

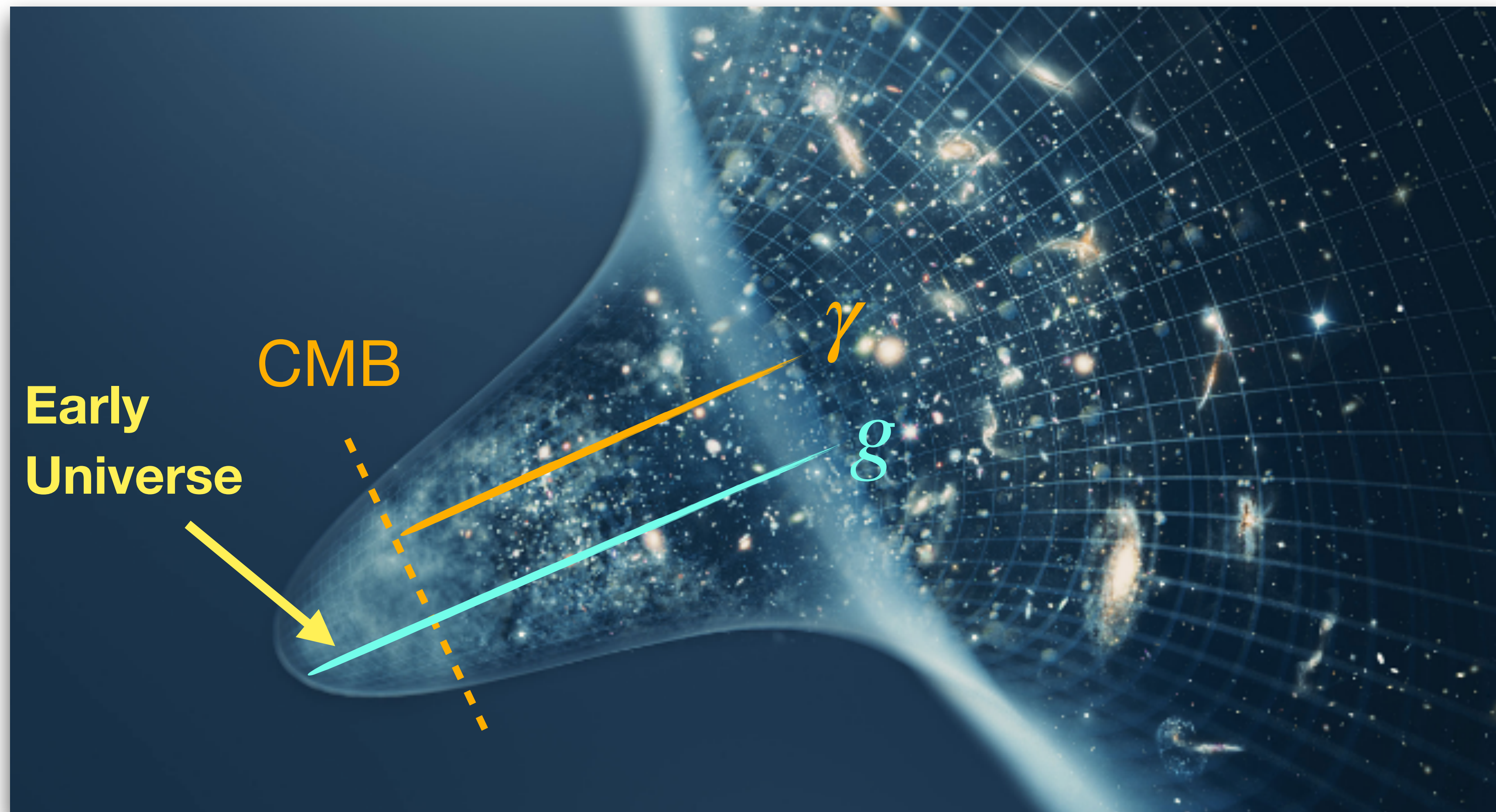


Slow bubbles from a hot plasma: droplets and other heating effects

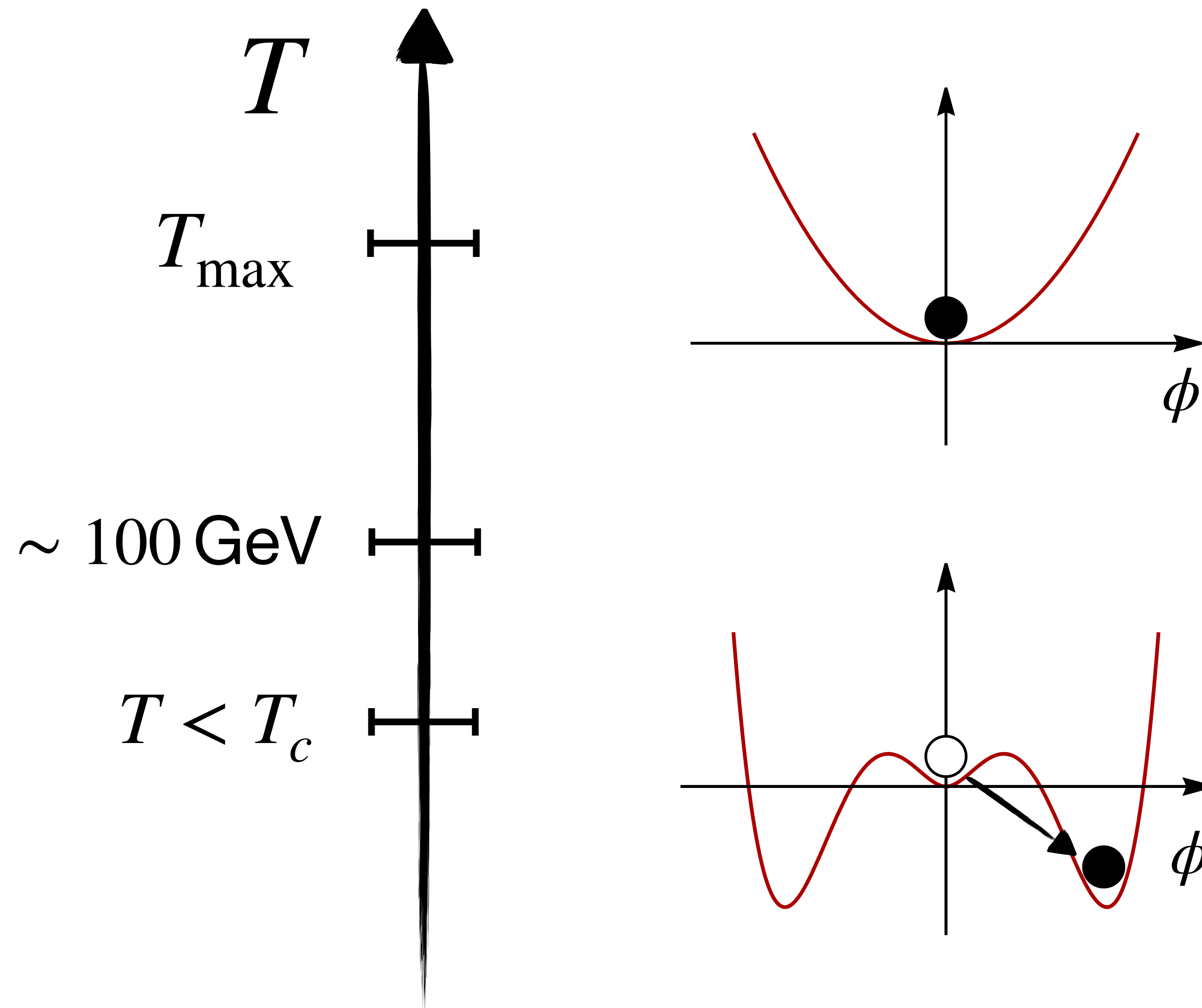
Simone Blasi
DESY Hamburg

N. Bhusal, **SB**, T. Konstandin, E. Perboni, J. van de Vis,
JCAP 07 (2026) 068 [arXiv:2603.22397]

Introduction



Introduction



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

$$\mathcal{F} = e - Ts$$

Spontaneous breaking while the Universe expands and cools down

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

Introduction

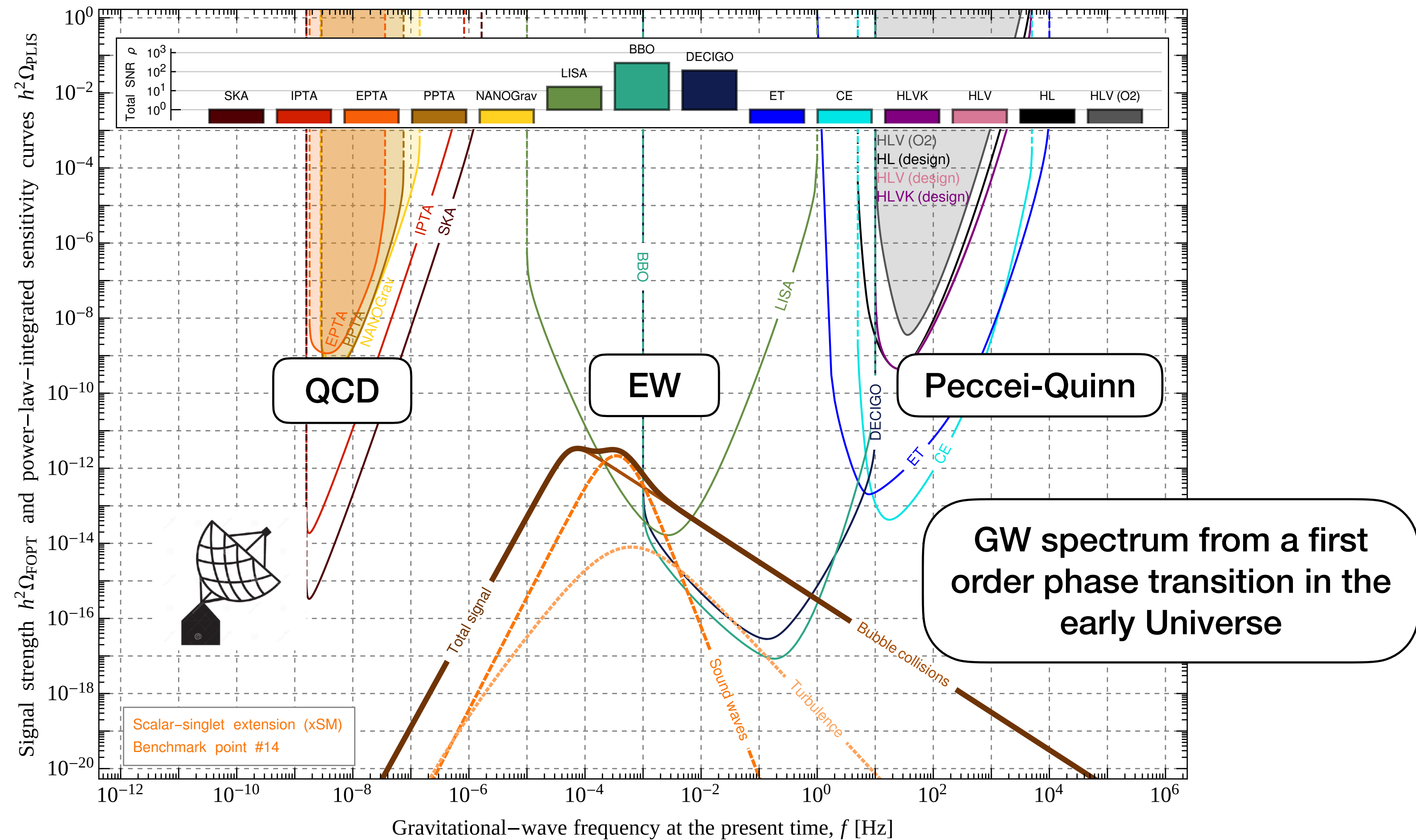
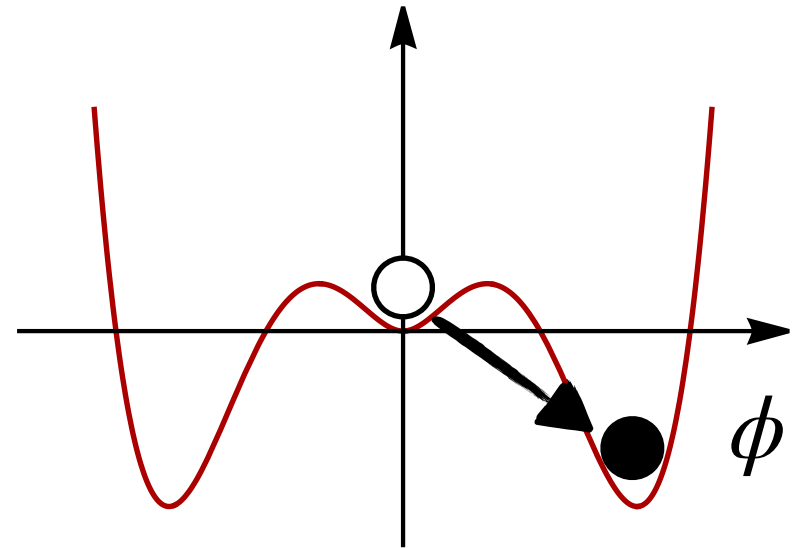


Fig. from Schmitz [2002.04615] JHEP

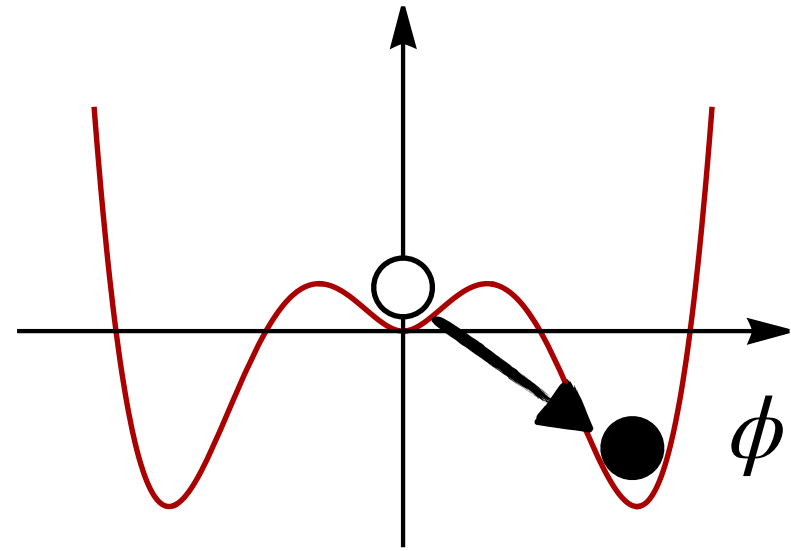
Phase transitions source GWs



Phase transition at T_c

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

Phase transitions source GWs

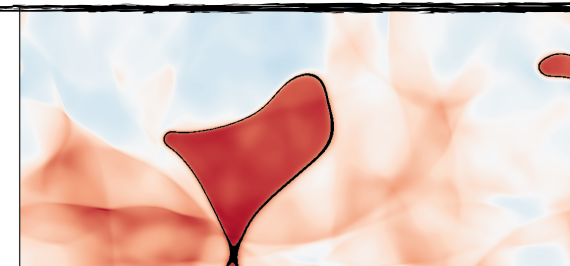
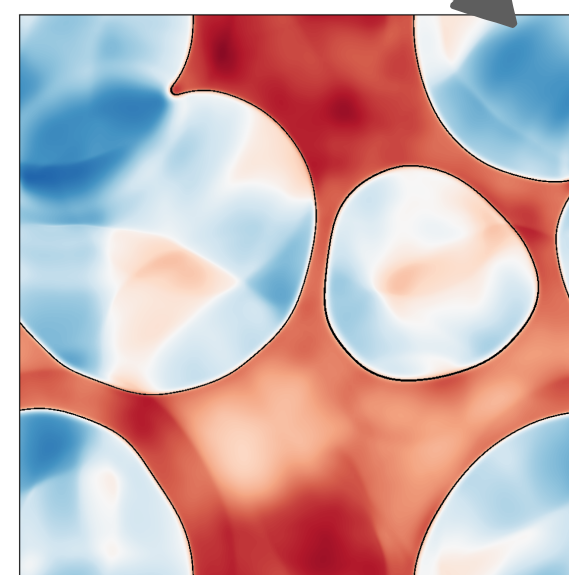
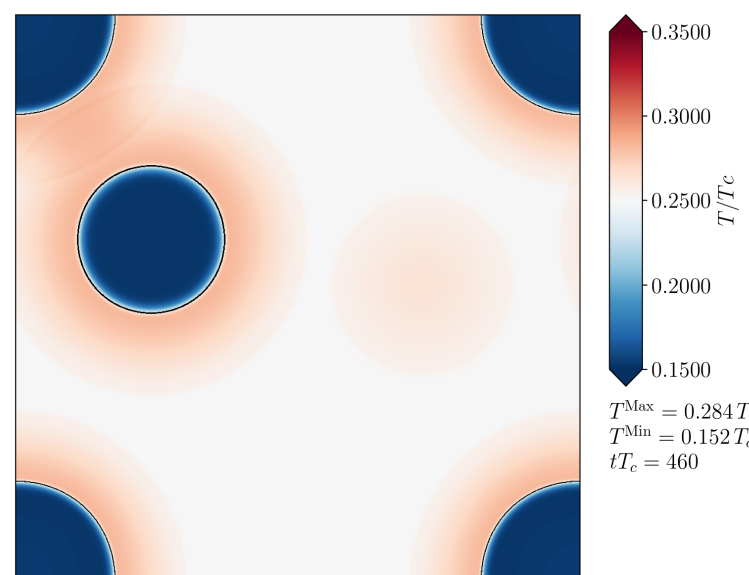


Phase transition at T_c

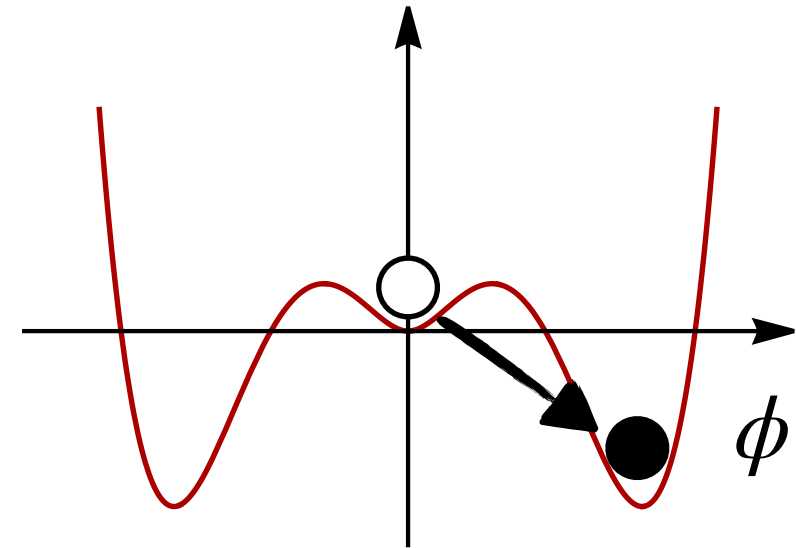
$$\langle \phi \rangle : G \rightarrow H$$

Strength:

Bubble collisions,
hydrodynamics



Phase transitions source GWs

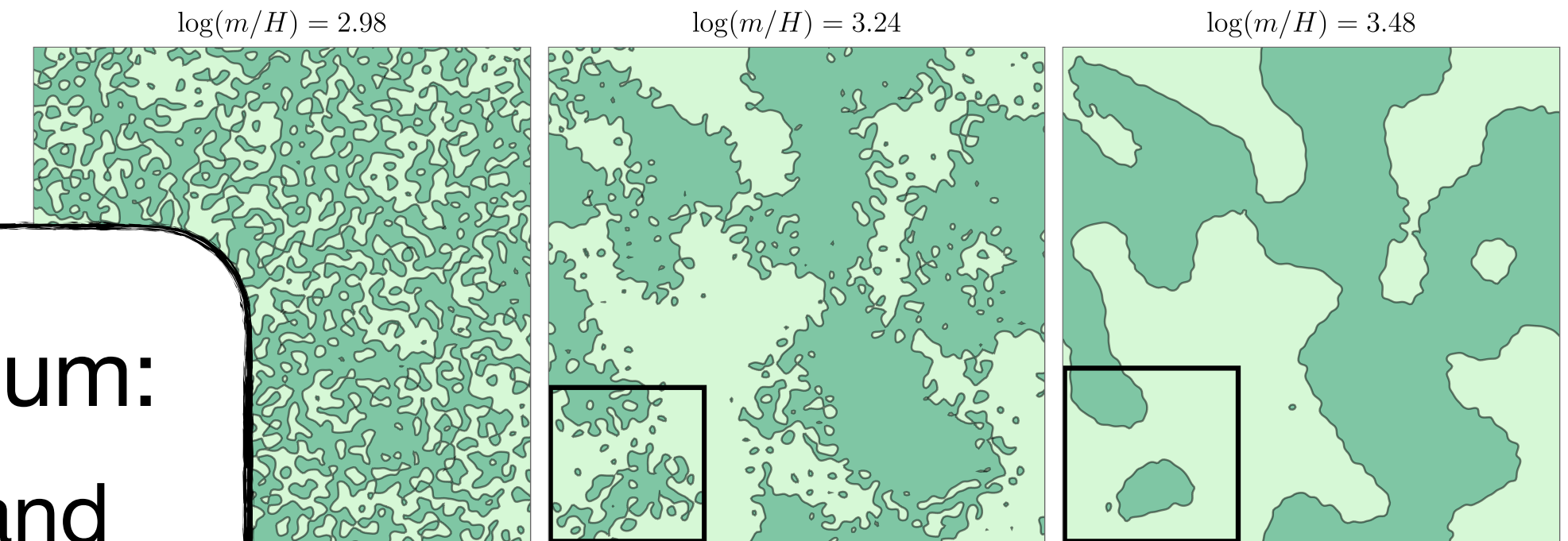


Phase transition at T_c

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

Fig. from **SB**, Mariotti, Rase,
Vanvlasselaer [2511.16649] JCAP

Topology of the vacuum:
Formation of defects and
annihilation



Strength:

Bubble collisions,
hydrodynamics

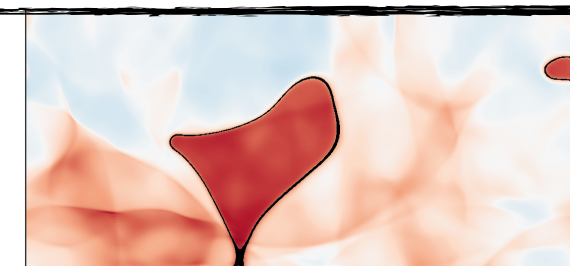
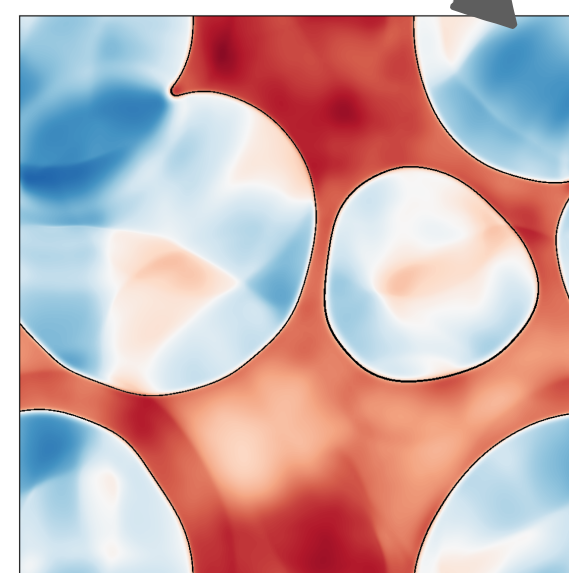
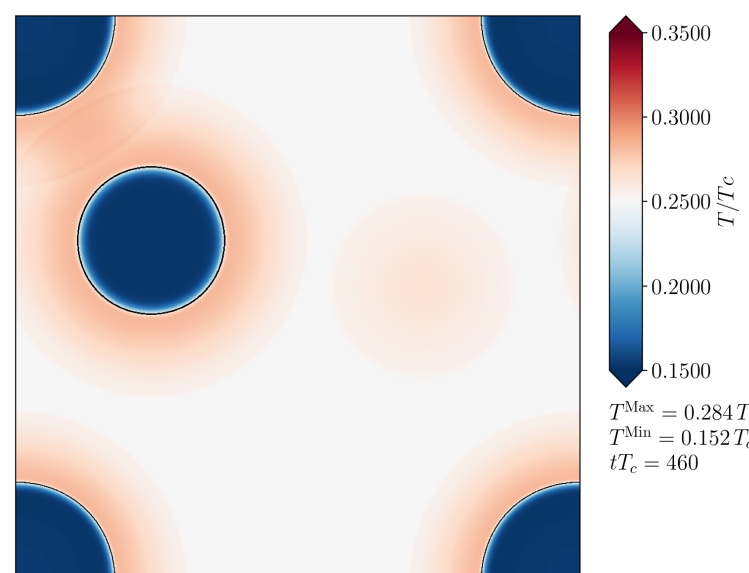


Fig. from Cutting, Hindmarsh,
Weir [2204.03396] PRL (2020)

Phase transitions source GWs

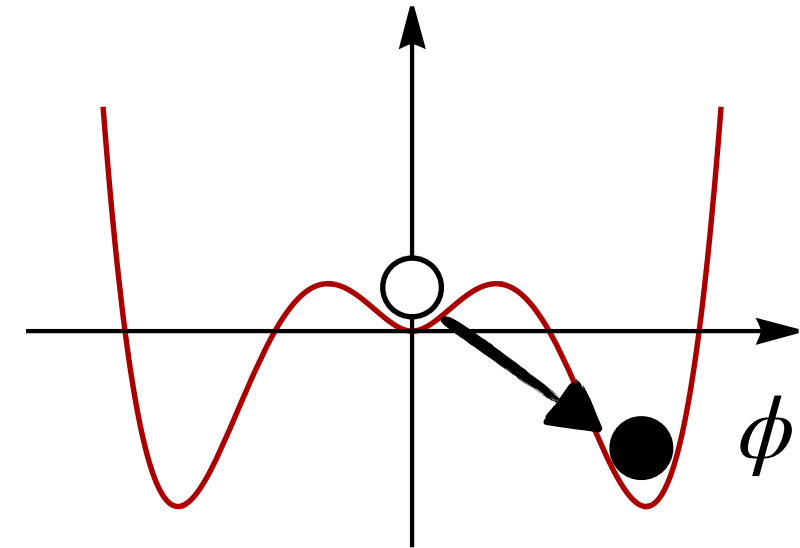
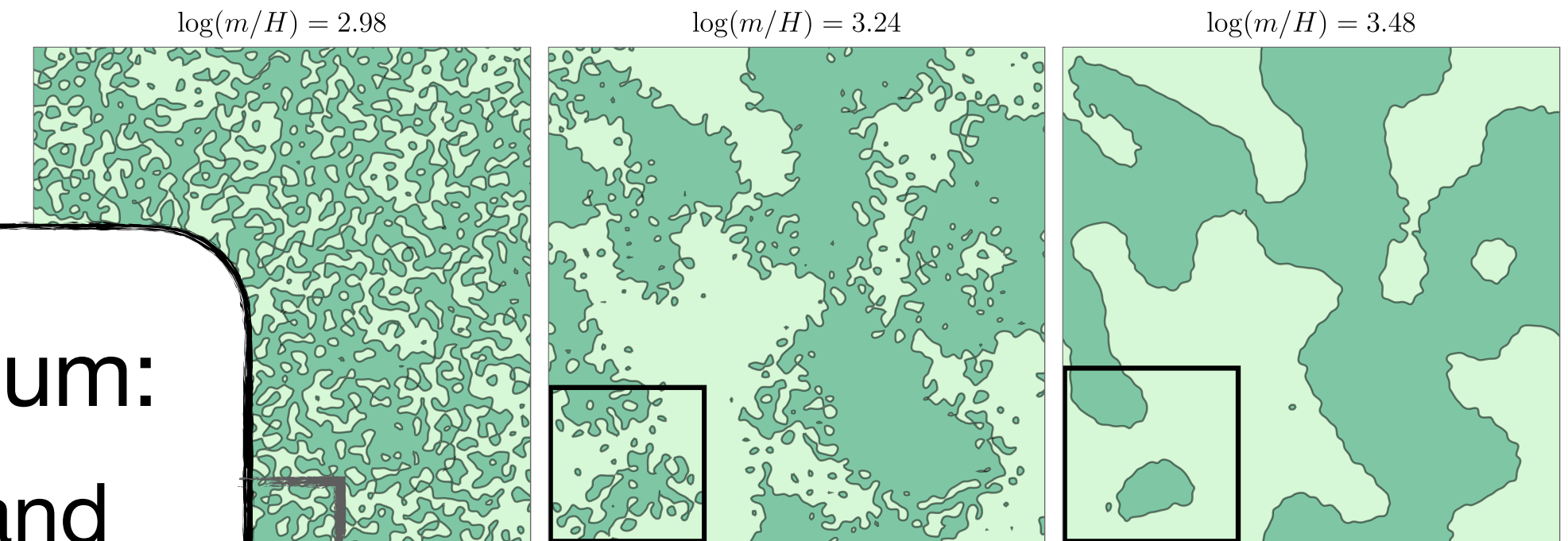


Fig. from **SB**, Mariotti, Rase, Vanvlasselaer [2511.16649] JCAP

Topology of the vacuum:
Formation of defects and annihilation



Phase transition at T_c

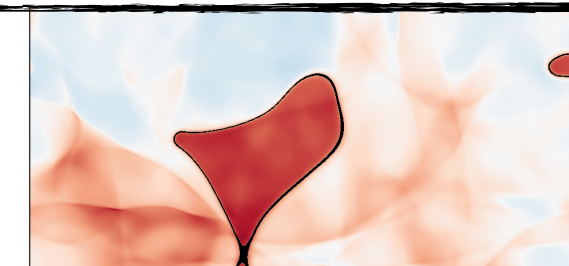
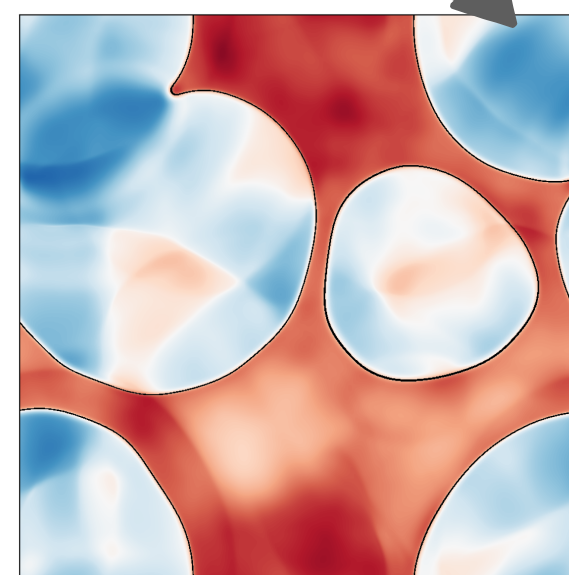
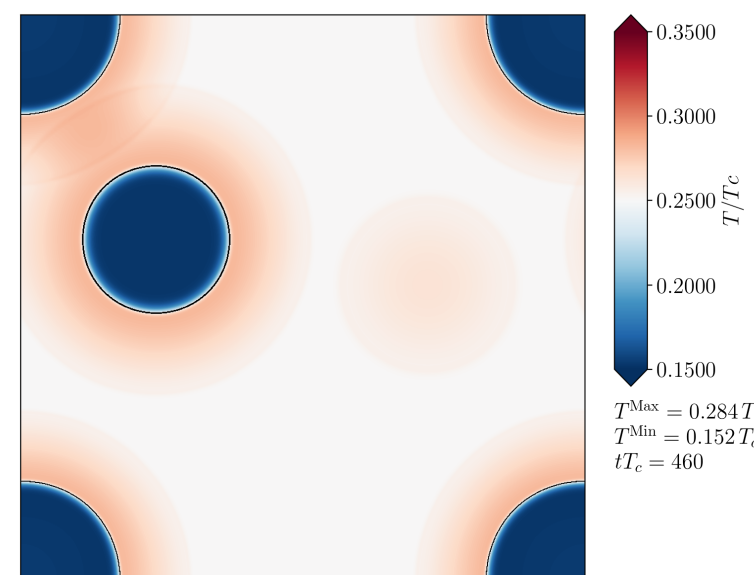
$$\langle \phi \rangle : G \rightarrow H$$

Non-trivial interplay:

Defects as seeds for bubble nucleation

Strength:

Bubble collisions, hydrodynamics



8

Fig. from Cutting, Hindmarsh, Weir [2204.03396] PRL (2020)

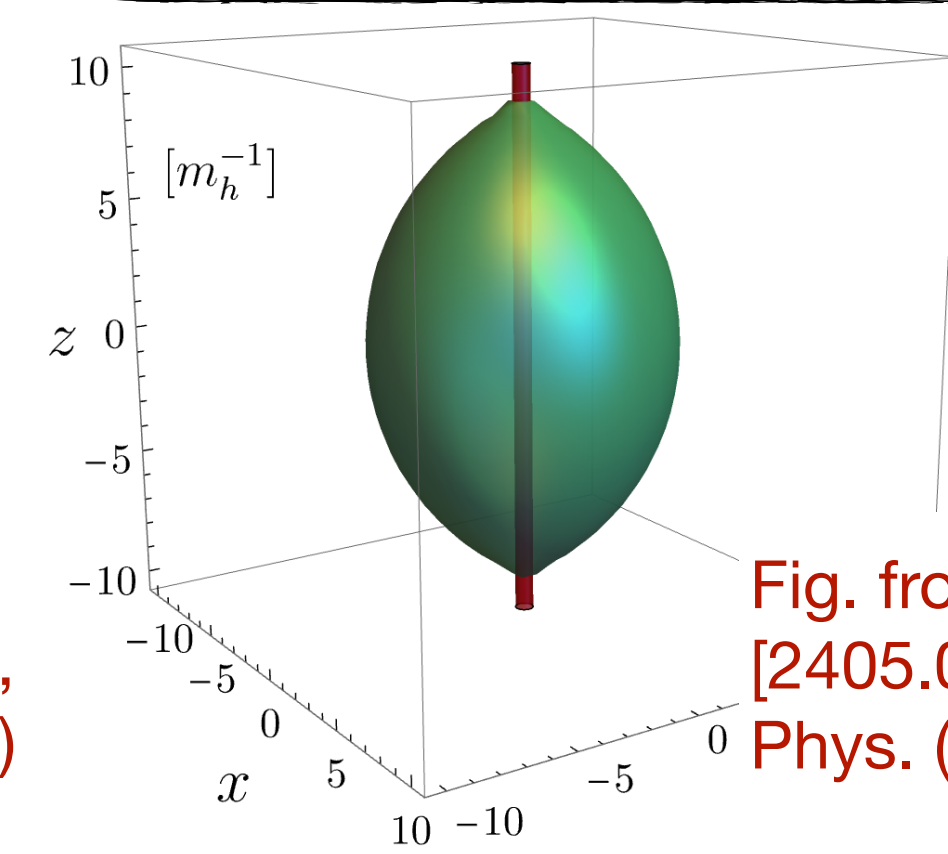
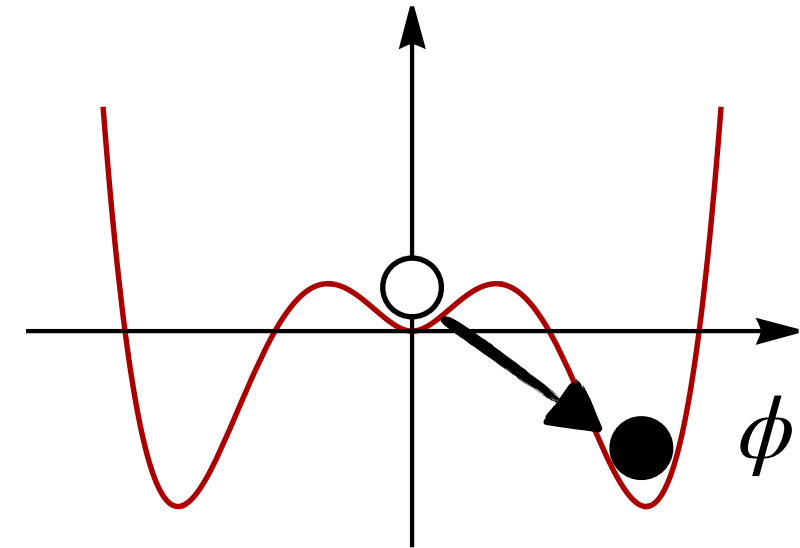


Fig. from **SB**, Mariotti [2405.08060] SciPost Phys. (2025)

Phase transitions source GWs



Phase transition at T_c

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

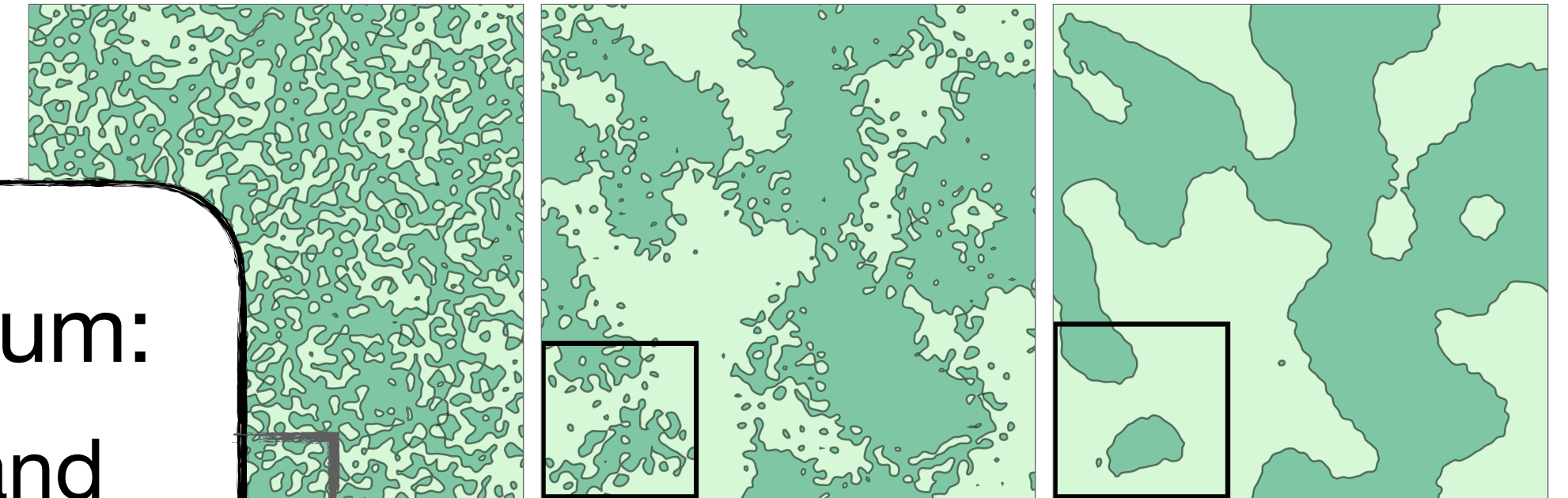
Fig. from **SB**, Mariotti, Rase,
Vanvlasselaer [2511.16649] JCAP

Topology of the vacuum:
Formation of defects and
annihilation

$\log(m/H) = 2.98$

$\log(m/H) = 3.24$

$\log(m/H) = 3.48$



Non-trivial interplay:

Defects as seeds for
bubble nucleation

This talk

Strength:

Bubble collisions,
hydrodynamics

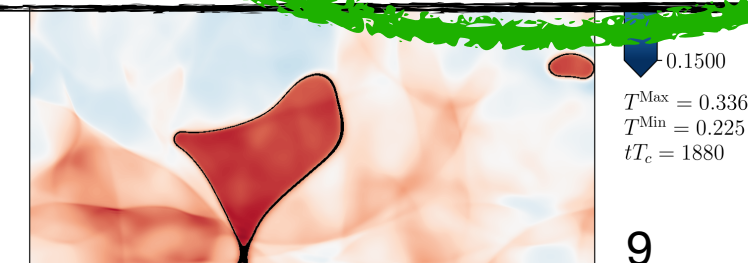
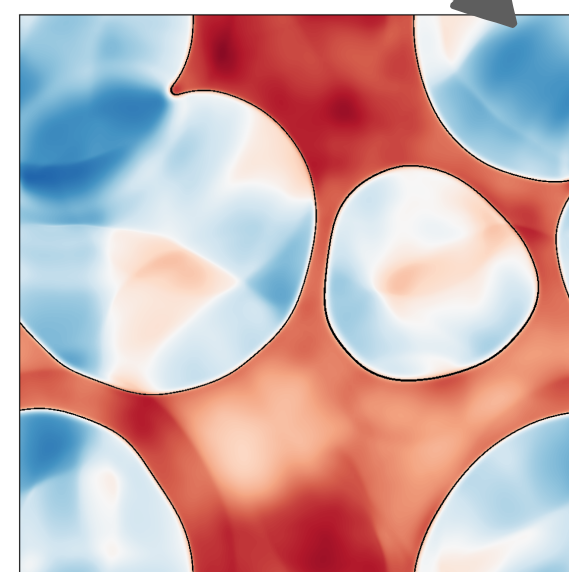
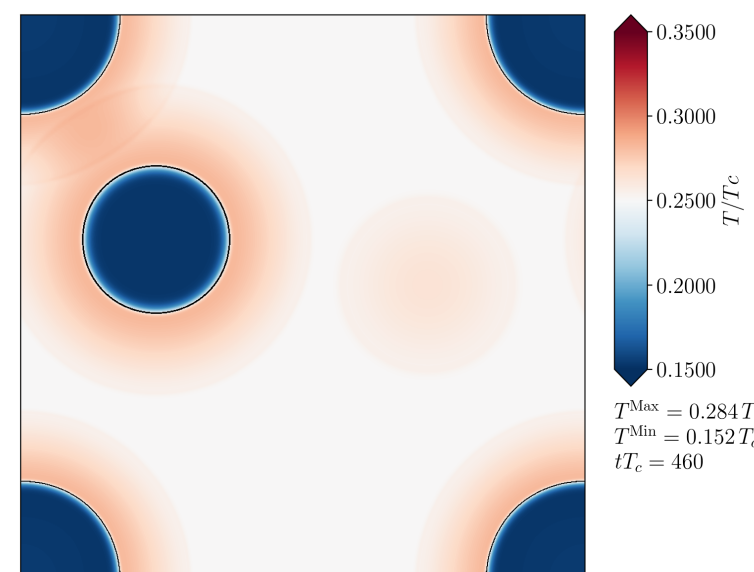


Fig. from Cutting, Hindmarsh,
Weir [2204.03396] PRL (2020)

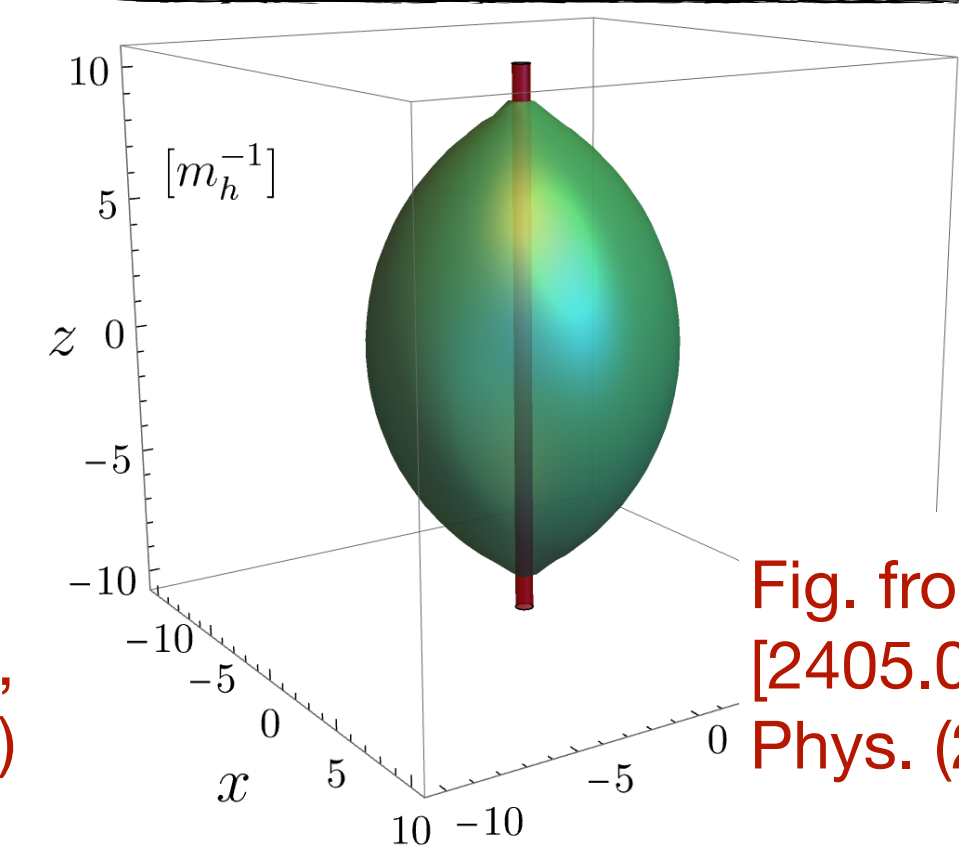
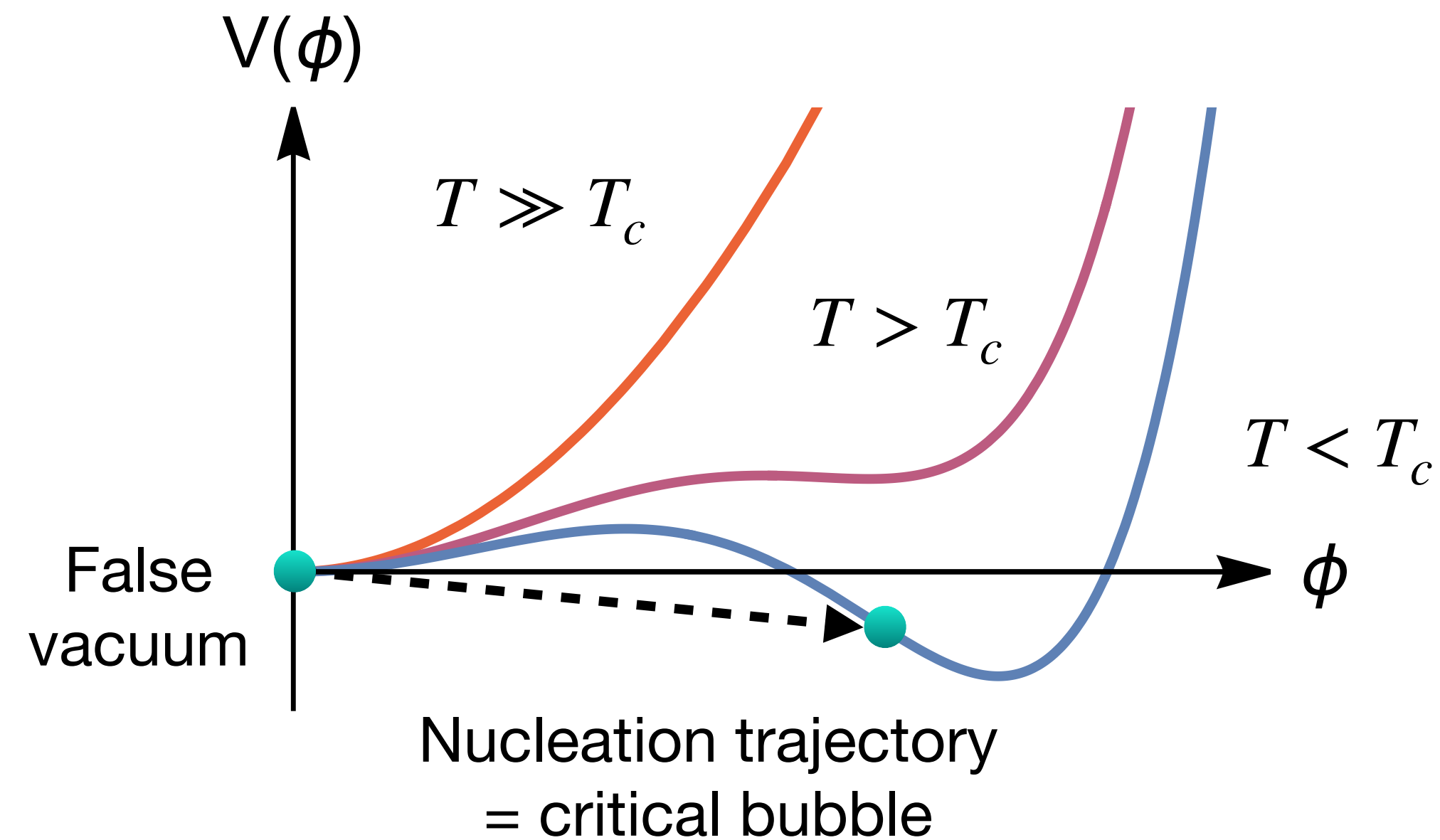


Fig. from **SB**, Mariotti
[2405.08060] SciPost
Phys. (2025)

