1 Overview

2 FOPT & GWs

3 Defect-driven FOPTs

4 Summary

Gravitational waves from defect-driven phase transitions: domain walls

Ryusuke Jinno (Kobe Univ.)

HPNP2025@Osaka, 2025/6/10

w/ Simone Blasi, Chiara Caprini, Thomas Konstandin, Alberto Roper Pol, Henrique Rubira, Isak Stomberg, Jorinde van de Vis

[Caprini, RJ, Konstandin, Roper Pol, Rubira, Stomberg '24]

[RJ, Konstandin, Rubira, *JCAP* 04 (2021) 014 (2010.00971)] [RJ, Konstandin, Rubira, Stomberg, *JCAP* 02 (2023) 011 (2209.04369)]

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OVERVIEW

- Impurities (= mostly domain walls in this talk)

  may seed bubble nucleation in the early-Universe plasma

- In such cases, the correlation length of the impurities determines the distribution of bubbles and resulting GW production

- For larger correlation length, the GW spectrum shifts towards lower frequencies and tends to have larger energy density

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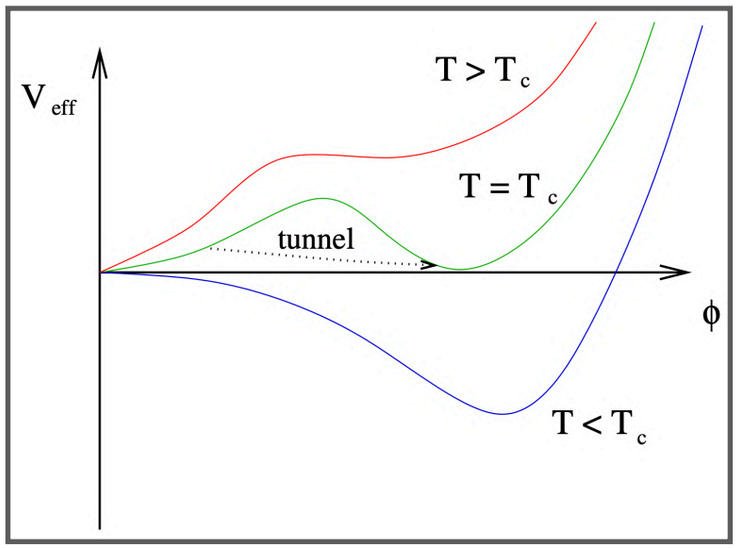
FIRST-ORDER PHASE TRANSITION: MOTIVATIONS

➤ Electroweak baryogenesis [Kuzmin, Rubakov, Shaposhnikov '85] [Morrissey & Ramsey-Musolf '12]

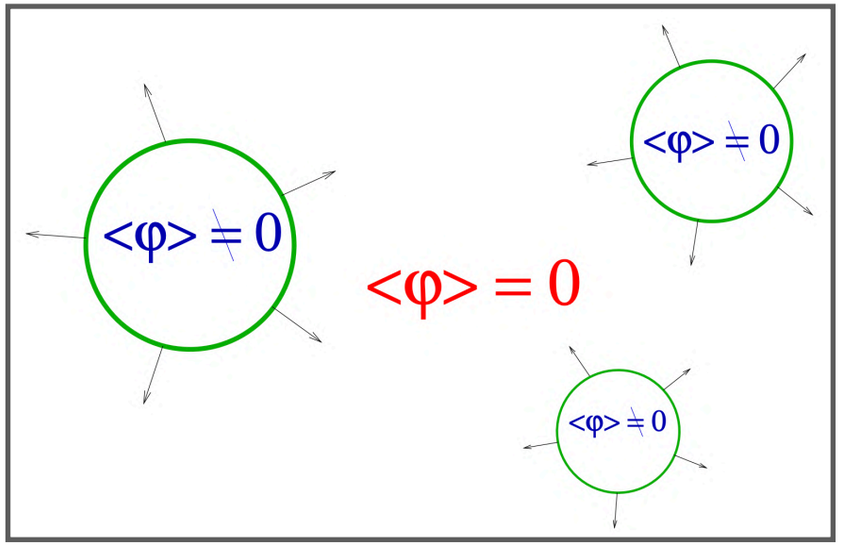
- A scenario producing baryon asymmetry at *the scale provided by Nature*

- Provides a clear target in new particle searches and Higgs precision studies

Microphysics



Macrophysics



➤ Observational test with GWs

- Forthcoming observations in the next decades

- Complementary test of EWBG

COSMOLOGICAL FIRST-ORDER PHASE TRANSITIONS

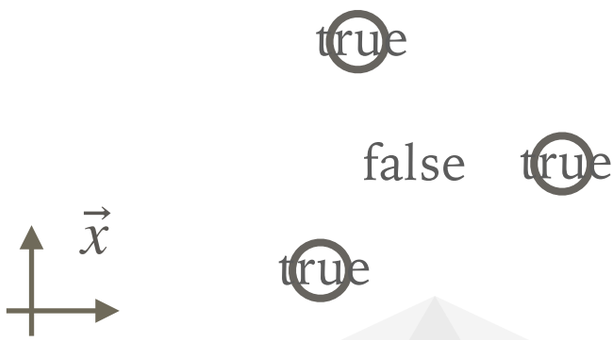
microphysics

Dynamics of bubbles

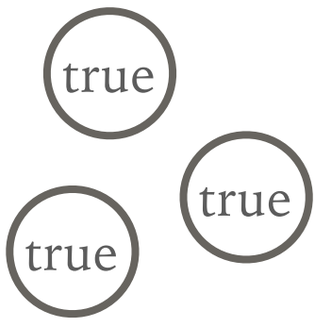
macrophysics

time or scale →

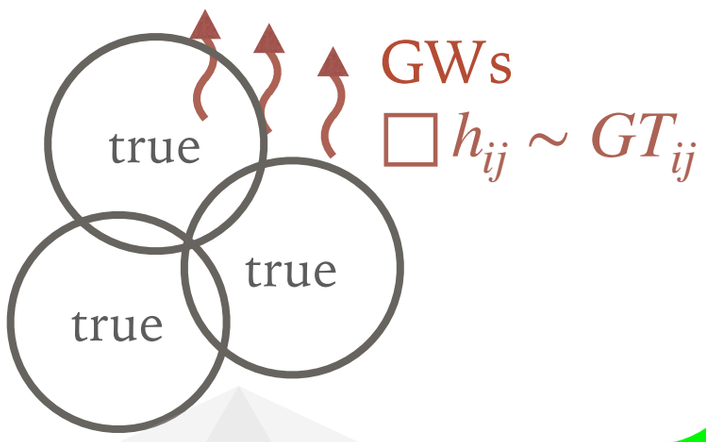
(1) nucleation (核生成)



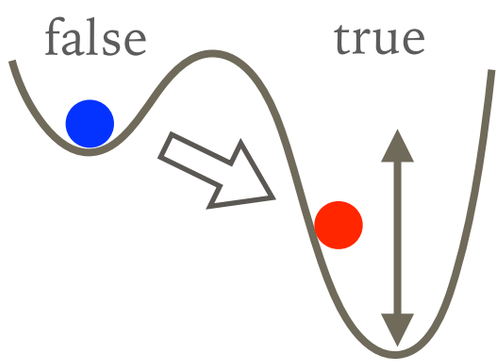
(2) expansion (拡大)



(3) collision (衝突)



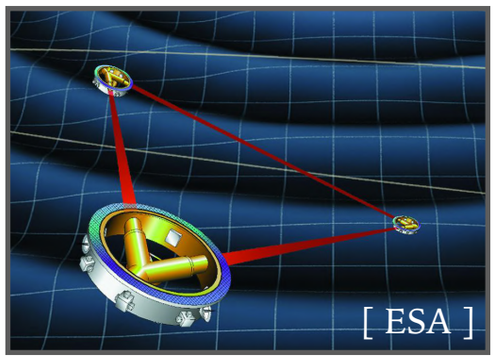
Physics of the Higgs sector



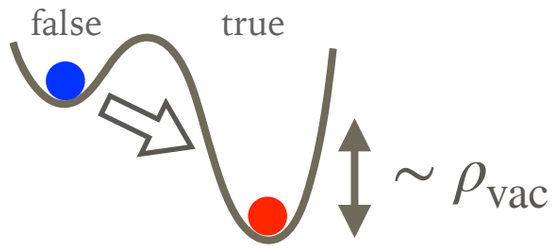
FOPTs in BSM

GWs

GW observations



BUBBLE EXPANSION



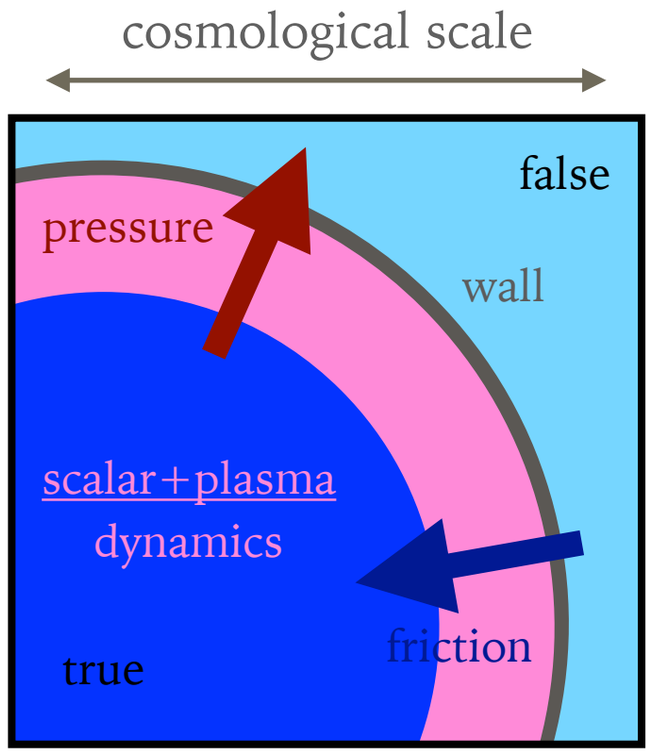
- "Pressure vs. Friction" determines the behavior:

  (1) Pressure: wall is pushed by the released energy

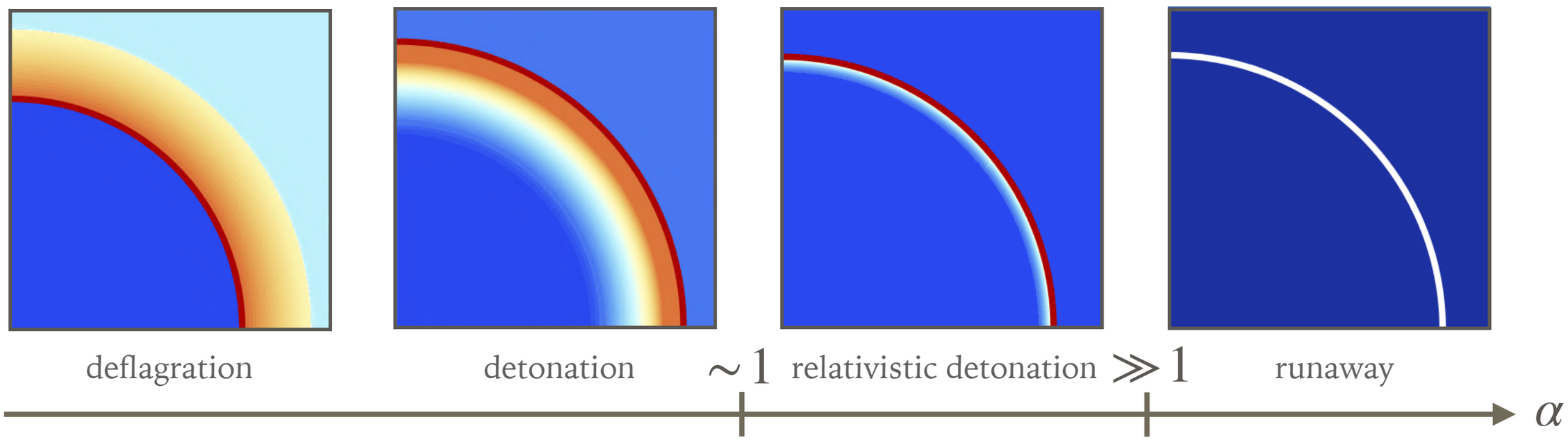
  Determined by $\alpha \equiv \rho_{\rm vac}/\rho_{\rm plasma}$

  see e.g. [Espinosa et al. '10, Hindmarsh et al. '15, Giese et al. '20, +Schmitz '21]

