GRAVITATIONAL-WAVE SIGNALS FROM A SUPERCOOLED PHASE TRANSITION AND HOW TO COMPUTE THEM

Bogumiła Świeżewska

University of Warsaw

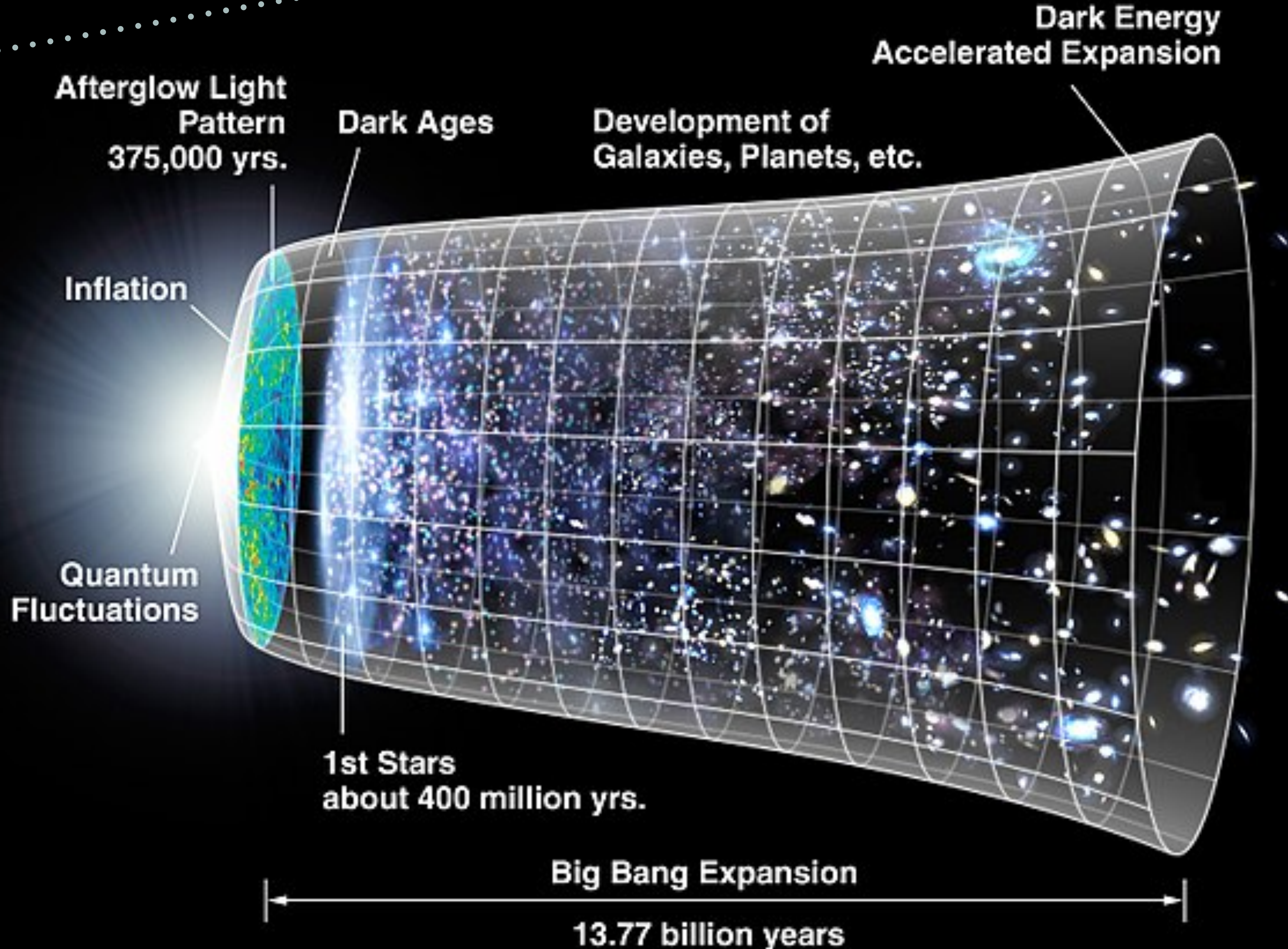
in collaboration with
Maciej Kierkla, Alexandros Karam,
Jorinde van de Vis, Tuomas Tenkanen

based on
JHEP 03 (2023) 007
and work in progress

SCALARS 2023, Warsaw, 15.09.2023

PHASE TRANSITION IN THE VERY EARLY UNIVERSE

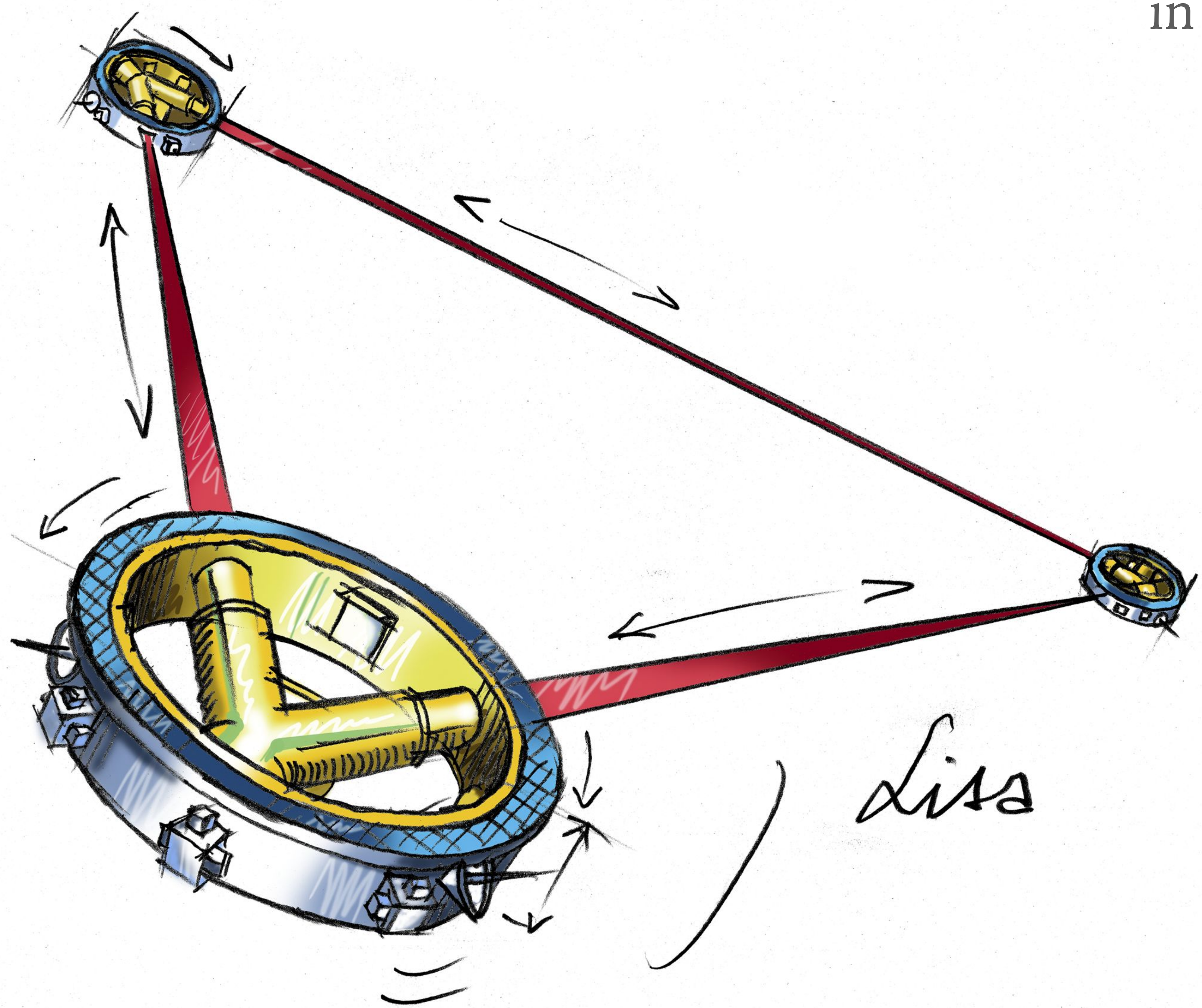
phase transition $\sim 10^{-11}$ s



[Image Credit: NASA]

LISA IS COMING!

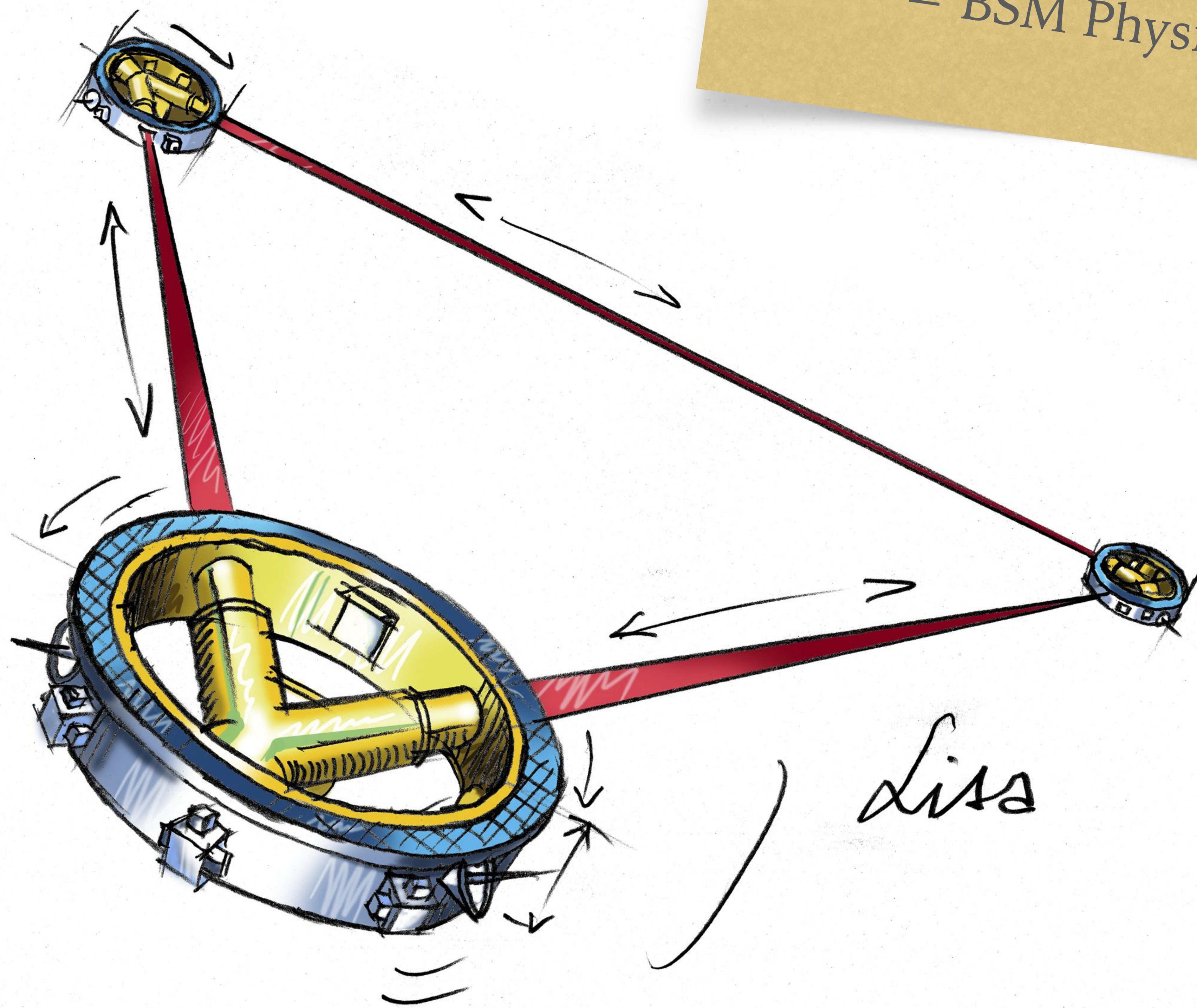
in the 2030's



[Image credit: ESA-C. Vijoux]

LISA IS COMING!

First-order phase transition
= BSM Physics!

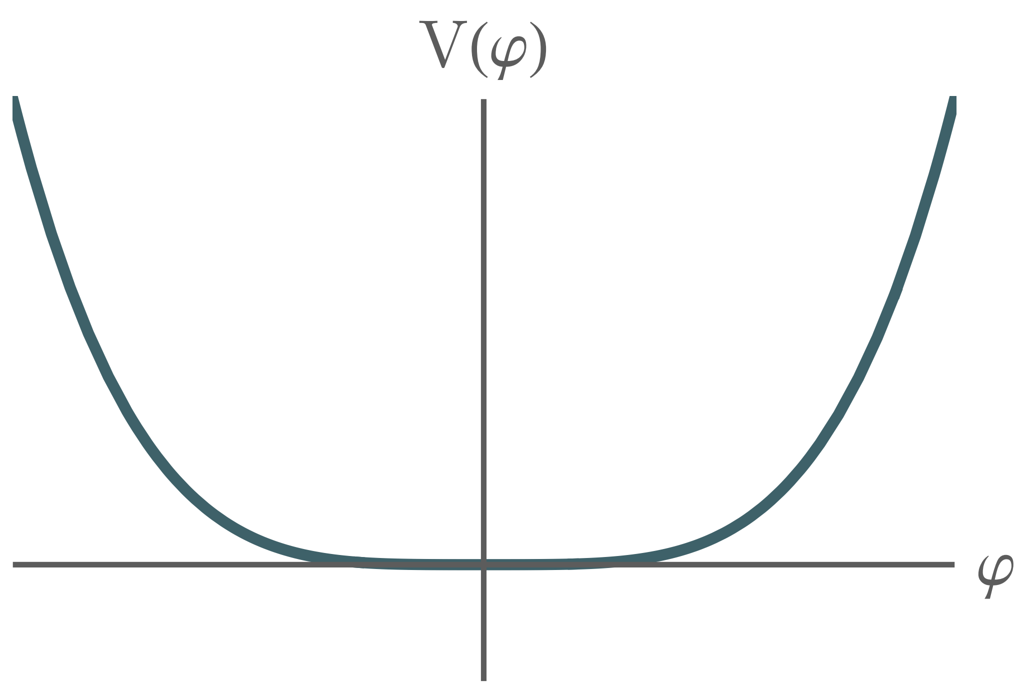


[Image credit: ESA-C. Vijoux]

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

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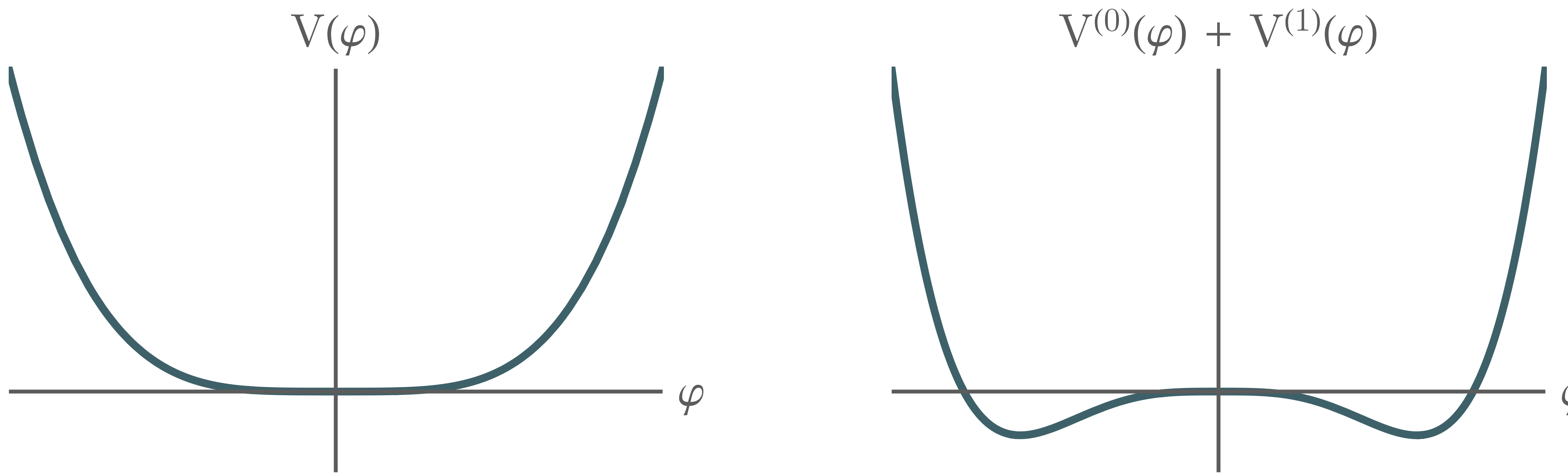


Symmetry broken by loop corrections (dimensional transmutation)

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

WHY CLASSICAL CONFORMAL SYMMETRY?

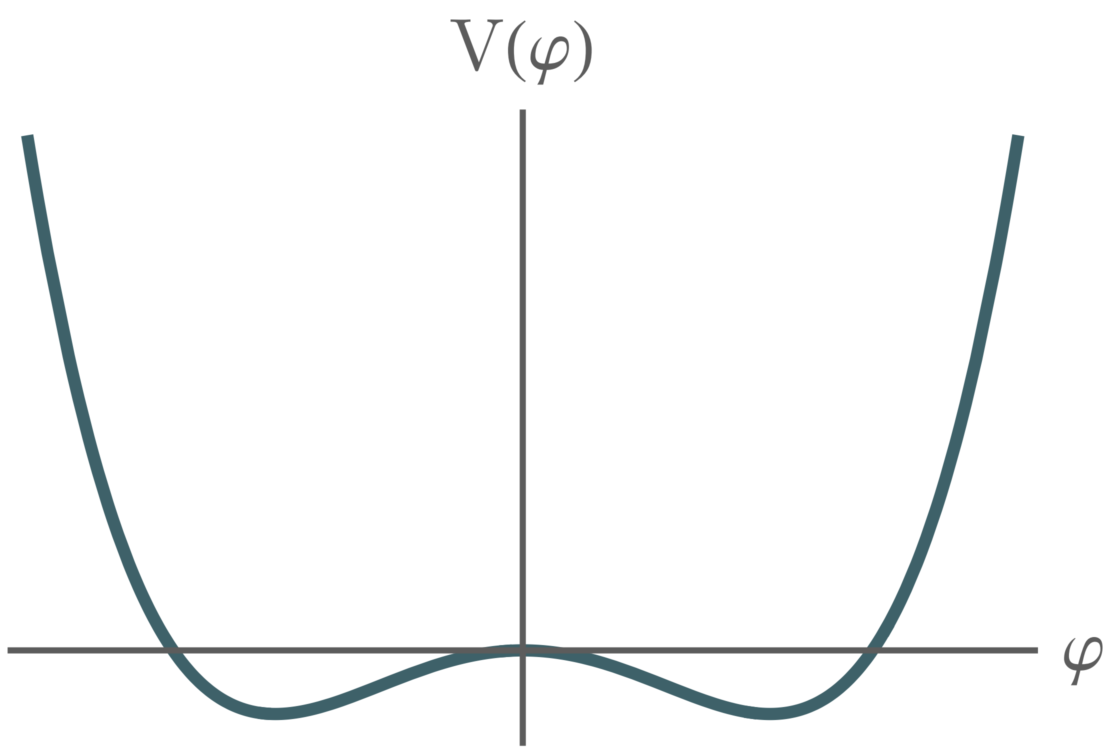
dynamical generation of all mass scales

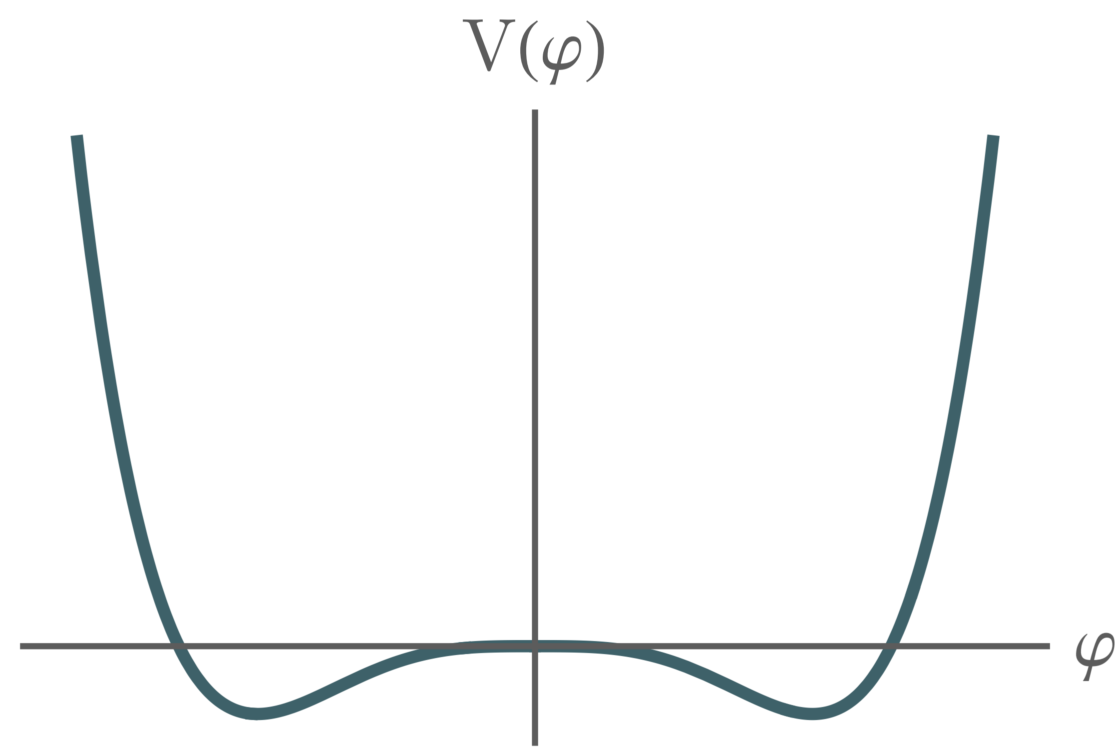
predictivity - few free parameters

generically strong GW signal testable with LISA

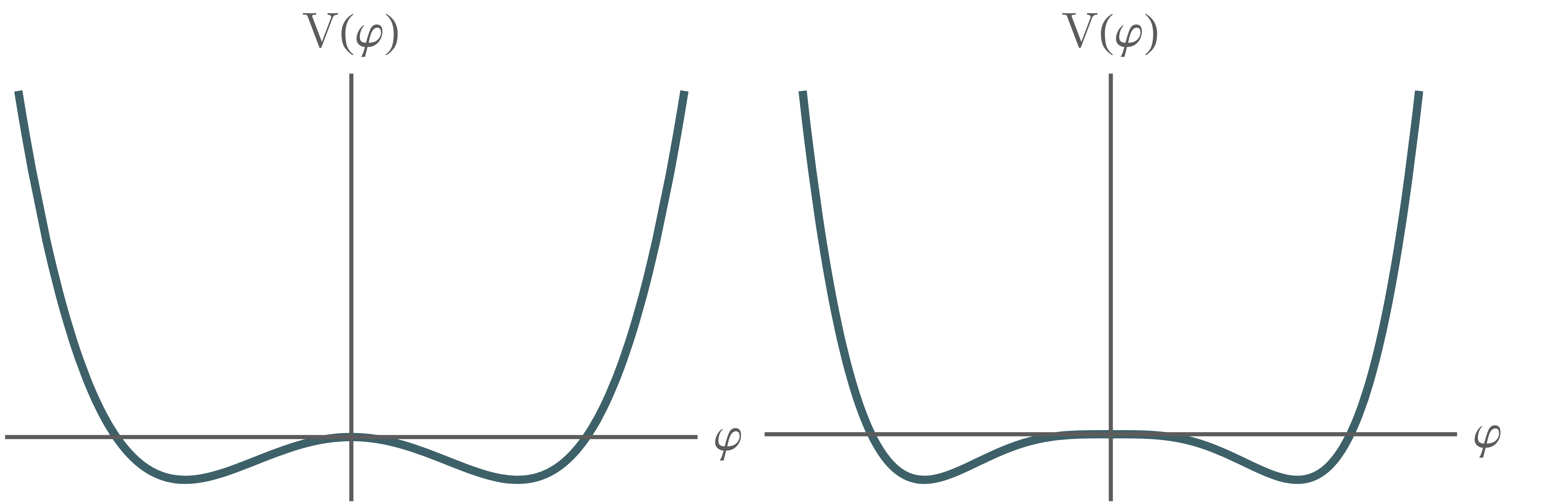
+ DM candidate

CONFORMAL VS "NORMAL" POTENTIAL





CONFORMAL VS "NORMAL" POTENTIAL



The thermal barrier can last until low temperatures

↓

Potential for supercooling and strong transition

THE MODEL: SU(2)CSM

cSM:
$SU(2)_L \times U(1)_Y$
h

Hidden sector:
$SU(2)_X$
φ

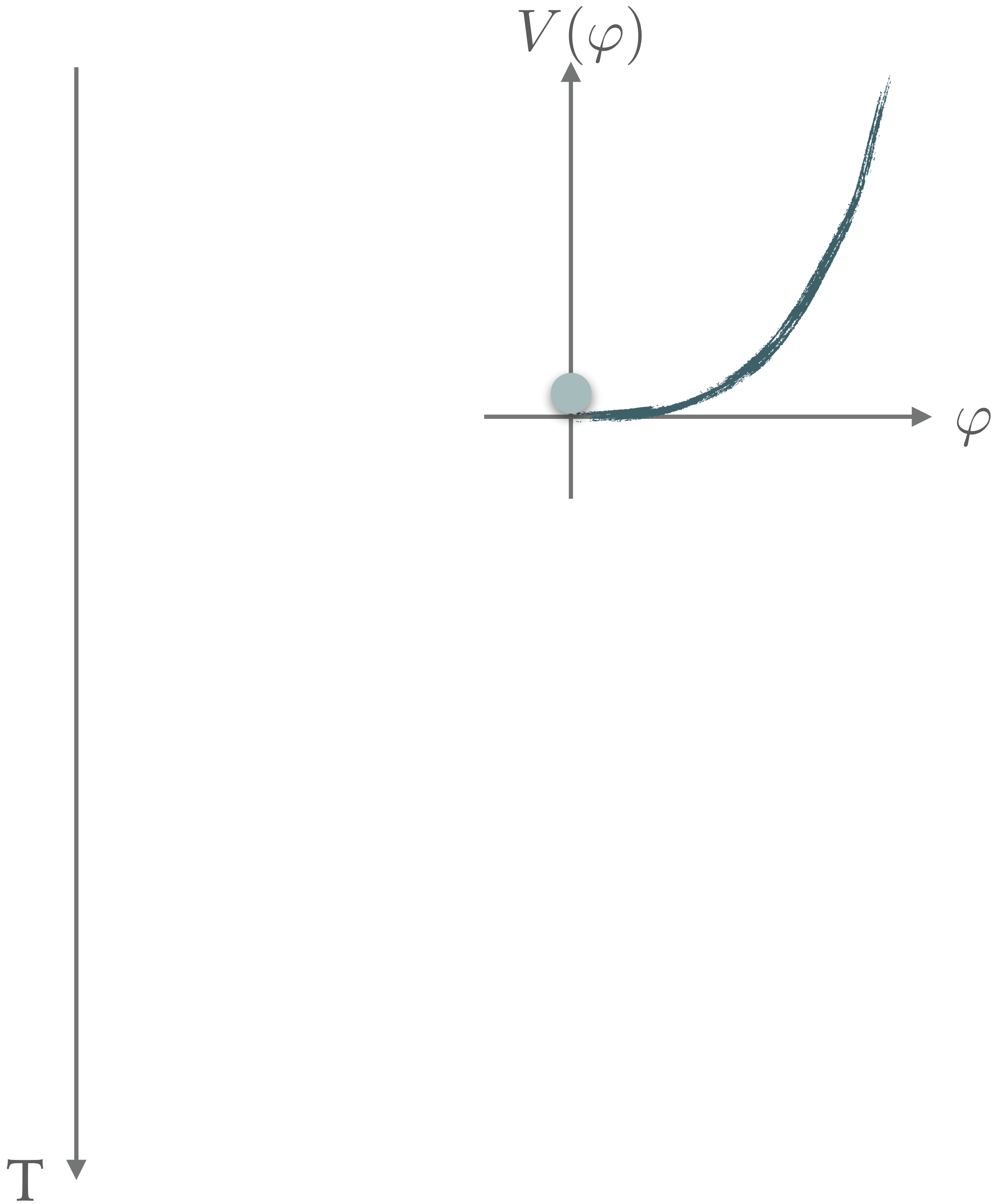
$$V = \frac{1}{4}\left(\lambda_1 h^4 + \lambda_2 h^2\varphi^2 + \lambda_3\varphi^4\right)$$

