PARTICLE PHYSICS IN THE EARLY UNIVERSE, PARIS, 16.09.2026

SUPERCOOLED COSMOLOGICAL PHASE TRANSITIONS: PRECISE PREDICTIONS AND PARTICLE PRODUCTION

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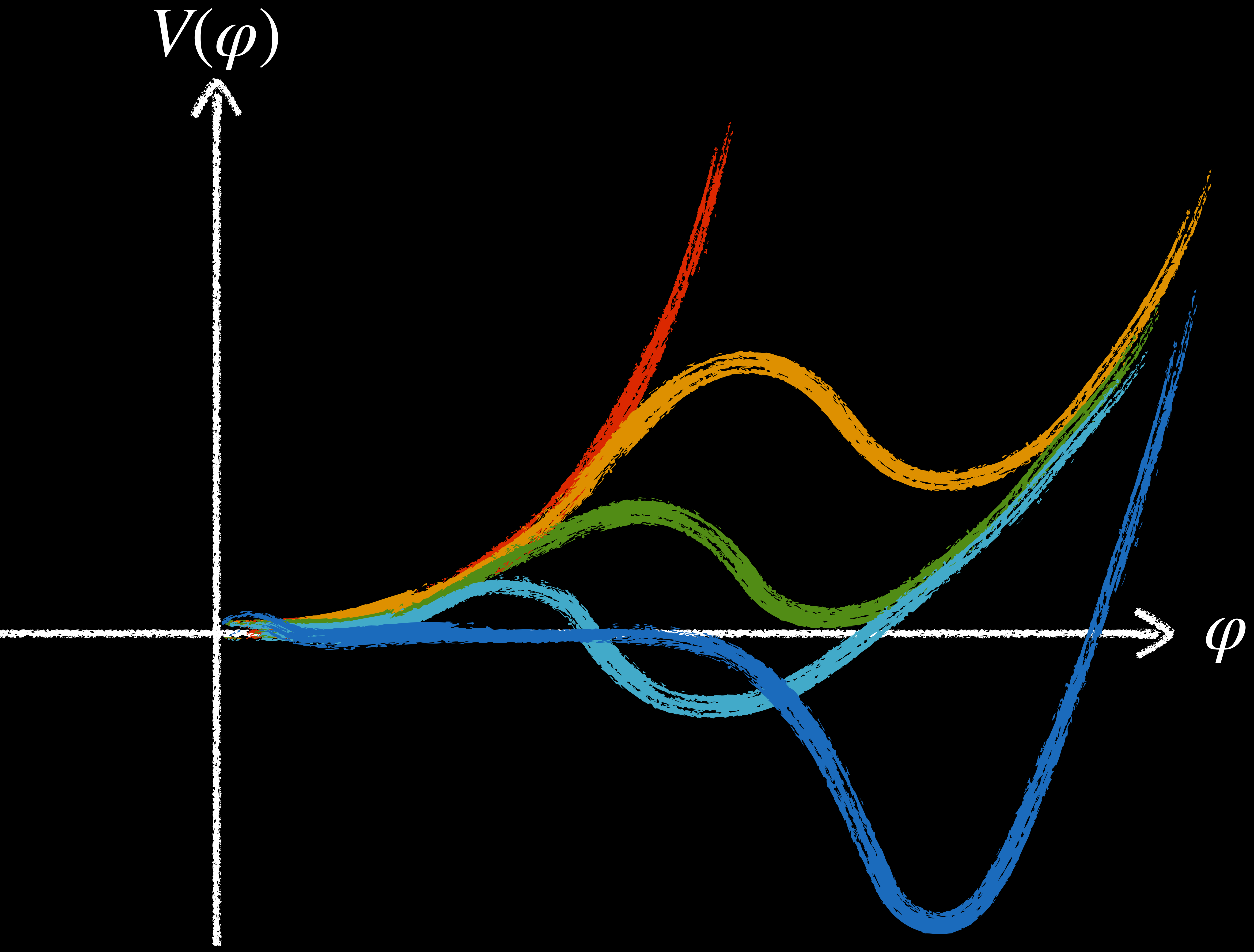
UNIVERSITY OF WARSAW

Based on work in collaboration with:
M. Kierkla, M. Kulejewski, M. Lewicki, T.V.I. Tenkanen, P. Schicho, D. Schmitt, J. van de Vis
JHEP 02 (2024) 234, JHEP 07 (2025) 153, 2607.18233 and 2609.XXXXX

SUPERCOOLED PHASE TRANSITIONS AND GRAVITATIONAL WAVES

SUPERCOOLED PHASE TRANSITION



natural with
classical scaling symmetry

generically strong,
observable GW signal

possible explanation
of the PTA signal?

Production of
primordial black holes (?)

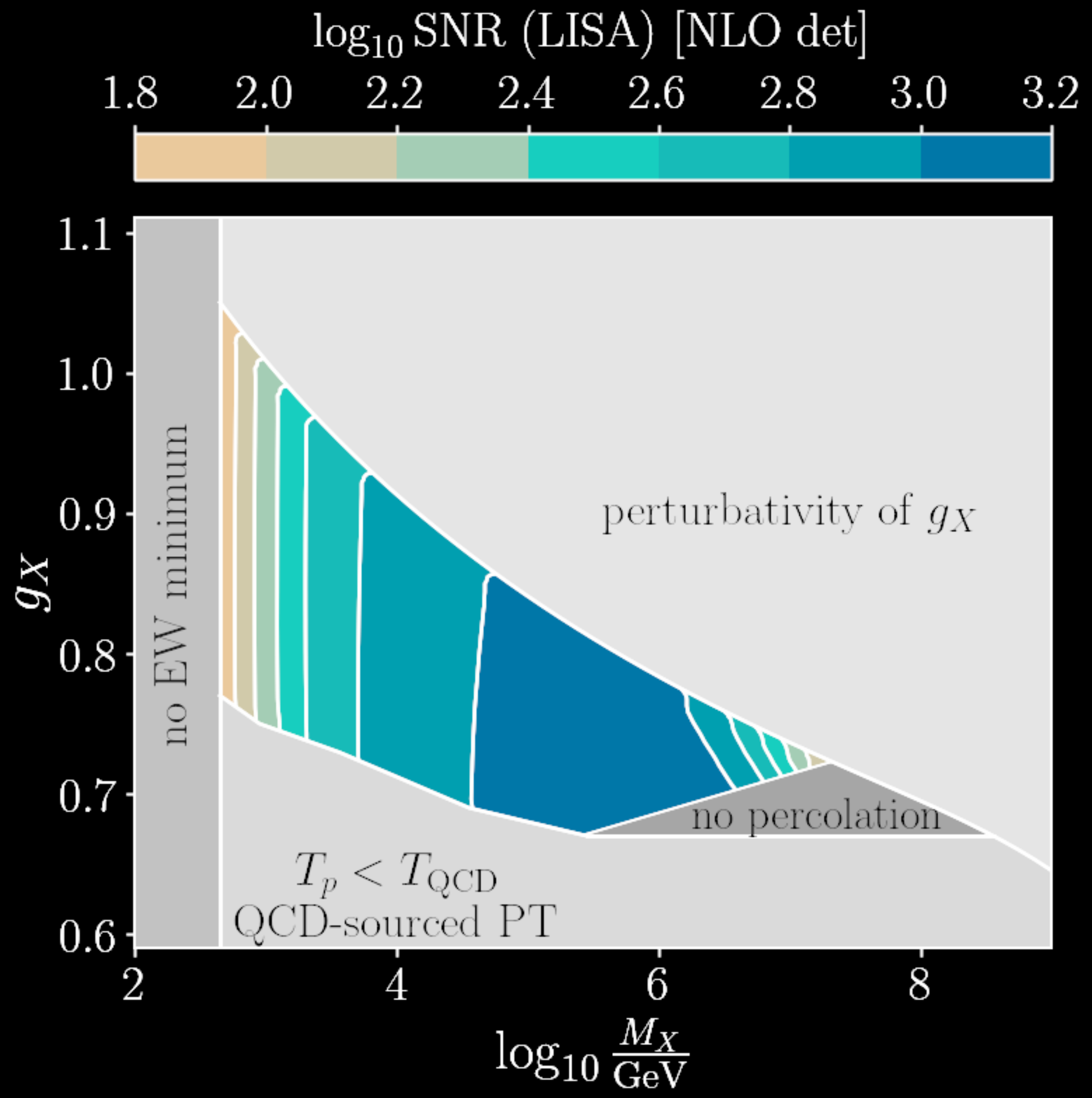
THE MODEL

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. Marfatia, P. Tseng, JHEP 02 (2021) 022]

STRONG GW SIGNAL



[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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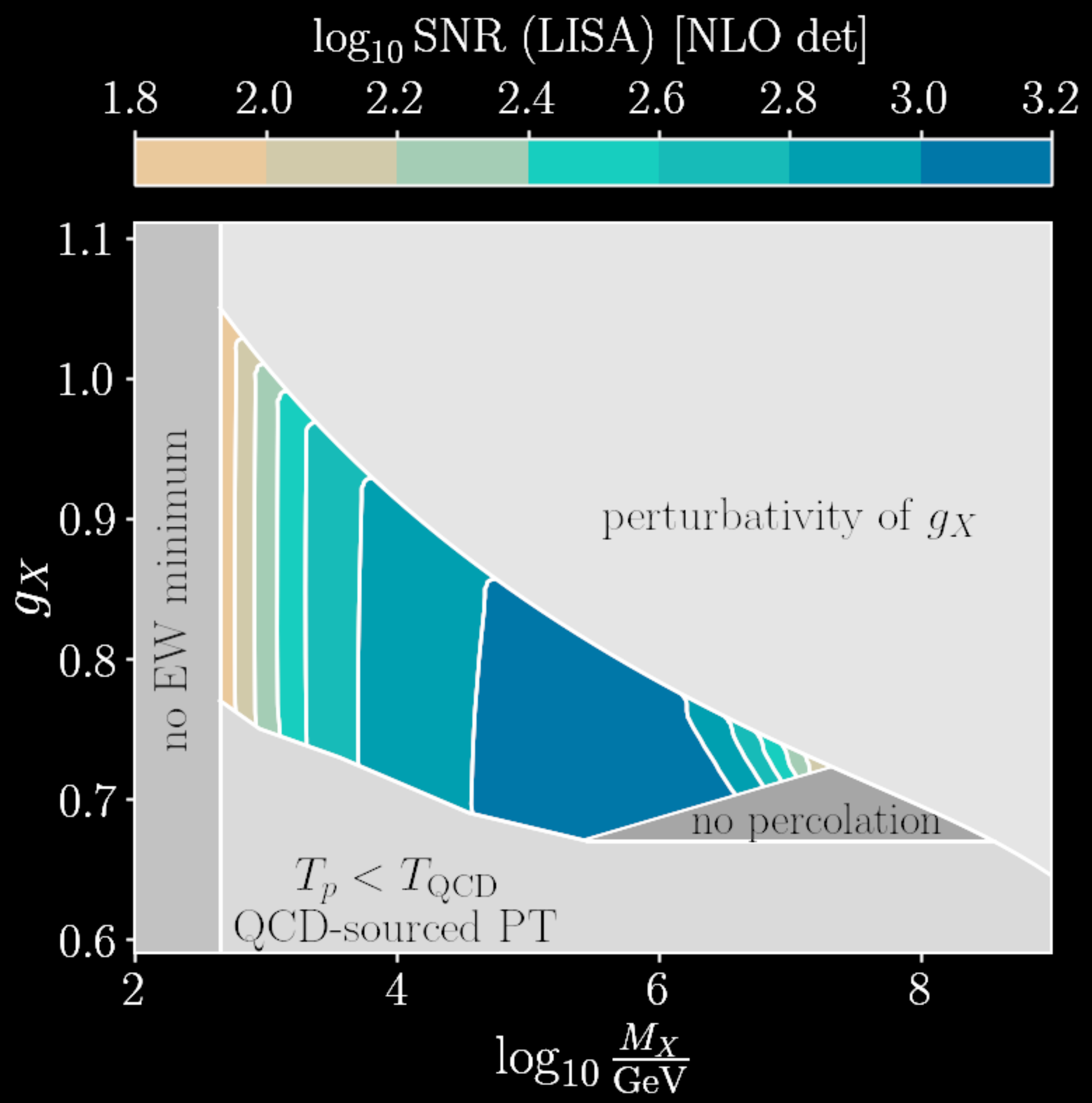

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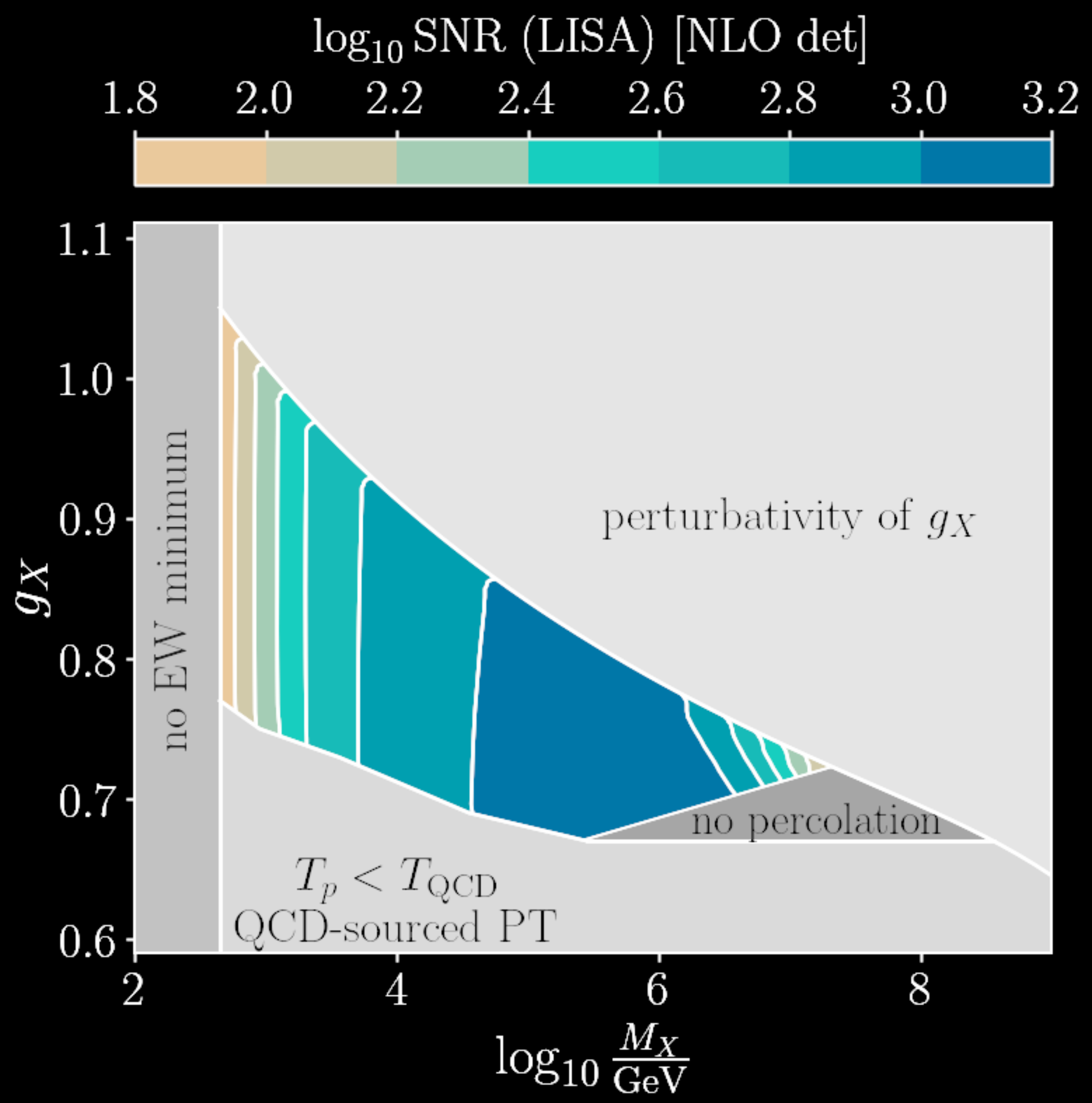
The typical scenario in SU(2)cSM is falsifiable through GW.

STRONG GW SIGNAL



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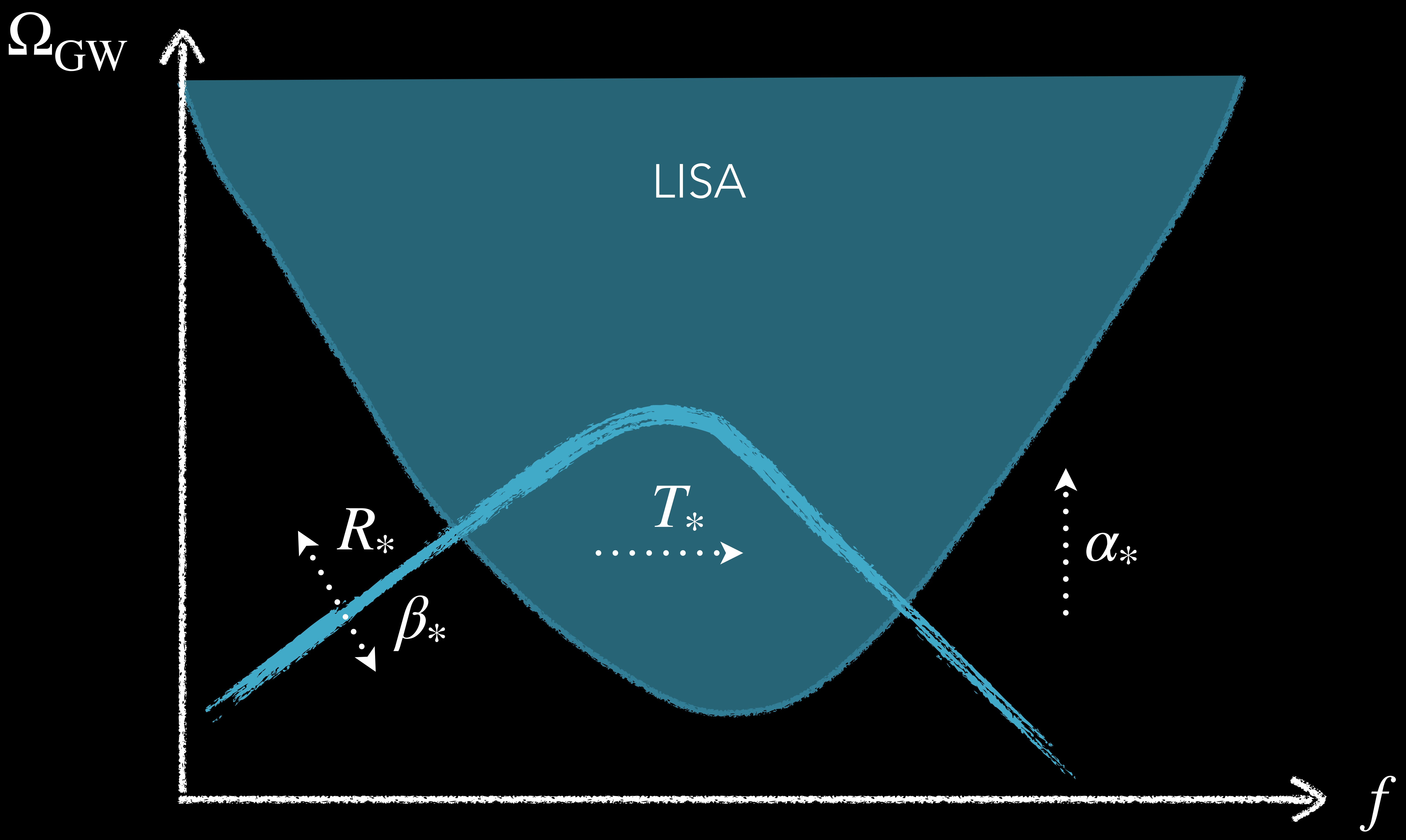
The typical scenario in SU(2)cSM is falsifiable through GW.

How robust are these predictions?
How well can we infer from the data?

