Summary

Effect of density pert.

Hybrid simulation

Intro

GWs from first-order phase transitions: A hybrid simulation & signal enhancement from density perturbations

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9th LISA CosWG workshop, Dec. 2021

T. Konstandin

J.v.d.Vis

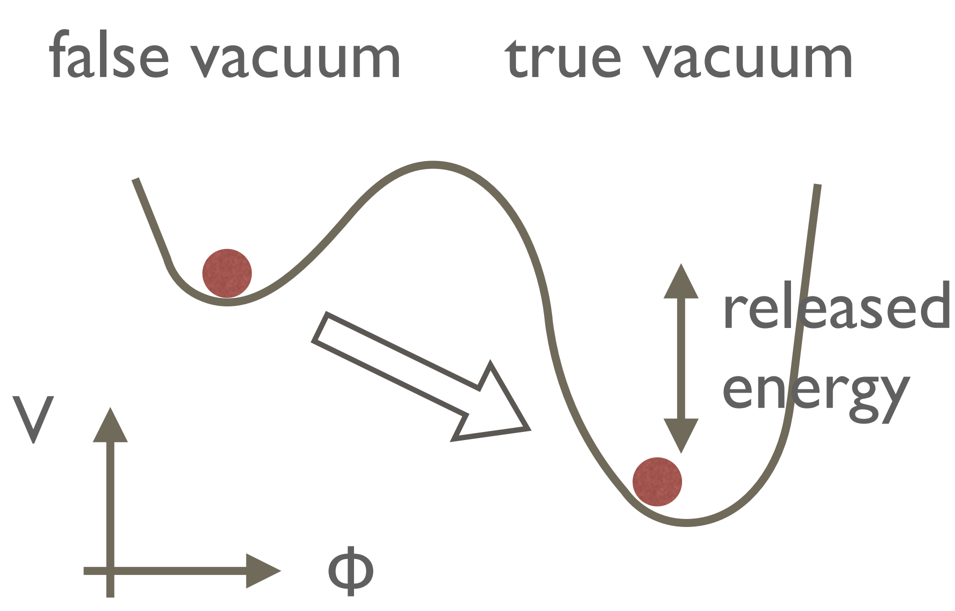
H. Rubira

[Jinno, Konstandin, Rubira, v.d.Vis, JCAP 12 (2021) 019, 2108.11947]
[Jinno, Konstandin, Rubira, JCAP 04 (2021) 014, 2010.00971]

1ST-ORDER PT & GW PRODUCTION: A BRIEF SKETCH

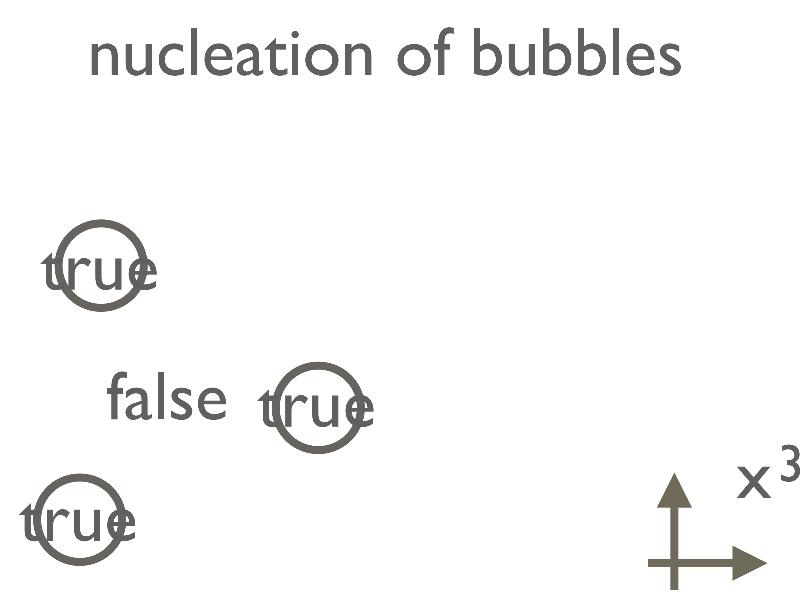
➤ Bubbles nucleate, expand, collide and disappear

Field space



Quantum tunneling

Position space



Bubble dynamics & GW production

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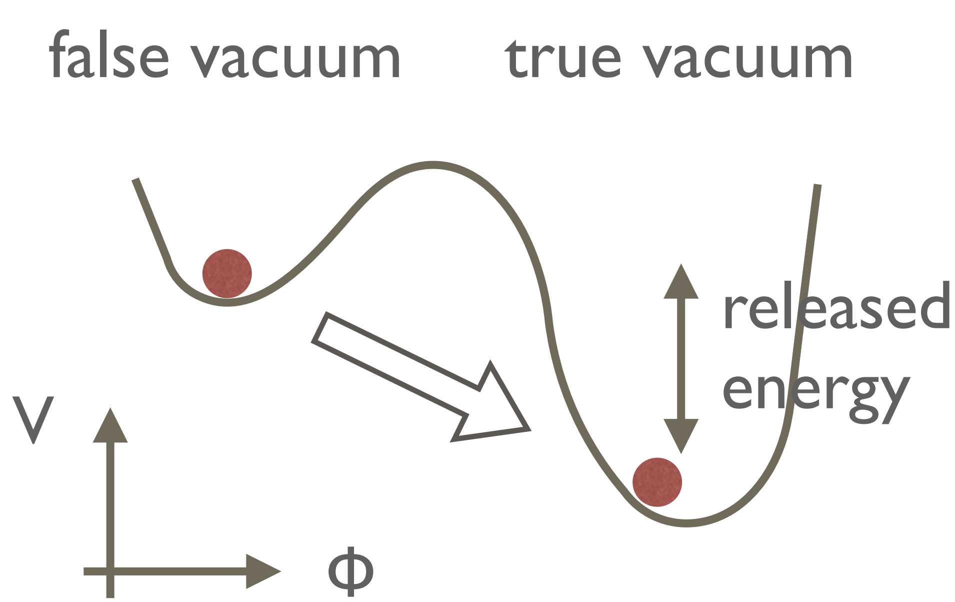

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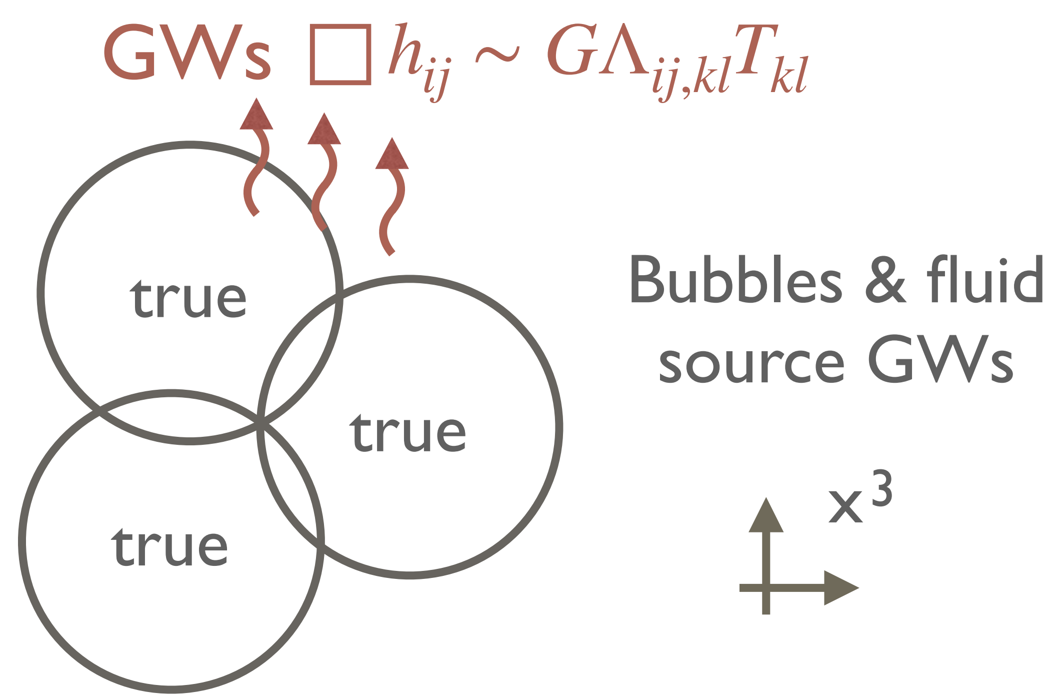
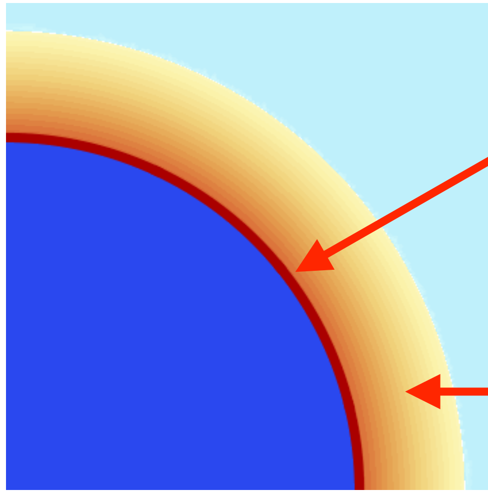


