Primordial Gravitational Waves in Non-standard Cosmologies

Based on
NB & Fazlollah Hajkaim – arXiv:1905.10410 [astro-ph.CO]

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CoCo 2019
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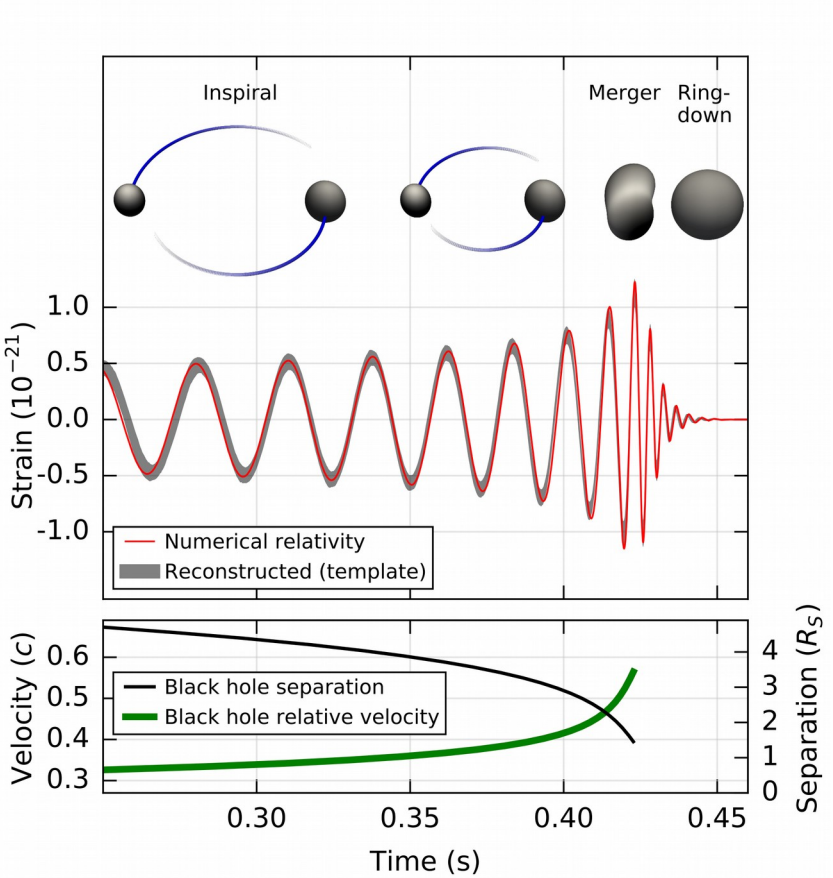
Gravitational Waves have been detected!



- $O(10)$ solar mass black hole exists
- BH-BH merger – test BH paradigm
- NS-NS merger – test NS paradigm
- GR can be further tested
- We can observe the Universe through GWs!

