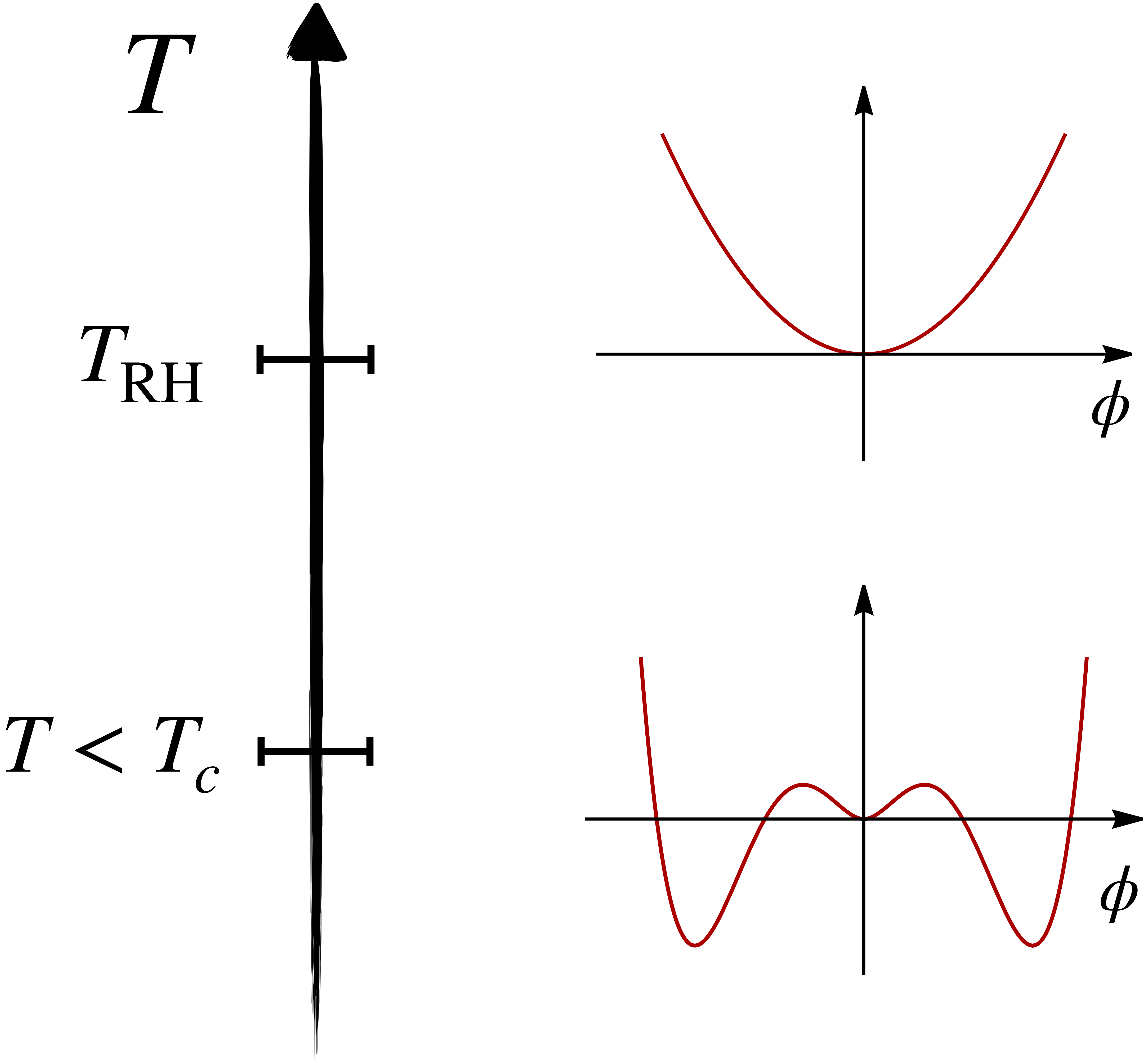
Phase transitions in the early Universe:
defects, bubbles, and gravitational waves

Simone Blasi
DESY Hamburg

4th BIG meeting - University of Barcelona - 29.11.24

Introduction



Symmetries are **restored** at high temperatures/early times

Spontaneous breaking while the Universe expands and cools down

Introduction

$\Rightarrow$ Cosmological phase transitions

Key to address open questions: **baryogenesis**

Aftermath directly observable in **GWs**

Evidence for **new** fundamental **physics**

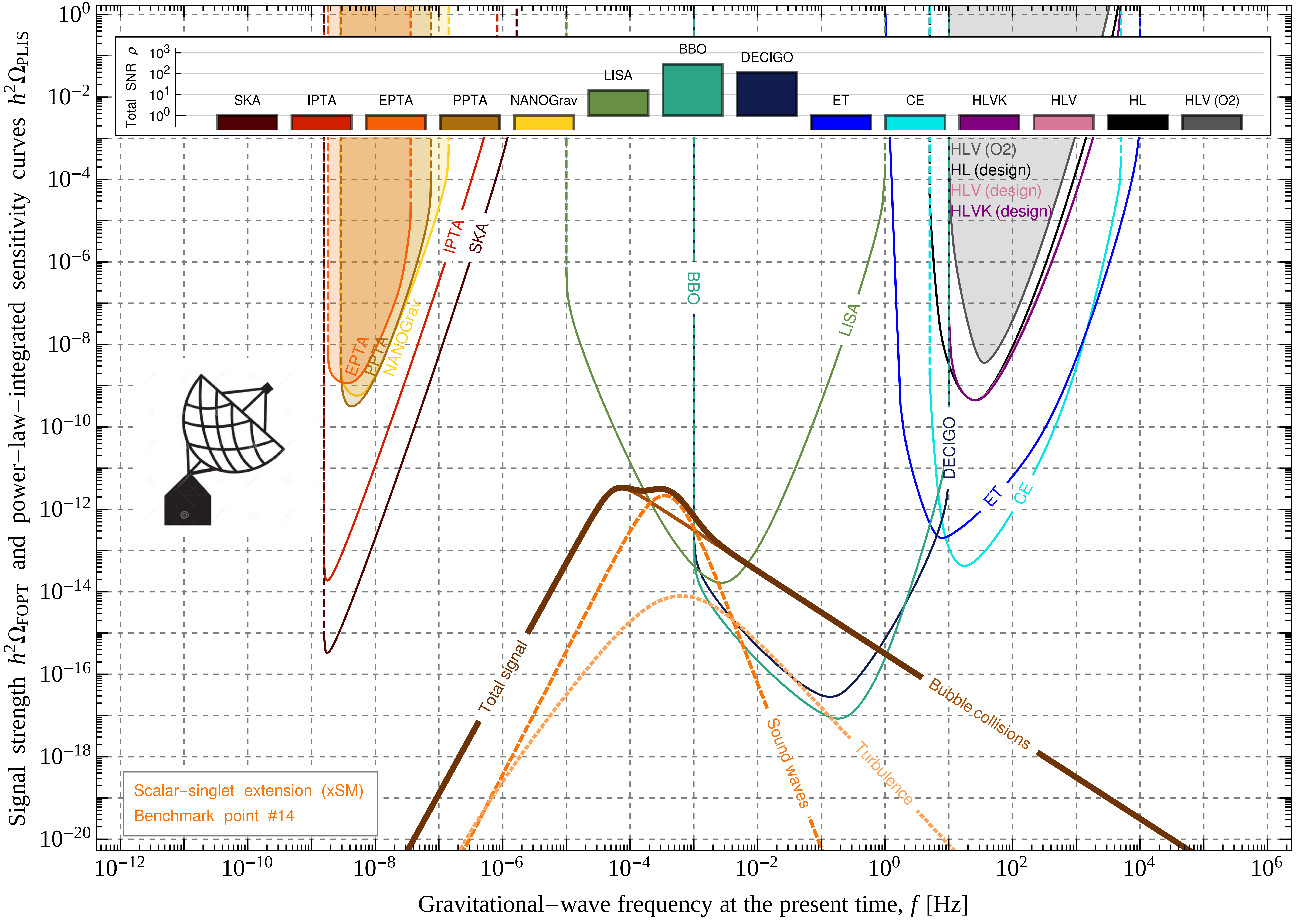


Fig. from Schmitz [2002.04615] JHEP

Phase transitions source GWs

Phase transition at T_c

$\langle\phi\rangle : G \to H$

Phase transitions source GWs

Phase transition at T_c

$\langle\phi\rangle : G \to H$

1

Strength:

Bubble collision,
hydrodynamics

Phase transitions source GWs

Phase transition at T_c

$\langle \phi \rangle : G \to H$

2

Topology of the vacuum:

Formation of defects and annihilation

1

Strength:

Bubble collision, hydrodynamics

Phase transitions source GWs

What scale of new physics?

- GW emitted at time t_* with frequency $2\pi f_* = H_*/\epsilon_*$. Today's frequency f_0 :

Book by Michele Maggiore, vol. 2

$$f_0 \simeq 2.65 \times 10^{-8} \frac{1}{\epsilon_*} \left(\frac{T_*}{1\,\mathrm{GeV}} \right) \left(\frac{g_*}{106.75} \right)^{1/6} \mathrm{Hz}$$

Sub-horizon modes $\epsilon_* < 1$

What scale of new physics?

- GW emitted at time t_* with frequency $2\pi f_* = H_*/\epsilon_*$. Today's frequency f_0 :

Book by Michele Maggiore, vol. 2

$$f_0 \simeq 2.65 \times 10^{-8} \, \frac{1}{\epsilon_*} \left(\frac{T_*}{1\,\mathrm{GeV}} \right) \left(\frac{g_*}{106.75} \right)^{1/6} \mathrm{Hz}$$

Sub-horizon modes $\epsilon_* < 1$

$T_* = 1\,\mathrm{GeV}$

PTAs

$T_* = 100\,\mathrm{GeV}$

LISA

What scale of new physics?

- GW emitted at time t_* with frequency $2\pi f_* = H_*/\epsilon_*$. Today's frequency f_0 :

Book by Michele Maggiore, vol. 2

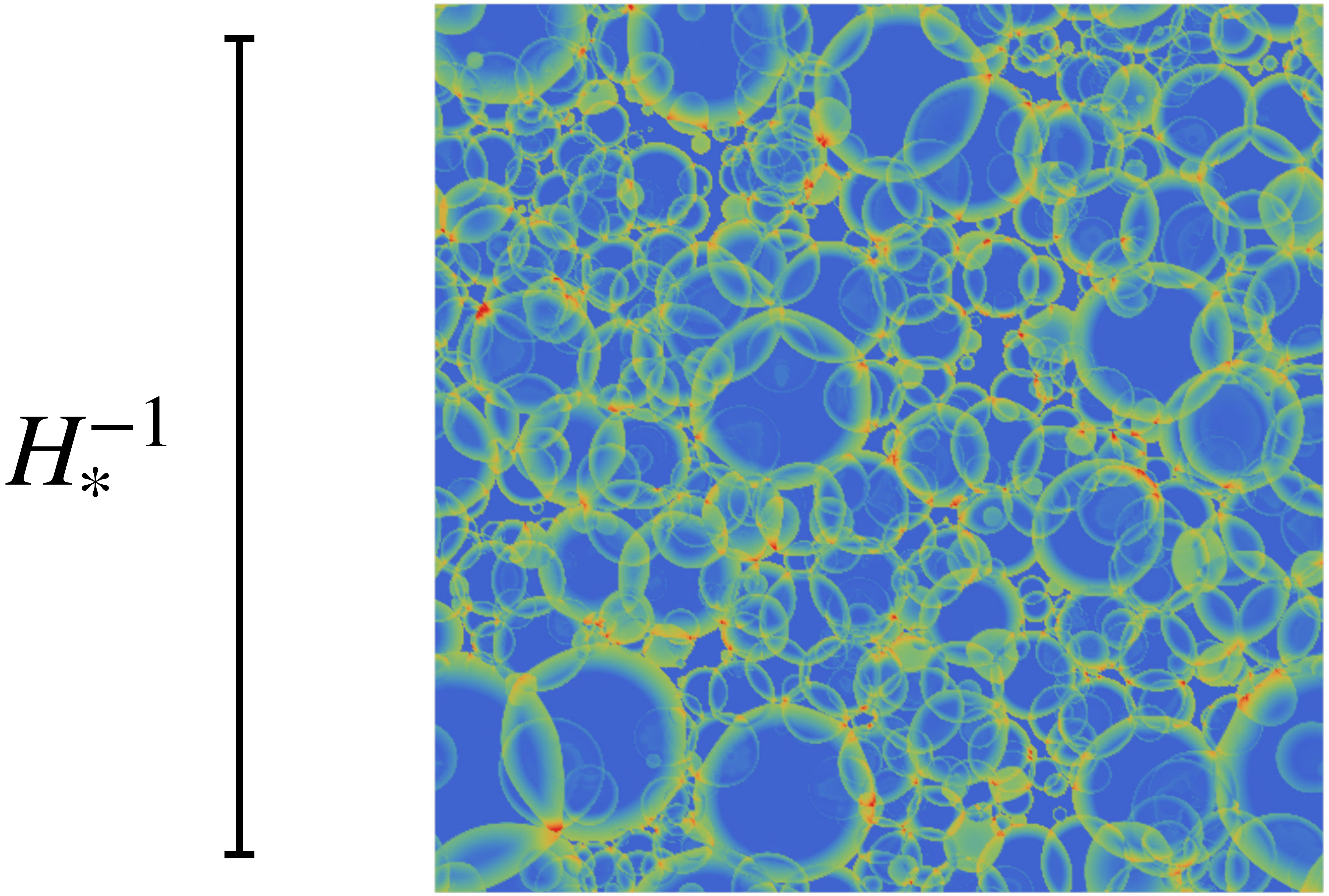
$$f_0 \simeq 2.65 \times 10^{-8} \frac{1}{\epsilon_*} \left(\frac{T_*}{1\,\mathrm{GeV}}\right) \left(\frac{g_*}{106.75}\right)^{1/6} \mathrm{Hz}$$

Sub-horizon modes $\epsilon_* < 1$

$$T_* = 10^8\,\mathrm{GeV}$$

What scale of new physics?

- Previous estimate works only for sources that are active for a short period of time:



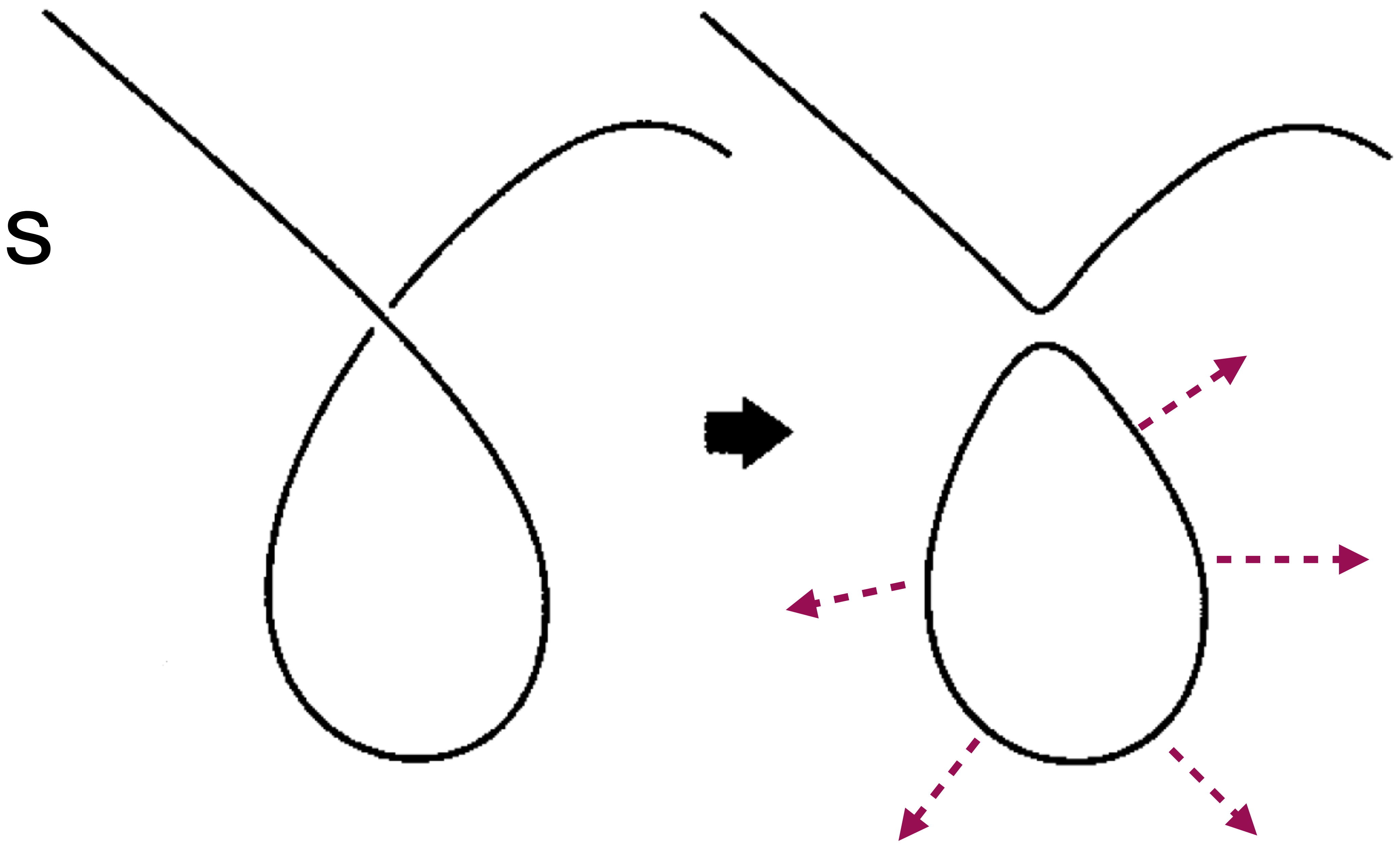
Bubbles nucleated during a 1st order phase transition

Fig. from Jinno, Konstandin, Rubira, [2010.00971], JCAP

What scale of new physics?

- Different story for defects: loops **continuously produced** and decay via GWs

Cosmic strings



Fundamental scale enters via **string tension**

How loud?

- Cosmological backgrounds should not spoil Big Bang Nucleosynthesis:

Book by Michele Maggiore, vol. 2

$$(h_0^2\Omega_{\rm gw})_* < \frac{1.3\times 10^{-6}}{\log(f_{\rm max}/f_{\rm min})}\left(\frac{N_{\rm eff}-3.046}{0.234}\right) \qquad f_0 \gtrsim 10^{-10}\ \text{Hz}$$

↓ Peak value

How loud?

