1 Overview

2 First-order phase transitions

3 Dynamics of bubbles

4 Gravitational waves

5 Recent progress

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

Ryusuke Jinno (Kobe Univ.)

Seminar@IBS-CTPU, 2025/9/11

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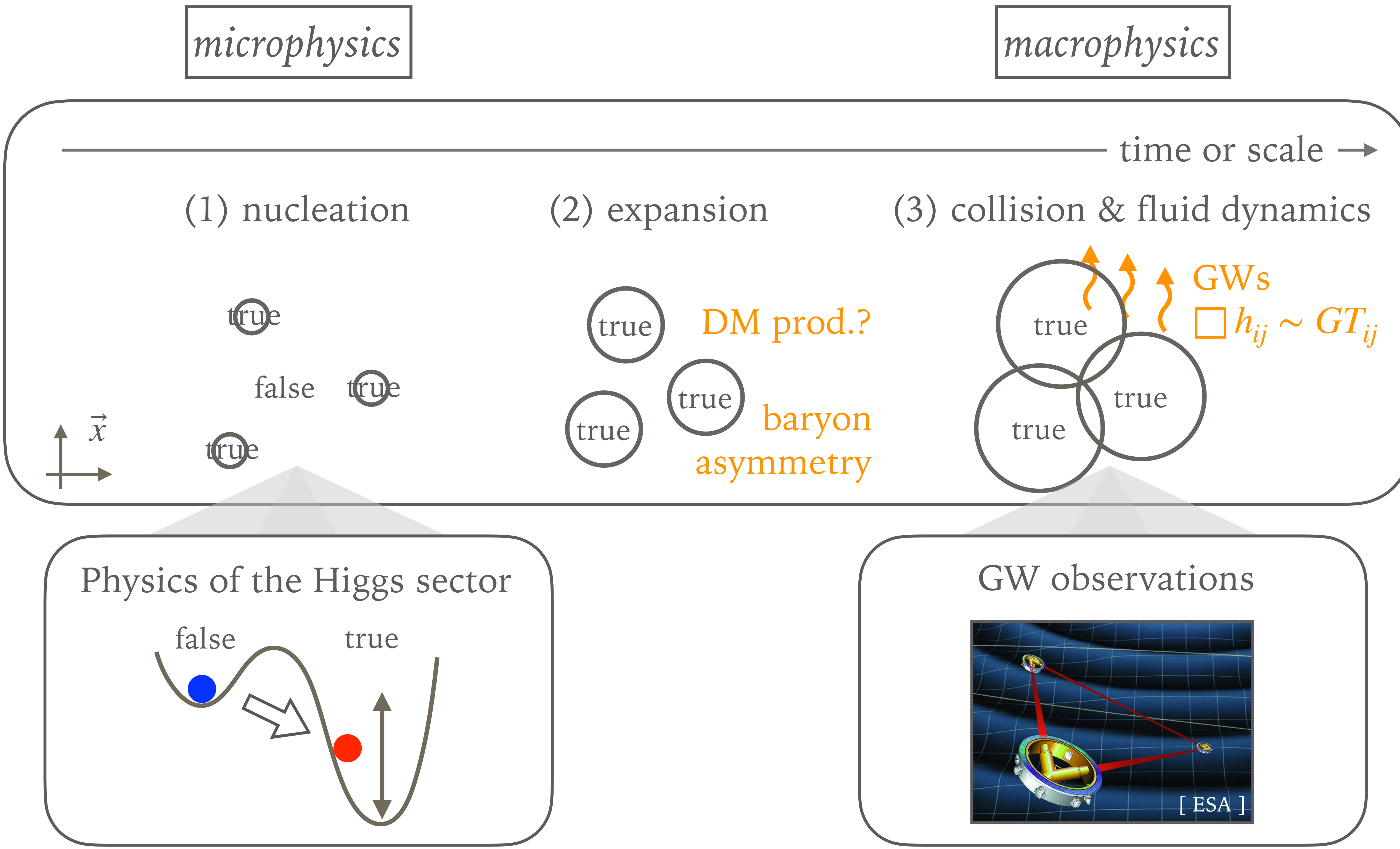
FIRST-ORDER PHASE TRANSITIONS IN THE EARLY UNIVERSE



FIRST-ORDER PHASE TRANSITIONS IN THE EARLY UNIVERSE

microphysics

Dynamics of bubbles

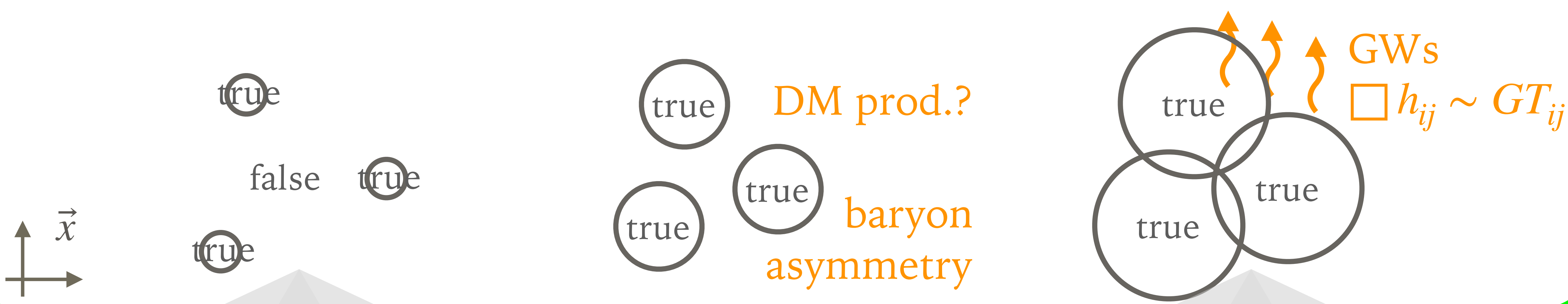
macrophysics

time or scale →

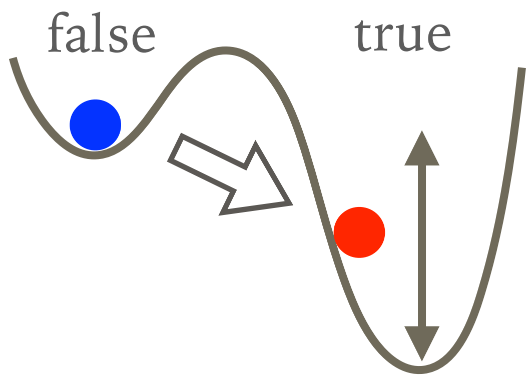
(1) nucleation

(2) expansion

(3) collision & fluid dynamics



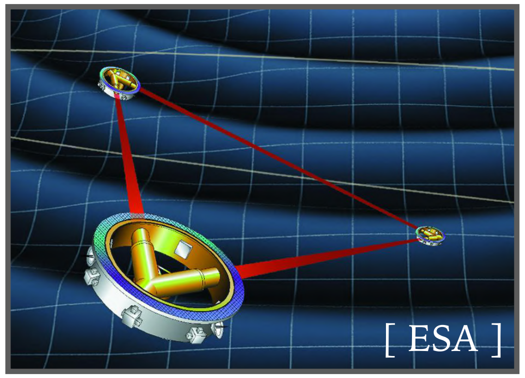
Physics of the Higgs sector



FOPTs in BSM

GWs

GW observations



TALK PLAN

~20min

2. First-order phase transitions in beyond the Standard Model

3. Dynamics of bubbles

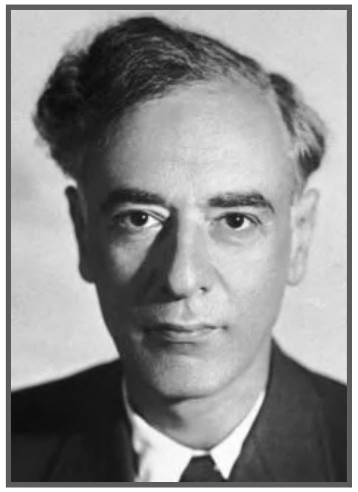
4. Gravitational wave production & observational prospects

~25min

5. Recent progress

PHASE TRANSITIONS

- Classification of phase transitions (a la Landau)

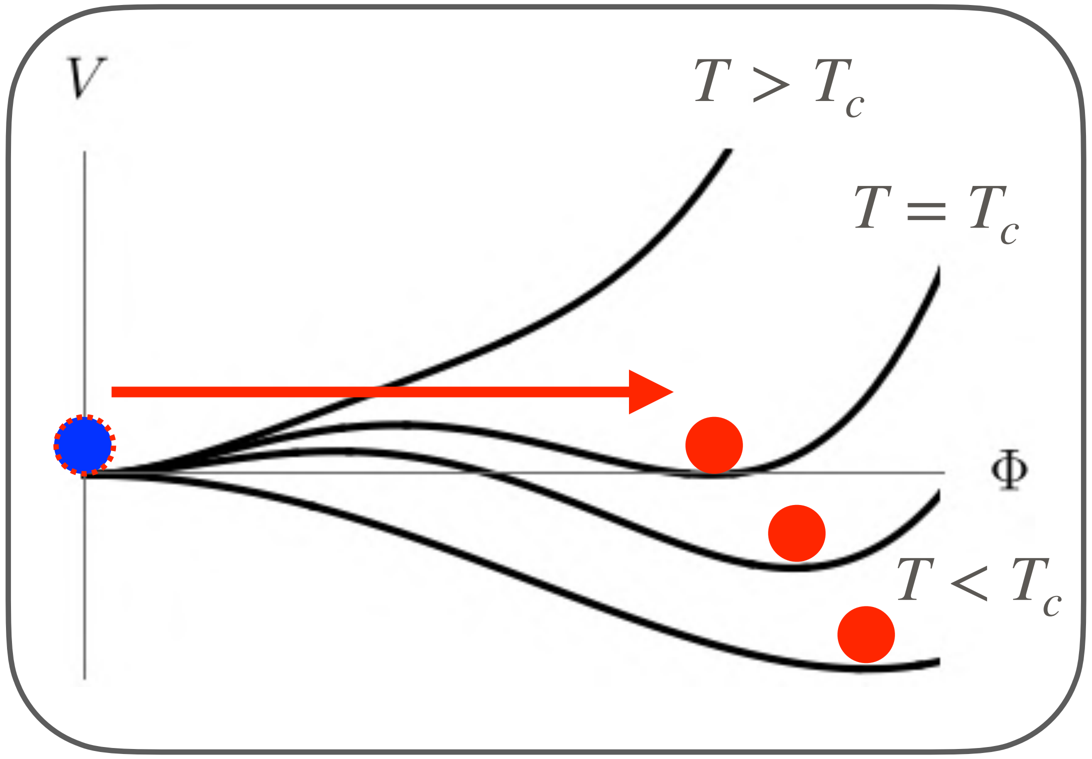


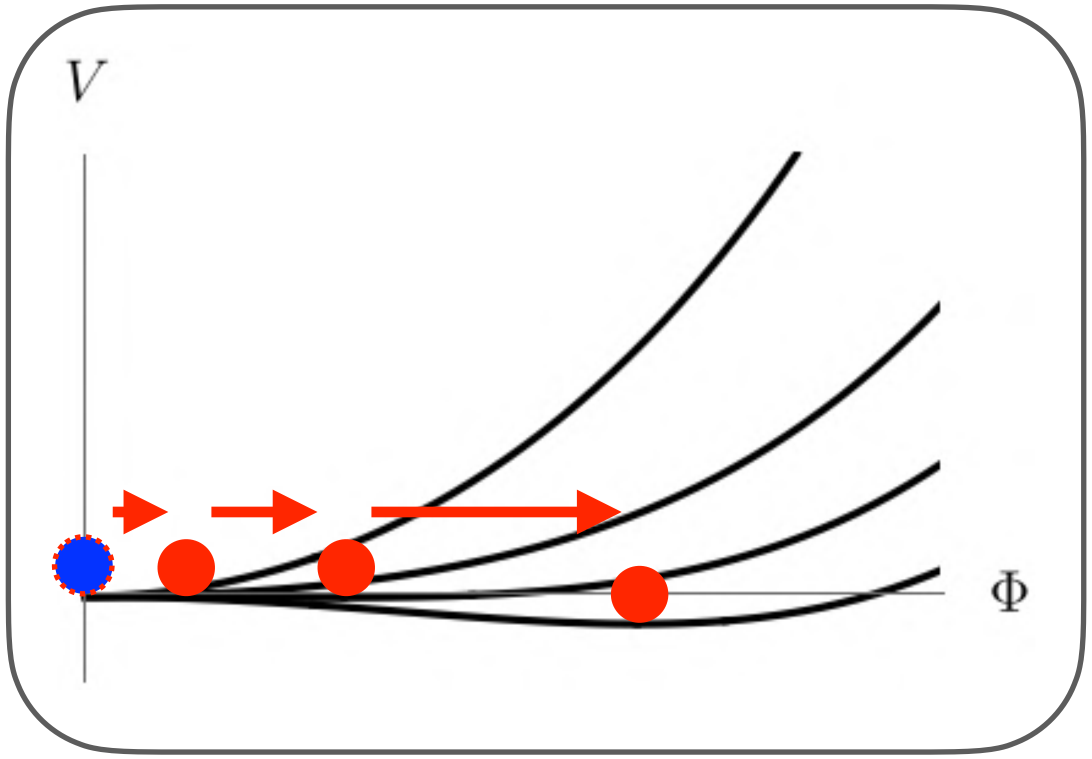
[Landau, from Wikipedia]

Order parameter (= scalar field)

discontinuous → first-order

continuous → second-order

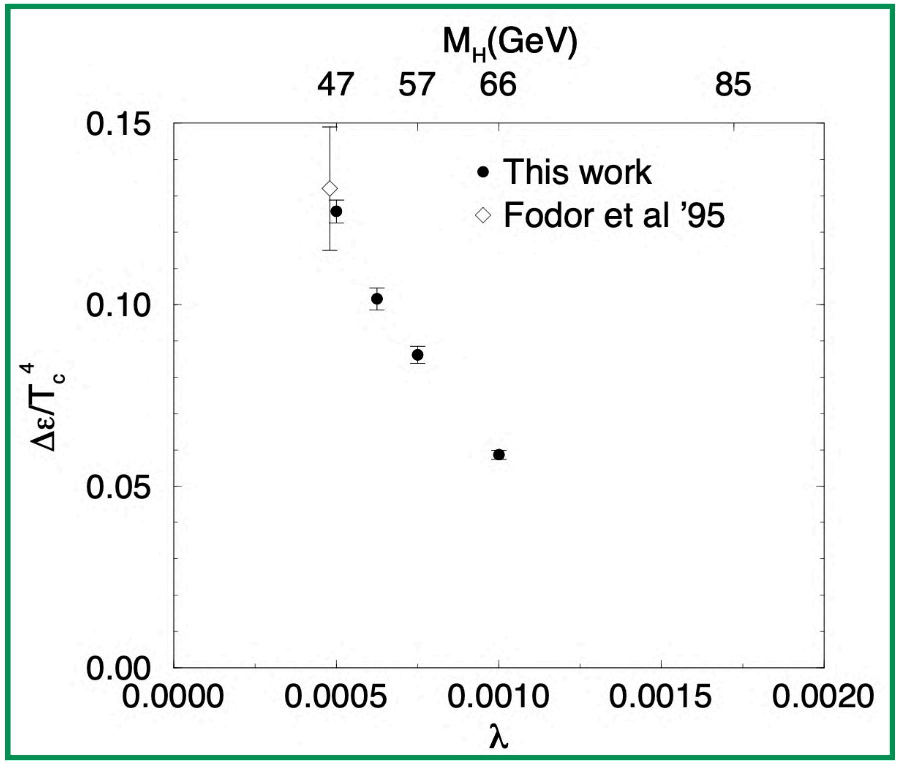


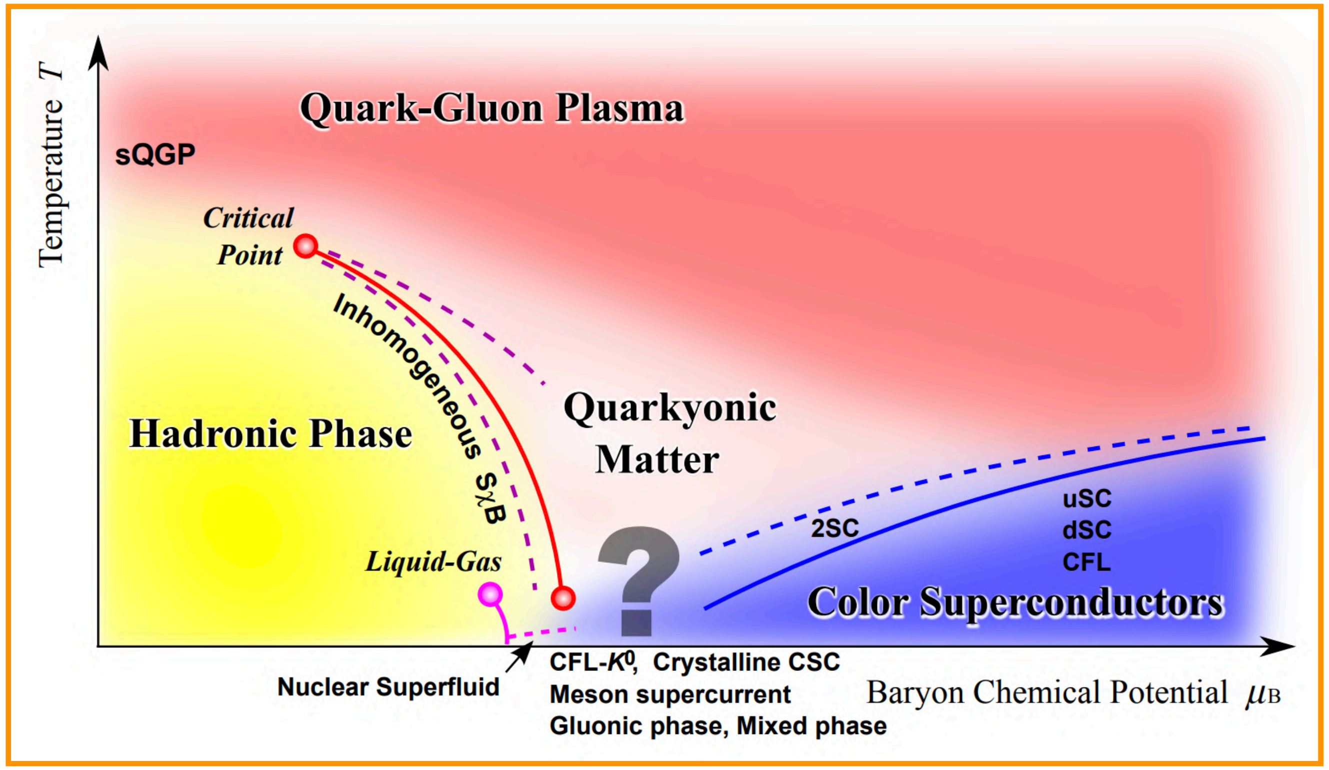


THERMAL HISTORY OF THE UNIVERSE

➤ 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]

[Fukushima, Hatsuda '11]

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

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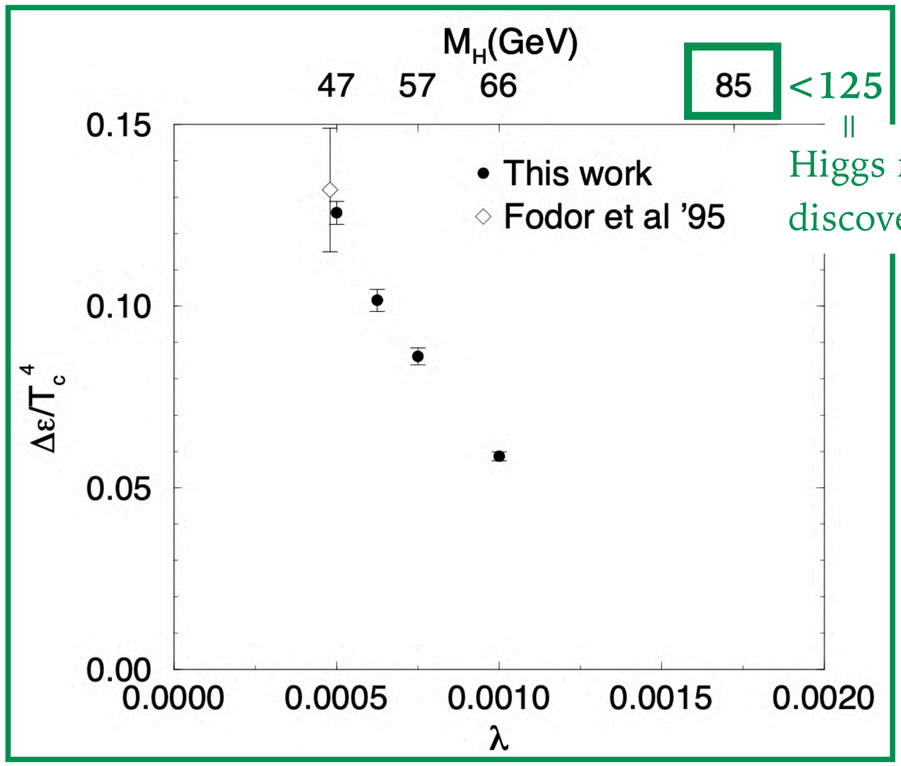

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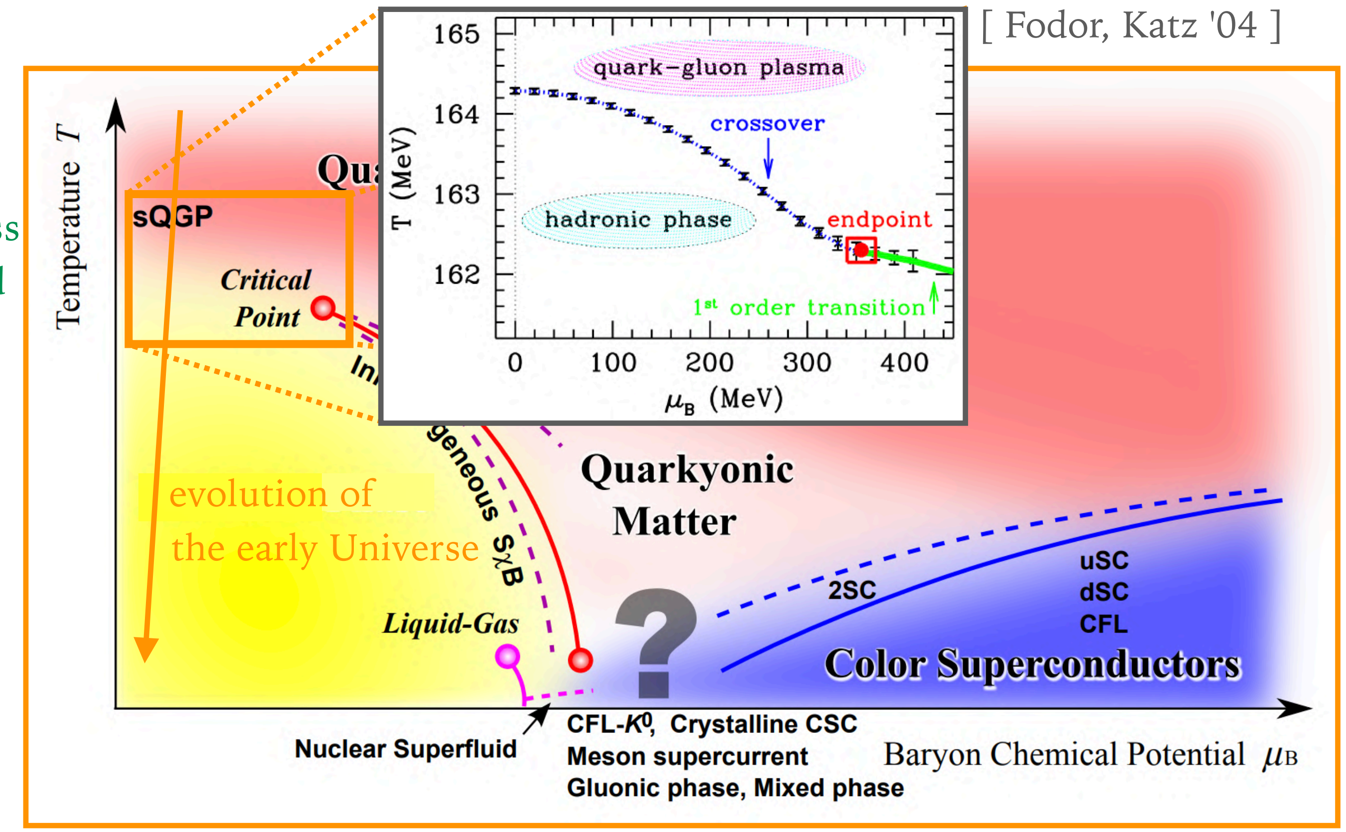
Higgs mass
discovered

[Fodor, Katz '04]



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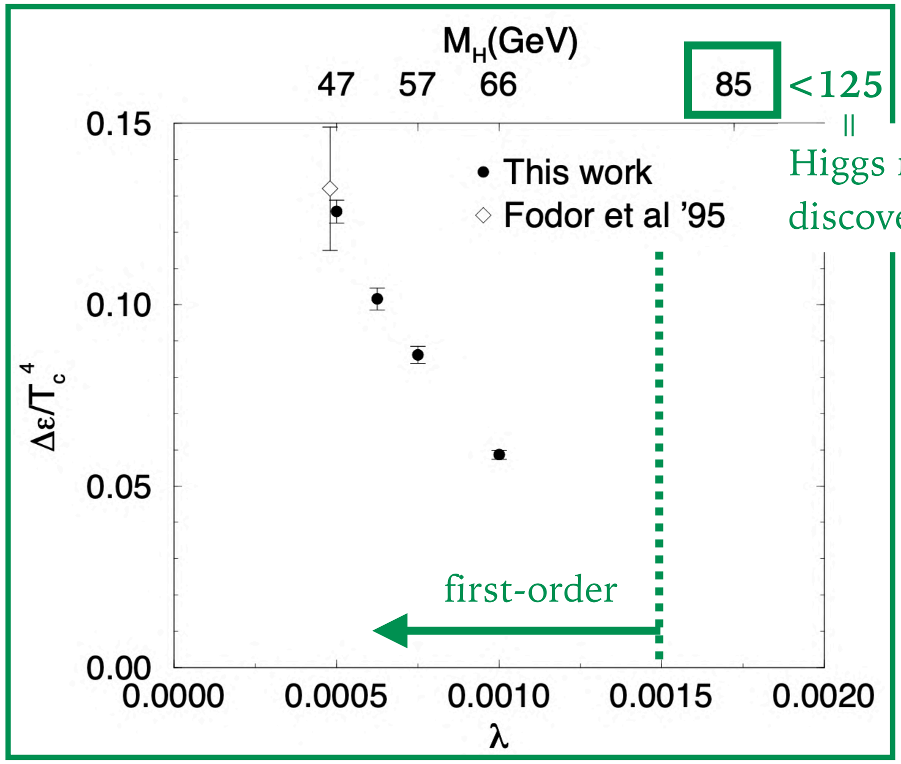

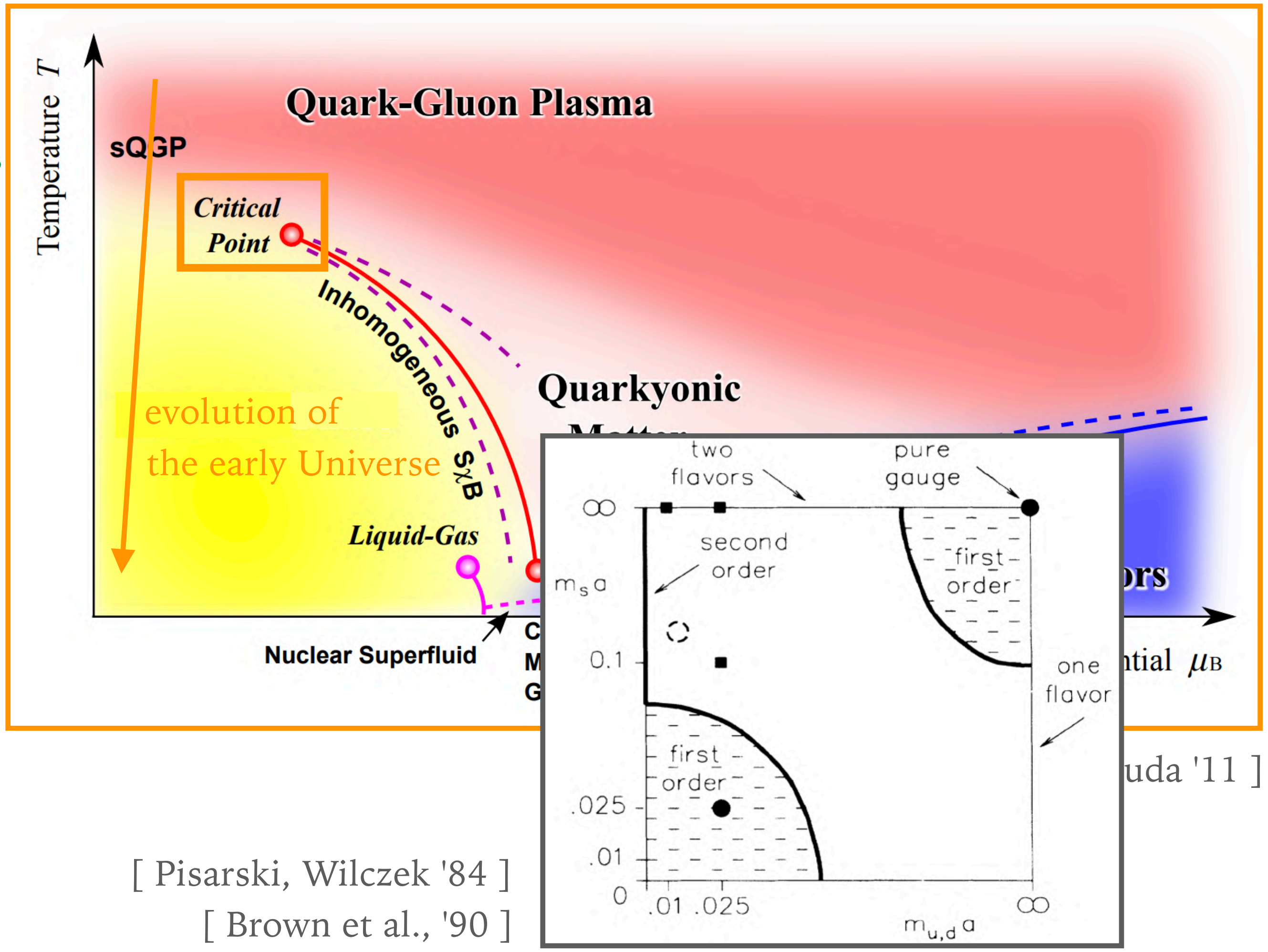

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[Pisarski, Wilczek '84]
[Brown et al., '90]

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MOTIVATIONS FOR FIRST-ORDER PHASE TRANSITIONS

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

- Spontaneous symmetry breaking that might have happened

  - Breaking of the GUT group (→ GUT)

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

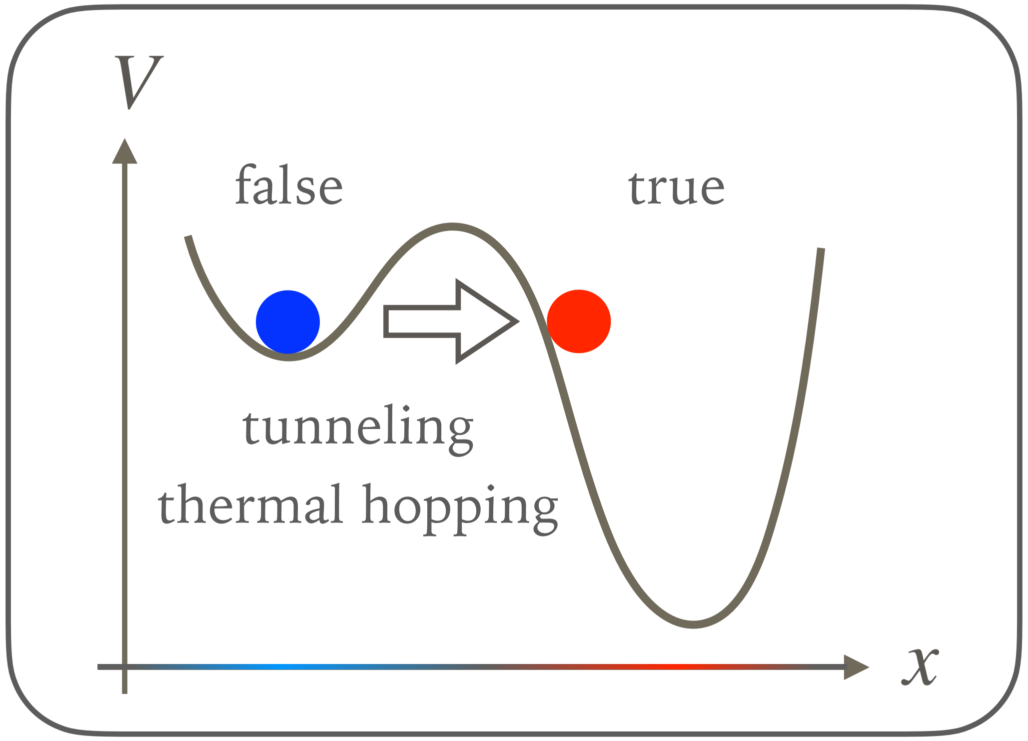
  - Breaking of B-L symmetry $U(1)_{\mathrm{B-L}}$ (→ neutrino masses)