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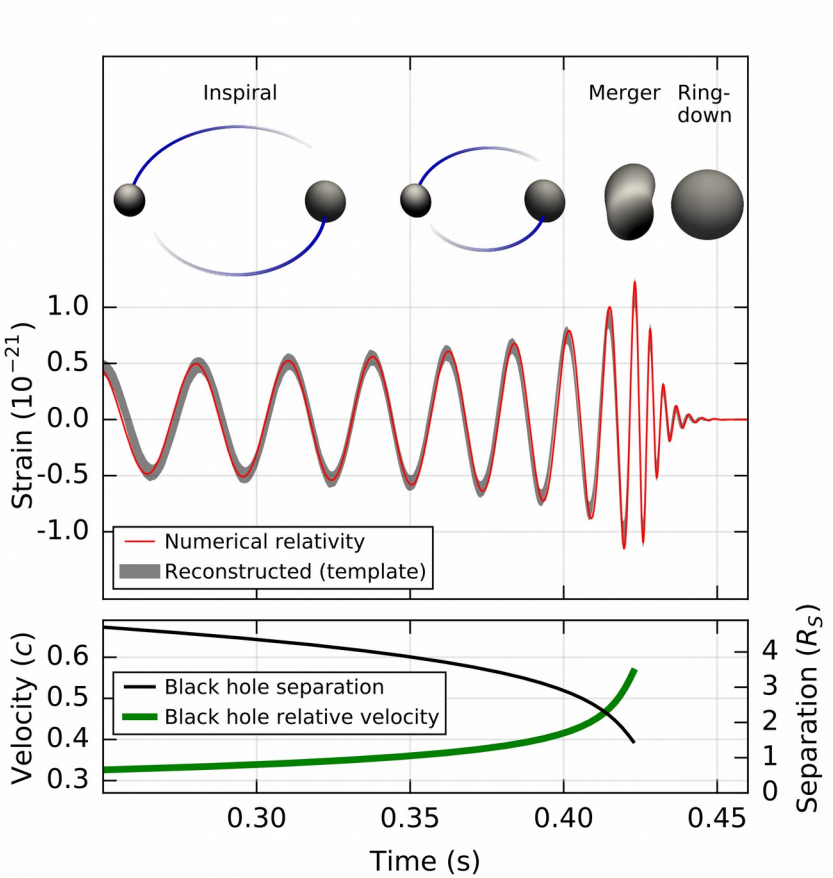

- $O(10)$ solar mass black hole exists
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- GR can be further tested
- We can observe the Universe through GWs!
- We can observe the **early** Universe through GWs!

GWs as probes of the early Universe

- GWs decouple upon production
- GWs spectrum:
  * Primordial spectrum at production
  * Propagation
- But difficult to detect :-/

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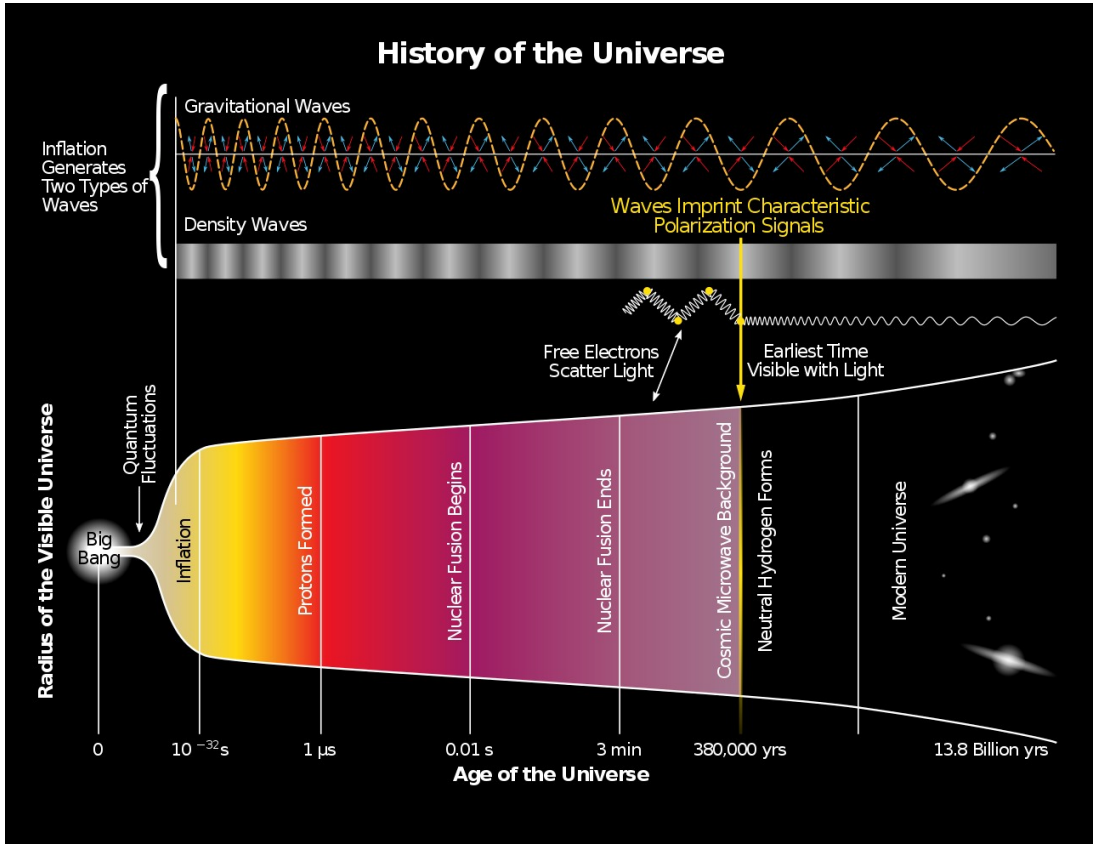
→ **GWs can probe the early Universe**

