Introduction

GWs from sound-wave sources

GWs from free-streaming sources

Summary

Gravitational waves from first-order phase transitions: model distinction from sound-wave and free-streaming sources

Ryusuke Jinno (Kobe Univ.)

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

Hearing BSM with Cosmic Sources of GWs @ICTS, 2024/12/31

KOBE UNIVERSITY

[RJ, Konstandin, Rubira 2010.00971] [RJ, Konstandin, Rubira, Stomberg 2209.04369]

[RJ, Shakya, van de Vis 2211.06405] [Caprini, RJ, Konstandin, Roper Pol, Rubira, Stomberg 2409.03651]

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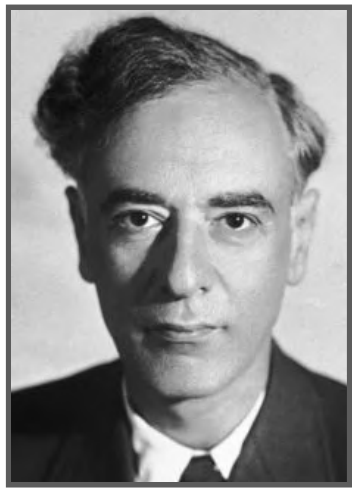
PHASE TRANSITIONS

- Classification of phase transitions (a la Landau)

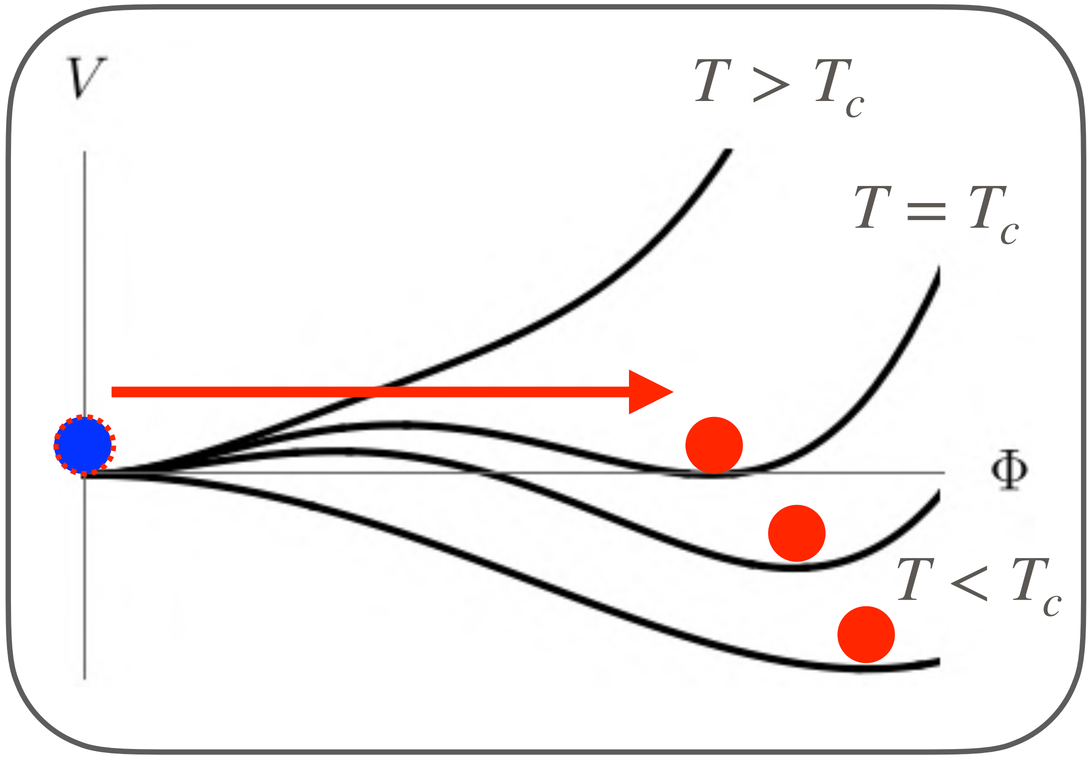


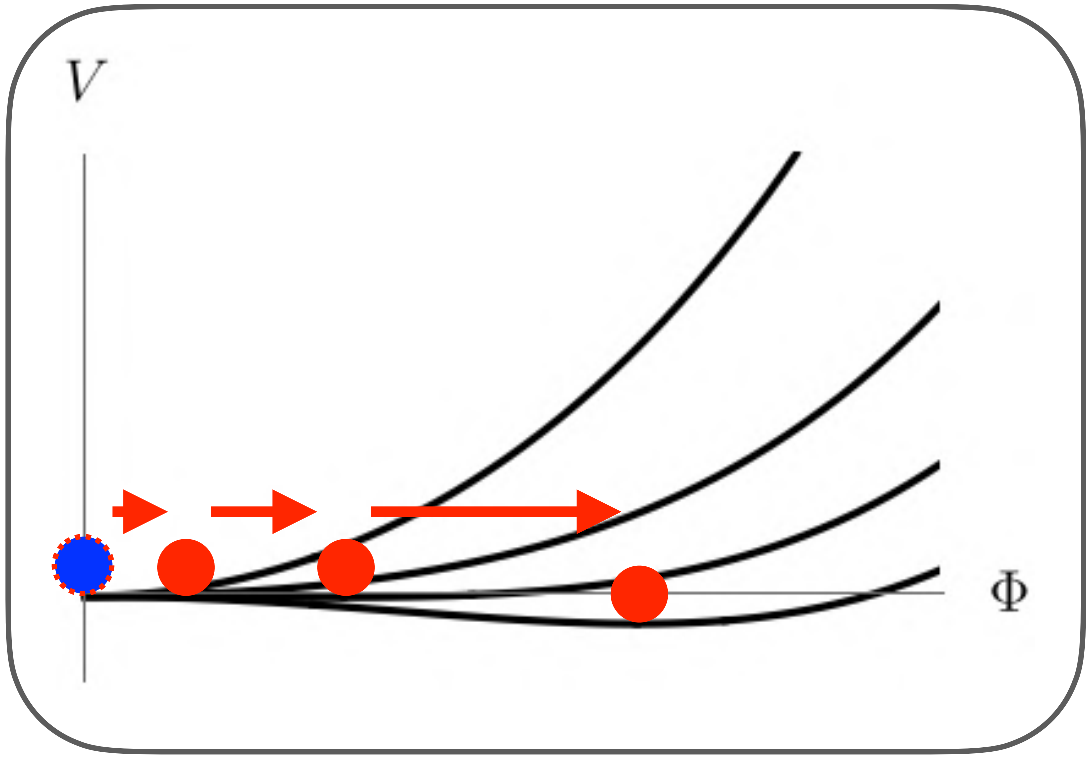
[Landau, from Wikipedia]

Order parameter (= scalar field)

discontinuous → first-order

continuous → second-order

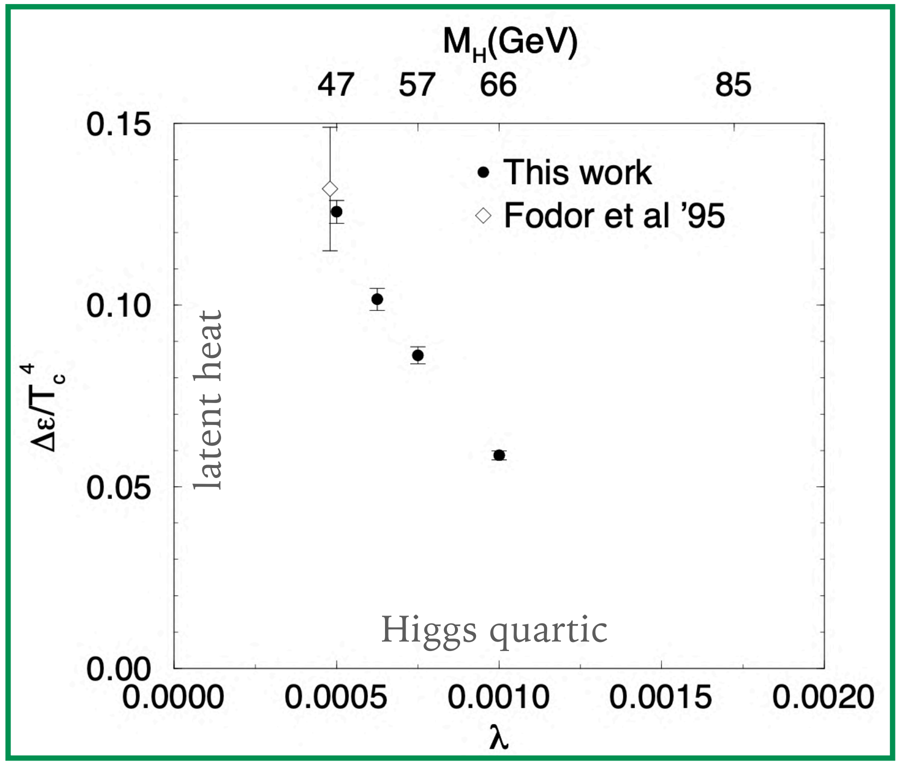


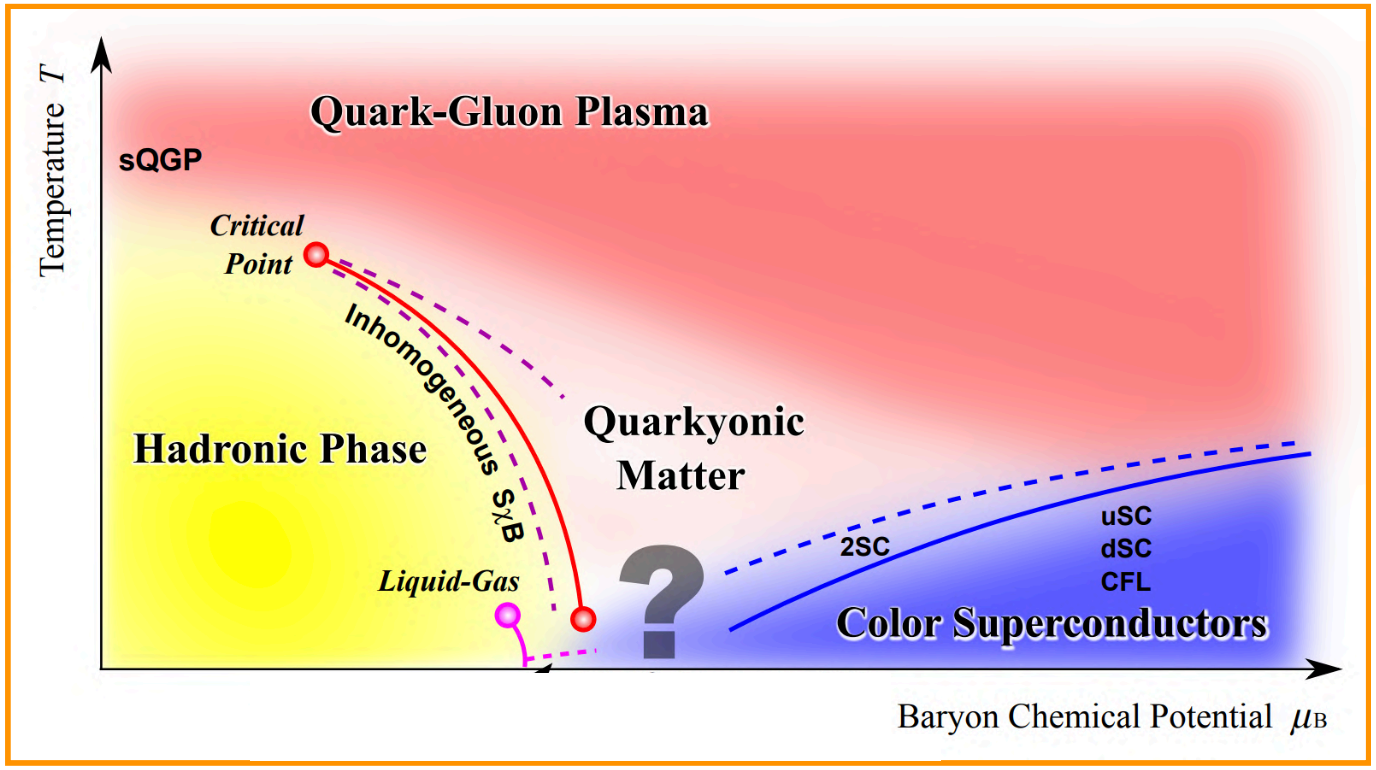


THERMAL HISTORY OF THE UNIVERSE

➤ Two candidates for FOPTs in the Standard Model (SM)

Electroweak phase transition & QCD phase transition





[Aoki '97]
see also
[Kajantie, Laine, Rummukainen, Shaposhnikov '96]
[Karsch, Neuhaus, Patkós, Rank '97]

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→ Unfortunately both are crossover

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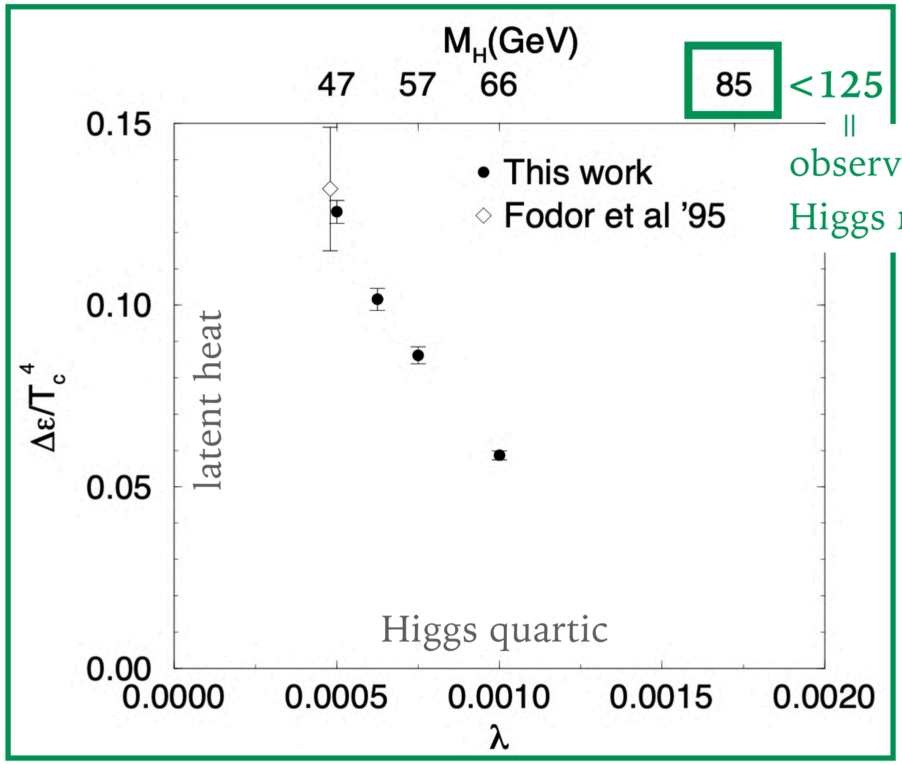

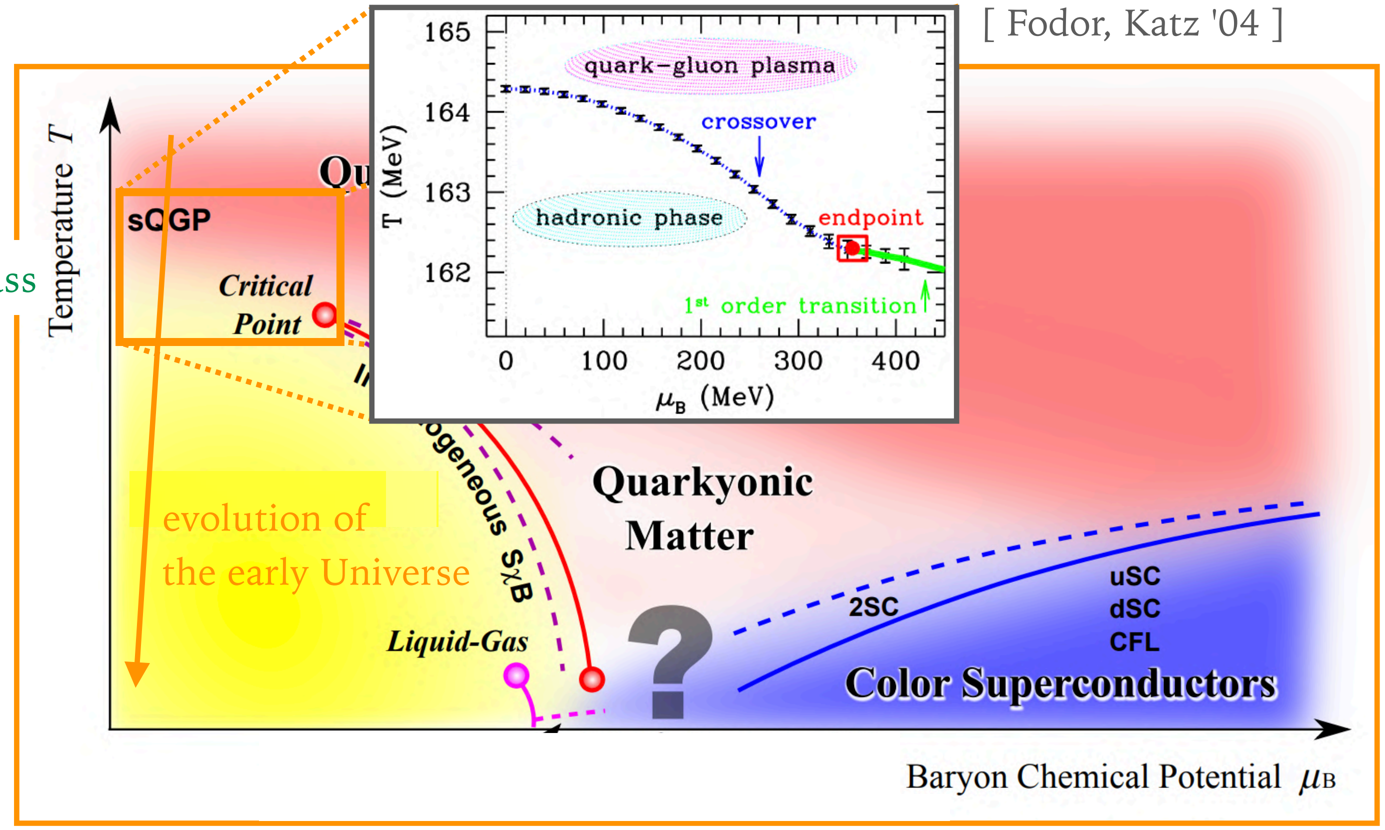

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→ Unfortunately both are crossover

WHY DO WE CONSIDER FIRST-ORDER PHASE TRANSITIONS?