[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]

SUPERCOOLED PHASE TRANSITION IN THE EARLY UNIVERSE

TEMPERATURE EVOLUTION

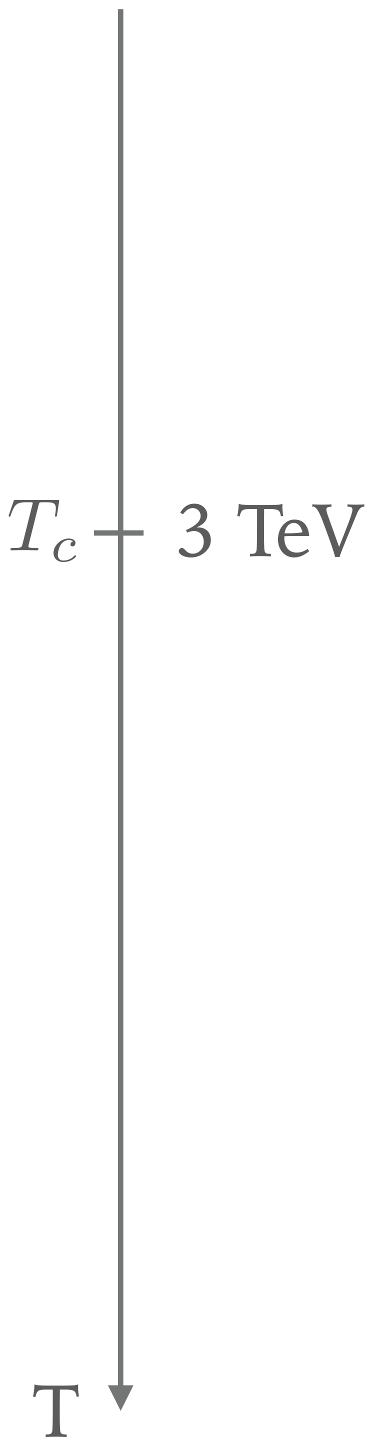
$M_X = 9$ TeV, $g_X = 0.9$

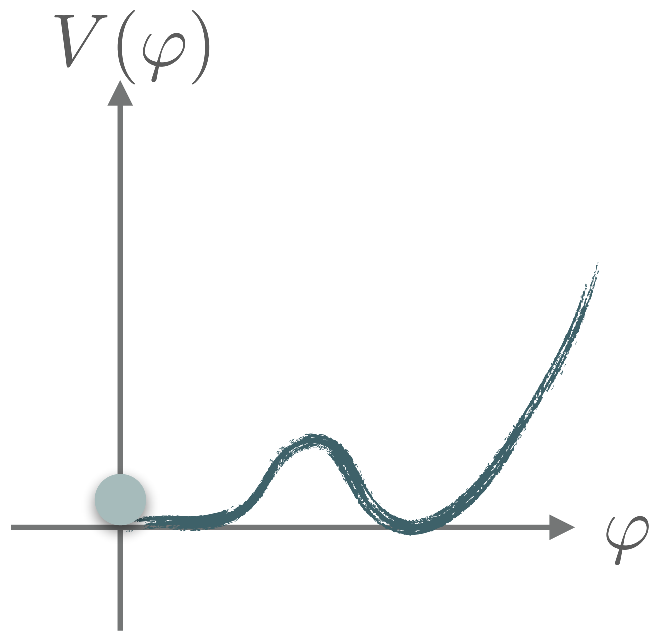


high temperature:
EW and conformal
symmetry restored

TEMPERATURE EVOLUTION

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

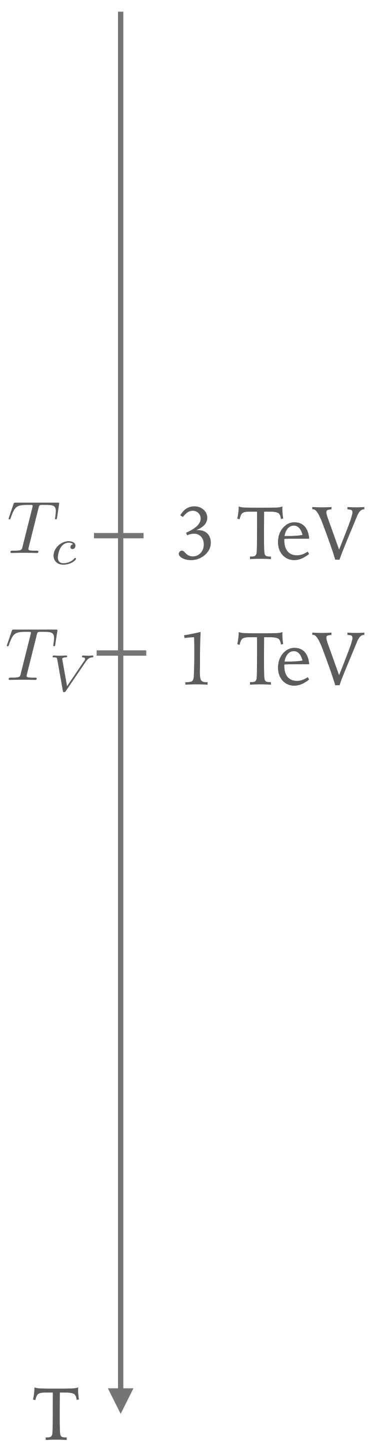


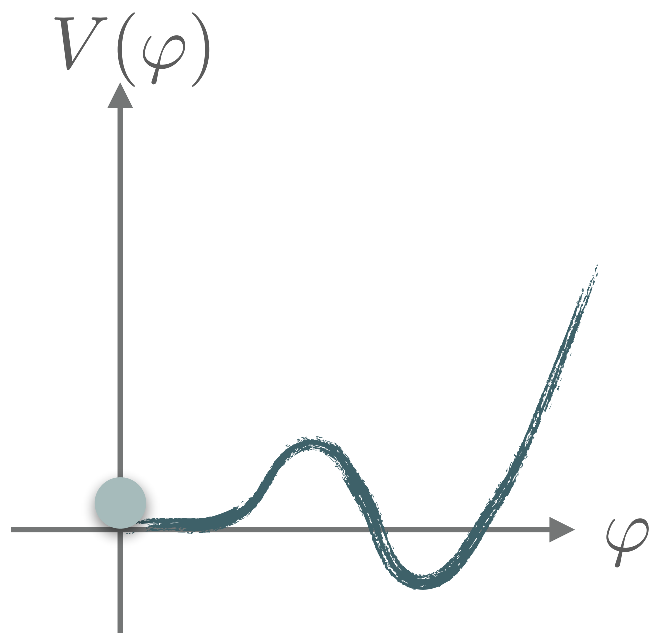


critical temperature:
two degenerate
minima

TEMPERATURE EVOLUTION

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



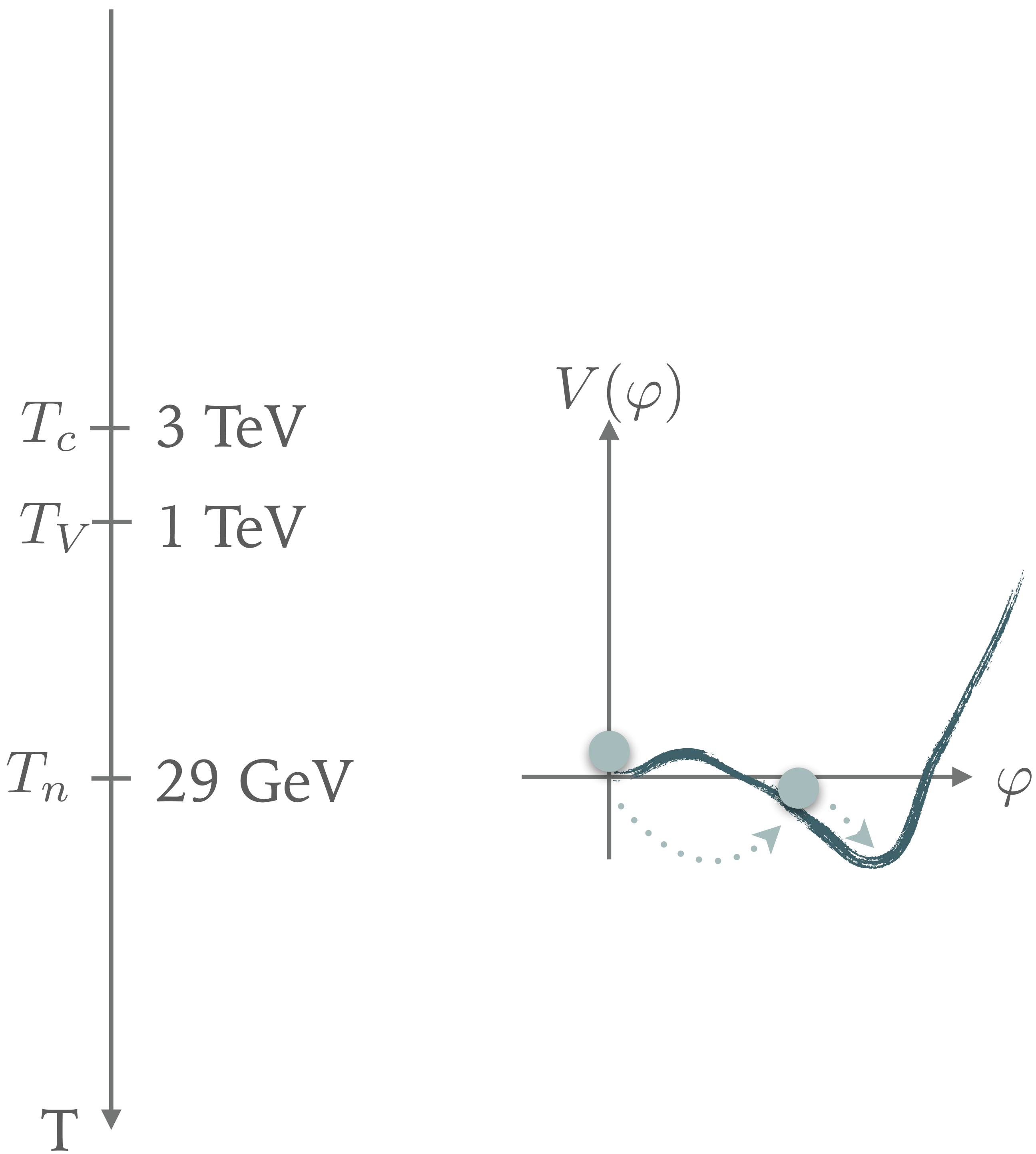


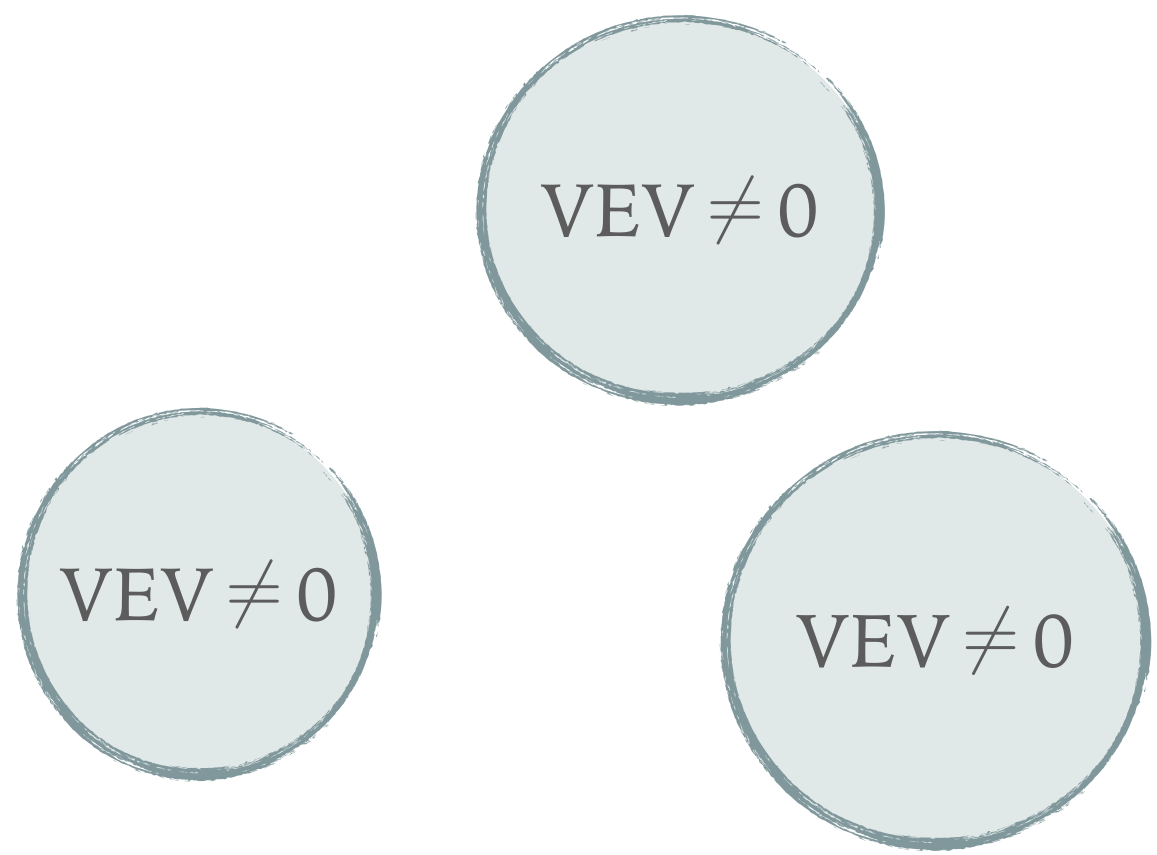
vacuum domination begins

TEMPERATURE EVOLUTION

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

nucleation:
one bubble nucleates
per Hubble volume

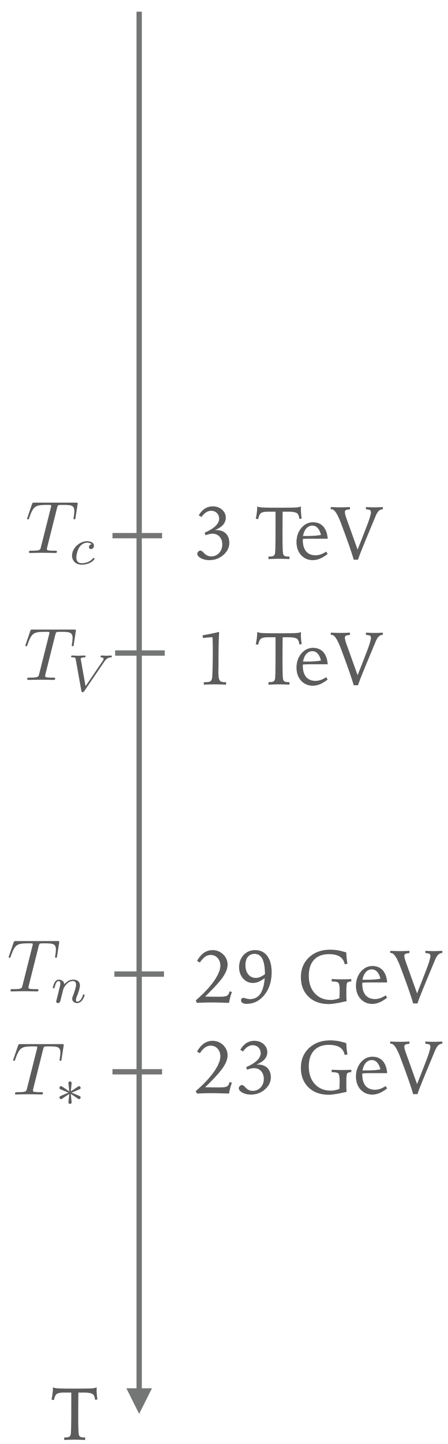


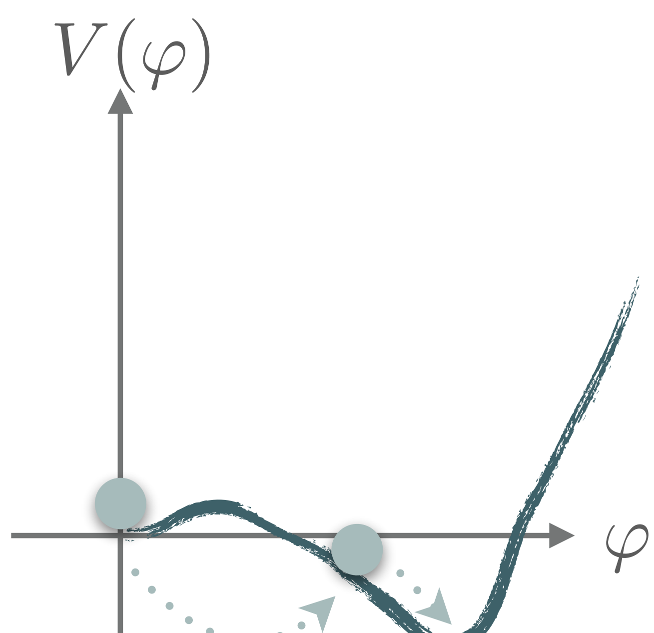


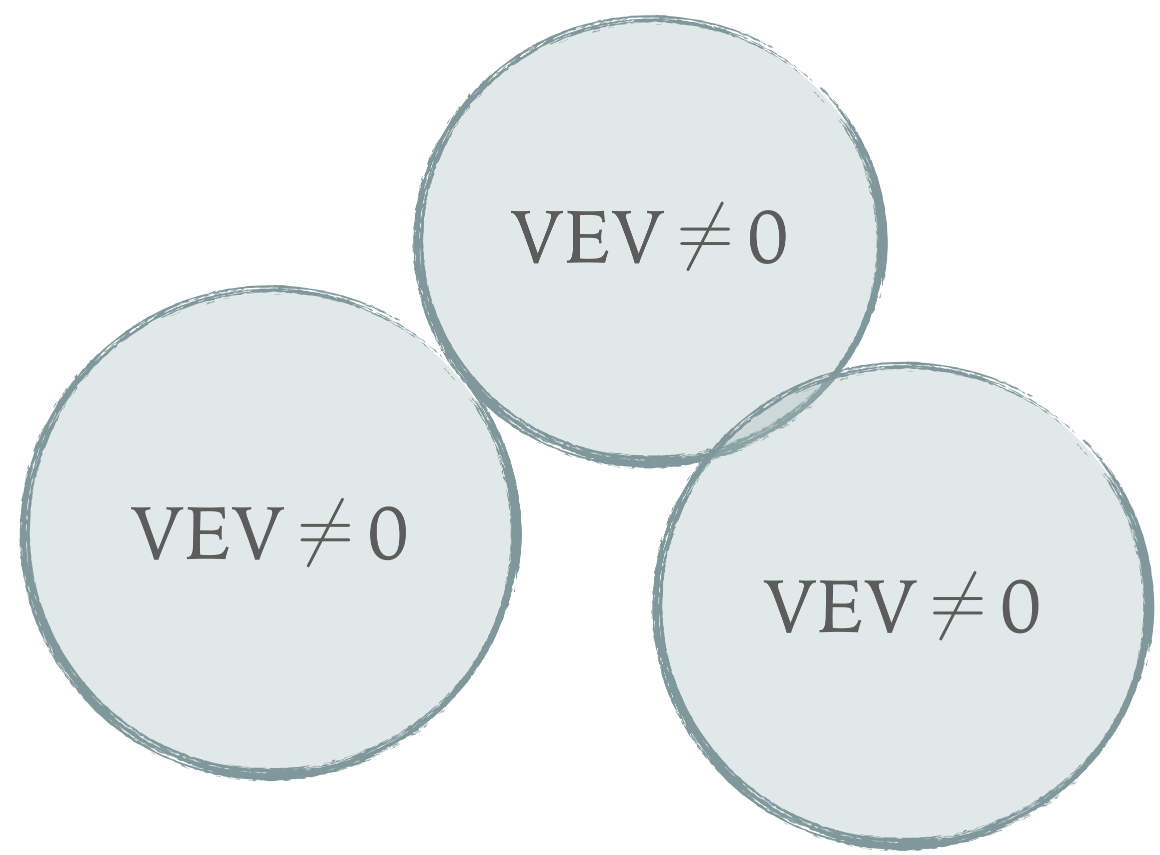
TEMPERATURE EVOLUTION

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

Percolation: phase transition completes







TEMPERATURE EVOLUTION

