Gravitational Waves From Inflaton Decays

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- Review to the GW detections and Motivation
- Model of Reheating
- Gravitons from the Inflaton Decay during Reheating
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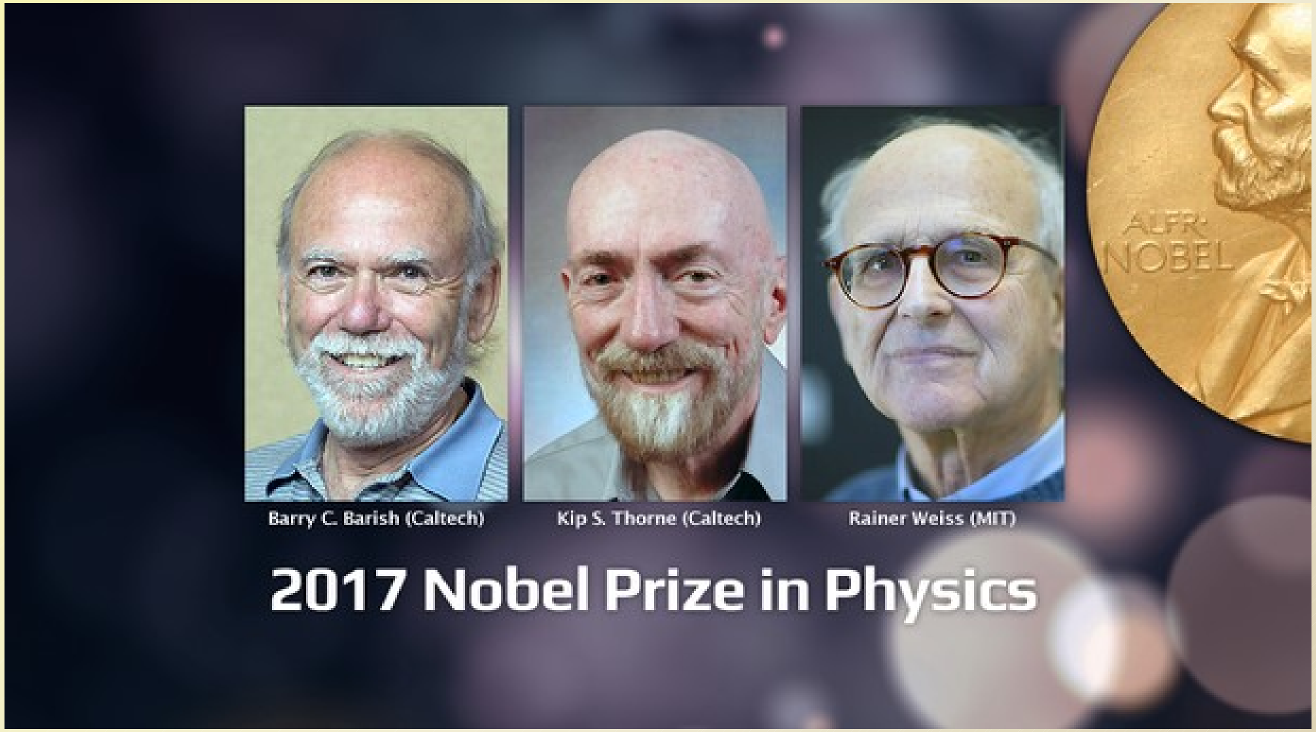
Introduction

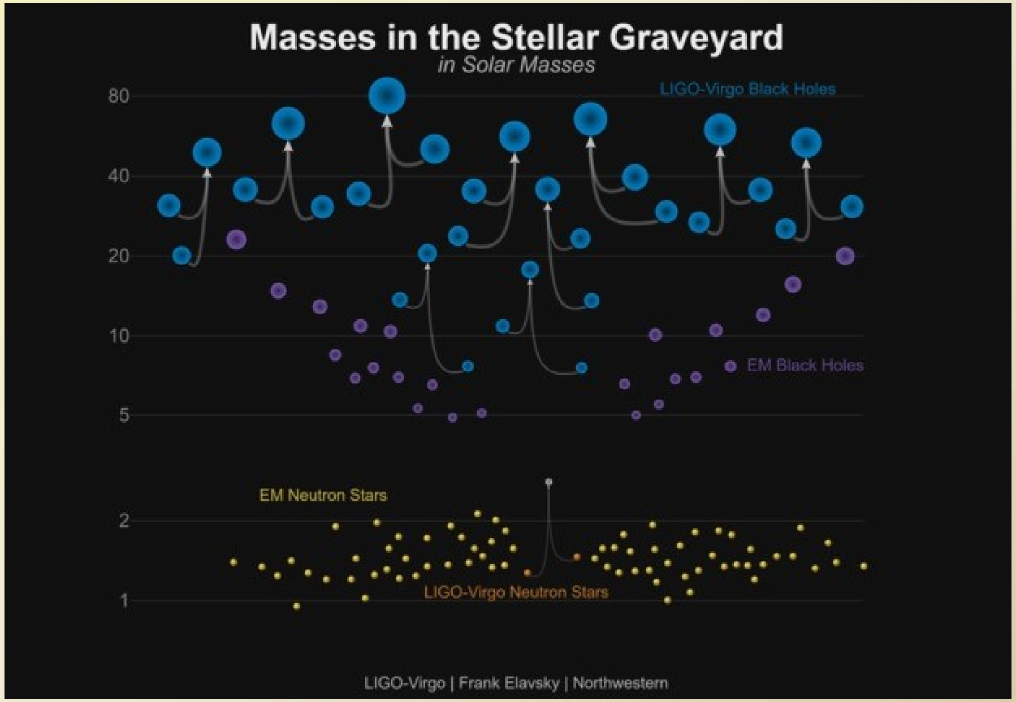
- In 2015, the aLIGO Collaboration directly observed the gravitational waves (GWs) from the binary black hole (BH) merger. This discovery not only tested the Einstein's General Relativity once more, but also represented the beginning of the era to study our Universe with the GWs.