- Weinberg formula:

$$\Omega_{\rm GW}(q) \equiv \frac{1}{\rho_{\rm tot}} \frac{d\rho_{\rm GW}}{d\ln q} = \frac{q^3}{4\pi^2 \rho_{\rm tot} M_P^2 V} \int \frac{d\Omega_k}{4\pi} \left[\Lambda_{ij,kl} T_{ij}(q,\vec{k}) T^*_{kl}(q,\vec{k}) \right]_{q=k}$$

Anisotropic component

Energy momentum tensor of the source

First order transitions 1

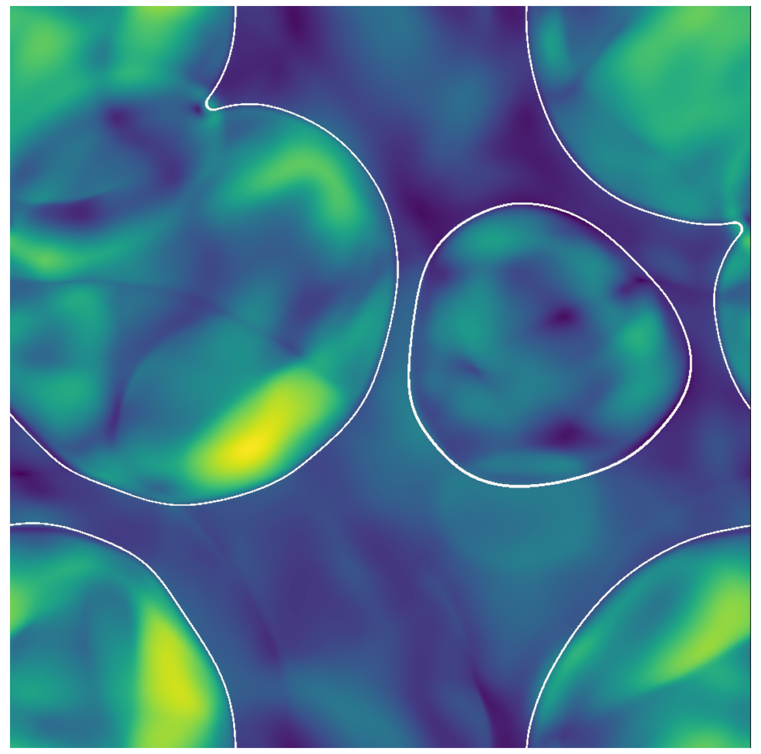


Fig. from Cutting, Hindmarsh, Weir, [1906.00480], PRL

Runaway bubbles

$$h^2\,\Omega^0_{\rm GW} \sim 10^{-7}\left(\frac{\alpha}{1+\alpha}\right)^2\left(\frac{H_*}{\beta}\right)^2$$

Latent heat

Bubble size
$\sim$ time to complete the PT

Terminal velocity

$$h^2\,\Omega^0_{\rm GW} \sim 10^{-7}\,K^2\left(\frac{H_*}{\beta}\right)\times\ldots$$

Kinetic energy
of the fluid

$\ldots\times$ extra suppression if shocks form in less than a Hubble time

First order transitions 1

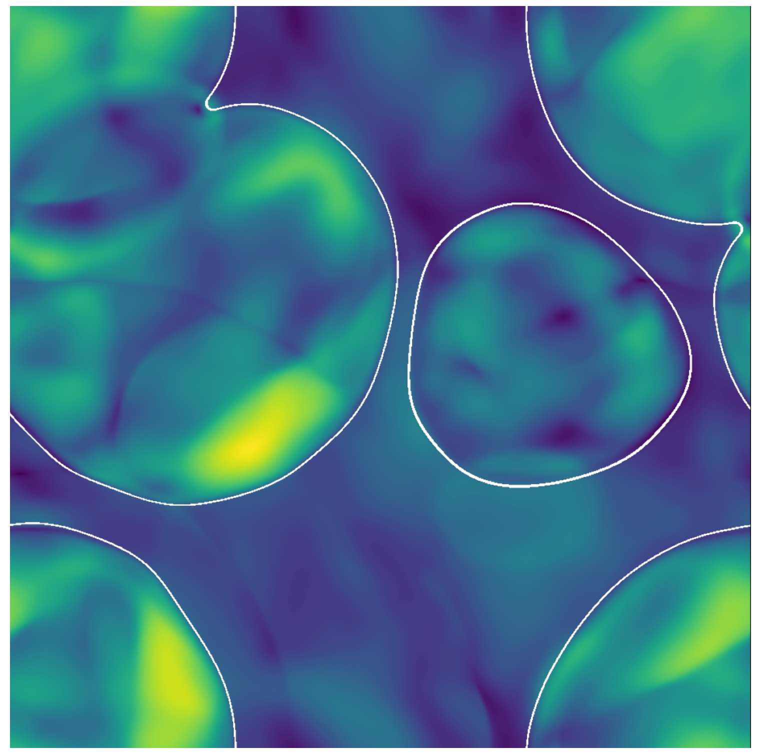
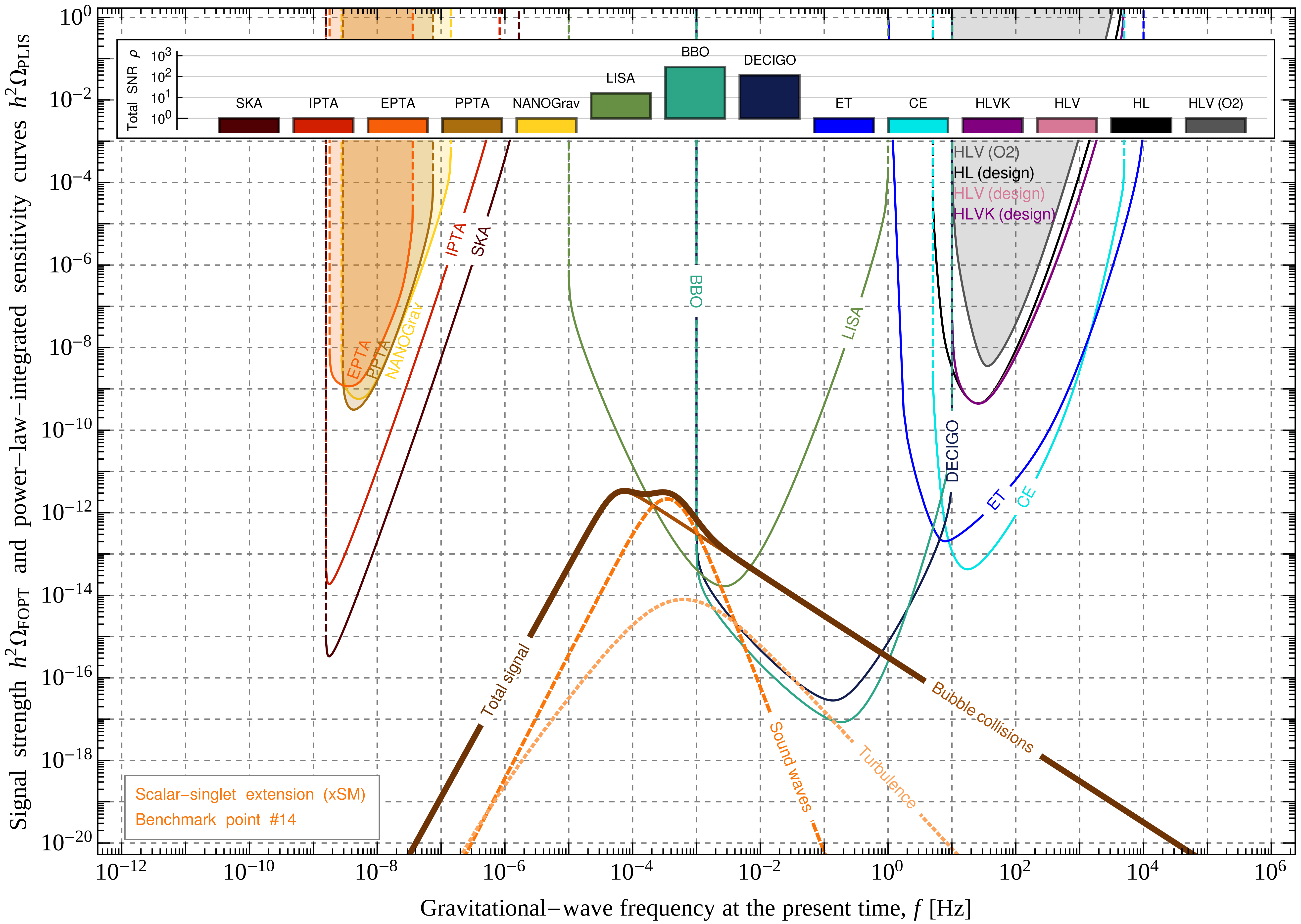


Fig. from Cutting, Hindmarsh, Weir, [1906.00480], PRL

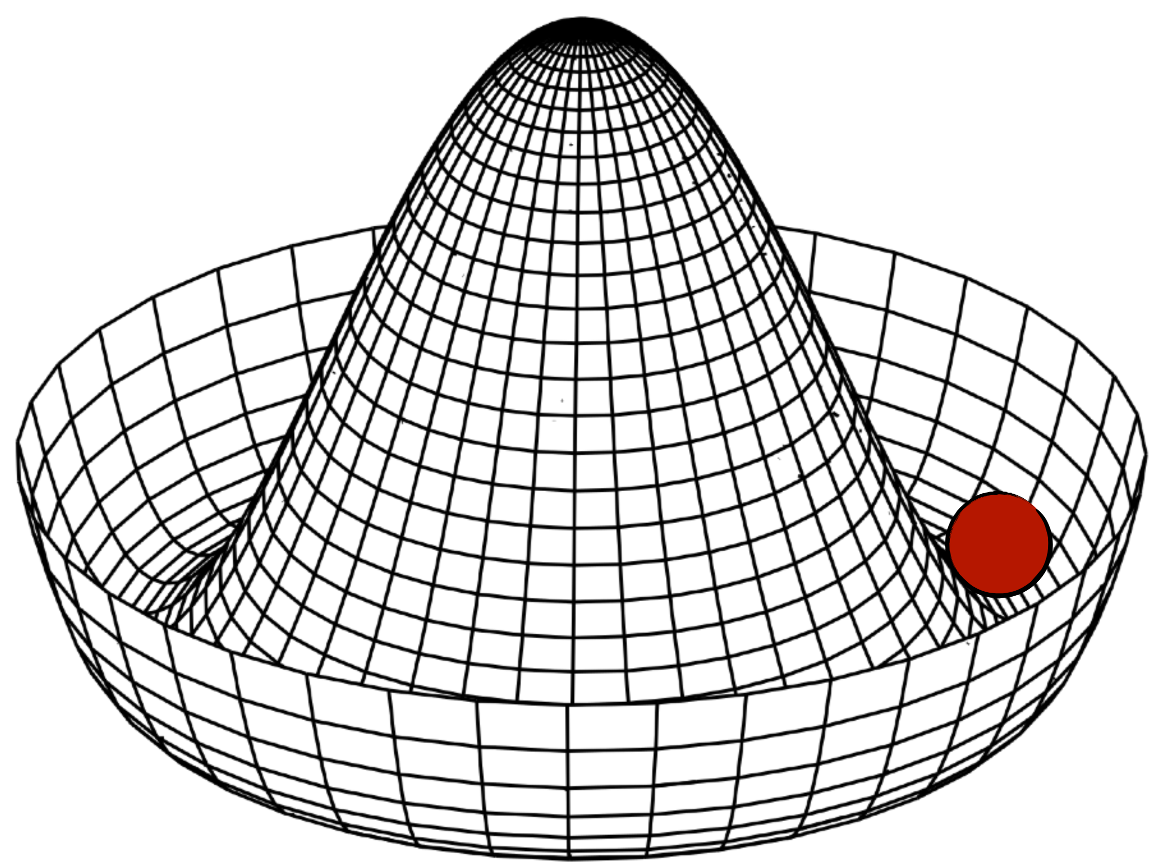


Defects in cosmology

QCD axion strings

- Potential for PQ field

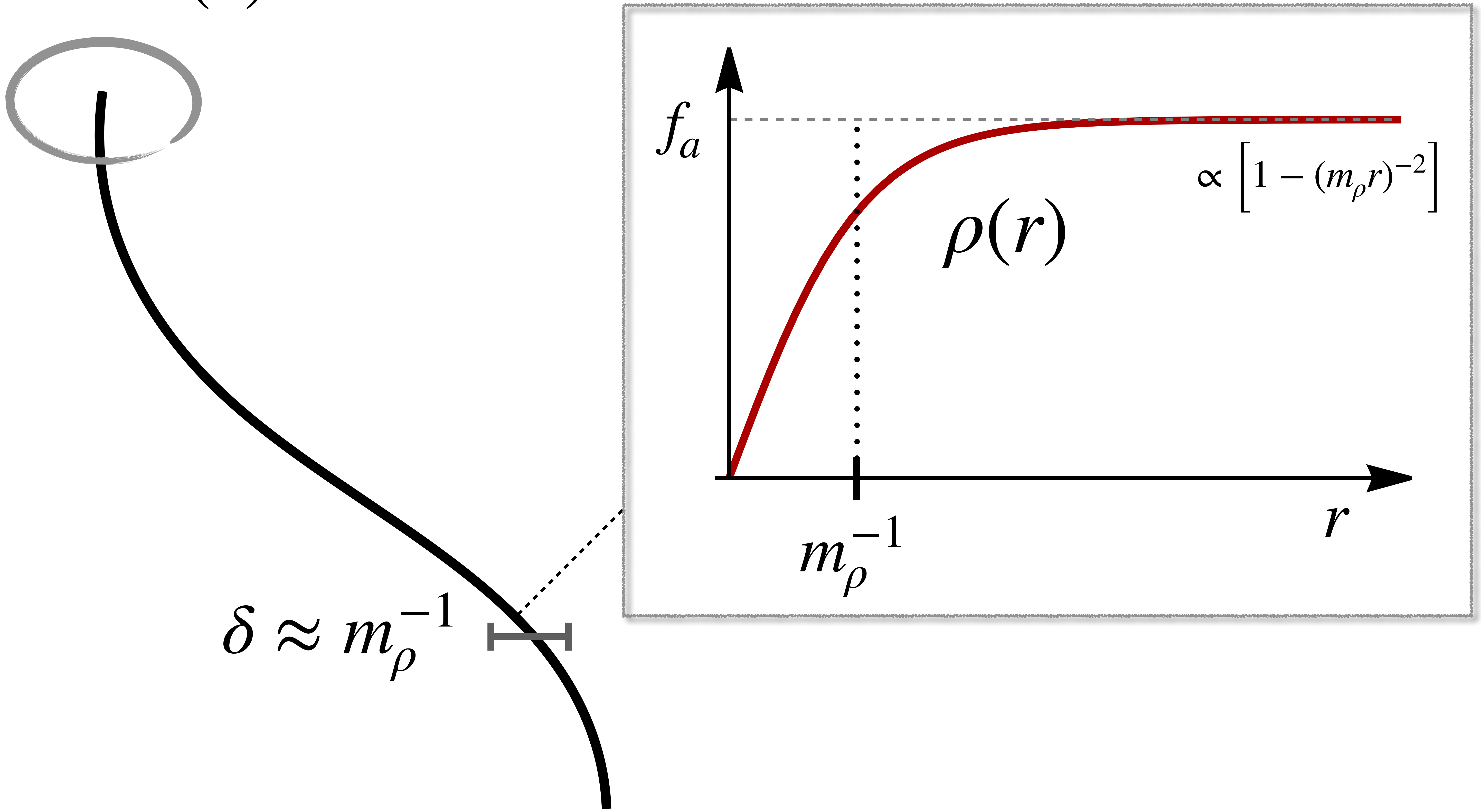
$$\Phi = \rho e^{i\alpha}$$



$V_{\rm PQ}(\Phi)$

- Global string solution

$\alpha(\theta) : 0 \to 2\pi$

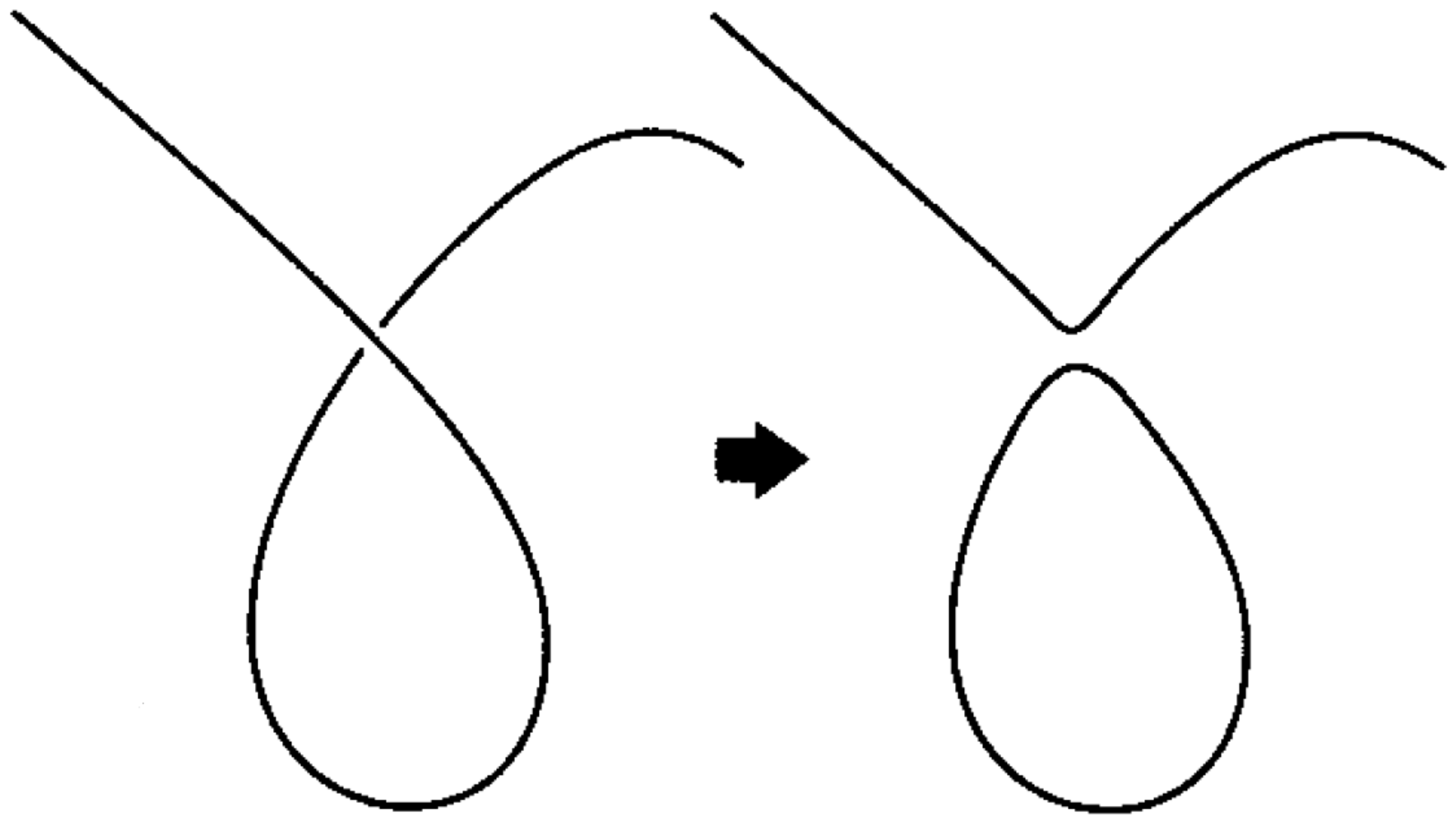


The scaling regime

- A network of topological defects approaches a **scaling regime** with $\xi = \mathcal{O}(1)$ defects per Hubble volume at any time, provided efficient energy losses

