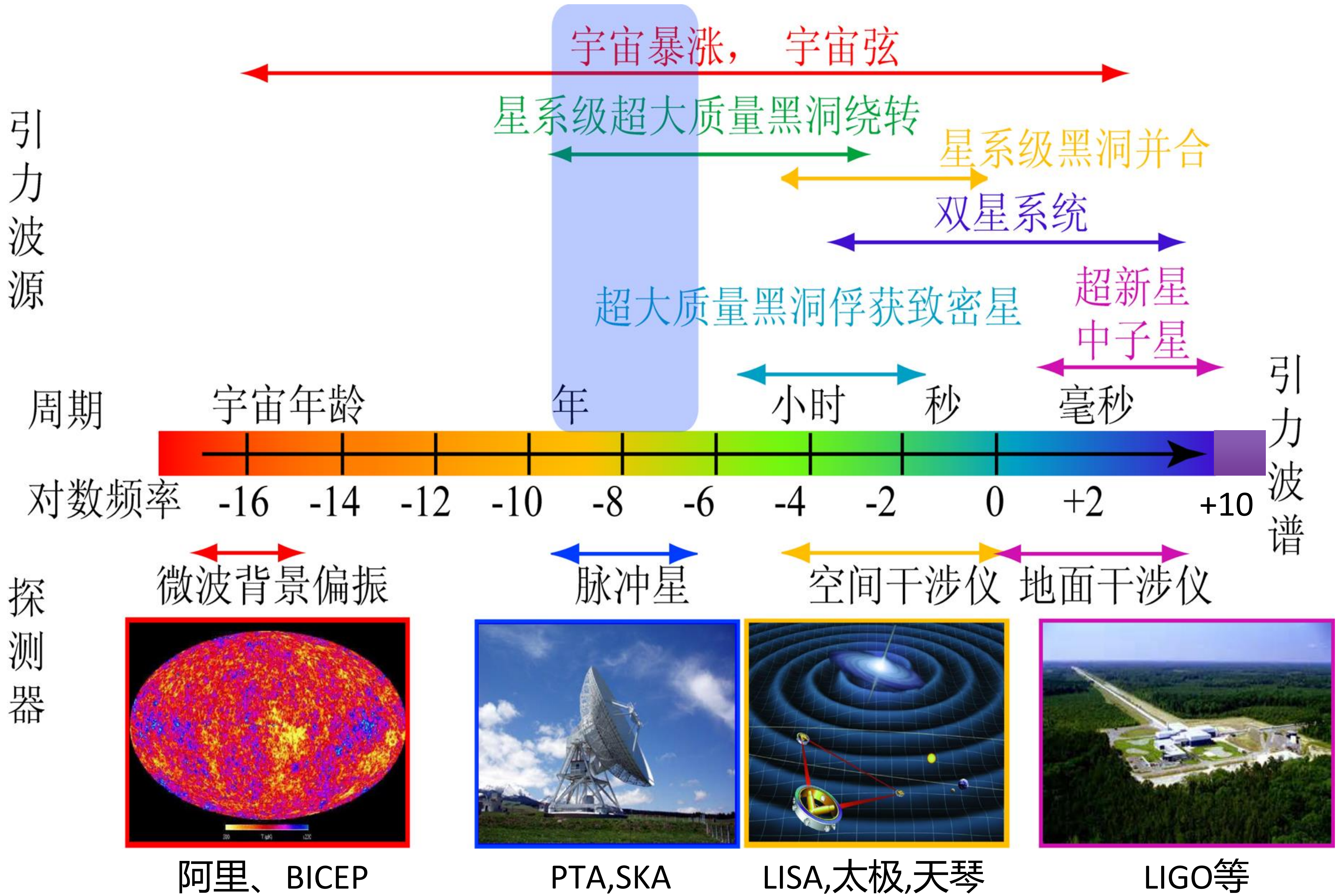
利用空间引力波探测器检验引力理论

韩文标 (HAN Wenbiao)
Shanghai Astronomical Observatory
HIAS,UCAS
2023/05/08@千岛湖

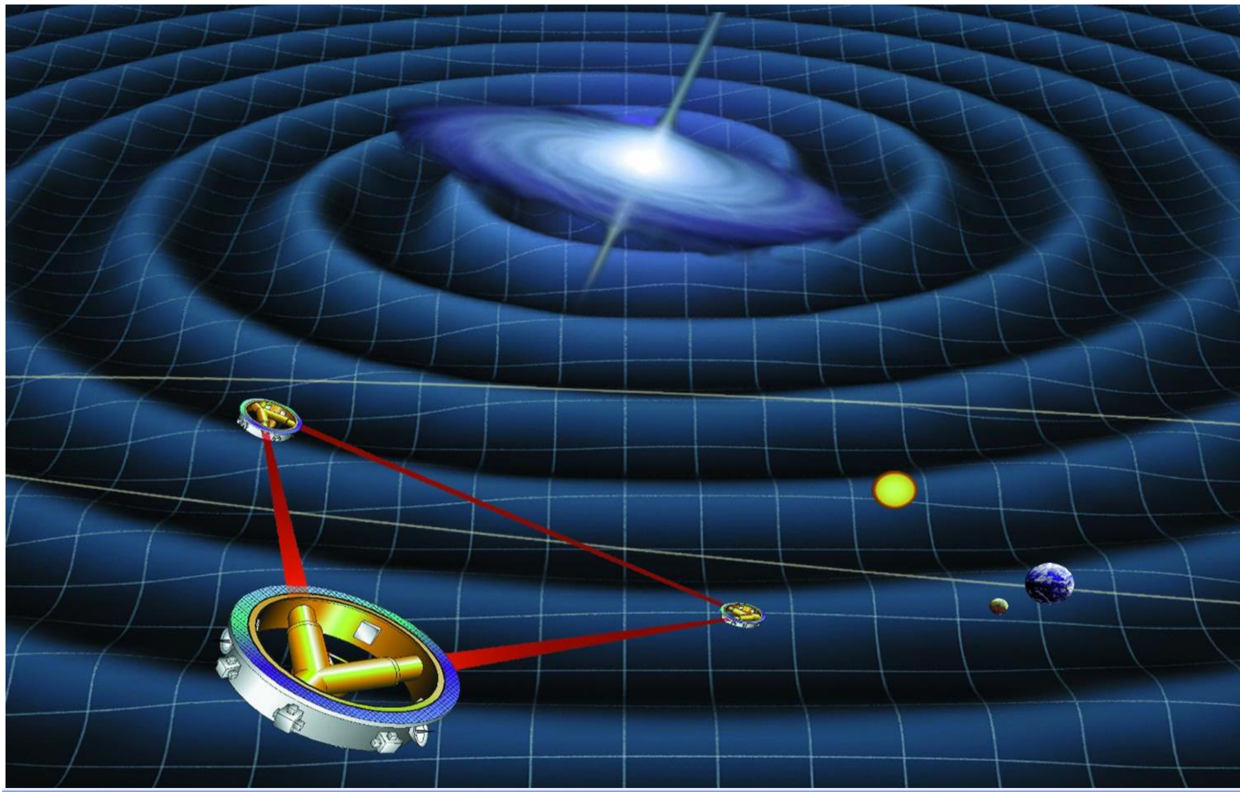
Outline

