Gravitational waves from a first-order phase transition of the 'Higgs' inflaton

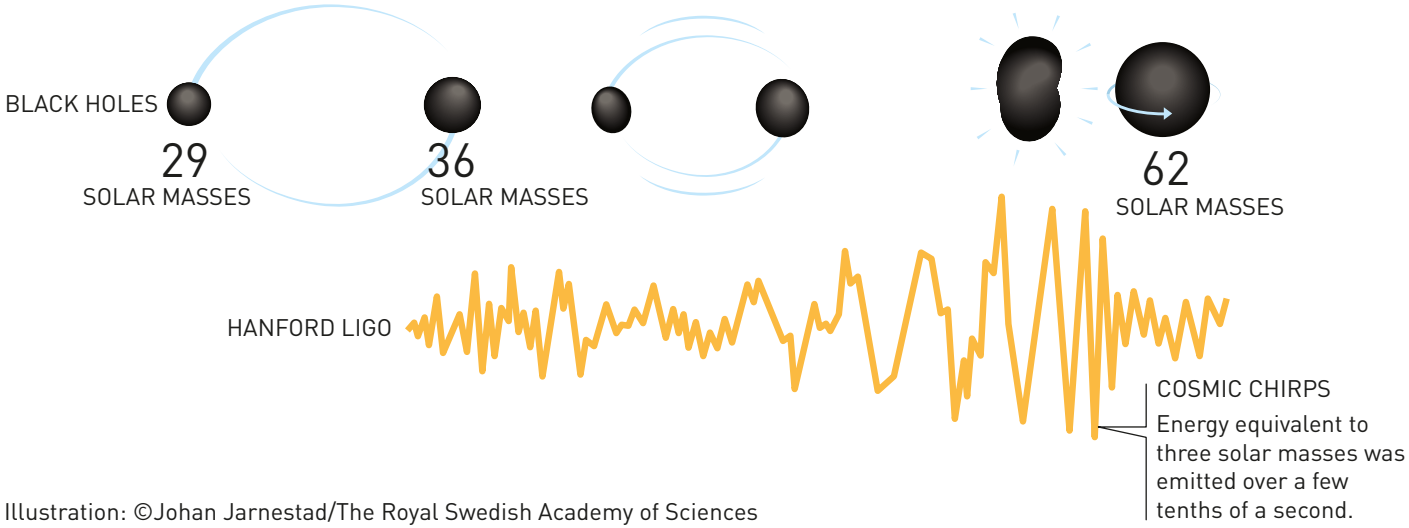
Seong Chan Park

Yonsei / KIAS

based on JCAP 04 (2025) 053, 2412.17278
with Jörn Kersten, Yeji Park, Juhoon Son, Liliana Velasco Sevilla