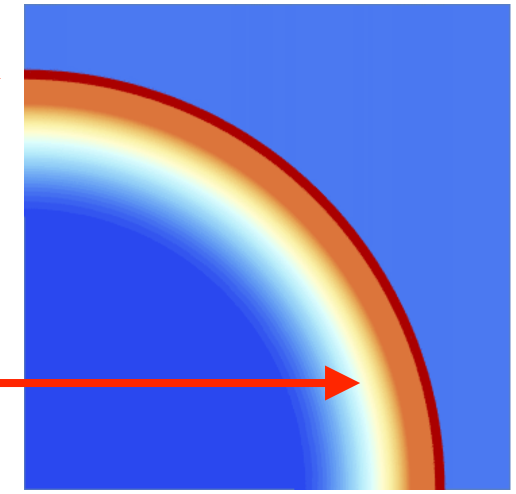
Bubble dynamics & GW production

Bubble dynamics is in reality a violent process involving fluid dynamics



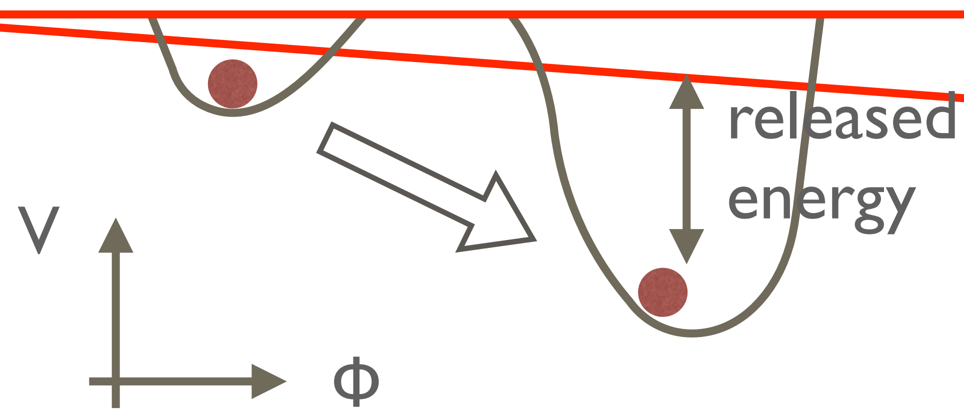
Higgs wall

Fluid

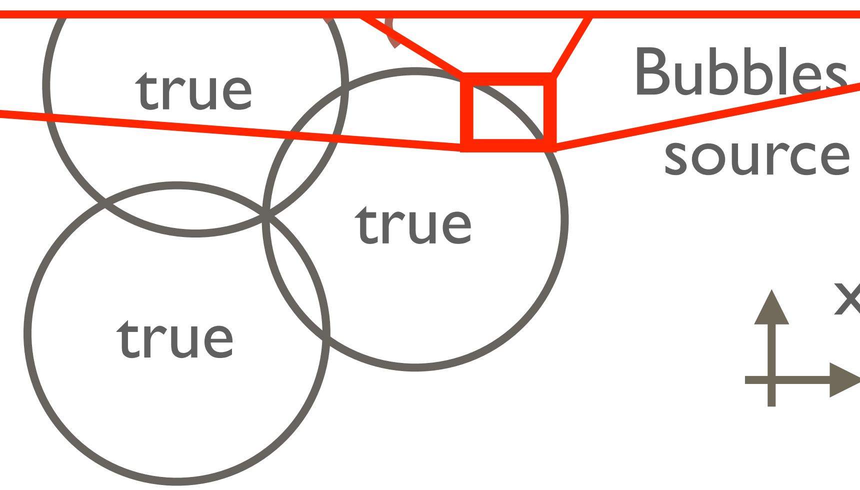


In this talk we focus on this type of weak/moderate transitions $\alpha \sim \dfrac{\rho_{\rm vac}}{\rho_{\rm rad}} \lesssim \mathcal{O}(0.1)$

(See Marek's talk for extremely strong transitions)

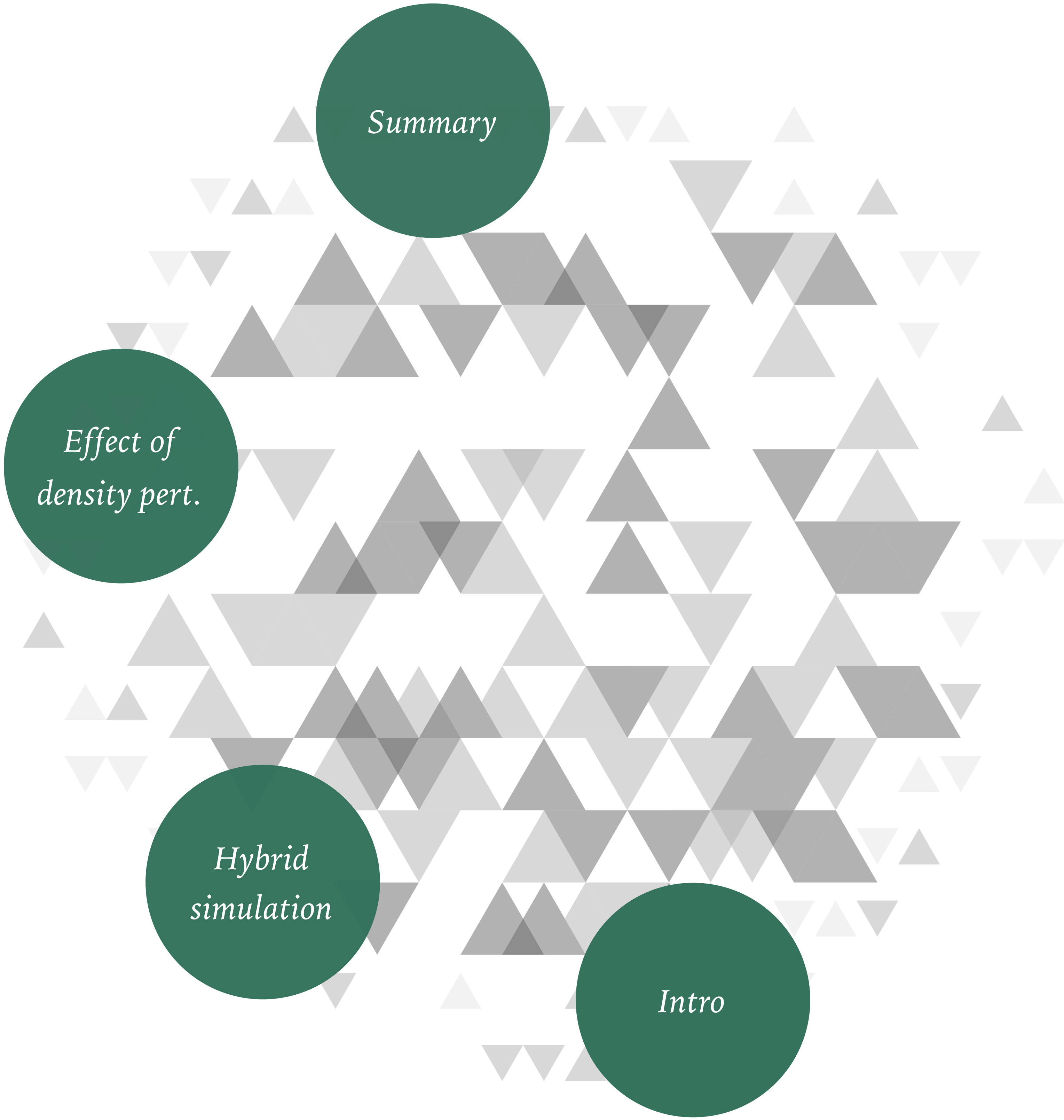


Quantum tunneling



Bubbles & fluid source GWs

Bubble dynamics & GW production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ANALYTICAL VS. NUMERICAL METHODS: STATE OF THE ART

