中国科学院理论物理研究所
Institute of Theoretical Physics, Chinese Academy of Sciences

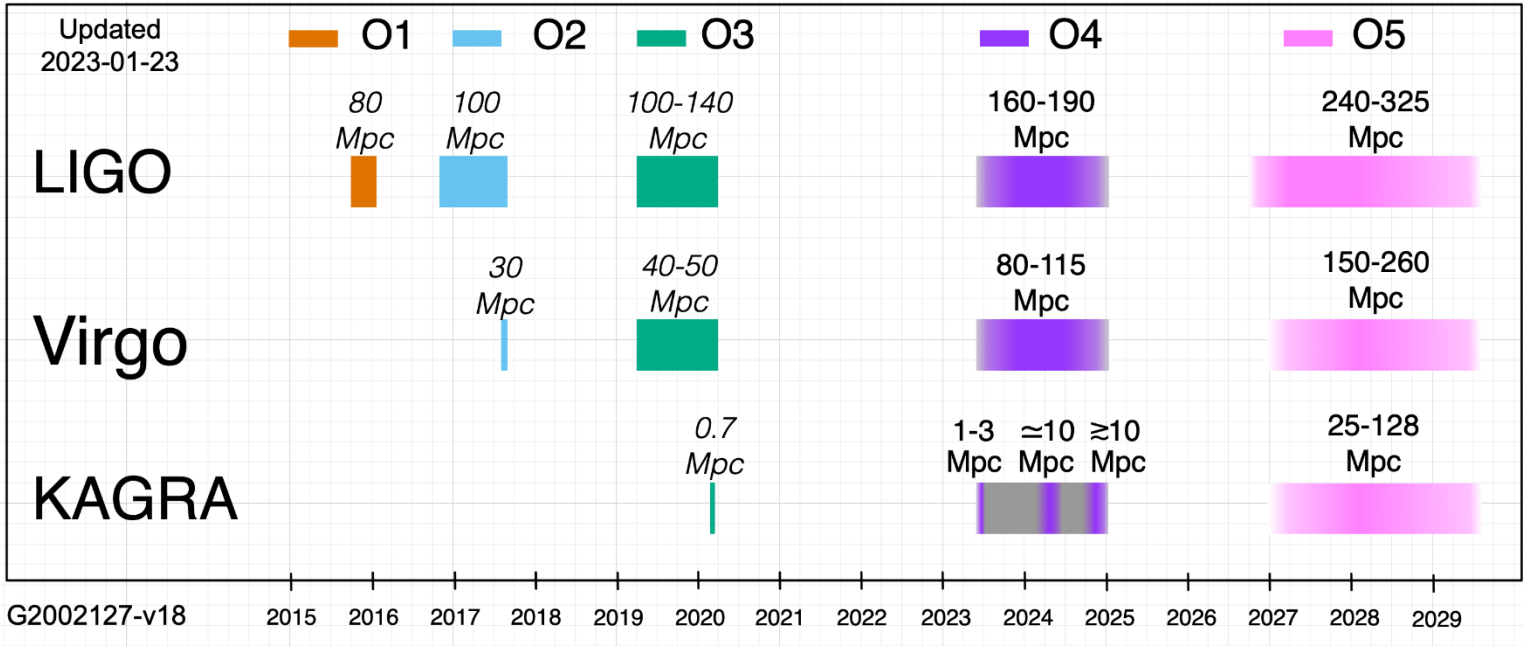
早期宇宙产生的随机引力波背景

郭宗宽

2023引力与宇宙学专题研讨会

2023.4.6-9

LIGO-Virgo-KAGRA (3 + 8 + 44 +35 = 90 events)



O1 (12 Sep 2015 – 19 Jan 2016) 3 events

O2 (30 Nov 2016 – 25 Aug 2017, Virgo jointed O2 on 1 Aug 2017) 8 events

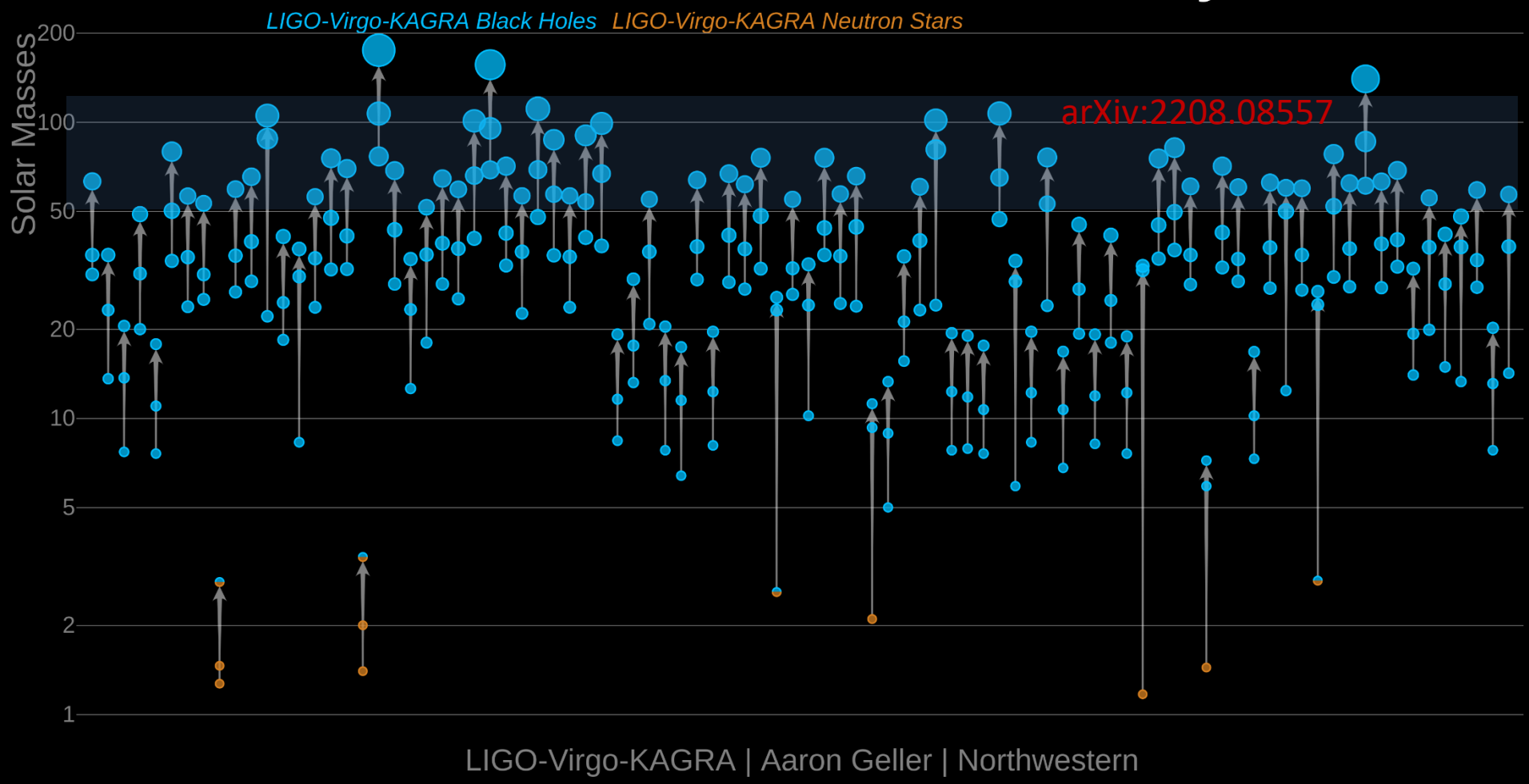
O3 (1 Apr 2019 – 27 Mar 2020)

O3a (1 Apr 2019 – 1 Oct 2019) see arXiv:2108.01045 44 events

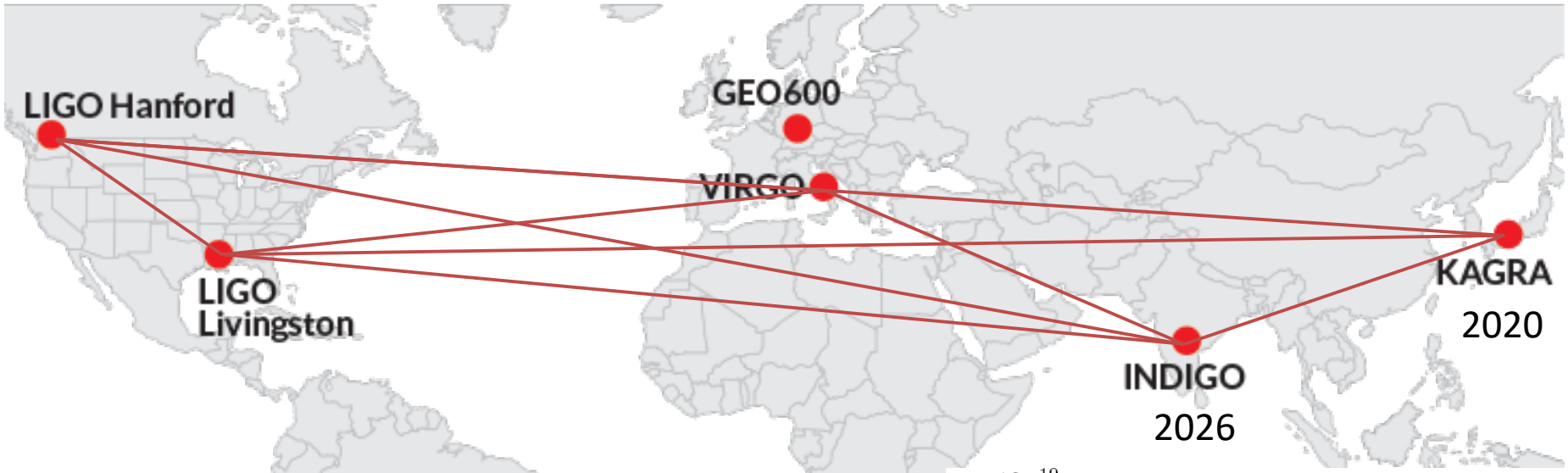
O3b (1 Nov 2019 – 27 Mar 2020, KAGRA jointed O3 on 25 Feb 2020) see arXiv:2111.03606 35 events

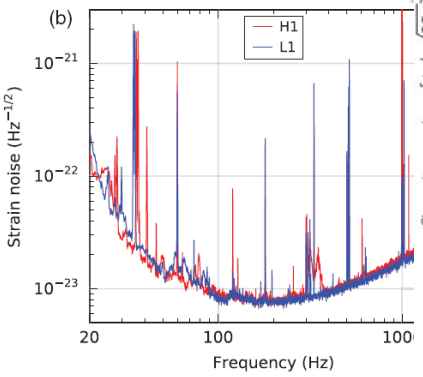
O4 (to commence in May 2023)

