Cosmological interpretation for the stochastic signal in pulsar timing arrays

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Based on 2307.00722 (SCPMA), 2307.03141 (SCPMA), 2312.01824 (PRD)

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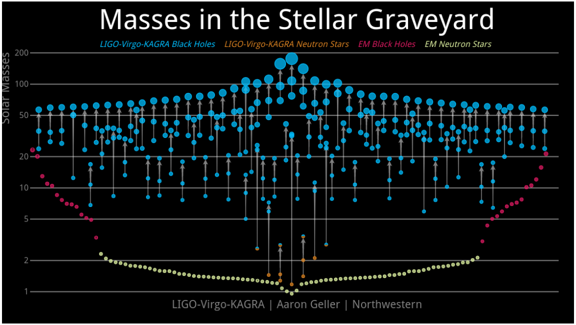
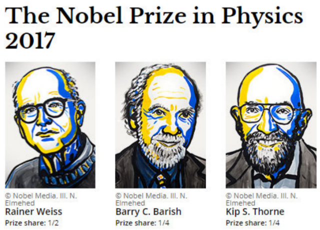
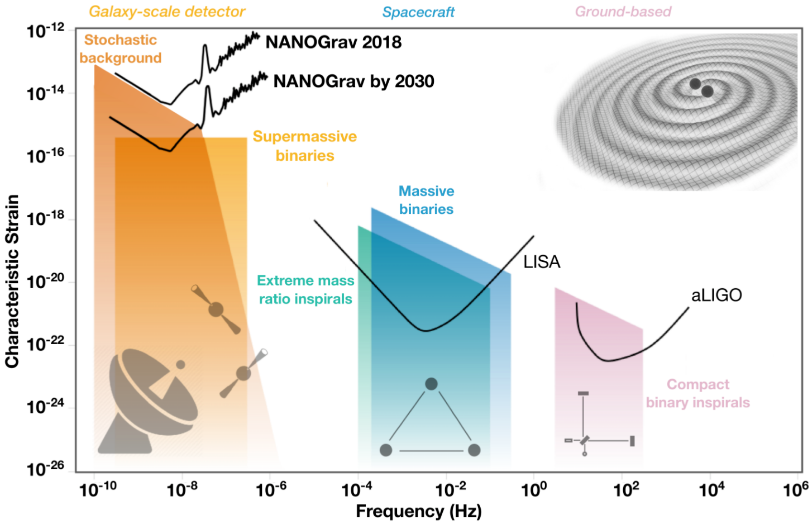
GWAC 2024
第五届引力波天体物理研讨会
暨NSFC引力波天文学创新群体项目交流会

Outline

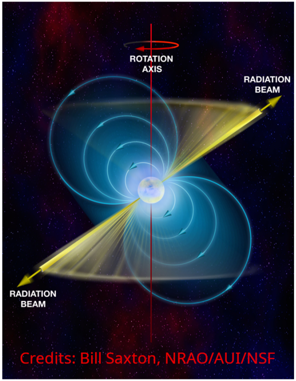


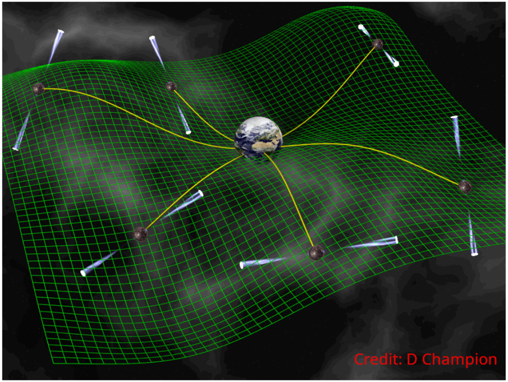


- New era of GW astronomy
- Multi-messenger astronomy


Galaxy-scale detector
Spacecraft
Ground-based
Stochastic background
NANOGrav 2018
NANOGrav by 2030
Supermassive binaries
Massive binaries
LISA
Extreme mass ratio inspirals
aLIGO
Compact binary inspirals
Characteristic Strain
Frequency (Hz)

