Probing primordial fluctuations through stochastic gravitational wave background anisotropies

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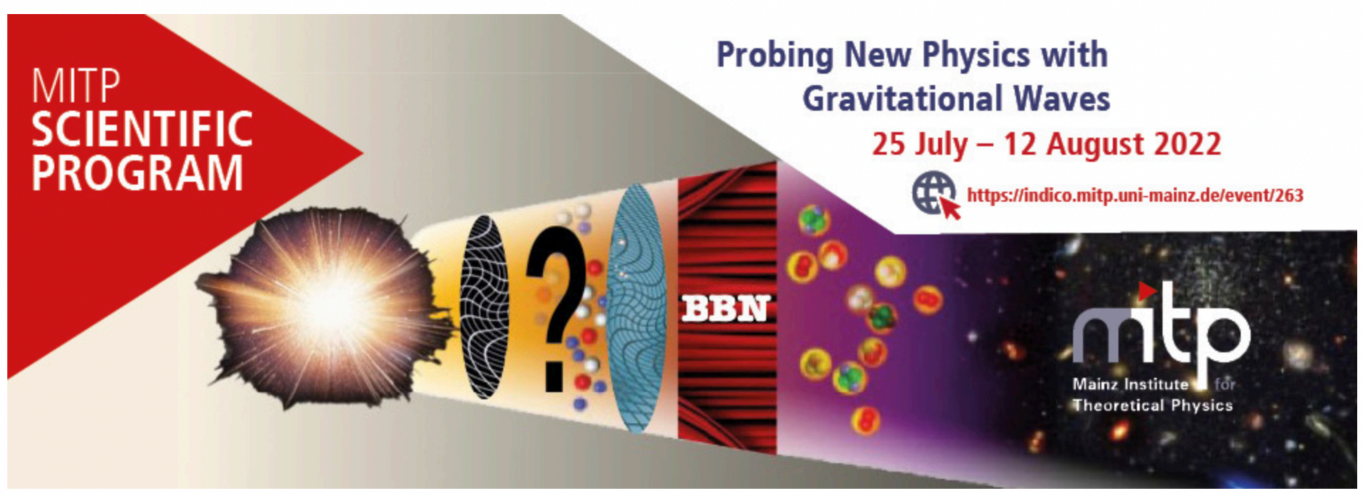
w/ Raman Sundrum and Yuhsin Tsai, 2102.05665, *JHEP* 11 (2021) 107
w/ Yanou Cui, Raman Sundrum and Yuhsin Tsai, in progress



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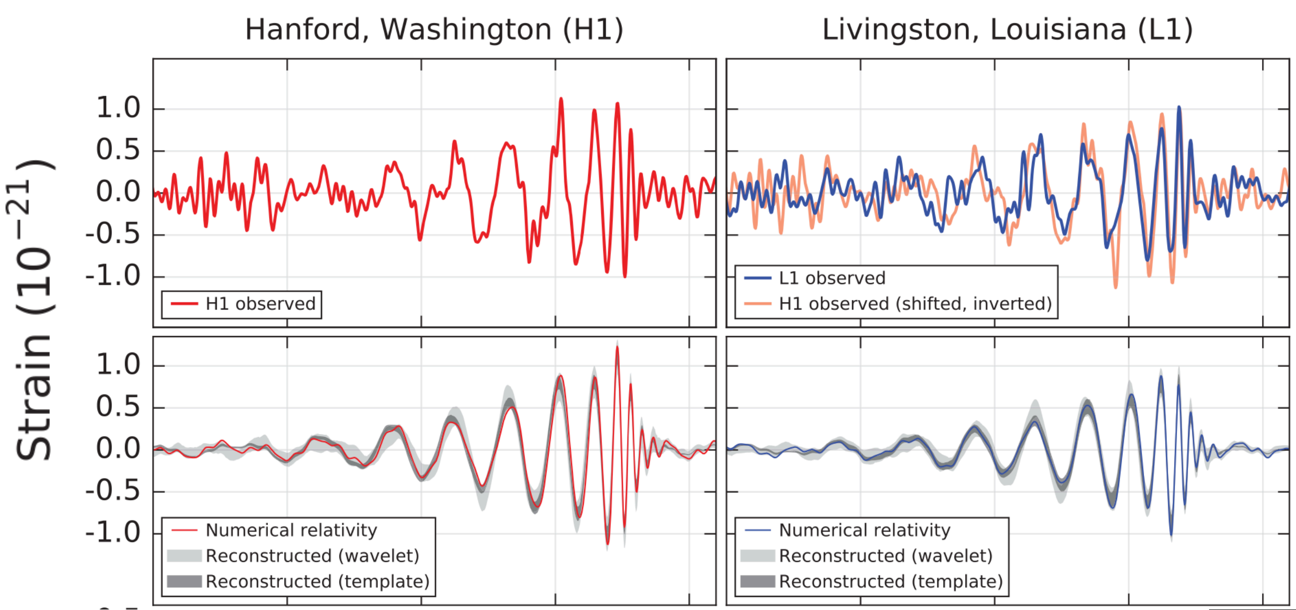
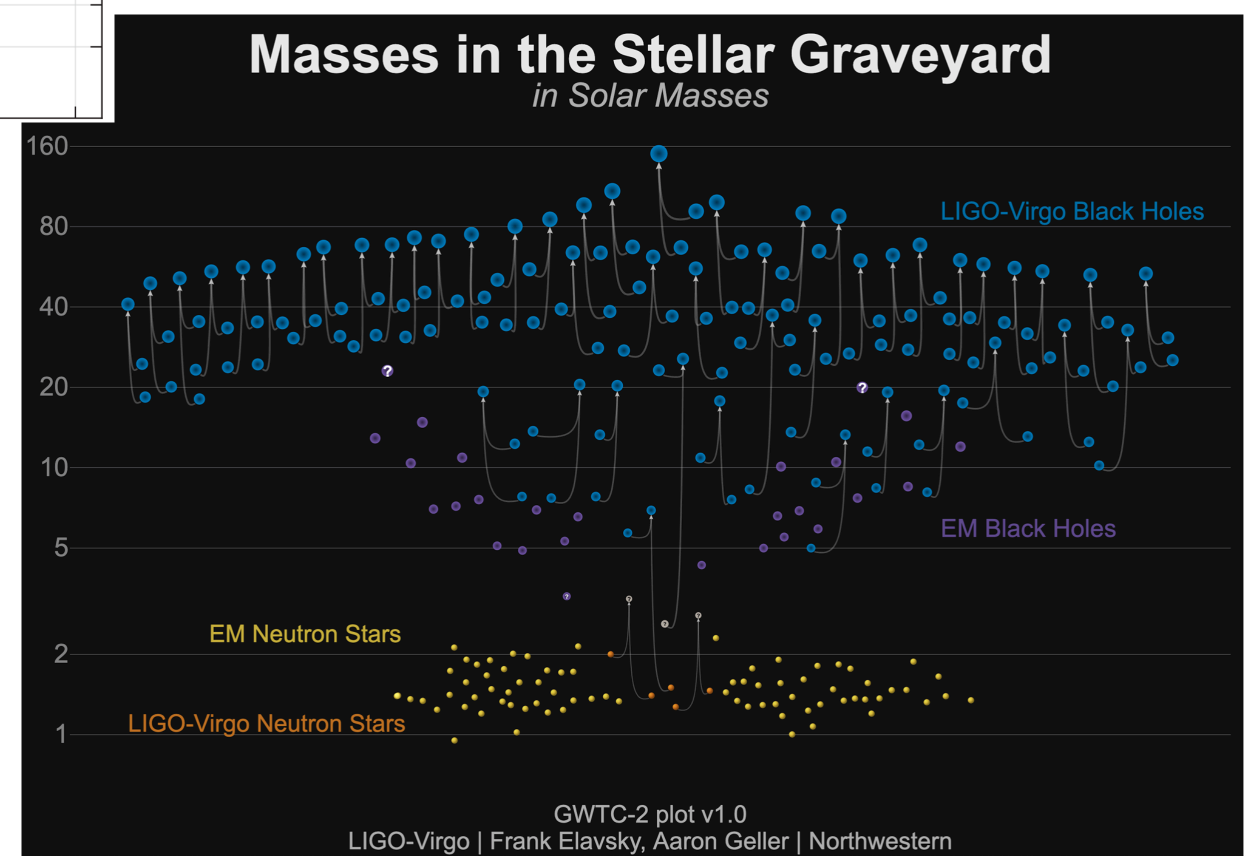
Gravitational waves are exciting!