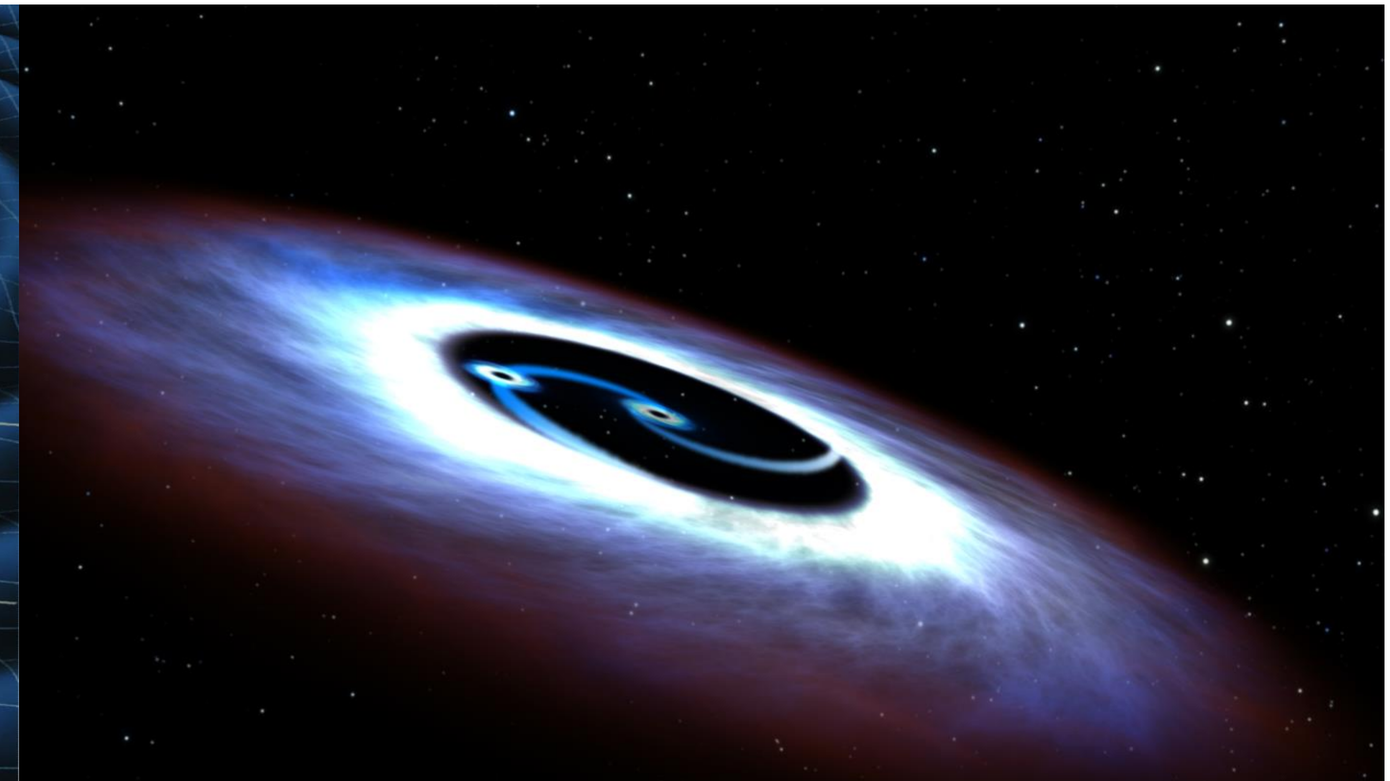
- Space-borne detectors and GW sources
- Science of low-frequency GW astronomy
- Testing GR with low frequency GWs
- Testing BHs with low frequency GWs
- Conlusions