THERMODYNAMICAL PARAMETERS VS GW



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

INCREASING THE PRECISION IN BUBBLE NUCLEATION

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)

BUBBLE NUCLEATION RATE - BASIC APPROACH

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

non-equilibrium effects

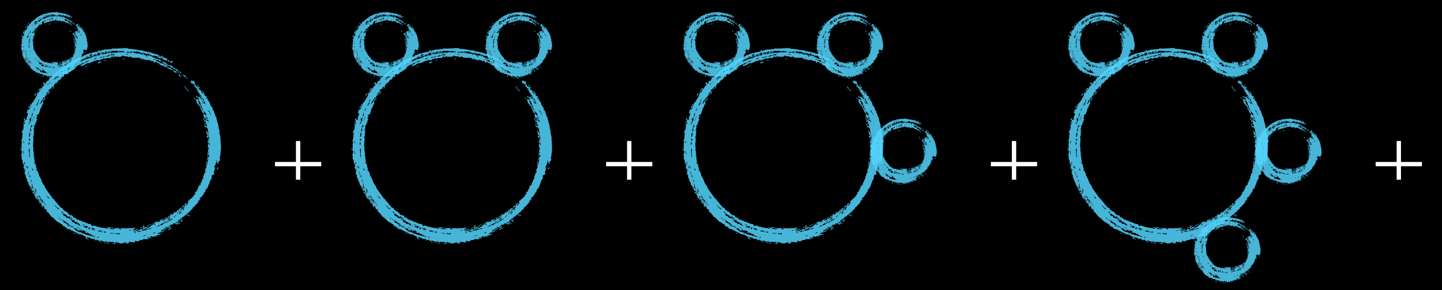
$\approx T$

quantum fluctuations

$\approx T^3$

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

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



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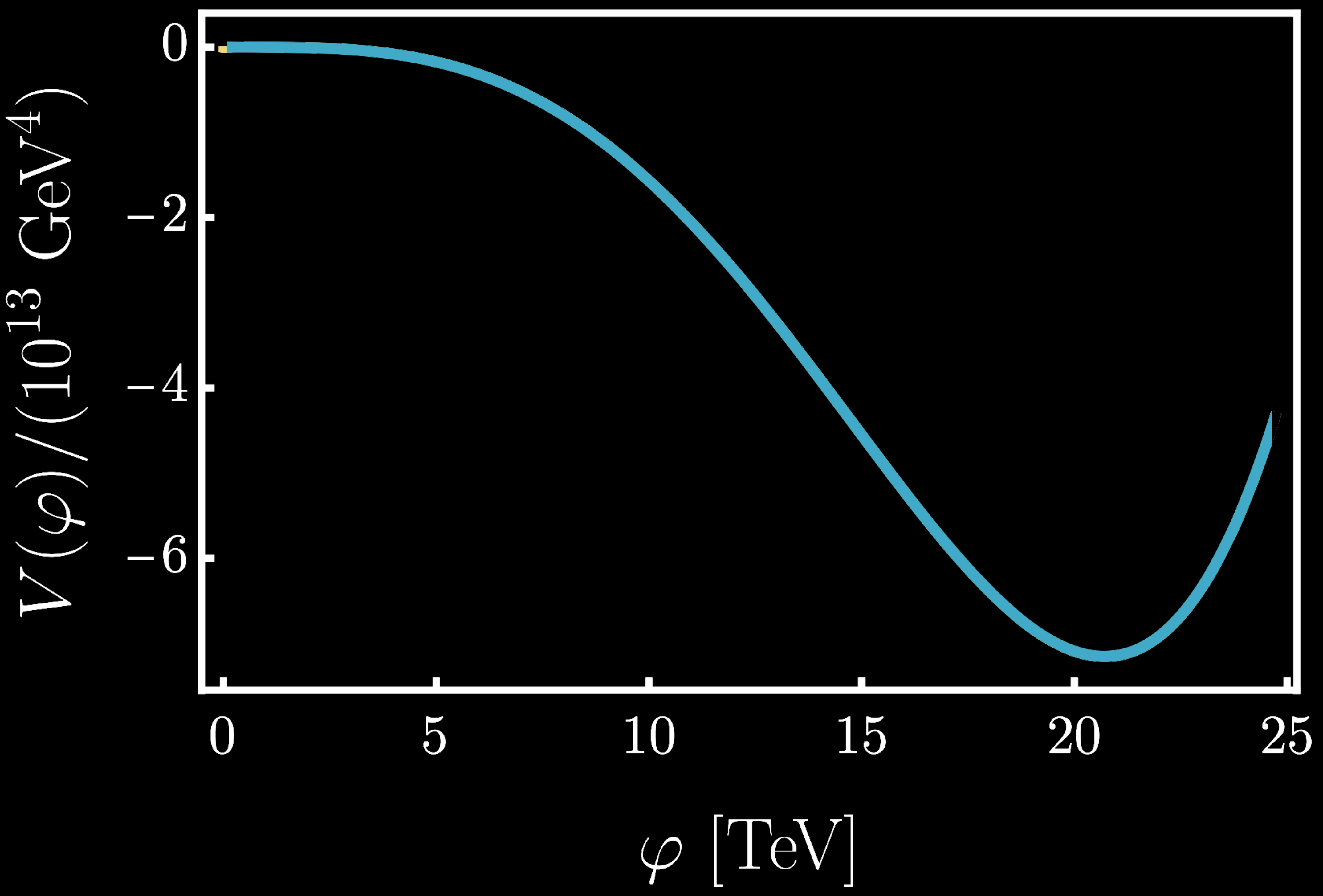
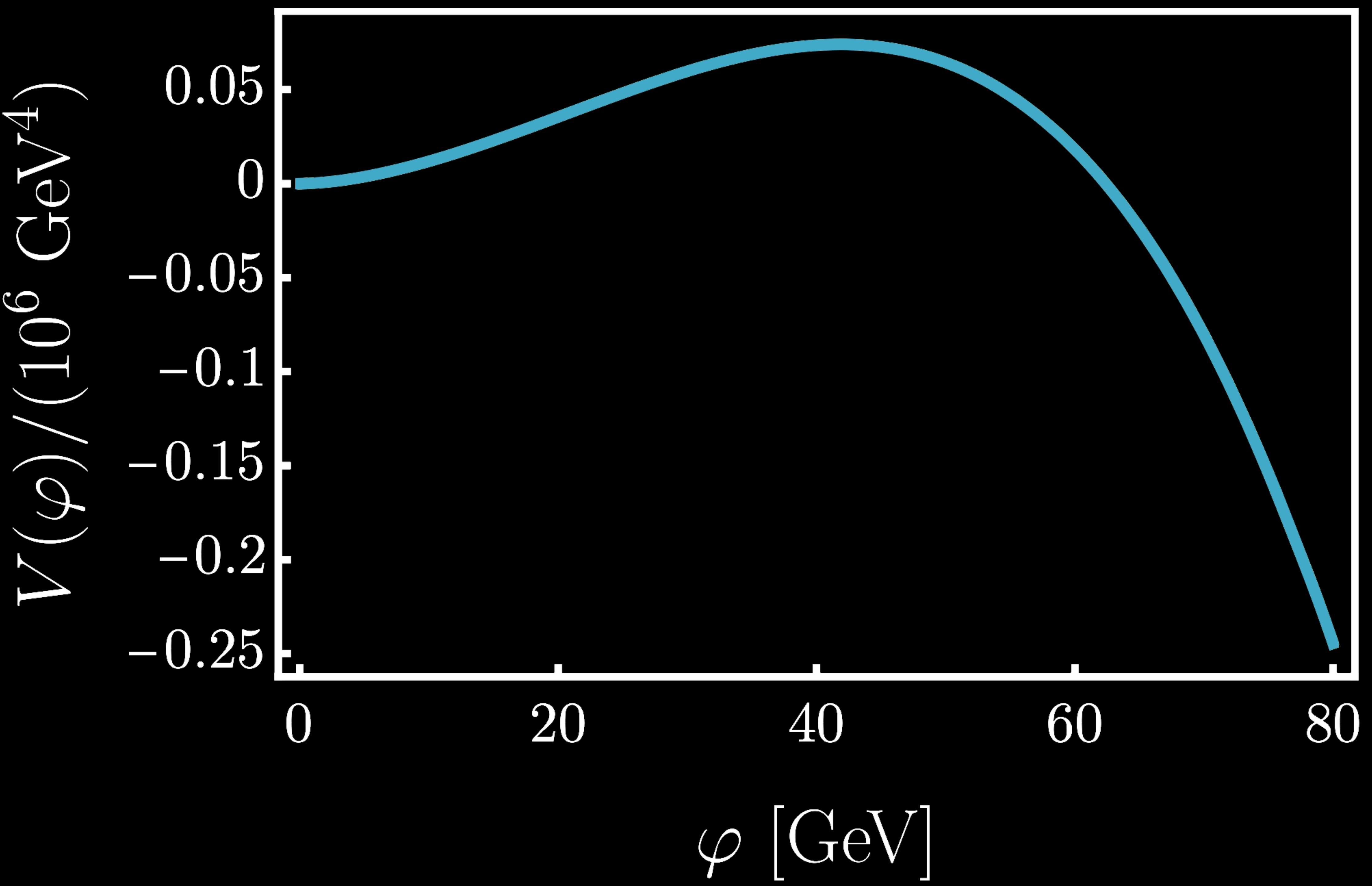
contributions from fluctutations of the fields that are not integrated out at the nucleation scale

the effective action at the nucleation scale

SUPERCOOLING VS HIGH-T EFT?





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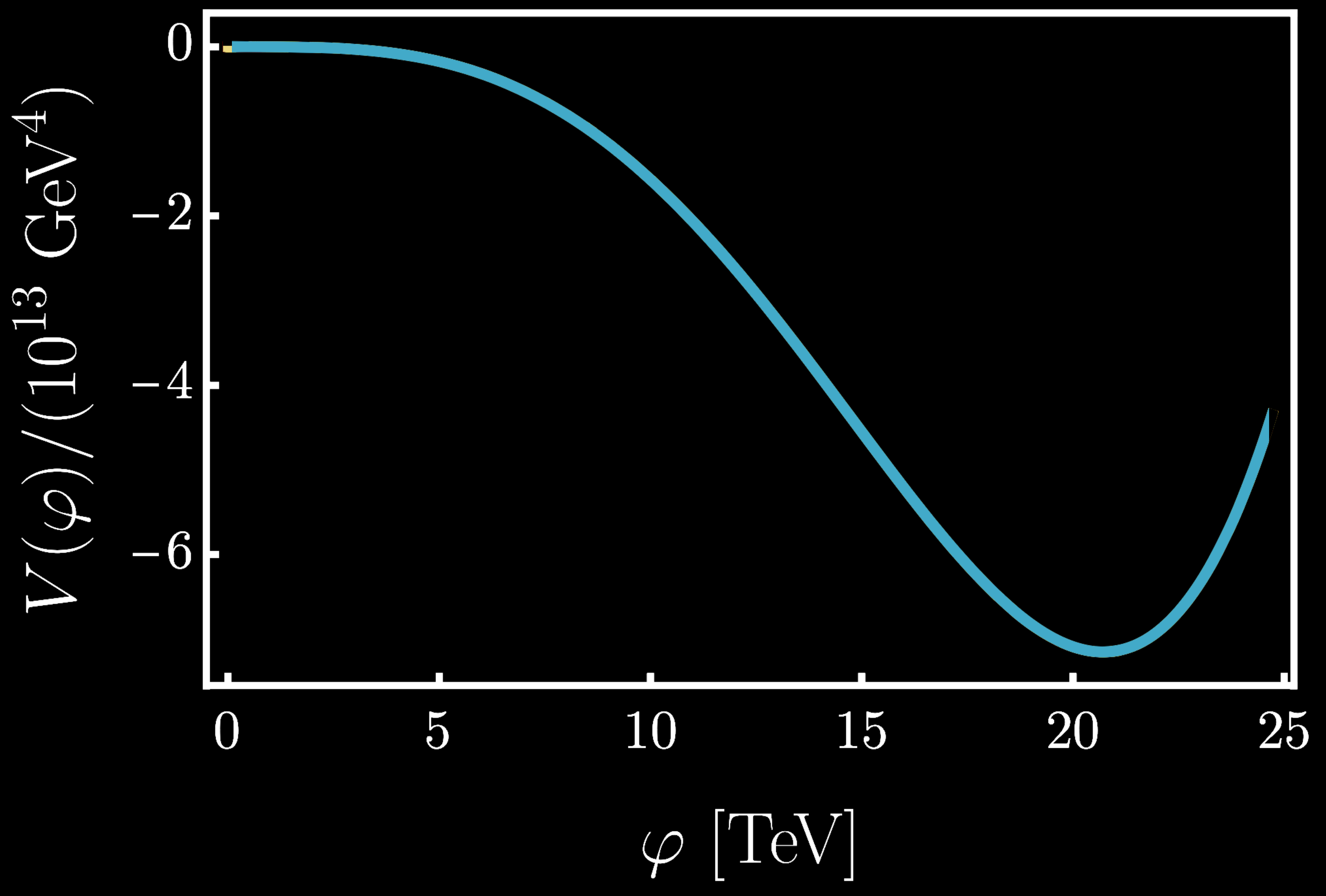
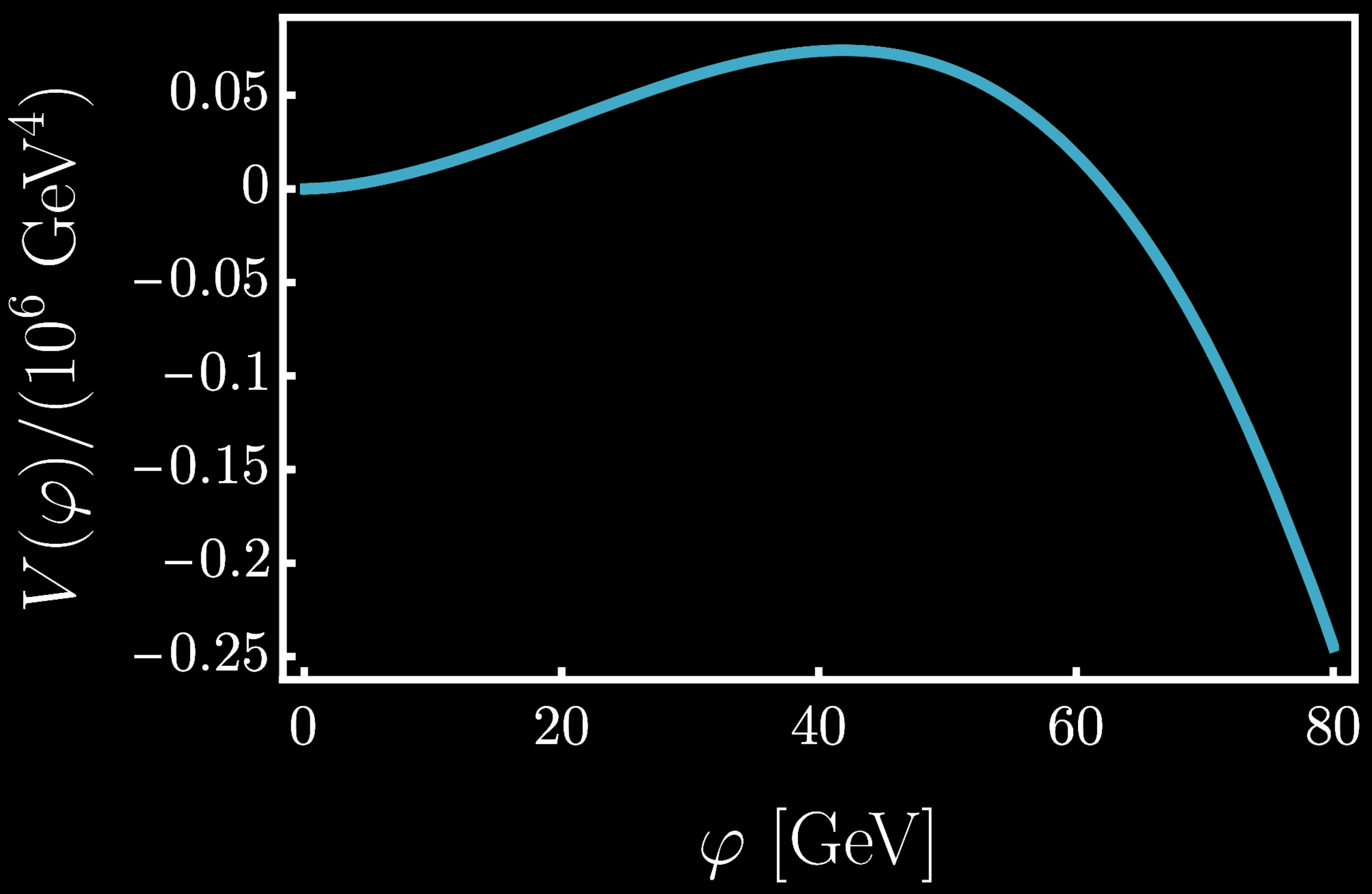
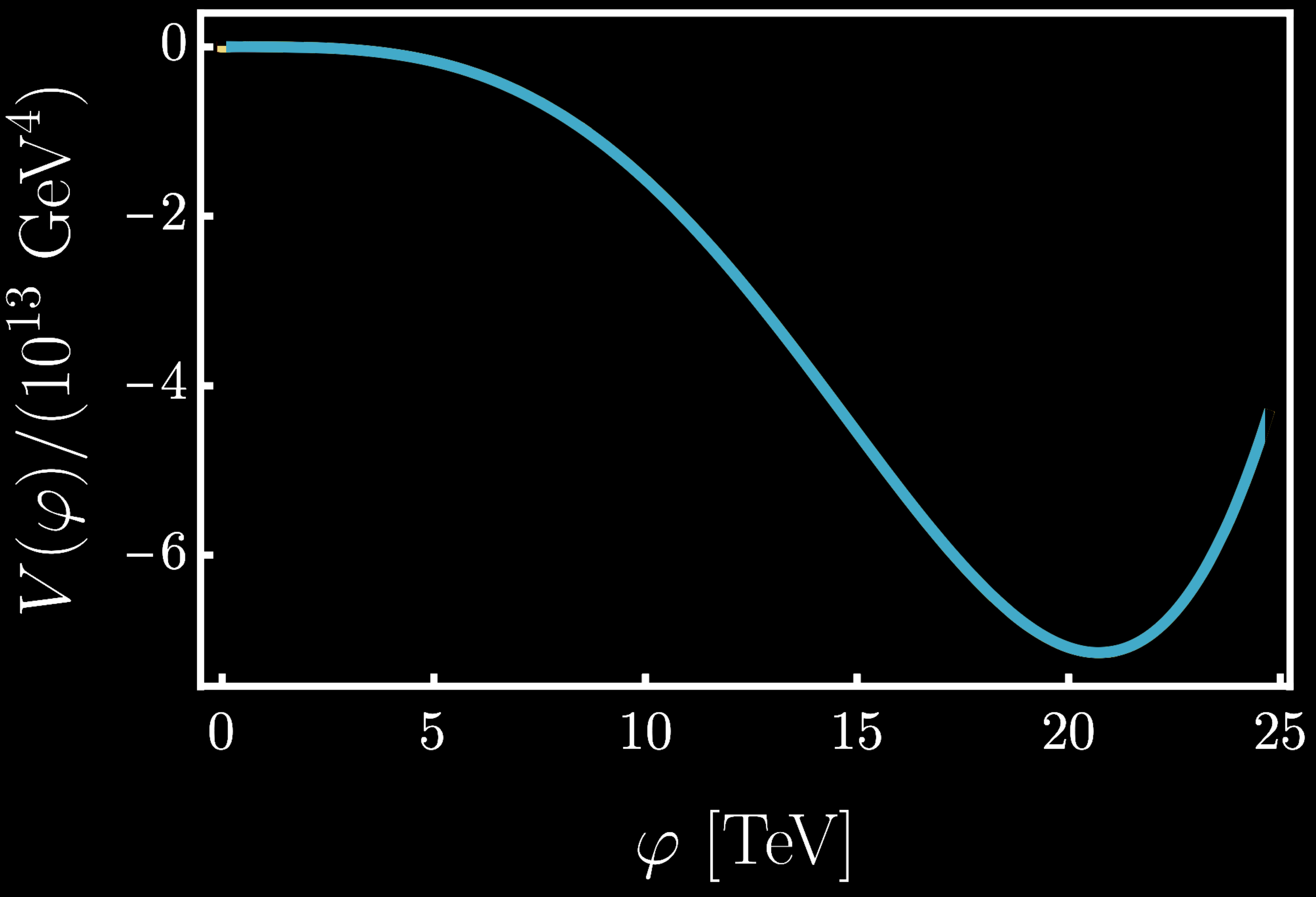


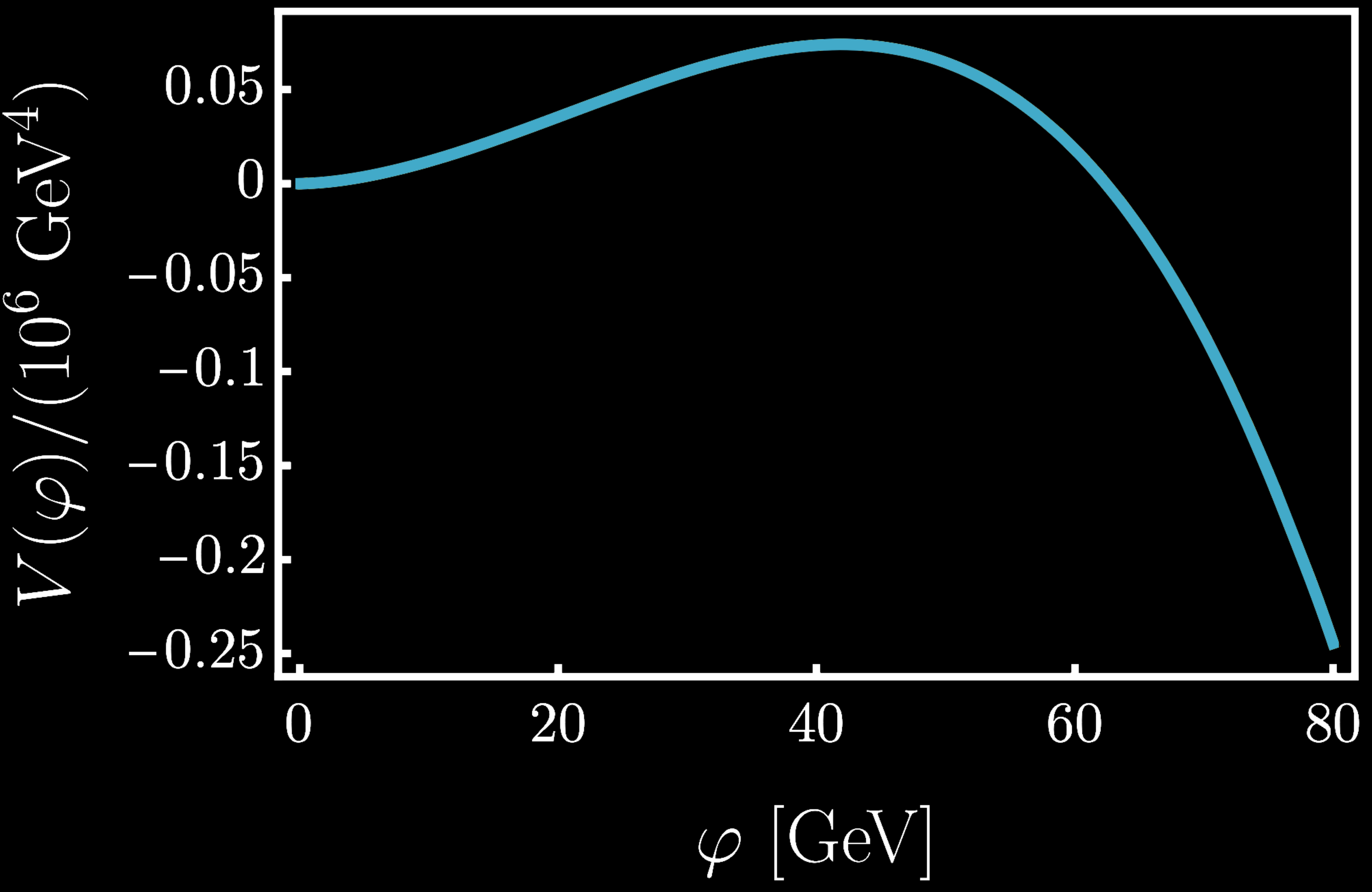


At large fields $M_X(\varphi)/T \gg 1$,
use LT approximation to compute $T_{\rm reh}$, ΔV

