SEWM, HELSINKI, 20TH AUGUST 2026

PRECISE PREDICTIONS FOR COSMOLOGICAL PHASE TRANSITIONS

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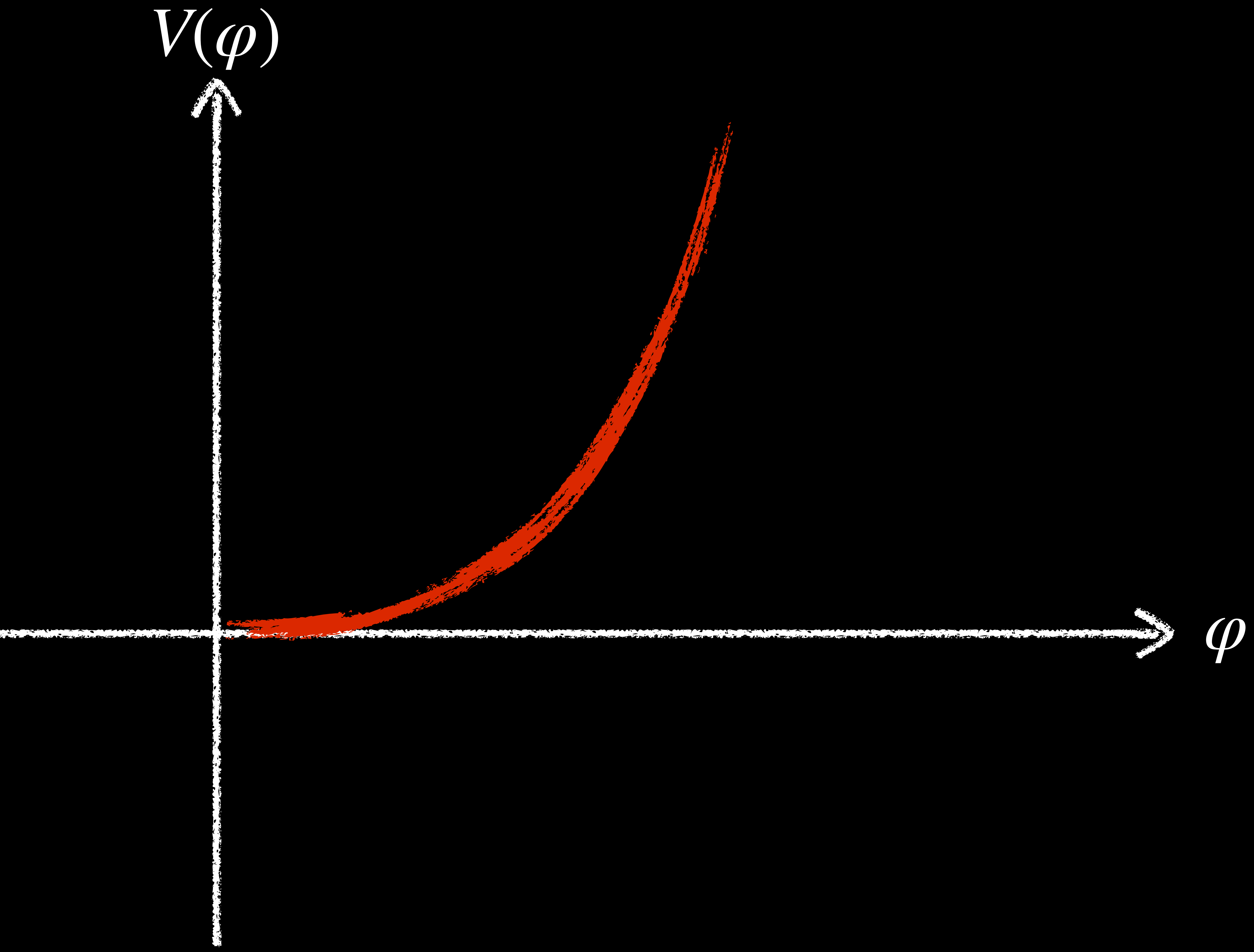
Based on work in collaboration with:
M. Kierkla, T.V.I. Tenkanen, J. van de Vis, P. Schicho, M. Lewicki, D. Schmitt,
JHEP 02 (2024) 234, JHEP 07 (2025) 153, 2607.18233

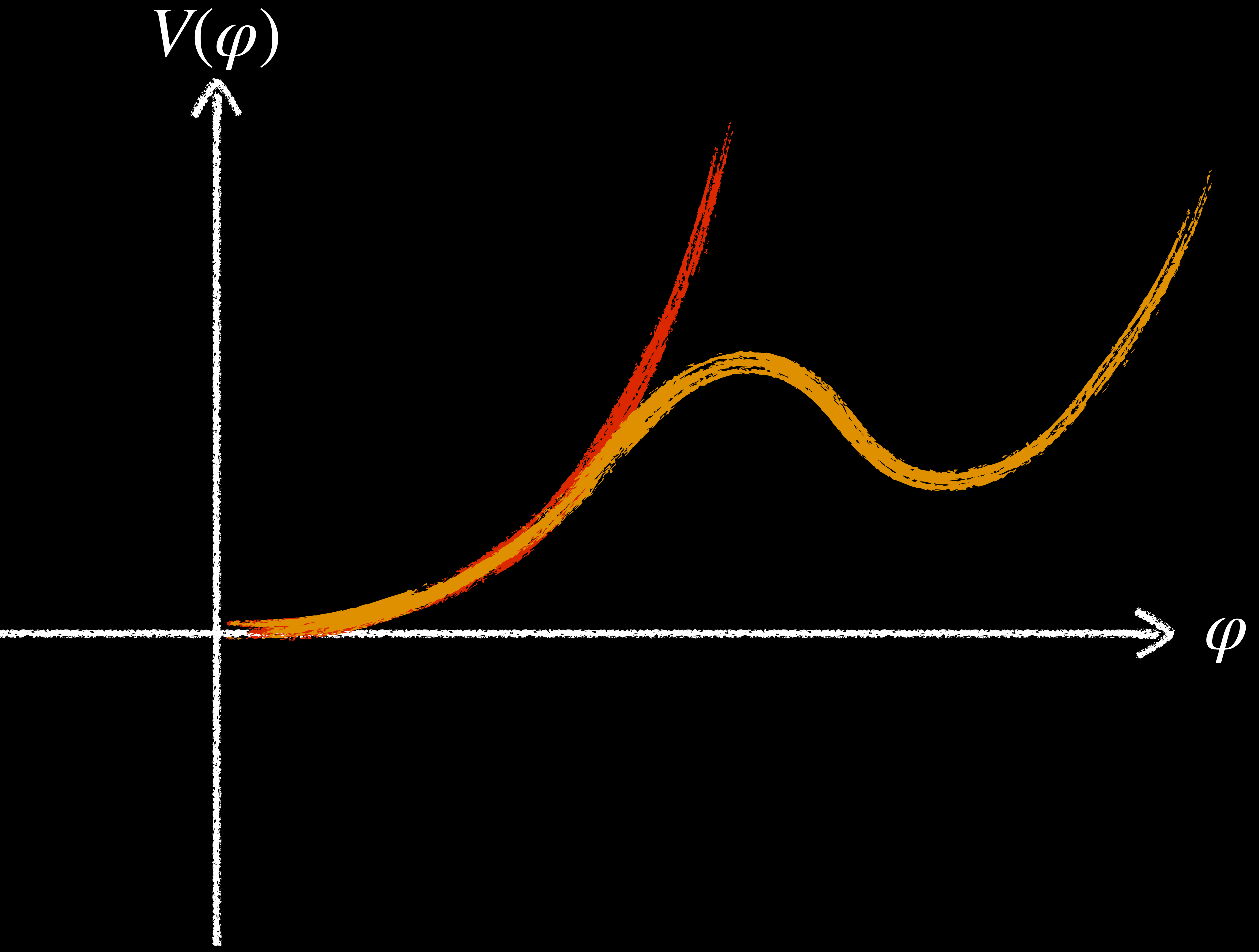
STOCHASTIC GRAVITATIONAL-WAVE BACKGROUND FROM FIRST-ORDER PHASE TRANSITIONS

FIRST-ORDER PHASE TRANSITION



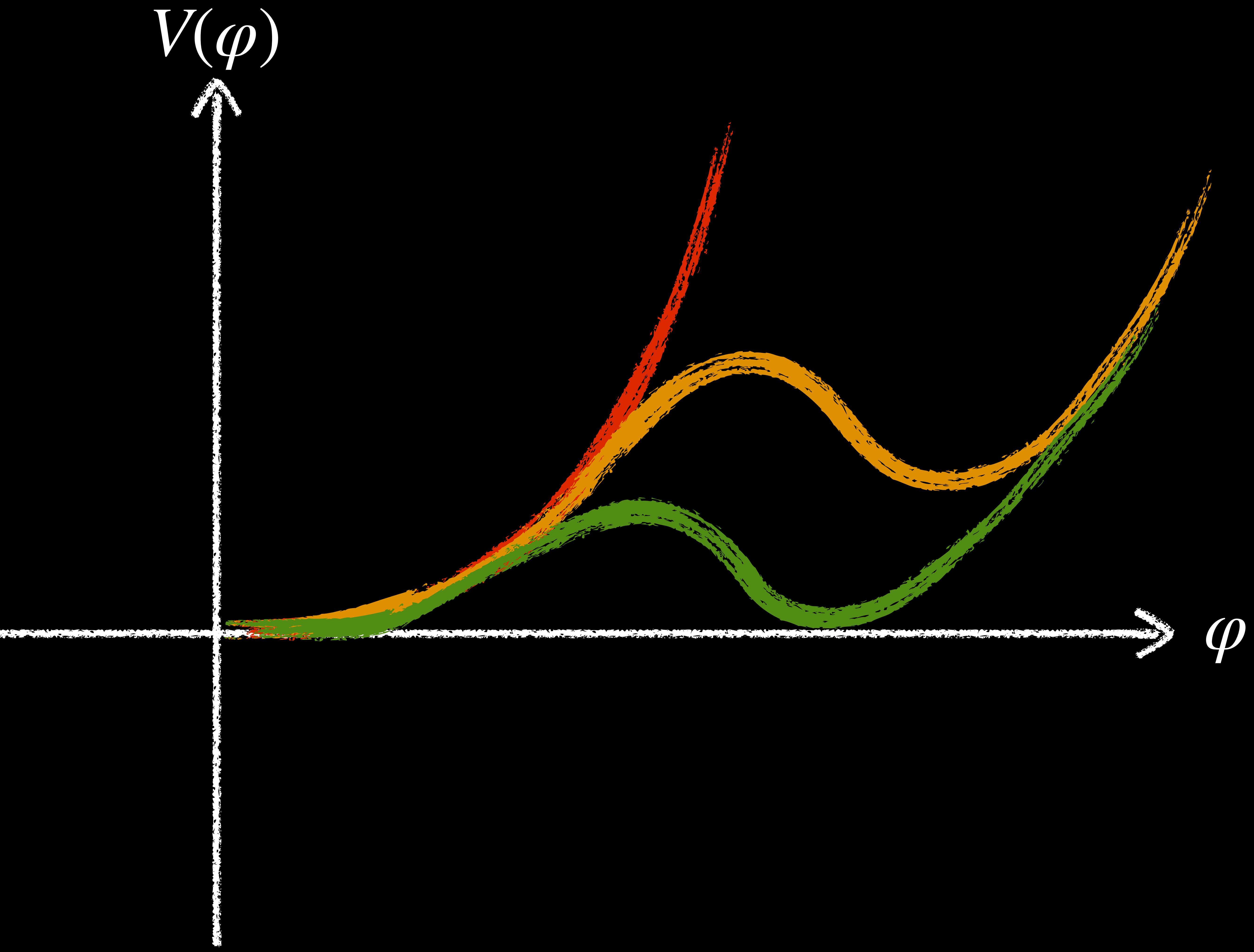
high temperature:
EW symmetry restored

FIRST-ORDER PHASE TRANSITION



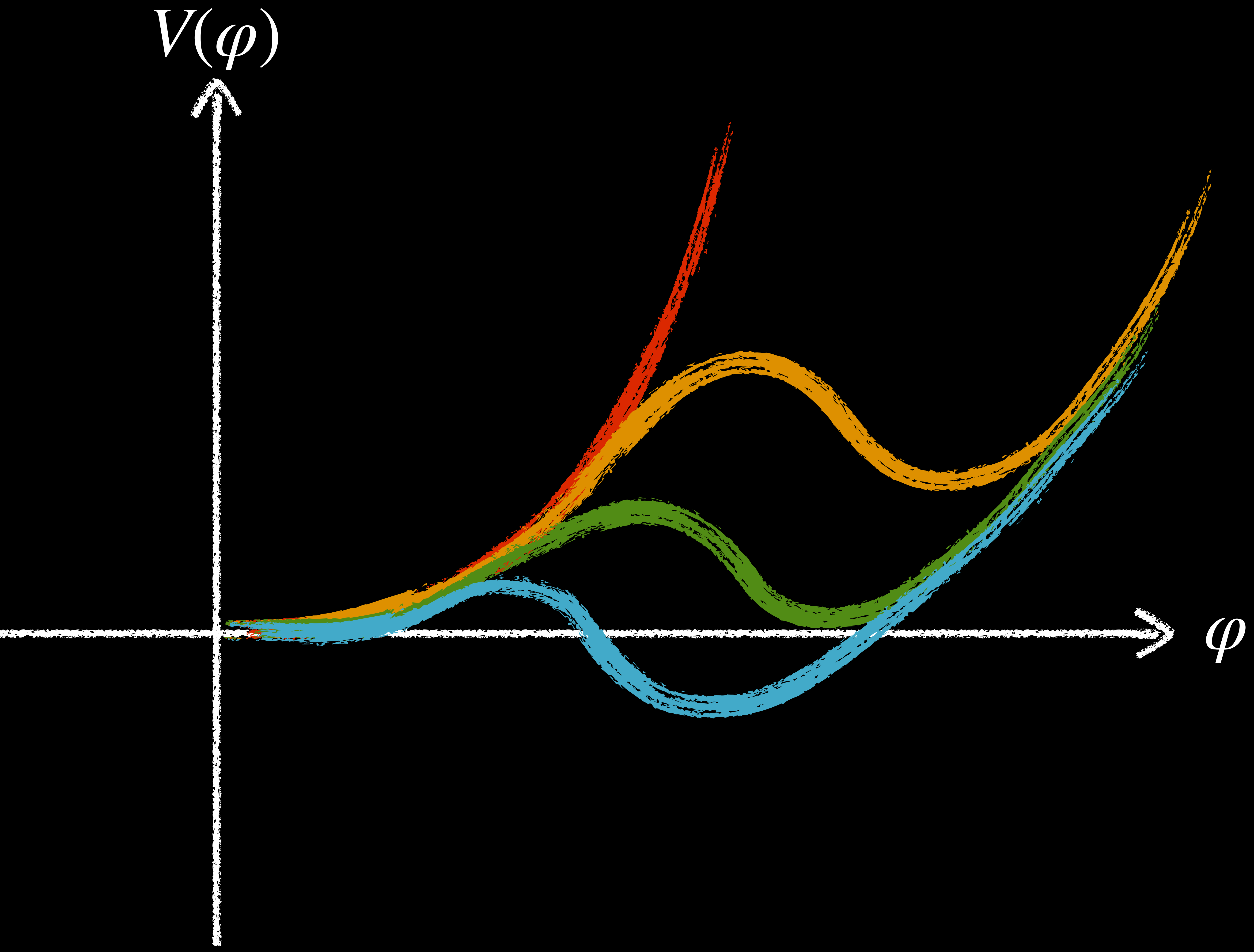
Secondary minimum forms

FIRST-ORDER PHASE TRANSITION



critical temperature:
two degenerate
minima

FIRST-ORDER PHASE TRANSITION



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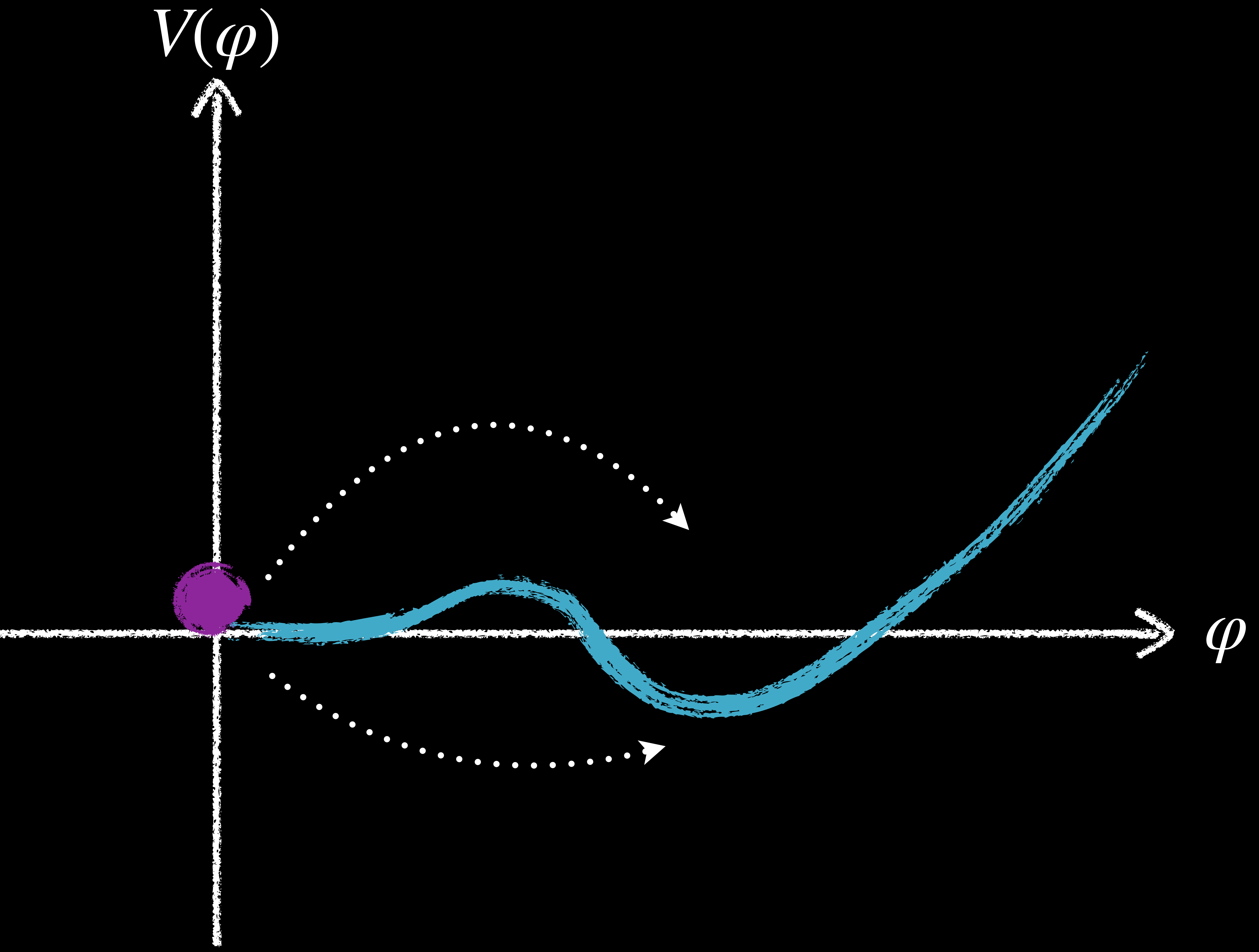