The Status of LIGO/Virgo

- Until the end of 2018, through the two run of observations, LIGO/Virgo Collaboration discovered 10 binary BH (BBH) mergers and one binary neutral star (BNS) merger in total.

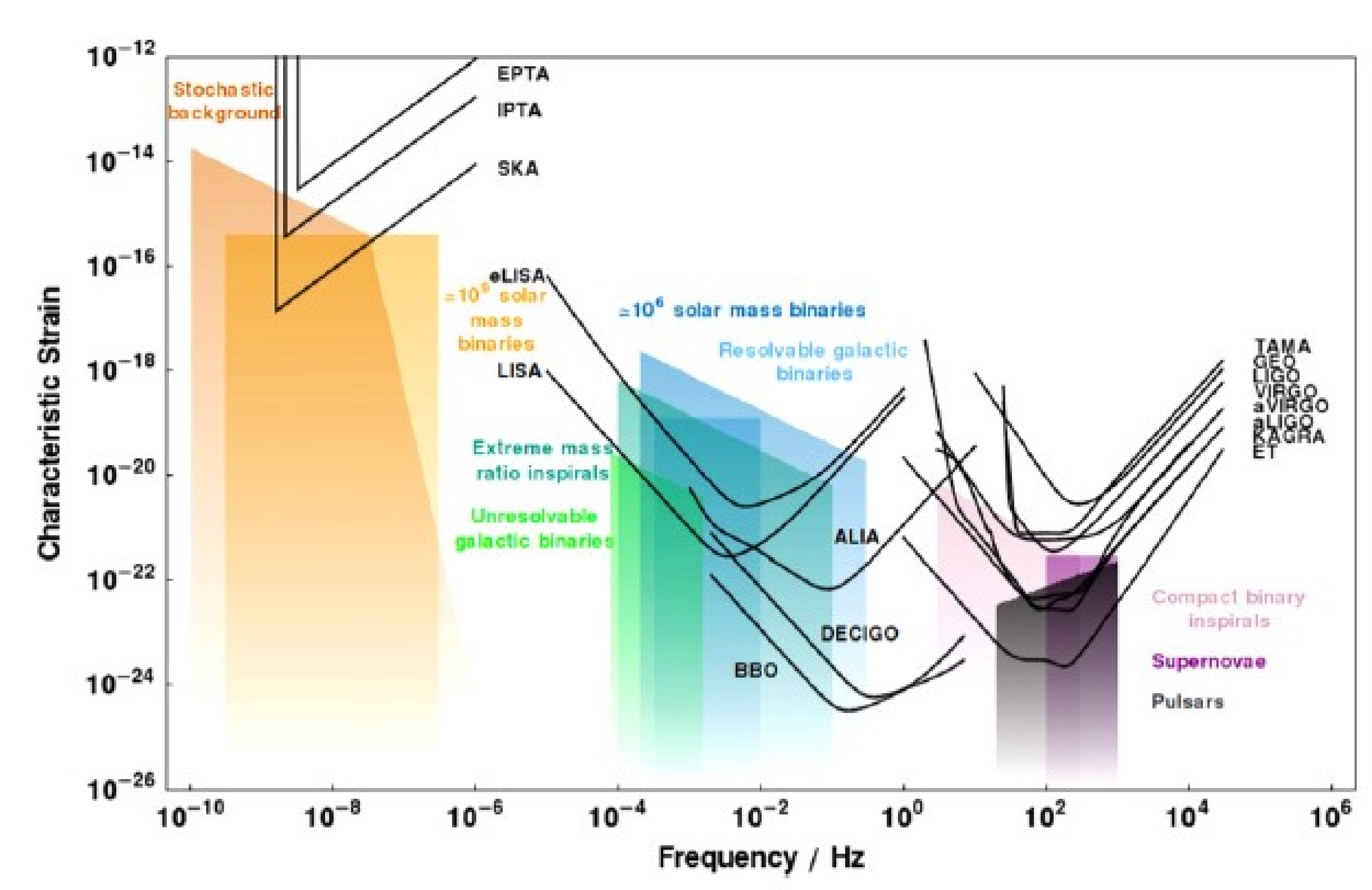
- In the April of 2019, LIGO/Virgo began the third observation (O3) run.



