Keemilise ja
Bioloogilise Füüsika Instituut

National Institute of Chemical Physics and Biophysics

UNIVERSITÀ
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Istituto Nazionale di Fisica Nucleare

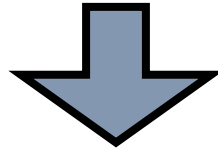# Slow and strongly supercooled first-order phase transitions

Ville Vaskonen

Porto, June 20, 2024.

Slow and supercooled transition
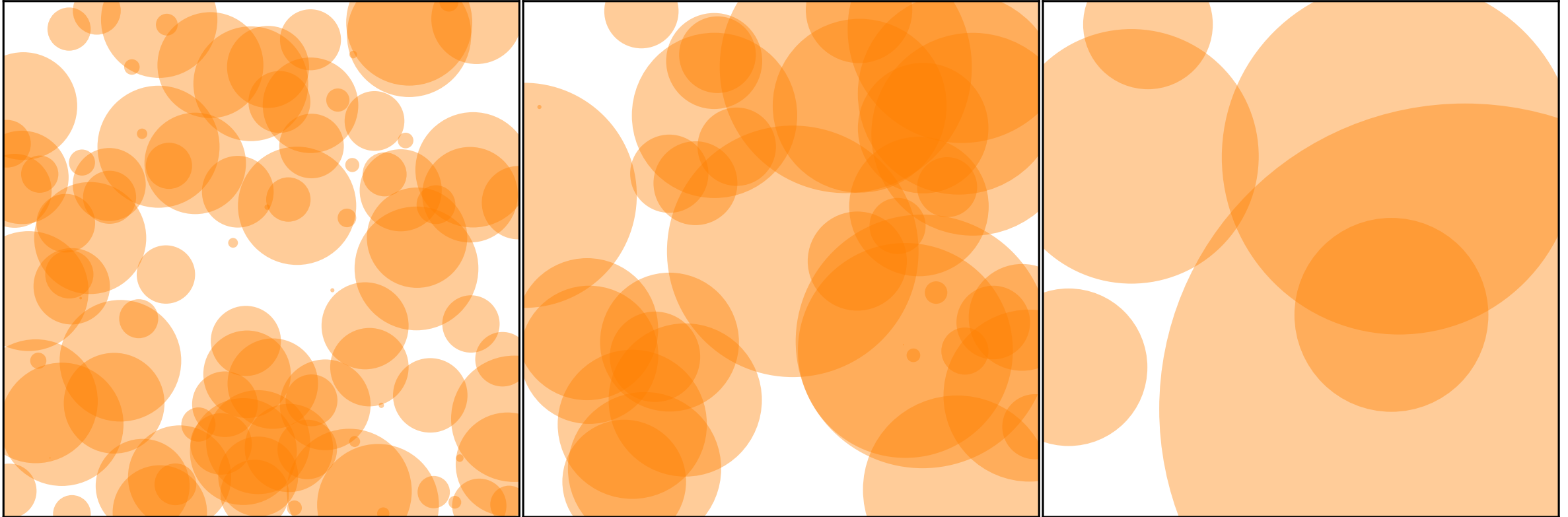
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Large density fluctuations

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PBHs and secondary GWs

Liu et al. PRD 105 (2022) 2, L021303,
Kawana, Kim, Lu, PRD 108 (2023) 10, 103531 } **PBHs**
Gouttenoire, Volansky, arXiv:2305.04942
Lewicki, Toczek, Vaskonen, arXiv:2402.04158
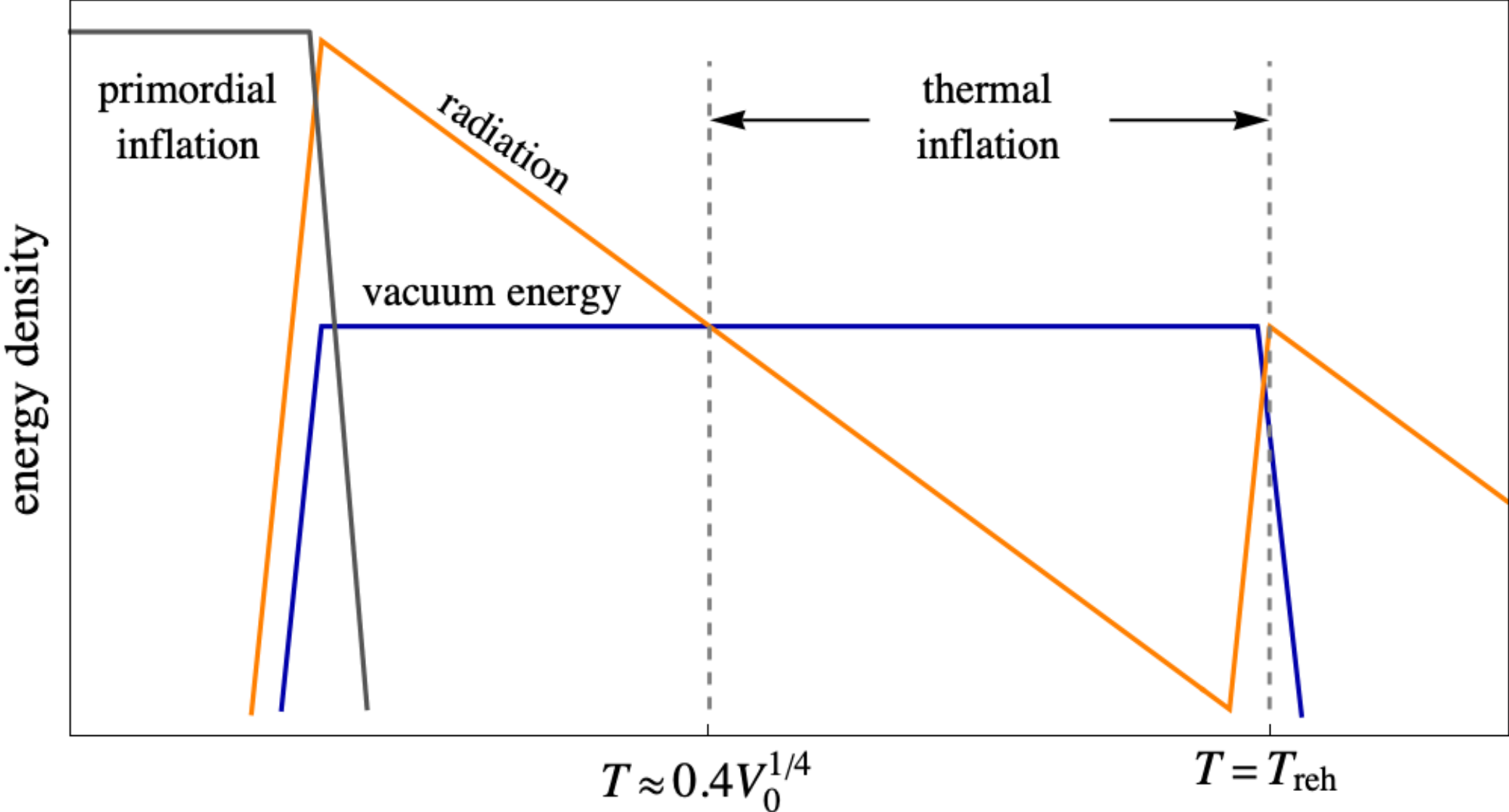
Slow