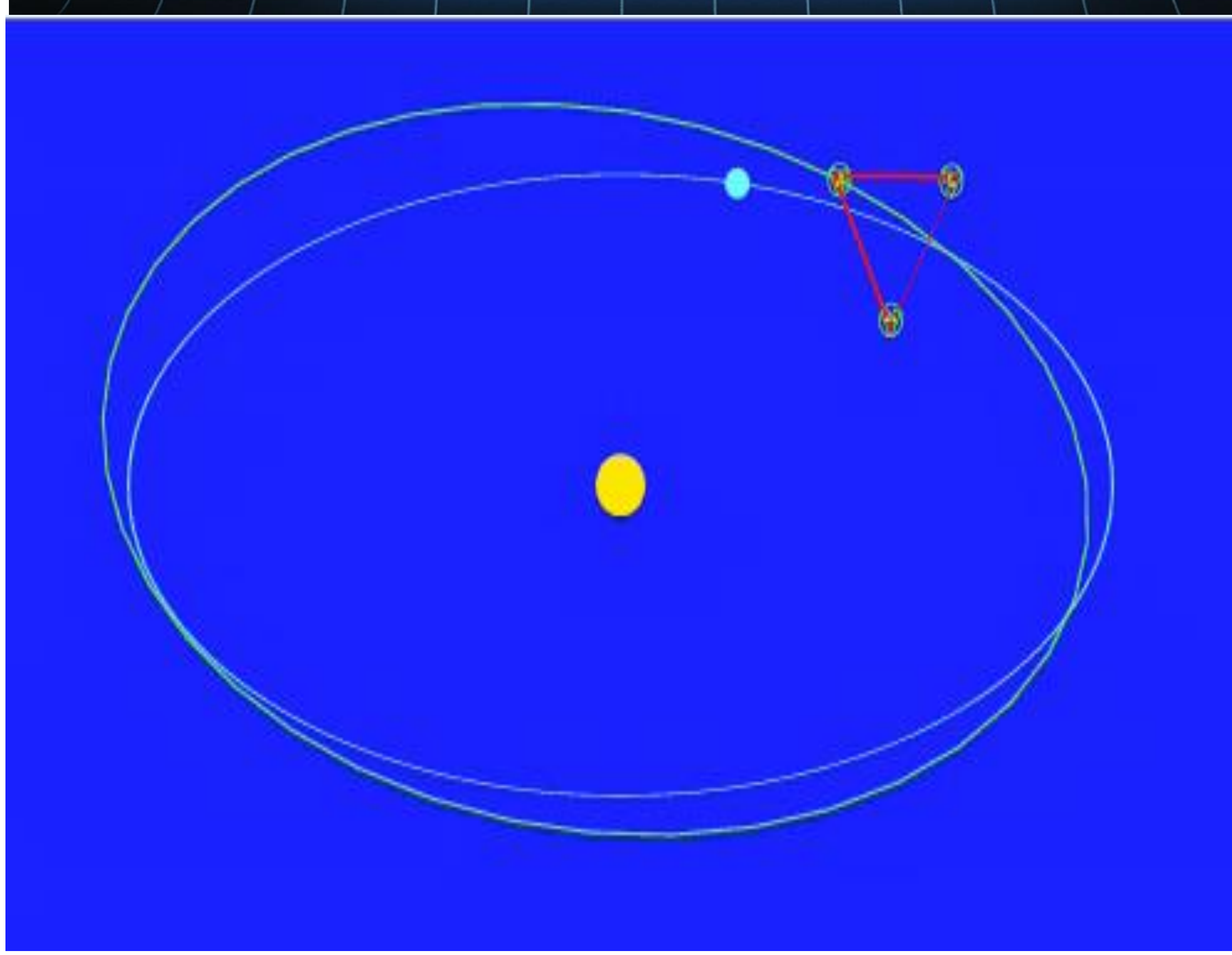
更多的探测手段

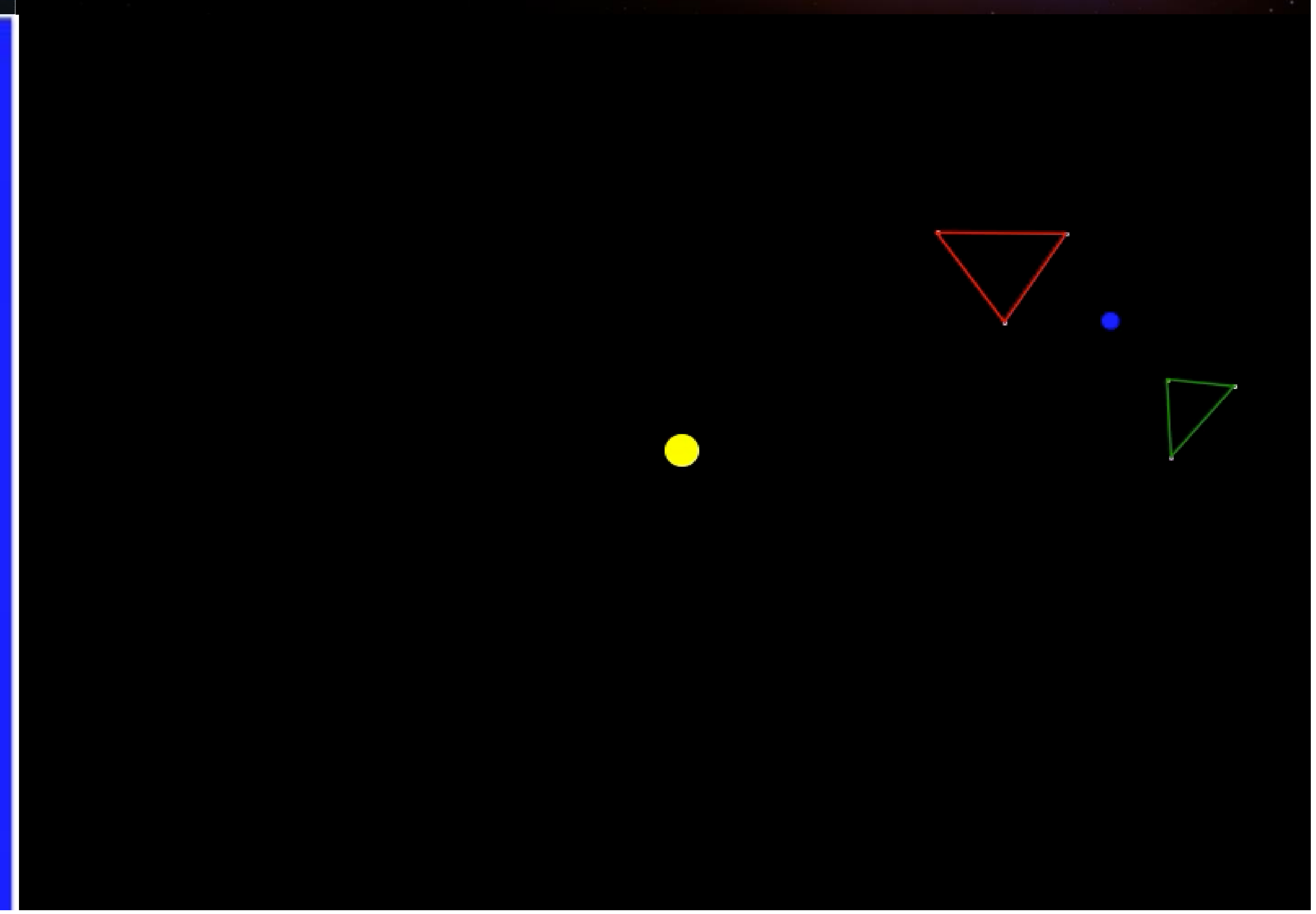

宇宙暴涨， 宇宙弦
星系级超大质量黑洞绕转
星系级黑洞并合
双星系统
超大质量黑洞俘获致密星
超新星
中子星
引力波源
周期
宇宙年龄
年
小时
秒
毫秒
对数频率
-16
-14
-12
-10
-8
-6
-4
-2
0
+2
+10
引力波谱
探测器
微波背景偏振
脉冲星
空间干涉仪
地面干涉仪
阿里、BICEP
PTA,SKA
LISA,太极,天琴
LIGO等