  - Breaking of dark groups

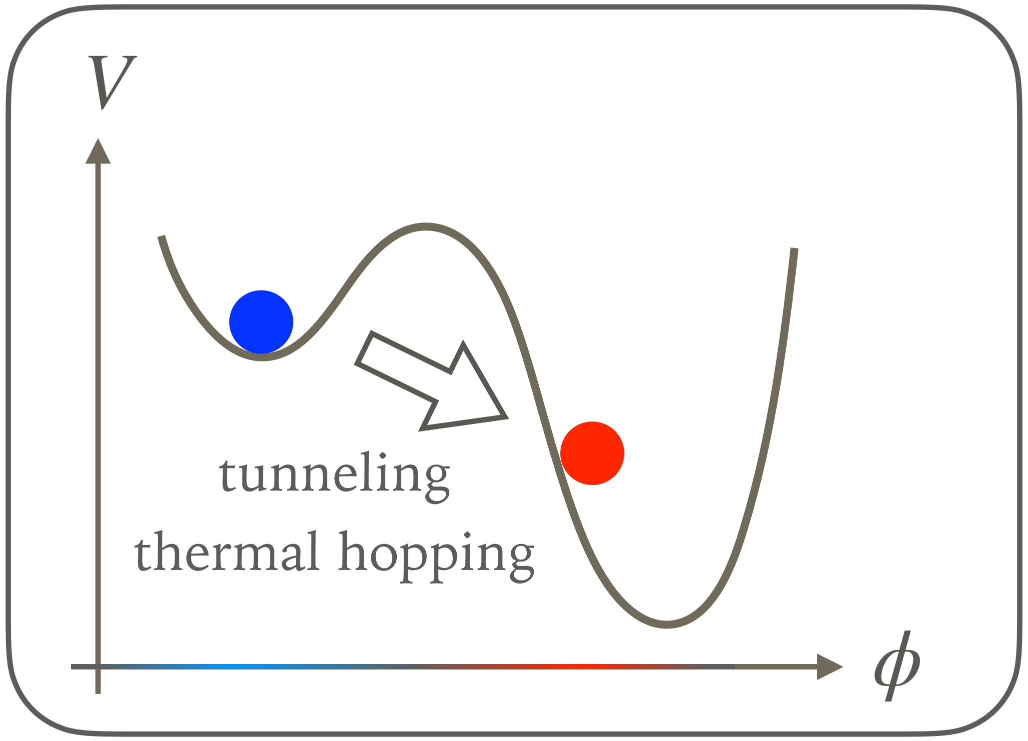
- Testability of the process in the coming 10-20 yrs with GWs

TUNNELING IN QUANTUM MECHANICS AND QFT

Quantum mechanics



Quantum field theory



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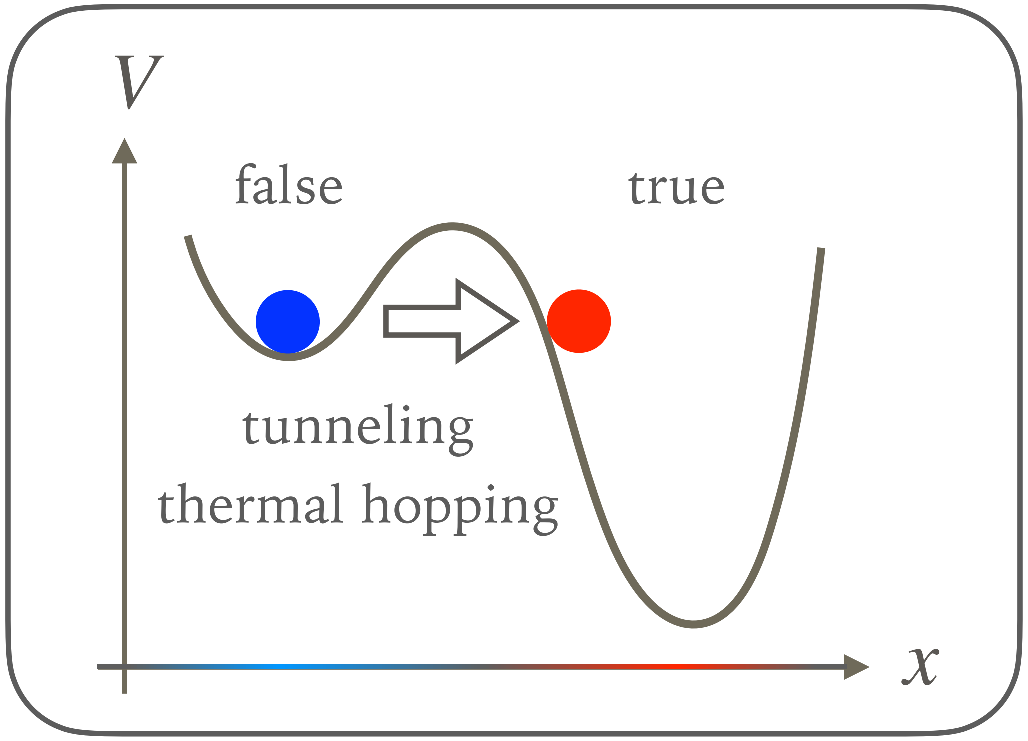

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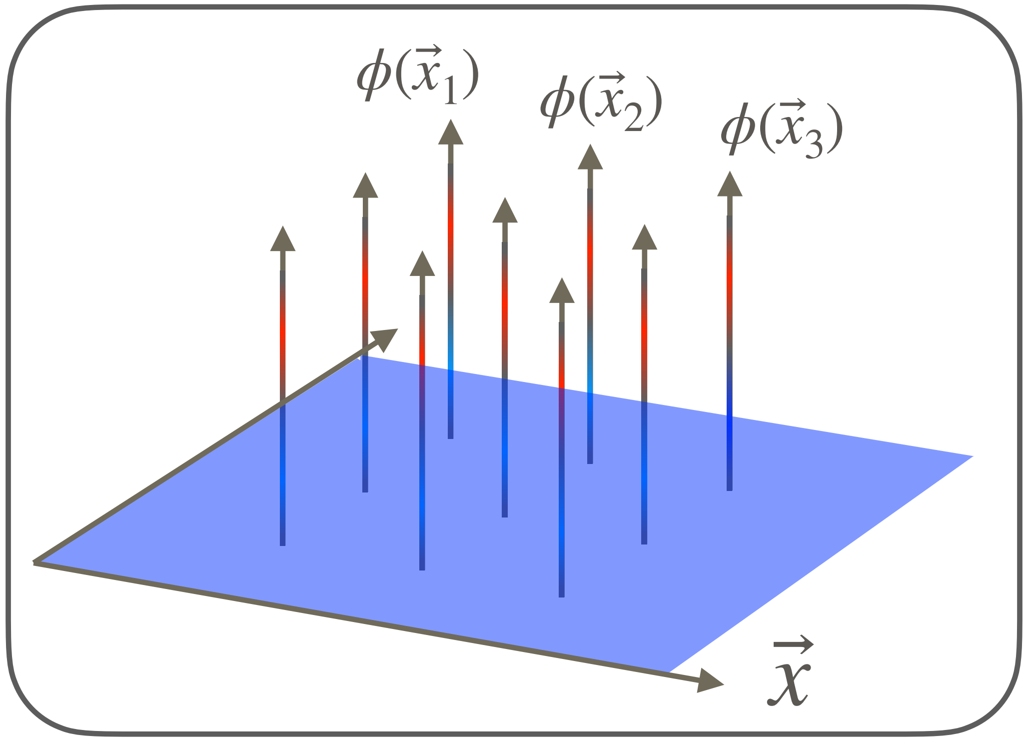

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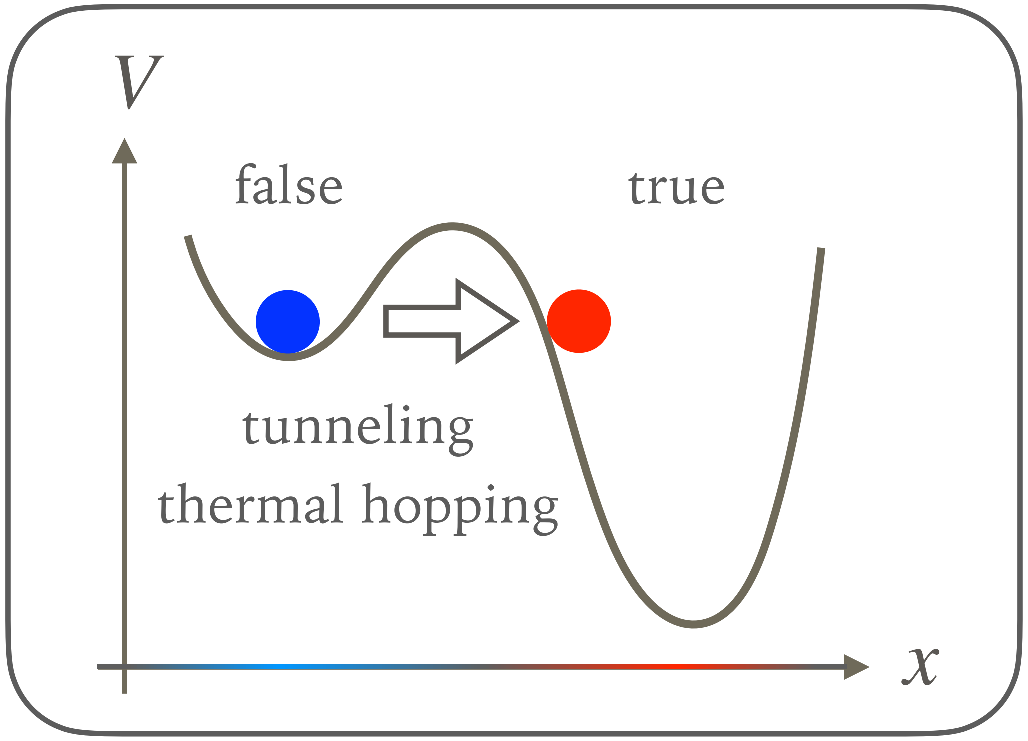
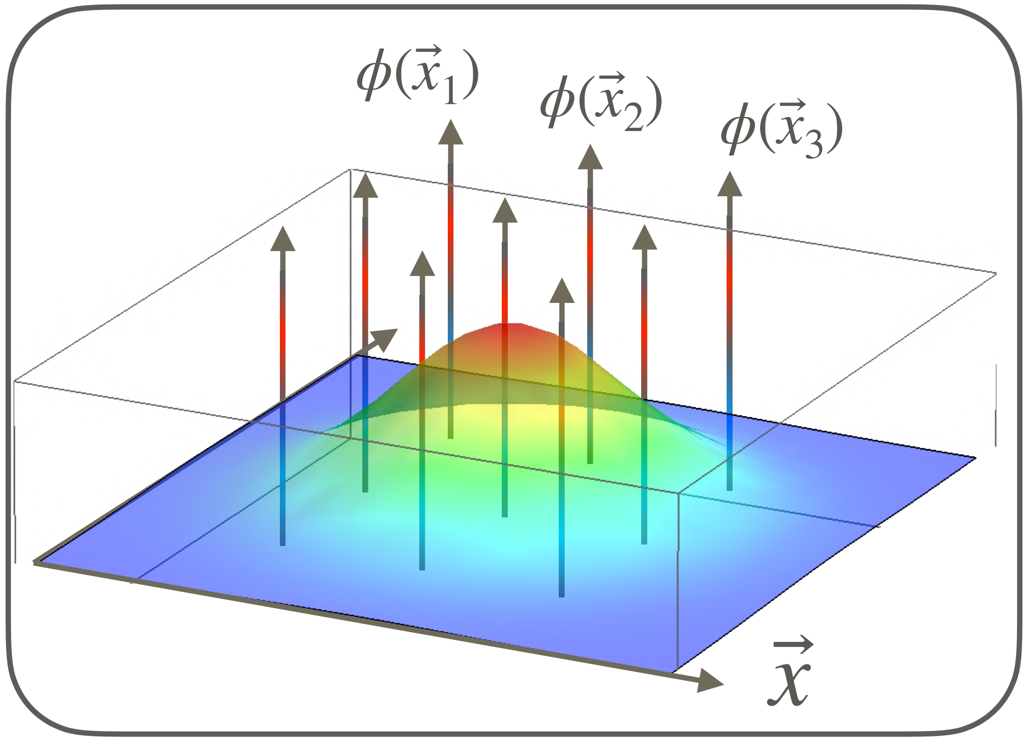
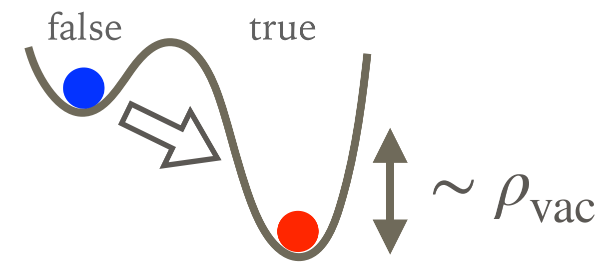




nucleation (核生成)

BUBBLE EXPANSION



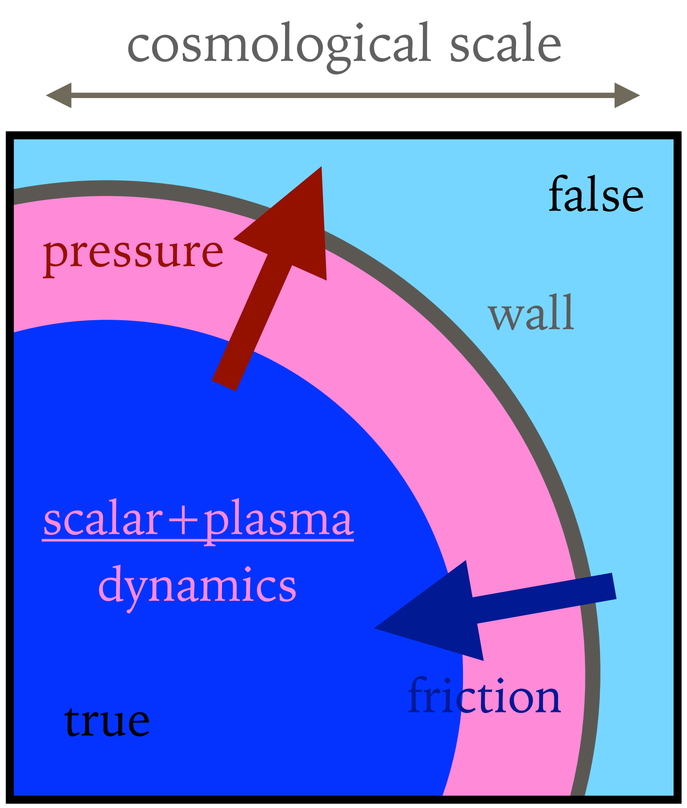
➤ "Pressure vs. Friction" determines the behavior:

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

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

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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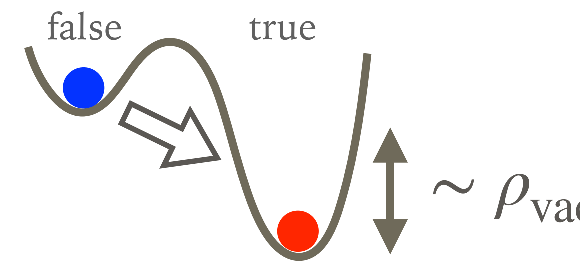

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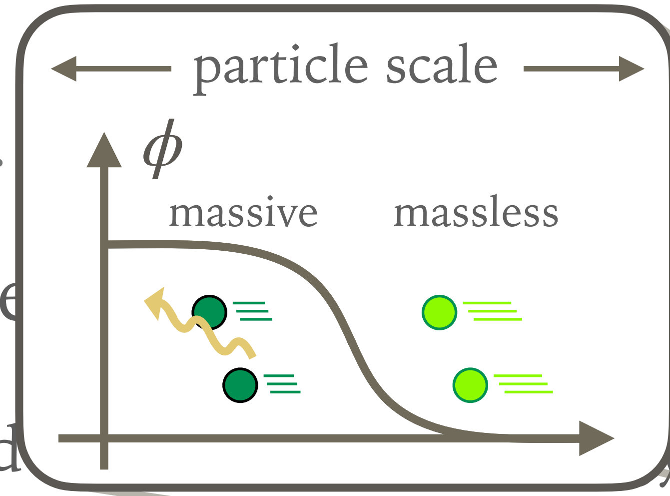

(1) **Pressure**: wall is pushed … y

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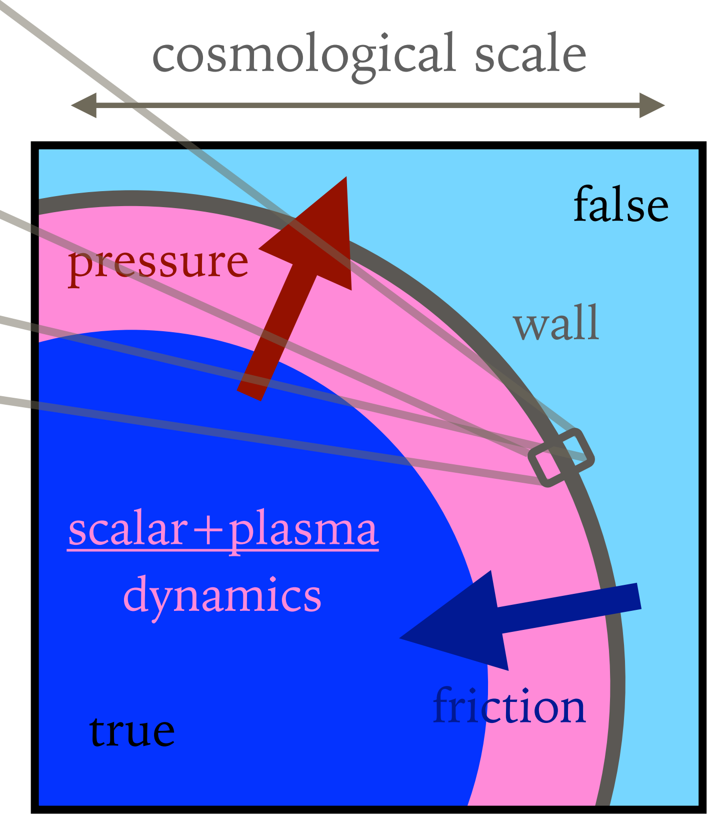

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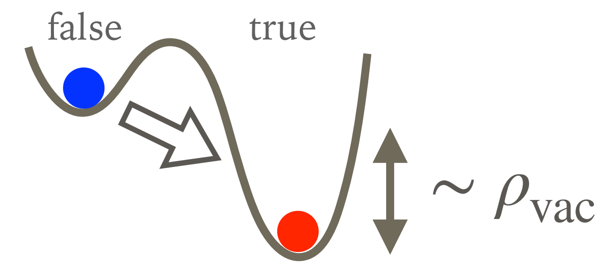

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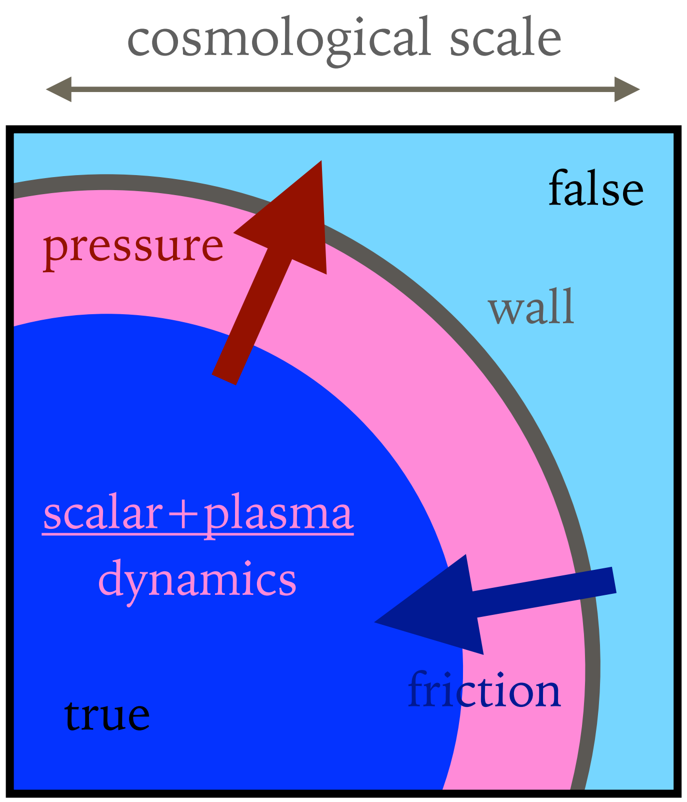
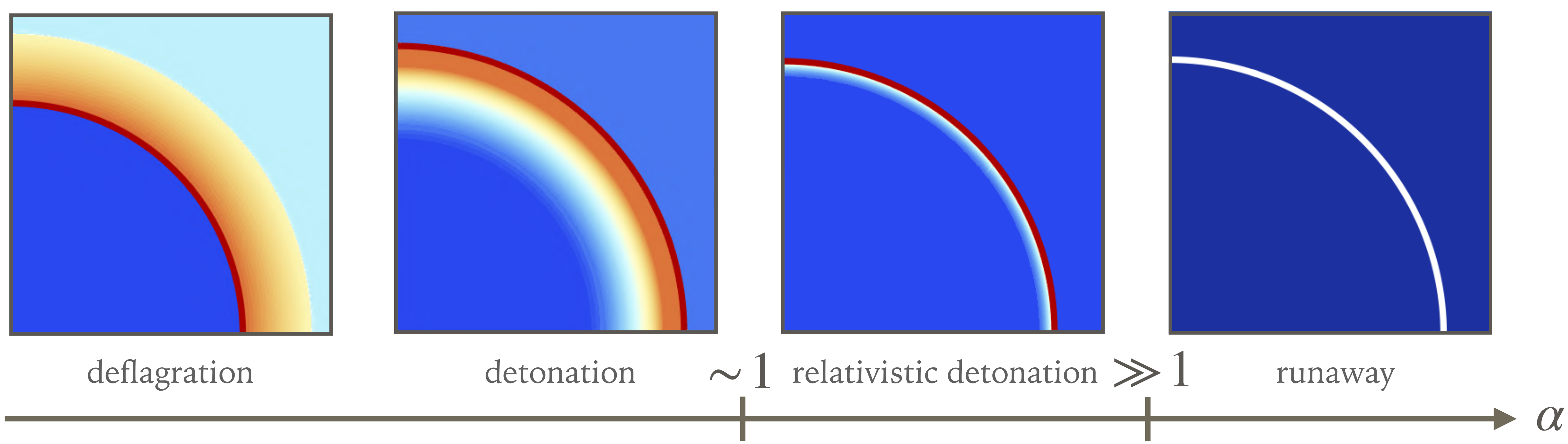


- Different types of bubble expansion



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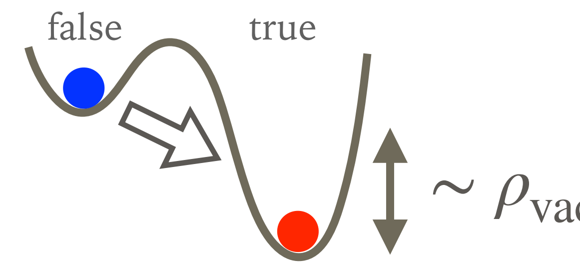
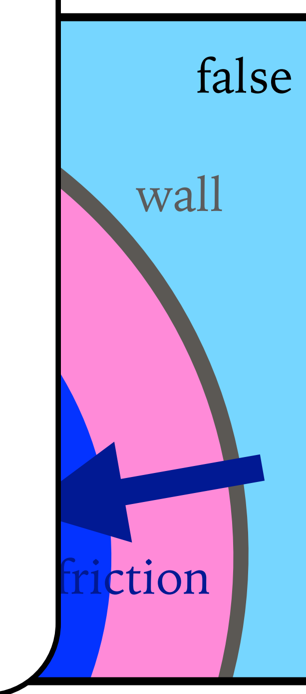
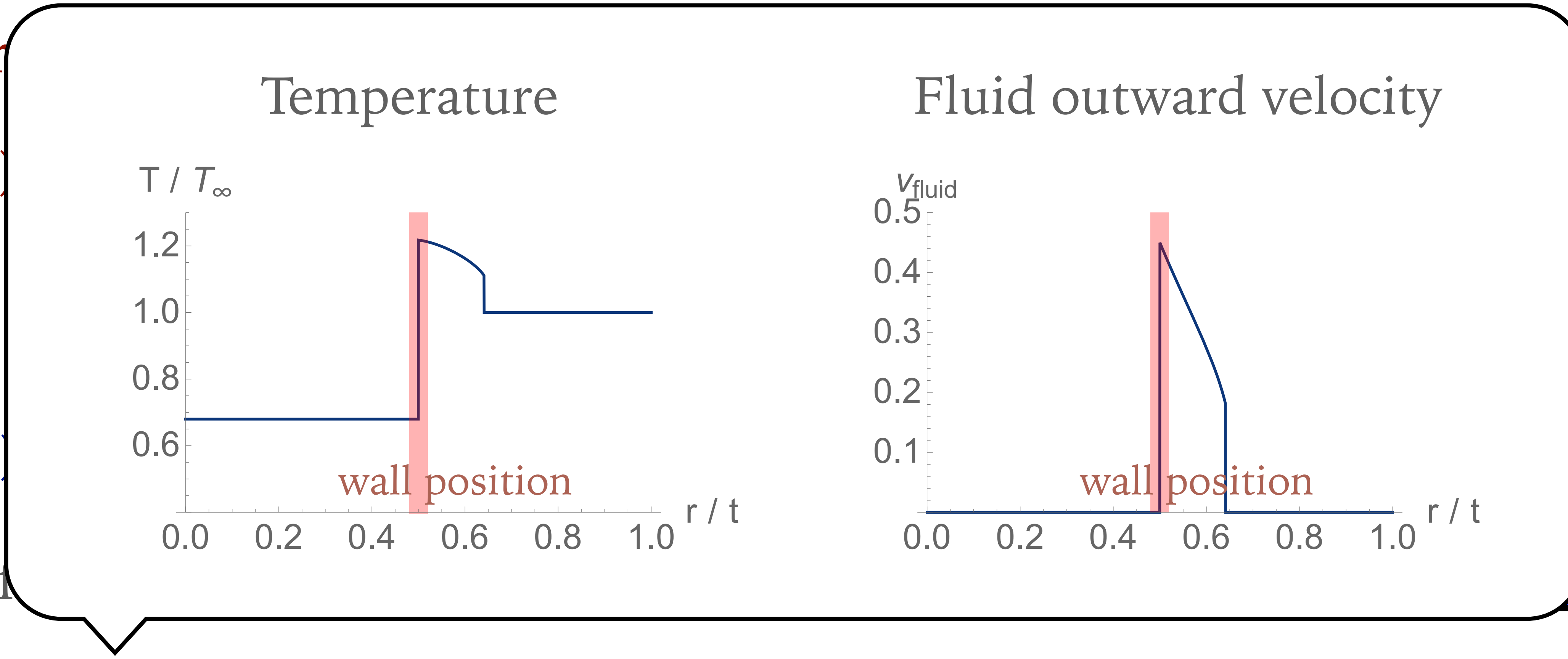


➤ "Pr ... al scale

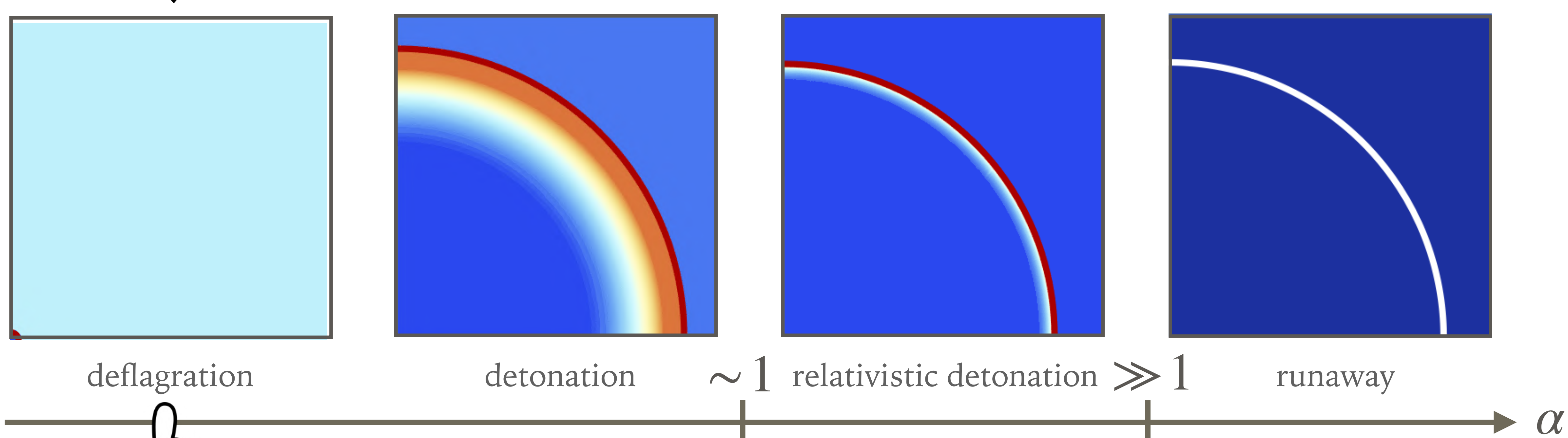
(1)

(2)





➤ Di



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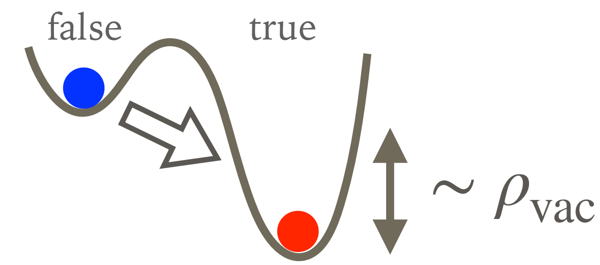
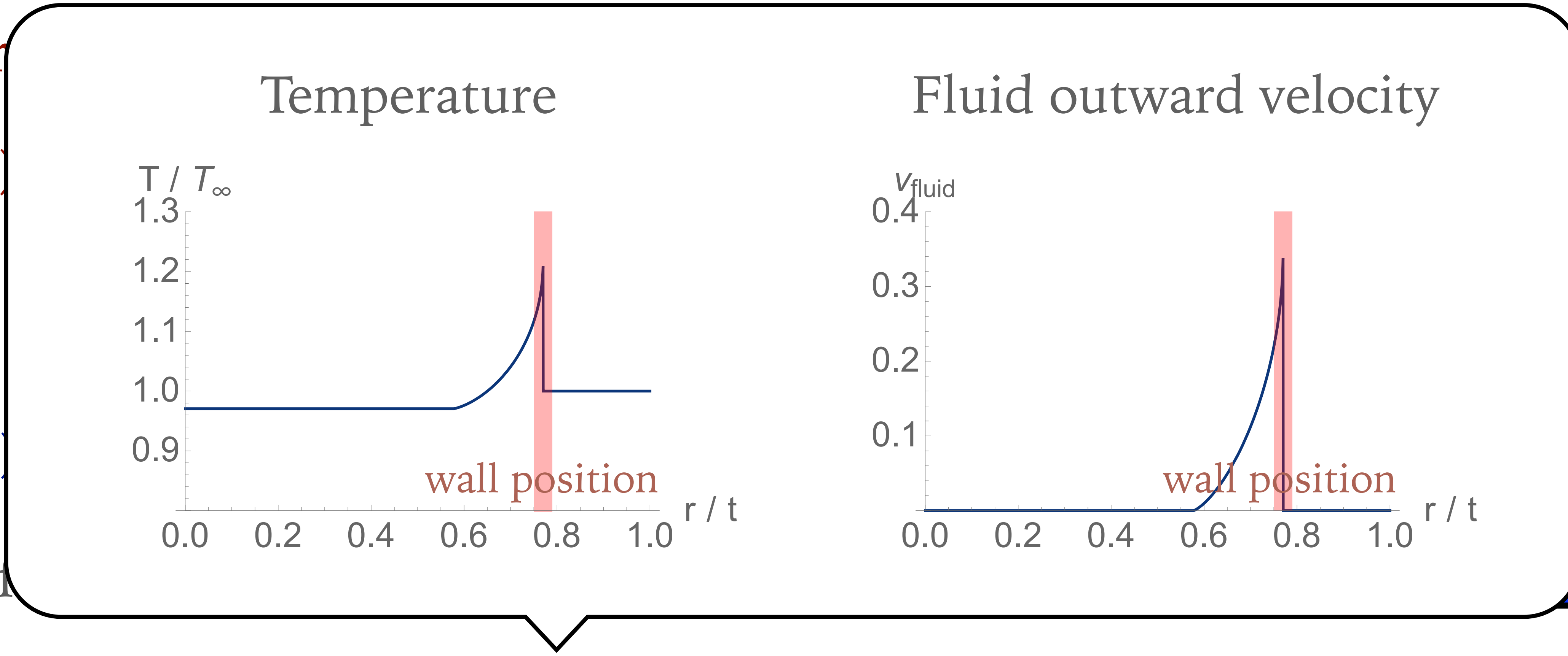


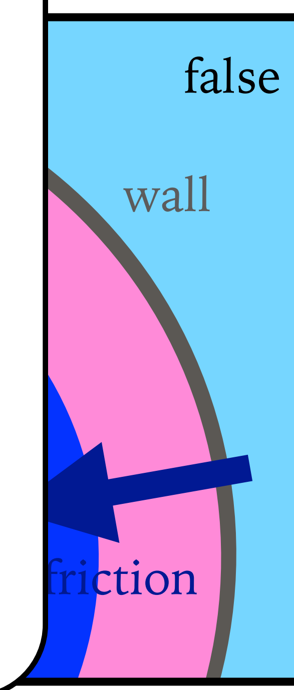
➤ "Pr... ...l scale

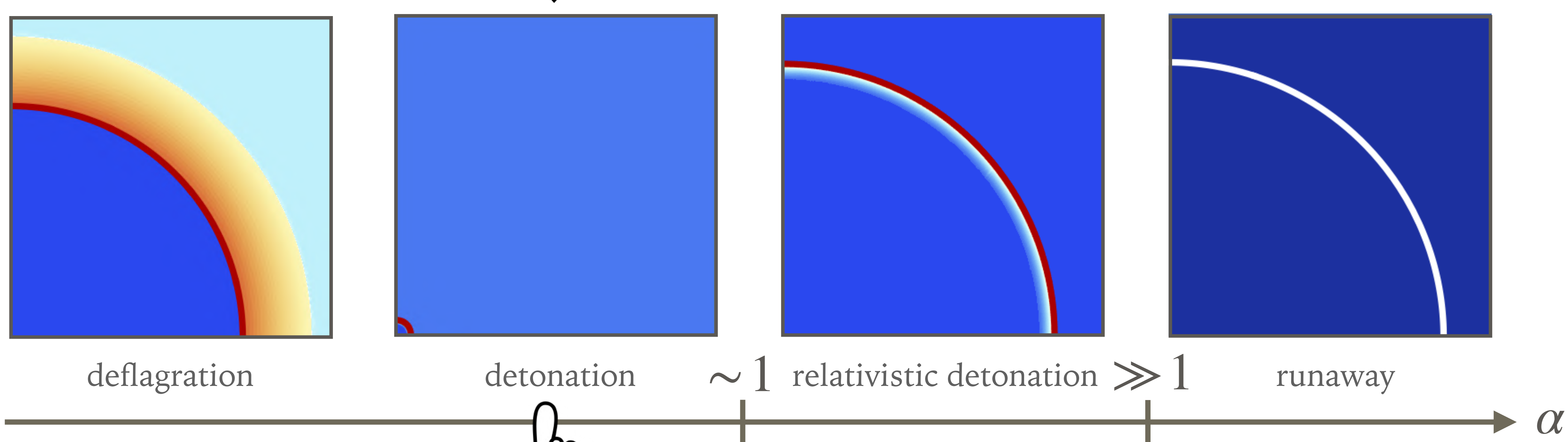
(1)

(2)

➤ Di...







