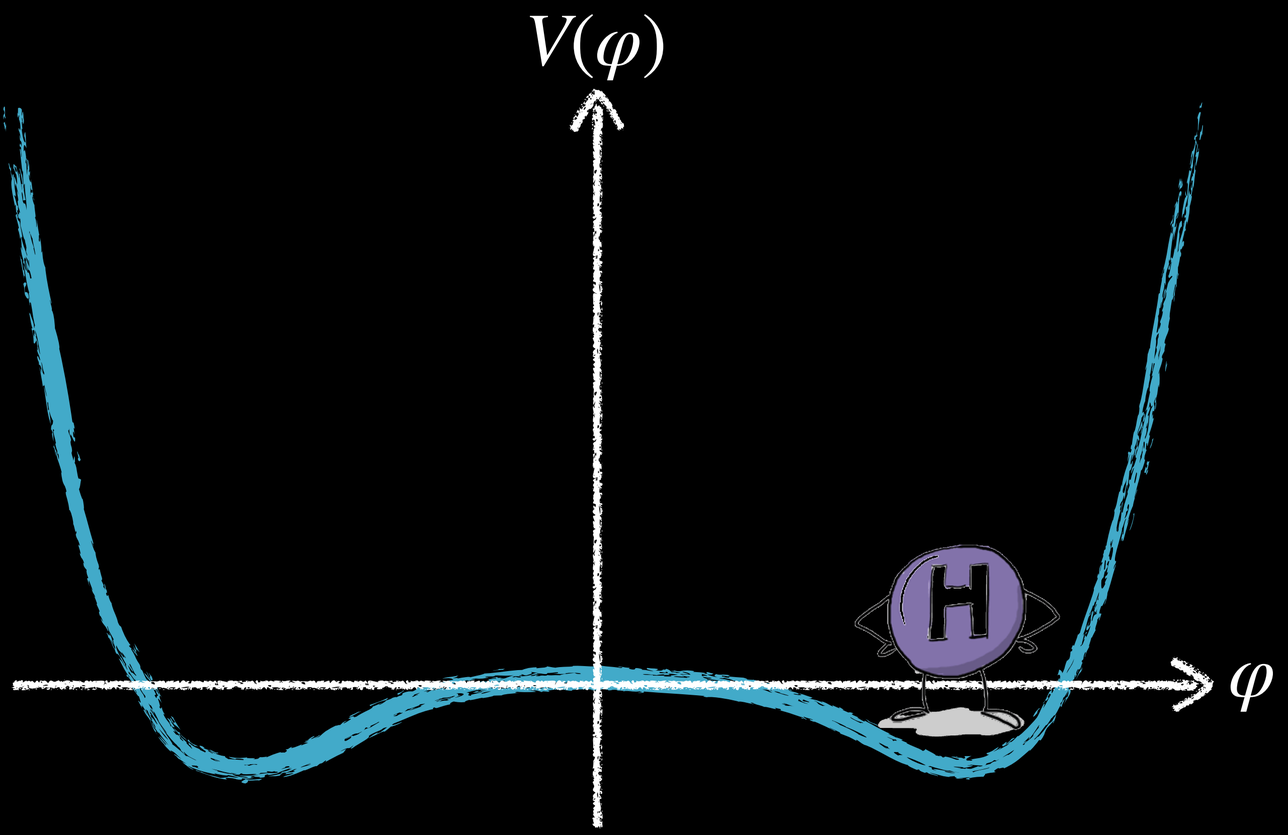
WORKSHOP ON "SELECTED TOPICS ON FUTURE DIRECTIONS IN PARTICLE PHYSICS"
NCBJ, 16-18 SEPTEMBER 2024

PHASE TRANSITION IN THE EARLY UNIVERSE

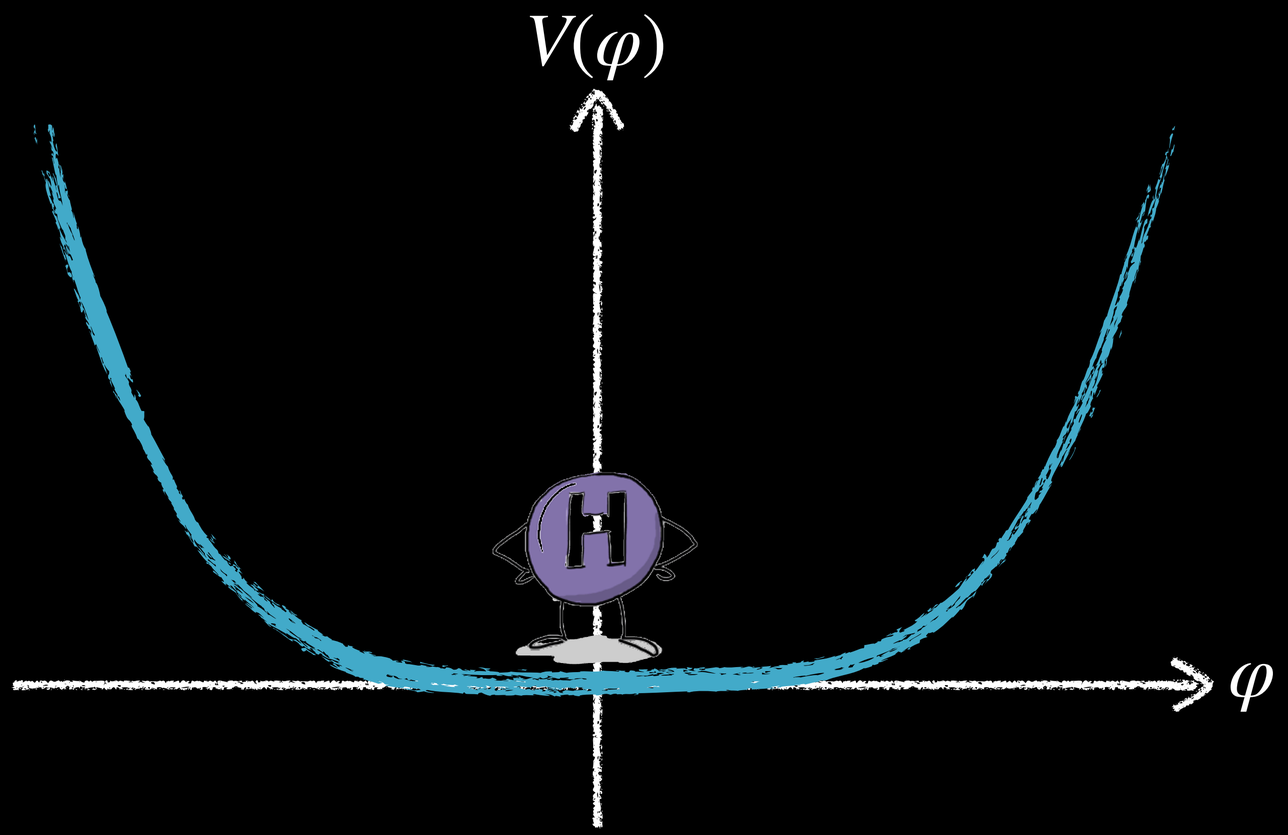
BOGUMIŁA ŚWIEŻEWSKA
UNIVERSITY OF WARSAW

EXPERIMENT: HIGGS EXISTS

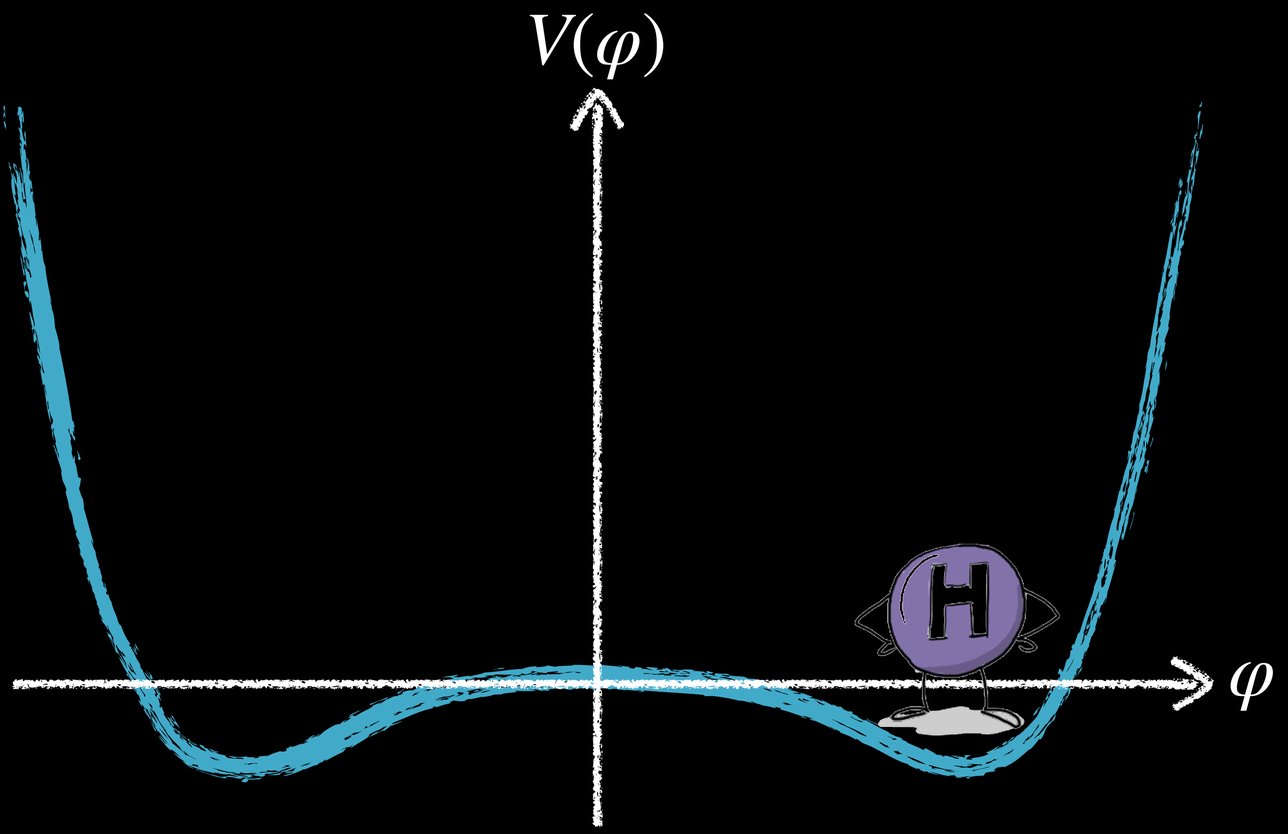


[Image from PhD Comics]

THEORY: NO VEV IN THE PAST

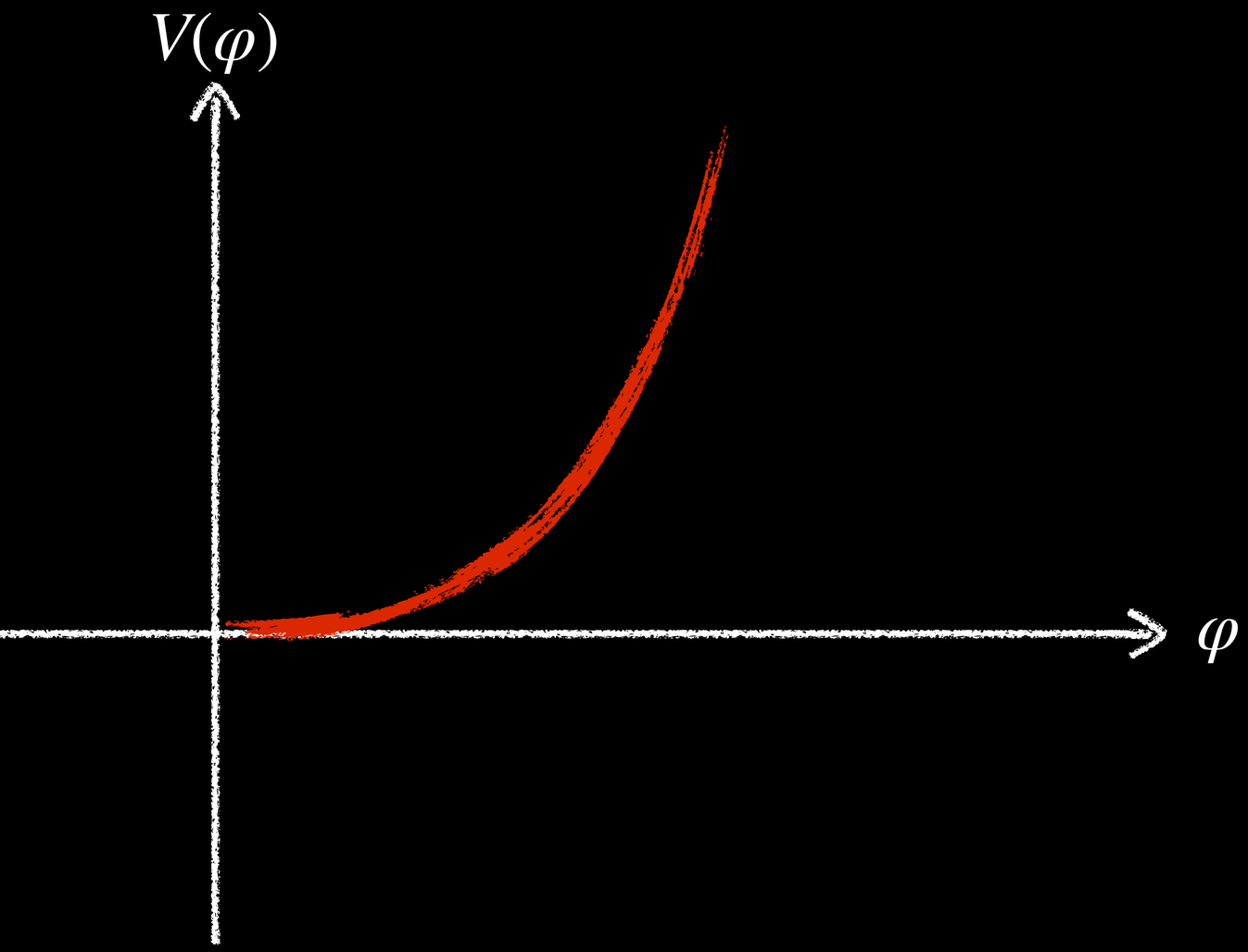


PHASE TRANSITION HAPPENED!



[Image from PhD Comics]

FIRST-ORDER PHASE TRANSITION



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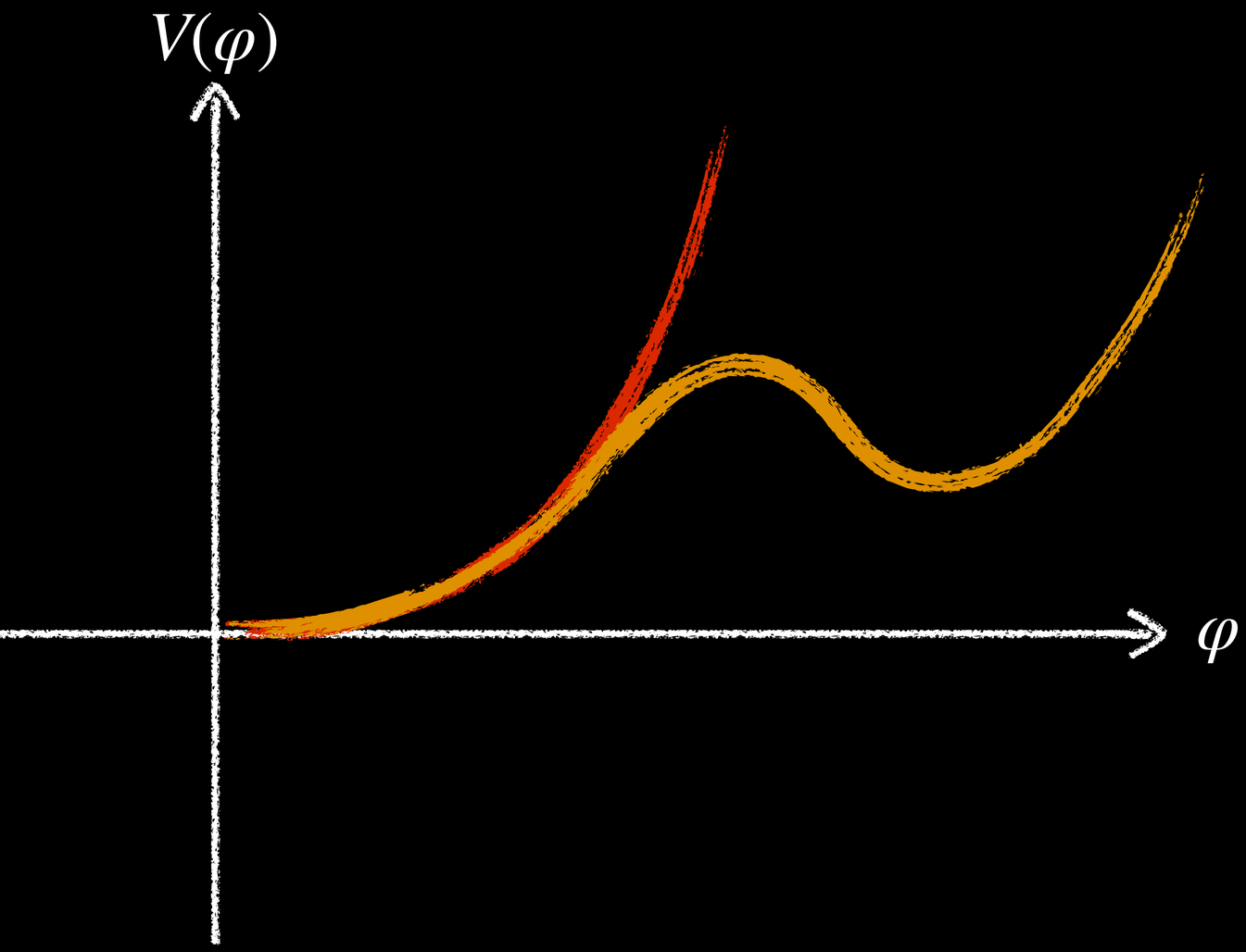