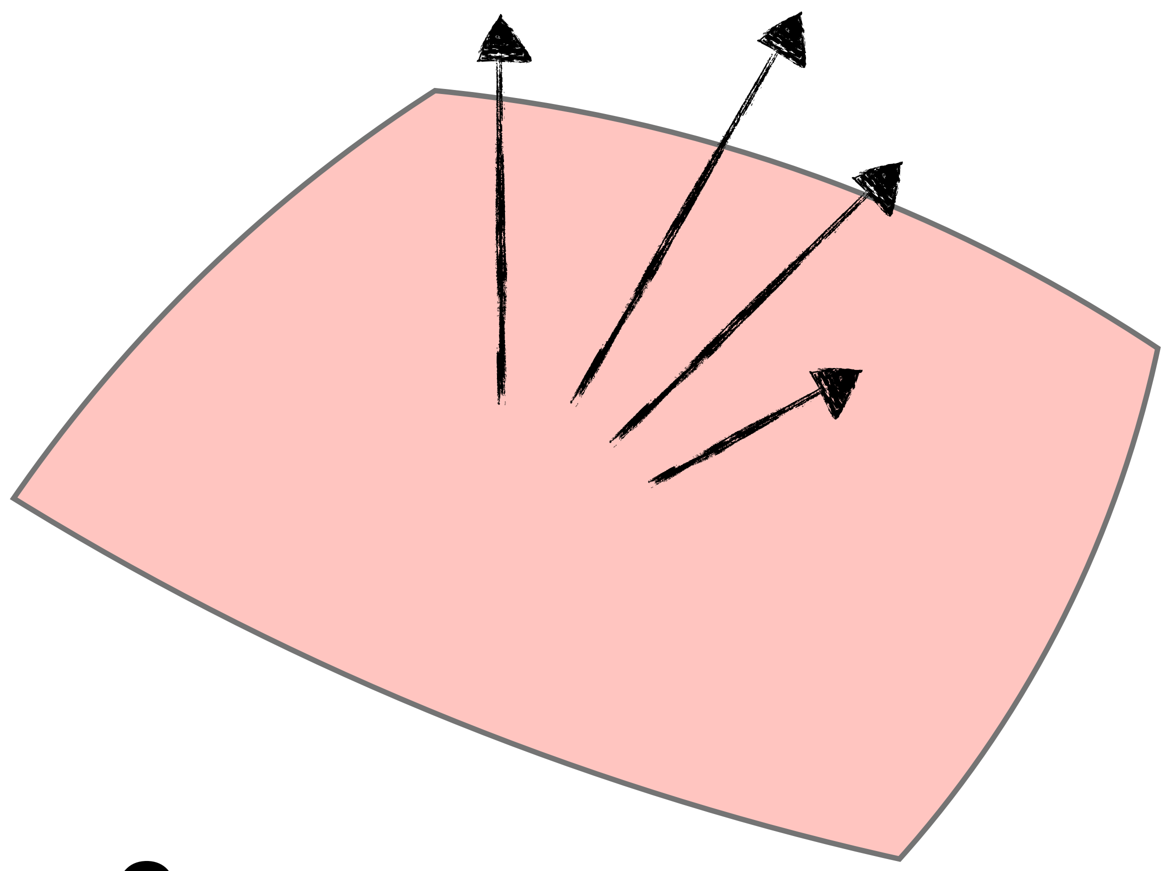
[Press, Ryden, Spergel 1989]

Strings



$\mu \sim f_a^2$

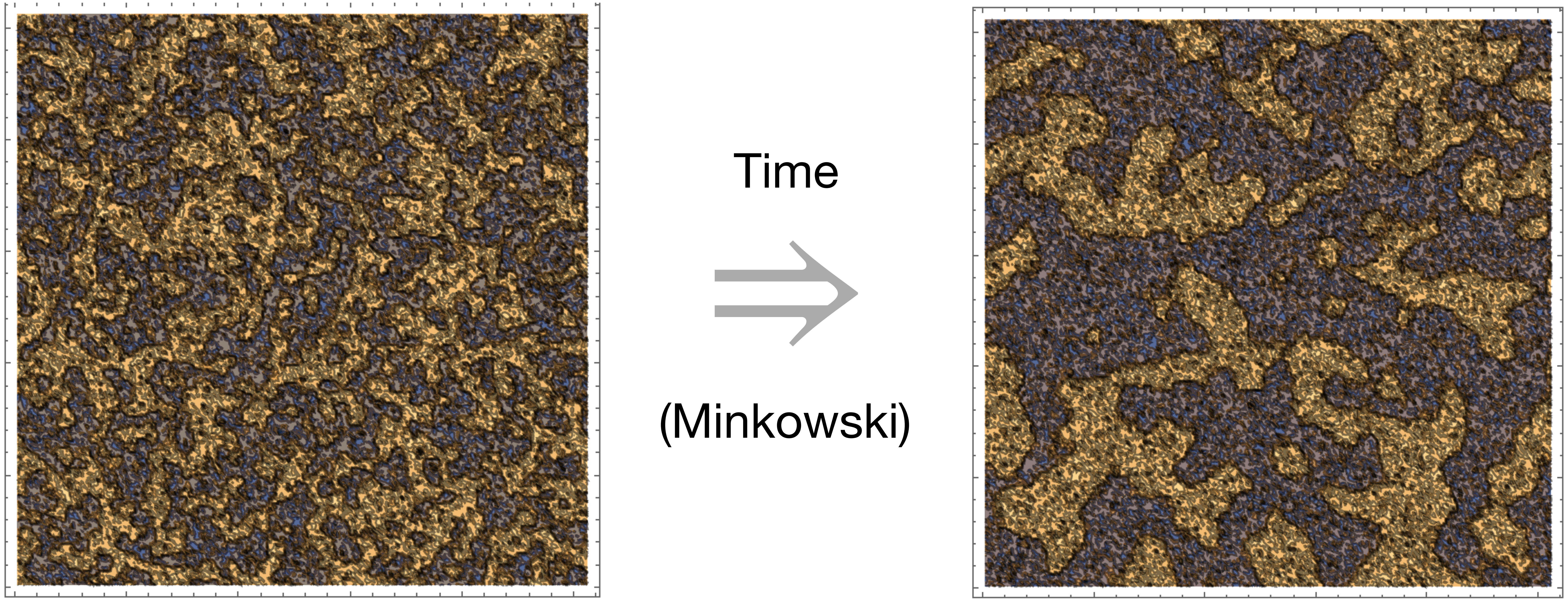
Walls



$\sigma \sim m_a f_a^2$

The scaling regime

- A network of topological defects approaches a **scaling regime** with $\xi = \mathcal{O}(1)$ defects per Hubble volume at any time, provided efficient energy losses

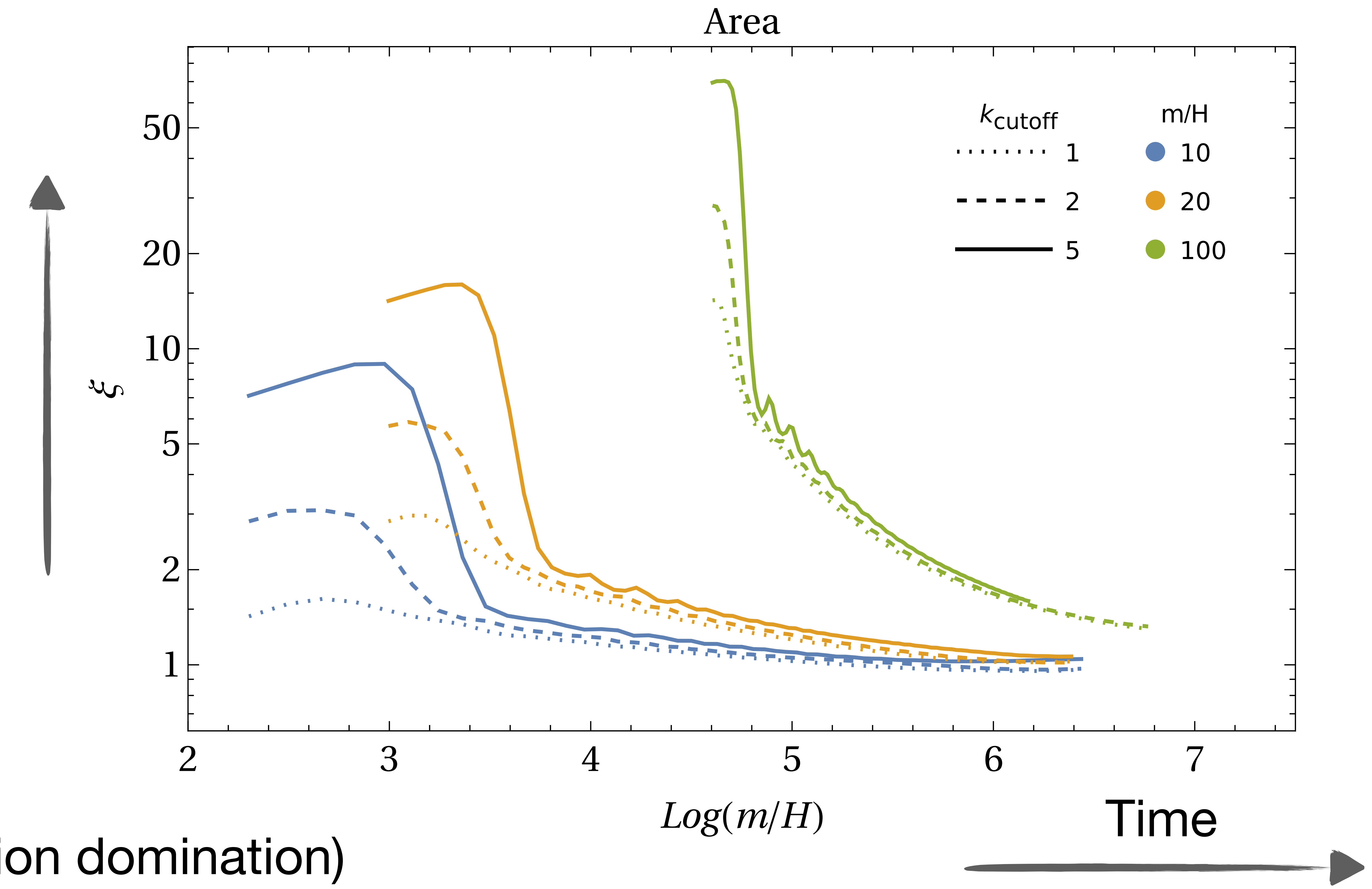


$\mathbb{Z}_2$ scalar field simulation with CosmoLattice

The scaling regime

- A network of topological defects approaches a **scaling regime** with $\xi = \mathcal{O}(1)$ defects per Hubble volume at any time, provided efficient energy losses

# of walls per Hubble volume



Time

(Radiation domination)

Fig. from **SB**, Mariotti, Rase, Vanvlasselaer, in prep.

The scaling regime

- A network of topological defects approaches a **scaling regime** with $\xi = \mathcal{O}(1)$ defects per Hubble volume at any time, provided efficient energy losses

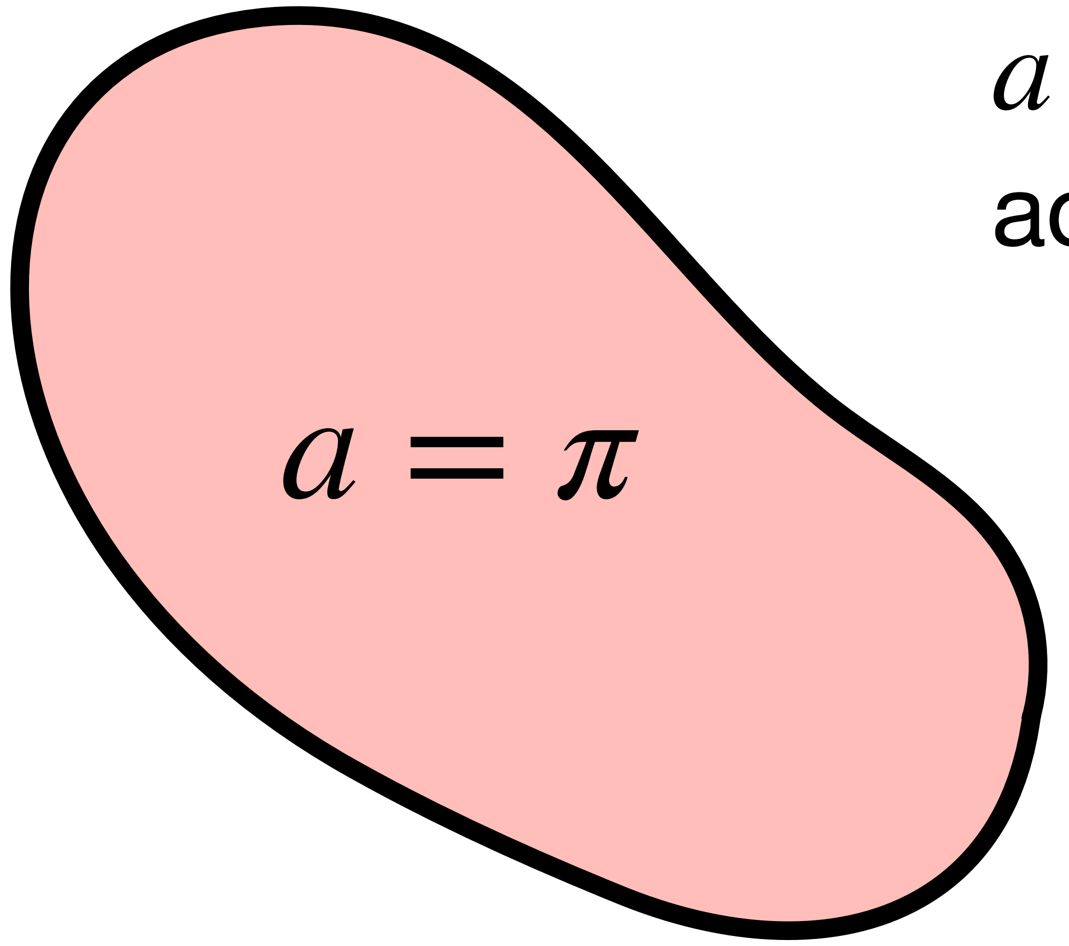
	Energy density	Energy fraction
Cosmic strings	$\rho_{cs} = \dfrac{\mu H^2}{\xi(t)^2}$	$\Omega \sim G\mu \ll 1$
Domain walls	$\rho_{dw} = \dfrac{\sigma H}{\xi(t)}$	$\Omega \sim G\sigma t$

"Domain wall problem"

Problem or blessing?

- Domain walls have observable implications! But need to annihilate before dominating the critical density (or inflated away)

$$N_{\rm DW} = 1$$

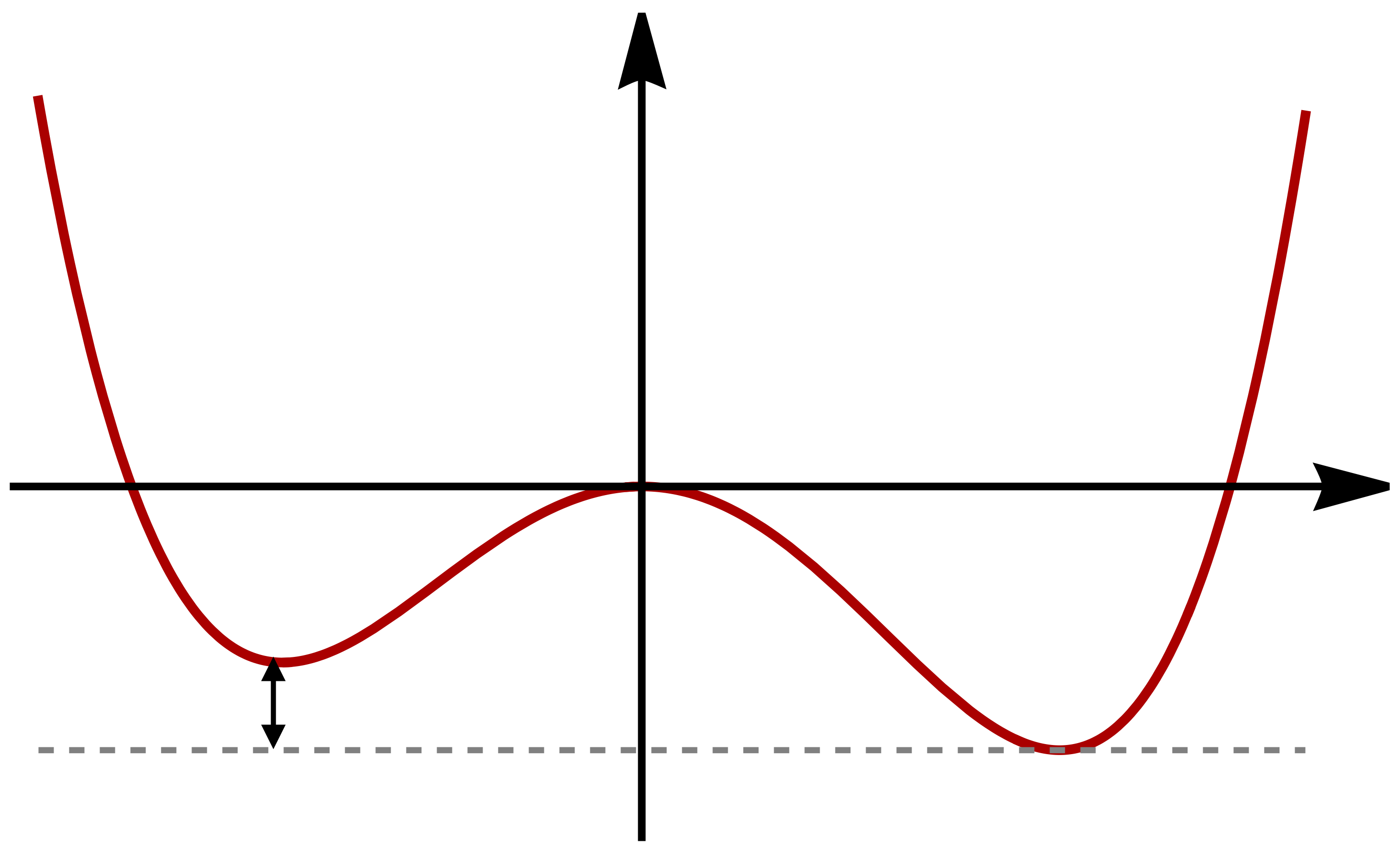


a goes from $0 \to 2\pi$ across the wall..