- The vast energy scale the Universe might have experienced from inflation ($\lesssim 10^{15}\mathrm{GeV}$) to the present ($\sim 10^{-4}\mathrm{eV}$)
- Spontaneous symmetry breaking that might have happened

  - Breaking of the GUT group

  - Breaking of Peccei-Quinn symmetry $U(1)_{\mathrm{PQ}}$

  - Breaking of B-L symmetry $U(1)_{\mathrm{B-L}}$

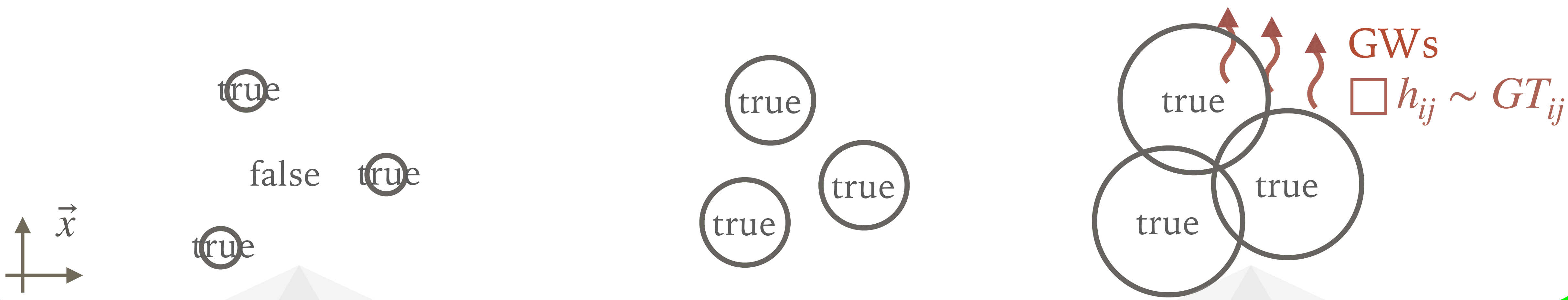
  - Breaking of dark groups ...
- Testable in the coming 10-20 yrs with GWs

OVERVIEW

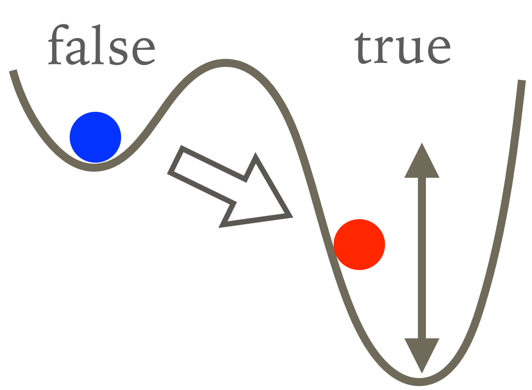
microphysics Dynamics of bubbles *macrophysics*

time or scale →

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



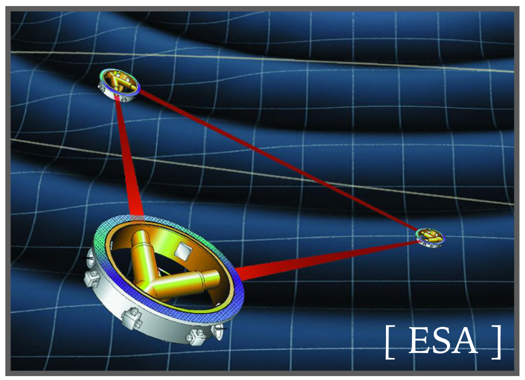
Physics of the Higgs sector



FOPTs in BSM

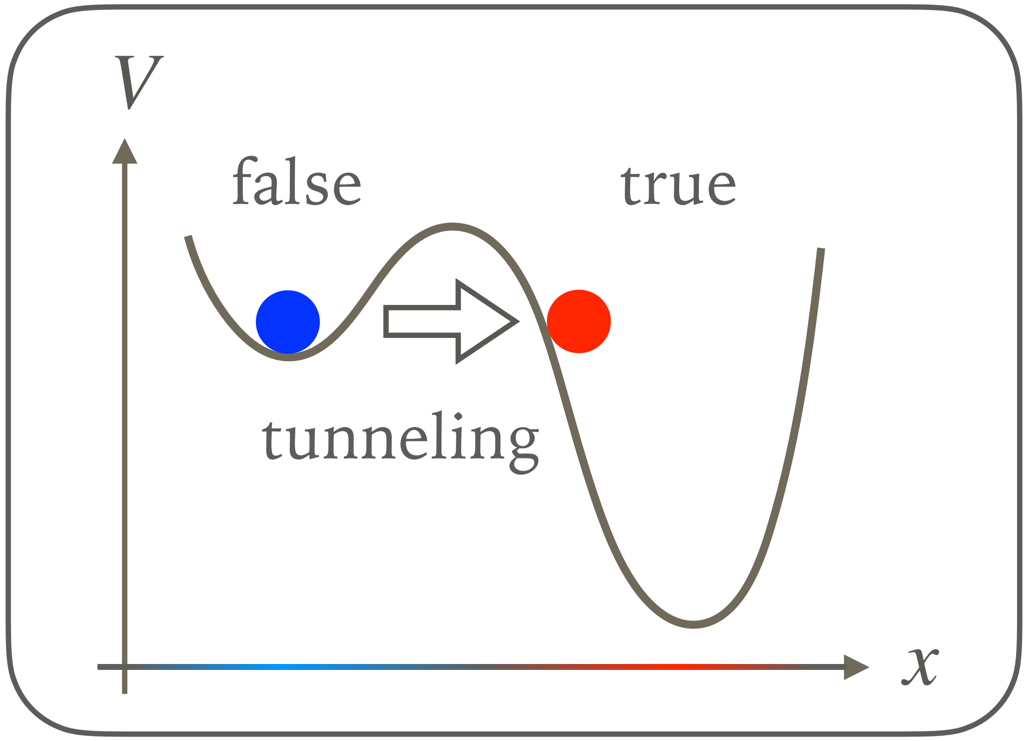
GWs

GW observations

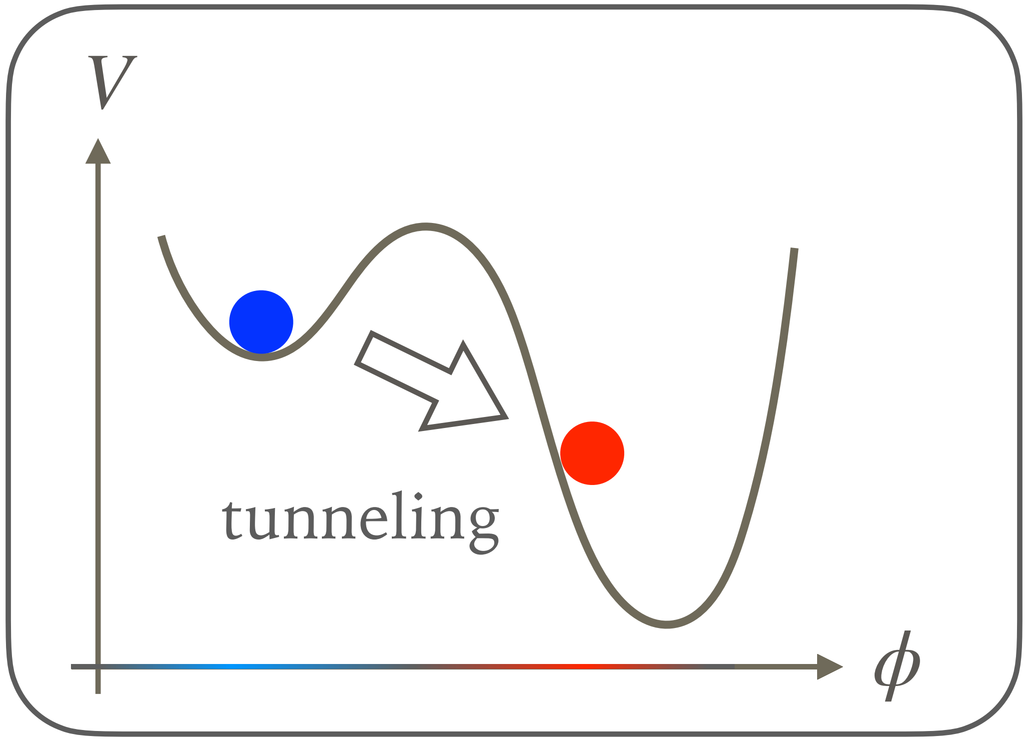


TUNNELING IN QUANTUM MECHANICS AND QFT

Quantum mechanics



Quantum field theory



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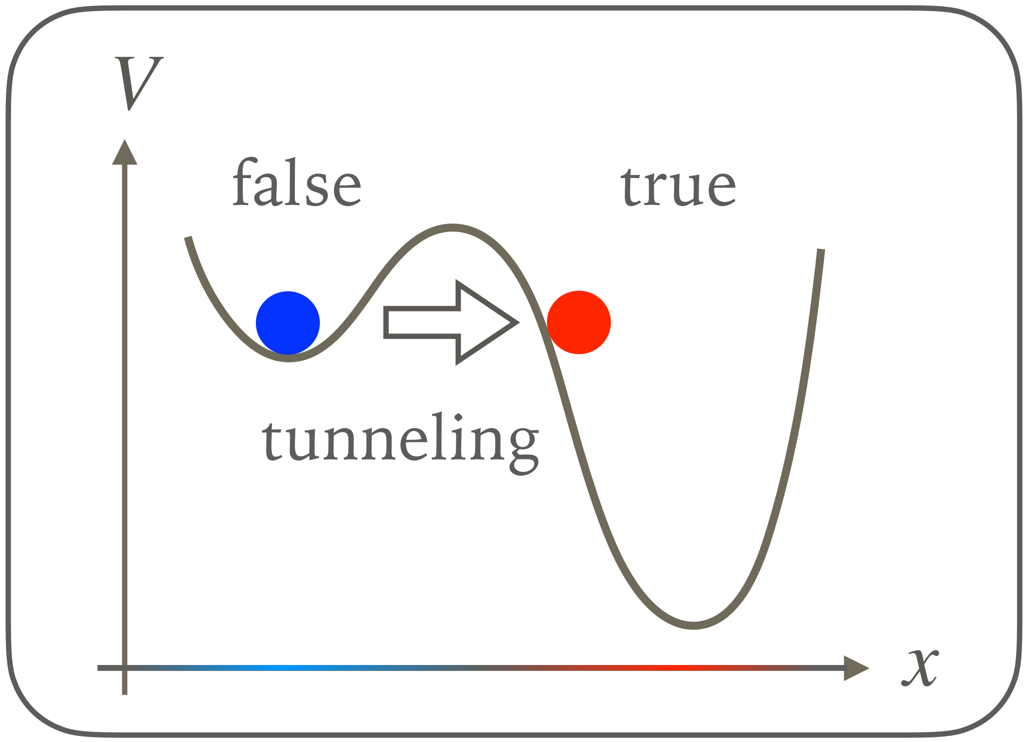

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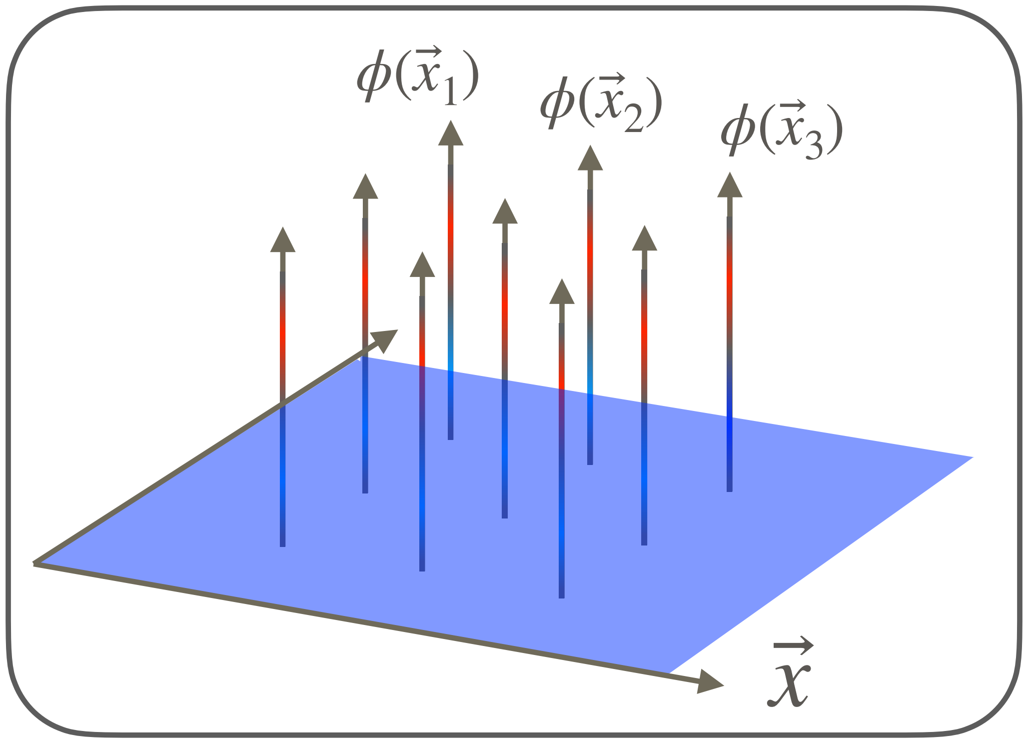

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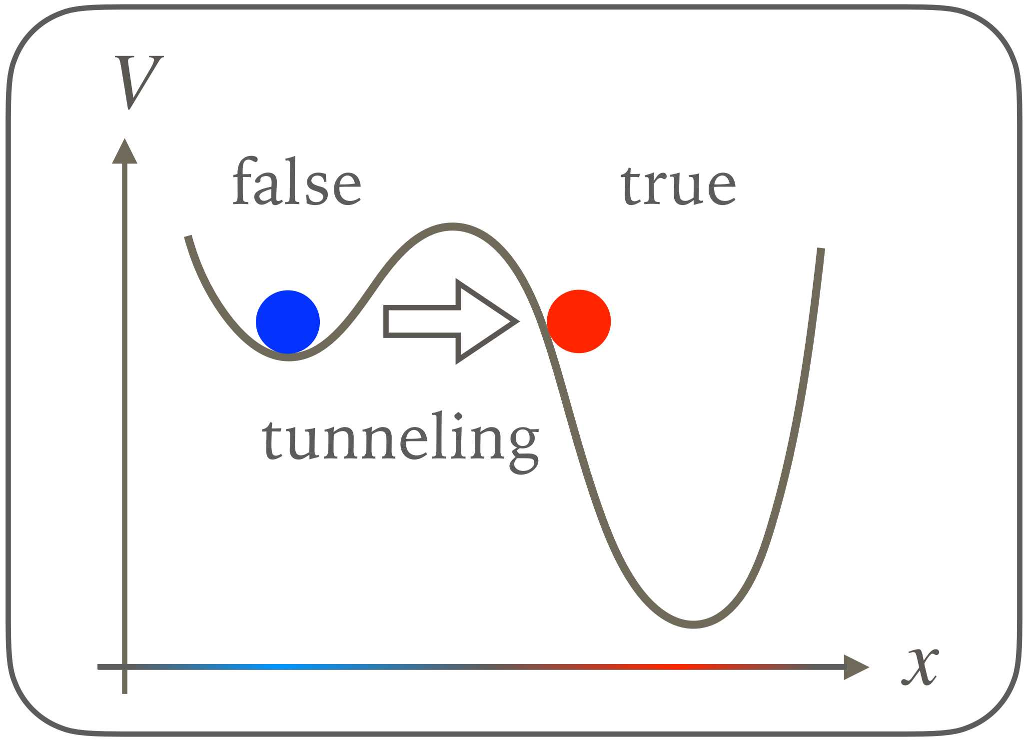

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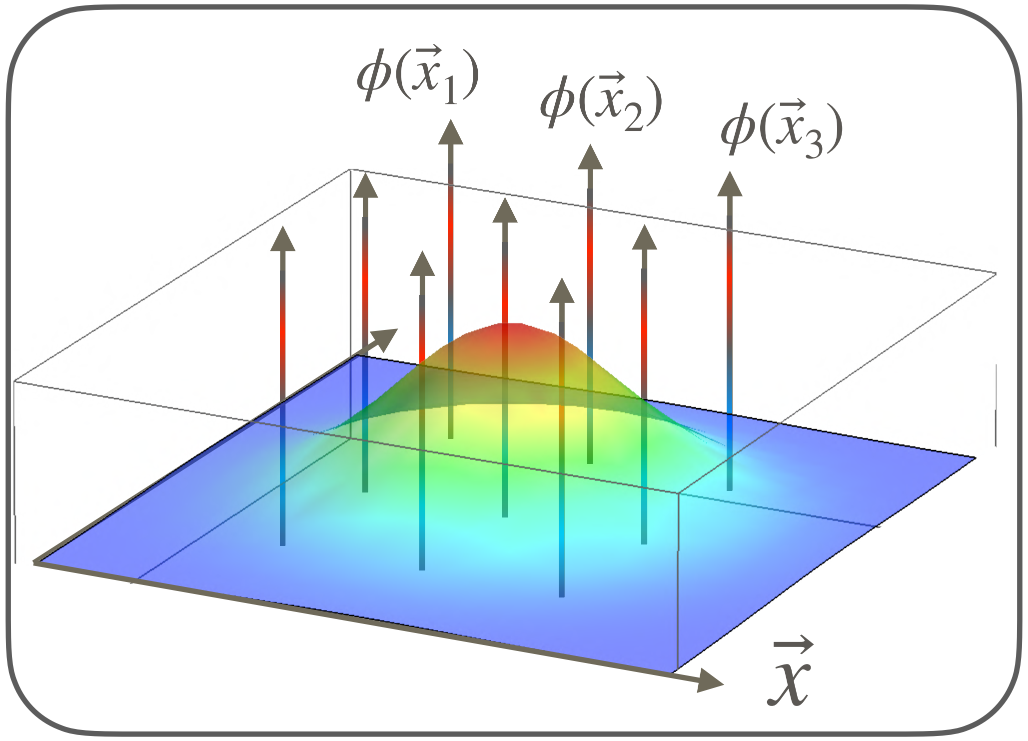
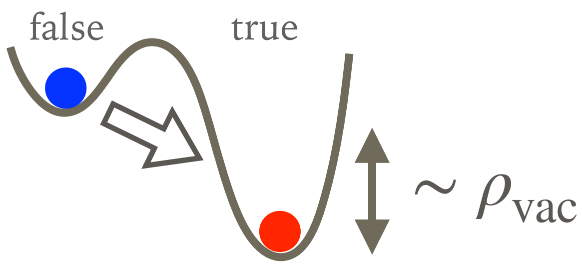


tunneling (nucleation, 核生成)

BUBBLE EXPANSION



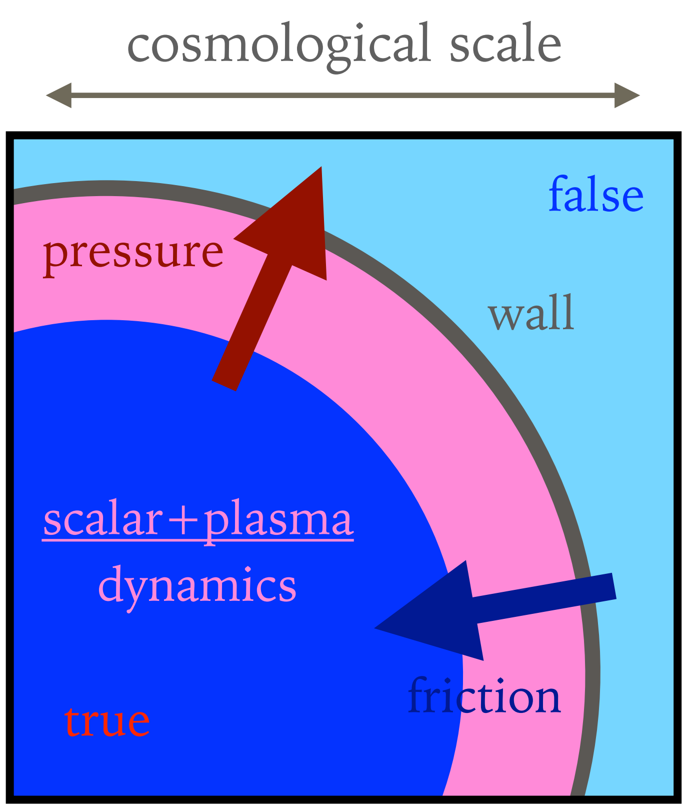
- "Pressure vs. Friction" determines the behavior:

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

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

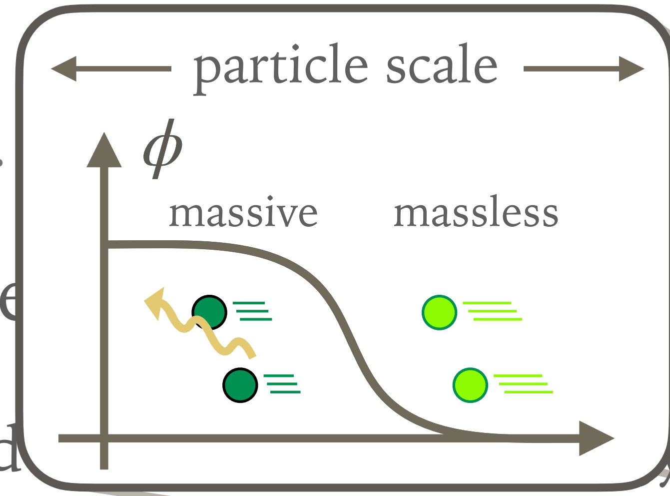
  see e.g. [Espinosa et al. '10, Hindmarsh et al. '15, Giese et al. '20]

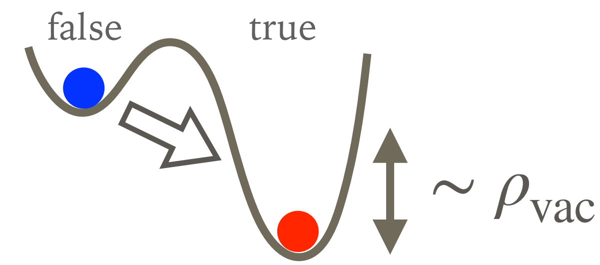
  (2) Friction: wall is pushed back by plasma particles



BUBBLE EXPANSION

[See Andrew's talk]