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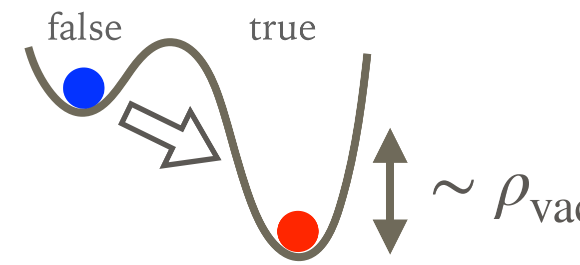
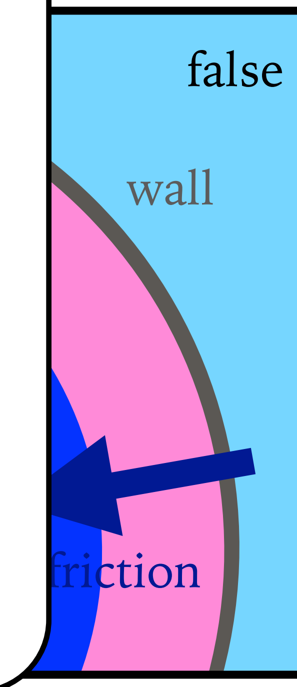
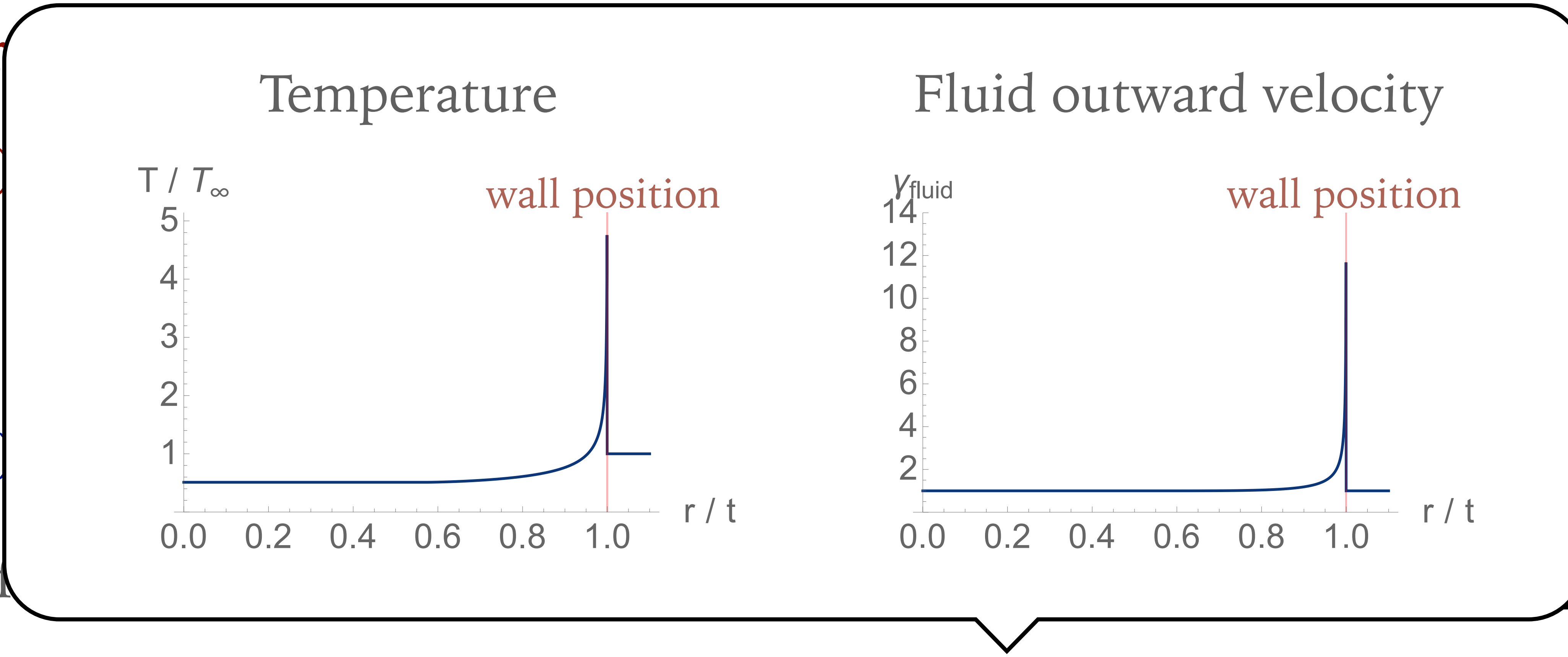
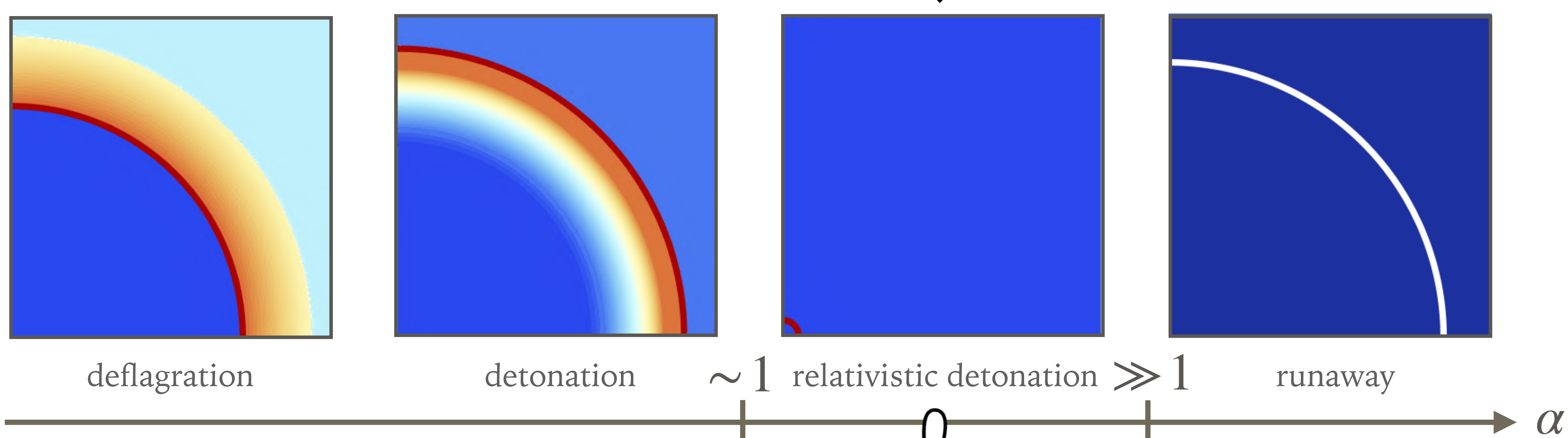


- "Pr … al scale
  (1) …
  (2) …
- Di…







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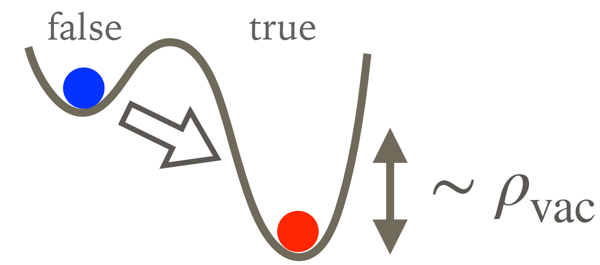
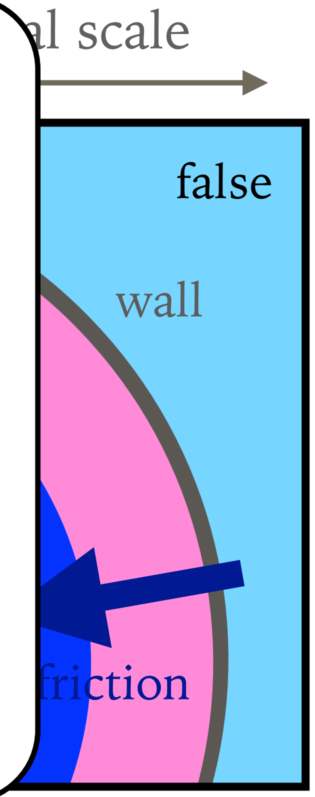


- "Pr

  (1)

  (2)

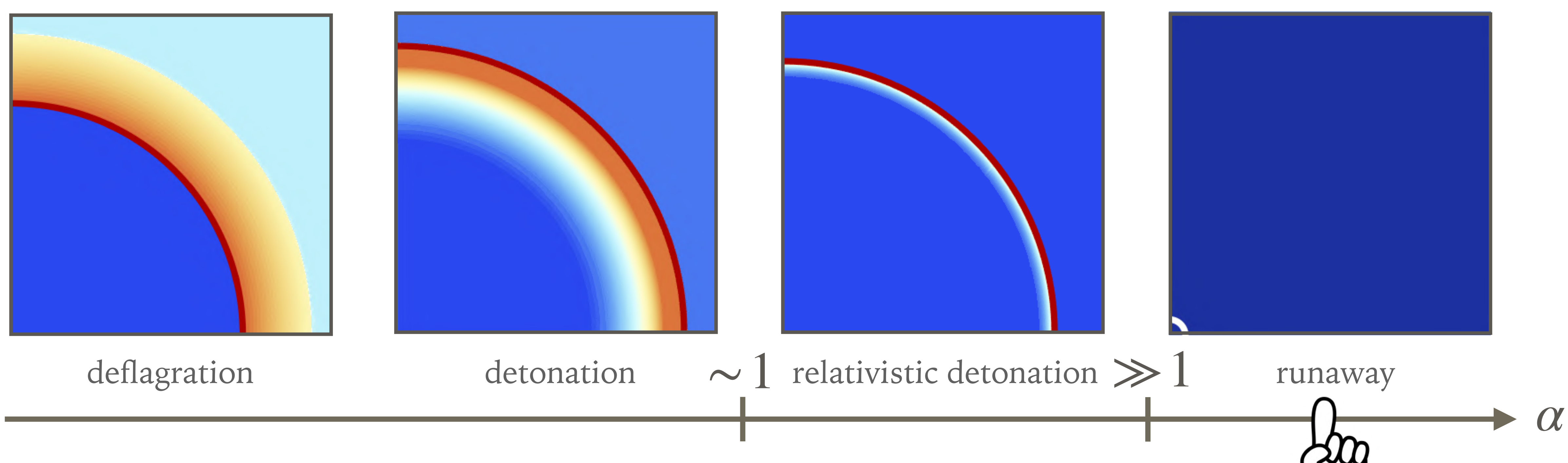
- Di



Plasma particles cannot stop the acceleration of the walls:

walls continue to accelerate until they collide with others

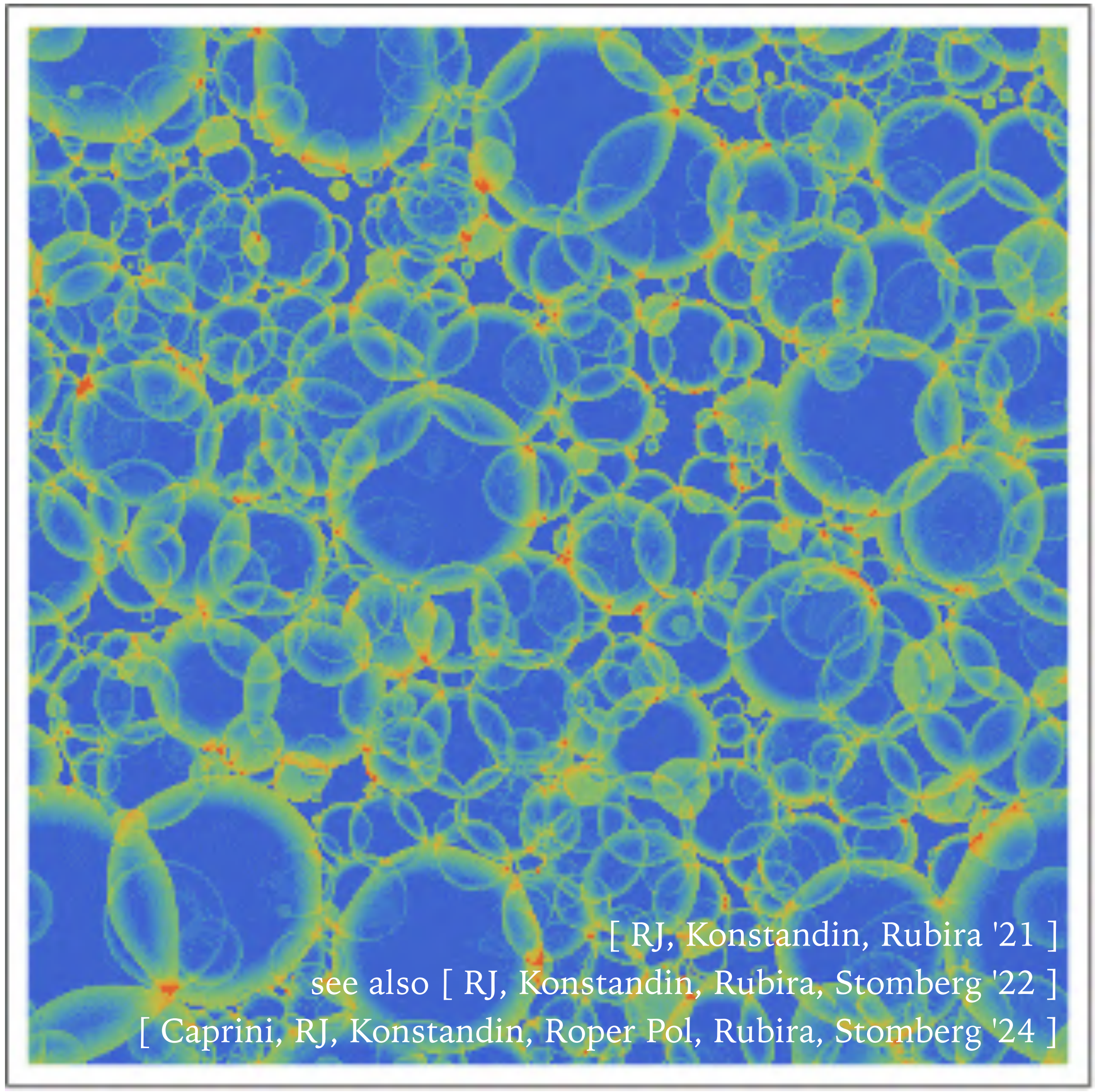
[Bodeker & Moore '09, '17]




Youtube "Explosions: 100 ton test detonation"

BUBBLE COLLISION & FLUID DYNAMICS

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



TRANSITION (≒ THERMODYNAMIC) PARAMETERS

- Remind the spirit of thermodynamics

  - Only a few parameters determine macroscopic properties

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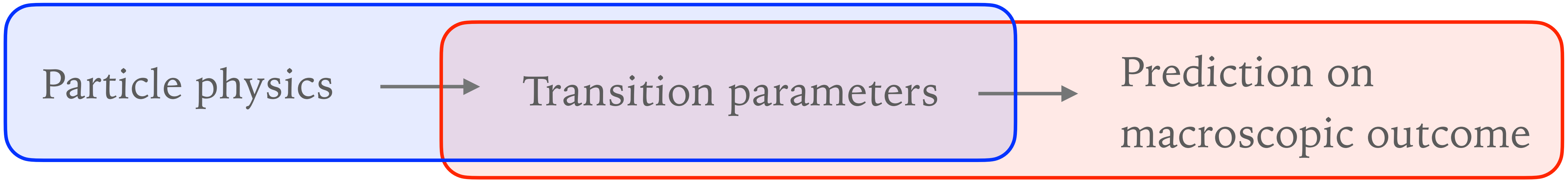
  - Only a few parameters determine macroscopic properties

- What are parameters that describe the present macroscopic system?



Lagrangian $\mathscr{L}$

α : transition strength

β : nucleation increase rate

v_w : wall velocity

T_* : transition temperature

GW spectrum $\Omega_{\rm GW}$

Baryon asymmetry

PBHs

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 energy (= latent heat) is released, compared to the plasma energy

- The numerator $\rho_{\rm vac} = \rho_{\rm vac,false} - \rho_{\rm vac,true}$ is calculated from the Helmholtz free energy, through the relation $U = F + TS = F - T\left(\frac{\partial F}{\partial T}\right)_V$ as

$$\rho_{\rm vac,true} = V_{\rm eff}(\phi_{\rm true}, T) - T\left(\frac{\partial V_{\rm eff}(\phi_{\rm true}, T)}{\partial T}\right)$$

$$\rho_{\rm vac,false} = V_{\rm eff}(\phi_{\rm false}, T) - T\left(\frac{\partial V_{\rm eff}(\phi_{\rm false}, T)}{\partial T}\right)$$

- One might use trace anomaly instead as parametrization

TRANSITION (≒ THERMODYNAMIC) PARAMETERS

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

- Nucleation rate increase 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) ⇔ (cosmological time)

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

<u>Thermal field theory</u> <u>Cosmology</u>

$$\Gamma(T) \sim T^4 e^{-S_3/T} \quad = \quad H^4 \sim (T^2/M_P)^4$$

TRANSITION (≒ THERMODYNAMIC) PARAMETERS

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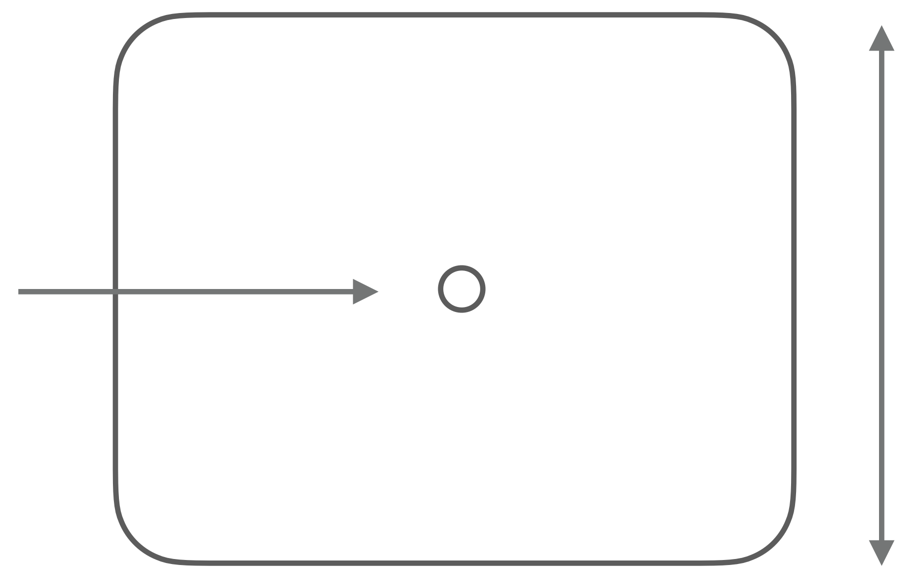

$$H^{-1} = \left(\frac{\dot{a}}{a}\right)^{-1}$$

TRANSITION (≒ THERMODYNAMIC) PARAMETERS

see e.g. [Caprini et al. '16]
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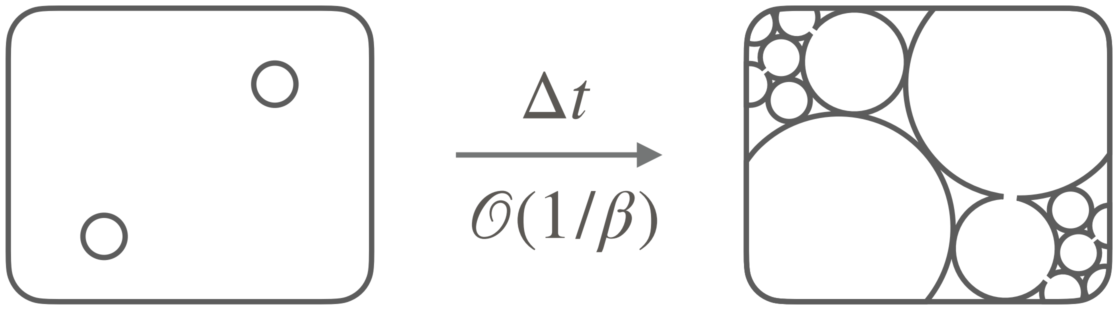
- Interesting property: v_w/β gives the typical bubble size at the time of collision

$t = t_*$

nucleation of
first bubbles



rapid nucleation of
other bubbles

TRANSITION (≒ THERMODYNAMIC) PARAMETERS

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

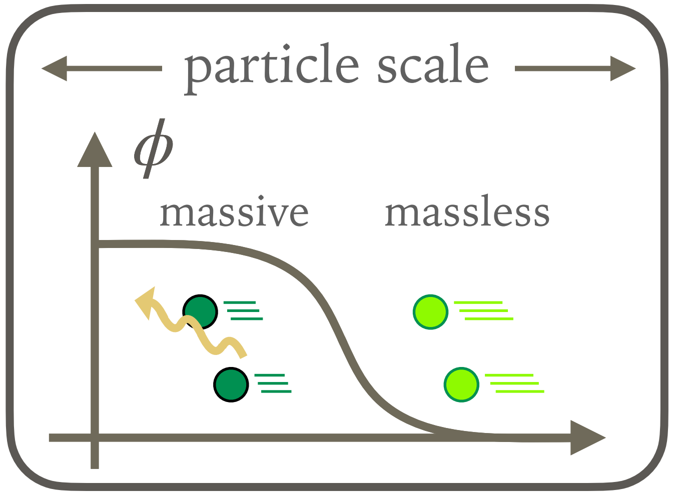
➤ Wall velocity v_w

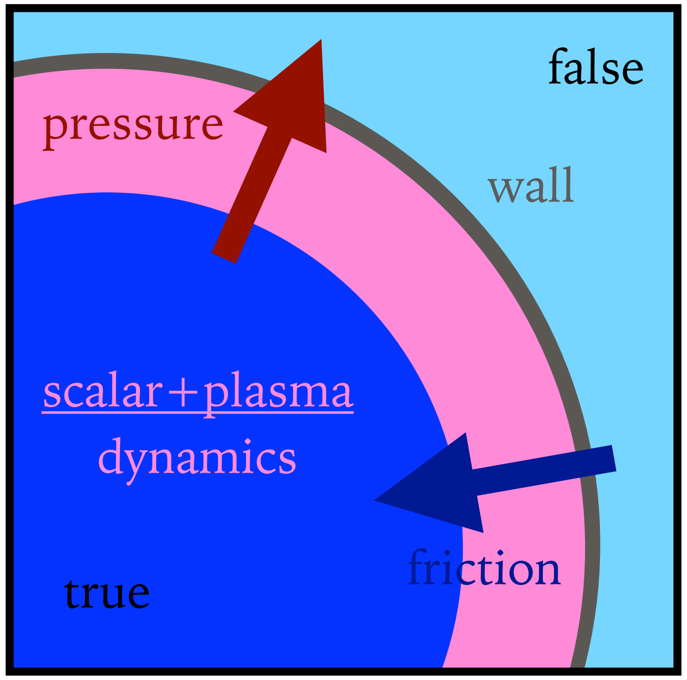
- Determined from "pressure vs. friction"

- In principle one should solve Boltzmann eq.,
  but people often put by hand
  (regarded as trade-off btwn. coupling ⇔ velocity)

➤ Transition temperature T_*

- Determined from your microphysical theory





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 $\mathscr{L}$

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GRAVITATIONAL WAVES: A NEW PROBE TO THE UNIVERSE

- Einstein equation:

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

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

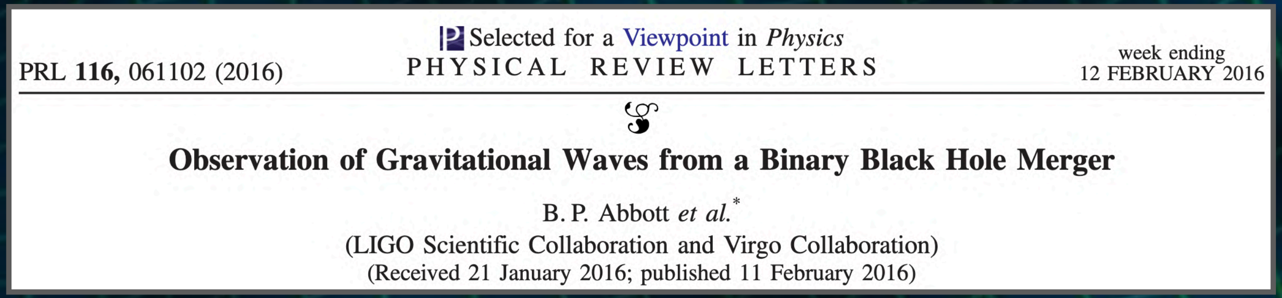
- Gravitational waves: transverse-traceless part of the metric

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

- 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



PRL **116,** 061102 (2016) Selected for a Viewpoint in *Physics* 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)

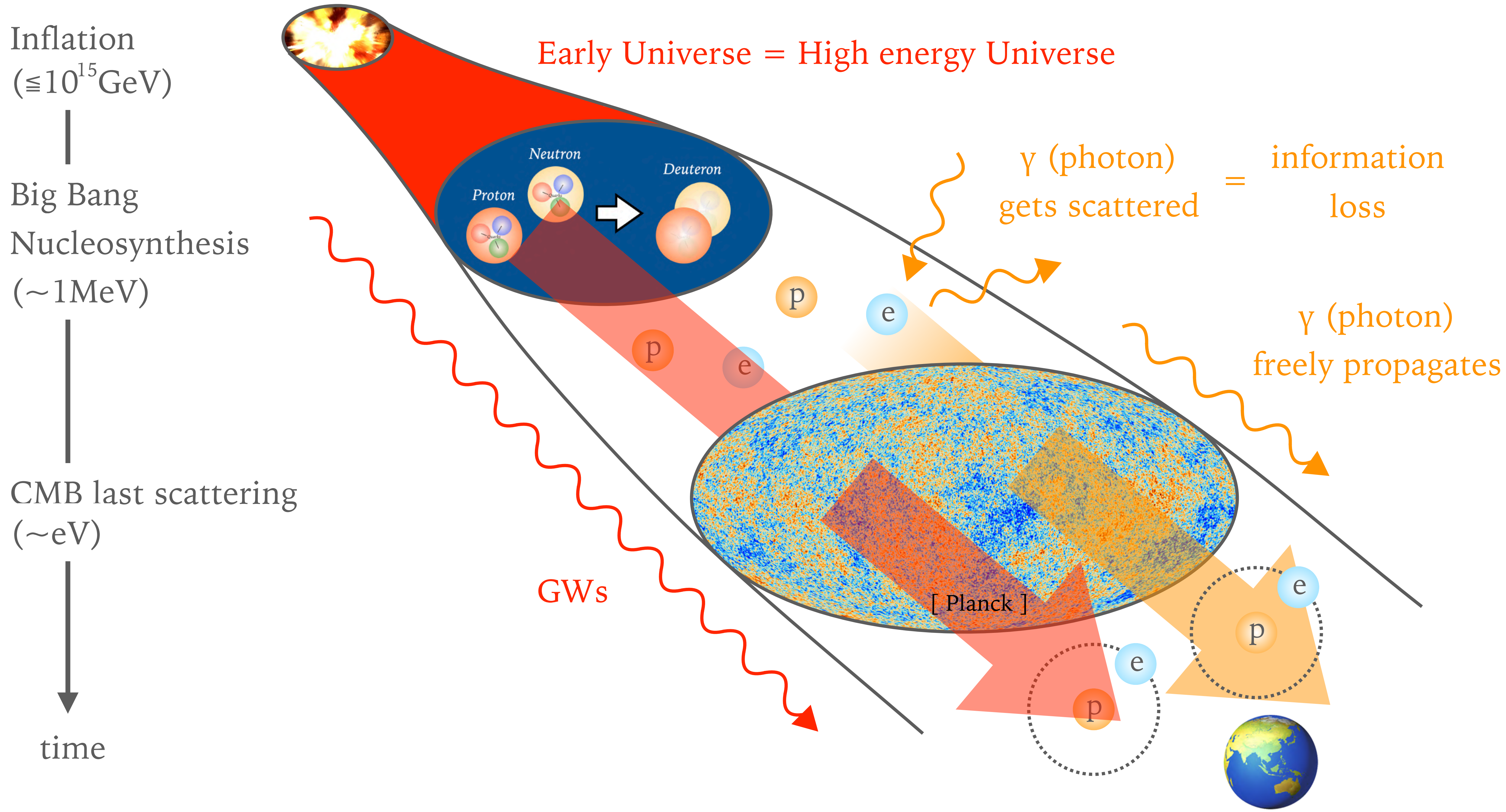
(Received 21 January 2016; published 11 February 2016)

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

[R. Hurt/Caltech-JPL]

GWS AS A PROBE OF THE EARLY UNIVERSE

- Comparison between CMB and GWs



PRESENT & FUTURE OBSERVATIONS

Pulsar timing arrays

$\sim 10^{-8}$ Hz

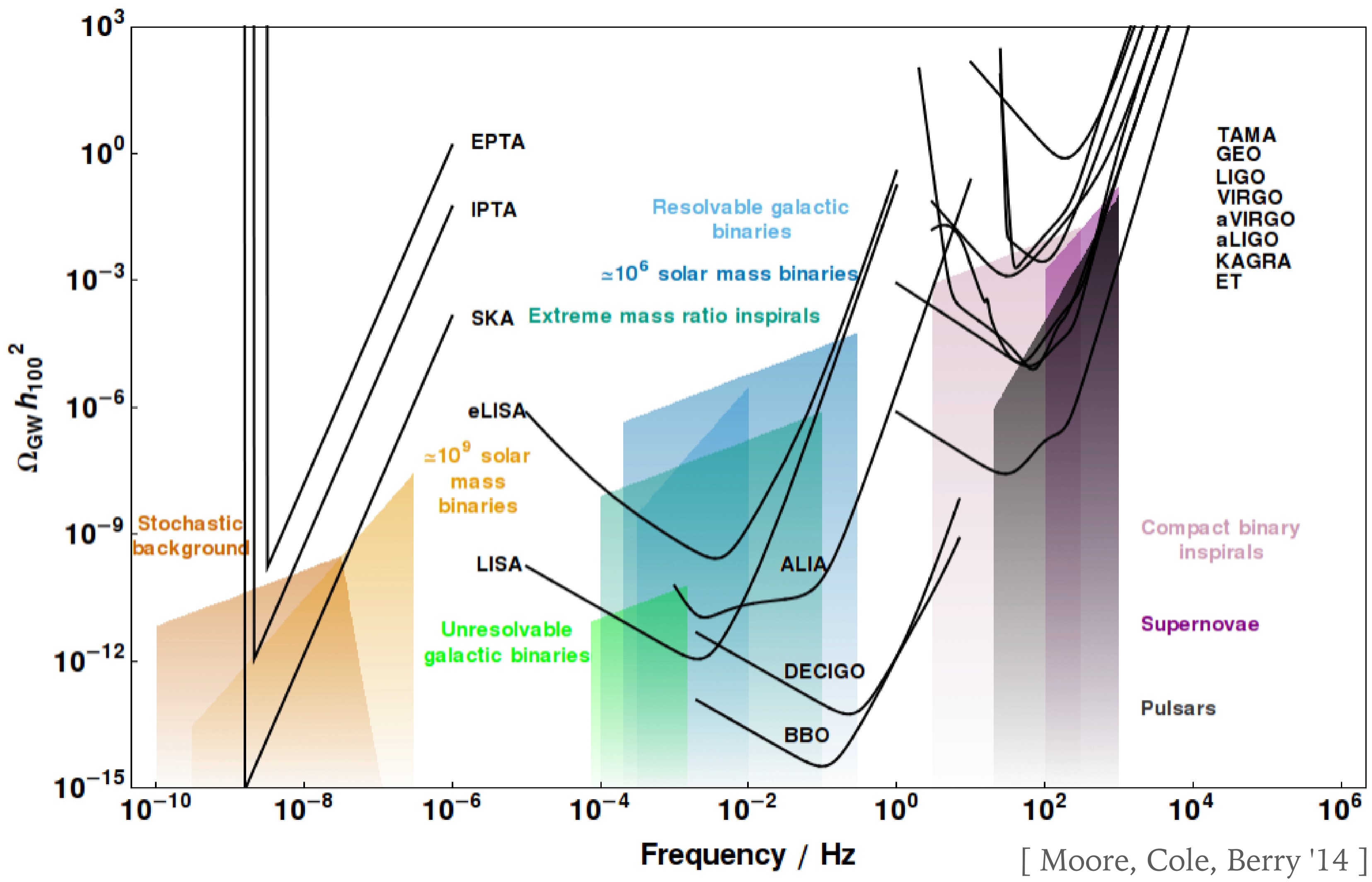
Space-borne interferometers

$\sim$ mHz – Hz

Ground-based interferometers

~ 100 Hz

GW energy density per unit log freq. / total energy density of the Universe

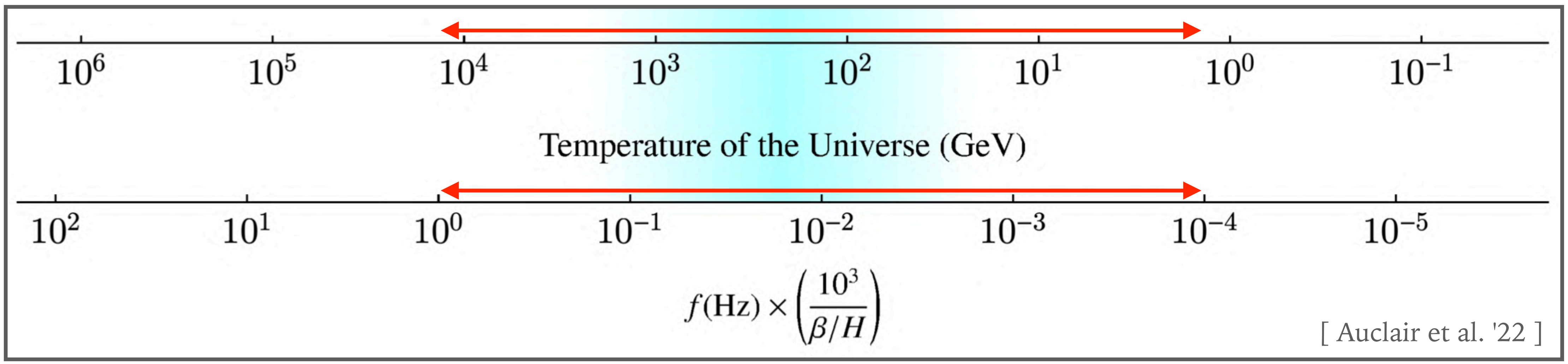


[Moore, Cole, Berry '14]