Nucleation rate: $\Gamma(t) \propto e^{\beta t}$
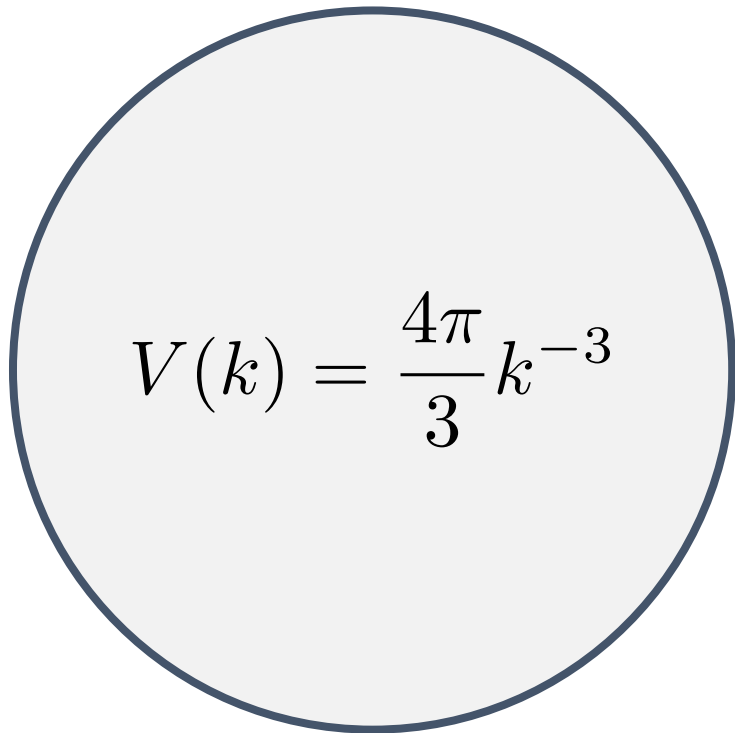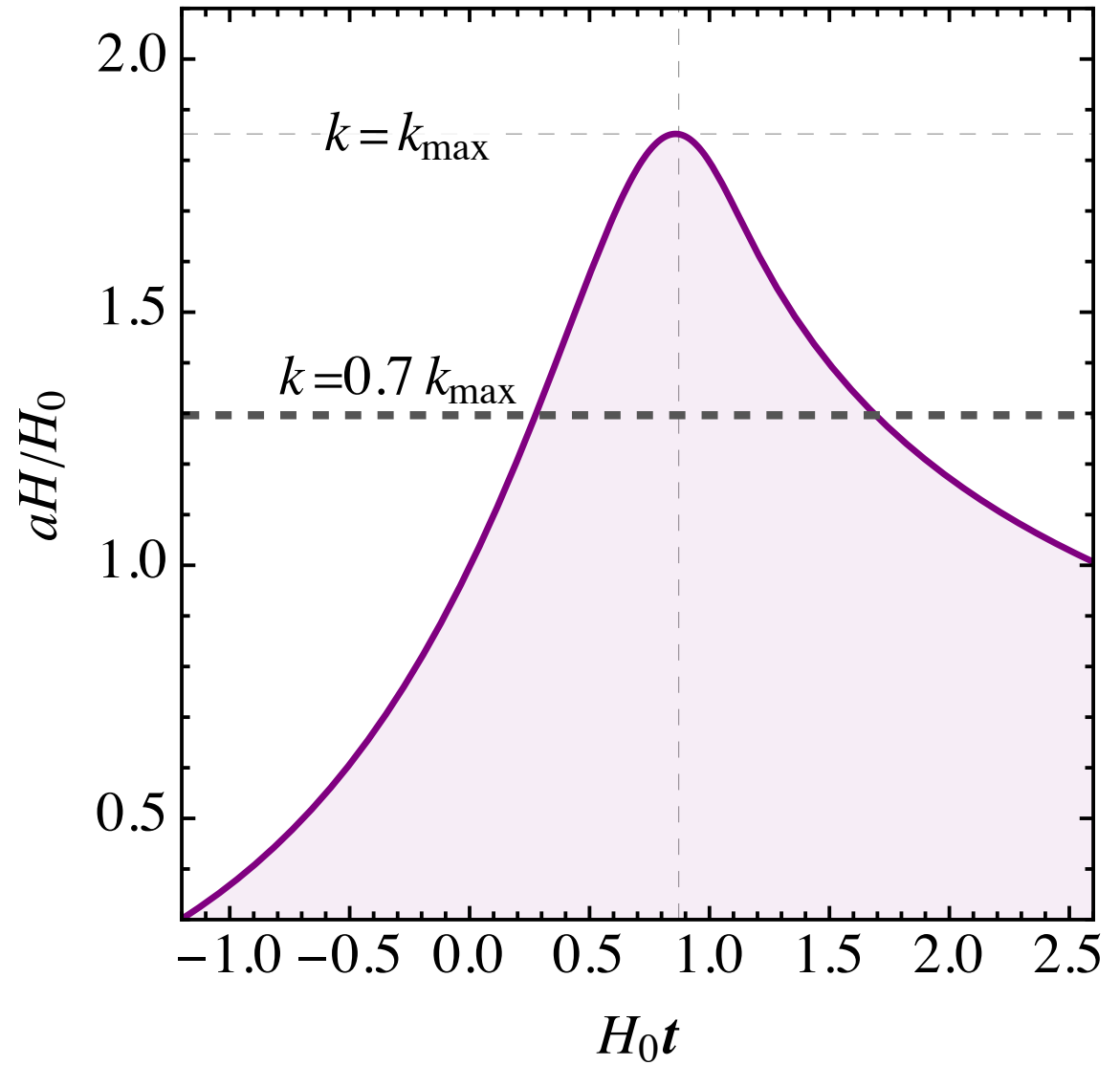