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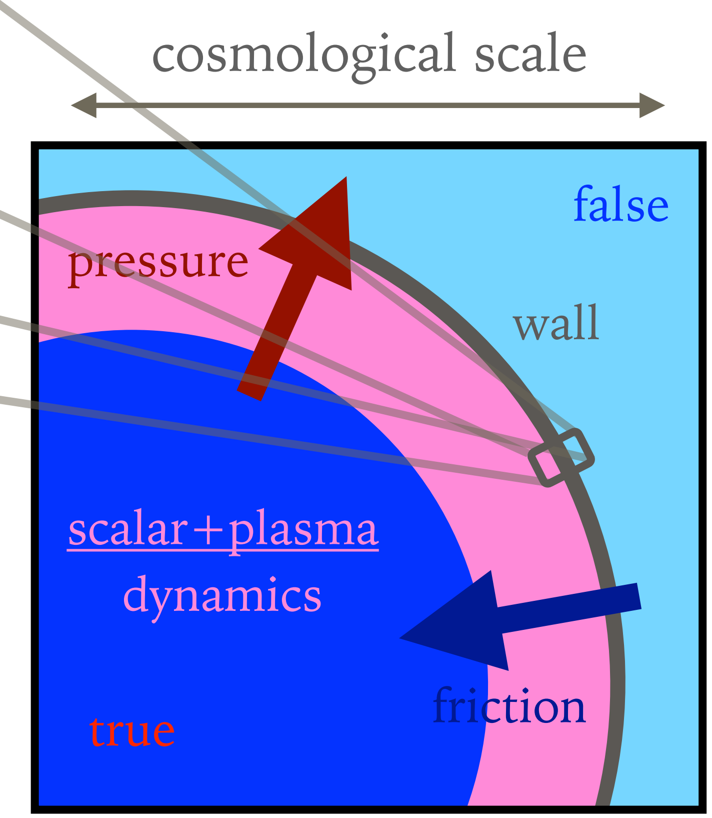

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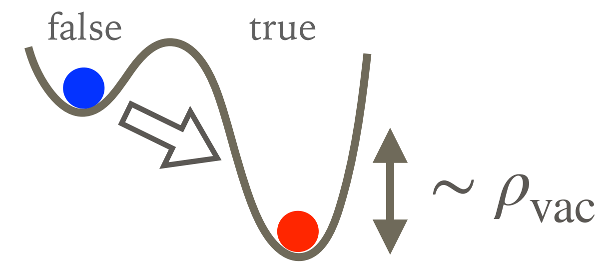

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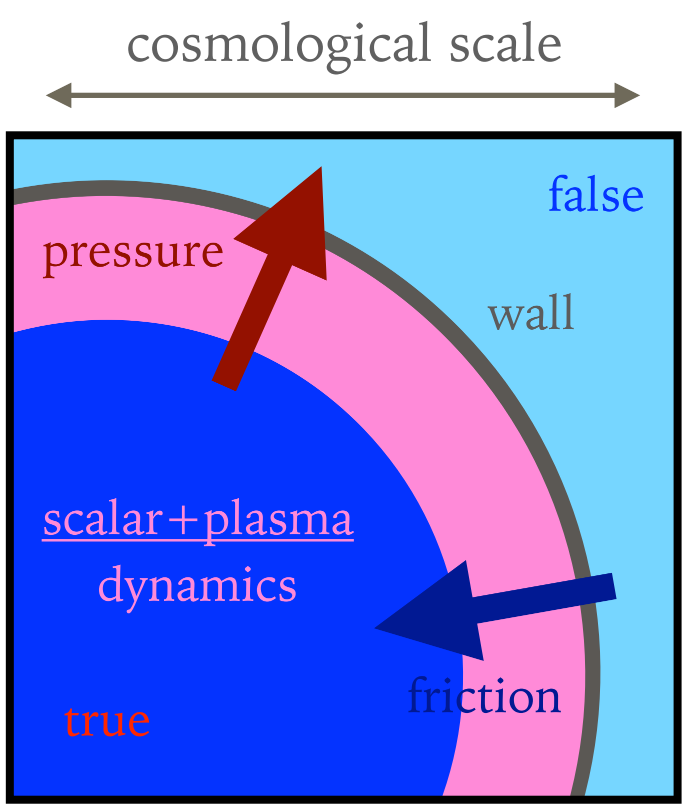
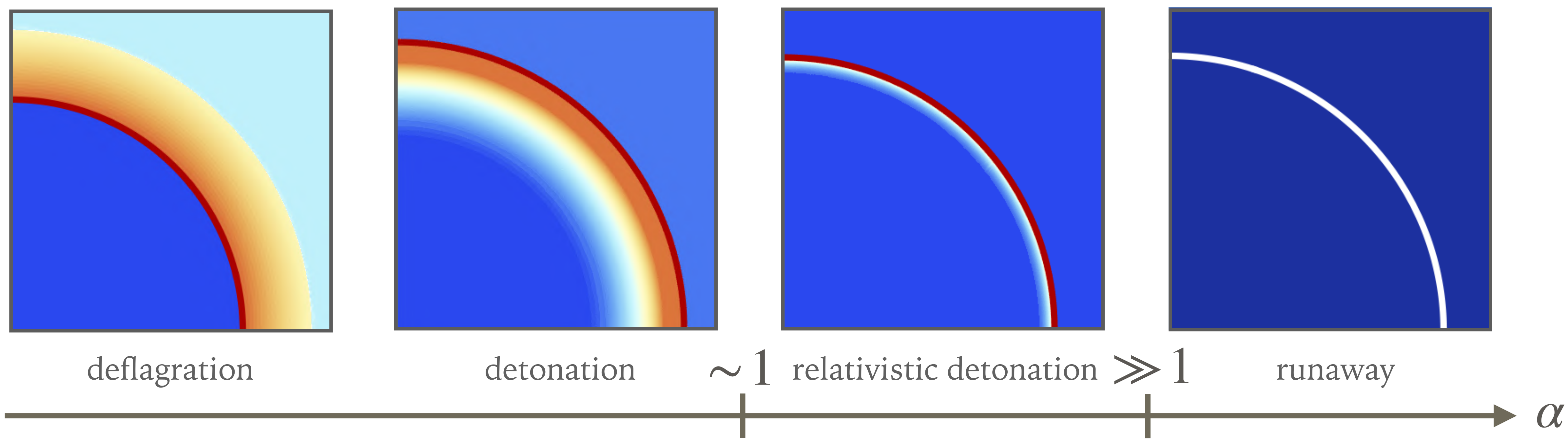


- Different types of bubble expansion



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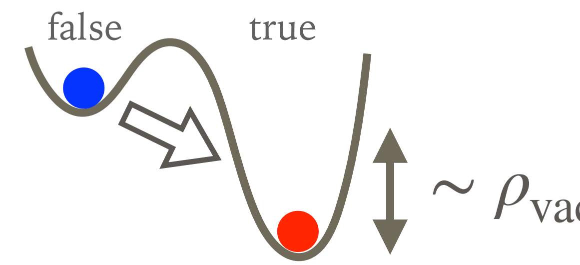
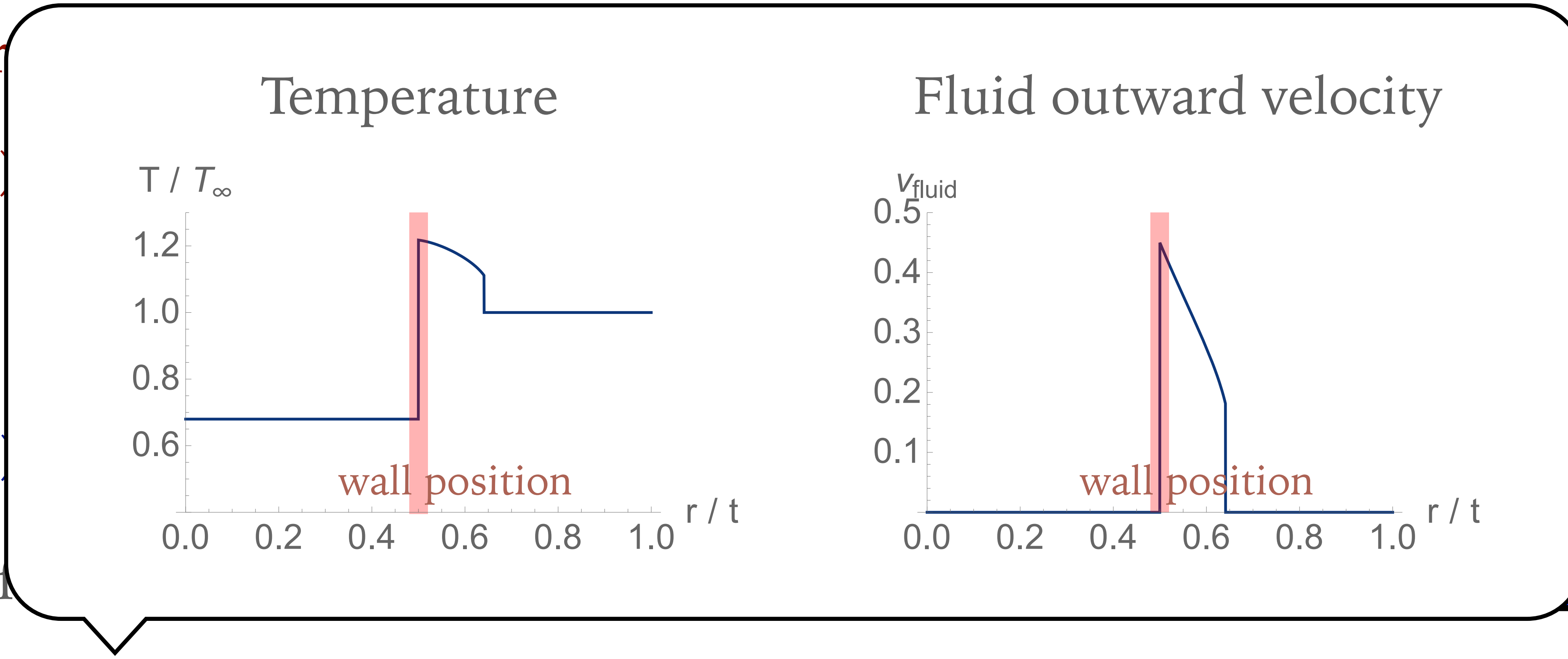


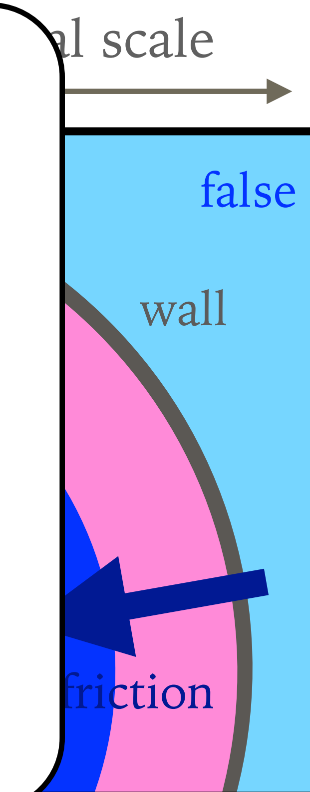
➤ "Pr

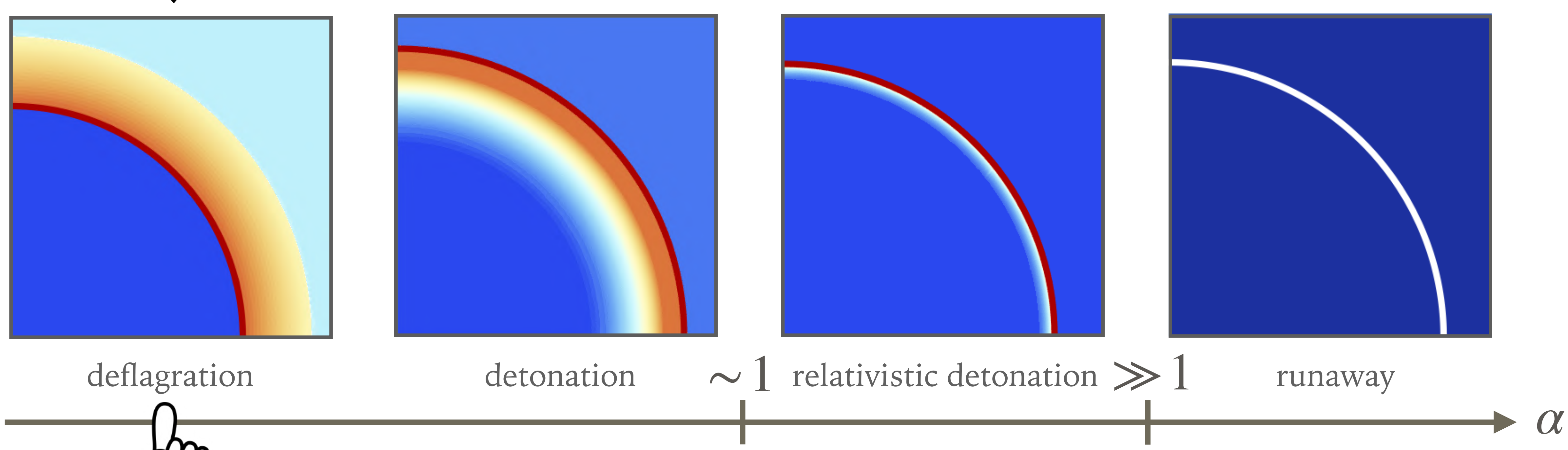
(1)

(2)

➤ Di







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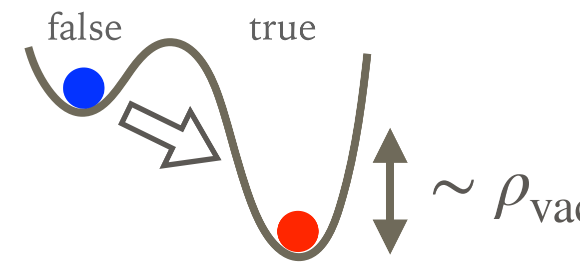
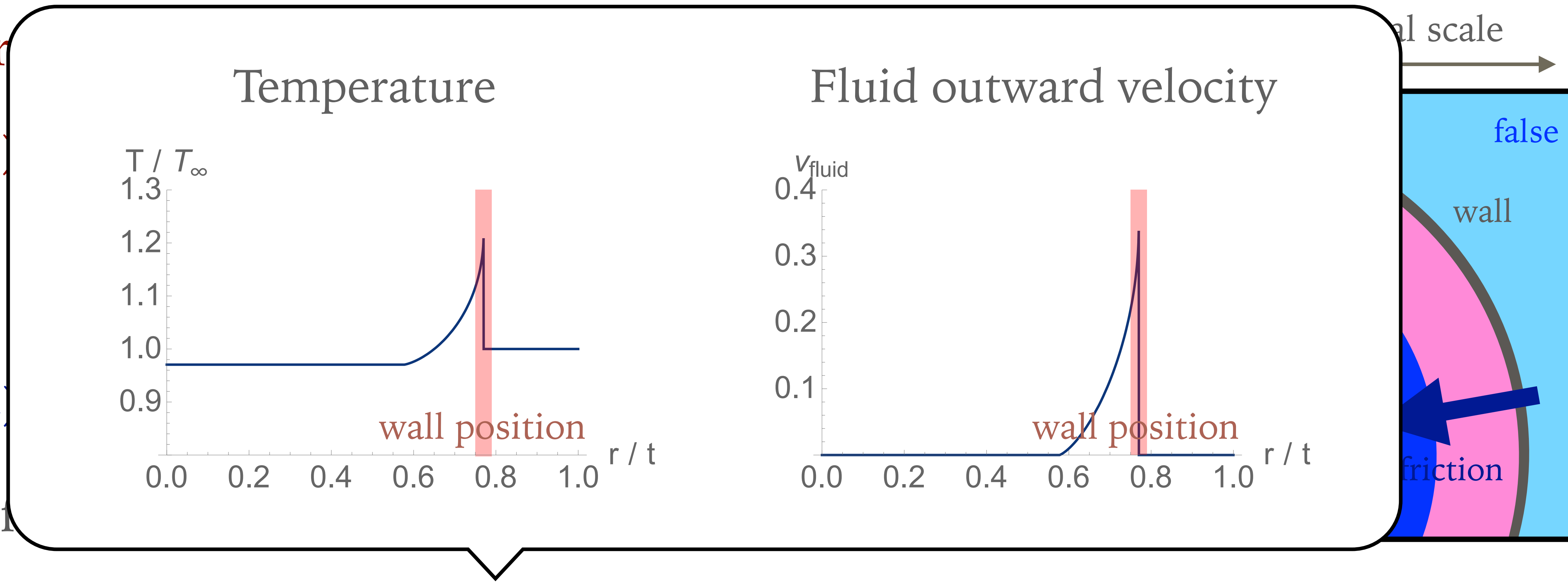


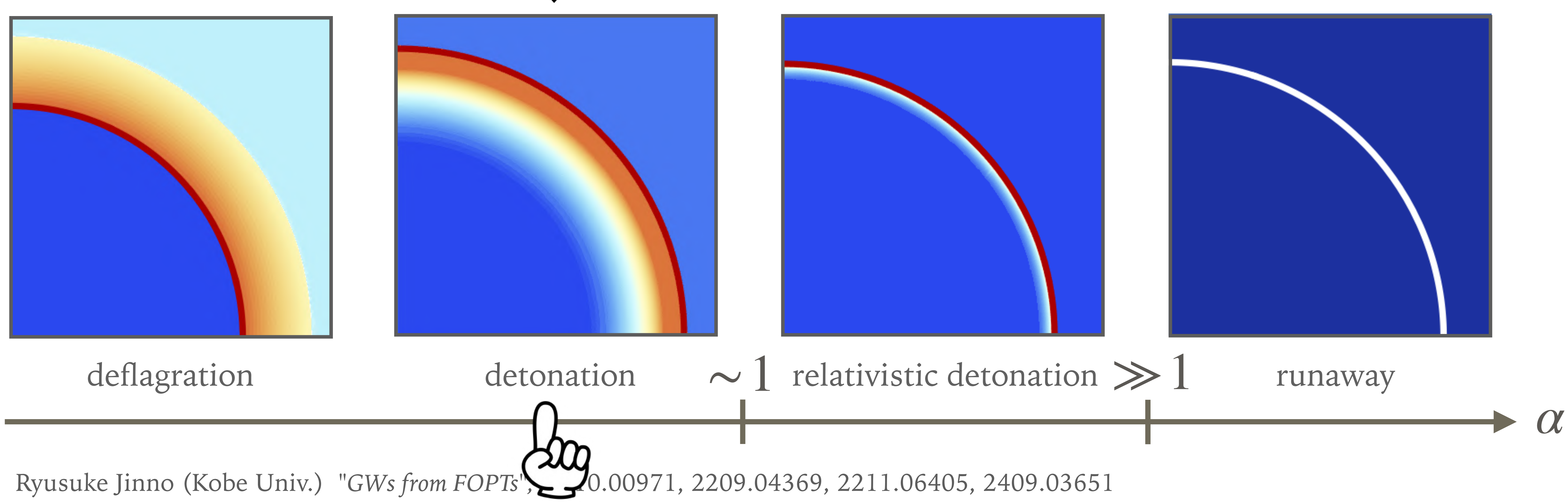
➤ "Pr… …l scale

(1)

(2)

➤ Di…





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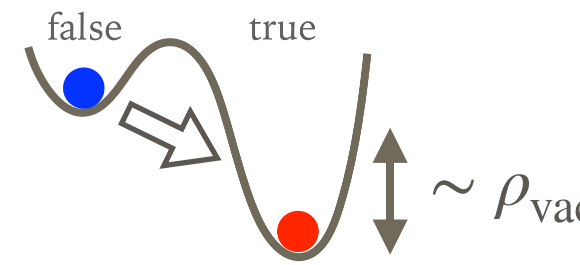

