First-order phase transitions in the early Universe:

Recent theoretical/experimental progress

Ryusuke Jinno (Kobe Univ.)

KEK-PH, 2026/2/19

OUTLINE

1. FOPTs in the early Universe: review ~15min

2. Some recent theoretical/experimental progress ~25min

   2-1) LISA status

   2-2) lab. experiments for QFT tunneling

   2-3) GW simulations

   2-4) particle splitting and NLO friction

   2-5) FOPTs with topological defects/free-streaming particles

3. Summary

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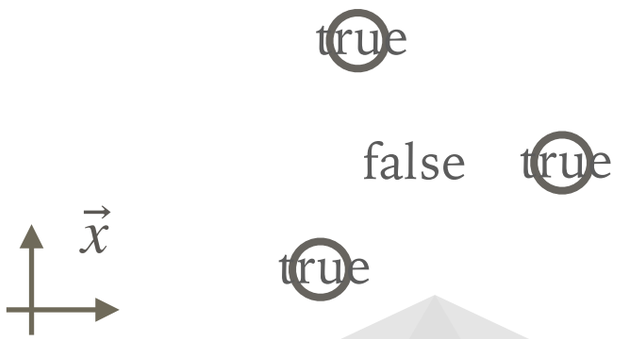
FIRST-ORDER PHASE TRANSITIONS IN THE EARLY UNIVERSE

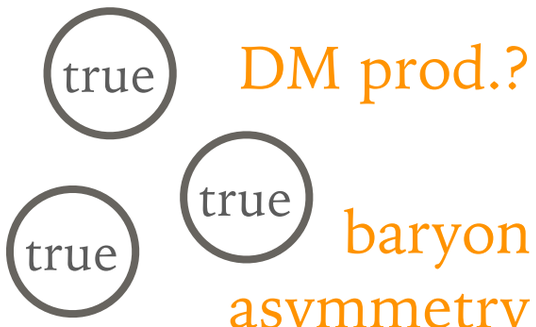
microphysics — Dynamics of bubbles — *macrophysics*

time or scale →

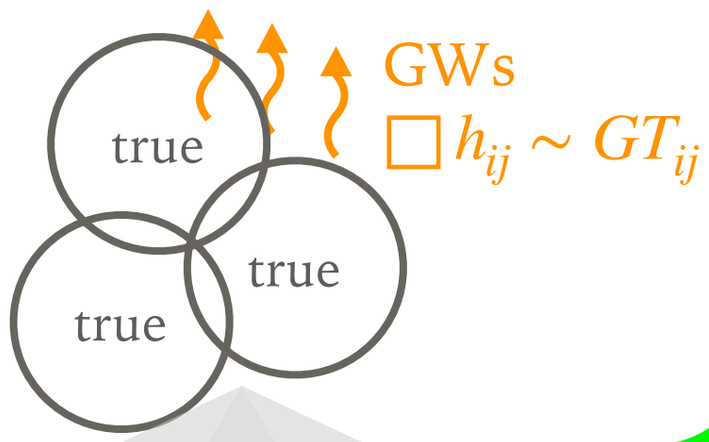
(1) nucleation



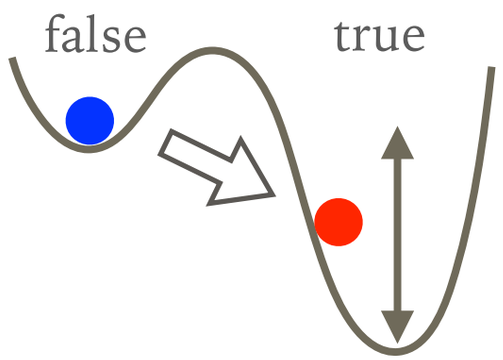
(2) expansion



(3) collision & fluid dynamics



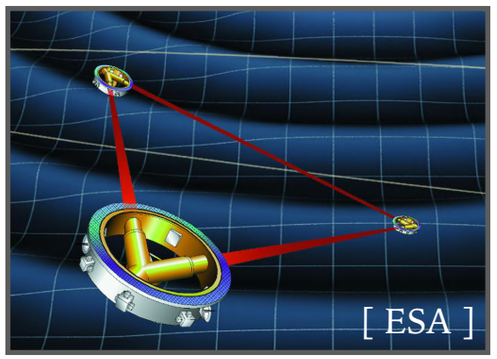
Physics of the Higgs sector



FOPTs in BSM

GWs & macroscopic observables

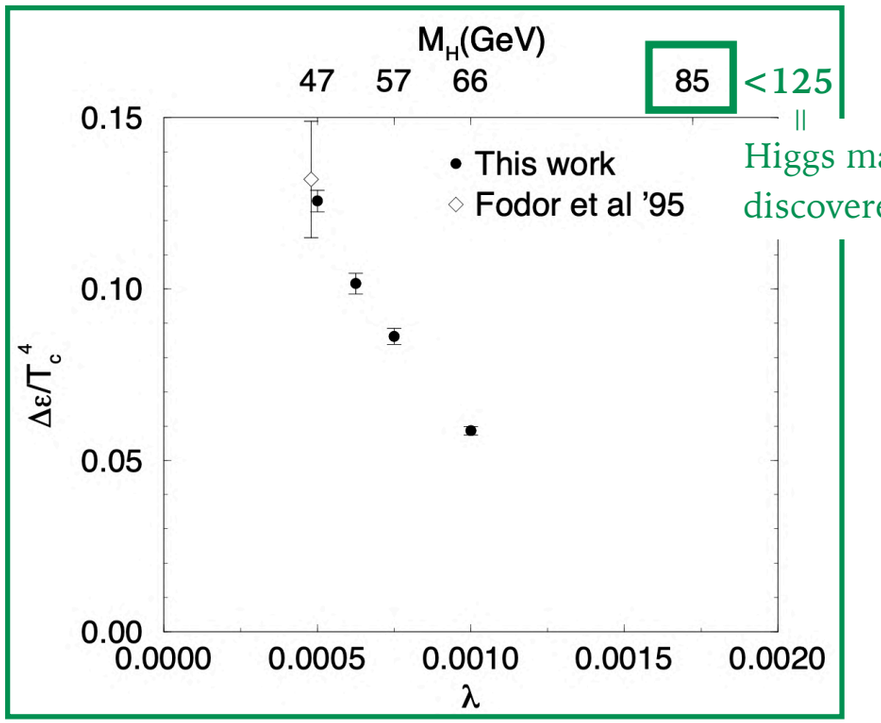
GW observations



THERMAL HISTORY OF THE UNIVERSE

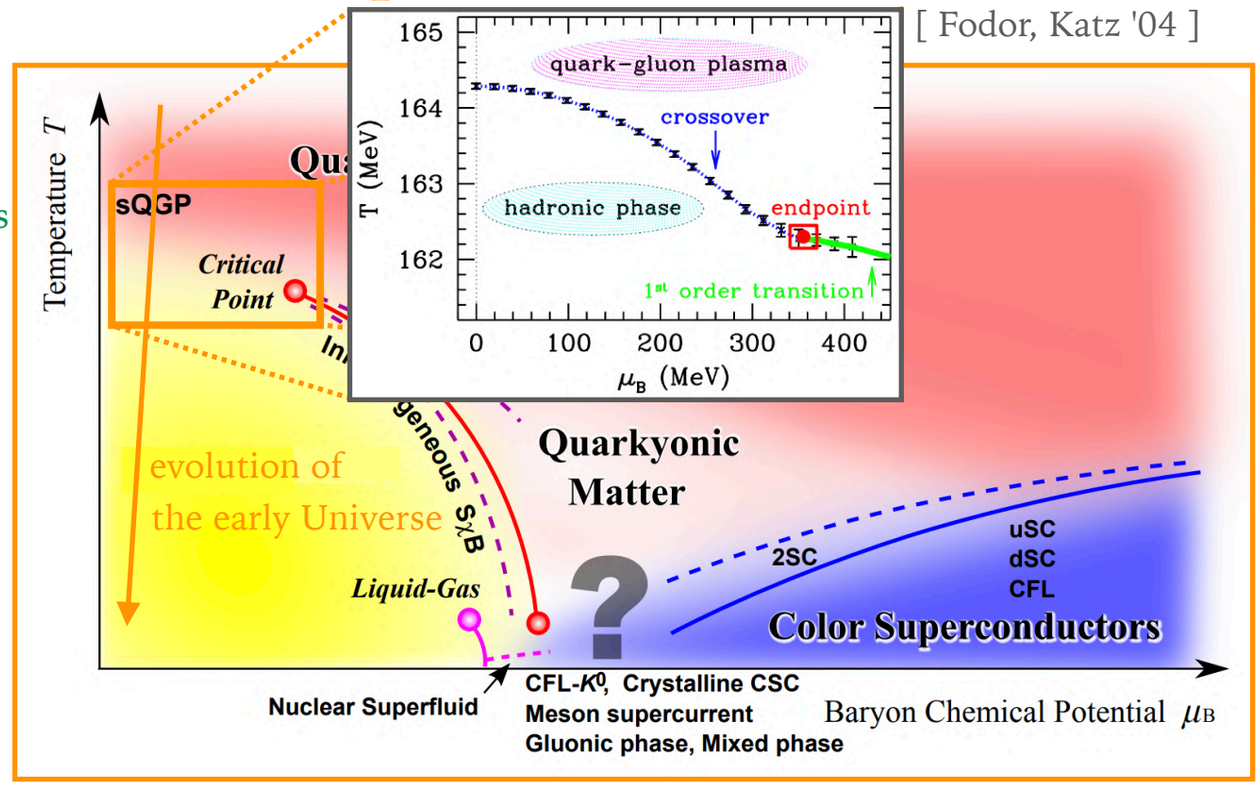
- Two candidates for FOPTs in the Standard Model (SM)

  Electroweak "phase transition" & QCD "phase transition"



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

[Fodor, Katz '04]



[Fukushima, Hatsuda '11]

→ Unfortunately, both are crossovers, meaning they are not even phase transitions

MOTIVATIONS FOR FIRST-ORDER PHASE TRANSITIONS

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

- Spontaneous symmetry breaking that might have happened

  - Breaking of the GUT group

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

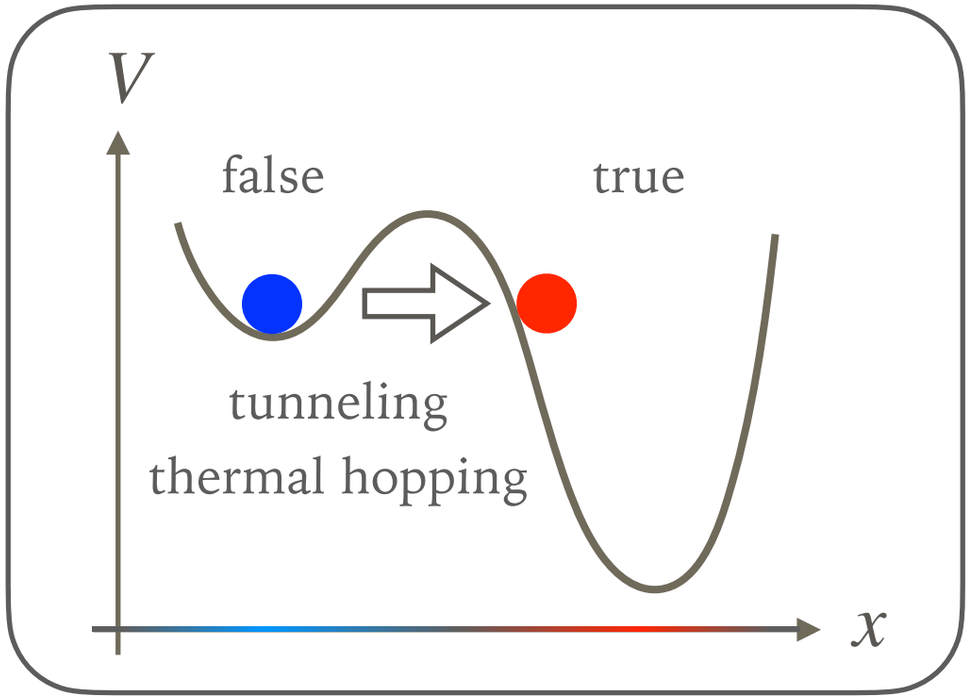
  - Breaking of B-L symmetry $U(1)_{\rm B-L}$

  - Breaking of dark groups

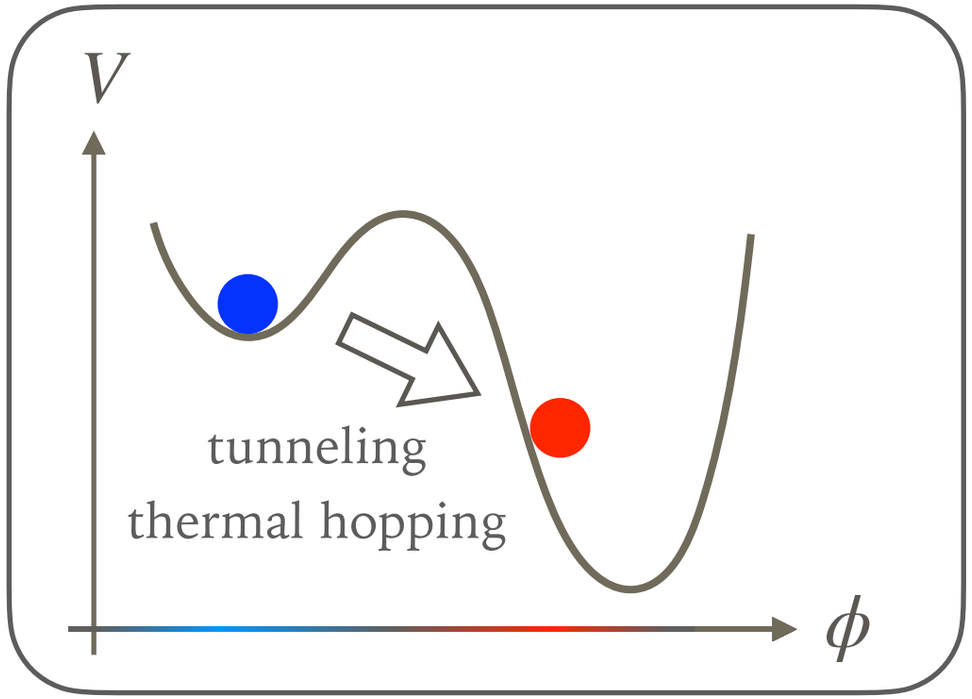
- Testability in the coming 10-20 yrs with GWs

TUNNELING IN QUANTUM MECHANICS AND QFT

Quantum mechanics



Quantum field theory



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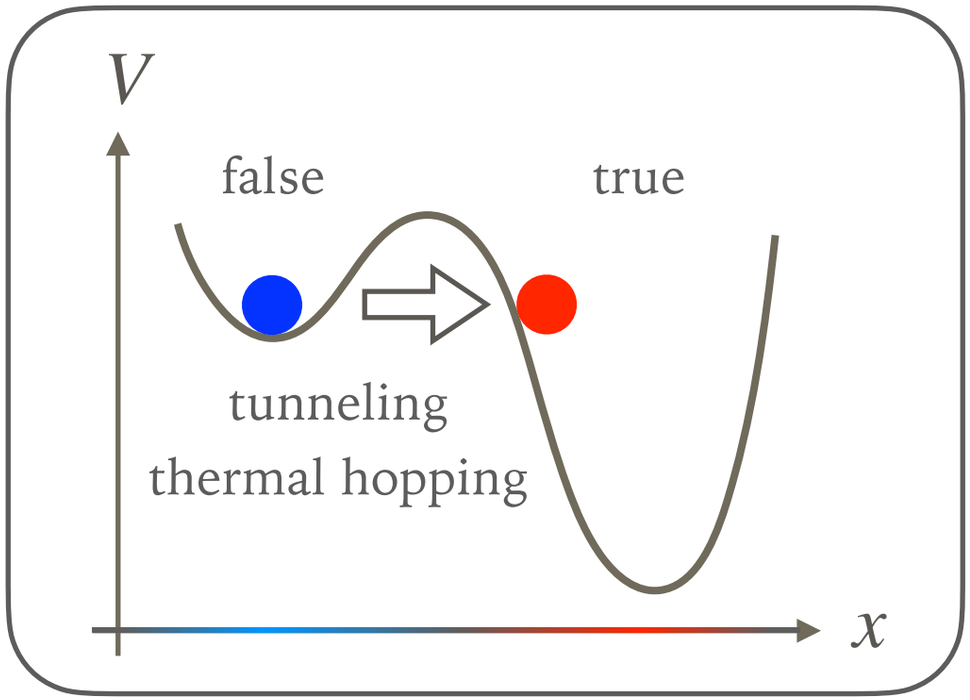

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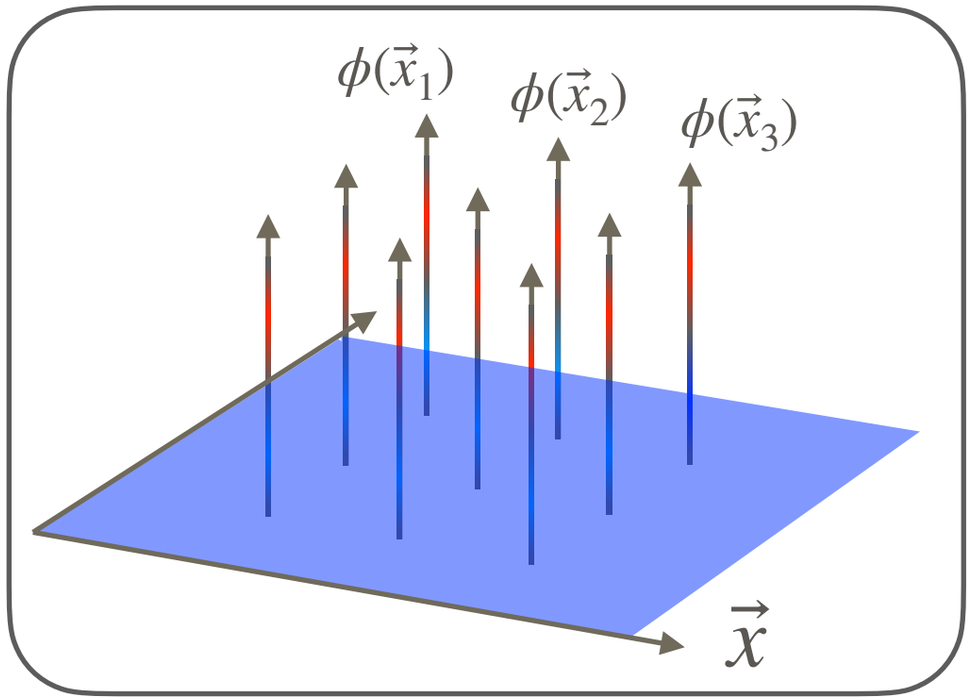

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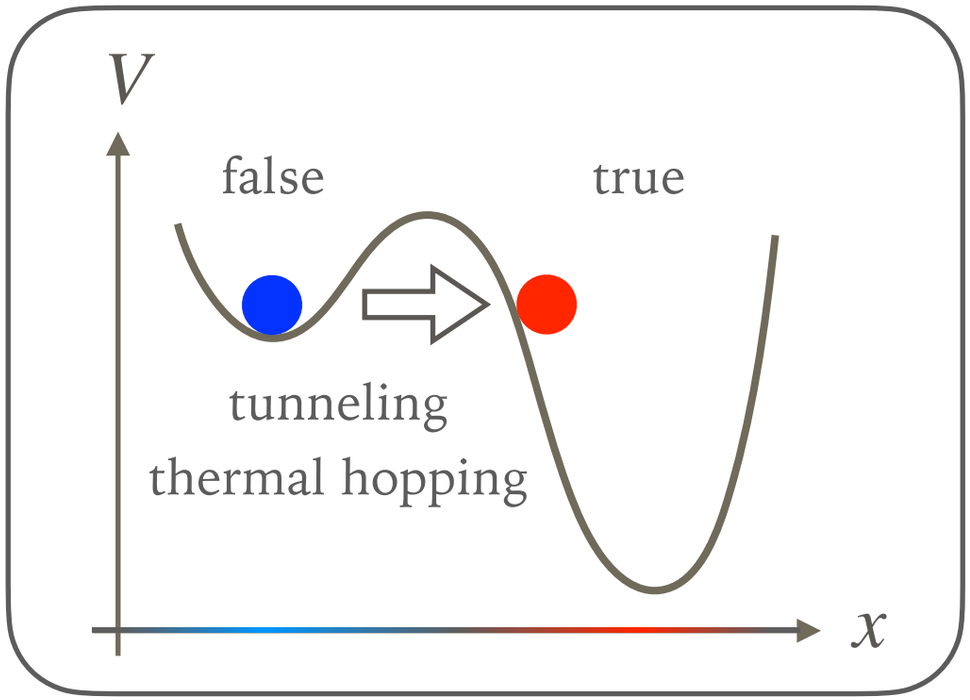

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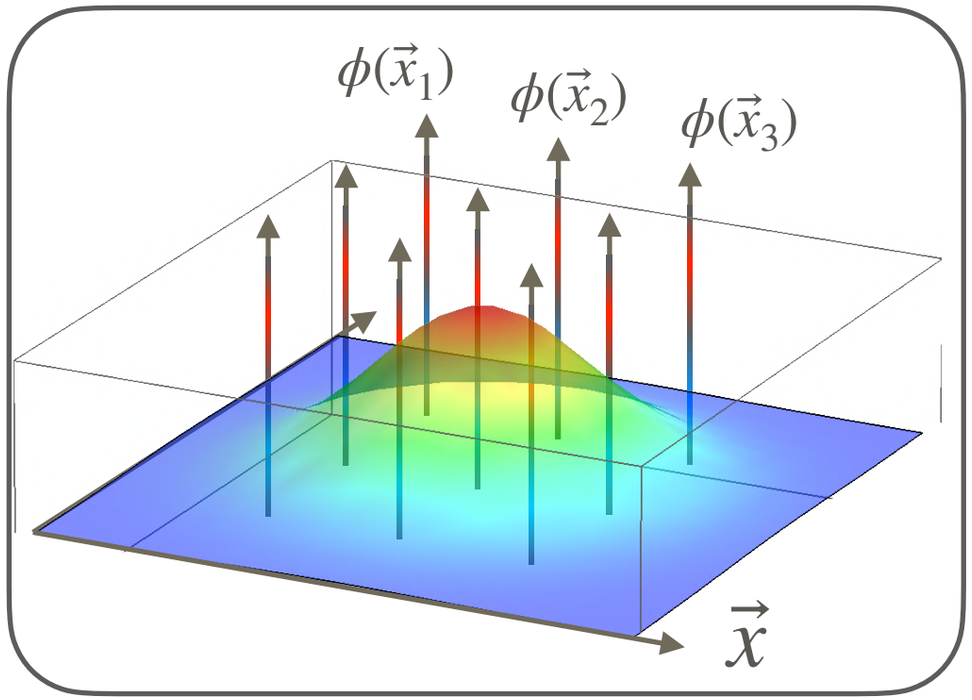
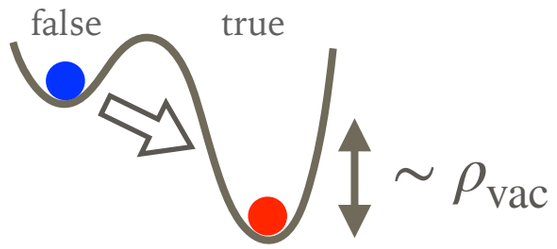


nucleation (核生成)