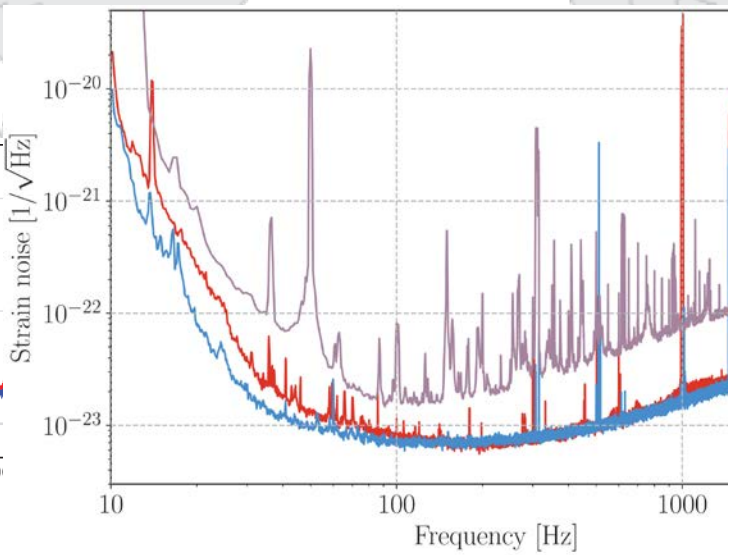
Masses in the Stellar Graveyard

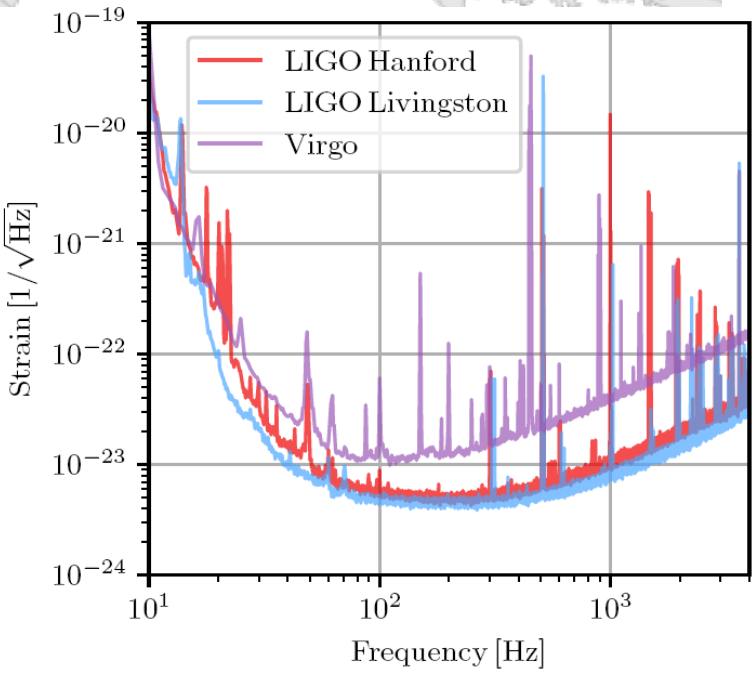


Ground-based GW detectors

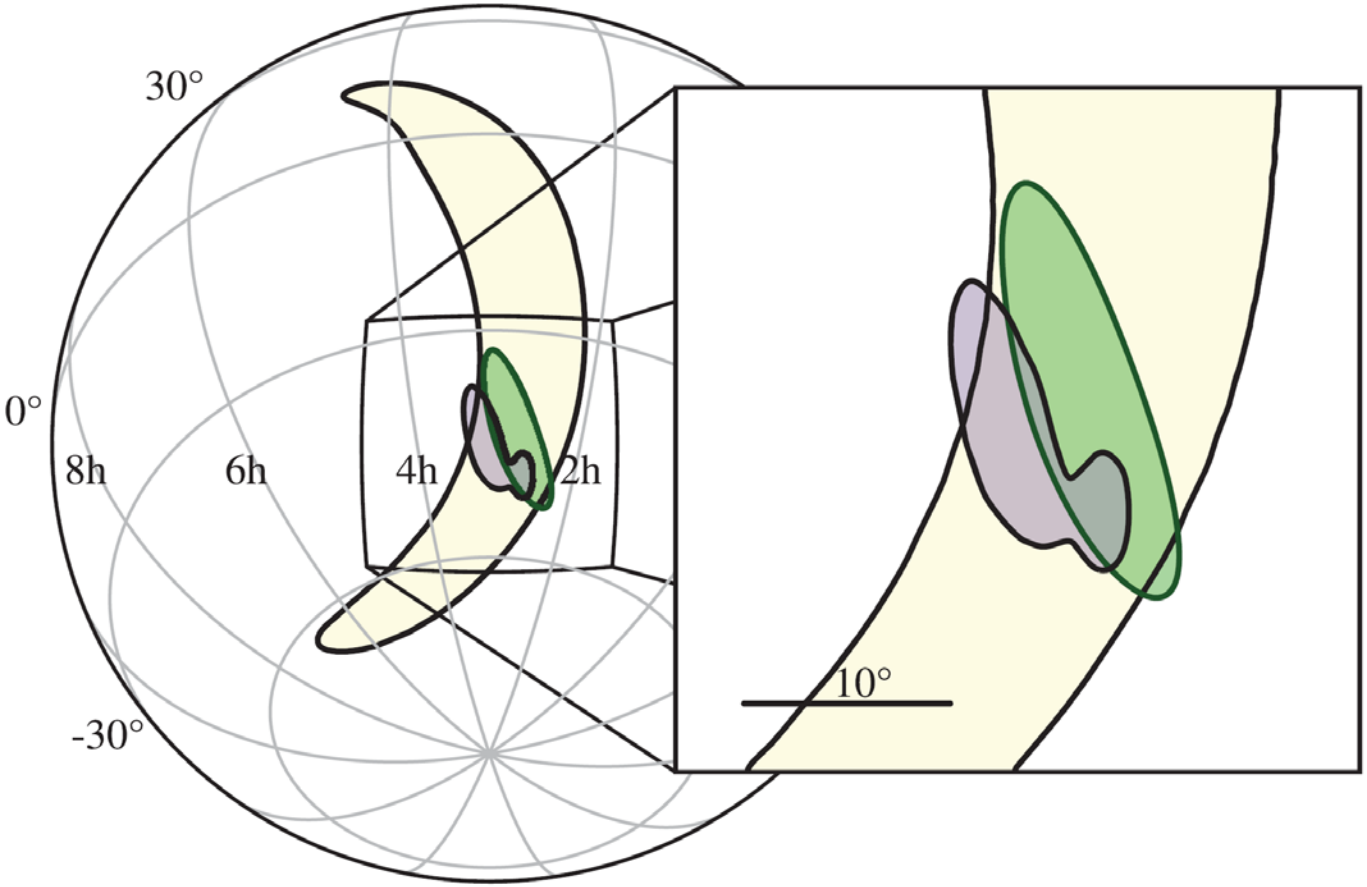


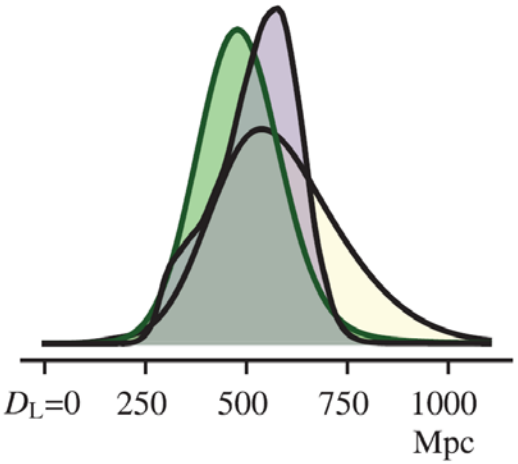






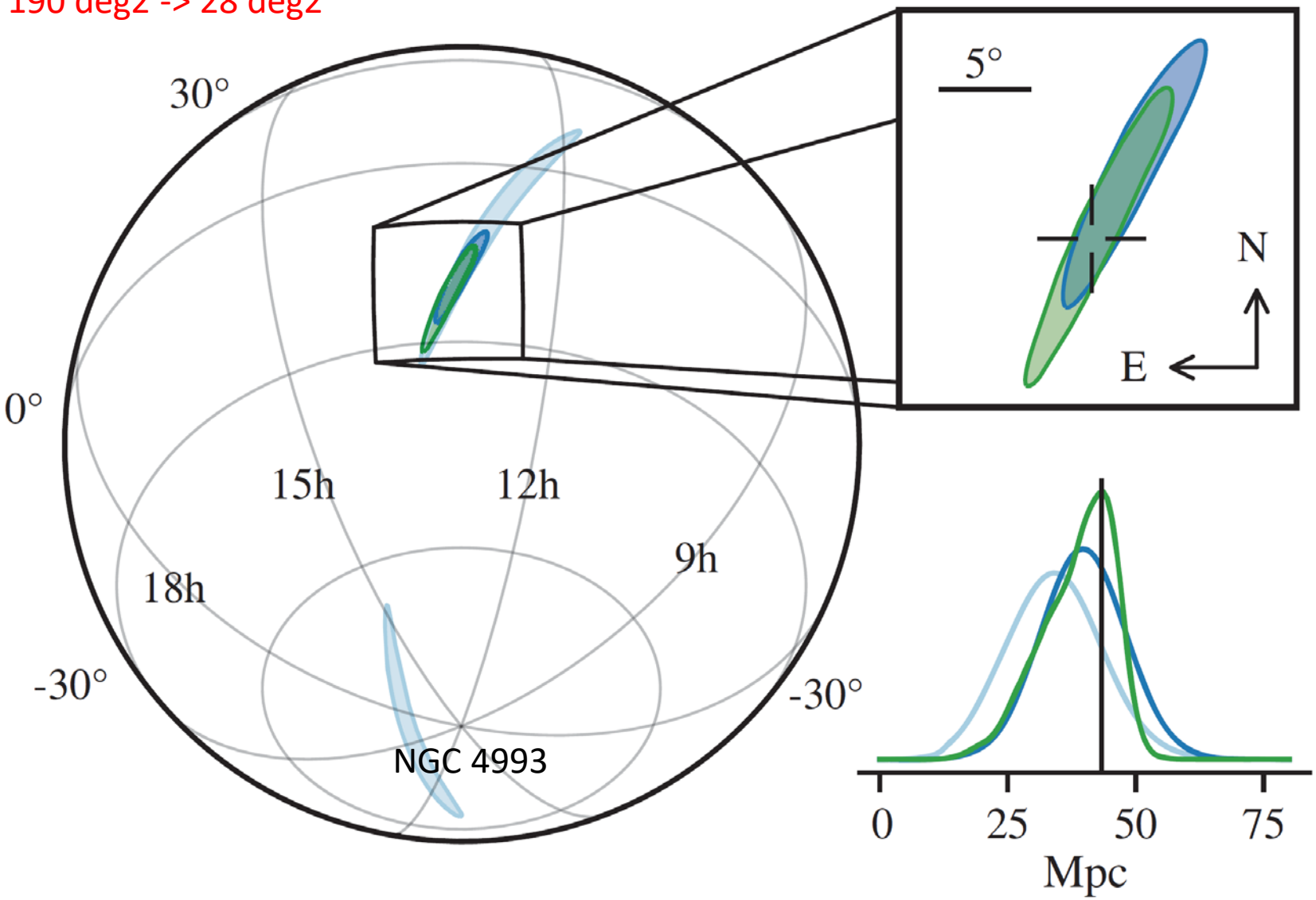
1160 deg2 -> 60 deg2





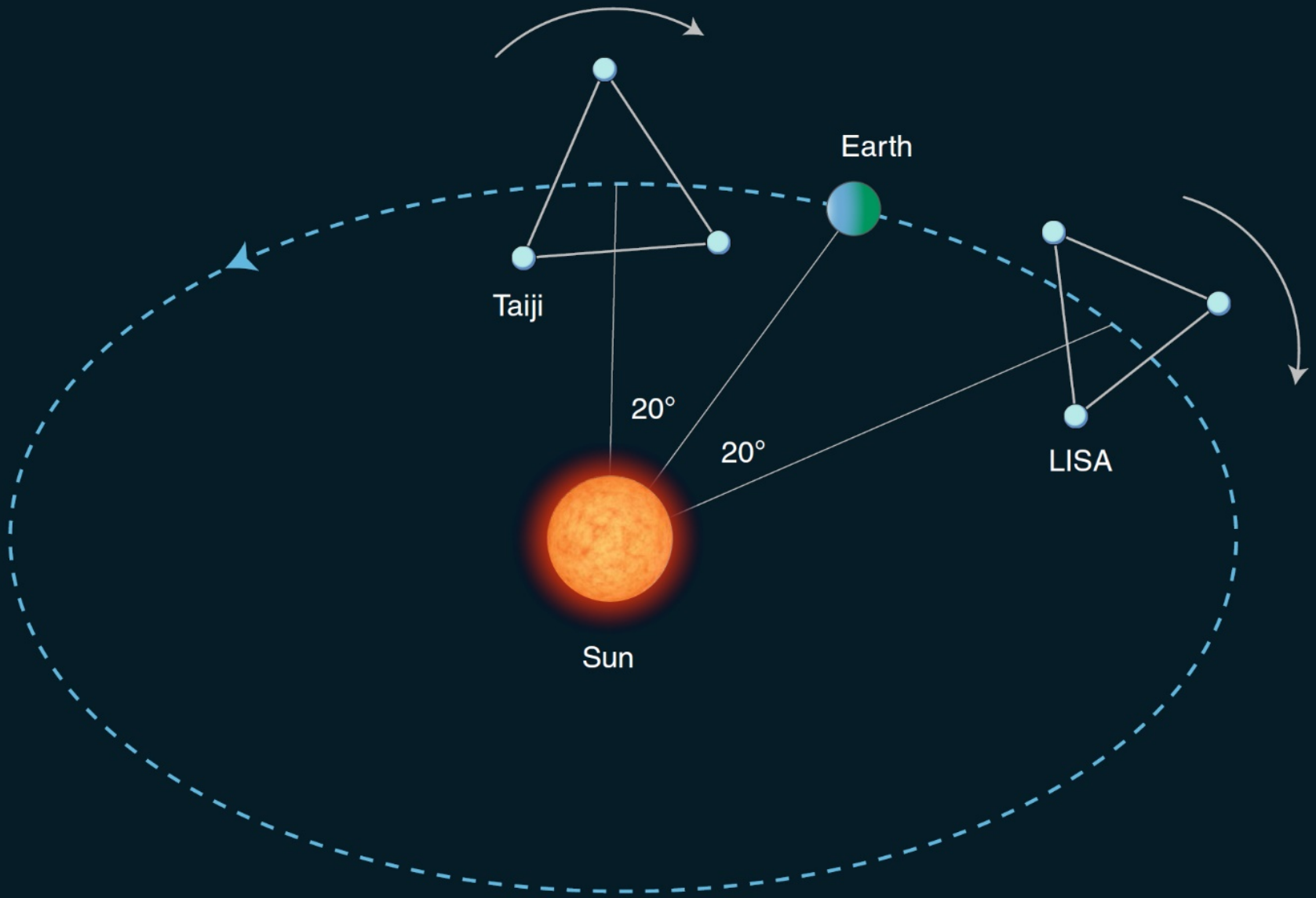
