First-order phase transitions in the early Universe: gravitational waves, black holes, and feebly-interacting particles

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collaborators

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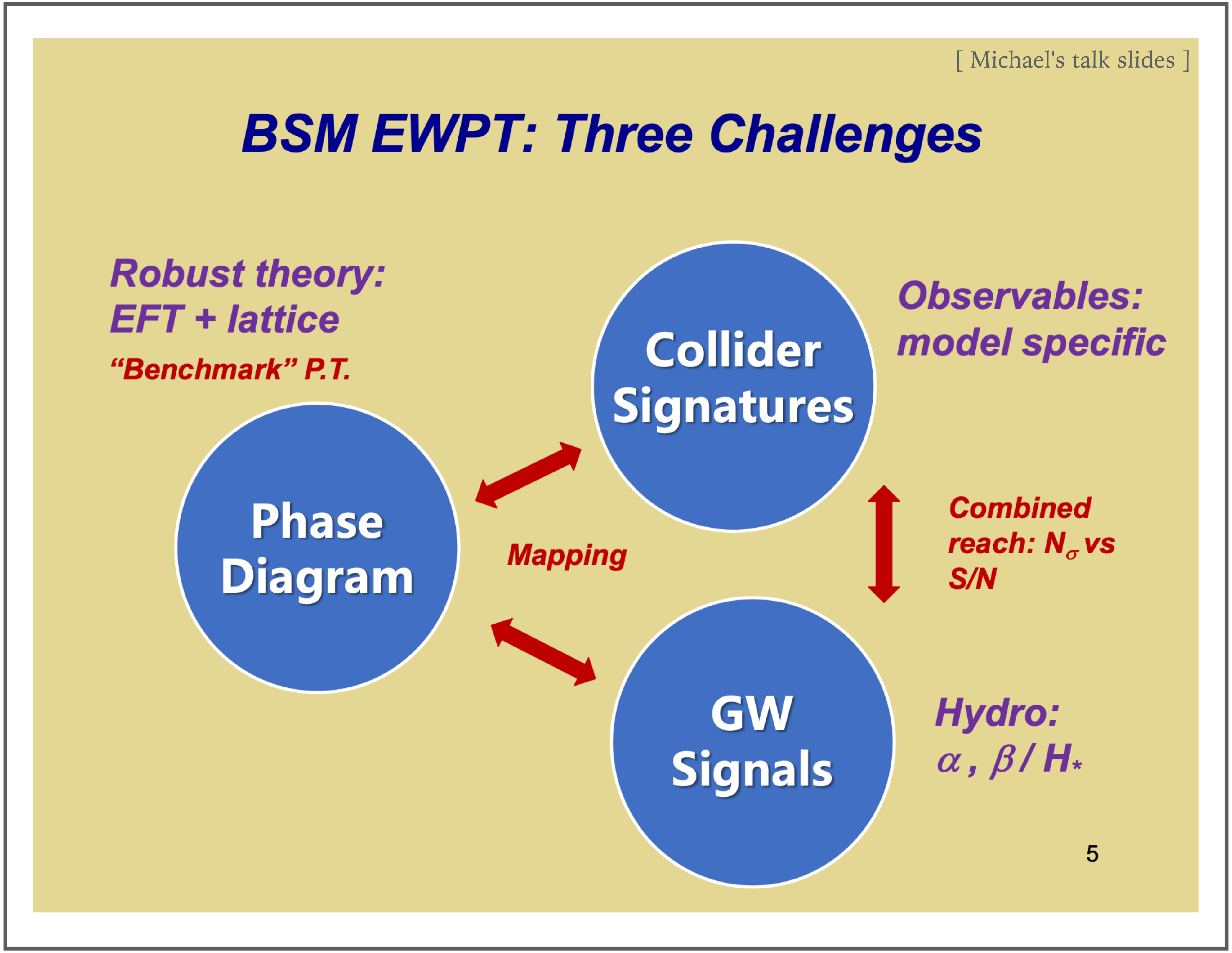
Gilly Ellor, Soubhik Kumar, Robert McGehee, Yuhsin Tsai, Gabriele Franciolini, Yann Gouttenoire
Bibhushan Shakya, Jorinde van de Vis

[Caprini, RJ, Konstandin, Roper Pol, Rubira, Stomberg JHEP07 (2025) 217, 2409.03651]
[Ellor, RJ, Kumar, McGehee, Tsai PRL 133 (2024) 21, 211003, 2311.16222] [Franciolini, RJ, Gouttenoire 2503.01962]
[RJ, Shakya, van de Vis 2211.06405]

THREE CHALLENGES FOR BSM EWPT



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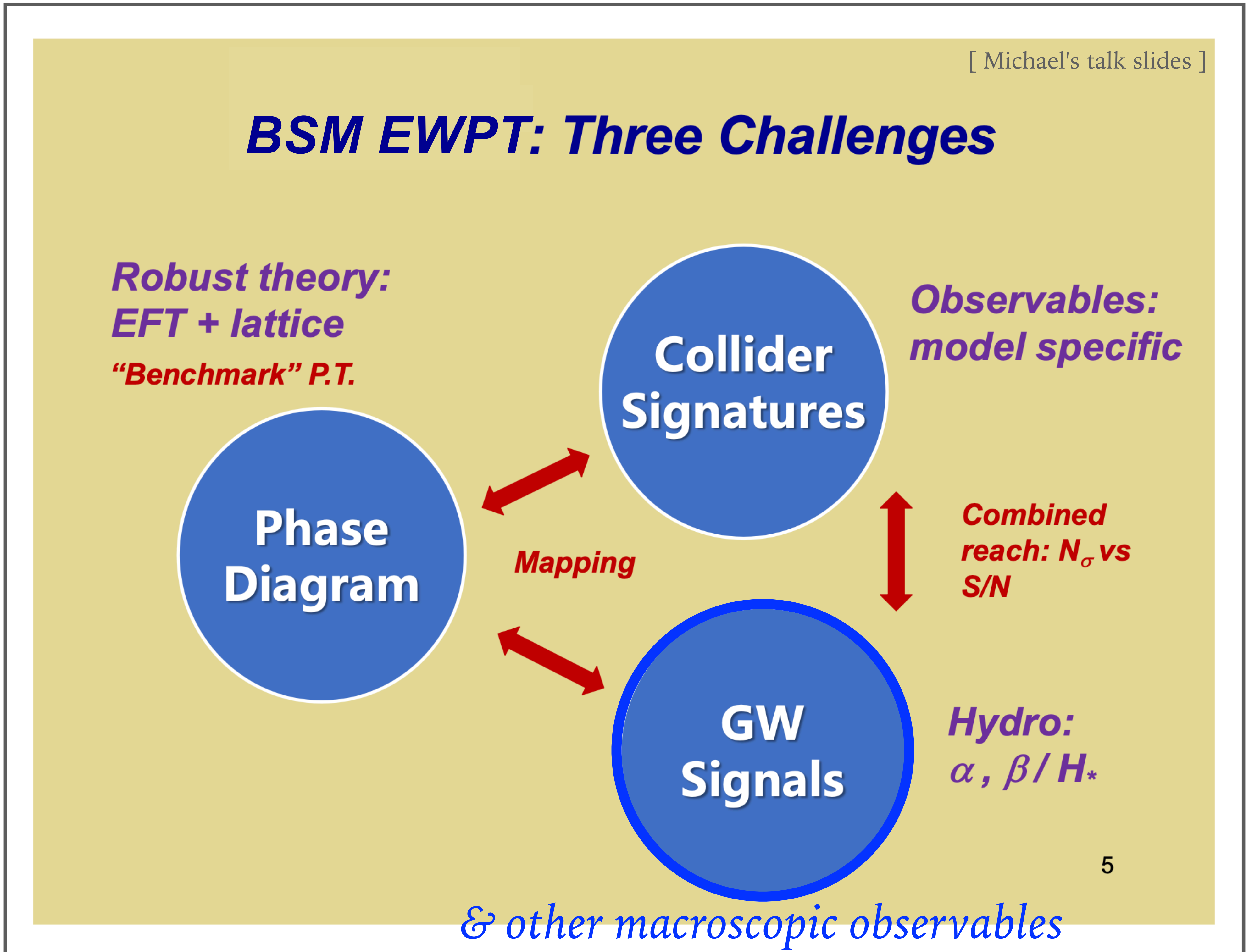
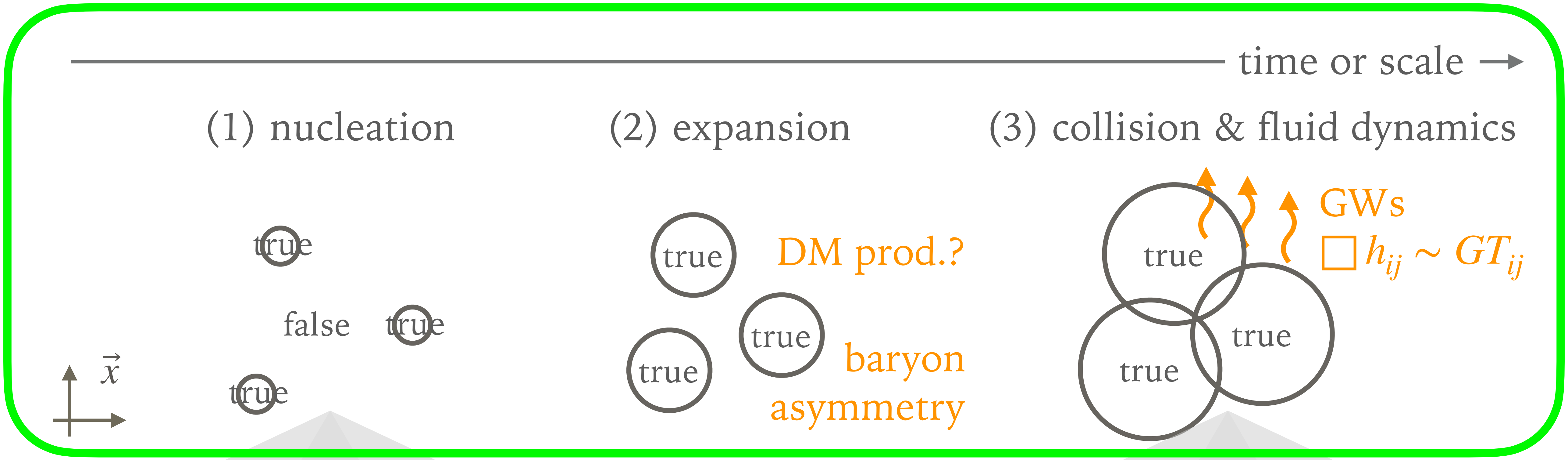
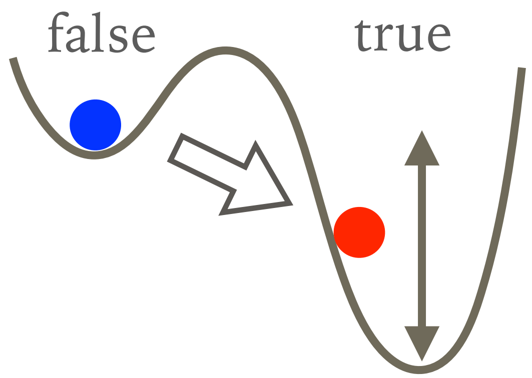


FIRST-ORDER PHASE TRANSITIONS IN THE EARLY UNIVERSE

microphysics | Dynamics of bubbles | *macrophysics*



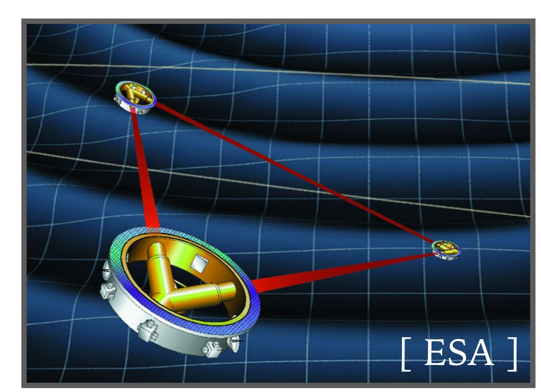
Physics of the Higgs sector



FOPTs in BSM

GWs
& macroscopic
observables

GW observations



FIRST-ORDER PHASE TRANSITION: MOTIVATIONS

- Baryon asymmetry of the Universe

  — "*Why does the Universe have more matter than antimatter?*"

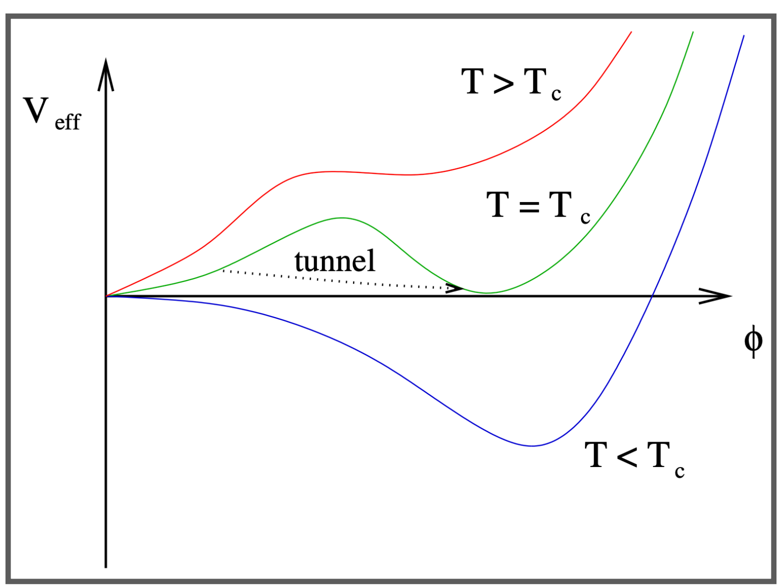
- Electroweak baryogenesis [Kuzmin, Rubakov, Shaposhnikov '85] [Morrissey & Ramsey-Musolf '12]

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

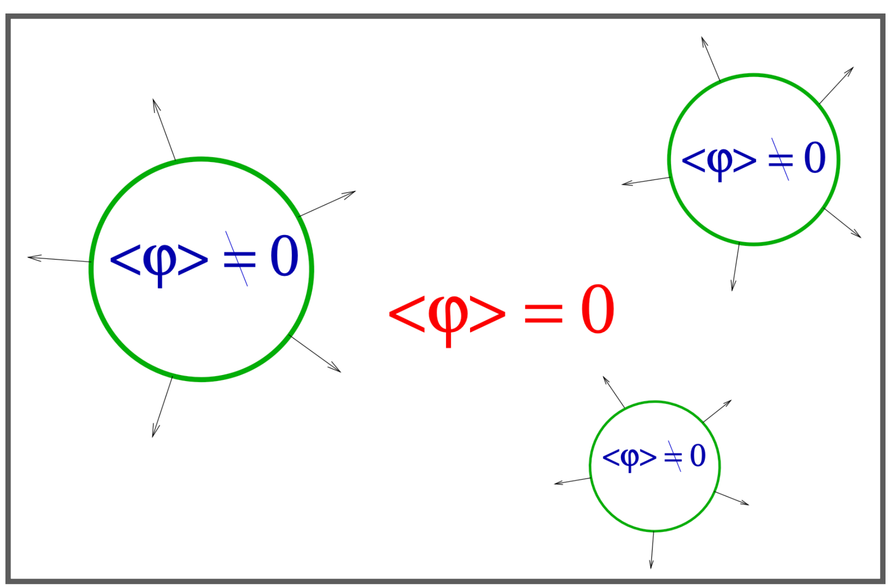
  - Provides a clear target in new particle searches and Higgs precision studies

  - Complementary test with gravitational waves?

Microphysics

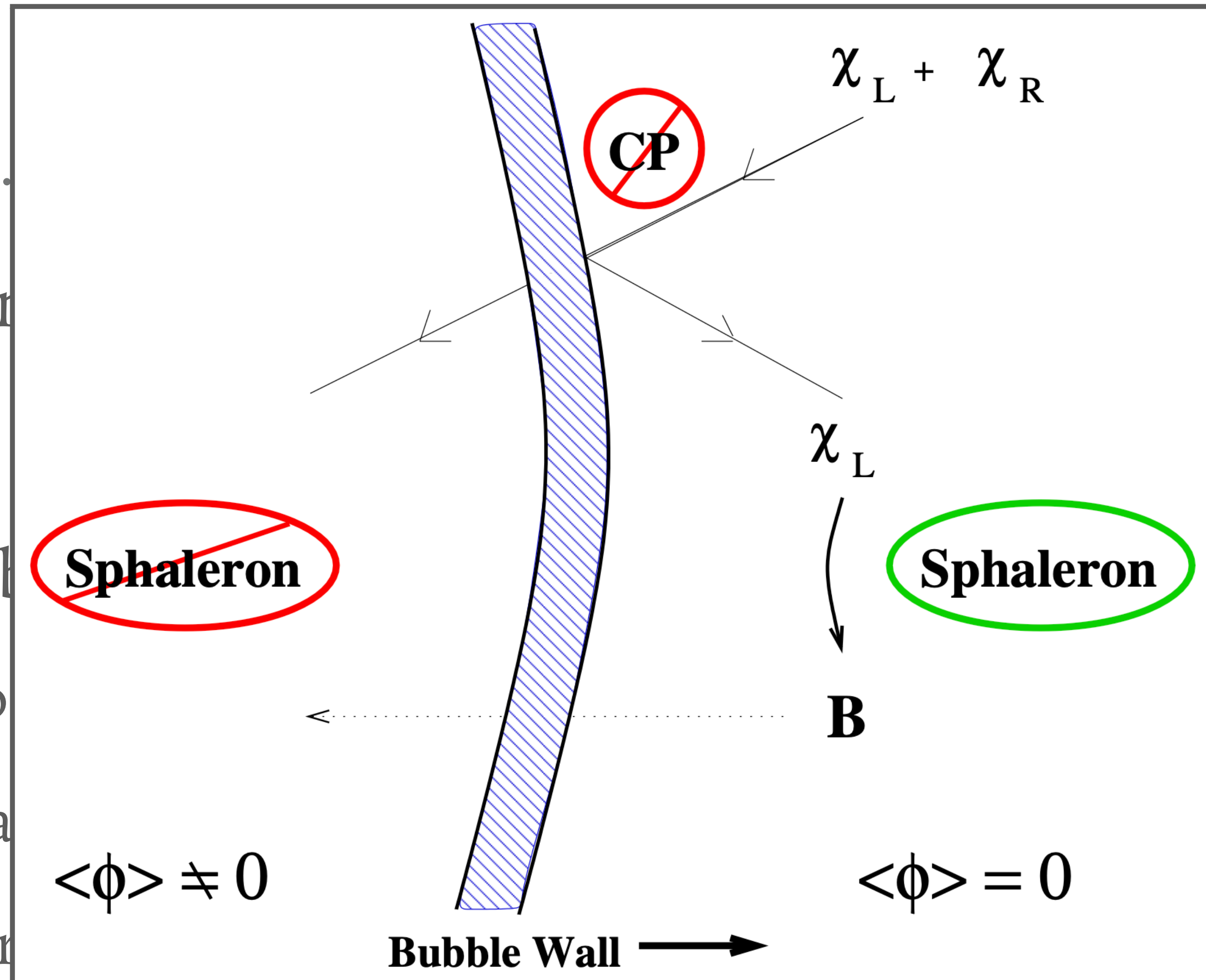


Macrophysics

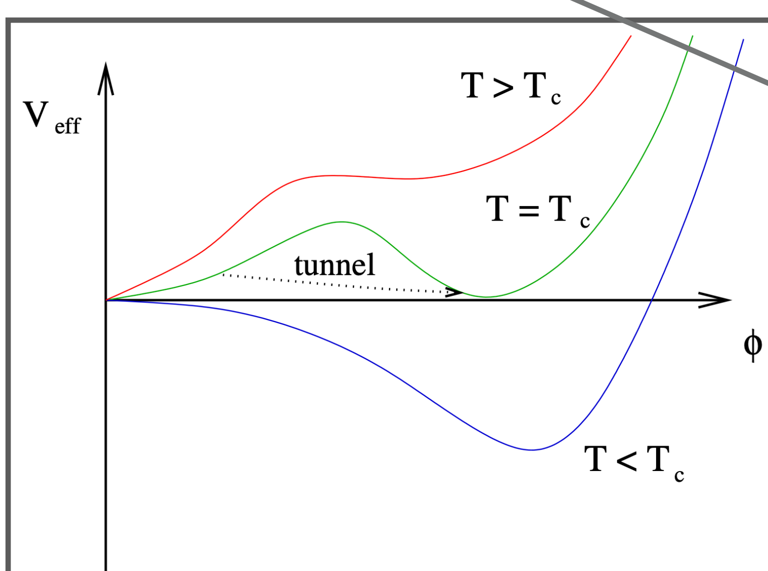


FIRST-ORDER S

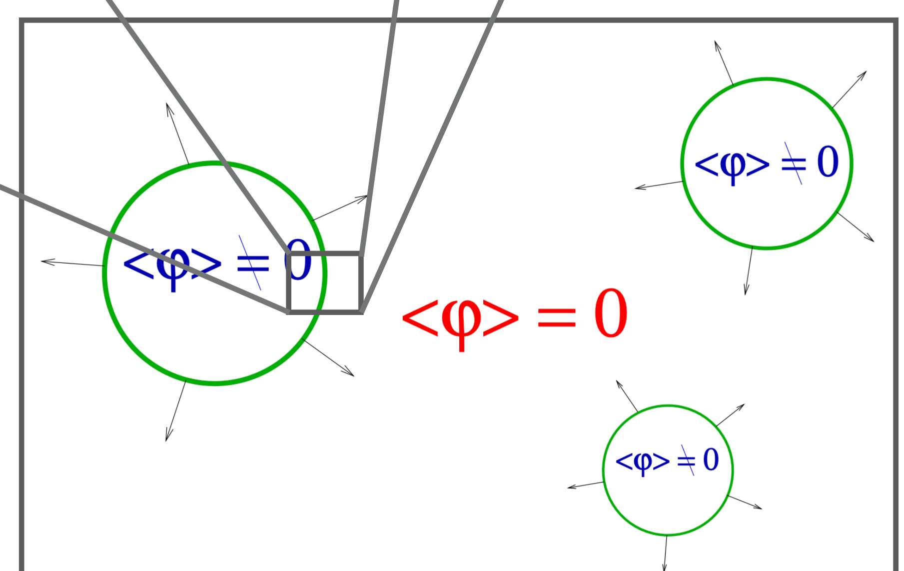
- Baryon asymm
  - — "*Why does the*
- Electroweak b & Ramsey-Musolf '12]
  - A scenario pro *by Nature*
  - Provides a clea recision studies
  - Complementar



Microphysics



Macrophysics



FIRST-ORDER PHASE TRANSITION: MOTIVATIONS

- The vast energy scales the Universe has experienced

  - From inflation $\lesssim 10^{15}\,\mathrm{GeV}$ down to $T_0 \sim 10^{-4}\,\mathrm{eV}$