BUBBLE EXPANSION



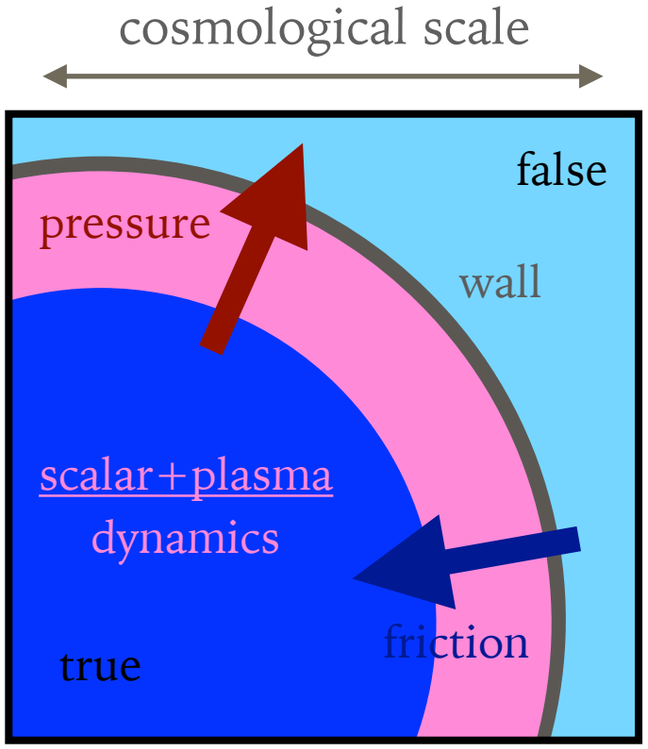
- "Pressure vs. Friction" determines the behavior:

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

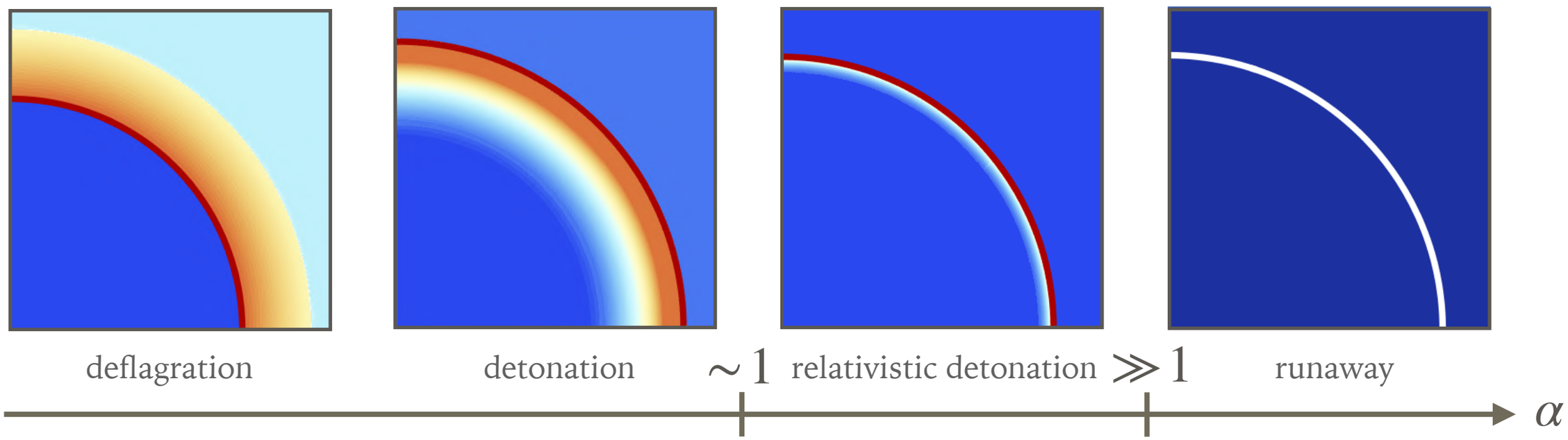
  Determined by $\alpha \equiv \rho_{\rm vac}/\rho_{\rm plasma}$

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

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



- Different types of bubble expansion



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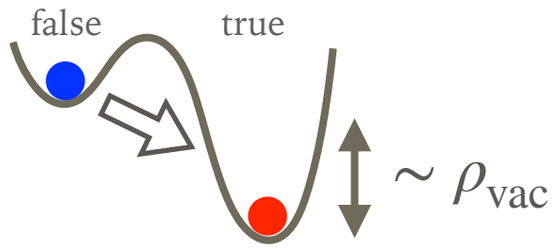

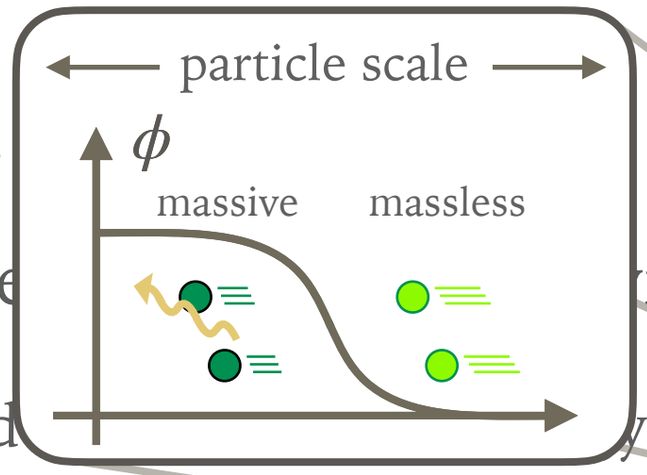

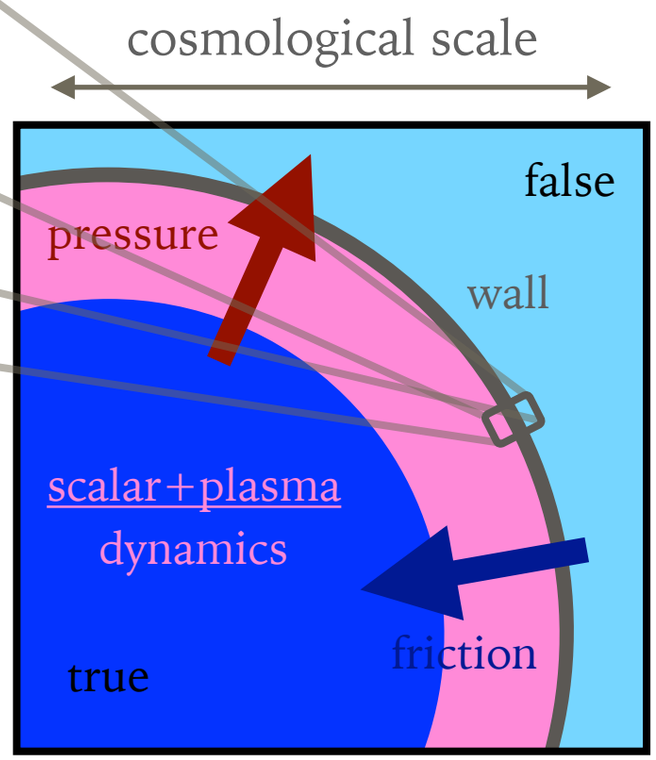

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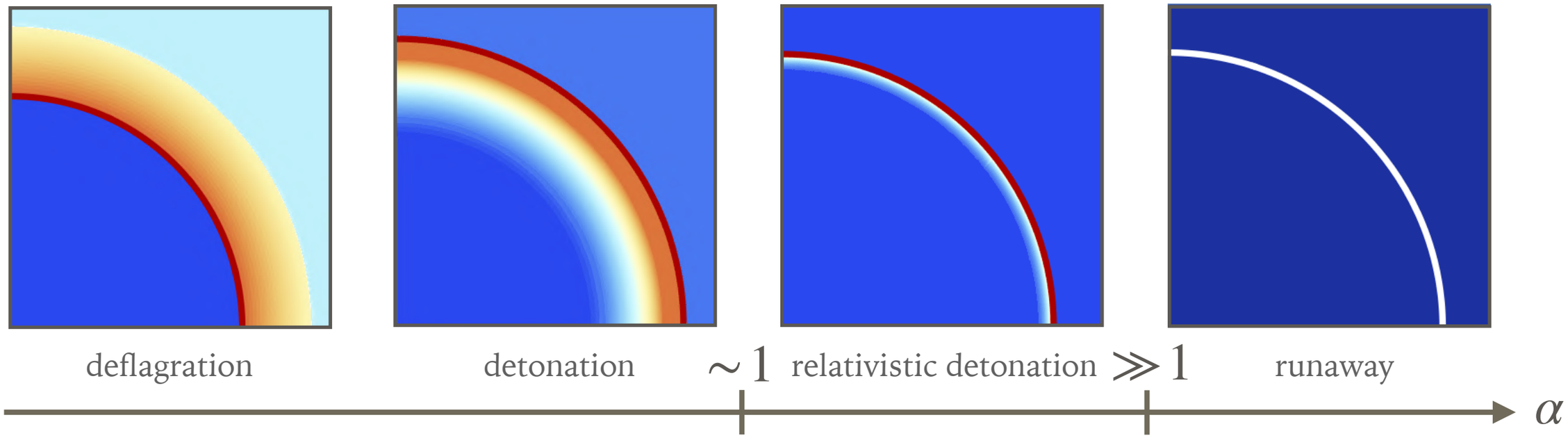
- Different types of bubble expansion



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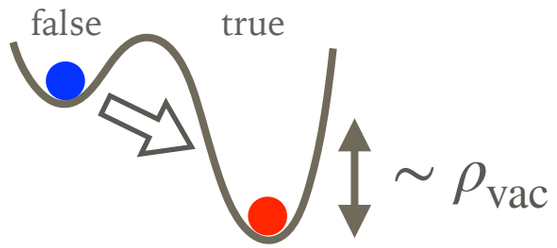
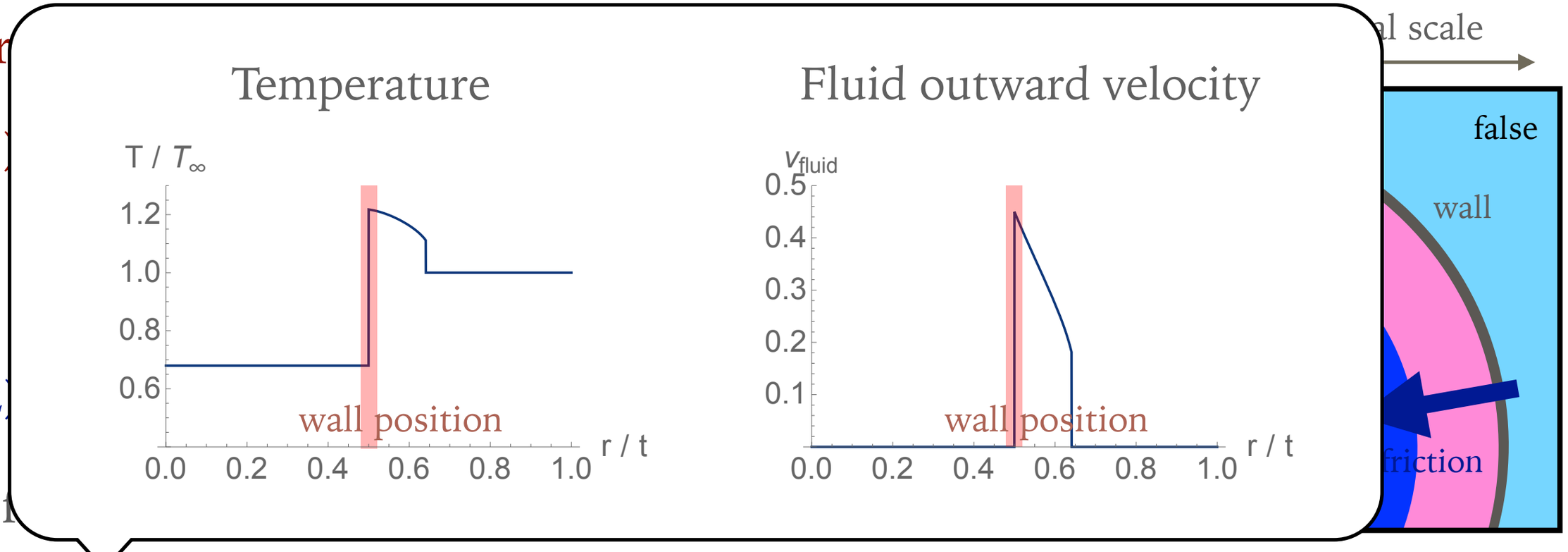
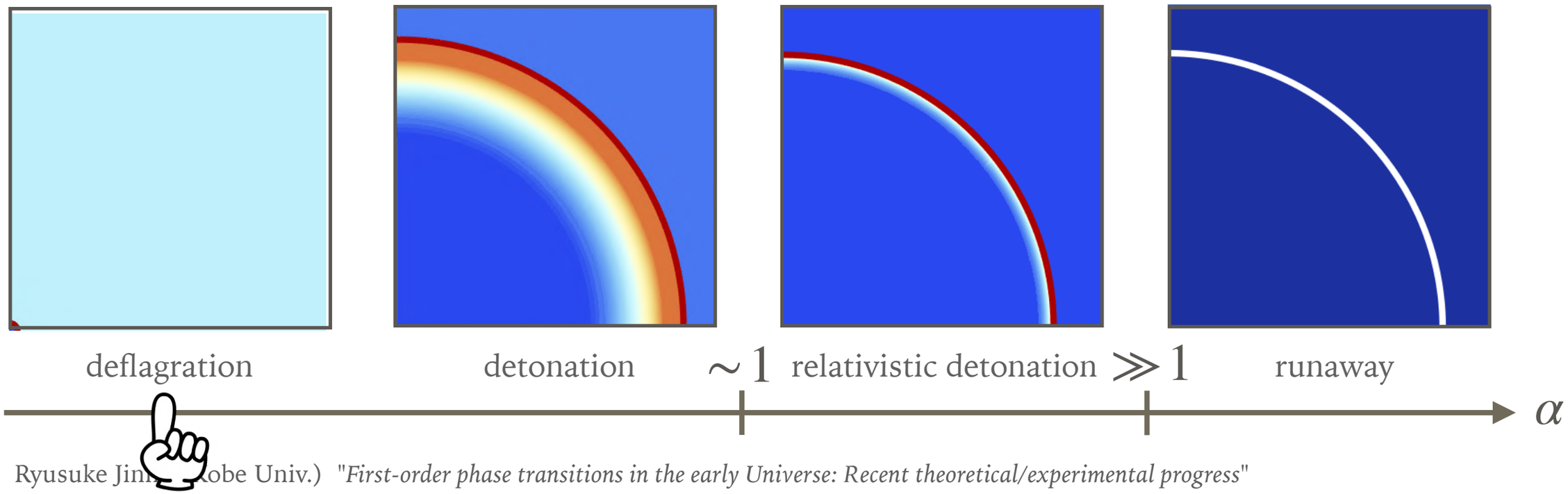


- "Pr
  (1)
  (2)
- Dif





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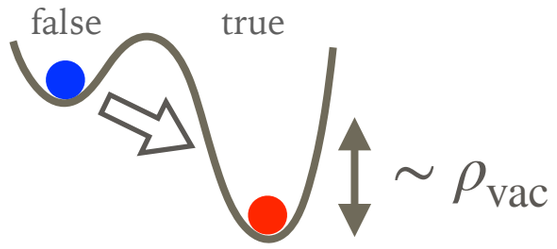

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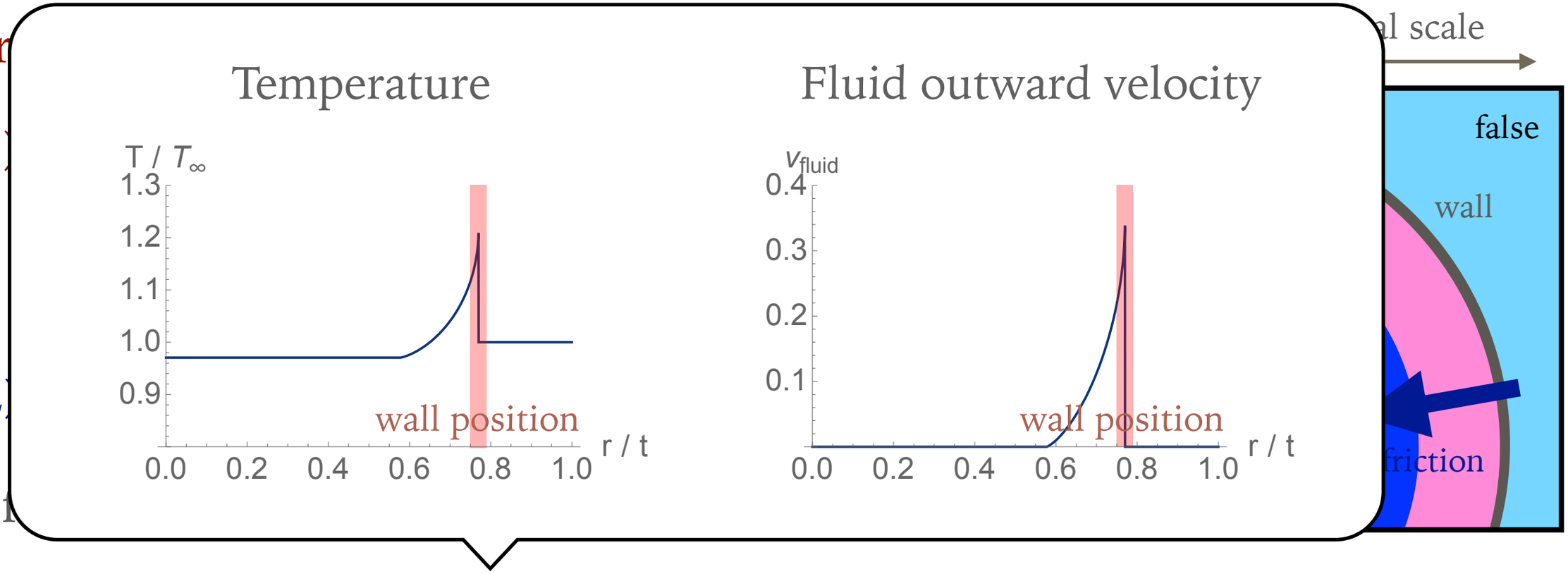

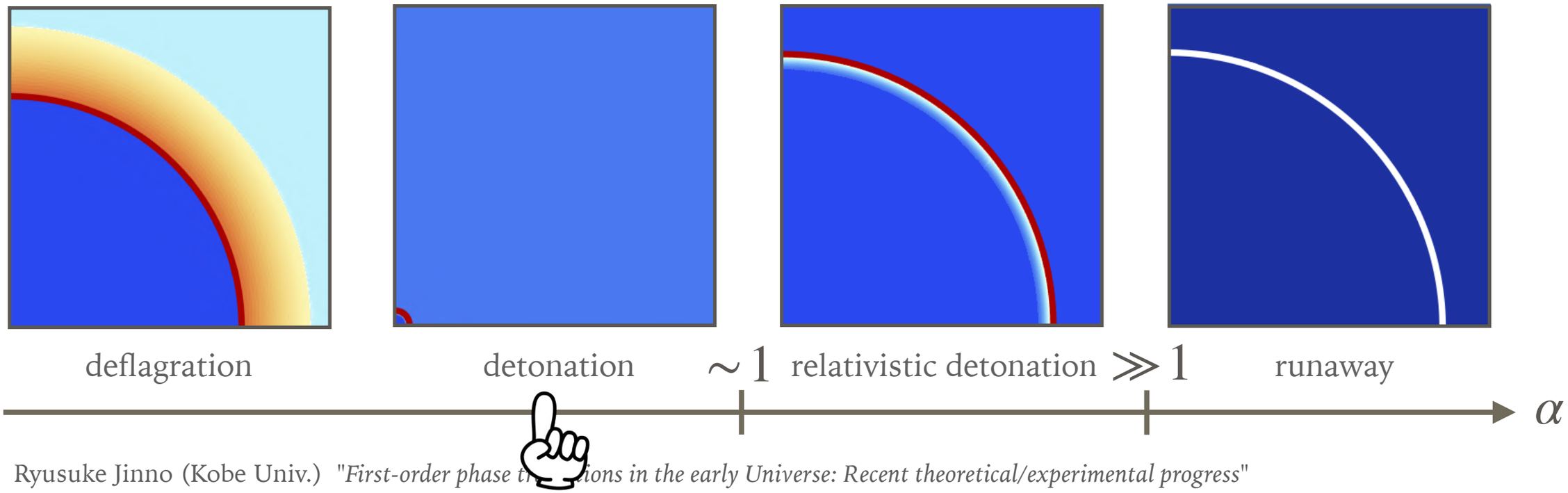

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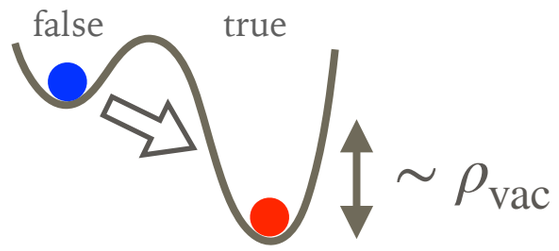

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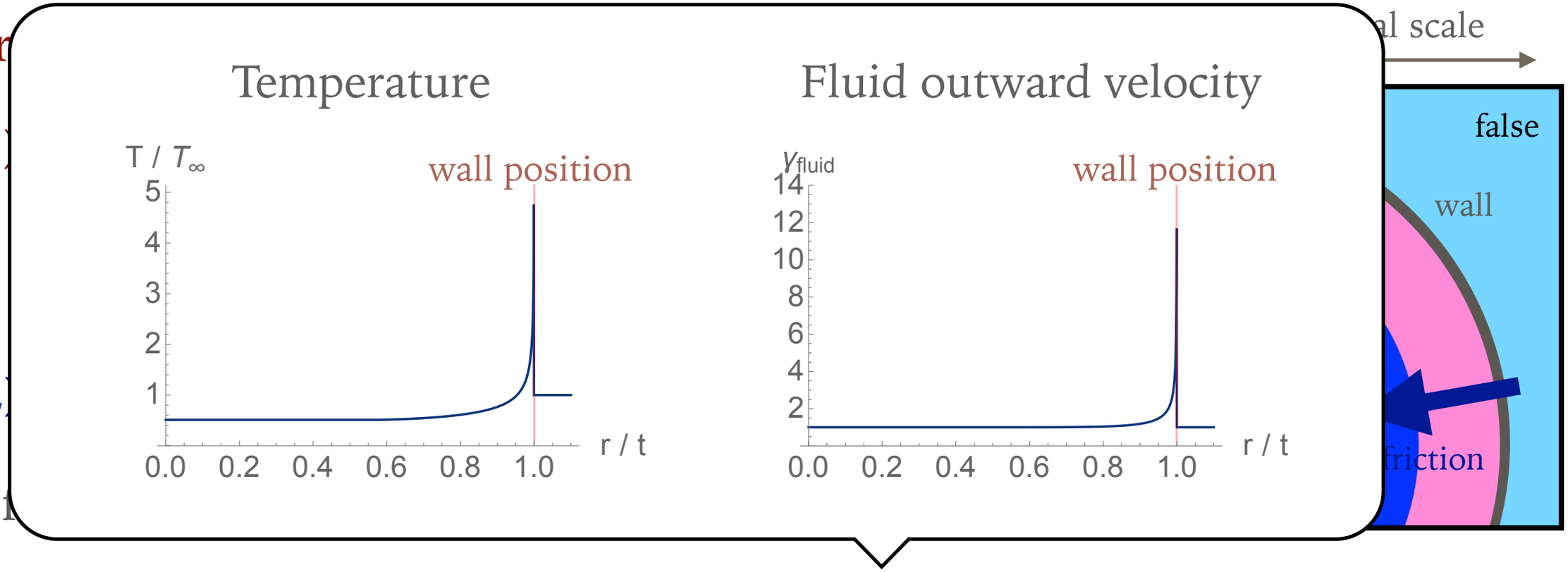