fast:
many small bubbles,
large β/H

slow:
a few large bubbles,
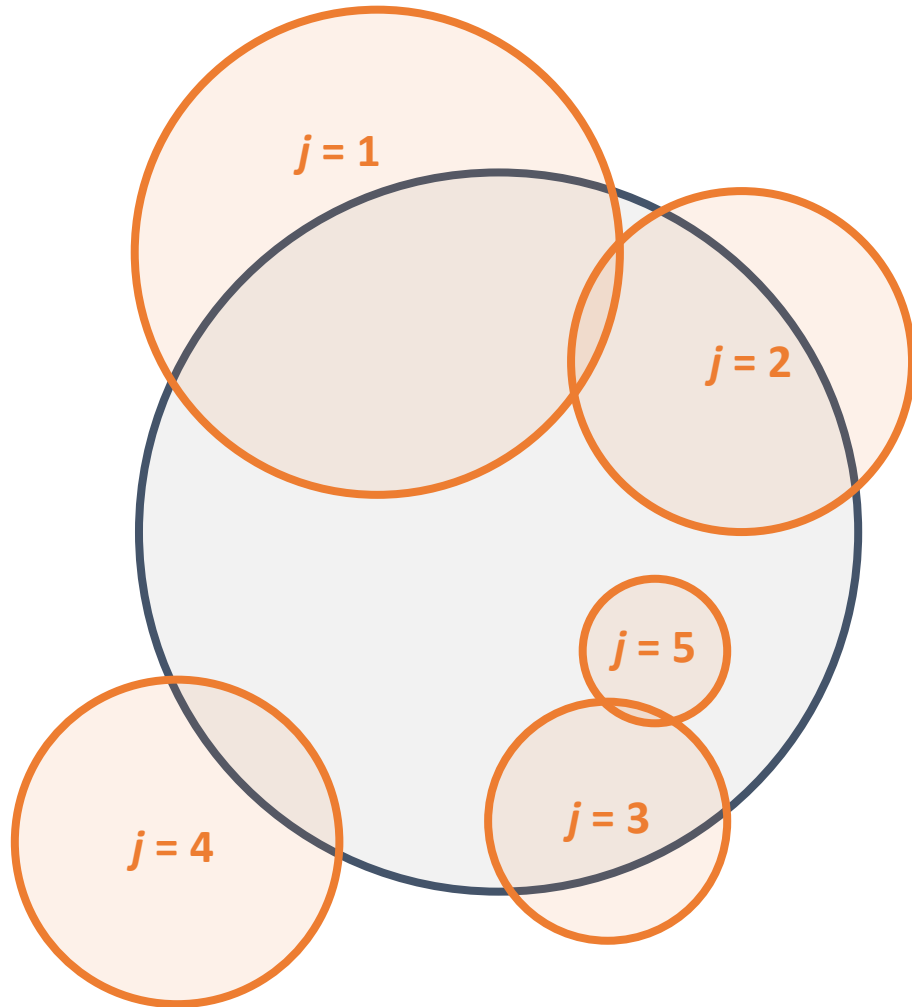small β/H

Strongly supercooled

Evolution of finite patches
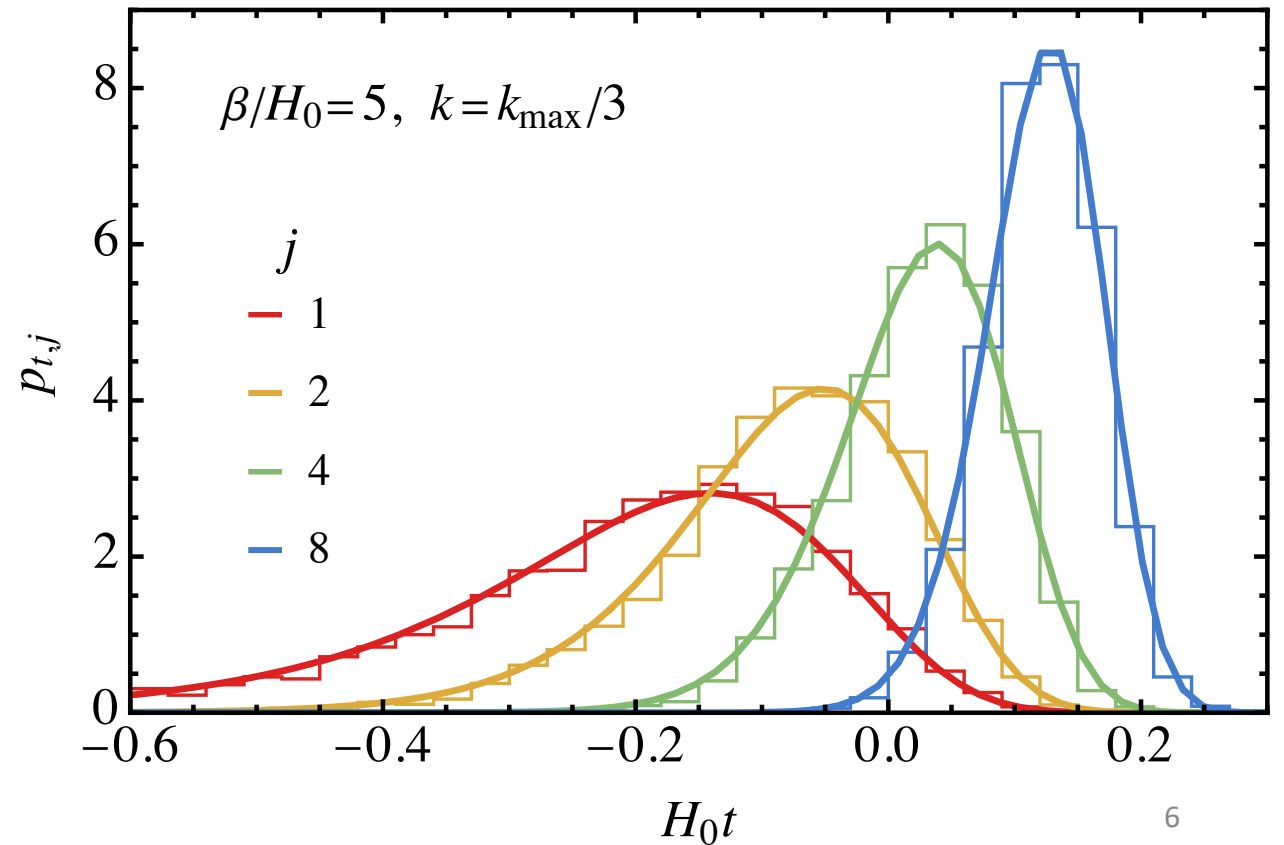
$$V(k) = \frac{4\pi}{3}k^{-3}$$

Evolution of finite patches

Large fluctuations in the times when jth bubble nucleates/reaches volume $V(k)$:

$$p_t \propto \bar{N}_k(t)^{j-1} e^{-\bar{N}_k(t)}$$

Evolution of finite patches
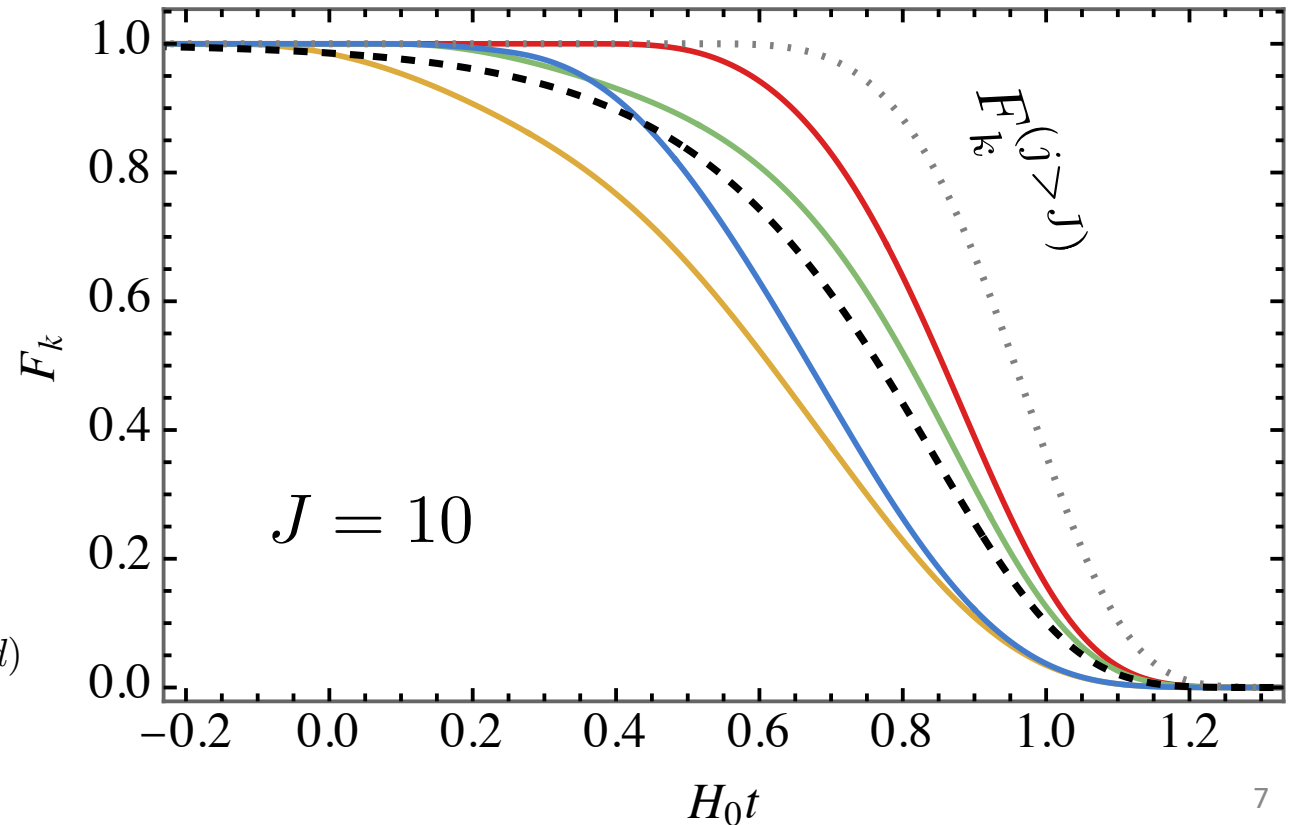
average evolution of the late bubbles:

$$F_k^{(j>J)}(t) \approx \exp\left[-\frac{4\pi}{3}\int \mathrm{d}t'\theta\left(\bar{N}_k(t') - J\right)\Gamma(t')a(t')^3 R(t;t')^3\right]$$

$$F_k(t) = F_k^{(j\leq J)}(t)F_k^{(j>J)}(t)$$

fluctuations from the first *J* bubbles:

$$F_k^{(j\leq J)}(t) \approx \prod_{j=1}^{J}\left[1 - \frac{V_{\mathrm{int}}(t;t_j,d_j)}{V(k)}\right]$$

$$p_d(d;t,k) = \frac{4\pi d^2}{\bar{N}_k(t)}\int_{-\infty}^{t}\mathrm{d}t_n\Gamma(t_n)a(t_n)^3\theta(k^{-1} + R(t;t_n) - d)$$
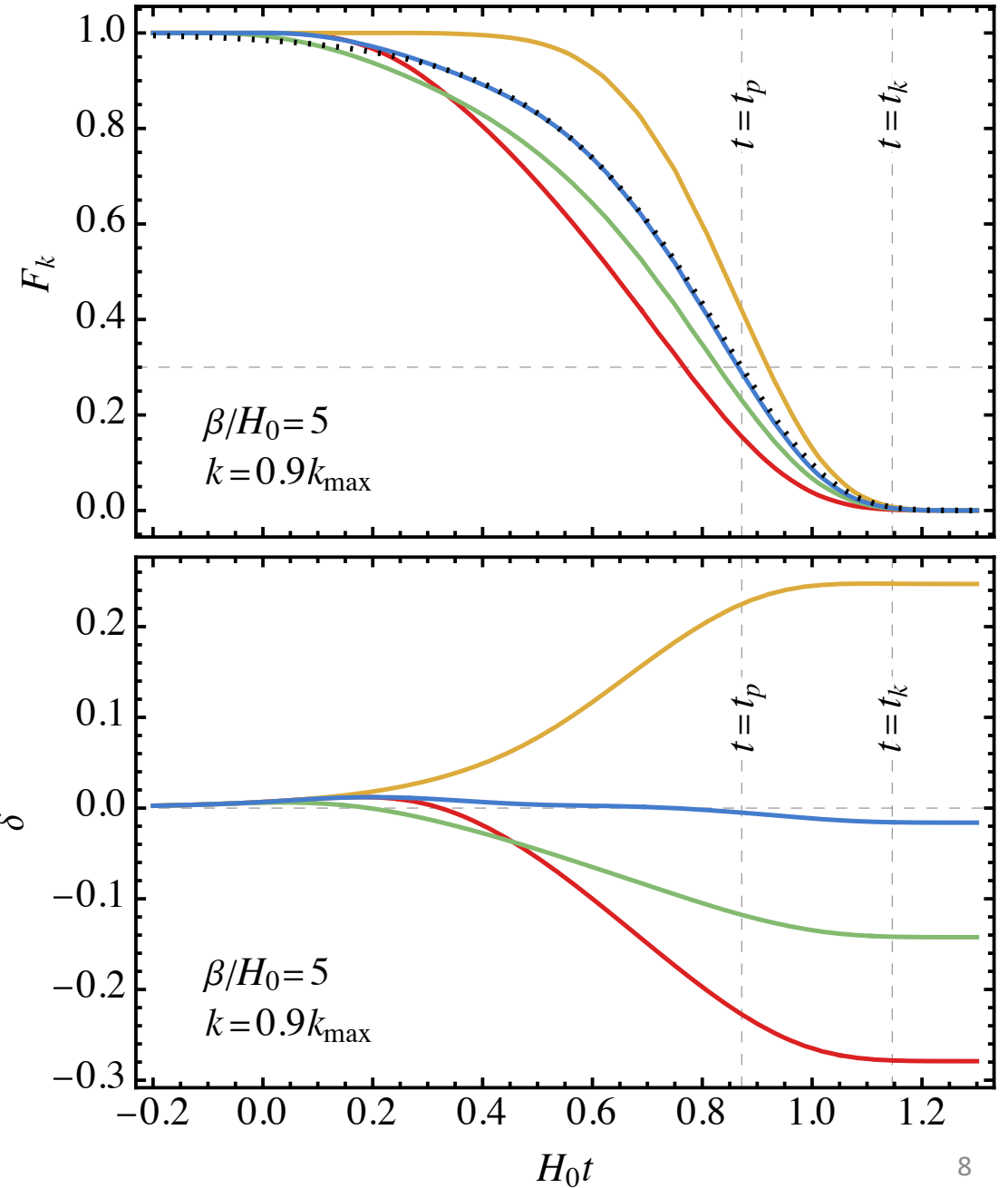

