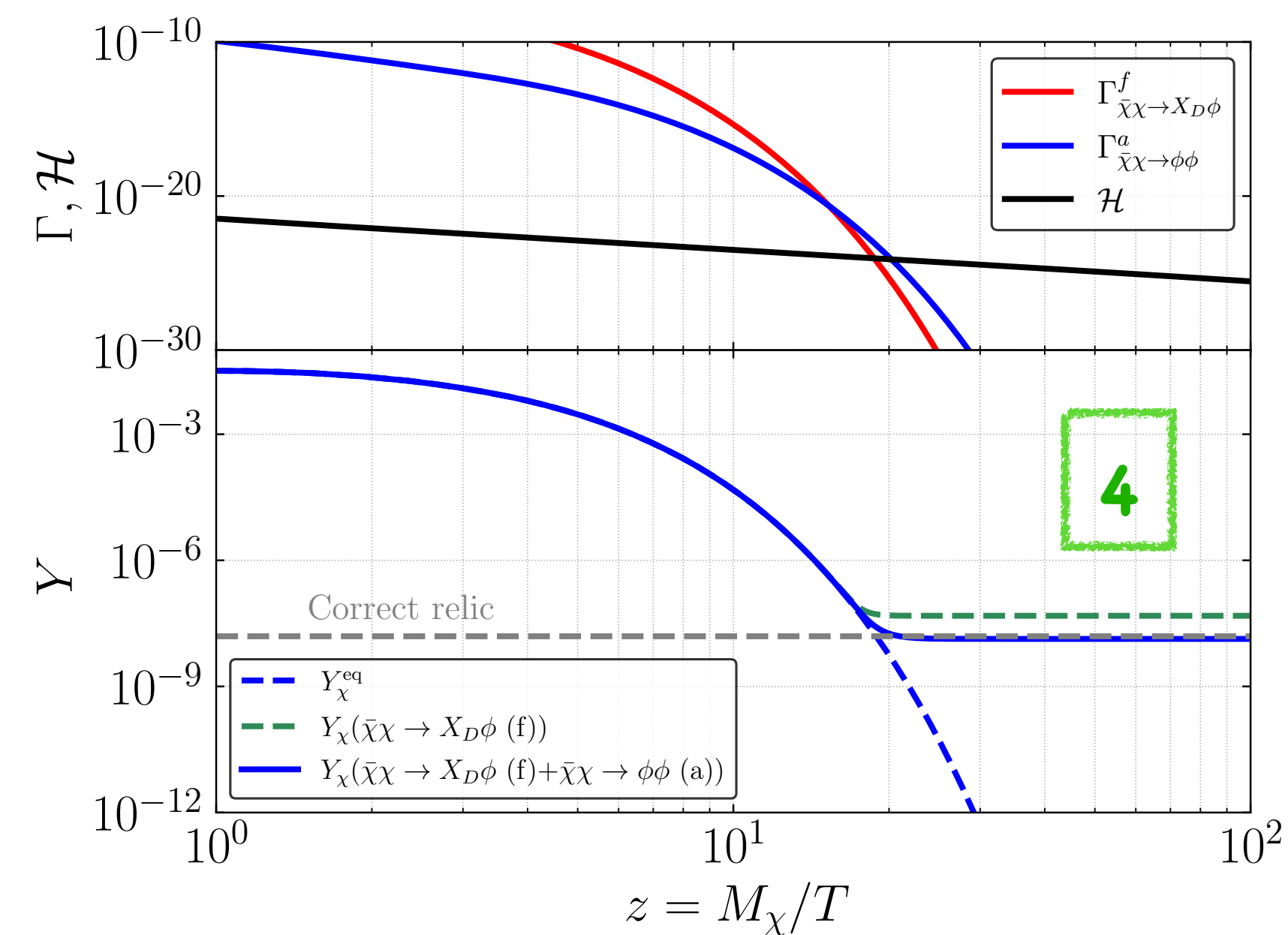
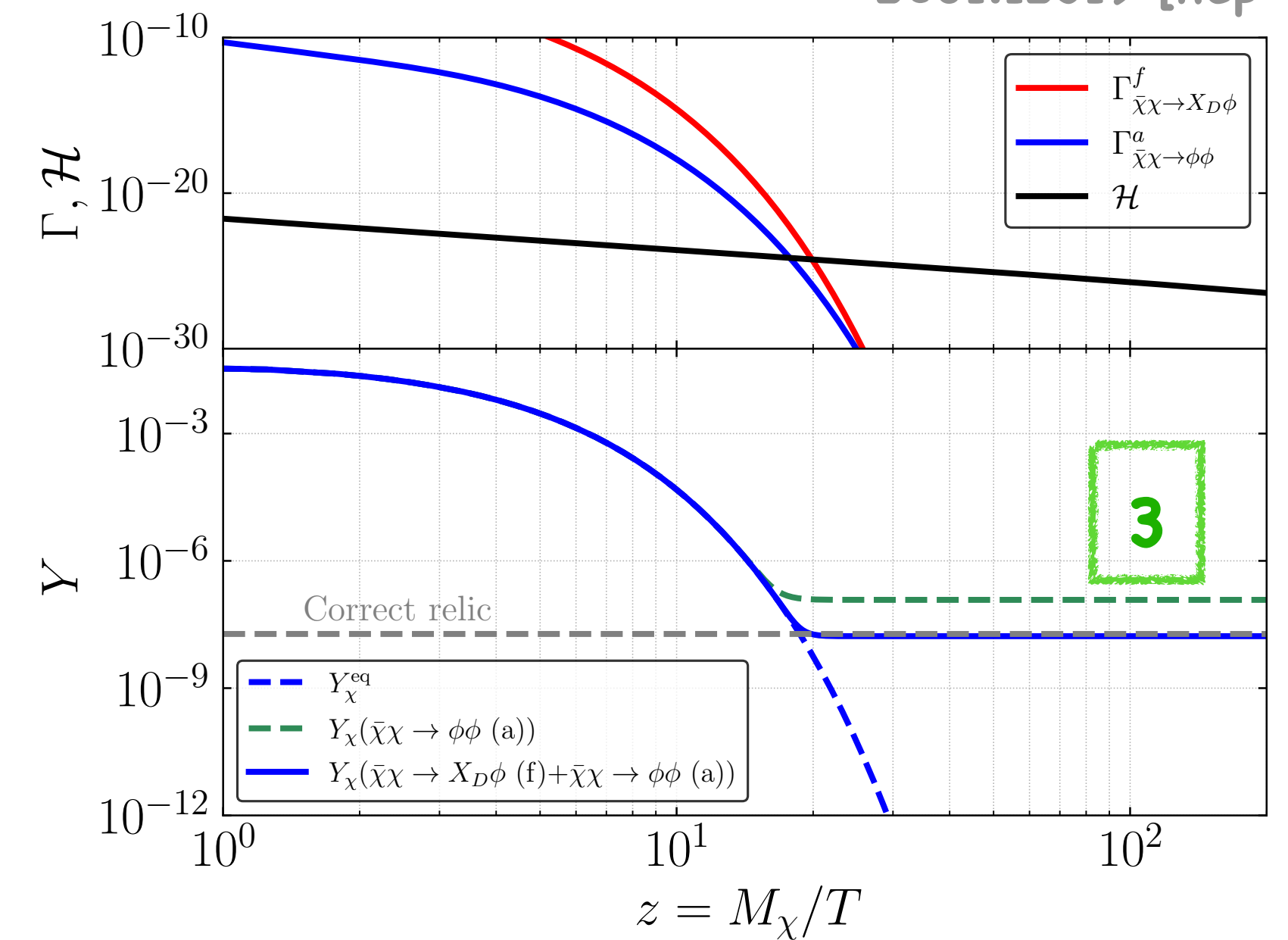
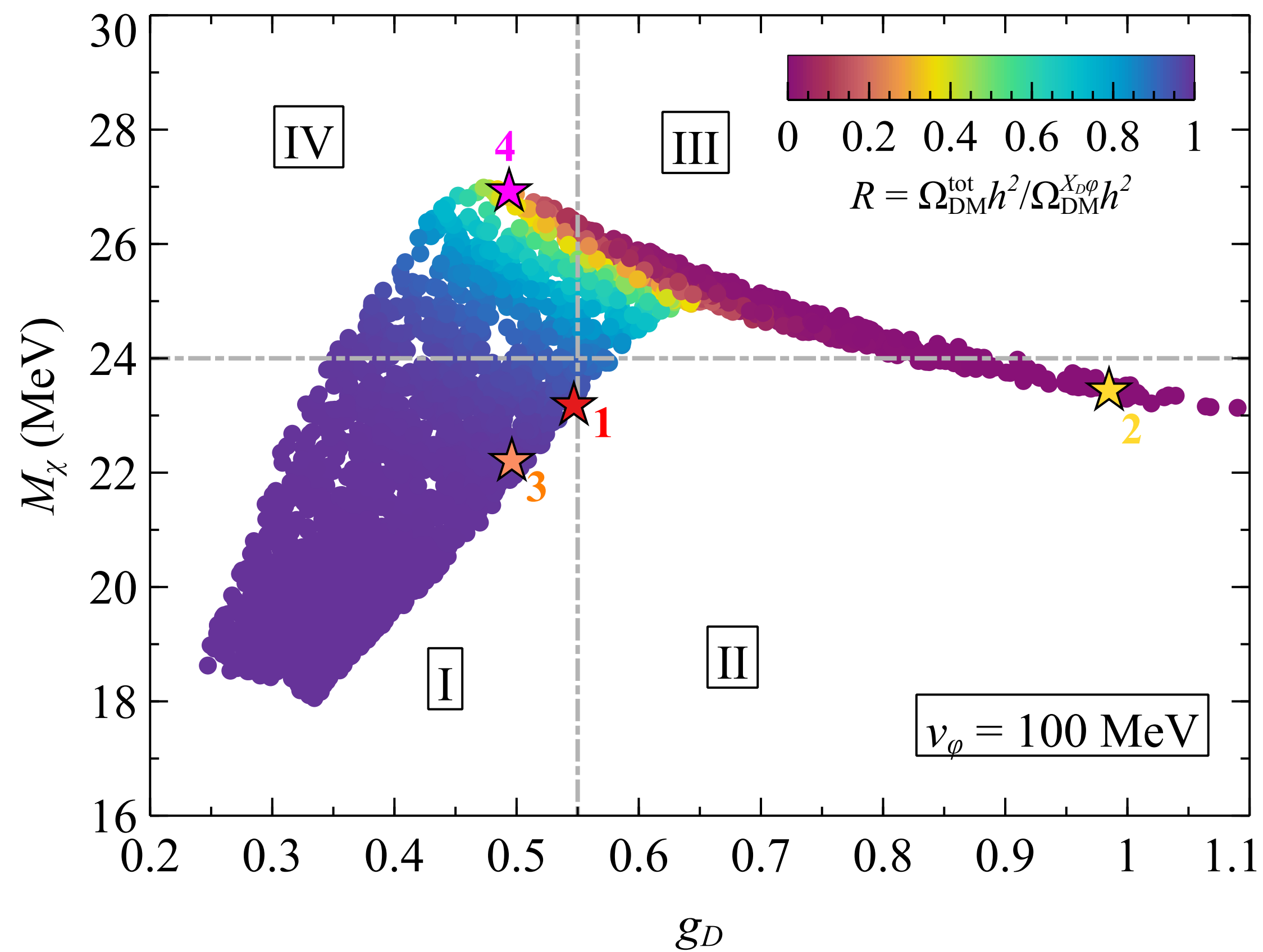
$$\frac{dY_\chi}{dz} = -\frac{sZ}{\mathcal{H}(M_\chi)} \left(\langle\sigma v\rangle_{\bar{\chi}\chi \rightarrow X_D\phi}^f + \langle\sigma v\rangle_{\bar{\chi}\chi \rightarrow \phi\phi}^a \right) \left(Y_\chi^2 - (Y_\chi^{eq})^2 \right)$$