  (2) Friction: backreaction to the wall from plasma



- Different types of bubble expansion



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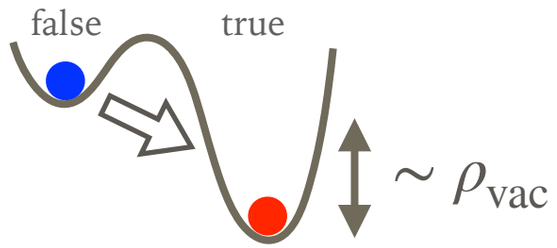
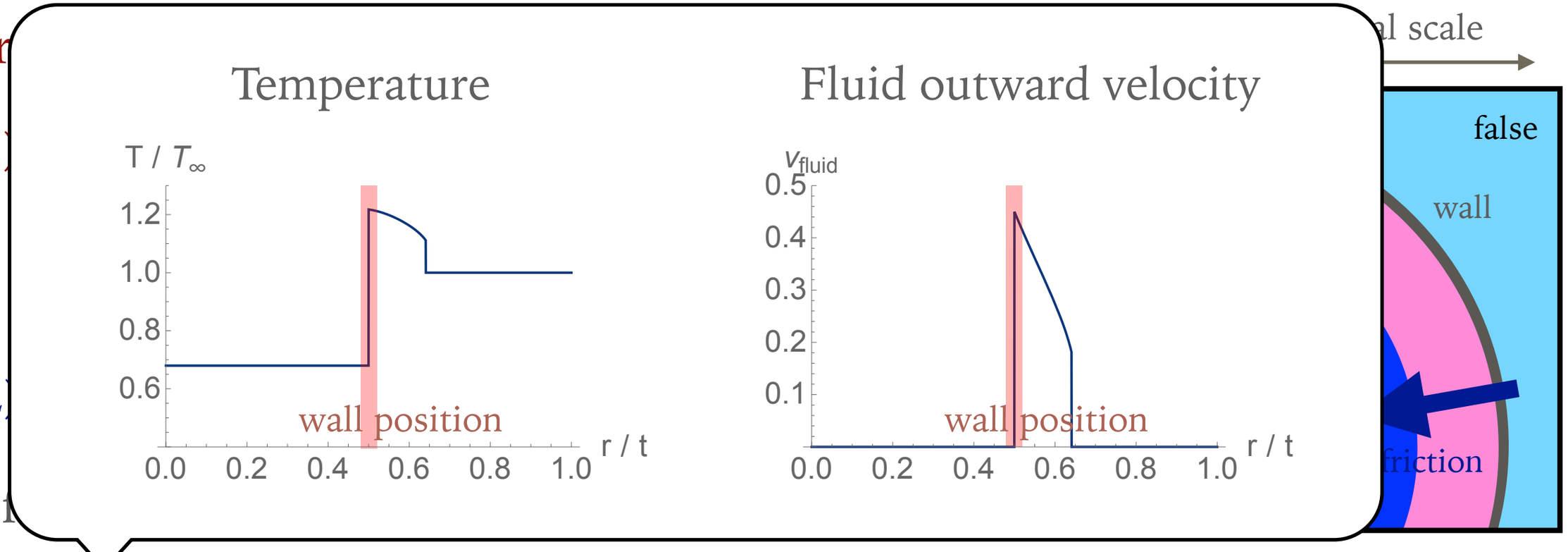
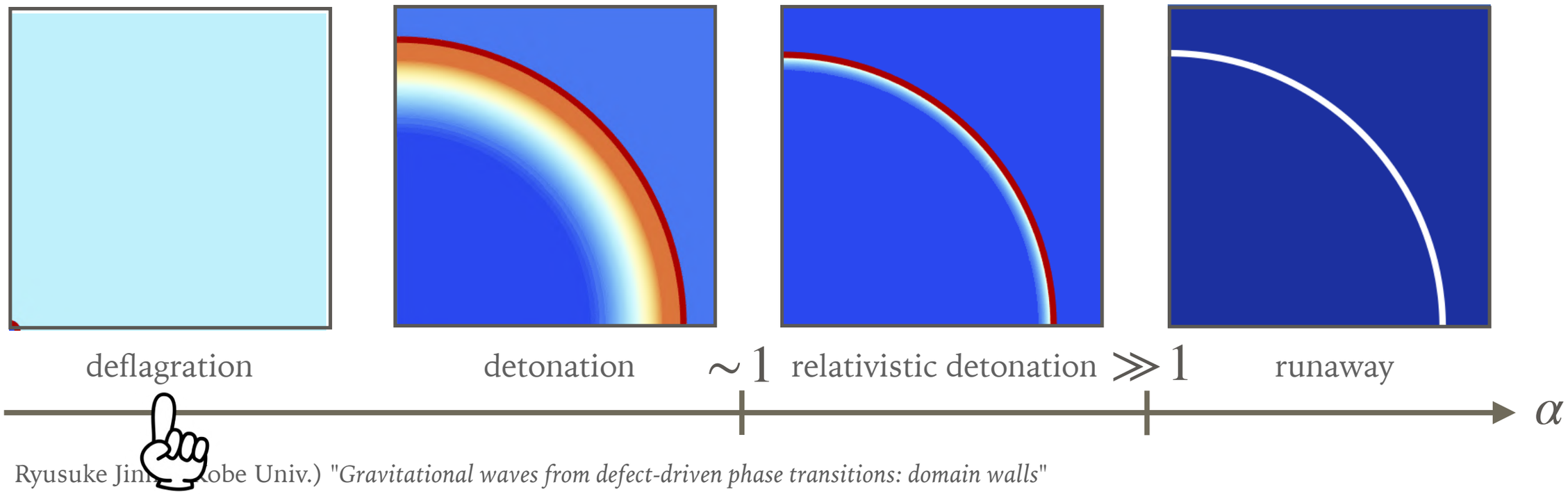


- "Pr
  (1)
  (2)
- Di





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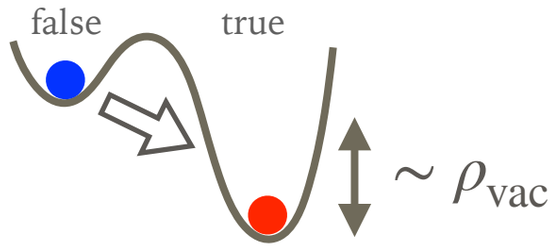
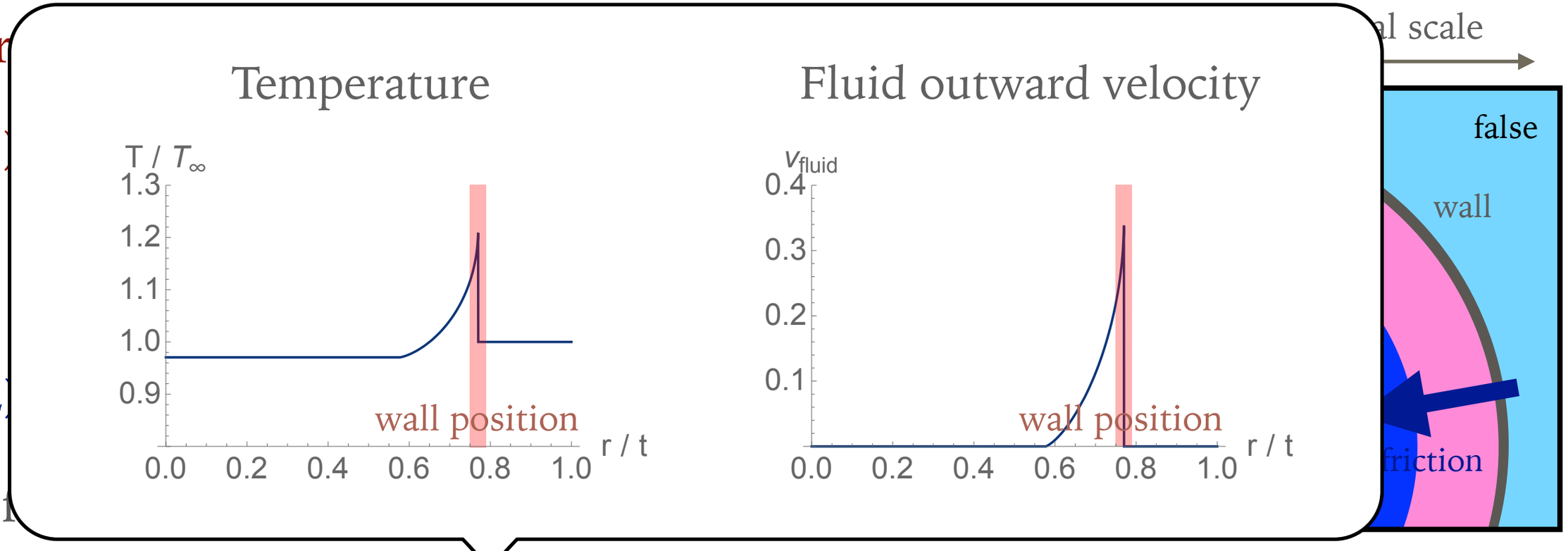


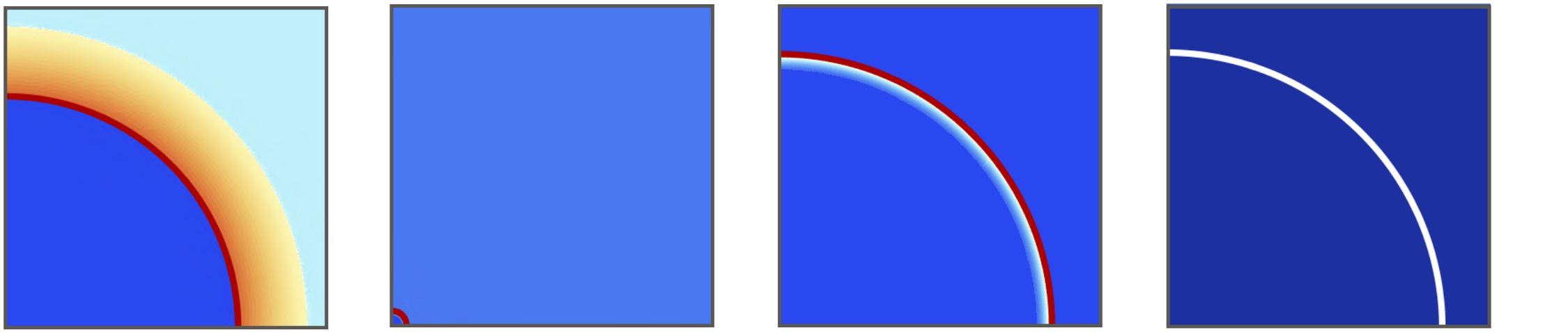
➤ "Pr

(1)

(2)

➤ Dif





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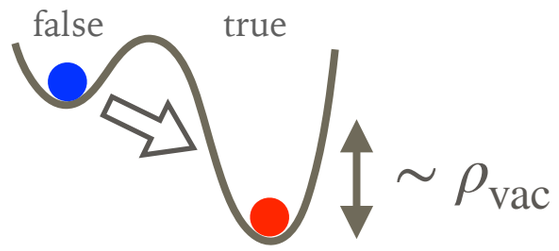

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(1)

(2)

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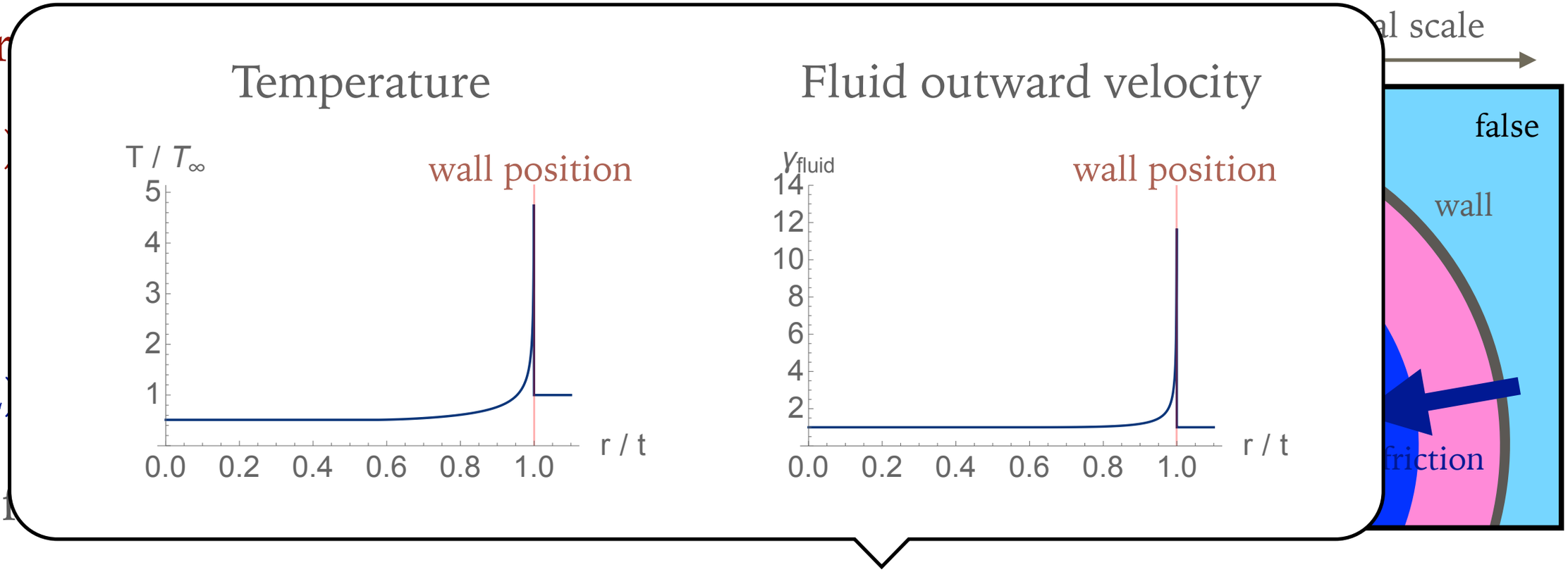

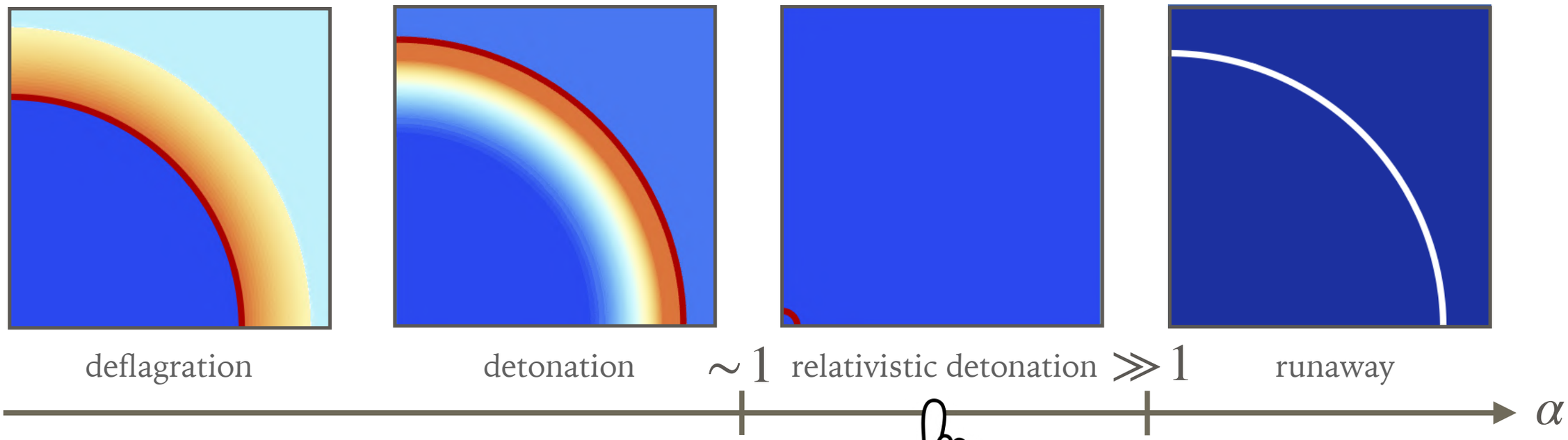

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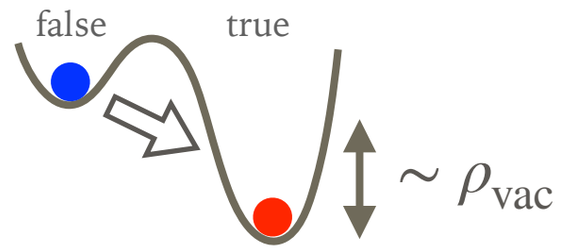


