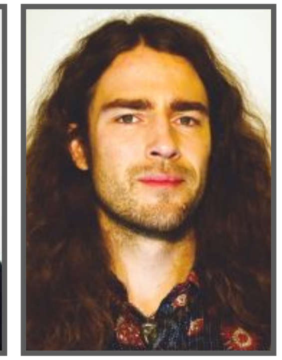

T. Konstandin


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)

Jeju workshop, 2023/11/16

[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

1 Introduction

2 GWs from sound waves in FOPT

3 GWs from FIPs in FOPT

4 Summary

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TAKE-HOME MESSAGE

- Feebly-interacting particles are a good target for new physics searches

  - sterile neutrinos - dark photon - axion-like particles - dilaton ...

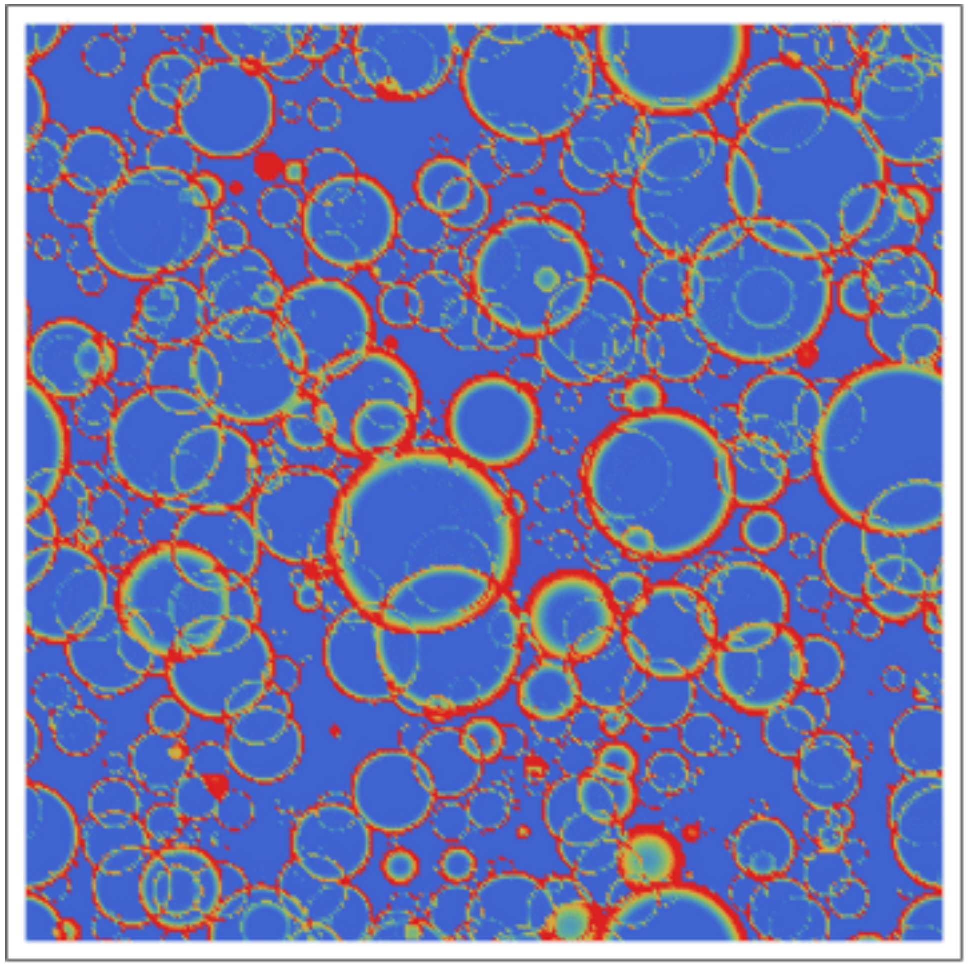
- If they are produced during a first-order phase transition,

  they leave a characteristic imprint on the GW spectrum

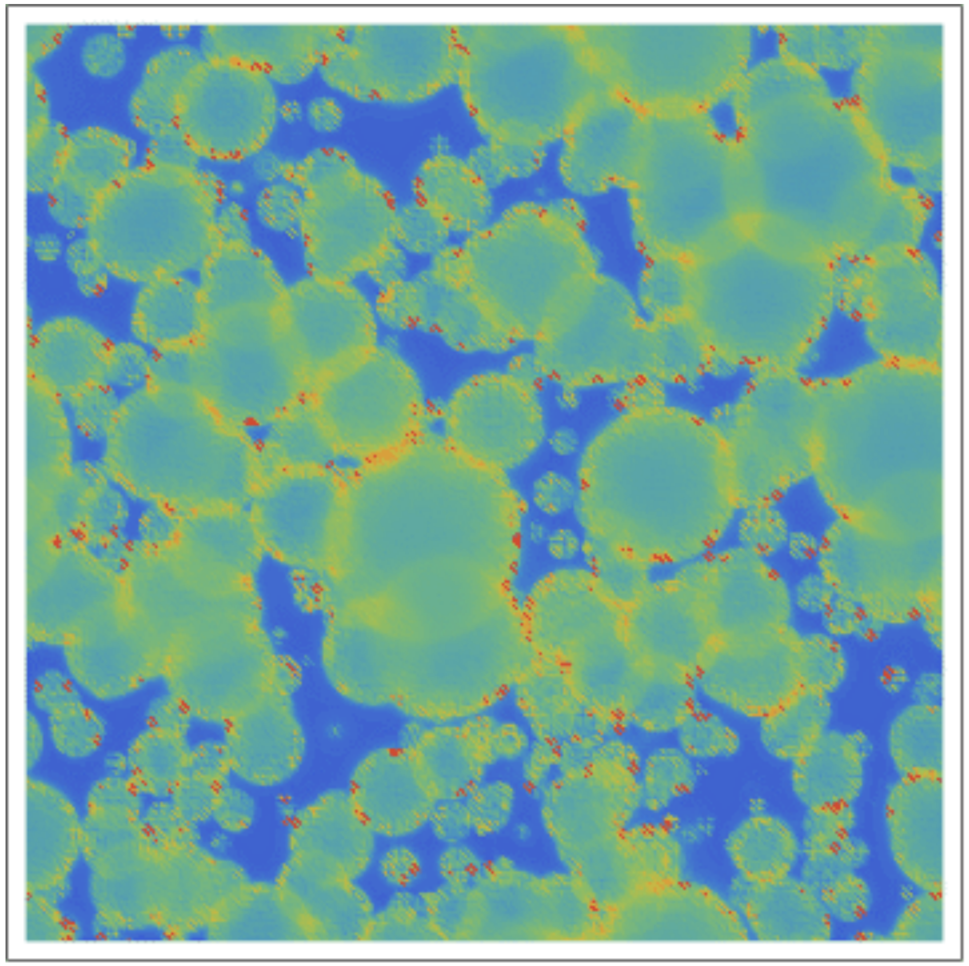
TAKE-HOME MESSAGE

- Fluid vs. Feebly-interacting particles in a first-order phase transition

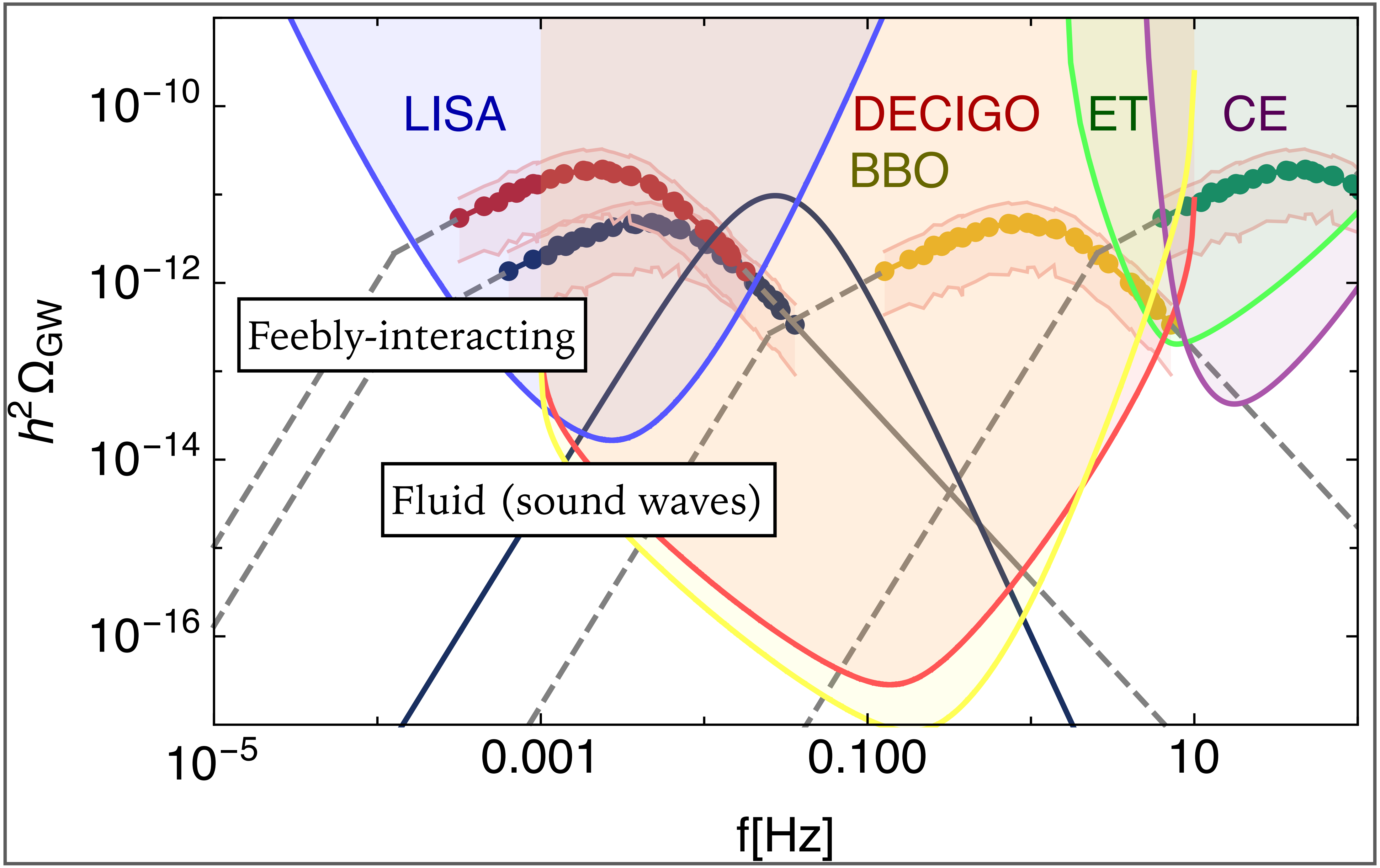
Fluid



Feebly-interacting



TAKE-HOME MESSAGE



OVERVIEW OF FIRST-ORDER PHASE TRANSITION & BUBBLE DYNAMICS

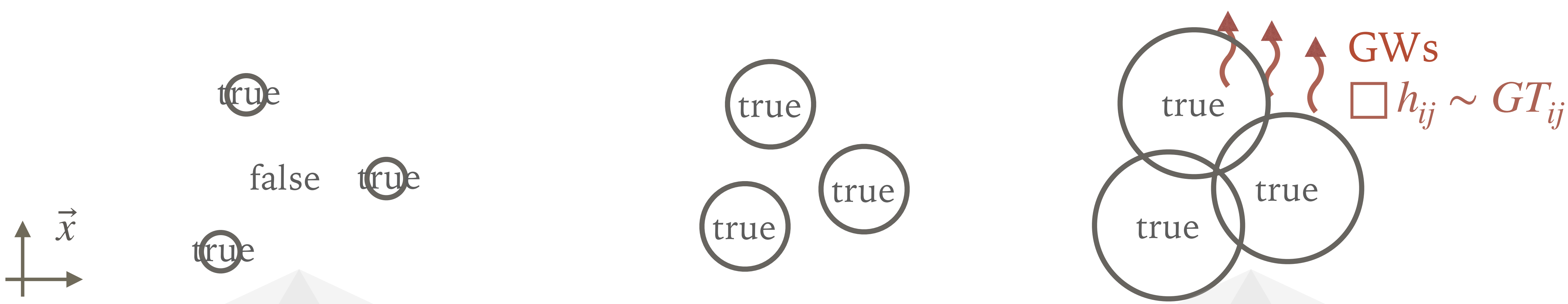
[Hogan '83] [Witten '84]

microphysics

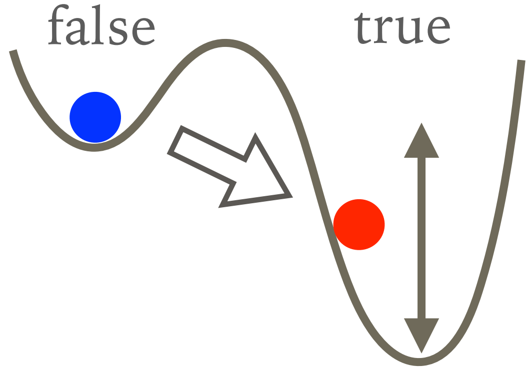
macrophysics

time or scale →

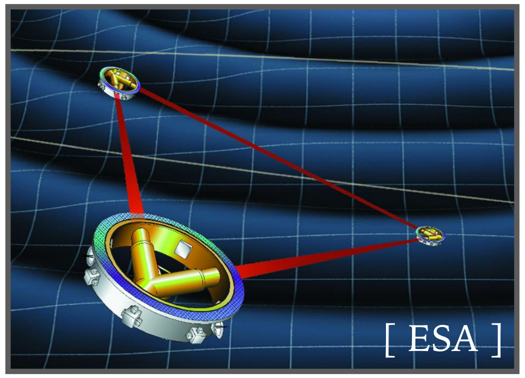
(1) nucleation (核生成) (2) expansion (拡大) (3) collision (衝突)