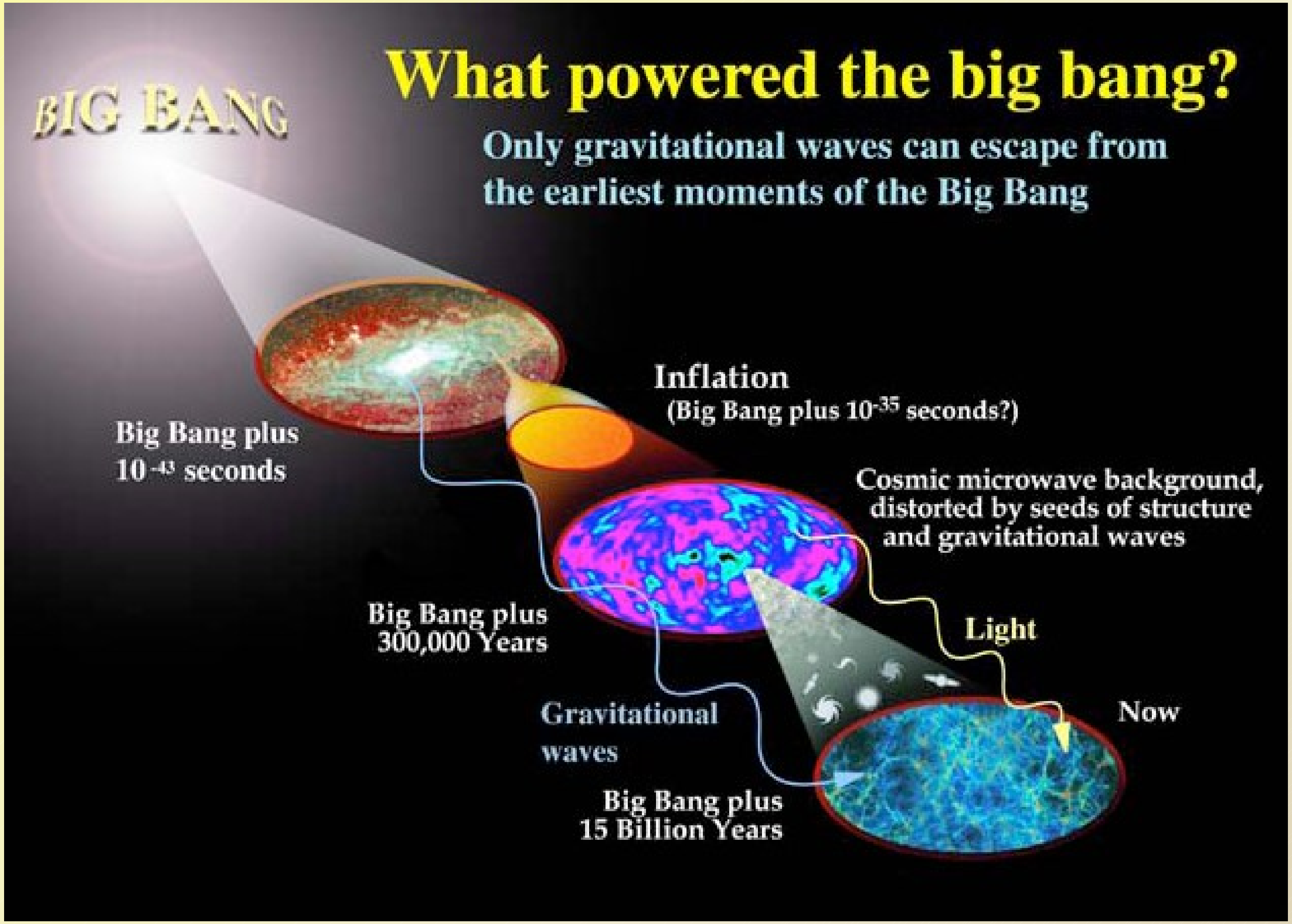
- Up to now, 23 GW events have been confirmed, in which there are 20 BBH mergers, 2 BNS mergers and 1 event is suspected to be a BH-NS merger.

The future of GW Detections

Credit: C.J. Moore et al., arXiv: 1408.0740



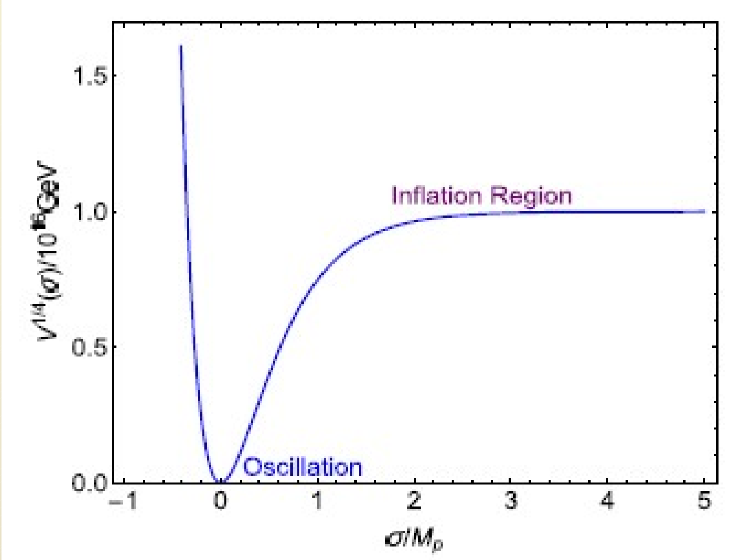
GW: the Messenger of Early Universe



Credit: Nelson Christensen

Motivation: GWs from Reheating

- Inflation theory elegantly solves many puzzles in the standard Big Bang Cosmology, such as the horizon problem, the flatness problem and the monopole problem, while naturally generates the primordial fluctuations as the seeds for the large scale structure formation.
- After the end of the inflation, the inflaton coherently oscillates around its potential bottom, which behaves as a nonrelativistic matter.
- The reheating process describes how to transfer the energy from the inflaton field into the SM dofs, leaving us a hot Universe, which is required by the BBN.