..but it is the same point! (gauge symmetry)

$$N_{\rm DW} > 1$$

$\mathbb{Z}_{2N}$ is only approximate (biased)



GWs from domain walls

2

- GWs are radiated by domain walls during:
  - the scaling regime (long-lasting source, dominated by later times)
  - the final phase of collapse and annihilation
- Given the collapse at $T = T_*$:

$$\Omega^0_{\rm peak} \sim 10^{-6}\, \Omega^{*\,2}_{\rm DW}$$

with standard f_0 relation to T_*

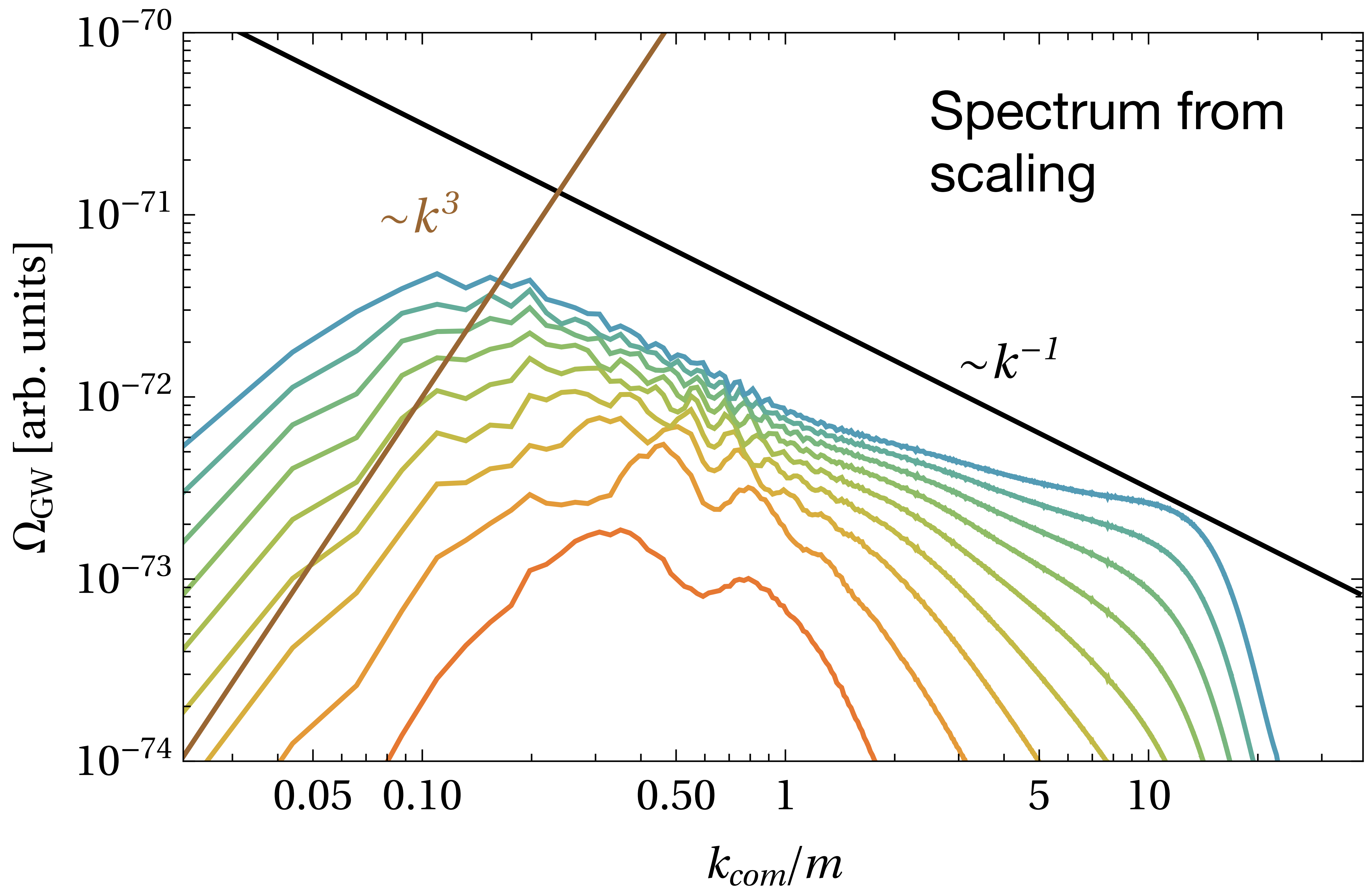


Fig. from **SB**, Mariotti, Rase, Vanvlasselaer, in prep.

GWs from domain walls

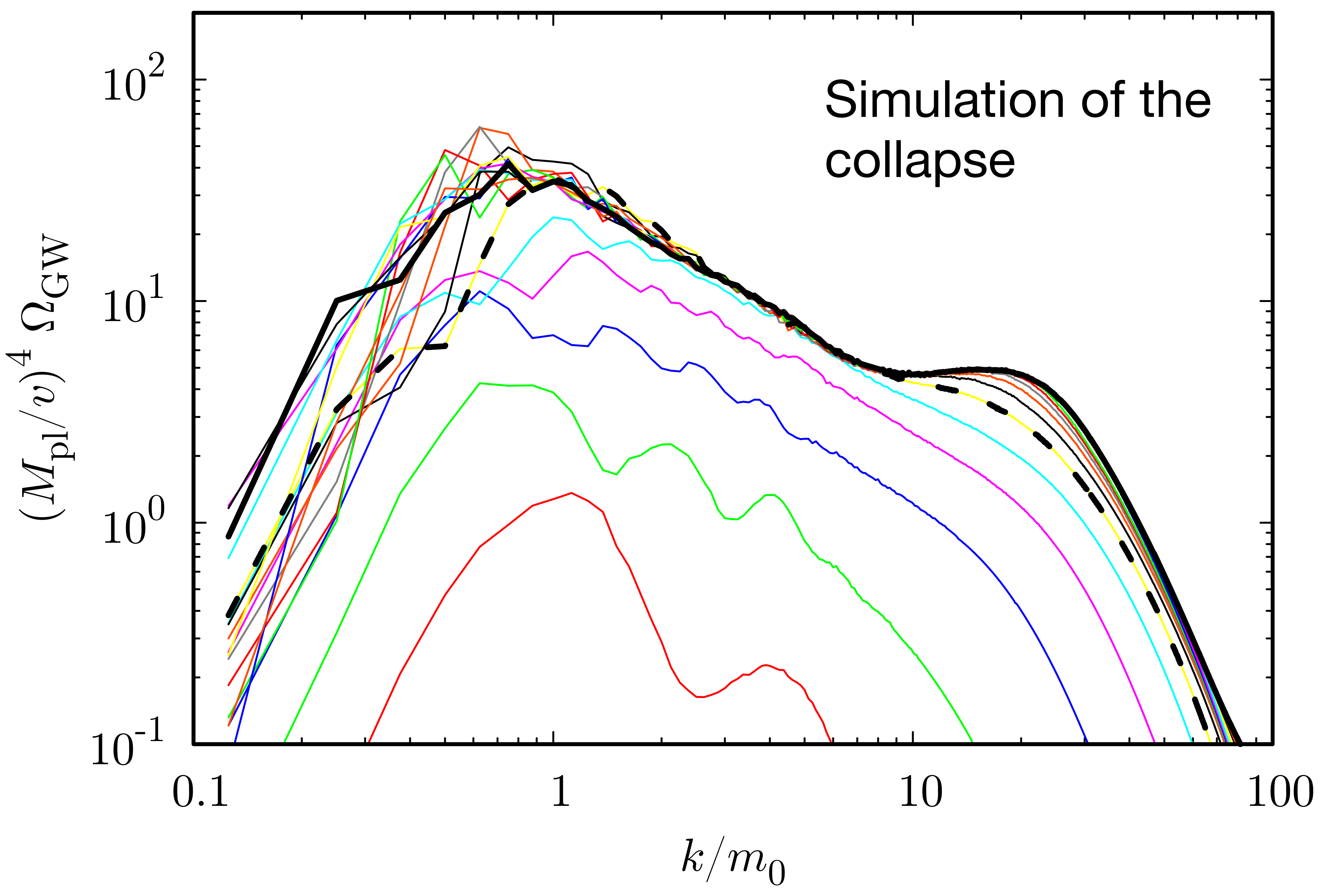
2

- GWs are radiated by domain walls during:
  - the scaling regime (long-lasting source, dominated by later times)
  - the final phase of collapse and annihilation

- Given the collapse at $T = T_*$:

$$\Omega^0_{\rm peak} \sim 10^{-6}\,\Omega^{*\,2}_{\rm DW}$$

with standard f_0 relation to T_*



Kitajima, Lee, Murai, Takahashi, Yin, PLB [2306.17146]
Ferreira, Notari, Pujolàs, Rompineve, JCAP [2401.14331]

GWs from cosmic strings 2

- Loops are continuously chopped off the long string network:
  - GW emission dominated by the decay of these loops
  - Spectrum is flat up to matter-radiation equality
- GW amplitude (flat spectrum):

$$\Omega^0_{\rm flat} \sim 10^{-4} \left(\frac{G\mu}{\Gamma}\right)^{1/2}$$

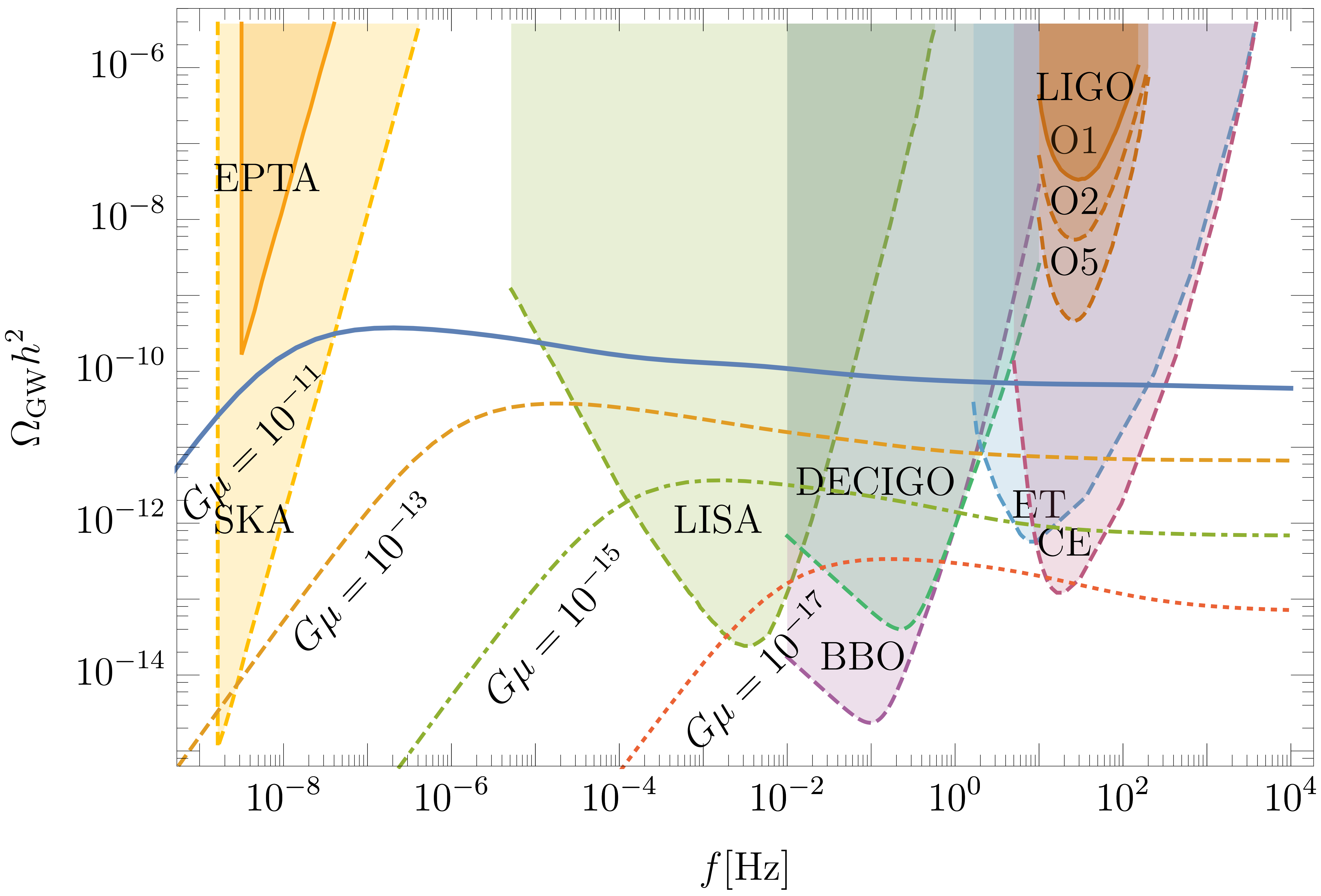
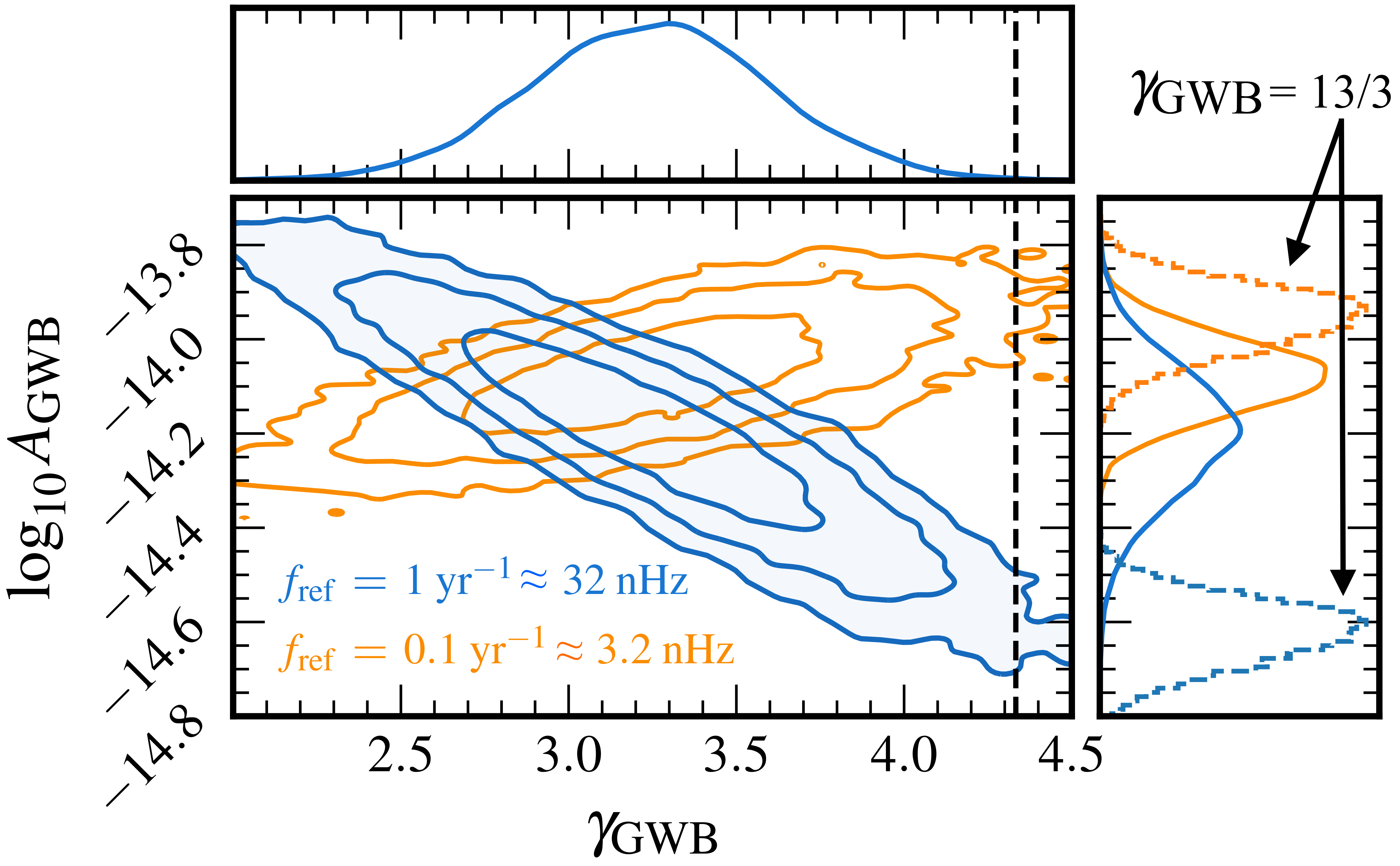


Fig. from Cui et al. [1808.08968], JHEP

NANOGrav 15yr dataset

- Cosmic strings no longer a good fit (as it was for NG 12.5yr)