- Spontaneous symmetry breaking that might have happened

  - Breaking of the GUT group G_{GUT}

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

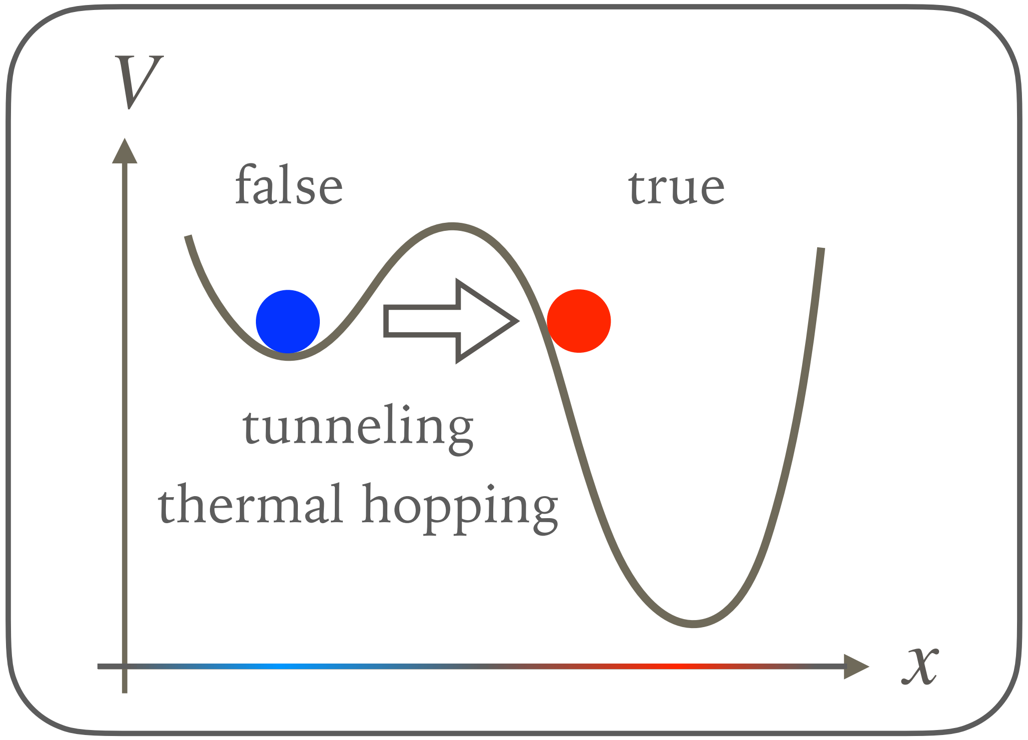
  - Breaking of B-L symmetry $U(1)_{\mathrm{B-L}}$

  - Breaking of other dark symmetries

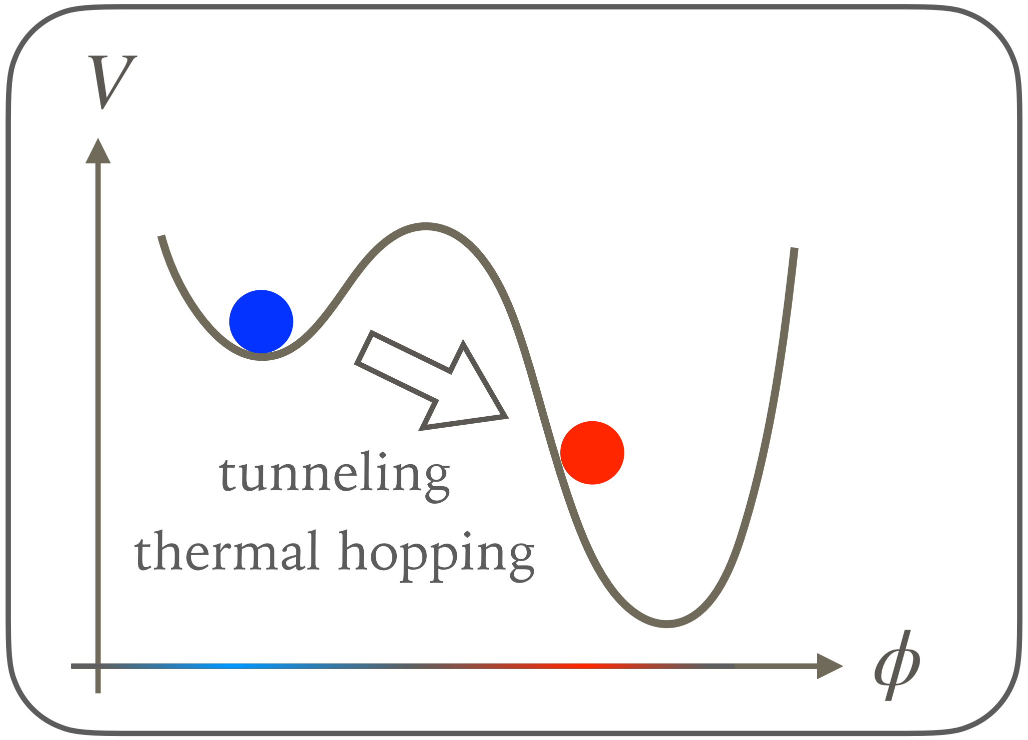
- Testability of the process in the coming 10-20 yrs with GWs

TUNNELING IN QUANTUM MECHANICS AND QFT

Quantum mechanics



Quantum field theory



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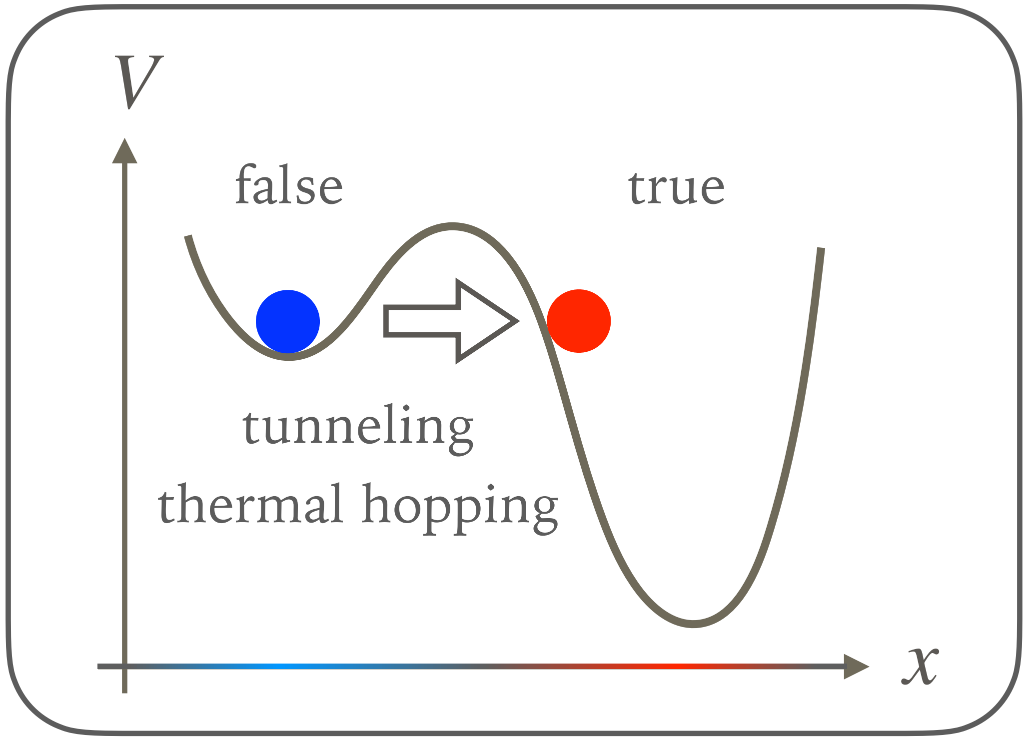
Quantum mechanics



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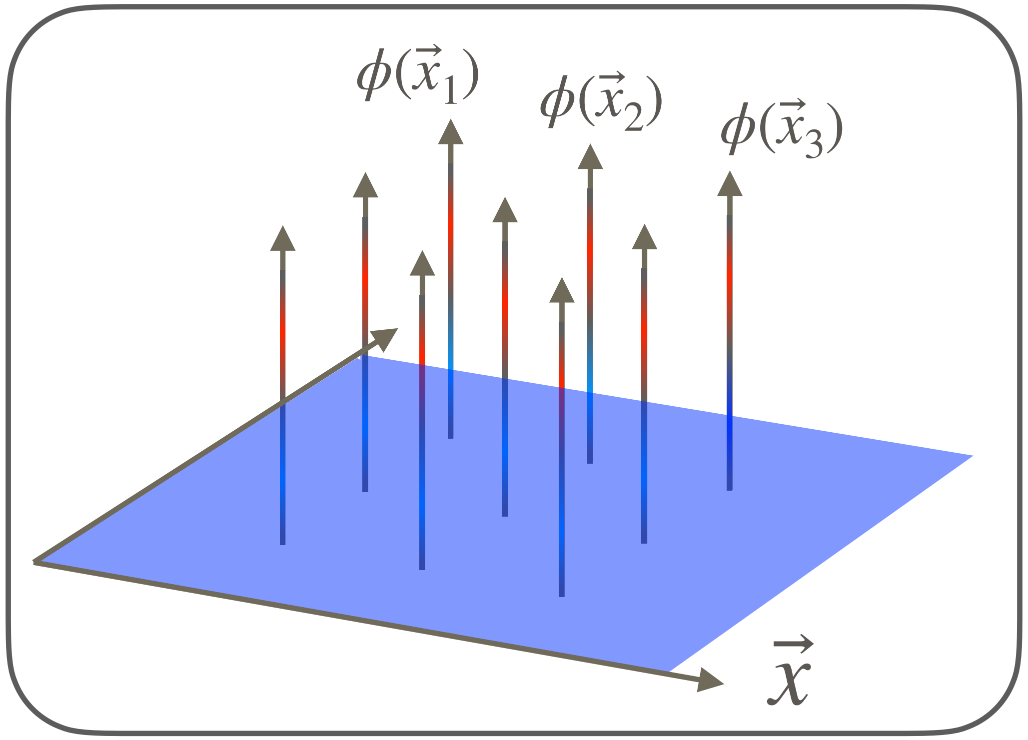

TUNNELING IN QUANTUM MECHANICS AND QFT

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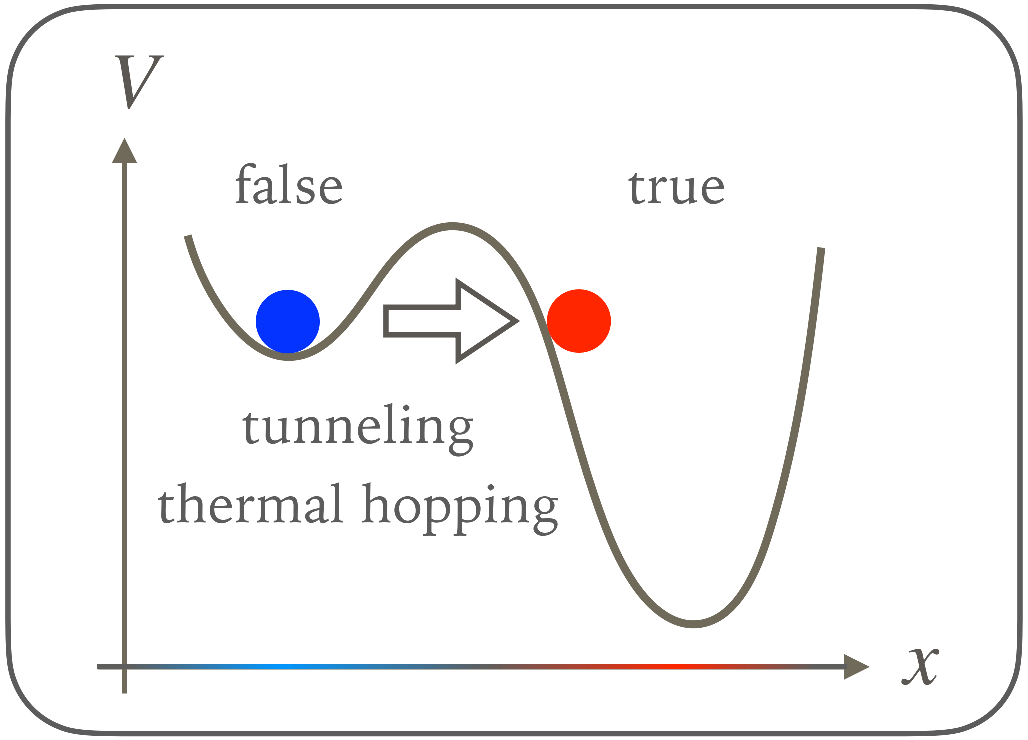
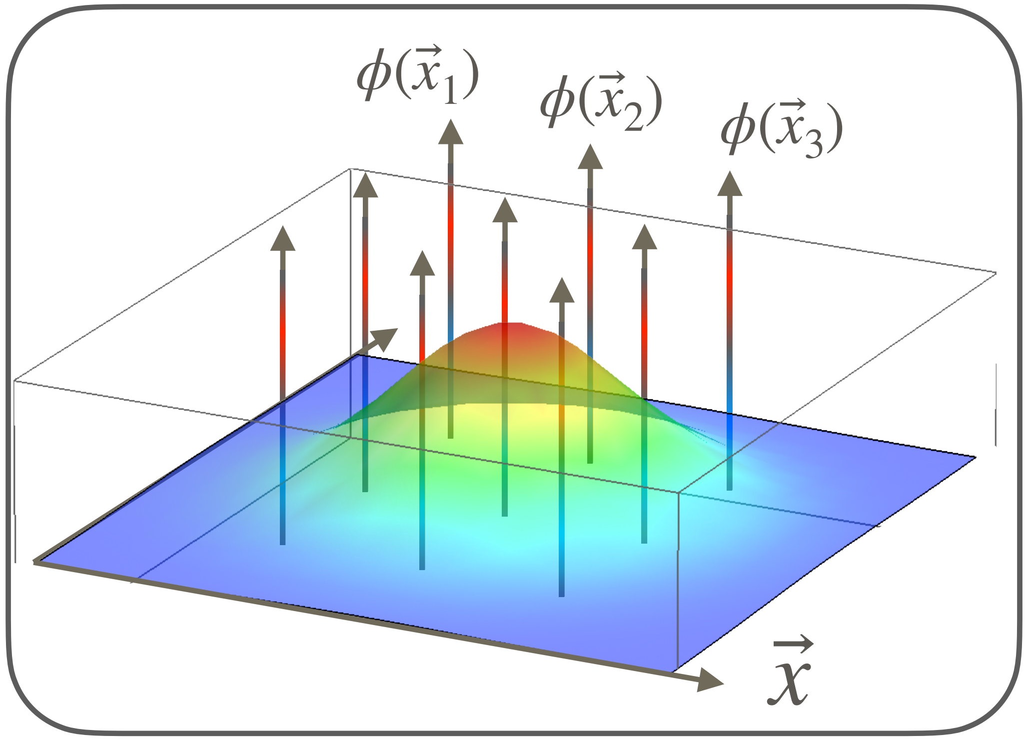




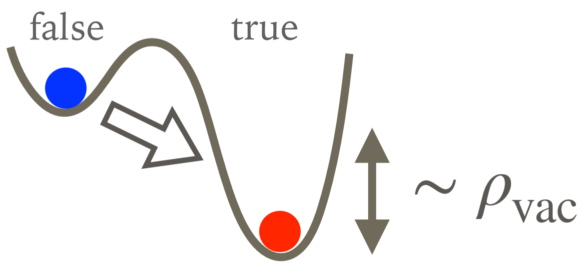
nucleation (核生成)

Usefulness of 3d EFT & Importance of gauge dependence:

[Hirvonen, Löfgren, Ramsey-Musolf, Schicho, Tankanen '22]

[Löfgren, Ramsey-Musolf, Schicho, Tankanen '23]

BUBBLE EXPANSION



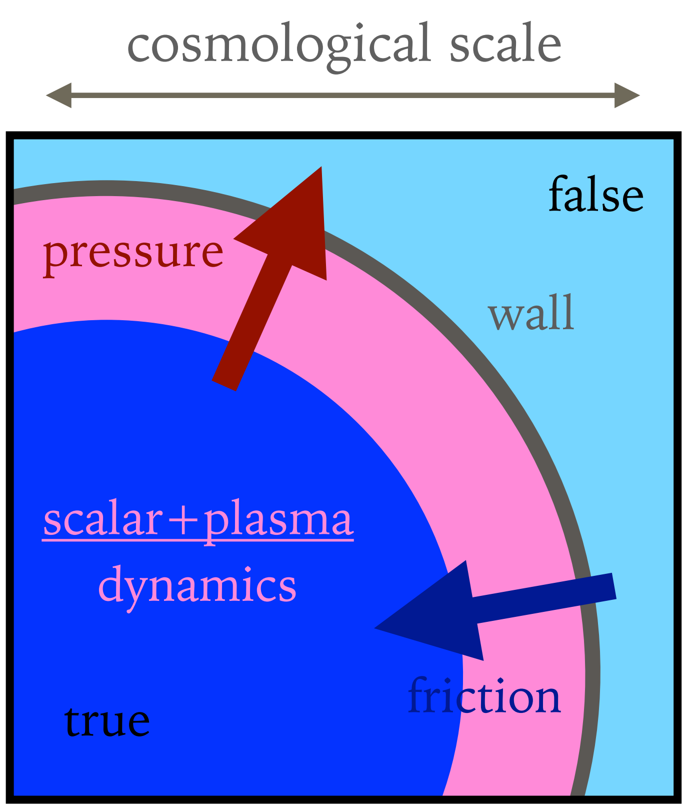
➤ "Pressure vs. Friction" determines the behavior:

(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



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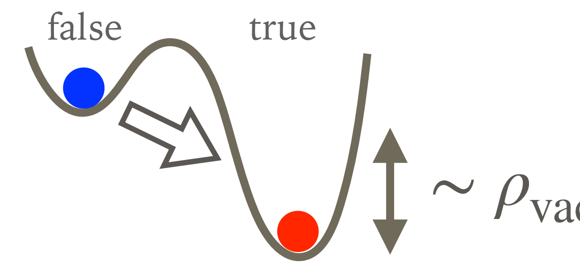

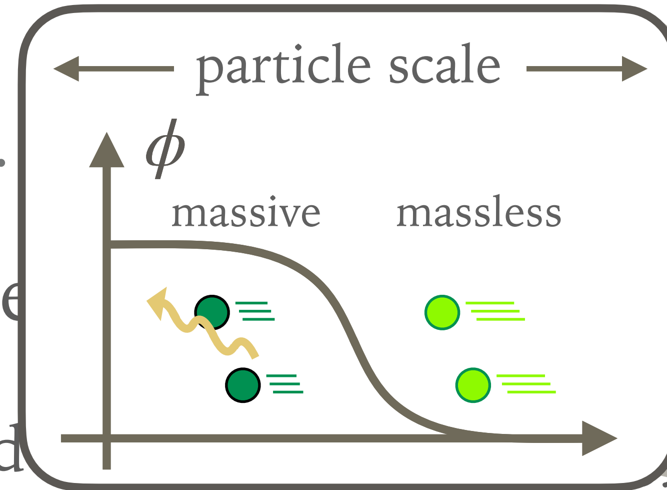

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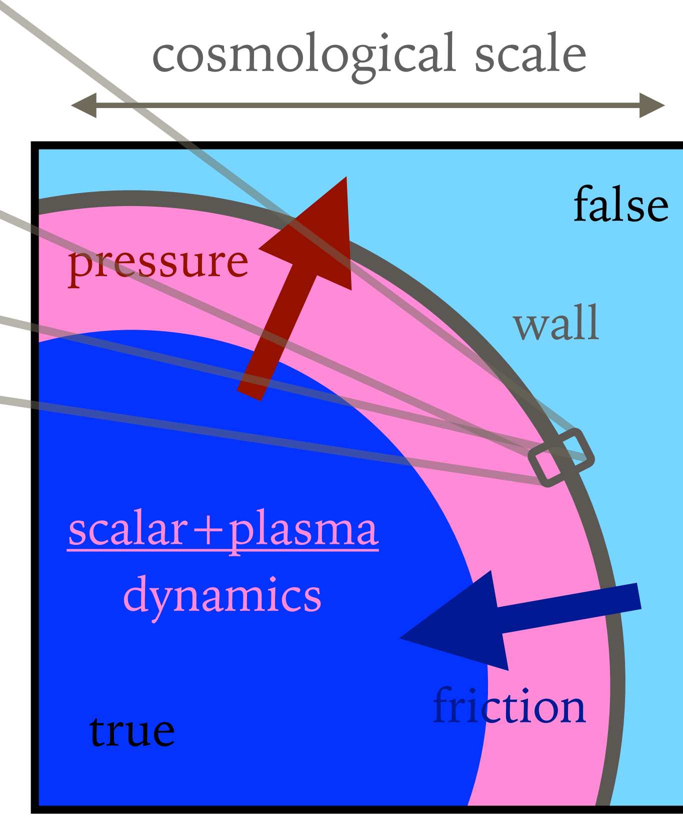

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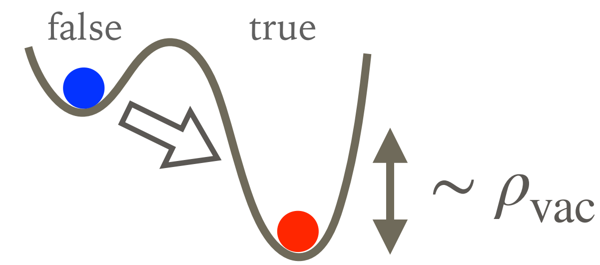

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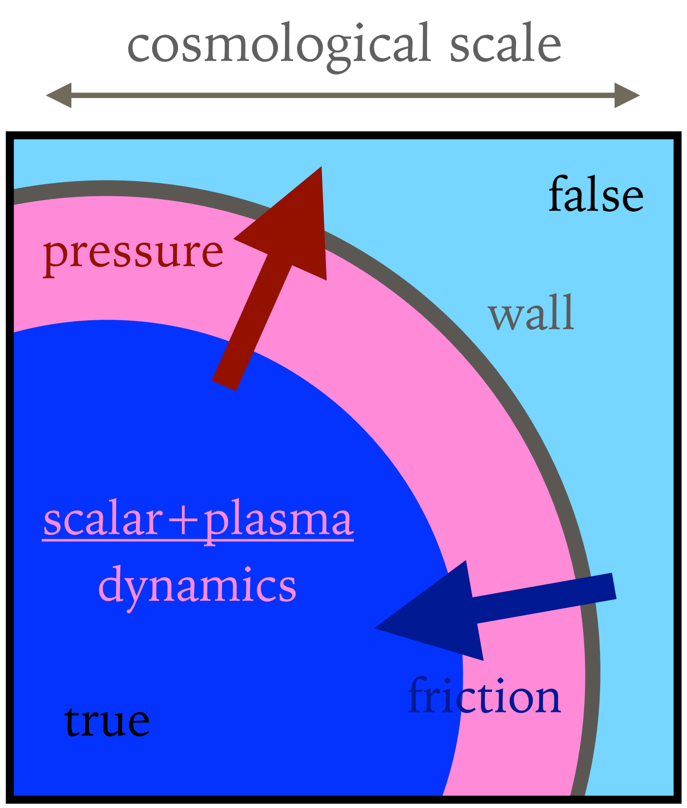
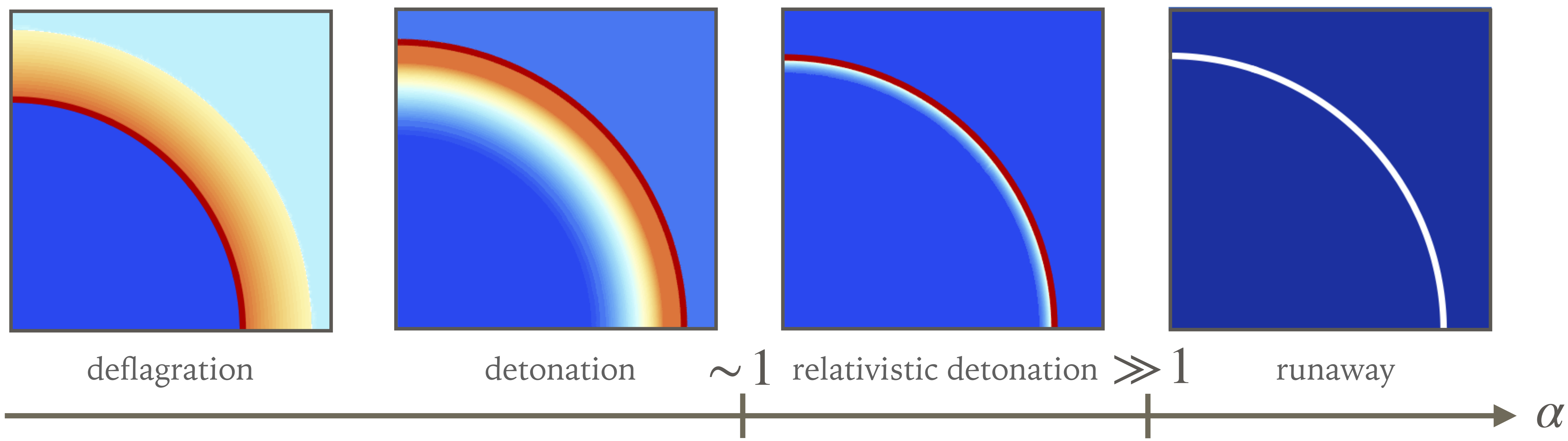
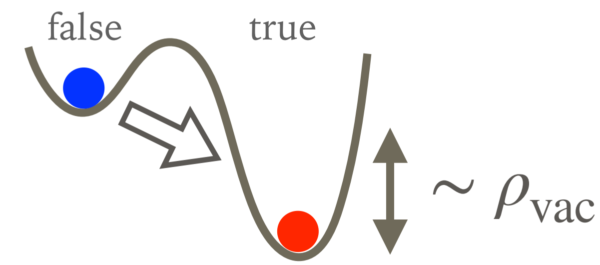


