CLASSICAL SCALE INVARIANCE AS A SOURCE OF MASSES, DARK MATTER AND GRAVITATIONAL WAVES

Bogumiła Świeżewska
University of Warsaw

in collaboration with
Maciej Kierkla and Alexandros Karam,

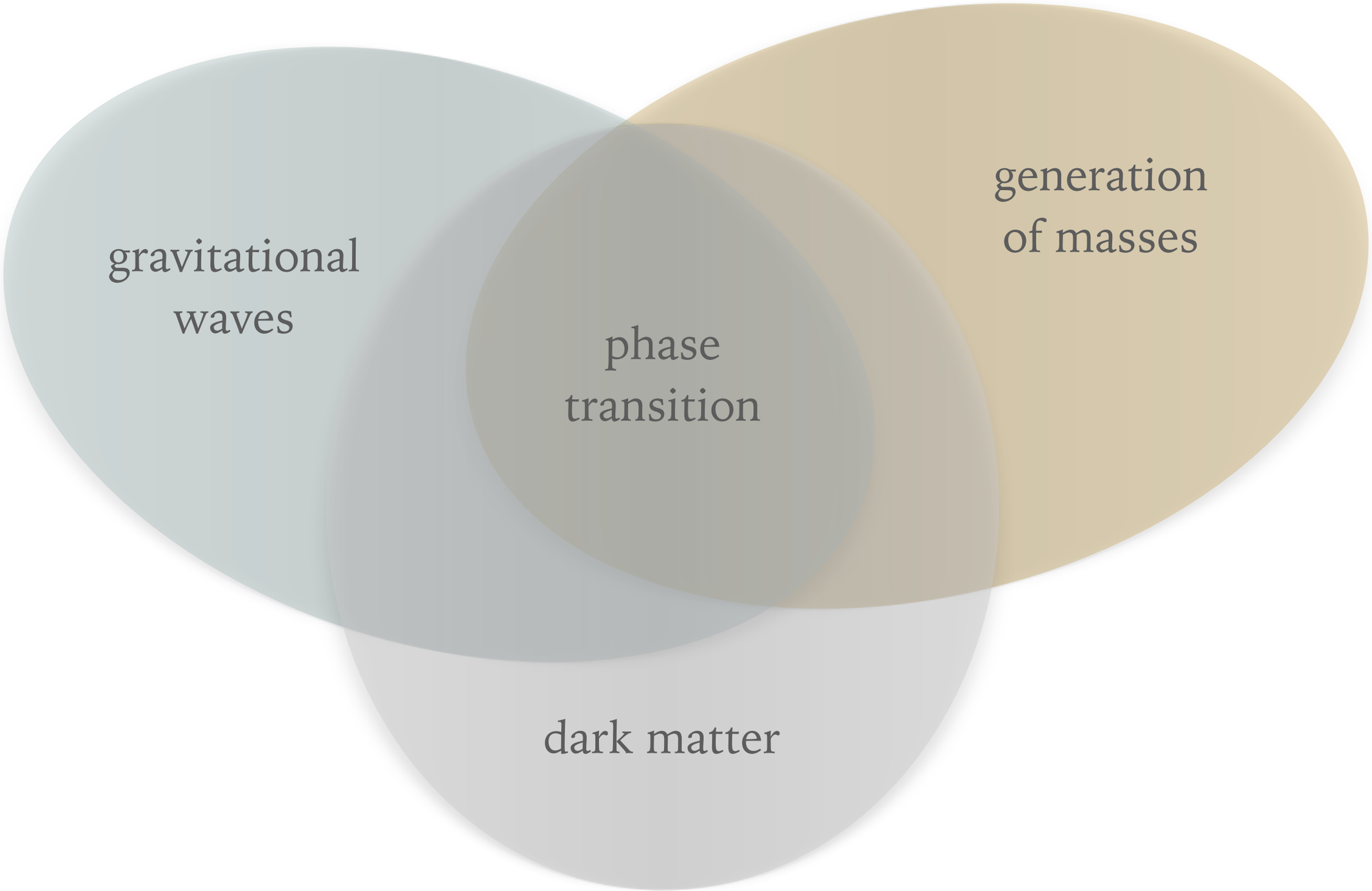
based on
arXiv:22xx.xxxx

Workshop on Multi-Higgs Models, 31.08.2022

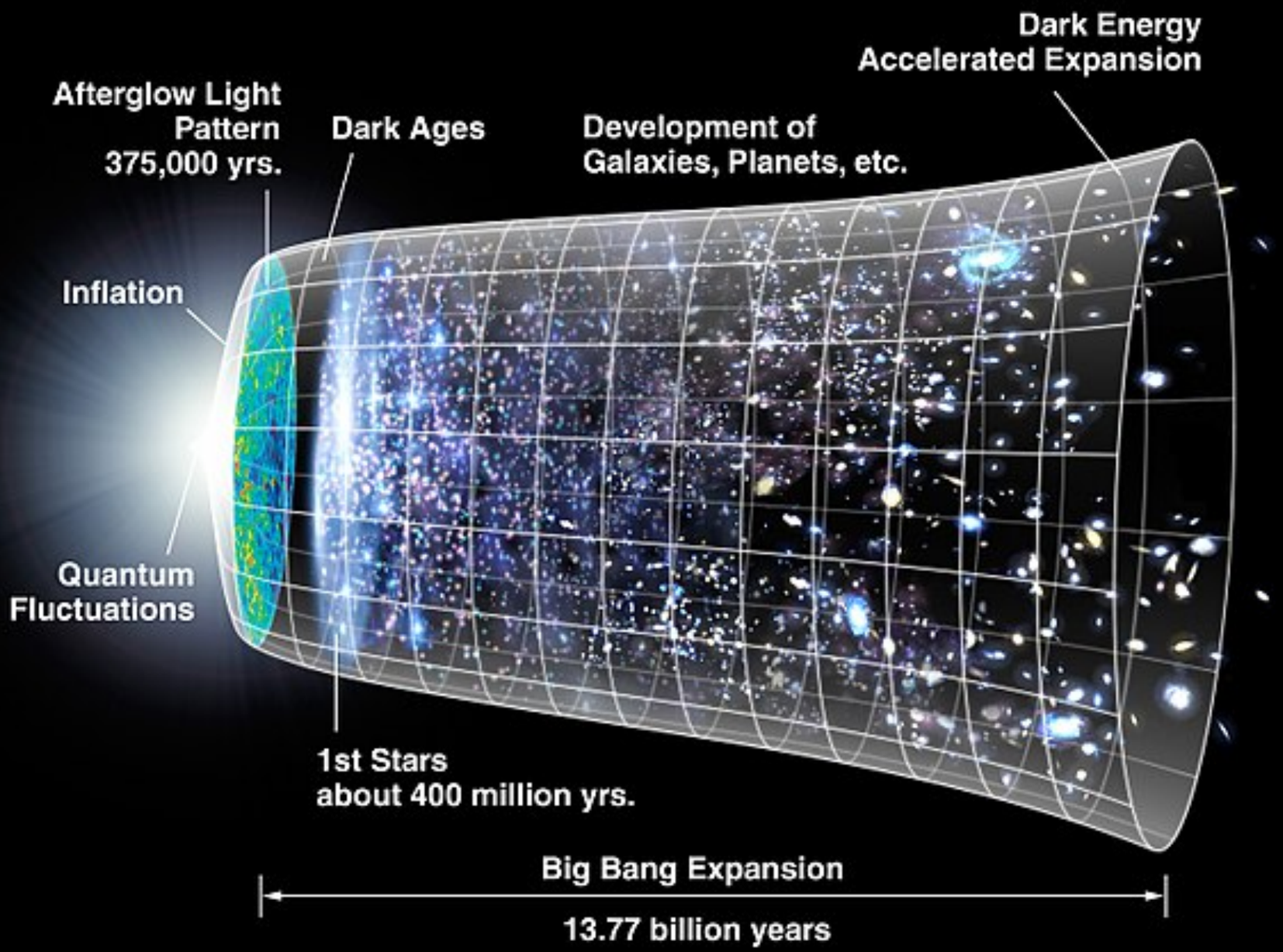
IN MEMORY OF PROFESSOR MARIA KRAWCZYK

MOTIVATION

PT - A LINK BETWEEN DIFFERENT OBSERVABLES



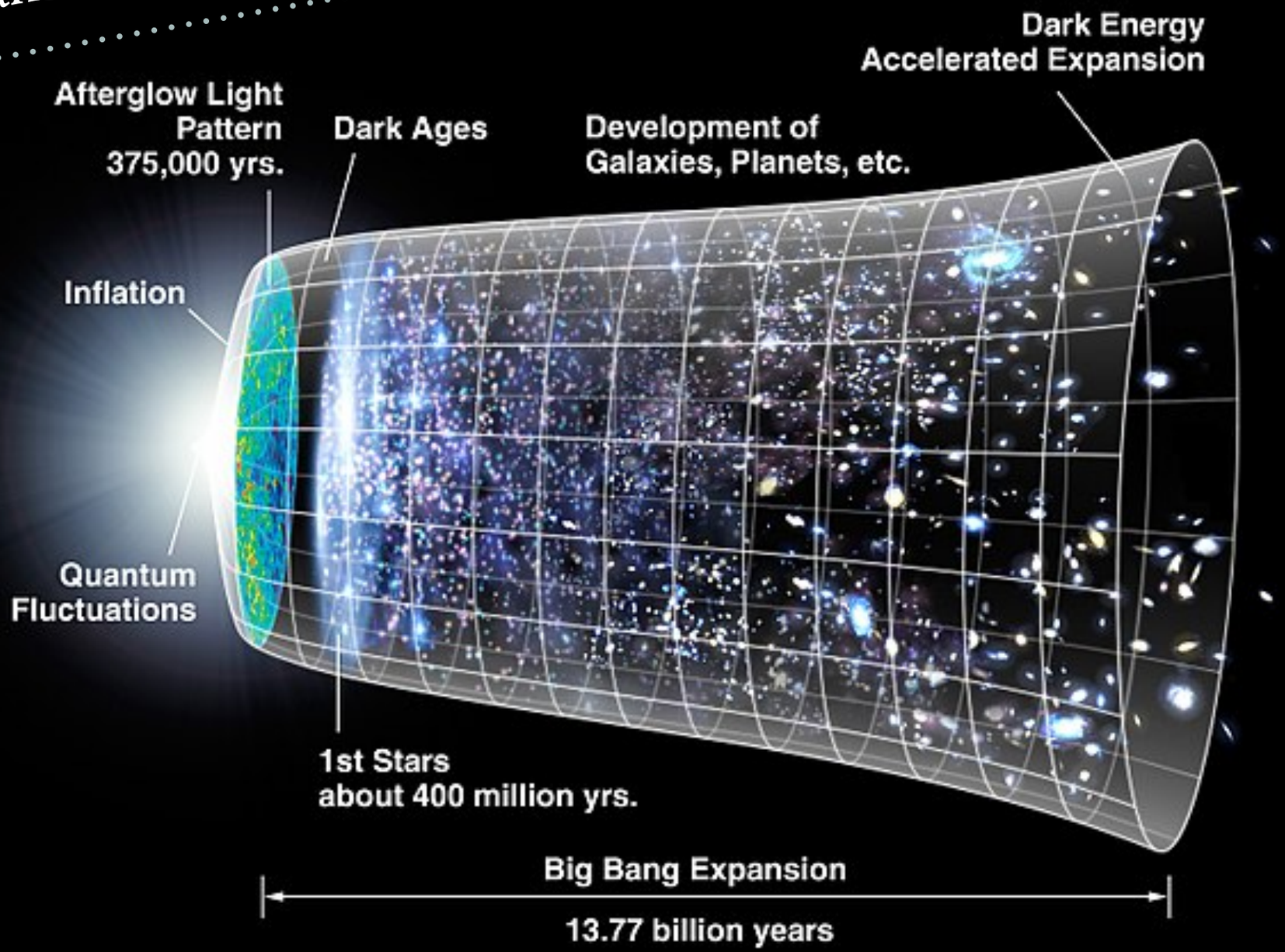
OBSERVING CHILDHOOD OF THE UNIVERSE?



[Image Credit: NASA]

OBSERVING CHILDHOOD OF THE UNIVERSE?

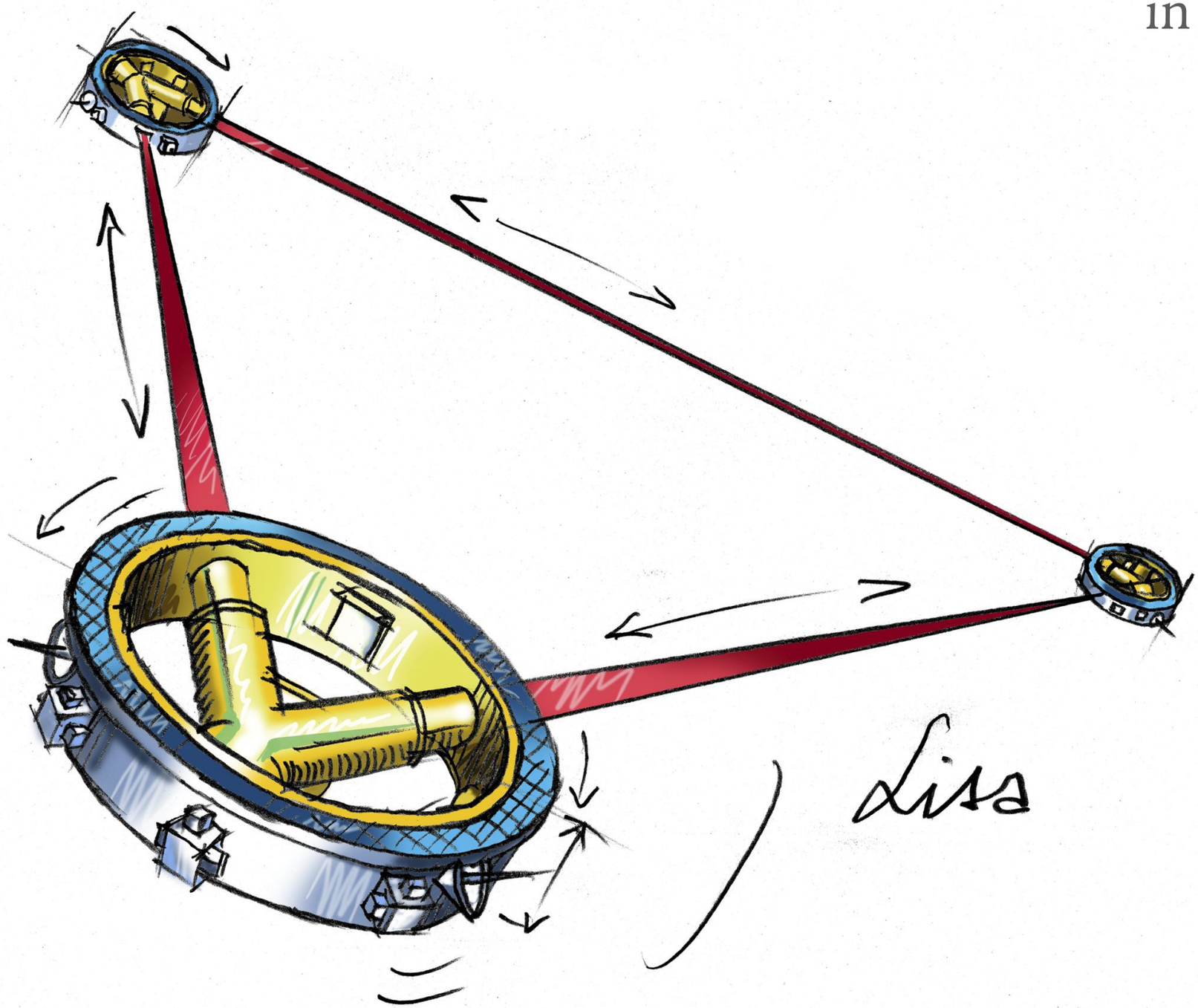
phase transition $\sim 10^{-11}$ s



[Image Credit: NASA]

LISA IS COMING!

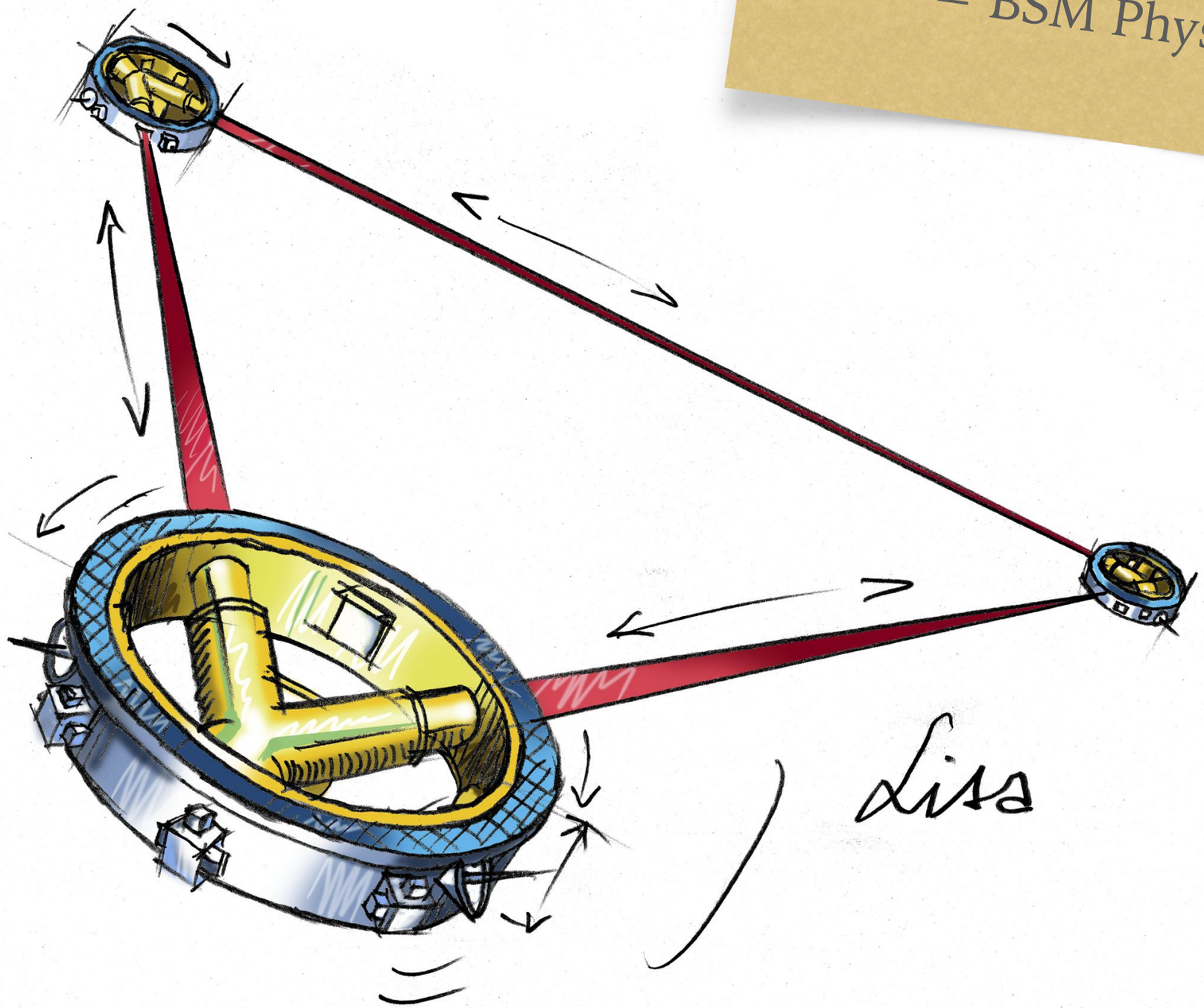
in the 2030's



[Image credit: ESA-C. Vijoux]

LISA IS COMING!

First-order phase transition
= BSM Physics!

