Take-home messages

Effect of density pert.

Hybrid simulation

Intro

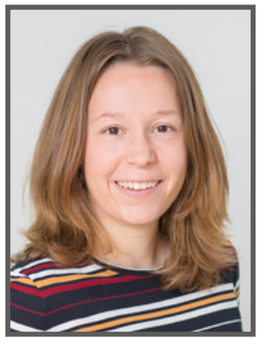
GWs from first-order phase transitions: A hybrid simulation & signal enhancement from density perturbations

Ryusuke Jinno (DESY)

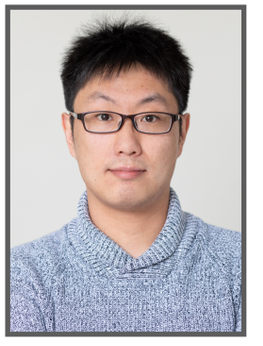
SUSY 2021, 8.24.2021@Shanghai

T. Konstandin

J.v.d.Vis



H. Rubira



[Jinno, Konstandin, Rubira, v.d.Vis, to appear]

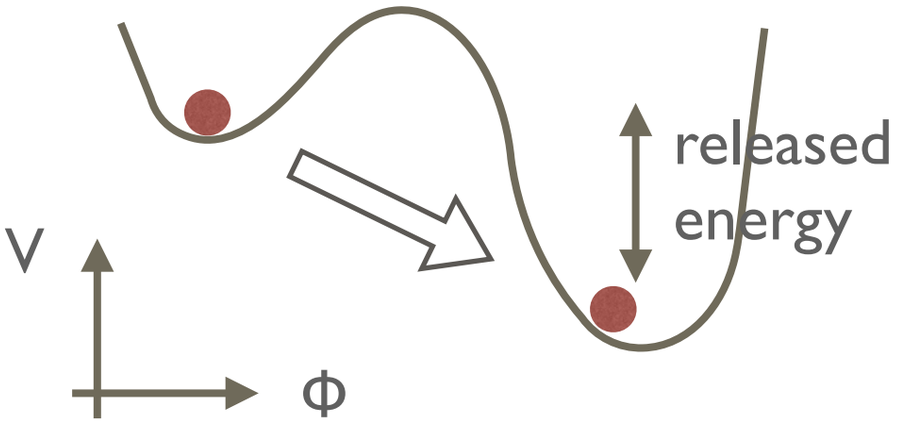
[Jinno, Konstandin, Rubira, JCAP 04 (2021) 014, 2010.00971]

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

- Bubbles nucleate, expand, collide and disappear

Field space

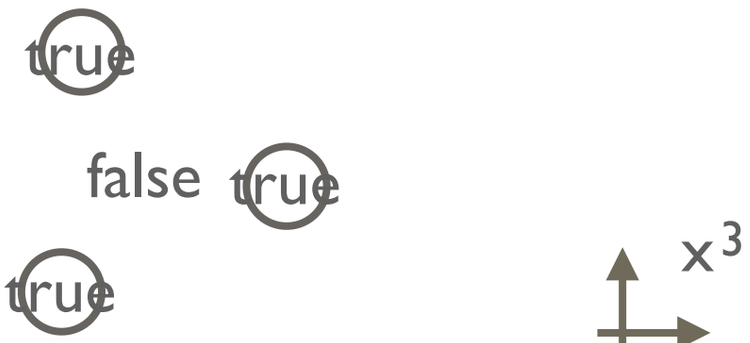
false vacuum true vacuum



Quantum tunneling

Position space

nucleation of bubbles

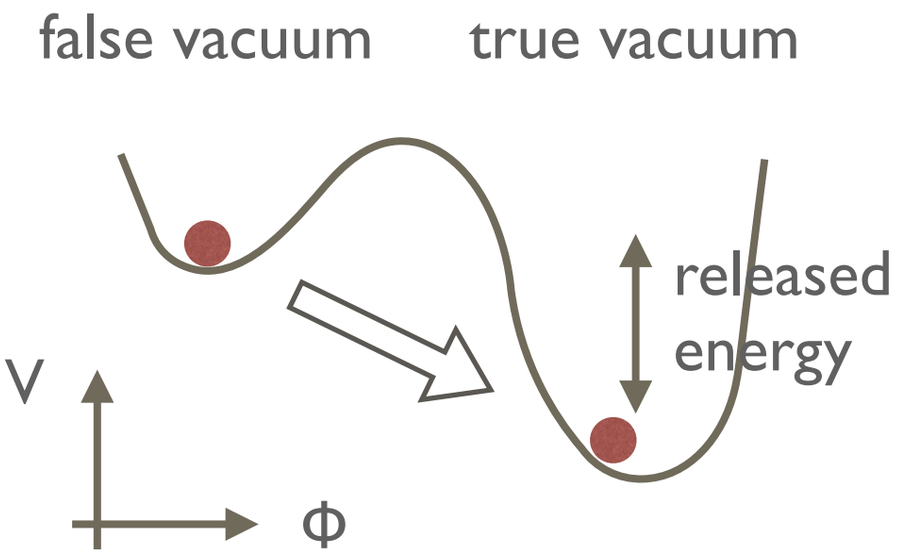


Bubble dynamics & GW production

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

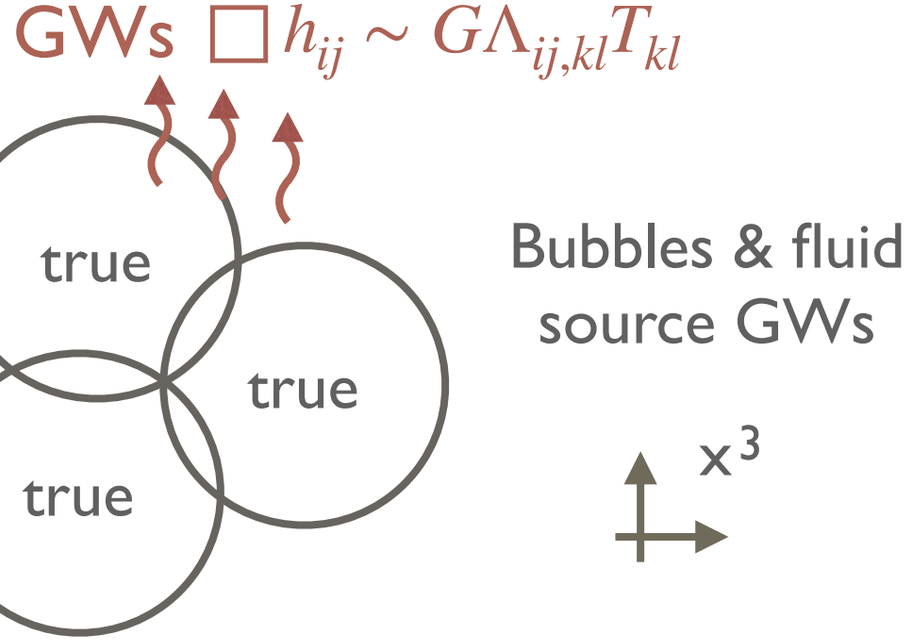
- Bubbles nucleate, expand, collide and disappear