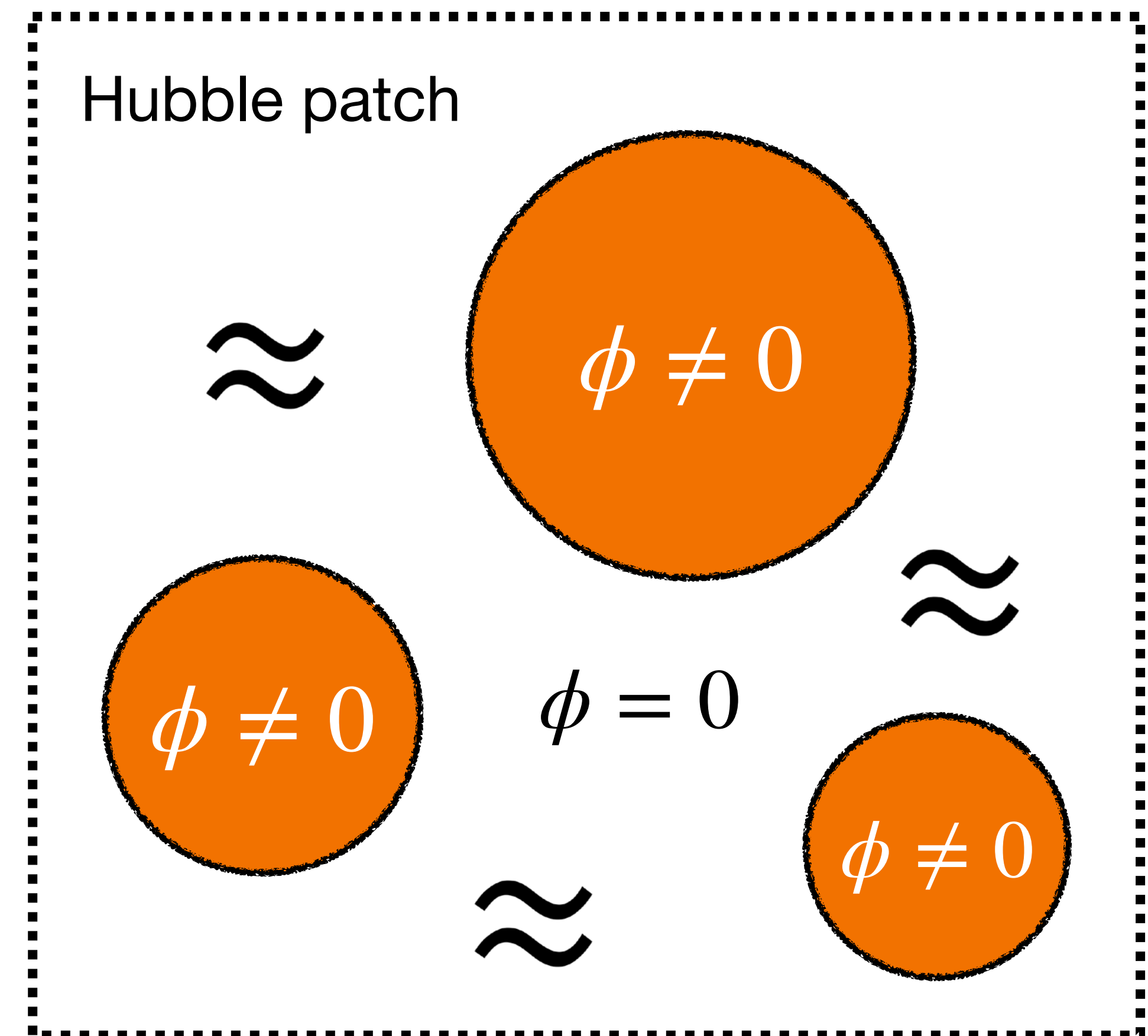
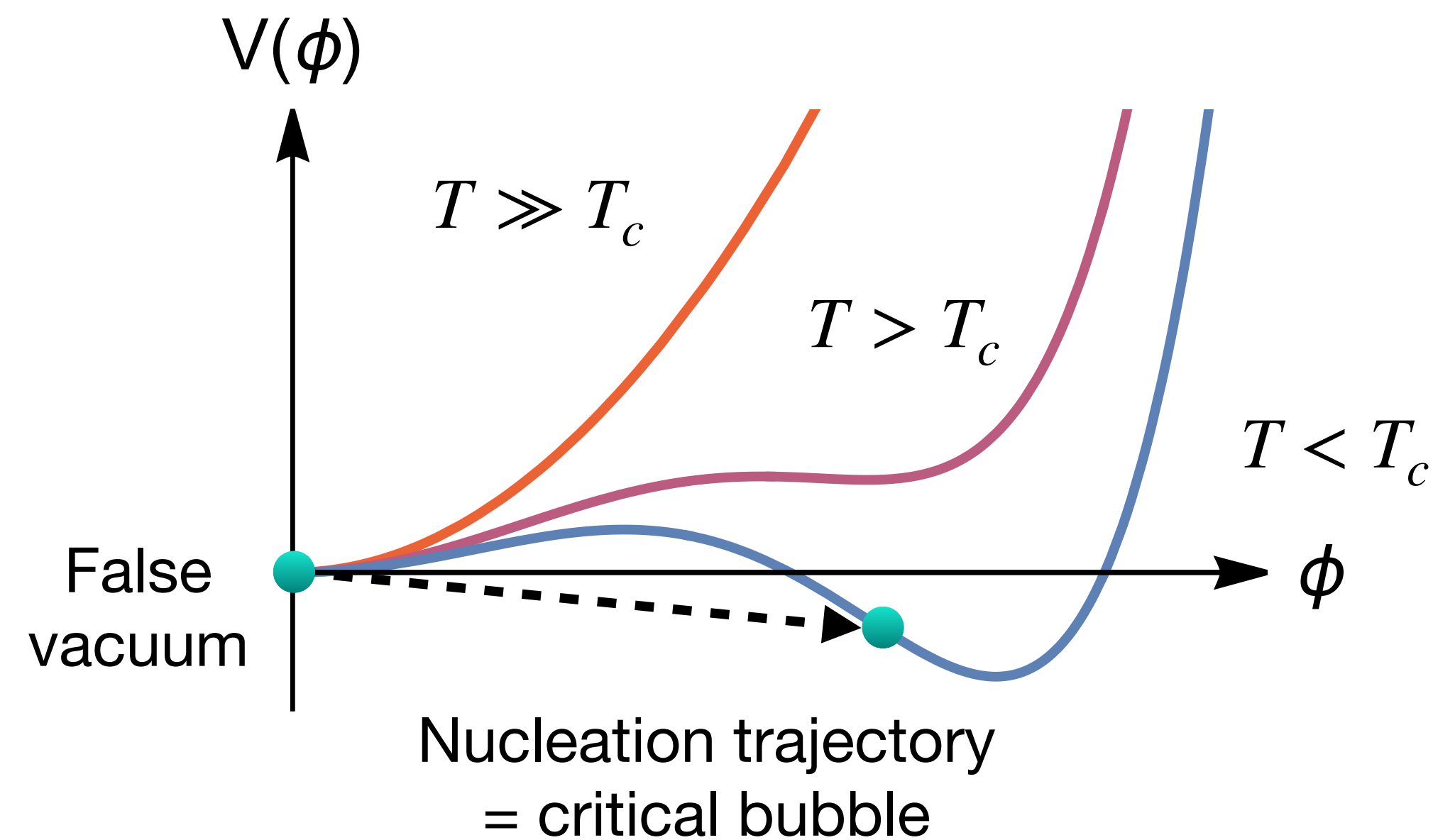
First order phase transitions

- When nucleation rate meets the Hubble expansion, bubbles of the new phase start forming and expanding in the surrounding plasma



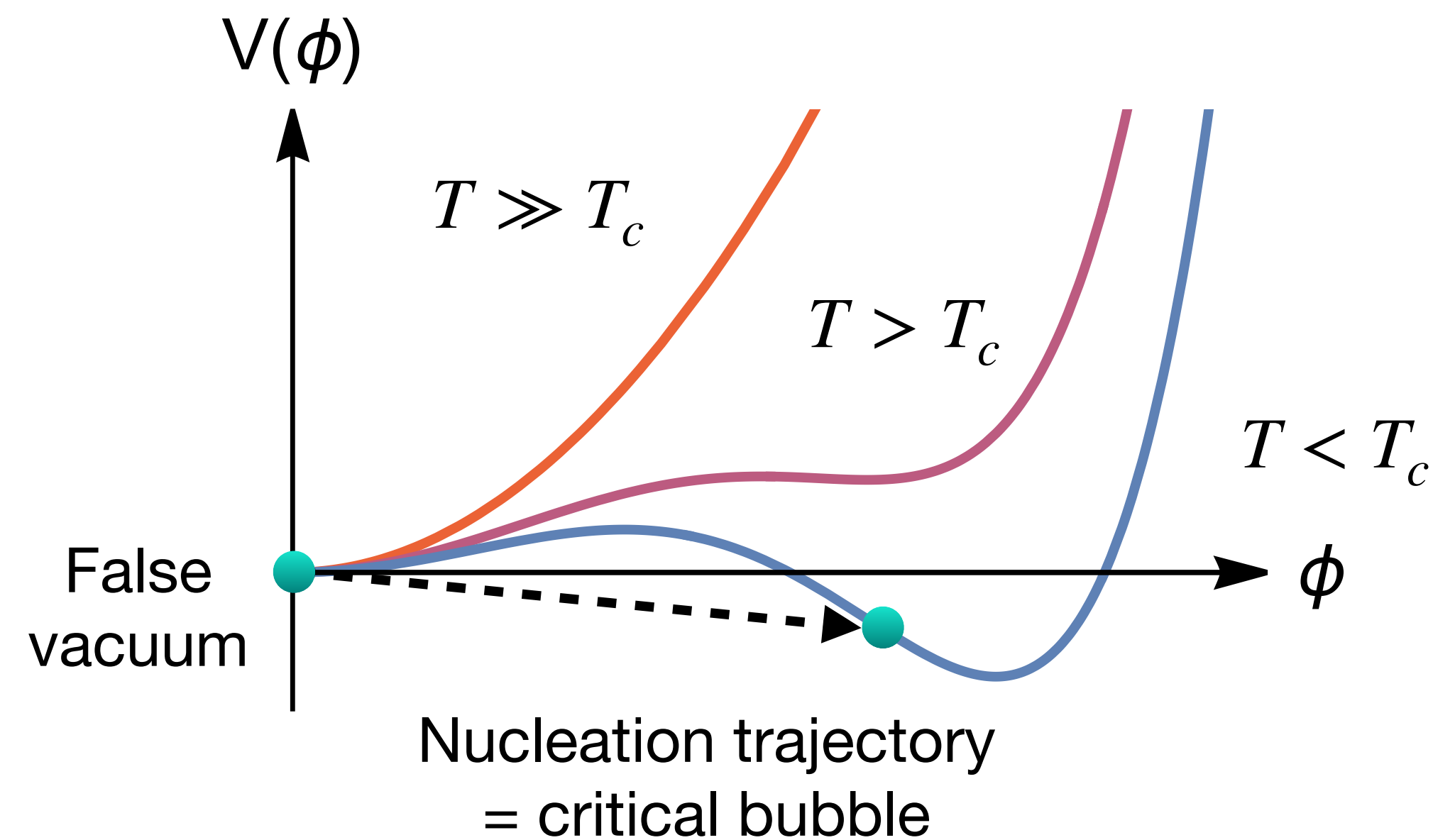
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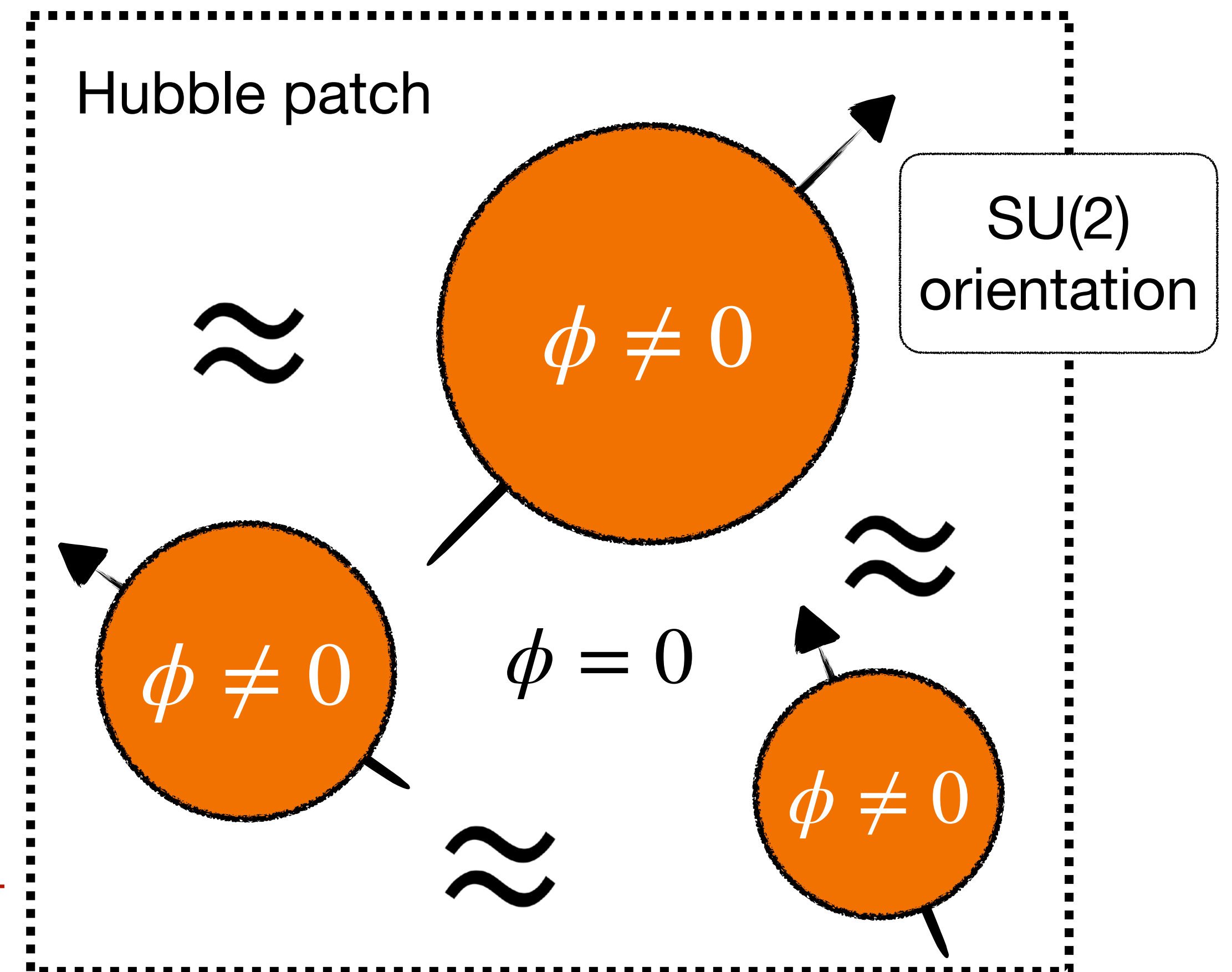


First order phase transitions

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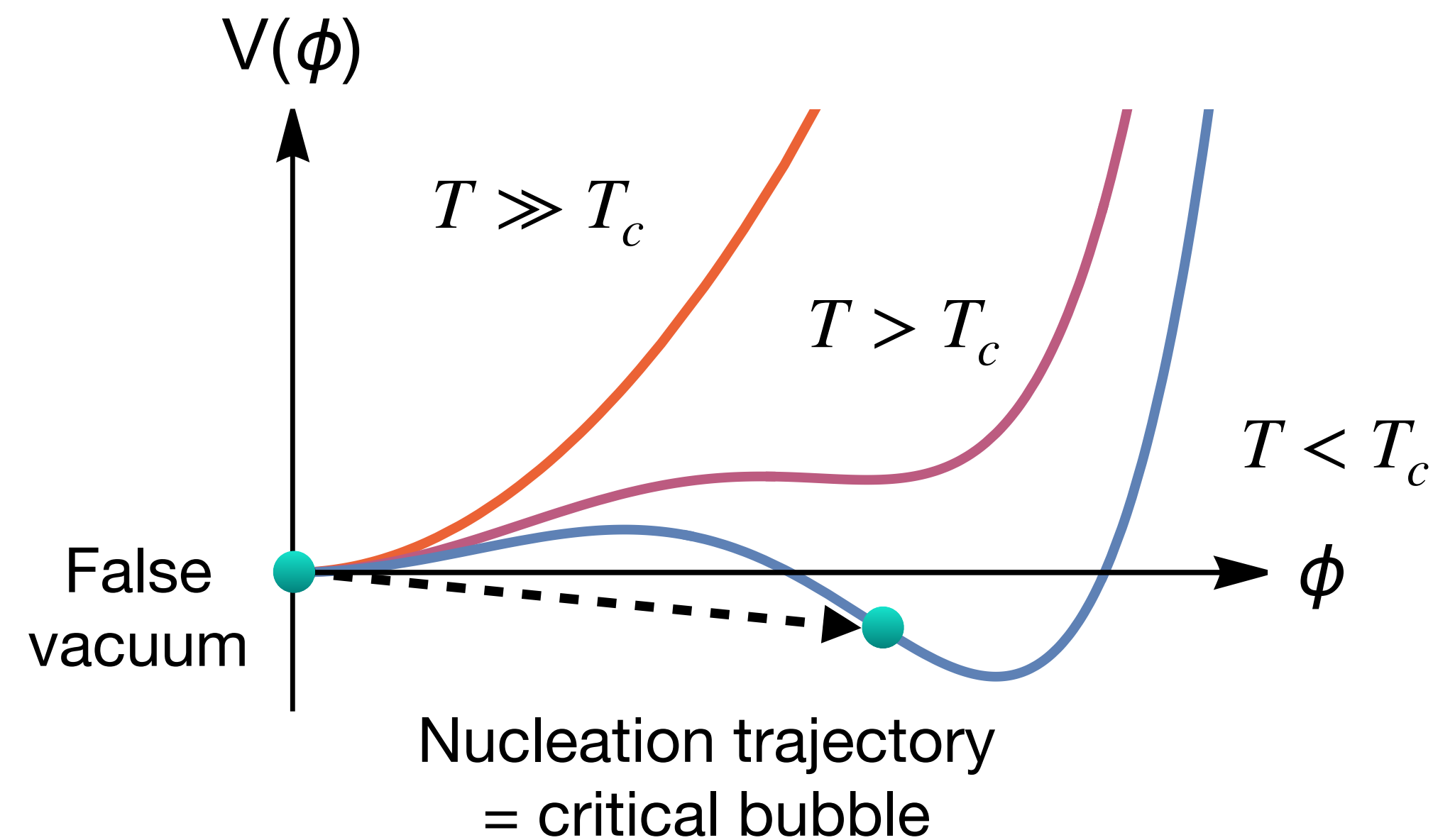


Bhusal, **SB**, Cataldi, Chatrchyan,
Gorghetto, Servant, 2508.21825 PRL



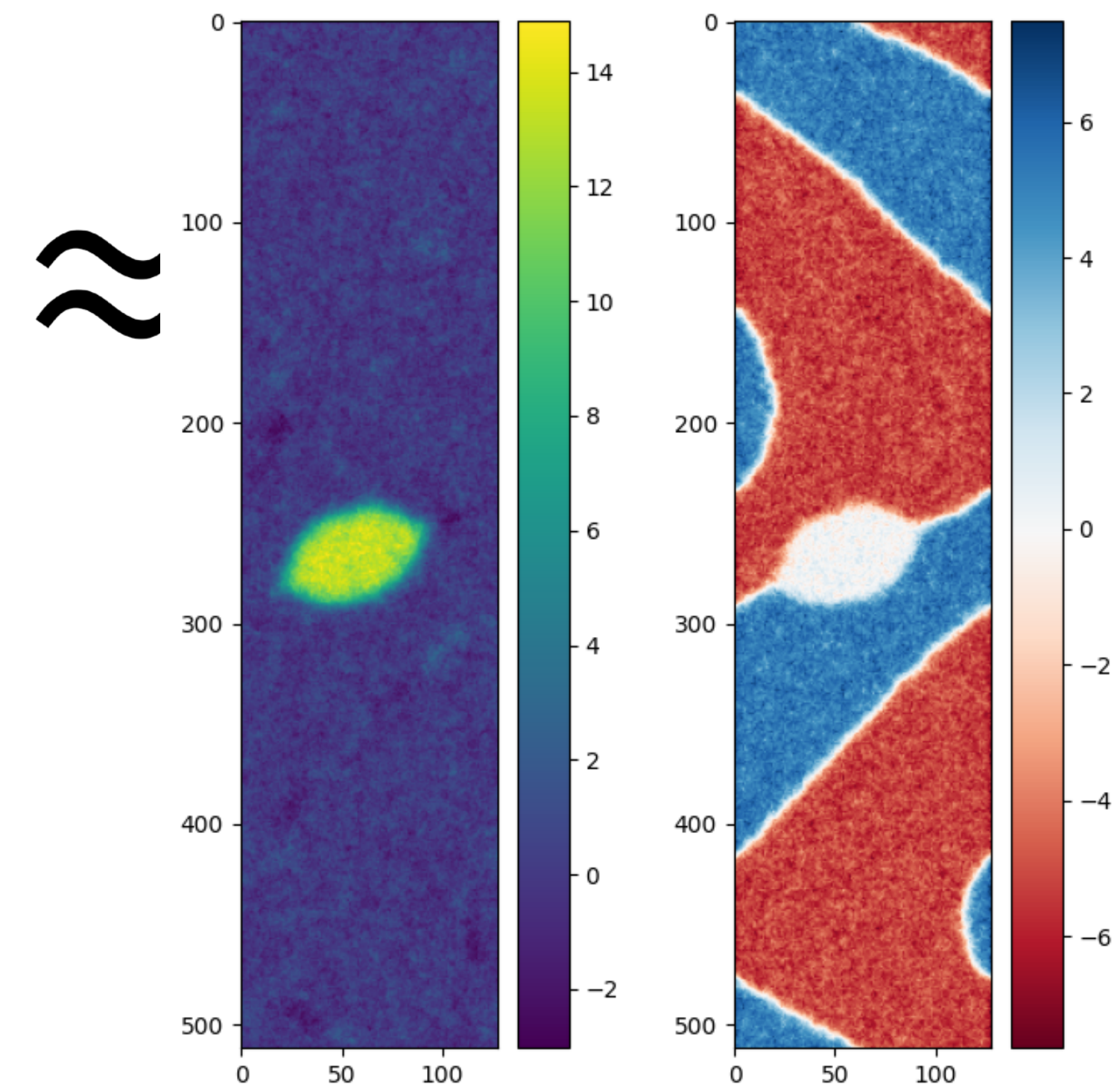
First order phase transitions

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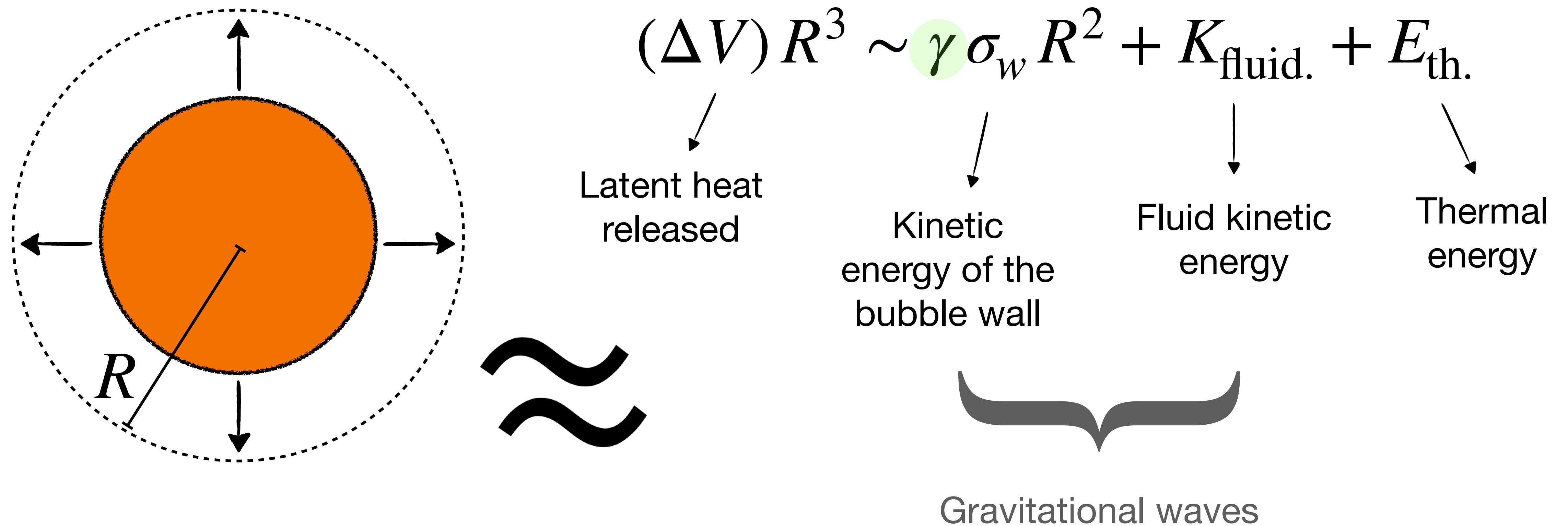
SB, Ekstedt, Hällfors,
Rummukainen [2605.31194]

Hubble patch



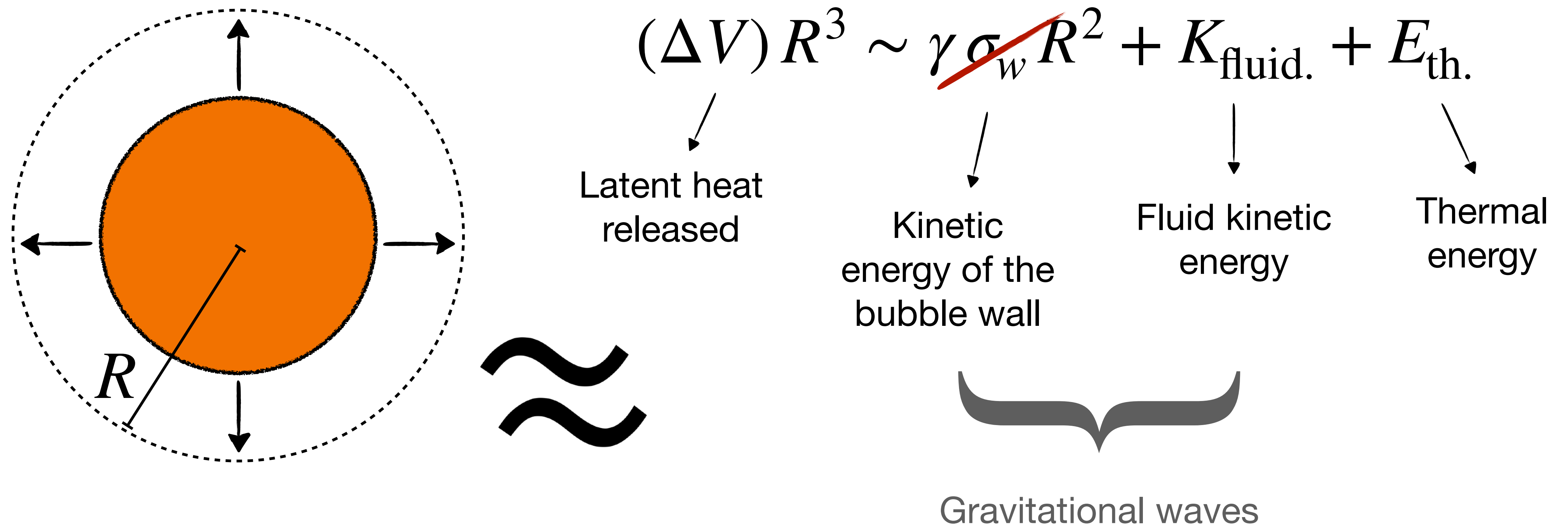
First order phase transitions

- Energy budget from a bubble of the new phase expanding in isolation:



First order phase transitions

- Energy budget from a bubble of the new phase expanding in isolation:



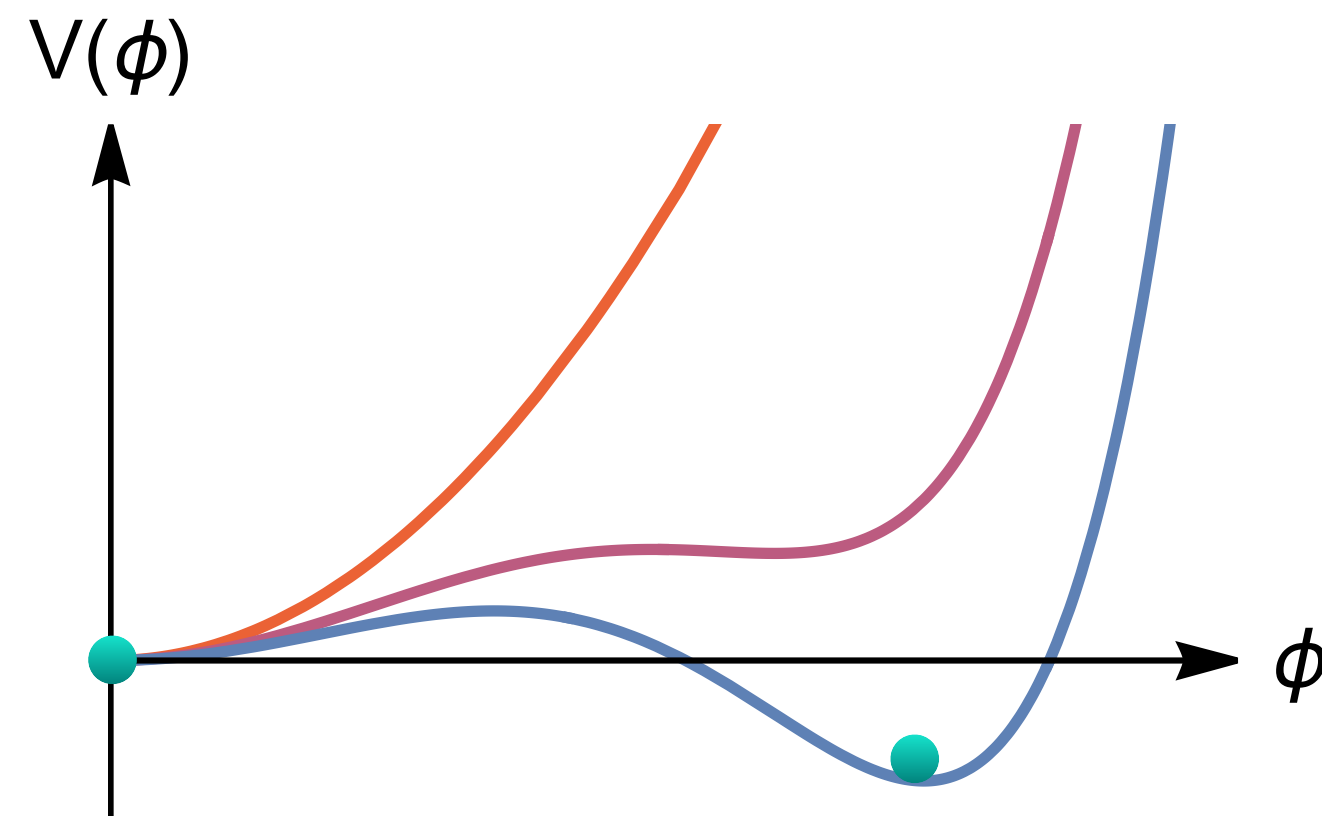
Hydrodynamics

- Scalar field (Higgs) $\longleftrightarrow$ • Perfect fluid

$$T_{\phi}^{\mu\nu} = (\partial^{\mu}\phi)\partial^{\nu}\phi - g^{\mu\nu} \left[\frac{1}{2}(\partial\phi)^2 - V(\phi) \right]$$

$$T_f^{\mu\nu} = (e_f + p_f)u^{\mu}u^{\nu} - g^{\mu\nu}p_f$$

Fluid 4-velocity



+

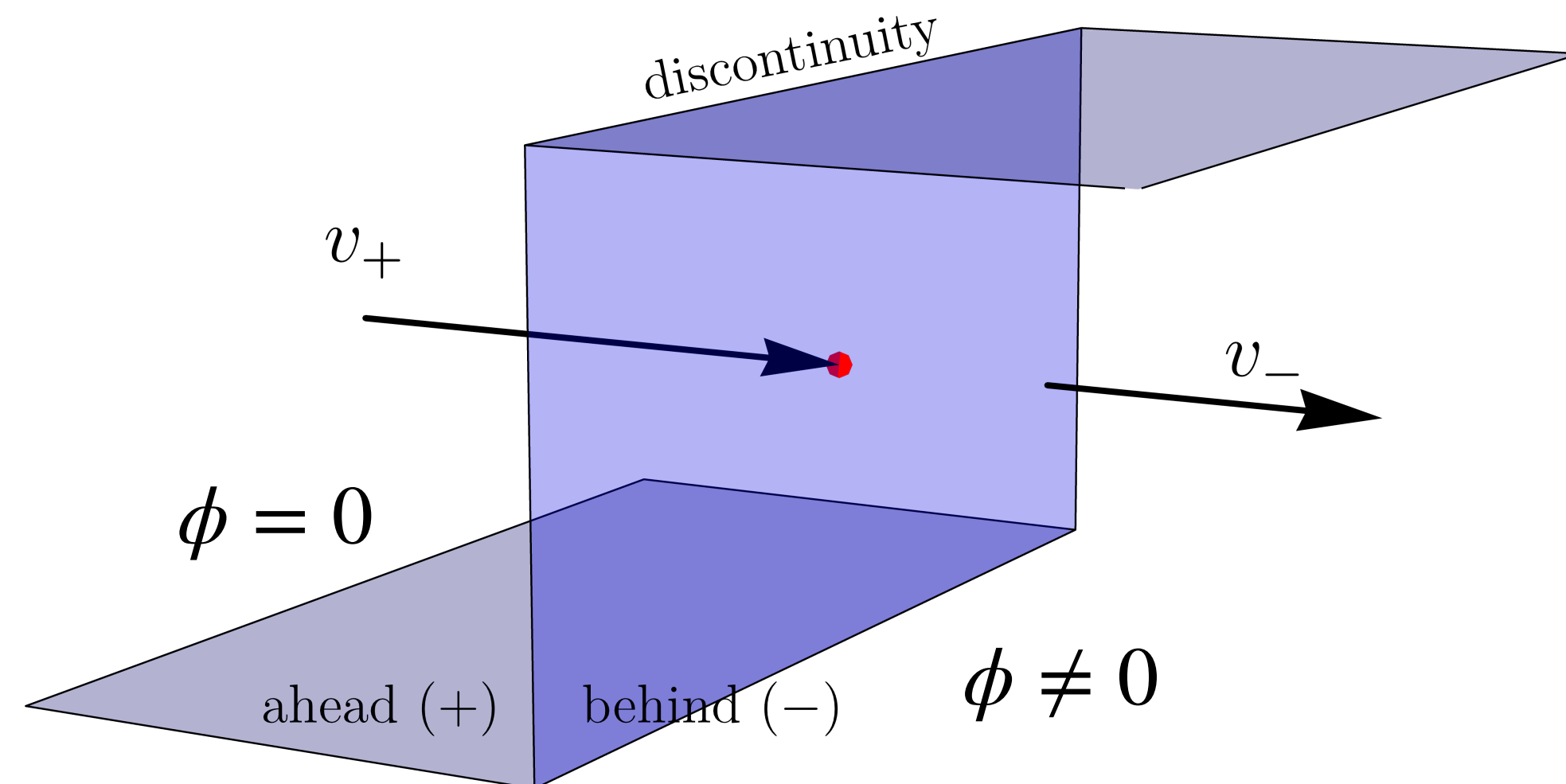
$\approx$

$$\nabla_{\mu}T^{\mu\nu} = \nabla_{\mu} \left(T_{\phi}^{\mu\nu} + T_f^{\mu\nu} \right) = 0$$

Hydrodynamics

- **Matching conditions** across a discontinuity (e.g., planar bubble interface between the two phases), assuming **stationary velocity**:

$$\partial_z T^{zz} = \partial_z T^{z0} = 0$$



$$w_+ \gamma_+^2 v_+ = w_- \gamma_-^2 v_- ,$$

$$w_+ \gamma_+^2 v_+^2 + p_+ = w_- \gamma_-^2 v_-^2 + p_-$$

$$w = e + p$$

Hydrodynamics

- A simplified “Bag” Equation of State for the electroweak plasma:

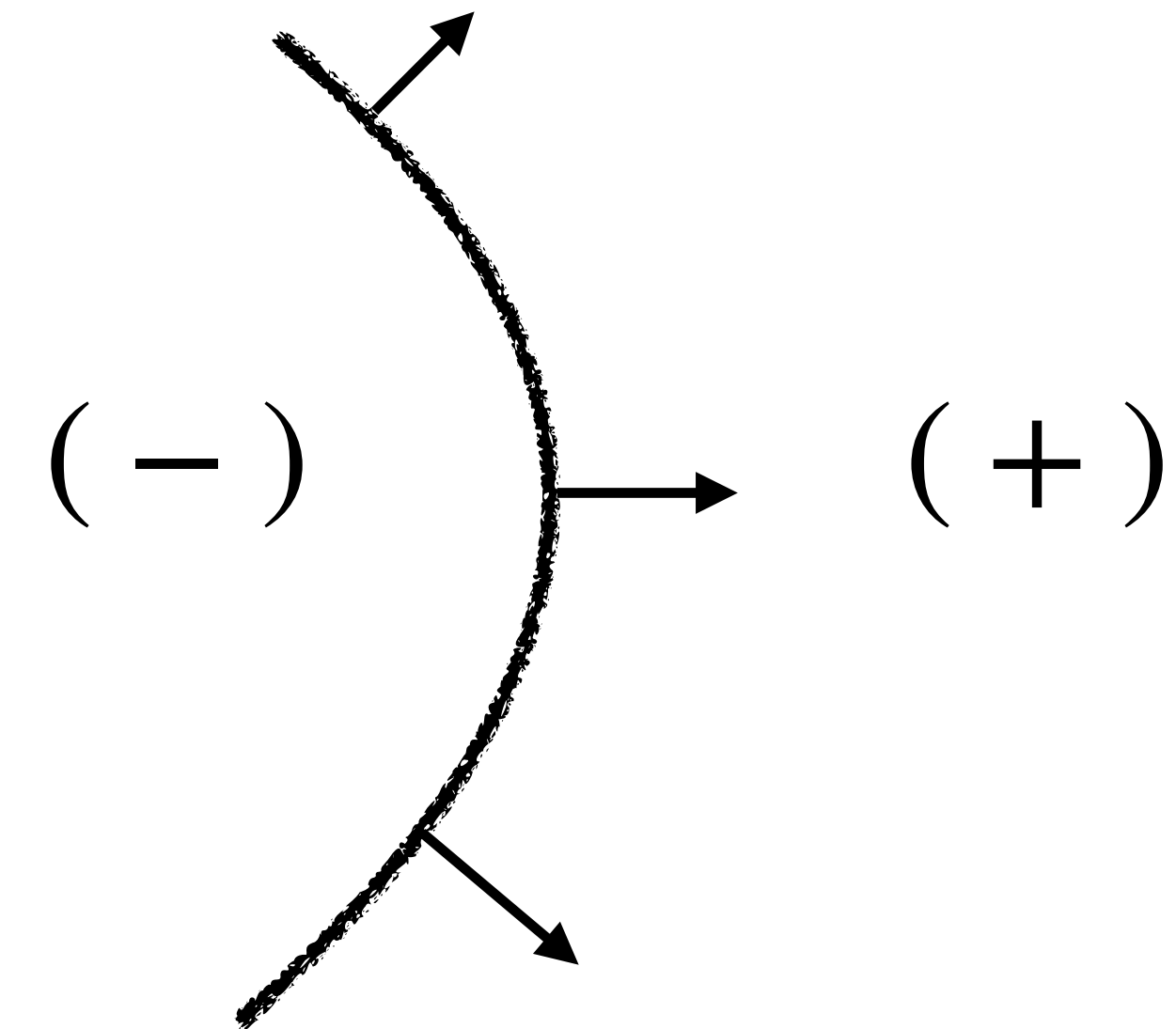
$$p_+(T) = \frac{1}{3}a_+T^4 - \epsilon_+$$

$$p_-(T) = \frac{1}{3}a_-T^4 - \epsilon_-$$

$$c_{s,\pm}^2 = \frac{1}{3}$$

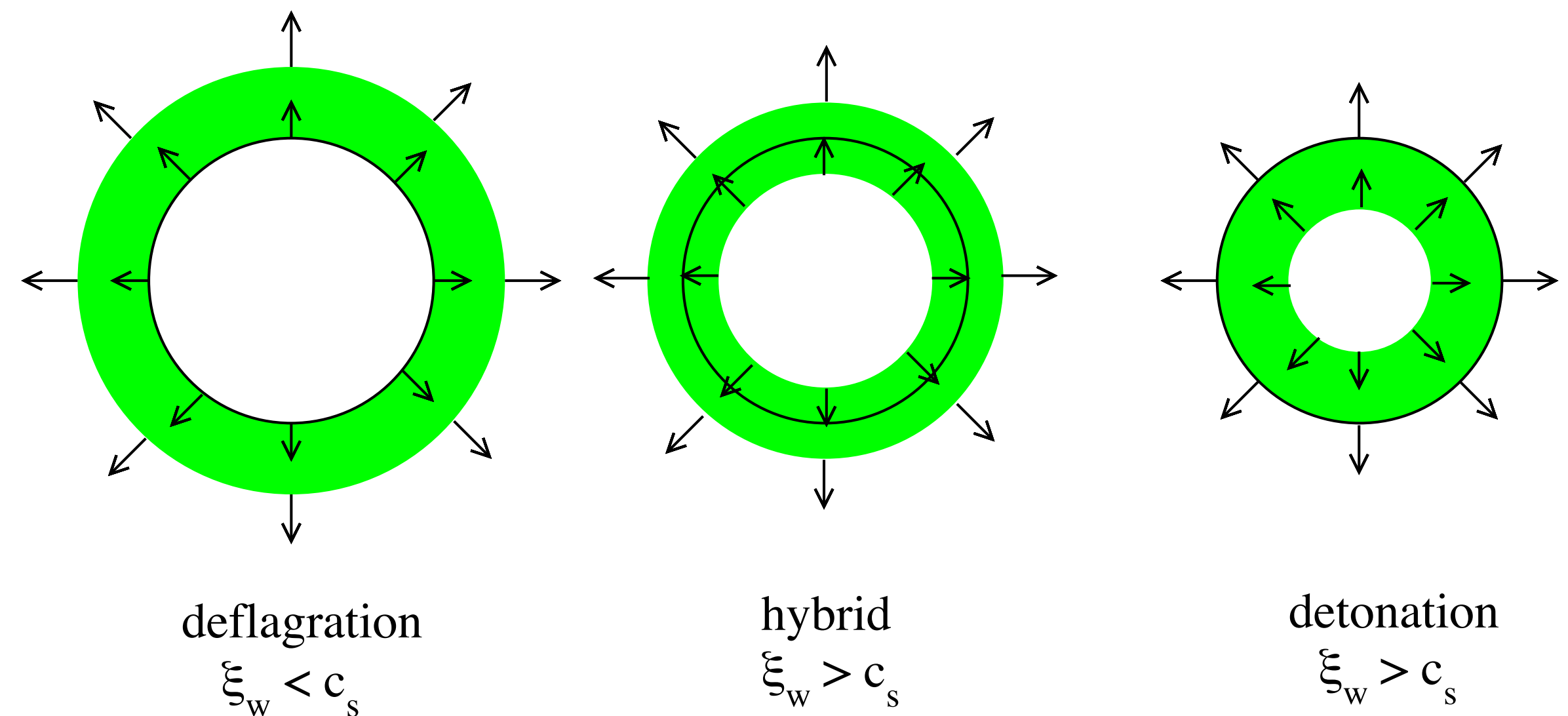
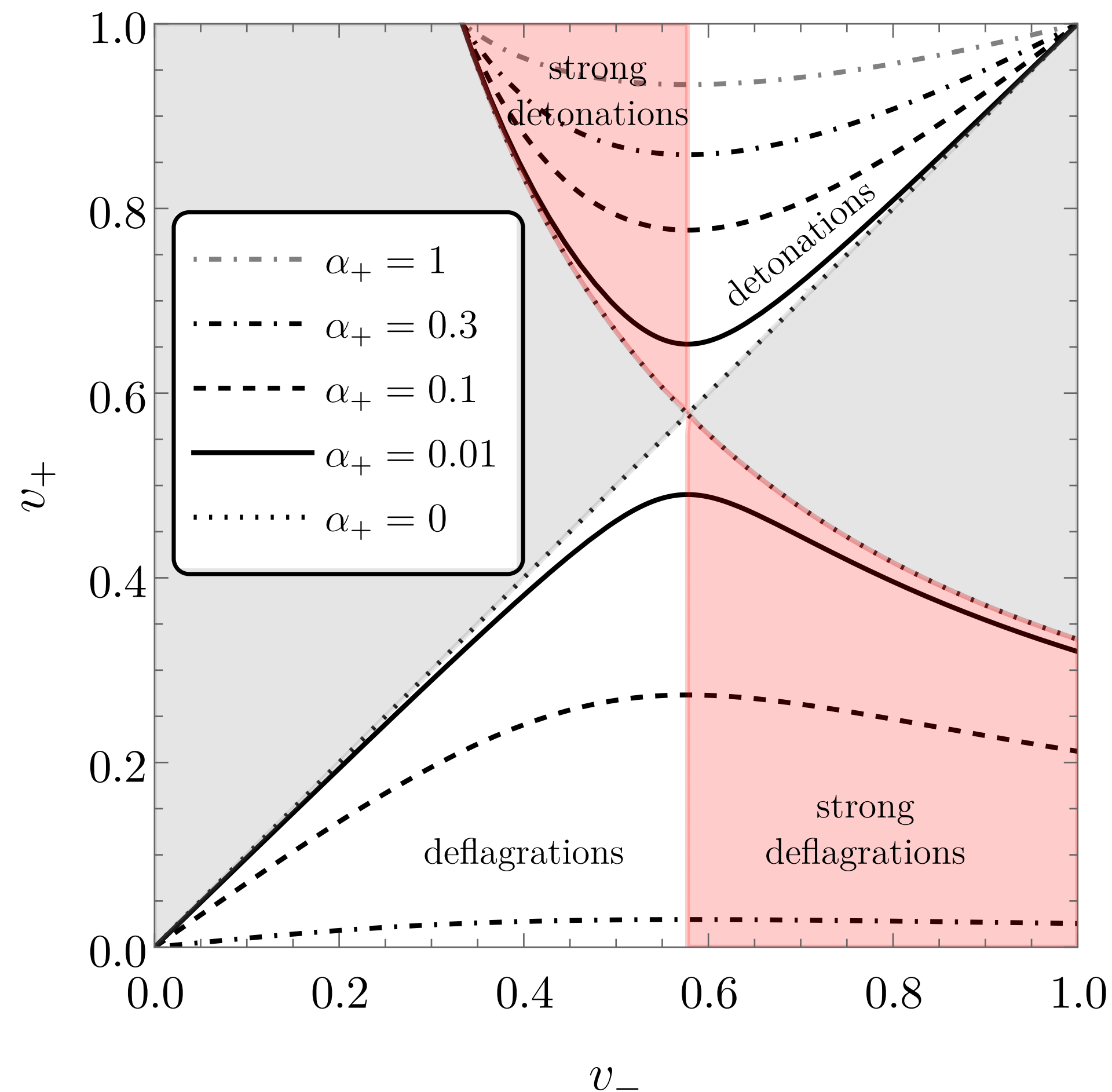
- Strength of the phase transition parameterized by:

$$\alpha_+ \equiv \frac{\epsilon_+ - \epsilon_-}{a_+T_+^4}$$



Hydrodynamics

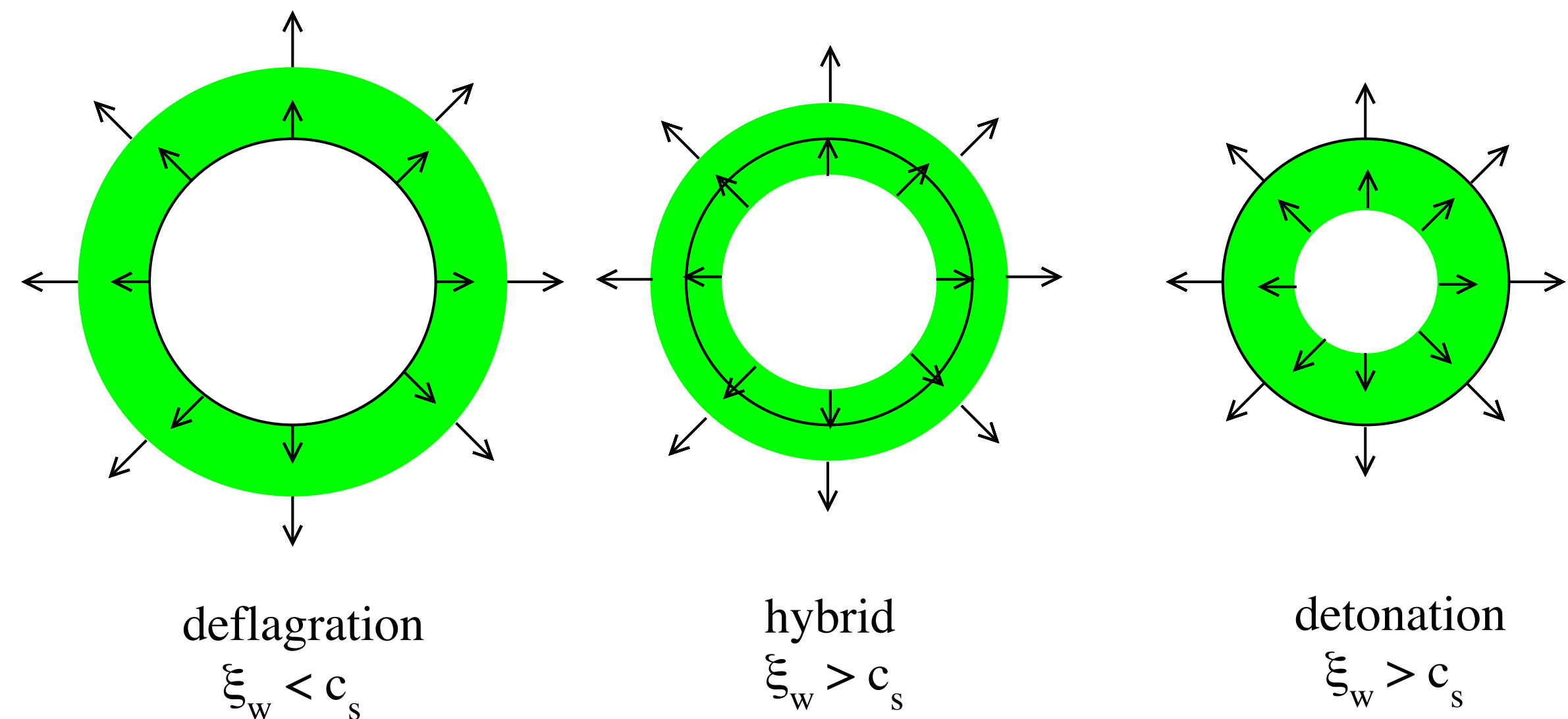
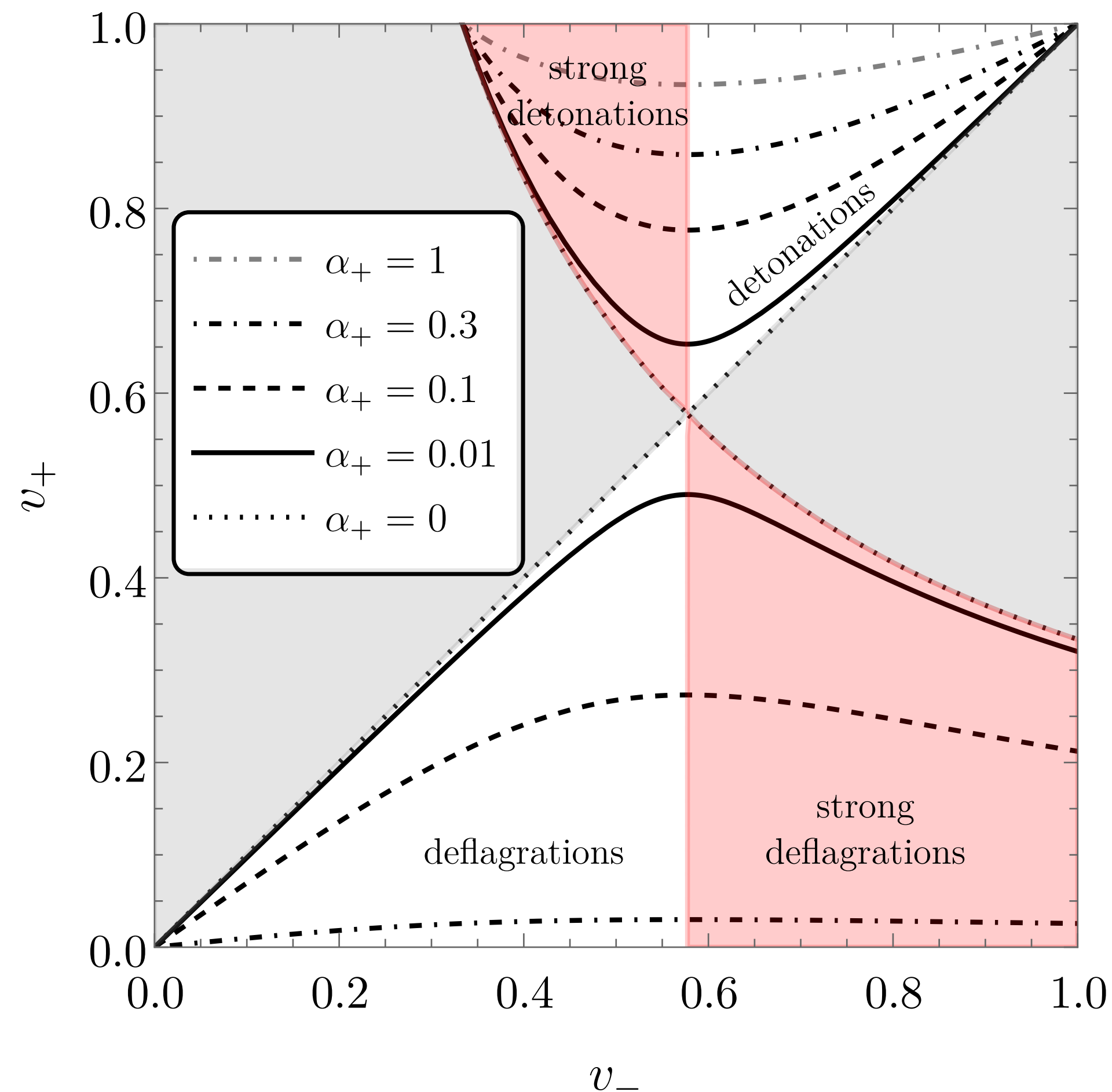
- One-parameter family of up(down) stream fluid velocity at fixed strength α_+



