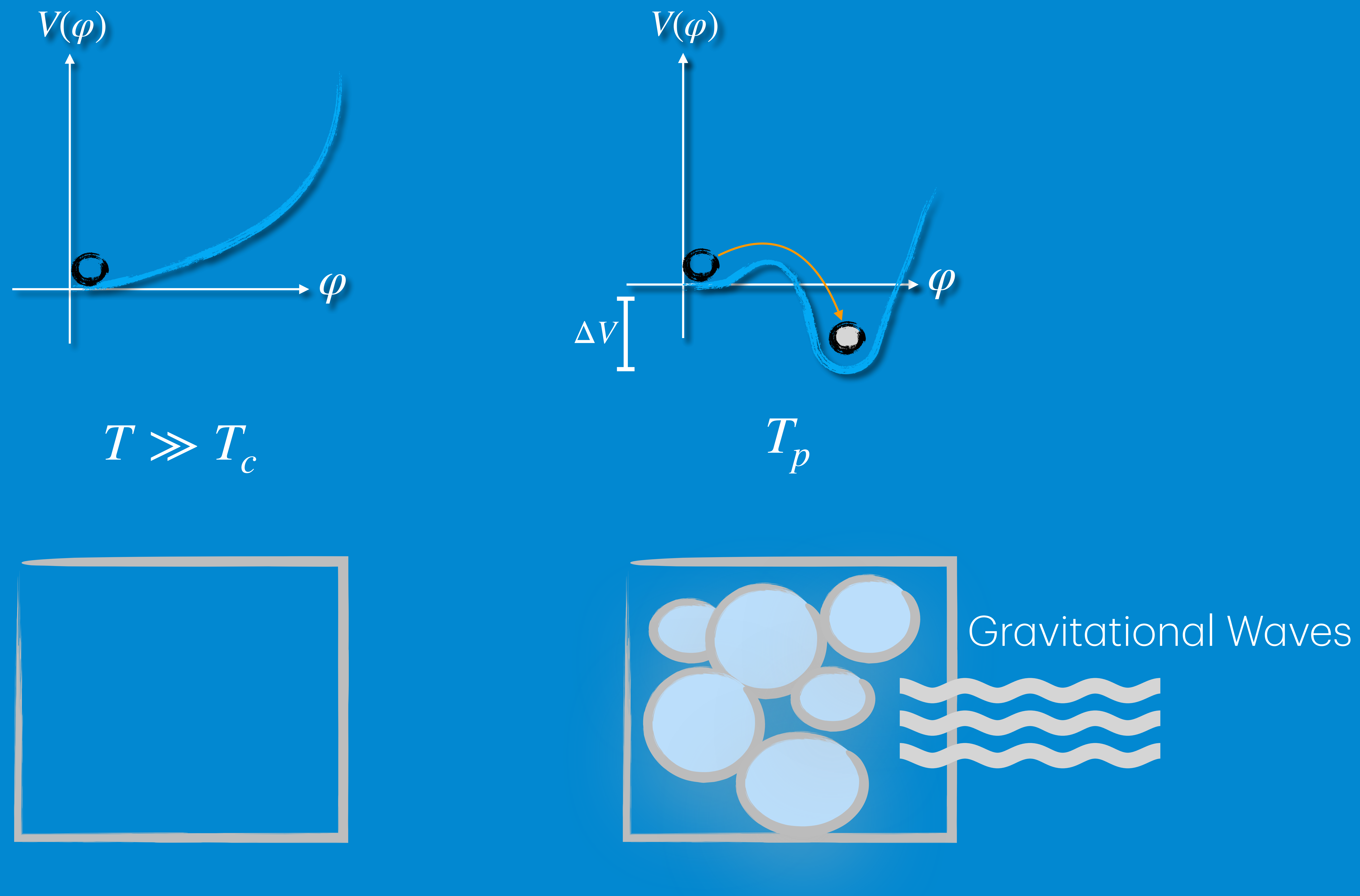
Effective methods for bubble nucleation in cosmological phase transitions *(and some pheno)*

Maciej Kierkla, Uppsala University

Based on: 2312.12413, 2503.13597, 2506.15496, 2607.18233

Field theory picture

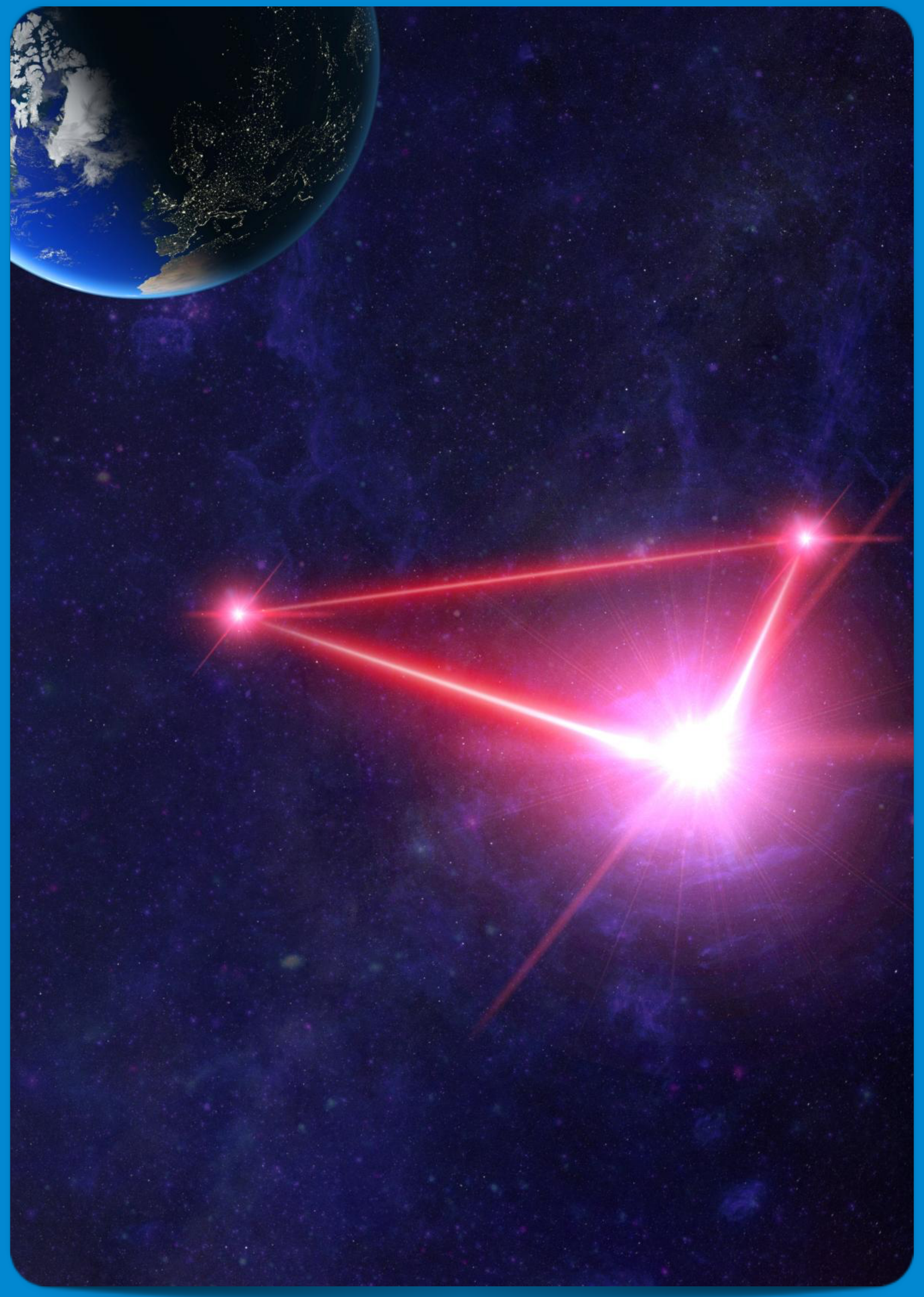
Cosmology picture



See also: LISA Cosmology Working Group, 2403.03723

Motivation

- LISA detector will start collecting data in the late 2030’s
- LISA will be sensitive to the frequencies of order mHz, which includes PT at the EW scale
- Detection of such a signal is a “smoking gun” for new physics!
- There could be associated phenomena, e.g., dark matter, primordial black holes, and baryogenesis
- We need to be able to provide robust predictions

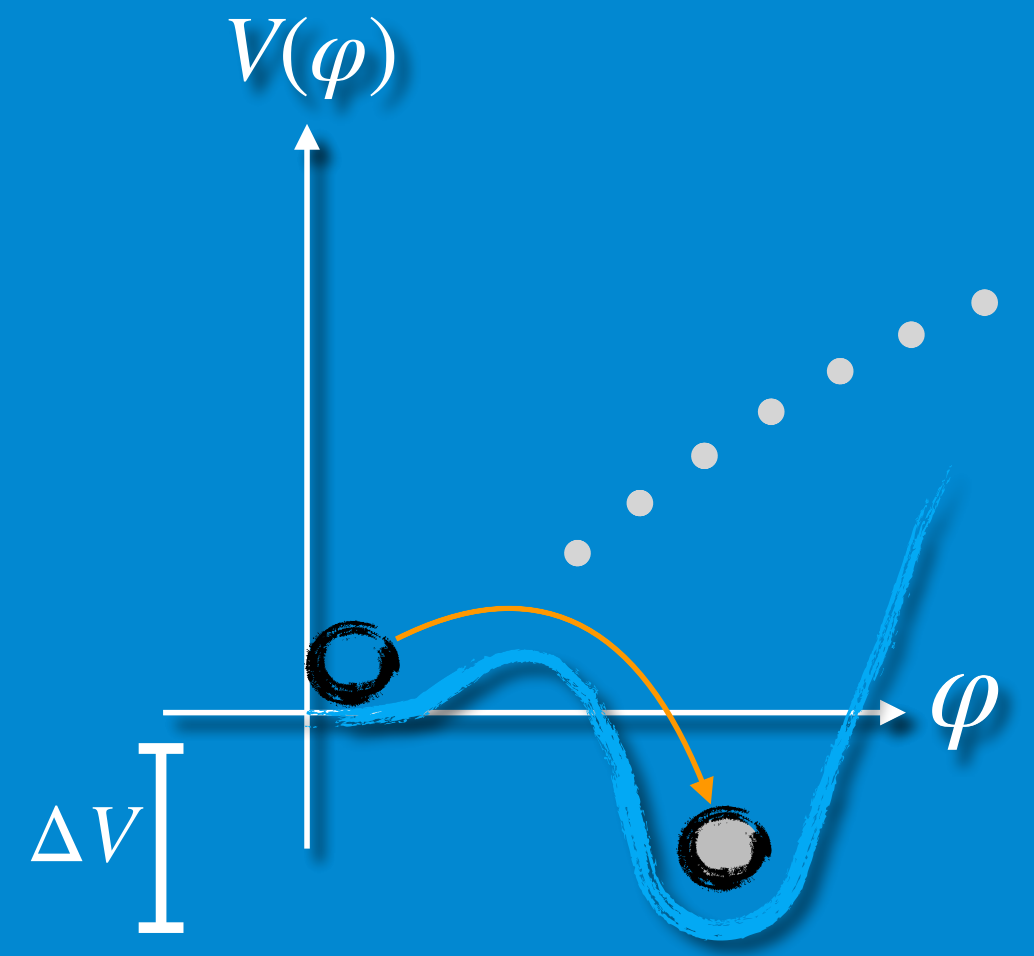


NASA/JPL-Caltech/NASAEA/ESA/CXC/STScI/GSFCSVS/S.Barke (CC BY 4.0).