Motivation: GWs from Reheating

- Currently, there are already many reheating models, including
  - Inflaton perturbative decays

    D.J.H. Chung, et al., PRD60 (1999) 063504
  - Non-perturbative scenarios such as preheating

    A.D.Dolgov & D. P. Kirilova, 1990; J. H. Traschen & R. H. Brandenherger, 1990; L. Kofman, A. D. Linde & A. A. Starobinsky, PRL73(1994)3195; PRD56(1997)3258; M. A. Amin et al, Int. J.Mod. Phys. D24 no.01,(2014) 1530003, …
- Problem: How to test the reheating？
- It was shown that GWs could be exploited as a probe to the dynamics of reheating. However, most studies have been focused on to the non-perturbative preheating scenarios. A salient feature is that the produced GWs can be observed by the near future aLIGO-O5 run.

S.Y. Khlebnikov & I.I. Tkachev, PRD56(1997)653; Easther, et al. PRL99(2007)221301; J. Garcia-Bellido & D.G. Figueroa, PRL98(2007)061302; S. Antusch et al, PRL118(2017)011303; J. Liu, et al, PRL120(2018)031301; …

GWs from Inflaton Decay: Basic Picture

- More recently, K. Nakayama and Y. Tang in PLB788(2019)341 pointed out that the reheating from the inflaton perturbative decays could also produce observable stochastic GW background.
- In the case in which the reheating proceeds via the inflaton decay into a pair of intermediate particles, whose further decays or scatterings would generate SM particles and thermalize the Universe.
- Due to the universality of the gravitational interaction, it is unavoidable to emit gravitons during this inflaton decay, but with a rate suppressed by a factor of $(M/M_{\rm Pl})^2$, with M the inflaton mass.
- As a result, when the inflaton mass is of $O(M_{Pl})$, a fraction of $O(10^{-2})$ of the inflaton field energy could be carried away by gravitons. By redshifting, these gravitons would form a stochastic GW background.

Motivation: GWs from Inflaton Decays

- Possible Problems:
  - ✓ The predicted peak frequency of the GW spectrum is typically $O(10^9\ \mathrm{Hz})$, which is too high to be observed
  - ✓ This study only restricted to the models with a pair of scalars or fermions as the final inflaton decay products
- In the light of the importance of this GW signal, we should explore models beyond this restriction. Here we consider the GW production in models where the reheating proceed via the inflaton dominantly decays into a pair of vector particles.
- At the same time, we are interested in the question if we could tune the model parameters to allow the GW signal to be detected by the ongoing and upcoming GW experiments.

GWs from Inflaton Decays: Models

- Lagrangian for inflaton σ decays: DH & L. Yin, PRD100(2019)043538

$$S = \int d^4x \sqrt{|g|} \left[\frac{M_{\rm Pl}^2}{2} R + \frac{1}{2} g^{\mu\nu} \partial_\mu \sigma \partial_\nu \sigma - V(\sigma) - \frac{1}{4} g^{\mu\rho} g^{\nu\sigma} F_{\mu\nu} F_{\rho\sigma} - \frac{m_A^2}{2} g^{\mu\nu} A_\mu A_\nu - \delta\mathcal{L} \right],$$

in which A_μ represents the vector particle as the decay products.

- V(σ) is the inflaton potential, which can be approximated as

$$V(\sigma) = M^2\sigma^2/2$$

near the bottom of the potential, in which M is the inflaton mass.

- $\delta\mathcal{L}$ describes the interaction between σ and A:
  - ✓ Higgs-like: $$\delta\mathcal{L}^H = \frac{\mu}{2} g^{\mu\nu} \sigma A_\mu A_\nu$$
  - ✓ Axionlike: $$\delta\mathcal{L}^A = \frac{1}{f} \sigma \tilde{F}^{\mu\nu} F_{\mu\nu},$$

GWs from Inflaton Decays: Models

- The dominant inflaton two-body decay rates:
  - ✓ Higgs-like: $$\Gamma_0^H(\sigma \to AA) = \frac{M}{64\pi}\left(\frac{\mu}{M}\right)^2 \frac{1}{y^4}(1-4y^2)^{3/2},$$
  - ✓ Axionlike: $$\Gamma_0^A(\sigma \to AA) = \frac{M}{4\pi}\left(\frac{M}{f}\right)^2 (1-4y^2)^{3/2},$$

  where $y \equiv m_A/M$.