Espinosa, Konstandin, No, Servant [1004.4187] JCAP

Hydrodynamics

- One-parameter family of up(down) stream fluid velocity at fixed strength α_+



Espinosa, Konstandin, No, Servant [1004.4187] JCAP

Note: bubble wall velocity cannot be determined by hydrodynamics only

Self-similar solutions

- Spherically symmetric flows with no characteristic scale described by self-similar profiles:

$$(\xi - v) \frac{\partial_\xi e}{w} = 2 \frac{v}{\xi} + [1 - \gamma^2 v(\xi - v)] \partial_\xi v$$

$$(1 - v\xi) \frac{\partial_\xi p}{w} = \gamma^2 (\xi - v) \partial_\xi v .$$

$$\xi = \frac{r}{t}$$

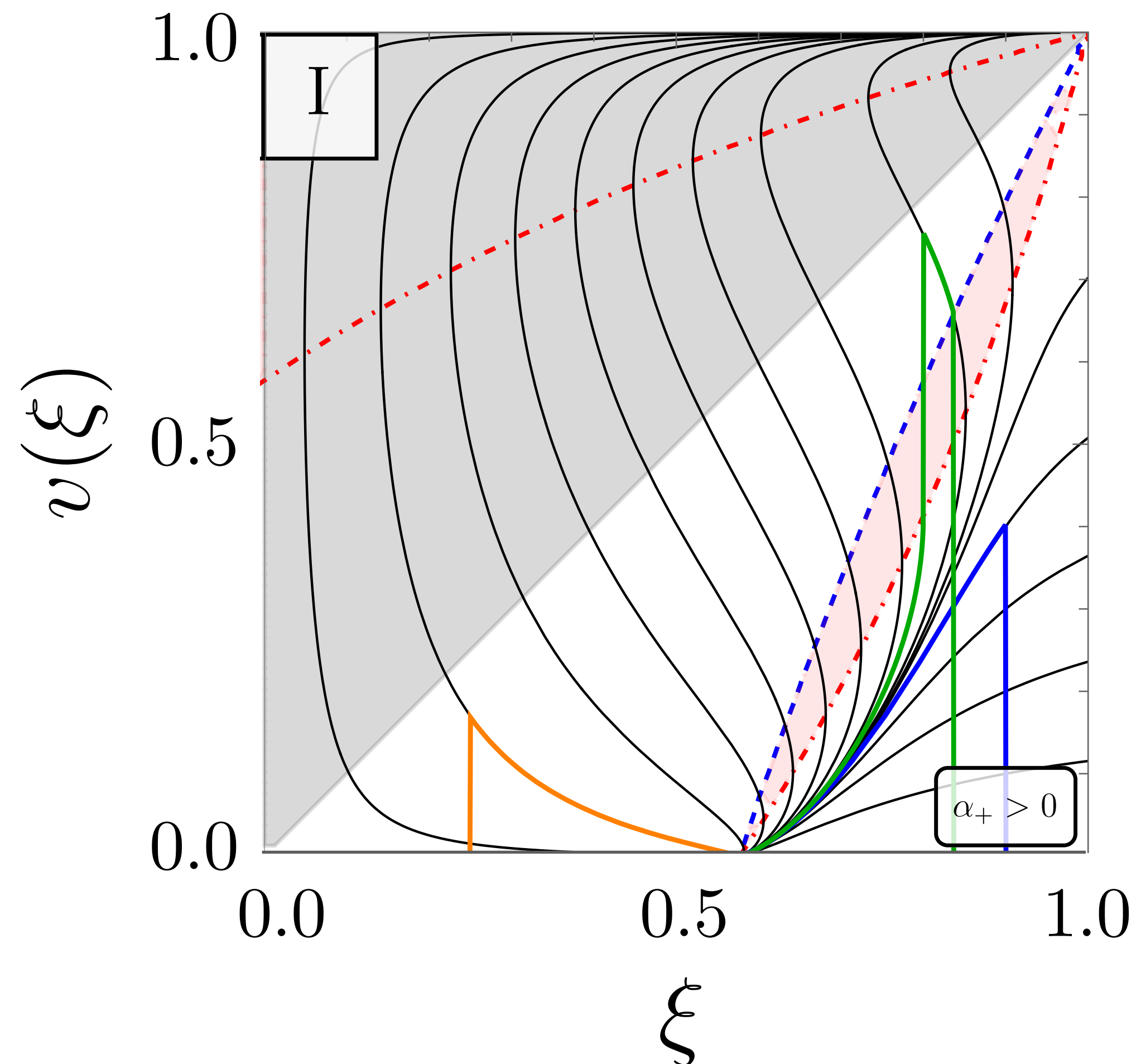
- Bag EoS has constant speed of sound, relating $c_s^2 = dp/de = 1/3$

$$2 \frac{v}{\xi} = \gamma^2 (1 - v\xi) \left[\frac{\mu_{p \rightarrow w}^2}{c_s^2} - 1 \right] \partial_\xi v$$

Symmetric for: $\xi \rightarrow -\xi \quad v \rightarrow -v$

Self-similar solutions

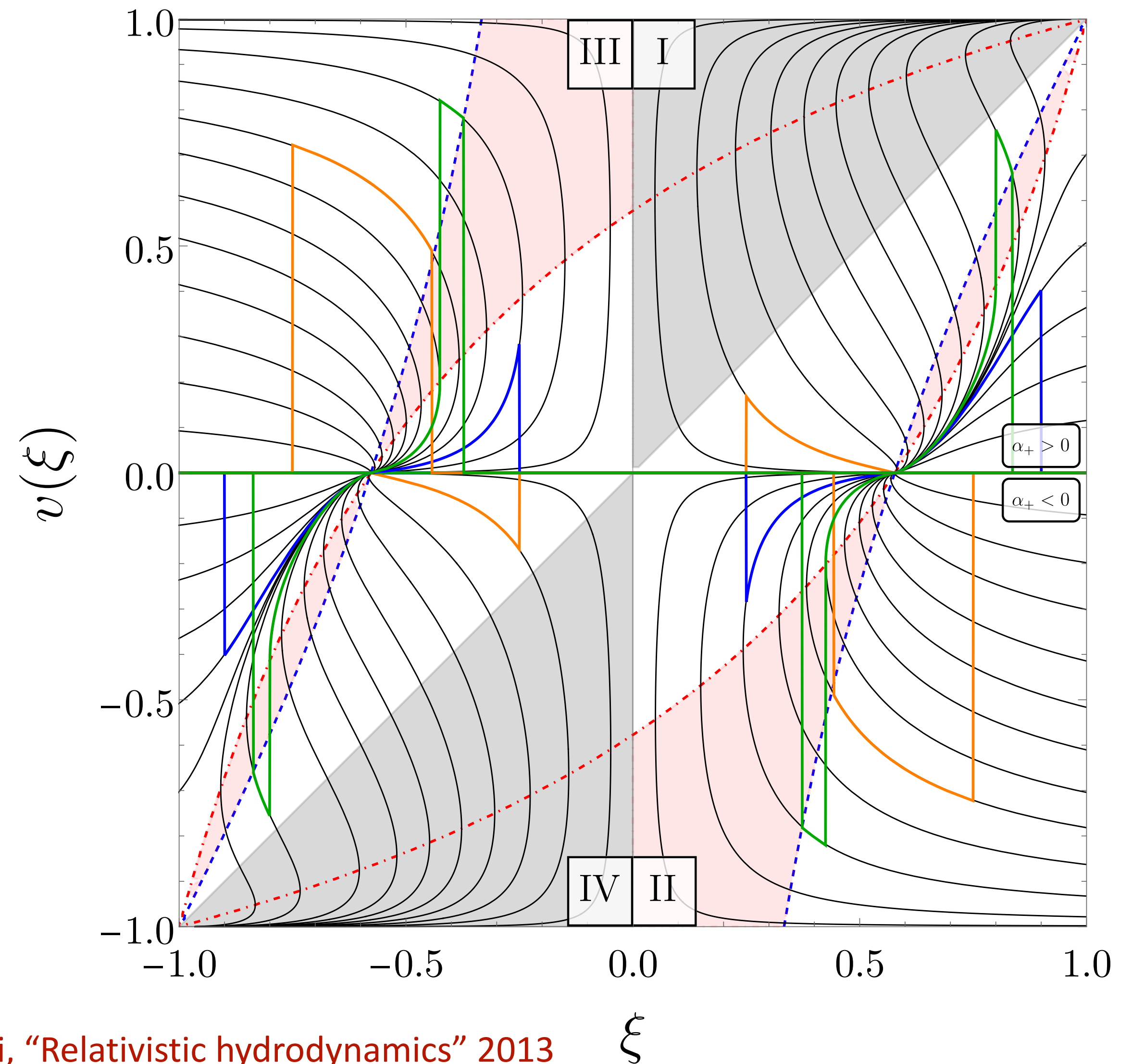
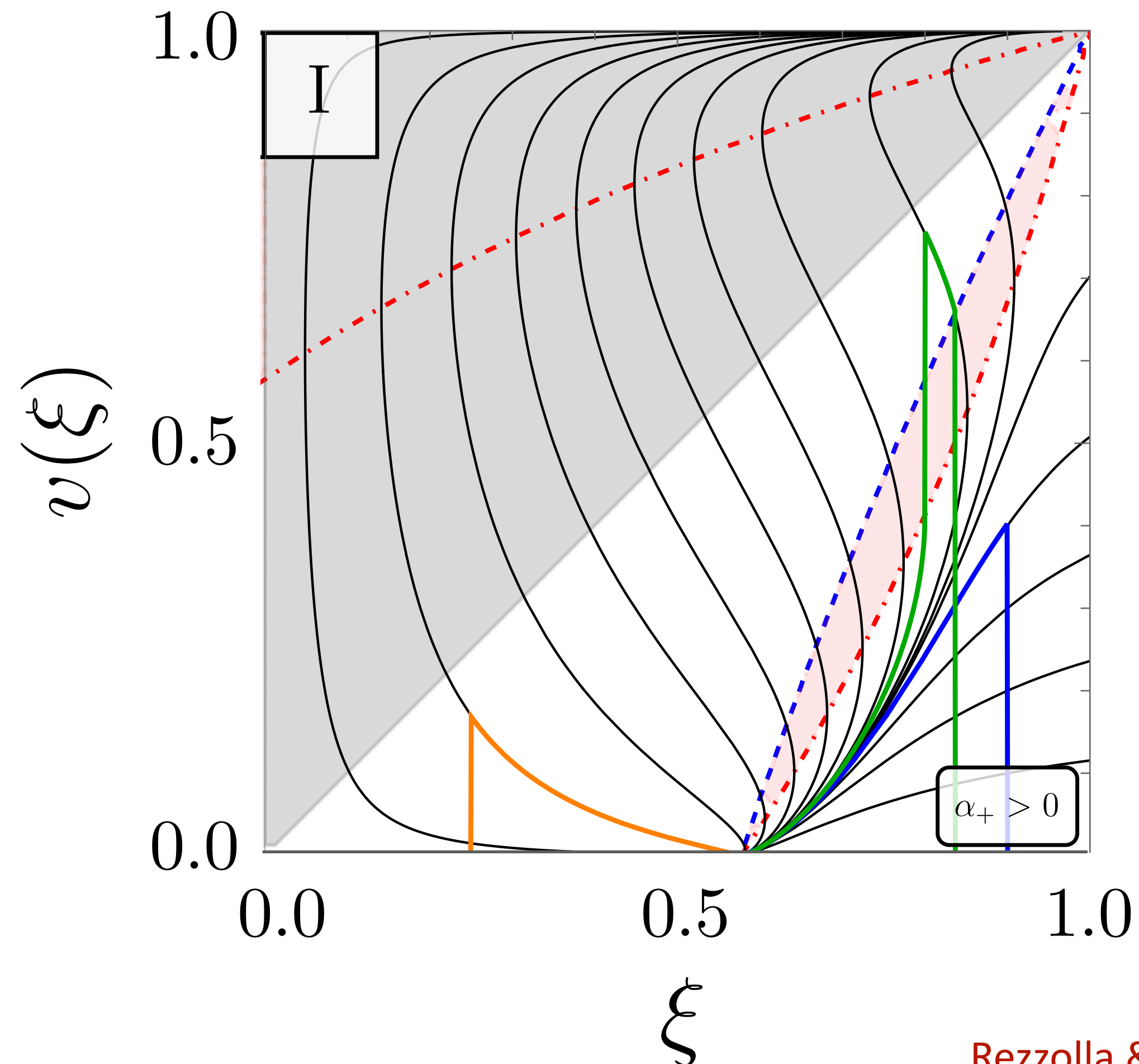
- All possible self-similar flows:



Self-similar solutions

$$\bullet \quad \xi \rightarrow -\xi \quad v \rightarrow -v$$

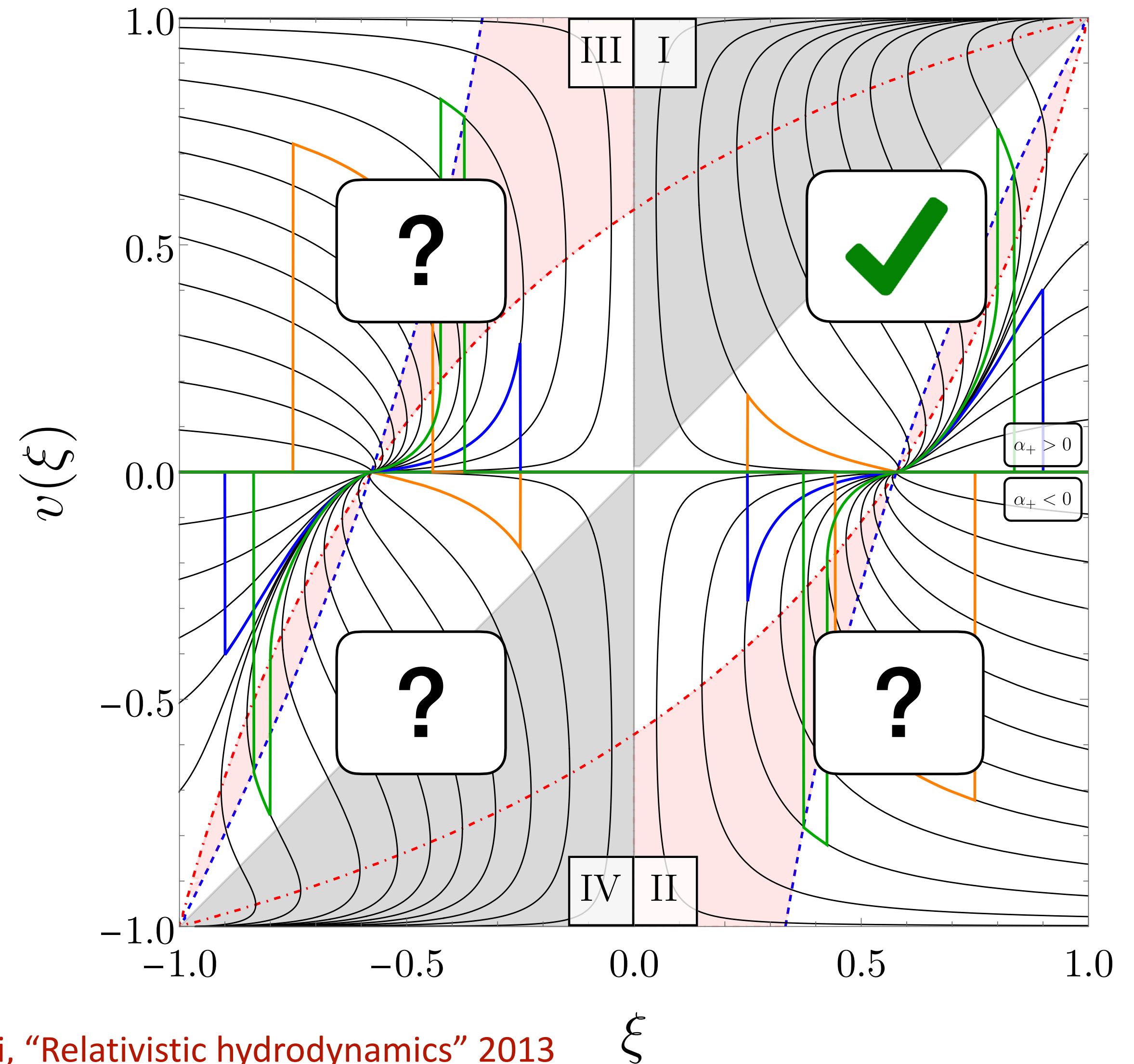
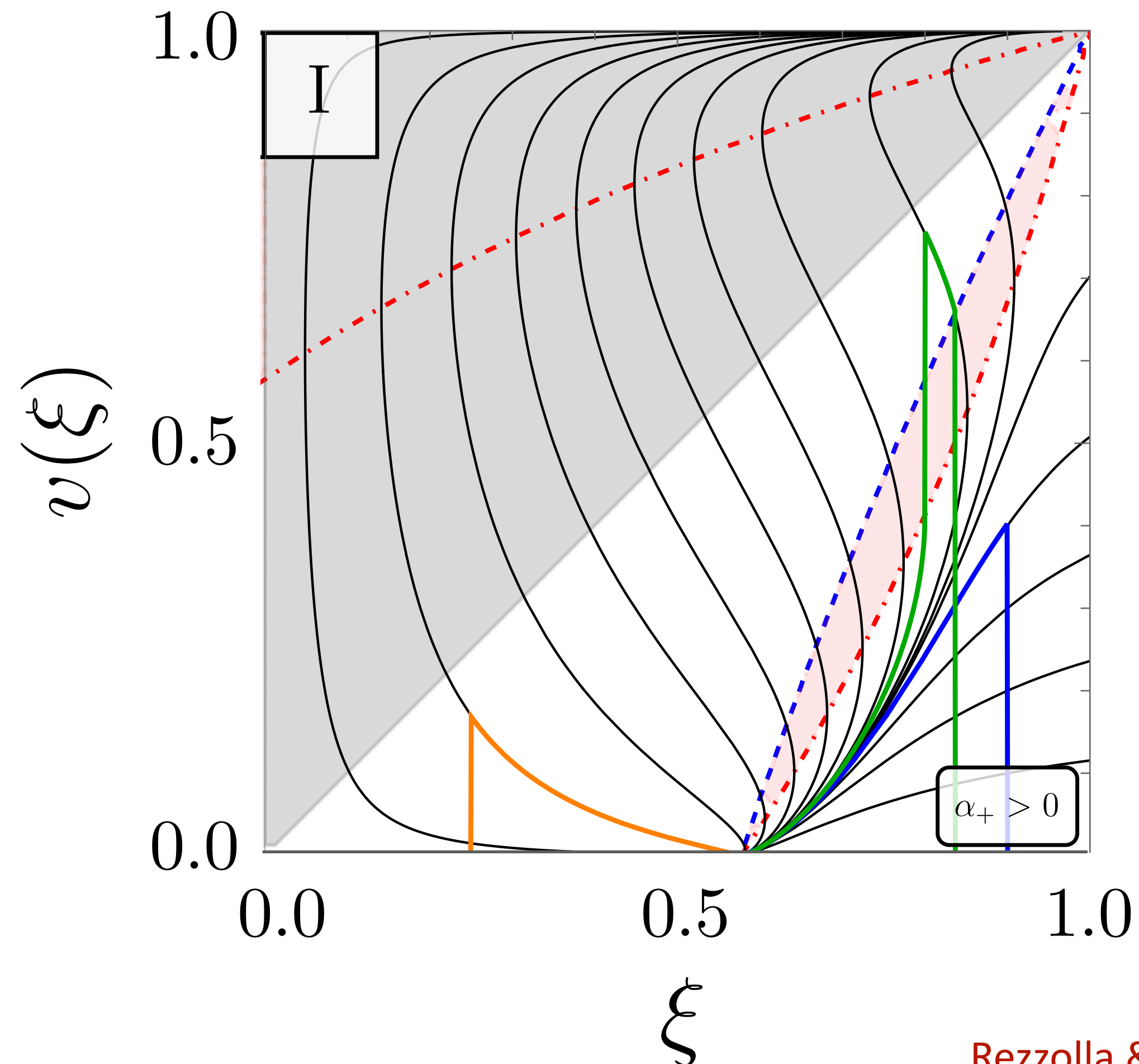
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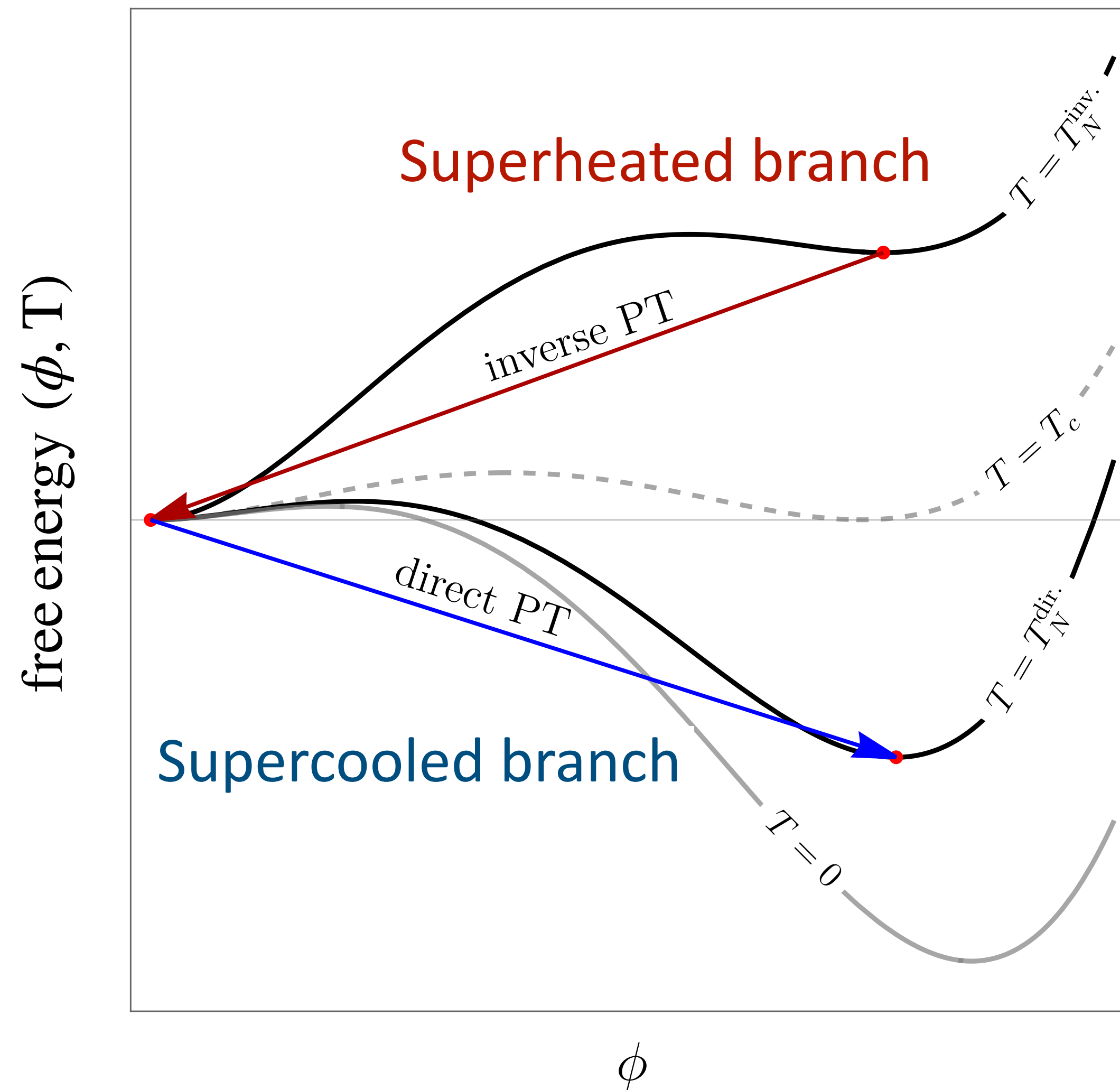
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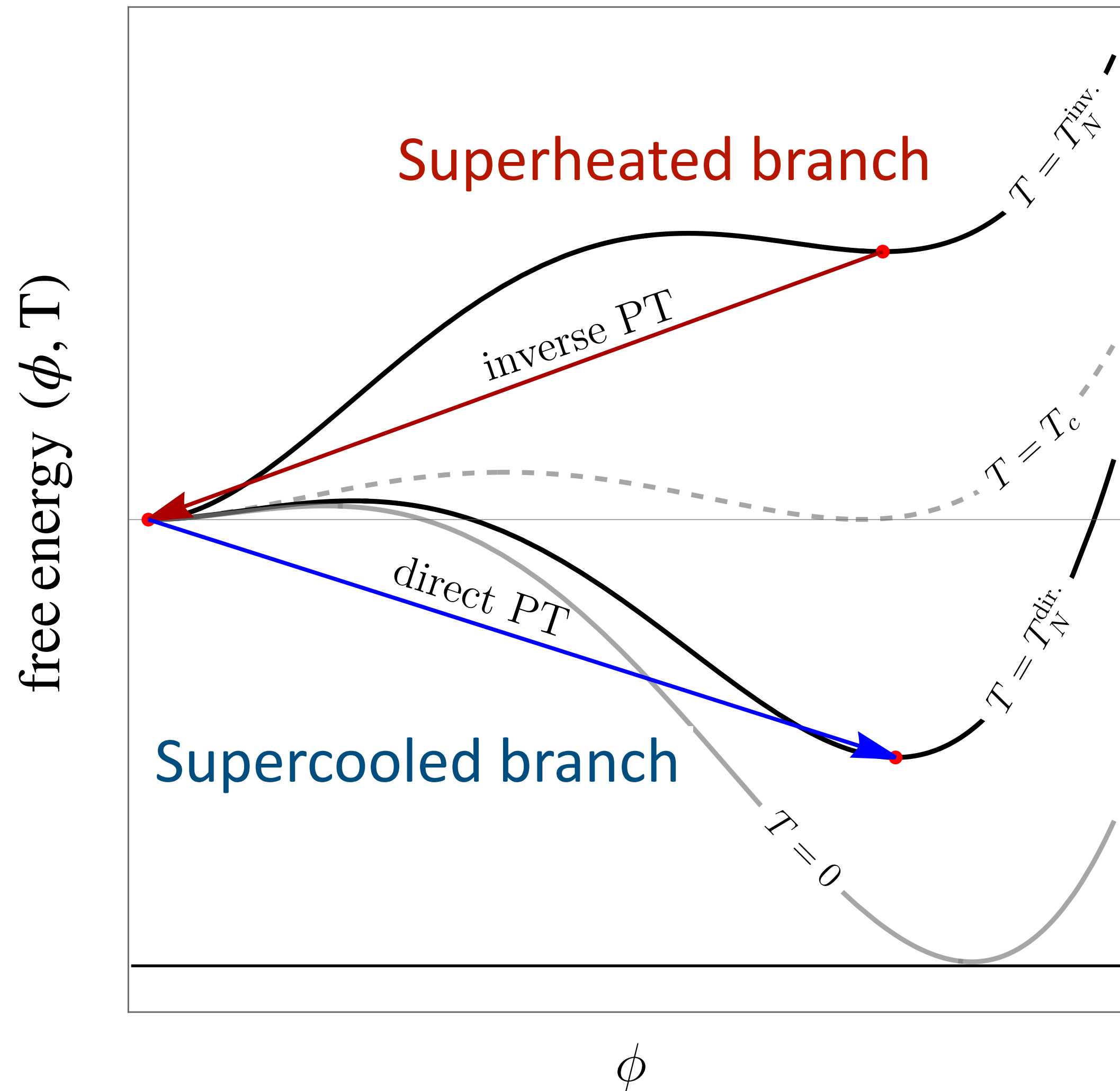


“Inverse” hydrodynamics



- Is the hydrodynamics of these two phase transitions qualitatively the same?

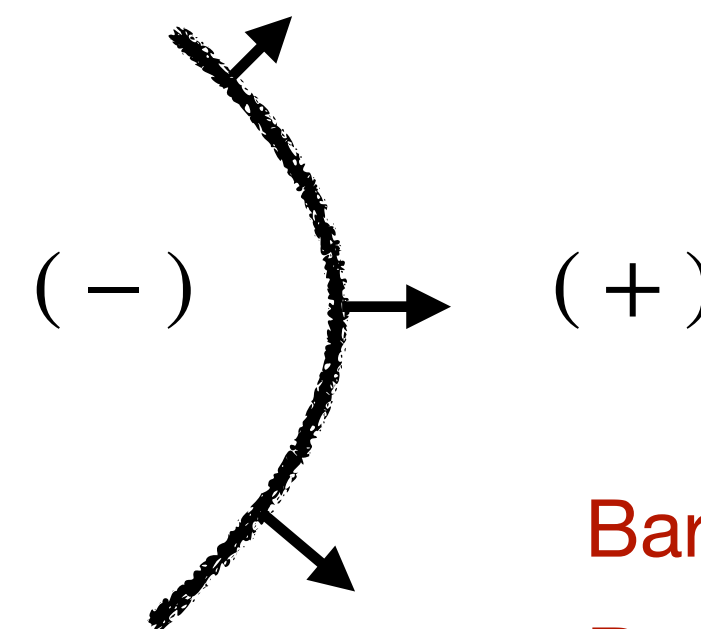
“Inverse” hydrodynamics



- Is the hydrodynamics of these two phase transitions qualitatively the same?
- Within the Bag equation of state:

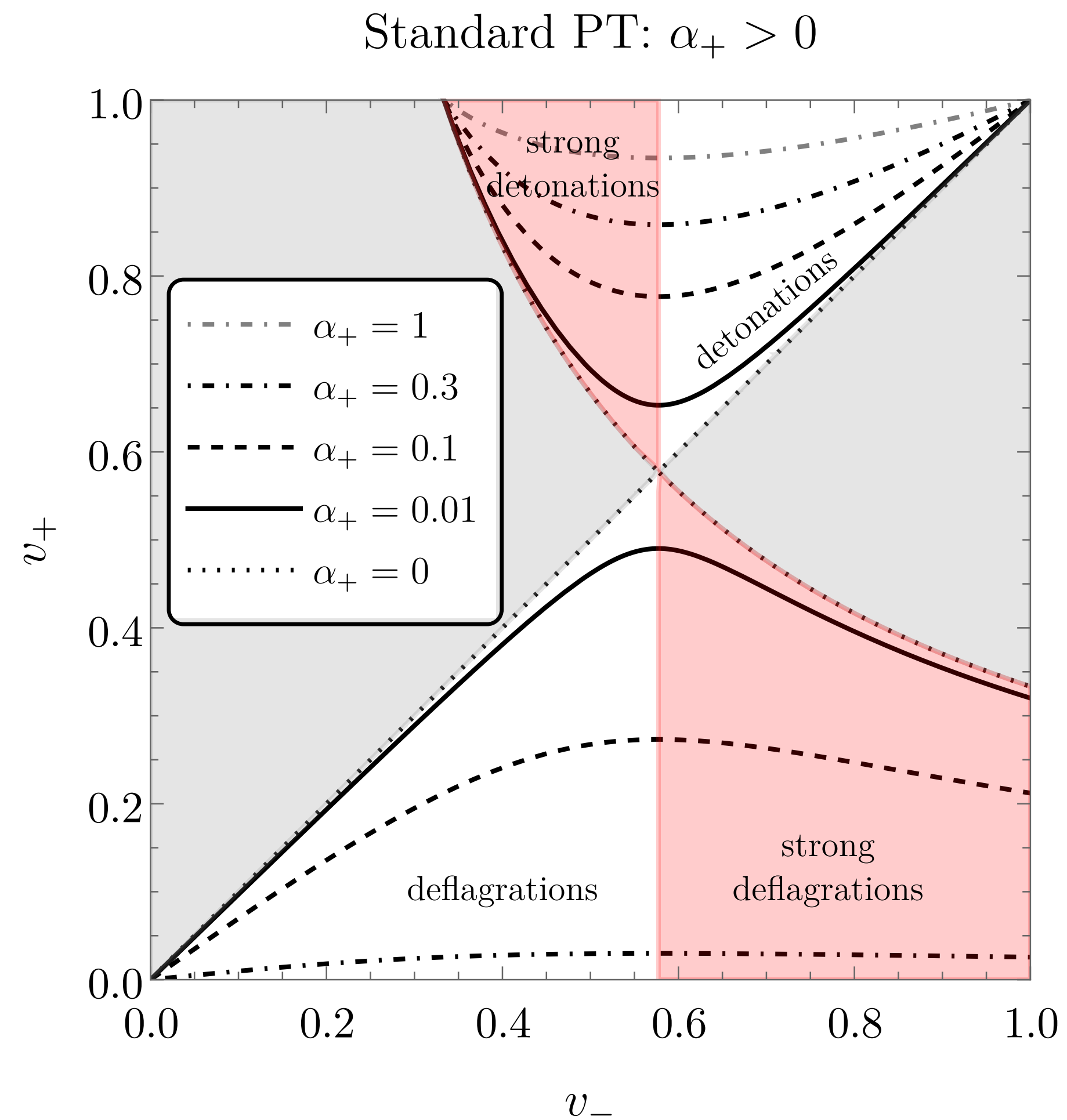
Direct: $\alpha_+ \equiv \frac{\epsilon_+ - \cancel{\epsilon_-}}{a_+ T_+^4} > 0$

Inverse: $\alpha_+ \equiv \frac{\cancel{\epsilon_+} - \epsilon_-}{a_+ T_+^4} < 0$



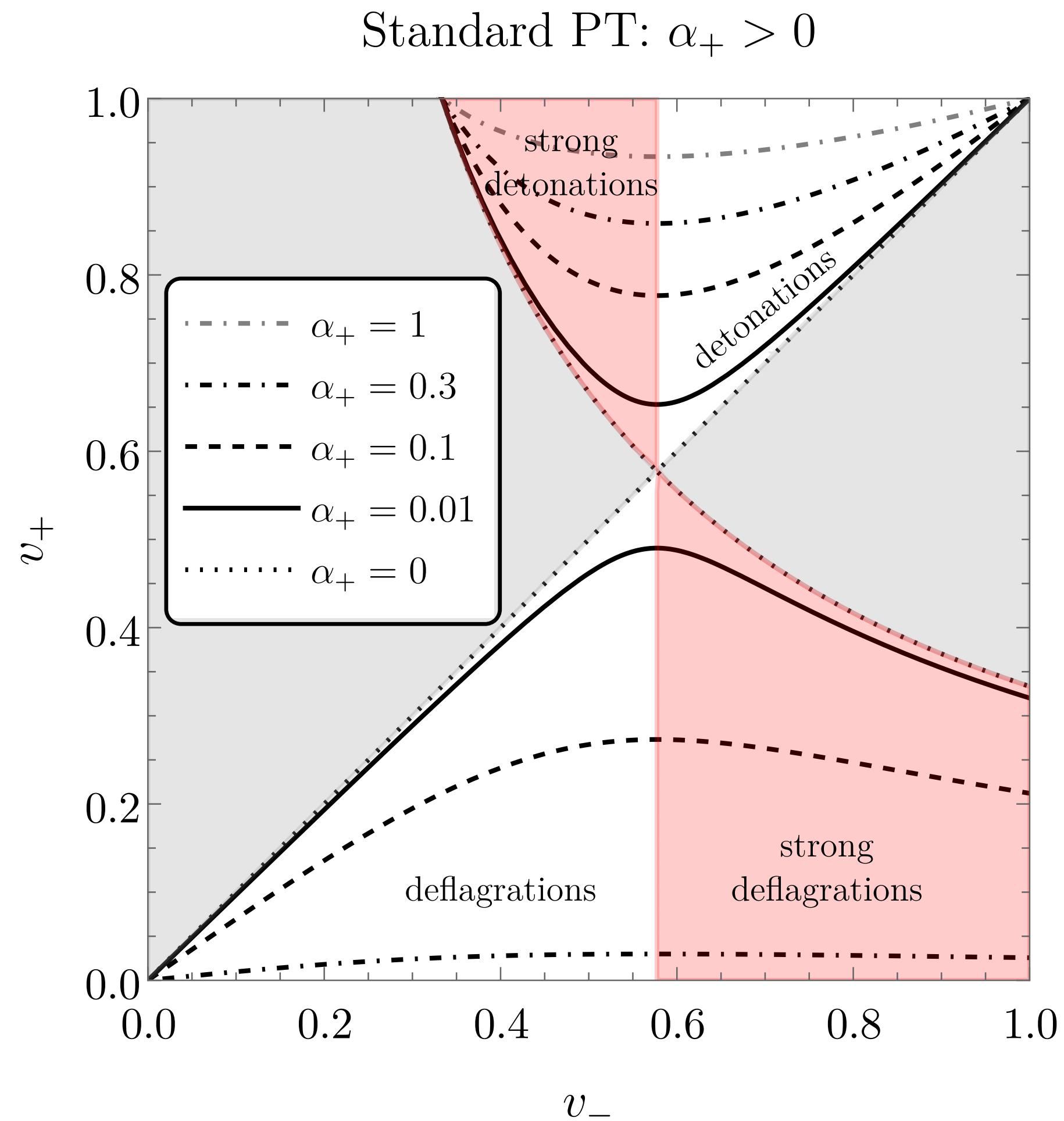
Barni, **SB**, Vanvlasselaer [2406.01596] JCAP (2024)
 Bea, et al. [2406.14450] PRD (2025)