See also: 2403.03723, 2508.09989, 2503.01962

Key quantity for PT dynamics

Field theory

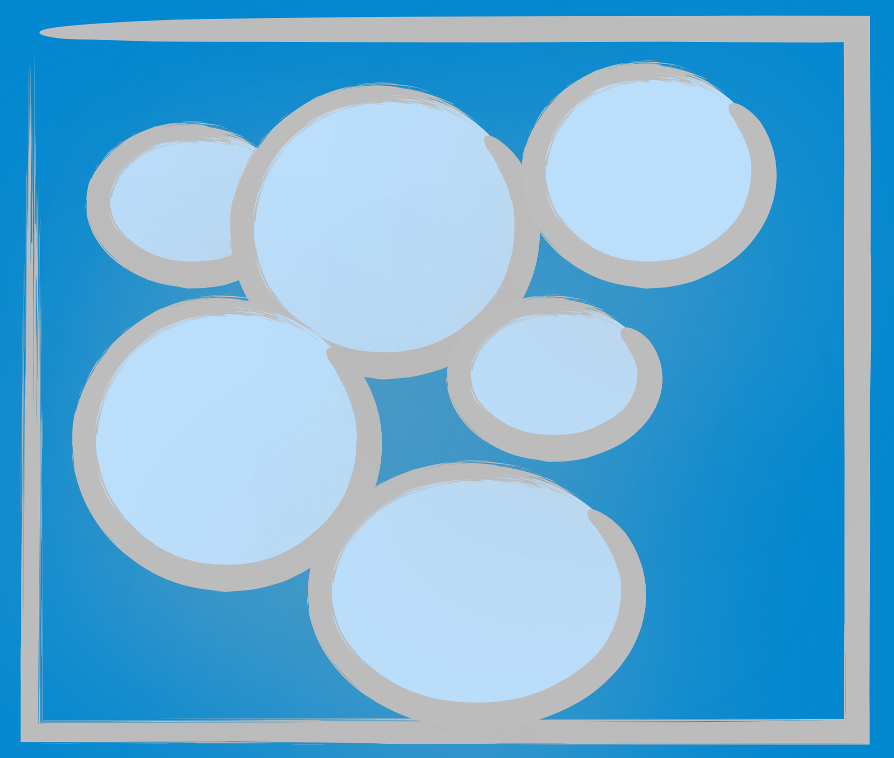


T_p

Bubble nucleation rate

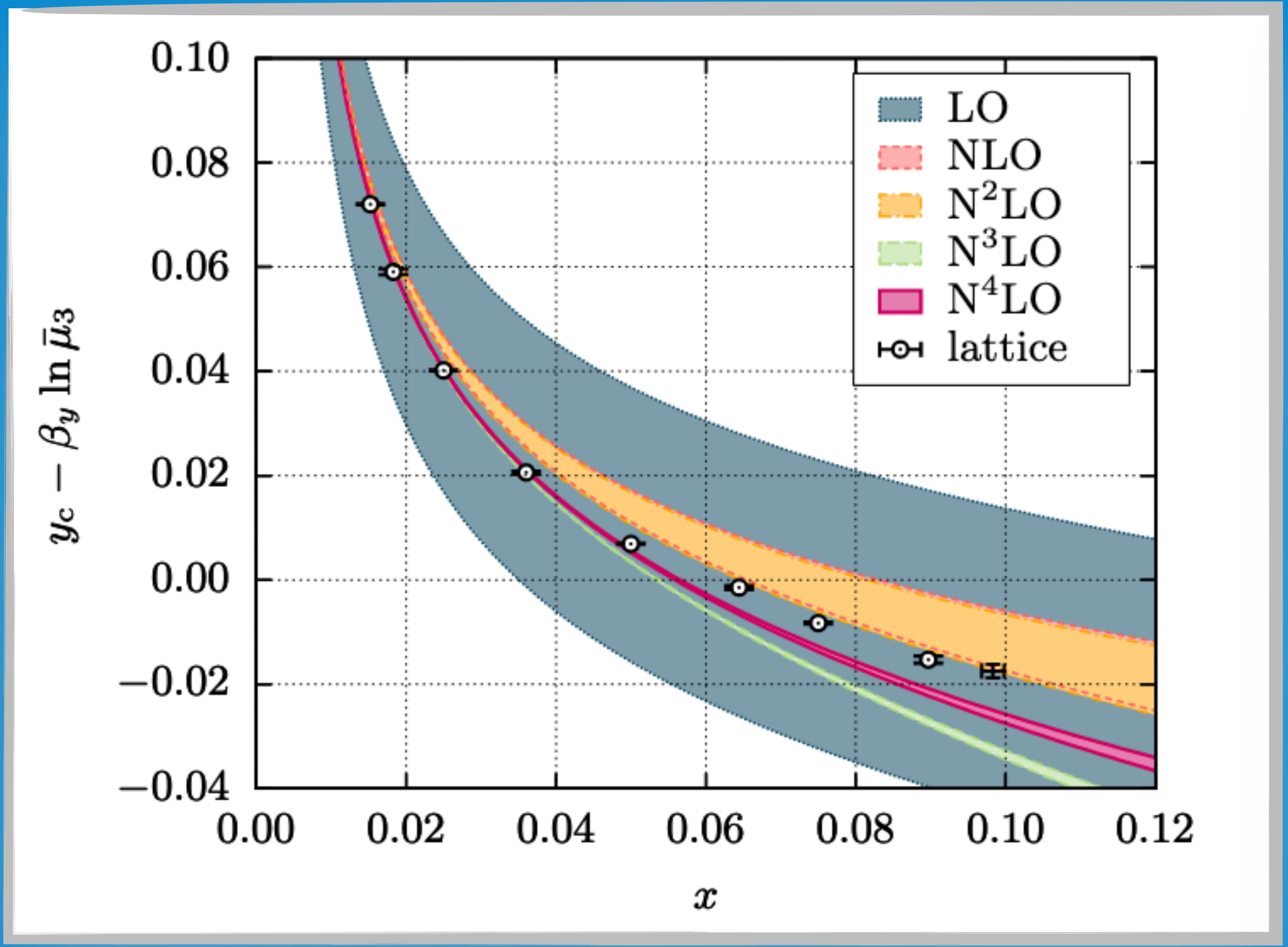
$$\frac{\Gamma}{H^4}$$

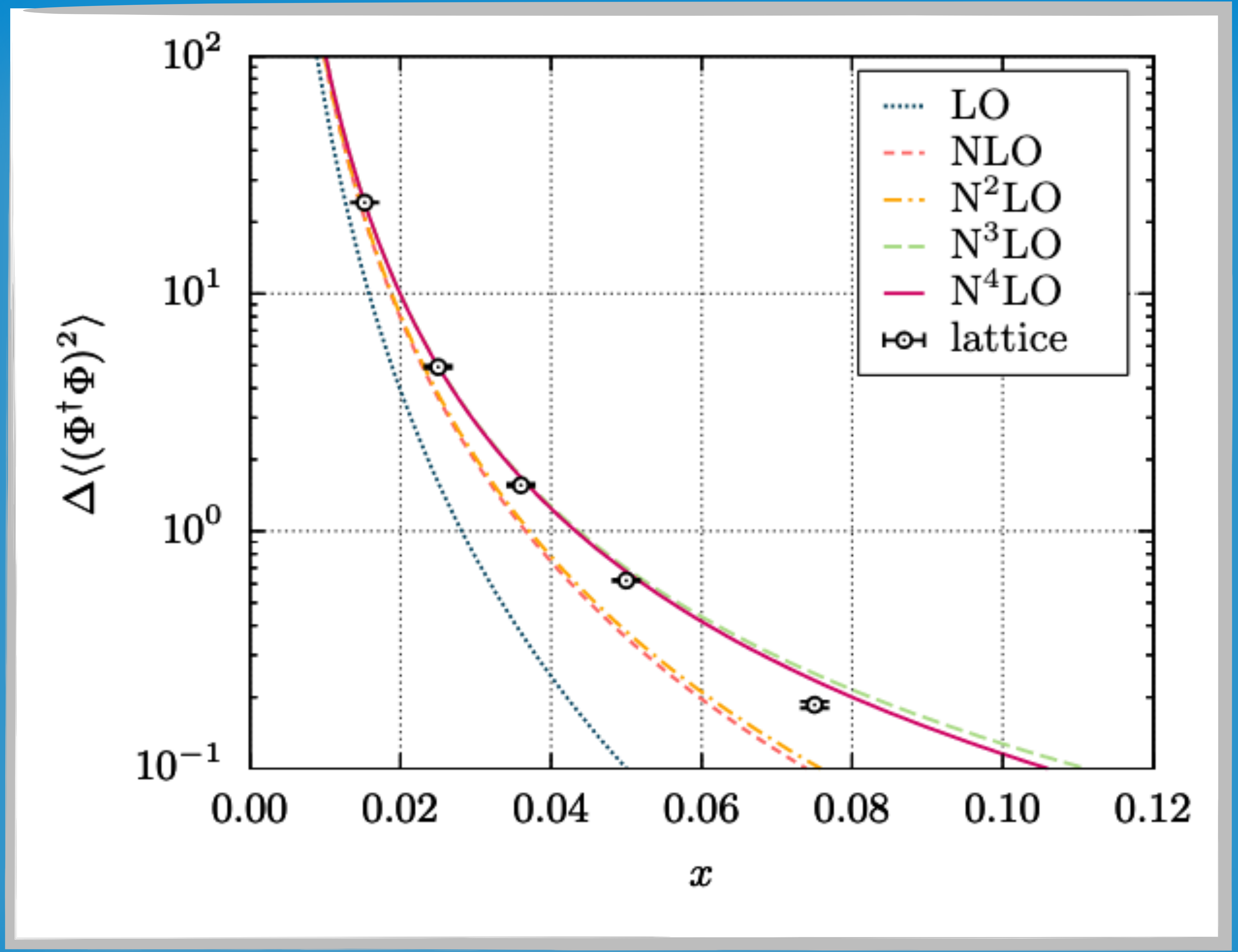
Cosmology



Some recent works: 2608.00169, 2607.09233, 2108.04377

Equilibrium thermodynamics (pert. th.) done ✅

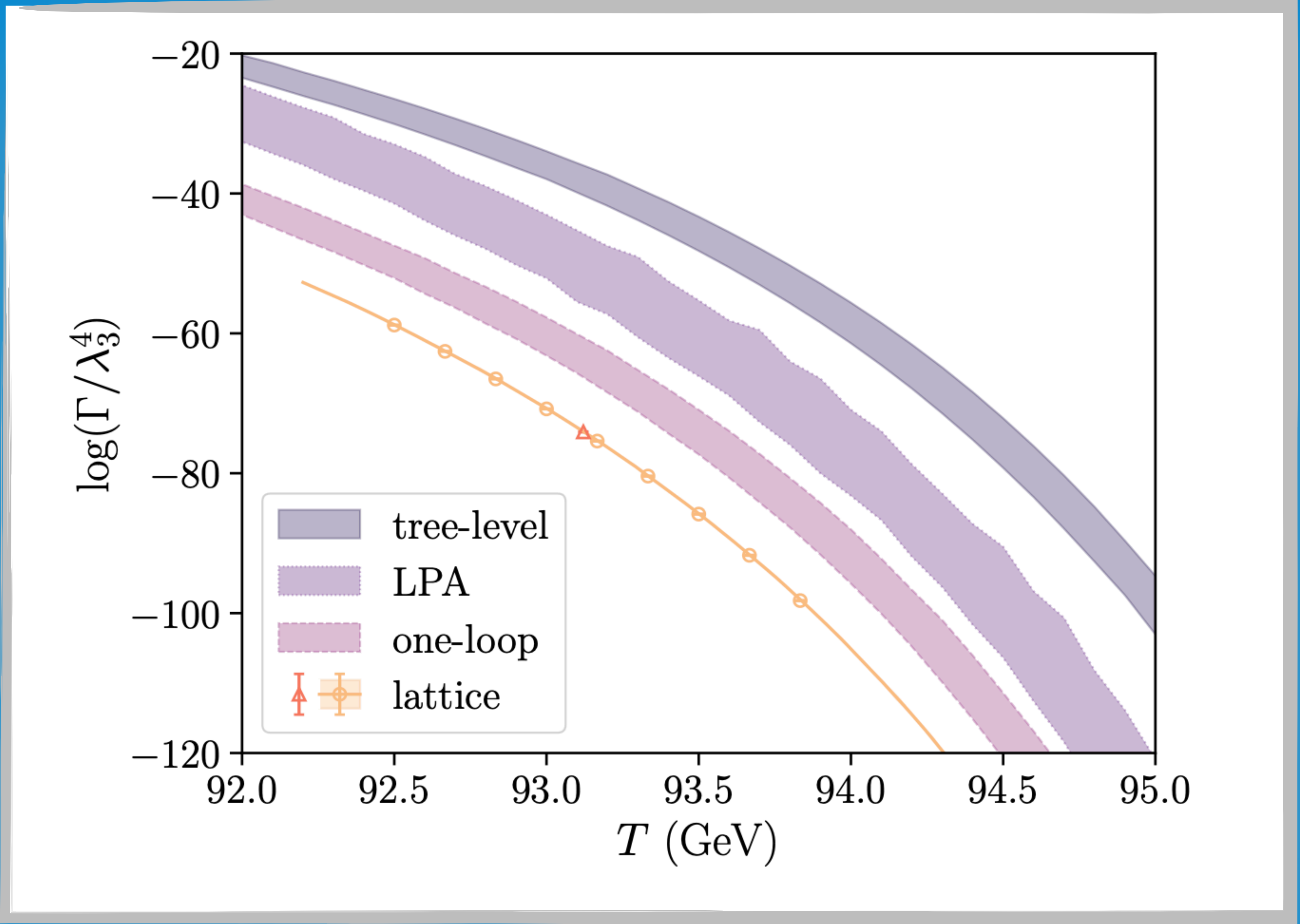




A. Ekstedt, P. Schicho, T. Tenkanen, Phys.Rev.D 110 (2024) 9, 096006

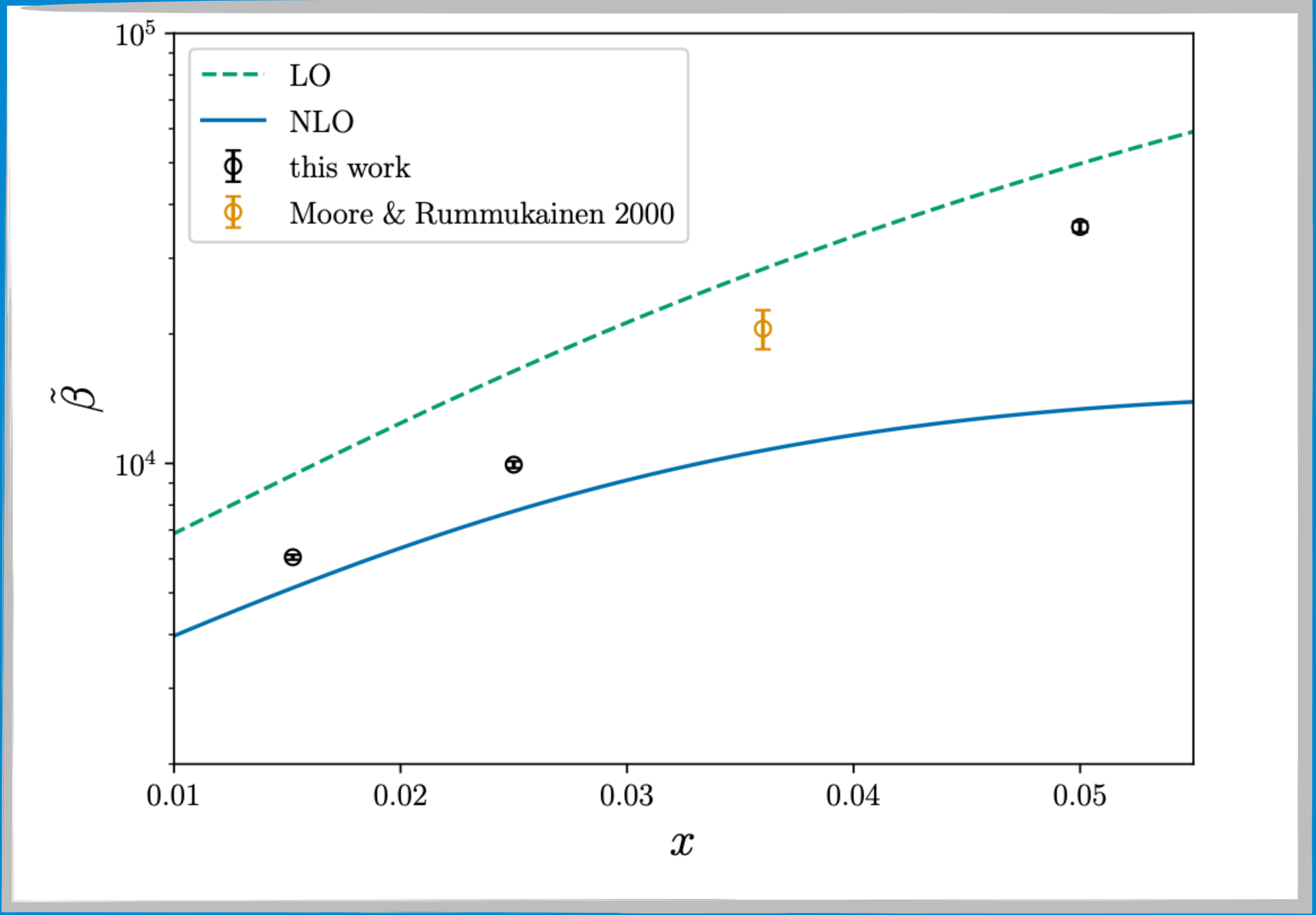
But for nucleation there's still a lot of stuff to do!

Real-scalar model



O. Gould, A. Kormu, D. Weir, Phys.Rev.D 111 (2025) 5, 5

SU(2)+Higgs 3d-EFT



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

Langer's classical nucleation theory

$$\Gamma(T) = A_{\mathrm{dyn}} \times A_{\mathrm{stat}}$$

Non-equilibrium effects

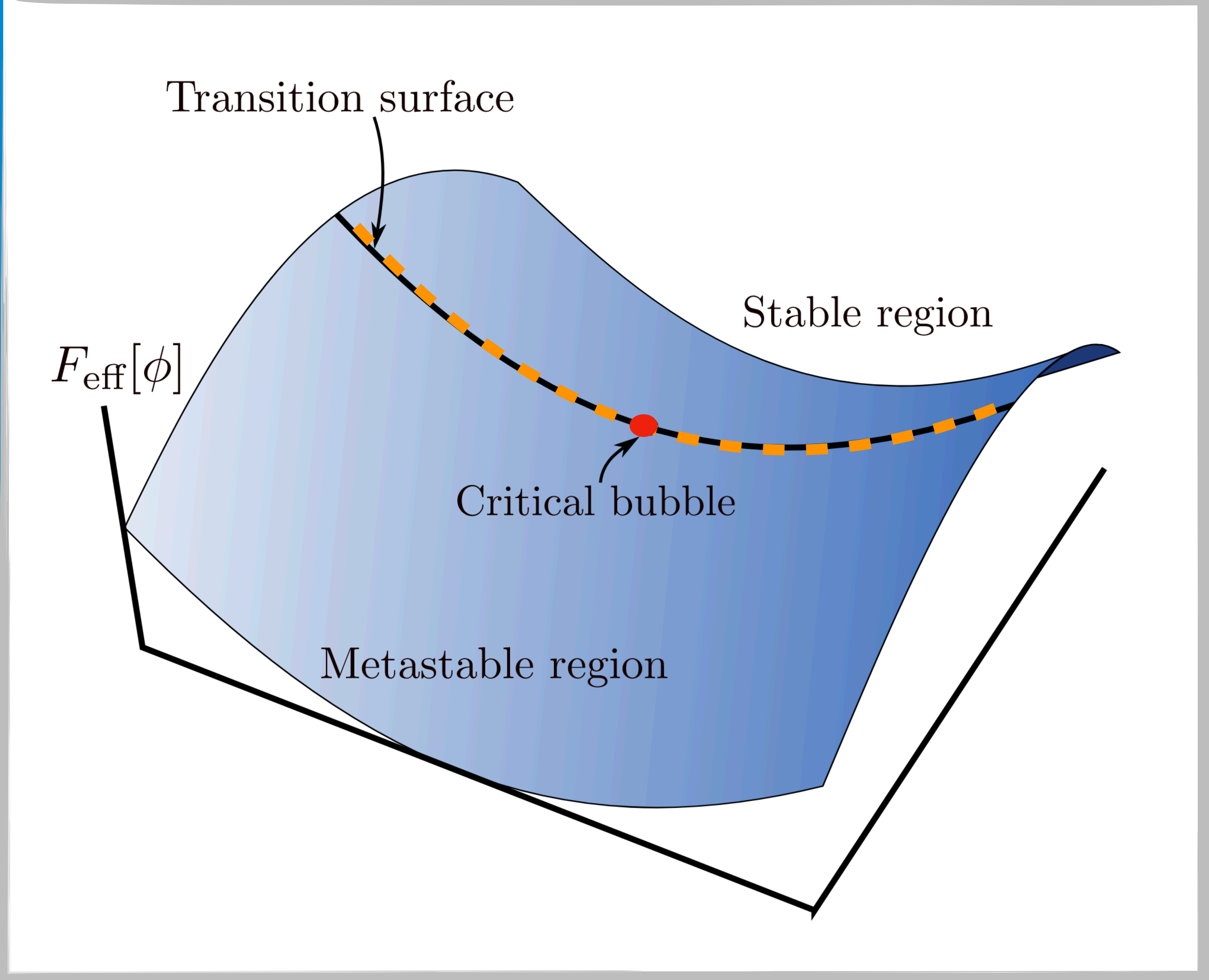
Dimension $[T]$

Equilibrium effects

Dimension $[T^3]$

See also: J.Hirvonen, O. Gould, 2108.04377, J. Hirvonen, 2403.07987, A. Ekstedt 2201.07331

We use a saddle-point of free energy



J.Hirvonen, O. Gould, 2108.04377

Nucleation rate can be obtained as the probability "flux" over the transition surface.

