KBFI Tallinn

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Black holes and gravitational waves from slow and strongly supercooled phase transitions

Ville Vaskonen

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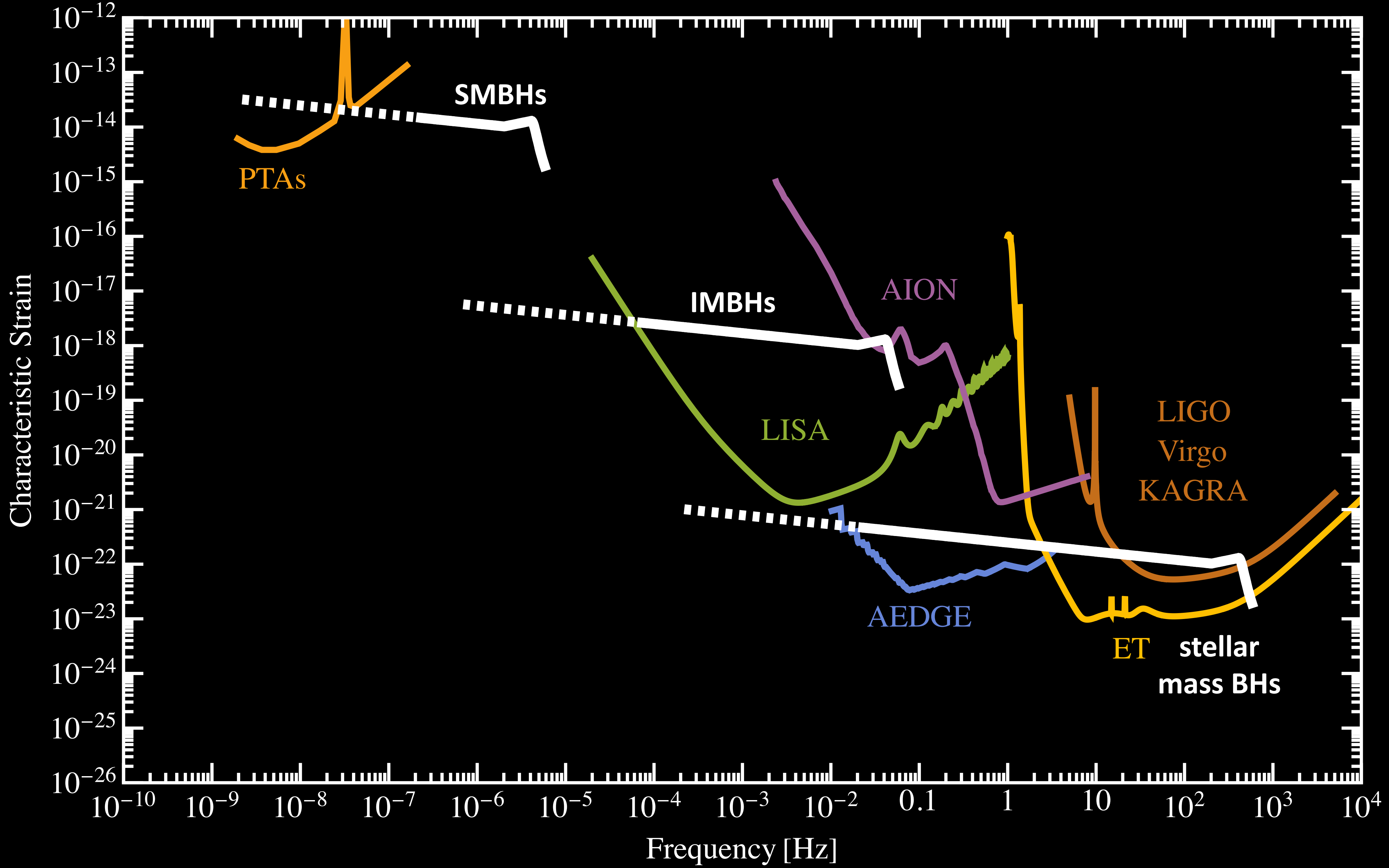
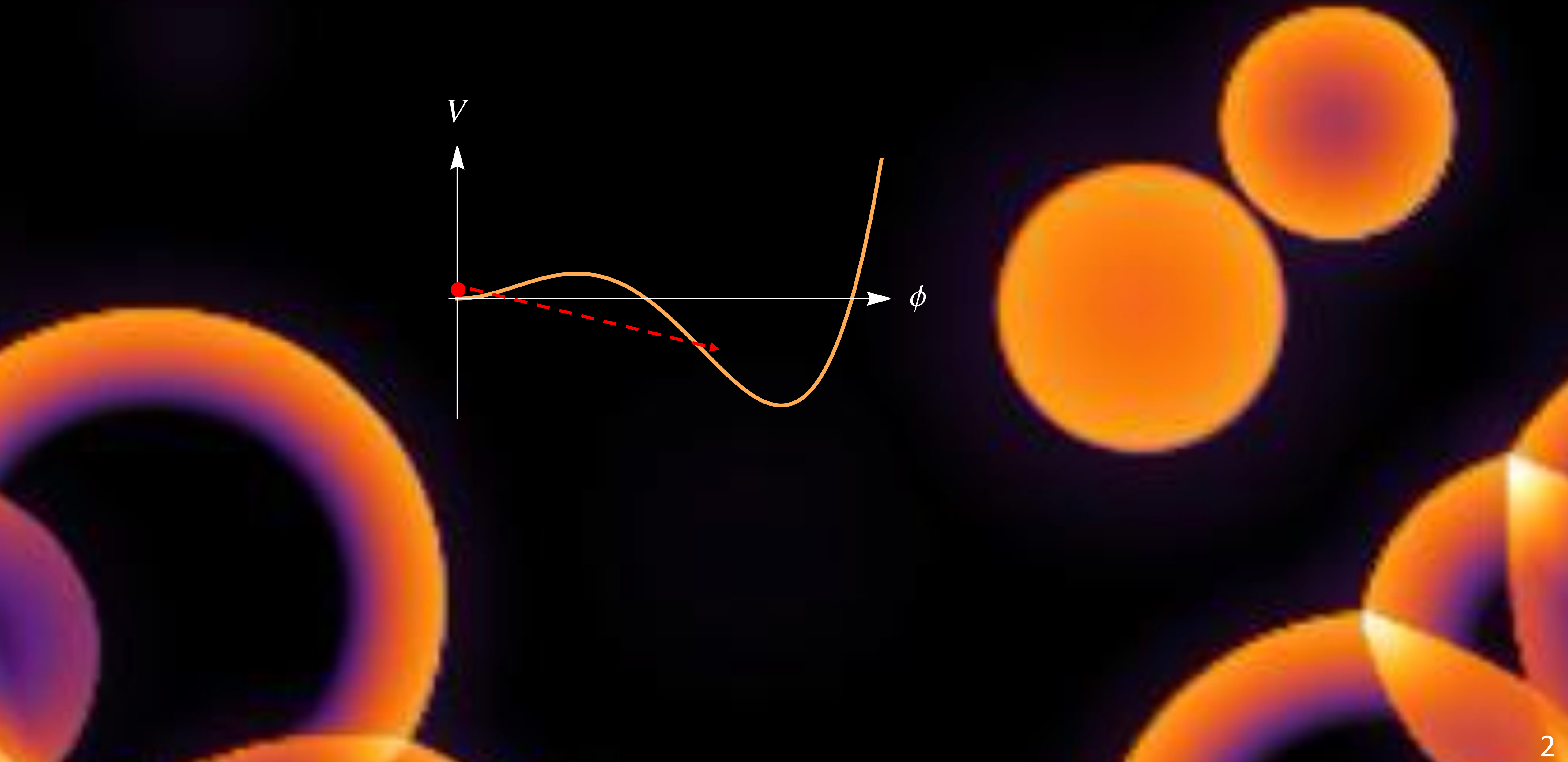
CERN, November 20, 2024.

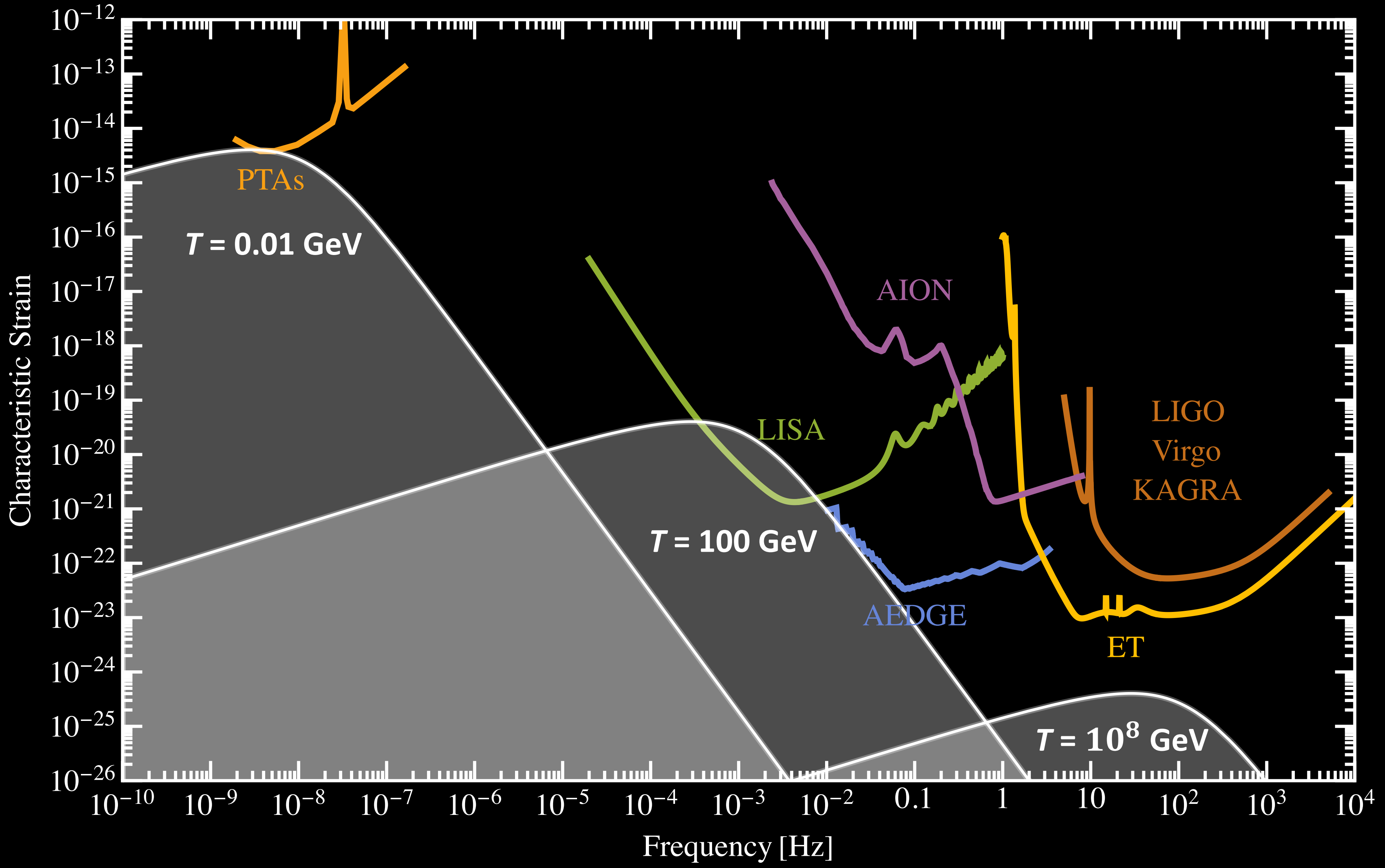


SMBHs
PTAs
IMBHs
AION
LISA
LIGO
Virgo
KAGRA
AEDGE
ET
stellar mass BHs
Characteristic Strain
Frequency [Hz]
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
0.1
1
10
10^{2}
10^{3}
10^{4}

