Summary

GW spectral "deformation"

Enhancement of GWs in FOPT

Instituto de Física Teórica UAM-CSIC

The interplay between density perturbations and GWs

Ryusuke Jinno (IFT)

Mainz workshop, July-August 2022

[Jinno, Konstandin, Rubira, v.d.Vis, 2108.11947]
[Domcke, Jinno, Rubira, 2002.11083]

V. Domcke

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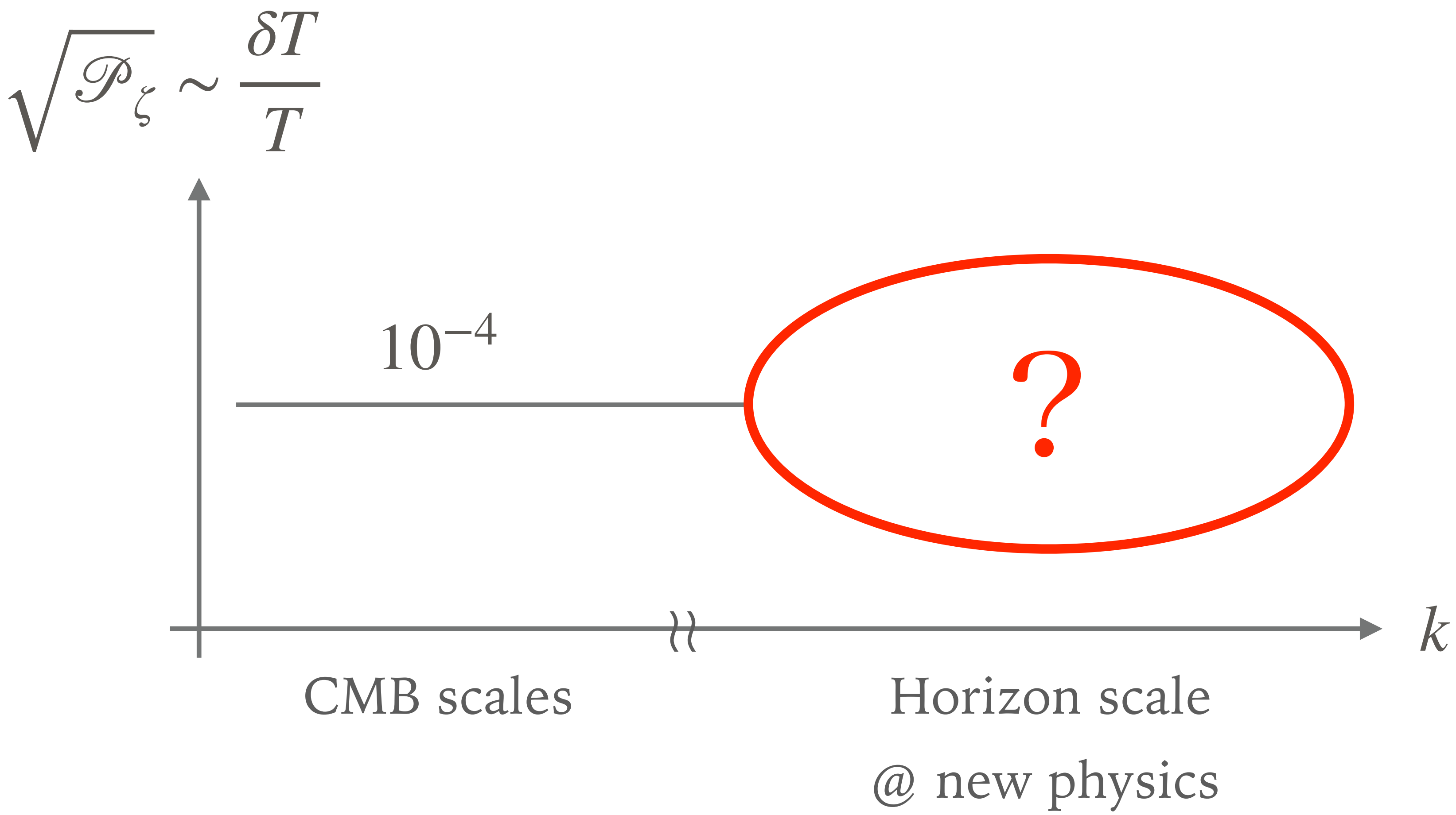
SUMMARY

➤ Density (curvature) perturbations

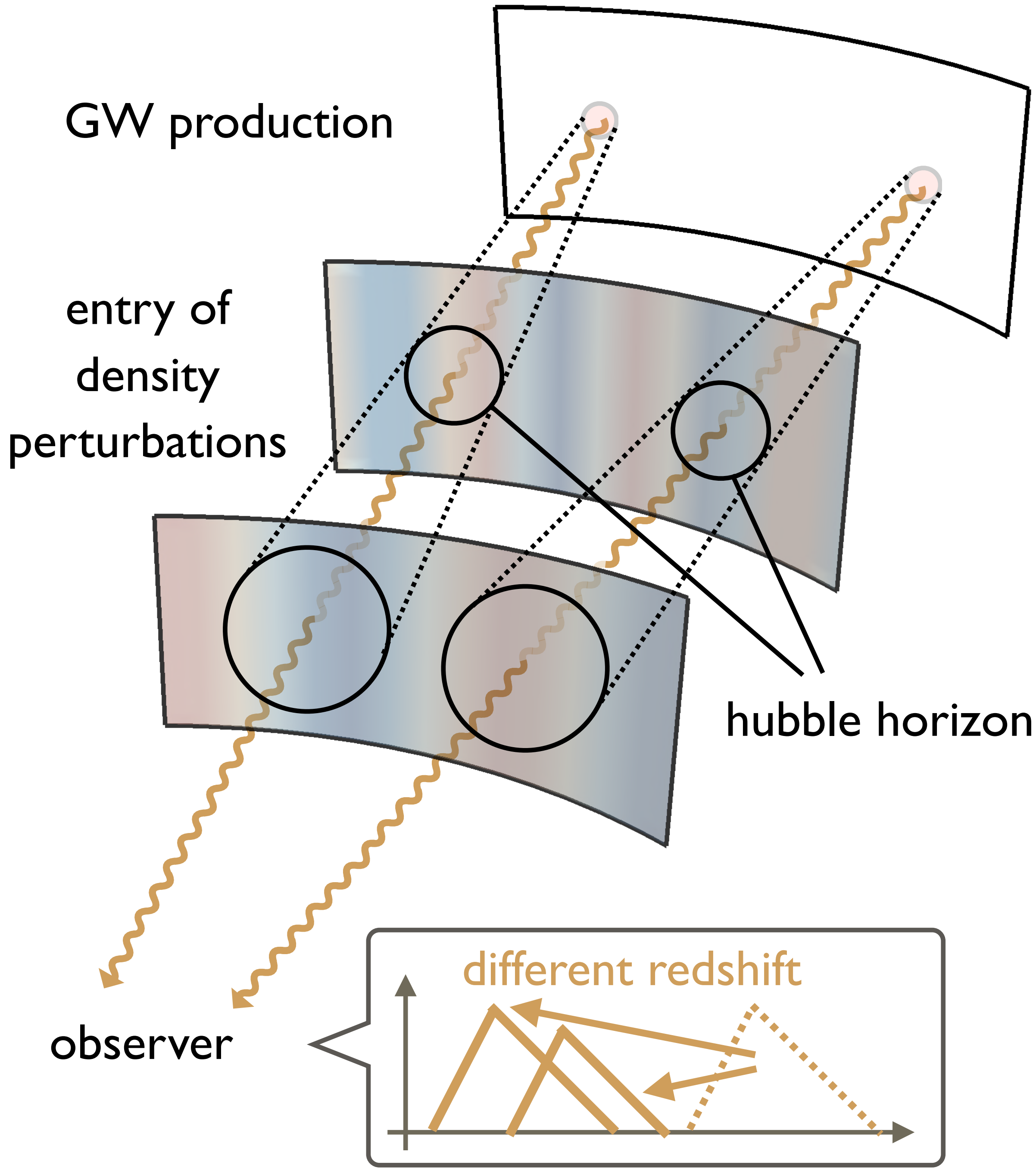
- Constrained to $\zeta \sim \frac{\delta T}{T} \sim 10^{-4}$ at CMB scales

- Almost unconstrained at smaller scales (large k)



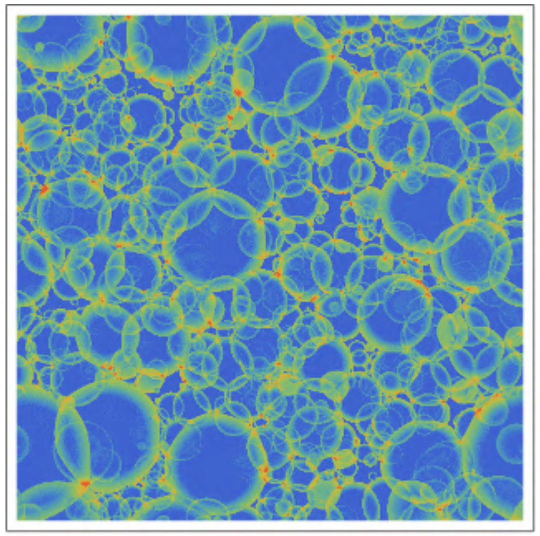
SUMMARY

Part 1

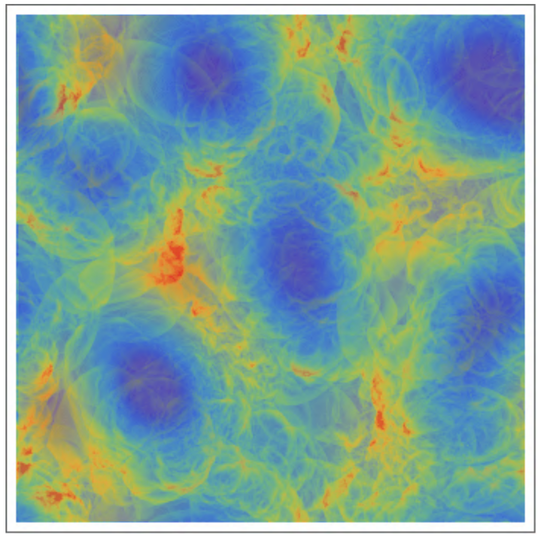


Part 2

Without density perturbations



With density perturbations



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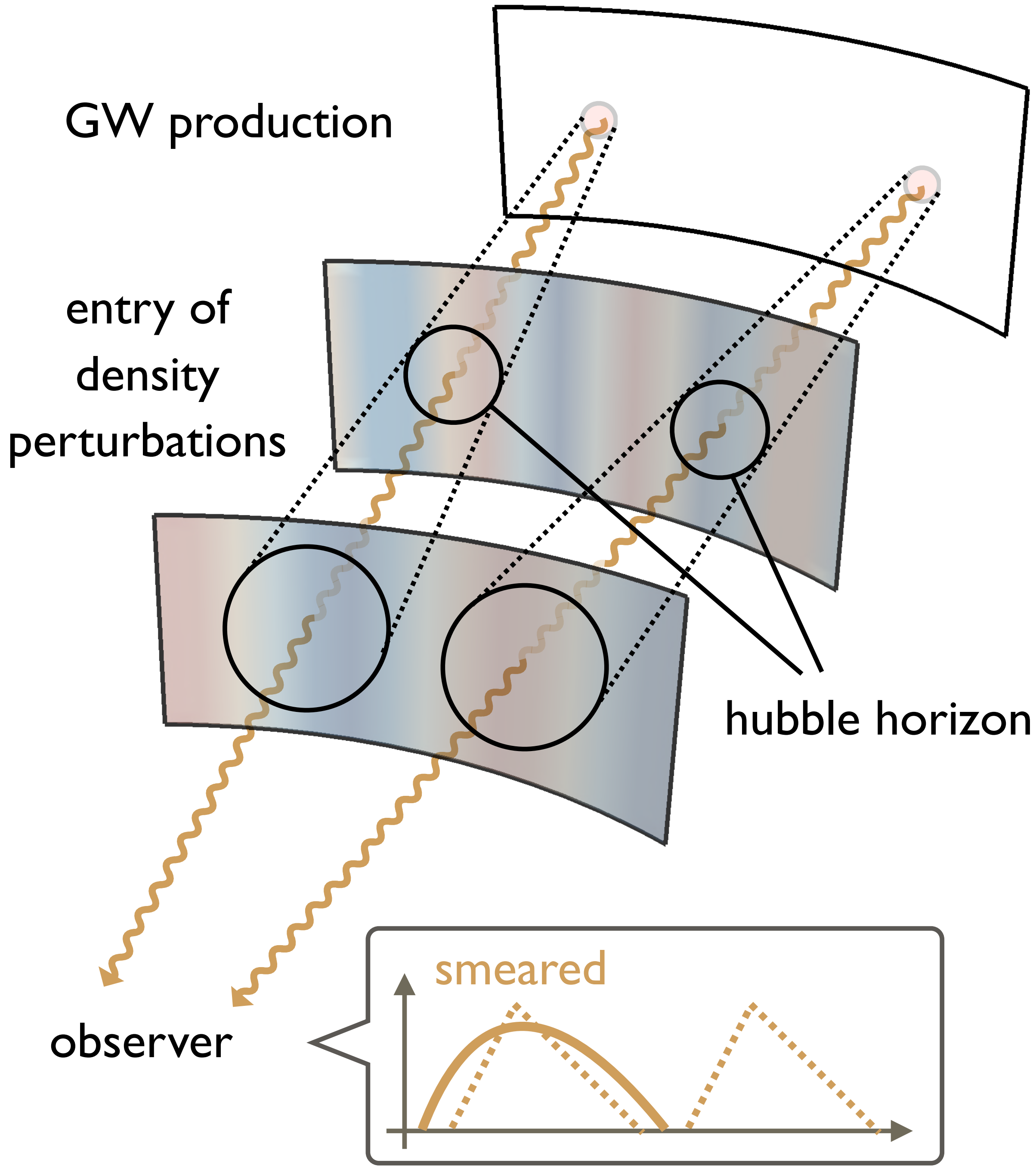
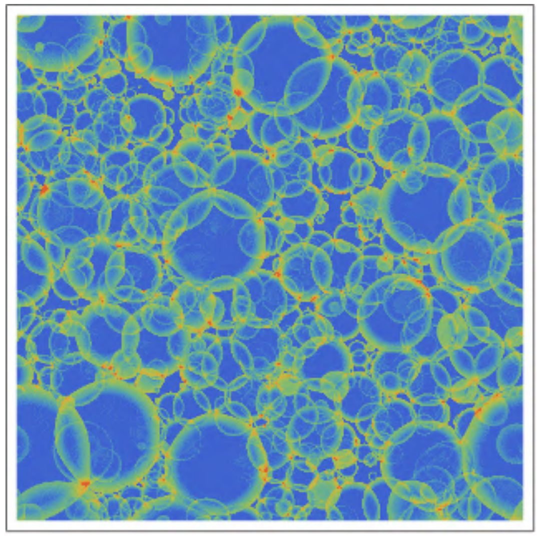
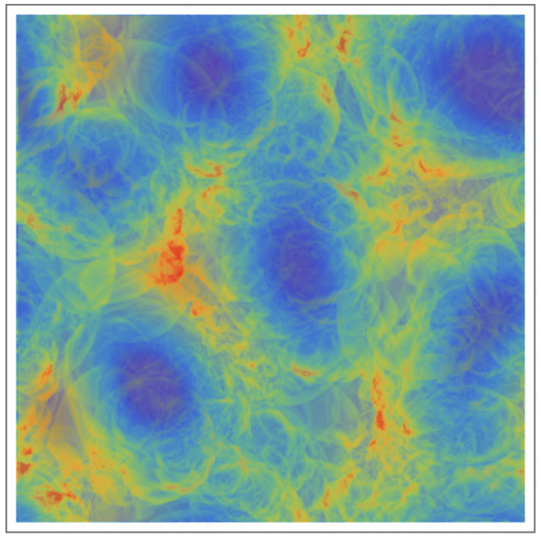


