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KIAS KOREA INSTITUTE FOR ADVANCED STUDY

Sensitivity to Dark Sector Scales from Gravitational Waves Signature

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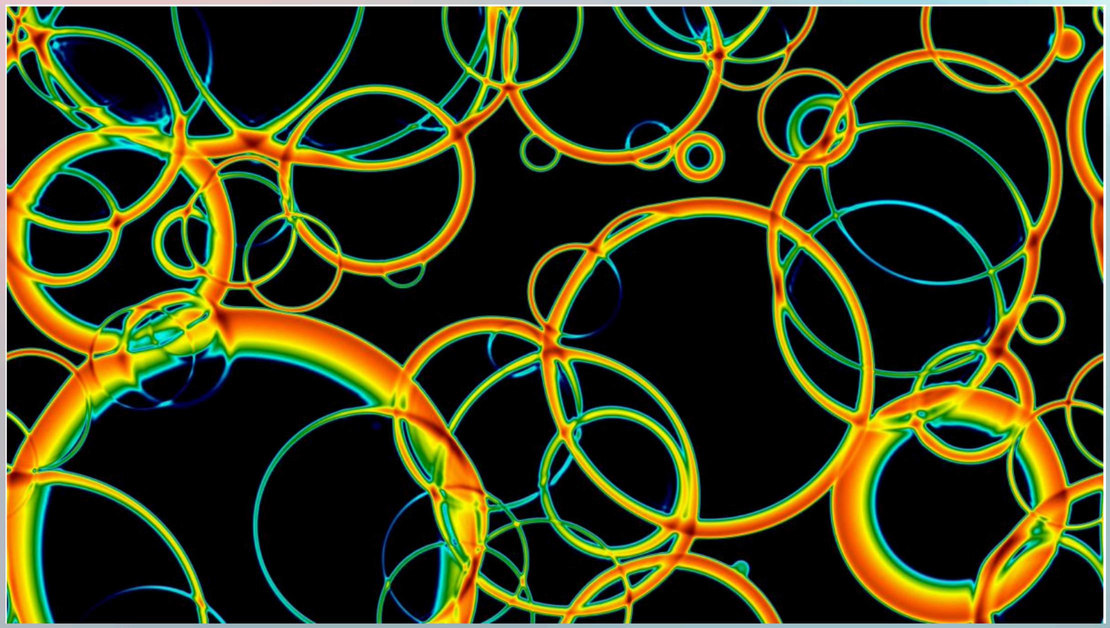
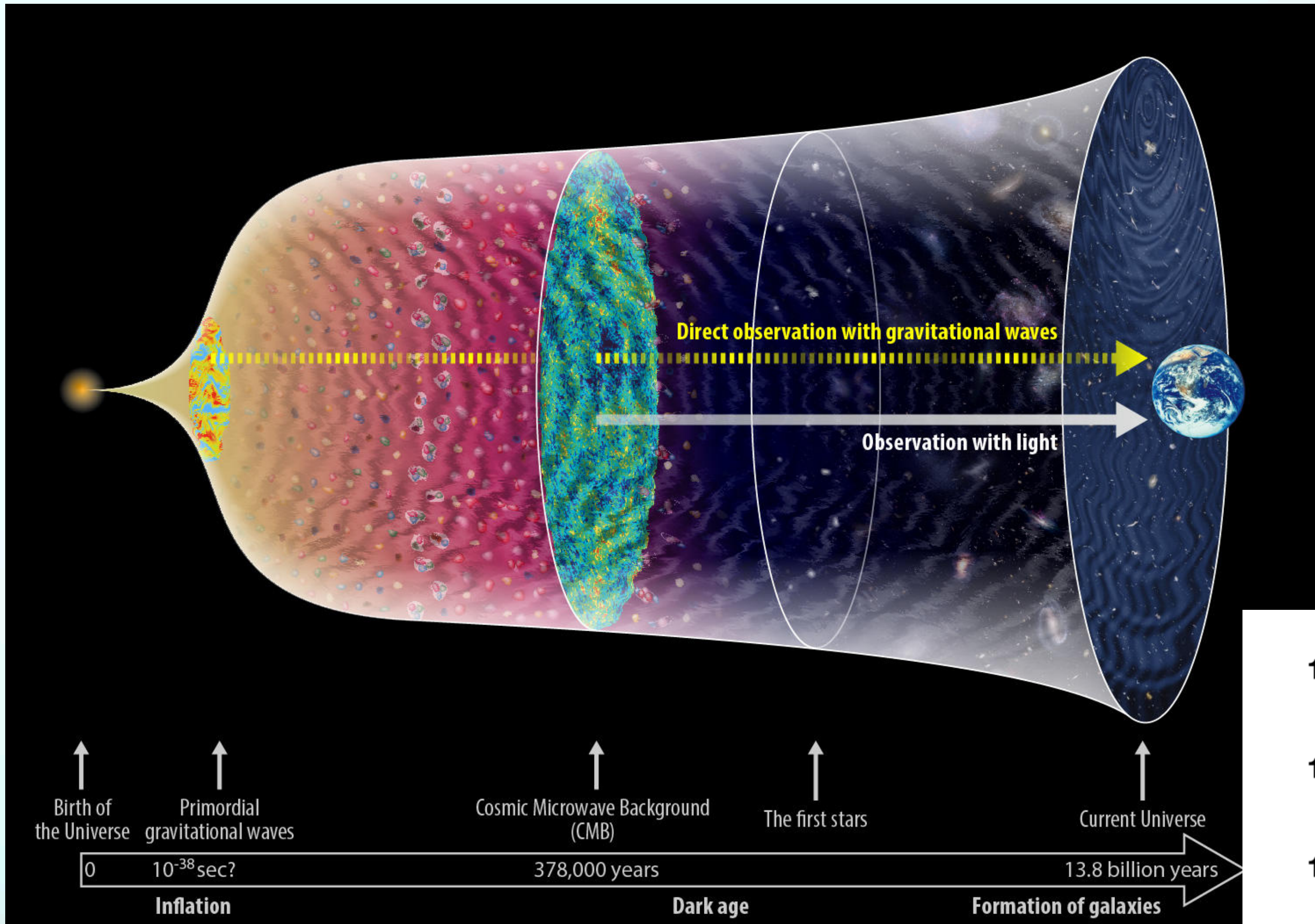
based on: arXiv 2203.11736 [JHEP 08 (2022) 300]

w/J. B. Dent, B. Dutta, J. Kumar, J. Runburg.