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

SUPERCOOLING ♥ HIGH-T EFT





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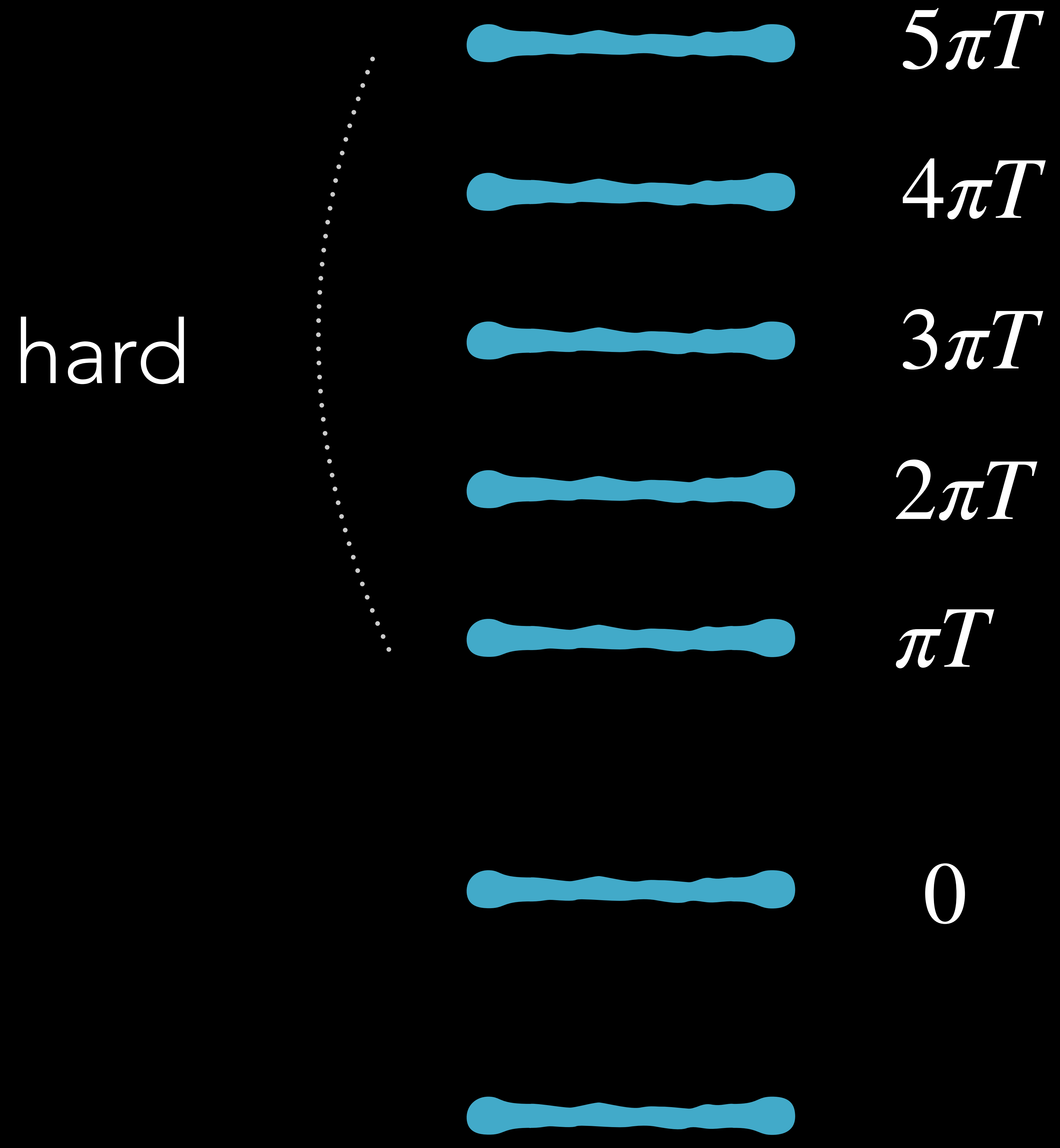
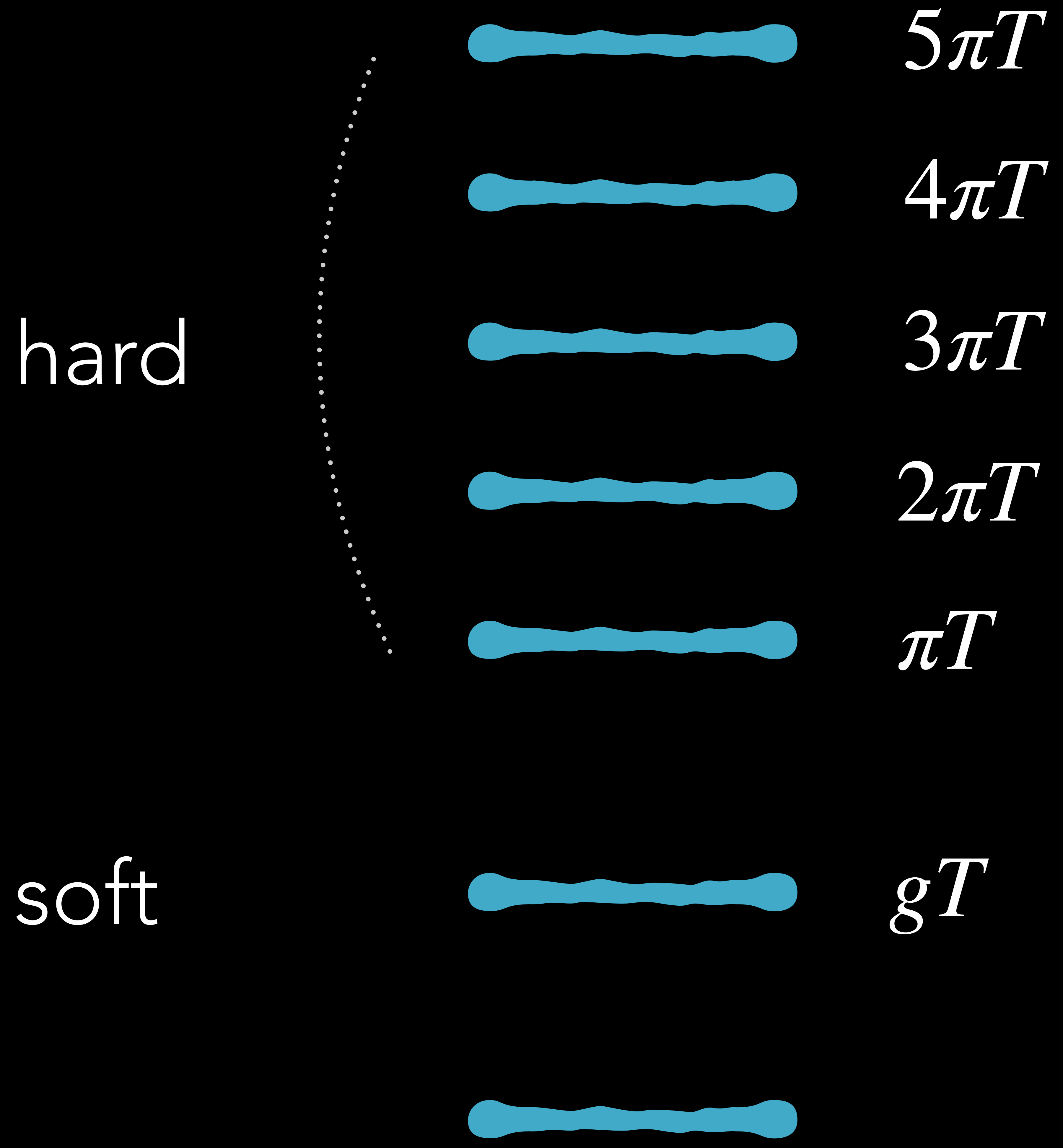
use HT approximation to compute T_p, $R_* H_*$

HT EFT CONSTRUCTION



HT EFT CONSTRUCTION



(gauge bosons, scalar)

HT EFT CONSTRUCTION

$5\pi T$

$4\pi T$

hard $3\pi T$

$2\pi T$

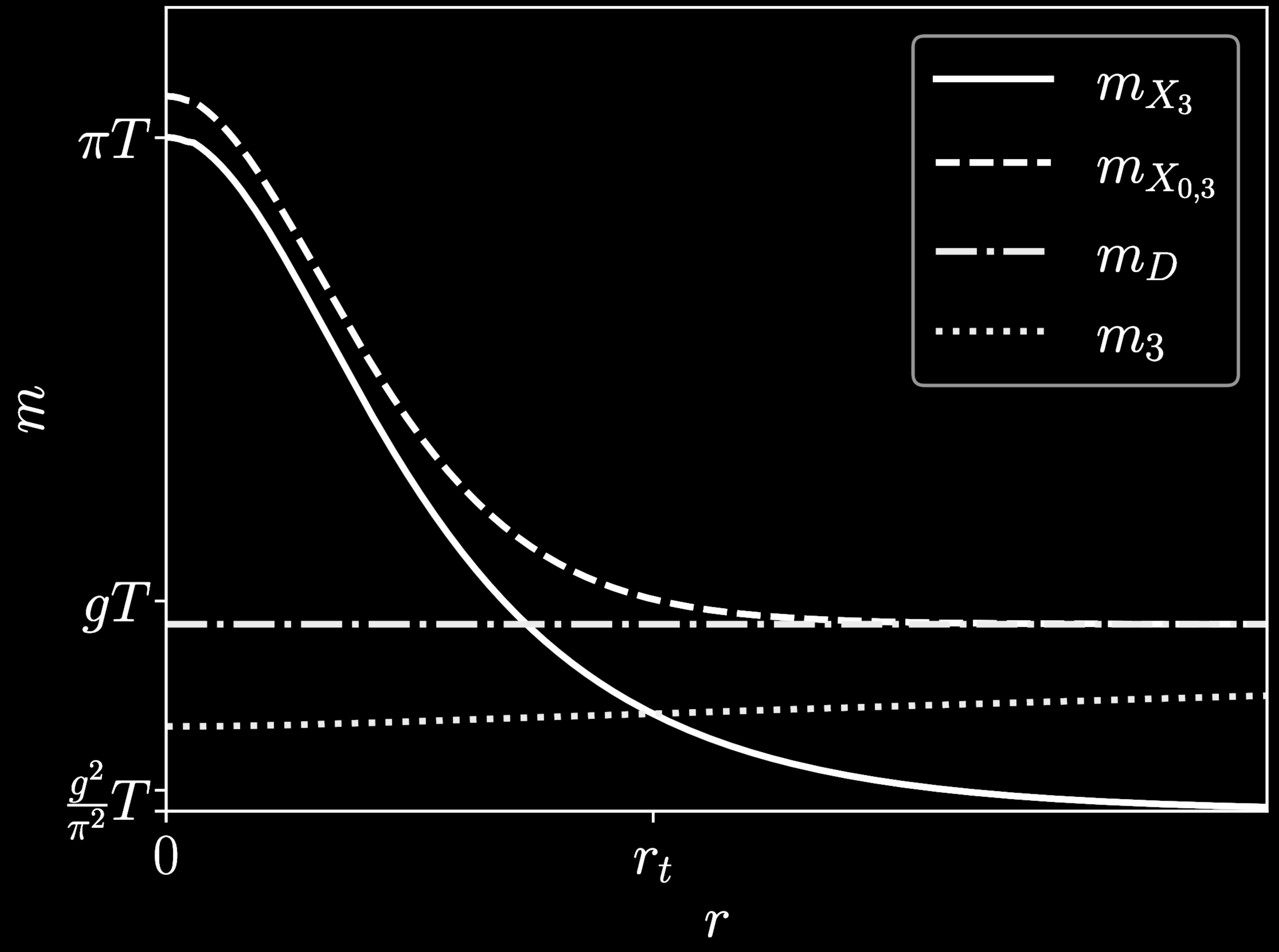
πT

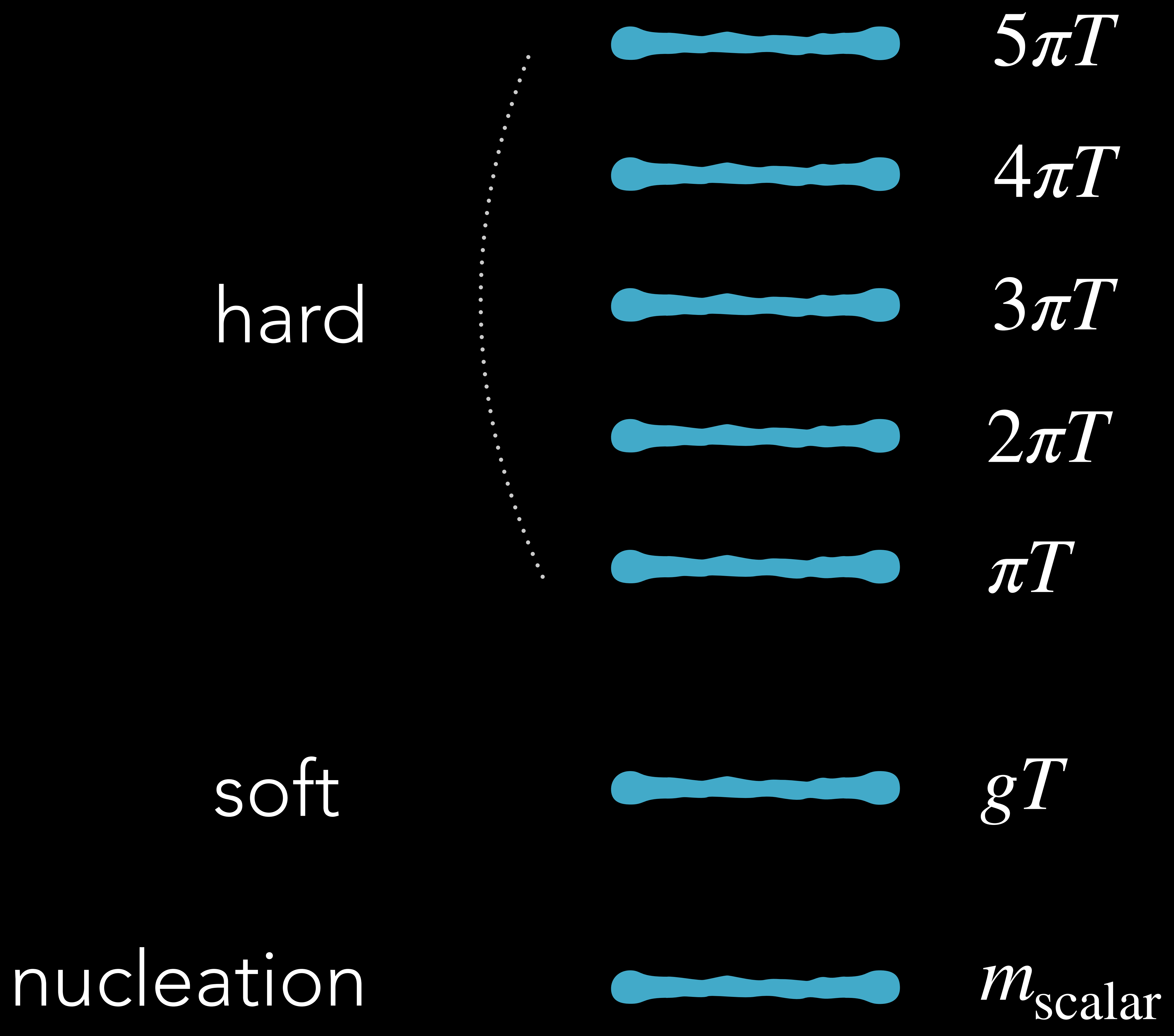
(gauge bosons, scalar) soft gT

(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]

NUCLEATION RATE BEYOND LEADING ORDER

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

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

Remove the contribution from the scale shifting fields

Inclusion of fluctuations from the scale-shifting fields

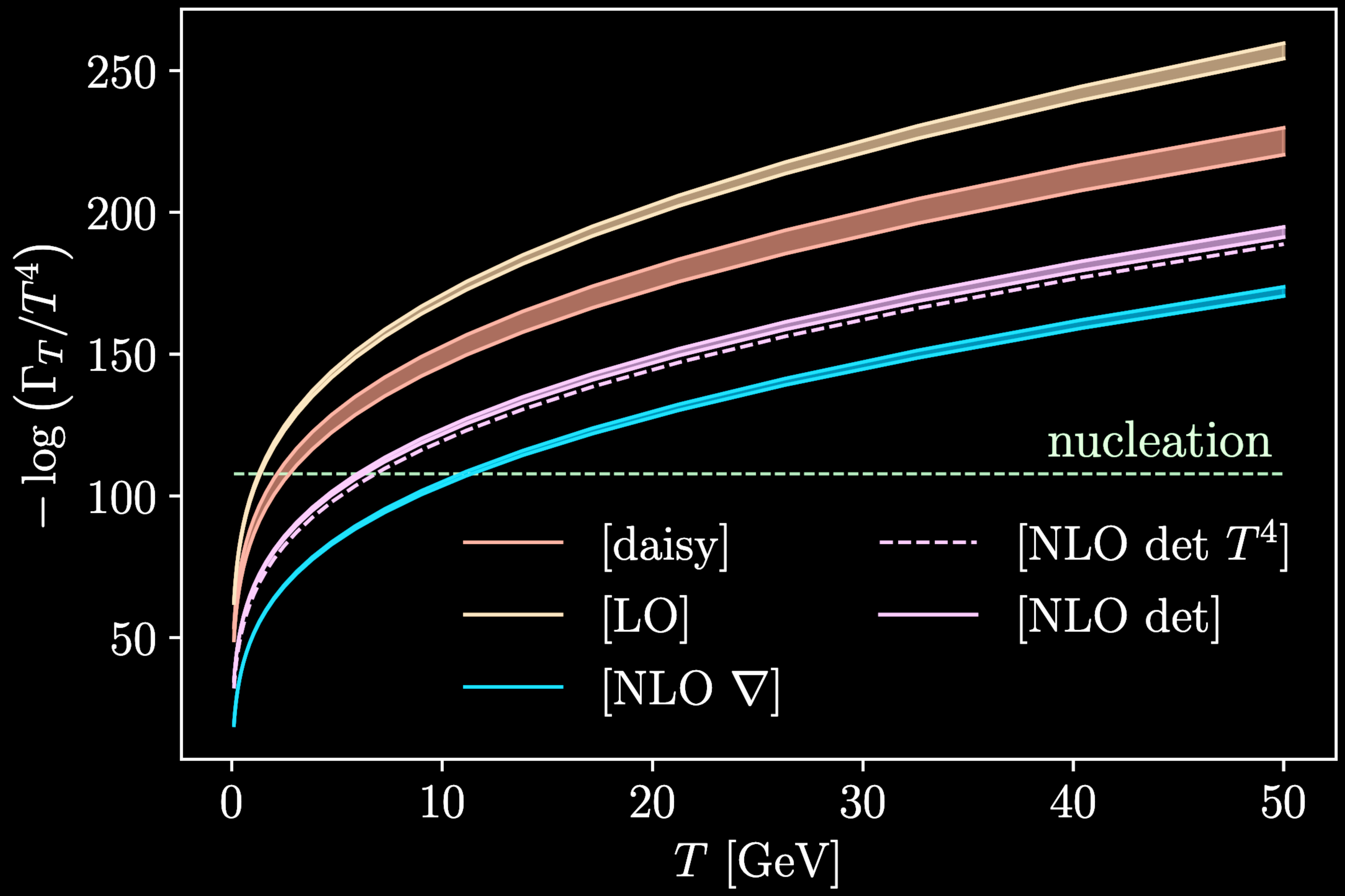
Test of validity of the momentum expansion

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

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



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

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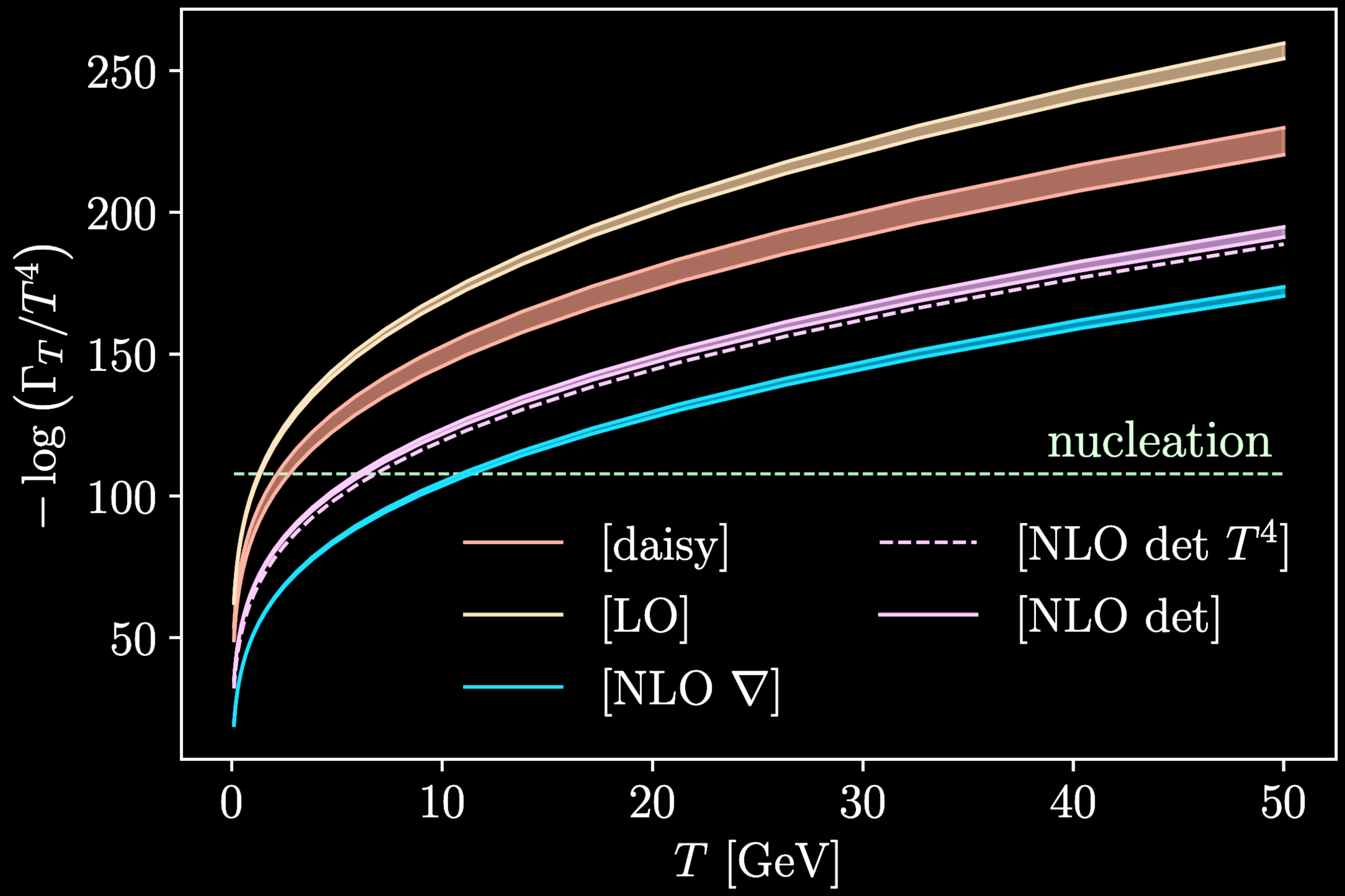
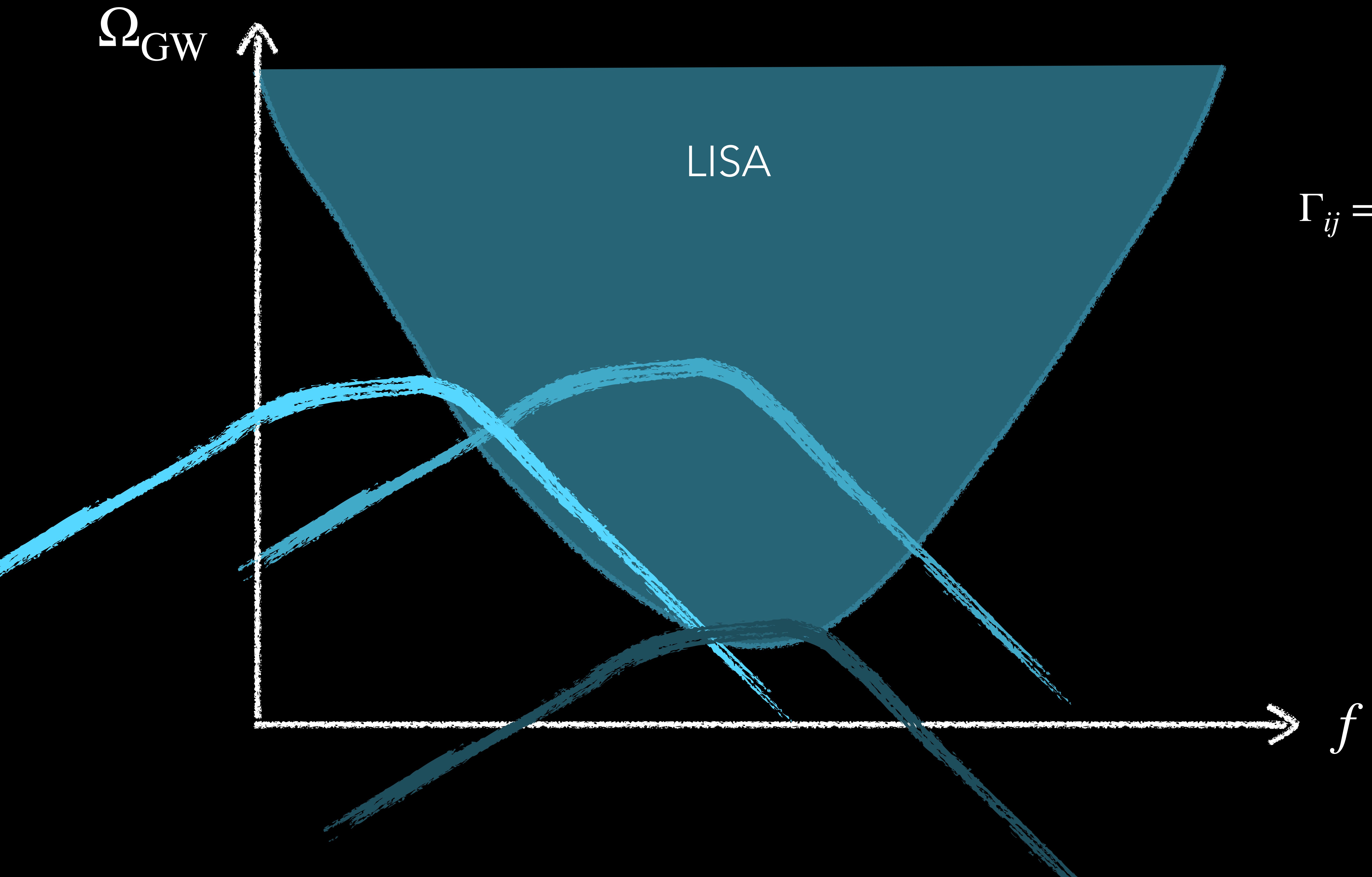