Part 2

Without density perturbations



With density perturbations

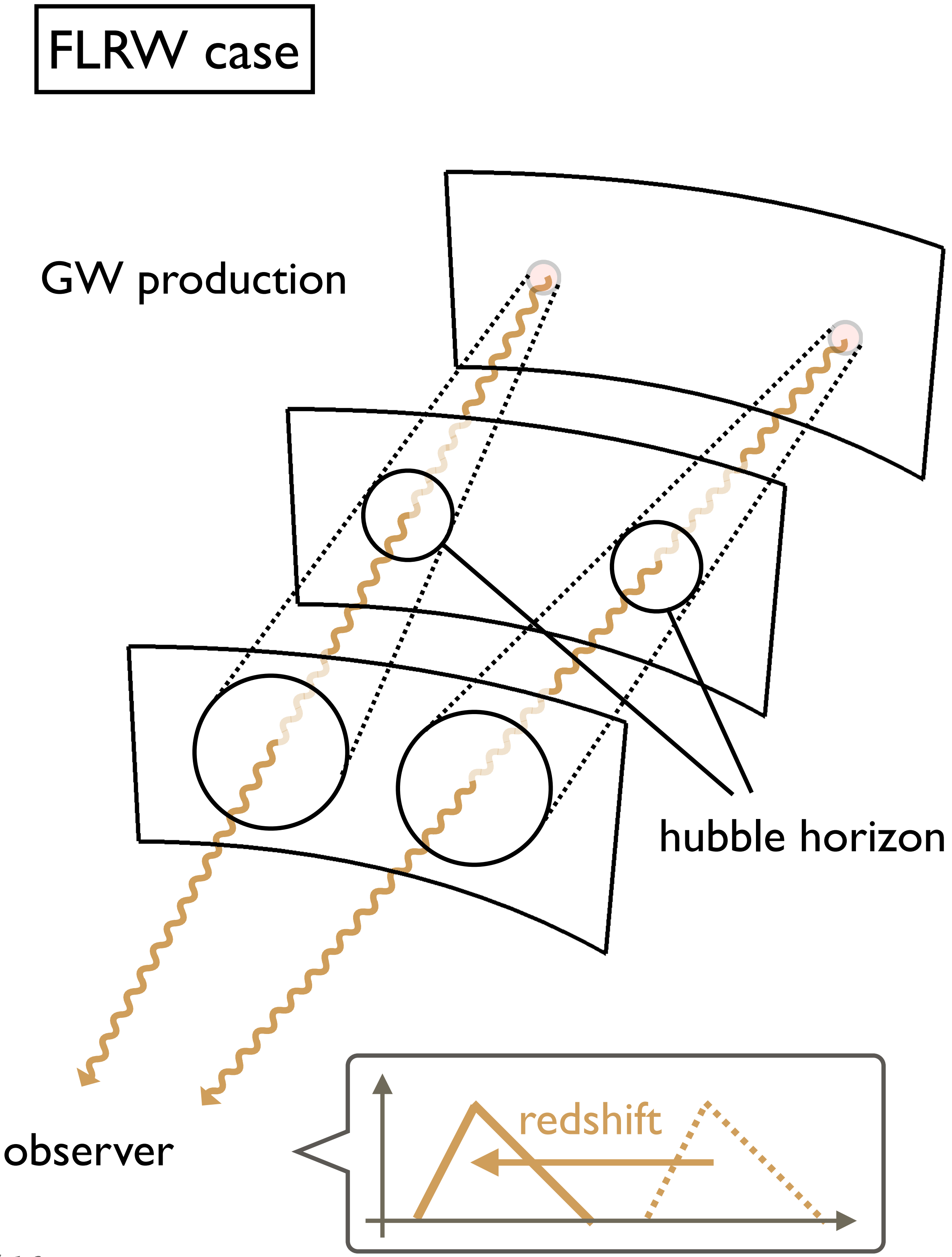


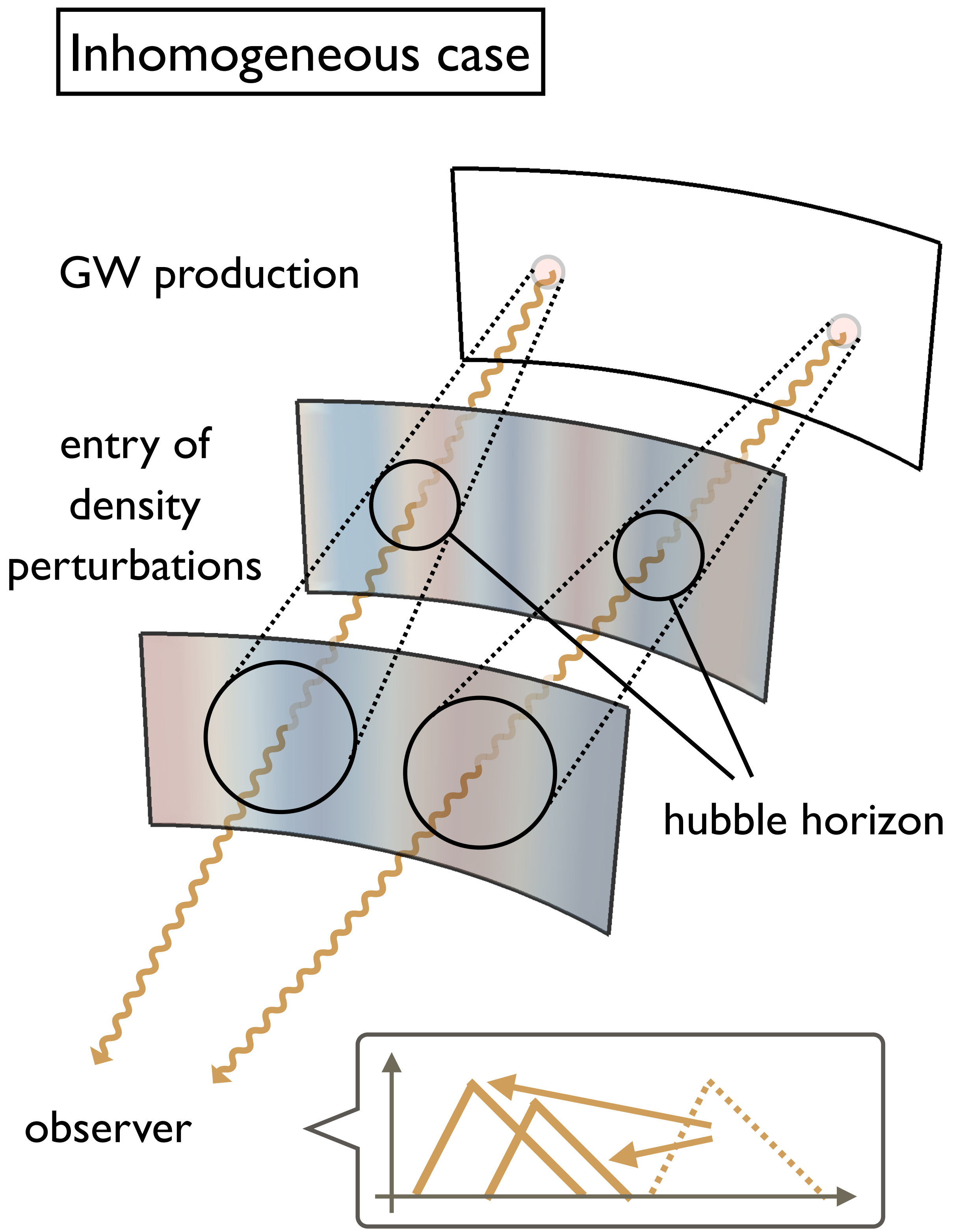
0 *Summary*

1 *GW spectral "deformation"*

2 *Enhancement of GWs in FOPT*

MAIN IDEA


FLRW case
GW production
hubble horizon
observer
redshift


Inhomogeneous case
GW production
entry of
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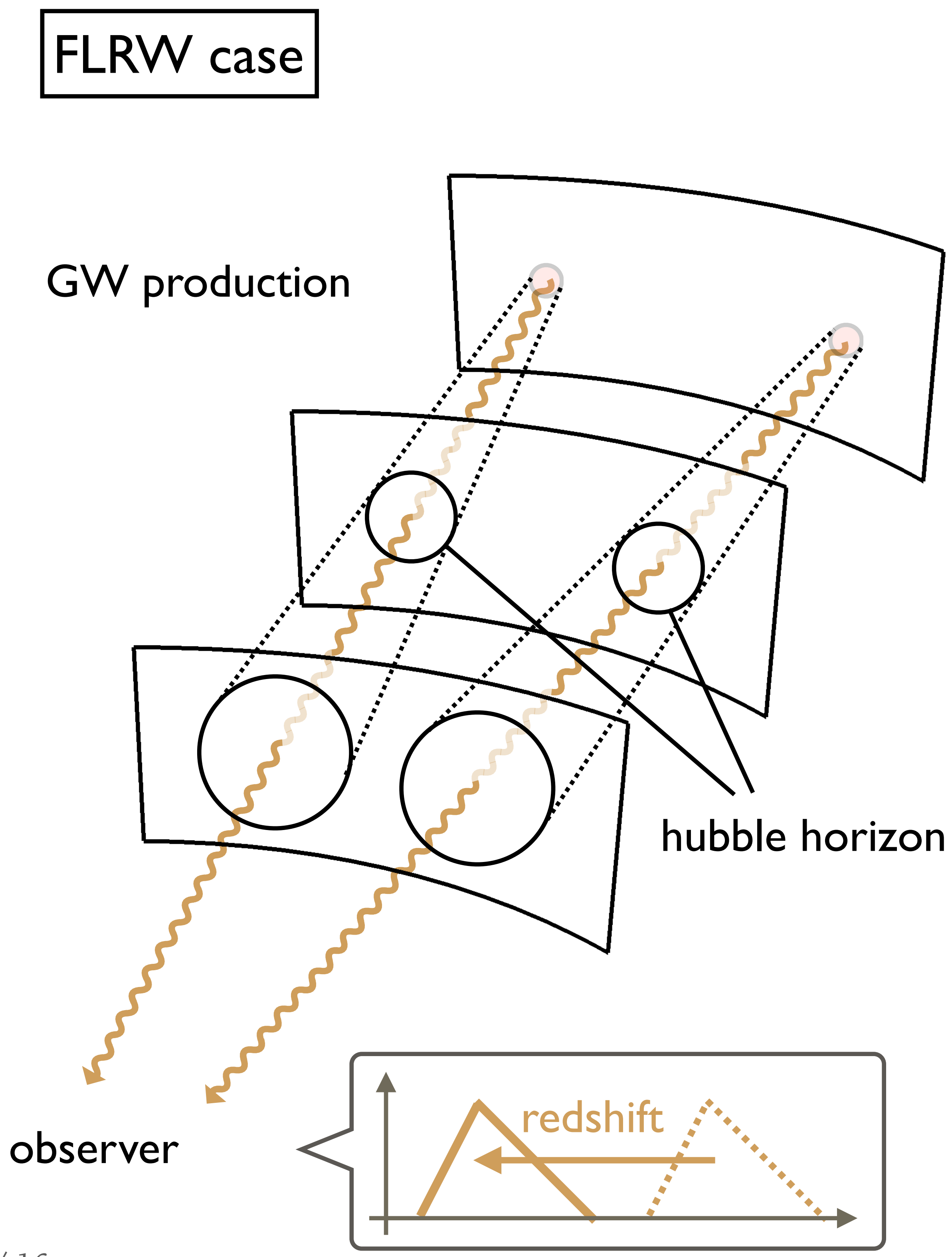
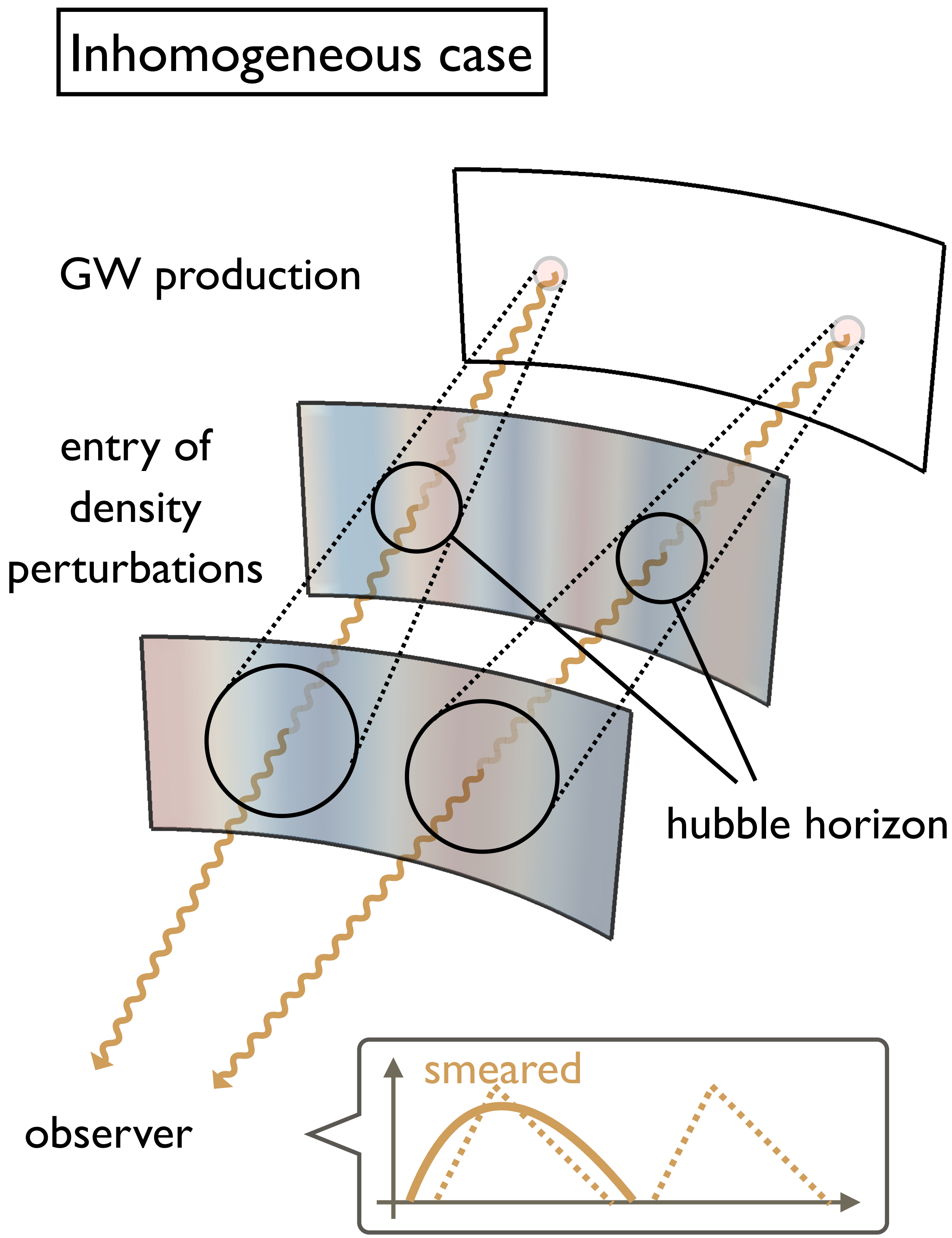
MAIN IDEA



FLRW case
GW production
hubble horizon
observer
redshift



Inhomogeneous case
GW production
entry of
density
perturbations
hubble horizon
observer
smeared

DEFORMATION OF THE GW SPECTRUM

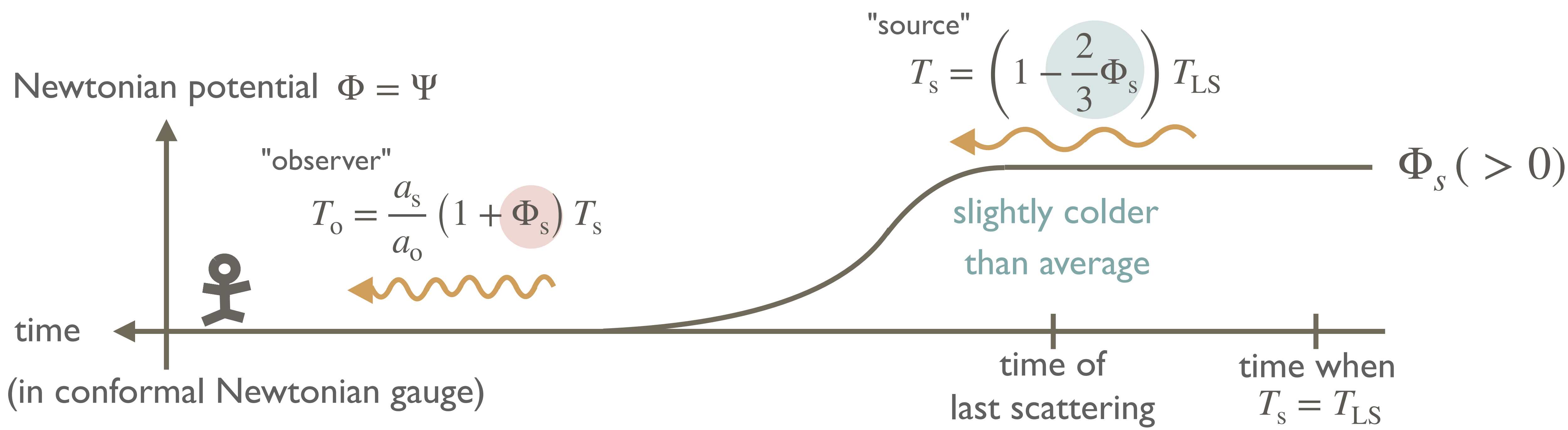
- Sachs-Wolfe effect (in CMB context) [Sachs & Wolfe '67] [Hu & White '97]

$$\boxed{\frac{\Delta T}{T} = \Phi_s - \frac{2}{3}\Phi_s}$$

where

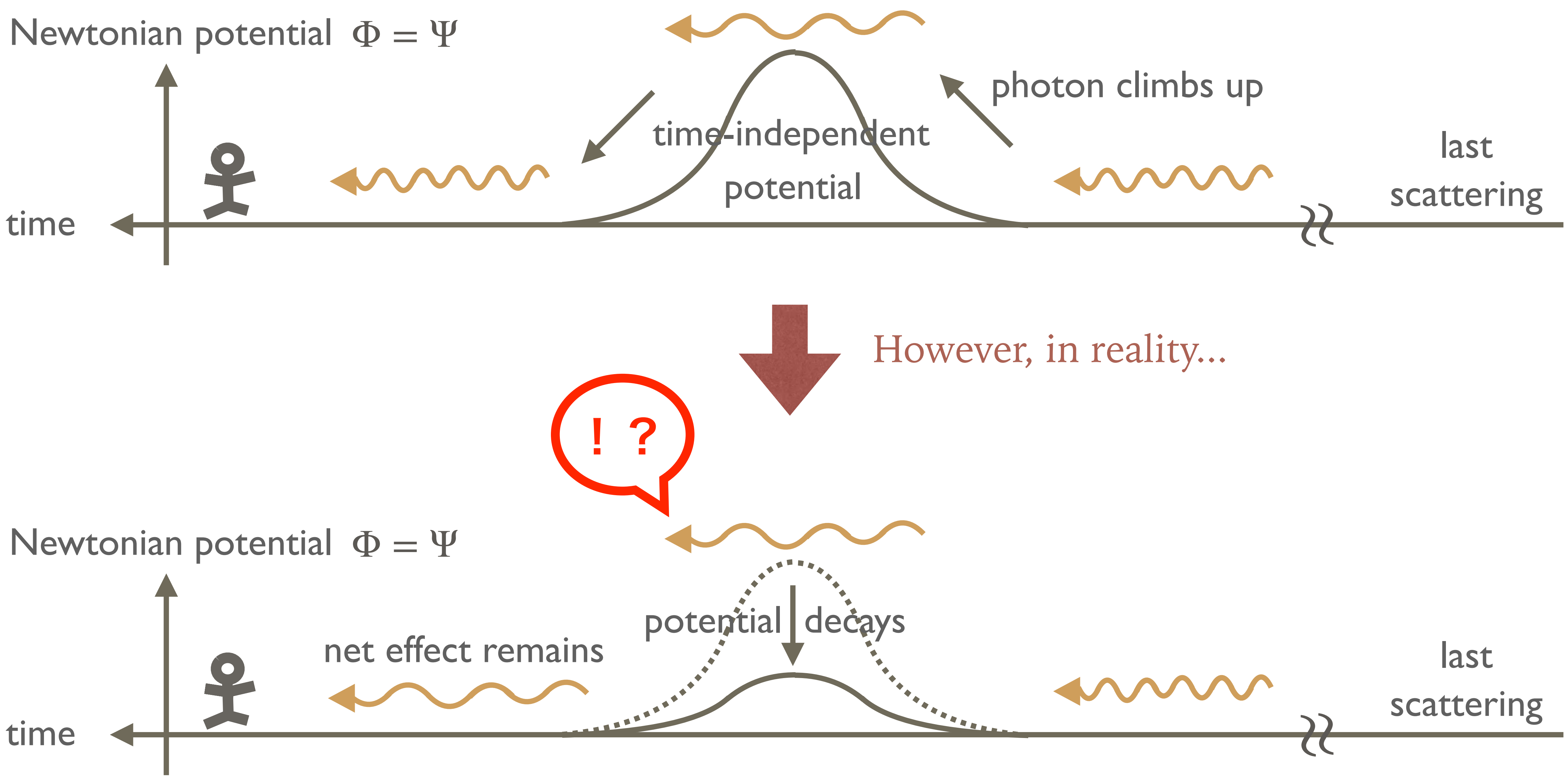
$$ds^2 = -a^2(1+2\Phi)\,d\tau^2 + a^2\delta_{ij}(1-2\Psi)\,dx^i dx^j \quad \text{(conformal Newtonian gauge)}$$

$$\Phi = \Psi \quad \text{(absence of anisotropic stress)}$$



DEFORMATION OF THE GW SPECTRUM

