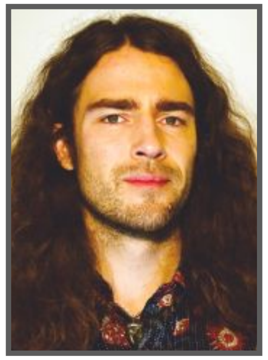

T. Konstandin


H. Rubira


B. Shakya


I. Stomberg


J.v.d.Vis

Gravitational waves from feebly-interacting particles in a first-order phase transition

Ryusuke Jinno (RESCEU, UTokyo)

2023/11/9, "Gravitational Wave Probes of Physics Beyond Standaerd Model", Osaka City University

[RJ, Shakya, van de Vis 2211.06405]

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

T. Konstandin H. Rubira B. Shakya I. Stomberg J.v.d.Vis

Introduction

GWs from sound waves in FOPT

GWs from FIPs in FOPT

Summary

Gravitational waves from feebly-interacting particles in a first-order phase transition

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OVERVIEW OF FIRST-ORDER PHASE TRANSITION & BUBBLE DYNAMICS

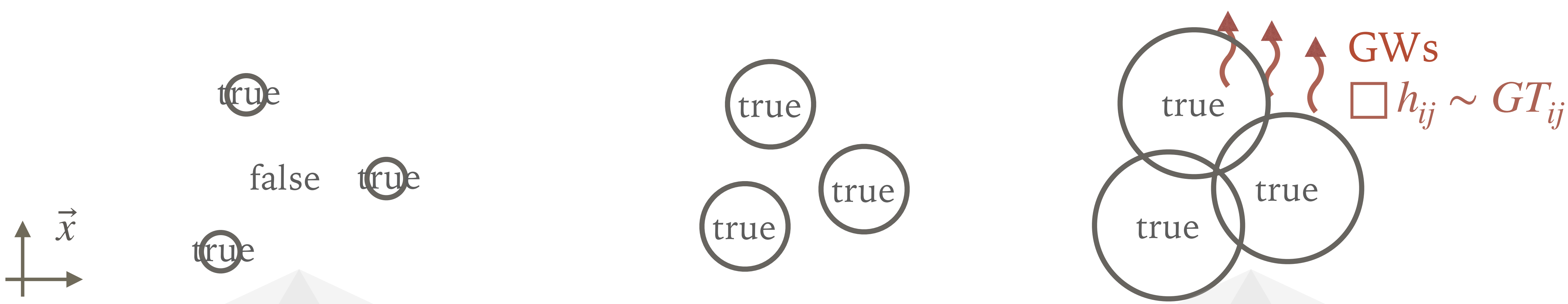
[Hogan '83] [Witten '84]

microphysics

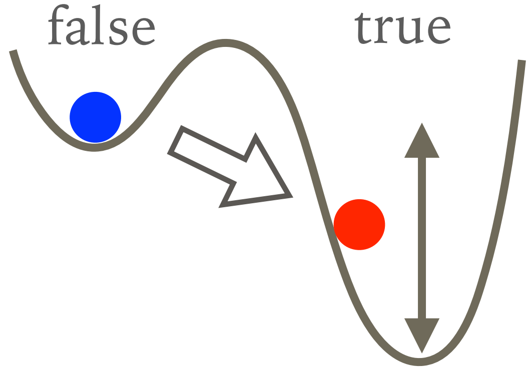
macrophysics

time or scale →

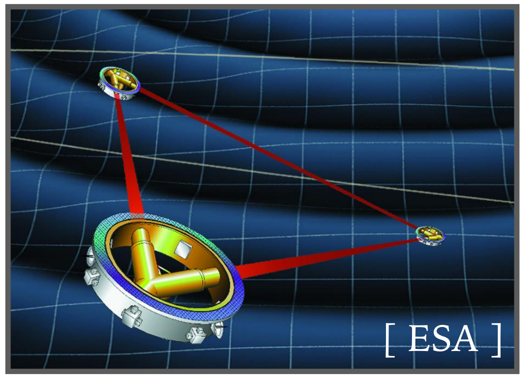
(1) nucleation (核生成) (2) expansion (拡大) (3) collision (衝突)



Physics of the Higgs sector



GW observations



GW PRODUCTION: THE STANDARD LORE & BEYOND

- GW sources e.g. [Caprini et al. '16] [Caprini et al. '20]

Bubble walls [Kosowsky, Turner, Watkins '92] [Kosowsky, Turner '92] ...

Energy released accumulates in the walls (= scalar field kinetic & gradient)

Fluid = Sound waves & Turbulence [Kamionkowski, Kosowsky, Turner '93] ... [Hindmarsh, Huber, Rummukainen, Weir '14] ...

Particles in the broken phase frequently interact and can be described by fluid picture.

Aren't we missing one possibility?

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Particles in the broken phase frequently interact and can be described by fluid picture.

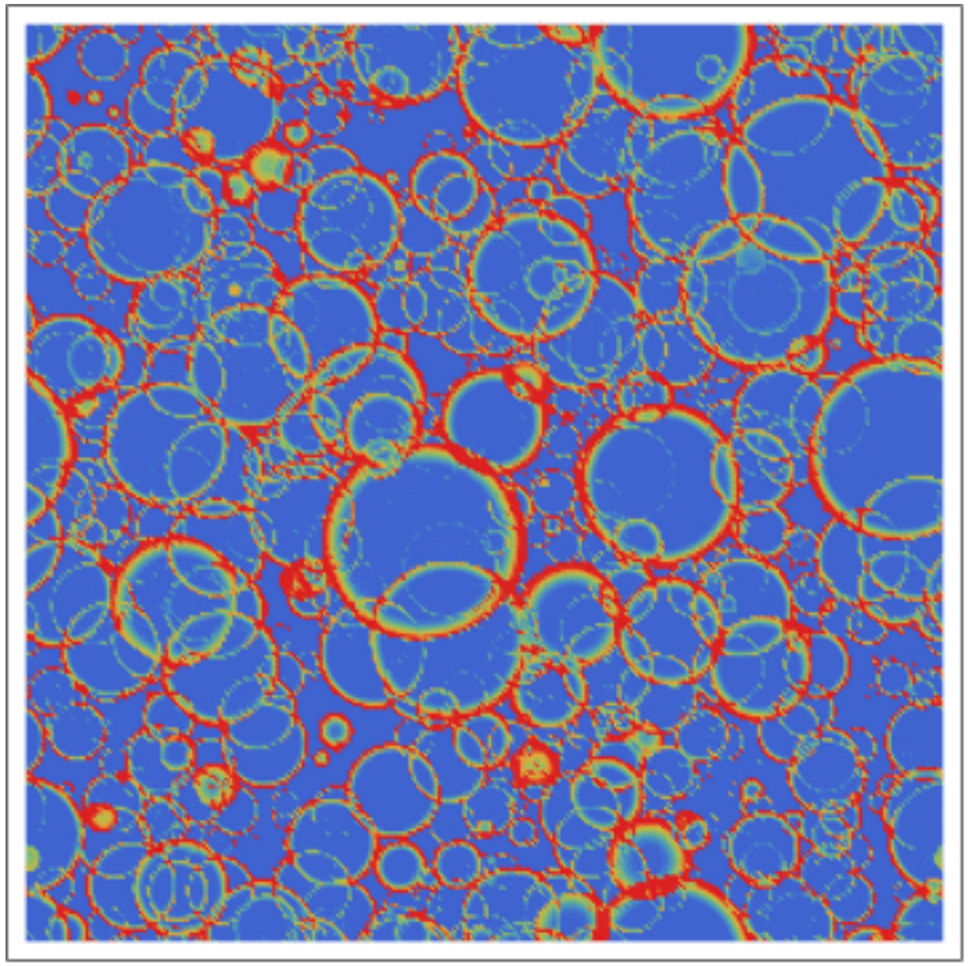
Feebly-interacting particles

Particles in the broken phase are only feebly interacting and free-stream.