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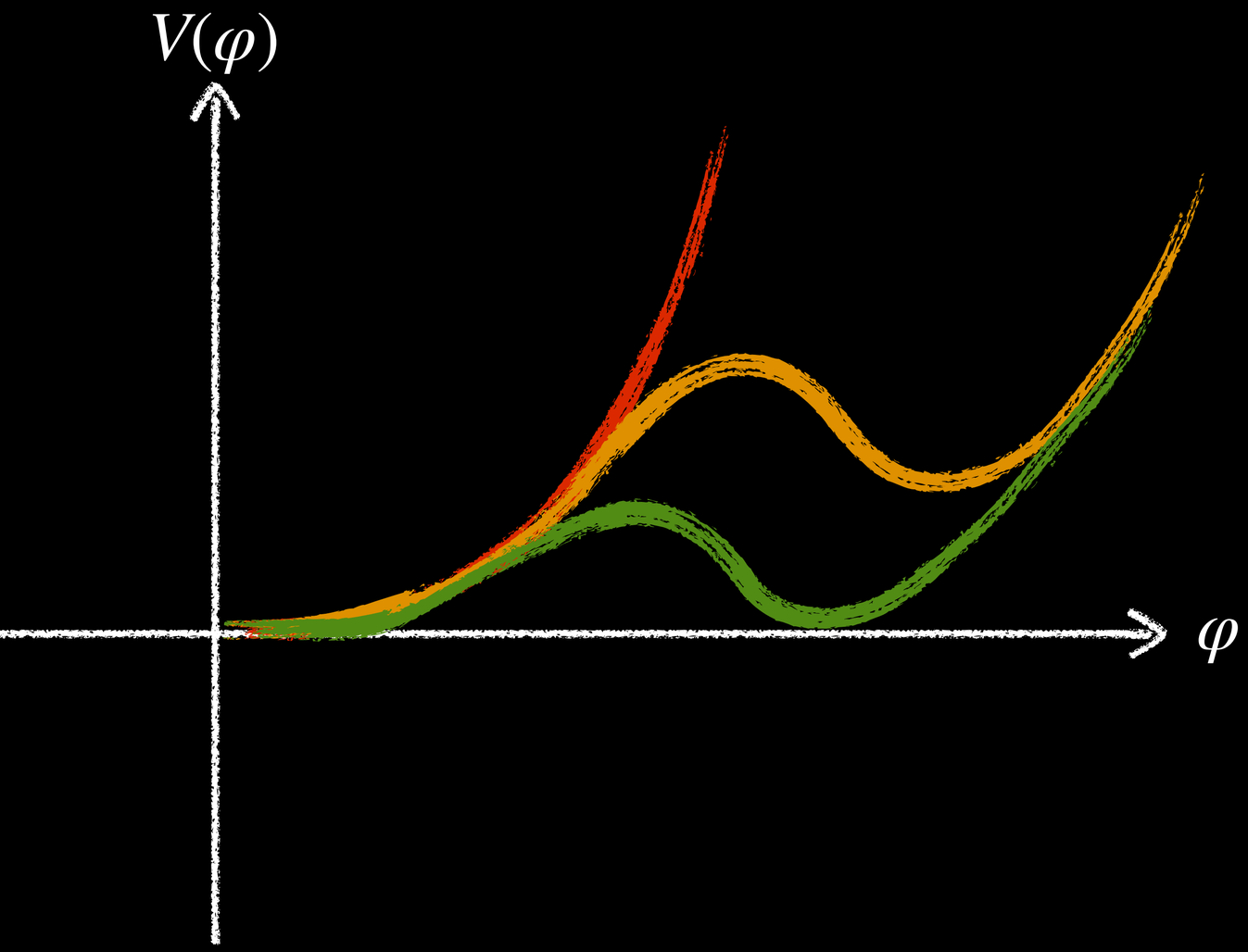

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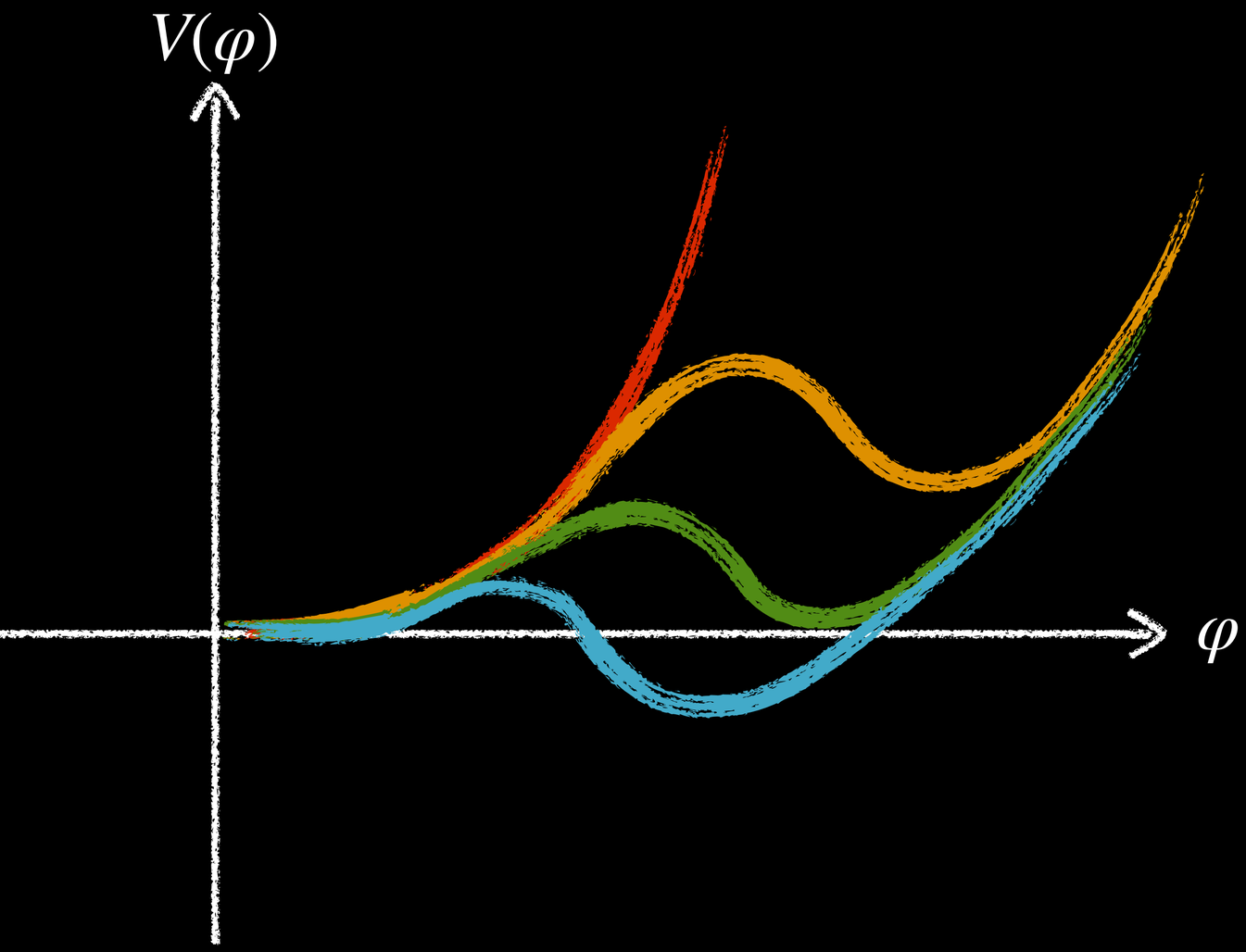

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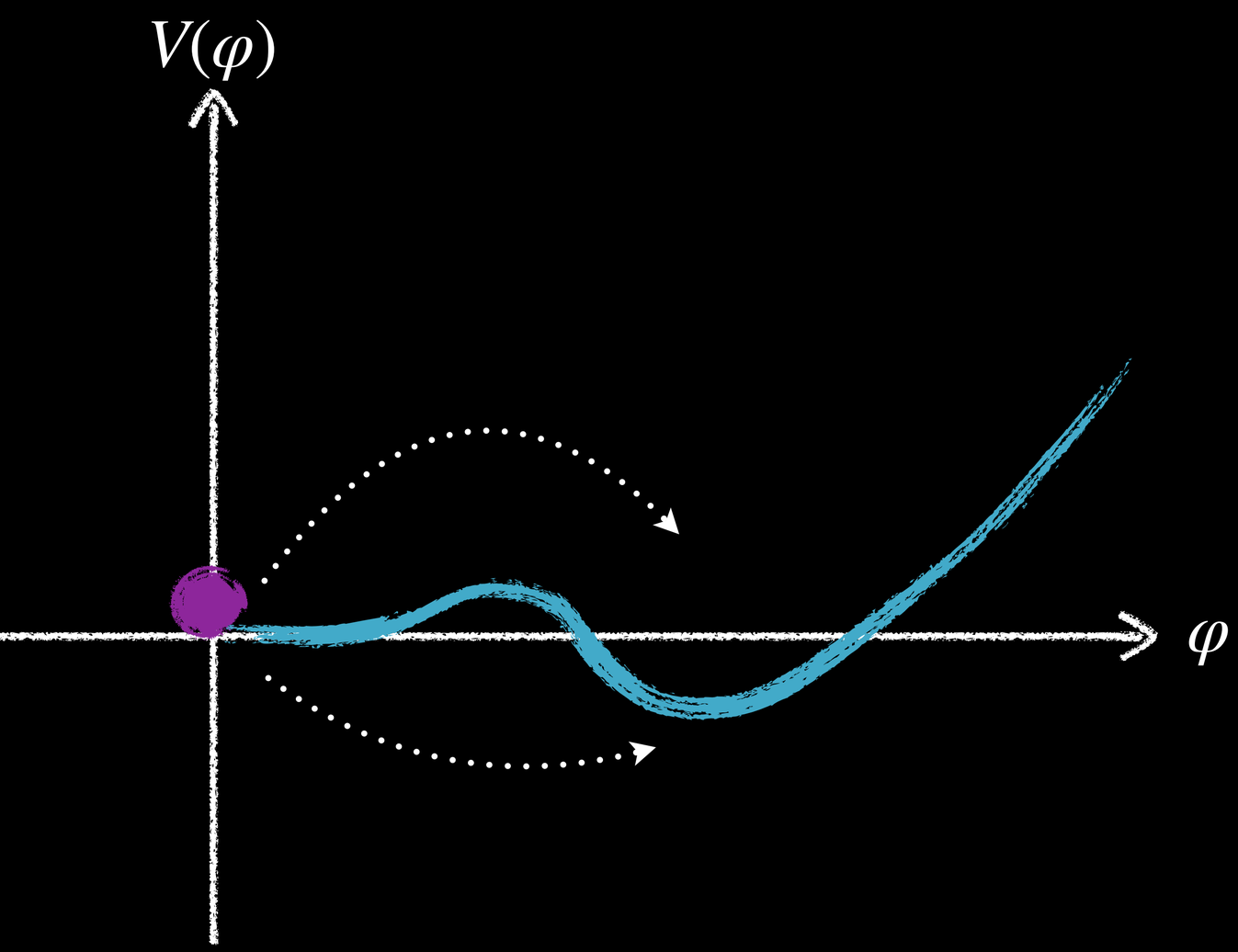

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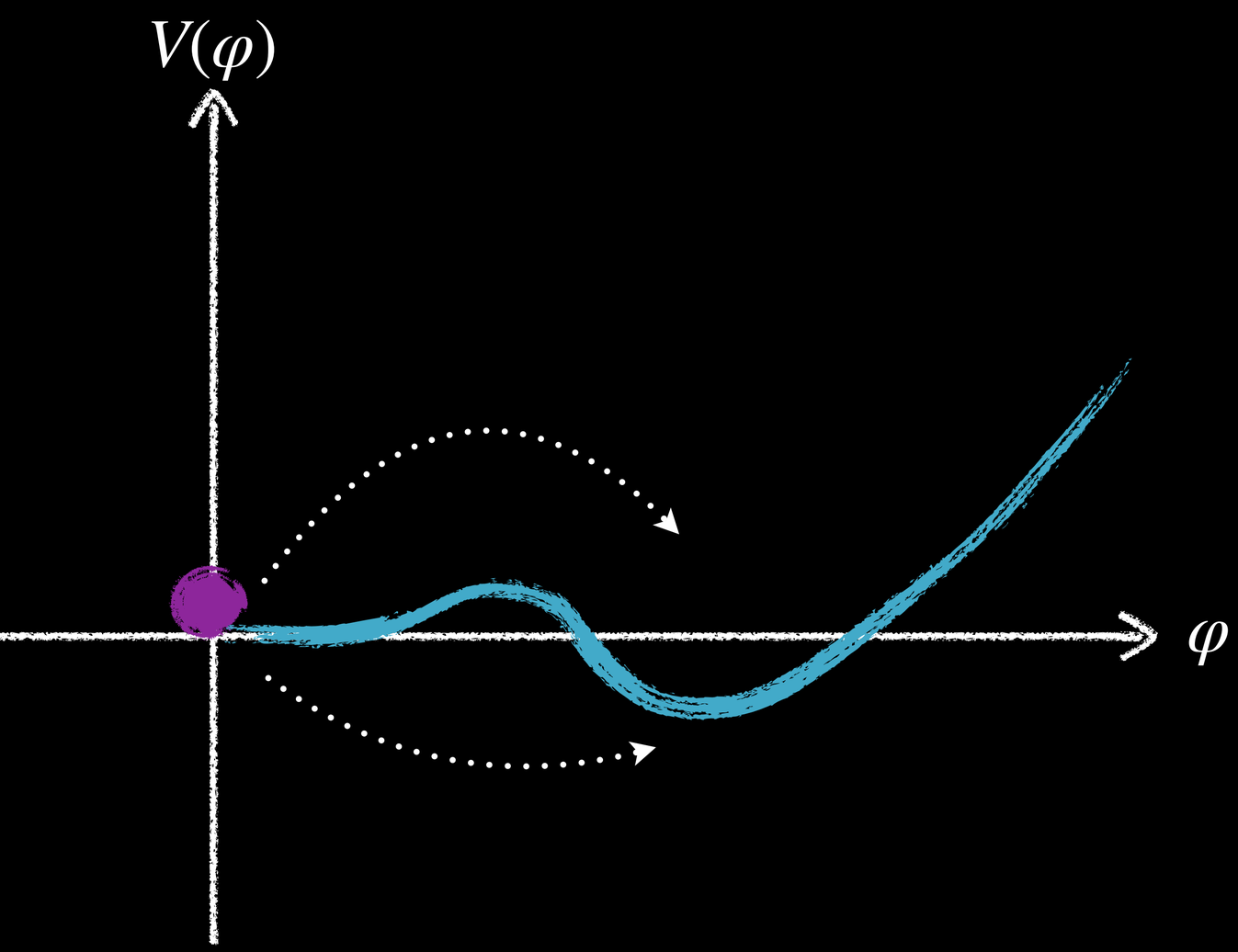

$\langle\varphi\rangle \neq 0$

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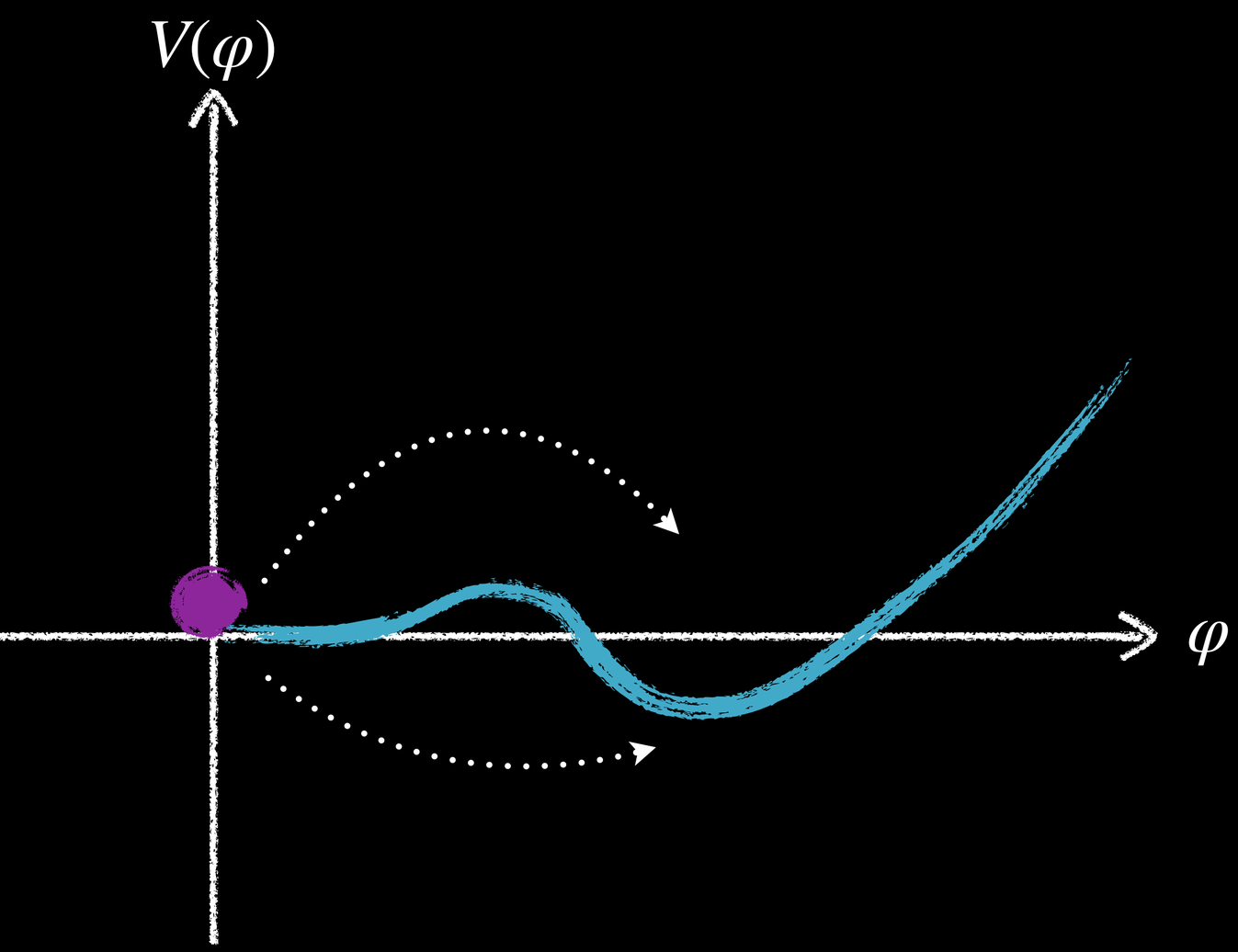
FIRST-ORDER PHASE TRANSITION