➤ Integrated Sachs-Wolfe effect (in CMB context) [Rees & Sciama '68]



QUICK "DERIVATION"

- We average the random walk of the frequency and amplitude caused by the curvature perturbations

$$\Delta_h^{2,(\mathrm{o})}(\ln f) \simeq \left\langle \left(1 + 2\underline{\Delta \ln A}\right) \Delta_h^{2,(\mathrm{s})}(\ln f - \underline{\Delta \ln f}) \right\rangle_{\text{scalar ens. ave.}}$$

...using linear-order results from geometric optics [Laguna, Larson, Spergel, Yunes '10]

$$\text{amplitude} \quad \Delta \ln A = \underbrace{- \Psi_{\mathrm{s}} - \frac{1}{2}\Phi_{\mathrm{s}}}_{} \quad + \text{lensing (neglected)}$$

$$\text{frequency} \quad \Delta \ln f = \underbrace{\Phi_{\mathrm{s}} - \frac{1}{2}\Phi_{\mathrm{s}}}_{\text{SW}} \quad \underbrace{+ \int_{\lambda_{\mathrm{s}}}^{\lambda_{\mathrm{o}}} d\lambda\, \partial_\tau(\Phi + \Psi)}_{\text{ISW}}$$

- Then the scalar average is calculable

$$\Delta_h^{2,(\mathrm{o})}(\ln f) \simeq \int d\ln f'\ \Delta_h^{2,(\mathrm{s})}(\ln f')\, K(f, f') \qquad K(f, f') = \frac{1}{\sqrt{2\pi\sigma^2}}[1 + b(\ln f - \ln f')]e^{-\frac{(\ln f - \ln f')^2}{2\sigma^2}}$$