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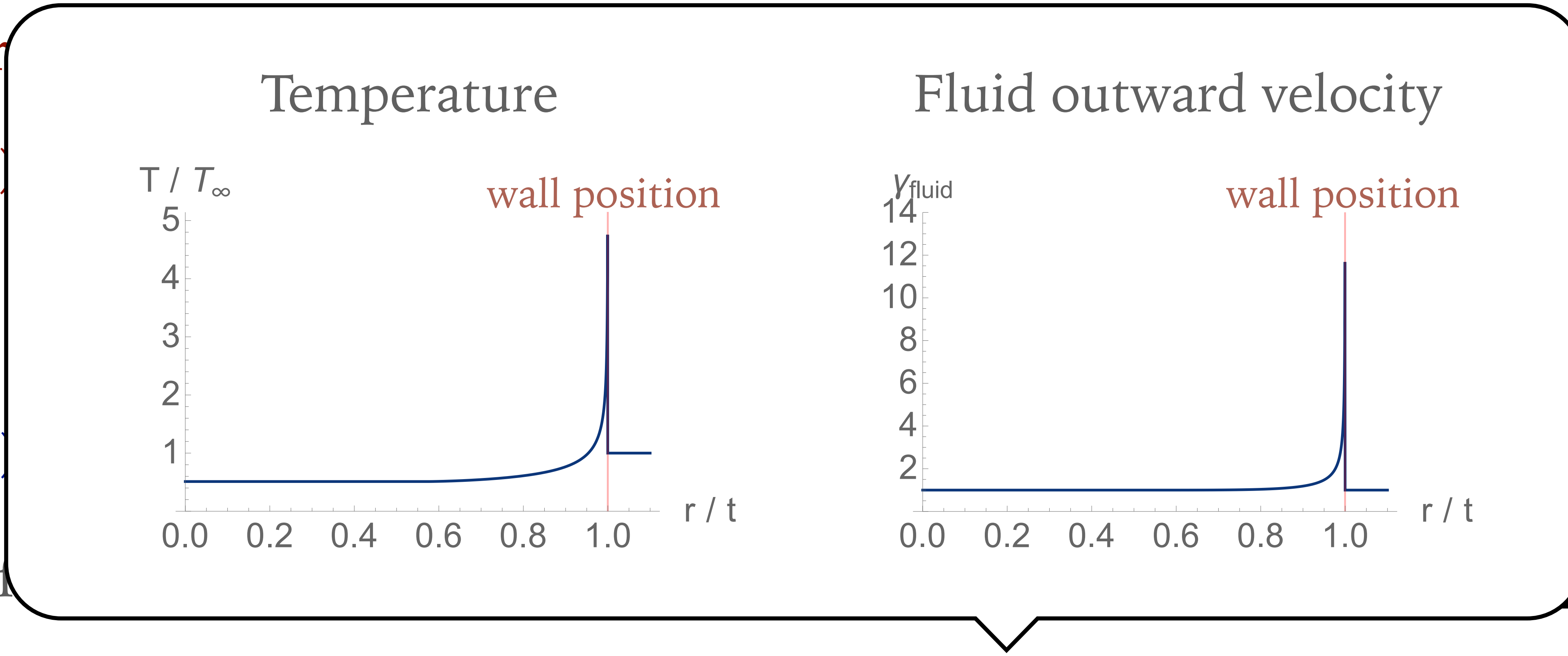
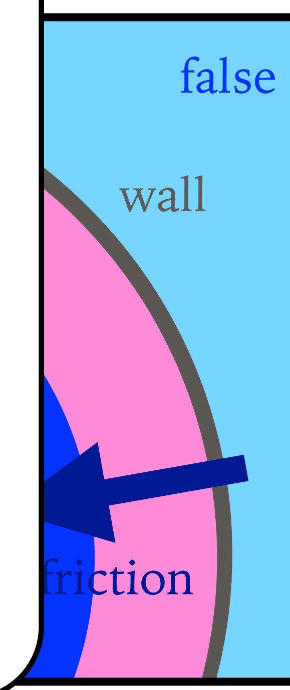
(1)

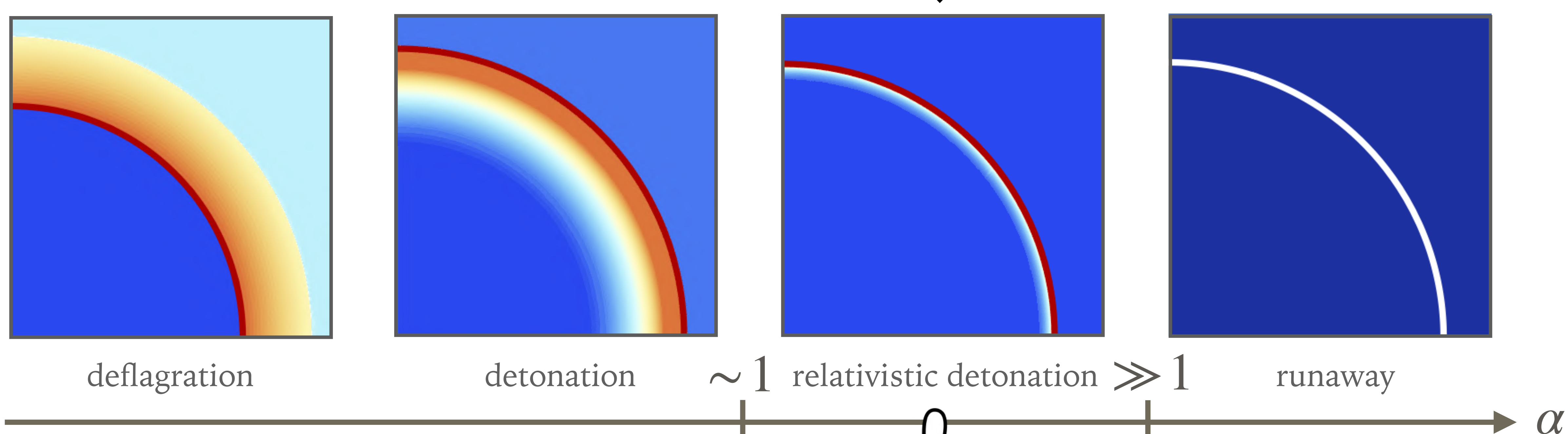
(2)

➤ Di

al scale







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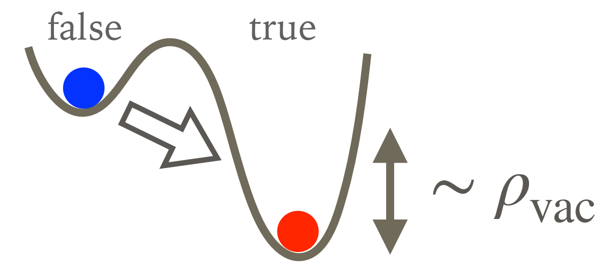

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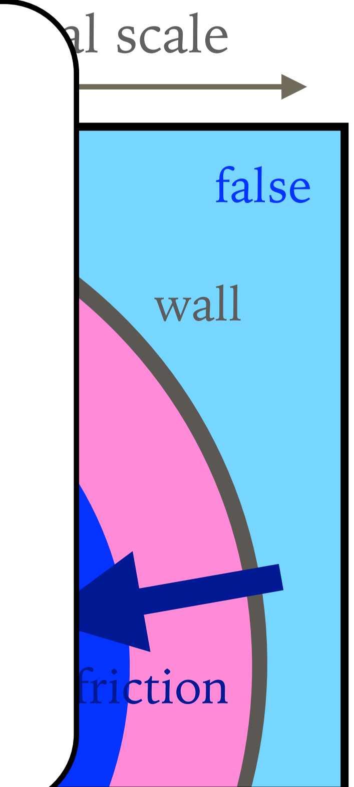
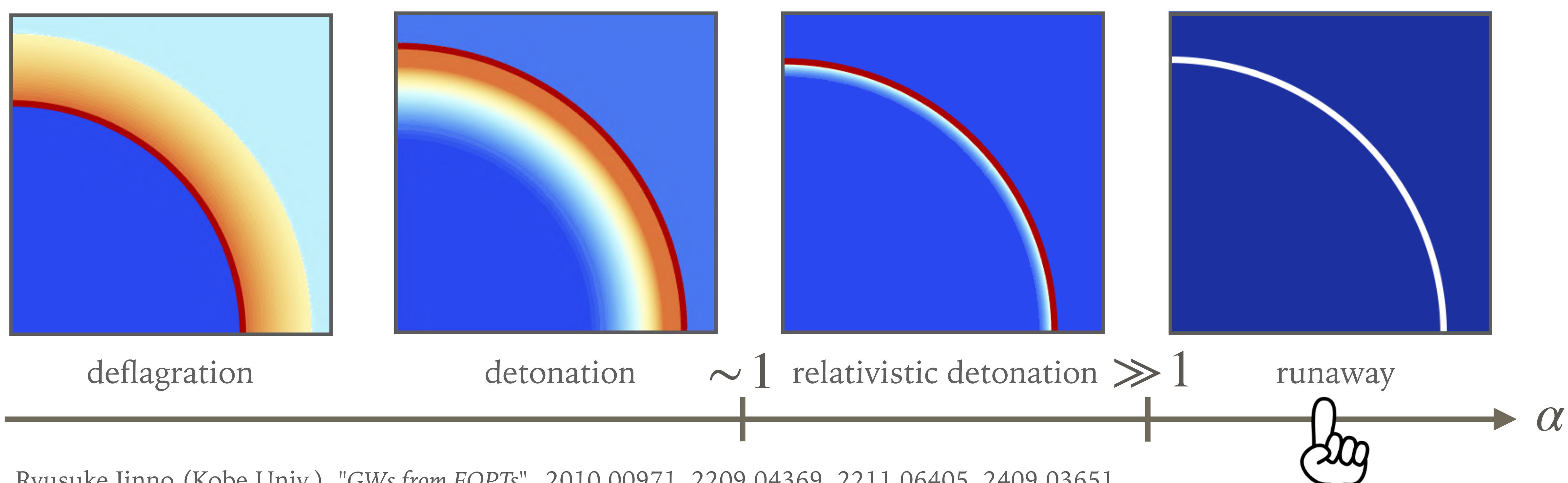


Plasma particles cannot stop the acceleration of the walls:

walls continue to accelerate until they collide with others

[Bodeker & Moore '09, '17]




Youtube "Explosions: 100 ton test detonation"

GRAVITATIONAL WAVES: A NEW PROBE TO THE UNIVERSE

[See Subhendra's lecture]

- Einstein equation:

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi G T_{\mu\nu}$$

"Spacetime tells matter how to move. Matter tells spacetime how to curve."

- Gravitational waves: transverse-traceless part of the metric

$$ds^2 = -dt^2 + a^2(\delta_{ij}+h_{ij})dx^i dx^j \qquad \partial_i h_{ij} = h_{ii} = 0$$

- After expanding the Einstein equation,

GWs obey a wave equation sourced by energy-momentum tensor

$$\Box h_{ij} = 16\pi G \Lambda_{ij,kl} T_{kl}$$

- LIGO/Virgo detected GWs from binary black holes for the first time in 2015

Selected for a Viewpoint in *Physics*

PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

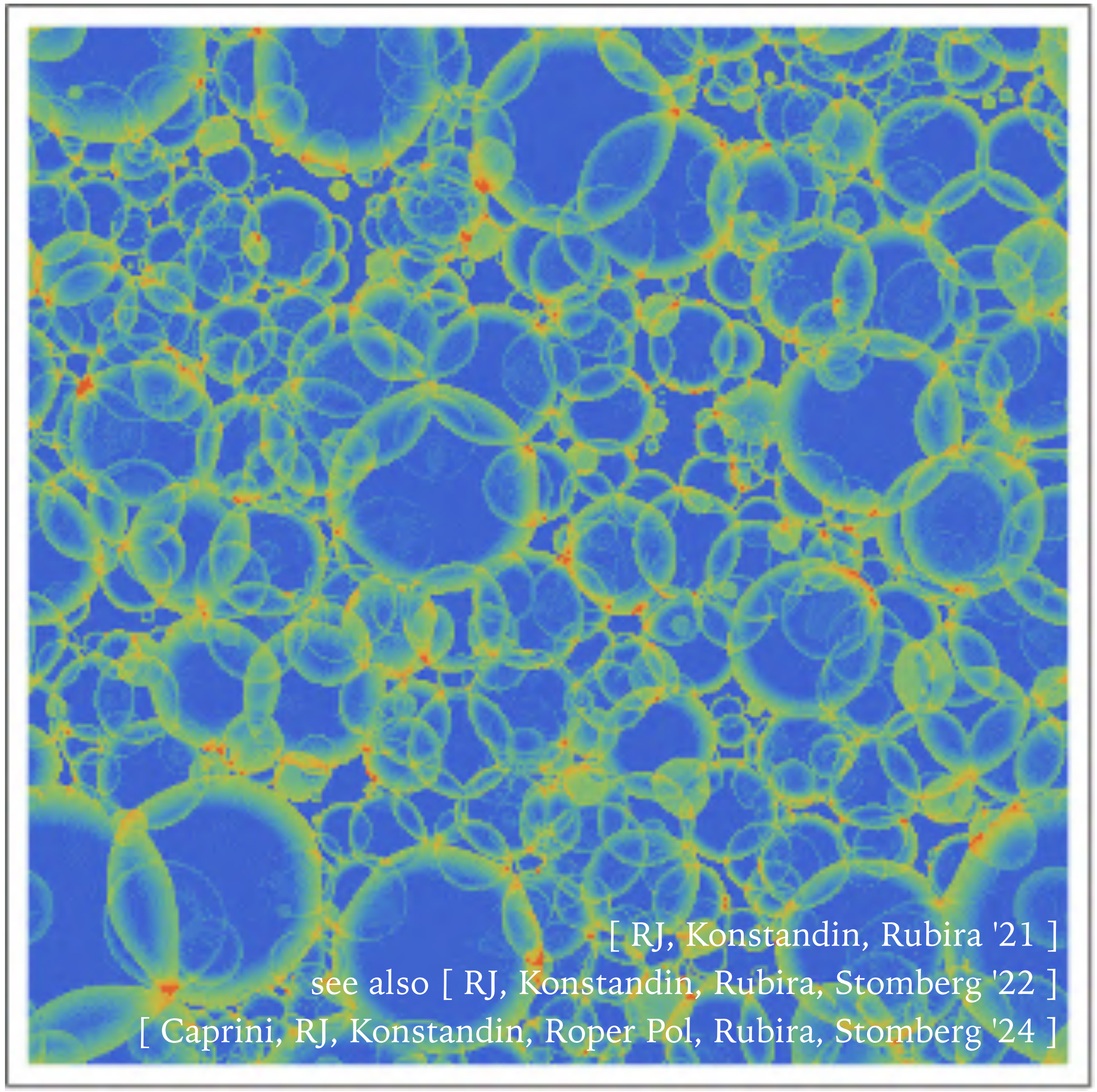
(Received 21 January 2016; published 11 February 2016)

$$36M_\odot + 29M_\odot \rightarrow 62M_\odot + 3M_\odot \text{ (GWs)}$$

[R. Hurt/Caltech-JPL]

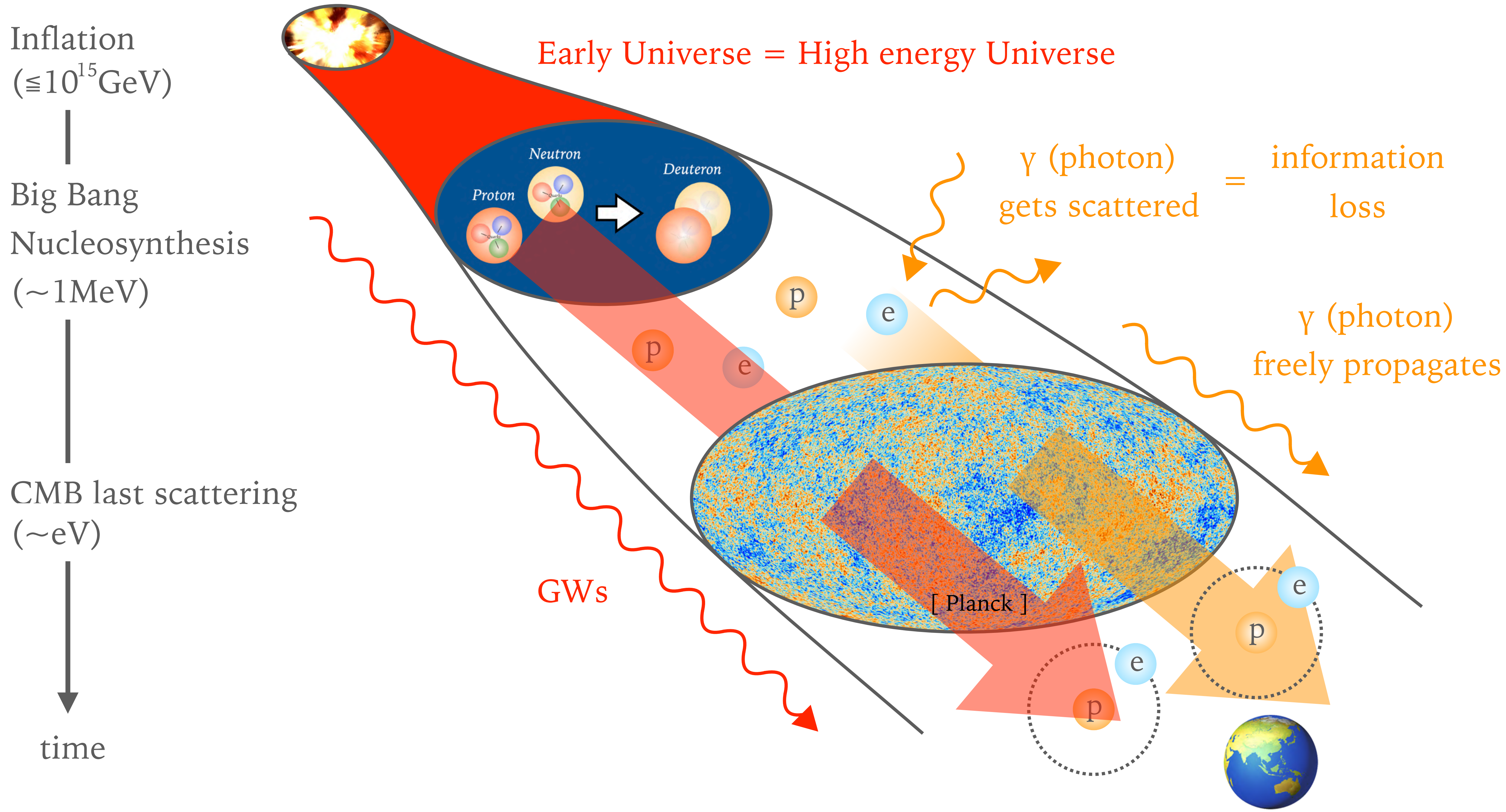
BUBBLE COLLISION & FLUID DYNAMICS

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



GWS AS A PROBE OF THE EARLY UNIVERSE

➤ Cosmic Microwave Background (CMB) vs. Gravitational Waves (GWs)

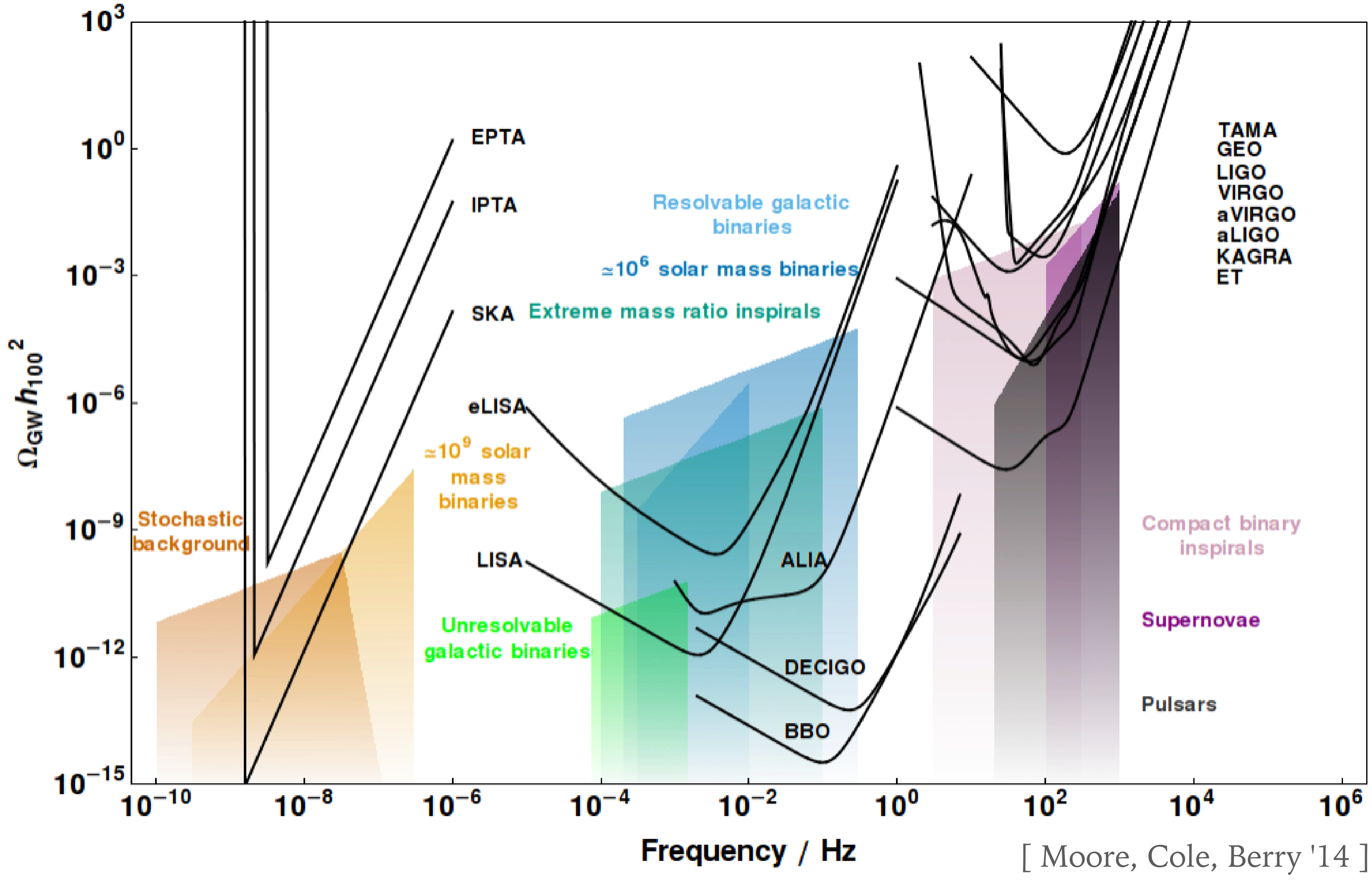


PRESENT & FUTURE OBSERVATIONS

Pulsar timing arrays	Space-borne interferometers	Ground-based interferometers
$\sim 10^{-8}$ Hz	$\sim$ mHz – Hz	$\sim$ 100 Hz