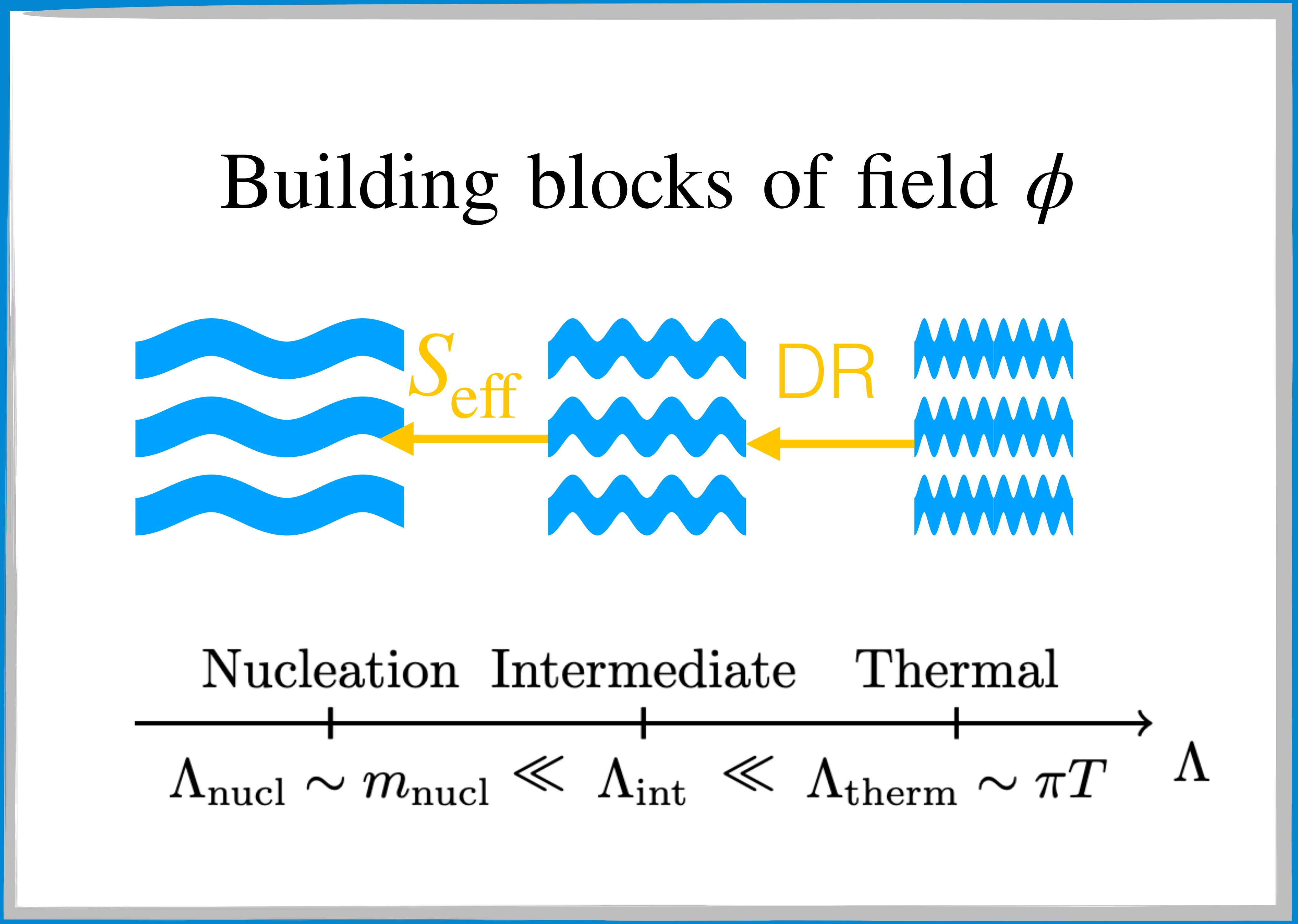
In the saddle-point approximation:

$$A_{\rm stat} \simeq \mathscr{V} \left| \frac{\det F''_{\rm eff}[\phi_{\rm CB}]}{\det F''_{\rm eff}[\phi_{\rm meta}]} \right|^{-\frac{1}{2}} \times e^{-\beta \Delta F_{\rm eff}[\phi_{\rm CB}]}$$

$$A_{\rm dyn} \simeq \sqrt{|\lambda_-|}$$

See also: J.Hirvonen, O. Gould, 2108.04377, J. Hirvonen, 2403.07987, A. Ekstedt 2201.07331

Idea: use EFT for long-range modes



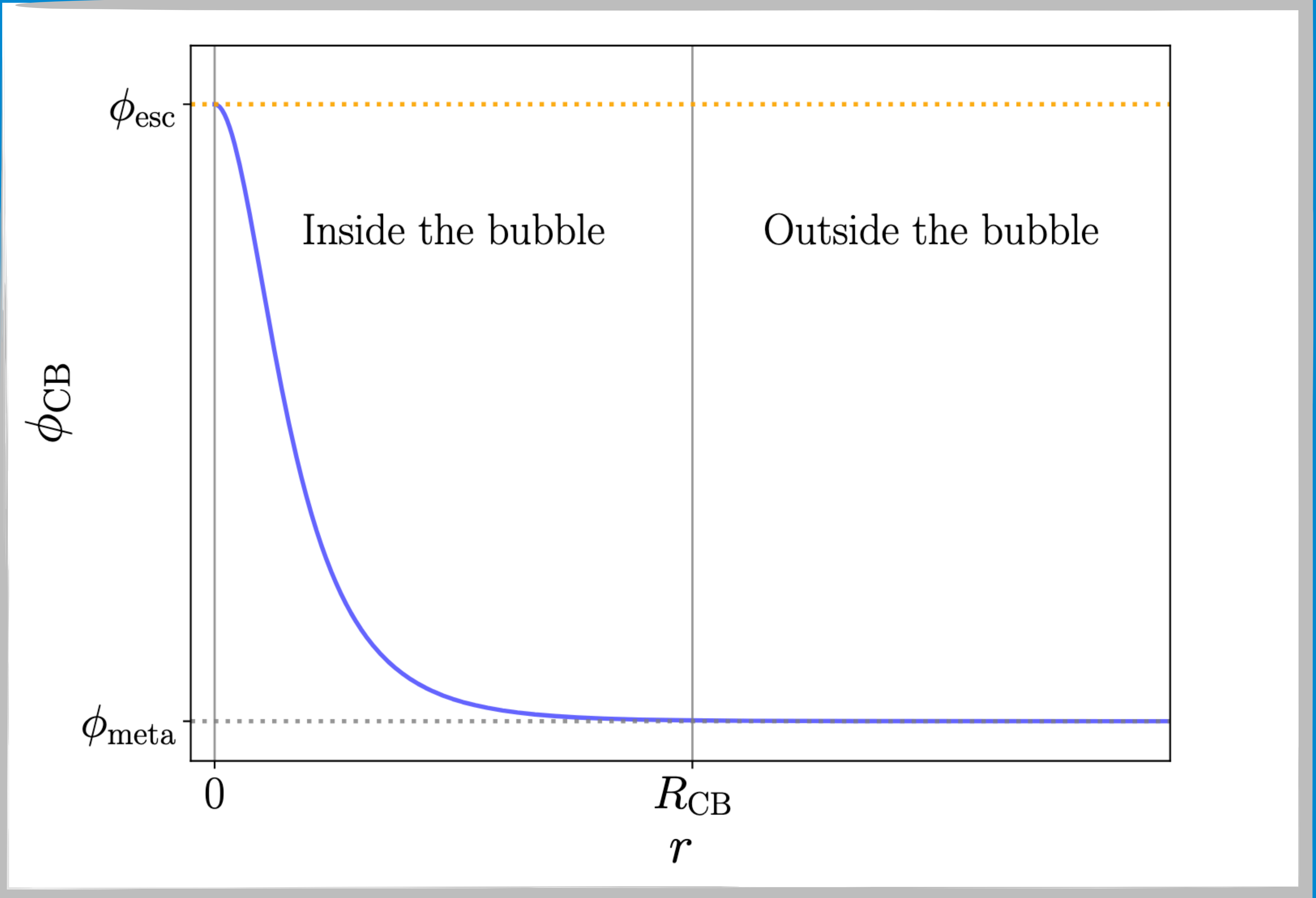
Take quantum fields, integrate out UV modes, and obtain nucleation EFT

$$F_{\text{eff}} \longleftrightarrow S_{\text{nucl}}$$

$$F''_{\text{eff}} \longleftrightarrow S''_{\text{nucl}}$$

See also: J.Hirvonen, O. Gould, 2108.04377, J. Hirvonen, 2403.07987, A. Ekstedt 2201.07331

Idea: use EFT for long-range modes



We expand around the O(3)-symmetric stationary point of the action

$$A_{\rm stat} = \underbrace{\mathscr{V} \left| \frac{\det' S''_{\rm nucl}[\phi_{\rm CB}]}{\det S''_{\rm nucl}[\phi_{\rm meta}]} \right|^{-\frac{1}{2}}}_{\text{modes } E<\Lambda_{\rm nucl}} \underbrace{e^{-\Delta S_{\rm nucl}[\phi_{\rm CB}]}}_{\text{modes } E>\Lambda_{\rm nucl}}$$

See also: J.Hirvonen, O. Gould, 2108.04377, J. Hirvonen, 2403.07987, A. Ekstedt 2201.07331

Nucleation rate in EFT language

$$\Gamma(T) = \sqrt{\lambda_-} \times \mathscr{V} \left| \frac{\det' S''_{\rm nucl}[\phi_{\rm CB}]}{\det S''_{\rm nucl}[\phi_{\rm meta}]} \right|^{-\frac{1}{2}} e^{-\Delta S_{\rm nucl}[\phi_{\rm CB}]}$$

Non-equilibrium effects

Dimension $[T]$

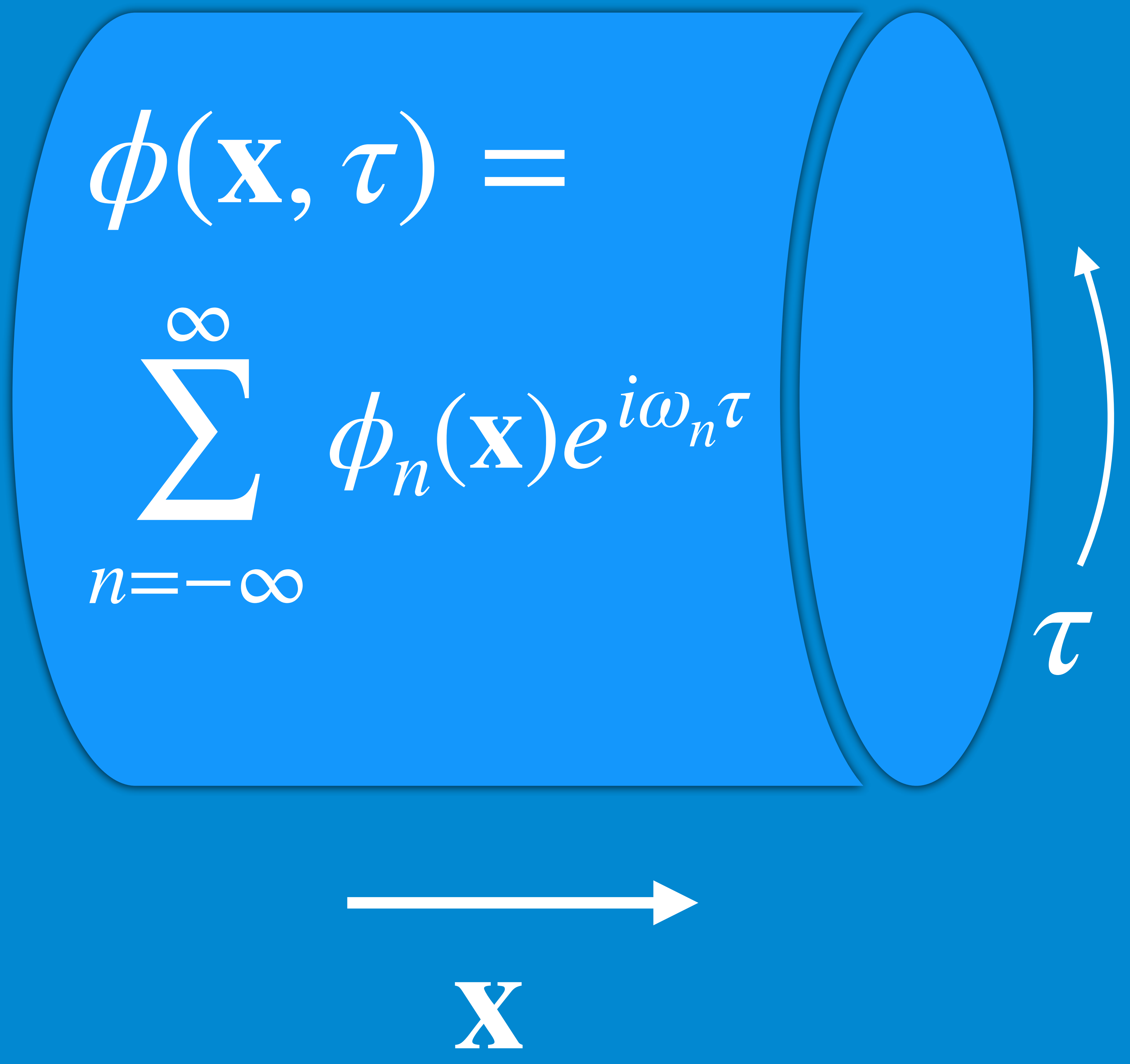
Equilibrium effects

Dimension $[T^3]$

See also: J.Hirvonen, O. Gould, 2108.04377, J. Hirvonen, 2403.07987, A. Ekstedt 2201.07331

Thermal field theory in imaginary time formalism

$$\phi(\mathbf{x}, \tau) = \sum_{n=-\infty}^{\infty} \phi_n(\mathbf{x}) e^{i\omega_n \tau}$$

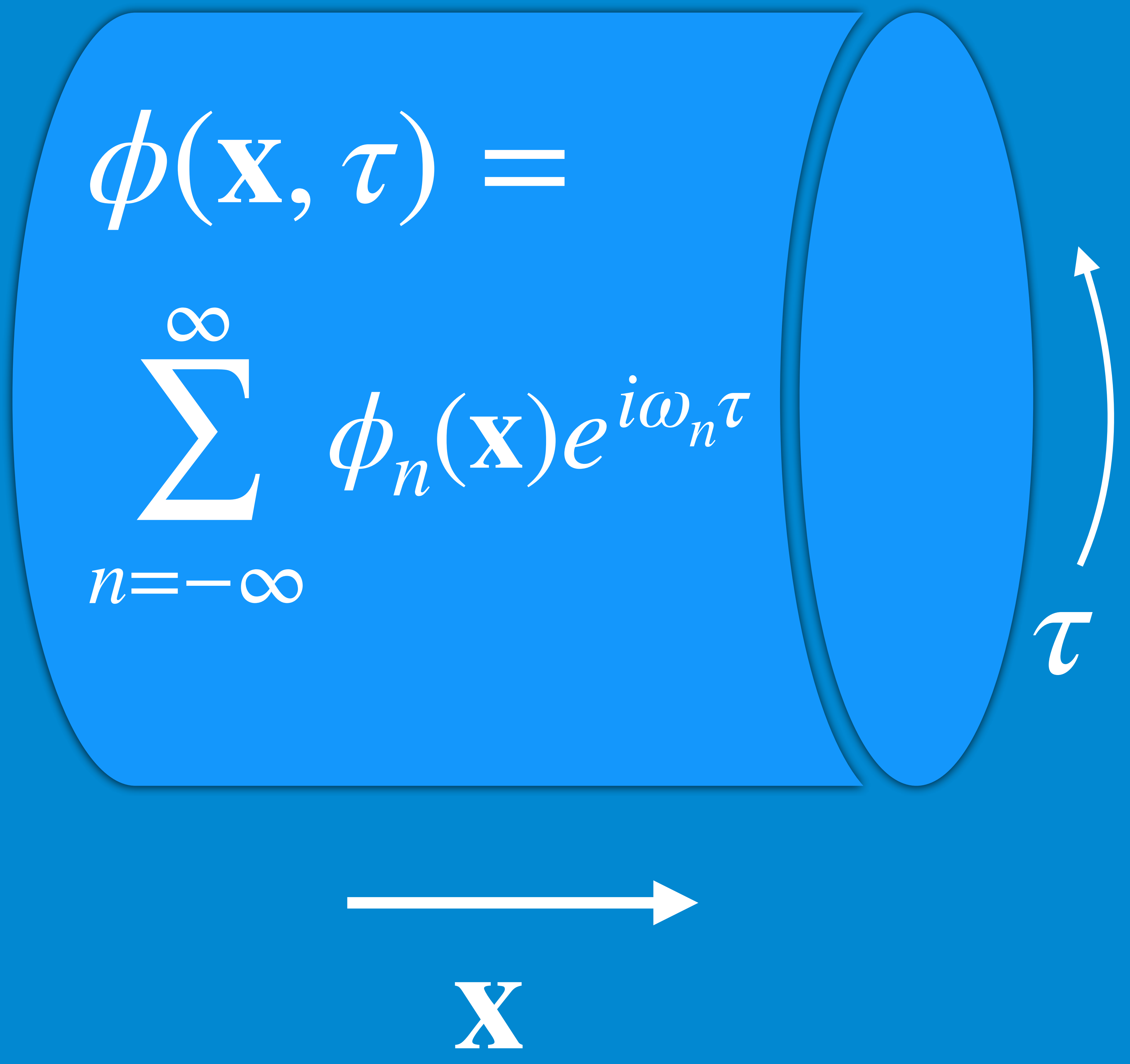


$$\omega_n^{\text{bosons}} = 2\pi T n$$

$$S = \frac{1}{T} \int d^3x \sum_{n=0}^{\infty} \left[\frac{1}{2} (\partial_i \phi_n)^2 + \frac{1}{2} (2\pi n T)^2 \phi_n^2 + \frac{1}{2} m^2 \phi_n^2 \right]$$

See also: M. Laine, A. Vuorinen, "Basics of thermal field theory"

Thermal field theory in imaginary time formalism



$$\omega_n^{\text{bosons}} = 2\pi T n$$

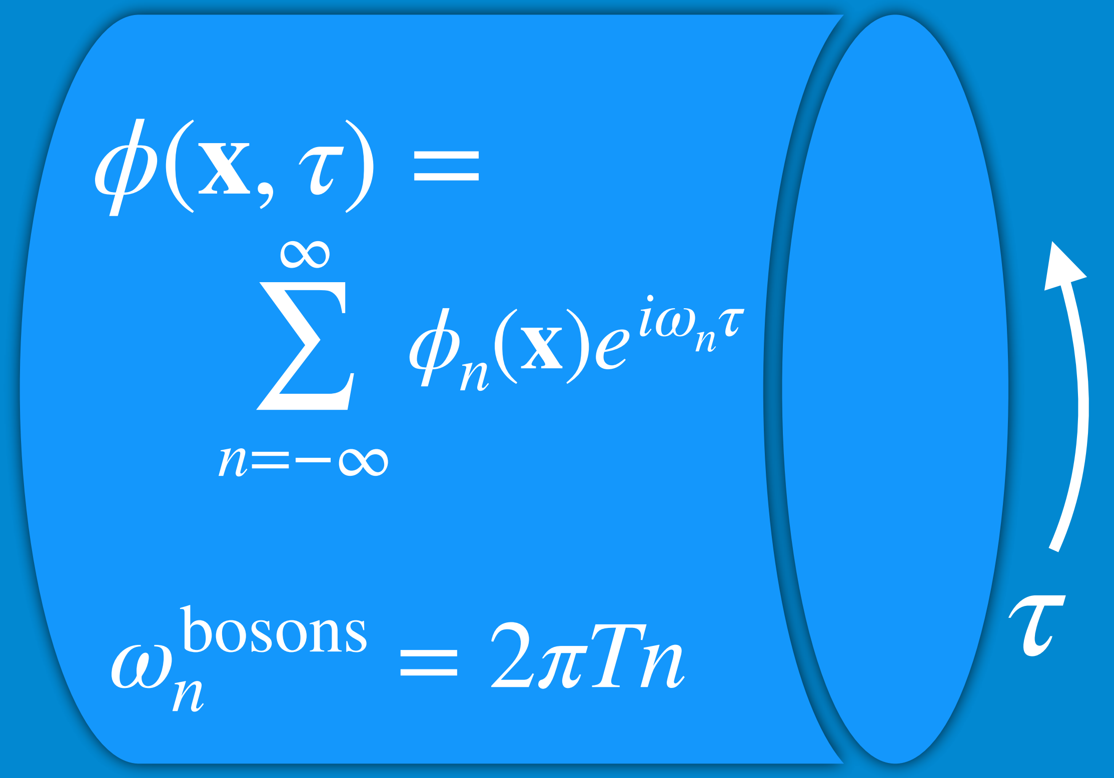
$$S = \frac{1}{T}\int d^3x \sum_{n=0}^{\infty}\left[\frac{1}{2}(\partial_i\phi_n)^2 + \frac{1}{2}(2\pi n T)^2\phi_n^2 + \frac{1}{2}m^2\phi_n^2\right]$$