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

reheating: vacuum energy $\rightarrow$ radiation

T_c — 3 TeV

T_V — 1 TeV $T_{\rm reh}$

T_n — 29 GeV

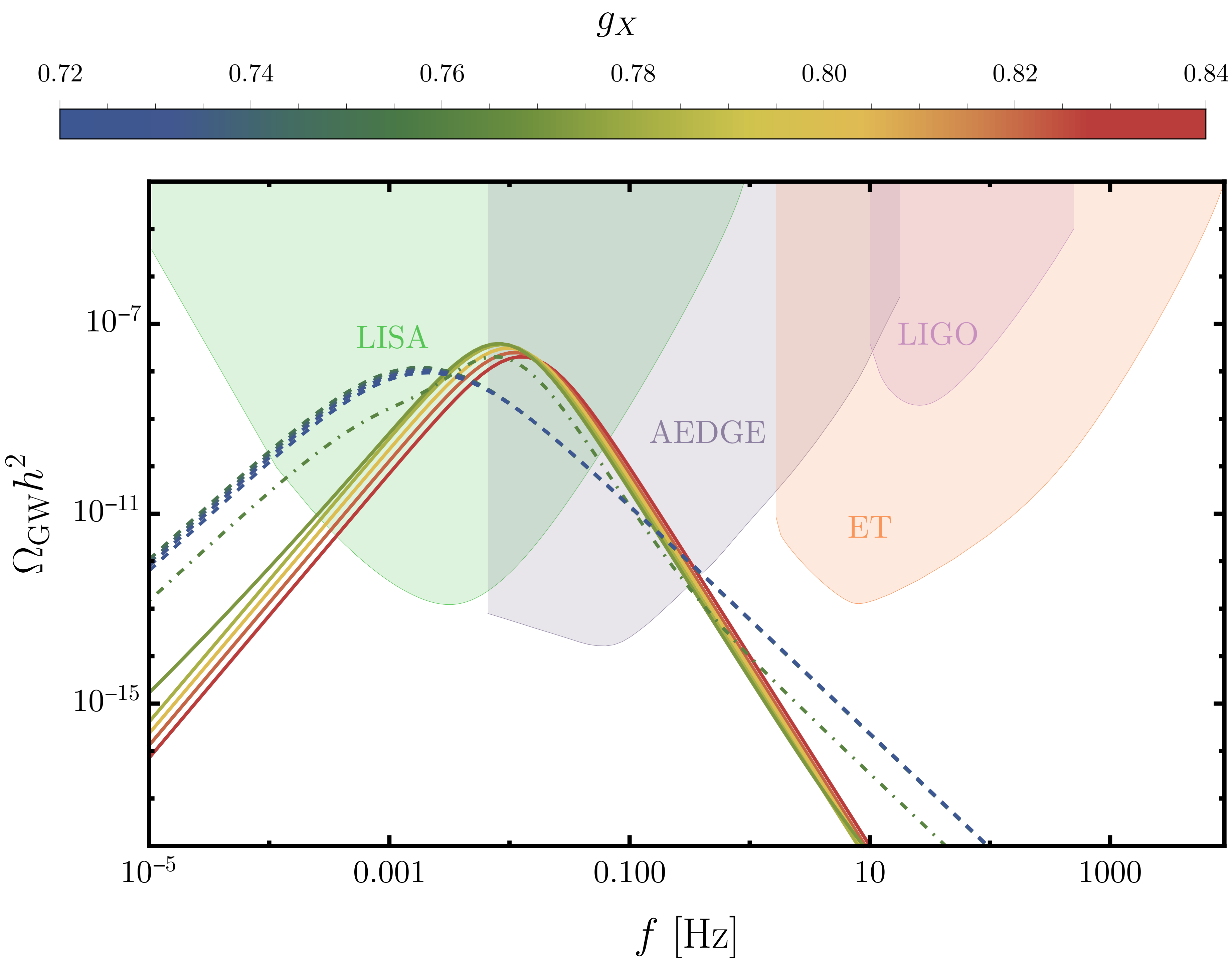
T_* — 23 GeV

T

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

GRAVITATIONAL WAVES IN SU(2)CSM

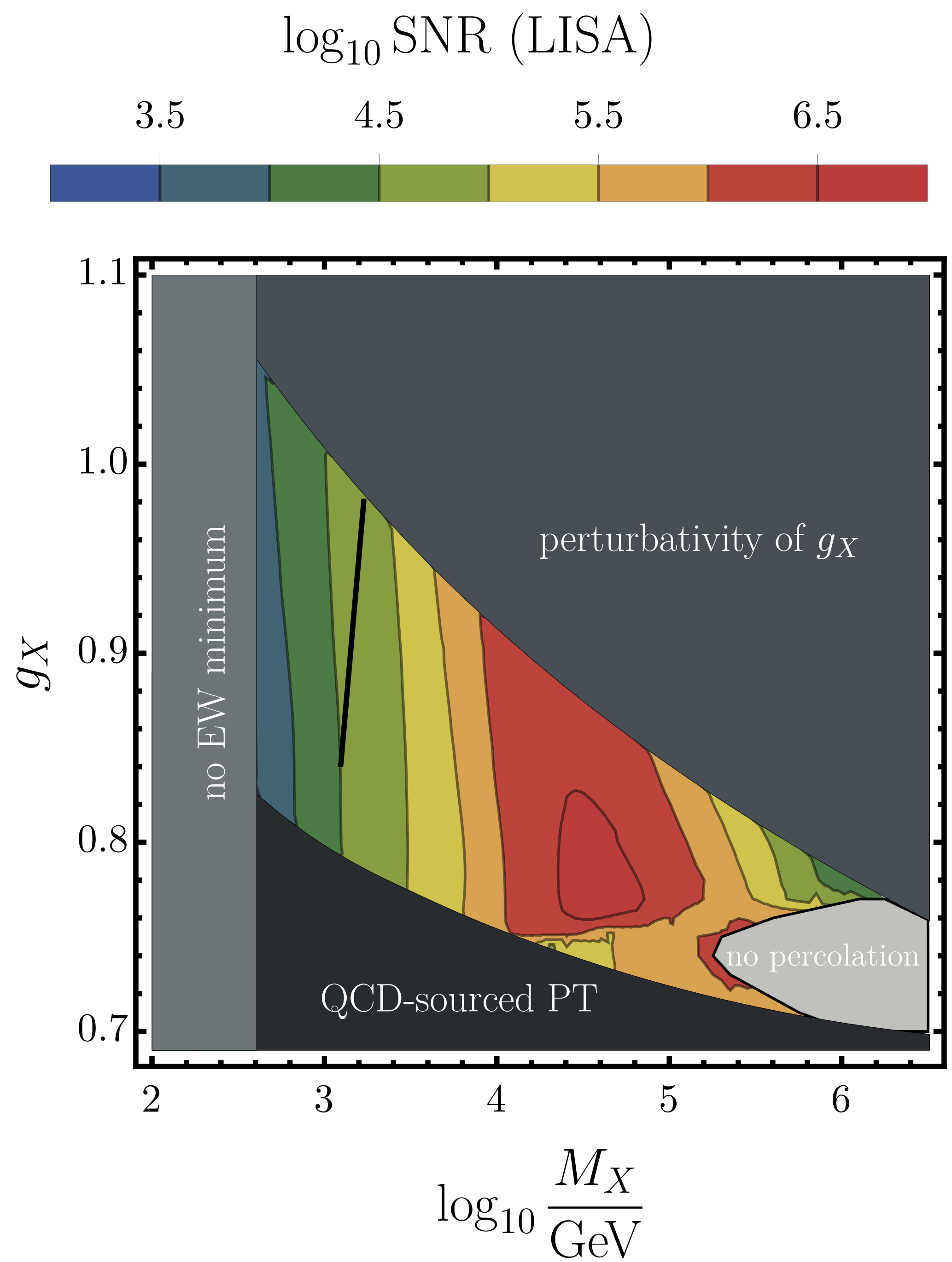
GRAVITATIONAL WAVE SPECTRA



$M_X = 10^5\,\mathrm{GeV}$

[M.Kierkla, A.Karam, BS, JHEP 03 (2023) 007]

SIGNAL-TO-NOISE RATIO



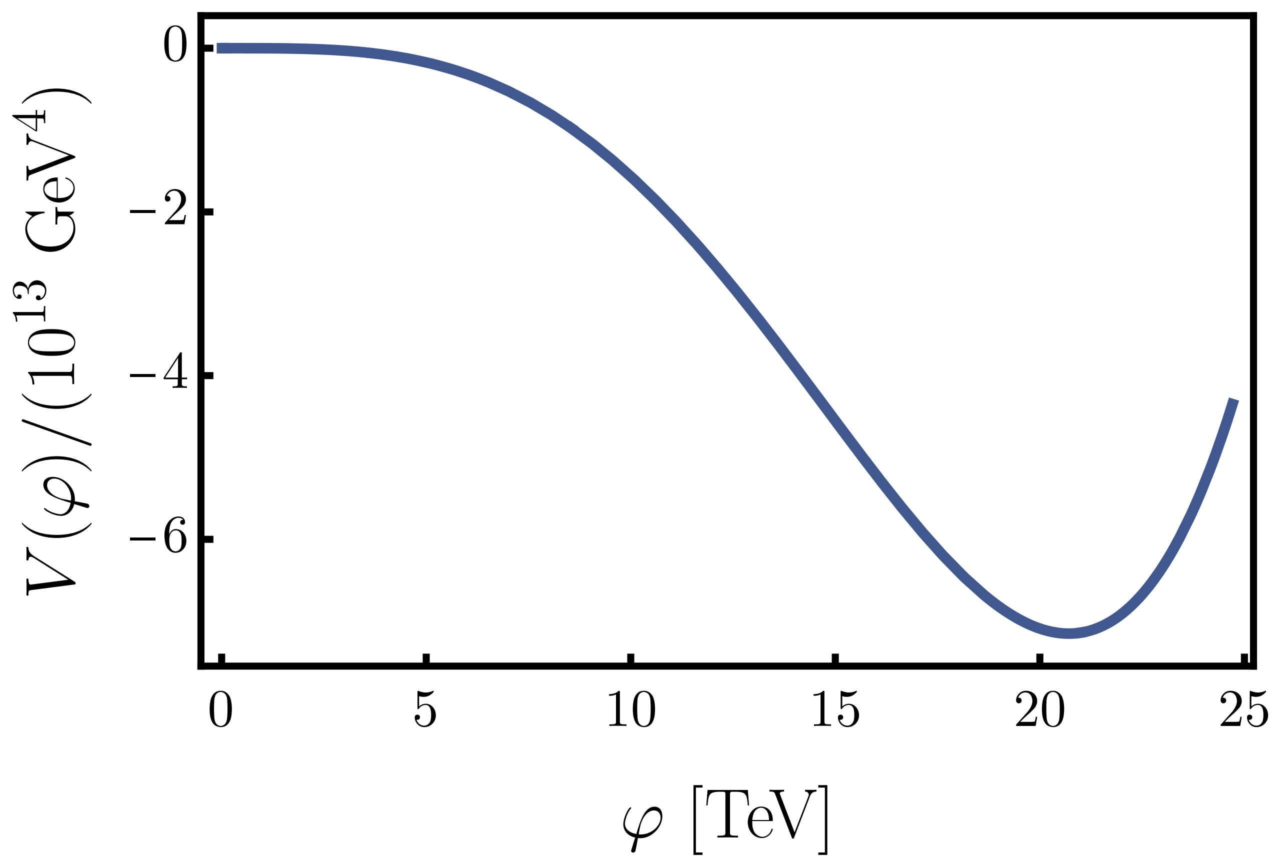
[M.Kierkla, A.Karam, BS, JHEP 03 (2023) 007]

TAKE-HOME MESSAGE

First-order phase transition in SU(2)cSM
falsifiable through GW!

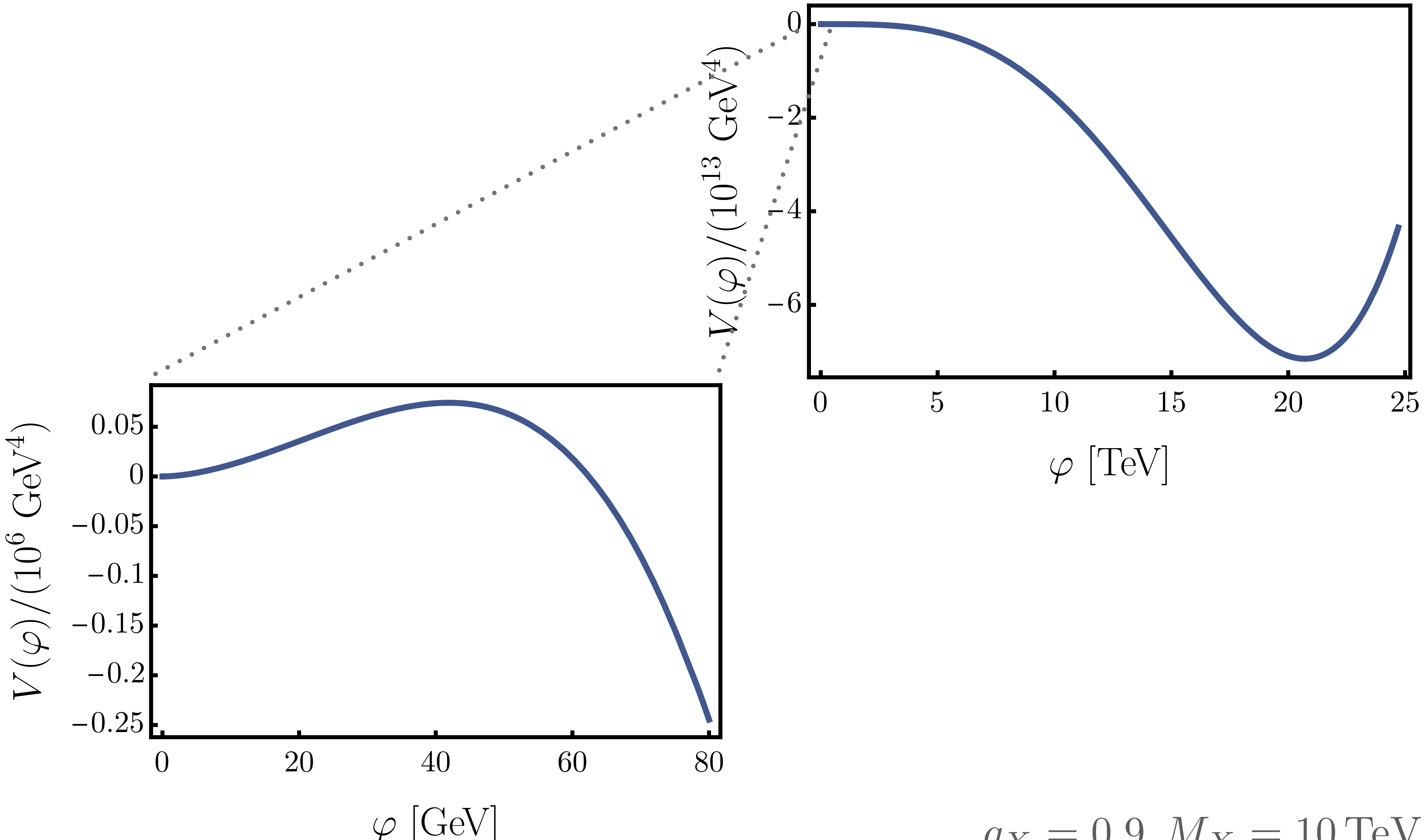
. . . AND HOW TO COMPUTE THEM

DIFFERENT SCALES INVOLVED



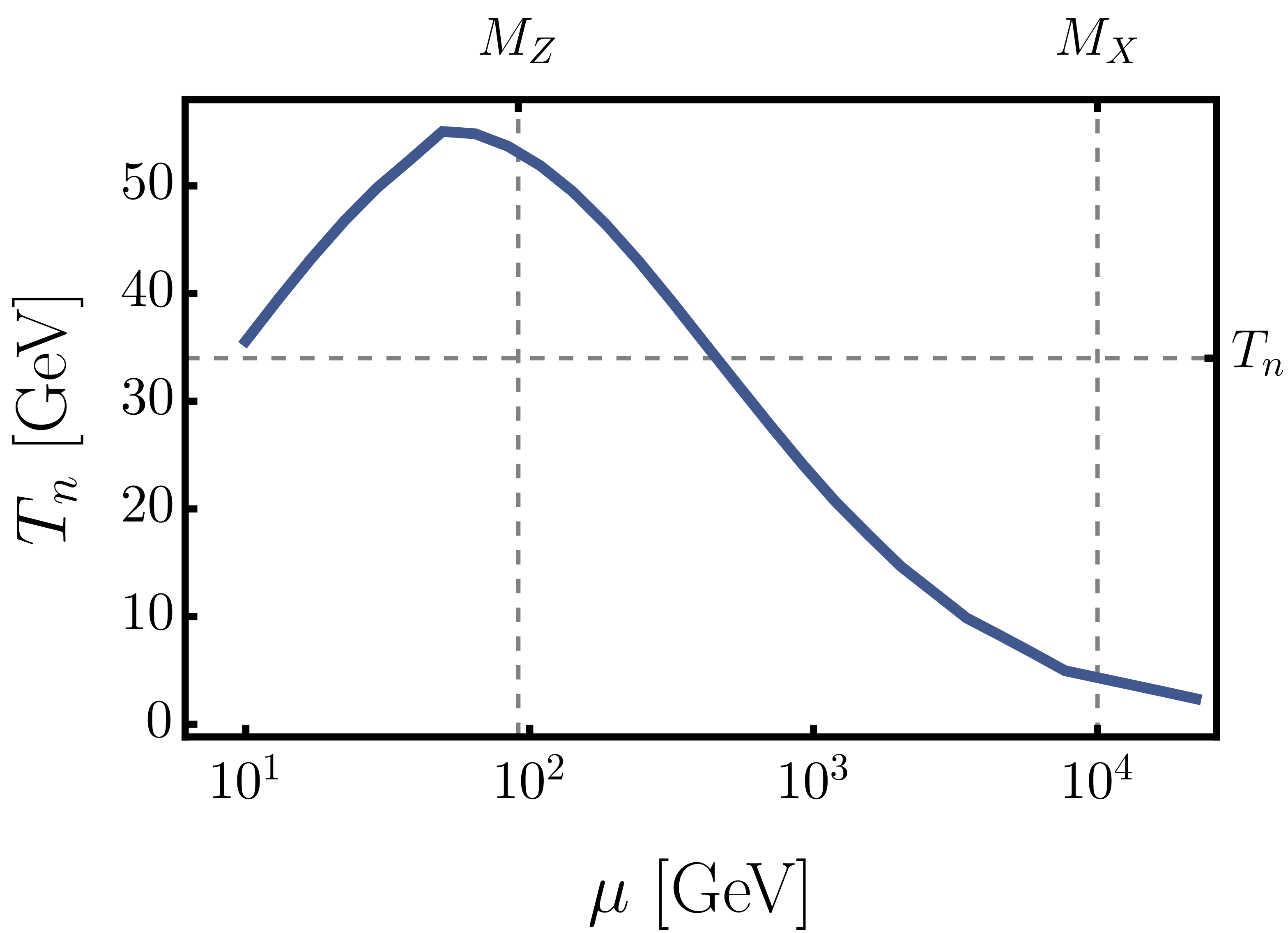
$g_X = 0.9, M_X = 10\,\mathrm{TeV}$

DIFFERENT SCALES INVOLVED

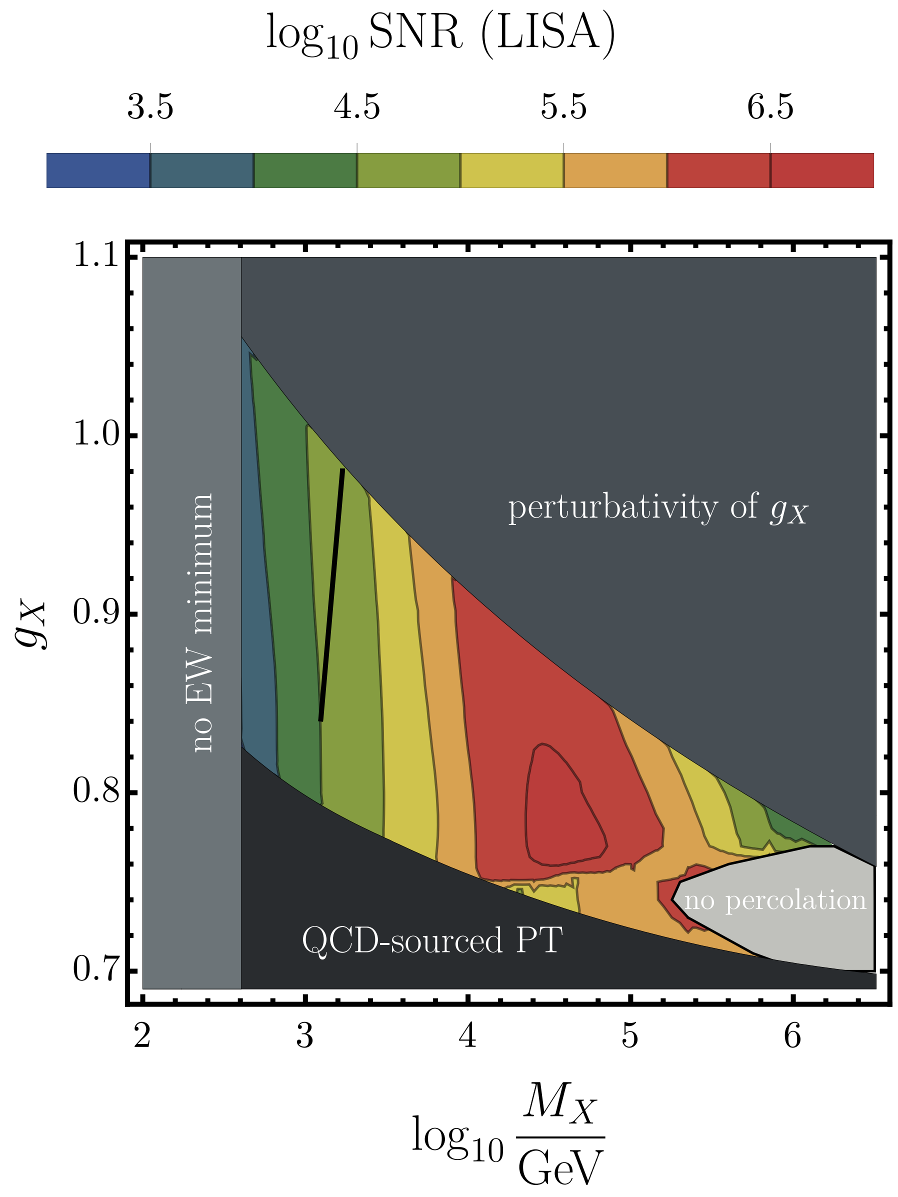


$g_X = 0.9, M_X = 10\,\mathrm{TeV}$

SCALE DEPENDENCE OF NUCLEATION

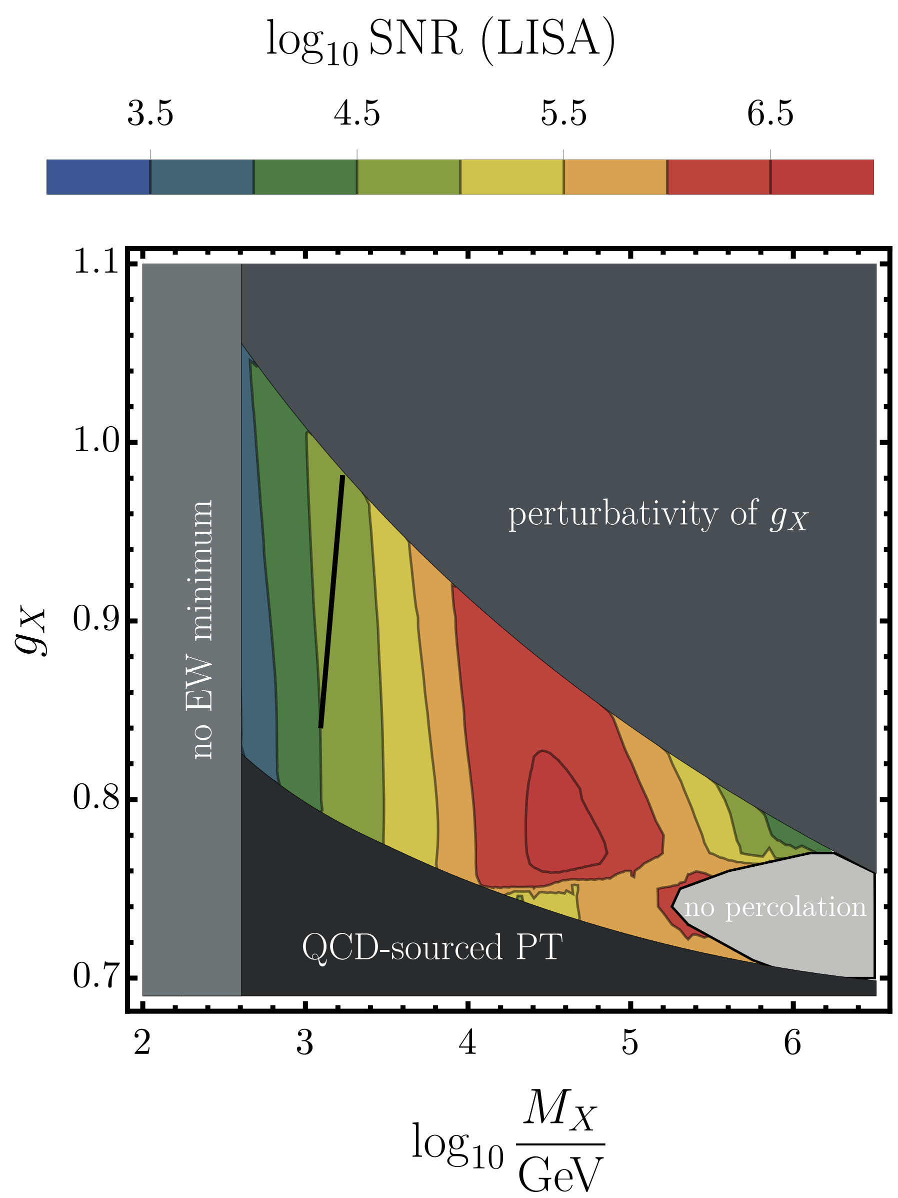


SCALE DEPENDENCE OF SNR



[M.Kierkla, A.Karam, BS, JHEP 03 (2023) 007]