The Early Universe



See talk by Camilo!

Primordial Gravitational Waves

- GW are represented by spatial metric perturbations (transverse & traceless).
- The evolution of GWs is described by the linearized Einstein eq.

$$\ddot{h}_{ij} + 3H\,\dot{h}_{ij} - \frac{\nabla^2}{a^2} h_{ij} = 16\pi\, G\, \Pi_{ij}^{TT}$$

Π^{TT} is the transverse-traceless part of the anisotropic stress tensor $\Pi_{ij} = \dfrac{T_{ij} - p\, g_{ij}}{a^2}$

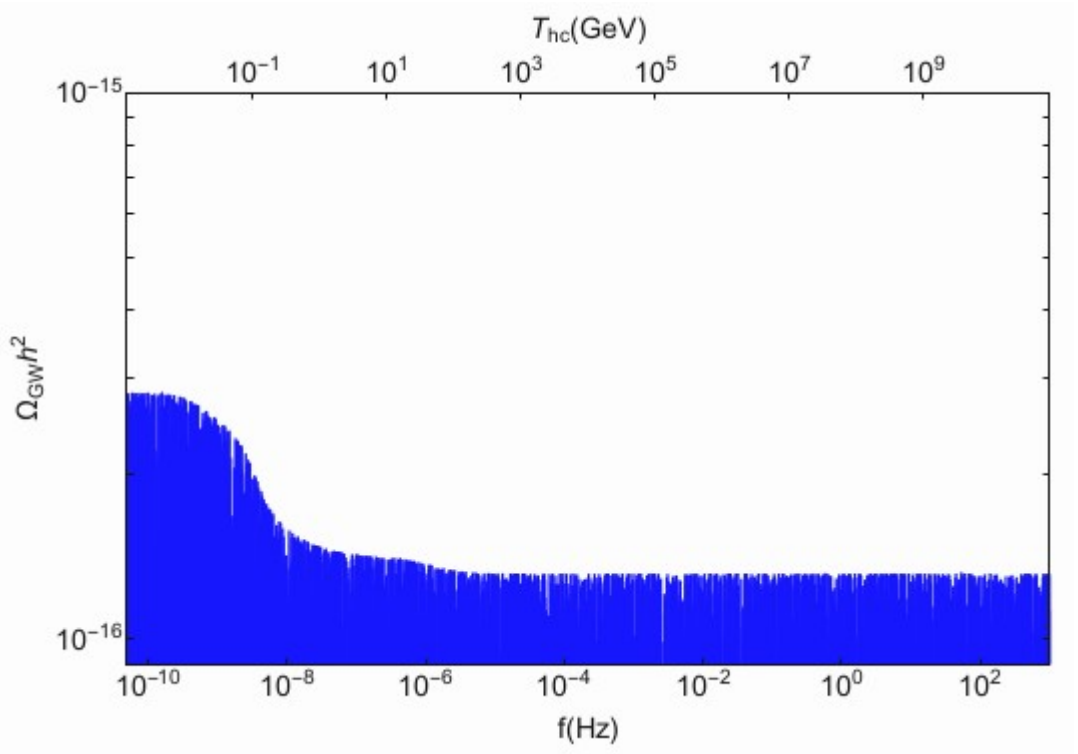
- Primordial GW spectrum

$$\Omega_{\rm GW}(t,k) = \frac{1}{\rho_c(t)} \frac{d\rho_{\rm GW}(t,k)}{d\ln k} = \frac{1}{12\, a^2(\eta)\, H^2(\eta)} \mathcal{P}_T(k)\, \left[X'(\eta,\, k)\right]^2$$

with the primordial tensor power spectrum $\mathcal{P}_T(k) = A_T \left(\dfrac{k}{\tilde{k}}\right)^{n_T}$

and the transfer function $\dfrac{d^2X(u)}{du^2} + \dfrac{2}{a(u)} \dfrac{da(u)}{du} \dfrac{dX(u)}{du} + X(u) = 0.$