$J = 10$

$F_k^{(j>J)}$

Evolution of finite patches

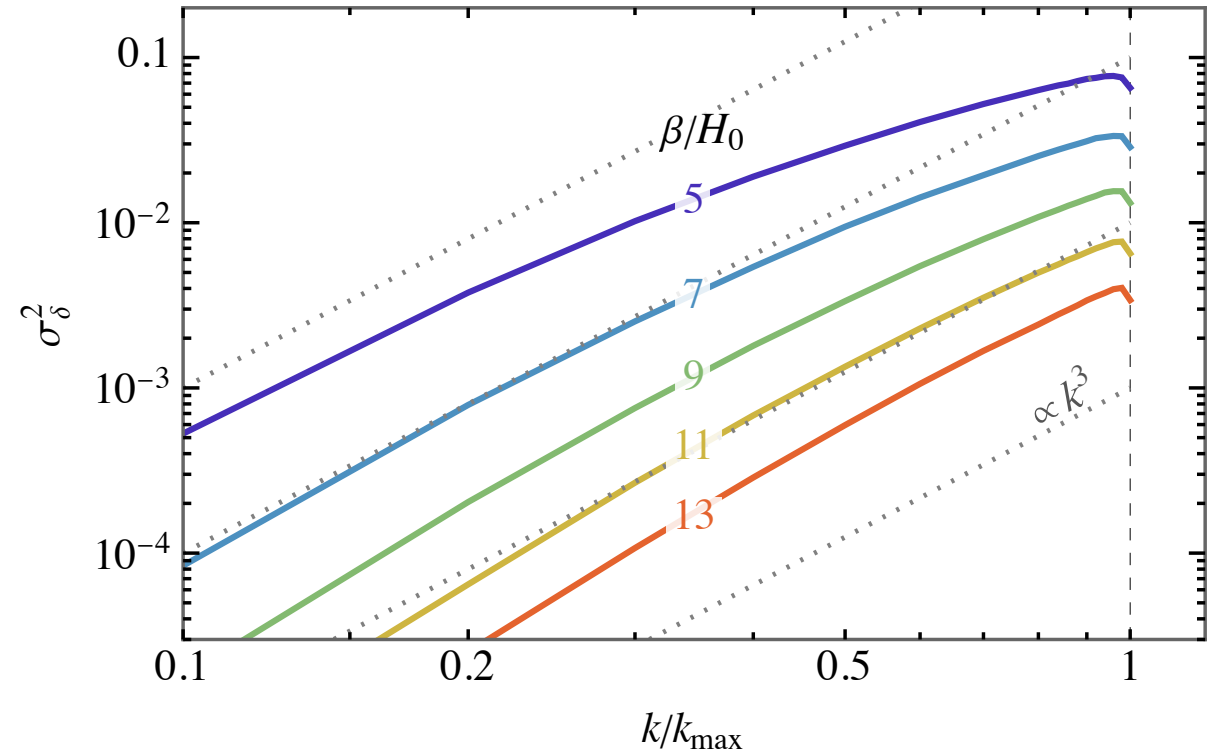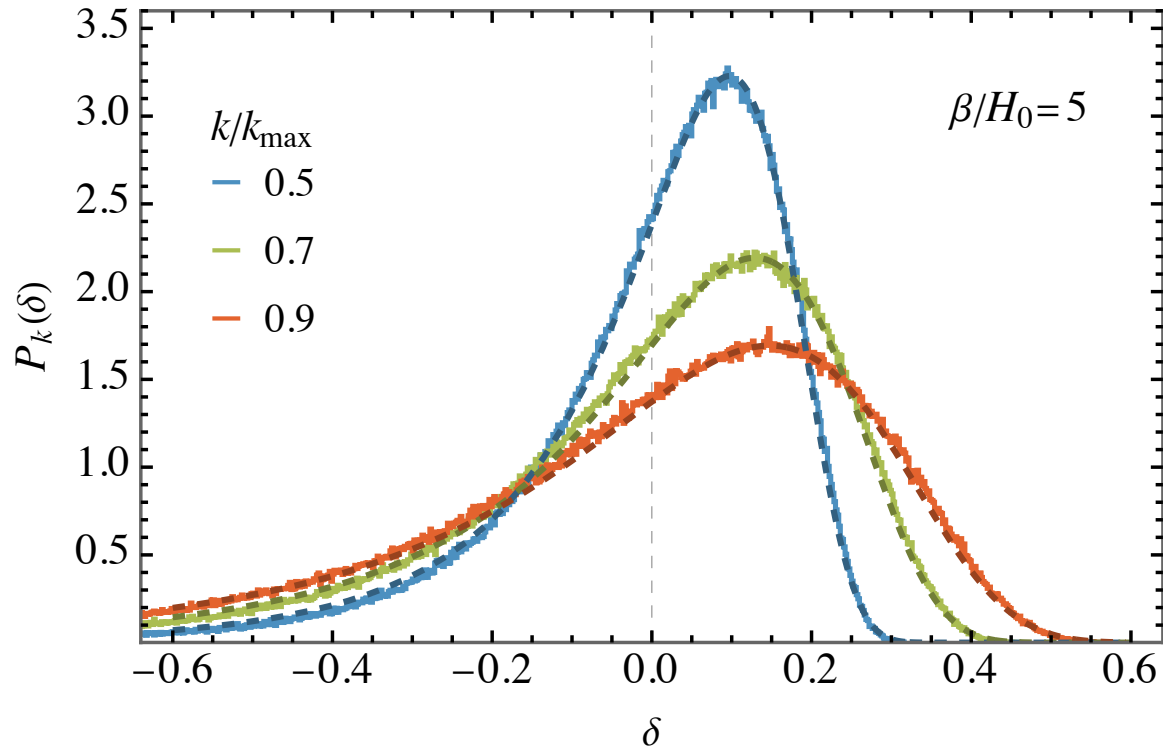$$\begin{cases} \rho_{v,k}(t) = F_k(t)\Delta V \\ \\ \dot{\rho}_{r,k} + 4H\rho_{r,k} = -\dot{\rho}_{v,k} \end{cases}$$