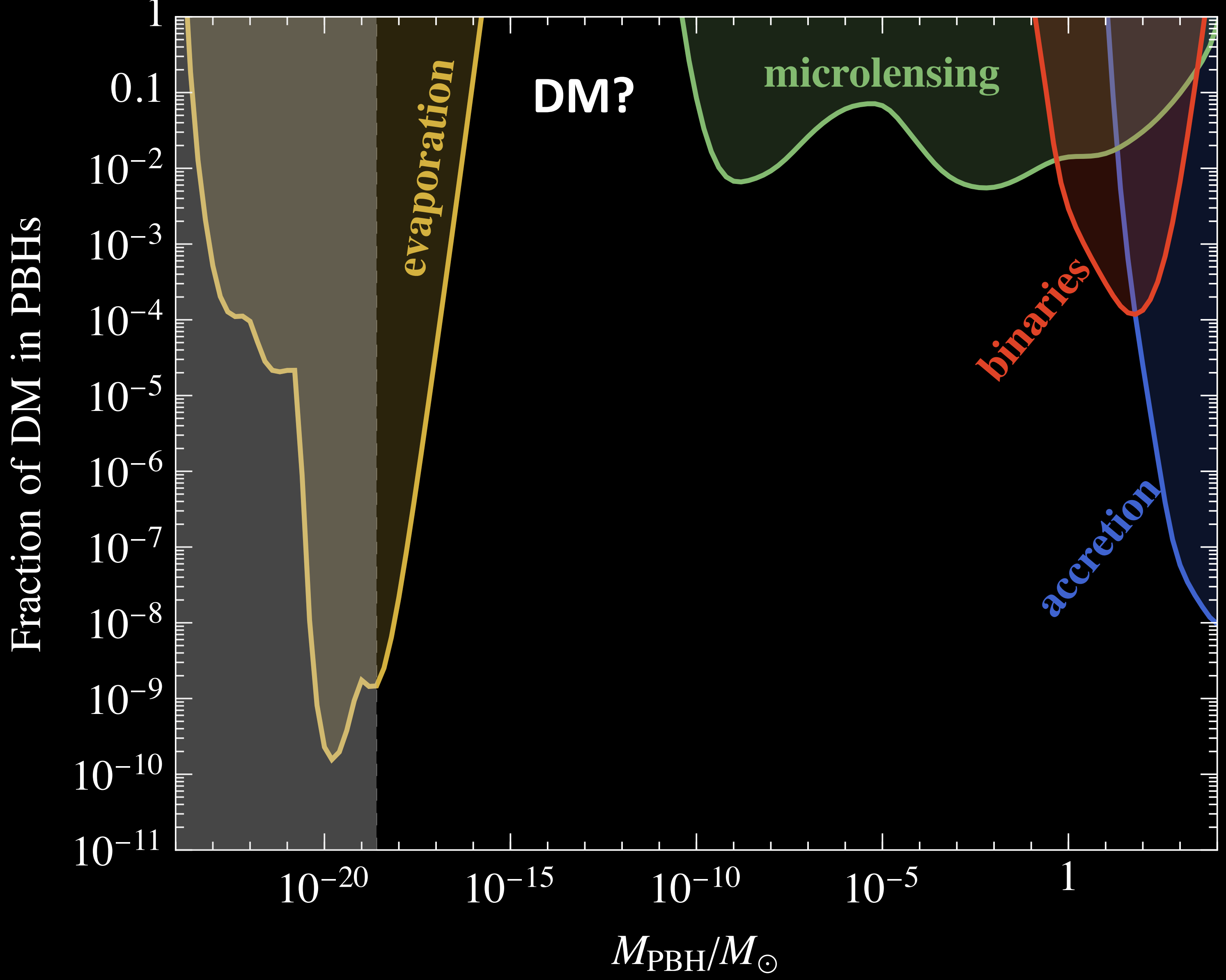
First order phase transitions



GWs from phase transitions

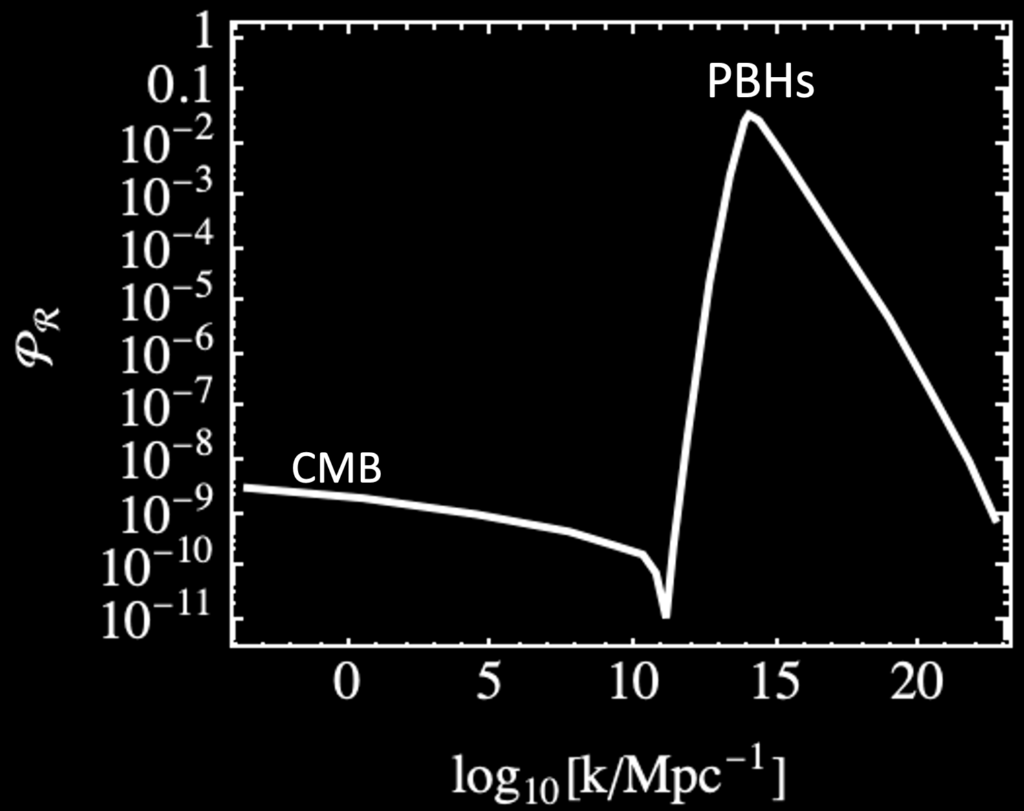


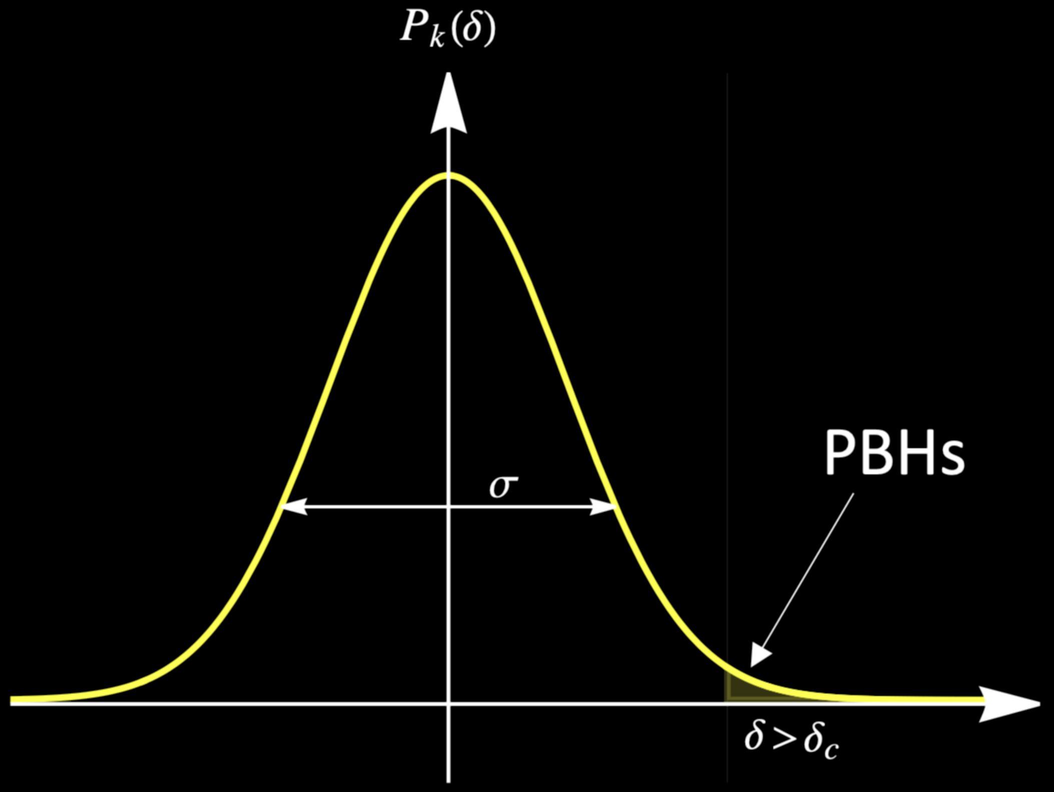
Primordial black hole constraints



Primordial black hole formation

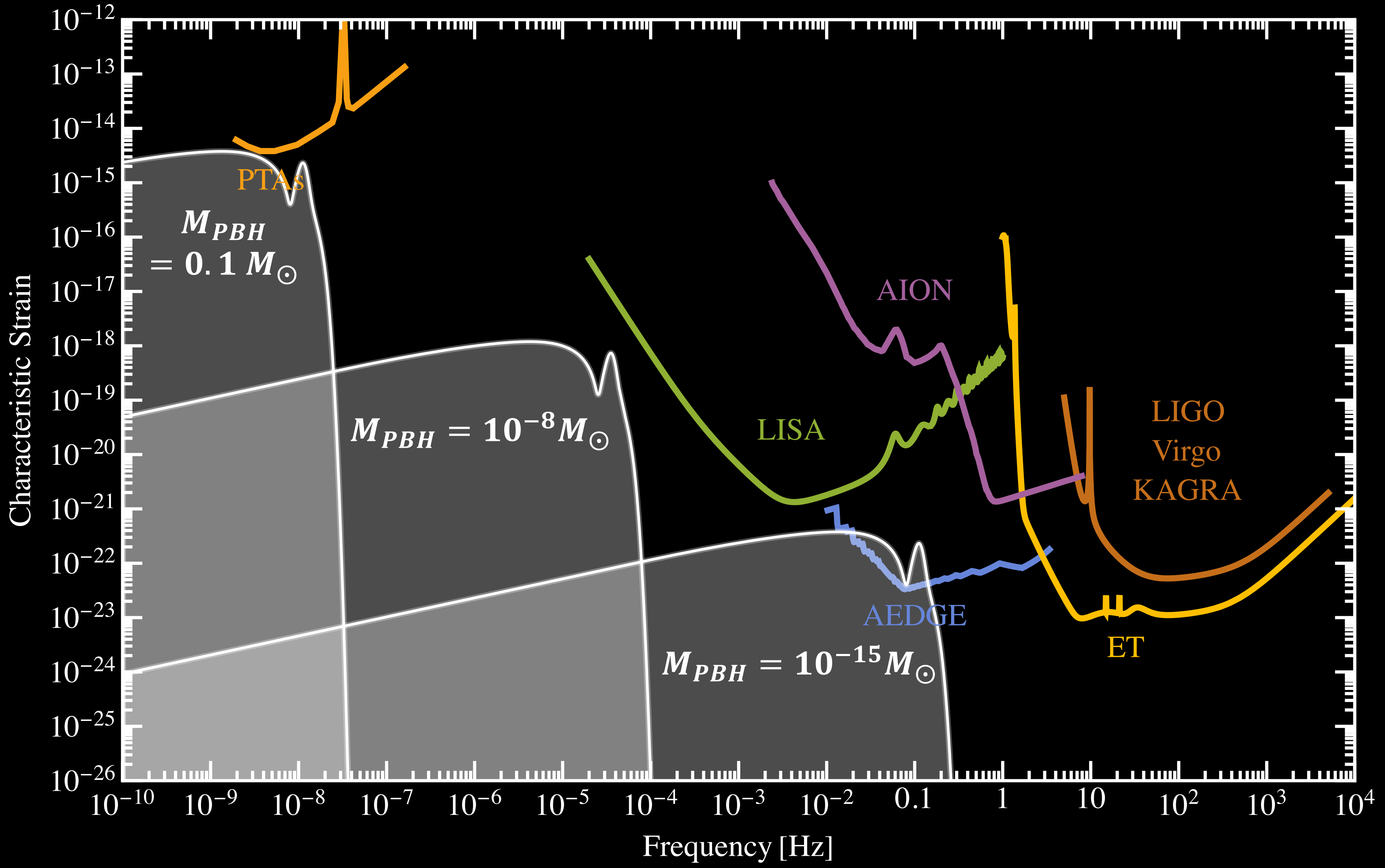
Large fluctuations collapse against the fluid pressure to BHs at horizon reentry.





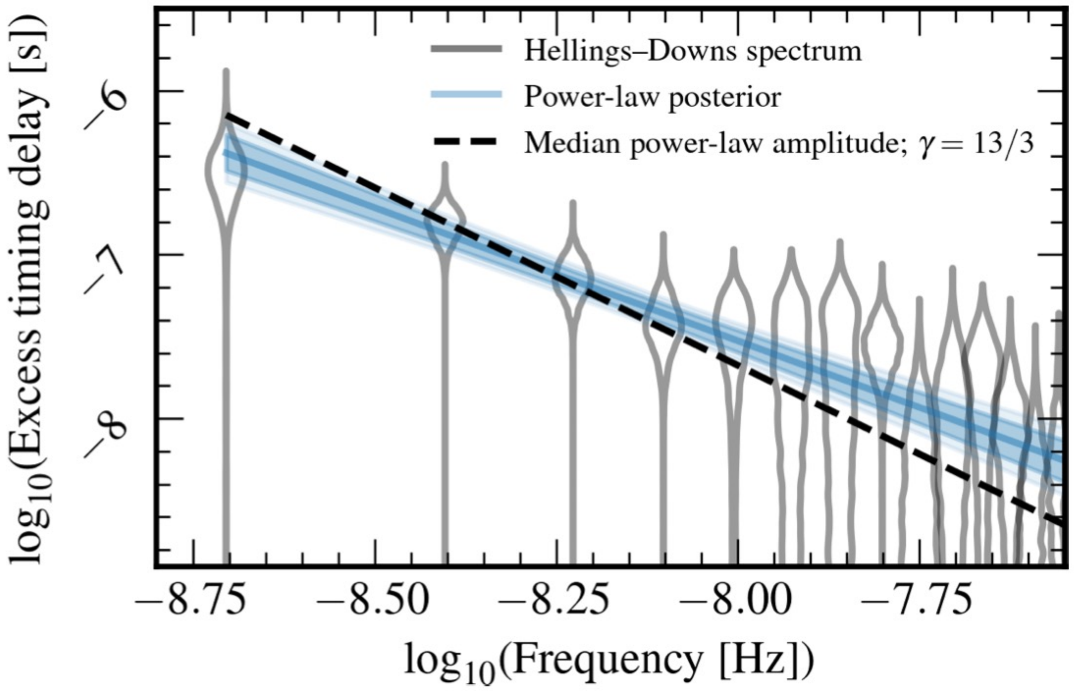
Large fluctuations source also scalar-induced GWs.

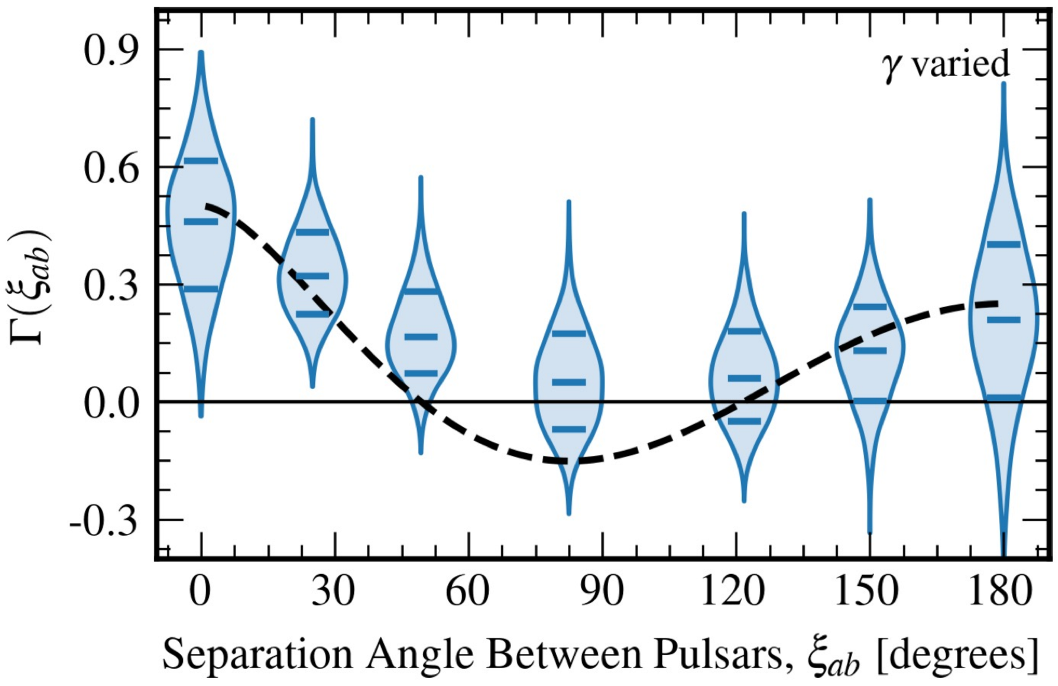
Scalar-induced GWs



Strong evidence for nHz GW background

NANOGrav, *ApJ. Lett. 951* (2023), 2306.16213





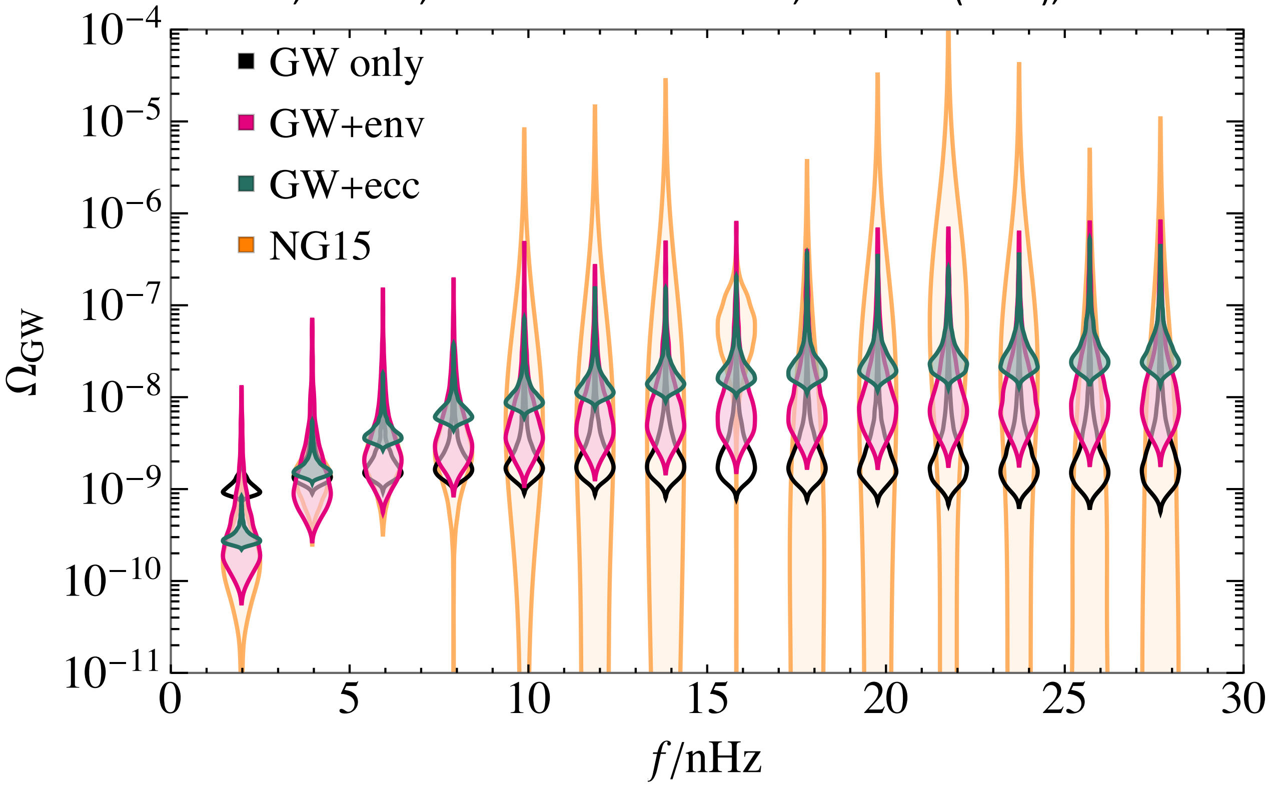
common spectrum noise + Hellings-Downs angular correlation.

Seen also by EPTA, InPTA, PPTA and CPTA.

What is the source?