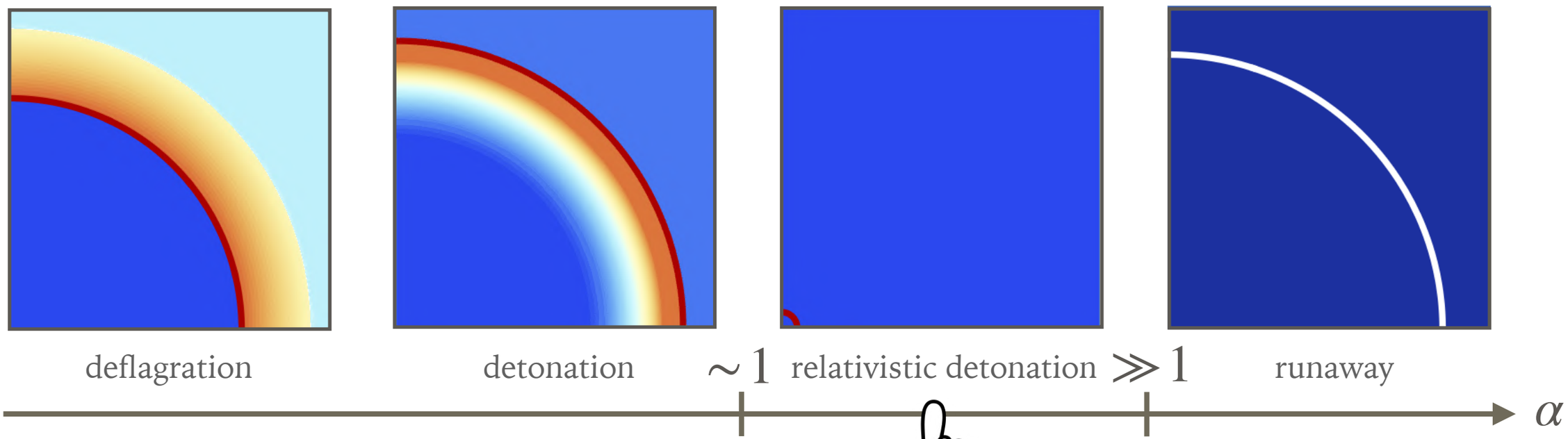

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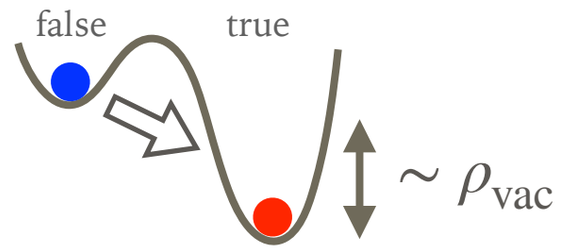


➤ "Pr

(1)

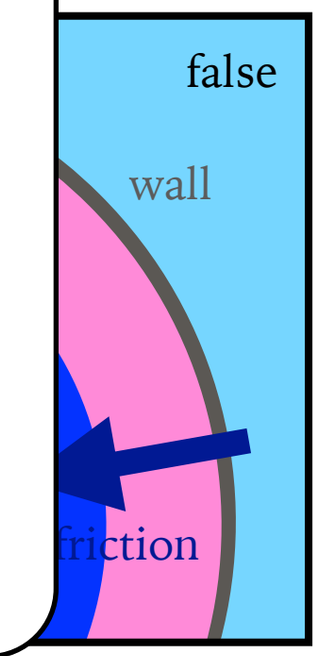
(2)

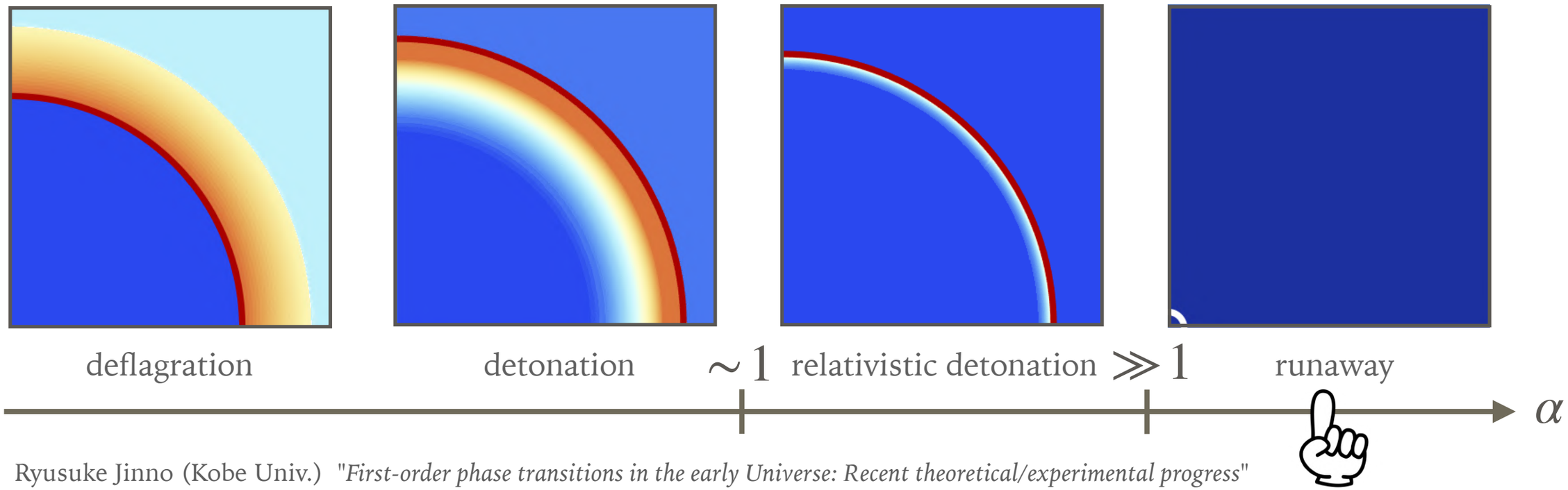
➤ Dif

Plasma particles cannot stop the acceleration of the walls:

walls continue to accelerate until they collide with others

[Bodeker & Moore '09, '17]

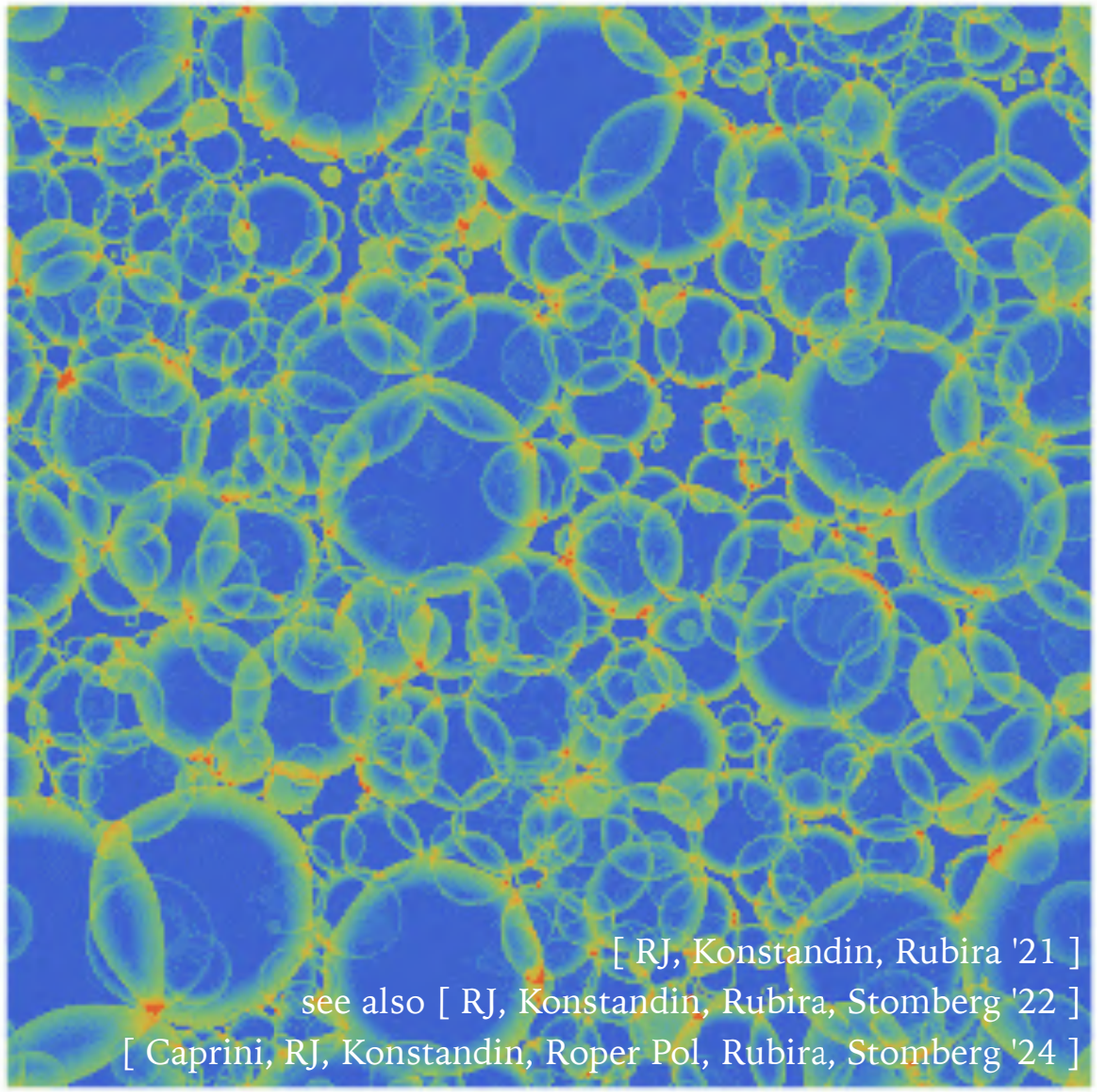




BUBBLE COLLISION & FLUID DYNAMICS

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

)



[RJ, Konstandin, Rubira '21]
see also [RJ, Konstandin, Rubira, Stomberg '22]
[Caprini, RJ, Konstandin, Roper Pol, Rubira, Stomberg '24]

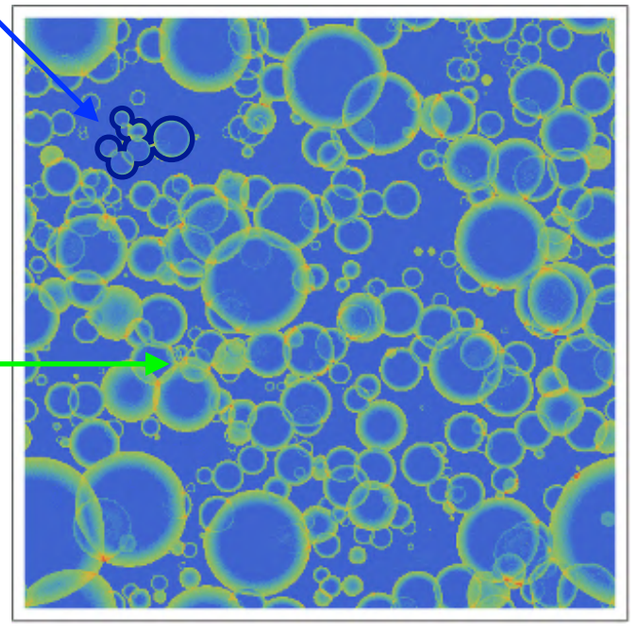
GRAVITATIONAL WAVE SOURCES

[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

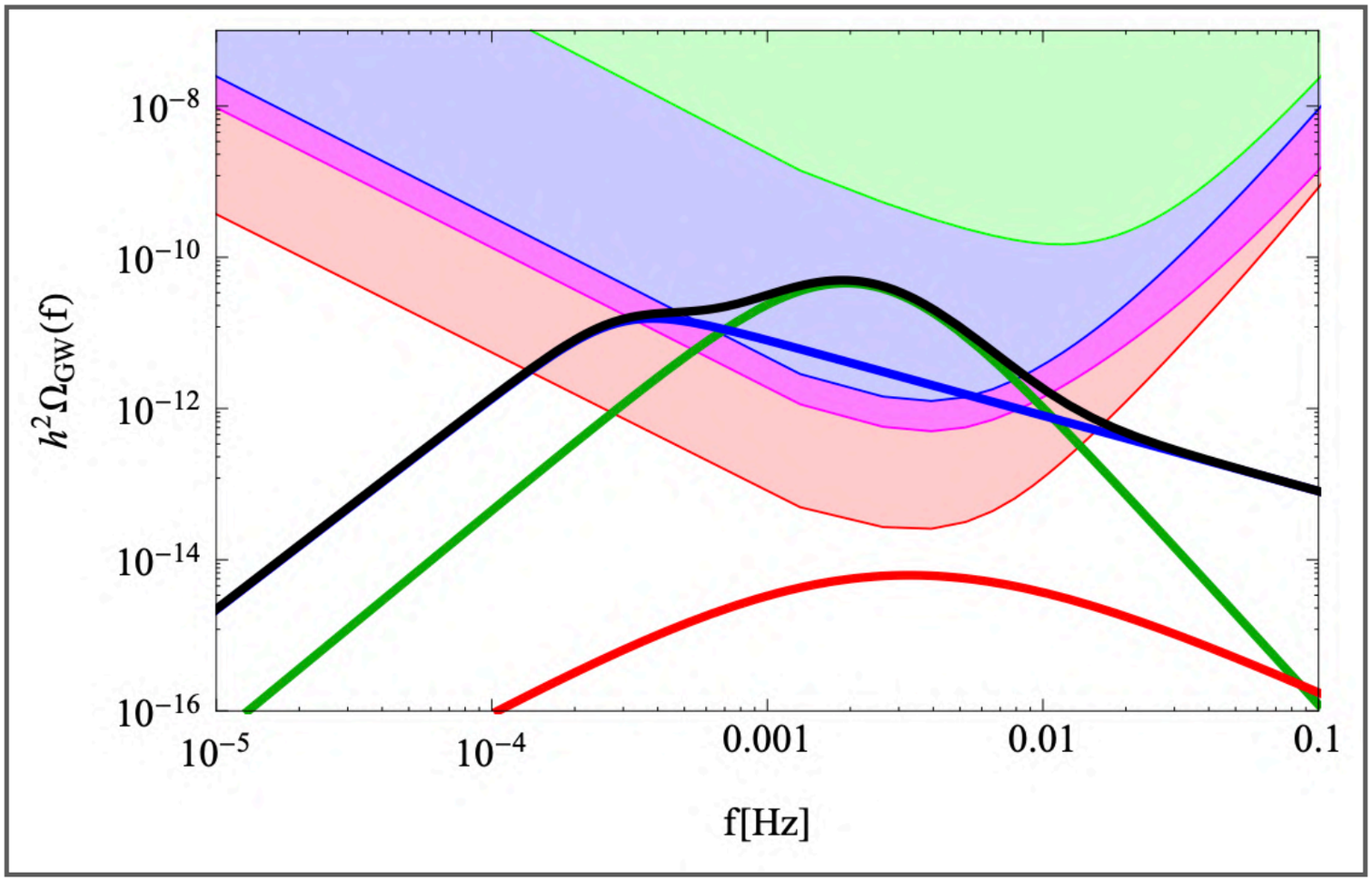
- Sound waves
  - Compression mode of the fluid motion
  - Dominant unless the transition is extremely strong

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



important at later stage

GRAVITATIONAL WAVE SPECTRUM

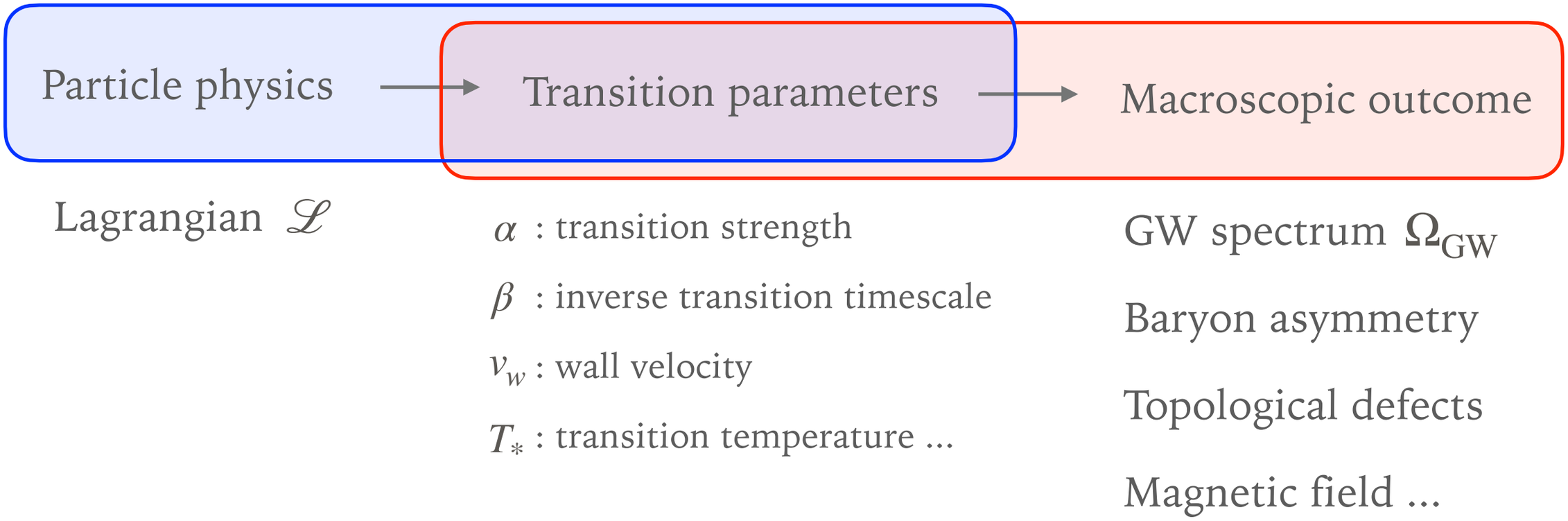


TRANSITION (≒ THERMODYNAMIC) PARAMETERS

- Remind the spirit of thermodynamics

  - Only a few parameters determine macroscopic properties

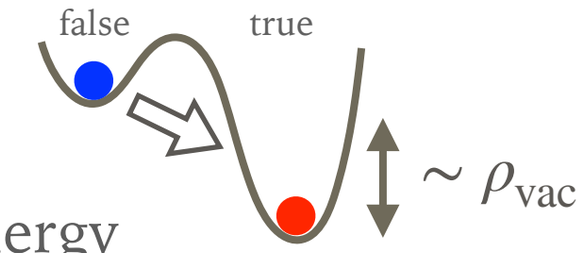
- What are parameters that describe the present macroscopic system?