➤ "Pr

(1)

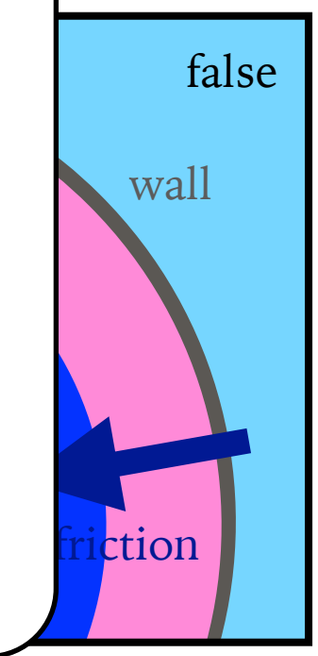
(2)

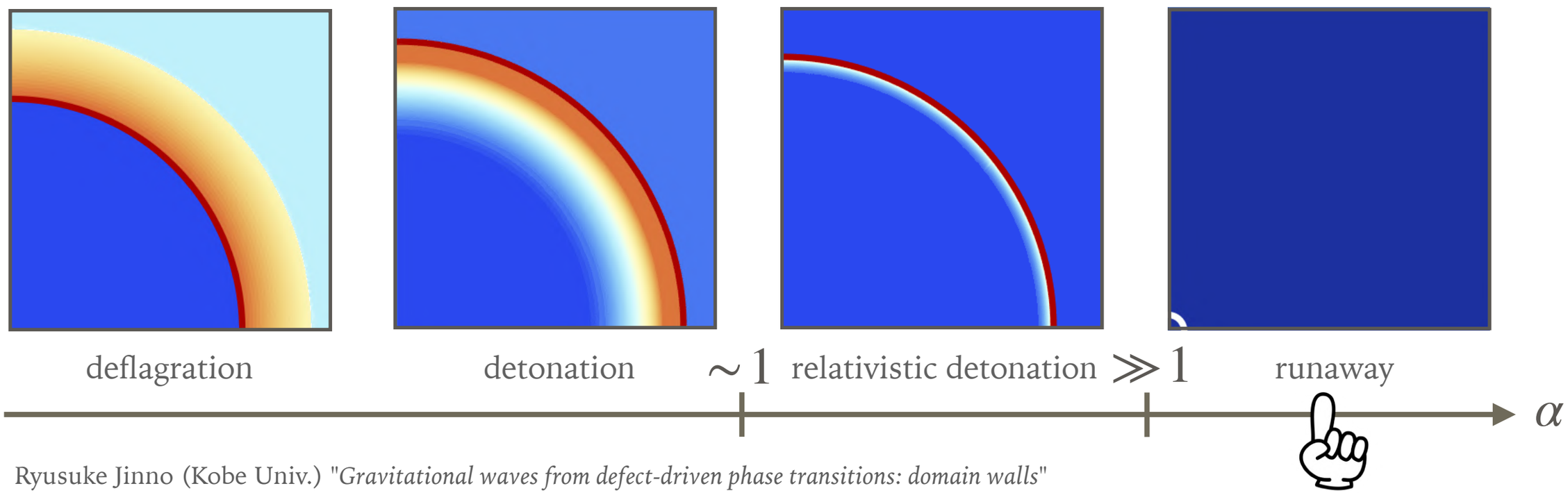
➤ Dif

Plasma particles cannot stop the acceleration of the walls:

walls continue to accelerate until they collide with others

[Bodeker & Moore '09, '17]



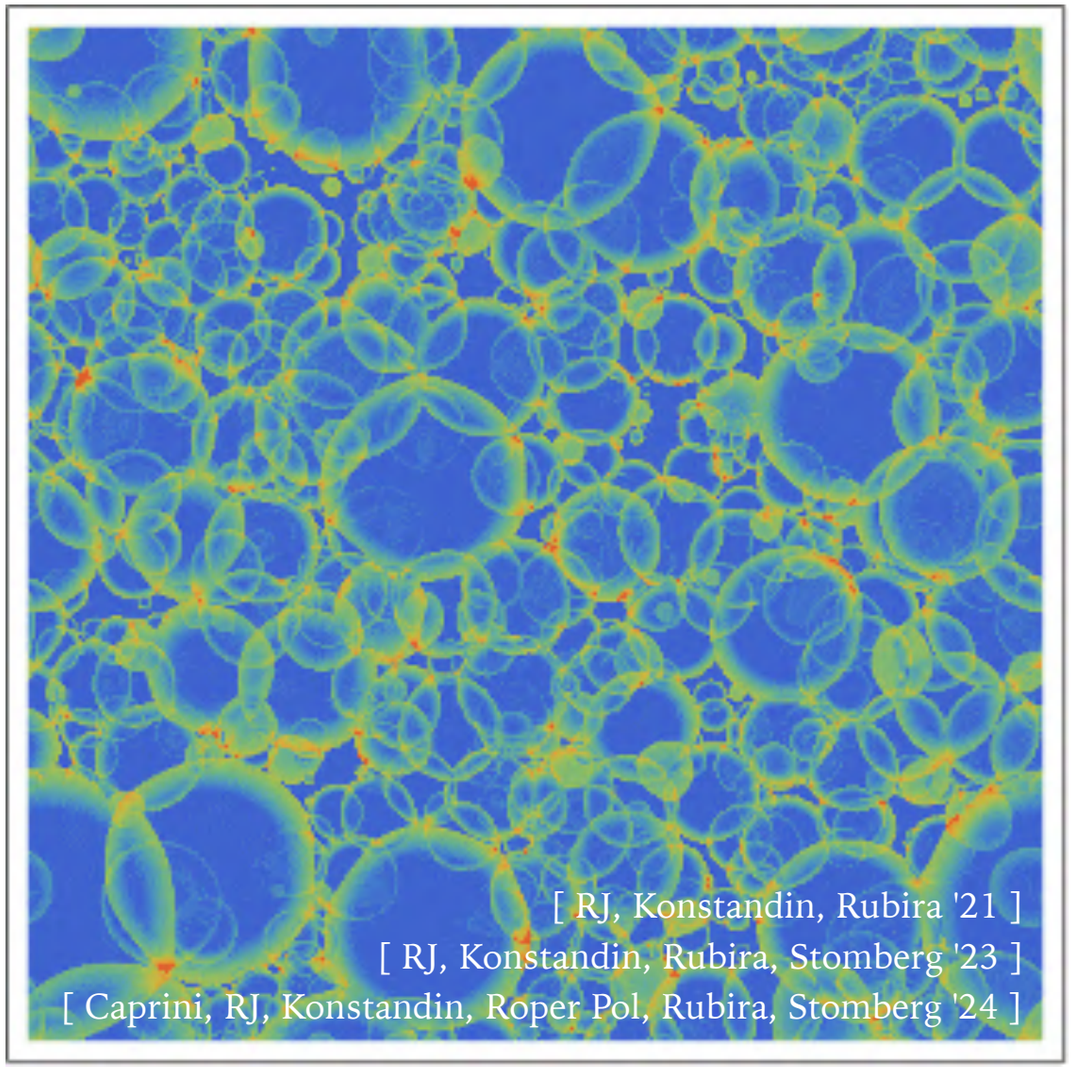


BUBBLE COLLISION & FLUID DYNAMICS

see also [Hindmarsh, Huber, Rummukainen, Weir, '14, '15, '17]

- Bubbles collide, and fluid dynamics sets in (example for)

  - Time evolution is calculated with our "Higgsless scheme"

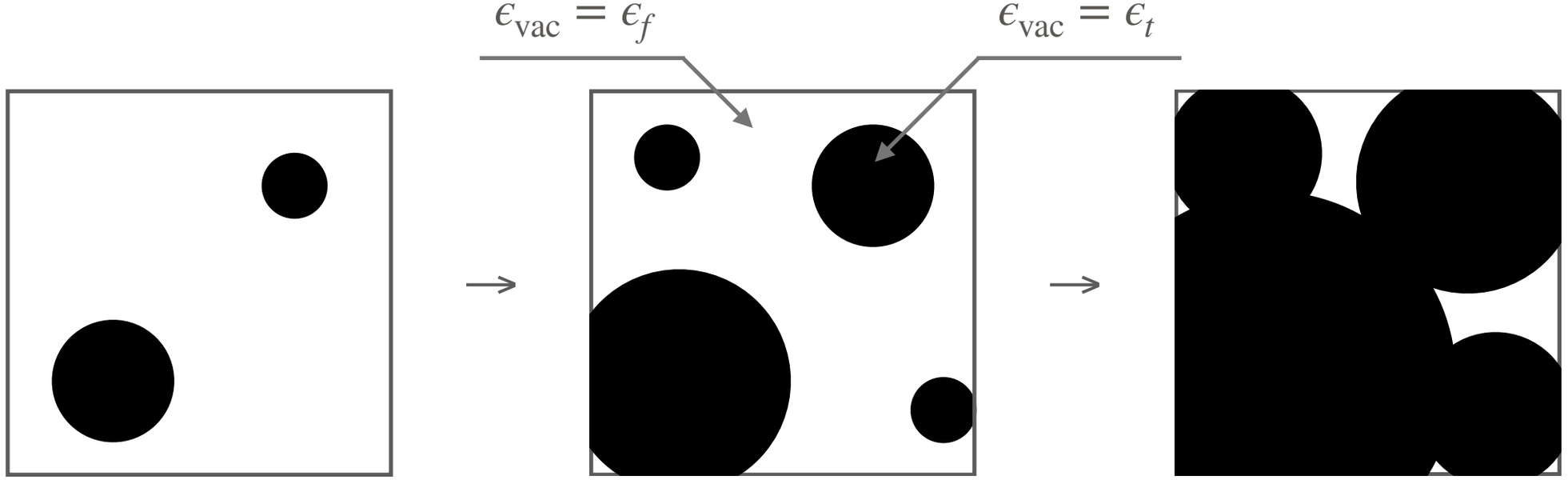


RECIPE FOR THE HIGGSLESS SIMULATION

[RJ, Konstandin, Rubira '21]
[RJ, Konstandin, Rubira, Stomberg '23]
[Caprini, RJ, Konstandin, Roper Pol, Rubira, Stomberg '24]

- A scheme that "integrates out" the Higgs as energy-injecting b.c.
- We first numerically generate nucleation points,

  and determine the false-true boundary of the bubbles



- We then evolve the fluid in this box according to $\begin{cases} \partial_0 K^0 + \partial_i K^i = 0 \\ \partial_0 K^i + \partial_j T^{ij}(K^0, K^i) = 0 \end{cases}$

  → Fluid automatically develops profiles

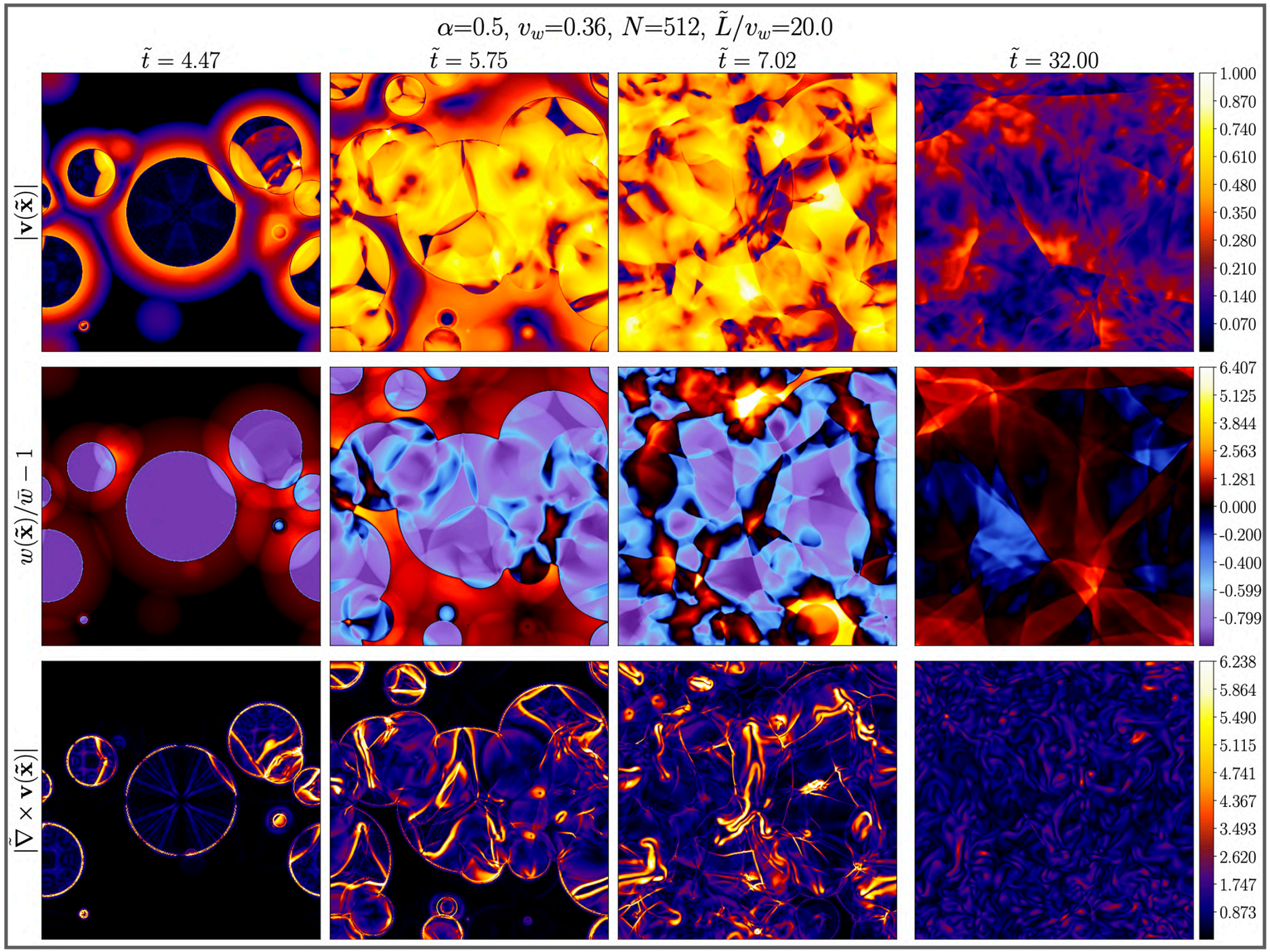
RECIPE FOR THE HIGGSLESS SIMULATION

[RJ, Konstandin, Rubira '21]
[RJ, Konstandin, Rubira, Stomberg '23]
[Caprini, RJ, Konstandin, Roper Pol, Rubira, Stomberg '24]