SMBH fit:

Ellis et al., PRD 109 (2024), 2306.17021
Raidal, Urrutia, Vaskonen and Veermäe, A&A 691 (2024), 2406.05125

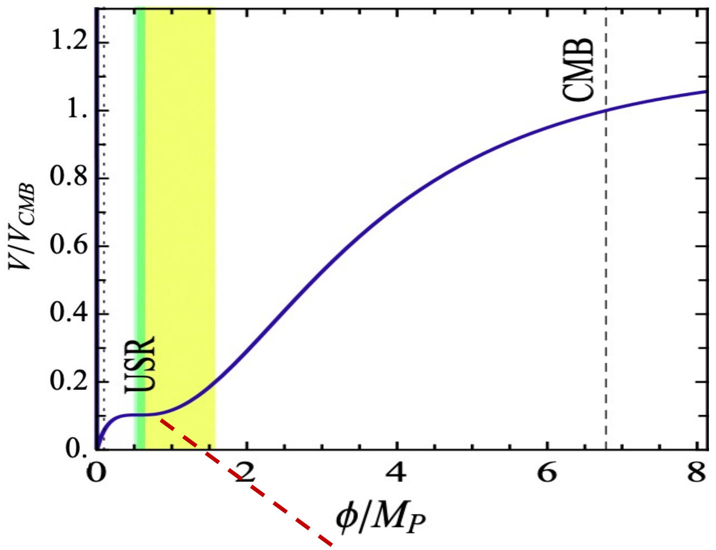


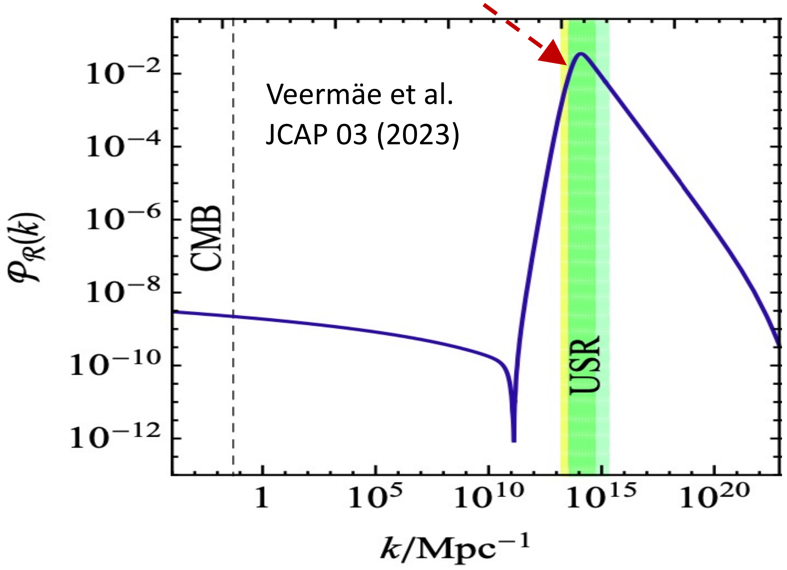
MMA:

Ellis et al., PRD 109 (2024), 2308.08546

Scenario	Best-fit parameters	ΔBIC
GW-driven SMBH binaries	$p_{\rm BH} = 0.07$	6.0
GW + environment-driven SMBH binaries	$p_{\rm BH} = 0.84$ $\alpha = 2.0$ $f_{\rm ref} = 34$ nHz	Baseline (BIC = 53.9)
Cosmic (super)strings (CS)	$G\mu = 2 \times 10^{-12}$ $p = 6.3 \times 10^{-3}$	-1.2 (4.6)
Phase transition (PT)	$T_* = 0.34$ GeV $\beta/H = 6.0$	-4.9 (2.9)
Domain walls (DWs)	$T_{\rm ann} = 0.85$ GeV $\alpha_* = 0.11$	-5.7 (2.2)
Scalar-induced GWs (SIGWs)	$k_* = 10^{7.7}$/Mpc $A = 0.06$ $\Delta = 0.21$	-2.1 (5.8)
First-order GWs (FOGWs)	$\log_{10} r = -14$ $n_t = 2.6$ $\log_{10}(T_{\rm rh}/\text{GeV}) = -0.67$	-2.0 (6.0)
"Audible" axions	$m_a = 3.1 \times 10^{-11}$ eV $f_a = 0.87\, M_P$	-4.2 (3.7)

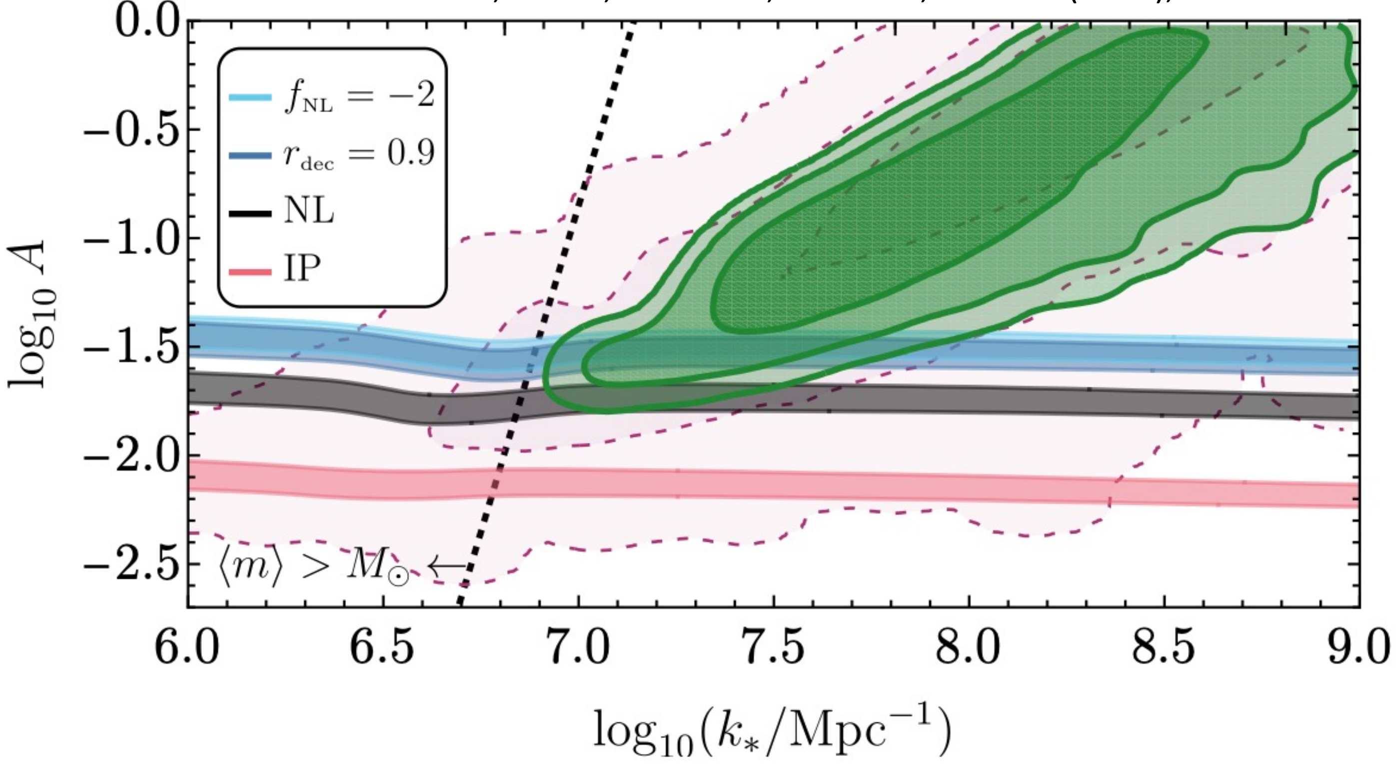
PBHs from primordial inflation





SIGW fit of the PTA signal:

Franciolini, Iovino, Vaskonen, Veermäe, PRL 131 (2023), 2306.17149



$\Longrightarrow$ tension with PBH overproduction

Slow and supercooled first-order phase transition

↓

Large density fluctuations

↓

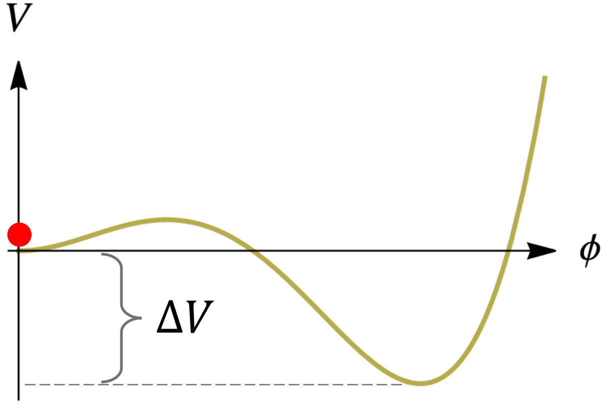
PBHs and GWs

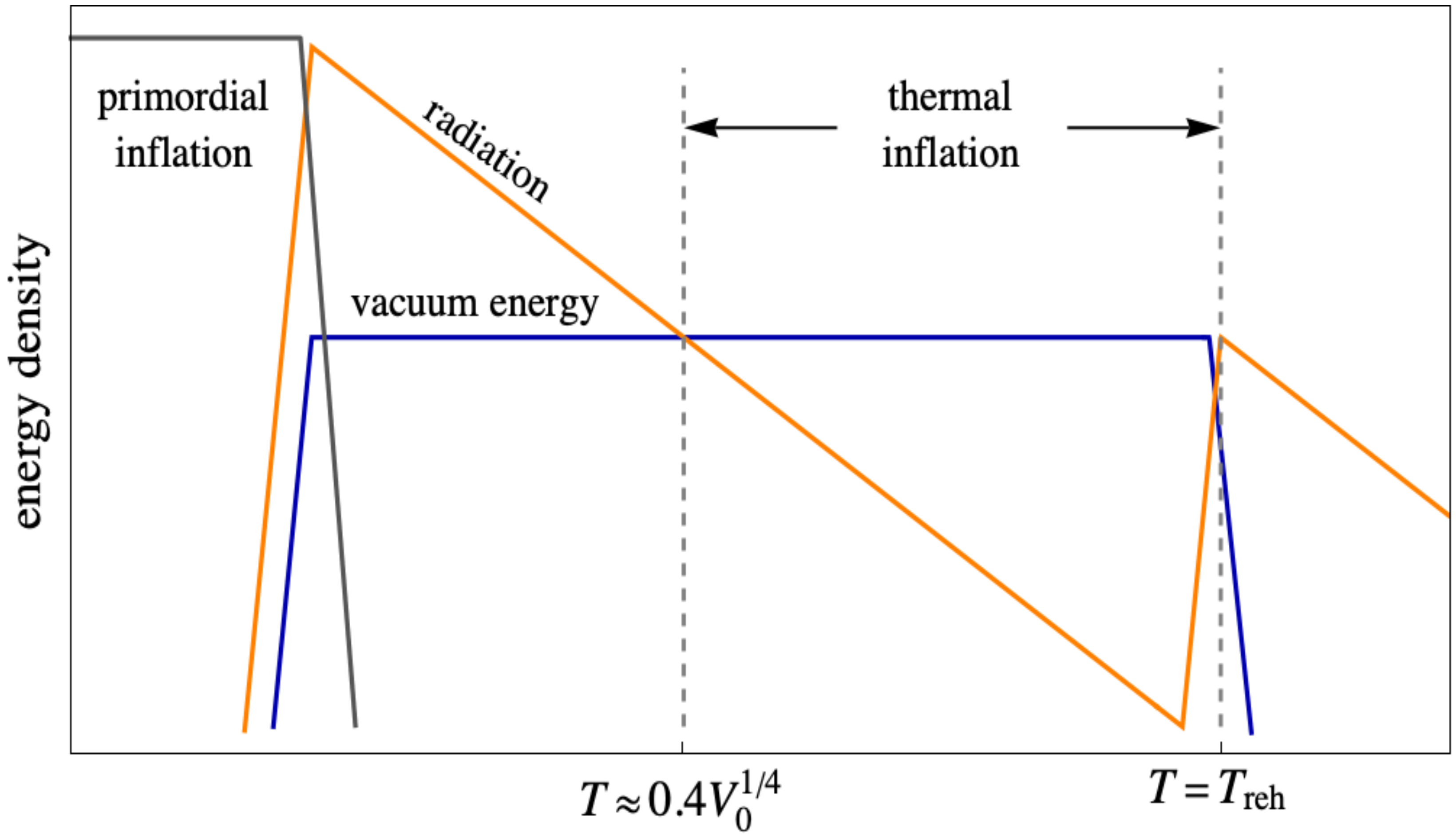
Liu et al. PRD 105 (2022), 2106.05637,
Kawana, Kim, Lu, PRD 108 (2023), 2212.14037
Gouttenoire, Volansky, PRD 110 (2024), 2305.04942 } **PBHs**

Lewicki, Toczek, Vaskonen, 2402.04158, accepted to PRL **PBHs + GWs**

Strong supercooling

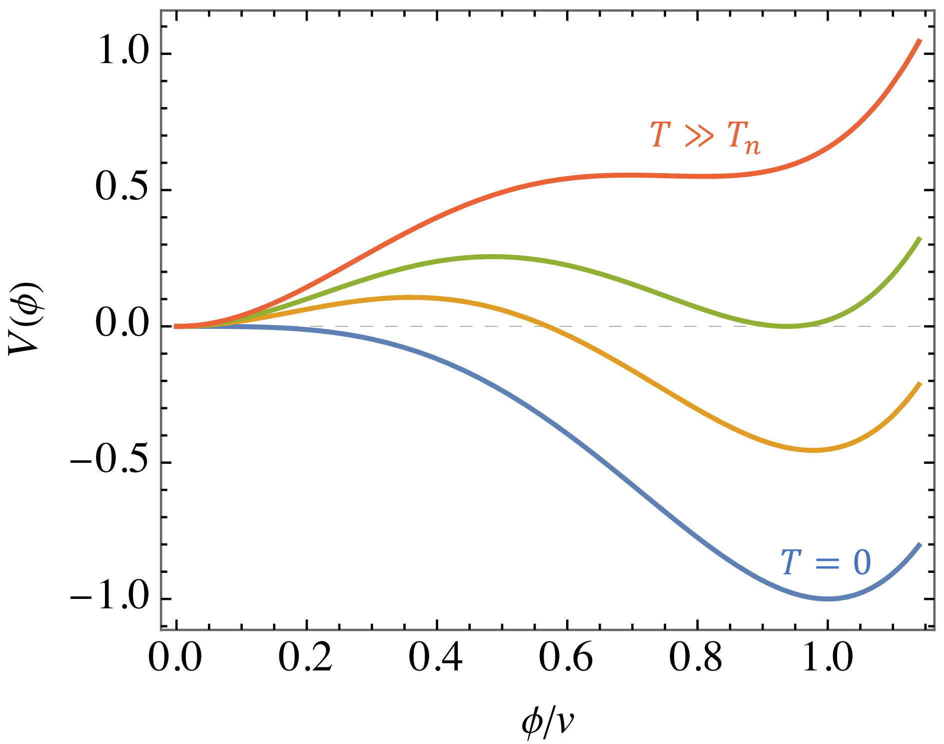
Period of inflation before the transition happens, $\Delta V > \rho_{\rm rad}$.

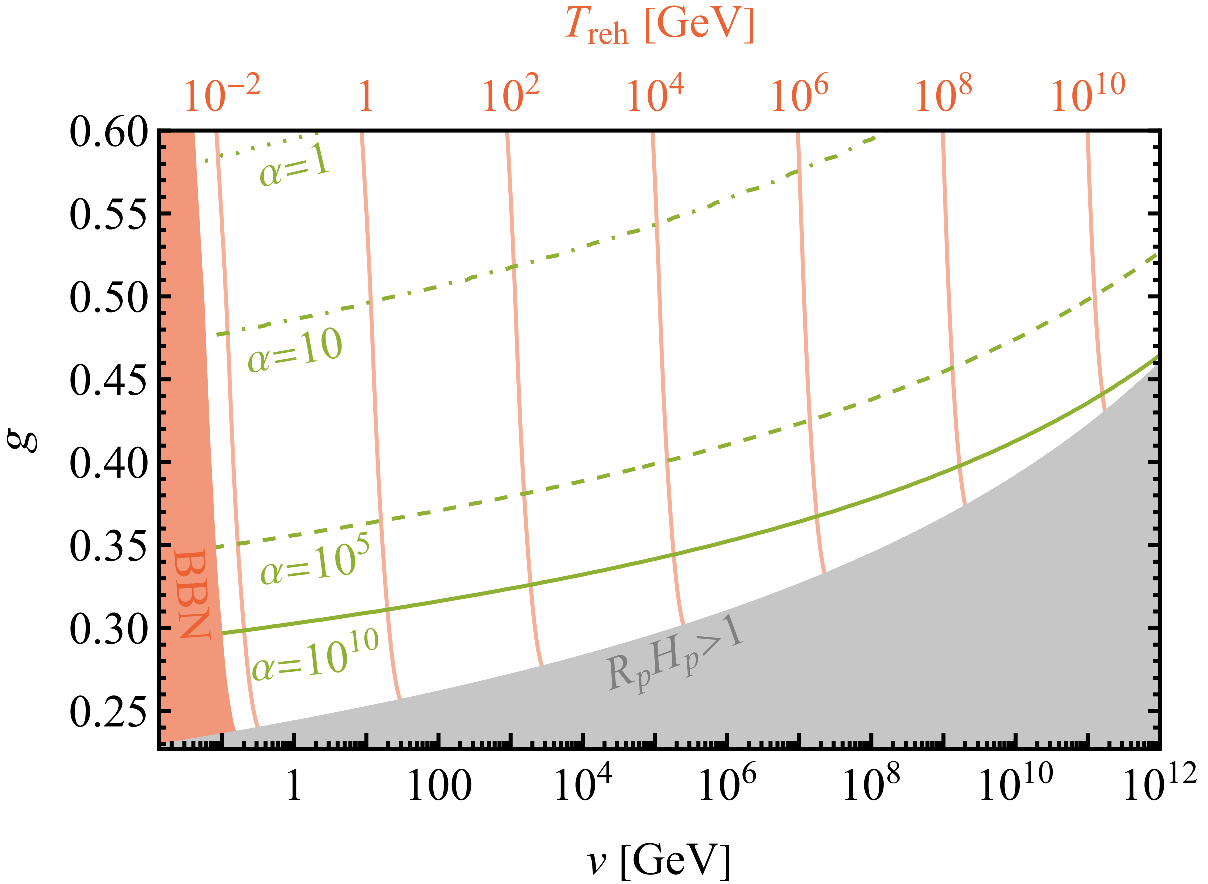




Realistic model

$$V(\phi, T) = V_0 + \frac{3g^4}{4\pi^2}\phi^4\left[\ln\frac{\phi^2}{v^2} - \frac{1}{2}\right] + \frac{g^2T^2}{2}\phi^2$$