- Up to 300% difference in percolation temperature
- 30% difference in the bubble radius

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

THE INVERSE PROBLEM AND THE FISHER MATRIX

EXTRACTING INFRMATION FROM GW SPECTRUM



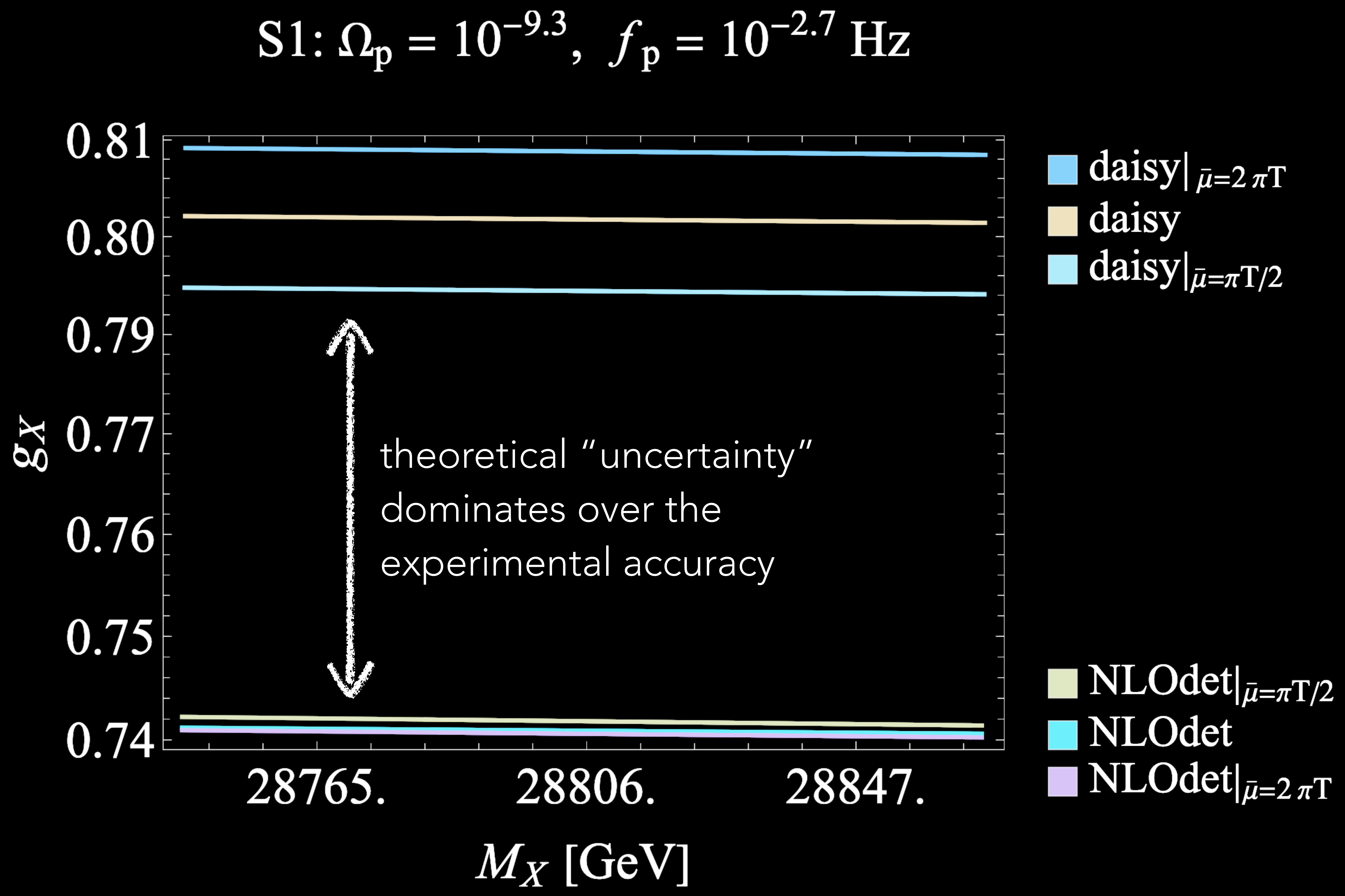
$$\Gamma_{ij} = T \int \frac{\mathrm{df}}{\Omega_{\rm tot}(f)^2} \frac{\partial \Omega_{\rm GW}}{\partial \theta_i} \frac{\partial \Omega_{\rm GW}}{\partial \theta_j}$$

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

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

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

RECONSTRUCTION OF U(1) MODEL PARAMETERS



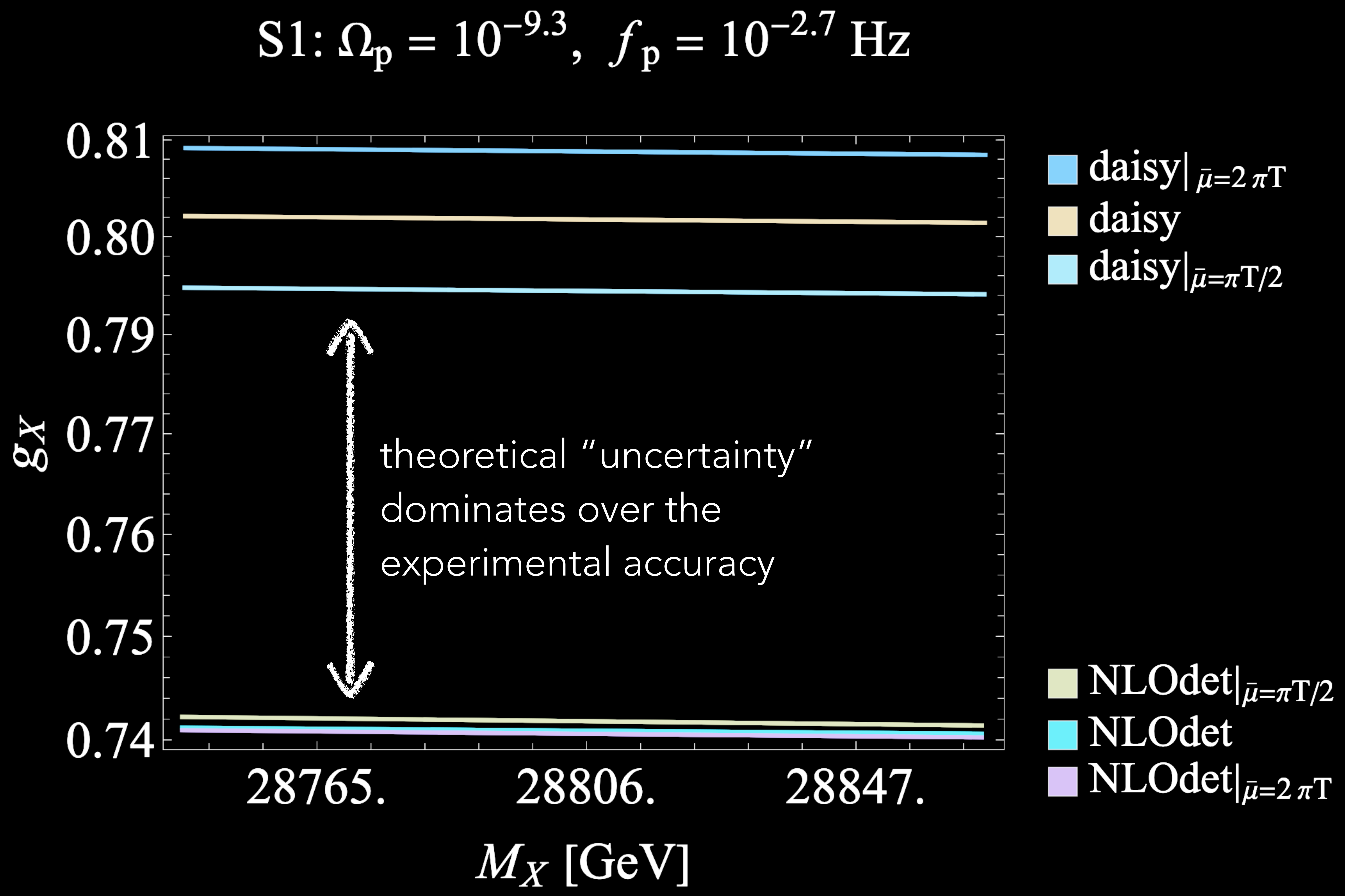
[M. Kierkla, M. Lewicki, P. Schicho, D. Schmitt, B. Świeżewska, 2607.18233]

RECONSTRUCTION OF U(1) MODEL PARAMETERS

difference between
4d daisy and 3d NLOdet

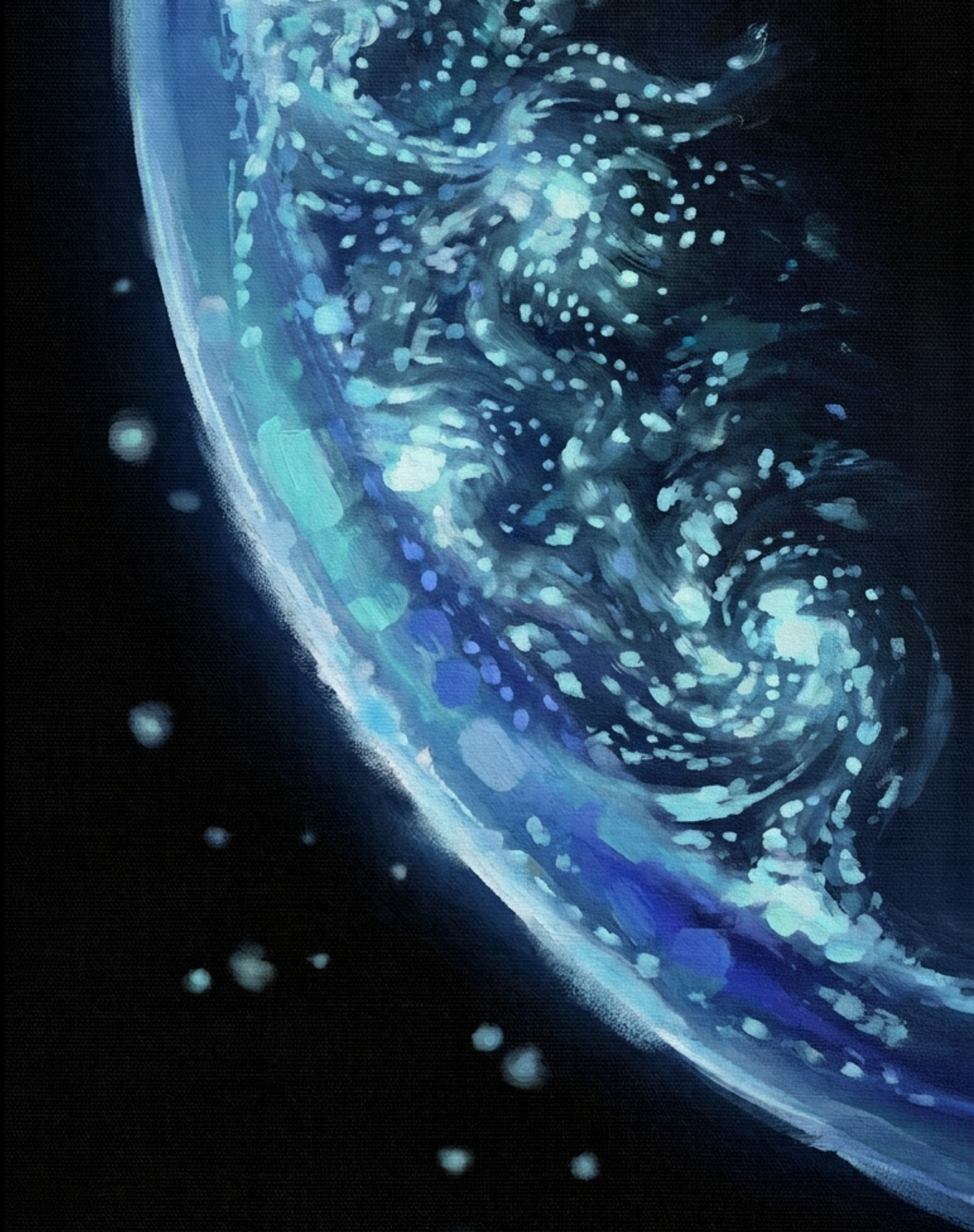
scale dependence
in the 3d daisy approach

experimental error ~
residual scale dependence
in 3d NLOdet approach

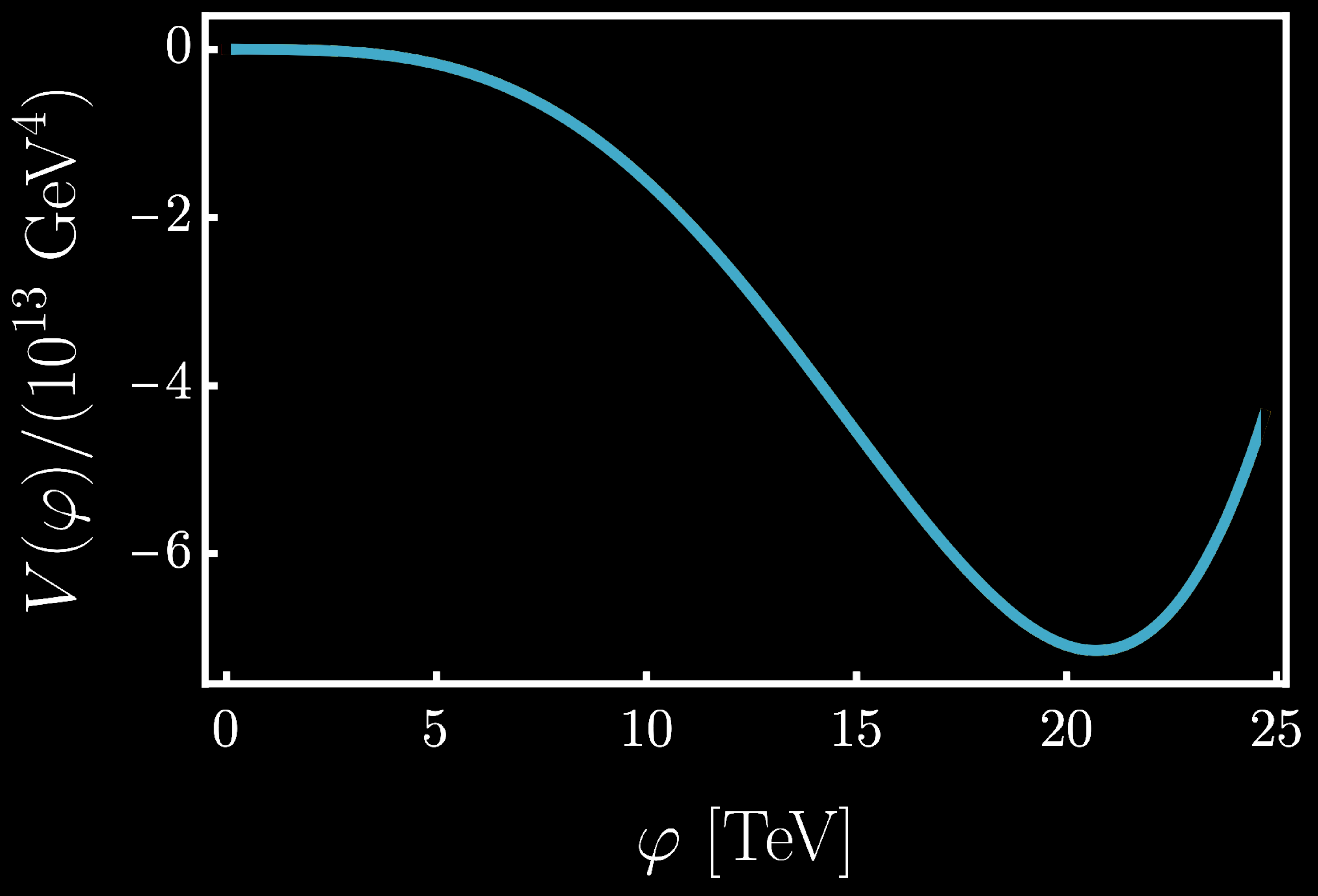


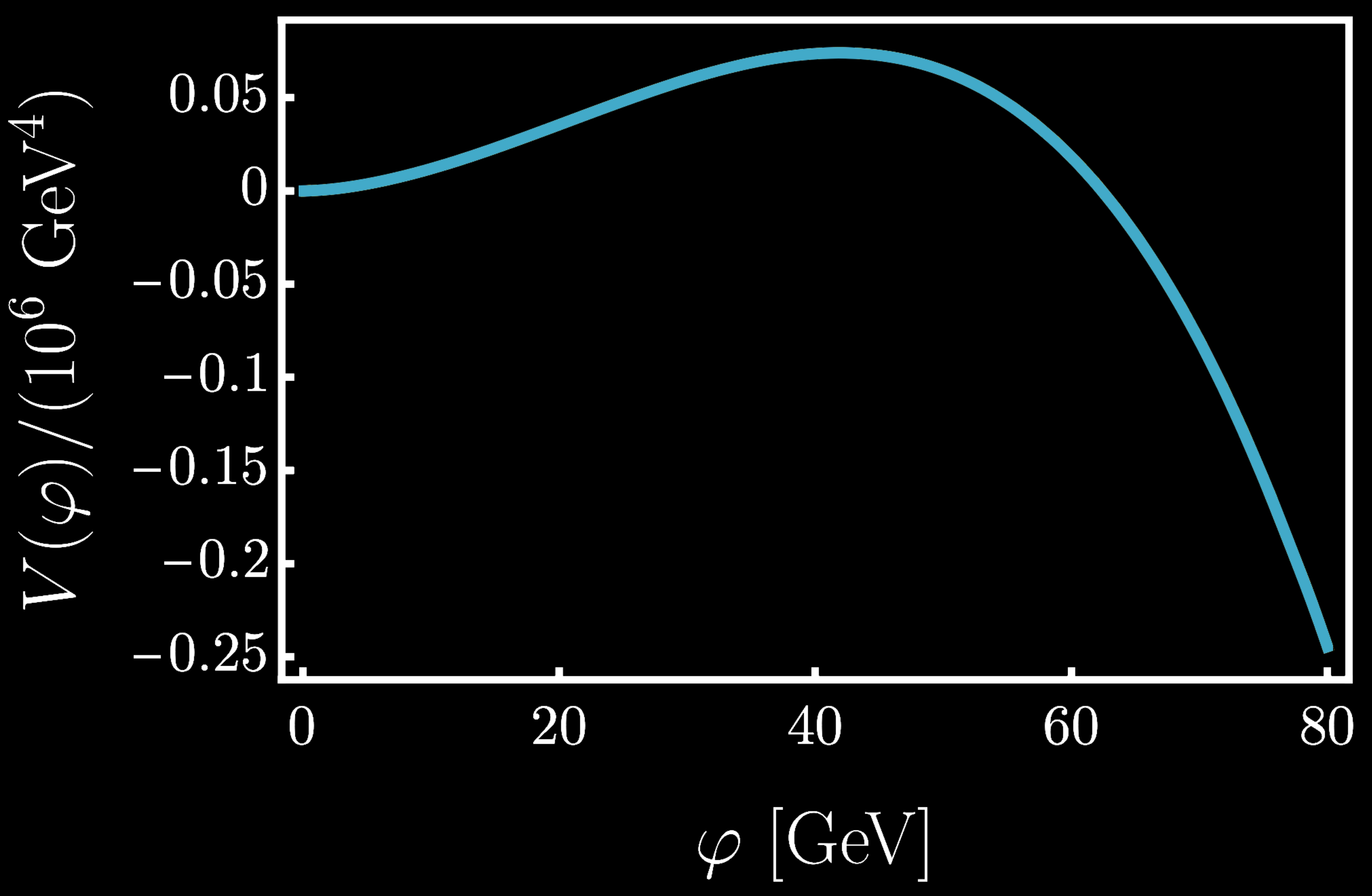
[M. Kierkla, M. Lewicki, P. Schicho, D. Schmitt, B. Świeżewska, 2607.18233]