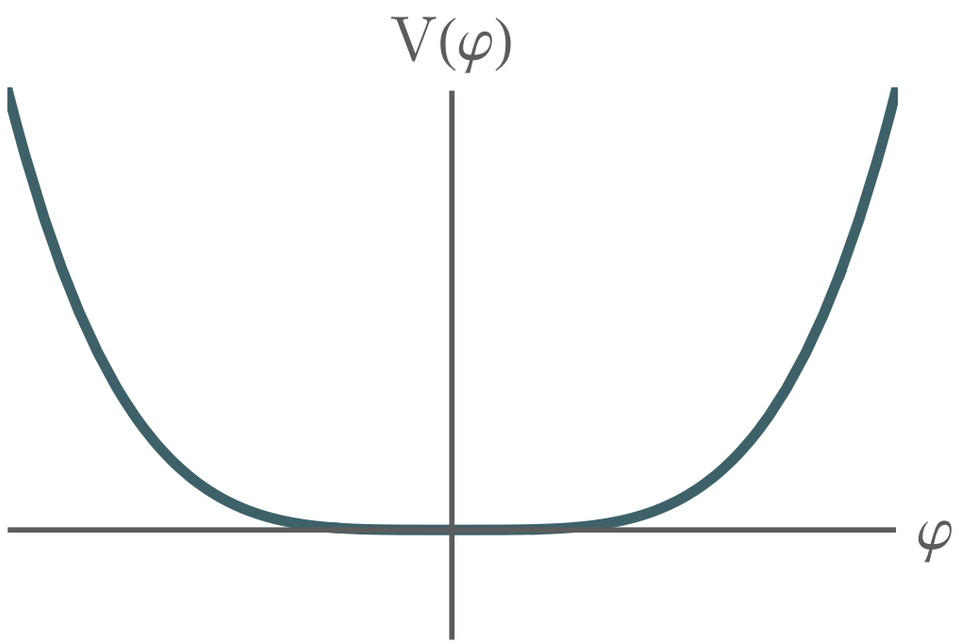


[Image credit: ESA-C. Vijoux]

CLASSICAL CONFORMAL SYMMETRY

CLASSICAL CONFORMAL SYMMETRY

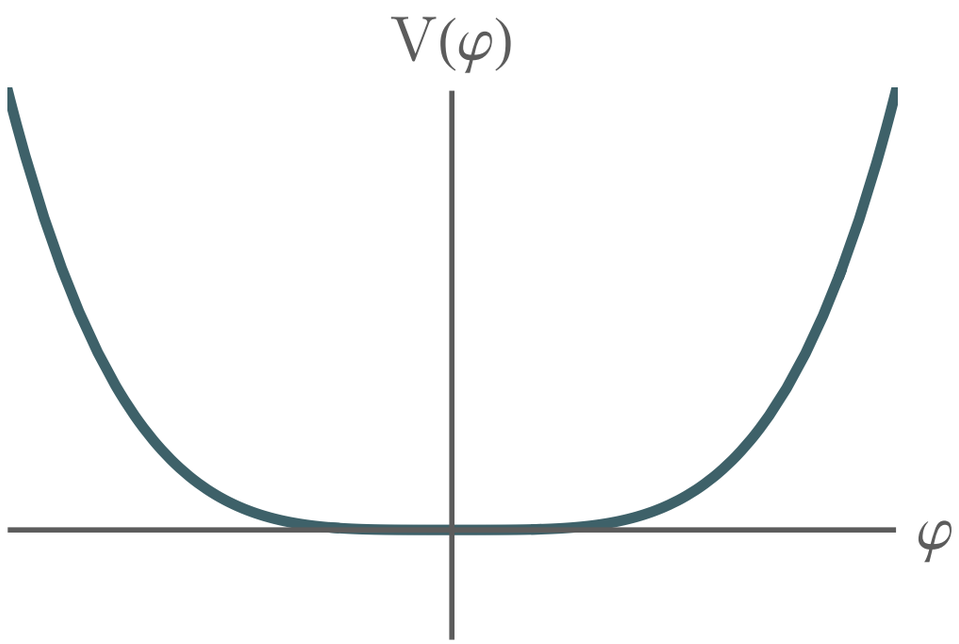
No dimensionful parameters at tree level

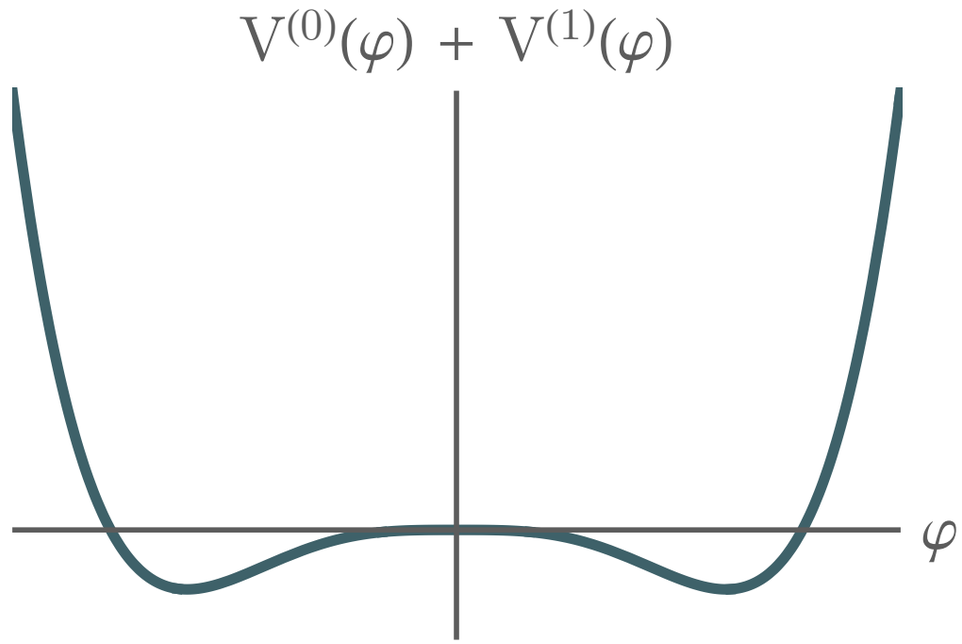


[S. R. Coleman, E. J. Weinberg, Phys.Rev. D7 (1973) 1888]

CLASSICAL CONFORMAL SYMMETRY

No dimensionful parameters at tree level





Symmetry broken by loop corrections (dimensional transmutation)

[S. R. Coleman, E. J. Weinberg, Phys.Rev. D7 (1973) 1888]

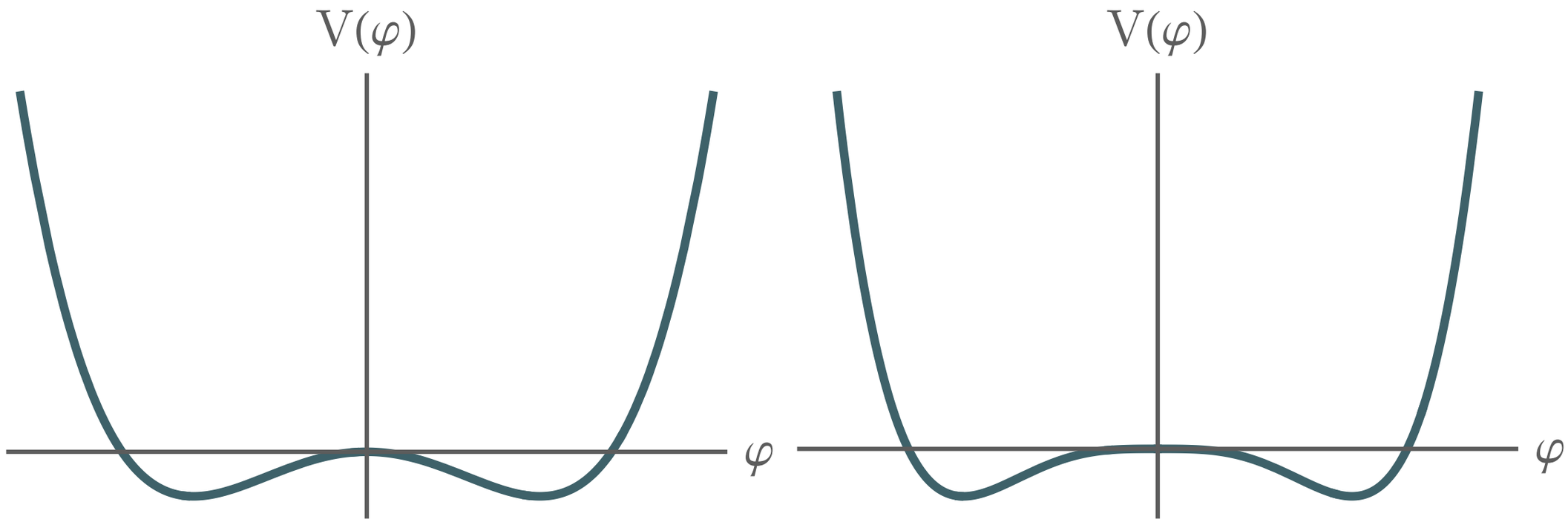
WHY CLASSICAL CONFORMAL SYMMETRY?

dynamical generation of all mass scales

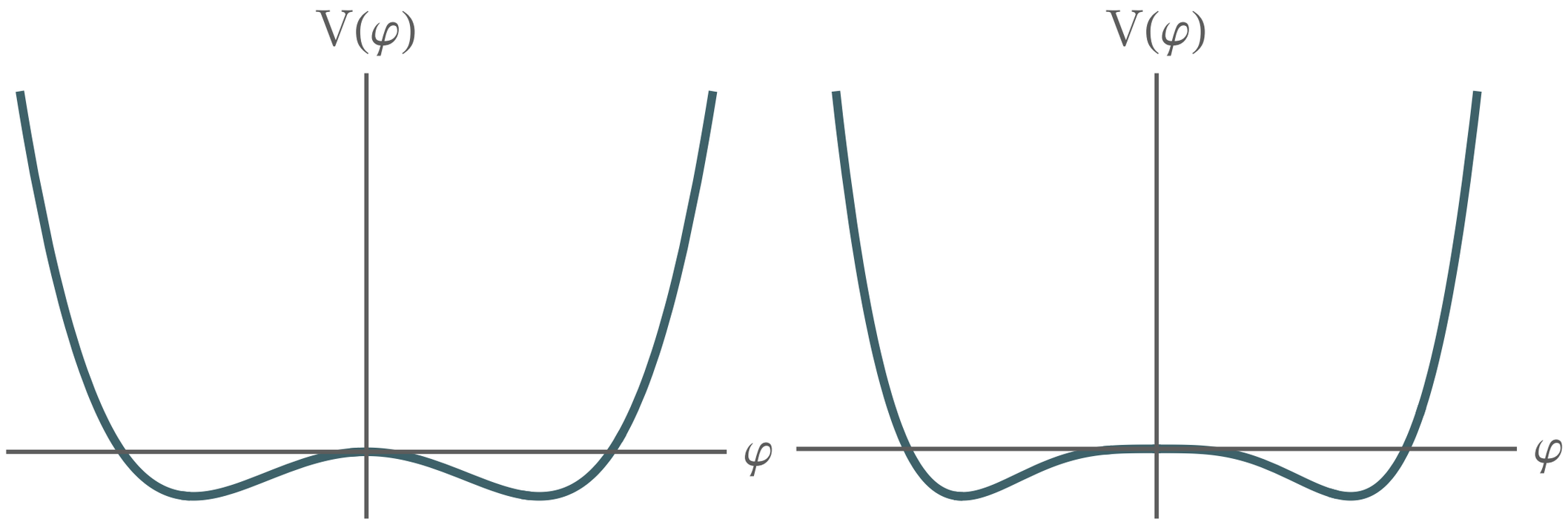
predictivity - few free parameters

Generically strong GW signal testable with LISA

CONFORMAL VS "NORMAL" POTENTIAL



CONFORMAL VS "NORMAL" POTENTIAL



The thermal barrier can last until low temperatures

↓

Potential for supercooling and strong transition

SU(2)CSM

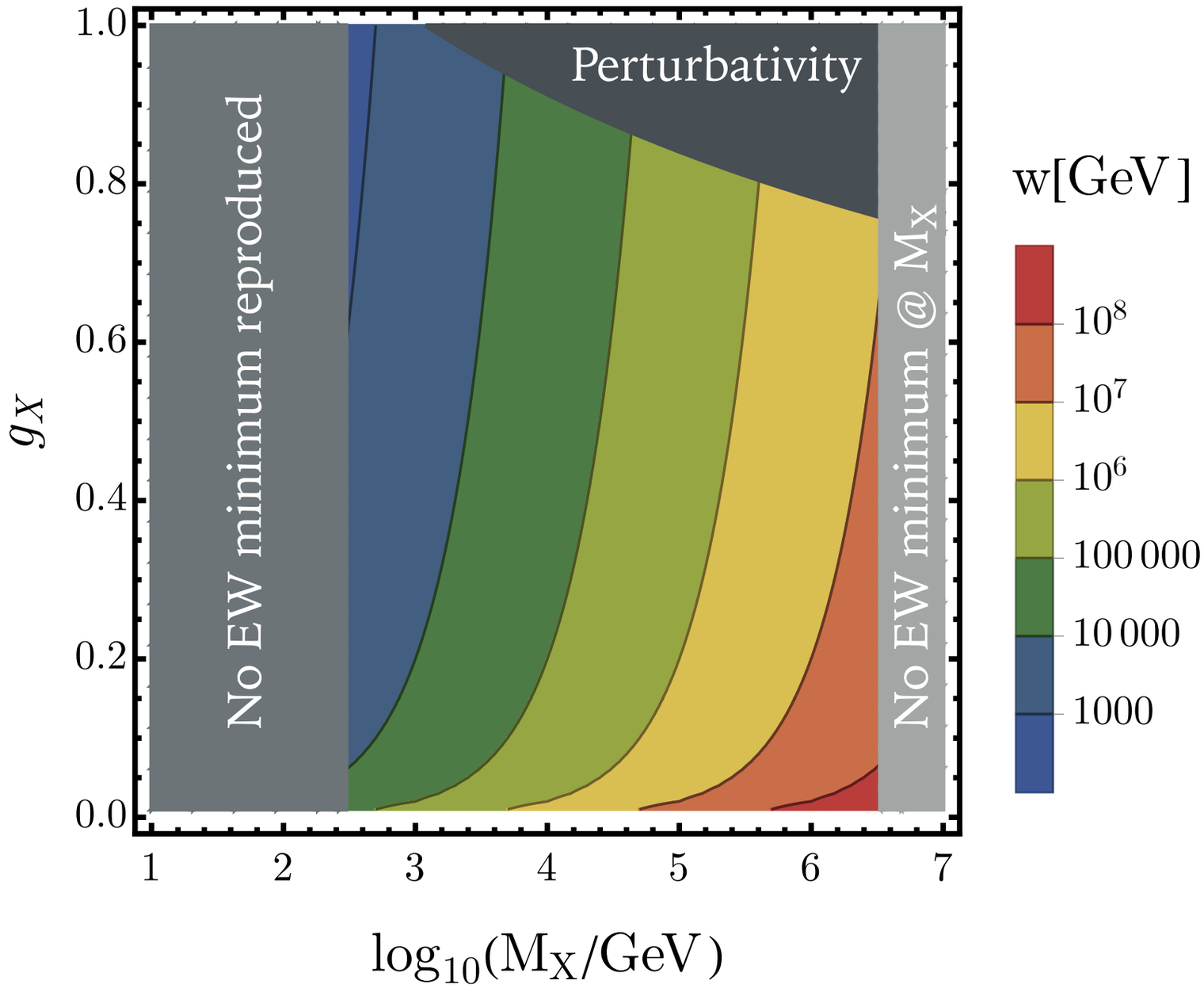
cSM:
$SU(2)_L \times U(1)_Y$
Φ

Hidden sector:
$SU(2)_X$
Ψ

$$V^{(0)}(\Phi,\Psi) = \lambda_1 \left(\Phi^\dagger\Phi\right)^2 + \lambda_2 \left(\Phi^\dagger\Phi\right)\left(\Psi^\dagger\Psi\right) + \lambda_3 \left(\Psi^\dagger\Psi\right)^2,$$

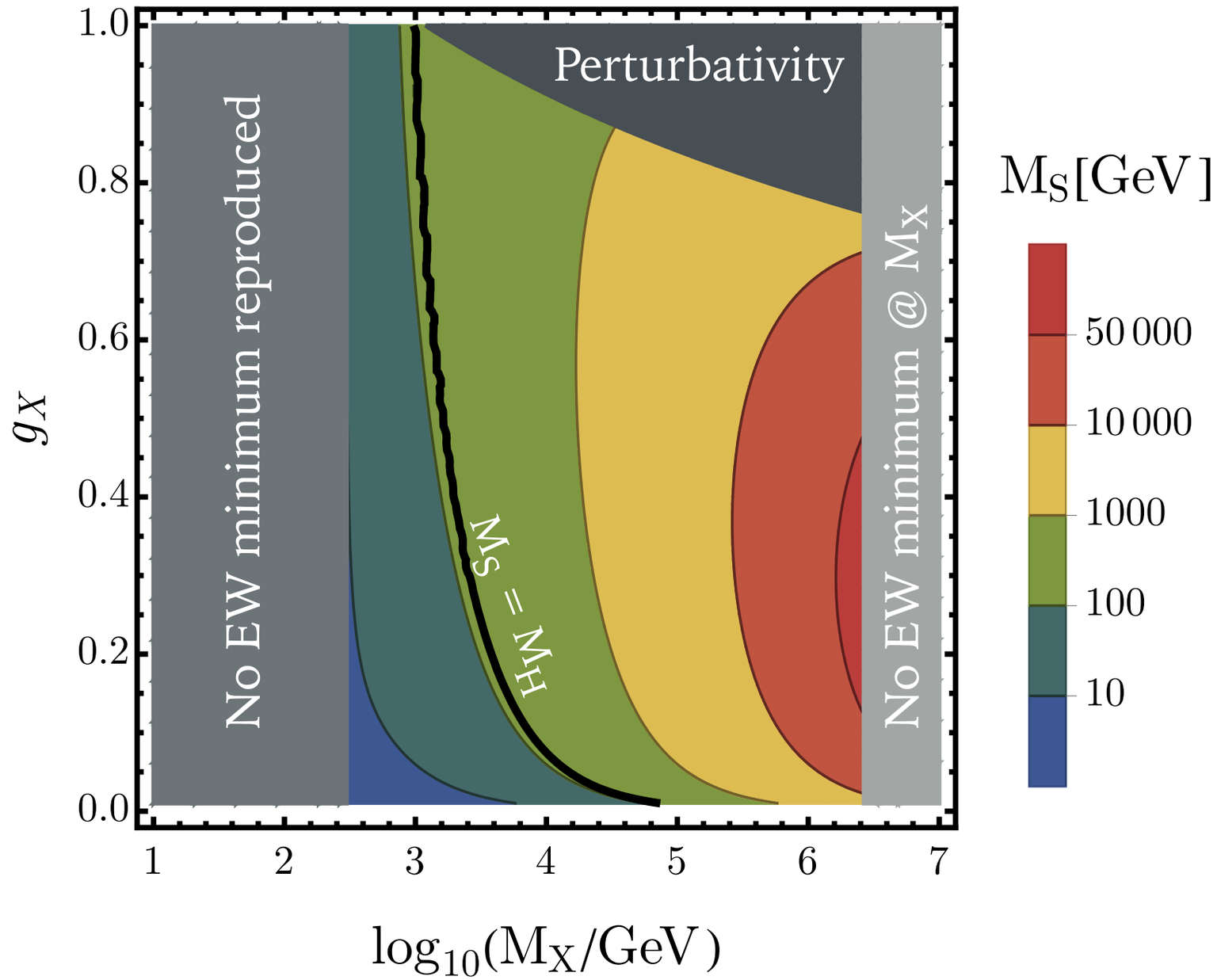
[See also: T.Hambye, A.Strumia, PRD88 (2013) 055022, C.Carone, R.Ramos, PRD88 (2013) 055020, V.V.Khoze, C.McCabe, G.Ro, JHEP 08 (2014) 026, T. Hambye, A.Strumia, D.Teresi, JHEP 1808 (2018) 188, I.Baldes, C. Garcia-Cely, JHEP 05 (2019) 190, T.Prokopec, J.Rezacek, BS, JCAP02(2019)009, D. Marfaria, P. Tseng, JHEP 02 (2021) 022]

RADIATIVE SYMMETRY BREAKING IN SU(2)CSM



[See also: L. Chataignier, T. Prokopec, M.G. Schmidt, BS, JHEP 08 (2018) 083]

RADIATIVE SYMMETRY BREAKING IN SU(2)CSM



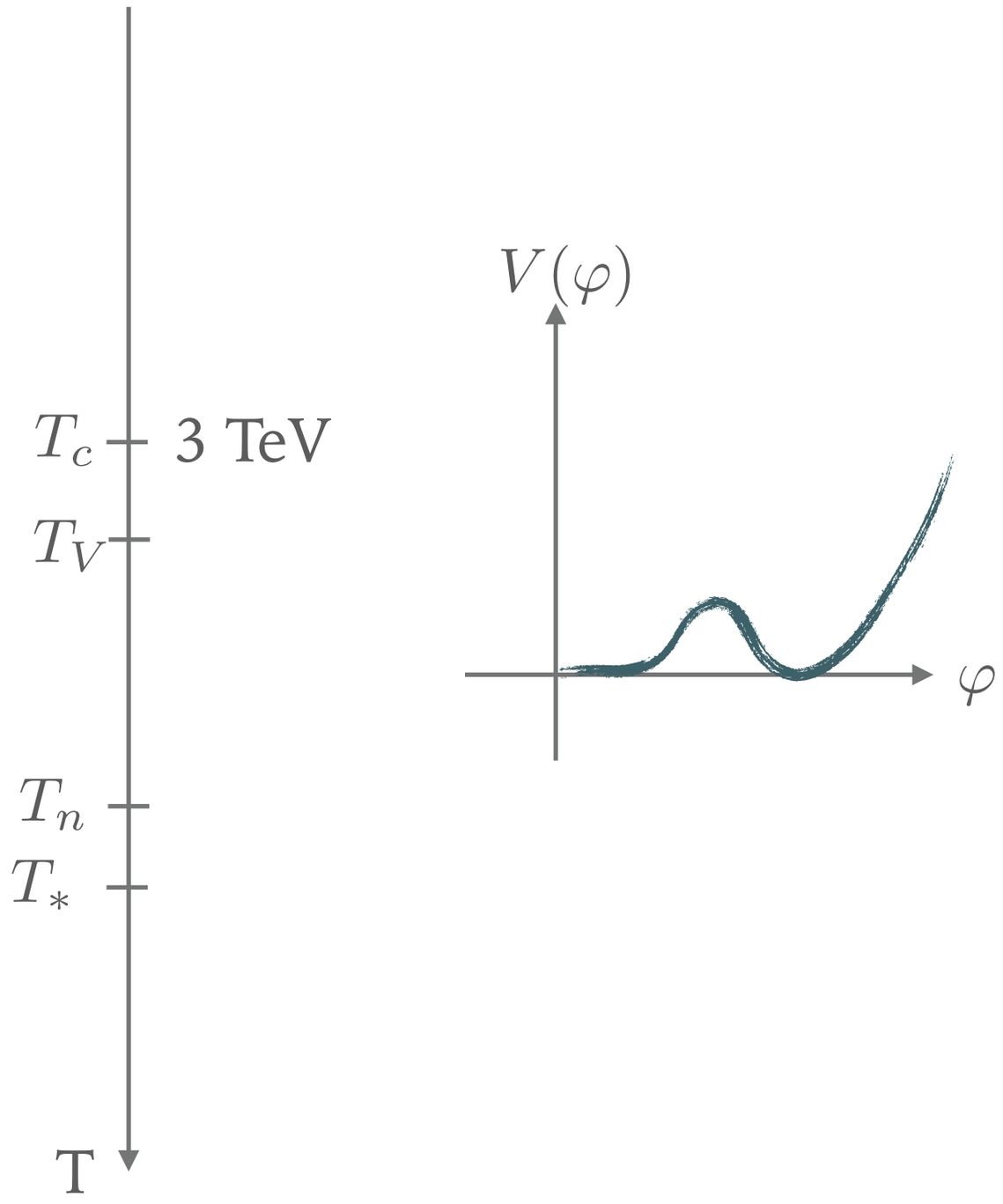
[See also: L. Chataignier, T. Prokopec, M.G. Schmidt, BS, JHEP 08 (2018) 083]