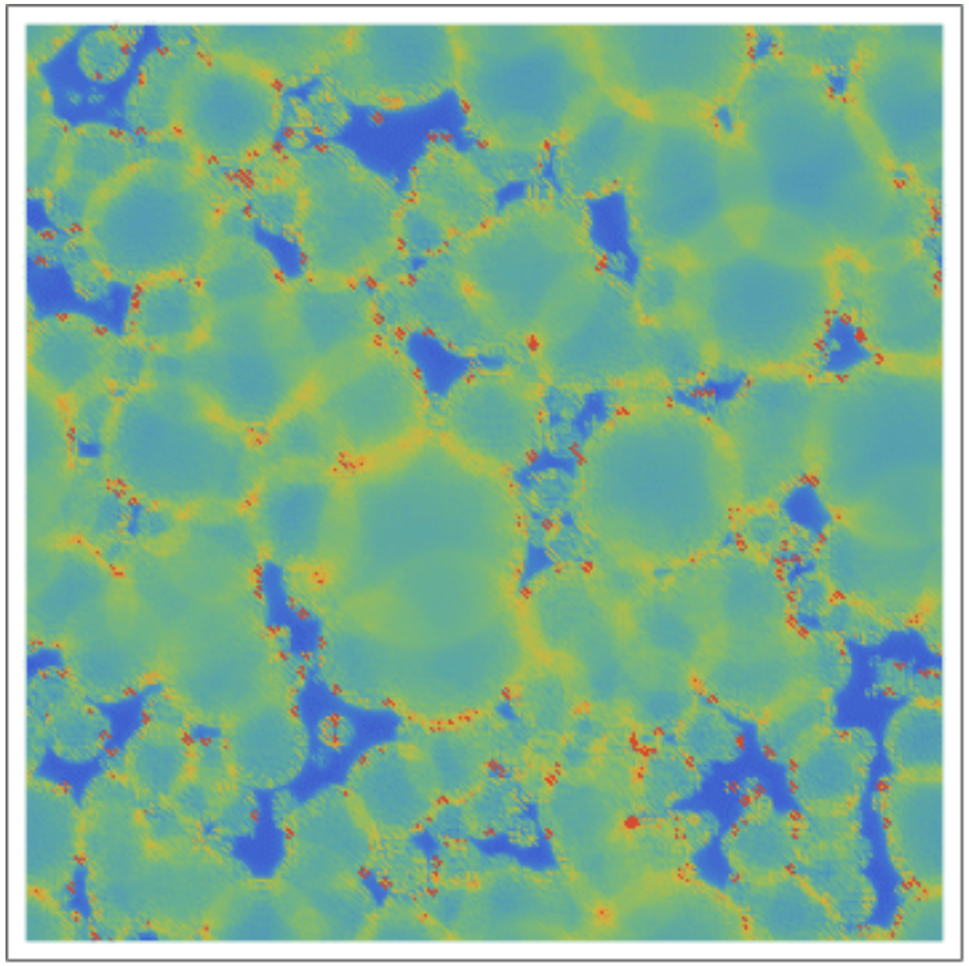
EVOLUTION OF BUBBLES WITH FEEBLY-INTERACTING PARTICLES

- Fluid case vs. feebly-interacting case

Fluid



Feebly-interacting



- Introduction
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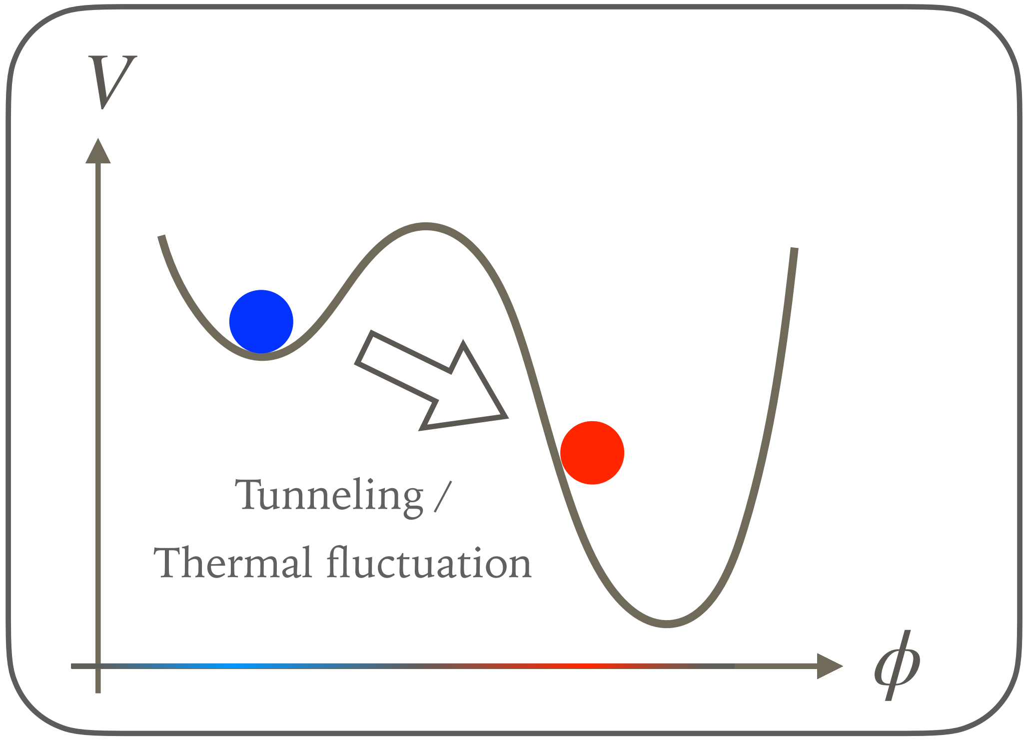
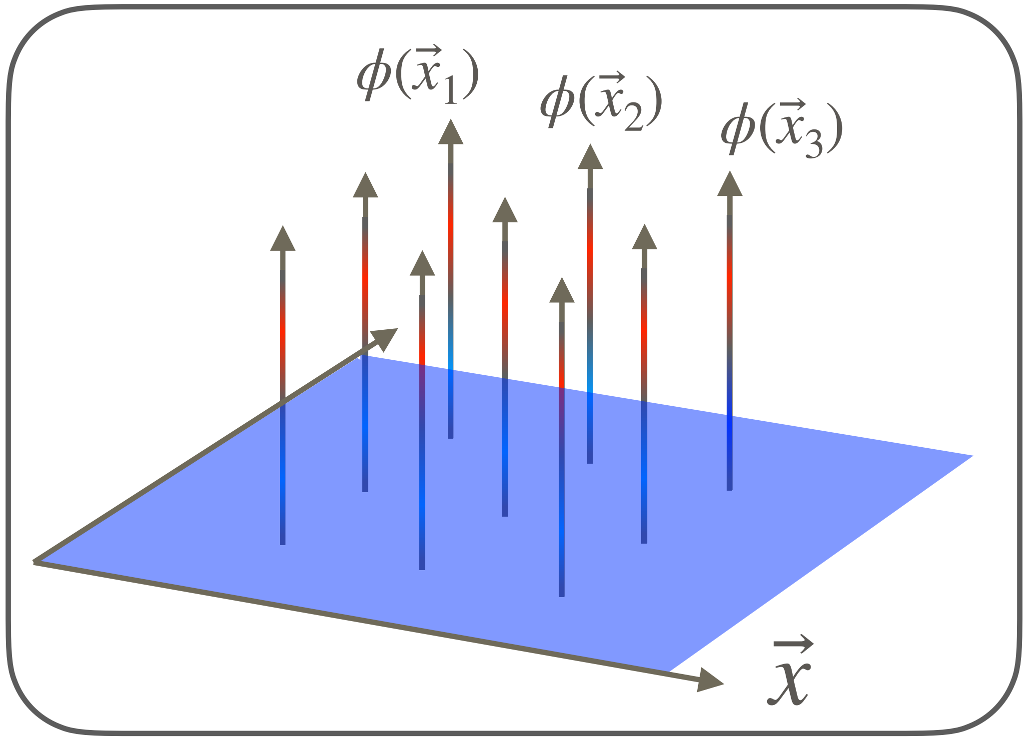
- GWs from FIPs in FOPT
- Summary

TUNNELING IN QUANTUM MECHANICS AND QFT

Field space



Position space



TUNNELING IN QUANTUM MECHANICS AND QFT

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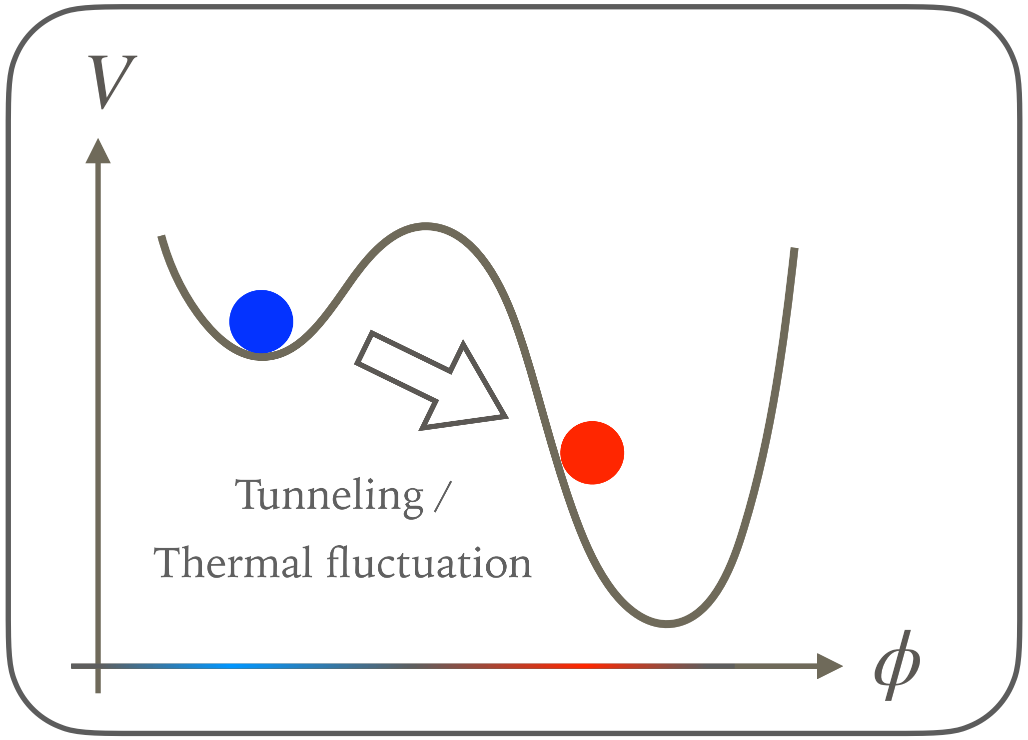

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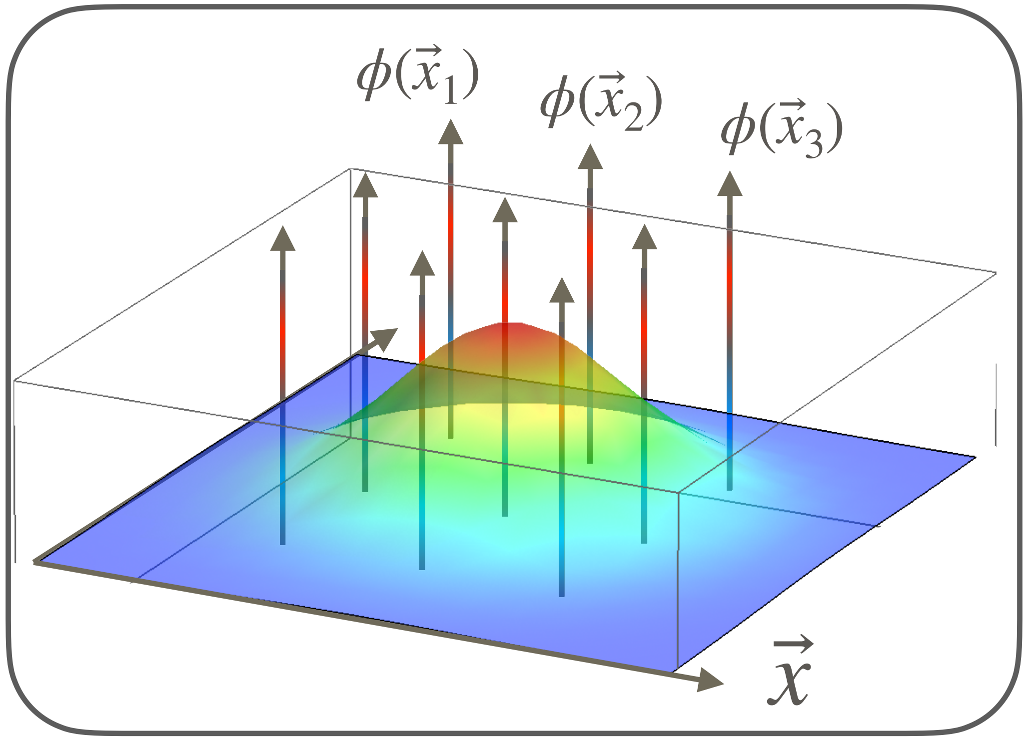
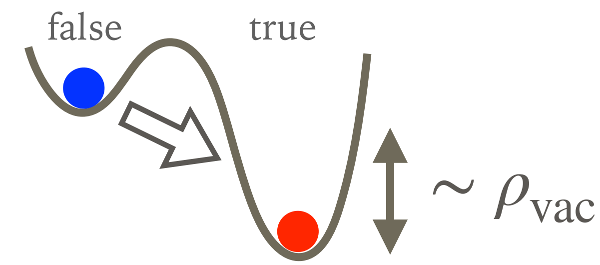


nucleation (核生成)

STEP 2 : BUBBLE EXPANSION



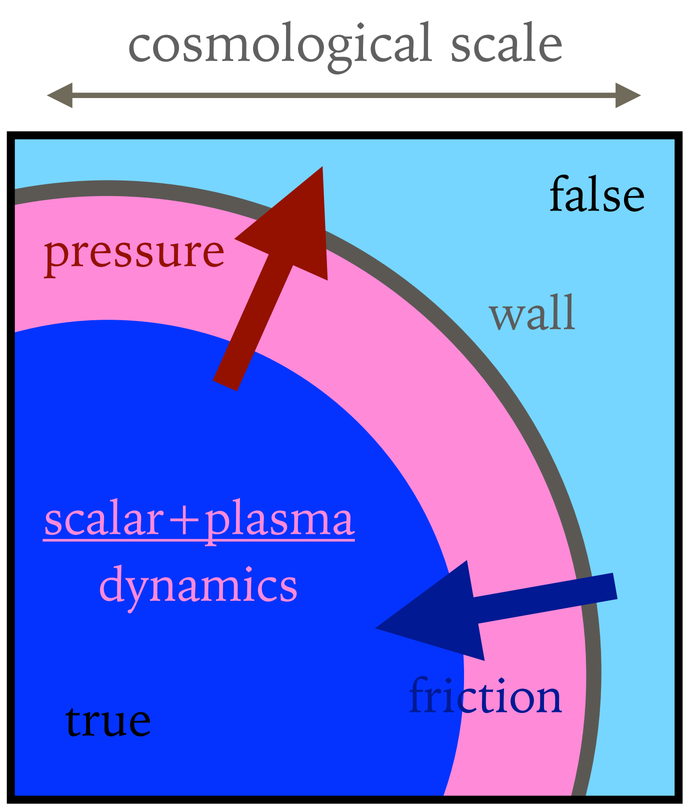
- "Pressure vs. Friction" determines the behavior:

  (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, Giese et al. '21]

  (2) Friction: wall is pushed back by plasma particles



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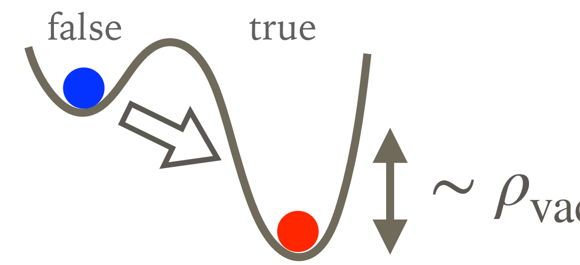