Physics of the Higgs sector

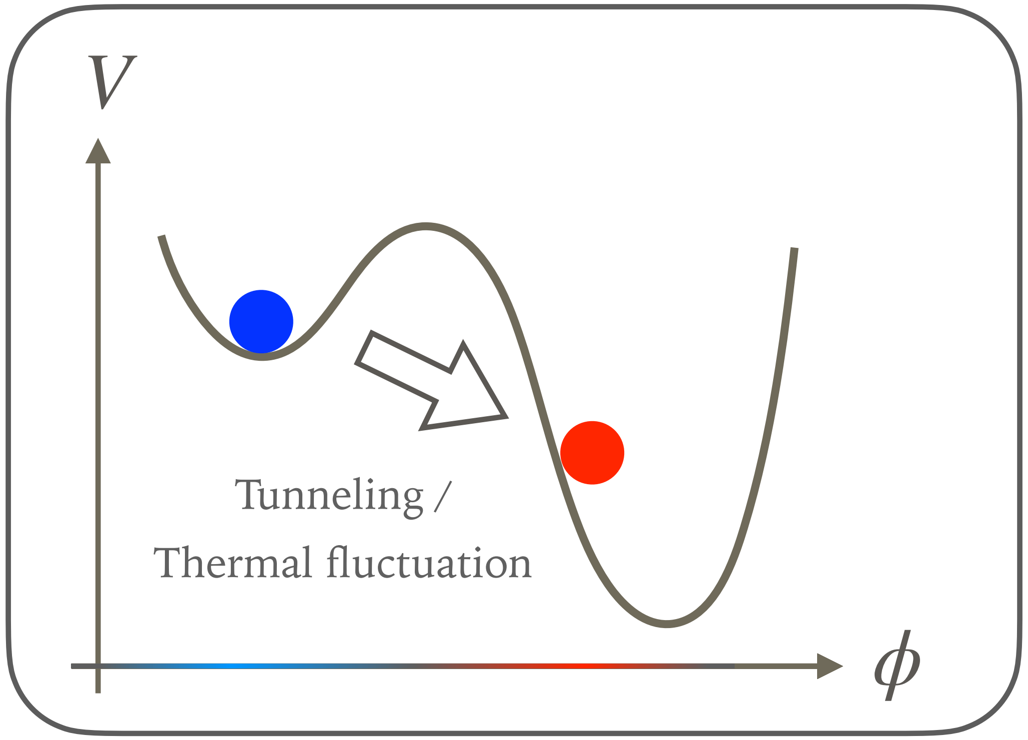


GW observations

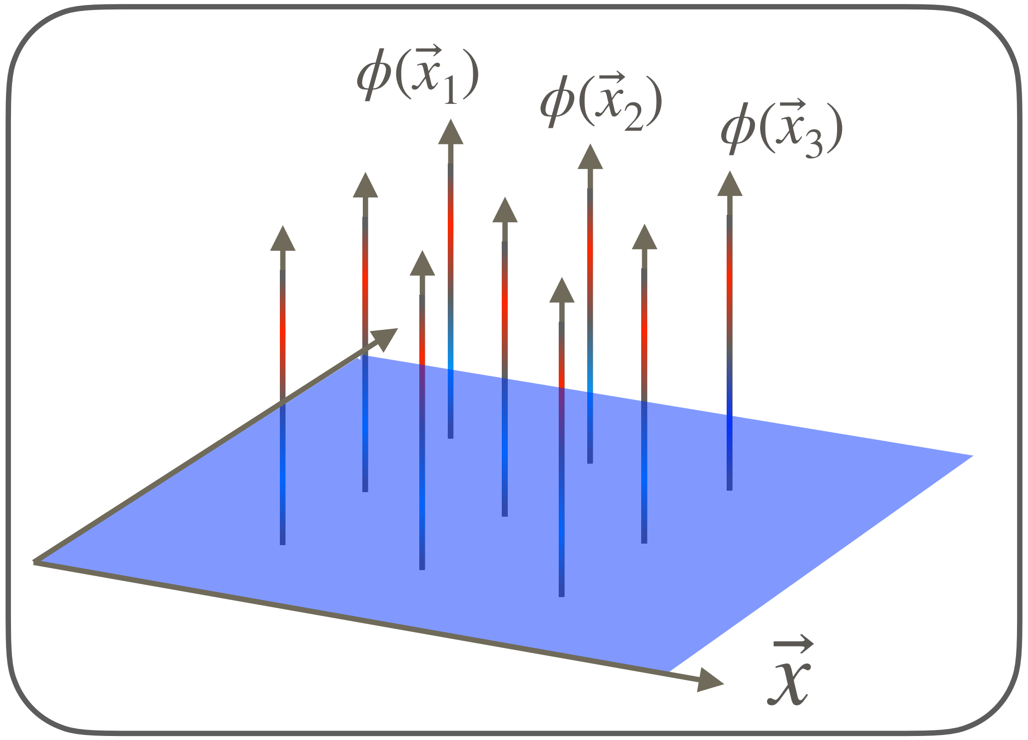


STEP 1 : NUCLEATION

Field space



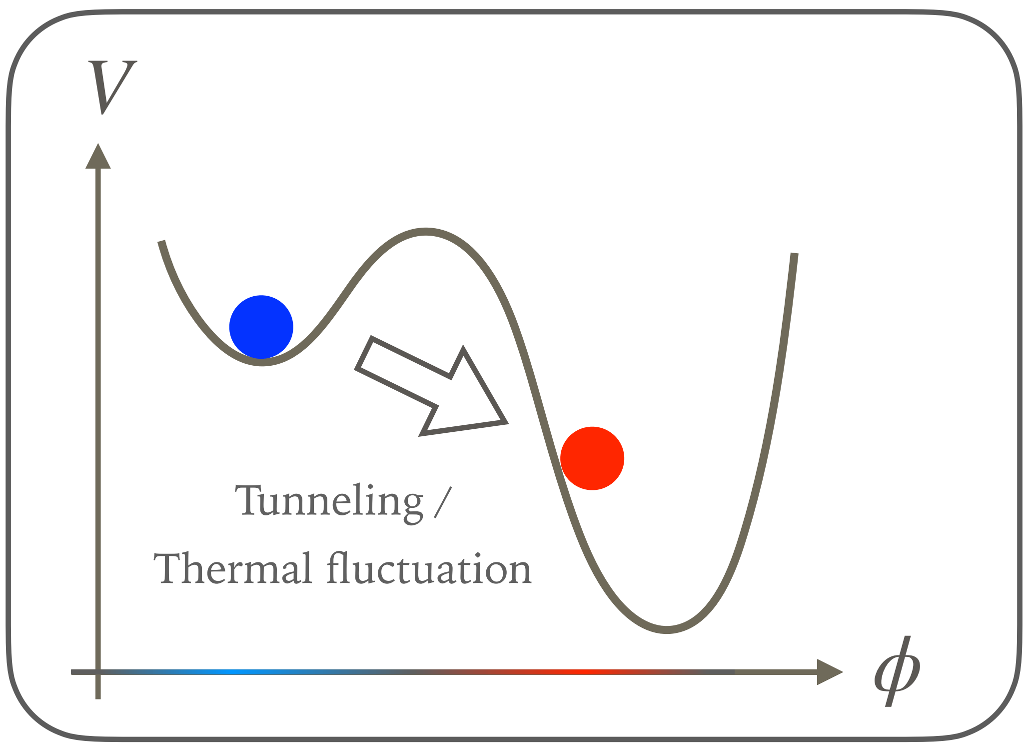
Position space

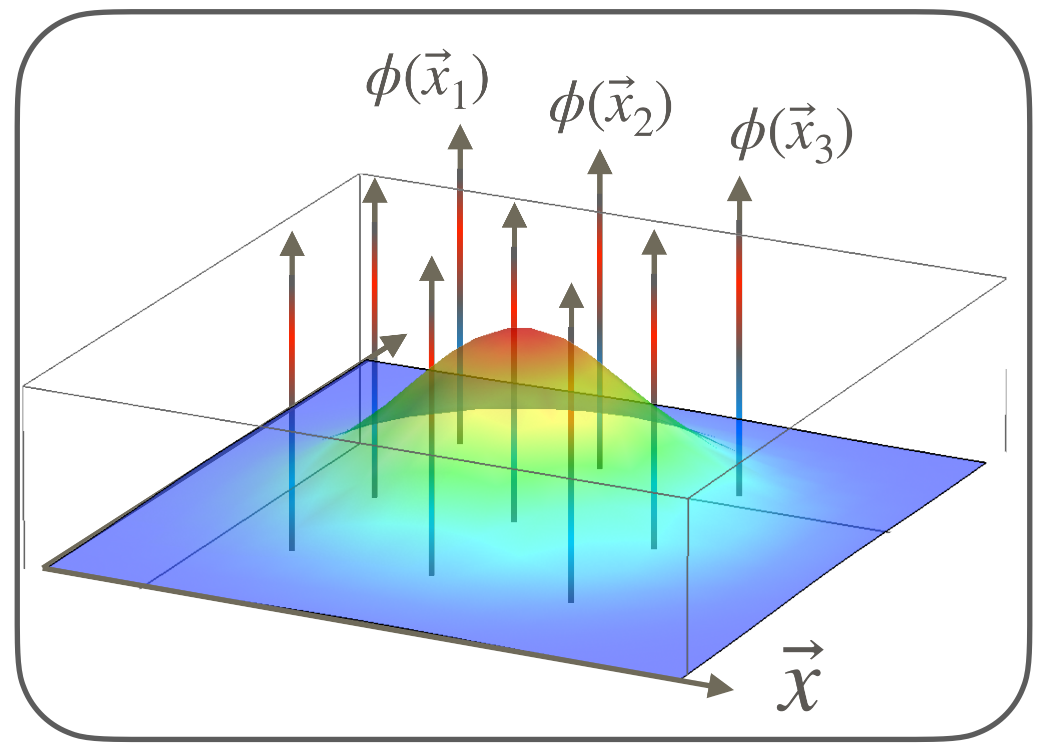


STEP 1 : NUCLEATION

Field space

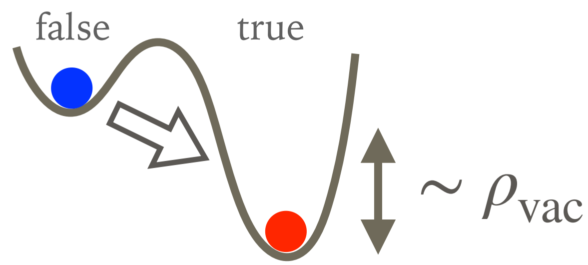
Position space





nucleation (核生成)