“Inverse” hydrodynamics

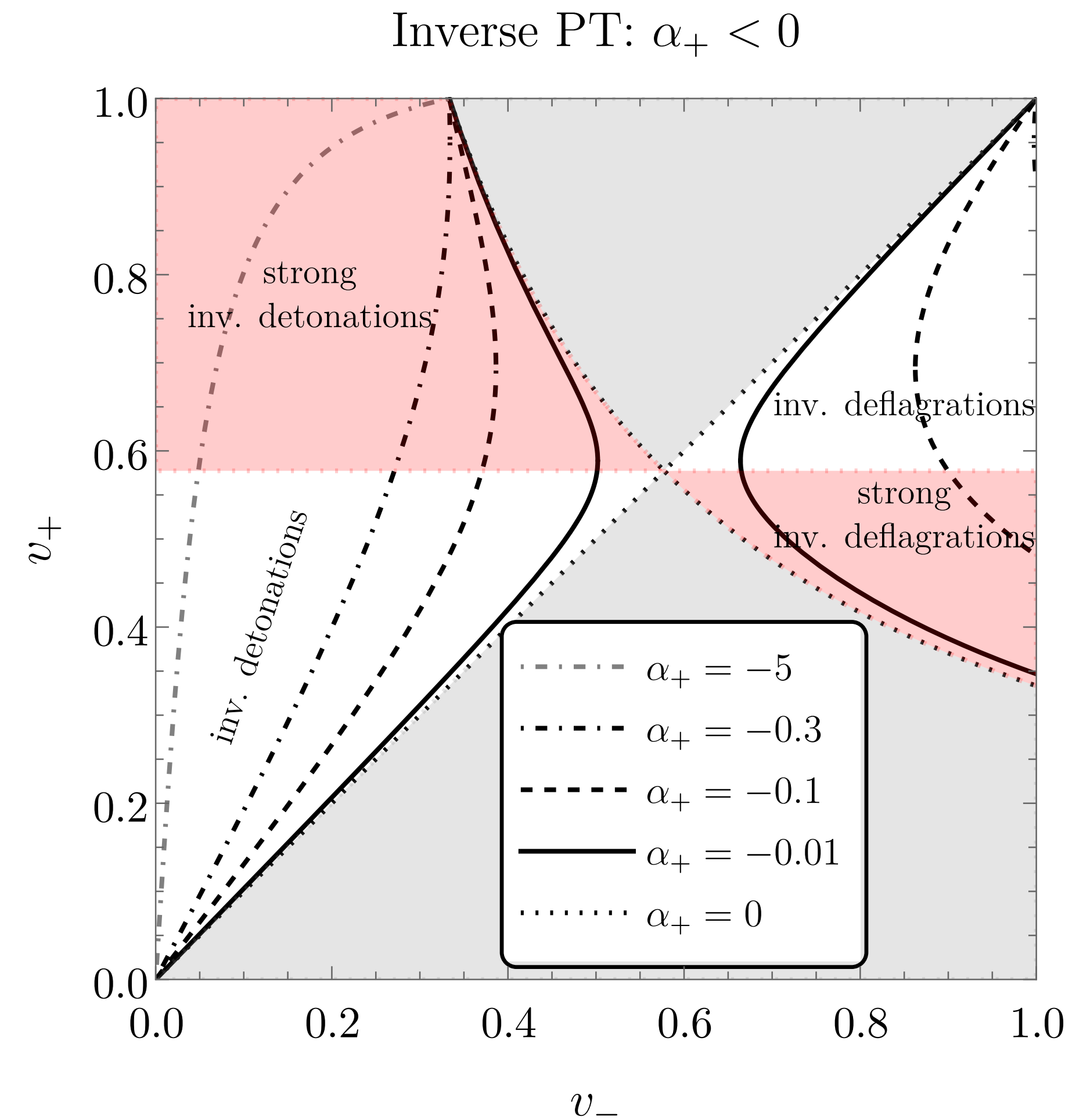


Espinosa, Konstandin, No,
Servant [1004.4187] JCAP

“Inverse” hydrodynamics



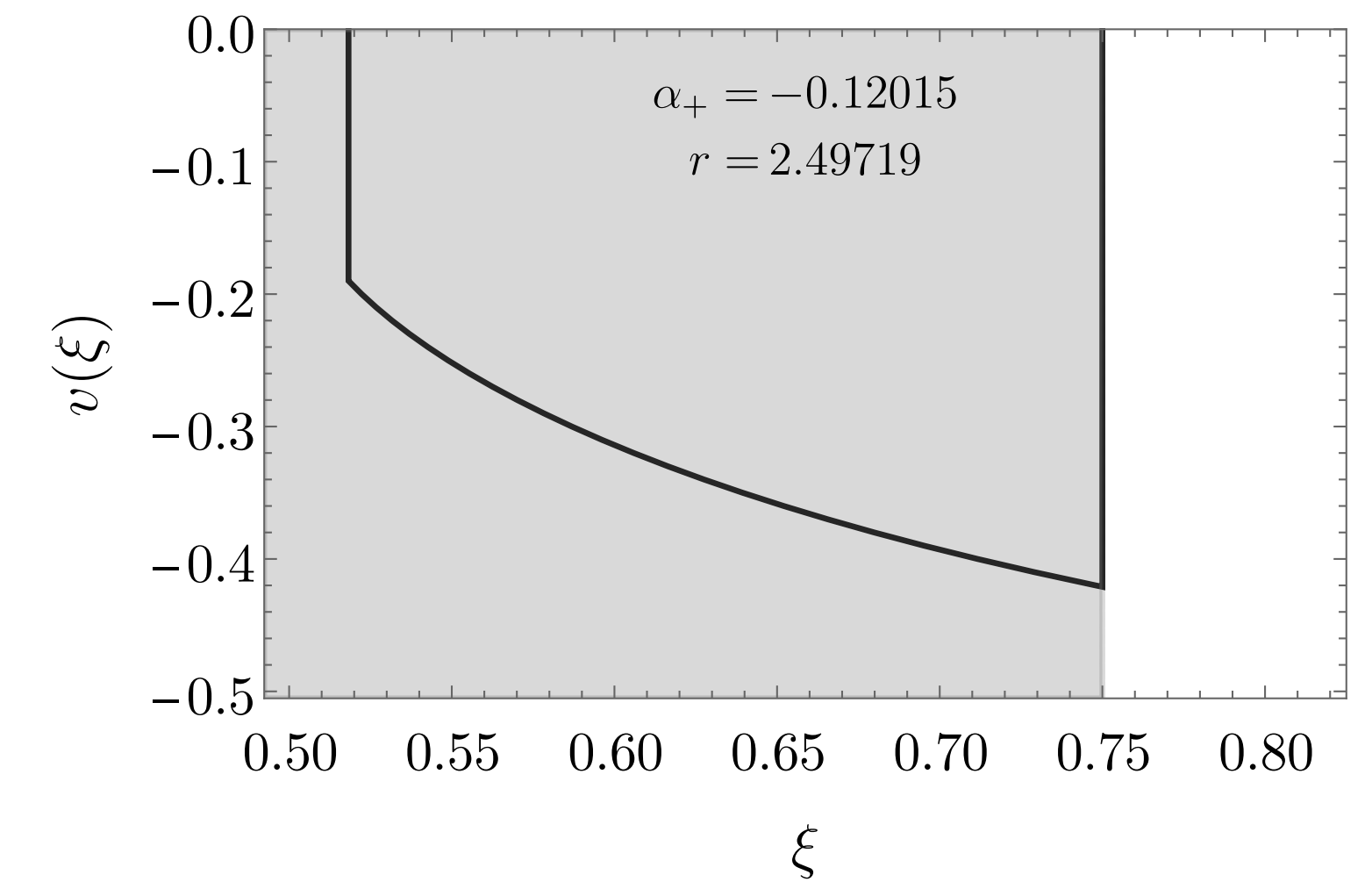
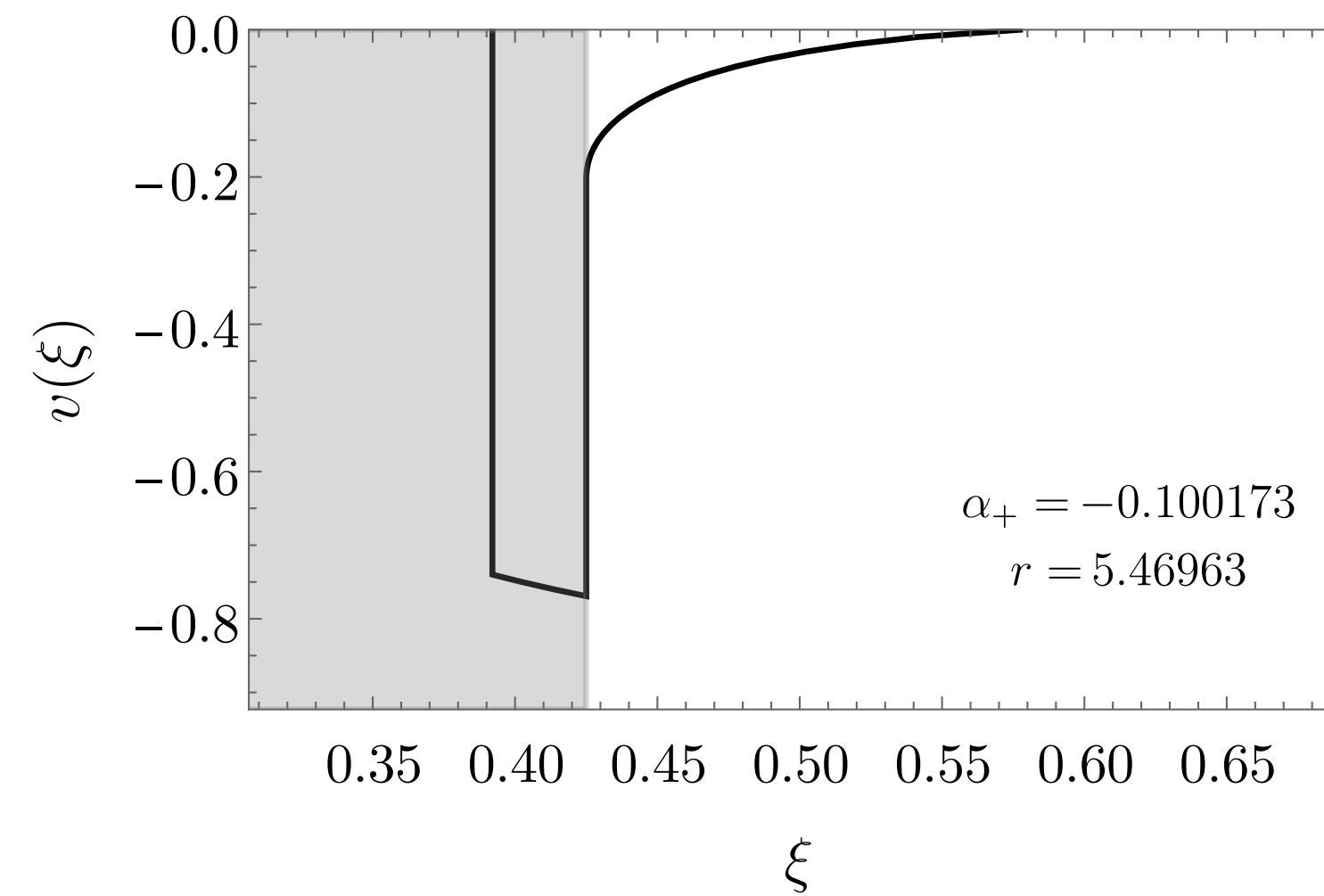
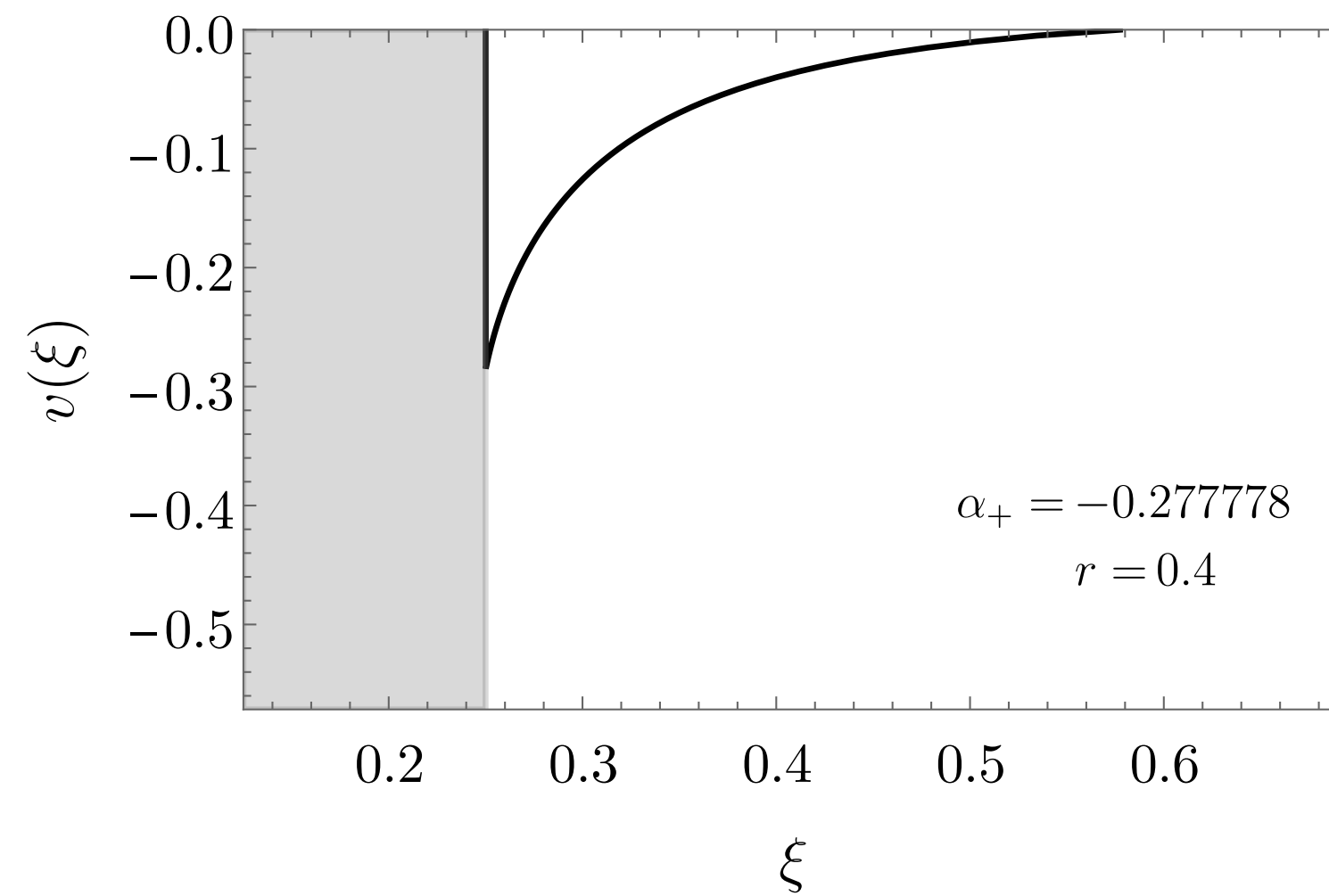
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Barni, **SB**, Vanvlasselaer
[2406.01596] JCAP (2024)

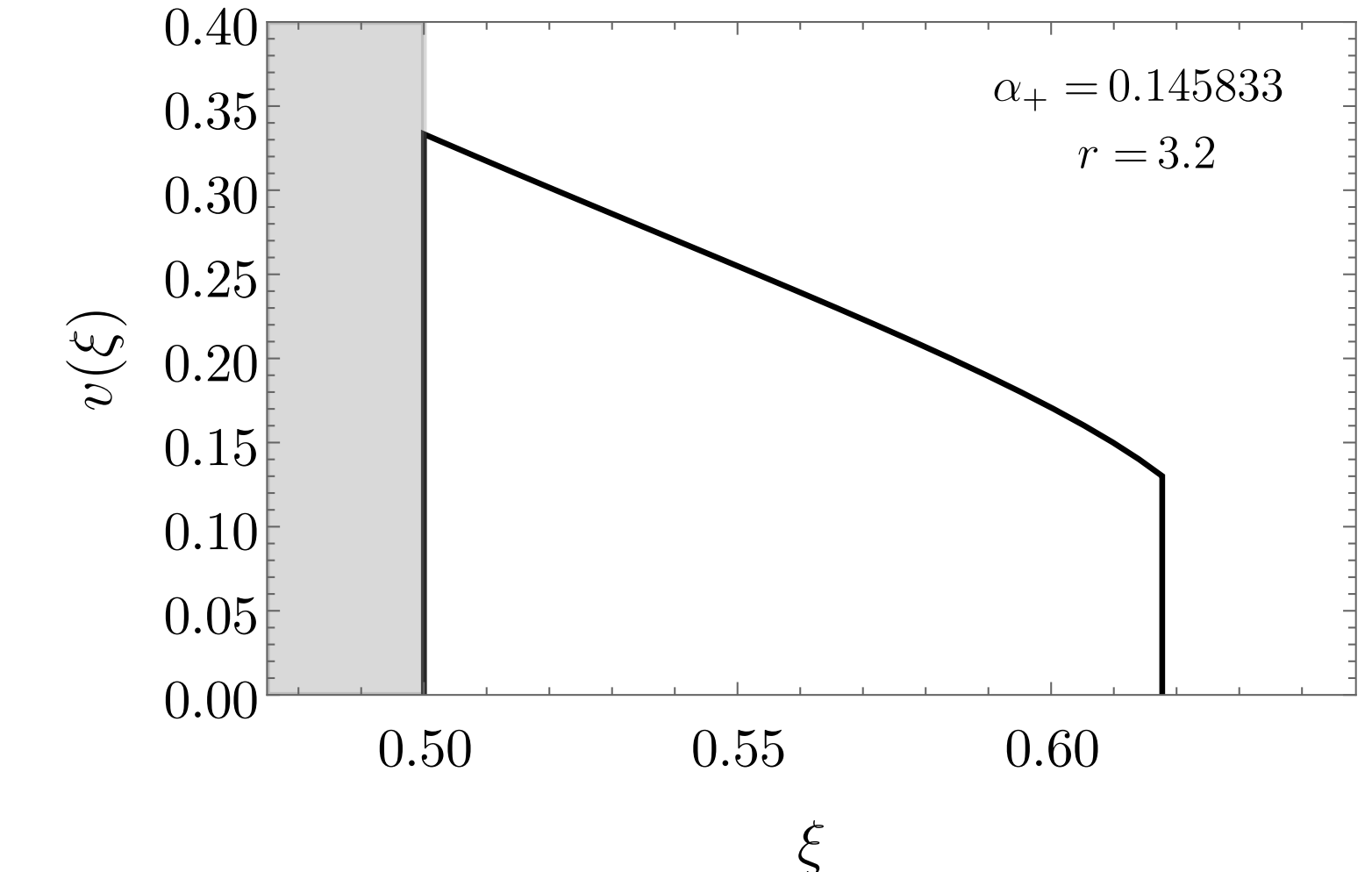
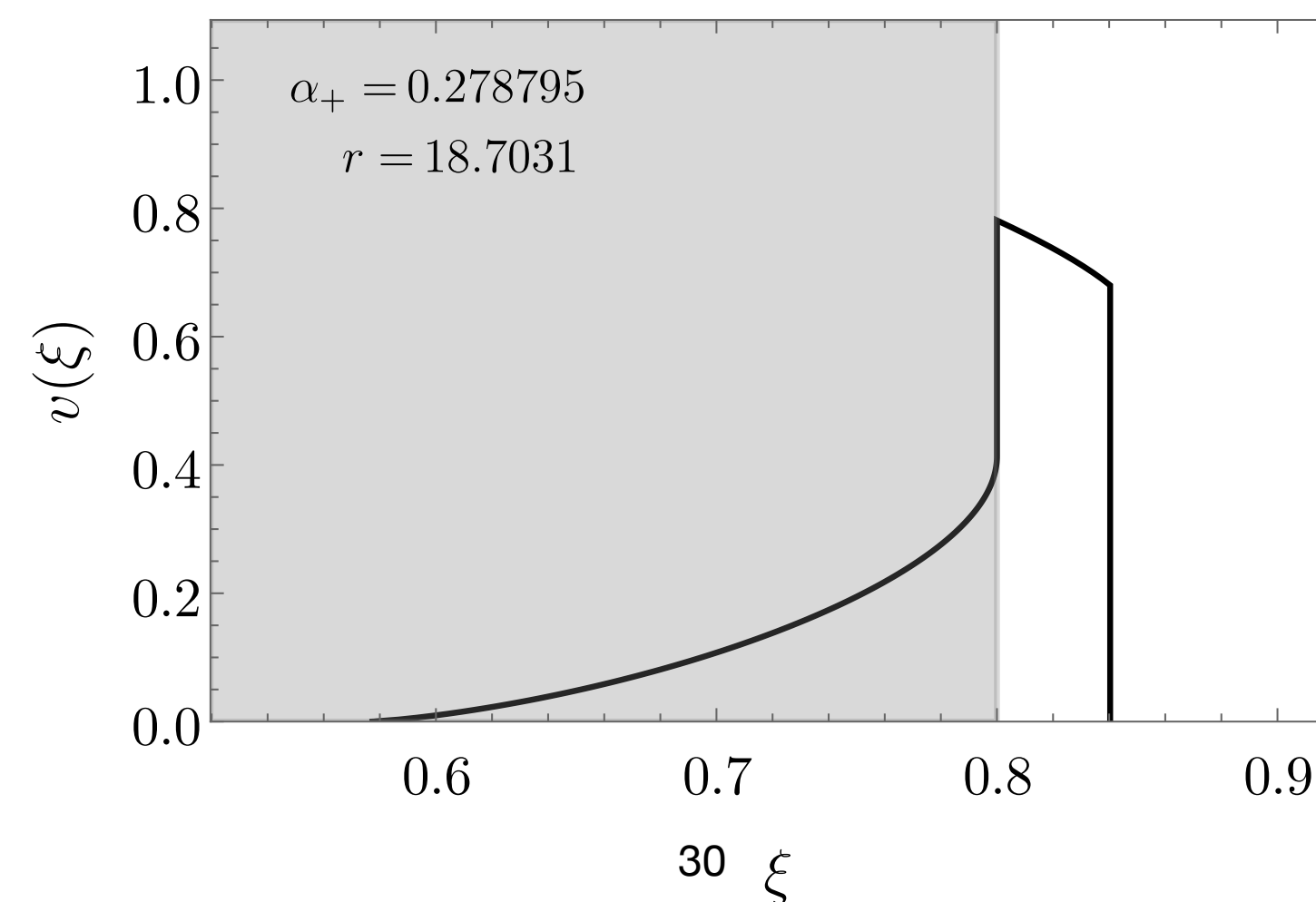
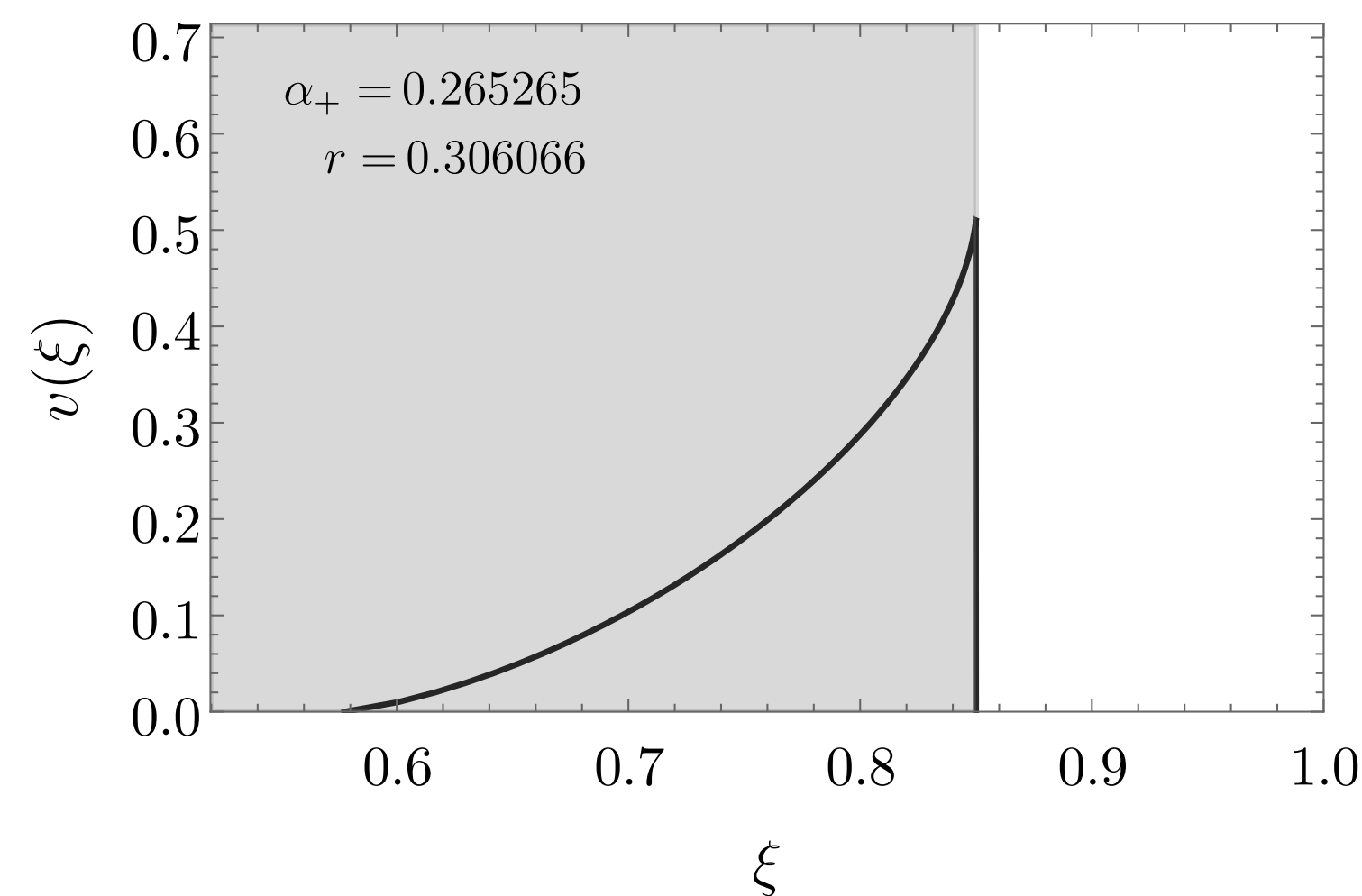
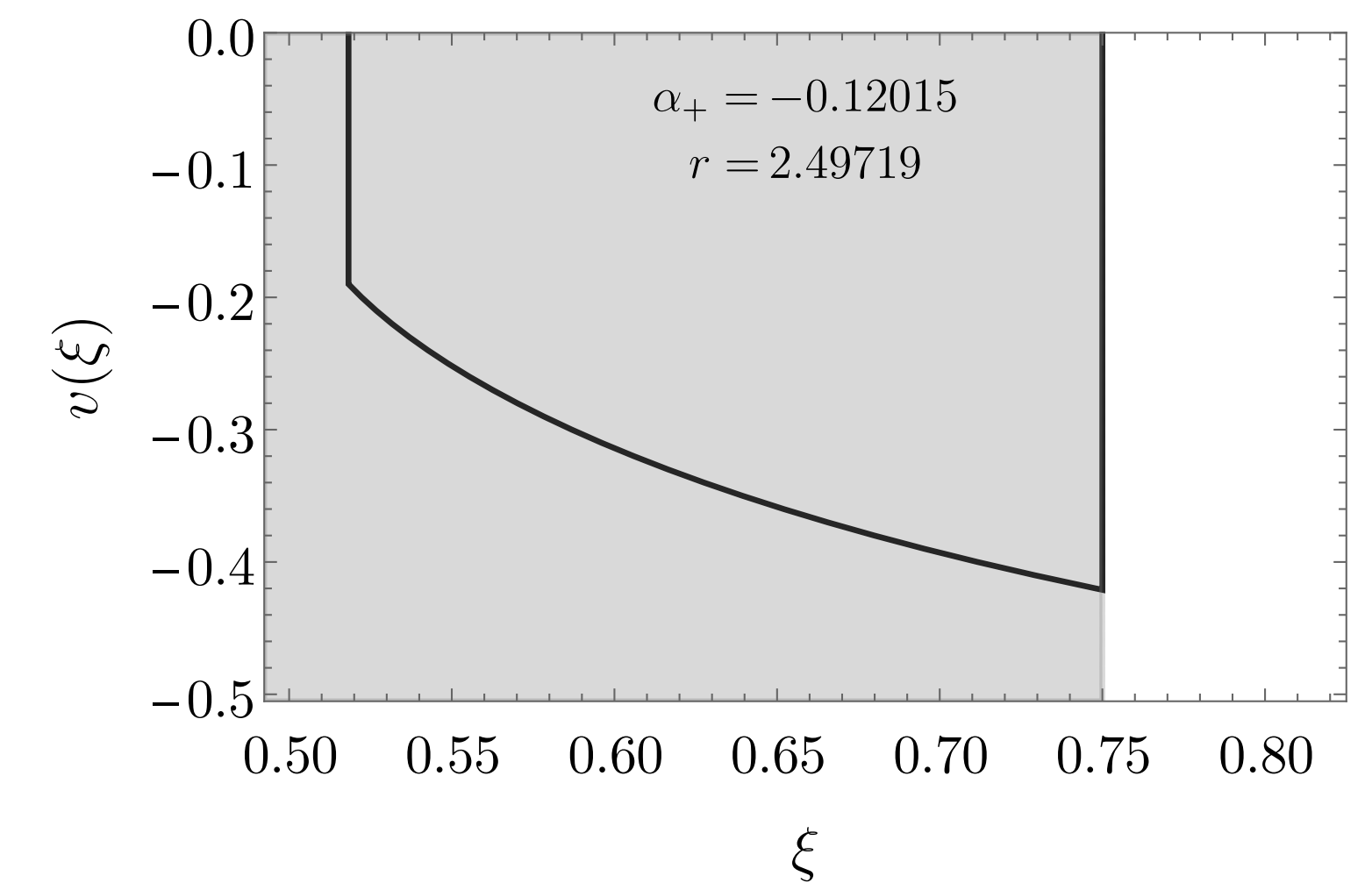
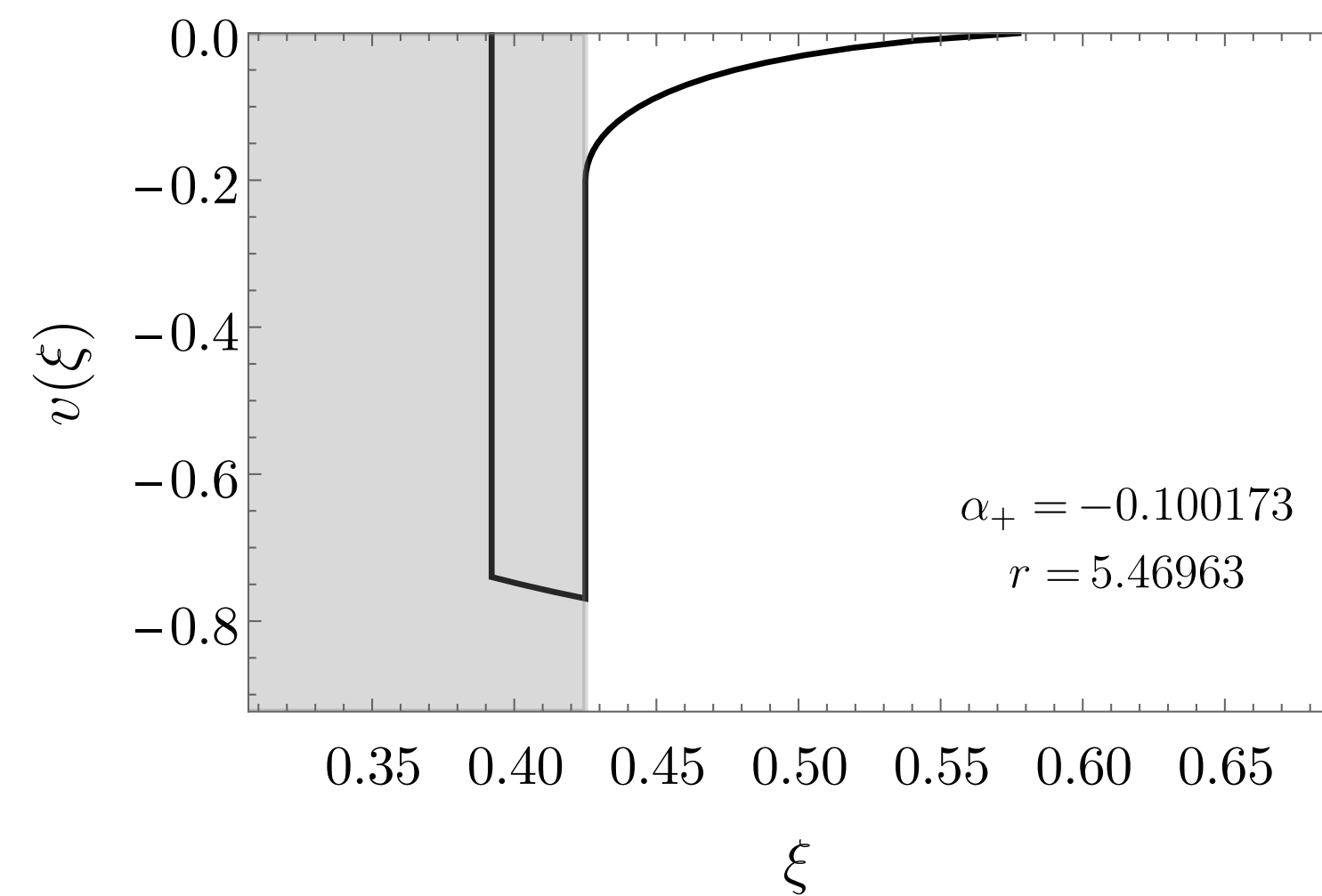
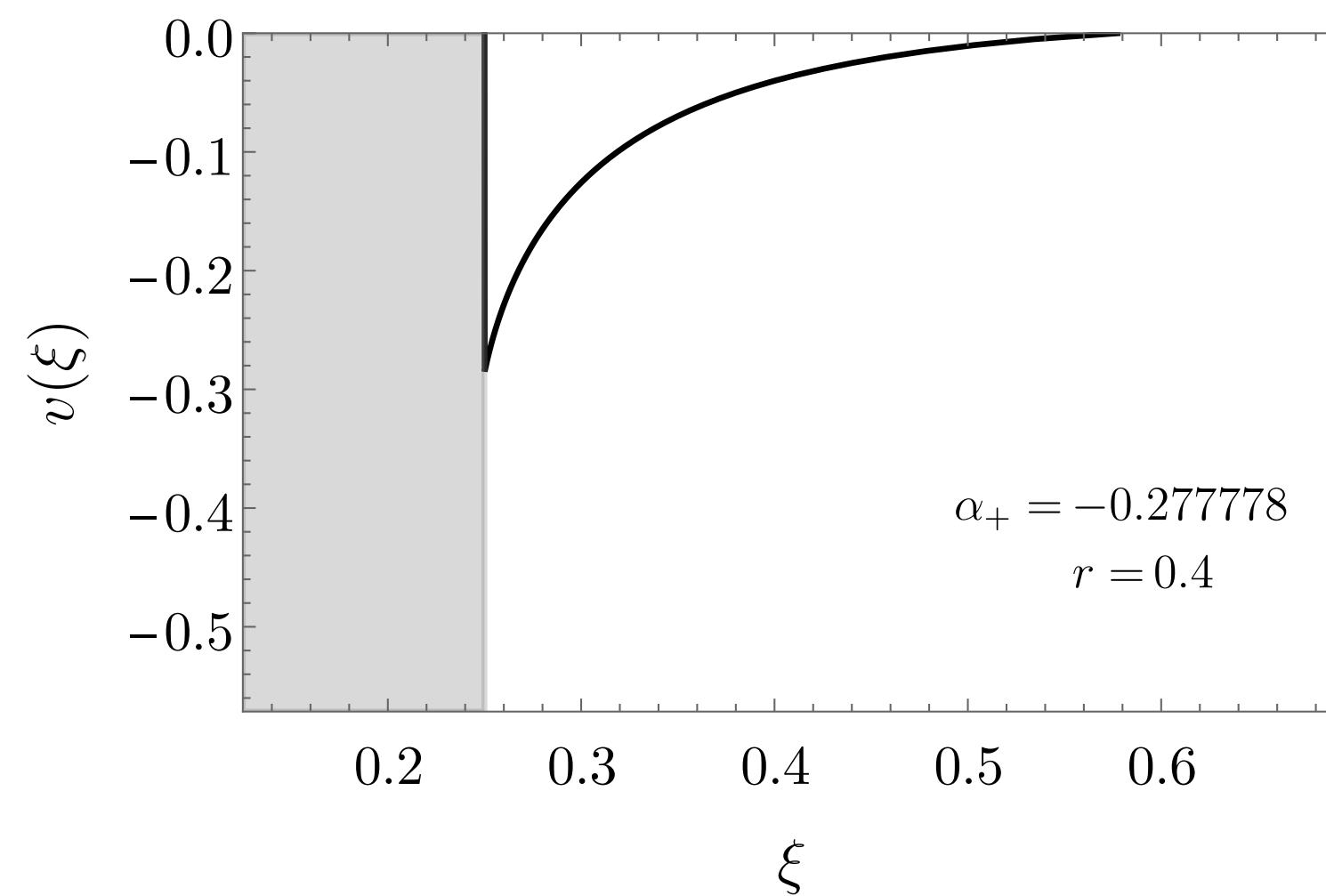
“Inverse” hydrodynamics

- Fluid is sucked in by the advancing bubble wall:



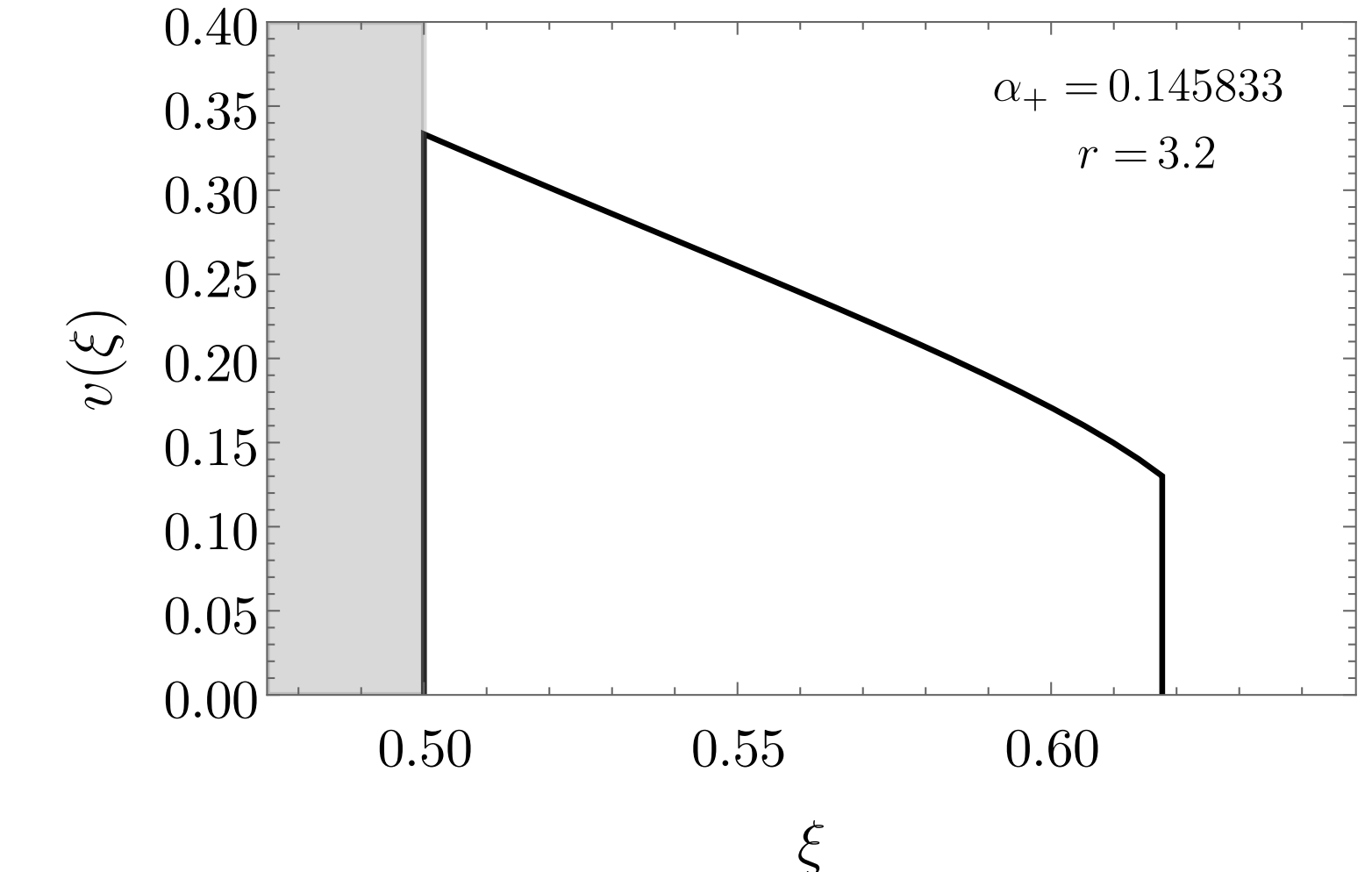
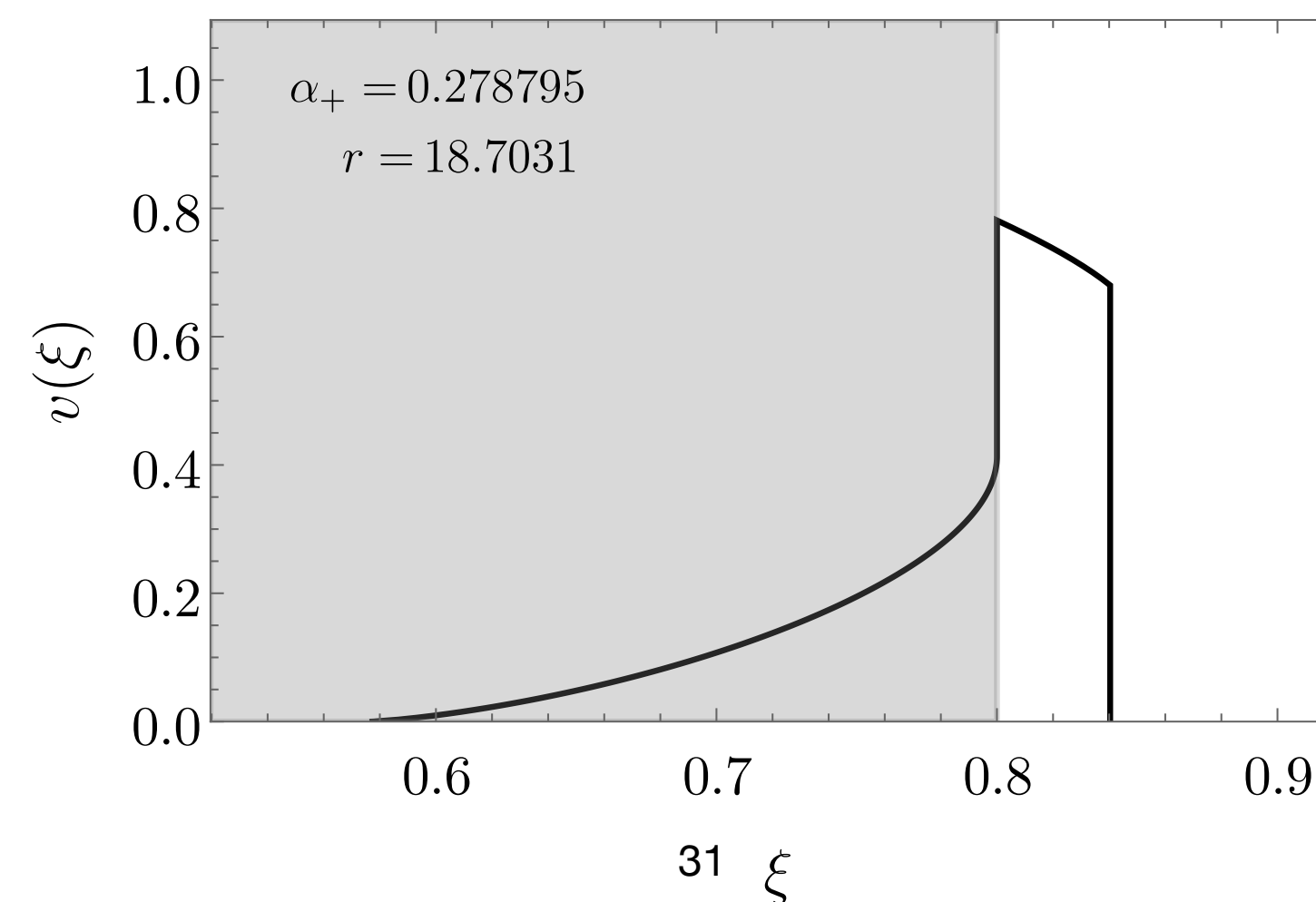
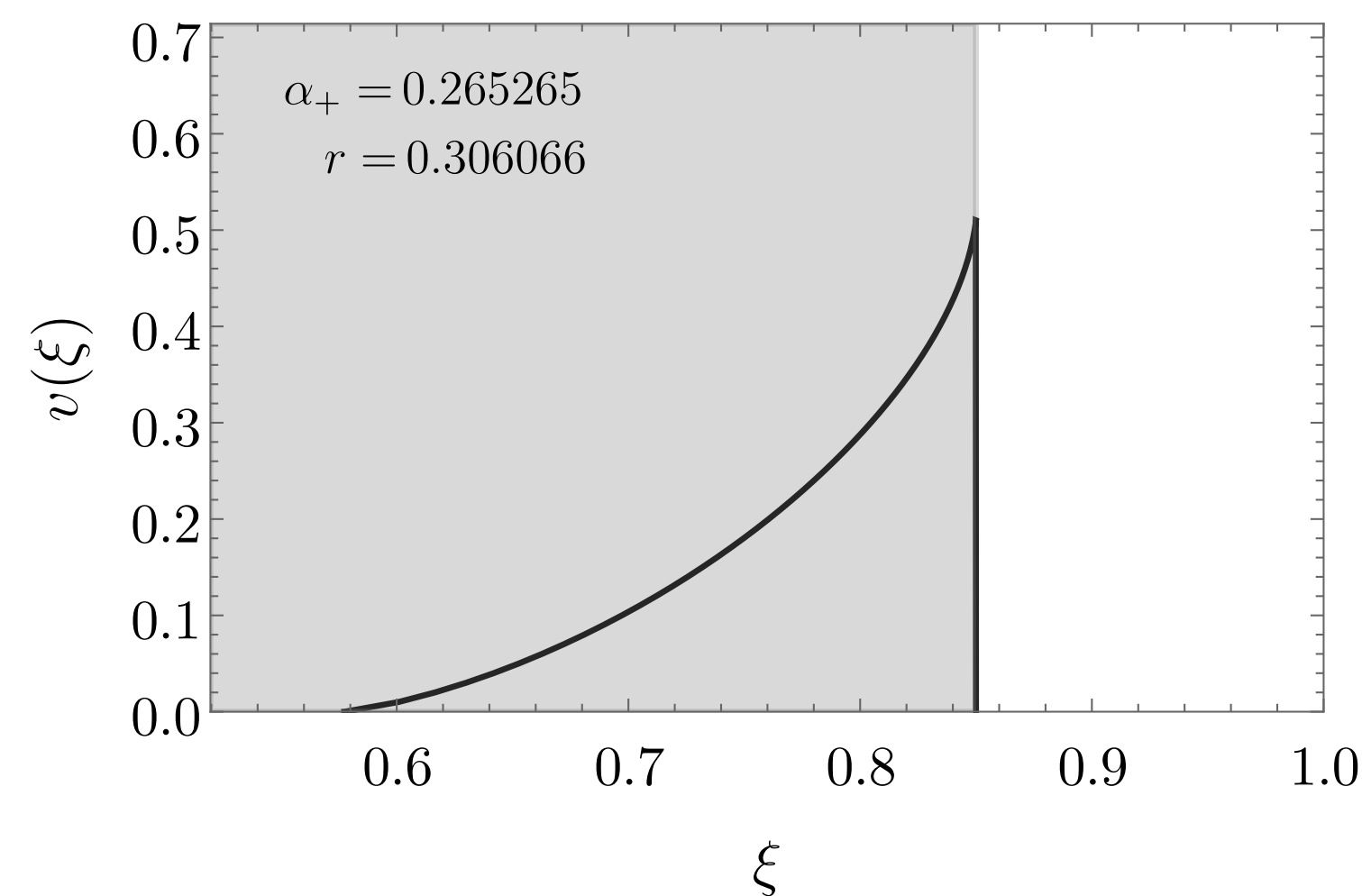
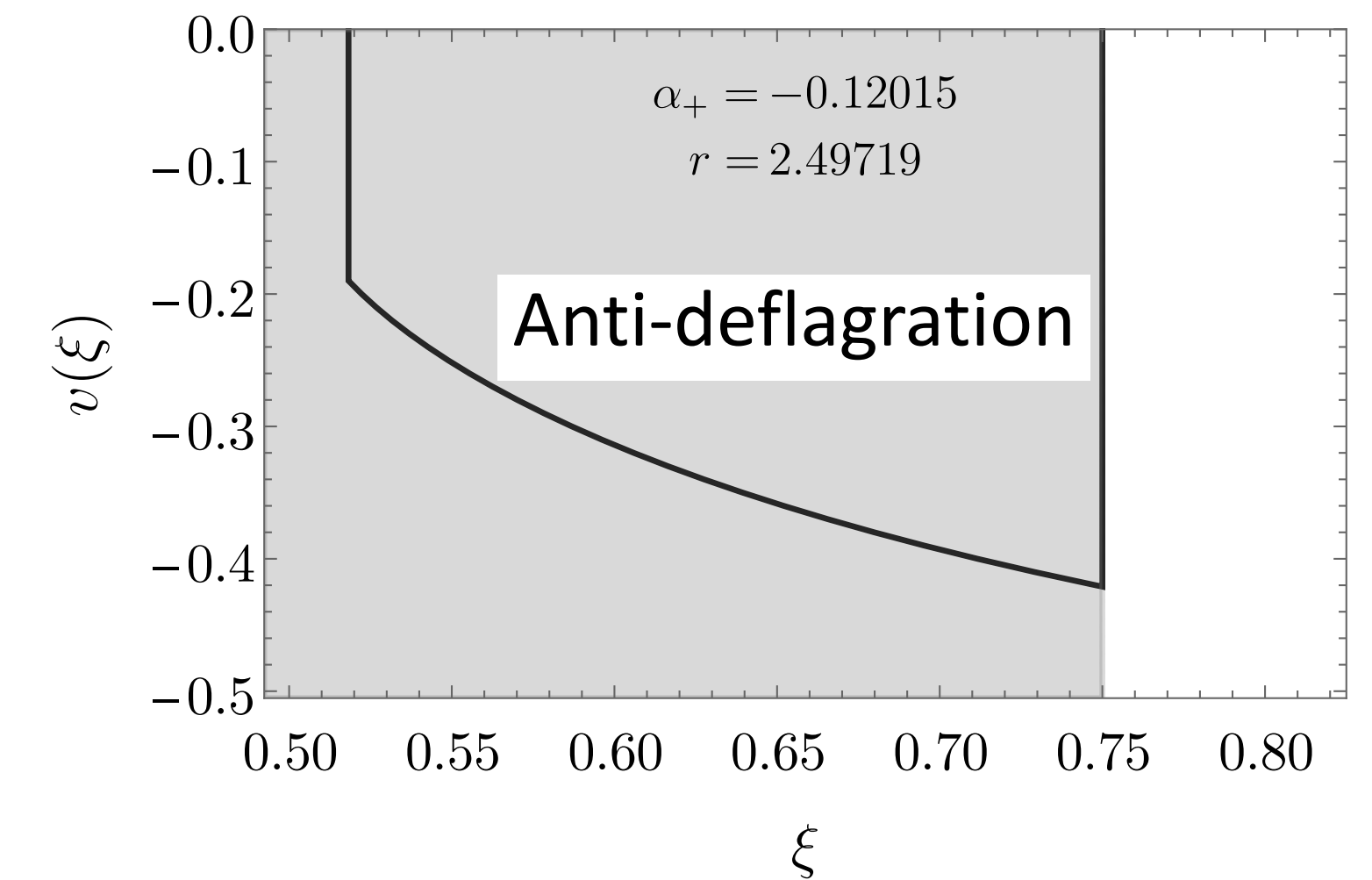
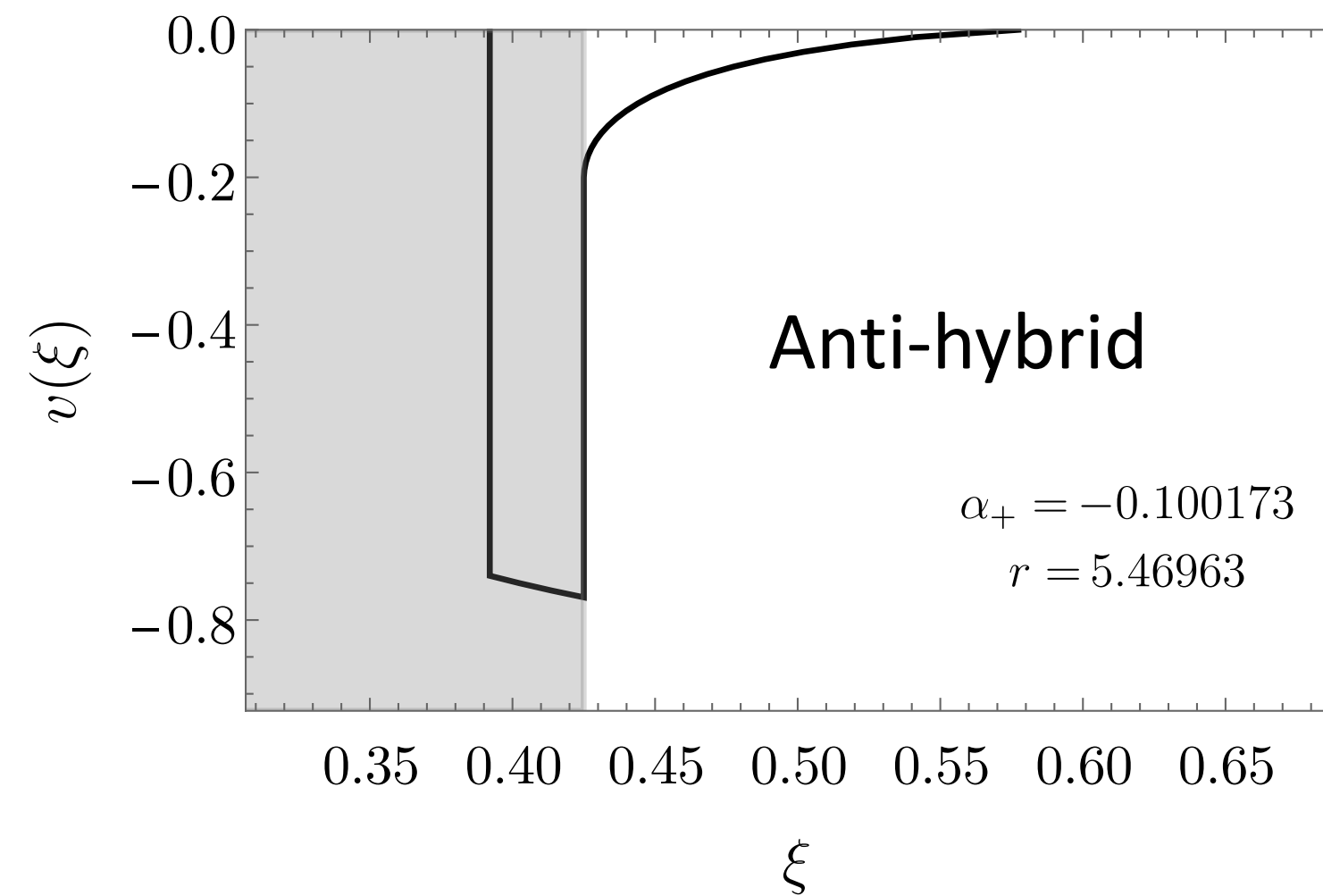
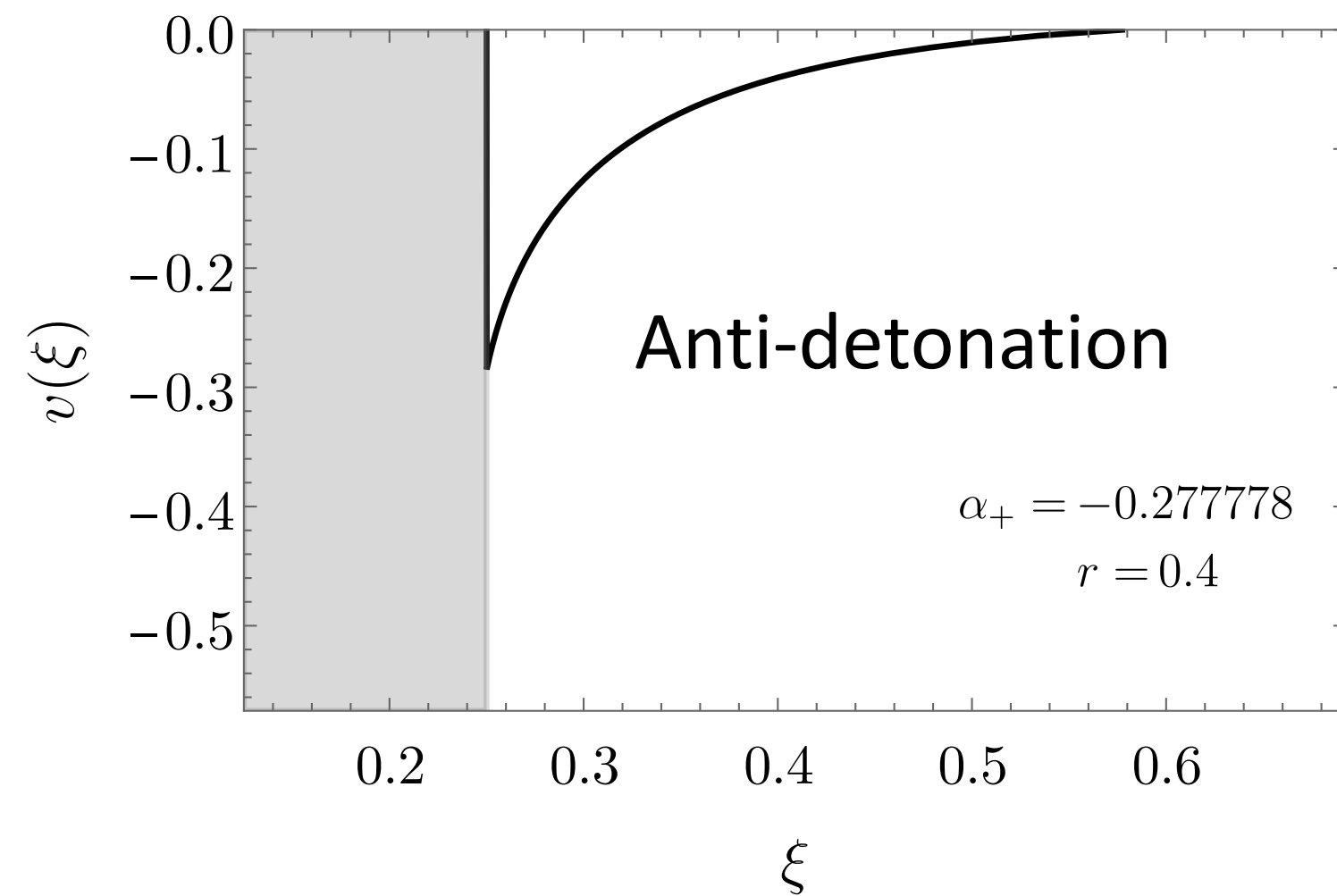
“Inverse” hydrodynamics

