Cosmological first-order phase transitions

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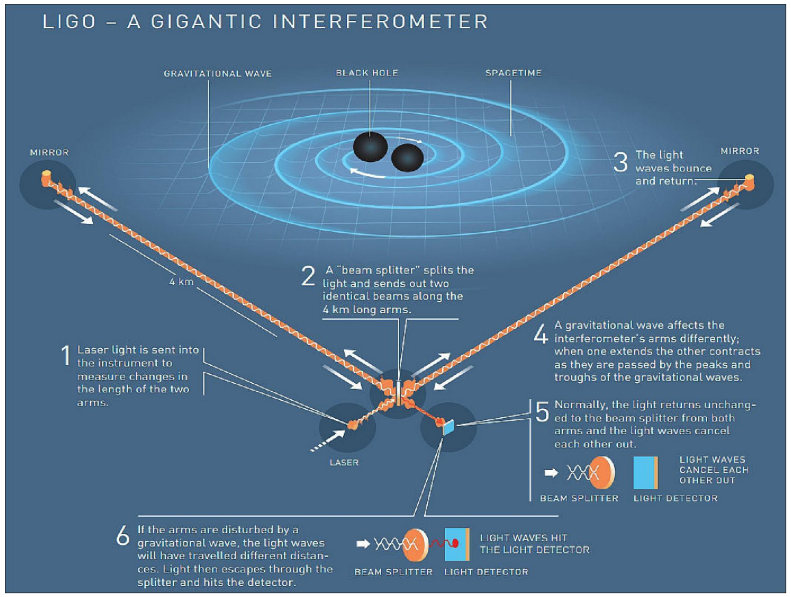
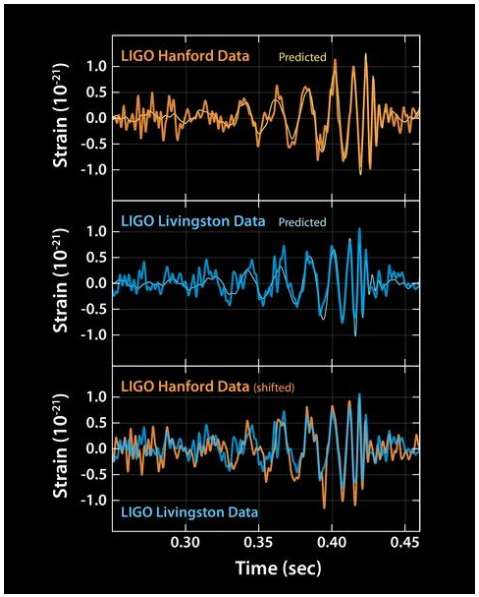
Gravitational-wave era

There must be new physics beyond the Standard Model of particle physics:

Dark Matter, Inflation, Hierarchy problem, Matter-anti-matter asymmetry…Where is it?

Energy frontier **Cosmic frontier** Intensity frontier





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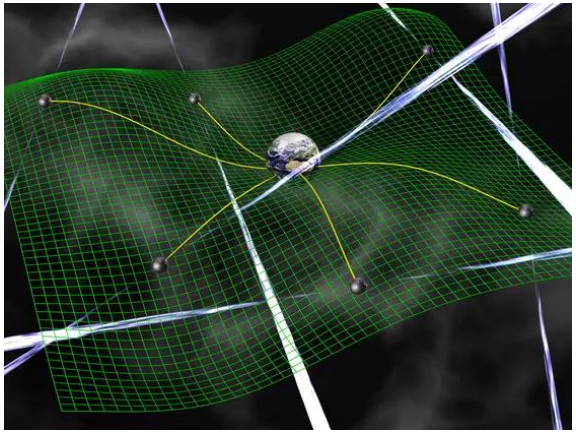
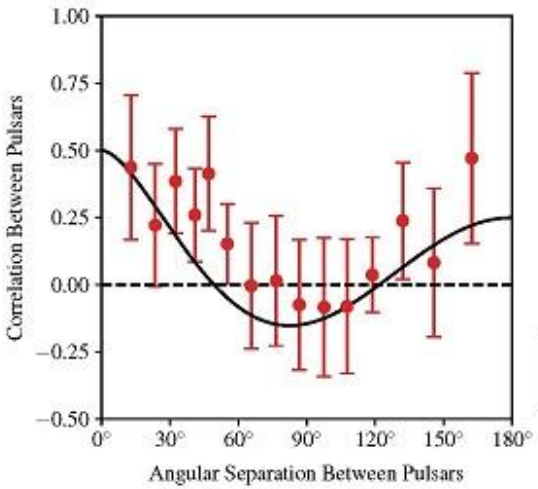
(Nobel Laureates for Physics in 2017)

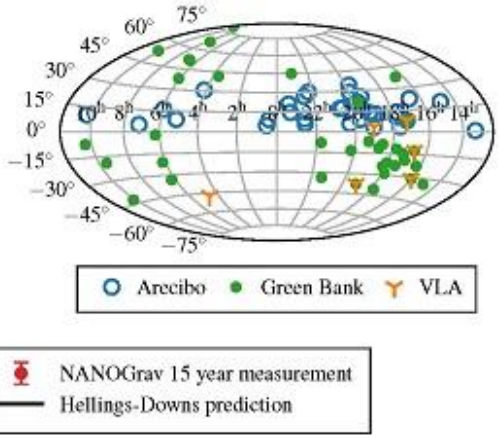
Opens an extremely promising window to detecting new physics!

Stochastic GW background

Evidence for a gravitational-wave (GW) background







In 2023, NANOGrav, EPTA, PPTA, and CPTA independently announced compelling evidence for this Hellings-Downs correlation

GWs are everywhere!