$$\rho_k = \rho_{r,k} + \rho_{v,k}$$

$$\delta = \frac{\rho_k(t_k)}{\bar{\rho}(t_k)} - 1$$
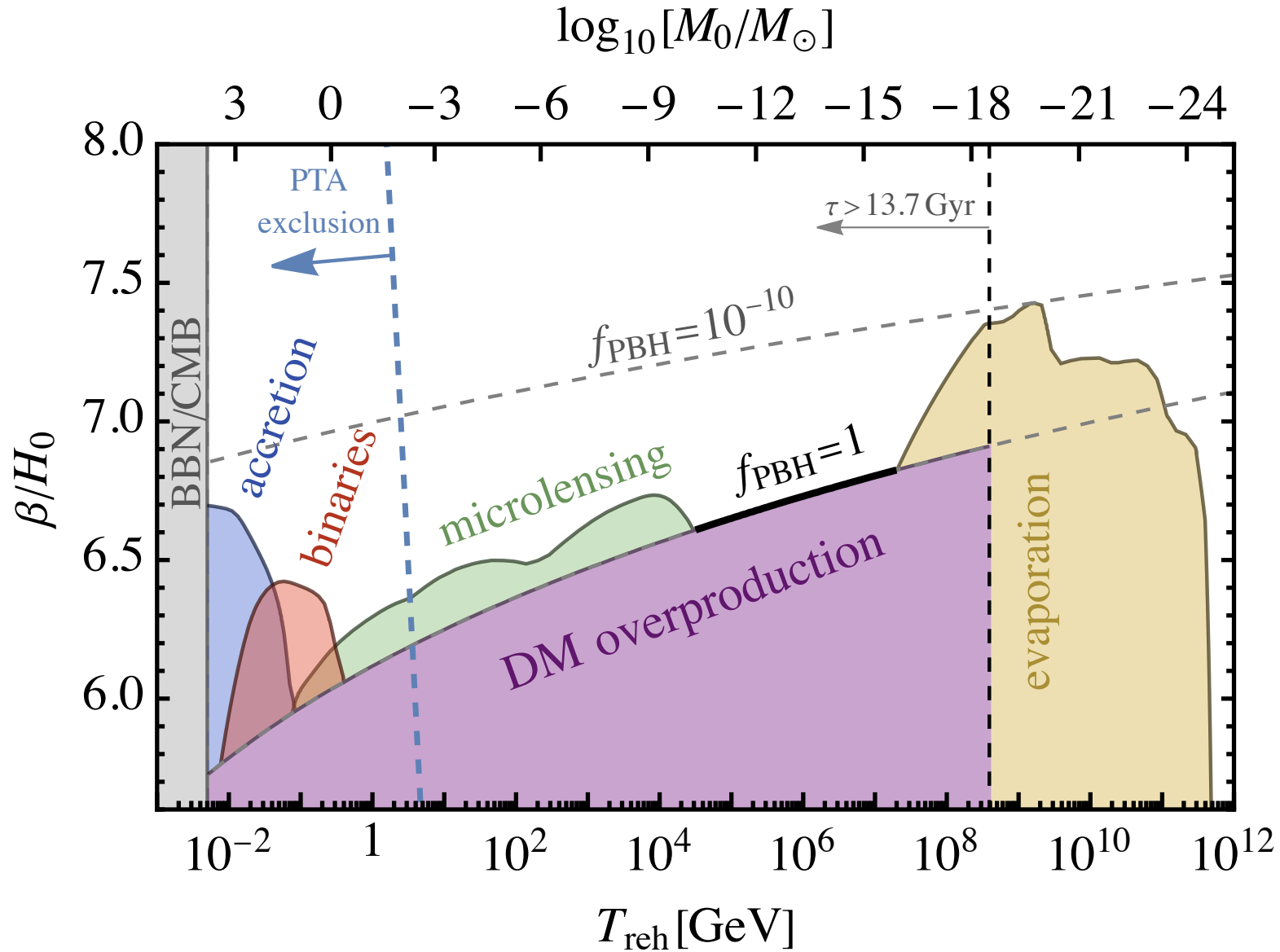
Distribution of density constrast

- distribution of the fluctuations has **negative non-Gaussianity**

- small $\beta/H_0 \implies$ slow transition $\implies$ large variance of δ

$$\Gamma(t) \propto e^{\beta t}$$

Primordial black holes

GW spectrum from slow transitions

1. GWs from bubble collisions:
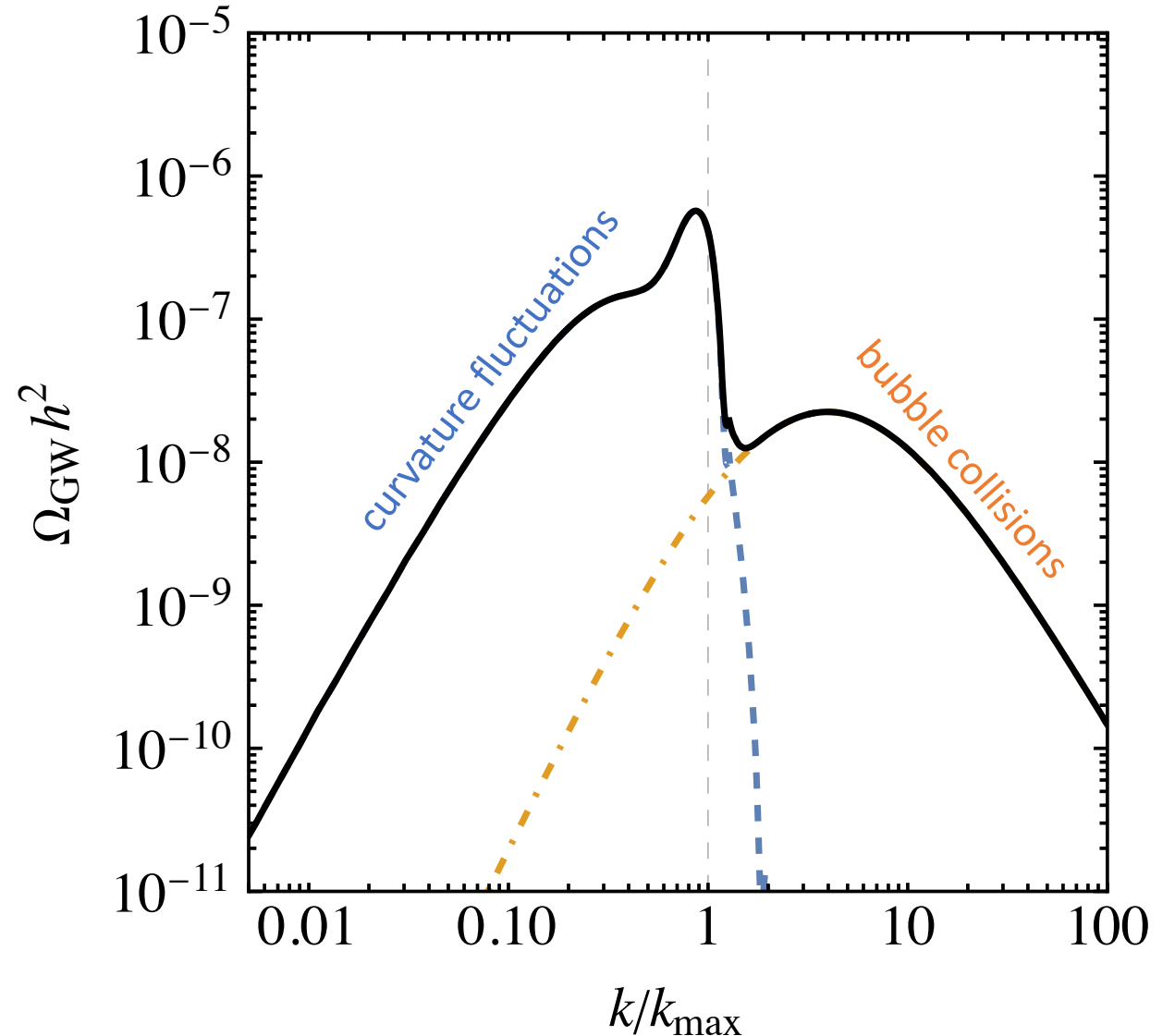
$$k_{\mathrm{peak}} \approx k_{\max} \beta / H_0$$