fluid velocity

enthalpy

vorticity

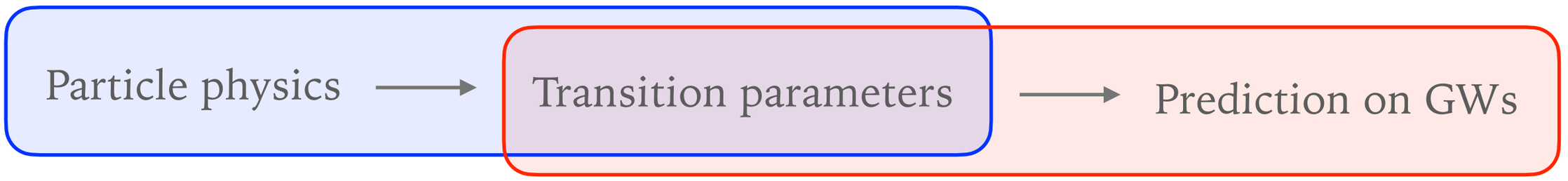


TRANSITION (≒ THERMODYNAMIC) PARAMETERS

- Remind the spirit of thermodynamics

  - Only a few parameters determine macroscopic properties

- What are parameters that describe the present macroscopic system?



TRANSITION (≒ THERMODYNAMIC) PARAMETERS

➤ Nucleation rate increase β : $\Gamma(t) \propto e^{\beta(t-t_*)+\cdots}$

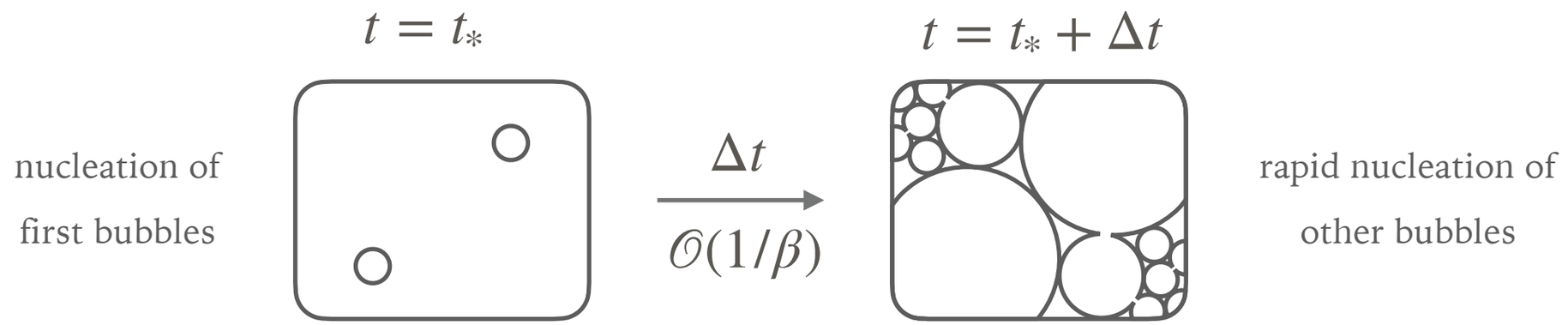
- How to obtain β

1) $\Gamma(T)$ is calculated as a function of temperature using thermal field theory,

and then translated into $\Gamma(t)$ using (temperature) $\Leftrightarrow$ (time) relation

2) Exponent of $\Gamma(t)$ is Taylor-expanded around the typical transition time $t = t_*$

- Interesting property: v_w/β gives the typical bubble size at the time of collision



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DEFECT-DRIVEN FOPTS

- Impurities can seed bubble nucleation

  - Black holes

    e.g. [Hiscock '87] [Green, Silverstein, Starr '06] [Gregory, Moss, Withers '14] [Burda, Gregory, Moss '15] [Mukaida, Yamada '17] [Canko, Gialamas, Jelic-Cizmek, Riotto, Tetradis '17] [Oshita, Yamada, Yamaguchi '20] [Dan, Gregory, Stojkovic '19] [El-Menoufi, Huber, Manuel '20], ...

  - Topological defects like domain walls, cosmic strings, monopoles

    e.g. [Steinhardt '81] [Hosotani '83] [Jensen, Steinhardt '83] [Yajnik '86] [Preskill & Vilenkin '93] [Yajnik, Padmanabhan '87] [Kumar, Yajnik '09] [Lee, Lee, MacKenzie, Paranjape, Yajnik, Yeom '13] [Blasi, Mariotti '22], ...

  - Overdensities

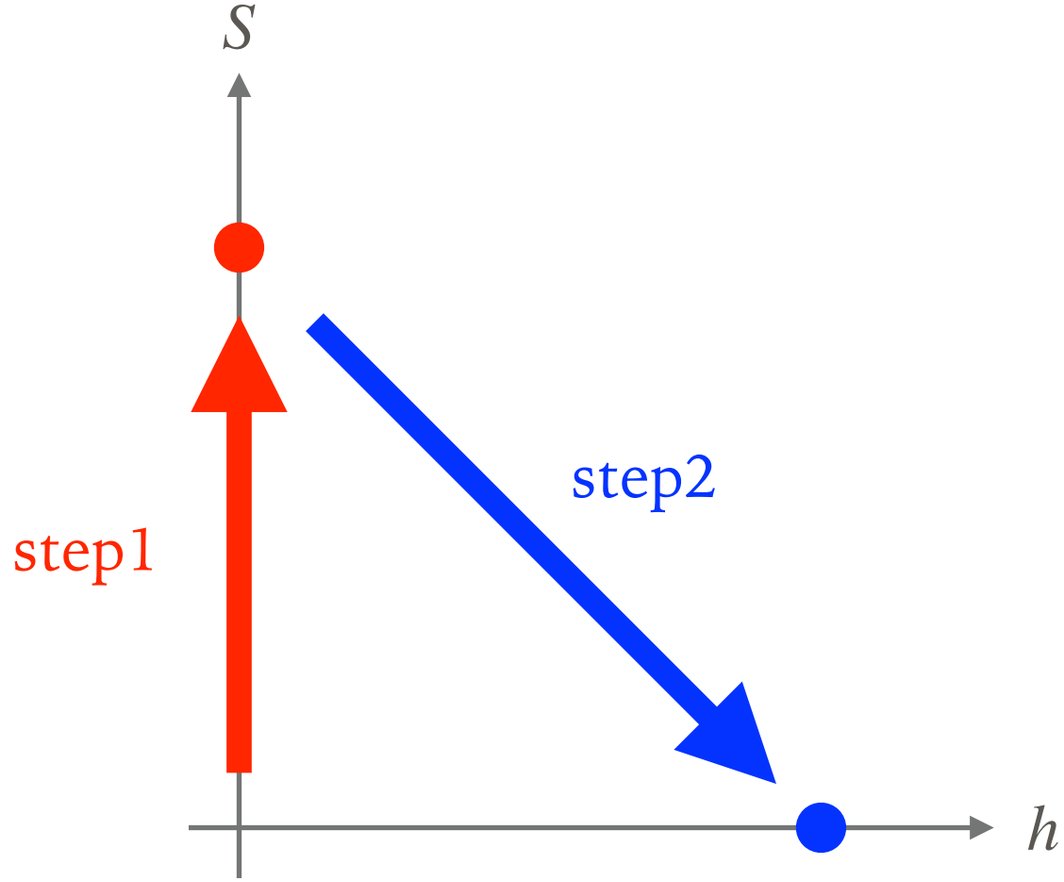
    e.g. [Balkin, Serra, Springmann, Stelzl, Weiler '21] [RJ, Konstandin, Rubira, van de Vis, '*21*], ...

REAL SINGLET EXTENSION OF THE SM

- SM + real singlet (w/$\mathbb{Z}_2$)

  - Potential: $V = -\frac{\mu^2}{2}h^2 + \frac{\lambda}{4}h^4 - \frac{m^2}{2}S^2 + \frac{\eta}{4}S^4 + \frac{\kappa}{2}h^2S^2$ (unitary gauge)

- Two-step transition $(0,0) \to (0,v_s) \to (v_h,0)$



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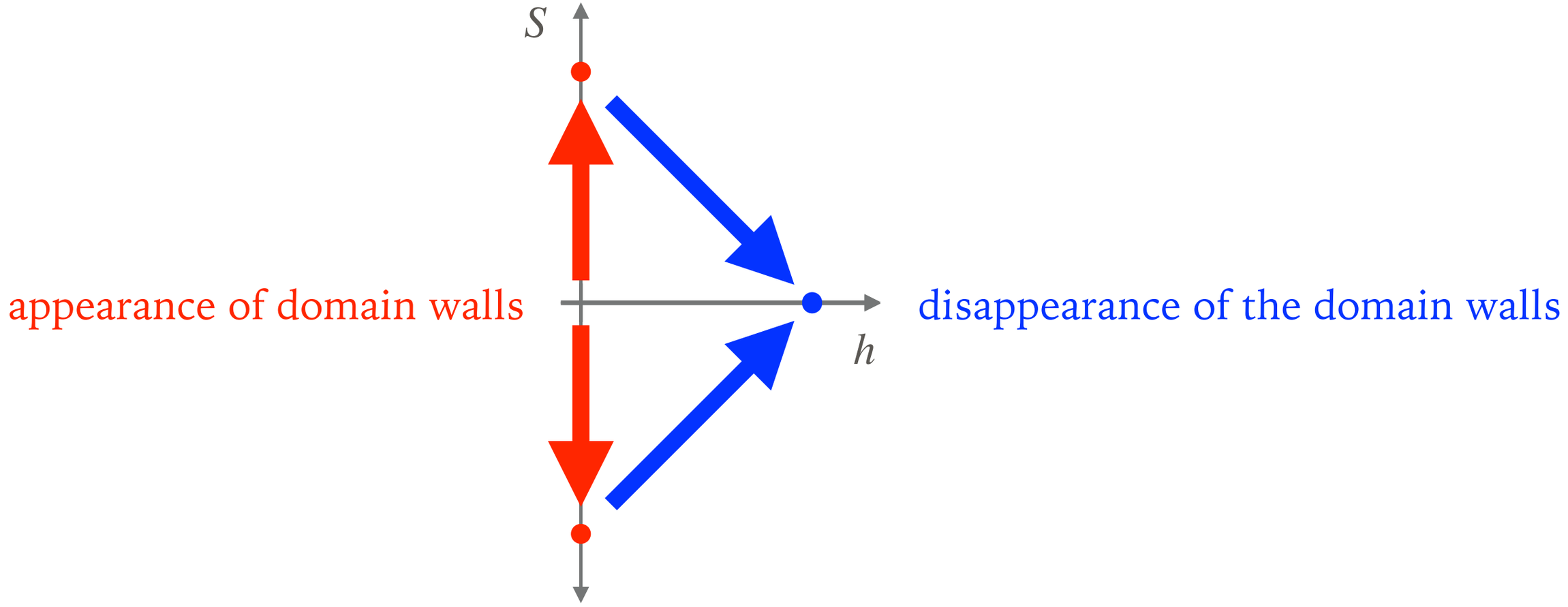