Field space



Quantum tunneling

Position space

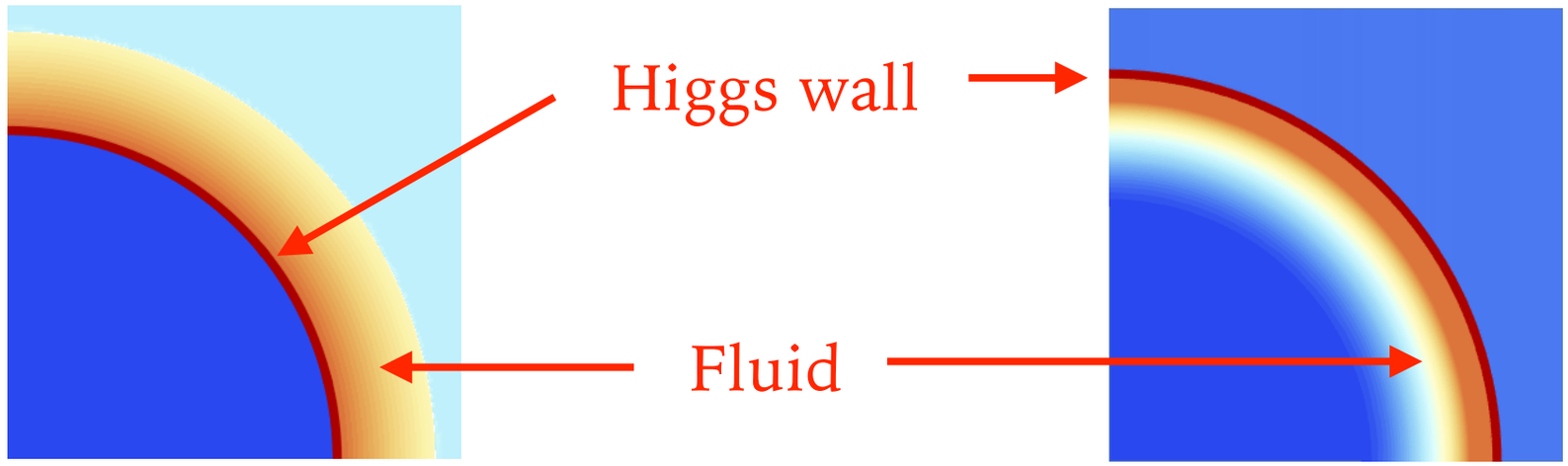


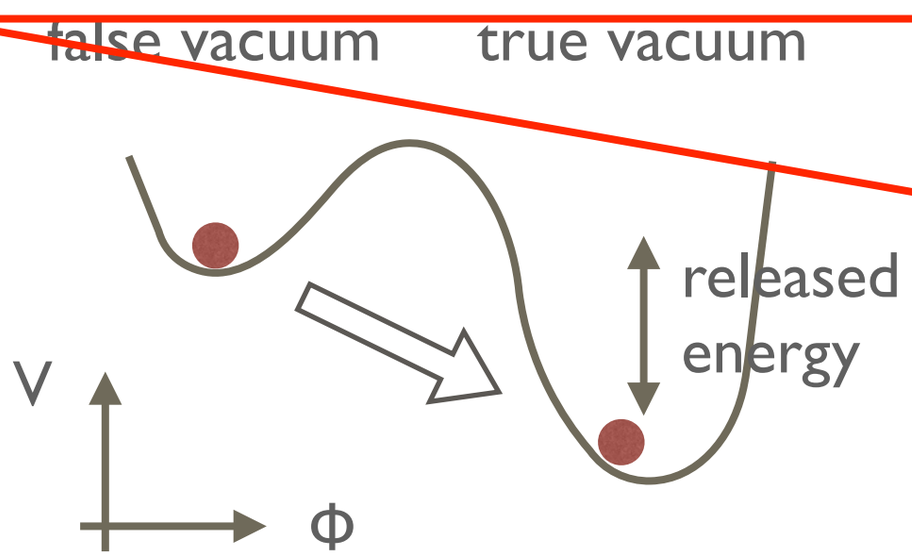
Bubble dynamics & GW production

1ST ORDER PT & GW PRODUCTION: A BRIEF SKETCH

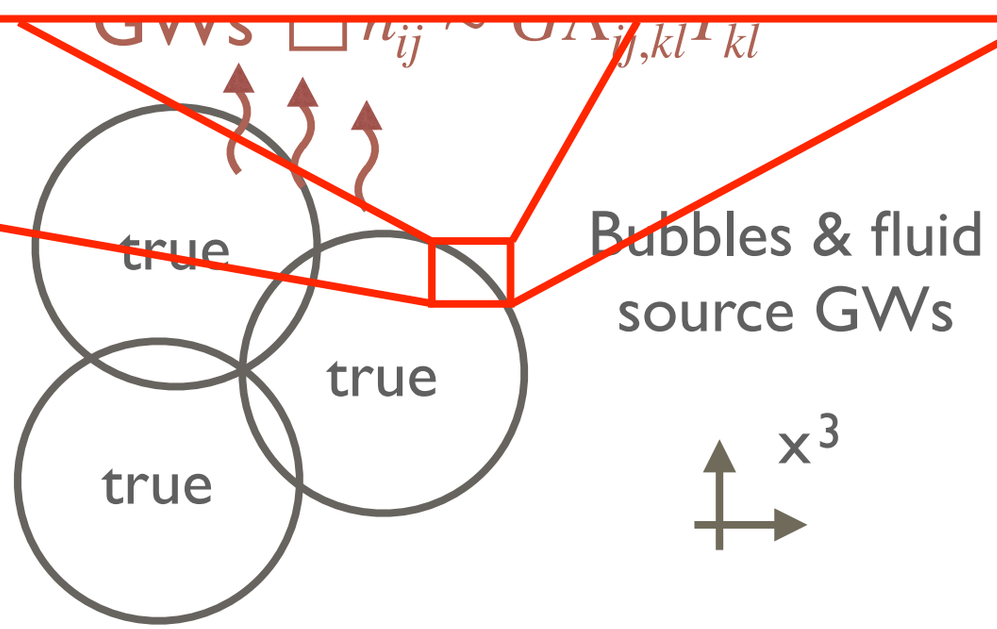
- ...

Bubble dynamics is in reality a violent process involving fluid dynamics



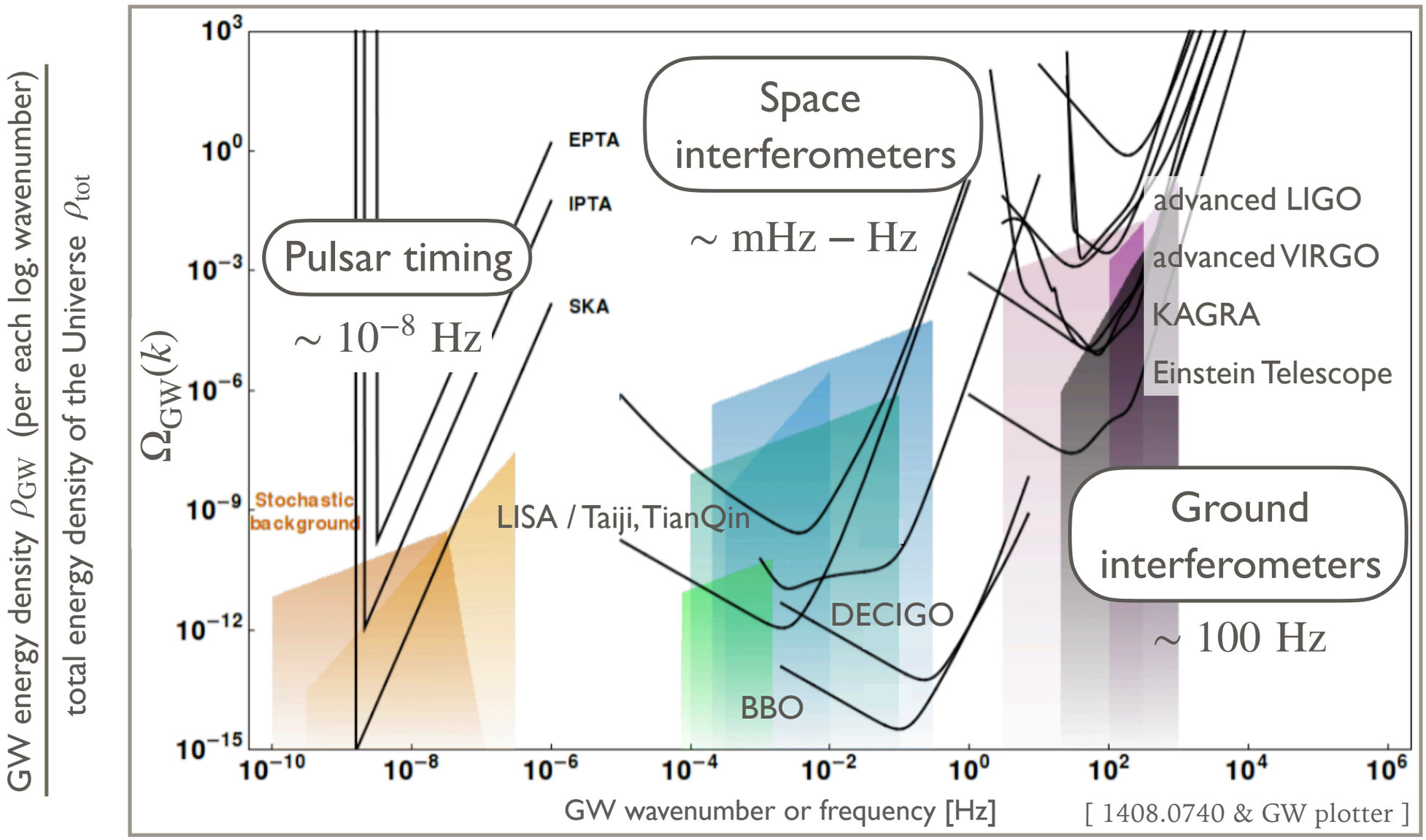


Quantum tunneling



Bubble dynamics & GW production

SUMMARY ON ONGOING/FUTURE GW OBSERVATIONS



➤ Time to develop robust theoretical predictions

Take-home messages

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Intro

ANALYTICAL VS. NUMERICAL METHODS: STATE OF THE ART

from T. Konstandin's talk

	(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)

ANALYTICAL VS. NUMERICAL METHODS: STATE OF THE ART

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Pros.		Less cost Better analytical understanding	Less *a priori* assumptions More robust predictions
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ONE PROBLEM ABOUT NUMERICAL SIMULATIONS

- "Artifact" from the Higgs field?