	(Semi-)analytical	Numerical
	e.g. envelope, bulk flow, sound shell, ... [Kosowsky, Turner, Watkins '92] [Kosowsky, Turner '93] [Huber, Konstandin '08] [Jinno, Takimoto '17] [Caprini, Durrer, Servant '08] [Jinno, Takimoto '19] [Konstandin '17] [Hindmarsh '18] [Hindmarsh, Hijazi '19] [Lewicki, Pujolas, Vaskonen '21] [Megevand, Membiela '21] ...	[Hindmarsh, Huber, Rummukainen, Weir '13,'15,'17] [Cutting, Hindmarsh, Weir '18,'19] [Cutting, Escartin, Hindmarsh, Weir '20] [Gould, Sukuvaara, Weir '21] ...
Pros.	Less cost Better analytical understanding	Less *a priori* assumptions More robust predictions
Cons.	Modeling = Assumptions	More cost "Artifact" from Higgs field (→ next slide)

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ONE PROBLEM ABOUT NUMERICAL SIMULATIONS

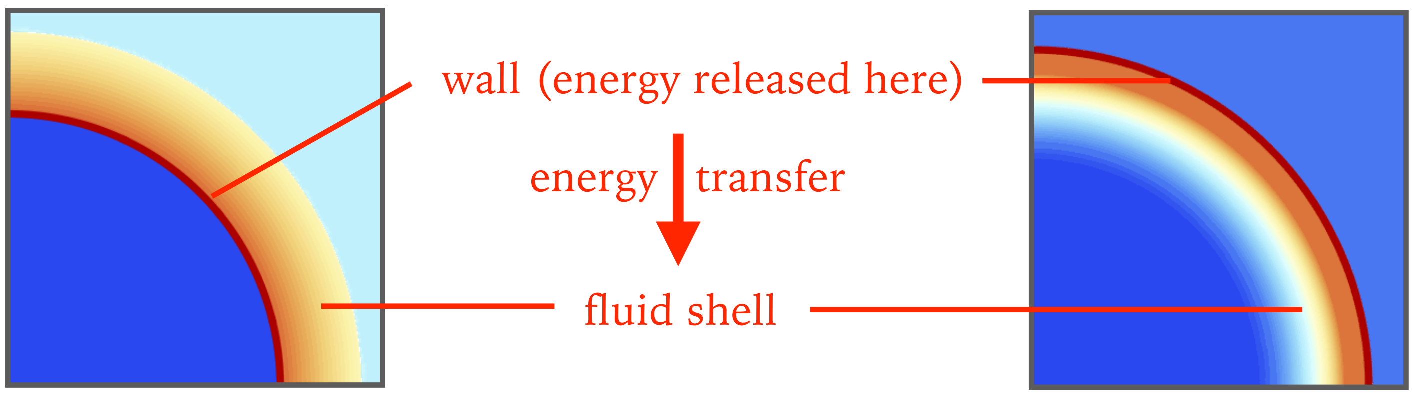
➤ "Artifact" from the Higgs field?

In **physical** phase transition

wall thickness < < < < < < < < < < < < < < < < fluid shell < bubble size

Energetically negligible

Scale (~1/100GeV) far separate from other scales (~ cosmological)



In **simulations**

grid spacing < (wall thickness < fluid shell < bubble size) < box size

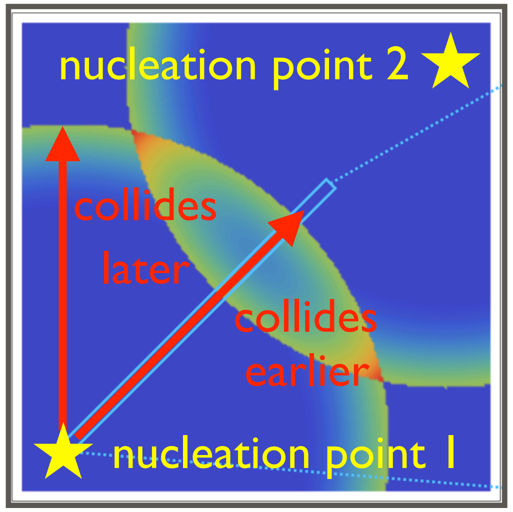
appears as "artifact"

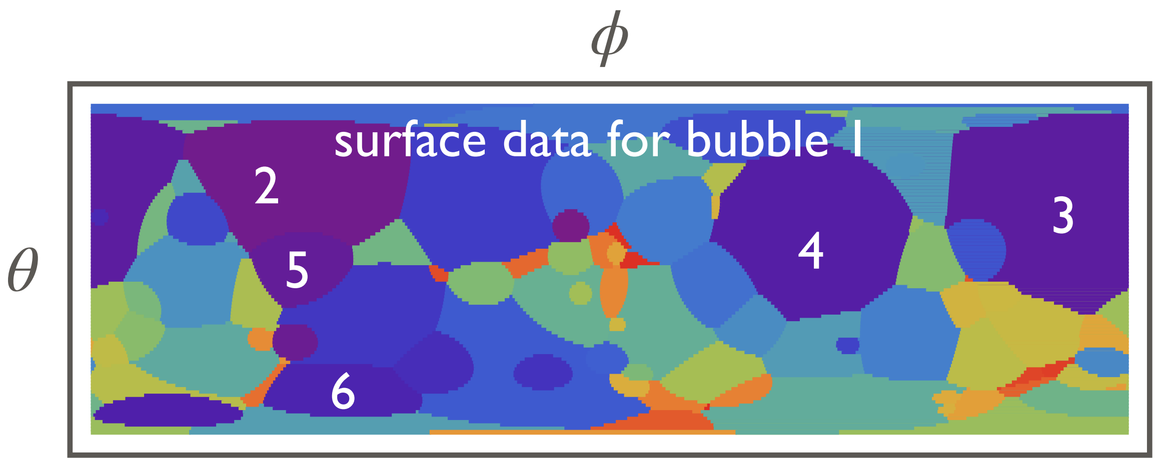
HYBRID SIMULATION: THE IDEA

➤ Central idea: To get rid of the Higgs field & simulate only with fluid

Step1: Generate nucleation points (★) and create surface data for collision time

Surface data is obtained without simulation, just from the distribution of the nucleation points





surface data = when, and with which bubble each bubble fragment collides

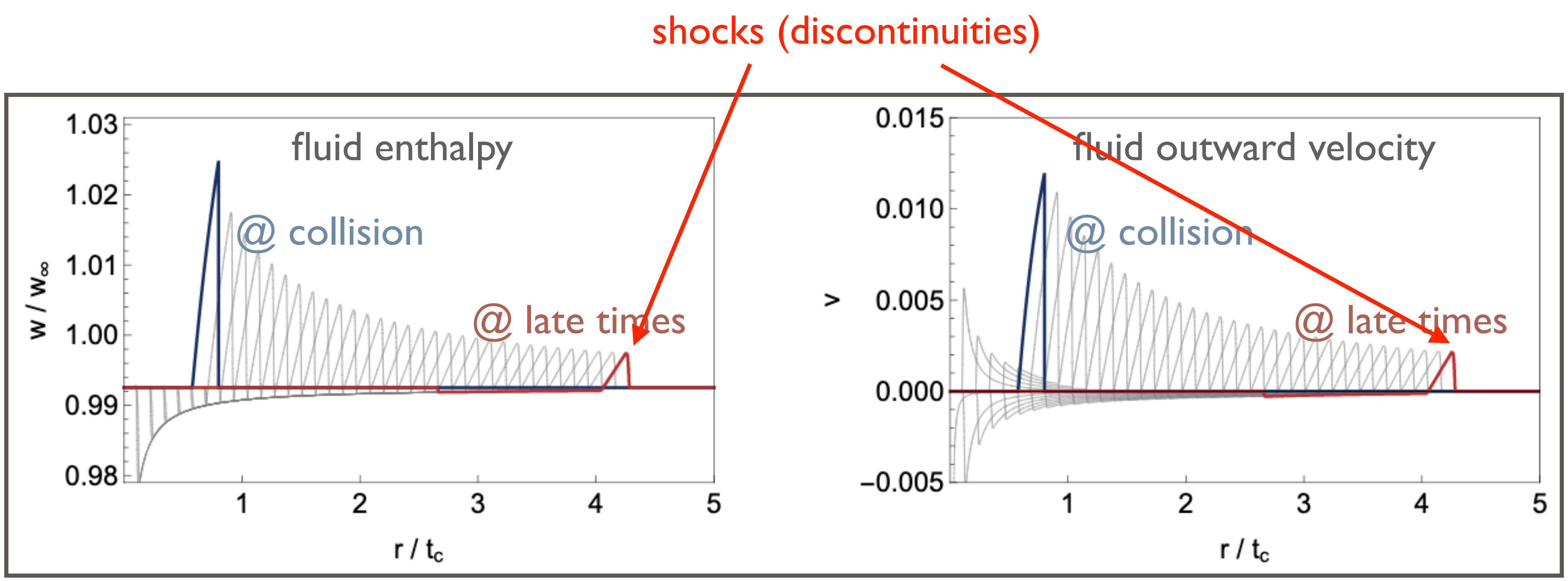
HYBRID SIMULATION: THE IDEA

➤ Central idea: To get rid of the Higgs field & simulate only with fluid

Step2: Simulate radial 1d fluid evolution after collision

We do not need to evolve the profile before collision, since it is well known from the literature.
[Espinosa, Konstandin, No, Servant '10]

We solve the radial evolution using a shock-conserving scheme (Kurganov-Tadmor).