TACHYONIC
PARTICLE
PRODUCTION

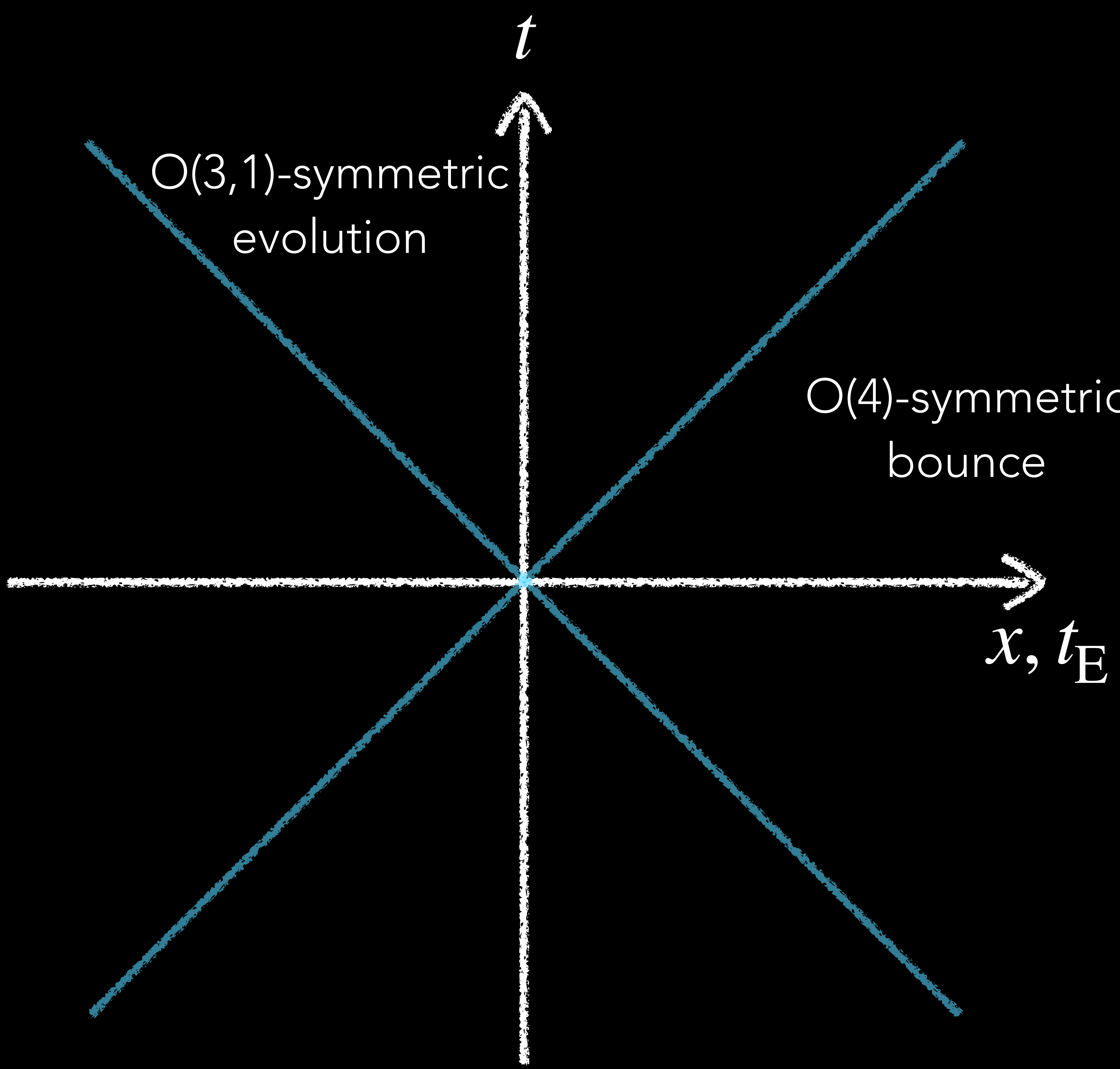


THICK BUBBLES AND SUBSEQUENT EVOLUTION





THE METHOD



Nucleation (Euclidean)

$$\ddot{\varphi}(\xi) + \frac{3}{\xi}\dot{\varphi}(\xi) - V'(\varphi(\xi)) = 0$$

Evolution (Milne)

$$\ddot{\varphi}(s) + \frac{3}{s}\dot{\varphi}(s) + V'(\varphi(s)) = 0$$

[K. Yamamoto, T. Tanaka, and M. Sasaki, PRD 51 (1995) 2968, T. Hamazaki, M. Sasaki, T. Tanaka, and K. Yamamoto, PRD 53 (1996) 2045, N. Herring, S. Cao, and D. Boyanovsky, PRD 109 (2024), 105021]

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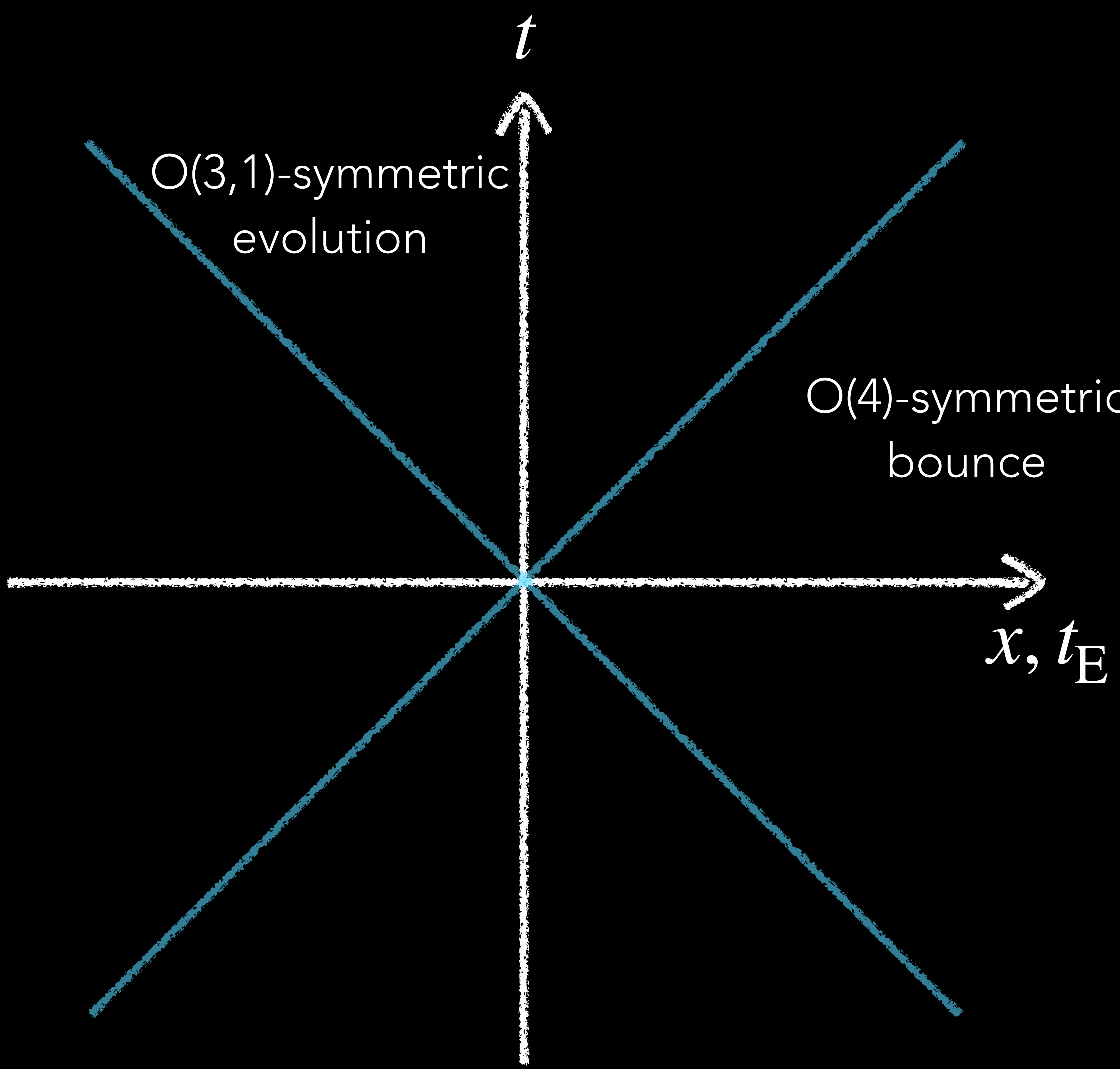

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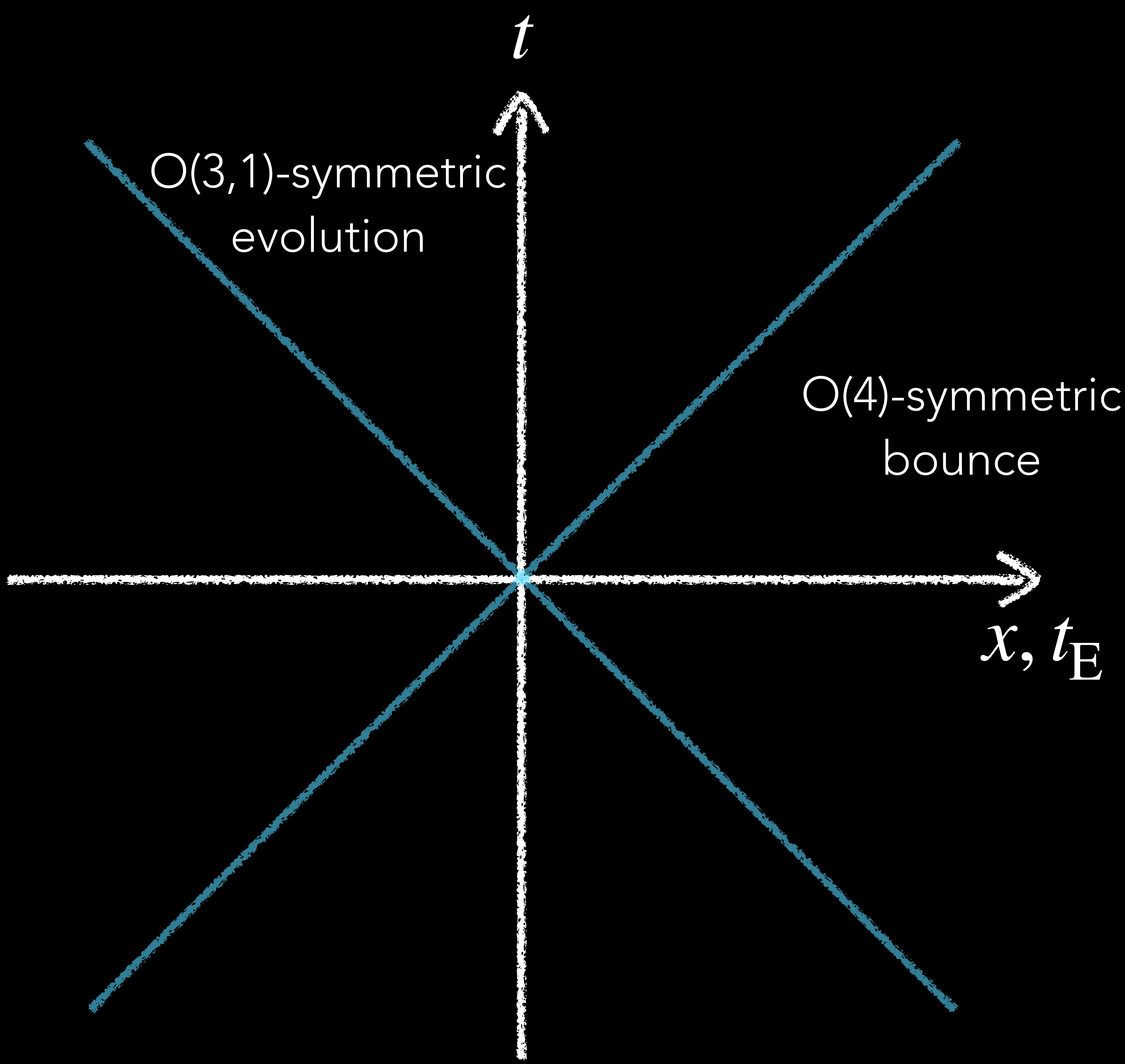

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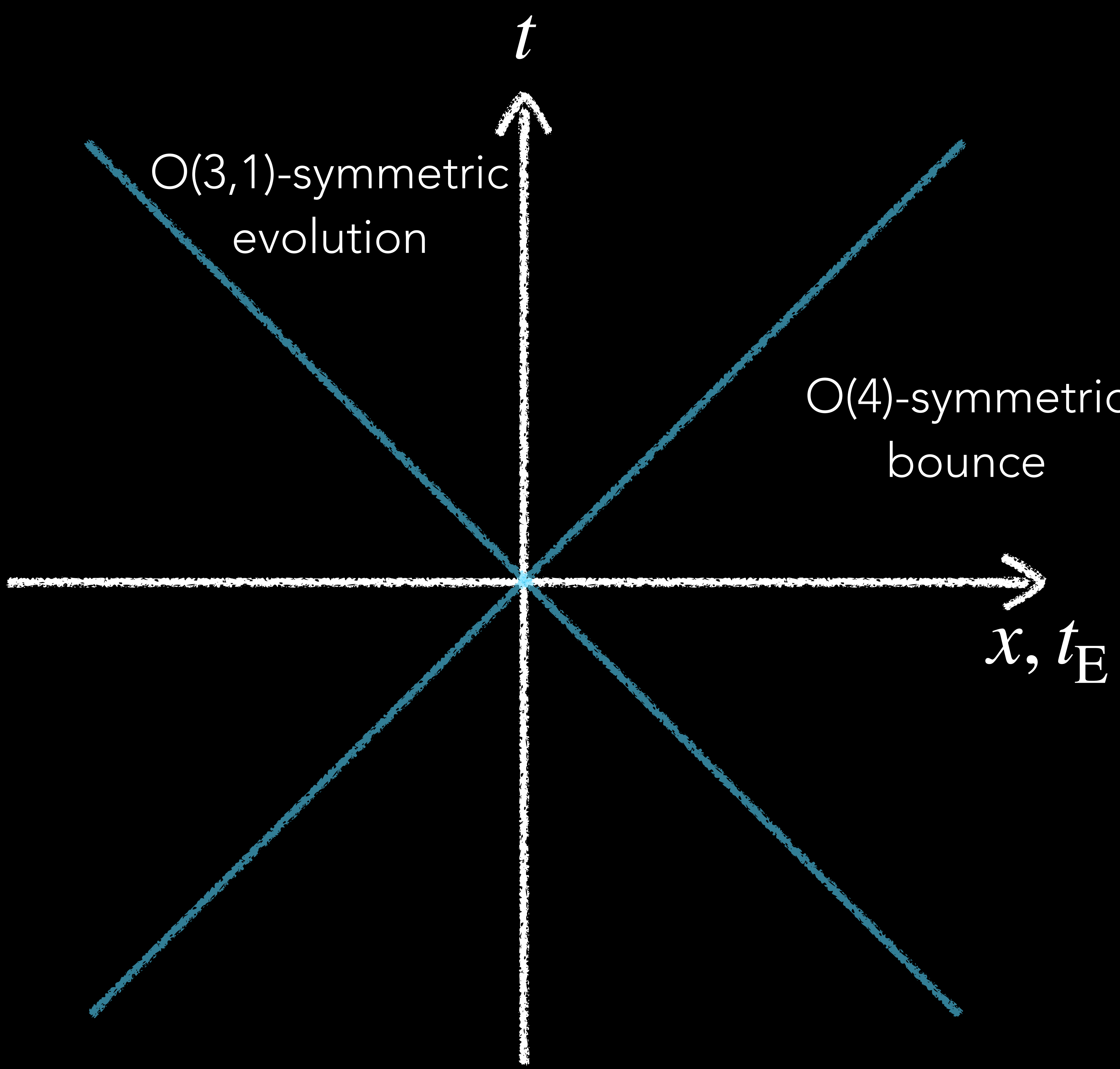

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Evolution (Milne)

$$\ddot{\varphi} + \frac{3}{s}\dot{\varphi} + V'(\varphi) + \frac{1}{2}V'''(\varphi)\langle\delta\hat{\varphi}^{2'}\rangle = 0$$

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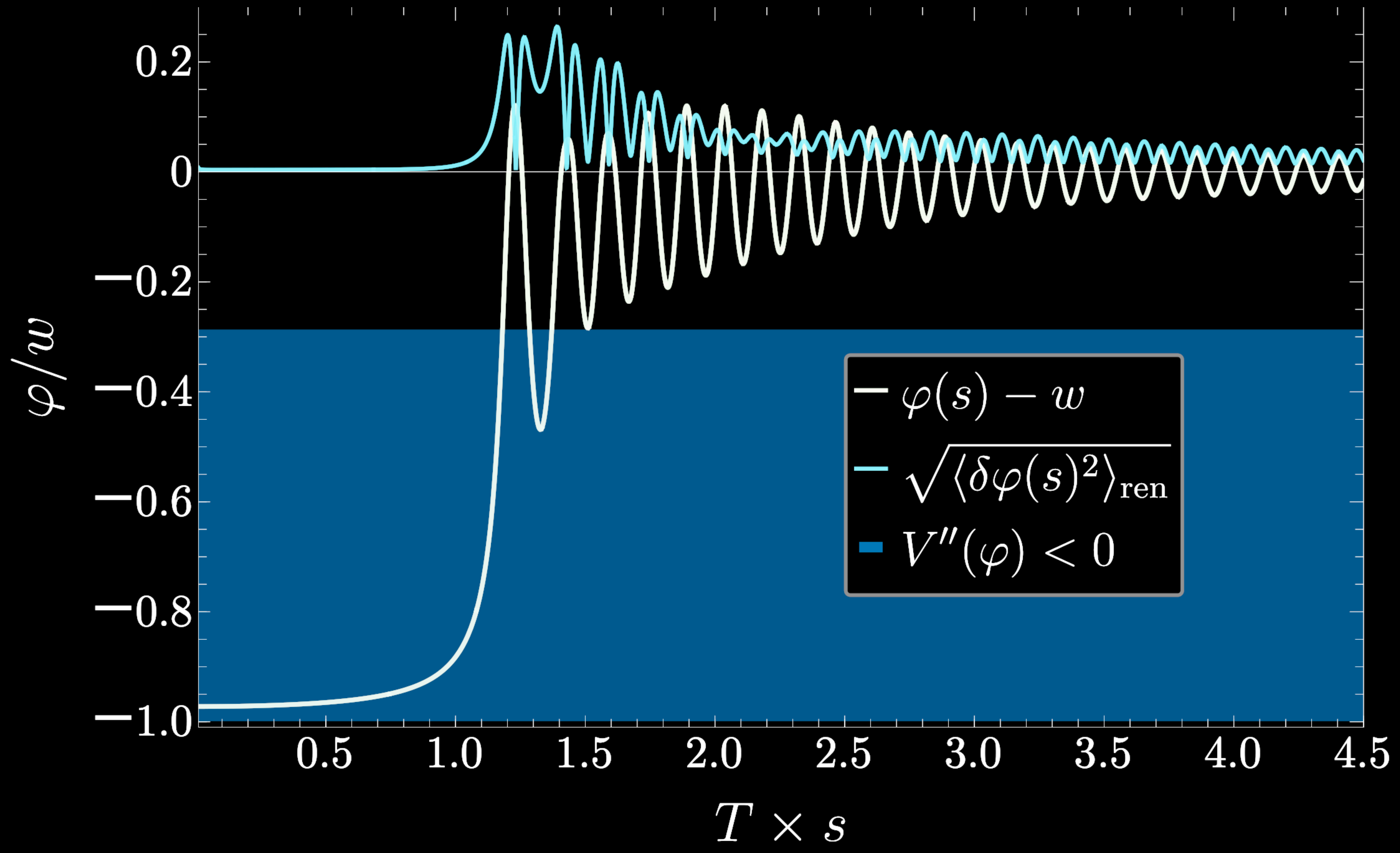
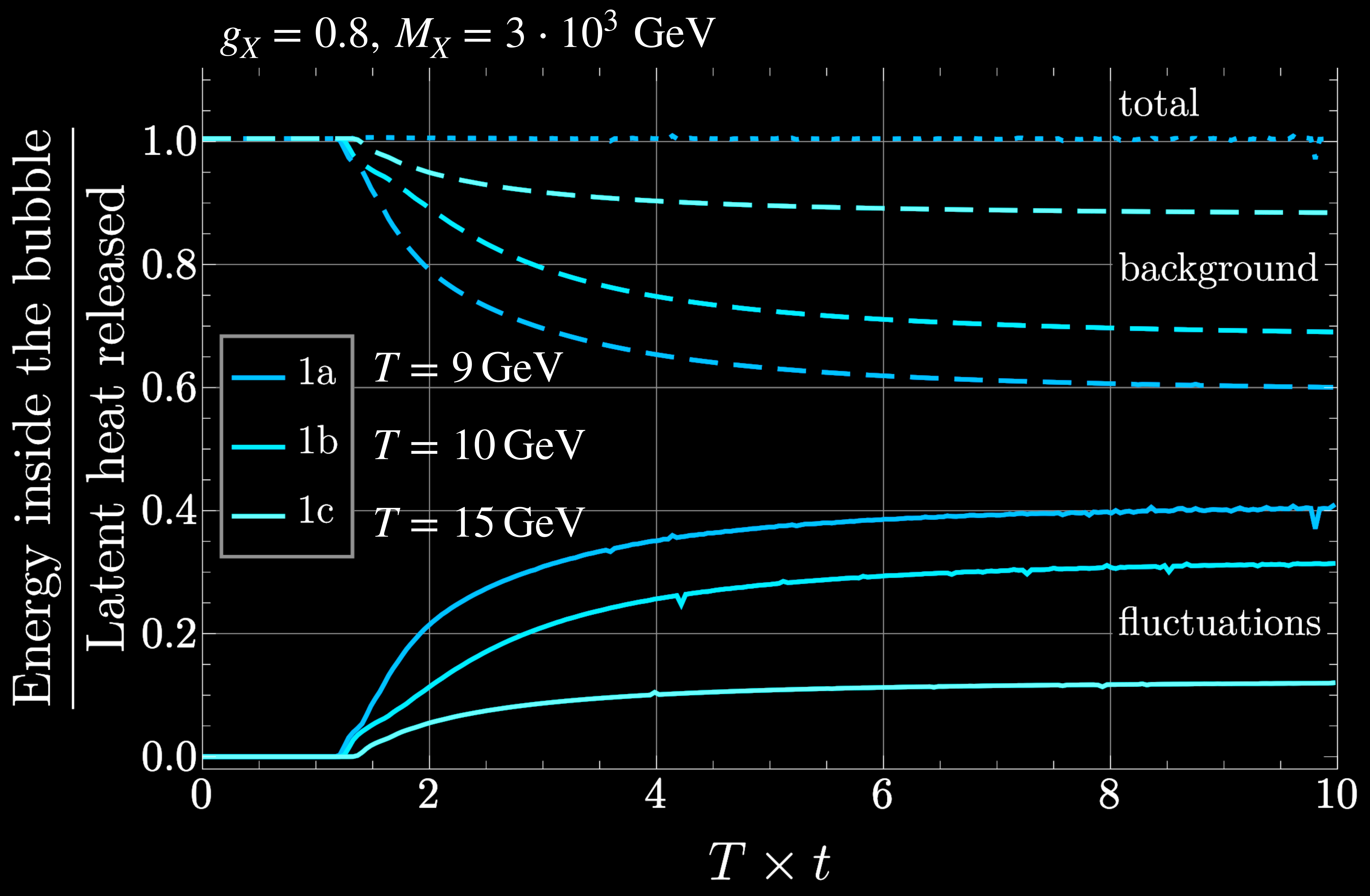
EVOLUTION



$s = \sqrt{t^2 - r^2}$

[M. Kulejewski, BŚ, Jorinde van de Vis, work in progress]