Credit: D.Weir

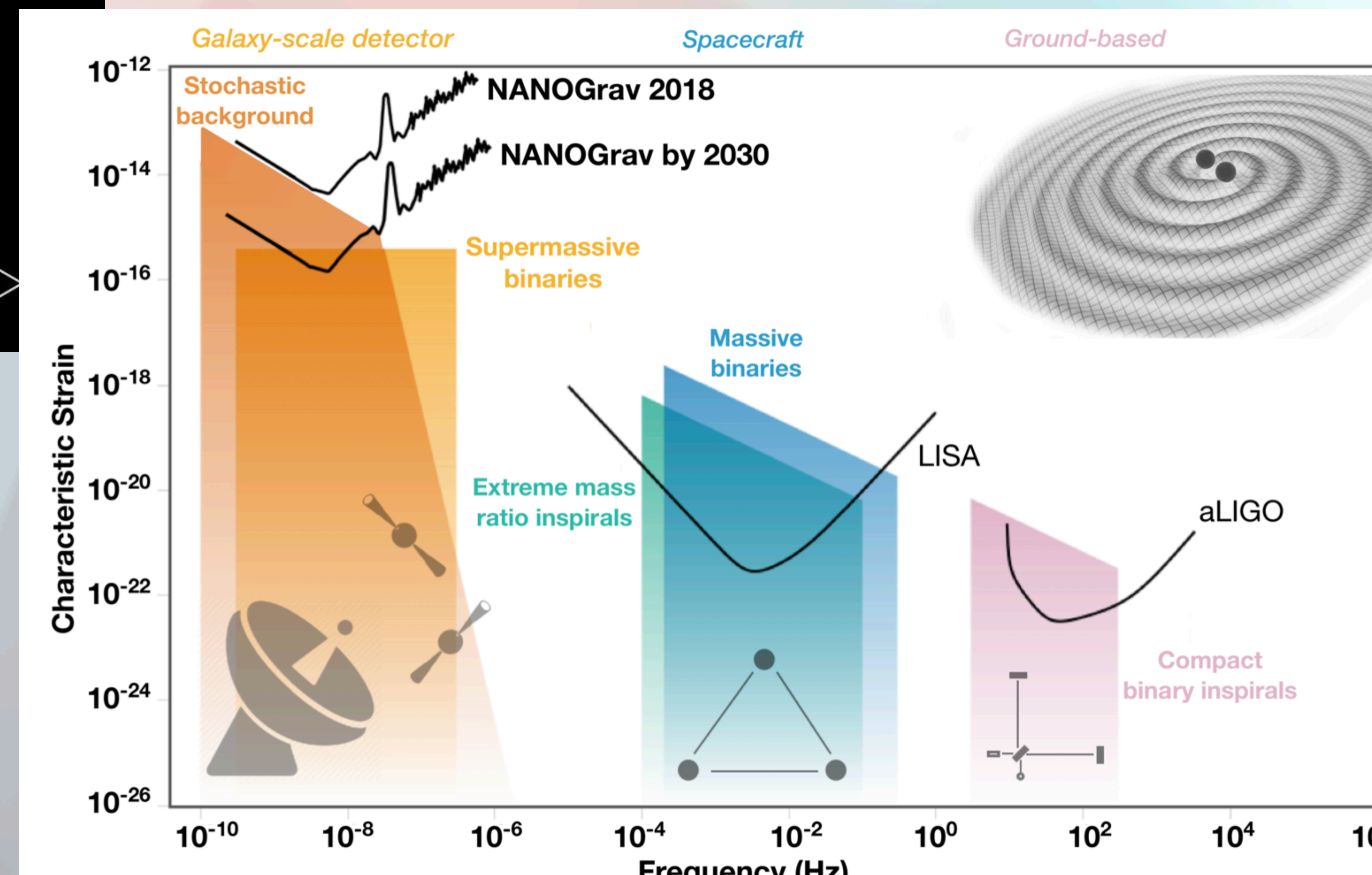
GW as a probe of FOPT



https://gwpo.nao.ac.jp

- Propagate freely after production, carry information about the process that produced them.

- Sensitivity over a wide range of frequency.



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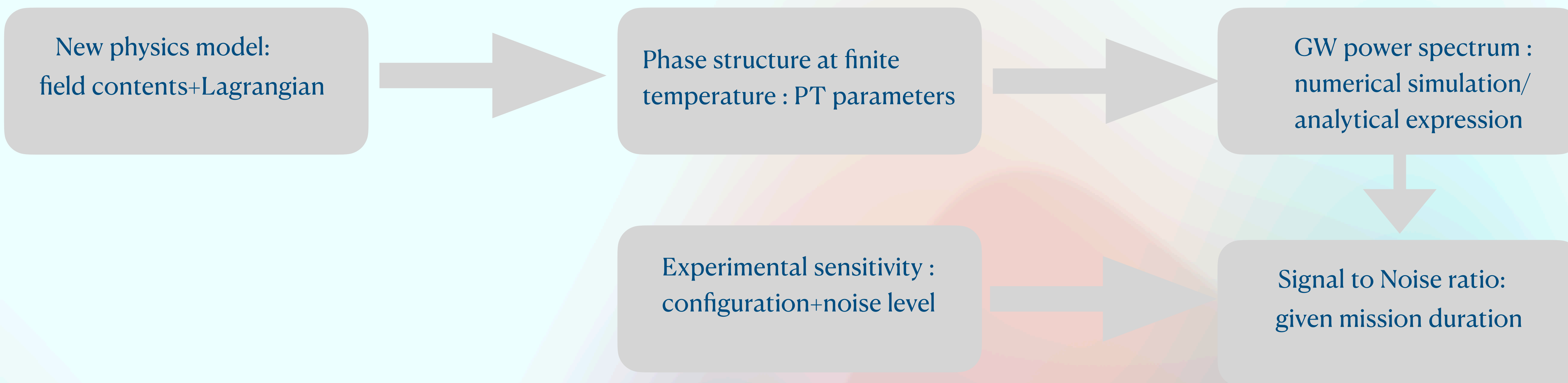
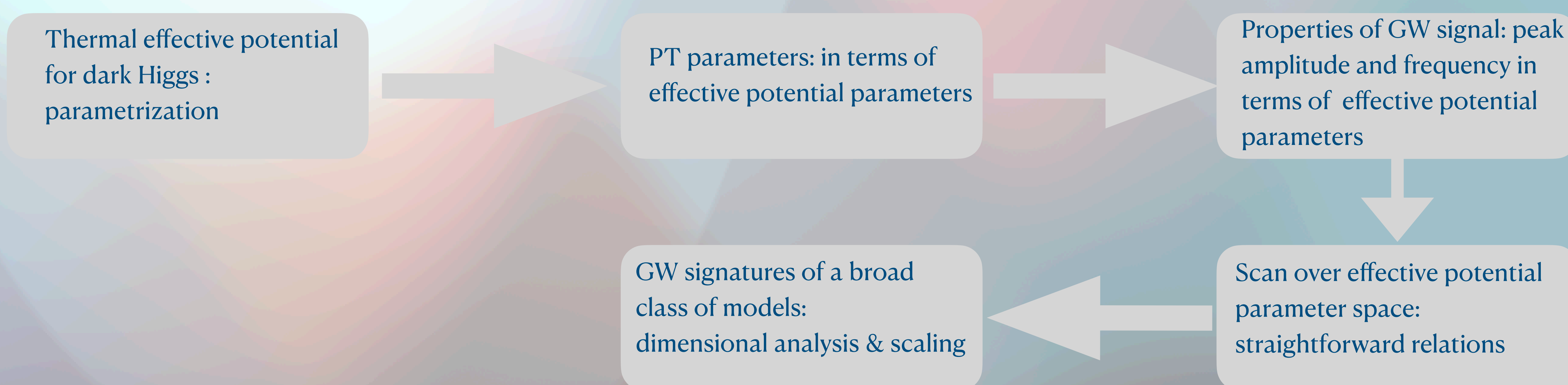
OUR APPROACH

- Standard blueprint:

1910.13125



- Our approach:



Thermal Effective Potential

- Renormalizable thermal effective potential of power law form, in the high T limit.

$$V(T,\phi) = \Lambda^4 \left[\left(-\frac{1}{2} + c \times \left(\frac{T}{v}\right)^2 \right) \left(\frac{\phi}{v}\right)^2 + b \times \left(\frac{T}{v}\right) \left(\frac{\phi}{v}\right)^3 + \frac{1}{4} \left(\frac{\phi}{v}\right)^4 \right].$$

  - $V(T=0,\phi)$ has minimum at $\phi = \pm\, v$ with mass $m^2/v^2 = 2(\Lambda/v)^4$
  - we take $\Lambda/v \leq 1$ and $b < 0$

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- Introduce scale free parameters: $\tilde{\phi} = \phi/v$, $\tilde{T} = T/v$ and rescale the potential.

$$\Lambda^{-4} V(T,\phi) = \tilde{V}(\tilde{T},\tilde{\phi}) = \left(-\frac{1}{2} c\tilde{T}^2 \right) + b\tilde{T}\tilde{\phi}^3 + \frac{1}{4}\tilde{\phi}^4$$

  – condition for FOPT are: $c/b^2 > 1$ and $c\tilde{T}_N^2 > 1/2$.