STEP 2 : BUBBLE EXPANSION



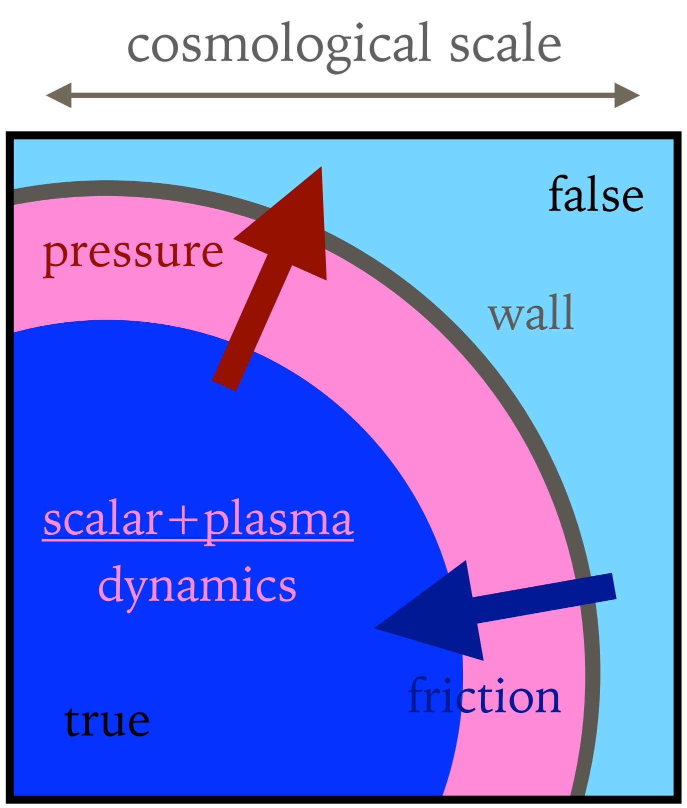
- "Pressure vs. Friction" determines the behavior:

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

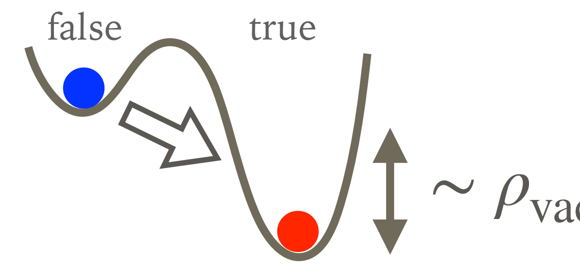
  Determined by $\alpha \equiv \rho_{\rm vac}/\rho_{\rm plasma}$

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

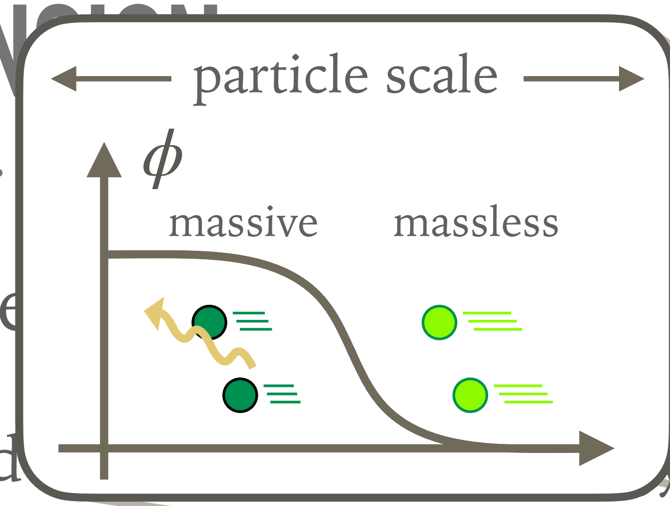
  (2) Friction: wall is pushed back by plasma particles

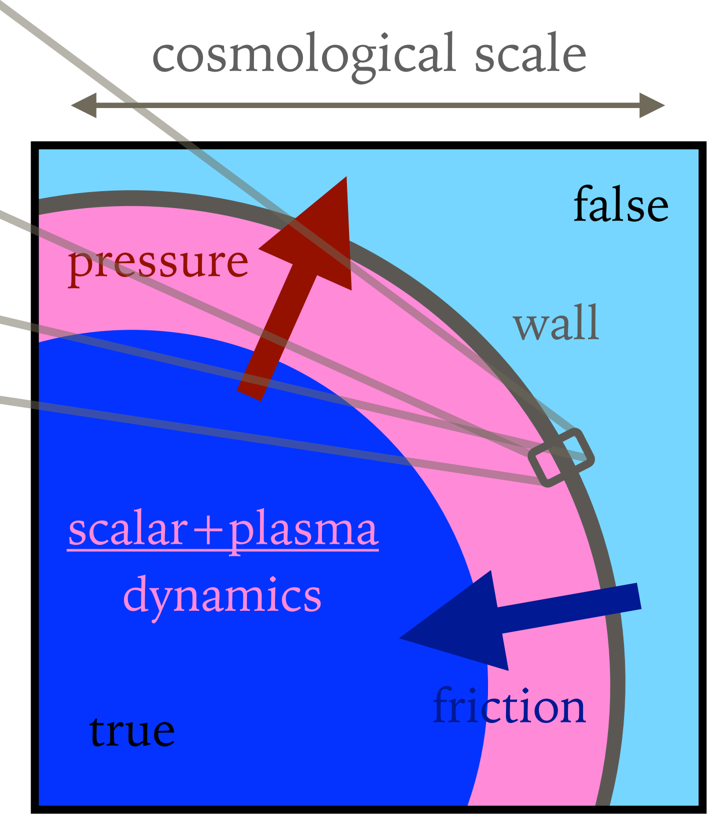


STEP 2 : BUBBLE EXPAN



➤ "Pressure vs. Friction" de … ior:





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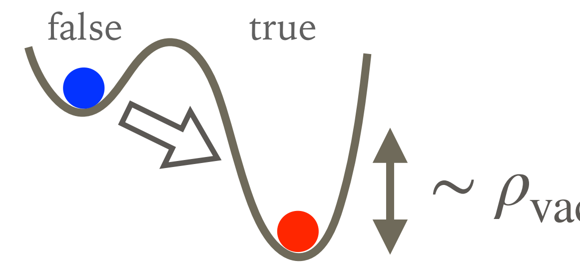

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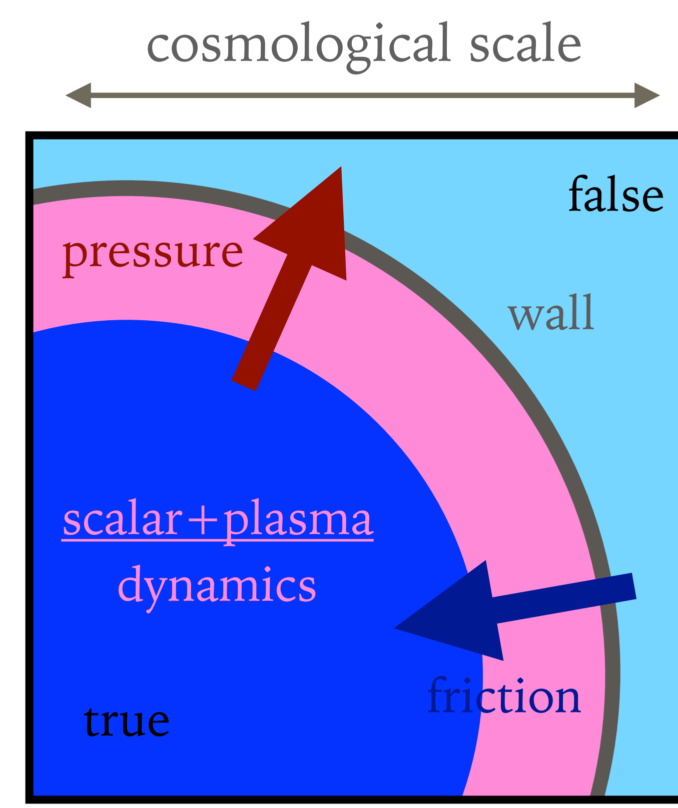
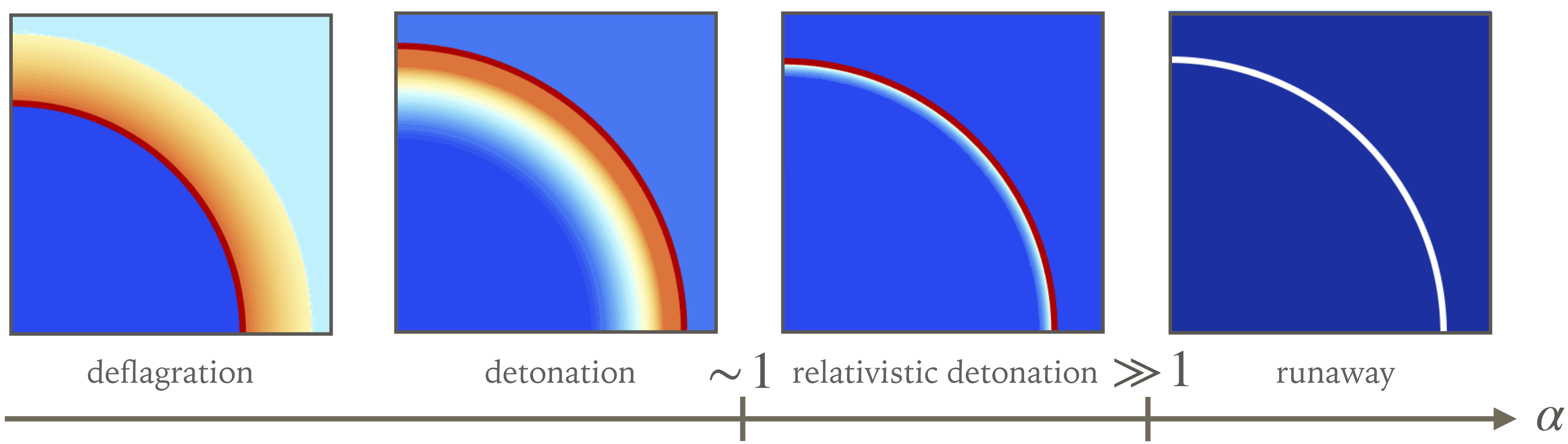
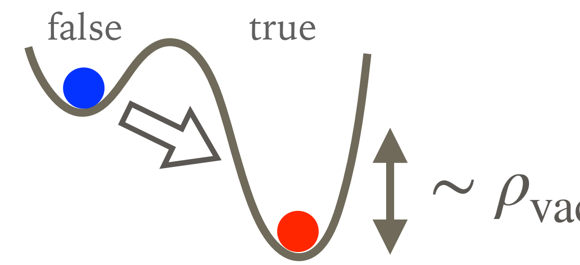