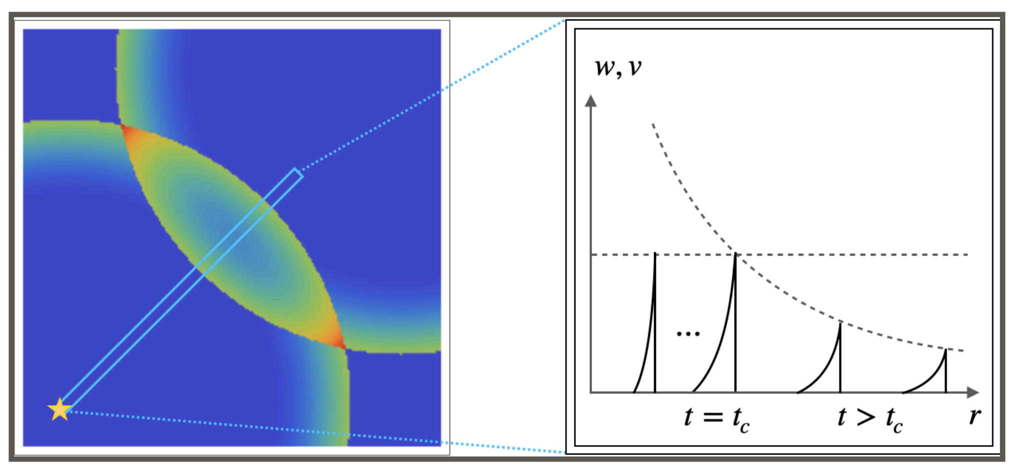
HYBRID SIMILATION: THE IDEA

- Central idea: To get rid of the Higgs field & simulate only with fluid

Step3: Embed 1d back into 3d (①) and calculate GWs (②)