GW from Binary BH mergers first detected in 2015 by LIGO

Abbott et al., ’16, LIGO-Virgo



Since then many more, including NS-BH, NS-NS

Multi-messenger astronomy

Abbott et al., ’17, LIGO-Virgo

Stochastic GW Background (SGWB)

- However, far-away mergers not individually detected

- Combine to give a Stochastic GW Background (random temporal phase)

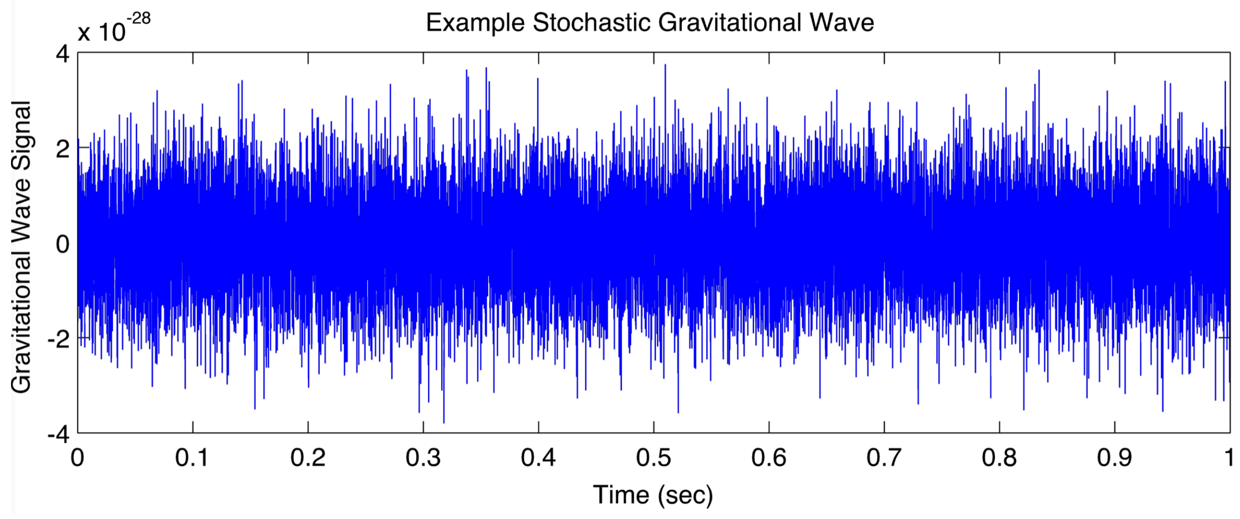


Image from LIGO

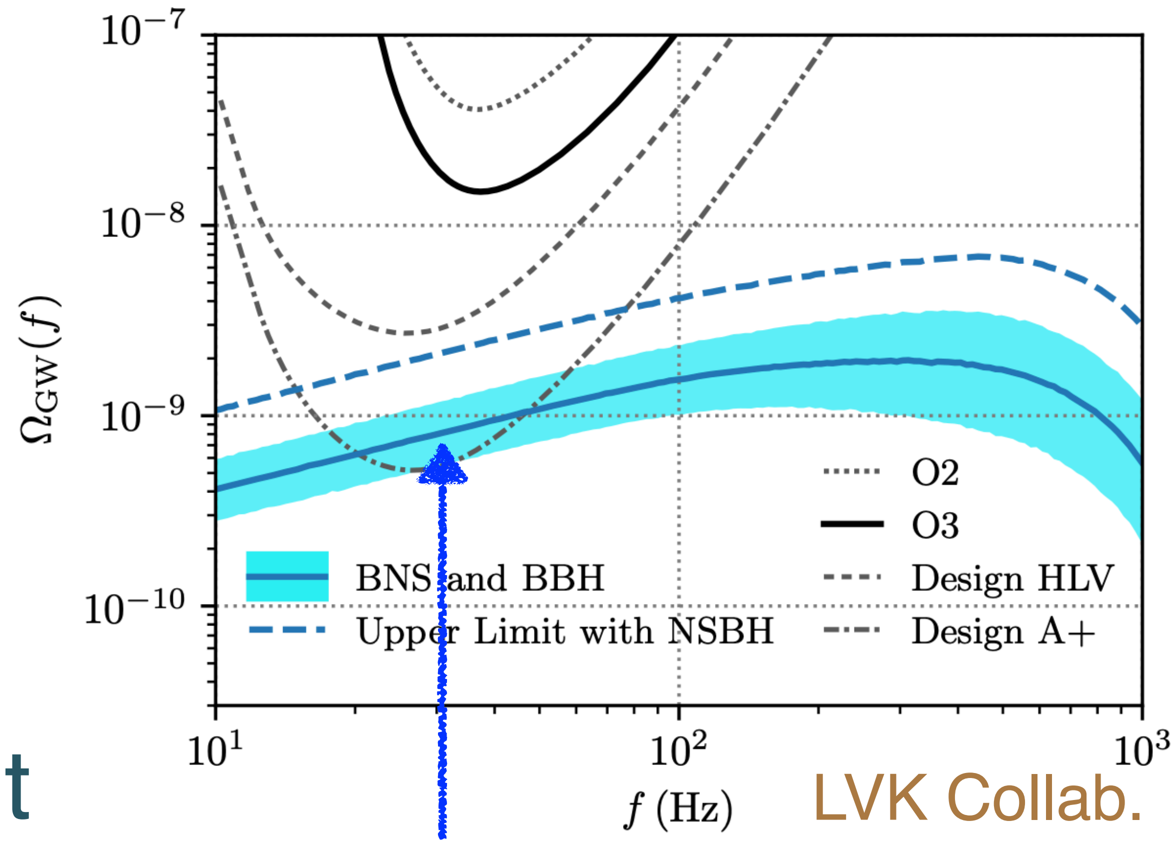
- Also a rich source of information and similar to CMB

Astrophysical SGWB

- Might be visible with LIGO upgrade
- ALIGO-AVirgo bound for $\alpha = 2/3, \Omega_{GW} \leq 3.4 \times 10^{-9}$ (at 25 Hz)
- Also relevant for LISA. Additionally WD contributions are also important. Learn about astrophysics.

$$\Omega_{GW}(f) = \Omega_{GW}(f_{ref}) \left(\frac{f}{f_{ref}} \right)^{2/3}$$

uncertain

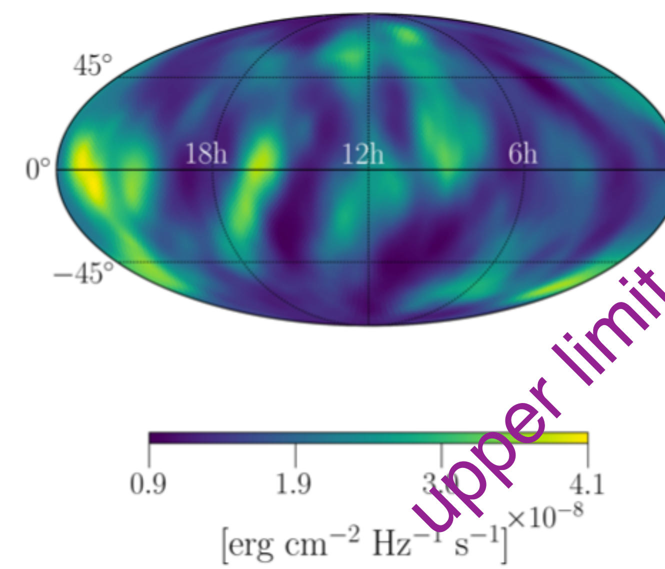


could be detected soon!