- Different types of bubble expansion



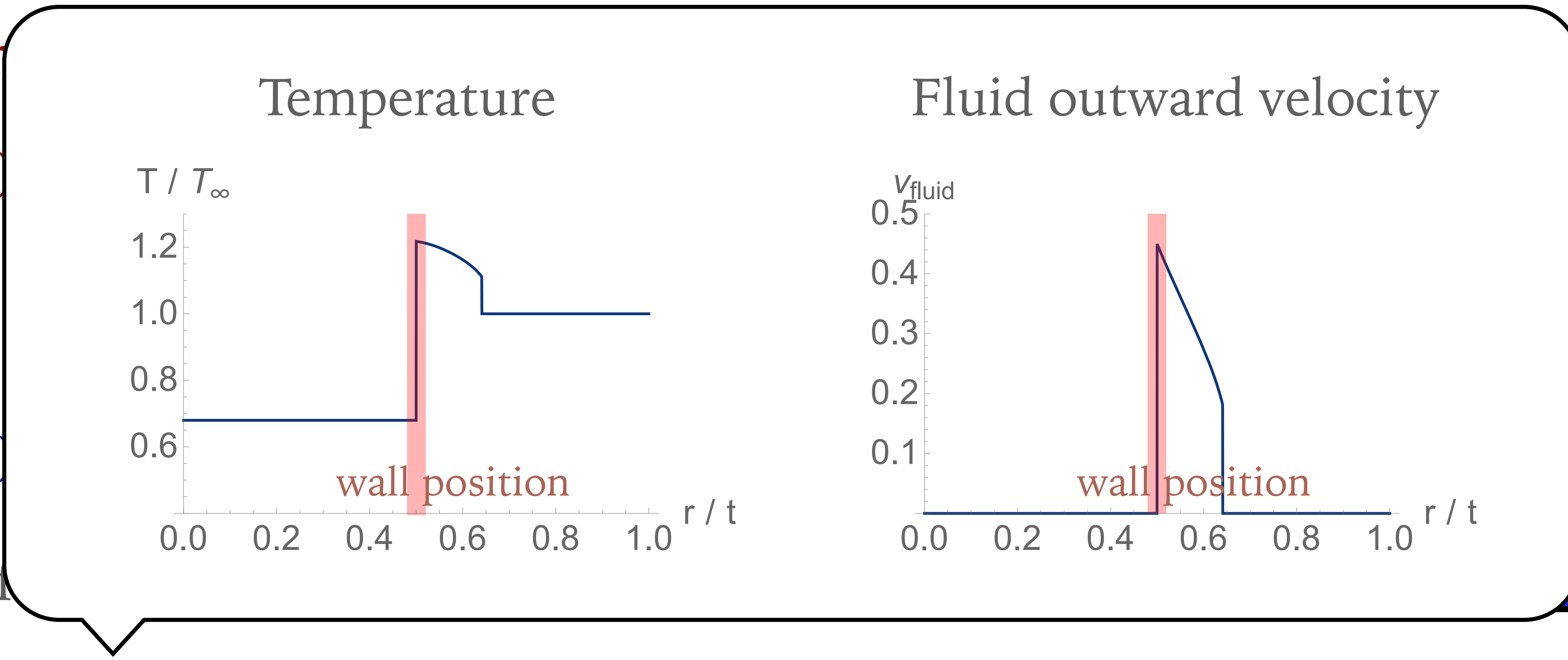


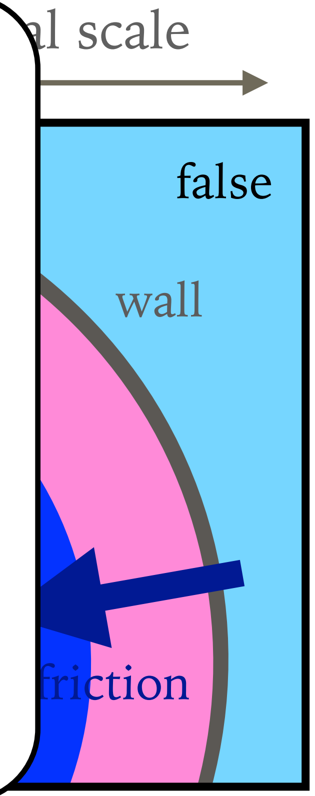
STEP 2 : BUBBLE EXPANSION

➤ "Pr

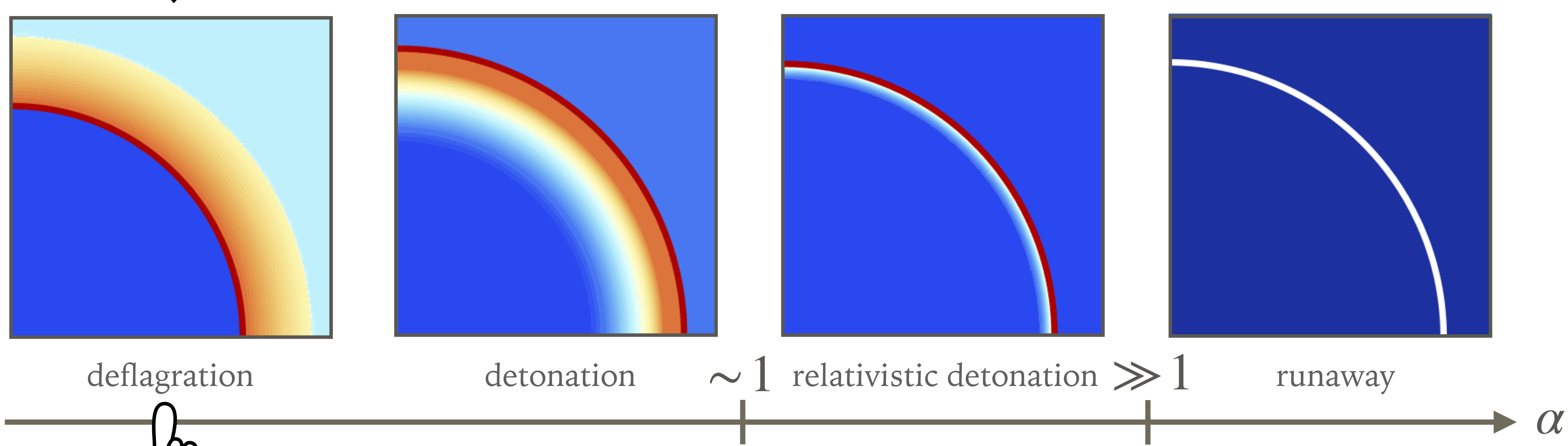
(1)

(2)





➤ Di



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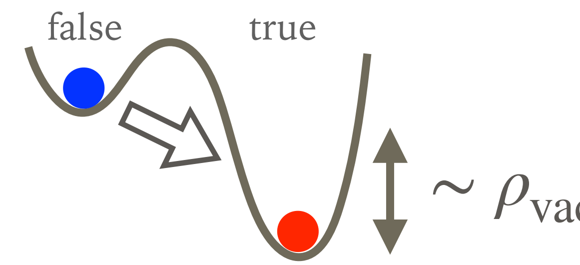
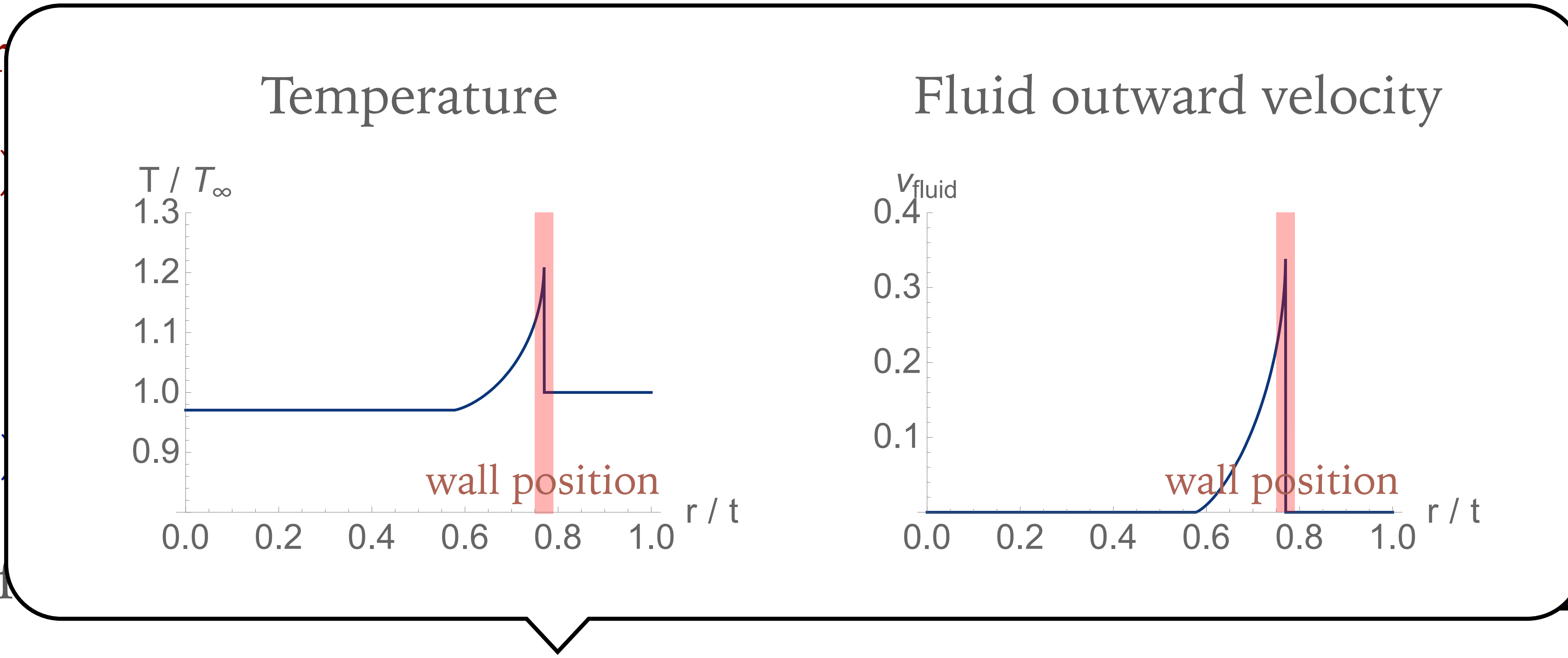


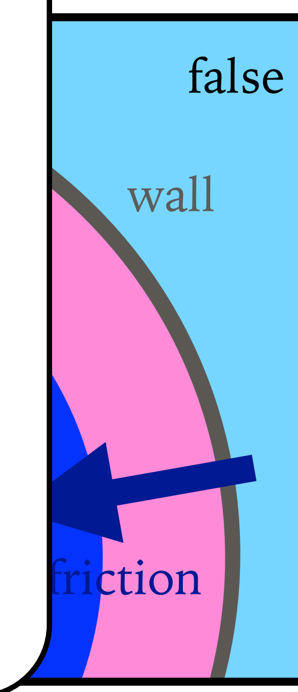
➤ "Pr … al scale

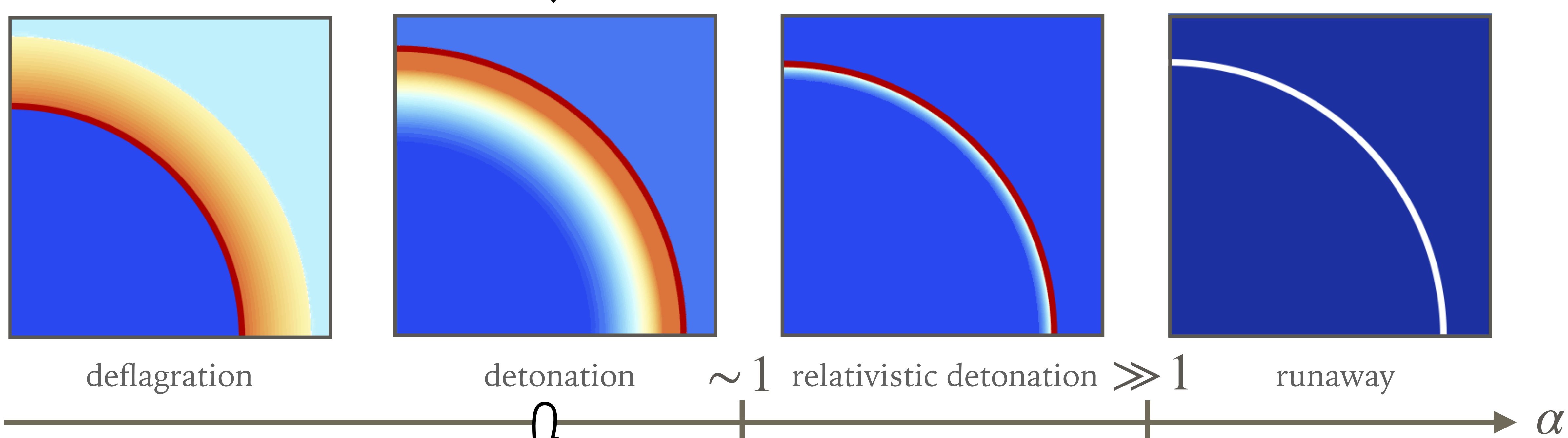
(1)

(2)

➤ Di







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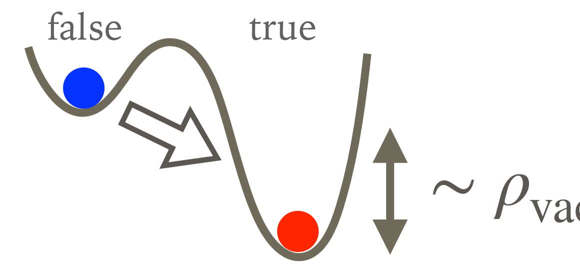