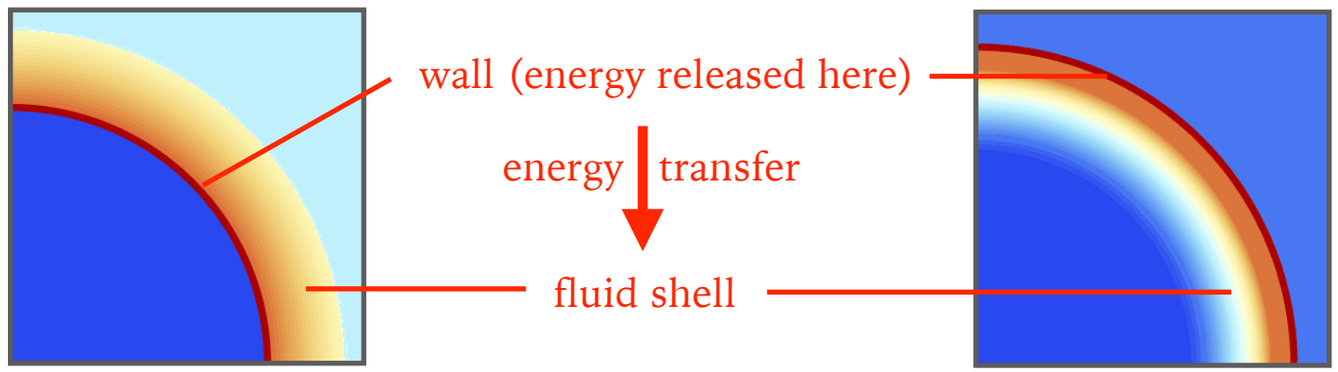
from T. Konstandin's talk

In the physical phase transition

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

energetically negligible

far separate scale (~1/100GeV) from others



In simulations

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

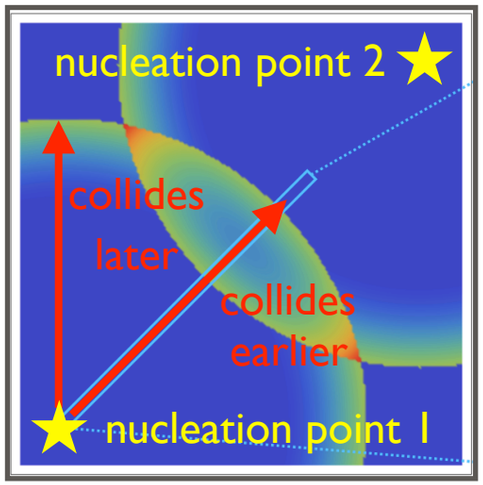
appears as "artifact"

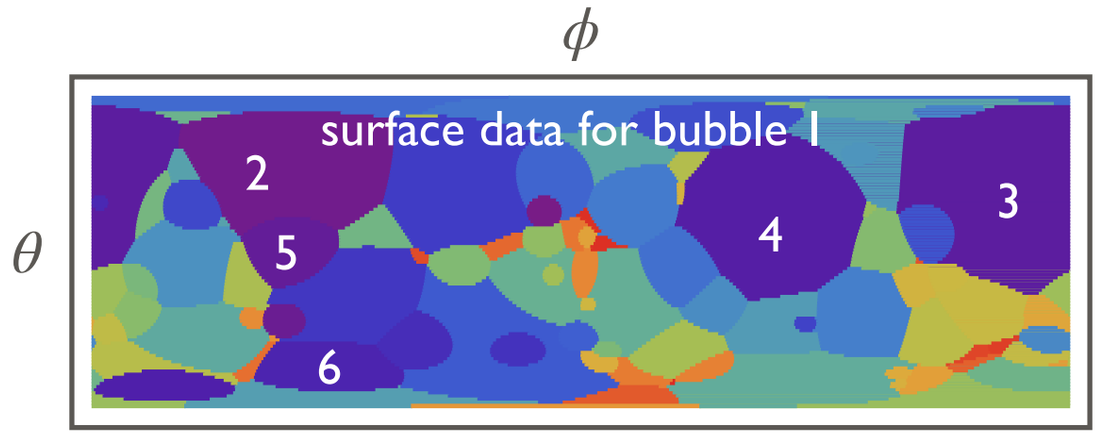
HYBRID SIMULATION: THE IDEA

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

Step1: Create surface data for collision time

This is possible without simulation, just from the distribution of the nucleation points (★)





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

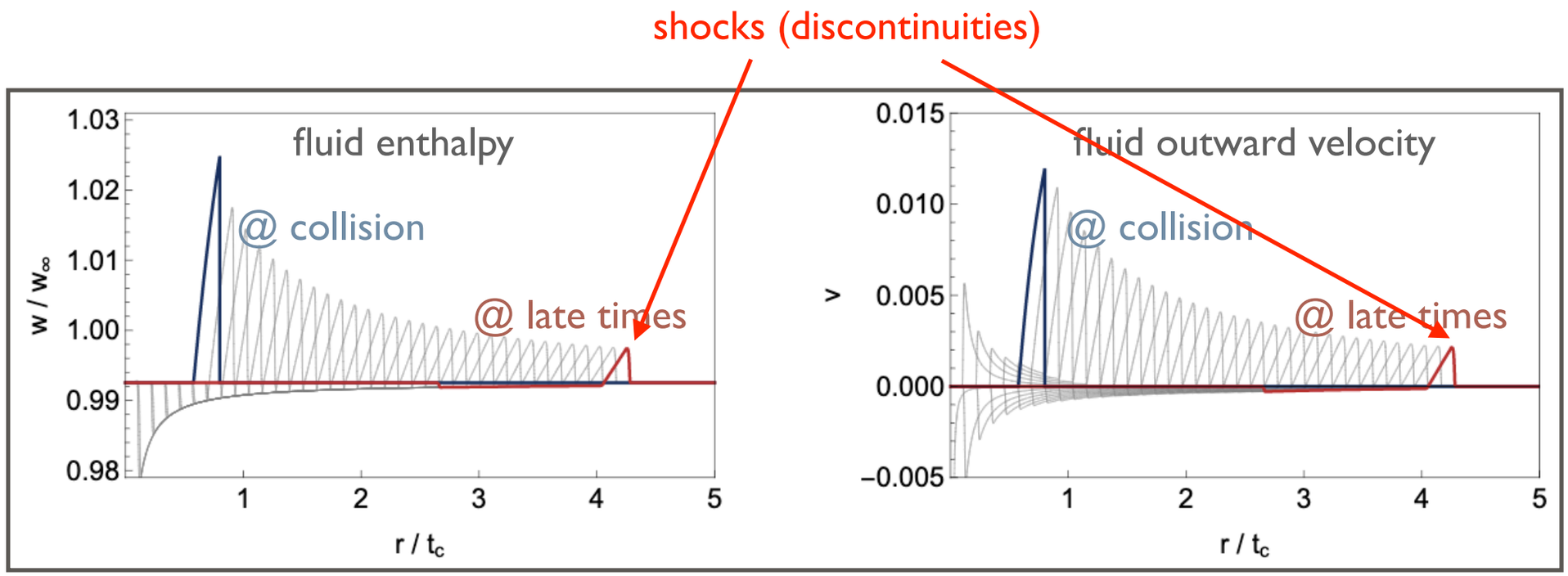
HYBRID SIMULATION: THE IDEA

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

Step2: Simulate radial 1d evolution after collision only with fluid

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 SIMULATION: THE IDEA

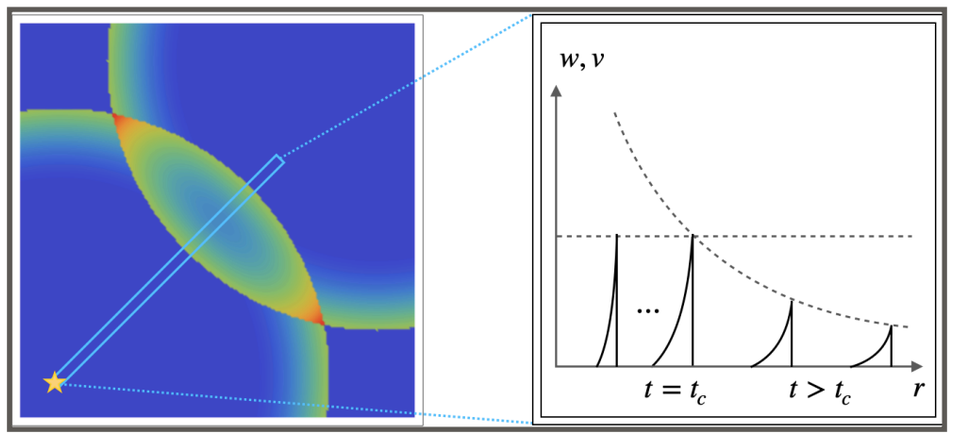
- Central idea: To get rid of the Higgs field & simulate only with fluid