PHASE TRANSITION AND GRAVITATIONAL WAVES

TEMPERATURE EVOLUTION

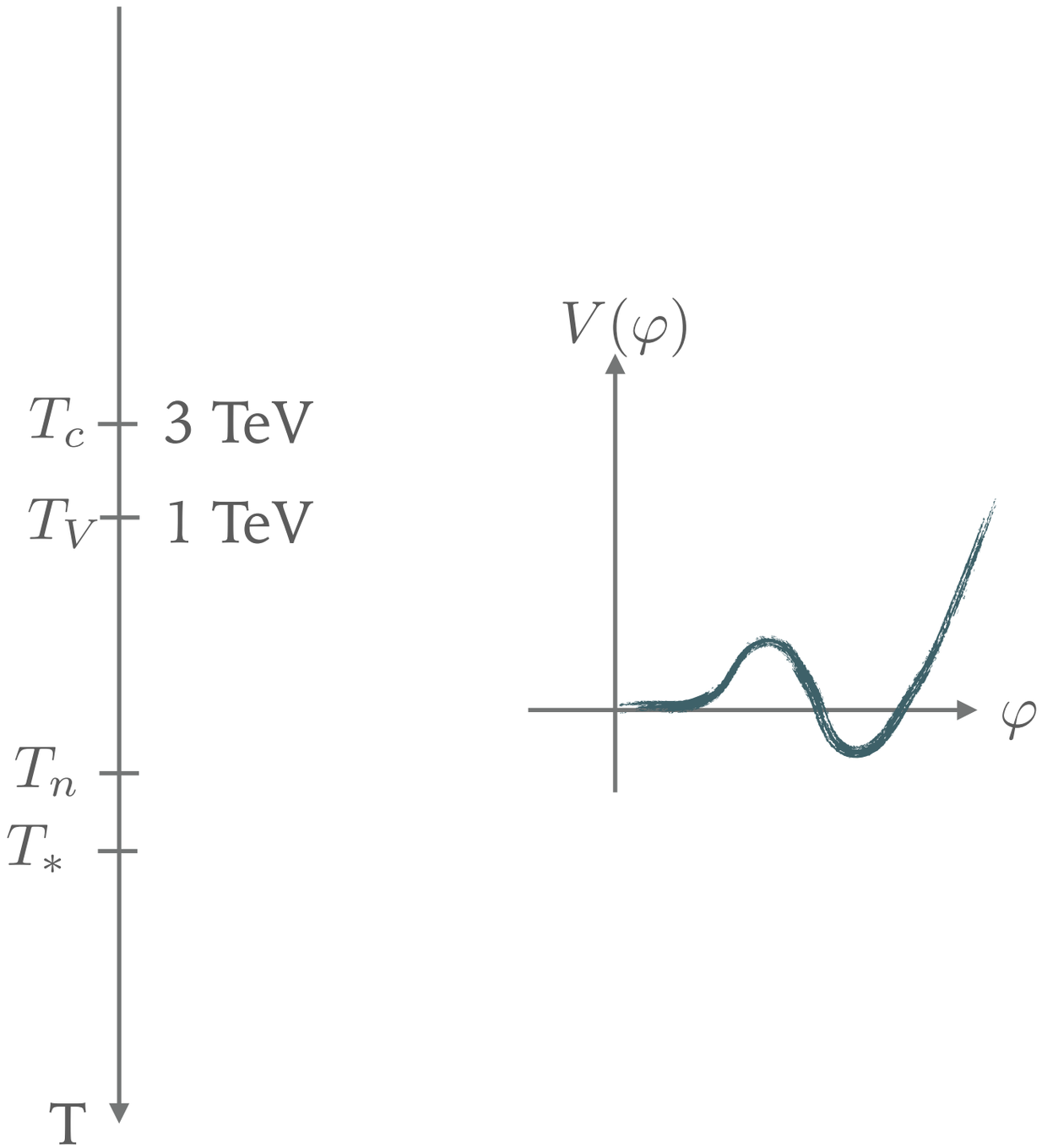
$M_X = 9$ TeV, $g_X = 0.9$

critical temperature: two degenerate minima



TEMPERATURE EVOLUTION

$M_X = 9$ TeV, $g_X = 0.9$

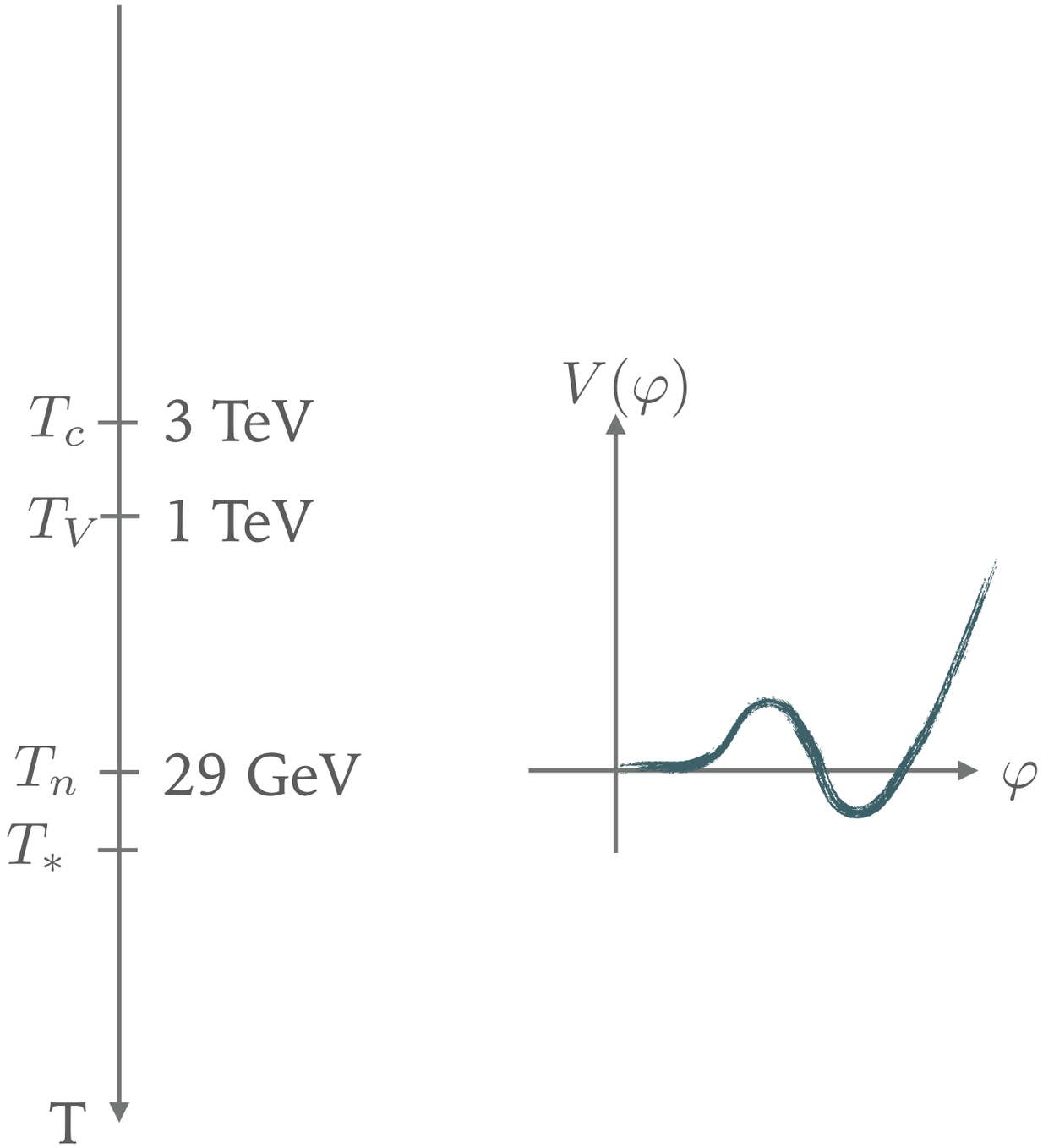


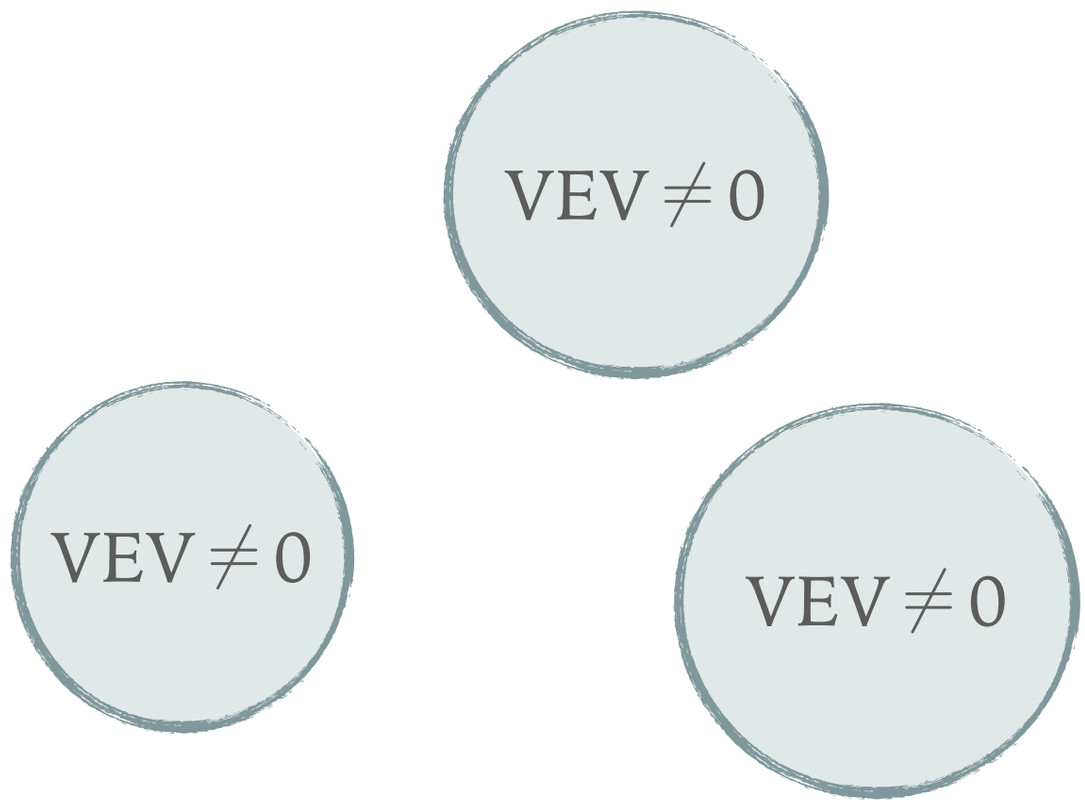
vacuum domination begins

TEMPERATURE EVOLUTION

$M_X = 9$ TeV, $g_X = 0.9$

nucleation:
one bubble nucleates
per Hubble volume





TEMPERATURE EVOLUTION

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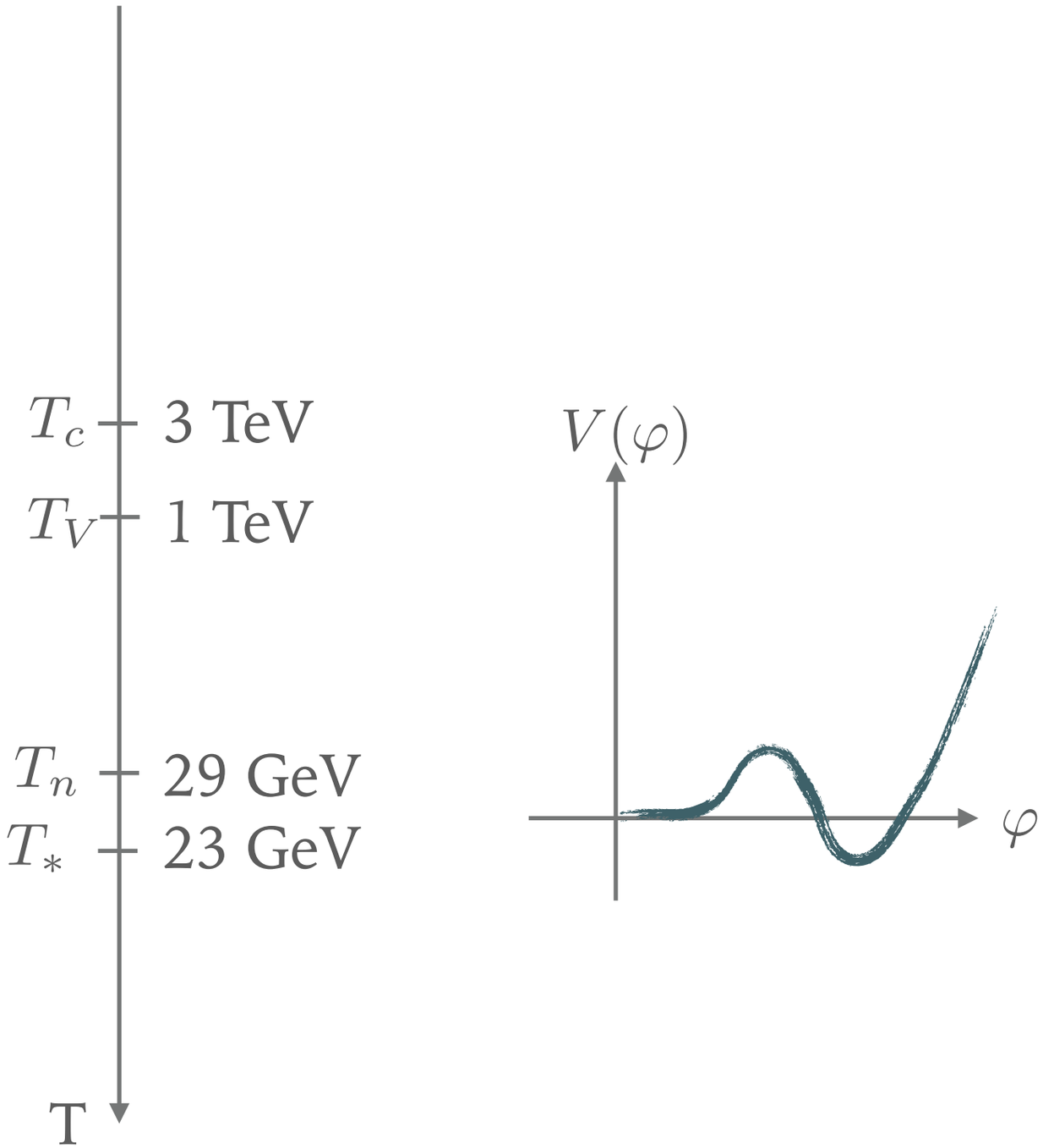
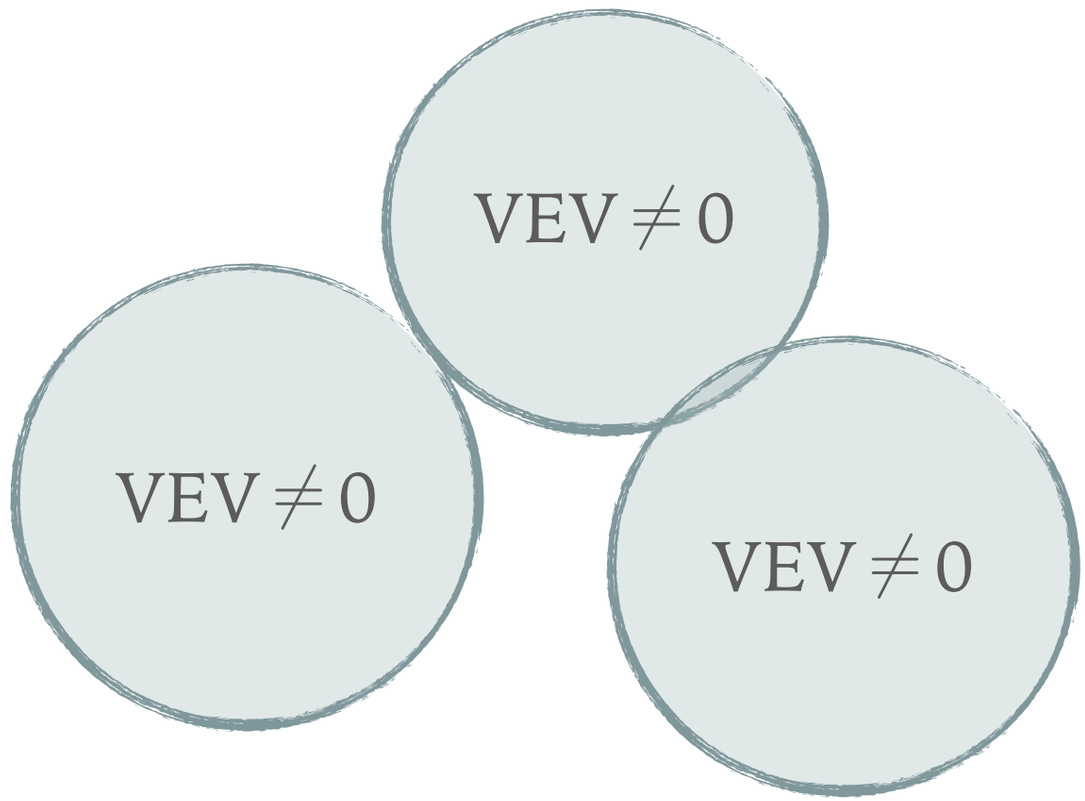
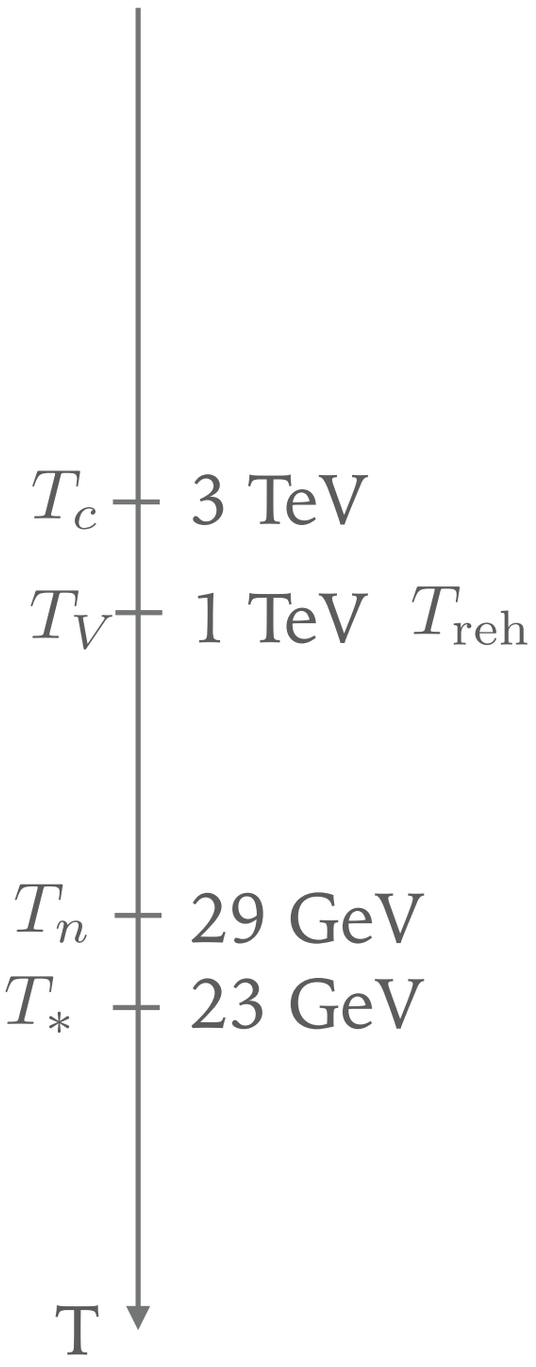