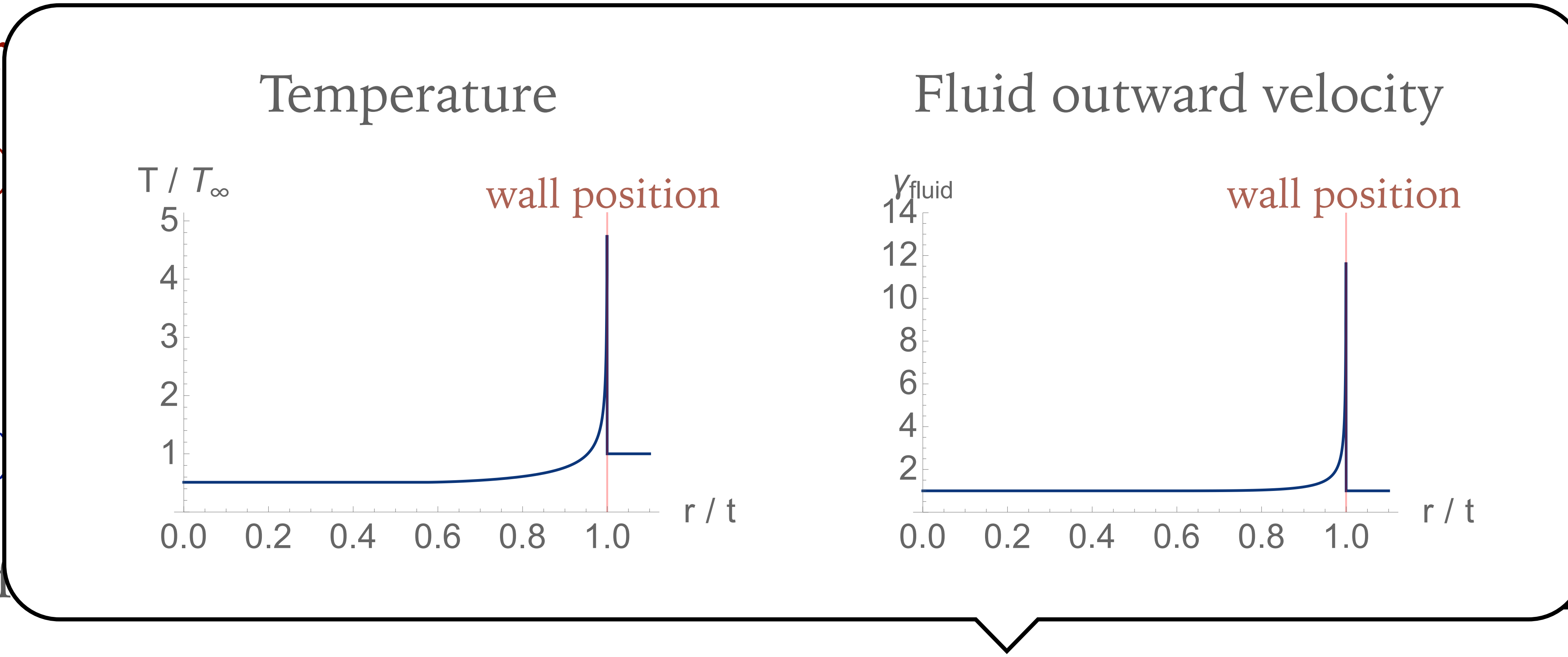
- "Pr

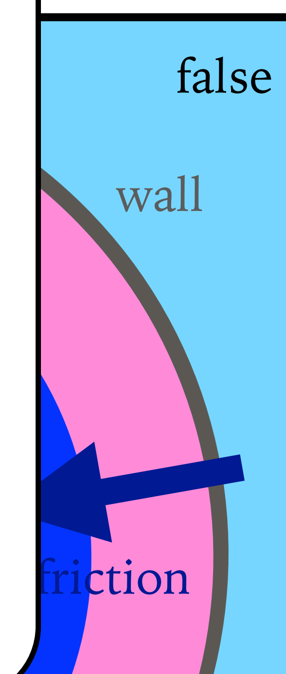
l scale

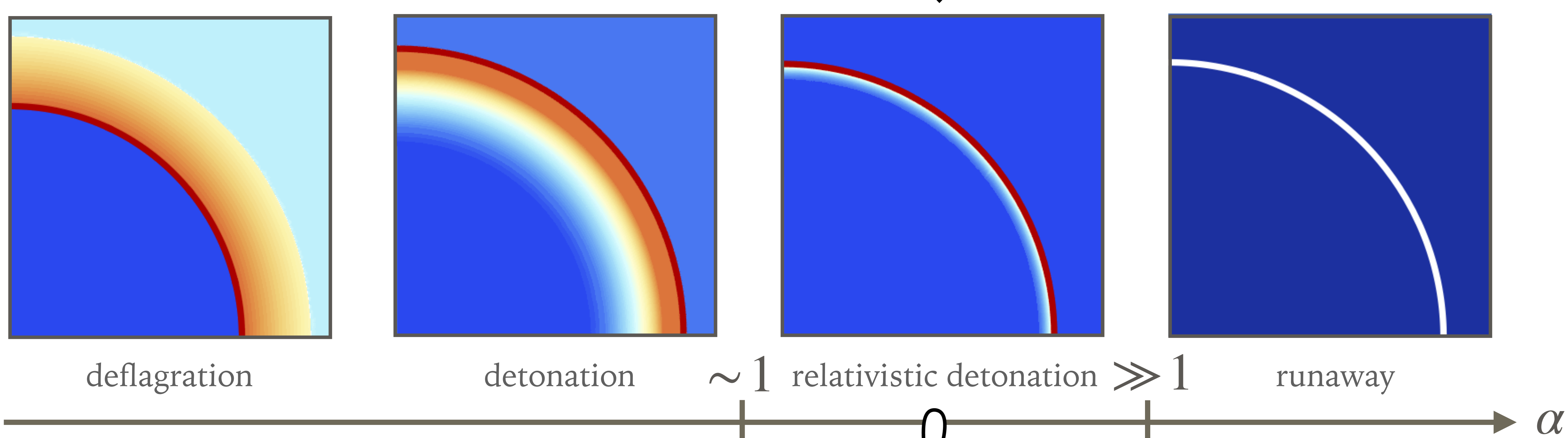
(1)

(2)

- Di







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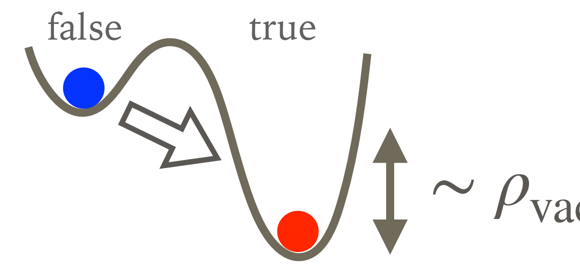


➤ "Pr ... al scale

(1)

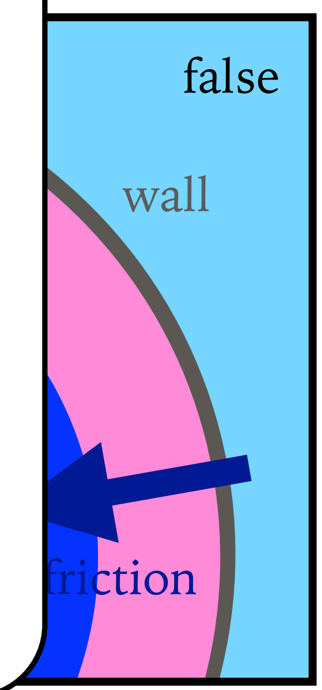
(2)

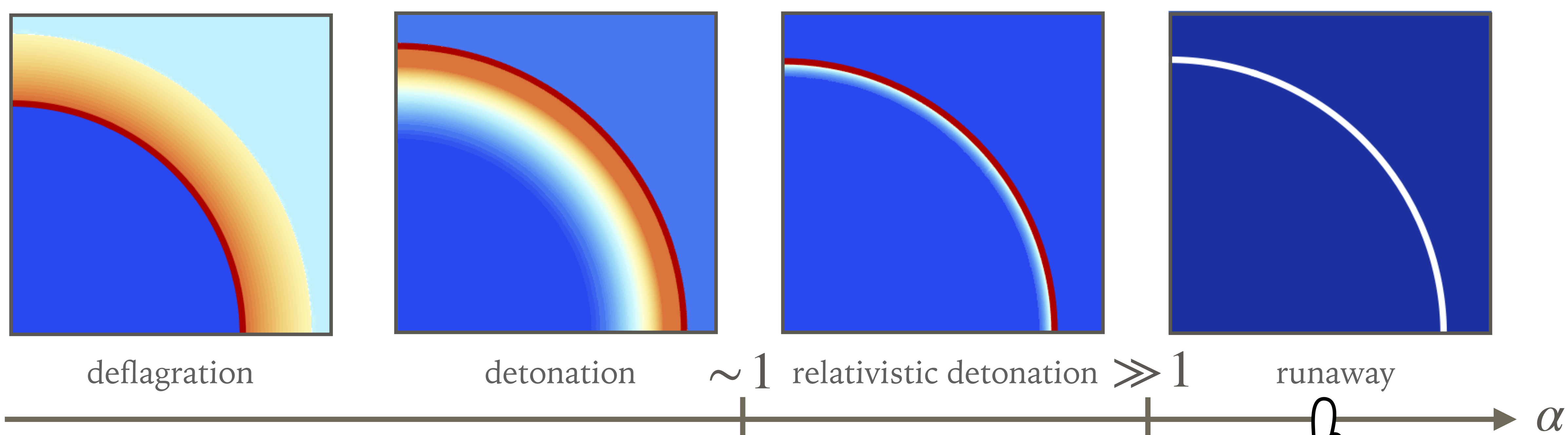
➤ Di

Plasma particles cannot stop the acceleration of the walls:

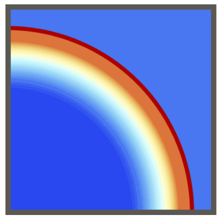
walls continue to accelerate until they collide with others

[Bodeker & Moore '09, '17] [Azatov & Vanvlasselaer '20] [Höche, Kozaczuk, Long, Turner, Wang '20]
[Gouttenoire, RJ, Sala '21] [Azatov, Barni, Petrossian-Byrne, Vanvlasselaer '23] ...

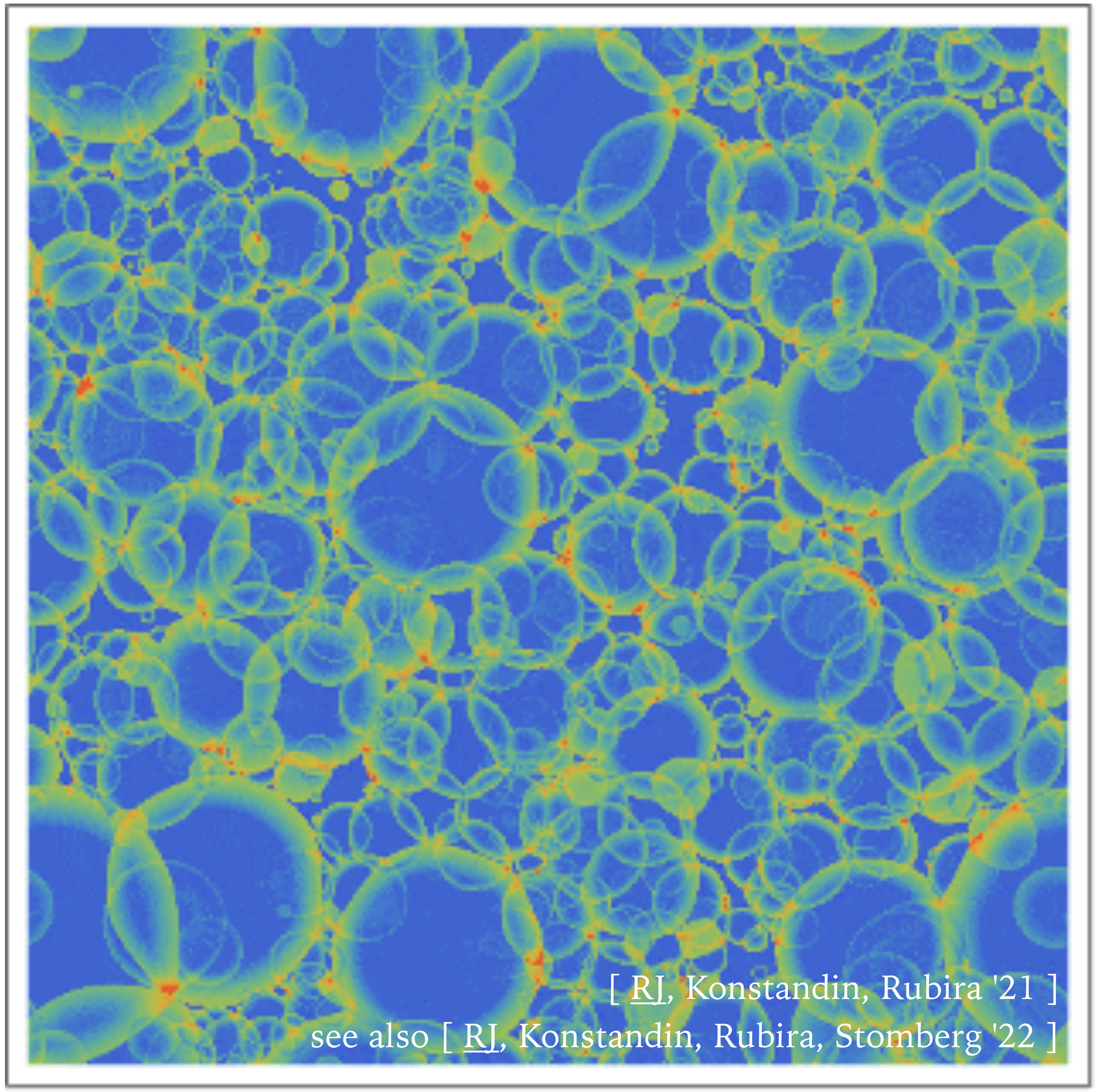




STEP 3: BUBBLE COLLISION & FLUID DYNAMICS

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

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



STEP 3: BUBBLE COLLISION & FLUID DYNAMICS

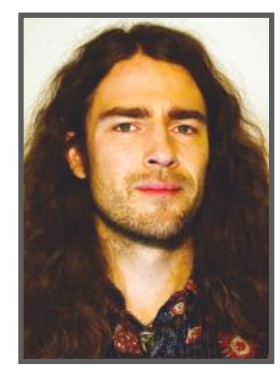
➤ We are developing a new simulation scheme for GW production from sound waves

"*The Higgsless scheme*"

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


T. Konstandin


H. Rubira


I. Stomberg

➤ Advantages:

- less artifact (from scalar walls), better resolution for shock waves, ...