$$N_{\rm TI} \approx \ln(1/\alpha)$$

Realistic model

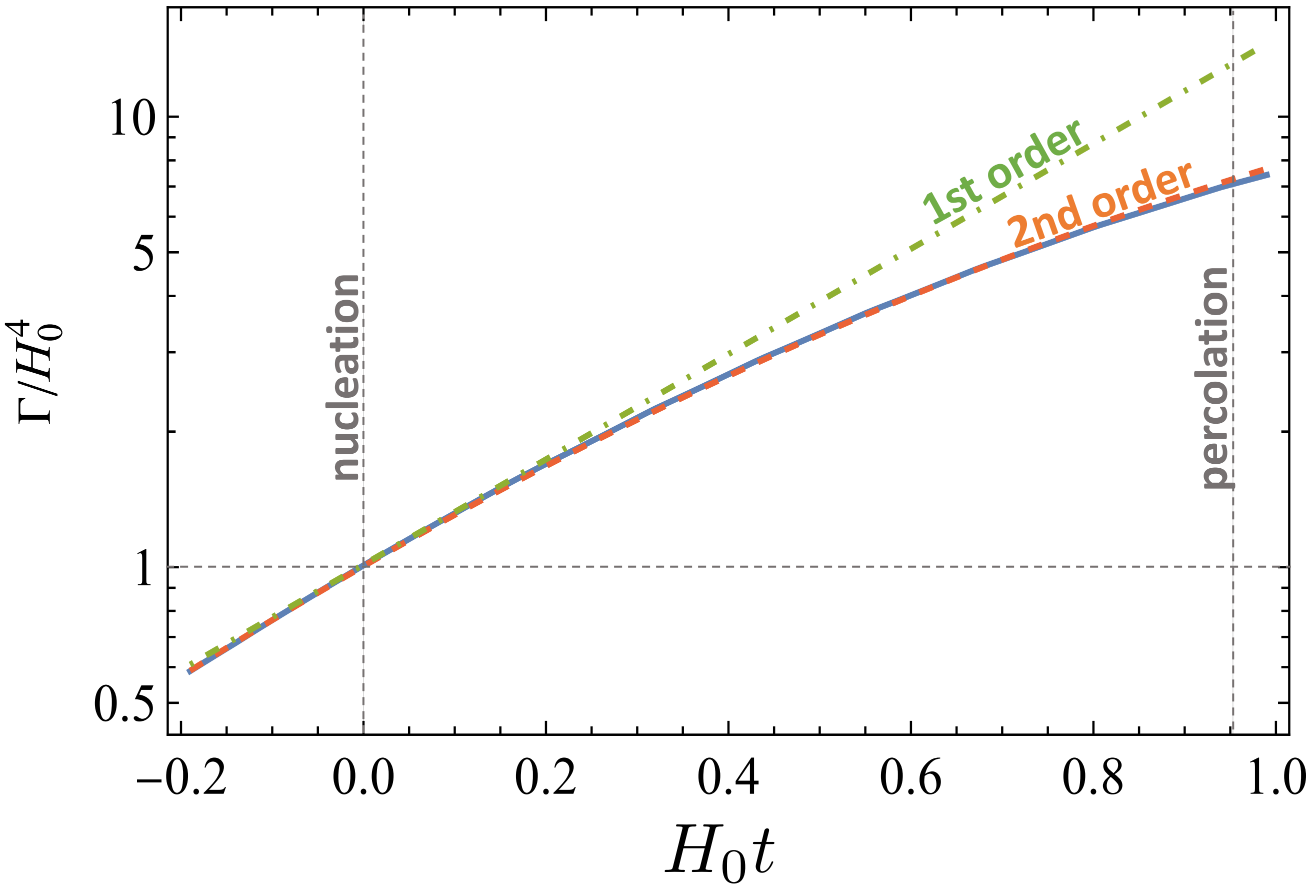
Nucleation rate:

$$\Gamma = \left(\frac{S_3}{2\pi T}\right)^{\frac{3}{2}} T^4 e^{-S_3/T} = \Lambda^4 e^{-S(T)}$$

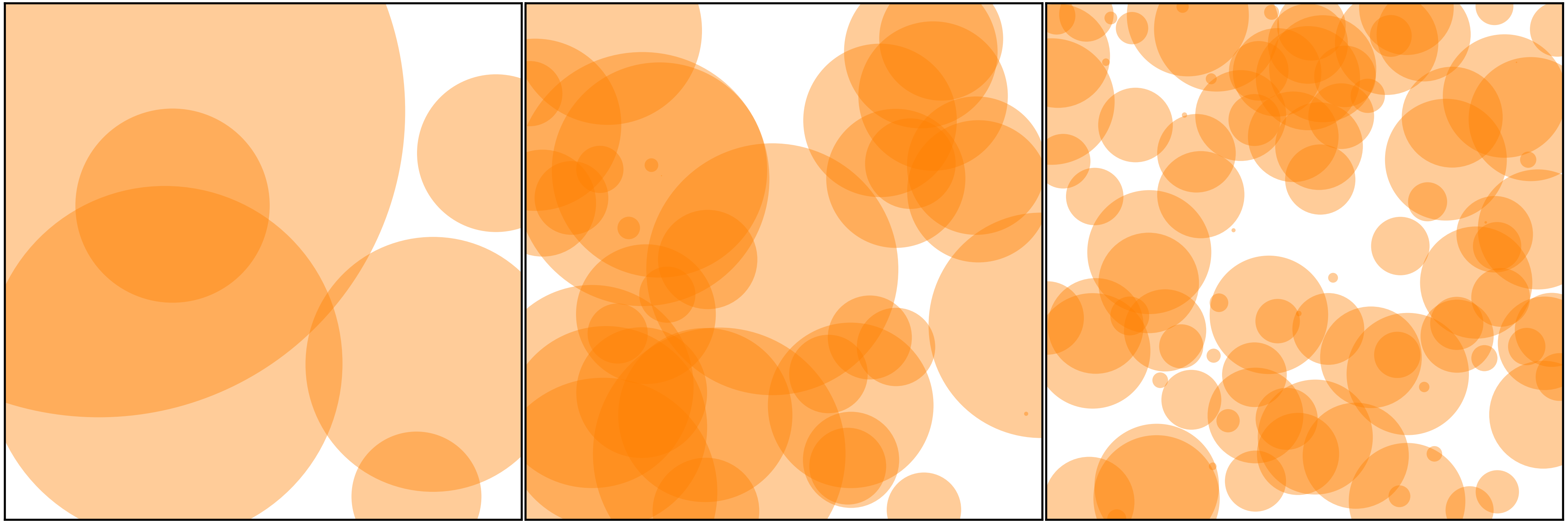
$$S_3 = 4\pi \int_0^\infty \mathrm{d}r\, r^2 \left[\frac{1}{2}\left(\frac{\mathrm{d}\phi}{\mathrm{d}r}\right)^2 + V(\phi, T)\right]$$

Approximation:

$$\Gamma \propto \exp\left[\beta t - \frac{1}{2}\gamma^2 t^2 + \dots\right]$$



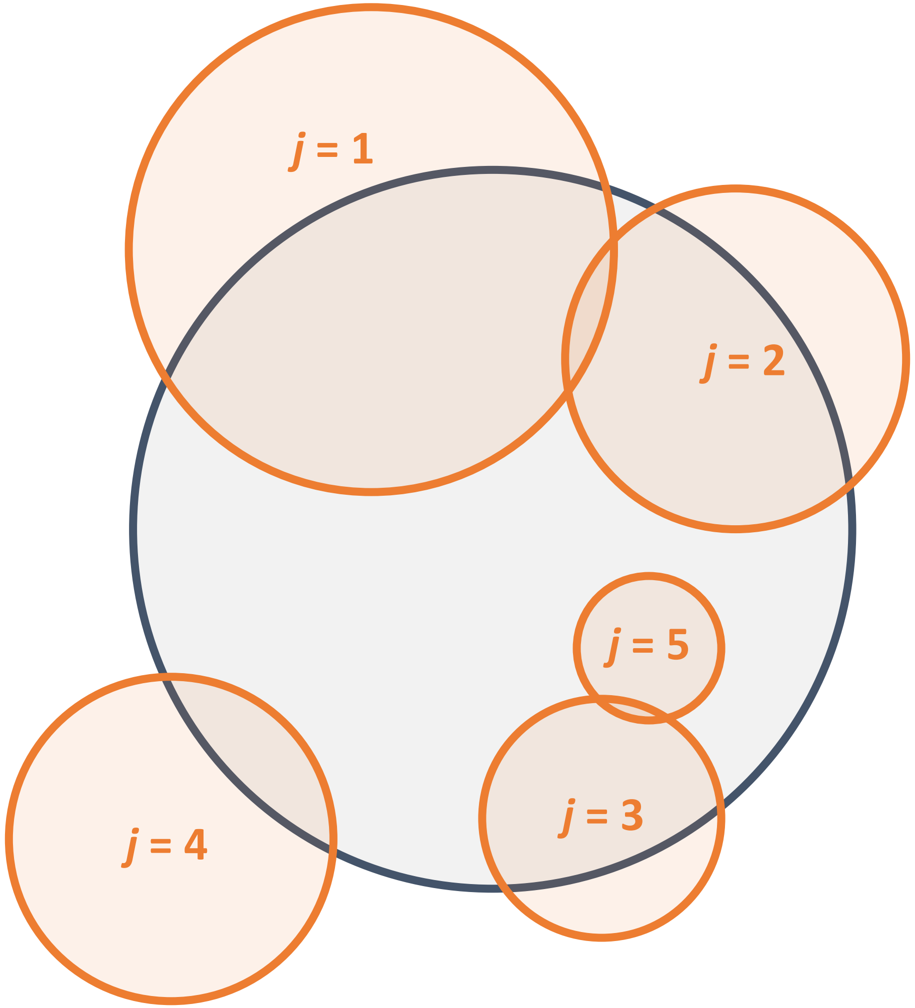
Bubble nucleation



slow:
few small bubbles
small β or large γ

fast:
many small bubbles
large β and small γ

Evolution of finite patches

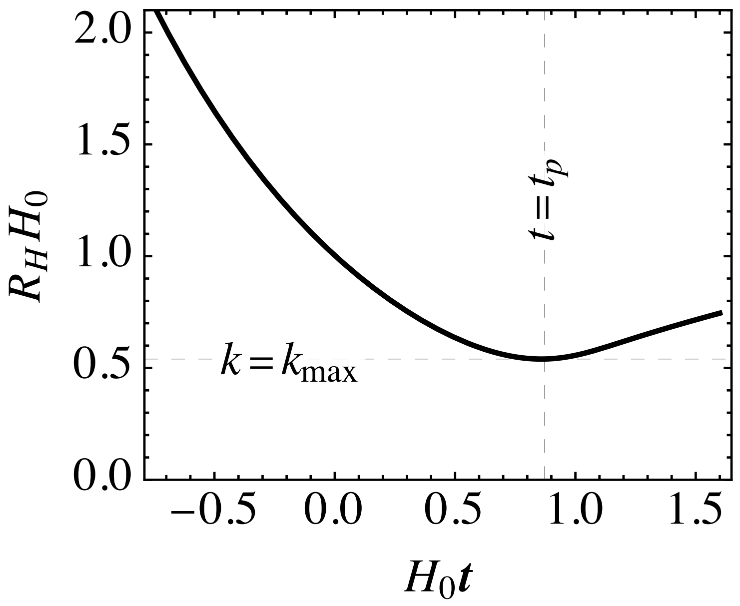


Bubbles convert vacuum energy into radiation:

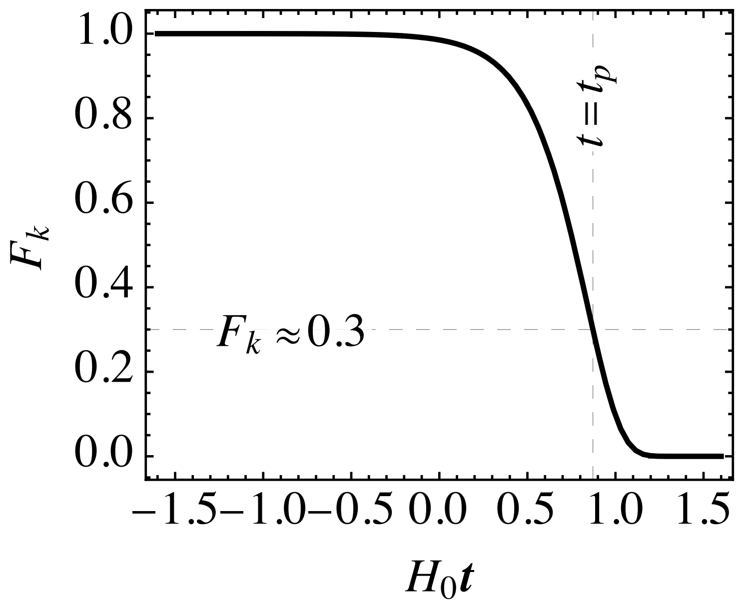
$$\dot{\rho}_r + 4H\rho_r = -\dot{\rho}_v$$

$$\rho_v = F_k(t)\Delta V$$

Comoving Hubble radius:

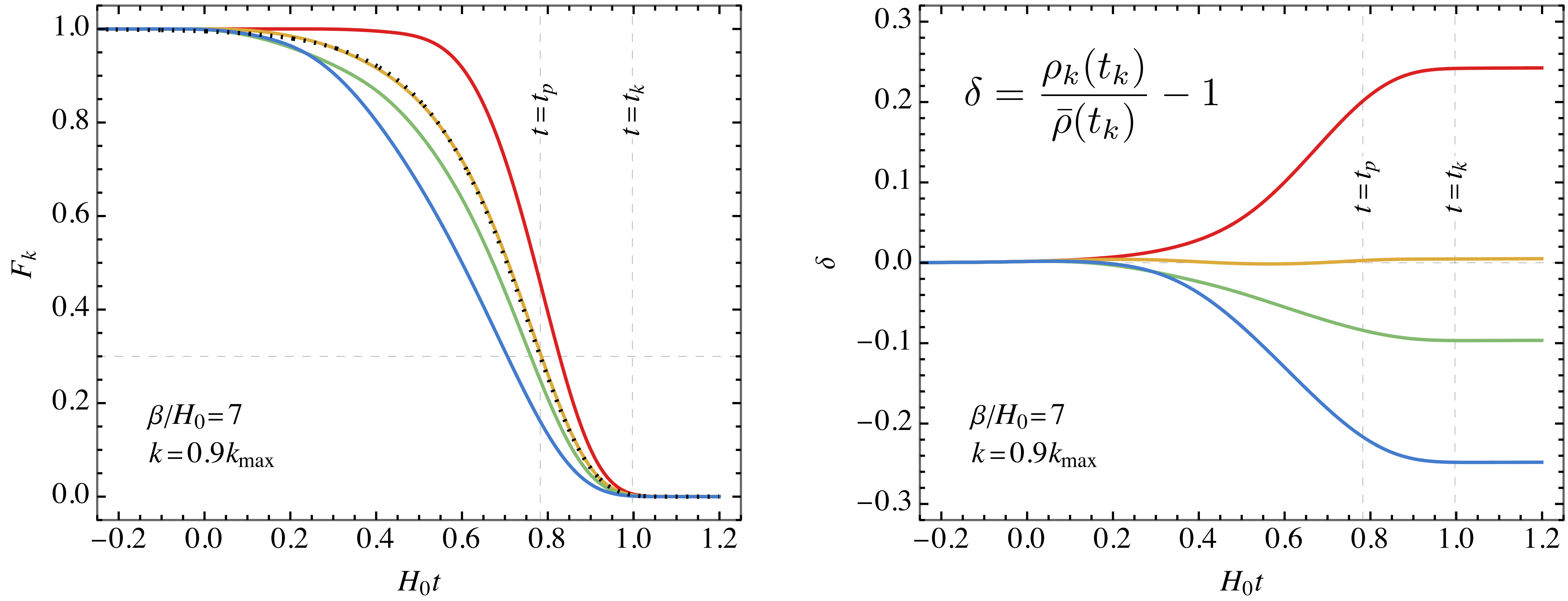


False vacuum fraction:



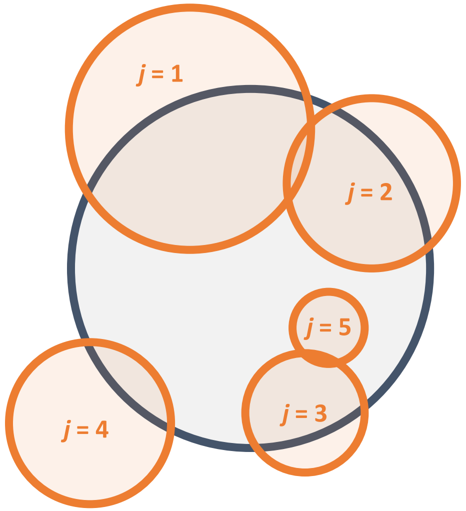
Evolution of finite patches

Four examples:



Computation

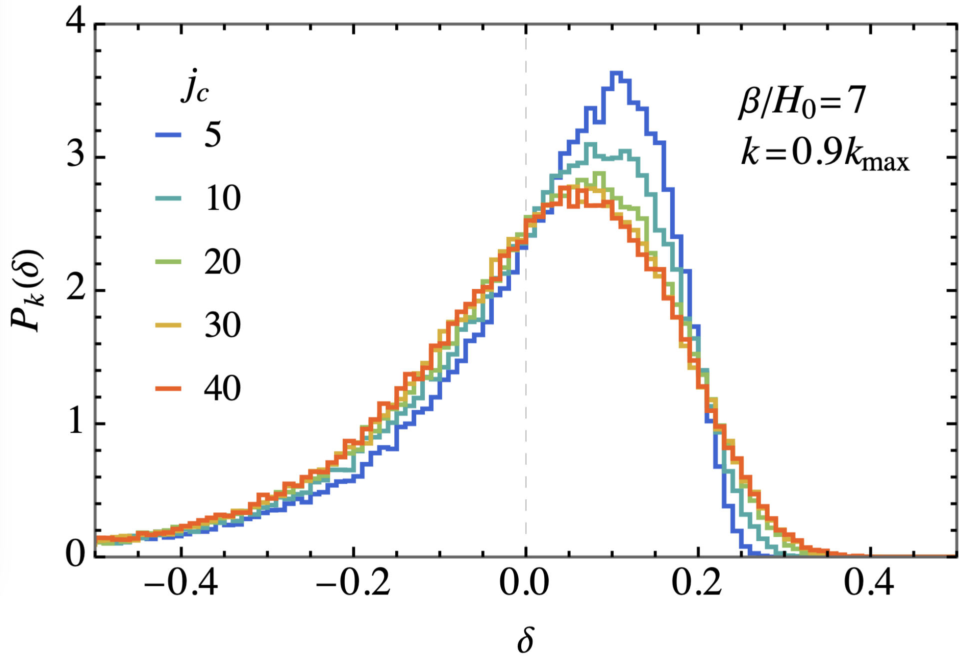
We want to generate $\sim 10^6$ realizations.