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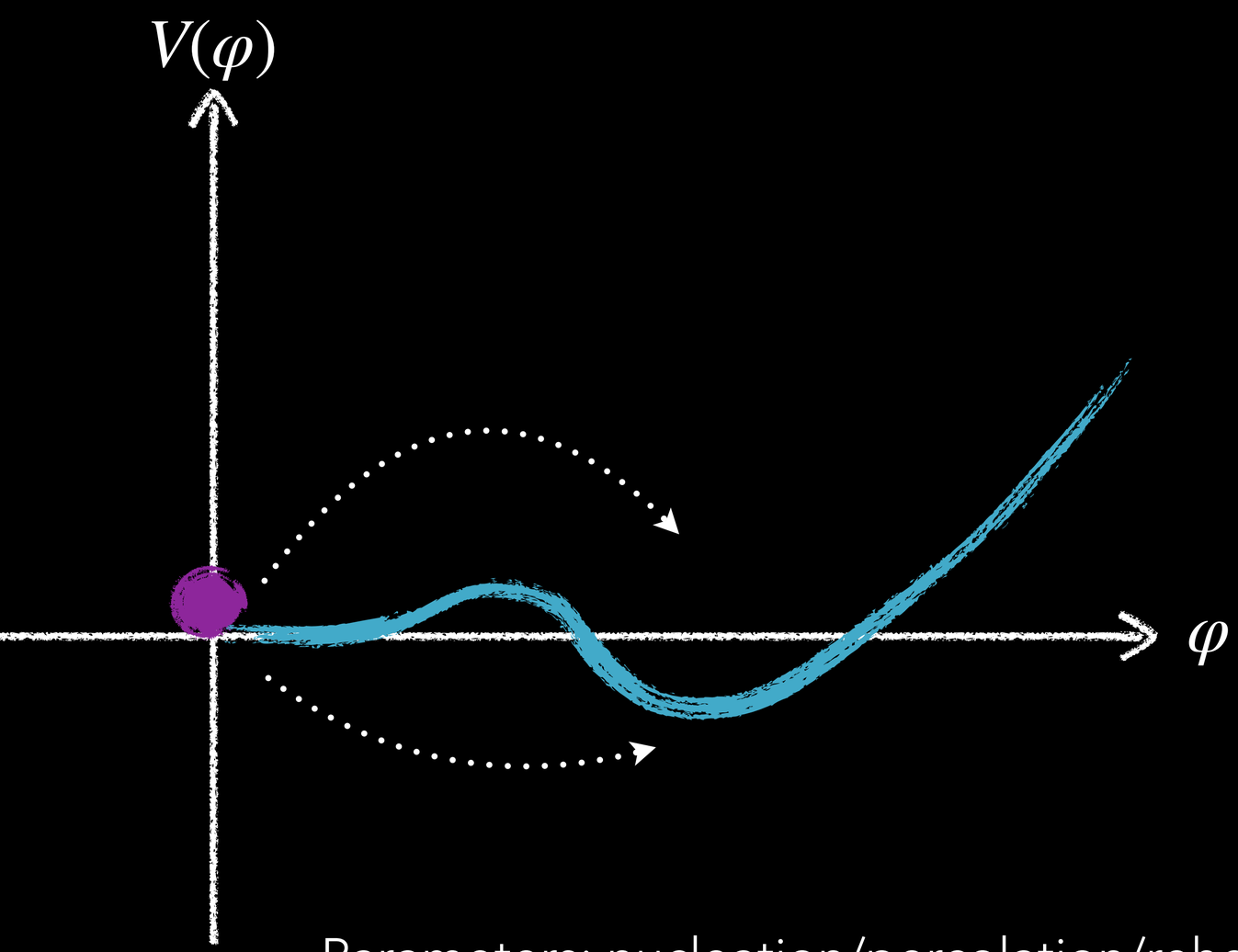
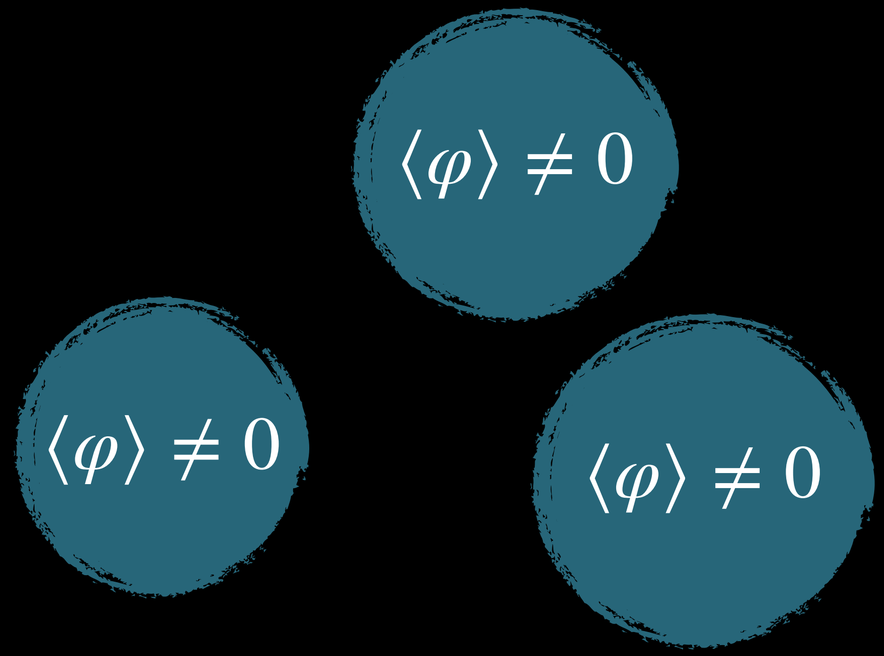




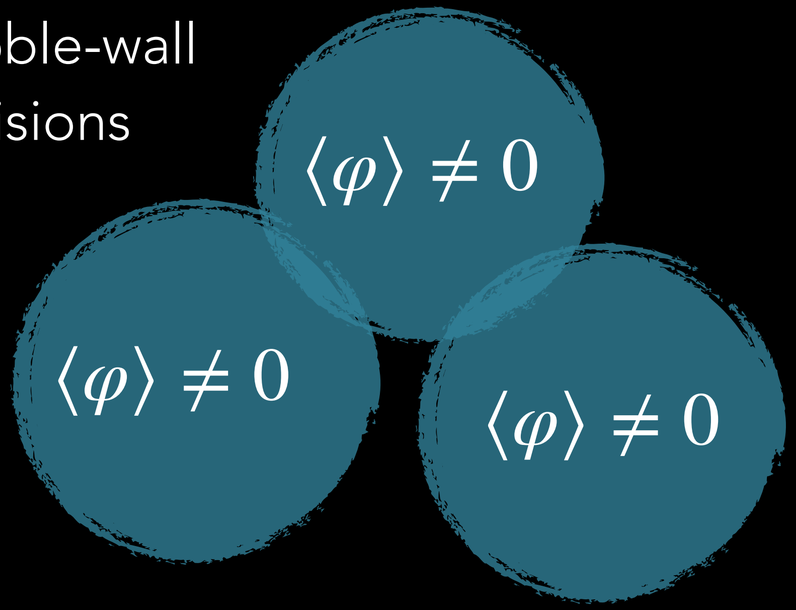
Parameters: nucleation/percolation/reheating temperature T_*, bubble size/ transition rate R_*/β_*, transition strength α, bubble-wall velocity v_w