TRANSITION (≒ THERMODYNAMIC) PARAMETERS

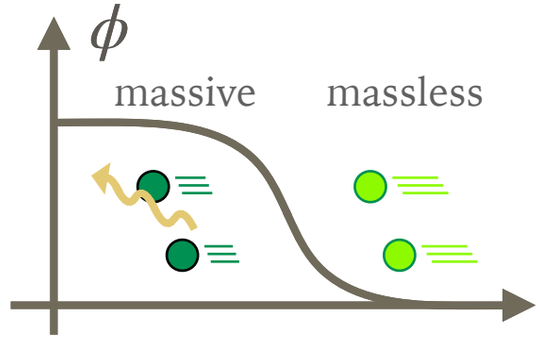
see e.g. [Caprini et al. '16] [Caprini et al. '20]

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



  - How much latent heat is released, compared to the plasma energy

- Wall velocity v_w



  - Determined from "pressure vs. friction"

  - In principle one should solve Boltzmann eq.,

  but often put by hand (regarded as changing couplings in the microphysical theory)

- Transition temperature T_*

  - Determined from your microphysical theory

  - EW scale transitions roughly corresponds to ~mHz GWs

TRANSITION (≒ THERMODYNAMIC) PARAMETERS

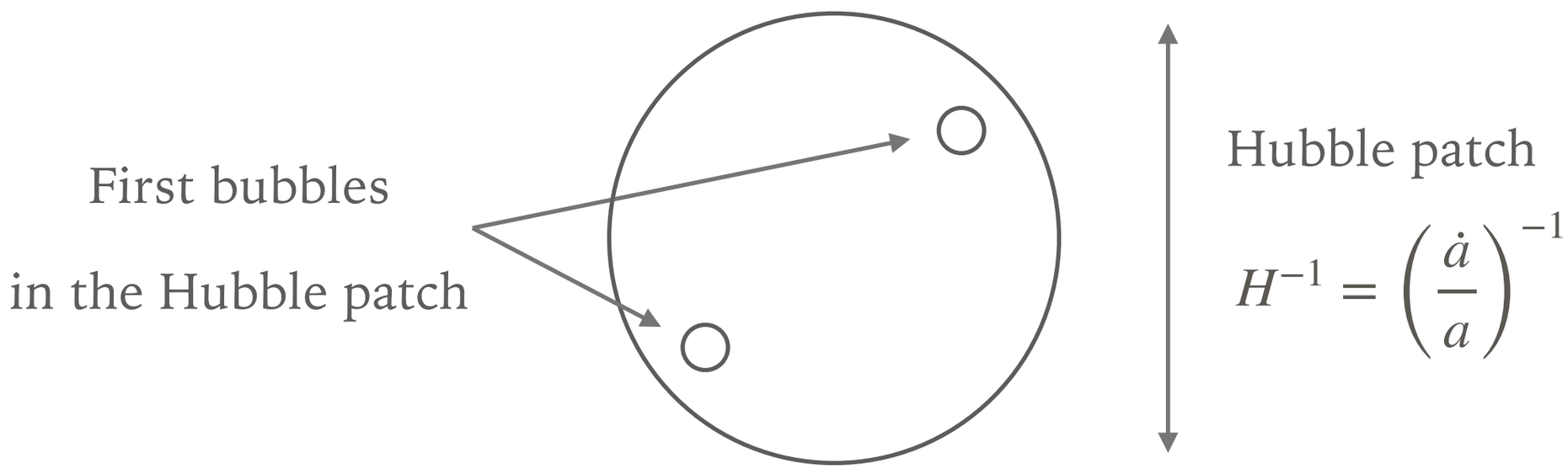
see e.g. [Caprini et al. '16] [Caprini et al. '20]

- Inverse transition timescale β : $\Gamma(t) \propto e^{\beta(t-t_*)+\cdots}$

  - Calculate $\Gamma(T)$ as a function of temperature, using thermal field theory

  - Translate $\Gamma(T)$ into $\Gamma(t)$ using (cosmological temperature) $\Leftrightarrow$ (cosmological time)

  - Taylor-expand the exponent around the typical transition time $t = t_*$



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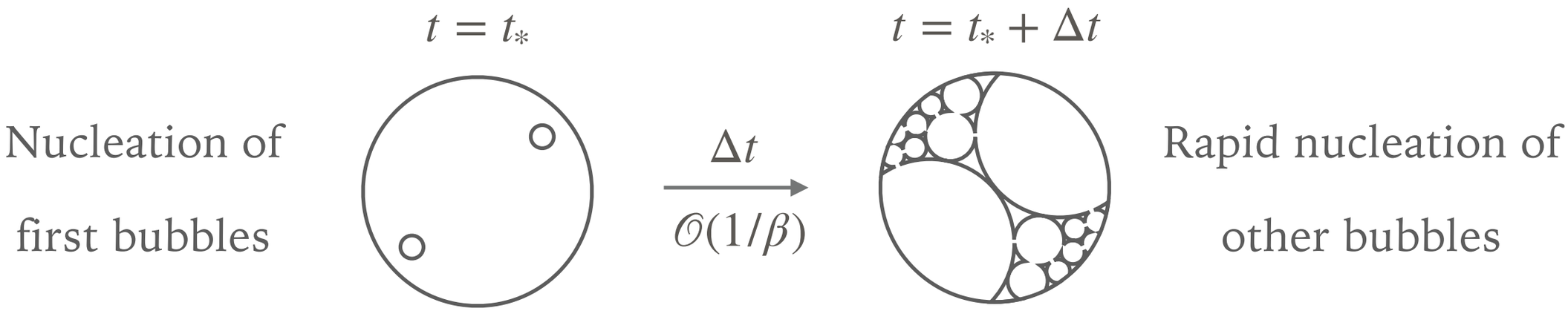
  - Taylor-expand the exponent around the typical transition time $t = t_*$

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



OUTLINE

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2. Some recent theoretical/experimental progress

   2-1) LISA status

   2-2) lab. experiments for QFT tunneling

   2-3) GW simulations

   2-4) particle splitting and NLO friction

   2-5) FOPTs with topological defects/free-streaming particles

3. Summary

GRAVITATIONAL WAVES: A NEW PROBE TO THE UNIVERSE

- Einstein equation:

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

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

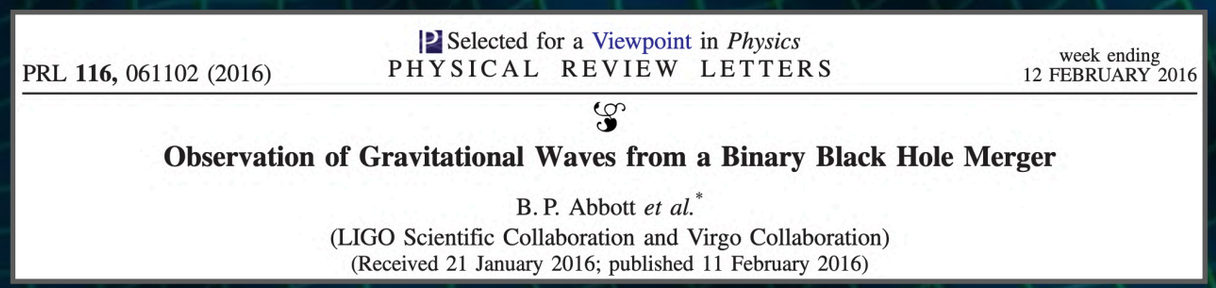
- Gravitational waves: transverse-traceless part of the metric

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

- After expanding the Einstein equation, GWs obey a wave equation sourced by the energy-momentum tensor of the system

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

- 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)

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

[R. Hurt/Caltech-JPL]

PRESENT & FUTURE OBSERVATIONS

Pulsar timing arrays

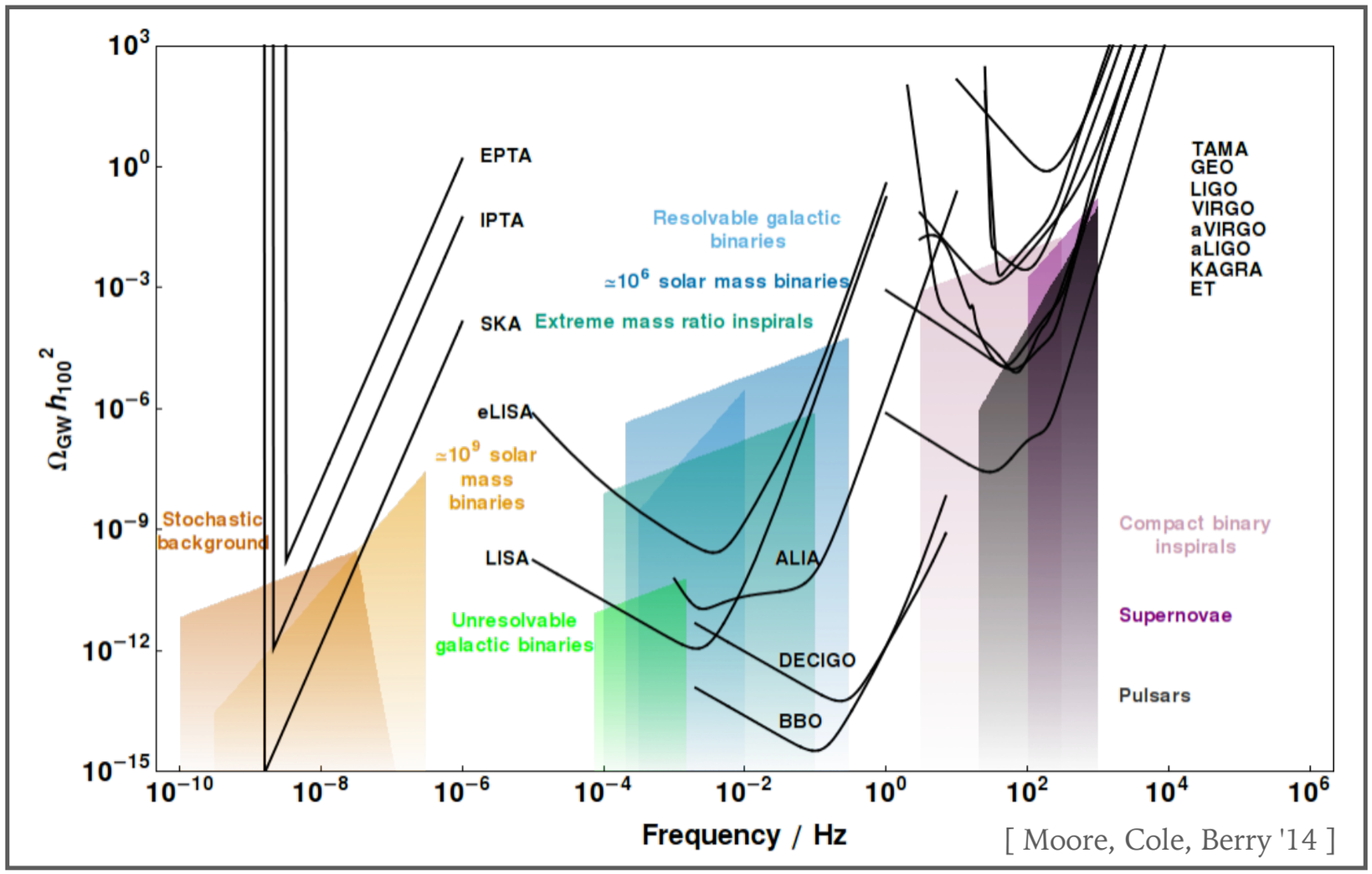
$\sim 10^{-8}$ Hz

Space-borne interferometers

$\sim$ mHz – Hz

Ground-based interferometers

$\sim$ 100 Hz

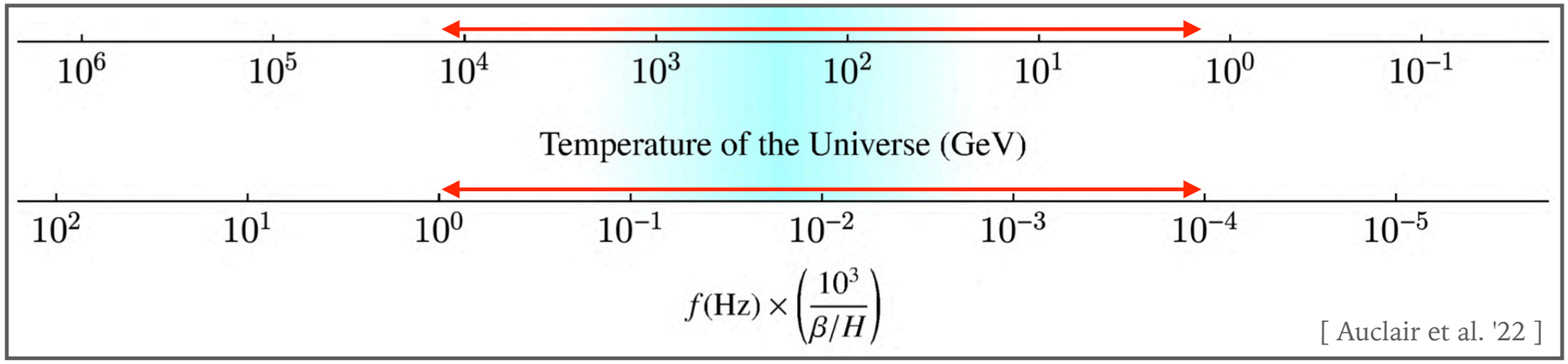


[Moore, Cole, Berry '14]

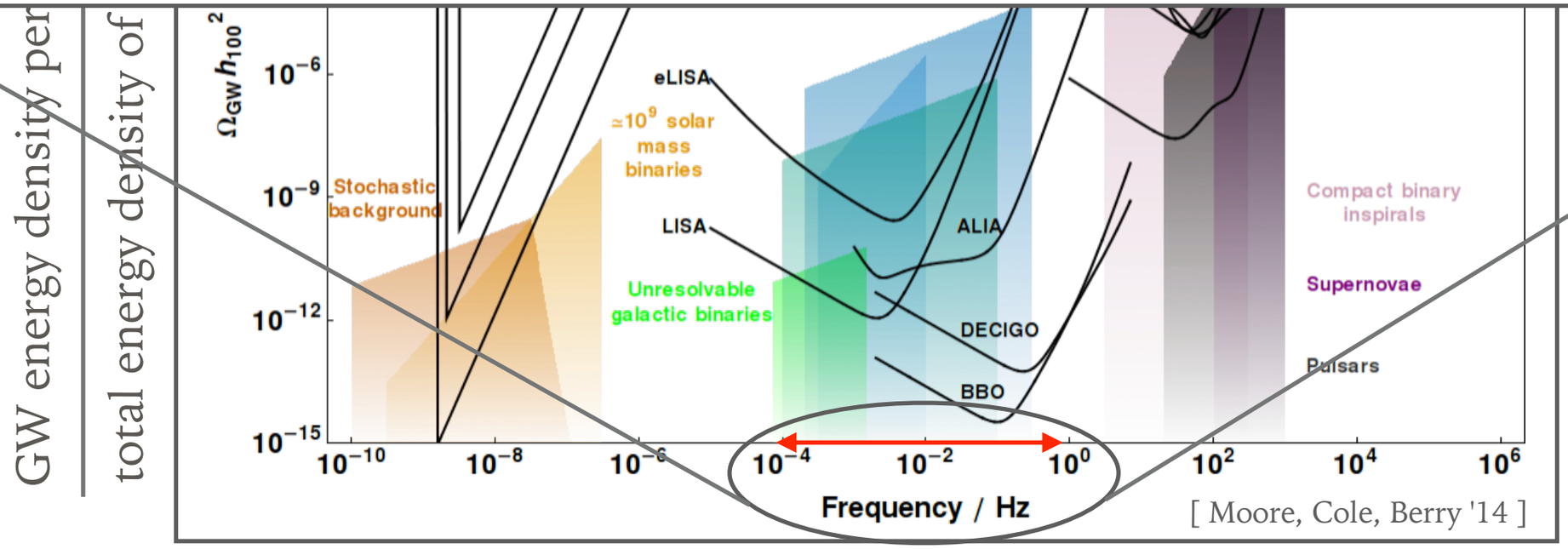
Present frequency of cosmological GWs

$\propto$ Energy scale (temperature) at the time of production

TeV scale physics



[Auclair et al. '22]

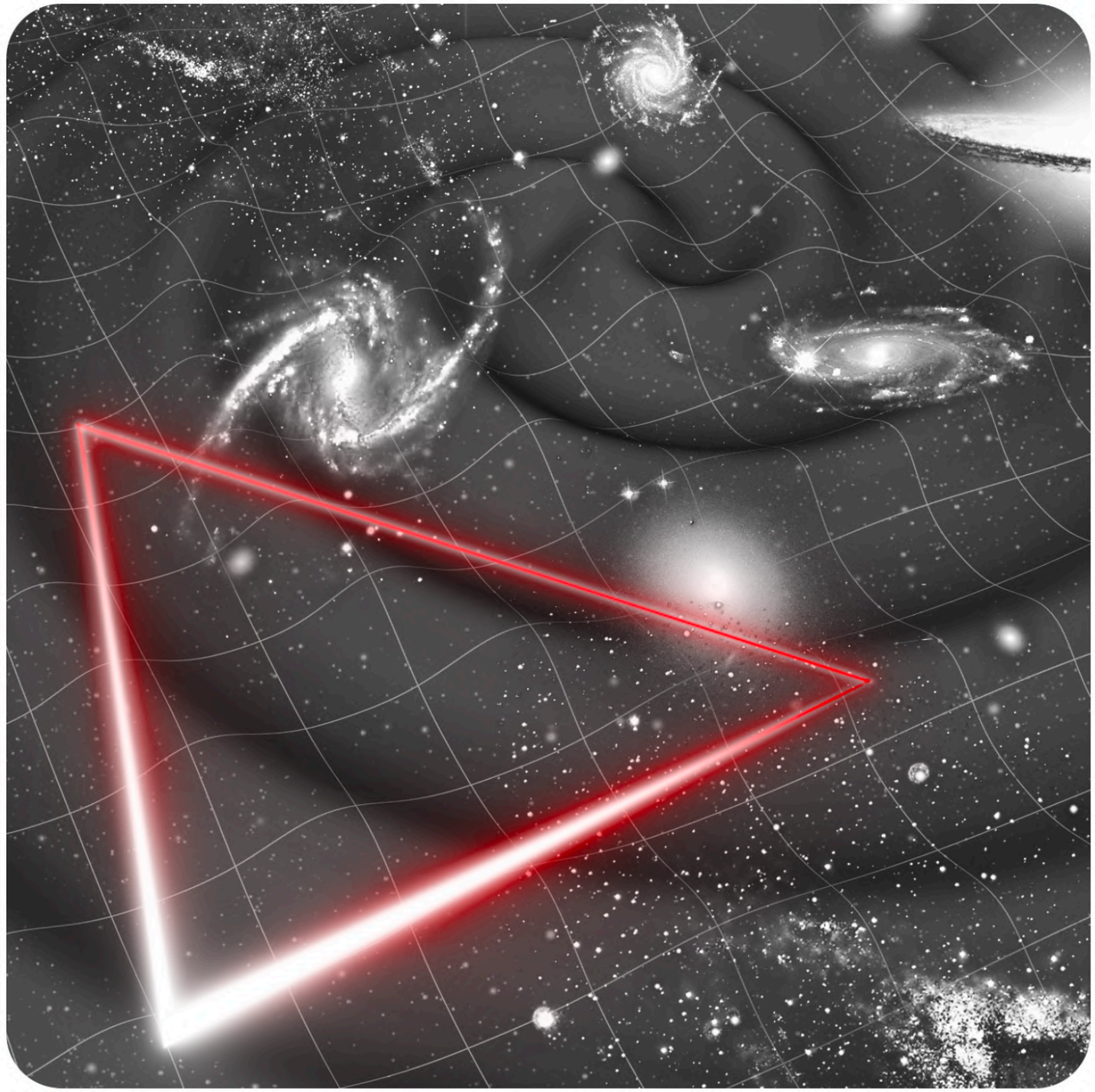


[Moore, Cole, Berry '14]

LISA MISSION

LISA

Laser Interferometer Space Antenna



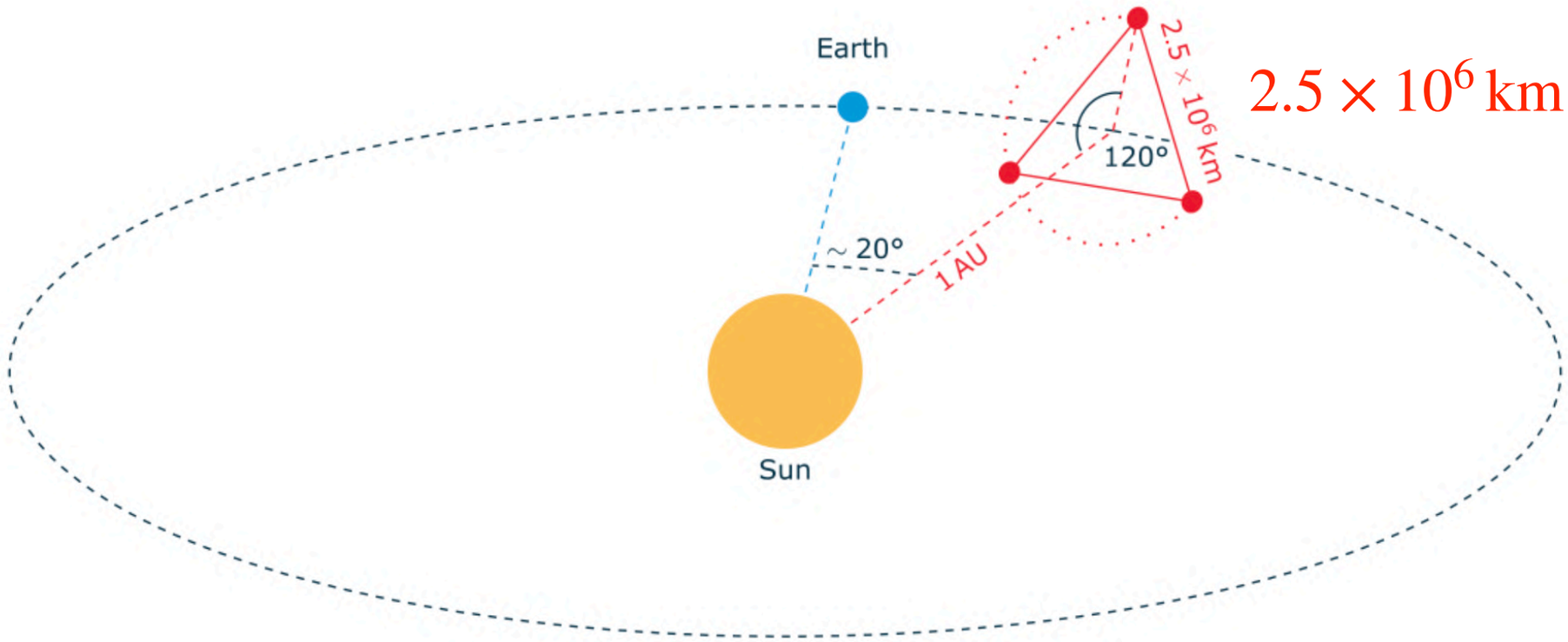
"LISA Red book"

LISA MISSION SUMMARY

Science Objectives

- Study the formation and evolution of **compact binary stars** and the structure of the Milky Way Galaxy
- Trace the origins, growth and merger histories of **massive Black Holes** across cosmic epochs
- Probe the properties and immediate environments of Black Holes in the local Universe using **extreme mass-ratio inspirals** and **intermediate mass-ratio inspirals**
- Understand the astrophysics of **stellar-mass Black Holes**
- Explore the **fundamental nature of gravity** and Black Holes
- Probe the rate of **expansion of the Universe** with standard sirens
- Understand **stochastic gravitational wave backgrounds** and their implications for the early Universe and TeV-scale particle physics
- Search for gravitational wave bursts and **unforeseen sources**