ENERGY BUDGET



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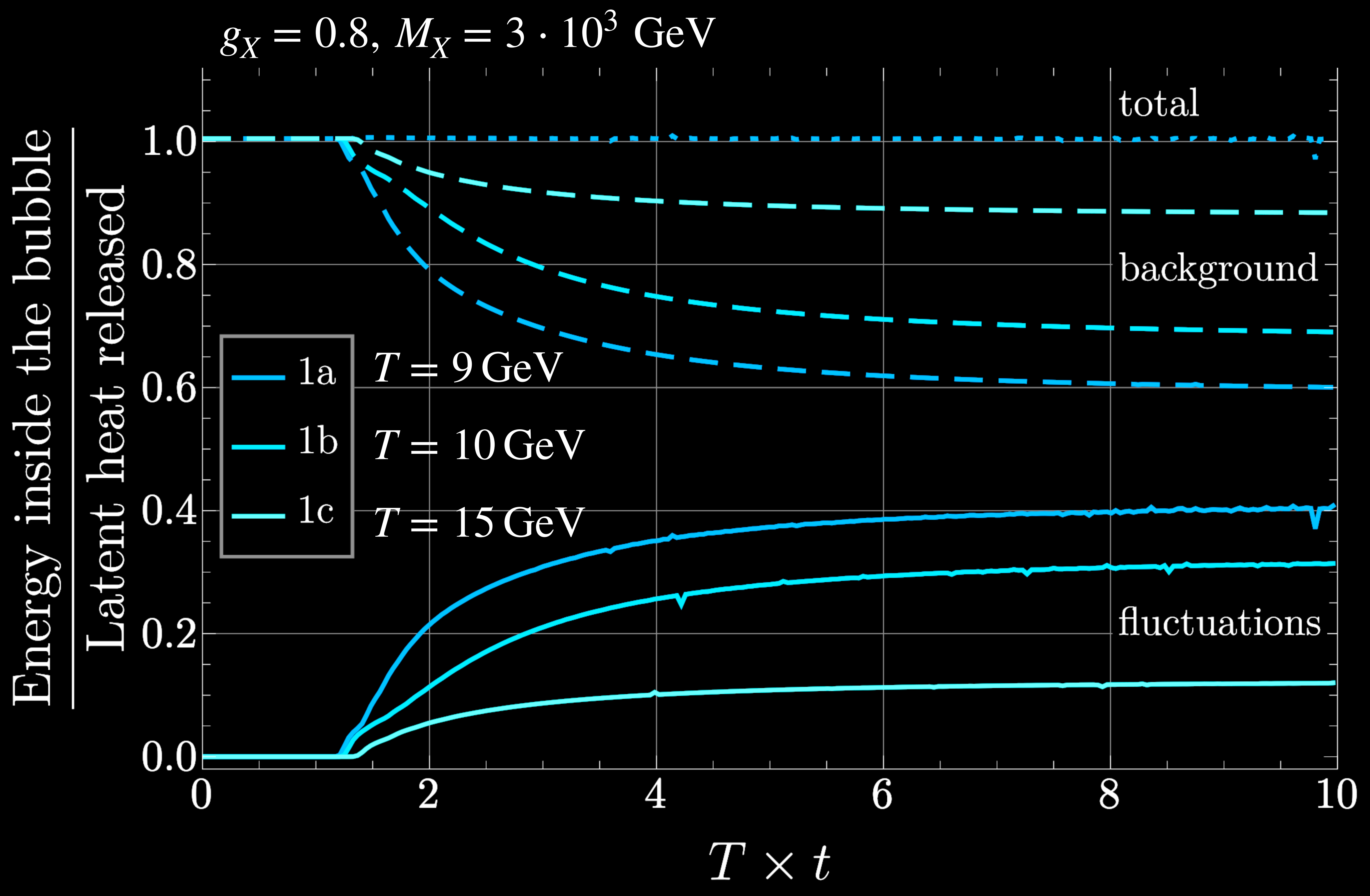
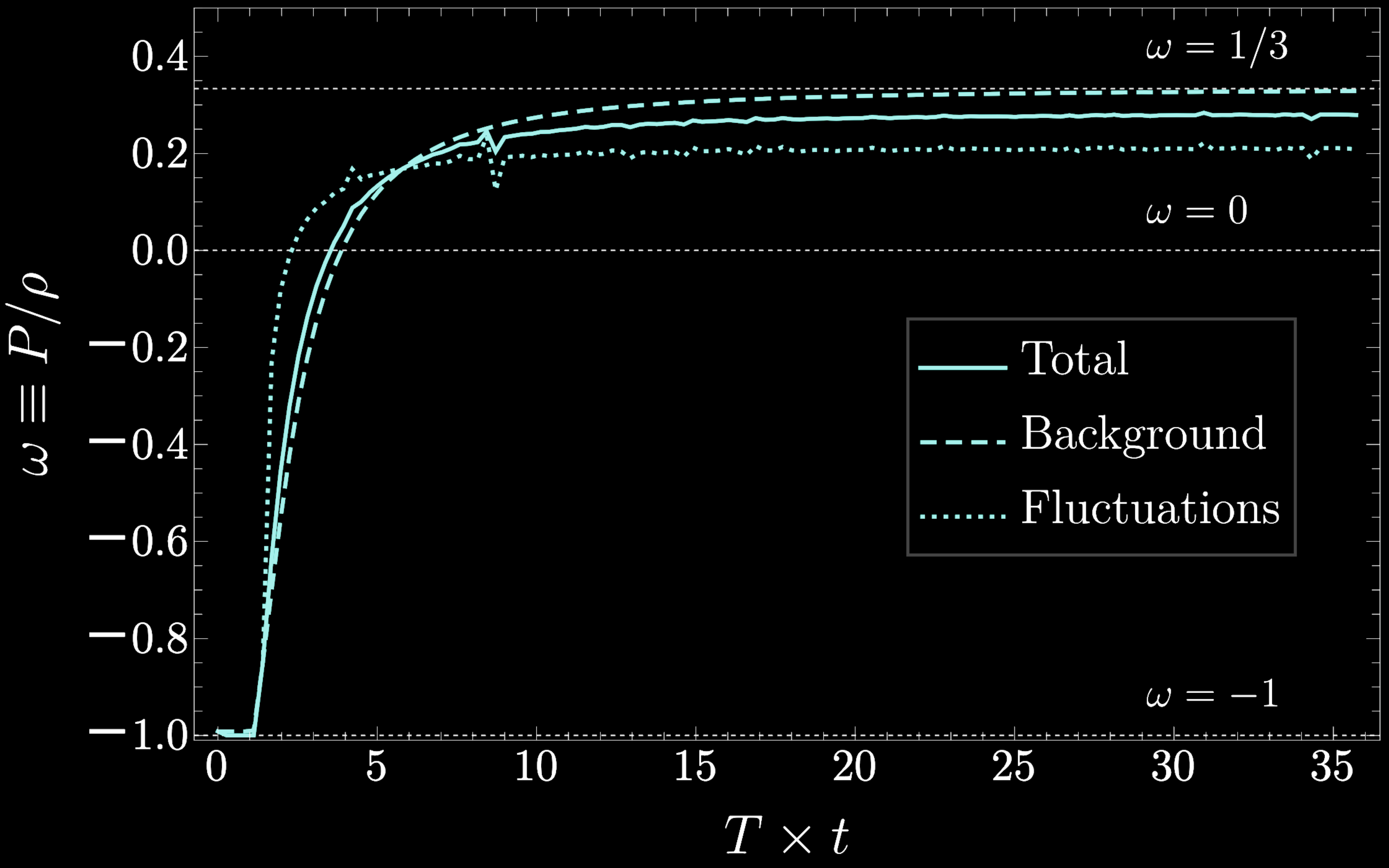


[M. Kulejewski, BŚ, Jorinde van de Vis, work in progress]

Energy budget for GW predictions is altered.

EQUATION OF STATE



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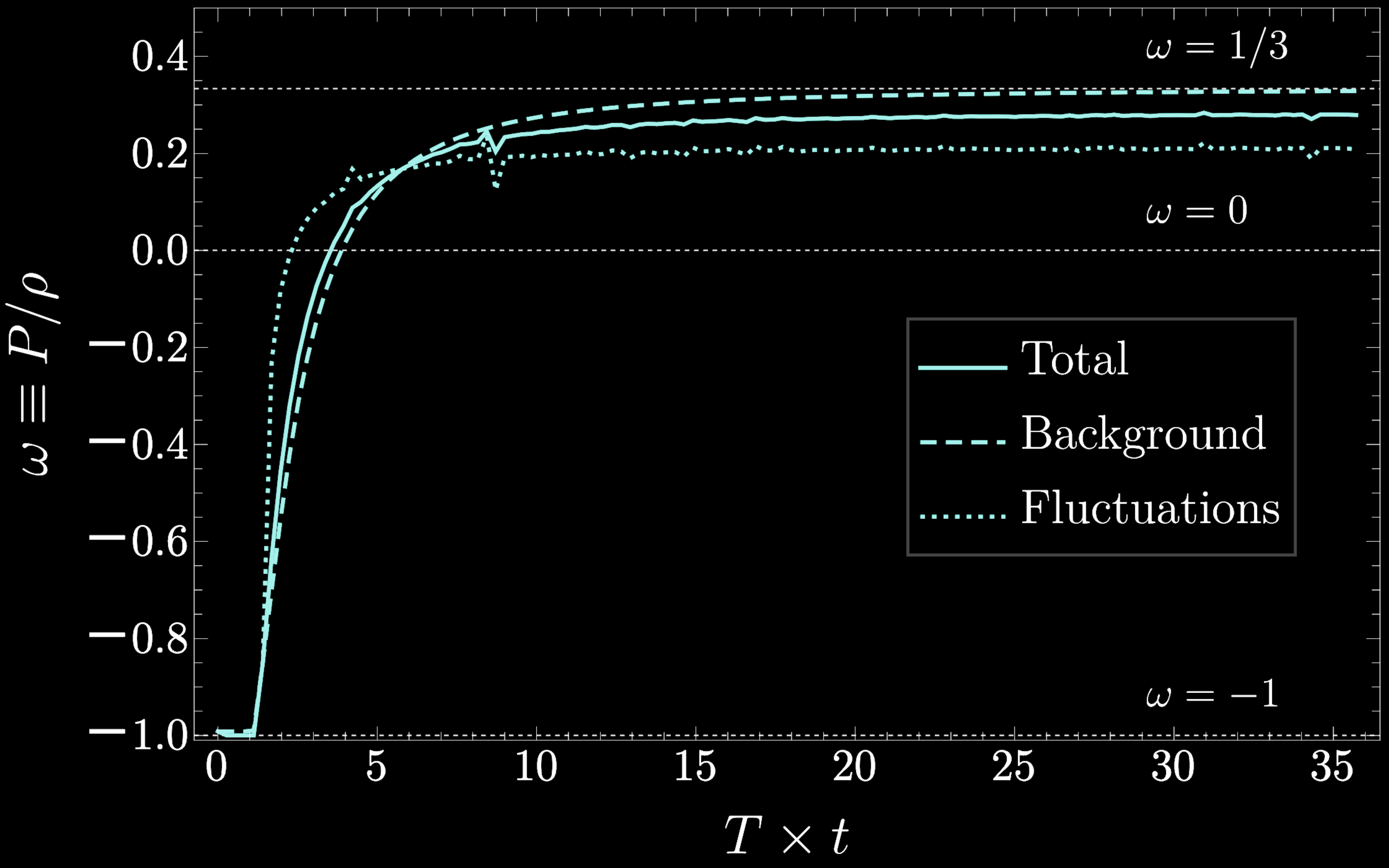

[M. Kulejewski, BŚ, Jorinde van de Vis, work in progress]

The bubble-fluctutations system does not behave as radiation

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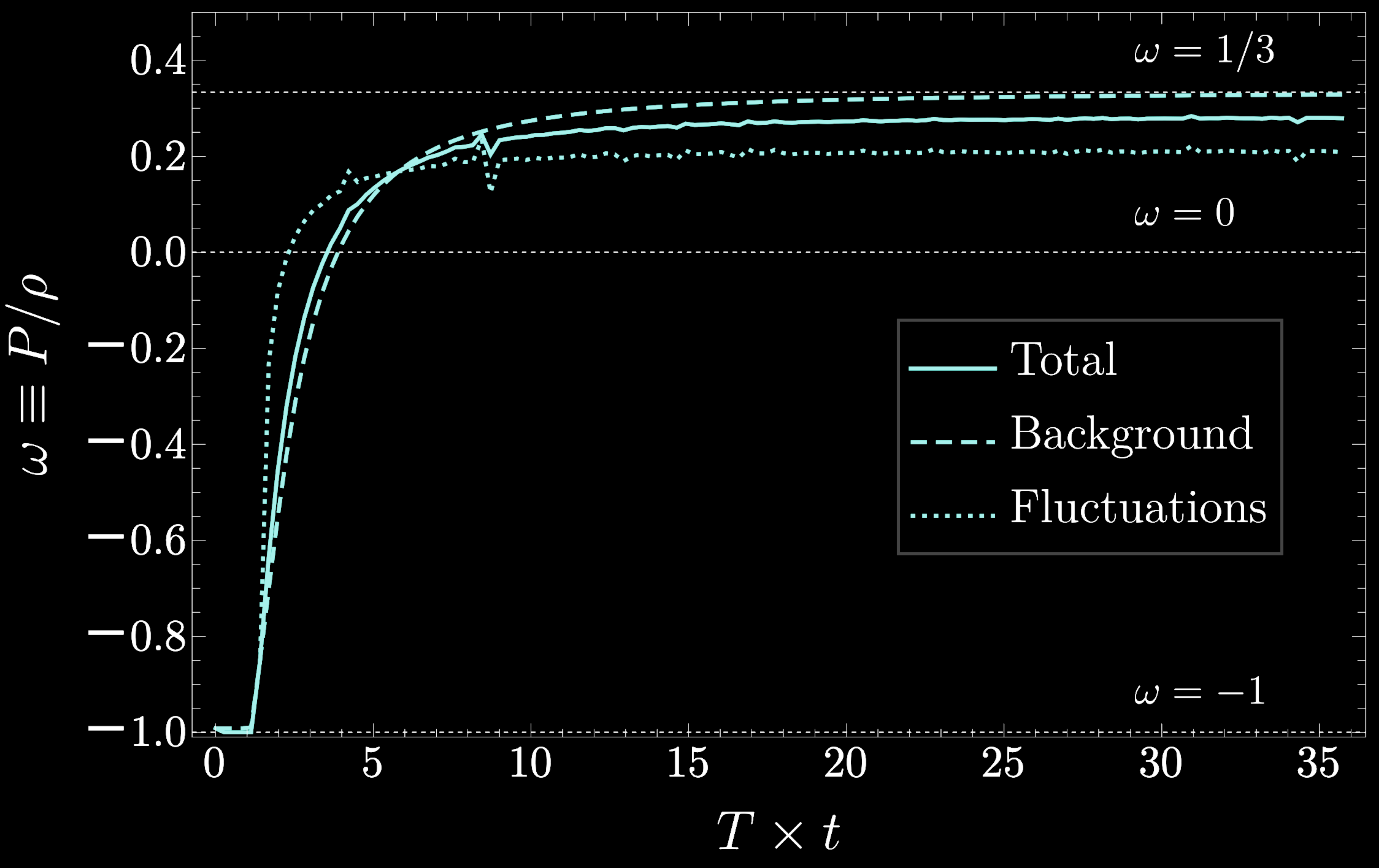
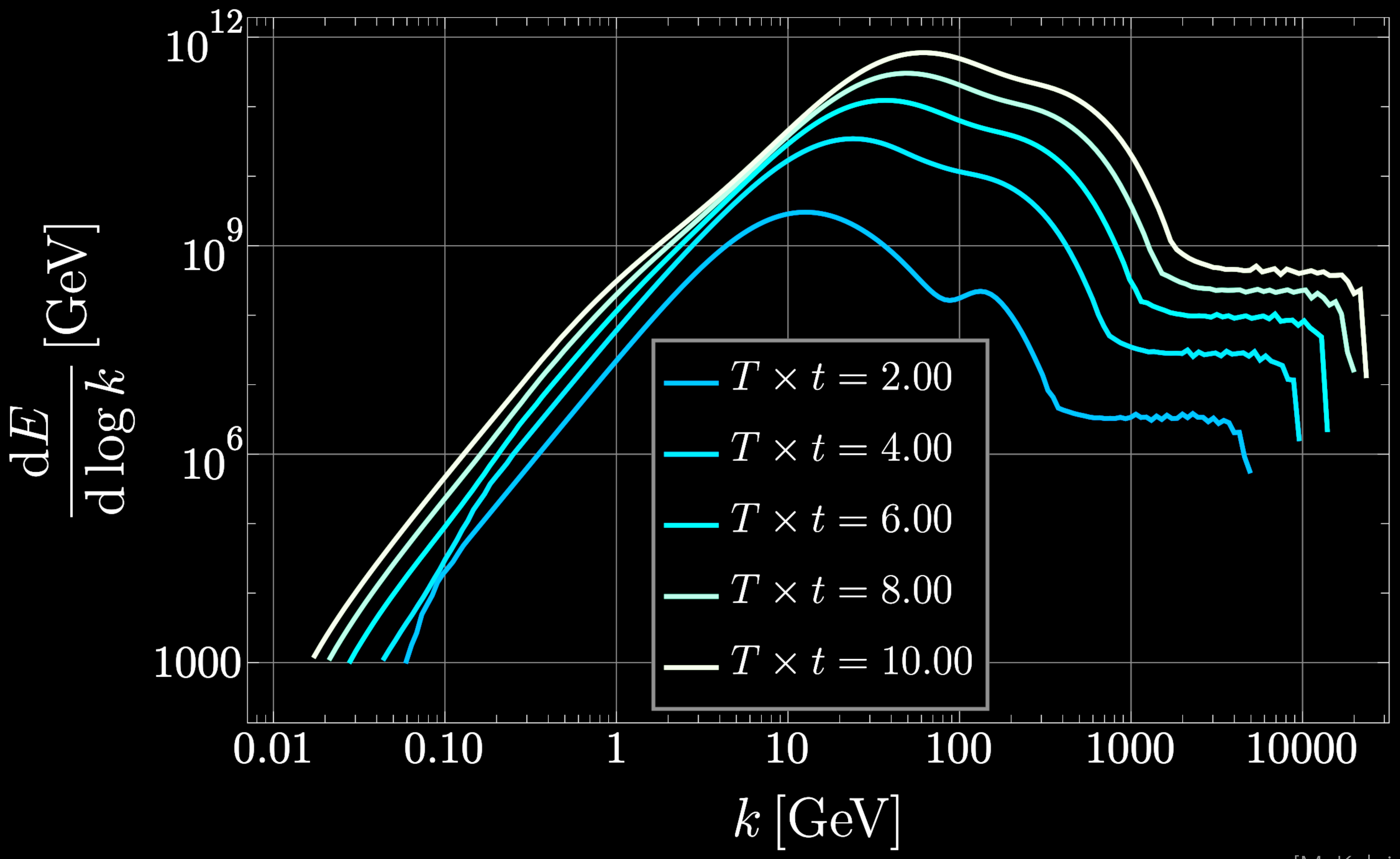


[M. Kulejewski, BŚ, Jorinde van de Vis, work in progress]

The bubble-fluctutations system does not behave as radiation

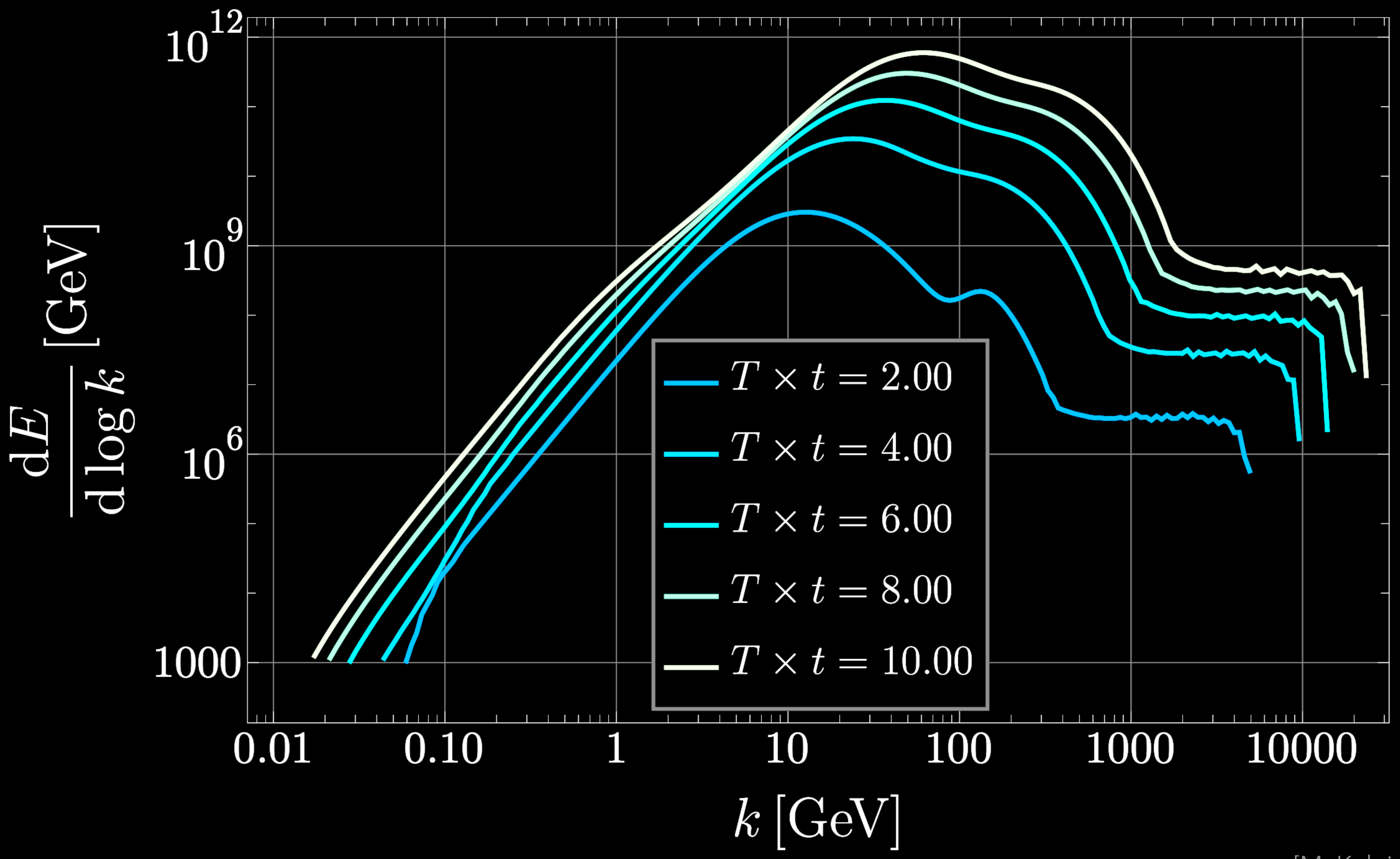
Possible consequences for reheating, GW spectrum and PBH formation

ENERGY SPECTRUM



[M. Kulejewski, BŚ, Jorinde van de Vis, work in progress]

ENERGY SPECTRUM



High-frequency GW signal similar to the one from preheating after inflation?

[M. Kulejewski, BŚ, Jorinde van de Vis, work in progress]

SUMMARY

CONCLUSIONS

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Strong GW signals need strong theory.

CONCLUSIONS

Strong GW signals need strong theory.

And weak as well

CONCLUSIONS

Strong GW signals need strong theory.

And weak as well

Supercooled PTs are accompanied by efficient particle production.

CONCLUSIONS

Strong GW signals need strong theory.

And weak as well

Supercooled PTs are accompanied by efficient particle production.

It changes the energy budget, EoS and can source GWs.