$\frac{M_\chi}{T}$ (blue arrow pointing to dz)
 $\frac{n_\chi}{s}$ (green arrow pointing to Y_χ)



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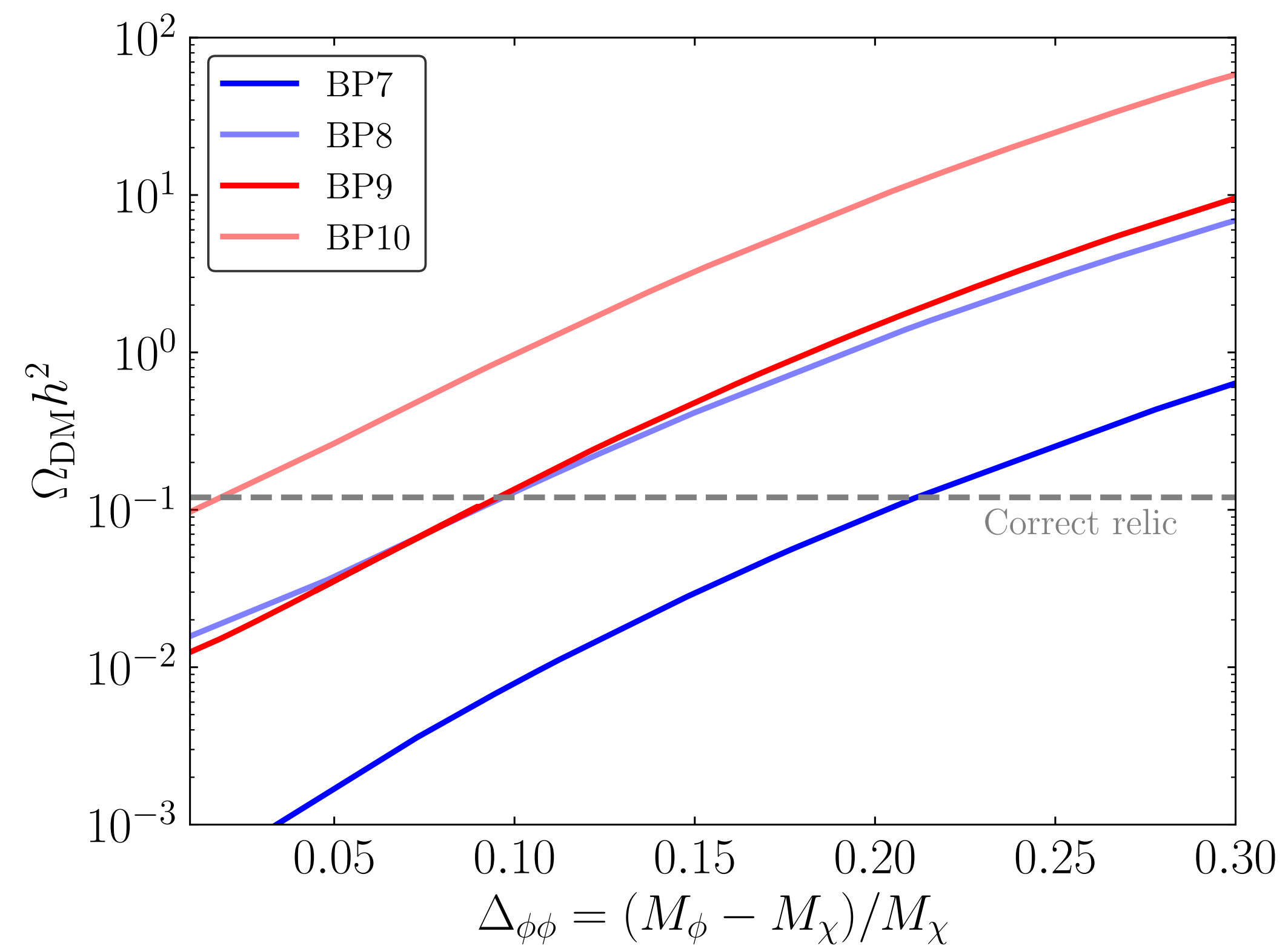
Case-2: $\bar{\chi}\chi \rightarrow X_D\phi$ is forbidden $\bar{\chi}\chi \rightarrow \phi\phi$ is forbidden