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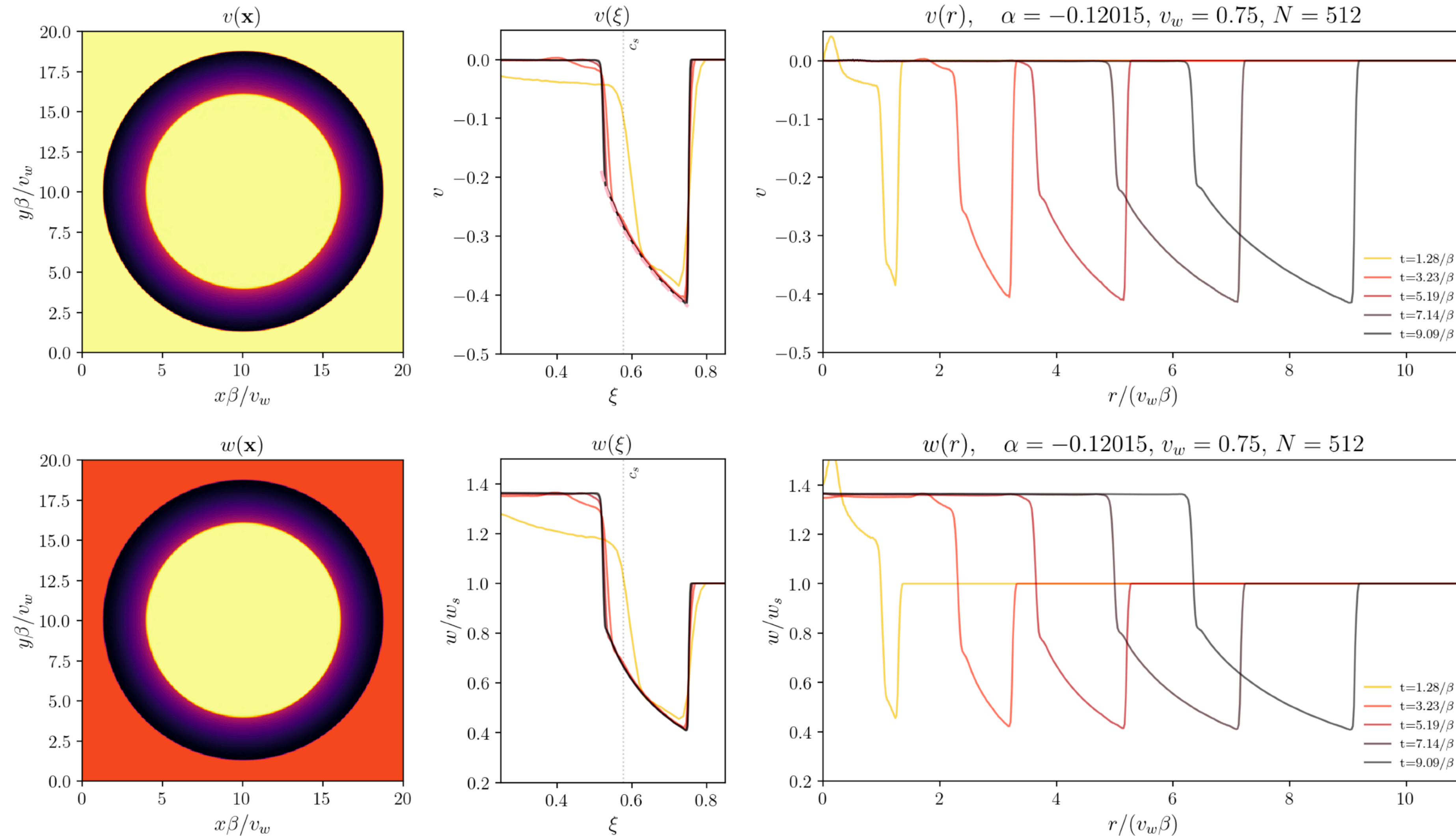


“Inverse” hydrodynamics

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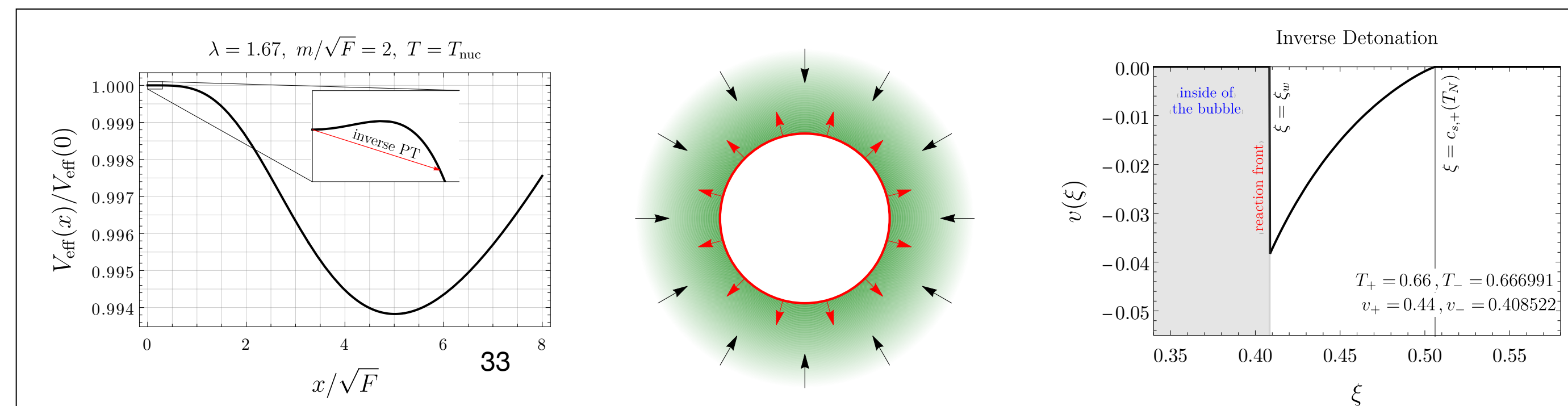
Inverse solutions from Higgsless simulation



Courtesy of Isak Stomberg :)

Applications of “inverse” hydro

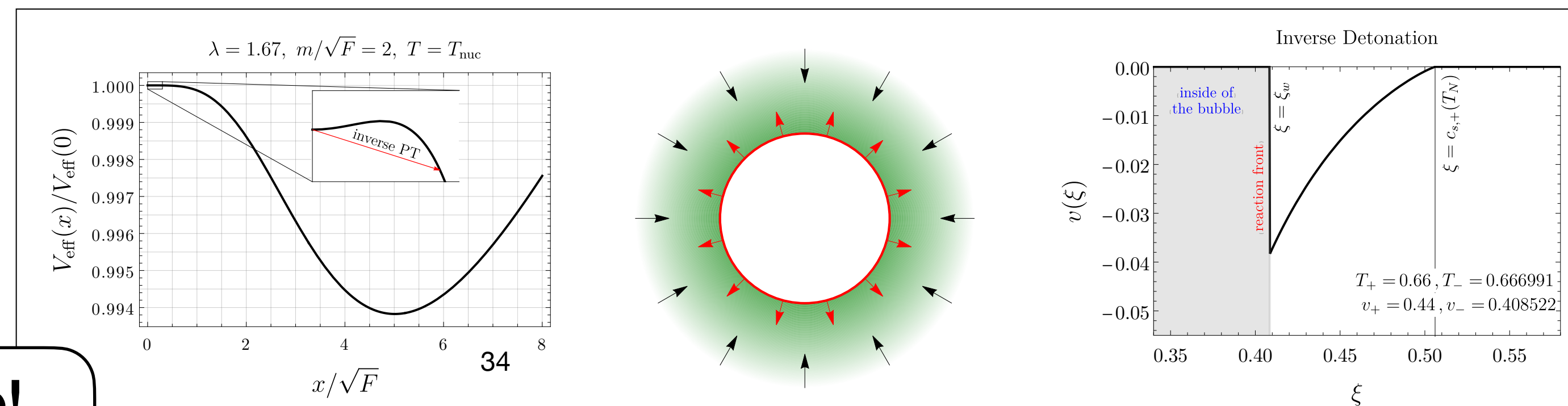
- Reheating (e.g. inflaton decay) Buen-Abad, Chang, Hook [2305.09712] PRD
- Heating by rarefaction waves and baryogenesis Caprini, No [1111.1726] JCAP
- Hadron-to-quark-matter transition in neutron stars?
Bea, Casalderrey-Solana, Mateos, Sanchez-Garitaonandia [2406.14450] Bleau, Kopp, Lee, van de Vis [2603.18153]
- Supercooled cosmological R-symmetry breaking phase transition in SUSY
Barni, **SB**, Vanvlasselaer [2503.01951] PRD (2025)

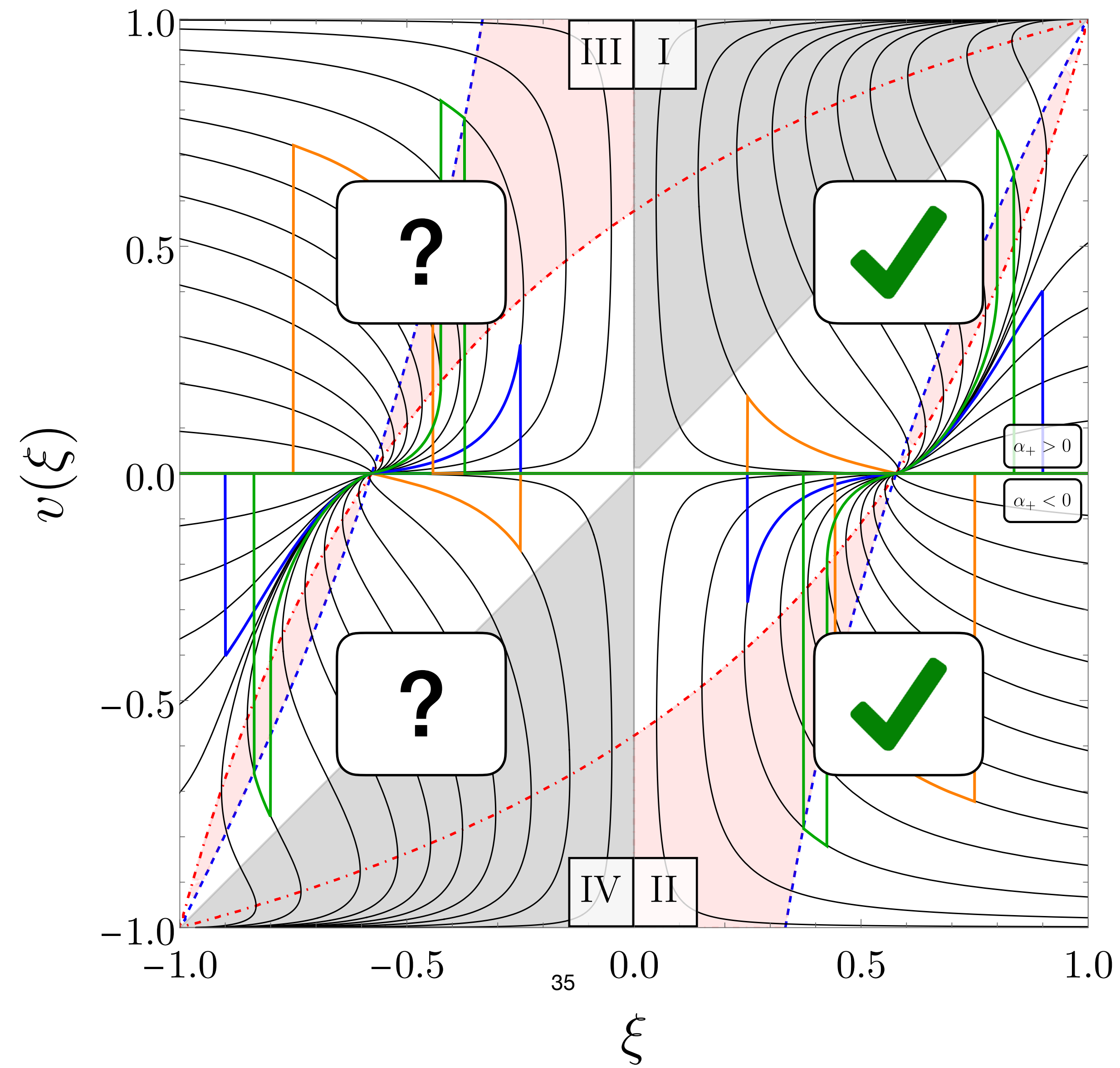


Applications of “inverse” hydro

- Reheating (e.g. inflaton decay) Buen-Abad, Chang, Hook [2305.09712] PRD
- Heating by rarefaction waves and baryogenesis Caprini, No [1111.1726] JCAP
- Hadron-to-quark-matter transition in neutron stars?
Bea, Casalderrey-Solana, Mateos, Sanchez-Garitaonandia [2406.14450] Bleau, Kopp, Lee, van de Vis [2603.18153]
- Supercooled cosmological R-symmetry breaking phase transition in SUSY
Barni, **SB**, Vanvlasselaer [2503.01951] PRD (2025)

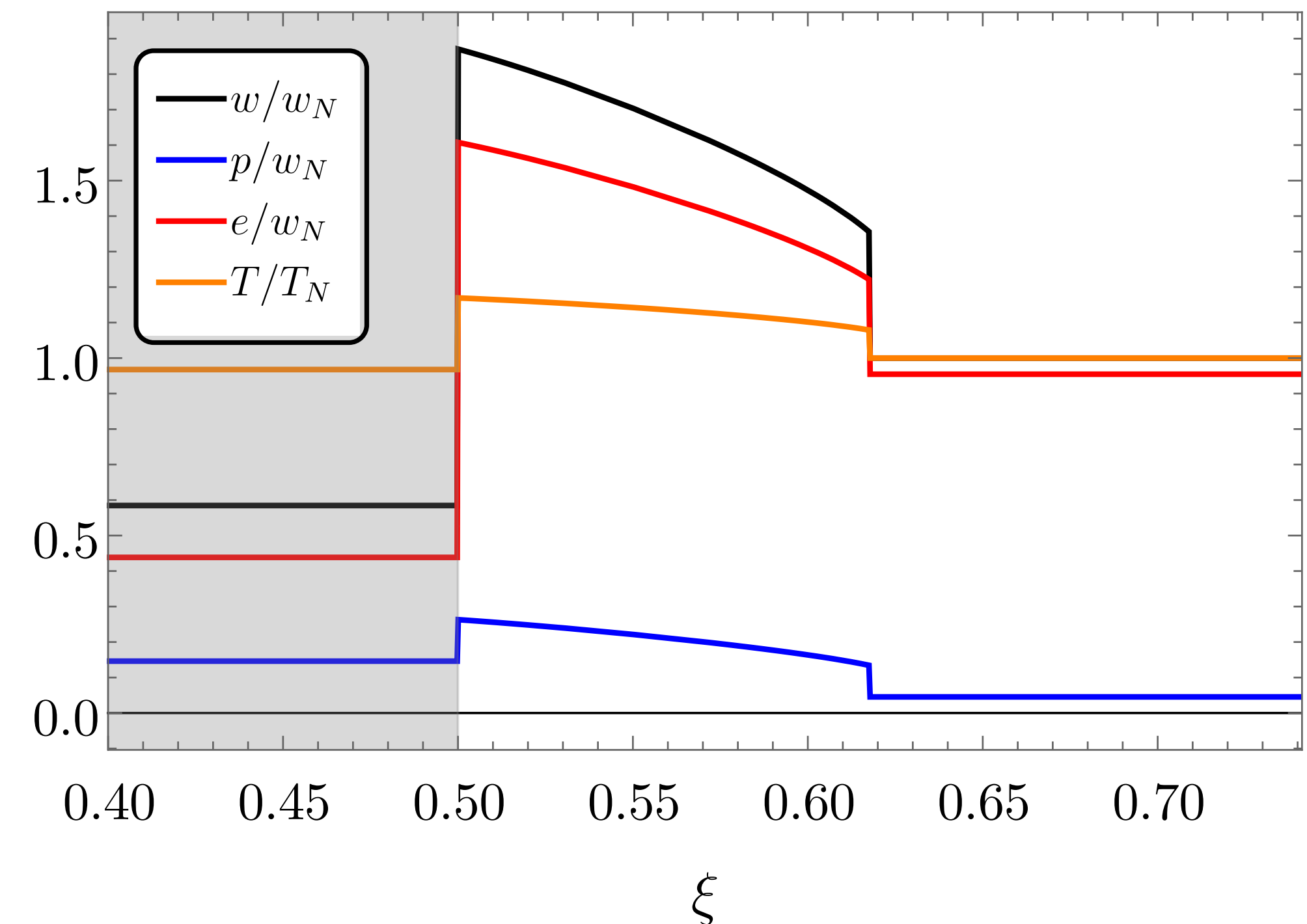
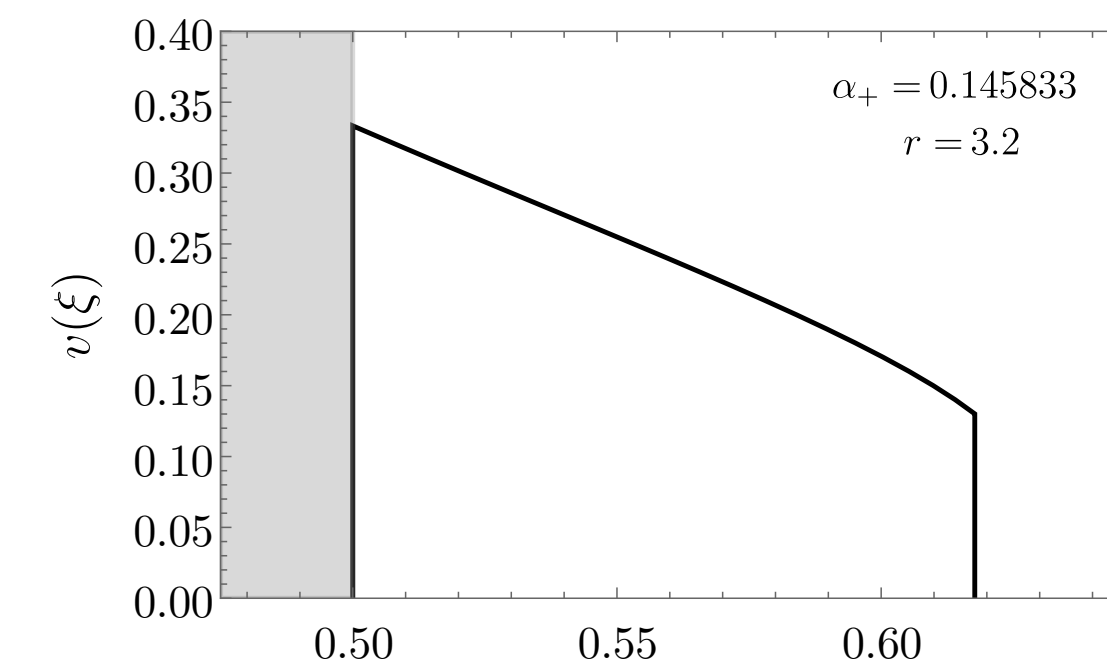
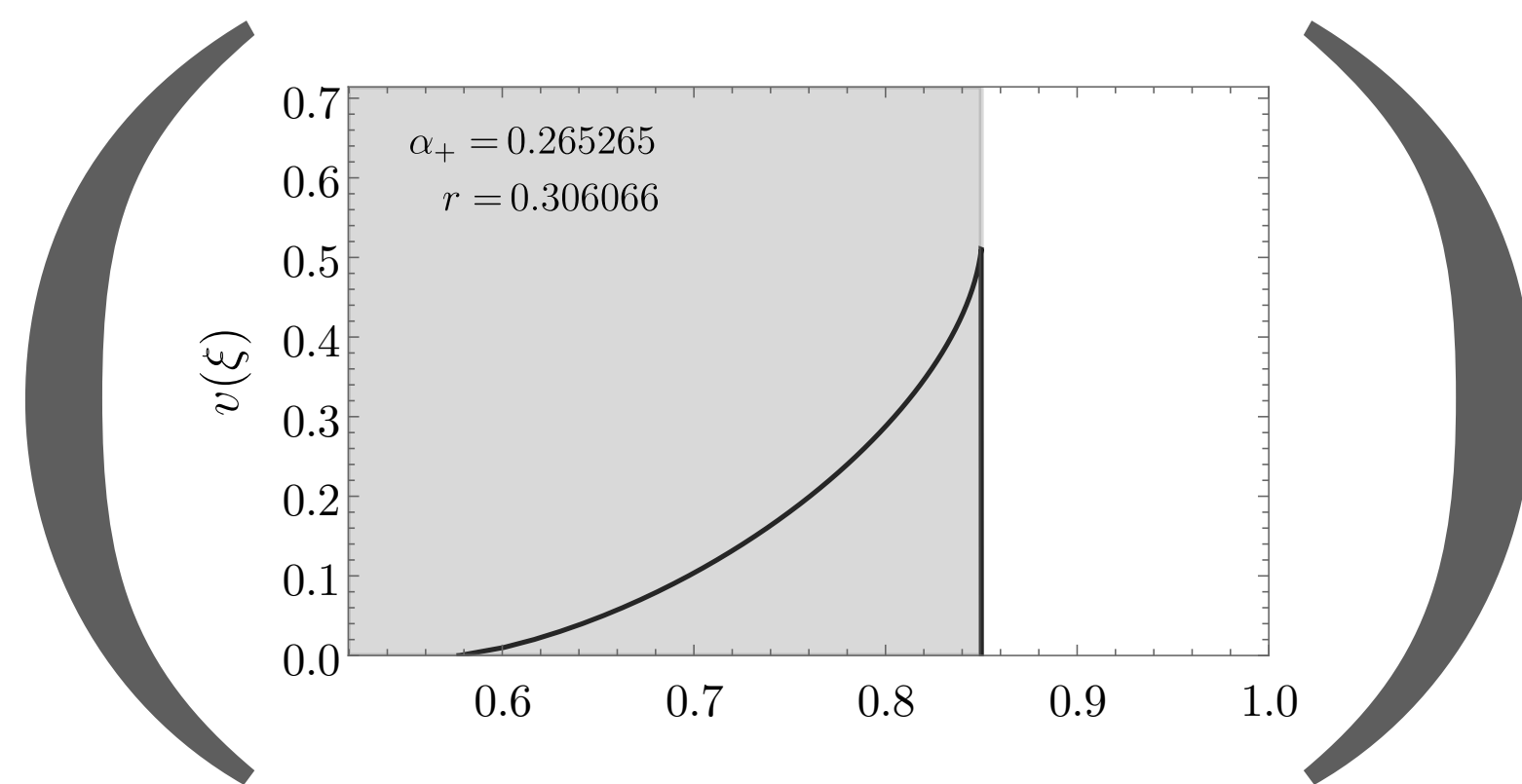
First example!





Heating effects

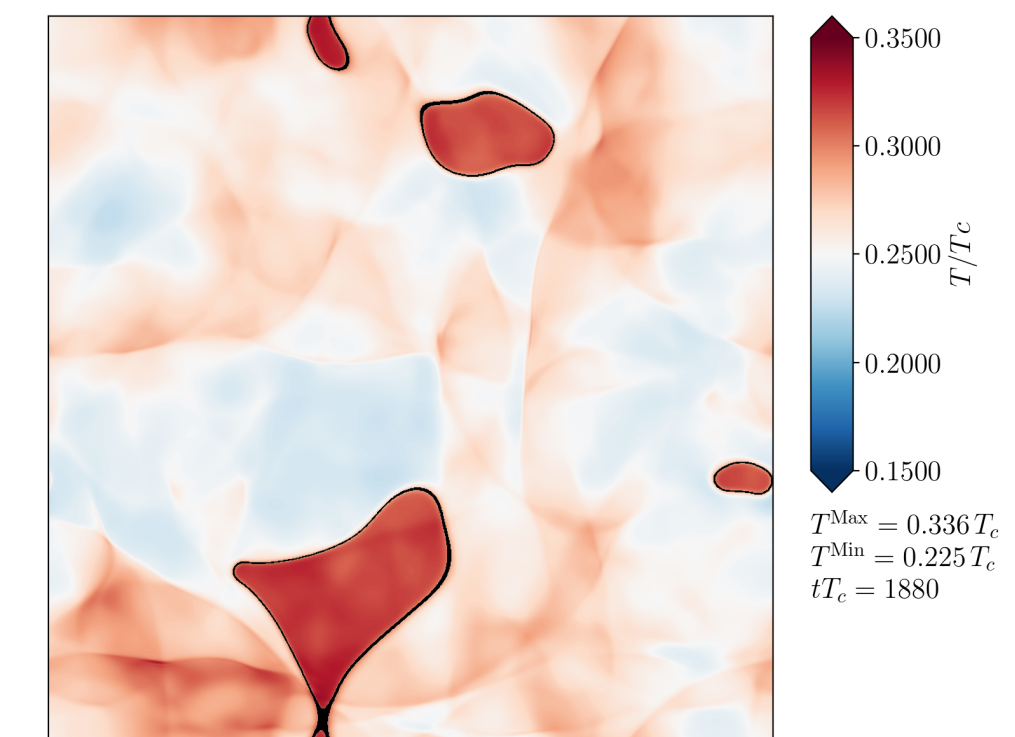
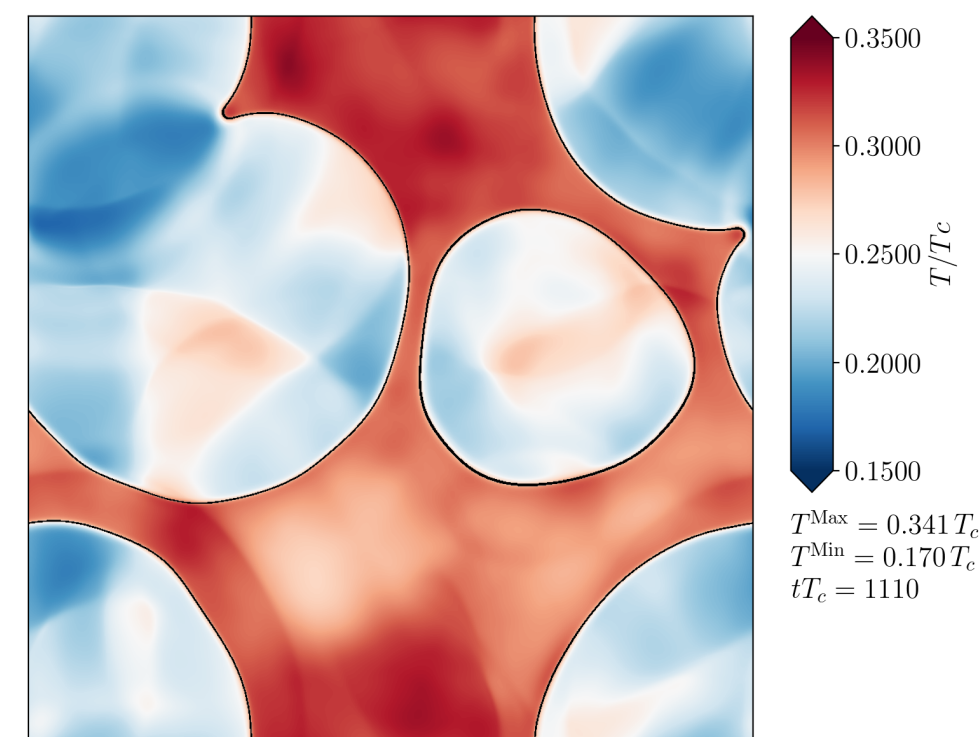
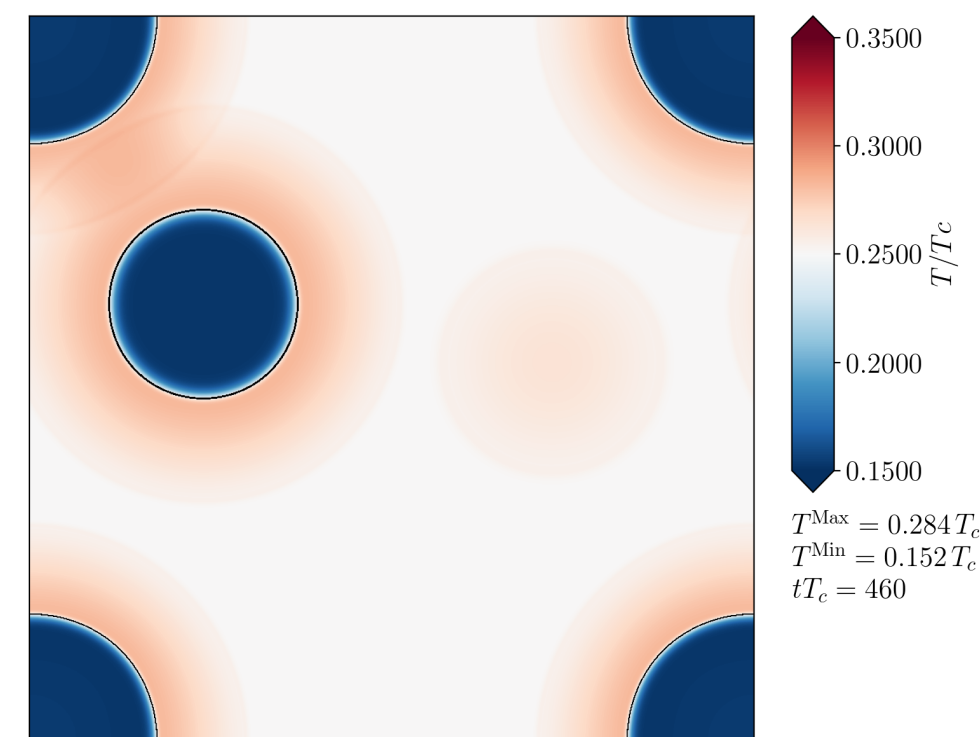
- Bubbles expanding as **deflagrations/hybrids** heat the plasma ahead (compression waves)
- Heated fluid shells change the environment where bubbles expand around percolation
- Not the case for **detonations**, where fluid ahead of the bubble wall is at rest



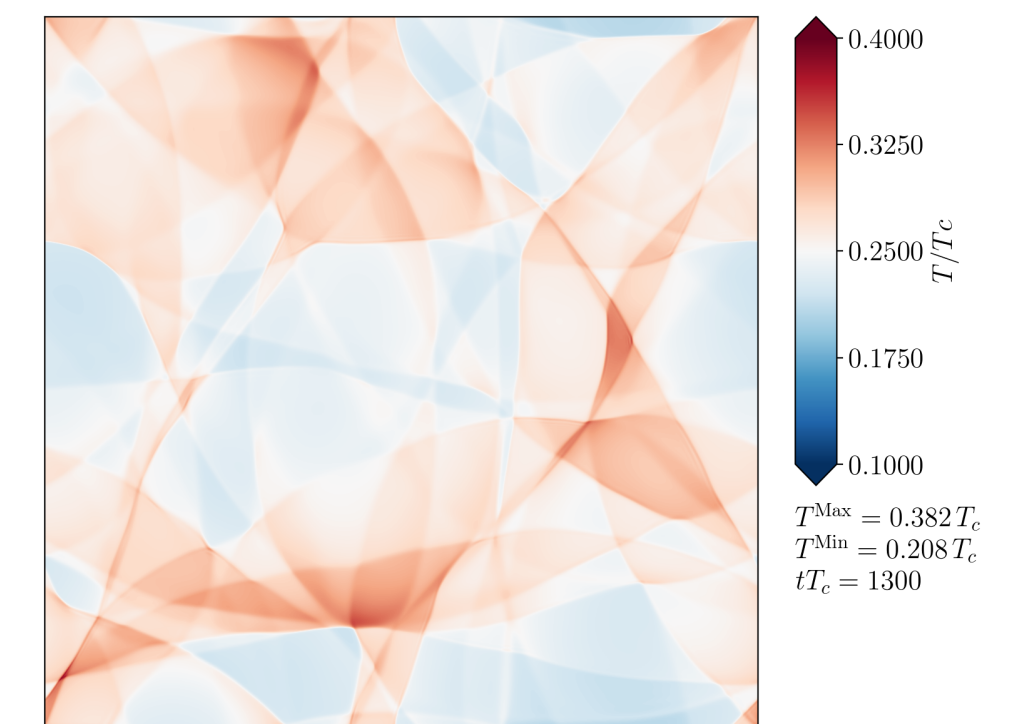
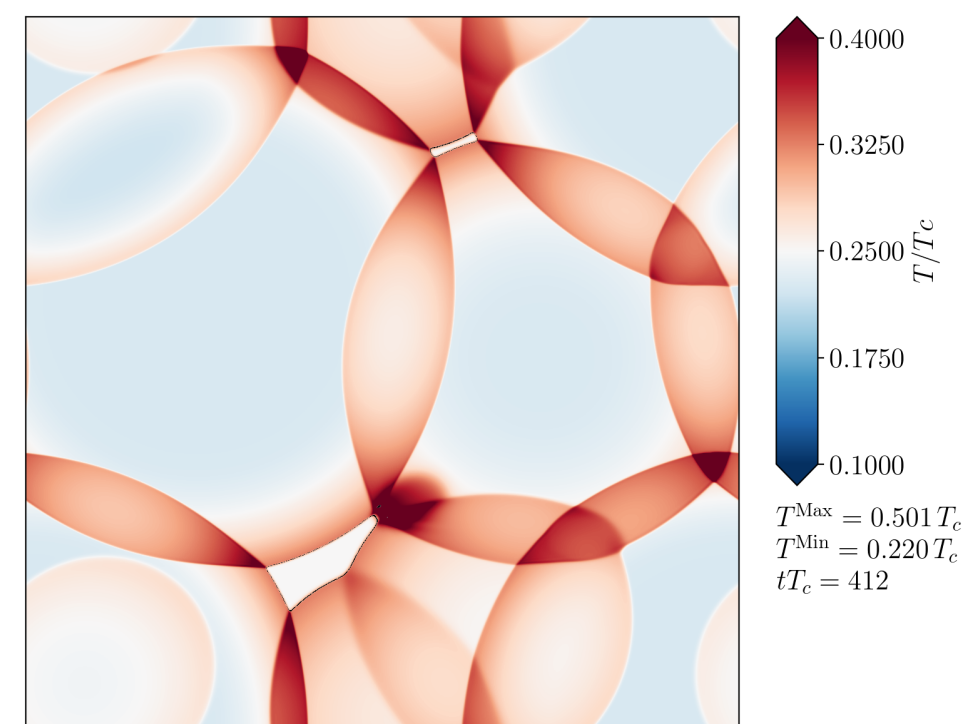
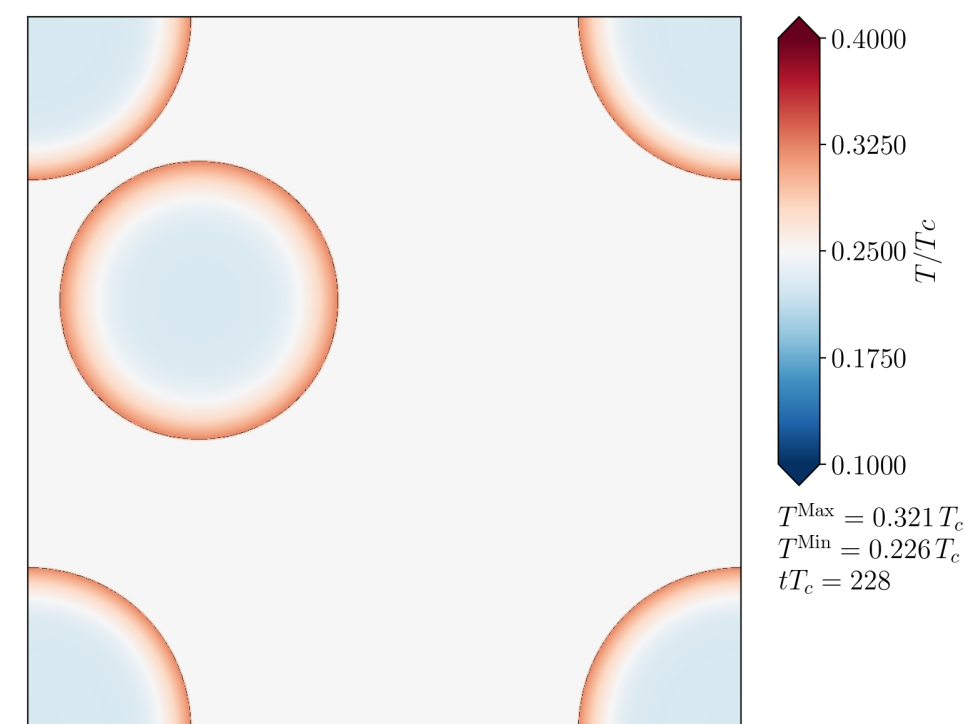
Heating effects

- Heating effects first observed in fully 3D numerical simulations of the Higgs-fluid system:

I. Deflagration

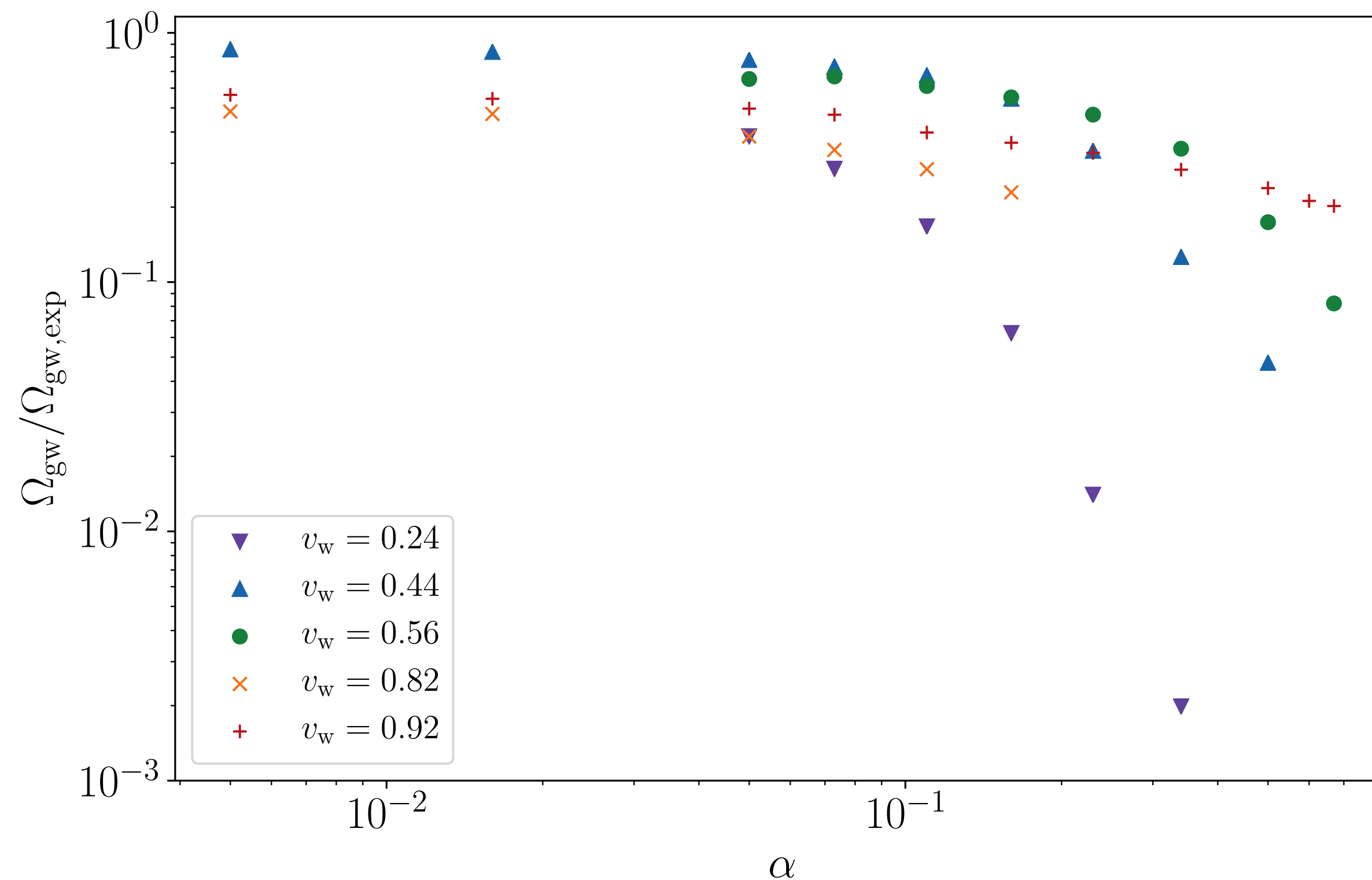


II. Detonation



Heating effects

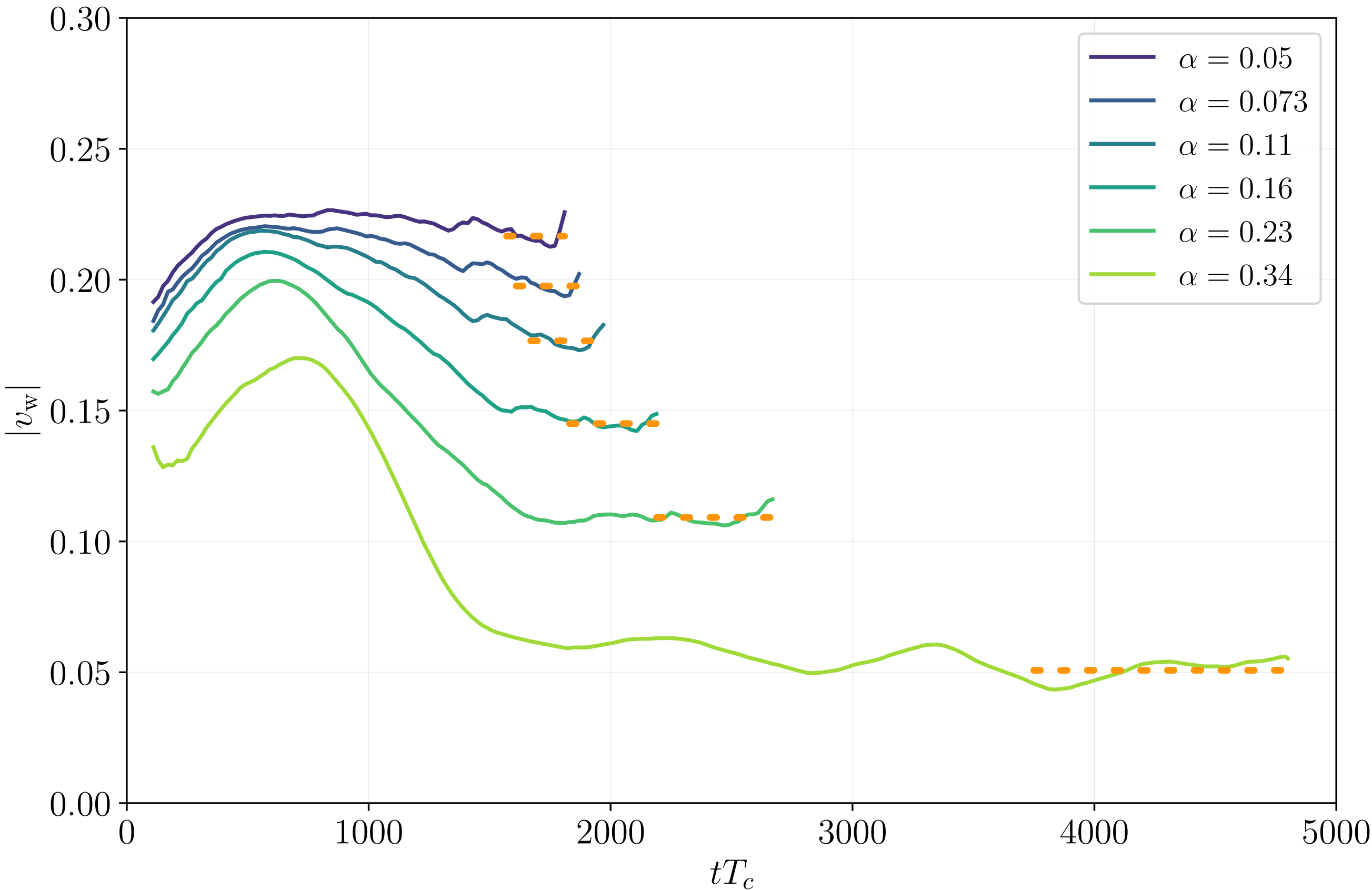
- Deflagrations/hybrids were shown to have a large suppression of the GW emission compared to single-bubble predictions



v_w	α	$\left(\frac{\Omega_{\text{gw}}}{H_n t}\right) \frac{1}{H_n R_*}$	$\frac{\Omega_{\text{gw,exp}}}{H_n t} \frac{1}{H_n R_*}$
0.24	0.050	4.6×10^{-8}	1.2×10^{-7}
0.24	0.073	1.4×10^{-7}	5.0×10^{-7}
0.24	0.11	4.1×10^{-7}	2.4×10^{-6}
0.24	0.16	6.0×10^{-7}	9.5×10^{-6}
0.24	0.23	4.6×10^{-7}	3.3×10^{-5}
0.24	0.34	2.3×10^{-7}	1.2×10^{-4}