GW170814 [arXiv:1709.09660]

190 deg2 -> 28 deg2

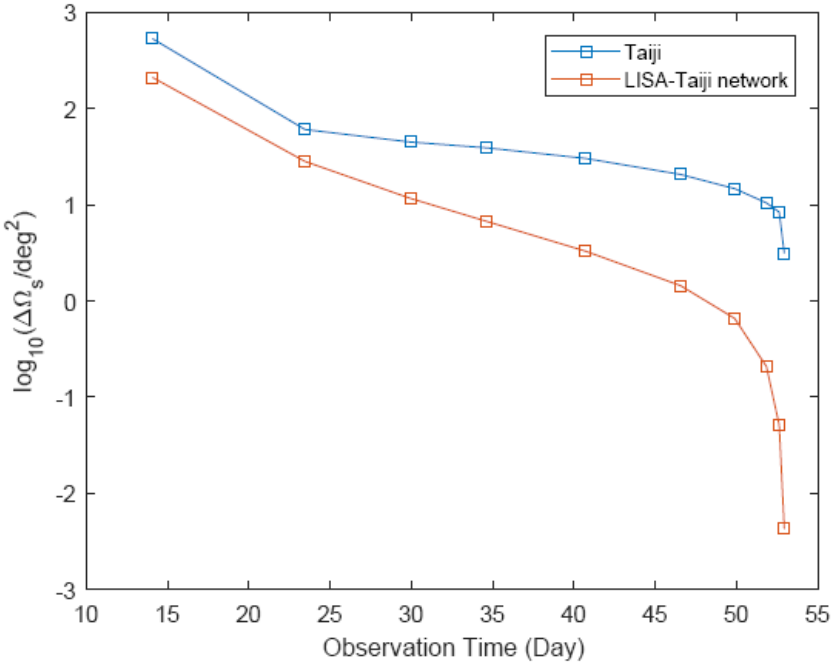


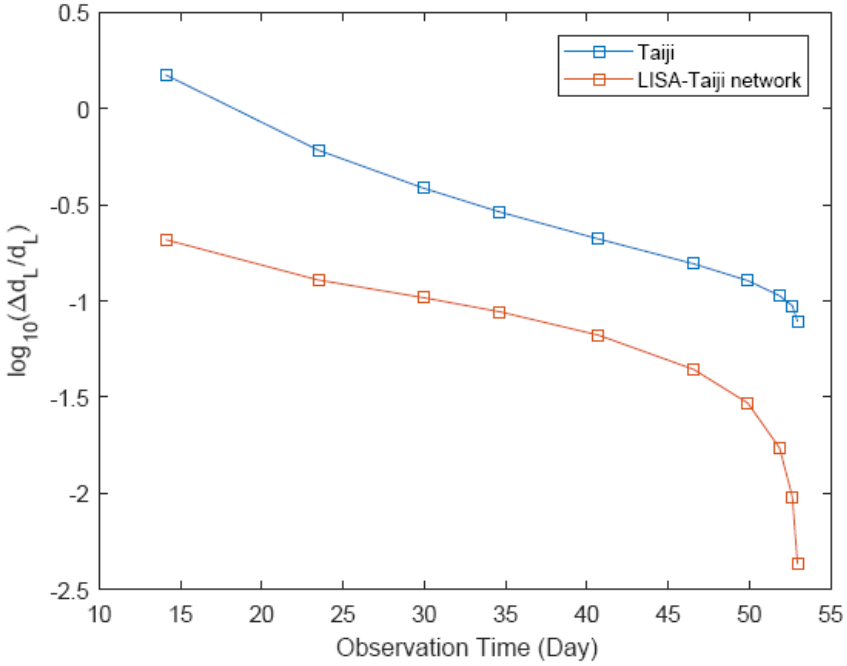
GW170817 [arXiv:1710.05832]

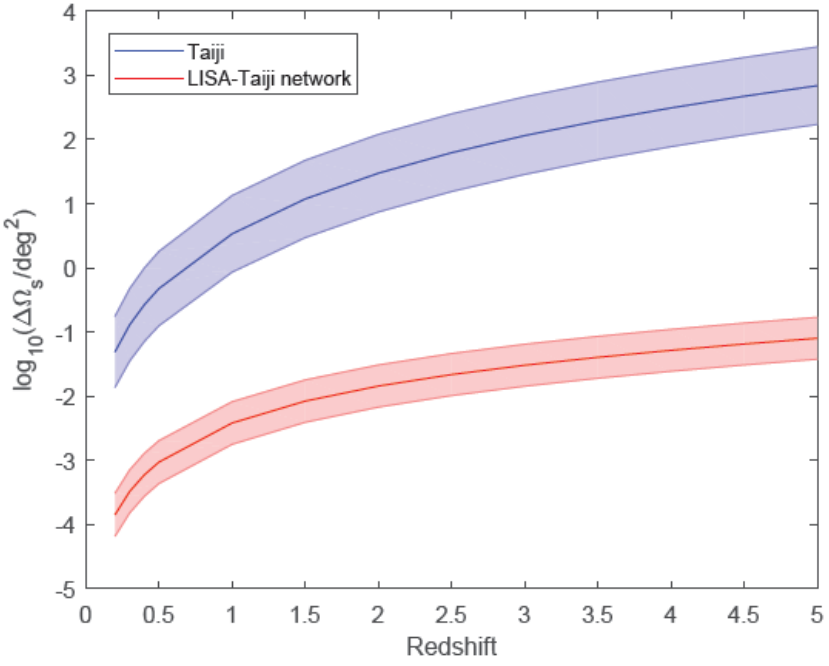
LISA-Taiji network

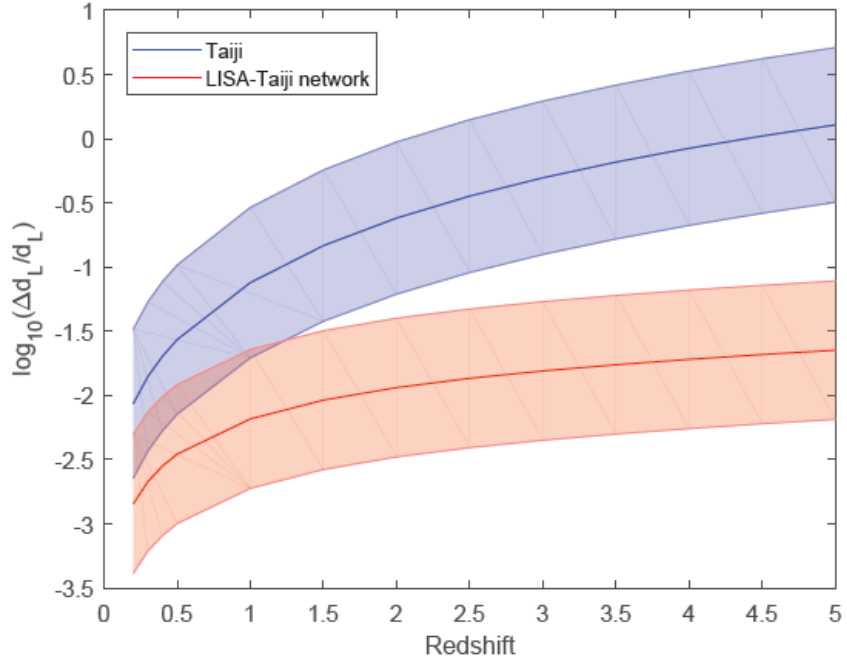


W.H. Ruan, C. Liu, ZKG, Y.L. Wu, R.G. Cai, Nature Astronomy 4 (2020) 108 [arXiv:2002.03603]