BUBBLES AND PLASMA SOURCE GRAVITATIONAL WAVES

$$\langle \varphi \rangle \neq 0$$

BUBBLES AND PLASMA SOURCE GRAVITATIONAL WAVES

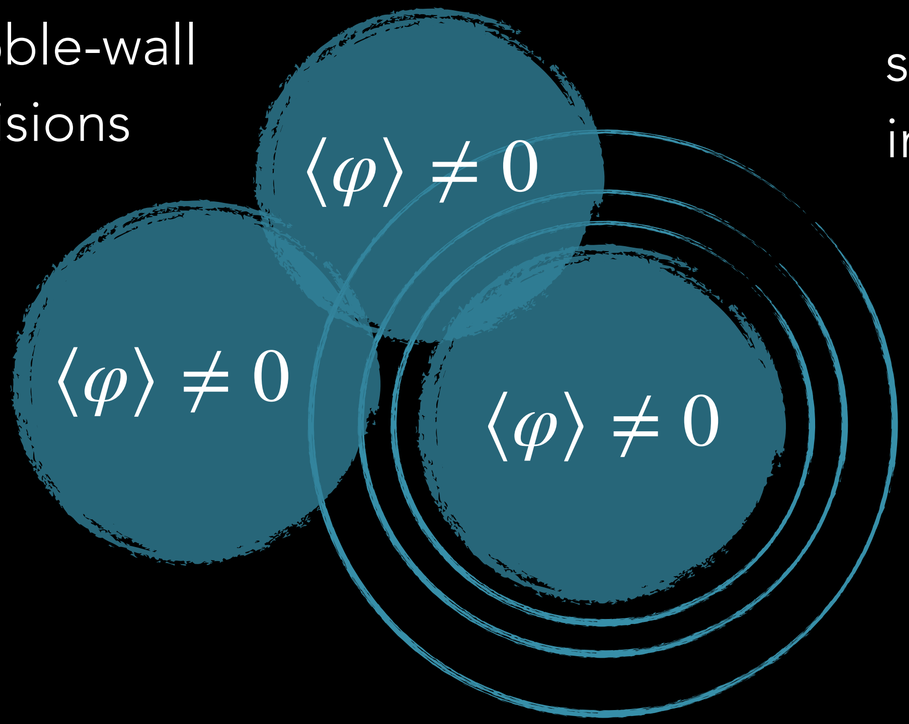
bubble-wall collisions



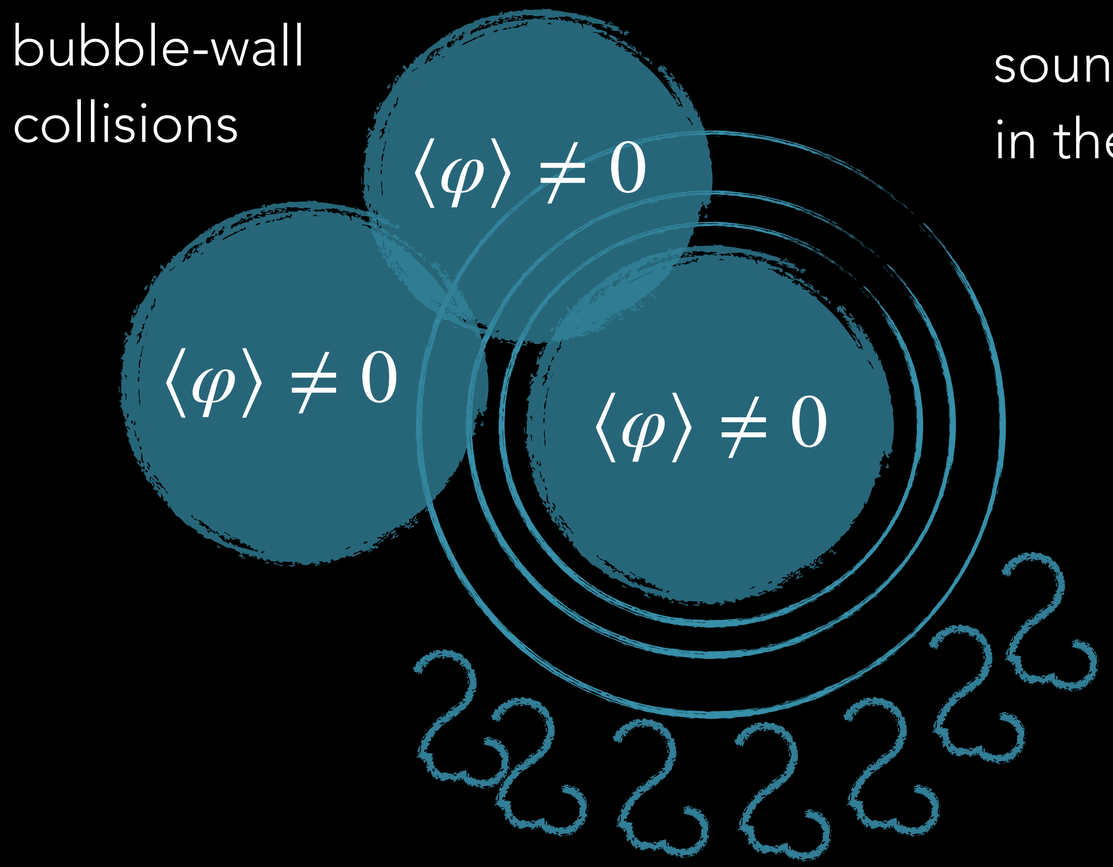
BUBBLES AND PLASMA SOURCE GRAVITATIONAL WAVES

bubble-wall collisions

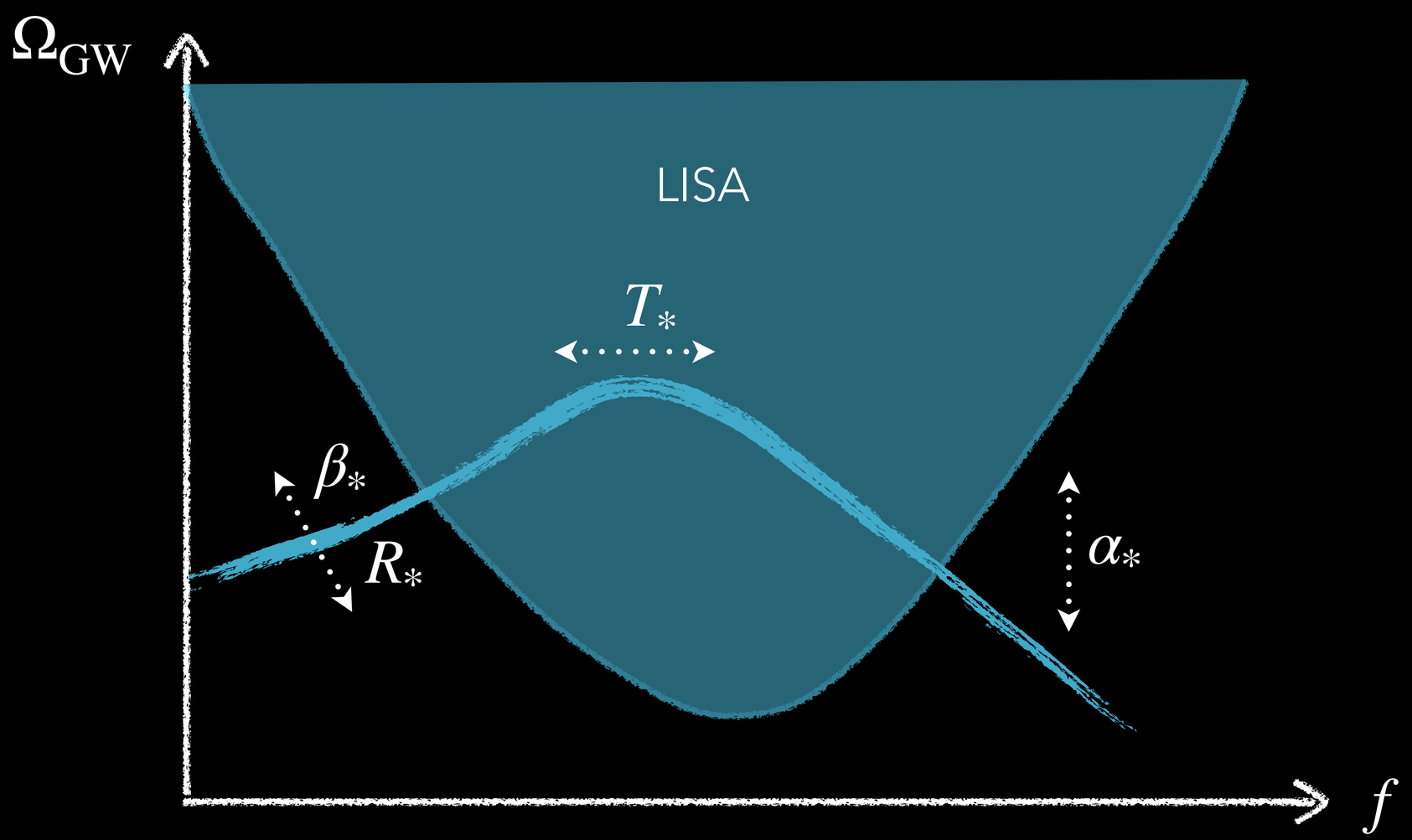
sound waves in the plasma



BUBBLES AND PLASMA SOURCE GRAVITATIONAL WAVES



THERMODYNAMICAL PARAMETERS VS GW



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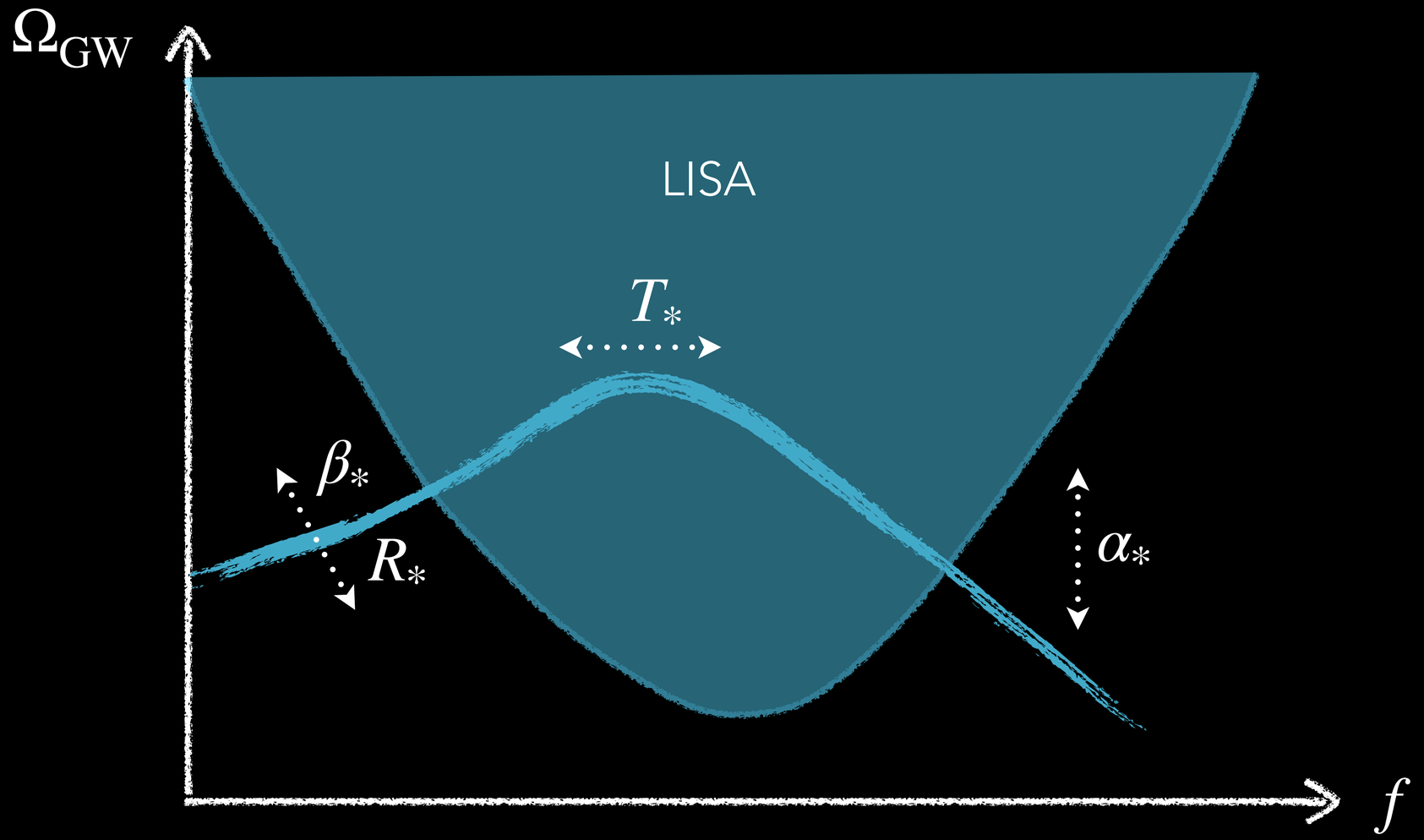
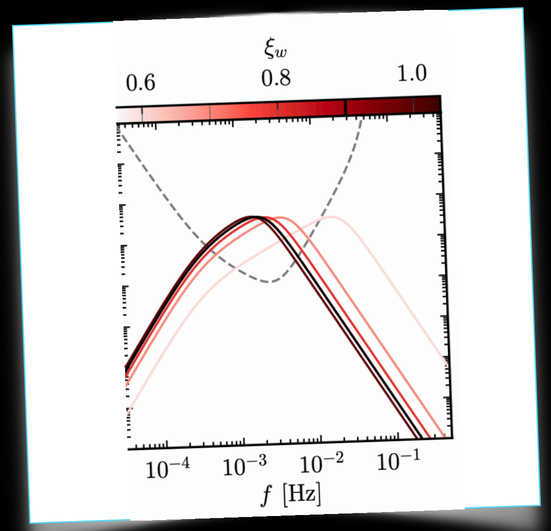


+ wall velocity $v_{\rm w}$



[C. Caprini at al., LISA CosWG, 2403.03723]

In SM the PT is crossover.

The search for a first-order PT is a search for New Physics!

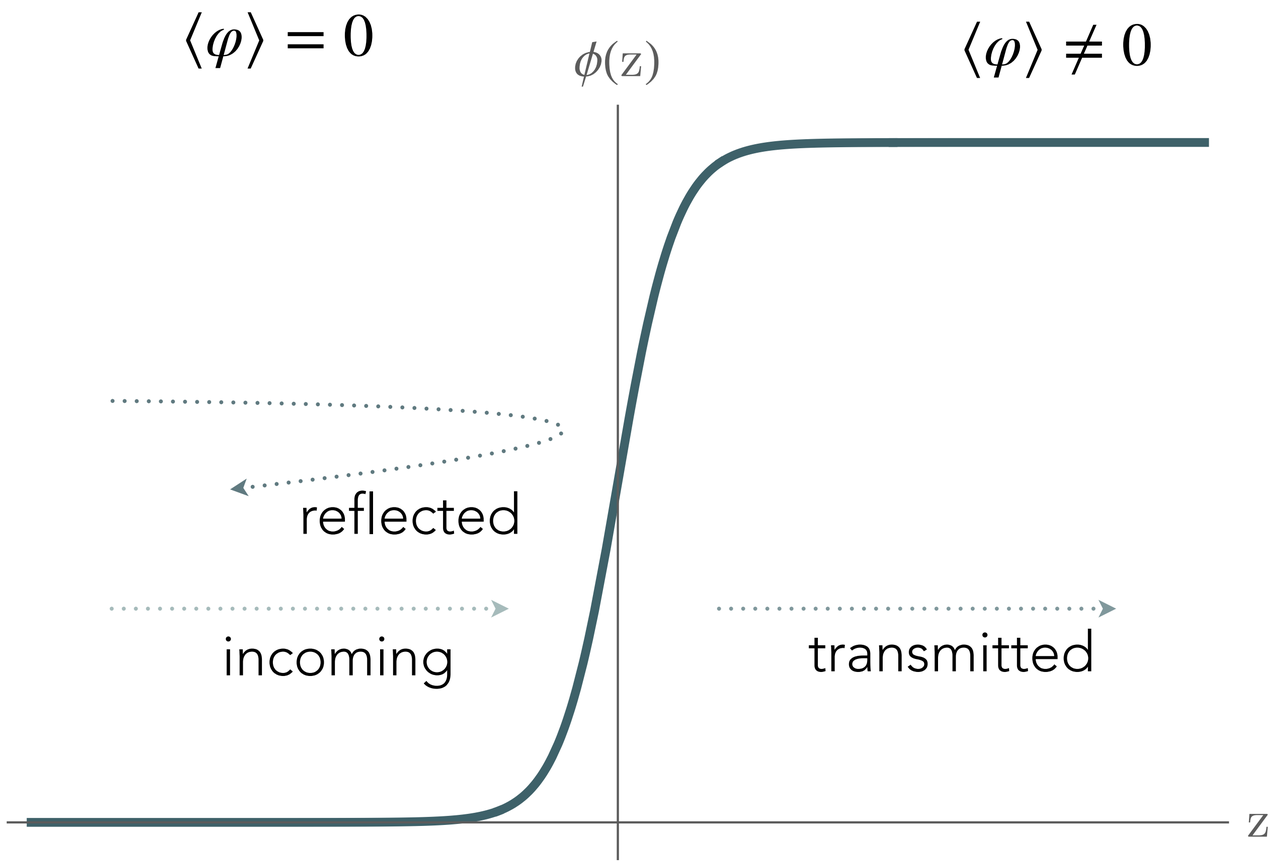
[K. Kajantie, M. Laine, K. Rummukainen and M. E. Shaposhnikov, Phys. Rev. Lett. 77, 2887 (1996); K. Rummukainen, M. Tsypin, K. Kajantie, M. Laine and M. E. Shaposhnikov, Nucl. Phys. B 532, 283 (1998); F. Csikor, Z. Fodor and J. Heitger, Phys. Rev. Lett. 82, 21 (1999)]

SEE BLACKBOARD

FROM LAGRANGIAN TO BUBBLES

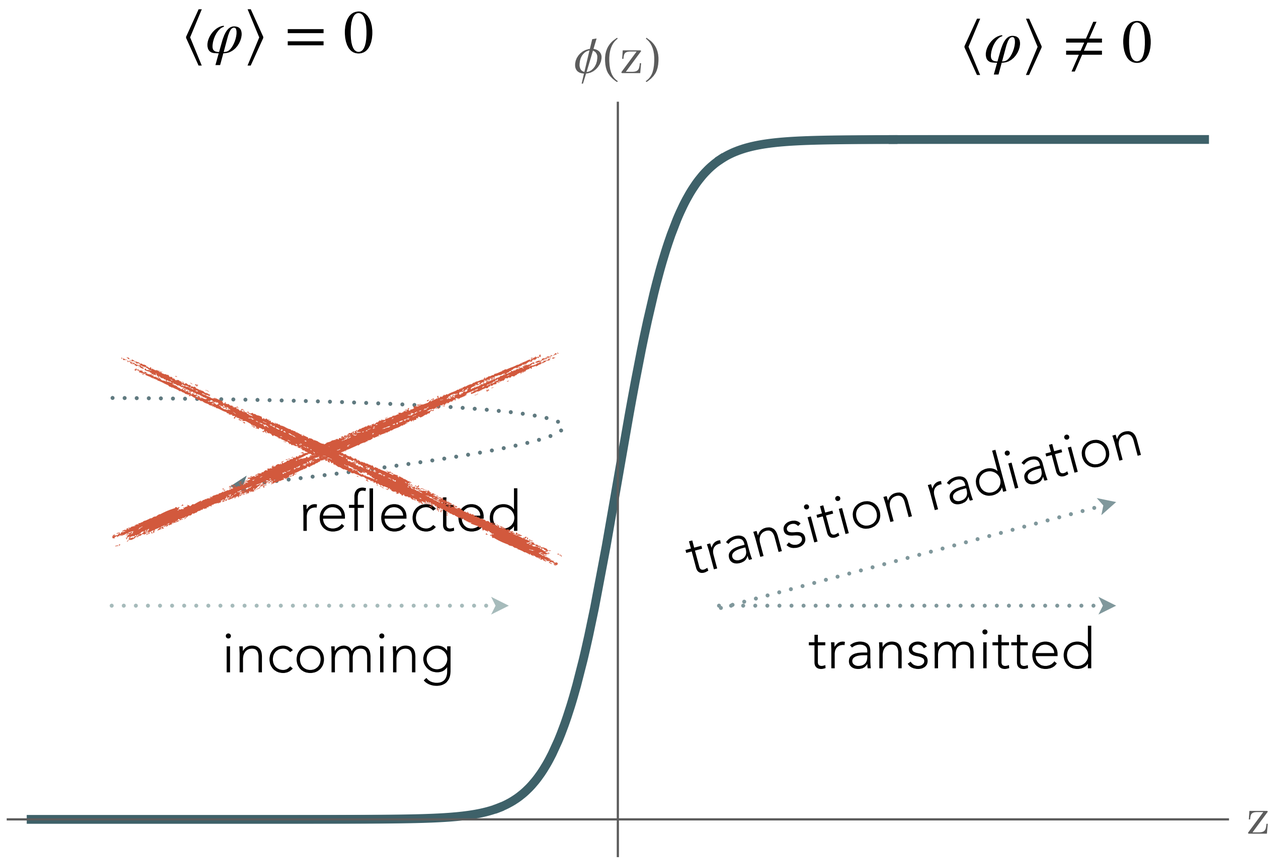
WALL VELOCITY AND SUPERCOOLING

WALL VELOCITY



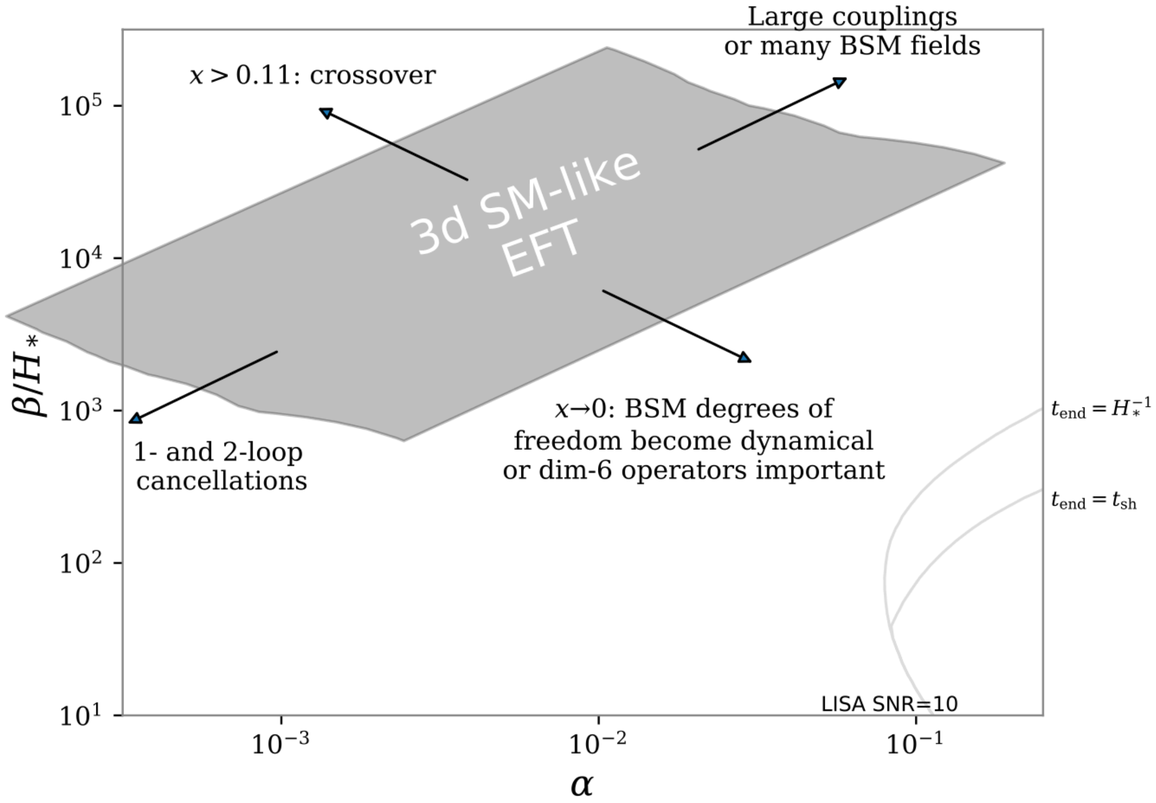
[G. D. Moore and T. Prokopec, Phys. Rev. D 52 (1995) 7182–7204, Phys. Rev. Lett. 75 (1995) 777–780 ,
B. Laurent and J. M. Cline, Phys. Rev. D 102 no. 6, (2020) 063516, Phys. Rev. D 106 no. 2, (2022) 023501,
G. C. Dorsch, S. J. Huber, and T. Konstandin, JCAP 12 (2018) 034]

RUNAWAY BUBBLES?



[D. Bodeker and G. D. Moore, JCAP 05 (2009) 009, JCAP 05 (2017) 025,
S. Höche, J. Kozaczuk, A. J. Long, J. Turner, and Y. Wang, JCAP 03 (2021) 009 ,
Y. Gouttenoire, R. Jinno, and F. Sala, JHEP 05 (2022) 004]

FIRST-ORDER PT CANNOT BE SM-LIKE



[Figure from: Phys.Rev.D 100 (2019) 11, 115024, O. Gould, J. Kozaczuk, L. Niemi, M. J. Ramsey-Musolf, T. V.I. Tenkanen, D. J. Weir]

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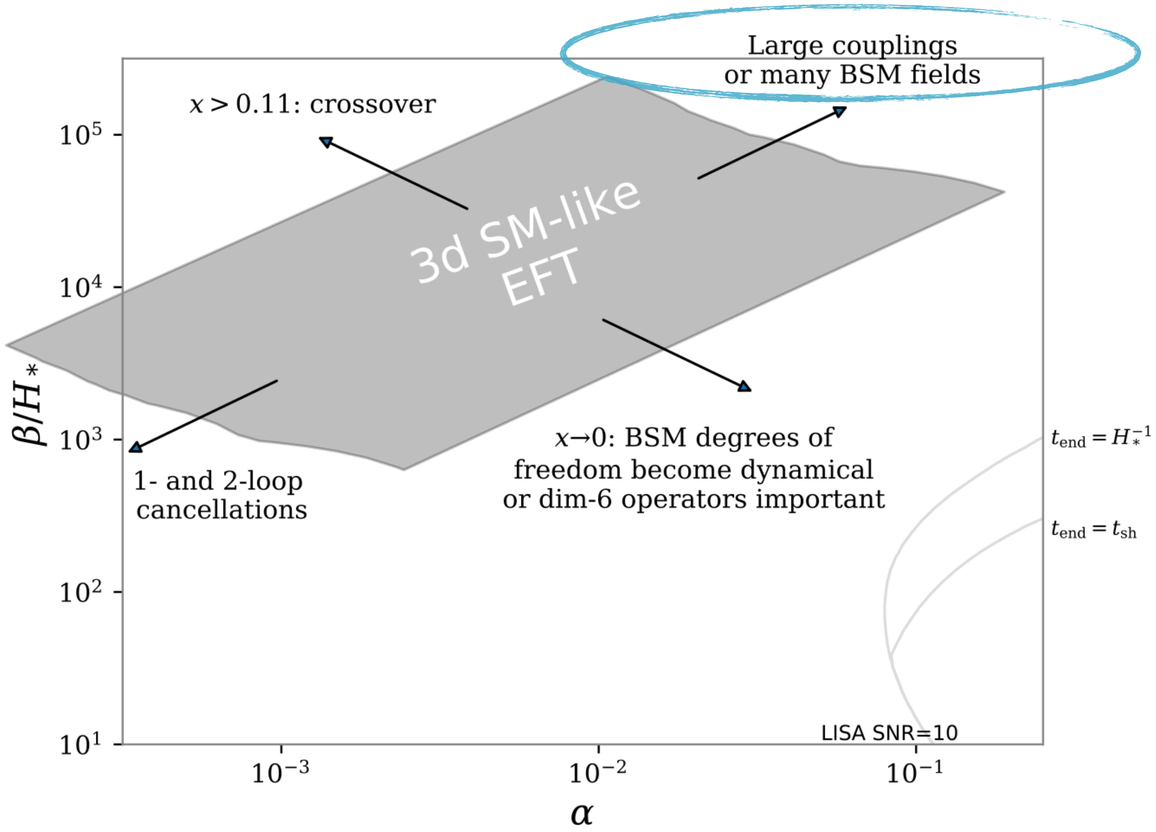

Scalar extensions of the SM (large coupling)

[Figure from: Phys.Rev.D 100 (2019) 11, 115024, O. Gould, J. Kozaczuk, L. Niemi, M. J. Ramsey-Musolf, T. V.I. Tenkanen, D. J. Weir]