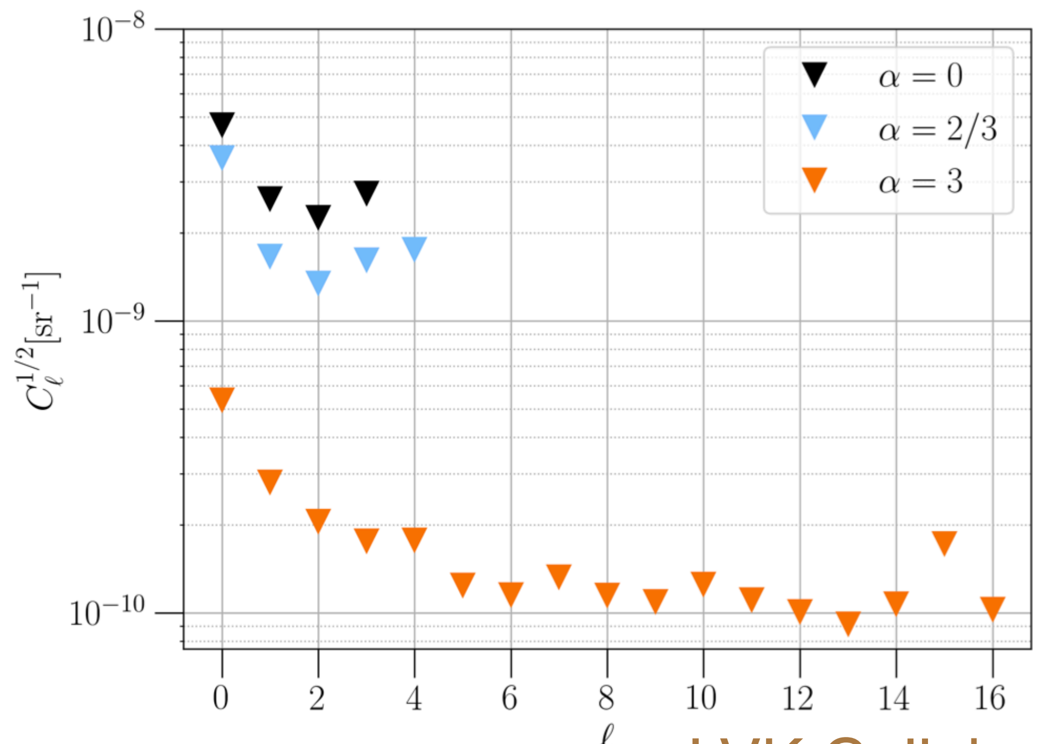
LVK Collab. 2101.12130

Anisotropic SGWB

- Anisotropies in astrophysical SGWB are also expected.
- Astrophysical SGWB biased tracer of δ_m.
- Already constraint up to $\ell = 4$ by LIGO & VIRGO for the astrophysical component



upper limit sky map



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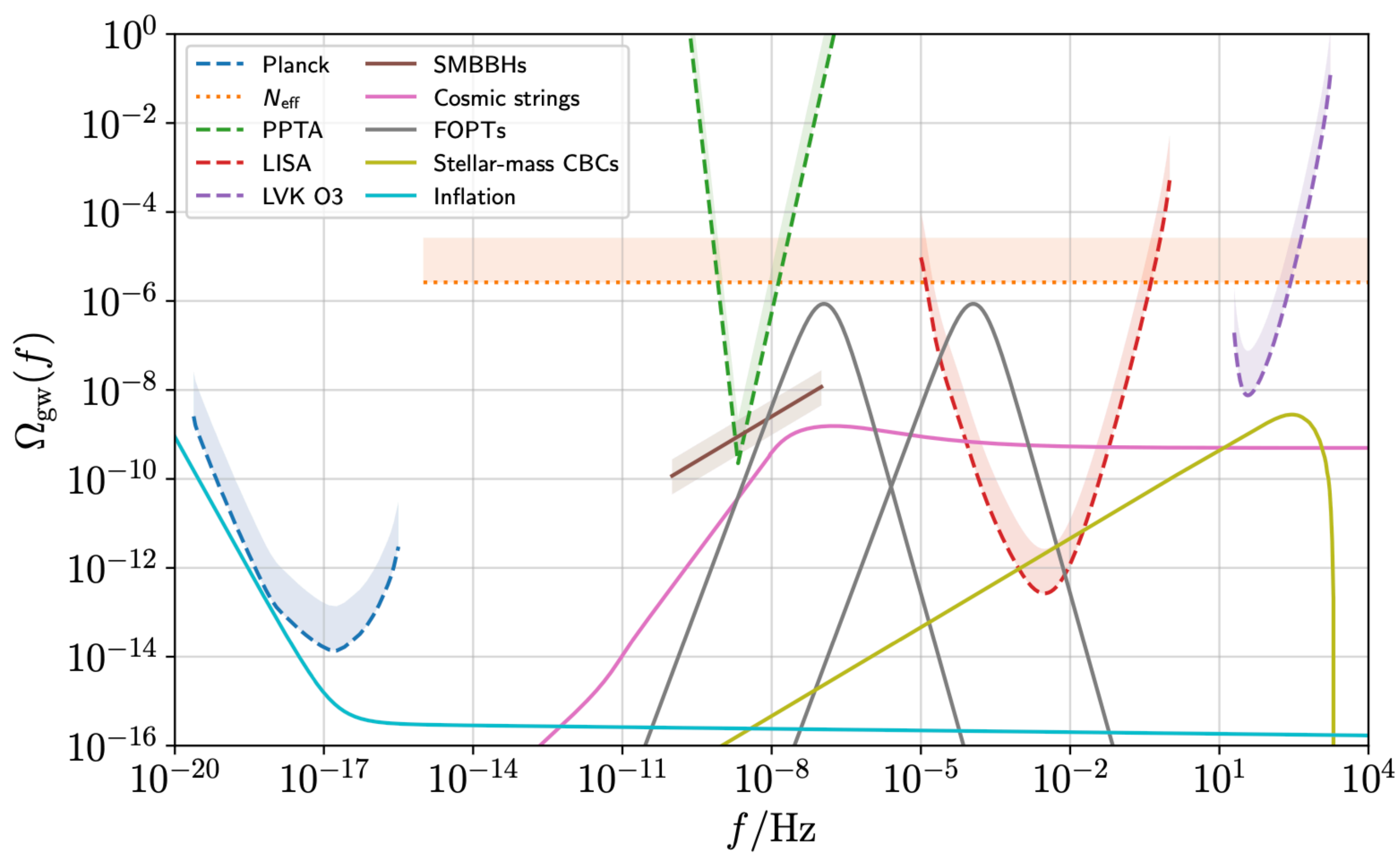
Cosmological SGWB

- A variety of cosmological sources as well, e.g., phase transition, cosmic string, preheating, inflation etc.
- Strength is model dependent, but can be above astrophysical SGWB



Renzini et al. 2202.00178

Anisotropic Cosmological SGWB

- However, anisotropies will also generically be present in cosmological component.

- Very important from particle physics point of view, since GW “free stream” and can preserve pristine primordial info.

- Potentially new map independent of the CMB

Broad question:

suppose we detect an anisotropic SGWB, what can we learn from it?