Present frequency of cosmological GWs

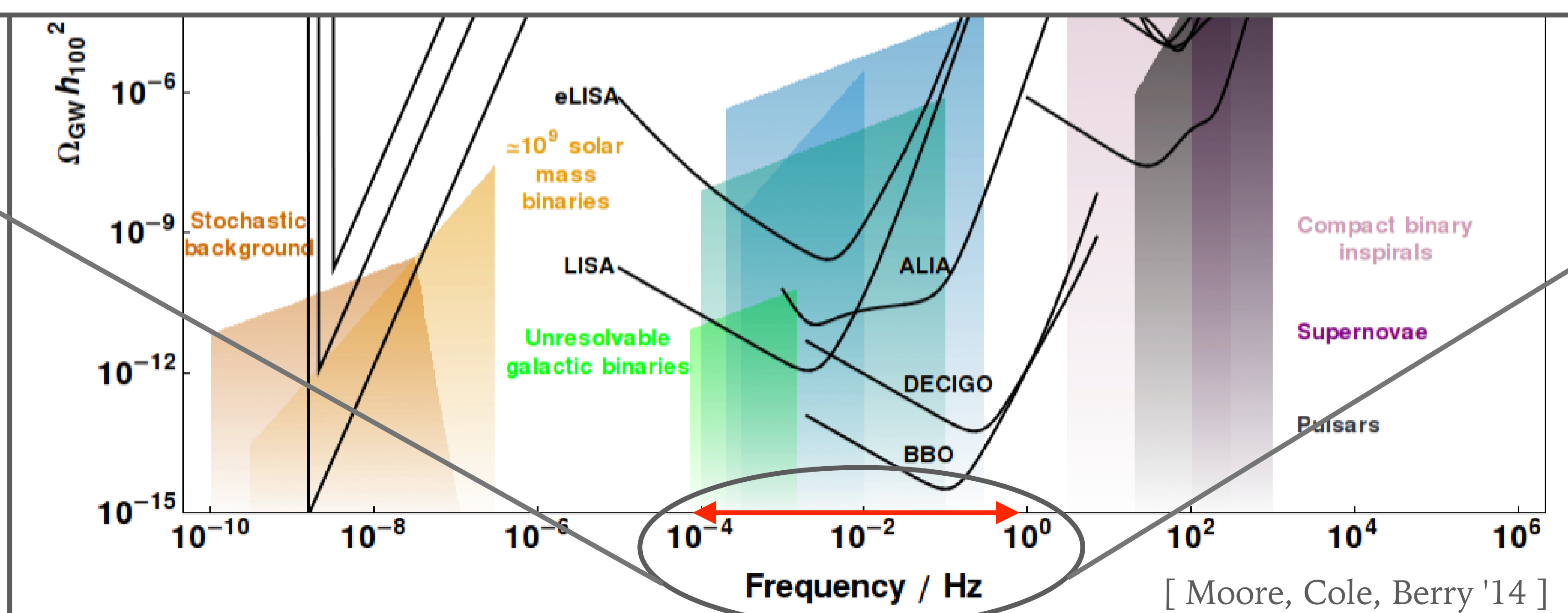
$\propto$ Energy scale (temperature) at the time of production

TeV scale physics



GW energy density per

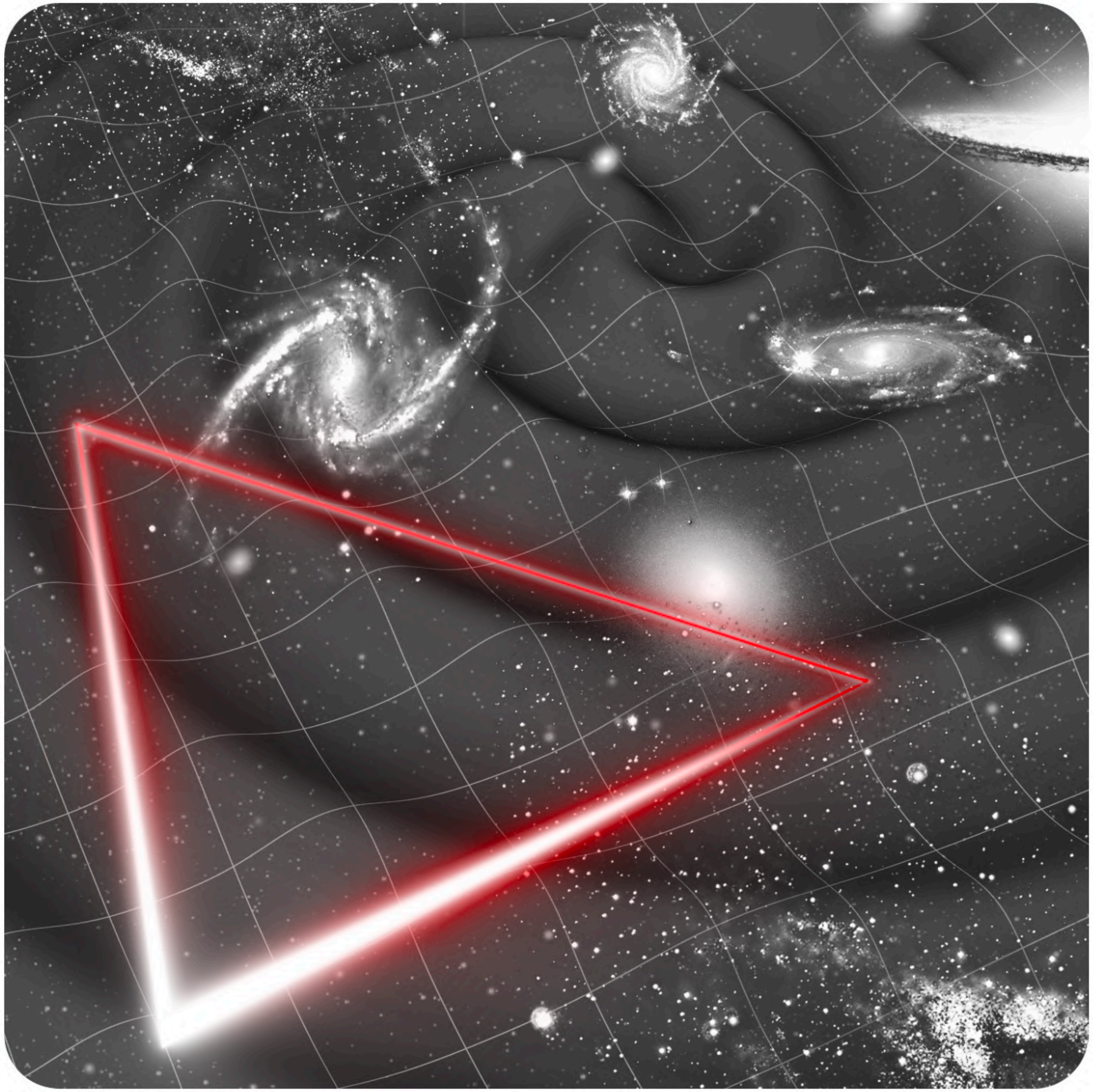
total energy density of



LISA MISSION

LISA

Laser Interferometer Space Antenna



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: OUTLINE

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

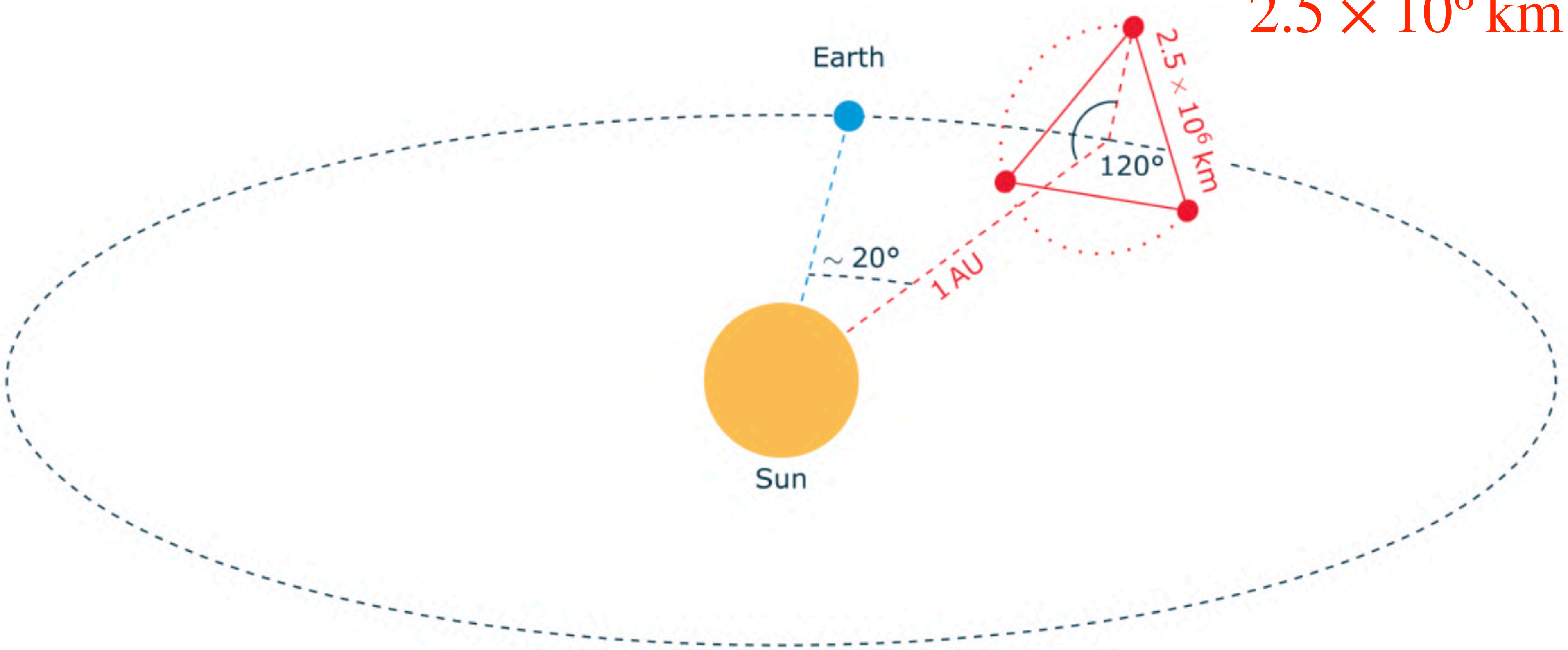


Figure 2.3: Schematic depiction of the LISA orbit, not to scale. The three satellites are arranged in a equilateral triangle, the constellation barycentre follows a heliocentric orbit lagging or leading approximately 20°, or about 50×10^6 km, behind Earth. The plane of the constellation (marked with 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: OUTLINE

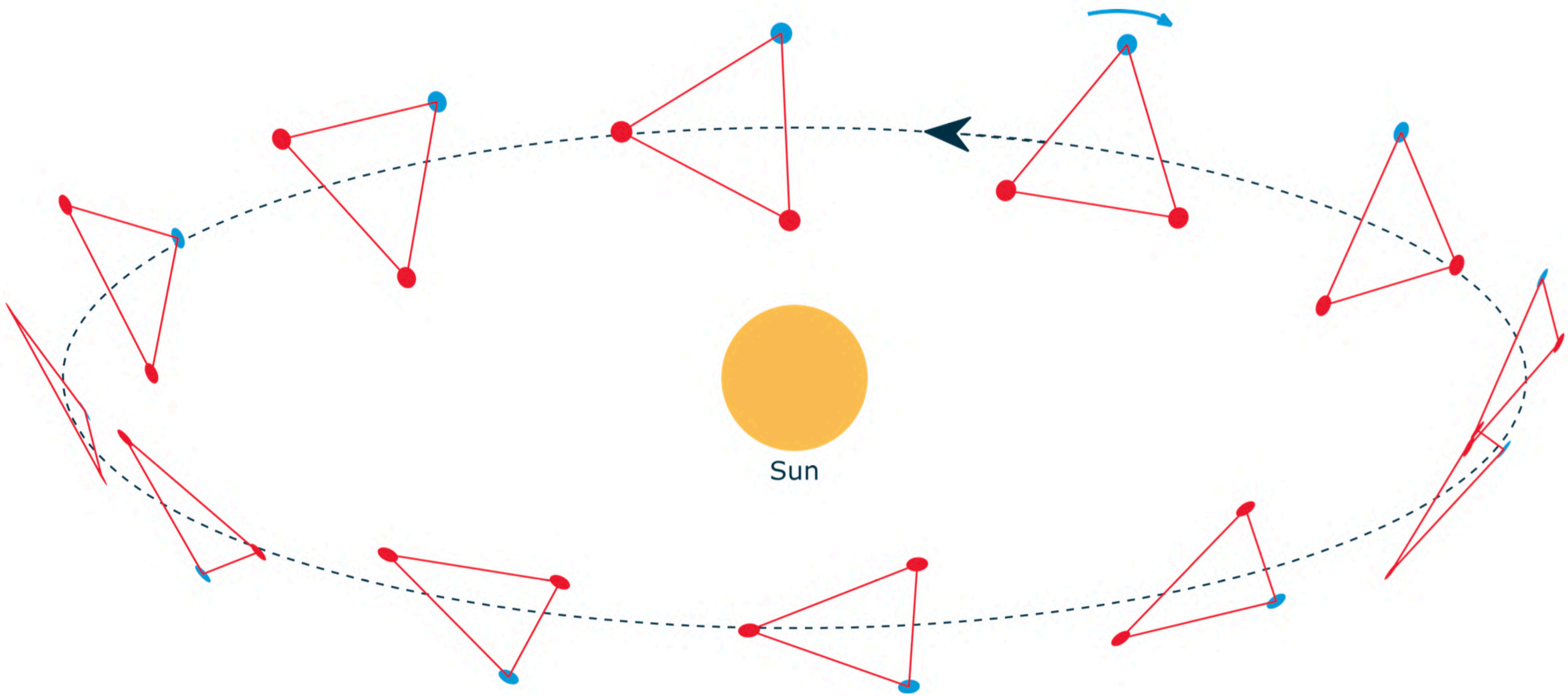
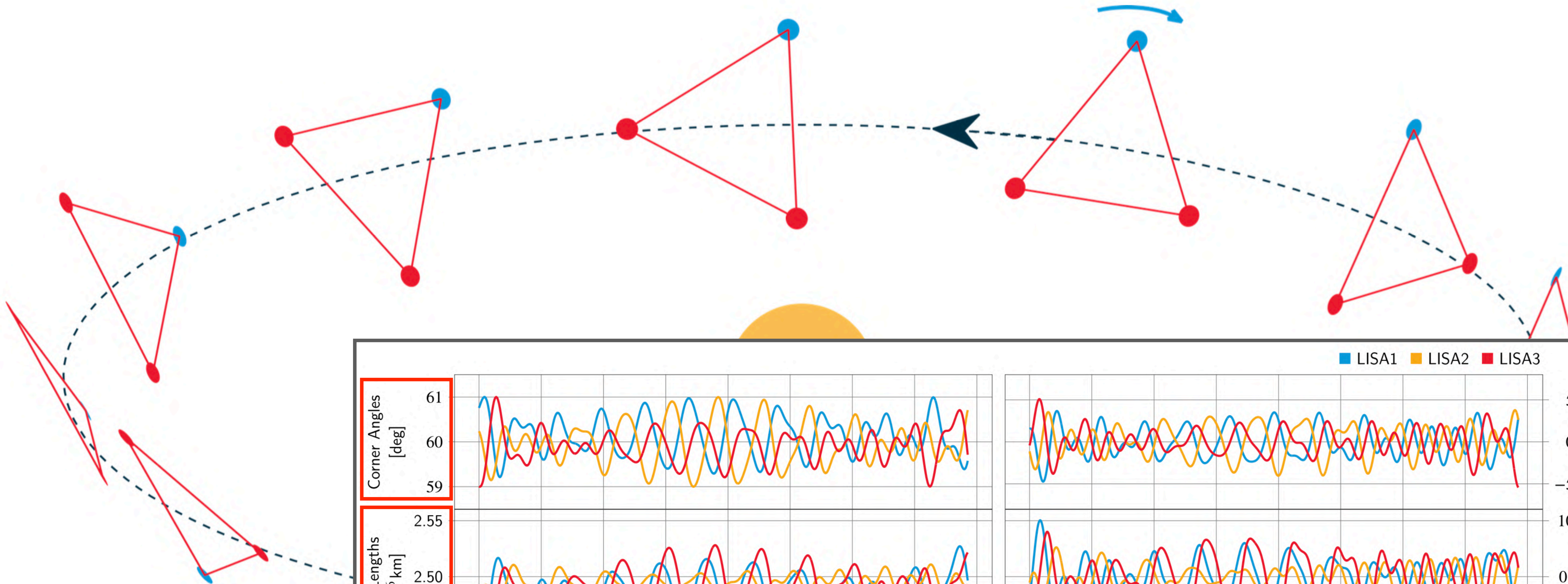


Figure 6.3: LISA orbits for the three individual spacecraft. The centre of mass of the constellation follows a heliocentric, circular orbit with no inclination. The orbits of the spacecraft have a small eccentricity $e = \eta/(2\sqrt{3}$ and an inclination of $\iota = \arcsin(\eta/2)$ where $\eta = L/1$ AU ≈ 0.017 ($L/2.5 \times 10^6$ km) is the armlength measured in AU. The 60° inclination of the constellation results in a backwards rotation of the constellation (blue arrow).

LISA MISSION: OUTLINE



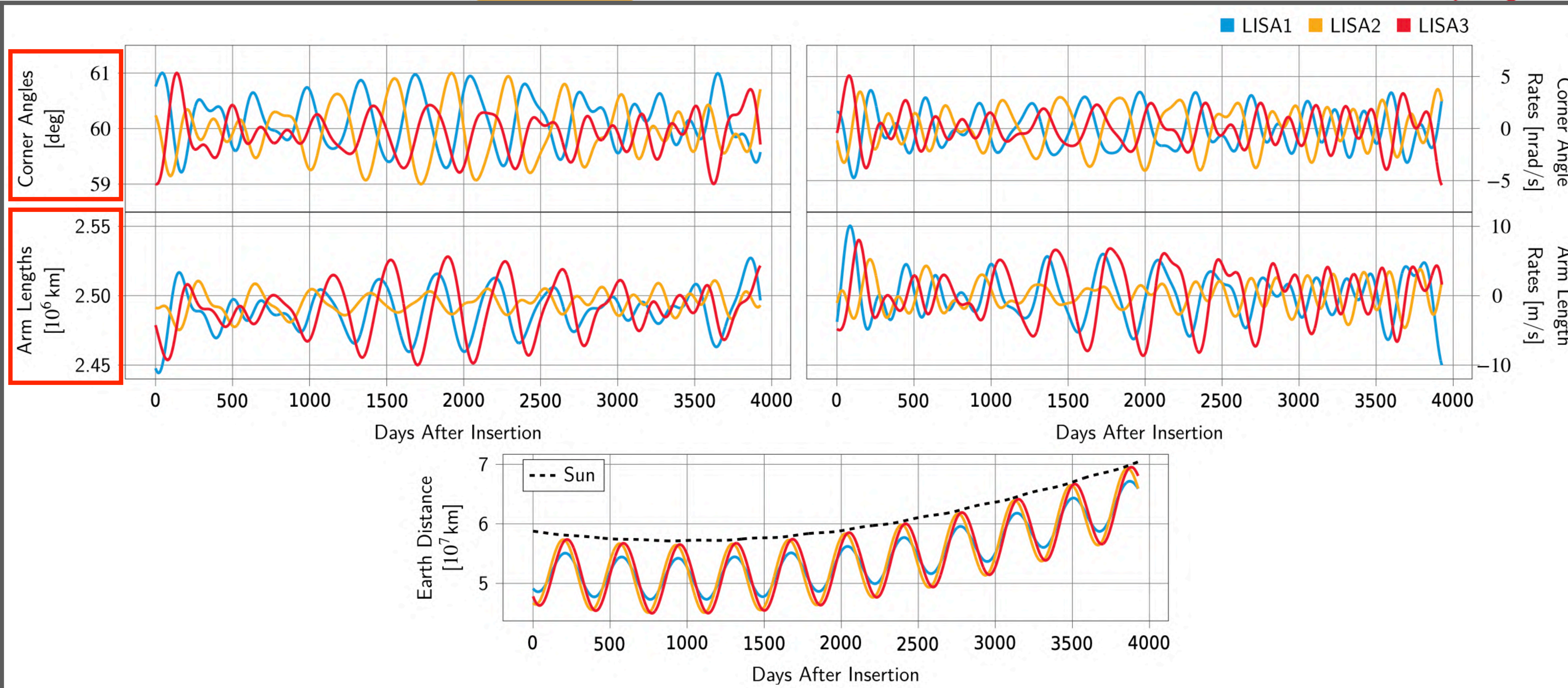
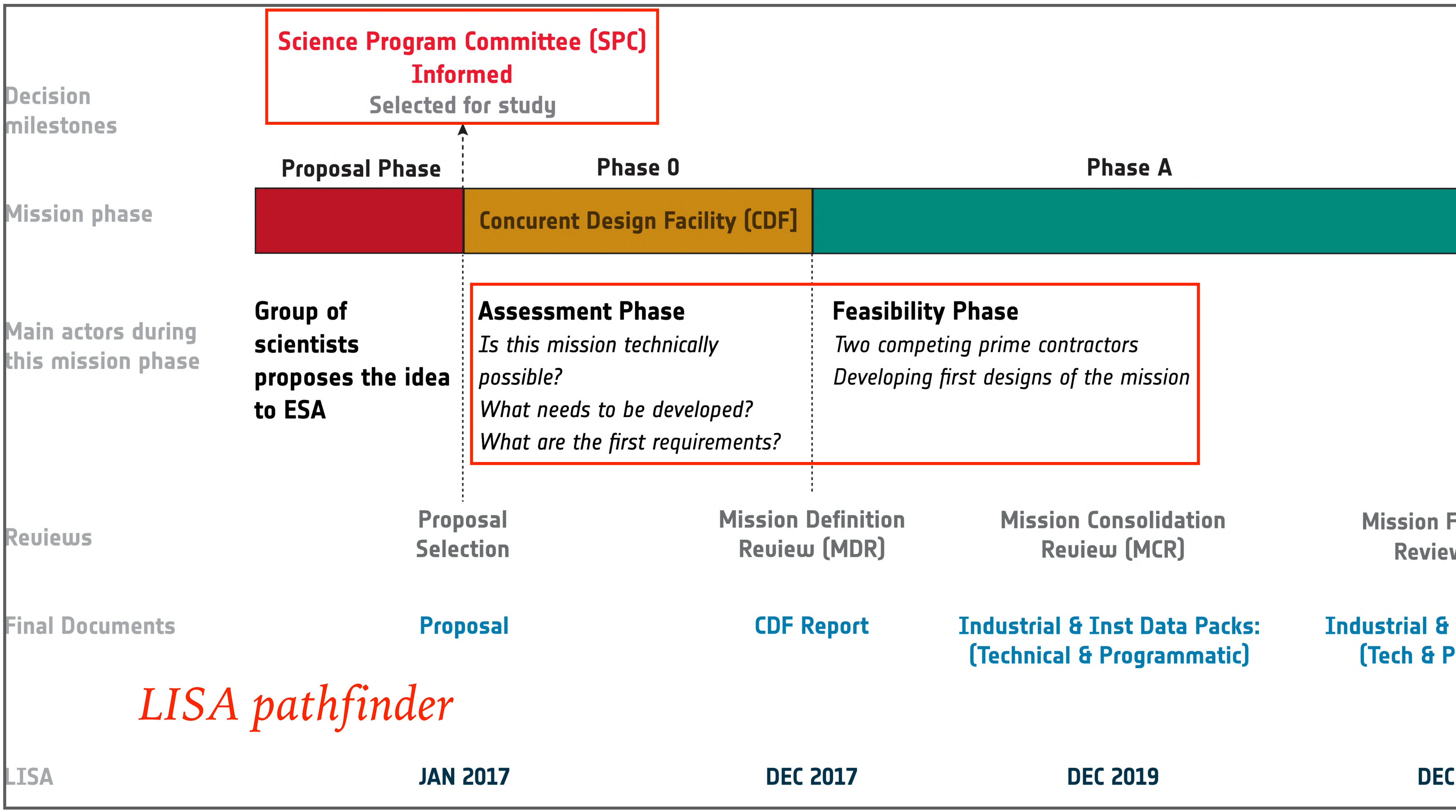


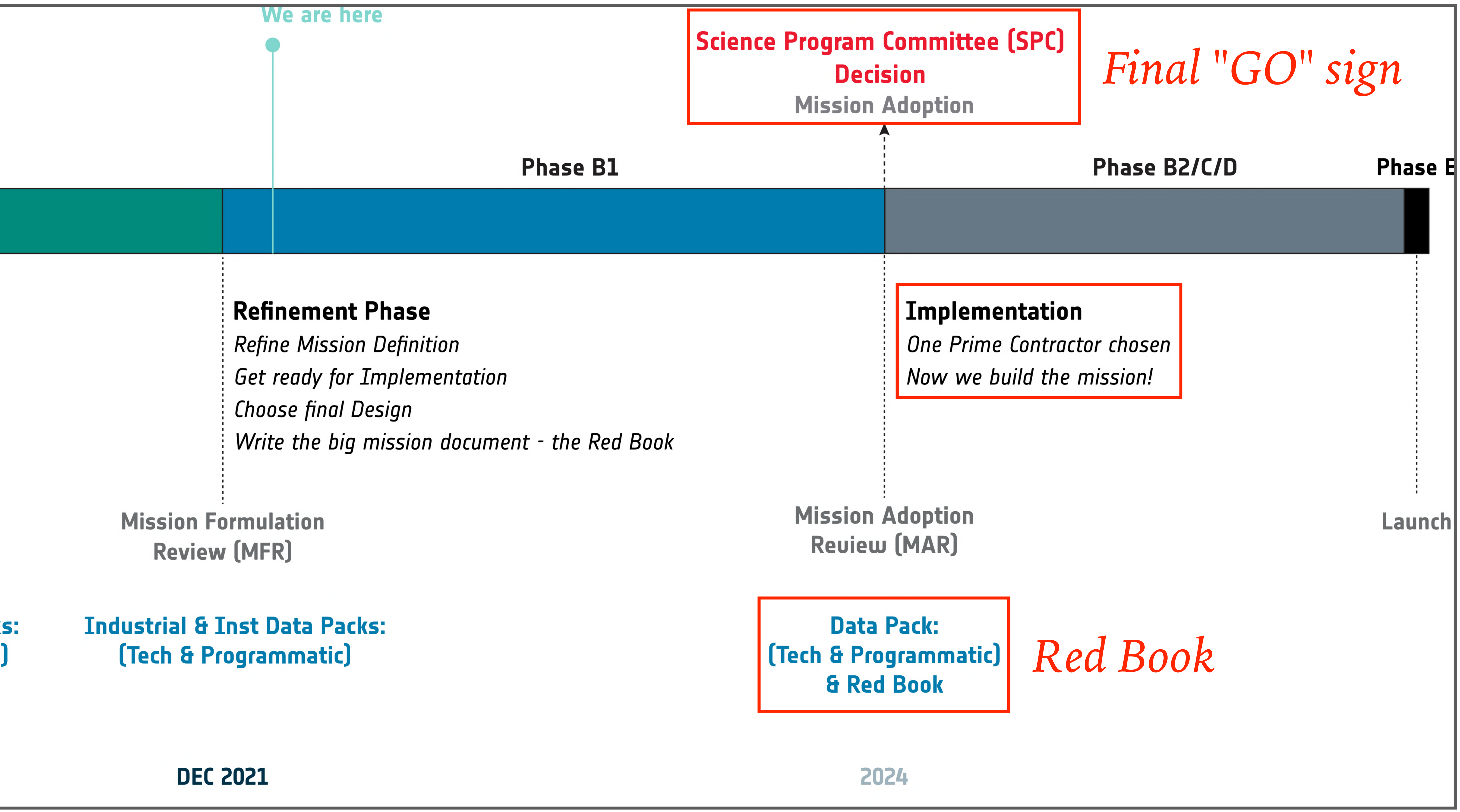
Figure 6.2: Overview of the orbital parameters for the baseline orbit.

Figure 6.3: LISA orbits
heliocentric, circular orbit
an inclination of $\iota =$ arcsi
60° inclination of the con

LISA MISSION: TIMELINE



LISA MISSION: TIMELINE



LISA MISSION: TARGETS

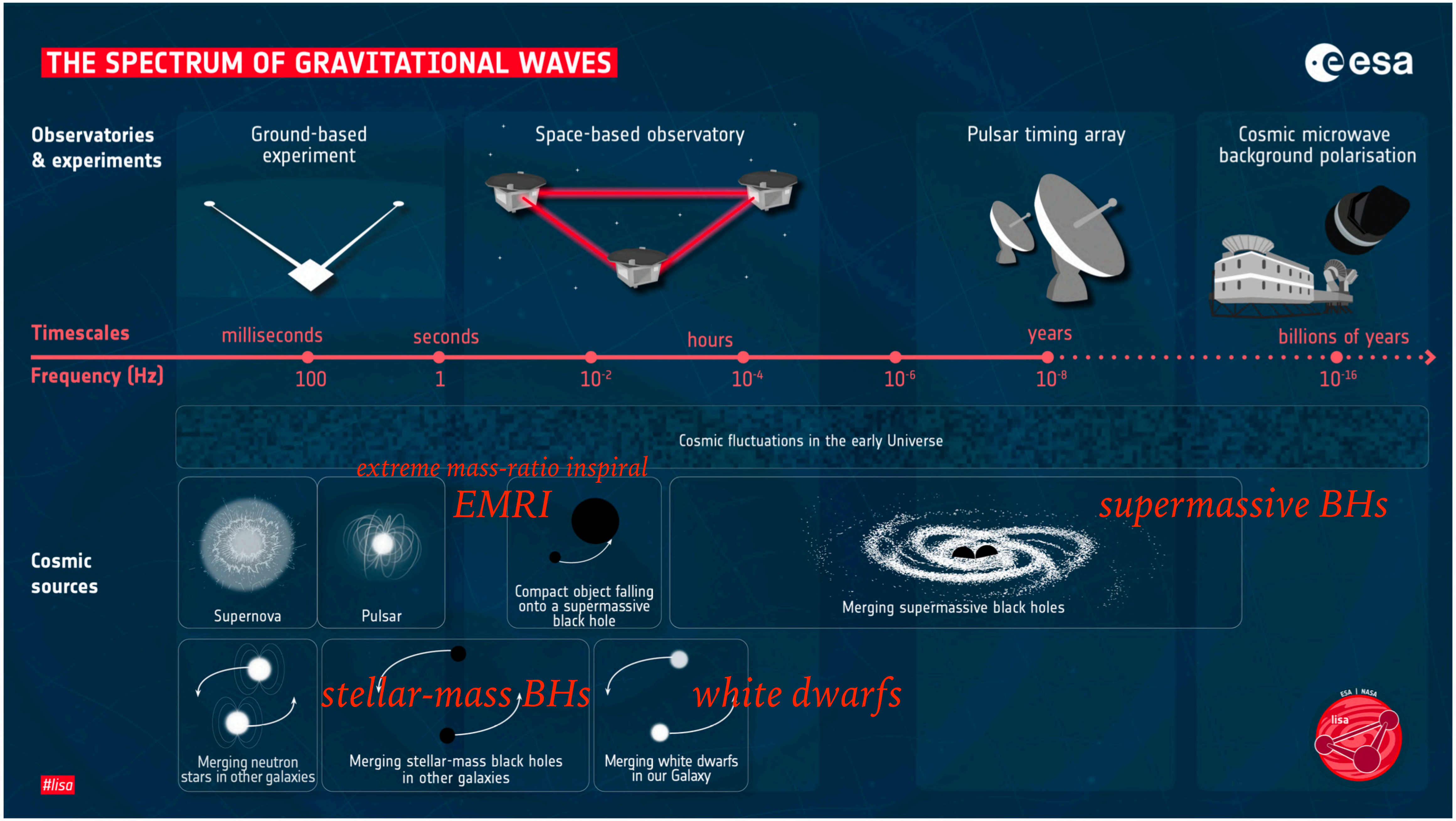


Figure 2.1: LISA targets the millihertz band of gravitational waves, lying between the nanohertz regime probed by pulsar timing arrays and the decahertz regime accessible to ground-based detectors. Several types of astrophysical sources produce gravitational waves (GWs) in this band.