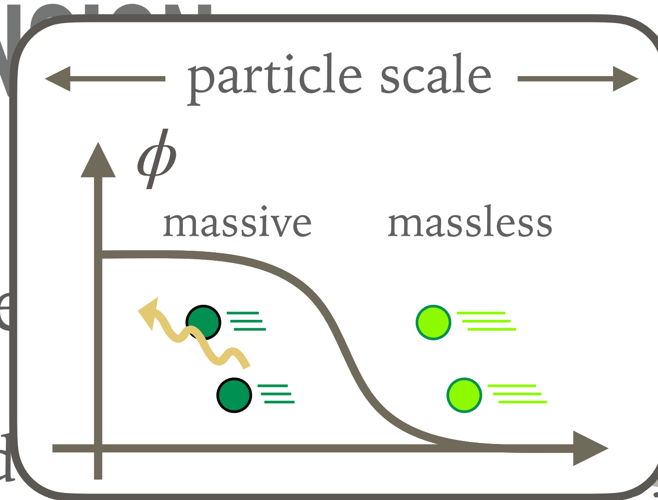

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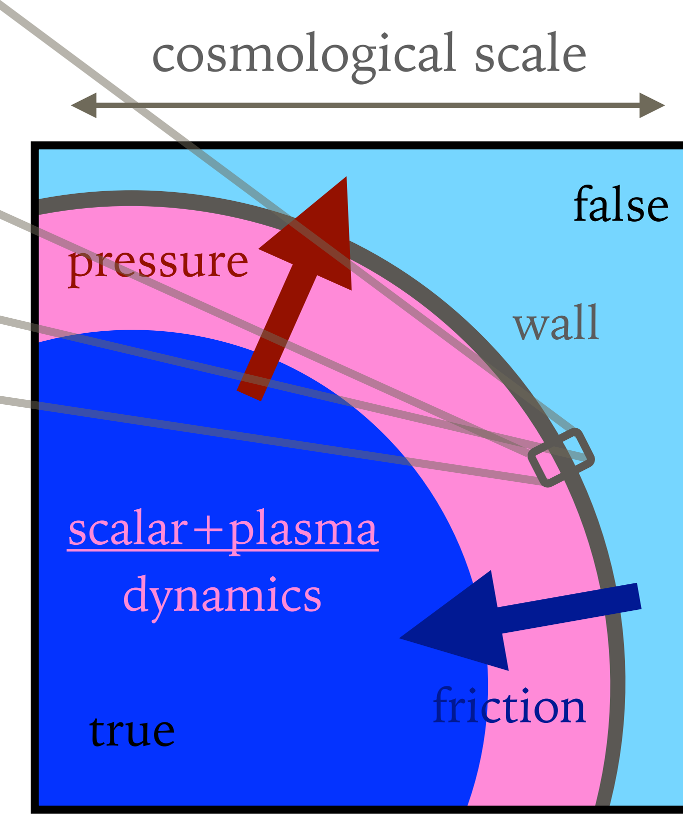

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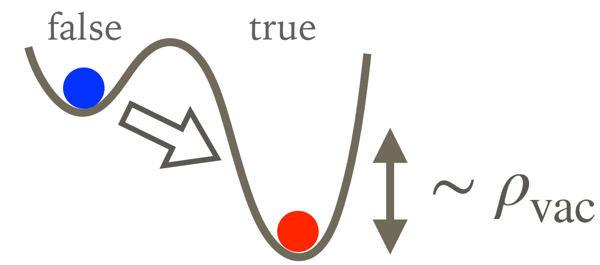

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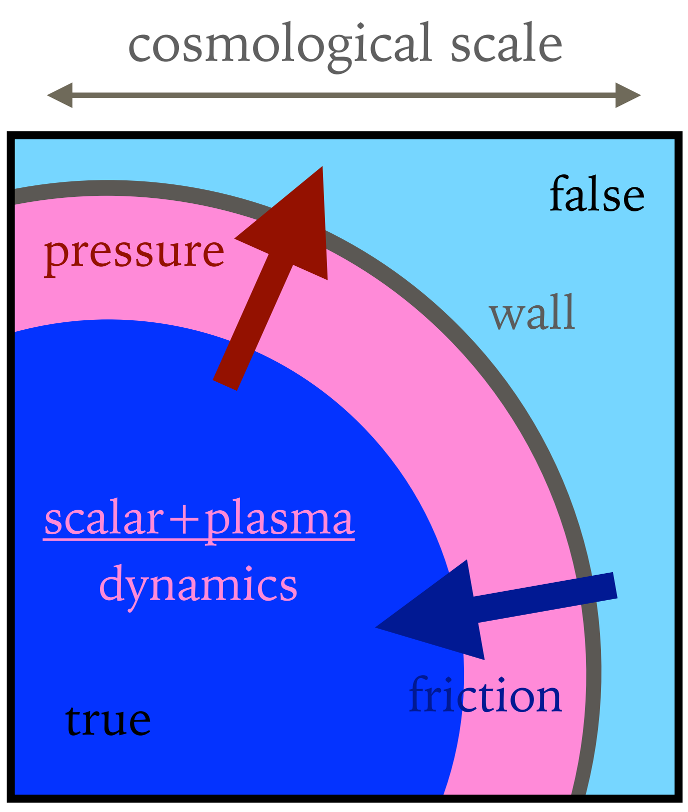
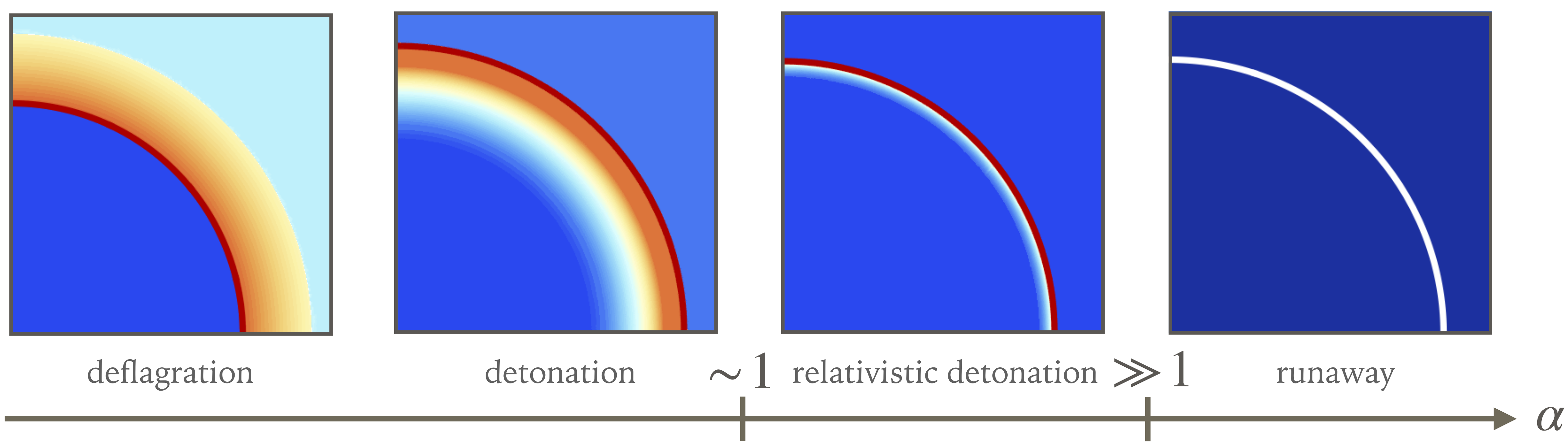
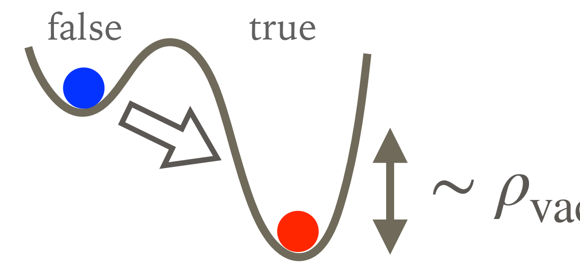


- Different types of bubble expansion



STEP 2 : BUBBLE EXPANSION



➤ "Pr

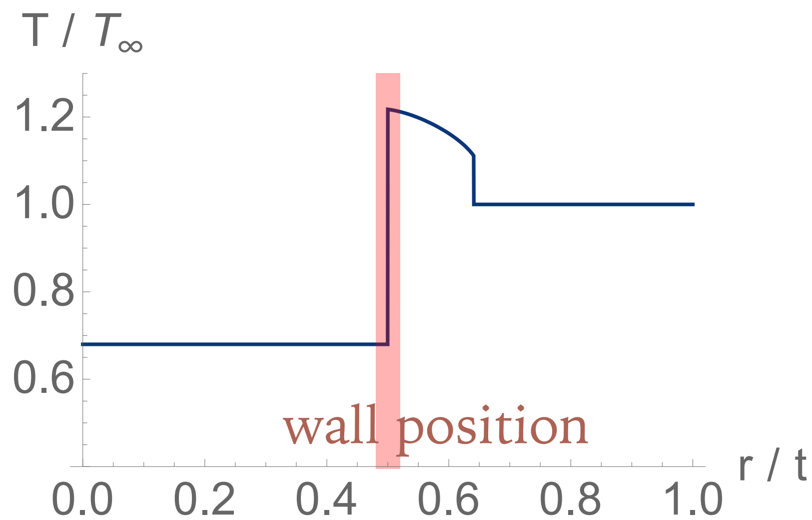
(1)

(2)