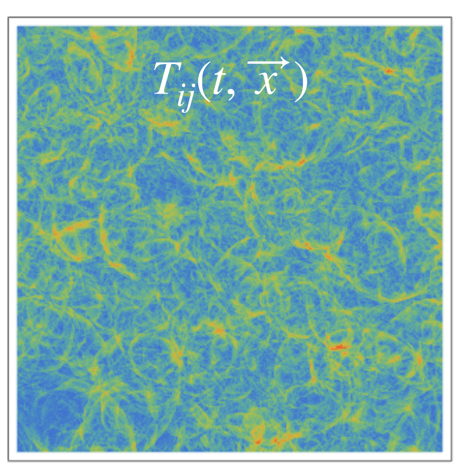
3d box　　　1d evolution

①



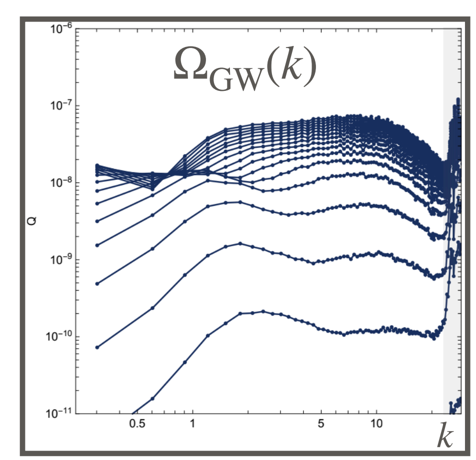
3d box

②

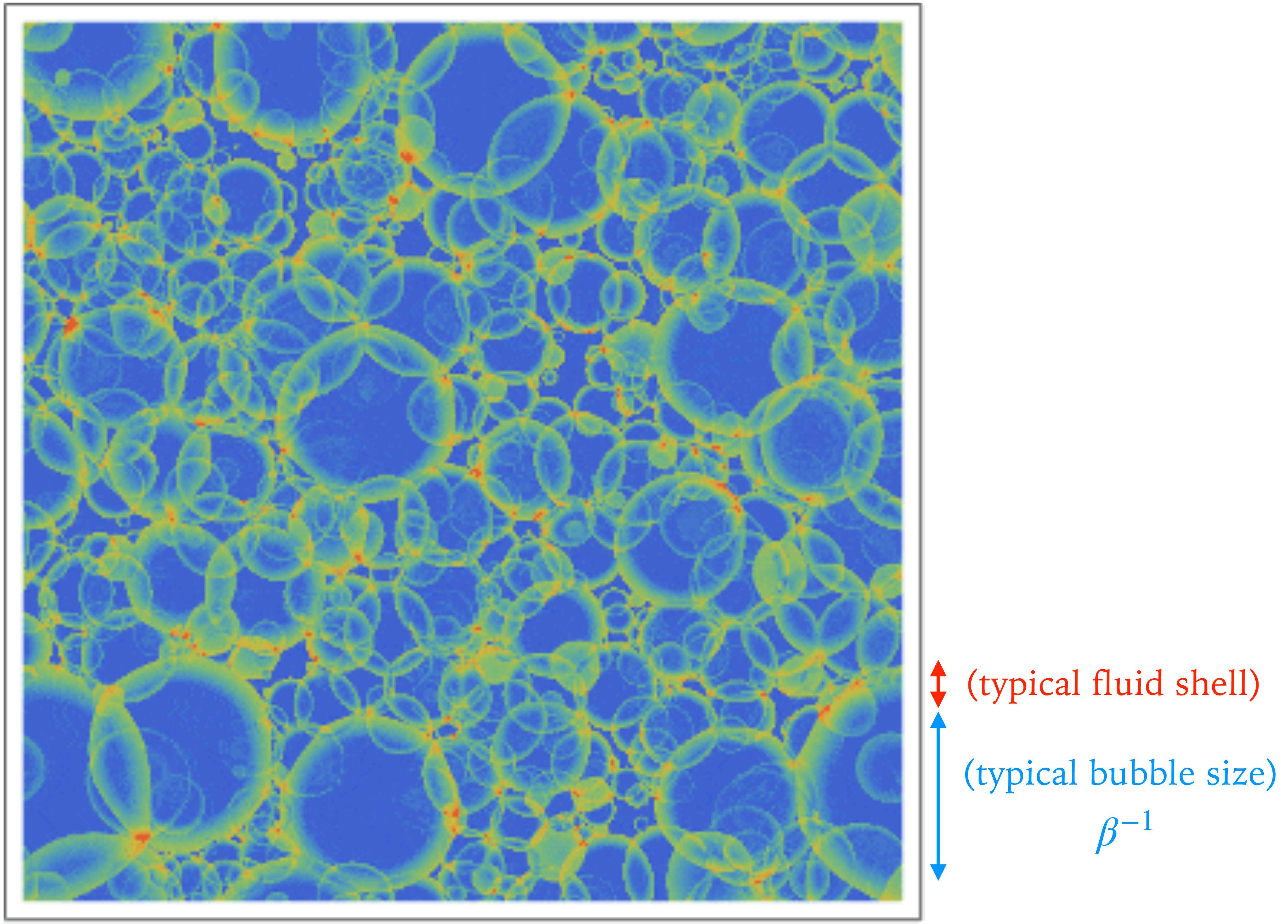


$$\Box h_{ij} \sim G\Lambda_{ij,kl}T_{kl}$$

GW spectrum



HYBRID SIMULATION: EXAMPLE ANIMATION

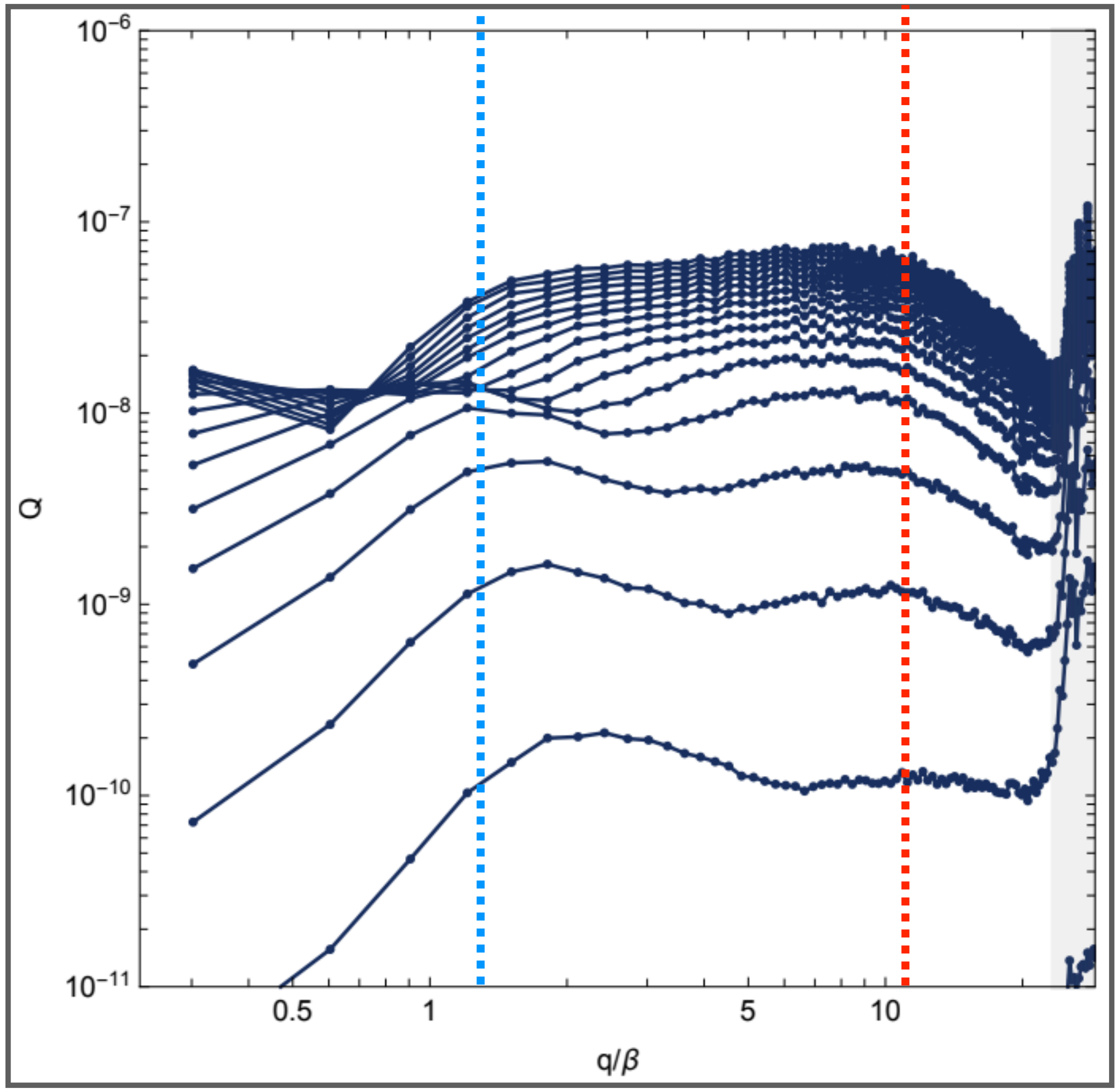


HYBRID SIMULATION: RESULTS

$\alpha = 0.0046, \; v_{\text{wall}} = 0.52$

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

GW spectrum

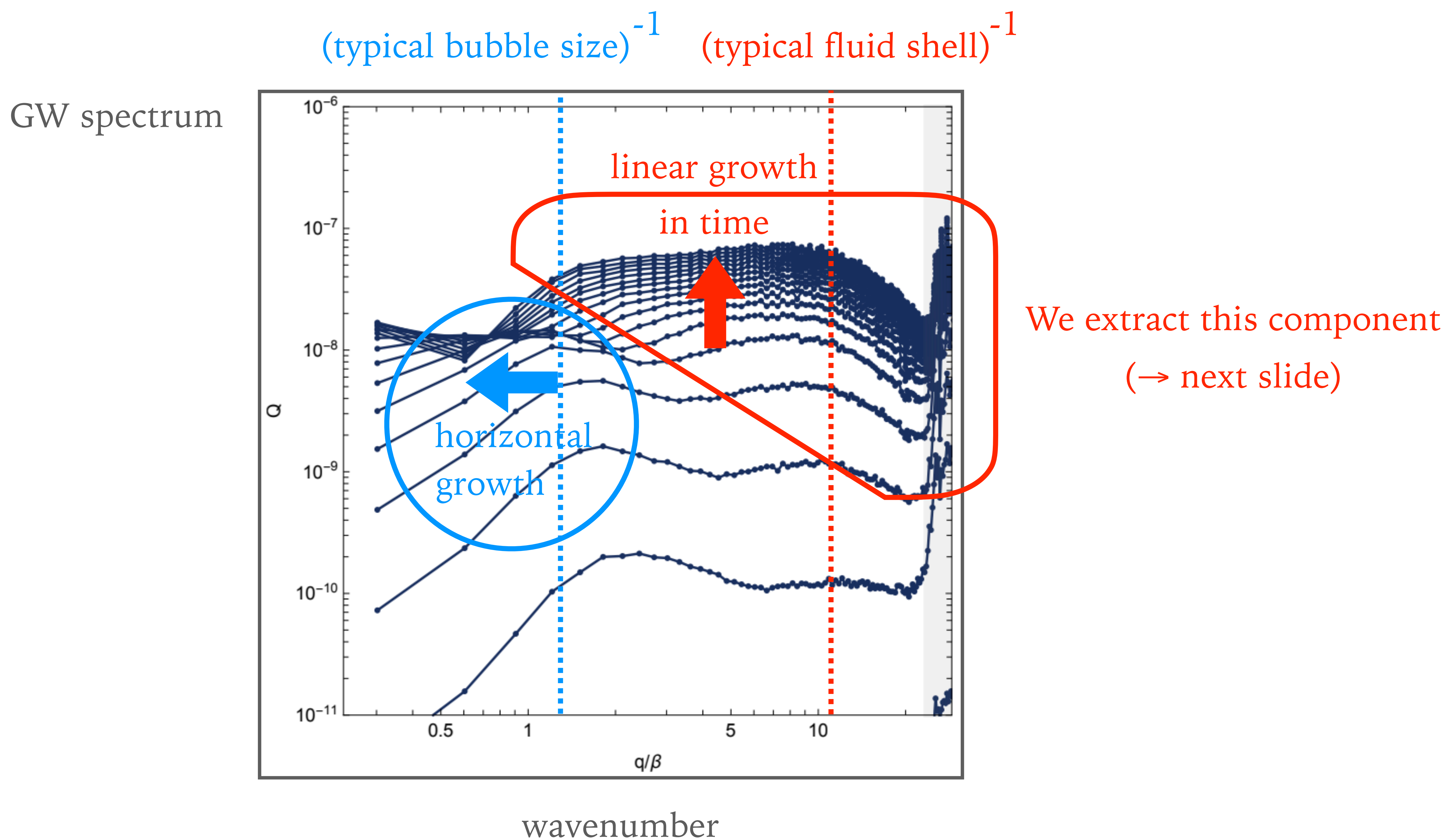