Primordial Gravitational Waves



$$\mathcal{P}_T(k) = A_T \left(\frac{k}{\tilde{k}}\right)^{n_T}$$

For a primordial scale invariant spectrum and standard cosmology

Standard Cosmology

- Total energy density dominated by SM radiation
  from end of inflation until matter-radiation equality

  → SM energy density: $\rho_R \sim a^{-4}$
  → Photon temperature: $T \sim a^{-1}$

- Hubble expansion rate

  → $H \sim T^2/M_P$
  → $H \sim a^{-2}$

See talk by Alan!

Non-standard Cosmologies

- The energy density of the Universe was dominated by ϕ with an equation of state $\omega_\phi \equiv p_\phi / \rho_\phi$
- ϕ decays into SM radiation before BBN

See talk by Alan!

$$\frac{d\rho_\phi}{dt} + 3(1+\omega_\phi)\, H\, \rho_\phi = -\Gamma_\phi\, \rho_\phi\,,$$

$$\frac{ds_R}{dt} + 3\, H\, s_R = +\frac{\Gamma_\phi\, \rho_\phi}{T}$$

$$\rho_R(T) = \frac{\pi^2}{30}\, g_\star(T)\, T^4\,.$$

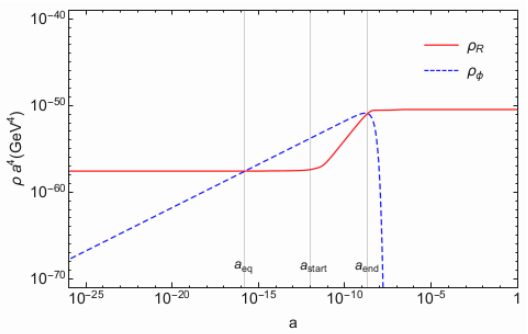
$$s_R(T) = \frac{\rho_R + p_R}{T} = \frac{2\pi^2}{45}\, h_\star(T)\, T^3\,,$$

$$H^2 = \frac{\rho_\phi + \rho_R + \rho_m + \rho_\Lambda}{3\, M_{Pl}^2}$$

- Initial conditions: T_{end} and $\xi \equiv \left.\frac{\rho_\phi}{\rho_R}\right|_{T=T_{\rm max}}$ with $T_{max}=10^{14}$ GeV (pivot scale)

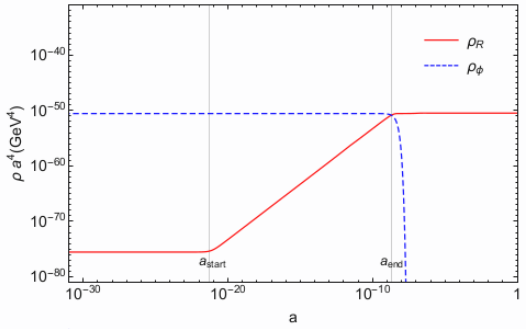
Non-standard Cosmologies

ω = 0
ξ = 10^{-11}



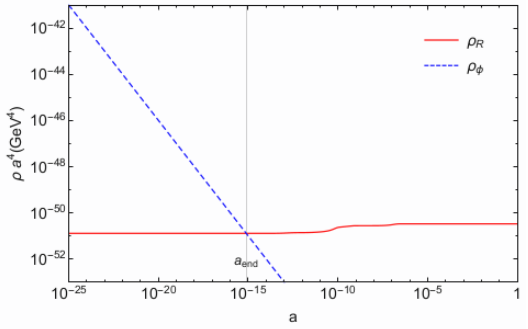
$$\rho_\phi(a) \propto a^{-3(1+\omega_\phi)}$$