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

3d box

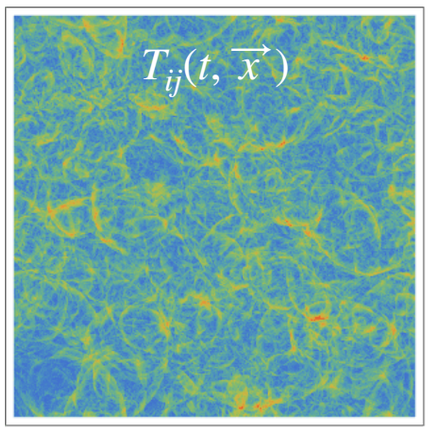
1d evolution

①



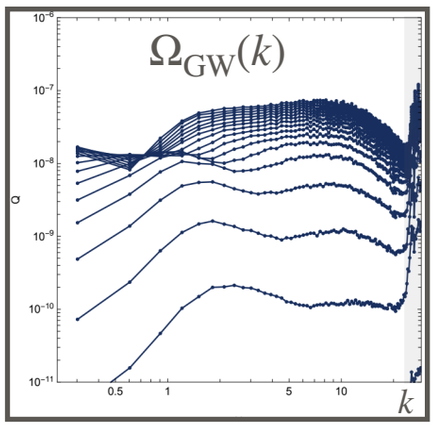
3d box

②

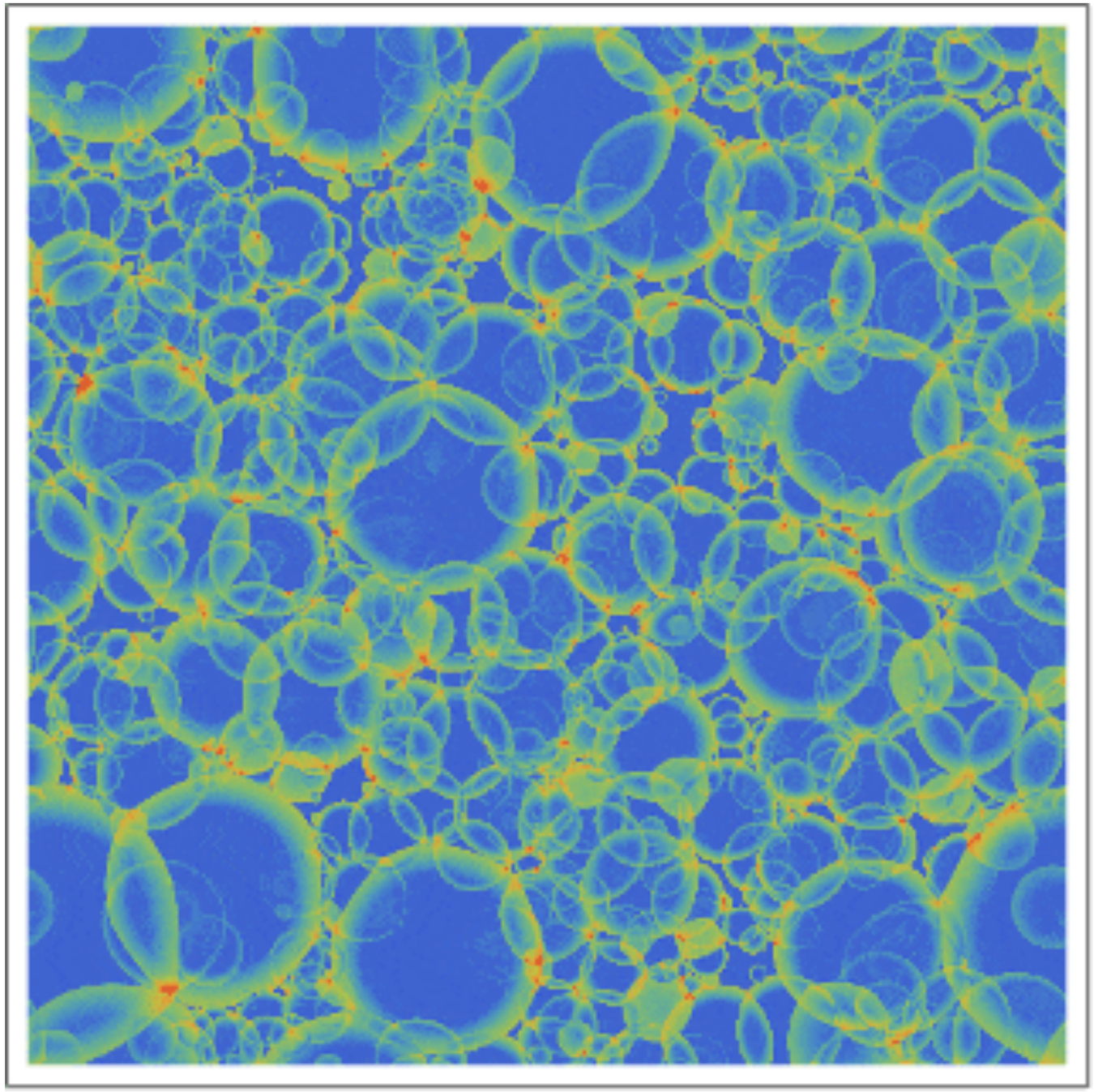


$$\Box h_{ij} \sim G\Lambda_{ij,kl}T_{kl}$$

GW spectrum



HYBRID SIMULATION: EXAMPLE ANIMATION

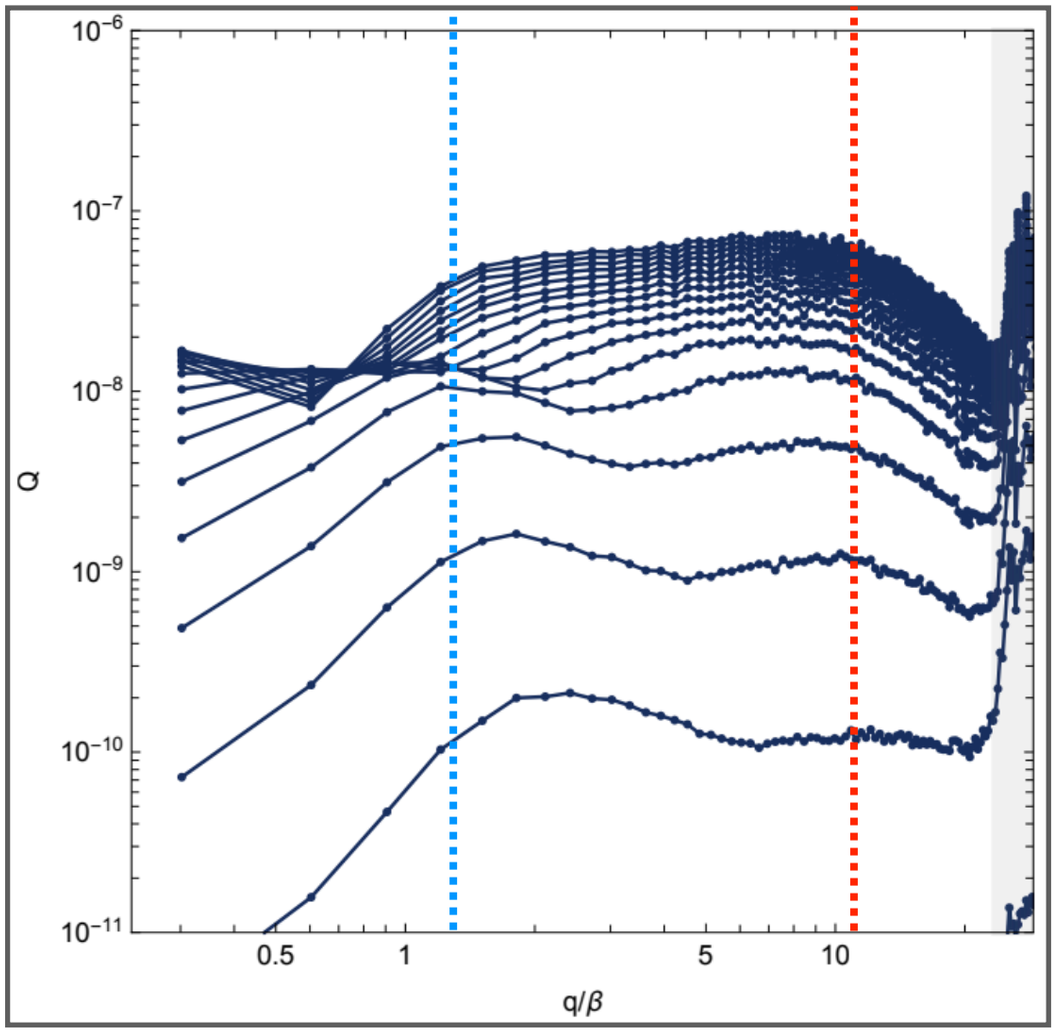


HYBRID SIMULATION: RESULTS

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

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

GW spectrum



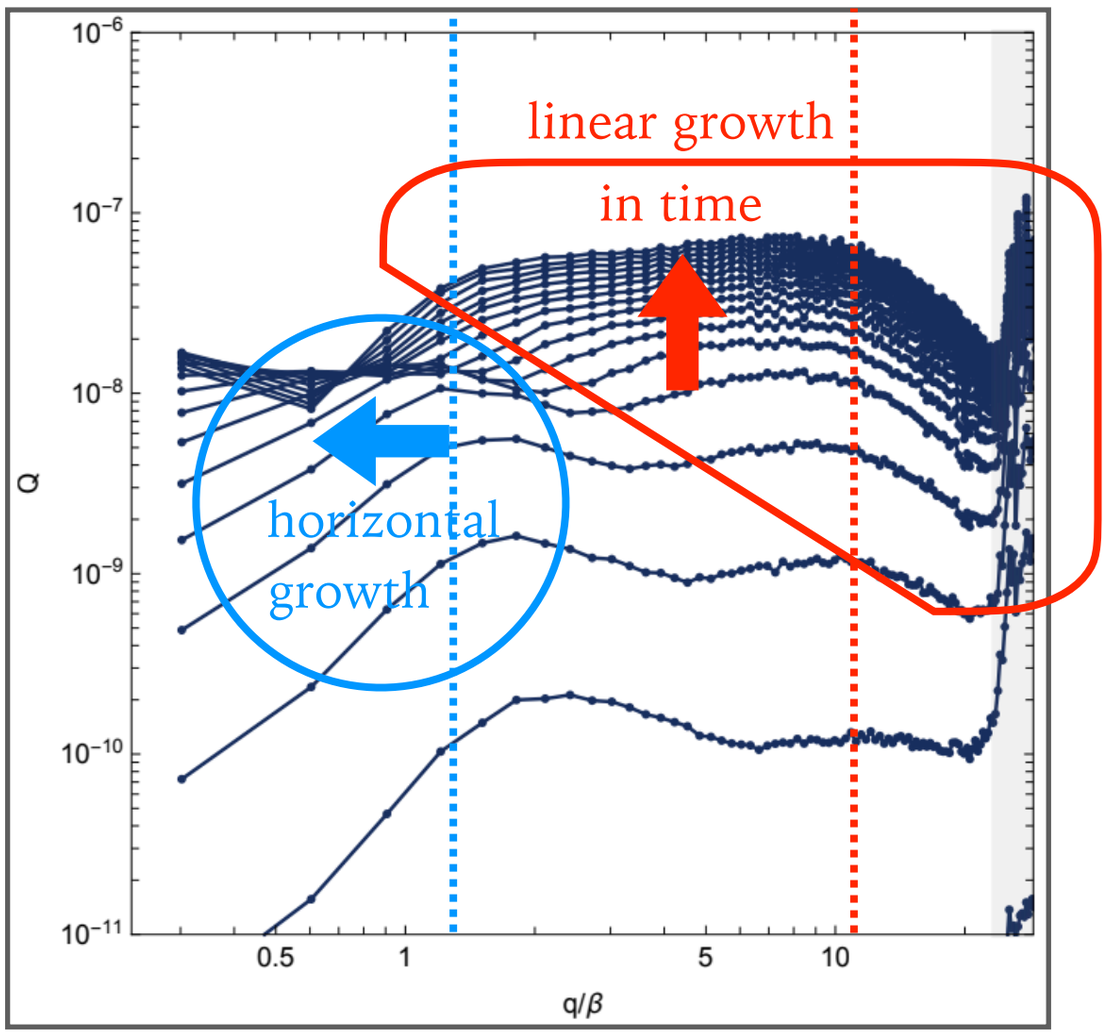