LISA MISSION: PRIMARY SOURCES

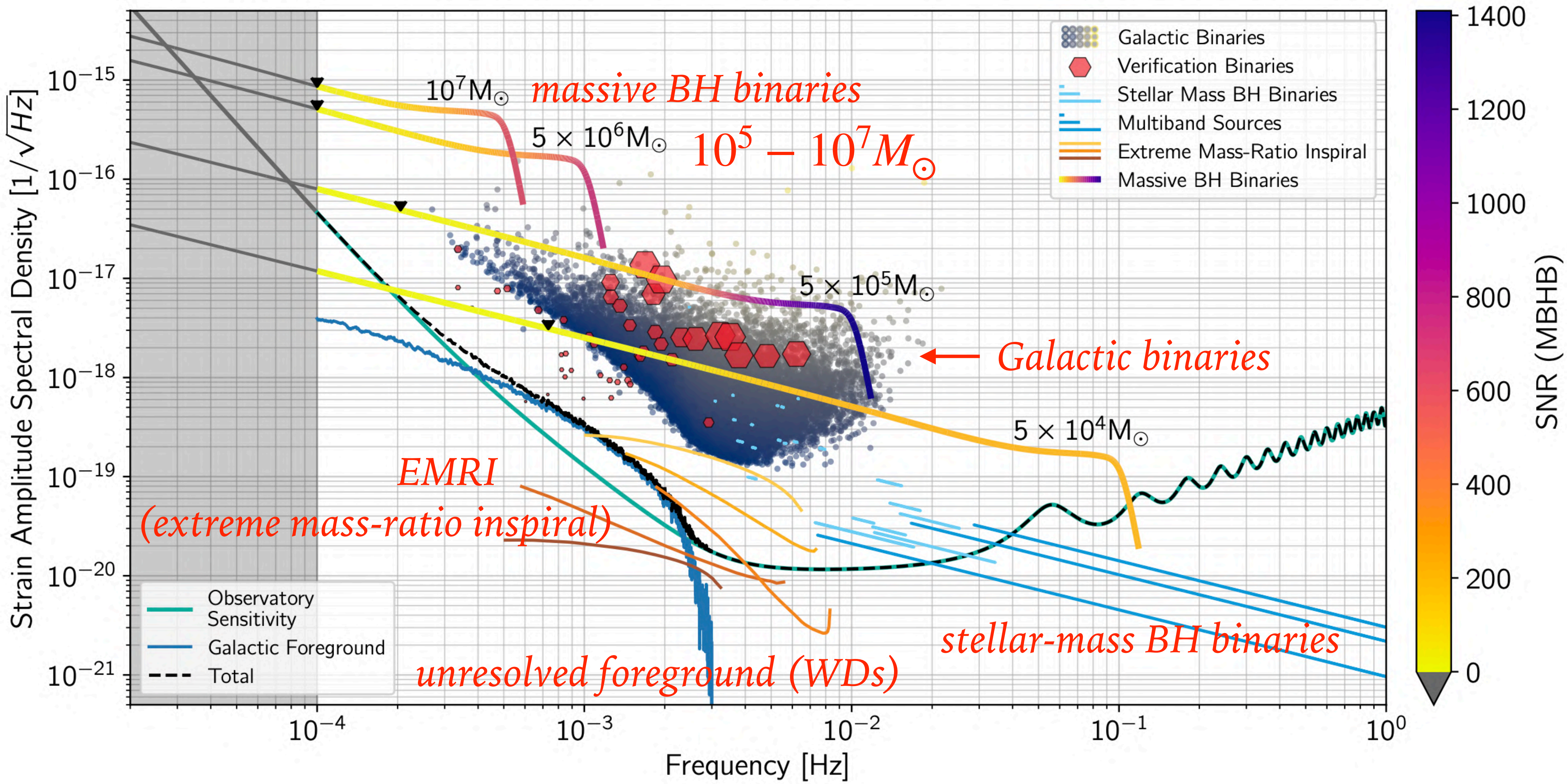


Figure 2.2: Illustration of the primary LISA source classes in the gravitational wave (GW) frequency-amplitude plane. Included are merging massive Black Hole binaries (MBHBs) and an extreme mass-ratio inspiral (EMRI) at moderate redshift; stellar-mass Black Holes (sBHs), including potential multiband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

LISA MISSION: PRIMARY SOURCES

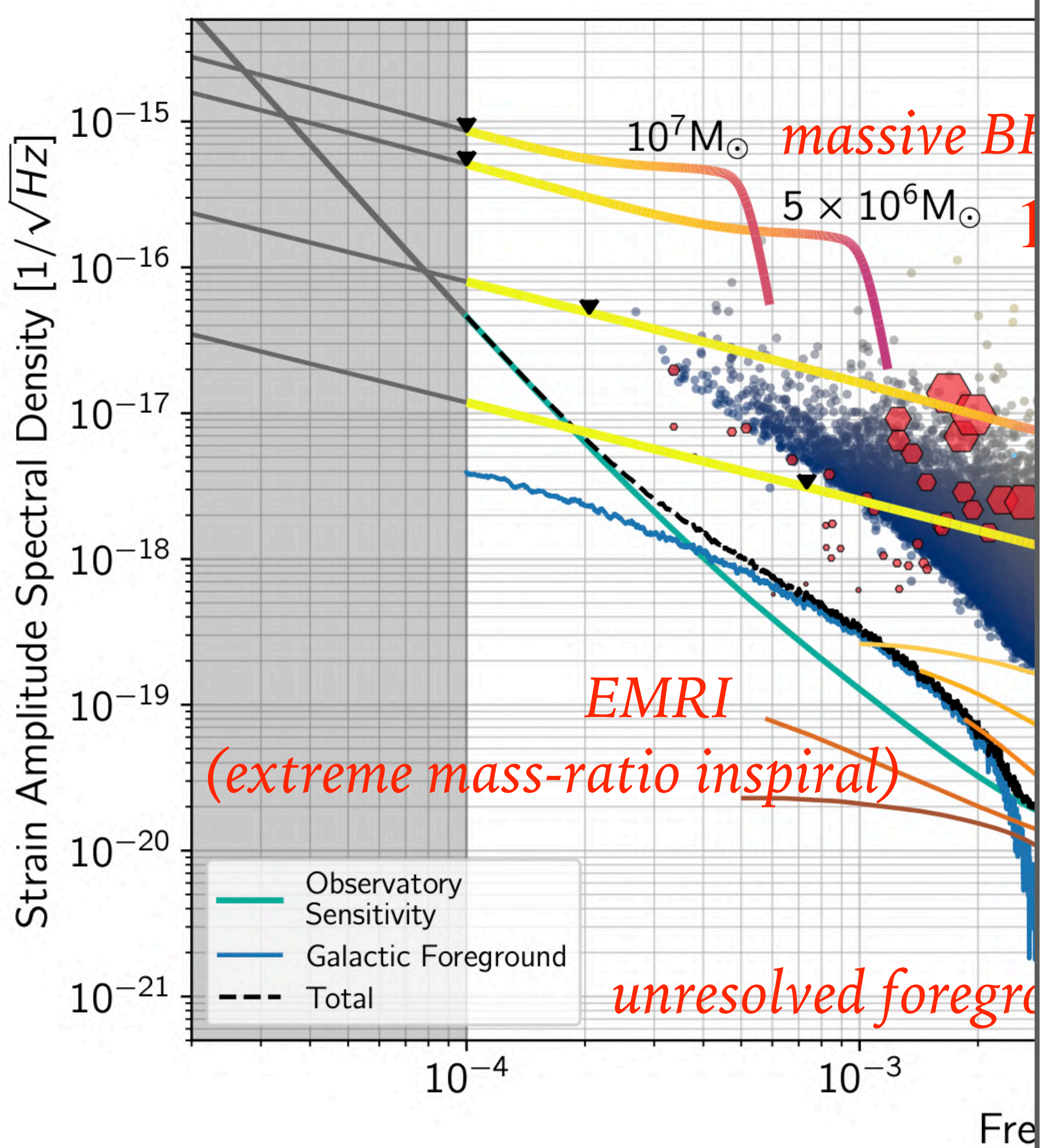


Figure 2.2: Illustration of the primary LISA source c
Included are merging massive Black Hole binaries (M
redshift; stellar-mass Black Holes (sBHs), including p
(GBs), including verification binaries (VBs), in the

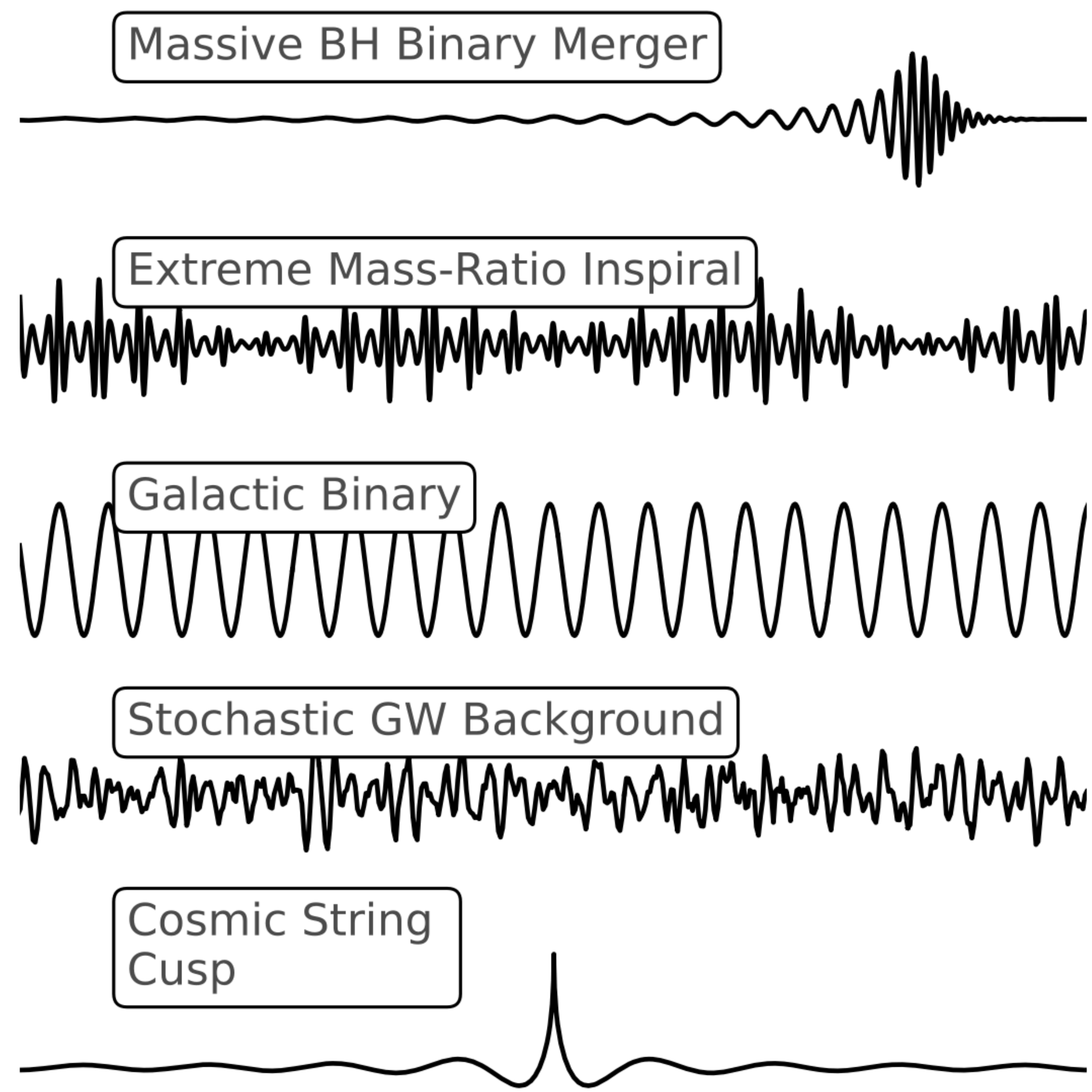


Figure 8.3: Shapes of the waveforms corresponding to the GW emission of (from top to bottom): Massive BH binary mergers; Extreme-mass-ratio inspirals; a single Galactic binary; a typical stochastic process; and a cosmic string cusp.

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)

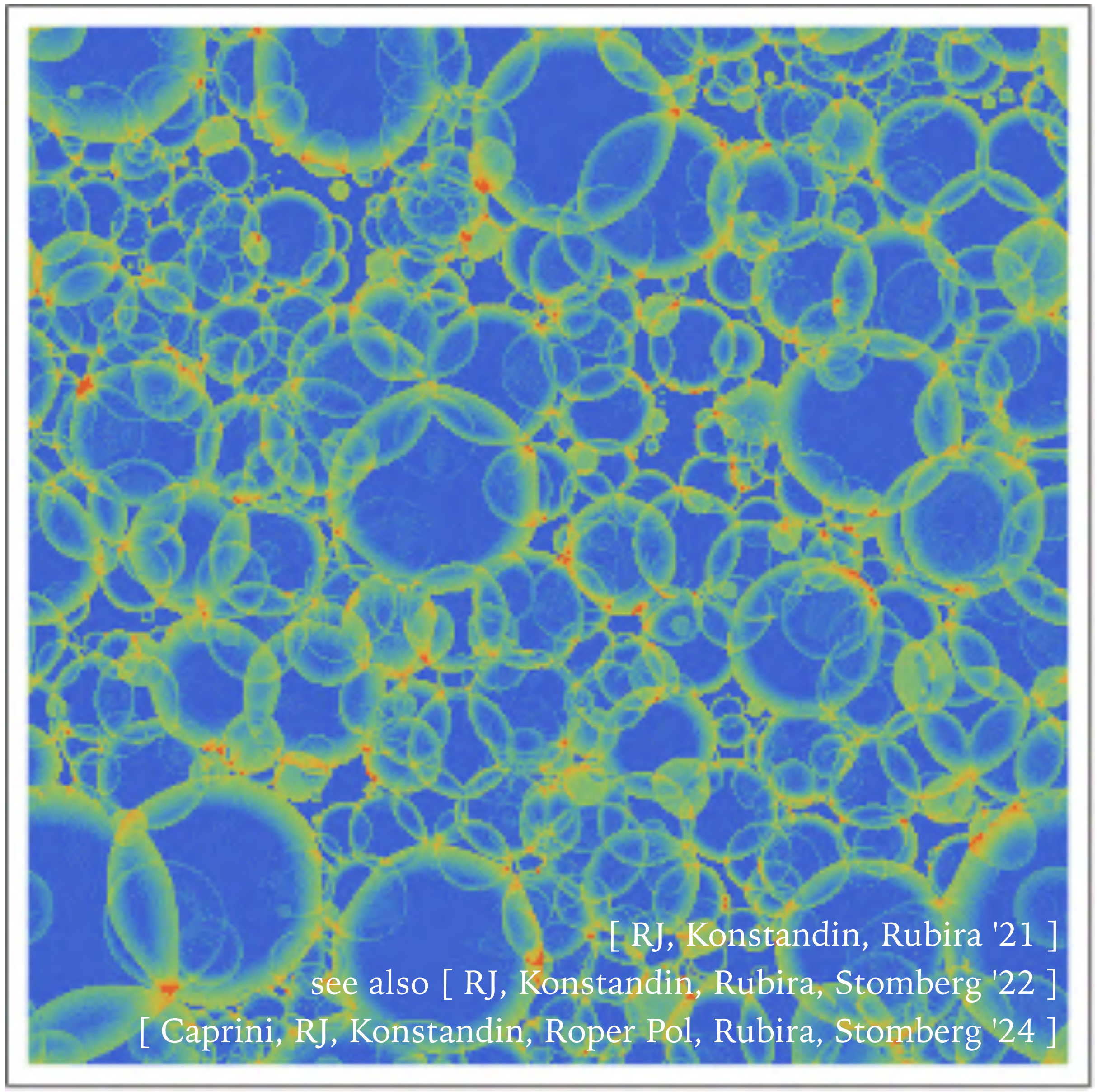
Planned launch: ~2035

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.

BUBBLE COLLISION & FLUID DYNAMICS

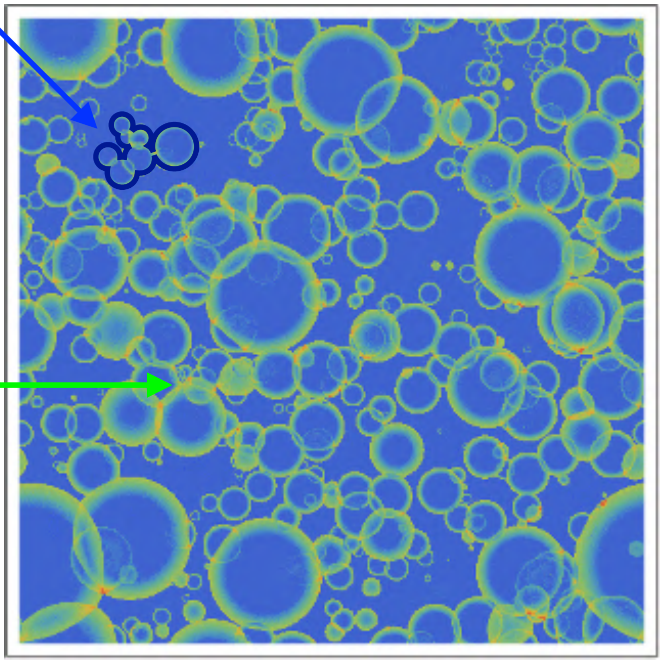
- Bubbles collide, and fluid dynamics sets in (example for )



GRAVITATIONAL WAVE SOURCES

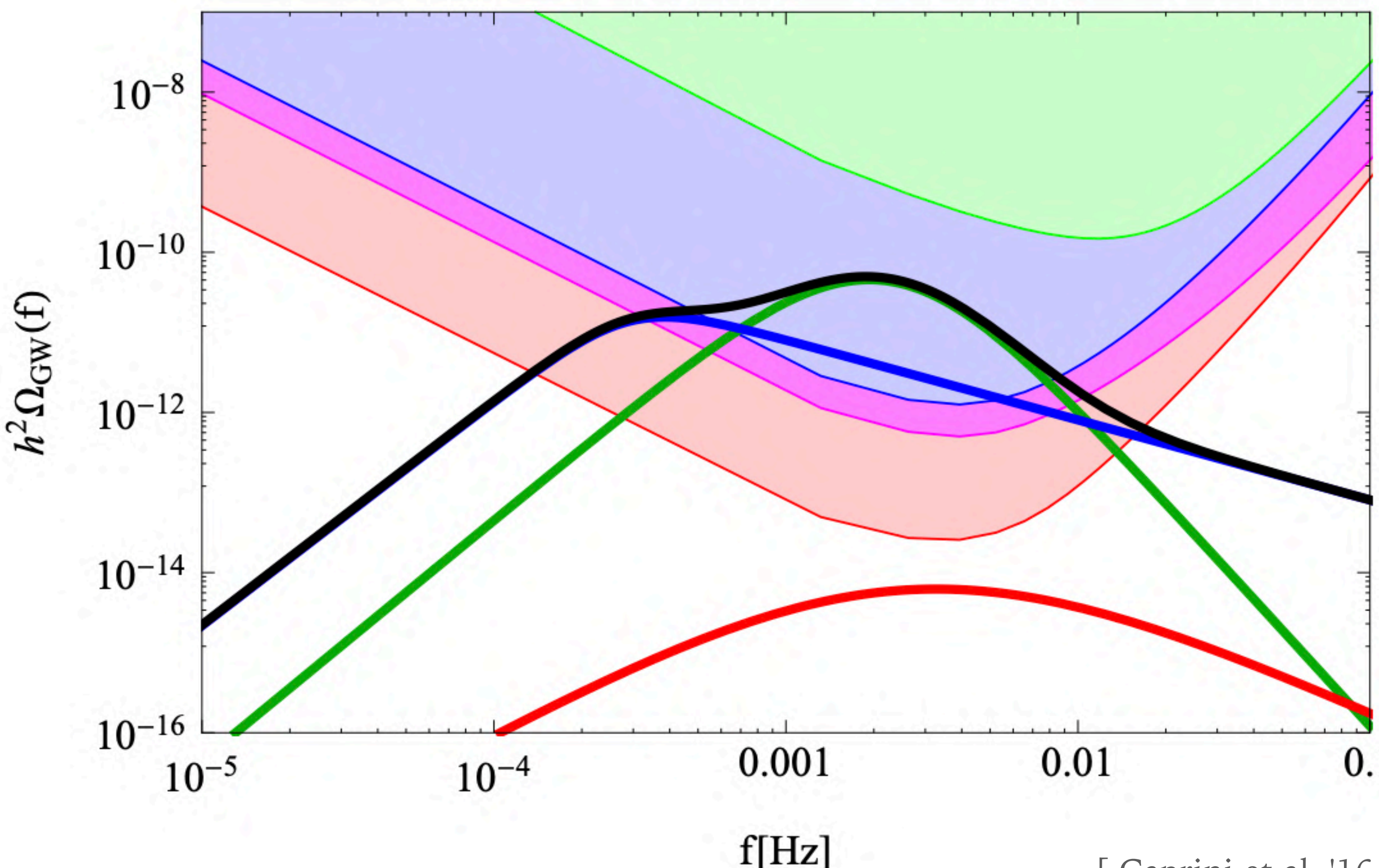
[Kosowsky, Turner, Watkins '92]
[Kosowsky, Turner '92]
[Kamionkowski, Kosowsky, Turner '93]
and e.g. [Caprini et al. '16] [Caprini et al. '20]

- **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



[Caprini et al. '16]

1. Overview
2. First-order phase transitions
3. Dynamics of bubbles
4. Gravitational waves
5. Recent progress

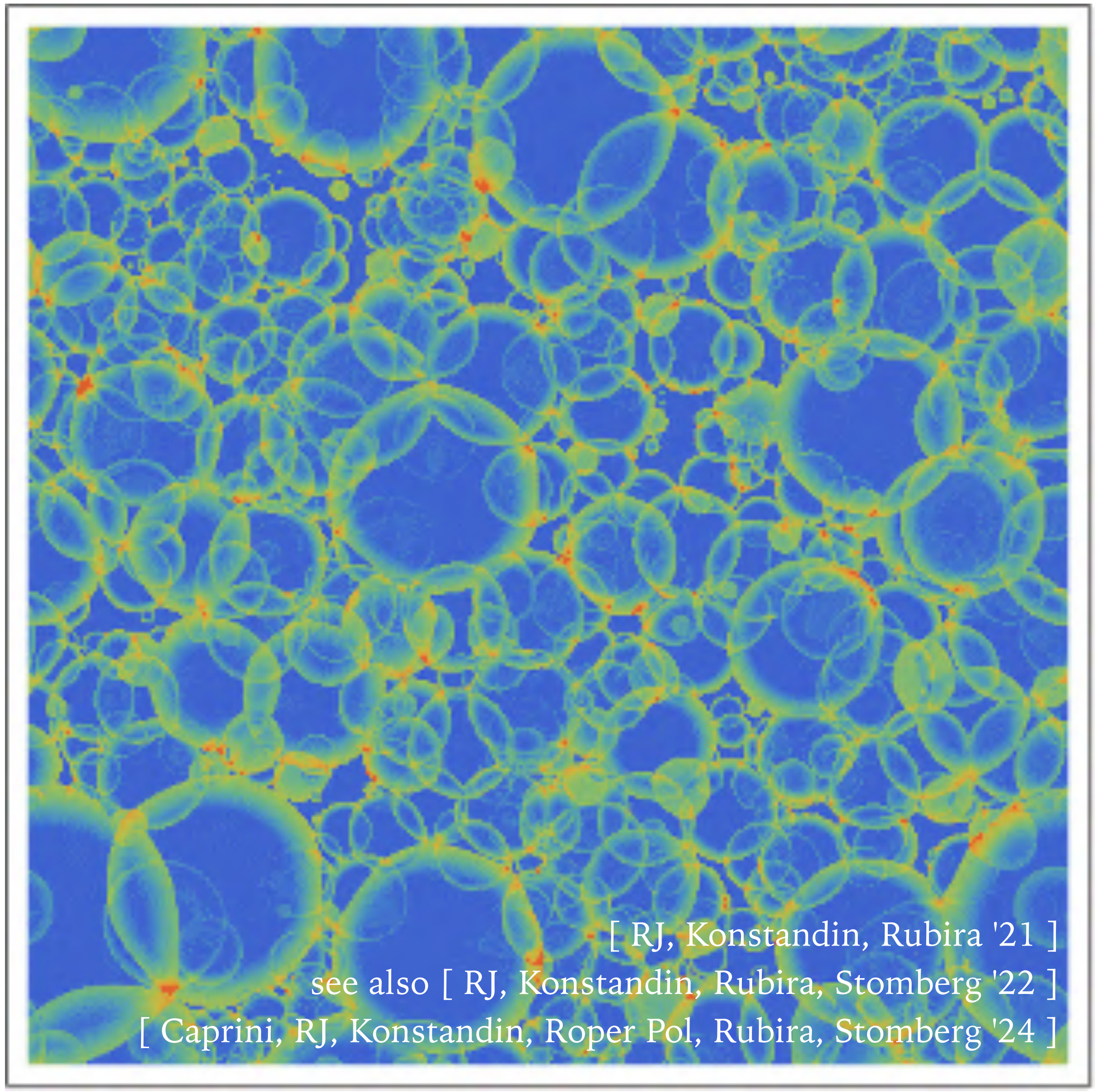
RECENT PROGRESS

First-order phase transitions in the early Universe:

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

BUBBLE COLLISION & FLUID DYNAMICS

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



HIGGSLESS SIMULATION

- Requirements for fluid 3d simulations

  - Dealing with shock waves
  - Controlling numerical viscosity → currently 2 groups working on large-scale sound wave simulations
  - Computational resources

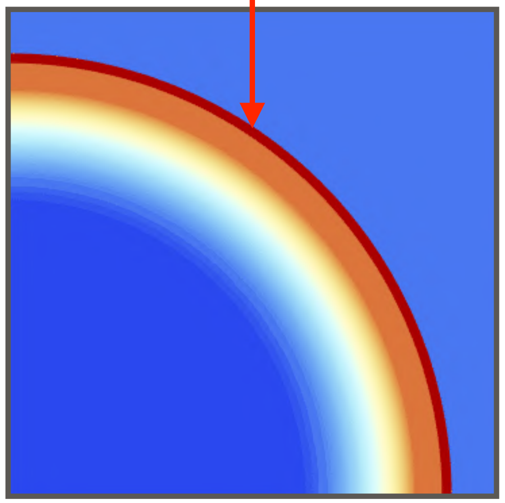
- Our proposal: Higgsless scheme

  [RJ, Konstandin, Rubira '21] [RJ, Konstandin, Rubira, Stomberg '22]

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

  - We do ***not*** solve both the scalar field and fluid but rather "integrate out" the scalar field (= treat the scalar field as non-dynamical boundary)

non-dynamical energy-injecting boundary for fluid



ALGORITHM 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 can we implement these in simulations?

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

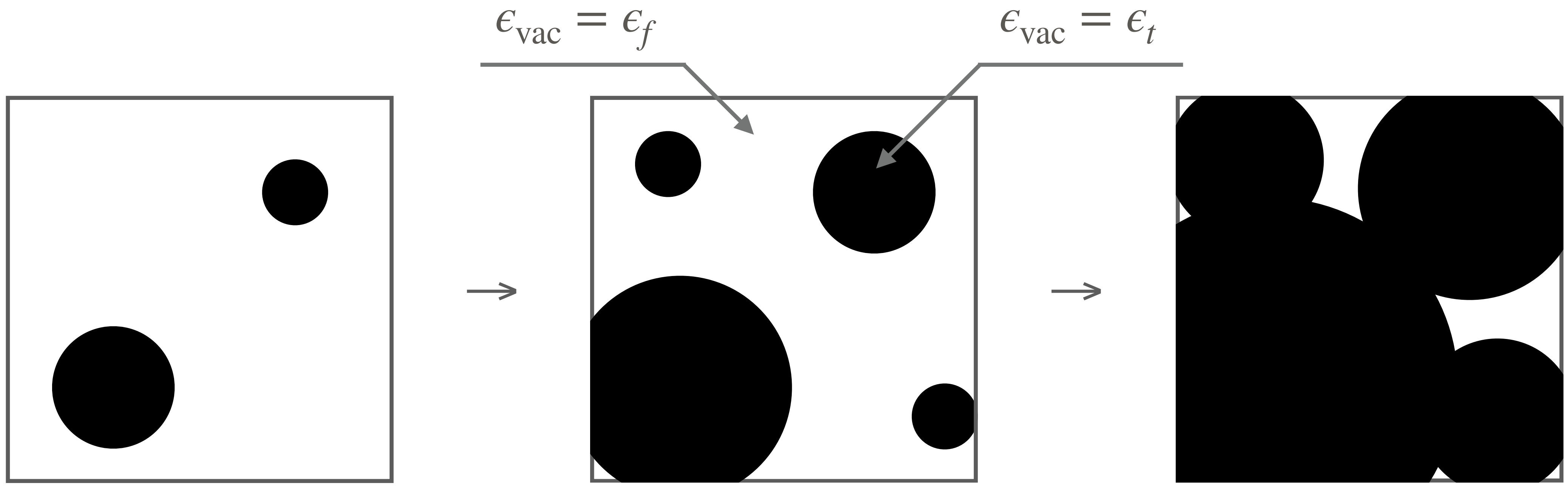
  ③ Where does the energy injection enter? Answer: in $T^{ij}(K^0, K^i)$

$$T^{ij}(K^0, K^i) = \frac{3}{2} \frac{K^i K^j}{(K^0 - \epsilon_{\rm vac}) + \sqrt{(K^0 - \epsilon_{\rm vac})^2 - \frac{3}{4} K^i K^i}}$$

ALGORITHM FOR HIGGSLESS SIMULATION

- We first numerically generate nucleation points,

  and determine the false-true boundary of the bubbles



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

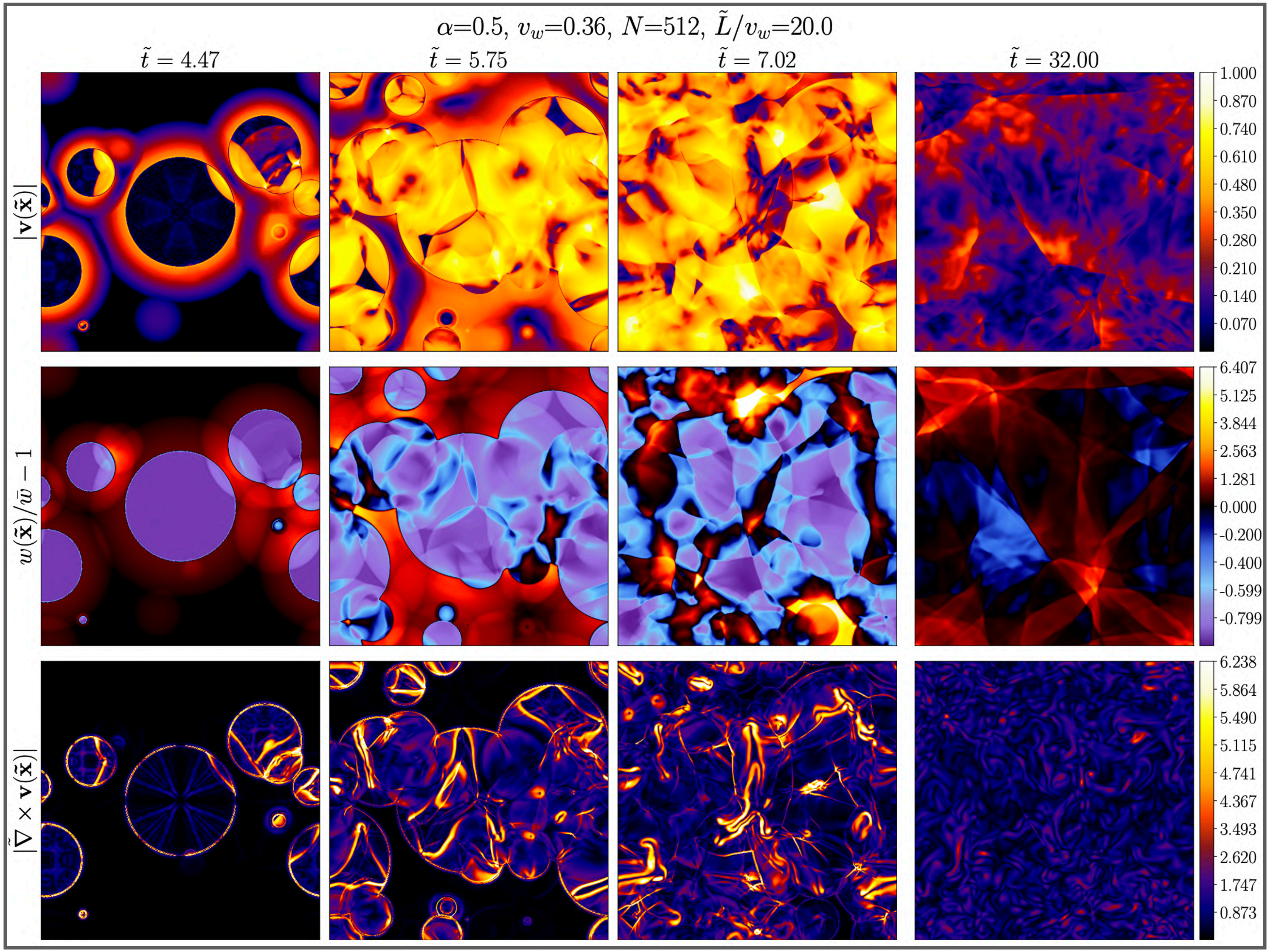
  $\rightarrow$ Fluid automatically develops profiles