1. When $T \gg m$, the effective mass is
$M_n^2 \simeq (2\pi n T)^2$

2. There is a hierarchy between the modes
$M_0 \ll M_1 \ll M_2 \ll \dots$

See also: M. Laine, A. Vuorinen, "Basics of thermal field theory"

High-temperature Dimensional Reduction (DR)



$\mathbf{x}$

$\phi_3(\mathbf{x})$

Integrating out $\omega_{n\neq 0}$

$\mathbf{x}$

$$Z = \int D\phi \exp\left(-\int_0^{\frac{1}{T}} \mathrm{d}\tau \int \mathrm{d}^3\mathbf{r} \ \mathscr{L}_E\right) \longrightarrow Z_3 = \int D\phi_{n=0} \exp\left(-\frac{1}{T}\int \mathrm{d}^3\mathbf{r} \ \mathscr{L}_3\right)$$

Fields: ϕ, X

Couplings: g, λ

Fields: $\phi_3, X_3, X_{0,3}$

Couplings: $m_3(T), g_3(T), \lambda_3(T)$

High-temperature Dimensional Reduction (DR)

$$\phi(\mathbf{x}, \tau) = \sum_{n=-\infty}^{\infty} \phi_n(\mathbf{x}) e^{i\omega_n \tau}$$

$$\omega_n^{\text{bosons}} = 2\pi T n$$

τ

$\mathbf{x}$

Integrating out

$\omega_{n\neq 0}$

$m_3(T), g_3(T), \lambda_3(T)$

$\mathbf{x}$

πT	Hard
$g T$	Soft
$\frac{1}{\sqrt{\pi}} g^{3/2} T$	Supersoft
$\frac{1}{\pi} g^2 T$	Ultrasoft

Soft scale 3d EFT

The action of the 3d theory becomes

$$S_3 = \int \mathrm{d}^3\mathbf{x} \left\{ \frac{1}{4} F^a_{ij} F^a_{ij} + \left(D_i \phi\right)^\dagger \left(D_i \phi\right) + \frac{1}{2}\left(D_i X^a_0\right)^2 + V_3\left(\phi, X^a_0\right) \right\}$$

The potential of scalar field is simple

$$V_3 = \frac{1}{2} m_3^2 \phi_3^2 + \frac{1}{4} \lambda_3 \phi_3^4$$

$$m_3 \sim m_D = gT \neq 0$$

$$m^2_{X,3} = \frac{1}{4} g^2_{X,3} \phi_3^2, \quad m^2_{X_0,3} = m^2_{D,X} + \frac{1}{2} h_3 \phi_3^2 .$$

See also: MK, B. Świeżewska, T.V.I Tenkanen, J. van de Vis, 2312.12413

Soft scale 3d EFT

The action of the 3d theory becomes

$$S_3 = \int d^3\mathbf{x} \left\{ \frac{1}{4} F^a_{ij} F^a_{ij} + \left(D_i\phi\right)^\dagger \left(D_i\phi\right) + \frac{1}{2}\left(D_i X^a_0\right)^2 + V_3\left(\phi, X^a_0\right) \right\}$$

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$$V_3 = \frac{1}{2} m_3^2 \phi_3^2 + \frac{1}{4} \lambda_3 \phi_3^4$$

Thermal mass

$$m_3 \sim m_D = gT \neq 0$$

$$m^2_{X,3} = \frac{1}{4} g^2_{X,3}\phi_3^2, \quad m^2_{X_0,3} = m^2_{D,X} + \frac{1}{2} h_3 \phi_3^2 .$$

See also: MK, B. Świeżewska, T.V.I Tenkanen, J. van de Vis, 2312.12413

Effective action perturbatively

$$S_{\text{eff}}[\phi_b] = \underbrace{S^{\text{LO}}[\phi_b^{\text{LO}}]}_{\mathcal{O}(g^3)} + \underbrace{S^{\text{NLO}}[\phi_b^{\text{LO}}]}_{\mathcal{O}(g^4)} + \ldots$$

I will refer to this as *soft expansion*

One can get to NLO just with the LO bounce solution!

See also: A. Ekstedt 2201.07331, 2104.11804

Computing effective action - 3D toy model

$$\mathscr{L}_3 = \frac{1}{2}(\partial_i\Phi)^2 + \frac{1}{2}(\partial_i\chi)^2 + \frac{1}{2}m^2\Phi^2 + \frac{\lambda}{4}\Phi^4 + \kappa\chi^2\Phi^2 + \frac{1}{2}M^2\chi^2$$

Expand field on its background

$$\Phi \rightarrow \phi_b(r) + H(x)$$

At 1-loop we need quadratic terms only

$$\mathscr{L} \supset \chi \underbrace{\left(-\nabla^2 + M^2 + \kappa\phi_b^2\right)}_{\mathscr{M}_\chi} \chi$$

Performing the $\int \mathscr{D}\chi$

$$e^{iS_{\mathrm{eff}}[\phi_b]} \sim \left[\det\left(-\nabla^2 + M^2 + \kappa\phi_b^2\right)\right]^{-\frac{1}{2}} e^{-S_3[\phi_b]}$$

Computing 1PI effective action - 3D toy model

$$\mathscr{L}_3 = \frac{1}{2}(\partial_i\Phi)^2 + \frac{1}{2}(\partial_i\chi)^2 + \frac{1}{2}m^2\Phi^2 + \frac{\lambda}{4}\Phi^4 + \kappa\chi^2\Phi^2 + \frac{1}{2}M^2\chi^2$$

Integrating out both

χ- and H-fluctuations

$$e^{i(S_{\text{eff}}[\phi_b]-S_{\text{eff}}[\phi_F])} \sim \underbrace{\left|\frac{\det'\left(\partial^2 + V''[\phi_b]\right)}{\det\left(\partial^2 + V''[\phi_F]\right)}\right|^{-\frac{1}{2}}}_{E<\Lambda\sim m} \underbrace{\left[\frac{\det\left(-\nabla^2 + M^2 + \kappa\phi_b^2\right)}{\det\left(-\nabla^2 + M^2 + \kappa\phi_F^2\right)}\right]^{-\frac{1}{2}} e^{-(S_3[\phi_b]-S_3[\phi_F])}}_{E>\Lambda\sim m}$$

1-loop nucleation rate in gauge-scalar 3D EFT

$$\Gamma = A_{\mathrm{dyn}} \underbrace{\mathrm{Det}_S}_{E<\Lambda} \underbrace{\mathrm{Det}_{X_0} \mathrm{Det}_{XG}\, e^{-\Delta S_3[\phi_{\mathrm{b}}]}}_{E>\Lambda}$$

Derivative expansion of gauge-Goldstone det

$$\boxed{\frac{m_3}{m_X} \ll 1}$$

$$\delta Z = -\frac{11}{16\pi}\frac{g_3}{\phi_b}$$

$$-\log \mathrm{Det}_{XG} \simeq \underbrace{\int_x \frac{-3}{48\pi} g^3 \phi_b^3}_{\mathcal{O}(g^3)\ \mathrm{LO}} + \underbrace{\int_x \frac{1}{2}\delta Z[\phi_b](\partial\phi_b)^2}_{\mathcal{O}(g^4)\ \mathrm{NLO}} + \ldots$$

Barrier generating term

Terms with higher powers in derivatives

See also: A. Ekstedt, O. Gould, J. Hirvonen, 2308.15652; A. Ekstedt 2104.11804, J. Hirvonen et al 2112.08912, MK, B. Świeżewska, T.V.I Tenkanen, J. van de Vis, 2312.12413

Reminder:

$$S_{\text{eff}}[\phi_b] = \underbrace{S^{\text{LO}}[\phi_b^{\text{LO}}]}_{\mathcal{O}(g^3)} + \underbrace{S^{\text{NLO}}[\phi_b^{\text{LO}}]}_{\mathcal{O}(g^4)} + \ldots$$

$$S^{\text{LO}}[\phi_b^{\text{LO}}] = 4\pi \int \mathrm{d}r\ r^2 \left[\frac{1}{2}\left(\partial_i \phi_b^{\text{LO}}\right)^2 + V^{\text{LO}}[\phi_b^{\text{LO}}]\right]$$

$$S^{\text{NLO}}[\phi_b^{\text{LO}}] = 4\pi \int \mathrm{d}r\ r^2 \left[\frac{1}{2}\delta Z[\phi_b](\partial\phi_b)^2 + V^{\text{NLO}}[\phi_b^{\text{LO}}]\right]$$

$$V^{\text{LO}}[\phi_b^{\text{LO}}] = \frac{1}{2}m_3^2\phi_3^2 + \frac{1}{4}\lambda_3\phi_3^4 - \frac{1}{12\pi}\left(6(m_{X,3}^2)^{\frac{3}{2}} + 3(m_{X_0,3}^2)^{\frac{3}{2}}\right)$$

$\mathcal{O}(\partial^0)$-terms in deriv. expansion of gauge dets

See also: MK, B. Świeżewska, T.V.I Tenkanen, J. van de Vis, 2312.12413

Reminder:

$$S_{\text{eff}}[\phi_b] = \underbrace{S^{\text{LO}}[\phi_b^{\text{LO}}]}_{\mathcal{O}(g^3)} + \underbrace{S^{\text{NLO}}[\phi_b^{\text{LO}}]}_{\mathcal{O}(g^4)} + \ldots$$

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$$S^{\text{NLO}}[\phi_b^{\text{LO}}] = 4\pi \int \mathrm{d}r\ r^2 \left[\frac{1}{2}\delta Z[\phi_b](\partial \phi_b)^2 + V^{\text{NLO}}[\phi_b^{\text{LO}}]\right]$$

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$\mathcal{O}(\partial^2)$-terms in the expansion of gauge determinants

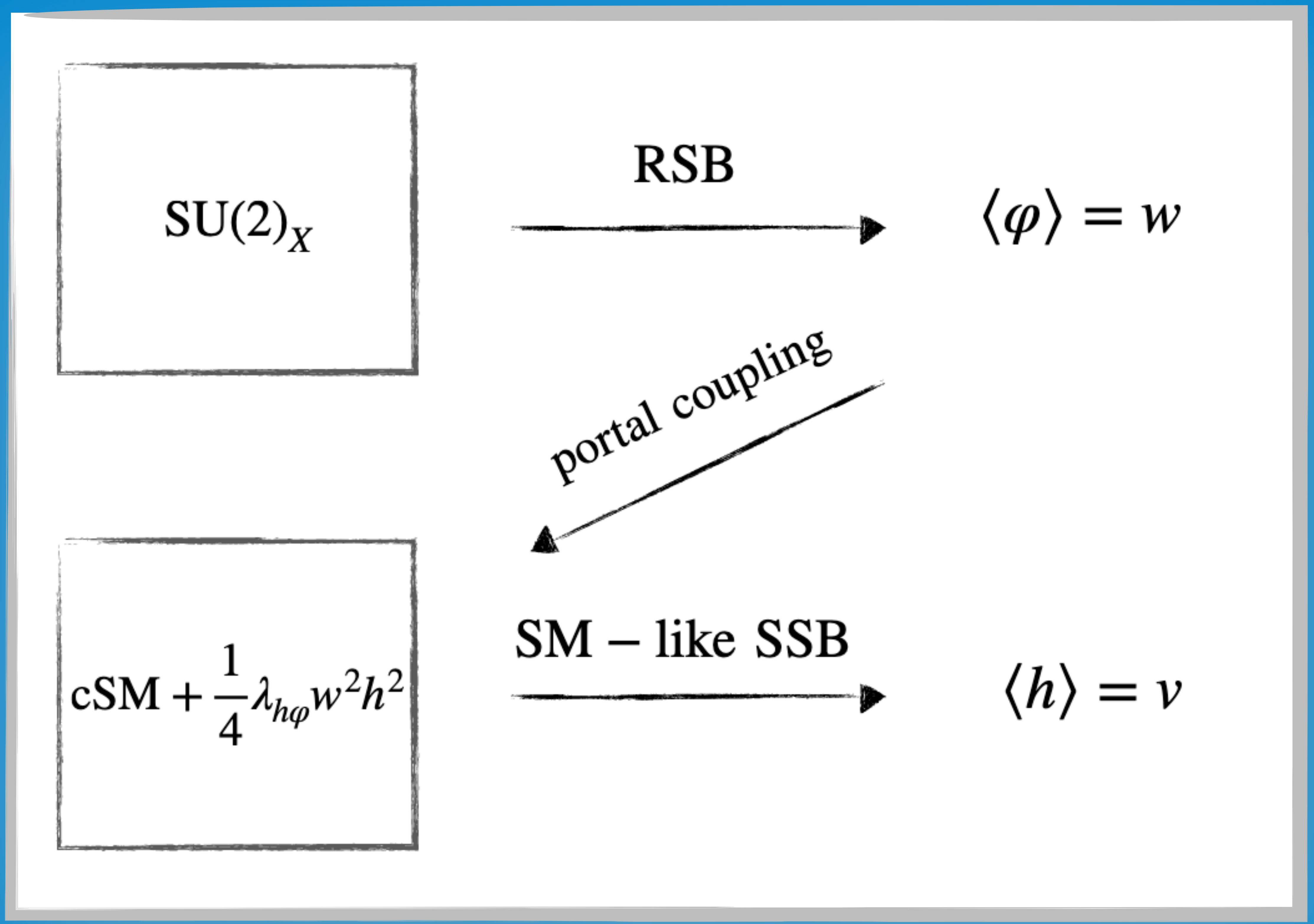
$\mathcal{O}(\partial^0)$-terms in expansion of gauge determinants

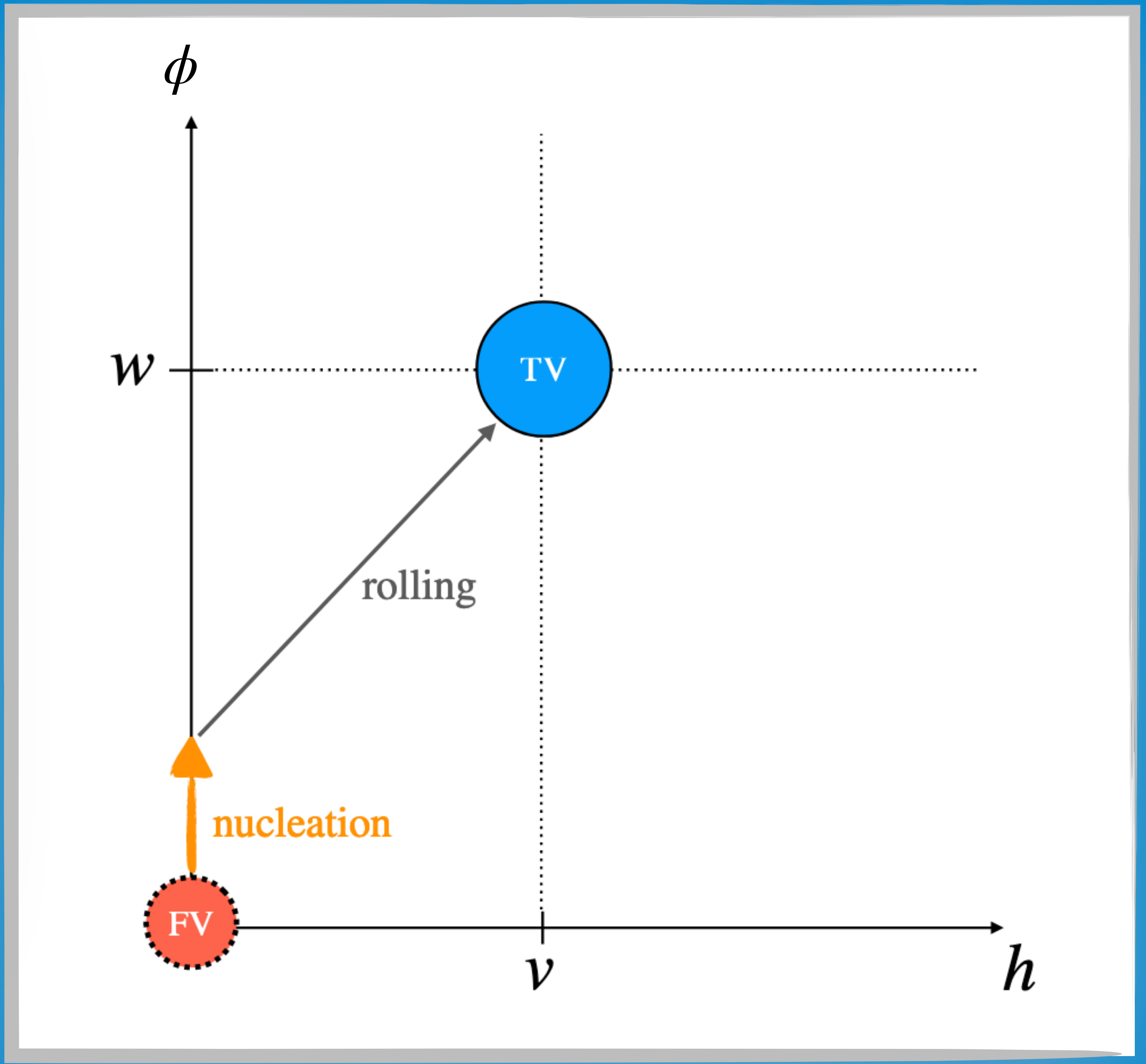
2-loop gauge contributions to the effective potential