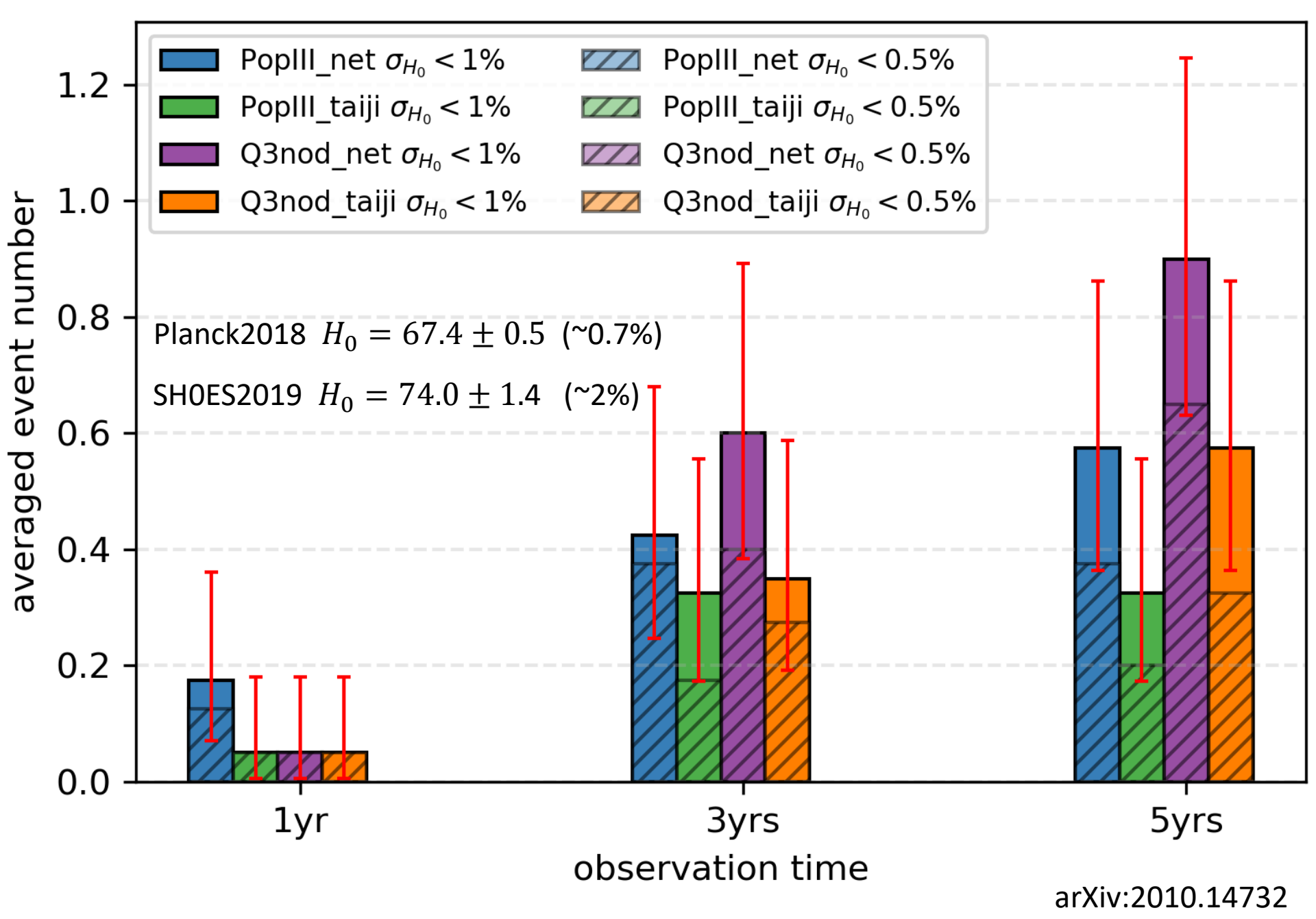




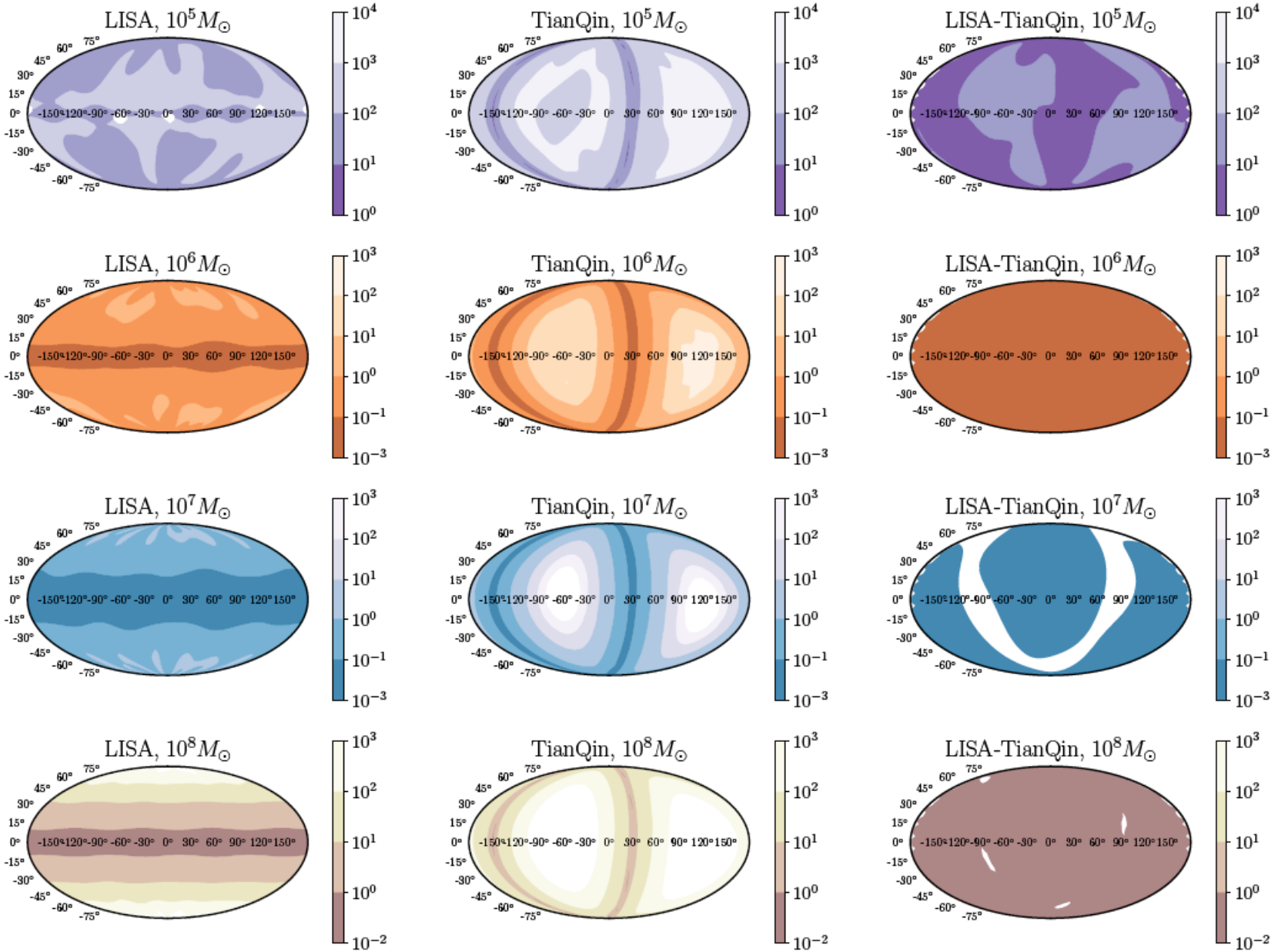




W.H. Ruan, C. Liu, ZKG, Y.L. Wu, R.G. Cai, Research 2021 (2021) 6014164 [arXiv:1909.07104]