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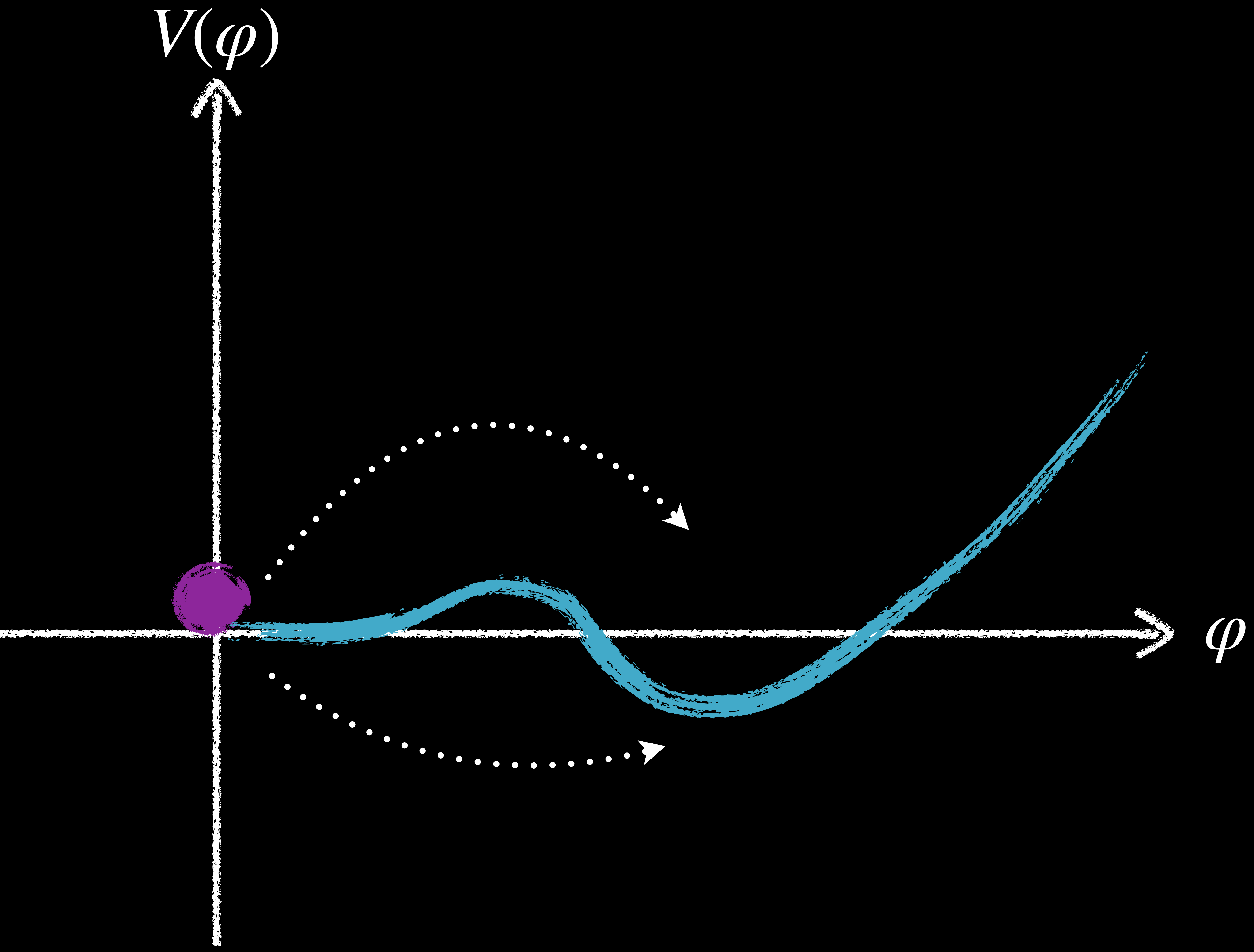
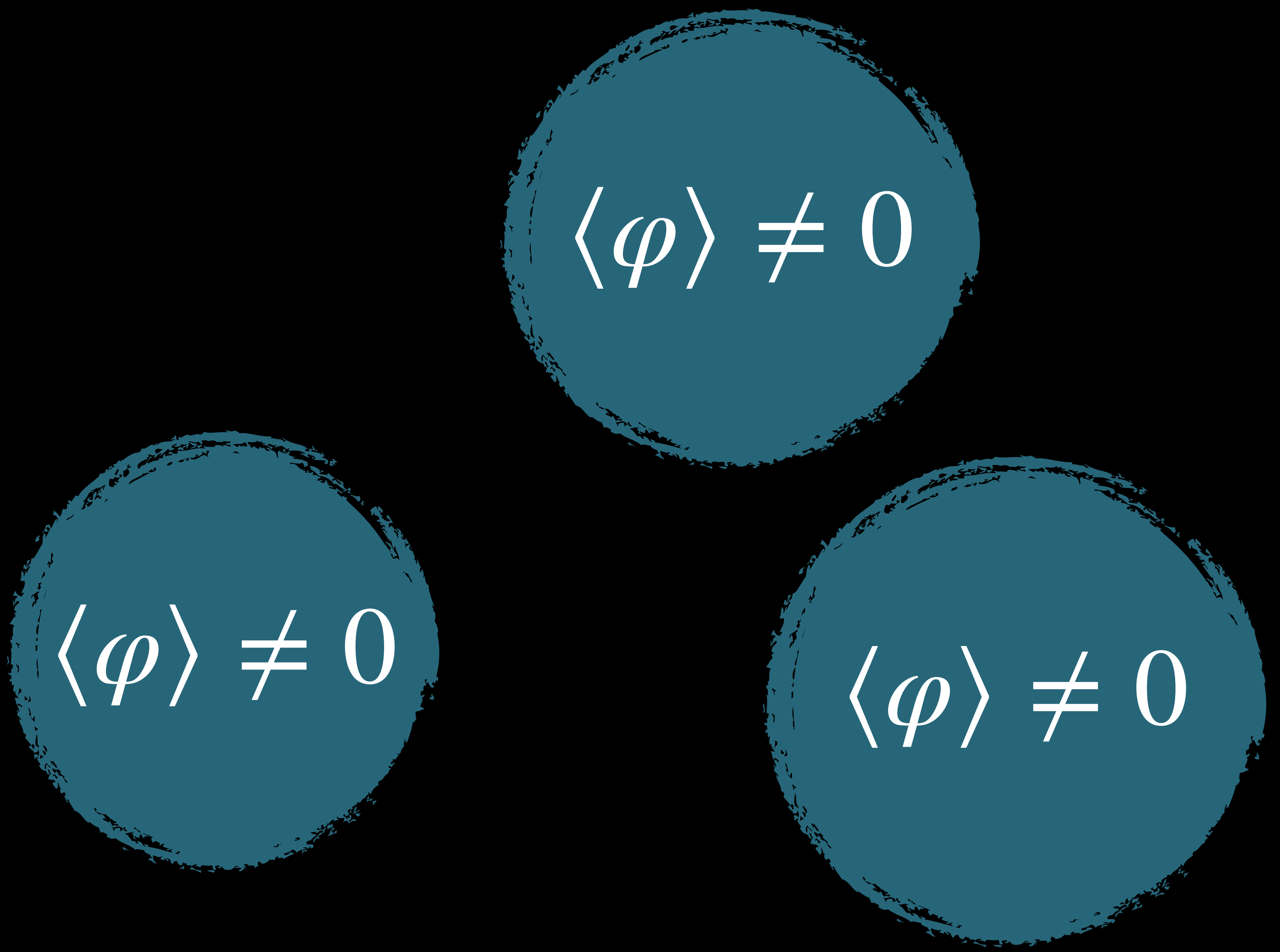
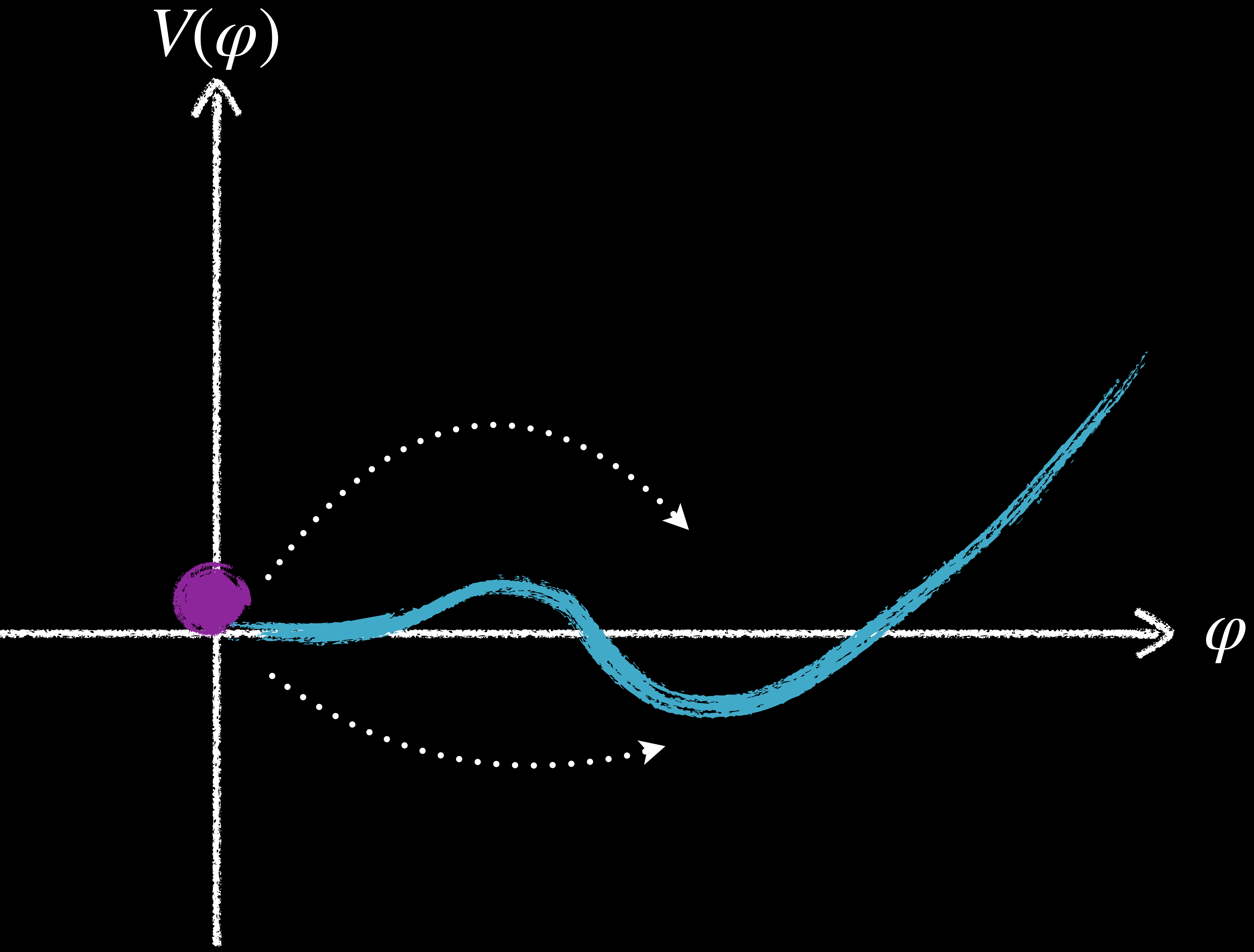


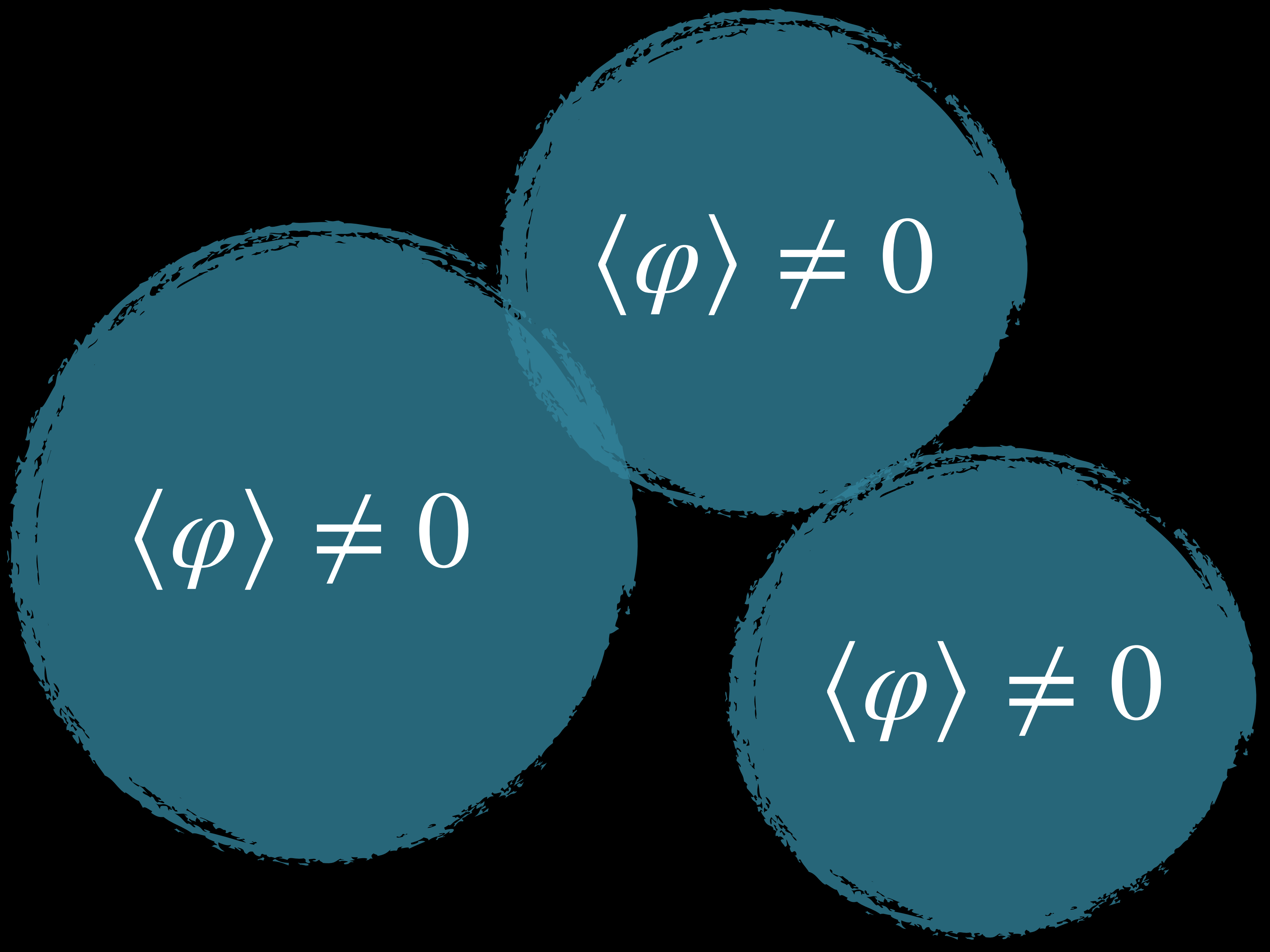
nucleation:
one bubble nucleates
per Hubble volume



FIRST-ORDER PHASE TRANSITION



percolation: phase transition completes

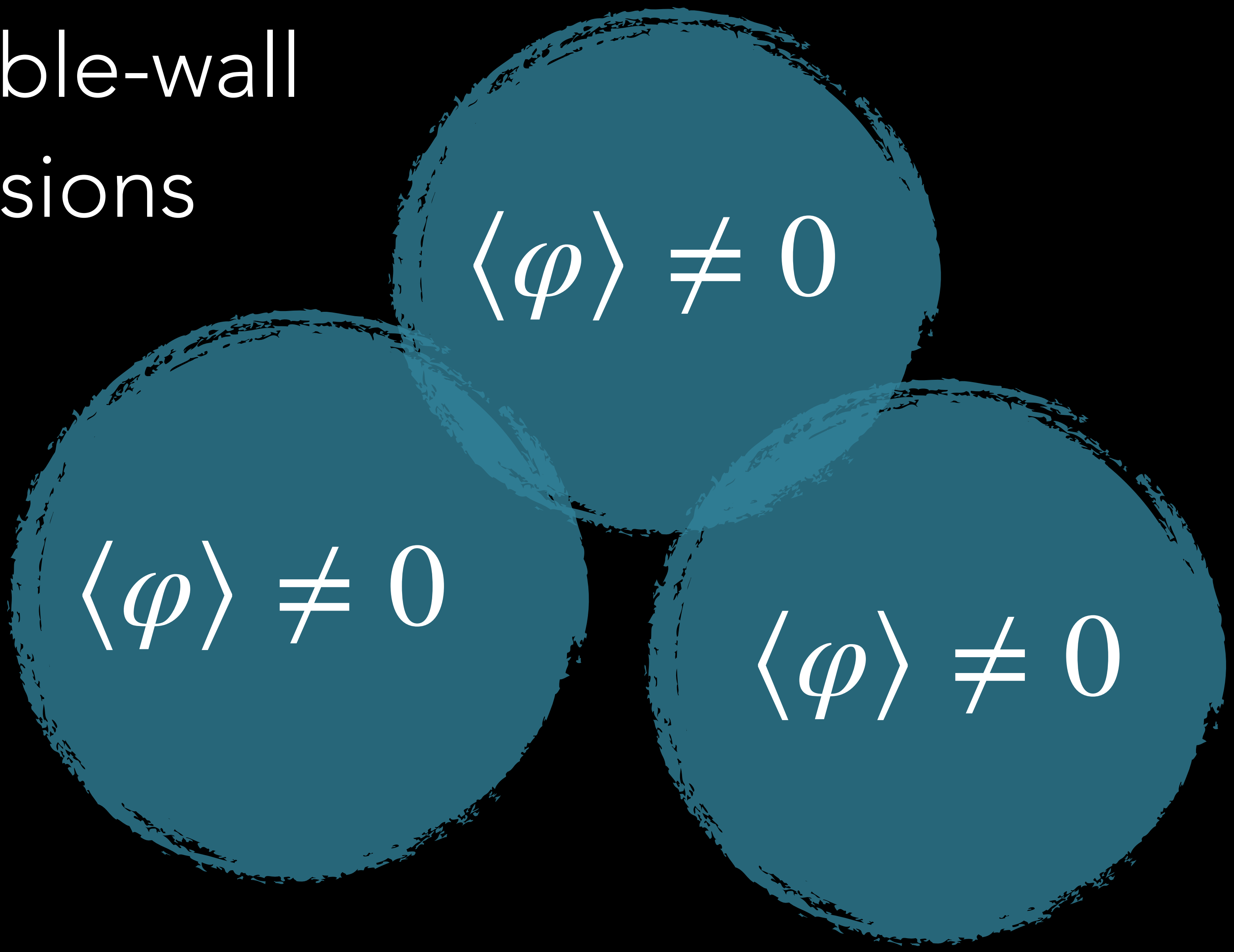


SOURCES OF GRAVITATIONAL WAVES

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

SOURCES OF GRAVITATIONAL WAVES

bubble-wall collisions



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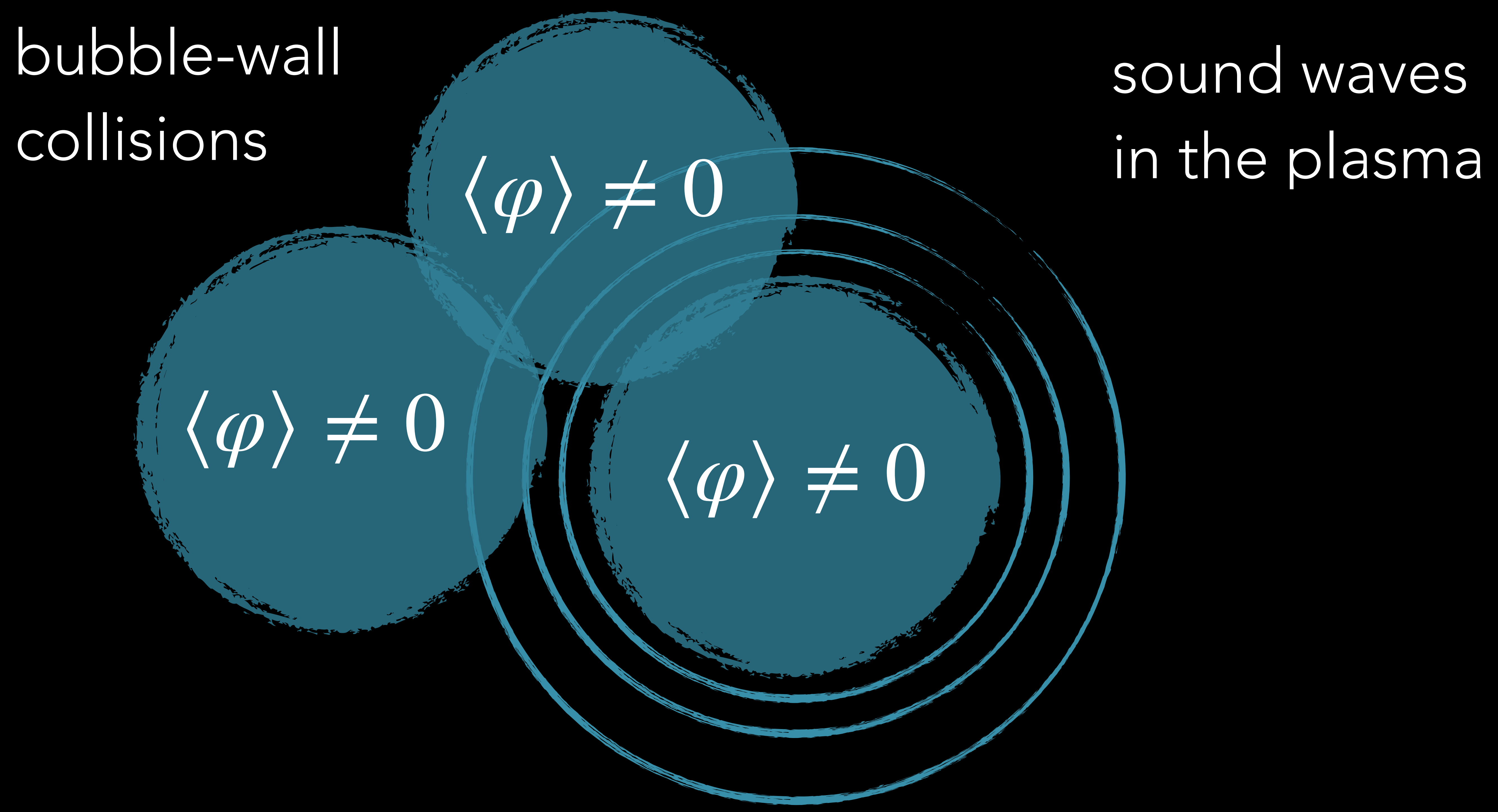