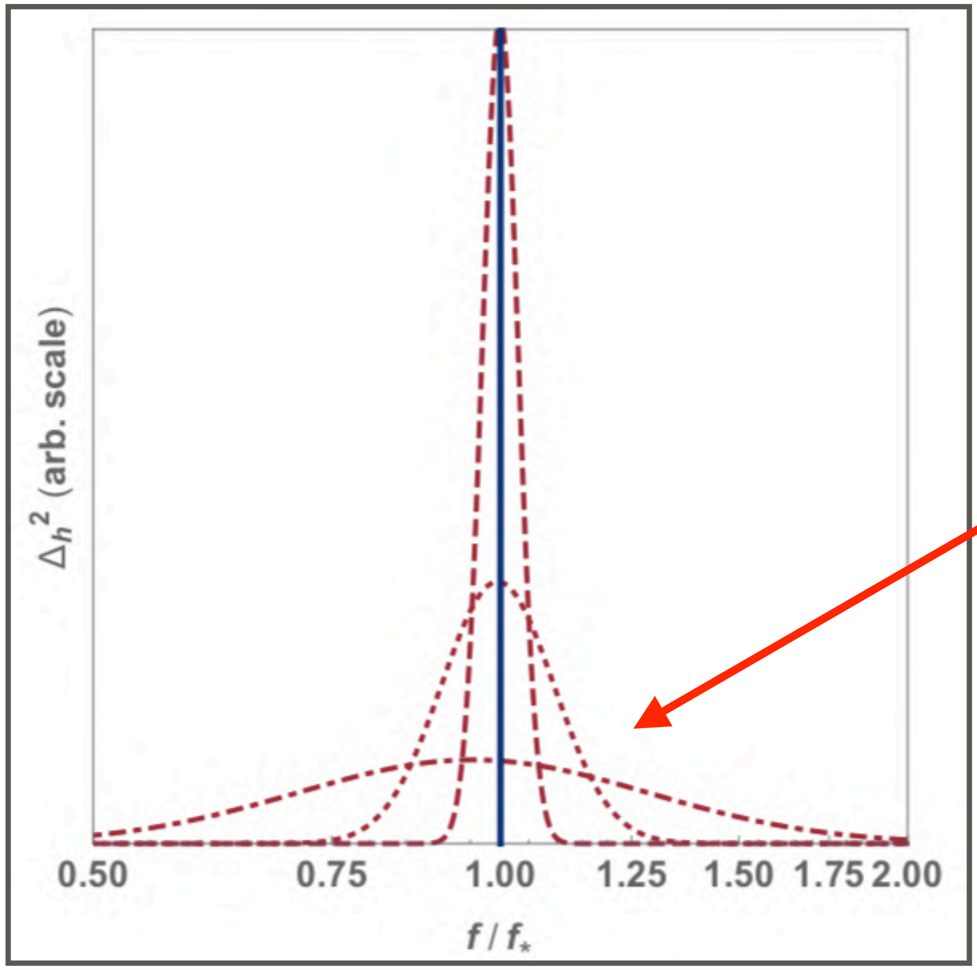
bias $b \simeq -0.52$

linearly biased Gaussian

variance $\sigma^2 \sim \int d\ln k\ \Delta_\zeta^2$

RESULTS

➤ If the GW spectrum is spiky at the sourcing time…



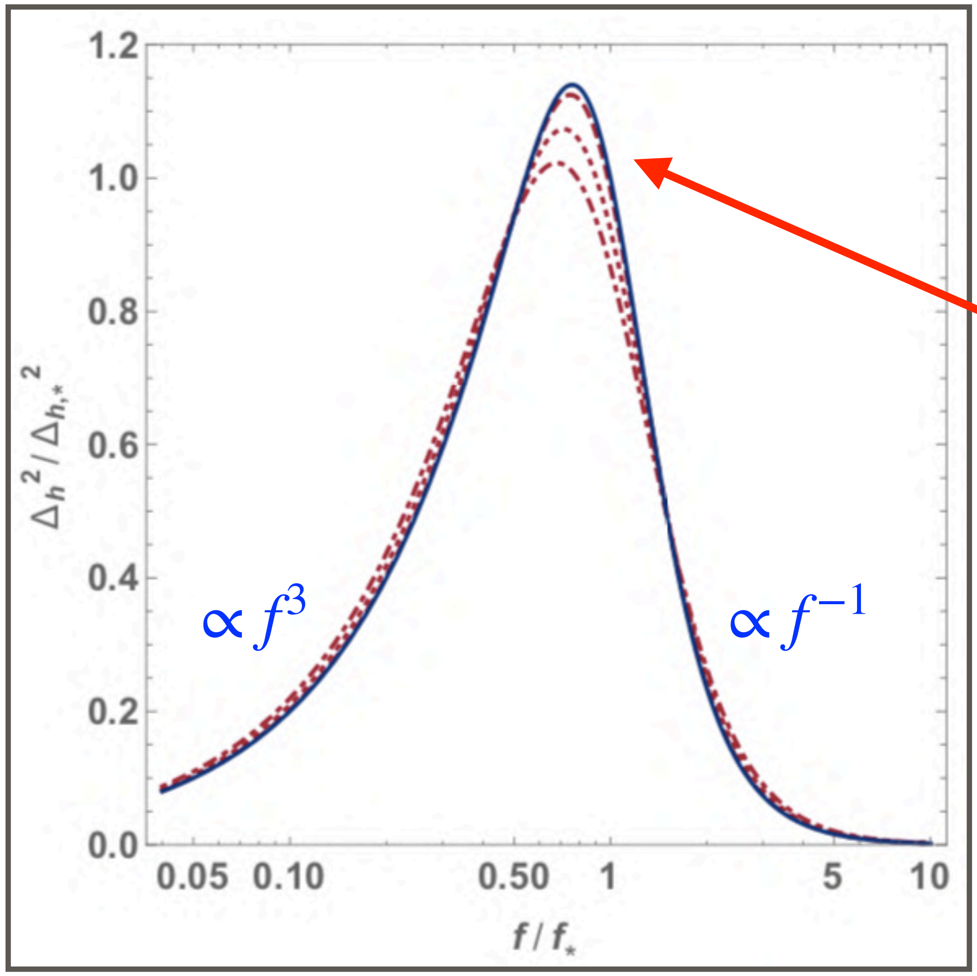
$$\int d \ln k \, \Delta_\zeta^2$$

$$= 10^{-3}, 10^{-2}, 10^{-1}$$

blue = original (= source) / red = deformed (= observed)

RESULTS

- If the GW spectrum is smooth at the sourcing time...



$$\int d \ln k \, \Delta_\zeta^2$$

$= 0.01,\ 0.05,\ 0.1$

This result should be taken as order-of-magnitude estimate at best (→ discussion 2)

blue = original (= source) / red = deformed (= observed)

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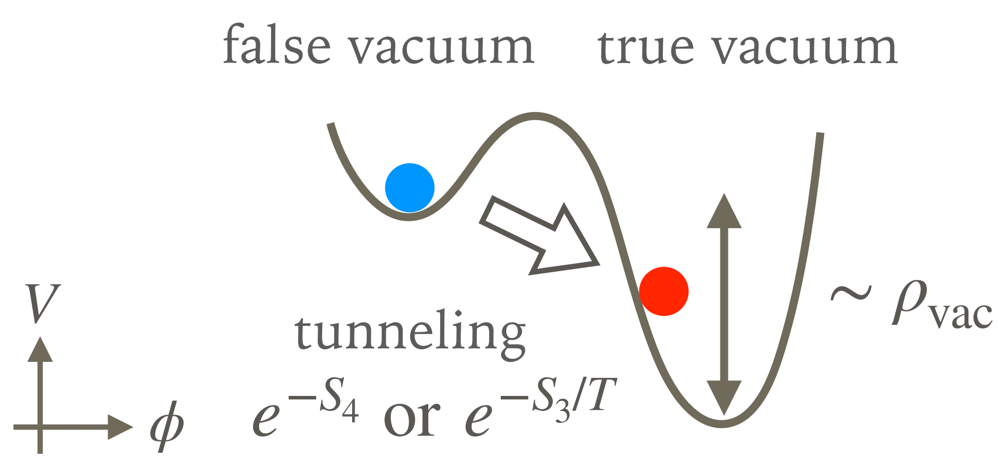
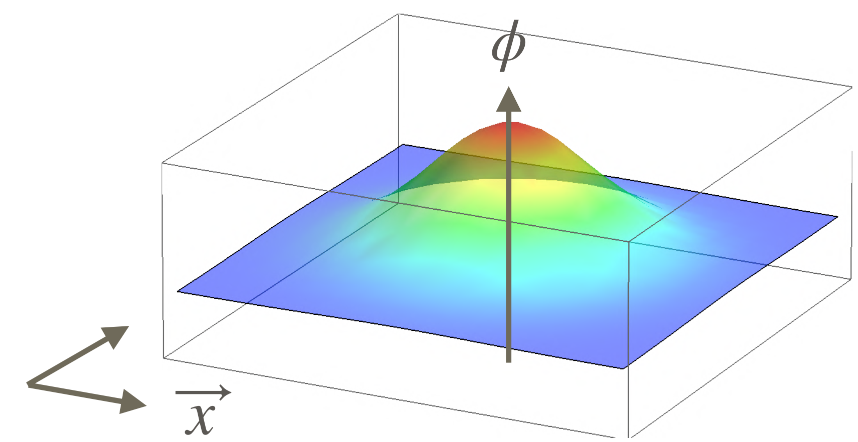
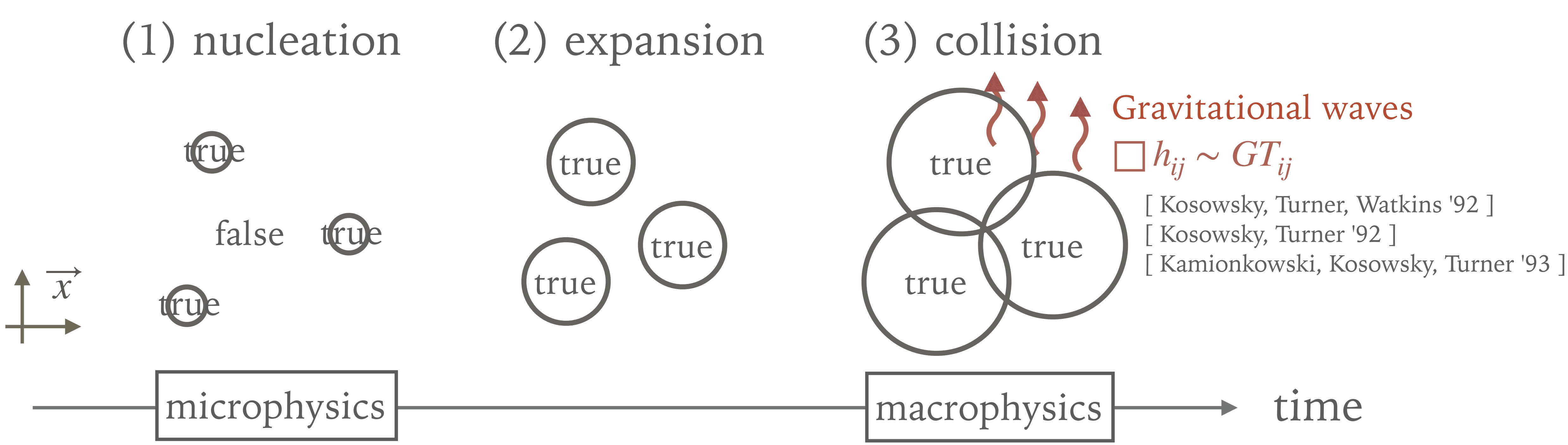
GW ENHANCEMENT IN FIRST-ORDER PHASE TRANSITIONS

- In field space: discontinuous transition in the order parameter field

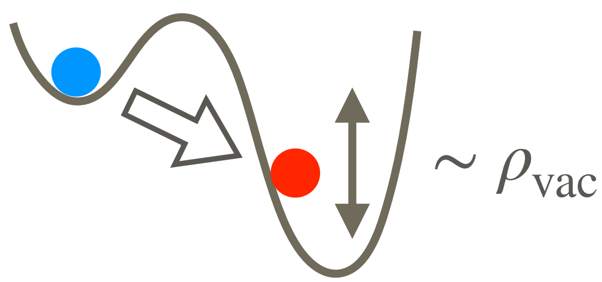




- In position space: bubble nucleation, expansion, and collision, invloving fluid