HPNP 2025, Osaka June 9

GW: A New Window to the Universe

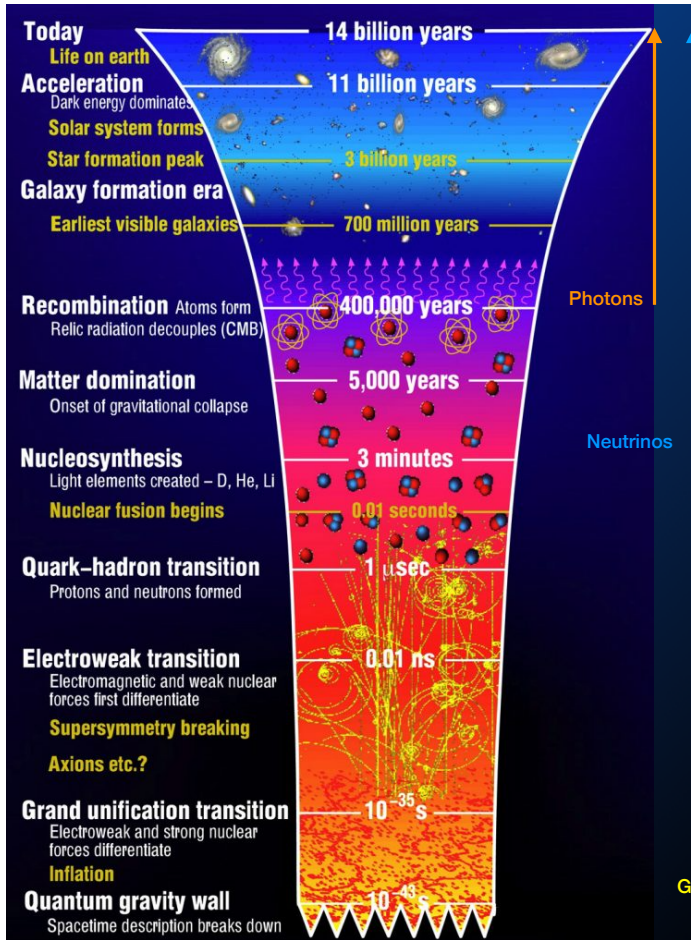


- Discovery of gravitational waves (GW) by LIGO & Virgo
  LIGO/Virgo, PRL **116** (2016), PRL **118** (2017)
- Source: mergers of black holes and neutron stars
- Proof of dynamical nature of spacetime: GR
  (cf) post-Newtonian correction for light bending, precession of Mercury

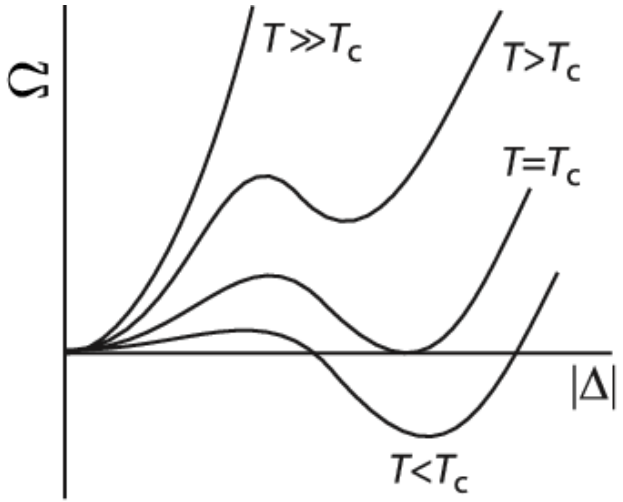
$\rightsquigarrow$ GW astronomy and cosmology has started

A Window to the Very Early Universe?

- Pulsar Timing Arrays
  ⇝ Supporting evidence for Stochastic GW Background NANOGrav, ApJL **951** (2023)
  EPTA, InPTA, A&A **678** (2023)
  Parkes PTA, ApJL **951** (2023)
  CPTA, RAA **23** (2023)
- Lower frequency than LIGO/Virgo events
  ⇝ Mergers of supermassive black holes?
- More interesting: particle physics origin
  - First-Order Phase Transition (FOPT)
  - Cosmic strings
  - Look forward to More discoveries (10^{-16} – 10^{9} Hz) covering a wide range of scales



First-Order Phase Transitions: Schematics



Kinnunen et al., Rep. Prog. Phys. **81** (2018)

1. After inflation $T \sim T_{reh} > T_c$ potential minimum at $\phi = 0$
2. $T < T_c$: true mimimum at $\phi = v \neq 0$, separated by barrier
3. Tunneling $\rightsquigarrow$ bubbles of true vacuum
4. GW from violent bubble collisions and turbulence
5. $\rightarrow$ visible signature ('FOPT' PNP)

Gravitational Waves in SM

- No FO electroweak PT for Higgs mass $\gtrsim 70$ GeV
  Kajantie et al., PRL **77** (1996); Karsch et al., NP Proc. Suppl. **53** (1997)
  Csikor et al., PRL **82** (1999)
- FOPT may still be needed in the context of baryogenesis, especially at EW scale
- New Physics!
- Many recent works Review: Roshan & White, arXiv:2401.04388

Inflation

Sato, Starobinsky, Guth, Linde, Lebedev, Steinhardt (1980-)