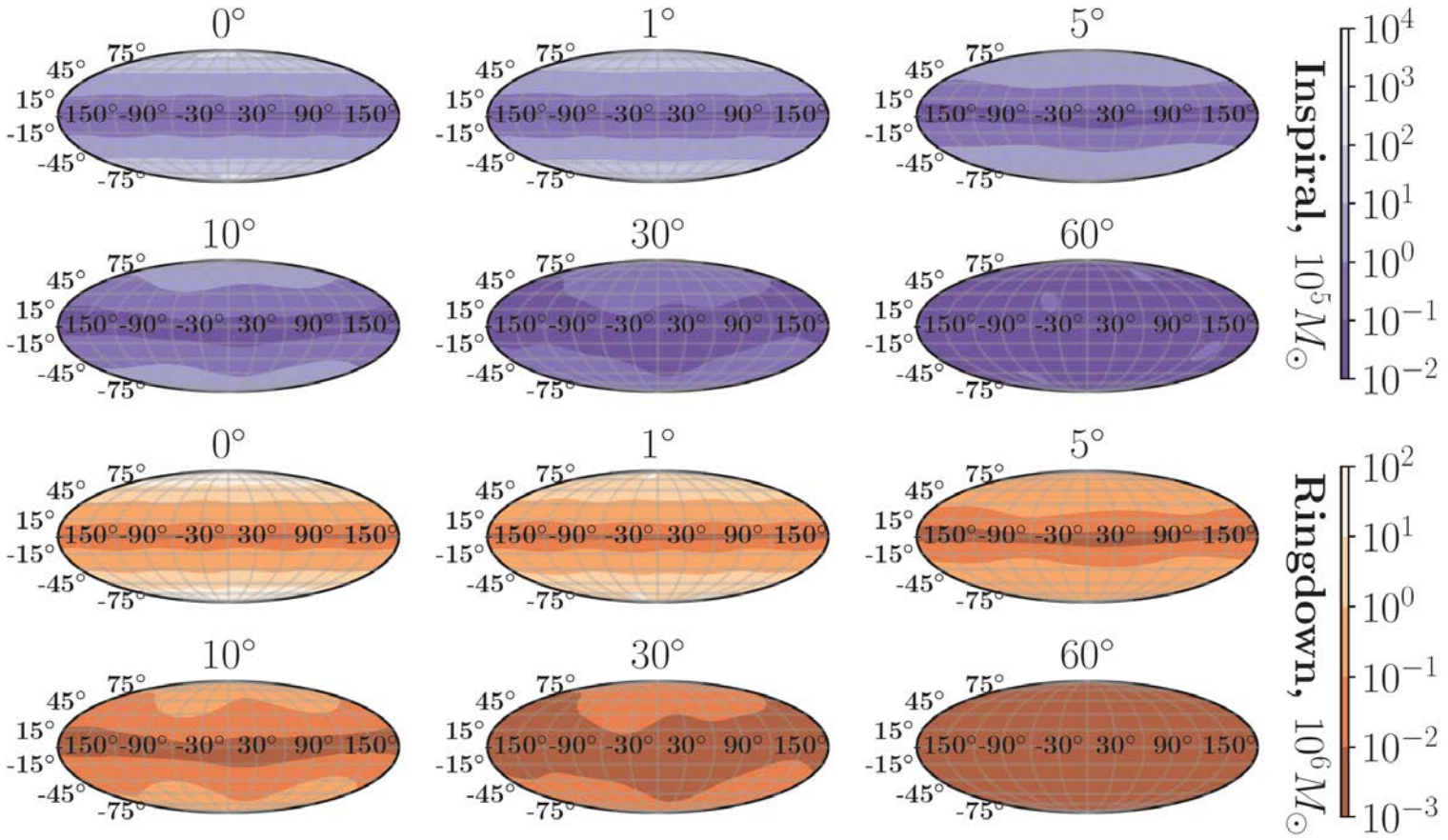


R. Wang, W.H. Ruan, Q. Yang, ZKG, R.G Cai, B. Hu, Natl. Sci. Rev. 9 (2021) nwab054.



C. Zhang, Y. Gong, C. Zhang, Phys. Rev. D 104 (2021) 083038

两个类似天琴的探测器，通过改变两个探测器平面法向之间的夹角来分析夹角对定位的影响空间引力波探测器对超大质量双黑洞系统的空间定位能力。



C. Zhang, Y. Gong, C. Zhang, Phys. Rev. D106 (2022) 024004.

"*Observing gravitational wave polarizations with the LISA-Taiji network*", Phys. Rev. D103 (2021) 064021.

"*Alternative LISA-Taiji networks: Detectability of the isotropic stochastic gravitational wave background*", Phys. Rev. D104 (2021) 104015.

"*Measuring parity violation in the stochastic gravitational wave background with the LISA-Taiji network*", JCAP 03 (2021) 069.

"*On detecting stellar binary black holes via the LISA-Taiji network*", RAA 21 (2021) 285.

"*Tracing astrophysical black hole seeds and primordial black holes with LISA-Taiji network*", MNRAS 512 (2022) 6217-6224.

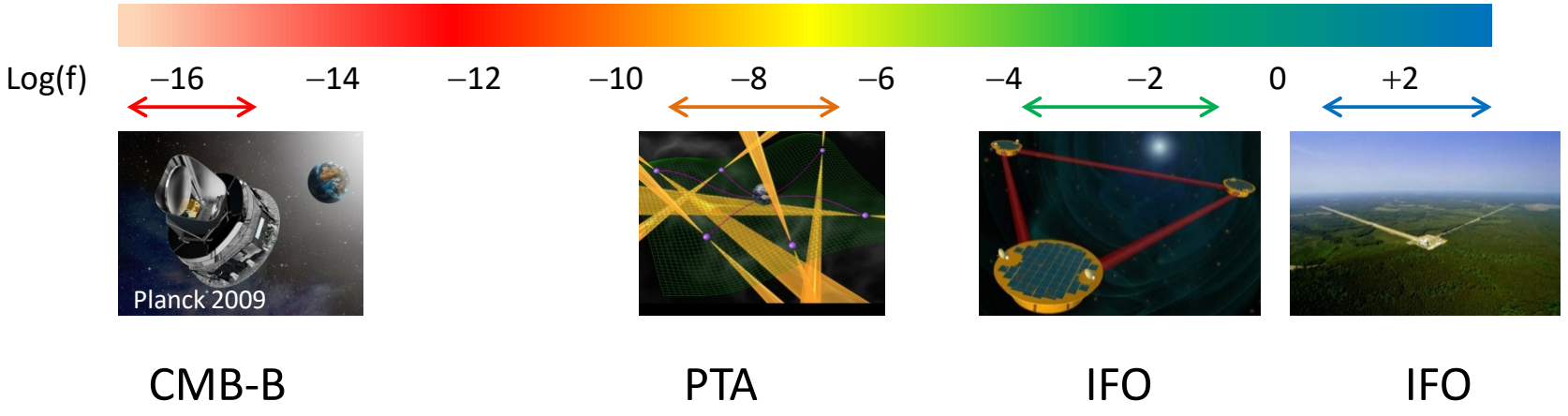
"*Forecast for cosmological parameter estimation with gravitational-wave standard sirens from the LISA-Taiji network*", Sci. China-Phys. Mech. Astron. 65 (2022) 210411.

致密双星产生的引力波

- a direction
- short time
- a waveform
- high frequency
- IFO, PTA
- probe later-Universe physics

早期宇宙产生的引力波

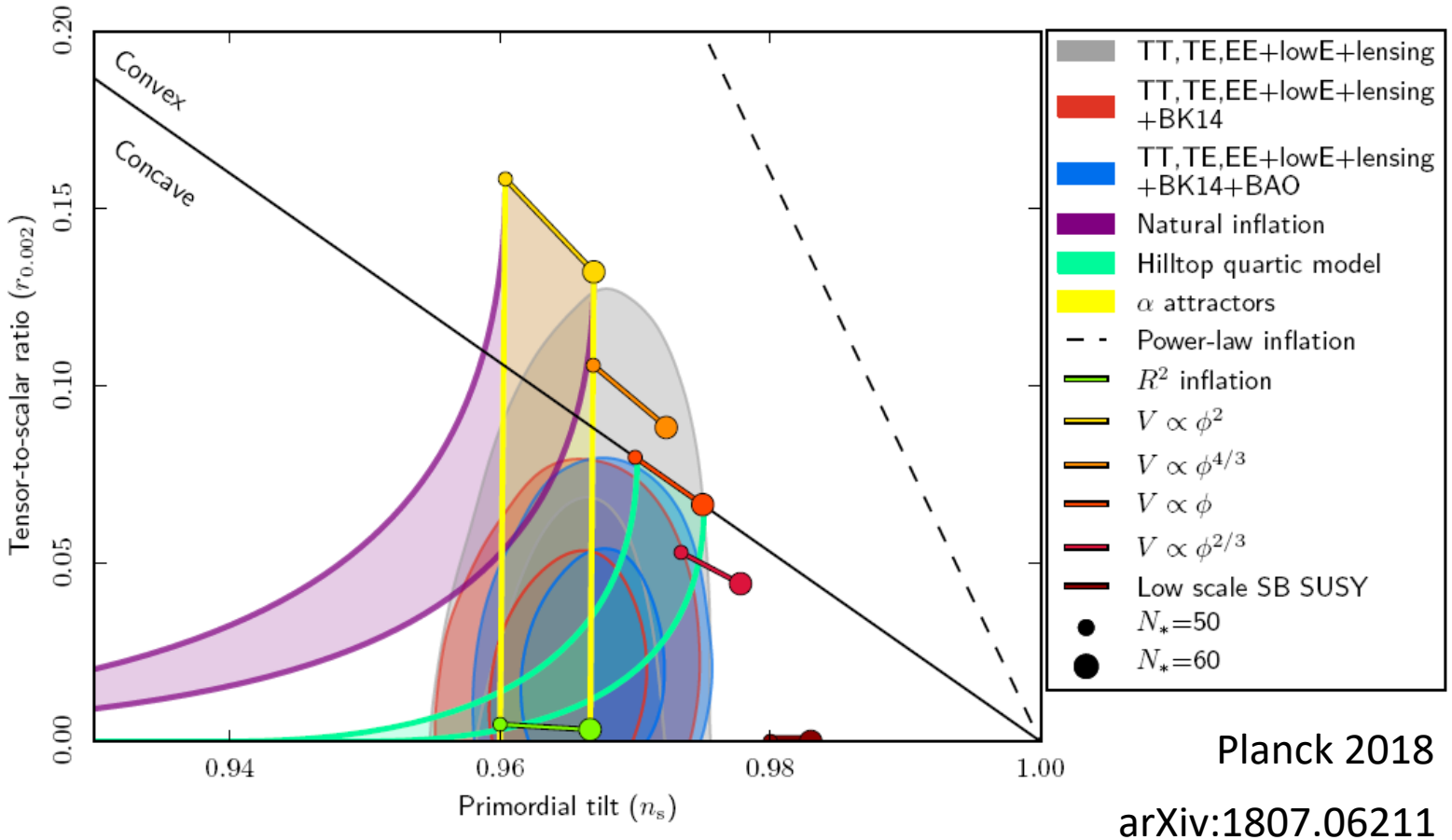
- all directions
- long time
- an overlapped waveform
- low frequency
- CMB-B, PTA, IFO
- probe early-Universe physics



早期宇宙产生的引力波

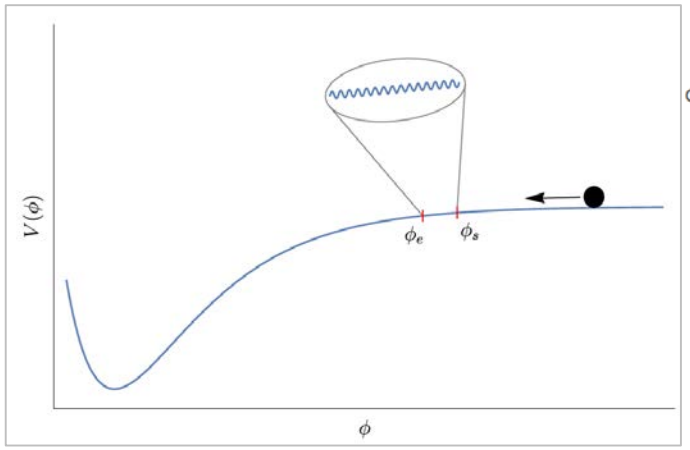
- 暴胀期间产生的原初引力波
- 重加热 / 预加热期间产生的引力波
- 原初曲率扰动诱导的引力波
- 宇宙相变产生的引力波
- 拓扑缺陷(宇宙弦、畴壁)产生的引力波