GW spectrum at different time slices

wavenumber

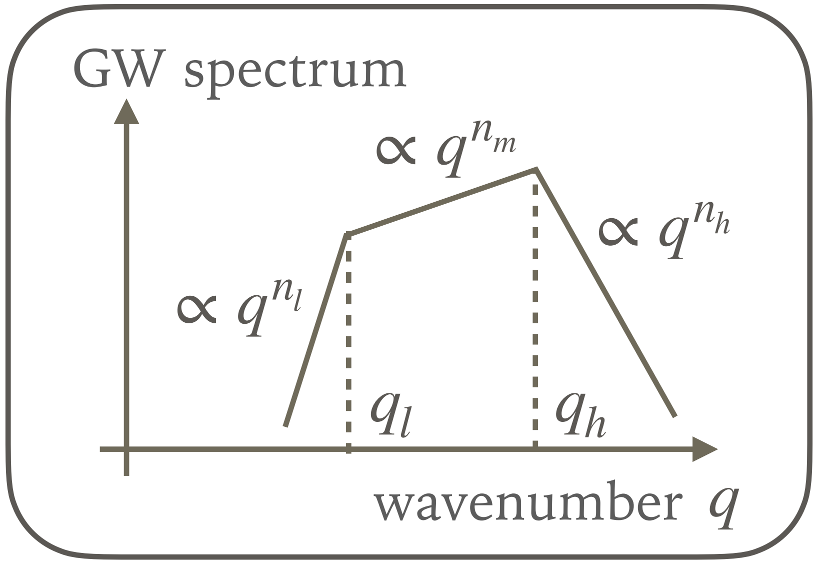
HYBRID SIMULATION: RESULTS

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

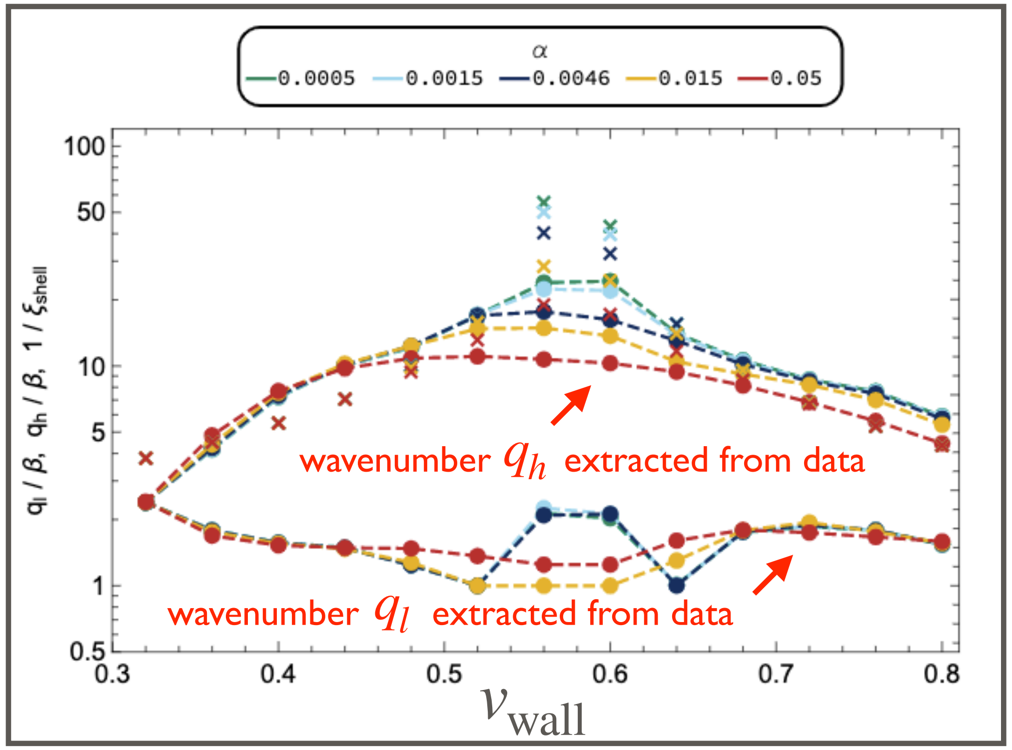


HYBRID SIMULATION: RESULTS

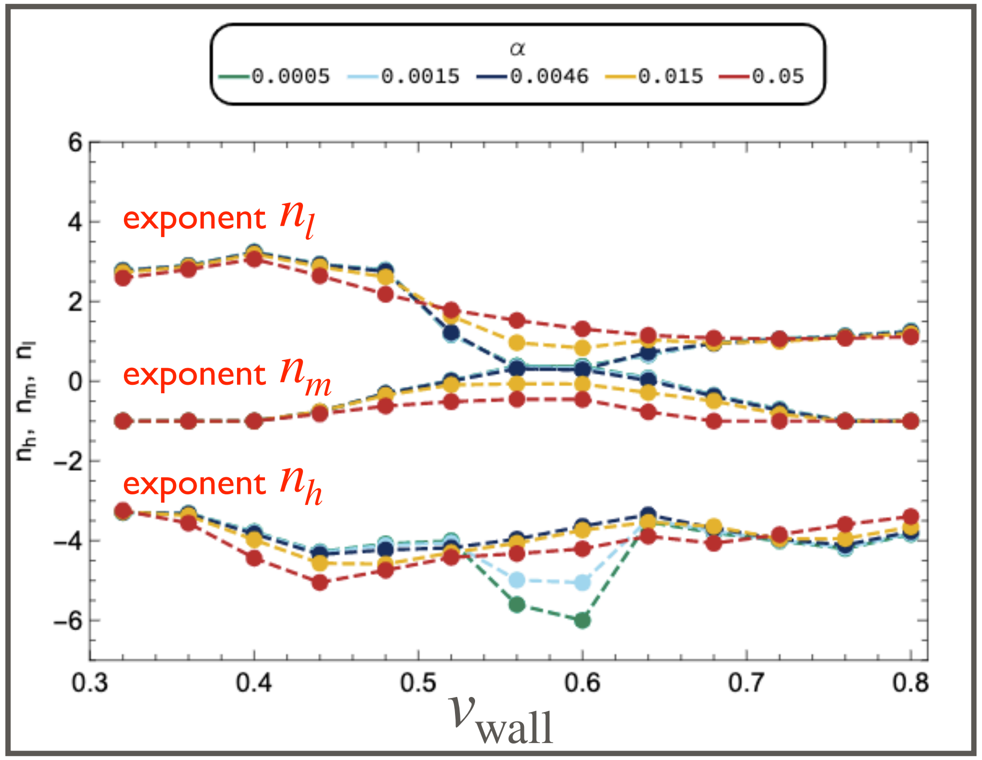
Parametrization of the GW spectrum



Characteristic wavenumeber q_l, q_h



Exponents n_l, n_m, n_h

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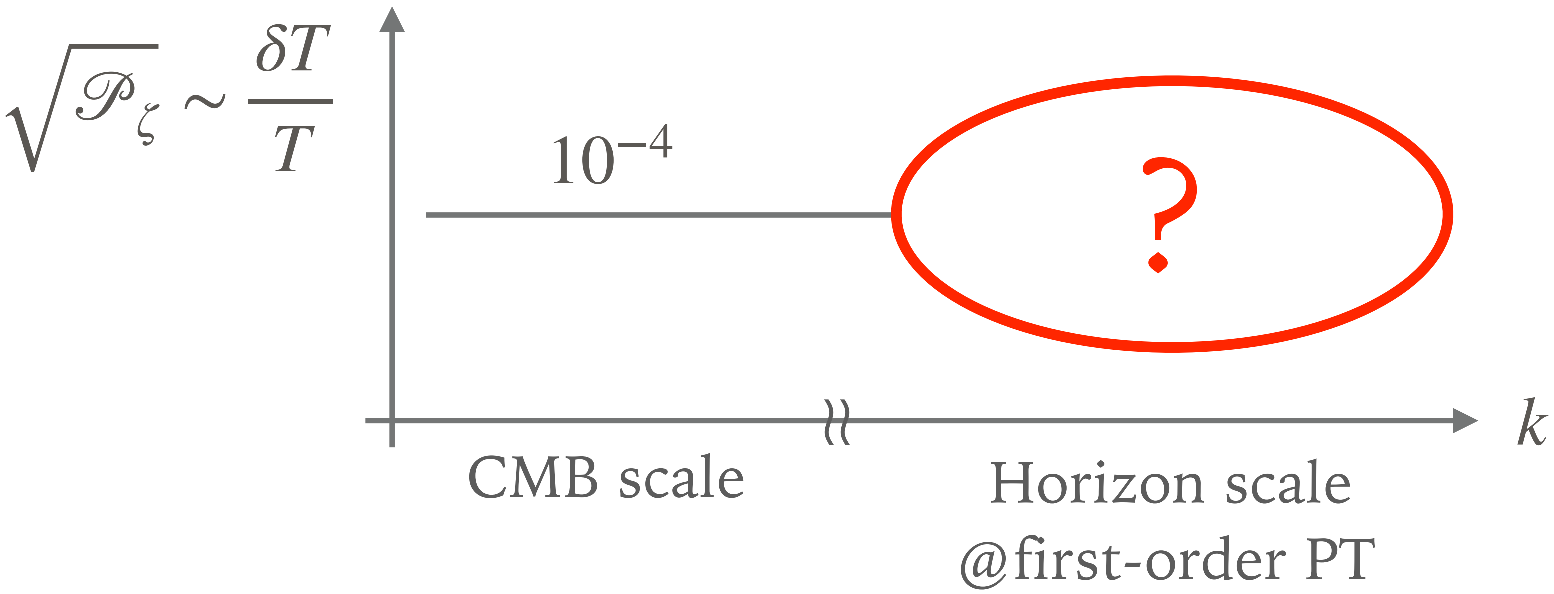
EFFECT OF DENSITY PERTURBATIONS