Possible sources for the PTA GWs

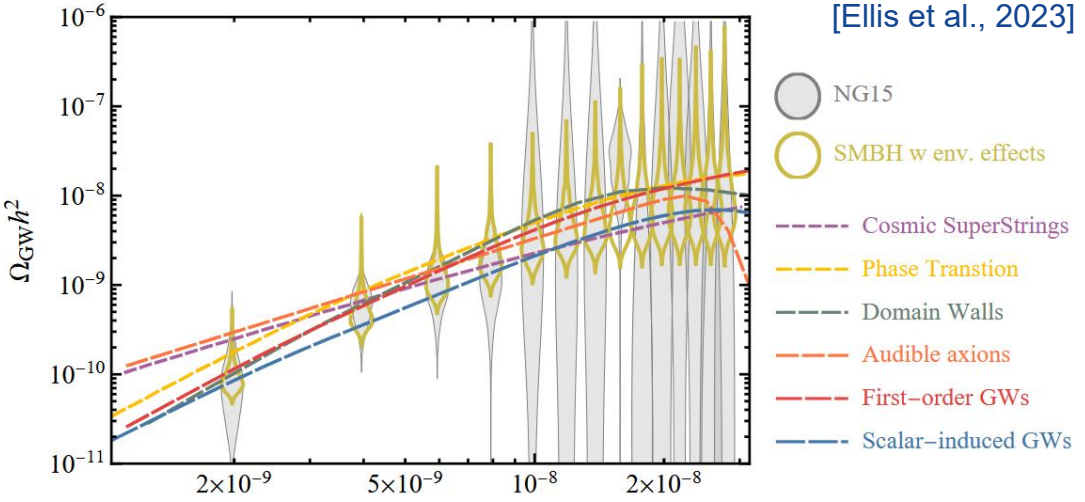
Astrophysical sources:

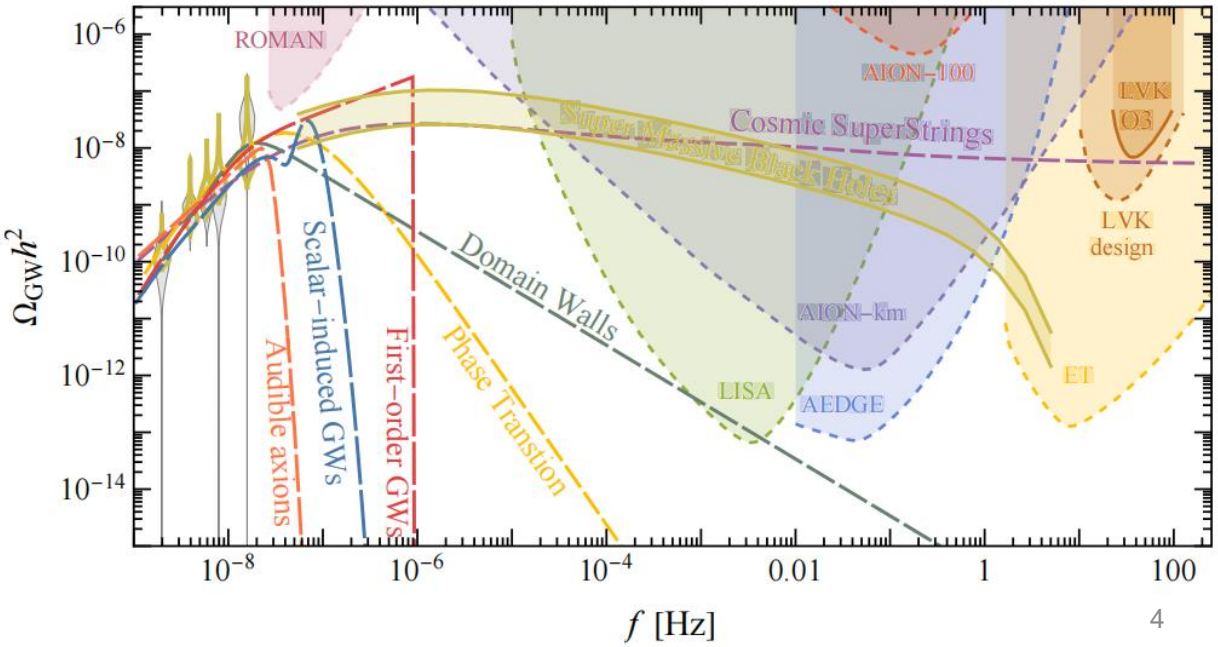
- Supermassive black holes (SMBHs)

Cosmological sources:

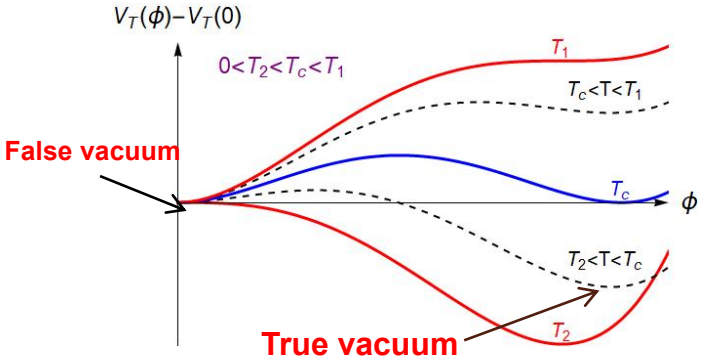
- Scalar-induced GWs
- Cosmological first-order phase transitions
- Cosmic strings
- Domian walls
- Audible axions

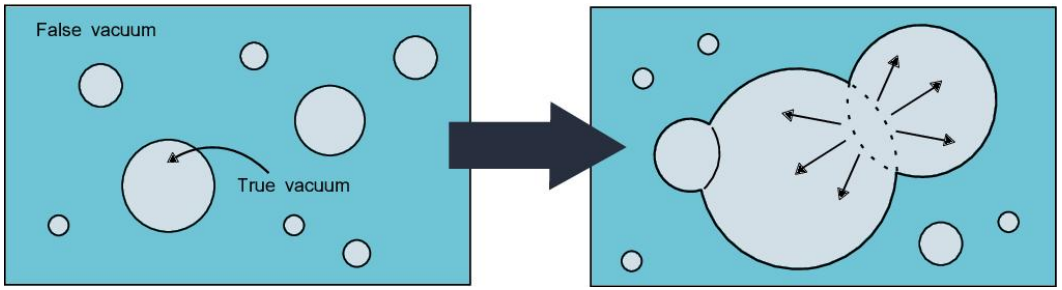
[Ellis et al., 2023]