- In order to compute three-body inflaton decays with a graviton emission, we first decompose the metric tensor as follows

$$g_{\mu\nu} = \eta_{\mu\nu} + \kappa h_{\mu\nu}$$

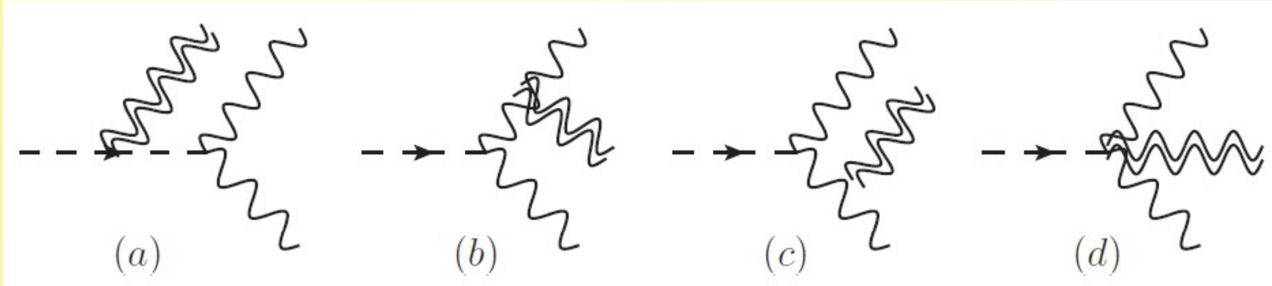
with $\kappa \equiv \sqrt{16\pi G} = \sqrt{2}/M_{\rm Pl}$, and expand the Lagrangian up to the leading order in h, which gives the following graviton interactions:

$$\delta\mathcal{L} \supset \frac{\kappa}{2} h_{\mu\nu} T^{\mu\nu}$$

with $T_{\mu\nu}$ denoting the stress-energy tensor of matter fields.

Inflaton Gravitational Decays

- Higgs-like Coupling:



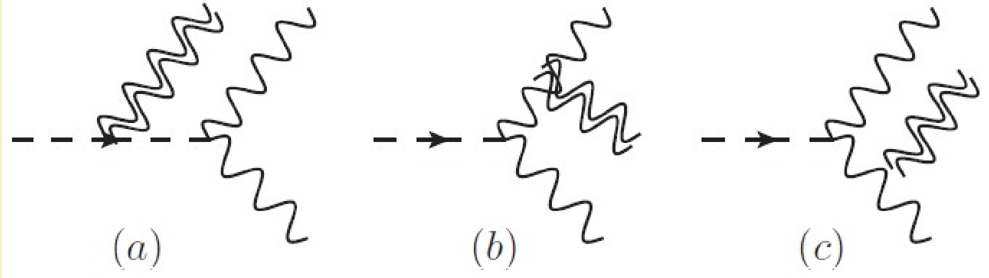
The graviton energy spectrum from this three-body decay:

$$
\begin{aligned}
\frac{d\Gamma_1^H}{M dx} = \frac{1}{64\pi^3}\left(\frac{\mu}{M_{\rm Pl}}\right)^2 \frac{1}{32xy^4}\Bigg\{ & \left[1-4x+4x^2-2y^2+12xy^2-48x^2y^2\right. \\
& \left.+64x^3y^2+4y^4-32xy^4+48x^2y^4+24y^6-48xy^6\right]\alpha \\
& -4y^2\left[1-2x-4x^2+8x^3-5y^2+8xy^2\right. \\
& \left.+16y^4-24xy^4-12y^6\right]\ln\left(\frac{1+\alpha}{1-\alpha}\right)\Bigg\},
\end{aligned}
$$

where $x = E/M\,, \qquad \alpha = \sqrt{1-\dfrac{4y^2}{1-2x}}\,.$

Inflaton Gravitational Decays

- Axionlike Coupling:



Only three diagrams are relevant, since the interaction $\delta\mathcal{L}^A = \frac{1}{f}\sigma\tilde{F}^{\mu\nu}F_{\mu\nu},$ does not involve the metric tensor.

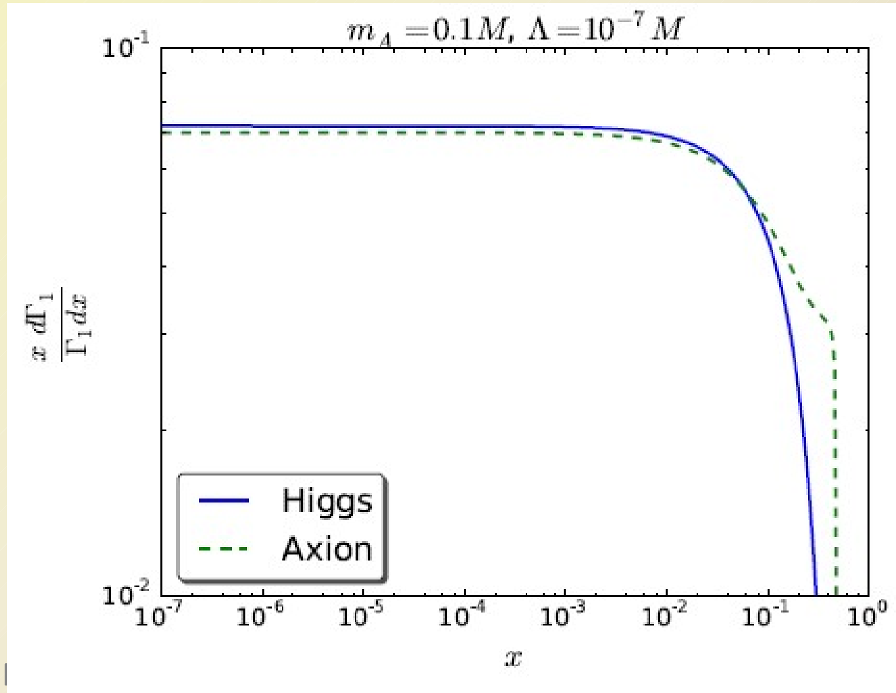
- The graviton energy spectrum:

$$\frac{d\Gamma_1^A}{M\,dx} = \frac{1}{64\pi^3}\left(\frac{M}{f}\right)^2\left(\frac{M}{M_{\rm Pl}}\right)^2\frac{1}{x}\left\{\left[1-4x+12x^2-16x^3+8x^4\right.\right.$$
$$\left.-2y^2+12xy^2-16x^2y^2-8y^4+16xy^4\right]\alpha$$
$$\left.-4y^2\left[1-2x+6x^2-4x^3-5y^2+8xy^2-8x^2y^2+4y^4\right]\ln\left(\frac{1+\alpha}{1-\alpha}\right)\right\},$$

Inflaton Gravitational Decays

- For a fixed y, both differential decay rates $d\Gamma_1^{H,A}/(M dx)$ are divergent as 1/x in the low graviton energy limit x→0, which is nothing but the usual soft graviton singularity.
- In order to yield a sensible decay rate $\Gamma_1^{H,A}$, we need to introduce an IR cutoff scale Λ for radiated graviton energy E. In terms of x, we define the integration lower limit as $x_L = \Lambda/M$.

- Normalized Graviton Energy Spectrum $x\, d\Gamma_1^{H,A}/(\Gamma_1 dx)$:

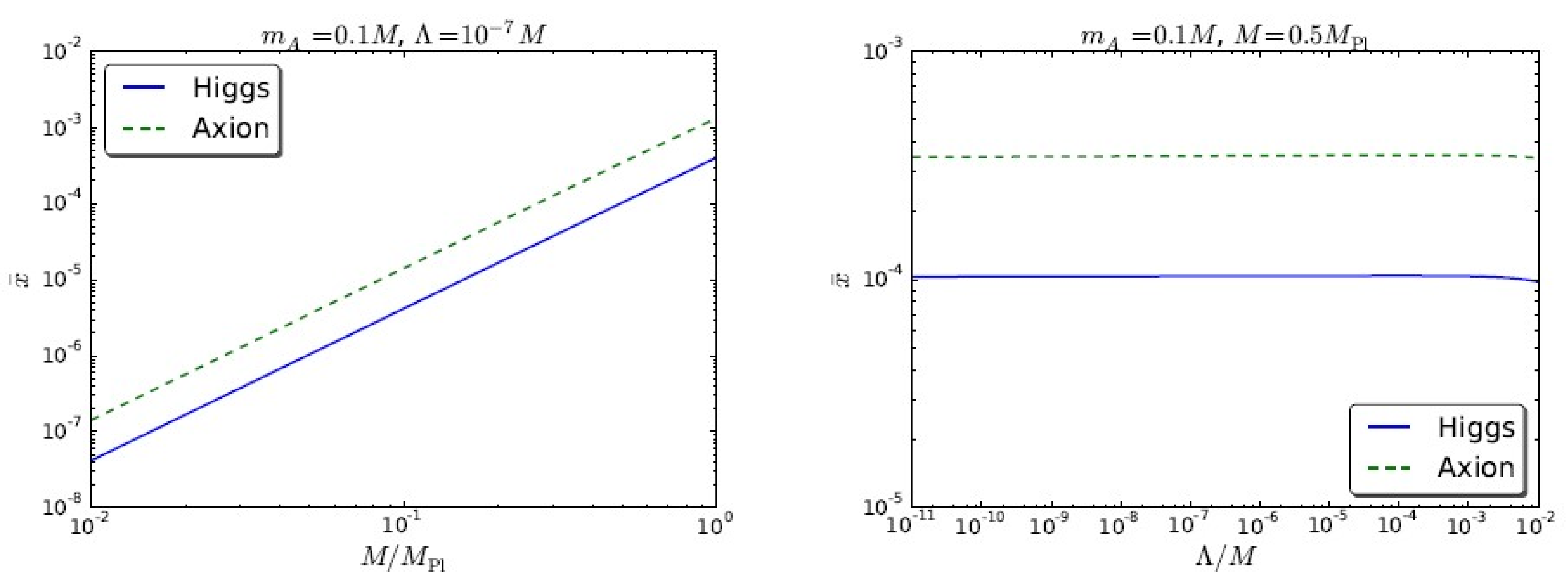


Inflaton Gravitational Decays

➤ Graviton Energy Fraction from the Inflaton Decays

$$\bar{x} \equiv \frac{\bar{E}}{M} = \frac{\Gamma_1}{\Gamma} \int_{x_L}^{x_M} \frac{x d\Gamma_1}{\Gamma_1 dx} dx \,,$$

where $\Gamma \equiv \Gamma_0 + \Gamma_1$ is the total inflaton decay rate, and the upper limit $x_M = (1 - 4y^2)/2$ is determined by three-body kinematics.