GW spectrum at different time slices

wavenumber

HYBRID SIMULATION: RESULTS

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

GW spectrum

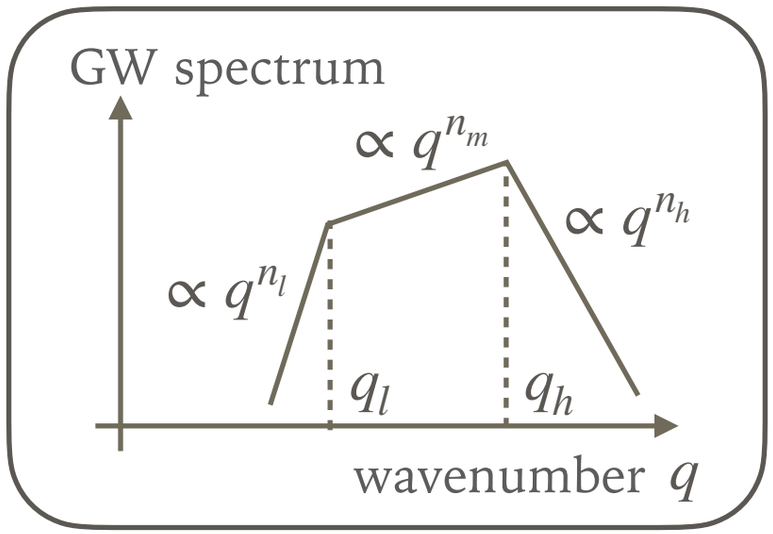


wavenumber

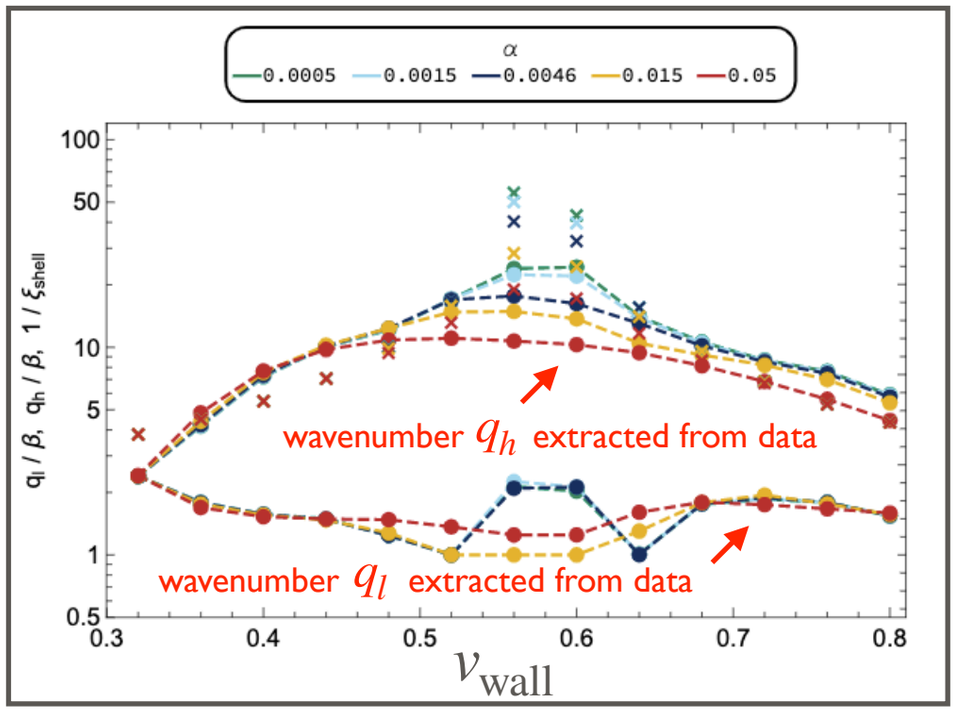
We extract this component
(→ next slide)

HYBRID SIMULATION: RESULTS

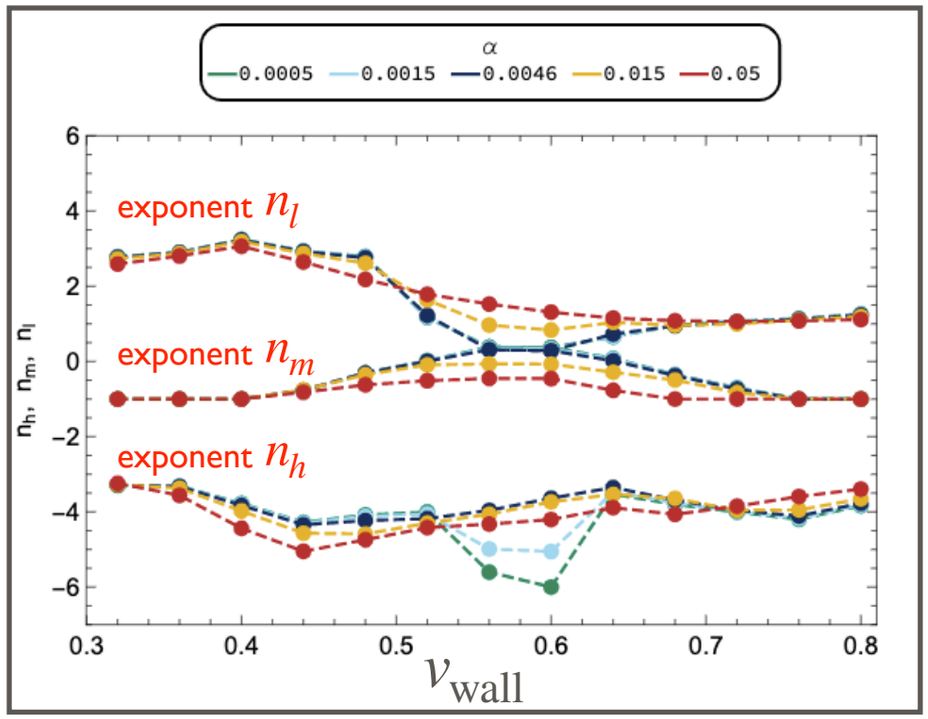
Parametrization of the GW spectrum



Characteristic wavenumeber q_l, q_h



Exponents n_l, n_m, n_h



Take-home messages

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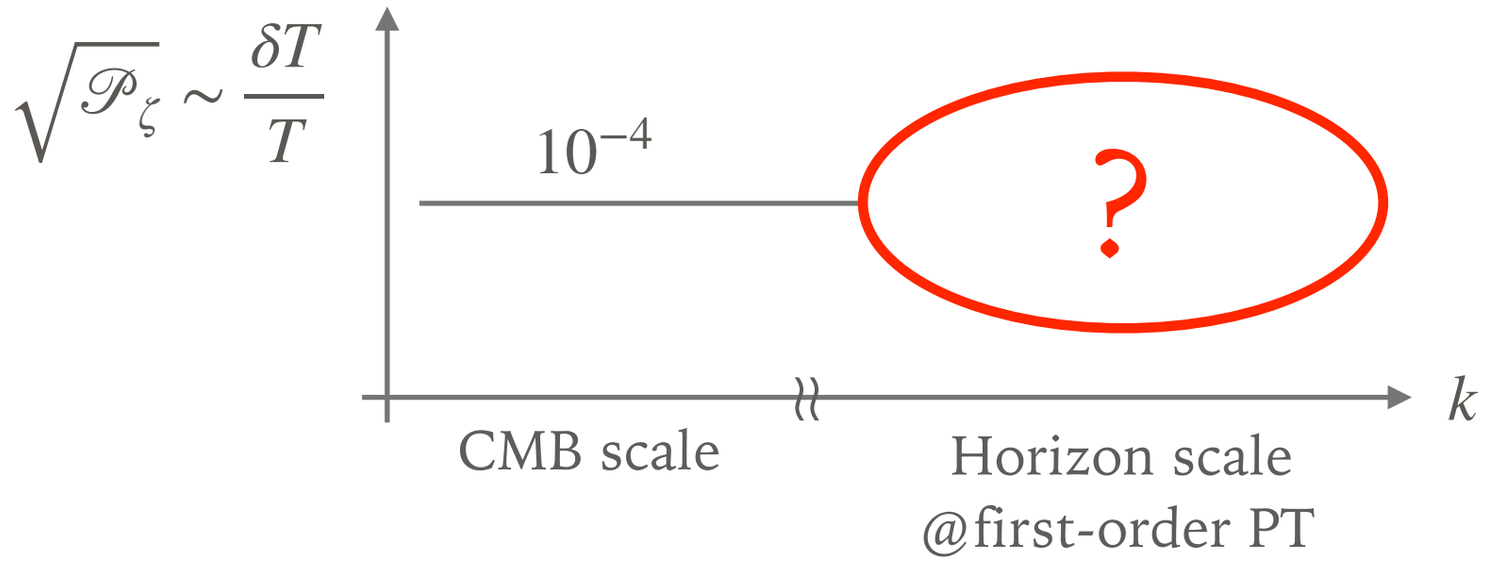
Intro