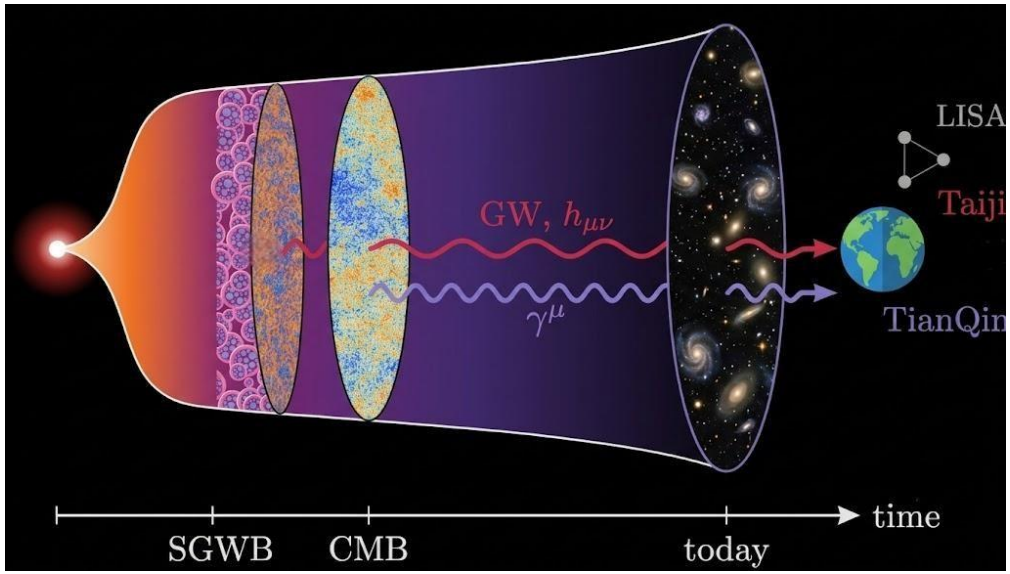




What is a first-order phase transition?



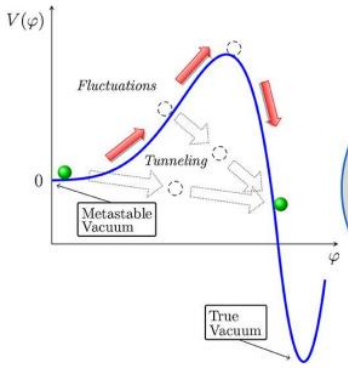




[adapted from Philipp Schicho's slide]

Different “stages” and some pheno questions

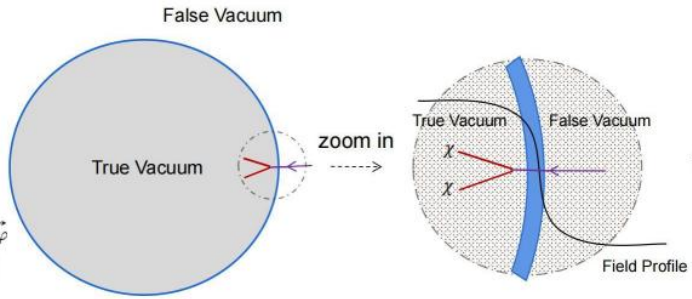
Bubble Nucleation



Are there any real-time, out-of-equilibrium effects in bubble nucleation?

See Li-Gong Bian’s talk!

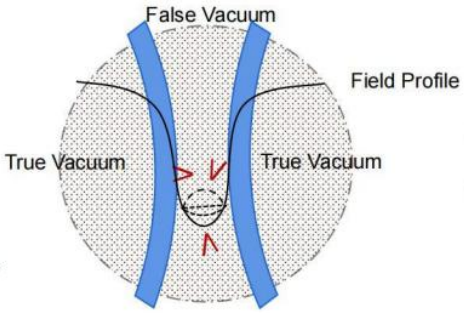
Bubble Expansion



Can we understand bubble wall dynamics from first principles?

What is the impact of the DM production from bubble expansion on CMB, matter power spectrum?

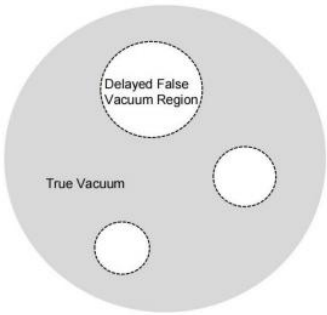
Bubble Collision



A new mechanism of baryogenesis from bubble collision? Available GUT baryogenesis?

See Wei Chao’s talk!

Bubble Coalescence



How to compute curvature perturbations from slow FOPTs efficiently?

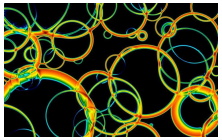
Is there a relation between slow FOPTs and stochastic tunnelling in inflation?