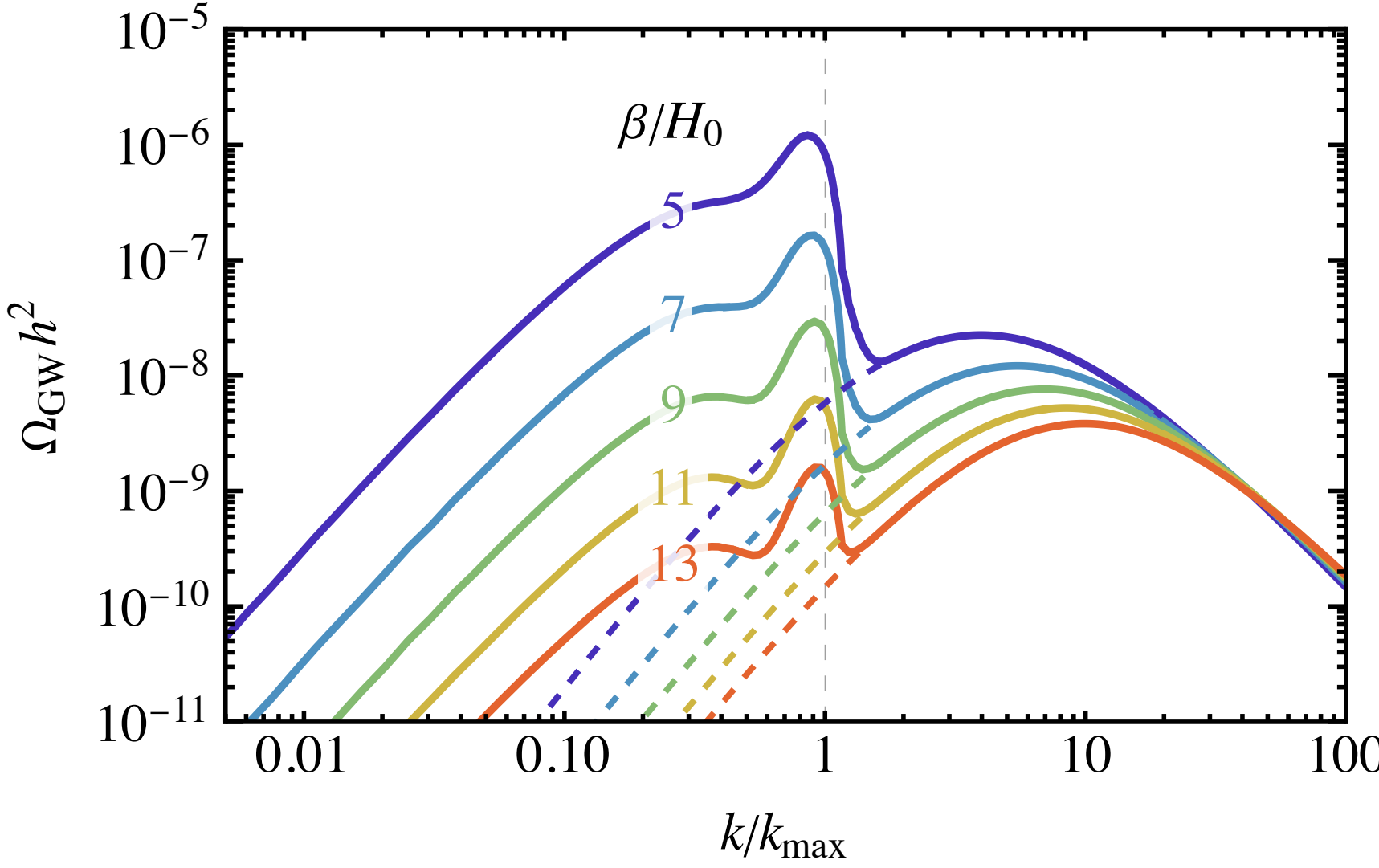$$\Omega_{\mathrm{PGW}} h^2 \propto \left(\frac{\beta}{H_0} \right)^{-2}$$

2. GWs induced by curvature fluctuations:
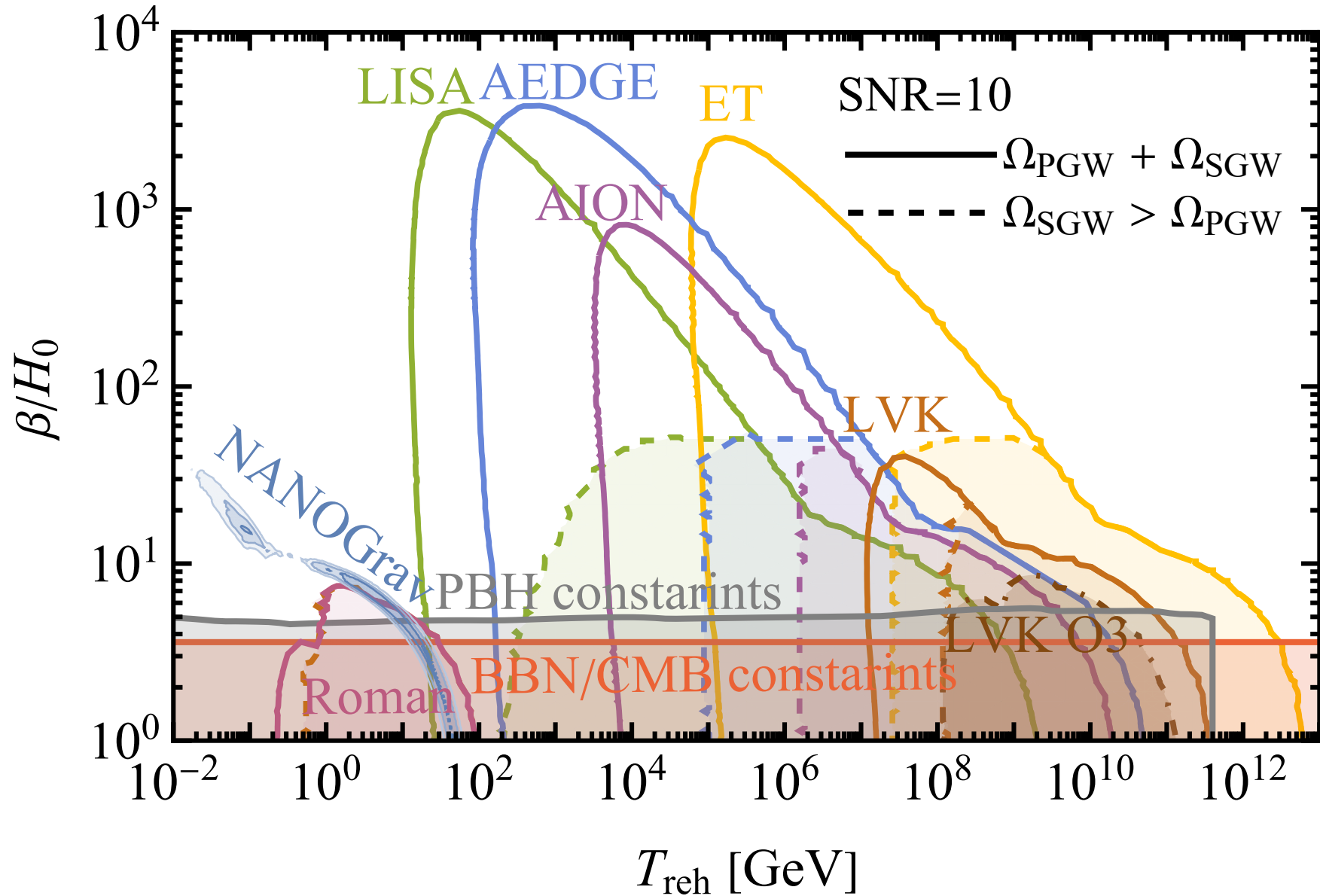
$$k_{\mathrm{peak}} \approx k_{\max}$$