See also: MK, B. Świeżewska, T.V.I Tenkanen, J. van de Vis, 2312.12413

Q: Is derivative expansion always valid? What are the errors? 🤔

Benchmark BSM model: SU(2)cSM

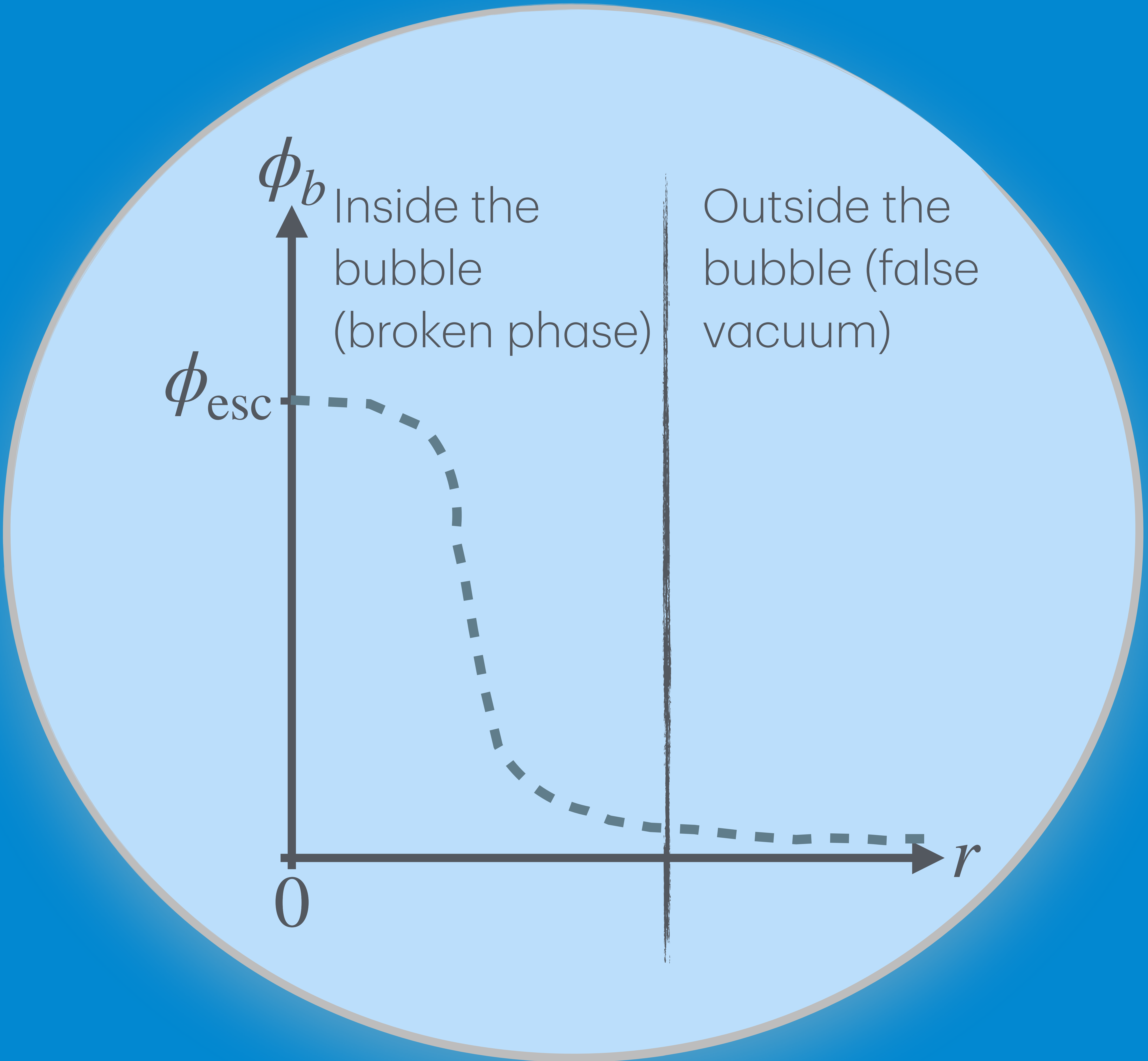




$$V_{\rm tree} = \frac{1}{4}\left(\lambda_1 h^4 + \lambda_2 h^2 \phi^2 + \lambda_3 \phi^4\right)$$

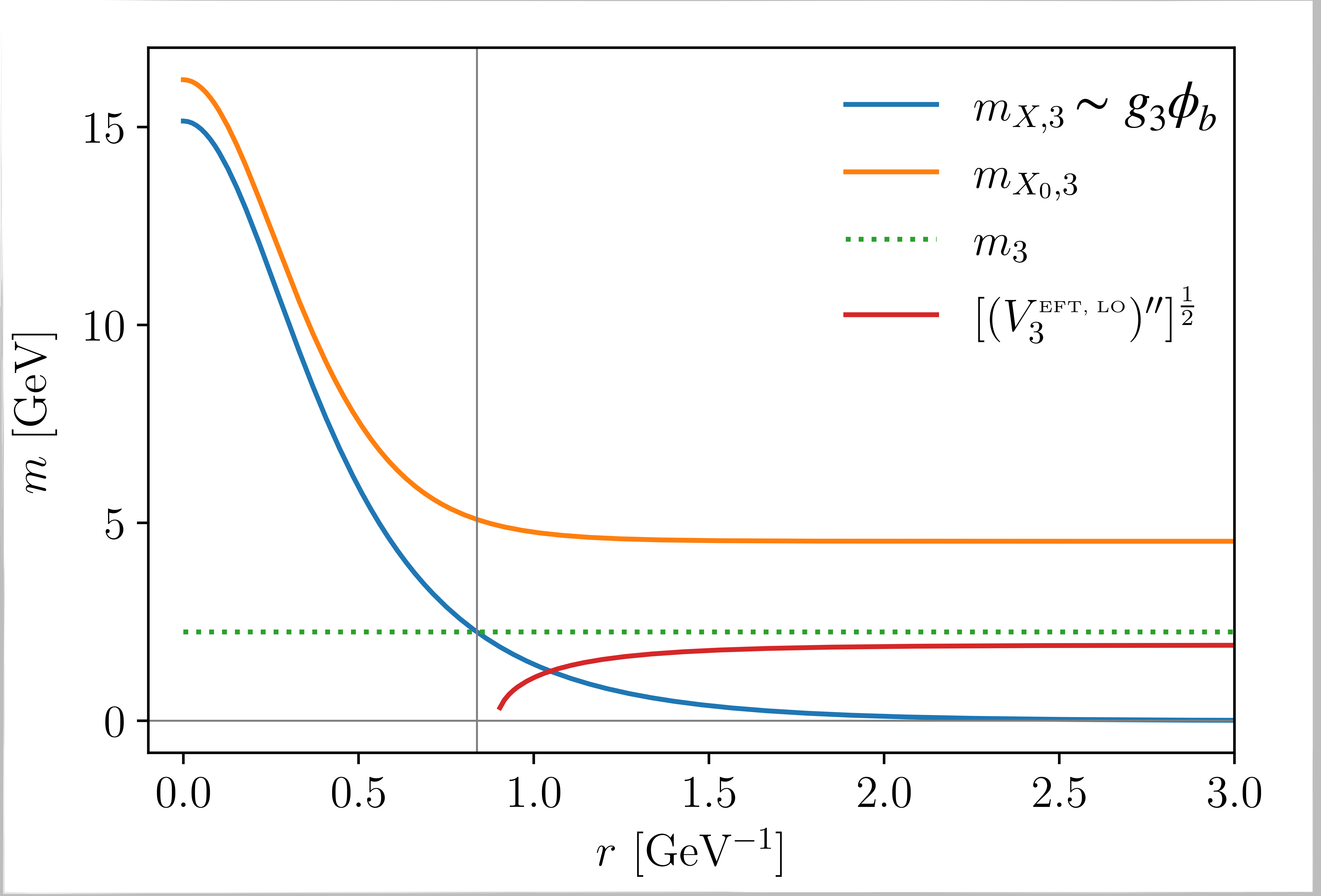
See also: C. D. Carone et al, 1307.8428, T. Hambye et al, 1306.2329, D. Marfatia et al, 2006.07313, I. Baldes et al, 1809.01198

LO bounce solution



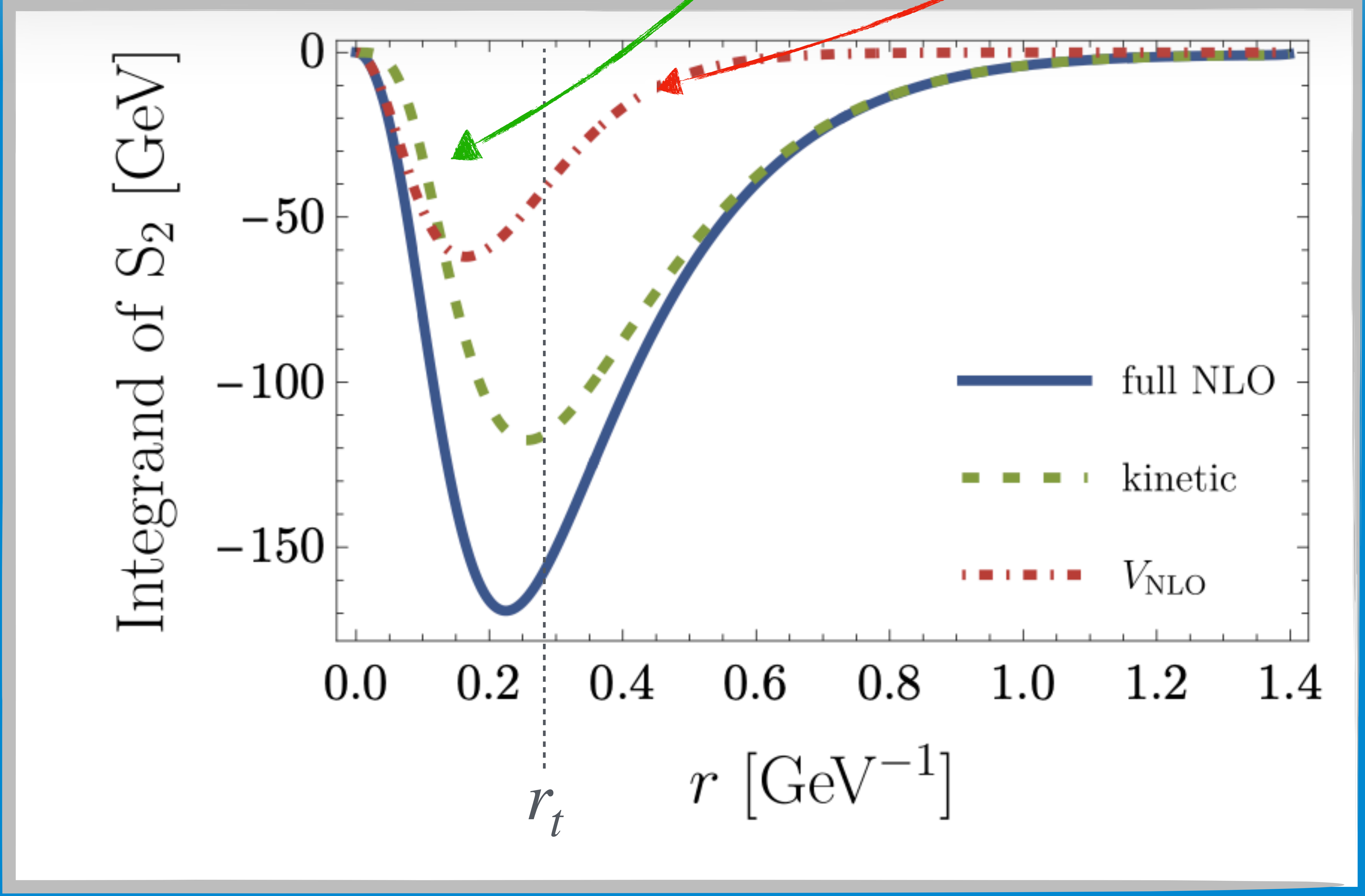
See also: S. Coleman Phys.Rev.D 15 (1977), A. Ekstedt 2201.07331, 2104.11804

Scale-shifters in SU(2)cSM



Z-factor contribution dominates the NLO terms

$$S_2 = S^{\mathrm{NLO}}[\phi_b^{\mathrm{LO}}] = 4\pi \int \mathrm{d}r\ r^2 \left[\frac{1}{2}\delta Z[\phi_b](\partial\phi_b)^2 + V^{\mathrm{NLO}}[\phi_b^{\mathrm{LO}}]\right]$$



See also: MK, B. Świeżewska, T.V.I Tenkanen, J. van de Vis, 2312.12413

Higher-order momentum terms of gauge-goldstone det

$$S_3^{\rm EFT}[v_{3,b}] \supset \int_{\mathbf{x}} \Big[V^{\rm EFT}(v_3) + \frac{1}{2} Z_{2,3} (\partial_i v_3)^2 + \frac{1}{2} Z_{4,3} (\partial^2 v_3)^2 \\ + \frac{1}{2} Y_{3,3} (\partial_i v_3)^2 \partial^2 v_3 + \frac{1}{8} Y_{4,3} (\partial_i v_3)^2 (\partial_j v_3)^2 + \mathcal{O}(\partial^6) \Big] \,,$$

See also: MK, P. Schicho B. Świeżewska, T.V.I Tenkanen, J. van de Vis, 2503.13597

Higher-order momentum terms

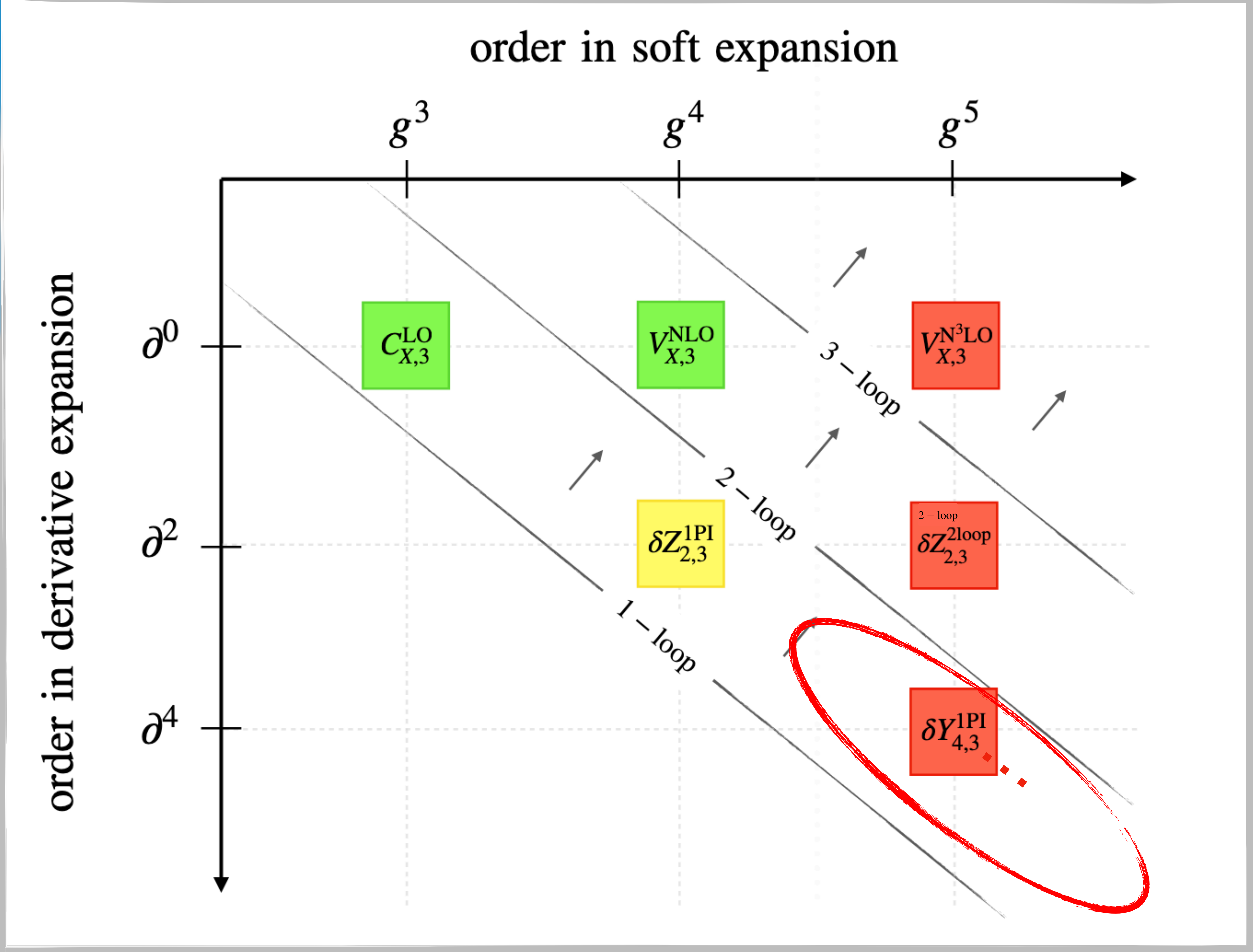
(Also blows-up at 2-loop)

$$S_3^{\mathrm{EFT}}[v_{3,b}] \supset \int_{\mathbf{x}} \Big[V^{\mathrm{EFT}}(v_3) + \frac{1}{2} Z_{2,3} (\partial_i v_3)^2 + \frac{1}{2} Z_{4,3} (\partial^2 v_3)^2 + \frac{1}{2} Y_{3,3} (\partial_i v_3)^2 \partial^2 v_3 + \frac{1}{8} Y_{4,3} (\partial_i v_3)^2 (\partial_j v_3)^2 + \mathcal{O}(\partial^6) \Big] ,$$

All of the red terms are divergent at large radius

See also: MK, P. Schicho B. Świeżewska, T.V.I Tenkanen, J. van de Vis, 2503.13597

$$S_3^{\mathrm{EFT}}[v_{3,b}] \supset \int_{\mathbf{x}} \Big[V^{\mathrm{EFT}}(v_3) + \frac{1}{2} Z_{2,3} (\partial_i v_3)^2 + \frac{1}{2} Z_{4,3} (\partial^2 v_3)^2 + \frac{1}{2} Y_{3,3} (\partial_i v_3)^2 \partial^2 v_3 + \frac{1}{8} Y_{4,3} (\partial_i v_3)^2 (\partial_j v_3)^2 + \mathcal{O}(\partial^6) \Big] ,$$



See also: MK, B. Świeżewska, T.V.I Tenkanen, J. van de Vis, 2312.12413

Q: Is derivative expansion always valid?