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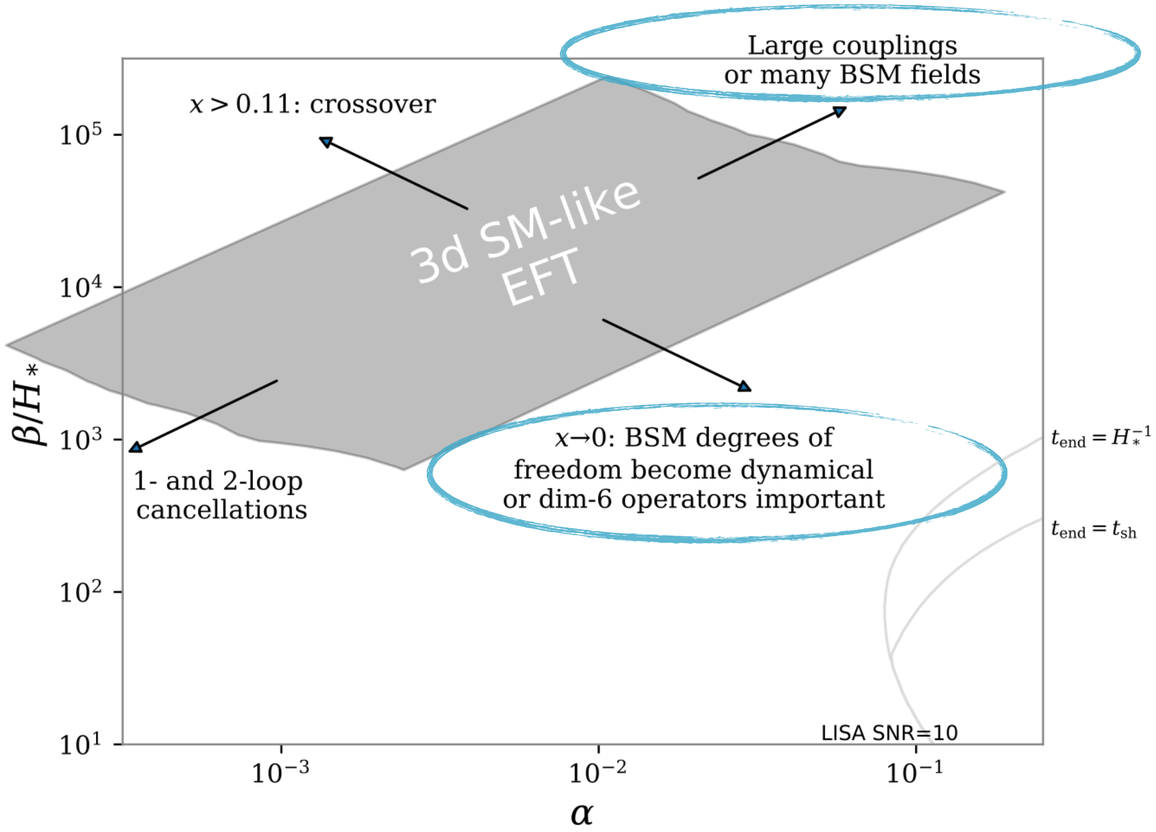


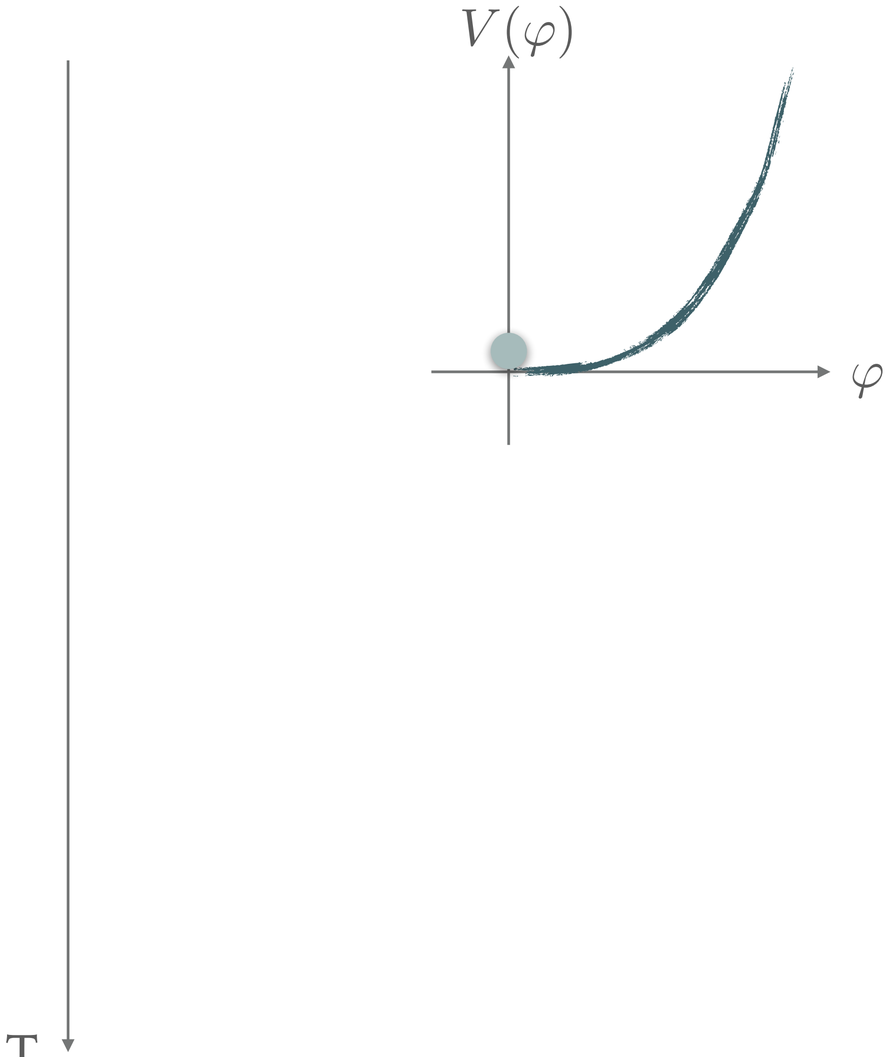
Scalar extensions of the SM (large coupling)

PT for a new field

[Figure from: Phys.Rev.D 100 (2019) 11, 115024, O. Gould, J. Kozaczuk, L. Niemi, M. J. Ramsey-Musolf, T. V.I. Tenkanen, D. J. Weir]