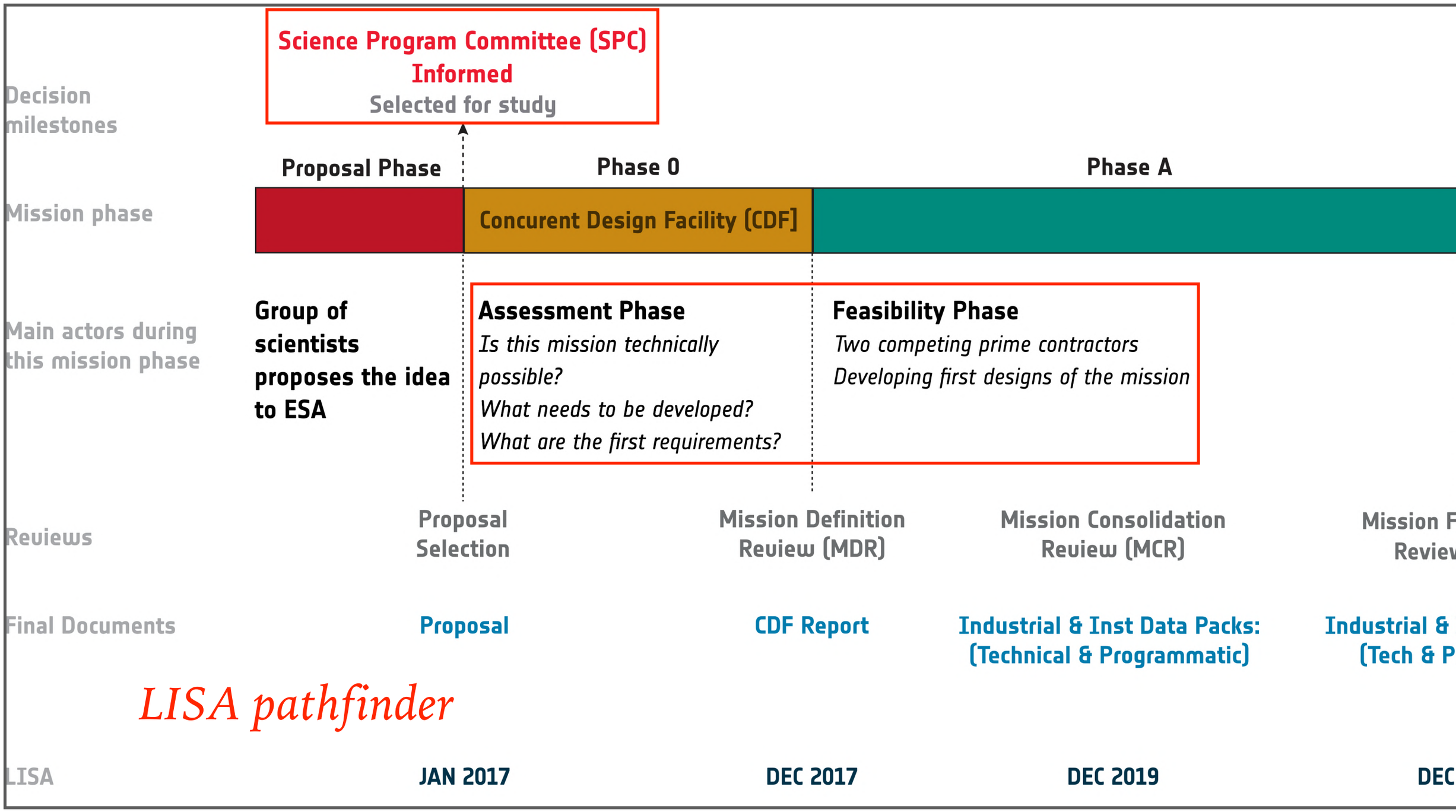
LISA MISSION: DETECTOR CONFIGURATION



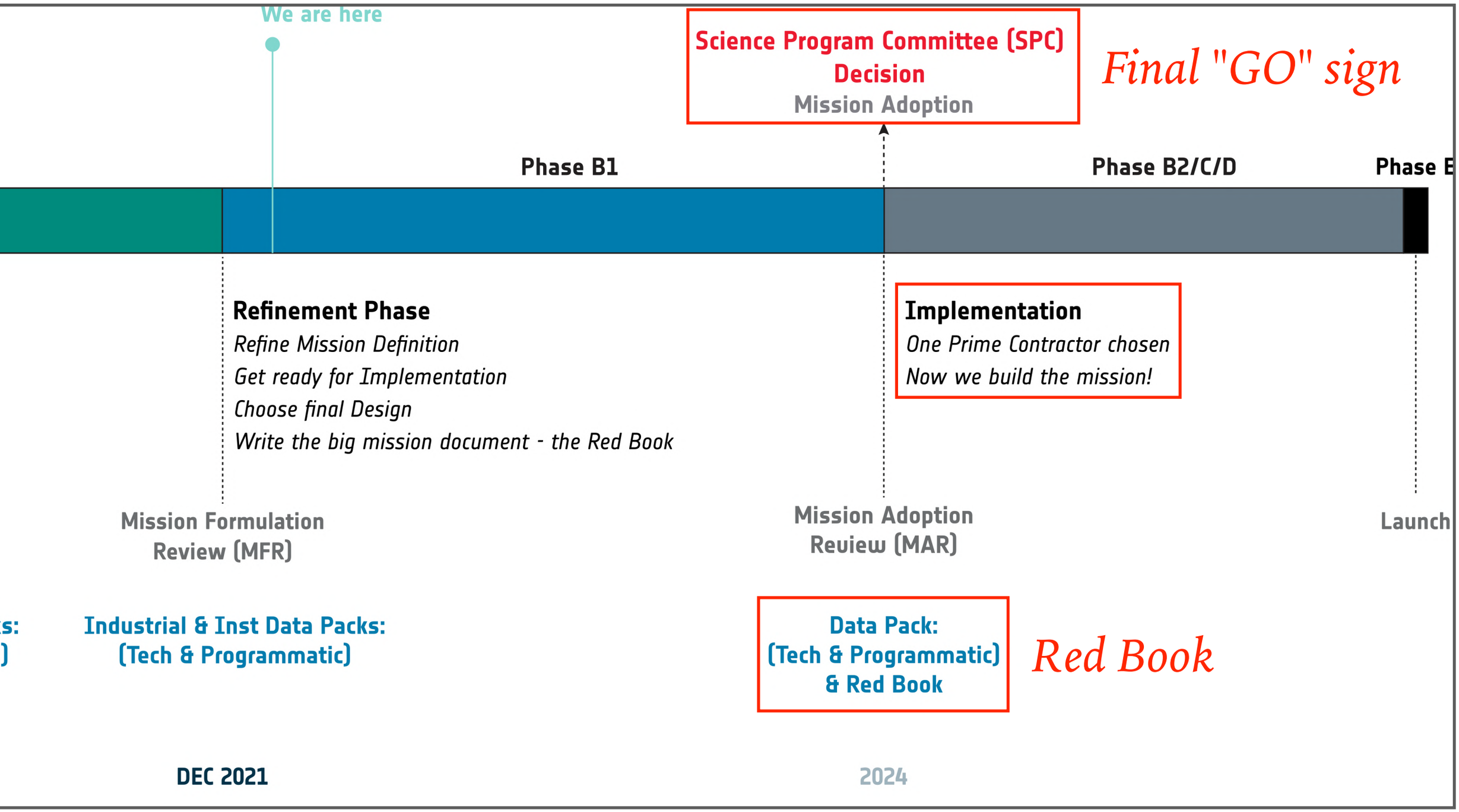
$2.5 \times 10^6\,\mathrm{km} \sim 30\,\mathrm{mHz}$

Figure 2.3: Schematic depiction of the LISA orbit, not to scale. The three satellites are arranged in a equilateral triangle, the constellation barycentre follows a heliocentric orbit lagging or leading approximately 20°, or about 50×10^6 km, behind Earth. The plane of the constellation (marked with the dotted line) is inclined at 60° with respect to the Ecliptic and the triangular array undergoes an annual rotation within the plane. See Chapter 6 for further details.

LISA MISSION: TIMELINE



LISA MISSION: TIMELINE



LISA MISSION: PRIMARY SOURCES

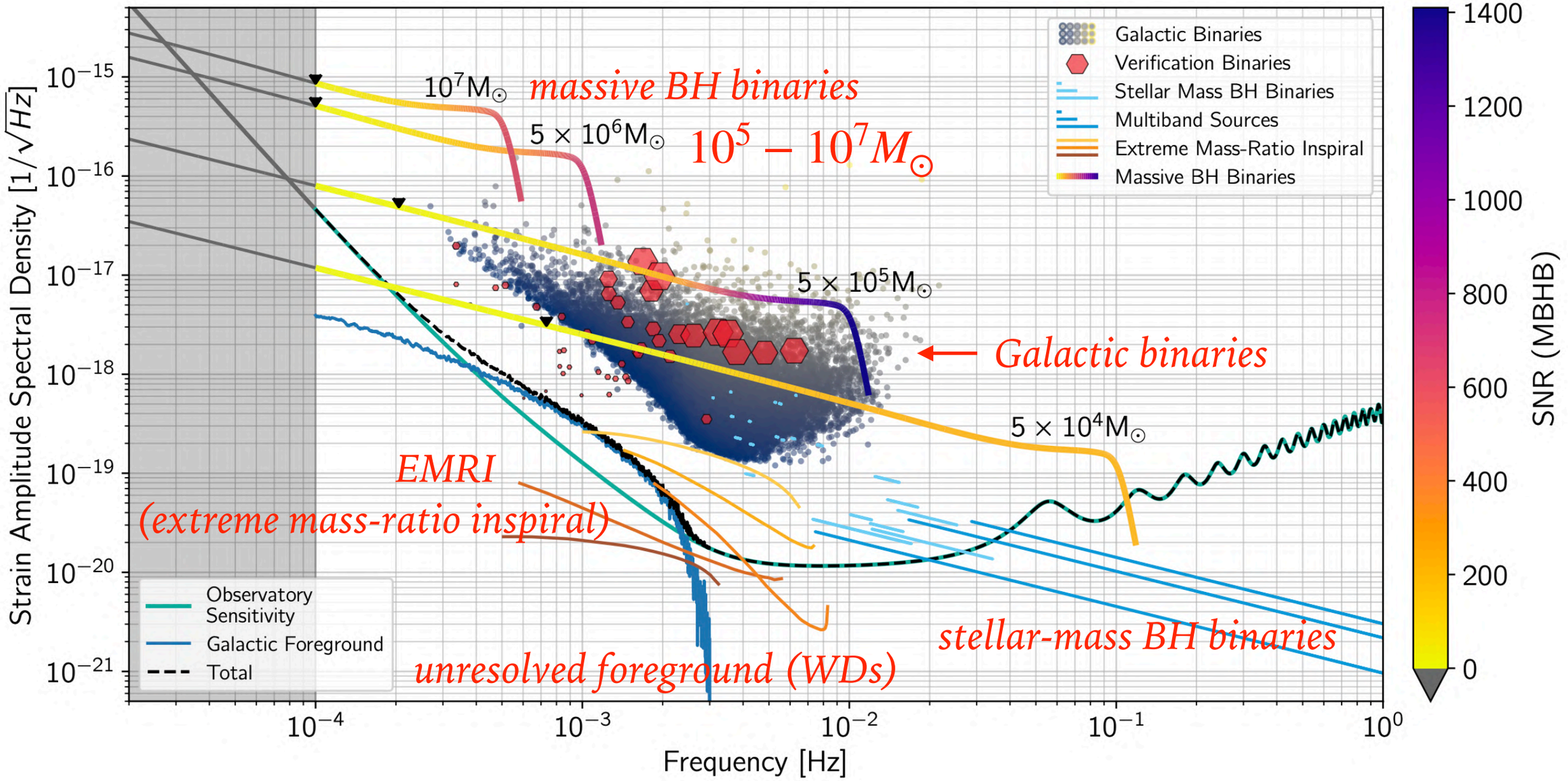


Figure 2.2: Illustration of the primary LISA source classes in the gravitational wave (GW) frequency-amplitude plane. Included are merging massive Black Hole binaries (MBHBs) and an extreme mass-ratio inspiral (EMRI) at moderate redshift; stellar-mass Black Holes (sBHs), including potential multiband sources, at low redshift; and Galactic binaries (GBs), including verification binaries (VBs), in the Milky Way.

LISA MISSION: PRIMARY SOURCES

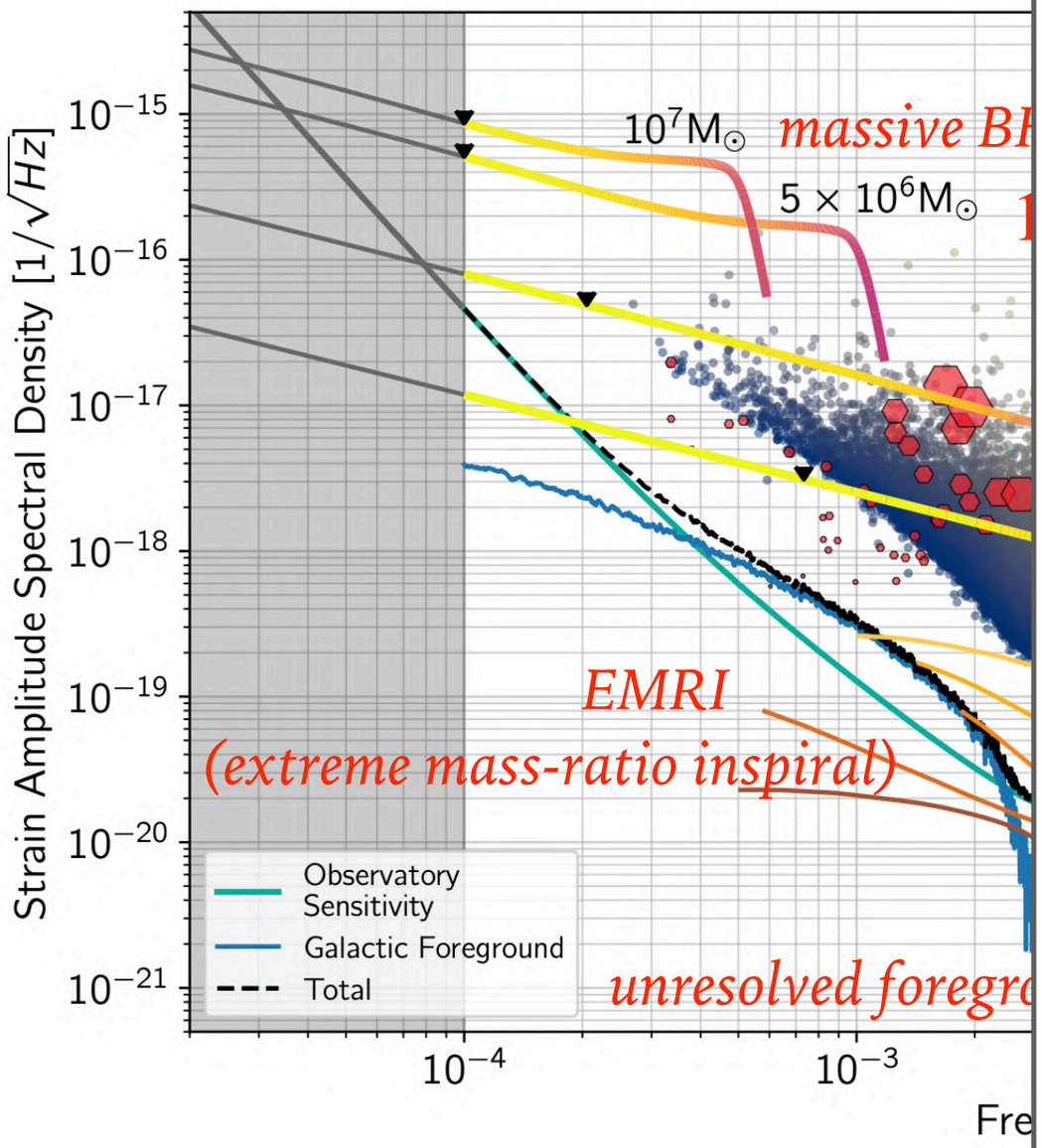


Figure 2.2: Illustration of the primary LISA source c
Included are merging massive Black Hole binaries (M
redshift; stellar-mass Black Holes (sBHs), including p
(GBs), including verification binaries (VBs), in the

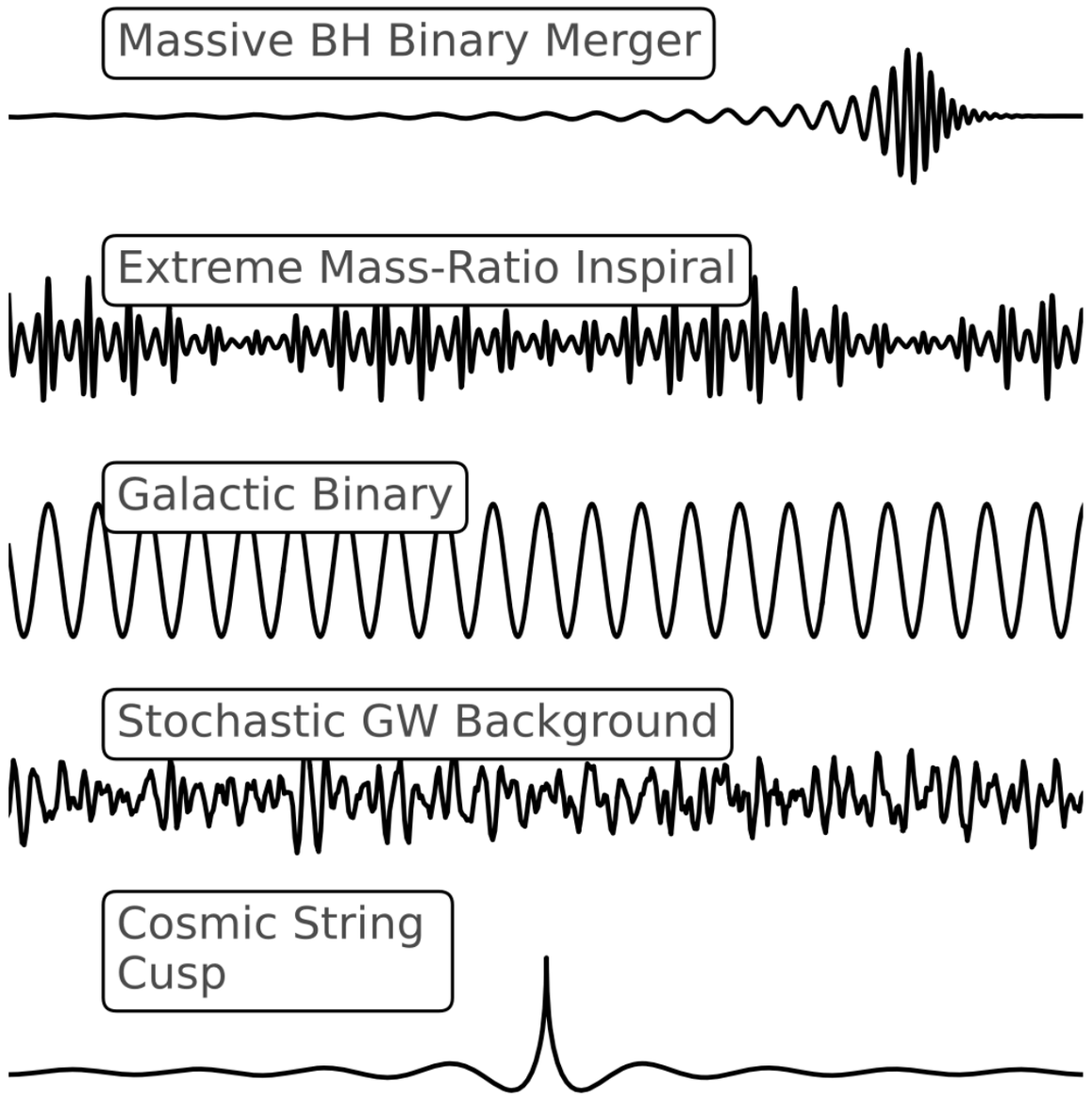


Figure 8.3: Shapes of the waveforms corresponding to the GW emission of (from top to bottom): Massive BH binary mergers; Extreme-mass-ratio inspirals; a single Galactic binary; a typical stochastic process; and a cosmic string cusp.

LISA MISSION: LISA PATHFINDER

→ THE EUROPEAN SPACE AGENCY

esa

LISA factsheet

19436 VIEWS 37 LIKES

ESA / Science & Exploration / Space Science

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.

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   2-1) LISA status

   2-2) lab. experiments for QFT tunneling

   2-3) GW simulations

   2-4) particle splitting and NLO friction

   2-5) FOPTs with topological defects/free-streaming particles

3. Summary

2025 NOBEL PRIZE: MACROSCOPIC QUANTUM TUNNELING

Nobel Prize in Physics 2025

Ill. Niklas Elmehed © Nobel Prize Outreach

John Clarke

© Nobel Prize Outreach. Photo: Clément Morin

Michel H. Devoret

© Nobel Prize Outreach. Photo: Clément Morin

John M. Martinis

The Nobel Prize in Physics 2025 was awarded jointly to John Clarke, Michel H. Devoret and John M. Martinis "for the discovery of macroscopic quantum mechanical tunnelling and energy quantisation in an electric circuit"

QFT TUNNELING IN LAB

nature physics

Article https://doi.org/10.1038/s41567-023-02345-4

False vacuum decay via bubble formation in ferromagnetic superfluids

A. Zenesini, A. Berti, R. Cominotti, C. Rogora, I. G. Moss, T. P. Billam, I. Carusotto, G. Lamporesi, A. Recati & G. Ferrari

➤ First observation in 2024

- Platform: cold atoms ($^{23}\mathrm{Na}$, 2 hyperfine levels)

- Described by two field operators: $\hat{\psi}_\uparrow(\boldsymbol{x})$, $\hat{\psi}_\downarrow(\boldsymbol{x})$

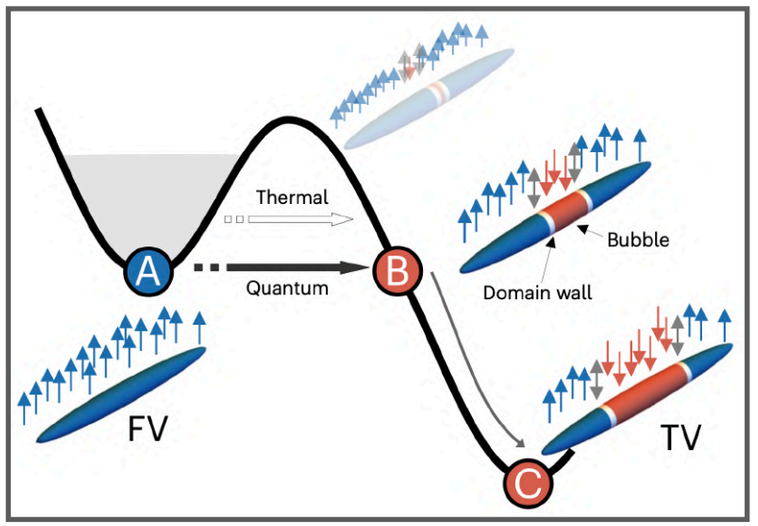
- Both undergo BEC: $\Phi_\uparrow(\boldsymbol{x}) = \left\langle \hat{\psi}_\uparrow(\boldsymbol{x}) \right\rangle \neq 0$, $\Phi_\downarrow(\boldsymbol{x}) = \left\langle \hat{\psi}_\downarrow(\boldsymbol{x}) \right\rangle \neq 0$

- Order parameter: magnetization $Z(\boldsymbol{x}) \simeq \dfrac{|\Phi_\uparrow(\boldsymbol{x})|^2 - |\Phi_\downarrow(\boldsymbol{x})|^2}{|\Phi_\uparrow(\boldsymbol{x})|^2 + |\Phi_\downarrow(\boldsymbol{x})|^2}$

- Potential is tuned with microwaves and magnetic field

$$V(Z) = -\hbar\left(|\kappa| n Z^2 + 2\Omega_{\mathrm{R}}\sqrt{1-Z^2} + 2\delta_{\mathrm{f}} Z\right)$$