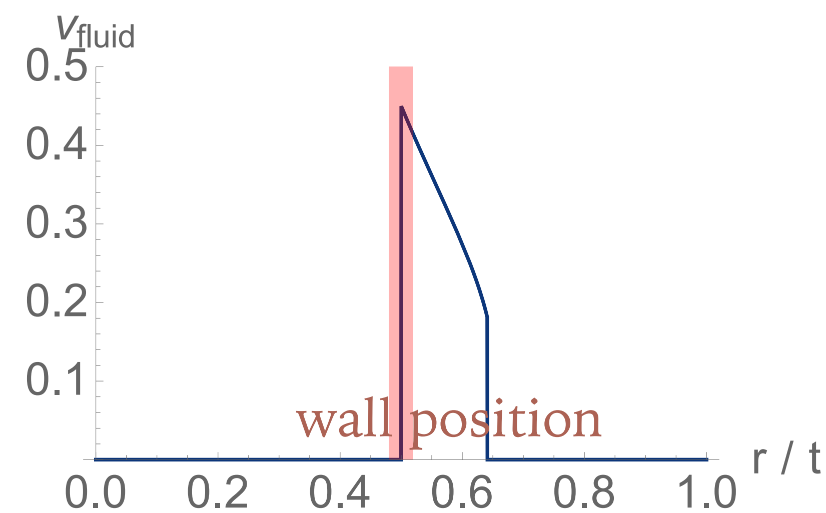
➤ Di

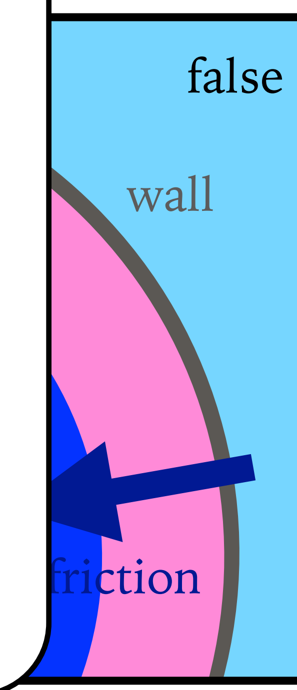
al scale

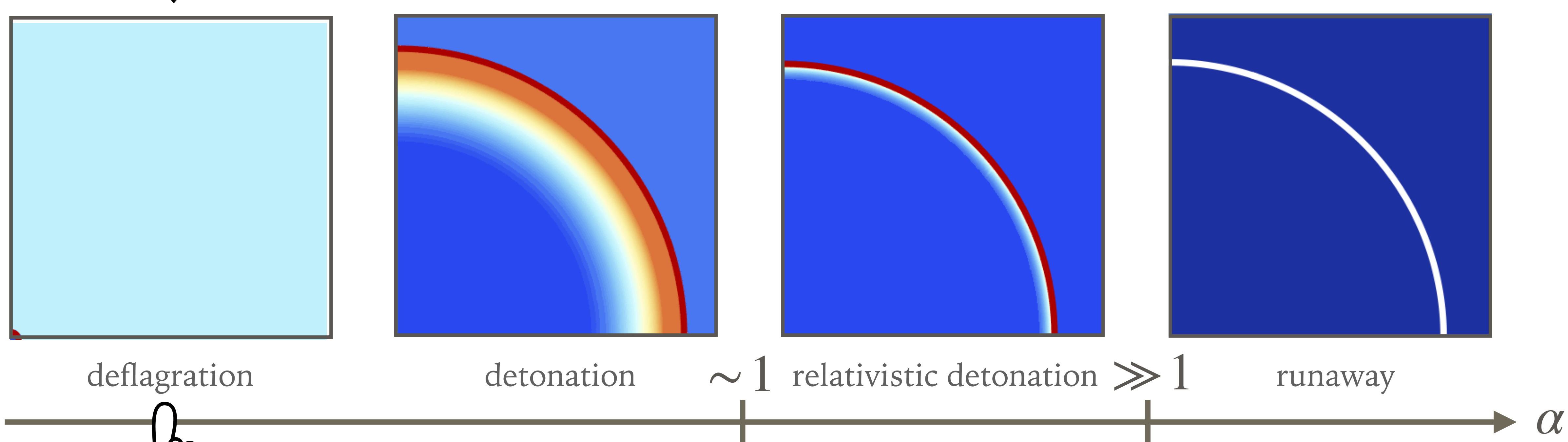
Temperature



Fluid outward velocity







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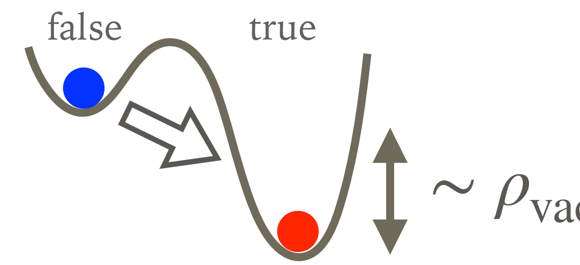
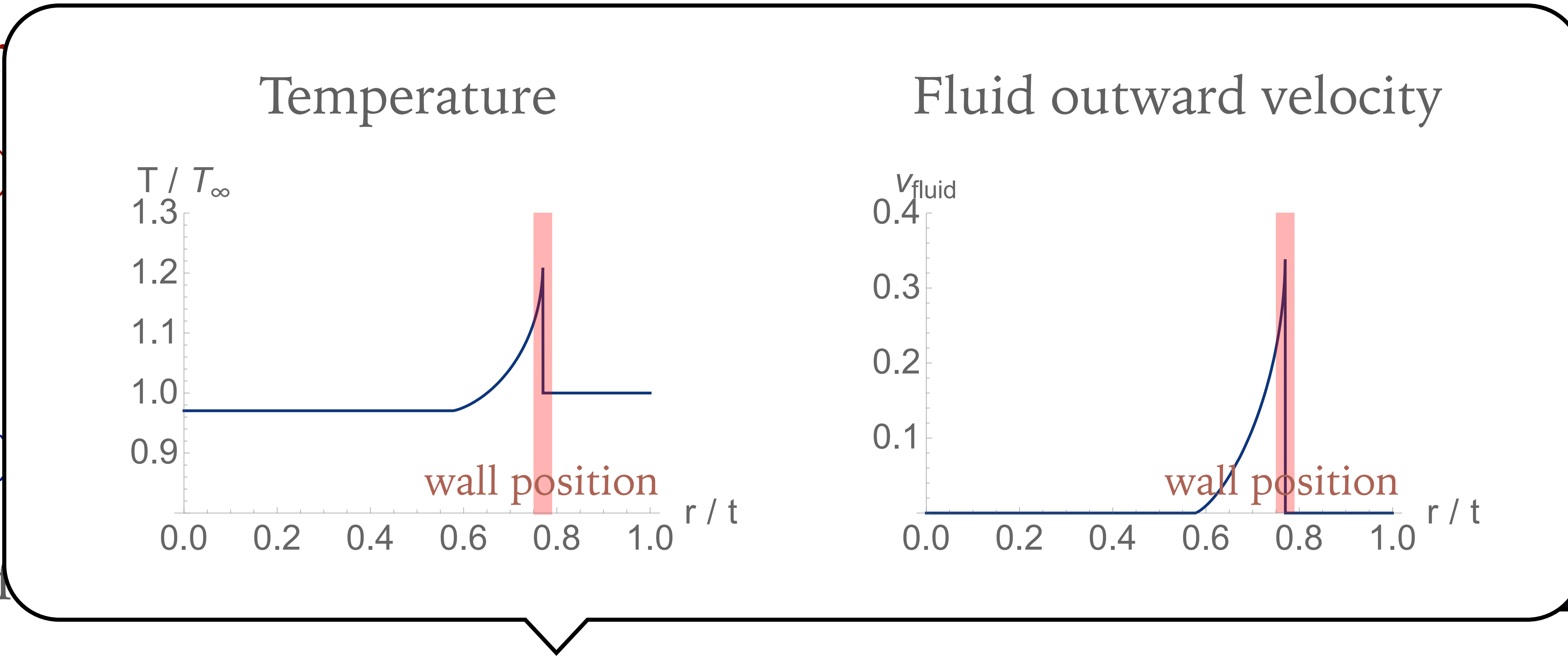
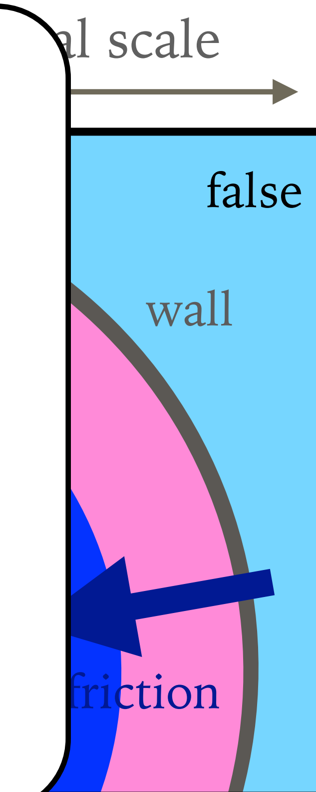


➤ "Pr

(1)

(2)





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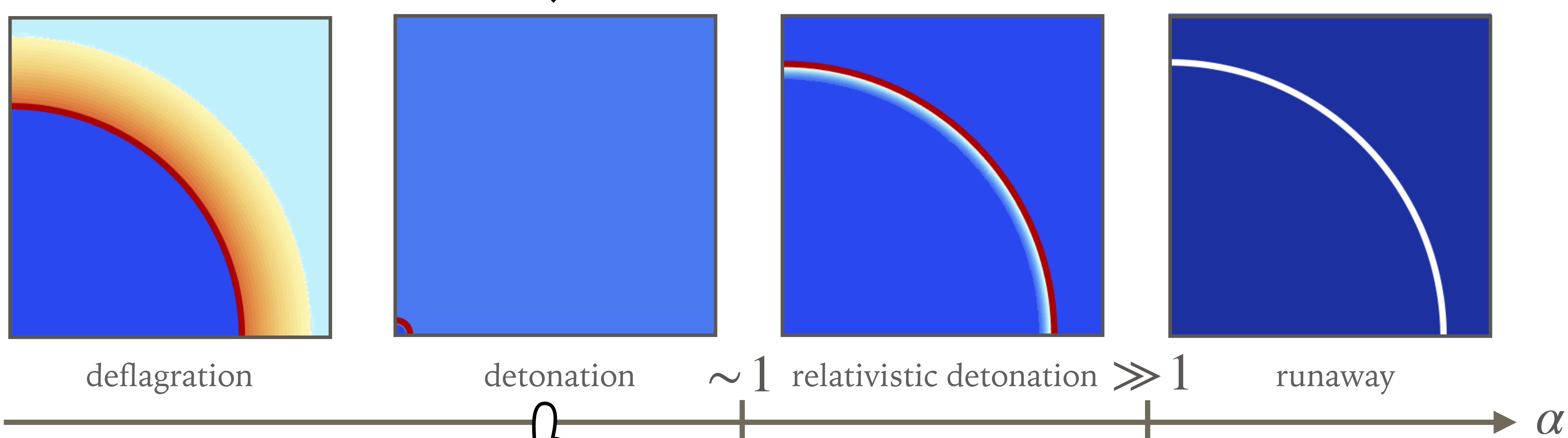

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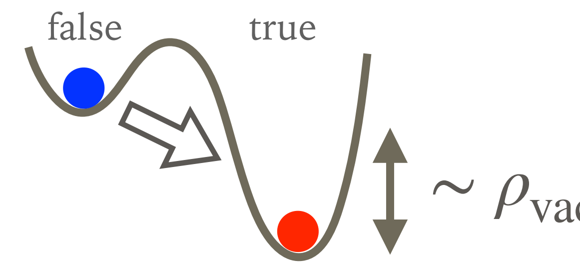
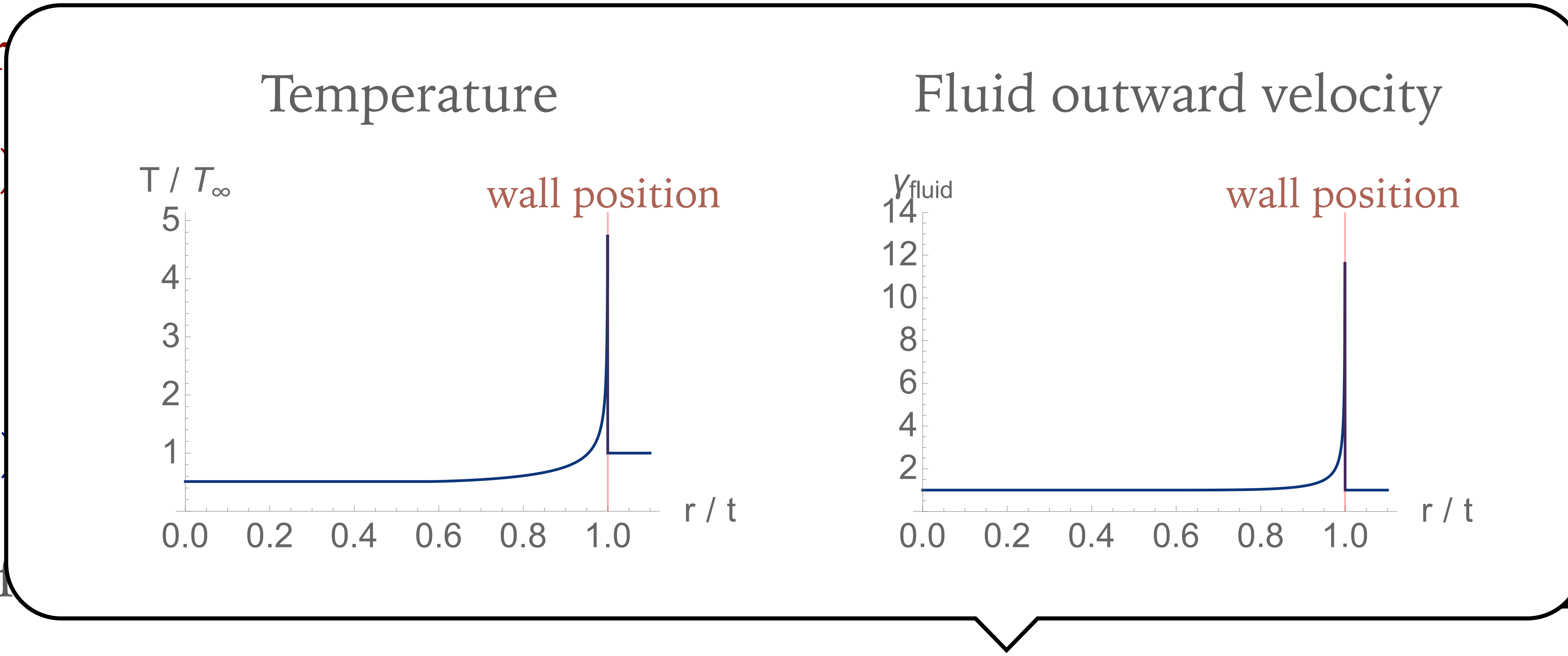


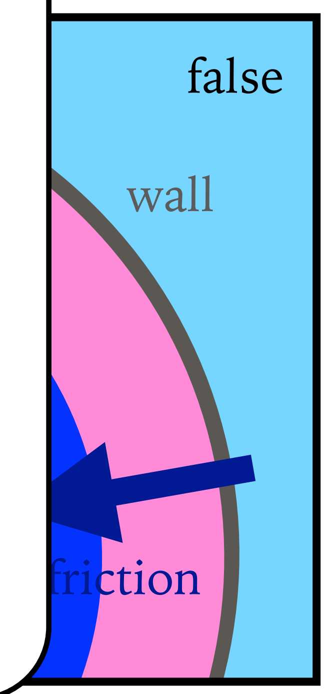
➤ "Pr

al scale

(1)