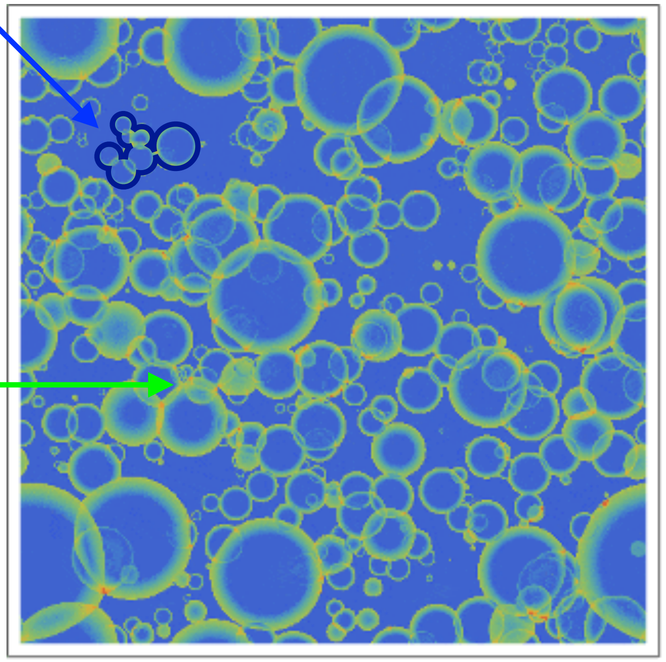
GRAVITATIONAL WAVE SOURCES

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

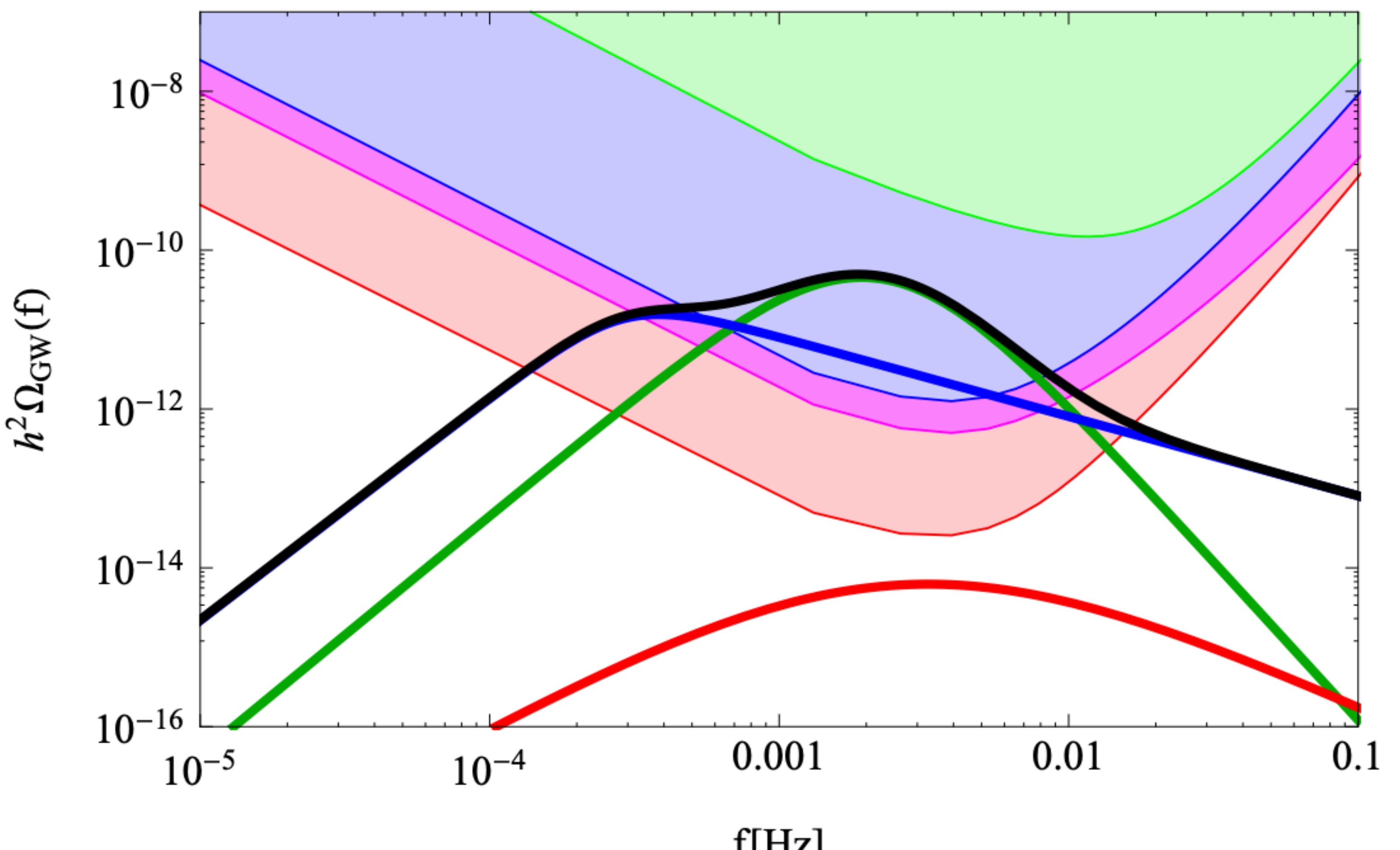
- Sound waves
  - Compression mode of the fluid motion
  - Dominant unless the transition is extremely strong

- 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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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?

GW PRODUCTION: THE STANDARD LORE & BEYOND

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

Feebly-interacting particles

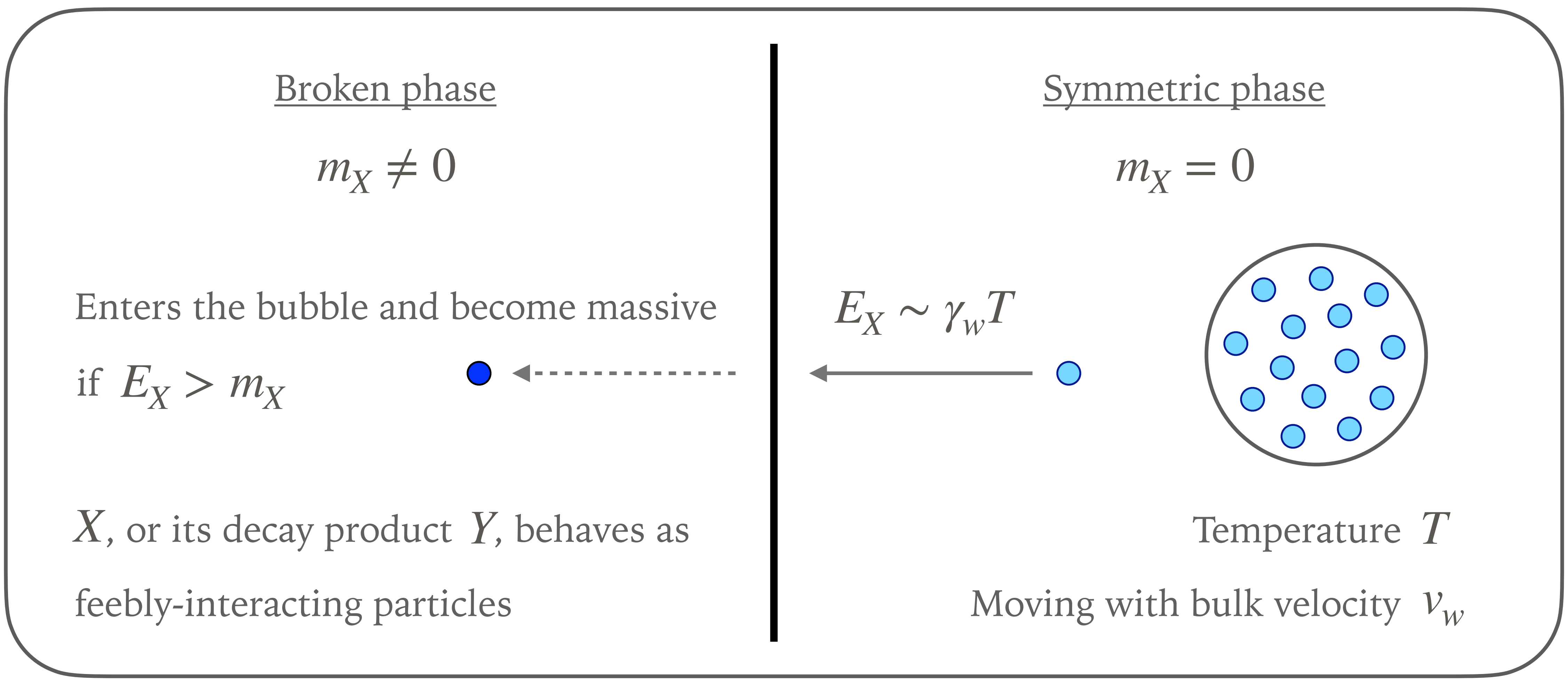
Particles in the broken phase are only feebly interacting and free-stream.

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 ϕ 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 or others
- ...and also produces feebly-interacting particles

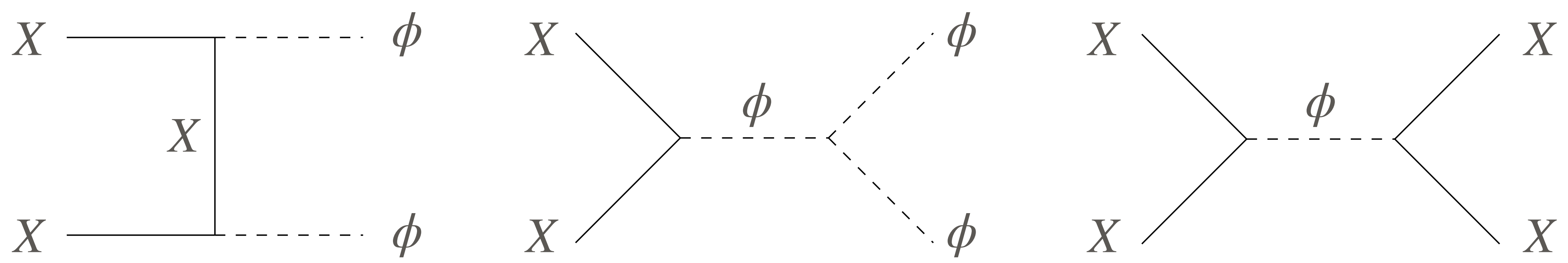
  - particle X becomes massive when crossing the wall

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

CONDITIONS FOR FEEBLE INTERACTION

- How do X particles interact?

  - couplings that gives rise to the mass of X also give rise to interactions



- Can $X = Z'$ boson free-stream? → yes, but a bit difficult

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

large

$$n_X \sigma R_* \sim T^3 \frac{g'^4}{(4\pi)^2} \frac{m_{Z'}^2}{m_\phi^4} \frac{1}{\beta} \sim \frac{1}{(4\pi)^2} \frac{g'^6}{\lambda_\phi^2} \frac{T M_P}{\langle \phi \rangle^2} \frac{H}{\beta} \lesssim 1$$

  - you can just suppress g', but then X particles become a subcomponent

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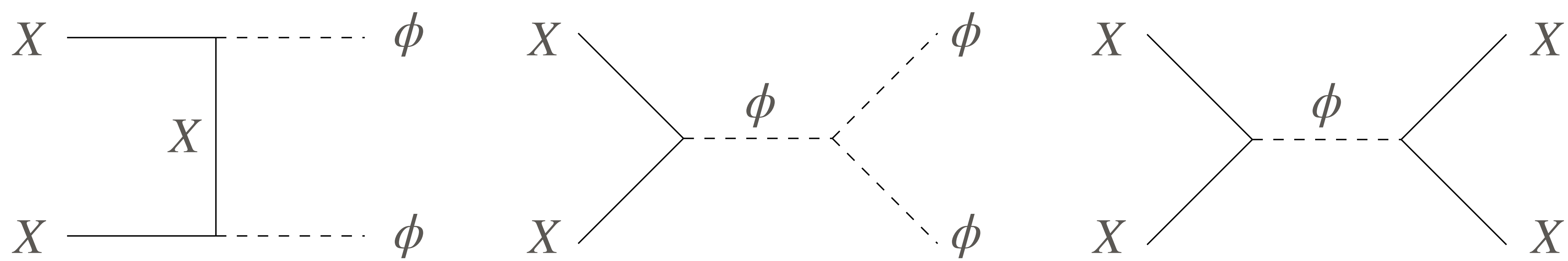

- Can $X = Z'$ boson free… difficult

  - condition to free-strea…

e.g.