- A part of the 'Standard Model' of Modern Cosmology
- Providing the Initial Conditions for the Hot Big Bang
  – solving the horizon problem, the Flatness problem, the seeds of structures in the Universe
- In the simplest realization, driven by Inflaton: a scalar particle
- The potential is 'slow-rolling' $\epsilon = \frac{1}{2}(V'/V)^2 \ll 1, \eta = V''/V \ll 1$
- Now tested by CMB precision measurements: (n_s, r, f_{NL})
  $\rightsquigarrow$ many models are ruled out!
- & GW, PBH ... more and more probes are coming

Higgs Inflation

Bezrukov & Shaposhnikov, PLB **659** (2008); also see SCP & S. Yamaguchi ,JCAP 08 (2008) 009

$$\mathcal{L}_J = \sqrt{-g_J}\left[\frac{M_P^2}{2}R_J + \xi H^\dagger H R_J - g_J^{\mu\nu}(D_\mu H)^\dagger (D_\nu H) - V_J(H) + \dots\right]$$

- An economical –deep– idea involving no other particle
- $V_J = \lambda(H^\dagger H - v^2/2)^2$: SM Higgs potential
- ξ: non-minimal coupling to gravity
  - Consistent with all SM symmetries
  - Required for renormalization in curved spacetime
  - $\lambda/\xi^2 \sim 10^{-9}$ for CMB normalization
  - $\xi \sim \mathcal{O}(1)$ with RGE 'critical Higgs inflation' with $m_t \simeq 171 - 172$ GeV

    Hamada, Kawai, Oda, SCP, PRL 112 (2014), PRD 91(2015)

Higgs = Starobinsky

3 lines proof:

$$\text{Higgs}: \frac{\mathcal{L}}{\sqrt{-g}} \ni \left(1+\xi\phi^2\right)R - \frac{\lambda}{4}\phi^4$$

$$\delta\phi: 2\xi\phi R - \lambda\phi^3 = 0 \rightsquigarrow \phi^2 = \frac{2\xi R}{\lambda}$$

$$\Rightarrow \frac{\mathcal{L}}{\sqrt{-g}} = R + \frac{\xi^2}{\lambda}R^2 : \text{Starobinsky}$$

- Predicts $n_s = 0.965$, $r = 0.003$, which is fully consistent with the data. THE BEST FIT MODEL so far

Higgs Inflation: a little more details

- Unitary gauge: $\phi = \begin{pmatrix} 0 \\ (\varphi + v)/\sqrt{2} \end{pmatrix}$
- Weyl transformation to Einstein frame: $g_J \to g_E \equiv \Omega^2(\varphi)\, g_J$
- Canonical normalization: $\chi = \int_0^{\varphi} \mathrm{d}\varphi \sqrt{\frac{3}{2}\frac{(\Omega^2{}_{,\varphi})^2}{\Omega^4} + \frac{1}{\Omega^2}}$

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$$\mathcal{L}_E = \sqrt{-g_E}\left[\frac{M_P^2}{2} R_E - \frac{1}{2} g_E^{\mu\nu}(\partial_\mu \chi)(\partial_\nu \chi) - V_E(\chi) + \dots\right]$$

- Gravity remains weak below cutoff $\sim M_P\, \Omega$
- $V_E = \frac{V_J}{\Omega^2} \propto \frac{\lambda h^4}{(\xi h^2)^2} \sim \frac{\lambda}{\xi^2} = const.$