Percolation: phase transition completes



TEMPERATURE EVOLUTION

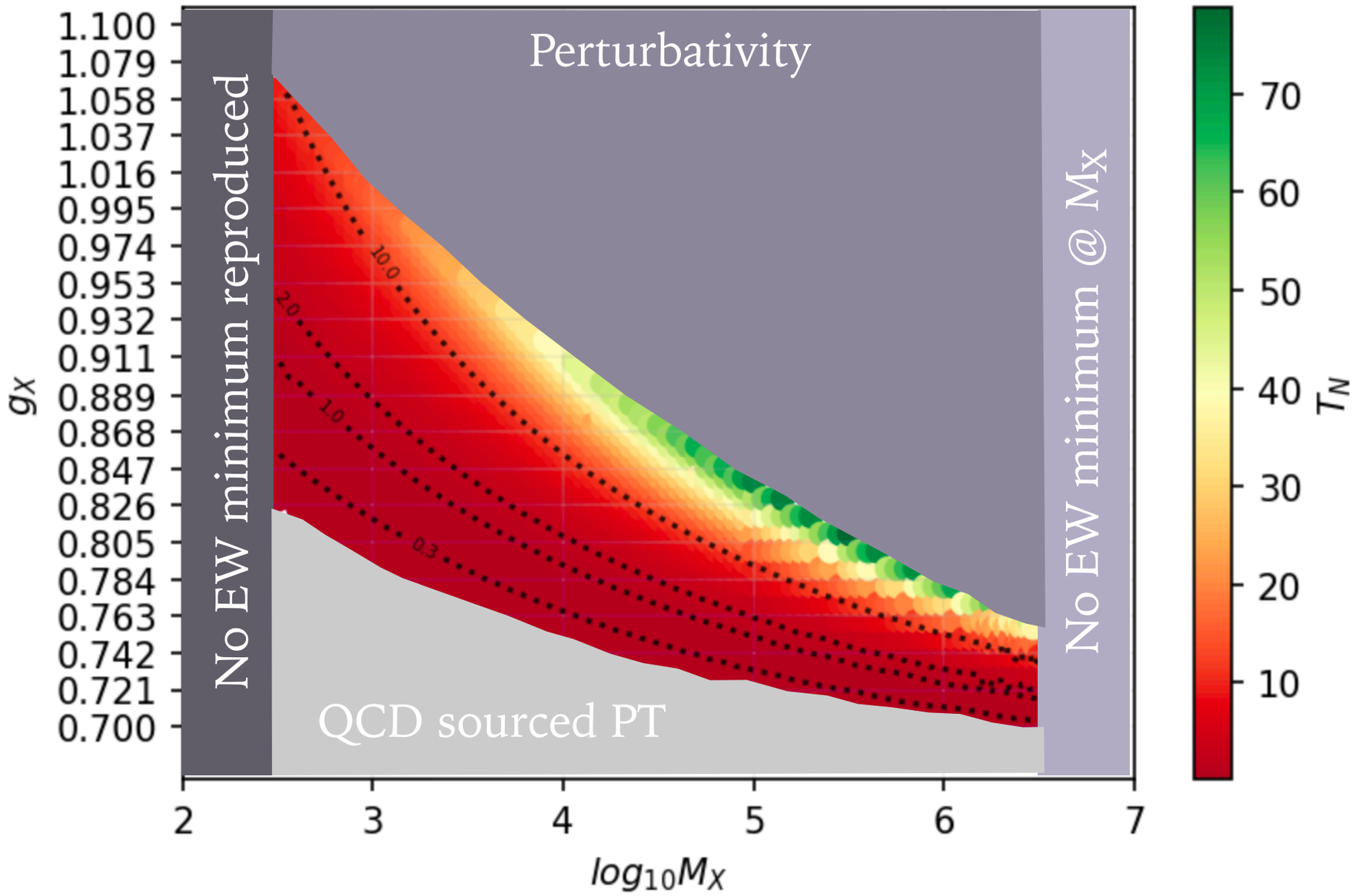
$M_X = 9$ TeV, $g_X = 0.9$



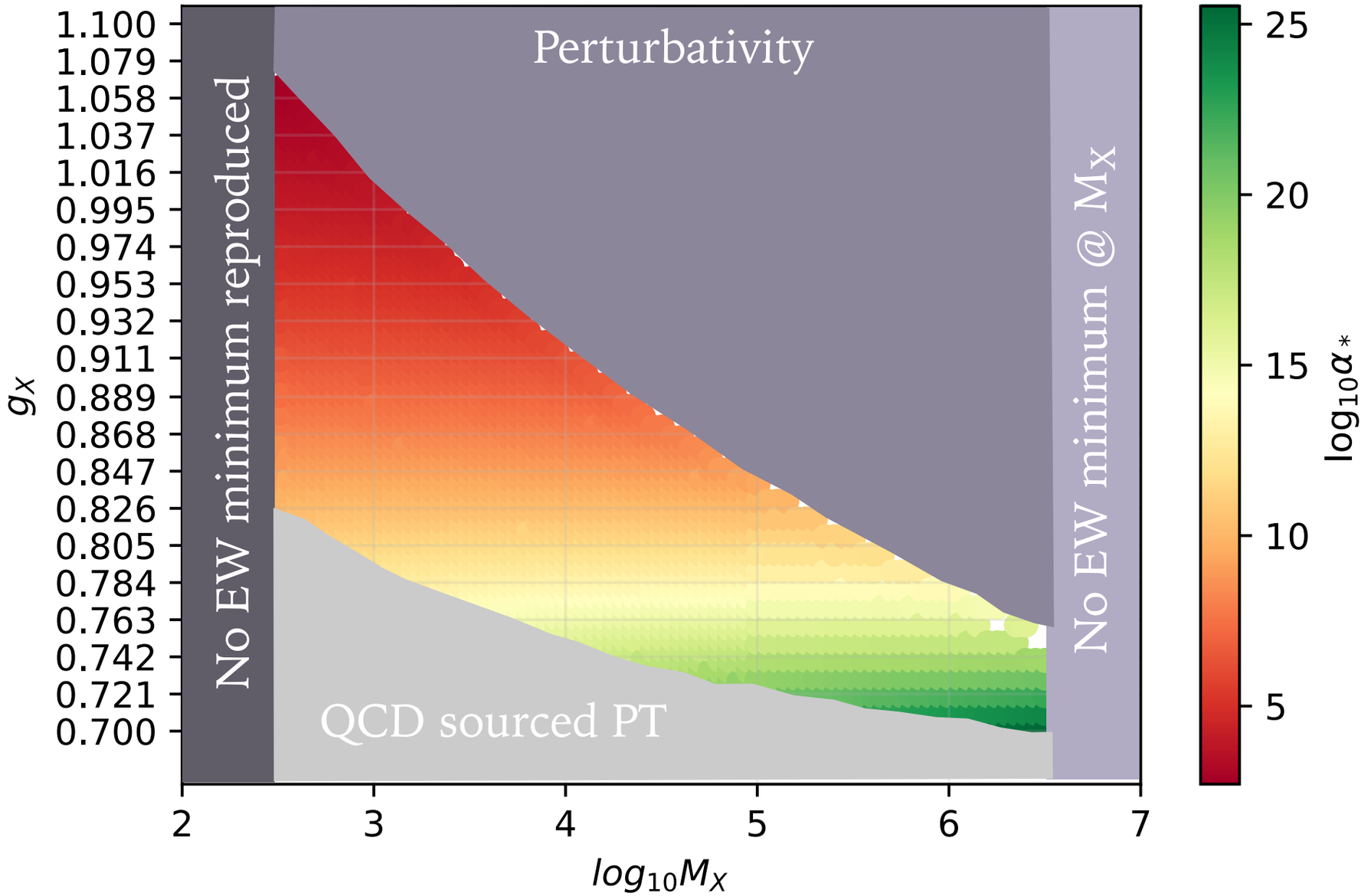
reheating

$$\alpha = \frac{\Delta V}{\text{energy of radiation}} \approx 4 \cdot 10^6$$

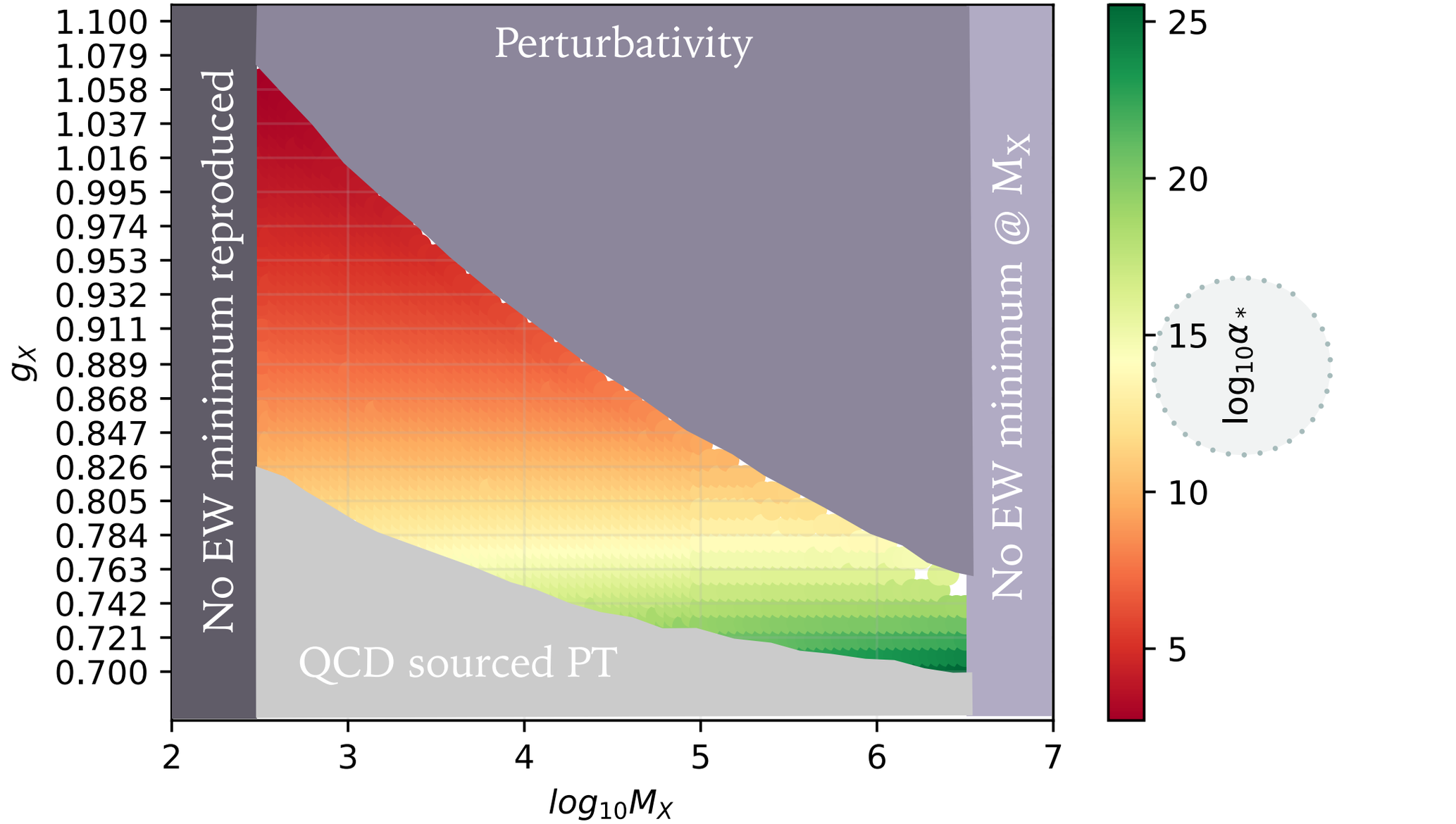
SCANNING THE PARAMETER SPACE



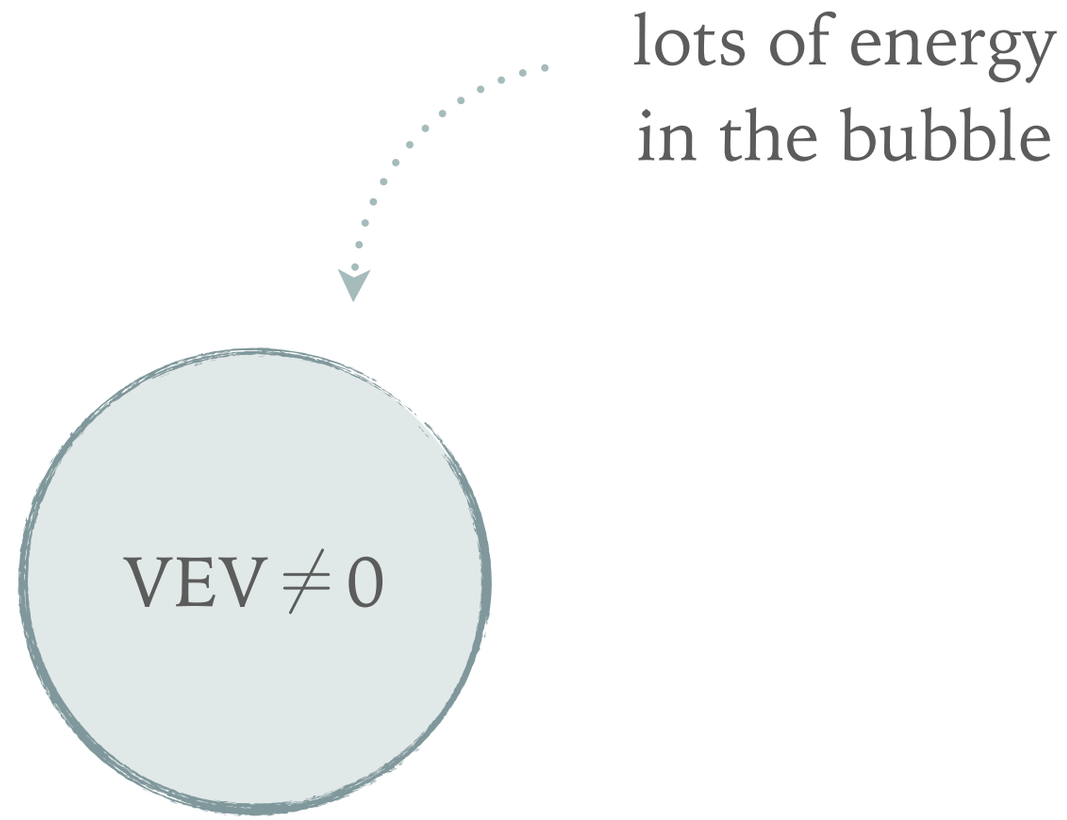
SCANNING THE PARAMETER SPACE



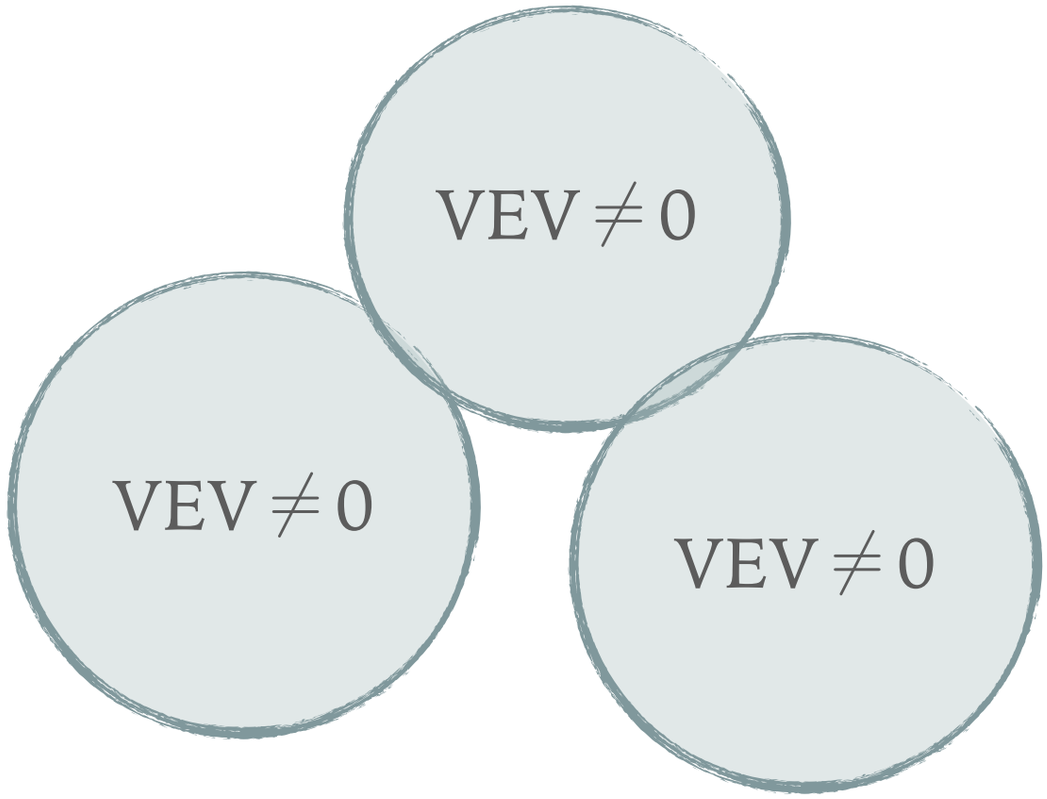
SCANNING THE PARAMETER SPACE



SOURCES OF GRAVITATIONAL WAVES

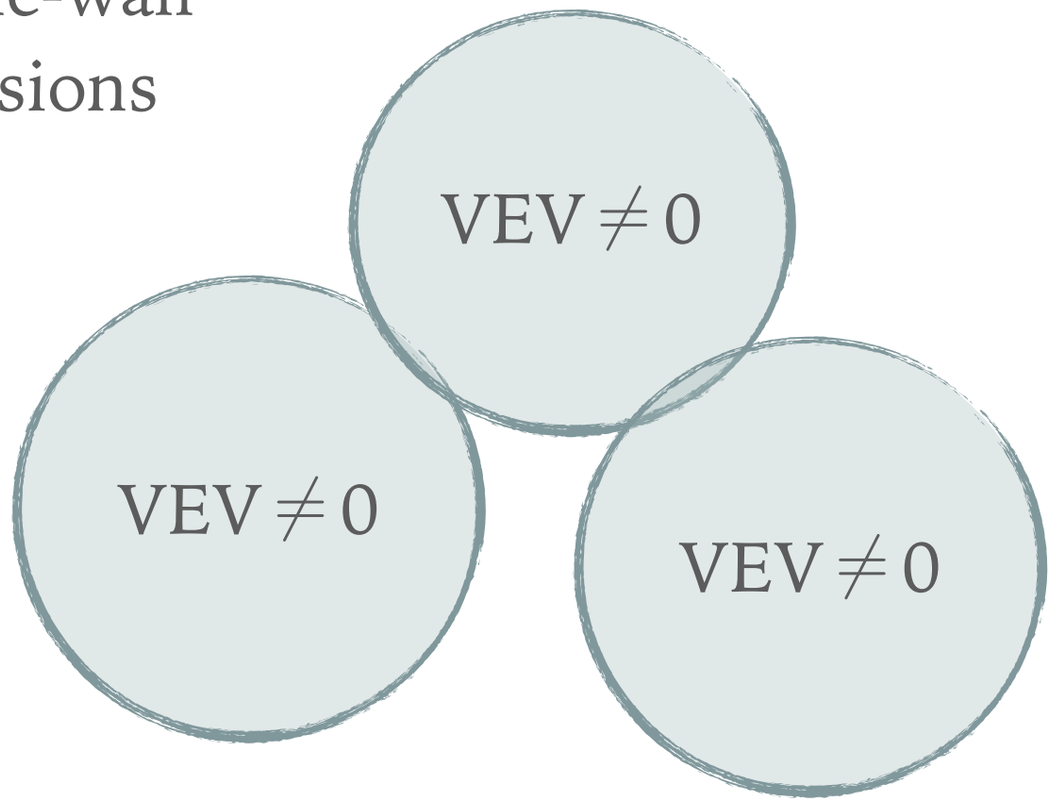


SOURCES OF GRAVITATIONAL WAVES



SOURCES OF GRAVITATIONAL WAVES

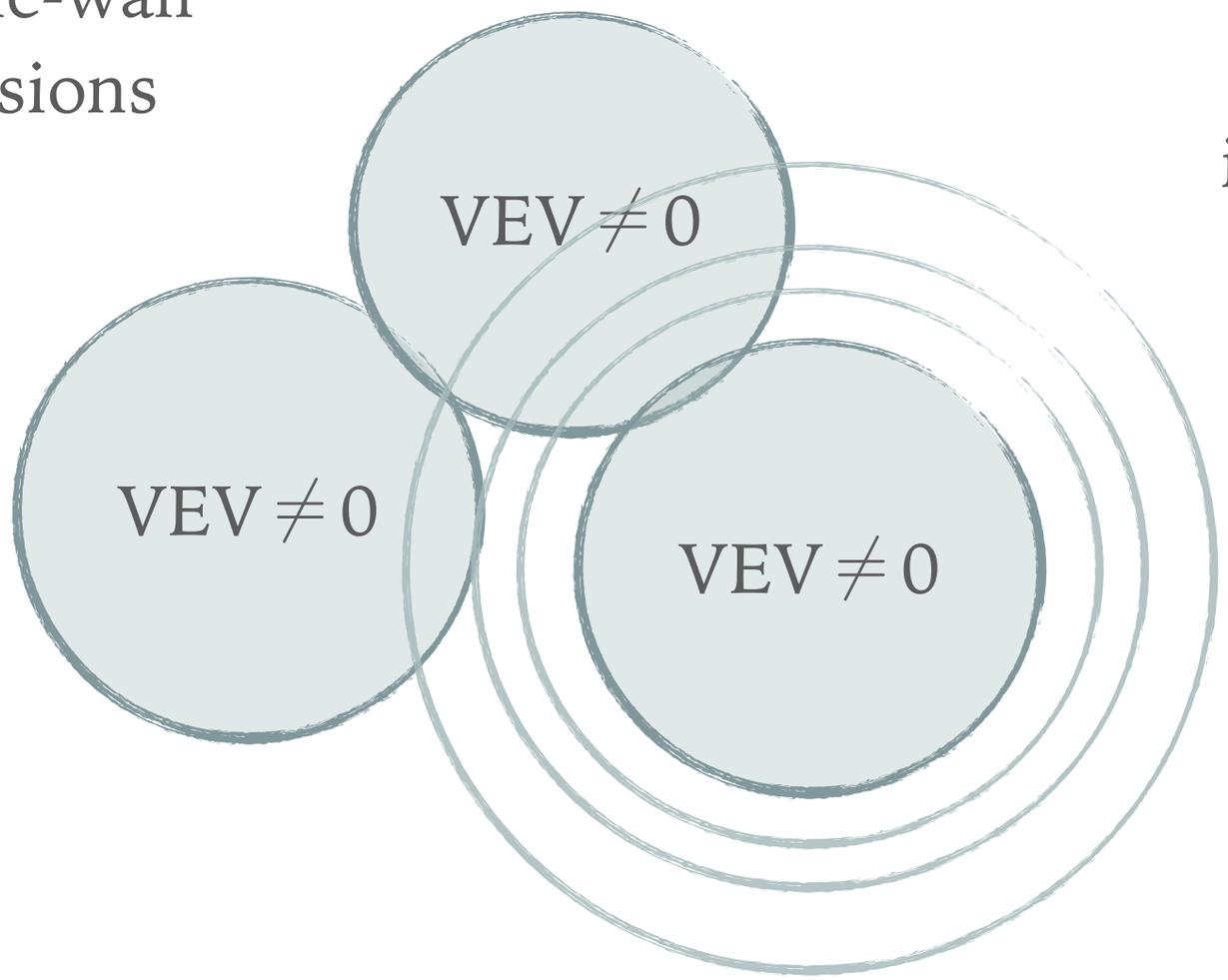
bubble-wall collisions



SOURCES OF GRAVITATIONAL WAVES

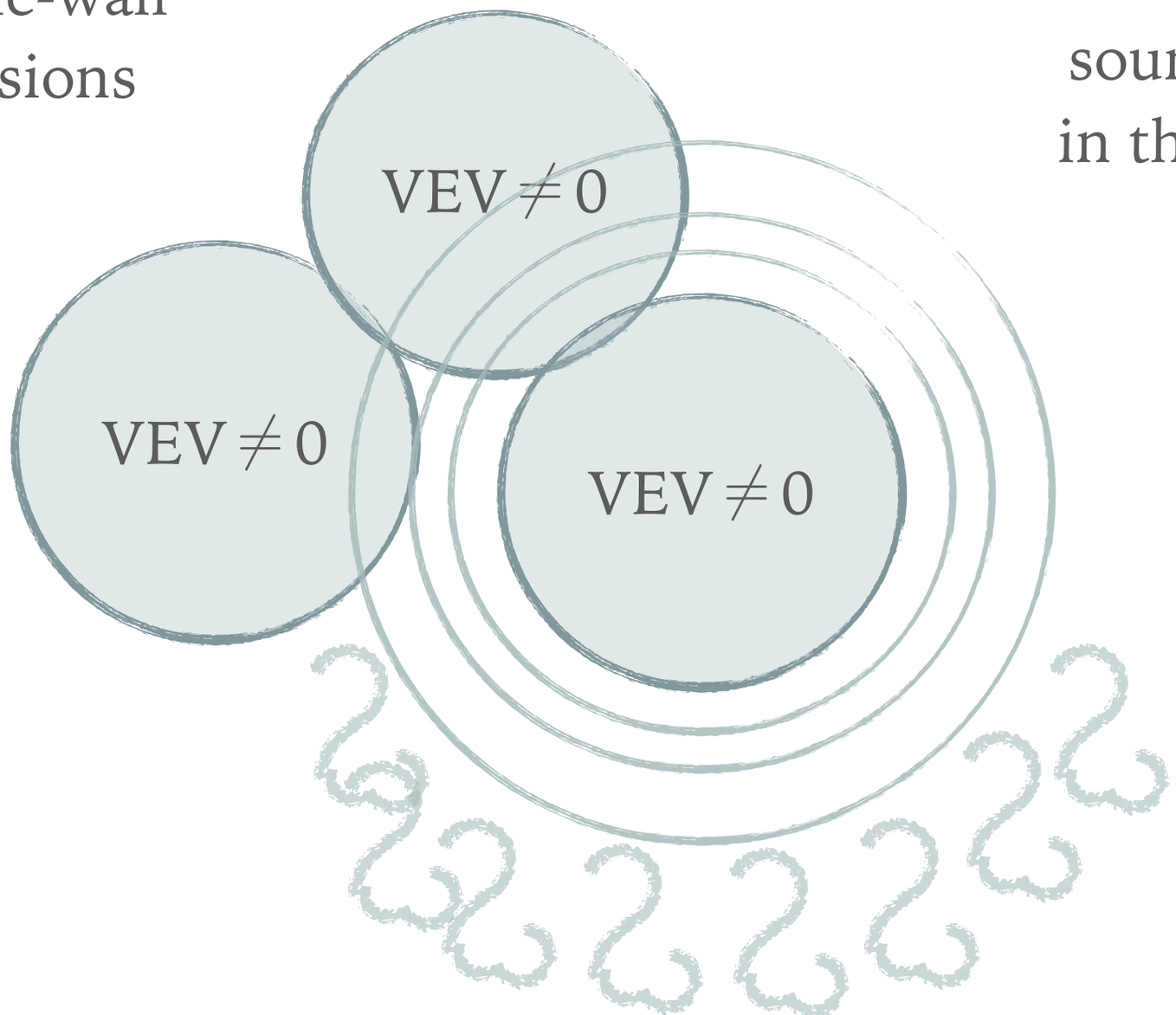
bubble-wall collisions

sound waves in the plasma



SOURCES OF GRAVITATIONAL WAVES

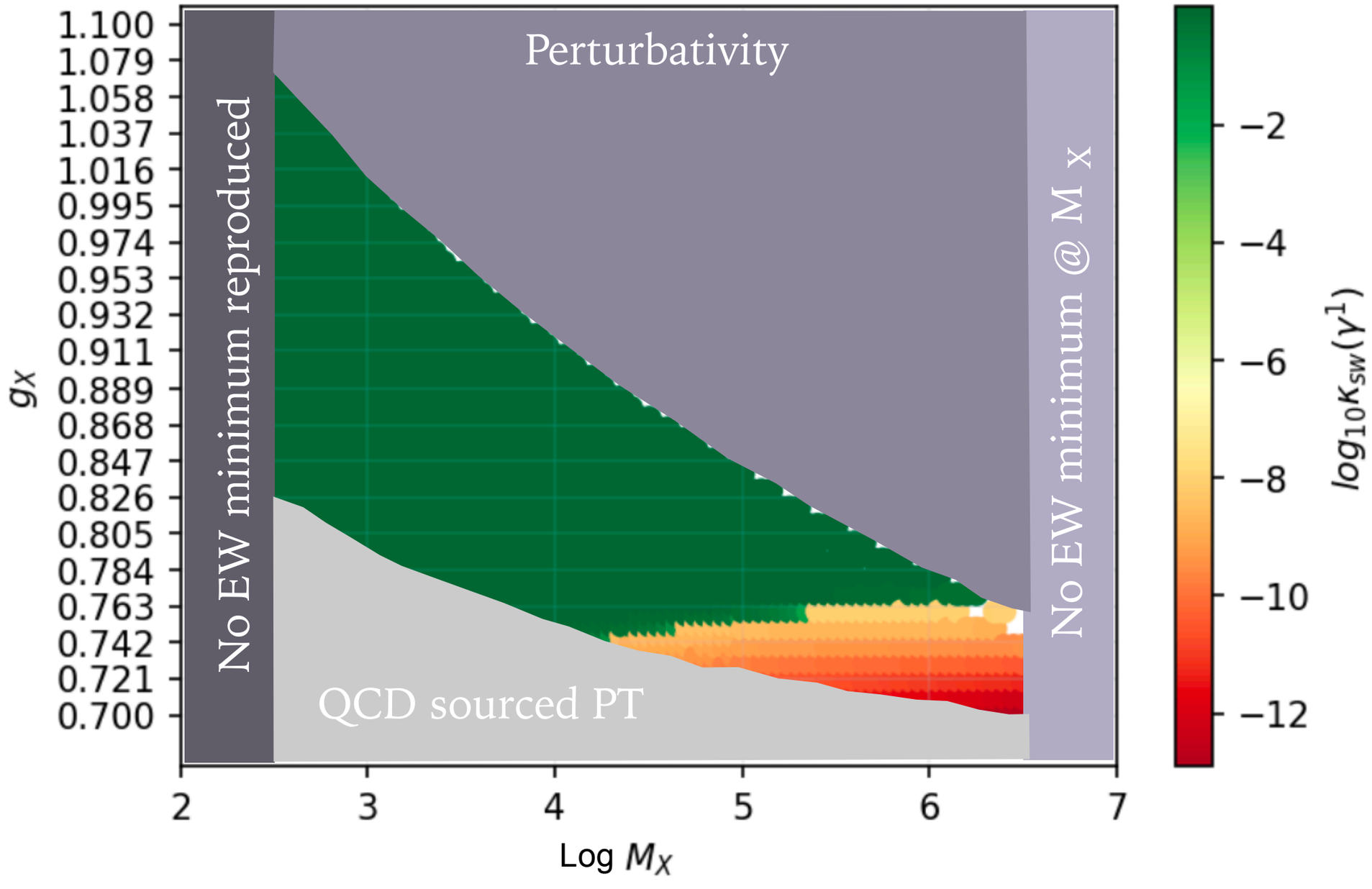
bubble-wall collisions



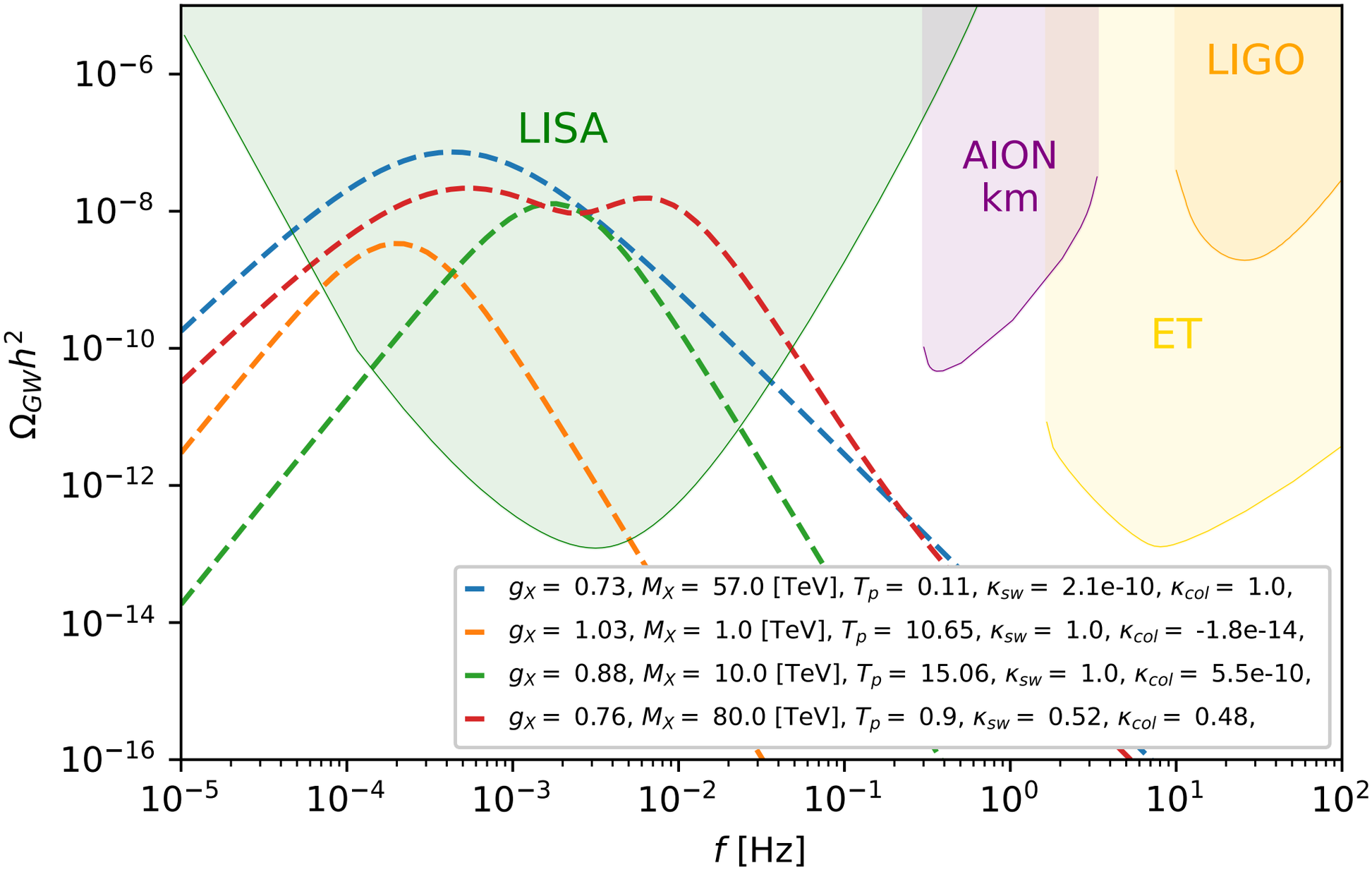
sound waves in the plasma

turbulence in the plasma

SOURCES OF GRAVITATIONAL WAVES



GRAVITATIONAL WAVE SPECTRA



[sensitivity curves courtesy M. Lewicki]

DARK MATTER PRODUCTION

SU(2)CSM

cSM:
$SU(2)_L \times U(1)_Y$
Φ

Hidden sector:
$SU(2)_X$
Ψ