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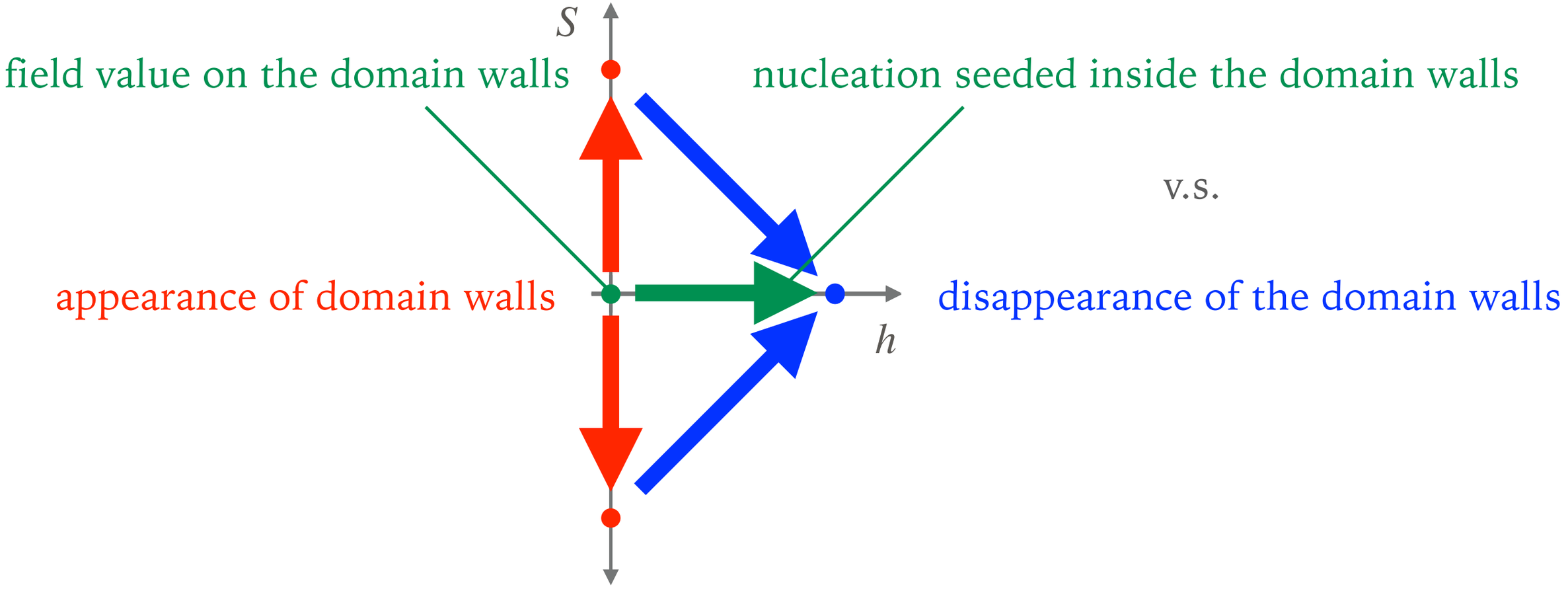
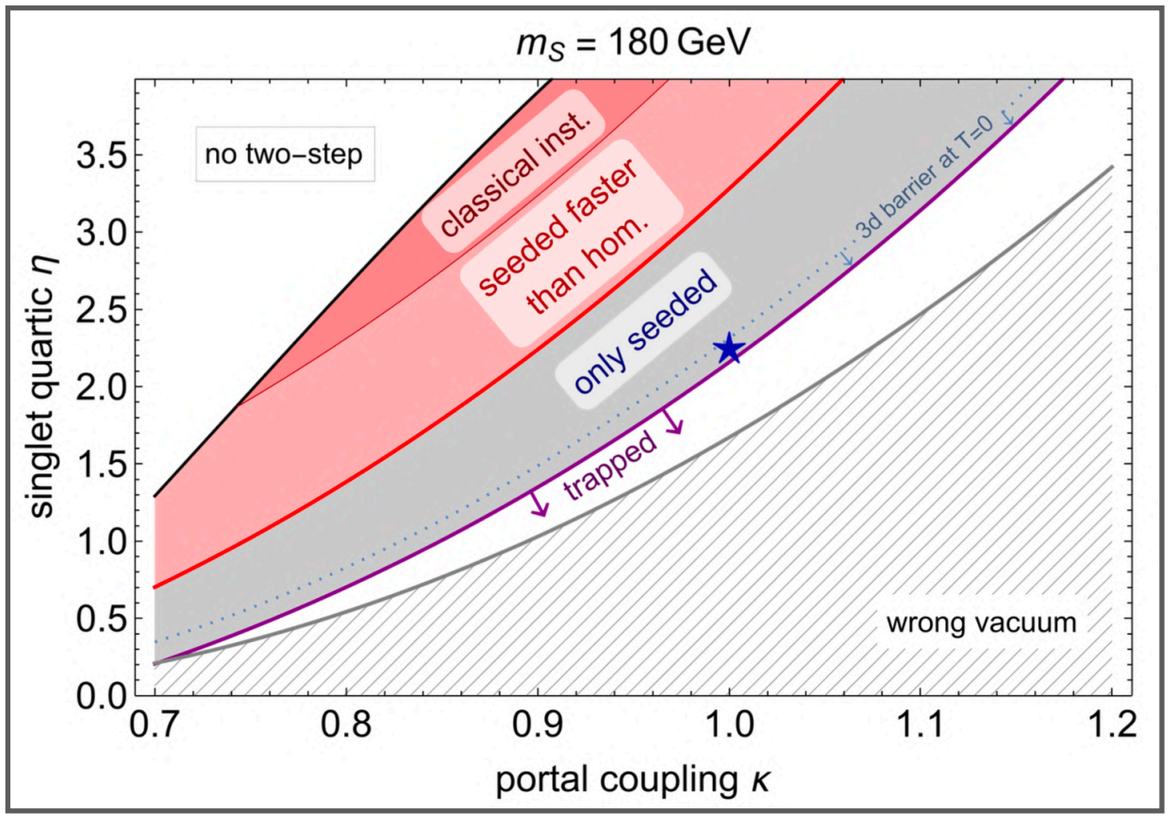
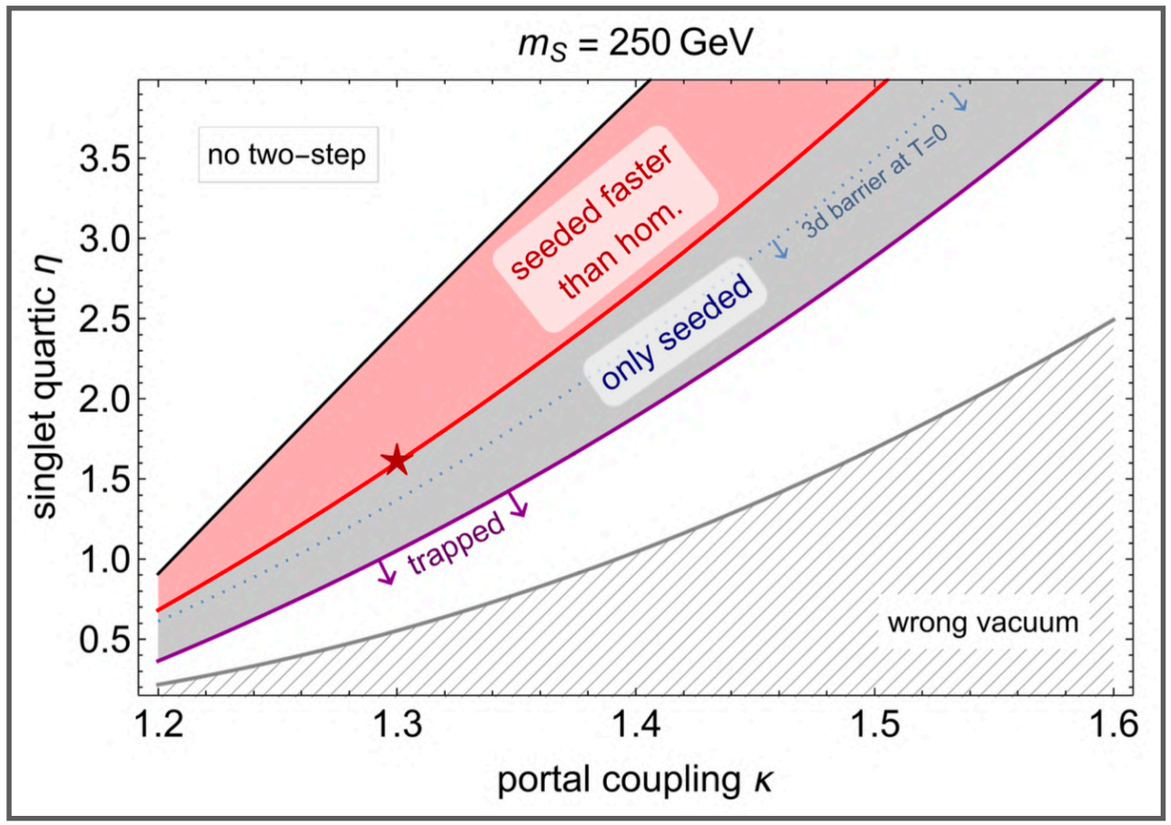


HOMOGENEOUS VS. SEEDED TRANSITIONS

- Completion of the transition by seeded bubbles





[Blasi, Mariotti '22]

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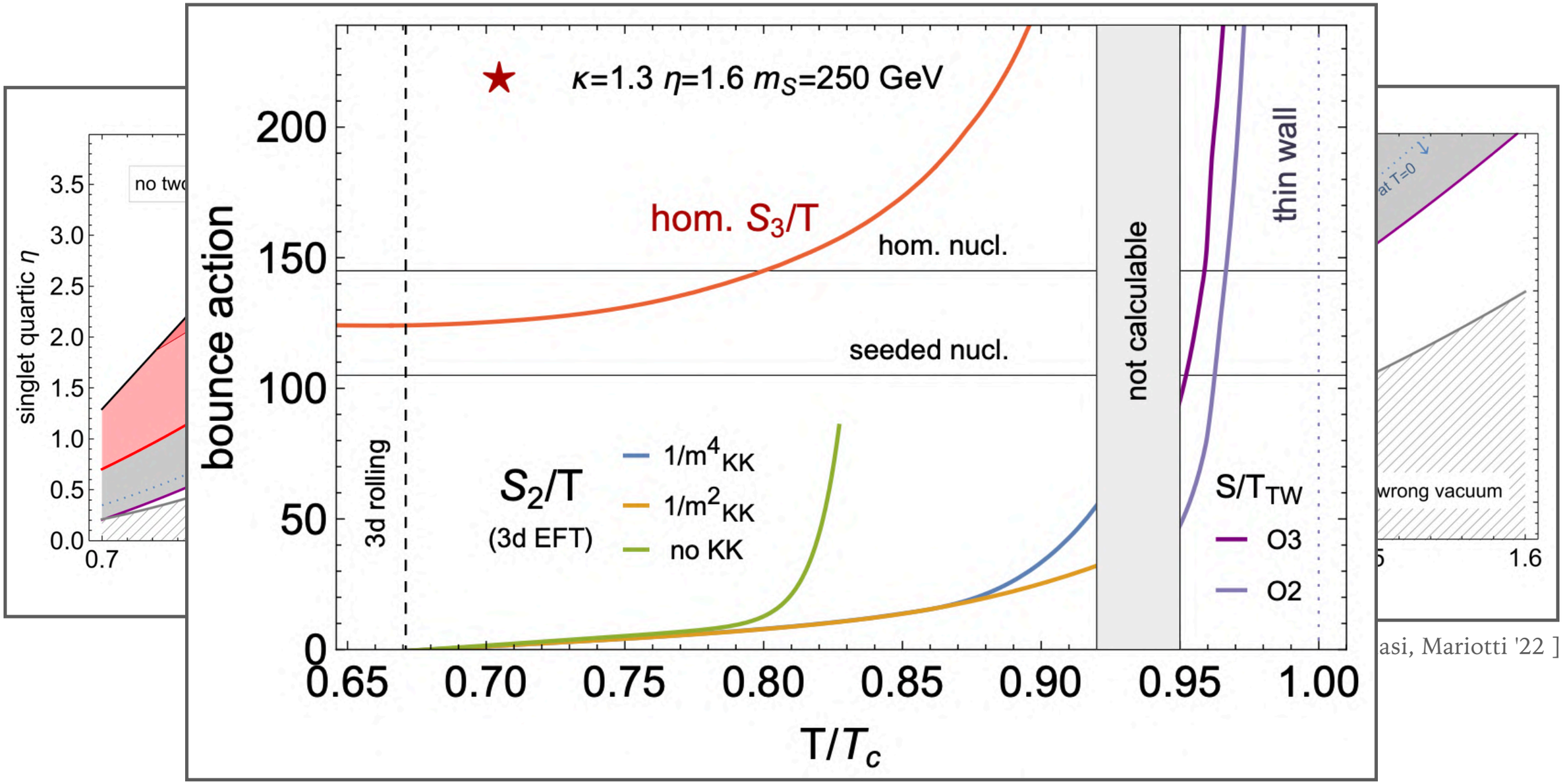


GW PRODUCTION

[Blasi, RJ, Konstandin, Rubira, Stomberg, '23]

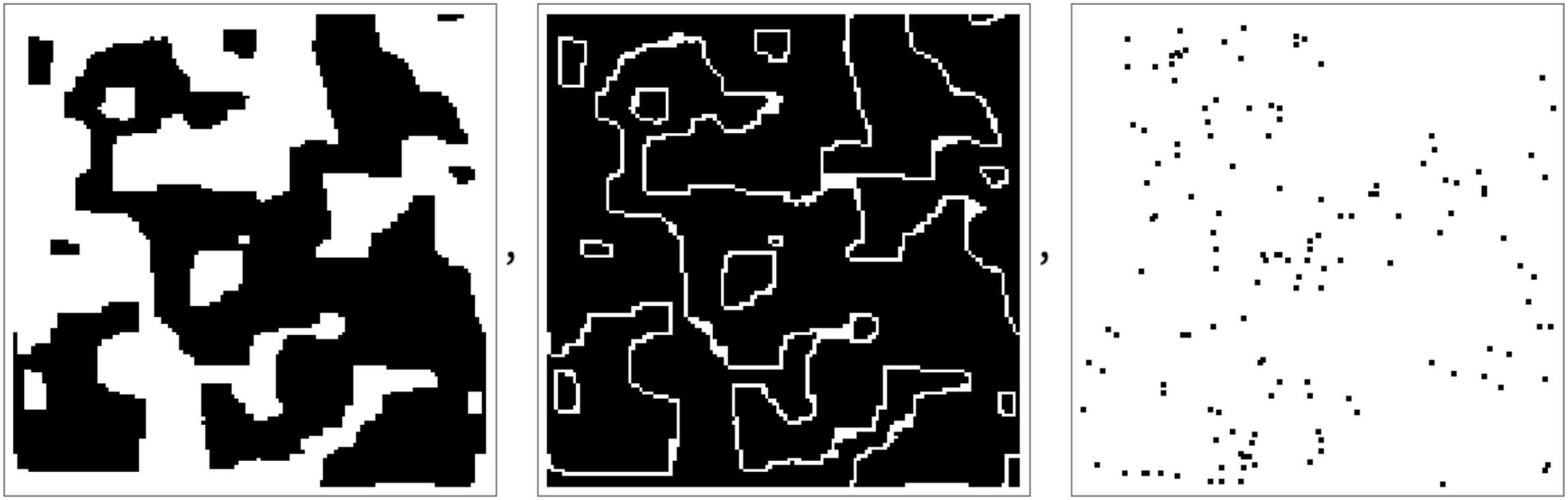
- We mimic the domain wall network using the Ising model