THANK YOU

NATIONAL SCIENCE CENTRE
POLAND

BACKUP SLIDES

MODE DECOMPOSITION

$$\delta\hat{\varphi}(s,\chi,\Omega) = \int_0^\infty \mathrm{dp} \sum_{\mathrm{l=0}}^{\infty} \sum_{\mathrm{m=-1}}^{1} \left[\delta\varphi_{\mathrm{plm}}(\mathrm{s})\mathrm{Y}_{\mathrm{plm}}(\chi,\Omega)\,\hat{\mathrm{b}}_{\mathrm{plm}} + \delta\varphi^*_{\mathrm{plm}}(\mathrm{s})\mathrm{Y}^*_{\mathrm{plm}}(\chi,\Omega)\,\hat{\mathrm{b}}^\dagger_{\mathrm{plm}}\right]$$

ENERGY DENSITY AND PRESSURE

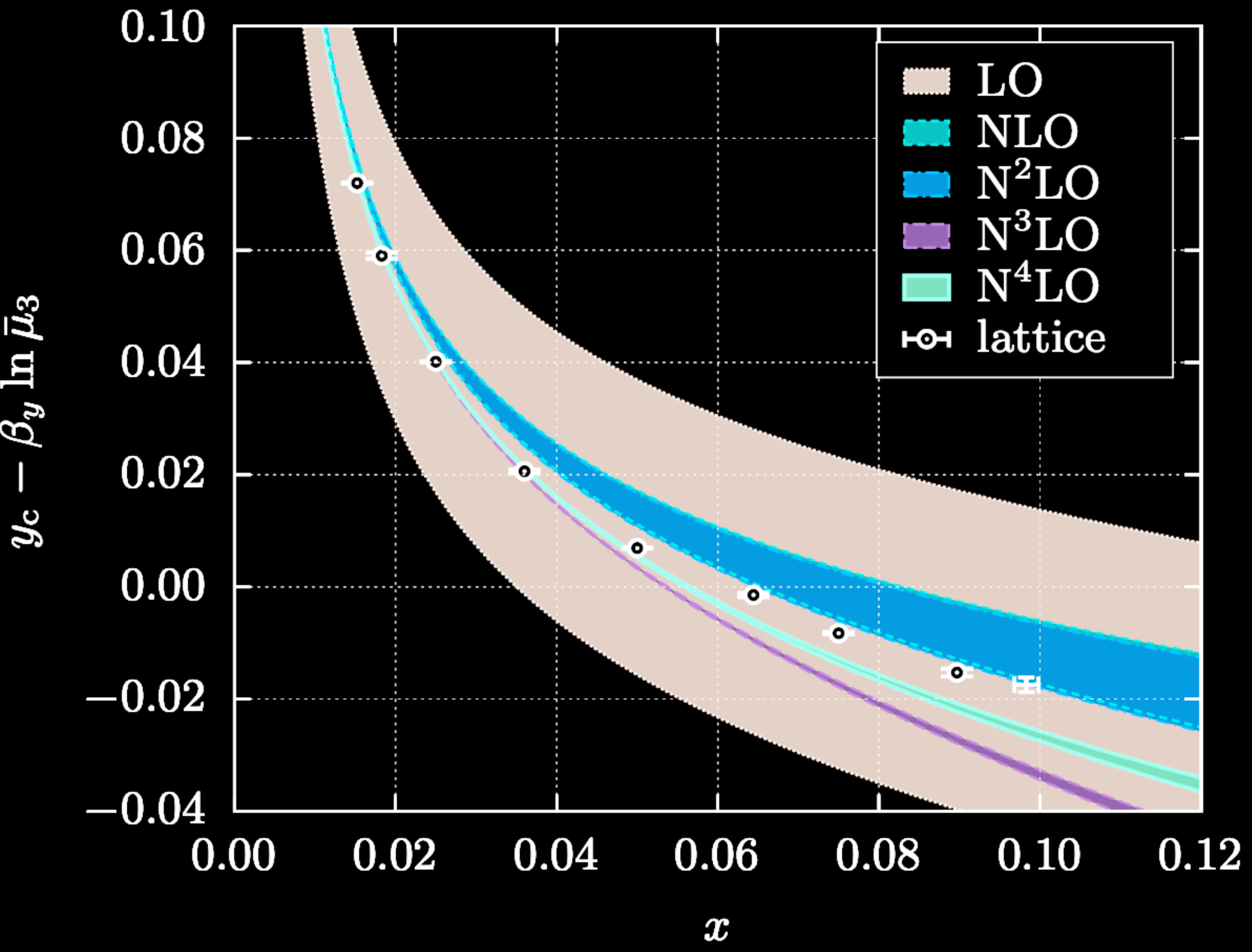
$$\rho = \tilde{\rho}\,\cosh^2\chi + \tilde{P}\,\sinh^2\chi$$

$$P_r = \tilde{\rho}\,\sinh^2\chi + \tilde{P}\,\cosh^2\chi$$

$$\tilde{\rho} = \int_0^\infty \frac{p^2\mathrm{dp}}{4\pi^2}\left[\,|\delta\dot{\varphi}_p|^2 + \frac{p^2+1}{s^2}|\delta\varphi_p|^2 + m^2|\delta\varphi_p|^2\right]$$

$$\tilde{P} = \int_0^\infty \frac{p^2\mathrm{dp}}{4\pi^2}\left[\,|\delta\dot{\varphi}_p|^2 - \frac{p^2+1}{3s^2}|\delta\varphi_p|^2 - m^2|\delta\varphi_p|^2\right]$$

IS THE PERTURBATIVE APPROACH RELIABLE?



[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]

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

WHAT'S NEW AT NLO?

$$S_3^{\text{EFT, NLO}} = 4\pi \int \mathrm{dr}\, \mathrm{r}^2 \left(\frac{1}{2} Z_3^{\text{NLO}}(v_3)(\partial_i v_3)^2 + V_3^{\text{EFT, NLO}}(v_3) \right)$$

- 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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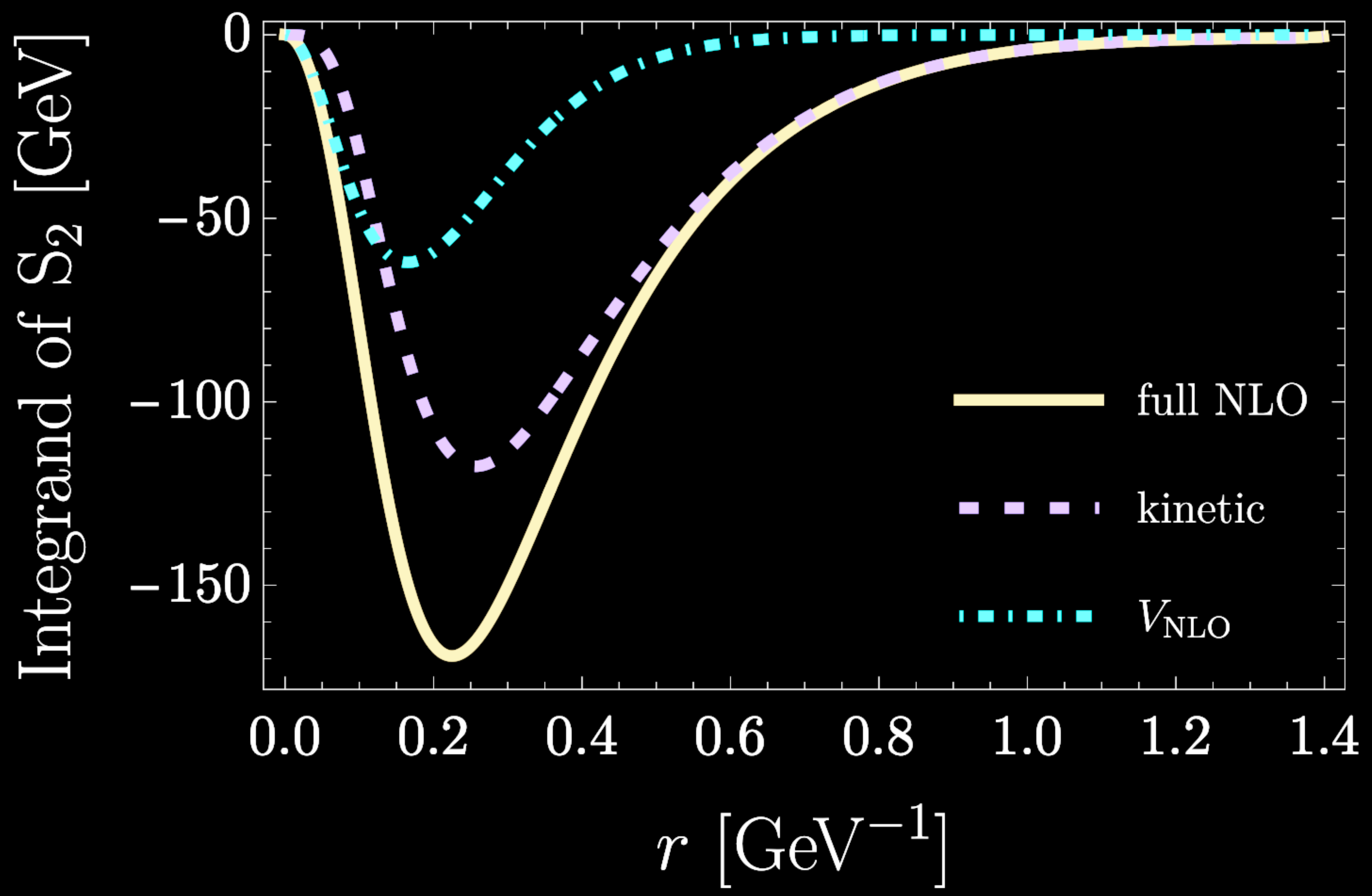
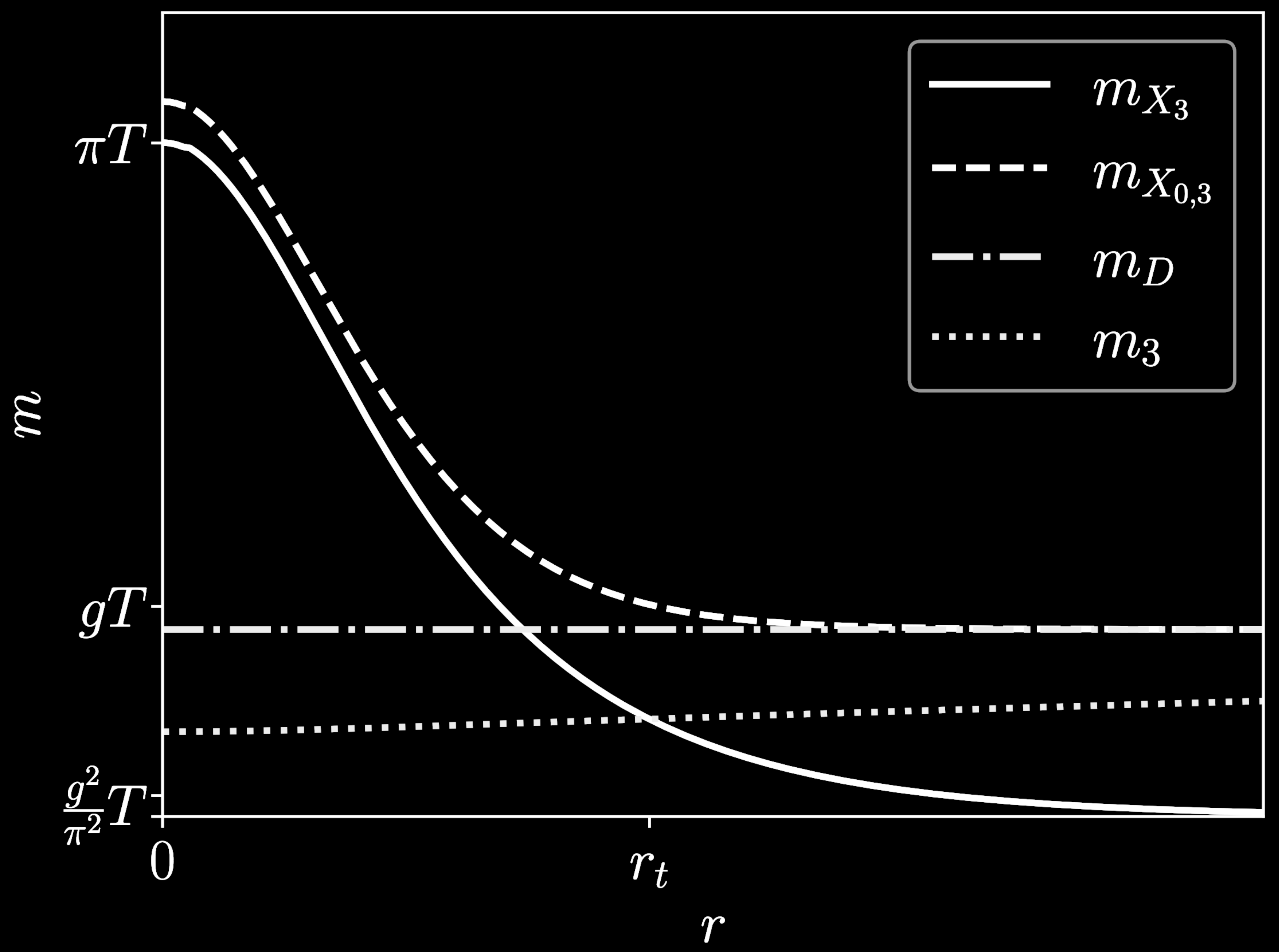
Up to 100% corrections to percolation temperature!

MOMENTUM EXPANSION



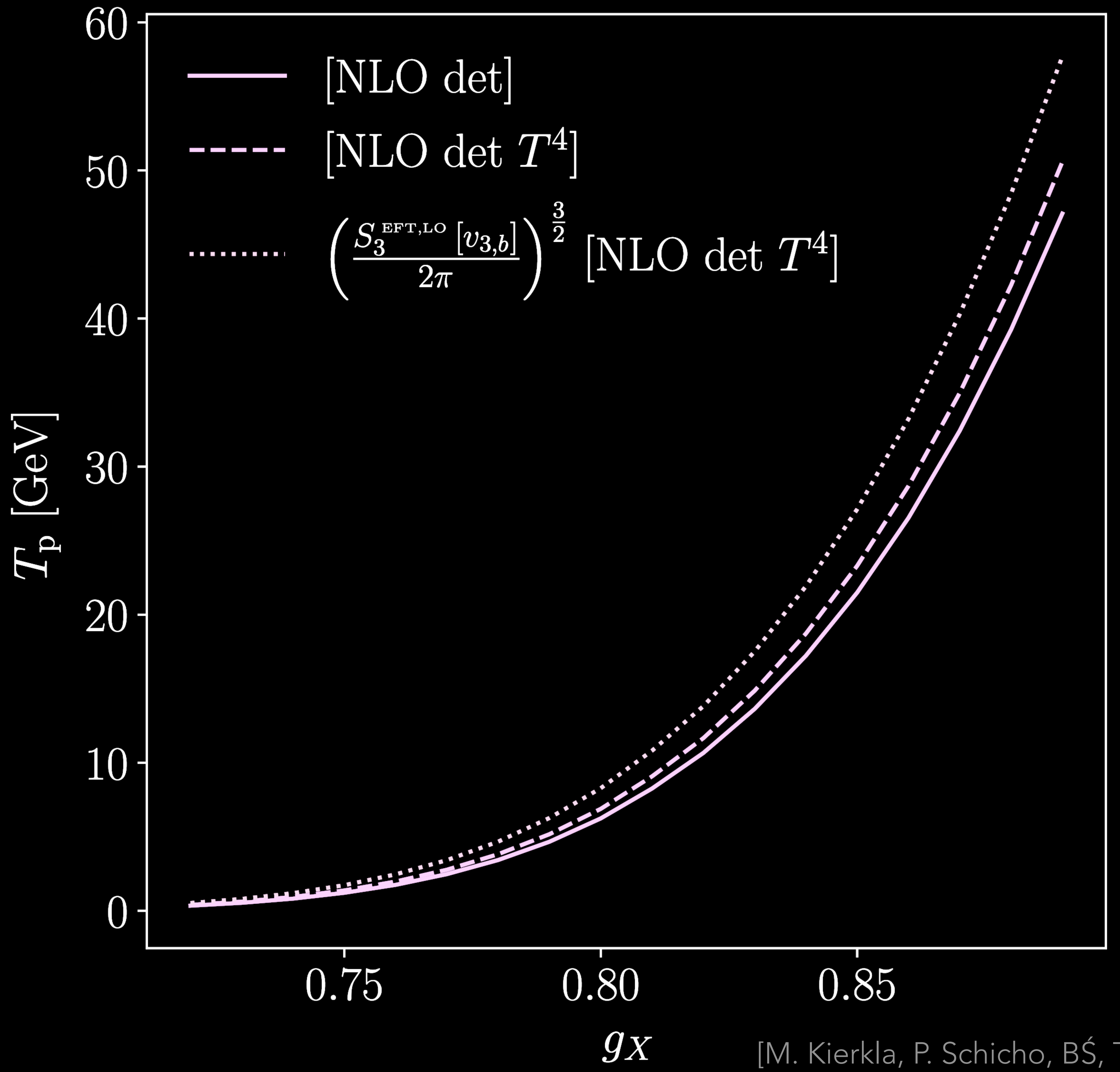
[M. Kierkla, BŚ, T.V.I. Tenkanen, J. van de Vis, JHEP 02 (2024) 234]