TEMPERATURE EVOLUTION

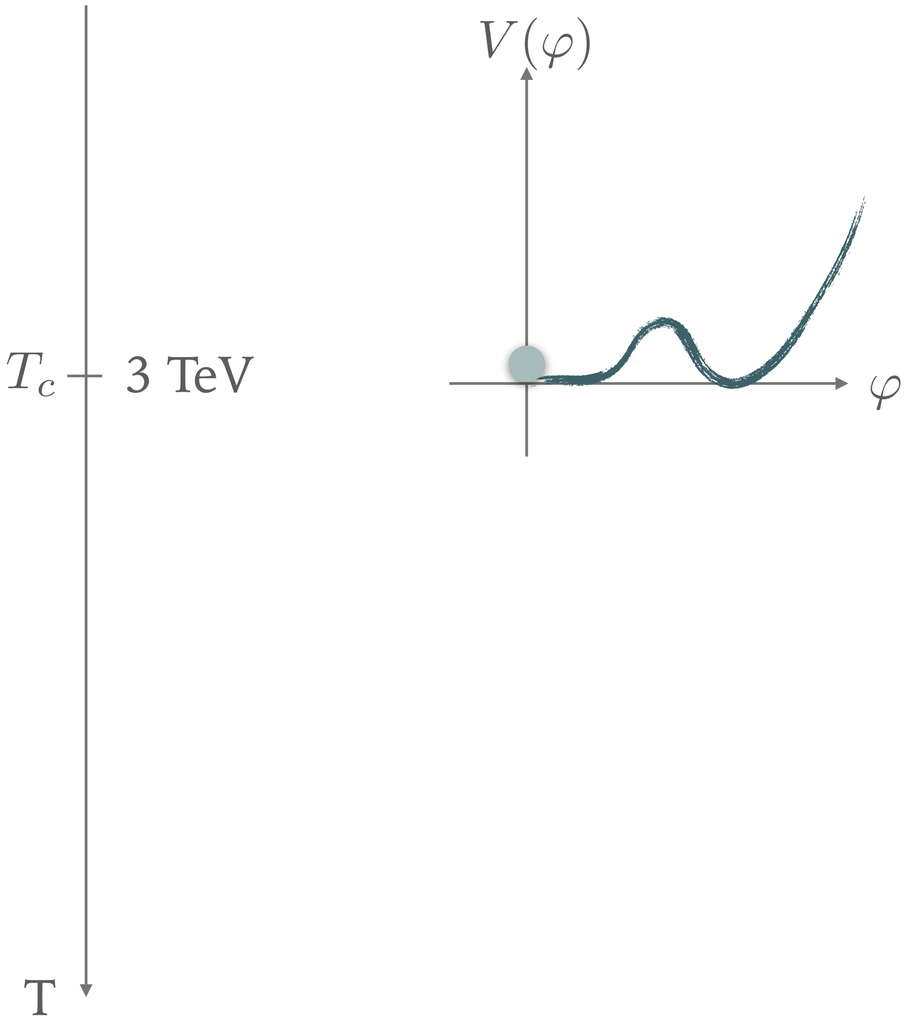
$M_X = 9$ TeV, $g_X = 0.9$



high temperature:
EW and conformal
symmetry restored

TEMPERATURE EVOLUTION

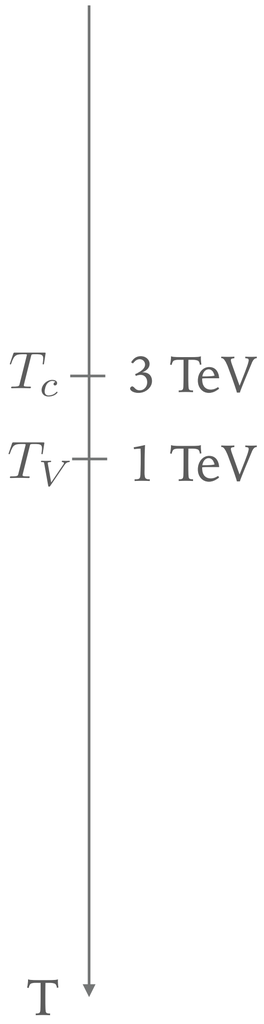
$M_X = 9$ TeV, $g_X = 0.9$

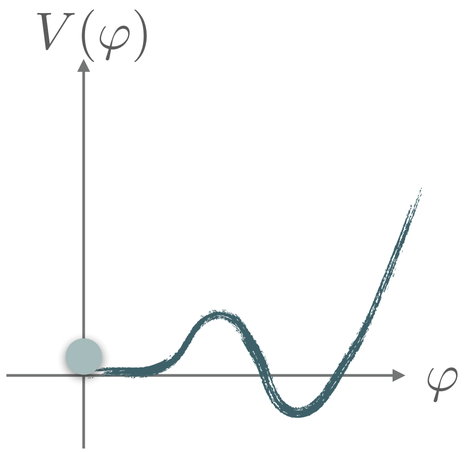


critical temperature: two degenerate minima

TEMPERATURE EVOLUTION

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



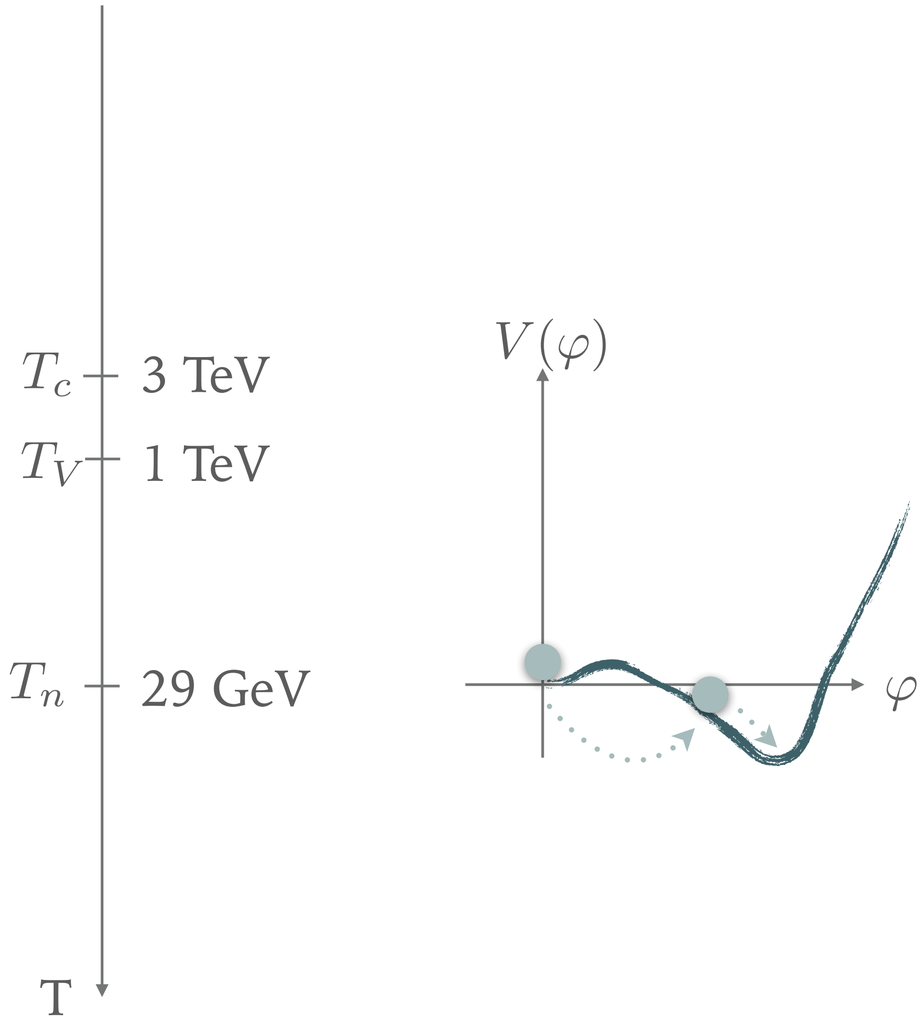


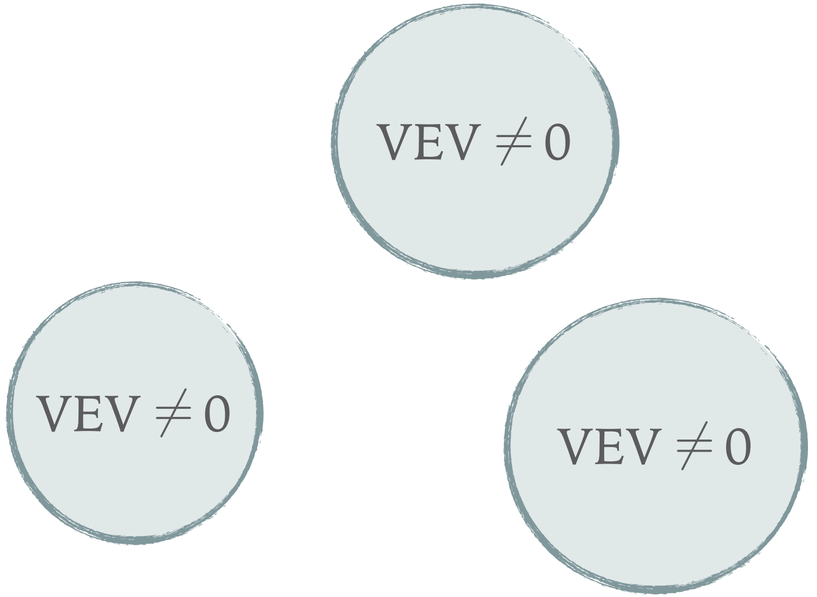
vacuum domination begins

TEMPERATURE EVOLUTION

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

nucleation:
one bubble nucleates
per Hubble volume

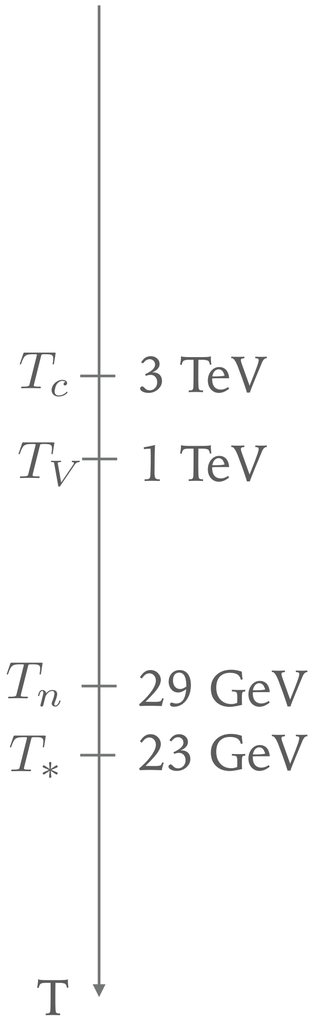


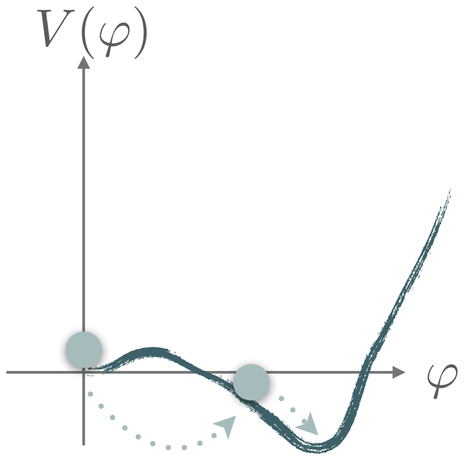


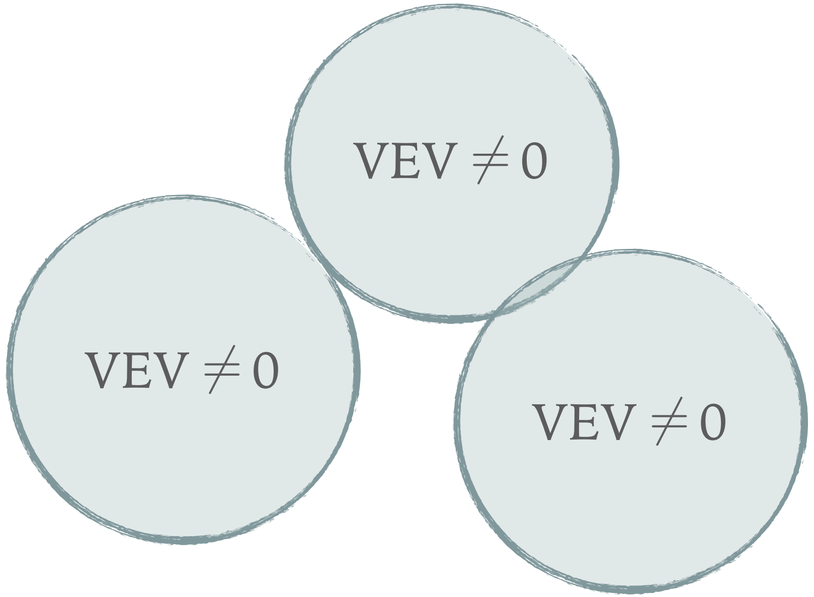
TEMPERATURE EVOLUTION

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

Percolation: phase transition completes







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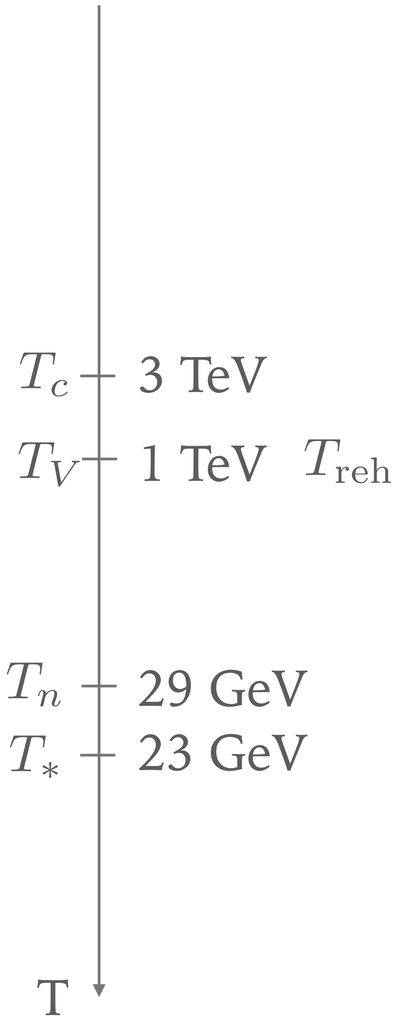
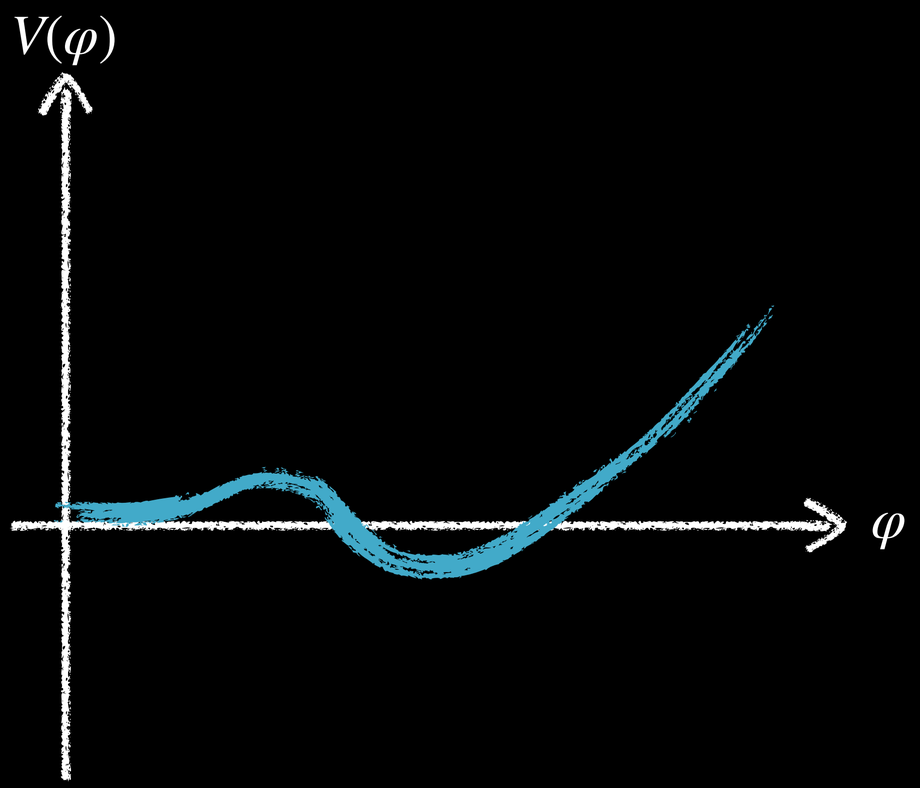
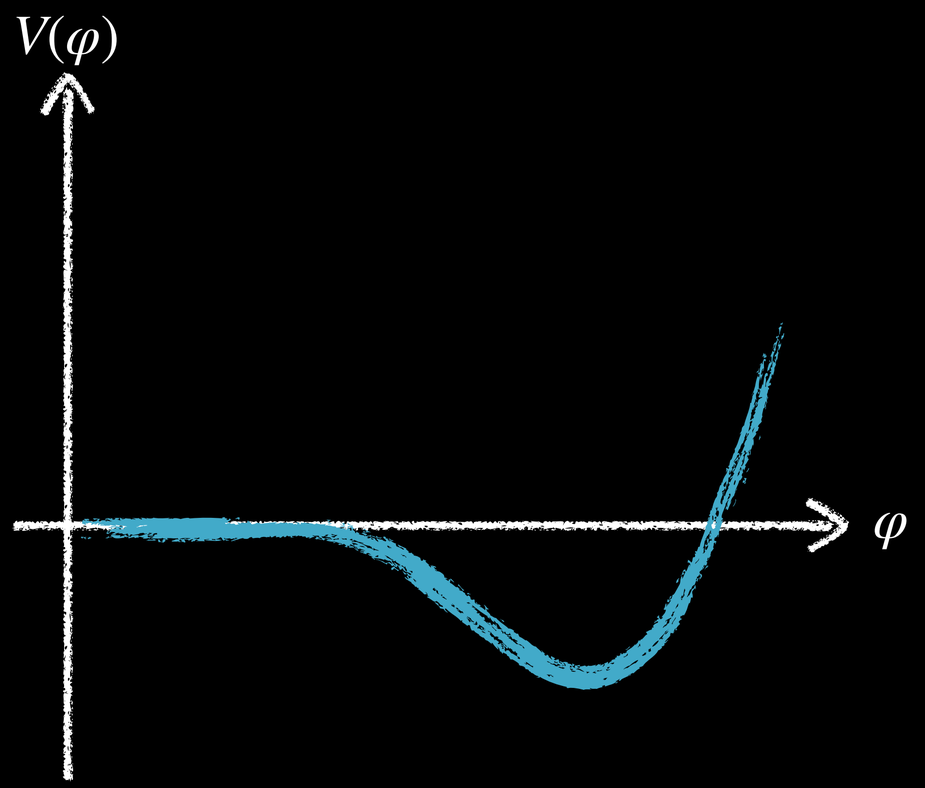


reheating: vacuum energy → radiation

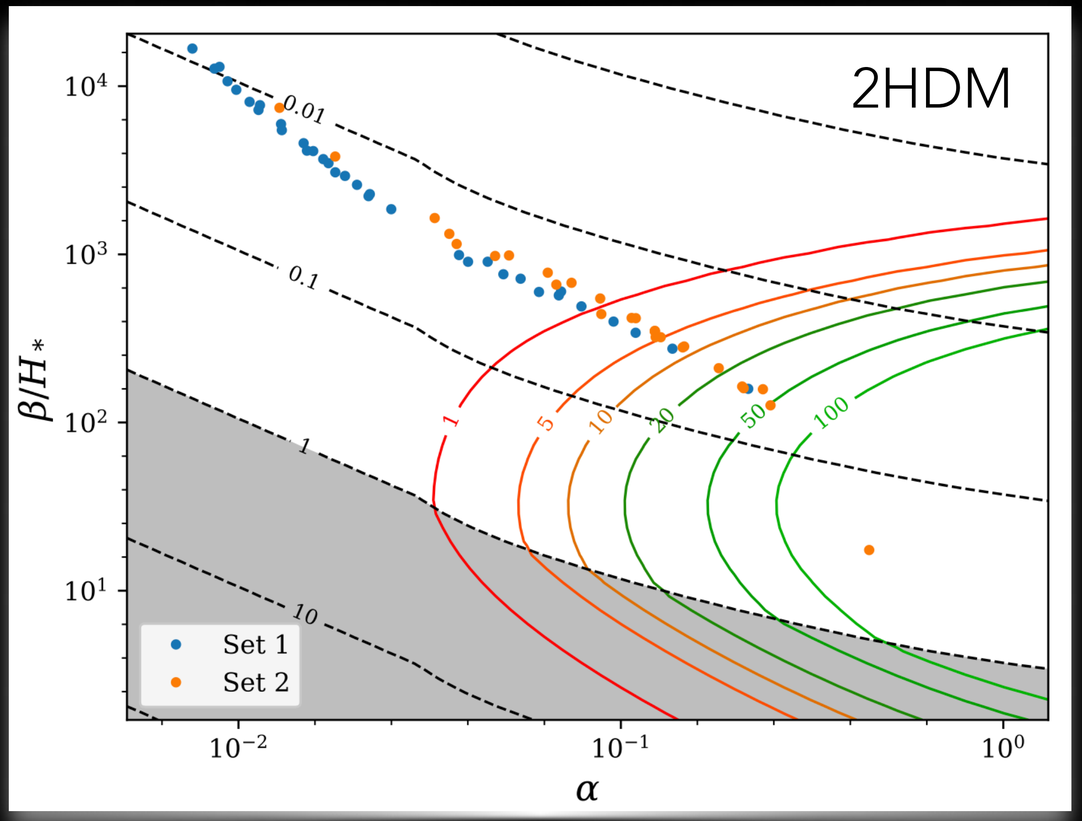
$$\alpha = \frac{\Delta V}{\text{energy of radiation}} \approx 4 \cdot 10^6$$

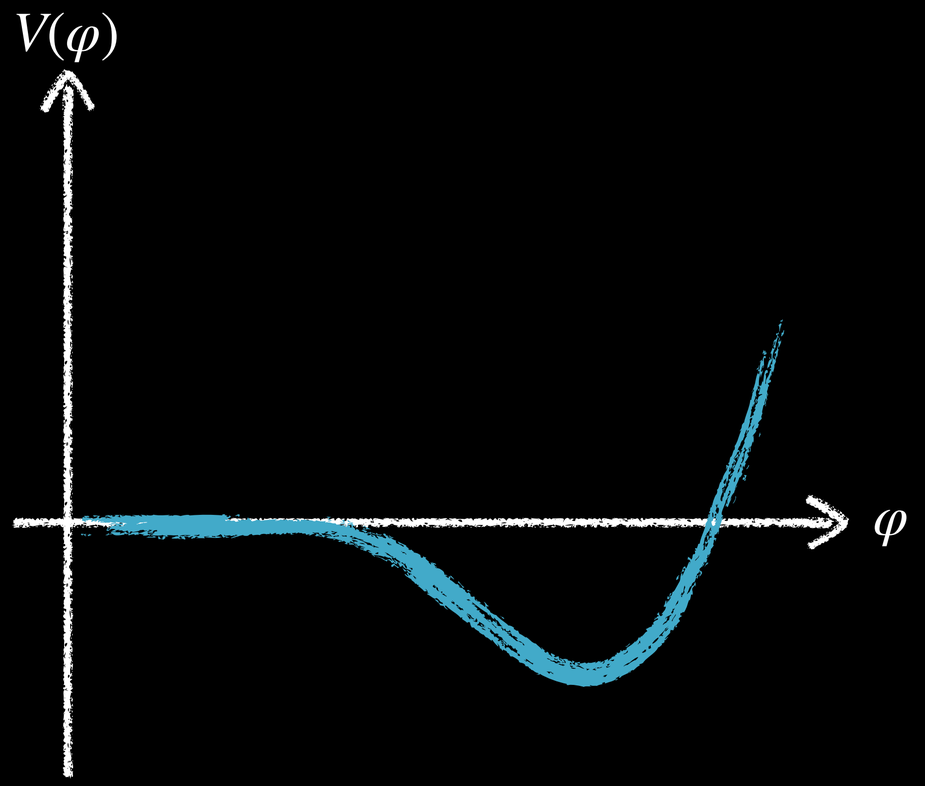
PHASE TRANSITION: ORDINARY VS SUPERCOOLED





PHASE TRANSITION: ORDINARY VS SUPERCOOLED





[C. Caprini et al., LISA CosWG, JCAP 03 (2020) 024]

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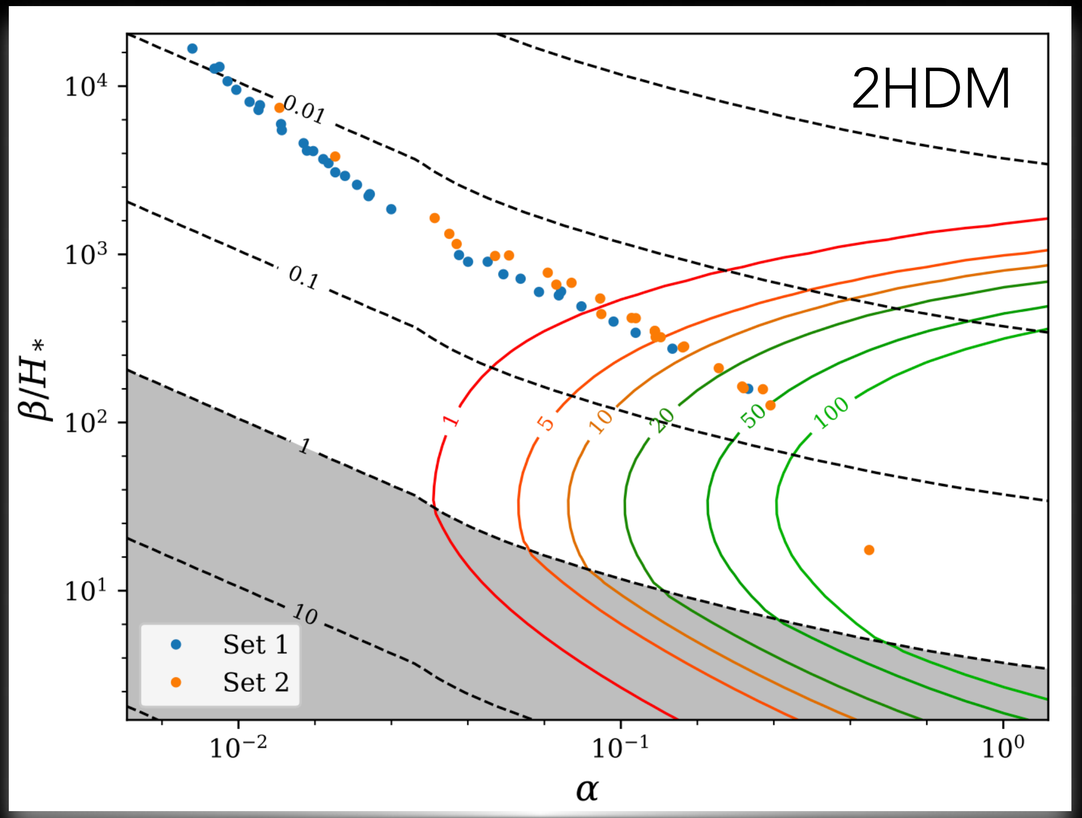