[Sriramkumar's lecture]

GW energy density per unit log freq. / total energy density of the Universe

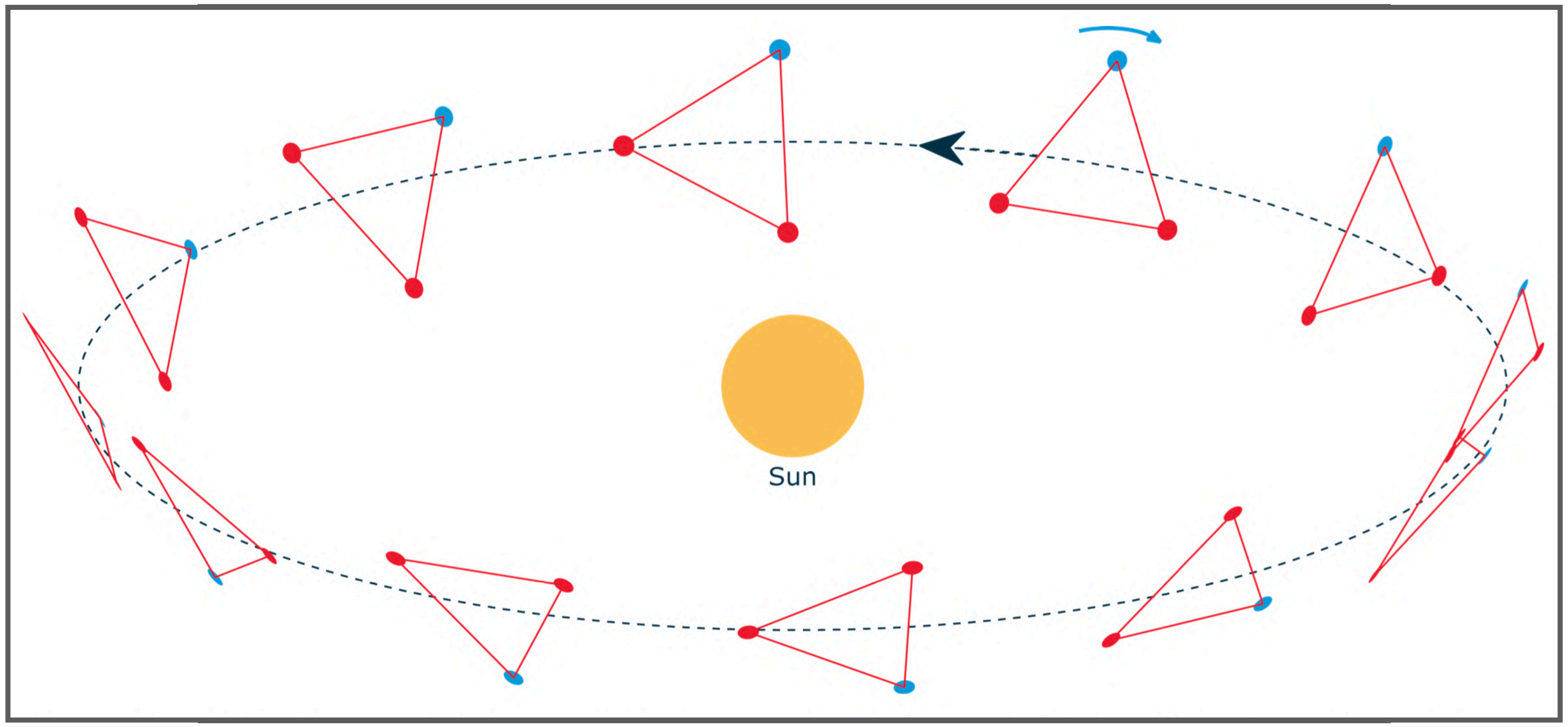


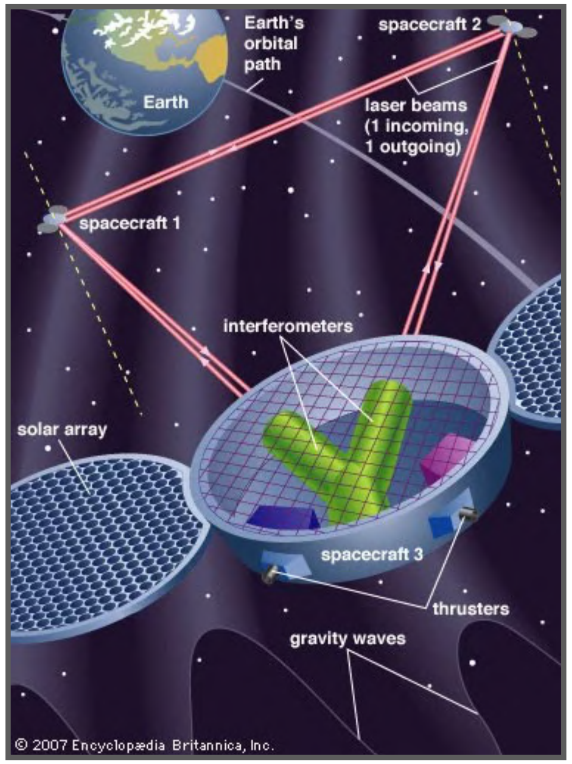
[Moore, Cole, Berry '14]

LISA (LASER INTERFEROMETER SPACE ANTENNA)

[LISA Mission L3 Proposal, https://www.elisascience.org/files/publications/LISA_L3_20170120.pdf] [Auclair et al. '22]

- Mission led by ***ESA*** and ***NASA***
- Launch is planned ***in the mid 2030's***
- ***3 satellites*** forming an equilateral triangle in an Earth-trailing orbit
- Distance between satellites $= \mathbf{2.5 \times 10^6}$ **km**
- Nominal mission of ***4.5 years***, with a duty cycle of ***82%***





[LISA Red book] [https://www.britannica.com/science/physics-science/The-study-of-gravitation]

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GWs from free-streaming sources

Summary

TRANSITION (≒ THERMODYNAMIC) PARAMETERS

- Remind the spirit of thermodynamics

  - Only a few parameters determine macroscopic properties

TRANSITION (≒ THERMODYNAMIC) PARAMETERS

- Remind the spirit of thermodynamics

  - Only a few parameters determine macroscopic properties

- What are parameters that describe the present macroscopic system?

Particle physics ⟶ Transition parameters ⟶ Prediction on GWs

Lagrangian $\mathscr{L}$

α : transition strength

β : nucleation rate parameter

v_w : wall velocity

T_* : transition temperature

GW spectrum $\Omega_{\rm GW}$

GW non-Gaussianity ...

TRANSITION (≒ THERMODYNAMIC) PARAMETERS

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

- Transition strength $\alpha \equiv \rho_{\rm vac}/\rho_{\rm plasma}$

  - How much energy (= latent heat) is released in comparison to the plasma energy

  - The numerator $\rho_{\rm vac} = \rho_{\rm vac,false} - \rho_{\rm vac,true}$ is calculated from the Helmholtz free energy, through the relation $U = F + TS = F - T\left(\frac{\partial F}{\partial T}\right)_V$ as

$$\rho_{\rm vac,true} = V_{\rm eff}(\phi_{\rm true}, T) - T\left(\frac{\partial V_{\rm eff}(\phi_{\rm true}, T)}{\partial T}\right)$$

$$\rho_{\rm vac,false} = V_{\rm eff}(\phi_{\rm false}, T) - T\left(\frac{\partial V_{\rm eff}(\phi_{\rm false}, T)}{\partial T}\right)$$

TRANSITION (≒ THERMODYNAMIC) PARAMETERS

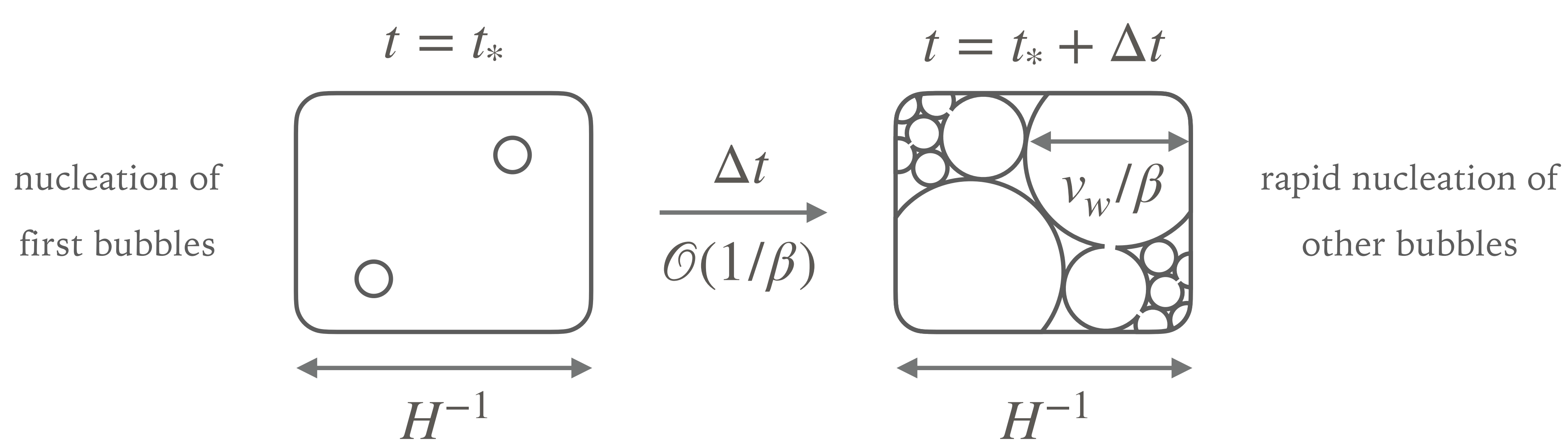
see e.g. [Caprini et al. '16]
[Caprini et al. '20]

- Nucleation rate parameter β

  - Taylor-expansion coefficient of the exponent of nucleation rate $\Gamma(t) \propto e^{\beta(t-t_*)+\cdots}$ (per unit time & vol.) around the typical transition time $t = t_*$

  - Thermal field theory is used to calculate $\Gamma(T)$, which is then converted into $\Gamma(t)$

  - Its inverse (precisely, v_w/β) gives the typical bubble size at the time of collision

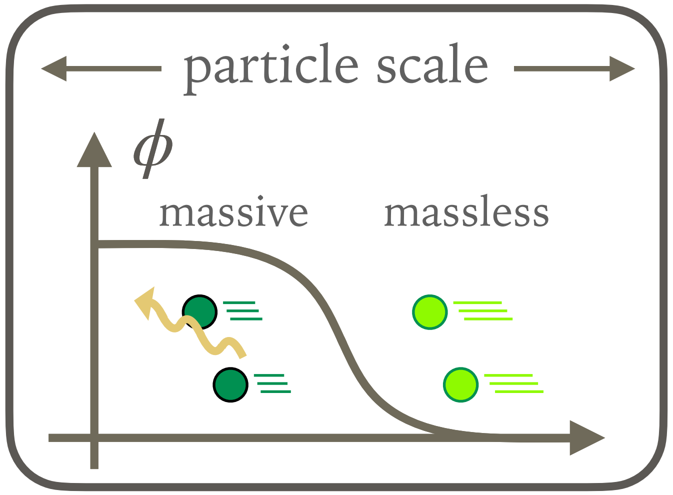


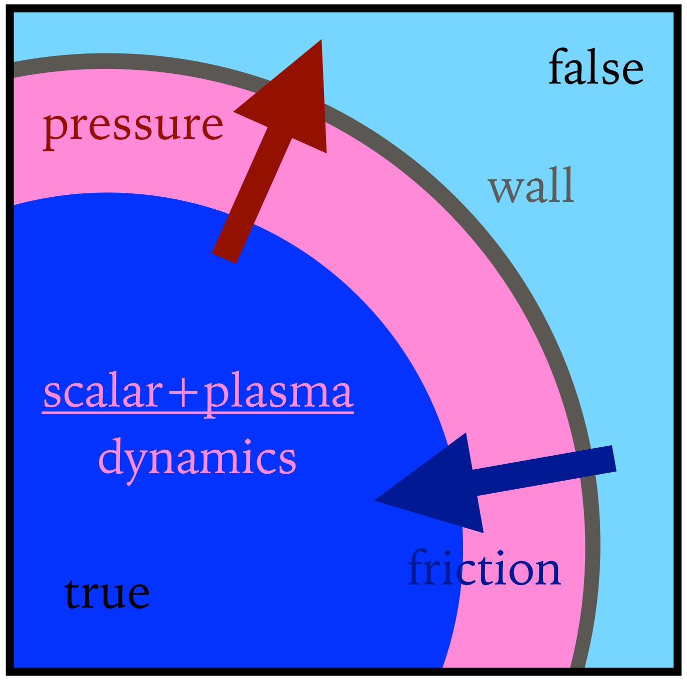
TRANSITION (≒ THERMODYNAMIC) PARAMETERS

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

[See Andrew's talk]

- ➤ Wall velocity v_w
  - Determined from "pressure vs. friction"
  - Should in principle be obtained from Boltzmann eq.,
    but in reality often put by hand
    (regarded as trade-off btwn. coupling ⇔ velocity)





- ➤ Transition temperature T_*
  - Determined from your microphysical theory

BUBBLE COLLISION & FLUID DYNAMICS

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

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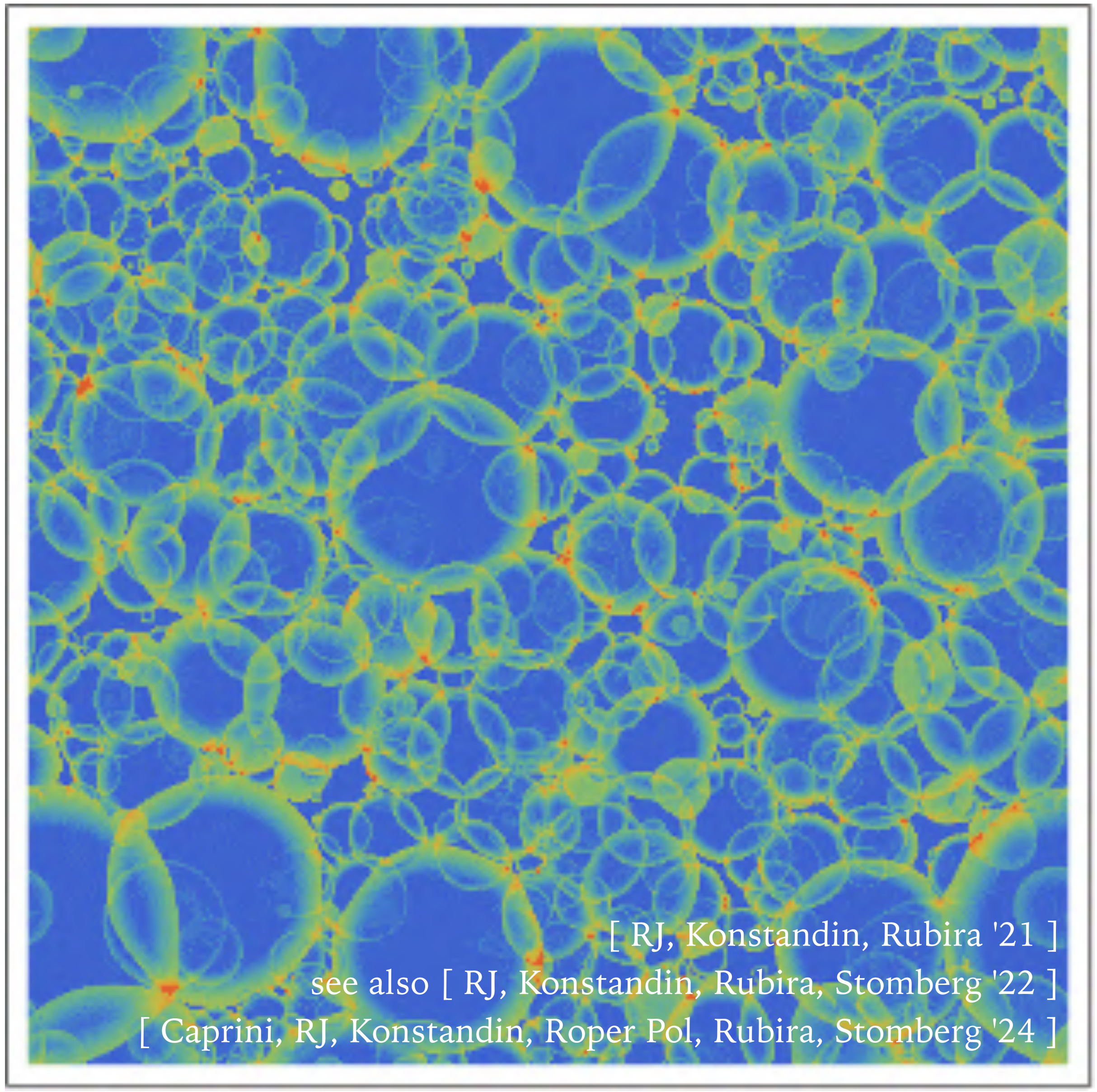
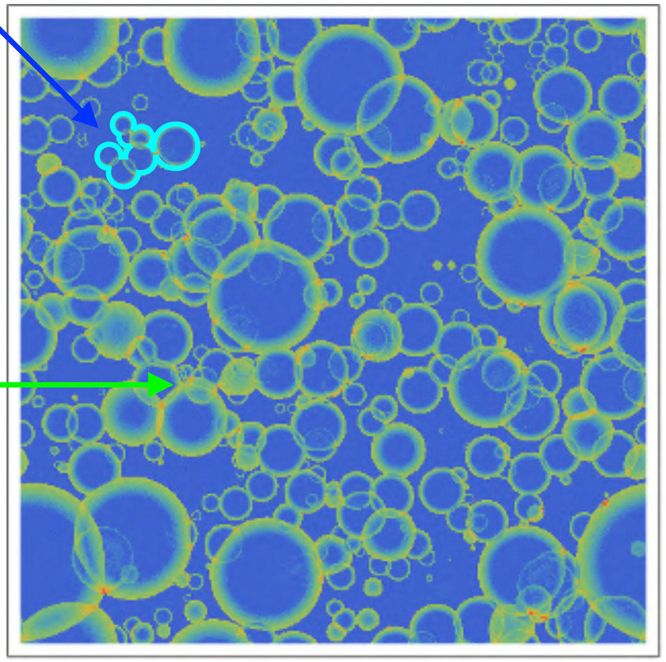