- Different types of bubble expansion



BUBBLE EXPANSION

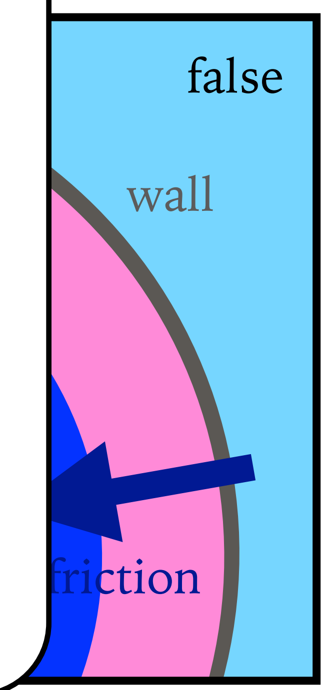


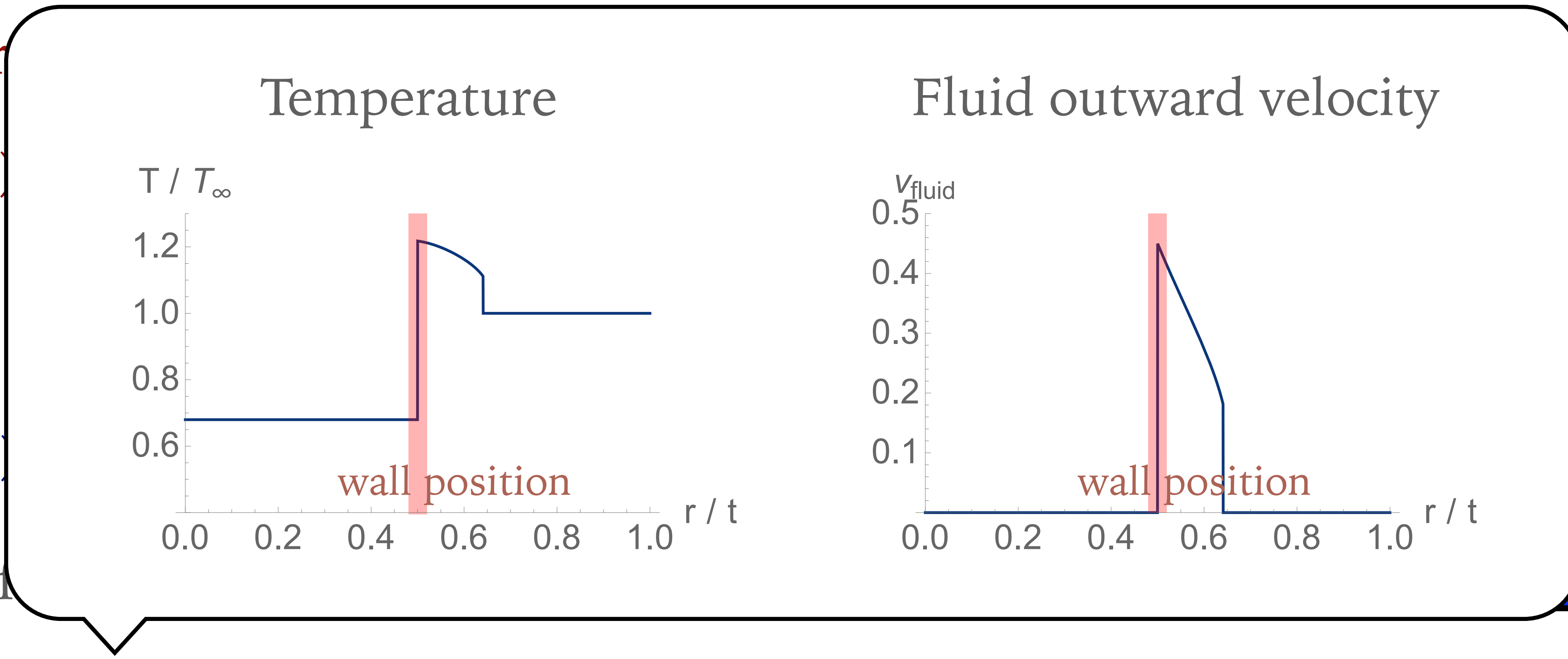
➤ "Pr

al scale

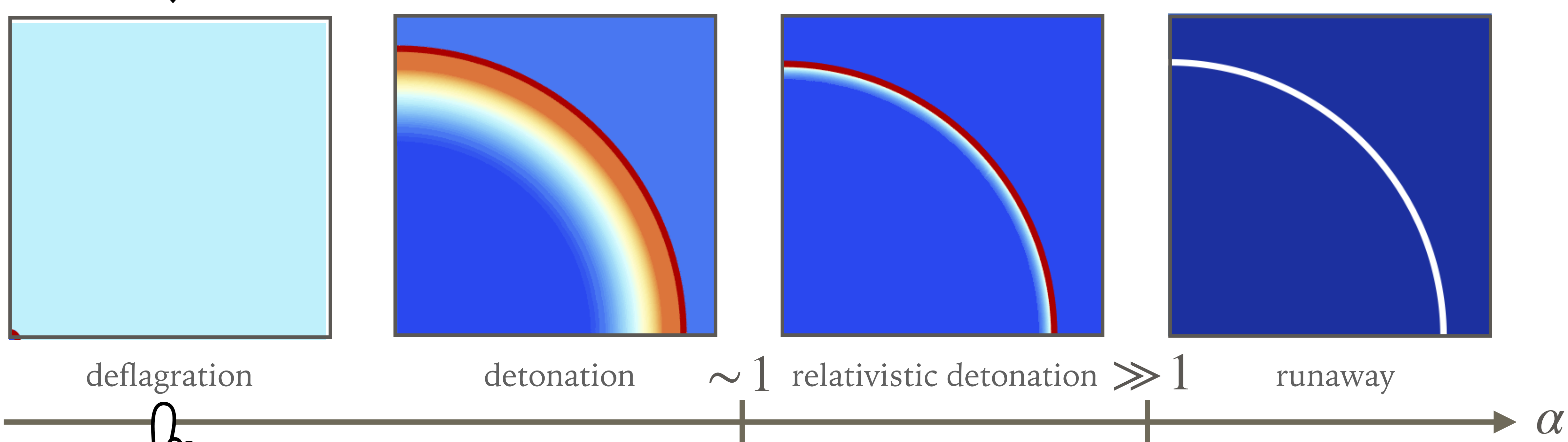
(1)

(2)





➤ Di



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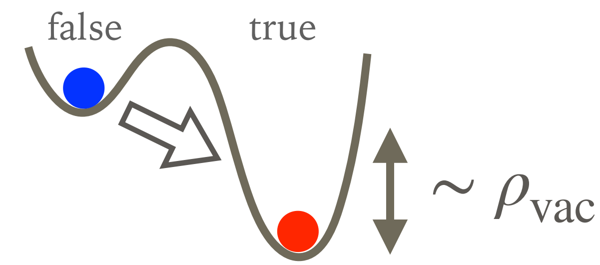

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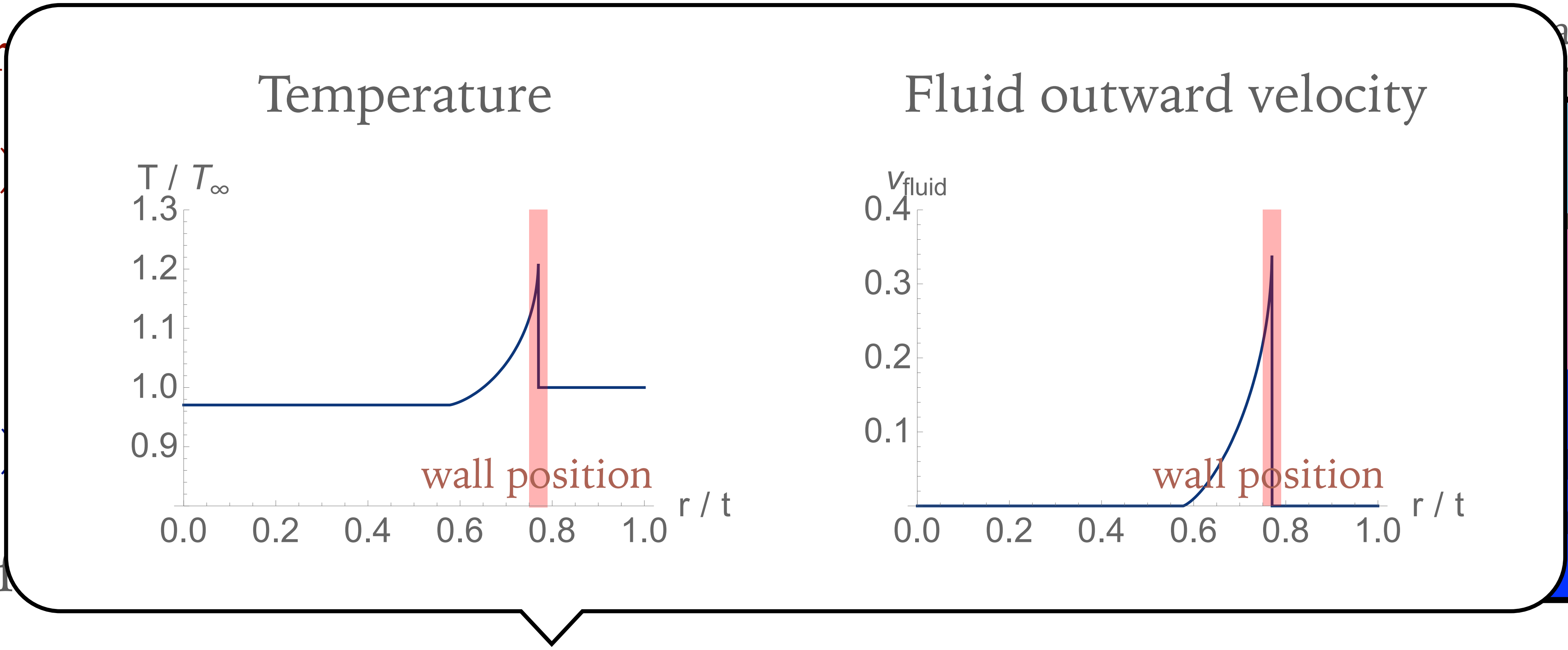

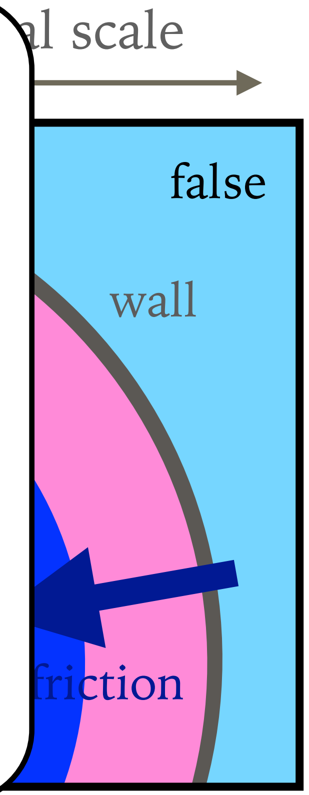

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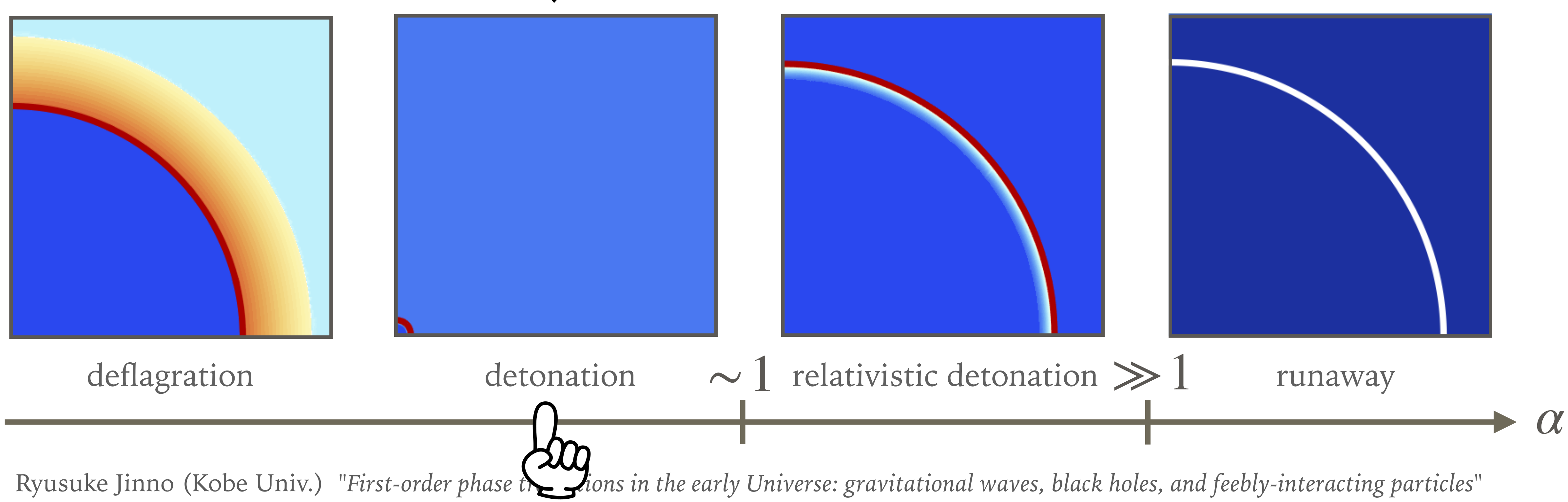

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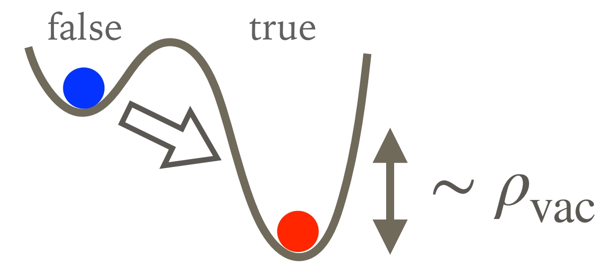

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(1)

(2)

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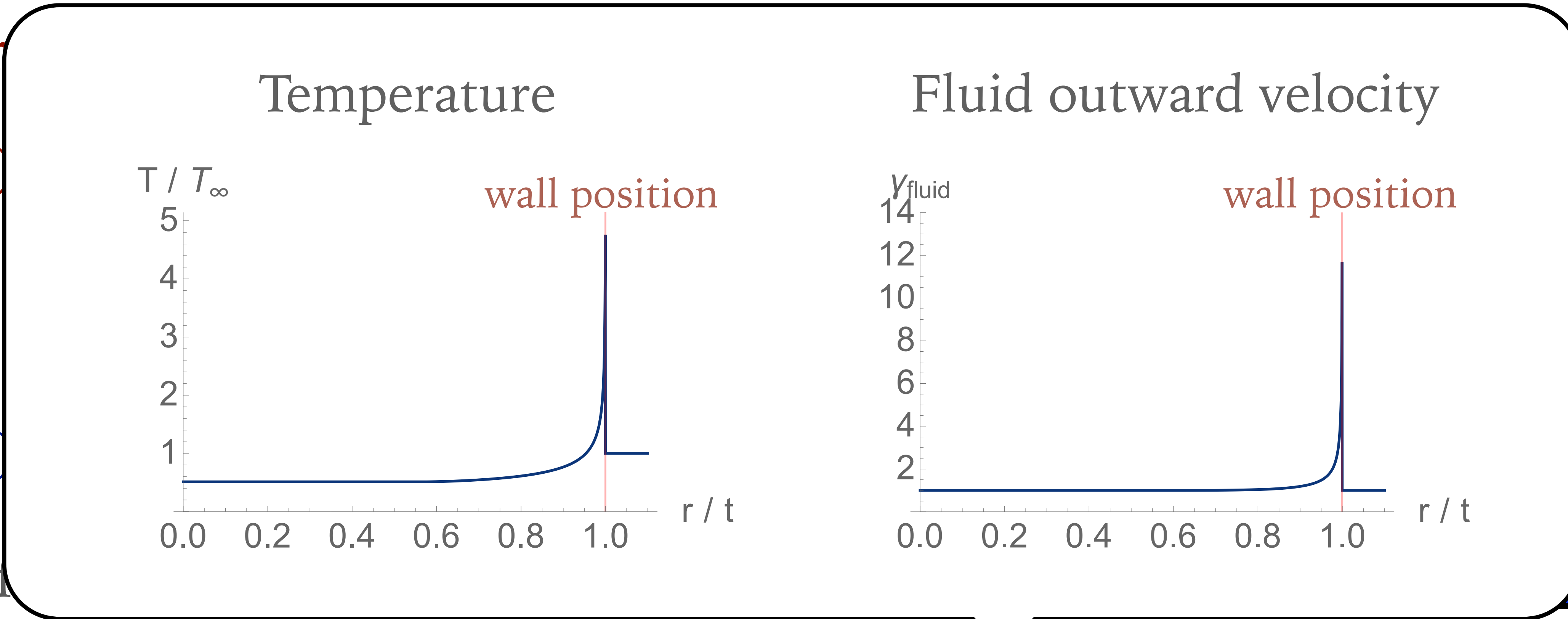
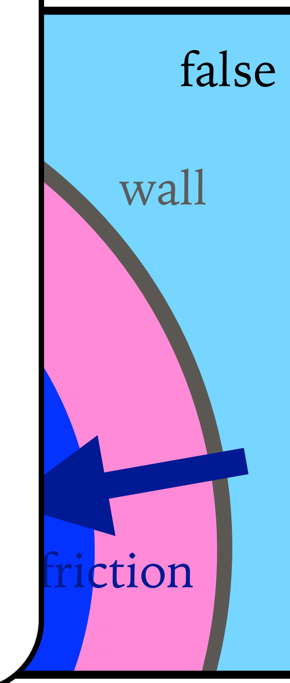
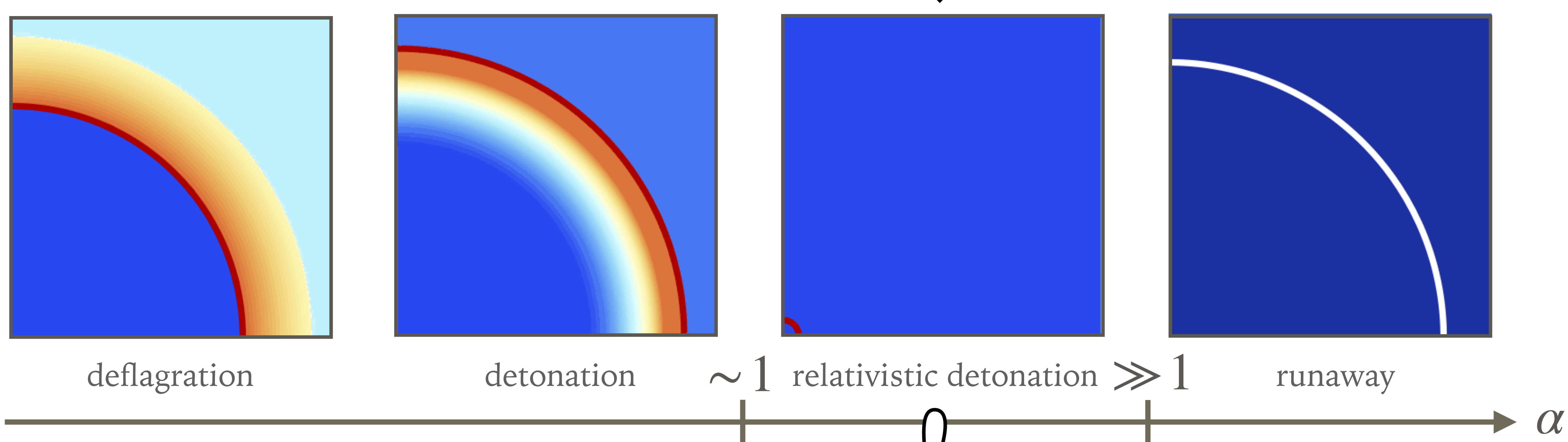


l scale





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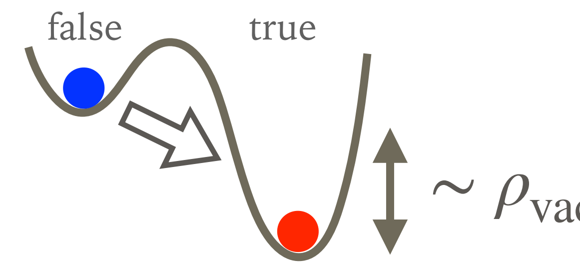


➤ "Pr

(1)

(2)