Heating effects

- Suppression in the GW emission comes with a significant slow-down of the bubble walls



 v_w	α	$\left(\frac{\Omega_{\text{gw}}}{H_n t}\right) \frac{1}{H_n R_*}$	$\frac{\Omega_{\text{gw,exp}}}{H_n t} \frac{1}{H_n R_*}$
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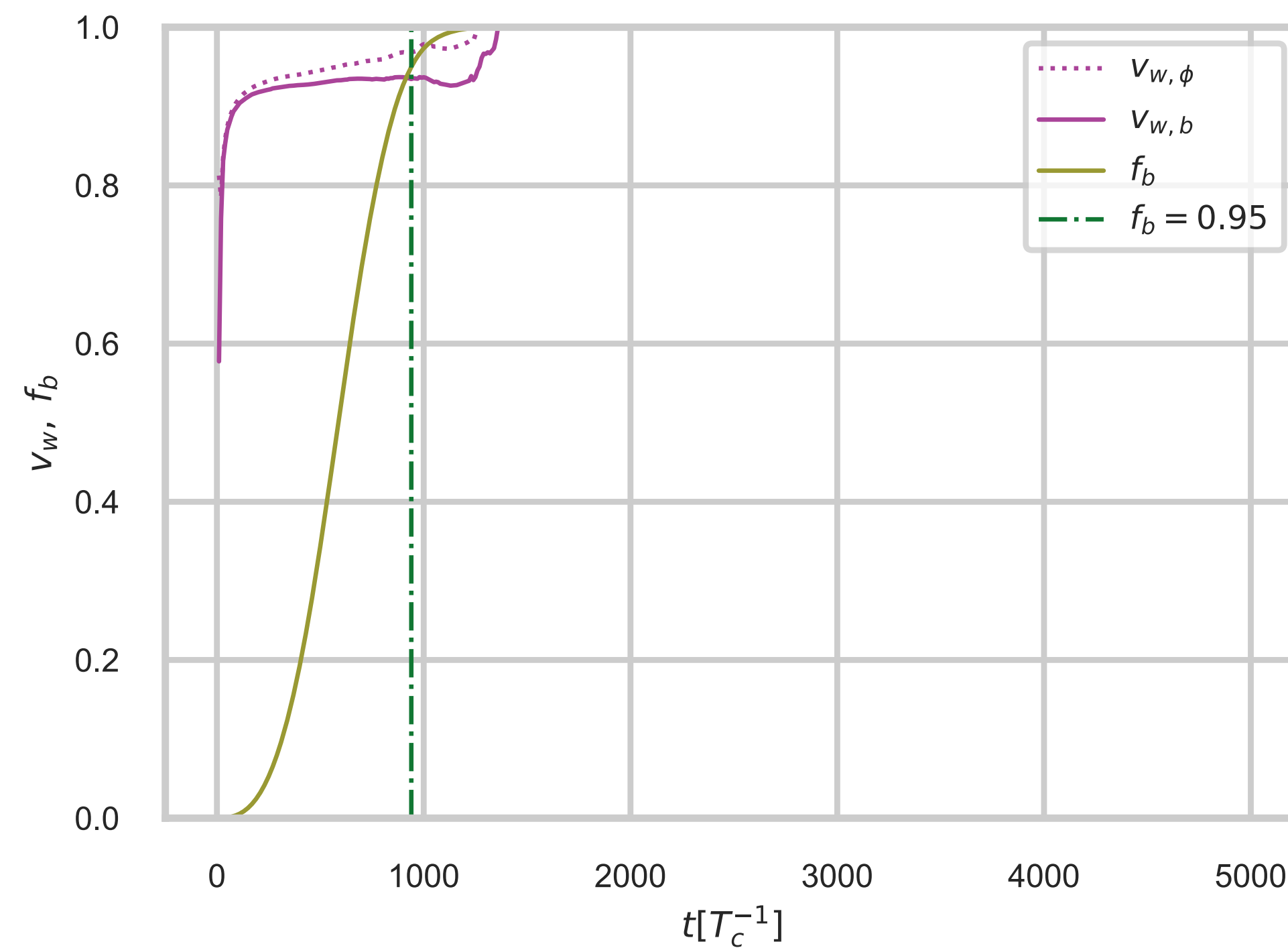
Cutting, Hindmarsh, Weir
[1906.00480] PRL (2020)

Cutting, Vilhonen, Weir [2204.03396]
PRD (2022)

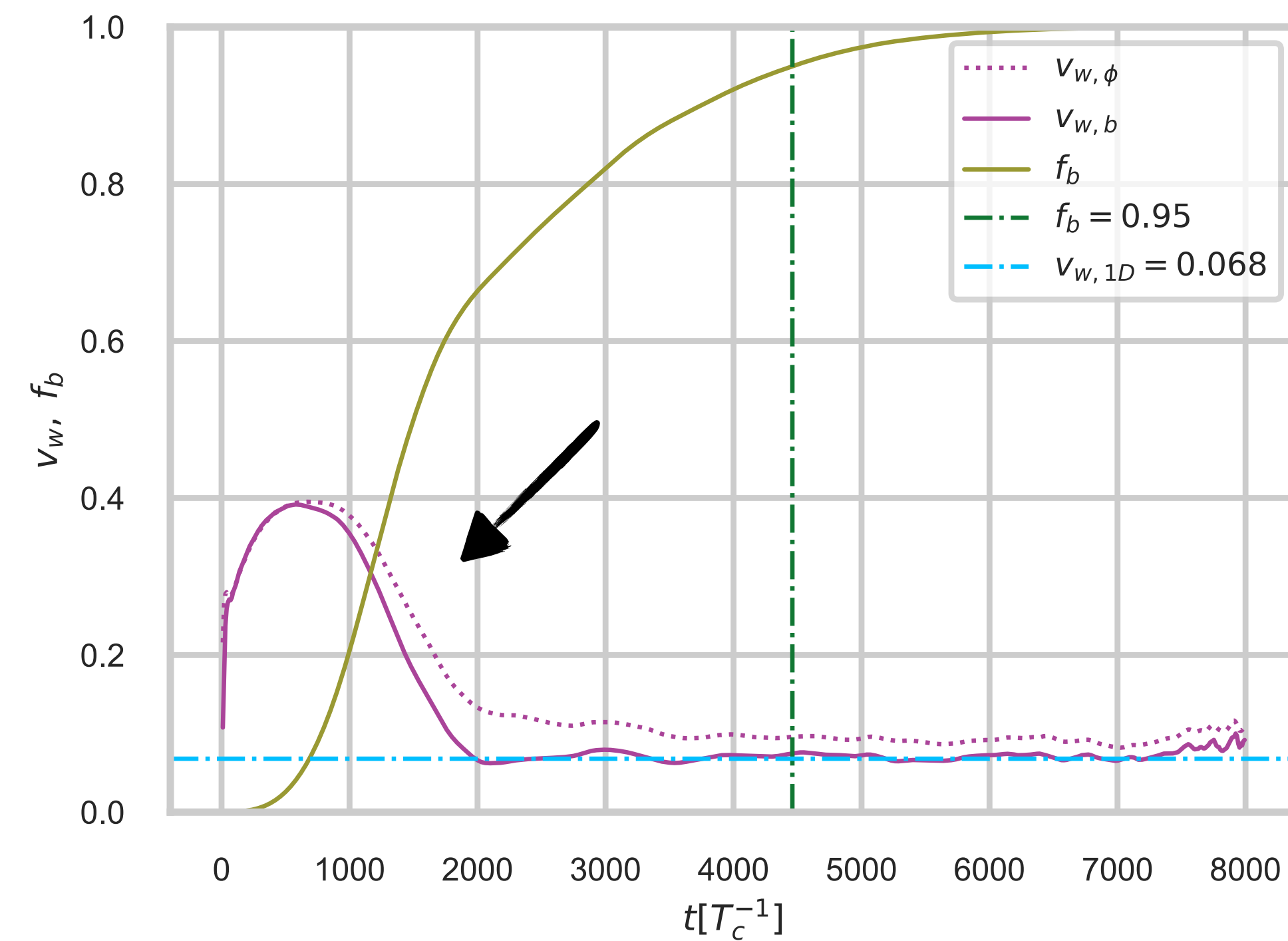
Heating effects

- Same slow-down observed in later studies of strong phase transitions:

Detonation



Deflagration

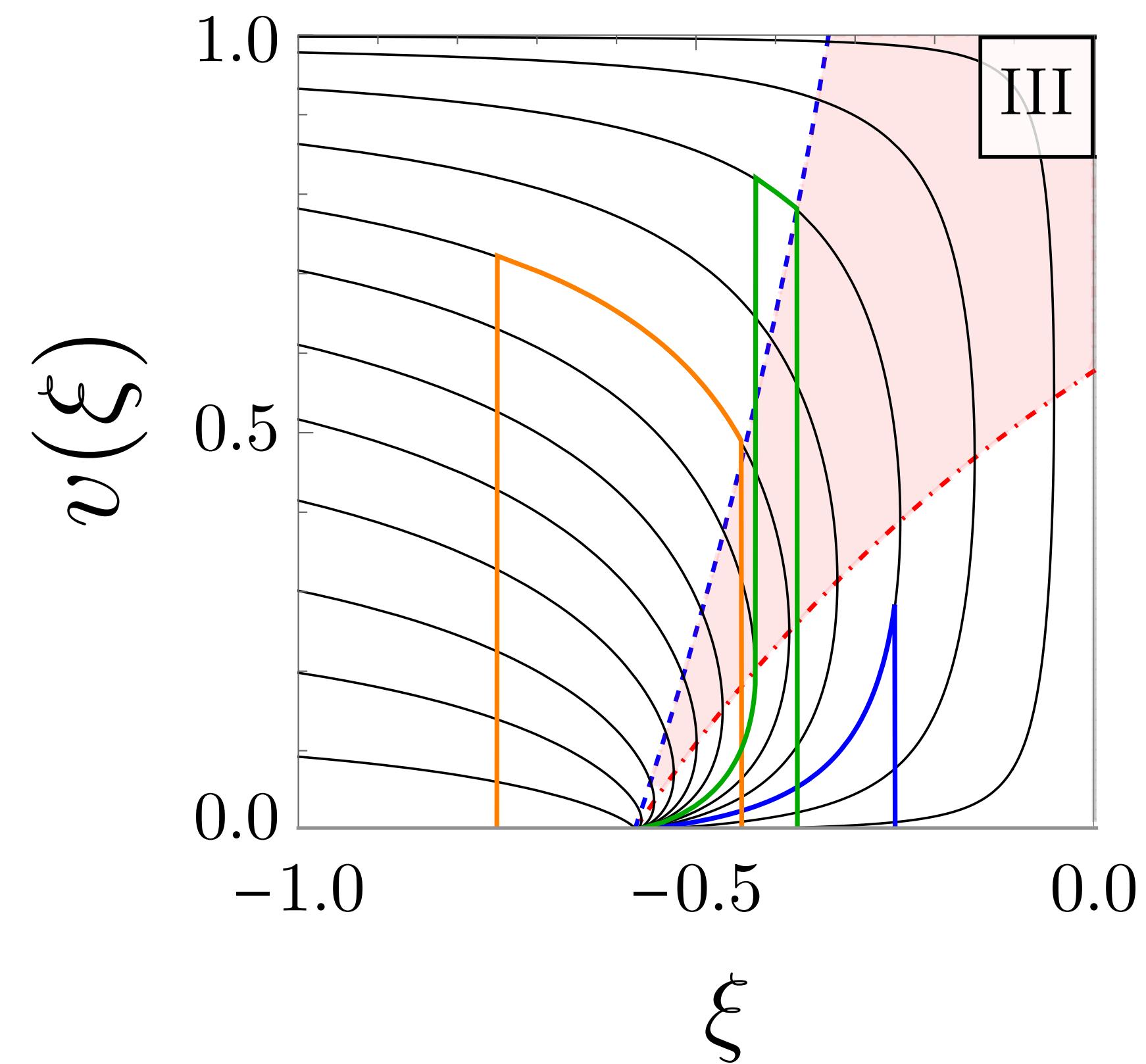
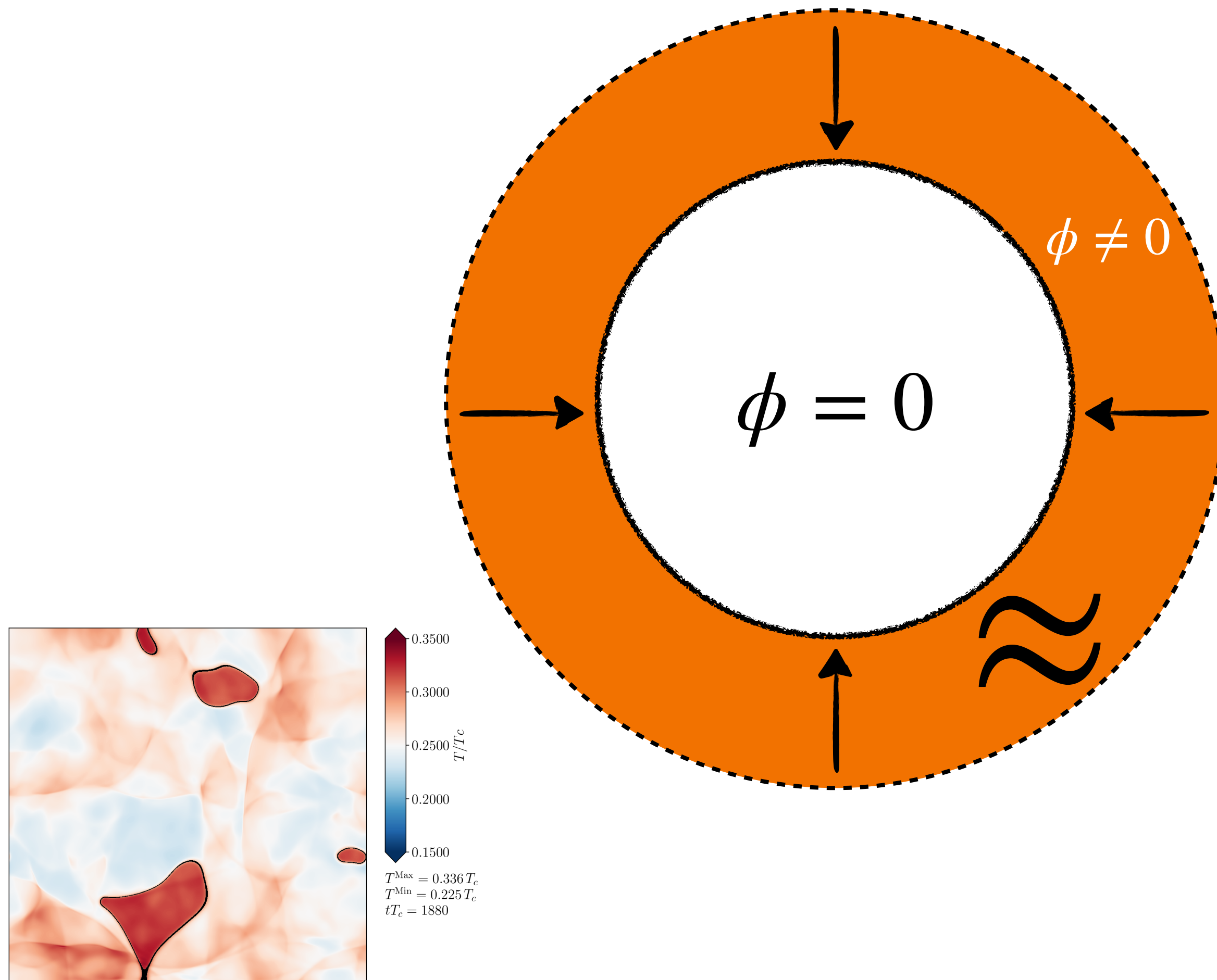


Correia, Hindmarsh, Rummukainen,
Weir [2505.17824] PRD (2025)

Phase transition	T_n/T_c	η/T_c
$\alpha_n = 0.67, v_w = 0.92$	0.23	0.15
$\alpha_n = 0.50, v_w = 0.44$	0.25	3.5

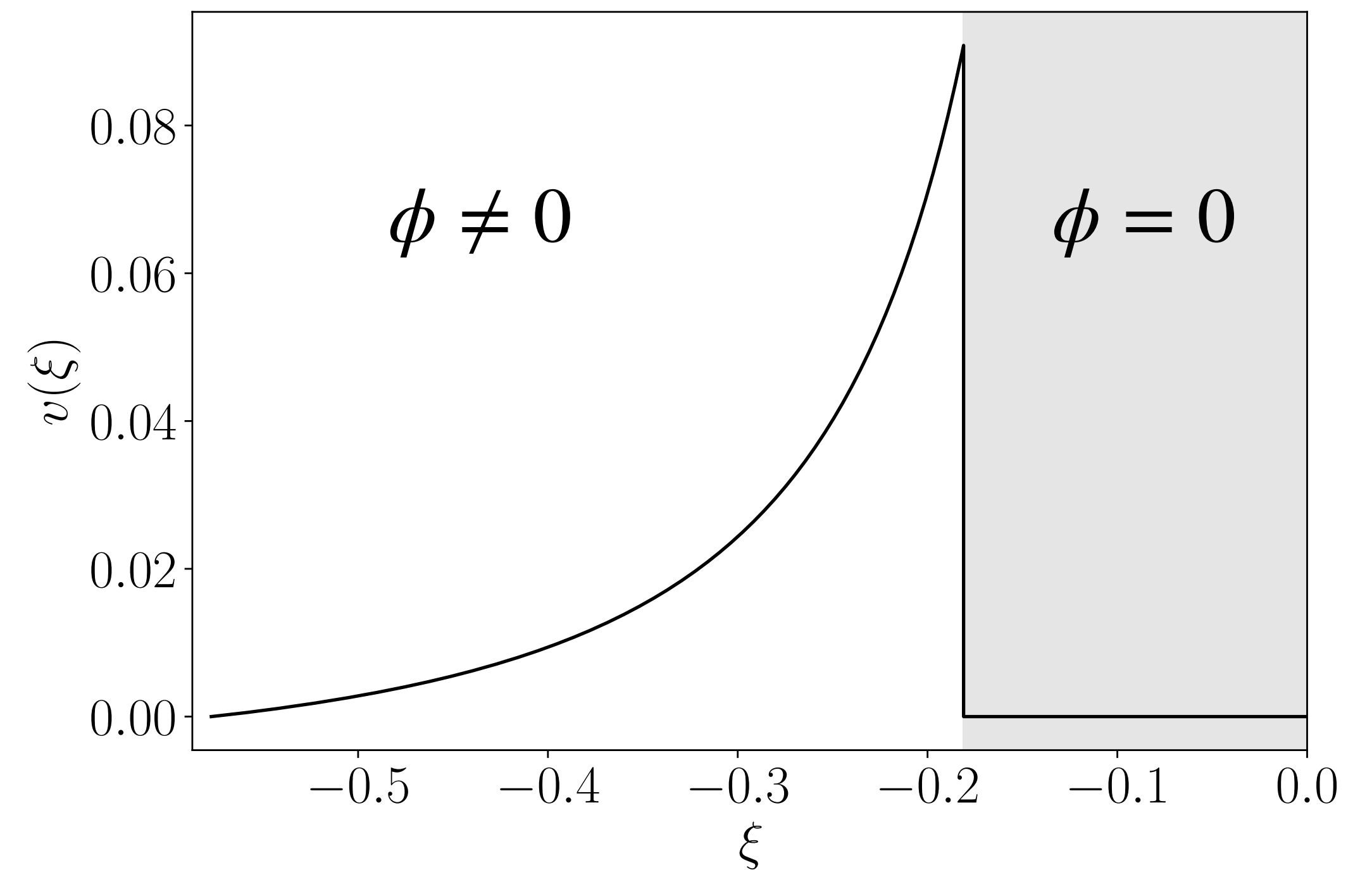
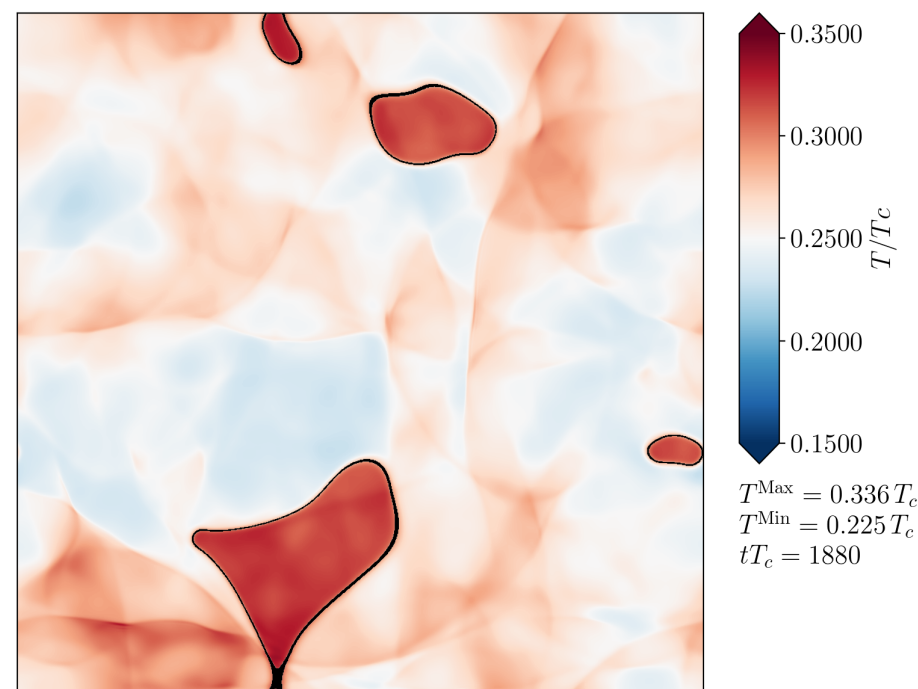
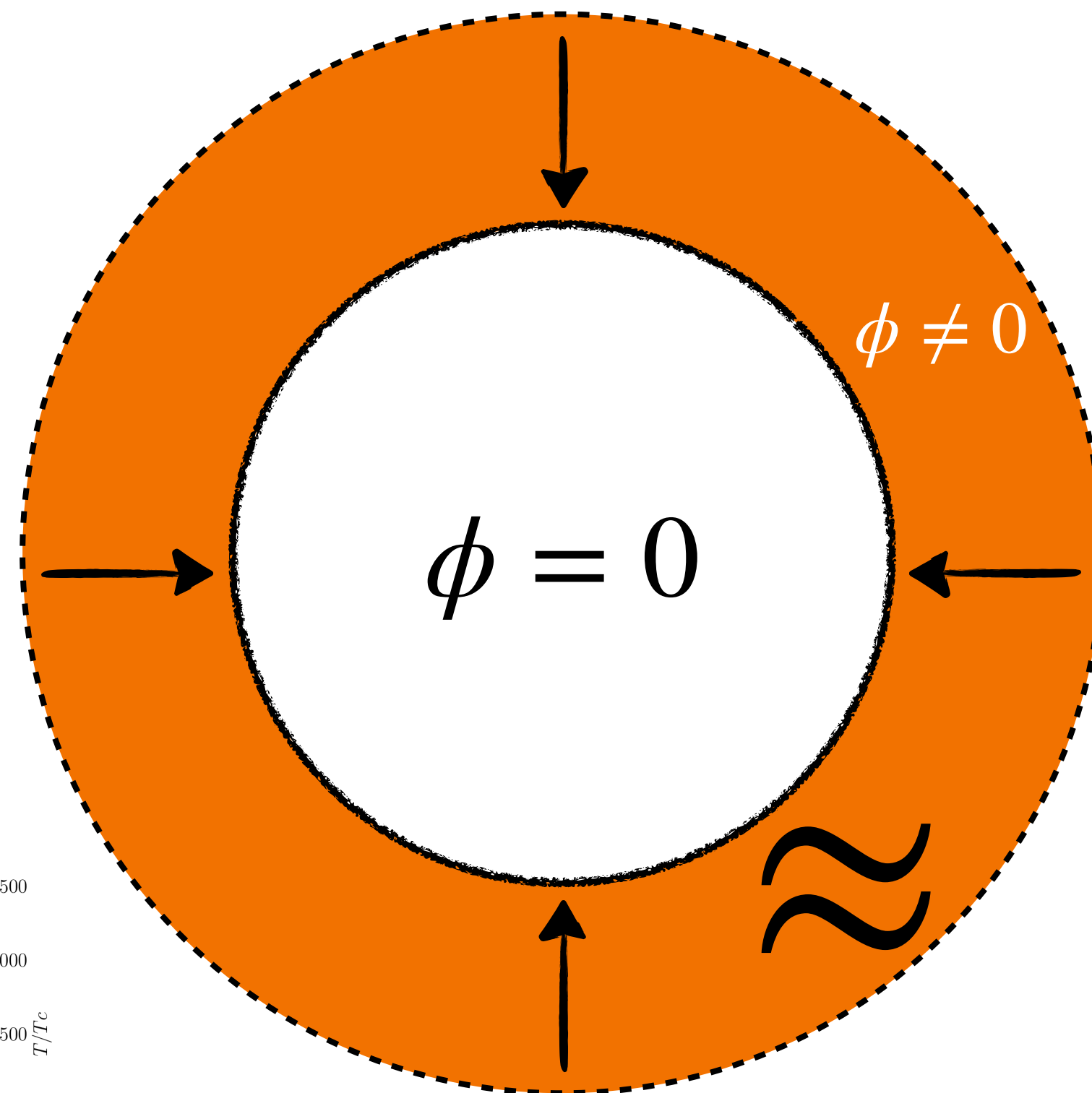
Droplets from heating

- Slow-down of the bubble walls in relation to the formation of droplets, shrinking regions of false vacuum



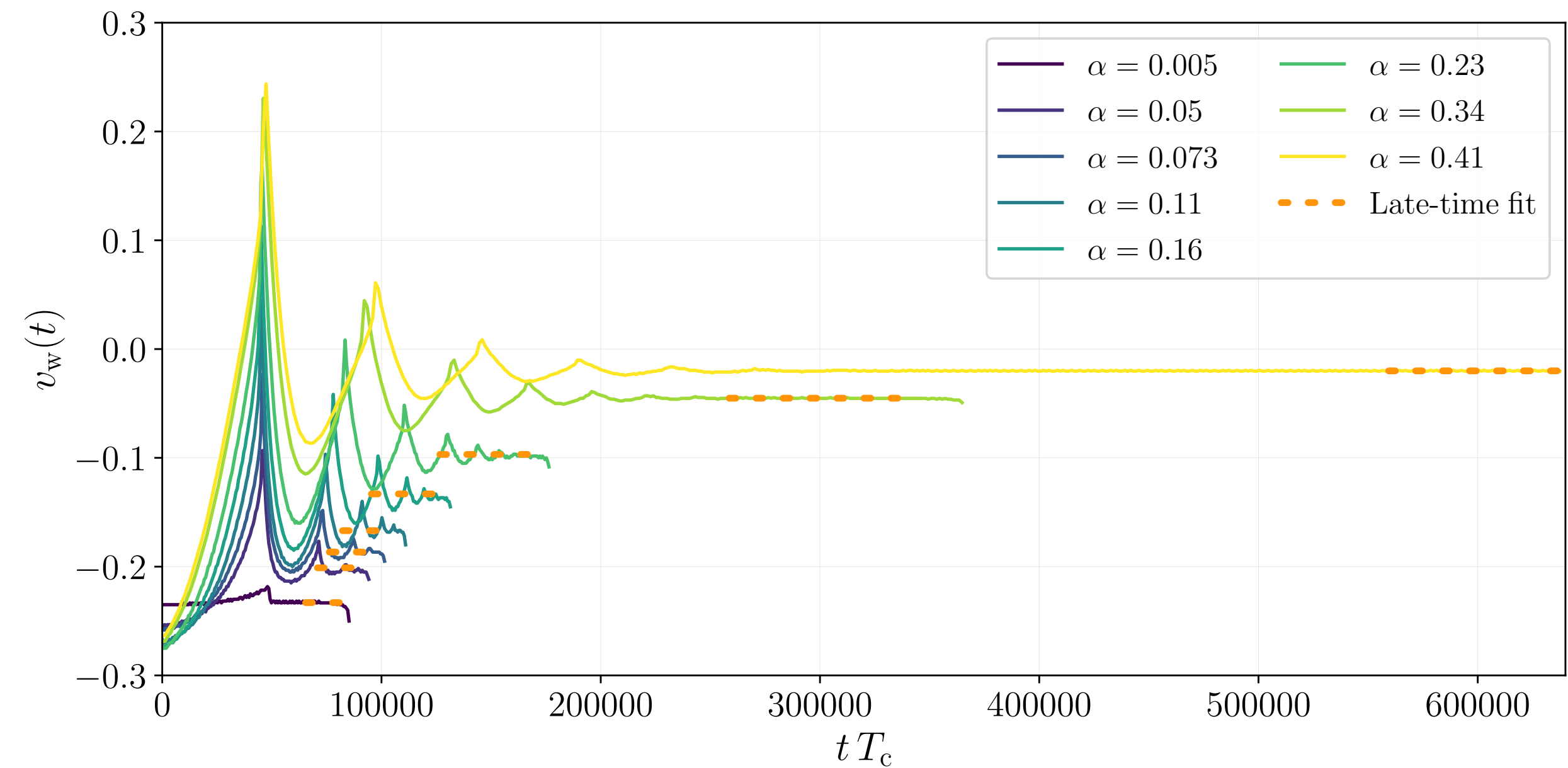
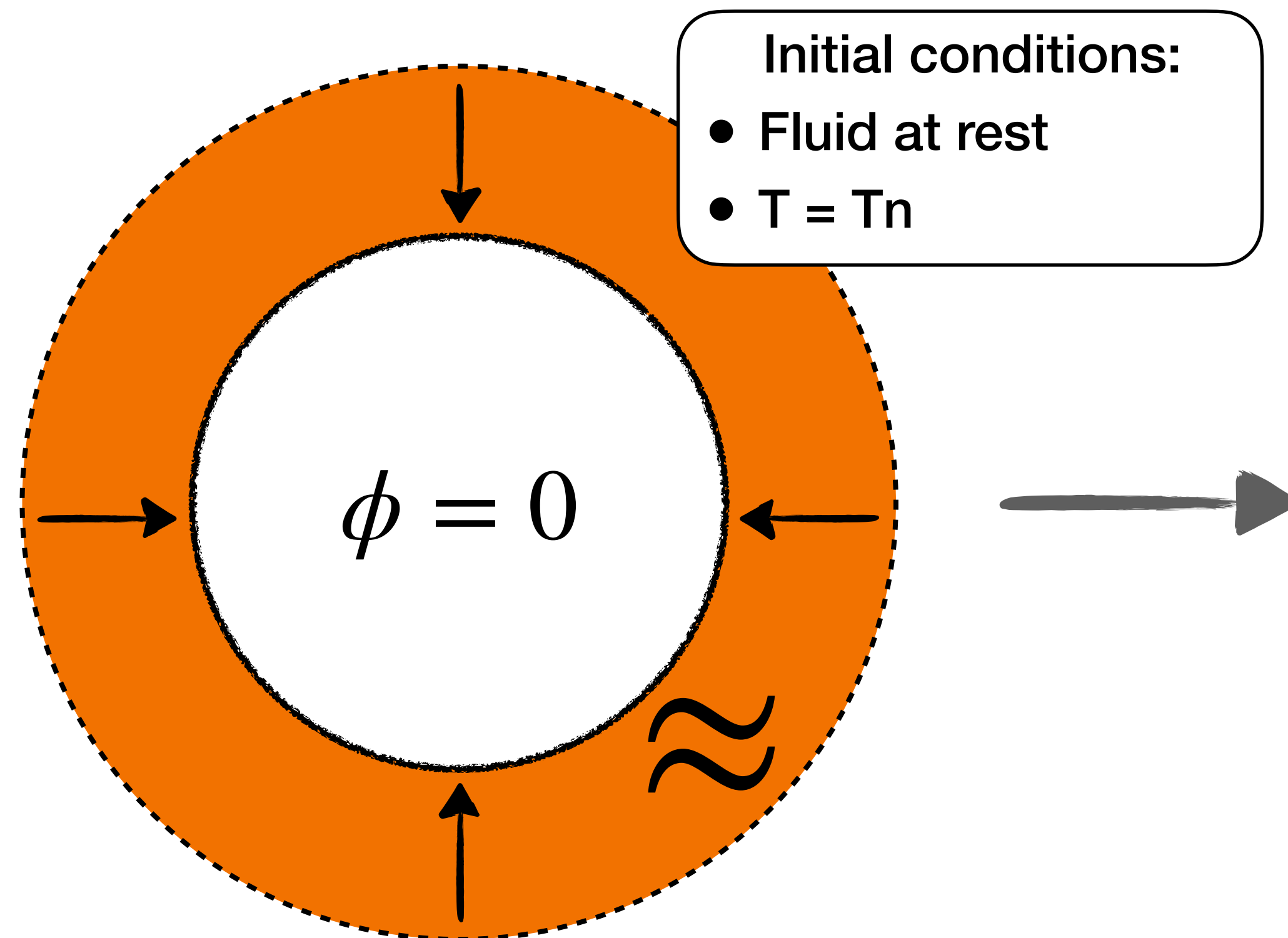
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Droplets from heating

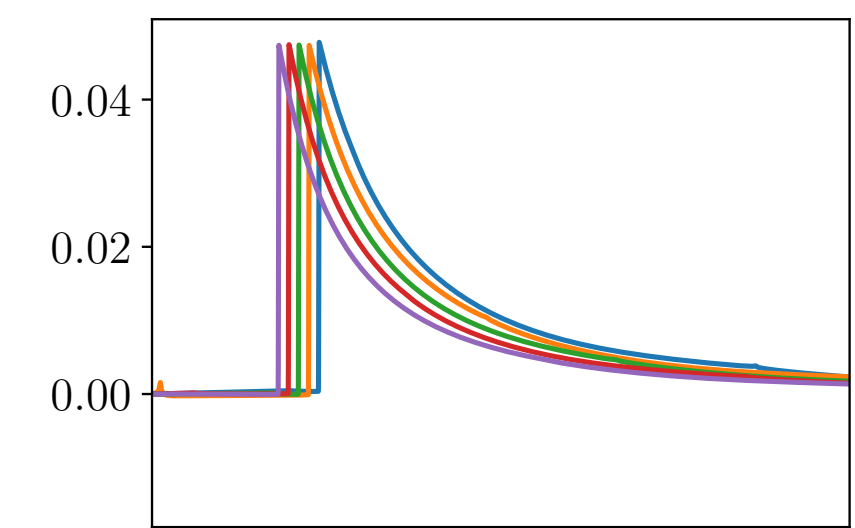
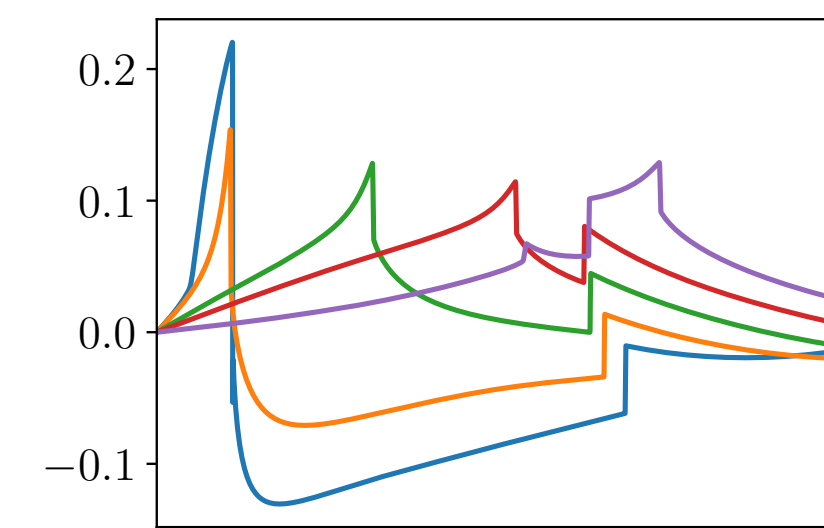
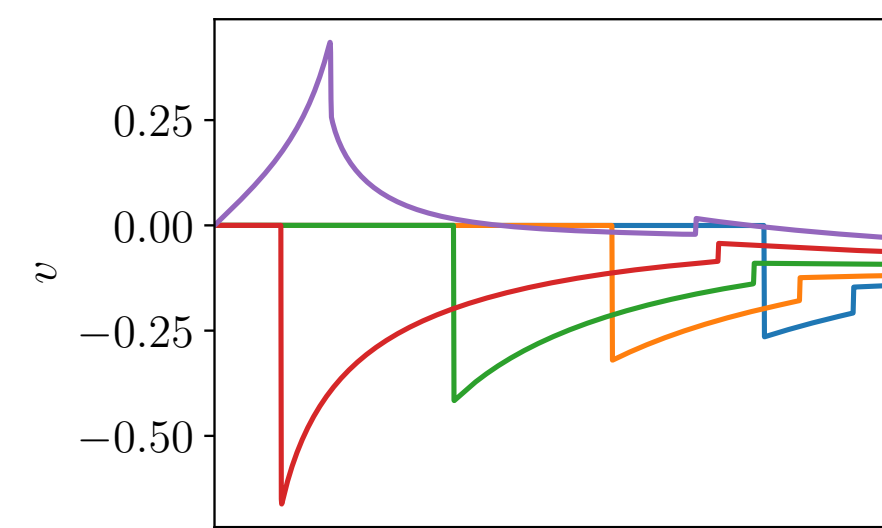
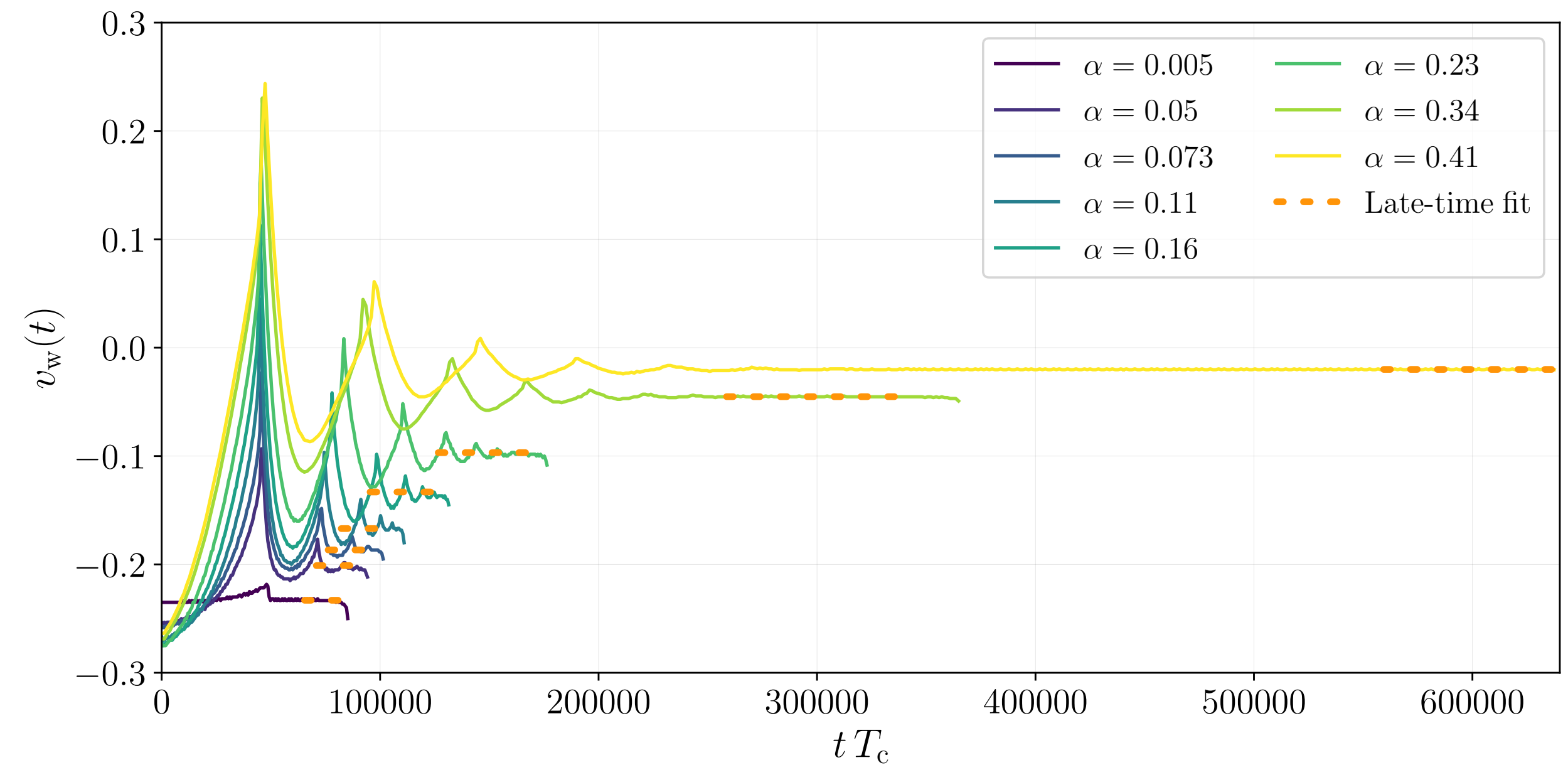
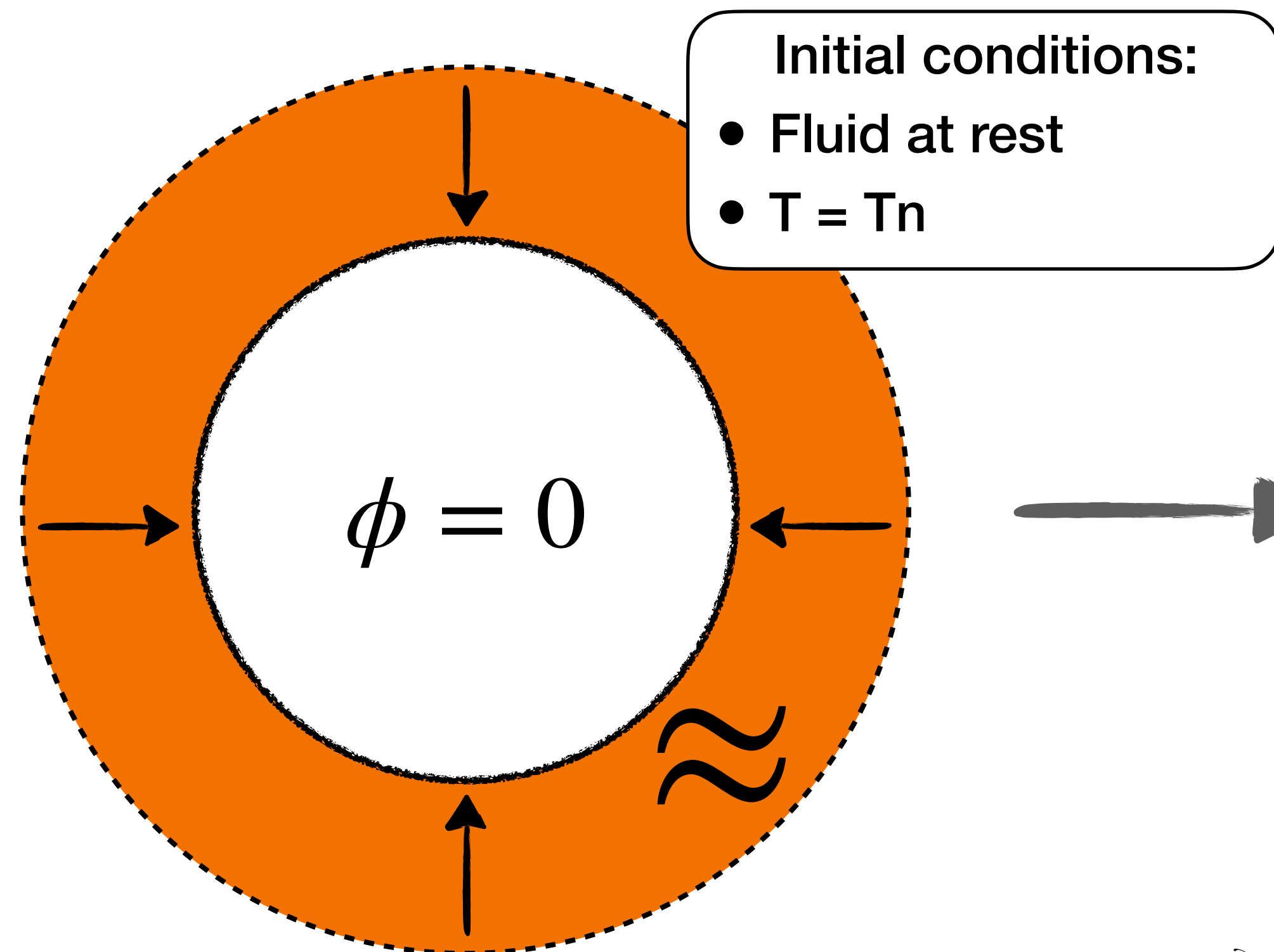
- Spherical simulations of droplet collapse:



Cutting, Vilhonen, Weir [2204.03396]
PRD (2022)

Droplets from heating

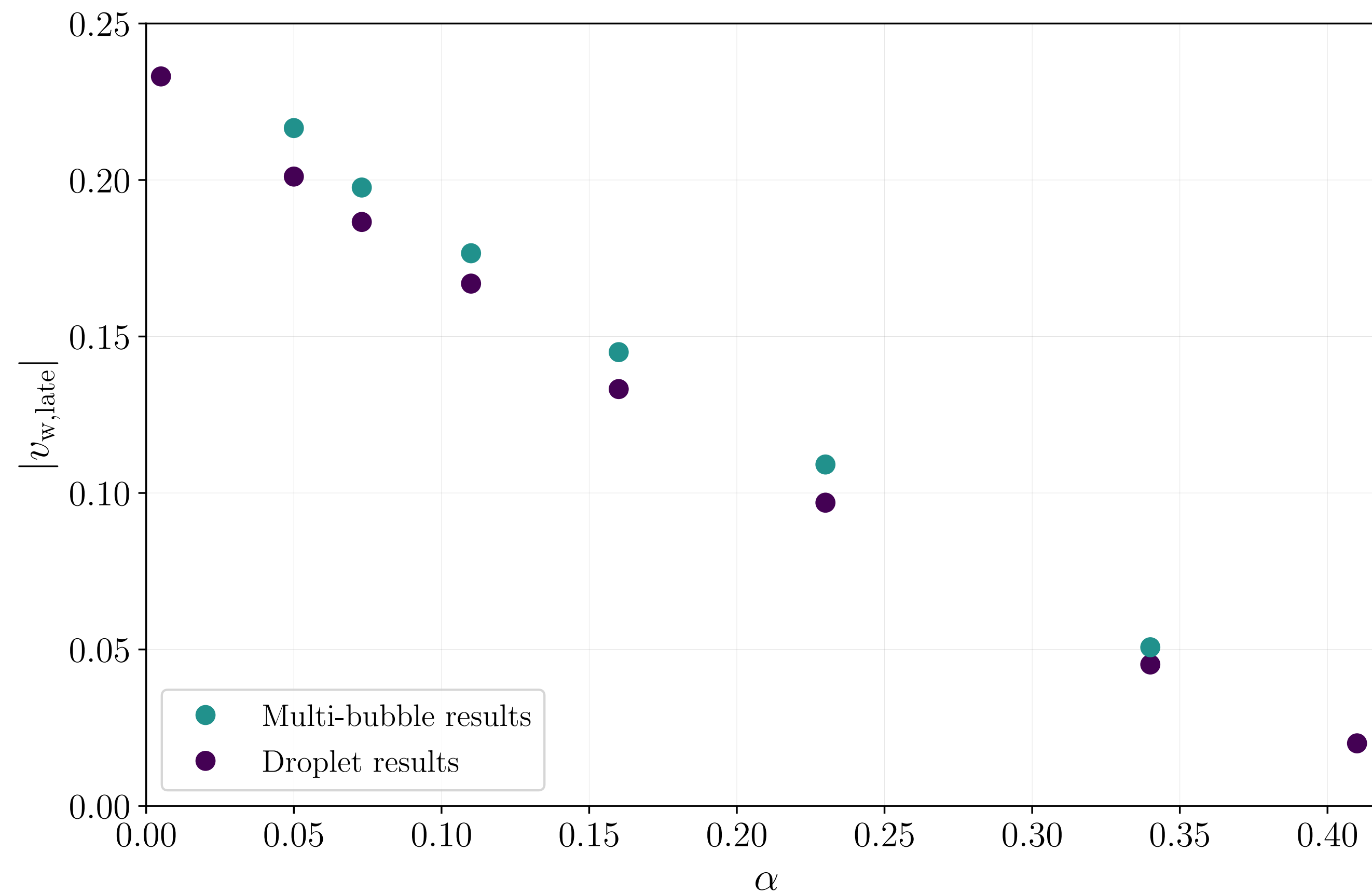
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Droplets from heating