Gravitational waves from a FOPT

泡泡成核关键物理量：
相变温度T_n，相变强度α，
相变速率β/H

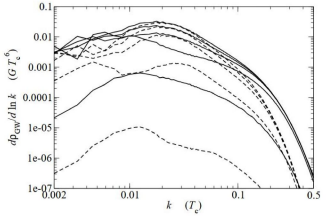
泡泡膨胀关键物理量：
泡泡壁速度v_w

作为参数输入至

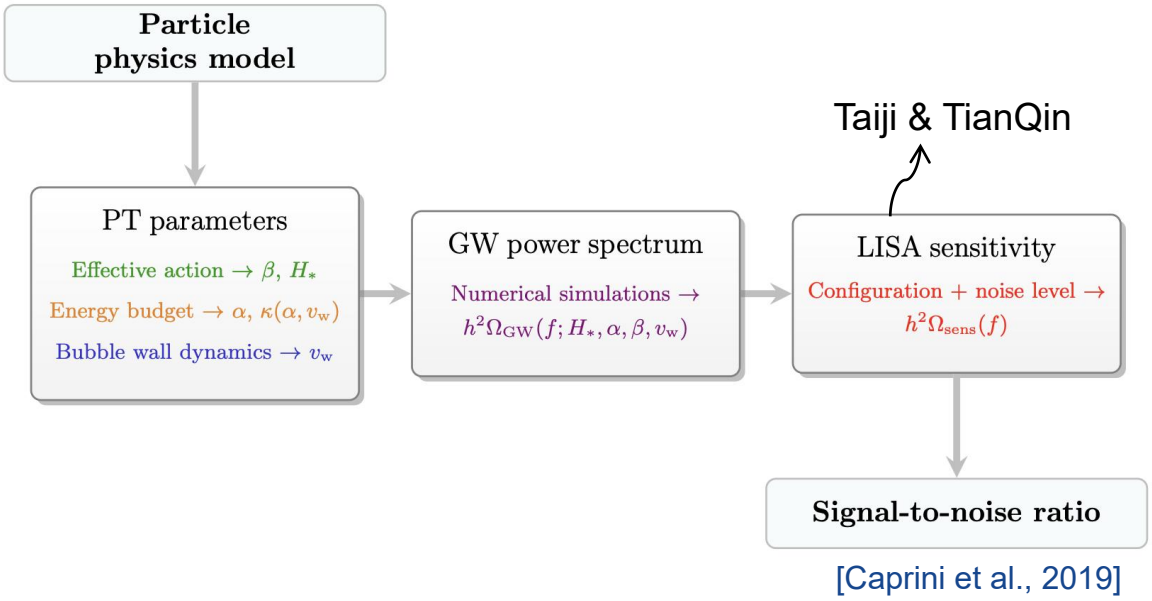


泡泡碰撞与融合：大型数值模拟

引力波功率谱



[WA, general grant proposal, 2026]



[Caprini et al., 2019]

Bubble collision and percolation

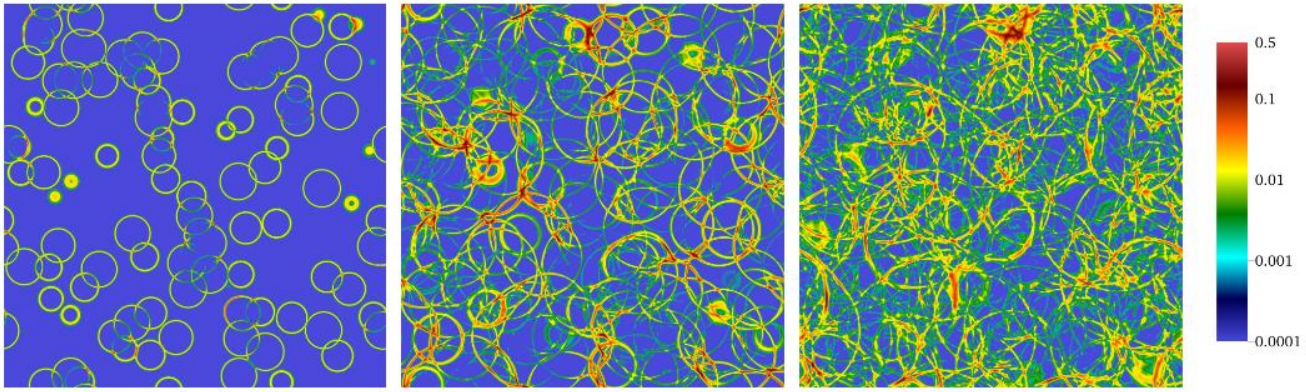


FIG. 4. Slices of fluid kinetic energy density E/T_c^4 at $t = 500\,T_c^{-1}$, $t = 1000\,T_c^{-1}$ and $t = 1500\,T_c^{-1}$ respectively, for the $\eta/T_c = 0.15$, $N_b = 988$ simulation.

[Hindmarsh, Huber, Rummukainen, Weir 2014]

GW sources:

- Bubble wall collisions
- Sound waves
- (Magneto)hydrodynamic turbulence

T_n nucleation temperature

α transition strength

β/H avg. bubble separation

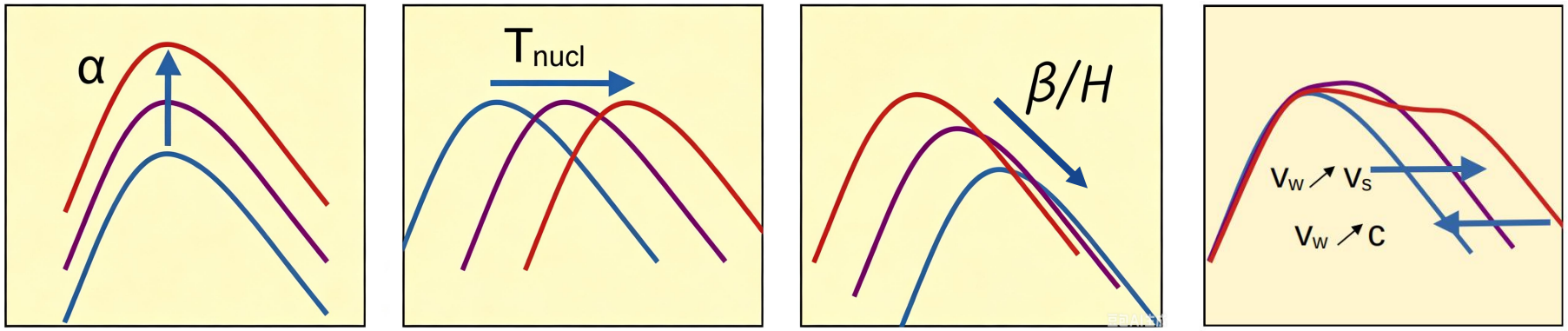
v_w bubble wall speed

....