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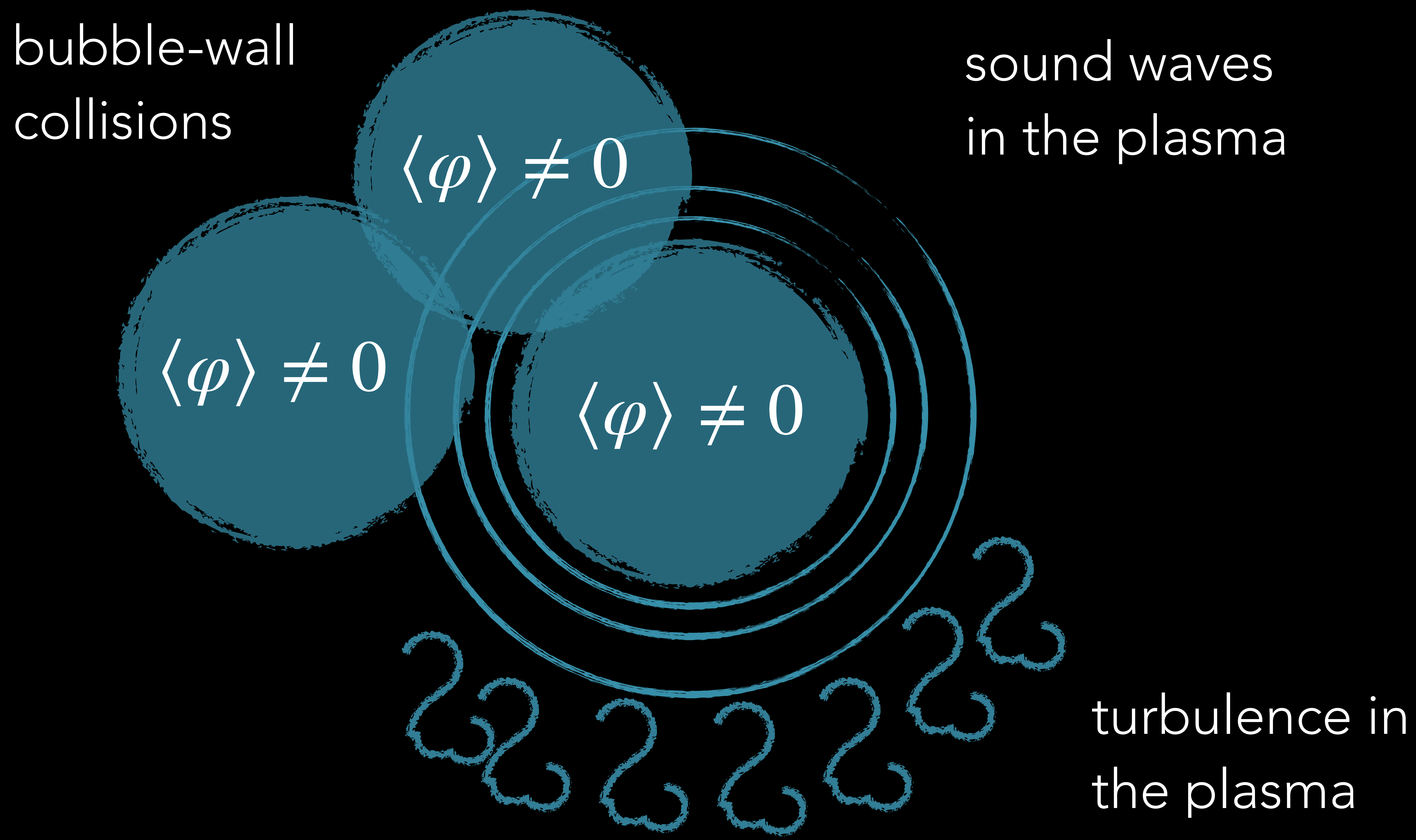
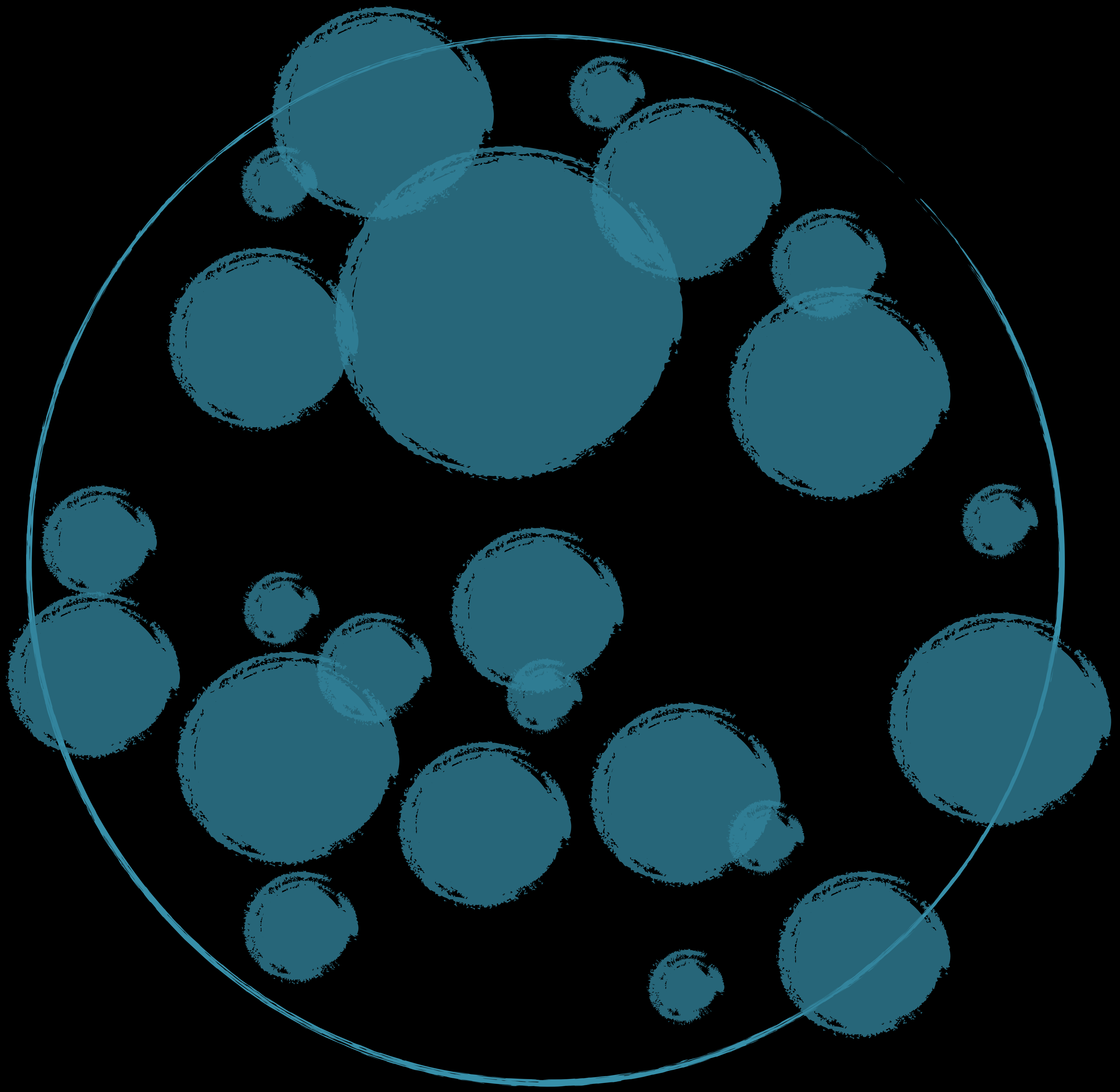
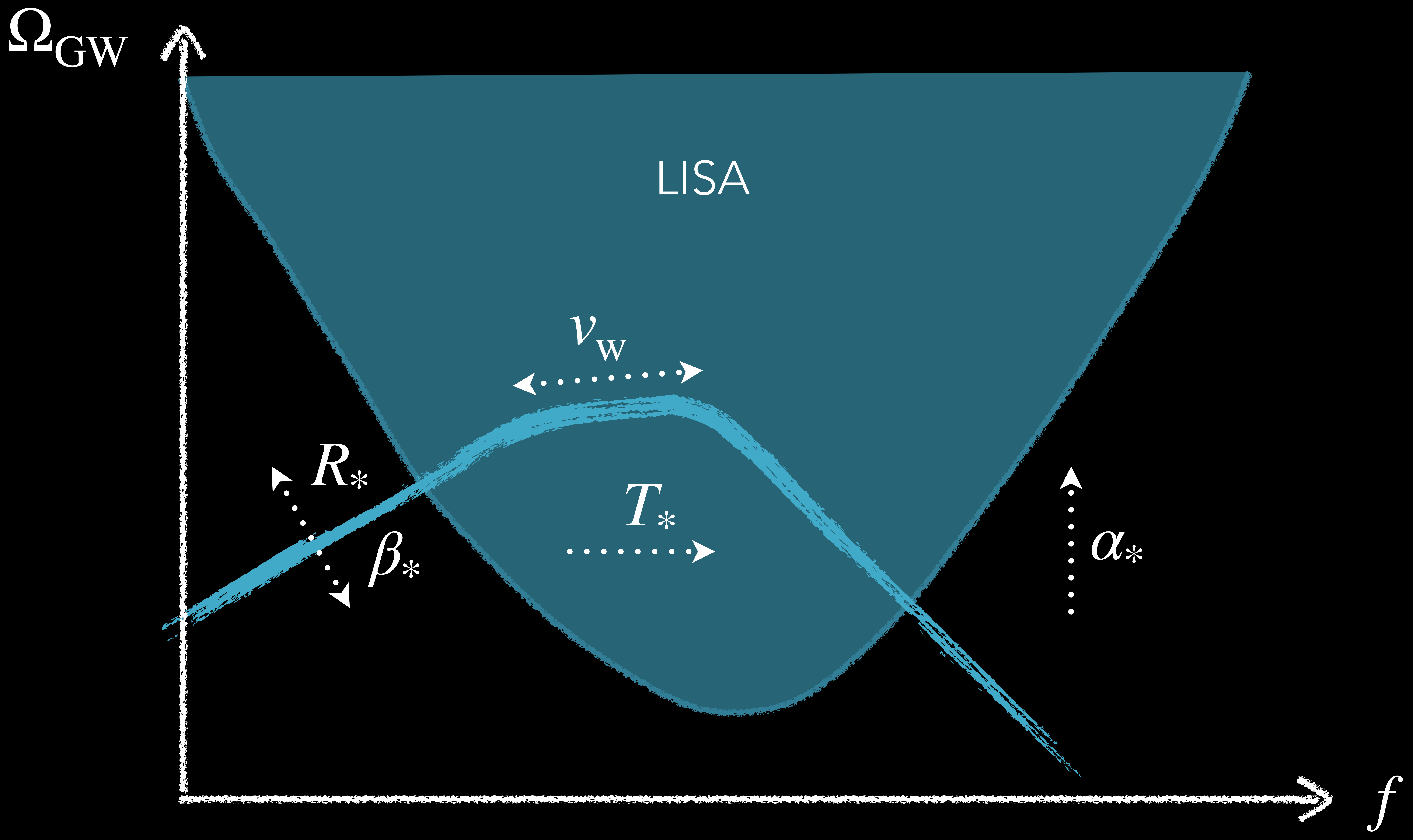


STOCHASTIC GW BACKGROUND



THERMODYNAMICAL PARAMETERS VS GW



- α_* - phase-transition strength ≈ latent heat released
- β_* (R_*) - inverse time (length) scale of the transitions
- T_* - characteristic temperature
- v_w - bubble-wall velocity

GW FROM PT: JOURNEY THROUGH SCALES

Macrophysics	gravitational waves (+baryogenesis, DM)
Intermediate	plasma and bubble dynamics, wall velocity
Microphysics	quantum fields at high T, bubble nucleation

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Macrophysics	gravitational waves (+baryogenesis, DM)
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data

BUBBLE NUCLEATION RATE

$$\Gamma = A_{\text{dyn}} \cdot A_{\text{stat}} = A_{\text{dyn}} \cdot A_{\text{det}} \cdot \exp(-S_{\text{eff}}[\varphi_b])$$

non-equilibrium effects

quantum fluctuations

solution of the classical Euclidean equation of motion (the bounce)

SOURCES OF UNCERTAINTY

$\Delta\Omega_{\rm GW}/\Omega_{\rm GW}$	4d approach	3d approach
RG scale dependence	$\mathcal{O}(10^2 - 10^3)$	$\mathcal{O}(10^0 - 10^1)$
Gauge dependence	$\mathcal{O}(10^1)$	$\mathcal{O}(10^{-3})$
High-T approximation	$\mathcal{O}(10^{-1} - 10^0)$	$\mathcal{O}(10^0 - 10^2)$
Higher loop orders	unknown	$\mathcal{O}(10^0 - 10^1)$
Nucleation corrections	unknown	$\mathcal{O}(10^{-1} - 10^0)$
Nonperturbative corrections	unknown	unknown

[Table adapted from JHEP 04 (2021) 055, D. Croon, O. Gould, P. Schicho, T. V. I. Tenkanen, G. White]

[O. Gould, T. V. I. Tenkanen, JHEP 06 (2021) 069]

Two-loop corrections necessary to recover RG-scale invariance of the thermally-corrected effective potential.

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[J. Hirvonen, J. Löfgren, M. J. Ramsey-Musolf, P. Schicho, T. V. I. Tenkanen, *JHEP* 07 (2022) 135, Phys.Rev.Lett. 130 (2023) 25, 251801]

Consistent power-counting assures gauge independence, using the LO bounce solution to evaluate NLO contributions to the effective action.

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[F. Bernardo, P. Klose, P. Schicho, T. V. I. Tenkanen, *JHEP* 08 (2025) 109]

Higher-order operators may significantly affect the predictions — in some cases high-T expansion breaks down entirely.

[P. Navarrete, R. Paatelainen, K. Seppänen, T. V. I. Tenkanen, JHEP 01 (2026) 113]

Go beyond high-T expansion with full four-dimensional resummed thermal effective potential.

→ See the talks by M. Kierkla and A. Dashko

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[A. Ekstedt, P. Schicho, T. V. I. Tenkanen, Phys.Rev.D 110 (2024) 9, 096006]

Equilibrium thermodynamics of PT computed to the last perturbative order. Agreement with lattice in the region of validity of the EFT.

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[O. Gould, J. Hirvonen, Phys.Rev.D 104 (2021) 9, 096015]

Construction of an EFT for nucleation.

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[Table adapted from JHEP 04 (2021) 055, D. Croon, O. Gould, P. Schicho, T. V. I. Tenkanen, G. White]

[O. Gould, S. Güyer, K. Rummukainen, Phys.Rev.D 106 (2022) 11, 114507]

Non-perturbative lattice calculation of PT thermodynamics.

[A. Kormu, O. Gould, D. Weir, Phys.Rev.D 111 (2025) 5, 5; D. Pîrvu, A. Shkerin, S. SibiryakovInt.J.Mod.Phys.A 39 (2024) 34, 2445007, J. Hirvonen, O. Gould, Phys.Rev.Lett. 136 (2026) 8, 081601]

Non-perturbative lattice computations of bubble nucleation rate.

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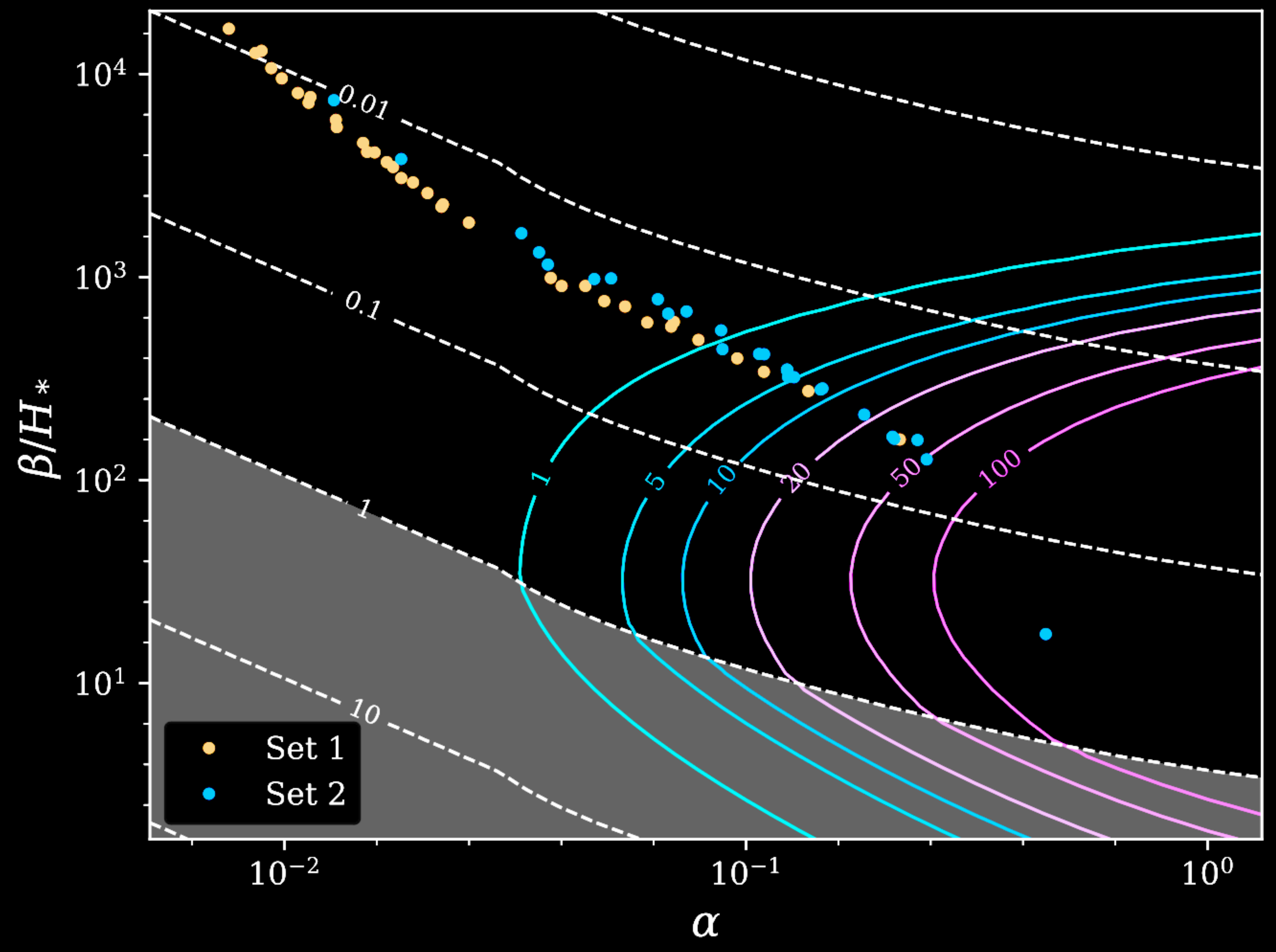
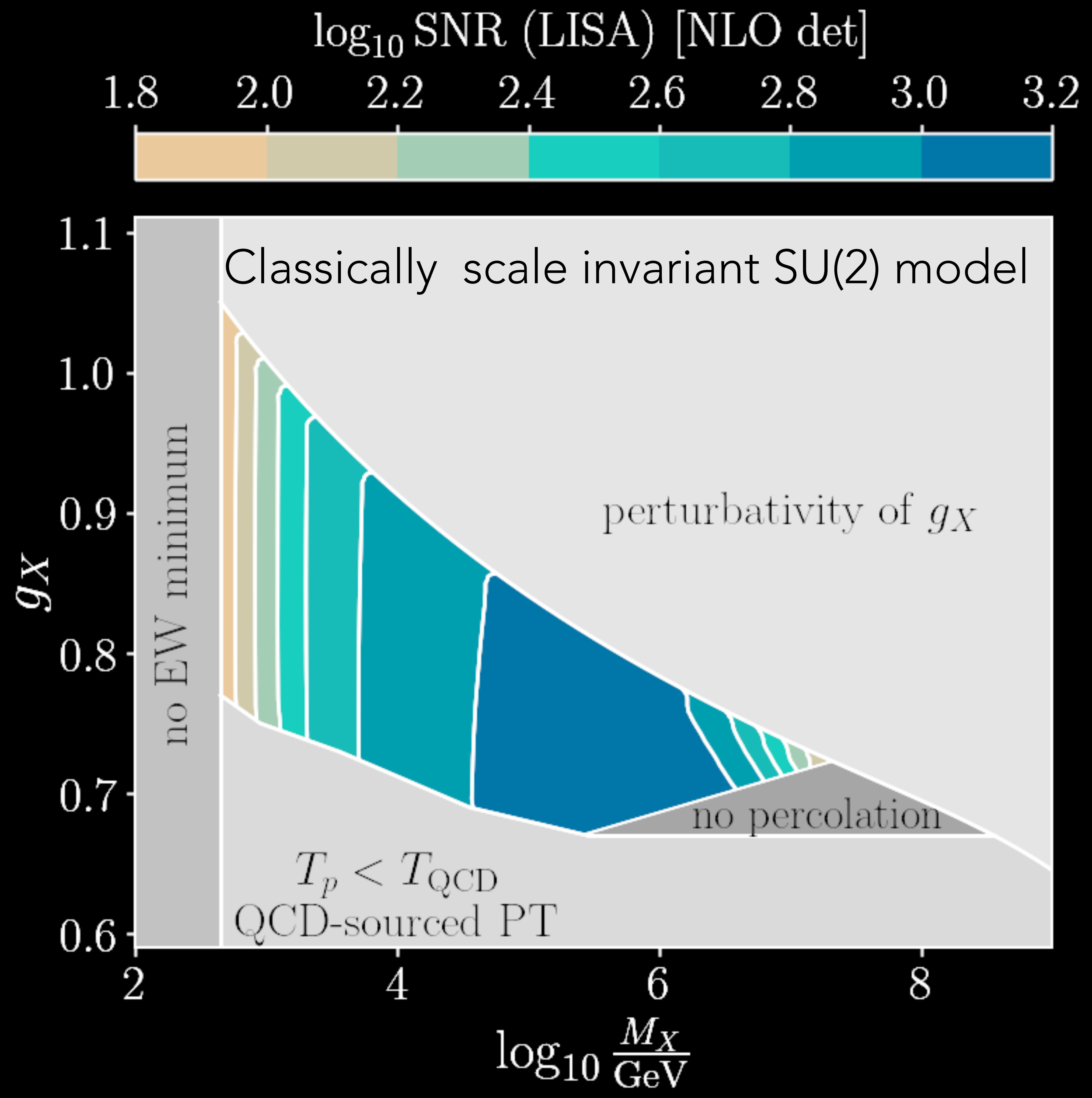
- out-of-equilibrium effects $\longrightarrow$ see the talks by J. Hirvonen and A. Shkerin

VARIOUS MODELS, VARIOUS PROBLEMS

2-Higgs doublet model



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



[Image adapted from: M. Kierkla, PhD thesis, University of Warsaw, 2025,
See also M. Kierkla, P. Schicho, BŚ, T.V.I. Tenkanen, J. van de Vis, JHEP 07 (2025) 153]

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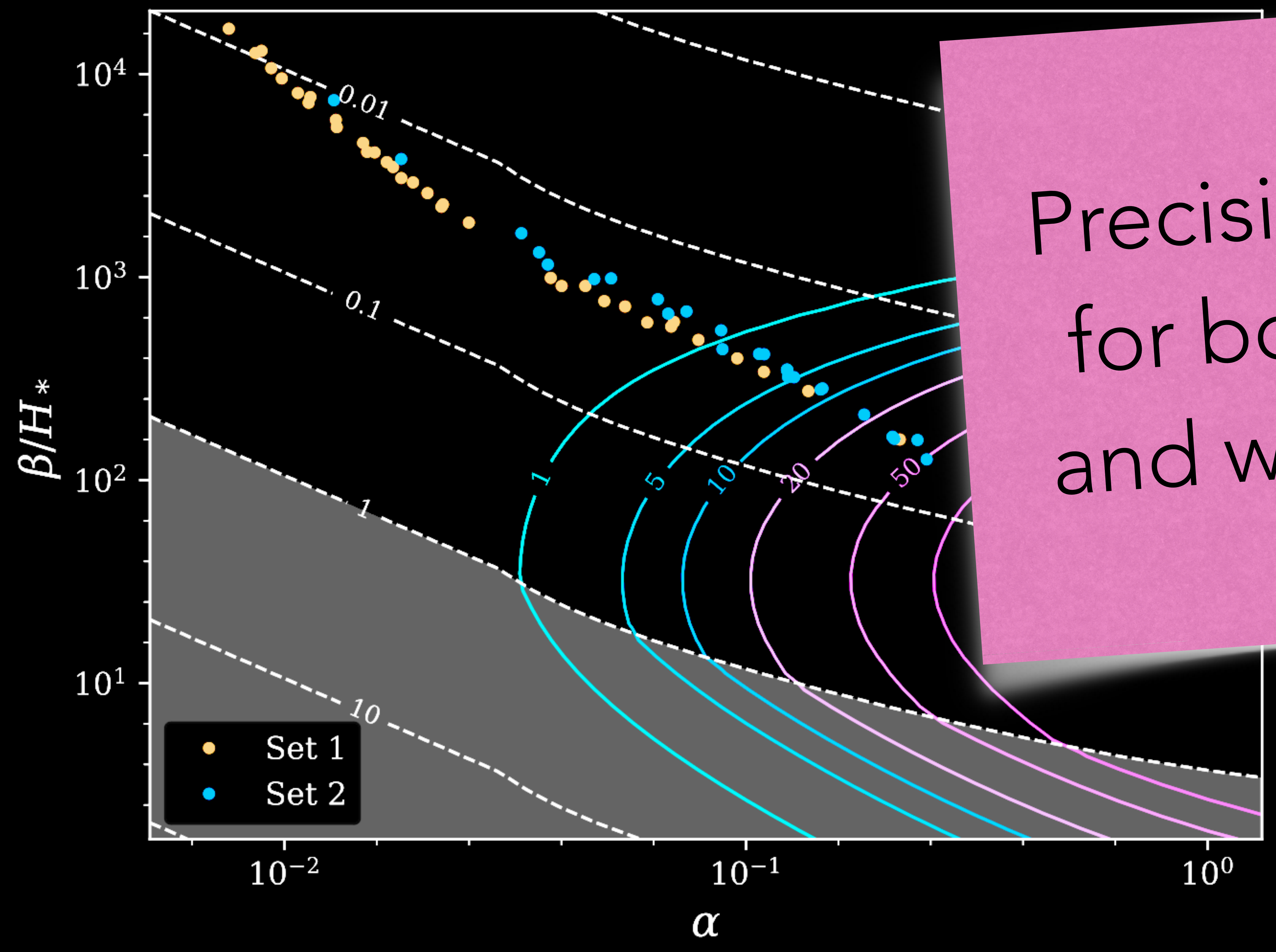