A: Nope 😢, gauge modes always break derivative expansion

Fluctuation determinants strike again

how to install bubbledet

Tryb AI | Wszystko | Krótkie filmy | Wideo | Grafika | Zakupy | Wiadomości | Więcej

Przegląd od AI

You can install BubbleDet by running `pip install BubbleDet` or `conda install -c conda-forge BubbleDet` in your terminal. University of Helsinki

`BubbleDet`: A Python package to compute functional determinants for bubble nucleation

Andreas Ekstedt*[1], Oliver Gould†[2], and Joonas Hirvonen‡[3]

(Works only for 1d operators!)

Me, spring of 2024

what is gelfand yaglom theorem

Wszystko | Grafika | Wideo | Krótkie filmy | Wiadomości | Sieć | Książki | Więcej

The Gelfand-Yaglom formula relates functional determinants of the one-dimensional second order differential operators to the solutions of the corresponding initial value problem. 8 sie 2018

See also: MK, P. Schicho B. Świeżewska, T.V.I Tenkanen, J. van de Vis, 2503.13597

Joonas & Oliver recipe for taming scale-shifters

[NLO det] recipe

Step 1. Obtain LO bounce solution ϕ_b^{LO} using S^{LO} (grad. expan.)

Step 2. Evaluate determinants numerically $\mathrm{Det}_{VG}[\phi_b^{\mathrm{LO}}]$

Step 2. Get the NLO bosons contribution $S^{\mathrm{NLO}} \sim V_3^{\mathrm{NLO}}$ on ϕ_b^{LO}

Step 3. Obtain the action

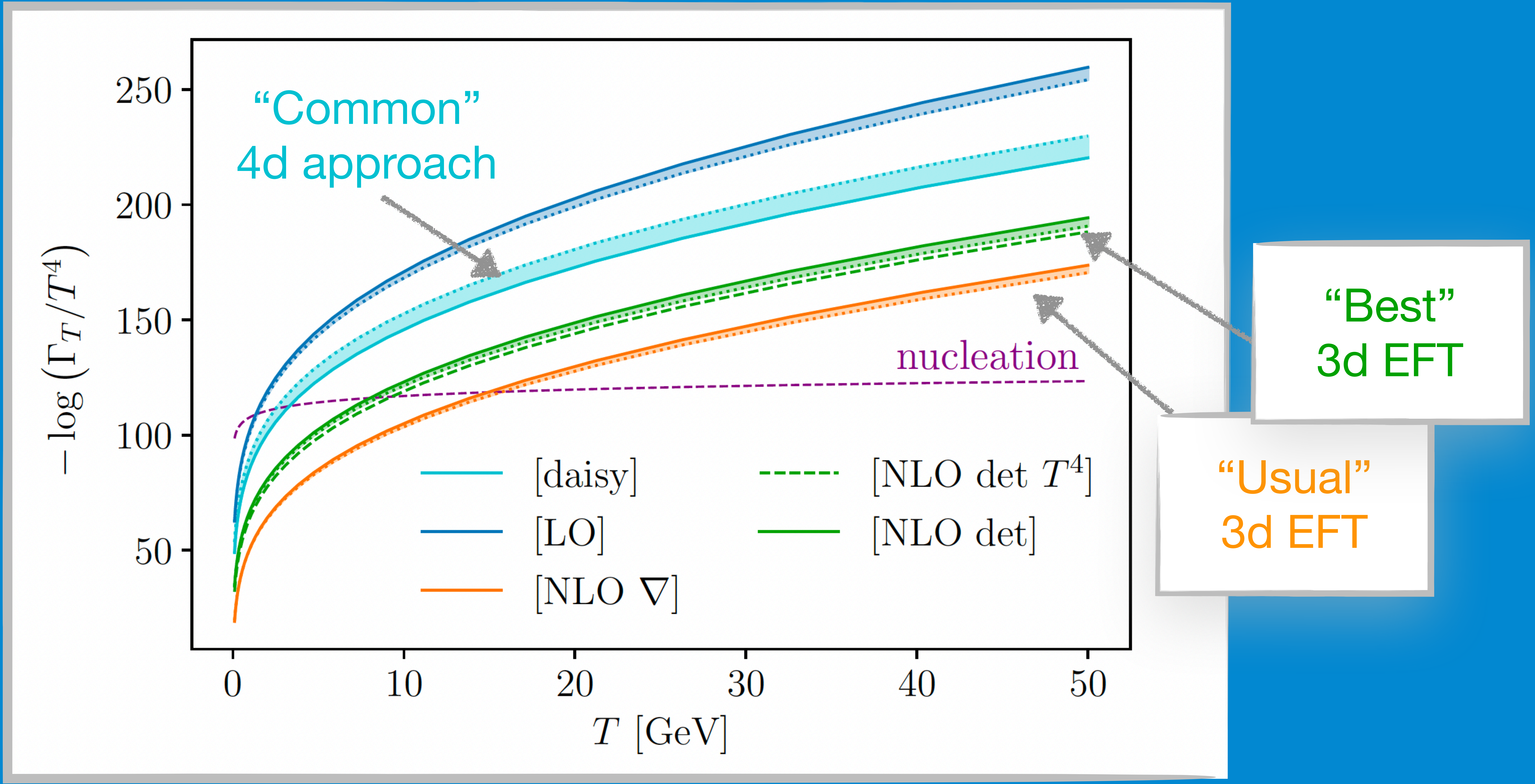
$$S_{\mathrm{eff}} = (S^{\mathrm{LO}} - S^{\mathrm{LO}}_{\mathrm{bosons}}) - \log \mathrm{Det}_{VG} - S^{\mathrm{pot}}_{\mathrm{NLO}}$$

Step 4. Calculate nucleation rate

$$\Gamma_T = A_{\mathrm{dyn}}\, \mathrm{Det}_H\, e^{-S_{\mathrm{eff}}[\phi_b]}$$

See also: O. Gould, J. Hirvonen, 2108.04377, MK, P. Schicho, B. Świeżewska, T. Tenkanen, J. Van de Vis 2503.13597

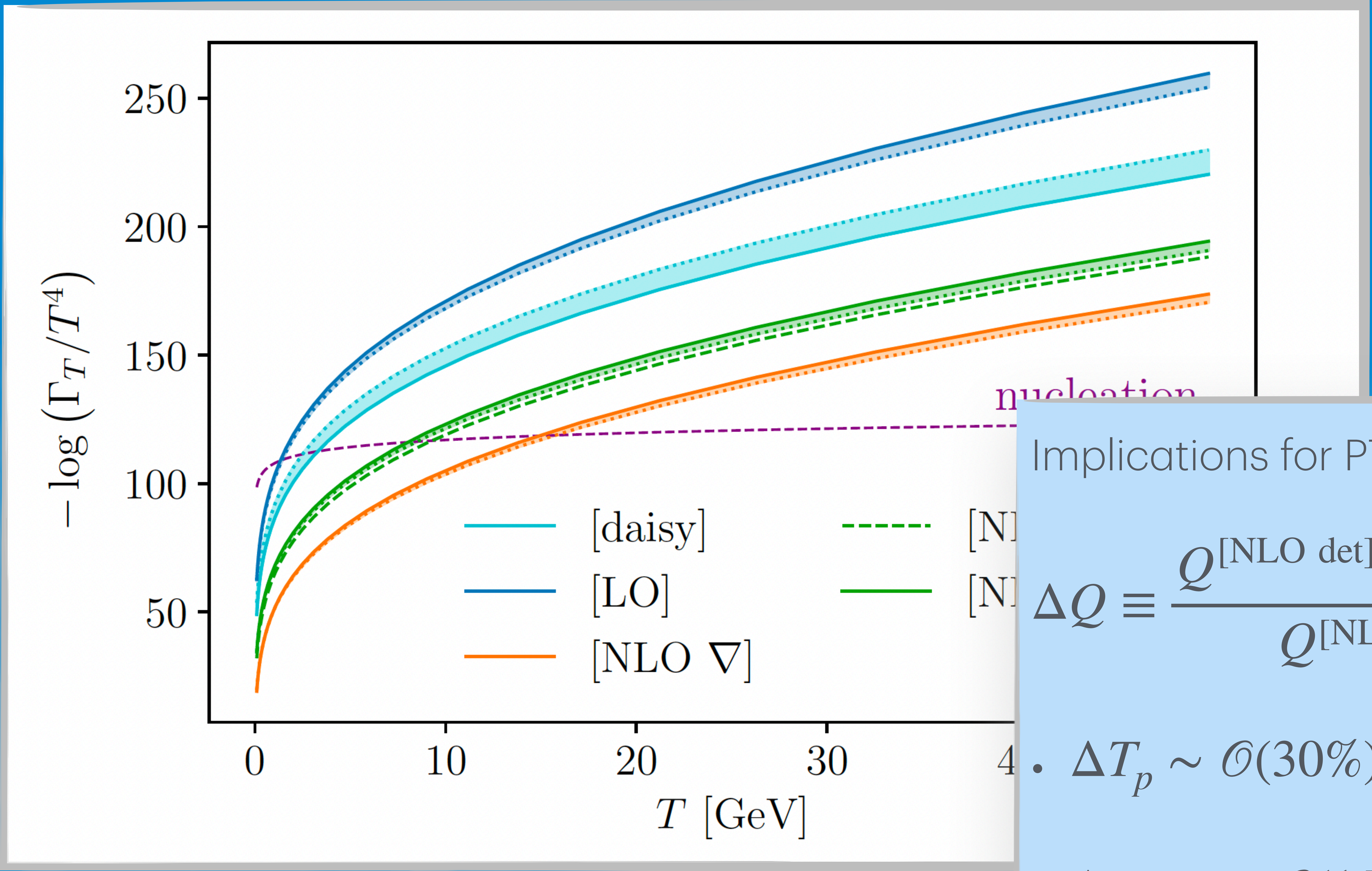
Results: nucleation rate from different "recipes"



Note:
$A_{\rm dyn}\det_S \simeq T^4$
everywhere
except [NLO det]

[2503.13597, with P. Schicho, B. Świeżewska, T.V.I. Tenkanen and J. van de Vis,]

Results: nucleation rate from different "recipes"



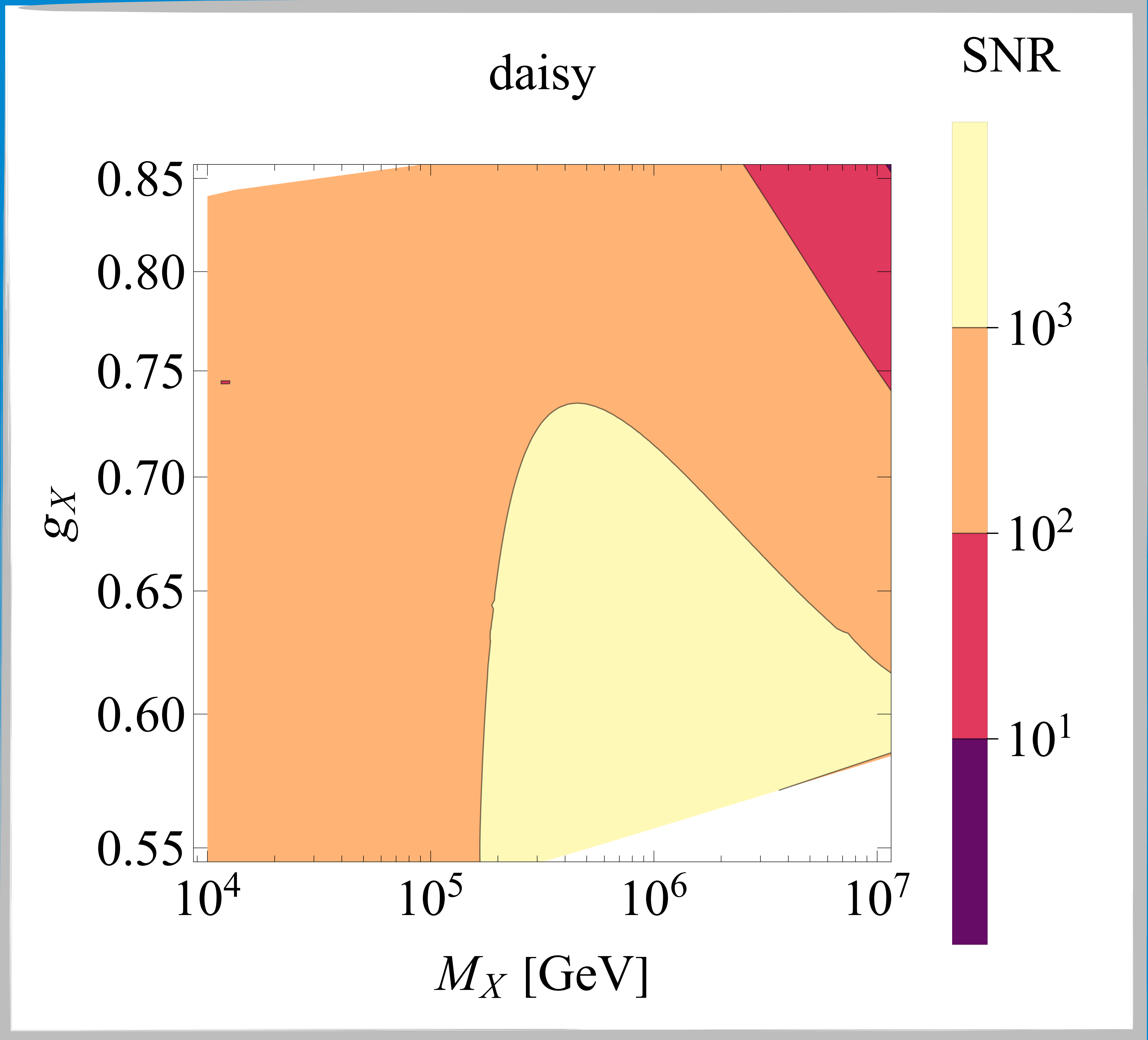
Implications for PT parameters:

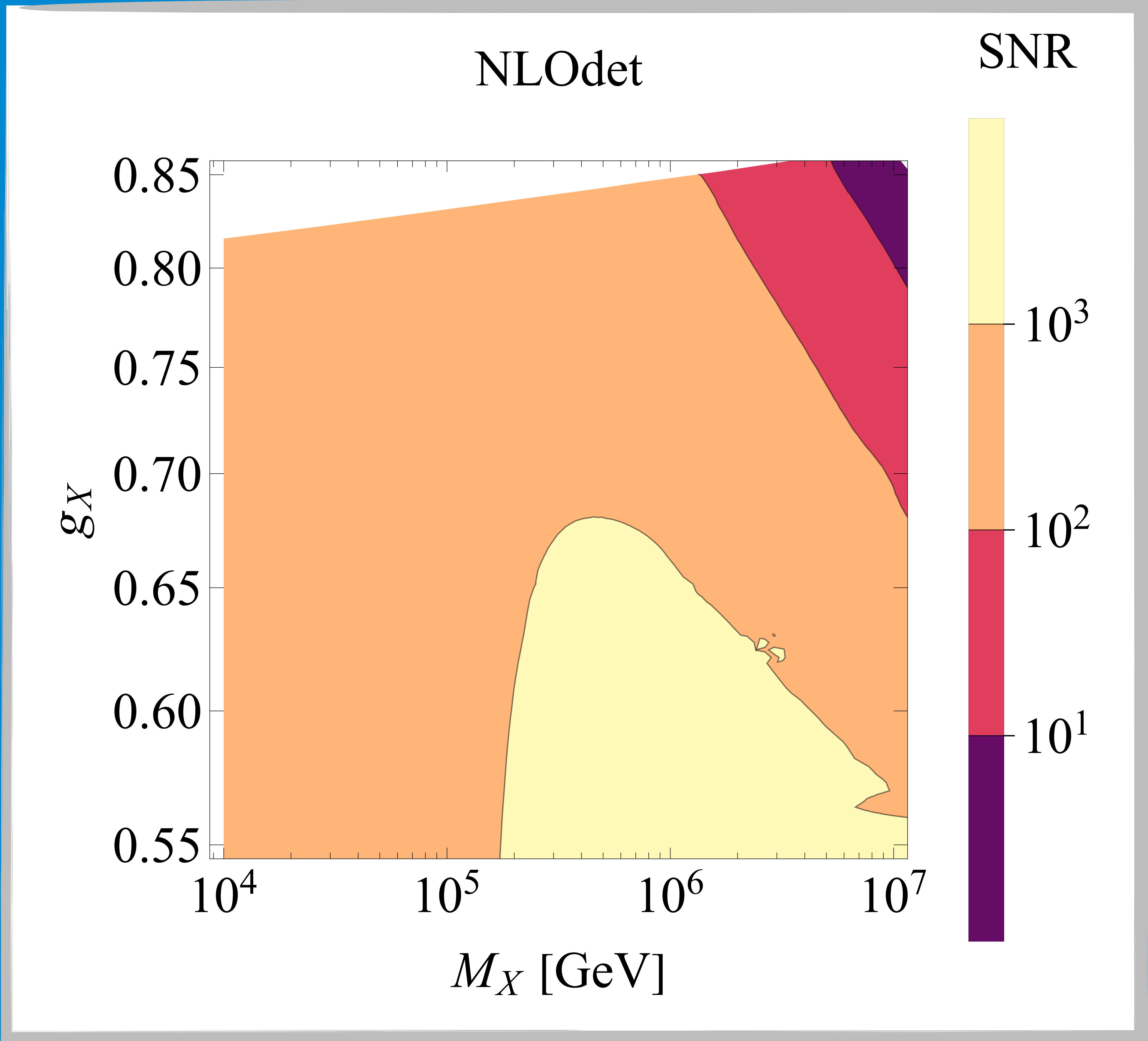
$$\Delta Q \equiv \frac{Q^{[\text{NLO det}]} - Q^{[\text{daisy}]}}{Q^{[\text{NLO det}]}}$$