Ω_R : Rabi frequency $\delta_f \supset$ Zeeman splitting



QFT TUNNELING IN LAB

- First obser
  - Platform: c
  - Described b
  - Both under
  - Order para
  - Potential is

$$V(Z) =$$

Ω_R : Ra

nature physics

https://doi.org/10.1038/s41567-023-02345-4

ble formation
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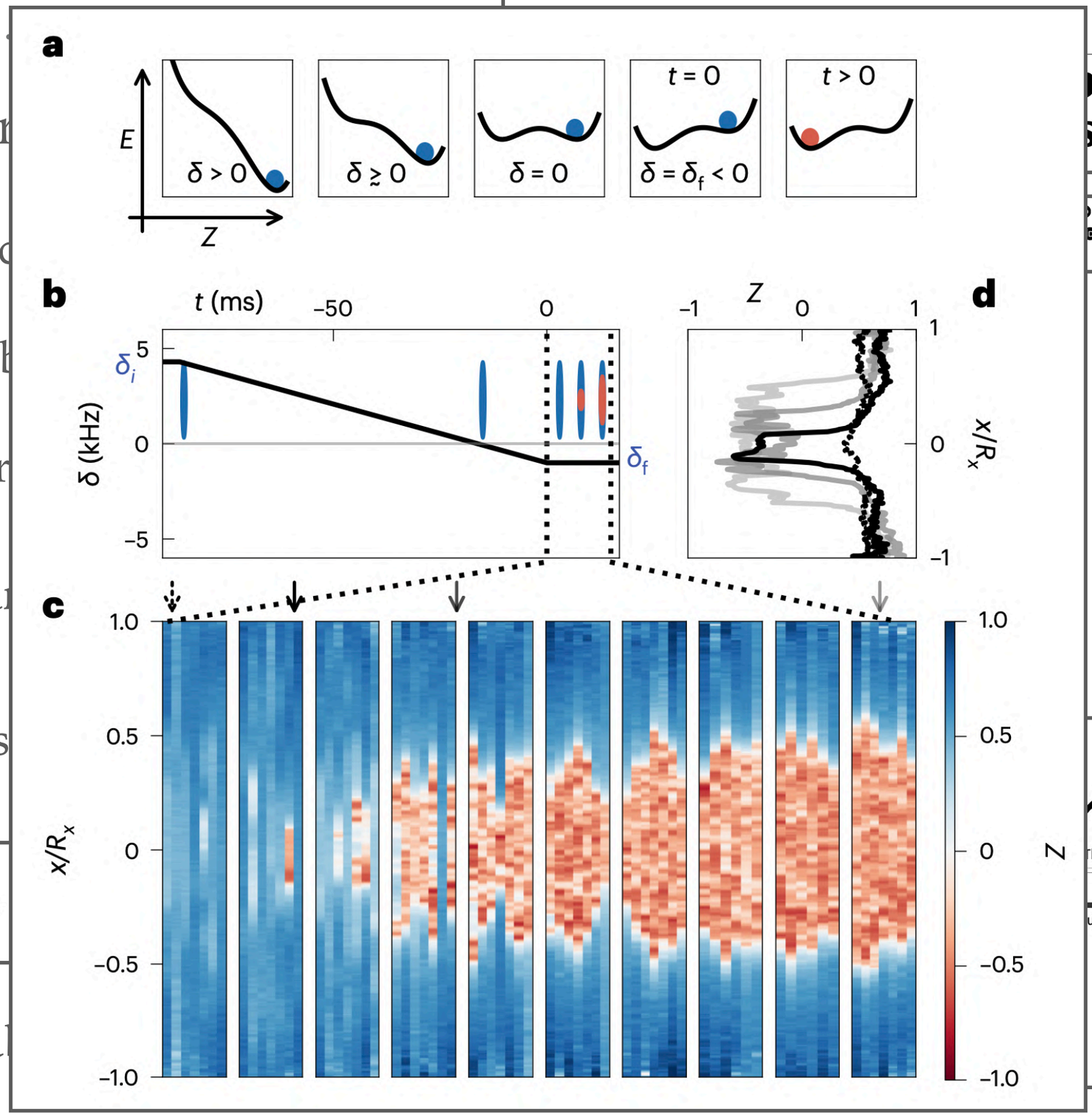
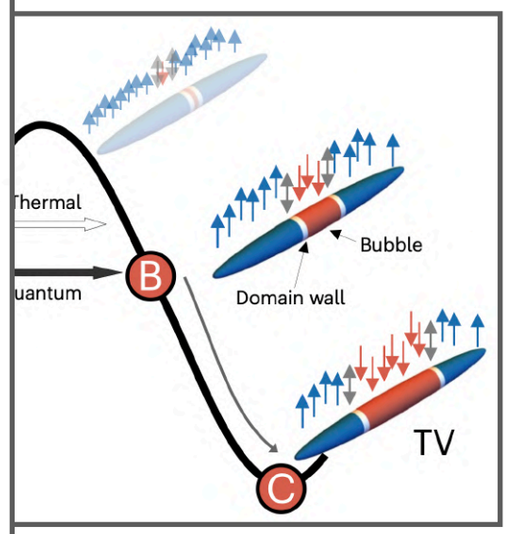
, R. Cominotti, C. Rogora, I. G. Moss, , G. Lamporesi, A. Recati &





QFT TUNNELING IN LAB

- Subsequent/other progress

  - Observation of finite-temperature effects →

    [Cominotti et al., PRL, 2504.03528]

  - Proposal for using Rydberg atoms

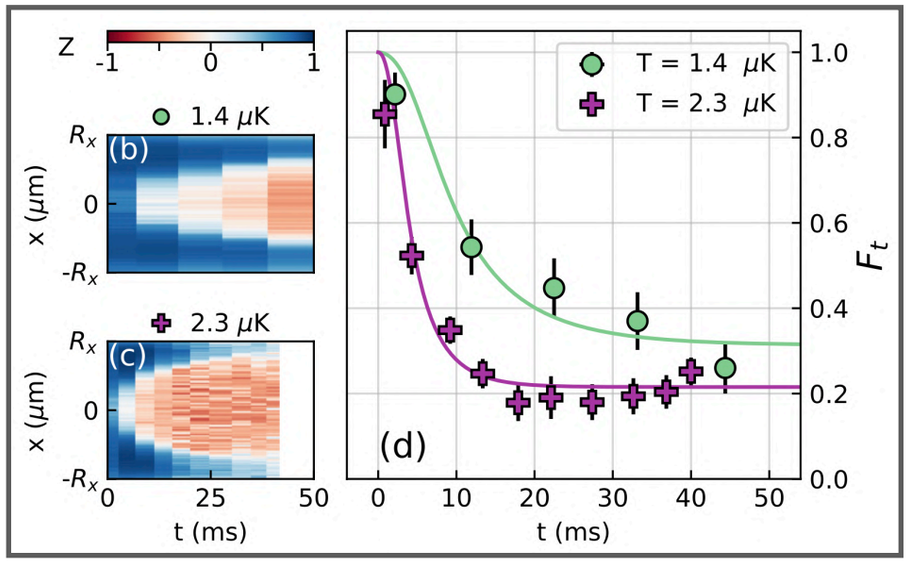
    [Darbha et al., PRB, 2404.12360] [Chao et al., 2512.04637] [Borla et al., 2601.04305]

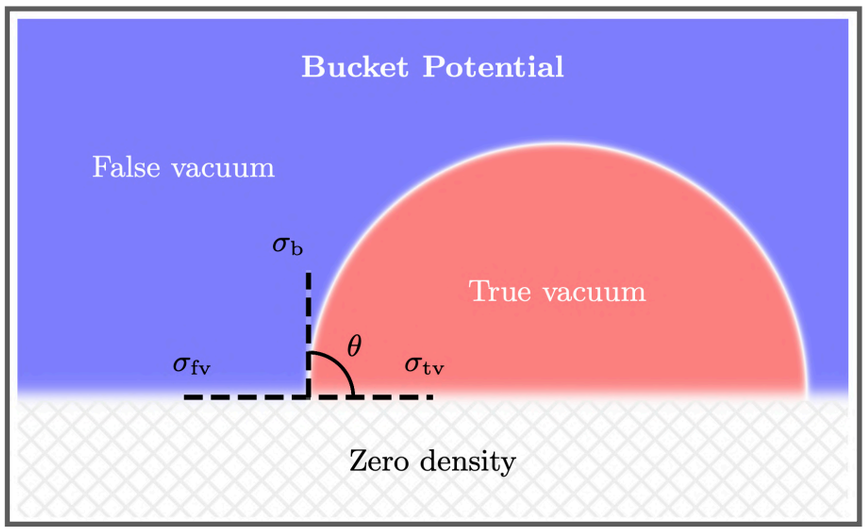
  - Proposal for using annealing ↘

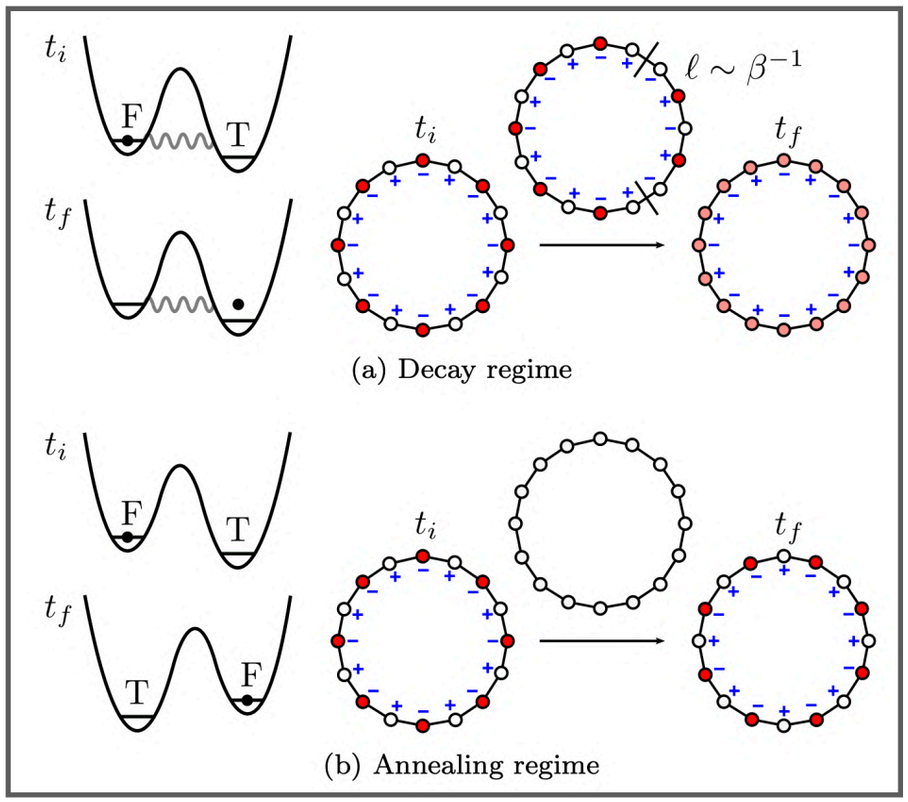
    [Darbha et al., PRB, 2404.12360]

  - Importance of boundary effects ↓

    [Jenkins, Peiris, Pontzen, 2504.02829]







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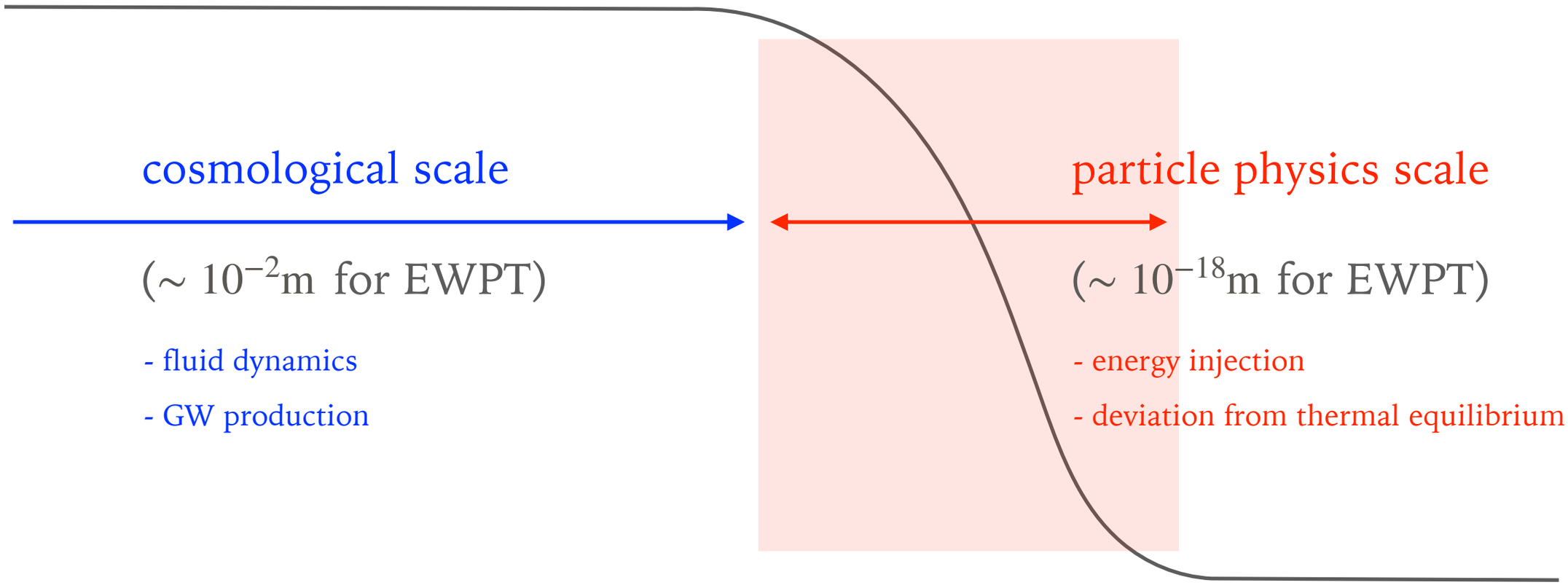
HIERARCHY IN SCALES AND THE HIGGSLESS SCHEME

[RJ, Konstandin, Rubira, JCAP, 2010.00971] [+Stomberg, JCAP, 2209.04369] [+Caprini, +Roper Pol, +Stomberg, JHEP, 2409.04651]

- Hierarchy in scales in the present system



- To simulate the macroscopic dynamics, we may regard the Higgs wall as non-dynamical energy-injecting boundary: ***Higgsless scheme***

  (i.e. we can "integrate out" the Higgs)

RECIPE FOR HIGGSLESS SIMULATION

- 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 the energy injection

  ① Assume relativistic perfect fluid (for simplicity), $T^{\mu\nu} = w u^\mu u^\nu - g^{\mu\nu} p$

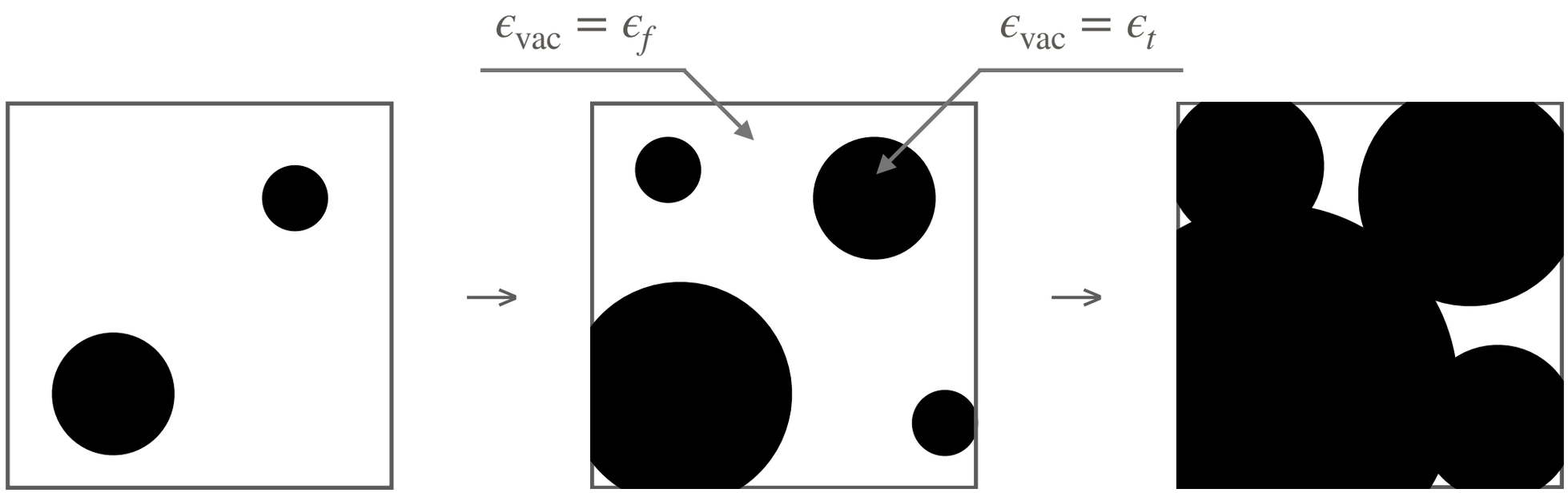
  ② Define $K^\mu \equiv T^{\mu 0}$, then $\partial_\mu T^{\mu\nu} = 0$ reduces to $\begin{cases} \partial_0 K^0 + \partial_i K^i = 0 \\ \partial_0 K^i + \partial_j T^{ij}(K^0, K^i) = 0 \end{cases}$

  ③ Where does the energy injection enter? Answer: 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 HIGGSLESS SIMULATION

- We first determine the evolution of the false-true boundary from nucleation points generated numerically



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

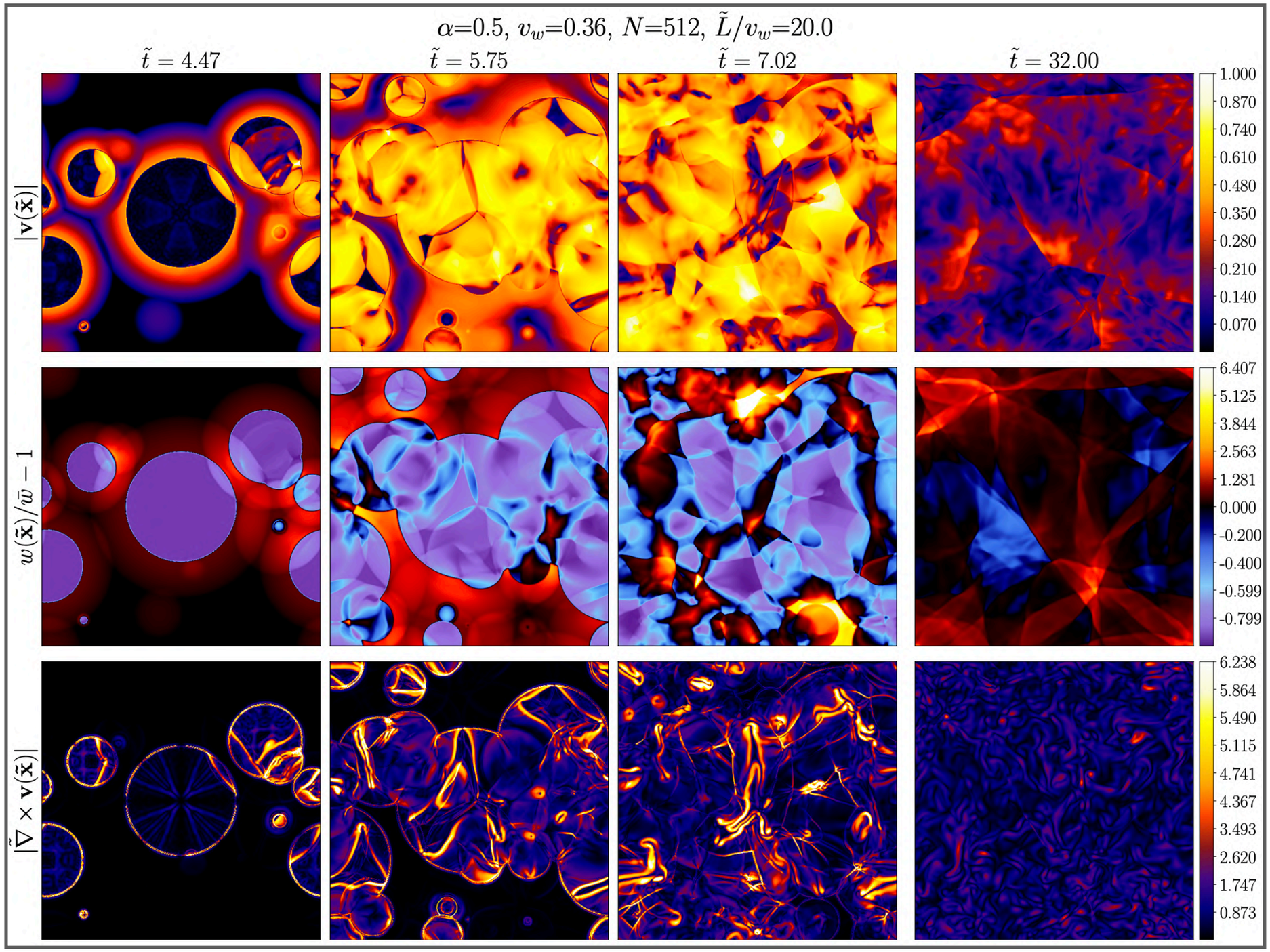
  → Fluid automatically develops a profile

HIGGSLESS SIMULATION: TYPICAL TIME EVOLUTION

fluid velocity

enthalpy

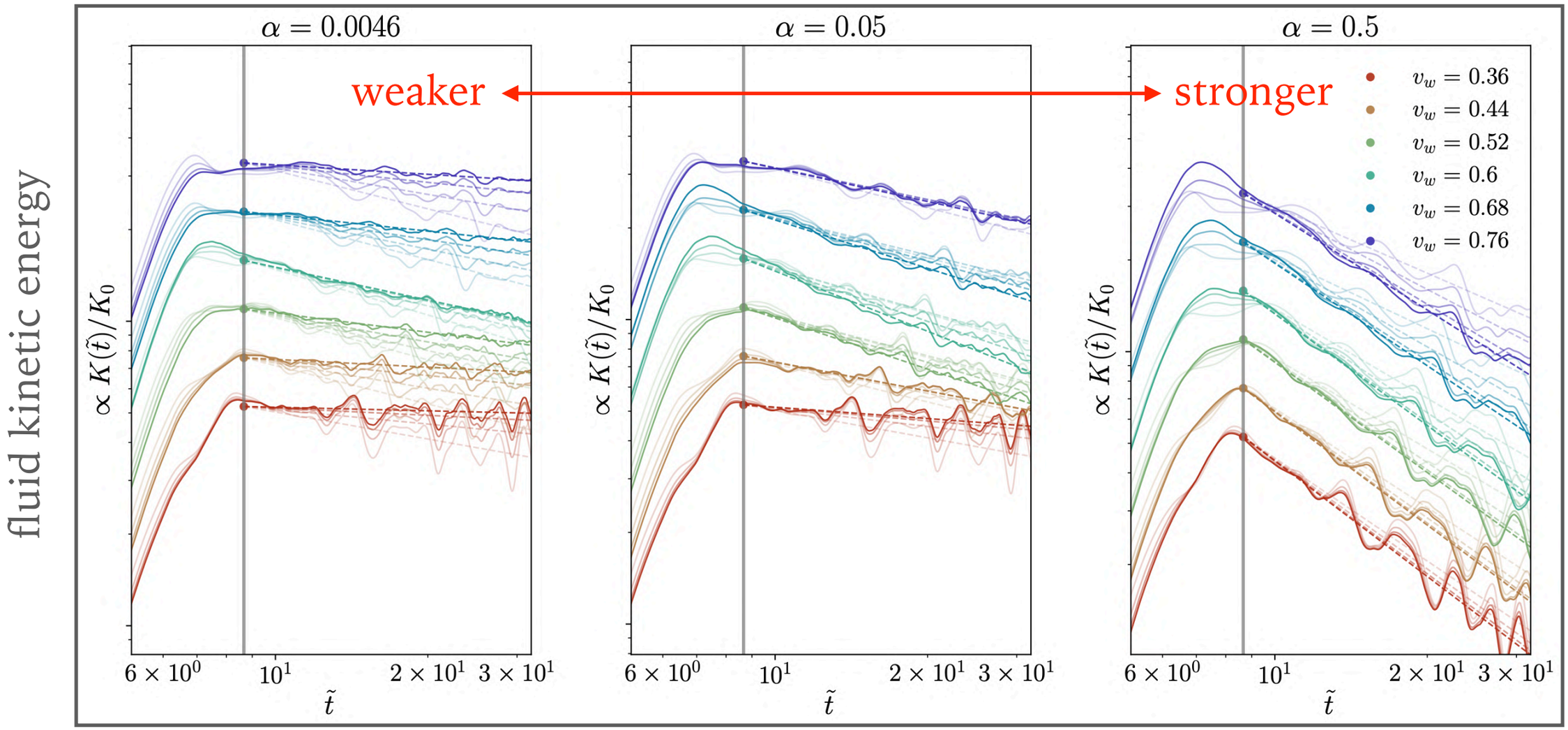
vorticity



[Caprini, RJ, Konstandin, Roper Pol, Rubira, Stomberg, JHEP, 2409.04651]