$$V^{(0)}(\Phi,\Psi) = \lambda_1 \left(\Phi^\dagger\Phi\right)^2 + \lambda_2 \left(\Phi^\dagger\Phi\right)\left(\Psi^\dagger\Psi\right) + \lambda_3 \left(\Psi^\dagger\Psi\right)^2,$$

$$\mathrm{SU}(2) \to \mathbb{Z}_2 \times \mathbb{Z}_2$$

DM stability protected by a symmetry

[See also: T.Hambye, A.Strumia, PRD88 (2013) 055022, C.Carone, R.Ramos, PRD88 (2013) 055020, V.V.Khoze, C.McCabe, G.Ro, JHEP 08 (2014) 026, T. Hambye, A.Strumia, D.Teresi, JHEP 1808 (2018) 188, I.Baldes, C. Garcia-Cely, JHEP 05 (2019) 190, T.Prokopec, J.Rezacek, BS, JCAP02(2019)009, D. Marfaria, P. Tseng, JHEP 02 (2021) 022]

NON-STANDARD DM PRODUCTION

supercooling

hot Universe, massless particles

PT and reheating

cool Universe, diluted massless particles

reheated Universe, diluted massive particles

NEW PRODUCTION MECHANISM

Standard freezeout

With nonstandard initial condition

$T_{\rm dec} < T_{\rm reh}$

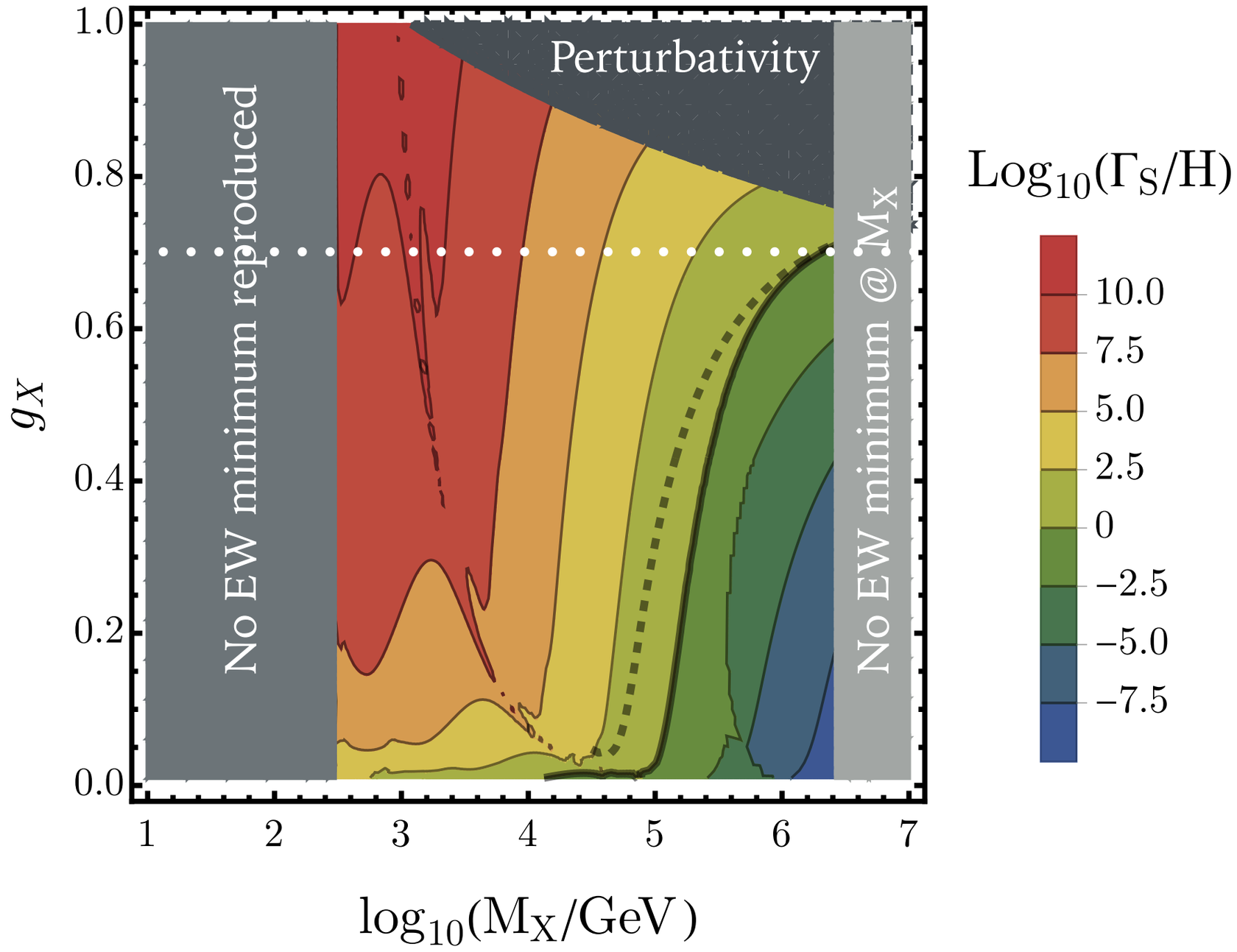
Supercool DM

DM diluted by thermal inflation

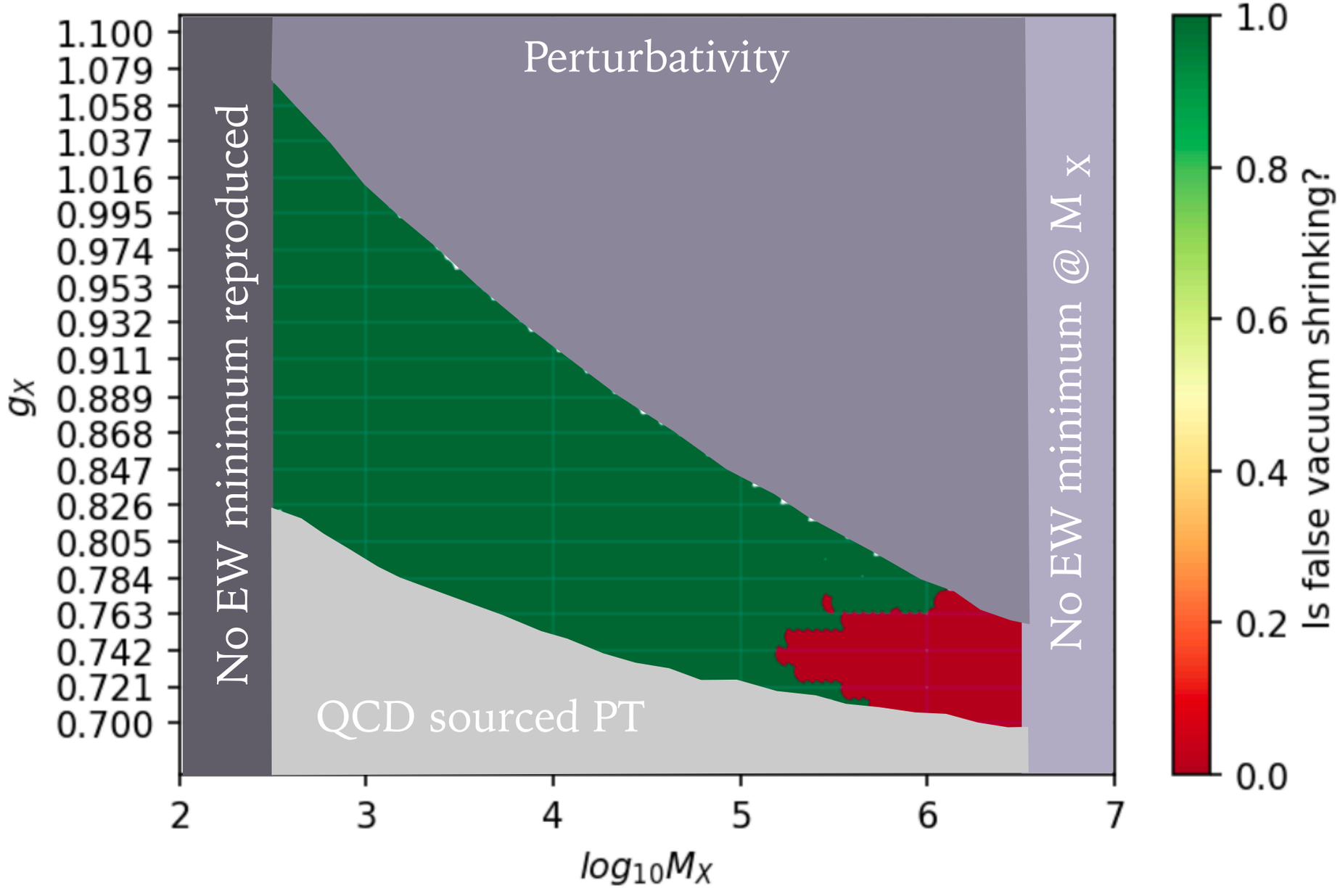
$T_{\rm dec} > T_{\rm reh}$

[T.Hambye, A.Strumia, PRD88 (2013) 055022, C.Carone, R.Ramos, PRD88 (2013) 055020, V.V.Khoze, C.McCabe, G.Ro, JHEP 08 (2014) 026, T. Hambye, A.Strumia, D.Teresi, JHEP 1808 (2018) 188, I.Baldes, C. Garcia-Cely, JHEP 05 (2019) 190, D. Marfaria, P. Tseng, JHEP 02 (2021) 022]