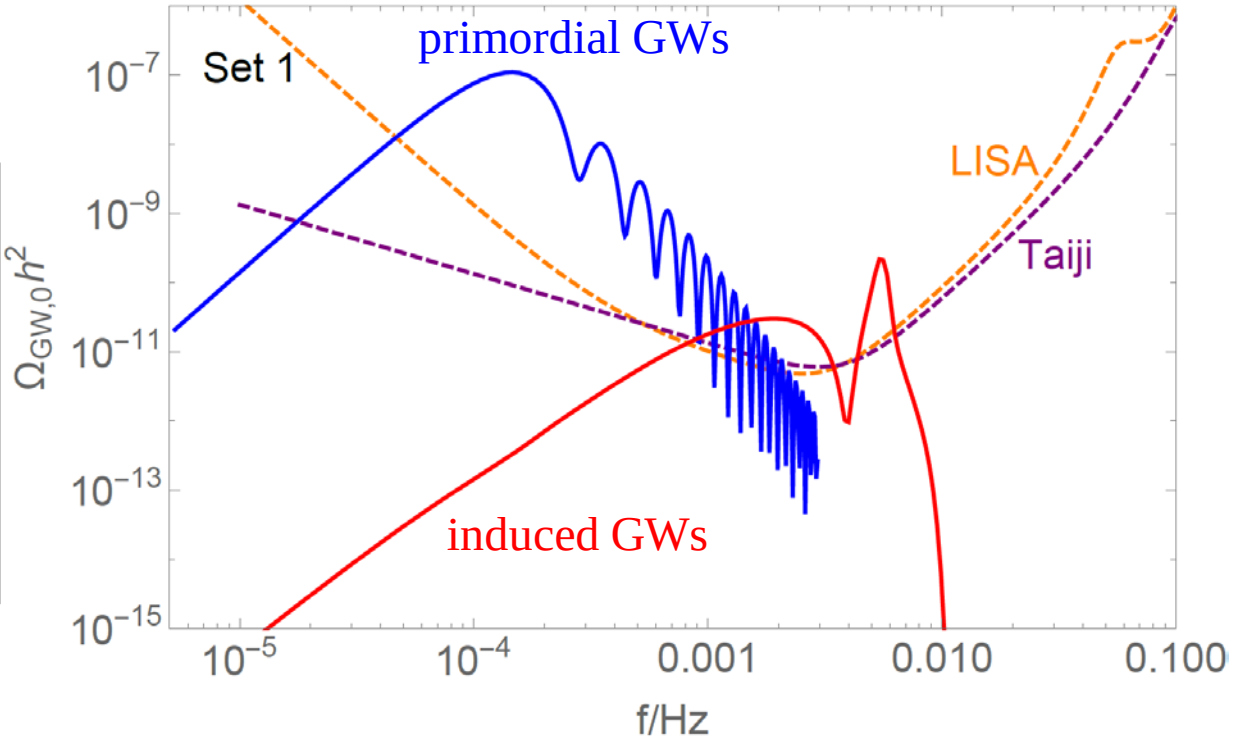
➢ 暴胀期间产生的原初引力波



Planck 2018

arXiv:1807.06211

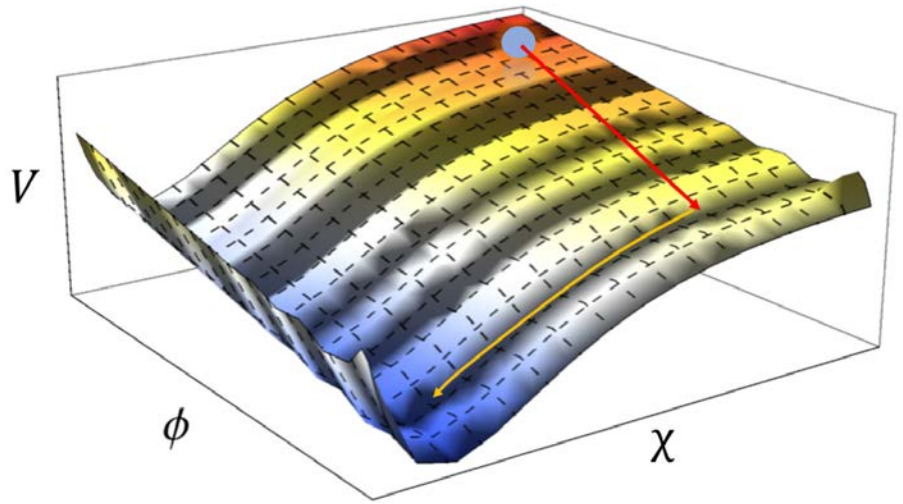




R.G Cai, ZKG, J. Liu, L. Liu, X.Y. Yang, JCAP 06 (2020) 013 [arXiv:1912.10437];
Z.Z. Peng, C. Fu, J. Liu, ZKG, R.G. Cai, JCAP 10 (2021) 050 [arXiv:2106.11816].

$$\mathcal{L} = -\frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}(\partial_\mu \chi)^2 - V(\phi, \chi)$$

$$V(\phi, \chi) = g\Lambda_0^3 \phi + \Lambda^4(\phi)\cos\left(\frac{\phi}{f_a}\right) + \xi\Lambda_0^3 \chi + V_0$$

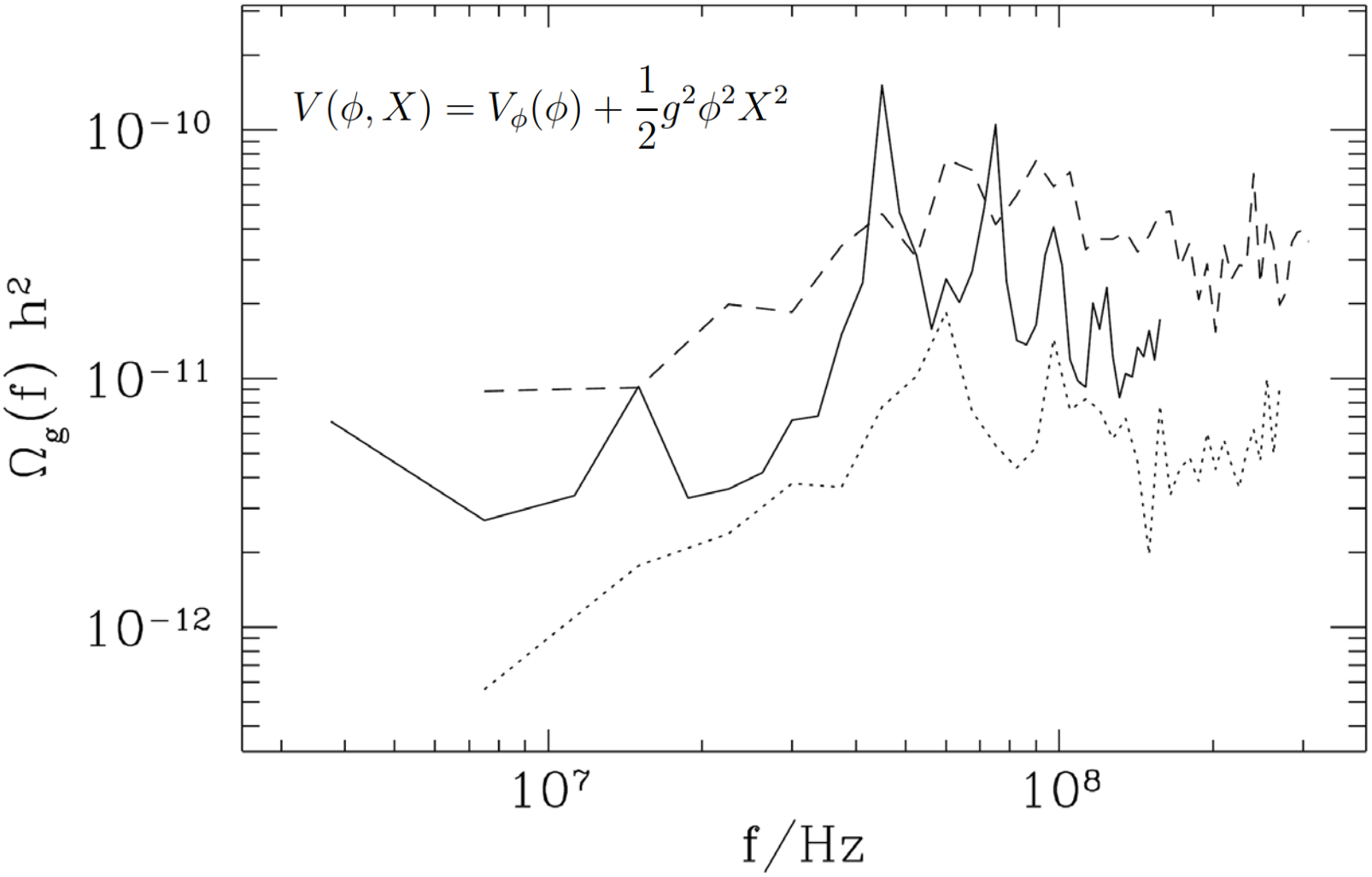


$$\ddot{\delta\chi}_k + 3H\dot{\delta\chi}_k + \frac{k^2}{a^2}\delta\chi_k \simeq \frac{\dot{\chi}\ddot{\phi}}{M_p^2 H}\delta\phi_k \,,$$

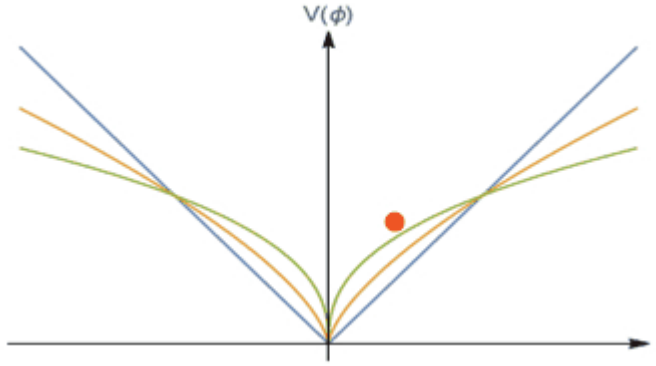
$$\ddot{\delta\phi}_k + 3H\dot{\delta\phi}_k + \left(\frac{k^2}{a^2} - \frac{\Lambda^4(\phi)}{f_a^2}\cos\left(\frac{\phi}{f_a}\right)\right)\delta\phi_k = 0 \,.$$

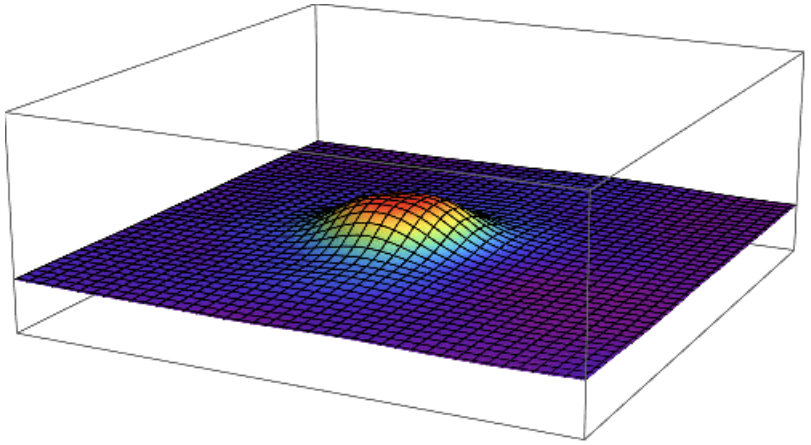
Z. Zhou, J. Jiang, Y.F. Cai, M. Sasaki, S. Pi, Phys. Rev. D102 (2020) 103527 [arXiv:2010.03537].