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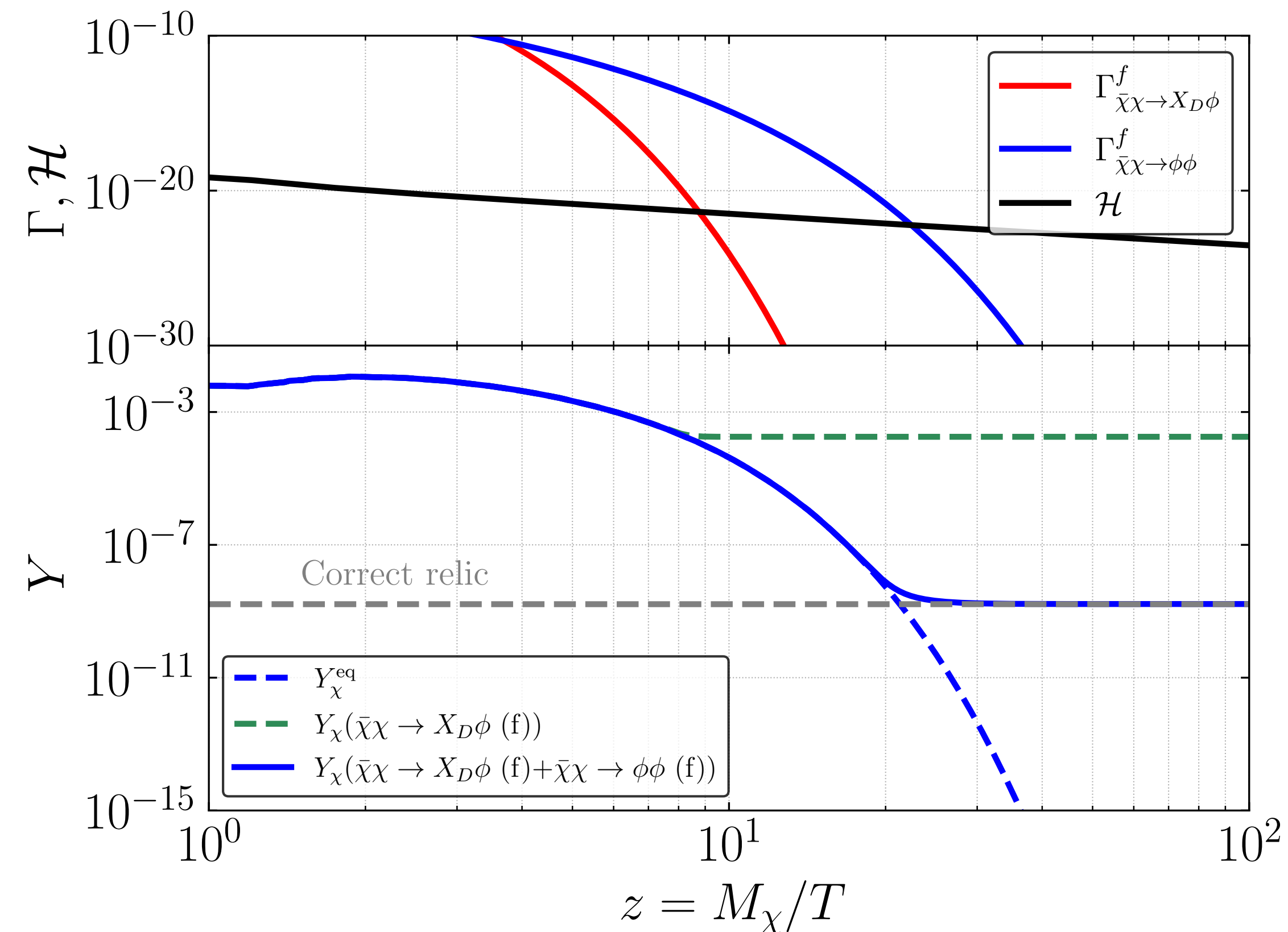
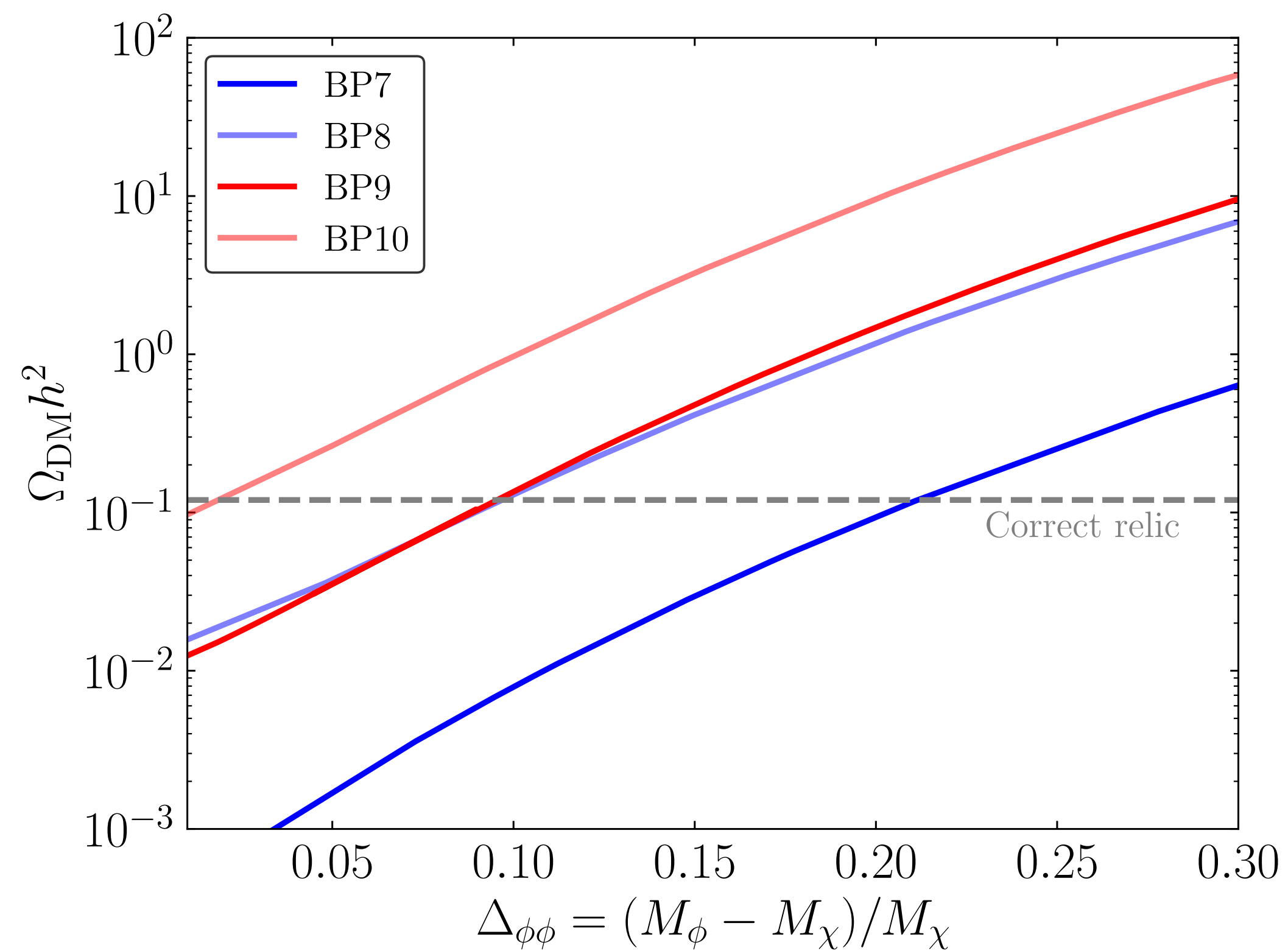