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Outline

- Phase transition and SGWB anisotropy
- Non-Gaussianity of SGWB
- Adiabatic vs. Isocurvature scenario
- Conclusion

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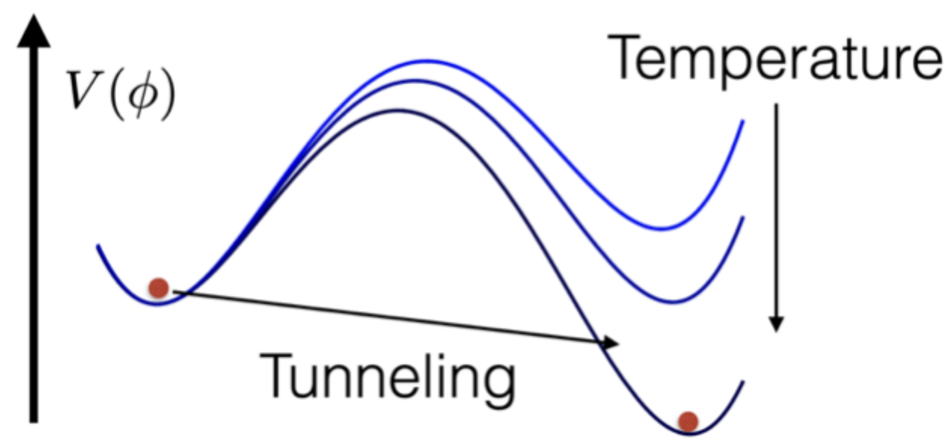
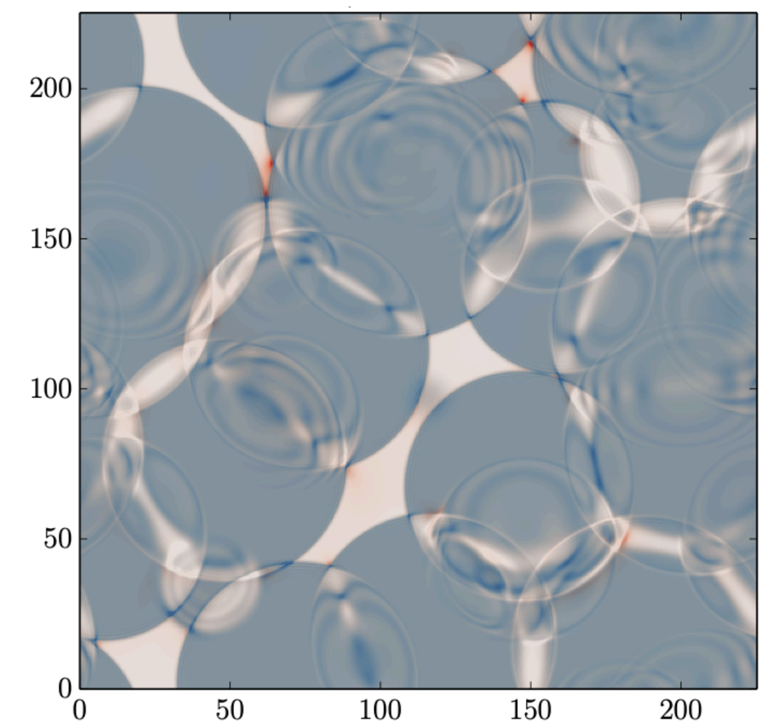
GW from first order phase transitions





Cutting et al. 1802.05712

- Bubble collisions, sound waves, turbulence

$$\Omega_{\rm GW}^{\rm peak} h^2 = 1.3 \times 10^{-6} \left(\frac{H_{\rm PT}}{\beta}\right)^2 \left(\frac{\alpha}{1+\alpha}\right)^2$$

$\alpha = \rho_{\rm vac}/\rho_{\rm rad}$ fractional energy density

$$\omega_{\rm GW}^{\rm peak} = 0.04\,{\rm mHz} \left(\frac{\beta}{H_{\rm PT}}\right)\left(\frac{T_n}{\rm TeV}\right)$$

$\beta/H_{\rm PT} \equiv d\ln\Gamma/dt$ duration

Huber, Konstandin, 0806.1828

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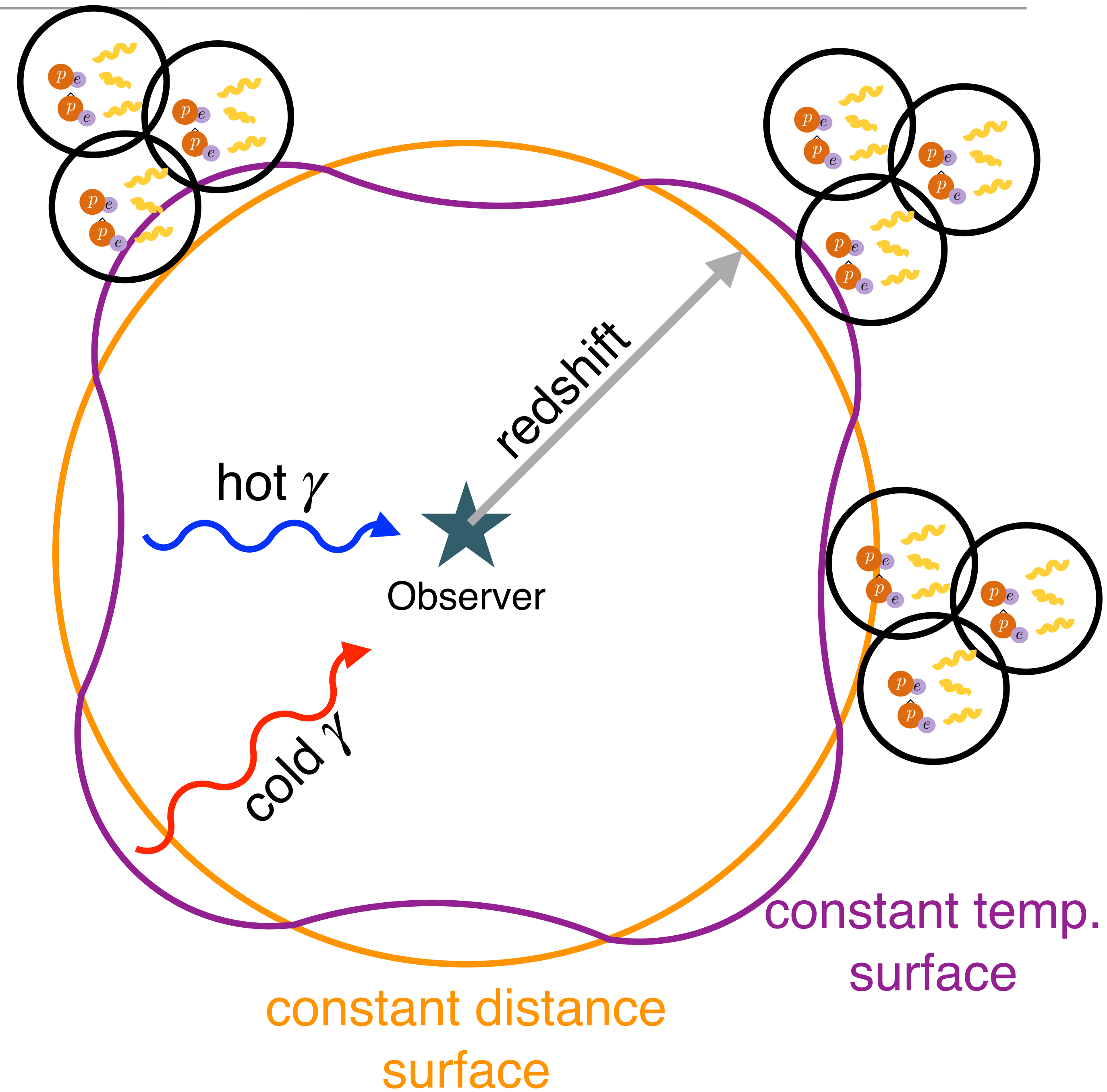
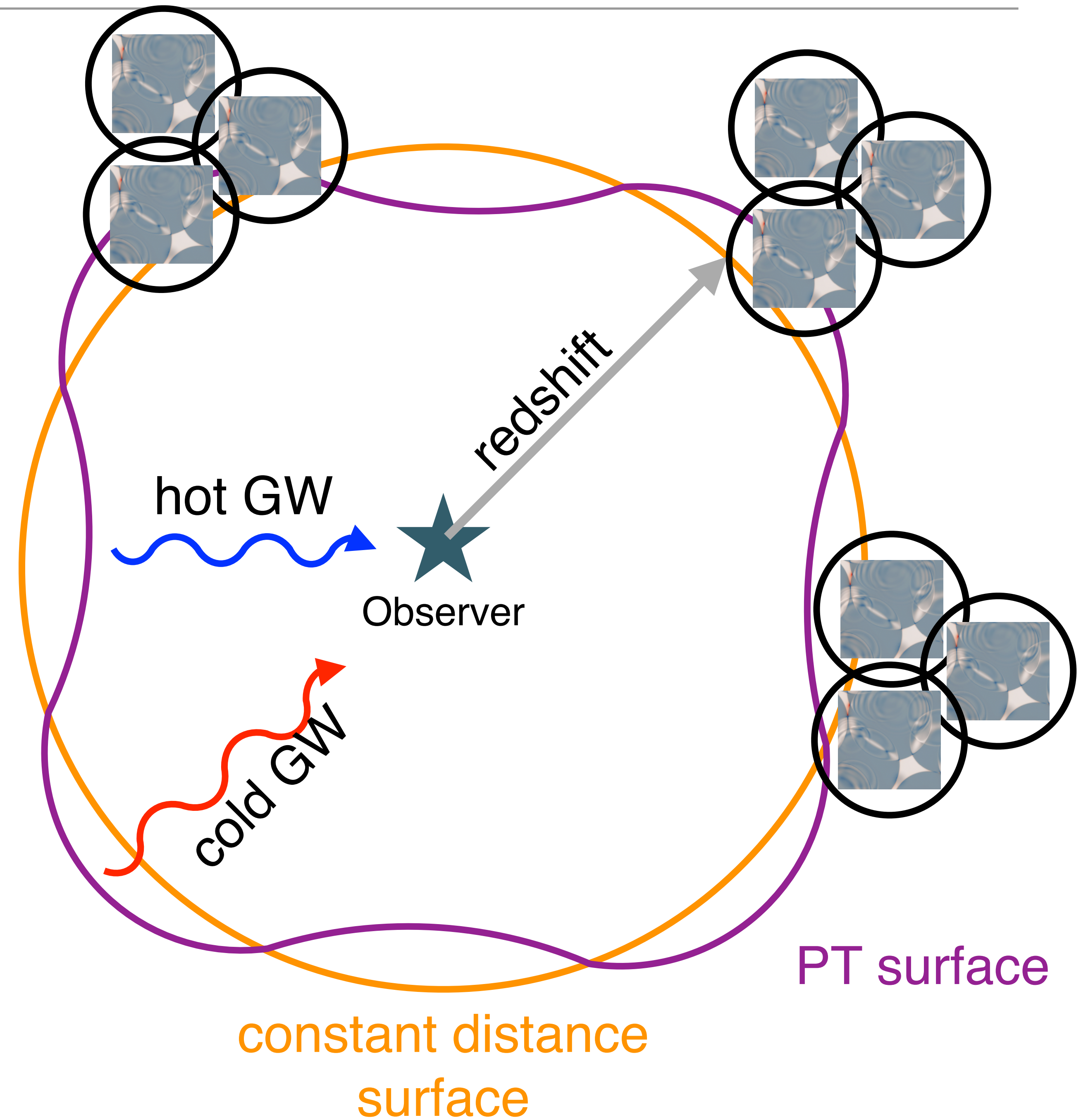
Anisotropy in CMB