ω = 1/3
ξ = 10^{25}



$$\rho_R(a) \propto \begin{cases} a^{-4} & \text{for} \quad a \ll a_{\rm start}, \\ a^{-\frac{3}{2}(1+\omega_\phi)} & \text{for} \quad a_{\rm start} \ll a \ll a_{\rm dec}, \\ a^{-4} & \text{for} \quad a_{\rm dec} \ll a, \end{cases}$$

ω = 2/3
ξ = 10^{10}



$$T(a) \propto \begin{cases} a^{-1} & \text{for} \quad a \ll a_{\rm start}, \\ a^{-\frac{3}{8}(1+\omega_\phi)} & \text{for} \quad a_{\rm start} \ll a \ll a_{\rm dec}, \\ a^{-1} & \text{for} \quad a_{\rm dec} \ll a. \end{cases}$$

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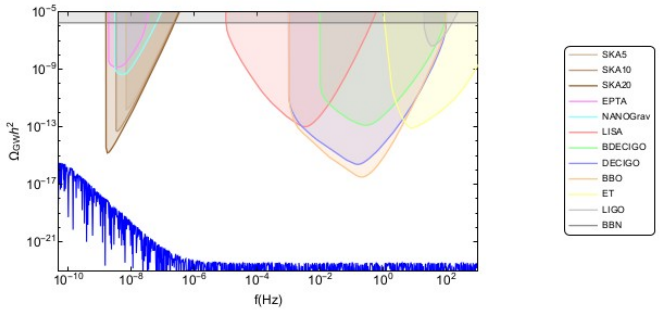
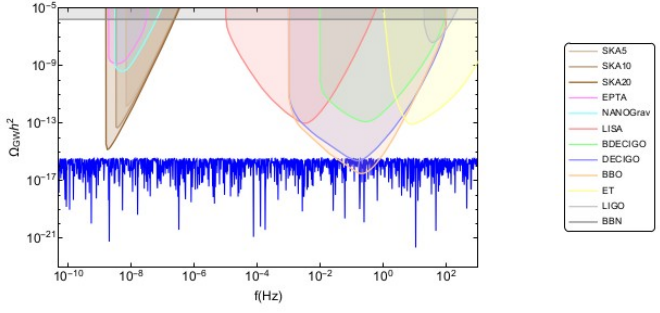
Primordial GW in Non-standard Cosmologies



Scale invariant primordial spectrum

$V_{inf}^{1/4} = 1.5 \times 10^{16}$ GeV and $T_{end} = 10$ MeV

$\omega = 0 \quad \& \quad \xi = 10^{-11}$



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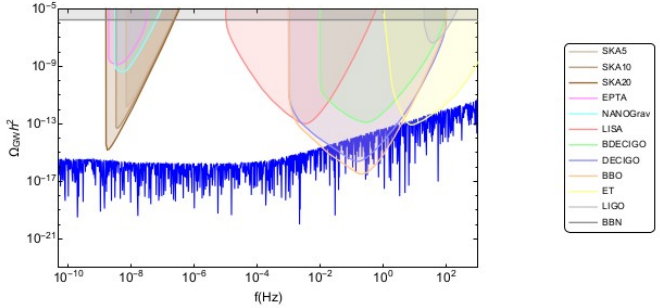