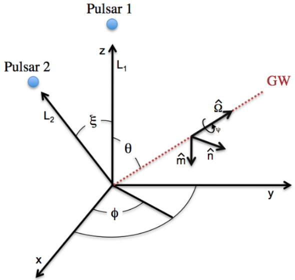
Pulsar and pulsar timing array (PTA)





- Pulsars are highly magnetized, rotating neutron stars that emit regular pulses of electromagnetic radiation.
- GWs can cause tiny distortion in spacetime inducing variations in the time of arrivals (ToAs).
- A PTA pursues to detect nHz GWs by regularly monitoring ToAs from an array of the ultra rotational stable millisecond pulsars.

Timing residual induced by a GWB



- Redshift

$$z(t,\hat\Omega) = \frac{\nu_e - \nu_p}{\nu_p} = \frac{\hat p^i \hat p^j}{2(1+\hat\Omega\cdot\hat p)}\left[h_{ij}\left(t_p,\hat\Omega\right) - h_{ij}\left(t_e,\hat\Omega\right)\right]$$

$$z(t) = \int_{S^2} d\hat\Omega\, z(t,\hat\Omega)$$

- Timing residual in frequency-domain

$$\tilde r(f,\hat\Omega) = \frac{1}{2\pi i f}\left(1 - e^{-2\pi i f L(1+\hat\Omega\cdot\hat p)}\right) \times \sum_A h_A(f,\hat\Omega) F^A(\hat\Omega)$$

- Antenna pattern

$$F^A(\hat\Omega) = e^A_{ij}(\hat\Omega)\frac{\hat p^i \hat p^j}{2(1+\hat\Omega\cdot\hat p)}$$

Detecting a GWB with PTA

- Assume the GWB is isotropic, unpolarized, and stationary

$$\left\langle h_A^*(f,\hat{\Omega})h_{A'}(f',\hat{\Omega}')\right\rangle = \frac{3H_0^2}{32\pi^3 f^3}\delta^2(\hat{\Omega},\hat{\Omega}')\delta_{AA'}\delta(f-f')\Omega_{\rm gw}(f)$$

- Spectrum of GWB

$$\Omega_{\rm gw}(f) \equiv \frac{1}{\rho_{\rm crit}}\frac{d\rho_{\rm gw}}{d\ln f}, \qquad \rho_{\rm crit} = \frac{3H_0^2}{8\pi}, \quad \rho_{\rm gw} = \frac{1}{32\pi}\left\langle \dot{h}_{ij}(t,\vec{x})\dot{h}^{ij}(t,\vec{x})\right\rangle,$$

- Cross-power spectral density

$$S_{IJ} = \langle \tilde{r}_I^*(f)\tilde{r}_J(f')\rangle = \frac{1}{\gamma}\frac{H_0^2}{16\pi^4 f^5}\delta(f-f')\Gamma_{IJ}(f,L_I,L_J,\xi)\,\Omega_{\rm gw}(f)$$

- Overlap reduction function (ORF) is function of f, L_I, L_J, ξ

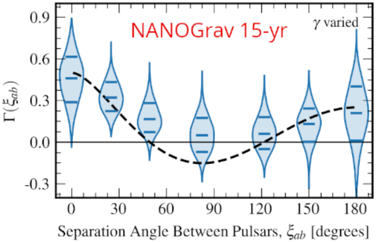
$$\Gamma_{IJ} = \gamma\sum_A\int d\hat{\Omega}\left(e^{2\pi i f L_I(1+\hat{\Omega}\cdot\hat{p}_I)}-1\right)\times\left(e^{-2\pi i f L_J(1+\hat{\Omega}\cdot\hat{p}_J)}-1\right)F_I^A(\hat{\Omega})F_J^A(\hat{\Omega})$$