(2)





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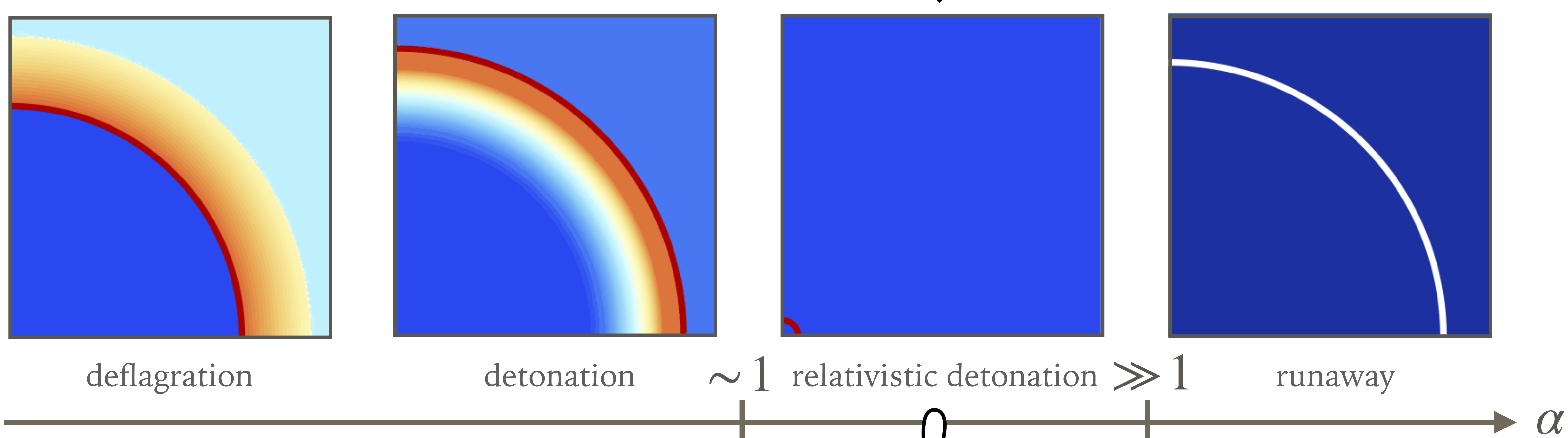

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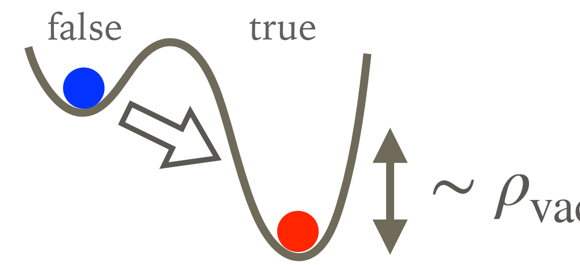


➤ "Pr ... al scale

(1)

(2)

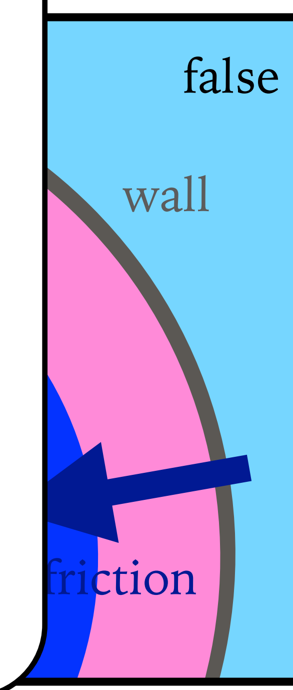
Plasma particles cannot stop the acceleration of the walls:

walls continue to accelerate until they collide with others

[Bodeker & Moore '09, '17] [Azatov & Vanvlasselaer '20] [Gouttenoire, RJ, Sala '21]

[Höche, Kozaczuk, Long, Turner, Wang '20] [Barroso Mancha, Prokopec, Świeżewska '21]

[Azatov, Barni, Petrossian-Byrne, Vanvlasselaer '23] ...



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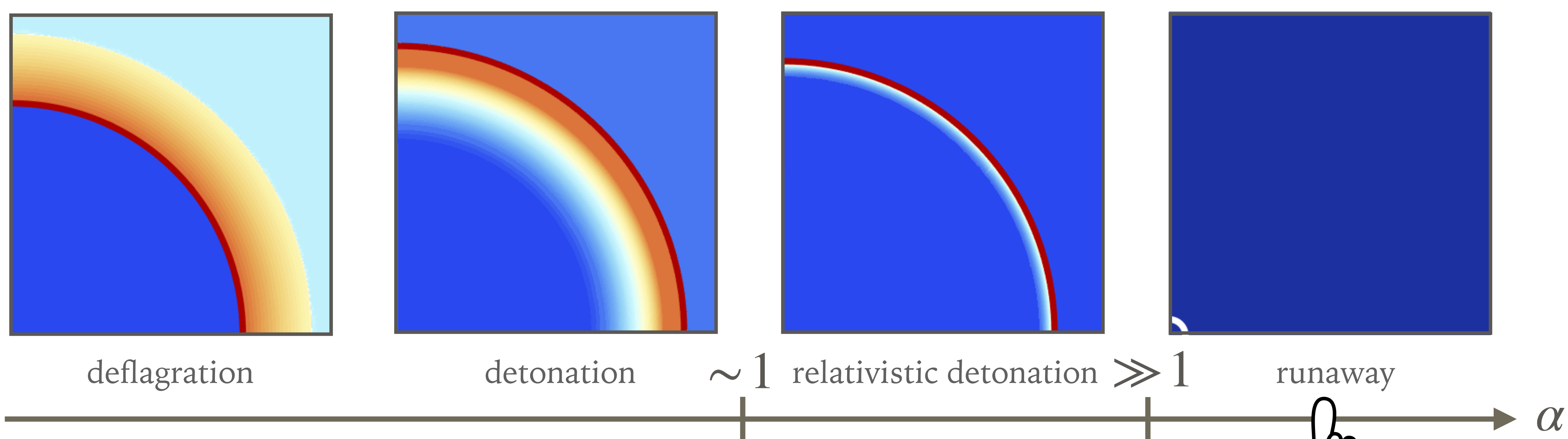
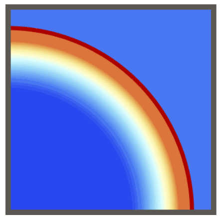
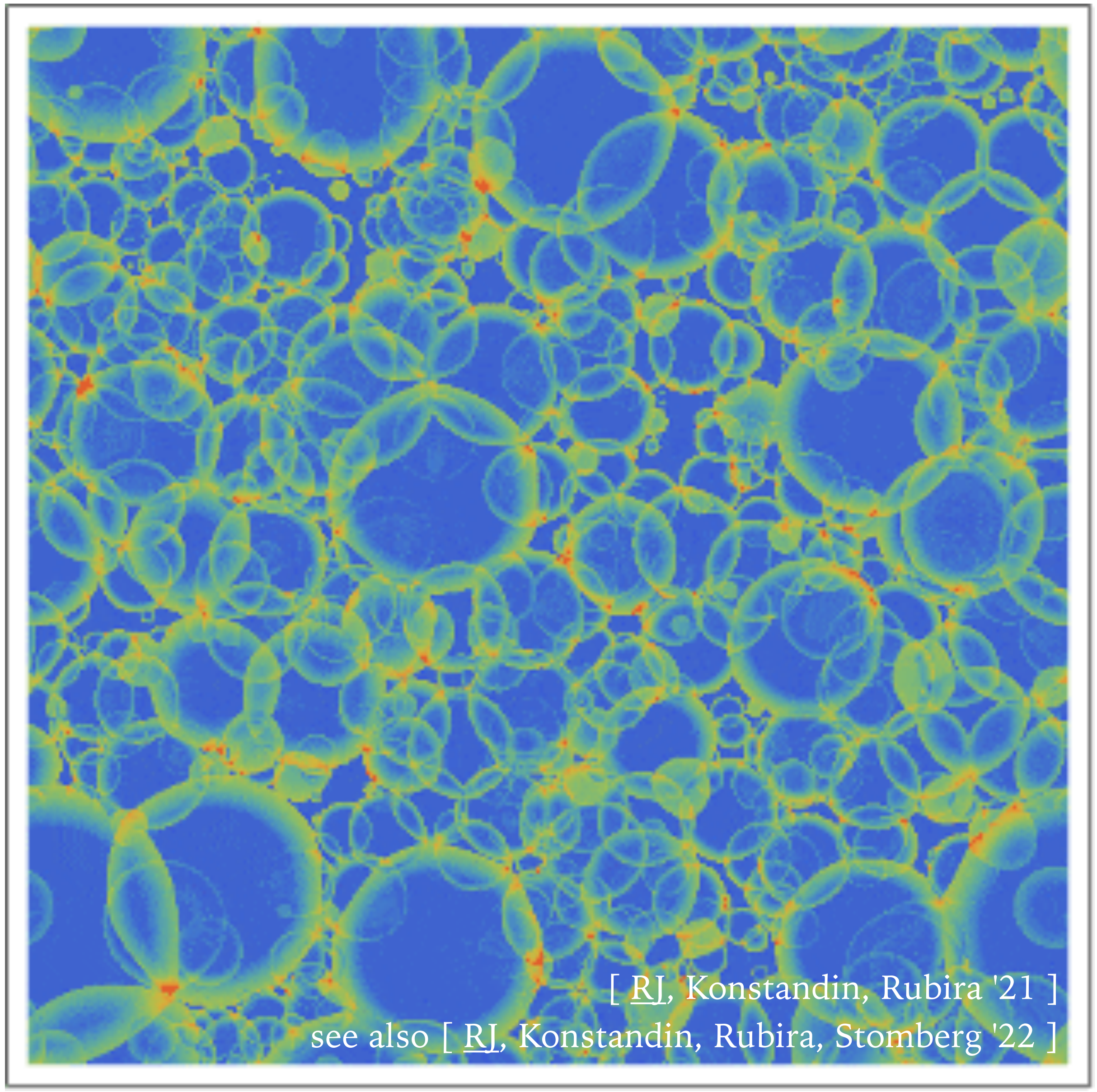


STEP 3: BUBBLE COLLISION & FLUID DYNAMICS

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

  [Hindmarsh, Huber, Rummukainen, Weir '14, '15, '17] [Hindmarsh '15, +Hijazi '19]

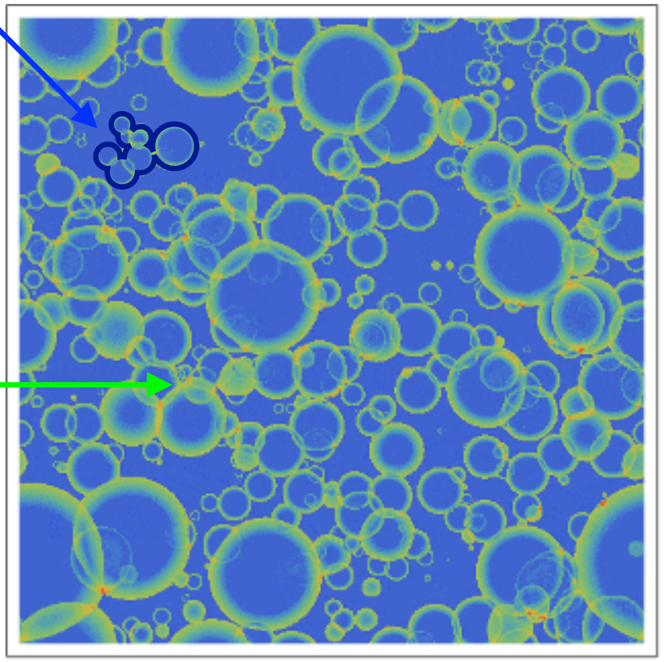


[RJ, Konstandin, Rubira '21]
see also [RJ, Konstandin, Rubira, Stomberg '22]

GRAVITATIONAL WAVE SOURCES

see e.g. [Caprini et al. '16] [Caprini et al. '20]

- **Bubble collision**
  - Kinetic & gradient energy of the scalar field (= order parameter field)
  - Dominant when the transition is extremely strong and the walls runaway