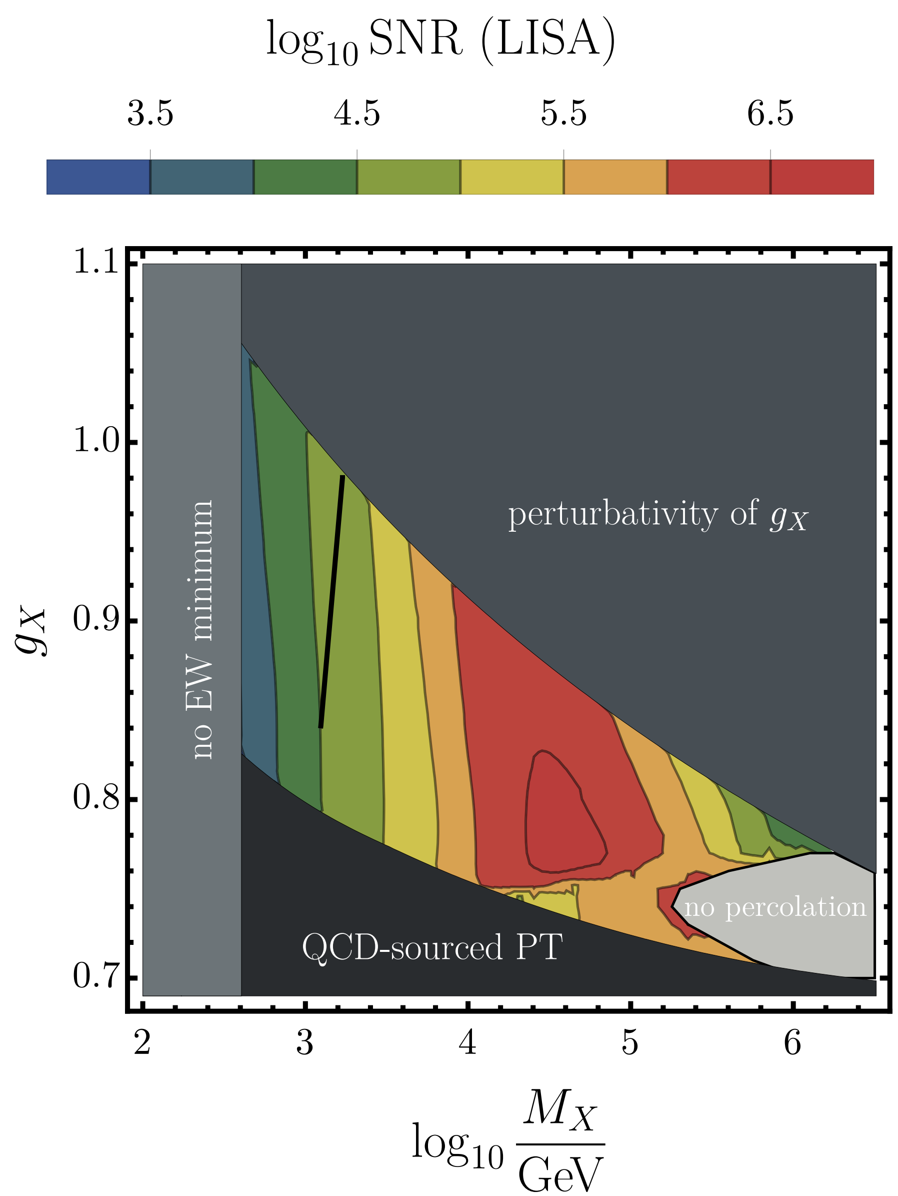
SCALE DEPENDENCE OF SNR

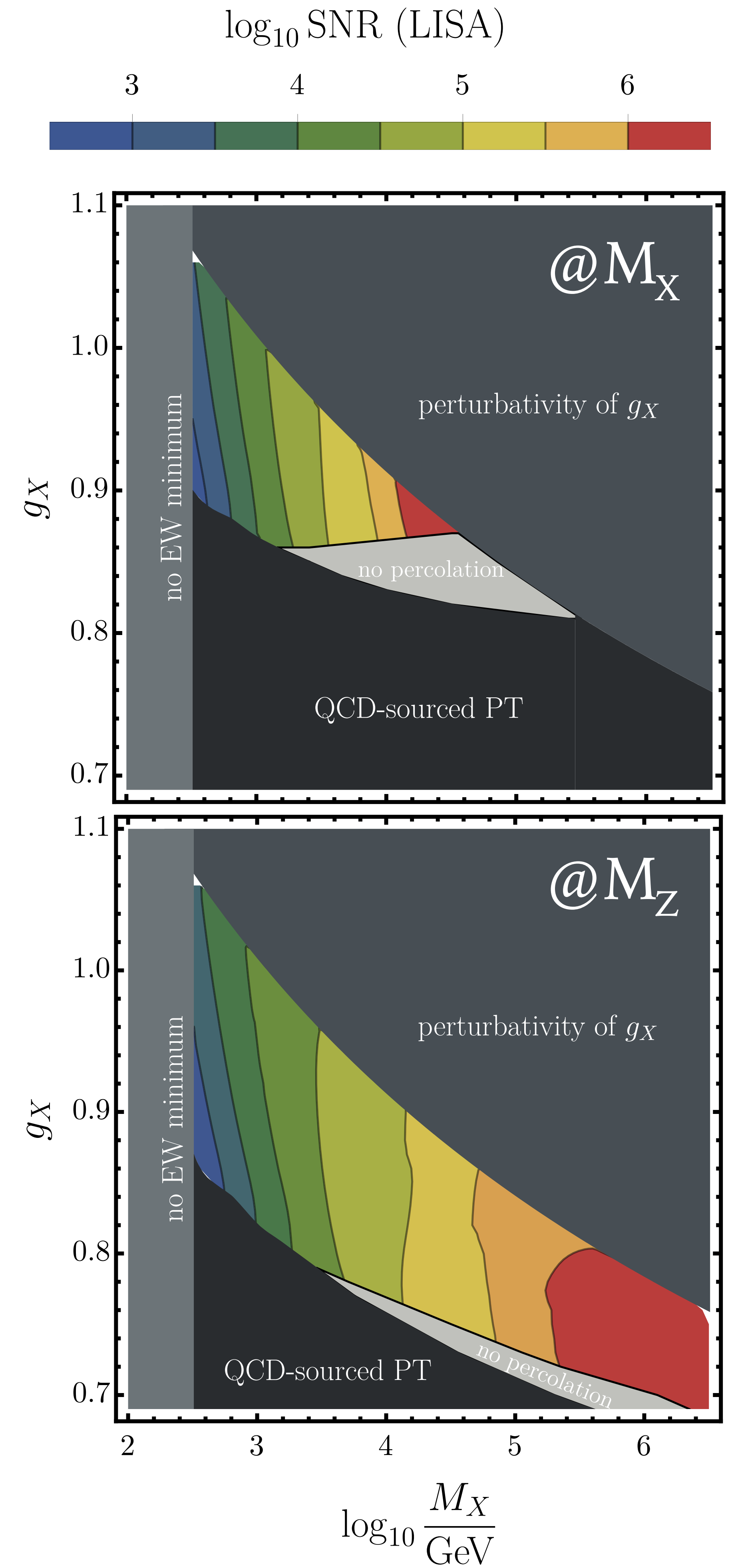


- RG-improvement
- Careful expansion in g_X

[M.Kierkla, A.Karam, BS, JHEP 03 (2023) 007]

SCALE DEPENDENCE OF SNR





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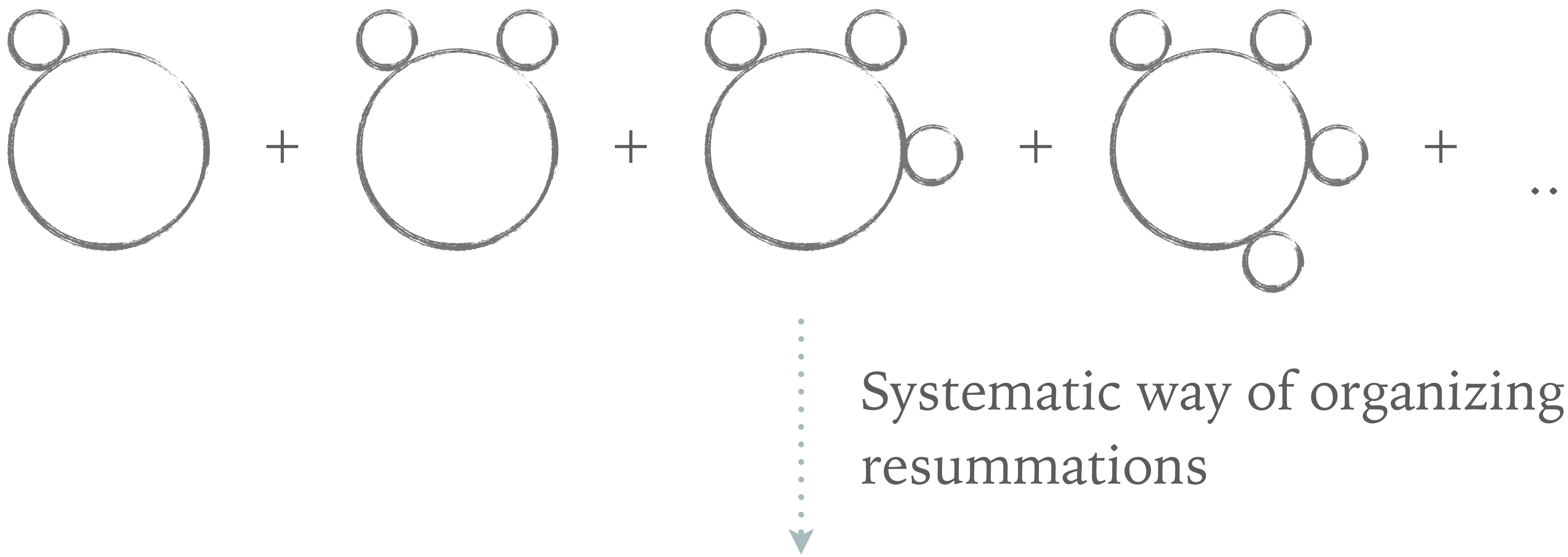
[M.Kierkla, A.Karam, BS, JHEP 03 (2023) 007]

DIMENSIONAL REDUCTION (DR)



Systematic way of organizing resummations

<u>Dimensional reduction:</u>
effective field theory in the presence of temperature-related energy scales

DIMENSIONAL REDUCTION FOR SUPERCOOLED TRANSITIONS

DRalgo can do DR for us

DR requires high-temperature expansion

[A. Ekstedt, P. Schicho, T. V.I. Tenkanen, Comput.Phys.Commun. 288 (2023) 108725]

DIMENSIONAL REDUCTION FOR SUPERCOOLED TRANSITIONS

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STAY TUNED

[A. Ekstedt, P. Schicho, T. V.I. Tenkanen, Comput.Phys.Commun. 288 (2023) 108725]

SUMMARY

SUMMARY

LISA will be able to probe models of fundamental interactions

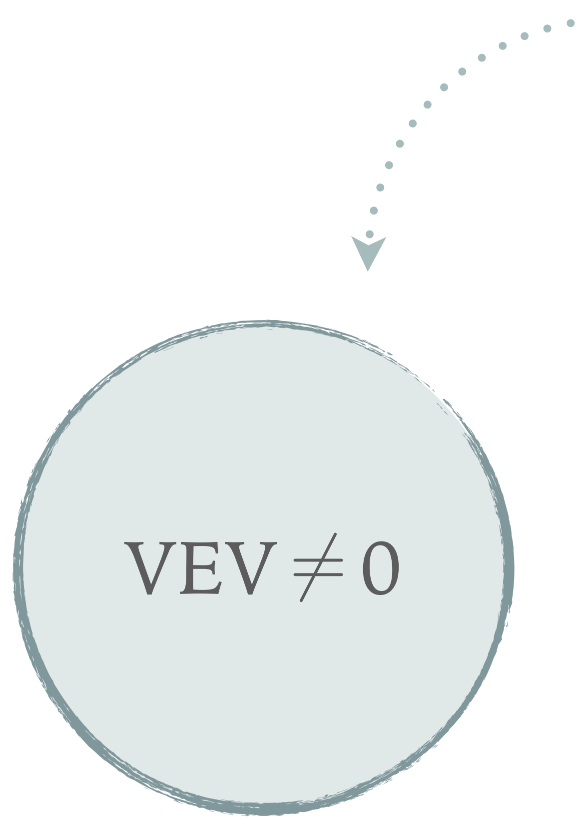
Theoretical uncertainties are still sizable: improvements needed before LISA