EFFECT OF DENSITY PERTURBATIONS

- Density (i.e. curvature) perturbations

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

  - Basically unconstrained at smaller scales (large k)



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

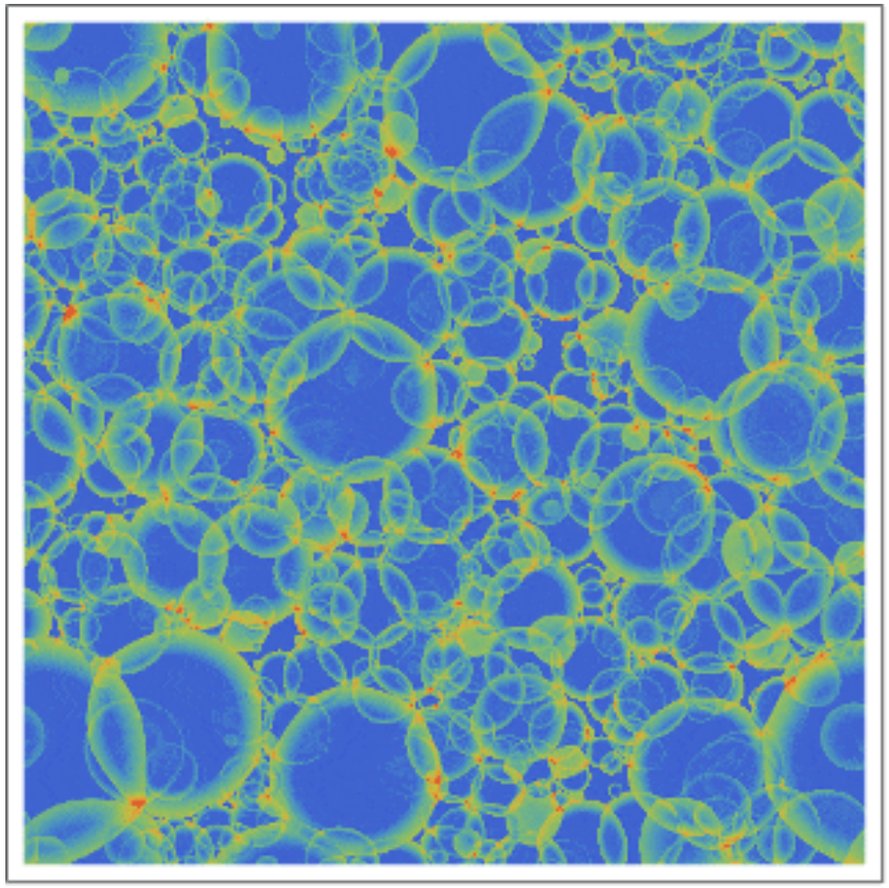
Summary:

- Density perturbations work as "effective big bubbles"

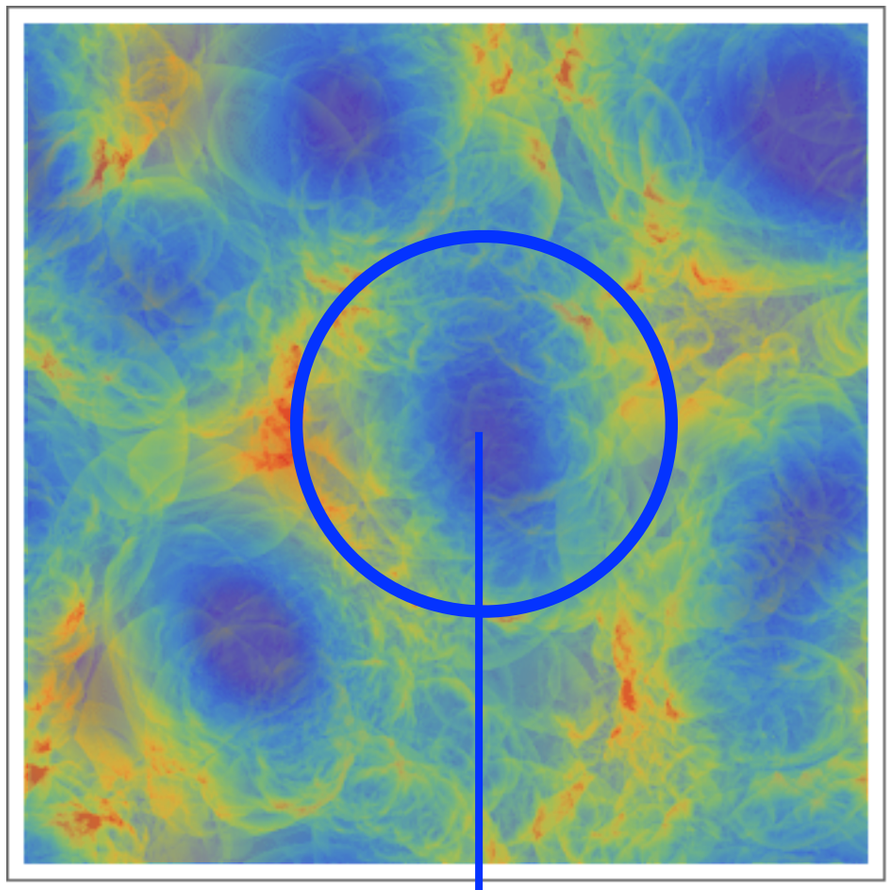
- To have interesting effects, their amplitude only needs to be $\dfrac{\delta T}{T} \sim \dfrac{H_*}{\beta} \ll 1$

CENTRAL IDEA

Without density perturbations



With density perturbations



formation of "effective big bubbles"
around the cold spots

EFFECT OF DENSITY PERTURBATIONS

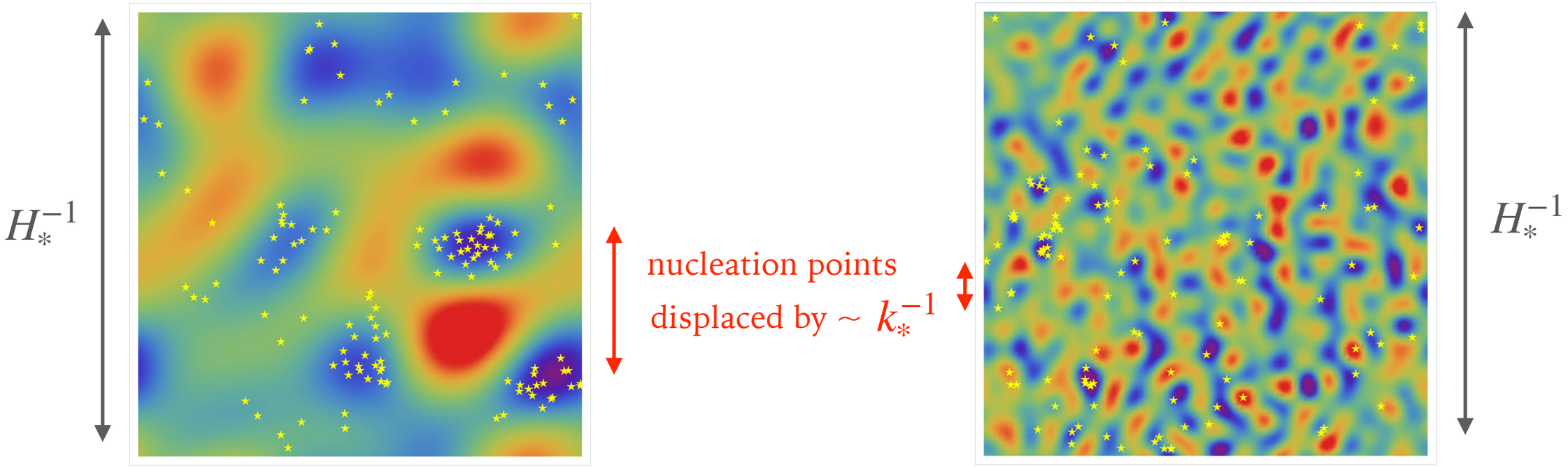
- Density perturbations are parameterized by two quantities

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

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

small k_* (= IR)

large k_* (= UV)