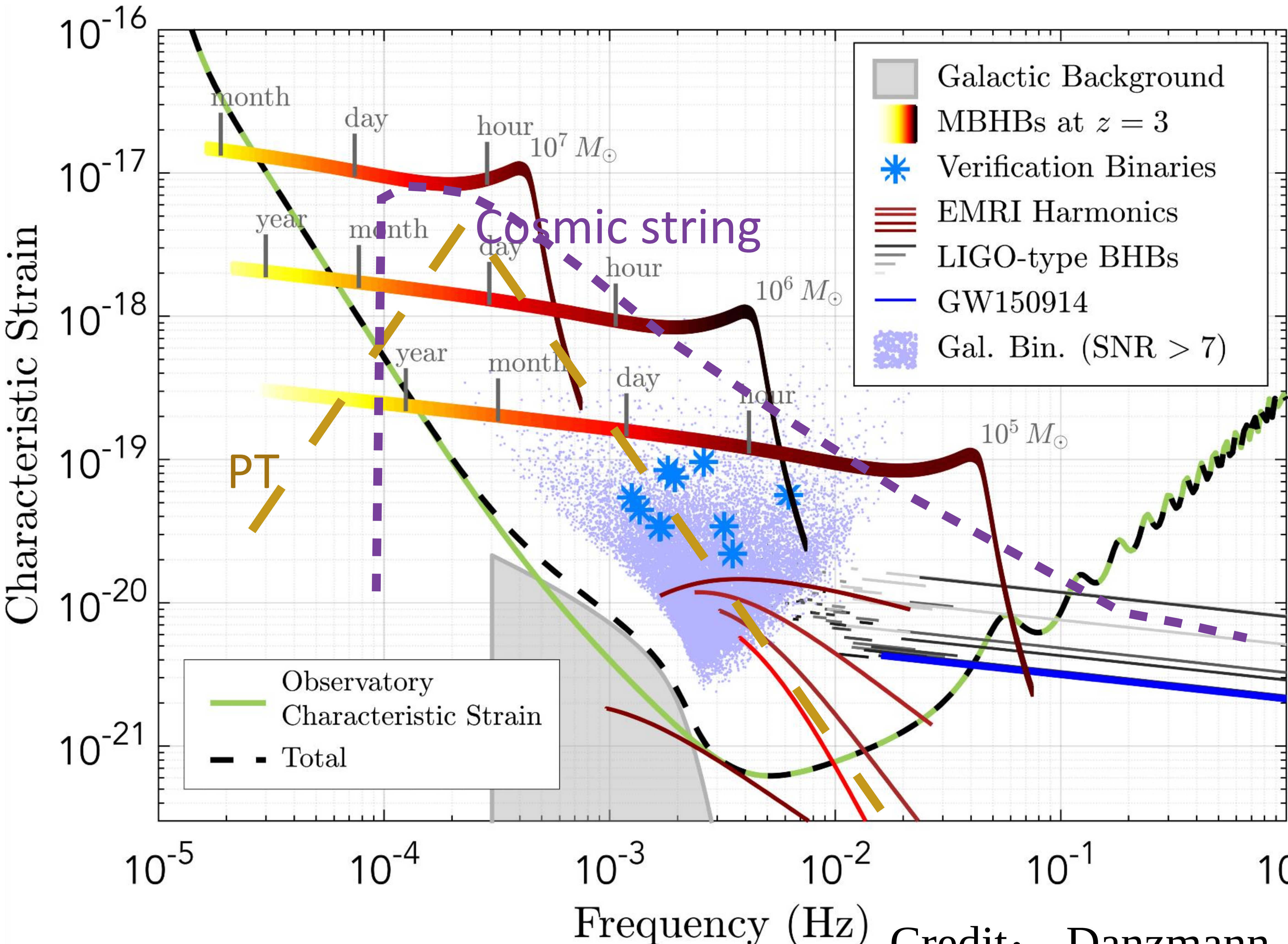
LISA, Taiji 等











Credit： Danzmann, 2017

MBHB

EMRI

GB,SOBHB

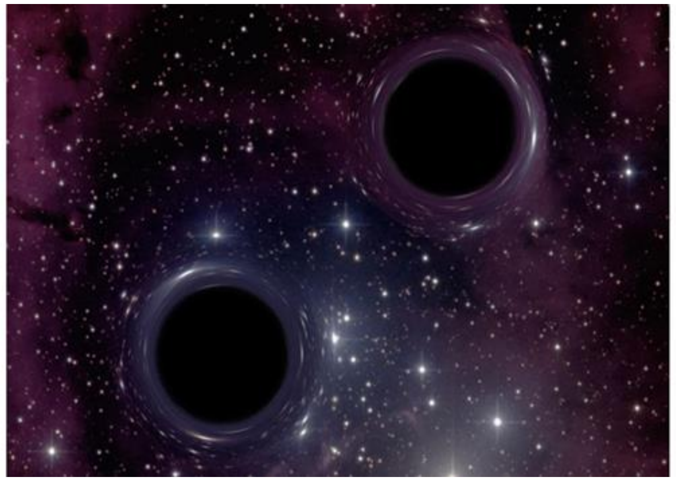
Cosmic string

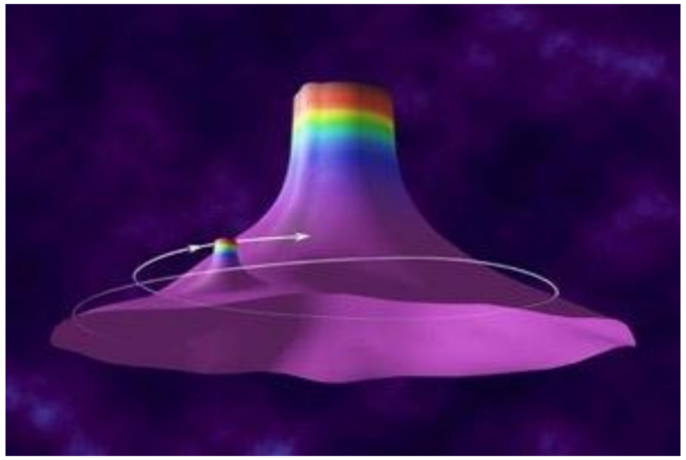
CSGWB

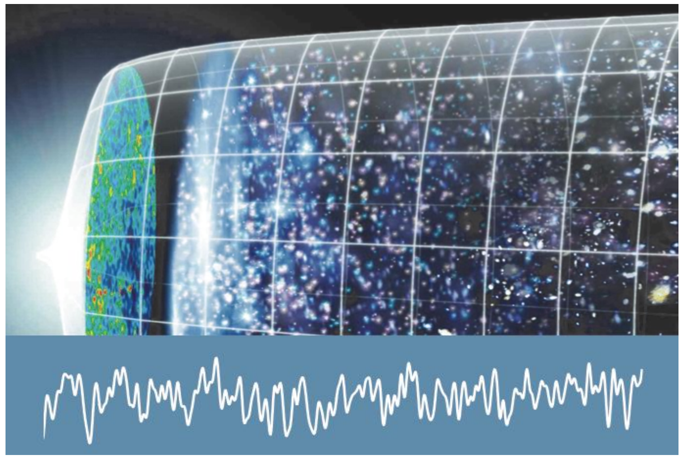
Source and Sciences with Low Frequency GWs