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- Analytical expression for the bounce solution.

$$\frac{S_E}{T} = \frac{4.85 M^3}{E^2 T^3} \left[1 + \frac{\alpha}{4} \left(1 + \frac{2.4}{1-\alpha} + \frac{0.26}{(1-\alpha)^2} \right) \right]$$

hep-ph/9203203

  – where, $M^2 = 2\frac{\Lambda^4}{v^2}\left(\frac{cT^2}{v^2} - \frac{1}{2}\right); \quad E = -\frac{b\Lambda^4}{v^4}; \quad \alpha = \frac{M^2\Lambda^4}{2E^2T^2v^4}$

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— the scale free action is $\frac{S_E}{T} = \left(\frac{\Lambda}{v}\right)^{-2}\frac{\tilde{S}_E}{\tilde{T}}$

Phase Transition Parameters

- Three parameters characterize FOPT.
  - nucleation temperature:

$$\frac{S_E}{T_N} = \frac{\tilde{S}_E}{\tilde{T}_N}\left(\frac{\Lambda}{v}\right)^{-2} \sim 140 \qquad \frac{\tilde{S}_E}{\tilde{T}_N} \sim 140\left(\frac{\Lambda}{v}\right)^{2}$$

  - speed parameter of the phase transition :

$$\left(\frac{\beta}{H}\right) = \left(\frac{\tilde{\beta}}{H}(b, c, \Lambda/v)\right) \times \left(\frac{\Lambda}{v}\right)^{-2} \qquad \frac{\tilde{\beta}}{H}(b, c, \Lambda/v) = \left(\tilde{T}\frac{d(\tilde{S}_E/\tilde{T})}{d\tilde{T}}\right)_{\tilde{T}=\tilde{T}_N}$$

  - latent heat strength parameter:

$$\xi = \tilde{\xi}(b, c, \Lambda/v) \times \left(\frac{\Lambda}{v}\right)^{4}\left(\frac{g^*}{100}\right)^{-1} \qquad \tilde{\xi}(b, c, \Lambda/v) = \left[\frac{1}{10\pi^2\tilde{T}^4}\left(\Delta\tilde{V} - \tilde{T}\Delta\frac{d\tilde{V}}{d\tilde{T}}\right)\right]_{\tilde{T}=\tilde{T}_N}$$

GW SIGNAL

- We are interested in the peak amplitude and the corresponding frequency for the sound wave.
  - — the peak amplitude is given by.

$$h^2\Omega_{sw}^{max} = h^2\tilde{\Omega}_{sw}^{max}(b,c,\Lambda/v) \times \left(\frac{\Lambda}{v}\right)^{10+8n} \left(\frac{g*}{100}\right)^{-5/3-2n} \times \left[1 - \frac{1}{\sqrt{1+2\tau_{sh}H_s}}\right]$$

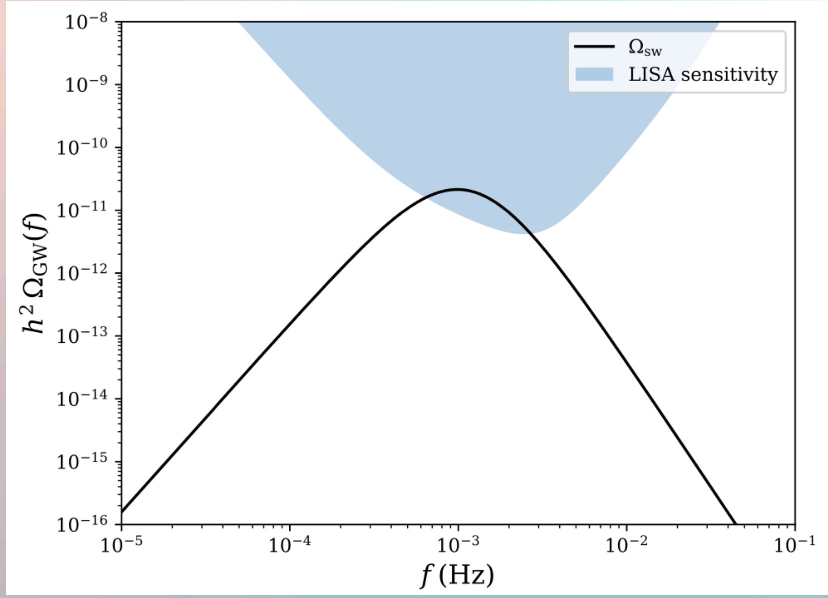
1705.01783

$$h^2\tilde{\Omega}_{sw}^{max}(b,c,\Lambda/v) = 8.5 \times 10^{-6} \left(\frac{\Gamma}{4/3}\right) \xi^{2n+2} \left(\frac{\tilde{\beta}}{H}\right)^{-1} v_w$$

  - — the corresponding frequency given by.

$$f_{sw} = \tilde{f}_{sw}(b,c,\Lambda/v) \times \left(\frac{\Lambda}{v}\right)^{-2} \left(\frac{T_N}{100GeV}\right) \left(\frac{g*}{100}\right)^{1/6}$$

$$\tilde{f}_{sw}(b,c,\Lambda/v) = 8.9 \times 10^{-3}\text{mHz}\frac{1}{v_w}\left(\frac{\tilde{\beta}}{H}\right)\left[\frac{1}{\frac{z_p}{10}\sqrt{1+2\tau_{sh}H_s}}\right]$$



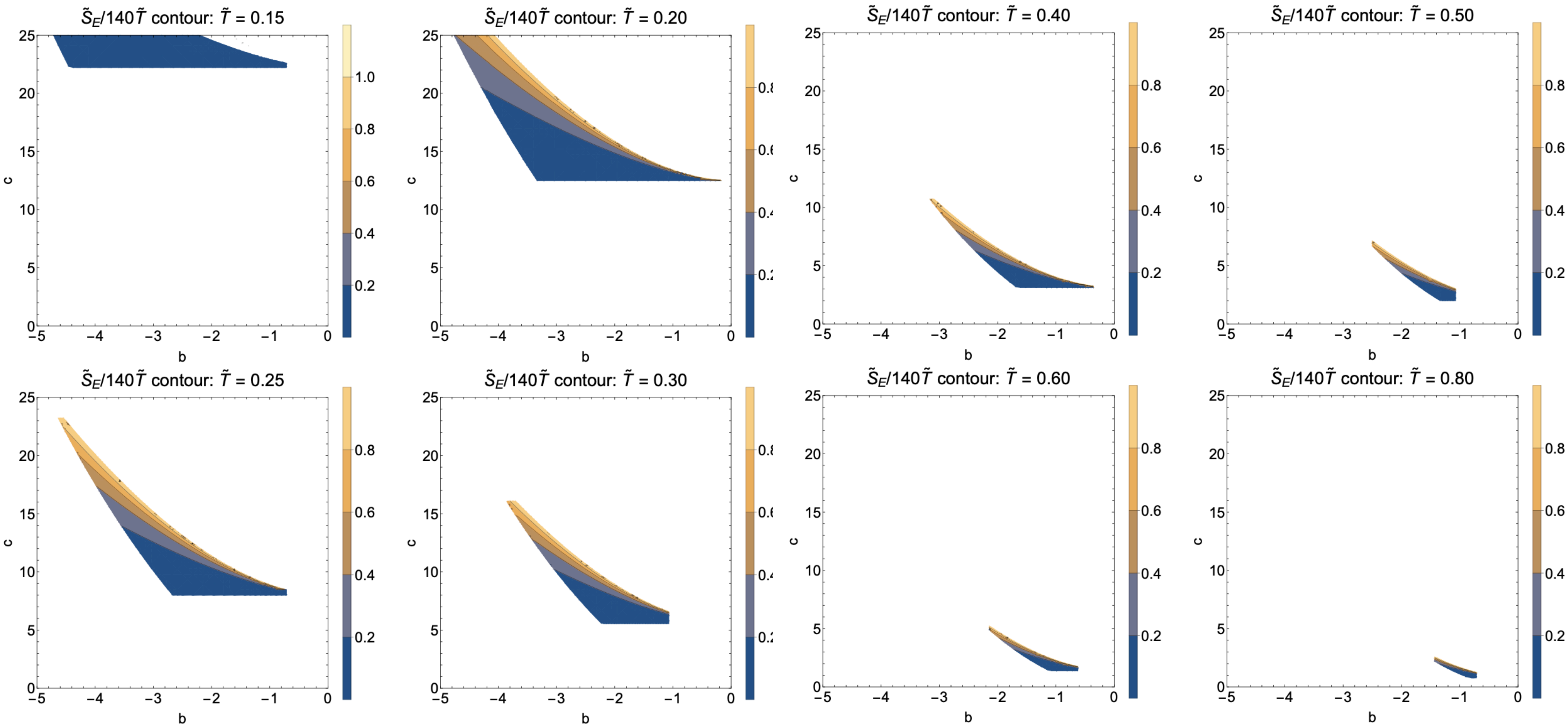
- If $T_N = T_c$ then peak amplitude and frequency determined by simple scaling.