GRAVITATIONAL WAVE SOURCES

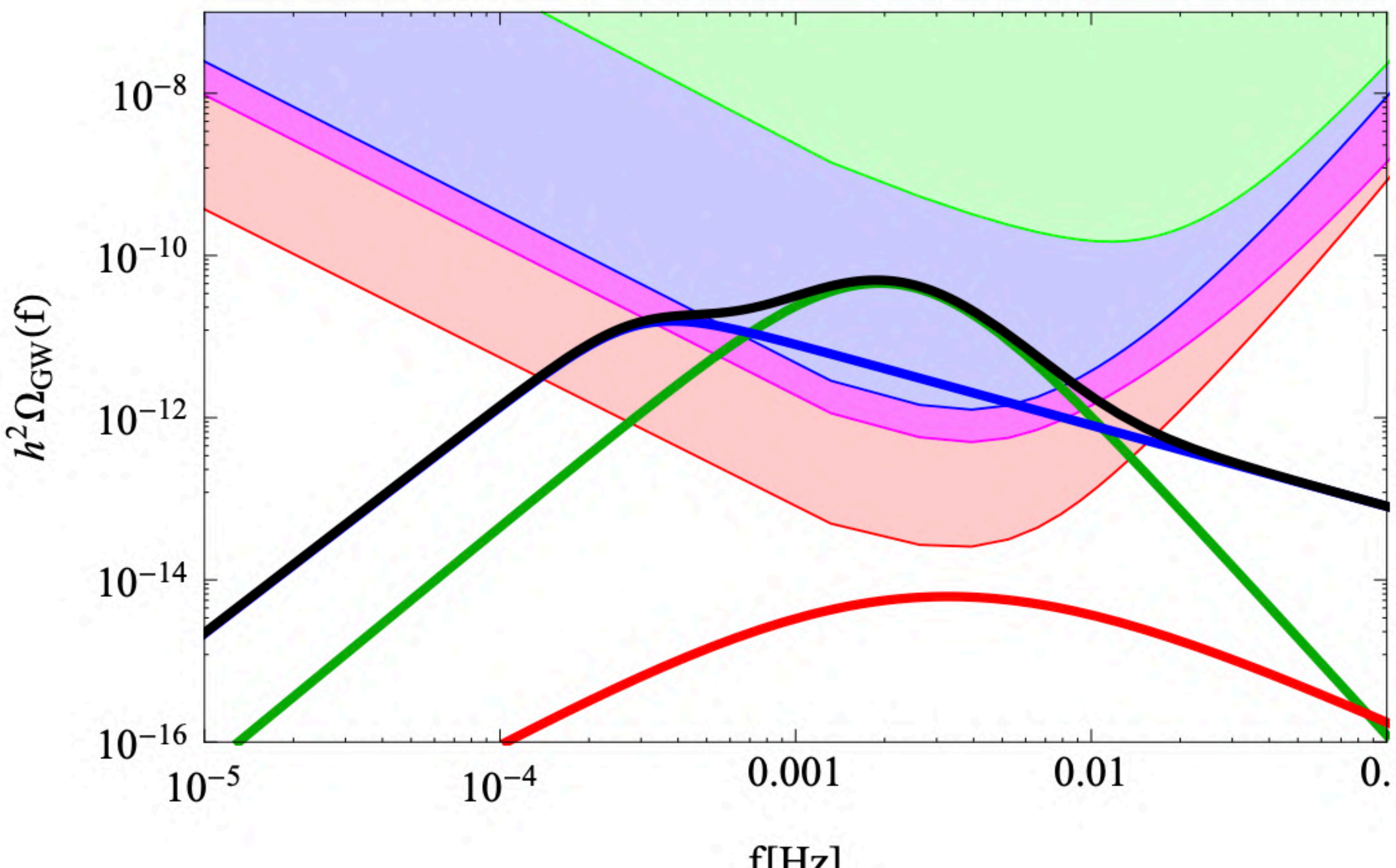
[Kosowsky, Turner, Watkins '92]
[Kosowsky, Turner '92]
[Kamionkowski, Kosowsky, Turner '93]
and e.g. [Caprini et al. '16] [Caprini et al. '20]

- **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** [See Alberto's talk]
  - Turbulent motion caused by fluid nonlinearity
  - Expected to develop at a later stage



important at later stage

GRAVITATIONAL WAVE SPECTRUM



[Caprini et al. '16]

ROUGH ESTIMATE ON GW PRODUCTION

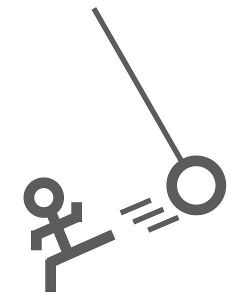
[See Subhendra's lecture]

➤ Big & relativistic objects radiate more GWs

- Integrate the GW equation of motion over the sourcing time Δt

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

oscillator



kicked oscillator

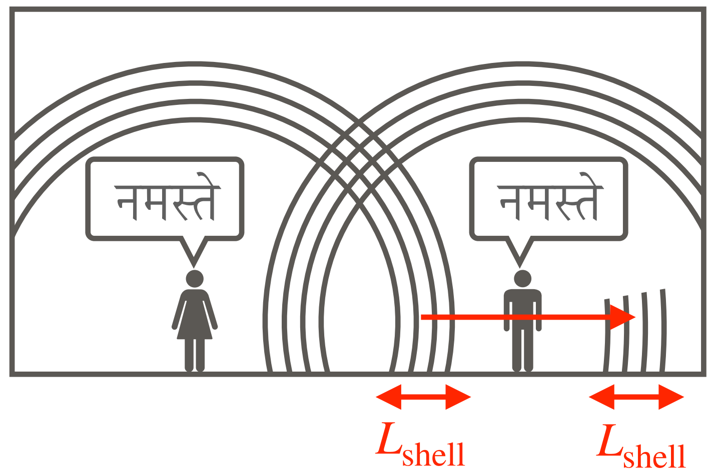
- GW energy density $\rho_{\rm GW} \sim G^{-1} \dot{h}_{ij}^2 \propto T_{ij}^2 \Delta t^2$ Note but: GWs from sound waves behave differently

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

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

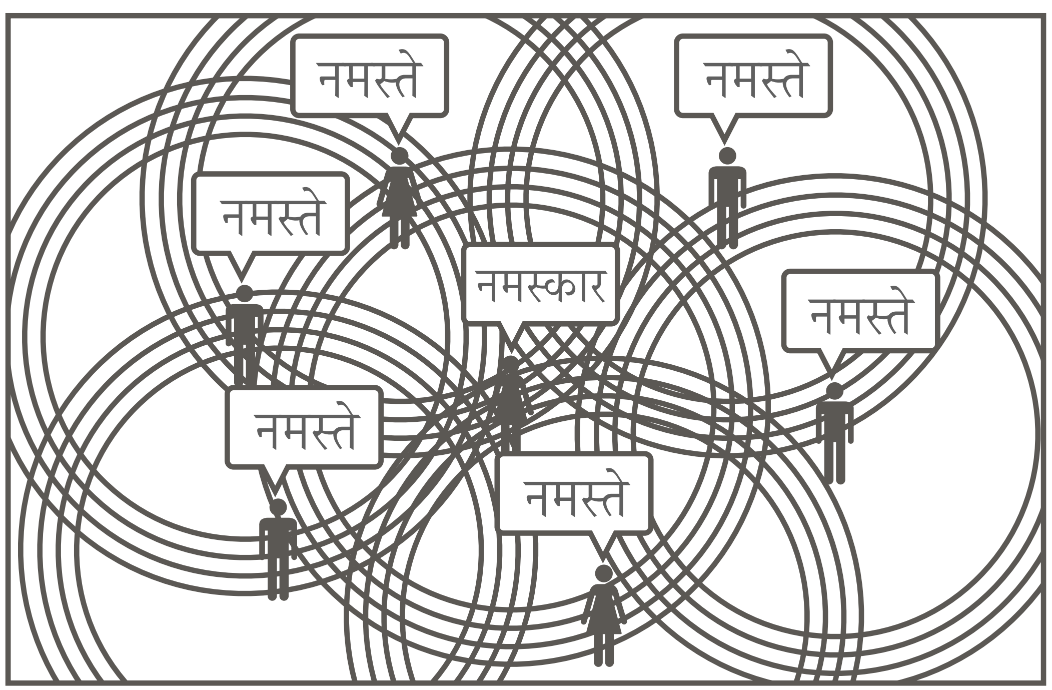
GRAVITATIONAL WAVES FROM SOUND WAVES

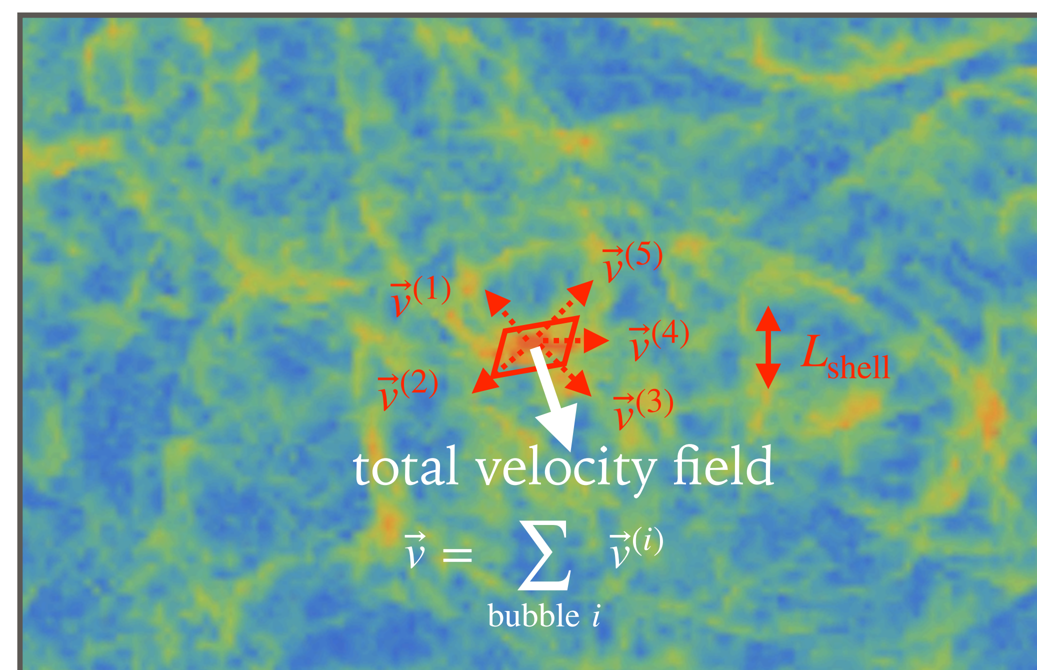
- Sound shells continue to propagate inside other bubbles



- Shell overlap creates random velocity fields, continuously sourcing GWs

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





SOUND WAVE SIMULATIONS

➤ Fluid 3d simulation is a bit hard

- Shock waves
- Numerical viscosity → currently 2 groups working on sound wave & GW production simulations
- Computational resources

➤ Our proposal: the Higgsless scheme [Thomas's talk]

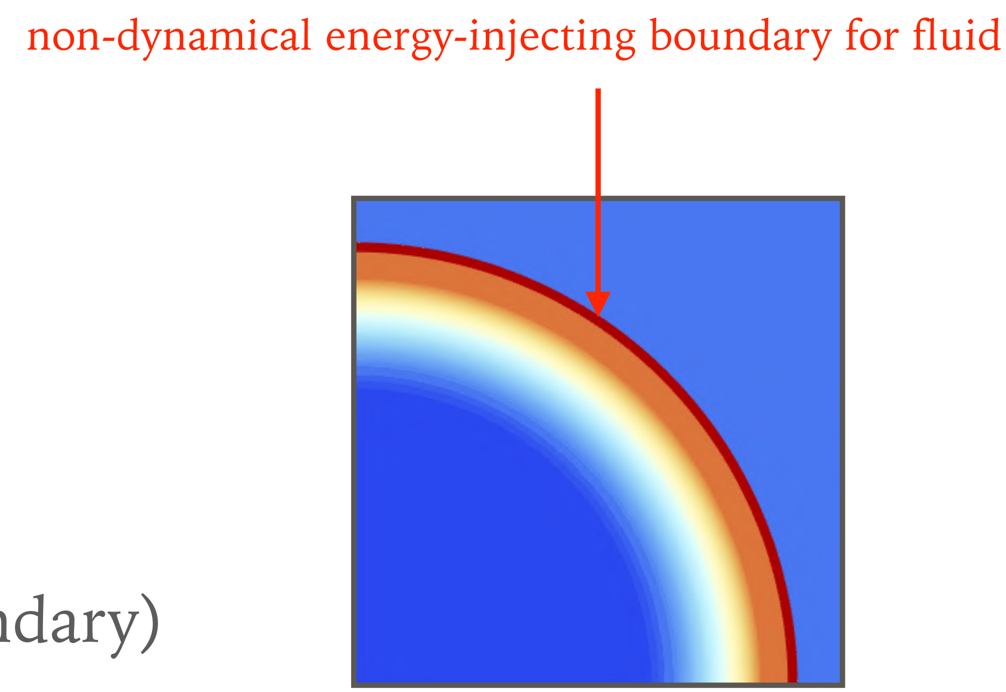
[RJ, Konstandin, Rubira '21] [RJ, Konstandin, Rubira, Stomberg '22]

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

- We do ***not*** solve both the scalar field and fluid

  but rather "integrate out" the scalar field

  (= treat the scalar field as non-dynamical boundary)



HOW TO "INTEGRATE OUT" THE HIGGS

- The fluid evolution is determined from

  ① Energy-momentum conservation of the fluid $\partial_\mu T^{\mu\nu} = 0$

  ② Energy injection at the wall, parametrized by $\epsilon_{\rm vac} = \begin{cases} \epsilon_f & \text{(false vac.)} \\ \epsilon_t & \text{(true vac.)} \end{cases}$

- How to implement fluid evolution in simulations

  ① Assume relativistic perfect fluid $T^{\mu\nu} = (\epsilon + p)u^\mu u^\nu - g^{\mu\nu} p$

  ② Define $K^\mu \equiv T^{\mu 0}$, then $\partial_\mu T^{\mu\nu} = 0$ reduces to $\begin{cases} \partial_0 K^0 + \partial_i K^i = 0 \\ \partial_0 K^i + \partial_j T^{ij}(K^0, K^i) = 0 \end{cases}$

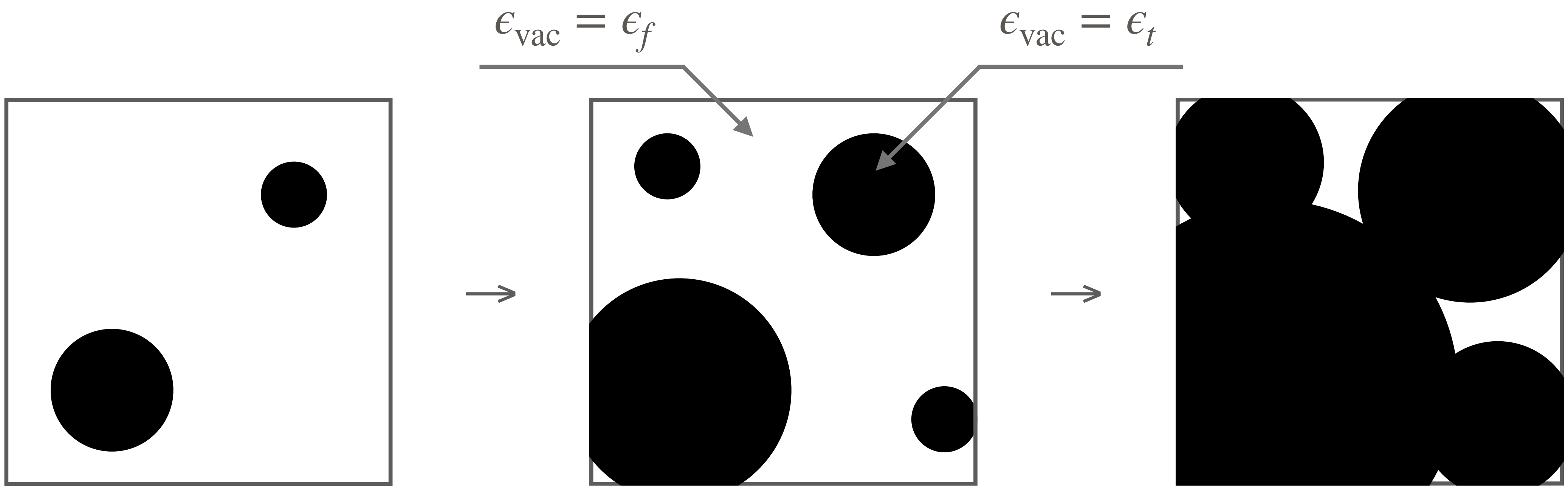
  ③ The effect of energy injection appears in $T^{ij}(K^0, K^i)$

$$T^{ij}(K^0, K^i) = \frac{3}{2} \frac{K^i K^j}{(K^0 - \epsilon_{\rm vac}) + \sqrt{(K^0 - \epsilon_{\rm vac})^2 - \frac{3}{4} K^i K^i}}$$

RECIPE FOR THE HIGGSLESS SIMULATION

➤ 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 $\begin{cases} \partial_0 K^0 + \partial_i K^i = 0 \\ \partial_0 K^i + \partial_j T^{ij}(K^0, K^i) = 0 \end{cases}$