- Single field inflation → each Hubble patch undergoes the same history, but with time delay
- Results into anisotropies in the CMB
- Independent of microphysics of decoupling



Anisotropic SGWB from PT

- Similar argument in the context of PT
- Surface CMB decoupling ↔ surface of PT
- Inflation generates large scale fluctuations in the fluid undergoing PT
- Imprinted in GW



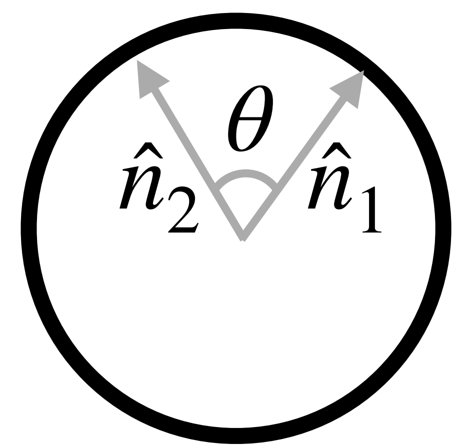
Hook et al. 1803.10780

Characterizing anisotropy

- Similar to CMB: $\delta_{\rm GW}(f,\hat{n}) \equiv \dfrac{\delta\rho_{\rm GW}}{\rho_{\rm GW}} = \dfrac{\rho_{\rm GW}(f,\hat{n}) - \bar{\rho}_{\rm GW}(f)}{\bar{\rho}_{\rm GW}(f)}$

$$C^{\rm GW}(\theta) \equiv \langle \delta_{\rm GW}(\hat{n}_1)\delta_{\rm GW}(\hat{n}_2)\rangle$$

$$C^{\rm GW}(\theta) = \frac{1}{4\pi}\sum_\ell (2\ell+1) C_\ell^{\rm GW} P_\ell(\cos\theta)$$



- For scale invariant spectrum,

$$C_\ell^{\rm GW} \propto [\ell(\ell+1)]^{-1} \quad \text{i.e.} \quad \delta_{\rm GW}(\theta \sim 1/\ell) \propto 1/\ell$$

small-scale modes have less power,
important restriction on the number of visible modes

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Angular sensitivity of future missions

$$\Omega_{\rm GW}^{\rm peak} h^2 = 1.3 \times 10^{-6} \left(\frac{H_{\rm PT}}{\beta}\right)^2 \left(\frac{\alpha}{1+\alpha}\right)^2$$

$$\delta_{\rm GW}(\theta \sim 1/\ell) \propto 1/\ell$$

small β motivated by approx. conformal theories

LISA benchmark

$$(\beta/H_{\rm PT})^2 = 10$$

$$T_n \approx 10 - 100 \text{ TeV}$$

$$\alpha \sim 0.1$$

$$\ell \lesssim 10$$

DECIGO/BBO benchmark

$$(\beta/H_{\rm PT})^2 = 100$$

$$T_n \approx 10^4 \text{ TeV}$$

$$\alpha \sim 0.1$$

$$\ell \lesssim 100$$

Konstandin, Servant 1104.4791
Agashe et al. 1910.06238

Future missions can be probe up to $\ell \lesssim 100$, also within their angular resolution

Summarizing cosmo. anisotropies

- Probing power spectrum is already very interesting, but we can have detectable anisotropies in SGWB
- First order PT are quite typical BSM phenomena that can imprint such anisotropies
- GW “free stream” so primordial information preserved and can be independent from CMB
- What can we learn from such a map?