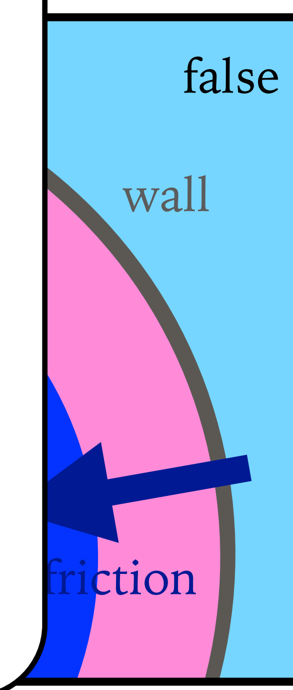
➤ Di

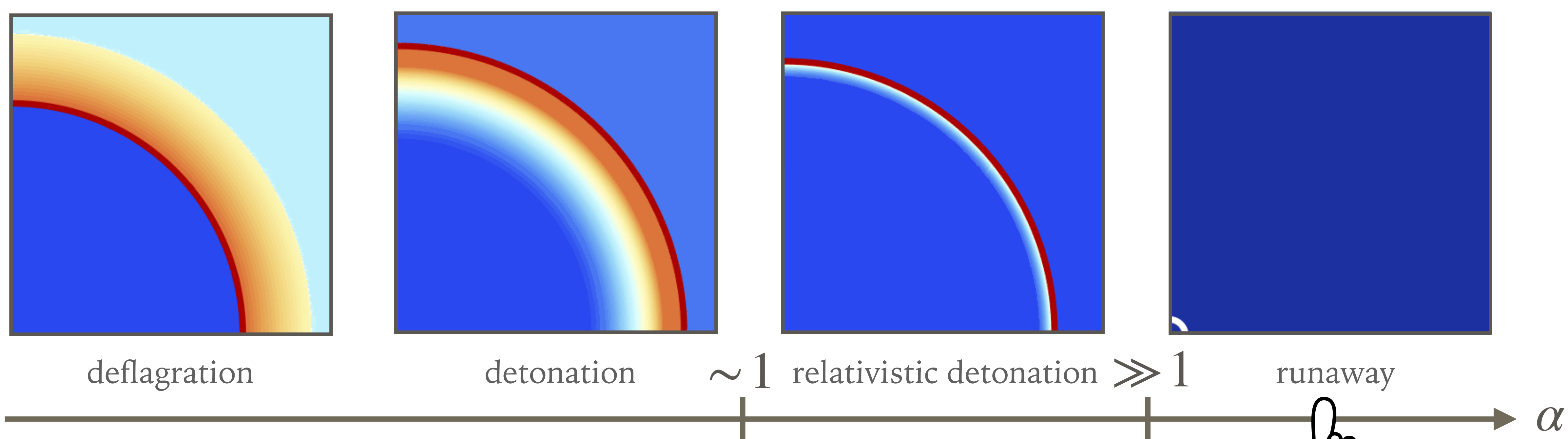
Plasma particles cannot stop the acceleration of the walls:

walls continue to accelerate until they collide with others

[Bodeker & Moore '09, '17]

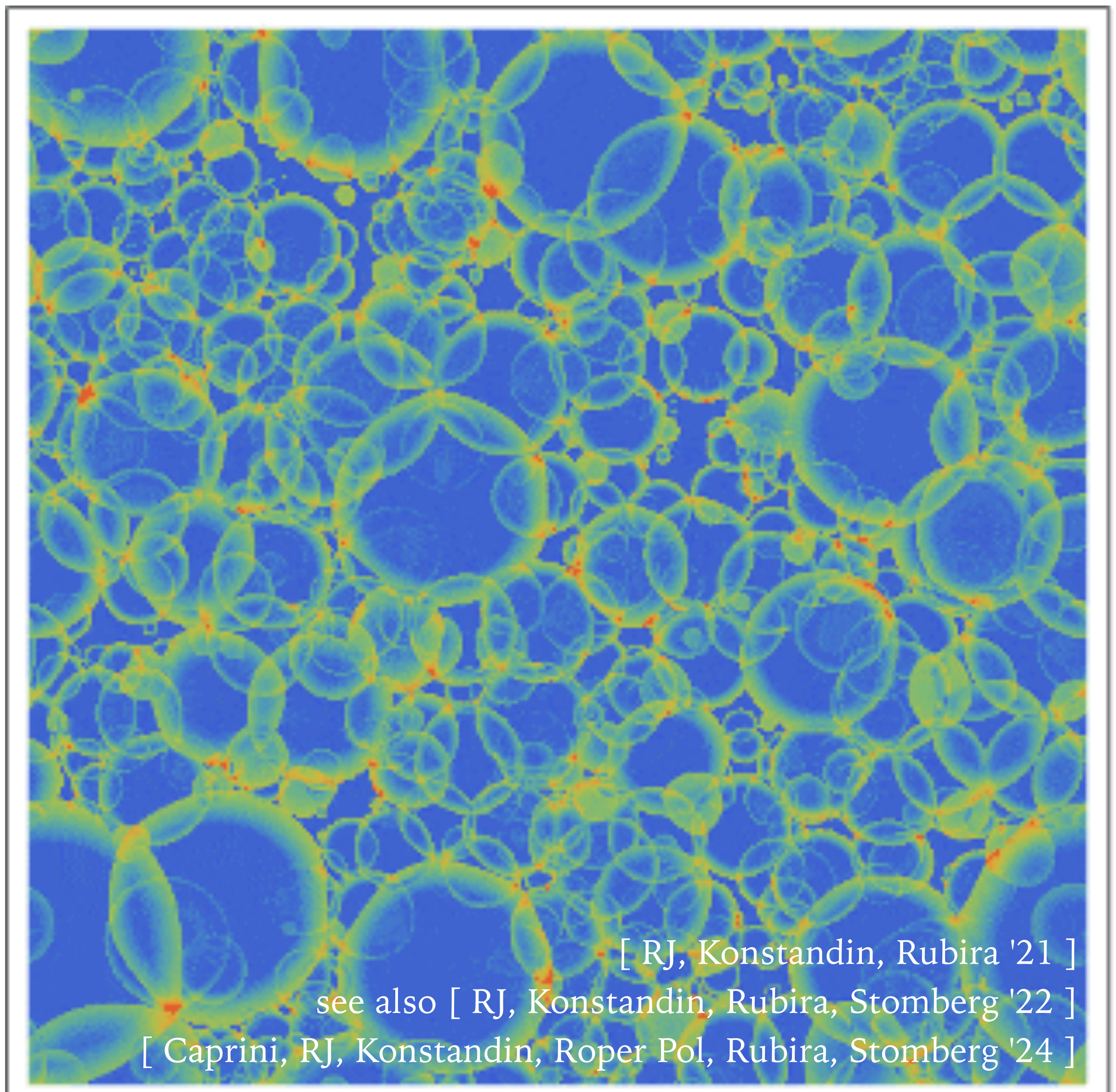
al scale





BUBBLE COLLISION & FLUID DYNAMICS

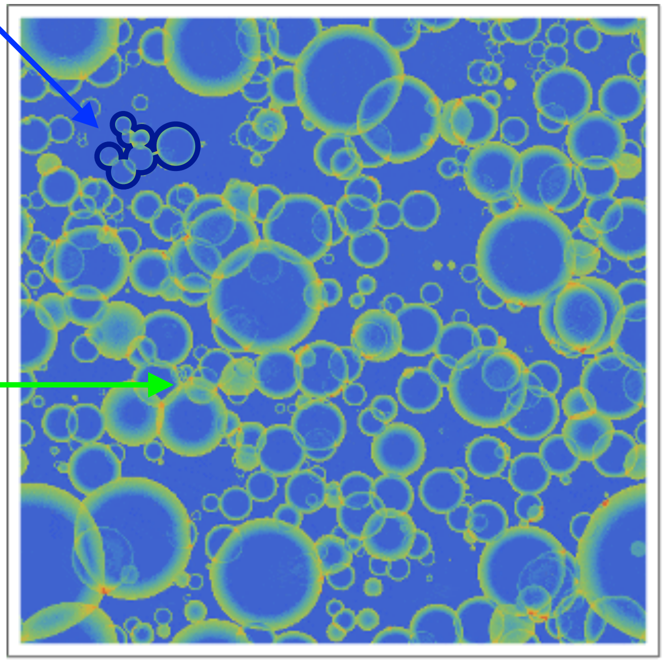
- Bubbles collide, and fluid dynamics sets in (example for )



GRAVITATIONAL WAVE SOURCES

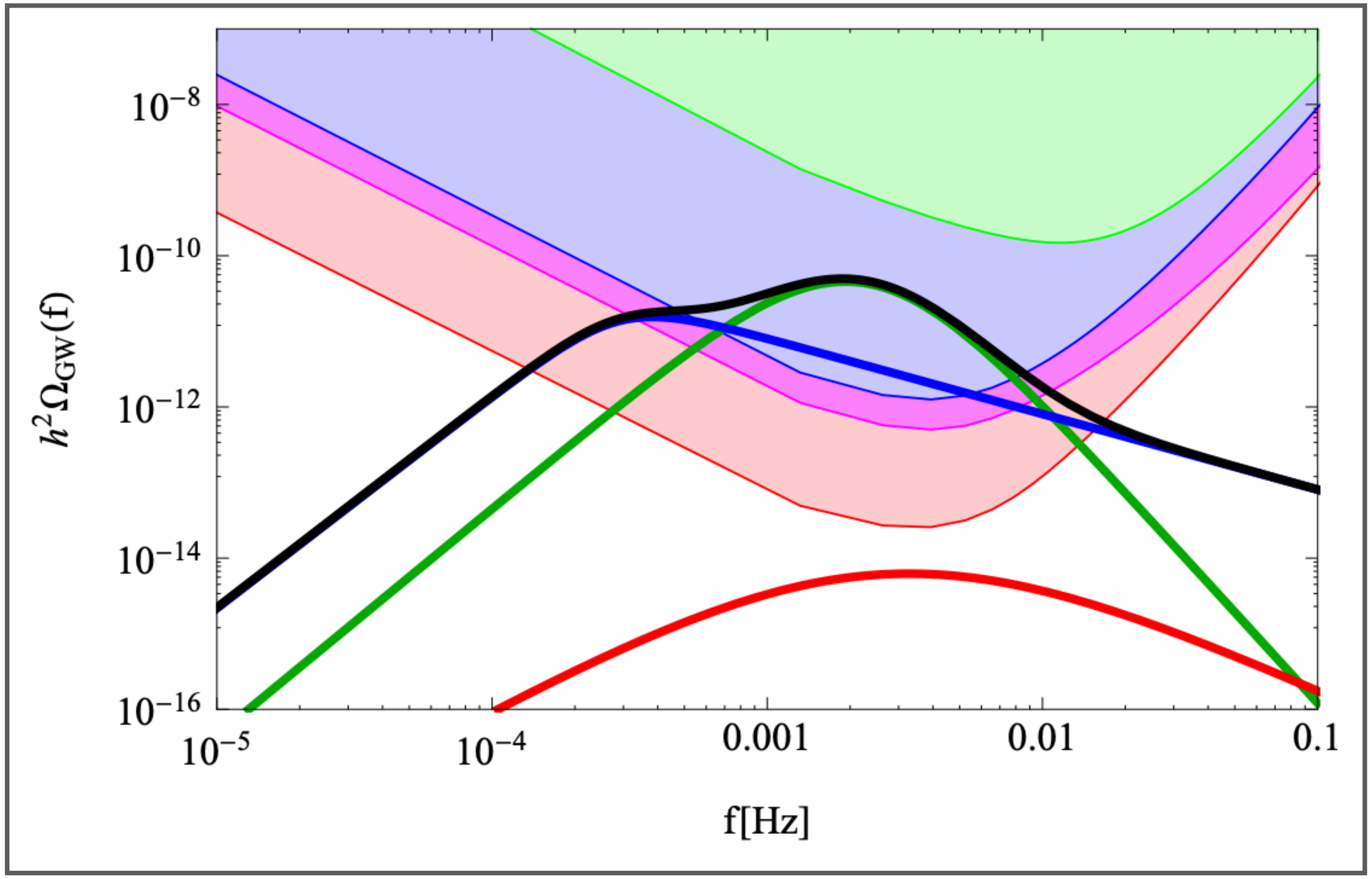
[Kosowsky, Turner, Watkins '92]
[Kosowsky, Turner '92]
[Kamionkowski, Kosowsky, Turner '93]
and e.g. [Caprini et al. '16] [Caprini et al. '20]

- ➤ 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?

Particle physics → Transition parameters → Prediction on macroscopic outcome

Lagrangian $\mathscr{L}$

α : transition strength

β : (inverse) transition timescale

v_w : wall velocity

T_* : transition temperature

GW spectrum Ω_{GW}

Curvature perturbations?

Black holes?

see [Caprini, RJ, Lewicki, Madge, Merchand, Nardini, Pieroni, Roper Pol, Vaskonen '24]

First-order phase transitions in the early Universe:

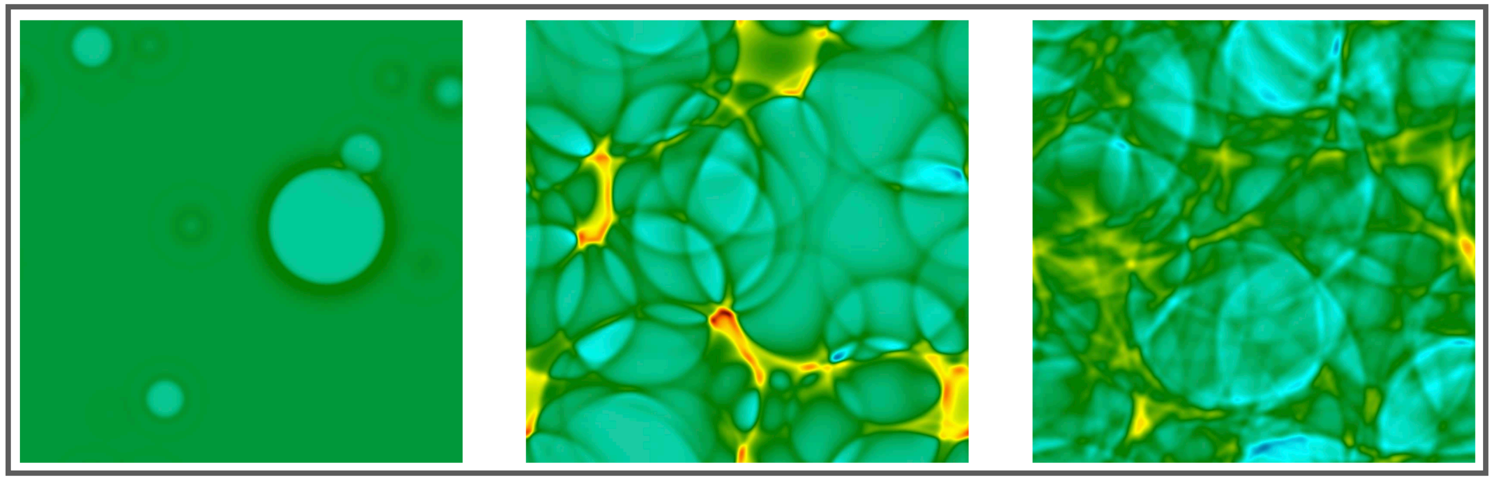
***gravitational waves**, black holes, and feebly-interacting particles*

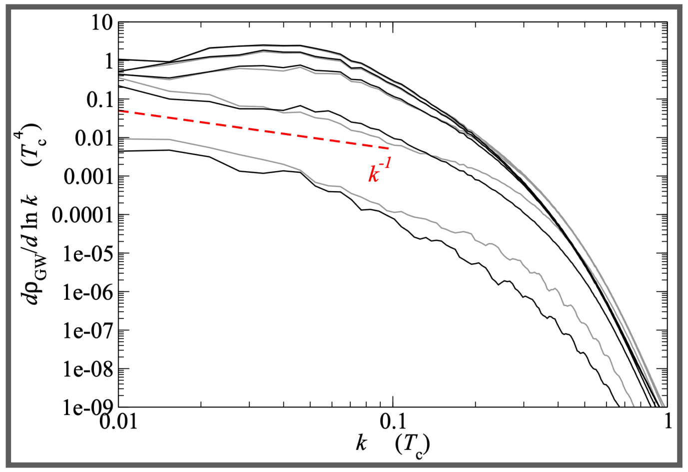
FLUID-HIGGS SIMULATIONS

- The system is a coupled system of fluid and the Higgs field

$$[\partial_\mu T^{\mu\nu}]_{\rm field} = (\partial_\mu \partial^\mu \phi)\partial^\nu \phi - \frac{\partial V}{\partial \phi}\partial^\nu \phi = \delta^\nu$$

$$[\partial_\mu T^{\mu\nu}]_{\rm fluid} = \partial_\mu[(\epsilon + p)U^\mu U^\nu] - \partial^\nu p + \frac{\partial V}{\partial \phi}\partial^\nu \phi = -\delta^\nu,$$





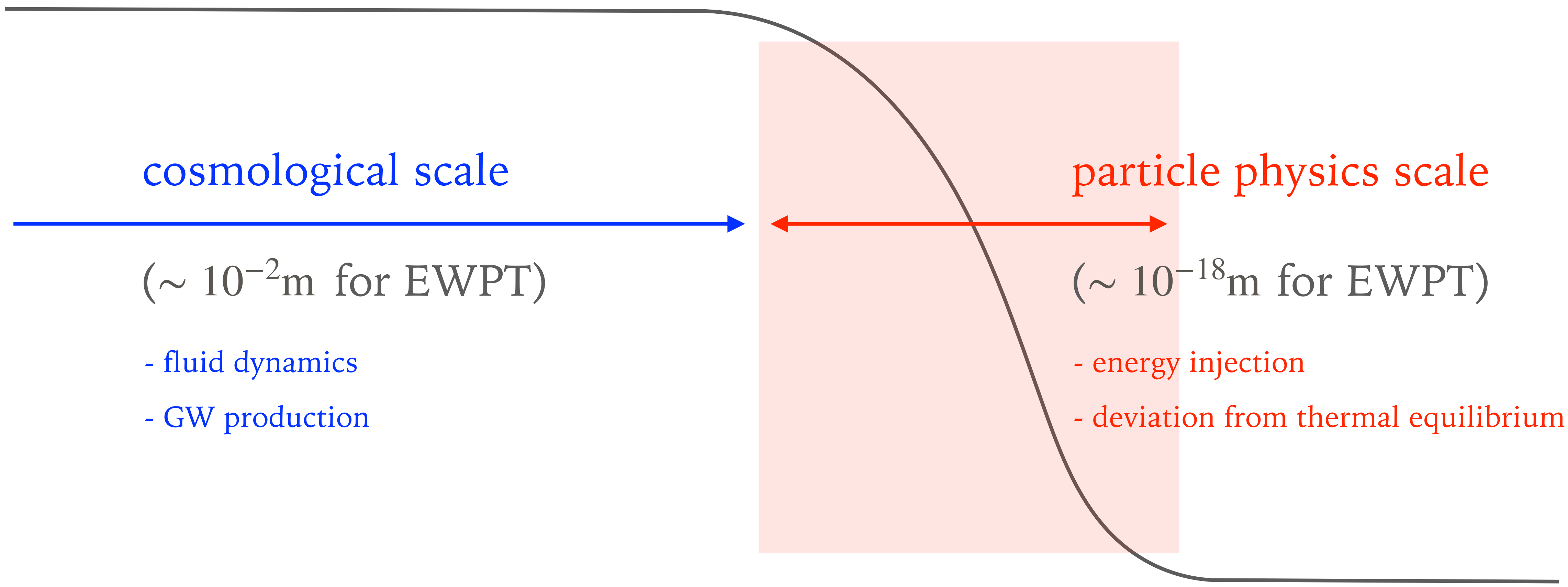
[Hindmarsh, Huber, Rummukainen, Weir '14, '15, '17]

- However, these simulations are very costly. How can we explore the vast parameter space? $\rightarrow$ ***Our proposal: Higgsless scheme***

HIERARCHY IN SCALES AND THE HIGGSLESS SCHEME

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

➤ 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), $T^{\mu\nu} = w u^\mu u^\nu - g^{\mu\nu} p$

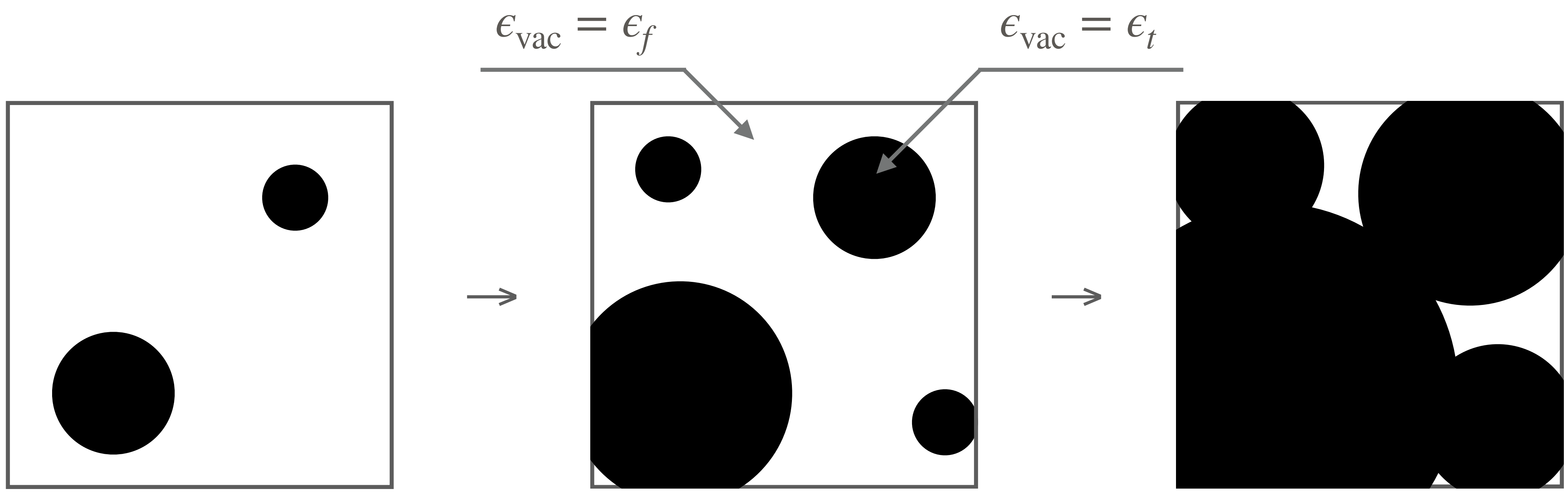
  ② Define $K^\mu \equiv T^{\mu 0}$, then $\partial_\mu T^{\mu\nu} = 0$ reduces to $\begin{cases} \partial_0 K^0 + \partial_i K^i = 0 \\ \partial_0 K^i + \partial_j T^{ij}(K^0, K^i) = 0 \end{cases}$

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

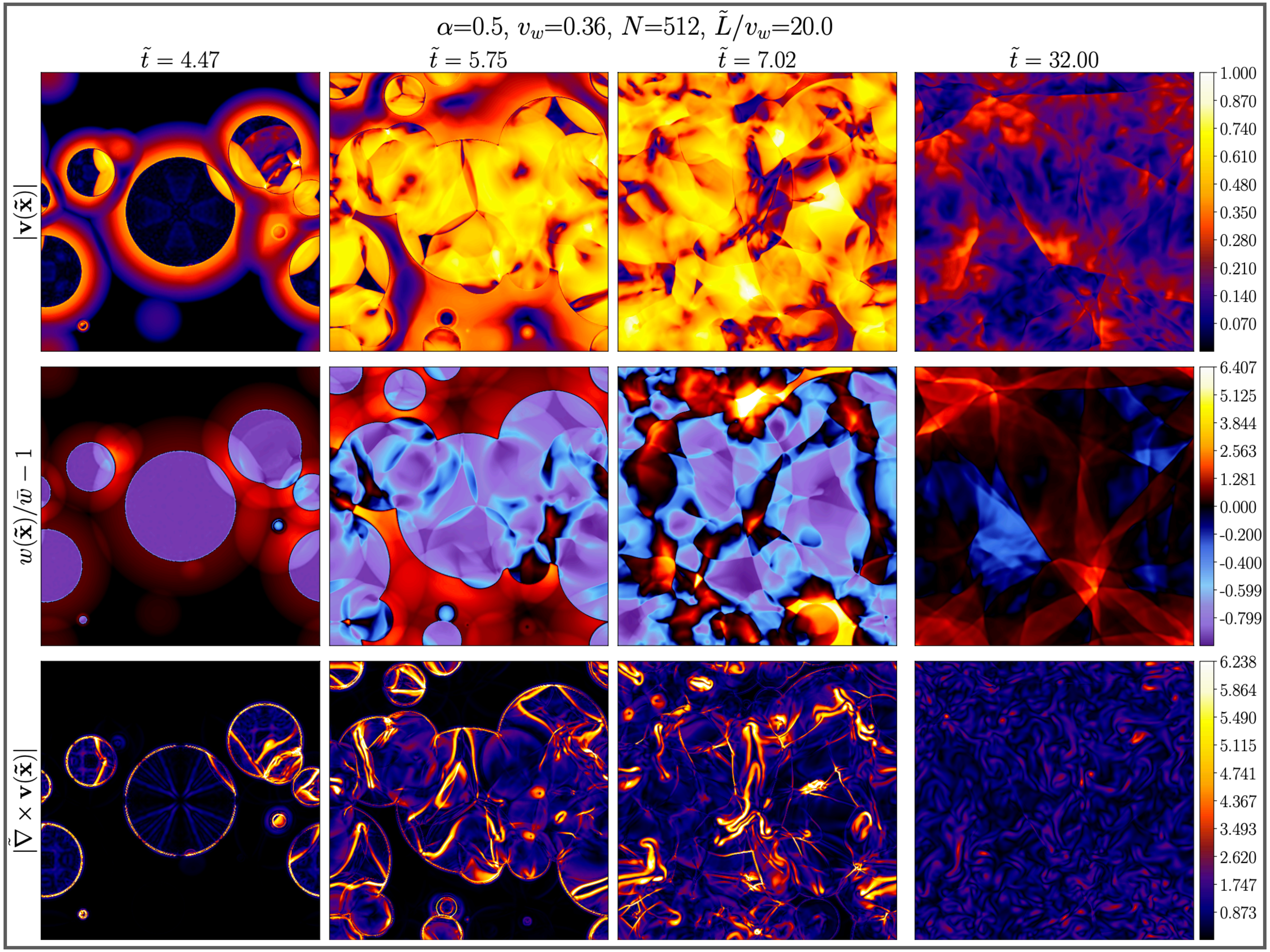
  $\rightarrow$ Fluid automatically develops profiles