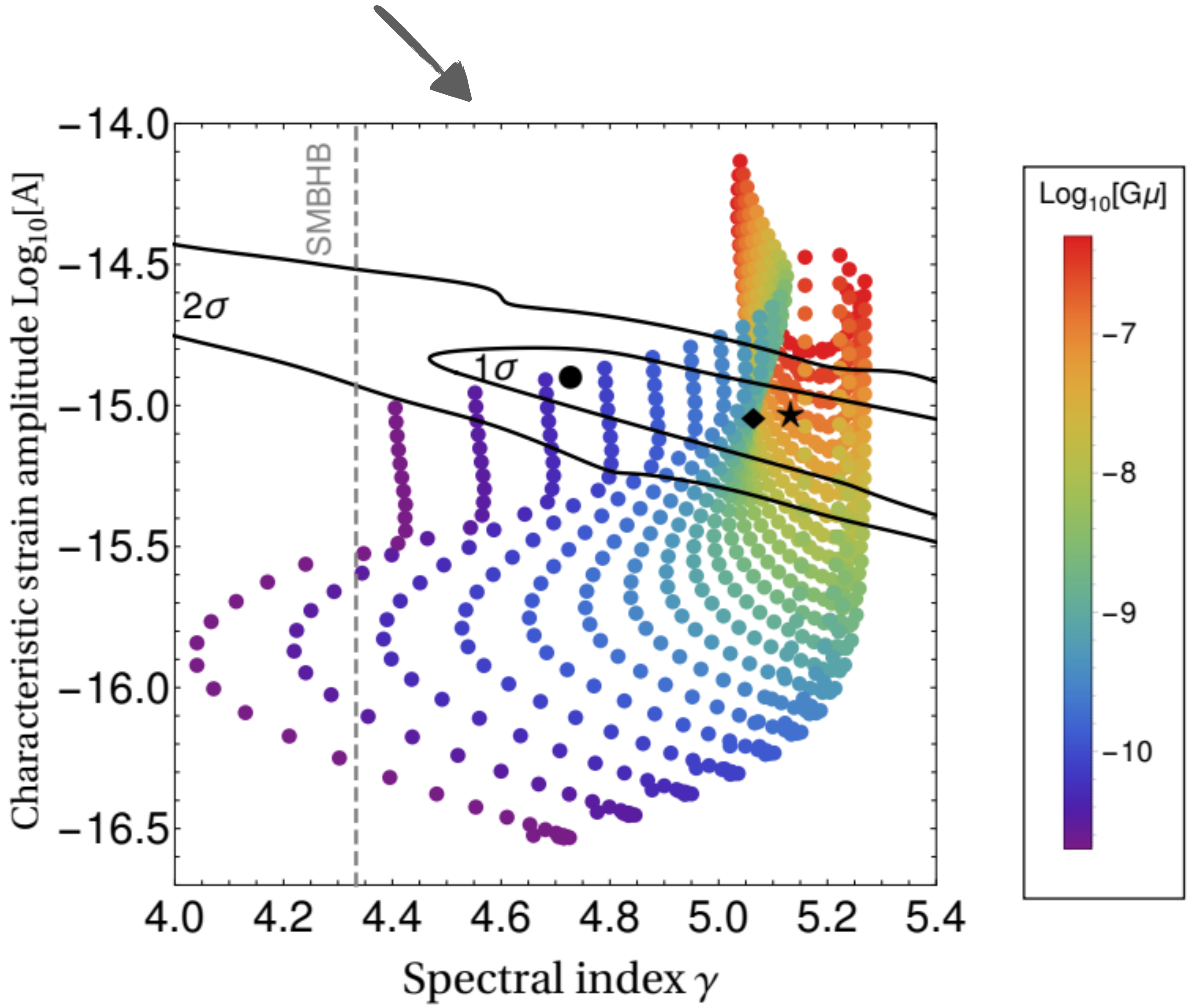
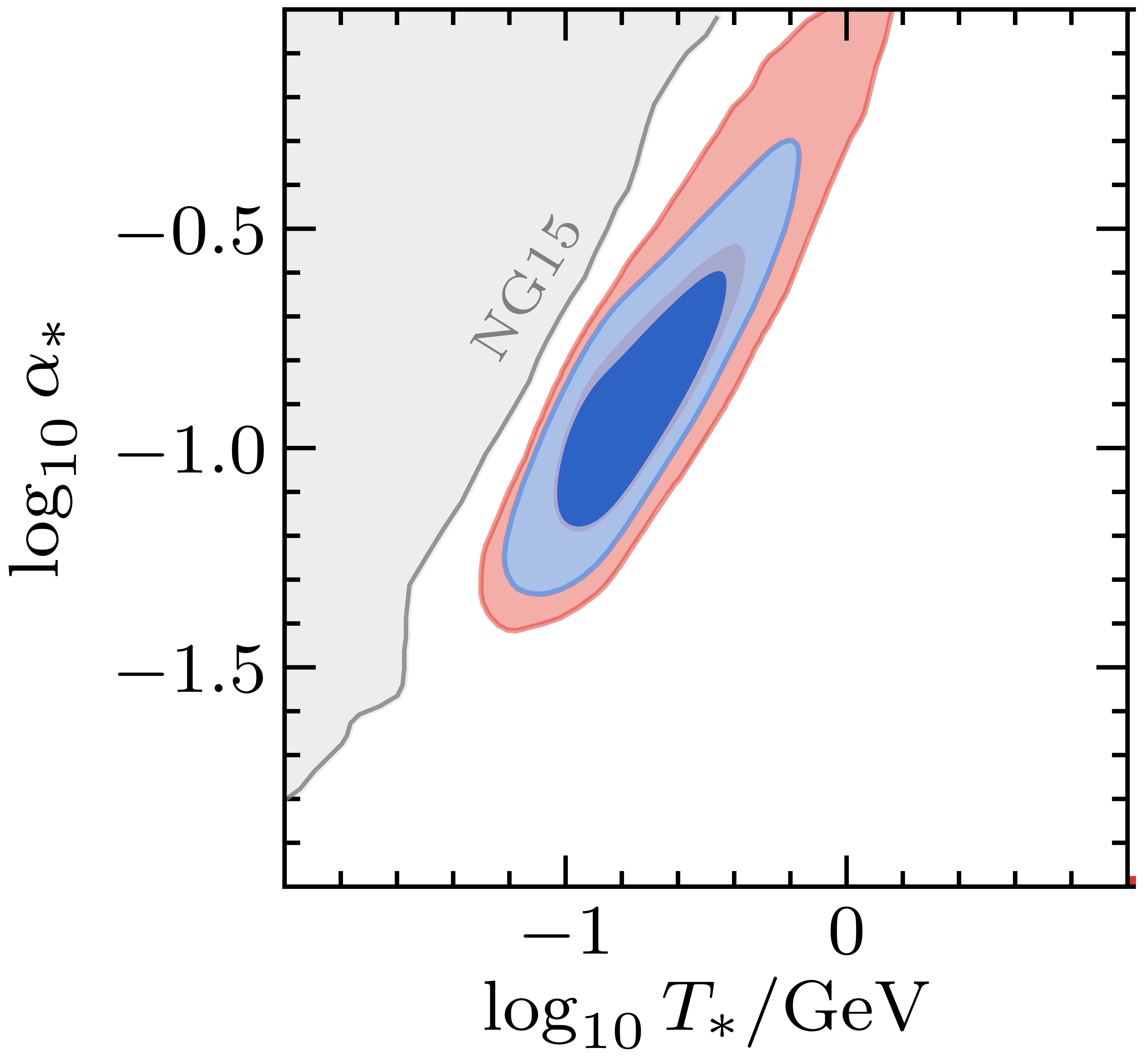


Fig. from **SB**, Brdar, Schmitz, [2009.06607], PRL

Domain walls at NG15



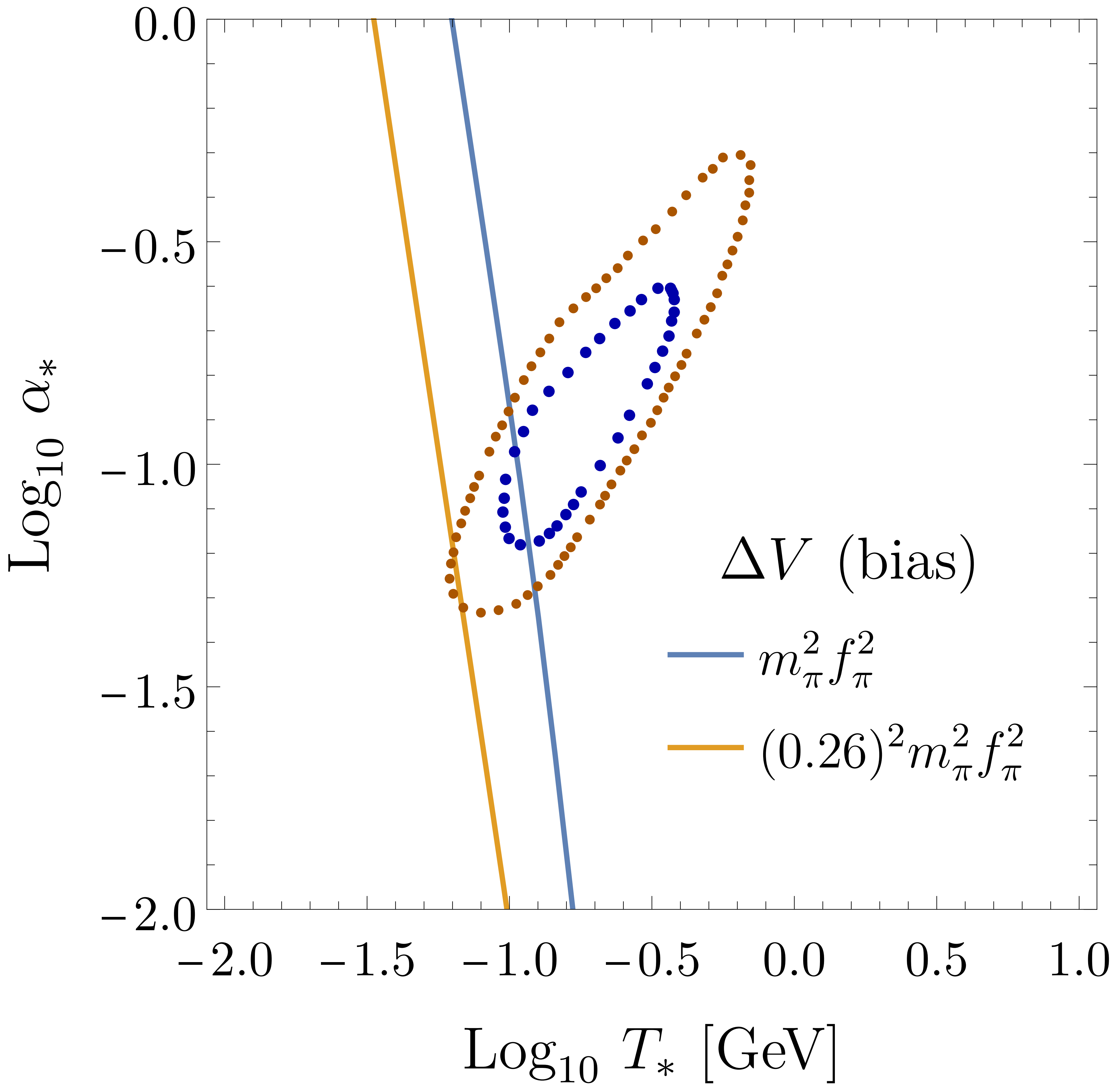
- Need network which is 10% energy budget, annihilating at QCD temperature
- QCD as a trigger: ALP domain walls biased by QCD potential*

$$\mathcal{L}_a \supset \frac{1}{4\pi} a \left(\alpha_d N_d G' \tilde{G}' + \alpha_s N_s G \tilde{G} \right)$$

SB, Mariotti, Rase, Sevrin, [2302.06952], JCAP

*no solution to the strong CP problem in general

Domain walls at NG15



- Need network which is 10% energy budget, annihilating at QCD temperature

- QCD as a trigger: ALP domain walls biased by QCD potential*

$$\mathcal{L}_a \supset \frac{1}{4\pi} a \left(\alpha_d N_d G' \tilde{G}' + \alpha_s N_s G \tilde{G} \right)$$

SB, Mariotti, Rase, Sevrin, [2302.06952], JCAP

*no solution to the strong CP problem in general

Interplay: impurities 3

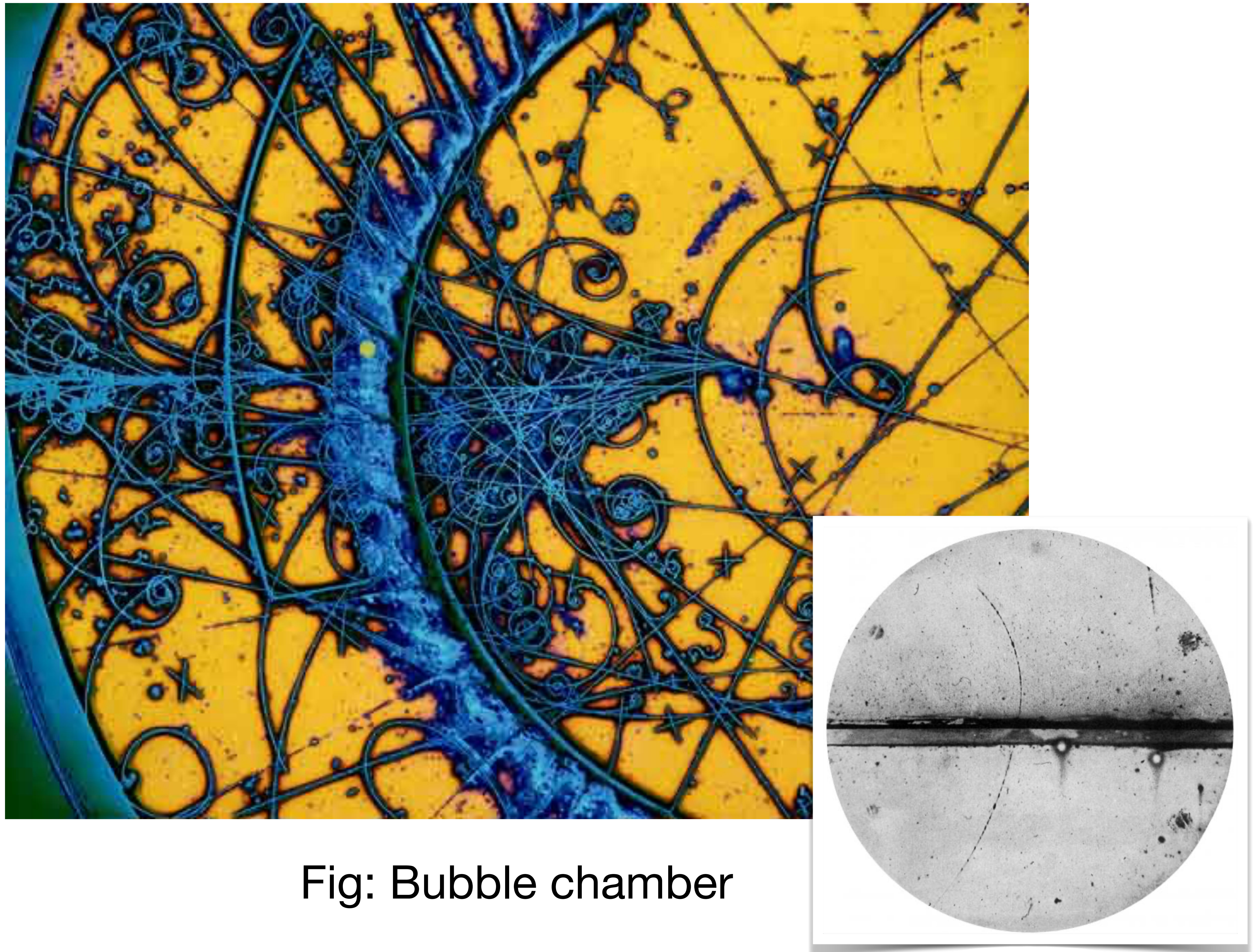


Fig: Bubble chamber

Thanks to M. Nee!

MONOPOLE AND VORTEX DISSOCIATION AND DECAY OF THE FALSE VACUUM

Paul Joseph STEINHARDT

Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138, USA

Received 17 February 1981

"**If monopole** (or vortex) **solutions exist** for a metastable or false vacuum, **a finite density of monopoles** (or vortices) **can act as impurity sites that trigger inhomogeneous nucleation** and decay of the false vacuum."

Impurities in the early universe

Yutaka Hosotani

Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19104

(Received 1 November 1982)

"Now one has to ask the following question: **Is the early universe really sufficiently pure in order for supercooling to take place**? The aim of this paper is to show that in most cases the early universe is very pure. […] In this paper we consider **ordinary particles as impurities**."

Cosmic separation of phases

Edward Witten*

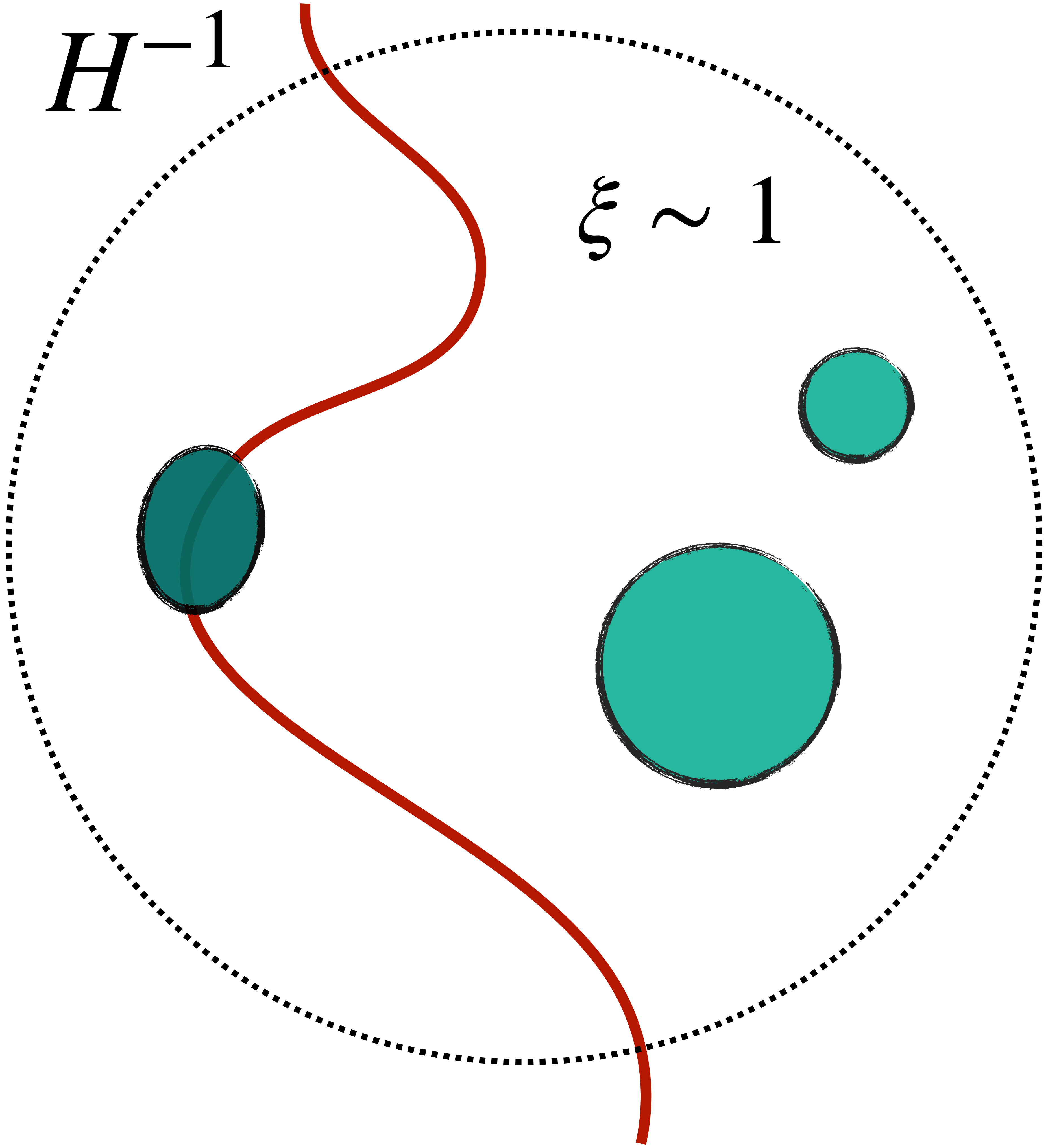
Institute for Advanced Study, Princeton, New Jersey 08540

(Received 9 April 1984)

"In particle physics it is often assumed that phase transitions are nucleated by thermal fluctuations. In practice, […] except in very pure, homogeneous samples, **phase transitions are often nucleated by various forms of impurities and inhomogeneities of nonthermal origin**."