  (assuming some universality in the wall network for different systems)

DW network

||

spin ↑ vs. ↓ | boundary btwn. ↑ and ↓ | nucleation sites



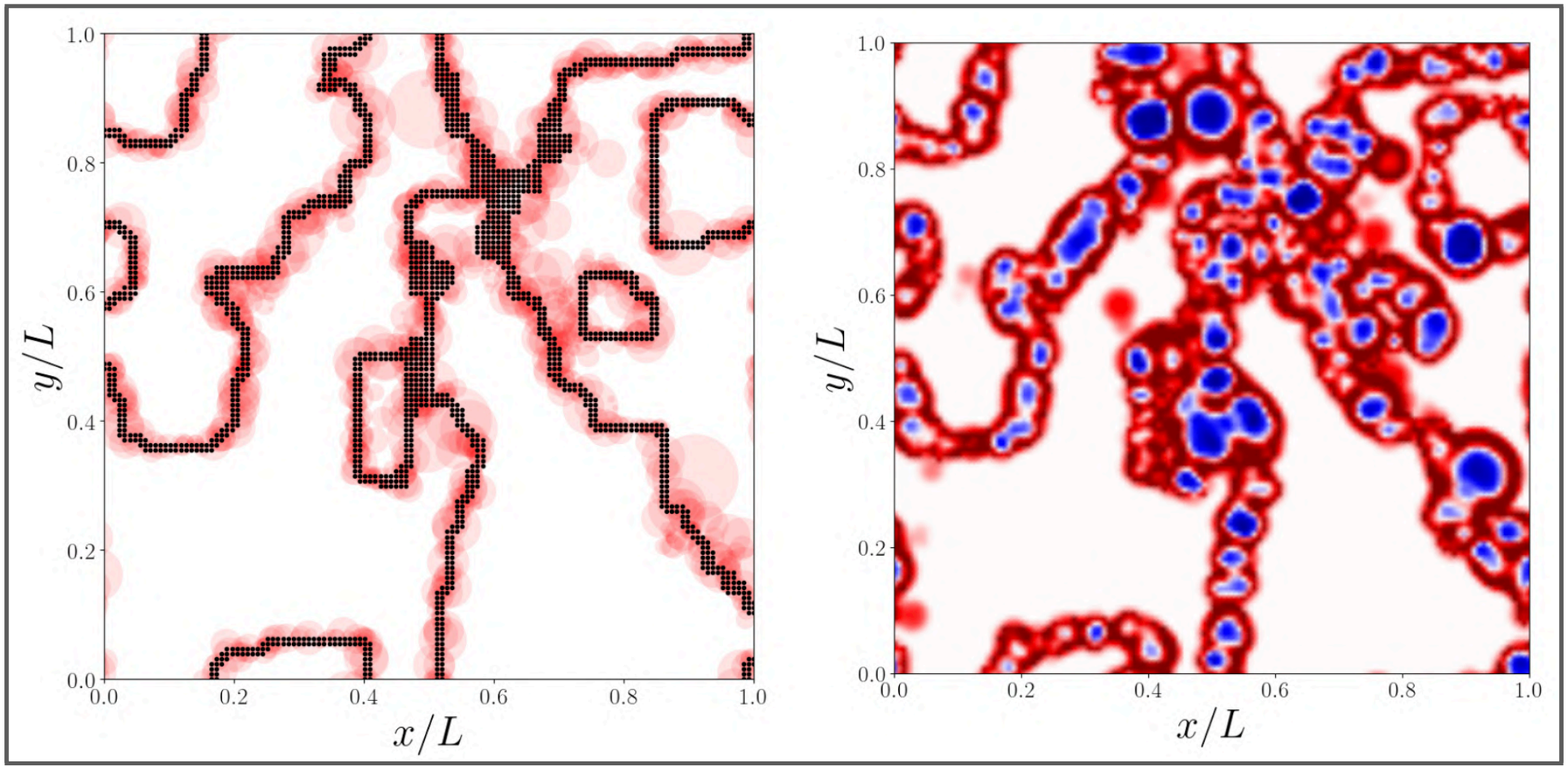
GW PRODUCTION

[Blasi, RJ, Konstandin, Rubira, Stomberg, '23]

➤ We mimic the domain wall network using the Ising model

DW network & expanding bubbles

fluid kinetic energy



each red disk = bubble

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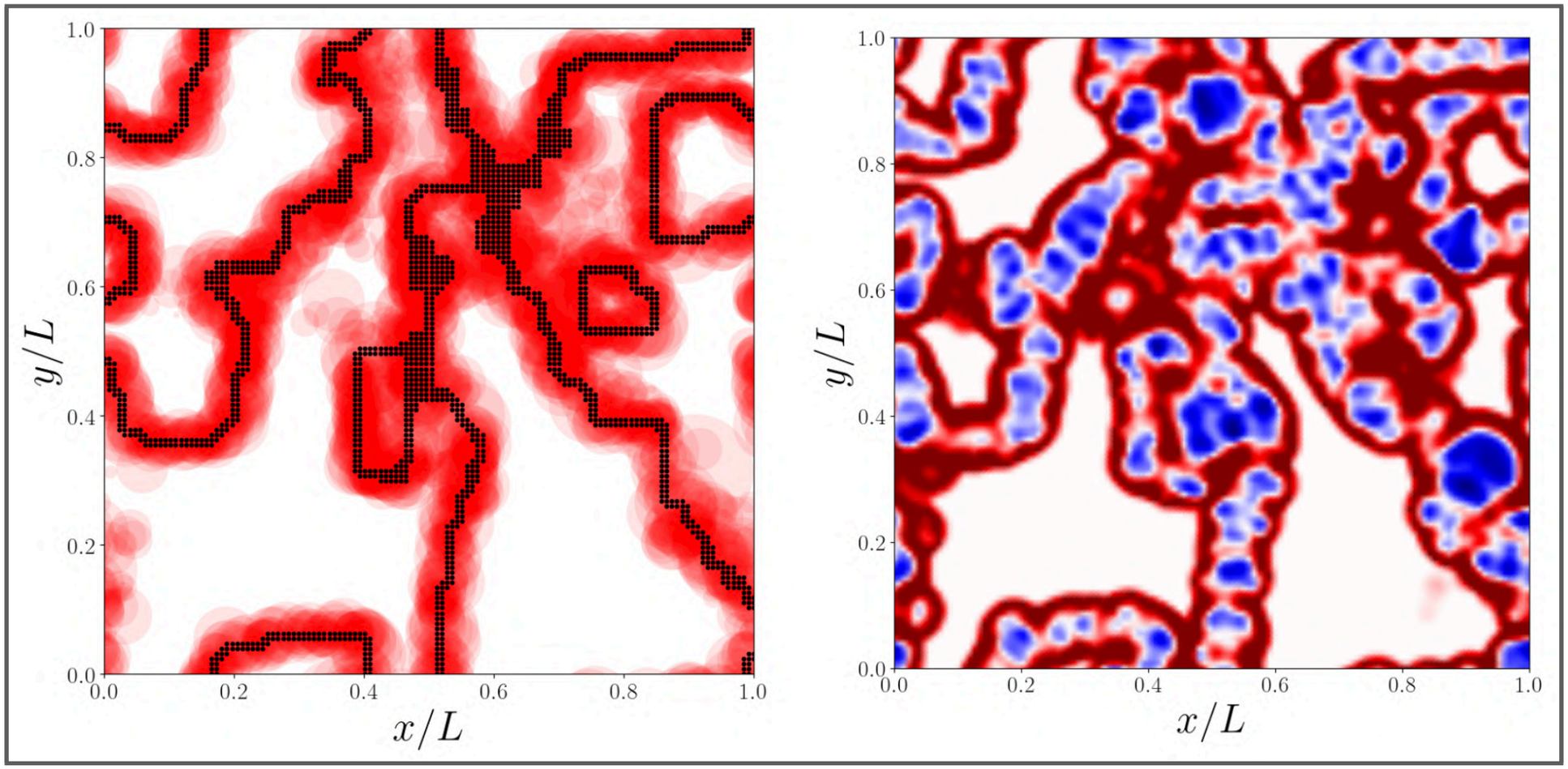

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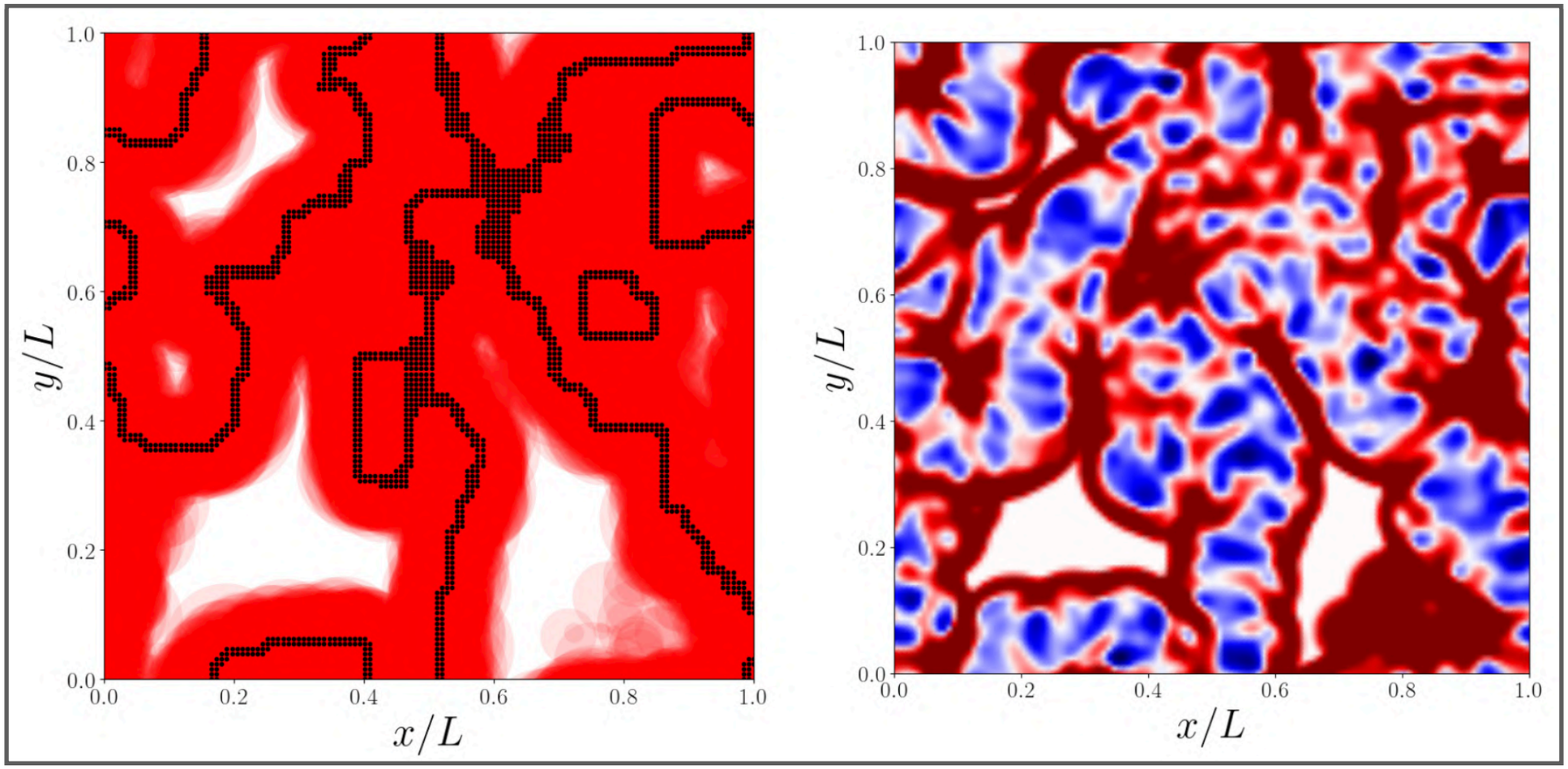
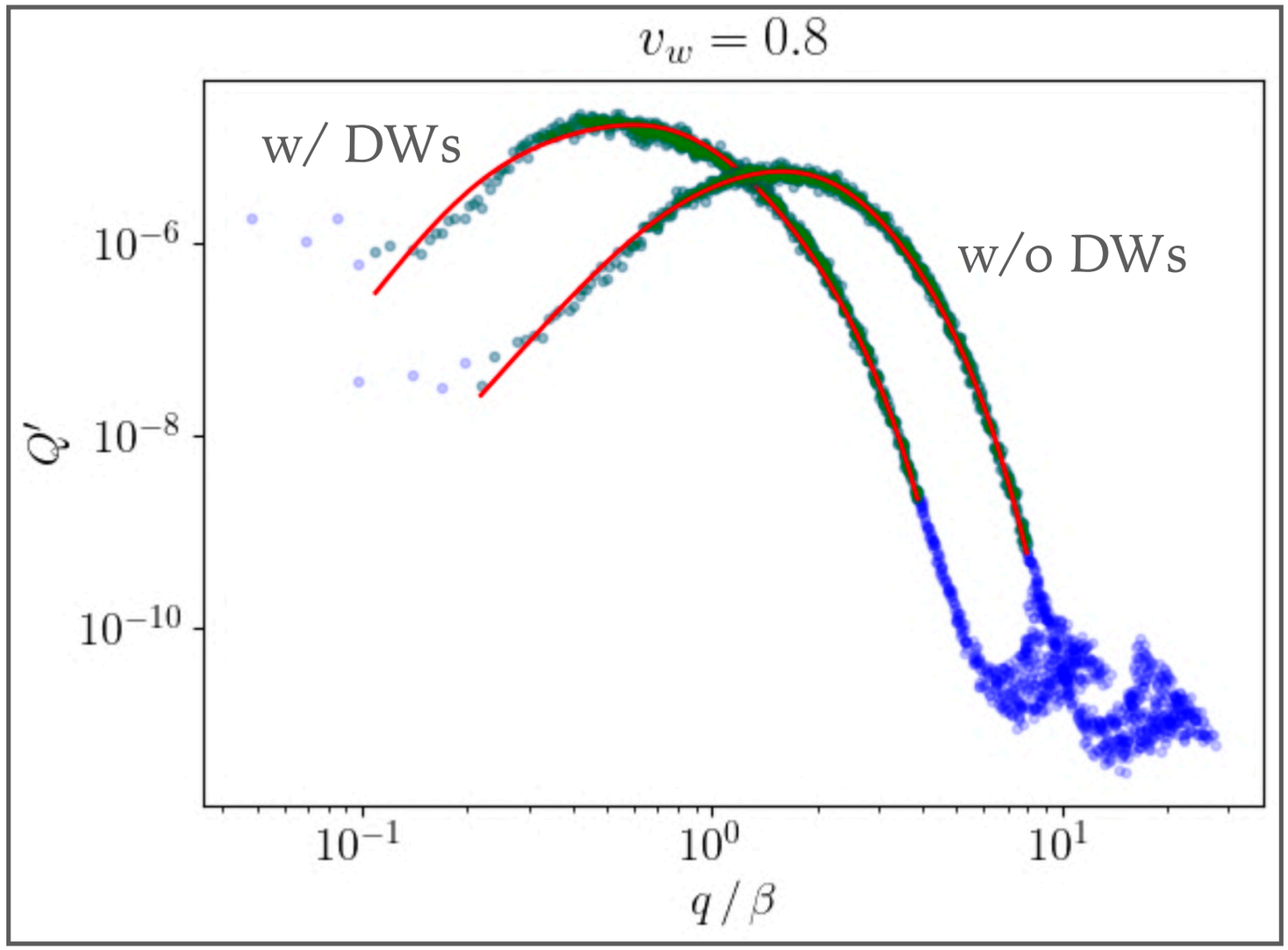