THE INTERMEDIATE STAGE: BUBBLE EXPANSION

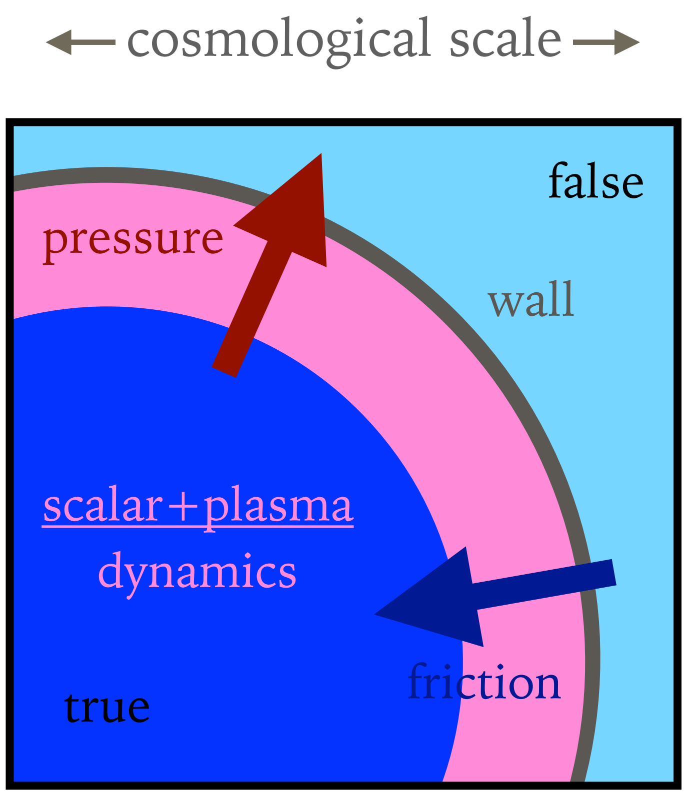


➤ "Pressure vs. Friction" determines the behavior of bubble walls

(1) Pressure: released energy pushes the wall outwards

Parametrized by $\alpha \equiv \dfrac{\rho_{\rm vac}}{\rho_{\rm plasma}}$

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



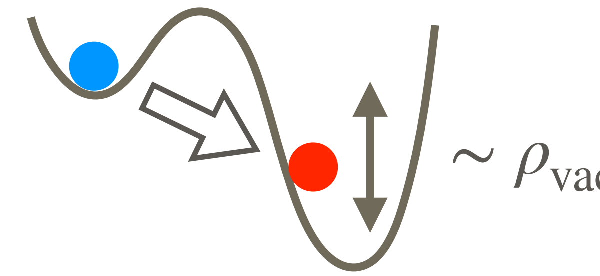
(2) Friction: plasma particles push back the wall

Parametrized by coupling η

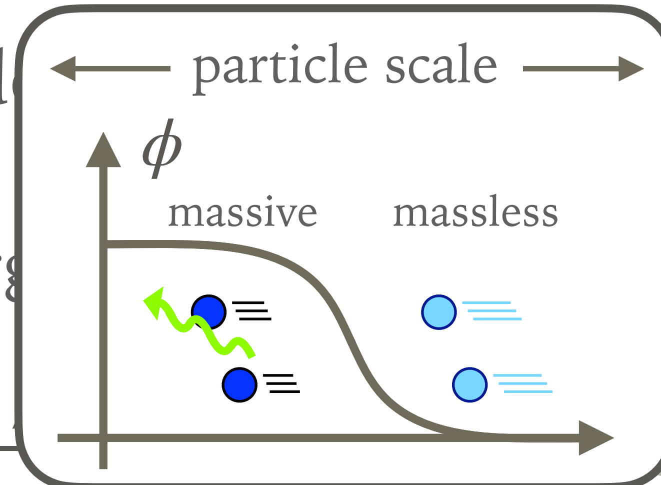
between the scalar field & plasma particles (that exist everywhere)

➤ In the next slide we see how bubbles behave for different α (with fixed η)

THE INTERMEDIATE STAGE: BUBBLE EXPANSION



➤ "Pressure vs. Friction" d

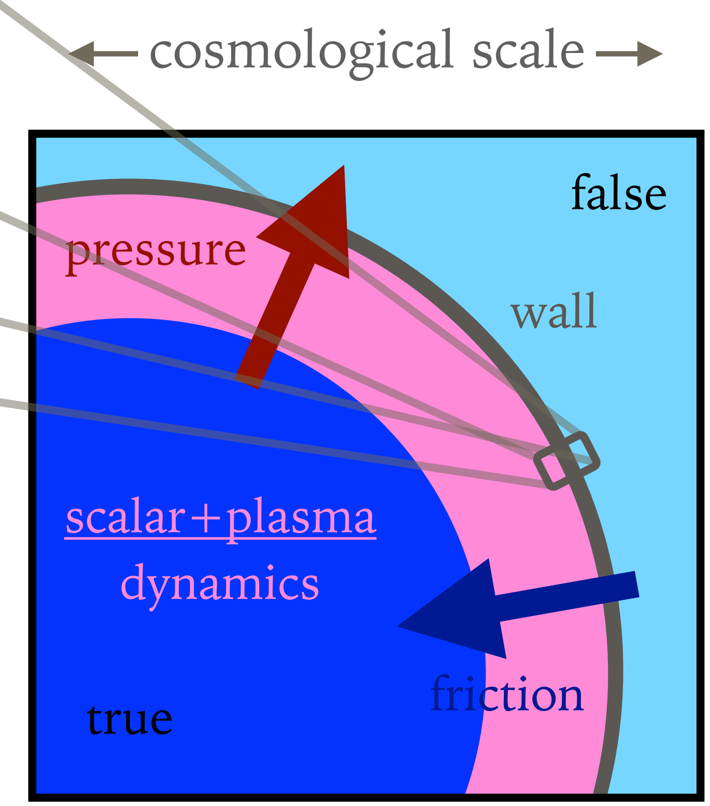


vior of bubble walls

(1) **Pressure**: released energ wards

Parametrized by $\alpha \equiv$ — ρ_{plasma}

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



(2) **Friction**: plasma particles push back the wall

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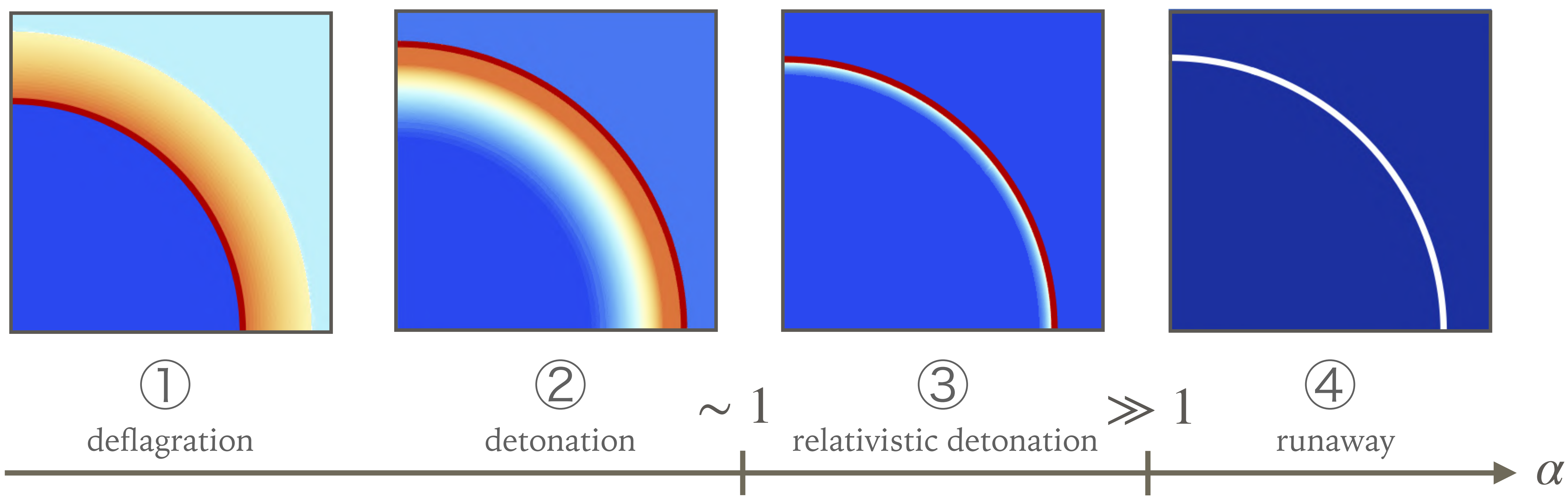
THE INTERMEDIATE STAGE: BUBBLE EXPANSION

➤ Classification of bubble expansion

Walls reach terminal velocity
because of the balance btwn. pressure & friction
Main energy carrier: fluid

Walls runaway
without caring about the plasma
Main energy carrier: wall (scalar field)

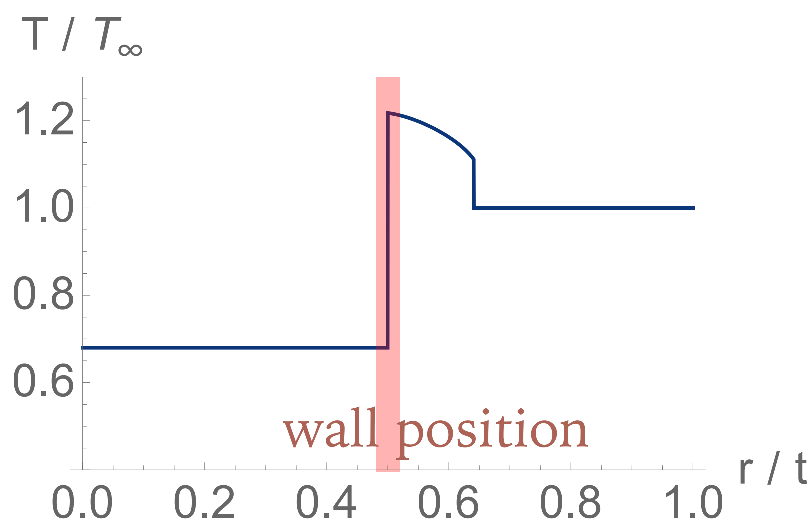


Every detail of these bubbles contain the information on particle physics

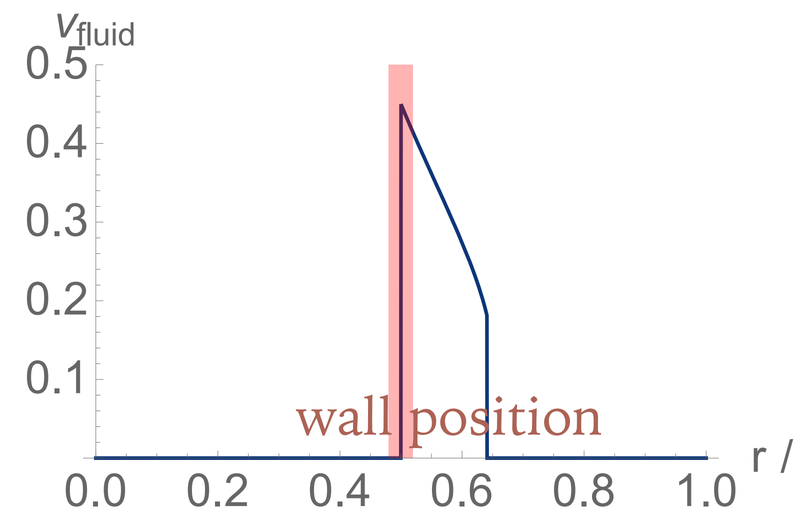
THE I

➤ Cl

Temperature

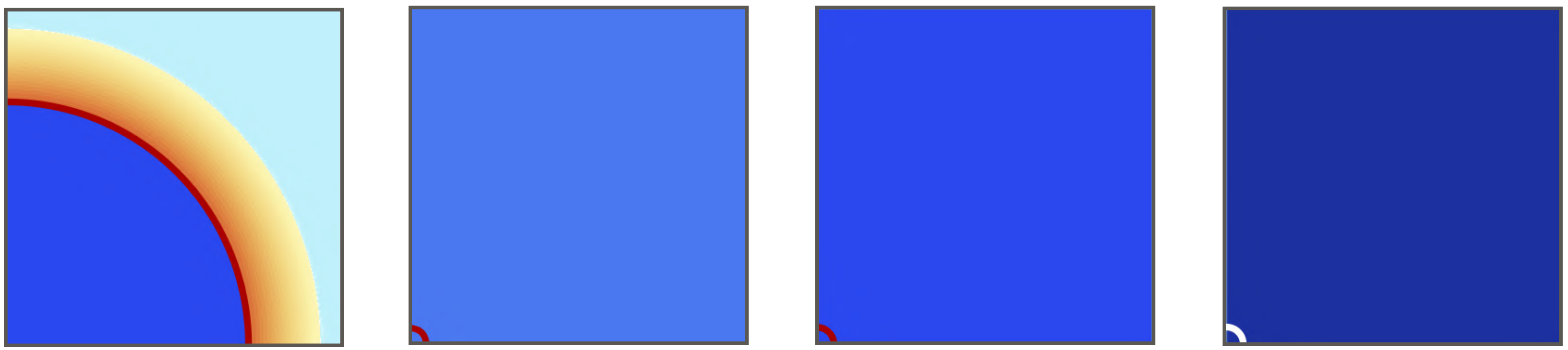


Fluid outward velocity



plasma

(scalar field)