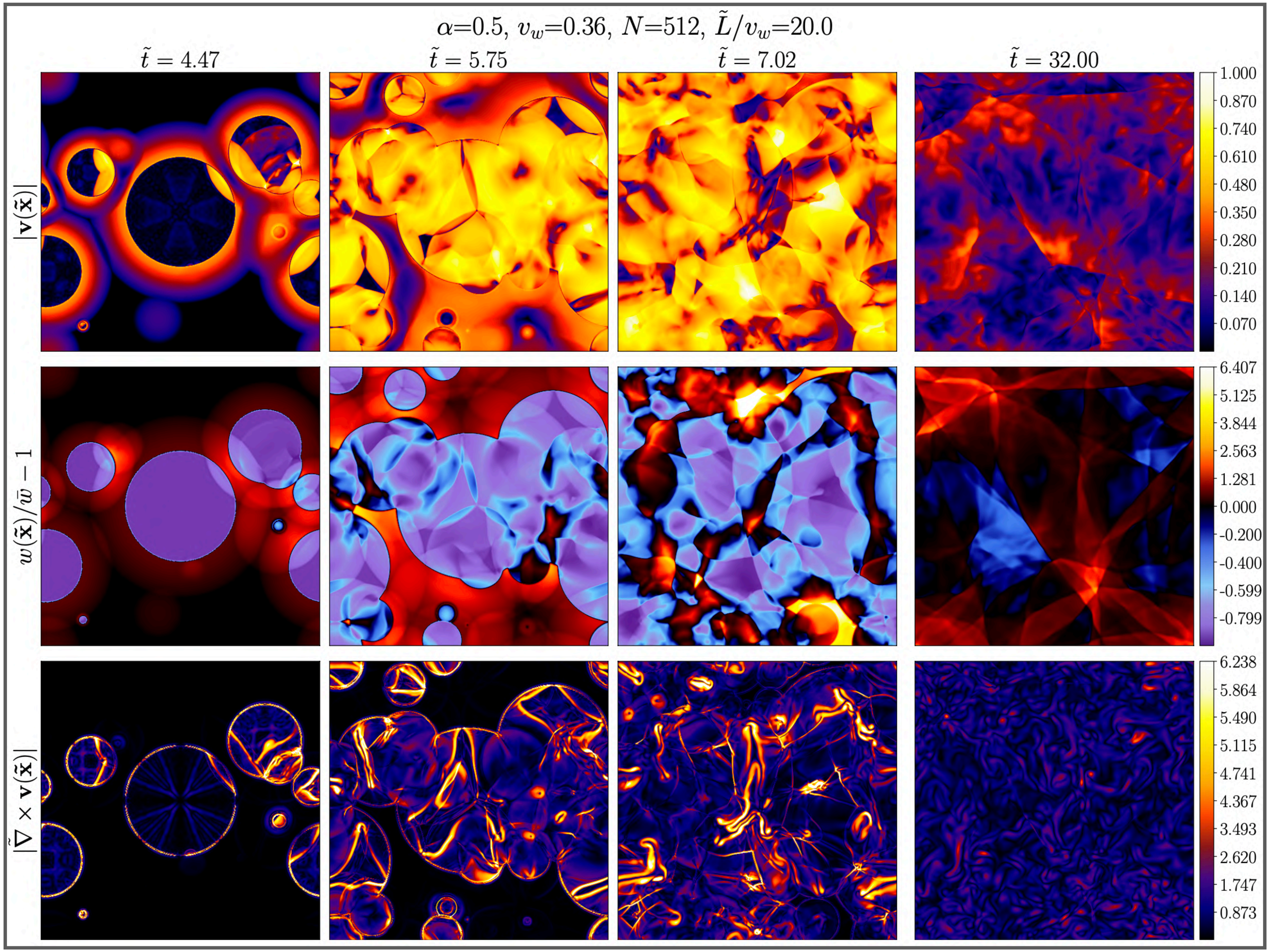
→ Fluid automatically develops profiles

RECIPE FOR THE HIGGSLESS SIMULATION

fluid velocity

enthalpy

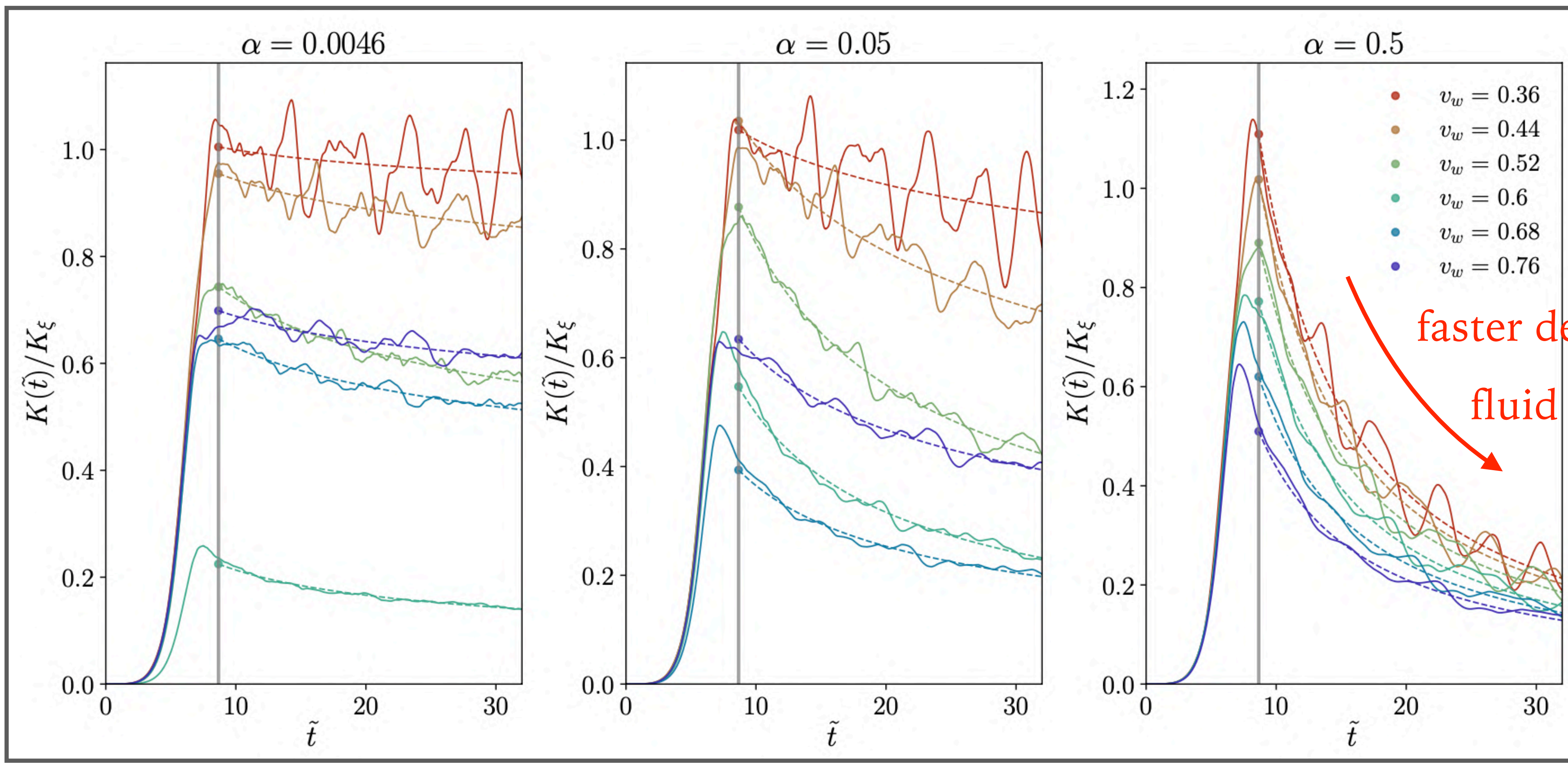
vorticity



RECIPE FOR THE HIGGSLESS SIMULATION

fluid kinetic energy

weak intermediate strong



faster decay of fluid kinetic energy

time

SUMMARY (PART 1)

- The Higgsless simulation is now one of the largest simulations (spatial resolution: $N^3 = 256^3$ or 512^3 grids; simulation time: $T = 32/\beta$)

- We are now able to simulate the strong transition regime $\alpha \sim 1$, which was previously difficult due to shocks and numerical viscosities

- Numerical data suggest that we might be observing sound waves developing into turbulence

Introduction

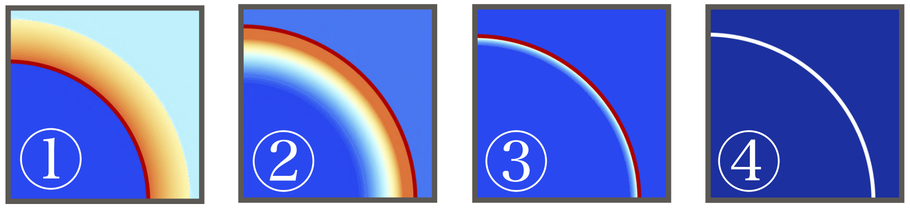
GWs from sound-wave sources

GWs from free-streaming sources

Summary

GW PRODUCTION: THE STANDARD LORE & BEYOND

➤ GW sources



Bubble walls (dominant in case ④)

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

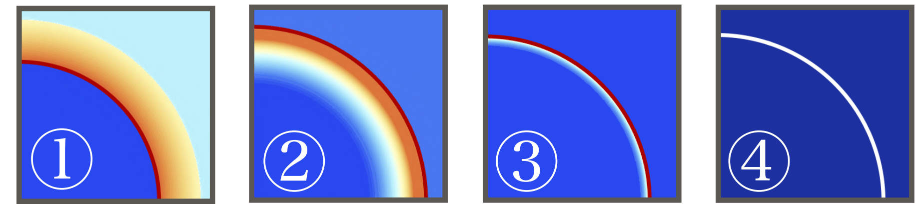
Fluid (dominant in case ①②③) = Sound waves & Turbulence

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

- GW sources



<u>Bubble walls</u> (dominant in case ④)

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

<u>Fluid</u> (dominant in case ①②③) = Sound waves & Turbulence

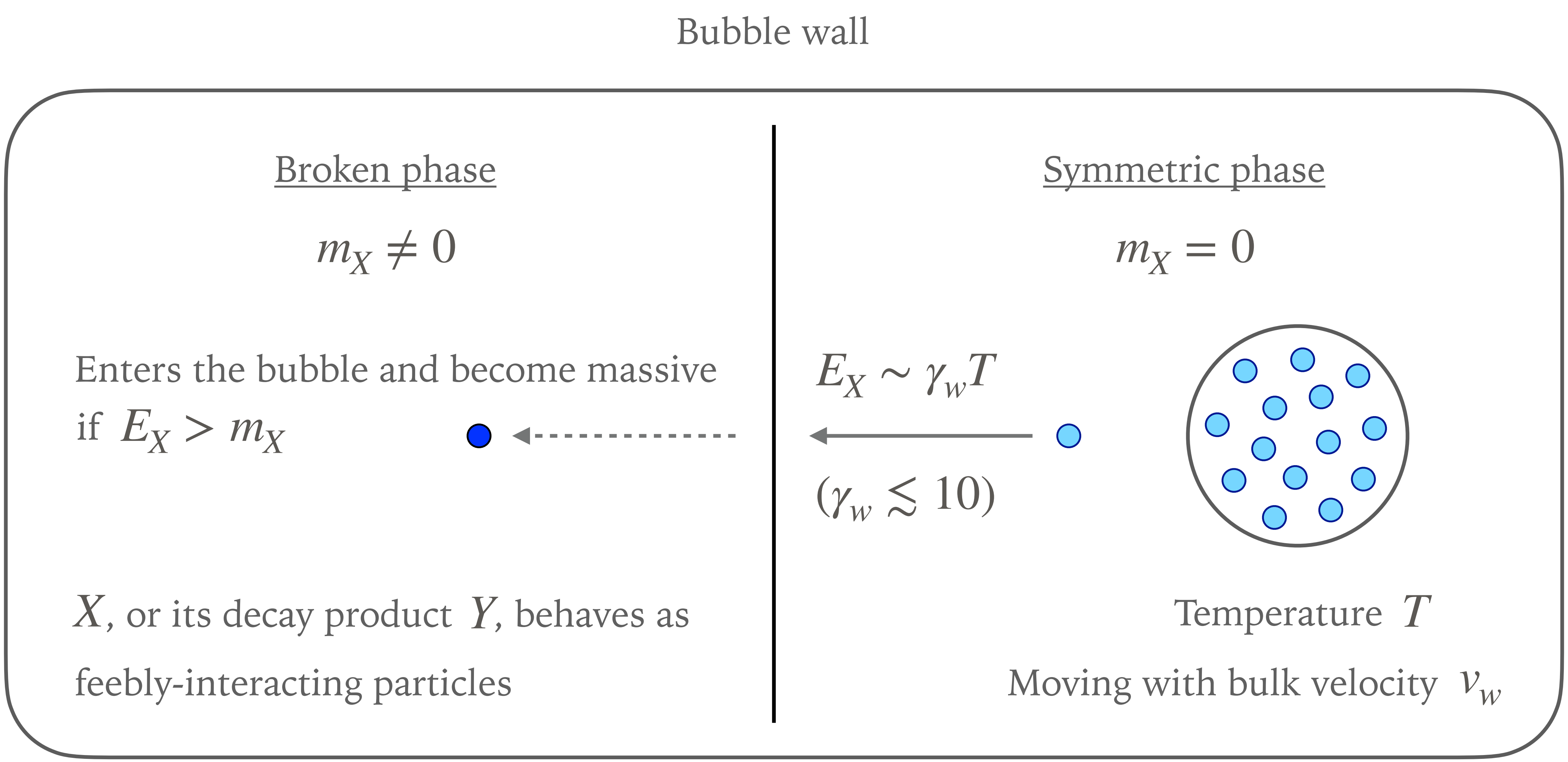
Particles in the broken phase frequently interact and can be described by fluid picture.

<u>Feebly-interacting particles</u>

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

GW PRODUCTION: THE STANDARD LORE & BEYOND

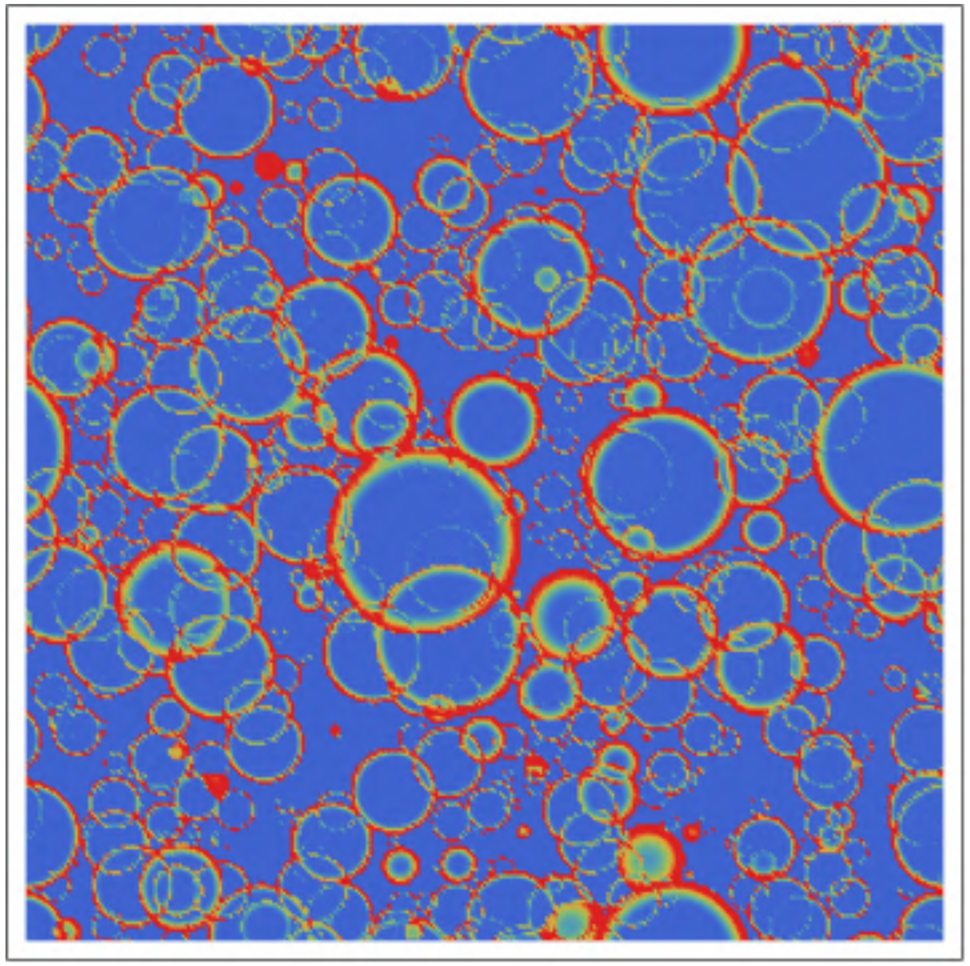
➤ Particle dynamics seen in the wall rest frame



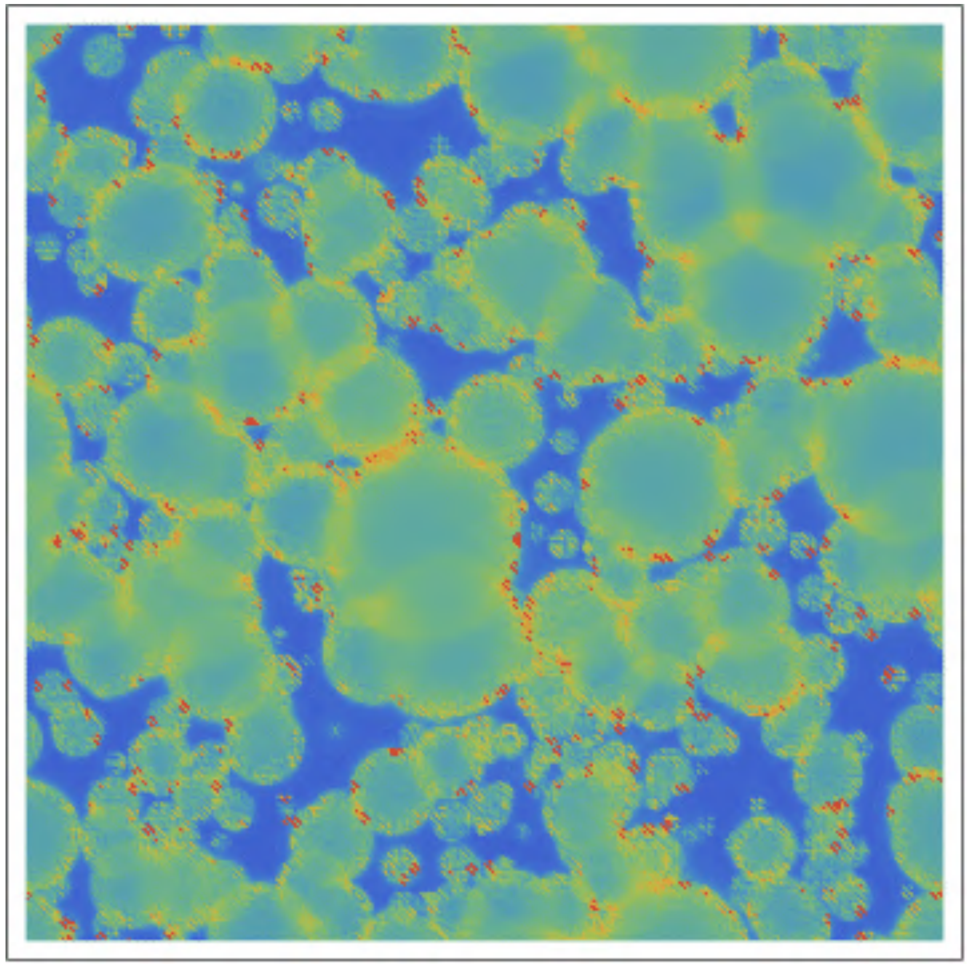
FLUID VS. FREE-STREAMING PARTICLES

- Evolution of the system for fluid and free-streaming sources

Fluid



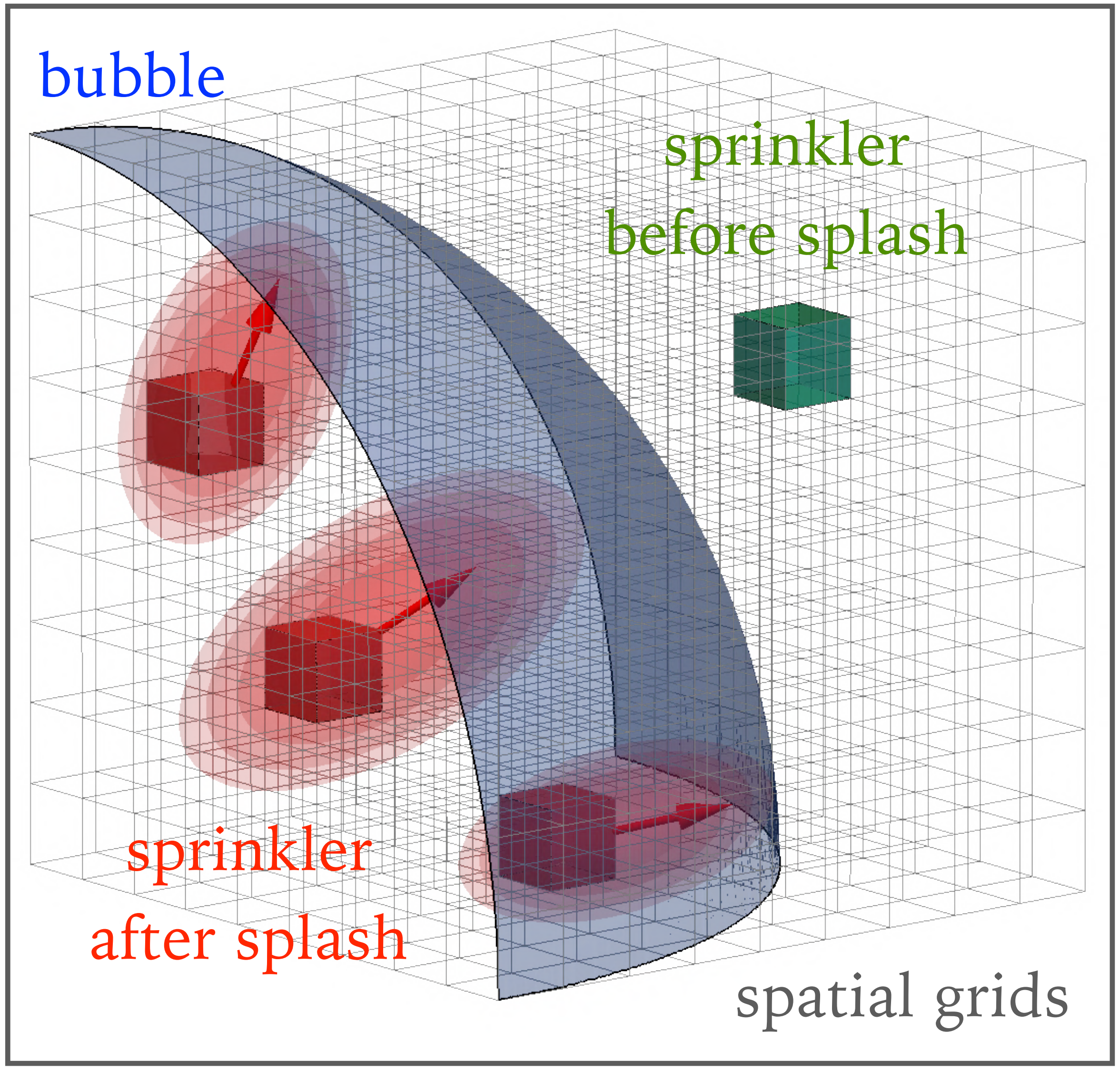
Free-streaming



HOW TO CALCULATE GW PRODUCTION

- To calculate the GW spectrum,

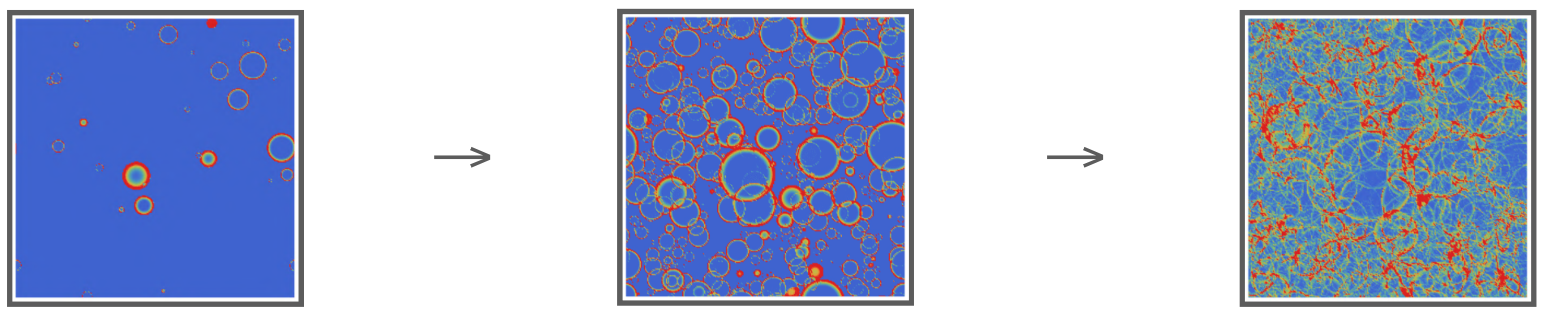
  we propose a new calculation scheme – "sprinkler picture"