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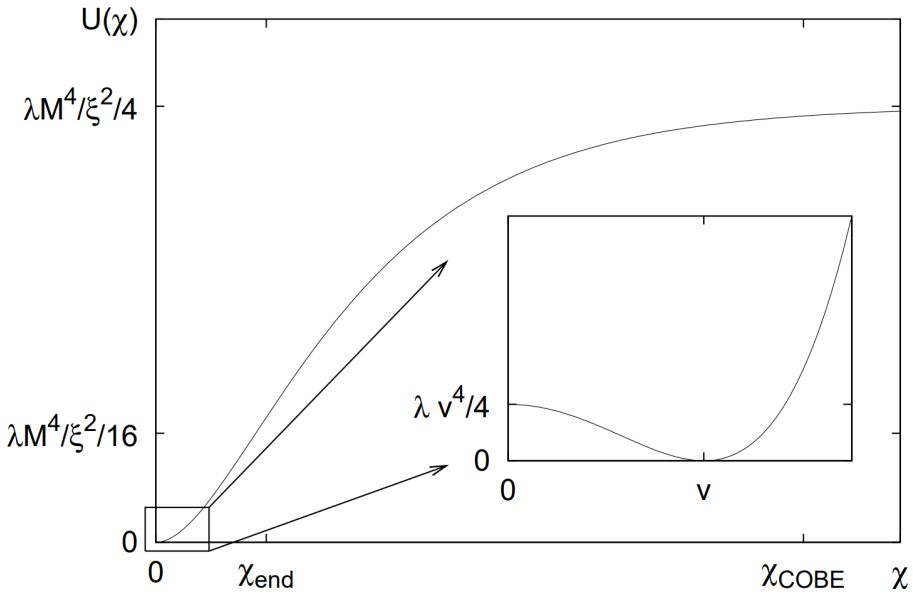

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Question: FOPT and Inflation from the 'same' Higgs?

- SM + higher-dimensional operators $\rightsquigarrow$ FO EWPT

$$V(H) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2 + \frac{c_6}{f^2}(H^\dagger H)^3 + \frac{c_8}{f^4}(H^\dagger H)^4$$

  - f: cutoff
  - c_6, c_8: dimensionless couplings
- SM + non-minimal coupling to gravity $\rightsquigarrow$ inflation

Can we have both?

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TEST: CMB measurements

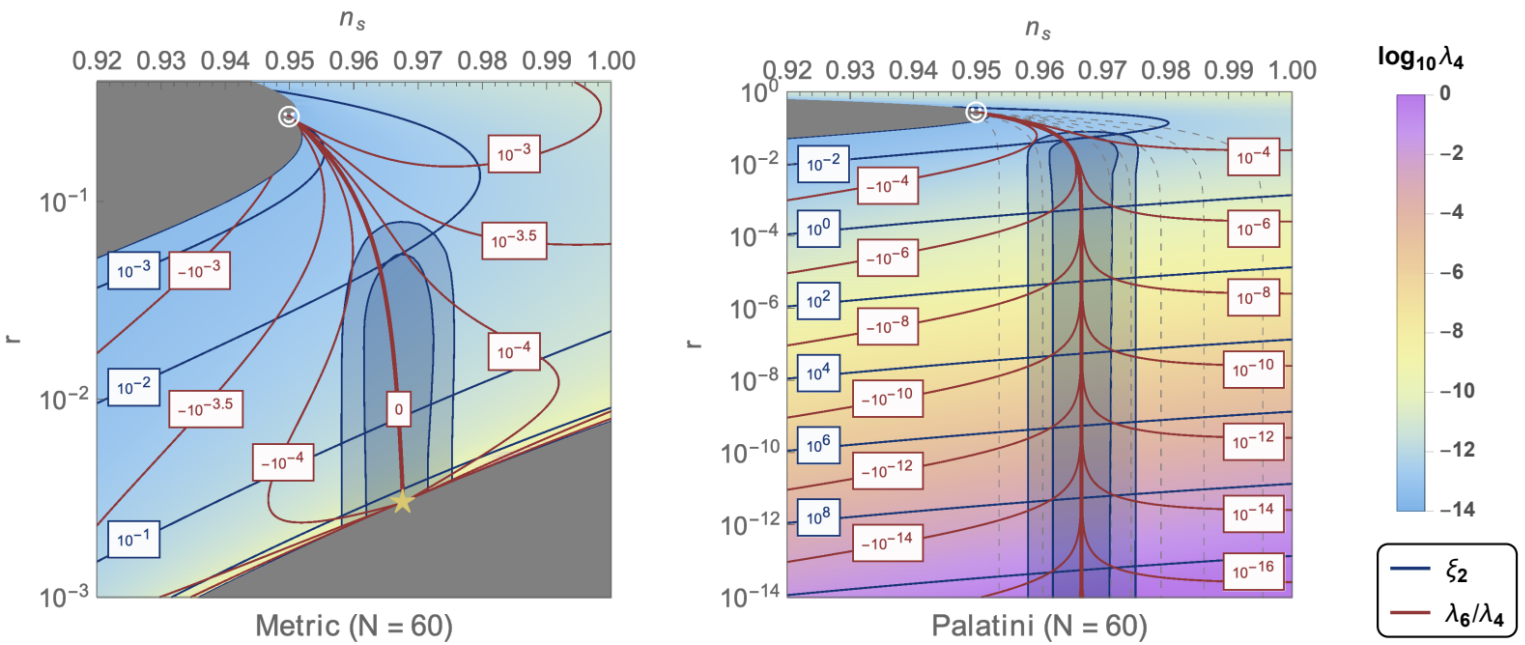
Scalar power spectrum amplitude	$\ln(10^{10} A_s) = 3.044 \pm 0.014$
Scalar spectral index	$n_s = 0.9649 \pm 0.0042$
Tensor-to-scalar power ratio	$r < 0.036$ (95% CL)