$$\Omega_{\mathrm{SGW}} h^2 \propto e^{-\beta / H_0}$$
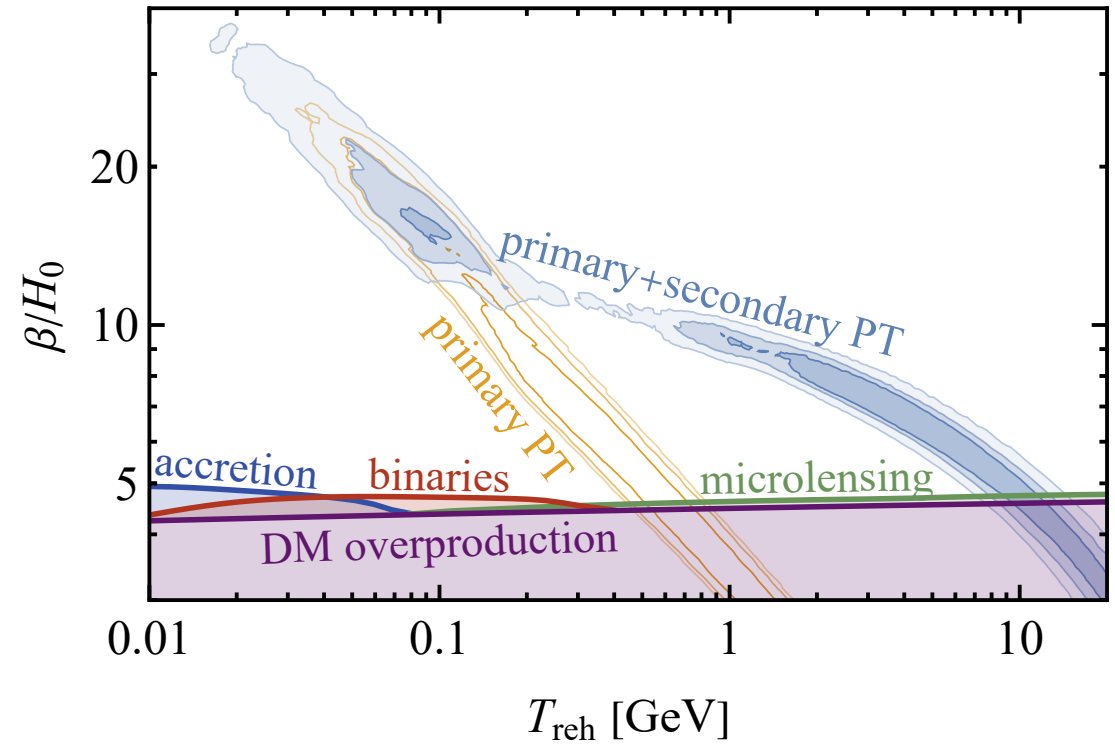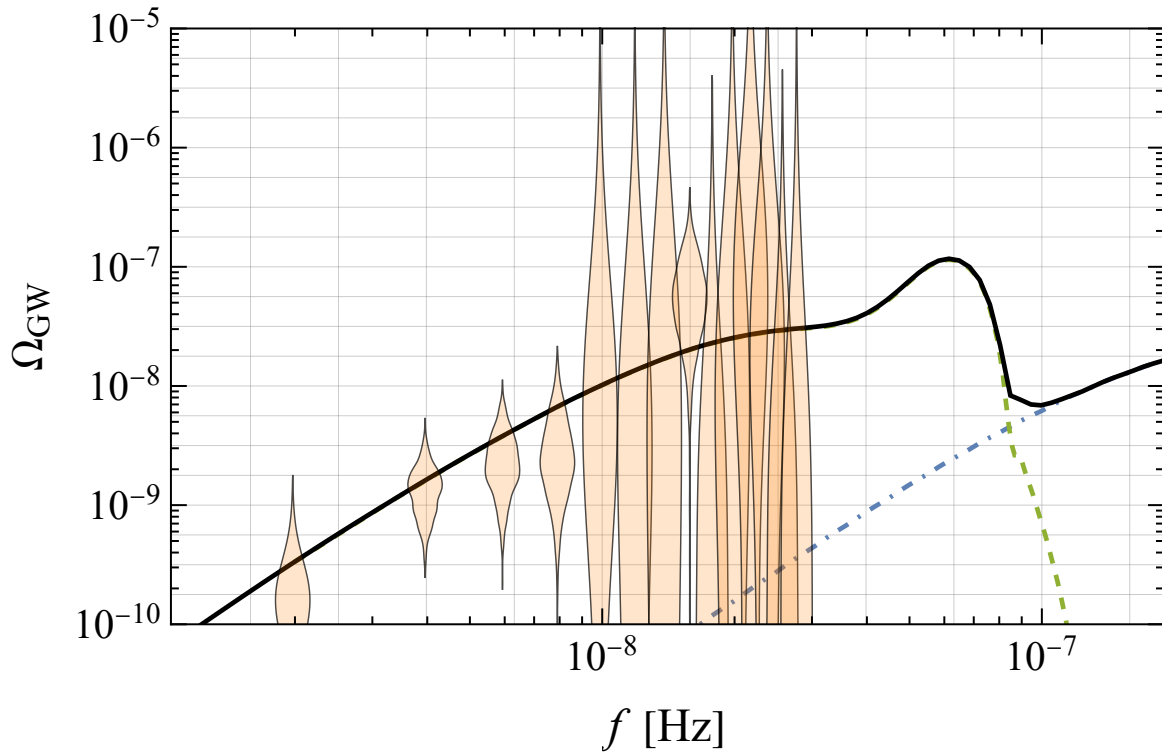
GW spectrum from slow transitions
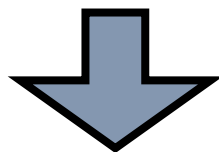
Prospects

PTA fit

negative non-Gaussianity $\Rightarrow$ the fit is not in tension with PBH production
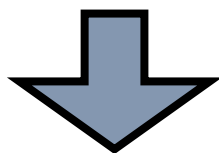
Summary

Slow and supercooled transition

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Large density fluctuations

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PBHs and secondary GWs