$\langle \phi \rangle \sim 10T \sim 10^{11}\,\mathrm{GeV}$

$g' \sim 0.3,\ \lambda_\phi \sim 1,\ \beta/H \sim 100$

large

$$n_X \sigma R_* \ \sim\ T^3 \frac{g'^4}{(4\pi)^2} \frac{m_{Z'}^2}{m_\phi^4} \frac{1}{\beta} \ \sim\ \frac{1}{(4\pi)^2} \frac{g'^6}{\lambda_\phi^2} \frac{T M_P}{\langle \phi \rangle^2} \frac{H}{\beta} \ \lesssim\ 1$$

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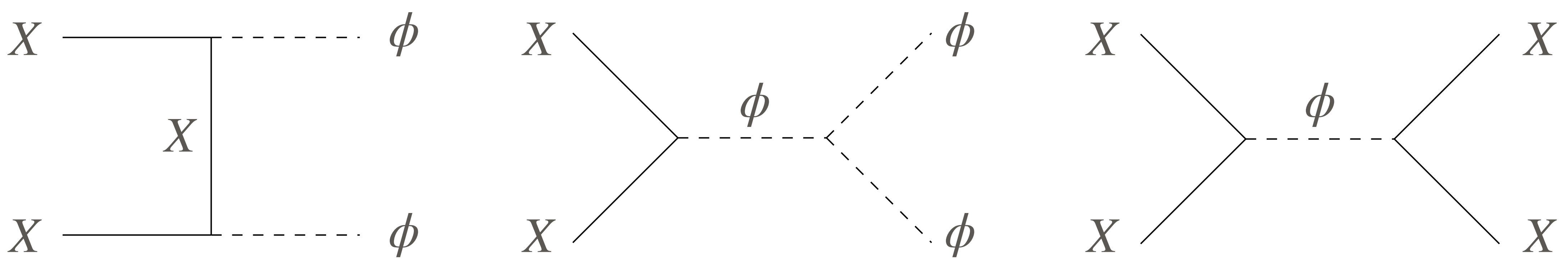

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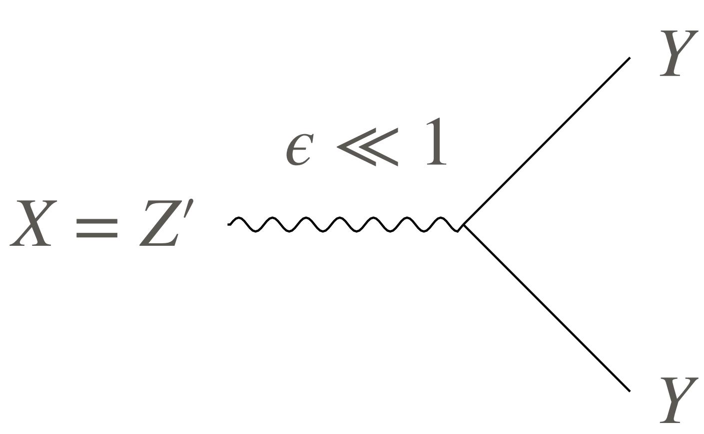
- Can a decay product of X free-stream? → yes



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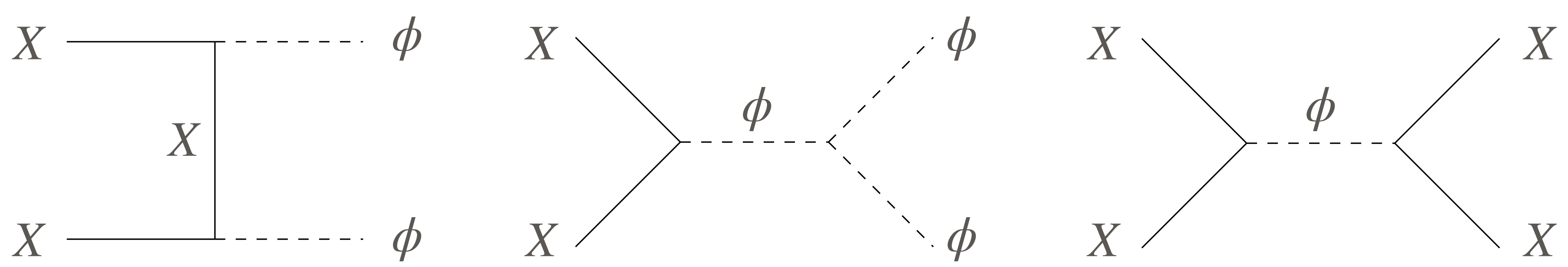


- Can $X = Z'$ boson free-stream? → yes, but a bit difficult

- Can a decay product of X free-stream? → yes

- In the following, we assume that the feebly-interacting particles form a dominant component in the broken phase

SINGLE-BUBBLE PROFILE

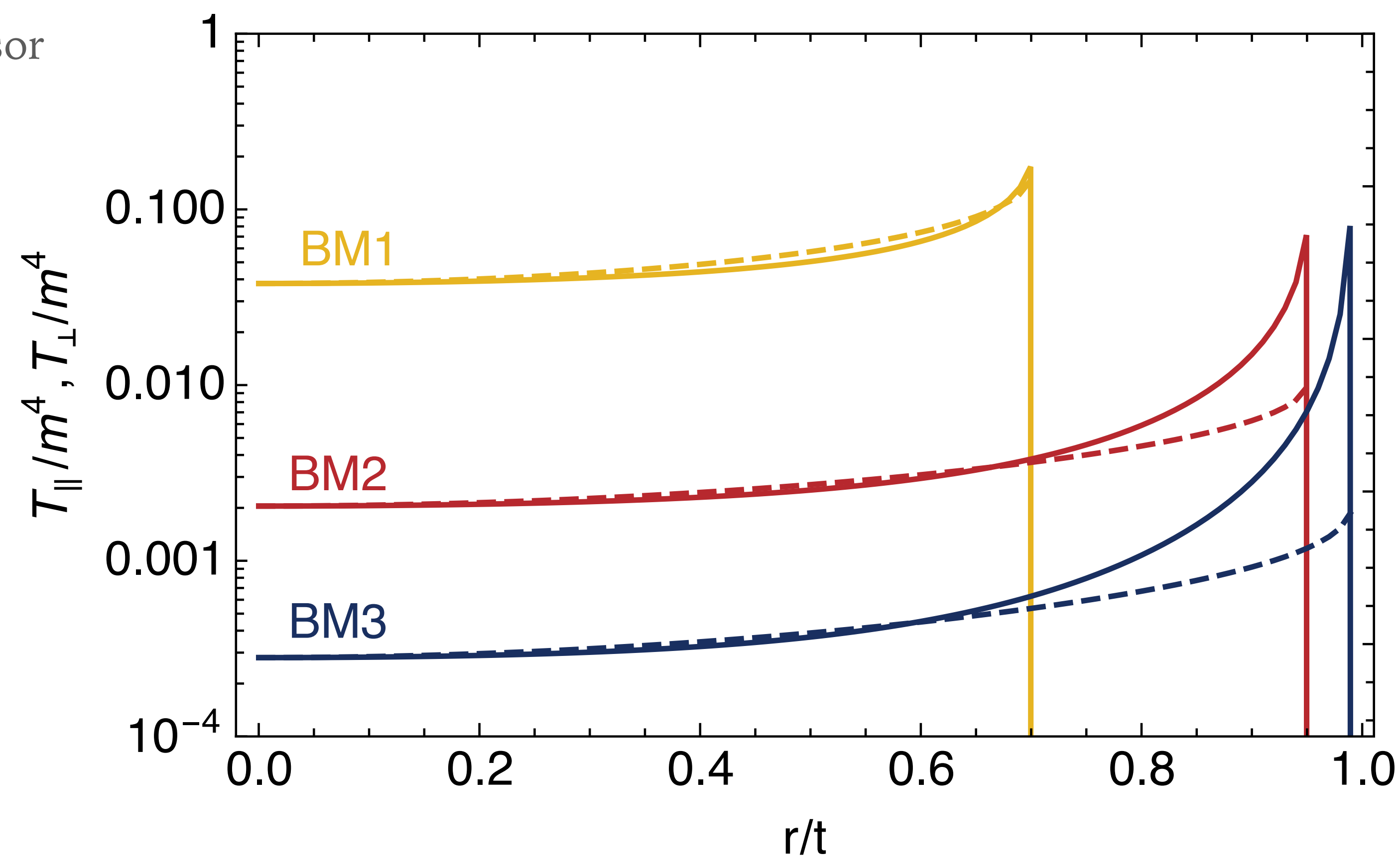
- Energy-momentum tensor of a single bubble before collision