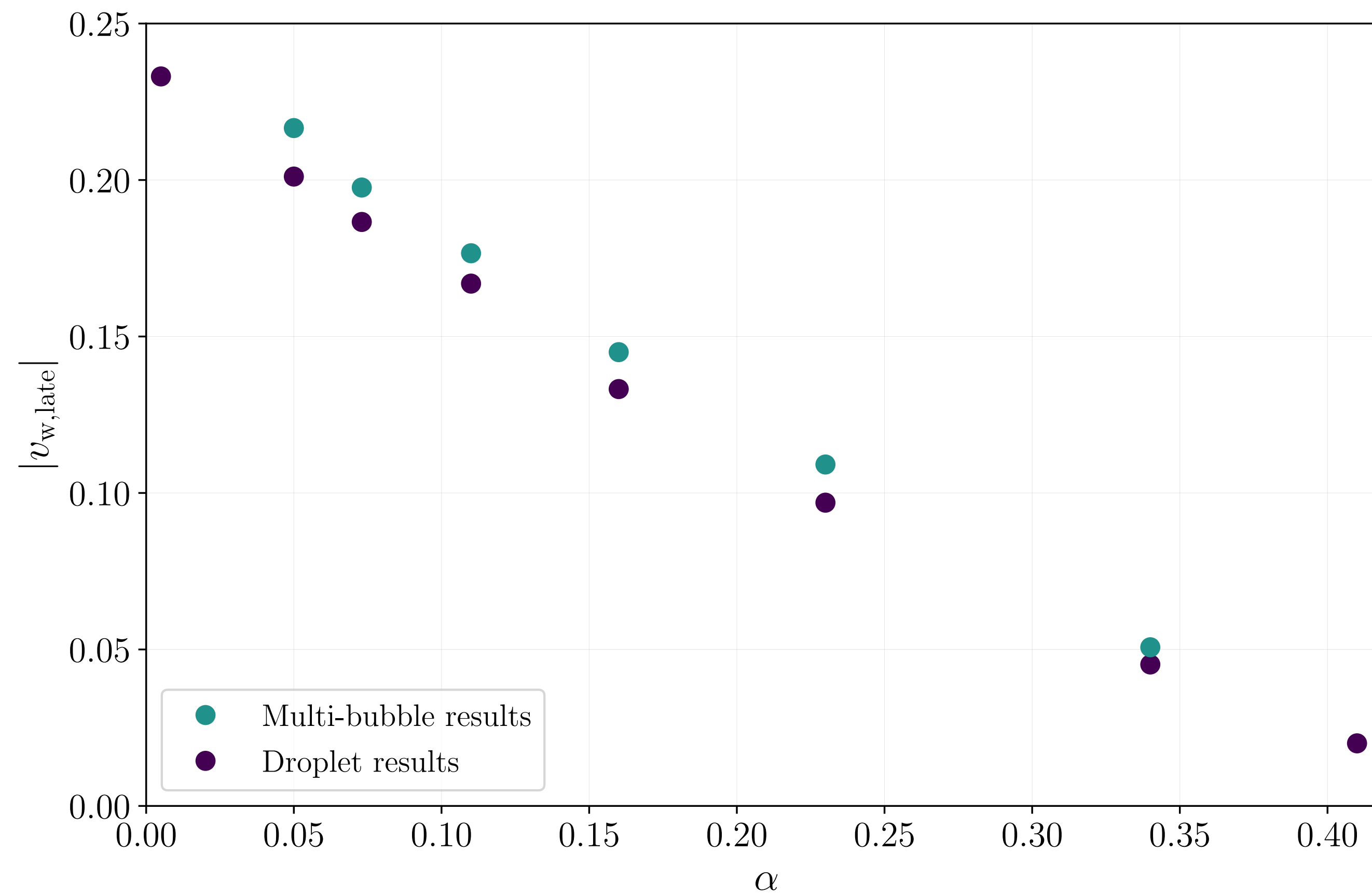
- Comparison between spherical simulations of droplet collapse and 3D bubble simulations:



α	$ v_{w,late} $	
	Droplet	Multi-bubble
0.0050	0.23	—
0.050	0.20	0.22
0.073	0.19	0.20
0.11	0.16	0.18
0.16	0.14	0.15
0.23	0.099	0.11
0.34	0.045	0.051
0.41	0.020	—

Droplets from heating

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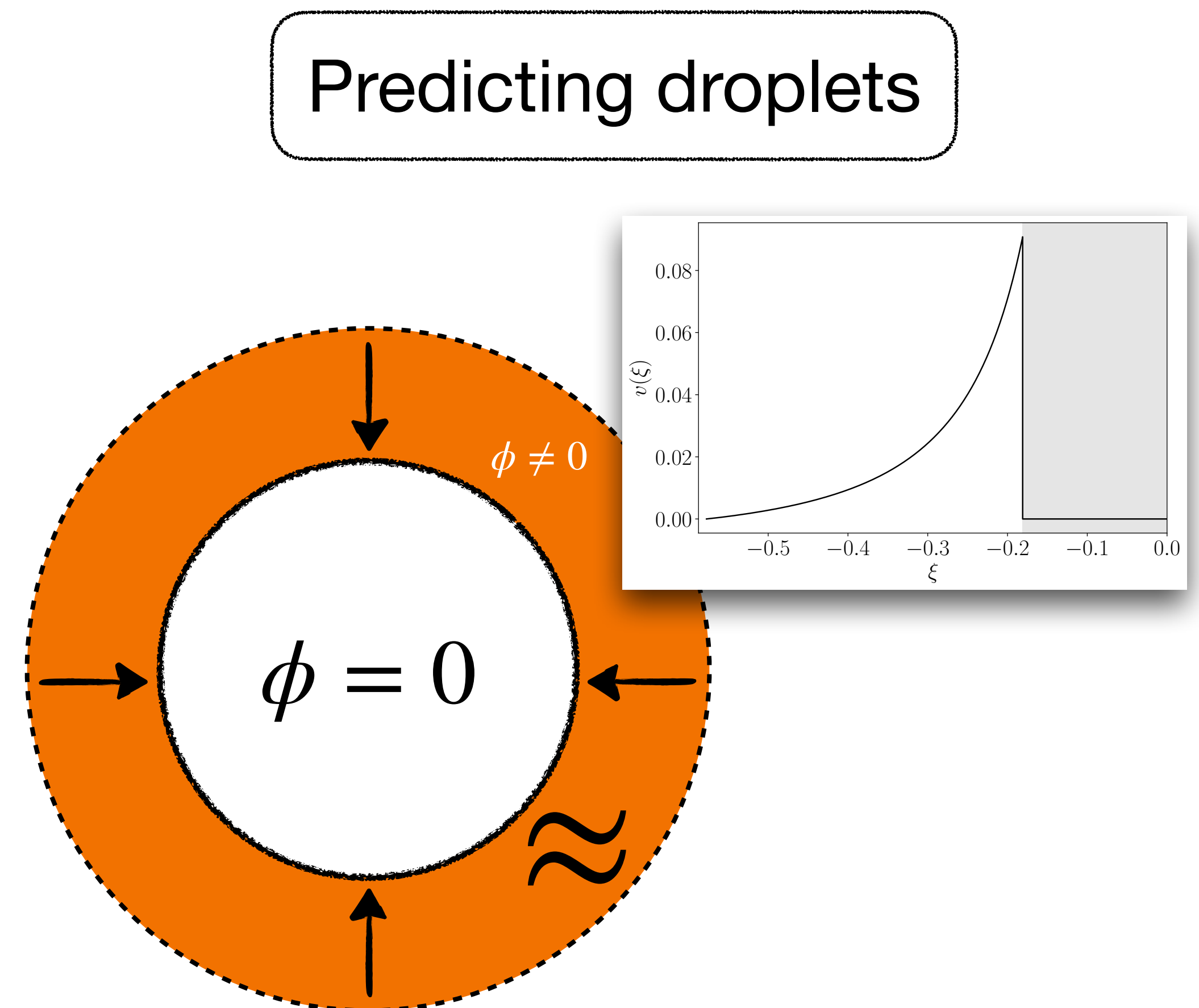
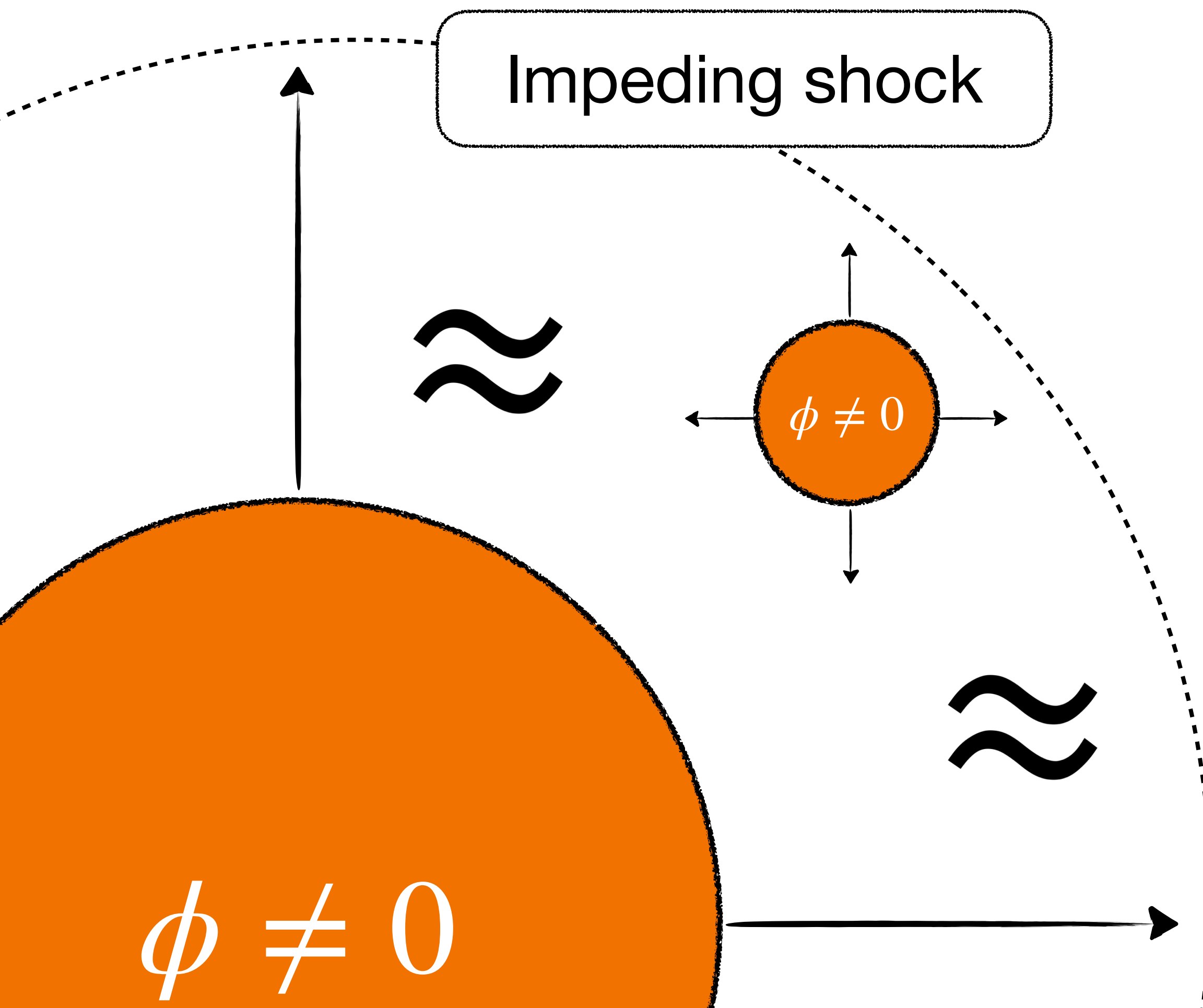


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0.41	0.020	—

**Can we predict this
from first principles?**

Modeling heating effects

- Build some understanding of heating effects knowing only the basics of the phase transition, e.g. nucleation temperature and friction between bubble and plasma



Impeding shock

- Fixing α_N (or the nucleation temperature) and friction determines the wall velocity of the bubble right at the beginning of the phase transition

$$\square\phi + \frac{\partial\mathcal{F}}{\partial\phi} + \mathcal{K}(\phi) = 0 \quad (\text{Higgs eom})$$

$$v^2 \gamma^2 \omega - \mathcal{F} + \frac{1}{2} (\partial_z \phi)^2 = k_1$$

(cons. laws)

$$v^2 \gamma^2 \omega = k_2$$

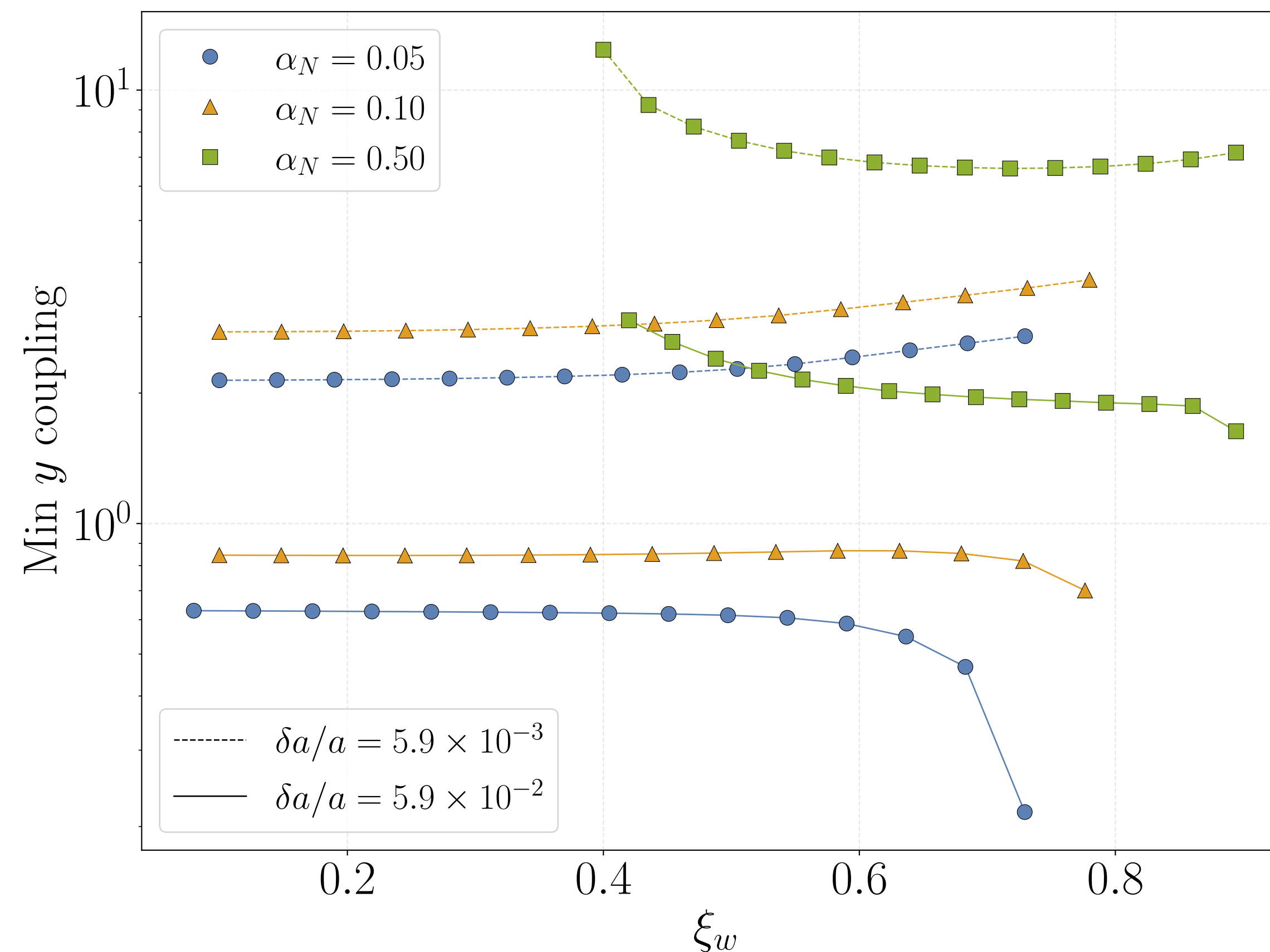
Choice for local friction:

$$\mathcal{K}(\phi) = T_c \eta u^\mu \partial_\mu \phi$$

$$\mathcal{K}(\phi) = \frac{\tilde{\eta} \phi^2}{T} u^\mu \partial_\mu \phi$$

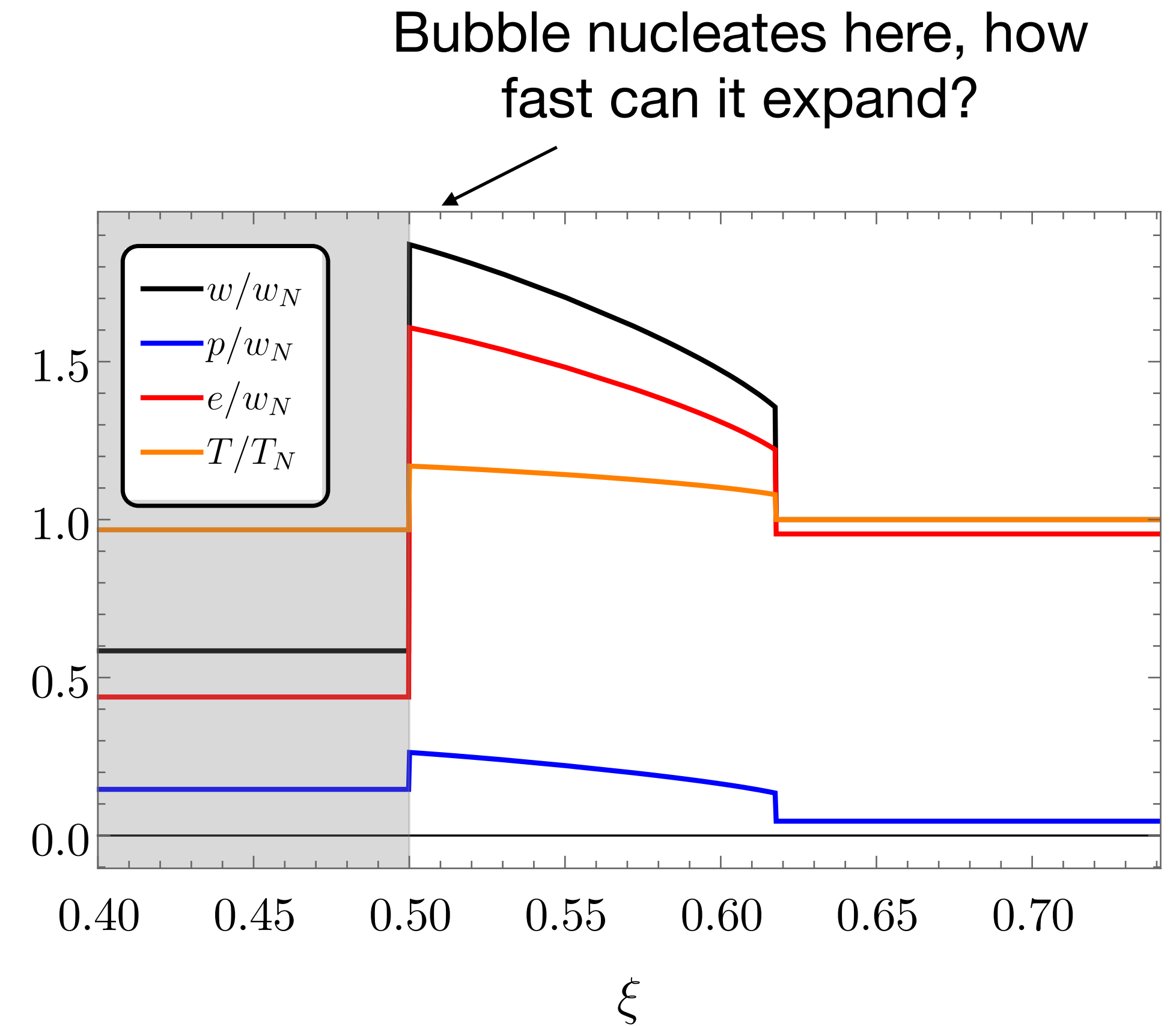
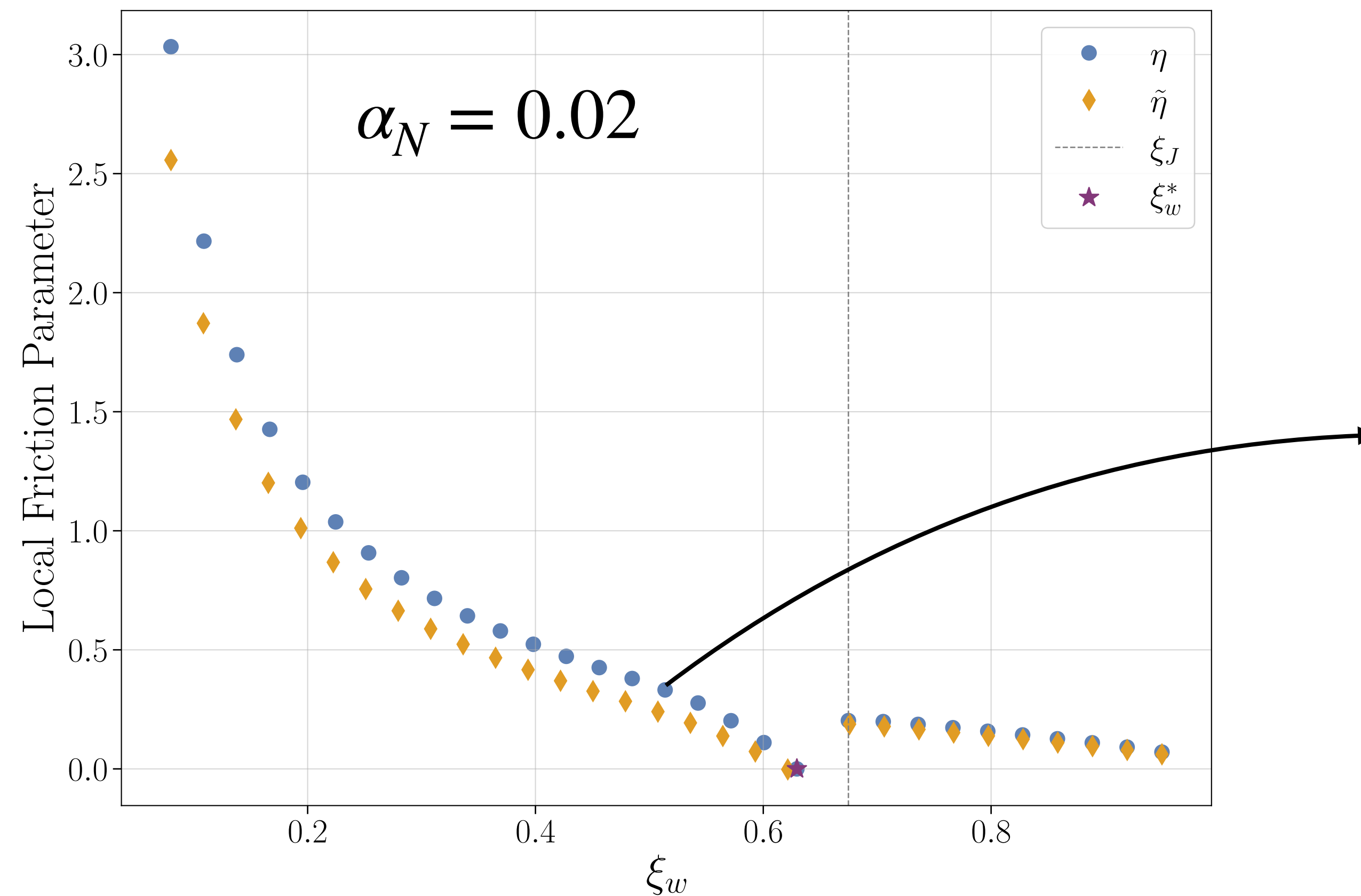
(Local friction and perturbation theory)

- For a given change in dofs, the local-friction coefficient η can be connected with the coupling constants of the microscopic theory, and therefore bounded by perturbativity



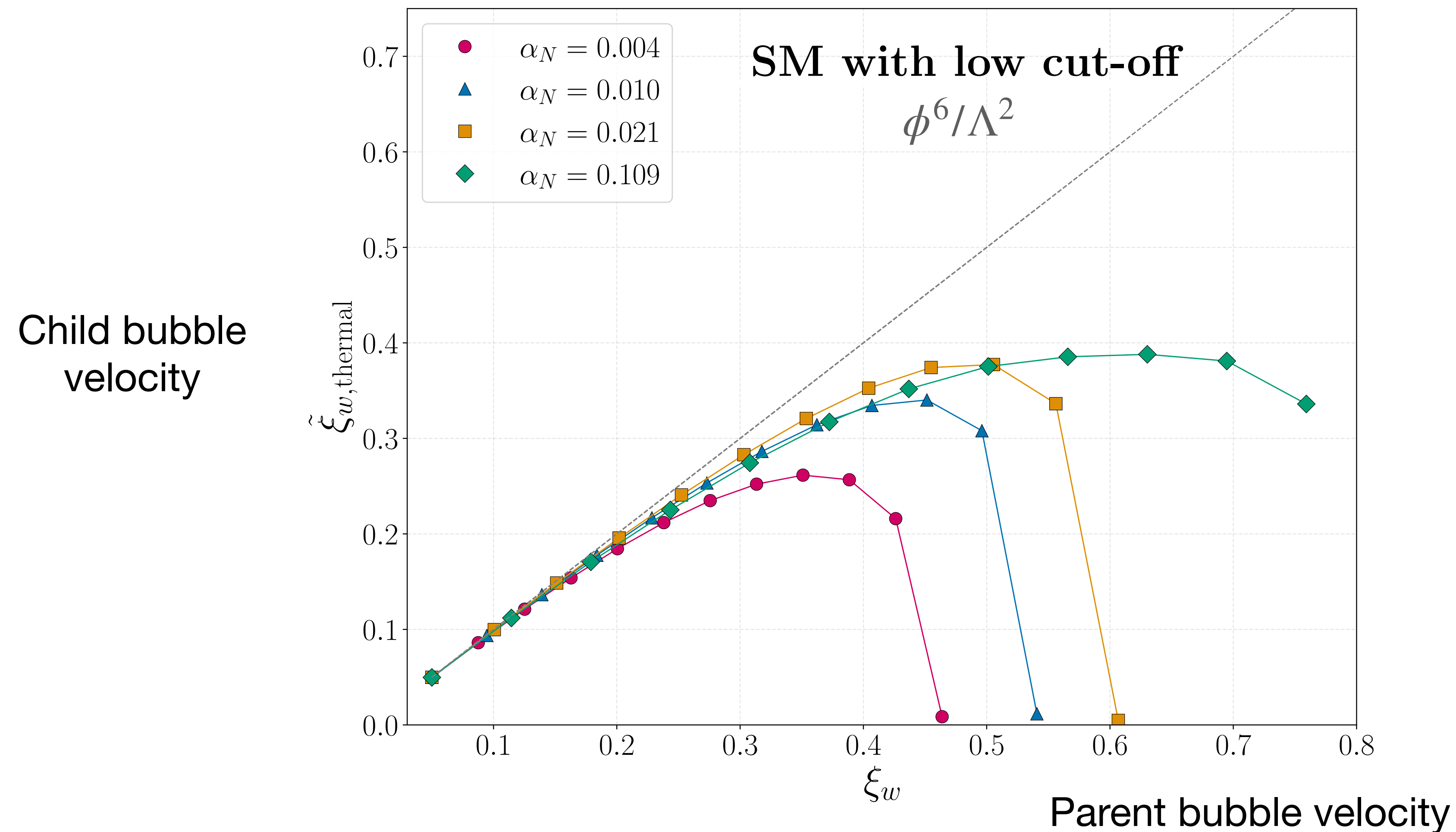
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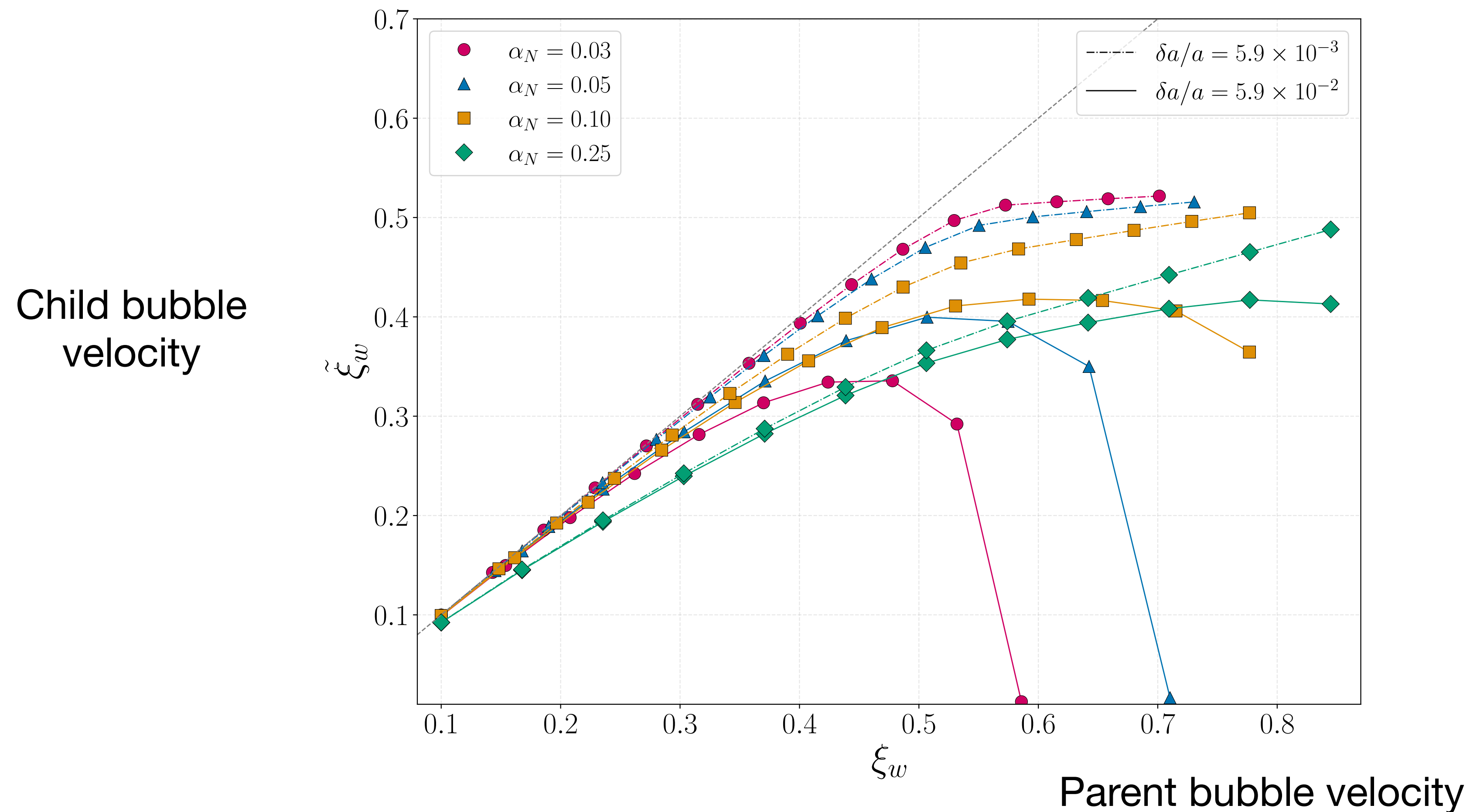
Impeding shock

- Effect due to a higher surrounding temperature:



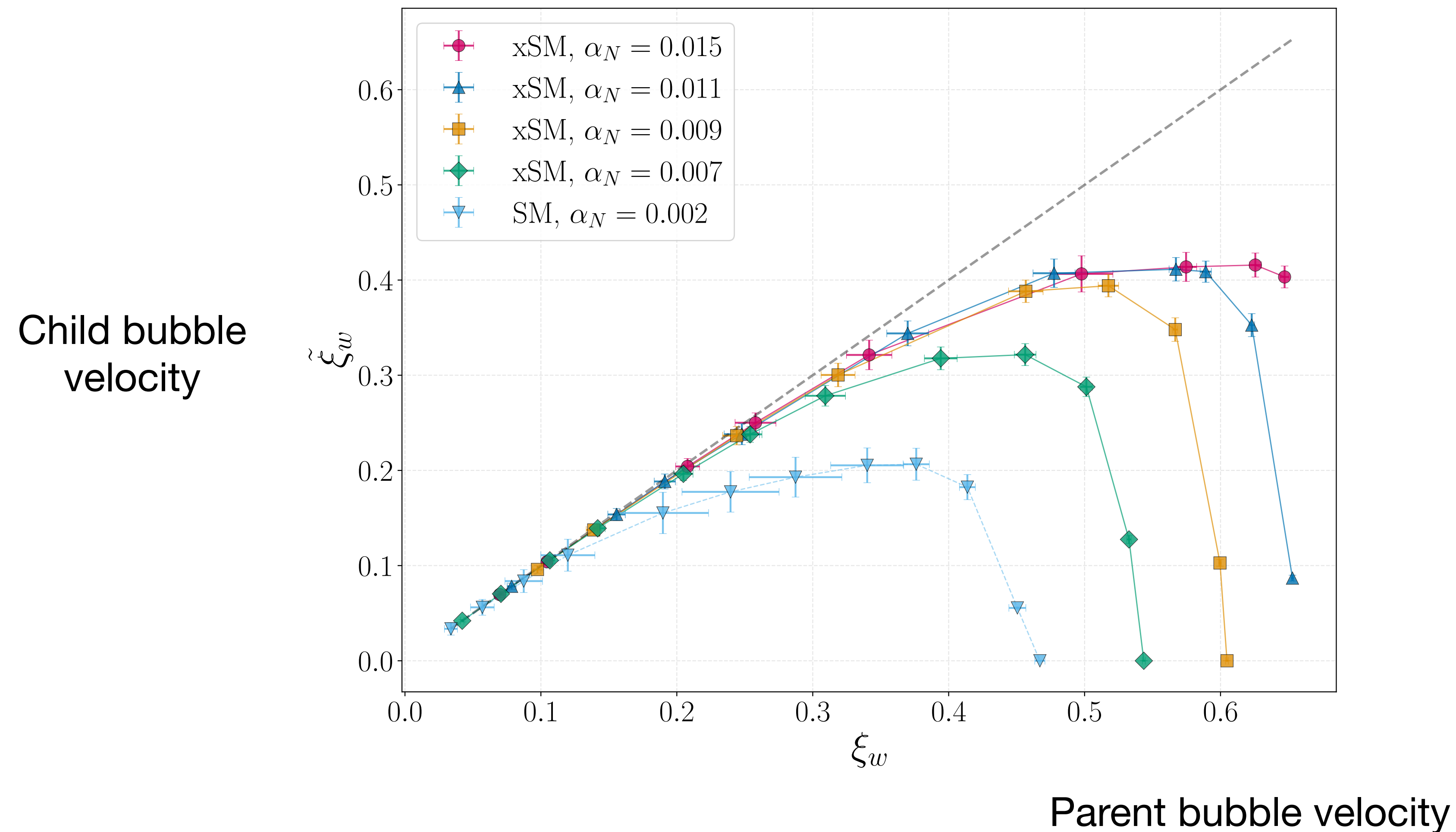
Impeding shock

- Effect due to a higher surrounding temperature: for the bag EoS, dependence on the change in relativistic dofs between the phases



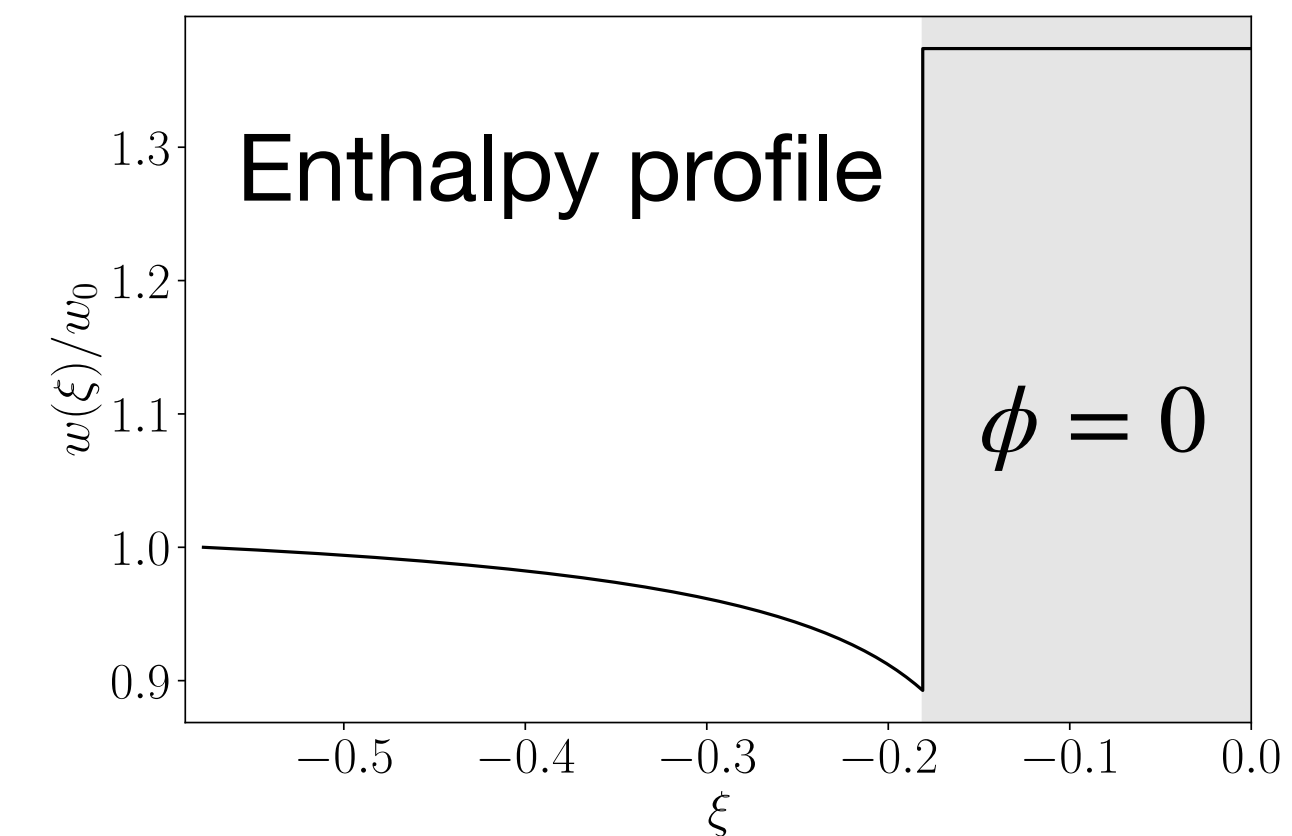
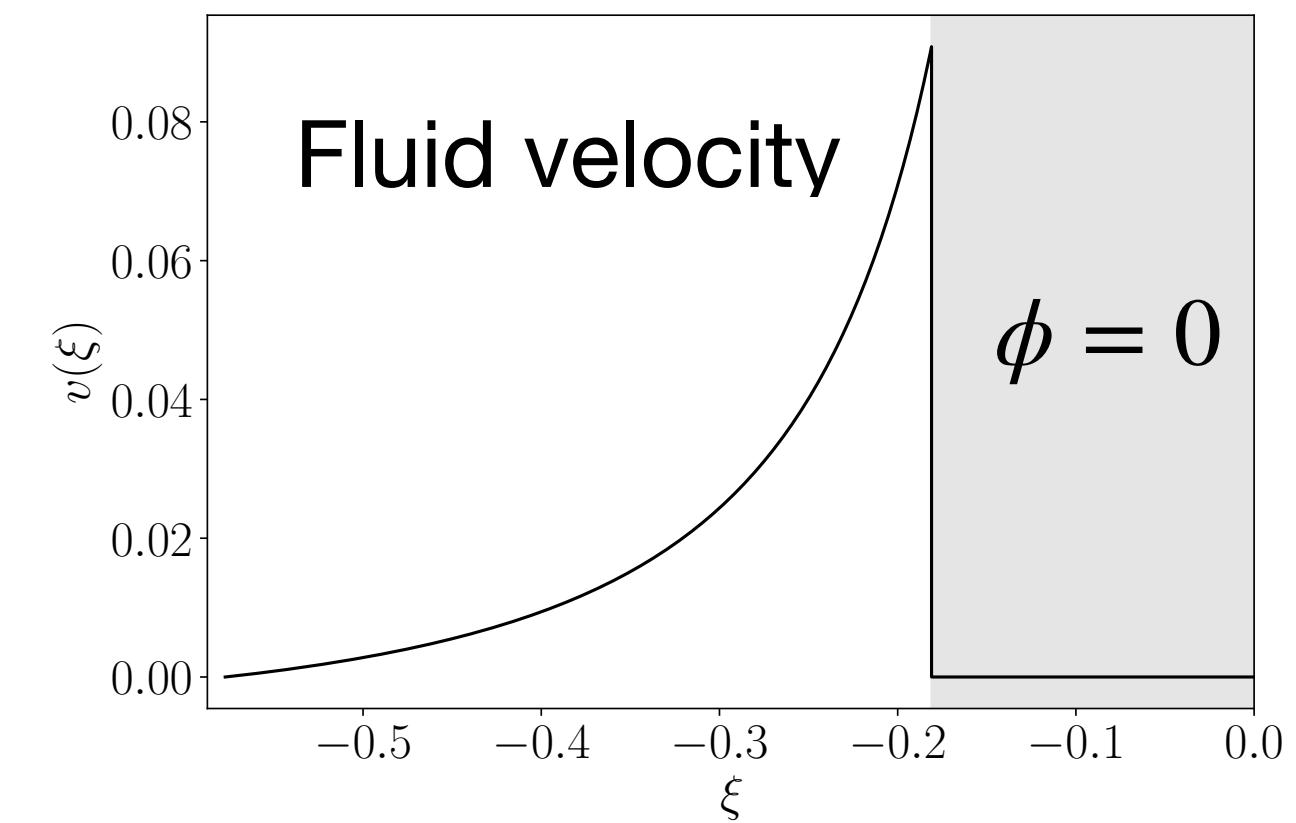
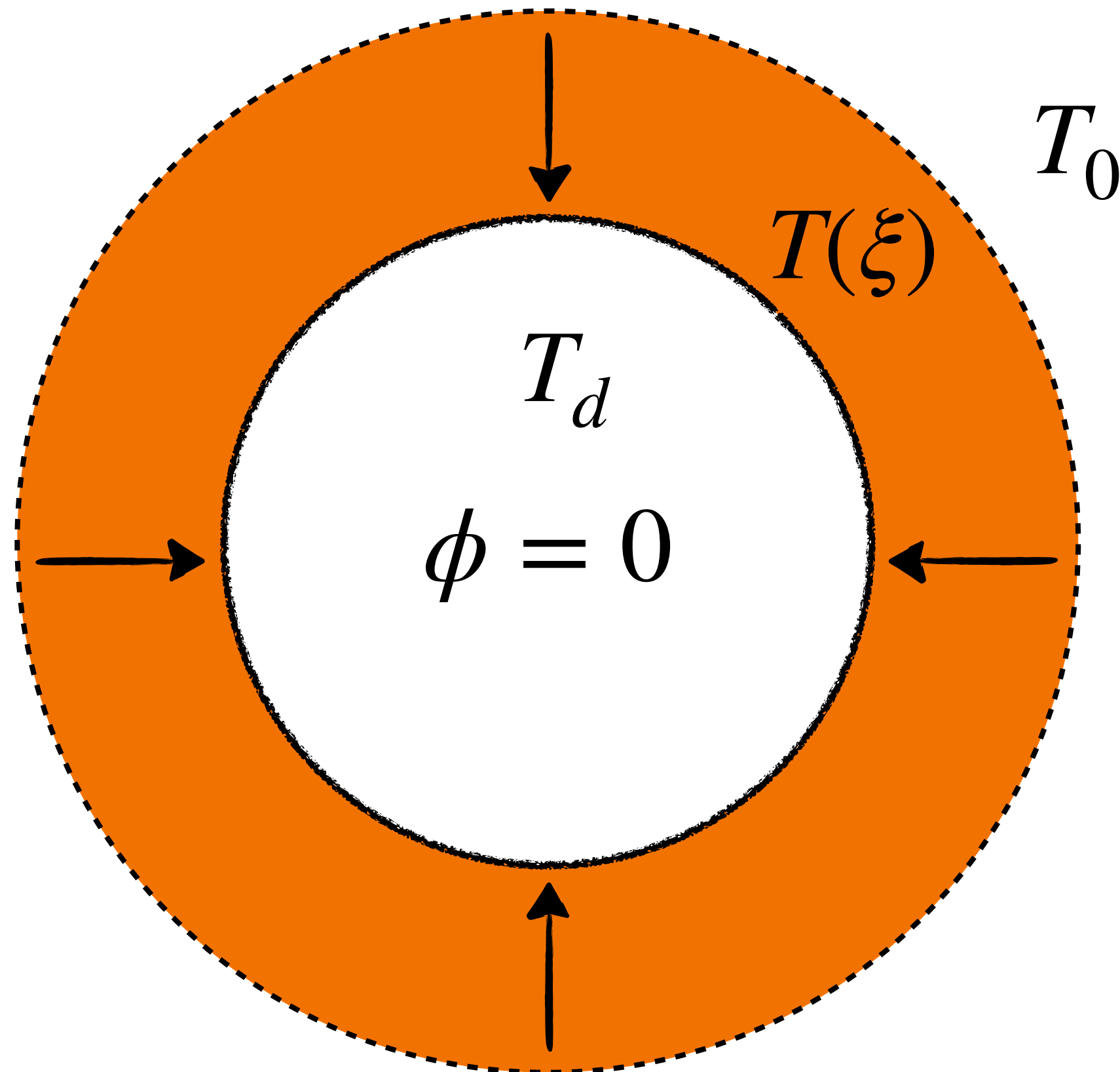
Impeding shock

- Effect due to a higher surrounding temperature: beyond local friction with WallGo



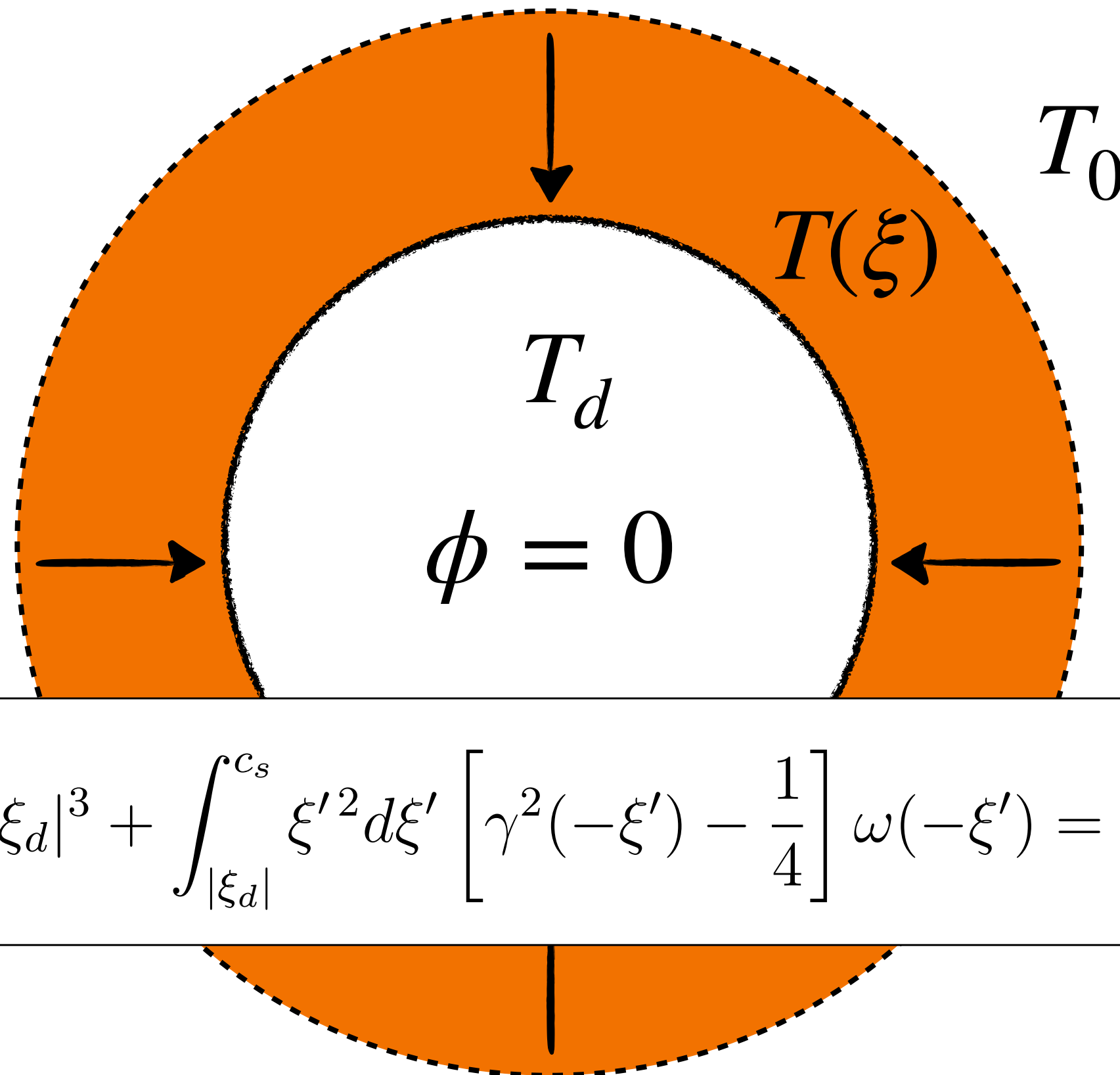
Droplet formation

- For predicting how slow droplets shrink, we only miss the boundary conditions for the temperature either far or inside the droplet