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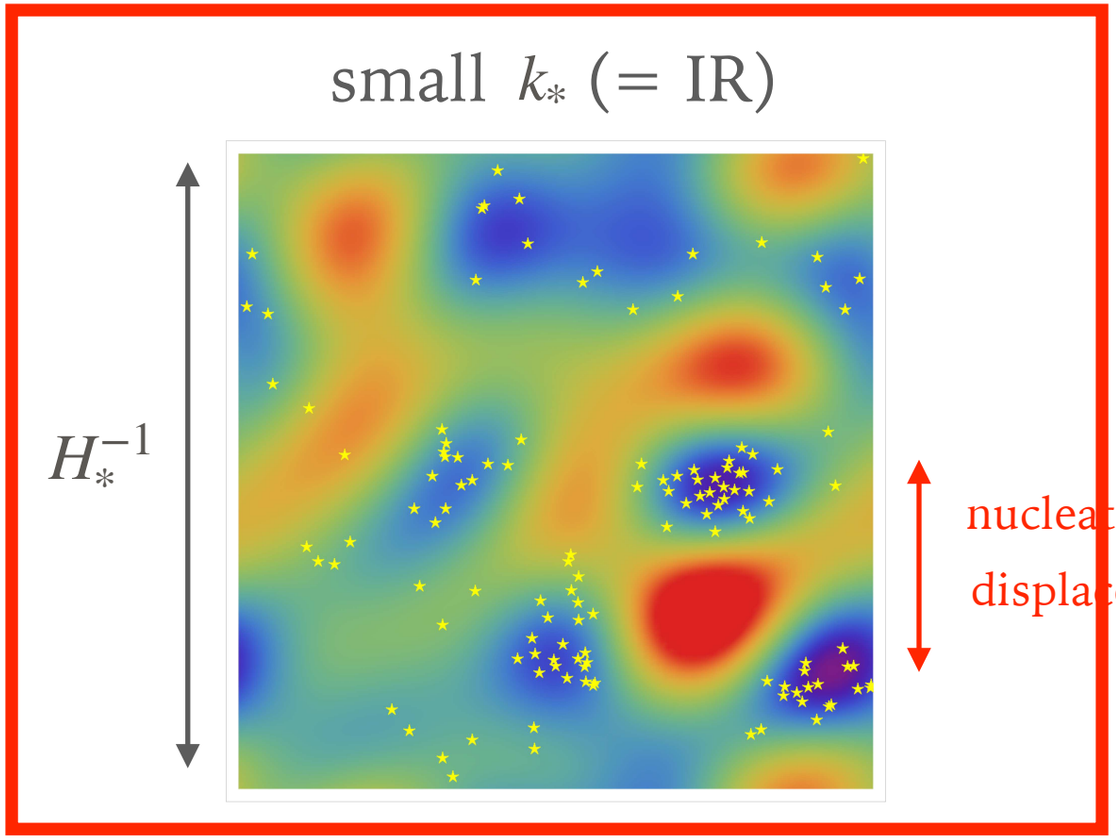
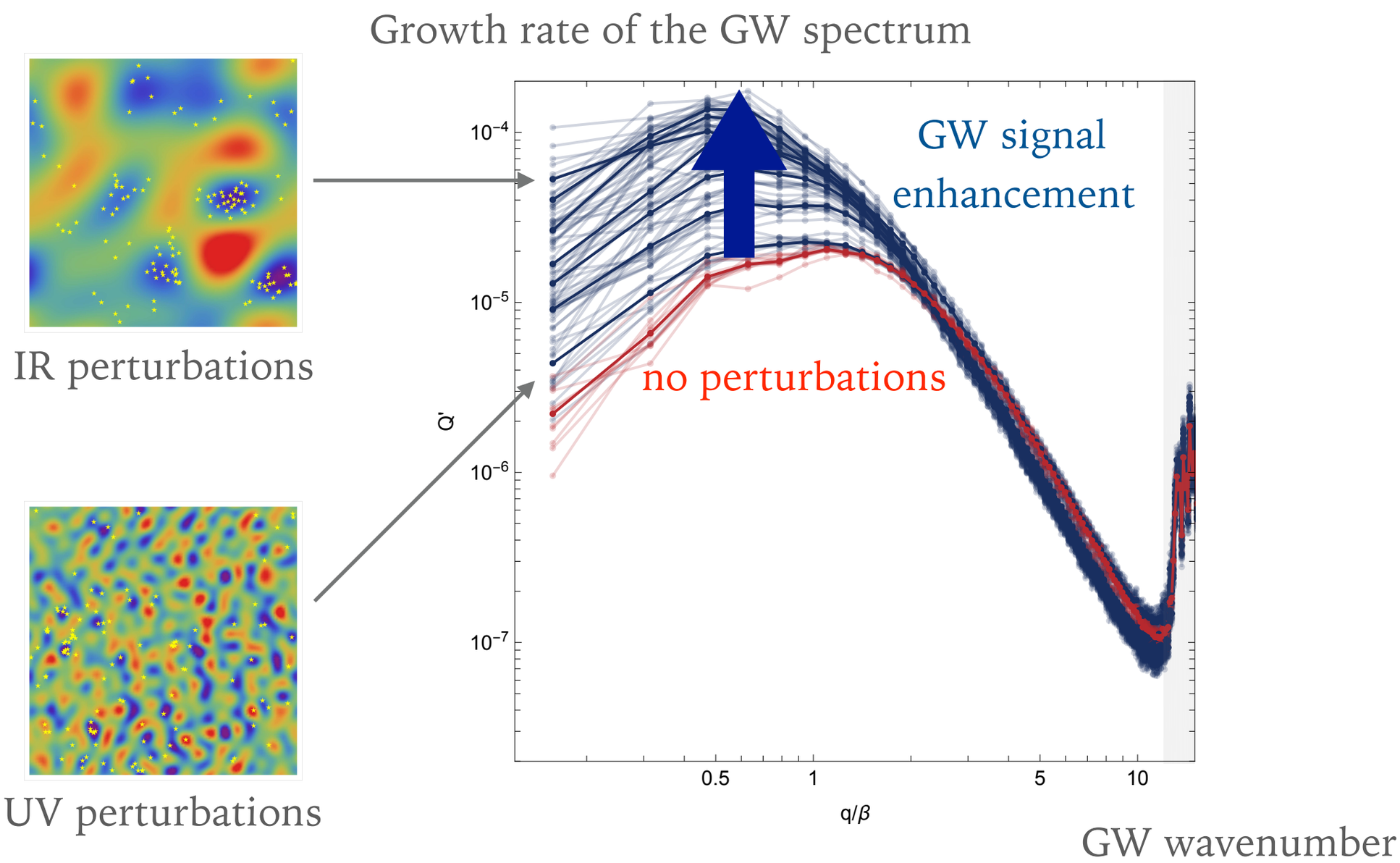


Density perturbations work as
"effective big bubbles"

GW ENHANCEMENT FROM DENSITY PERTURBATIONS

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



Take-home messages

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Intro

TAKE-HOME MESSAGES

- It's time to develop analytical & numerical methods for GW predictions in first-order phase transitions

- 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 $H_* < k_* < \beta$

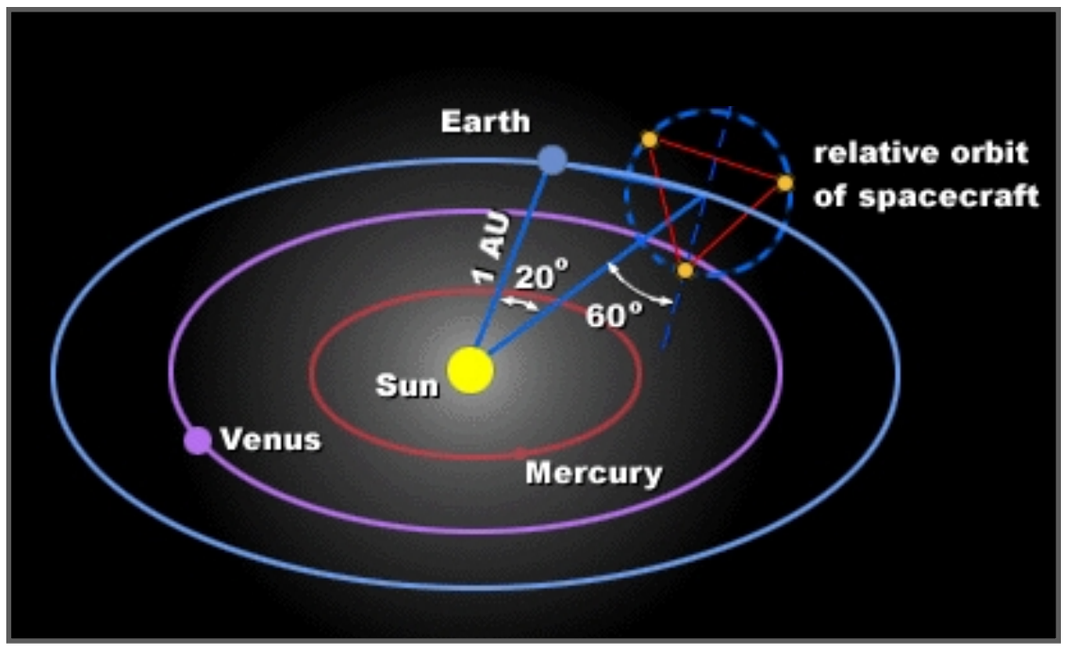
  - amplitude $\frac{\delta T}{T} \sim \frac{H_*}{\beta} \ll 1$ is enough to have this effect