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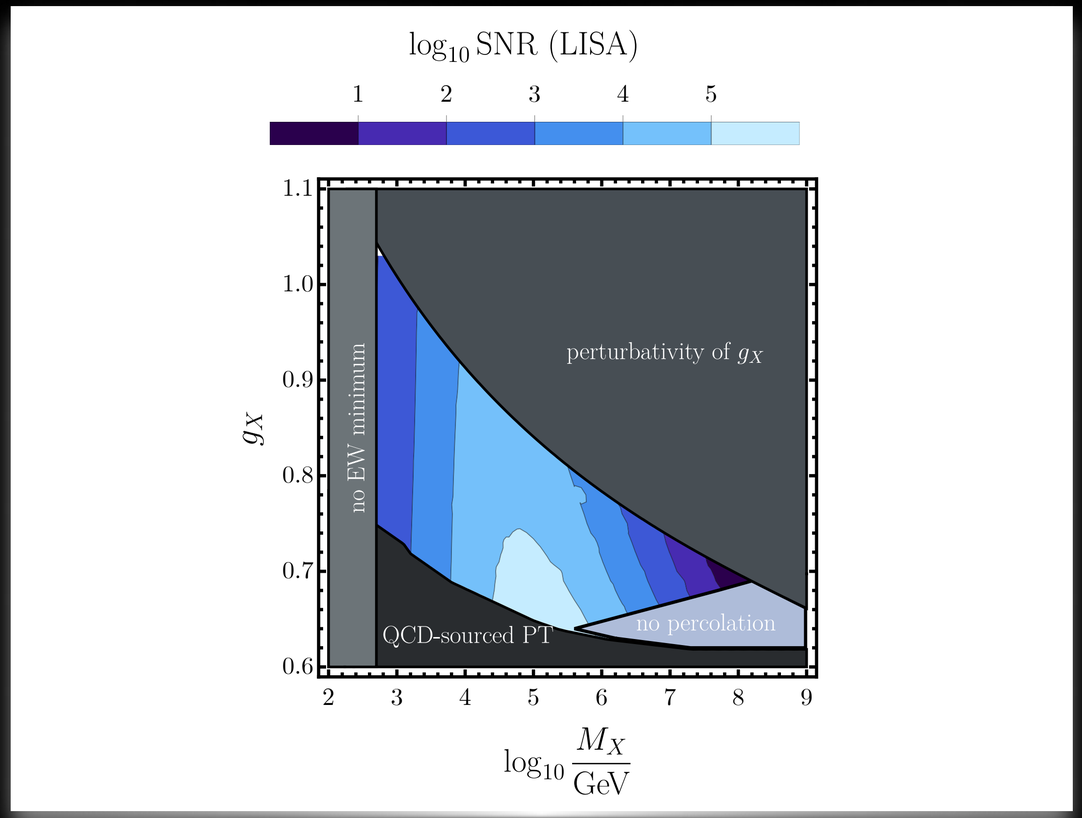
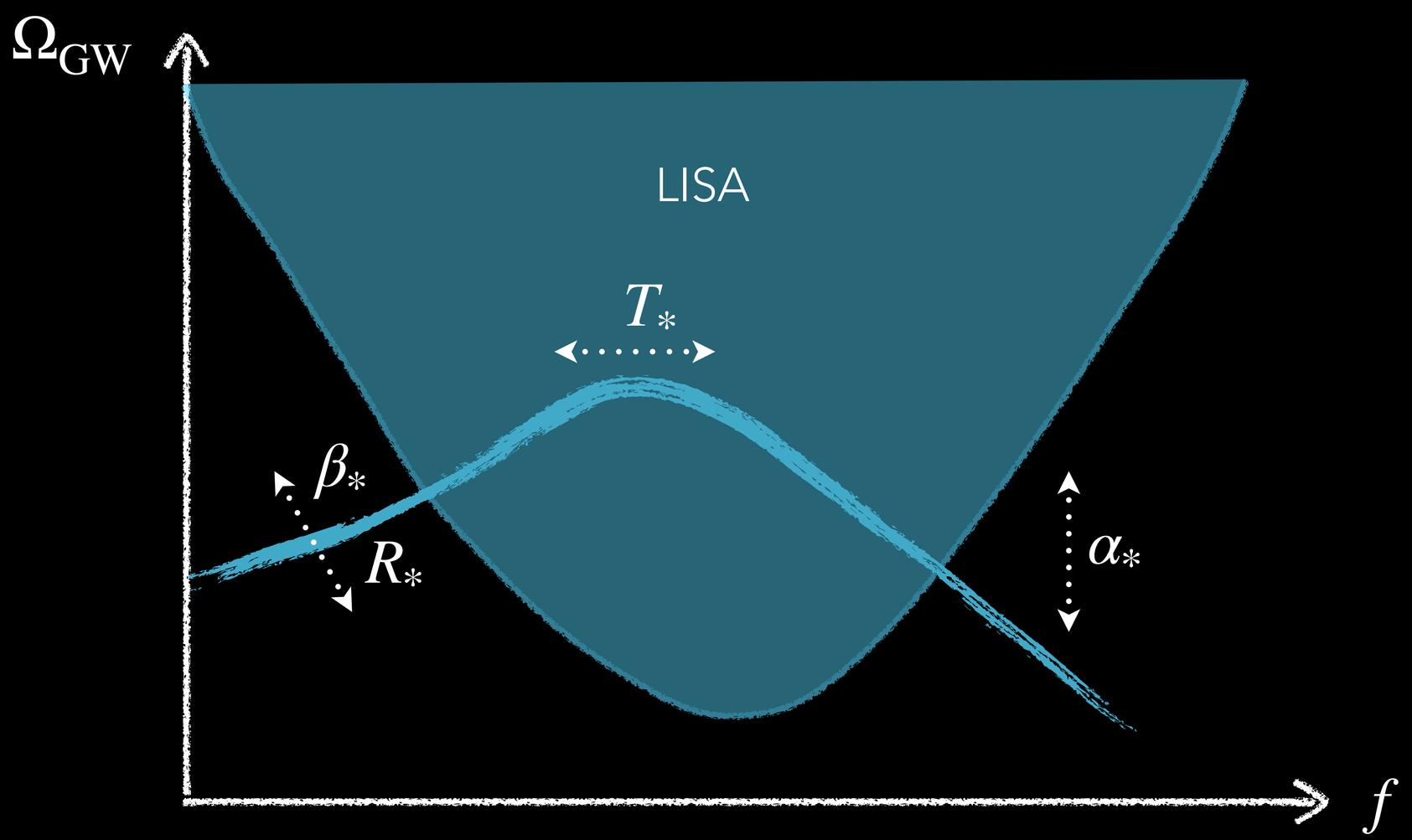


[M. Kierkla, BŚ, T.V.I. Tenkanen, J. van de Vis, *JHEP* 02 (2024) 234]

STOCHASTIC GRAVITATIONAL-WAVE BACKGROUND FROM FIRST-ORDER PHASE TRANSITIONS

THERMODYNAMICAL PARAMETERS VS GW



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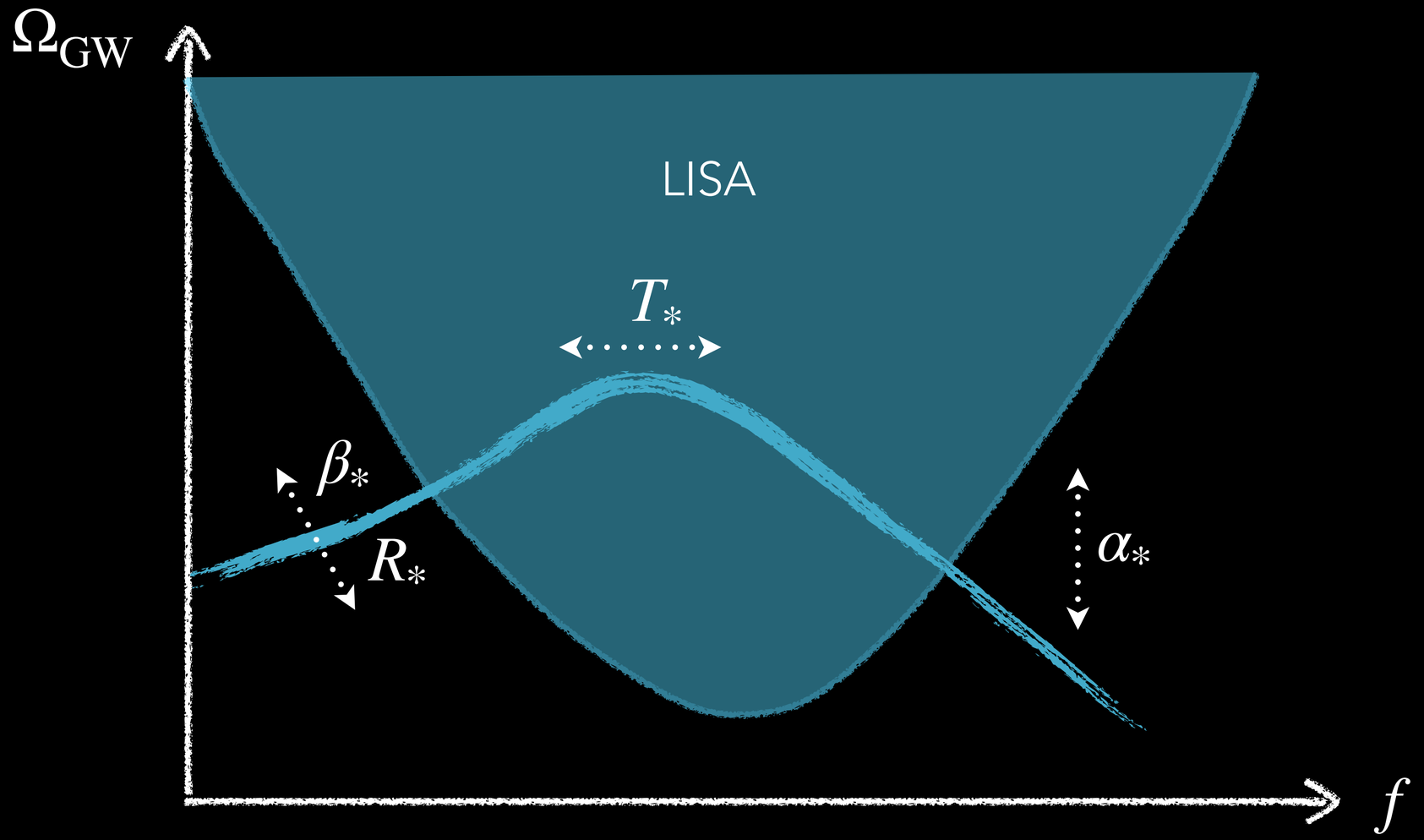
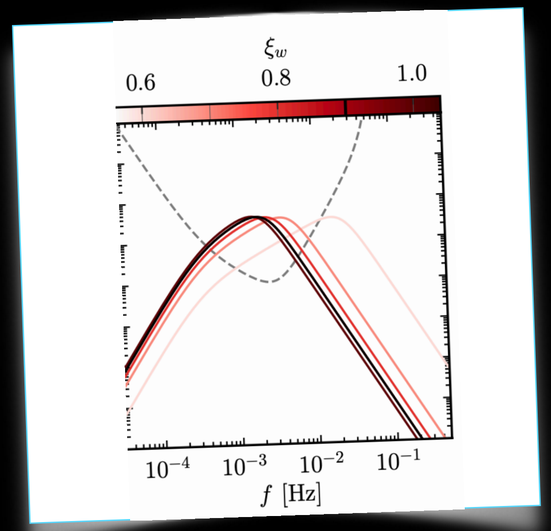


+ wall velocity $v_{\rm w}$



[C. Caprini at al., LISA CosWG, 2403.03723]

STRONG TRANSITIONS

BUBBLE WALL COLLISIONS AND HIGHLY ENERGETIC FLUID SHELLS

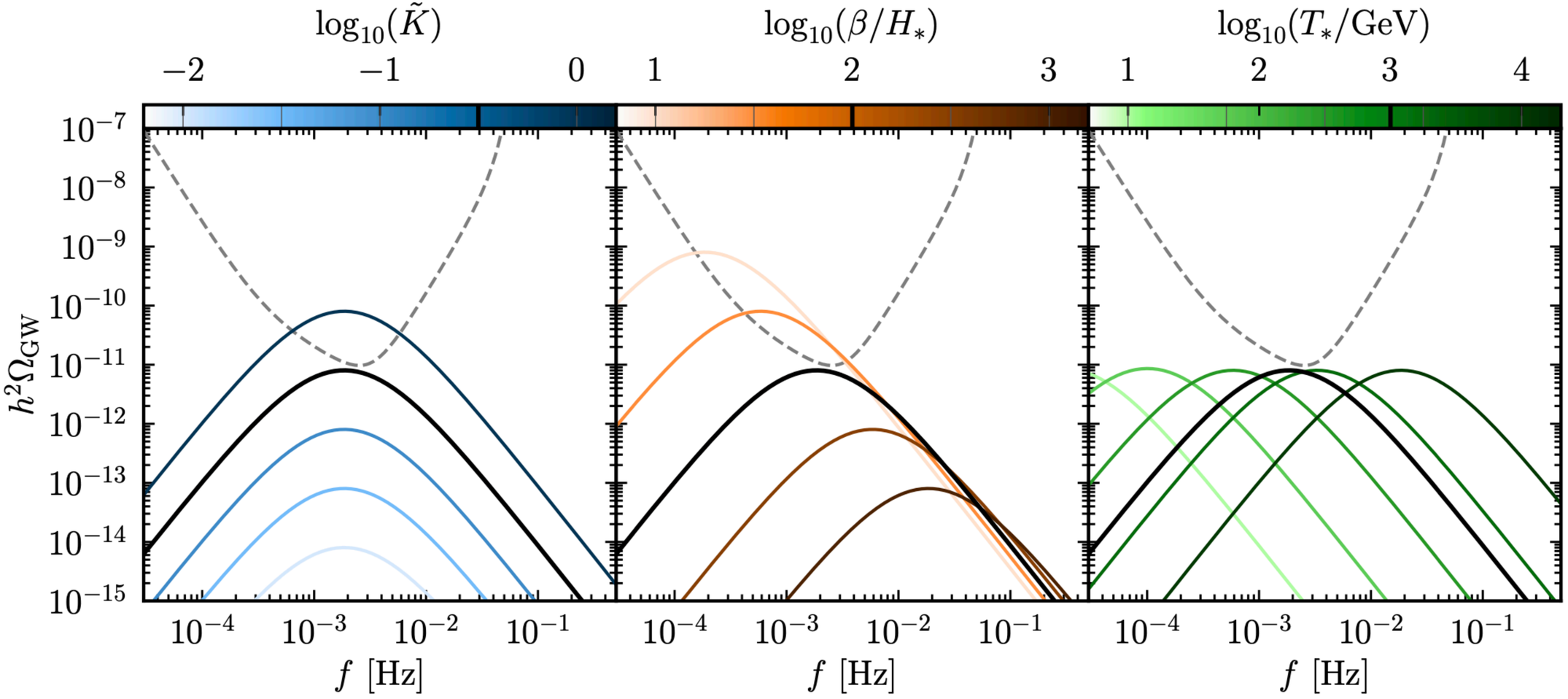
$$\Omega_{\rm GW}^{\rm BPL}(f,\vec{\theta}_{\rm Cosmo}) = \Omega_p \frac{(n_1-n_2)^{\frac{n_1-n_2}{a_1}}}{\left[-n_2\left(\frac{f}{f_p}\right)^{-\frac{n_1 a_1}{n_1-n_2}} + n_1\left(\frac{f}{f_p}\right)^{-\frac{n_2 a_1}{n_1-n_2}}\right]^{\frac{n_1-n_2}{a_1}}} \,.$$

GW source	power law template	n_1	n_2	n_3	a_1	a_2
strong PT, Sec. 2.1	BPL, Eq. (2.4)	2.4	−2.4	—	1.2	—
sound waves, Sec. 2.2.1	DBPL, Eq. (2.8)	3	1	−3	2	4
turbulence, Sec. 2.2.2	DBPL, Eq. (2.8)	3	1	−8/3	4	2.15

[source: LISA Cosomology Working Group, 2403.03723]

+ causal tail

DEPENDENCE ON THERMODYNAMICS



[source: LISA Cosomology Working Group, 2403.03723]

WEAKER TRANSITIONS - SOUND WAVES

$$\Omega_{\rm GW}^{\rm DBPL}(f, \vec{\theta}_{\rm Cosmo}) = \Omega_{\rm int} \times S(f) = \Omega_2 \times S_2(f),$$

$$S(f) = N \left(\frac{f}{f_1}\right)^{n_1} \left[1 + \left(\frac{f}{f_1}\right)^{a_1}\right]^{\frac{-n_1+n_2}{a_1}} \left[1 + \left(\frac{f}{f_2}\right)^{a_2}\right]^{\frac{-n_2+n_3}{a_2}},$$

GW source	power law template	n_1	n_2	n_3	a_1	a_2
strong PT, Sec. 2.1	BPL, Eq. (2.4)	2.4	−2.4	—	1.2	—
sound waves, Sec. 2.2.1	DBPL, Eq. (2.8)	3	1	−3	2	4
turbulence, Sec. 2.2.2	DBPL, Eq. (2.8)	3	1	−8/3	4	2.15

[source: LISA Cosomology Working Group, 2403.03723]