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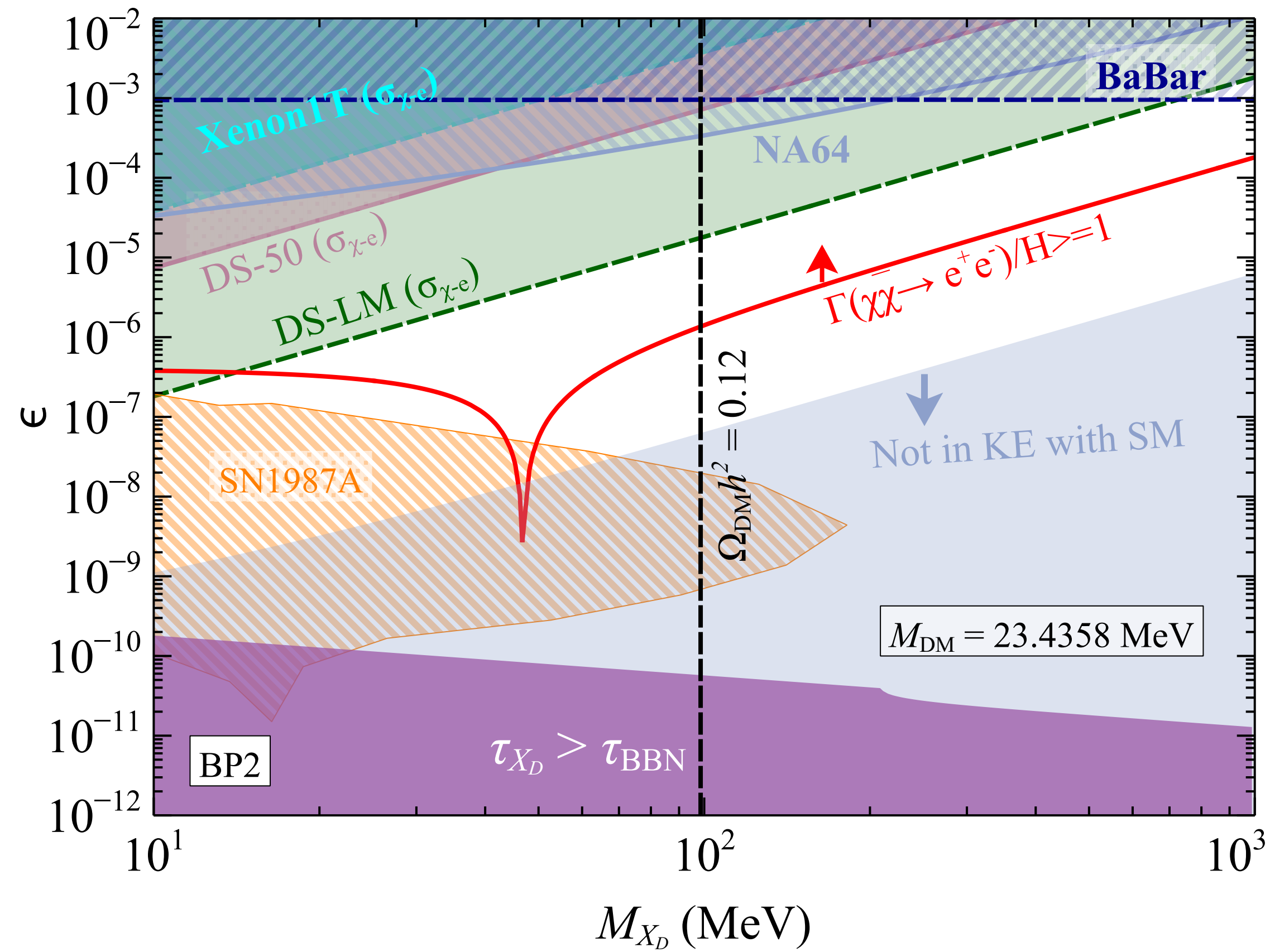