$$\left(h^2\Omega_{sw}^{max}\right)_{T_N=T_c} \propto \left(\frac{\Lambda}{v}\right)^{10+8n}; \qquad \left(f_{sw}\right)_{T_N=T_c} \propto \left(\frac{\Lambda}{v}\right)^{-2} v; \qquad n = 1 \text{ for } v_w \sim 1$$

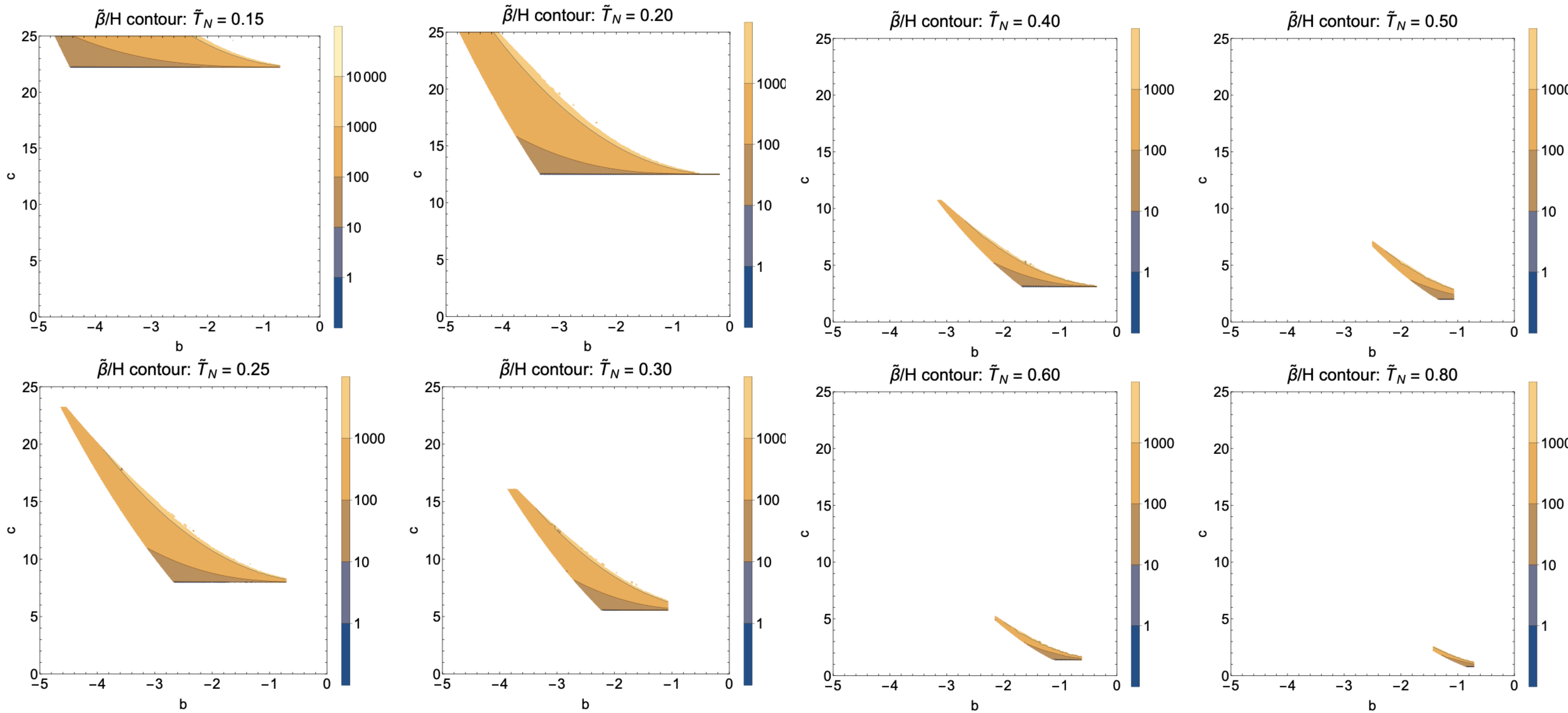
Conditions for Scanning

- $\Lambda/v < 1$: to ensures that the quartic coupling at zero temperature remains within the perturbative range.
- $c/b^2 > 1$: this condition is required for a phase transition to occur at all.
- $c\tilde{T}_N^2 > 1/2$: this requirement ensures that the transition is of the first-order. If not fulfilled, the barrier vanishes prior to reaching the nucleation temperature, resulting in a gradual phase transition.
- $\beta/H > 1$: necessary for the bubble growth rate to exceed the Hubble expansion, equivalent to $\tilde{\beta}/H > (\Lambda/v)^2$.
- $\xi > 0$: a first-order transition can only occur if the latent heat parameter is positive at the nucleation temperature.