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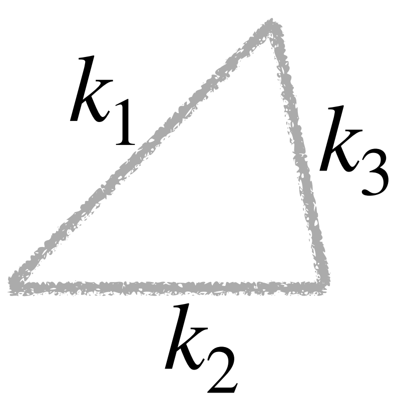
Outline

- Phase transition and SGWB anisotropy
- Non-Gaussianity of SGWB
- Adiabatic vs. Isocurvature scenario
- Conclusion

Non-Gaussianity of SGWB

- Primordial non-Gaussianity (NG) characterizes interactions of the inflaton (or metric) fluctuations ζ

$$F(k_1, k_2, k_3) = \frac{5}{6}\frac{B(k_1, k_2, k_3)}{P(k_1)P(k_2) + P(k_1)P(k_3) + P(k_2)P(k_3)}$$



$$P(k) = \langle \zeta_{\vec{k}} \zeta_{-\vec{k}} \rangle'$$

rotational invariance

$$B(k_1, k_2, k_3) = \langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \zeta_{\vec{k}_3} \rangle'$$

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Simplified definition of CMB NG

- On very large scales, CMB anisotropies approximated by Sachs-Wolfe effect

$$\delta_\gamma \equiv \frac{\delta\rho_\gamma}{\rho_\gamma} = 4\frac{\delta T}{T}\Bigg|_{\rm CMB} \approx -\frac{4}{5}\zeta$$

- Motivates a simplified definition,

$$F_{\rm CMB}(k_1, k_2, k_3) = \frac{2}{3}\frac{\langle \delta_\gamma(\vec{k}_1)\delta_\gamma(\vec{k}_2)\delta_\gamma(\vec{k}_3)\rangle}{P_\gamma(k_1)P_\gamma(k_2) + P_\gamma(k_1)P_\gamma(k_3) + P_\gamma(k_2)P_\gamma(k_3)}$$

Not using the standard $\langle a_{\ell_1 m_1} a_{\ell_2 m_2} a_{\ell_3 m_3}\rangle$ notation

Bartolo et al. 1912.09433

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Simplified definition of SGWB NG

- Compute the large scale anisotropy for GW (including only Sachs-Wolfe contribution)

$$\delta_{\rm GW} \equiv \frac{\delta\rho_{\rm GW}}{\rho_{\rm GW}} \approx -\frac{4}{3}\zeta$$

- Analogously

$$F_{\rm GW}(k_1,k_2,k_3) = \frac{10}{9}\frac{\langle \delta_{\rm GW}(\vec{k}_1)\delta_{\rm GW}(\vec{k}_2)\delta_{\rm GW}(\vec{k}_3)\rangle}{P_{\rm GW}(k_1)P_{\rm GW}(k_2)+P_{\rm GW}(k_1)P_{\rm GW}(k_3)+P_{\rm GW}(k_2)P_{\rm GW}(k_3)}$$

- Cosmic variance limited sensitivity on $\Delta F_{\rm GW}$

$$\delta_{\rm GW}\Delta F_{\rm GW} \sim \frac{1}{\sqrt{\ell_{\rm max}(\ell_{\rm max}+1)}} \sim \ell_{\rm max}^{-1} \Rightarrow \Delta F_{\rm GW} \sim \frac{10^4}{\ell_{\rm max}}$$

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Adiabatic perturbations

- Consider single-field inflation $\rightarrow$ single source of fluctuations $\rightarrow$ correlated large scale fluctuations in GW and CMB

$$\delta_{\mathrm{GW}} \approx \frac{5}{3}\delta_\gamma$$

- However, primordial non-Gaussianities are strongly constrained by existing data, e.g., Planck, $F_{\mathrm{CMB}} \lesssim 10$

$$\Delta F_{\mathrm{GW}} \sim \frac{1}{\delta_{\mathrm{GW}}} \times \frac{1}{\sqrt{\ell_{\max}(\ell_{\max}+1)}} \sim 10^4 \ell_{\max}^{-1}$$

- This along with $\ell_{\max} \lesssim 100$ implies CMB much better probe of NG

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Isocurvature perturbations

- But a very different conclusion arises in the presence of isocurvature perturbations

- The PT sector can get reheated differently than the other sector

$$\delta_{\rm GW} \not\approx \frac{5}{3}\delta_{\gamma}$$

- Consequently, large and observable NG in SGWB need no longer be in conflict with CMB constraints

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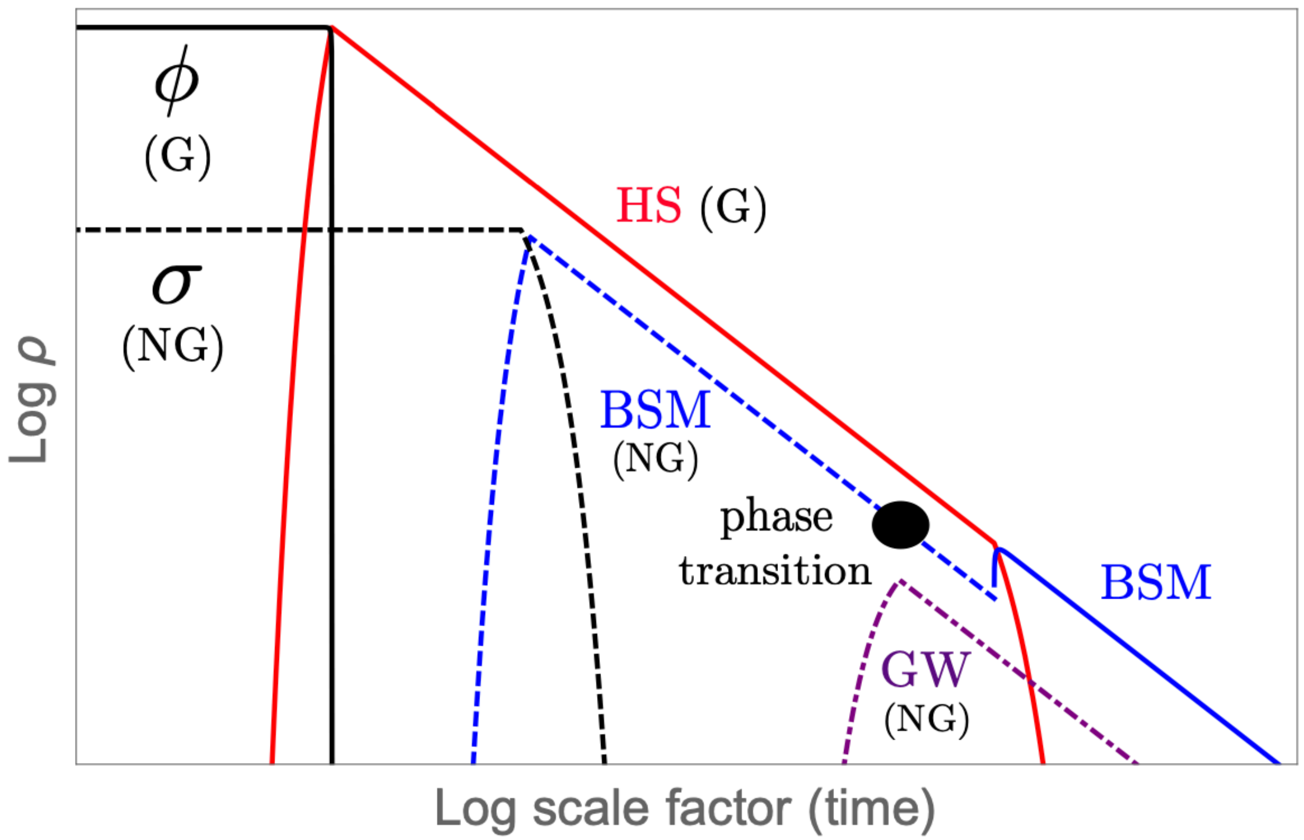
A multi-sector reheating scenario