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

Energy-momentum tensor

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

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

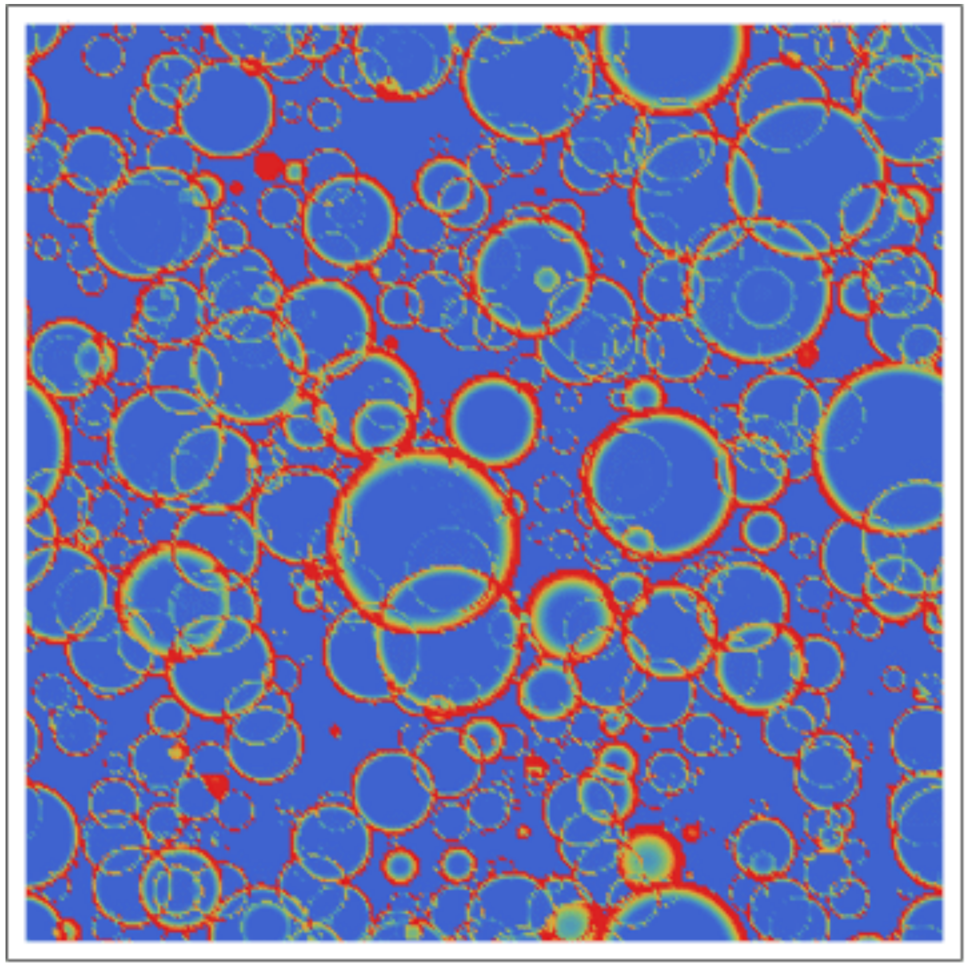


$\frac{\text{radius}}{\text{time after nucleation}}$

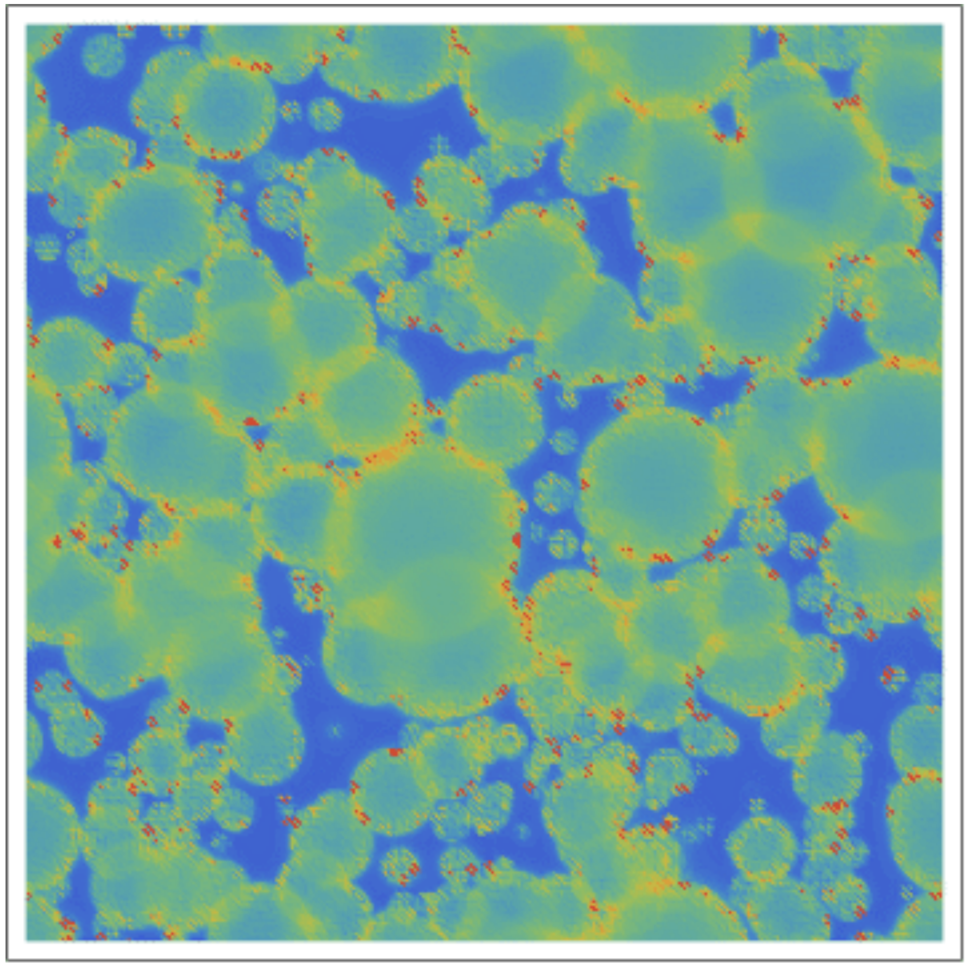
EVOLUTION OF BUBBLES WITH FEEBLY-INTERACTING PARTICLES

- Fluid vs. Feebly-interacting particles in a first-order phase transition

Fluid

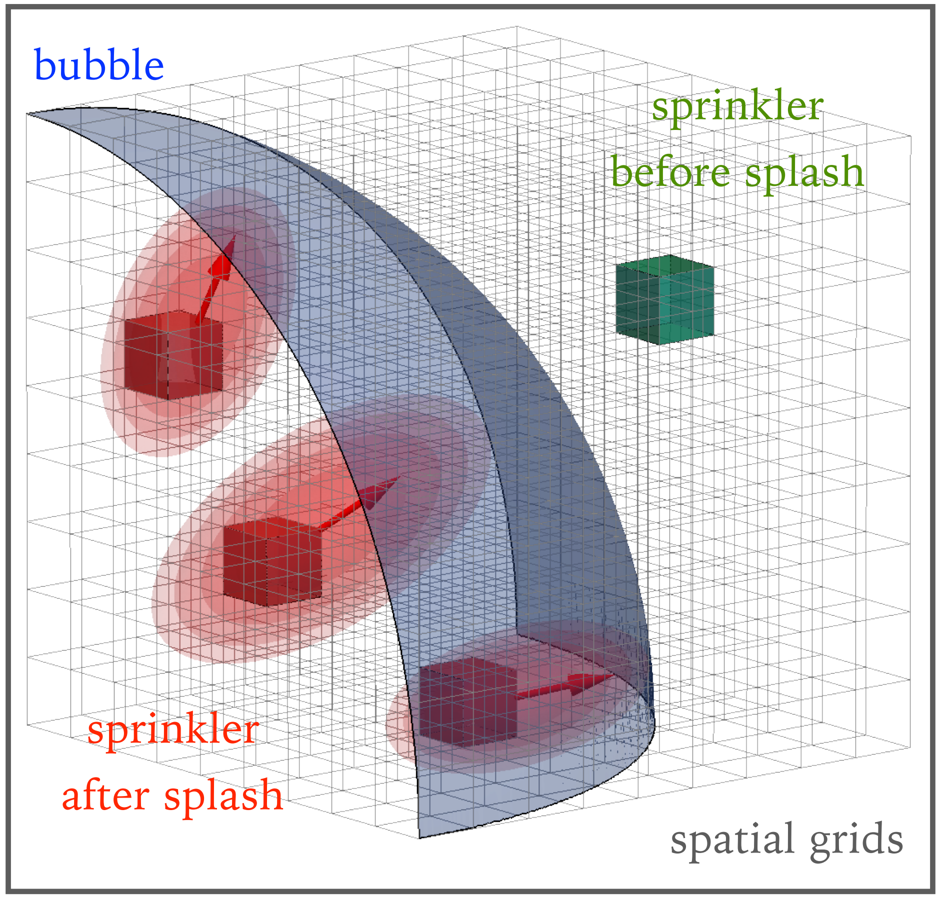


Feebly-interacting

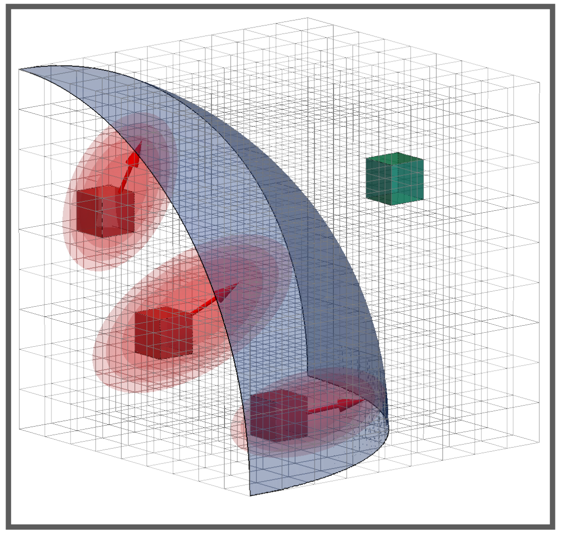


HOW TO CALCULATE THE GW SPECTRUM

- 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.

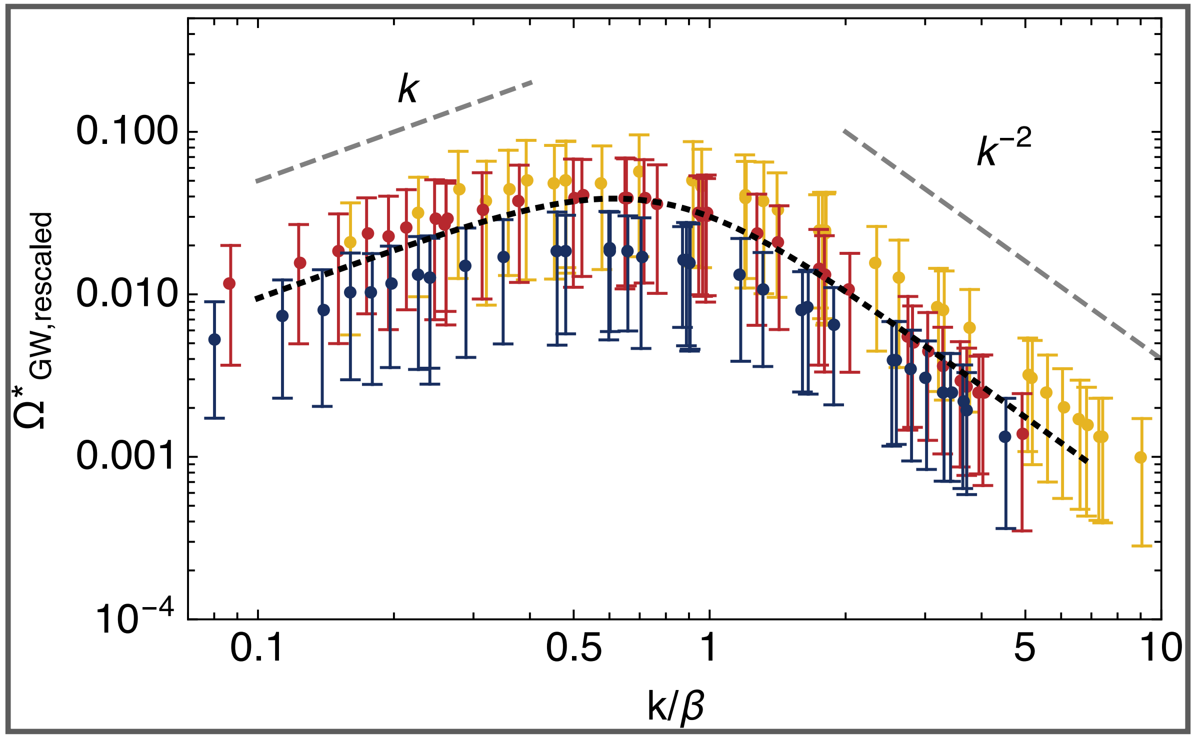
  Contributions from different sprinklers (= grids) are linearly superposed.

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

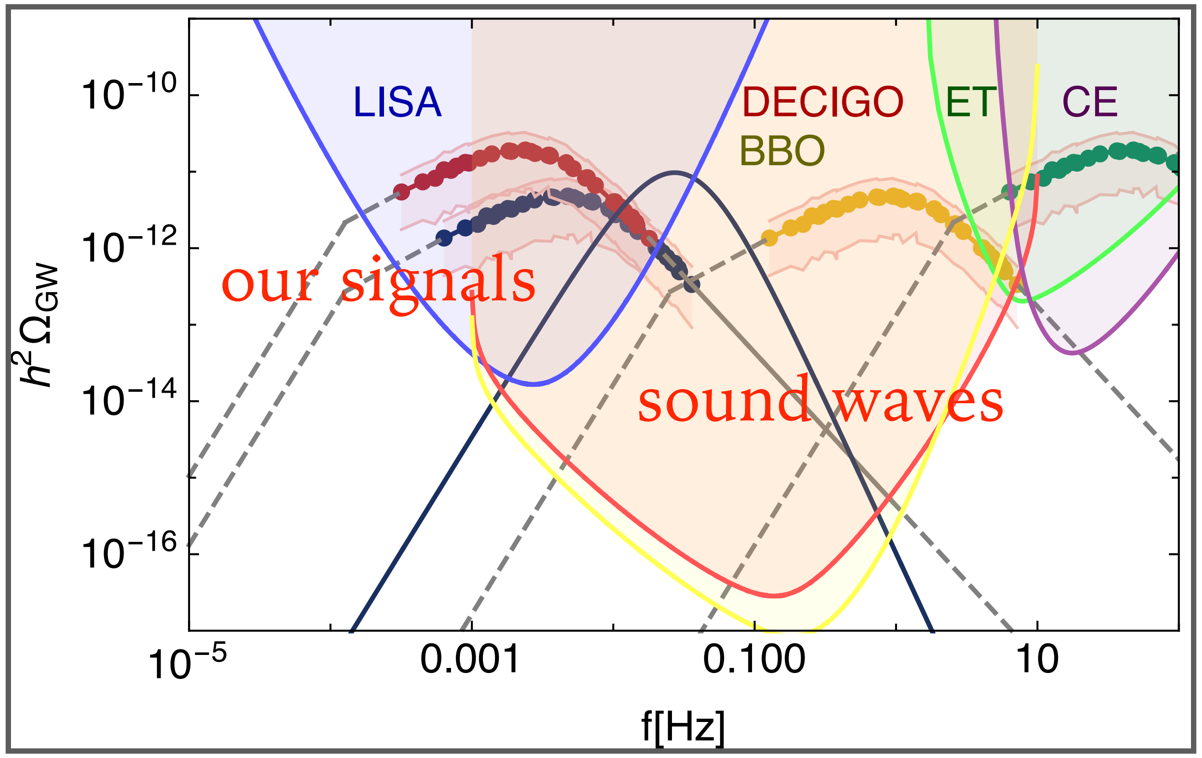
$$\Box h_{ij} \sim T_{ij} \sim \sum_{\text{sprinkler } p} T_{ij}^{(p)}$$

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

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

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

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

1 Introduction

2 GWs from sound waves in FOPT

3 GWs from FIPs in FOPT

4 Summary

SUMMARY

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

feebly-interacting particles

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

- Feebly-interacting particles are found to leave characteristic imprint on the GW spectrum

Backup

IR BEHAVIOR OF THE SPECTRUM

[RJ, Takimoto '19, Appendix E]