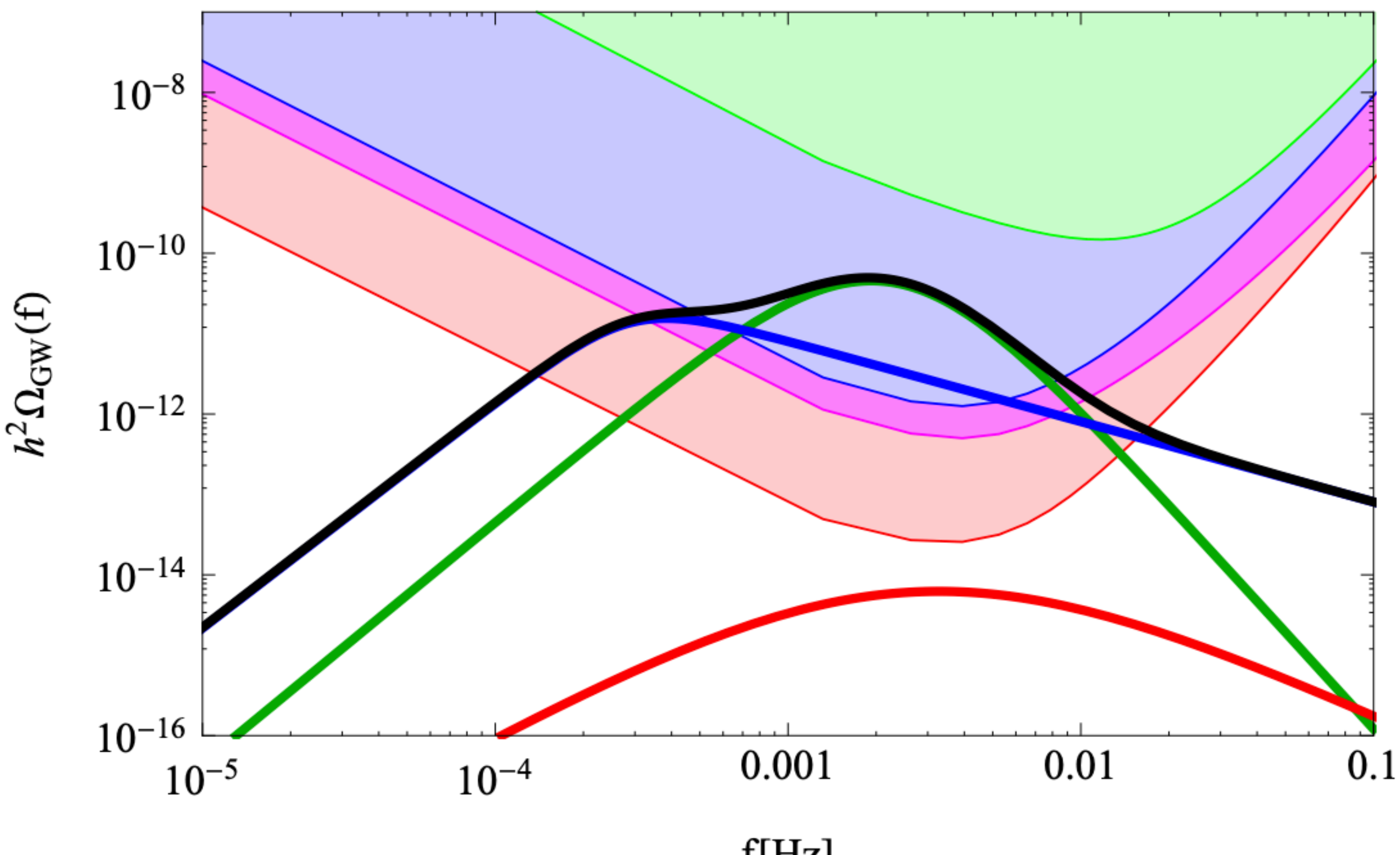


- **Sound waves**
  - Compression mode of the fluid motion
  - Dominant unless the transition is extremely strong

- **Turbulence**
  - Turbulent motion caused by fluid nonlinearity
  - Expected to develop at a later stage

important at later stage

GRAVITATIONAL WAVE SPECTRUM



[Caprini et al. '16]

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Particles in the broken phase frequently interact and can be described by fluid picture.

Feebly-interacting particles

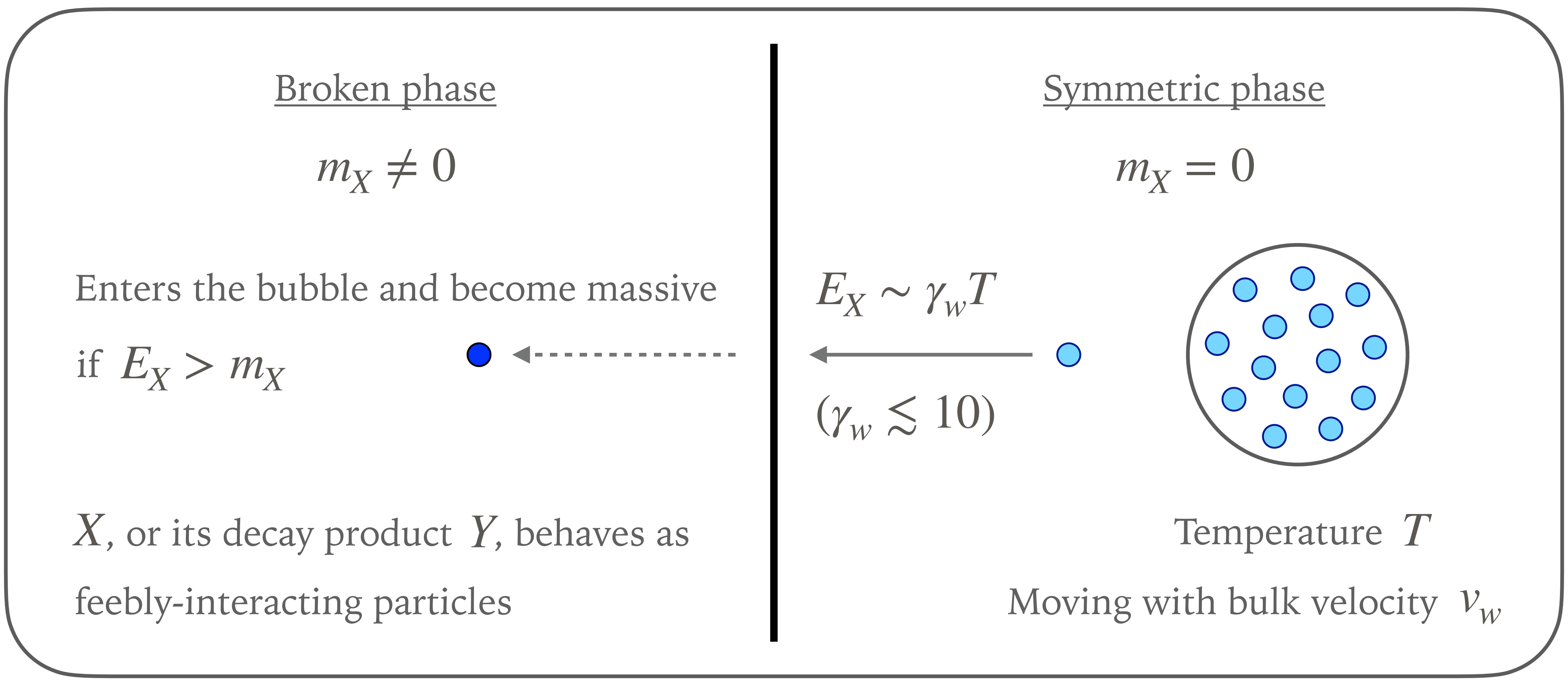
Particles in the broken phase are only feebly interacting and free-stream.

PARTICLE PHYSICS FRAMEWORK

- Setup:

  In the broken phase, particles or their decay product free-stream

Wall rest frame



PARTICLE PHYSICS FRAMEWORK

- Consider a dark-sector thermal bath, with temperature T
- ...that undergoes a first-order phase transition

  - scalar field s drives the transition

  - bubble walls reach a terminal velocity v_w (or equivalently $\gamma_w = 1\Big/\sqrt{1 - v_w^2}$)
    due to the coupling to particle X

- ...and also produces feebly-interacting particles

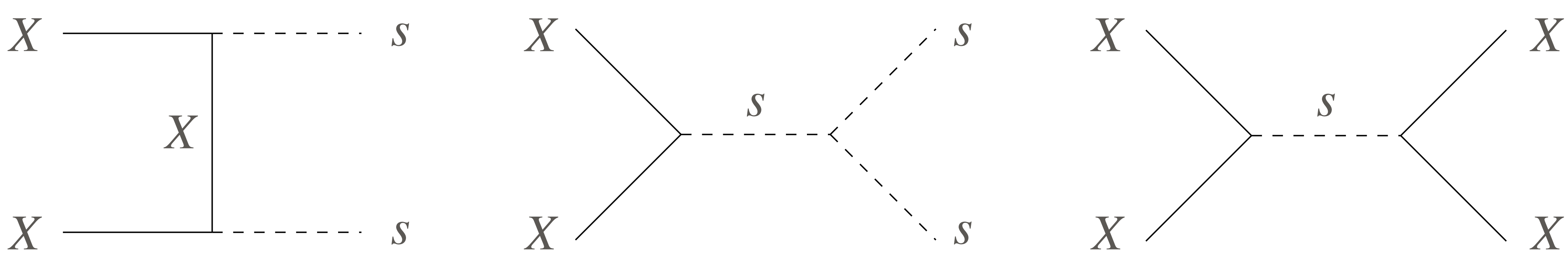
  - particle X becomes massive when crossing the wall

  - either X or its decay product behaves as feebly-interacting particles

CONDITIONS ON FEEBLE INTERACTION

- How do X particles interact?

  - Couplings that gives rise to mass also give rise to interactions

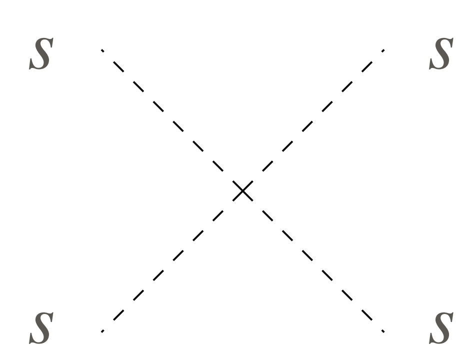


- Can $X = s$ free-stream? → No

  - s has to gain a large mass

    (for s particles to dominantly contribute to the friction),

    but this immediately means large quartic among s particles



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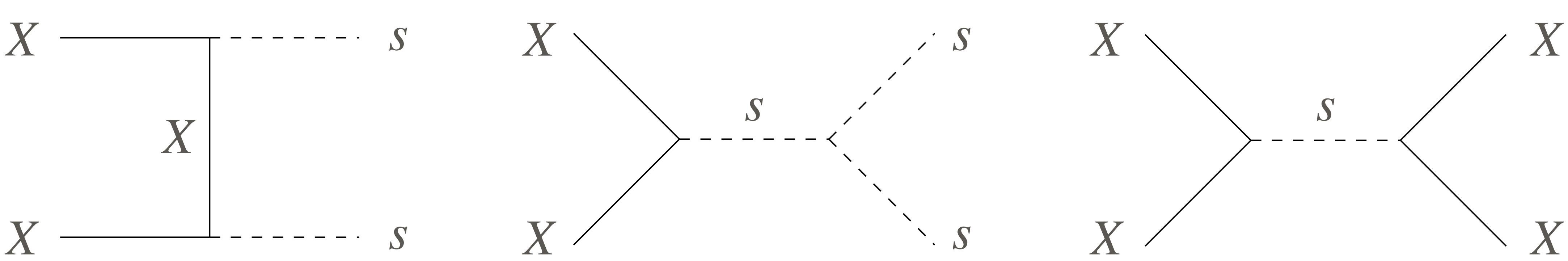

- Can $X = s$ free-stream? → No

- Can $X = Z'$ boson free-stream? → Doable, but not generic

  - Condition to free-stream over a typical bubble size R_*

$$n_X \sigma R_* \sim T^3 \frac{g'^4}{(4\pi)^2} \frac{m_{Z'}^2}{m_s^4} \frac{1}{\beta} \sim \frac{g'^6}{\lambda_s^2} \frac{T \overset{\text{large}}{M_P}}{\langle s \rangle^2} \frac{H}{\beta} \lesssim 1$$

CONDITIONS ON FEEBLE INTERACTION

- How do X particles interact?