Planck, A&A **641** (2020); BICEP/Keck, PRL **127** (2021)

$\rightsquigarrow$ Strong constraints on inflationary parameters

$\rightsquigarrow$ Strong bounds on higher-dimensional operators

Effects of Higher-Dimensional Operators



Jinno, Kubota, Oda, SCP, JCAP **03** (2020)

- Attractor point for $\xi \gg 1$ (interesting !)
- Strong constraints on c_6 and c_8 in metric and also in Palatini formulation
- No way to generate a sizable FOPT :-(
- $R^3, R^4, \cdots$ are also constrained Cheong, Lee, SCP, PLB **805** (2020)

A new attempt: Higgs Inflation in a Dark Sector

J. Kersten, SCP, Y. Park, J. Son, L. Velasco-Sevilla, JCAP 04 (2025) 053

- Okay. Let's forget about the elegant idea of 'Higgs inflation'
- Now allow $\phi \neq H$ and lives in hidden sector to avoid 'visible constraints' from particle physics
- ϕ with $U(1)_X$ charge (cotributing in RGE liking inflation and FO scales)
  - Spontaneously breaks $U(1)_X \rightsquigarrow$ FOPT $\rightsquigarrow$ GW
  - Non-minimal coupling to gravity $\rightsquigarrow$ Higgs-inflation-like inflation
- Fermions also affect the RG running (like the top quark in the SM)

Effective Scalar Potential at Finite Temperature

$$V(h_c, T) = V_{\text{tree}}(h_c) + V_{\text{1-loop}}(h_c) + V_{\text{th}}(h_c, T)$$

$$V_{\text{tree}}(h_c) = -\frac{\mu^2}{2} h_c^2 + \frac{\lambda}{4} h_c^4$$

$$V_{\text{1-loop}}(h_c) = \sum_{i=h,\chi,g,f} \frac{n_i}{64\pi^2} m_i^4(h_c) \left[\ln \frac{|m_i^2(h_c)|}{v^2} - C_i \right]$$

$$V_{\text{th}}(h_c, T) = \sum_{i=h,\chi,g} \frac{n_i}{2\pi^2} T^4 J_b\left(\frac{m_i^2(h_c)}{T^2} \right) + \frac{n_f}{2\pi^2} T^4 J_f\left(\frac{m_f^2(h_c)}{T^2} \right)$$

$$m_h^2(h_c) = -\mu^2 + 3\lambda h_c^2, m_\chi^2(h_c) = -\mu^2 + \lambda h_c^2$$

$$m_g^2(h_c) = \frac{g^2}{4} h_c^2, m_f^2(h_c) = \frac{y^2}{2} h_c^2$$

Scalar Potential with Barrier

To show the existence proof, we first focus on simple cases for generating the potential barrier for FOPT around $T \sim v$