Inflaton decay products are highly Gaussian

Curvaton decay products are highly *non*-Gaussian

$$\delta_{\rm GW} = -\frac{4}{3}\zeta_\phi + \frac{4}{3}S_\sigma\left(1 - \frac{4}{3}f_{\rm BSM}\right)$$

$$f_{\rm BSM} = \frac{\rho_{\rm BSM}}{\rho_{\rm BSM} + \rho_{\rm HS}}$$

$$\delta_\gamma = -\frac{4}{5}\zeta_\phi - \frac{4}{15}f_{\rm BSM}S_\sigma$$

suppression factor

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NG in CMB and GW

$$\delta_{\rm GW} = -\frac{4}{3}\zeta_\phi + \frac{4}{3}S_\sigma\left(1 - \frac{4}{3}f_{\rm BSM}\right) \qquad \delta_\gamma = -\frac{4}{5}\zeta_\phi - \frac{4}{15}f_{\rm BSM}S_\sigma$$

suspression factor

$$F_{\rm CMB} \approx -\frac{5}{6}\left(\frac{f_{\rm BSM}}{3}\right)^3\left(\frac{P_S(k_1)P_S(k_2) + \text{perms.}}{P_\phi(k_1)P_\phi(k_2) + \text{perms.}}\right)F_{S_\sigma}$$

common

$$F_{\rm GW} = \frac{5\left(P_S(k_1)P_S(k_2) + \text{perms.}\right)F_{S_\sigma}}{6\left(P_\phi(k_1) + P_S(k_1)\right)\left(P_\phi(k_2) + P_S(k_2)\right) + \text{perms.}}$$

$$F_{\rm CMB} \sim f_{\rm BSM}^3 F_{\rm GW}$$

NG in CMB can be easily hidden for $f_{\rm BSM} \ll 1$

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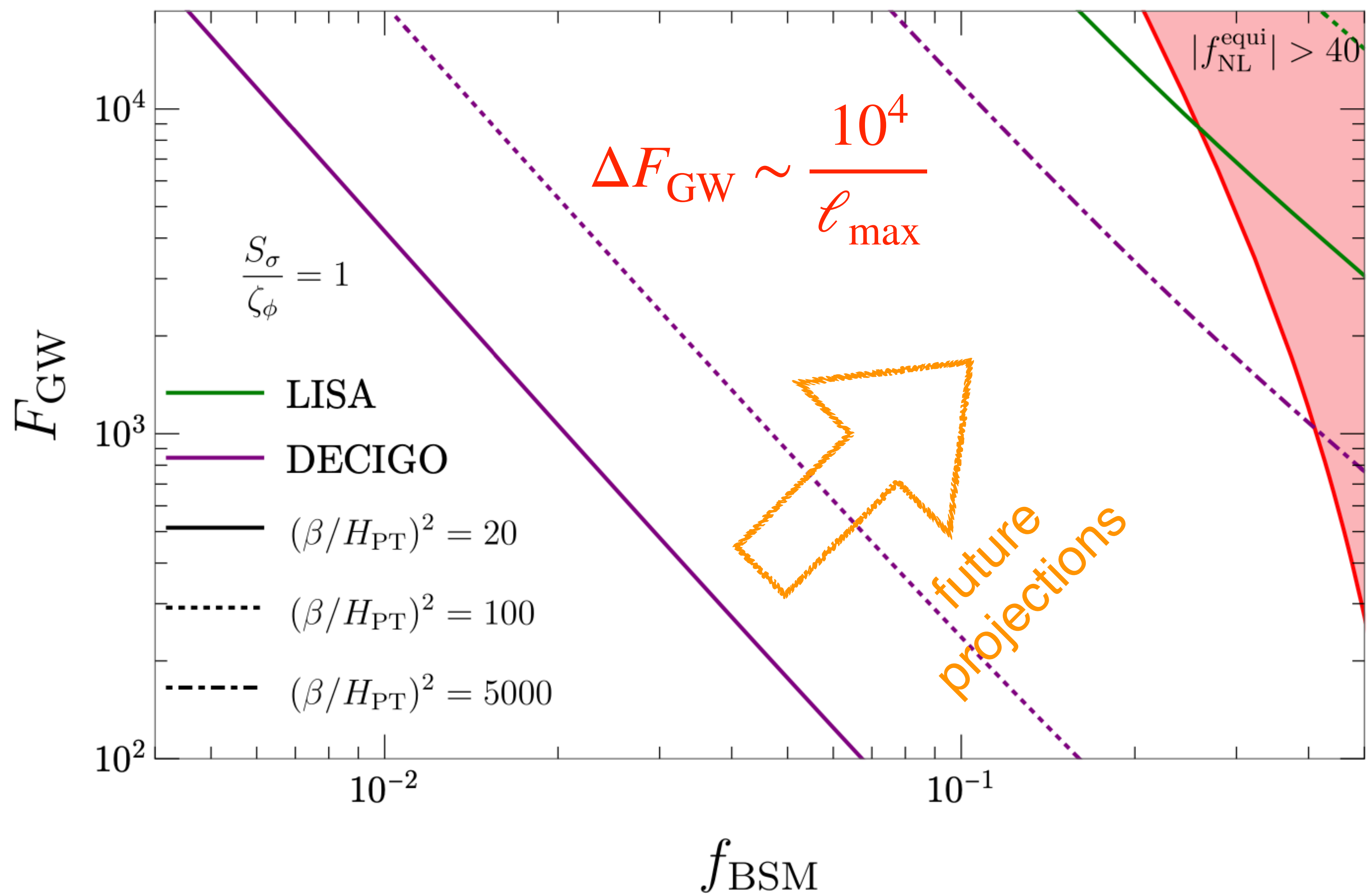
Reach of future missions



- SGWB more powerful than CMB or LSS in this scenario!
- No non-linear “clustering” unlike LSS

Details of non-Gaussian HS

- Fluctuations of σ are given by $S_\sigma = \frac{2\delta\sigma}{\sigma_0}$
- Light field, protected by shift symmetry

$$\mathcal{L}_\sigma = -\frac{1}{2}(\partial_\mu \sigma)^2 - \frac{1}{2} m_\sigma^2 \sigma^2 + \frac{1}{\Lambda_\sigma^4}(\partial_\mu \sigma)^2 (\partial_\nu \sigma)^2 + \cdots$$

- Non-trivial interactions $\mathcal{L}_\sigma \supset 4 \frac{\dot{\sigma}_0}{\Lambda_\sigma^4} \dot{\delta\sigma} (\partial \delta\sigma)^2$

$$\langle \delta\sigma(\vec{k}_1) \delta\sigma(\vec{k}_2) \delta\sigma(\vec{k}_3) \rangle' = -\frac{7}{3} \frac{\dot{\sigma}_0}{\Lambda_\sigma^4} \frac{H_{\rm inf}^5}{k^6} \qquad |F_{S_\sigma}| = \frac{14}{9} \frac{H_{\rm inf} \sigma_0 \dot{\sigma}_0}{\Lambda_\sigma^4}$$

- Benchmark $\dot{\sigma}_0^2 / \Lambda_\sigma^4 \lesssim 0.1$, $\dot{\sigma}_0 \sim H_{\rm inf}^2$, $\sigma_0 / H_{\rm inf} \sim 10^4$