GW SPECTRUM FOR SOUND-WAVE SOURCE

➤ How to calculate the GW spectrum for sound waves

① Calculate the time evolution of the system without GWs



② Calculate GWs from $\Box h_{ij} \sim G\Lambda_{ij,kl}T_{kl}$ using FFT

➤ Basically there is no shortcut, essentially because of nonlinarity:

Sound waves are linear phenomena $(\partial_t^2 - c_s^2\nabla^2)\vec{v}_{\rm fluid} \simeq 0$,

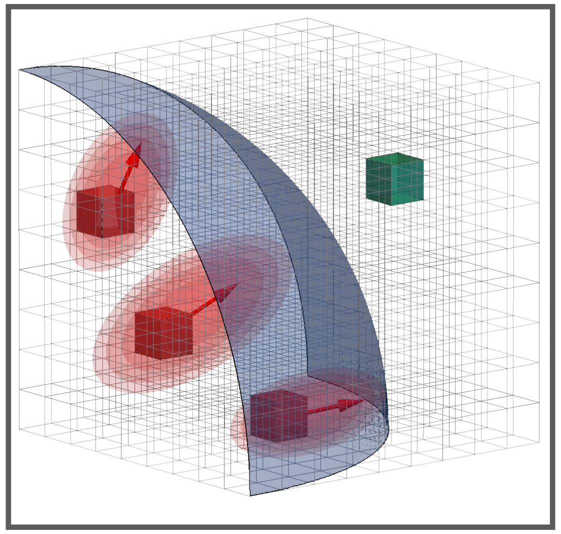
but GW production is nonlinear in $\vec{v}_{\rm fluid}$ because $\Box h_{ij} \sim T_{ij} \sim (v_{\rm fluid})_i (v_{\rm fluid})_j$

GW SPECTRUM FOR FREE-STREAMING SOURCE

- However, for free-streaming particles, GW production is linear in each free-streaming particle

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

- Thus we propose "sprinkler picture"



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

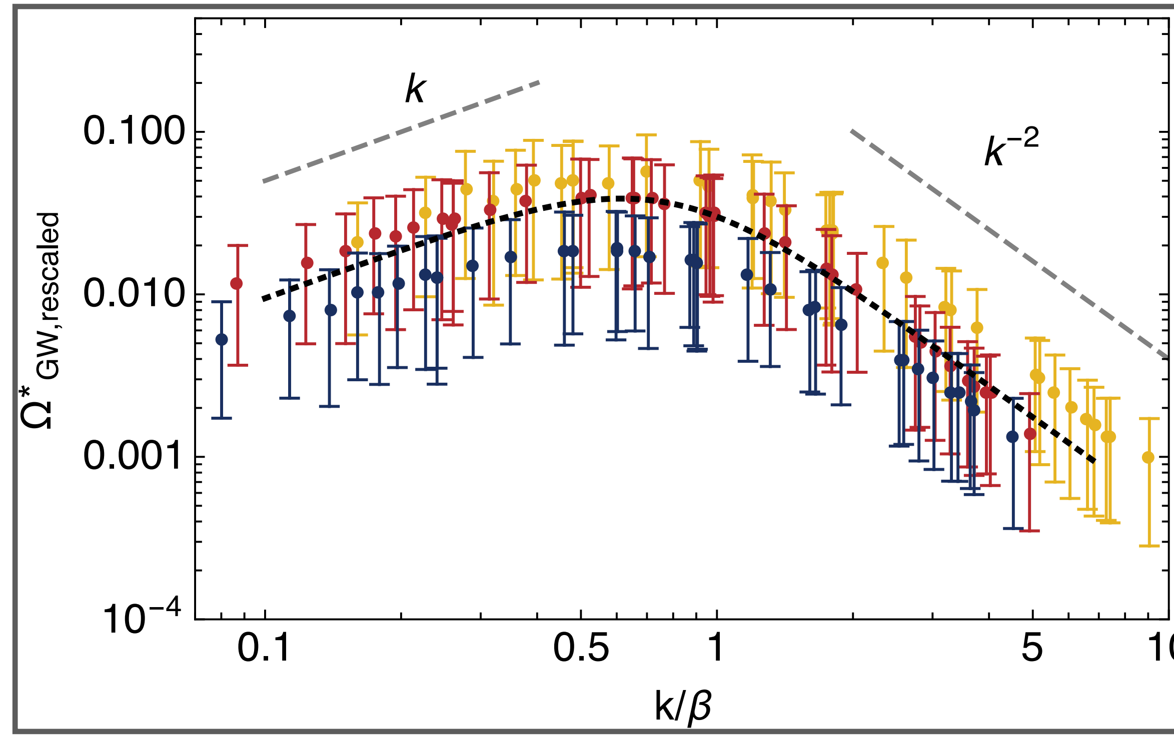
② Sprinklers are universal: their only difference is when and in which direction they are hit

③ GW production from one sprinkler is easily calculable, and the contributions from different sprinklers (= grids) are linearly superposed

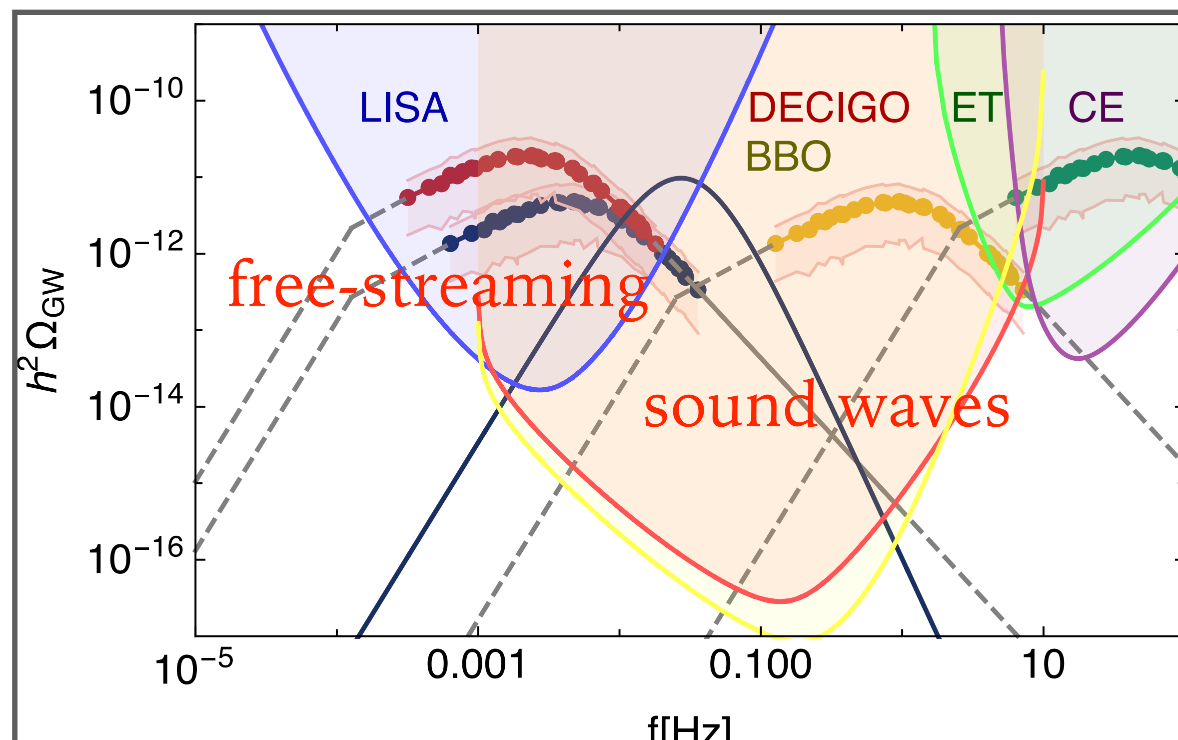
RESULT

➤ GW spectral shape is universal

(after normalizing by some factor)



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



PARTICLE PHYSICS FRAMEWORK

- Consider a dark-sector thermal bath, with temperature T

- Assume a first-order phase transition in this sector

  - scalar field s acquires a vev $\langle s \rangle$

  - nucleation of bubbles (with wall thickness $\sim 1/\langle s \rangle$)

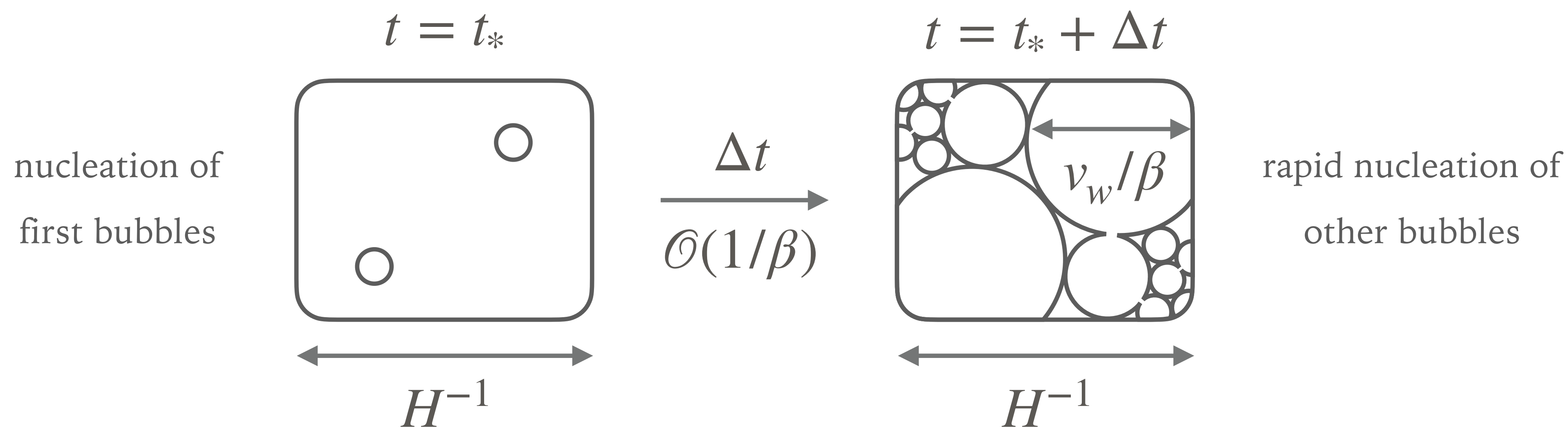
  - walls reach a terminal velocity v_w (or equivalently $\gamma_w = 1\Big/\sqrt{1 - v_w^2}$)

- Feebly-interacting particles can be generated during this transition

  - particle X becomes massive at the phase transition, due to coupling to s

CONDITIONS ON FEEBLE INTERACTION

- Free-streaming particle should free-stream over a cosmological scale, which we take the transition timescale $\Delta t \sim \mathcal{O}(1/\beta)$

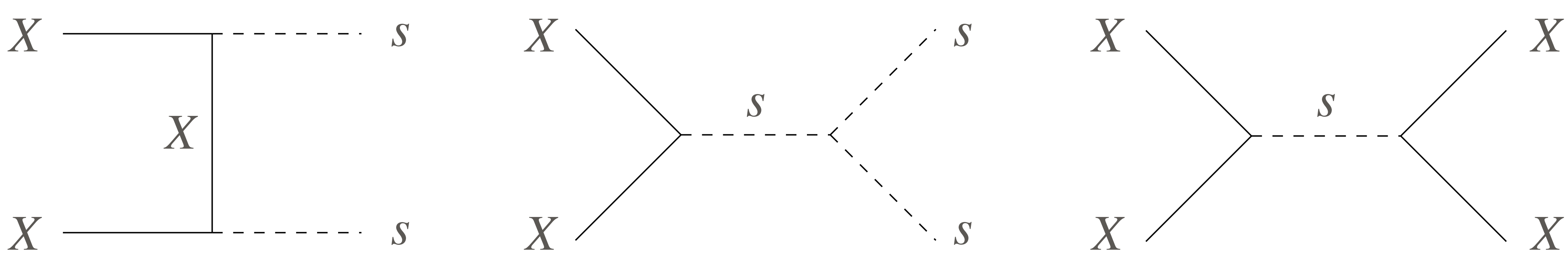


- So, we need the condition $n\sigma\Delta t \sim \dfrac{T^3\sigma}{\beta} \lesssim 1$

CONDITIONS ON FEEBLE INTERACTION

- How do X particles interact? $m_X = g'\langle s \rangle$

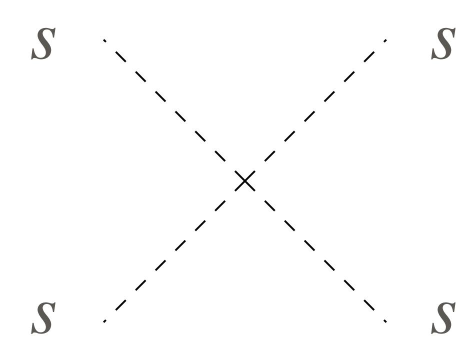
  The couplings that gives rise to mass also give rise to interactions



- Can X be the scalar particle s itself ?

  s needs to gain large mass (for the s particles to be dominant),

  but this means a large quartic coupling among s particles



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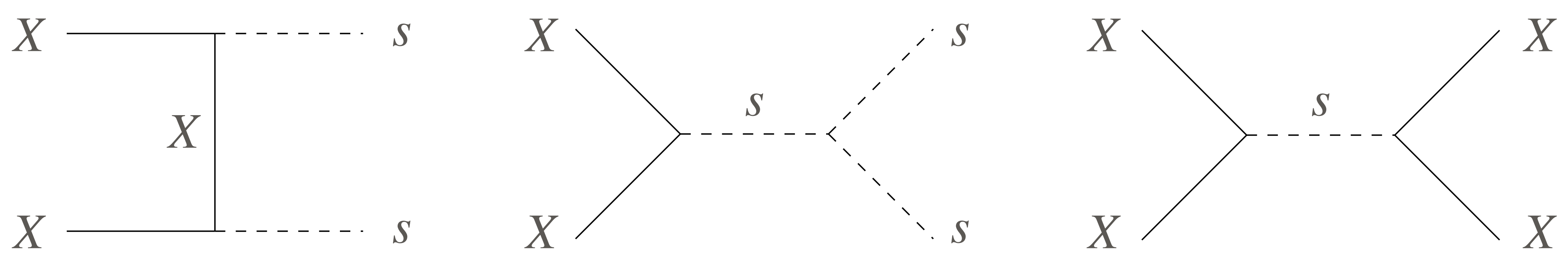

- Can X be a gauge boson $X = Z'$?

  Assuming $m_s \sim \langle s \rangle$, feeble-interaction condition reduces to

$$n\sigma\Delta t \sim \frac{T^3\sigma}{\beta} \sim \frac{T^3}{\beta}\frac{g'^4}{(4\pi)^2}\frac{m_{Z'}^2}{m_s^4} \lesssim 1 \longrightarrow \frac{\langle s \rangle}{g'^3 T} > 10^6 \quad \text{for TeV transitions}$$

CONDITIONS ON FEEBLE INTERACTION

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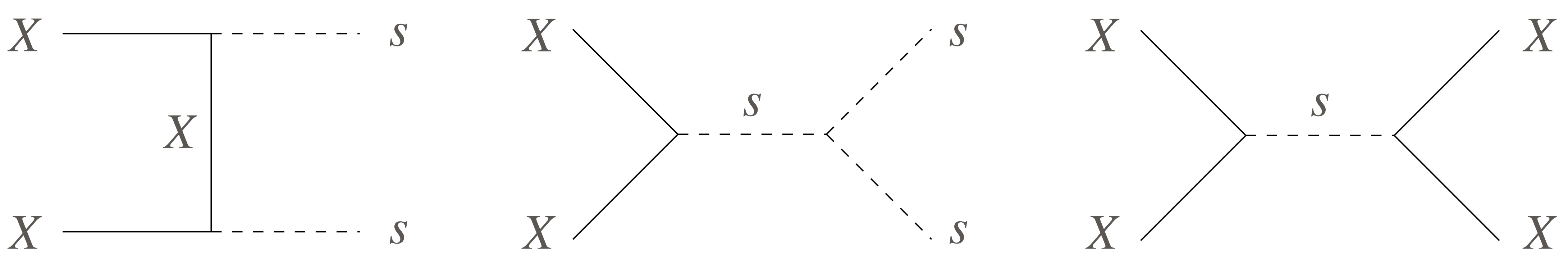

- Can X be a gauge boson $X = Z'$?

Assuming $m_s \sim \langle s \rangle$, feeble-interaction condition reduces to

Doable,
but not generic

$$n\sigma\Delta t \sim \frac{T^3\sigma}{\beta} \sim \frac{T^3}{\beta}\frac{g'^4}{(4\pi)^2}\frac{m_{Z'}^2}{m_s^4} \lesssim 1 \longrightarrow \frac{\langle s \rangle}{g'^3 T} > 10^6 \quad \text{for TeV transitions}$$

CONDITIONS ON FEEBLE INTERACTION

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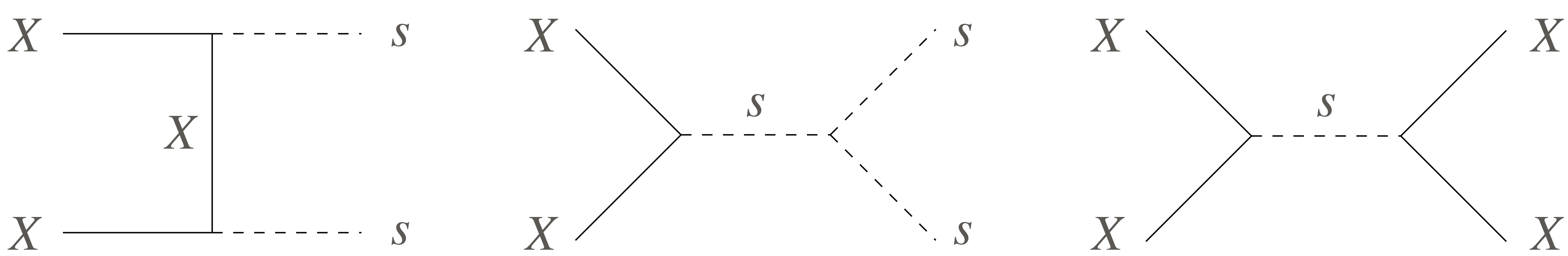
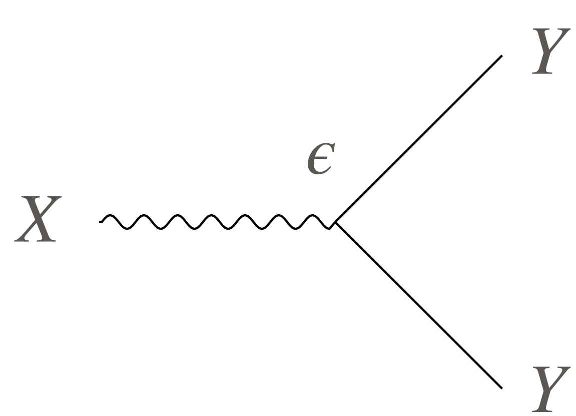


- More viable possibility: particle decay $X = Z' \to YY$ with $\epsilon \ll 1$



Introduction

GWs from sound-wave sources

GWs from free-streaming sources

Summary

SUMMARY (PART 2)

- GW spectrum from free-streaming particles differ from that from sound waves, because of the (non-)linearity of the source

- GW spectrum, if observed, will provide us with the information on the nature of the source