THANK YOU FOR YOUR ATTENTION

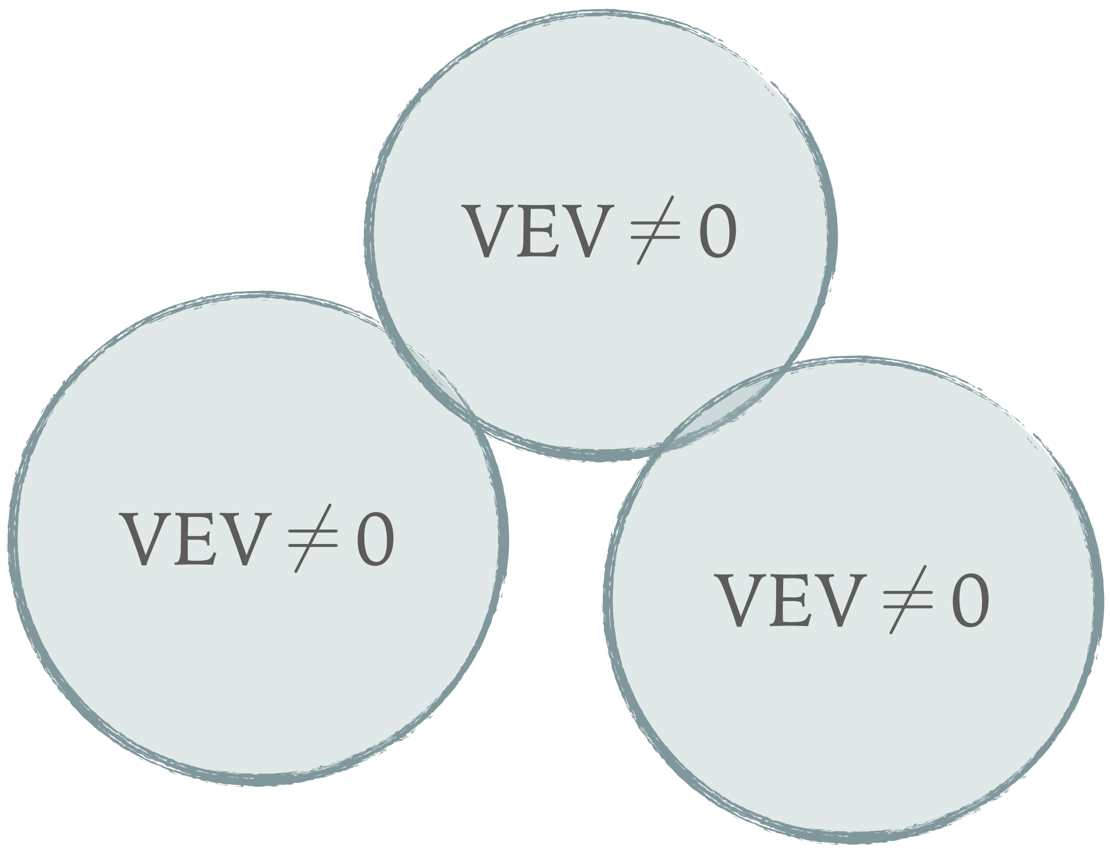
National Science Centre
Poland

GRAVITATIONAL-WAVE GENERATION DURING PT

SOURCES OF GRAVITATIONAL WAVES

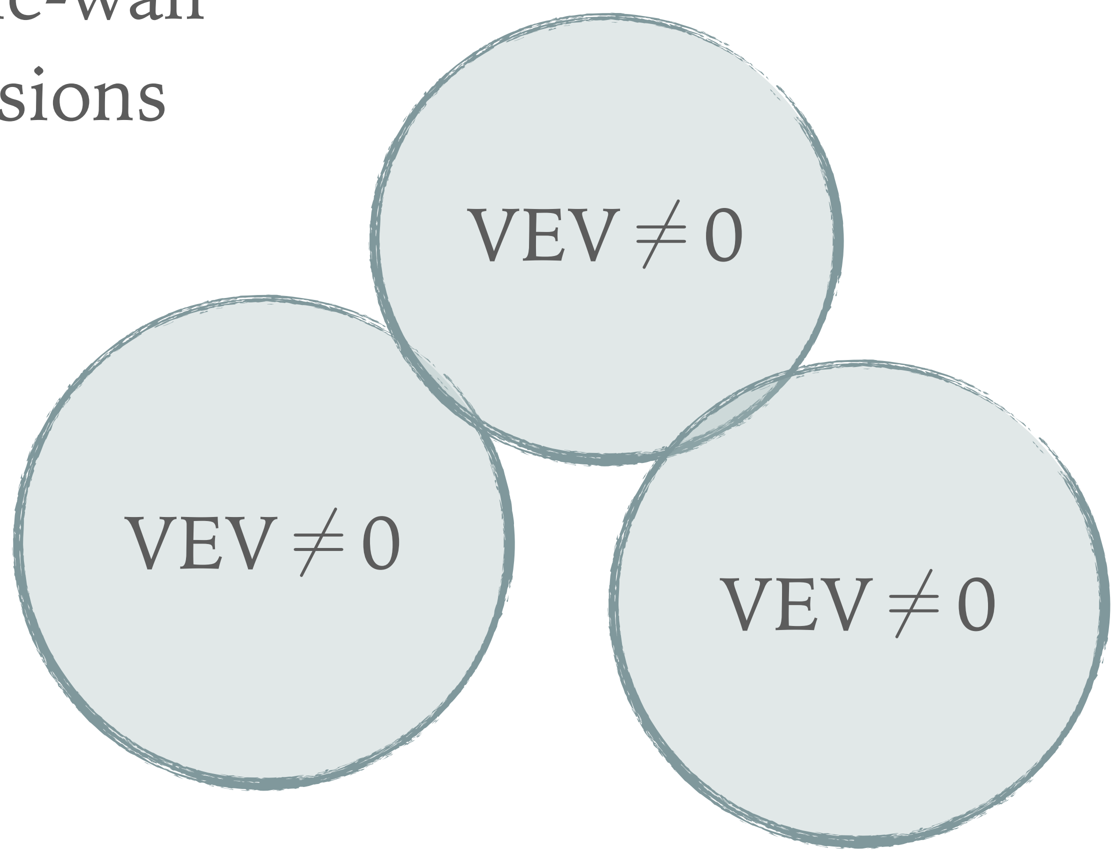


SOURCES OF GRAVITATIONAL WAVES

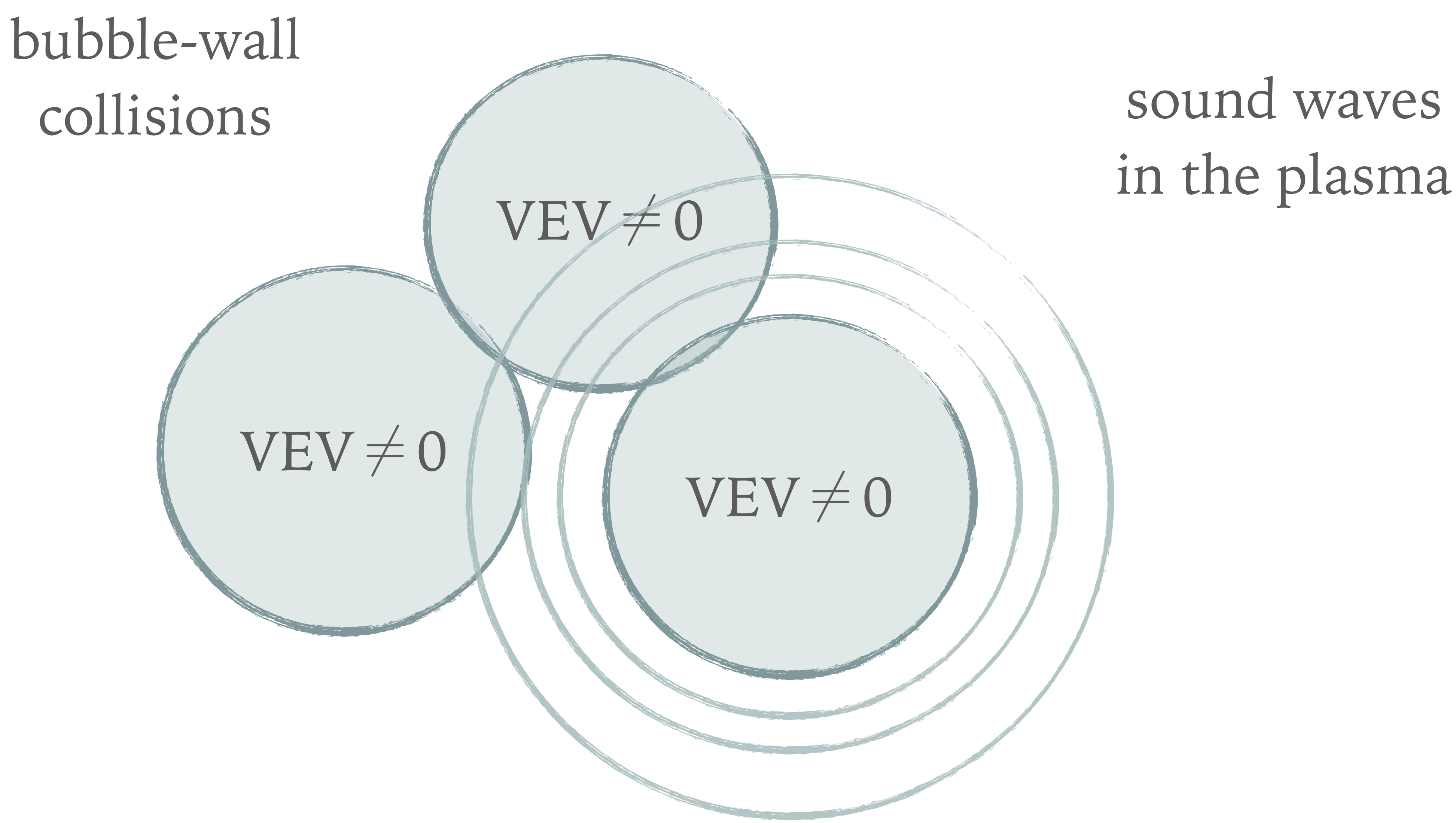


SOURCES OF GRAVITATIONAL WAVES

bubble-wall
collisions



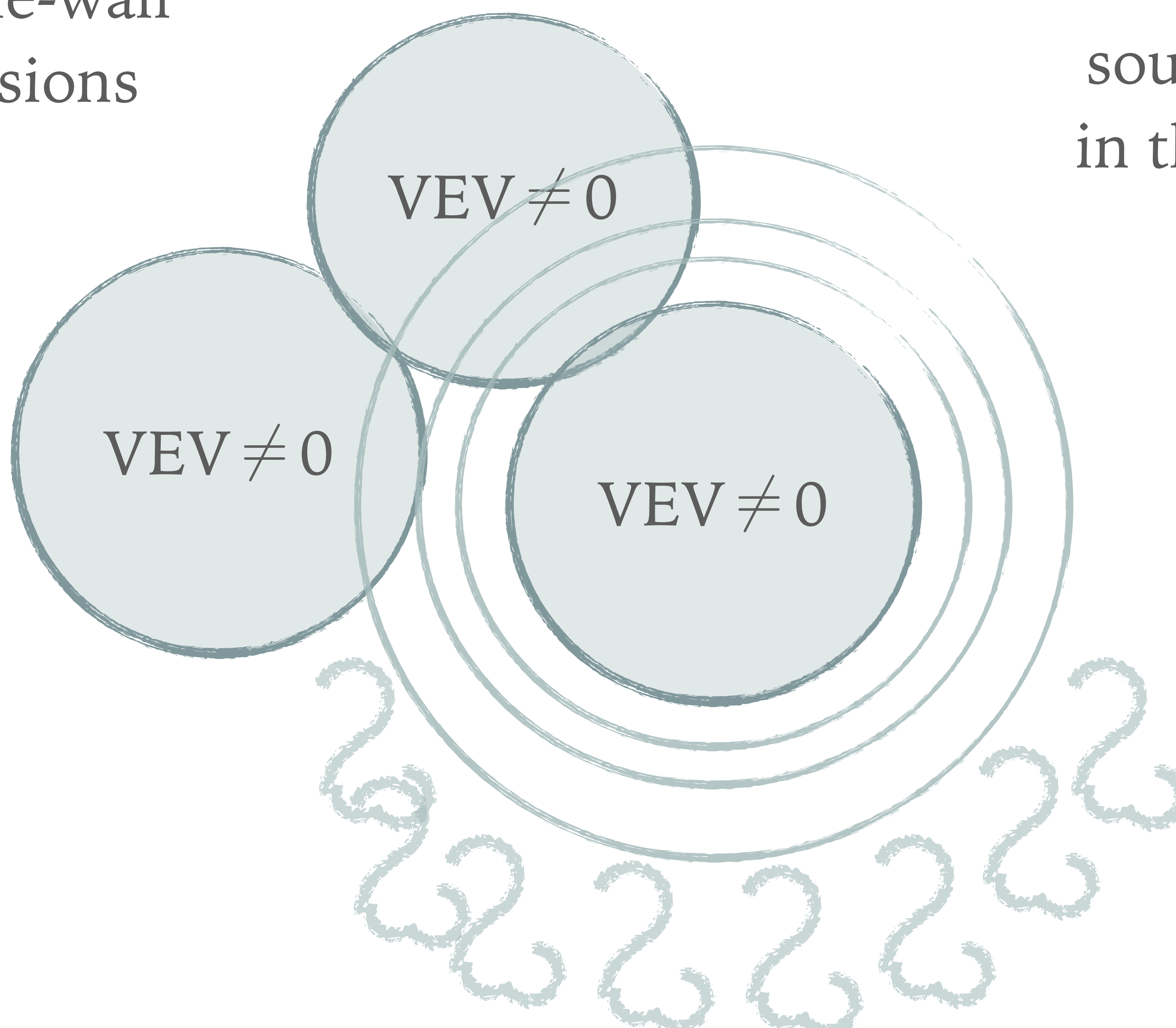
SOURCES OF GRAVITATIONAL WAVES



SOURCES OF GRAVITATIONAL WAVES

bubble-wall collisions

sound waves in the plasma

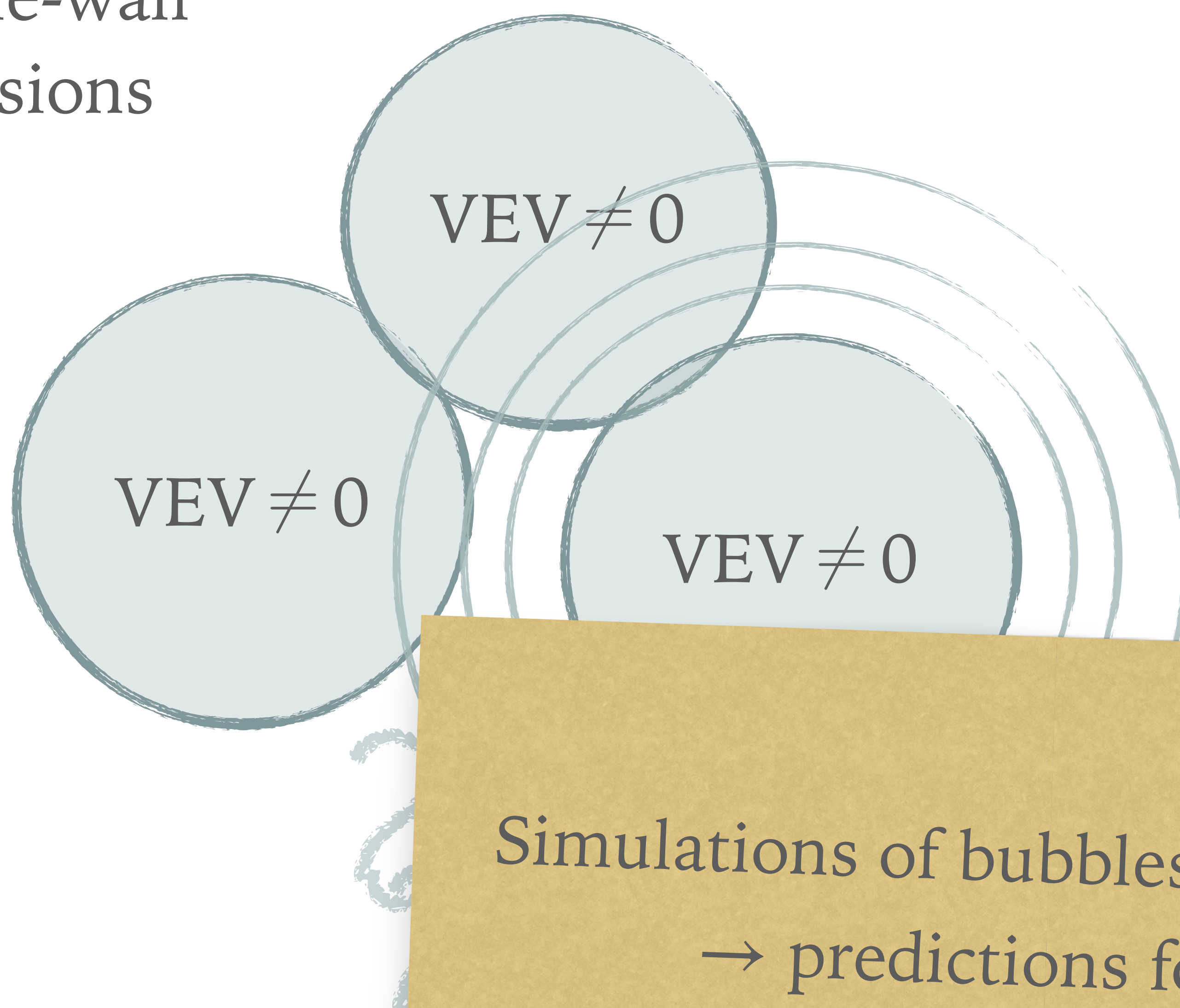


turbulence in the plasma

SOURCES OF GRAVITATIONAL WAVES

bubble-wall collisions

sound waves in the plasma



Simulations of bubbles and plasma motion
→ predictions for GW spectra

GRAVITATIONAL WAVES IN PULSAR TIMING ARRAYS?

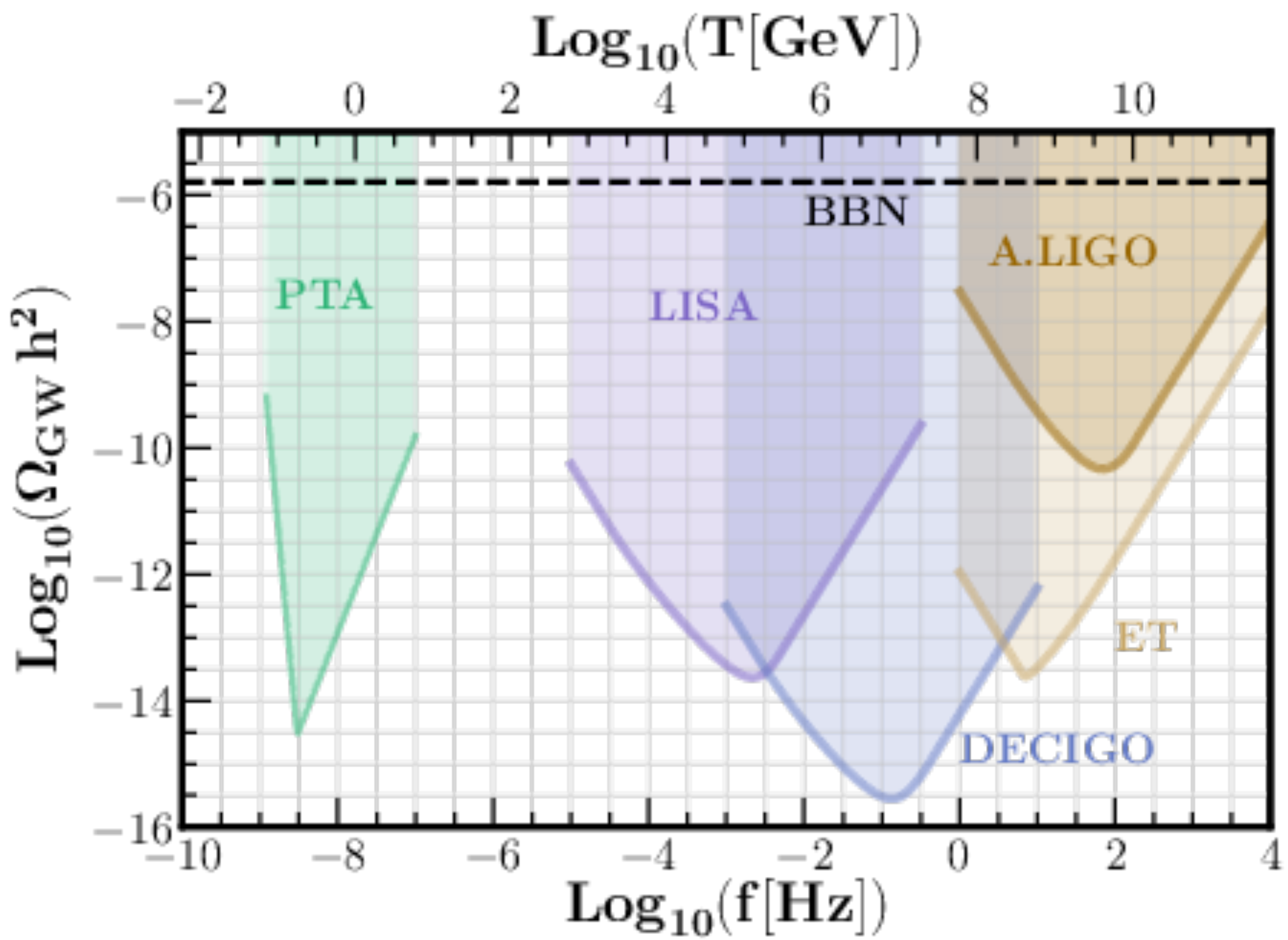
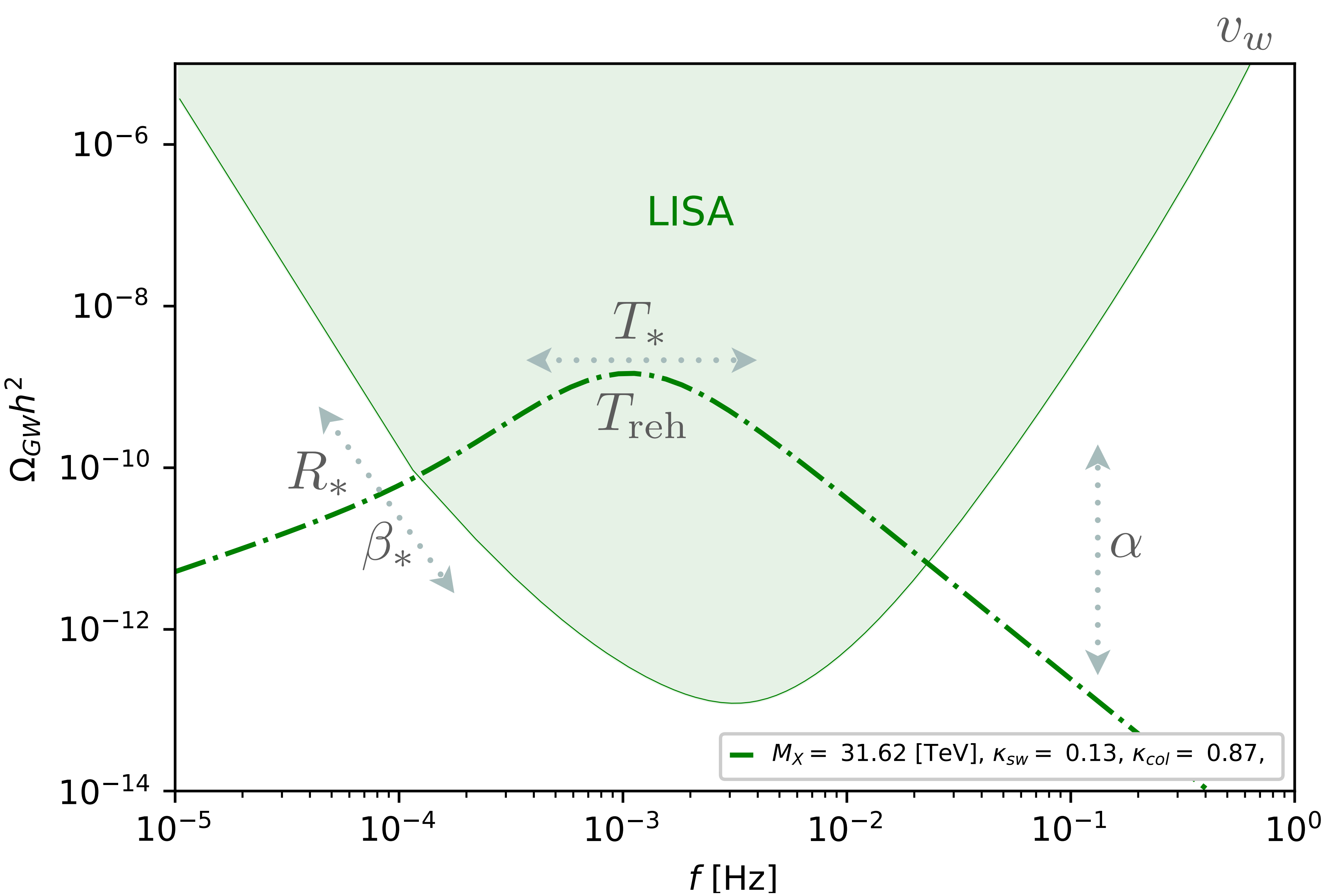


Figure from: G. Domenech, Universe 7 (2021) 11, 398

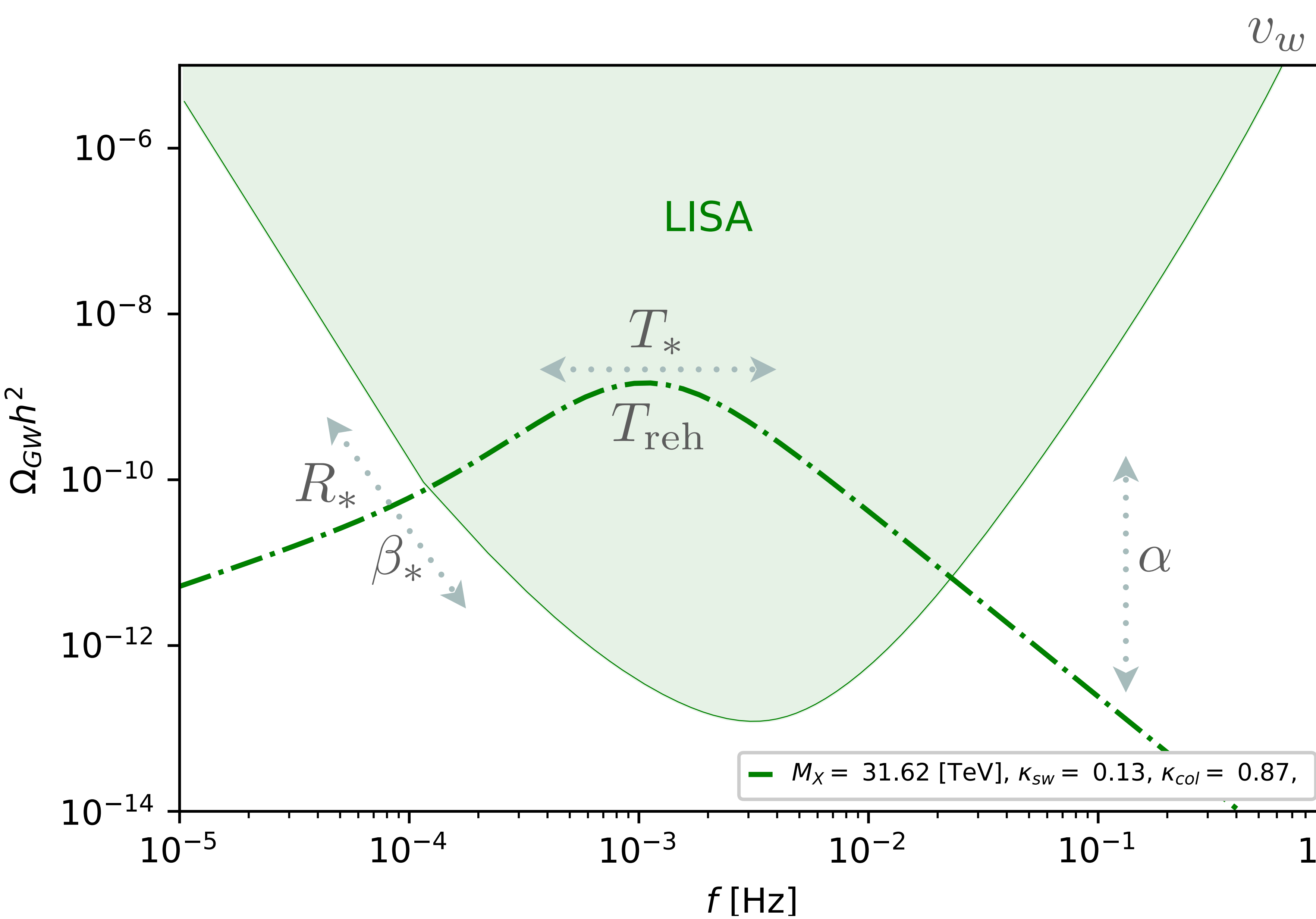
[See e.g. J. Ellis et al, 2308.08546 and references therein]

RELEVANT PARAMETERS



[Inspired by a talk by Pedro Schwaller]

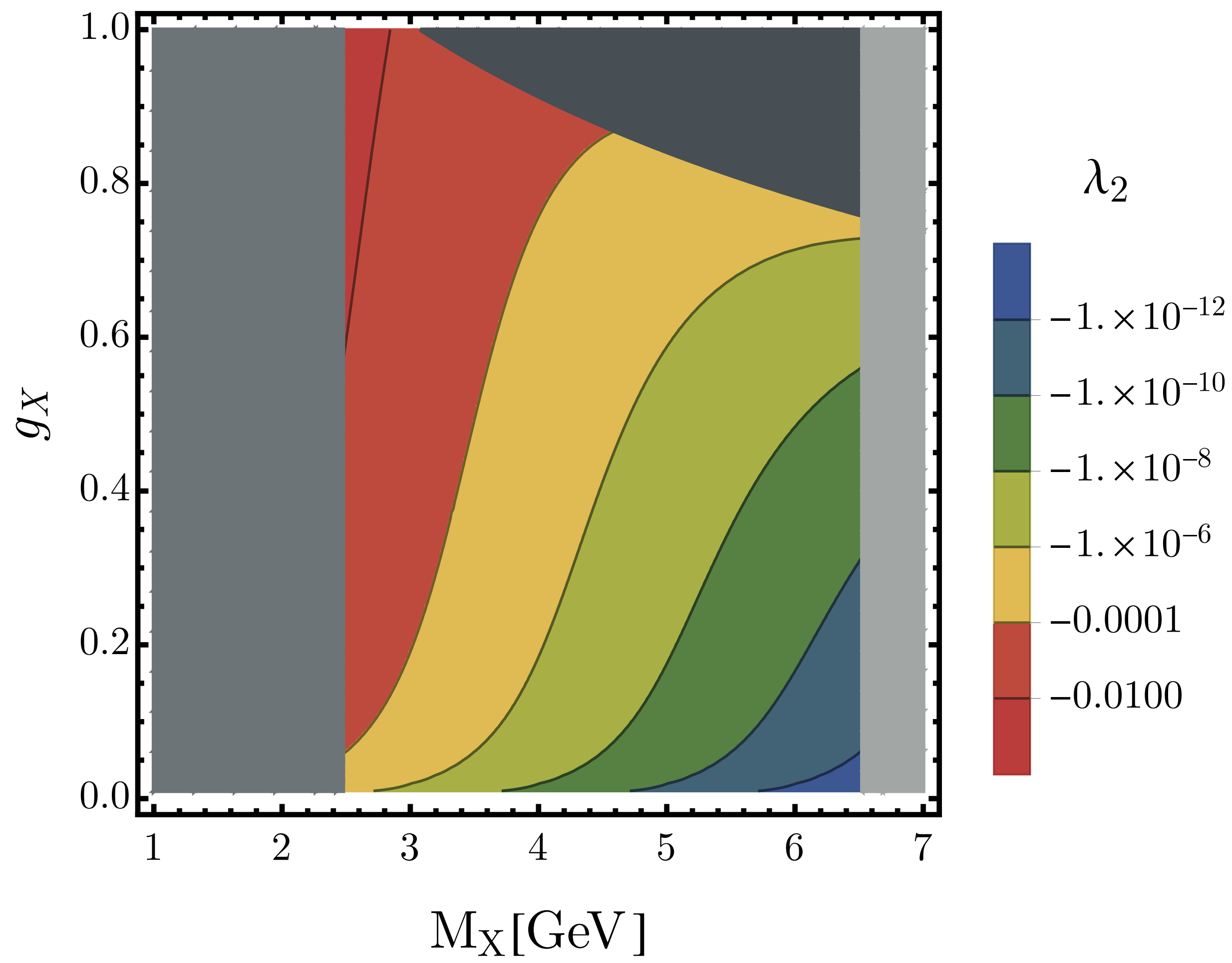
RELEVANT PARAMETERS

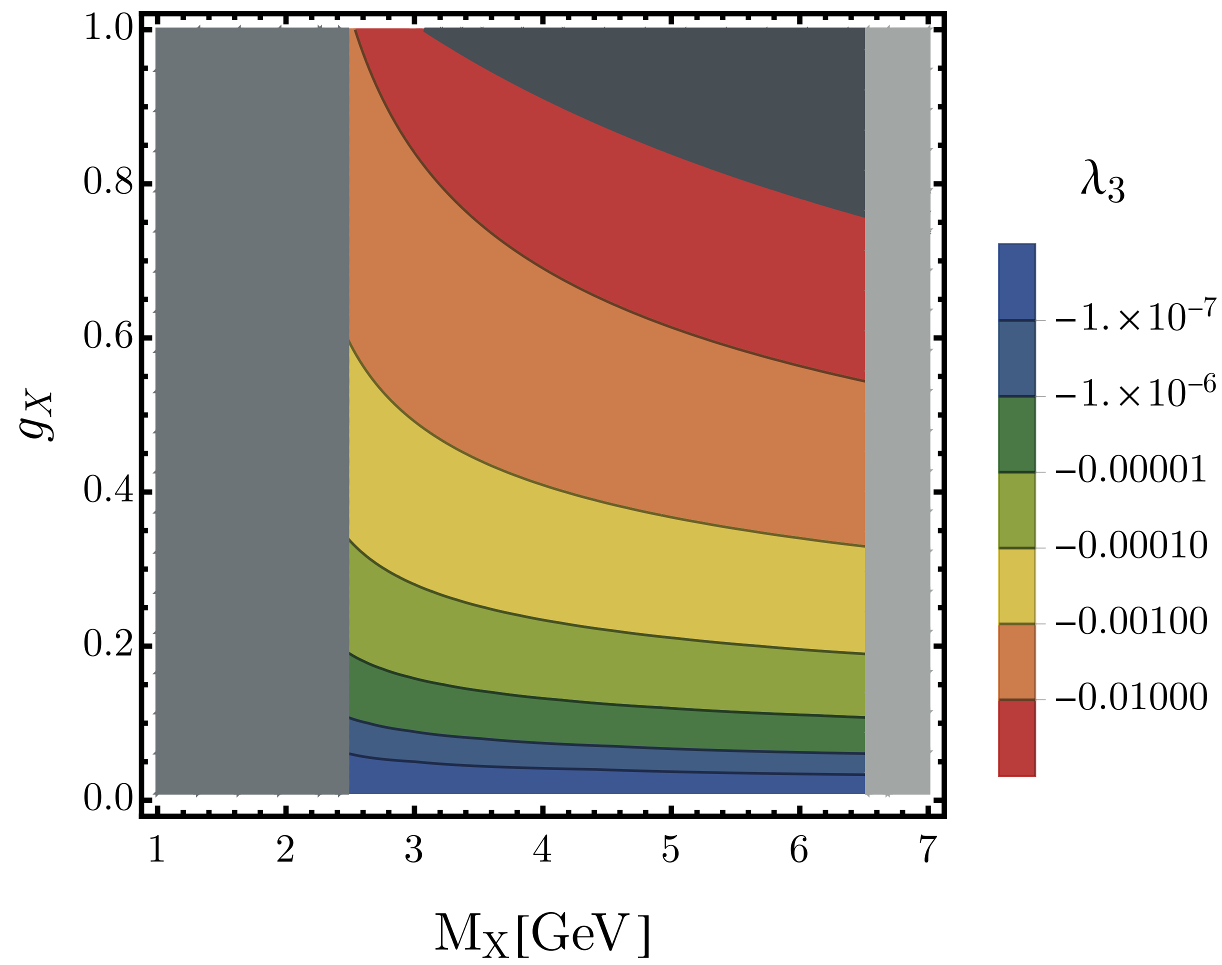


[Inspired by a talk by Pedro Schwaller]