Trace the formation, growth, and merger history of massive black holes	MBHB
Explore stellar populations and dynamics in galactic nuclei	EMRI
Test GR with observations	MBHB+EMRI
Probe new physics and cosmology	BHB+EMRI+MBHB CSGWB+CS\Unknown
Survey compact stellar-mass binaries and study the structure of the Galaxy	GB+SOBHB

Source and Sciences with Low Frequency GWs

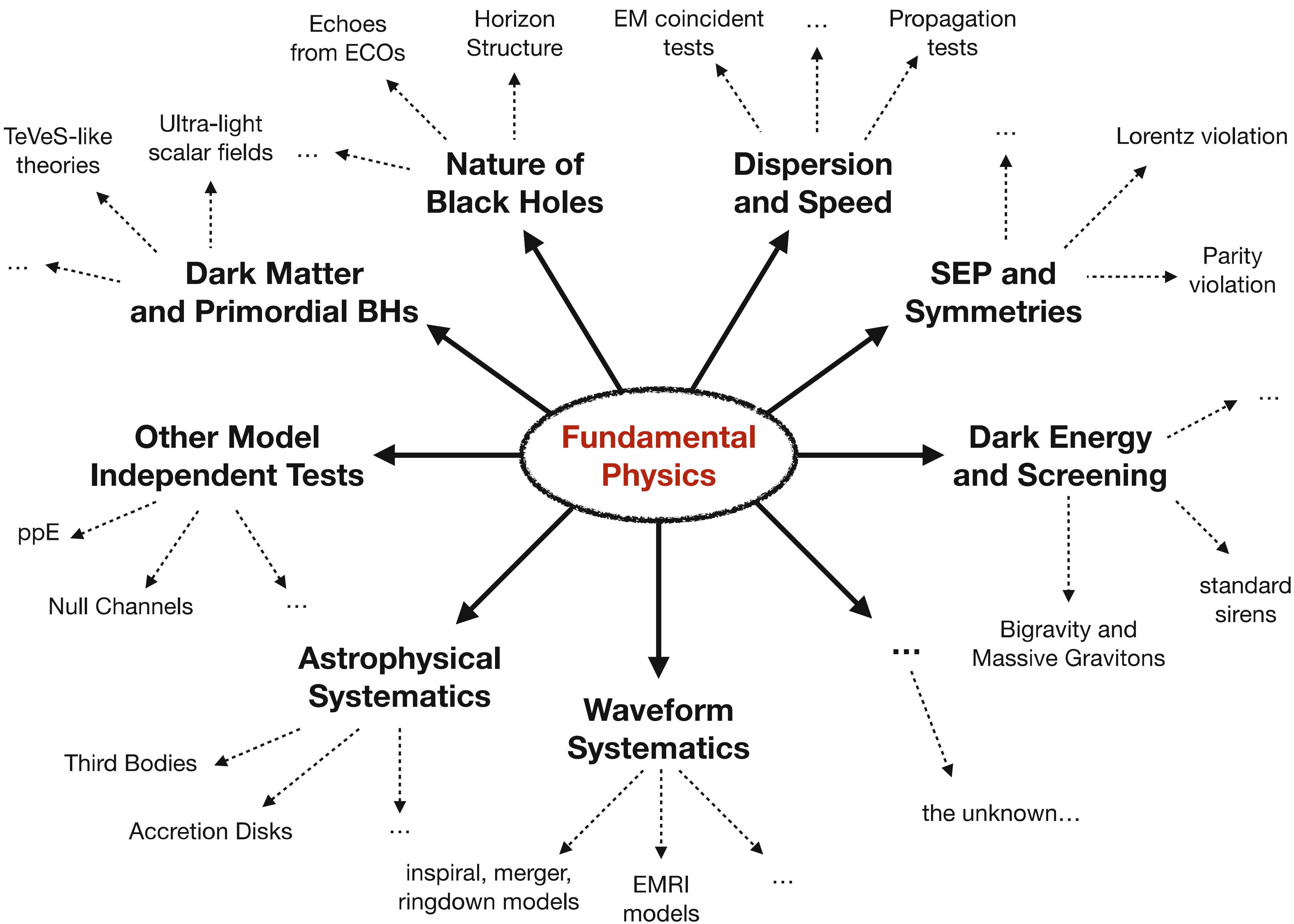






- 第一个星系级黑洞什么时候出现，质量和自旋?
- 黑洞形成的历史，黑洞在再电离、星系的演化和结构中作用
- 哈勃常数，宇宙学红移和时间关系
- 并合后的波形和GR的偏离，引力子质量?
- 星系核中的恒星动力学、动力学弛豫过程和质量沉降;
- 低质量星系中存在的黑洞比例?
- 黑洞的多极矩，偏离Kerr？致密天体视界面有无?
- 替代引力理论检验
- 宇宙极早期，Planck尺度的宇宙学；相变?
- Higgs场自耦合，超对称
- 亚毫米额外维？膜宇宙？宇宙弦?
- Unknown?