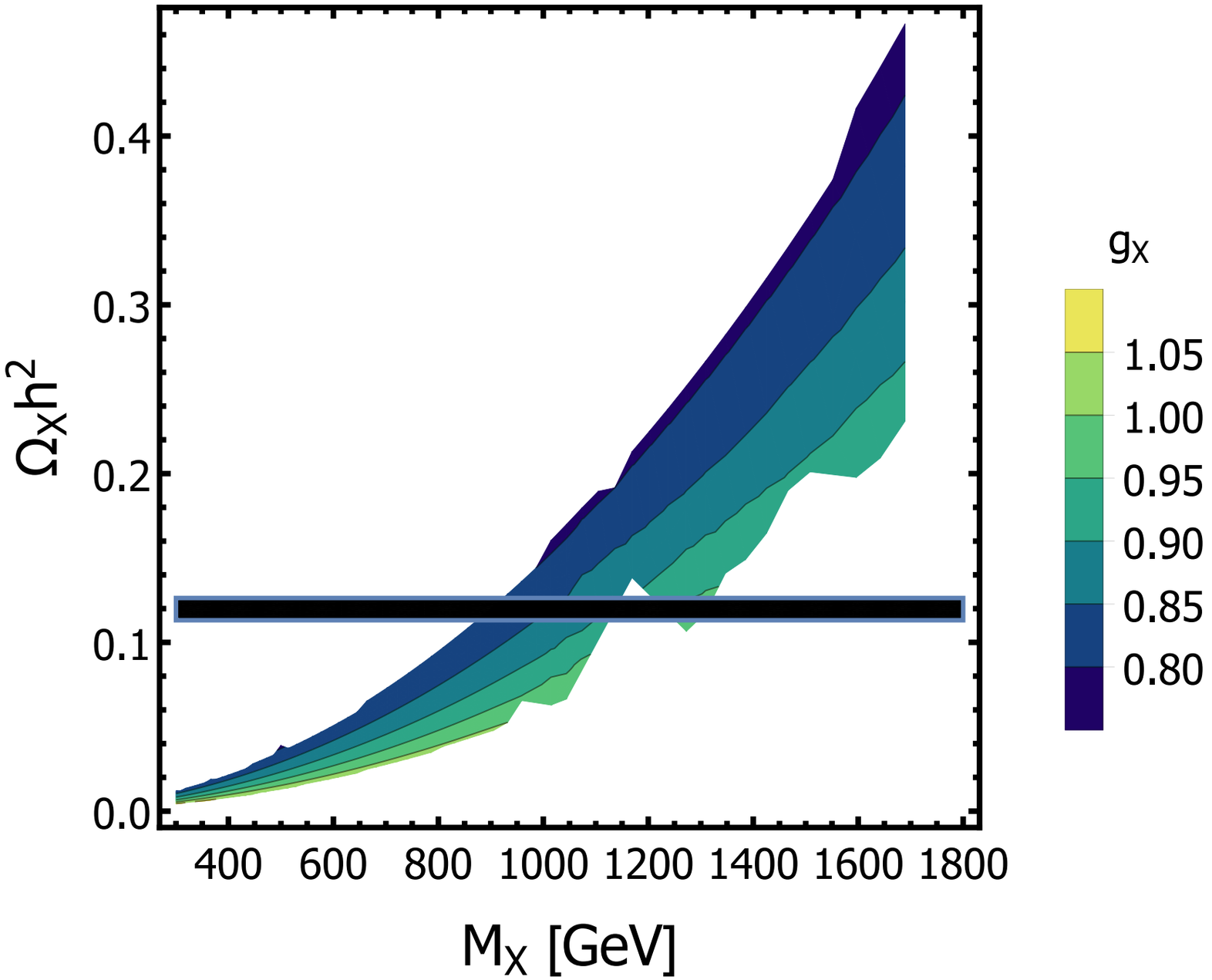
REHEATING


Perturbativity
No EW minimum reproduced
No EW minimum @ M_X
g_X
1.0
0.8
0.6
0.4
0.2
0.0
1
2
3
4
5
6
7
$\log_{10}(M_X/\mathrm{GeV})$
$\mathrm{Log}_{10}(\Gamma_S/H)$
10.0
7.5
5.0
2.5
0
−2.5
−5.0
−7.5

REHEATING

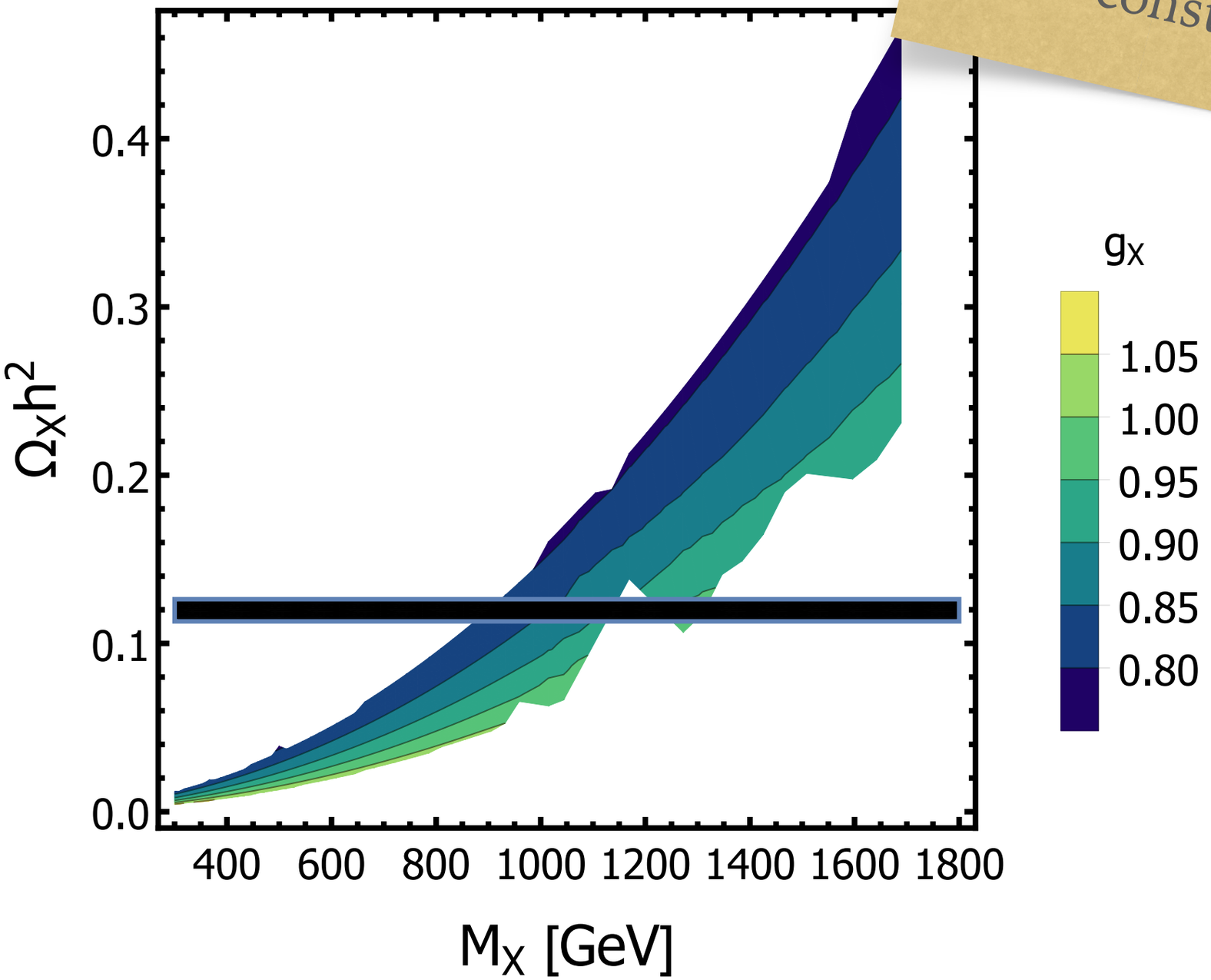

Perturbativity
No EW minimum reproduced
No EW minimum @ M x
QCD sourced PT
1.100
1.079
1.058
1.037
1.016
0.995
0.974
0.953
0.932
0.911
0.889
0.868
0.847
0.826
0.805
0.784
0.763
0.742
0.721
0.700
g_X
2
3
4
5
6
7
$log_{10}M_X$
1.0
0.8
0.6
0.4
0.2
0.0
Is false vacuum shrinking?