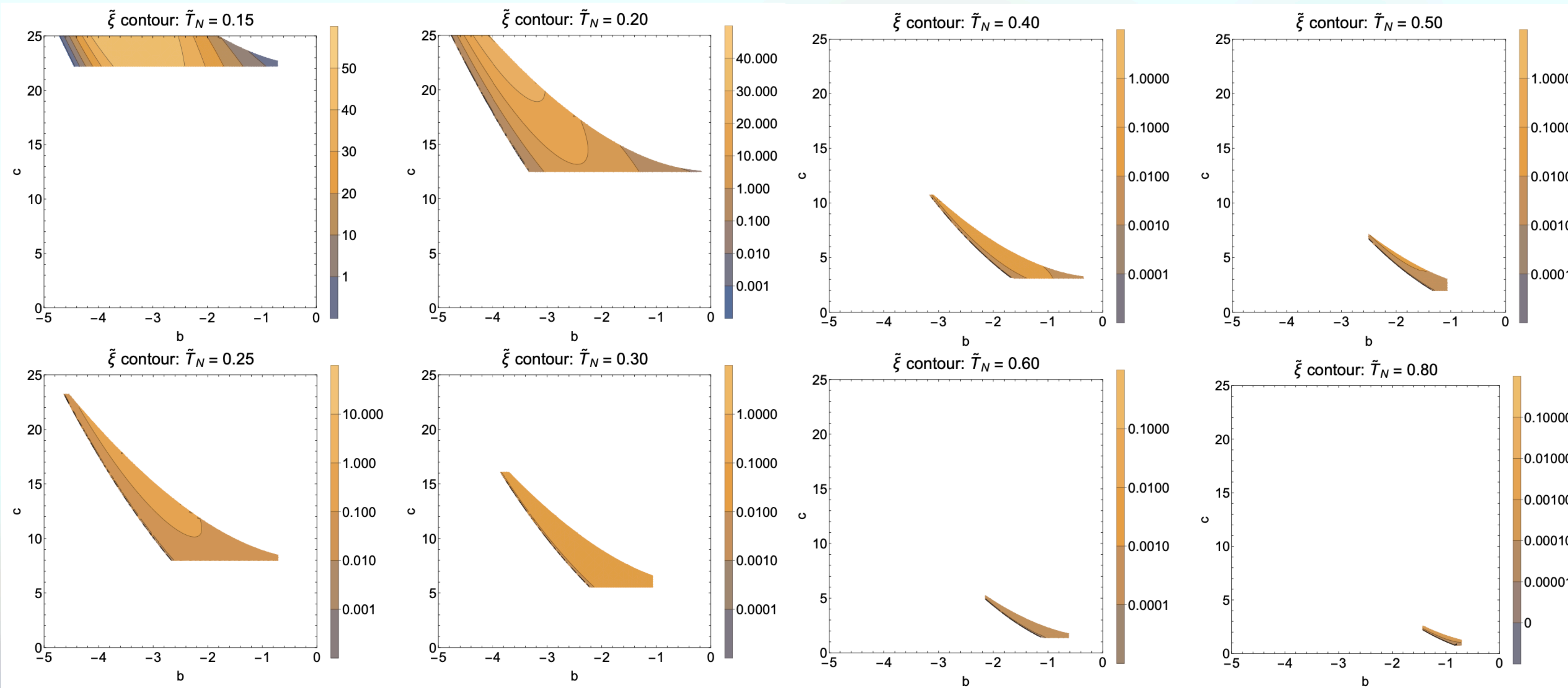
EUCLIDEAN ACTION



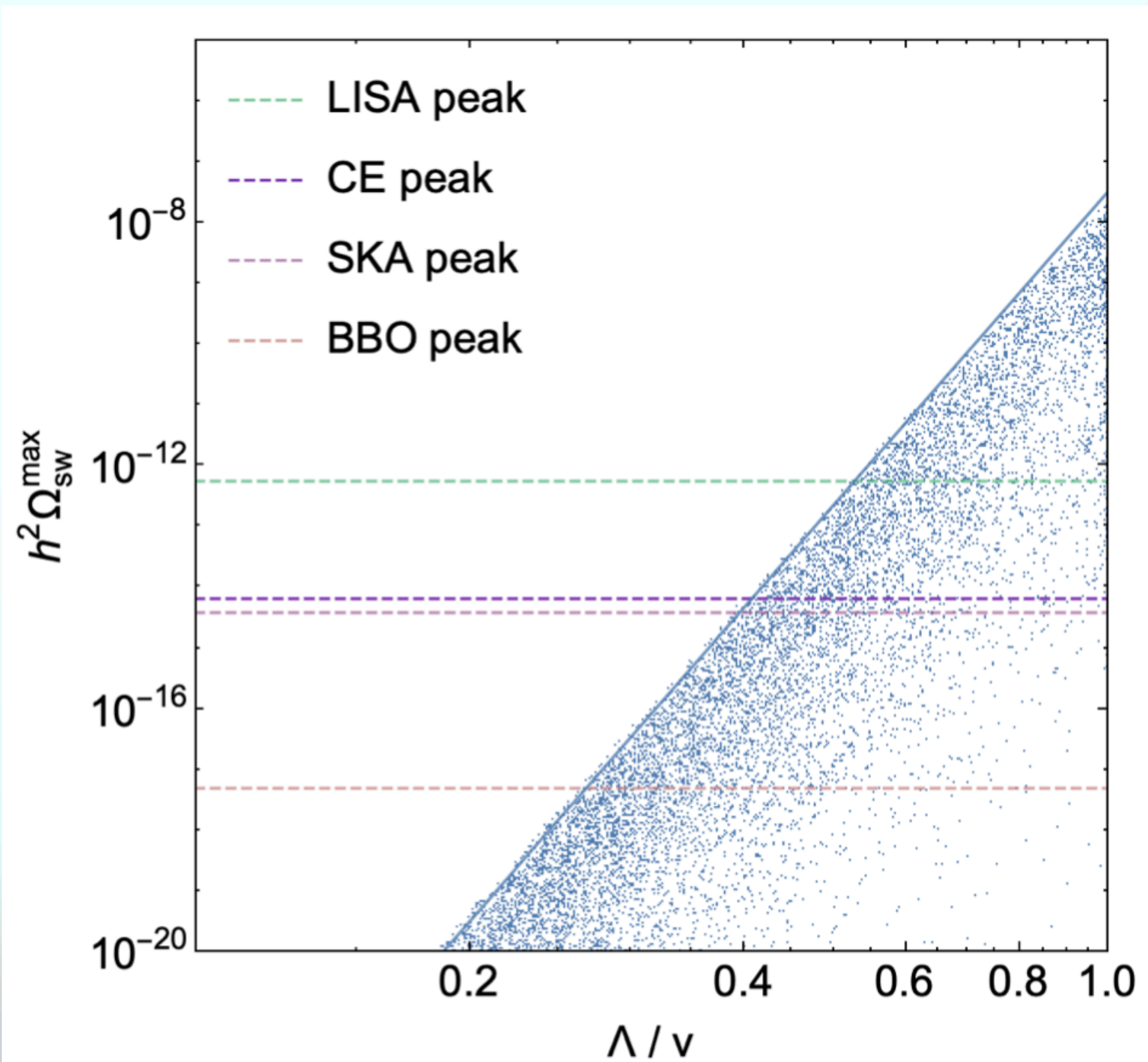
Speed Parameter

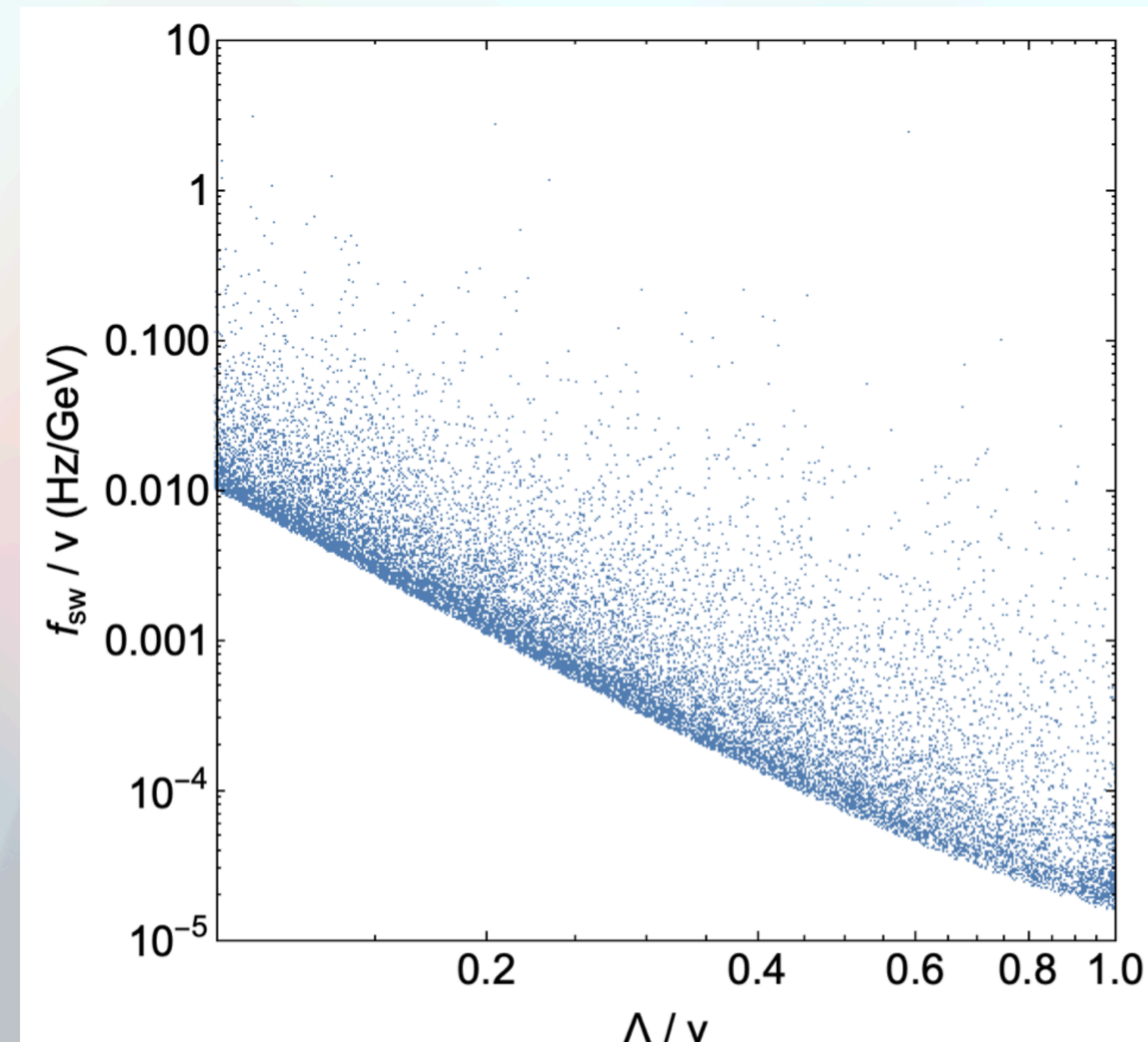


LATENT HEAT PARAMETER



Signal and Frequency Scaling



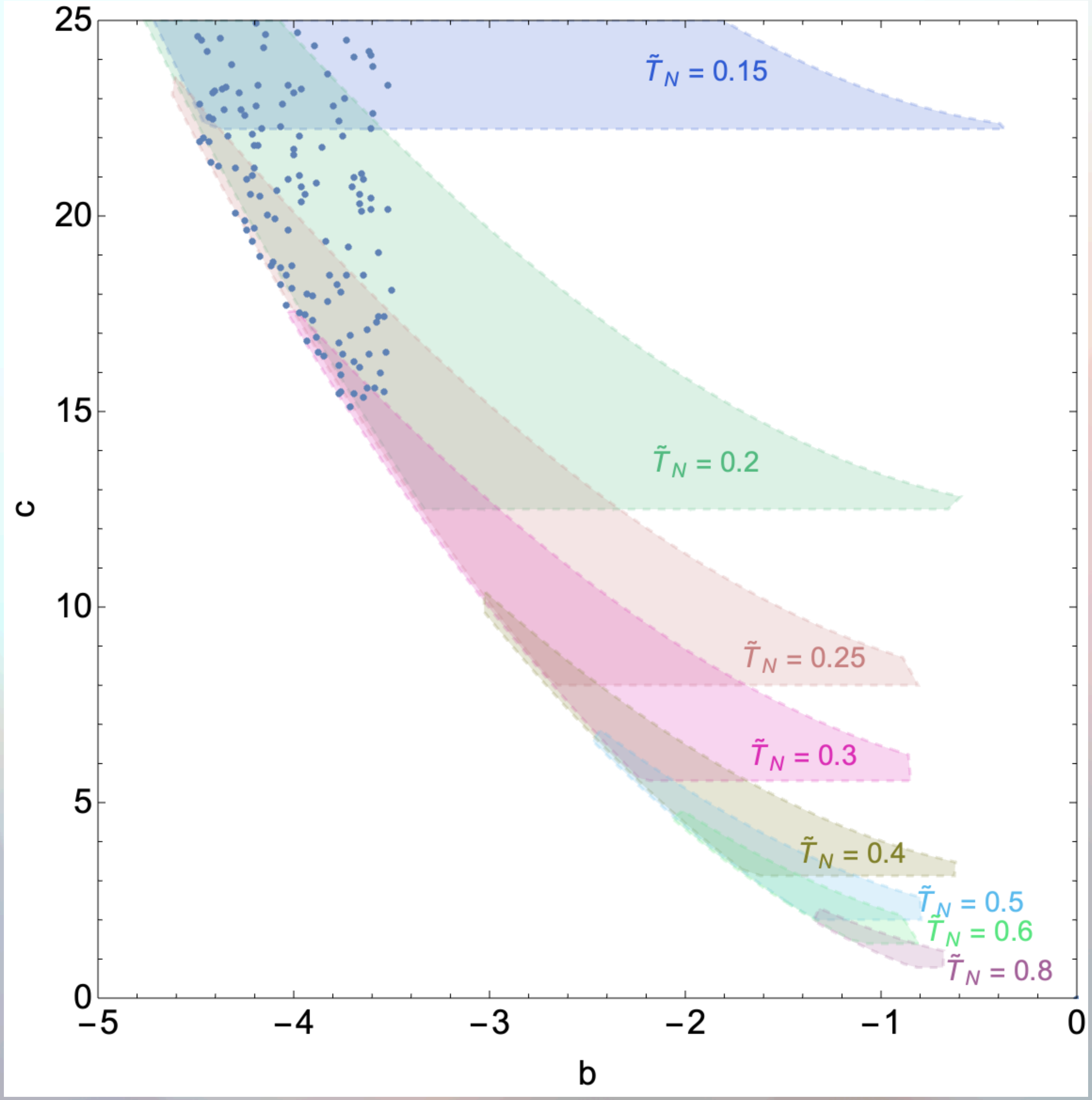


Expected slope: $h^2\Omega_{sw}^{max} \propto (\Lambda/v)^{18}$.

Actual slope: $h^2\Omega_{sw}^{max} \propto (\Lambda/v)^{17.2}$.

We find: $f_{sw}/v \propto (\Lambda/v)^{-2}$.

DEPENDENCE ON $\tilde{T}_N$



- Points in (b, c) plane for which $h^2\Omega_{sw}^{max}$ is within 2% of the maximum Value for a given Λ/v.