HIGGSLESS SIMULATION: DECAY OF KINETIC ENERGY

- Fluid kinetic energy decays faster for stronger transitions

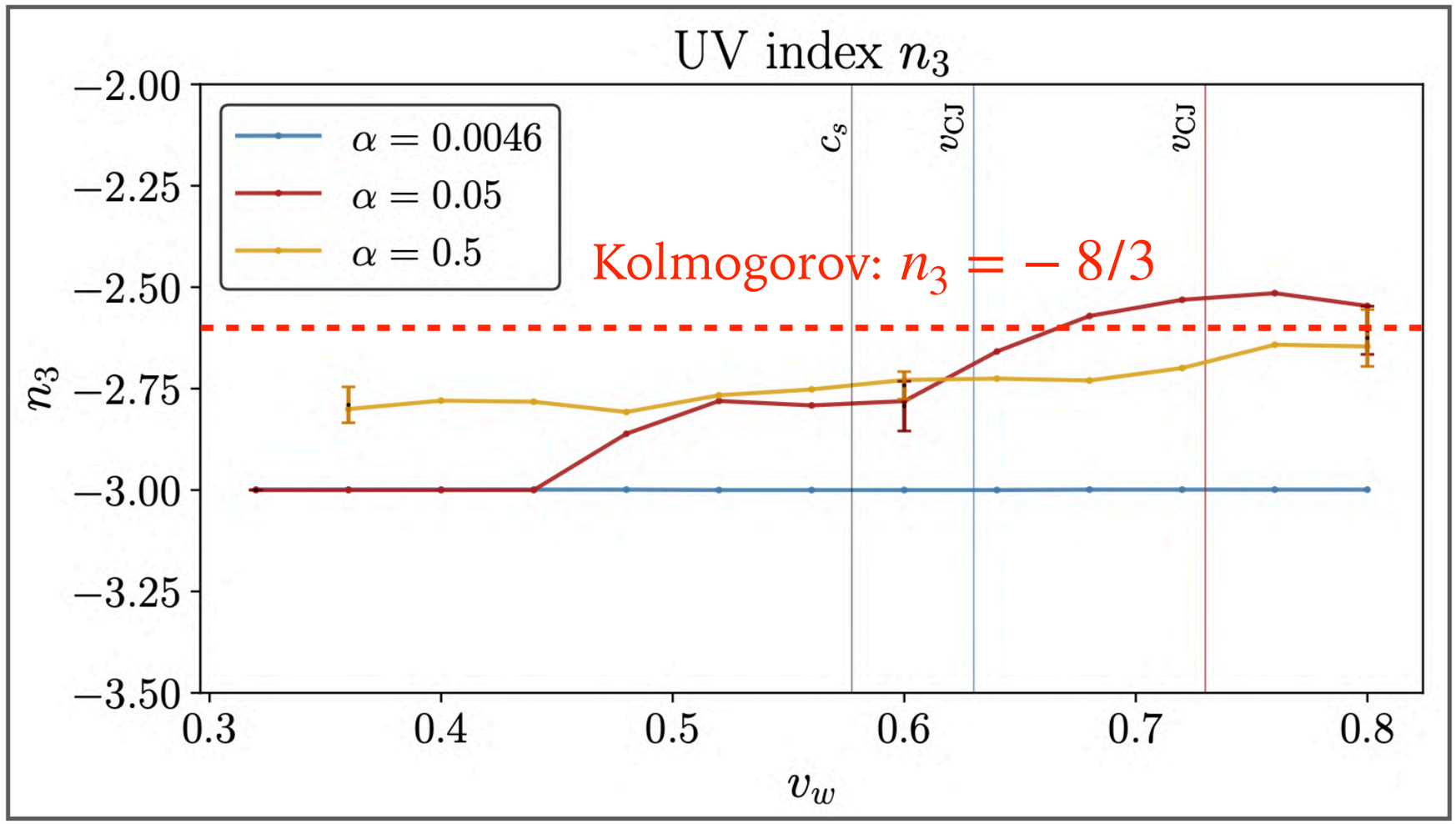


[Caprini, RJ, Konstandin, Roper Pol, Rubira, Stomberg, JHEP, 2409.04651]

- Based on these simulations, we report the resulting GW spectrum

HIGGSLESS SIMULATION: ONSET OF TURBULENCE

- We almost observe the onset of turbulence



[Caprini, RJ, Konstandin, Roper Pol, Rubira, Stomberg, JHEP, 2409.04651]

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3. Summary

IMPORTANCE OF PARTICLE SPLITTING

- Particle splitting is important for phenomenology of FOPT

heavy particle prod. ×

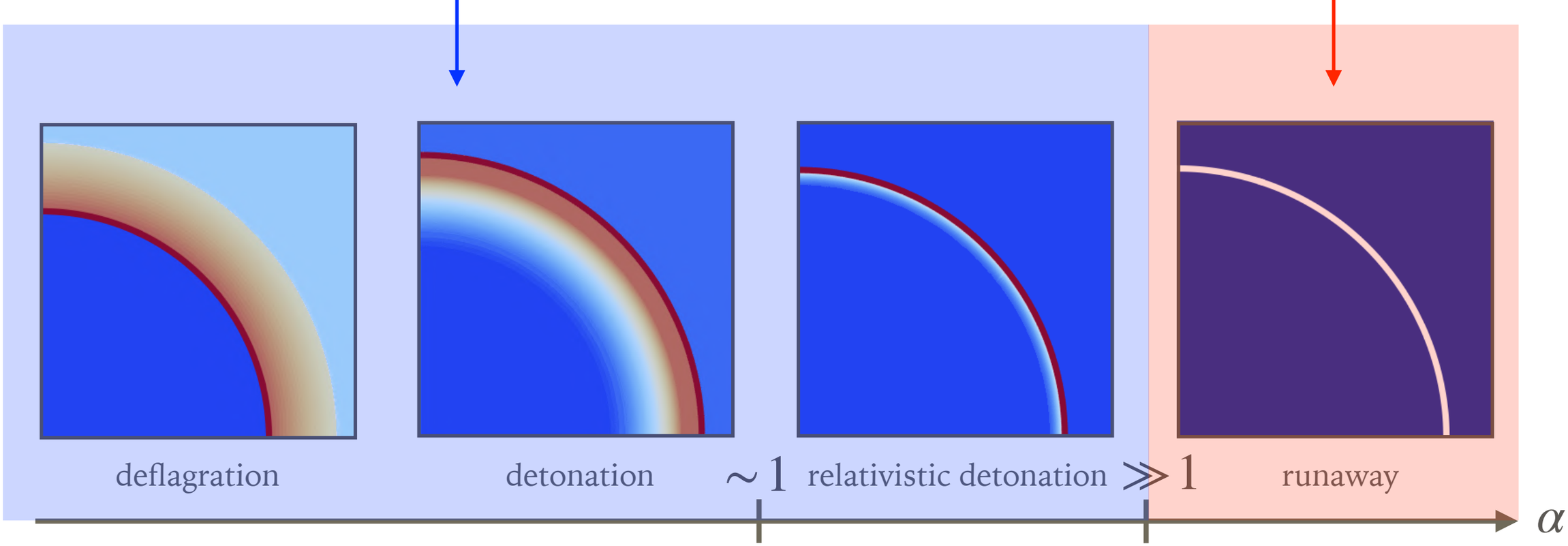
Terminal velocity

main energy carrier = fluid

heavy particle prod. ◯

Runaway

main energy carrier = scalar field



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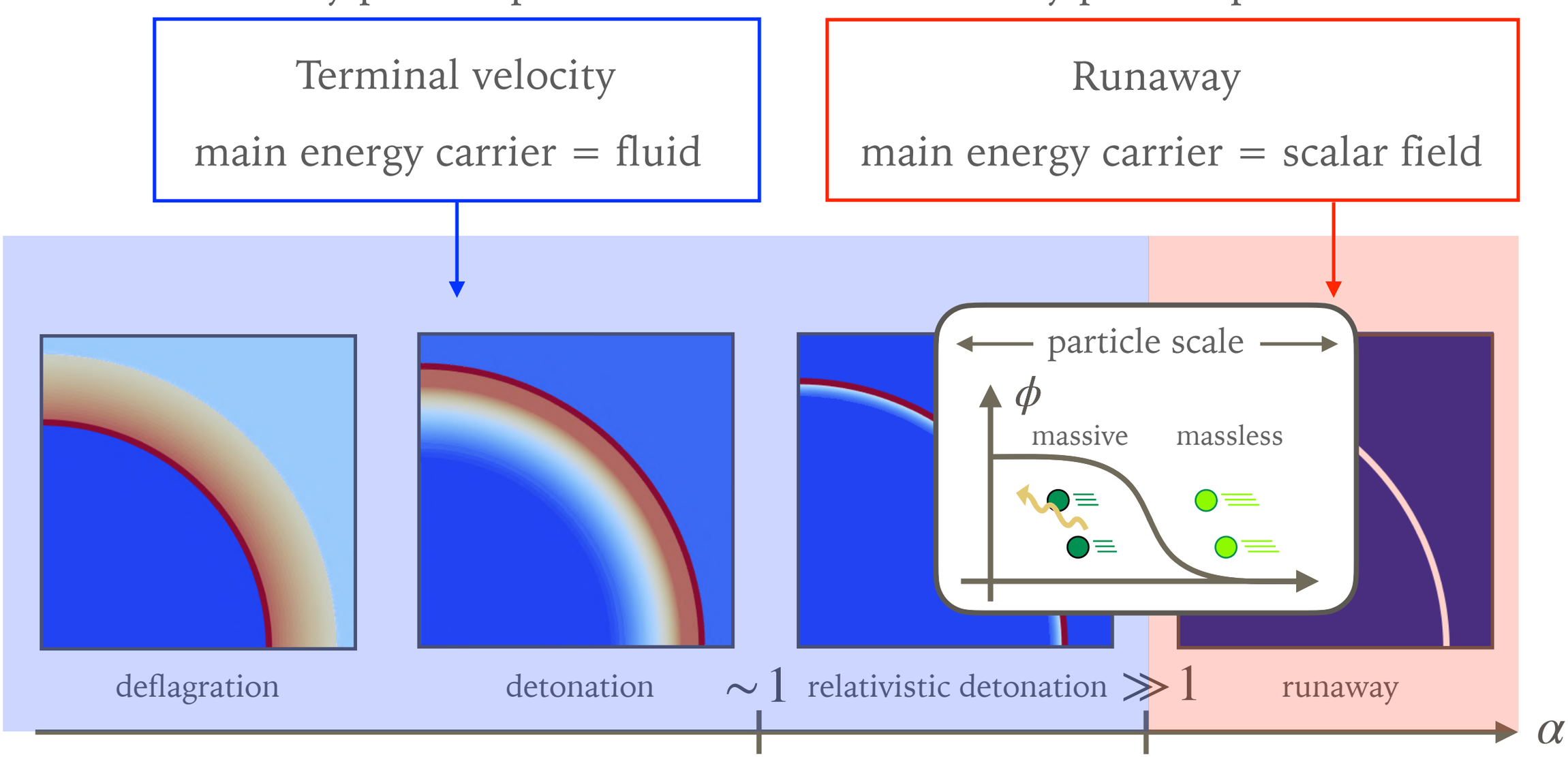
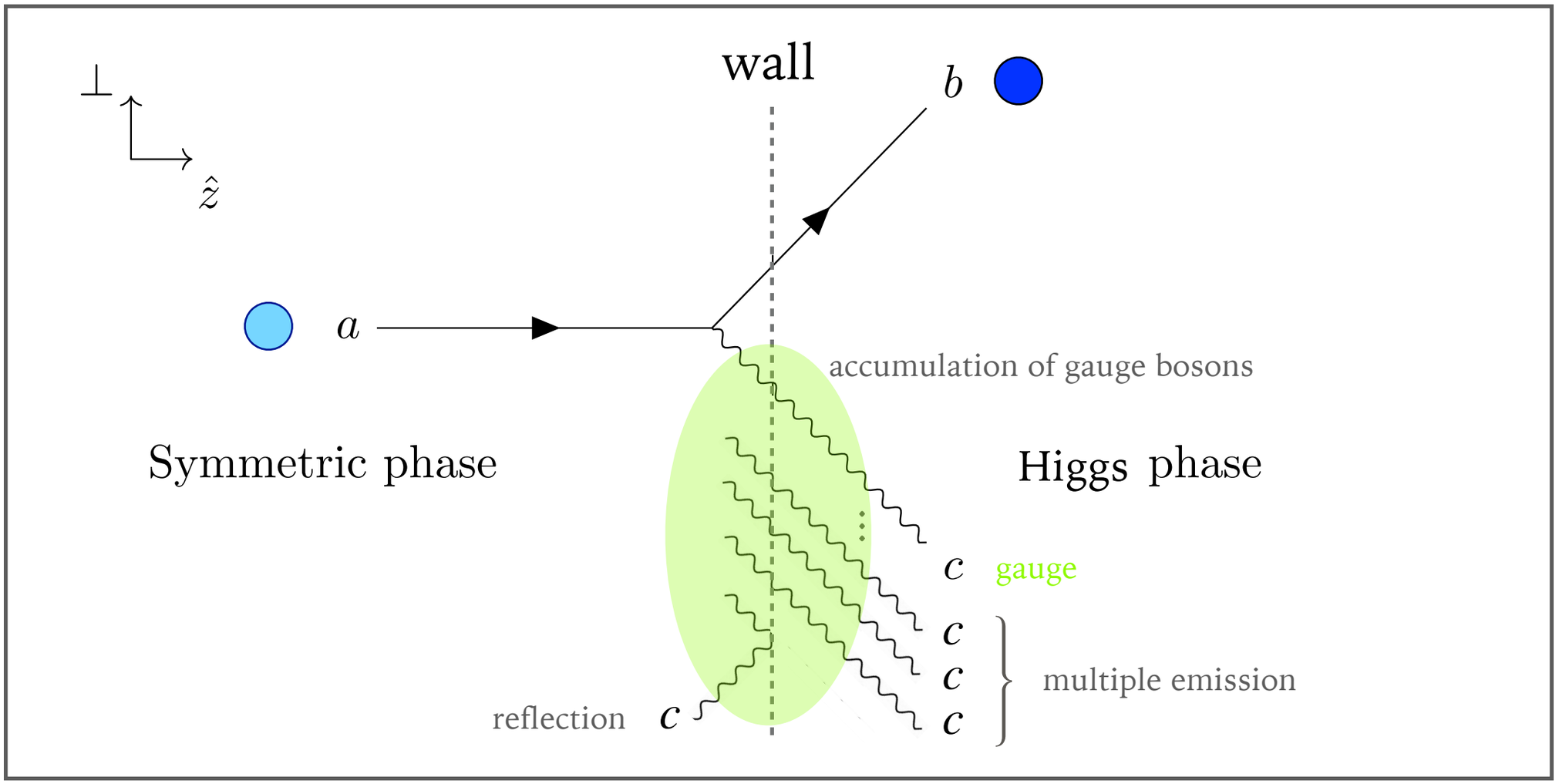


PARTICLE SPLITTING PROCESS

[Bodeker, Moore, JCAP, 1703.08215]
[Gouttenoire, RJ, Sala, JHEP, 2112.07686]

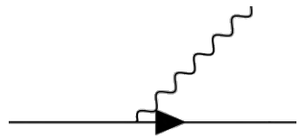


1) Momentum transfer from a particle to the wall, as a result of c emission: Δp

2) Averaged momentum transfer per each a particle impinging: $\langle \Delta p \rangle$

3) Friction pressure to the wall from a particles: $\mathcal{P} = \int \frac{d^3 p_a}{(2\pi)^3} f(p_a) \langle \Delta p \rangle \sim \gamma T_{\rm nuc}^3 \langle \Delta p \rangle$

MATRIX ELEMENT FOR SINGLE SPLITTING



[Bodeker, Moore, JCAP, 1703.08215] [Gouttenoire, RJ, Sala, JHEP, 2112.07686]

➤ Effect of Lorentz violation

- In Lorentz-conserving background, z-integration returns δ function

$$\int dz\ \chi_a(z)\,\chi_b^*(z)\,\chi_c^*(z) = \int dz\ e^{ip_{az}z}e^{-ip_{bz}z}e^{-ip_{cz}z} \sim \delta(\Sigma p_z)$$

- In the present case, the wall breaks z-translation

$$\mathscr{M} \sim \int dz\ V(z)\,\chi_a(z)\,\chi_b^*(z)\,\chi_c^*(z) \sim \int dz\ V(z)\ e^{ip_{az}(z)z}e^{-ip_{bz}(z)z}e^{-ip_{cz}(z)z}$$

giving rise to a nontrivial matrix element from the "mismatch" across the two phases

$$\mathscr{M} \sim 2iE_a\left(\frac{V_{\rm broken}}{A_{\rm broken}} - \frac{V_{\rm sym}}{A_{\rm sym}}\right)$$

which leads to the splitting probability that has soft-collinear divergence

collinear soft

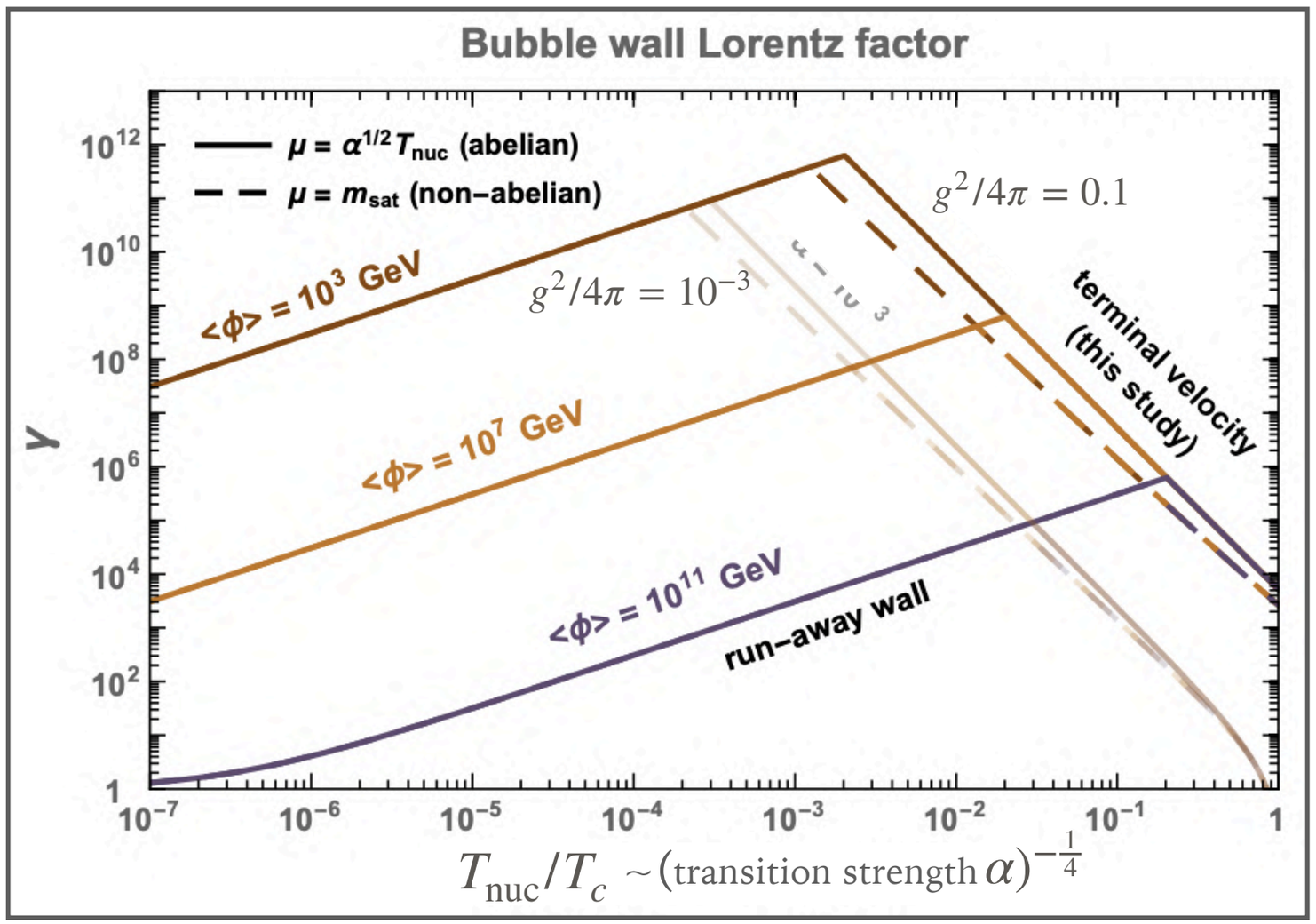
$$dP_{a\to bc} \simeq \frac{g^2}{4\pi^2}\frac{dk_\perp^2}{k_\perp^2}\frac{dx}{x}\left(\frac{k_\perp^2}{k_\perp^2+m_{c,\rm sym}^2}\right)^2\left(\frac{m_{c,\rm broken}^2-m_{c,\rm broken}^2}{k_\perp^2+m_{c,\rm broken}^2}\right)^2$$

BUBBLE LORENTZ FACTOR AT THE COLLISION TIME

[Gouttenoire, RJ, Sala, JHEP, 2112.07686]