- Relativistic hydrodynamics + order parameter field

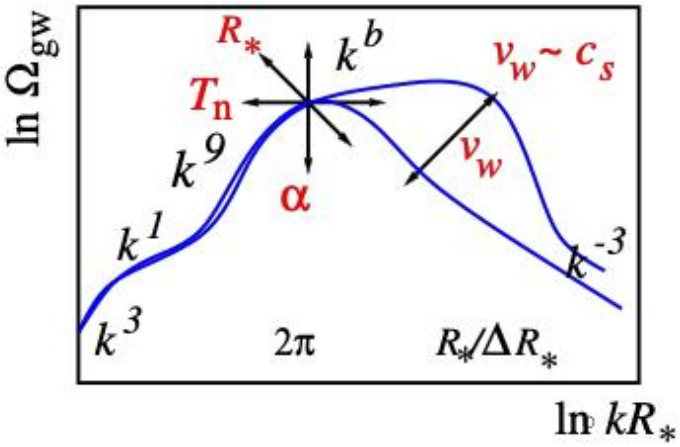
  [Hindmarsh et al. 2013–2019; Cutting et al. 2019; Dahl et al. 2021, 2024; Brandenburg et al. 2022; Jinno et al. 2022; Auclair et al. 2022; Caprini et al. 2024; Correia et al. 2025]
- Large dynamic range → large simulation volume
- Main source of GWs: sound waves

Fingerprinting the gravitational wave



[figure by Kari Rummukainen]

General shape of the GW power spectrum from sound waves



$$\Omega_{\rm sw}(f)h^2 = 2.65\times10^{-6}\left(\frac{H_{\rm pt}}{\beta}\right)\left(\frac{\kappa_{\rm sw}\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{1/3} \times v_w\left(\frac{f}{f_{\rm sw}}\right)^3\left(\frac{7}{4+3(f/f_{\rm sw})^2}\right)^{7/2}\Upsilon(\tau_{\rm sw})$$

$$\Upsilon = 1-(1+2\tau_{\rm sw}H_{\rm pt})^{-1/2}$$ (RD)

HG, Sinha, Vagie, White, JCAP [2007.08537]

$$\Upsilon = \frac{2[1-y^{3(w-1)/2}]}{3(1-w)}$$

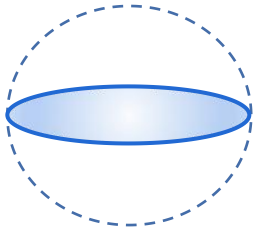
Yang Xiao, HG, Jia-Hang Hu, Jin Min Yang, Yang Zhang, PRD Letter [2410.23666]

See Huai-Ke Guo's talk!

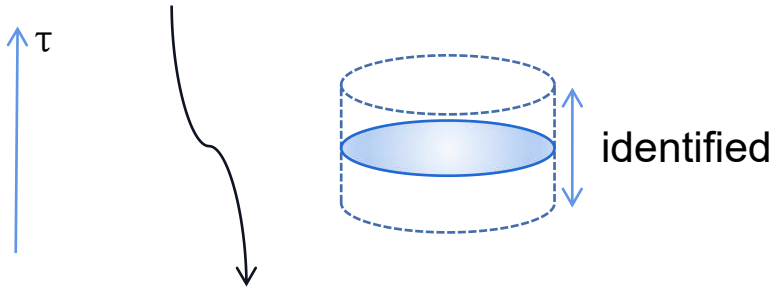
[Sharma, Dahl, Brandenburg, Hindmarsh (2023); Roper-Pol, Procacci, Caprini 2023; Giombi, Dahl, Hindmarsh 2024]

Effective potential and nucleation rate

O(4) bounce gives critical bubble at $\tau = 0$



O(3) bounce is the critical bubble



relevant for cosmological FOPTs ⟶ This is why we need dimensional reduction

- Effective potential directly gives
  - Critical temperature
  - Latent heat
  - Order-parameter change

DRalgo: [Ekstedt et al. 2025]

Dimensional reduction
+ high-T expansion
+ resummation

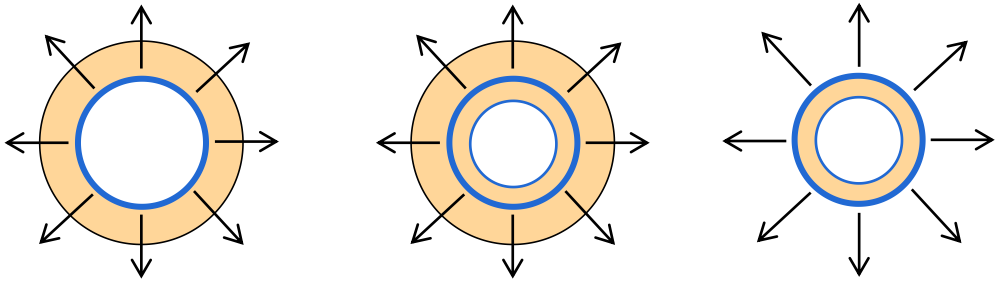
- Bubble nucleation rate

$$\Gamma = \frac{\kappa}{2\pi}\left[\frac{\det(-\vec{\nabla}^2 + V''(0))}{\det'(-\vec{\nabla}^2 + V''(\phi_c))}\right]^{1/2}\left(\frac{E_c}{2\pi T}\right)^{3/2} e^{-E_c/T}$$

  - New computation tools: `BubbleDet` [Ekstedt, Gould, Hirvonen 2023]
  - Gauge-independent rates [(Hirvonen) Löfgren, Ramsey-Musolf, Schicho, Tenkanen (2022), 2023; Liu, Qin, Bian 2025]
  - Self-consistent bounce [WA, Alexandre, & Sarkar 2023]

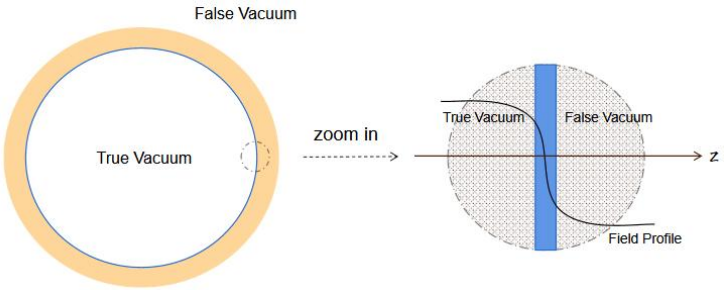
Bubble wall velocity

deflagration (爆燃) hybrid (混合) detonation (爆炸)

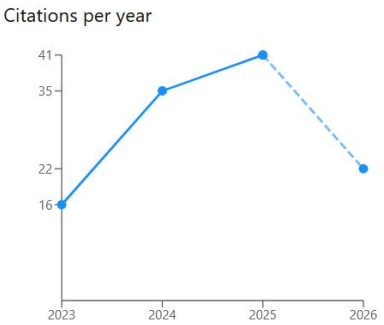


$v_w < c_s$ $c_s < v_w < v_J$ $v_J < v_w$

(Jouguet velocity)