"What if the transition was nucleated by impurities? In this case **the mean spacing between bubbles has nothing to do with free energies** of nucleation and is simply the spacing between the relevant impurities. "

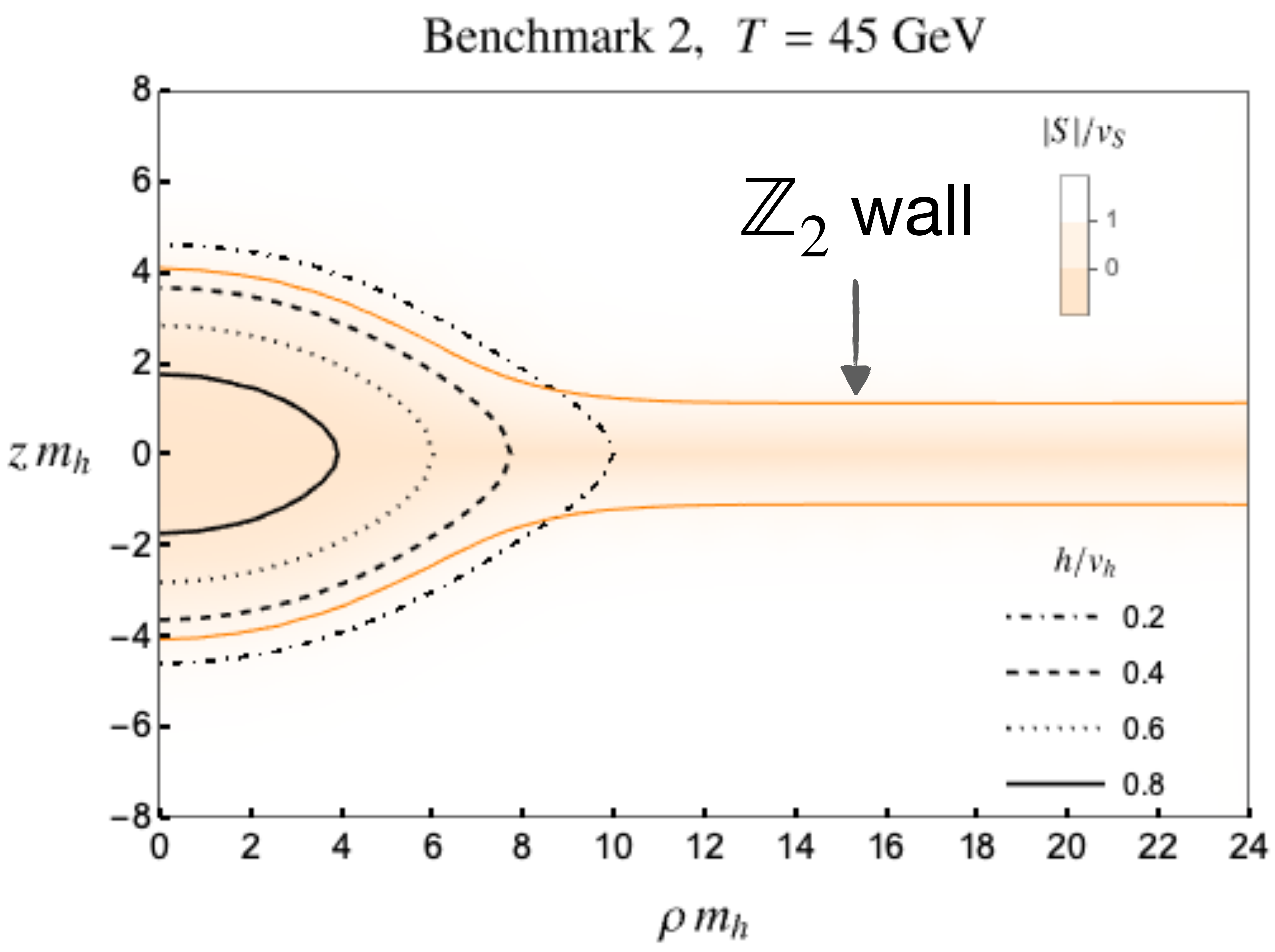
Seeded bubbles



- Nucleation probability no longer the same everywhere!
- Competition between seeded bubbles, and hom. bubbles far from the defect

Particle physics

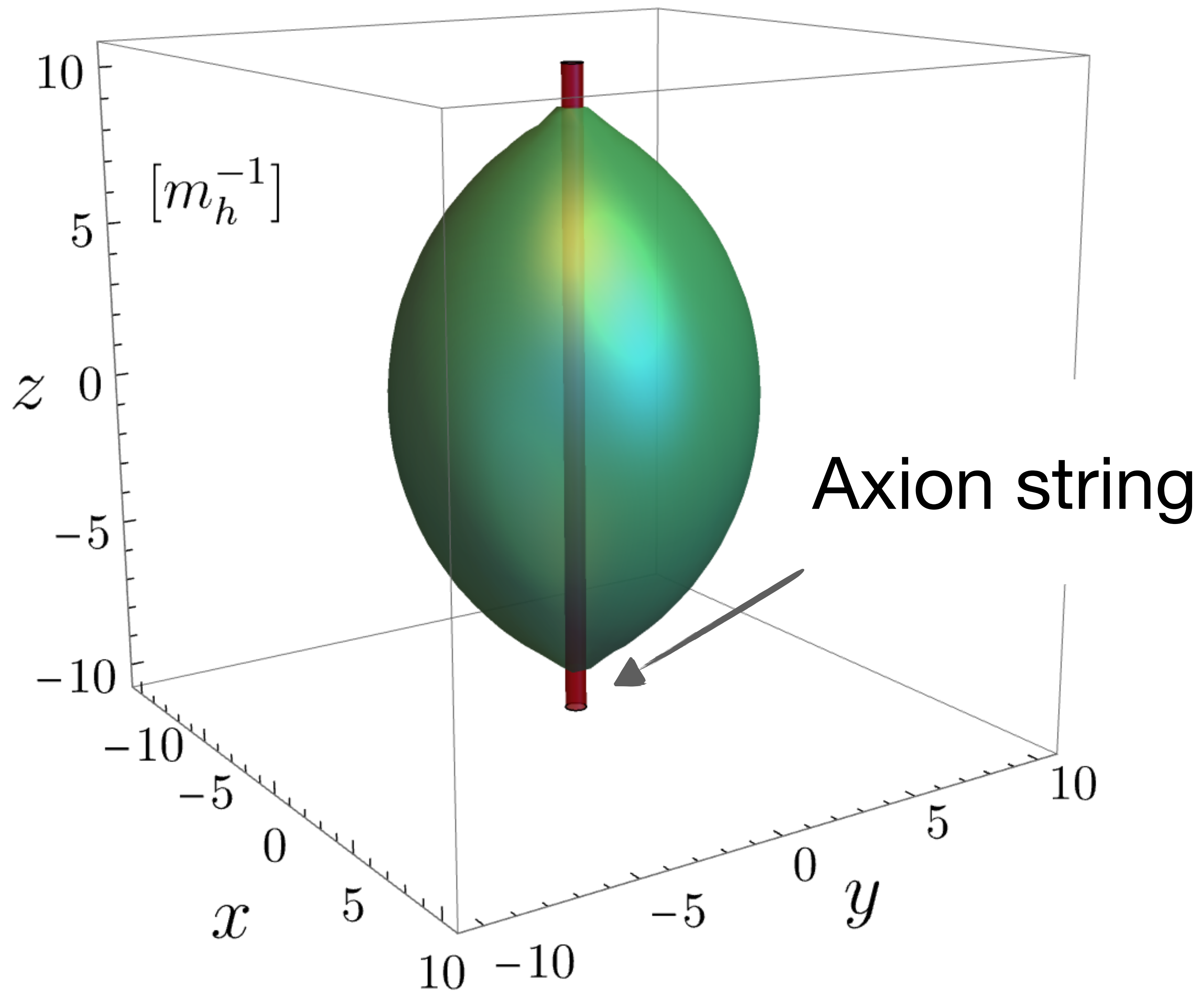
SM + $\mathbb{Z}_2$ scalar (xSM)



SB, Mariotti [2203.16450], PRL

Agrawal, **SB**, Mariotti, Nee [2312.06749], JHEP

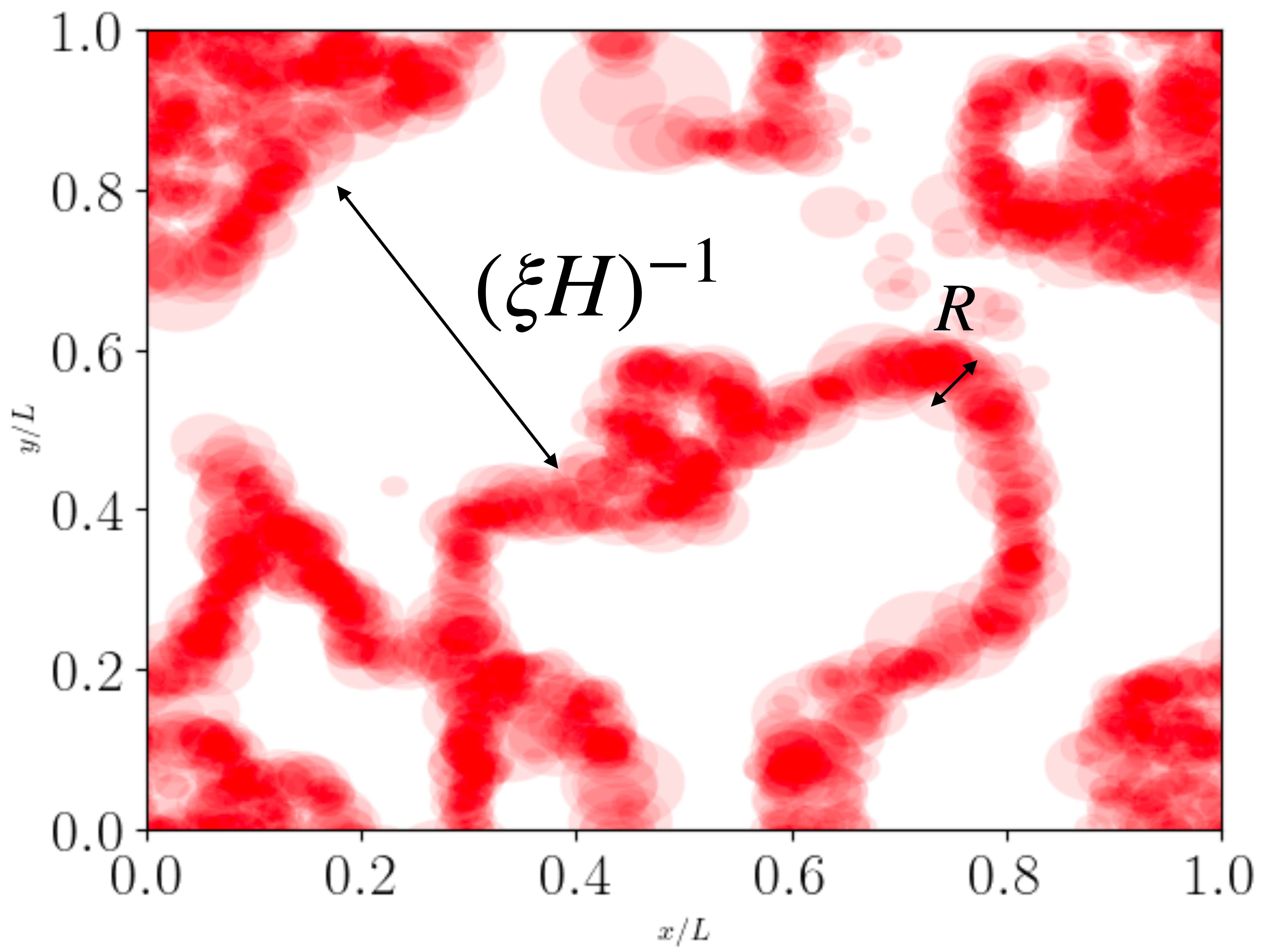
QCD axion



SB, Mariotti [2405.08060], SciPost

EWPT with a singlet

- Domain wall network mimicked by Ising model, bubbles nucleated on the walls



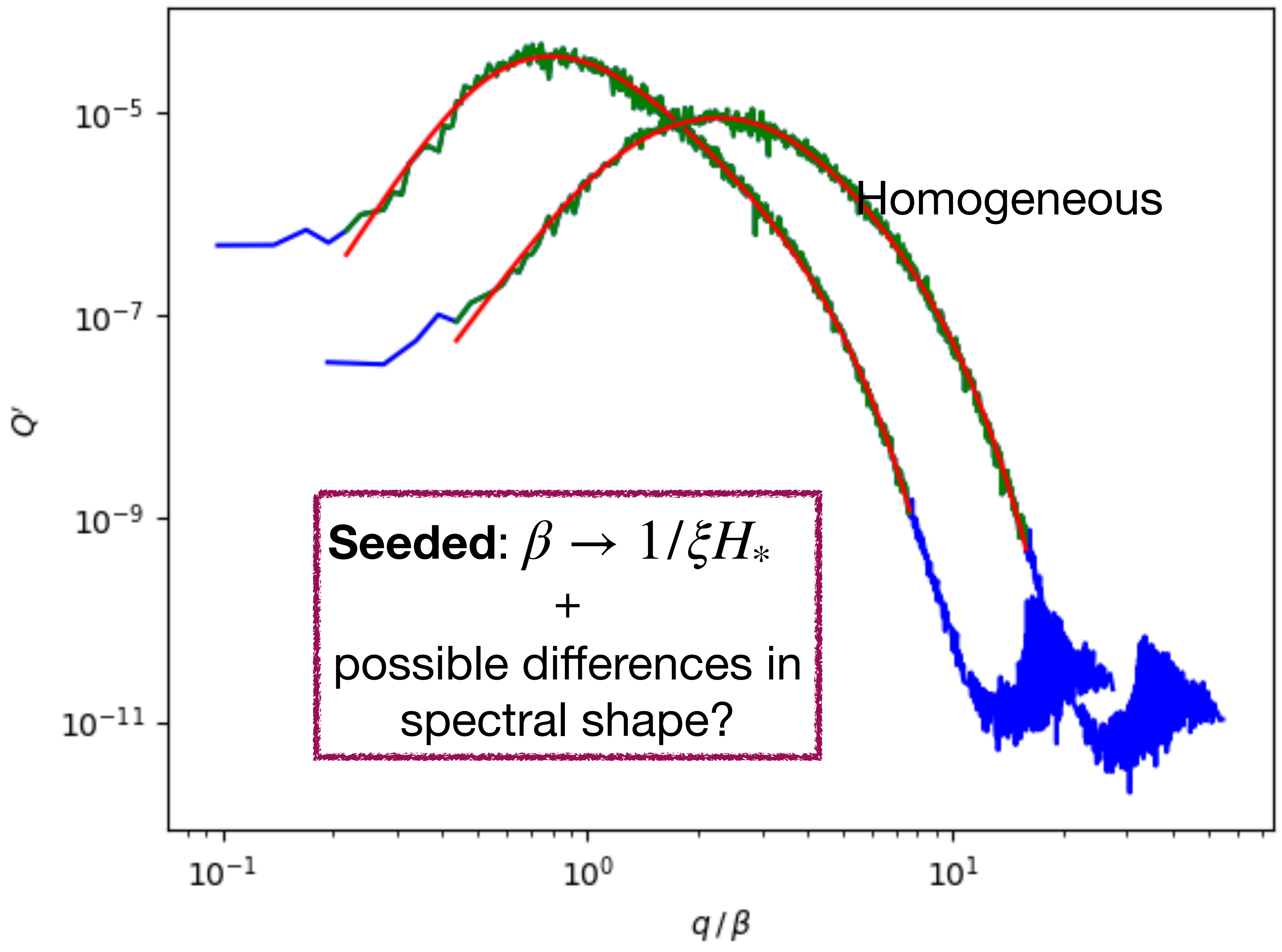
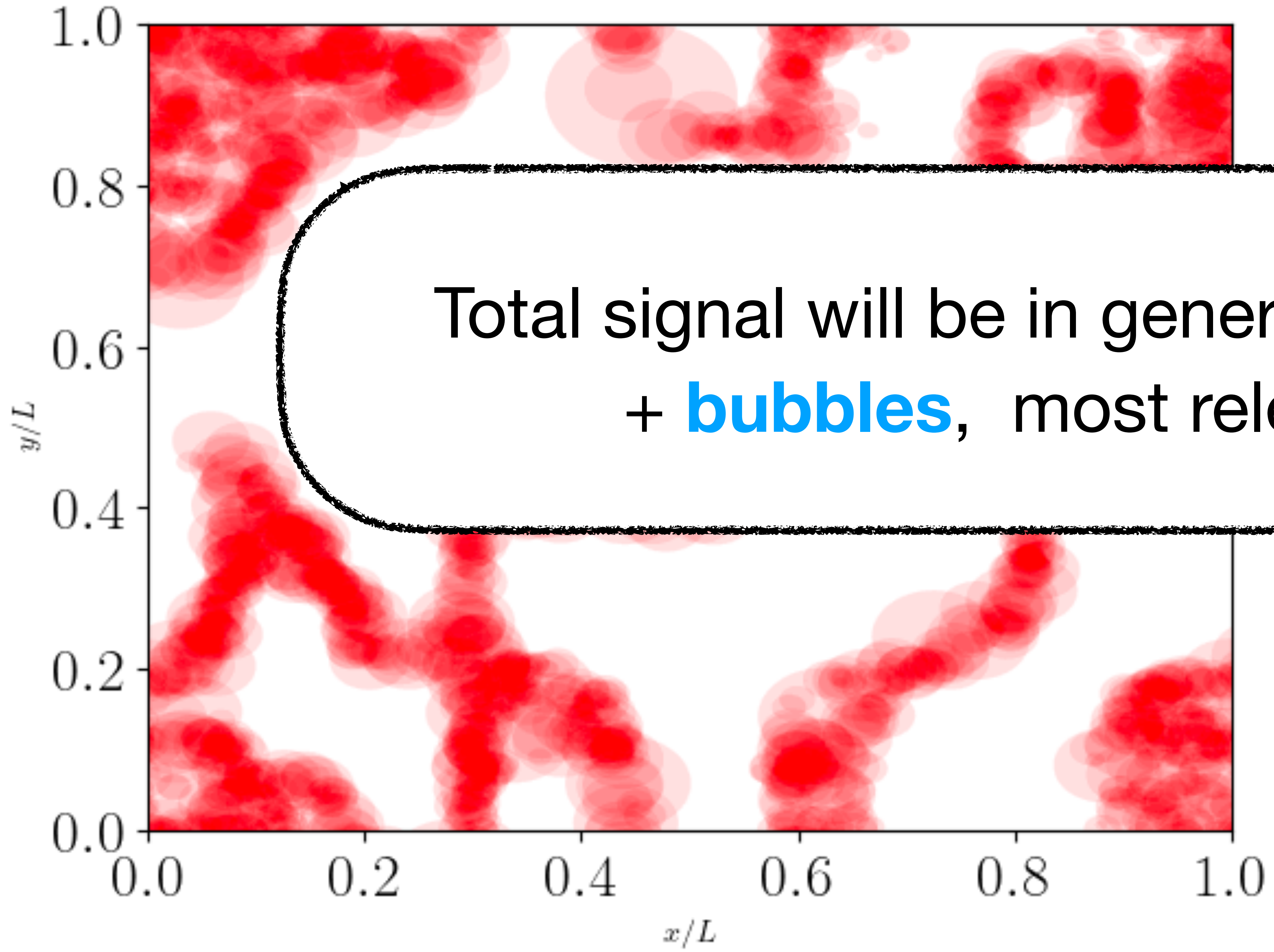