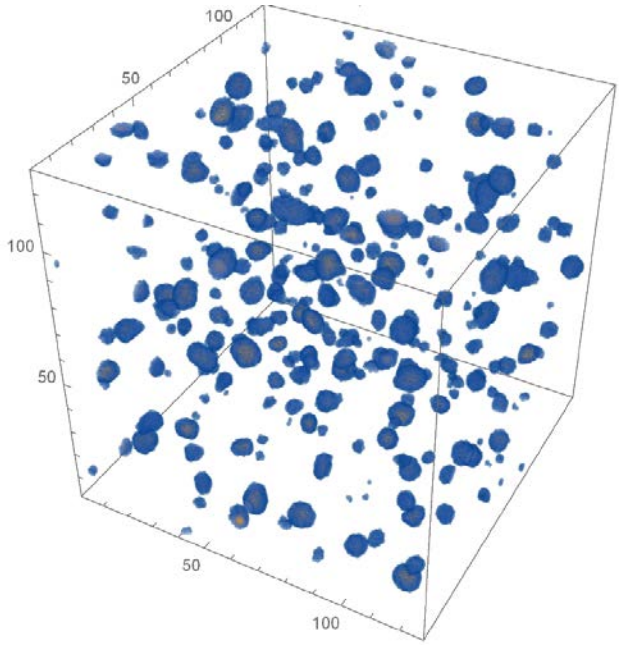
➢ 预加热期间产生的引力波

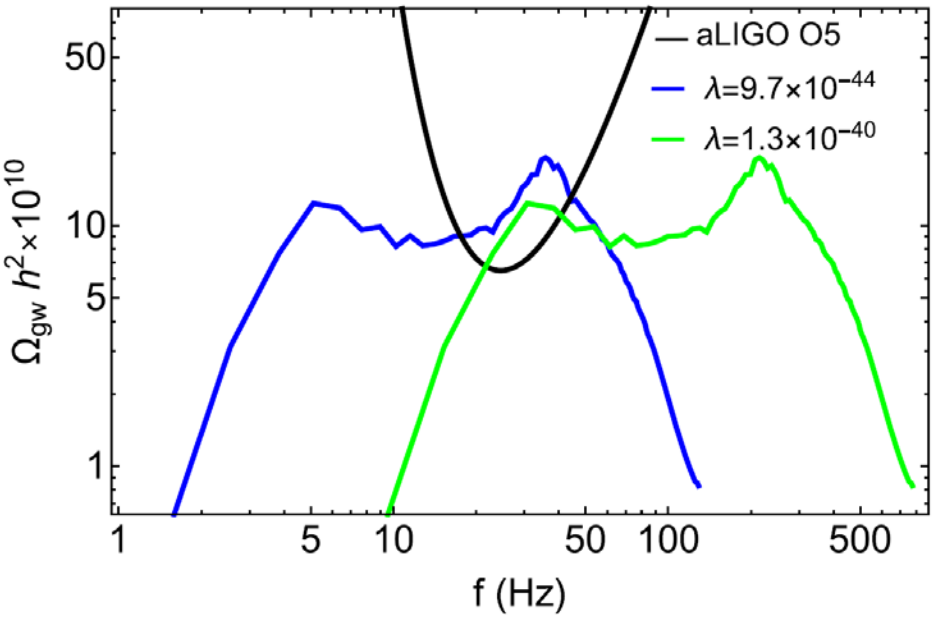


S.Y. Khlebnikov, I.I. Tkachev, Phys. Rev. D56 (1997) 653 [arXiv:hep-ph/9701423].





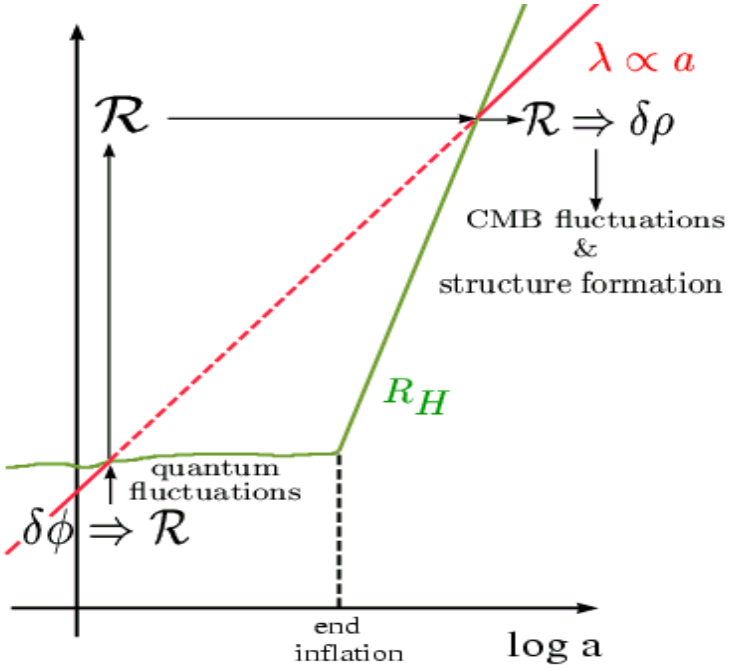




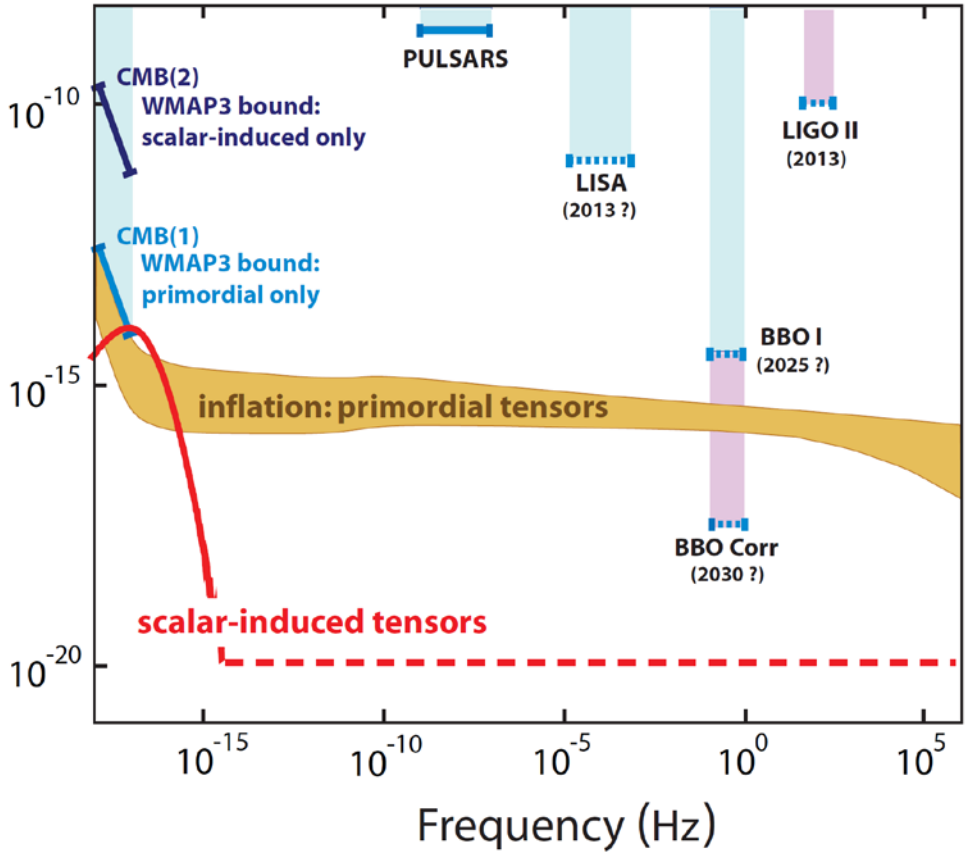
J. Liu, ZKG, R.G. Cai, G. Shiu, Phys. Rev. Lett. 120 (2018) 031301 [arXiv:1707.09841].

➢ 原初曲率扰动诱导的引力波

arXiv:hep-th/0703290

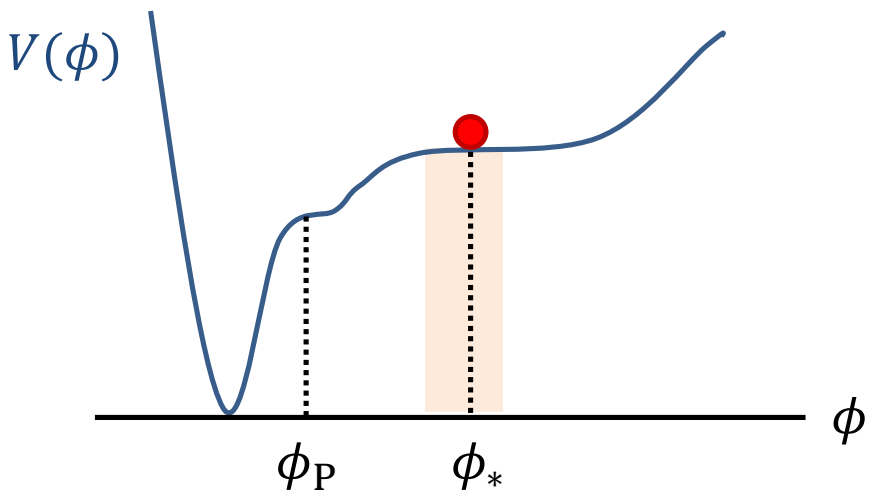


$\Omega_{GW}(f)$

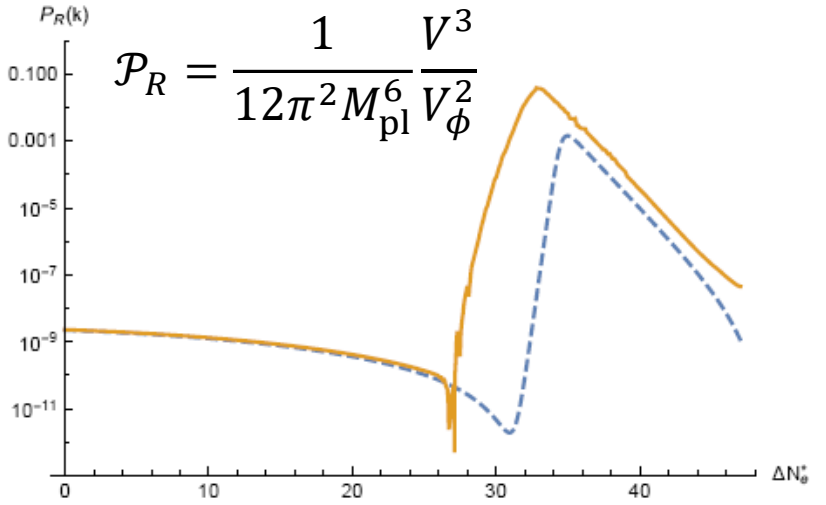


K.N. Ananda, C. Clarkson, D. Wands, Phys. Rev. D75 (2017) 123518 [arXiv:gr-qc/0612013].