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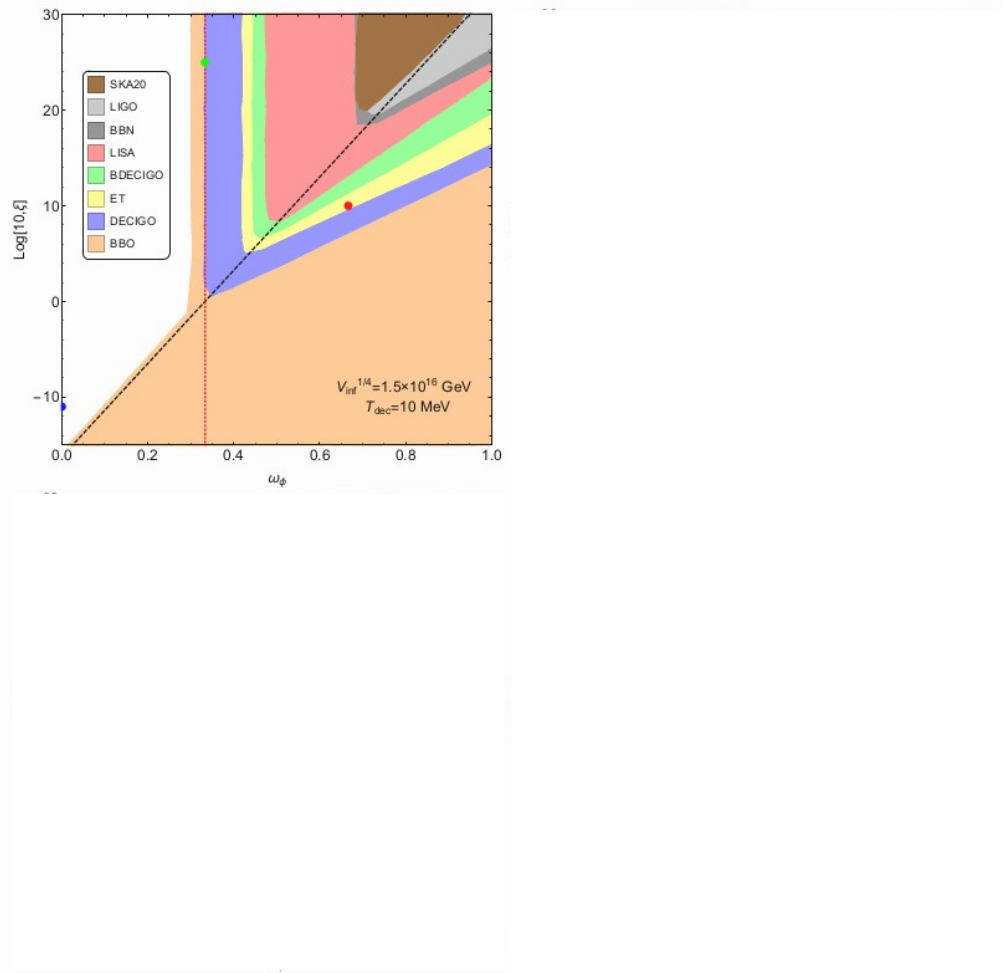
Primordial GW in Non-standard Cosmologies