Fig. from **SB**, Jinno, Konstandin, Rubira, Stomberg [2302.06952] JCAP

EWPT with a singlet

- Domain wall network mimicked by Ising model, bubbles nucleated on the walls



Total signal will be in general a superposition of **defects** + **bubbles**, most relevant for heavy defects

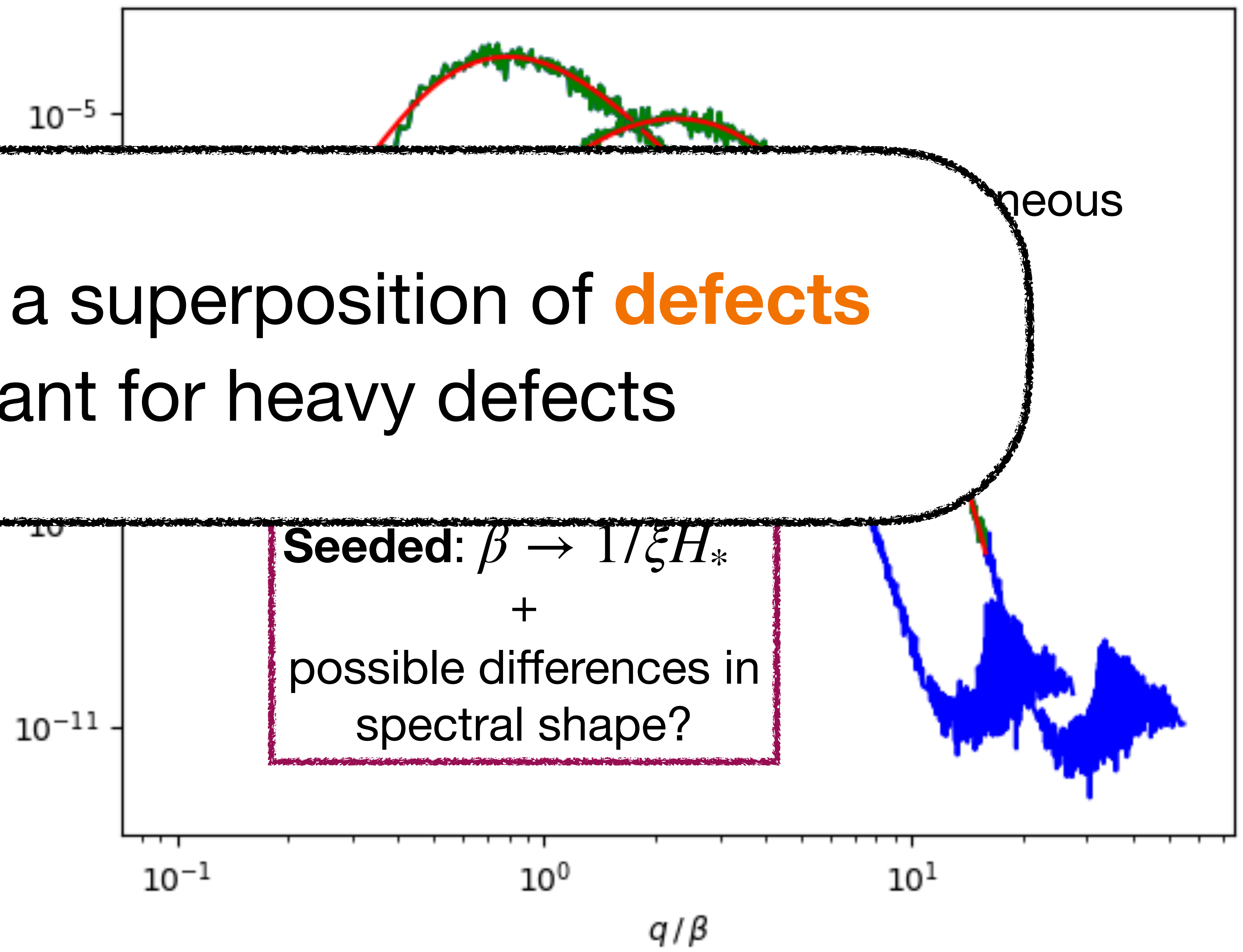
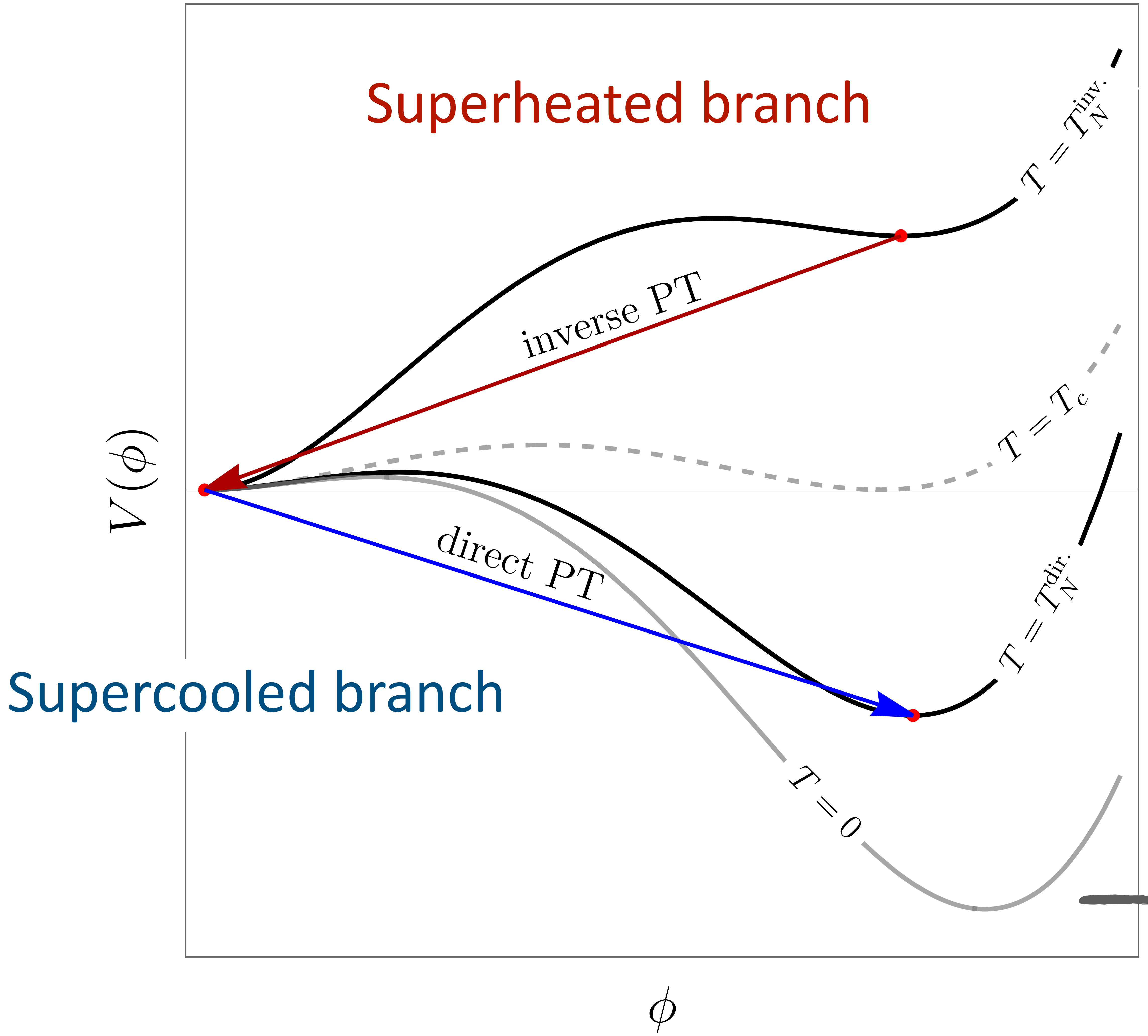


Fig. from **SB**, Jinno, Konstandin, Rubira, Stomberg [2302.06952] JCAP

Superheated bubbles



Are these two phase transitions qualitatively the same?

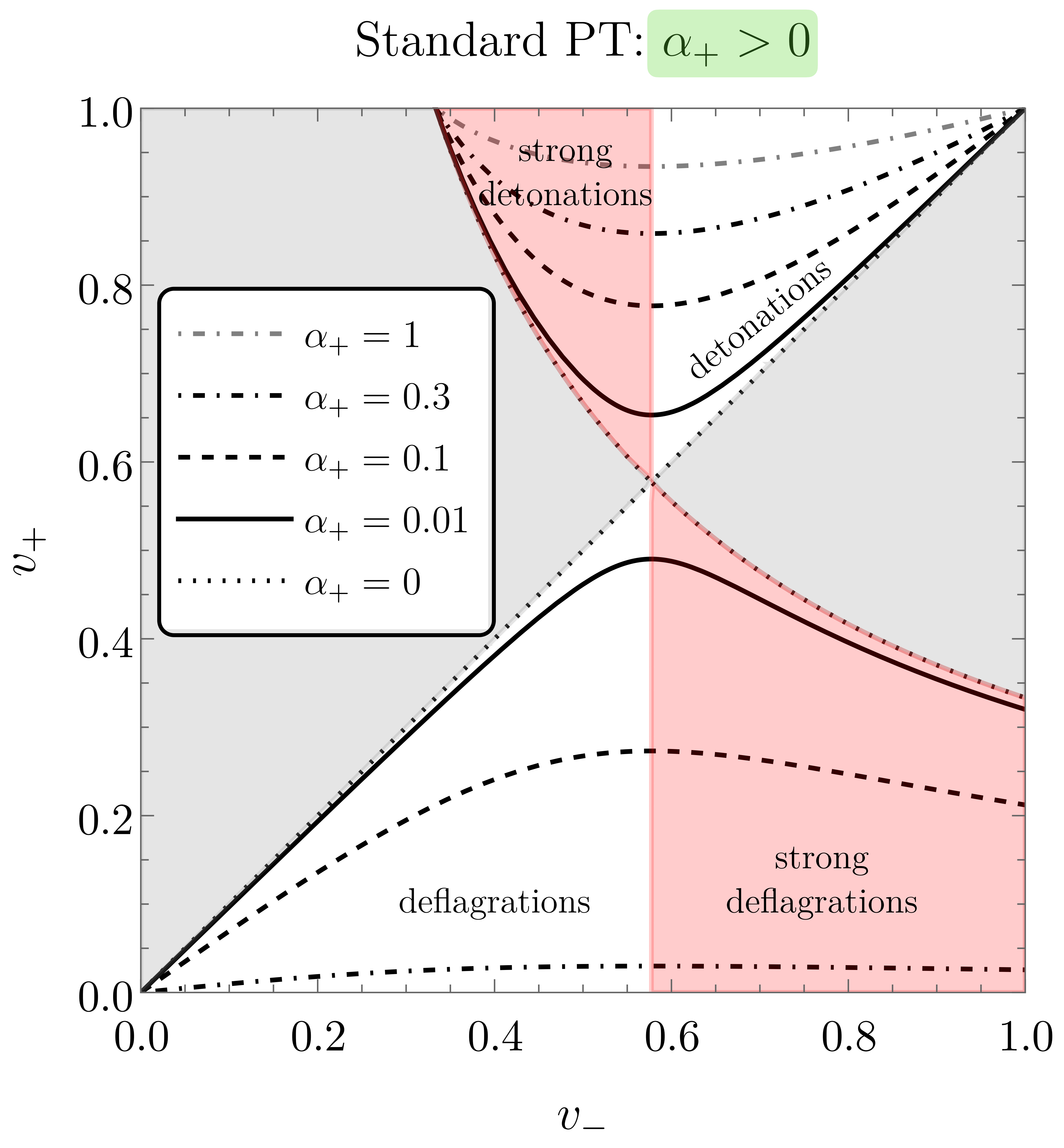
Barni, **SB**, Vanvlasselaer [2406.01596], JCAP

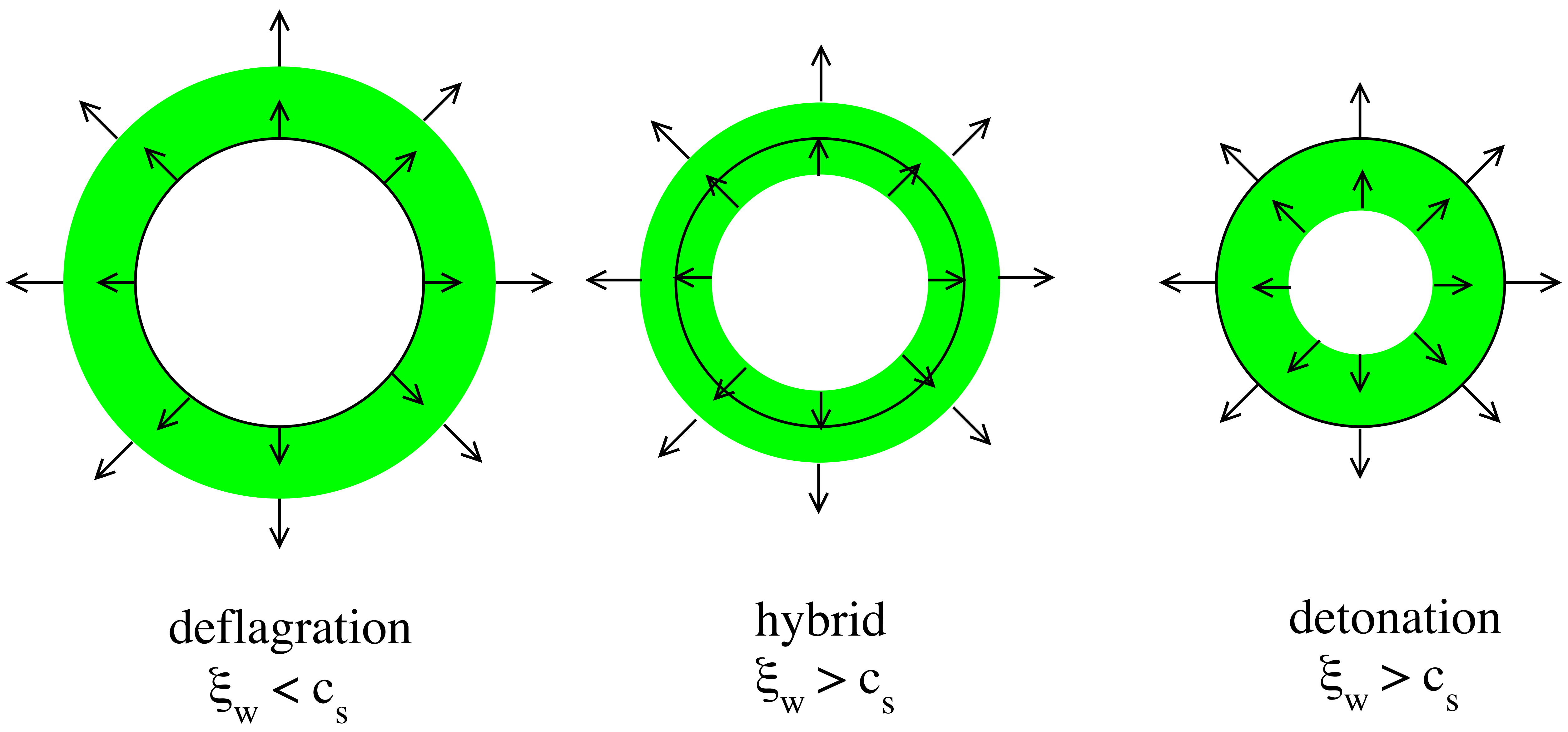
Bea, Casalderrey-Solana, Mateos, Sanchez-Garitaonandia [2406.14450]

(Buen-Abad, Chang, Hook [2305.09712] PRD)

The $T = 0$ potential matters!