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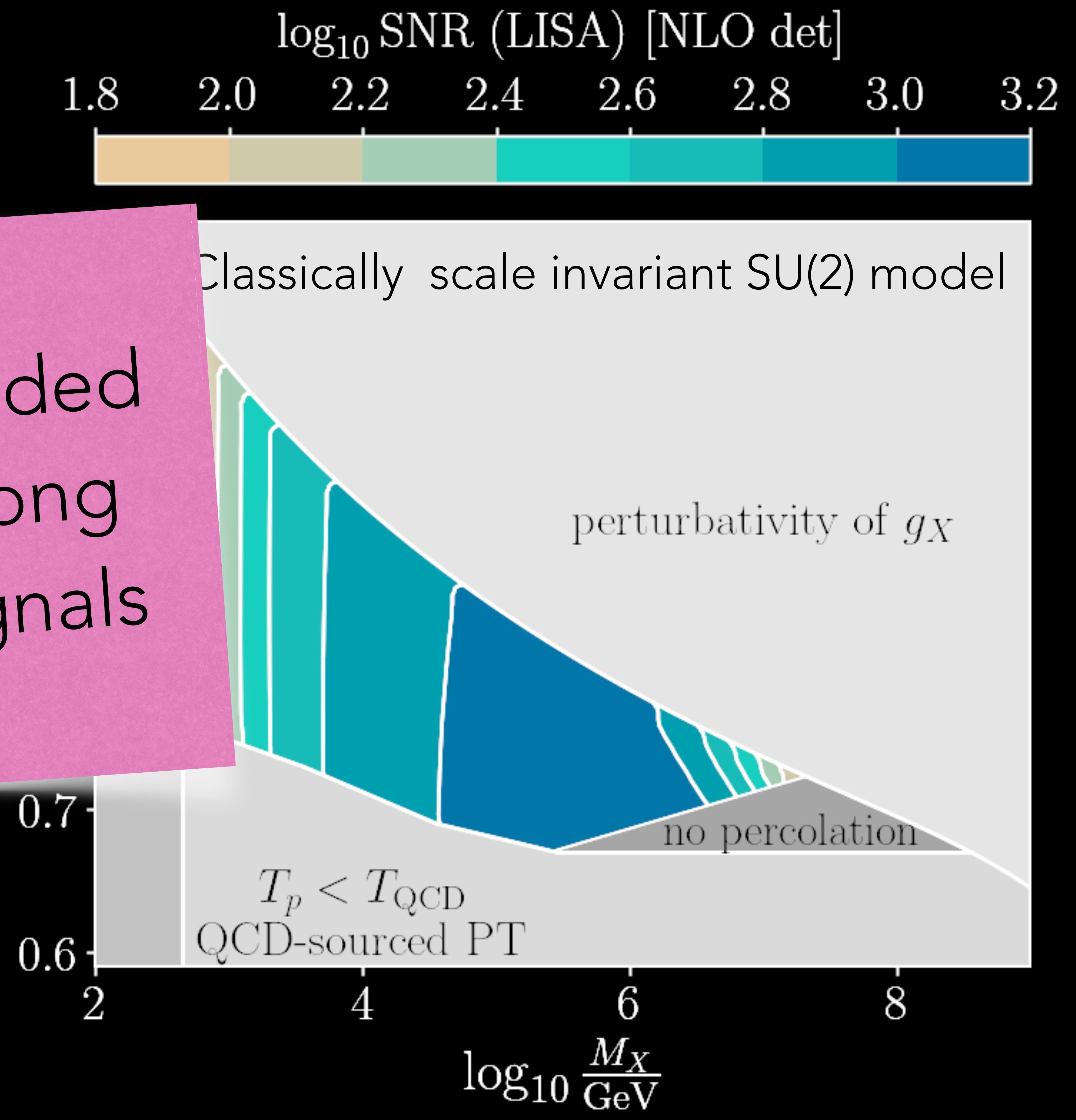
Precision needed for both, strong and weak signals



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See also M. Kierkla, P. Schicho, BŚ, T.V.I. Tenkanen, J. van de Vis, JHEP 07 (2025) 153]

INCREASING THE PRECISION IN BUBBLE NUCLEATION

BUBBLE NUCLEATION RATE

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non-equilibrium effects

quantum fluctuations

solution of the classical Euclidean equation of motion (the bounce)

BUBBLE NUCLEATION RATE - BASIC APPROACH

$$\Gamma = A_{\text{dyn}} \cdot A_{\text{stat}} = A_{\text{dyn}} \cdot A_{\text{det}} \cdot \exp(-S_{\text{eff}}[\varphi_b])$$

non-equilibrium effects

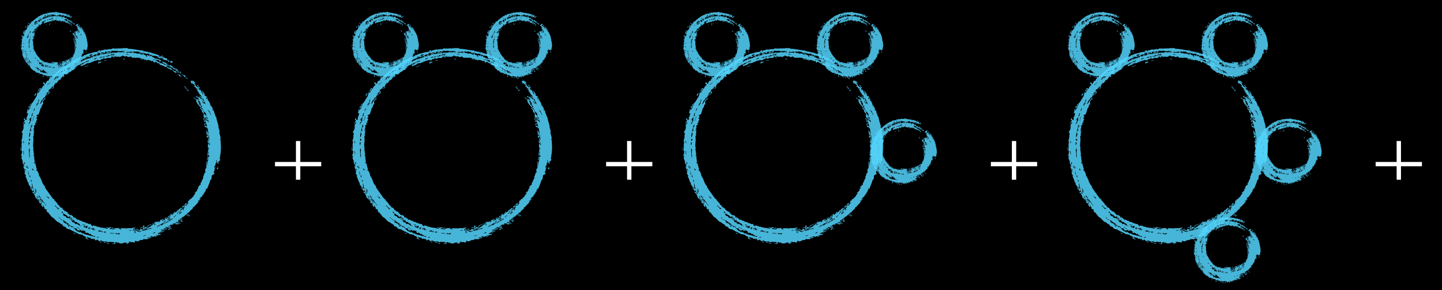
$\approx T$

quantum fluctuations

$\approx T^3$

solution of the classical Euclidean equation of motion (the bounce)

$$S_{\text{eff}} = \int_{\vec{x}} \left[\frac{1}{2}\left(\partial_i \varphi\right)^2 + V_{\text{tree}}(\varphi) + V^{(1)}(\varphi) + V_T^{(1)}(\varphi, T) + V^{\text{daisy}}(\varphi, T)\right]$$



EFFECTIVE FIELD THEORY FOR NUCLEATION

[O. Gould, J. Hirvonen, Phys.Rev.D 104 (2021) 9, 096015]

nucleation intermediate thermal

$$m_{\text{nucl}} \ll \Lambda_{\text{int}} \ll \pi T$$

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[O. Gould, J. Hirvonen, Phys.Rev.D 104 (2021) 9, 096015]

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contributions from fluctutations of the fields that are not integrated out at the nucleation scale

the effective action at the nucleation scale

EFFECTIVE FIELD THEORY FOR NUCLEATION

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The procedure:

1. Construct the EFT.
2. Compute the effective action consistently in power counting.
3. Solve the LO bounce equation. Use it also in the NLO action.
4. Compute the determinants for the light fields (or use approximations).

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THE MODEL

cSM

SU(2) x U(1)

H

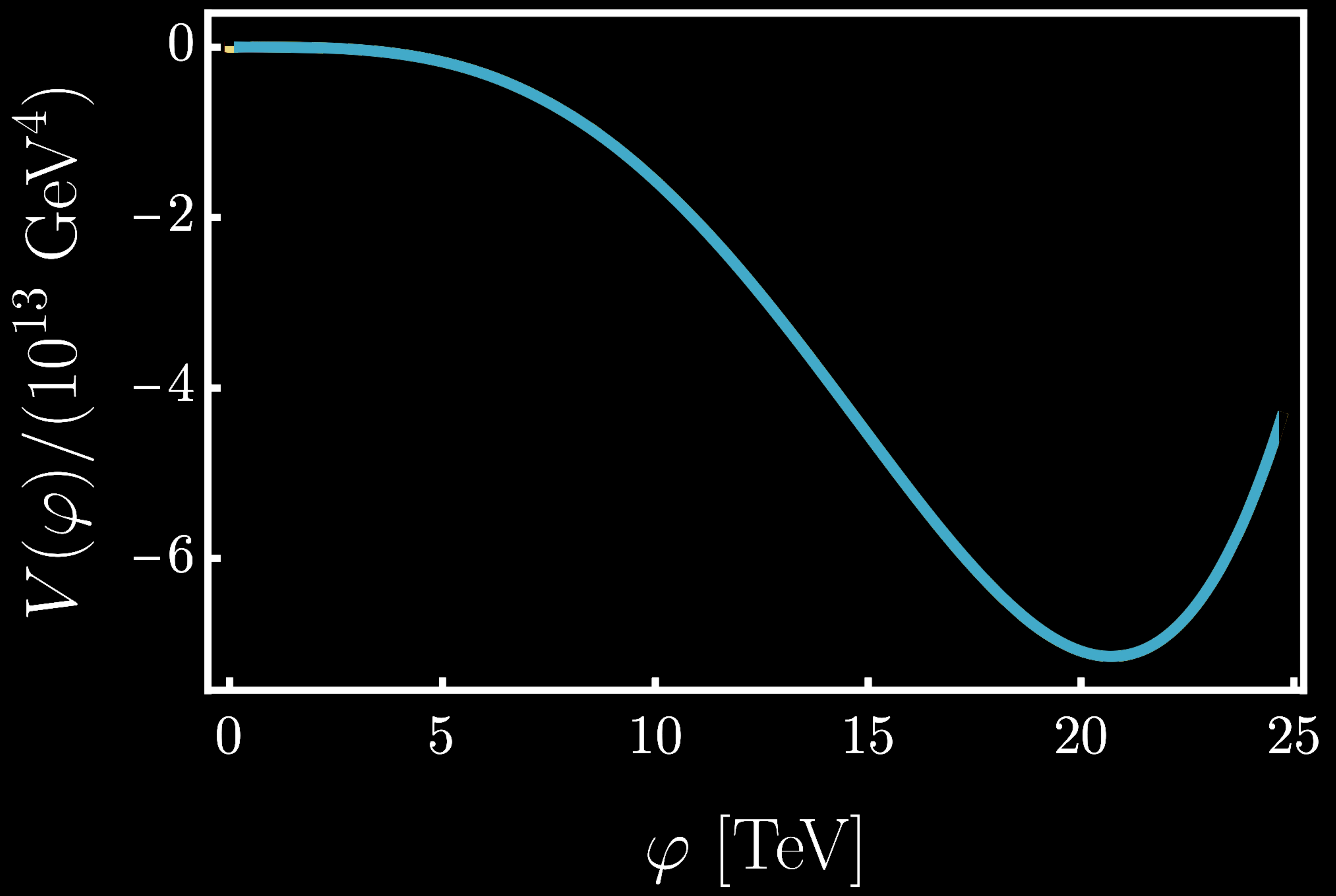
New SU(2)/U(1) sector

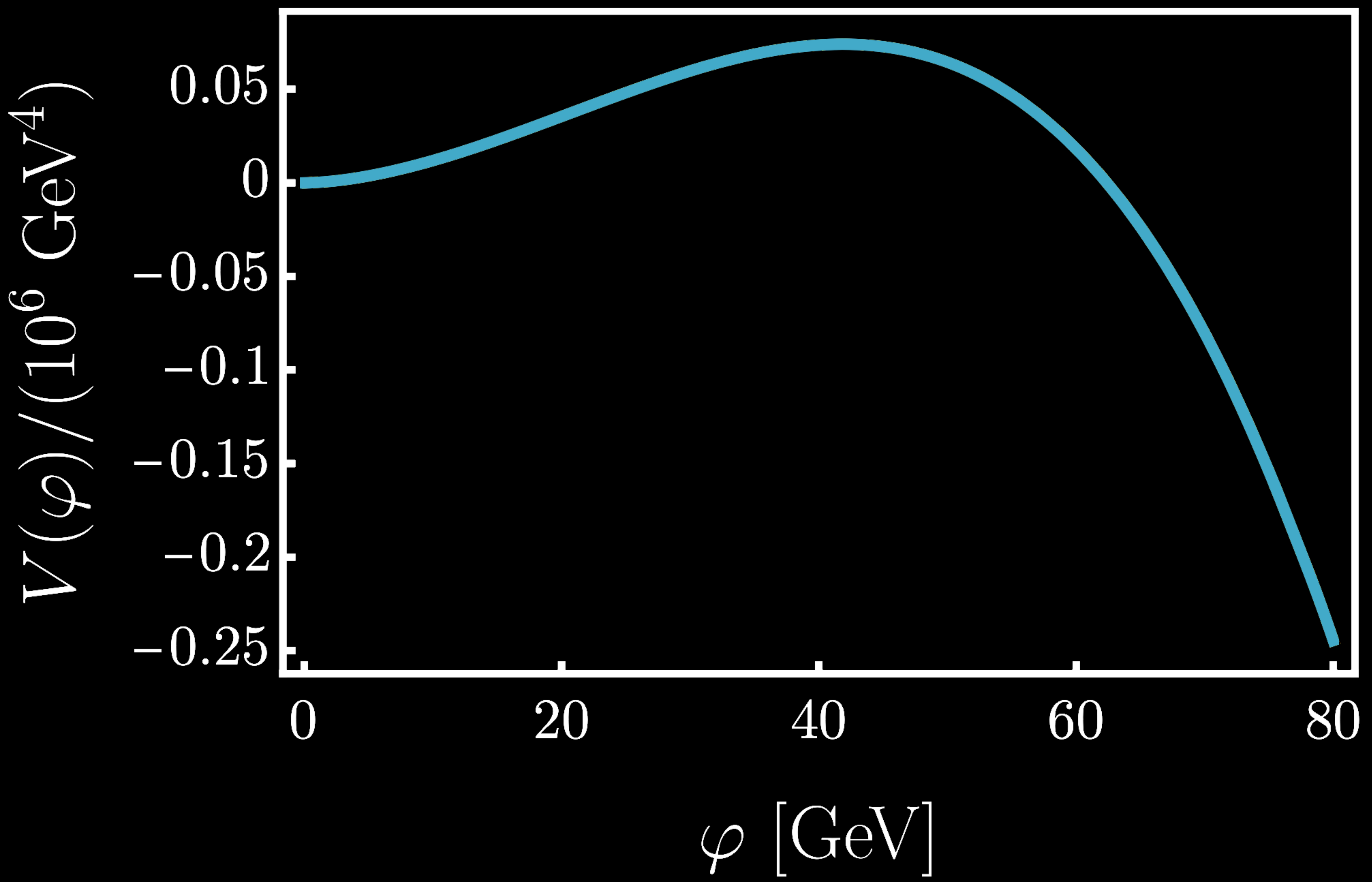
g_X, M_X

φ

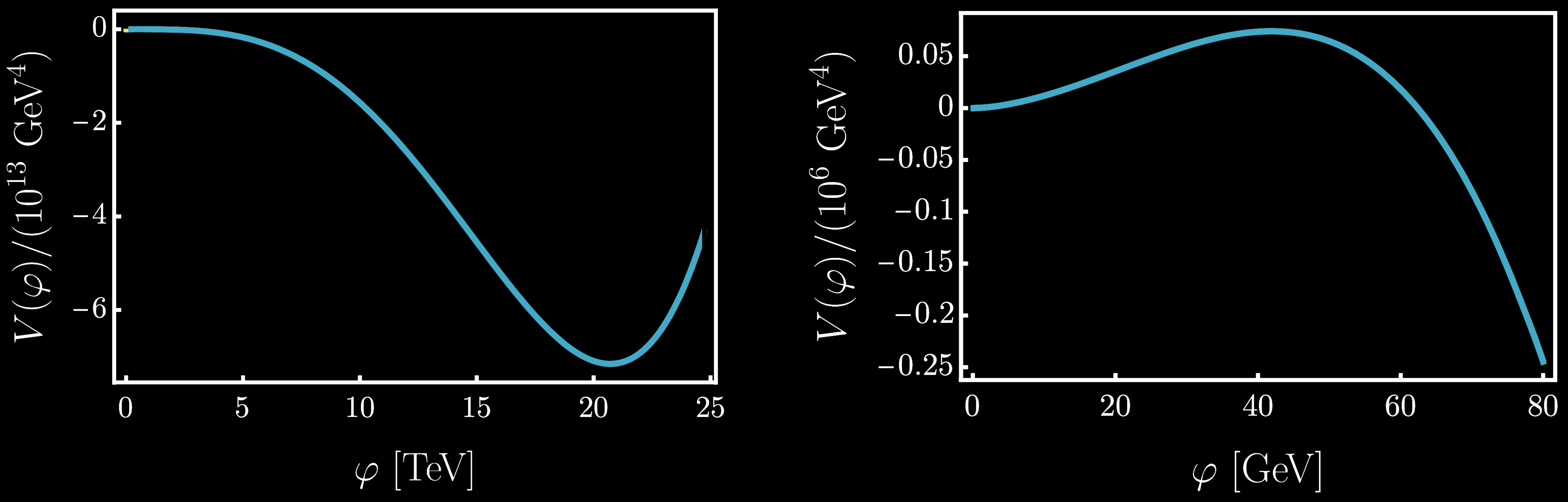
[See also: T.Hambye, A.Strumia, PRD88 (2013) 055022, C.Carone, R.Ramos, PRD88 (2013) 055020, V.V.Khoze, C.McCabe, G.Ro, JHEP 08 (2014) 026, T. Hambye, A.Strumia, D.Teresi, JHEP 1808 (2018) 188, I.Baldes, C. Garcia-Cely, JHEP 05 (2019) 190, T.Prokopec, J.Rezacek, BS, JCAP 02(2019)009, D. Marfaria, P.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