① deflagration

② detonation

~ 1

③ relativistic detonation

$\gg 1$

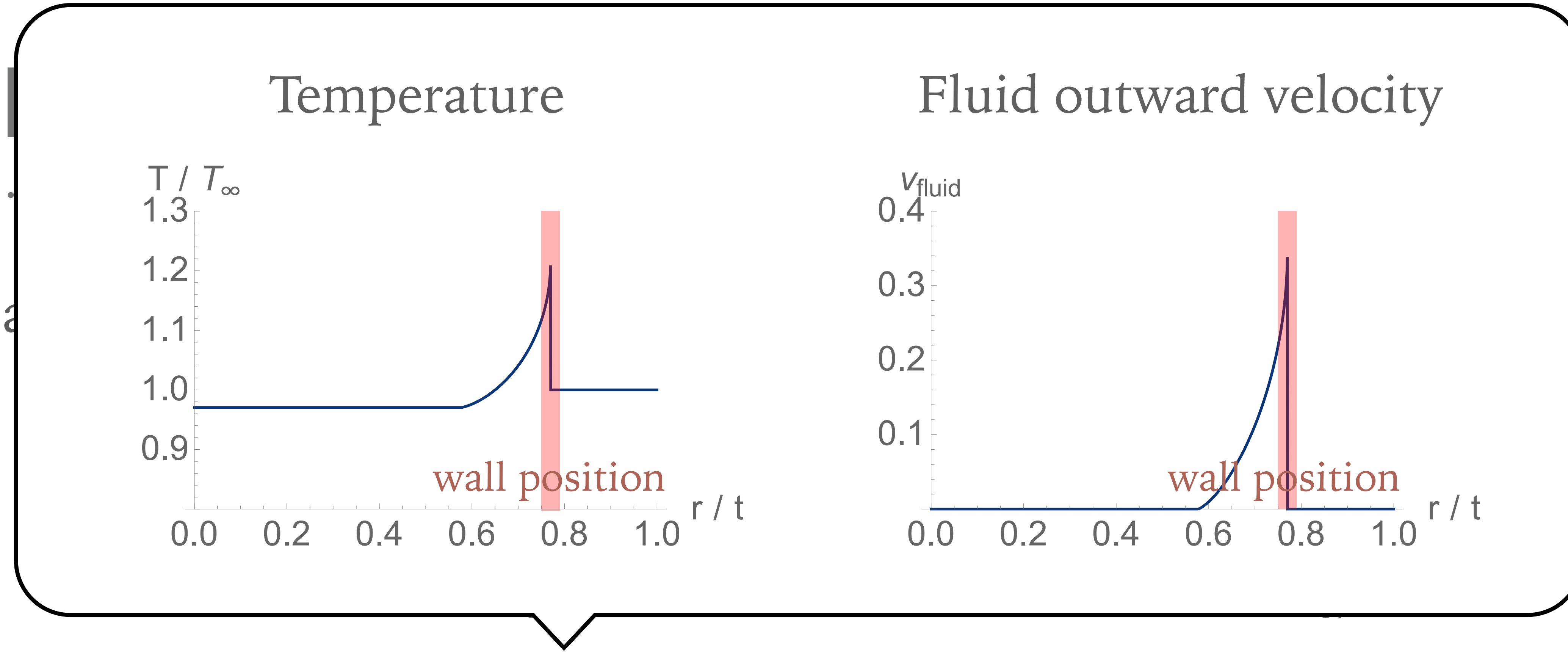
④ runaway

α

Every detail of these bubbles contain the information on particle physics

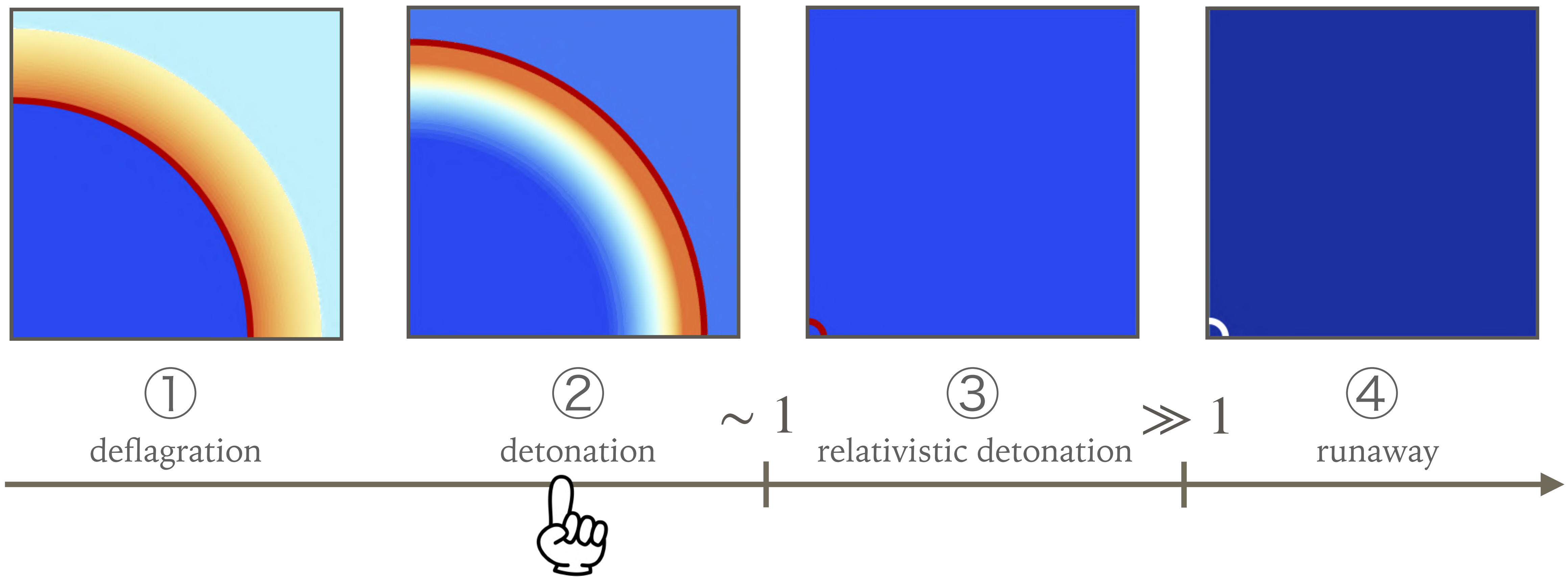
THE

➤ Cl



plasma

(scalar field)



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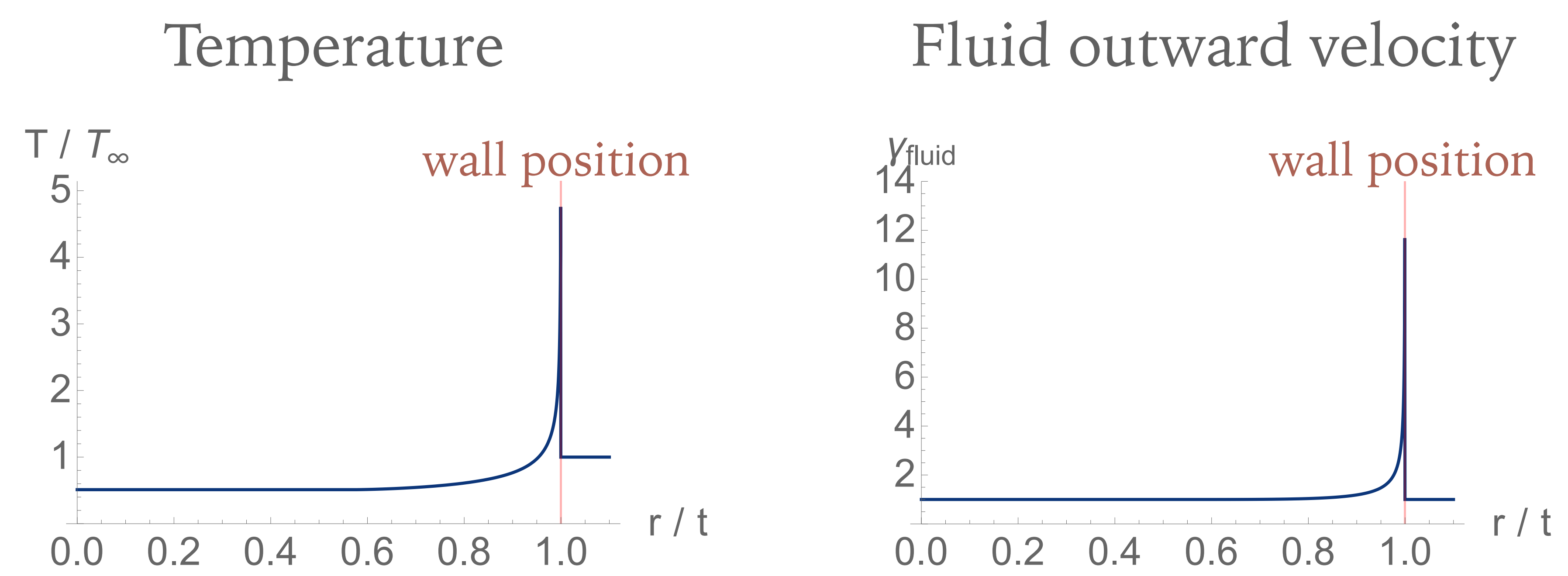
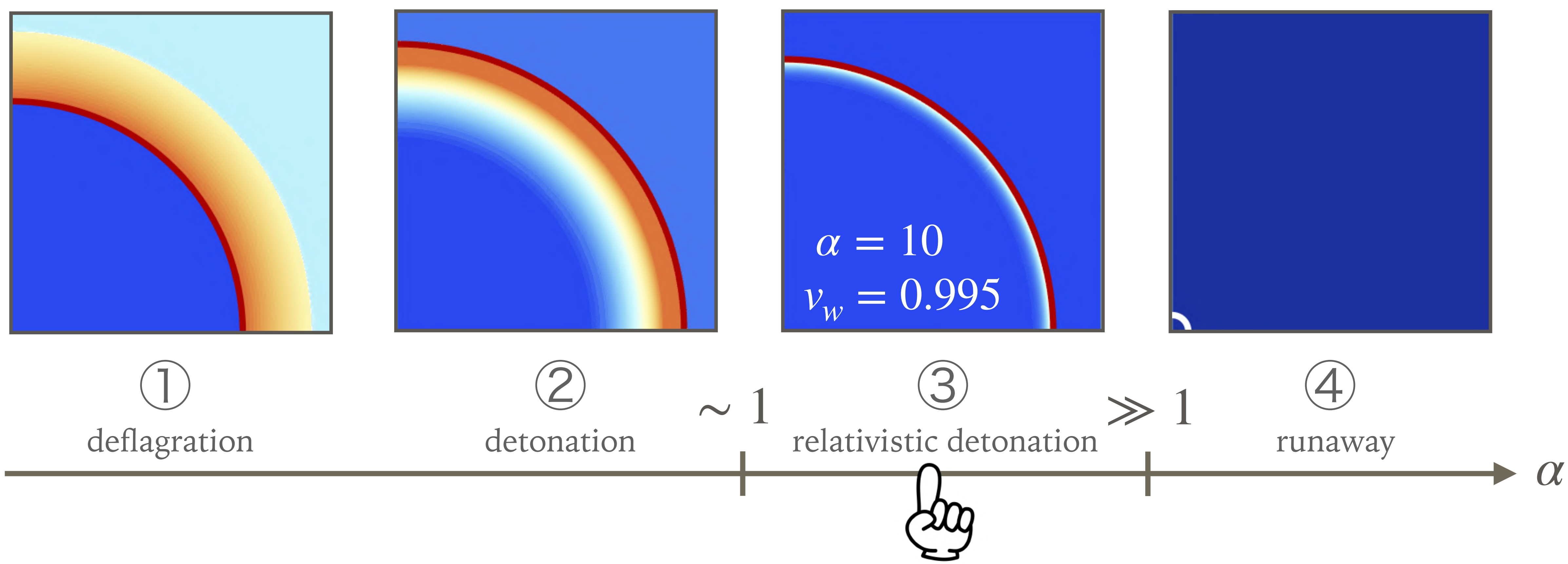
THE I

➤ Cl

plasma

(scalar field)