HIGGSLESS SIMULATION: TYPICAL TIME EVOLUTION

fluid velocity

enthalpy

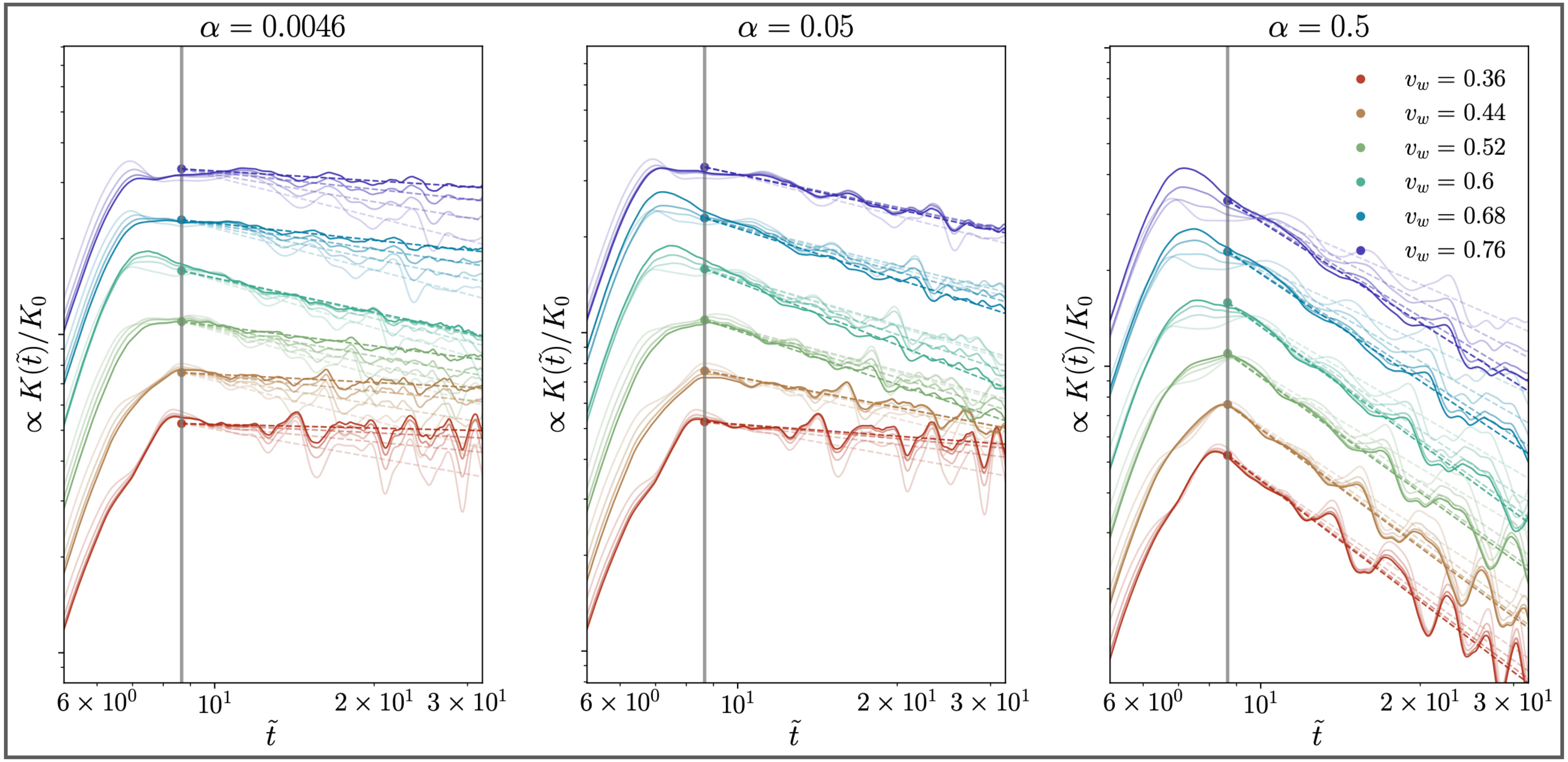
vorticity



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

HIGGSLESS SIMULATION: DECAY OF KINETIC ENERGY

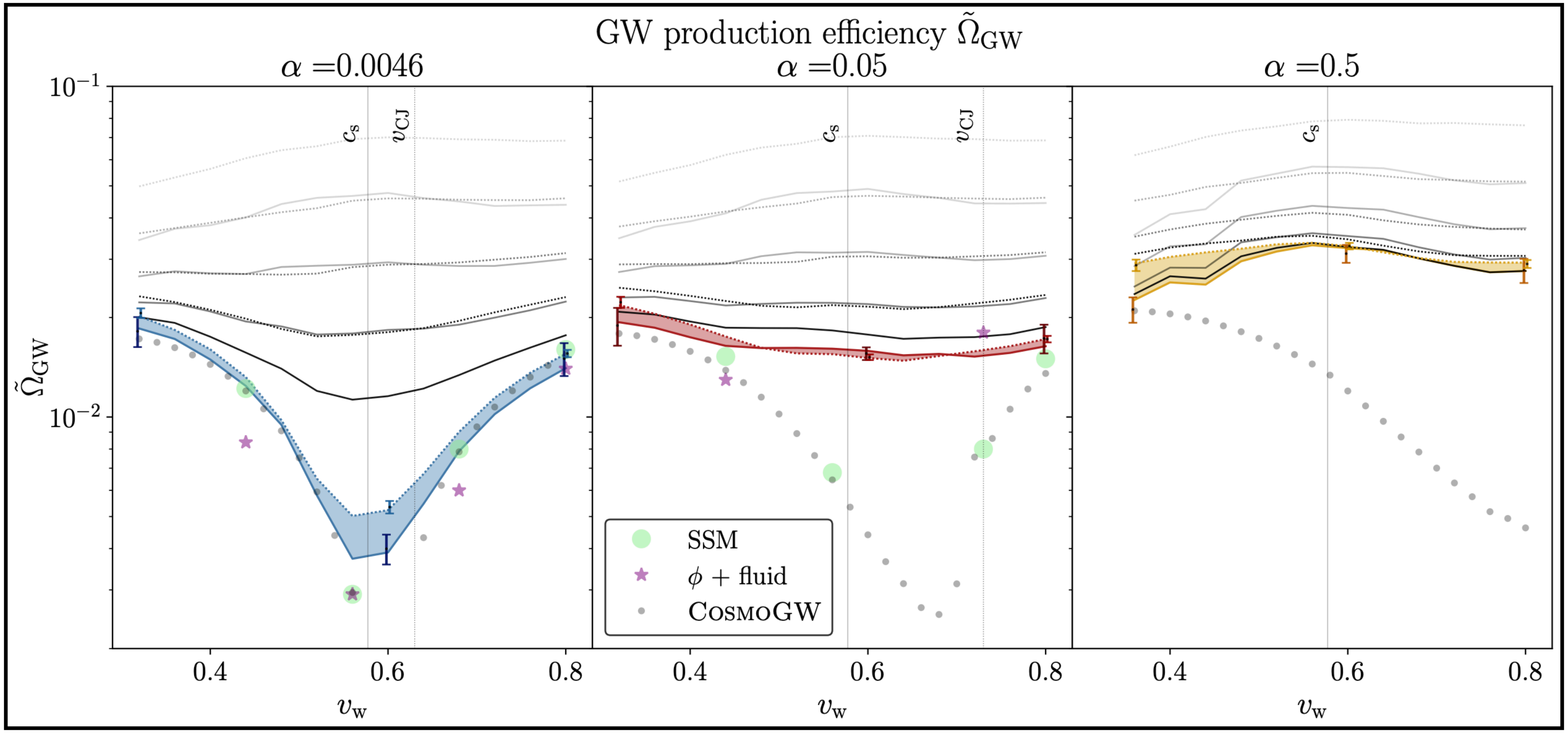
- Fluid kinetic energy decays faster for stronger transitions



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

HIGGSLESS SIMULATION: DECAY OF KINETIC ENERGY

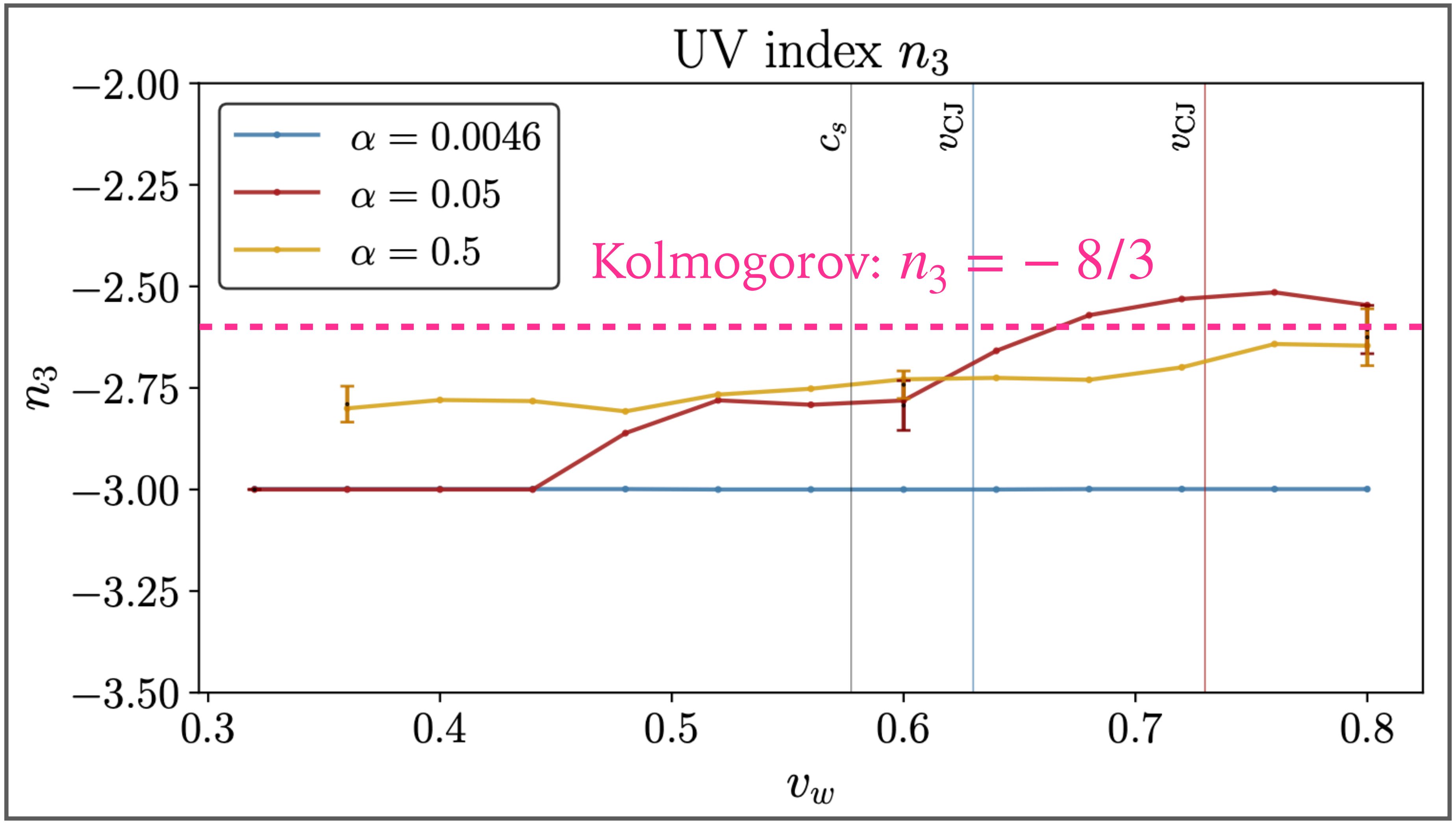
➤ GW amplitude agree with Sound Shell Model for weaker transitions, while it deviates for stronger transitions



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

HIGGSLESS SIMULATION: ONSET OF TURBULENCE

➤ Onset of turbulence observed?



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

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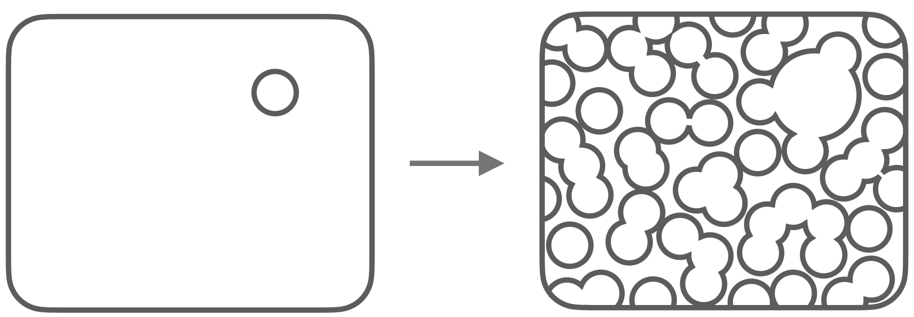
gravitational waves, ***black holes****, and feebly-interacting particles*

FOPT IN NEARLY CONFORMAL MODELS

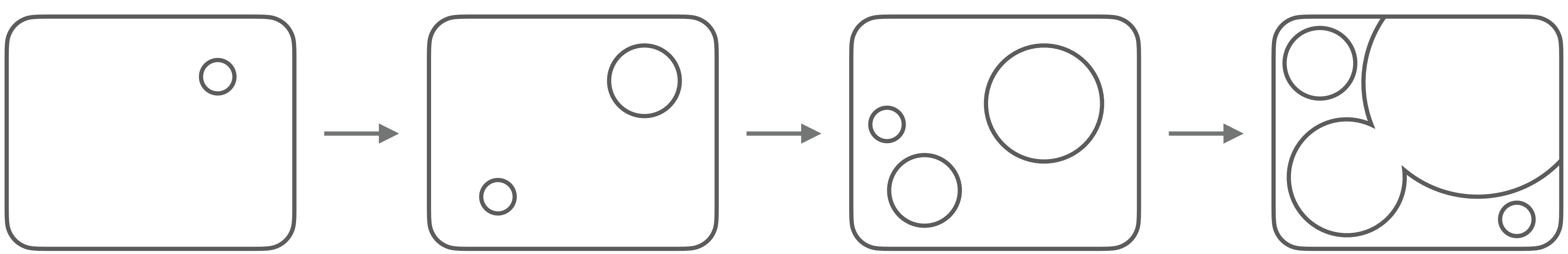
[Randall, Servant '07]
[Espinosa, Konstandin, No, Quiros '08]

➤ If the microphysics model is nearly scale invariant,
the typical bubble size is big and the resulting GW production is huge

Typical models



Nearly scale-invariant models How small can β/H be? → see [Kierkla, Ramberg, Schicho, Schmitt '25]



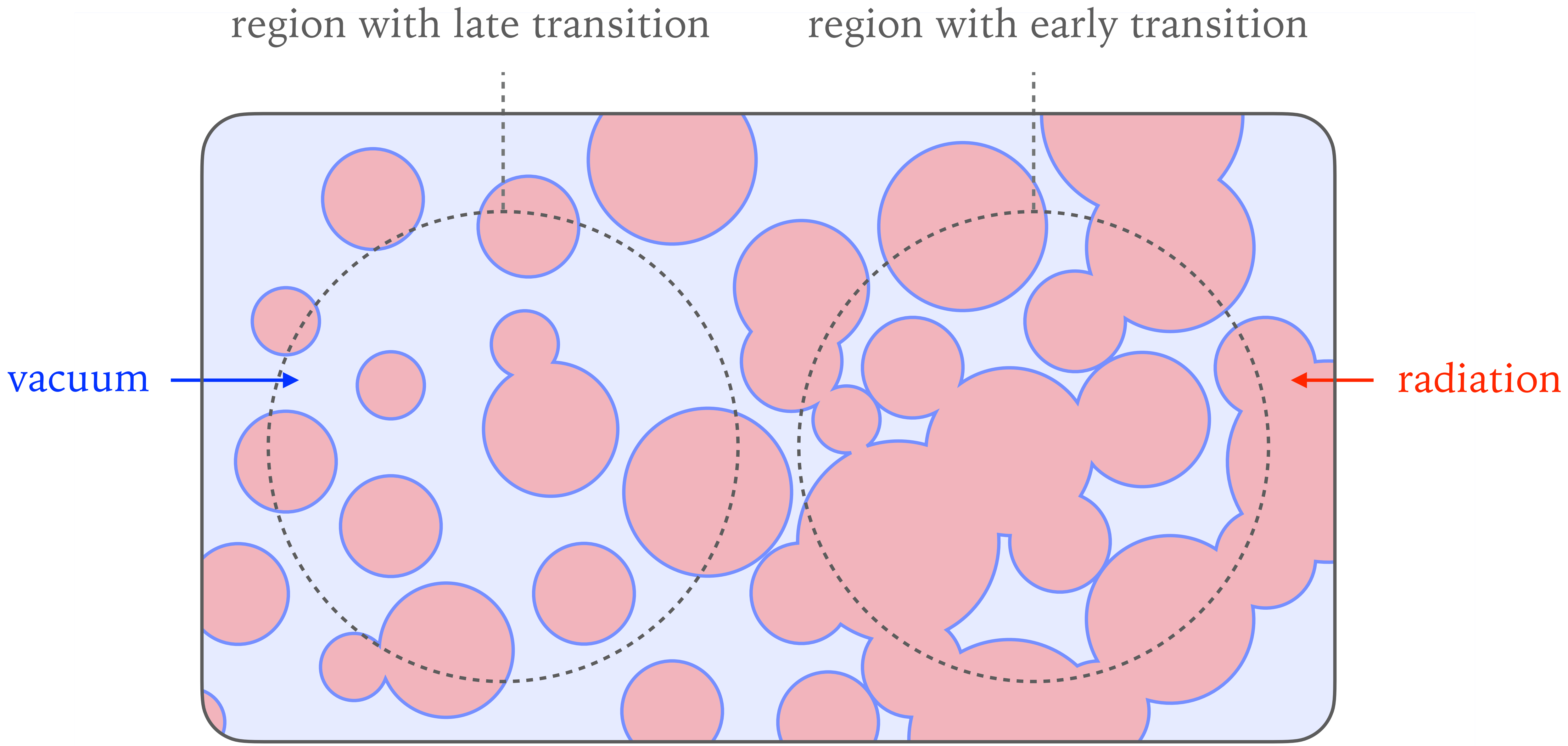
the system looks almost the same at different temperatures → slow nucleation of bubbles

time ↗
temperature ↘

$T = T_{\text{initial}}$ → $T \ll T_{\text{initial}}$

PBH FORMATION FROM VERY STRONG TRANSITIONS

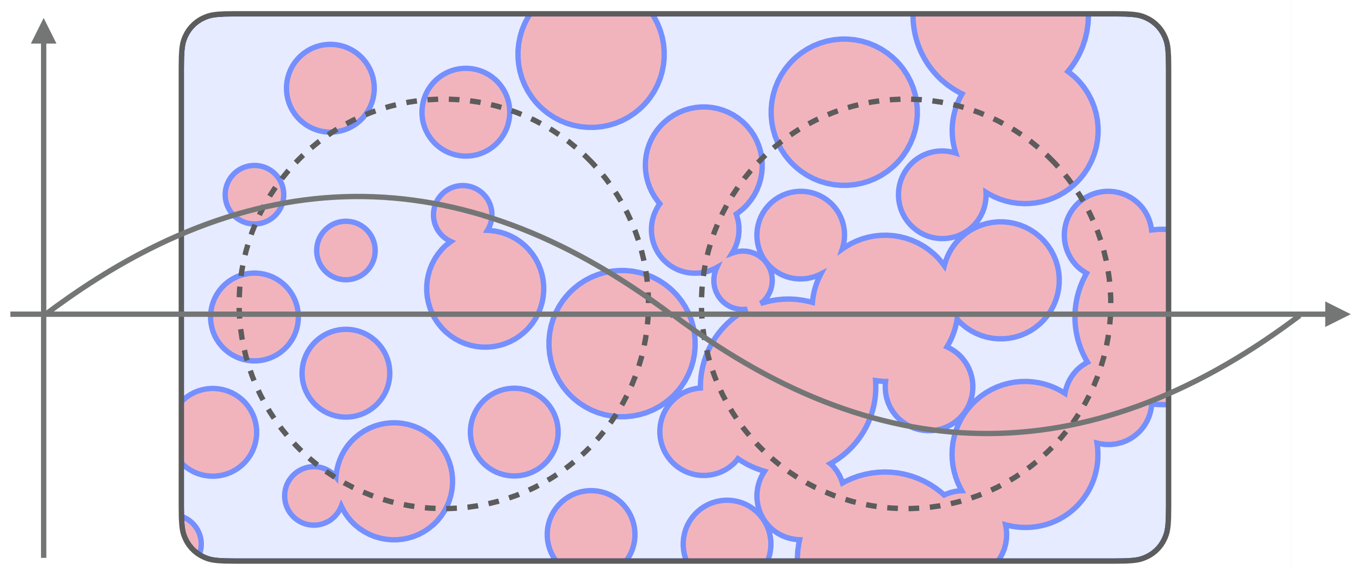
- How large can the curvature perturbation be? (→ PBHs? GWs?)



PBH FORMATION: ROUGH IDEA

- Can PBHs form from curvature perturbation generated by small β/H (but still $\gtrsim$ a few) FOPTs?