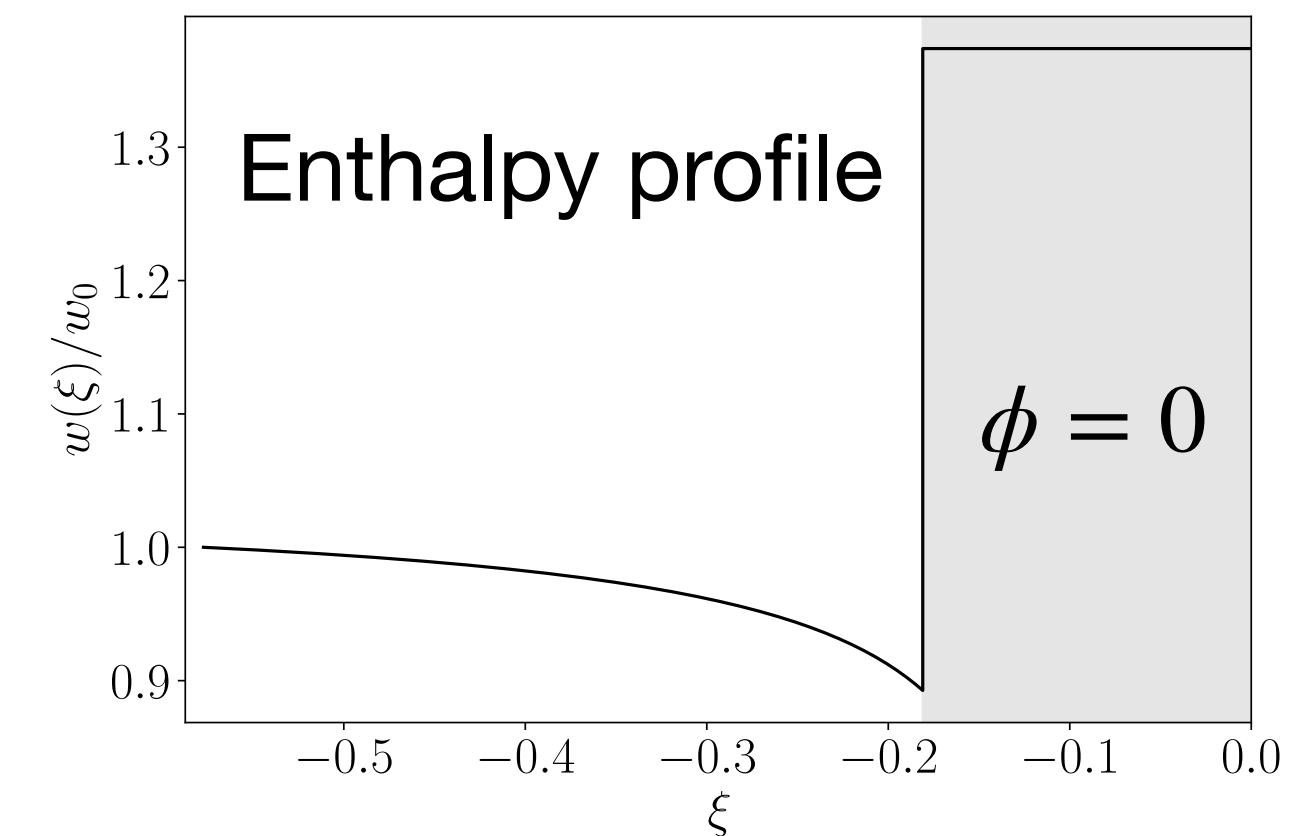
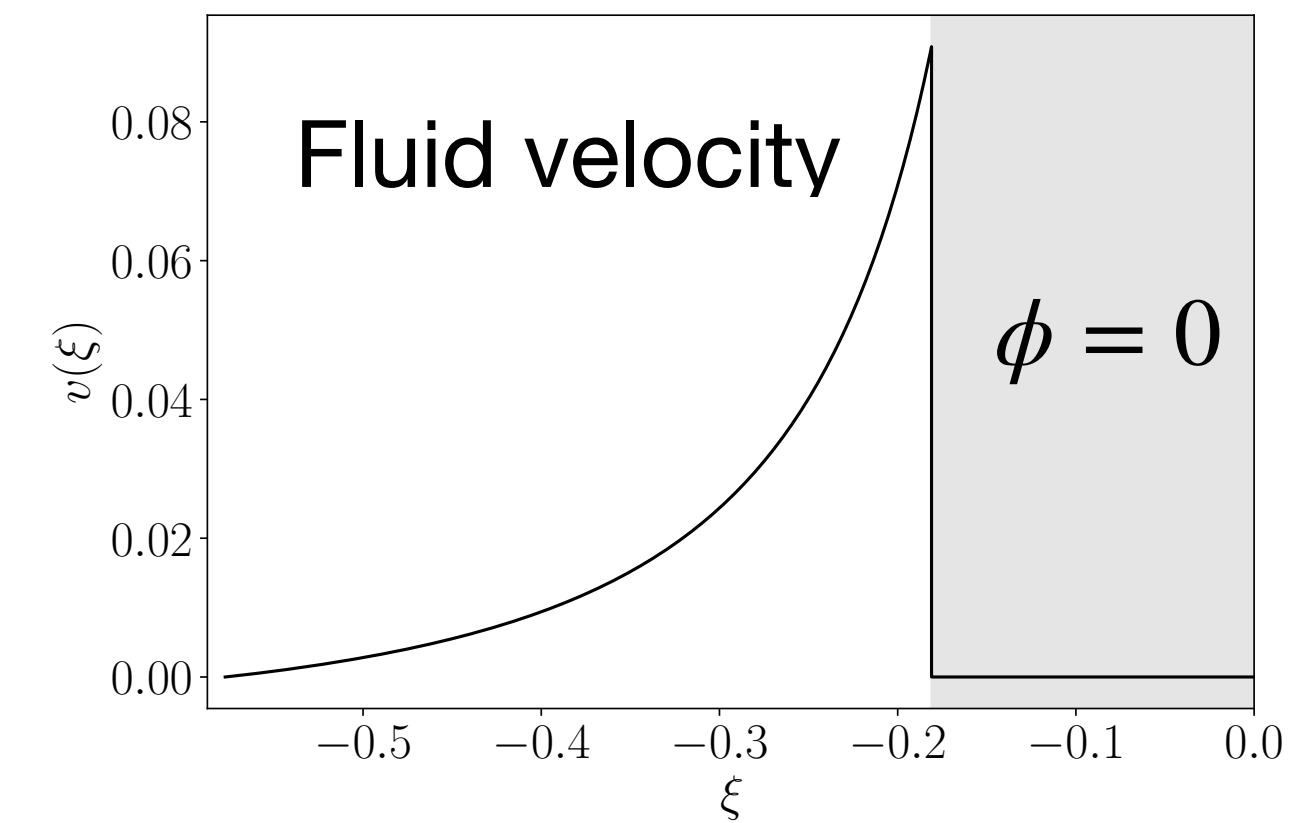


Droplet formation

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$$\frac{1}{3} \left(V_0 + \frac{3}{4} \omega_+ \right) |\xi_d|^3 + \int_{|\xi_d|}^{c_s} \xi'^2 d\xi' \left[\gamma^2(-\xi') - \frac{1}{4} \right] \omega(-\xi') = \frac{1}{4} \omega_0 c_s^3$$



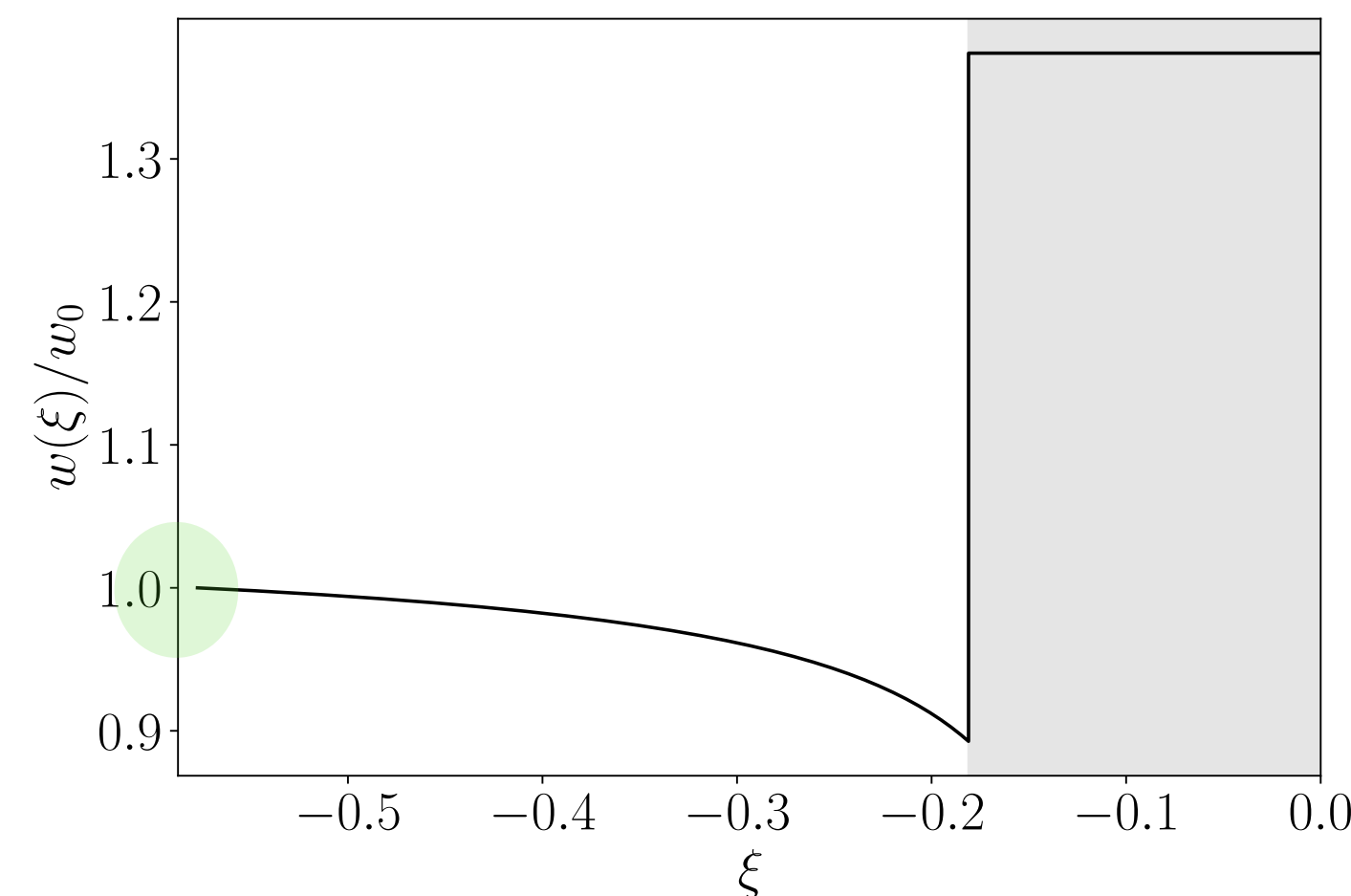
Droplet formation

- The droplet shrinks leaving nothing behind, we can use energy conservation to fix the droplet BCs by knowing the system at nucleation:

$$\frac{3}{4}\omega_0 + K = e_0 + K \stackrel{!}{=} e_N = \frac{3}{4}\omega_N(1 + \alpha_N),$$

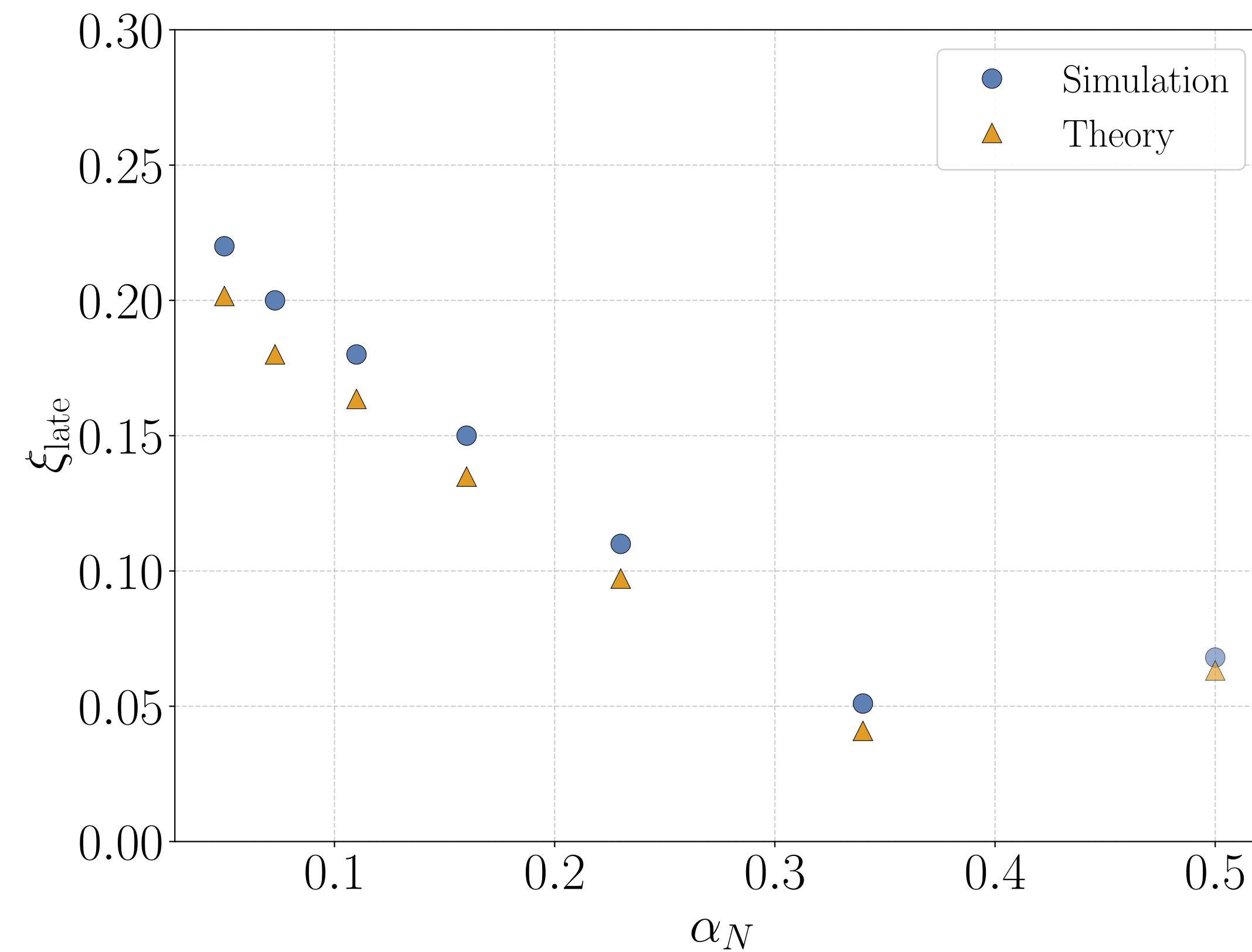
Energy upon completion,
 $\phi \neq 0$ phase + fluid kinetic

Energy at nucleation,
 $\phi = 0$ phase



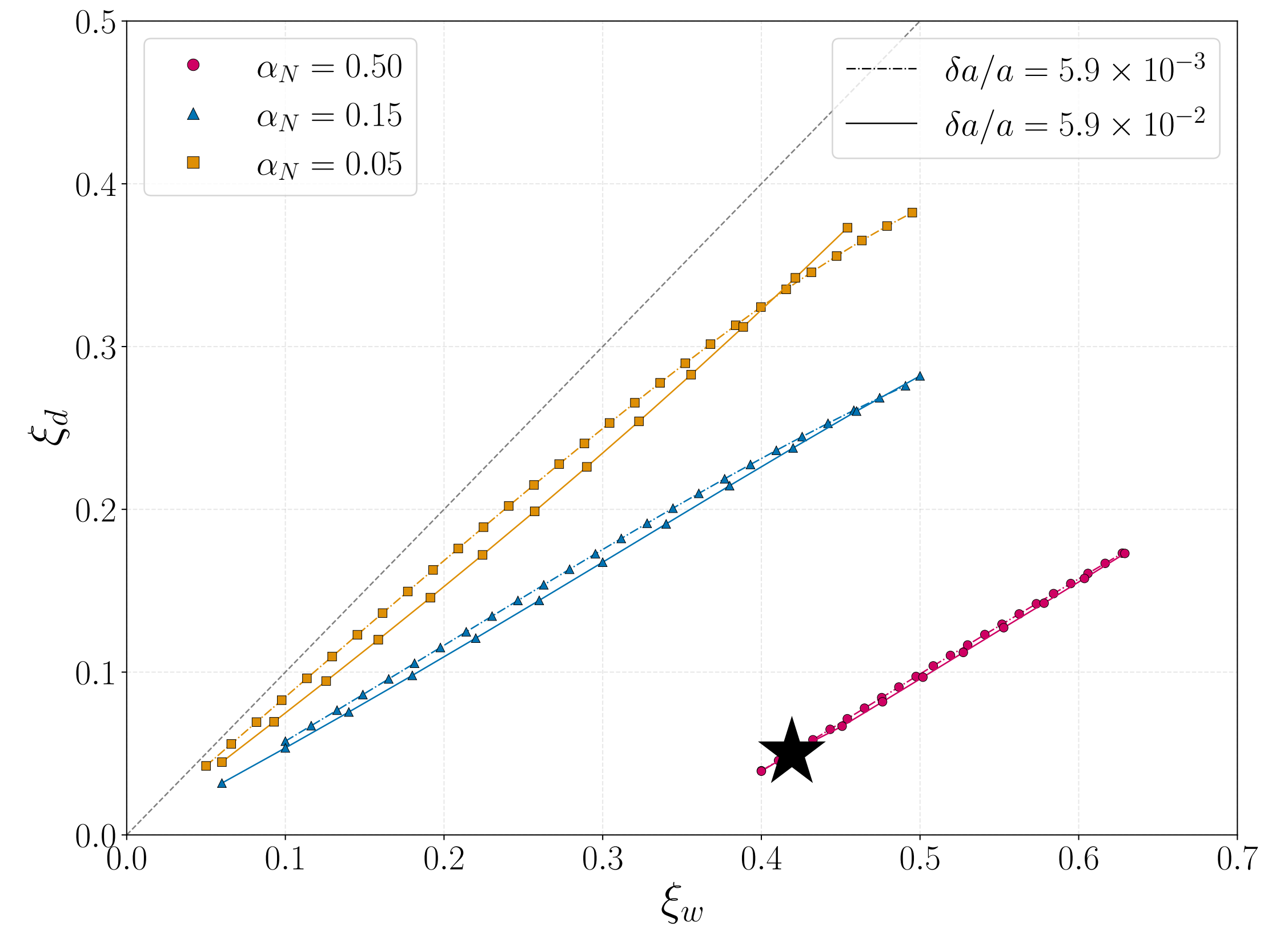
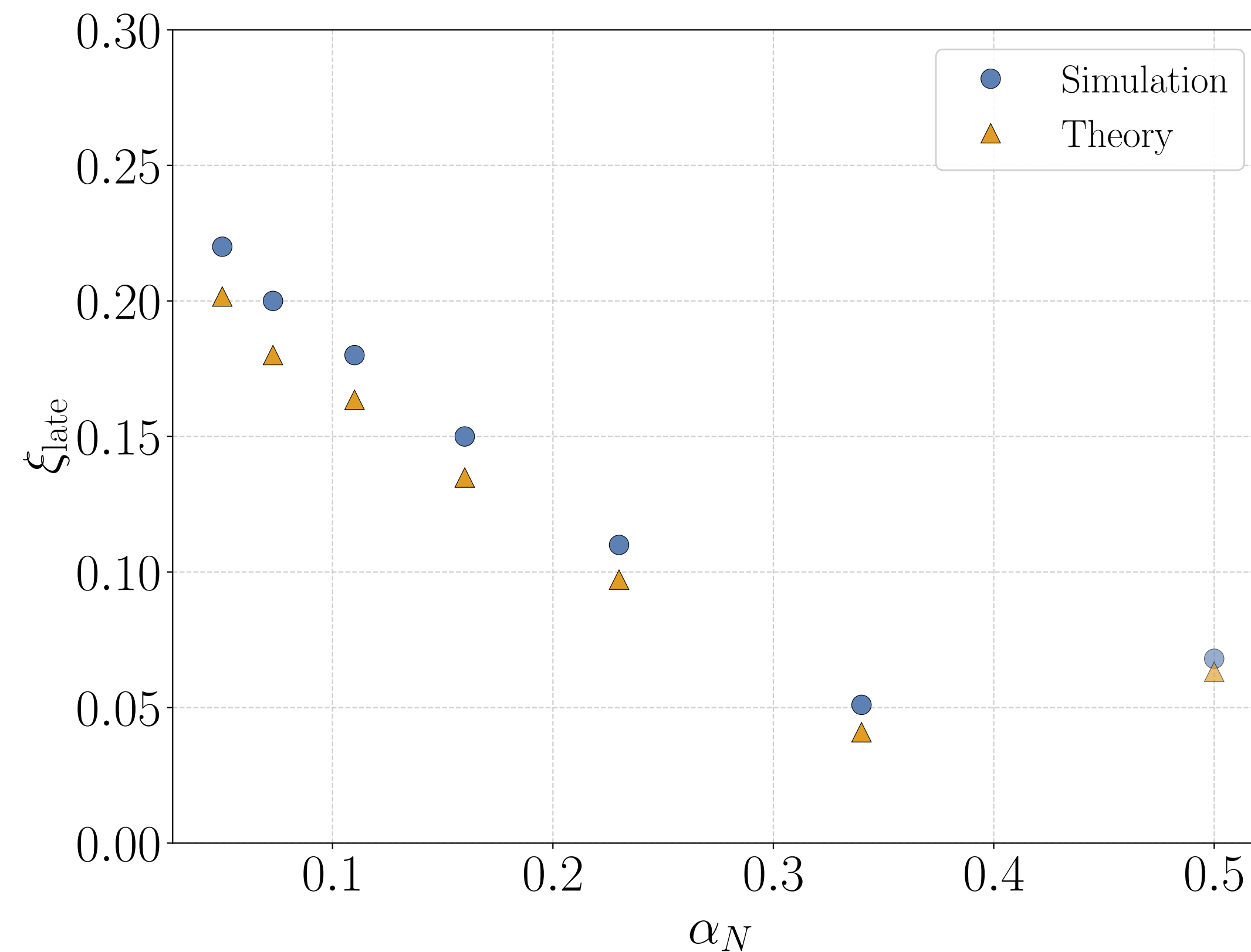
Droplet formation

- Compare theoretical predictions for the droplet velocity with numerical simulations



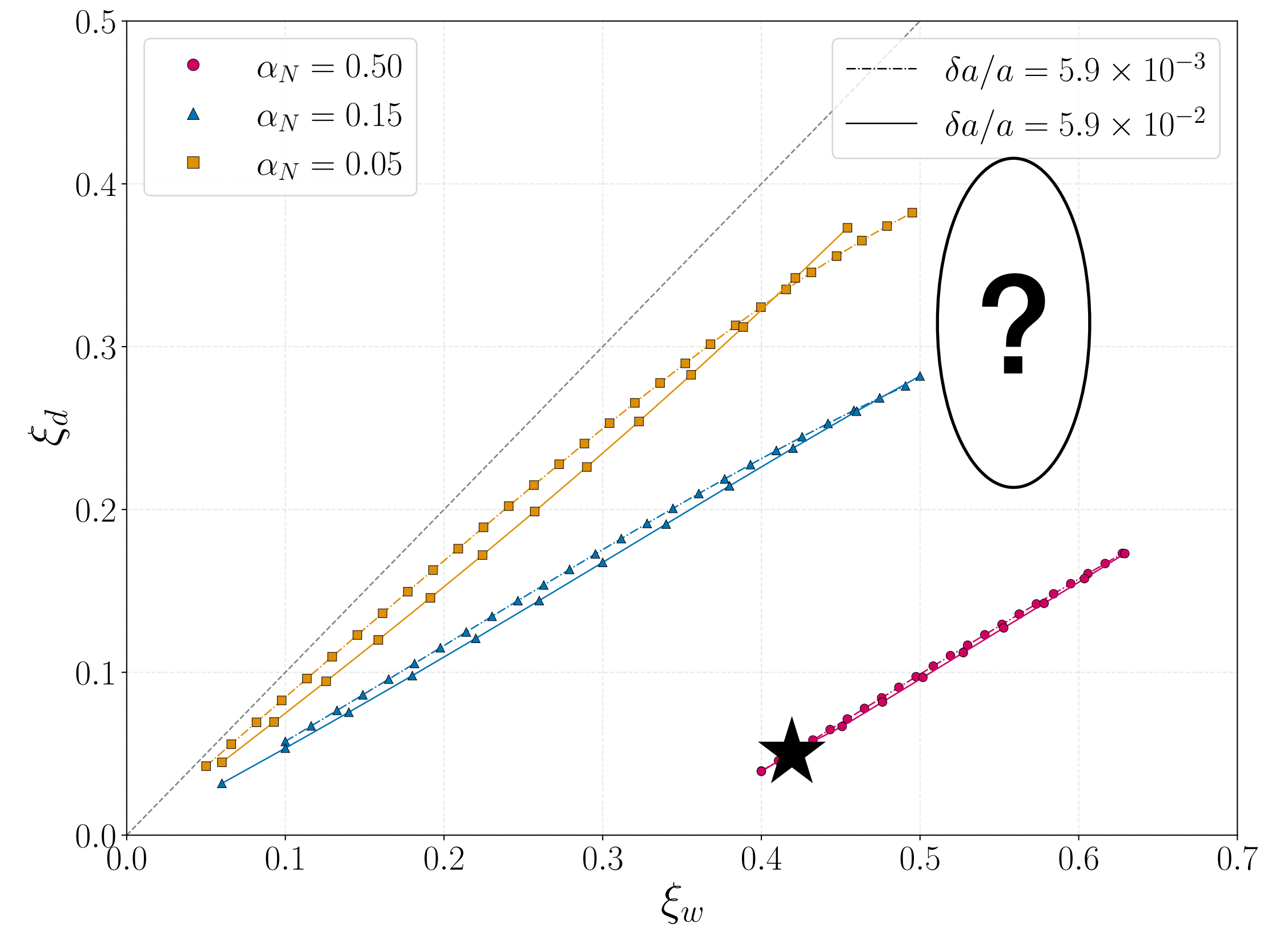
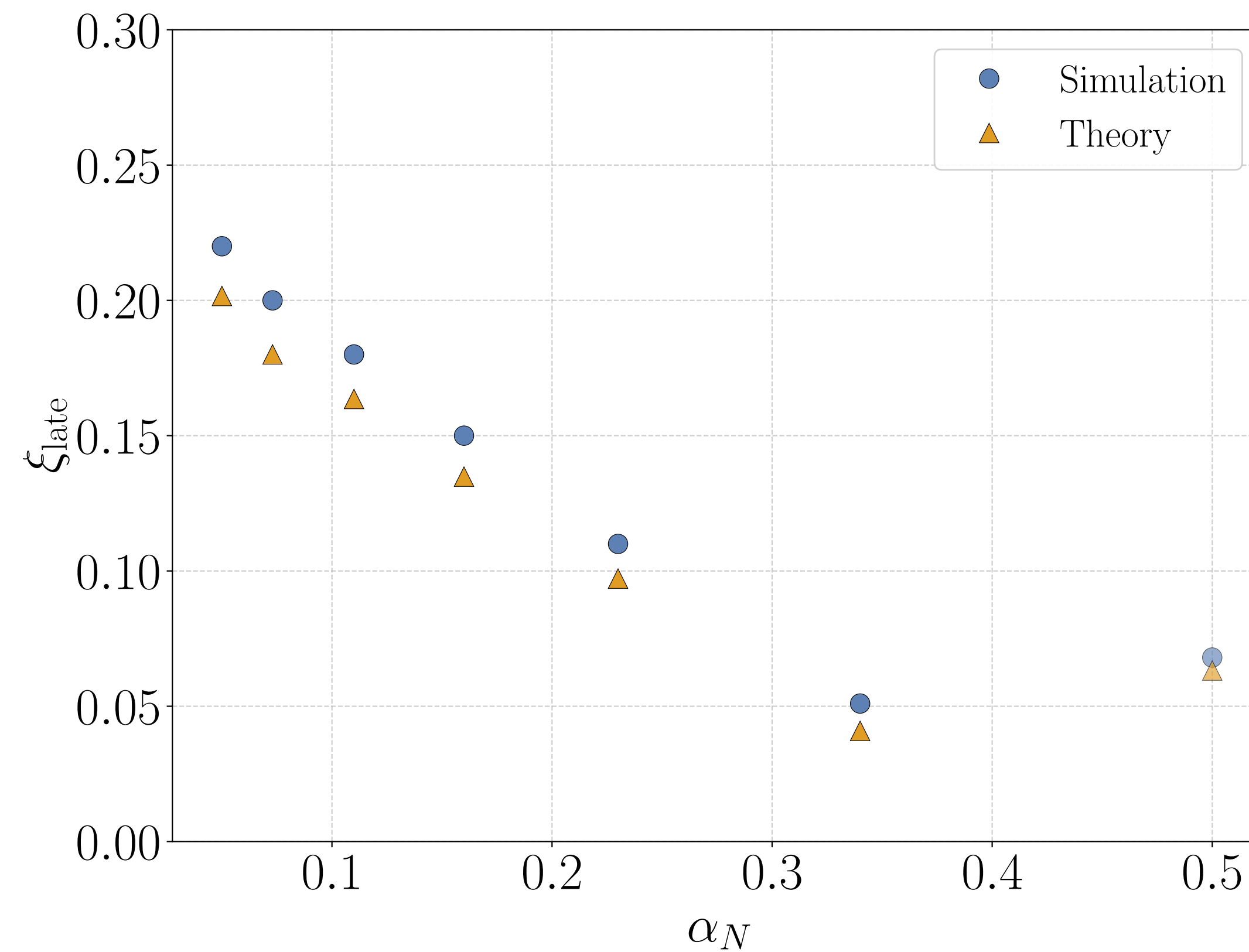
Droplet formation

- Compare theoretical predictions for the droplet velocity with numerical simulations, and make new predictions



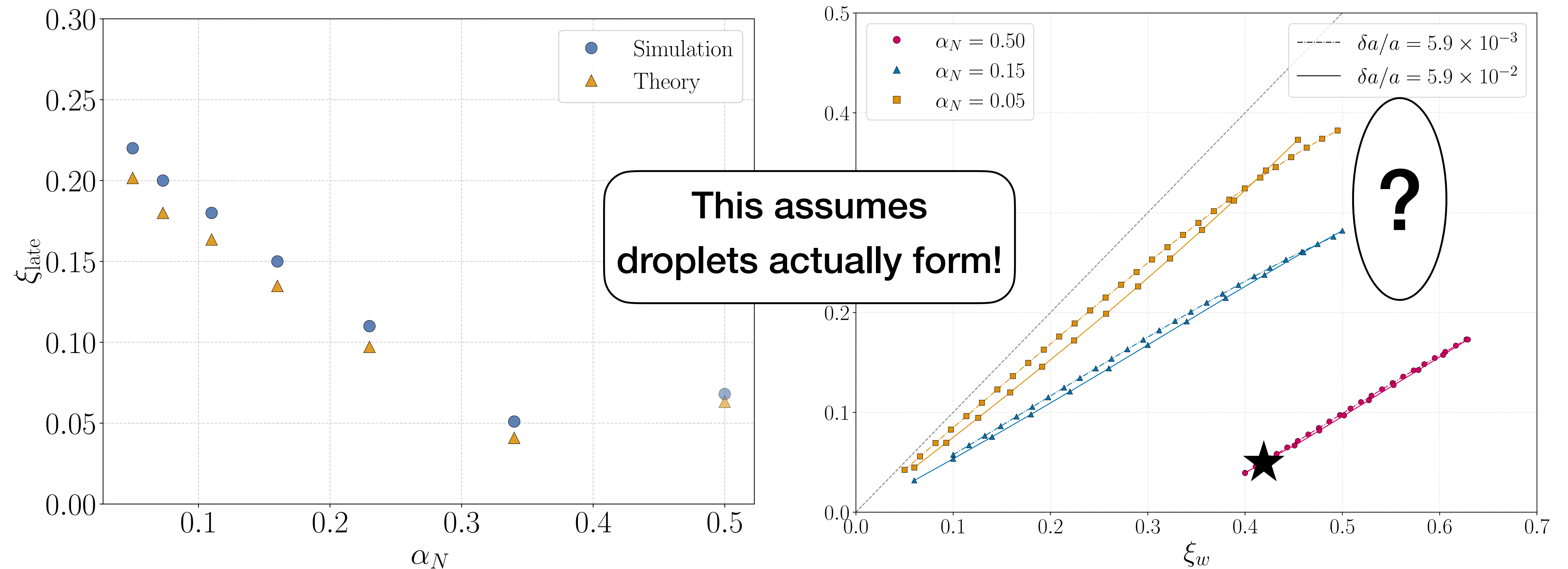
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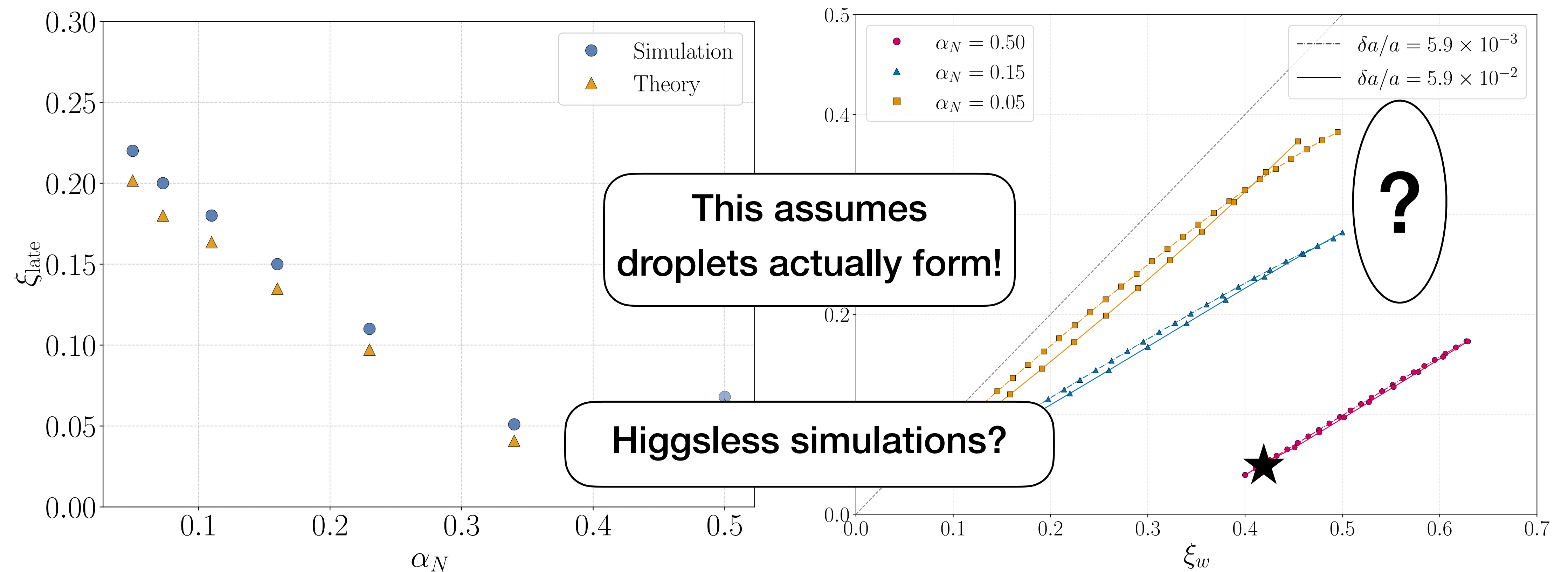
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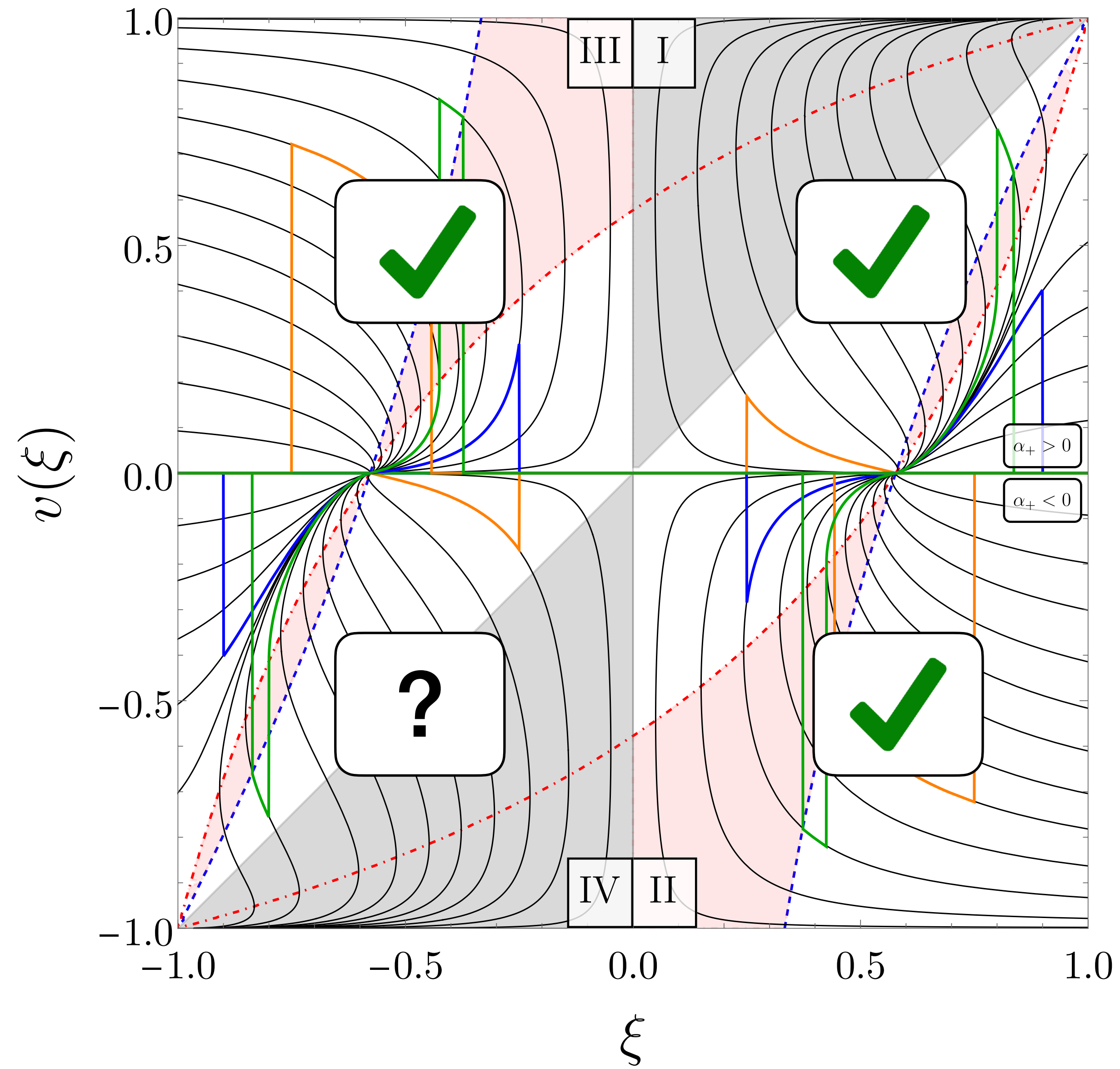
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Droplet formation

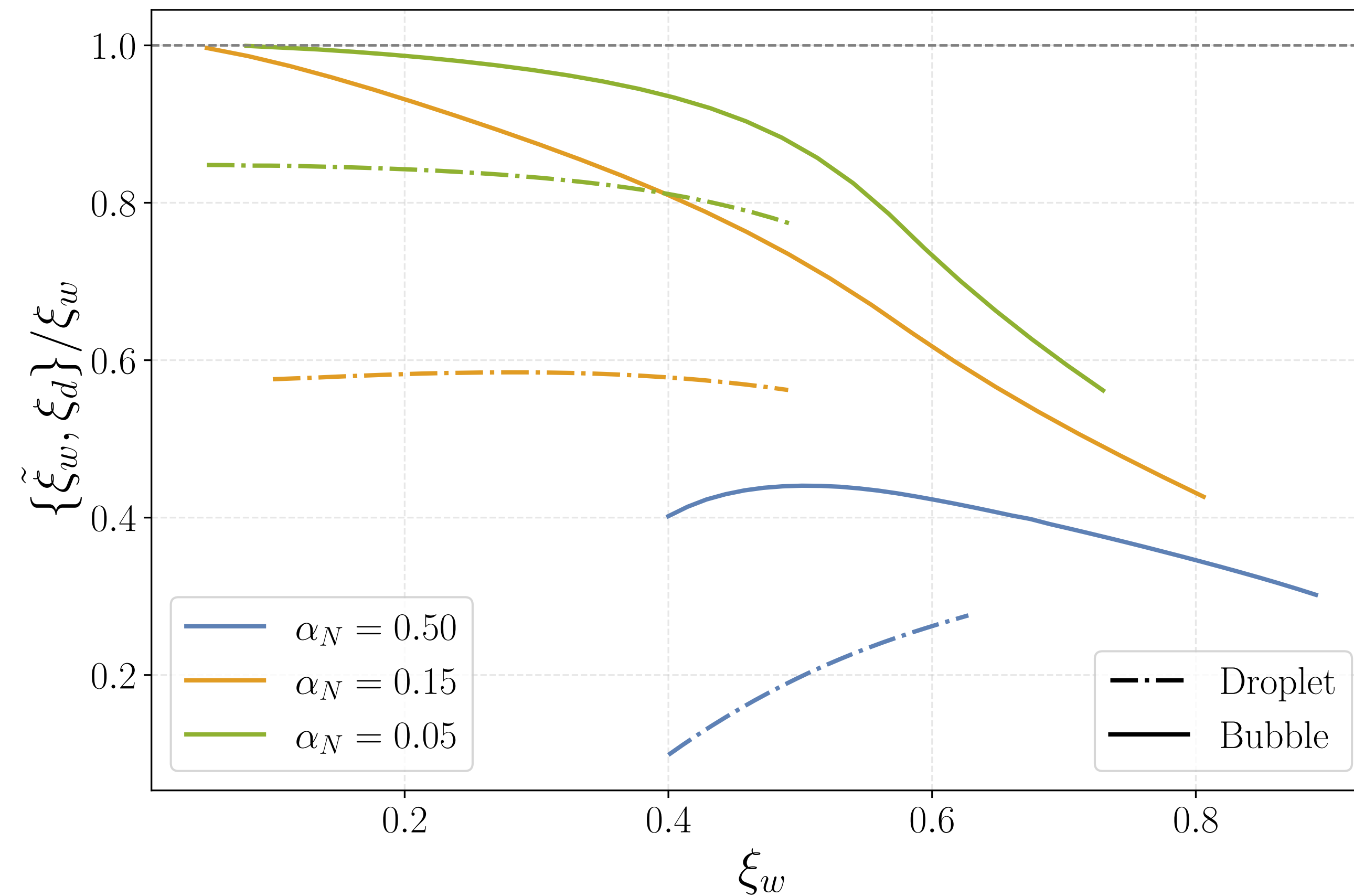
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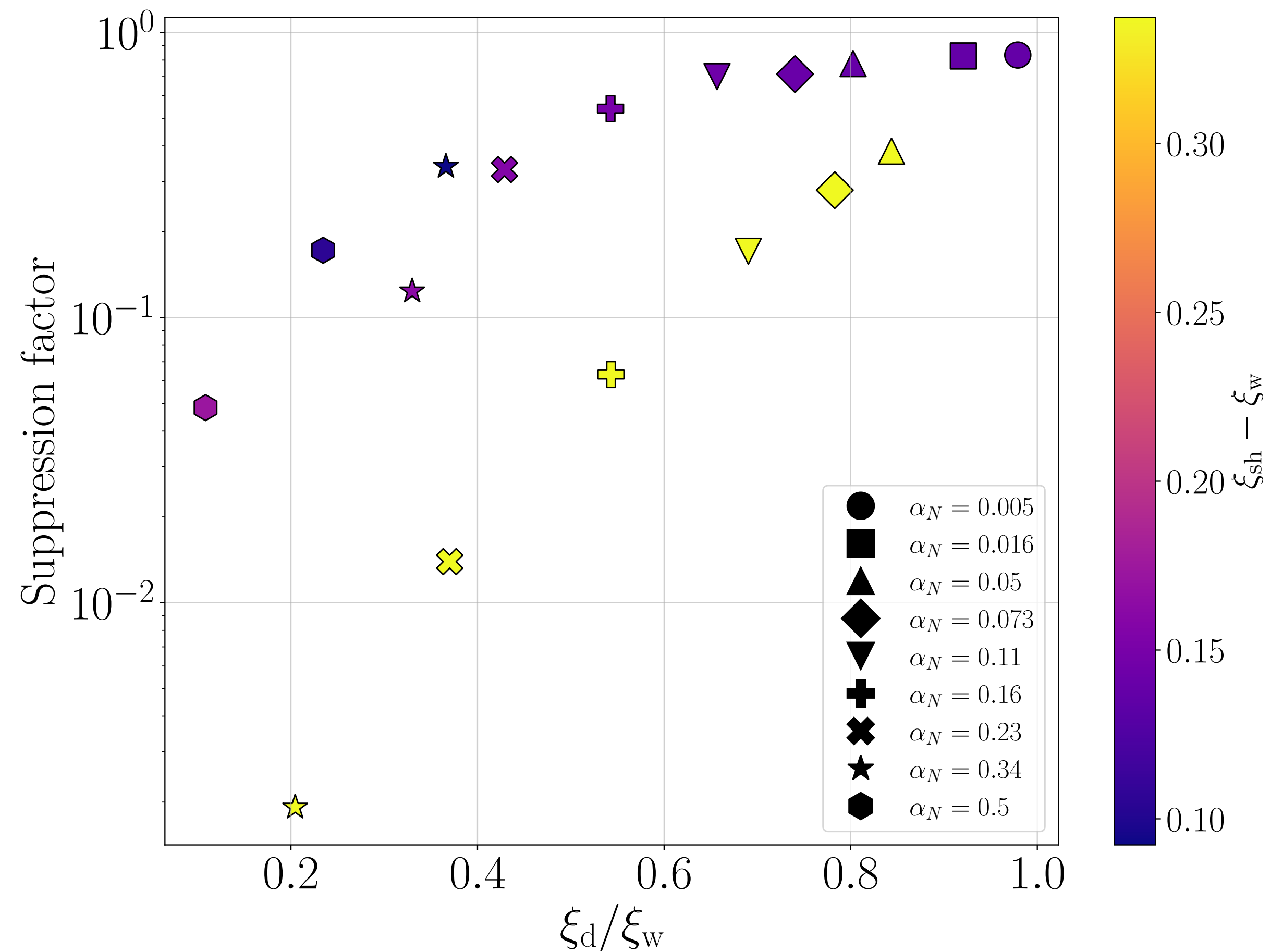
Droplets vs impeding shock

- Comparison of the slow-down from droplet formation and impeding shock



Correlation with gravitational waves

- Gravitational wave-suppression as a function of the droplet velocity and shock size:



Data from:

Cutting, Hindmarsh, Weir
[1906.00480] PRL (2020)

Summary

- Phase transitions are key events in the thermal history of our Universe that can shed light on new physics beyond the Standard Model via gravitational waves
- Their dynamics is complex as it involves non-perturbative and/or non-linear processes taking place across very different scales (e.g. bubble nucleation, bubble expansion)
- New “inverse” hydro solutions exist beyond standard deflagrations/detonations: applications in the early Universe (e.g., SUSY) and hadron-to-quark PT in neutron stars?
- Slow-down of bubble walls around percolation can be predicted in terms of “droplet” formation, opening to a theoretical modeling of heating effects to be incorporated in the gravitational-wave framework
- Dependence on the change of degrees of freedom?

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Thank you!