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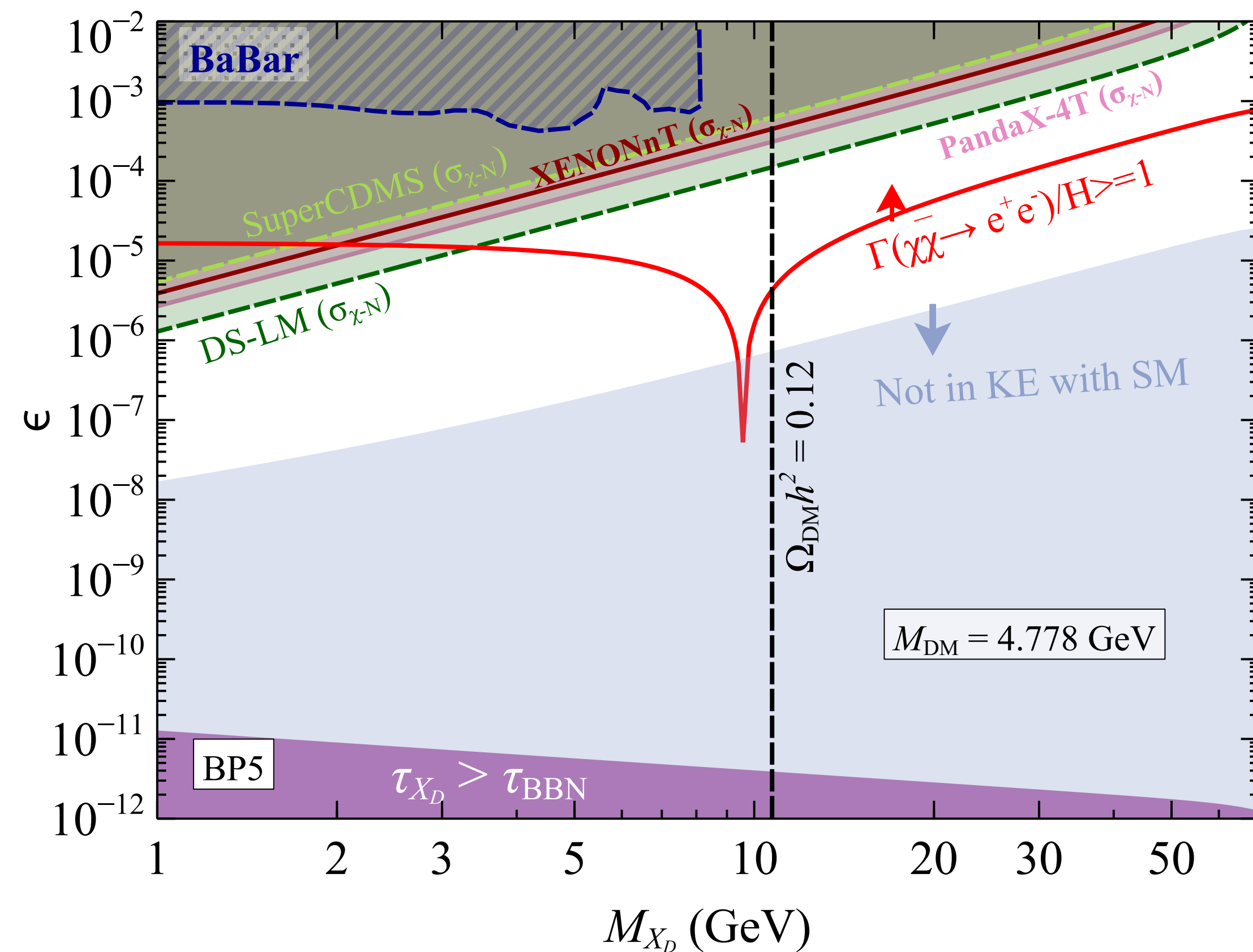
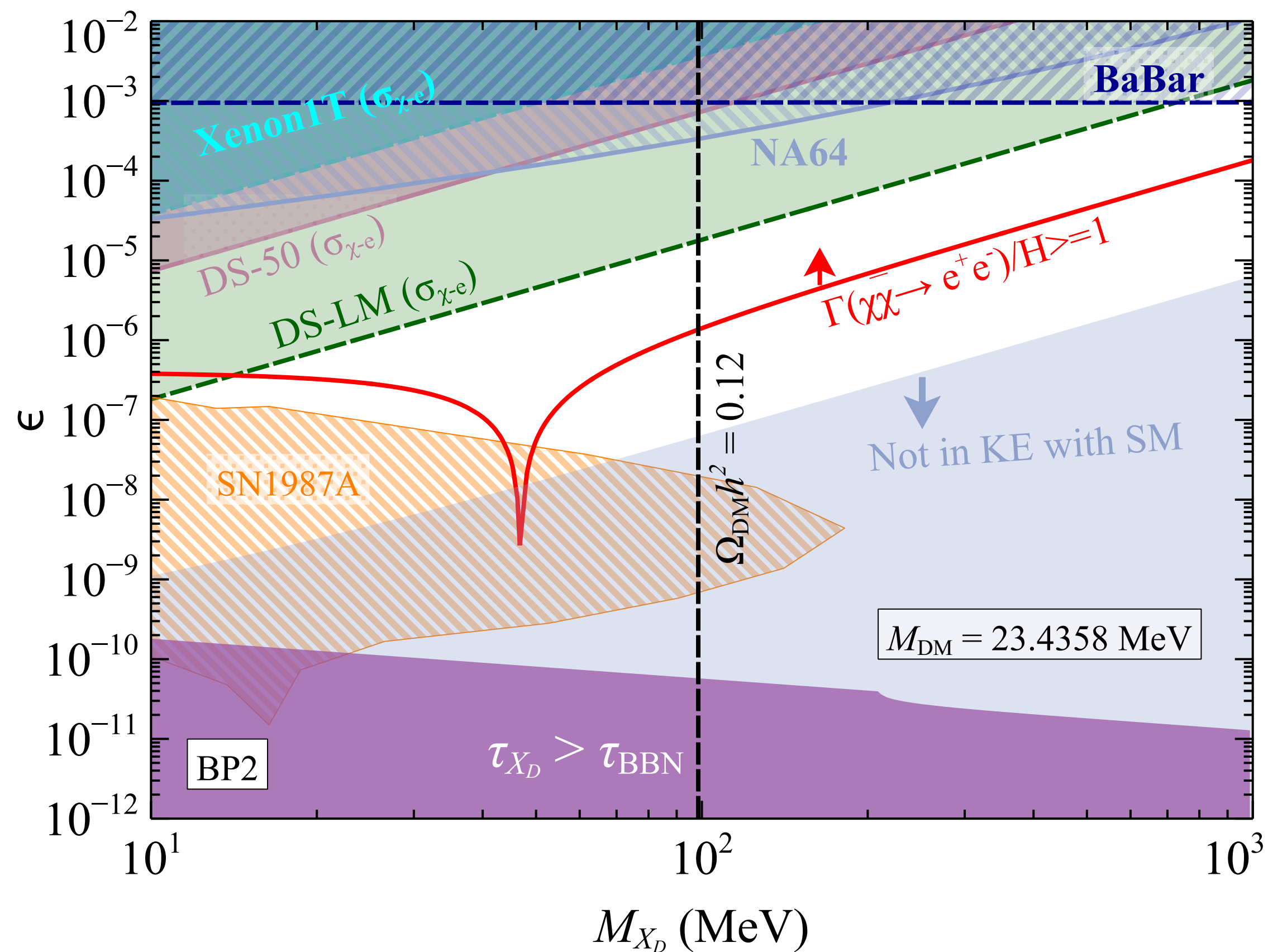