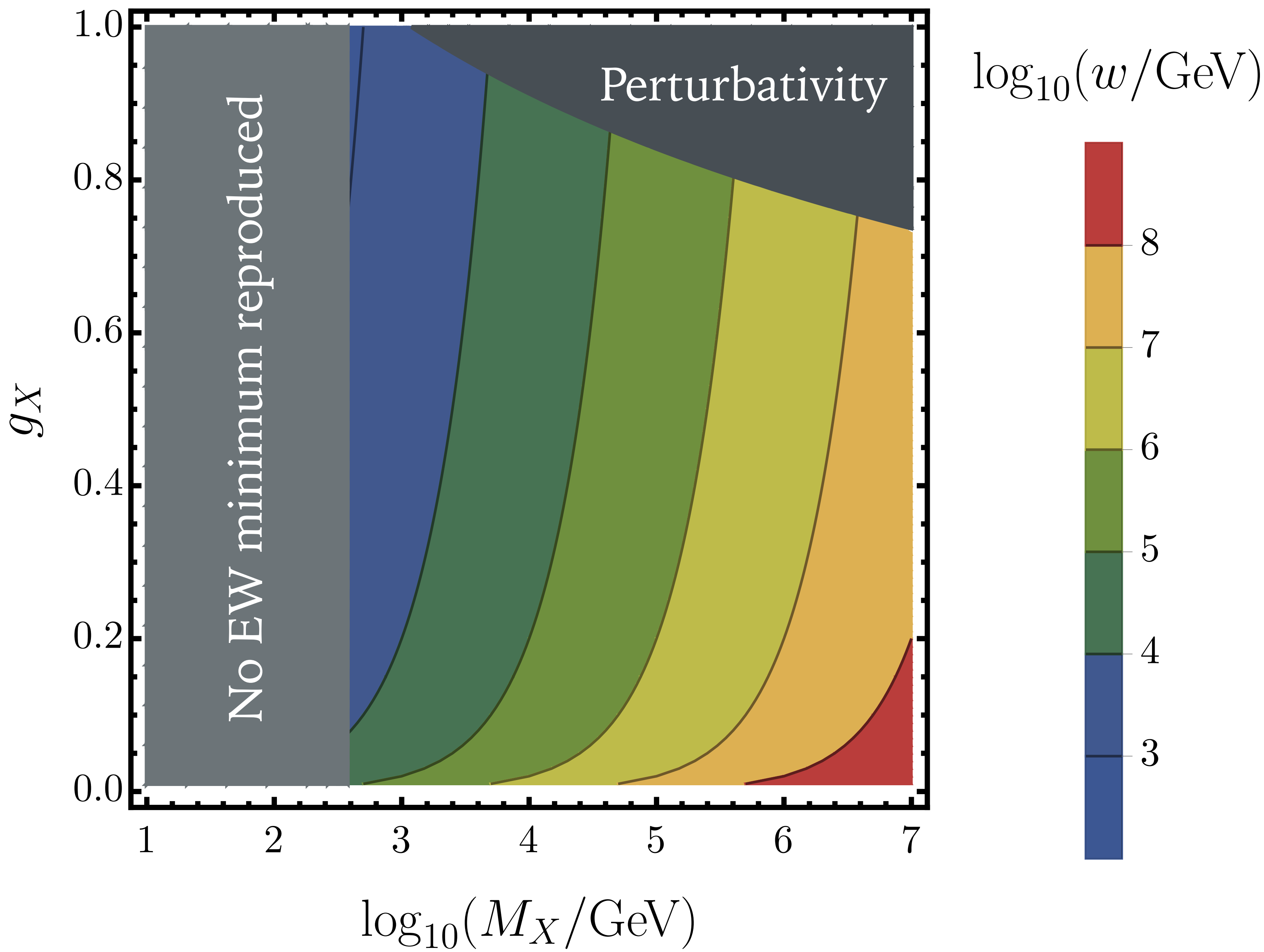
RSB IN SU(2)CSM

SCALAR COUPLINGS



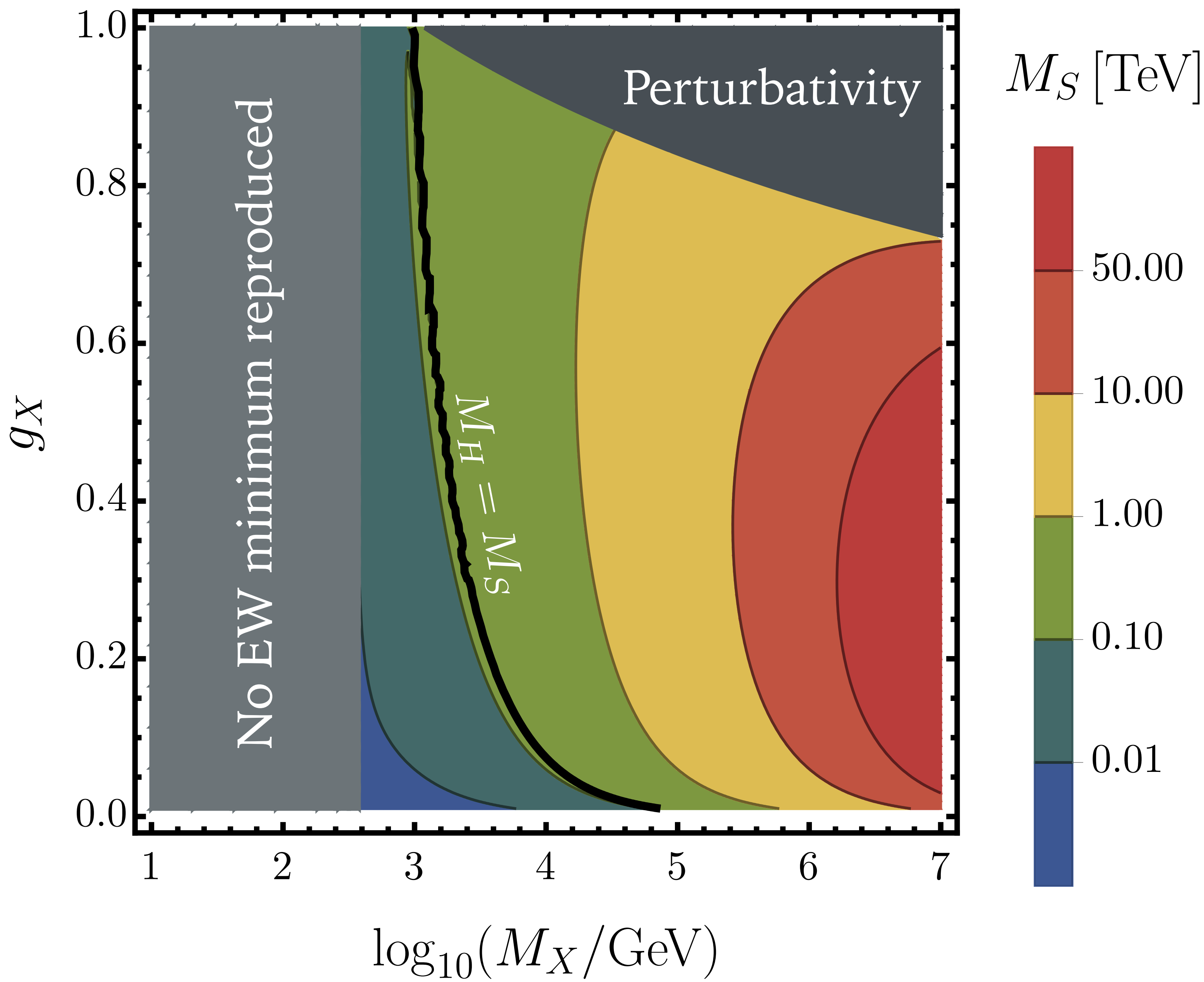


RADIATIVE SYMMETRY BREAKING IN SU(2)CSM



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

RADIATIVE SYMMETRY BREAKING IN SU(2)CSM



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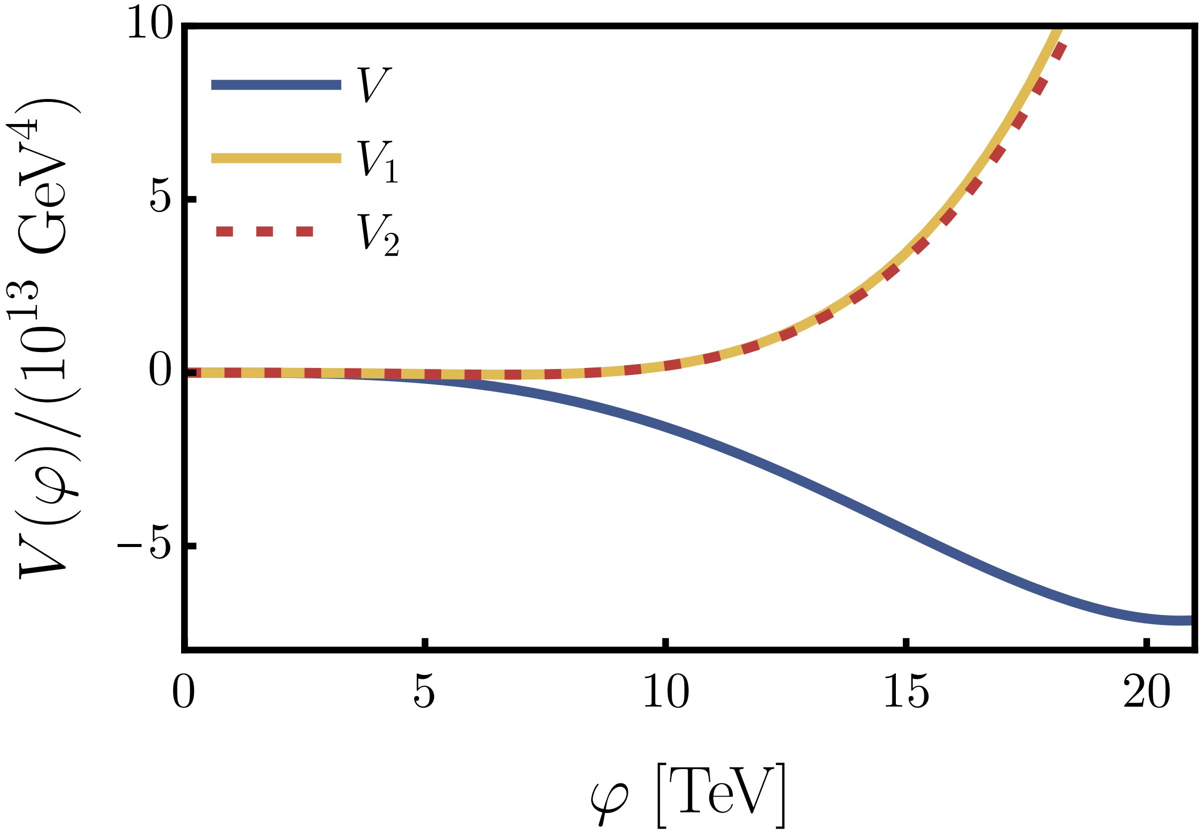
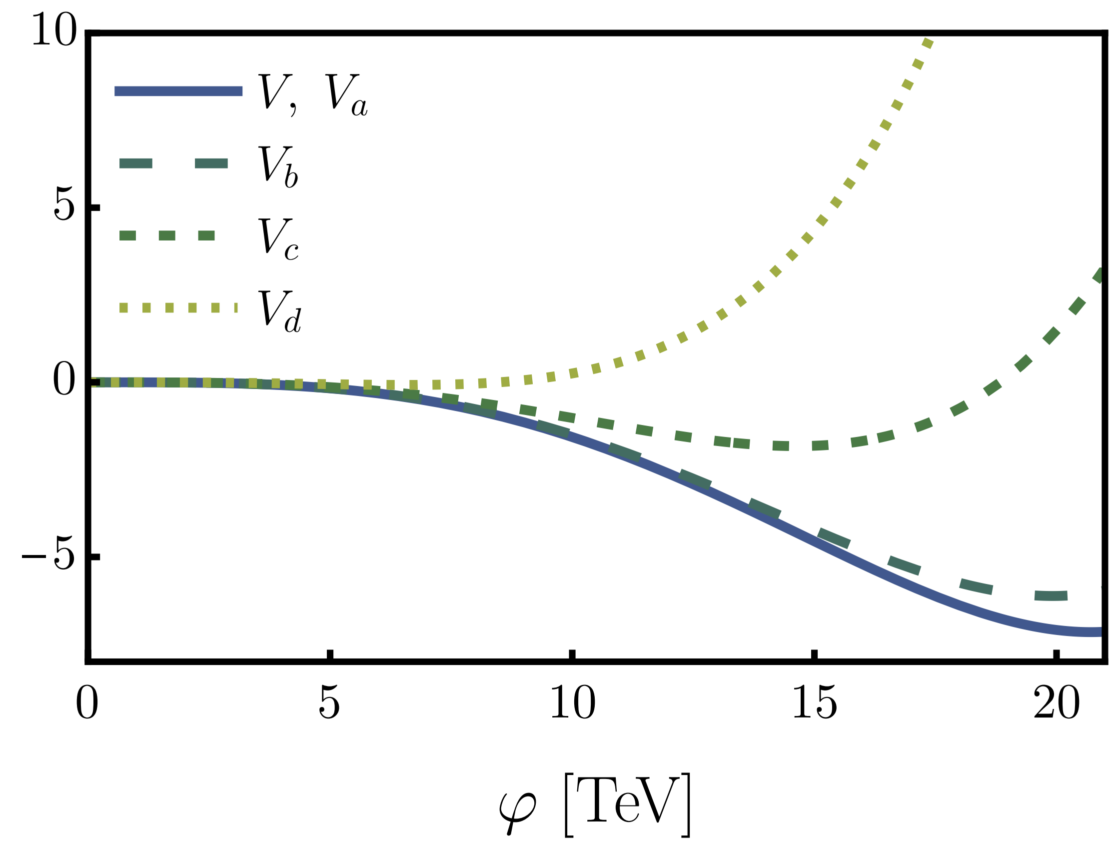
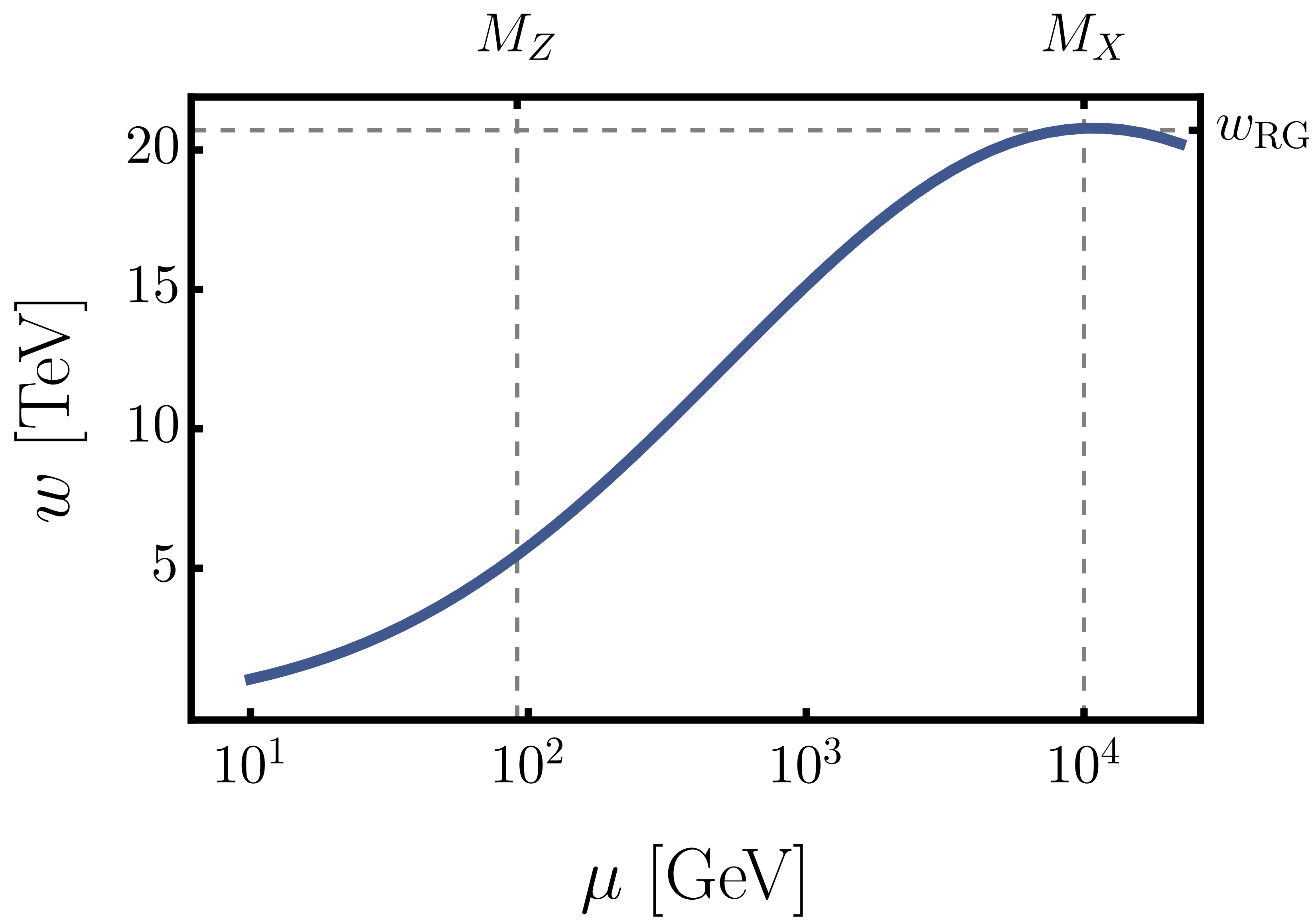
RG IMPROVEMENT