HIGH-T VS LOW-T





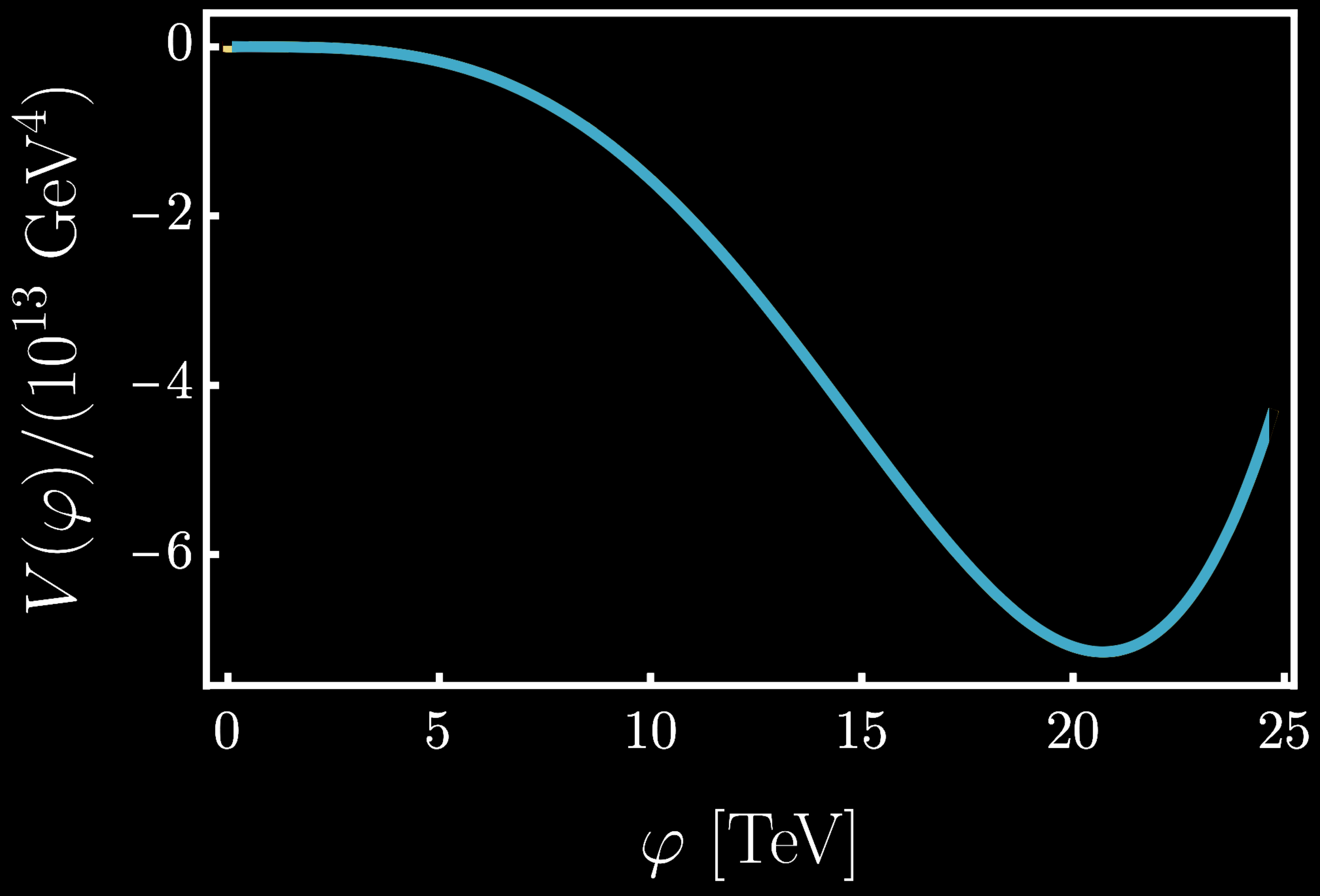
HIGH-T VS LOW-T

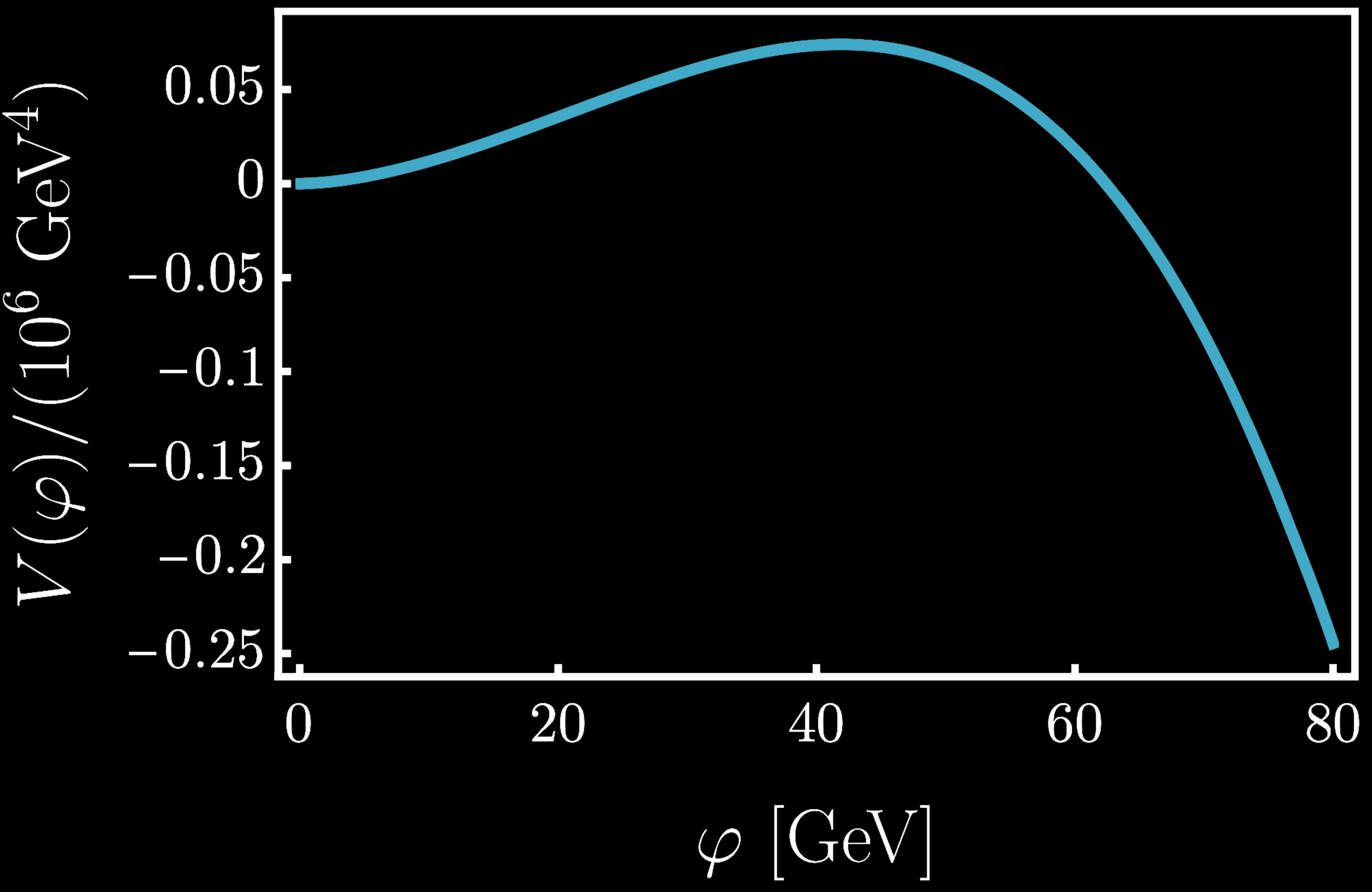


At large fields $M_X(\varphi)/T \gg 1$,
use LT approximation to compute T_{reh}, ΔV

At small fields $M_X(\varphi)/T \lesssim 1$,
use HT approximation to compute T_p, $R_* H_*$

HIGH-T VS LOW-T





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At small fields $M_X(\varphi)/T \lesssim 1$,
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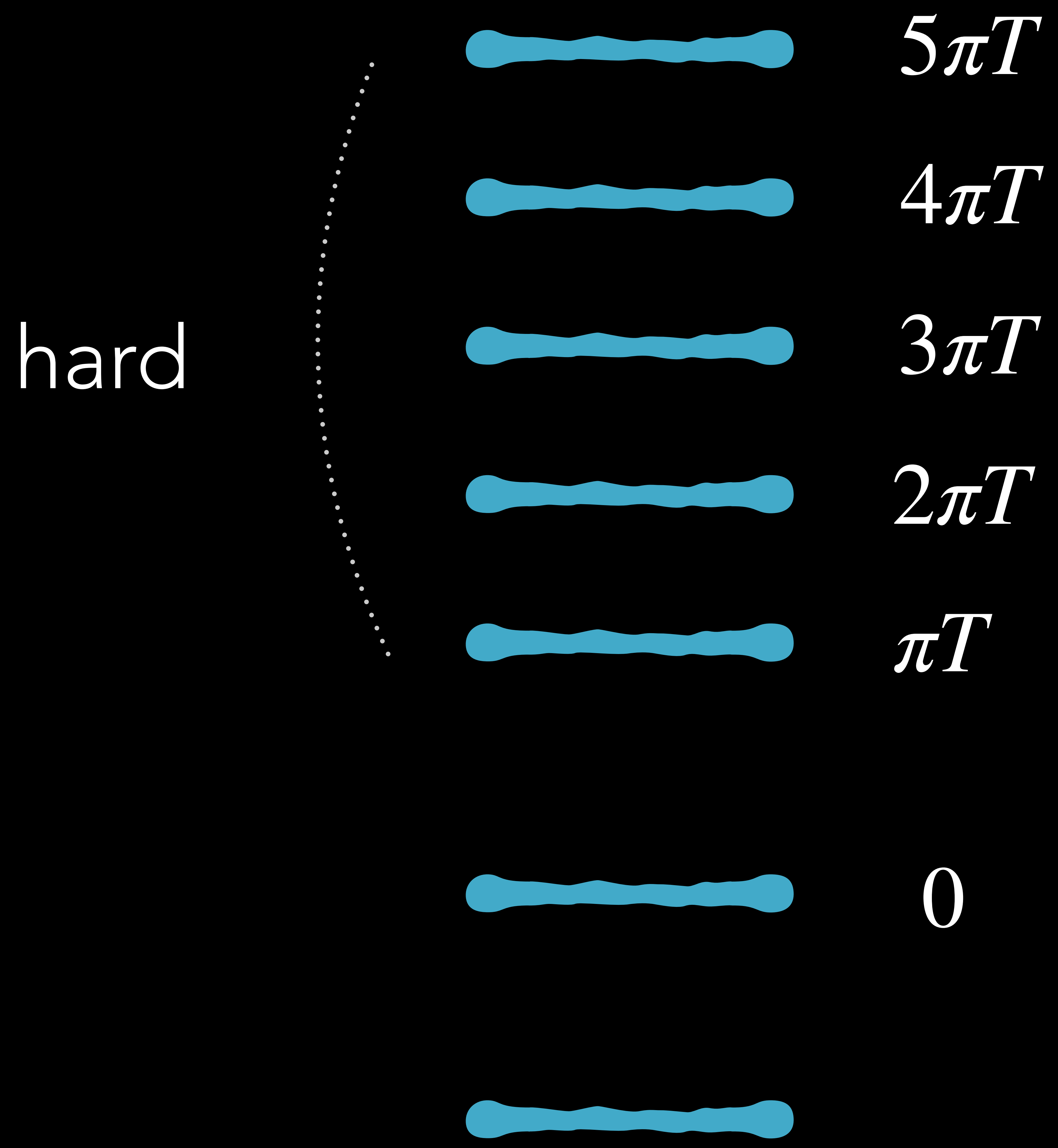
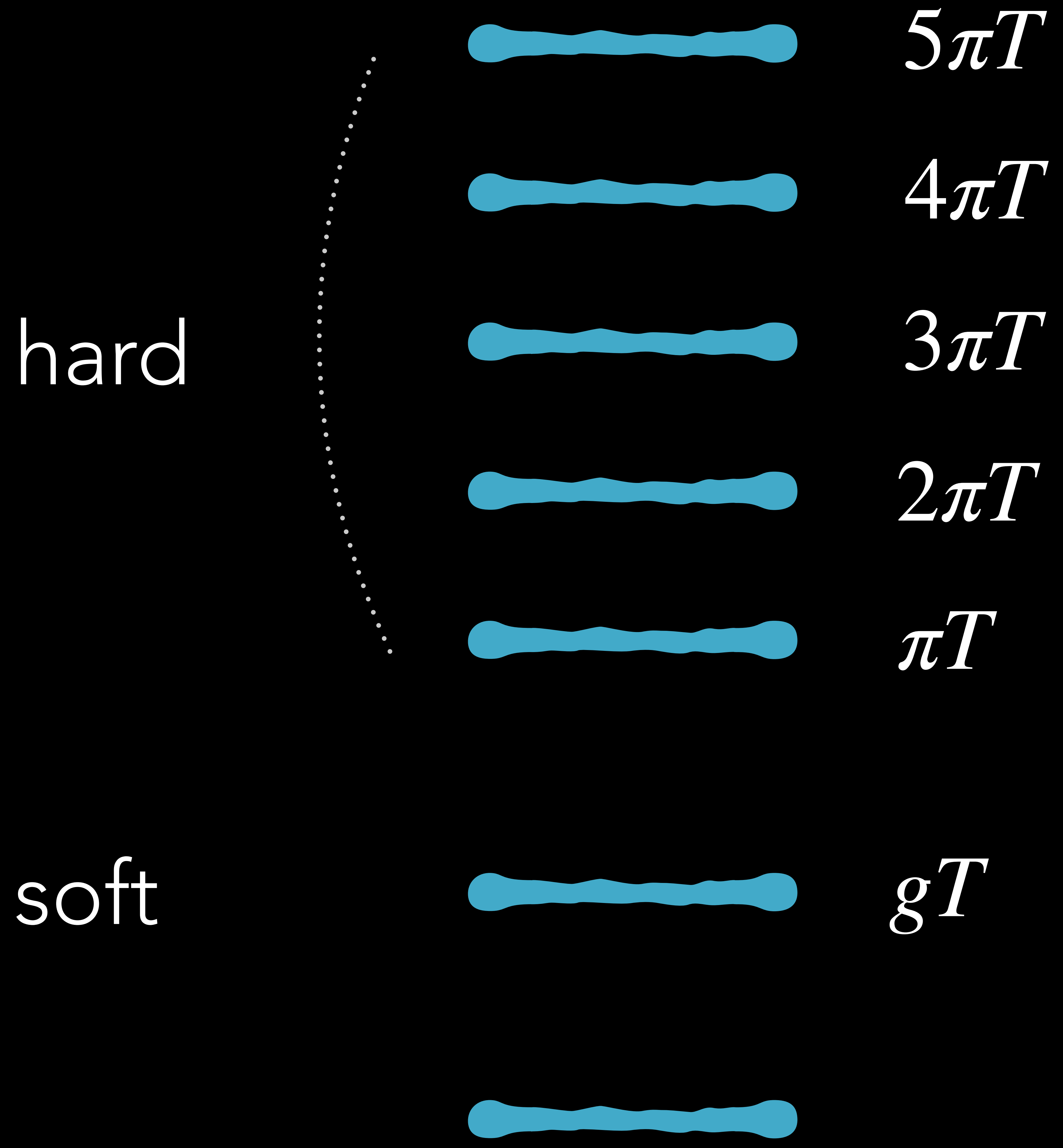
See the talk by M. Kulejewski for particle production from the field evolutioin

HT EFT CONSTRUCTION



HT EFT CONSTRUCTION

(gauge bosons, scalar)



HT EFT CONSTRUCTION

$5\pi T$

$4\pi T$

hard $3\pi T$

$2\pi T$

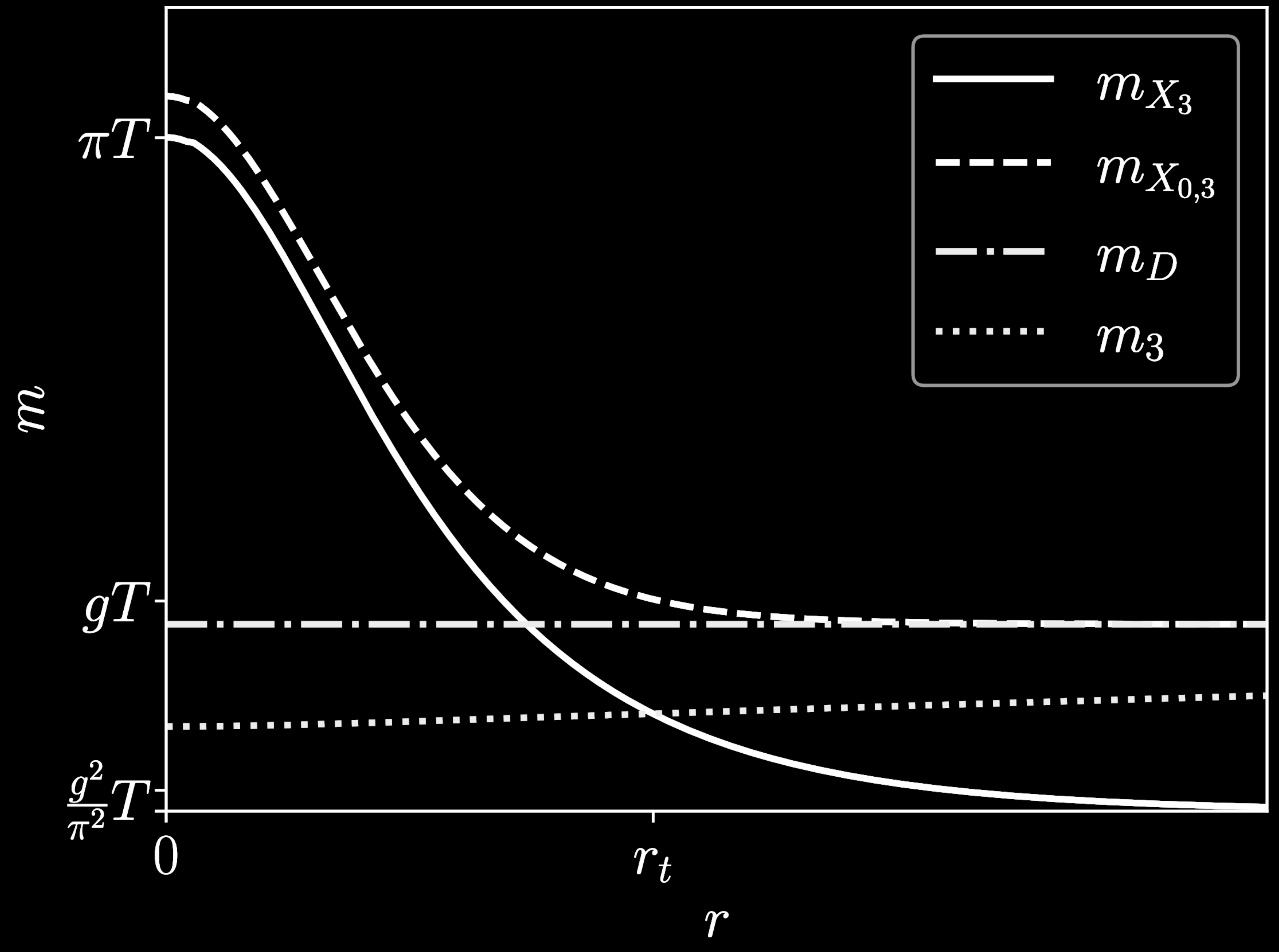
πT

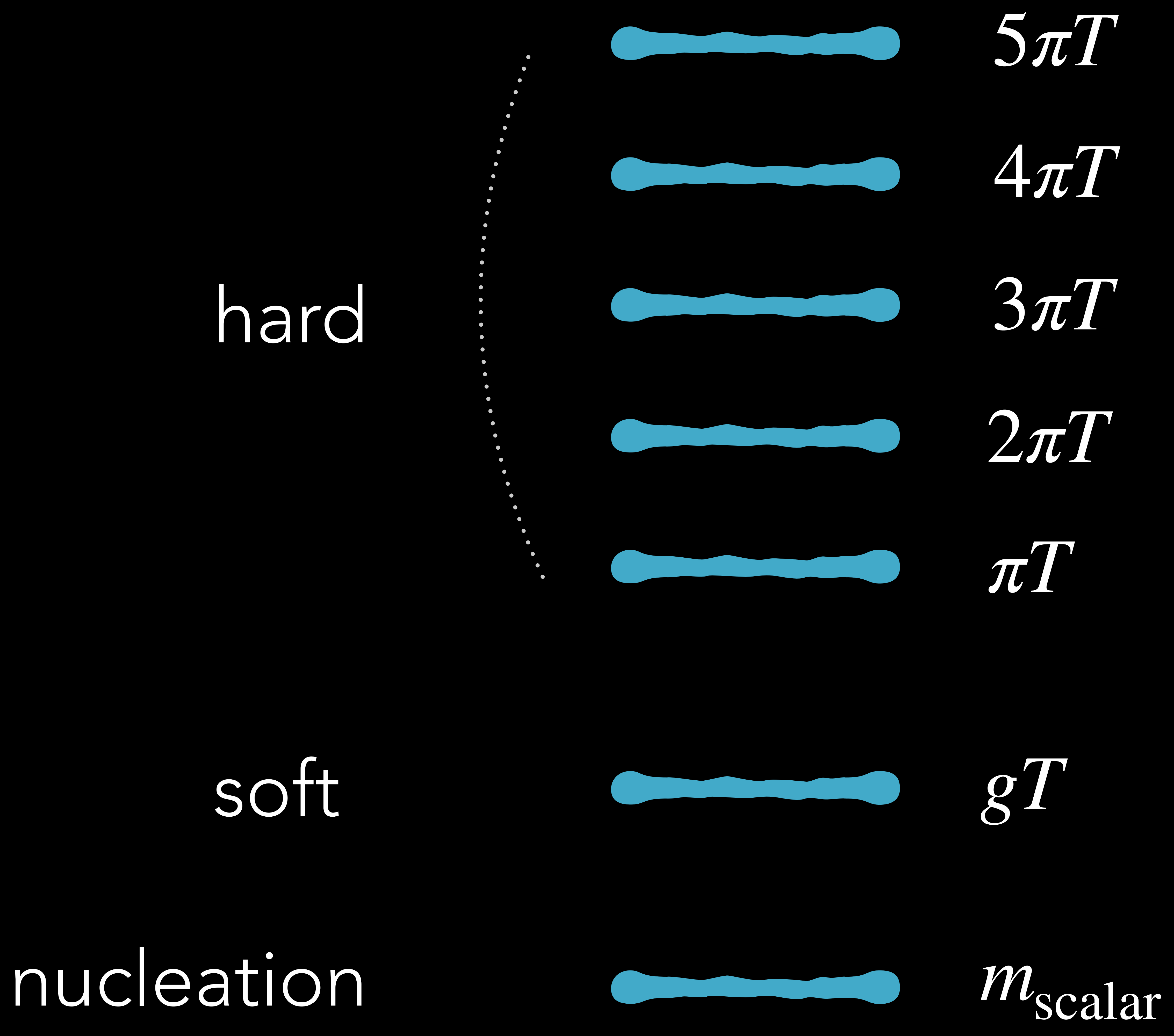
(gauge bosons, scalar) soft gT

(scalar) nucleation m_{scalar}

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

HT EFT CONSTRUCTION





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

HT EFT CONSTRUCTION

2-loop matching with DRalgo

hard: $5\pi T$, $4\pi T$, $3\pi T$, $2\pi T$, πT

(gauge bosons, scalar) soft: gT

(scalar) nucleation: m_{scalar}

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

WHAT'S NEW AT NLO?

$$S_3^{\mathrm{EFT,\ NLO}} = 4\pi \int \mathrm{dr}\ \mathrm{r}^2 \left(\frac{1}{2} \mathrm{Z}_3^{\mathrm{NLO}}(\mathrm{v}_3)(\partial_{\mathrm{i}} \mathrm{v}_3)^2 + \mathrm{V}_3^{\mathrm{EFT,\ NLO}}(\mathrm{v}_3) \right)$$

- New effective operator in the kinetic term
- Behaves badly for $\varphi_3 \to 0$

- two-loop matching
- NLO potential
- Includes missing (4d) RG scale dependence
- 3d scale invariant

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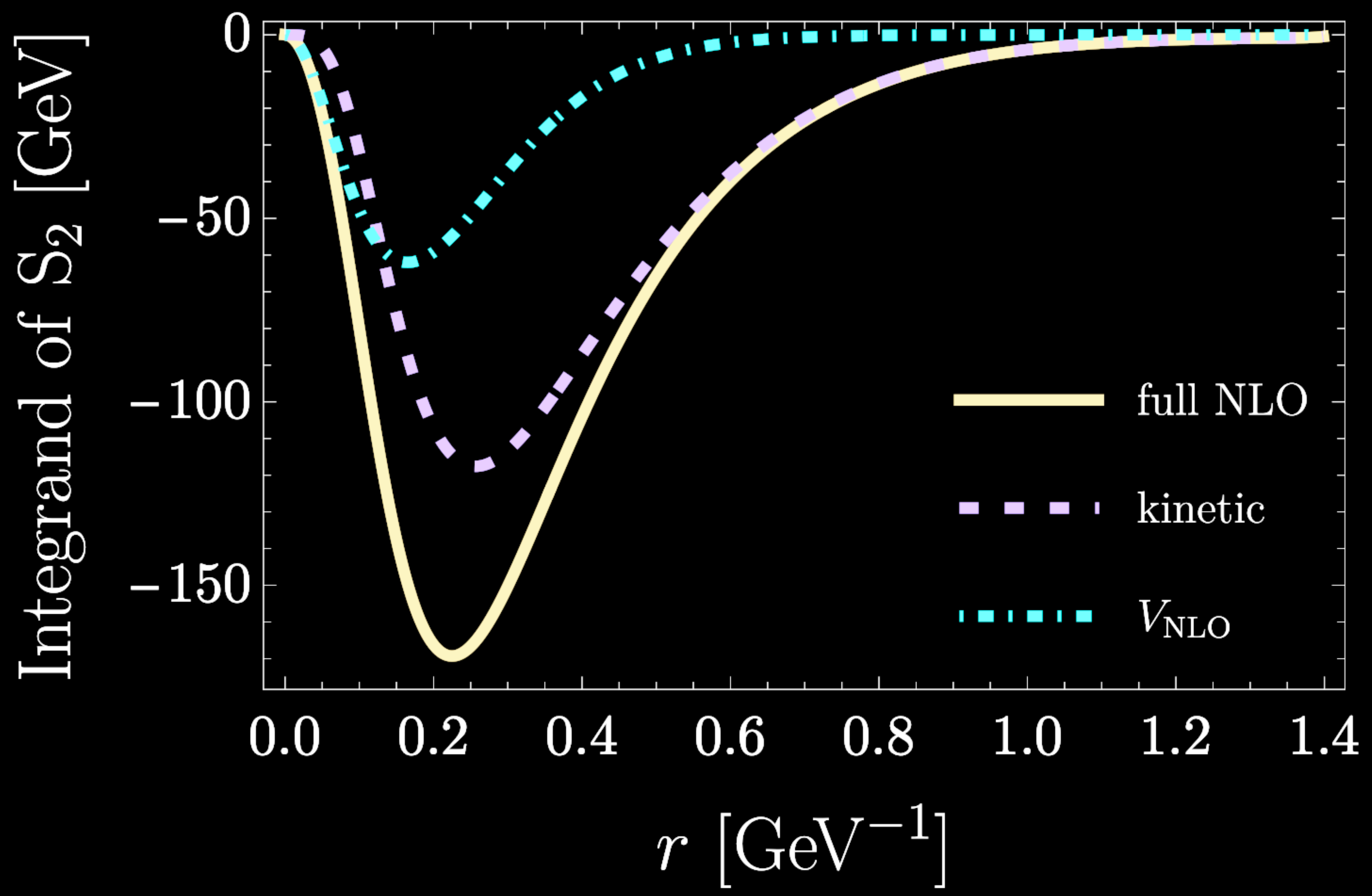
Up to 100% corrections to percolation temperature!