Test of FP with LISA



Arun+， LRR (2022)25:4

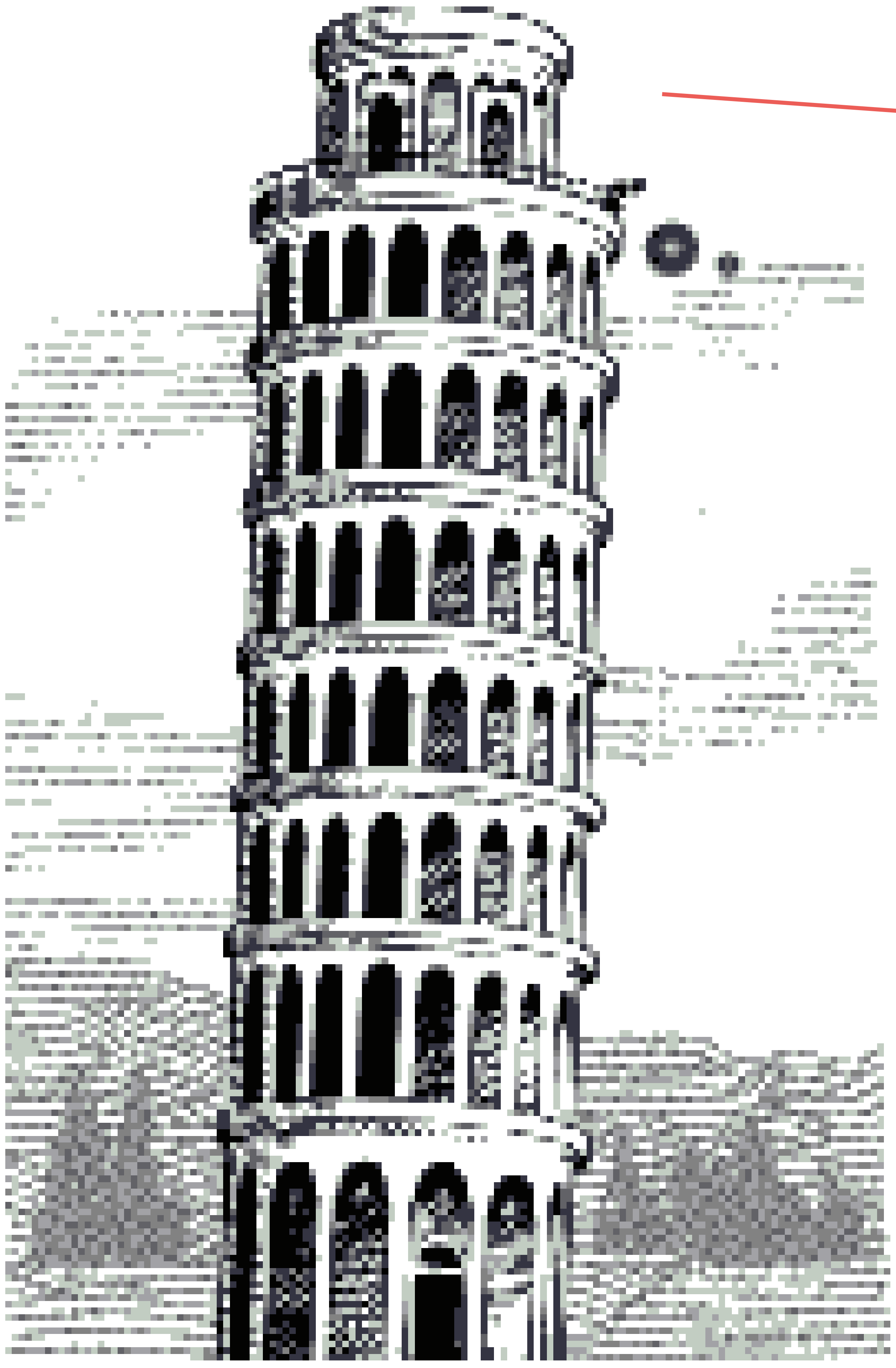
引力波检验引力理论 (GWs test GR)

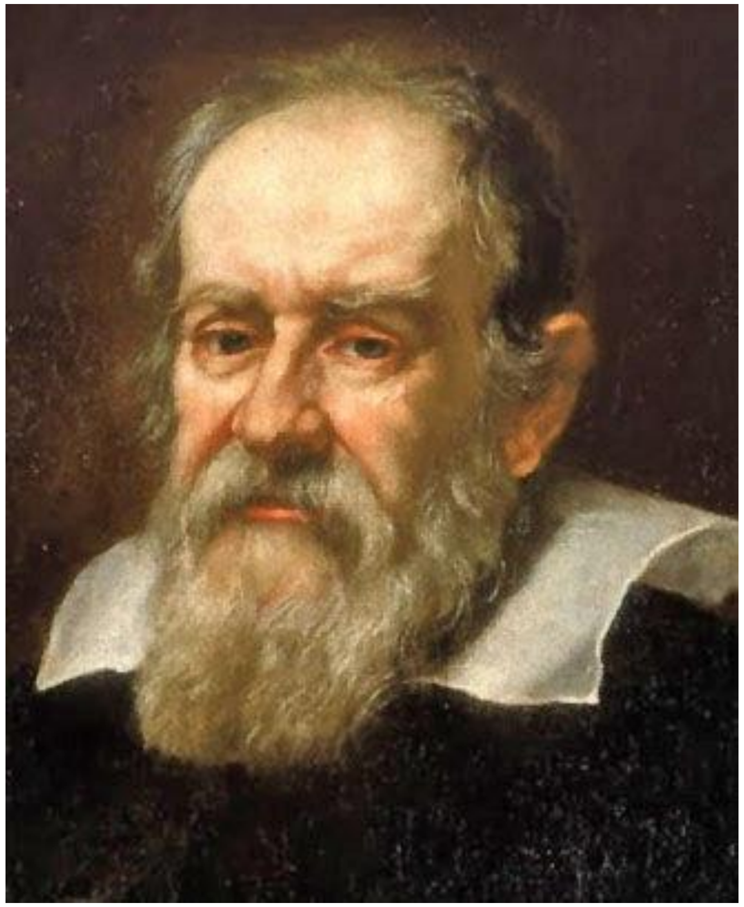
- 基本原理：WEP、LLI、LPI、EEP、SEP
- 引力波传播效应检验：WEP、dispersion
- 引力波偏振自由度检验 (GW polarization test)
- 多种引力理论检验（PPE test, quantum gravity…）
- 黑洞本质检验（no-hair theorem, ECO, horizon …）

引力波传播性质

- GR: gravitons are massless spin-2 particles
- Alternative theories: graviton may have mass (Will 1998, LVC, 2016b...)
- Dispersion: frequency, polarization, direction-dependent propagating velocities of GWs.
- Lorentz violation → additional polarizations → speed of extra polarizations may not c (Sotiriou 2018, Shao 2020)
- WEP violation: speed depends on frequency and gravity; Coupling with cosmology
- GW tests: gravition couplings and decays into other particle (Creminelli+2020) or oscillations (Hassan+2012): LISA\Taiji 3 order better than LIGO