HIGGSLESS SIMULATION: TYPICAL TIME EVOLUTION

fluid velocity

enthalpy

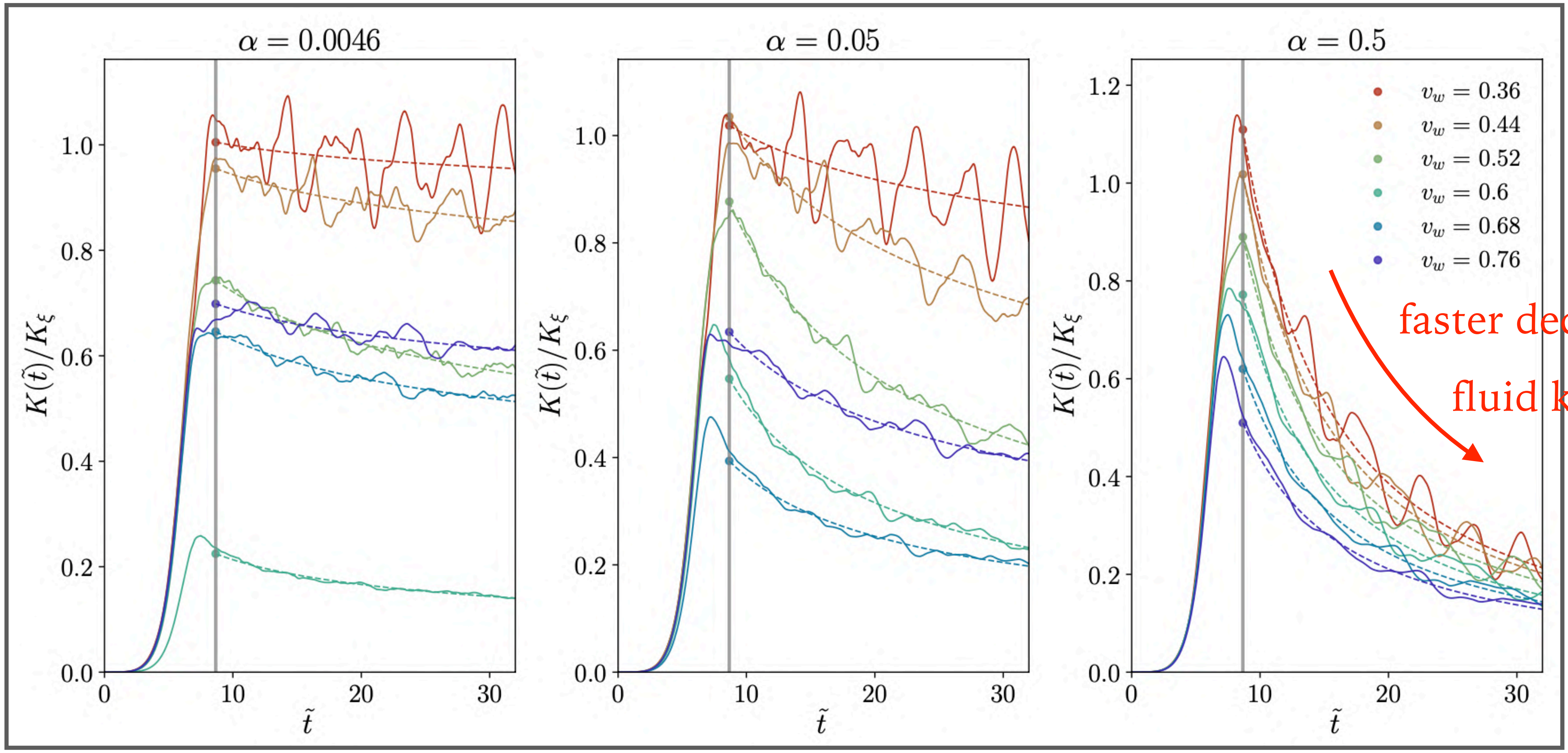
vorticity



HIGGSLESS SIMULATION: NUMERICAL RESULTS

fluid kinetic energy

weak intermediate strong



time

First-order phase transitions in the early Universe:

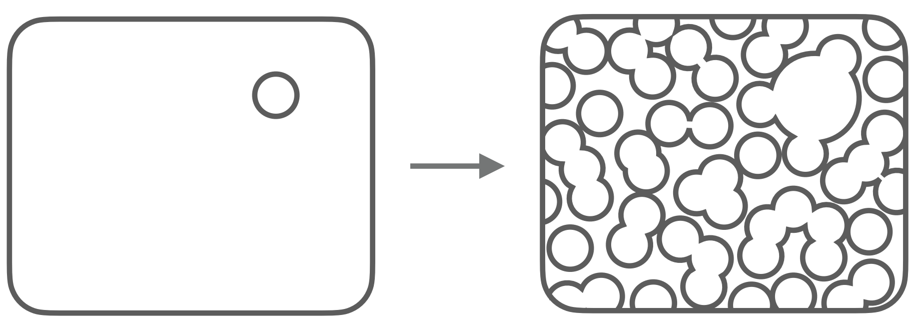
*gravitational waves, **black holes**, and feebly-interacting particles*

FOPT IN NEARLY CONFORMAL MODELS

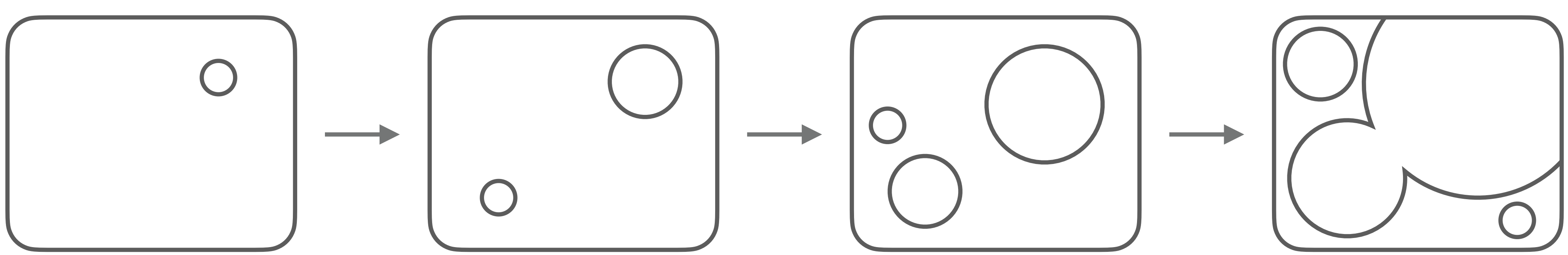
[Randall, Servant '07]
[Espinosa, Konstandin, No, Quiros '08]

- If the microphysics model is nearly scale invariant, bubbles grow big, resulting in huge GW production

Typical models



Nearly scale-invariant models



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

time ↗
temperature ↘

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

FOPT IN NEARLY CONFORMAL MODELS

[Iso, Okada, Orikasa '09]
[RJ, Takimoto '16]
[Iso, Serpico, Shimada '17]

➤ One example: Classically conformal B-L model

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
q_L^i	**3**	**2**	+1/6	+1/3
u_R^i	**3**	**1**	+2/3	+1/3
d_R^i	**3**	**1**	-1/3	+1/3
l_L^i	**1**	**2**	+1/6	-1
e_R^i	**1**	**1**	-1	-1
ν_R^i	**1**	**1**	0	-1
H	**1**	**2**	-1/2	0
Φ	**1**	**1**	0	+2

TABLE I: Matter contents of the classically conformal $B-L$ model. In addition to the standard model matters, three generations of right-handed neutrinos ν_R^i and a $B-L$ charged complex scalar field Φ are introduced.

FOPT IN NEARLY CONFORMAL MODELS

[Iso, Okada, Orikasa '09]
[RJ, Takimoto '16]
[Iso, Serpico, Shimada '17]

➤ Assumption: absence of mass scales

$$V_0 = \lambda_H |H|^4 + \lambda |\Phi|^4 - \lambda' |\Phi|^2 |H|^2$$

- Only quartic terms in the potential: no parameters with a finite mass dimension

- Scale dependence enters only through running of couplings

- Phase transition in Φ direction can be extremely strong

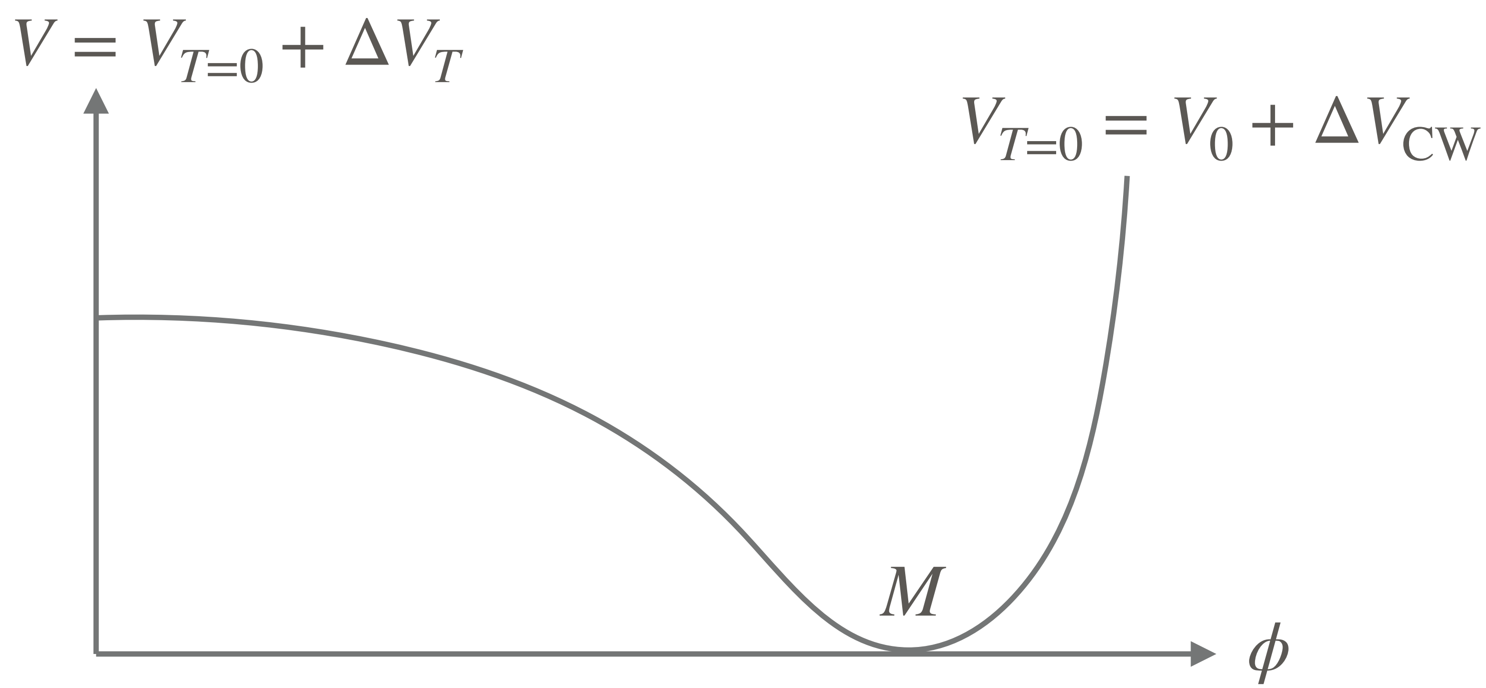
FOPT IN NEARLY CONFORMAL MODELS

- Zero-temperature behavior

  - The zero-temperature potential including loop corrections is governed by the running coupling constant as

$$V(\phi) \sim \lambda(\phi)\phi^4$$

  - The B-L scale M is generated a la Coleman-Weinberg

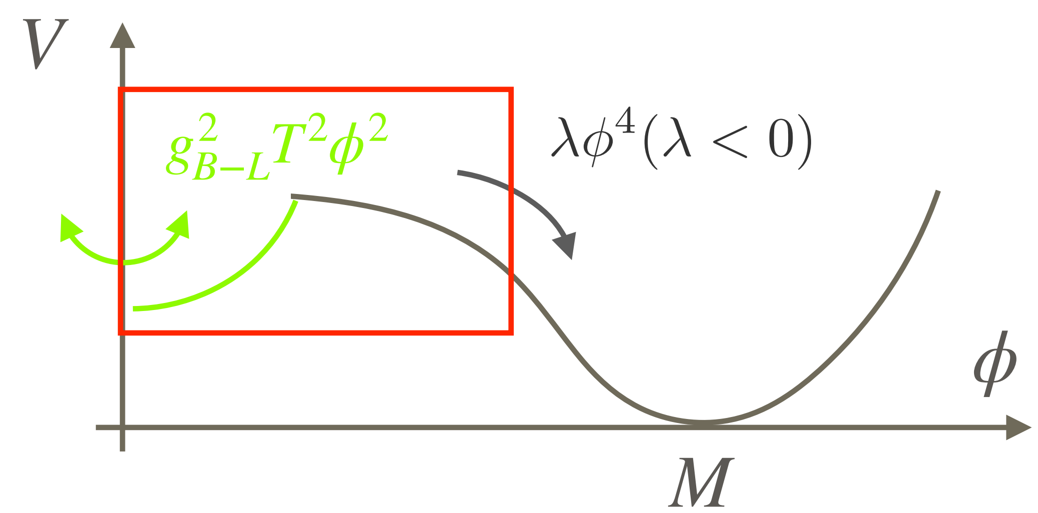


FOPT IN NEARLY CONFORMAL MODELS

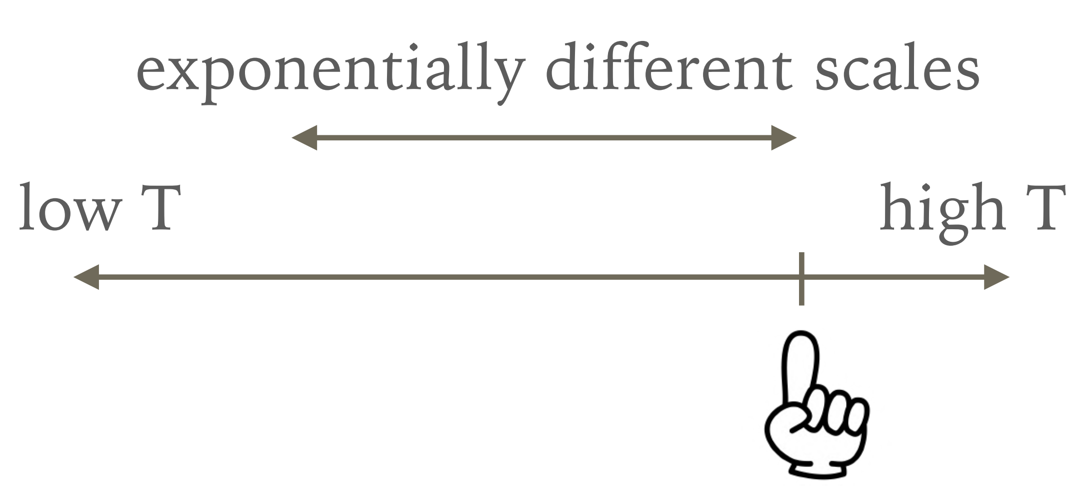
- Finite-temperature behavior

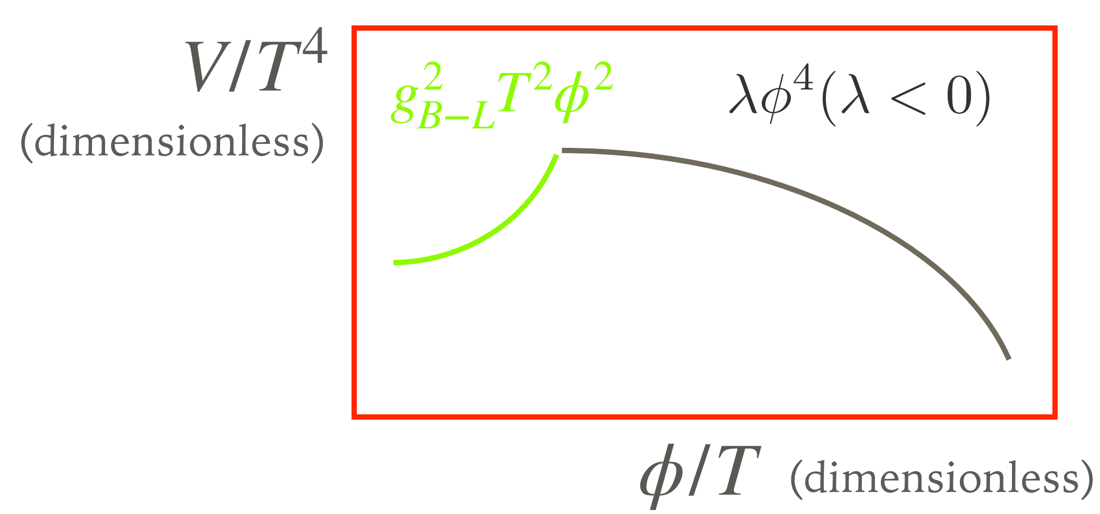
  - Thermal corrections create a quadratic trap, which persists down to small T

$$V \sim g_{B-L}^2 T^2 \phi^2 + \lambda(\max(T,\phi))\phi^4$$



  - Behavior of the potential as the temperature decreases





FOPT IN NEARLY CONFORMAL MODELS

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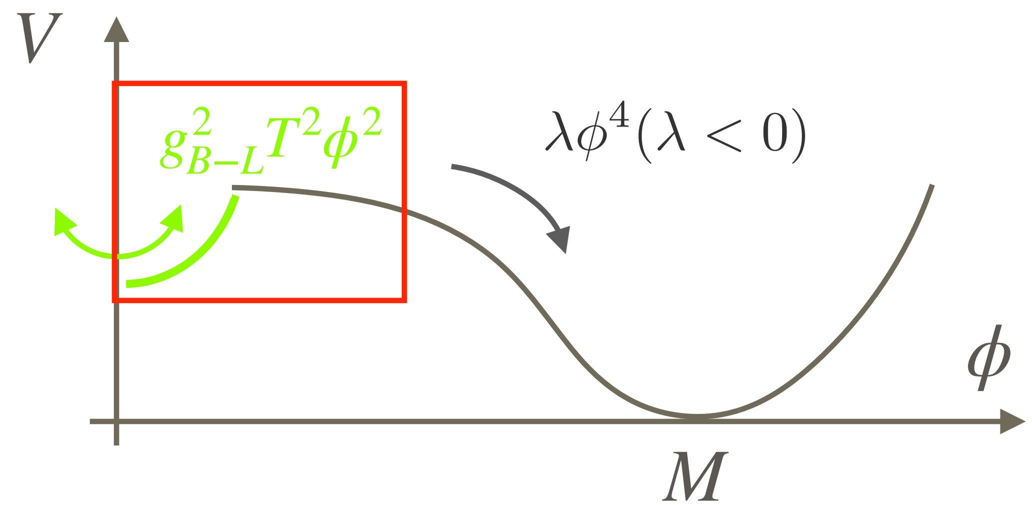

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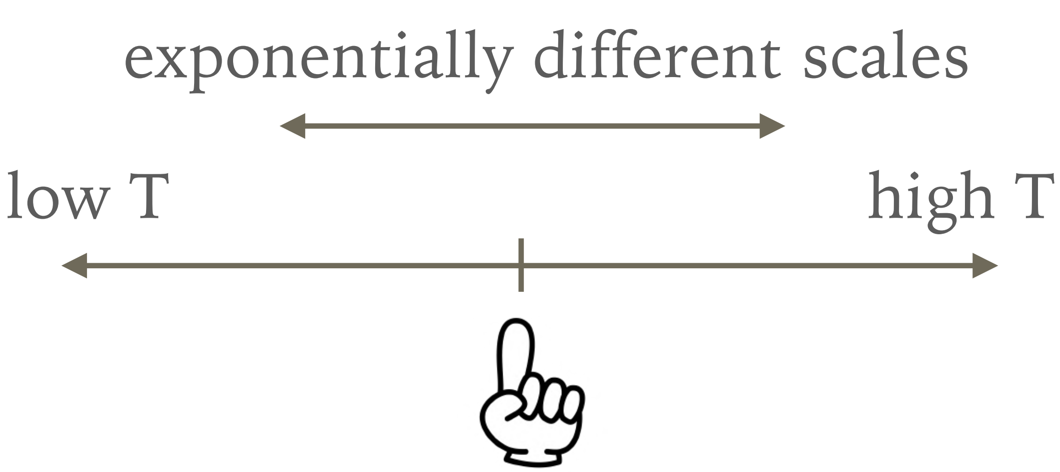
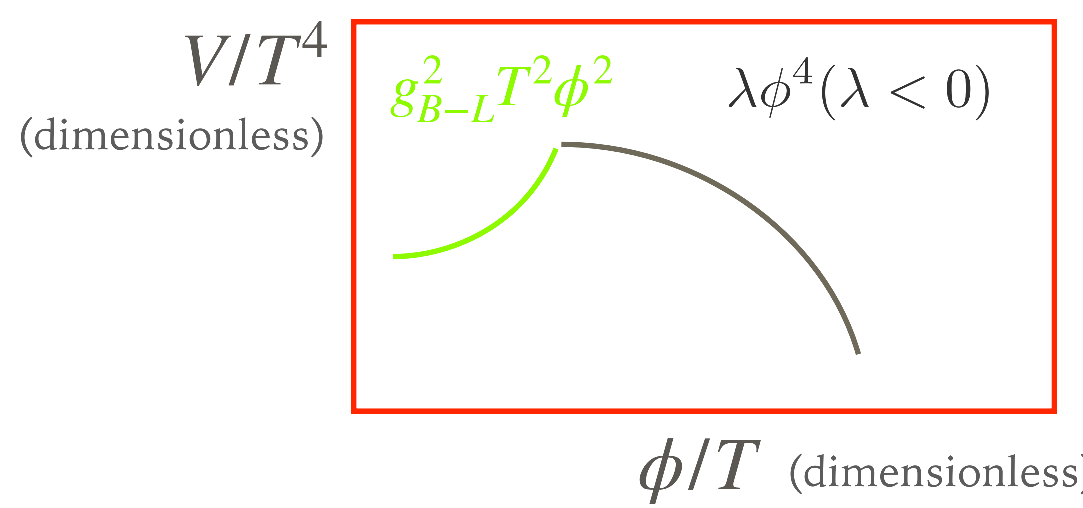


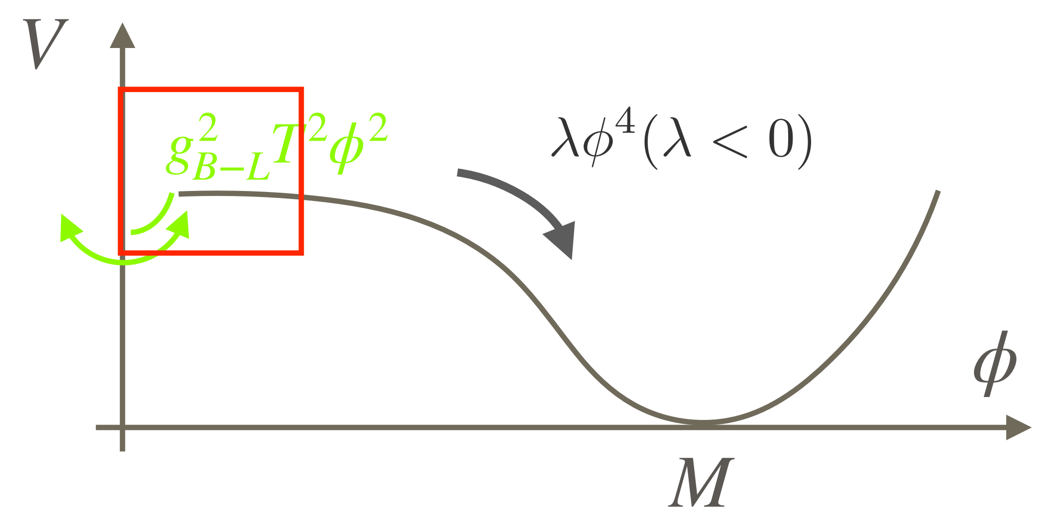


FOPT IN NEARLY CONFORMAL MODELS

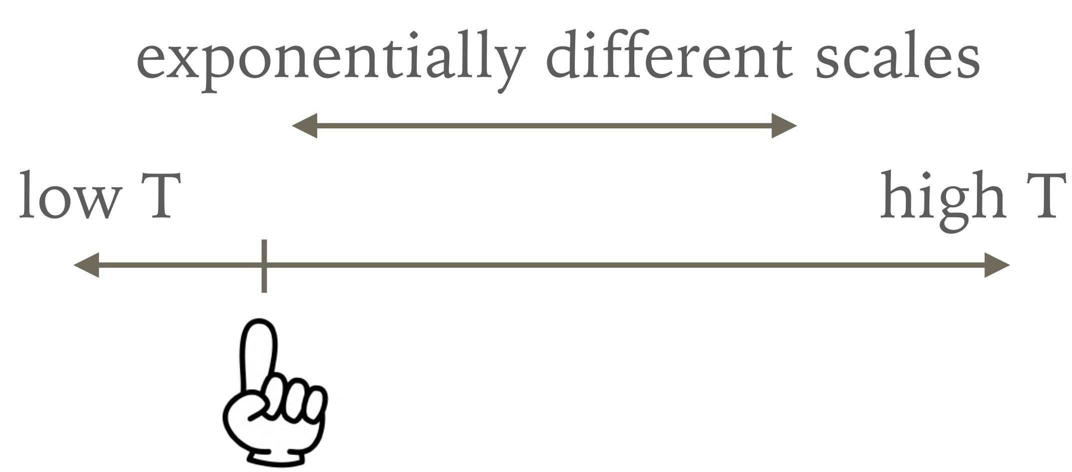
➤ Finite-temperature behavior

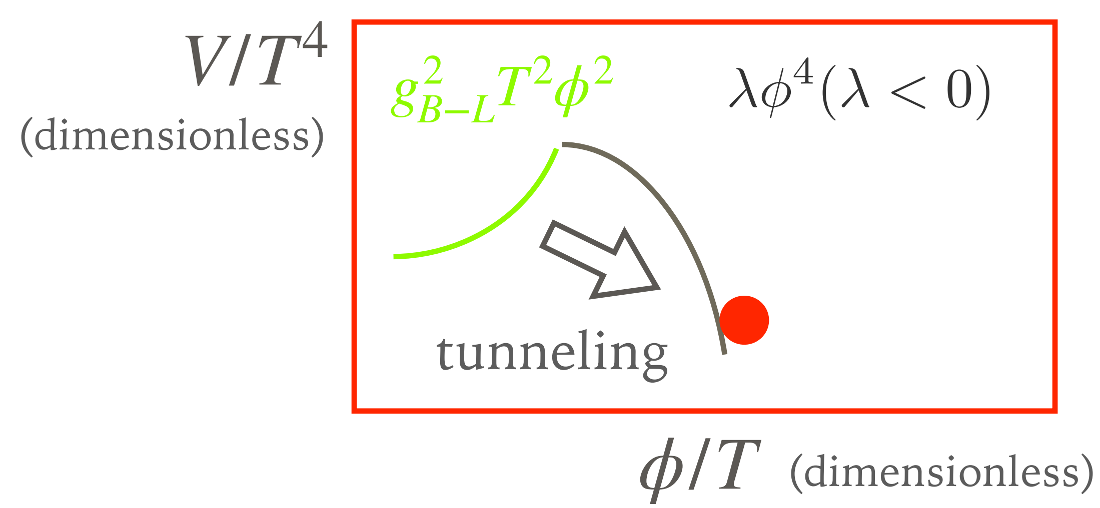
- Thermal corrections create a quadratic trap, which persists down to small T

$$V \sim g_{B-L}^2 T^2 \phi^2 + \lambda(\max(T, \phi))\phi^4$$



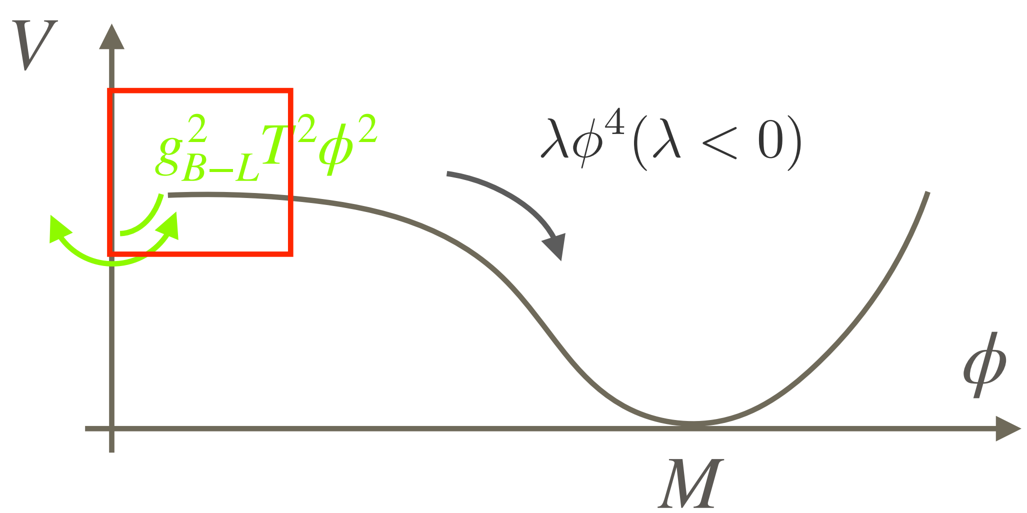
- Behavior of the potential as the temperature decreases





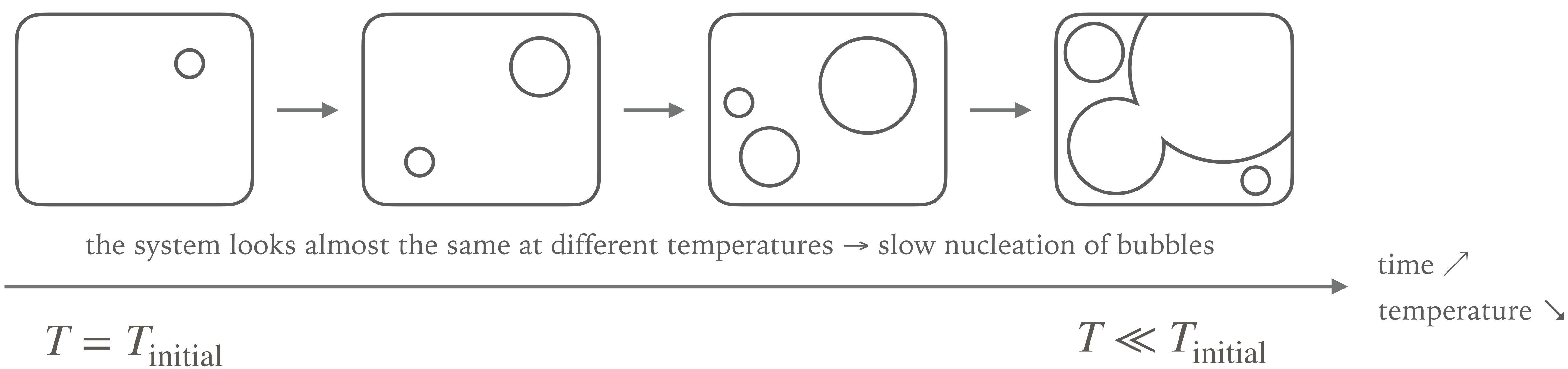
FOPT IN NEARLY CONFORMAL MODELS

➤ When the B-L field tunnels, we expect a huge amount of latent heat



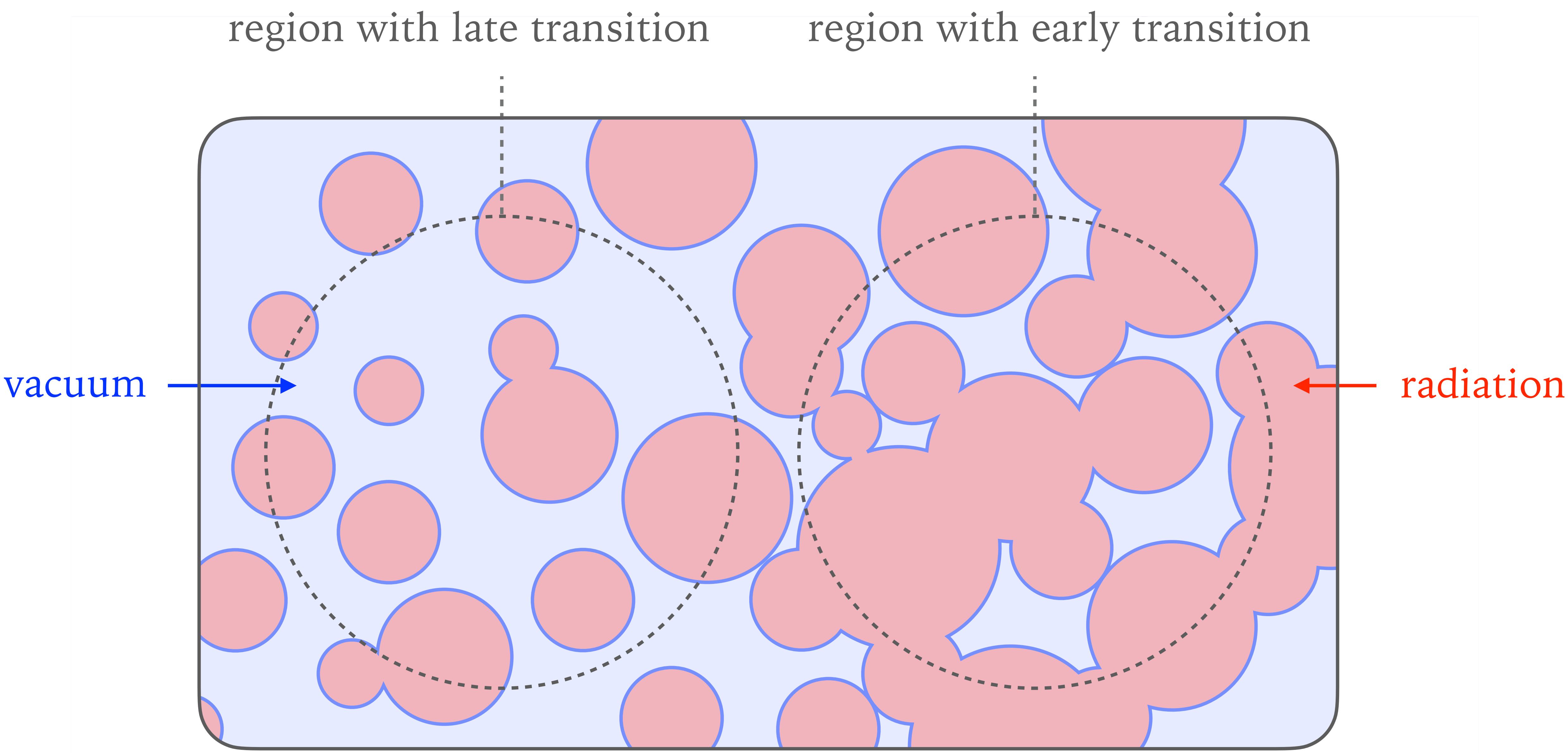
$\rightarrow$ large $\alpha \equiv \dfrac{\rho_{\mathrm{vac}}}{\rho_{\mathrm{rad}}}$