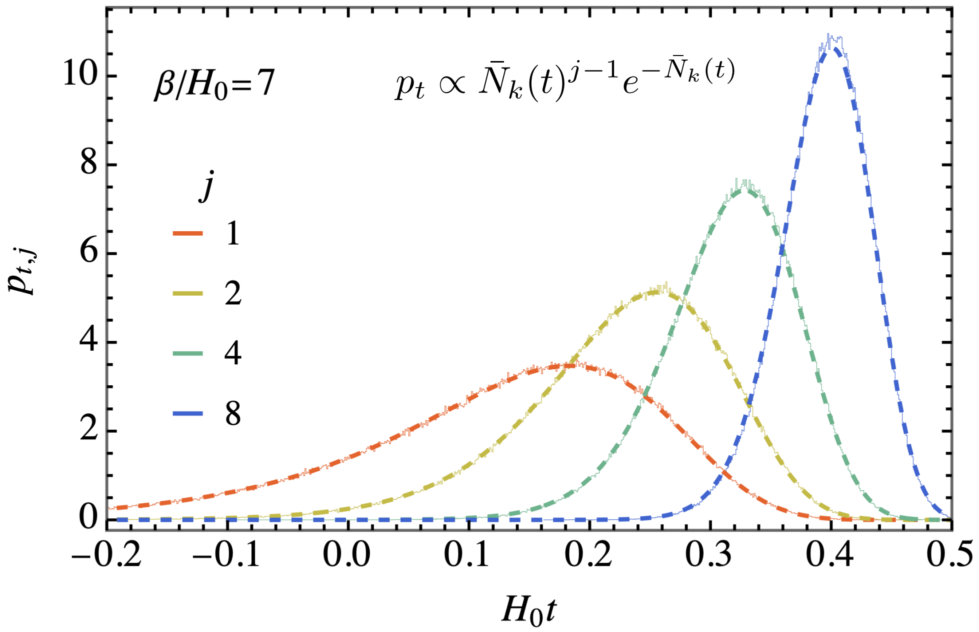
$$F_k(t) = F_k^{(j\le j_c)}(t) F_k^{(j>j_c)}(t)$$

$$F_k^{(j\le j_c)}(t) \approx \prod_{j=1}^{j_c} \left[1 - f(t; t_j, d_j, k)\right]$$

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



Code available at
github.com/vianvask/deltaPT

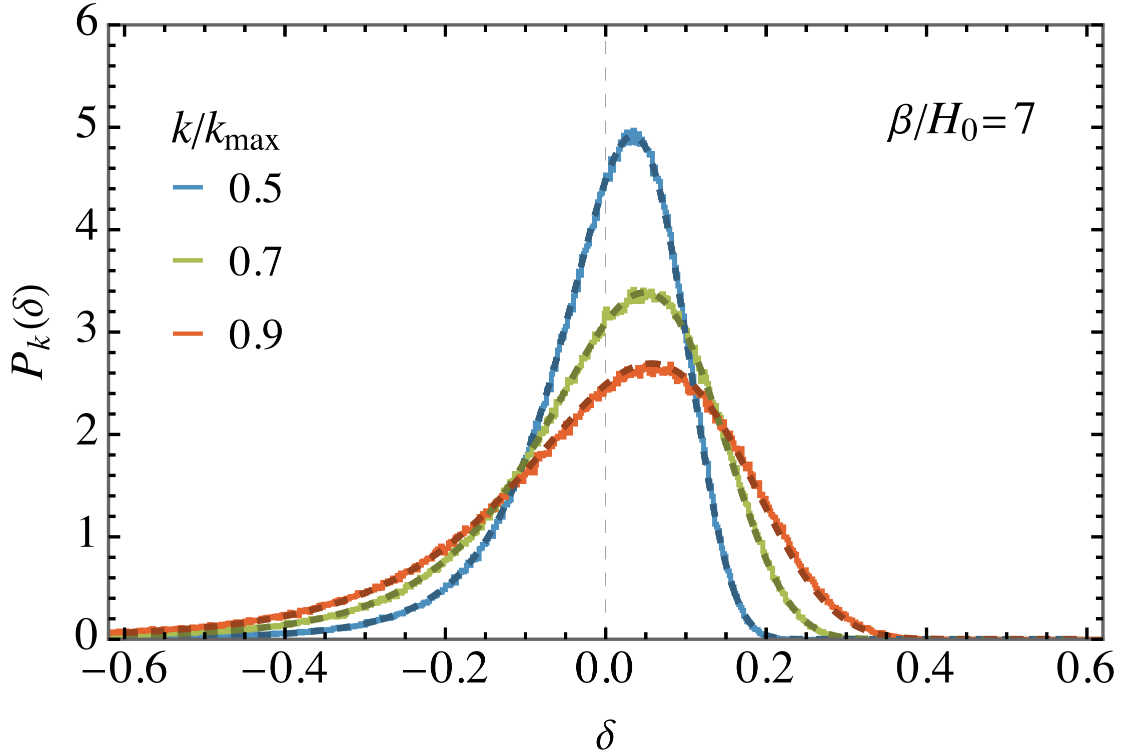


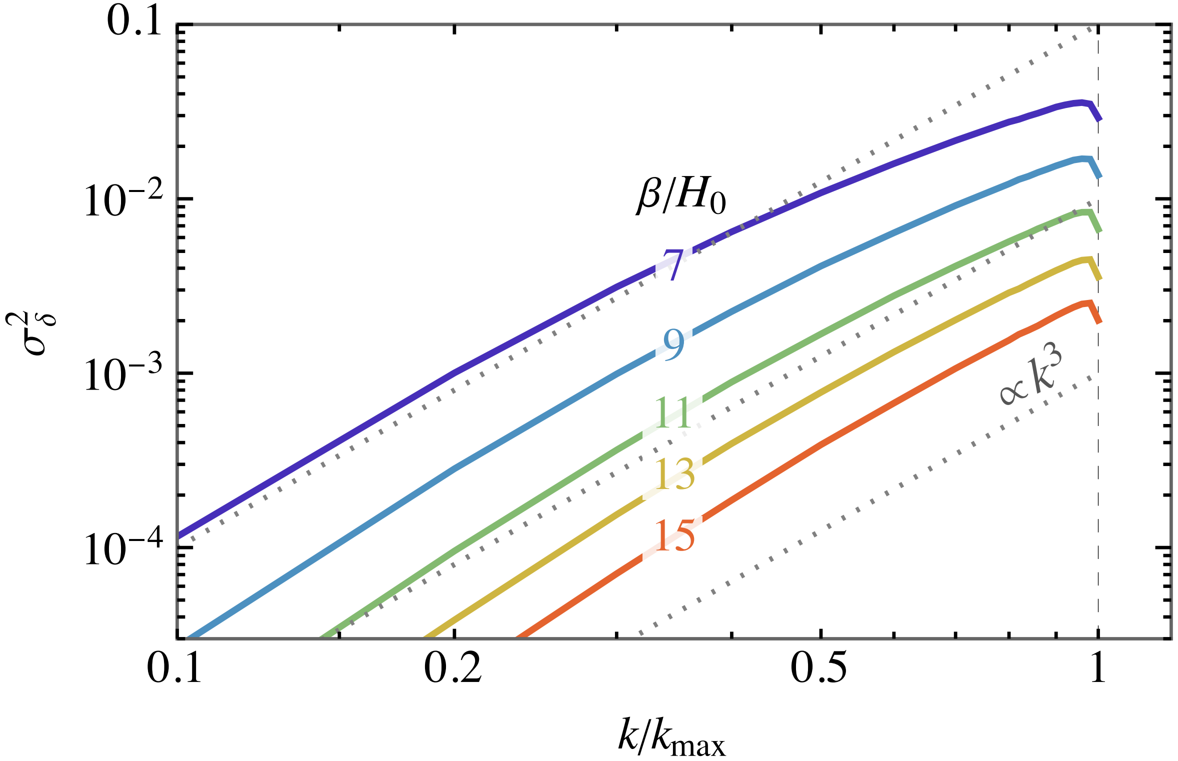
Distribution of density constrast

Lewicki, Toczek, Vaskonen, 2402.04158

Fitting function:

$$P_k(\delta) \propto \exp\left[\frac{\epsilon}{2}(\delta-\mu) - \frac{2}{\epsilon^2\sigma^2}\left(1-e^{\frac{\epsilon}{2}(\delta-\mu)}\right)^2\right]$$





- distribution of the fluctuations has **negative non-Gaussianity**
- small β/H_0 $\Longrightarrow$ slow transition $\Longrightarrow$ large variance of δ

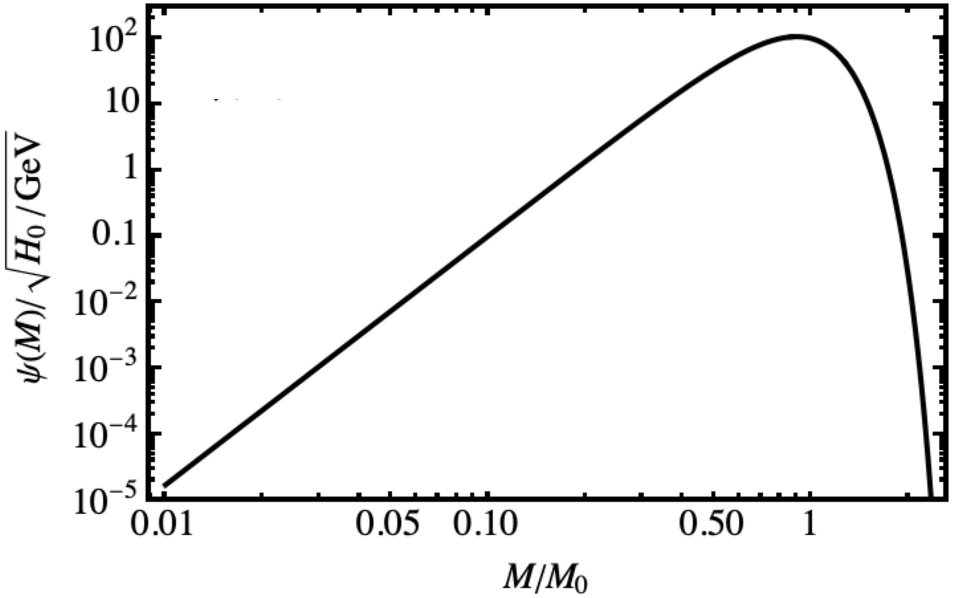
Primordial black holes

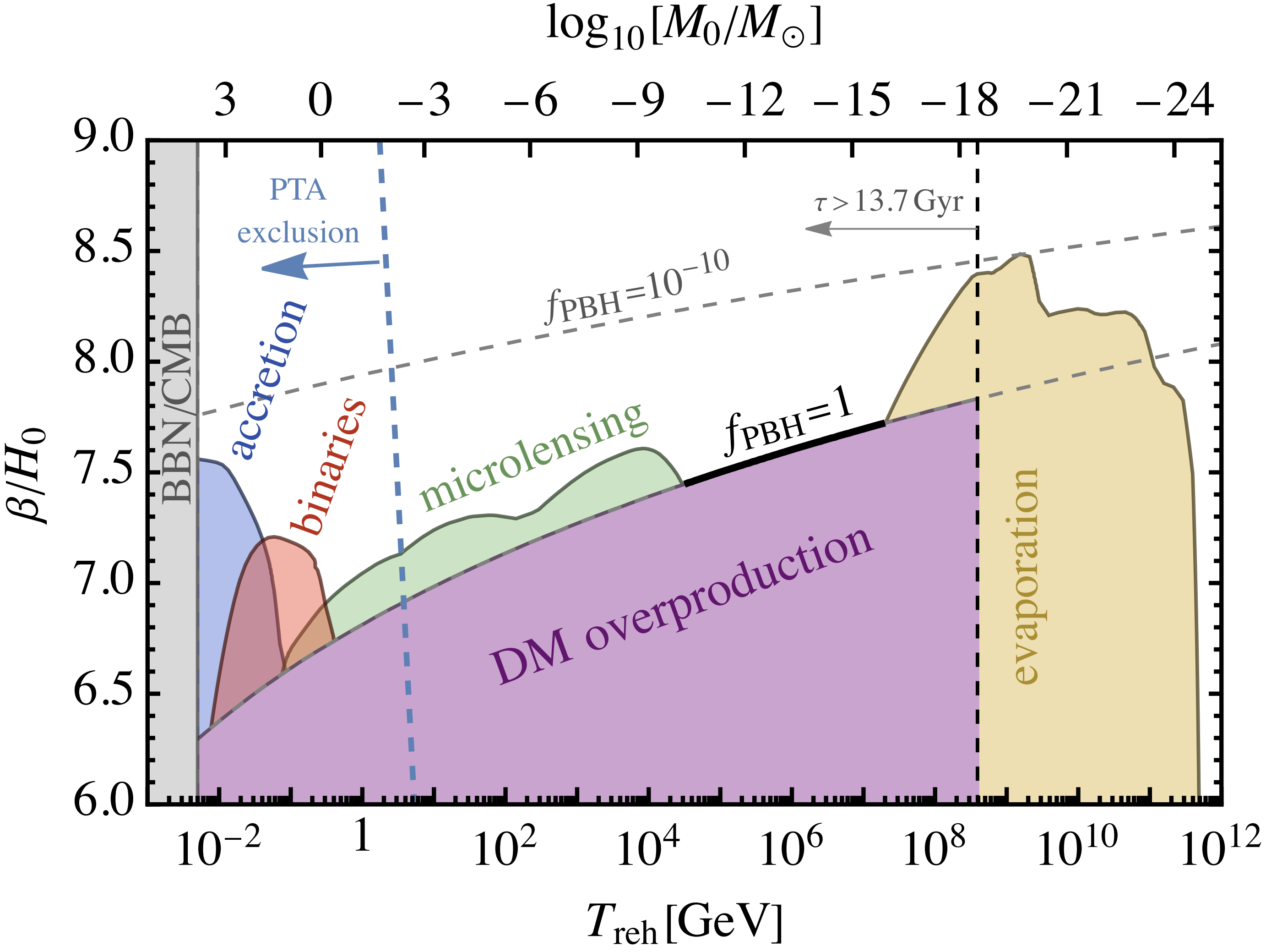
Lewicki, Toczek, Vaskonen, 2402.04158

$$f_{\rm PBH} \sim \int {\rm d}\ln k \int_{\delta_c} {\rm d}\delta P_k(\delta) \dots$$

$$M(\delta) = \kappa M_k (\delta - \delta_c)^\gamma$$

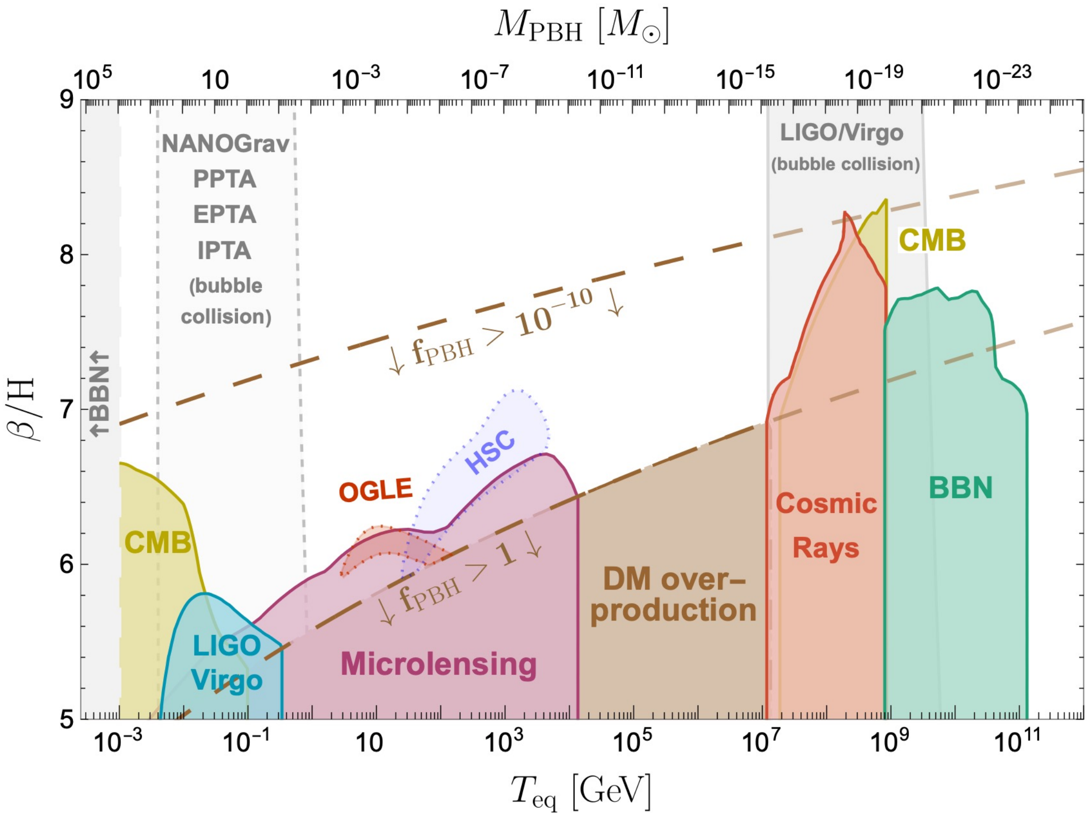
$$\gamma = 0.38, \quad \kappa = 4.2, \quad \delta_c = 0.55$$