Direct transitions

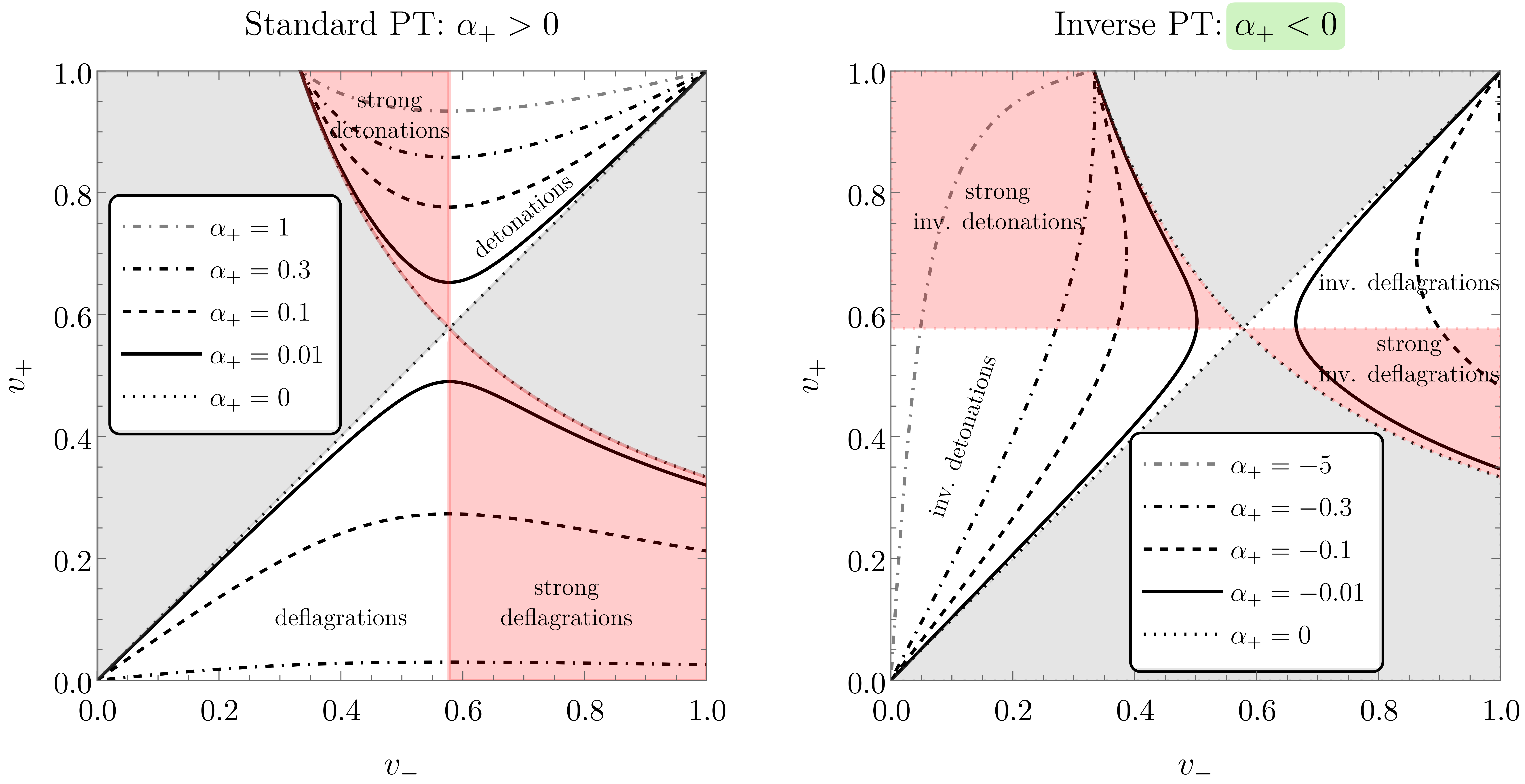




Espinosa, Konstandin, No, Servant [1004.4187] JCAP

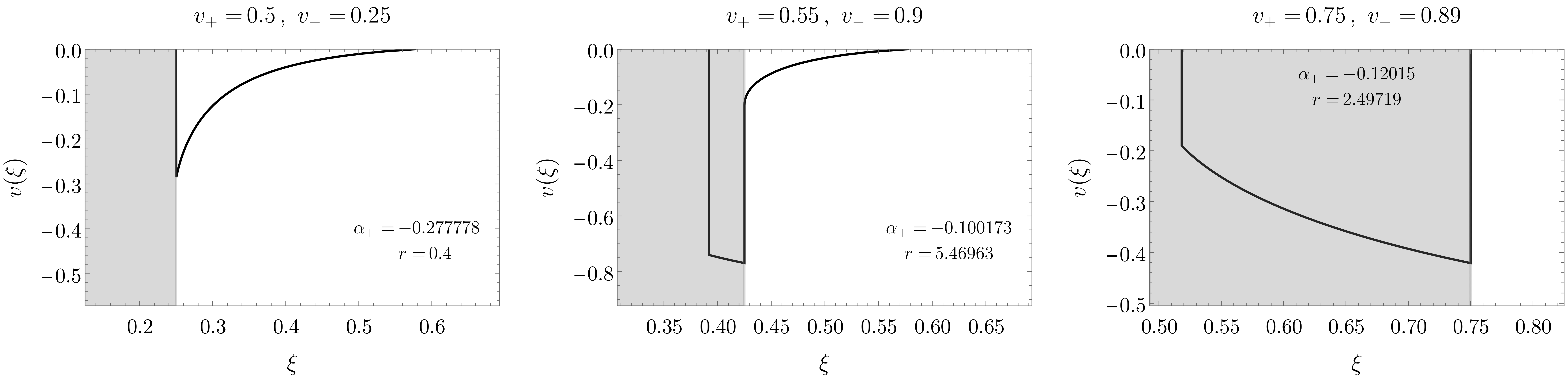
Direct transitions

G. Barni, **SB**, M. Vanvlasselaer
[2406.01596] JCAP



Inverse bubble expansion

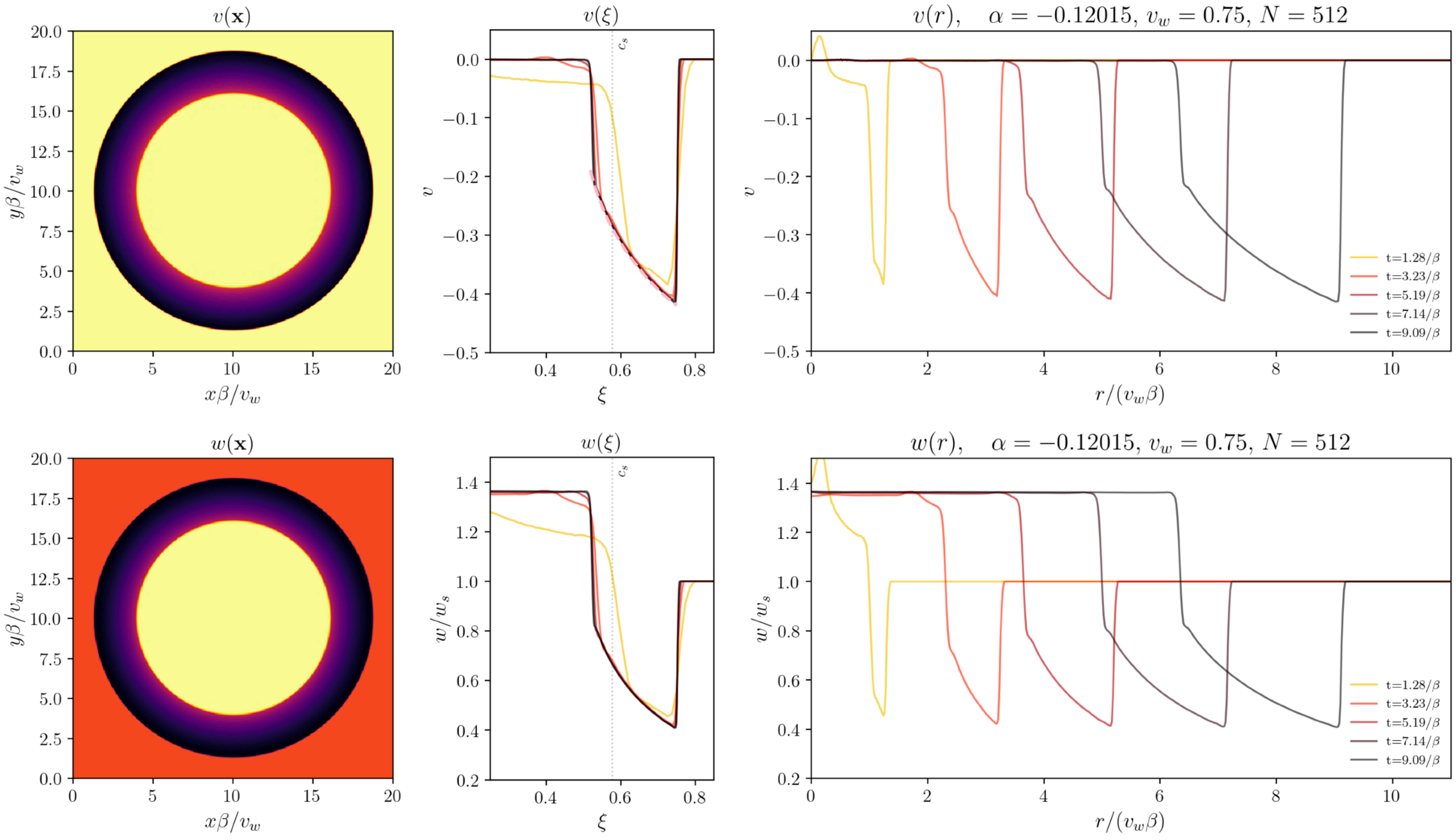
- Fluid is sucked in by the advancing bubble wall:



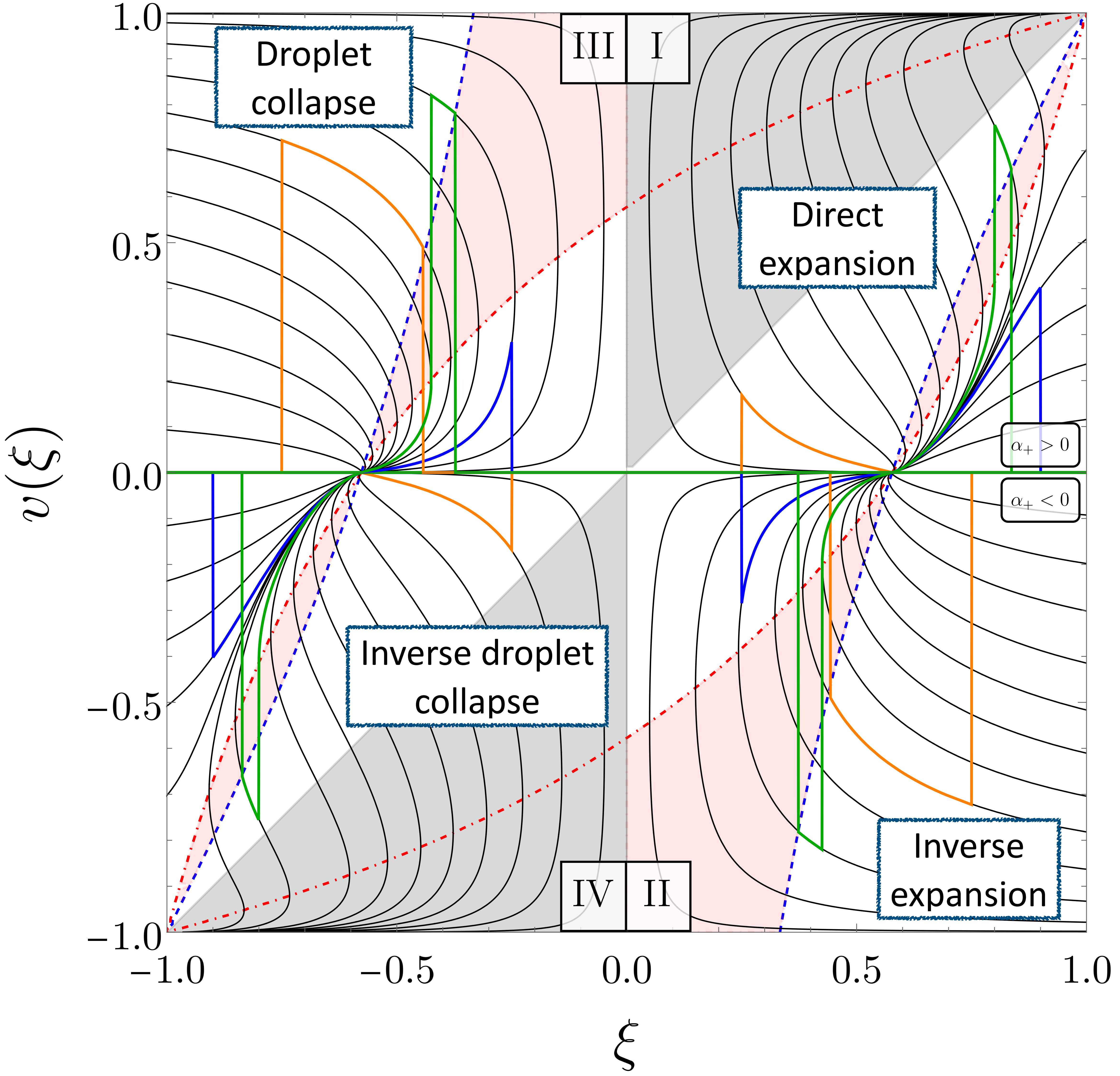
Anti-detonation | Anti-hybrid | Anti-deflagration

Higgsless simulation

Thanks to I. Stomberg



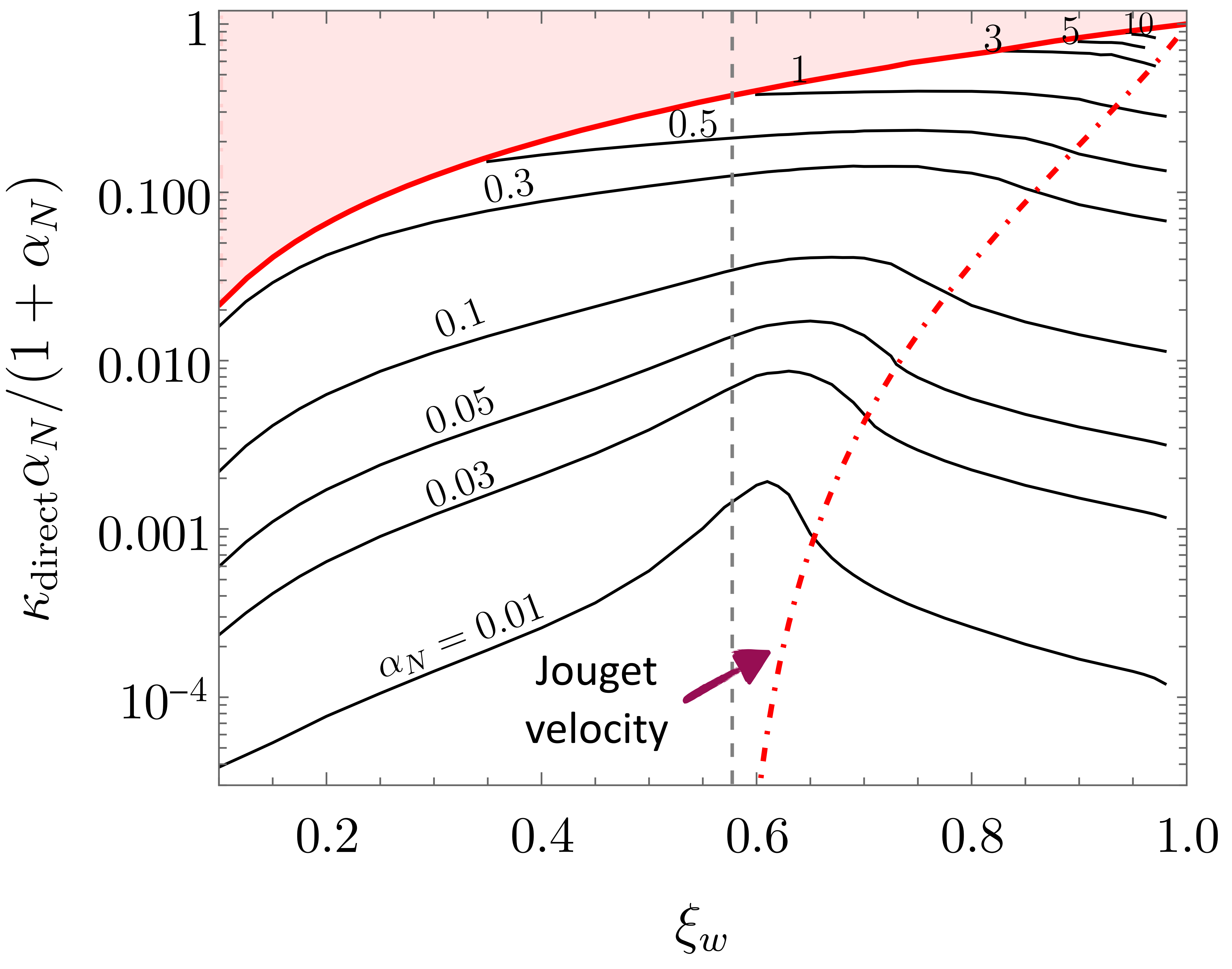
Fluid solutions

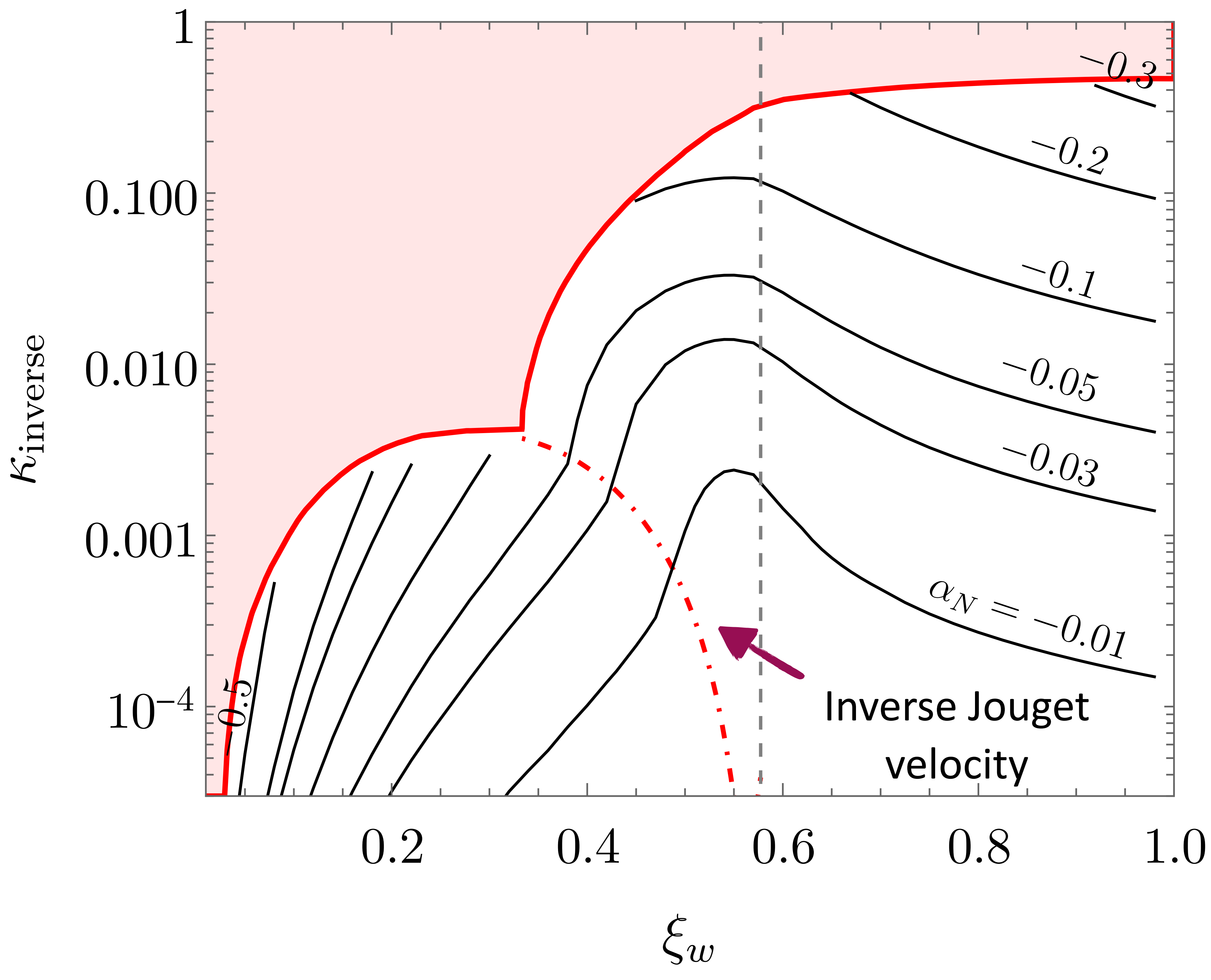


Kinetic energy of the fluid

- Fraction of the critical energy density that goes into bulk fluid motion:

Best efficiency (50%) for $\alpha_N = -1/3$





Thank you!