➤ Density (i.e. curvature) perturbations

- Exist for sure (as long as we assume inflation) $\rightarrow$ Effects need to be studied
- Constrained to $\zeta \sim \dfrac{\delta T}{T} \sim 10^{-4}$ at CMB scales, but unconstrained at larger k



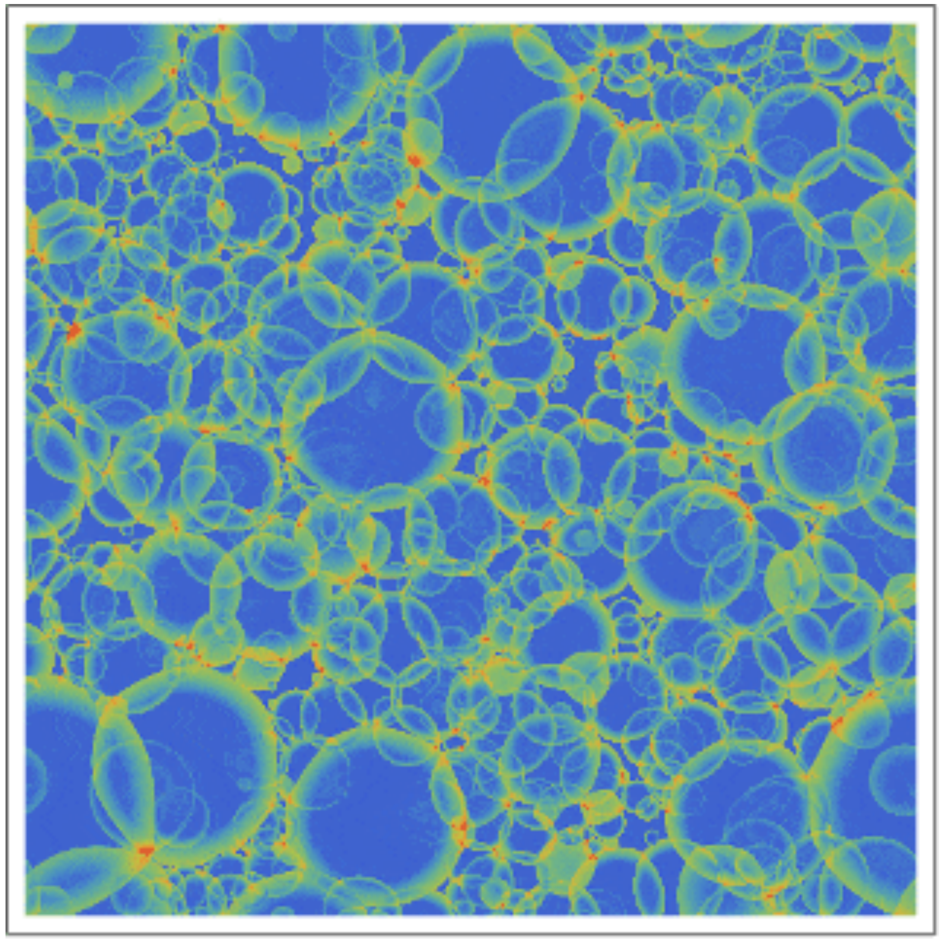
➤ Our interest: biased nucleation time & position from density perturbations

Summary:

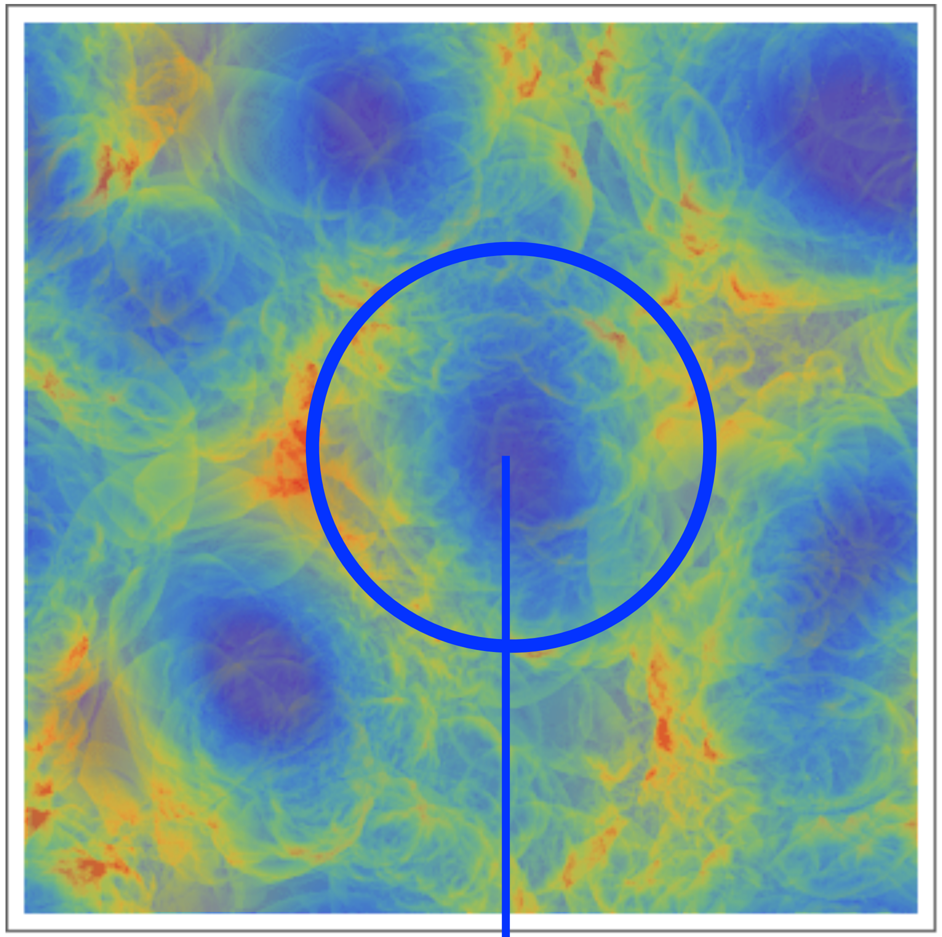
- Density perturbations work as "effective big bubbles"
- To have interesting effects, the amplitude only needs to be $\dfrac{\delta T}{T} \sim \dfrac{H_*}{\beta} \ll 1$