- Wall velocity bounds: [WA, Laurent, van de Vis 2025]
  - Local thermal equilibrium (LTE): upper bound [WA, Garbrecht, Tamarit 2021; WA, Laurent, van de Vis 2023; Wang, Yuwen 2023; Wang, Yuwen, Hao, Wang 2023; Si et al. 2025]
  - Ballistic: lower bound [WA, Laurent, van de Vis 2025]



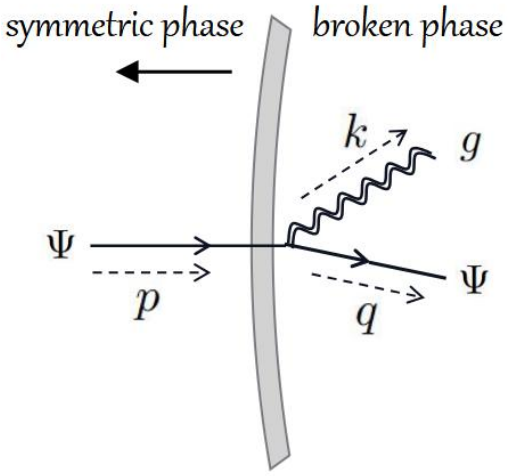
[WA, Laurent, van de Vis 2023]

- Linearised Boltzmann solutions: $(p\cdot\partial)\delta f = -m\partial_\mu m\dfrac{\partial f_{\rm eq}}{\partial p_\mu} - C[f_{\rm eq}+\delta f].$
  - Iterative solver [De Curtis et al 2022, 2024]
  - Chebyshev polynomials [Laurent, Cline 2025]
  - WallGo [Ekstedt et al. 2025]
  - Missing self-energy term [WA et al. 2025]

$$\Box\varphi + V'(\varphi) + \sum_{i=\phi,\chi}\frac{\mathrm{d}m_i^2(\varphi)}{\mathrm{d}\varphi}\int_{\mathbf{k},i} f_i(\mathbf{k},x) + \underbrace{\int \mathrm{d}^4x'\,\Pi_\varphi^{\rm R}(x,x')\varphi(x')}_{\text{not considered in earlier studies on the kinetic approach}} = 0\,.$$

High-frequency GWs from bubble expansion

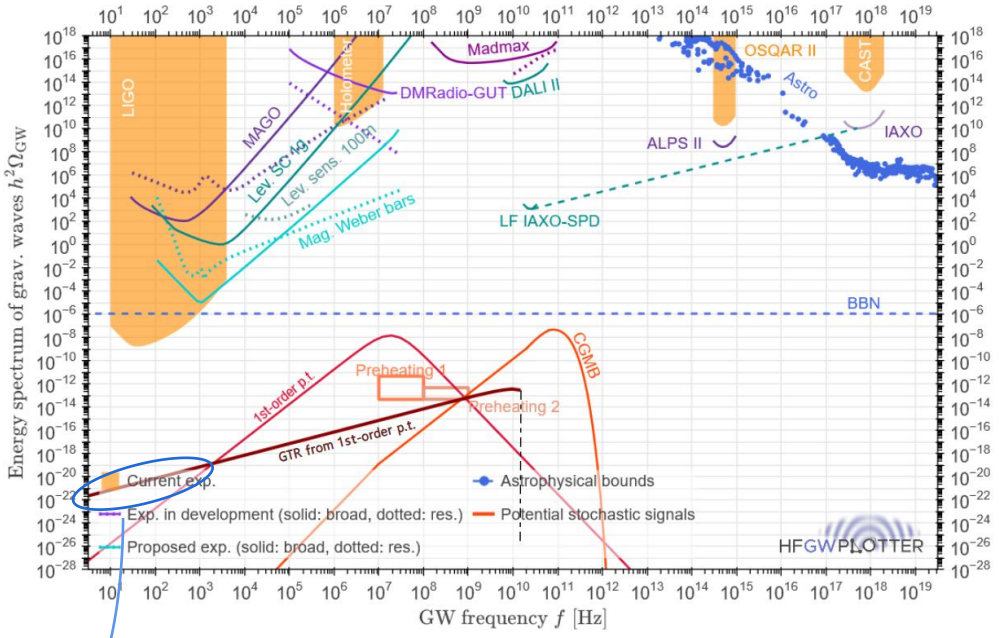
Gravitational transition radiation as a new source of GWs [WA 2026; Qiu, Jiang & Huang 2026]