➤ The system changes only logarithmically, so bubbles grow big



PBH FORMATION FROM VERY STRONG TRANSITIONS

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

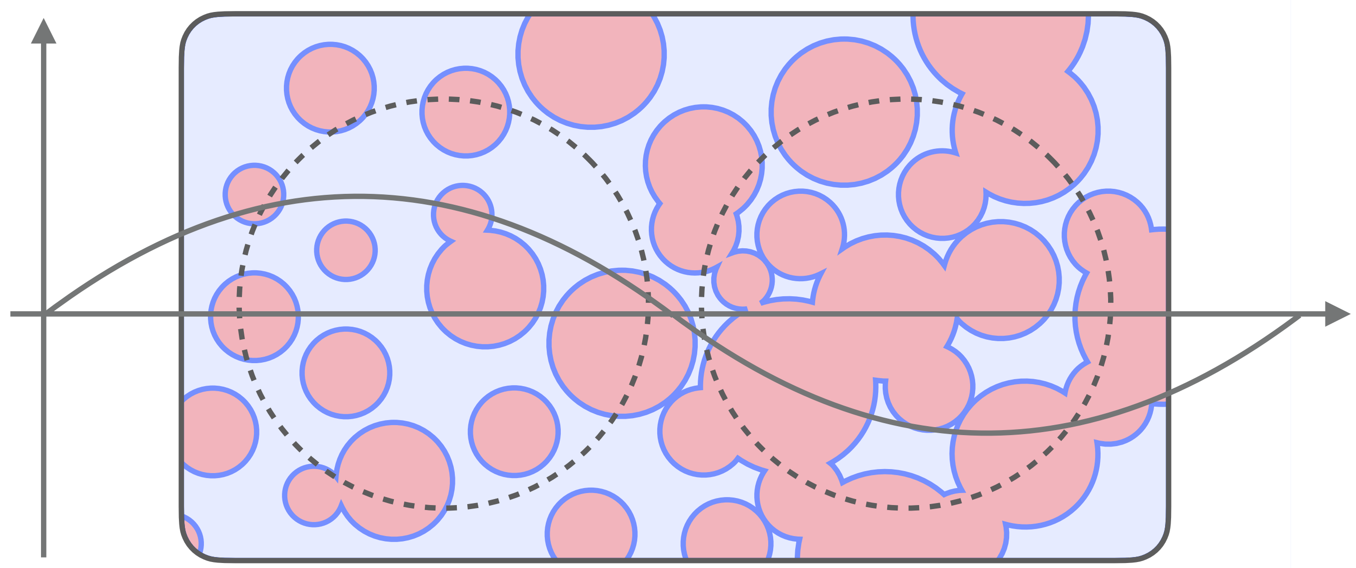


PBH FORMATION: ROUGH IDEA

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

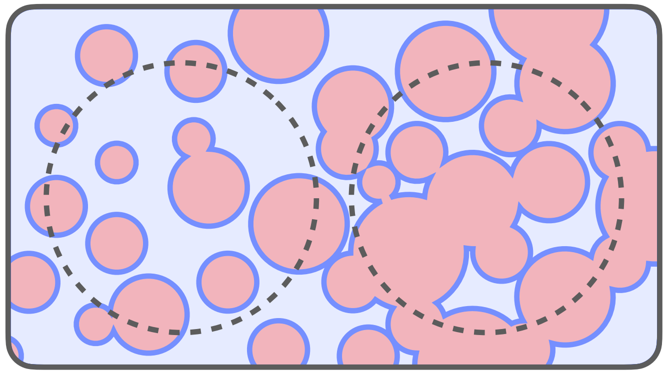
Intuitively

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



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

CLAIMS IN THE LITERATURE



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

① Background

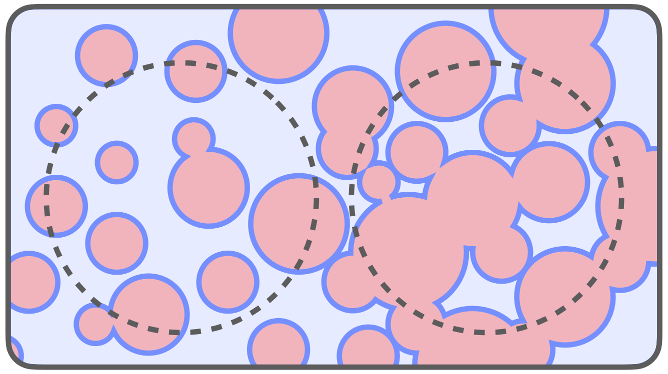
- Radiation & vacuum energy $\bar{\rho}_r' + 4\mathcal{H}\bar{\rho}_r = -\bar{\rho}_V'$
- Initially the universe is vacuum energy dominated $\bar{\rho}_V(t=-\infty) = \Delta V$, and then radiation takes over
- Vacuum energy decays with the exponential nucleation of bubbles

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

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

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

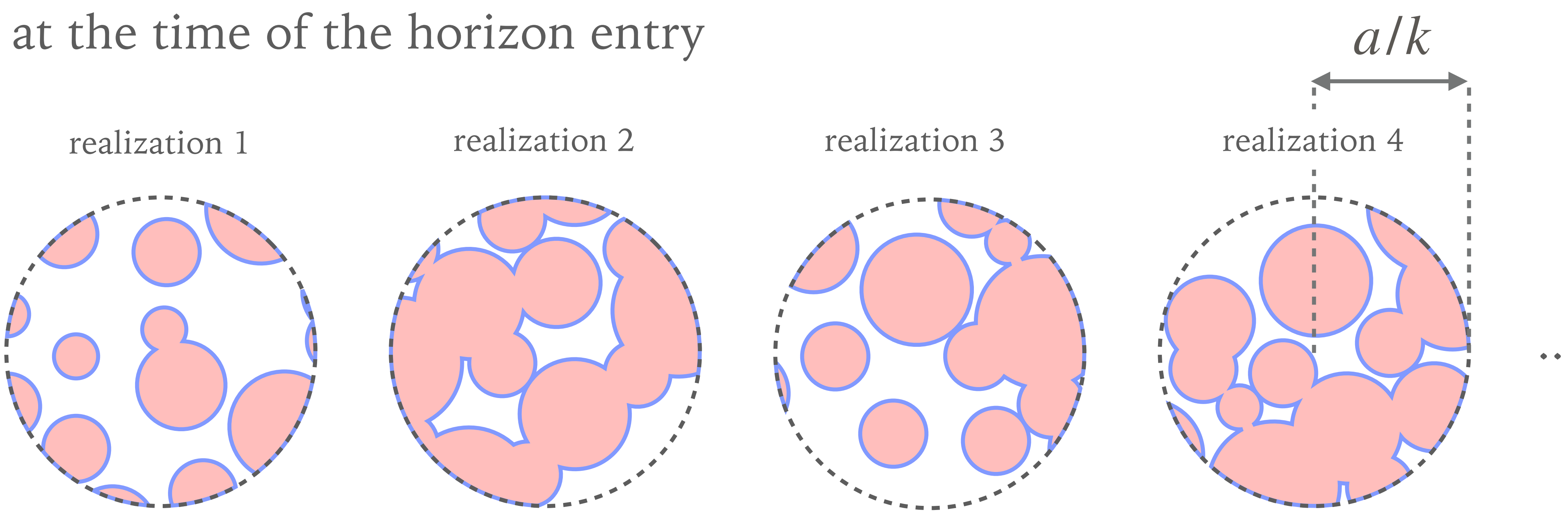
CLAIMS IN THE LITERATURE



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

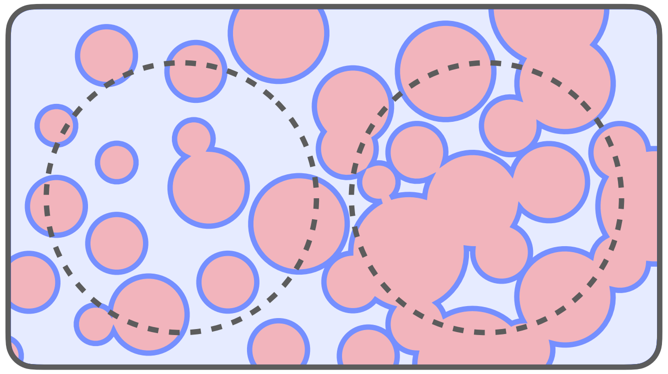
② Perturbation

- 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

CLAIMS IN THE LITERATURE



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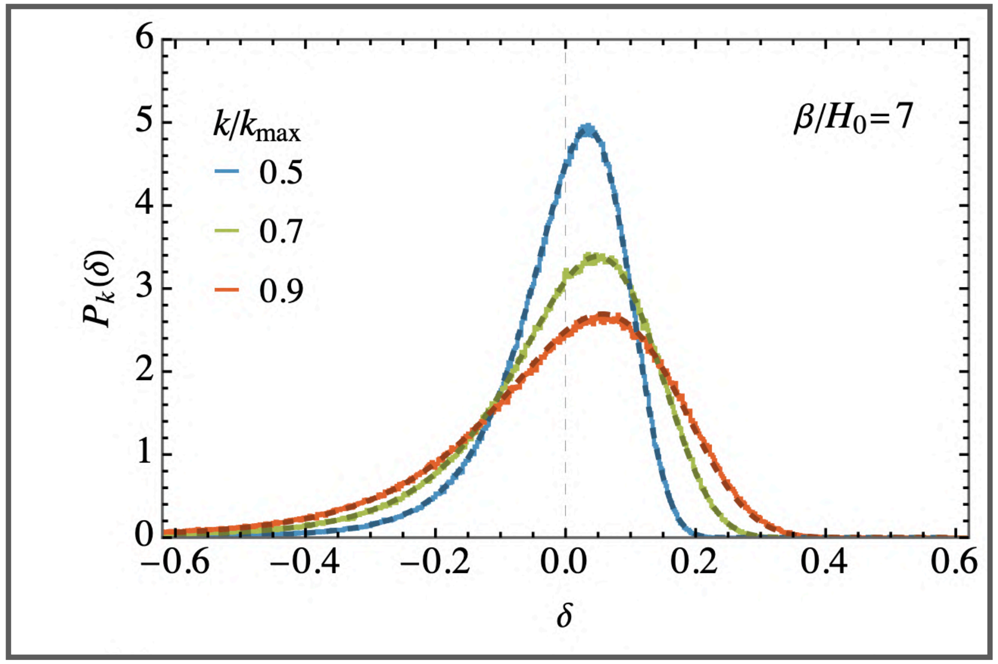

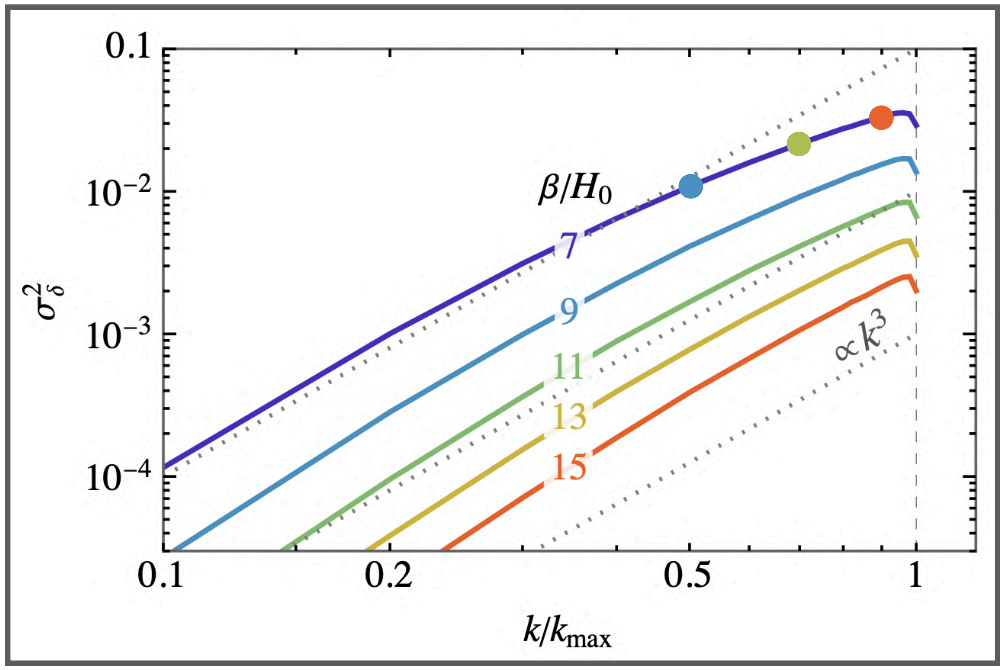

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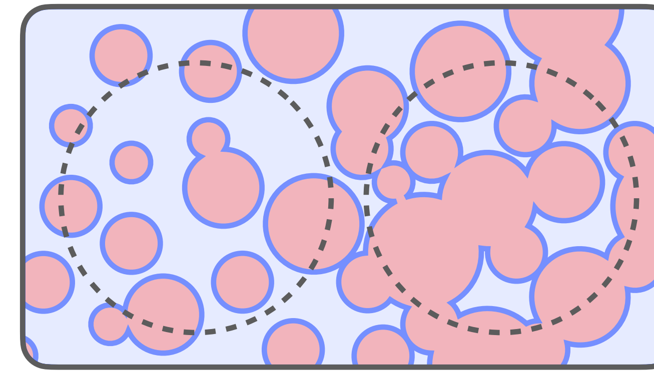

➤ Setu

② Pe

- …duces density fluctuations
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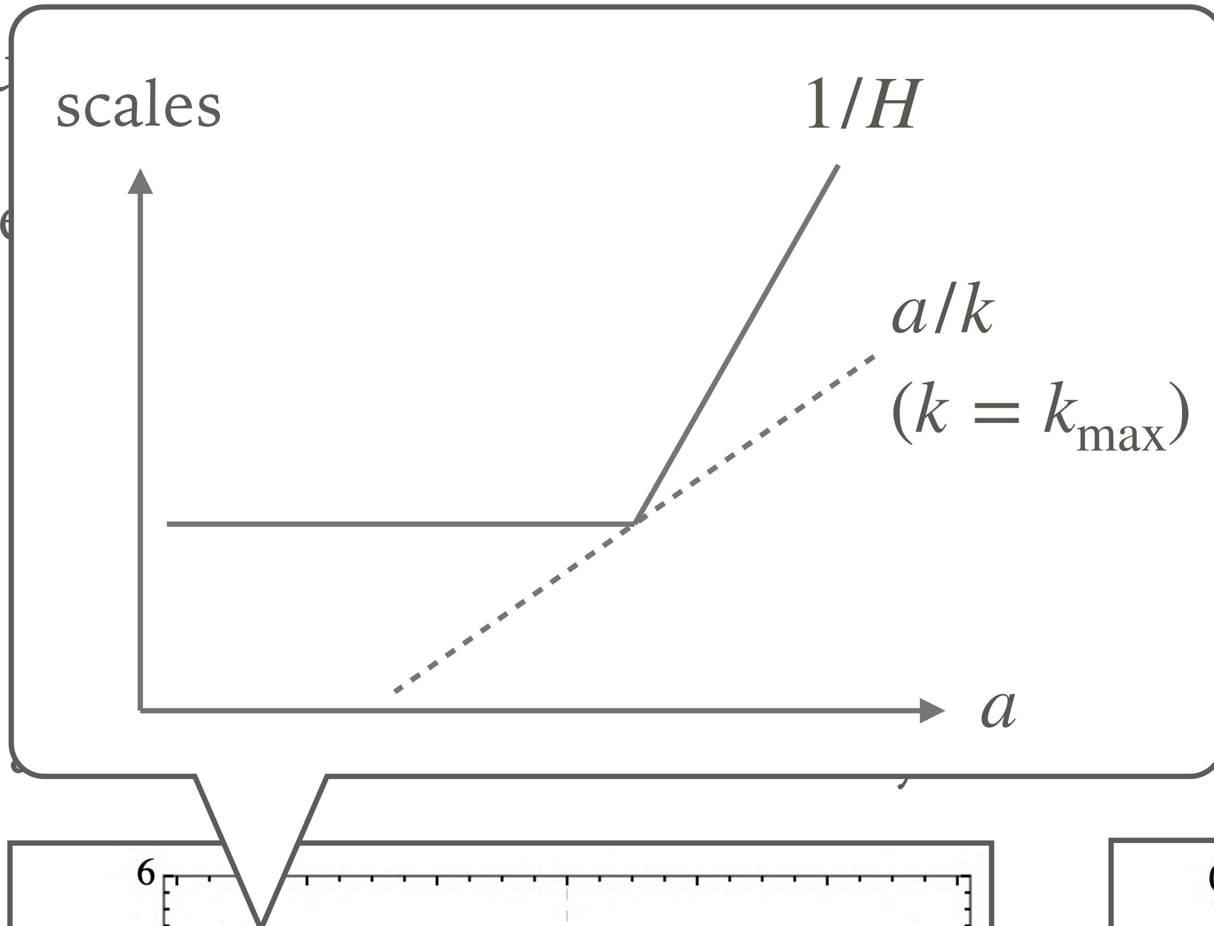

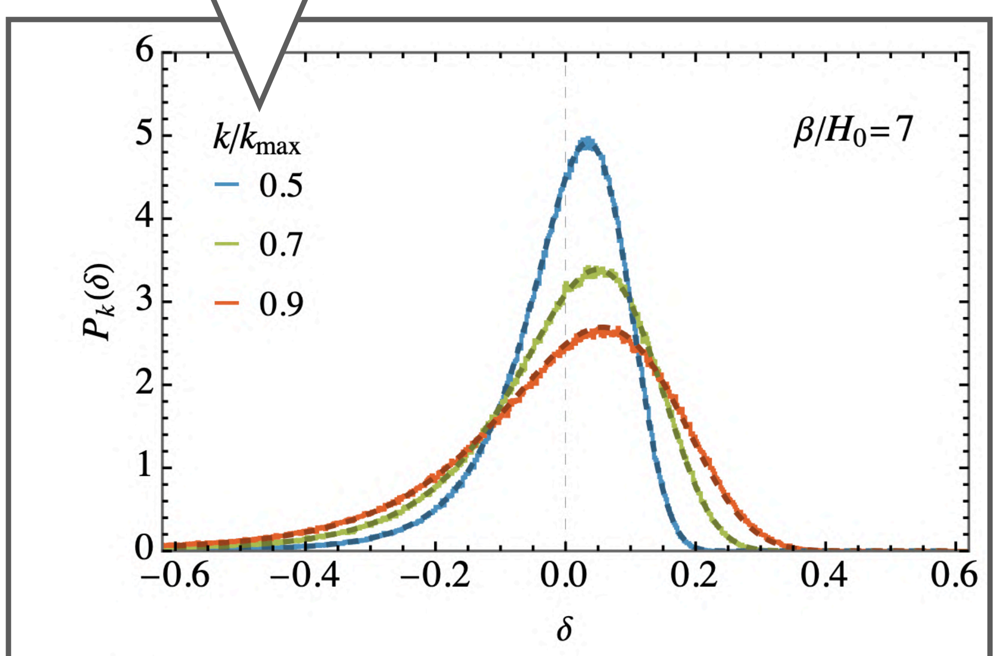

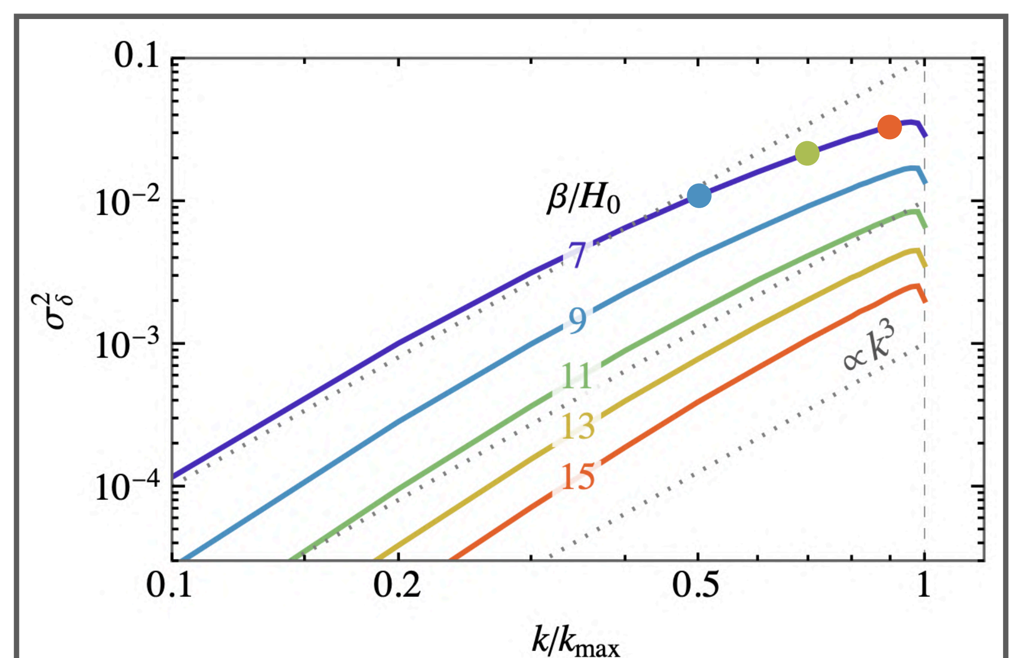

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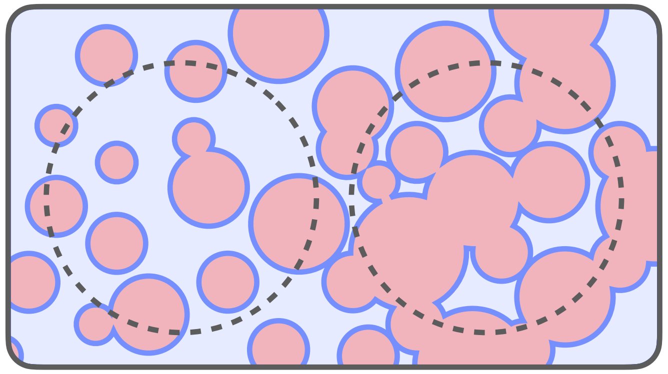
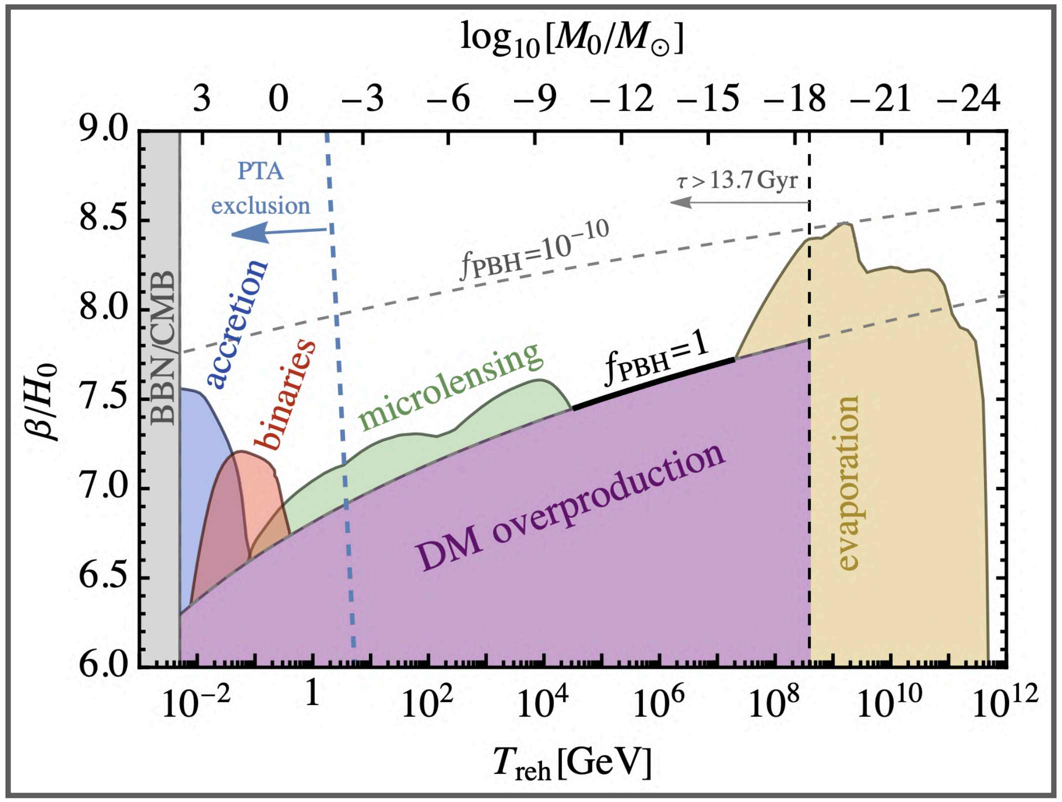


➤ Setup & findings of [Lewicki, Troczek, Vaskonen '24]

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 2503.01962]

- 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 2503.01962]

- Perturbation equations we solve

encodes the false-vacuum fraction

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

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

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

- 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 2503.01962]

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

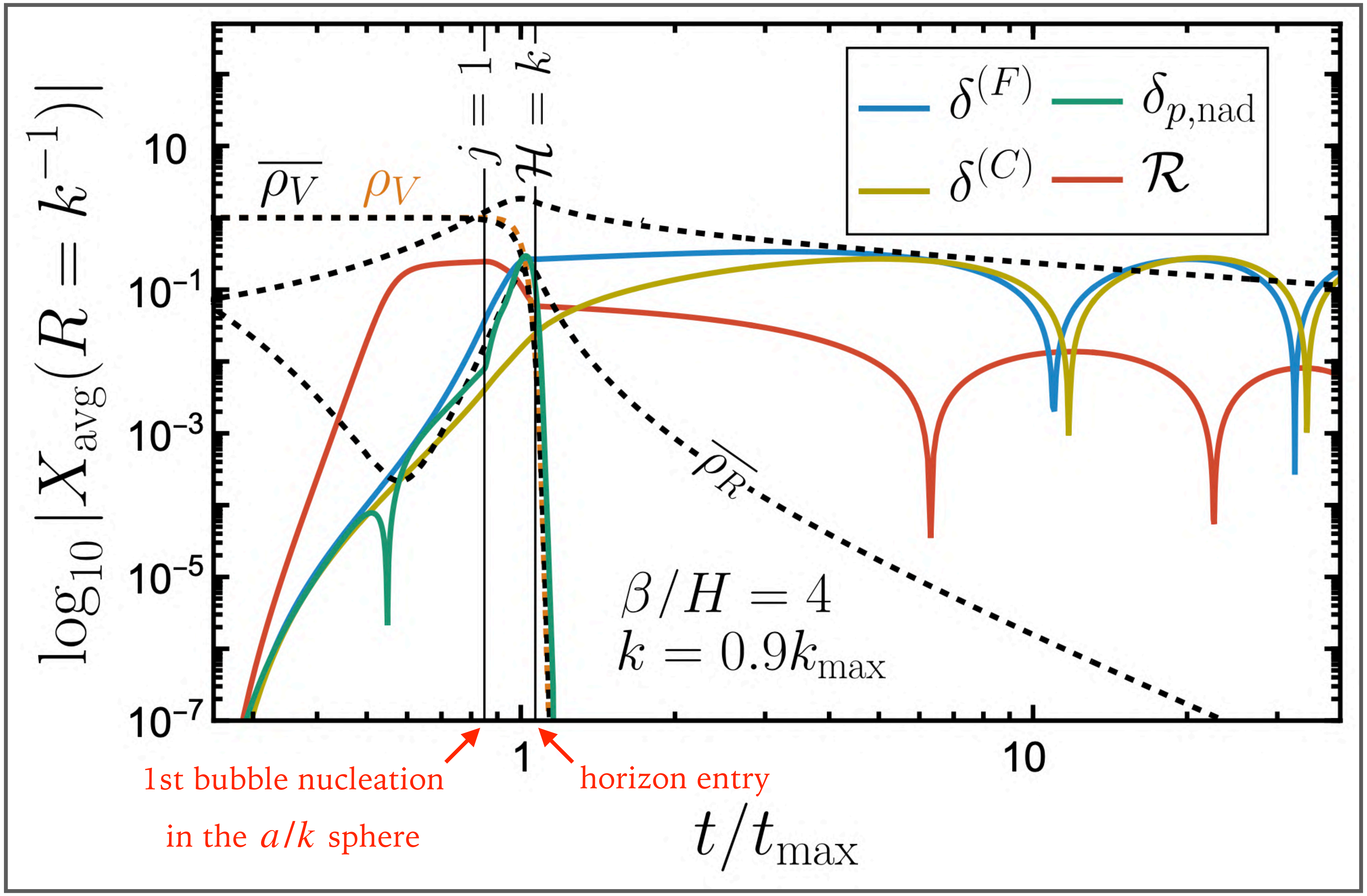
- The only difference is we identify it as the quantity in the flat gauge

- 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

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



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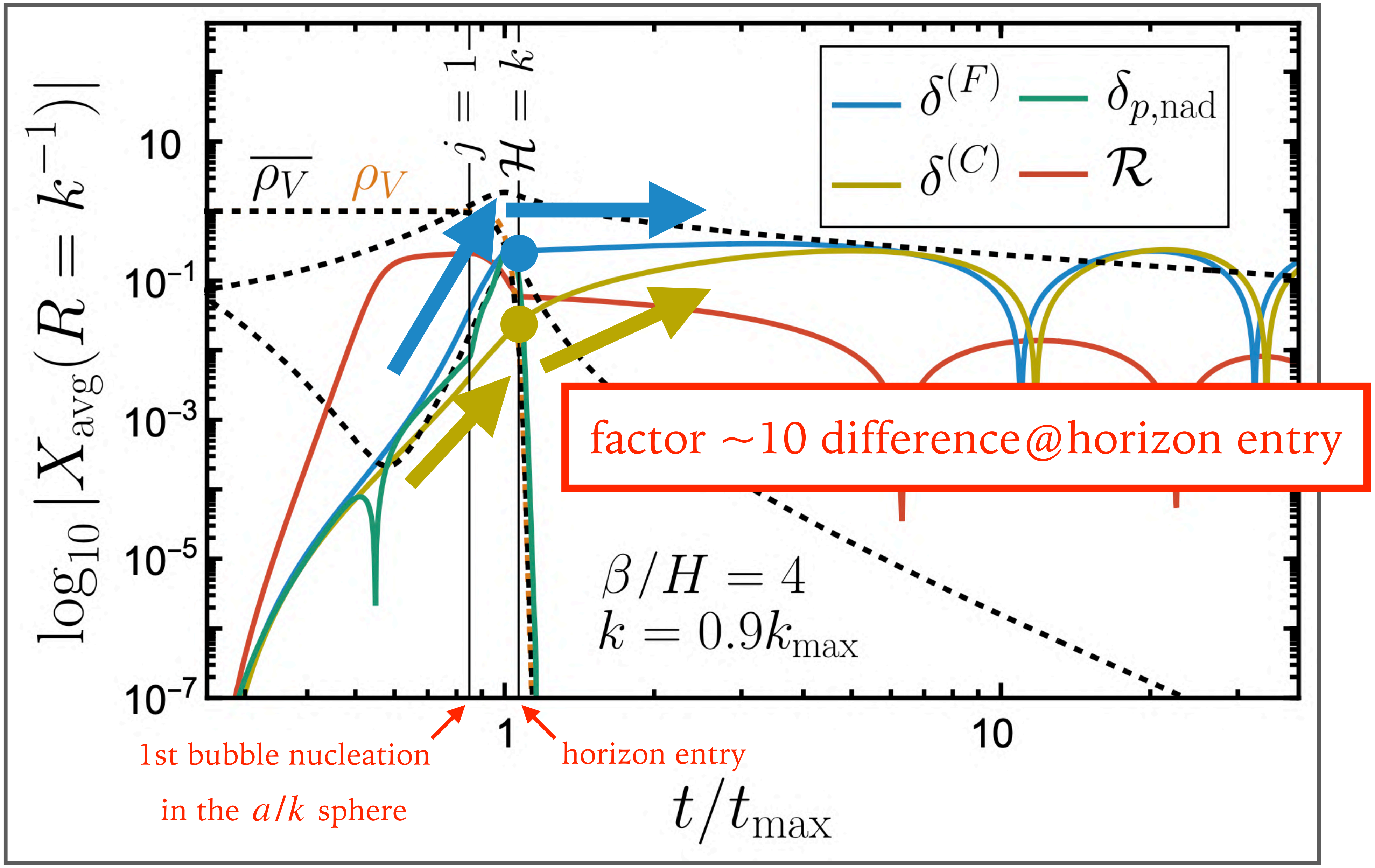
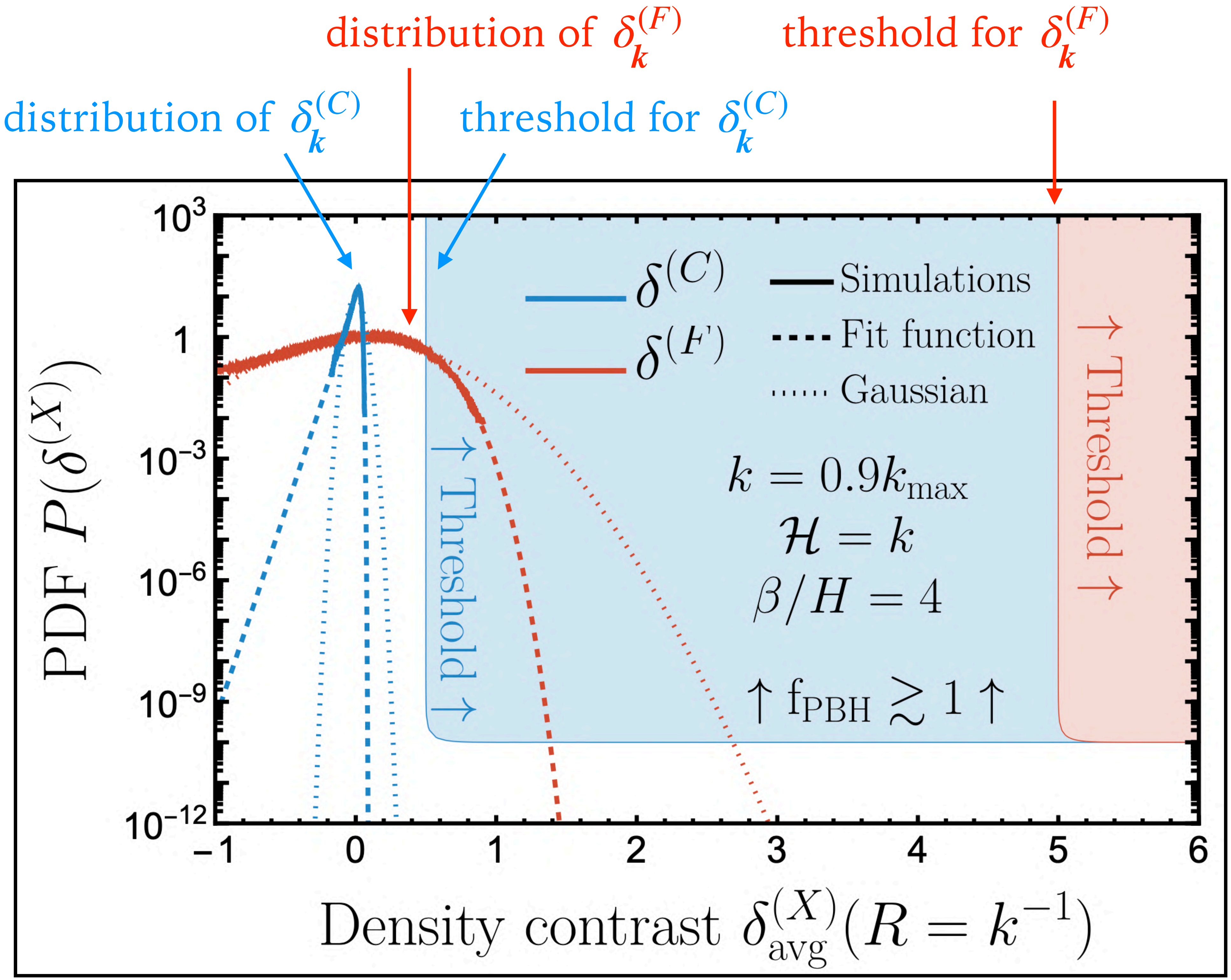


PBH FORMATION IS UNLIKELY

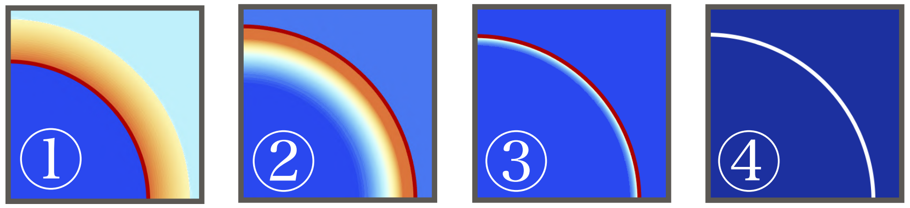


First-order phase transitions in the early Universe:

*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).