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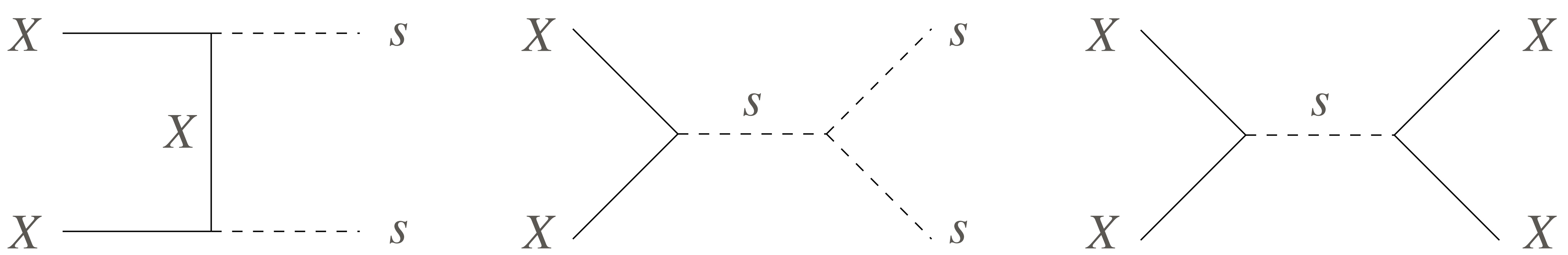
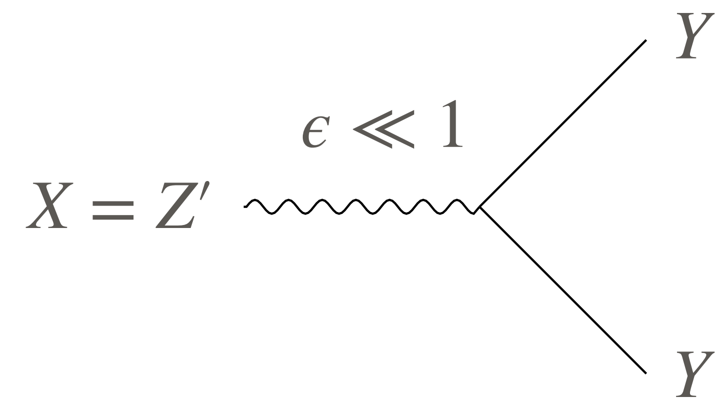


- Can $X = s$ free-stream? → No
- Can $X = Z'$ boson free-stream? → Doable, but not generic
- Can a decay product of X free-stream? → Yes



SINGLE-BUBBLE PROFILE

- Energy-momentum tensor of a single bubble before collision

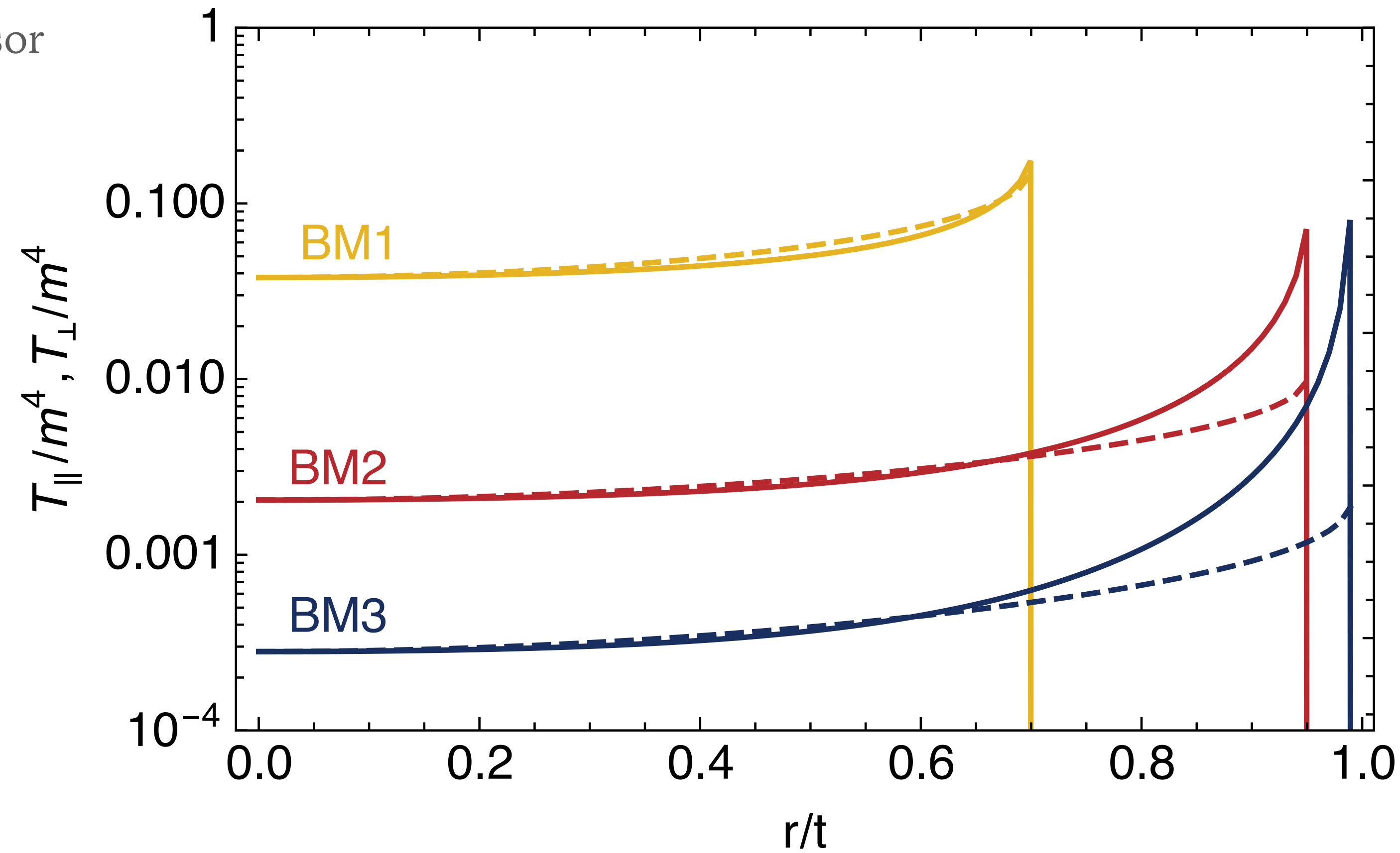
We take 3 benchmark points: $\begin{cases} m/T = 1, \;\; v_w = 0.7 & \text{(BM1)} \\ m/T = 2, \;\; v_w = 0.95 & \text{(BM2)} \\ m/T = 3, \;\; v_w = 0.99 & \text{(BM3)} \end{cases}$

see also [Lewicki, Vaskonen, Veermäe '22]

Energy-momentum tensor

$T_{\parallel} = T_{zz}$

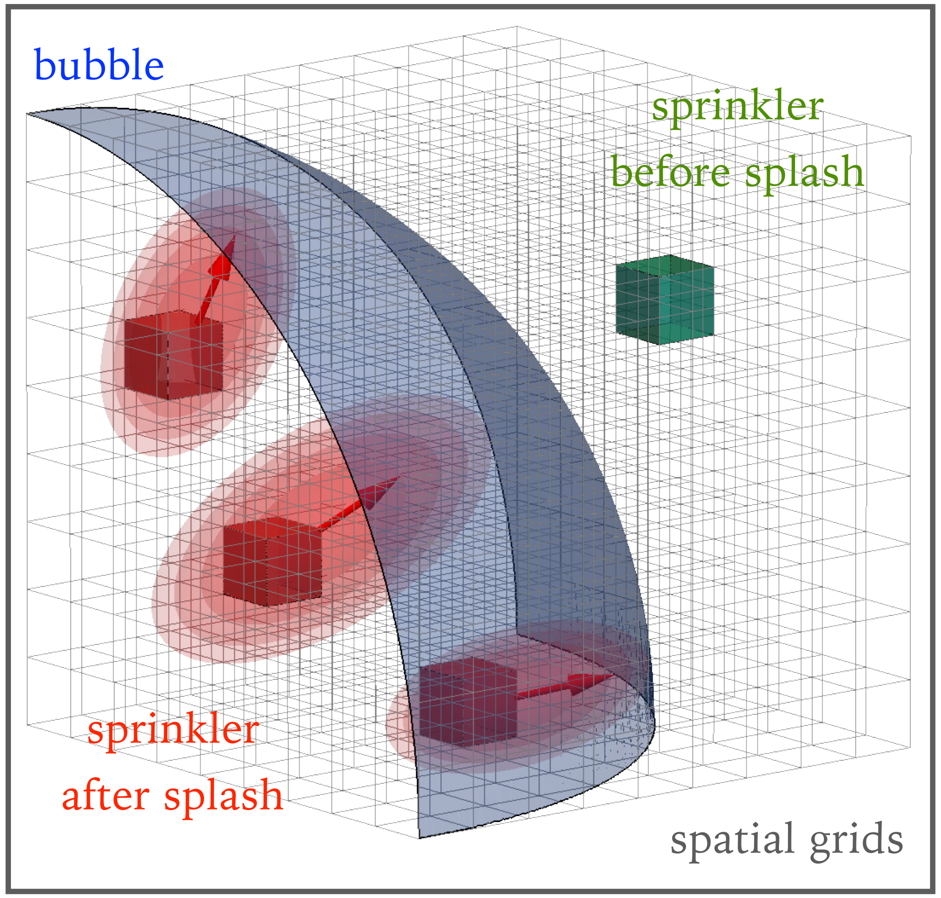
$T_{\perp} = T_{xx} = T_{yy}$



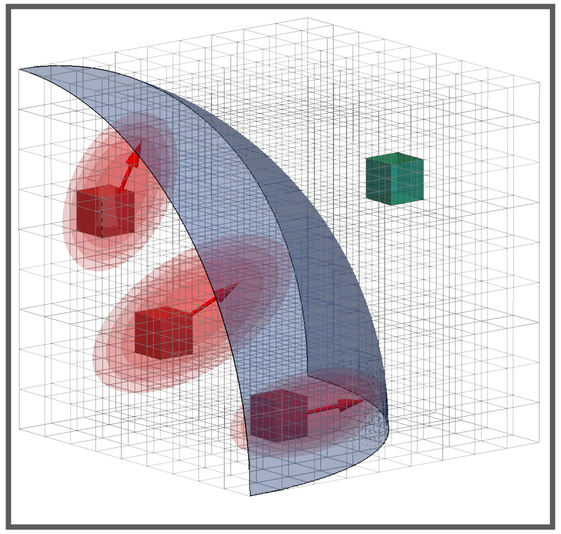
$\dfrac{\text{radius}}{\text{time after nucleation}}$

HOW TO CALCULATE THE GW SPECTRUM

- To calculate the GW spectrum, we don't use the time evolution shown in the animation in the previous slides
- We instead propose a new calculation scheme – "sprinkler picture"



SPRINKLER PICTURE FOR GW CALCULATION



- How the "sprinkler picture" works

  ① Imagine each grid point has a sprinkler that splashes free-streaming particles when hit by the wall

  ② The sprinklers are universal:
  their only difference is when and in which direction they are hit

  ③ GW production from one sprinkler is easily calculable.
  Contributions from different sprinklers (= grids) are linearly superposed.