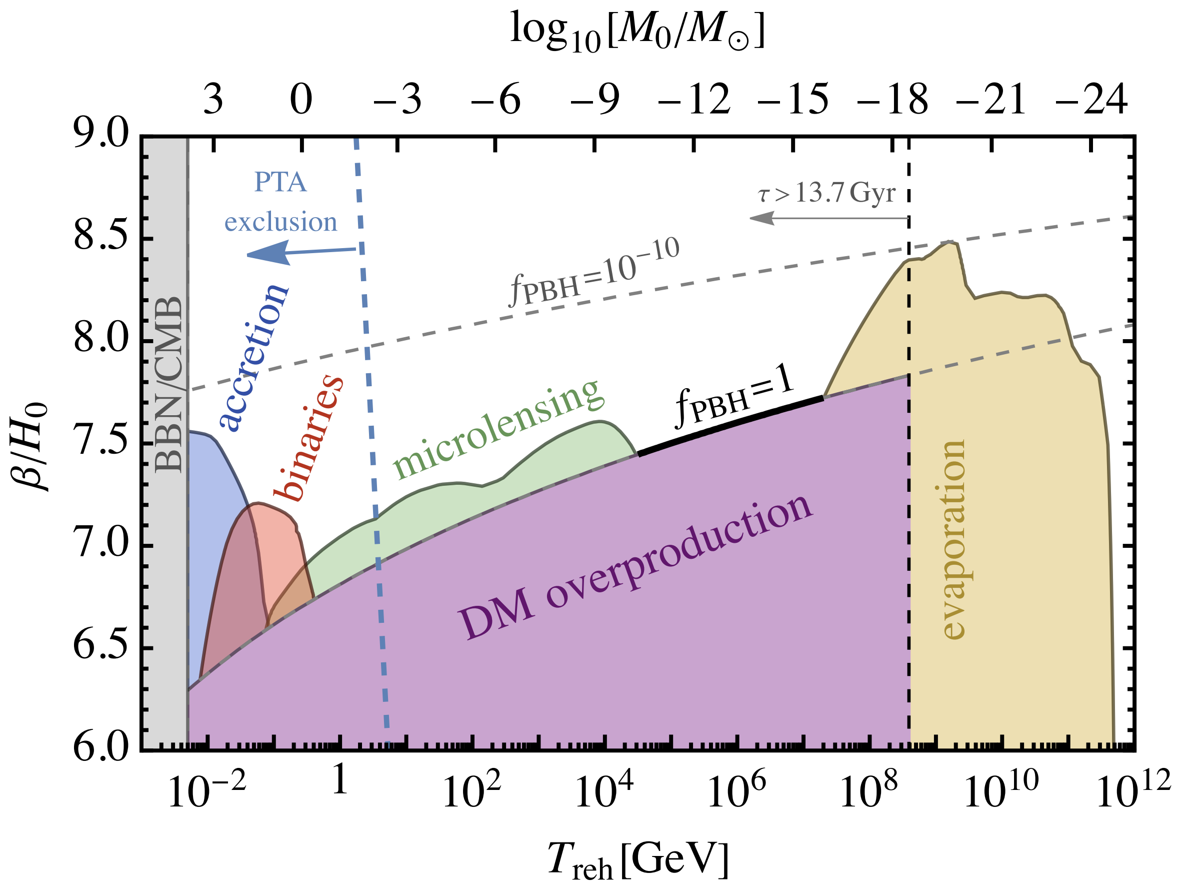




Comparison with Gouttenoire & Volansky 2305.04942

1. We account for fluctuations in the nucleation times of **several bubbles**, GV23 only in the time when nucleation started.
2. We compute the **distribution of the fluctuations** at $k < k_{\max}$, GV23 only at the scale of the largest fluctuations.

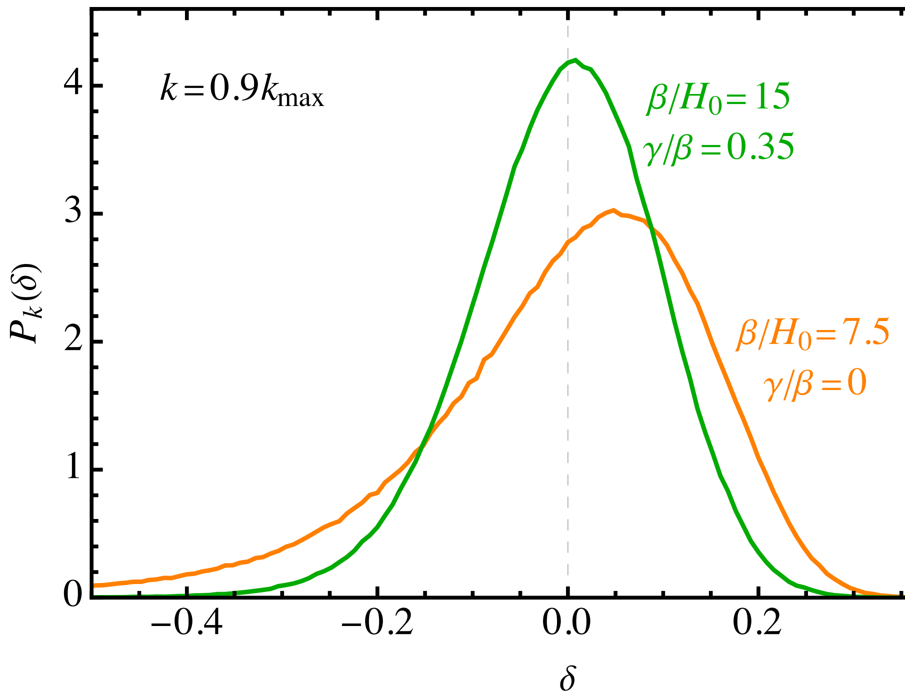


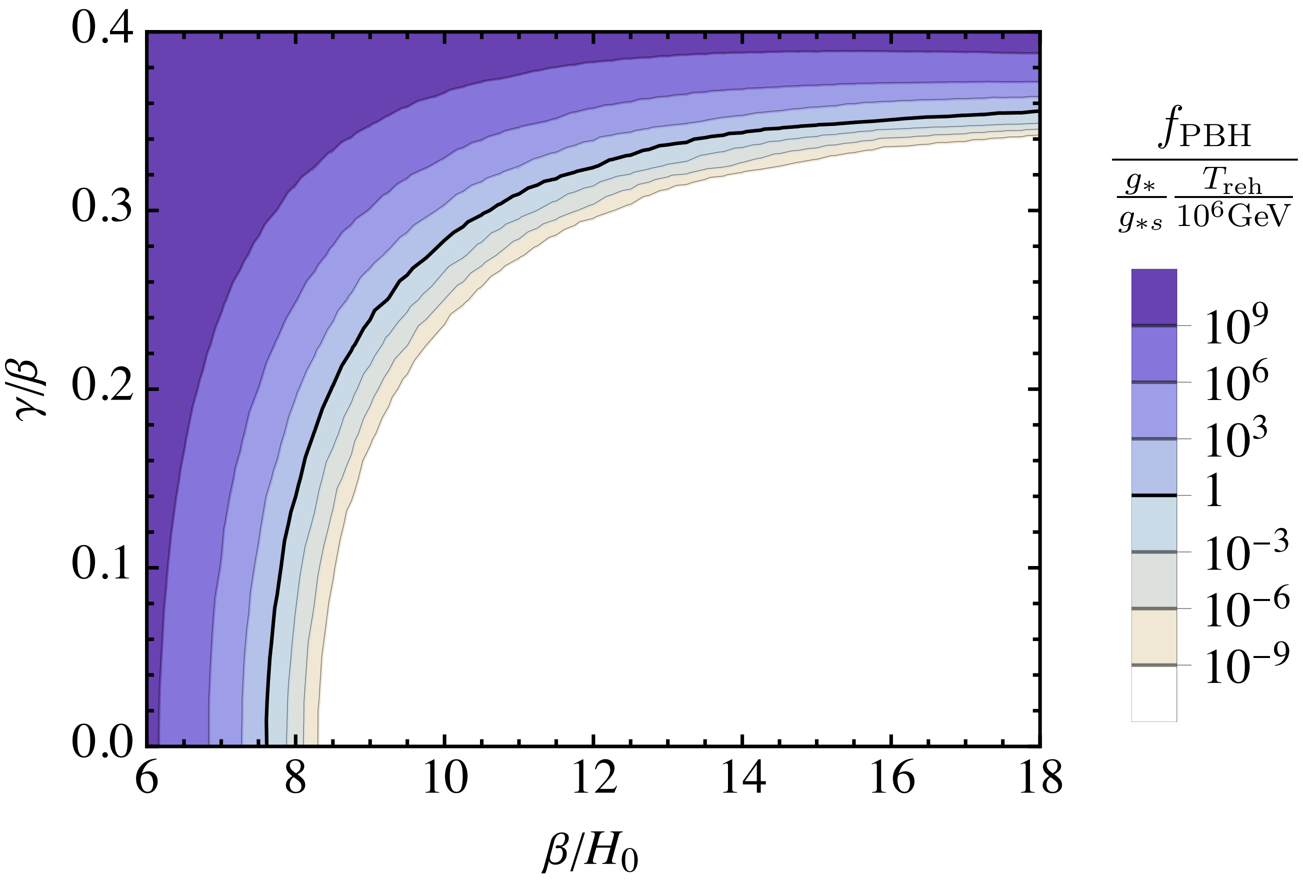


2nd order term in the nucleation rate

Lewicki, Toczek, Vaskonen, in preparation.

$$\Gamma \propto \exp\left[\beta t - \frac{1}{2}\gamma^2 t^2 + \ldots\right]$$





Results in the CSI model

$$V(\phi,T) = V_0 + \frac{3g^4}{4\pi^2}\phi^4\left[\ln\frac{\phi^2}{v^2} - \frac{1}{2}\right] + \frac{g^2T^2}{2}\phi^2$$

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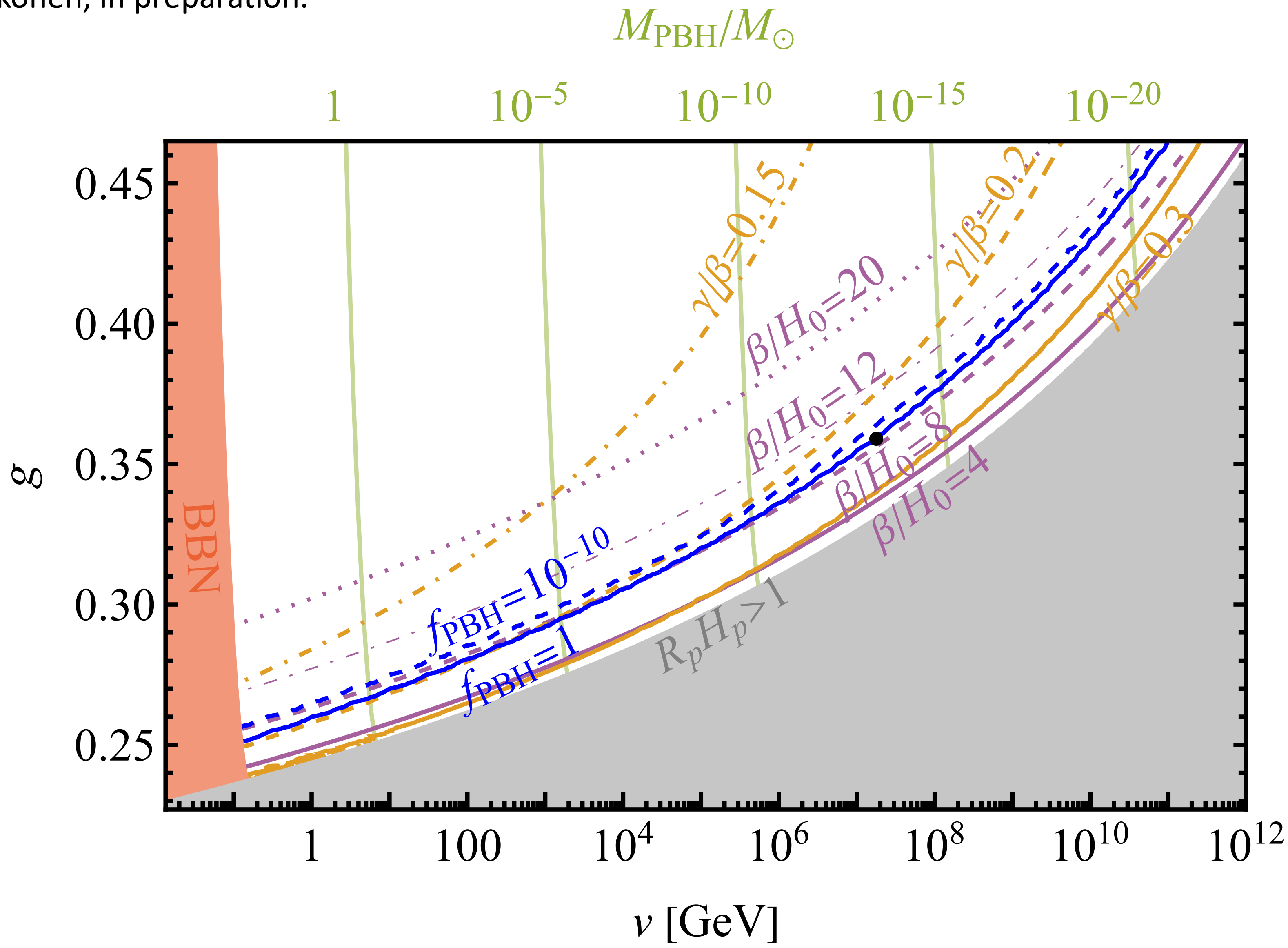
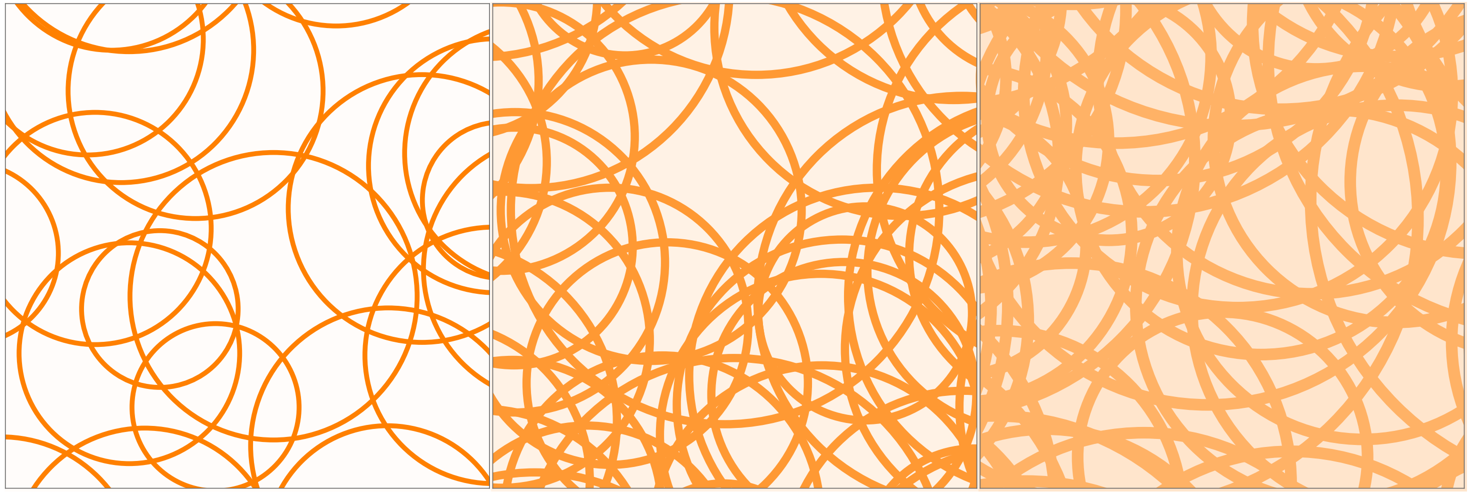