similar to gravitational bremsstrahlung

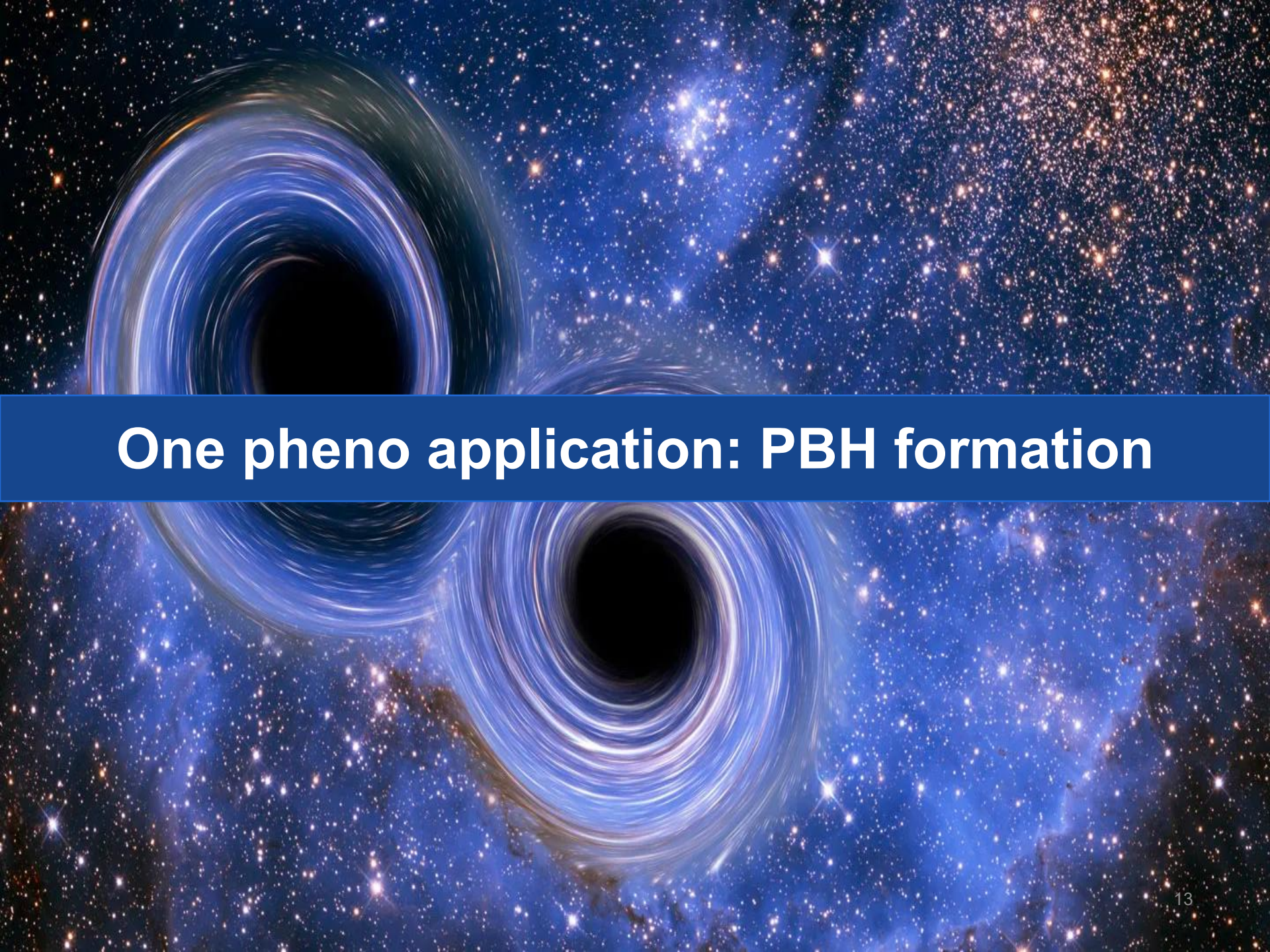
See Zhao-Yuan Yu's talk!

$$T = 10^{14}\,\mathrm{GeV},\ \gamma_w = 500,\ m_{\chi,b} = 50\,T,$$
$$T_{\max} = m_{\mathrm{pl}},\ \beta/H = 20,\ \alpha_n = 1,\ v_w \to 1$$



(unfortunately, subdominant compared to conventional sources)

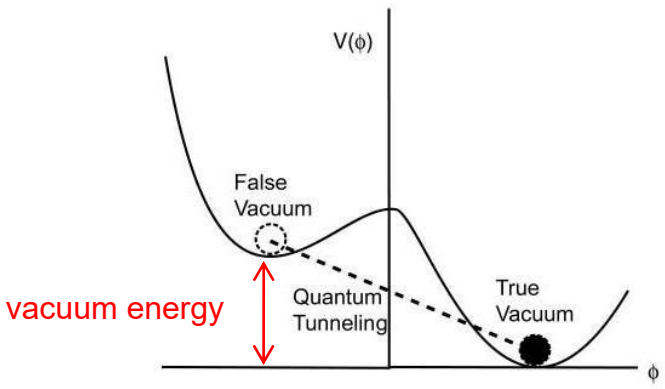
(not trustable)

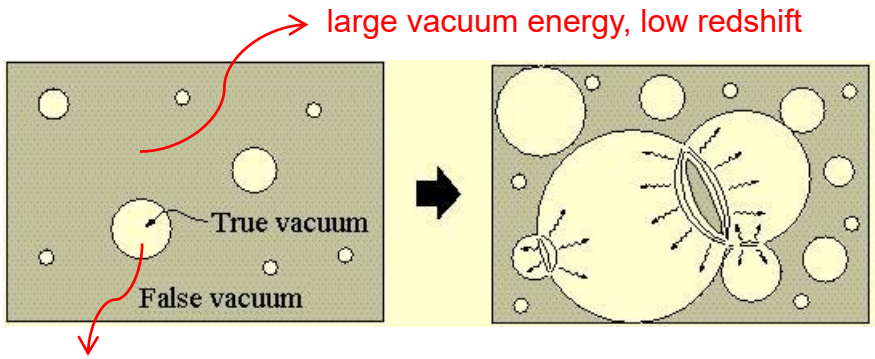


One pheno application: PBH formation

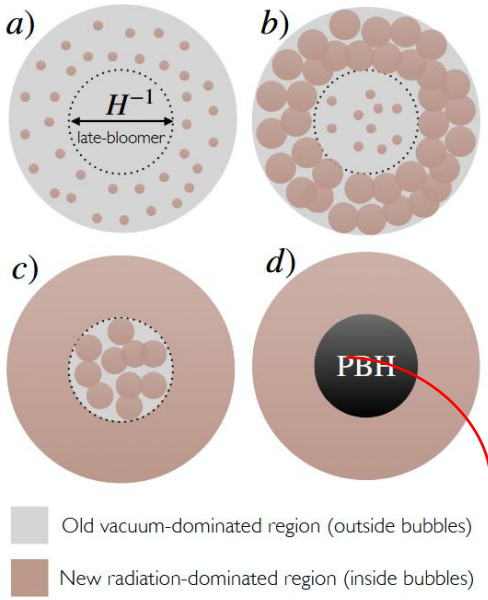
Primordial black holes from a slow FOPT

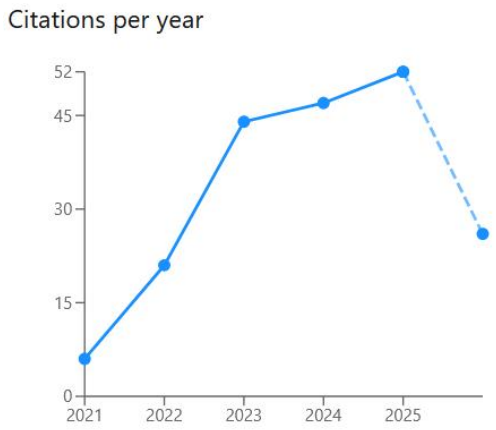
False vacuum has a nonvanishing vacuum energy