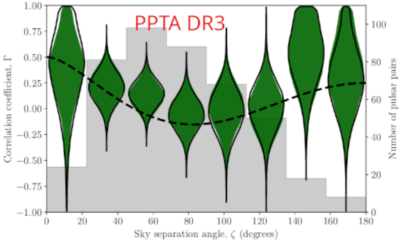
- Hellings-Downs correlations for $fL \gg 1$ (short-wavelength approximation)

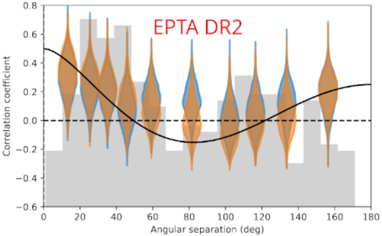
$$\Gamma_{IJ} = \frac{3}{2}\left(\frac{1-\cos\xi}{2}\right)\ln\frac{1-\cos\xi}{2} - \frac{1-\cos\xi}{8} + \frac{1}{2}$$

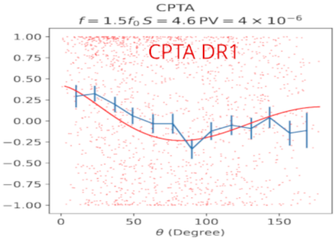
PTAs in operation

Evidence for a GWB in PTA data sets







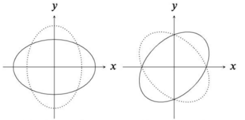


NANOGrav, 2306.16213 (ApJL); PPTA, 2306.16215 (ApJL)

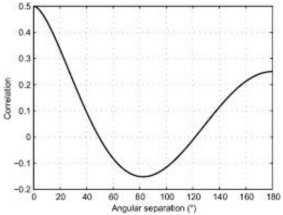
EPTA+InPTA, 2306.16214 (A&A); CPTA, 2306.16216 (RAA)

GWB from SMBHB

$$\langle \tilde{r}_I^*(f)\tilde{r}_J(f')\rangle = \frac{1}{\gamma}\frac{H_0^2}{16\pi^4 f^5}\delta(f-f')\,\Gamma_{IJ}(f,L_I,L_J,\xi)\,\Omega_{\rm gw}(f)$$

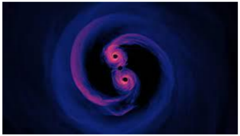


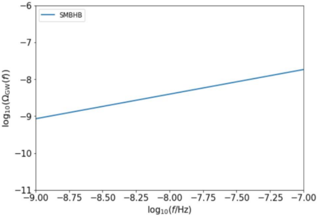
(a) plus mode (b) cross mode



Hellings-Downs curve

$$\Gamma_{ab}^{\rm TT} = \frac{1}{2}\left[1+\delta_{ab}+3\kappa_{ab}\left(\ln\kappa_{ab}-\frac{1}{6}\right)\right]$$
$$\kappa_{ab} \equiv (1-\cos\xi_{ab})/2$$

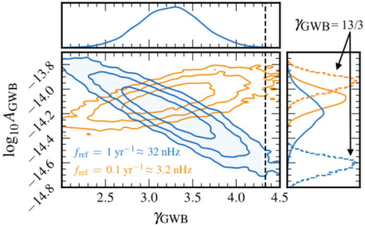




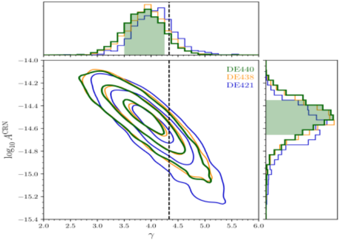
Power law

$$\Omega_{\rm gw}(f) = \frac{2\pi^2 A_{\rm GWB}^2}{3H_0^2}\left(\frac{f}{f_{\rm yr}}\right)^{5-\gamma_{\rm GWB}} f_{\rm yr}^2,$$
$$\gamma_{\rm GWB} = 13/3$$