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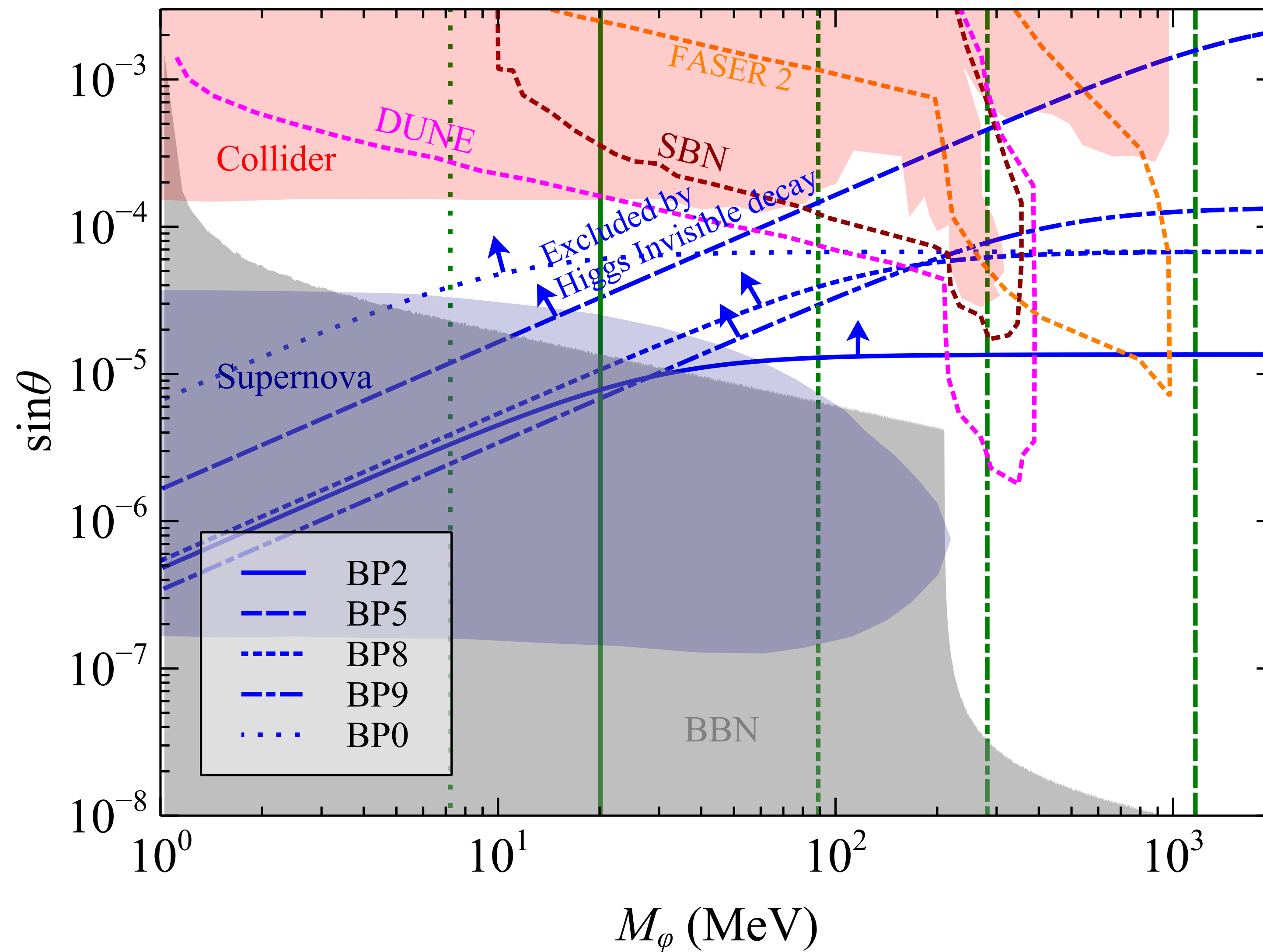
Parameter space