1. No fermions, $\lambda \sim 1$ (the conventional Higgs inflation)
2. A few fermion(s), $\lambda \ll 1$ (the critical Higgs inflation)

$\rightsquigarrow$ check if FOPT possible

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GW spectrum is determined by

- Critical Temperature T_c
- Nucleation temperature T_n
- $\alpha = \rho_{vac}/\rho_{rad}$ $\leftrightsquigarrow$ strength of PT
- $\beta/H = T\frac{d}{dT}\left(\frac{S_3}{T}\right)\Big|_{T=T_n}$ $\leftrightsquigarrow$ duration of PT
- v_w Bubble wall velocity

Calculated with help from `CosmoTransitions`
Wainwright, Comput. Phys. Commun. **183** (2012)
Our own code `CosmoFOptscope`
`https://github.com/hiilynn/cosmoT-FOPTscope`

CosmoFOptscope

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cosmofoptscope

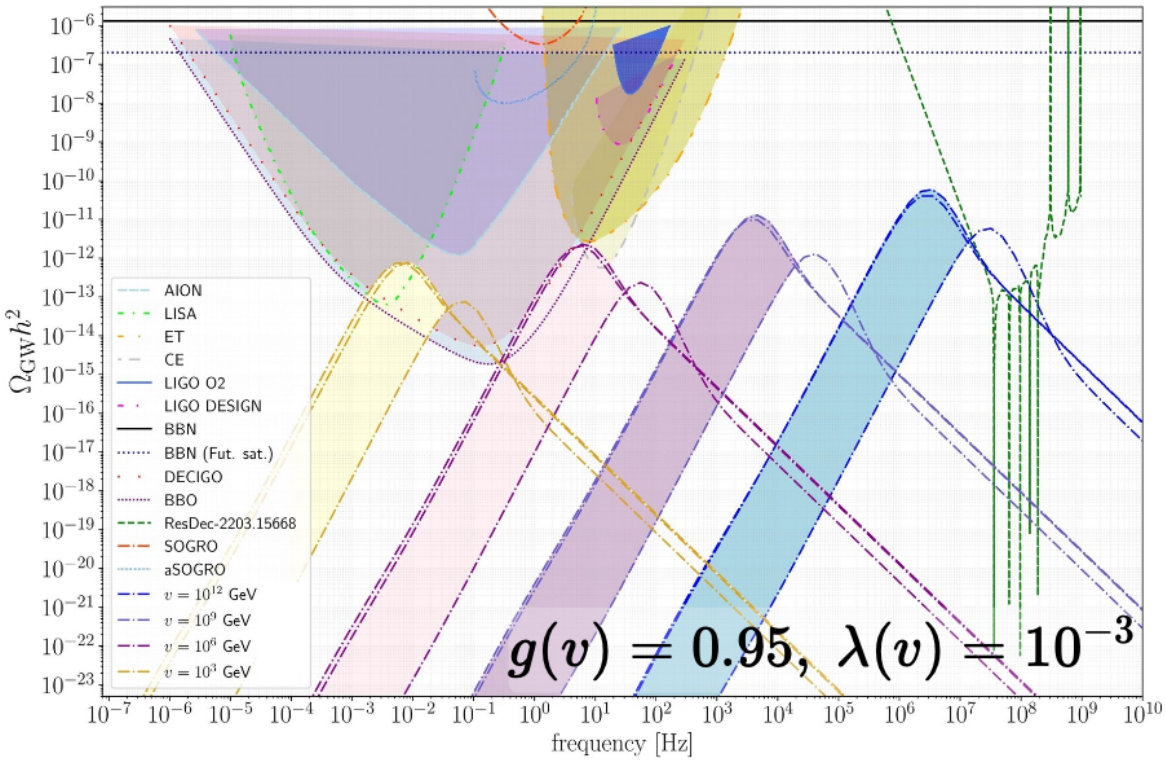
A Python package for analyzing First Order Phase Transitions (FOPT) in cosmological contexts. Built upon the CosmoTransitions package, this tool calculates nucleation temperatures for various theoretical models and computes essential phase transition parameters including phase transition strength (α) and inverse duration of phase transition (β).