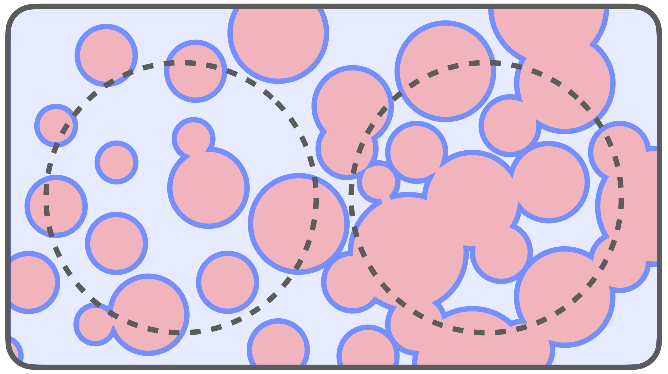
<u>Intuitively</u>



$$\delta \left(= \frac{\delta\rho}{\rho} \right)$$

- With a careful treatment of gauges (in cosmological perturbations), we answered to this question in the negative

FINDINGS IN THE LITERATURE



➤ Setup & findings of [Lewicki, Troczek, Vaskonen '24]

① Background

- Radiation & vacuum energy $\bar{\rho}_r' + 4\mathscr{H}\bar{\rho}_r = -\bar{\rho}_V'$

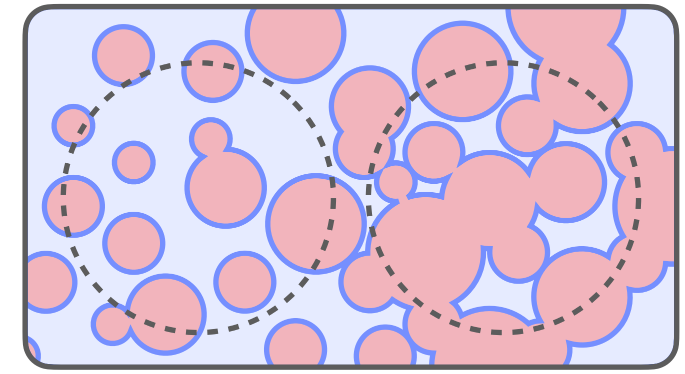
- Initially the universe is vacuum energy dominated $\bar{\rho}_V(t = -\infty) = \Delta V$, and then radiation takes over

- Vacuum energy decays with the exponential nucleation of bubbles

$$\Gamma(t) = H_*^4 \, e^{\beta(t - t_*)}$$

meaning that $\bar{\rho}_V$ decreases with the average false vacuum fraction $\bar{F}(t)$ as

$$\bar{\rho}_V = \bar{F}(t) \times \Delta V \qquad \bar{F}(t) = \exp\left[-\frac{4\pi}{3} \int_{-\infty}^{t} dt_n \, \Gamma(t_n) \, a(t_n)^3 \left(\int_{t_n}^{t} \frac{d\tilde{t}}{a(\tilde{t})} \right)^3 \right]$$

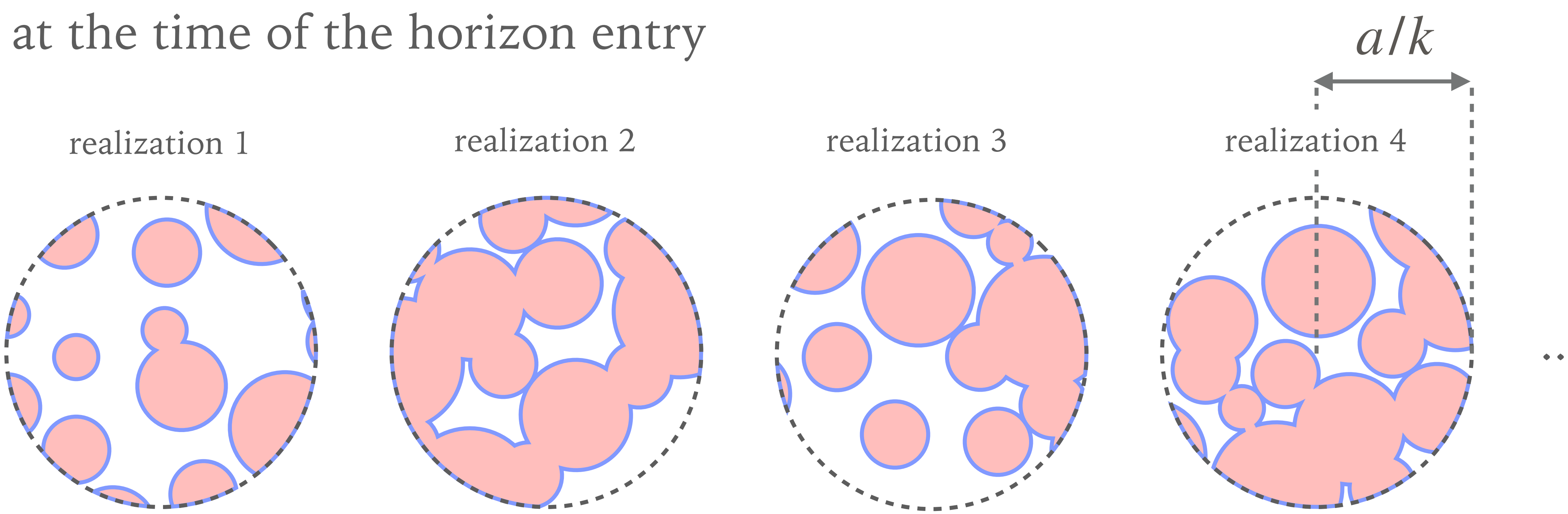


FINDINGS IN THE LITERATURE

- Setup & findings of [Lewicki, Troczek, Vaskonen '24]

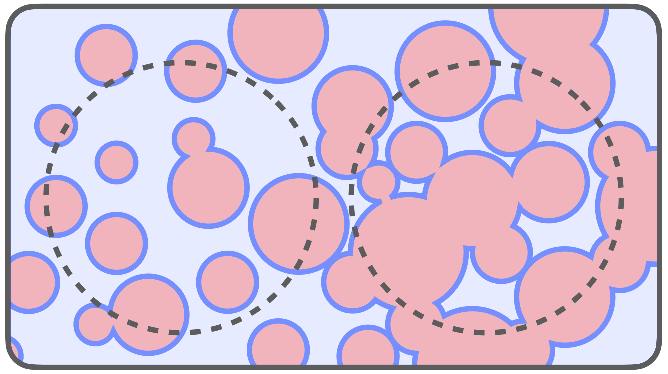
② Perturbation

- Stochastic process of bubble nucleation induces density fluctuations
- For a fixed comoving wavenumber k, consider a sphere of comoving radius $1/k$, and numerically calculate the PDF of the density contrast of this region at the time of the horizon entry



These pictures are just for illustration: they develop a much more efficient algorithm than naively generating bubbles

FINDINGS IN THE LITERATURE



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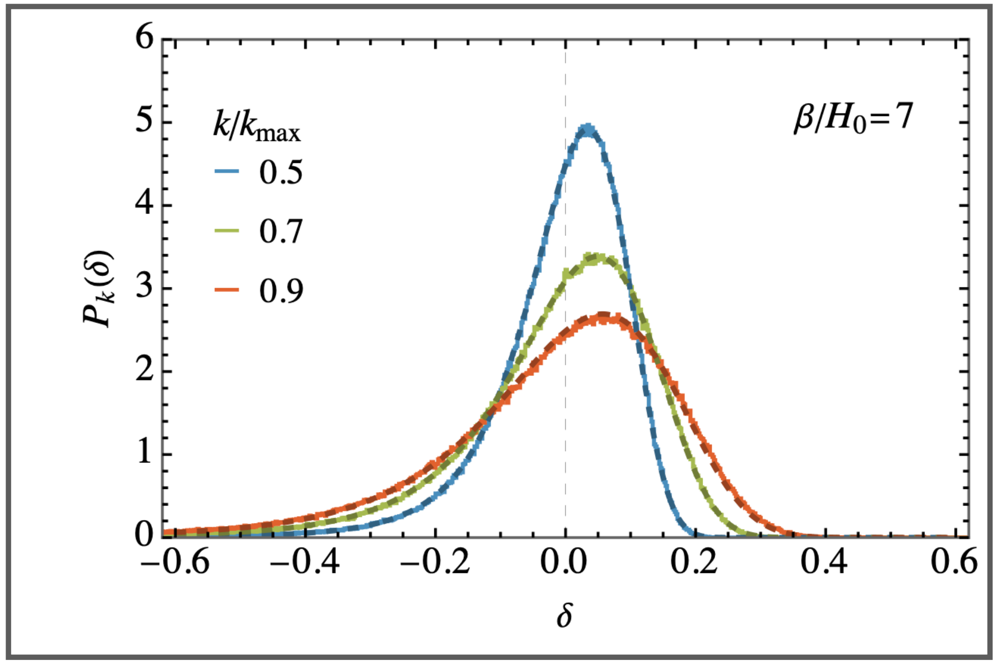

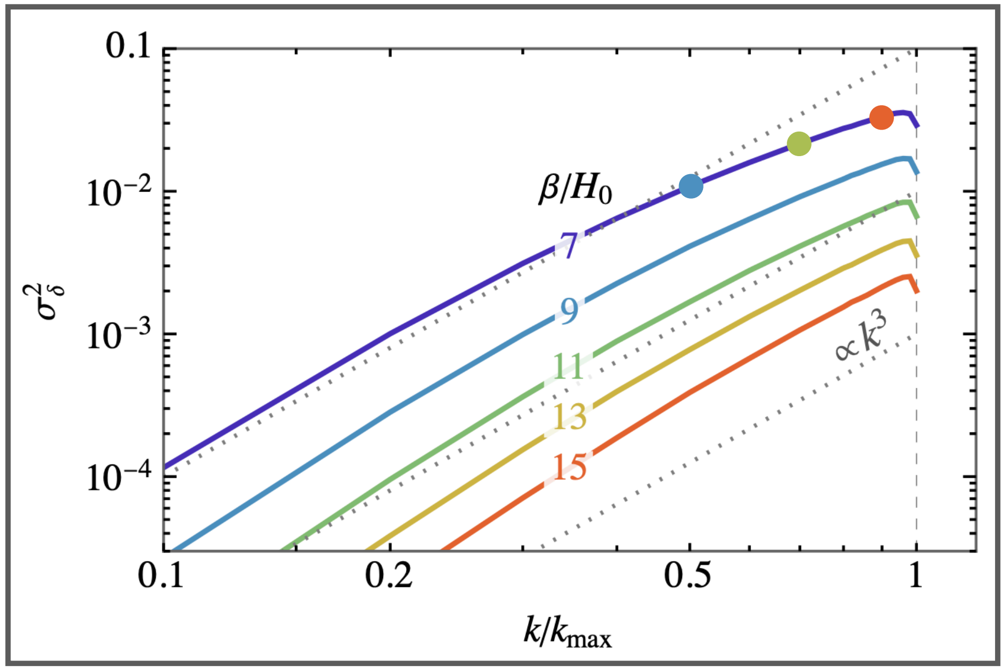

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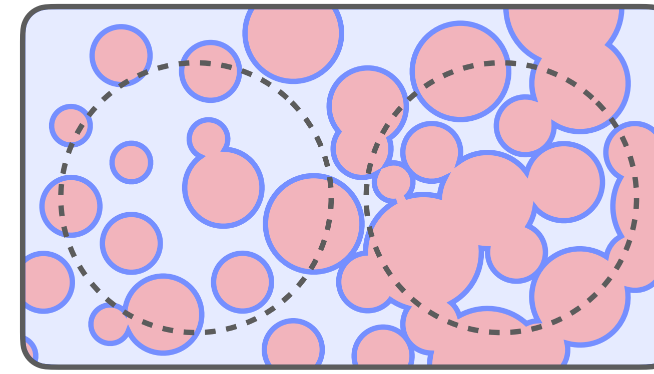

➤ Setu

② Pe

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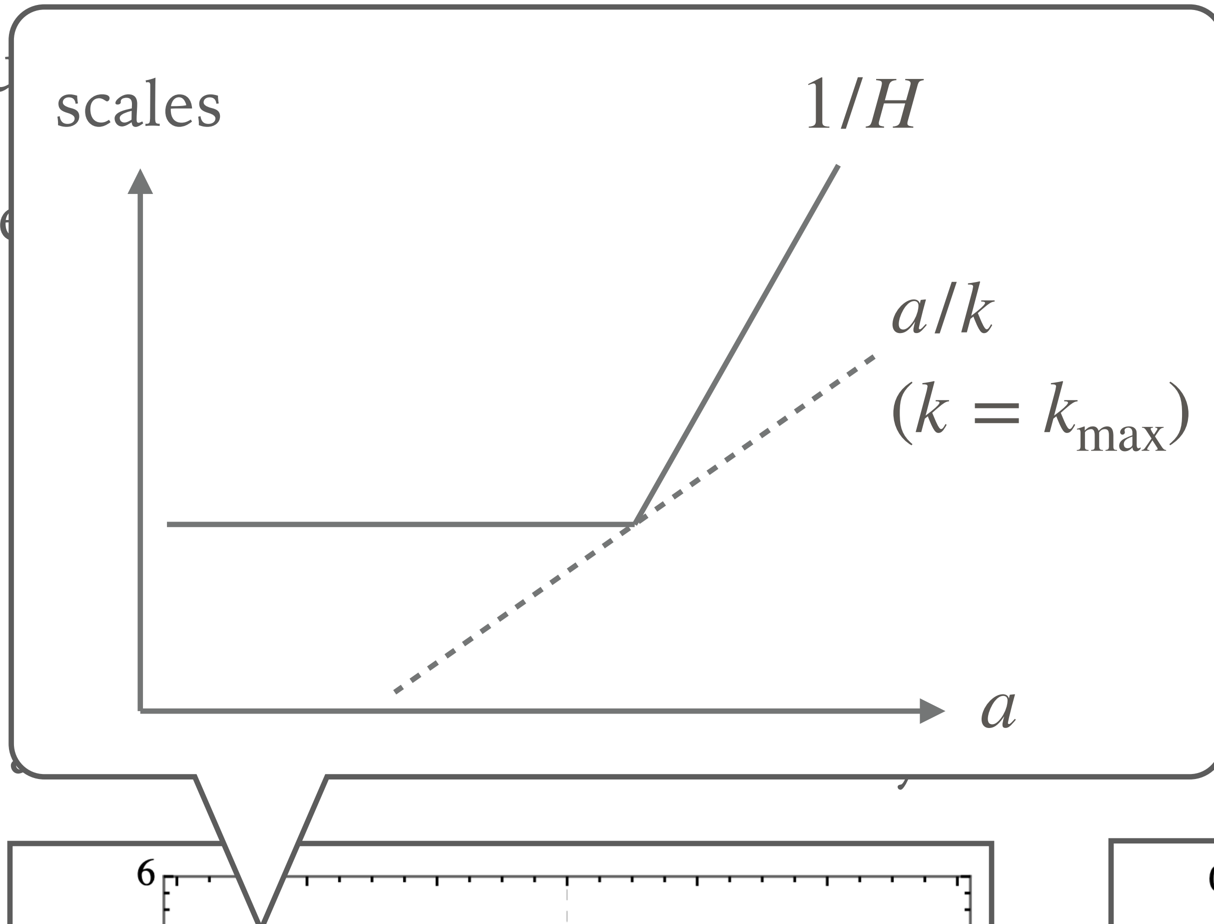

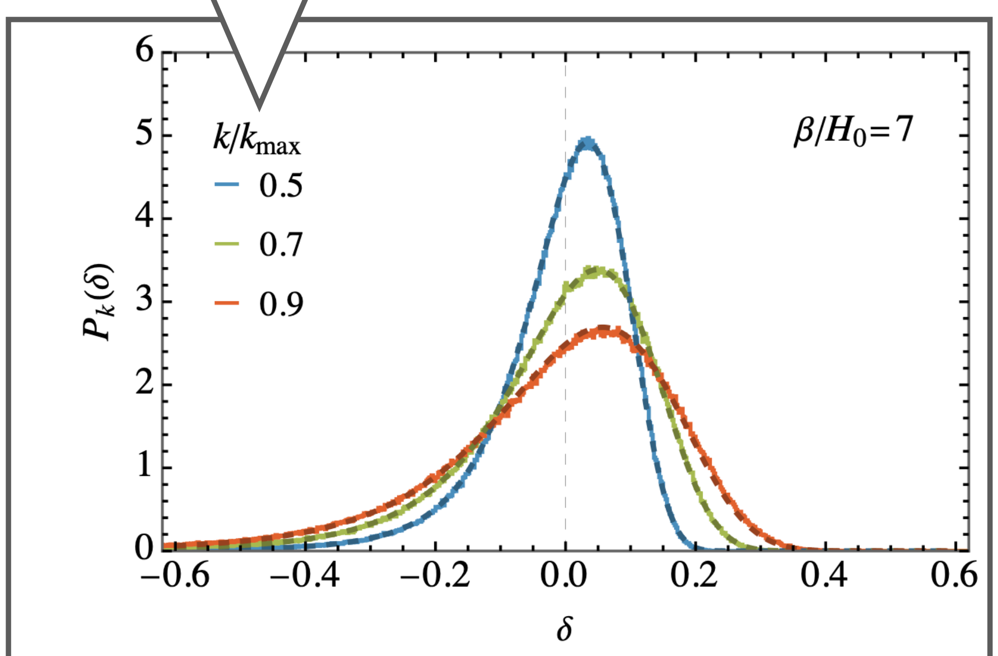

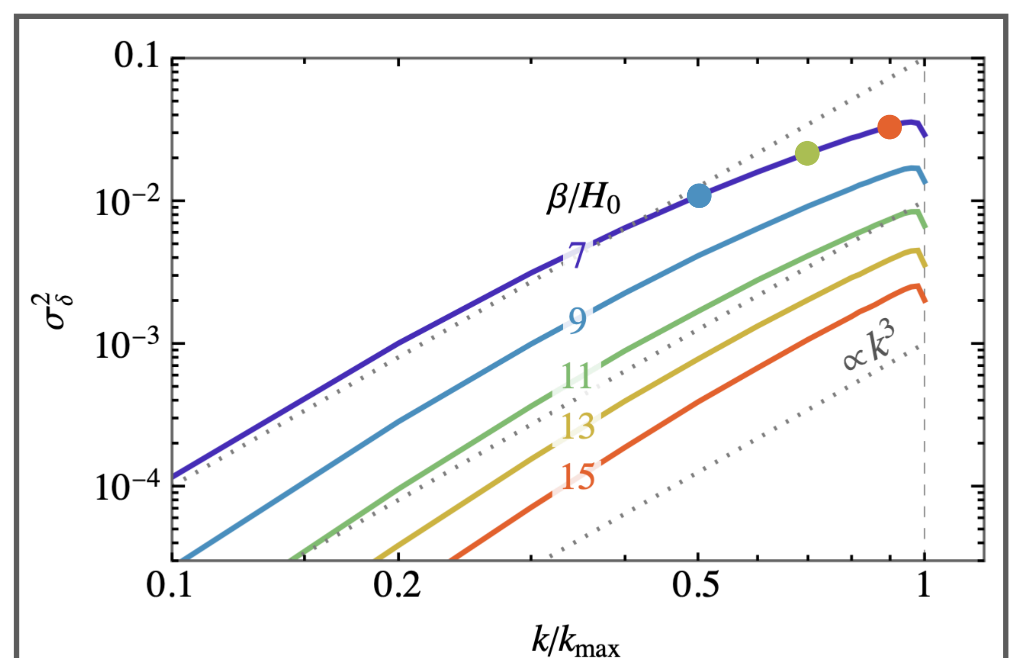

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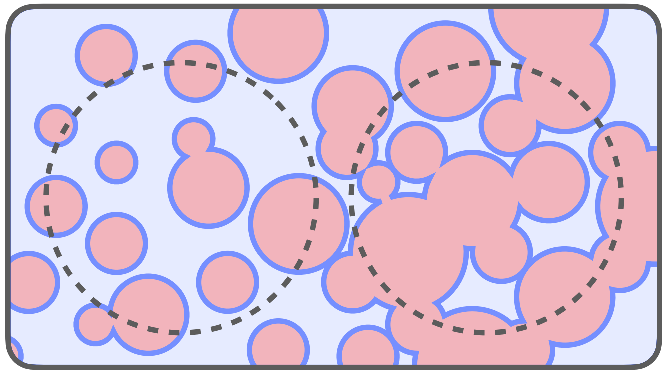
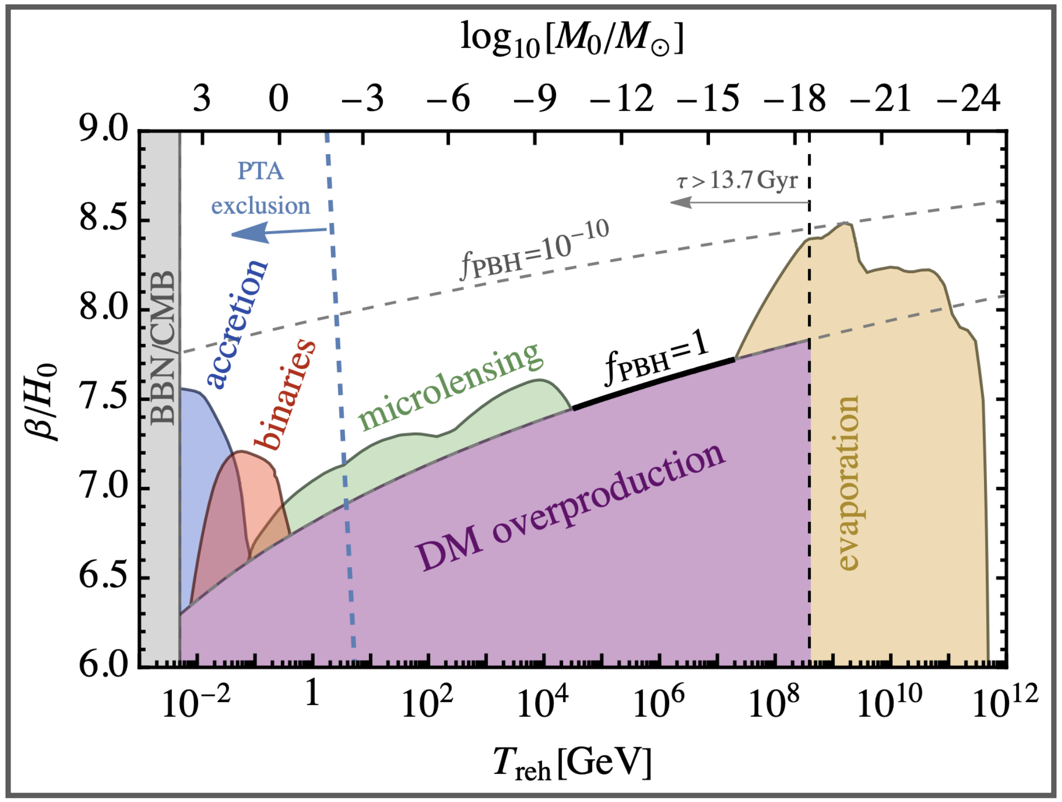


➤ Setup & findings of [Lewicki, Troczek, Vaskonen '24]

② Perturbation

- For $\beta/H_* \lesssim 7$ the variance of the density contrast is so large that the density contrast δ exceeds the threshold for PBH formation $\delta_c = 0.55$ frequently enough to explain the whole DM by PBHs



GAUGE ISSUES

[Franciolini, RJ, Gouttenoire '25]

- δ is the density contrast, but in which gauge?

- Our point: δ should be interpreted as the density contrast in the flat gauge $\delta^{(F)}$, since in the algorithm of [Lewicki, Troczek, Vaskonen '24] the density contrast is computed in a ***flat*** FLRW universe

- On the other hand, the threshold $\delta_c \sim 0.5$ is estimated in the comoving gauge

- How would the conclusion change if we use the gauge consistently?