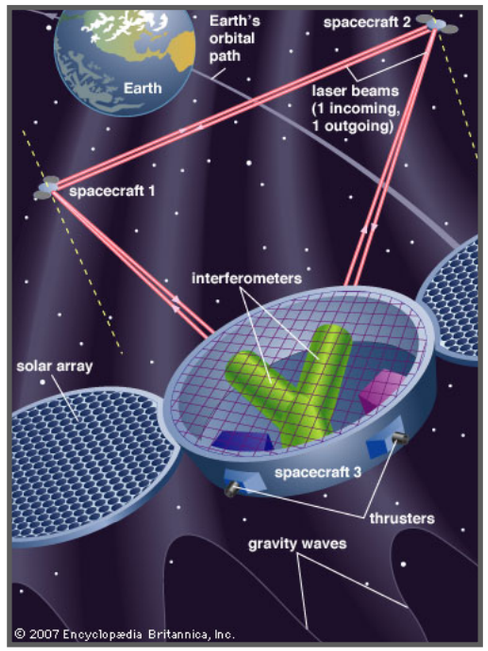
Backup

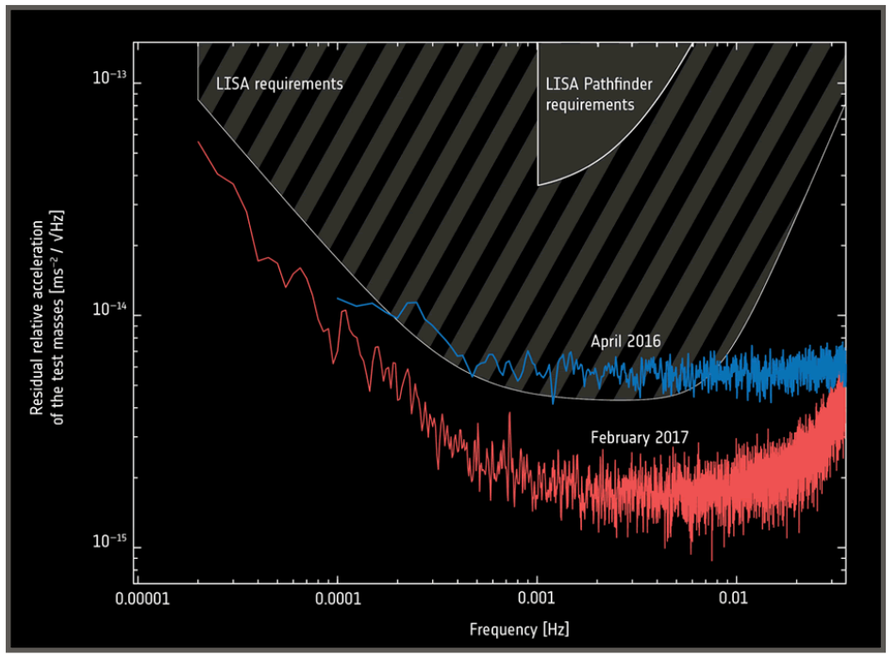
PRESENT & FUTURE OBSERVATIONS

LISA (Laser Interferometer Space Antenna)

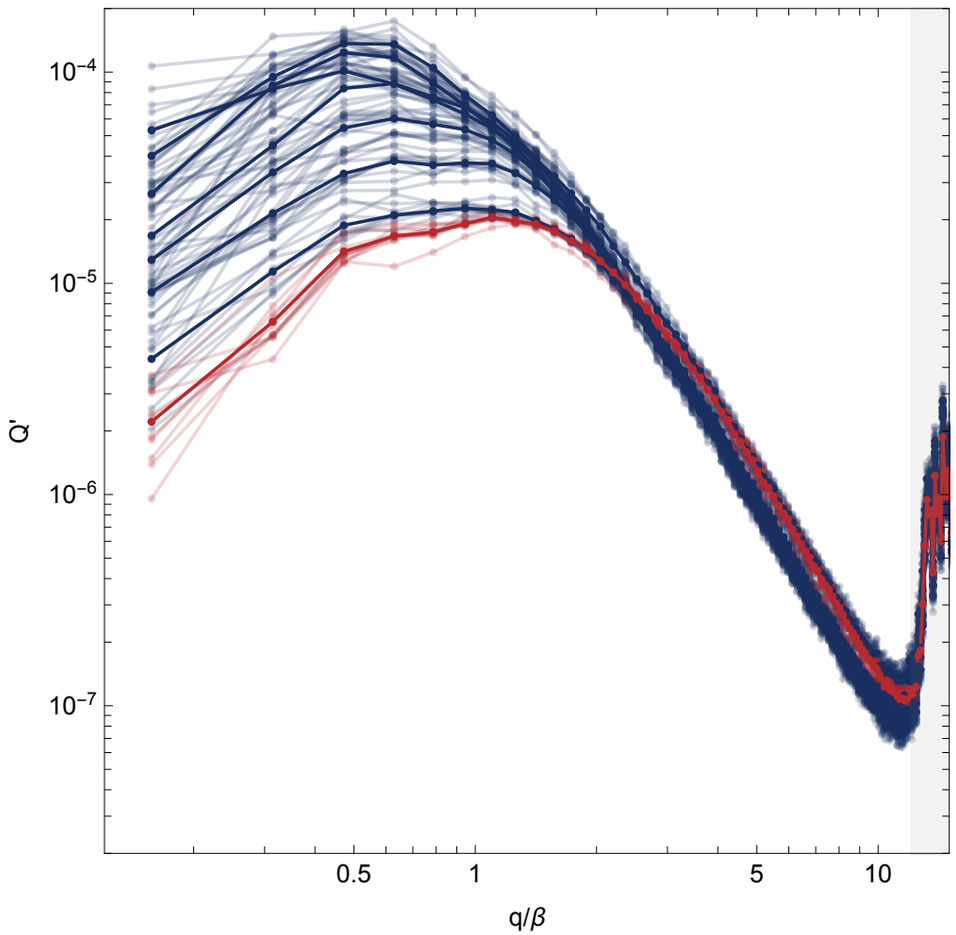
- Space interferometer project led by ESA & NASA
- Selected as third-large class mission(L3) in 2017. Operation from 2034.
- 3 spacecrafts orbitting around the Sun. Distance btwn spacecrafts $= 2.5 \times 10^6$ km.
- Tested necessary technologies with LISA pathfinder since 2015.



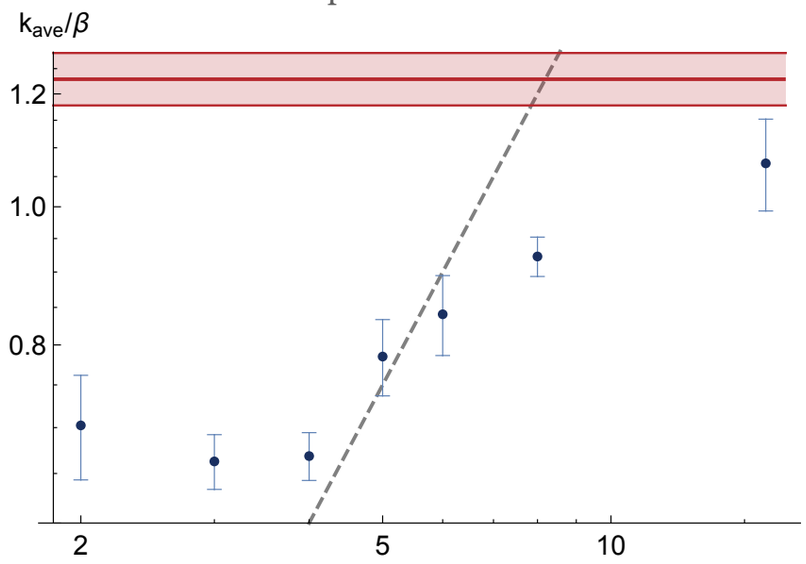




GW ENHANCEMENT FROM DENSITY PERTURBATIONS

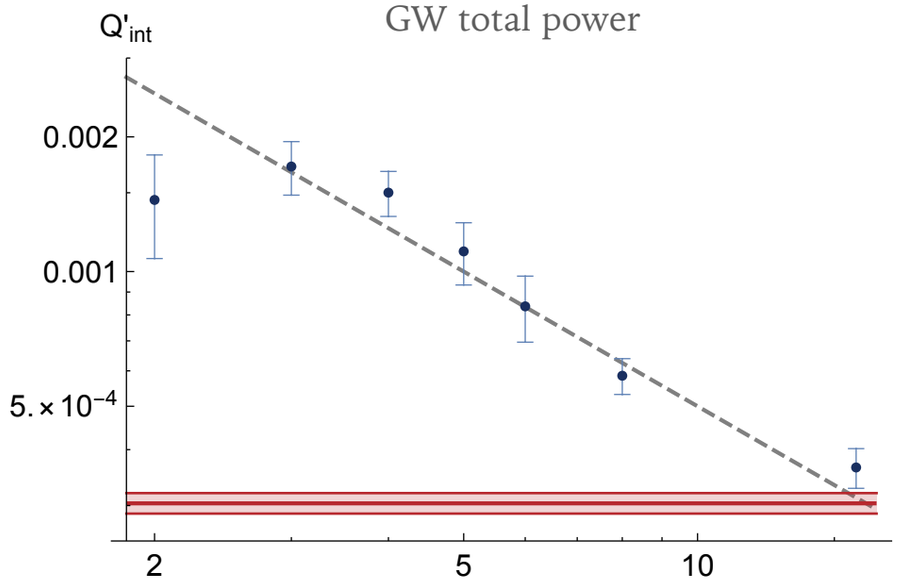


GW peak wavenumber



typical wenumber
of density perturbations

GW total power



typical wenumber
of density perturbations