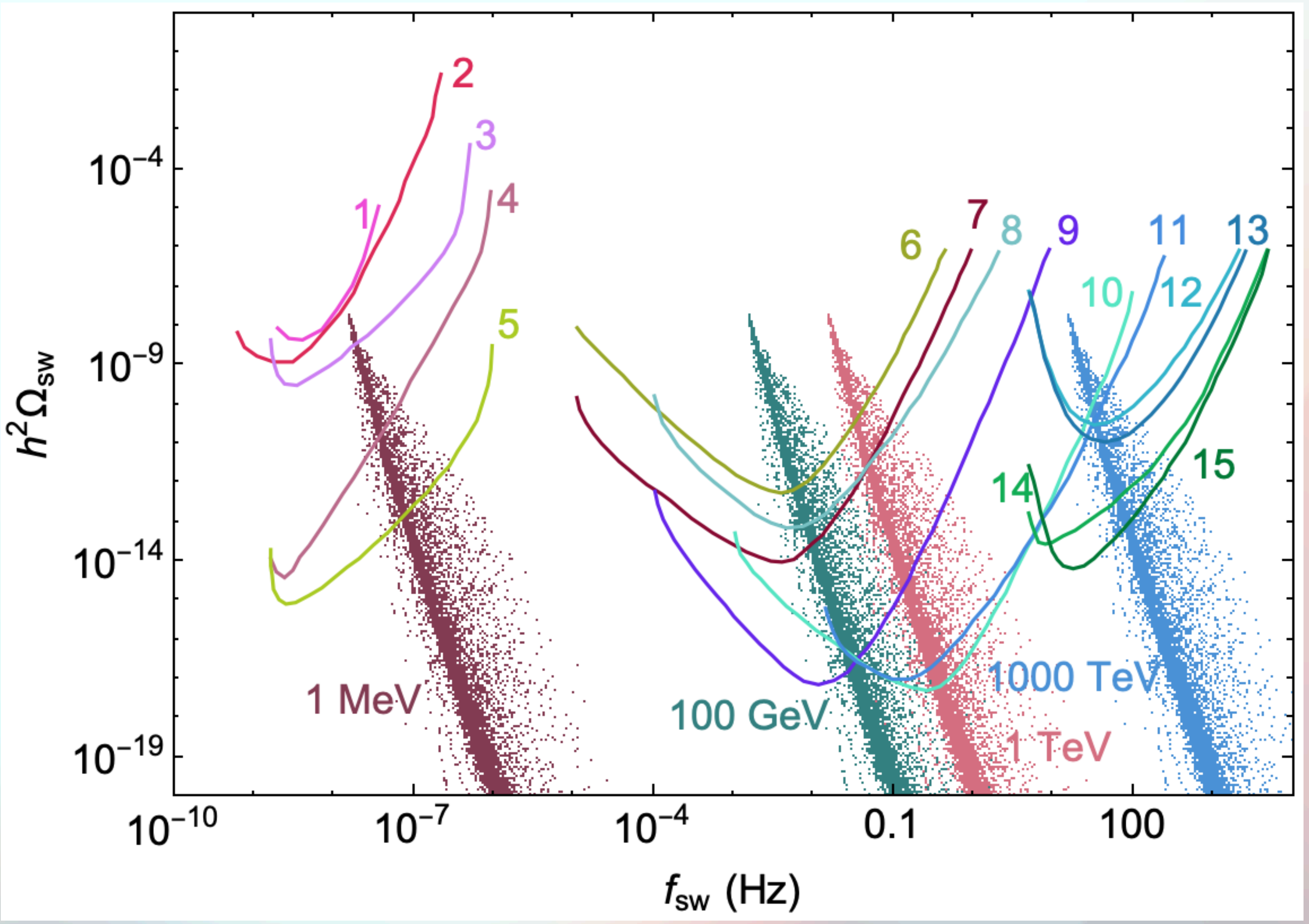
- Scatter is small

  — if $\tilde{T}_N$ dependence was negligible, would just be one point in (b, c), differing only in Λ/v.

  — focused near the edge of scan at small $\tilde{T}_N$.

  — near the edge where FOPT goes away or the amplitude is suppressed.

Sensitivity to VEV



- Scan over (b, c, Λ/v) taking $v_w = 1$.
- We find, $f_{sw} \propto v$ and for any v, $h^2\Omega_{sw}^{max} \propto f_{sw}^{-9}$

— can relate v to GW signature.

- Low frequency: Pulsar Timing/ Astrometry

1. EPTA 2. NANOGrav 3. Gaia 4. SKA 5. THEIA

— $\mathcal{O}(1 - 100)$ MeV.

- Mid frequency: Space based Interferometer

6. LISA 7. Taiji 8. TianQin 9. ALIA 10. BBO 11. DECIGO

— $\mathcal{O}(100 - 1000)$ GeV.

- High frequency: Ground based Interferometer

12. aLIGO 13. A+ 14. ET 15. CE

— $\mathcal{O}(1000)$ TeV.

Results

- A relatively straightforward relationship exists between the parameters of the gravitational wave signal and the parameters of the thermal effective potential.

— scanning the effective potential parameters provides a broad understanding of the gravitational wave signature.

— frequency scale of the GW signal determines the vev of the dark Higgs, v.

— amplitude of the GW signal sets the ratio Λ/v, which, in turn sets m/v.

- For values of m/v below $\mathcal{O}(10^{-2})$, the GW signal is too small to be detected by any current/future observatories.

— independent of the scale of the new physics.

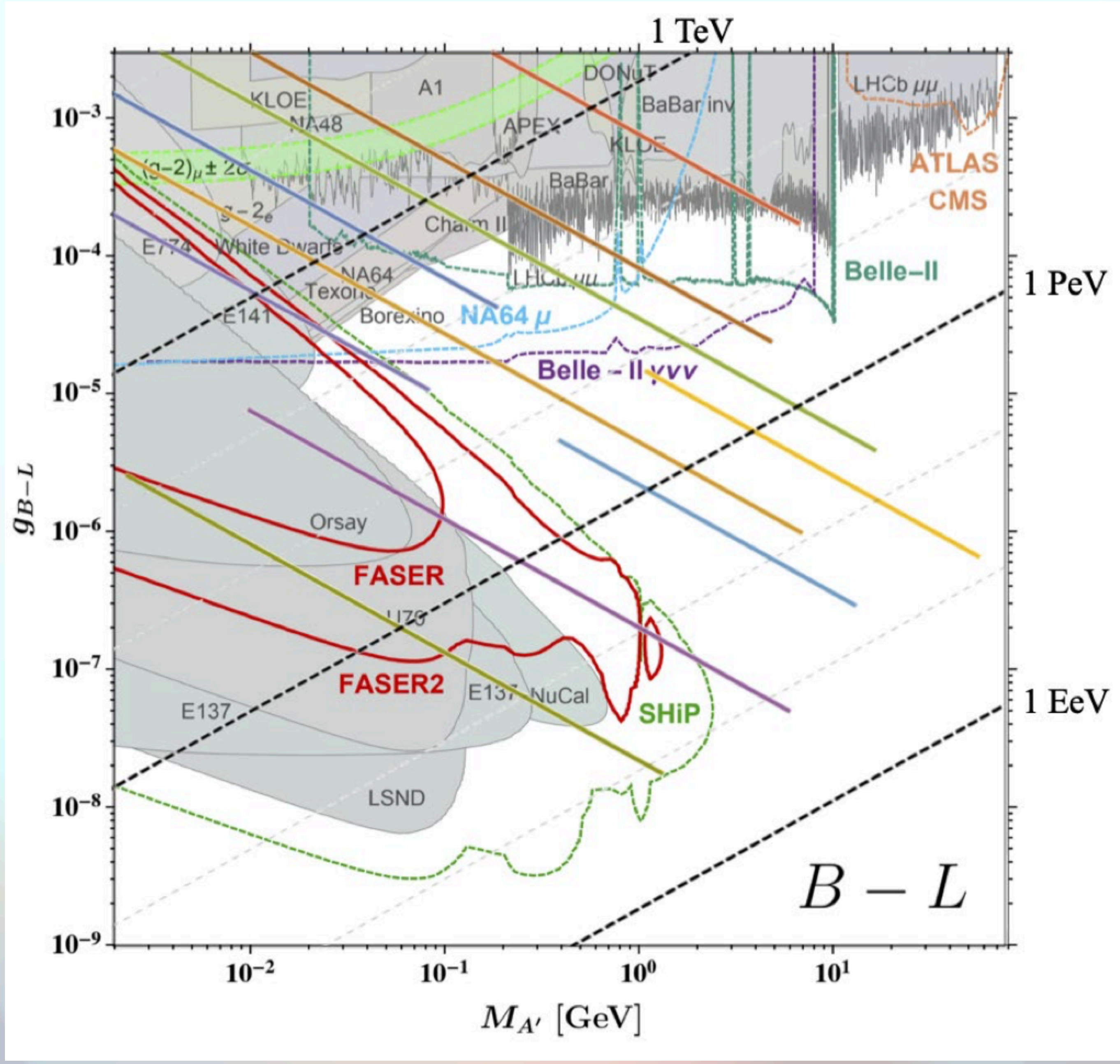
— robust to future corrections to sound wave amplitude, since it depends on m/v raised to a high power.