MOMENTUM EXPANSION



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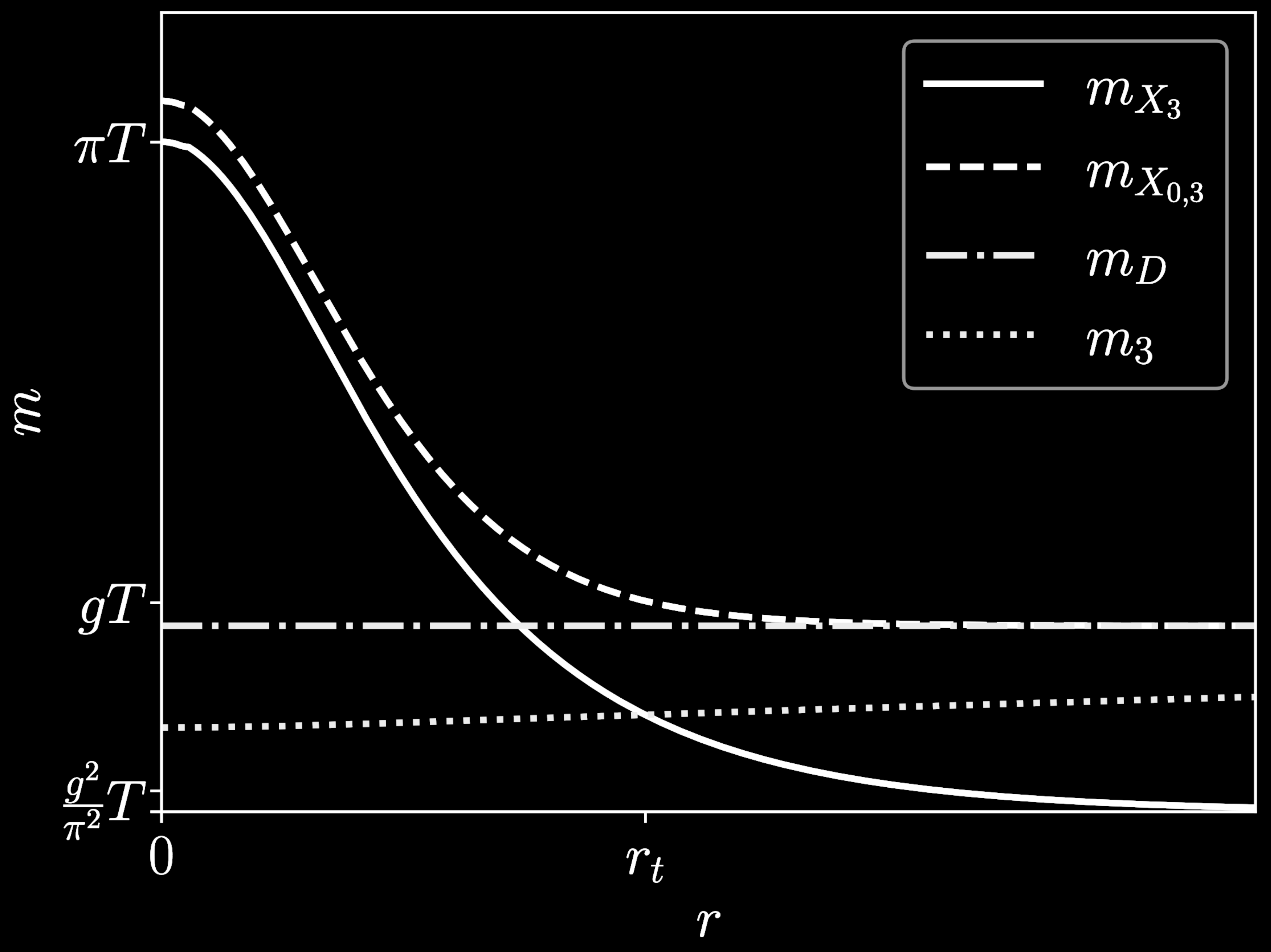
VALIDITY OF EFT — SCALE-SHIFTERS



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

NUCLEATION RATE BEYOND LEADING ORDER

$$\Gamma = A_{\text{dyn}} \cdot A_{\text{stat}}$$

$$A_{\text{stat}} = \prod_a \mathcal{I}_a \mathcal{V}_a \sqrt{\frac{\det \mathcal{O}_a(\varphi_F)}{\det' \mathcal{O}_a(\varphi_b)}} \mathcal{I}_\phi \sqrt{\left| \frac{\det \mathcal{O}_\phi(\varphi_F)}{\det' \mathcal{O}_\phi(\varphi_b)} \right|} e^{-(S[\varphi_b]+C[\varphi_b])}$$

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Remove the contribution from the scale shifting fields

Inclusion of fluctuations from the scale-shifting fields

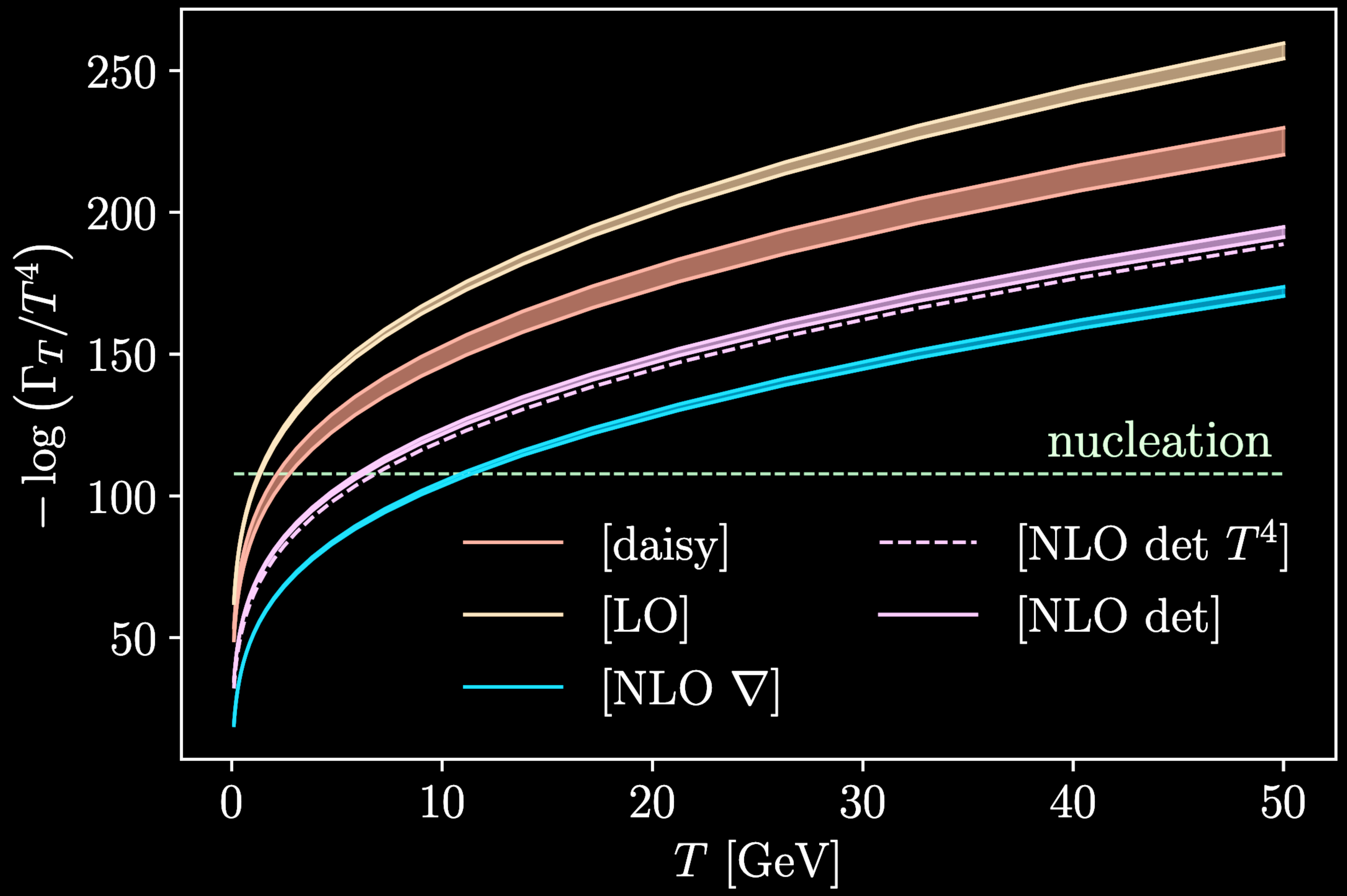
Test of validity of the momentum expansion

Test of the approximations for the scalar prefactor & quantum fluctuations

[M. Kierkla, P. Schicho, BŚ, T.V.I. Tenkanen, J. van de Vis, JHEP 07 (2025) 153, BubbleDet: A. Ekstedt, O.Gould, J. Hirvonen, *JHEP* 12 (2023) 056]

COMPARISON OF DIFFERENT APPROXIMATIONS

$$\Gamma = A_{\mathrm{dyn}} \cdot A_{\mathrm{stat}} \qquad A_{\mathrm{stat}} = \prod_a \mathcal{I}_a \mathcal{V}_a \sqrt{\frac{\det \mathcal{O}_a(\varphi_F)}{\det' \mathcal{O}_a(\varphi_b)}} \mathcal{I}_\phi \sqrt{\left| \frac{\det \mathcal{O}_\phi(\varphi_F)}{\det' \mathcal{O}_\phi(\varphi_b)} \right|} \, e^{-(S[\varphi_b]-S[\varphi_F])}$$



[M. Kierkla, P. Schicho, BŚ, T.V.I. Tenkanen, J. van de Vis, JHEP 07 (2025) 153]

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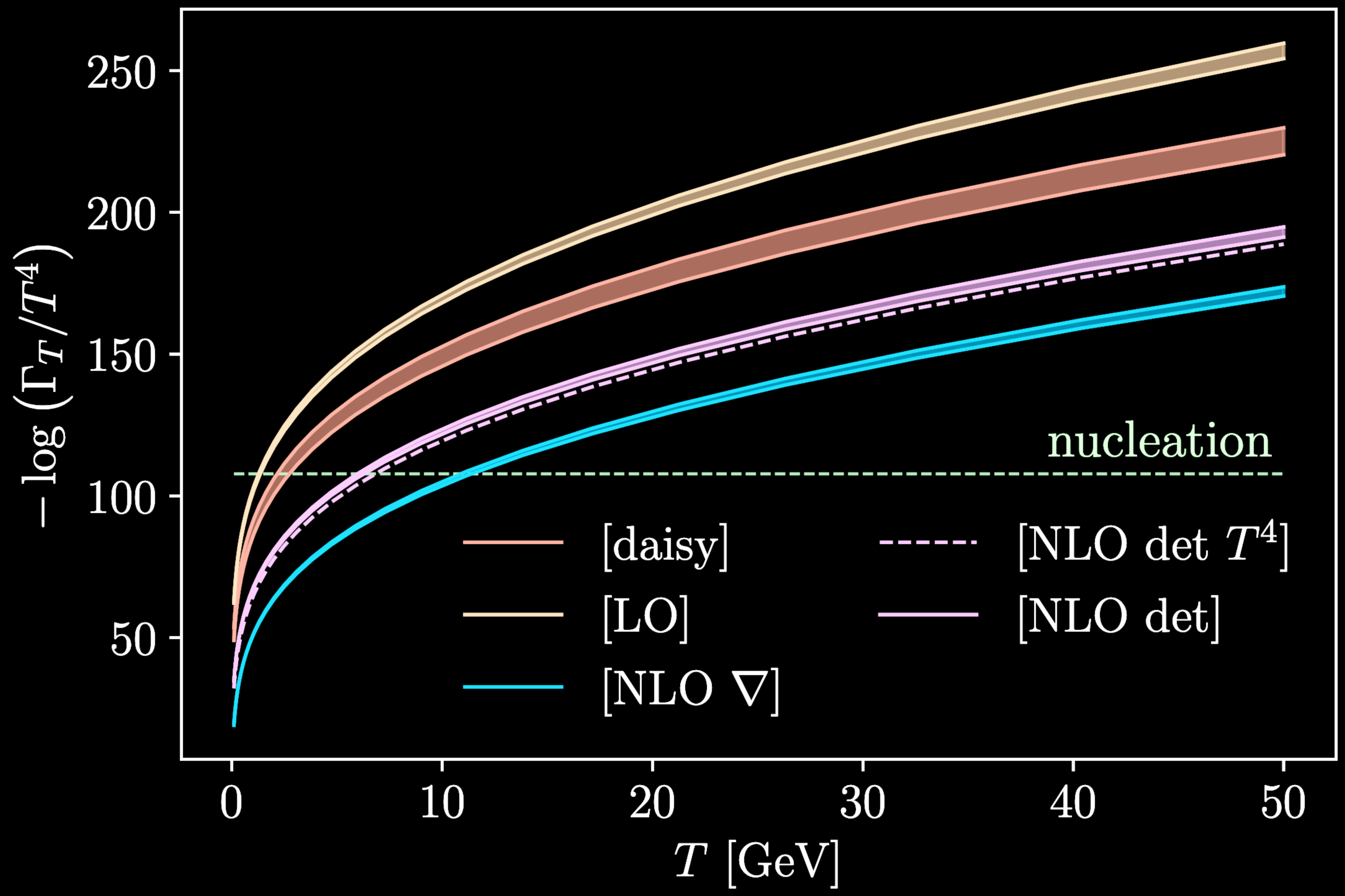
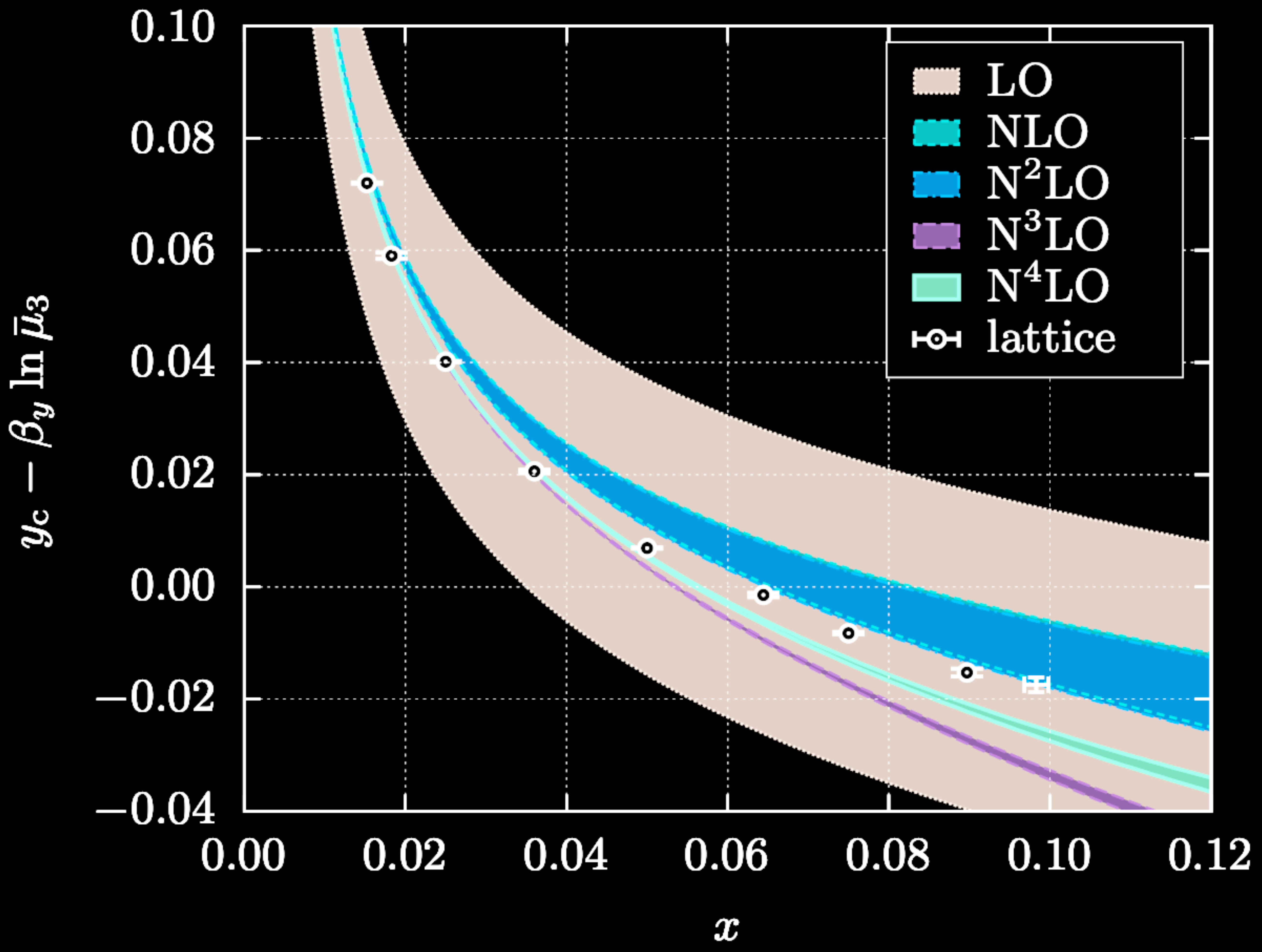


- Up to 300% difference in percolation temperature
- 30% difference in the bubble radius

[M. Kierkla, P. Schicho, BŚ, T.V.I. Tenkanen, J. van de Vis, JHEP 07 (2025) 153]

IS THE PERTURBATIVE APPROACH RELIABLE?