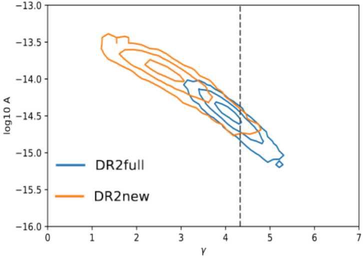
NANOGrav 15-yr



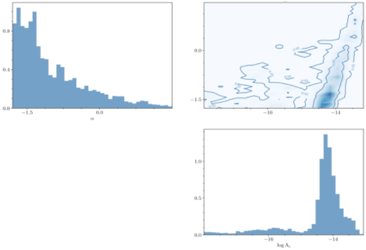
PPTA DR3



EPTA DR2



CPTA DR1



NANOGrav, 2306.16213 (ApJL); PPTA, 2306.16215 (ApJL)

EPTA+InPTA, 2306.16214 (A&A); CPTA, 2306.16216 (RAA)

Comparing results from different PTAs

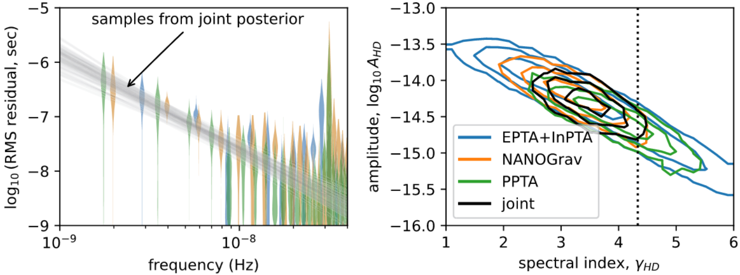
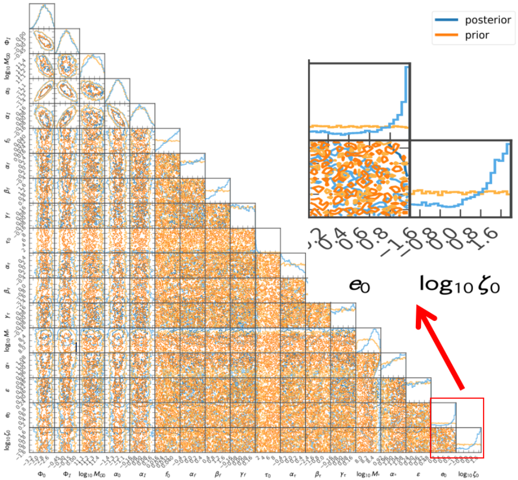


Figure 1. Left: free spectral posteriors for each PTA showing the measured HD-correlated GWB power in several frequency bins under no spectral shape assumption. Each PTA used a different Fourier basis set by their own maximum observing time. The semitransparent gray lines are 100 samples from the joint 2D power-law posterior distribution, showing the spread of power-law models that are consistent with all of the PTA's data. Right: 2D posterior for HD-correlated power-law GWB parameters. Contours show 68%, 95%, and 99.7% of the posterior mass. The vertical dotted line is at $\gamma = 13/3$.

IPTA, 2309.00693 (ApJ)

Astro-informed model from *Siyuan Chen, Alberto Sesana, and Walter Del Pozzo, 1612.00455 (MNRAS)*

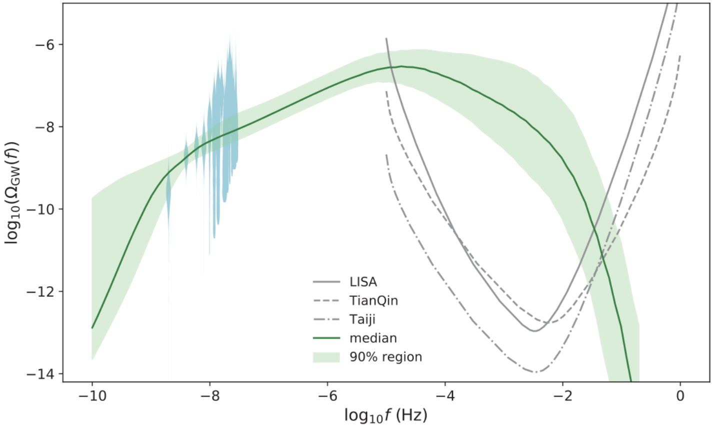


- A large eccentricity when GWs begin to dominate the SMBHB evolution.