each red disk = bubble

GW PRODUCTION

[Blasi, RJ, Konstandin, Rubira, Stomberg, '23]

- GW frequency vs. GW power (= energy emitted per unit time)
  - GW power enhances, if the correlation length of the DW > bubble size



INTUITIVE EXPLANATION

➤ Big & relativistic objects radiate more GWs

- Integrate the GW equation of motion over the coherence time Δt of the source

$$\Box h_{ij} \sim G T_{ij} \xrightarrow[\text{coherence time } \Delta t]{\text{integration over}} \dot{h}_{ij} \sim G T_{ij} \Delta t$$

oscillator

kicked oscillator

- GW energy density $\rho_{\rm GW} \sim G^{-1} \dot{h}_{ij}^2 \propto T_{ij}^2 \Delta t^2$ (n.b. GWs from sound waves behave a bit differently)

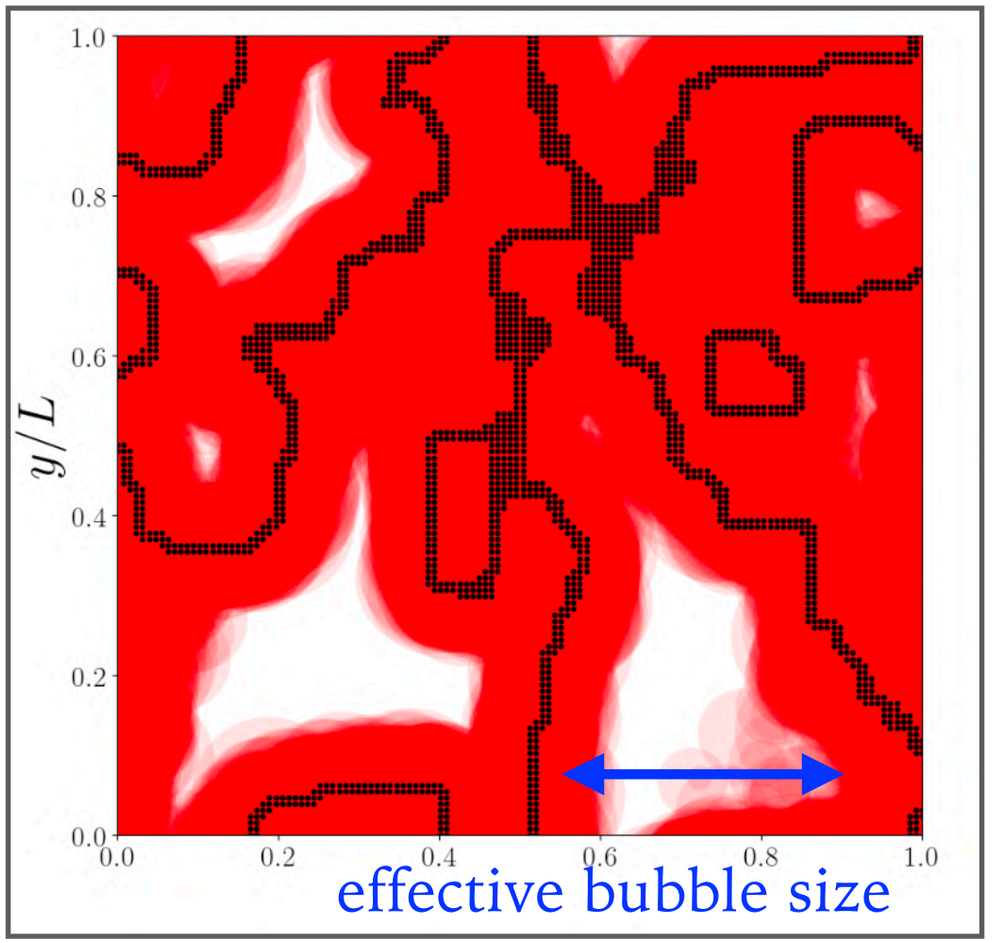
1. Relativistic objects have larger $T_{ij} \propto \alpha$

2. Big bubbles typically have longer coherence time $\Delta t \propto \beta^{-1}$

GW PRODUCTION

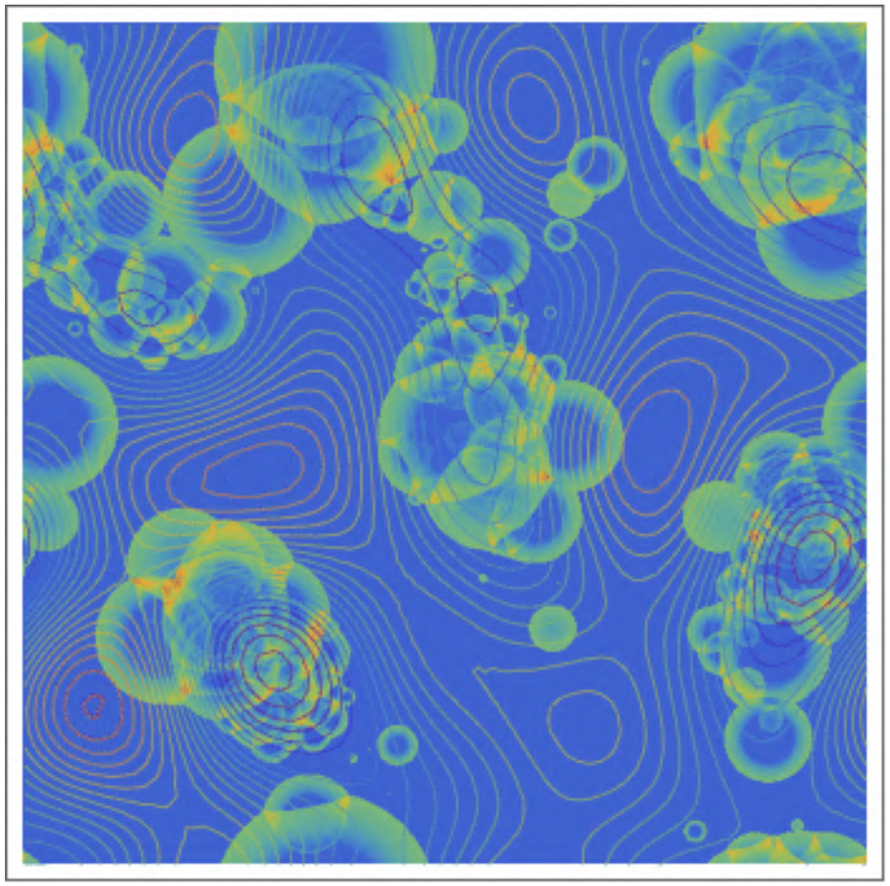
[Blasi, RJ, Konstandin, Rubira, Stomberg, '23]

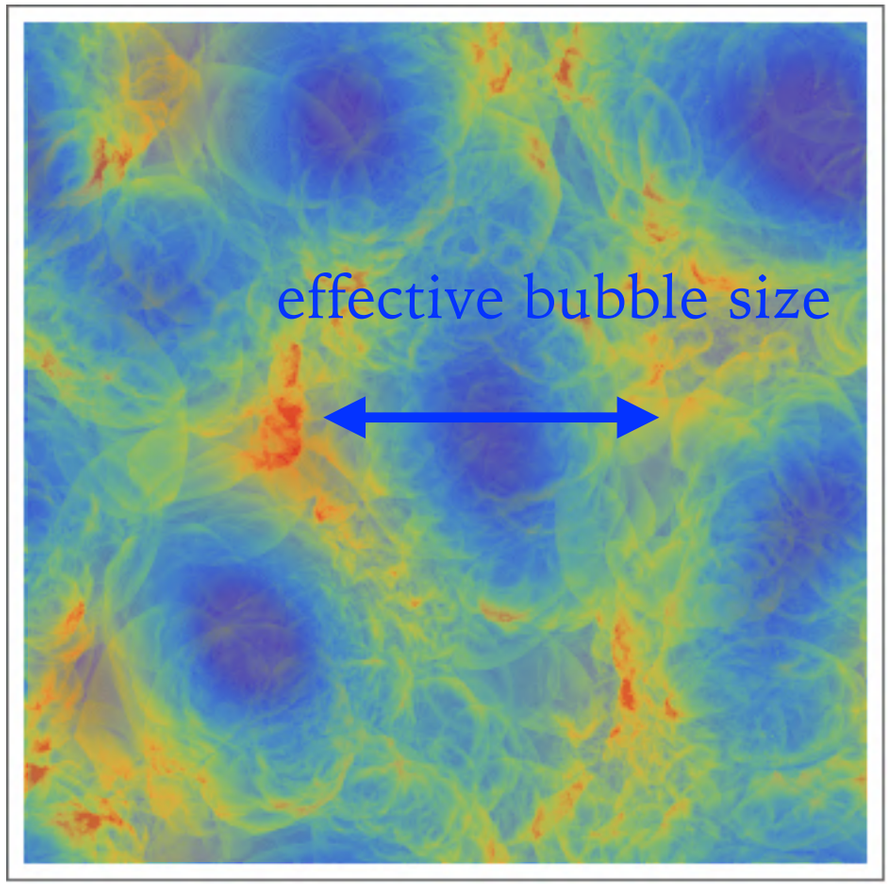
- In the present case, typical distance between DWs determines the size of the "effective bubble"



GW PRODUCTION

- In the present case, typical distance between DWs determines the size of the "effective bubble"
- Similar things happen for nucleation in density perturbations





[RJ, Konstandin, Rubira, van de Vis, '21]

1 *Overview*

2 *FOPT & GWs*

3 *Defect-driven FOPTs*

4 *Summary*

SUMMARY

- Impurities (= mostly domain walls in this talk)

  may seed bubble nucleation in the early-Universe plasma

- In such cases, the correlation length of the impurities determines the distribution of bubbles and resulting GW production

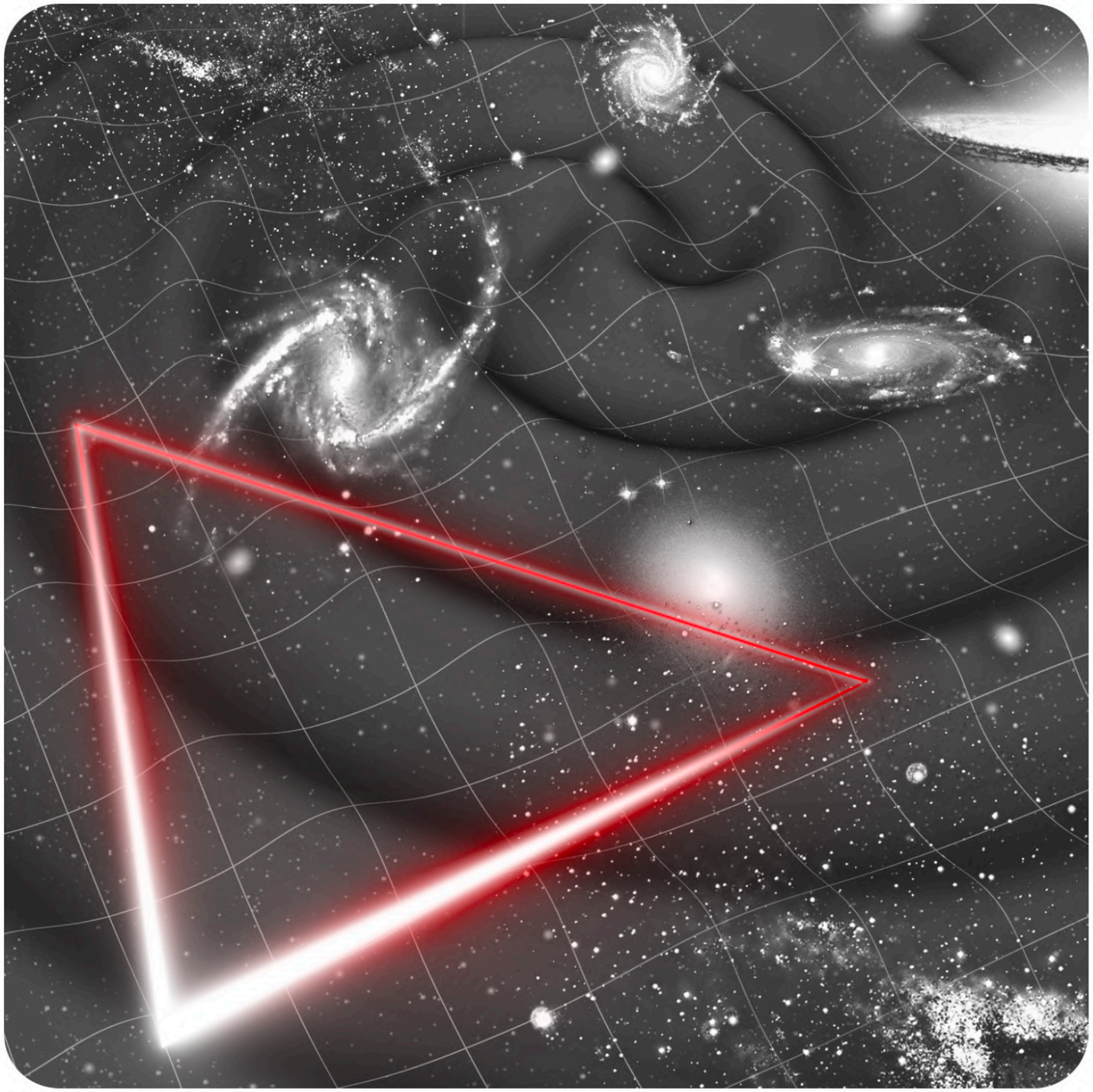
- For larger correlation length, the GW spectrum shifts towards lower frequencies and tends to have larger energy density