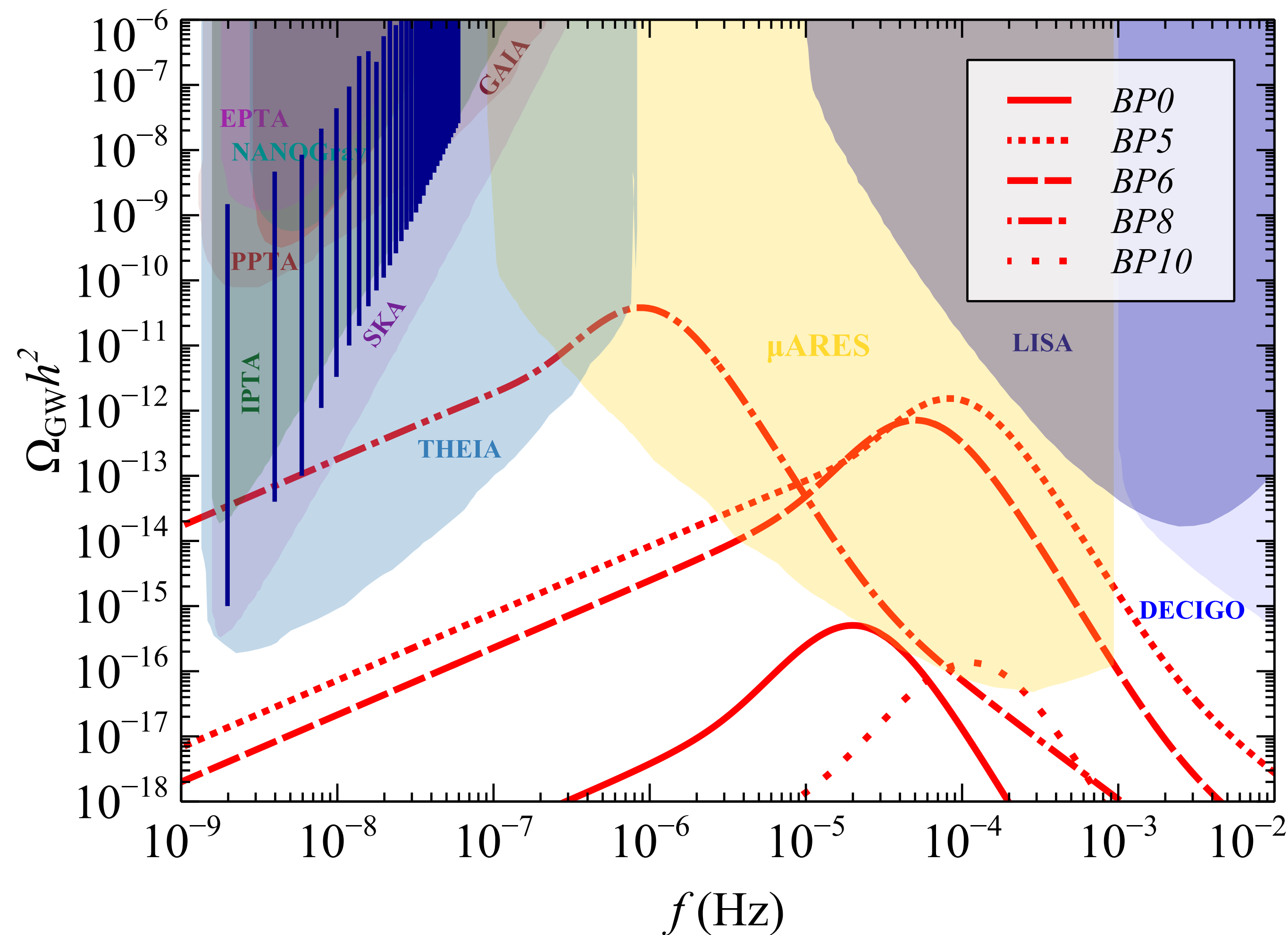
Parameter space



Constraints from scalar sector



Gravitational waves from dark sector FOPT



$$BP0 : T_n = 35.43 \text{ MeV}, M_\chi = 42.33 \text{ MeV}$$

$$BP8 : T_n = 71.69 \text{ MeV}, M_\chi = 81 \text{ MeV}$$

$$BP5 : T_n = 1.144 \text{ GeV}, M_\chi = 4.779 \text{ GeV}$$

$$BP10 : T_n = 1.869 \text{ GeV}, M_\chi = 1.768 \text{ GeV}$$

$$BP6 : T_n = 3.046 \text{ GeV}, M_\chi = 7.912 \text{ GeV}$$

Summary

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Thank you!

Backups

BP_s	$M_\chi(\text{MeV})$	$M_{X_D}(\text{MeV})$	$M_\phi(\text{MeV})$	λ_Φ	$v_\phi(\text{MeV})$	g_D	$T_c(\text{MeV})$	$T_n(\text{MeV})$
BP_0	42.326	112.059	7.222	0.000104	500	0.2241	52.0094	35.432
BP_1	23.1786	54.6895	5.840255	0.0017054	100	0.546895	17.41913	1.516388
BP_2	23.4358	98.49544	20.120645	0.02024	100	0.984954	35.27115	24.25950
BP_3	22.2034	49.60992	6.094203	0.00185696	100	0.496099	20.237876	13.308489
BP_4	26.919842	49.387419	26.60985	0.03540420	100	0.493874198	75.08041	74.9224079
BP_5	4778.9589	10713.3738	1164.1505	0.001694	20000	0.5356686	3564.6272	1143.8917
BP_6	7912.7921	19649.45091	3751.20211	0.017589	20000	0.98247254	6535.093	3046.63690
BP_7	30.53	145.41	36.96	0.06829	100	1.4541	47.3661	24.4982
BP_8	81	479.225	88.869	0.015796	500	0.95845	158.0208	71.6957
BP_9	257.181	1226.57	281.545	0.039634	1000	1.22657	408.497	241.9205
BP_{10}	1768.0408	6761.662	1792.5843	0.06426717	5000	1.35233	2453.449	1869.49