*Yan-Chen Bi, Yu-Mei Wu, **ZCC**, Qing-Guo Huang, 2307.00722 (SCPMA)*

see also talks from Shao-Jiang Wang and Qing-Juan Yu

Astro-informed formation model

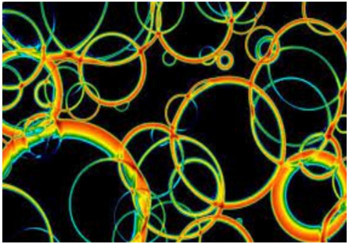


- The SGWB from SMBHBs should be detected by LISA, Taiji and TianQin.

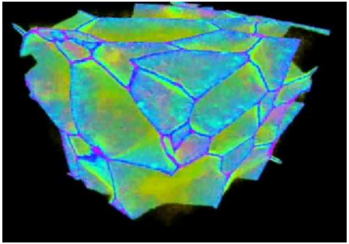
*Yan-Chen Bi, Yu-Mei Wu, **ZCC**, Qing-Guo Huang, 2307.00722 (SCPMA)*

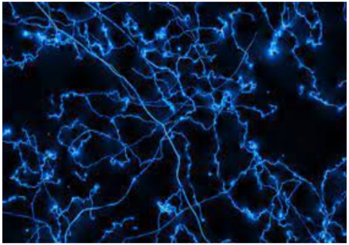
Cosmological sources

Phase transition

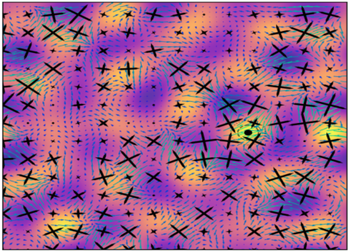


Domain wall





Cosmic string

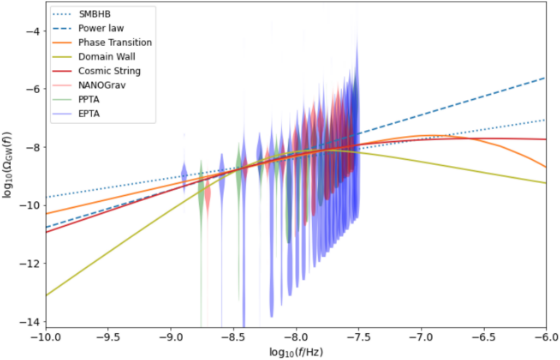


Scalar-induced GW

Overview of PTA constraints

TABLE II. Bayes factors (BFs) of the power-law (PL), first order phase transition (PT), domain wall (DW), and cosmic string (CS) models compared to the SMBHBs model.

Model	PL	PT	DW	CS
BF	0.569	0.799	0.009	1.699



- Domain wall model is strongly disfavored.