Every detail of these bubbles contain the information on particle physics

THE

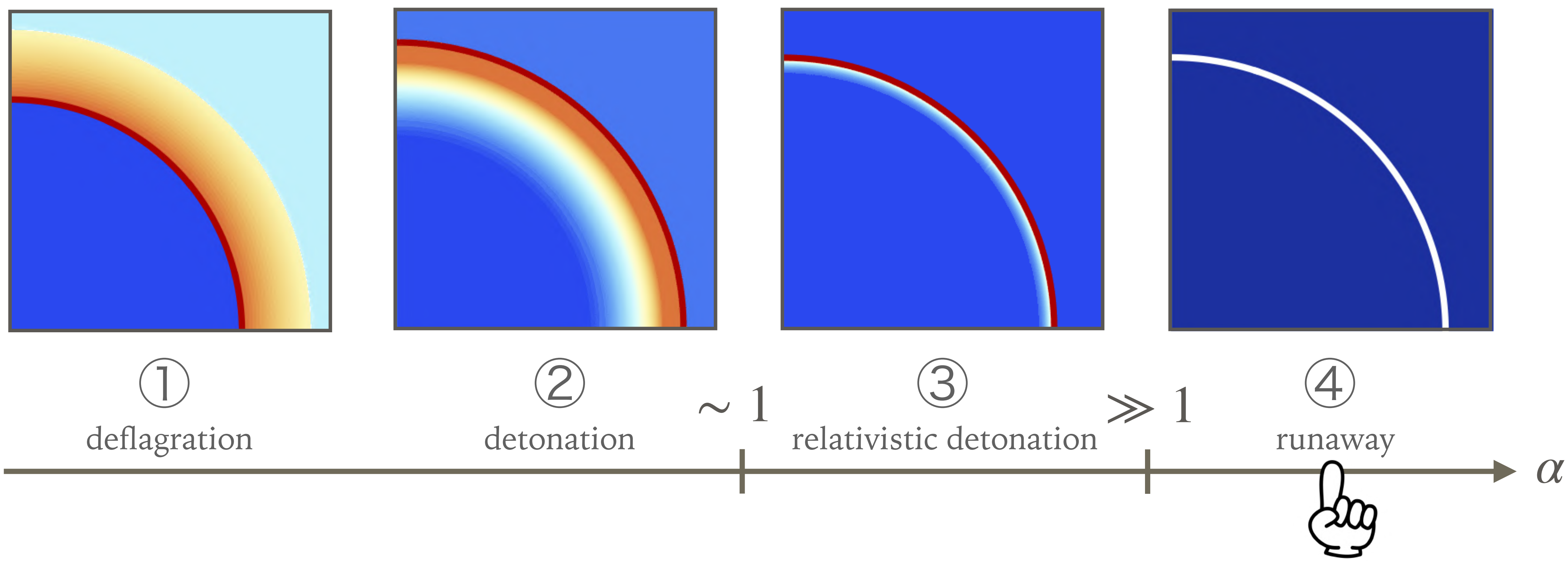
➤ Cl

Plasma particles cannot stop the acceleration of the walls:

walls continue to accelerate until they collide with others

plasma

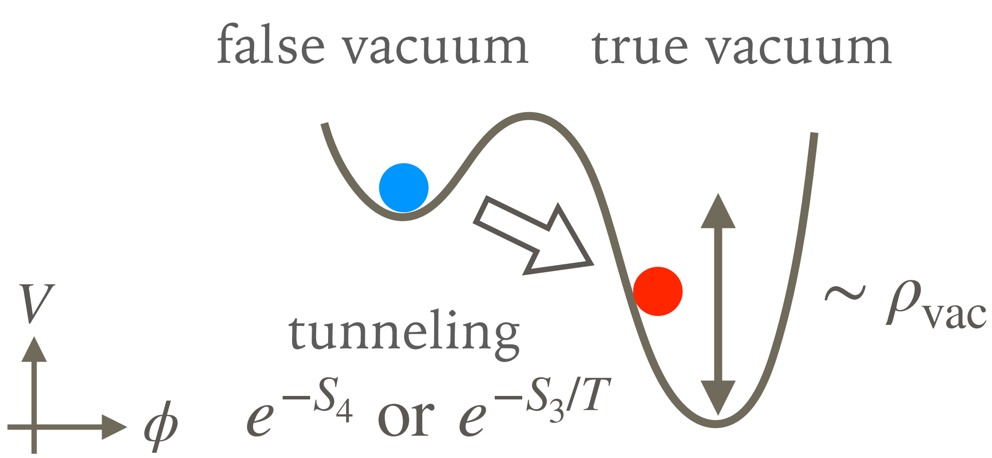
(scalar field)

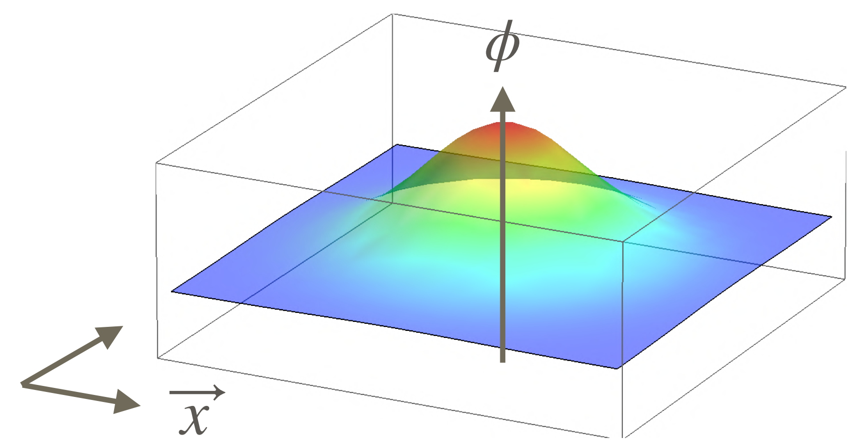


Every detail of these bubbles contain the information on particle physics

FIRST-ORDER PHASE TRANSITIONS: A QUICK OVERVIEW

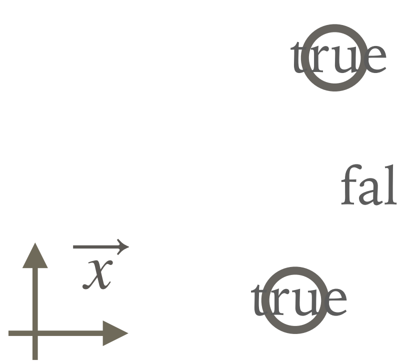
➤ In field space: discontinuous transition in the order parameter field



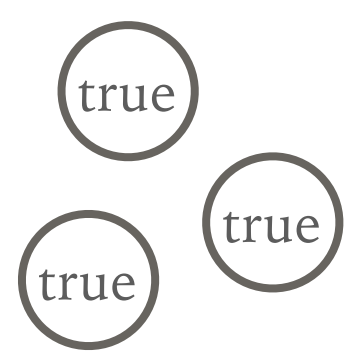


➤ In position space: bubble nucleation, expansion, and collision, invloving fluid

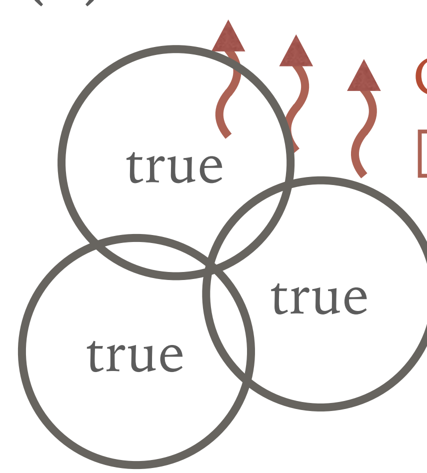
(1) nucleation



(2) expansion



(3) collision

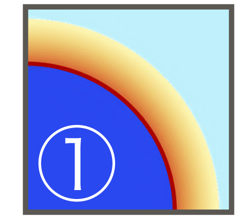


Gravitational waves

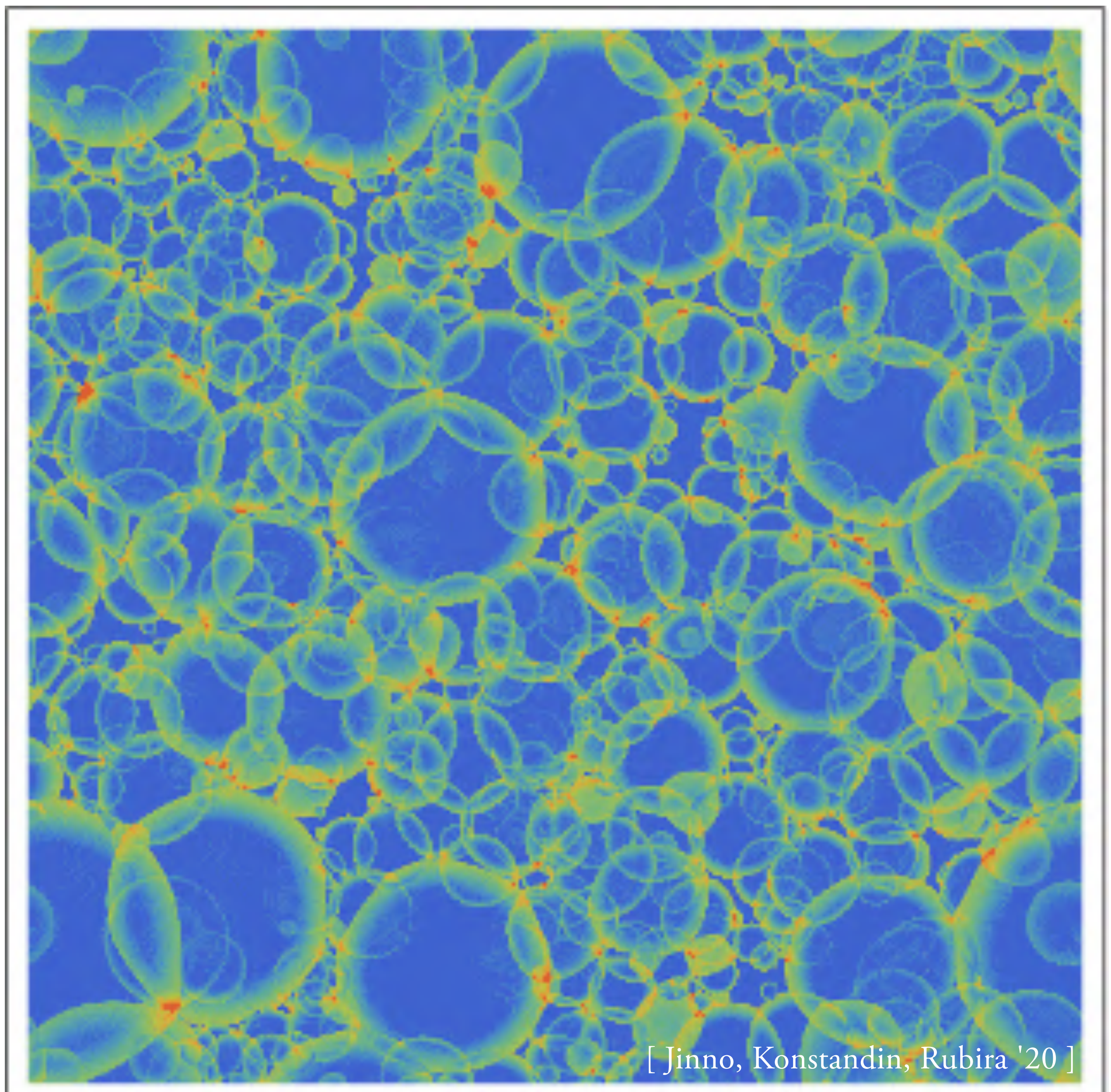
$\Box h_{ij} \sim G T_{ij}$

[Kosowsky, Turner, Watkins '92]
[Kosowsky, Turner '92]
[Kamionkowski, Kosowsky, Turner '93]

THE MACROPHYSICS SIDE: GW PRODUCTION



- In weak~moderate transitions ($\alpha \lesssim 1$), bubble walls drive sound waves, efficiently producing GWs [Hindmarsh, Huber, Rummukainen, Weir, '14] [Hindmarsh '17]



(typical fluid shell)

(typical bubble size)

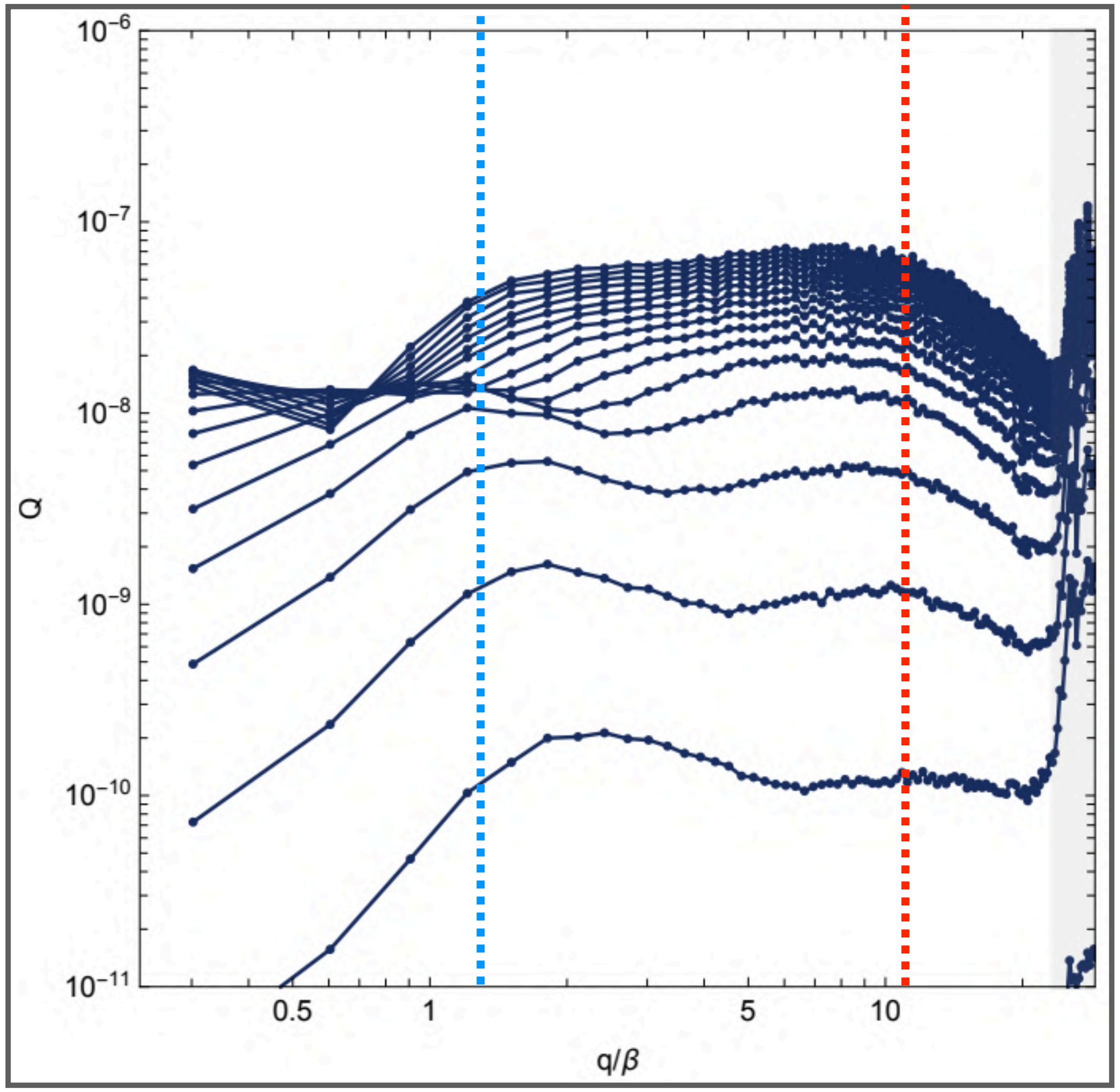
β^{-1}

GW SPECTRUM (WITHOUT DENSITY PERTURBATIONS)