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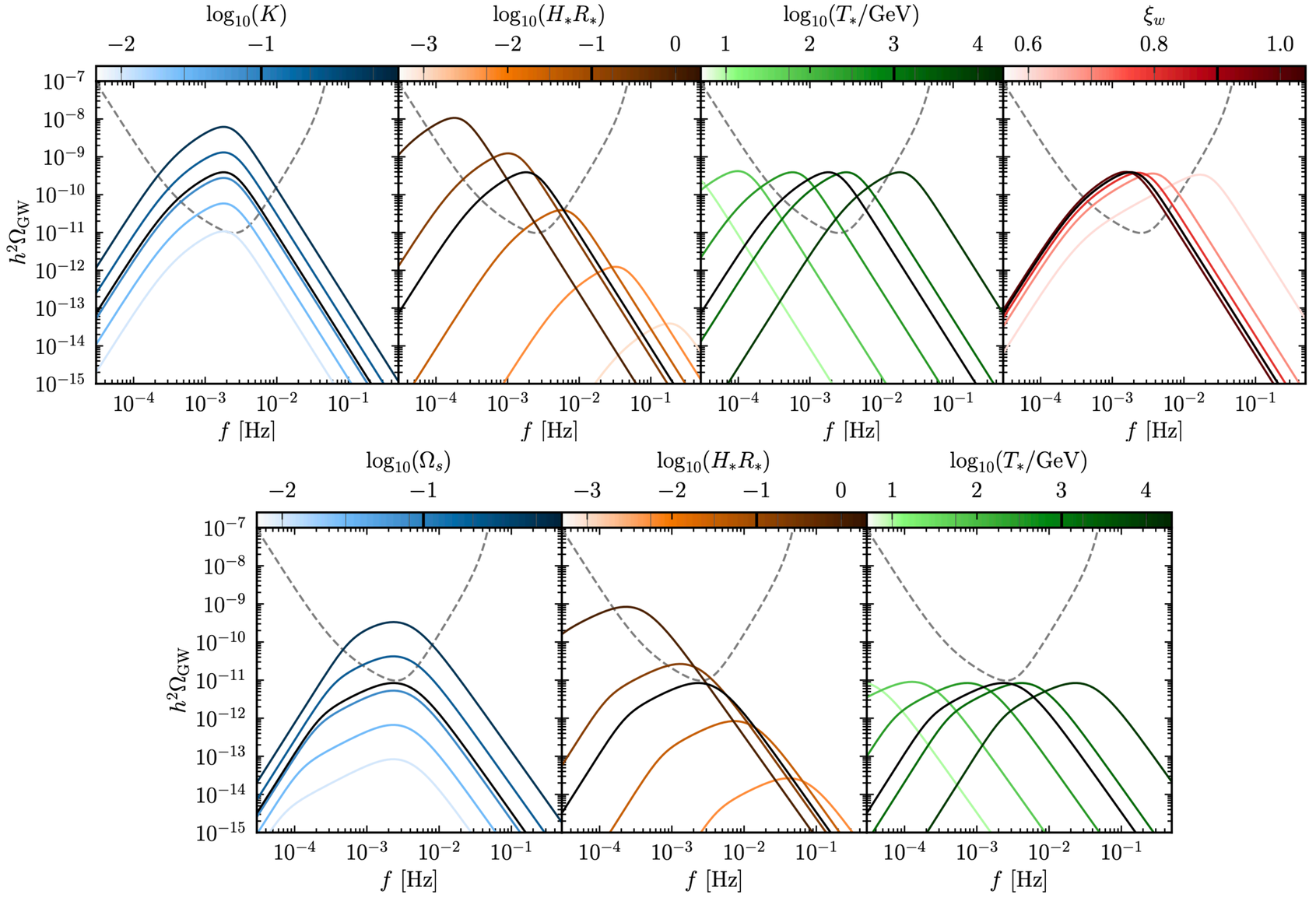
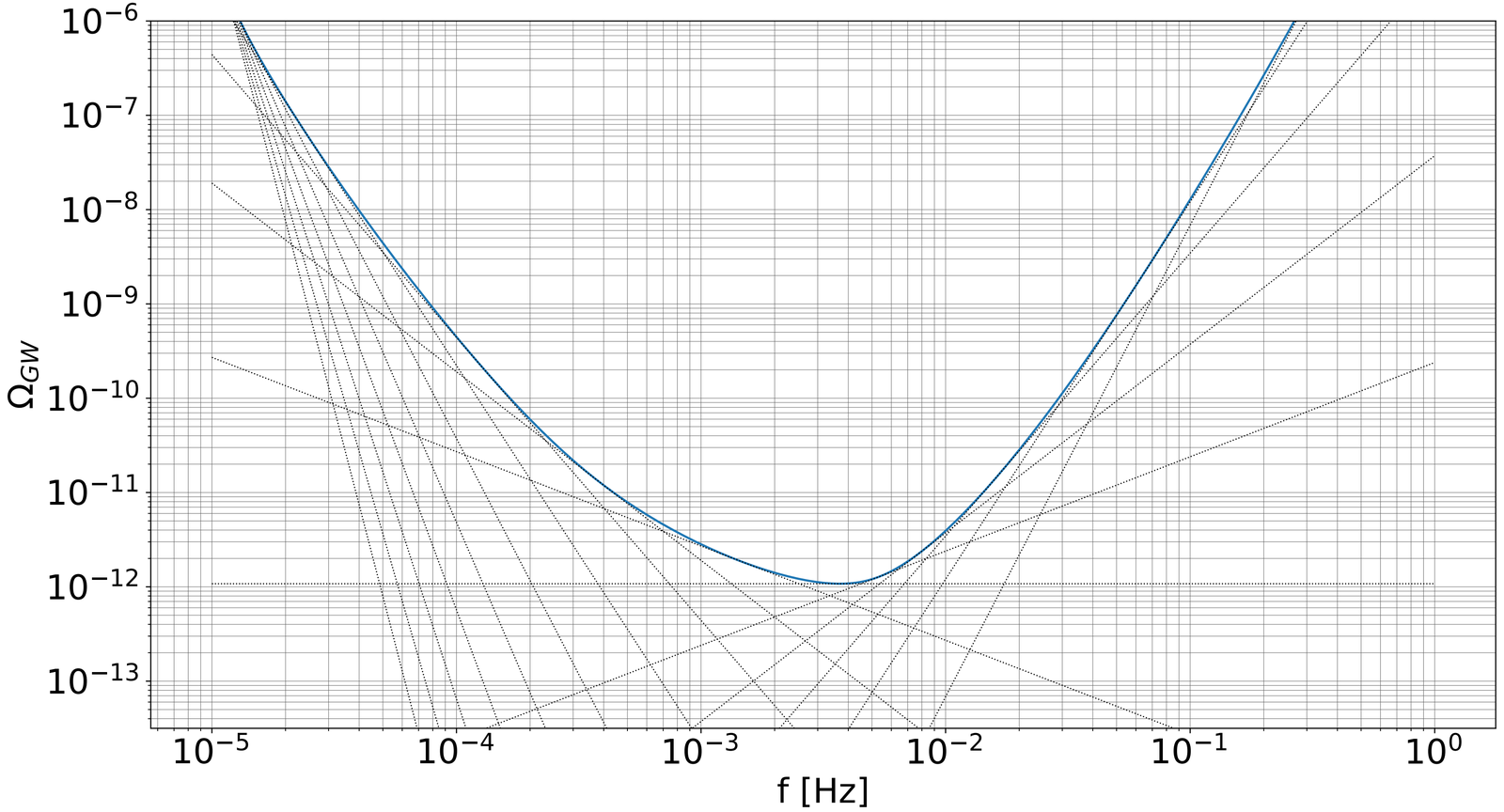


SIGNAL TO NOISE RATIO

$$\mathrm{SNR} = \sqrt{\mathcal{T} \int_{f_{\mathrm{min}}}^{f_{\mathrm{max}}} \mathrm{d}f \left[\frac{h^2 \Omega_{\mathrm{GW}}(f)}{h^2 \Omega_{\mathrm{Sens}}(f)} \right]^2}$$

SENSITIVITY CURVE

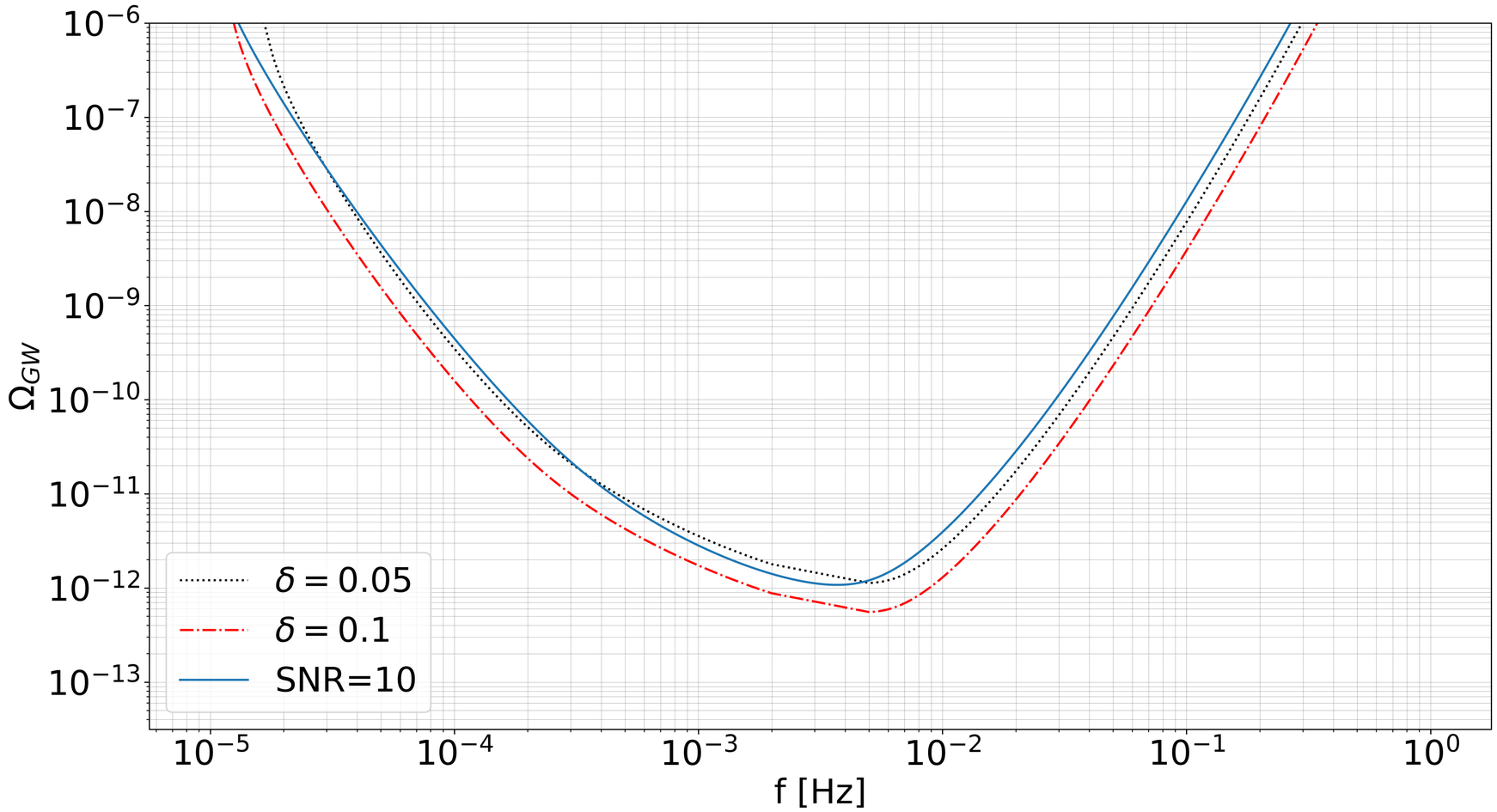
$$\Omega_{\mathrm{GW}} = \Omega_n \left(\frac{f}{f_{ref}} \right)^n$$



[A. Gonstal, MSc Thesis, 2023, Warsaw]

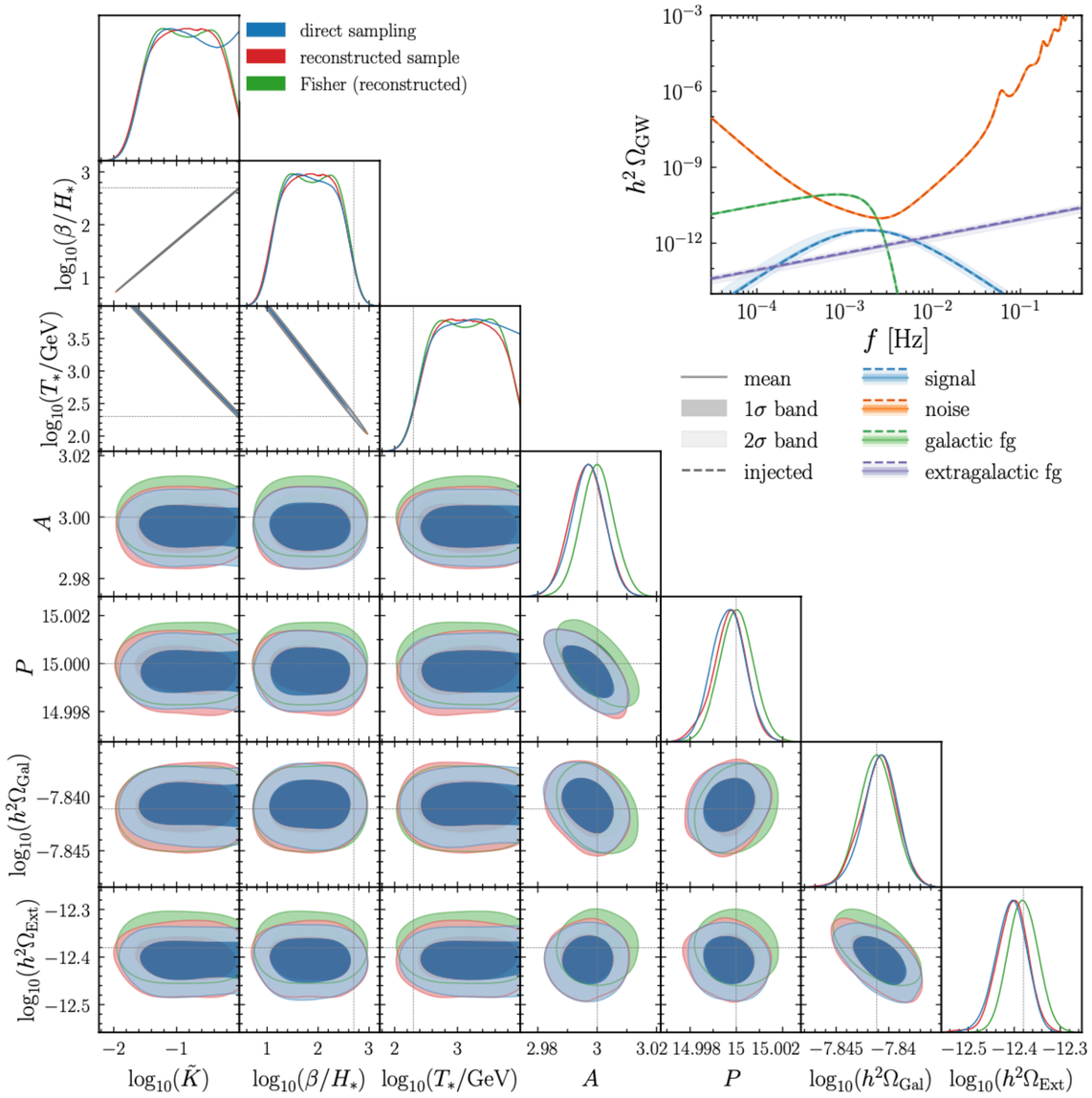
FISHER MATRIX ANALYSIS

$$\Omega_{\rm GW} = \Omega_n \left(\frac{f}{f_{ref}} \right)^n \qquad \delta = \frac{\Delta\Omega_n}{\Omega_n}$$



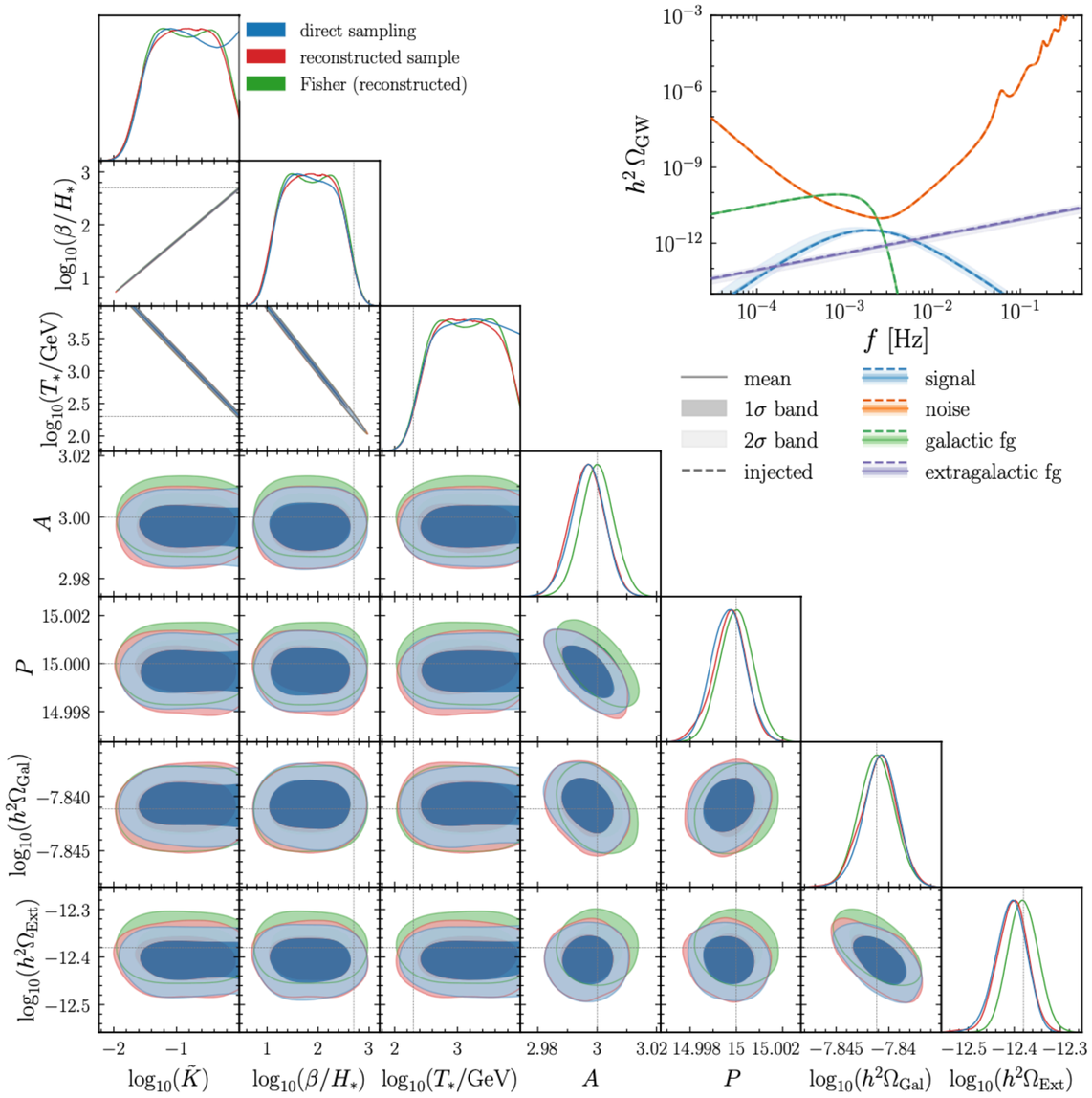
[A. Gonstal, MSc Thesis, 2023, Warsaw]

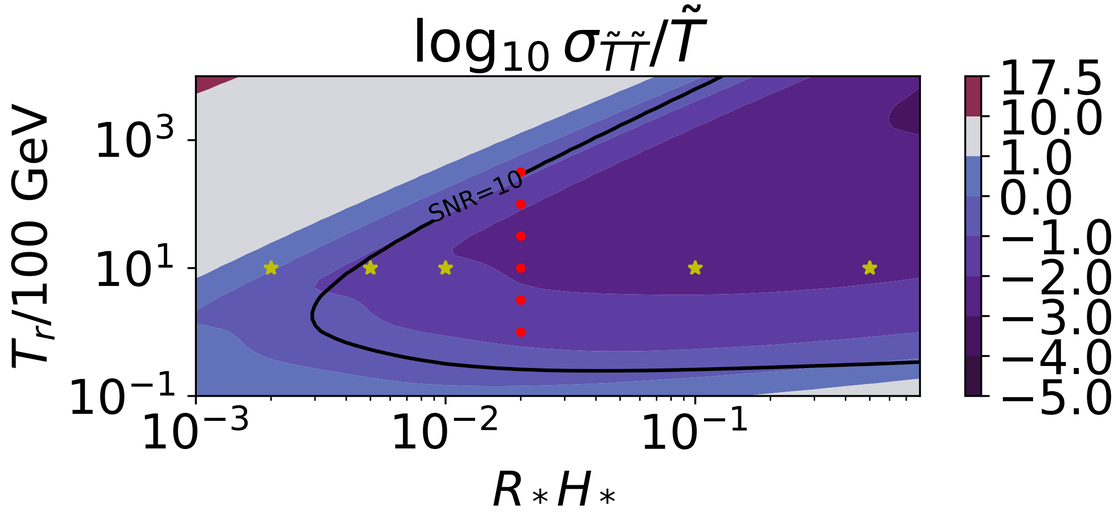
PARAMETER RECONSTRUCTION WITH LISA



[C. Caprini at al., LISA CosWG, 2403.03723]

PARAMETER RECONSTRUCTION WITH LISA





[A. Gonstal, Msc Thesis, 2023, Warsaw]

[C. Caprini at al., LISA CosWG, 2403.03723]