Density perturbations from randomness of bubble nucleations [**Liu et al. 2021**; Gouttenoire & Volansky 2023]





[Liu et al. 2021]

collapse into BH if $\delta > \delta_c$ (density contrast threshold)

A gauge-dependence issue

Last year, it was pointed out a gauge-dependence issue in previous studies: almost ruling out this mechanism

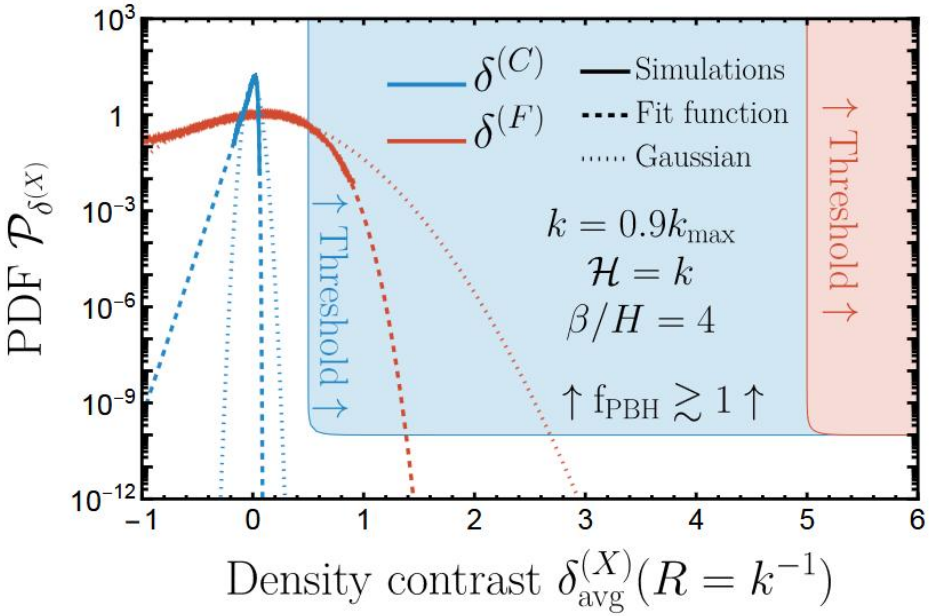
[Franciolini, Gouttenoire & Jinno 2025; Wang, Balázs, Ding, Tian 2026]

See Ran Ding's talk!

$$\delta^{(\text{gauge})} > \delta_c^{(\text{gauge})}$$

computed in the flat gauge

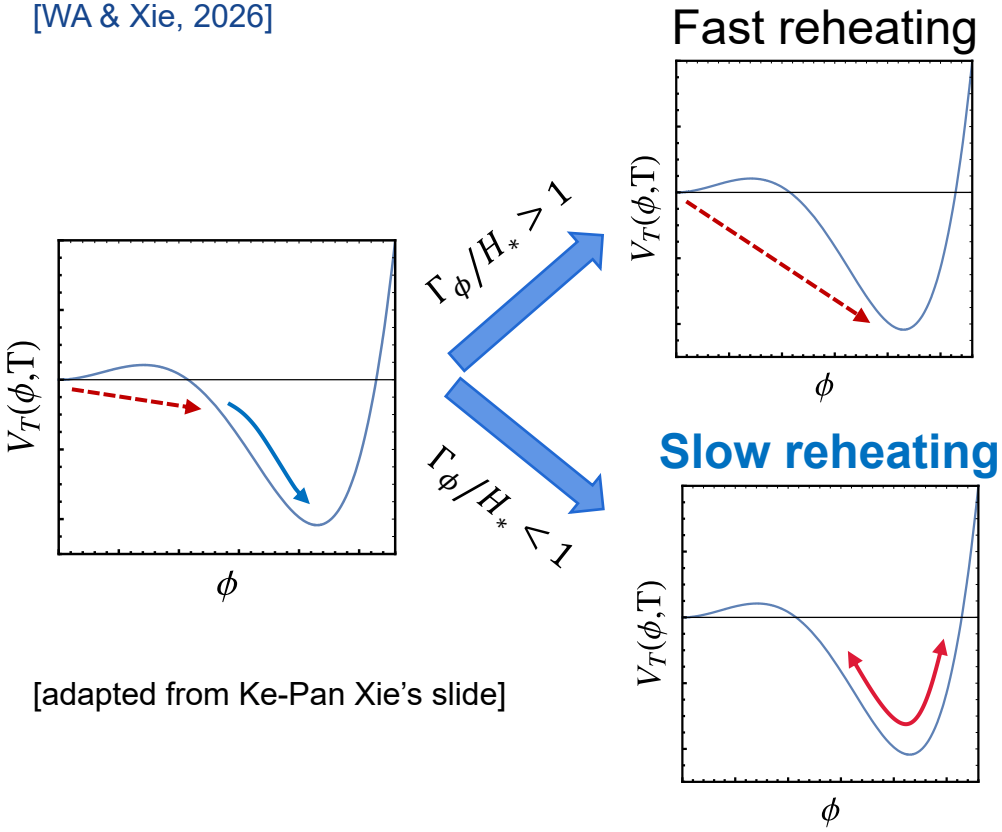
the value of 0.45 is obtained in the comoving gauge



[Franciolini, Gouttenoire & Jinno 2025]

Reviving this mechanism

[WA & Xie, 2026]



[adapted from Ke-Pan Xie's slide]

- ϕ coherently oscillates, decaying to SM particles, reheating the Universe
- **Early matter era** with $\rho_\phi \propto a^{-3}$, pressure ≈ 0
- Small $\delta^{(C)}$ grows and collapses, **forming PBHs**

A slow FOPT can still produce PBHs as all Dark Matter!

Summary

- FOPTs are a very interesting phenomenon:
  - Unique GW power spectrum
  - Smoking gun of new physics
  - Nonperturbative and nonequilibrium QFT
- There has been great progress in the past decade in understanding **bubble nucleation**, **bubble expansion** and **bubble percolation**
- Still many open questions
  - Real-time description of bubble nucleation?
  - Full 3D hydrodynamic simulations
  - Inverse problem
  - ....

Ultimate goal: make GWs as good as CMB!

Thank you!