$\alpha = 0.0046,\ v_{\rm wall} = 0.52$

(typical bubble size)$^{-1}$ (typical fluid shell)$^{-1}$

GW spectrum



wavenumber

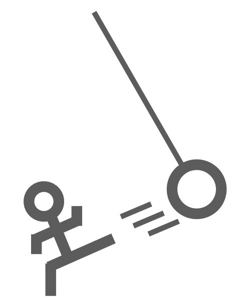
GW spectrum at different time slices

GW PRODUCTION FROM BUBBLES: INTUITIVE EXPLANATION

➤ BIG & RELATIVISTIC objects radiate more GWs

- Integrate the GW equation of motion over the coherence time Δt of the source

$$\underset{\text{oscillator}}{\Box h_{ij} \sim GT_{ij}} \xrightarrow[\text{coherence time } \Delta t]{\text{integration over}} \dot{h}_{ij} \sim GT_{ij}\Delta t$$



kicked oscillator

- GW energy density $\rho_{\rm GW} \sim G^{-1}\,\dot{h}_{ij}^2 \propto T_{ij}^2 \Delta t^2$

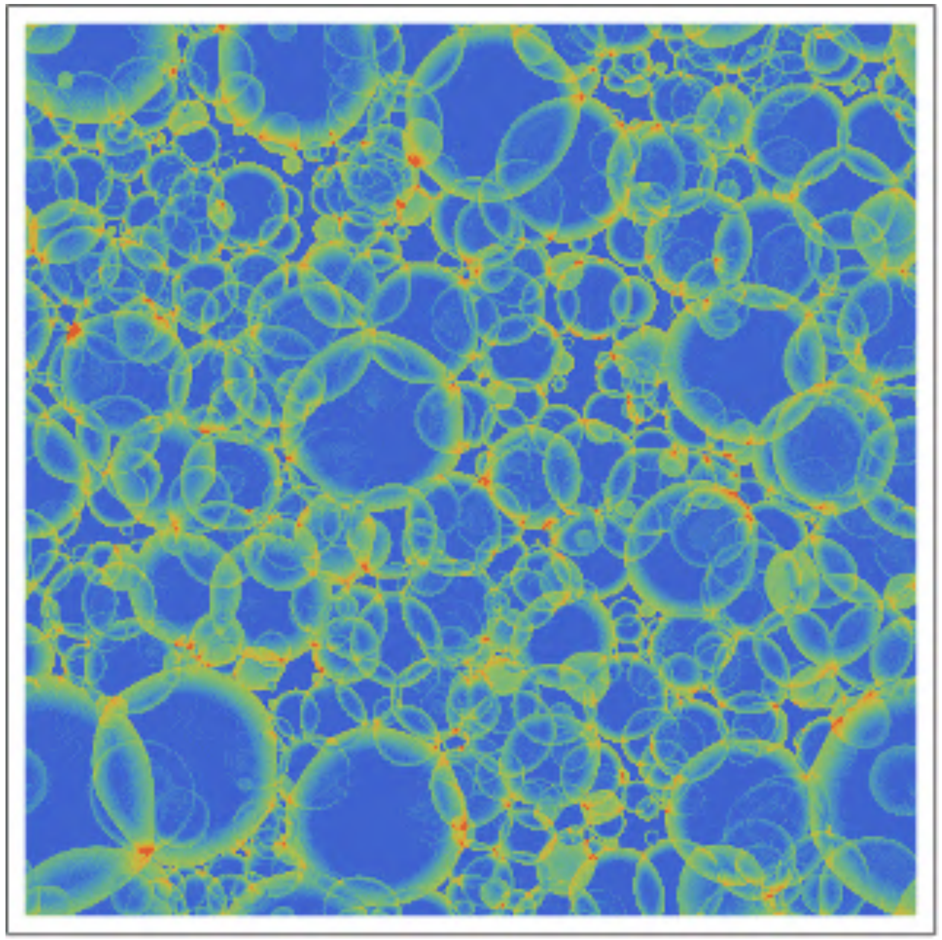
1. Relativistic objects have larger T_{ij}

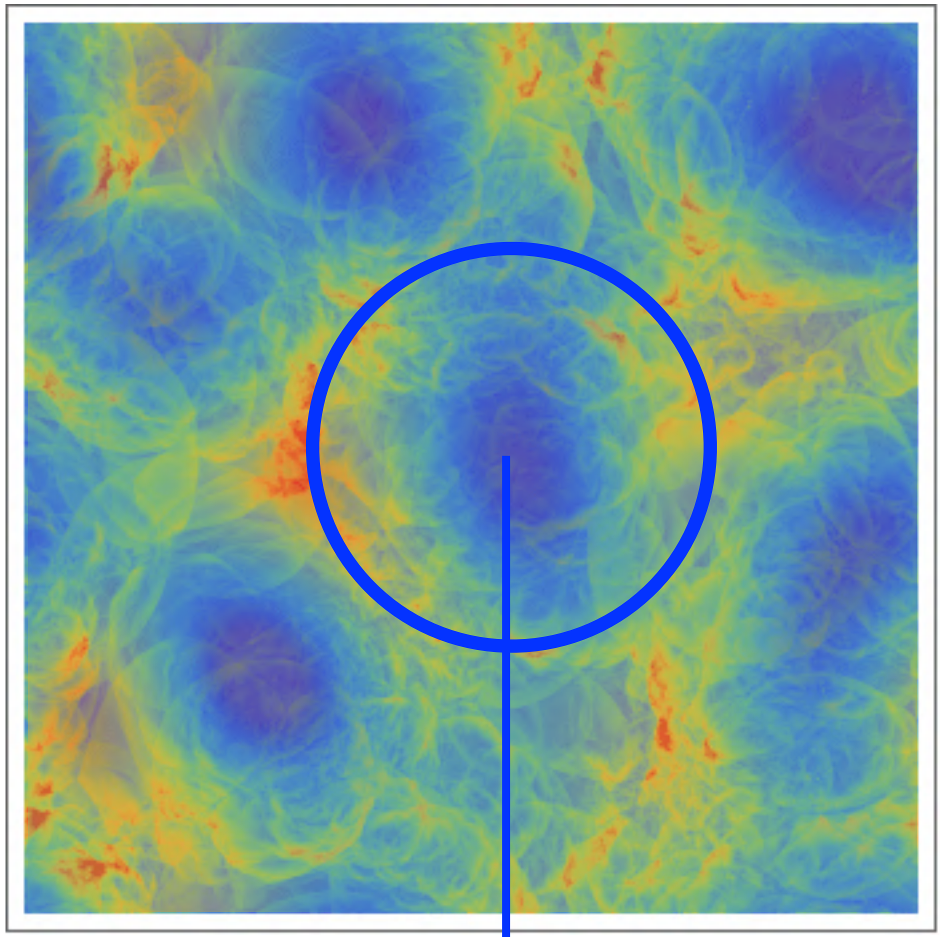
2. Big bubbles (size R) typically have longer coherent time ($\Delta t \sim R$)

HOW DENSITY PERTURBATIONS AFFECT THE TRANSITION

Without density perturbations

With density perturbations



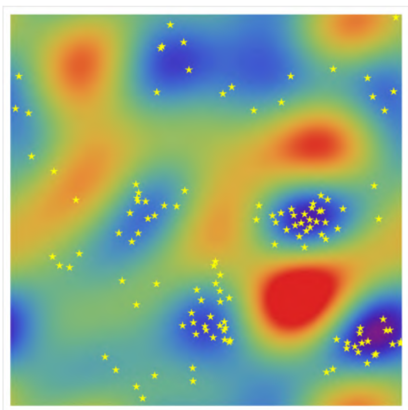


formation of "effective big bubbles"
around the cold spots

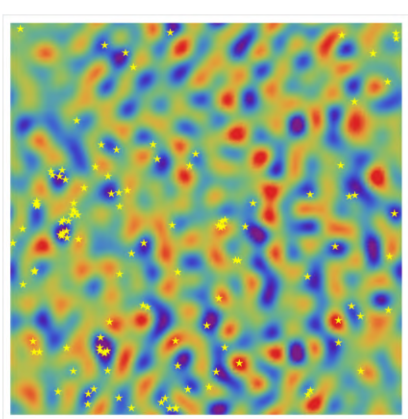
GW ENHANCEMENT FROM DENSITY PERTURBATIONS

- Density perturbations with $H_* < k_* < \beta$ enhance the GW signal

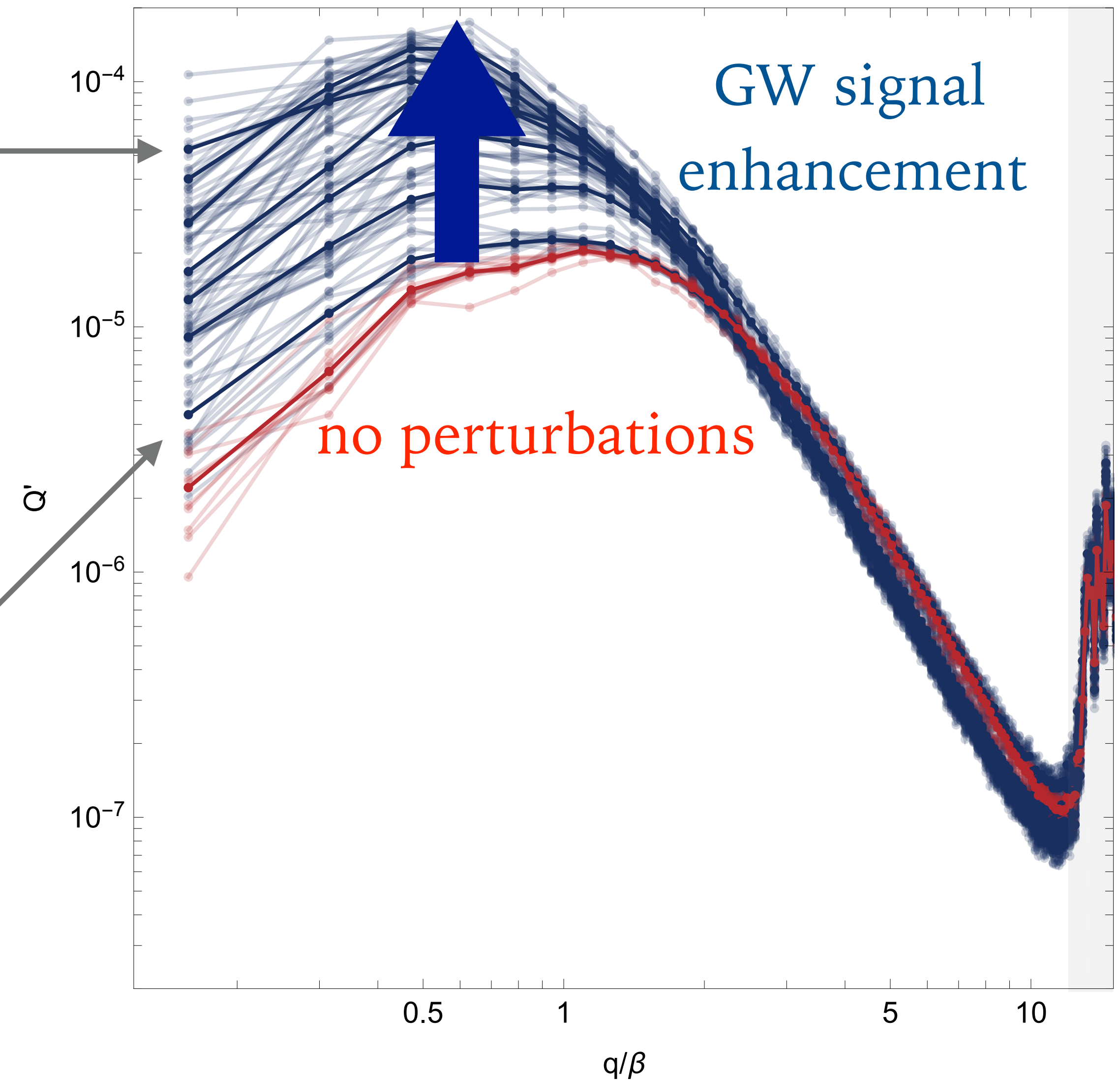
Growth rate of the GW spectrum



IR perturbations



UV perturbations



GW wavenumber

SUMMARY

- Nontrivial interplay between density perturbations and GWs:

  - Density perturbations deform GW isotropic spectrum

  - Density perturbations affect GW production from bubbles