within EFT control

$$F_{\rm GW} \sim 10^3$$

Conclusions

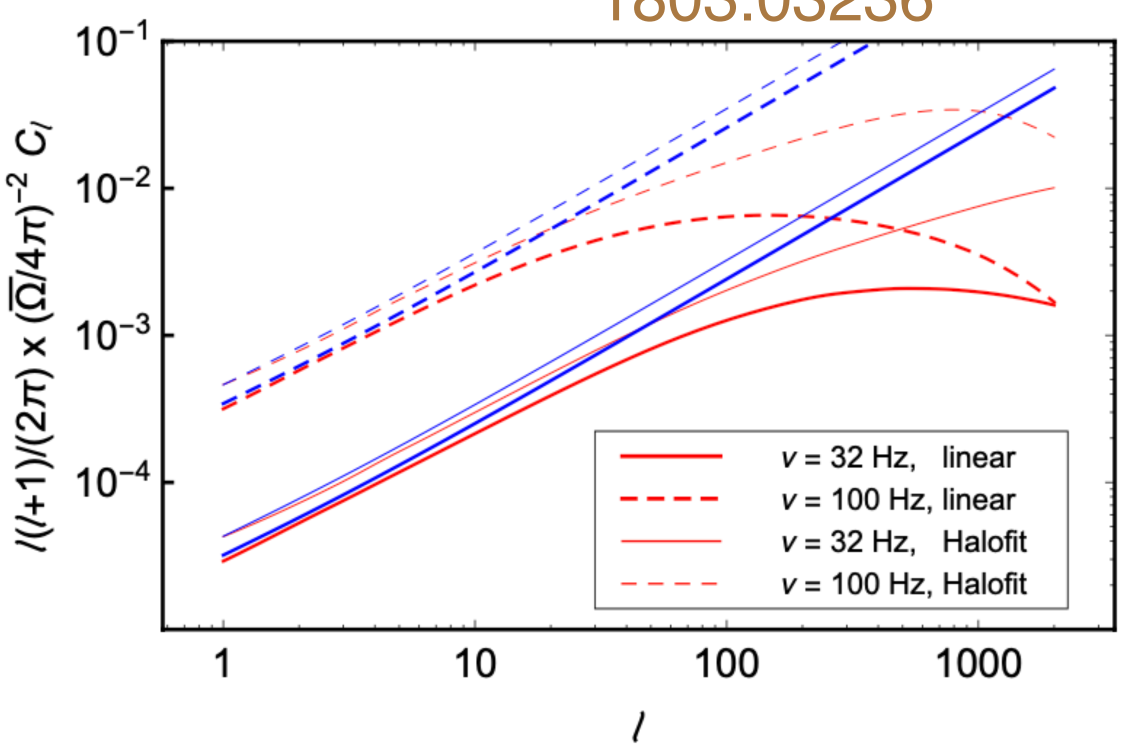
- SGWB expected from unresolved binary mergers, but also arise in various cosmological scenarios.
- Anisotropies in SGWB are especially interesting as probe of the early Universe.
- In particular, anisotropic SGWB can probe primordial NG in ways complementary to CMB or LSS.
- Disentangling from the astrophysical SGWB and its anisotropy: interesting and important challenge!

Thanks for your attention!

Anisotropy in astrophysical SGWB

- Astrophysical SGWB is a biased tracer of matter distribution

Cusin et al. 1803.03236



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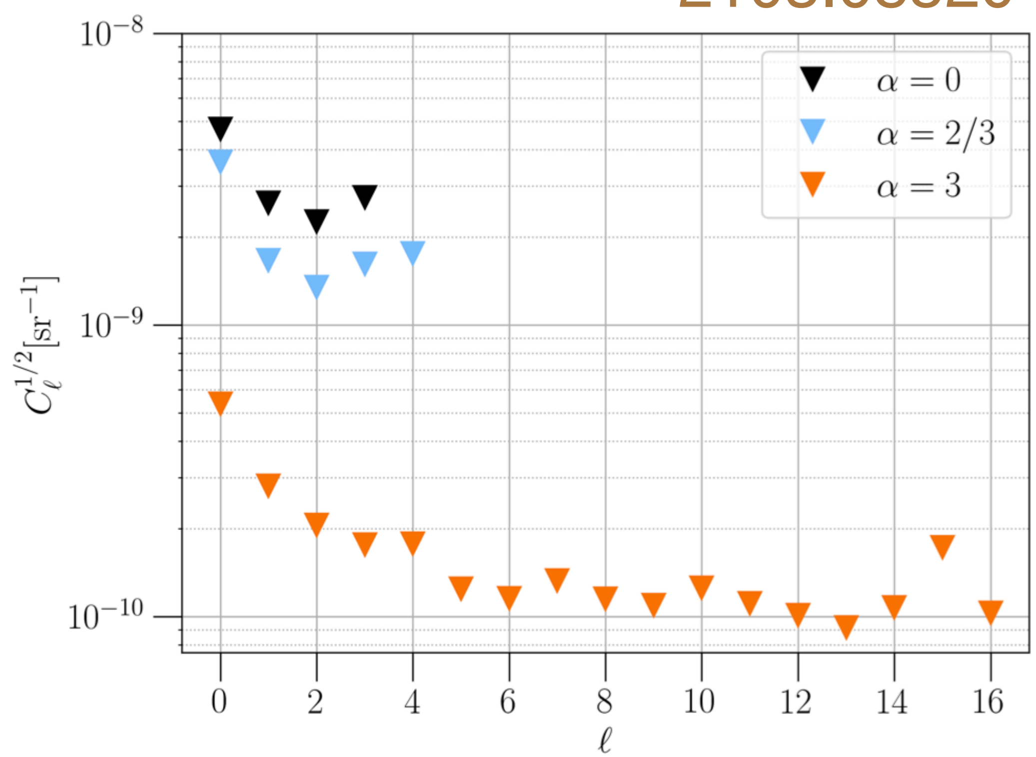

- For this talk, assume these are separable/subdominant

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Derivation of SW Effect

- Newtonian gauge $$ds^2 = a^2(\eta)\left(-(1+2\Phi)d\eta^2 + (1-2\Psi)d\vec{x}^2\right)$$

- Curvature and isocurvature perturbations

$$\zeta = -\Psi - H\frac{\delta\rho}{\dot\rho} \qquad \zeta_i = -\Psi - H\frac{\delta\rho_i}{\dot\rho_i} \qquad S_{\rm GW} \equiv 3(\zeta_{\rm GW} - \zeta_\gamma)$$

$$\zeta = -\Psi - \frac{2}{3(1+w)H}\left(H\Phi + \dot\Psi\right)$$

- CMB and GW anisotropy

$$\left.\frac{\Delta T}{T}\right|_{\rm CMB} = \frac{1}{4}\delta_\gamma^{\rm prim} + \Phi_{\rm MD} = \zeta_\gamma + 2\Phi_{\rm MD} = \zeta_\gamma - \frac{6}{5}\zeta_{\rm MD}$$

$$\left.\frac{\Delta T}{T}\right|_{\rm GW} = \frac{1}{4}\delta_{\rm GW}^{\rm prim} + \Phi_{\rm RD} = \zeta_{\rm GW} - \frac{4}{3}\zeta_{\rm RD}$$

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Derivation of SW Effect

$$\begin{aligned}\zeta_{\rm RD} =& (1-f_\nu - f_{\rm GW})\zeta_\gamma + f_\nu \zeta_\nu + f_{\rm GW}\zeta_{\rm GW} \\ =& \zeta_\gamma + \frac{1}{3} f_{\rm GW} S_{\rm GW},\end{aligned}$$

$$\left.\frac{\Delta T}{T}\right|_{\rm CMB} = -\frac{1}{5}\zeta_{\rm RD} + \frac{1}{15} f_{\rm GW} S_{\rm GW}.$$

$$\left.\frac{\Delta T}{T}\right|_{\rm GW} = -\frac{1}{3}\zeta_{\rm RD} + \frac{1}{3}(1 - f_{\rm GW}) S_{\rm GW}$$

$$\begin{aligned}\delta_\gamma \equiv 4\left.\frac{\Delta T}{T}\right|_{\rm CMB} &= -\frac{4}{5}\left(\zeta_{\gamma_{\rm HS}} + f_{\rm BSM}(\zeta_{\gamma_{\rm BSM}} - \zeta_{\gamma_{\rm HS}})\right) \\ &= -\frac{4}{5}\zeta_\phi - \frac{4}{15} f_{\rm BSM} S_\sigma,\end{aligned}$$

$$\begin{aligned}\delta_{\rm GW} \equiv 4\left.\frac{\Delta T}{T}\right|_{\rm GW} &= -\frac{4}{3}\zeta_{\rm RD} + \frac{4}{3}(1 - f_{\rm GW}) S_{\rm GW} \\ &\approx -\frac{4}{3}\zeta_\phi + \frac{4}{3} S_\sigma \left(1 - \frac{4}{3} f_{\rm BSM}\right)\end{aligned}$$