WEP broken: GWs propagation related to frequencies





WEP: $m_{\mathrm{I}}/m_{\mathrm{G}} = \mathrm{Const.}$

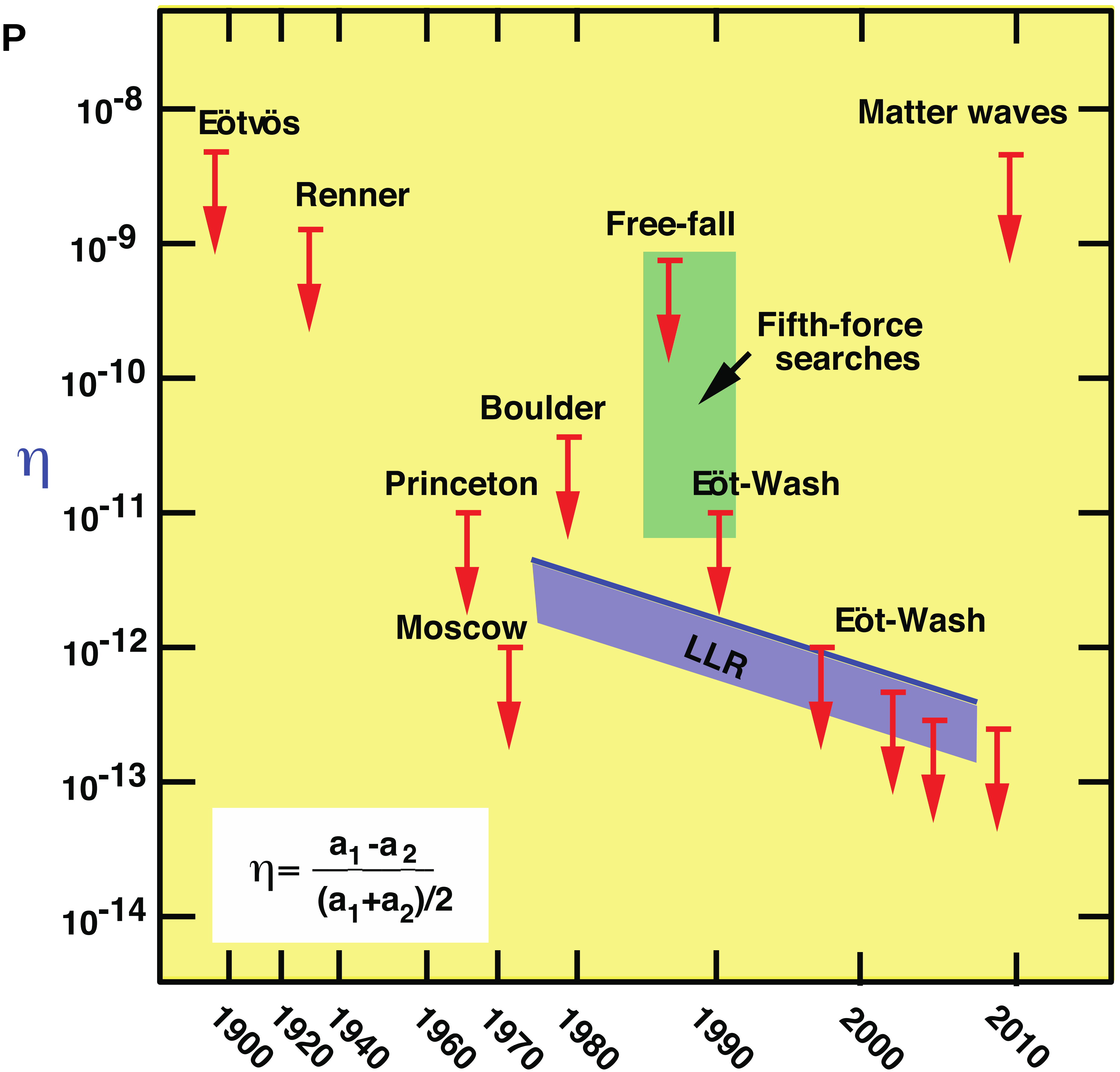
Curvature of spacetime

EP

- WEP. Dropping two different bodies in a gravitational field, WEP states that the bodies fall with the same acceleration.
- EEP： WEP + local Lorentz invariance (LLI) + local position invariance (LPI) ;
- SEP: WEP is valid for self-gravitating bodies + LLI + LPI including gravitational experiments.

通过自由落体实验检验WEP

$$m_{\mathrm{P}} = m_{\mathrm{I}} + \sum_A \frac{\eta^A E^A}{c^2}$$



Will 2014

Testing WEP with massless particles in cosmology

M. J. Longo, Phys. Rev. Lett. 60, 173 (1988).

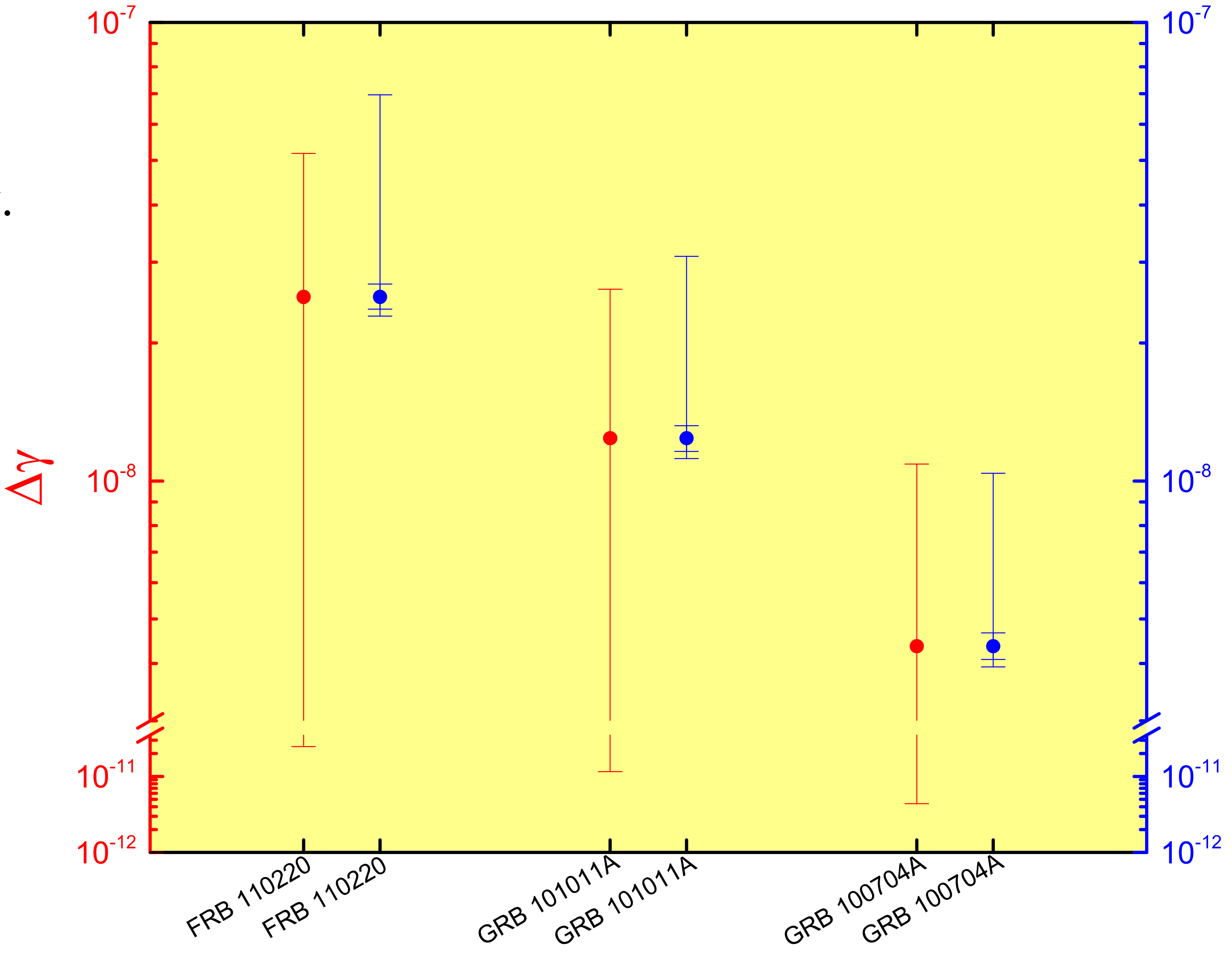
L. M. Krauss and S. Tremaine, Phys. Rev. Lett. 60, 176 (1988).