VALIDITY OF EFT — SCALE-SHIFTERS



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

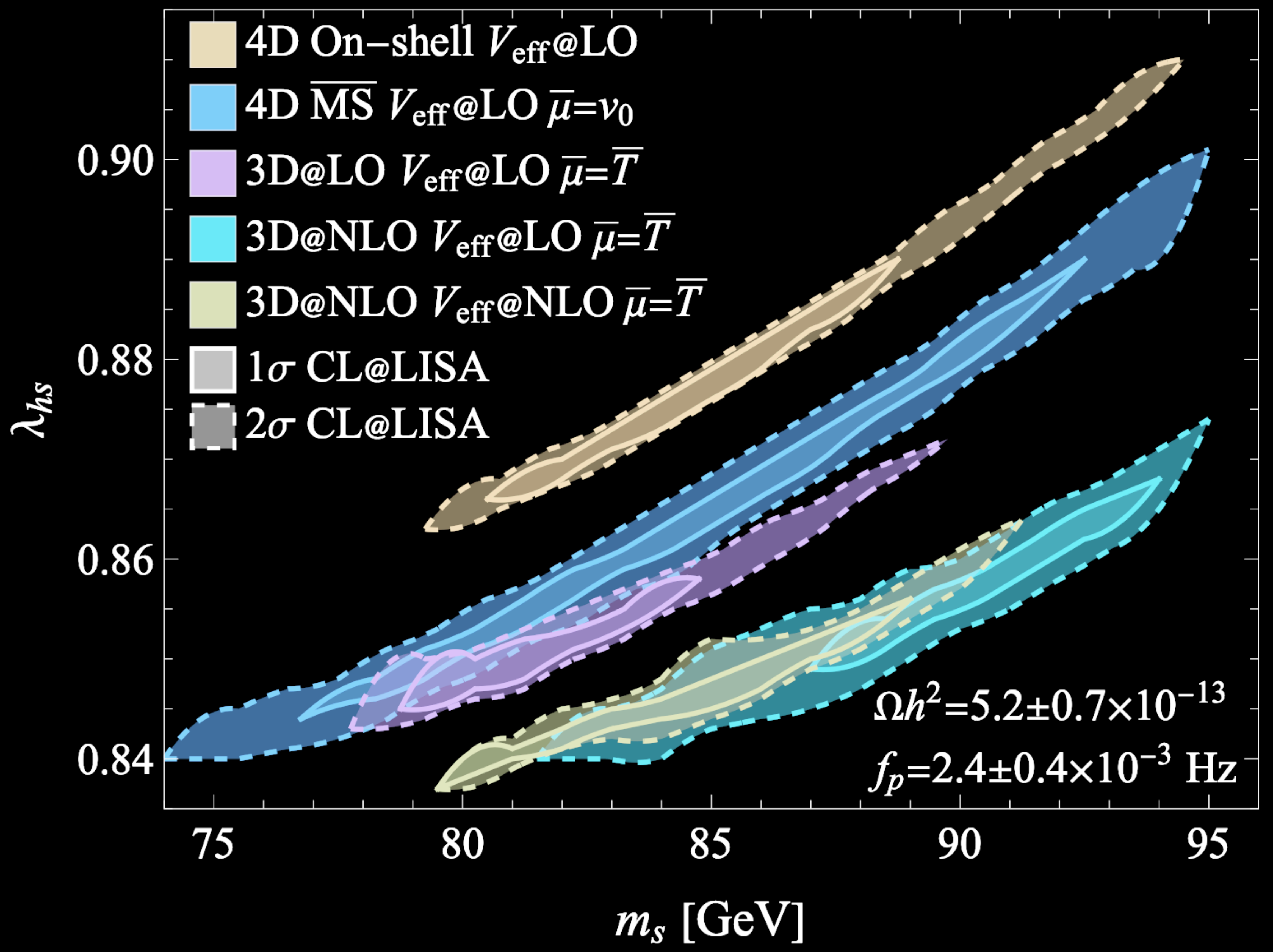
SCALAR DETERMINANT



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

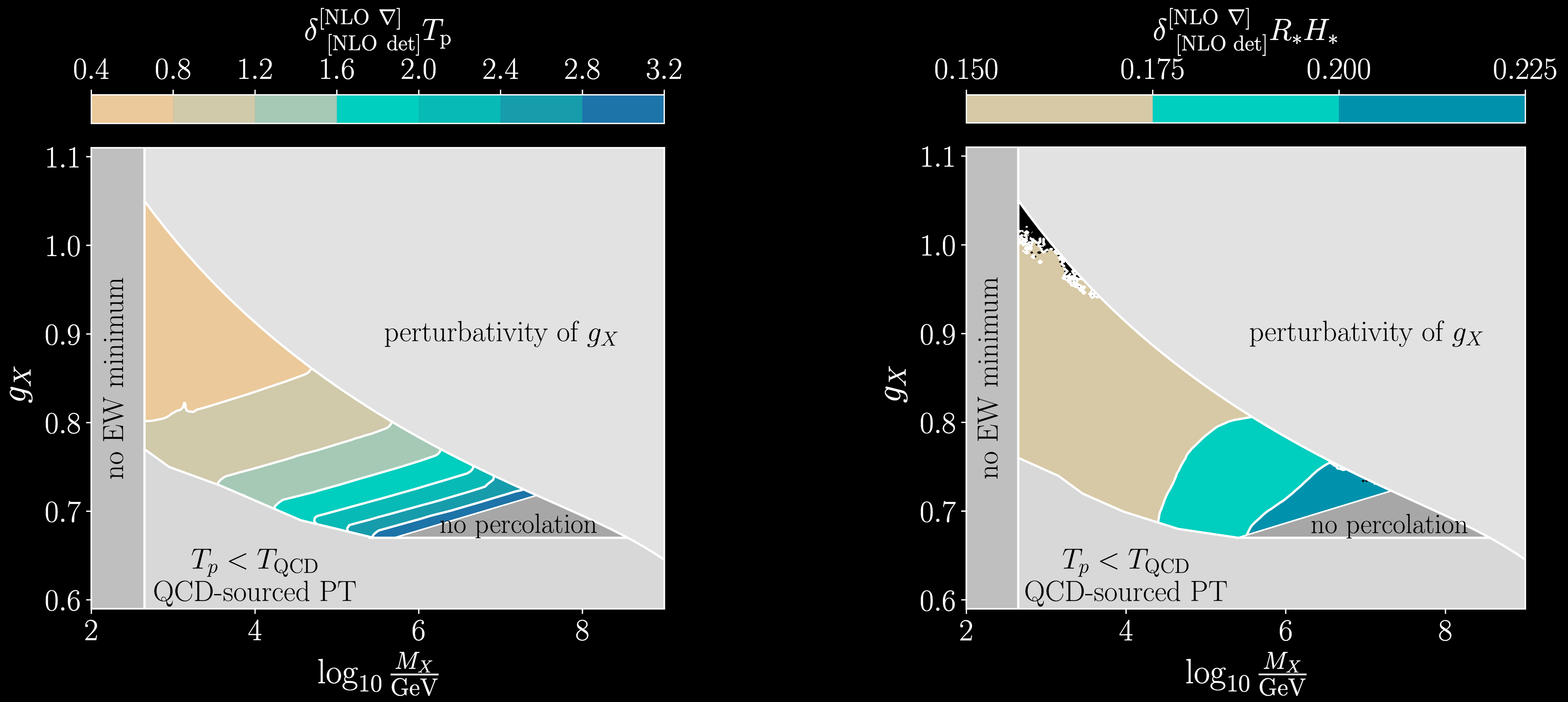
PRECISION FOR WEAKER SIGNALS

SM + singlet, SNR=10



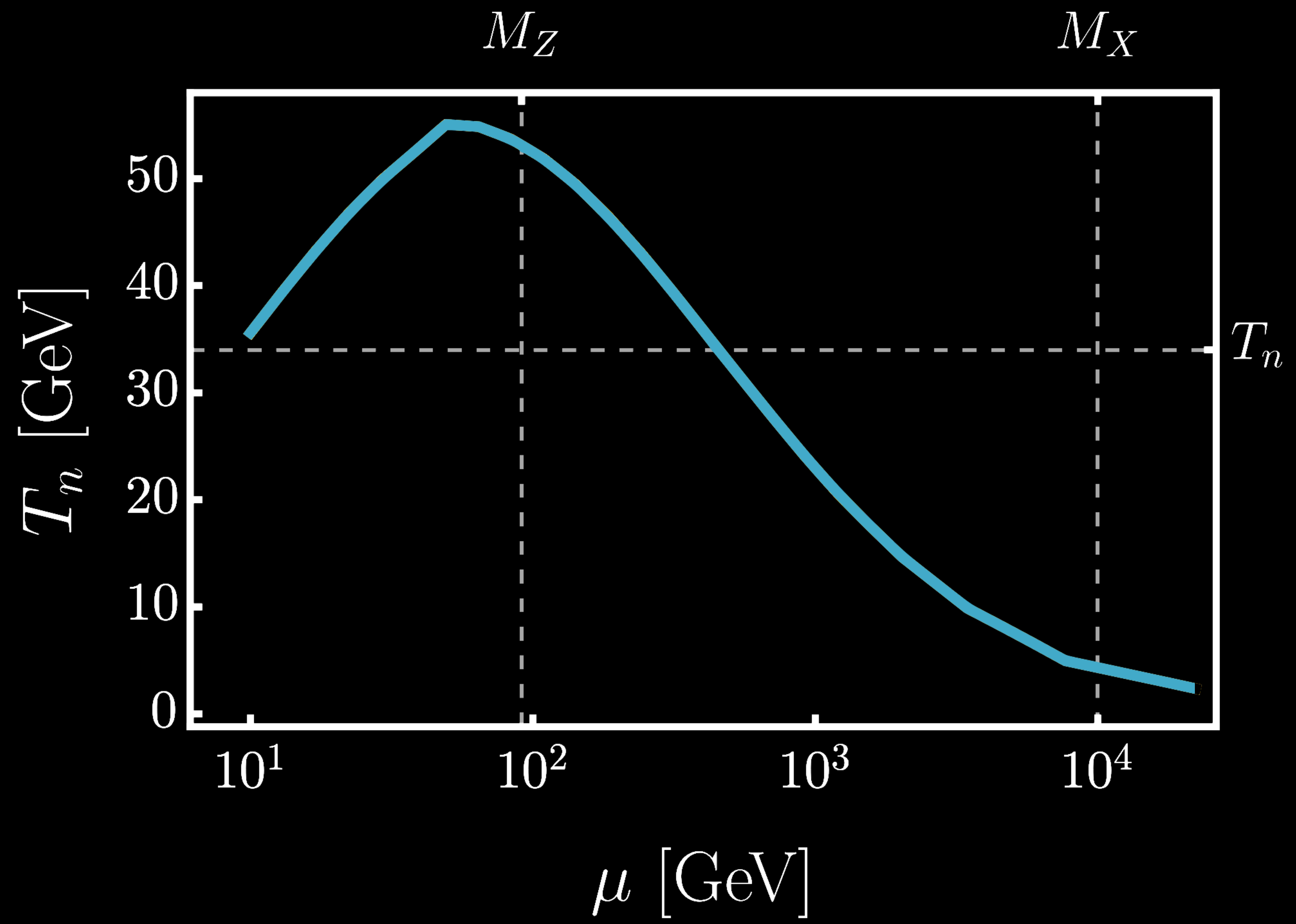
[M. Lewicki, M. Merchand, L. Sagunski, P. Schicho, D. Schmitt, Phys.Rev.D 110 (2024) 2, 023538]

ACCURACY OF PREDICTIONS



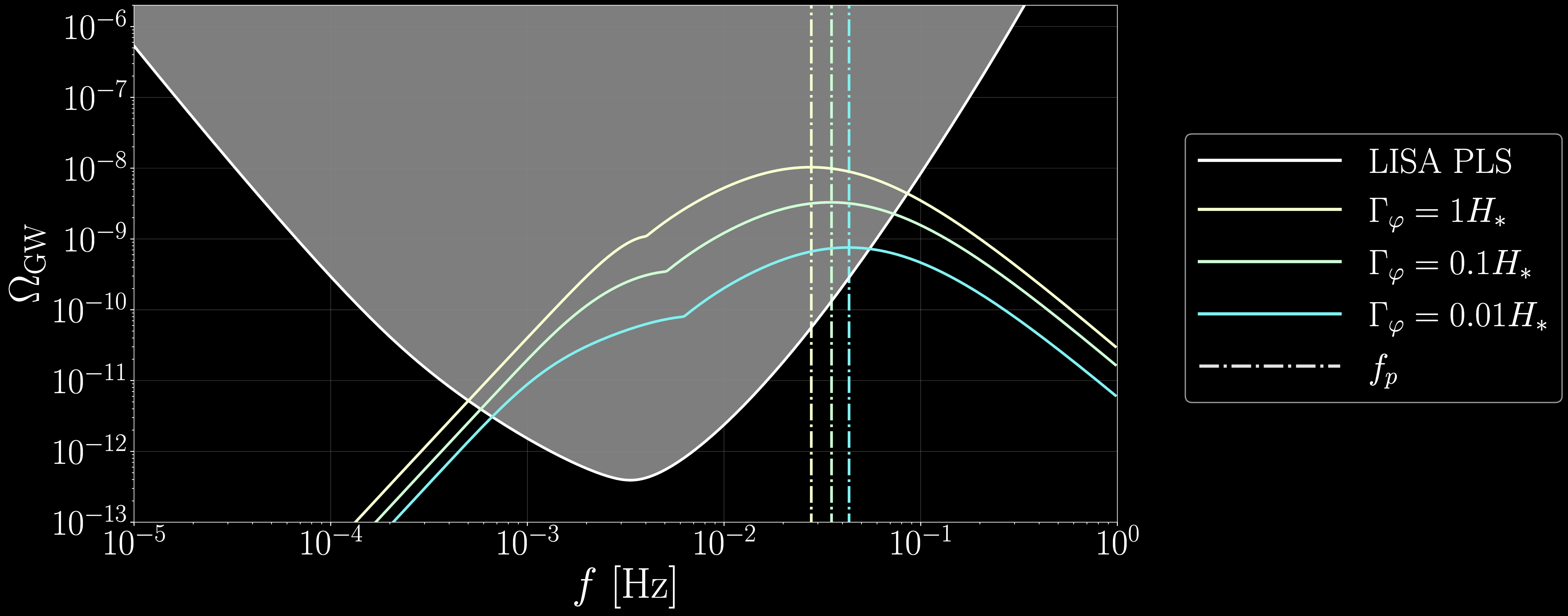
[M. Kierkla, P. Schicho, BŚ, T.V.I. Tenkanen, J. van de Vis, JHEP 07 (2025) 153]

SCALE DEPENDENCE - SOURCE OF UNCERTAINTY



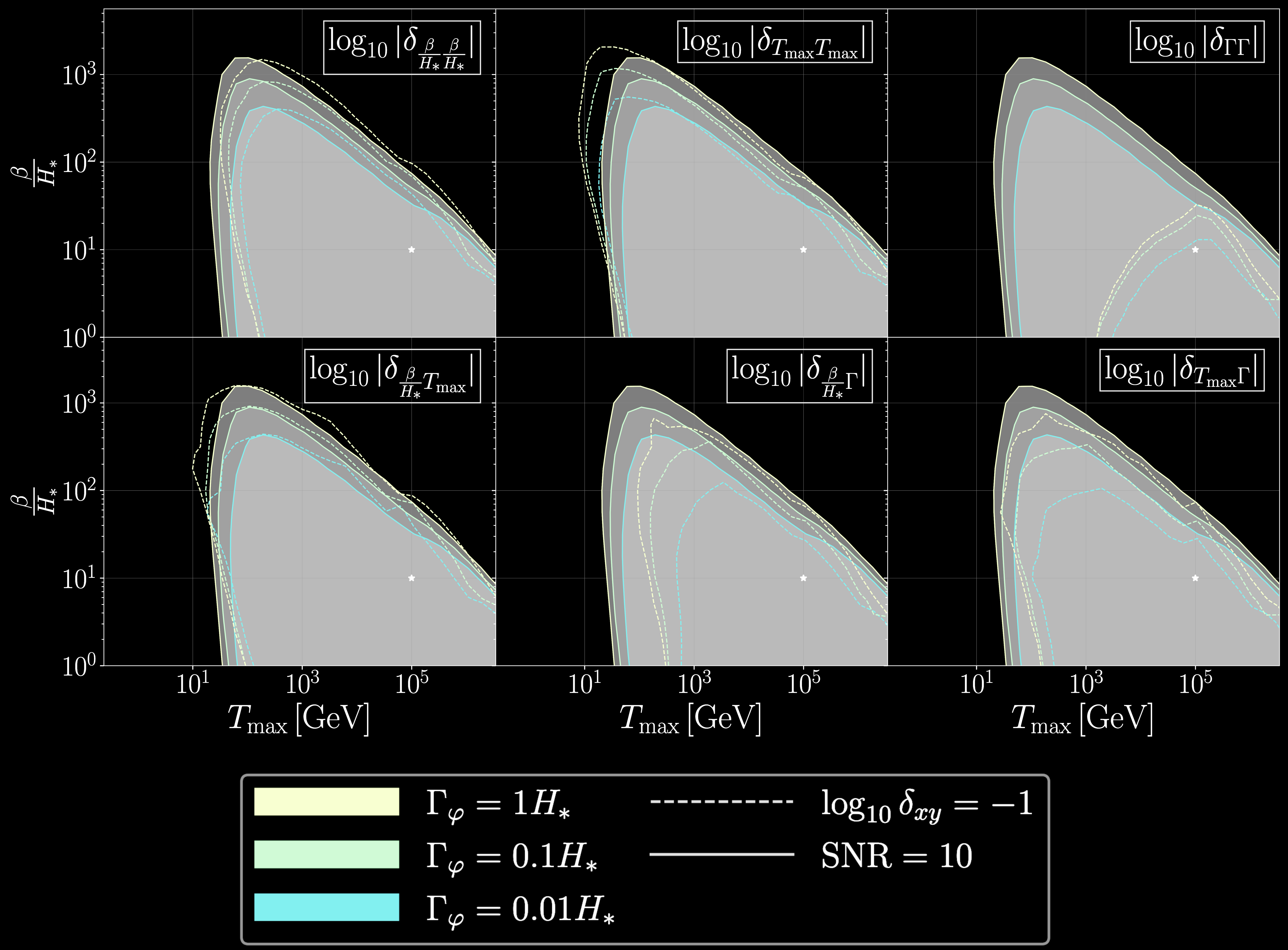
[M. Kierkla, A. Karam, BŚ, JHEP 03 (2023) 007]

MODIFIED EXPANSION AFFECTS THE SIGNAL



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

WHAT CAN WE LEARN FROM THE SIGNAL?



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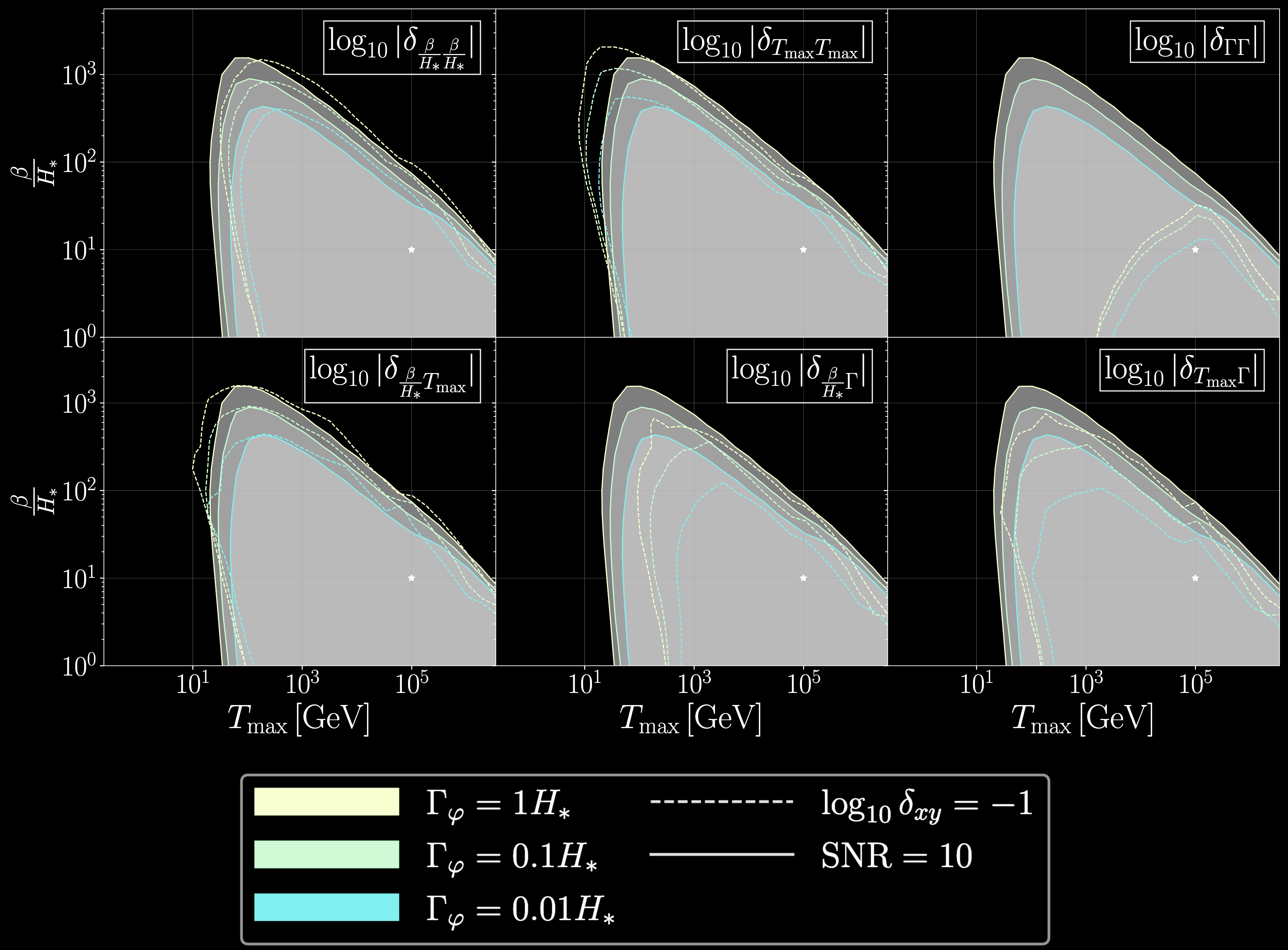

- Decay rate of the scalar (inaccessible at colliders?) can be determined from the spectrum

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

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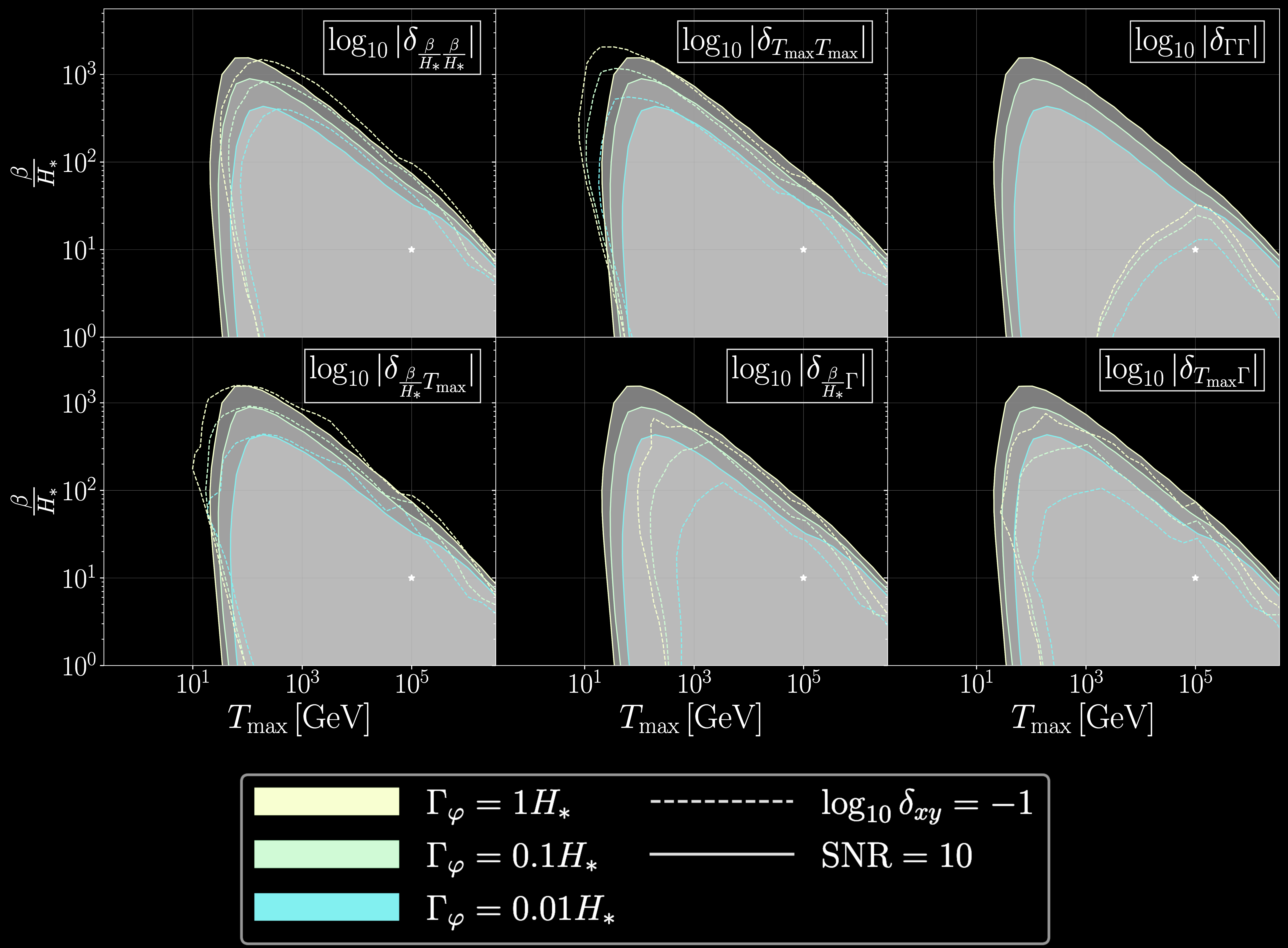
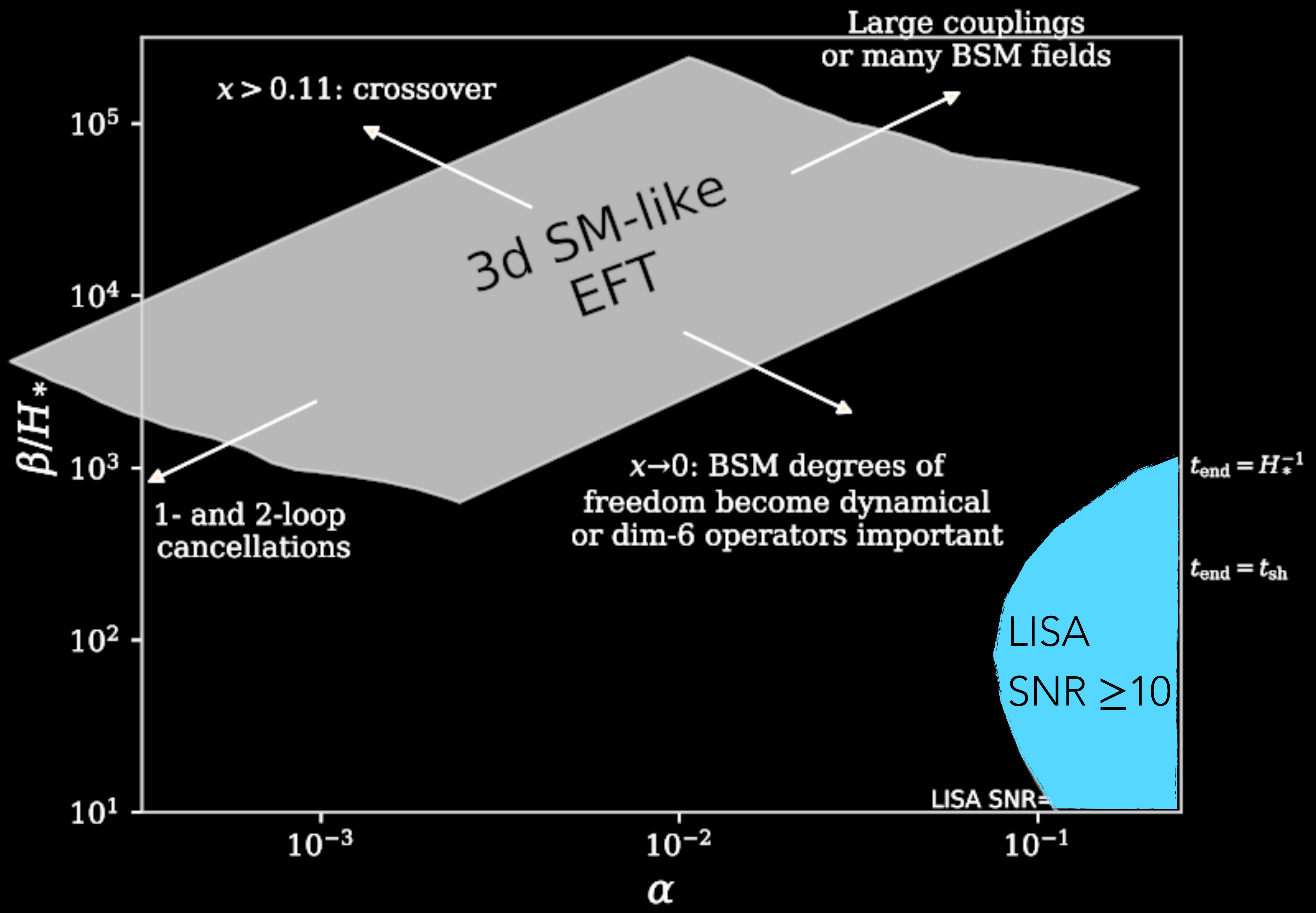


- Decay rate of the scalar (inaccessible at colliders?) can be determined from the spectrum
- Individual parameters can be determined with an accuracy better than 10%

[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]