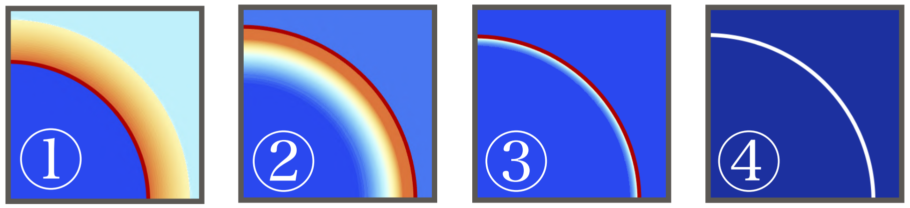
<u>Fluid</u> (dominant in case ①②③) = Sound waves & Turbulence

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



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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

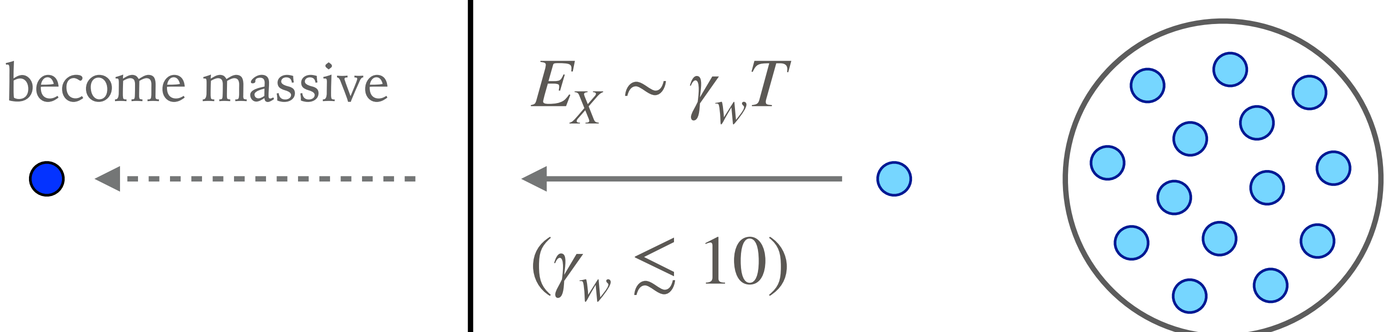
Particles in the broken phase are only feebly interacting and free-stream.

GW PRODUCTION: THE STANDARD LORE & BEYOND

- Particle dynamics seen in the wall rest frame

Bubble wall

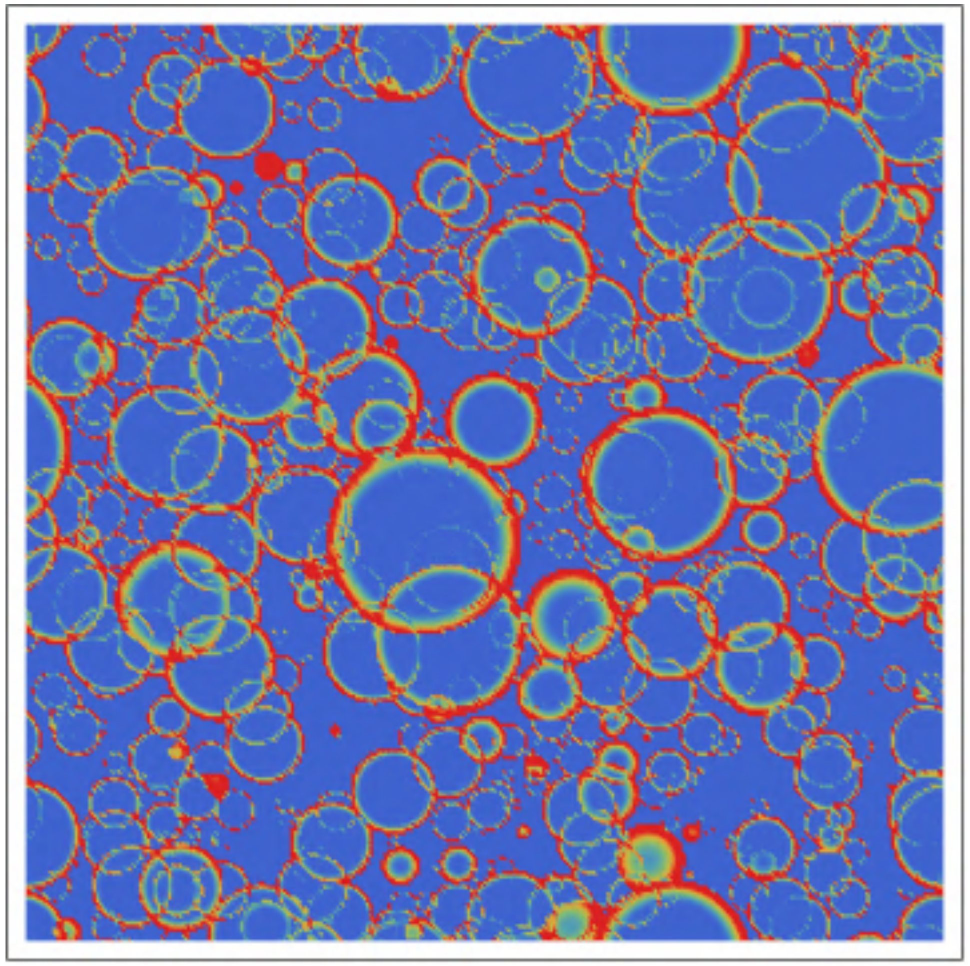
Broken phase	Symmetric phase
$m_X \neq 0$	$m_X = 0$
Enters the bubble and become massive if $E_X > m_X$	$E_X \sim \gamma_w T$ ($\gamma_w \lesssim 10$)
X, or its decay product Y, behaves as feebly-interacting particles	Temperature T Moving with bulk velocity v_w



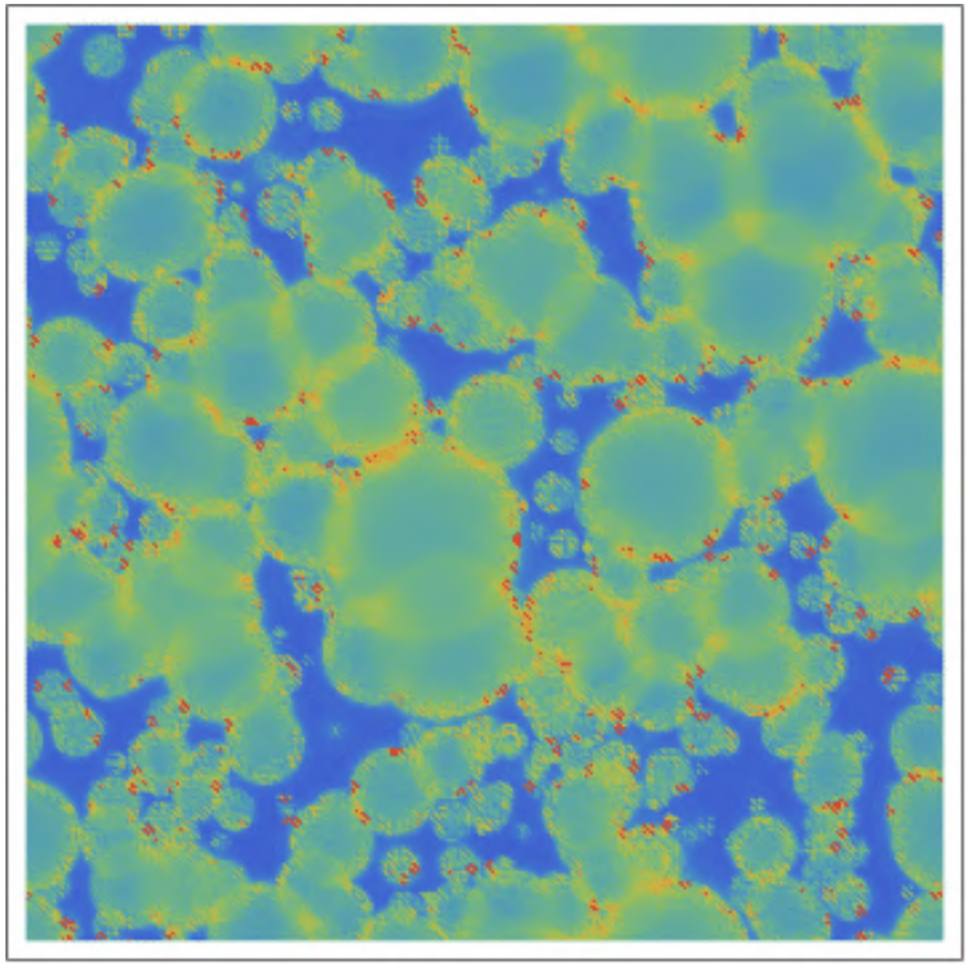
FLUID VS. FREE-STREAMING PARTICLES

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

<u>Fluid</u>



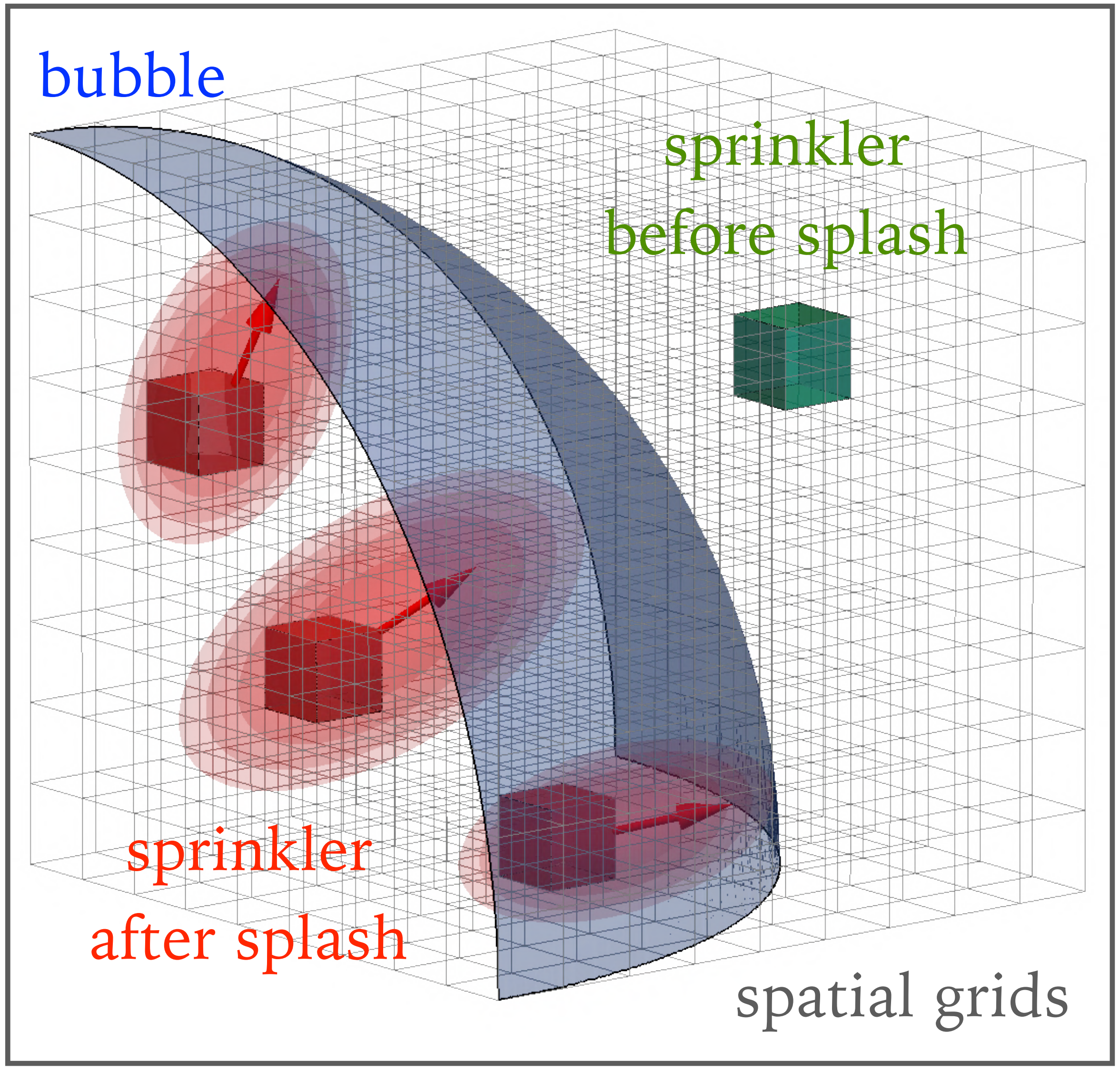
<u>Free-streaming</u>



HOW TO CALCULATE GW PRODUCTION

- To calculate the GW spectrum,

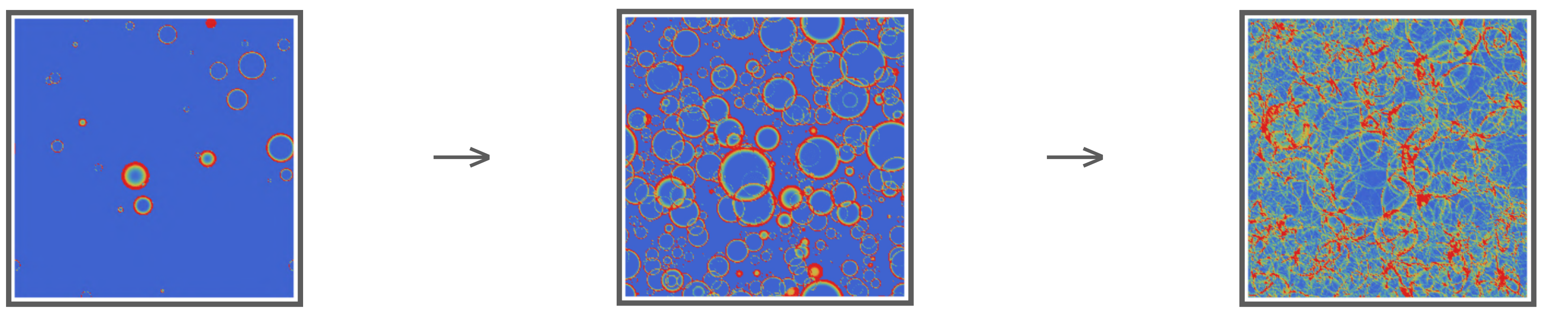
  we propose a new calculation scheme – "sprinkler picture"



GW SPECTRUM FOR SOUND-WAVE SOURCE

➤ 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 $(\partial_t^2 - c_s^2\nabla^2)\vec{v}_{\rm fluid} \simeq 0$,

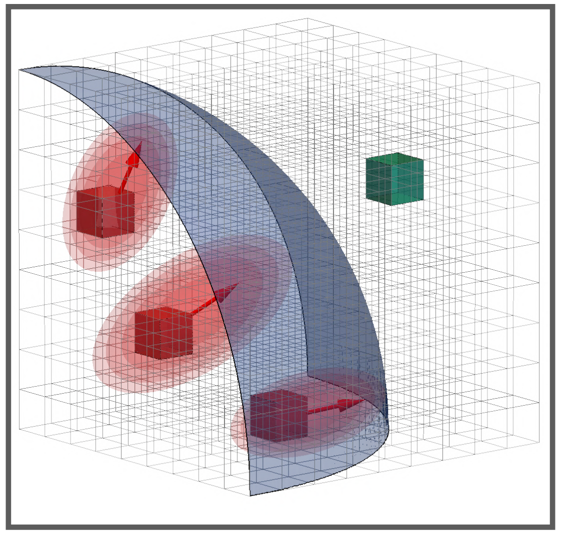
but GW production is nonlinear in $\vec{v}_{\rm fluid}$ because $\Box h_{ij} \sim T_{ij} \sim (v_{\rm fluid})_i (v_{\rm fluid})_j$

GW SPECTRUM FOR FREE-STREAMING SOURCE

- 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"



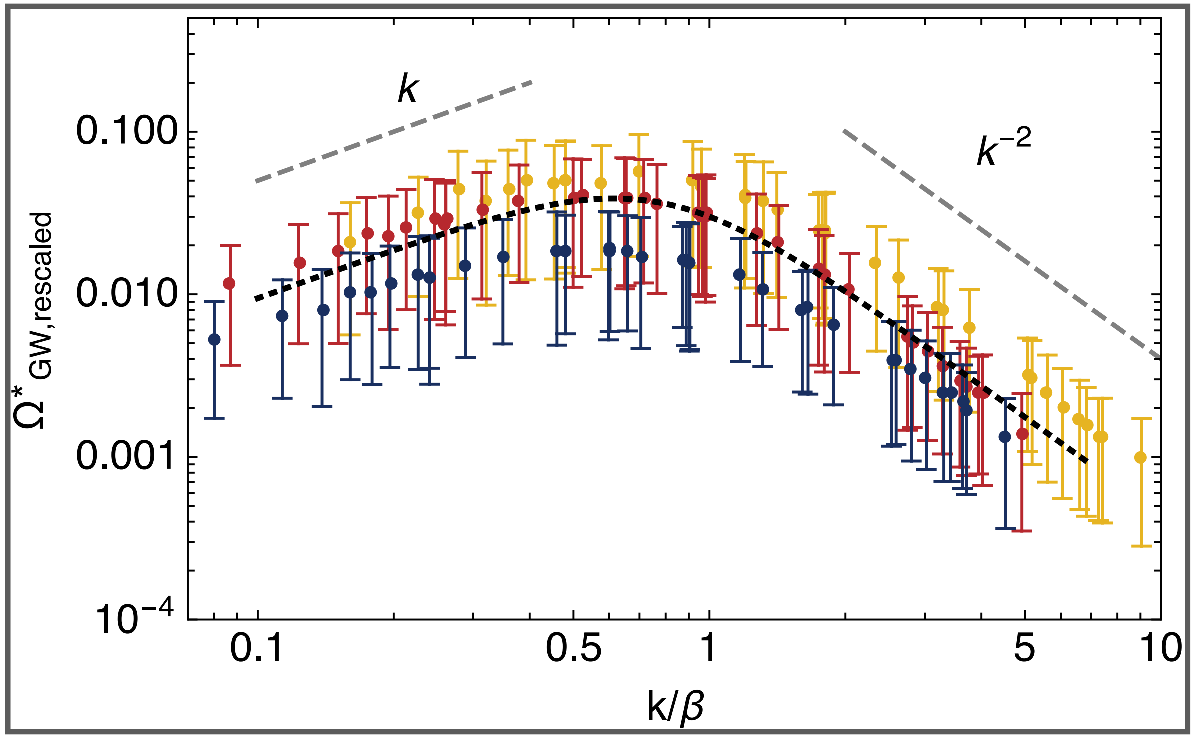
① Imagine each grid point has a sprinkler that splashes free-streaming particles when hit by the wall

② Sprinklers are universal: their only difference is when and in which direction they are hit

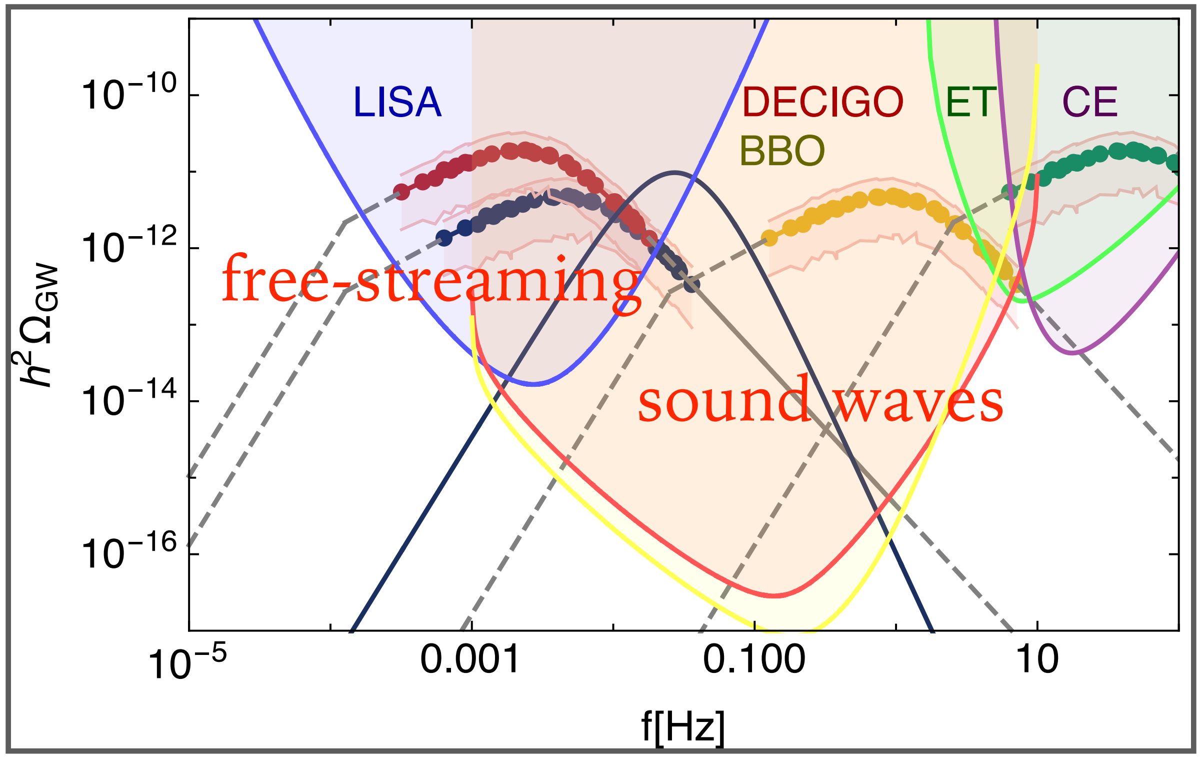
③ GW production from one sprinkler is easily calculable, and the contributions from different sprinklers (= grids) are linearly superposed

NUMERICAL RESULTS

- GW spectral shape is universal (after normalizing by some factor)



- GW spectrum is clearly different from sound-wave sources: it stretches over wider frequencies



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 $\gamma_w = 1\Big/\sqrt{1 - v_w^2}$)

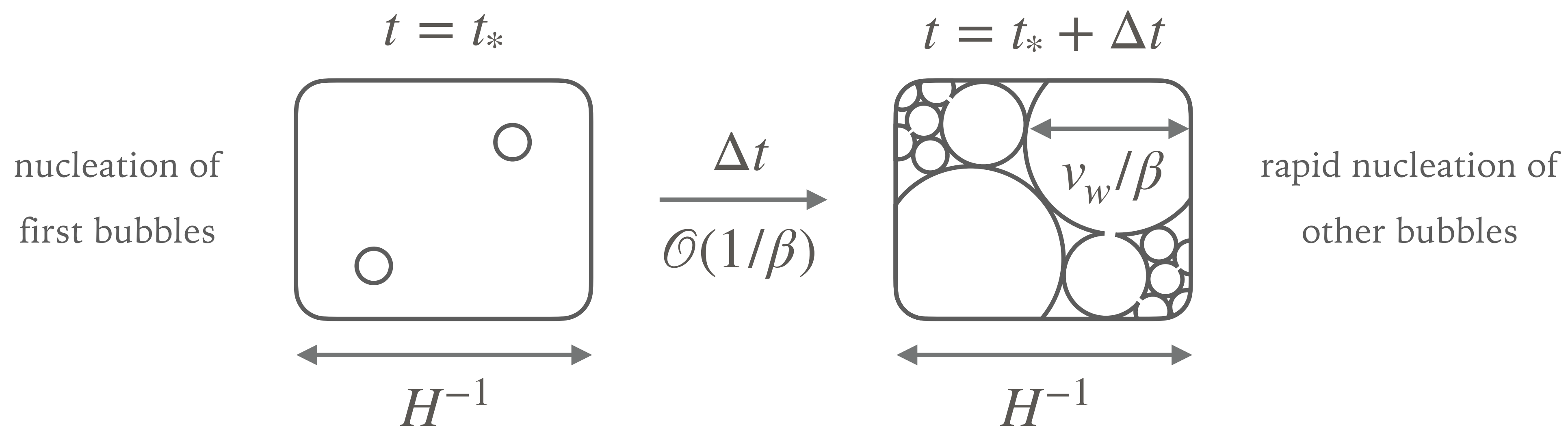
- Feebly-interacting particles can be generated during this transition

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

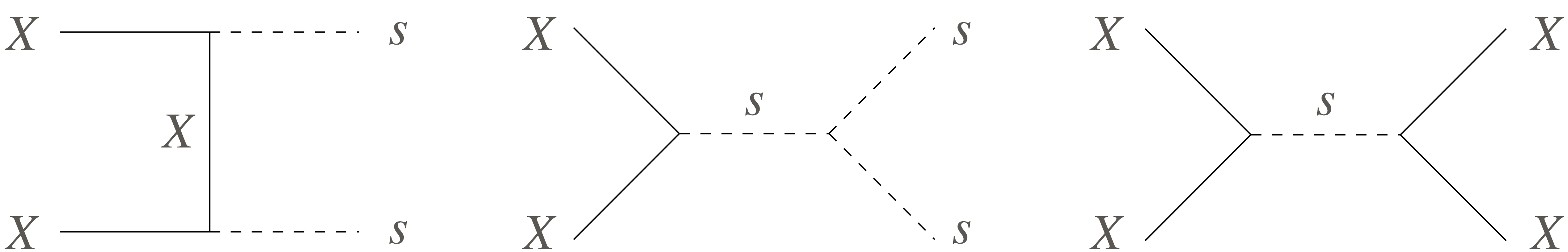


- So, we need the condition $n\sigma\Delta t \sim \dfrac{T^3\sigma}{\beta} \lesssim 1$

CONDITIONS ON FEEBLE INTERACTION

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

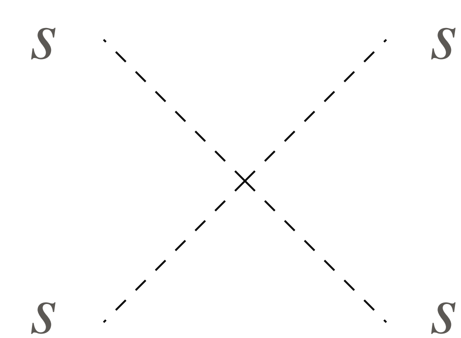
  The couplings that gives rise to mass also give rise to interactions



- 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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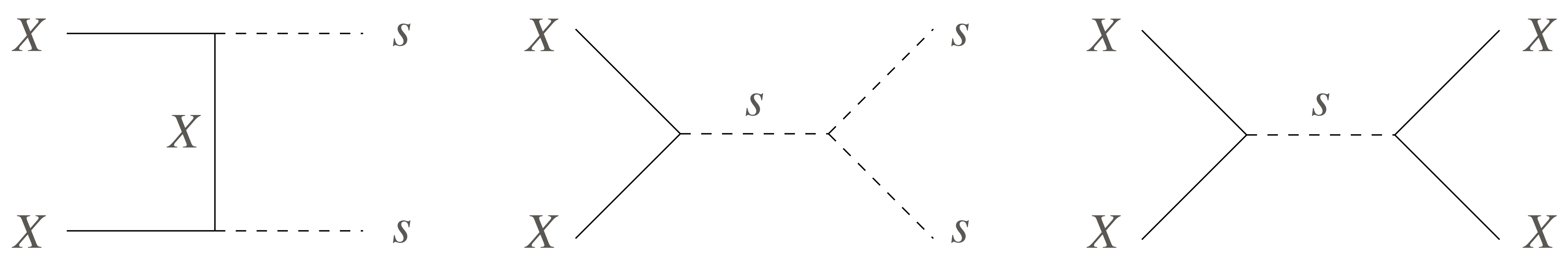

➤ Can X be a gauge boson $X = Z'$?

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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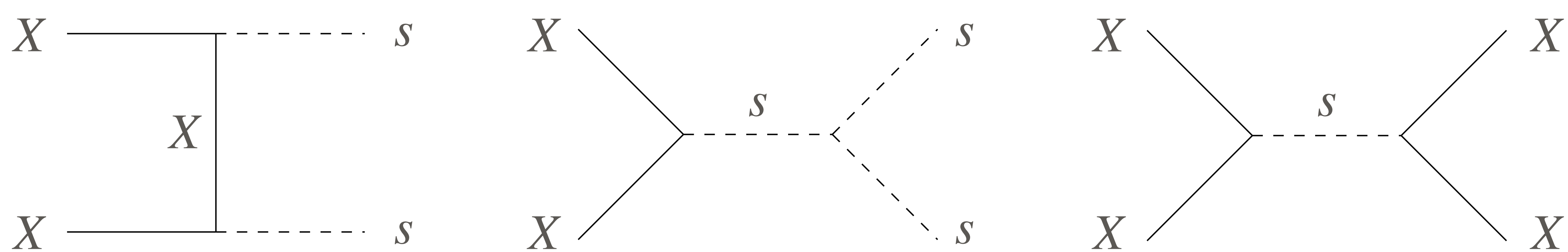

- Can X be a gauge boson $X = Z'$?

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Doable, but not generic

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

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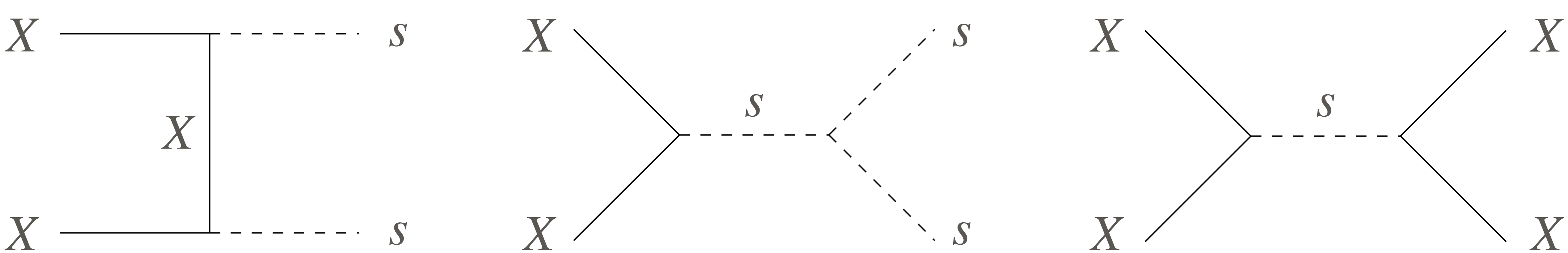
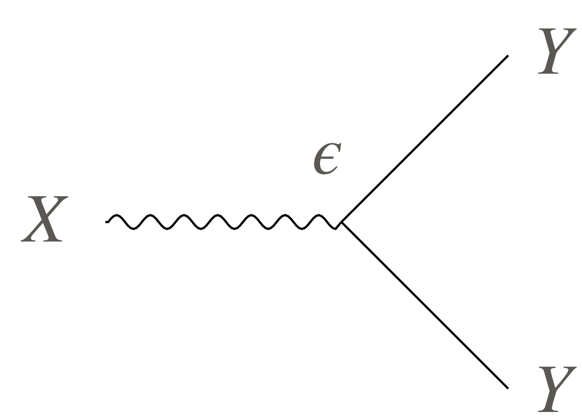


➤ More viable possibility: particle decay $X = Z' \to YY$ with $\epsilon \ll 1$



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