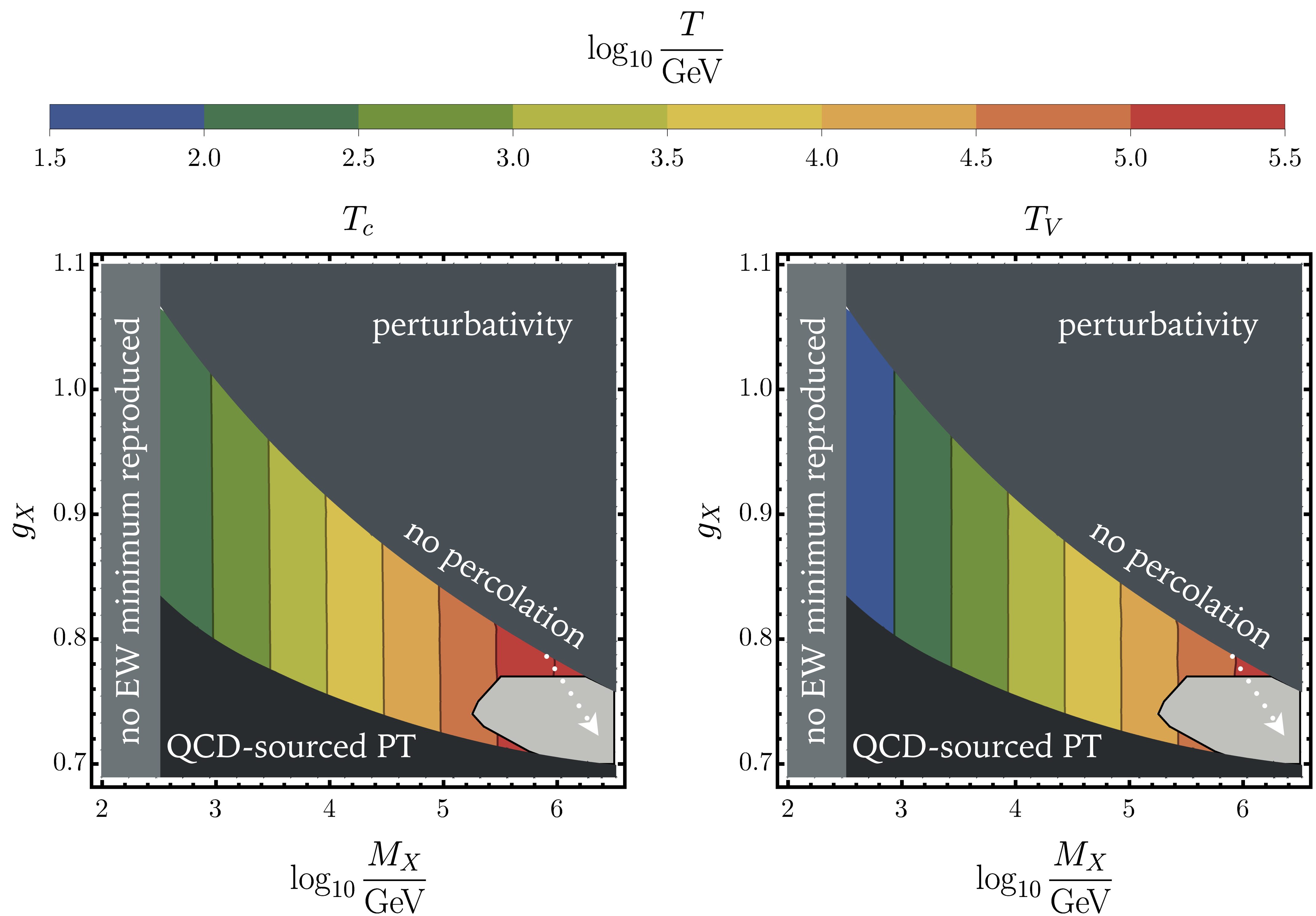


SCALE DEPENDENCE OF THE VEV

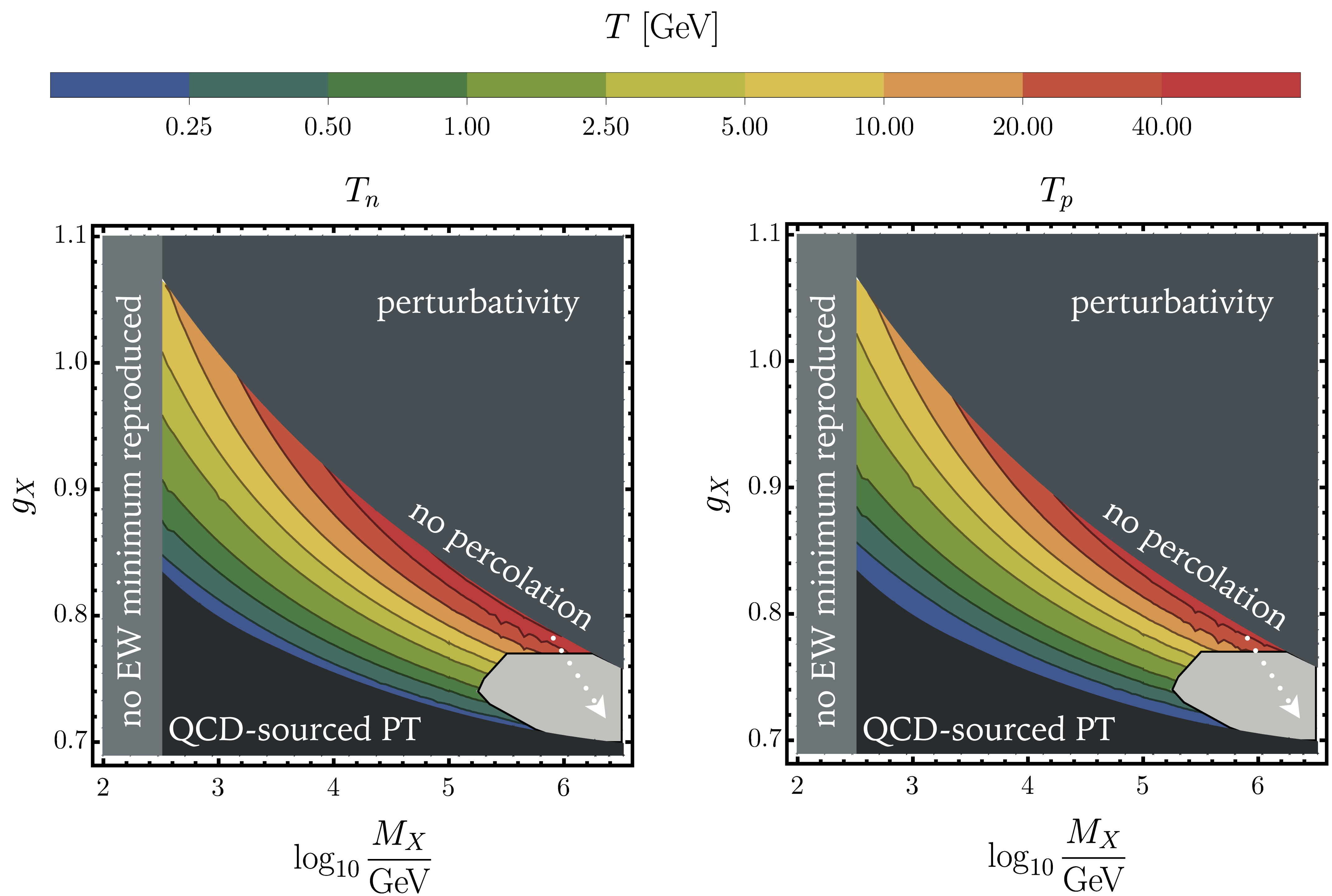


PHASE TRANSITION IN SU(2)CSM

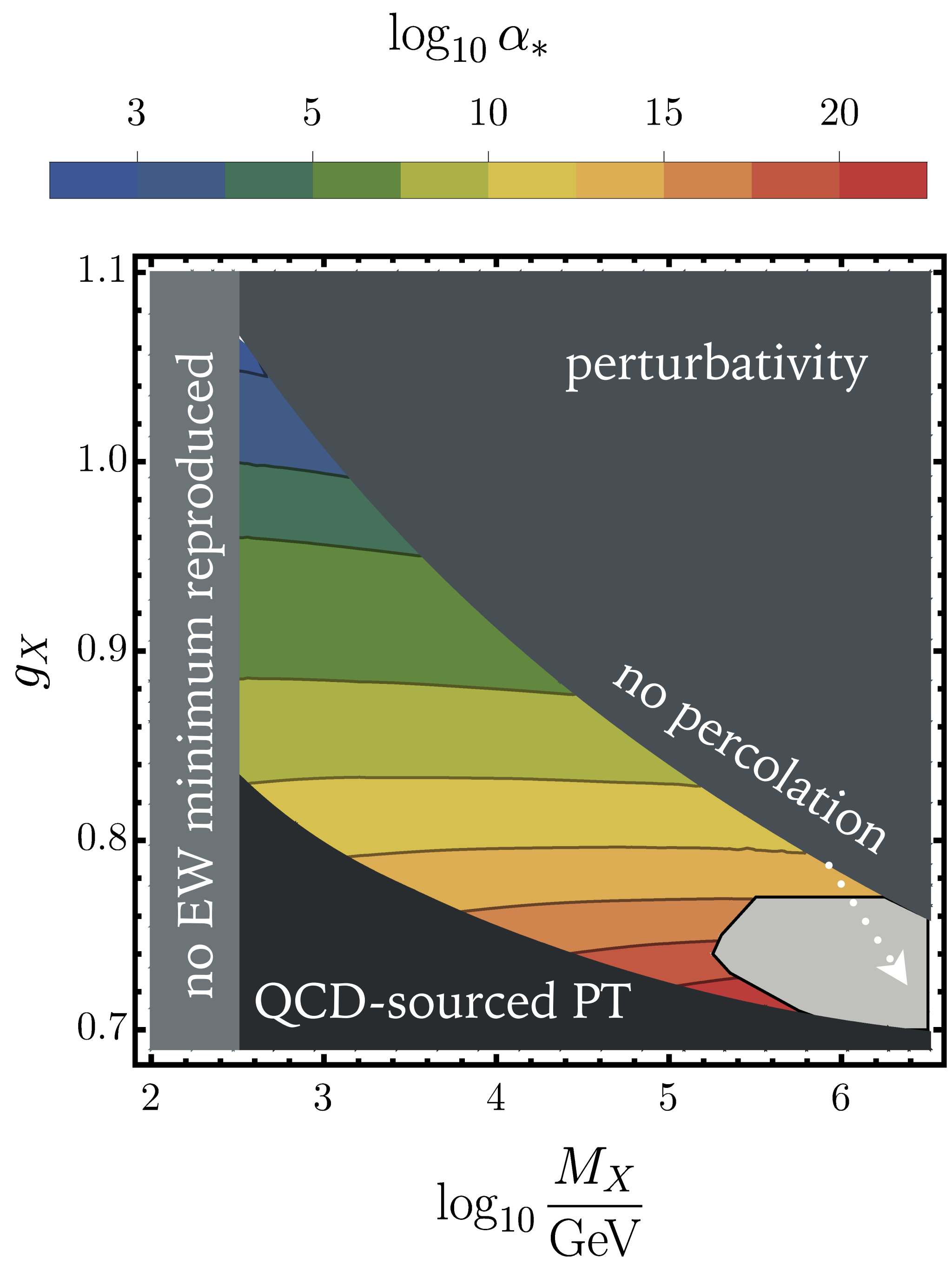
CRITICAL TEMPERATURE AND VACUUM DOMINATION



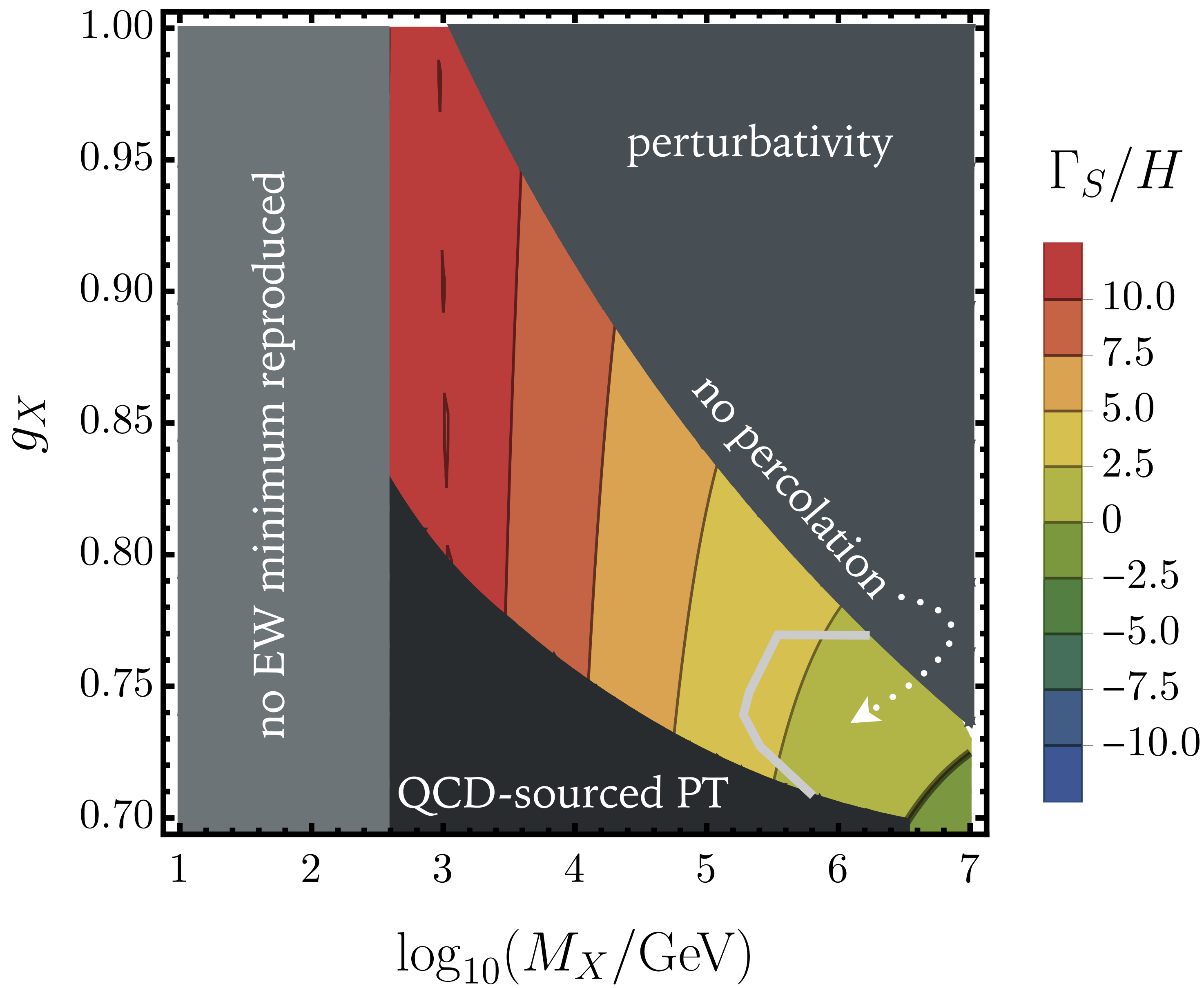
NUCLEATION AND PERCOLATION TEMPERATURE



STRENGTH OF THE TRANSITION



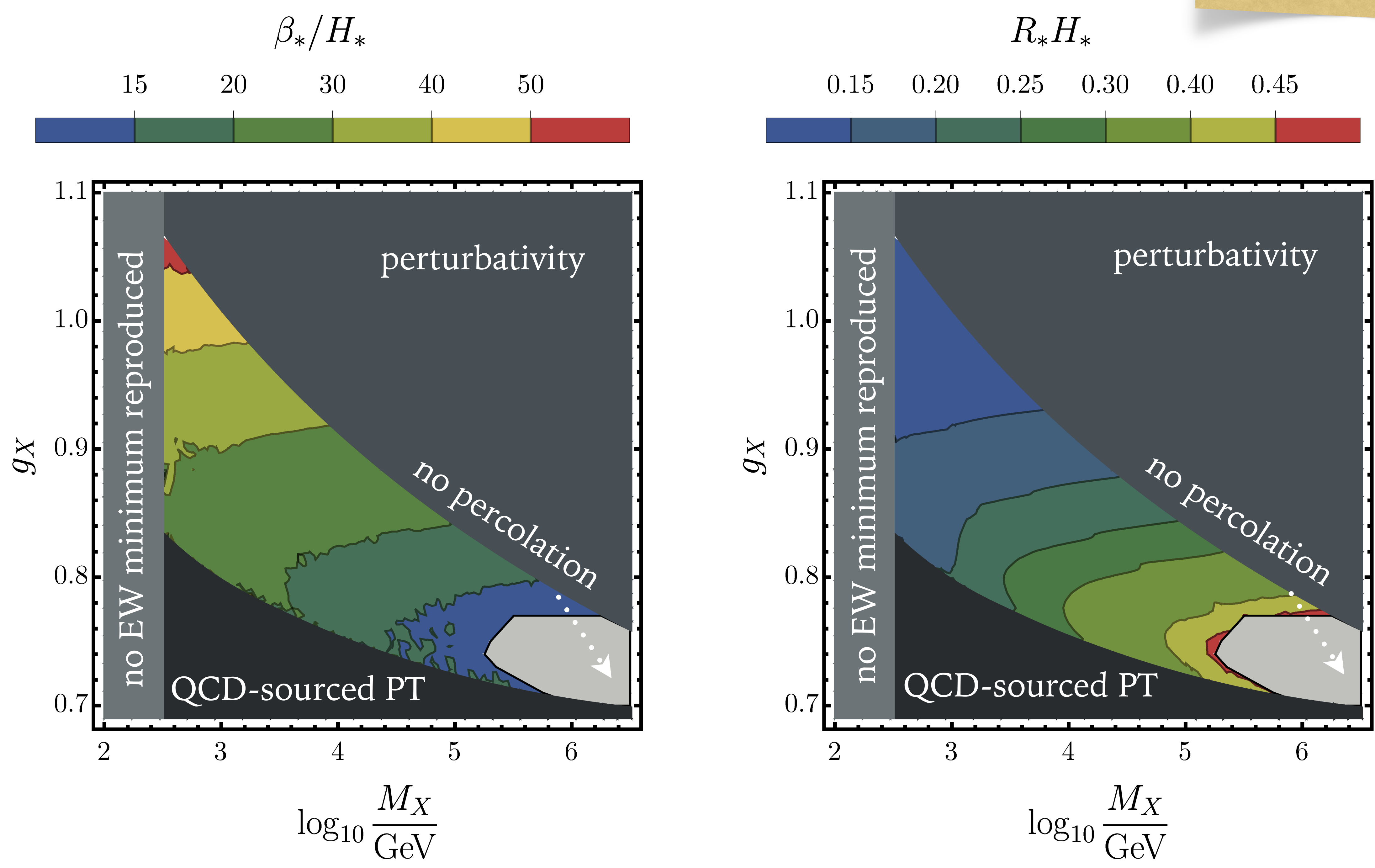
REHEATING



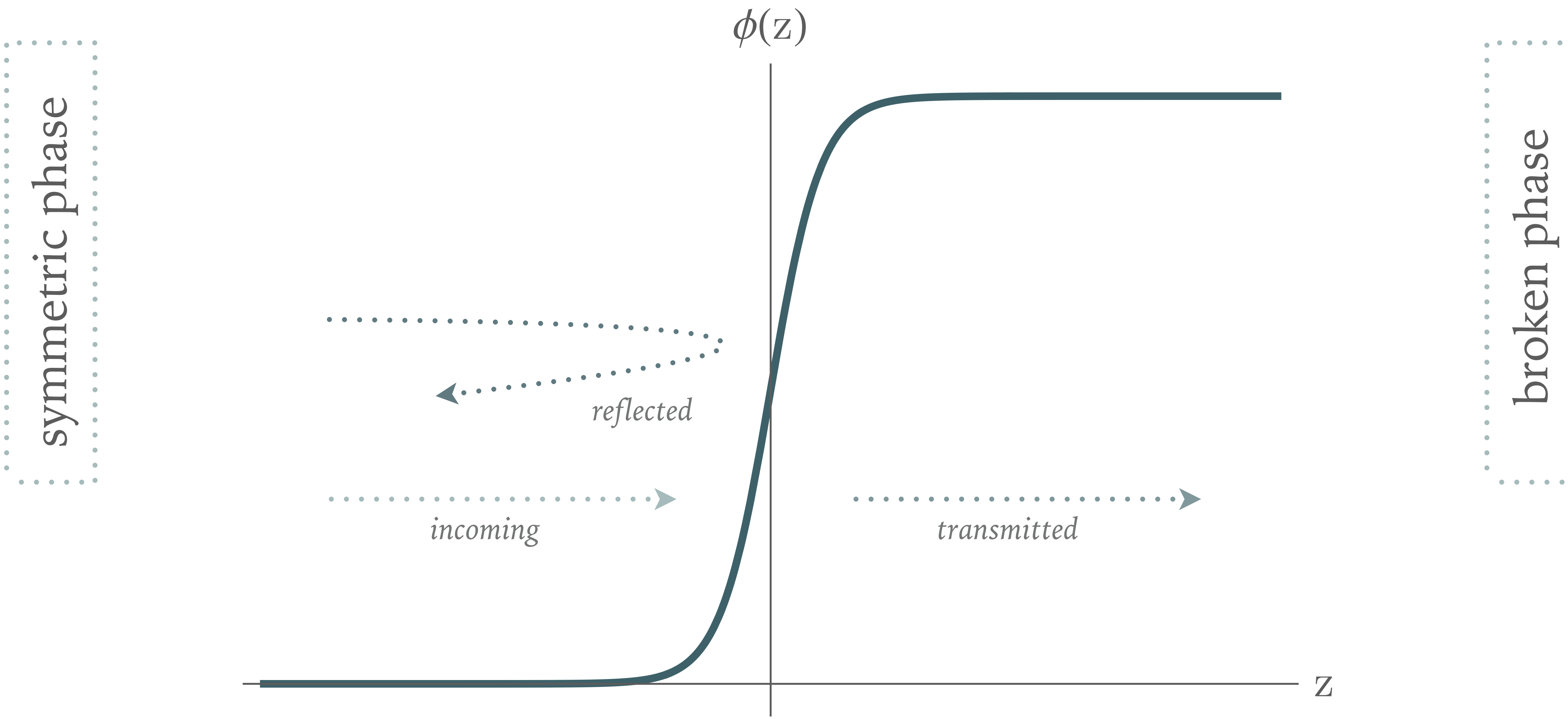
1.00
0.95
0.90
0.85
0.80
0.75
0.70
g_X
1
2
3
4
5
6
7
$\log_{10}(M_X/\mathrm{GeV})$
no EW minimum reproduced
perturbativity
no percolation
QCD-sourced PT
Γ_S/H
10.0
7.5
5.0
2.5
0
−2.5
−5.0
−7.5
−10.0

TIME/LENGTH SCALE OF THE TRANSITION

$$R_* \approx \frac{(8\pi)^{\frac{1}{3}}}{\beta_*}$$

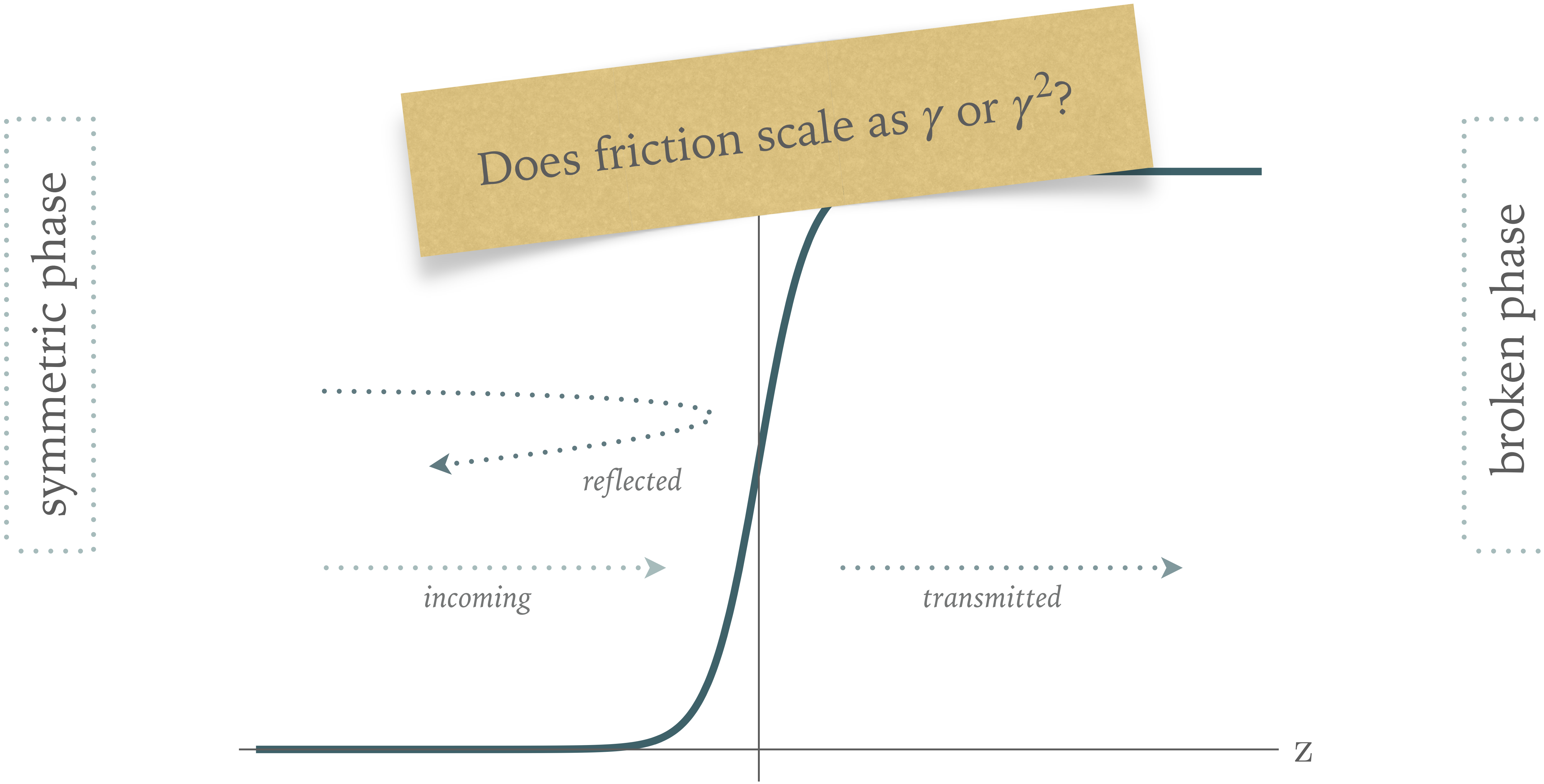


SOUND WAVES OR BUBBLE COLLISIONS?



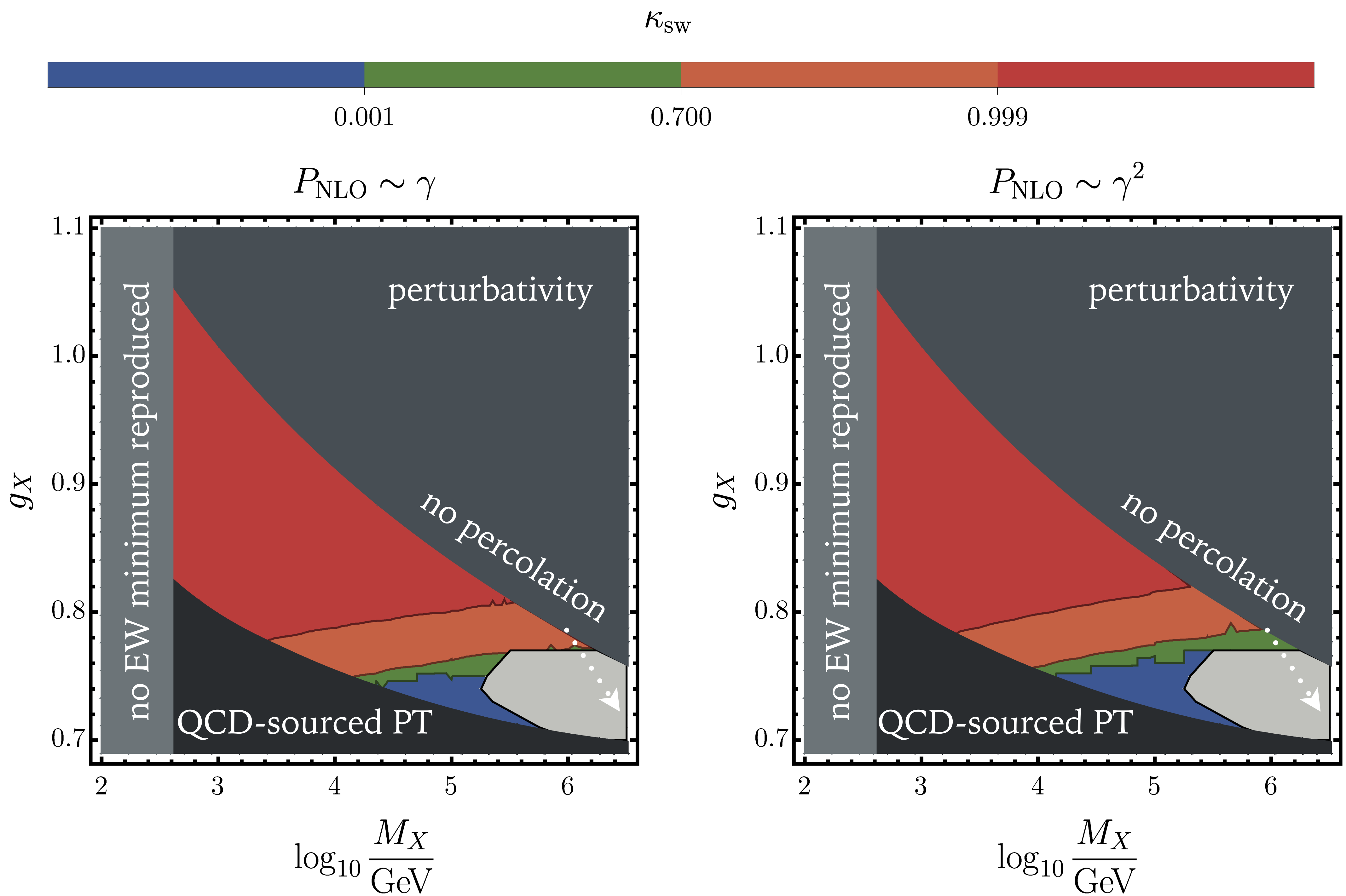
[G.D. Moore, T. Prokopec, PRL 75 (1995), PRD 52 (1995), P.B. Arnold, PRD 48 (1993) 1539, D. Bodeker, G.D. Moore, JCAP 0905 (2009) 009; JCAP 1705 (2017) 025, G.C. Dorsch, S. J. Huber and T. Konstandin, JCAP 12 (2018); 2106.06547, T. Konstandin, G. Nardini and I. Rues, JCAP 09 (2014), J.Kozaczuk, JHEP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

SOUND WAVES OR BUBBLE COLLISIONS?