- After Sudakov resummation etc., we get the splitting probability
- Then we can identify the parameter space for terminal-velocity and runaway

runaway



terminal velocity

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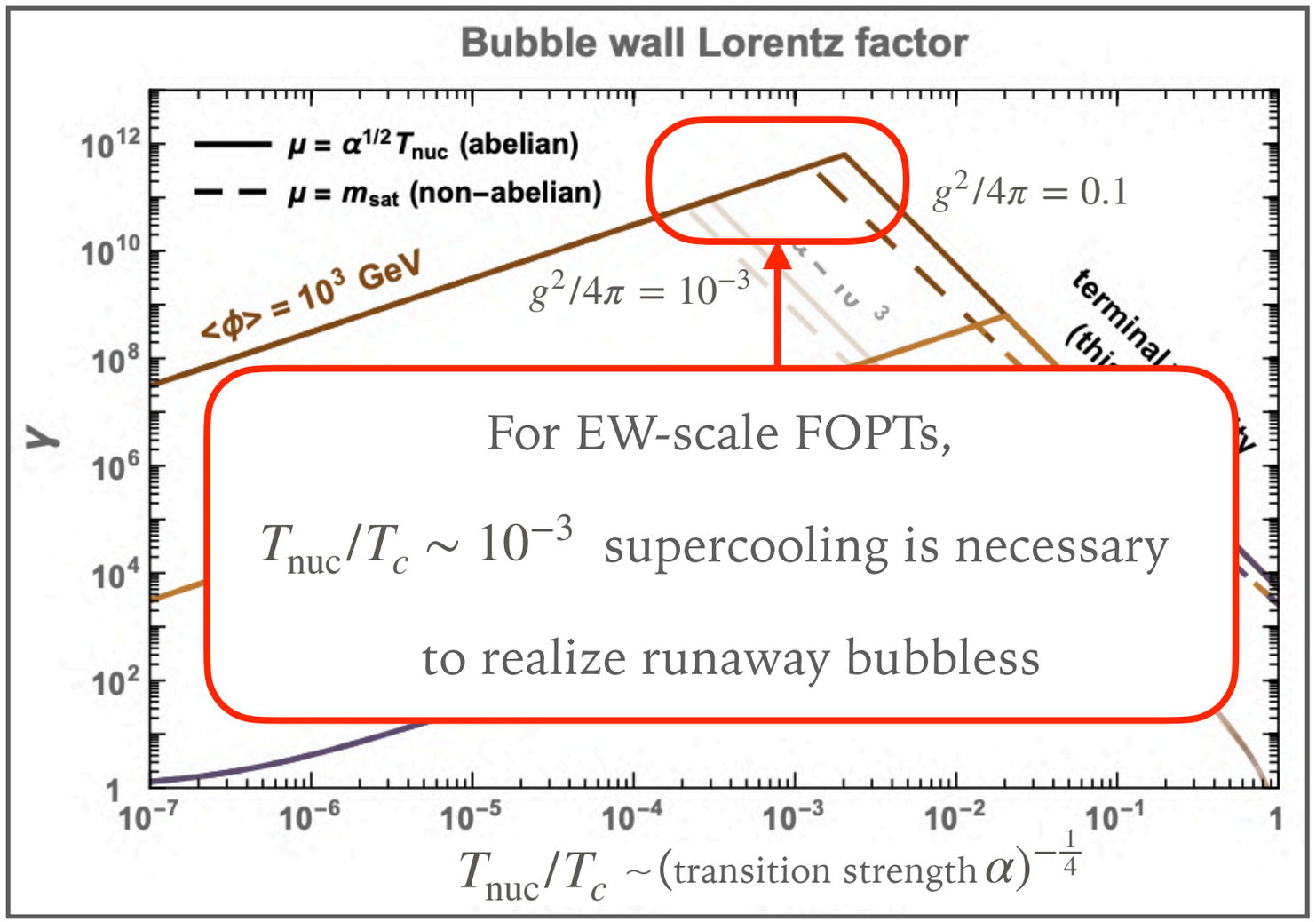

For EW-scale FOPTs,

$T_{\rm nuc}/T_c \sim 10^{-3}$ supercooling is necessary

to realize runaway bubbless

terminal velocity

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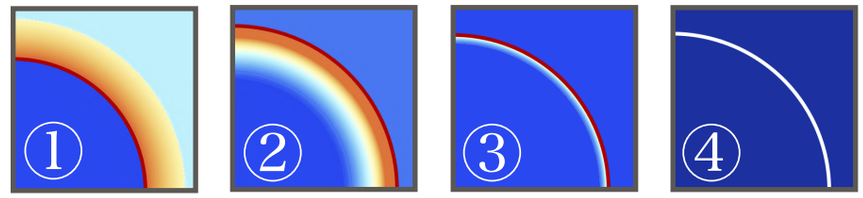
GW PRODUCTION: THE STANDARD LORE & BEYOND

- GW sources



Bubble walls (dominant in case ④)

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

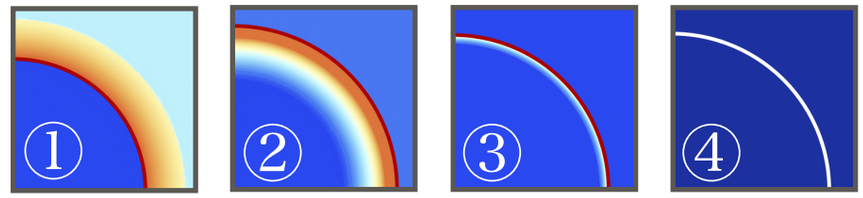
Fluid (dominant in case ①②③) = Sound waves & Turbulence

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



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.

Feebly-interacting particles

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

Bubble wall

Broken phase

$m_X \neq 0$

Enters the bubble and become massive if $E_X > m_X$

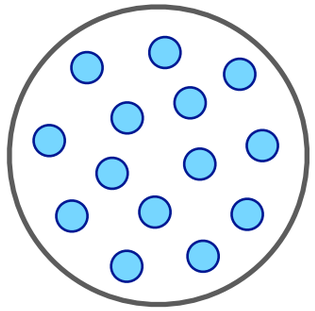
X, or its decay product Y, behaves as feebly-interacting particles

Symmetric phase

$m_X = 0$

$E_X \sim \gamma_w T$

$(\gamma_w \lesssim 10)$



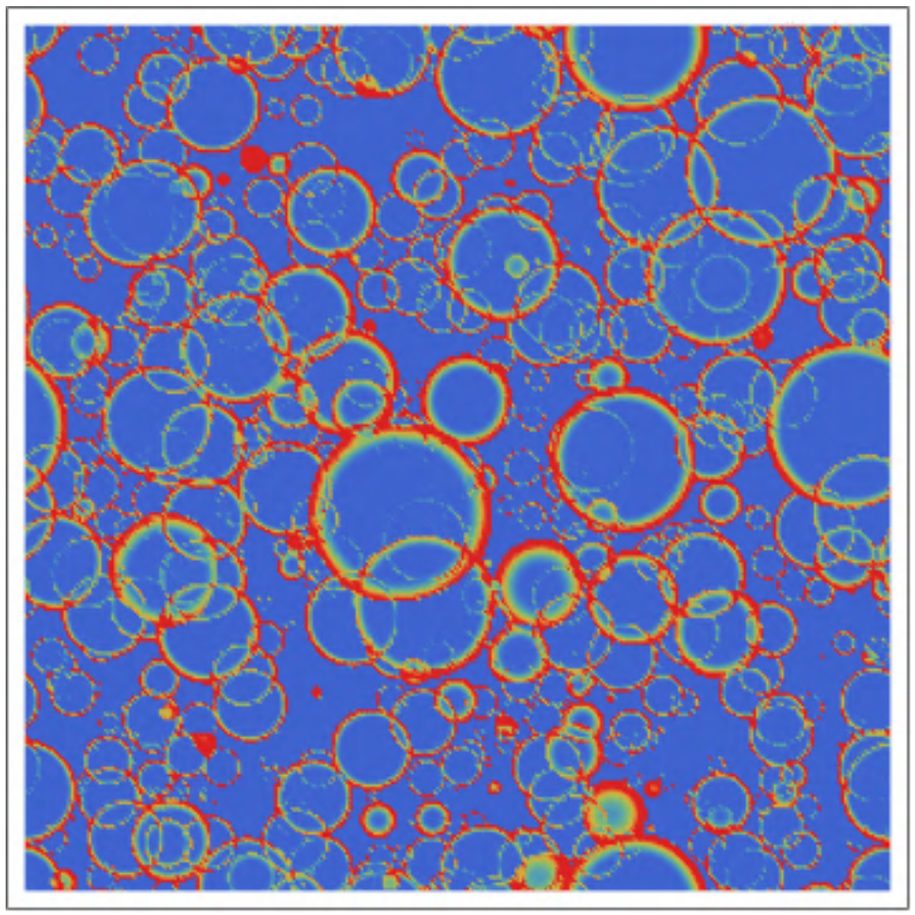
Temperature T

Moving with bulk velocity v_w

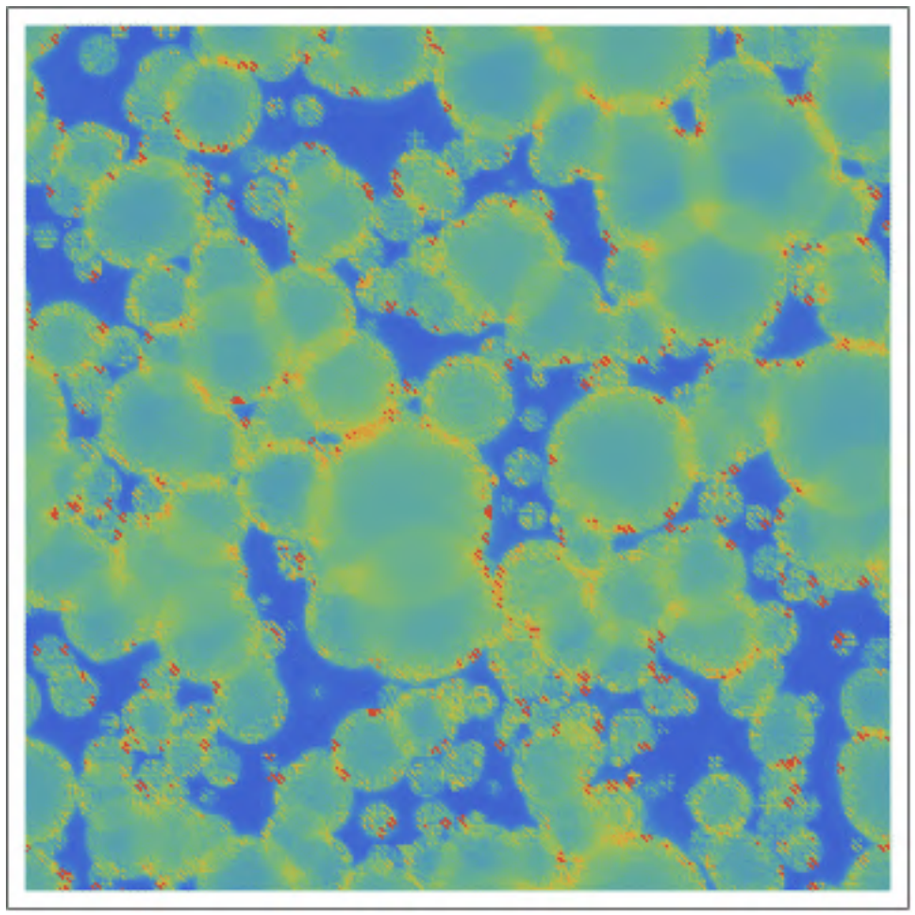
FLUID VS. FREE-STREAMING PARTICLES

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

Fluid



Free-streaming

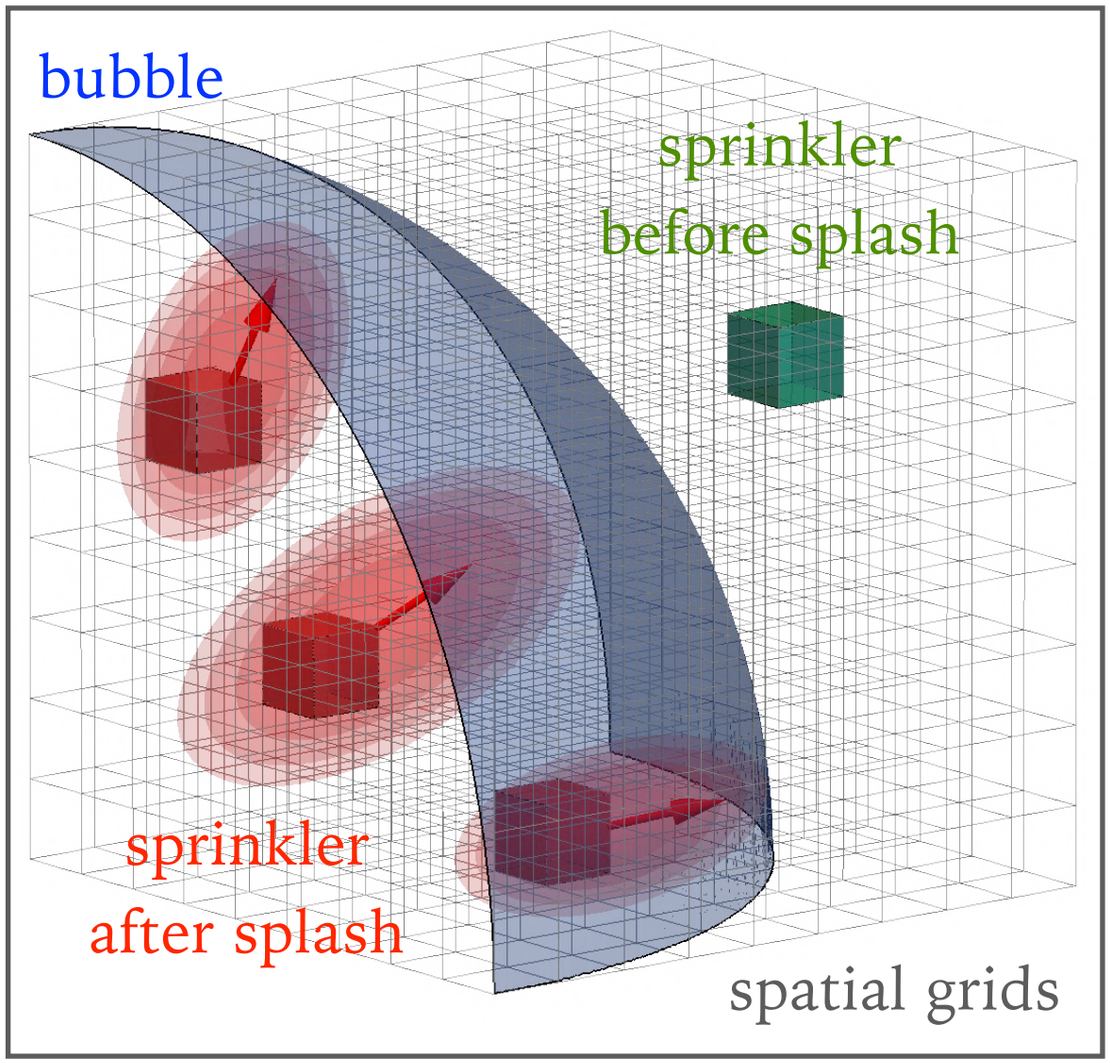


HOW TO CALCULATE GW PRODUCTION

[RJ, Shakya, van de Vis, PRL(accepted), 2211.06405]

- To calculate the GW spectrum,

  we propose a new calculation scheme – "sprinkler picture"

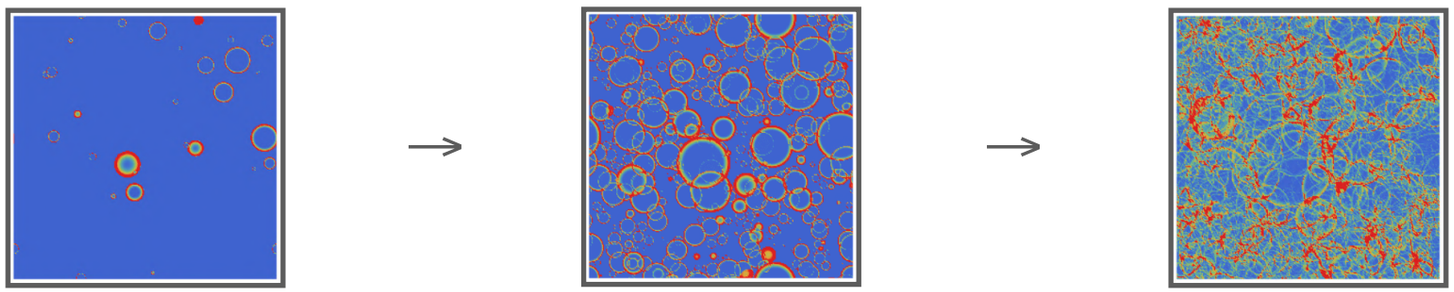


GW SPECTRUM FOR SOUND-WAVE SOURCE

[RJ, Shakya, van de Vis, PRL(accepted), 2211.06405]

➤ How to calculate the GW spectrum from fluid dynamics

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

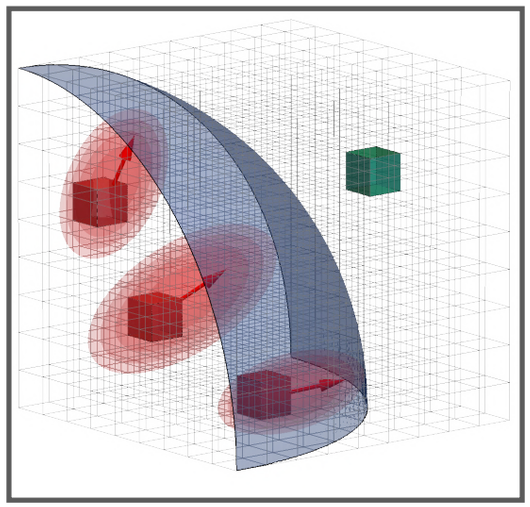
[RJ, Shakya, van de Vis, PRL(accepted), 2211.06405]

- 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,

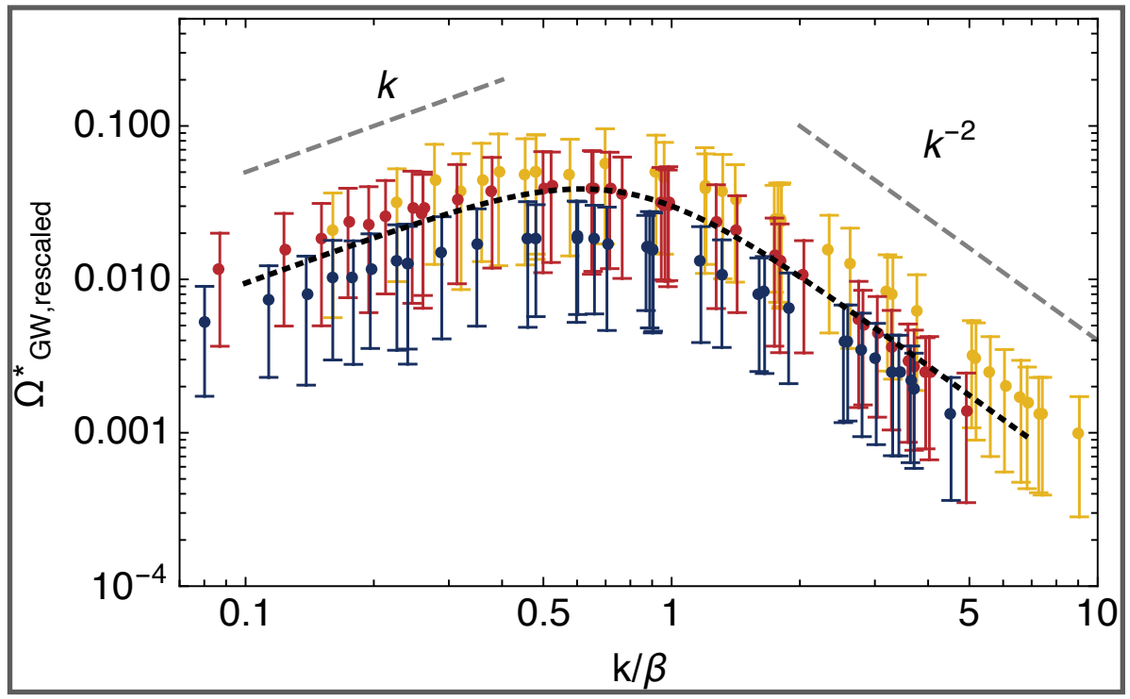
and the contributions from different sprinklers (= grids) are linearly superposed

NUMERICAL RESULTS

[RJ, Shakya, van de Vis, PRL(accepted), 2211.06405]

- GW spectral shape is universal

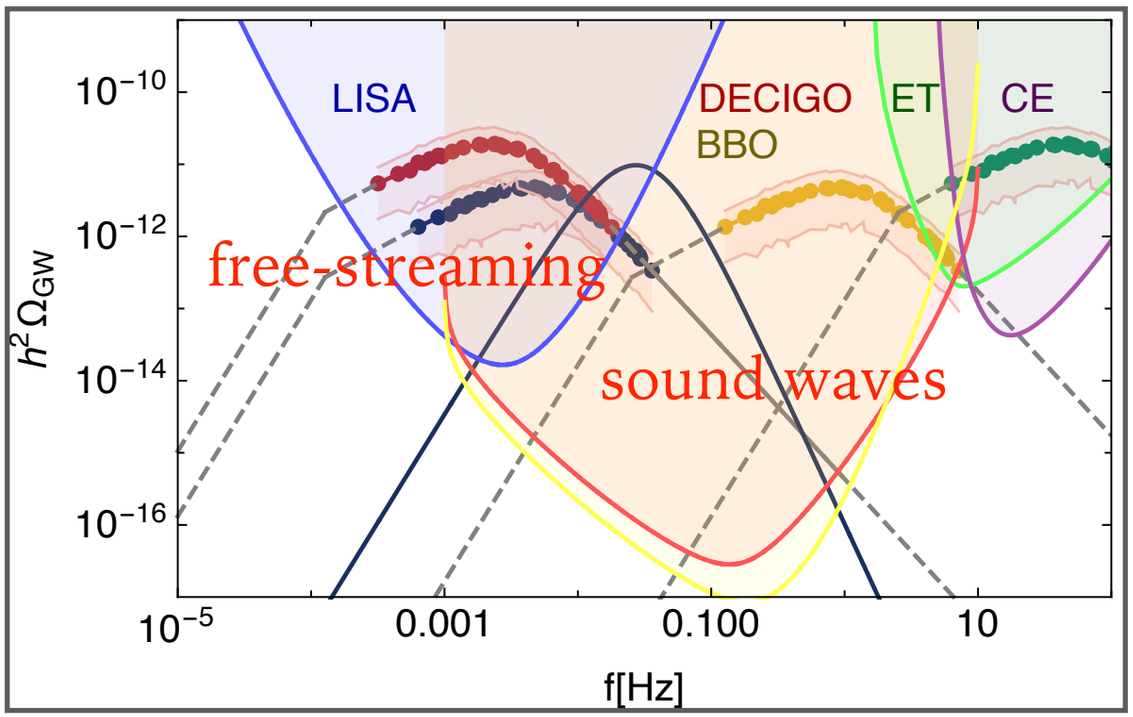
  (after normalizing by some factor)



- GW spectrum is clearly

  different from sound-wave sources:

  it stretches over wider frequencies



OUTLINE

1. FOPTs in the early Universe: review

2. Some recent theoretical/experimental progress

   2-1) LISA status

   2-2) lab. experiments for QFT tunneling

   2-3) GW simulations

   2-4) particle splitting and NLO friction

   2-5) FOPTs with topological defects/free-streaming particles

3. Summary

SUMMARY

- FOPTs in the early Universe require understanding across different scales, making them an interesting and challenging topic

- We reviewed several topics:

  1) LISA status
  2) lab. experiments for QFT tunneling
  3) GW simulations
  4) particle splitting and NLO friction
  5) FOPTs with topological defects/free-streaming particles