Gravitational Waves from Inflaton Decays

- After produced from inflaton decays during reheating, gravitons would propagate through the Universe without any further interactions.
- Due to the cosmic expansion, the energies of gravitons would be redshifted. Finally, a homogeneous and isotropic stochastic GW background can be formed.
- Partial energy density fraction of GW background:

$$\Omega_{\rm GW}(f) \equiv \frac{1}{\rho_c^0}\frac{d\rho_{GW}}{d\ln f},$$

where f denotes the GW signal frequency and $\rho_c^0 = 3M_{\rm Pl}^2 H_0^2$ is the present critical energy density.

Gravitational Waves from Inflaton Decays

➢ By accounting for the redshifting effects, we can relate the present GW background frequency spectrum with the graviton energy spectrum produced at reheating as follows:

$$\Omega_{\rm GW}(f) = \Omega_\gamma \left(\frac{g_s^0}{g_s^R}\right)^{1/3} \left(\frac{g_s^{\nu a}}{g_s^{\nu b}}\right)^{4/3} \frac{1}{1-\bar{x}} \frac{x^2 d\Gamma_1}{\Gamma dx},$$

where the GW frequency f can be related to the graviton energy at reheating as

$$x = \frac{E_R}{M} = \left(\frac{a_0}{a_R}\right) \frac{E_0}{M} = \left(\frac{T_R}{T_0}\right) \left(\frac{g_s^R}{g_s^0}\right)^{1/3} \left(\frac{g_s^{\nu b}}{g_s^{\nu a}}\right)^{1/3} \frac{2\pi f}{M}.$$

Here g^R_s=106.75 (g^0_s=2) represents the relativistic dofs in the SM sector at reheating(present), while g_s^{va}=43/4 (g_s^{vb}=11/2) denotes dofs before (after) the neutrino decoupling.

Gravitational Waves from Inflaton Decays

- Further assumptions:
  - ✓ Instantaneous reheating: H=Γ

    By energy conservation, the reheating temperature is given by

$$T_R = \left[\frac{90}{\pi^2 g_\rho(T_R)}\right]^{1/4} \sqrt{M_{\rm Pl}\Gamma} = 0.54\sqrt{M_{\rm Pl}\Gamma}\,,$$

  - ✓ The IR cutoff scale Λ is taken to be the Hubble parameter H at reheating, since the graviton cannot be viewed as a particle when its energy is lower than the Hubble scale H.

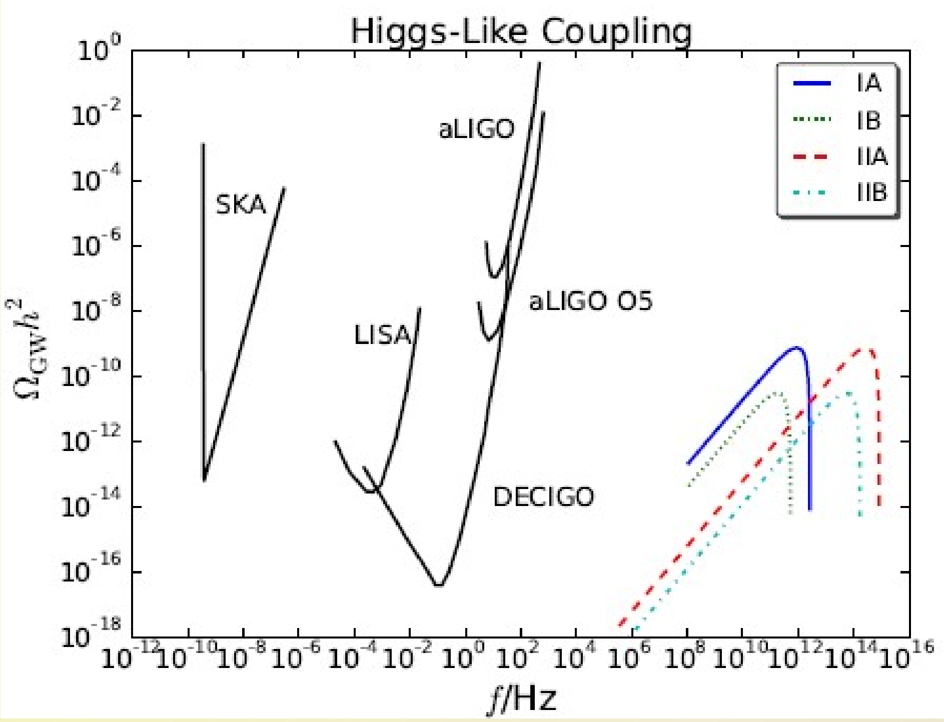
- Under the above two assumptions, the reheating model is only parameterized by the vector particle mass m_A, the inflaton mass M and its total decay rate Γ.