Suppression



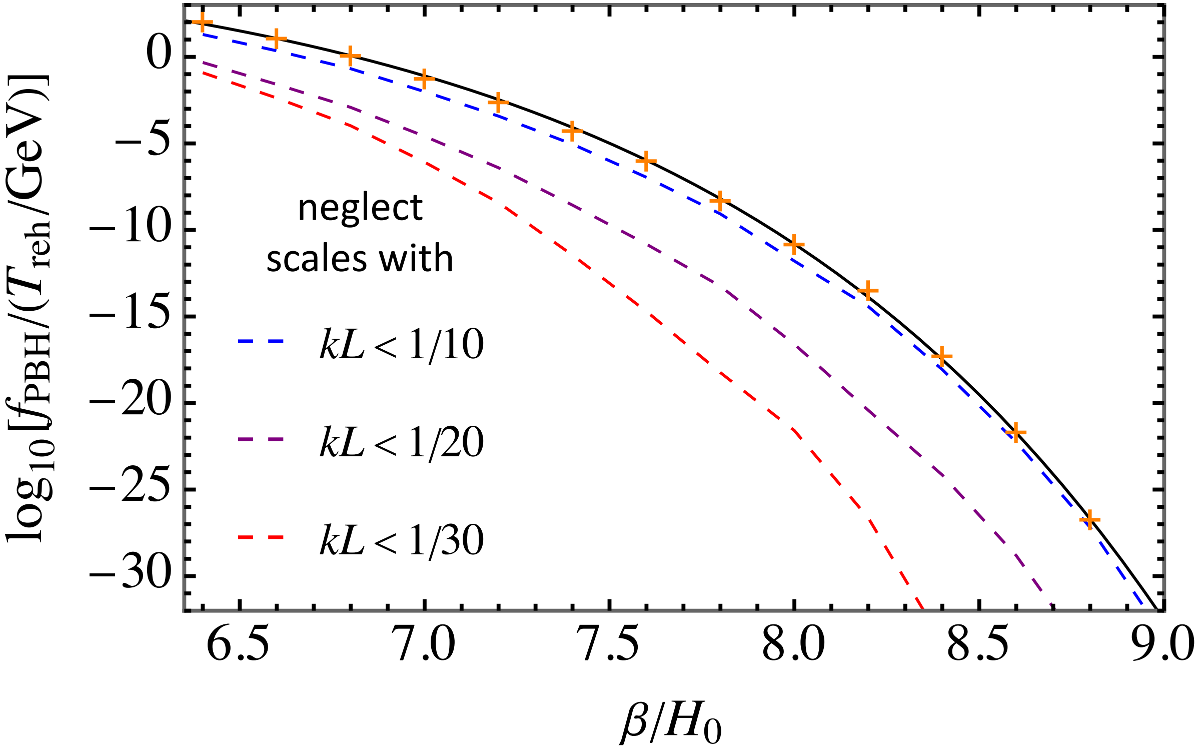
Energy is not distributed smoothly right after the phase transition.

The area of bubble surfaces inside a given volume increases.

⟹ The length scale of the subhorizon fluctuations

$$L = 3V_k/S_{\mathrm{tot}}$$

decreases.



Gravitational waves

Lewicki, Toczek, Vaskonen, 2402.04158

1. **Primary** GWs from bubble collisions:

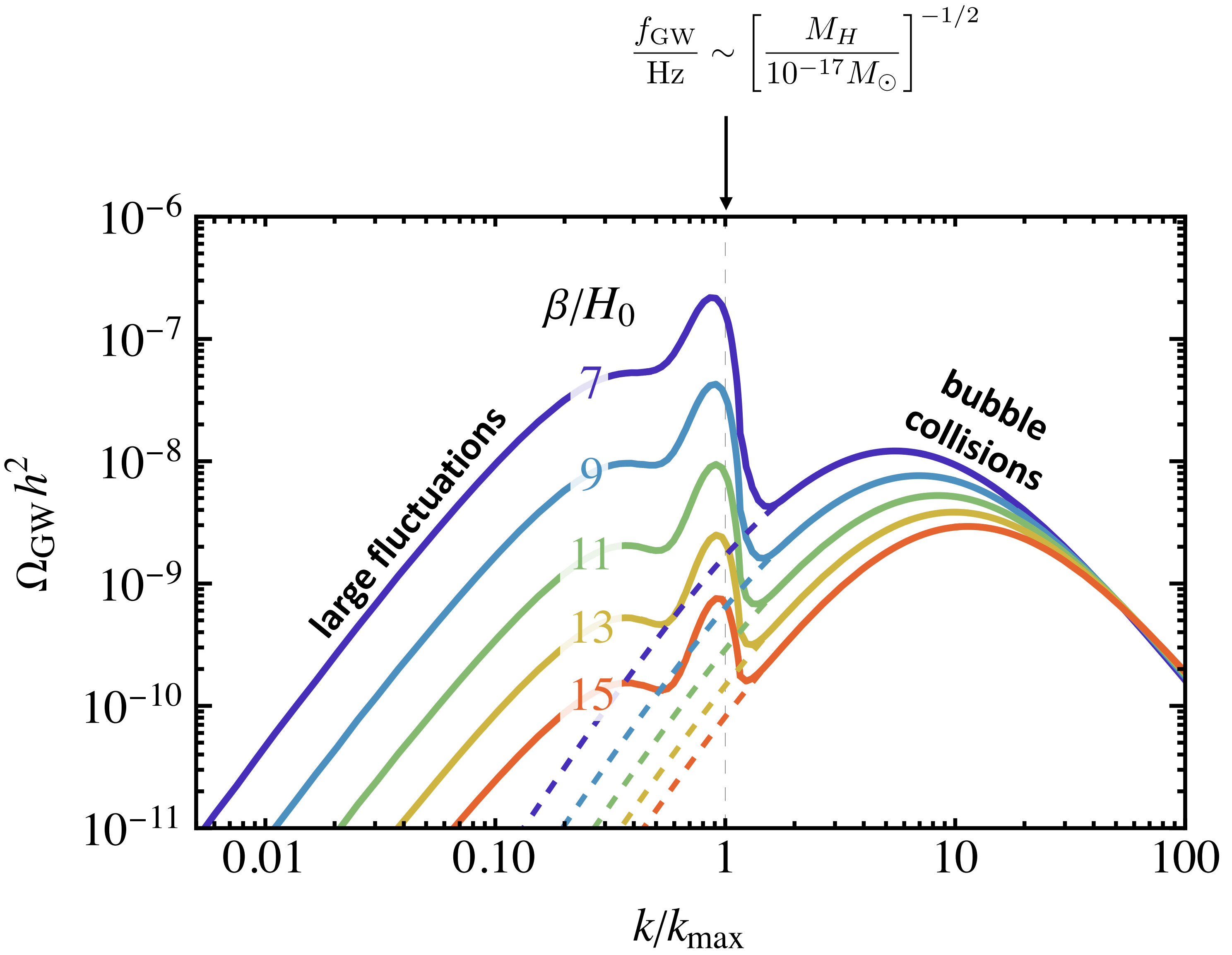
$$k_{\rm peak} \approx k_{\rm max}\, \beta/H_0$$

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

2. **Secondary** GWs induced by the large fluctuations:

$$k_{\rm peak} \approx k_{\rm max}$$

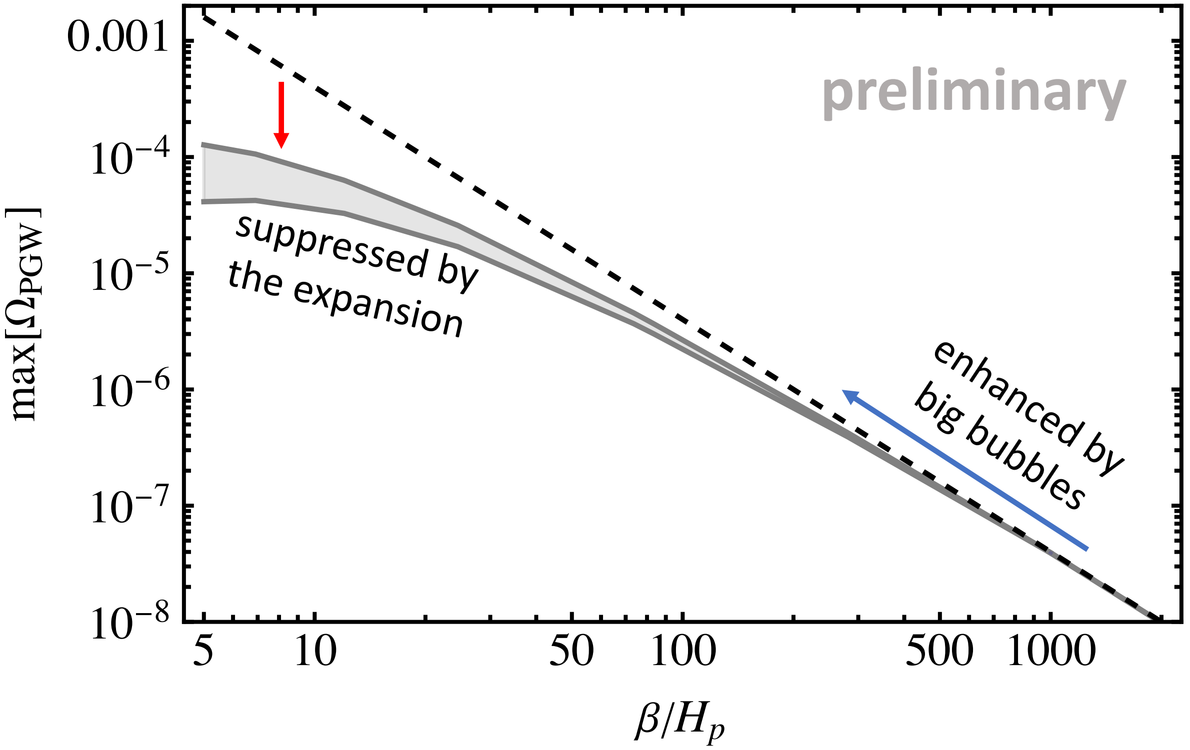
$$\Omega_{\rm SGW} h^2 \propto e^{-\beta/H_0}$$



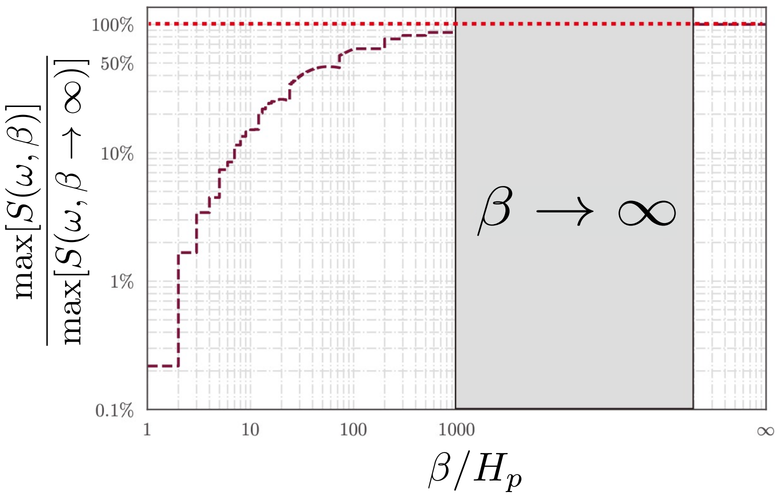
Suppression of the primary GWs

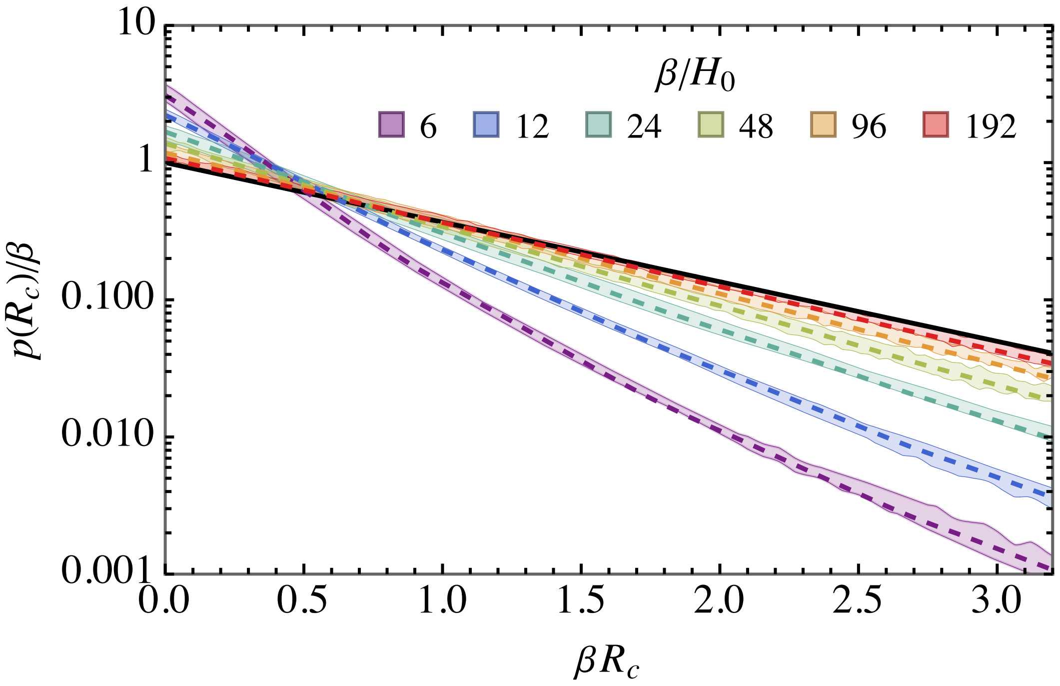
$$\Omega_{\rm PGW} \propto \left[\frac{H_p}{\beta}\right]^2 S(\omega,\beta)$$

Suppression for strongly supercooled transitions
[Lewicki, Vaskonen, in preparation]:



Suppression factor in RD
[Zhong, Gong, Qiu, JHEP 02 (2022)]:

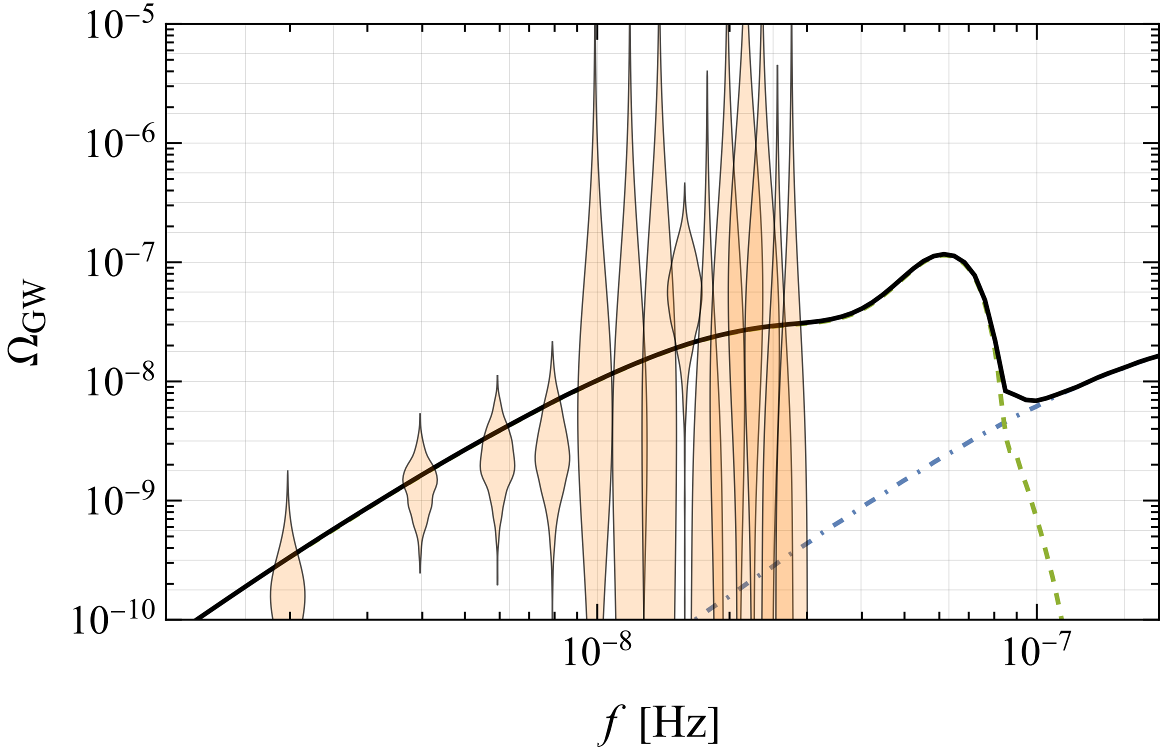


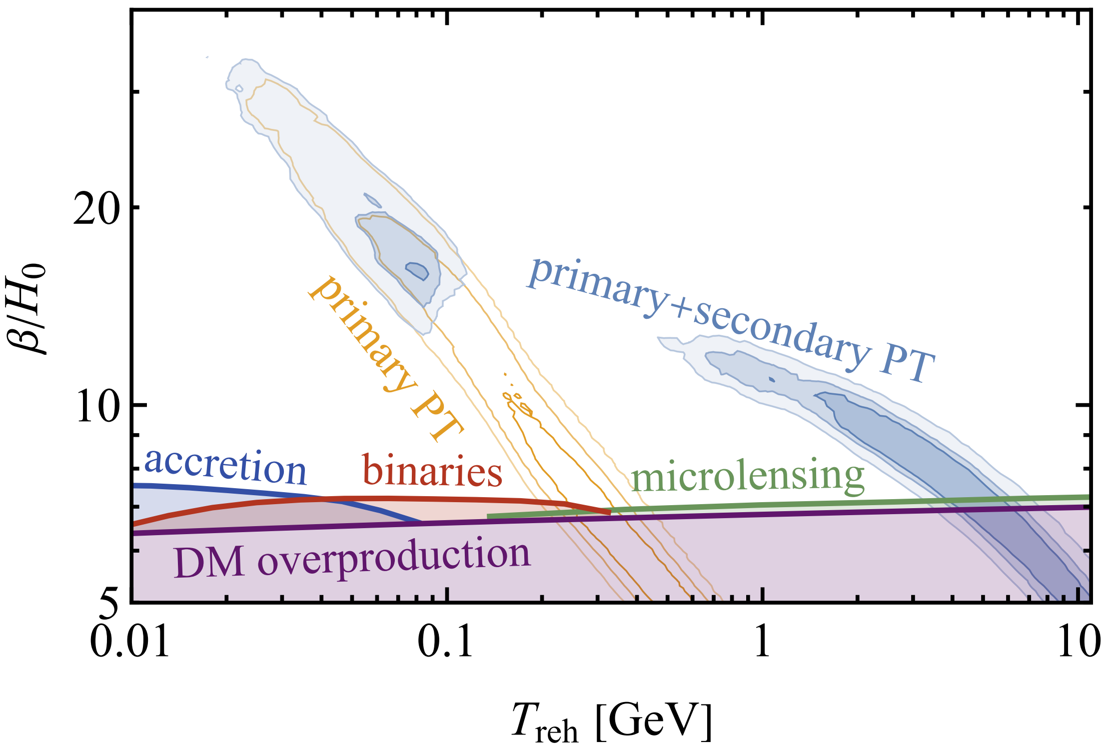


PTA fit

Lewicki, Toczek, Vaskonen, 2402.04158

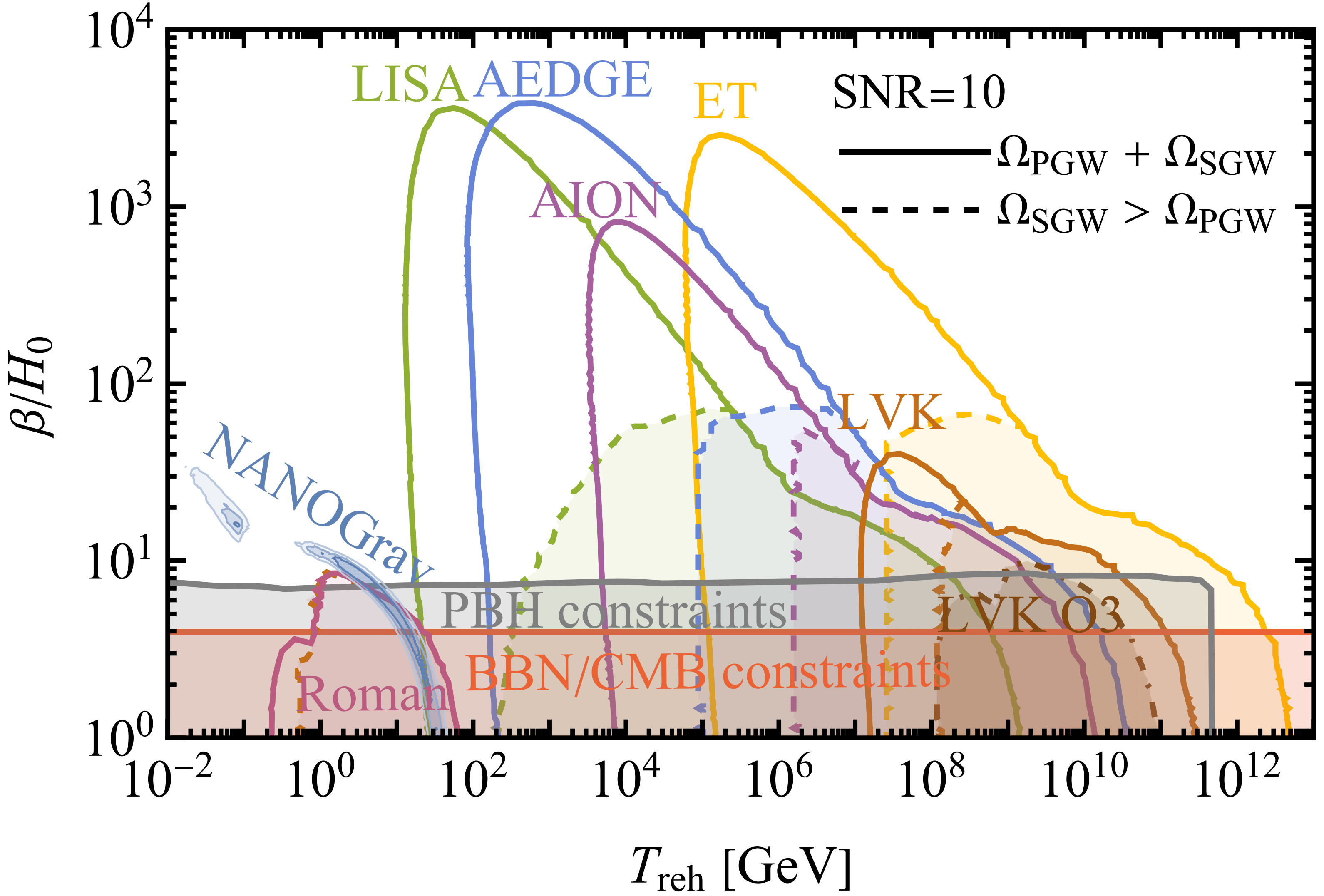
Negative non-Gaussianity $\Longrightarrow$ PTA fit is not in tension with PBH production





Prospects

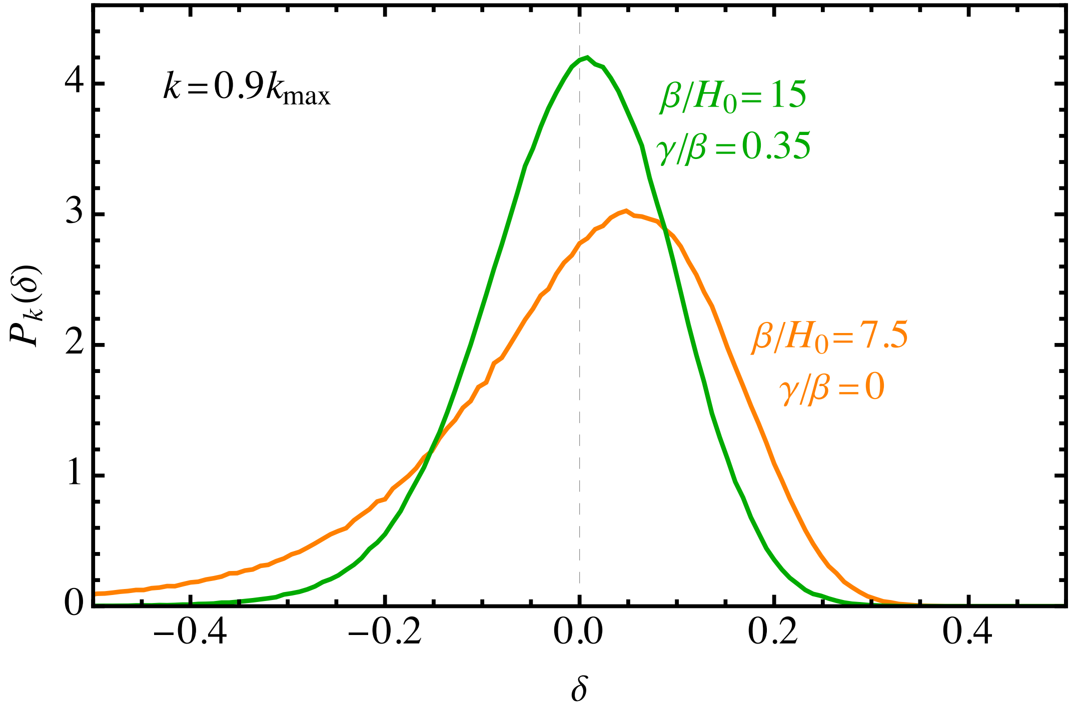
Lewicki, Toczek, Vaskonen, 2402.04158



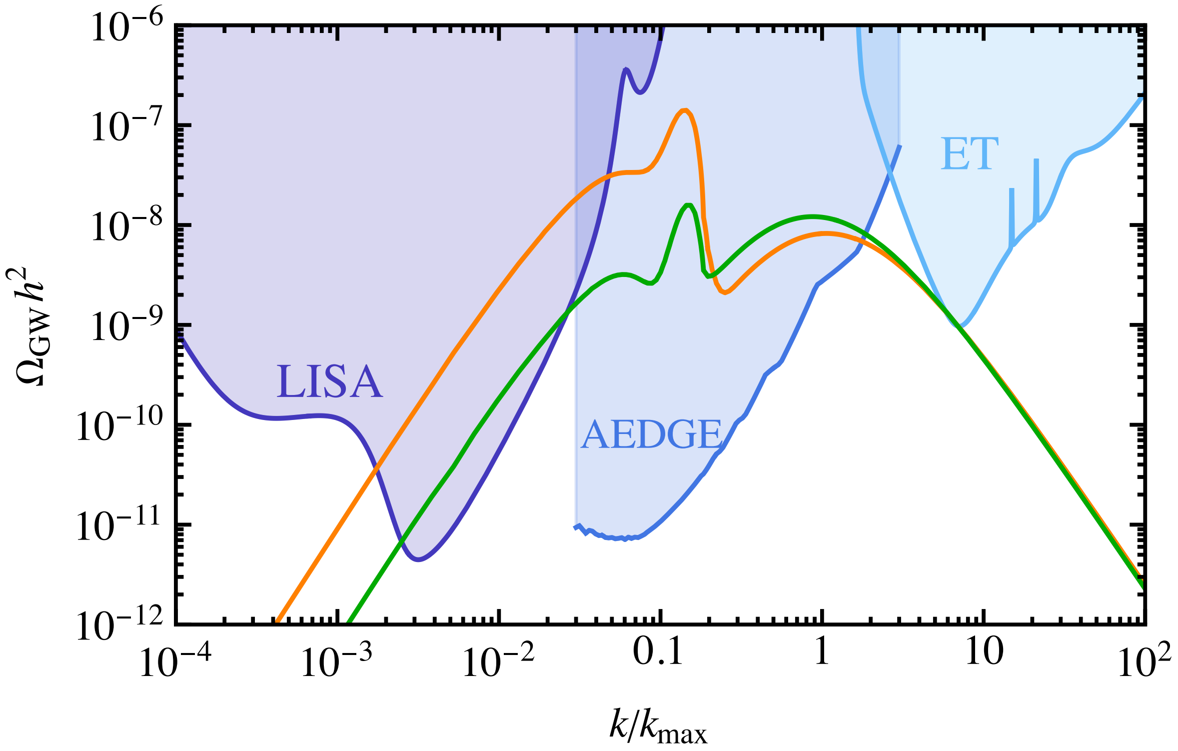
2nd order term in the nucleation rate

Lewicki, Toczek, Vaskonen, in preparation.

$$\Gamma \propto \exp\left[\beta t - \frac{1}{2}\gamma^2 t^2 + \dots\right]$$



Same PBH abundance, different GW spectra:



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Lewicki, Toczek, Vaskonen, in preparation.

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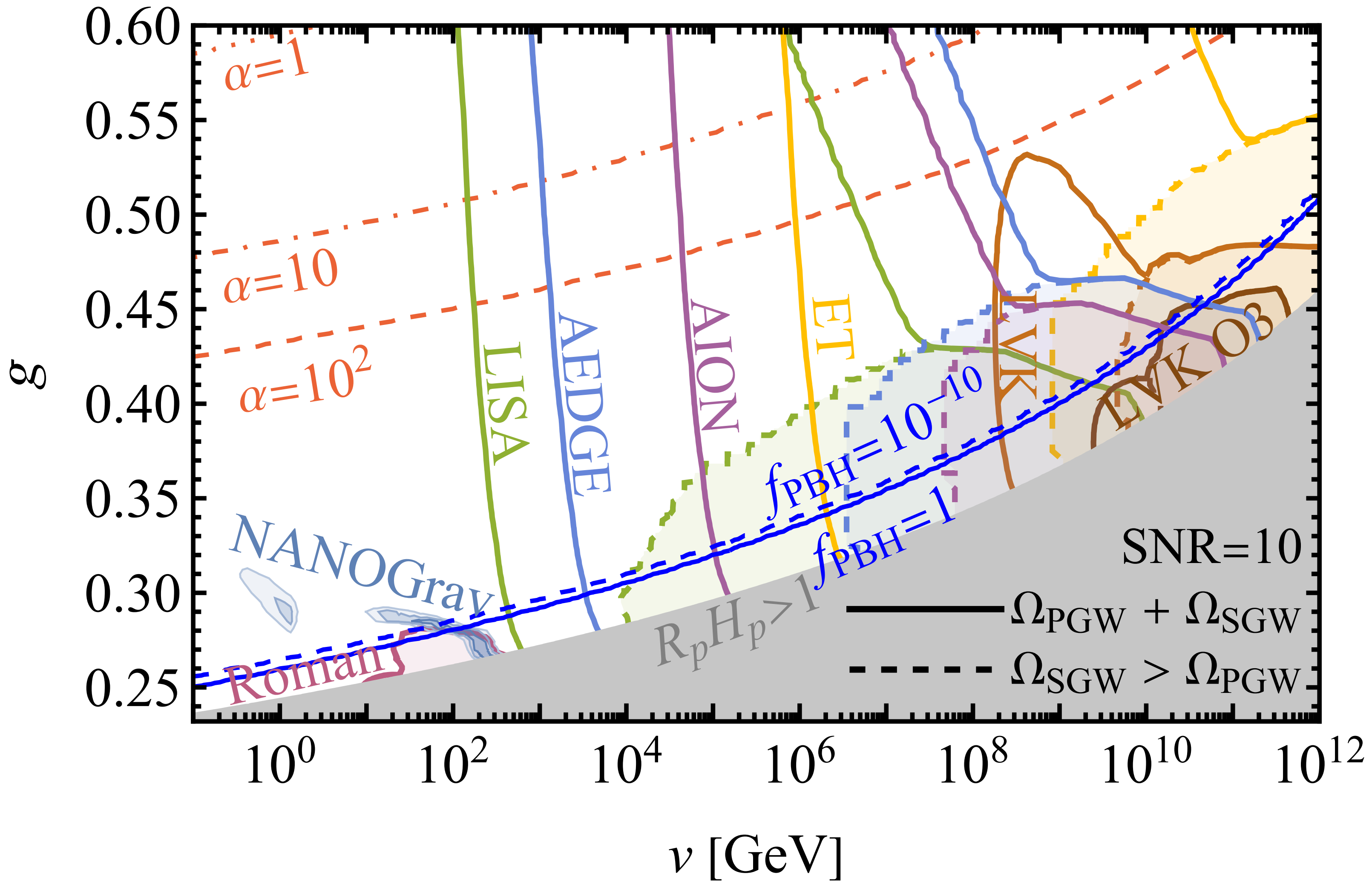

Summary

Slow and supercooled transition

e.g. in CSI models

Large density fluctuations

PBHs and scalar induced GWs

- Negative non-Gaussianity suppresses PBH formation.
- 2nd order term in the nucleation rate is relevant.
- Primary GWs are suppressed for slow transitions.