- $\Delta T_p \sim \mathcal{O}(30\%) - \mathcal{O}(80\%)$
- $\Delta R_* H_* \sim \mathcal{O}(15\%) - \mathcal{O}(20\%)$

Note:
$A_{\text{dyn}} \det{}_S \simeq T^4$
everywhere
except [NLO det]

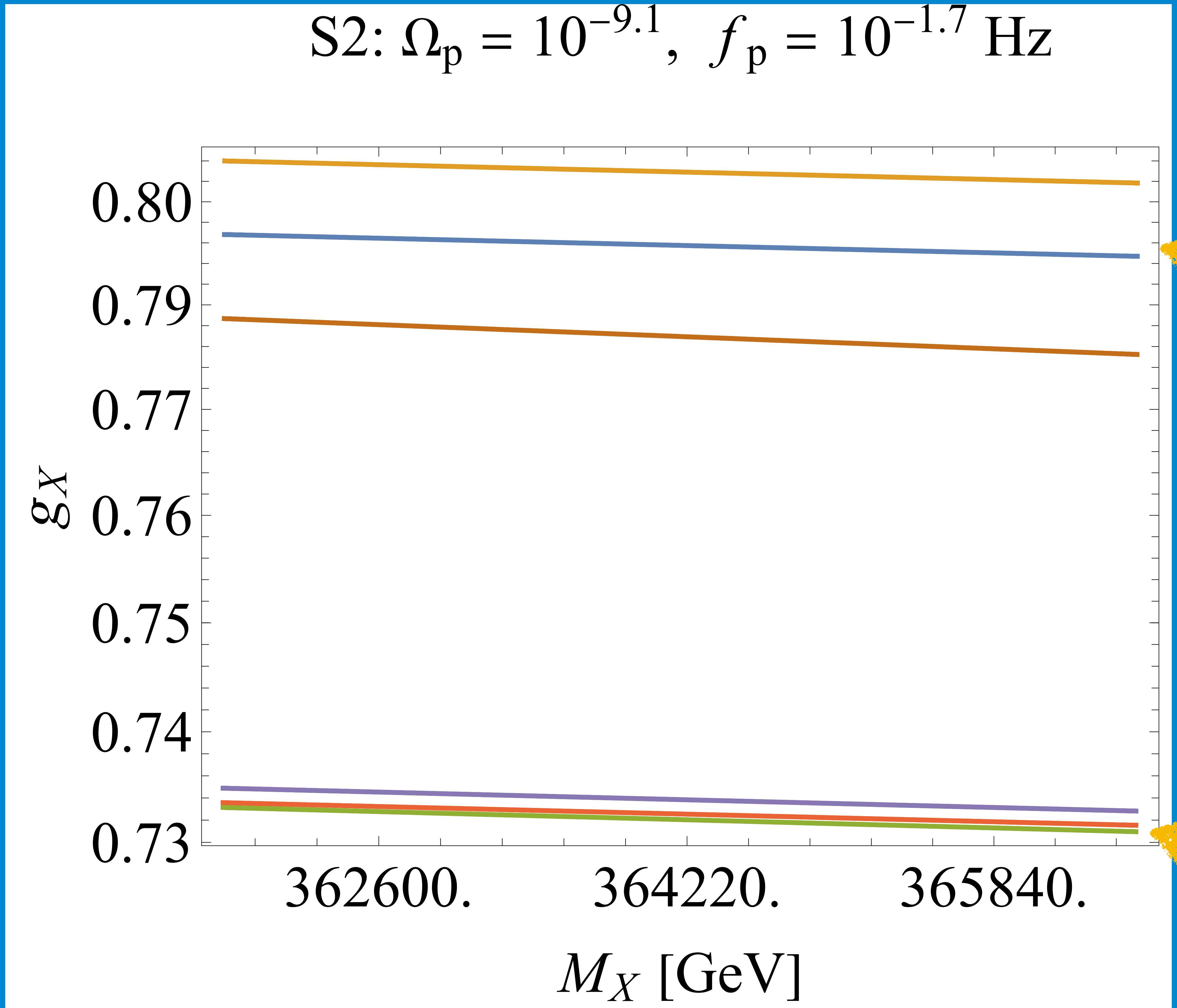
For supercooled PTs SNR looks similar for “daisy” and “NLOdet”, but...





MK, M. Lewicki, P. Schicho, D. Schmitt, B. Świeżewska 2607.18233

…NLO and daisy cannot be reconciled in signal reconstruction!

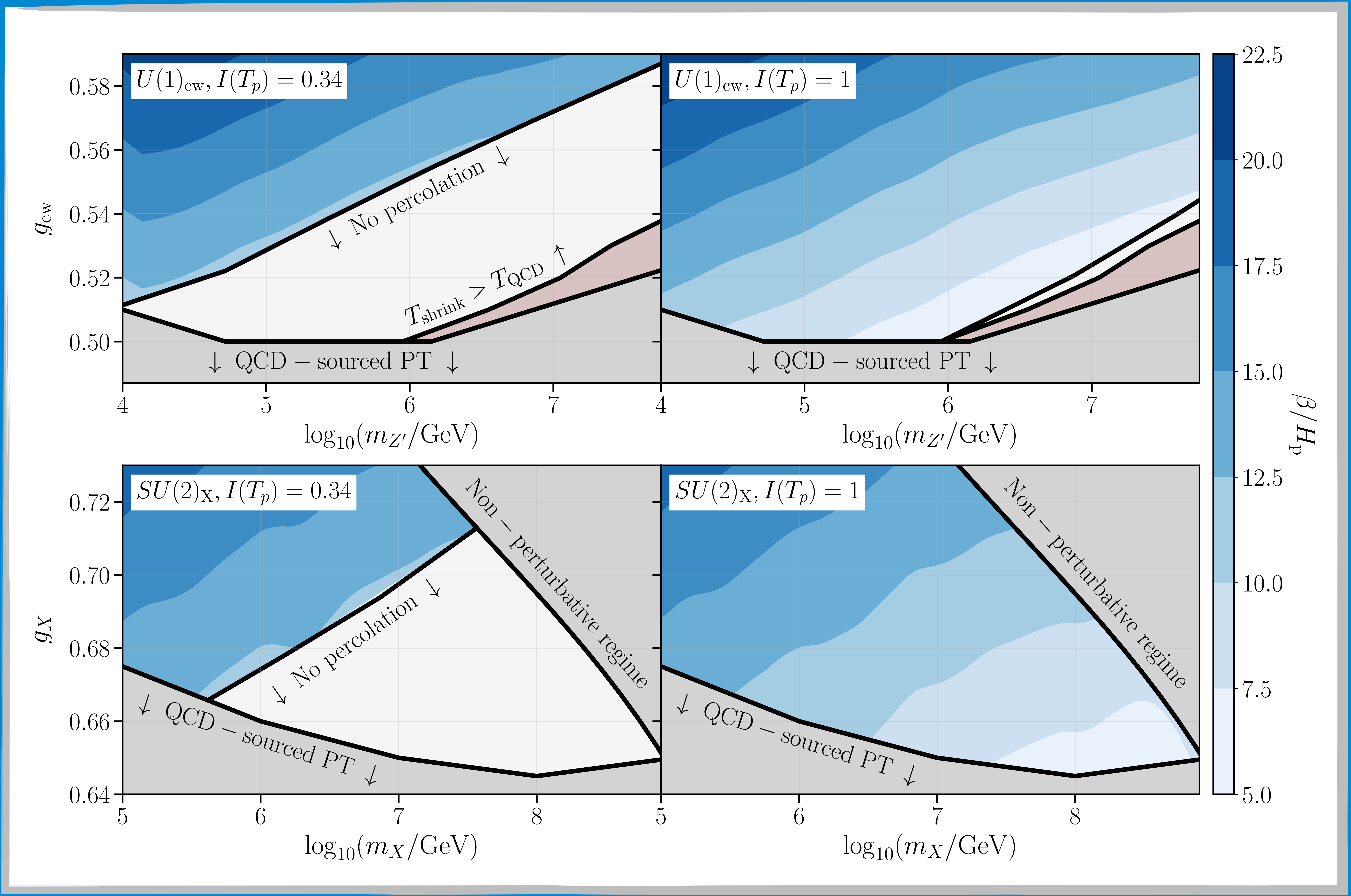


Daisy

NLO det

MK, M. Lewicki, P. Schicho, D. Schmitt, B. Świeżewska 2607.18233

It's unlikely to go below $\beta/H \sim 5$



MK, N. Ramberg, P. Schicho, D. Schmitt, 2506.15496

How do dim-6 operators affect the nucleation rate?

$$\mathscr{L}_1 = \alpha_{\phi^2F^2}F_{ij}F_{ij}\phi^\dagger\phi + \alpha_{D^2\phi^4}\left(D_i\phi^\dagger D_i\phi\right)\left(\phi^\dagger\phi\right)$$
$$+\alpha_{D^2\phi^2B_0^2}\left(D_i\phi^\dagger D_i\phi\right)B_0^2 + \alpha_{B_0^2\phi^4}B_0^2\left(\phi^\dagger\phi\right)^2 + \alpha_{\phi^6}\left(\phi^\dagger\phi\right)^3$$

Bounce sol
gets modified

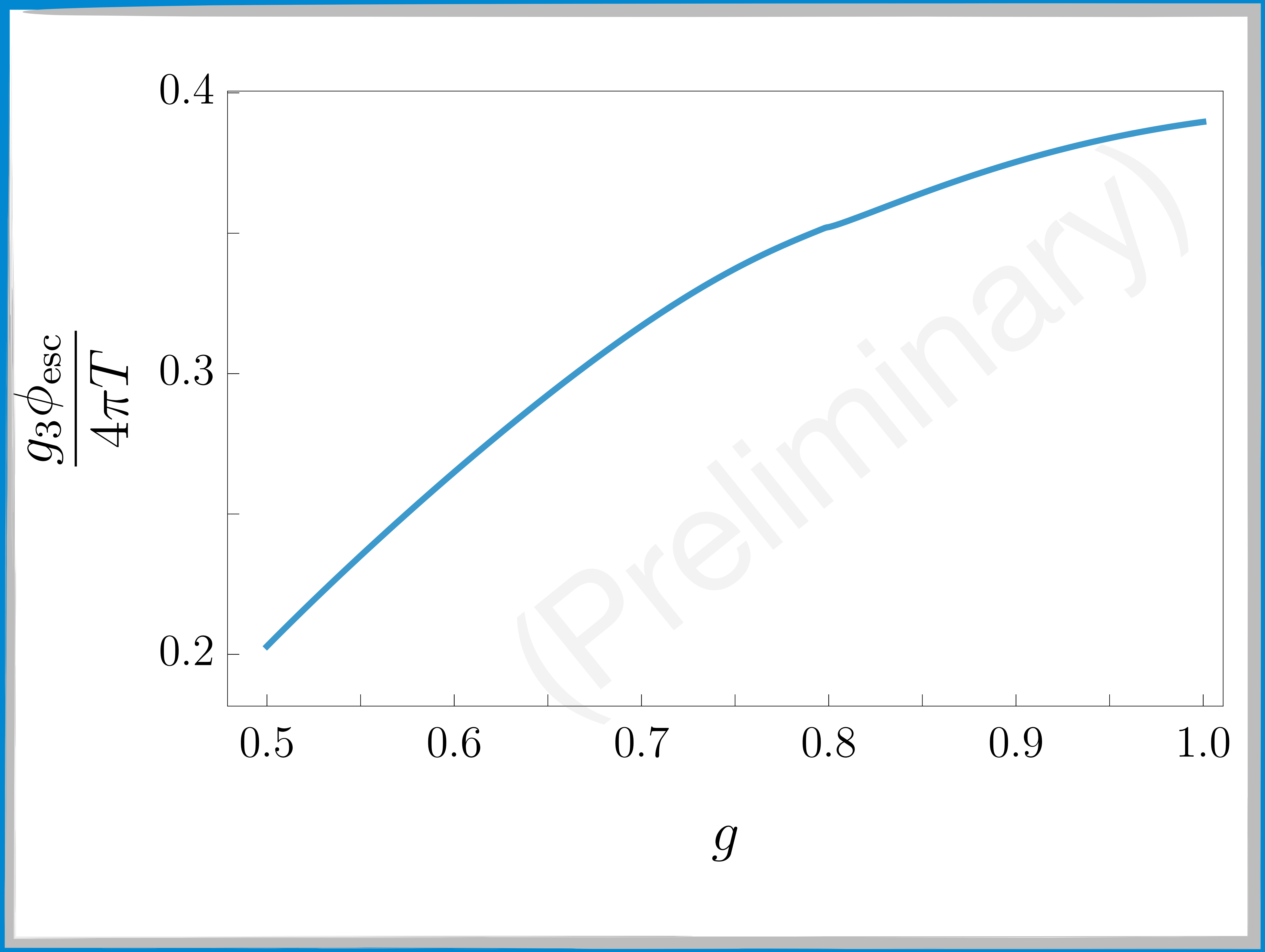
Quadratic terms
get modified

Example:

$$\mathrm{Det}_{X_0} = \mathrm{Det}\left(\partial^2 + m_{X_0}^2 + \frac{1}{2}\alpha_{\phi^4B_0^2}\phi_b^4 + \alpha_{D^2\phi^2B_0^2}\phi_b'^2\right)$$

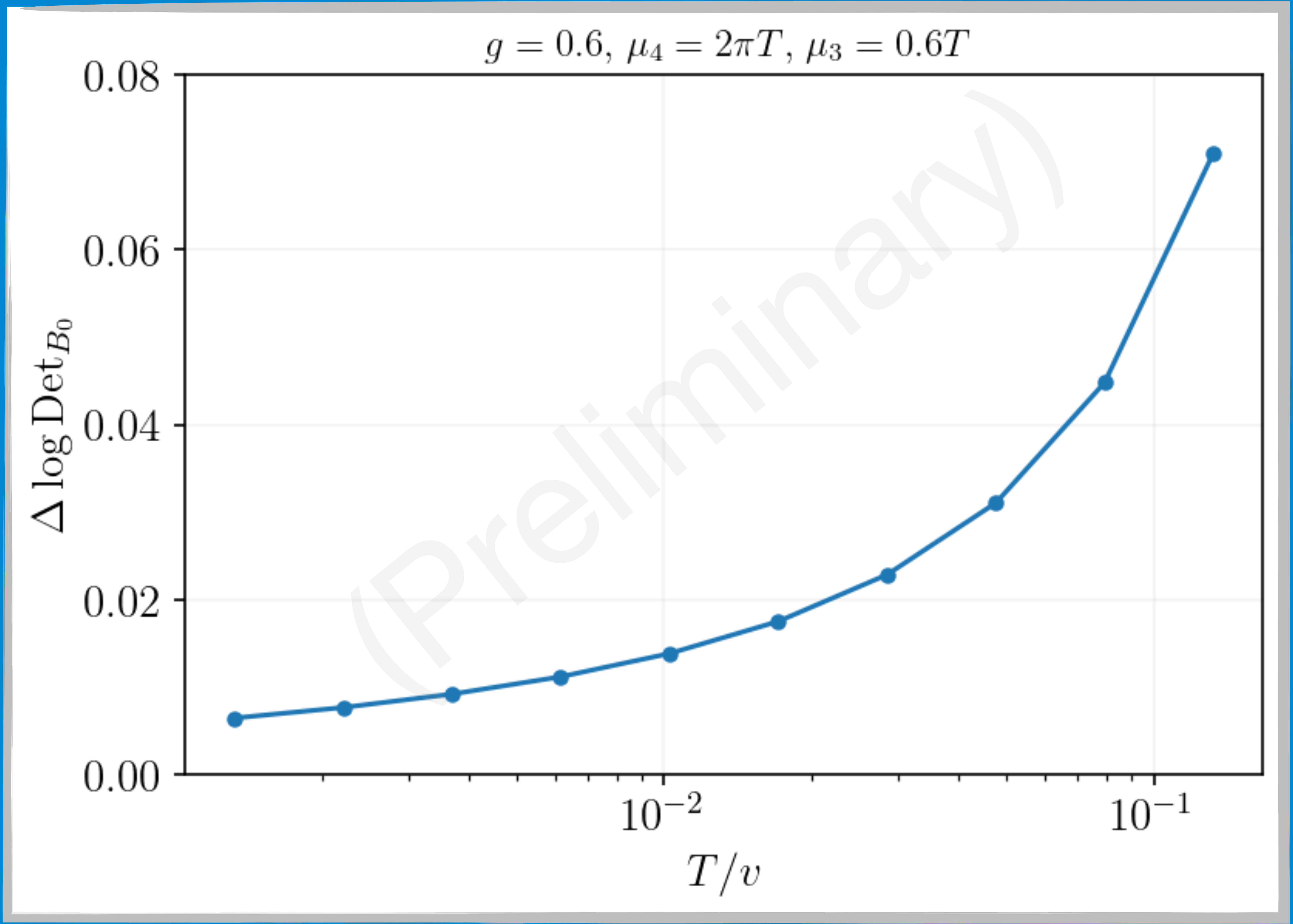
F. Bernardo, MK, N. Leister, P. Schicho, P. Schwaller, 2609.xxxxx