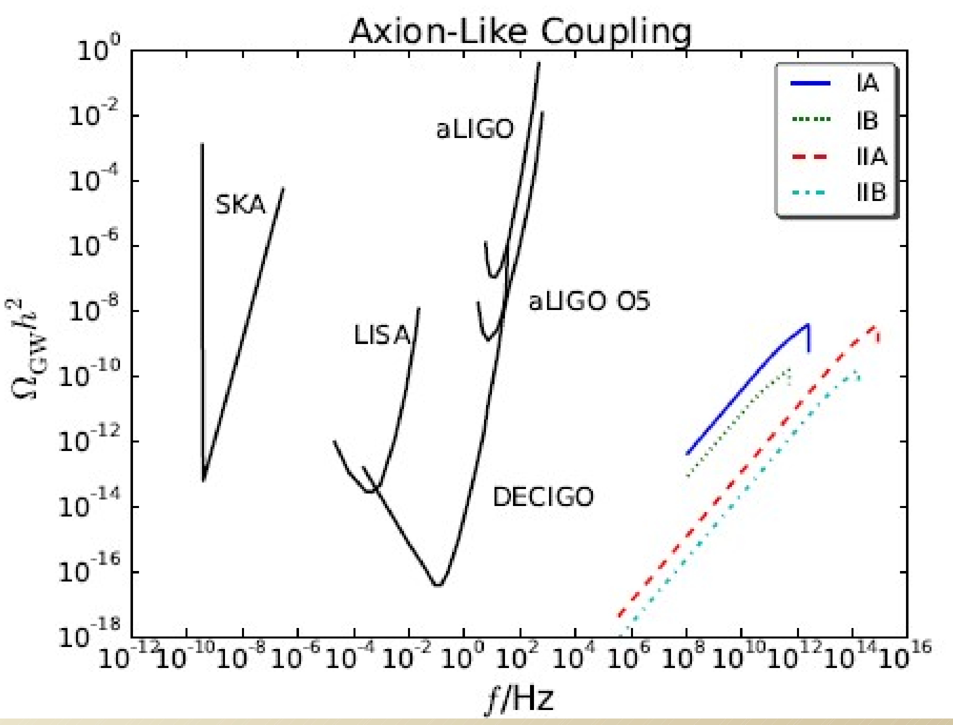
Gravitational Waves from Inflaton Decays

- Numerical Results:

  We fix $y=m_A/M=0.1$, and take the four benchmark sets of parameters

- IA: $M = 0.5M_{\rm Pl}$, $\Gamma = 10^{-5}M_{\rm Pl}$;
- IB: $M = 0.1M_{\rm Pl}$, $\Gamma = 10^{-5}M_{\rm Pl}$;
- IIA: $M = 0.5M_{\rm Pl}$, $\Gamma = 10^{-10}M_{\rm Pl}$;
- IIB: $M = 0.1M_{\rm Pl}$, $\Gamma = 10^{-10}M_{\rm Pl}$.





Gravitational Waves from Inflaton Decays

➢ From these plots, it is interesting to see the nontrivial dependences of the GW spectra on the inflaton mass M and its total decay rate Γ.

➢ Note that the GW spectra are totally determined by $x^2 d\Gamma_1/(\Gamma dx)$, which have a definite peak at $x_{\rm peak} \sim \mathcal{O}(0.1)$ for both inflaton couplings. Thus, we have the following two relations:

✓ The GW peak frequency is

$$f_{\rm peak} \sim M x_{\rm peak}(T_0/T_R) \propto M x_{\rm peak}/\sqrt{\Gamma},$$

✓ The GW peak amplitude scales with the inflaton mass M as $(M/M_{\rm Pl})^2$ without any dependence on Γ.

Gravitational Waves from Inflaton Decays

- The above plots show that the typical GW frequencies are too high to be probed by the ongoing and upcoming experiments.
- Question: Is it possible to tune the model parameters so that the GW signals can be detected by aLIGO-Virgo or LISA?
- Answer: No matter how we tune the parameters, if the GW peak frequency lies in the aLIGO or LISA sensitivity range, the amplitude of the obtained GW signals are always much smaller than the experimental sensitivities.
- Example: if $M = 1\ \mathrm{GeV}$ and $\Gamma = 0.1\ \mathrm{GeV}$, the GW peak frequency would be in the LIGO sensitivity range of O(10 Hz). However, the peak GW amplitude is only $\Omega_{\rm GW}(f_{\rm peak}) \sim \mathcal{O}(10^{-46})$, which cannot be probed experimentally.

GWs from Inflaton Decay: Constraint

- Note that the GWs would behave as a dark radiation in the Universe, this GW background could be constrained by the BBN and CMB observations on $\delta N_{\rm eff}$.
- Possible constraints:
  - ✓ Planck Collaboration: $\delta N_{\rm eff} = 0.085 \pm 0.32$
  - ✓ Future CMB exps like CMB-S4: $\delta N_{\rm eff} \sim 0.02\text{–}0.03$

- In our model, by assuming the instantaneous reheating, the GW contribution to the dark radiation is given by:

$$\delta N_{\rm eff} = \frac{4 g_s^R}{7} \left[\frac{g_s^{\nu\, a}}{g_s^R}\right]^{4/3} \frac{\bar{x}}{1-\bar{x}}$$

which can transform the constraint into $\bar{x} \simeq 10^{-2}$.

- However, as shown before, $\bar{x}$ cannot be larger than O(10^{-3}), which means that the present scenario cannot be constrained by the dark radiation observations.

Summary

- In the light of the hope to detect reheating dynamics from GW signals, we have studied the GW production in models where the reheating is achieved by the pertburbative inflaton decay into a pair of vector particles.

- We investigate two inflaton-vector couplings: Higgs-like and axionlike, and find that both yield the qualitatively similar stochastic GW spectra.

- As a result, the most promising GW signals come when the inflaton mass approaches the Planck scale. However, the predicted GW peak frequency is as high as $O(10^9$ Hz), which is too high to be observed.

- Finally, this GW background cannot be constrained by the existing and upcoming dark radiation observations.

THANKS FOR YOUR ATTANTION!