*Yu-Mei Wu, **ZCC**, Qing-Guo Huang, 2307.03141 (SCPMA)*

Phase transition

Bubble collisions + Sound Wave + MHD turbulence
see also Shao-Jiang Wang's talk

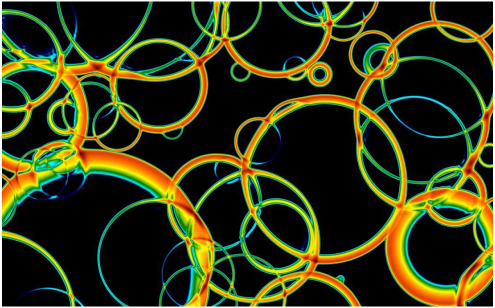
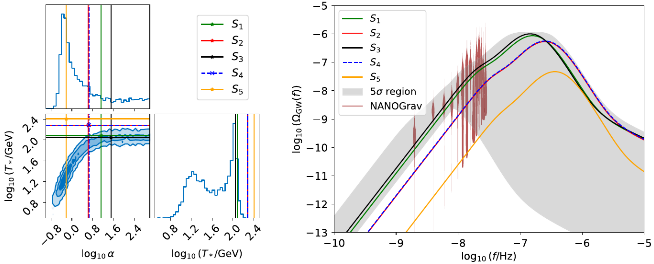


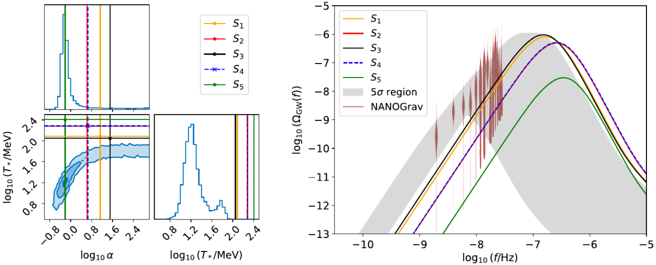
TABLE I. The ratio of the vacuum energy density α and critical temperature T_* from five holographical QCD-like models.

Model	QCD matter	Holographic QCD-like model	α	T_* (MeV)
S_1	Heavy static quarks with a zero chemical potential	Hard wall	13.5	122 [133,144]
S_2	Heavy static quarks with a zero chemical potential	Soft wall	4.27	191 [133,144]
S_3	Quarks with a finite chemical potential	Hard wall	32.2	112 [134]
S_4	Quarks with a finite chemical potential	Soft wall	4.56	192 [134]
S_5	Pure gluons	Quenched dynamical holographic QCD	0.611	255 [135]

- Jouguet detonation bubble scenario (a relatively violent PT process)



- nonrunaway bubble scenario (a more gradual and milder PT process)

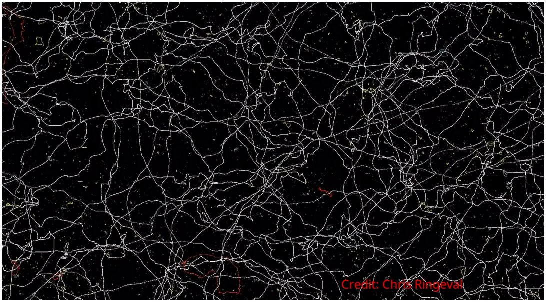


- PTA data prefer pure quark systems under the Jouguet detonations case.

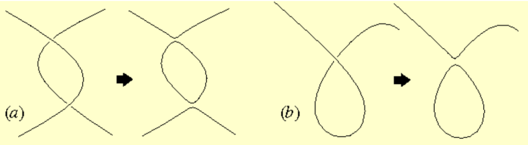
ZCC, Shou-Long Li, Puxun Wu, Hongwei Yu, 2312.01824 (PRD)

Cosmic String

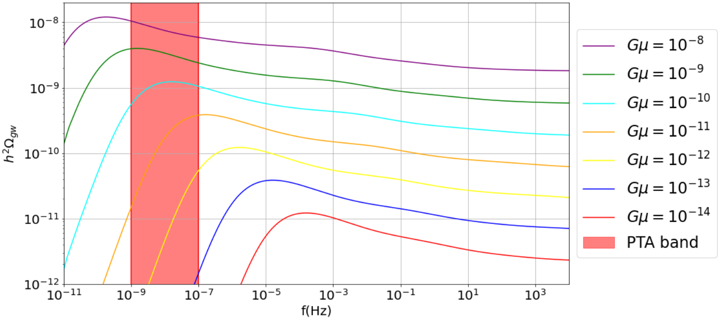
- Cosmic strings are linear topological defects that can form in the early Universe from symmetry-breaking phase transitions or be the fundamental strings of superstring theory stretched out to astrophysical lengths.