DM ABUNDANCE - FREEZEOUT



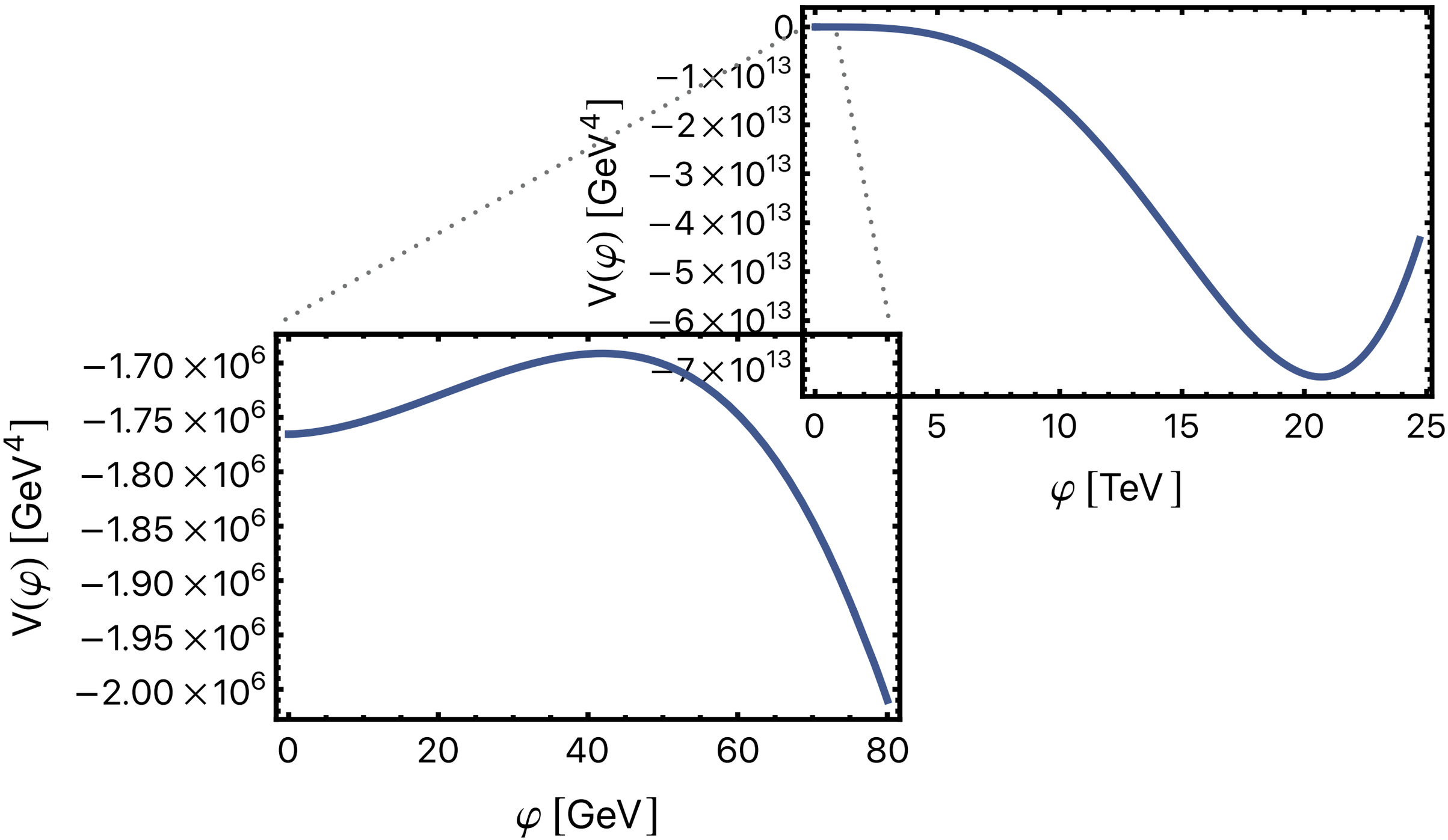
DM ABUNDANCE - FREEZEOUT

Parametr space for correct DM relic abundance significantly constrained

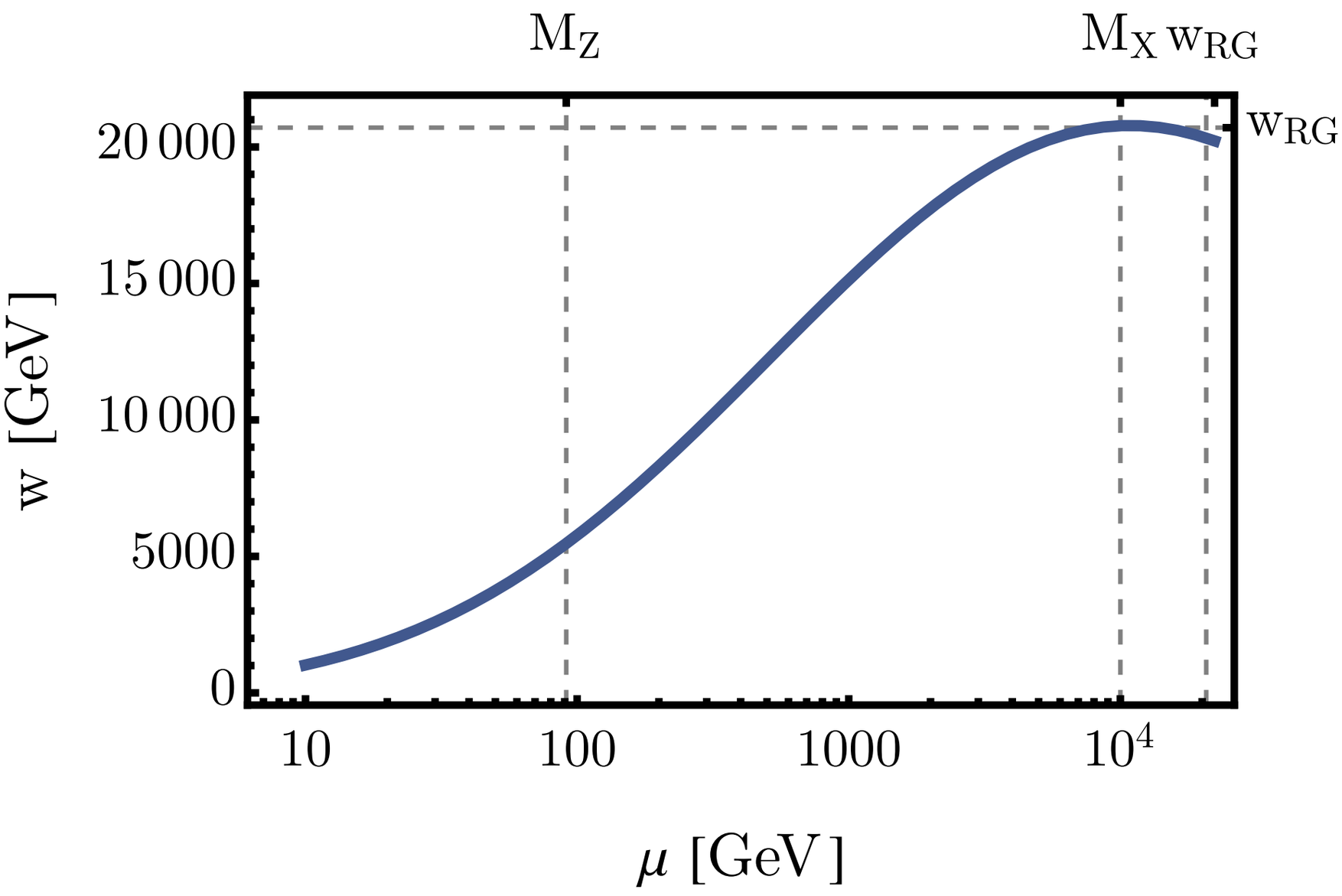


SCALE DEPENDENCE OF PT PARAMETERS

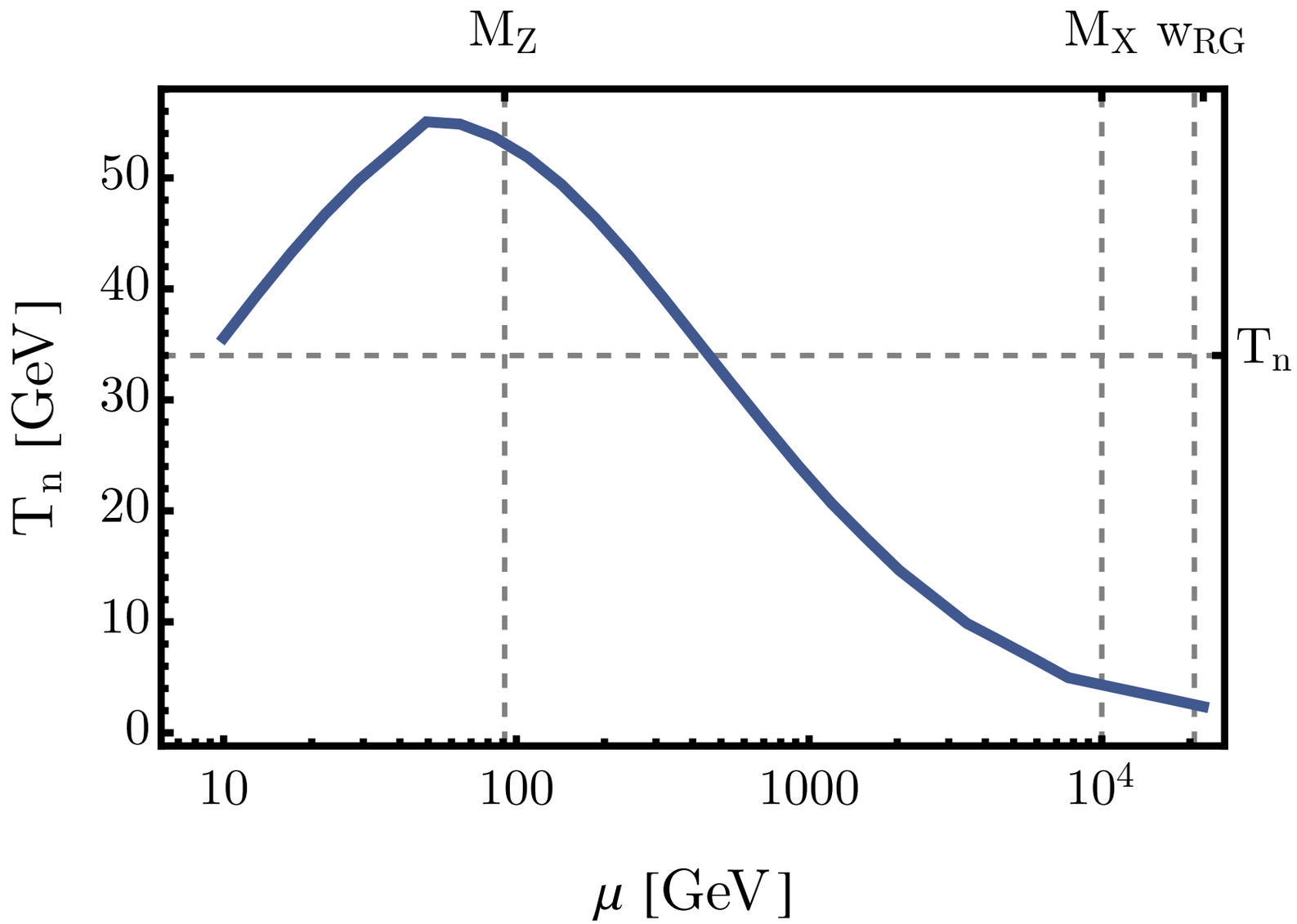
DIFFERENT SCALES INVOLVED



SCALE DEPENDENCE OF THE VEV

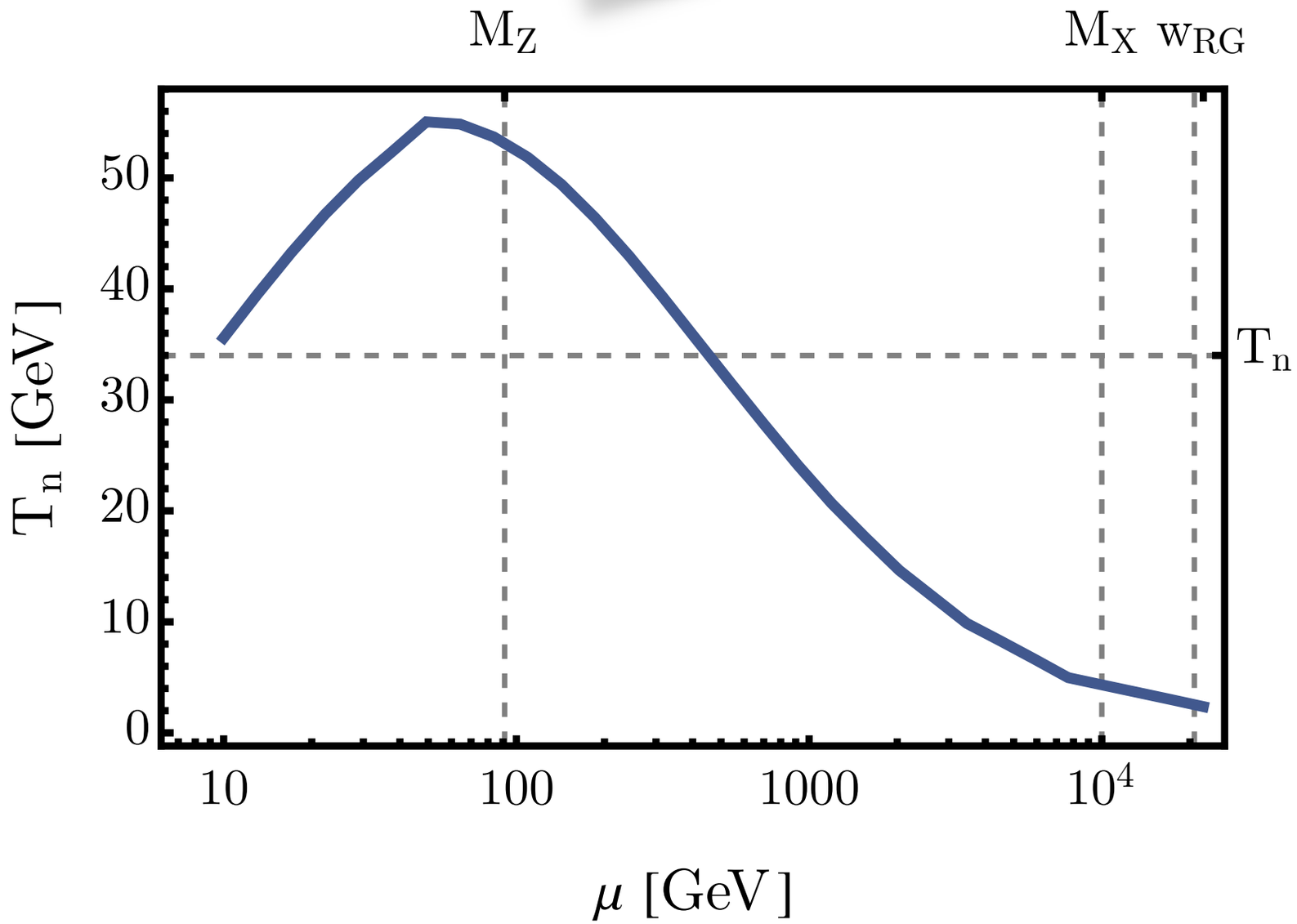


SCALE DEPENDENCE



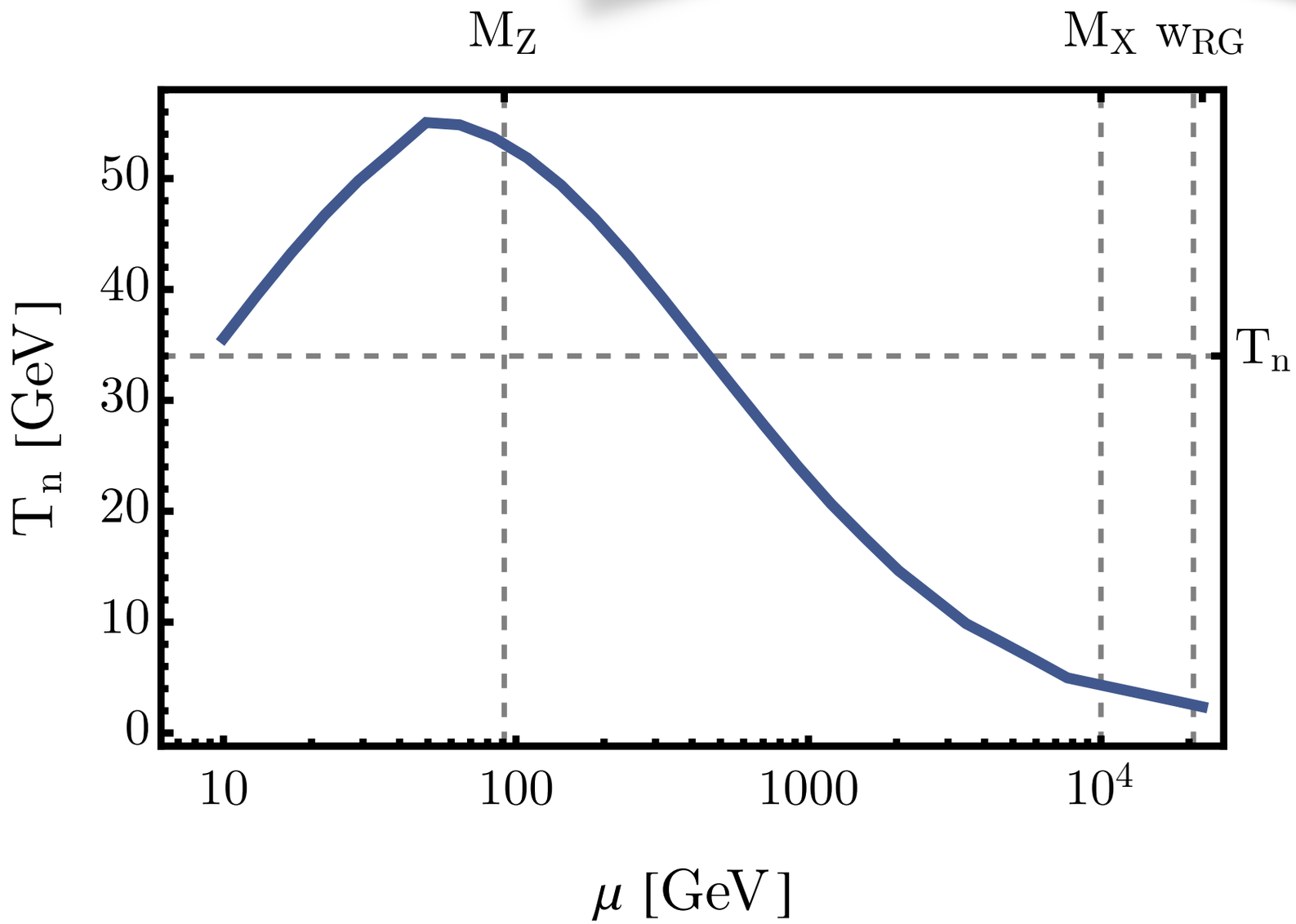
SCALE DEPENDENCE

Remedy: RG improvement



SCALE DEPENDENCE

Still to be improved



SUMMARY

SUMMARY

Phase transition is well testable in conformal modes

DM parameter space highly constrained from running of couplings

Theoretical uncertainties are still huge: improvements needed before LISA

THANK YOU FOR YOUR ATTENTION

NATIONAL SCIENCE CENTRE
POLAND

DM PRODUCTION MECHANISMS

Freeze-in

DM not in thermal equilibrium, produced by decays or annihilations in the visible sector

Dark freeze-out

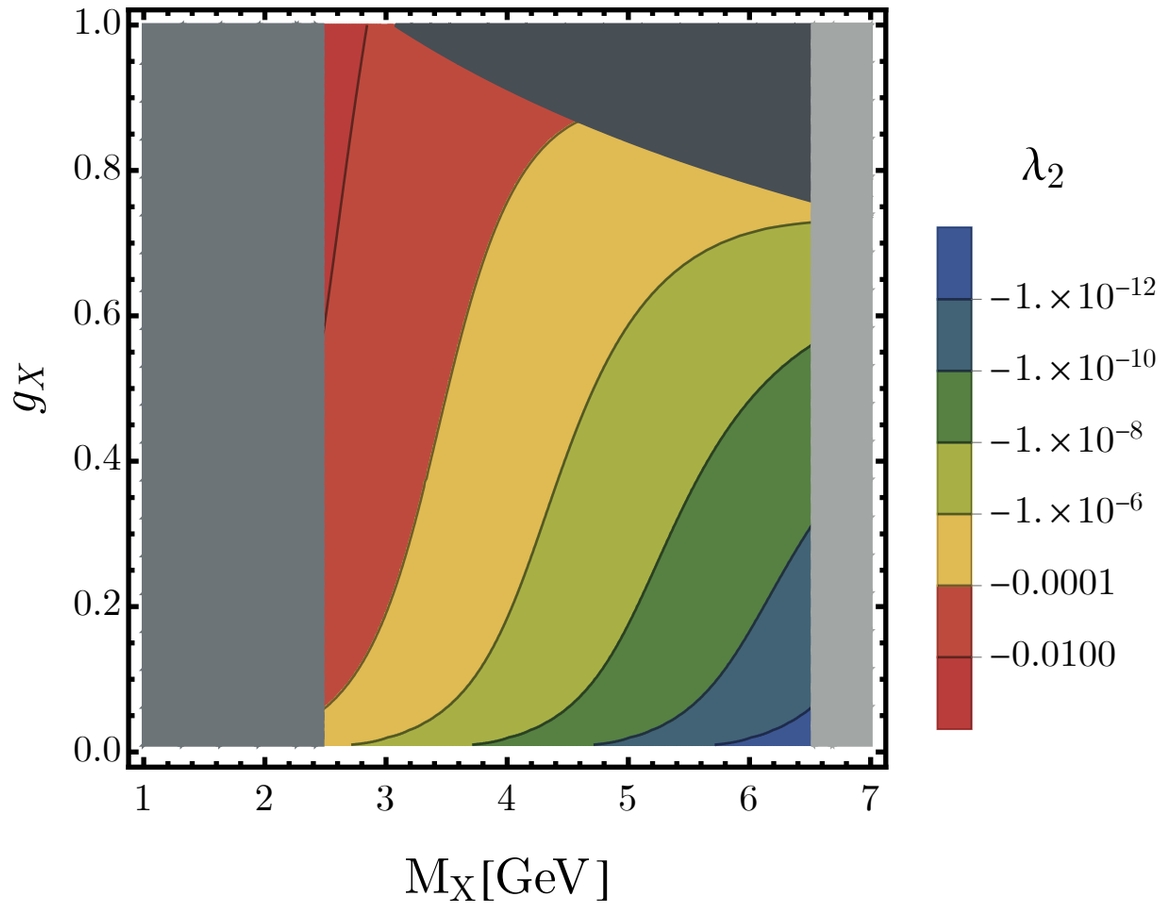
DM not in equilibrium with the visible sector, freeze-out within the dark sector

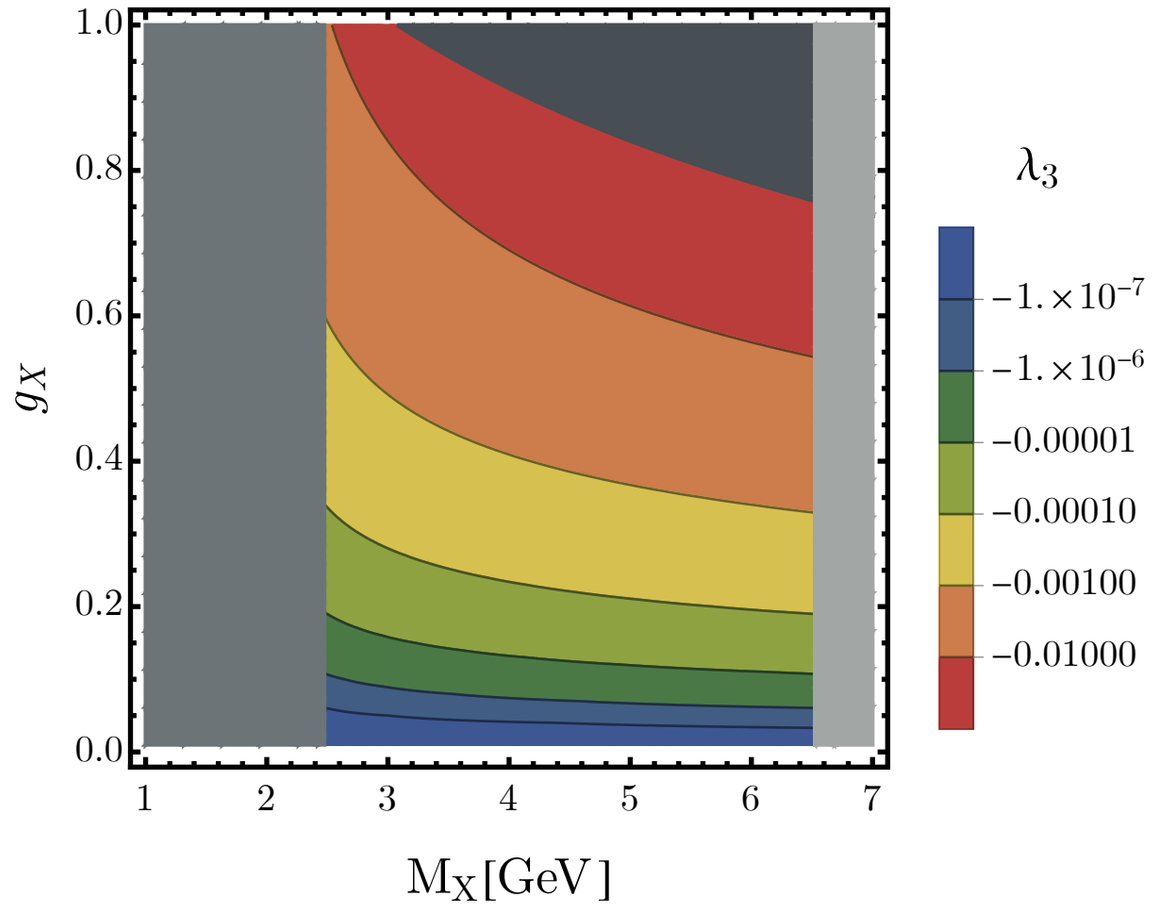
Reannihillation

DM frozen in the dark sector but produced by the visible sector, final freeze-out when the yield ends

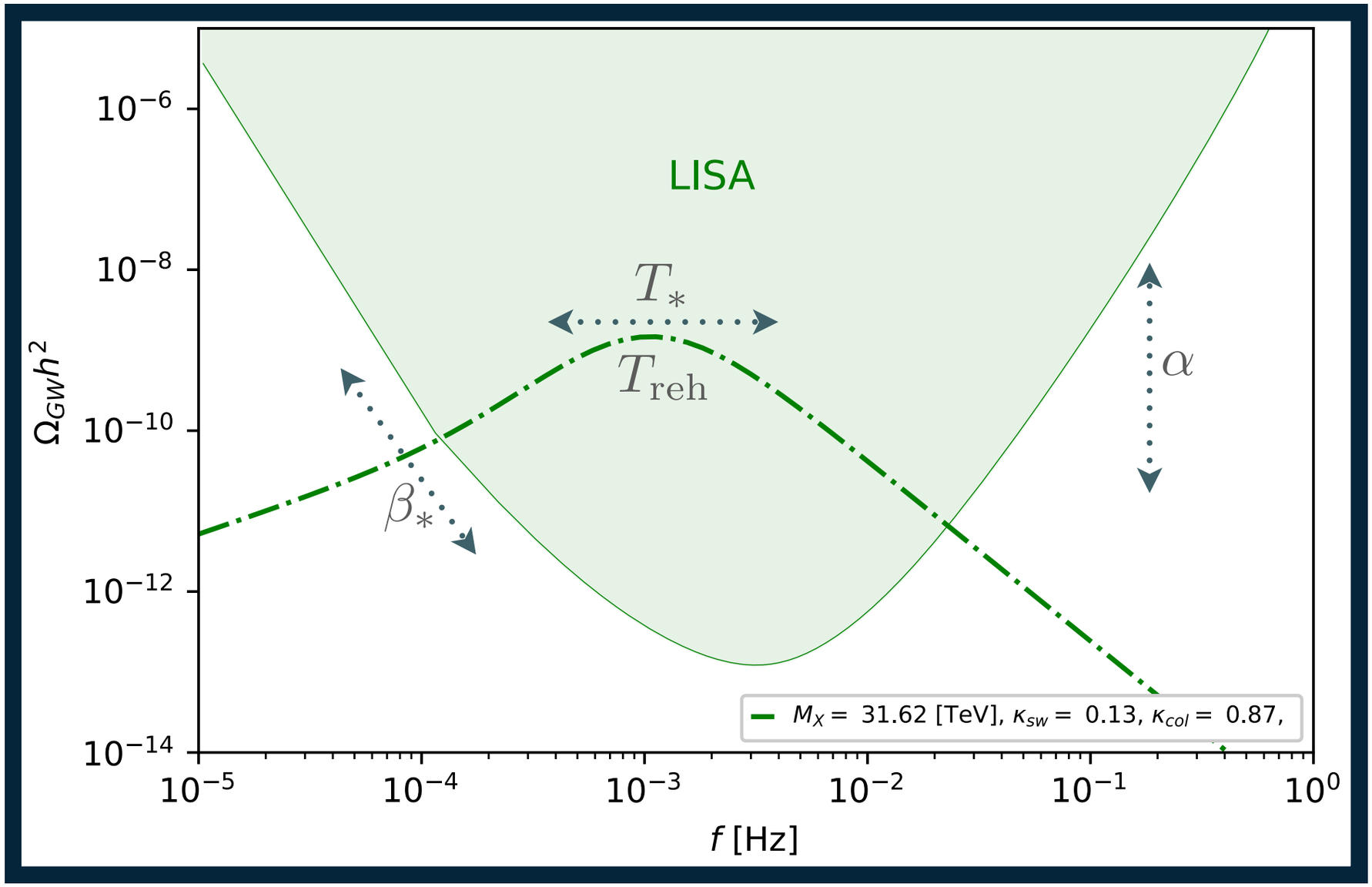
[N. Bernal et al, Int.J.Mod.Phys.A 32 (2017) 27, 1730023]