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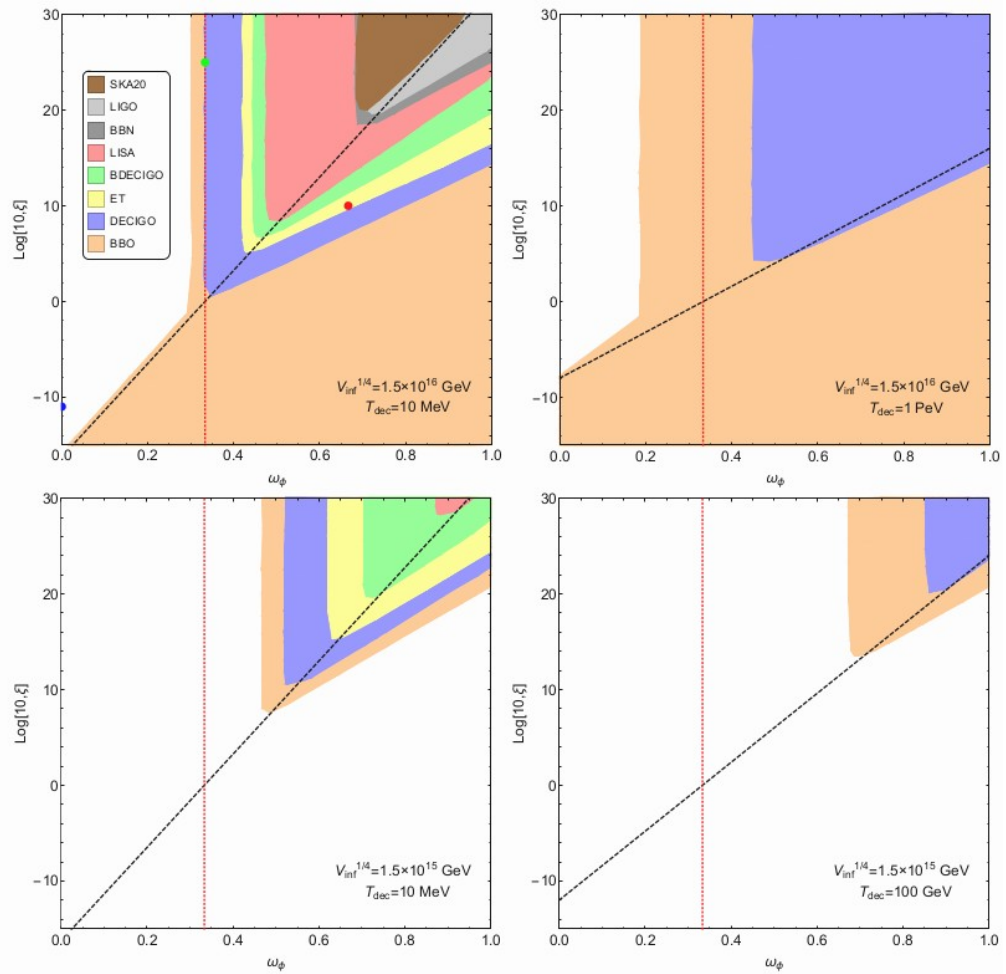

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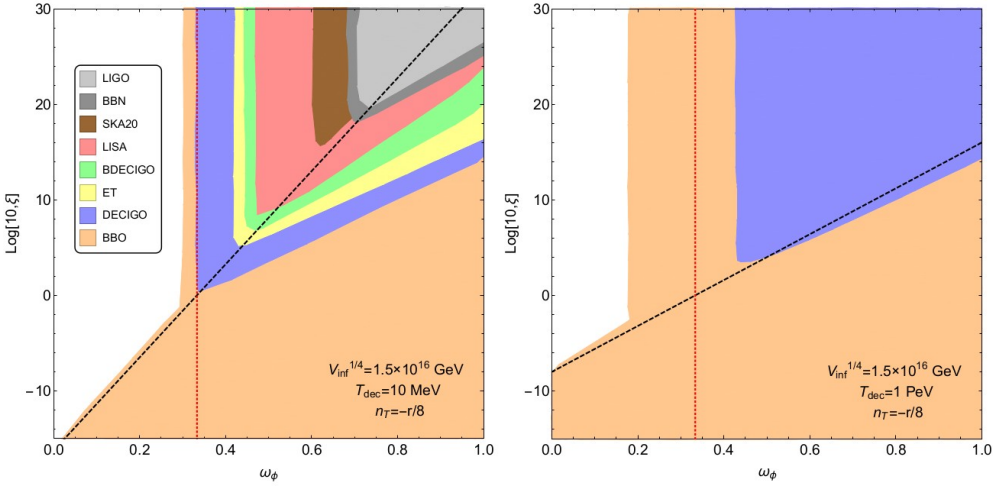

Consistency relation in the single-field slow-roll scenario:

$$r = -8\, n_T .$$

where $$r \equiv \frac{A_T}{A_S}$$

and $V_{inf}^{1/4} = 1.5 \times 10^{16}$ GeV

Conclusions & Outlook

- GWs offer a new messenger to explore the early Universe, beyond EM waves.
- The existence of a PGW background is one of the most crucial predictions of the inflationary scenario of the early Universe.
- The spectrum of the inflationary GWs depends on:
  * the power spectrum of primordial tensor perturbations
  * the expansion rate of the Universe.
- GWs can probe the early Universe!
- Upcoming GW observatories could shed light on the cosmological properties of the early Universe.

Muchas gracias!





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