- The intersection between cosmic strings can lead to reconnections and form loops, which will then decay due to relativistic oscillation and emit gravitational waves.

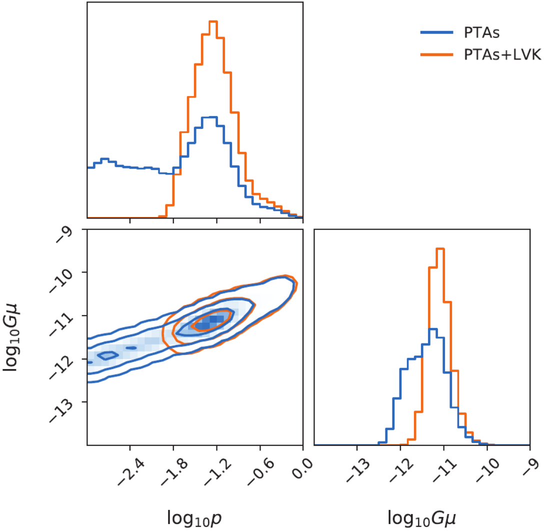


GW energy density spectrum of cosmic strings



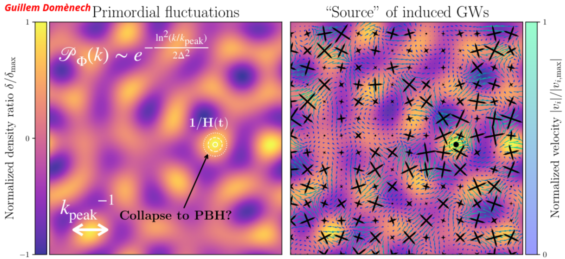
- $G\mu$ is string tension – the energy stored per unit length.
- p is the reconnection probability:
  - $p = 1$ for classical strings
  - $p < 1$ in the string-theory-inspired models

PE for Cosmic string model



- $p < 1$: strings in (super) string theory are more likely to explain the detected signal than classical field strings.
- Joint constraints from the LVK O3 data can significantly narrow down the parameter space.

Scalar-induced GW: see Lang Liu's talk



- Non-Gaussianity of curvature perturbations
  *Lang Liu, **ZCC**, Qing-Guo Huang, 2307.01102 (PRDL)*
- Equation of state and sound speed of the early Universe
  *Lang Liu, **ZCC**, Qing-Guo Huang, 2307.14911 (JCAP)*
  *Lang Liu, You Wu, **ZCC**, 2310.16500 (JCAP)*
- Speed of GW
  ***ZCC**, Jun Li, Lang Liu, Zhu Yi, 2401.09818 (PRDL)*
- Distinguish the adiabatic and isocurvature fluctuations
  ***ZCC**, Lang Liu, 2402.16781*
- Sound speed resonance
  *Jia-Heng Jin, **ZCC**, Zhu Yi, Zhi-Qiang You, Lang Liu, 2307.08687 (JCAP)*

Summary

$$\langle \tilde{r}_I^*(f)\tilde{r}_J(f')\rangle = \frac{1}{\gamma}\frac{H_0^2}{16\pi^4 f^5}\delta(f-f')\,\Gamma_{IJ}(f,L_I,L_J,\xi)\,\Omega_{\rm gw}(f)$$

- PTAs have been opening a new window at nHz frequencies.
- Cosmological implications:
  - Domain wall is strongly disfavored.
  - For PT, PTA data prefer pure quark systems under the Jouguet detonations case.
  - Strings in (super)strings theory are more likely to explain the PTA signal than classical field strings.

Thank you for your attention!