SCALAR COUPLINGS



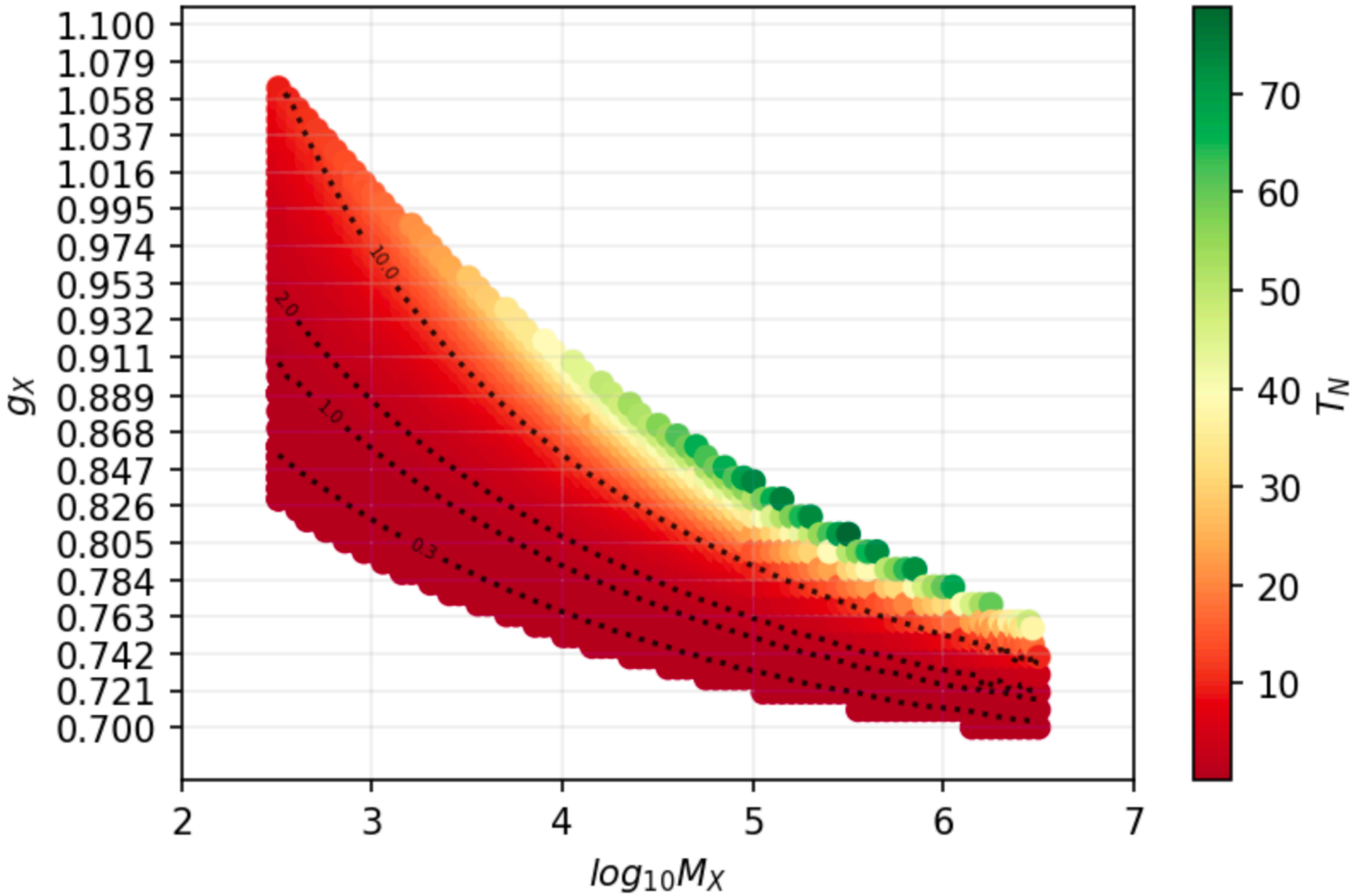


GW PARAMETERS

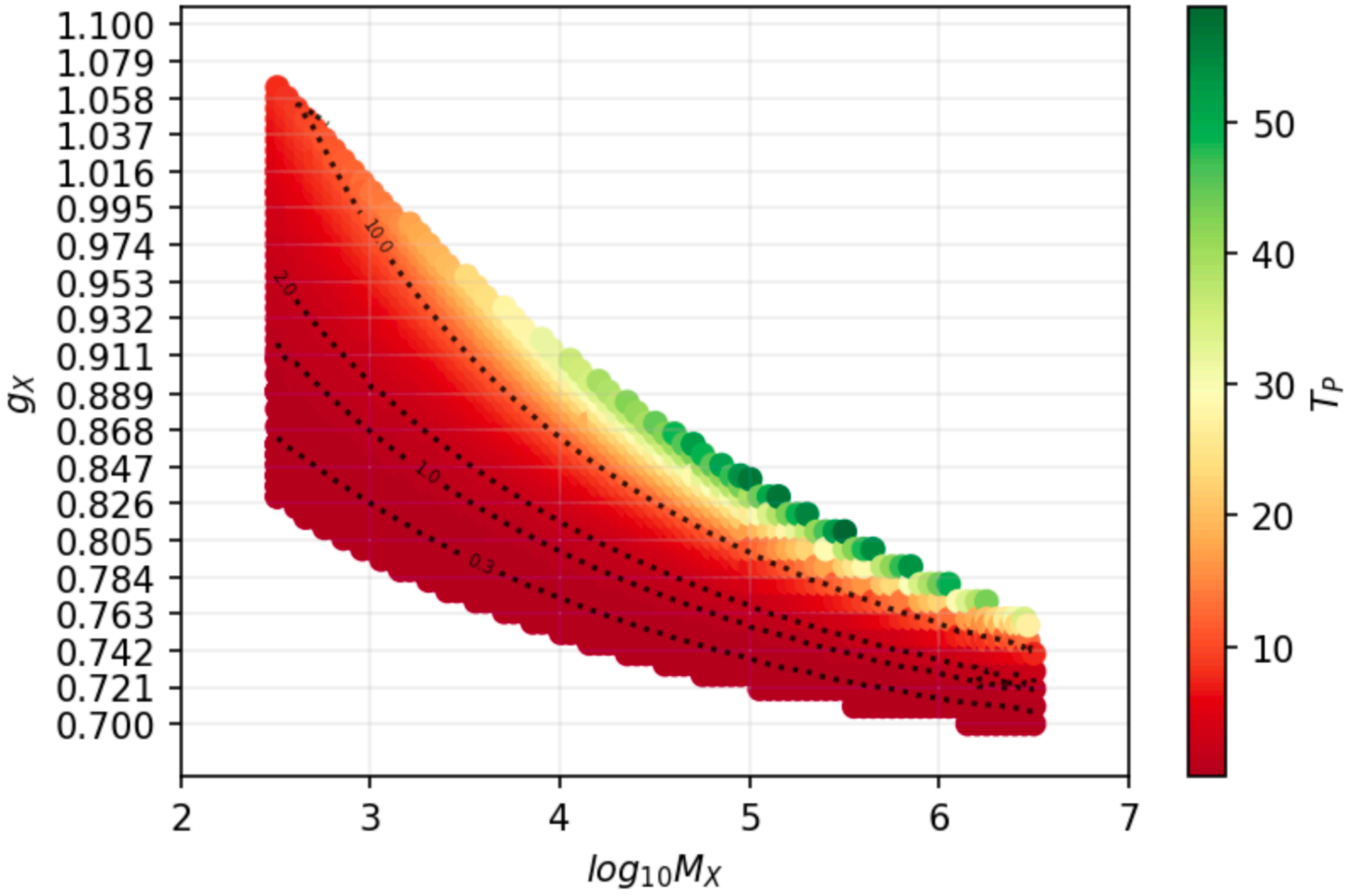


[Inspired by a talk by Pedro Schwaller]

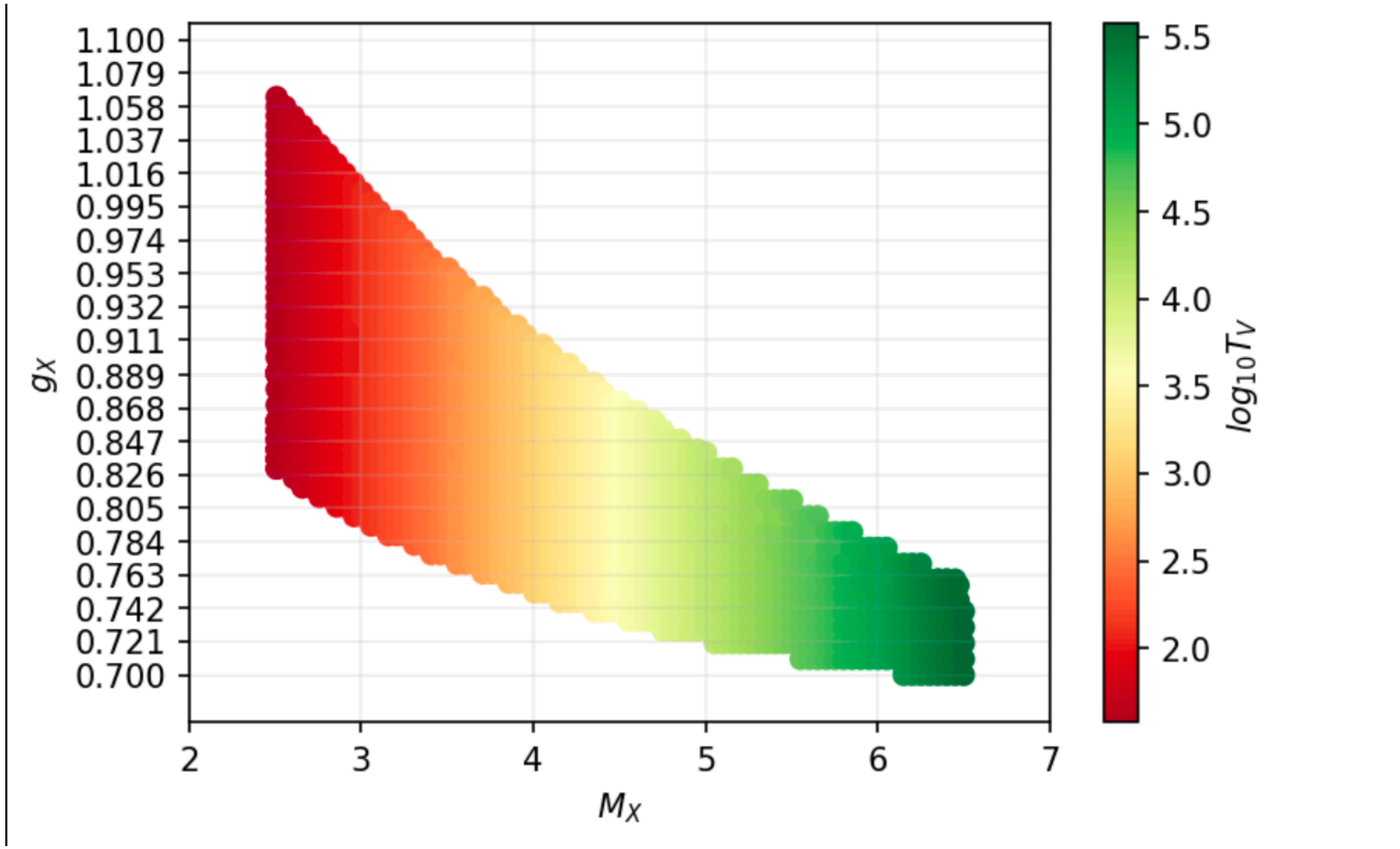
GW PARAMETERS



GW PARAMETERS



GW PARAMETERS



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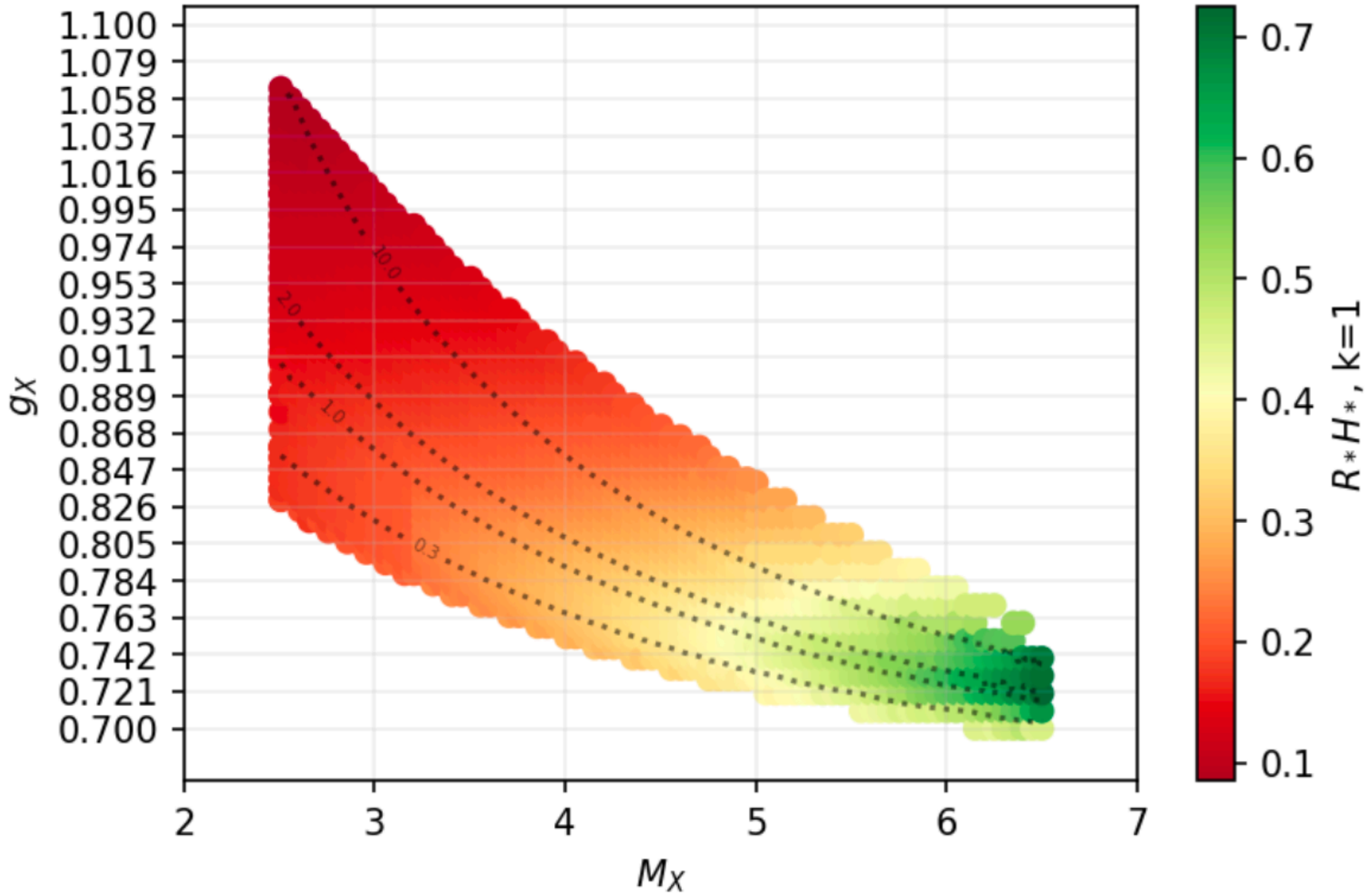
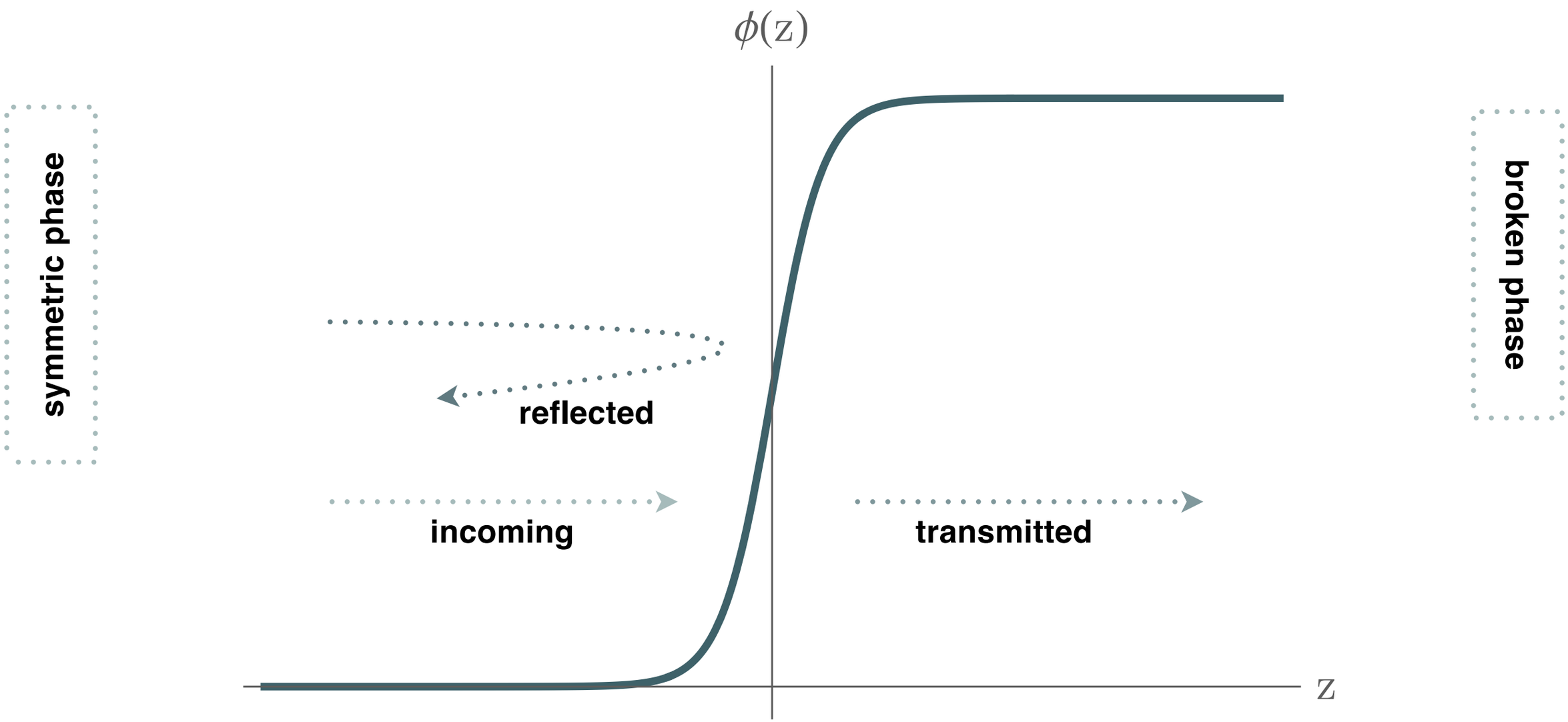
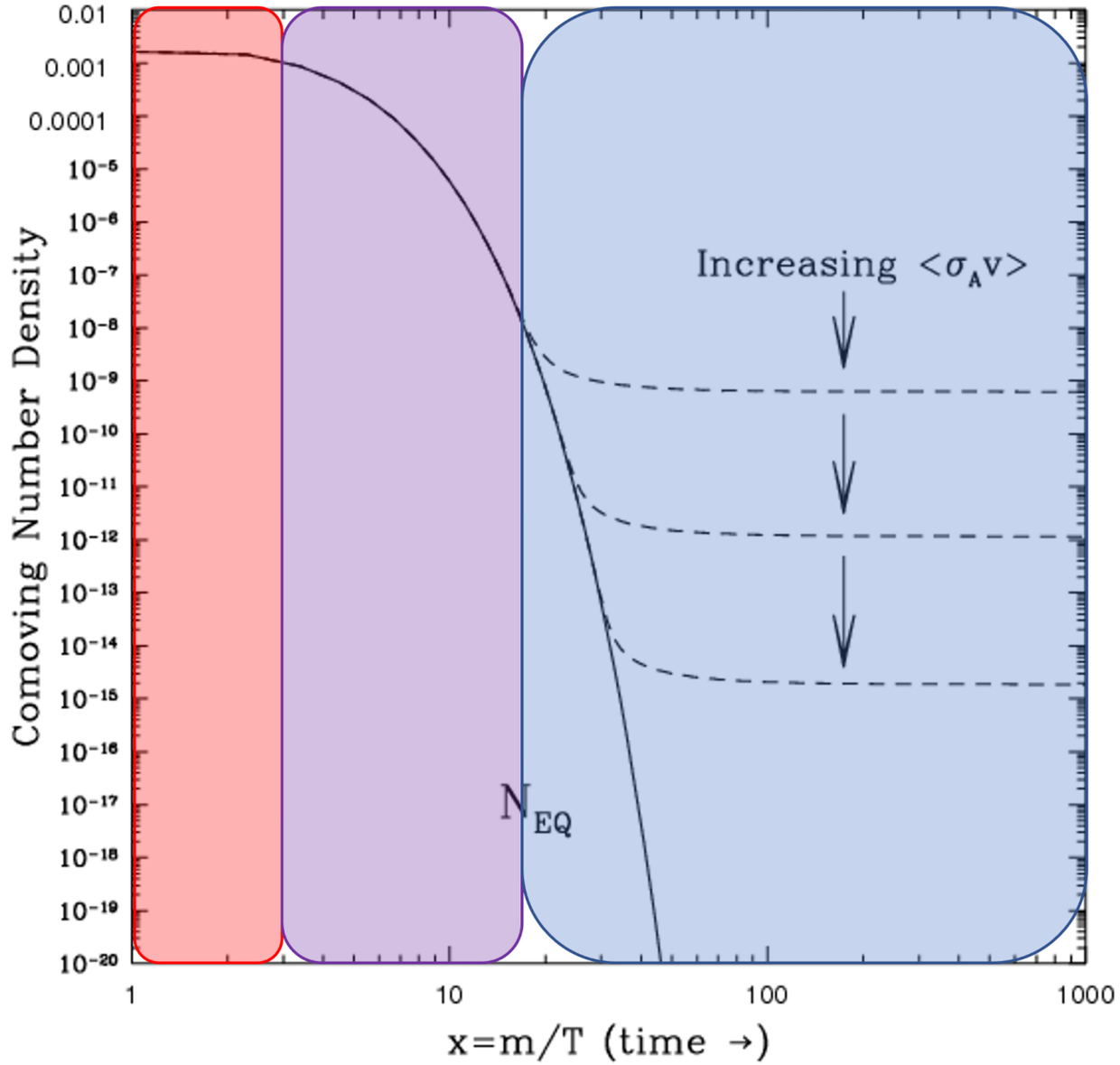


SOUND WAVES OR BUBBLE COLLISIONS?



[G.D. Moore, T. Prokopec, PRL 75 (1995), PRD 52 (1995), P.B. Arnold, PRD 48 (1993) 1539, D. Bodeker, G.D. Moore, JCAP 0905 (2009) 009; JCAP 1705 (2017) 025, G.C. Dorsch, S. J. Huber and T. Konstandin, JCAP 12 (2018); 2106.06547, T. Konstandin, G. Nardini and I. Rues, JCAP 09 (2014), J.Kozaczuk, JHEP 10 (2015), S. Höche et al, 2007.10343, Y. Gouttenoire, R. Jinno, F. Sala, 2112.07686]

STANDARD FREEZE-OUT



[from Colb and Turner, adapted by particle bites.com]