CENTRAL IDEA

Without density perturbations



With density perturbations



formation of "effective big bubbles"
around the cold spots

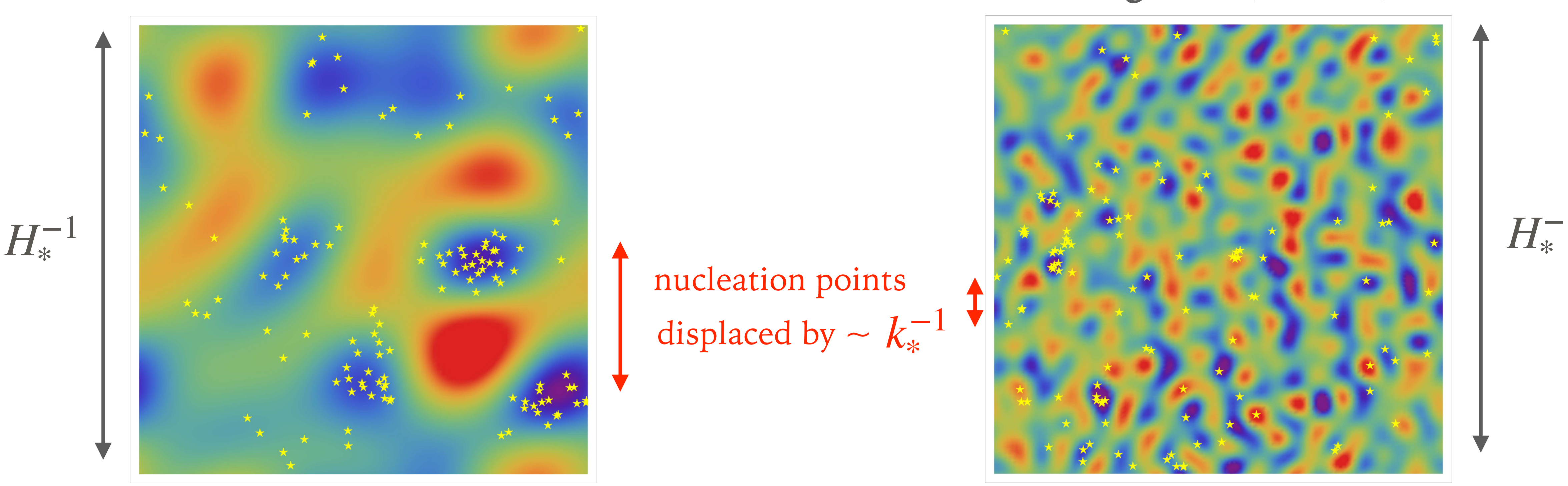
EFFECT OF DENSITY PERTURBATIONS

- Density perturbations are parameterized by two quantities

$$\begin{cases} \text{typical wavenumber } \; k_* & \to \; \text{see below} \\ \text{typical normalized amplitude } \; \sigma \sim \dfrac{\delta T}{T} \Big/ \dfrac{H_*}{\beta} & \to \; \text{effects set in once} > 1 \end{cases}$$

- Dependence of the nucleation points (★) on k_*

small k_* (= IR) large k_* (= UV)



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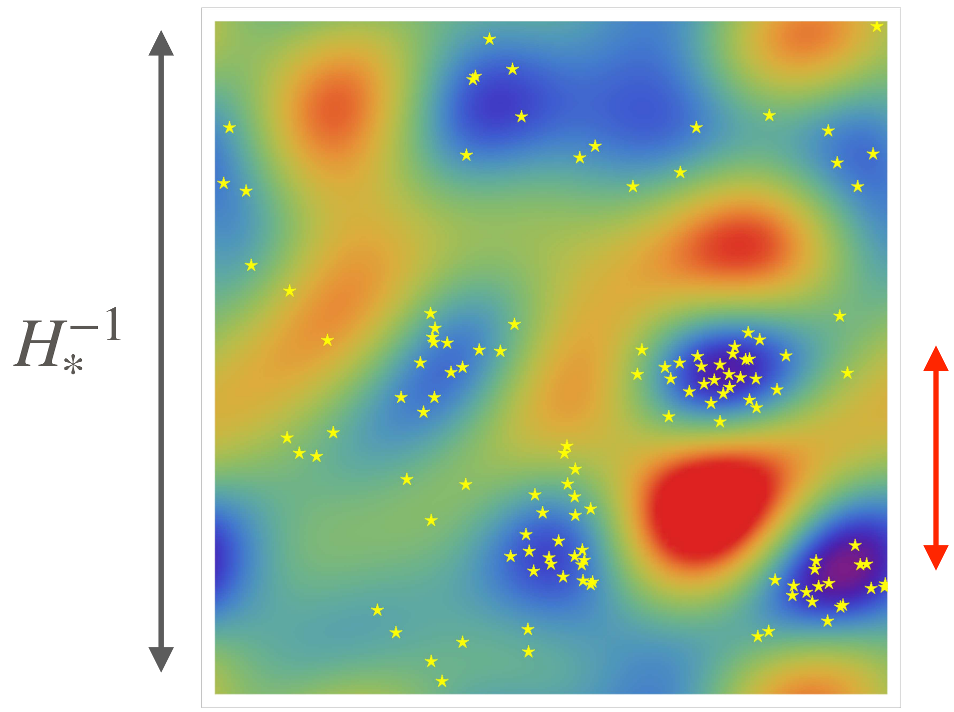
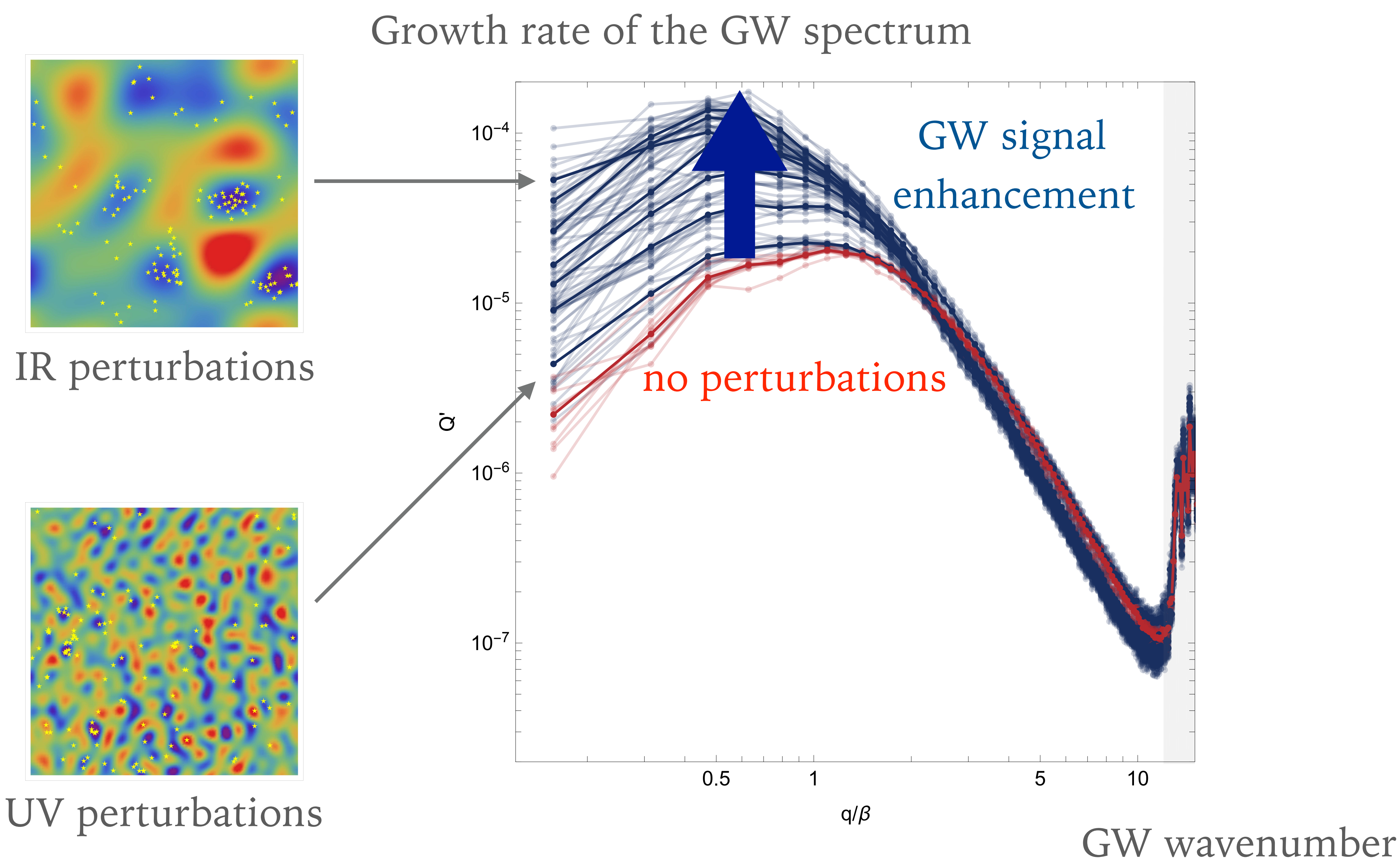


nucleation points
displaced by $\sim k_*^{-1}$

Density perturbations work as
"effective big bubbles"

GW ENHANCEMENT FROM DENSITY PERTURBATIONS

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

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SUMMARY

- We propose a "hybrid simulation" to get rid of the artifact from the scalar field

- We point out GW signal enhancement from density perturbations:

  - occurs for typical wavenumber $H_* < k_* < \beta$

  - amplitude $\dfrac{\delta T}{T} \sim \dfrac{H_*}{\beta} \ll 1$ is enough to have this effect

Backup

GW ENHANCEMENT FROM DENSITY PERTURBATIONS