HT validity => small effect of dim-6 operators



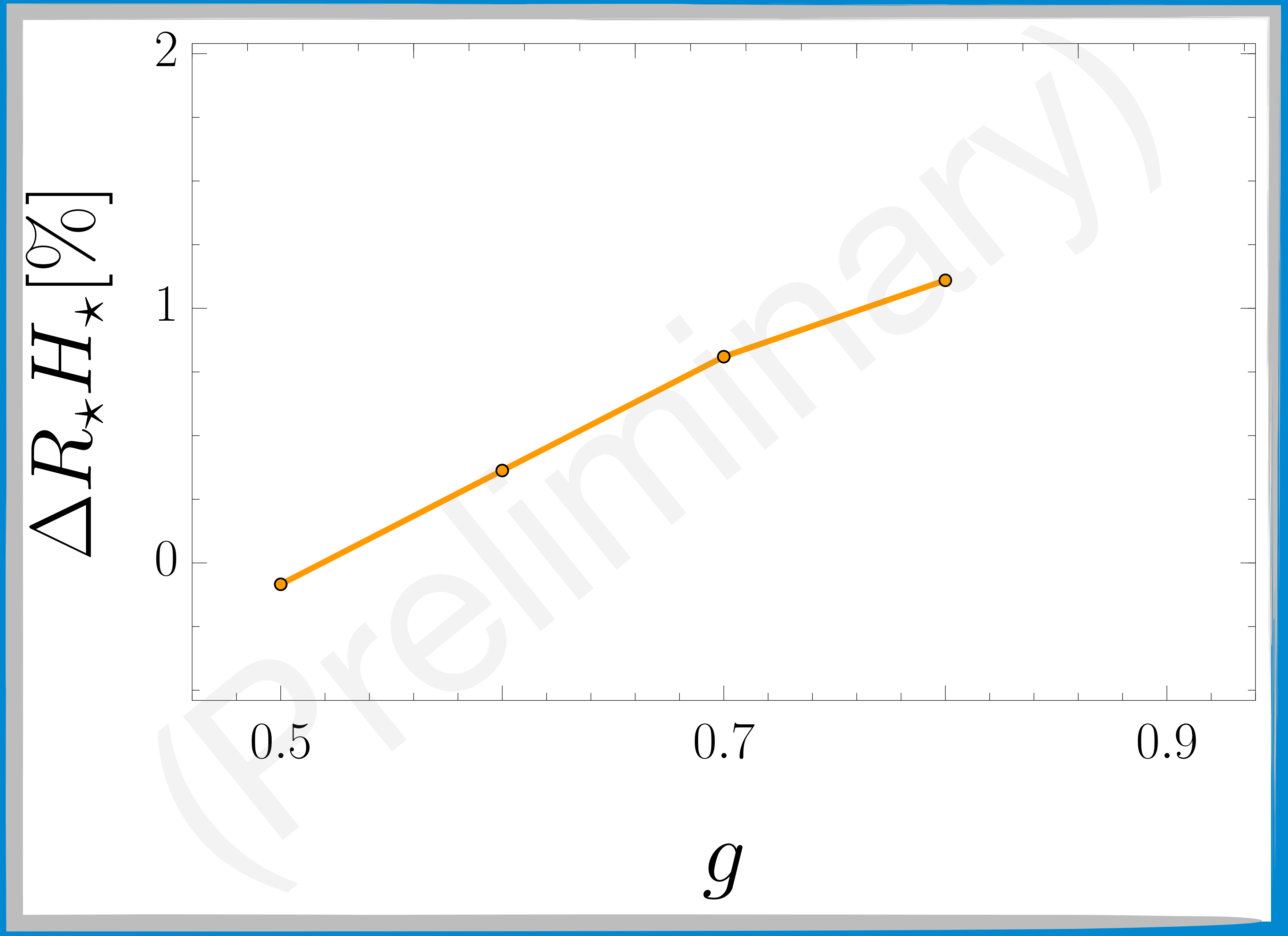
F. Bernardo, MK, N. Leister, P. Schicho, P. Schwaller, 2609.xxxxx

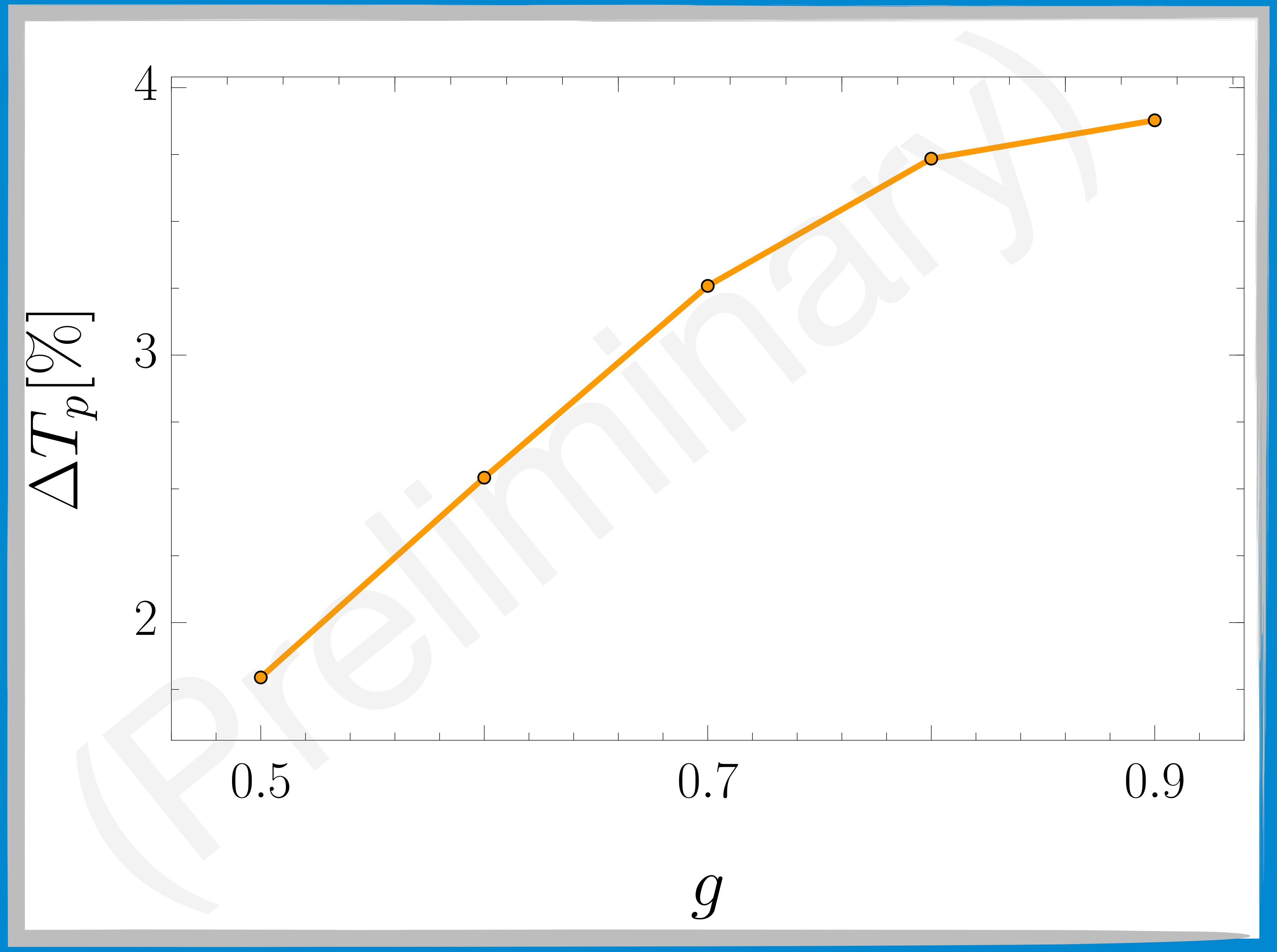
The relative difference for Det_{X_0} is up to 7%



F. Bernardo, MK, N. Leister, P. Schicho, P. Schwaller, 2609.xxxxx

T_p changes up to 4%, while $R_* H_*$ up to 1%





(Plots due to courtesy of N. Leister)

F. Bernardo, MK, N. Leister, P. Schicho, P. Schwaller, 2609.xxxxx

Summary

Dim-6 operators seem to have **little effect on nucleation**

Derivative expansion for **gauge modes** introduces significant **errors**.

NLO corrections are **mandatory** for reliable pheno predictions

Min value of $\beta/H \simeq 5$

Outlook

Go to NNLO to assert convergence of perturbative expansion

It'd be nice to have a comparison to nucl. rate on a lattice!

Precise predictions for PTA data

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Derivative expansion for **gauge modes** introduces significant **errors**.

Summary

NLO corrections are **mandatory** for reliable pheno predictions

Min value of $\beta/H \simeq 5$

Go to NNLO to assert convergence of perturbative expansion

Outlook

It'd be nice to have a comparison to lattice!

Use functional methods

(Naive) daisy resummation

- Captures the “general” behaviour, but:
- Uncancelled RG-scale dependence
- Naive use leads to imaginary parts in the effective potential
- Gauge-dependent predictions
- Usually double-counts scalar contributions

VS

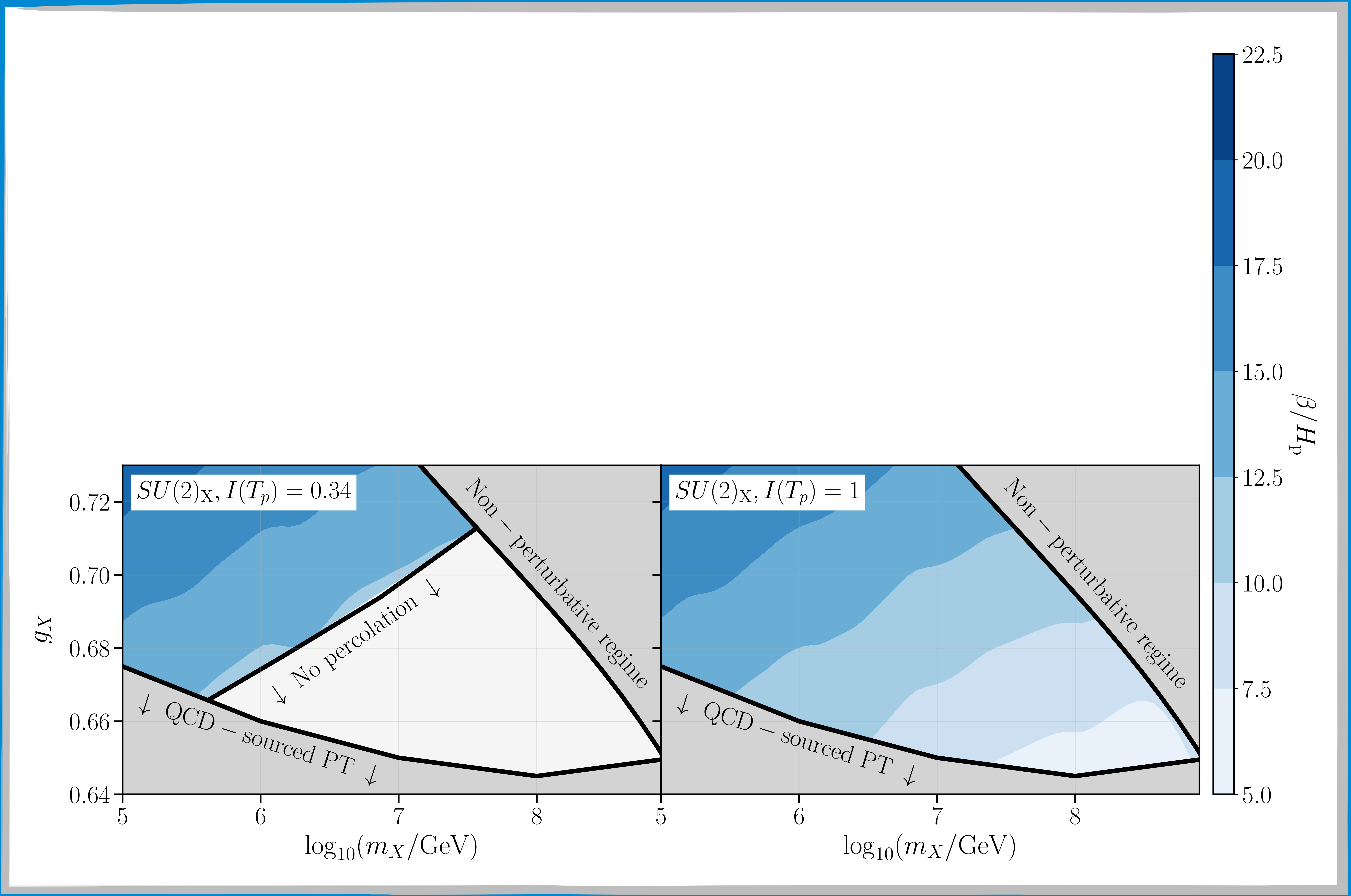
Dimensional Reduction

- Gets *all pert. contributions* at a given $\mathcal{O}(g)$
- Diminished RG-scale dependence
- No imaginary parts in the effective potential
- Gauge-invariant predictions
- One can increase precision consistently, order by order
- Can reproduce lattice very well (at least for eq. thermodynamics)

See also: J. Löfgren, “Stop comparing resummation methods”, J.Phys.G 50 (2023) 12, 125008

Thank you!

What can happen for extreme supercooling?



MK, N. Ramberg, P. Schicho, D. Schmitt, 2506.15496

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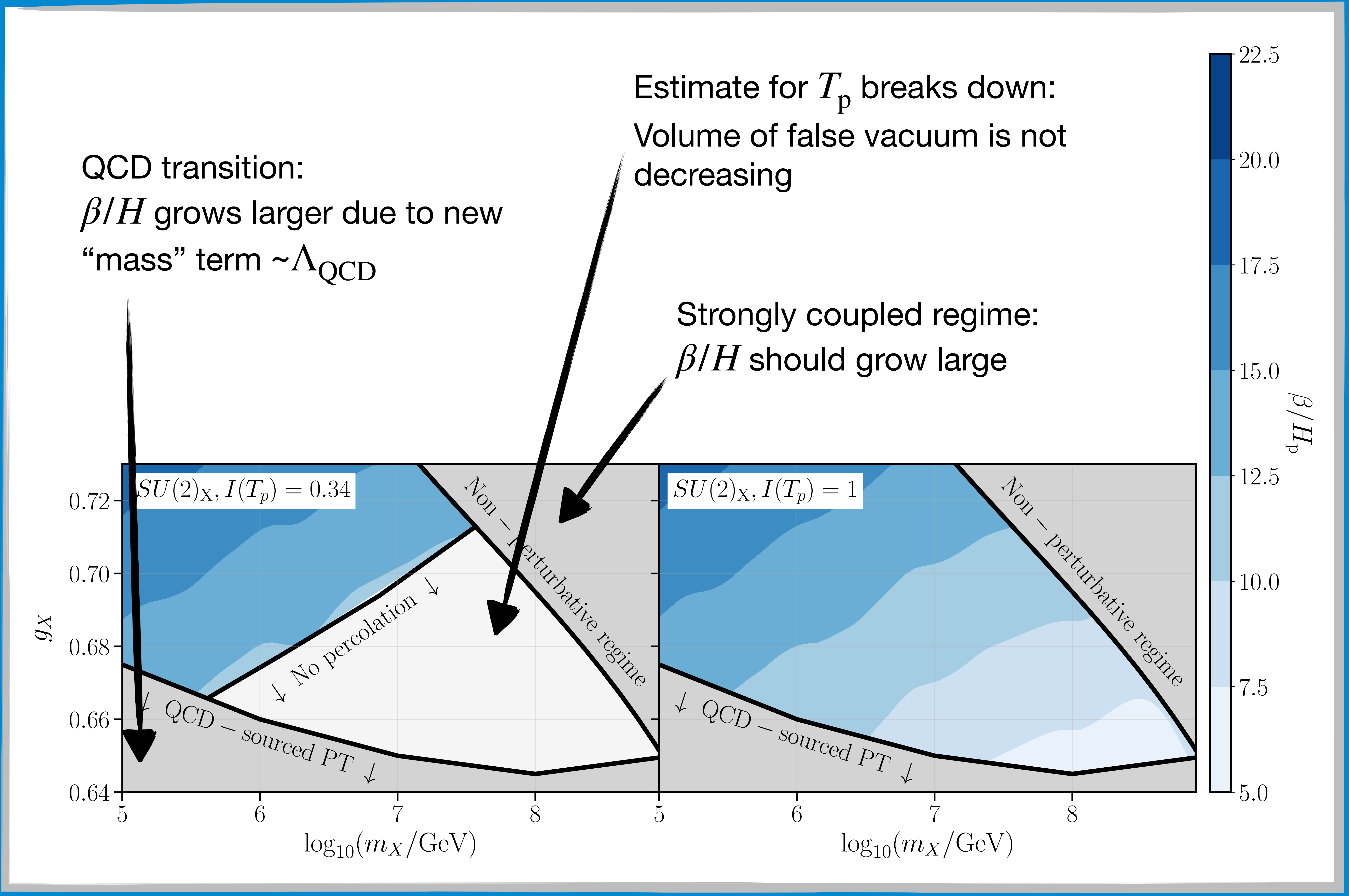

MK, N. Ramberg, P. Schicho, D. Schmitt, 2506.15496