GAUGE ISSUES

[Franciolini, RJ, Gouttenoire '25]

- Perturbation equations we solve

false-vacuum fraction is here

$$\delta_{\boldsymbol{k}}^{(F)\prime} + 3\mathscr{H}(c_s^2 - w)\delta_{\boldsymbol{k}}^{(F)} = (1+w)\mathscr{V}_{\boldsymbol{k}} - 3\mathscr{H}\underline{\delta_{p,\mathrm{nad},\boldsymbol{k}}}$$

$$\Phi_{\boldsymbol{k}}'' + 3(1+c_s^2)\mathscr{H}\Phi_{\boldsymbol{k}}' + \left[3(c_s^2 - w)\mathscr{H}^2 + c_s^2 k^2\right]\Phi_{\boldsymbol{k}} = \frac{3}{2}\mathscr{H}\underline{\delta_{p,\mathrm{nad},\boldsymbol{k}}}$$

$$\mathscr{V}_{\boldsymbol{k}} = -\frac{2}{3(1+w)}\frac{\Phi_{\boldsymbol{k}}' + \mathscr{H}\Phi_{\boldsymbol{k}}}{\mathscr{H}}$$

- Equation of state $w = \bar{p}/\bar{\rho}$ & sound speed $c_s^2 = \bar{p}'/\bar{\rho}'$

- Gauge-invariant Newtonian potential Φ & scalar velocity $\mathscr{V}$

- Gauge-invariant non-adiabatic pressure $\delta_{p,\mathrm{nad}} = \dfrac{\delta p_{\mathrm{nad}}}{\bar{\rho}}$, $\delta p_{\mathrm{nad}} = \delta p^{(F)} - c_s^2 \delta\rho^{(F)}$

- In the present case $\delta p_{\mathrm{nad}} = \dfrac{1-3c_s^2}{3}\bar{\rho}\delta^{(F)} + \dfrac{4}{3}\Delta V \underline{\delta F^{(F)}}$

fluctuation in the false-vacuum fraction

GAUGE ISSUES

[Franciolini, RJ, Gouttenoire '25]

- We use the (very efficient) code developed in [Lewicki, Troczek, Vaskonen '24] to calculate the distribution of the fluctuation $\delta F^{(F)}$

- The only difference is we identify it as the quantity in the flat gauge

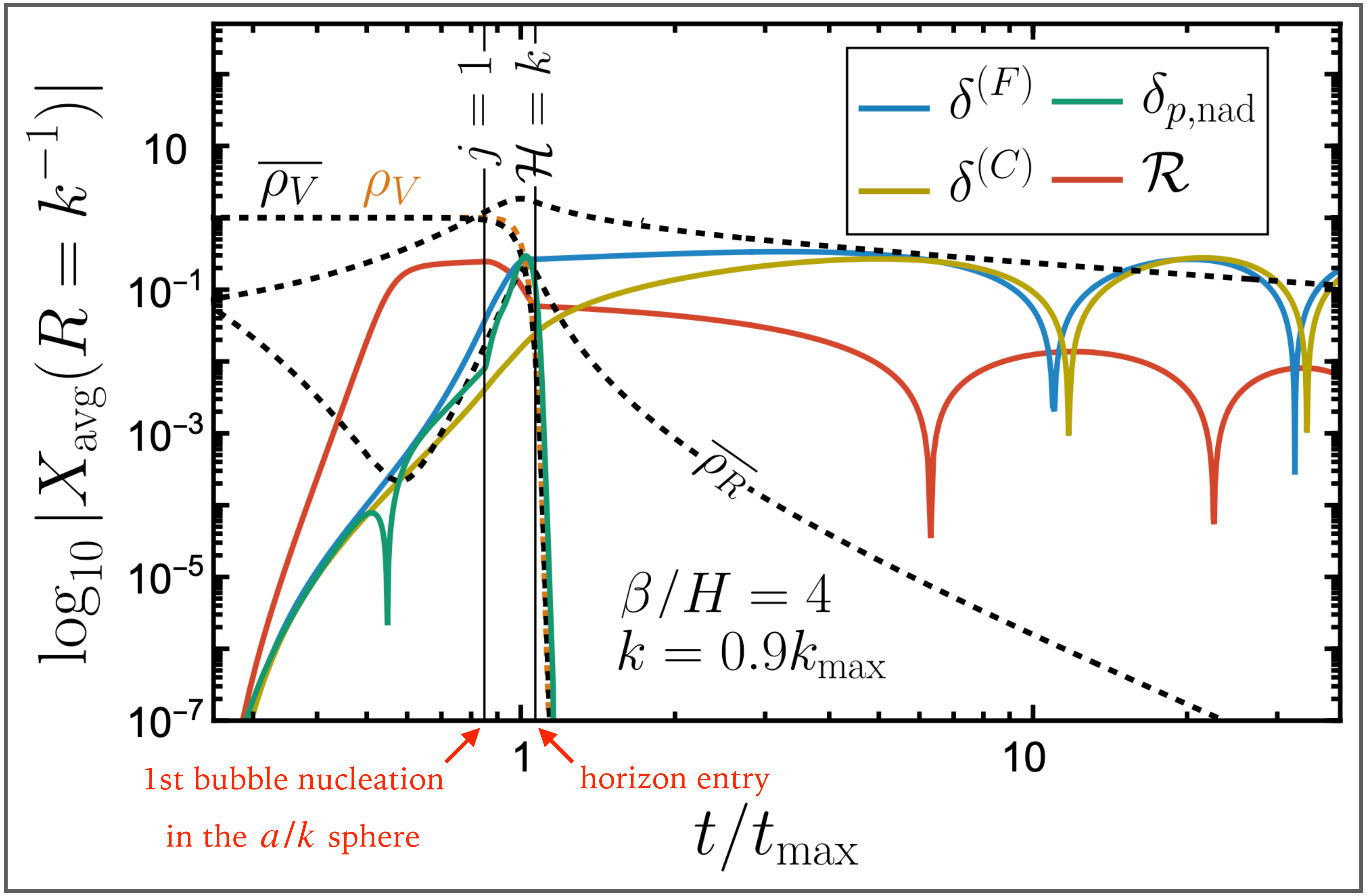
- Once the perturbation equations are solved, we also estimate $\delta_{\boldsymbol{k}}^{(C)}$ with

$$\delta_{\boldsymbol{k}}^{(C)} = \delta_{\boldsymbol{k}}^{(F)} + (5 + 3w)\Phi_{\boldsymbol{k}} + \frac{2\Phi'_{\boldsymbol{k}}}{\mathscr{H}}$$

TYPICAL TIME EVOLUTION

[Franciolini, RJ, Gouttenoire '25]

➤ Point: difference between $\delta_{\boldsymbol{k}}^{(F)}$ and $\delta_{\boldsymbol{k}}^{(C)}$ around the horizon entry



TYPICAL TIME EVOLUTION

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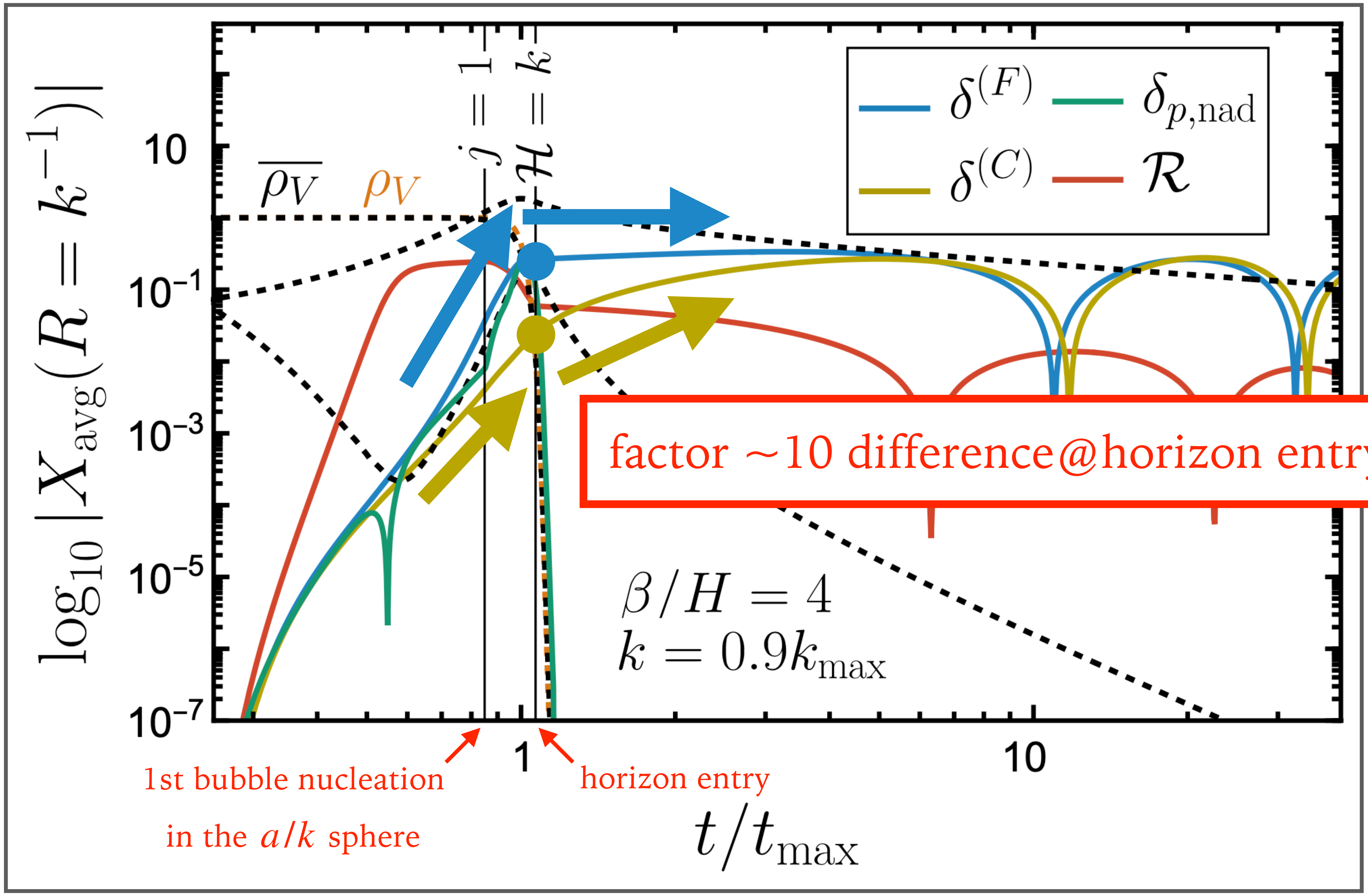
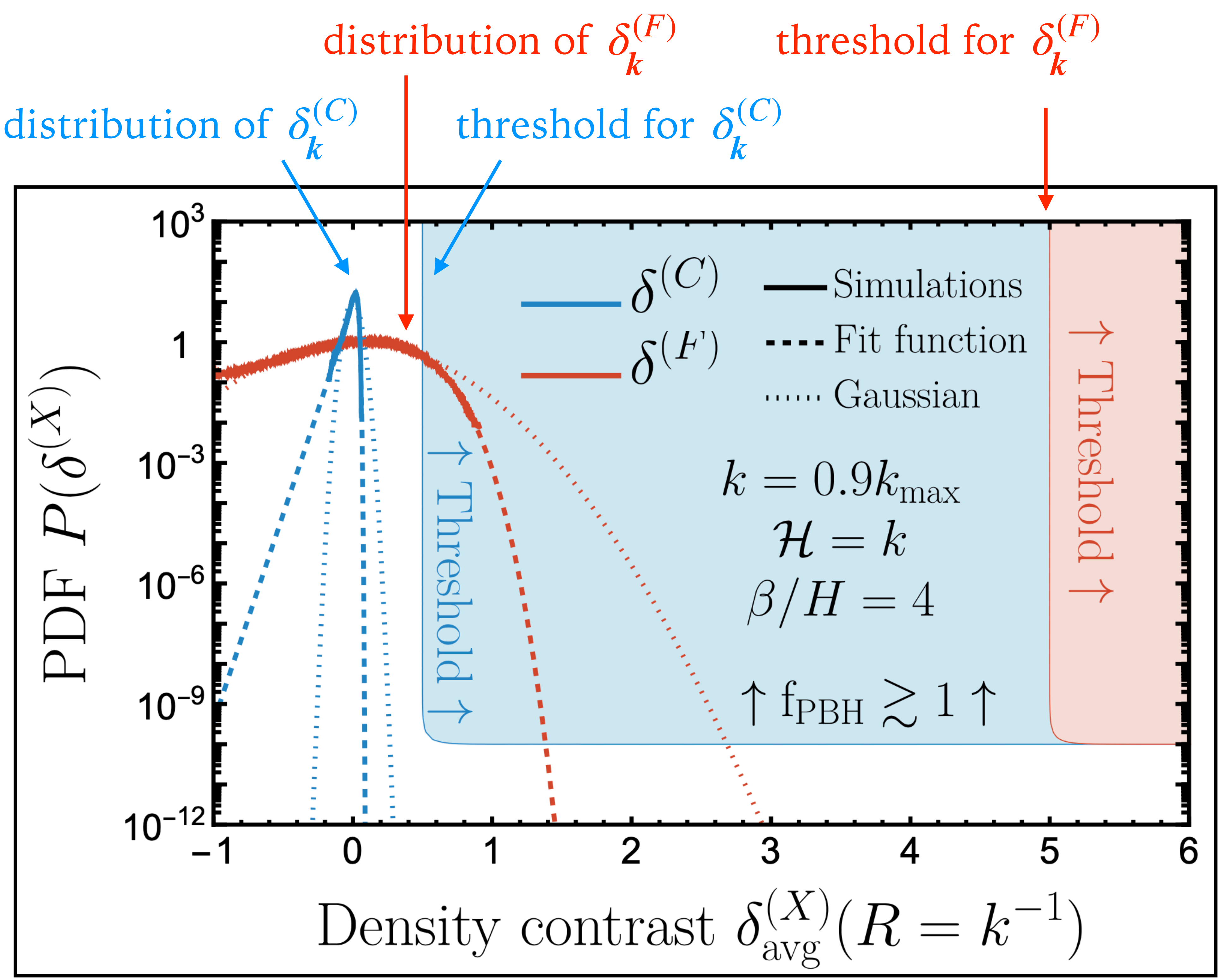


PBH FORMATION IS UNLIKELY

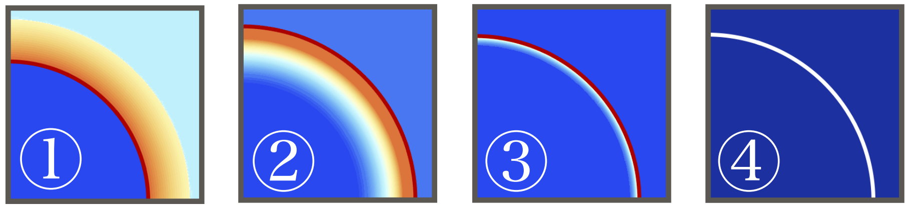
[Franciolini, RJ, Gouttenoire '25]



First-order phase transitions in the early Universe:

gravitational waves, black holes, and ***feebly-interacting particles***

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).

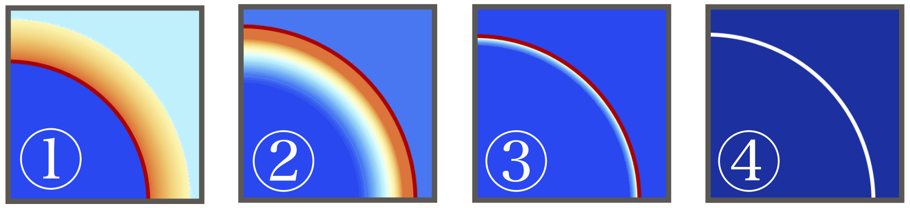
<u>Fluid</u> (dominant in case ①②③) = Sound waves & Turbulence

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

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

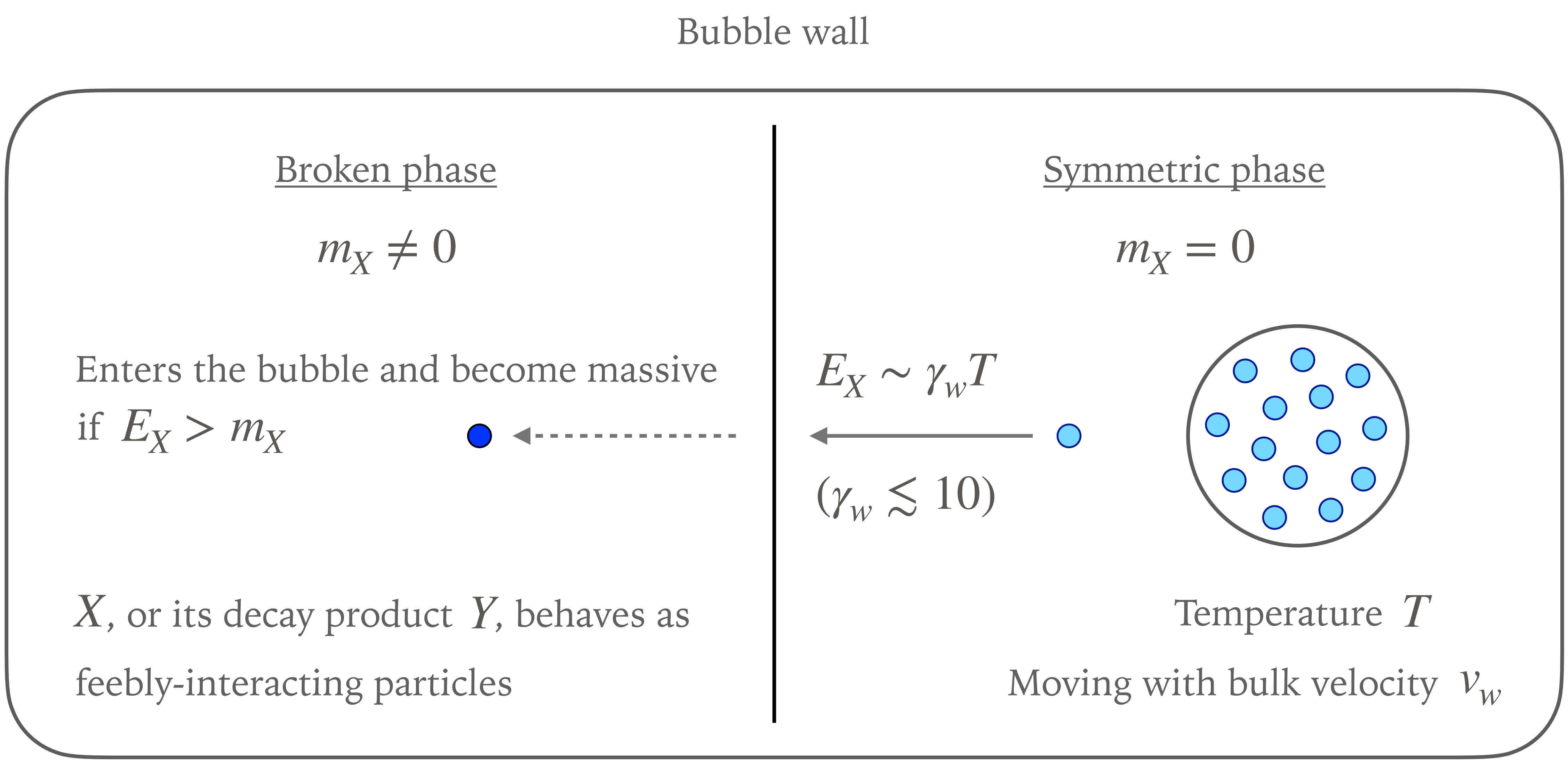
Particles in the broken phase frequently interact and can be described by fluid picture.

Feebly-interacting particles

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

GW PRODUCTION: THE STANDARD LORE & BEYOND

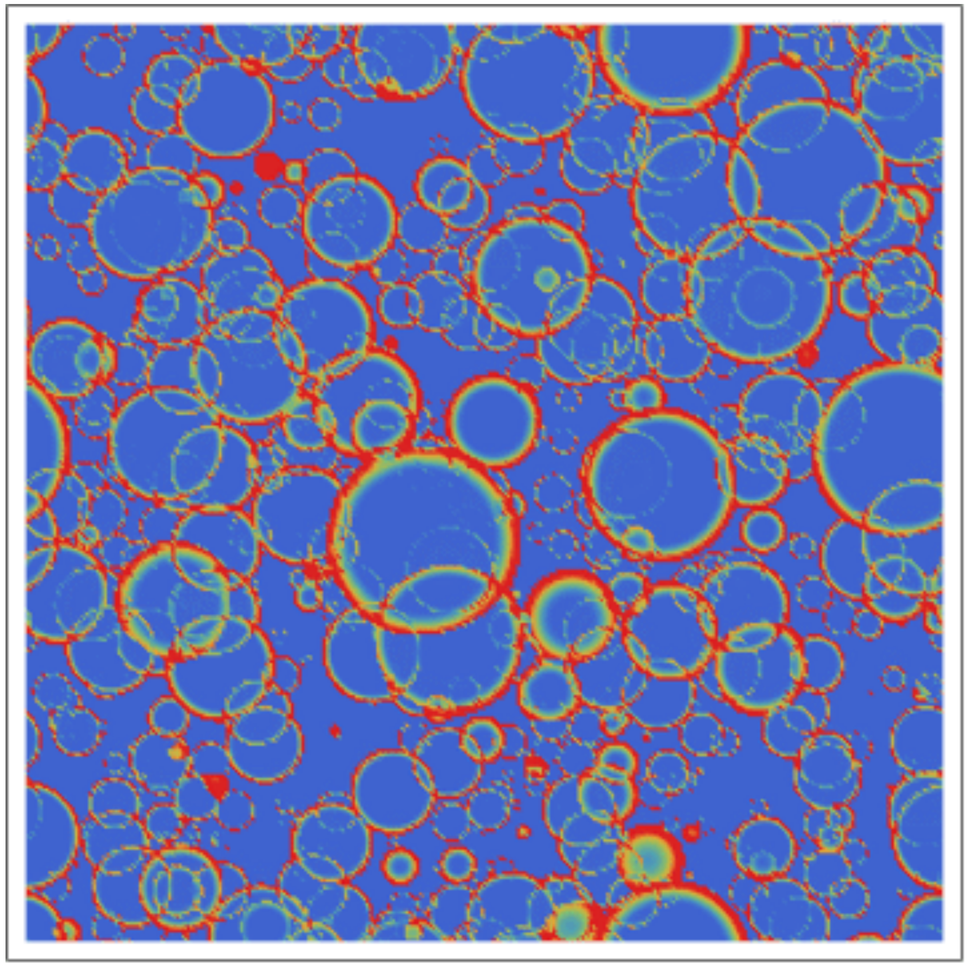
➤ Particle dynamics seen in the wall rest frame