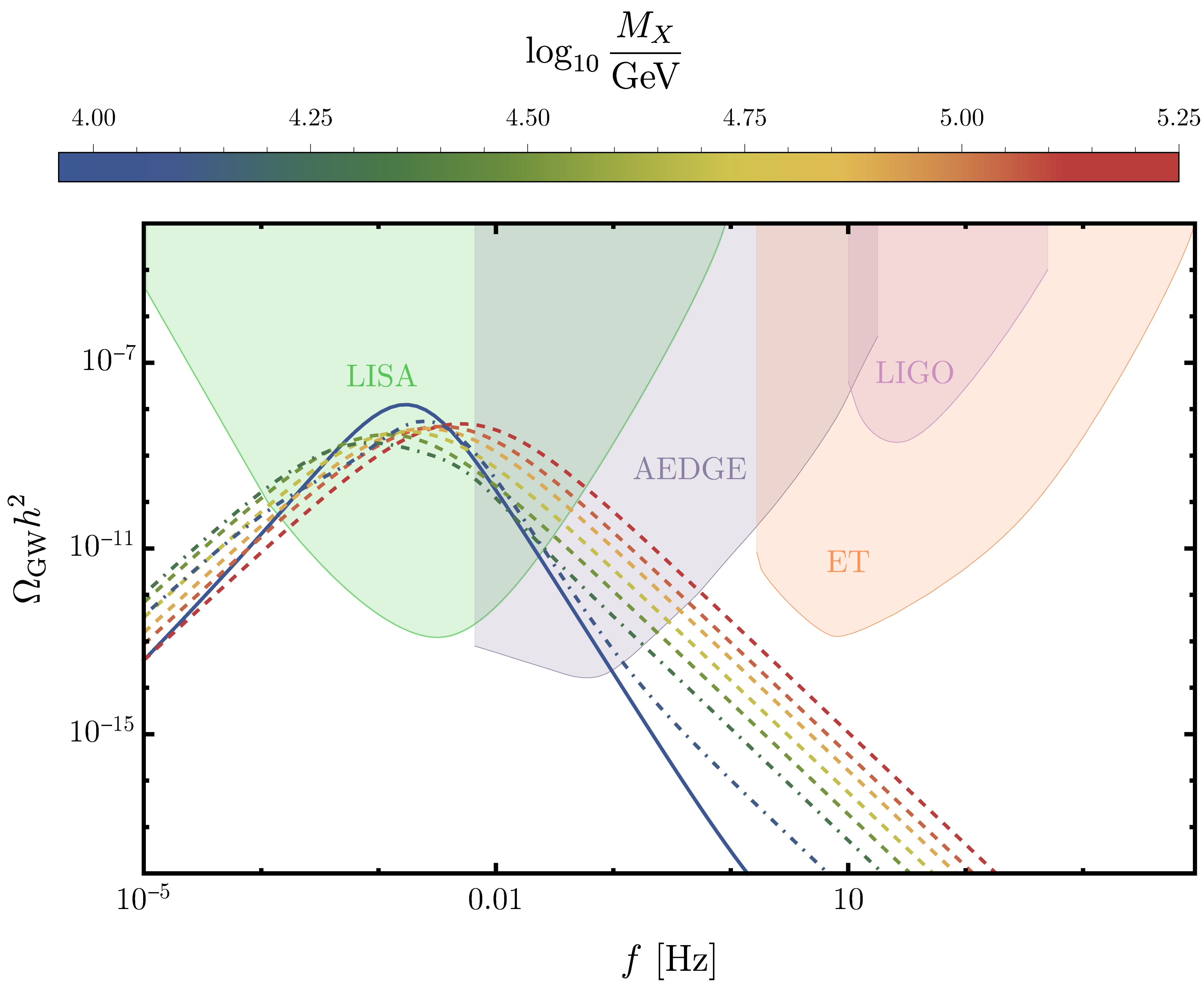


[G.D. Moore, T. Prokopec, PRL 75 (1995), PRD 52 (1995), P.B. Arnold, PRD 48 (1993) 1539, D. Bodeker, G.D. Moore, JCAP 0905 (2009) 009; JCAP 1705 (2017) 025, G.C. Dorsch, S. J. Huber and T. Konstandin, JCAP 12 (2018); 2106.06547, T. Konstandin, G. Nardini and I. Rues, JCAP 09 (2014), J.Kozaczuk, JHEP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

DETERMINING THE SOURCE



GRAVITATIONAL WAVE SPECTRA



[sensitivity curves courtesy M. Lewicki]

DARK MATTER PRODUCTION

THE MODEL: SU(2)CSM

cSM:
$SU(2)_L \times U(1)_Y$
h

Hidden sector:
$SU(2)_X$
φ

$$V = \frac{1}{4}\left(\lambda_1 h^4 + \lambda_2 h^2 \varphi^2 + \lambda_3 \varphi^4\right)$$

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

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 THERMAL EVOLUTION

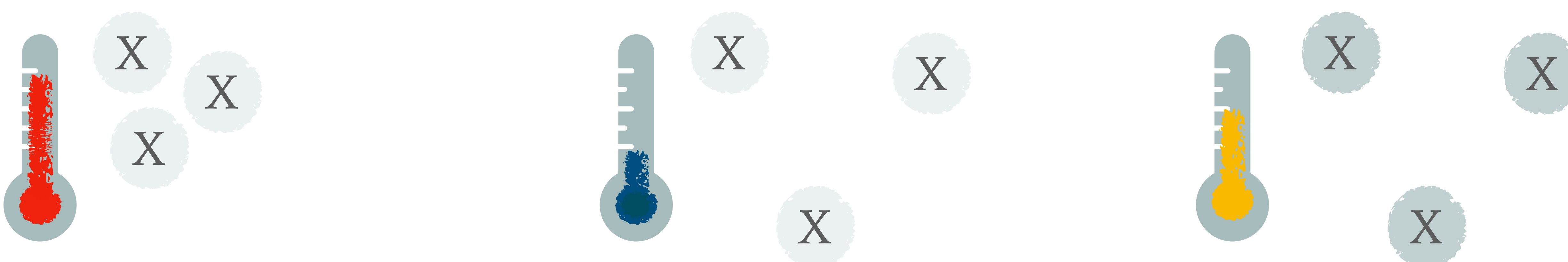
supercooling

PT and reheating

hot Universe, massless particles

cool Universe, diluted massless particles

reheated Universe, diluted massive particles



[Image credit: M. Kierkla]

NEW PRODUCTION MECHANISM

<u>Standard freezeout</u>
With nonstandard initial condition
$T_{\rm dec} < T_{\rm reh}$

<u>Supercool DM</u>
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]

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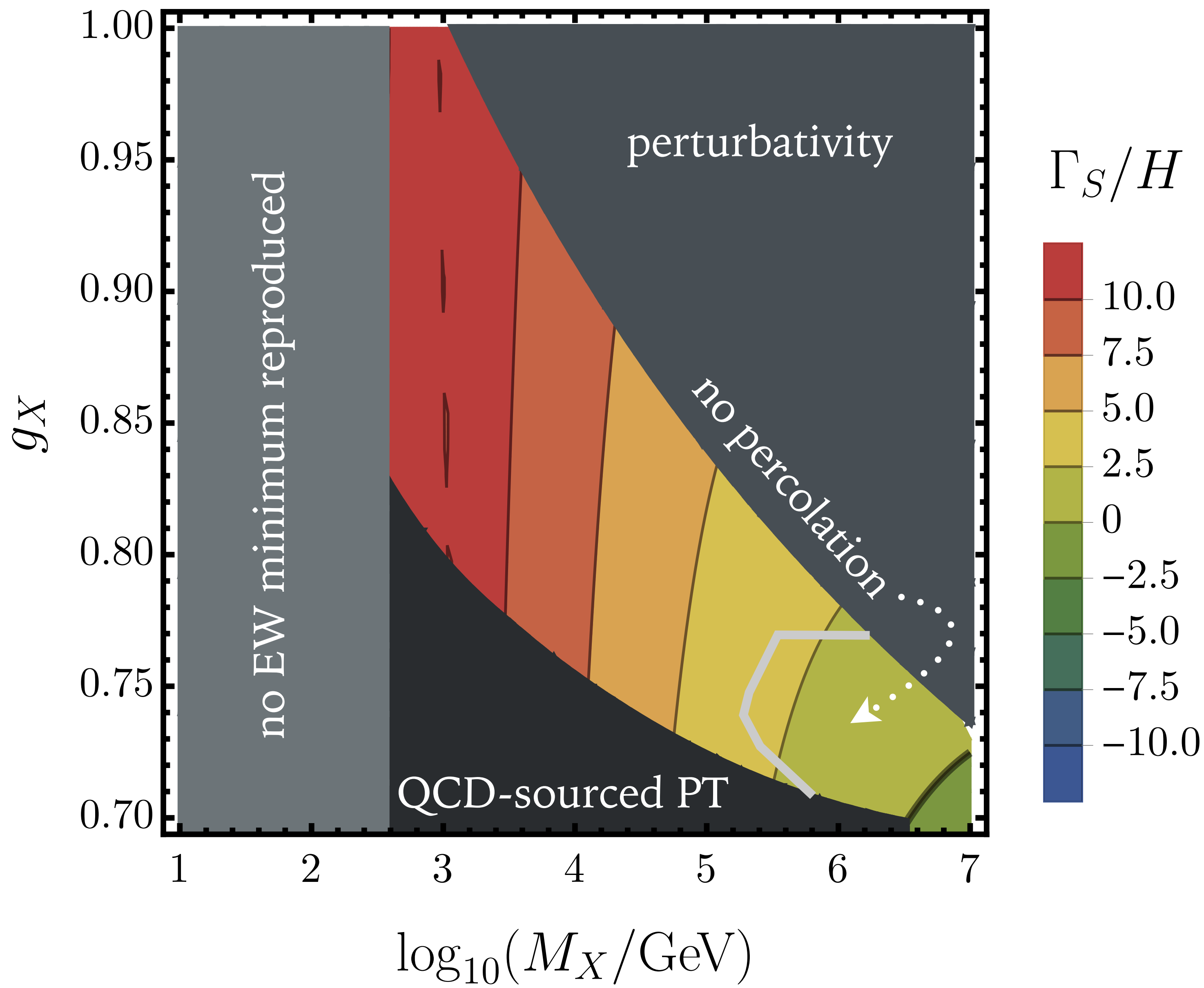
$$T_{\rm dec} \approx \frac{M_X}{25}$$

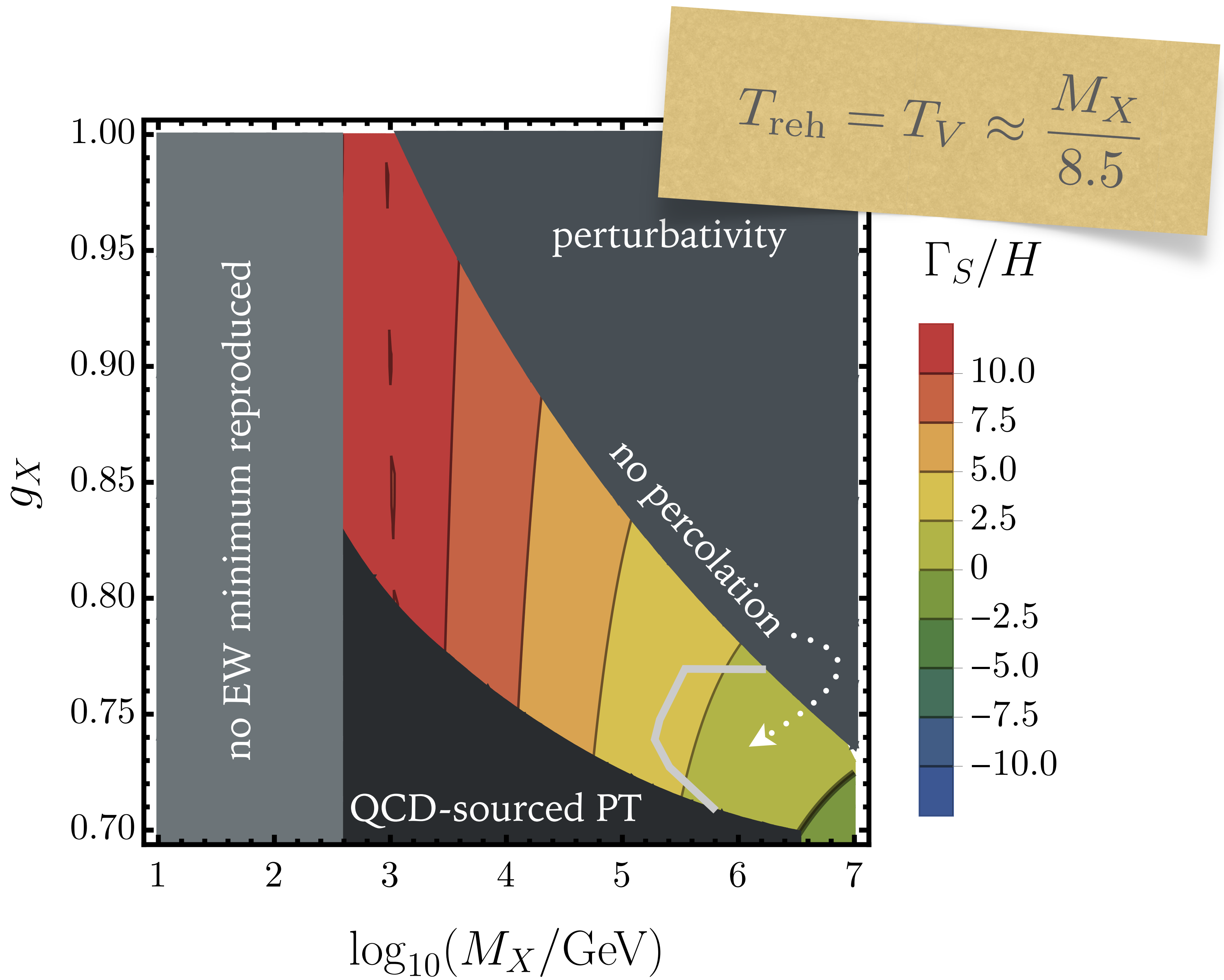
[T.Hambye, A.Strumia, PRD88 (2013) 055022, C.Carone, R.Ramos, PRD88 (2013) 055020, V.V.Khoze, C.McCabe, G.Ro, JHEP 08 (2014) 026, T. Hambye, A.Strumia, D.Teresi, JHEP 1808 (2018) 188, I.Baldes, C. Garcia-Cely, JHEP 05 (2019) 190, D. Marfaria, P. Tseng, JHEP 02 (2021) 022]

REHEATING



perturbativity
no EW minimum reproduced
no percolation
QCD-sourced PT
Γ_S/H
10.0
7.5
5.0
2.5
0
−2.5
−5.0
−7.5
−10.0
1.00
0.95
0.90
0.85
0.80
0.75
0.70
g_X
1
2
3
4
5
6
7
$\log_{10}(M_X/\mathrm{GeV})$

REHEATING



$T_{\rm reh} = T_V \approx \frac{M_X}{8.5}$
perturbativity
no EW minimum reproduced
no percolation
QCD-sourced PT
Γ_S/H
10.0
7.5
5.0
2.5
0
−2.5
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NEW PRODUCTION MECHANISM

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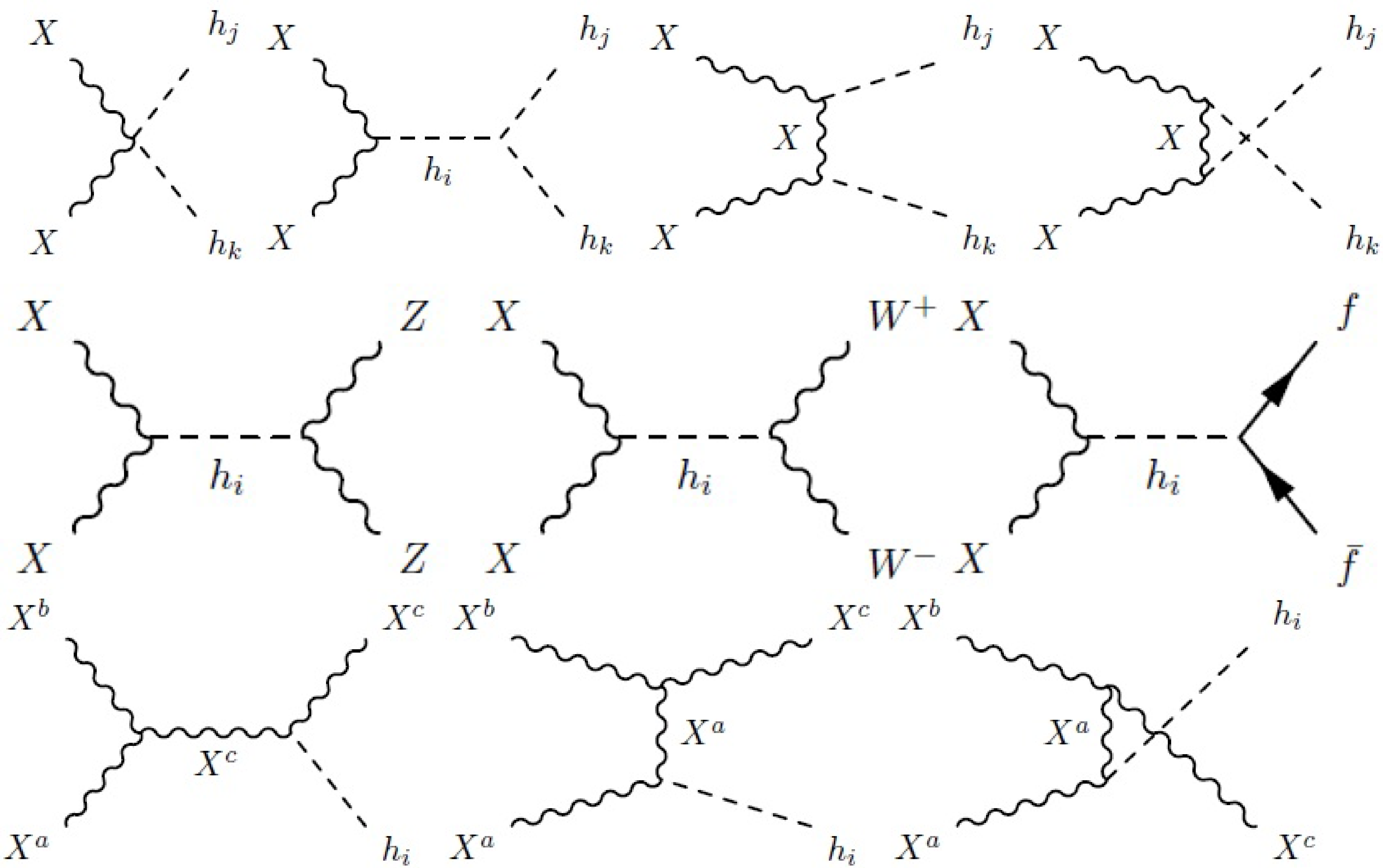
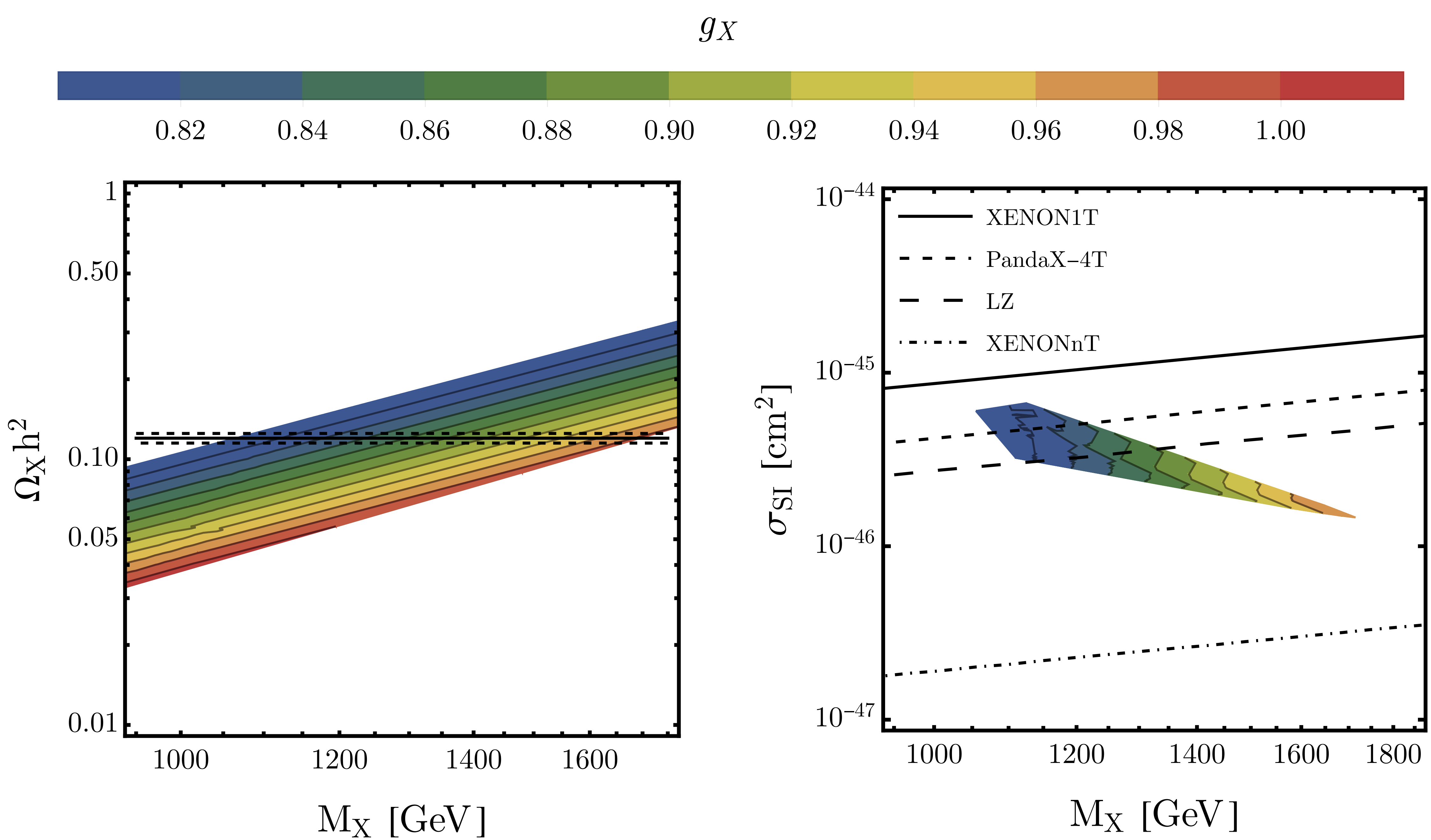
ANNIHILATION AND SEMIANNIHILATION



DM ABUNDANCE - FREEZEOUT



DM PRODUCTION MECHANISMS

<u>Freeze-in</u>

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

<u>Dark freeze-out</u>

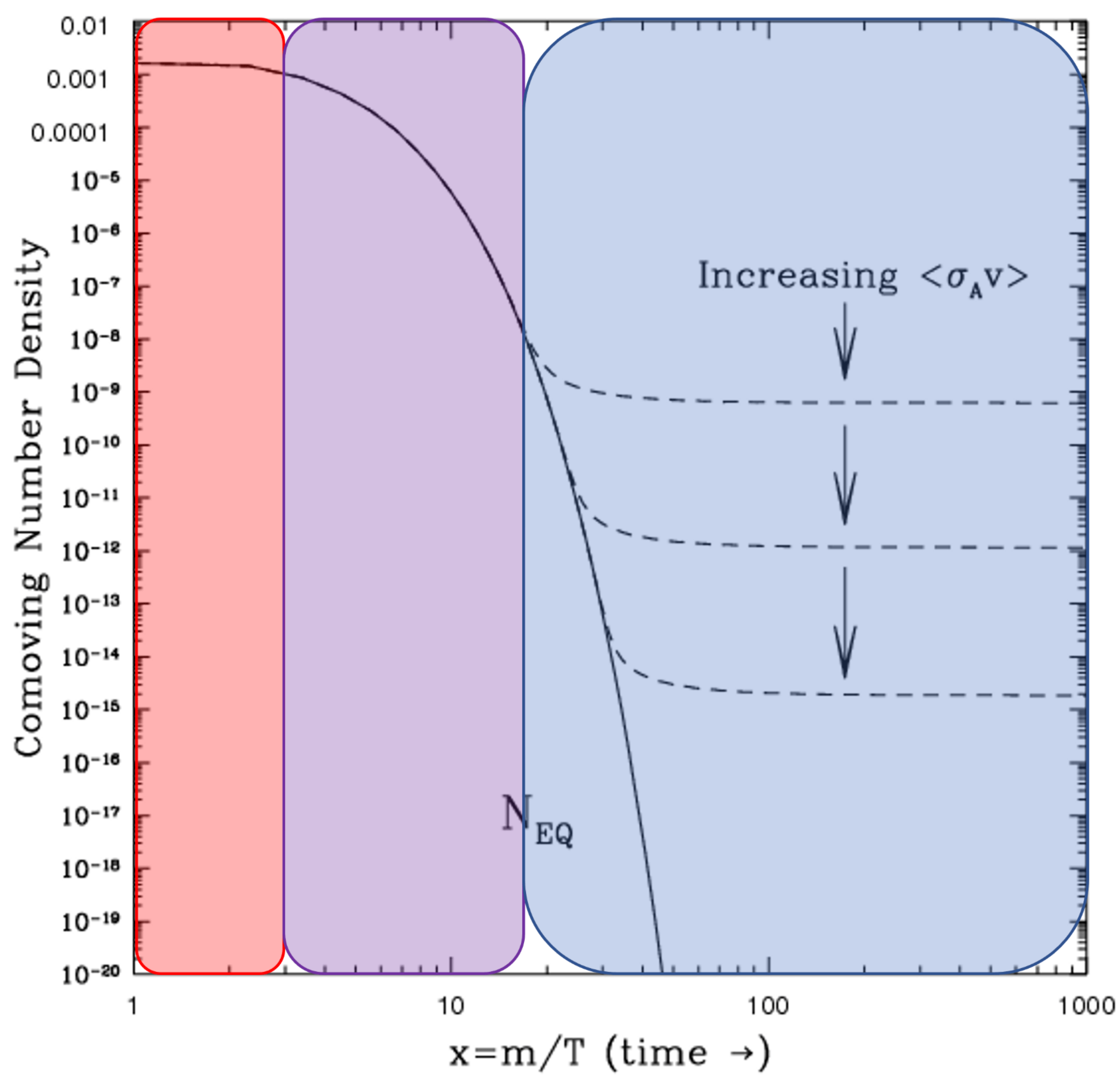
DM not in equilibrium with the visible sector, freeze-out within the dark sector

<u>Reannihillation</u>

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]

STANDARD FREEZE-OUT



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

OTHER FUTURE IMPROVEMENTS NEEDED

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Extend the range and precision of simulations

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Compute the wall velocity

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What could we learn from an observation of GW from PT?