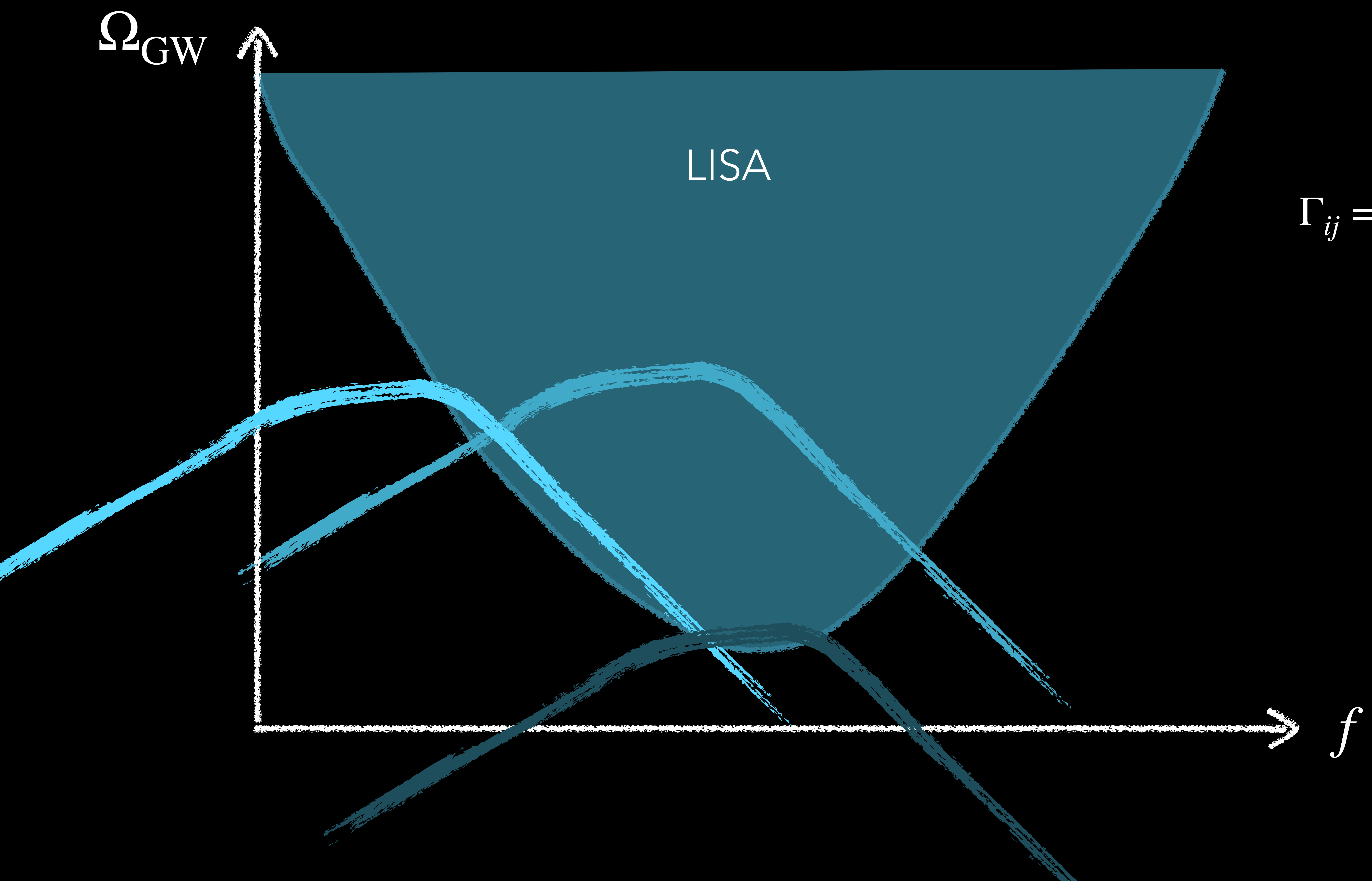
- Convergence in thermodynamical studies
- No lattice computation with $\lambda < 0$

[figure adapted from: A. Ekstedt, P. Schicho, T. V. I. Tenkanen, Phys.Rev.D 110 (2024) 9, 096006]

[See also: O. Gould and T. V. I. Tenkanen, JHEP 01 (2024) 048, L. Niemi et al. PRL 126 (2021) 171802, PRD 110 (2024) 115016]

THE INVERSE PROBLEM

EXTRACTING INFRMATION FROM GW SPECTRUM



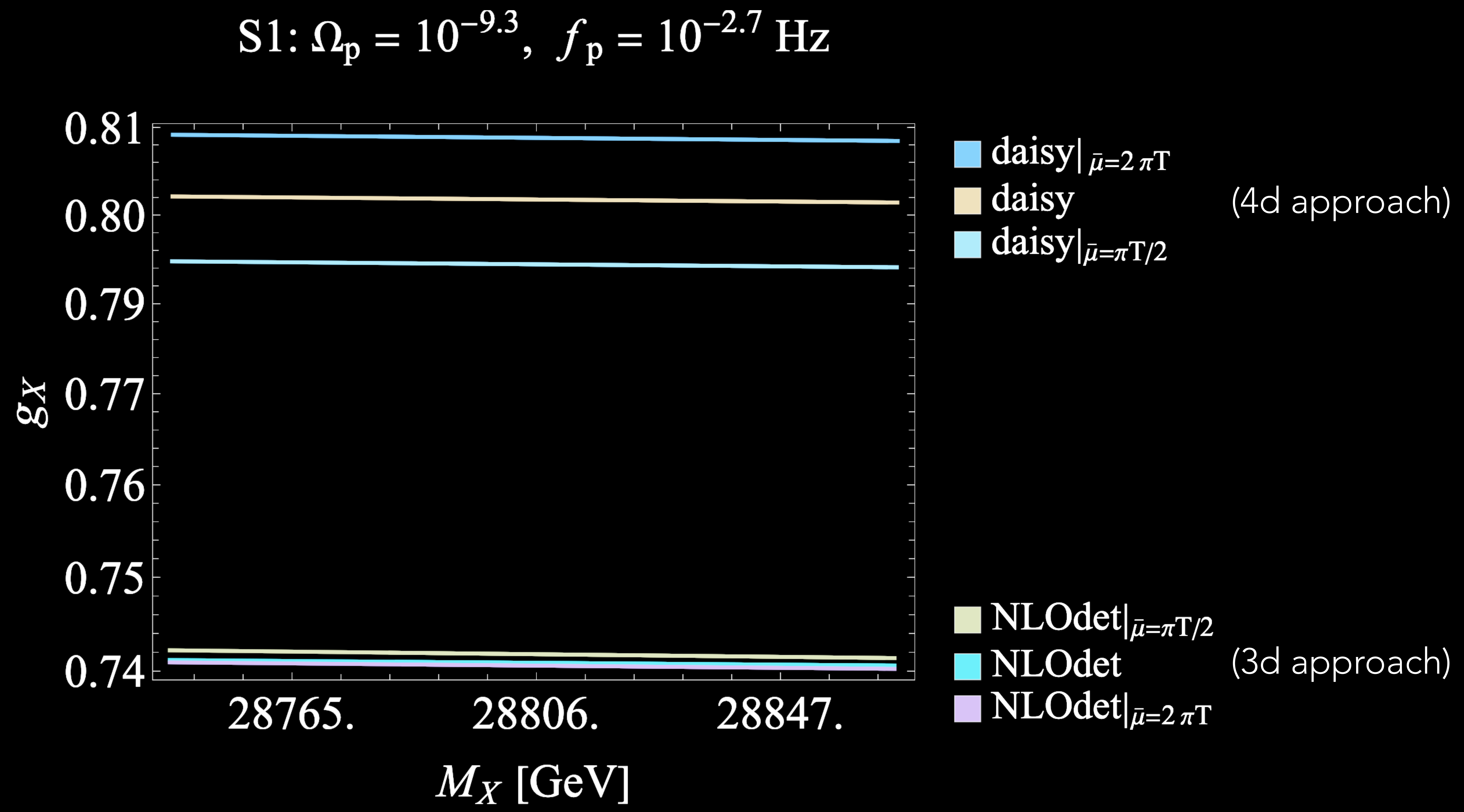
$$\Gamma_{ij} = T \int \frac{\mathrm{df}}{\Omega_{\mathrm{tot}}(f)^2} \frac{\partial \Omega_{\mathrm{GW}}}{\partial \theta_i} \frac{\partial \Omega_{\mathrm{GW}}}{\partial \theta_j}$$

$$\sigma_{ij}^2 = (\Gamma^{-1})_{ij}$$

$$\sigma_{g_X} = \sqrt{\sigma^2_{g_X g_X}}$$

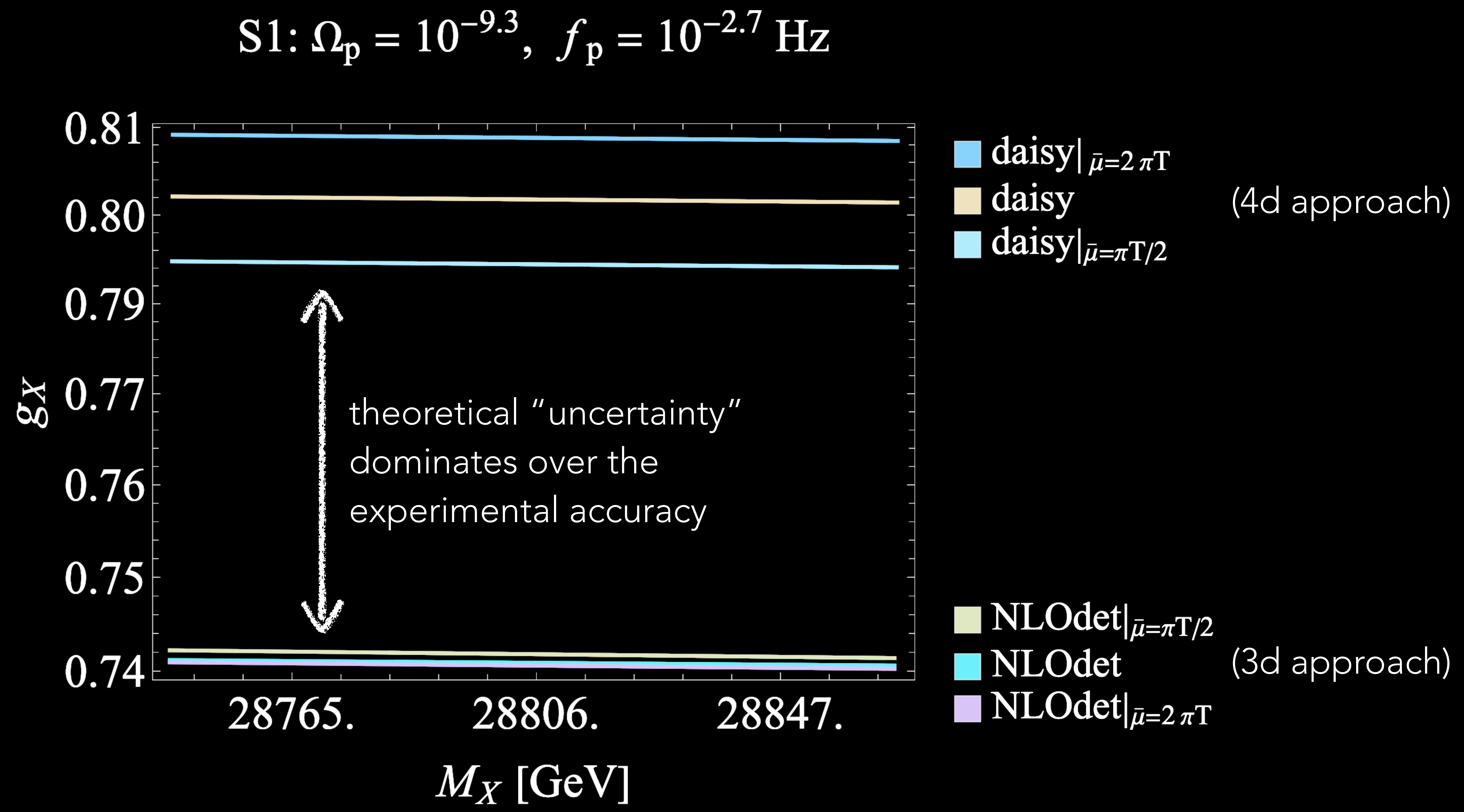
$$\sigma_{M_X} = \sqrt{\sigma^2_{M_X M_X}}$$

RECONSTRUCTION OF U(1) MODEL PARAMETERS



[M. Kierkla, M. Lewicki, P. Schicho, D. Schmitt, B. Świeżewska, 2607.18233]

RECONSTRUCTION OF U(1) MODEL PARAMETERS



[M. Kierkla, M. Lewicki, P. Schicho, D. Schmitt, B. Świeżewska, 2607.18233]

HIERARCHY OF ERRORS FOR STRONG TRANSITIONS

experimental error ~ residual scale dependence in 3d NLOdet approach

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$\Uparrow$

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$\Uparrow$

scale dependence in the 3d daisy approach

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$\Uparrow$

HIERARCHY OF ERRORS FOR STRONG TRANSITIONS

experimental error ~ residual scale dependence in 3d NLOdet approach

⩓

scale dependence in the 3d daisy approach

⩓

difference between 3d daisy and 4d NLOdet

SUMMARY

CONCLUSIONS

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Strong GW signals need strong theory.

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Strong GW signals need strong theory.

And weak as well

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Strong GW signals need strong theory.
And weak as well

Theoretical improvements needed for precise predictions…

CONCLUSIONS

Strong GW signals need strong theory.
And weak as well

Theoretical improvements needed for precise predictions…

but also to ensure the procedures are well-defined.

PHASE TRANSITIONS FROM MICROSCOPIC TO COSMOLOGICAL SCALES

MAINZ INSTITUTE FOR THEORETICAL PHYSICS (MITP)
SEPTEMBER 27 — OCTOBER 15, 2027

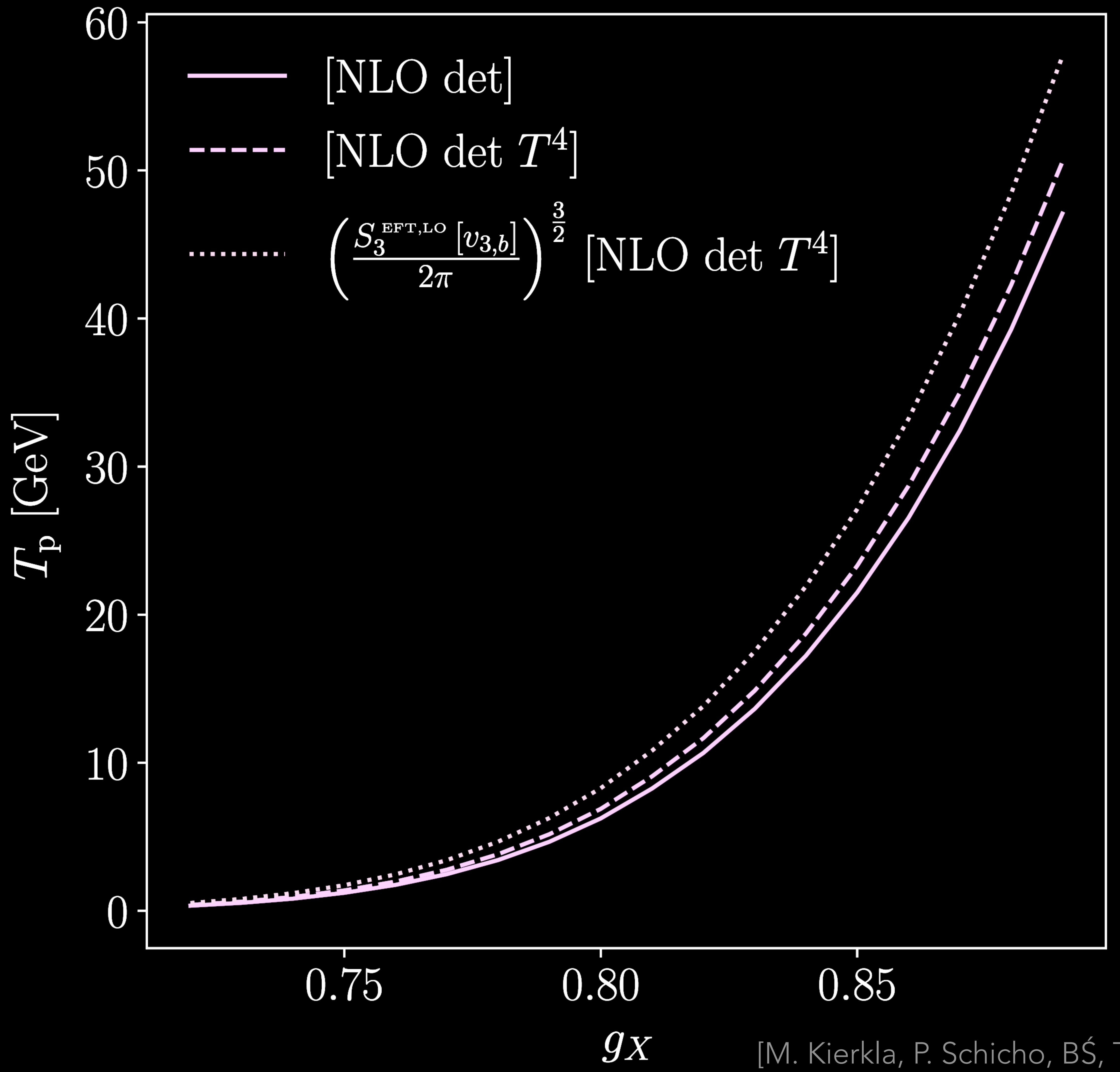
Mainz Institute for Theoretical Physics

Organisers:
Miha Nemevšek
Davide Racco
Alberto Roper Pol
Philipp Schicho
Pedro Schwaller
Bogumiła Świeżewska

THANK YOU

BACKUP SLIDES

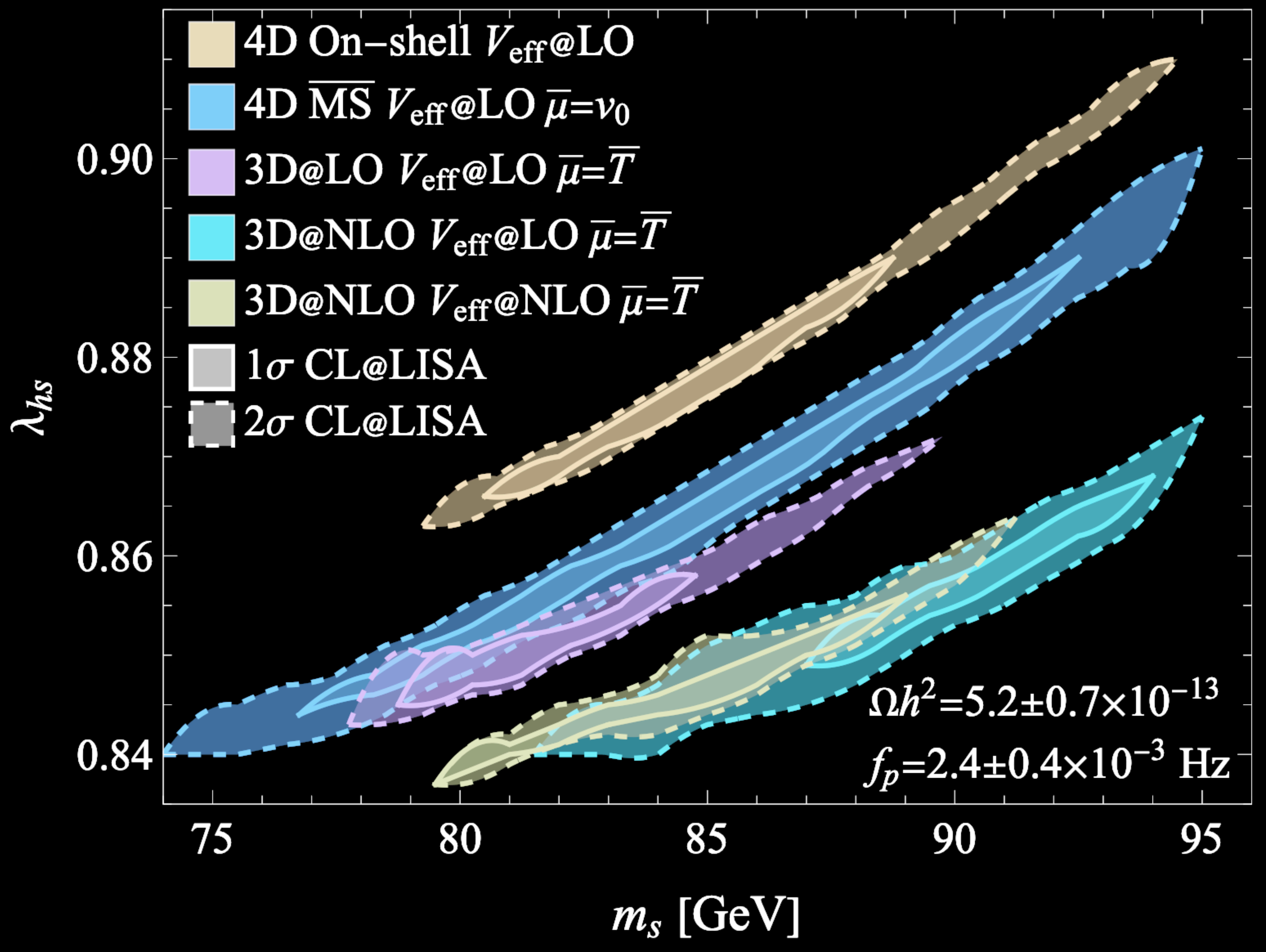
SCALAR DETERMINANT



[M. Kierkla, P. Schicho, BŚ, T.V.I. Tenkanen, J. van de Vis, JHEP 07 (2025) 153]