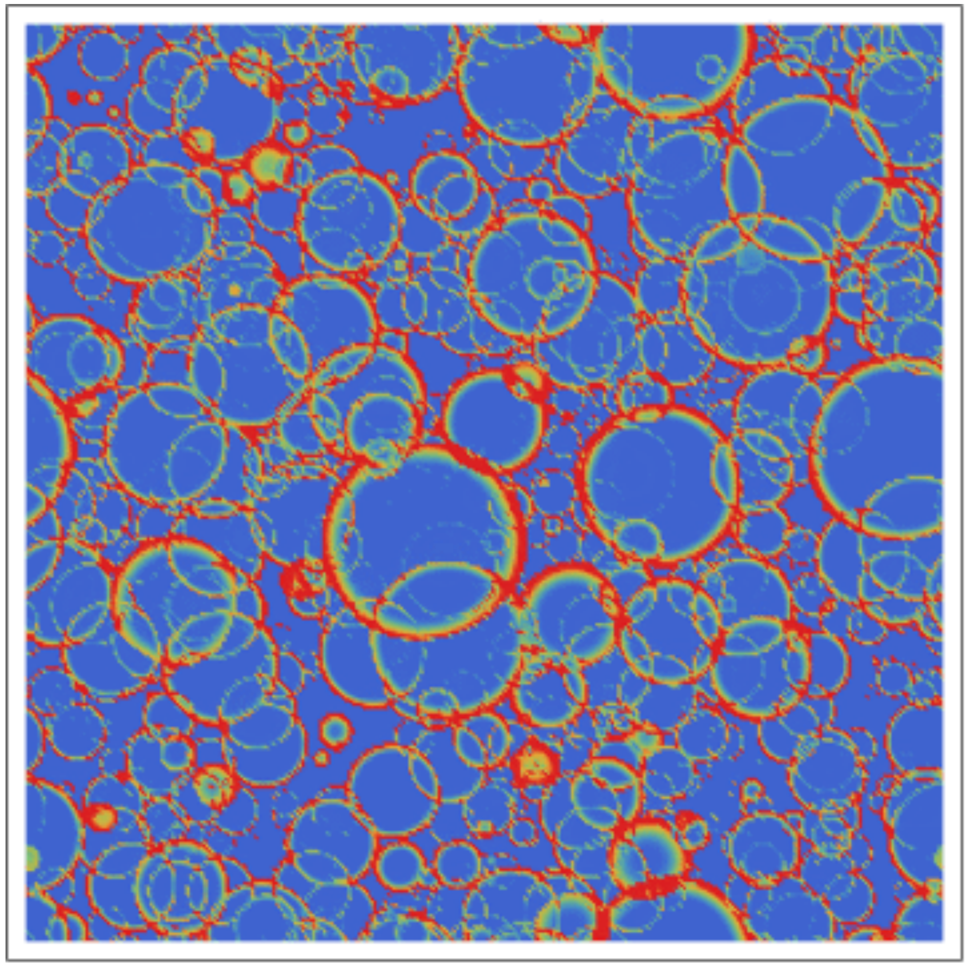
- This method is possible because GW production is linear in each sprinkler in the present system

$$\Box h_{ij} \sim T_{ij} \sim \sum_{\text{sprinkler } p} T_{ij}^{(p)}$$

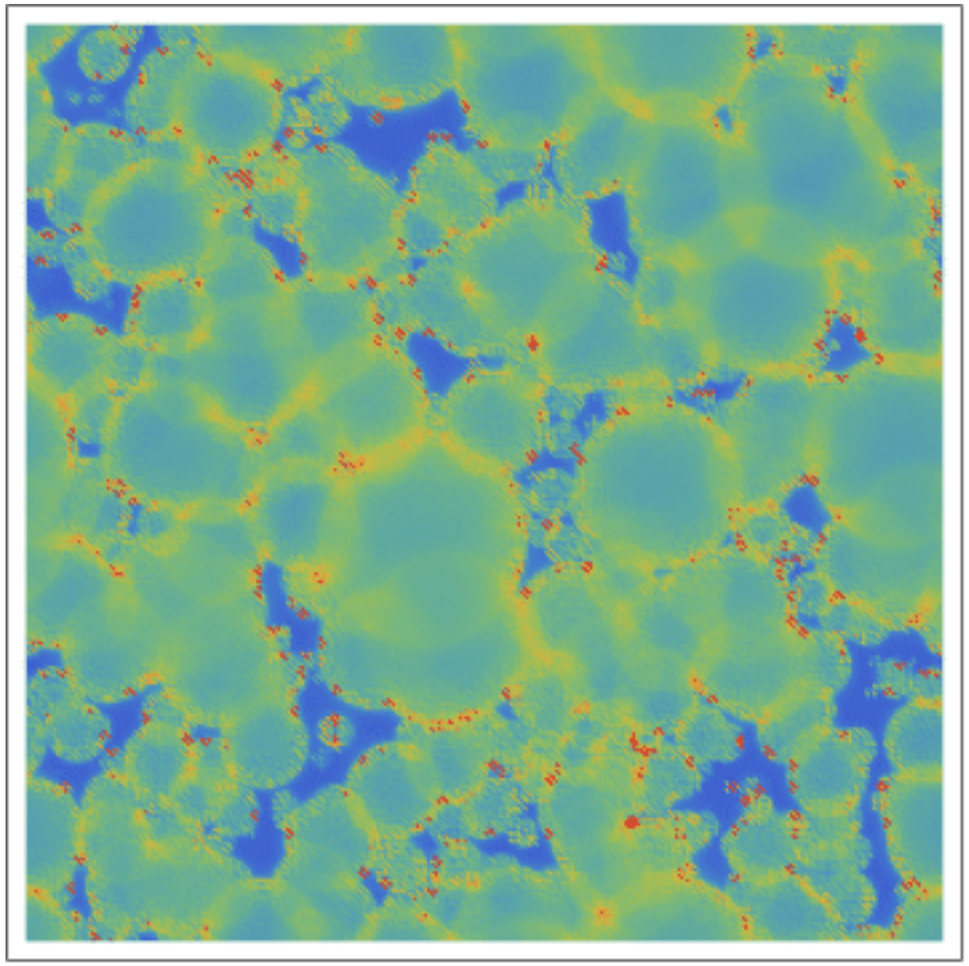
EVOLUTION OF BUBBLES WITH FEEBLY-INTERACTING PARTICLES

- Fluid case vs. feebly-interacting case

Fluid

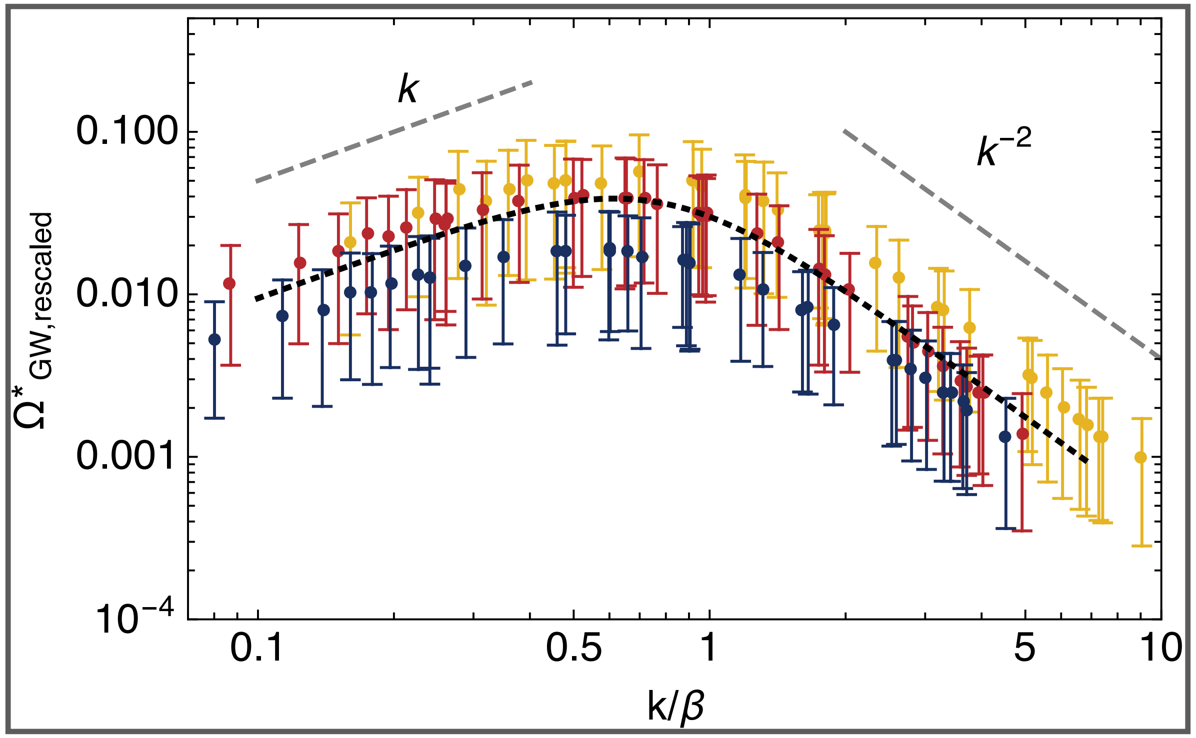


Feebly-interacting

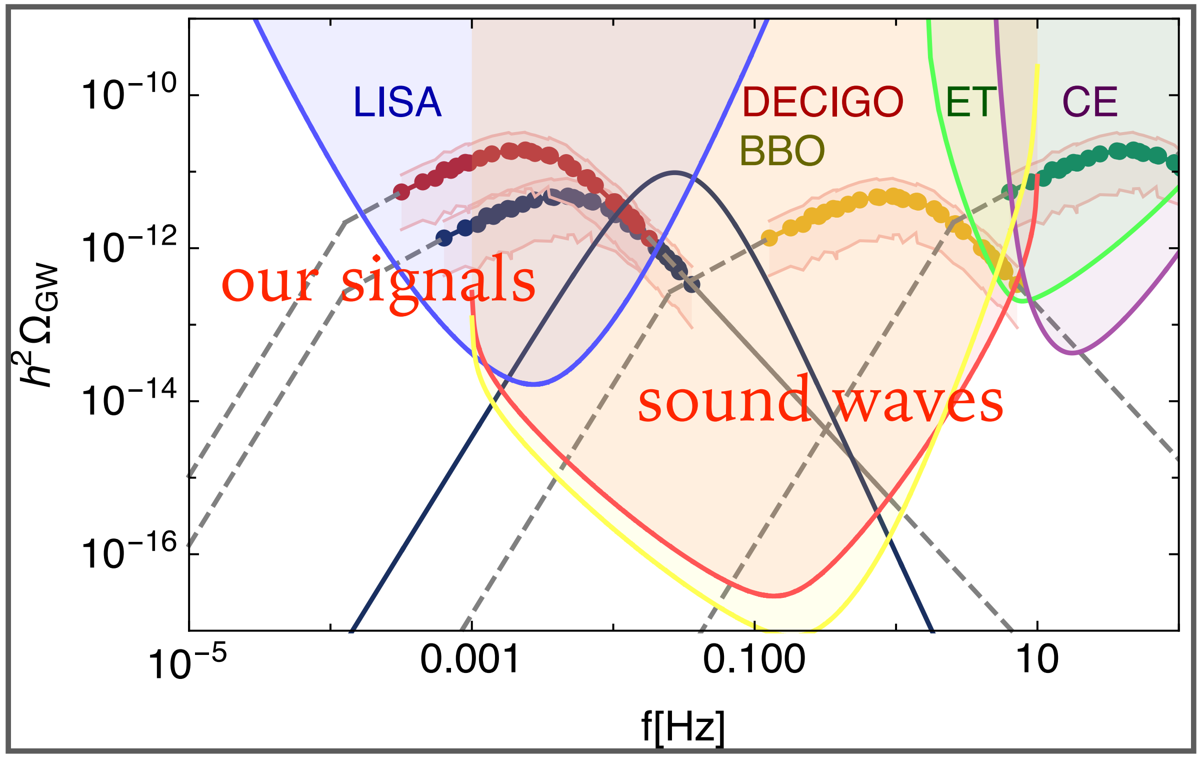


GW SPECTRUM

- GW spectral shape is universal for different benchmark points (after normalizing by some factor)



- GW spectral shape is clearly different from sound-wave sources: it stretches over wider frequencies



DISCUSSION

➤ What is the essential difference?

- Sound waves: it is fluid velocity $\vec{v}$ that superposes linearly

$$\boxed{\vec{v} = \sum_{I\,:\,\text{bubbles}} \vec{v}^{(I)} \quad \longrightarrow \quad T_{ij} \sim w v_i v_j \neq \sum_{I\,:\,\text{bubbles}} T_{ij}^{(I)}}$$

- Free-streaming particles: it is T_{ij} that superposes linearly

$$\boxed{T_{ij} = \sum_{I\,:\,\text{bubbles}} T_{ij}^{(I)}}$$

Introduction

GWs from sound waves in FOPT

GWs from FIPs in FOPT

Summary

SUMMARY

- We point out the missing possibility for GW sources in FOPT:

  free-streaming particles

- We propose a novel GW calculation scheme ("sprinkler picture") that makes use of the lineariry of GW production in each sprinkler

- Resulting GW signal is clearly different from the GW signal from the well-known sound waves