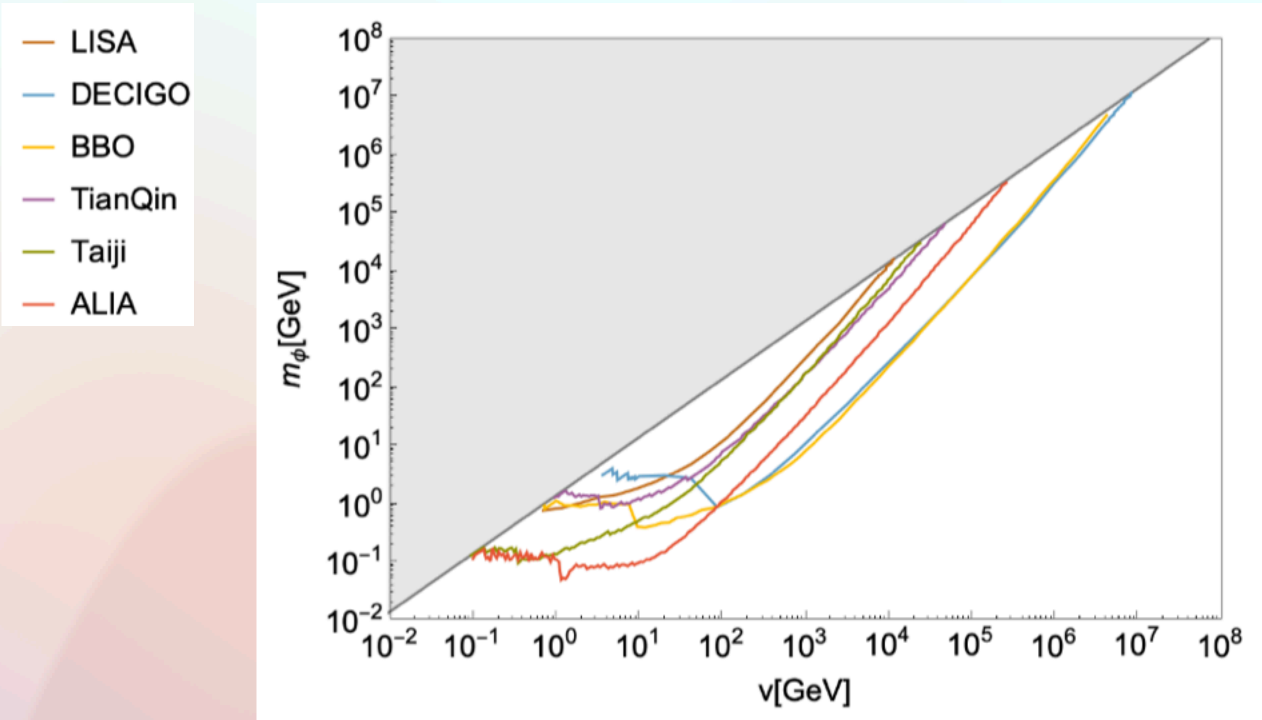
Scope of the Result

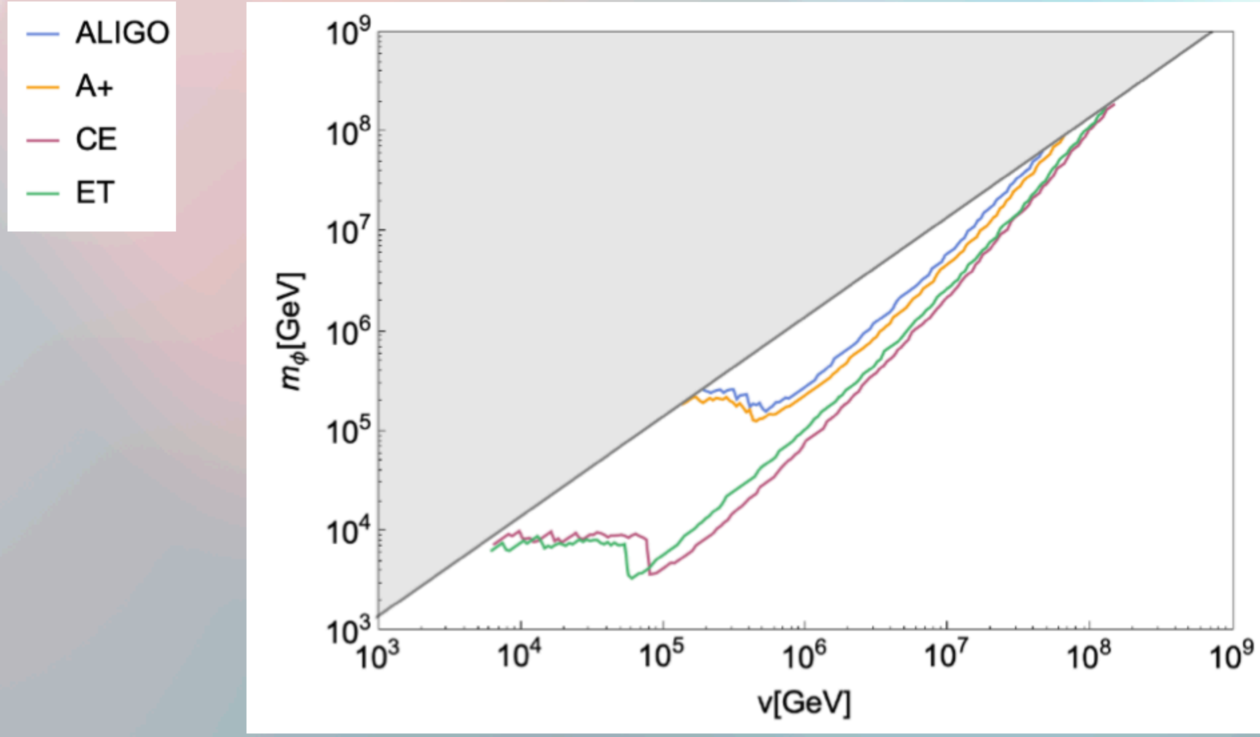
- For new MeV-scale physics, forward detectors at HL beam experiments could potentially determine the mass and coupling of the dark photon and help reveal the symmetry-breaking scale. Then, detecting a gravitational wave signal would establish a minimum value for the Higgs mass.

- Future high-energy beam experiments have the potential to generate a heavy dark Higgs ($> \mathcal{O}(\text{TeV})$), whereby the amplitude of a gravitational wave signal resulting from the phase transition would serve as an upper limit for the symmetry-breaking scale.

COMPLEMENTARITY : $U(1)_{B-L}$







Sensitivity laid on a plot from 2203.05090.

Courtesy: James B. Dent.

CONCLUSION

- Renormalizable thermal effective potential of power law form in the high T limit.

  — exhibit first order phase transition in the early universe.

  — generates GW signals detectable by current/upcoming experiments.

  — we can get broad predictions about the GW signals by scanning the parameters of the effective potential.