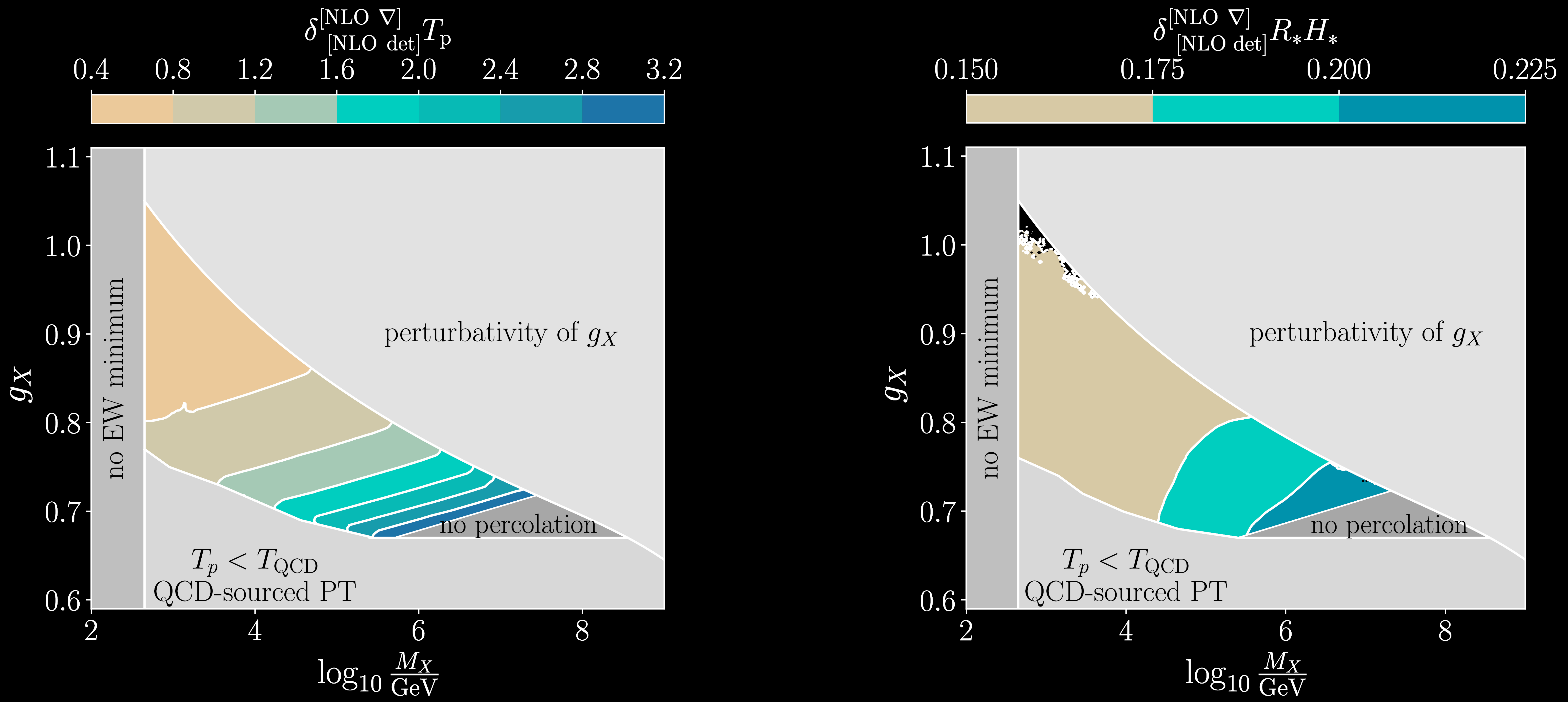
PRECISION FOR WEAKER SIGNALS

SM + singlet, SNR=10



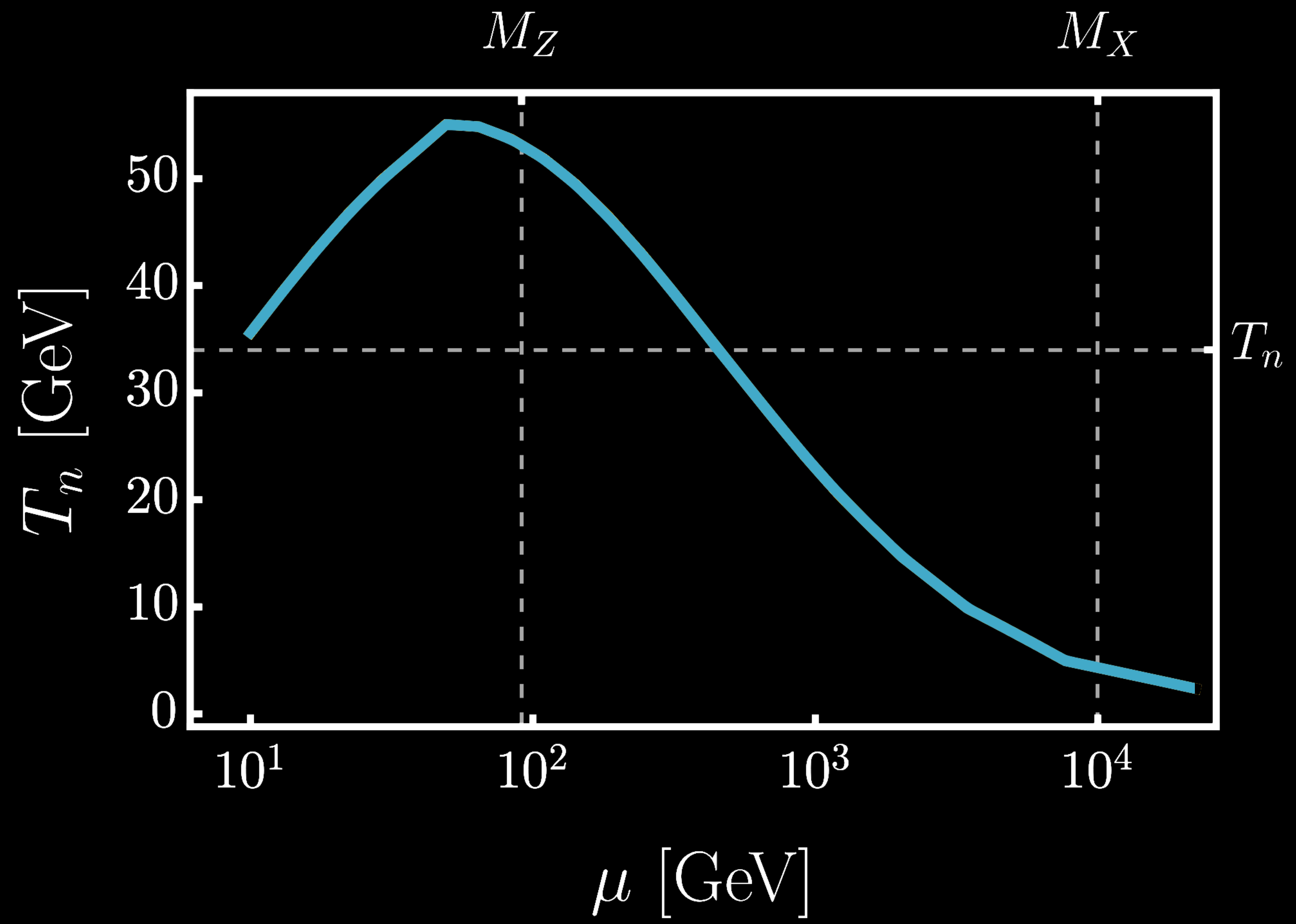
[M. Lewicki, M. Merchand, L. Sagunski, P. Schicho, D. Schmitt, Phys.Rev.D 110 (2024) 2, 023538]

ACCURACY OF PREDICTIONS



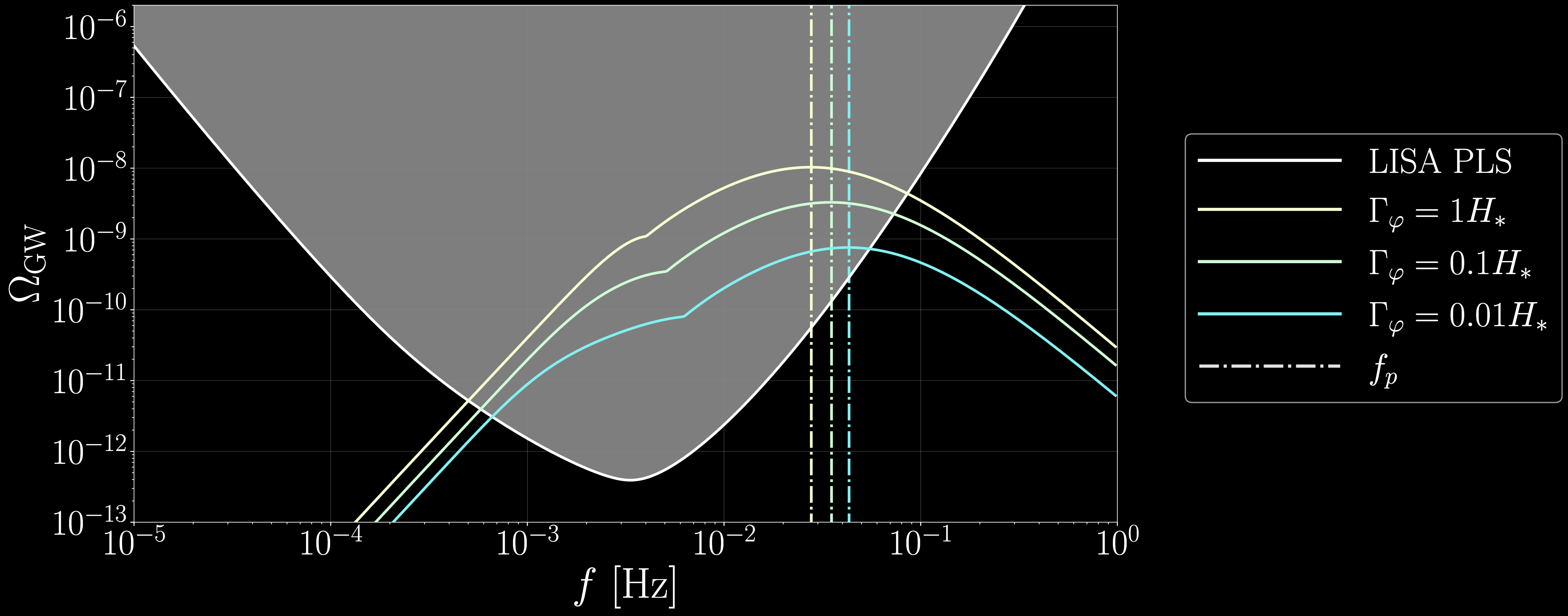
[M. Kierkla, P. Schicho, BŚ, T.V.I. Tenkanen, J. van de Vis, JHEP 07 (2025) 153]

SCALE DEPENDENCE - SOURCE OF UNCERTAINTY



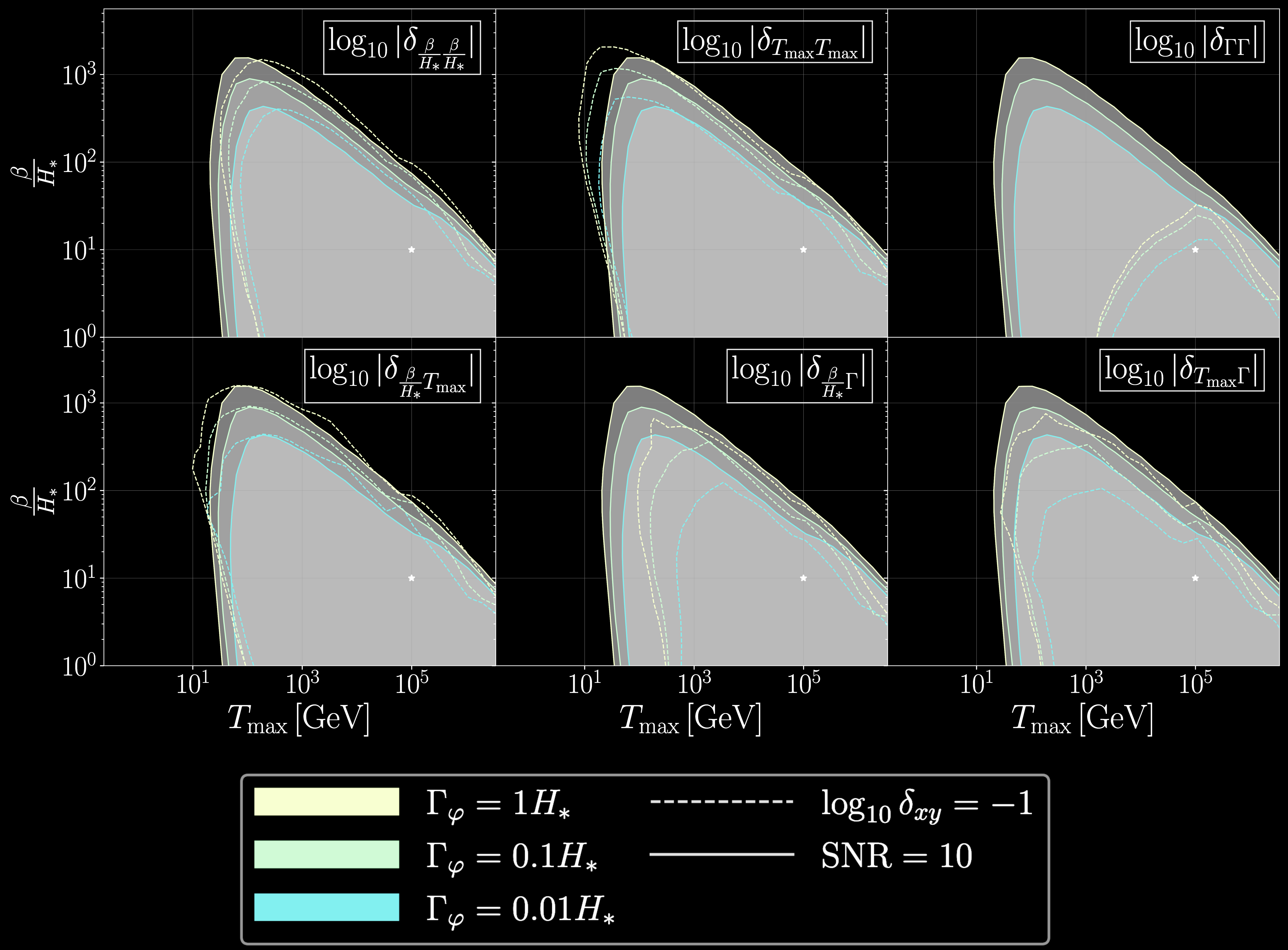
[M. Kierkla, A. Karam, BŚ, JHEP 03 (2023) 007]

MODIFIED EXPANSION AFFECTS THE SIGNAL



[A. Gonstal, M. Lewicki, B. Świeżewska, 2502.18436]

WHAT CAN WE LEARN FROM THE SIGNAL?



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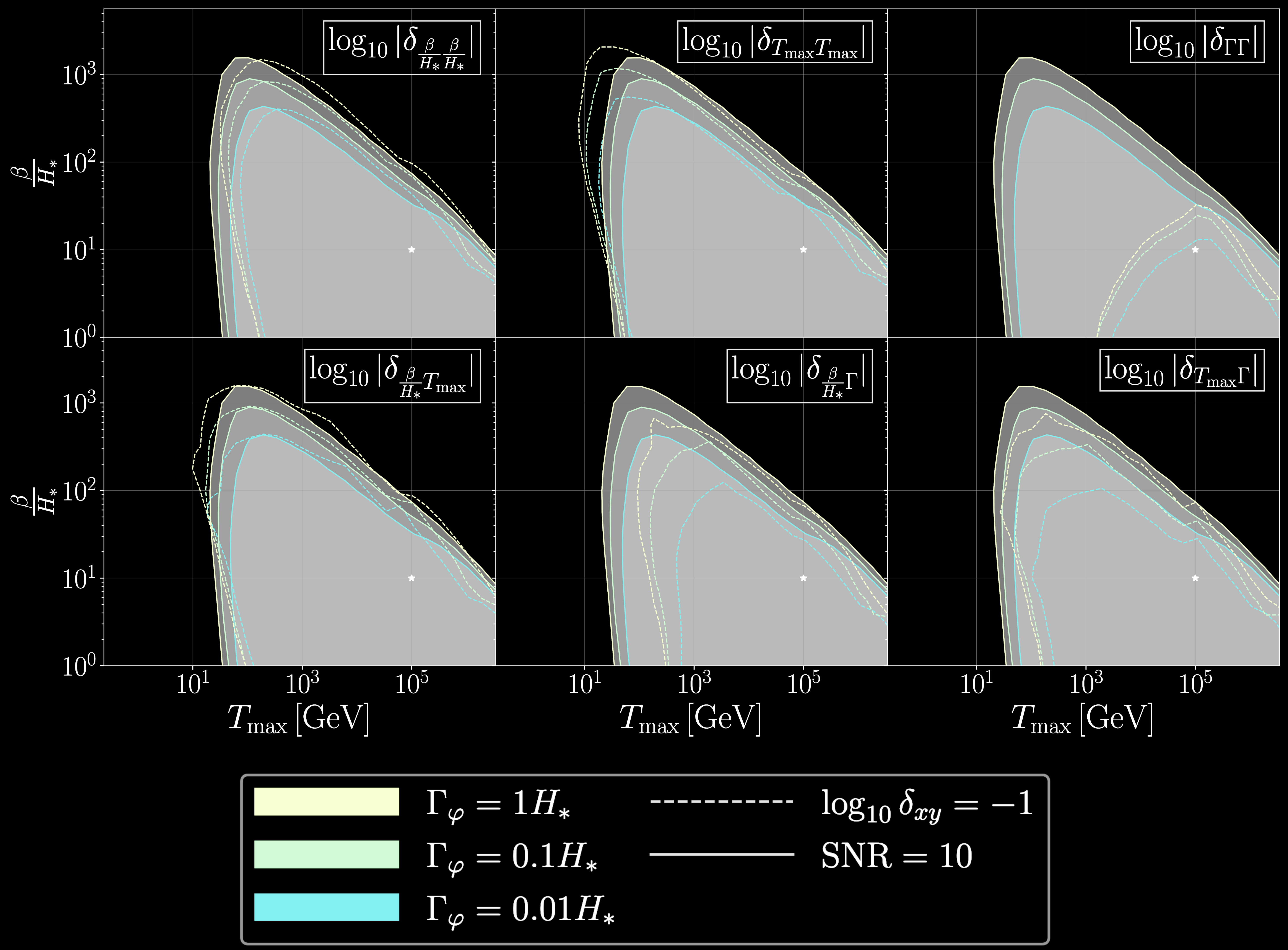

- Decay rate of the scalar (inaccessible at colliders?) can be determined from the spectrum

[A. Gonstal, M. Lewicki, B. Świeżewska, 2502.18436]

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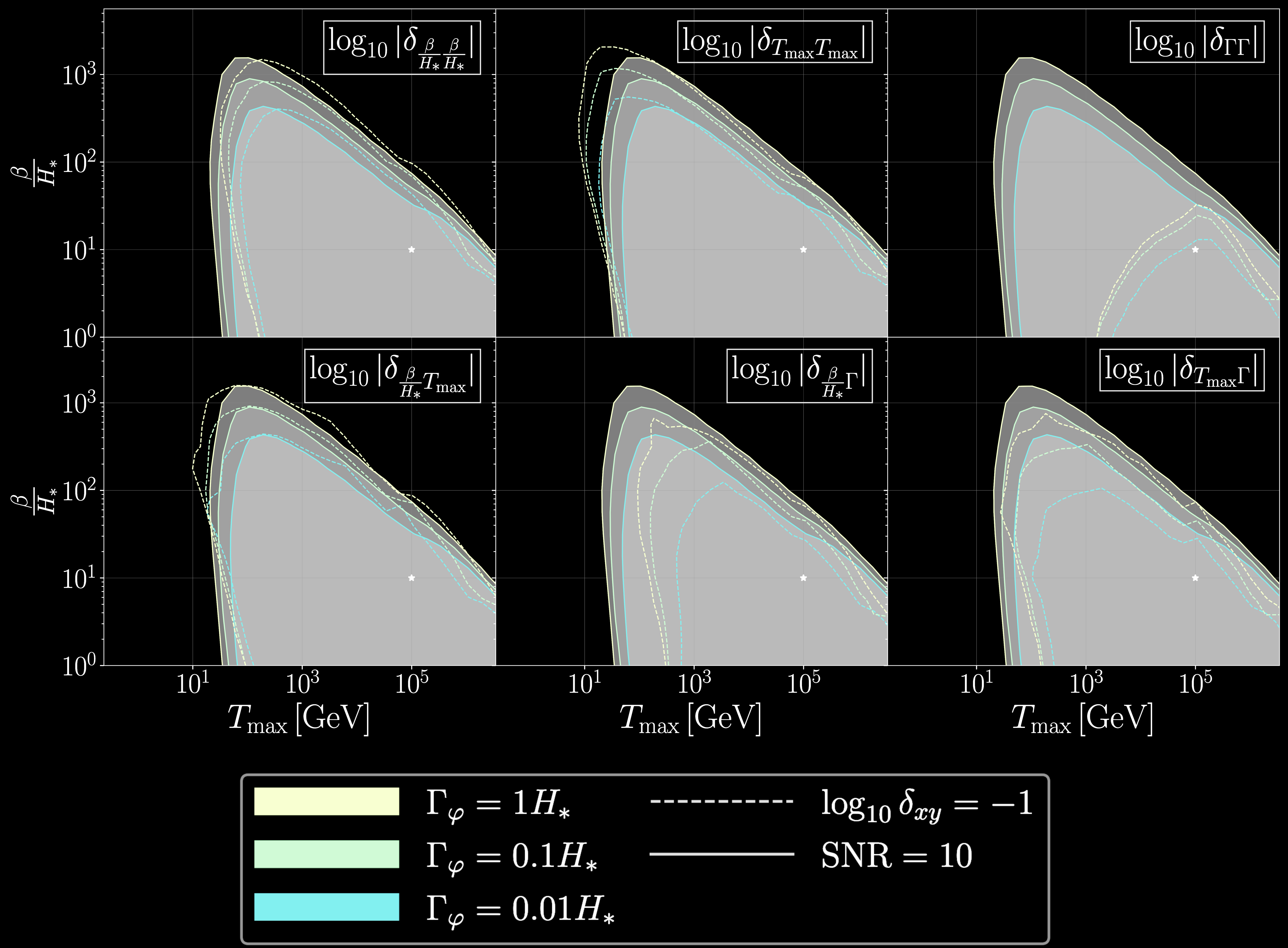
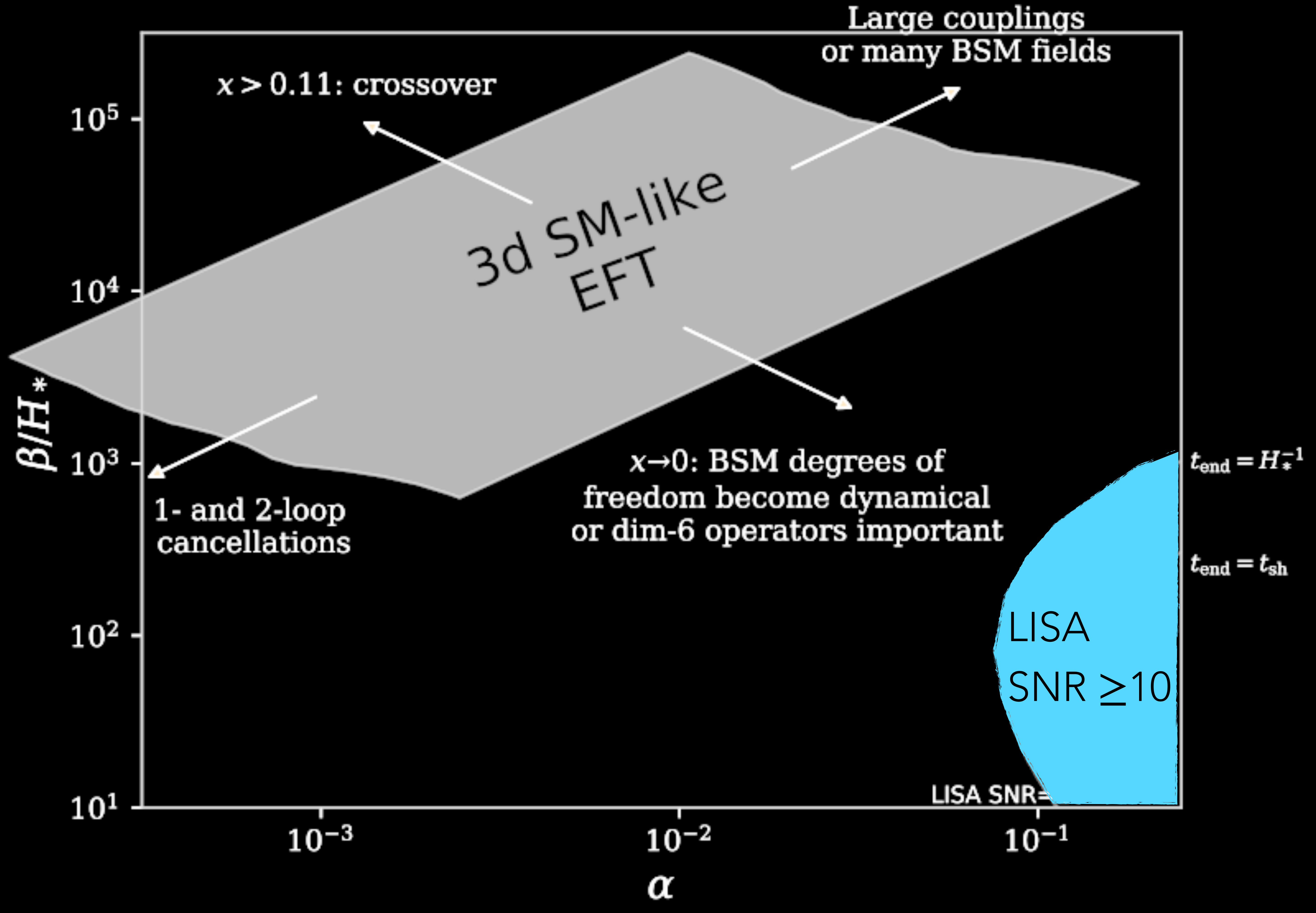


- Decay rate of the scalar (inaccessible at colliders?) can be determined from the spectrum
- Individual parameters can be determined with an accuracy better than 10%

[A. Gonstal, M. Lewicki, B. Świeżewska, 2502.18436]

WHAT KIND OF PT CAN BE OBSERVABLE?



[Figure adapted 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]