Double-inflection-point inflation



$$\mathcal{P}_R = \frac{1}{12\pi^2 M_{\rm pl}^6}\frac{V^3}{V_\phi^2}$$

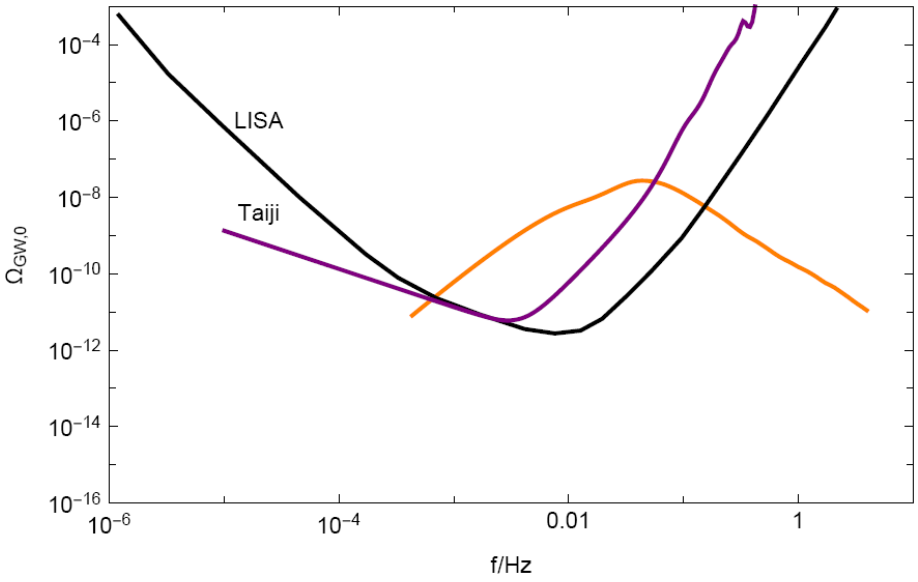


$$A_s = (2.10 \pm 0.03) \times 10^{-9}$$

$$n_s = 0.9649 \pm 0.0044$$

$$\alpha = -0.0065 \pm 0.0066$$

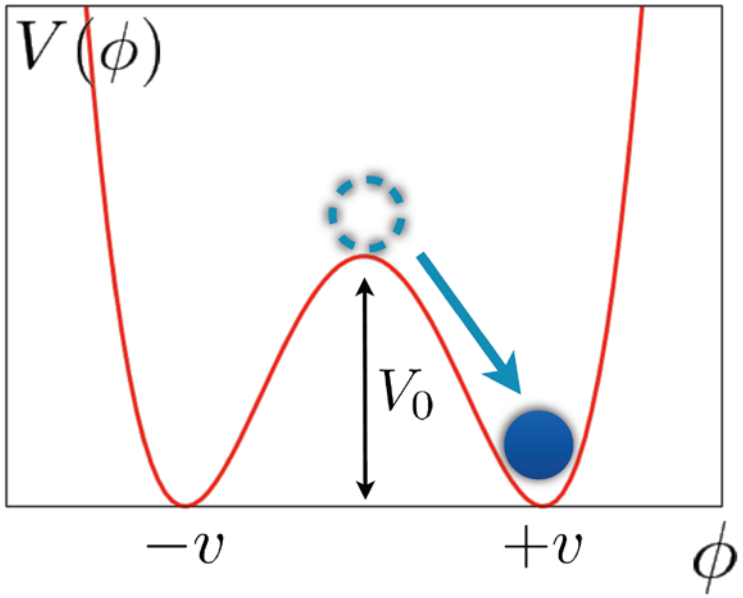
$$r < 0.07$$

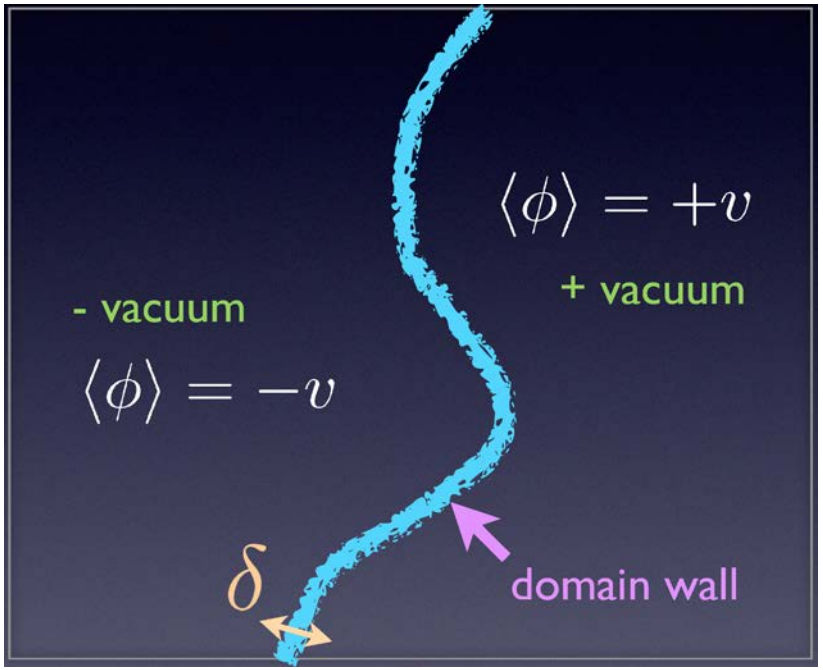


W.T. Xu, J. Liu, T.J. Gao, ZKG, Phys. Rev. D101 (2020) 023505 [arXiv:1907.05213].

➢ 畴壁塌缩产生的引力波

$$V = \frac{\lambda}{4}(\phi^2 - v^2)^2$$



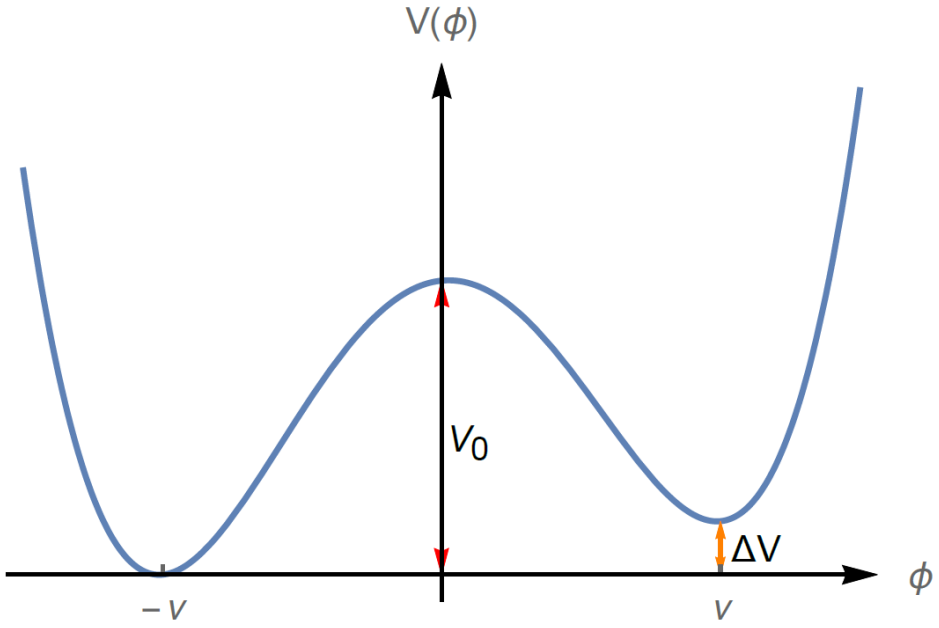


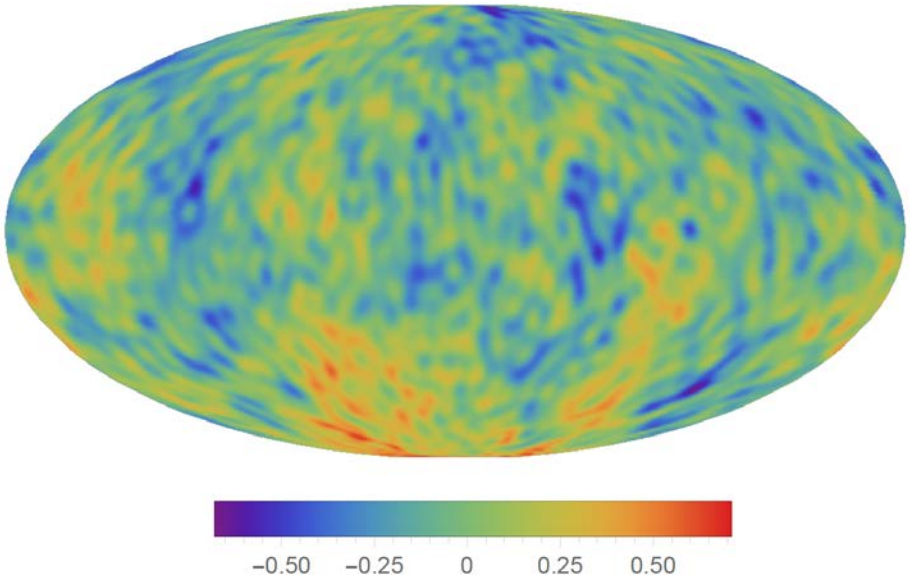
Width of wall: $\delta \sim \left(\sqrt{\lambda}v\right)^{-1}$

Surface energy density (tension): $\sigma \sim \sqrt{\lambda}v^3$

Energy density: $\rho \sim \sigma/t, w = 2/3$

M. Gleiser, R. Roberts, Phys. Rev. Lett. 81 (1998) 5497 [arXiv:astro-ph/9807260].





collapse $t_{ann} \sim \frac{\mathcal{A}\sigma}{\Delta V}$

$$\Omega_{\mathrm{GW,peak}}\left(t_{\mathrm{ann}}\right) = \frac{\tilde{\epsilon}_{\mathrm{GW}} \mathcal{A}^2 \sigma^2}{24\pi H^2\left(t_{\mathrm{ann}}\right)}$$

$$\delta\Omega_{\mathrm{GW},P}(\mathbf{x}) = c_1 \delta\phi(\mathbf{x})$$

$$c_1 = \frac{2}{\sqrt{\pi}\phi_i} \frac{\exp(-\alpha_{\mathrm{peak}}^2)\alpha_{\mathrm{peak}}}{\mathrm{erfc}(\alpha_{\mathrm{peak}})}$$

$$\alpha_{\mathrm{peak}} \equiv (\sqrt{2}\pi\phi_i / H_{\mathrm{inf}}\sqrt{N_{\mathrm{peak}}})$$

$$l(l+1)C_l \approx \begin{cases} \frac{\pi}{N_{\mathrm{peak}}}\alpha_{\mathrm{peak}}^2, & \alpha_{\mathrm{peak}} \gg 1 \\ \frac{1}{N_{\mathrm{peak}}}, & \alpha_{\mathrm{peak}} \ll 1 \end{cases}$$

$l(l+1)C_l \sim \mathcal{O}(10^{-2})$

J. Liu, R.G. Cai, ZKG, Phys. Rev. Lett. 126 (2021) 141303 [arXiv:2010.03225].

谢谢！