Features

- Built on CosmoTransitions framework for reliable phase transition analysis
- Calculation of nucleation temperature for different theoretical models
- Computation of phase transition strength (α)
- Evaluation of inverse duration of phase transition (β)
- Analysis of tunneling actions
- Multiple phase studies
- Support for parallel computation
- Customizable potential implementation

GW Spectrum(1) w/o fermions

- With $\xi \sim 10^4$, $\lambda \sim 1$, $v = 10^3, 10^6, 10^9, 10^{12}$ GeV



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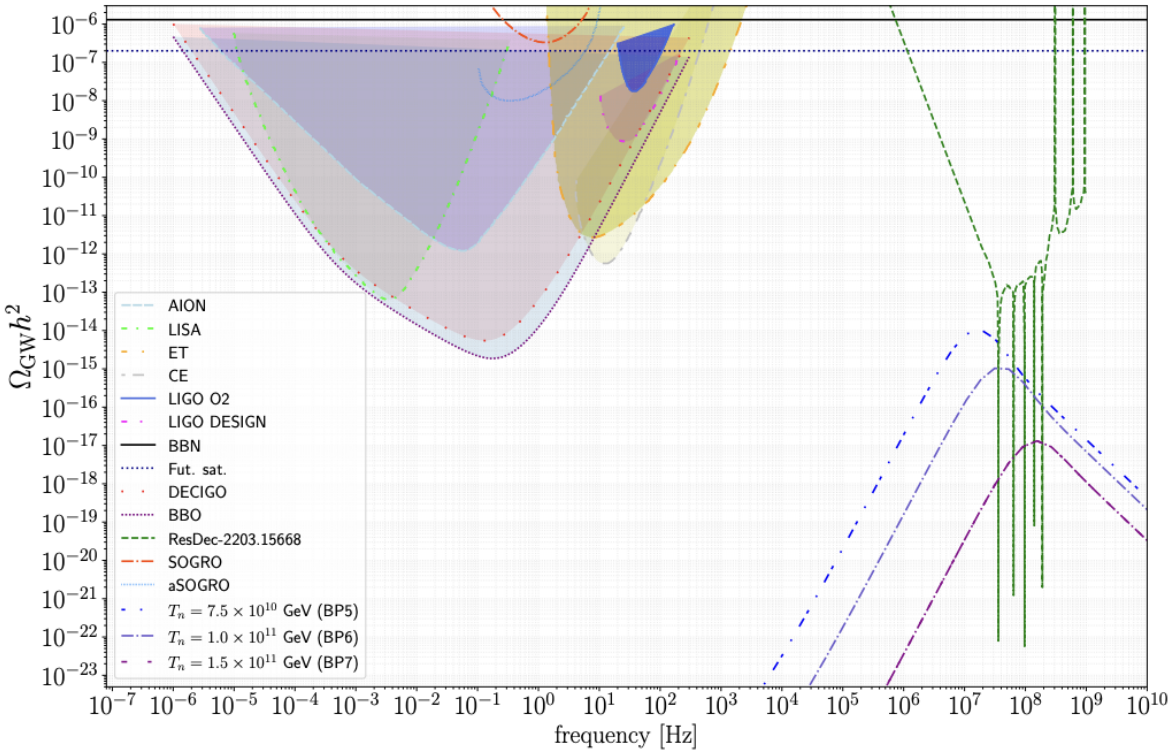
GW Spectrum(2) with fermions

- Allows $\xi \sim 1$, $\lambda \ll 1$, $v \sim 10^{12}$ GeV



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Conclusions and Outlook

- GW can probe properties of the particle physics models that the collider experiments will not be able to characterize
- LISA mission has recently been adopted from ESA and is set to start in 2035 $\rightsquigarrow$ Many well-motivated theories can be tested through GW
- We show 'Higgs' inflation + FOPT can be realized, then the details will be tested at the forthcoming experiments
- Discrimination of different mechanisms of GW production (also PBH) is on the way