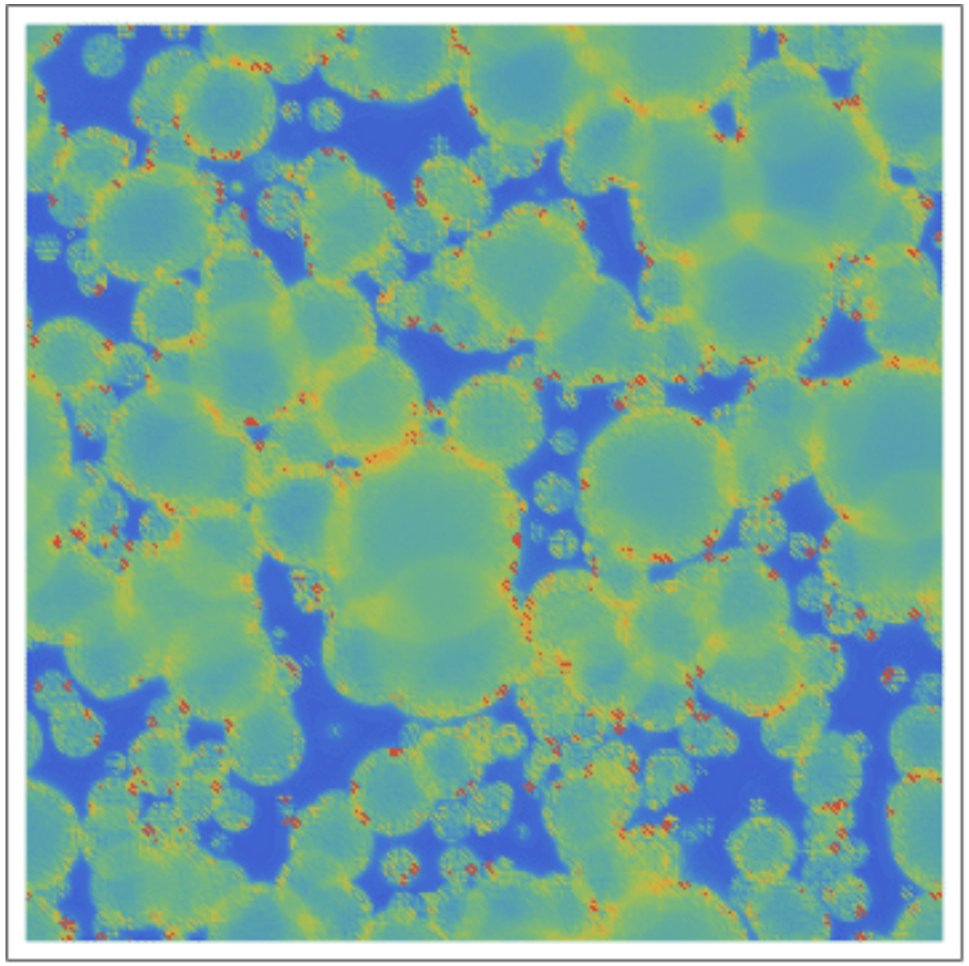
FLUID VS. FREE-STREAMING PARTICLES

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

Fluid



Free-streaming

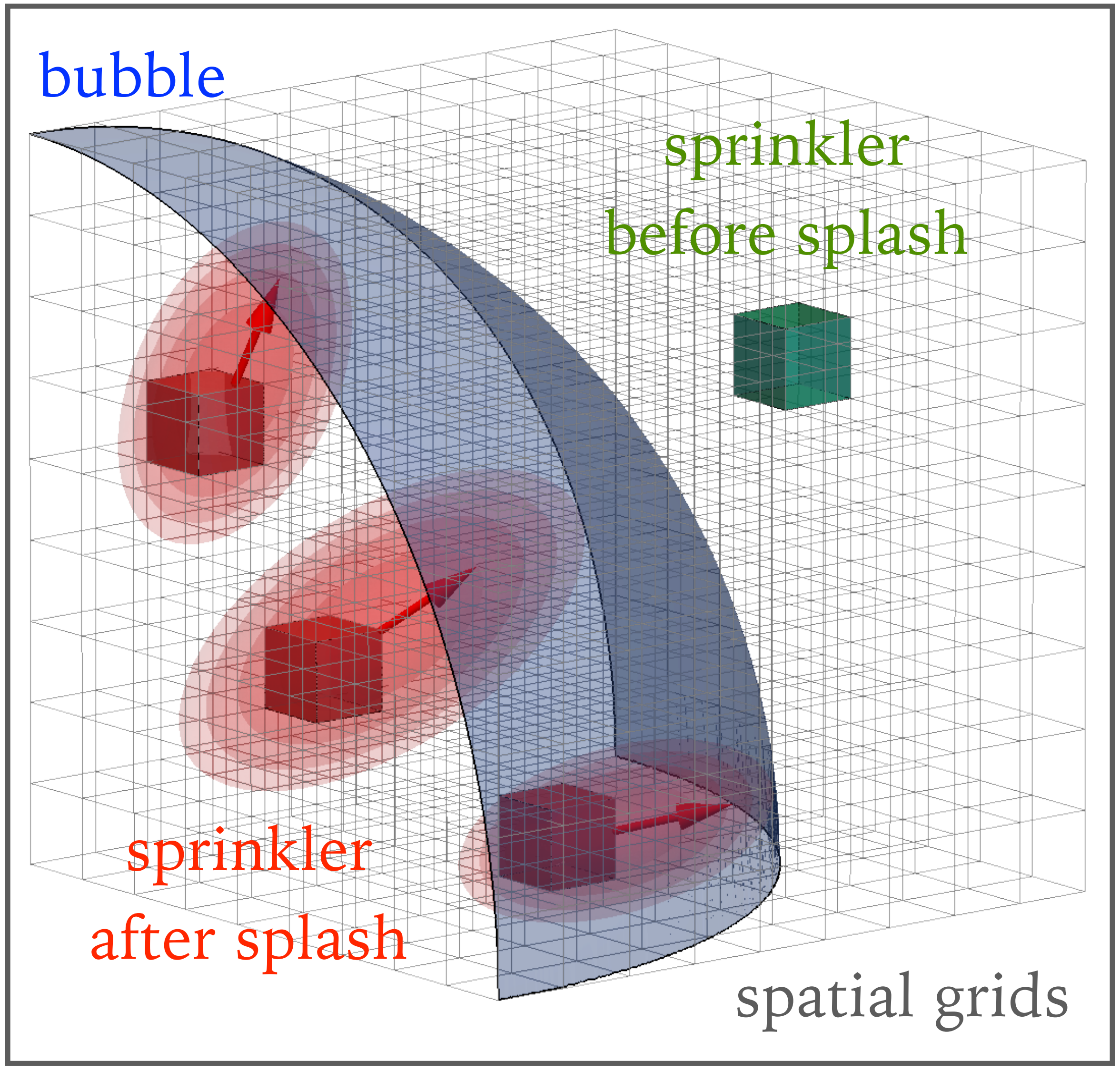


HOW TO CALCULATE GW PRODUCTION

[RJ, Shakya, van de Vis '22]

➤ To calculate the GW spectrum,

we propose a new calculation scheme – "sprinkler picture"

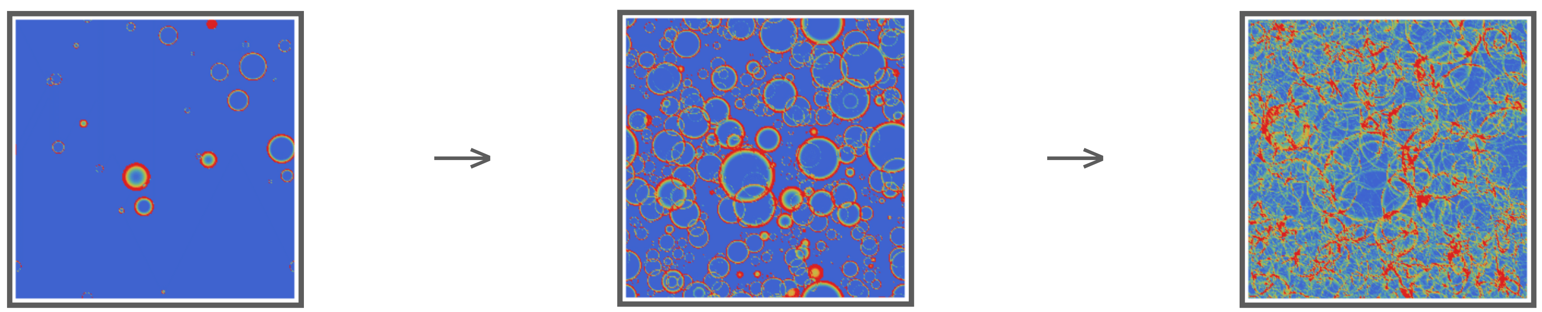


GW SPECTRUM FOR SOUND-WAVE SOURCE

[RJ, Shakya, van de Vis '22]

- 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 nonlinearity:

  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

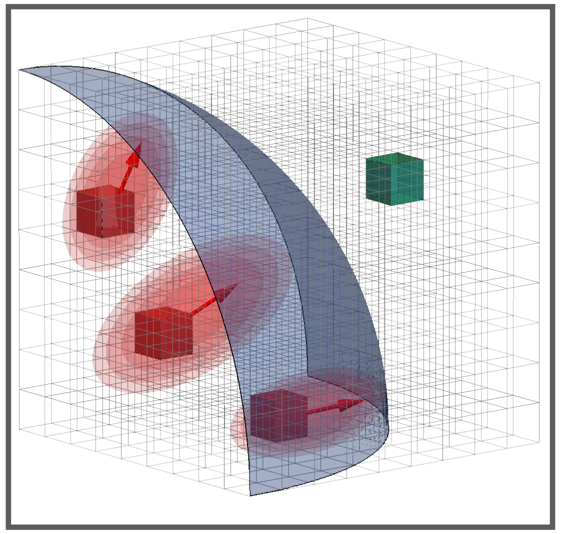
[RJ, Shakya, van de Vis '22]

➤ 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,

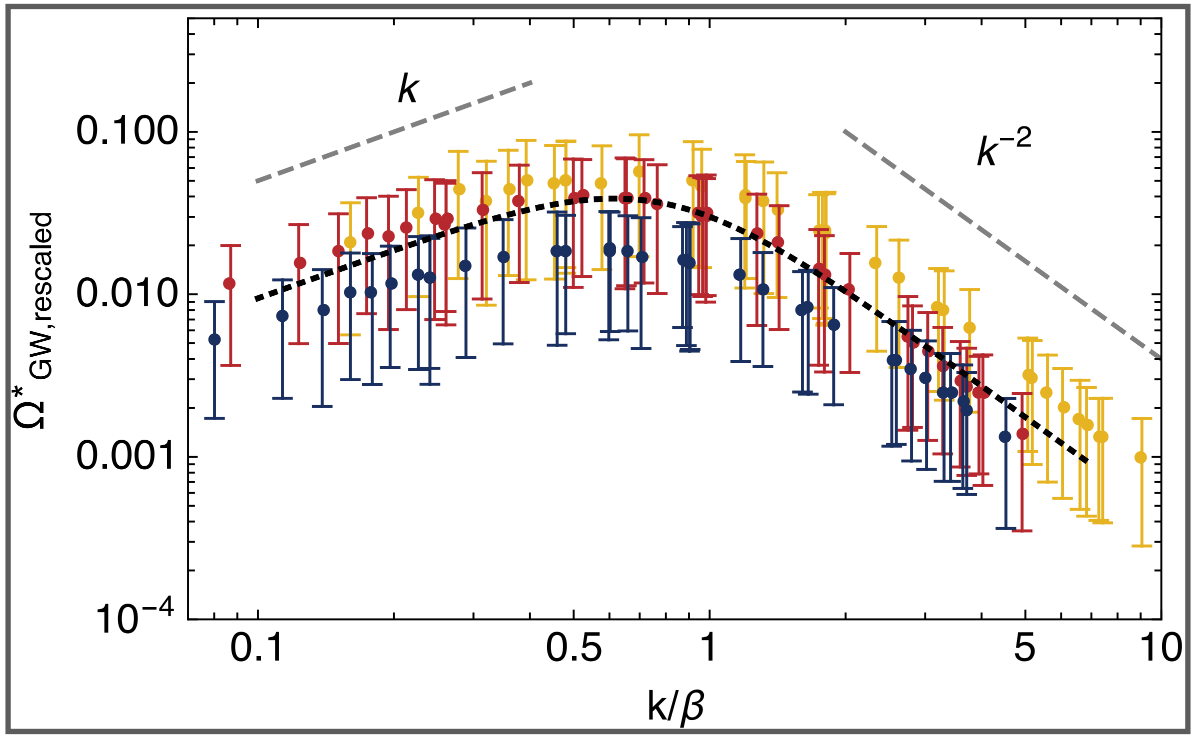
and the contributions from different sprinklers (= grids) are linearly superposed

NUMERICAL RESULTS

[RJ, Shakya, van de Vis '22]

- GW spectral shape is universal

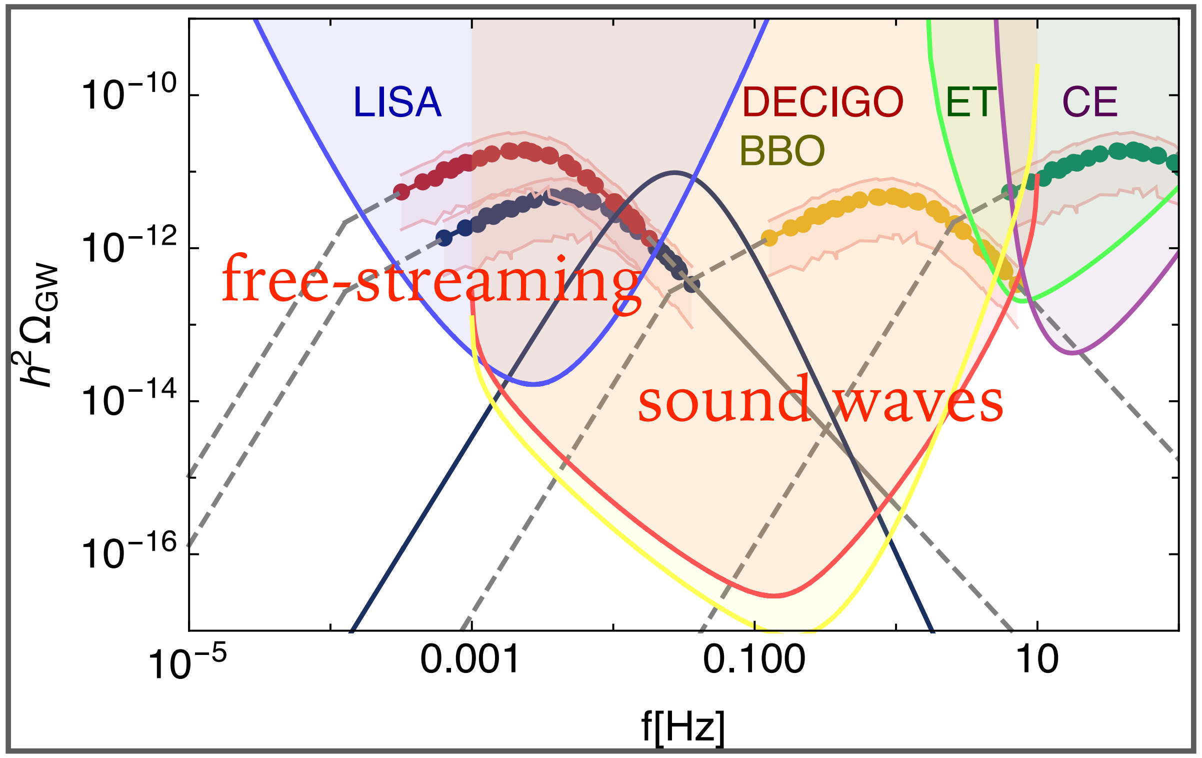
  (after normalizing by some factor)



- GW spectrum is clearly

  different from sound-wave sources:

  it stretches over wider frequencies



SUMMARY

- FOPTs in the early Universe require understanding across different scales, making them an interesting and challenging topic
- GW production from fluid dynamics from FOPTs is improving (our proposal: the Higgsless scheme)
- Very strong FOPTs can be realized in nearly conformal models, though PBH formation is unlikely
- If feebly-interacting particles are produced during the transition, they leave characteristic imprint on the GW spectrum

Backup

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 $\sim 1/\langle s \rangle$)

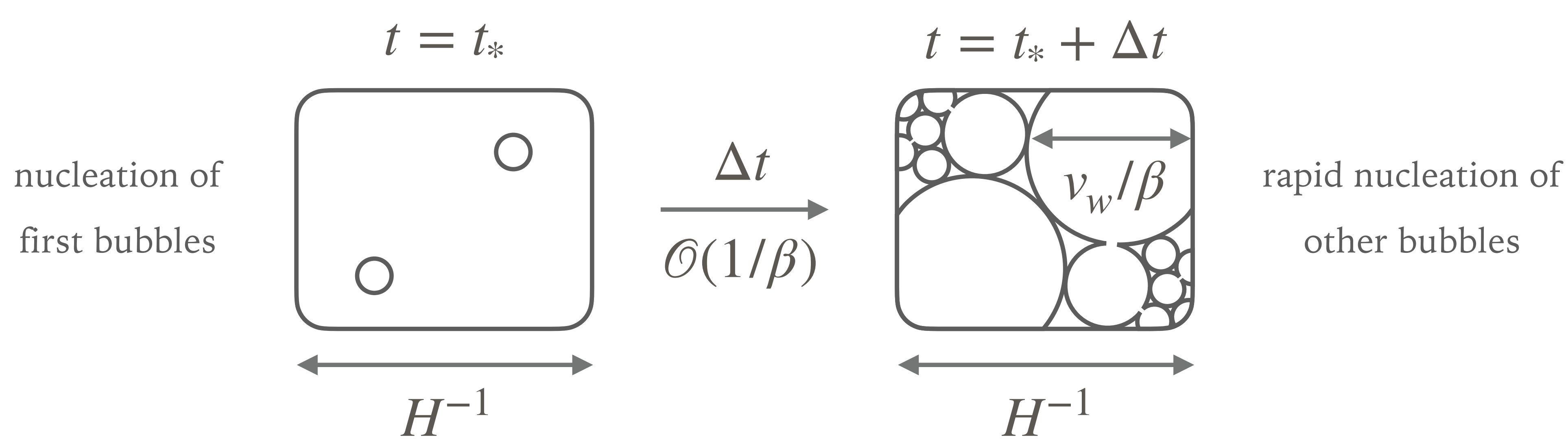
  - walls reach a terminal velocity v_w (or equivalently $\gamma_w = 1\Big/\sqrt{1 - v_w^2}$)

- 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 $\Delta t \sim \mathcal{O}(1/\beta)$

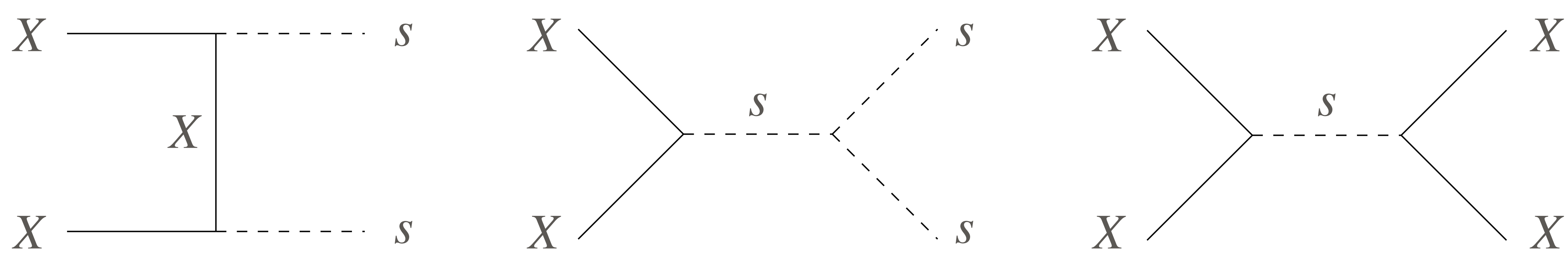


- So, we need the condition $n\sigma\Delta t \sim \dfrac{T^3\sigma}{\beta} \lesssim 1$

CONDITIONS ON FEEBLE INTERACTION

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

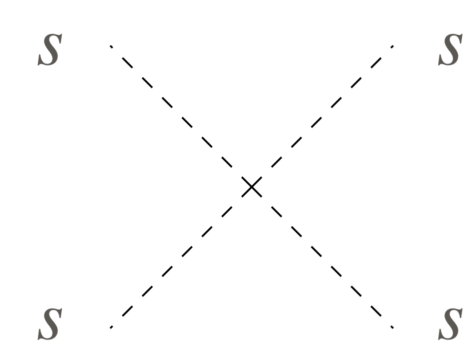
  The couplings that gives rise to mass also give rise to interactions



- 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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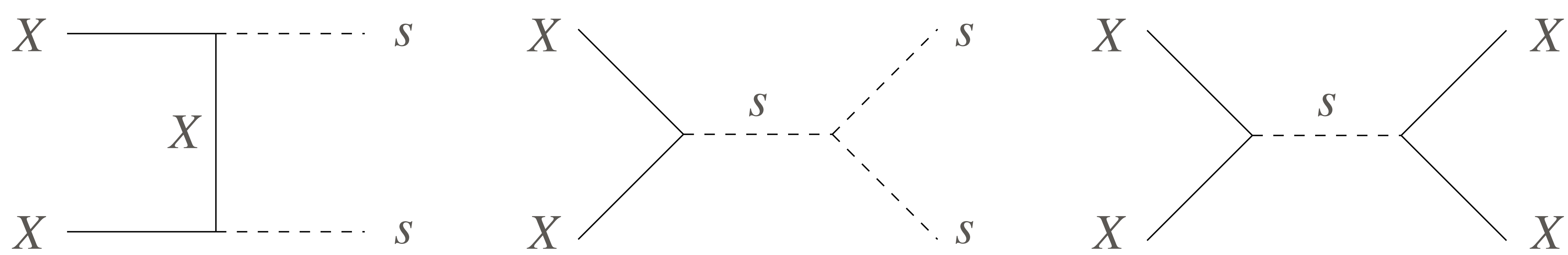

- Can X be a gauge boson $X = Z'$?

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

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

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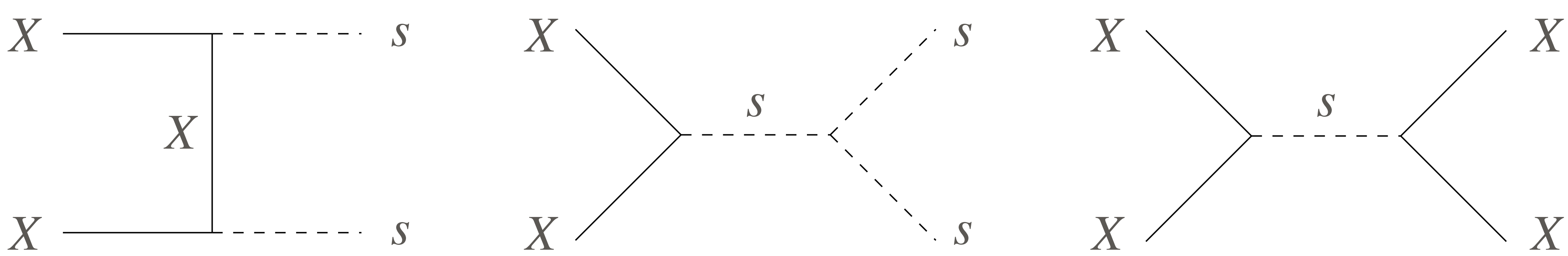

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Doable, but not generic

CONDITIONS ON FEEBLE INTERACTION

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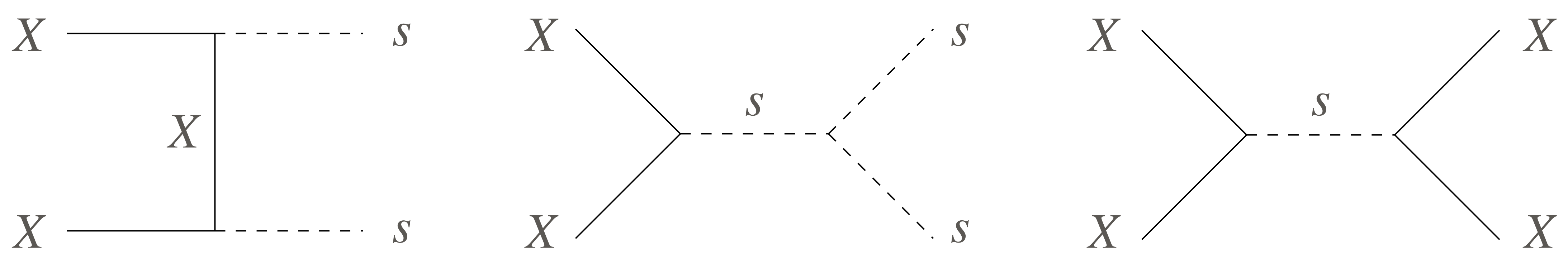
  The couplings that gives rise to mass also give rise to interactions



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