Backup

LISA MISSION

LISA

Laser Interferometer Space Antenna



LISA "Red Book" (Definition Study Report)

 Ryusuke Jinno (Kobe Univ.) "*Gravitational waves from defect-driven phase transitions: domain walls*"

LISA MISSION: DETECTOR CONFIGURATION

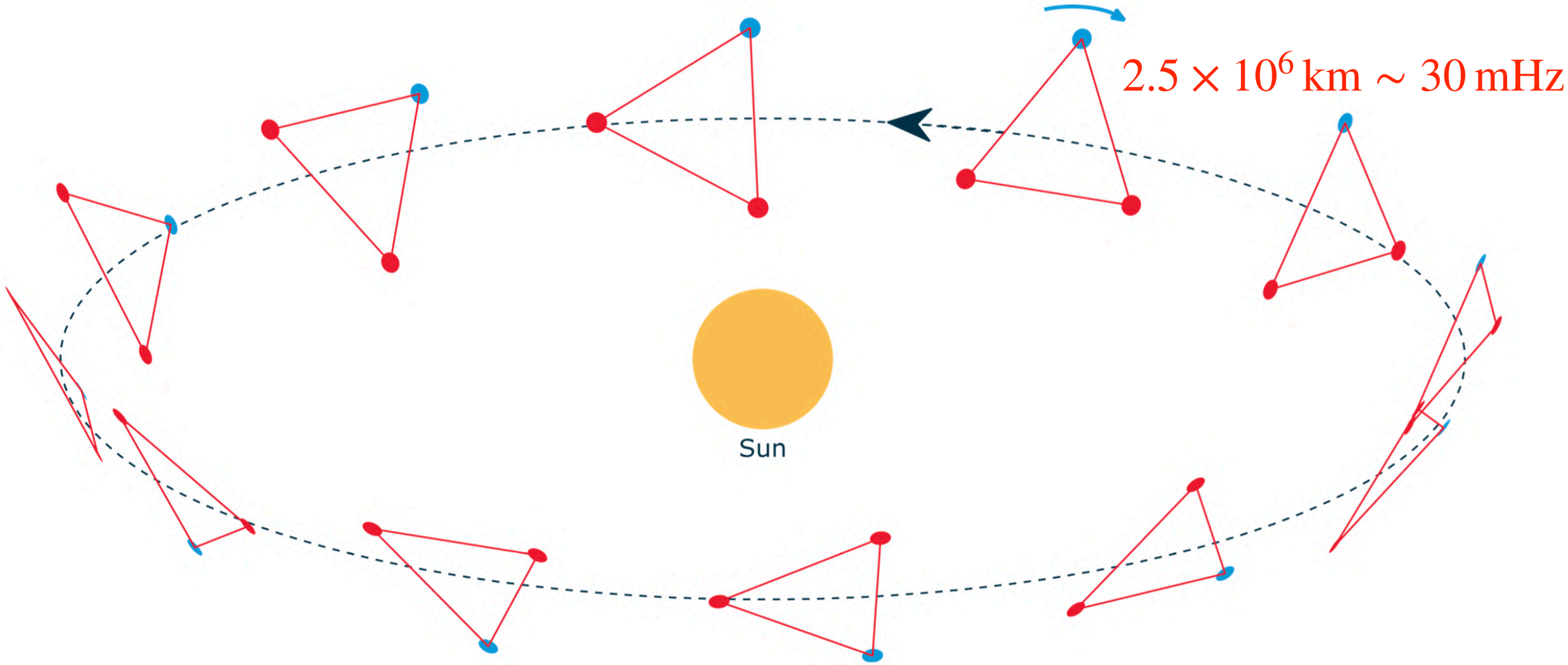
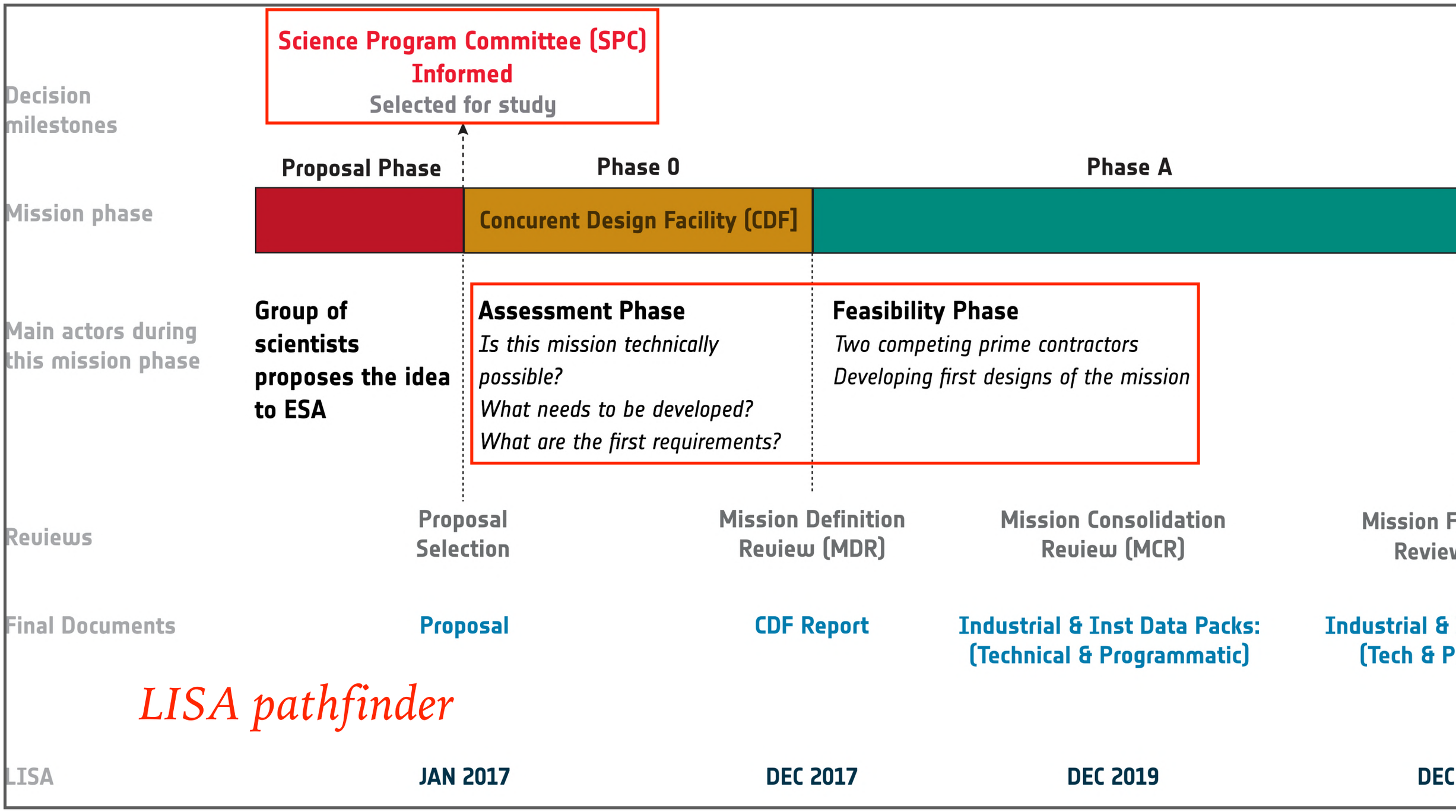
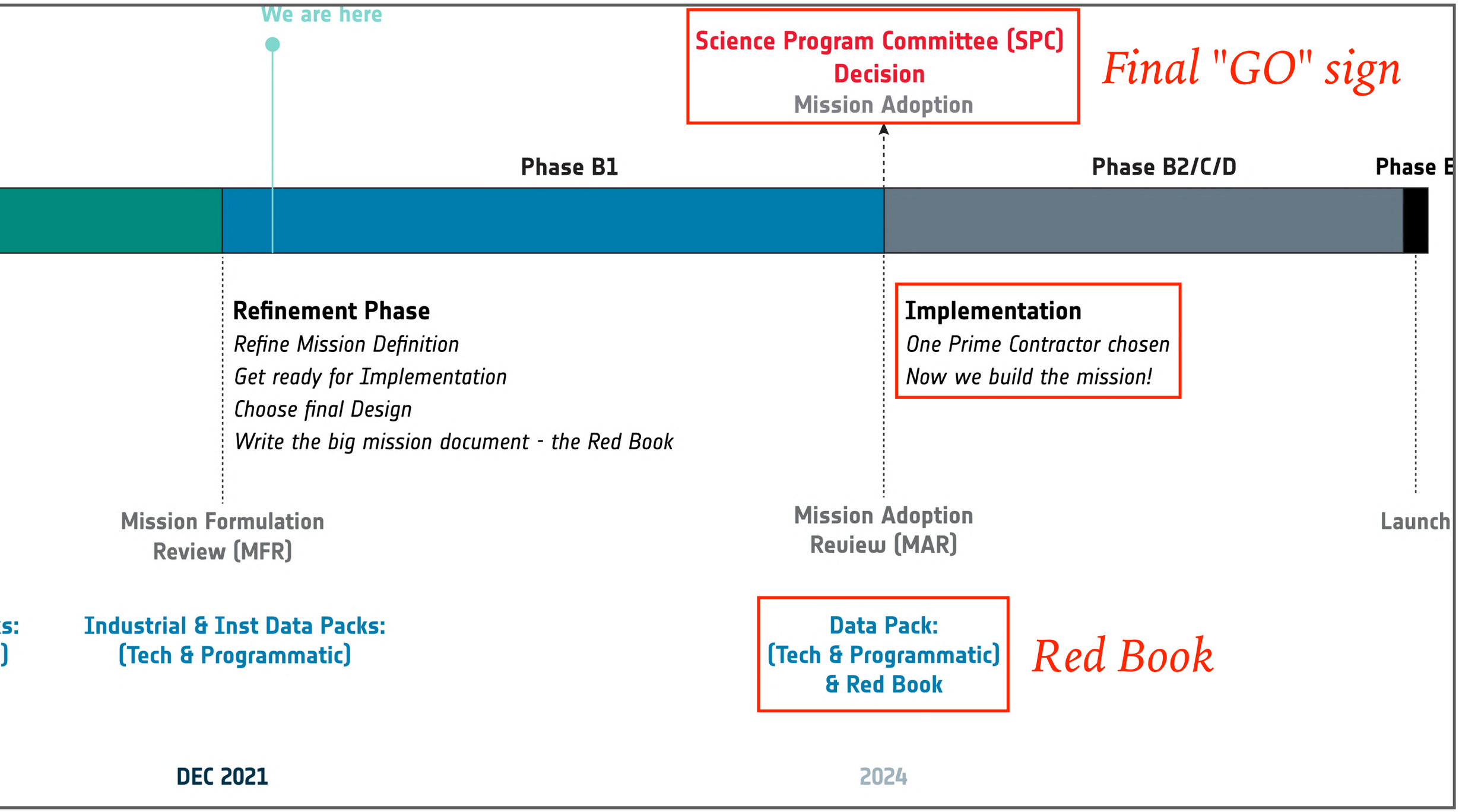


Figure 6.3: LISA orbits for the three individual spacecraft. The centre of mass of the constellation follows a heliocentric, circular orbit with no inclination. The orbits of the spacecraft have a small eccentricity $e = \eta/(2\sqrt{3}$ and an inclination of $\iota = \arcsin(\eta/2)$ where $\eta = L/1\,\mathrm{AU} \approx 0.017\,(L/2.5 \times 10^6\,\mathrm{km})$ is the armlength measured in AU. The 60° inclination of the constellation results in a backwards rotation of the constellation (blue arrow).

LISA MISSION: TIMELINE



LISA MISSION: TIMELINE



LISA MISSION: LISA PATHFINDER

→ THE EUROPEAN SPACE AGENCY

esa

LISA factsheet

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Overview of the LISA mission.

Name: Laser Interferometer Space Antenna (LISA)

Planned launch: ~2035

Mission: First gravitational wave detector in space.

Status: On 20 June 2017, LISA was selected as the third large-class mission, L3, under ESA's Cosmic Vision 2015-2025. It was then adopted on 25 January 2024. Construction will begin in January 2025 after a prime contractor has been chosen.