H. Gao, X.-F. Wu, and P. M´esz´aros, Astrophys. J. 810, 121 (2015).

Wu, X.-F. *et al. Phys. Rev. D* 94, 024061 (2016).

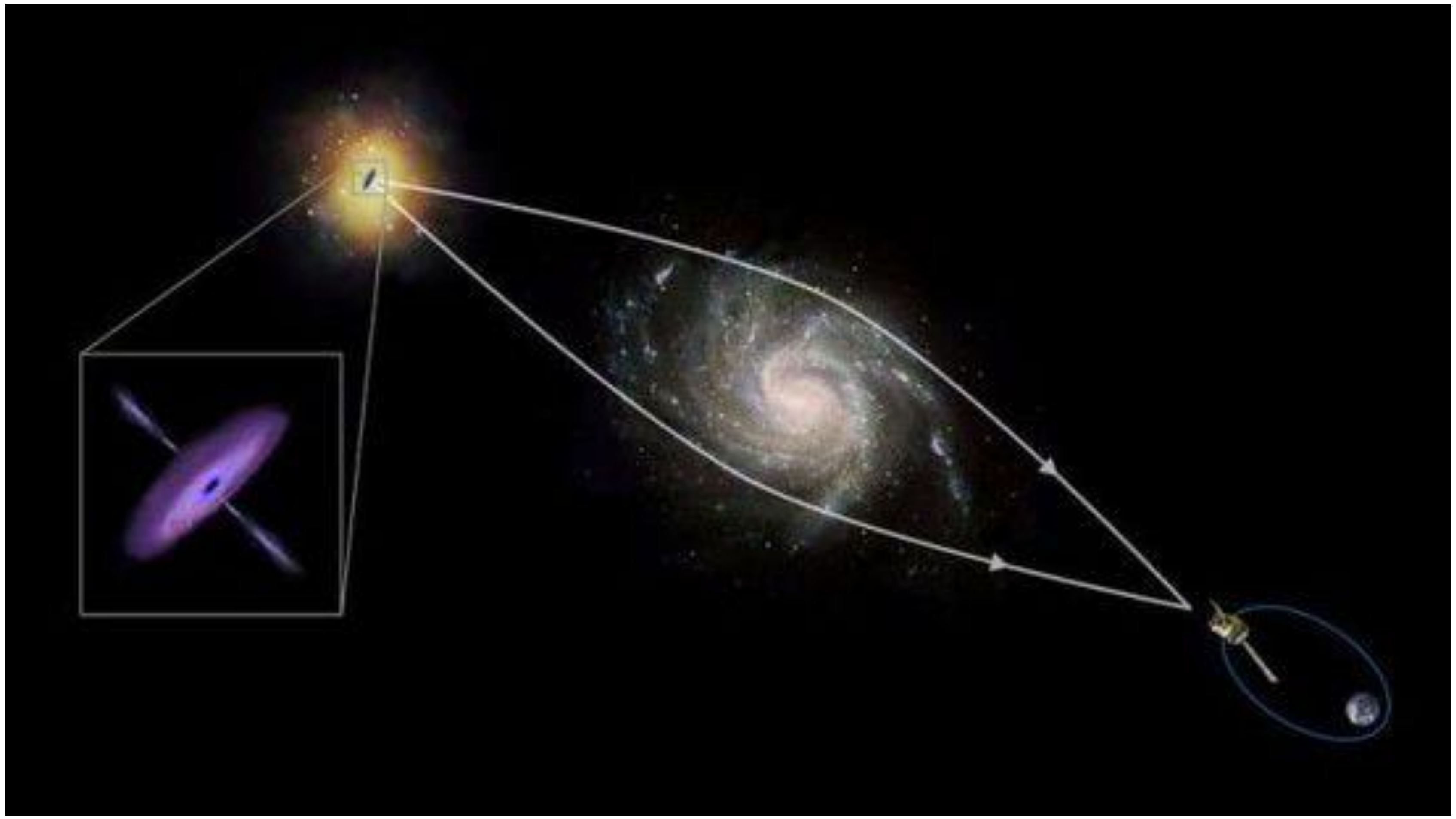
Wei,J.-J.,Wu,X.-F.,Gao,H.&Me´sza´ros,P.*J. Cosmol. Astropart. Phys* 2016, 031 (2016)

Wei, J.-J., Gao, H., Wu, X.-F. & Me´sza´ros, P. *Phys. Rev. Lett.* 115, 261101 (2015)



Wei, 2015

穿过银河系的自由落体实验



$$\Delta t_{gra} = \frac{\gamma_1 - \gamma_2}{c^3} \int_{r_o}^{r_e} U(r)dr$$

所有这些测试有一个简单但有缺陷的假设：把观测到的时延全部当成由弱等破坏导致的

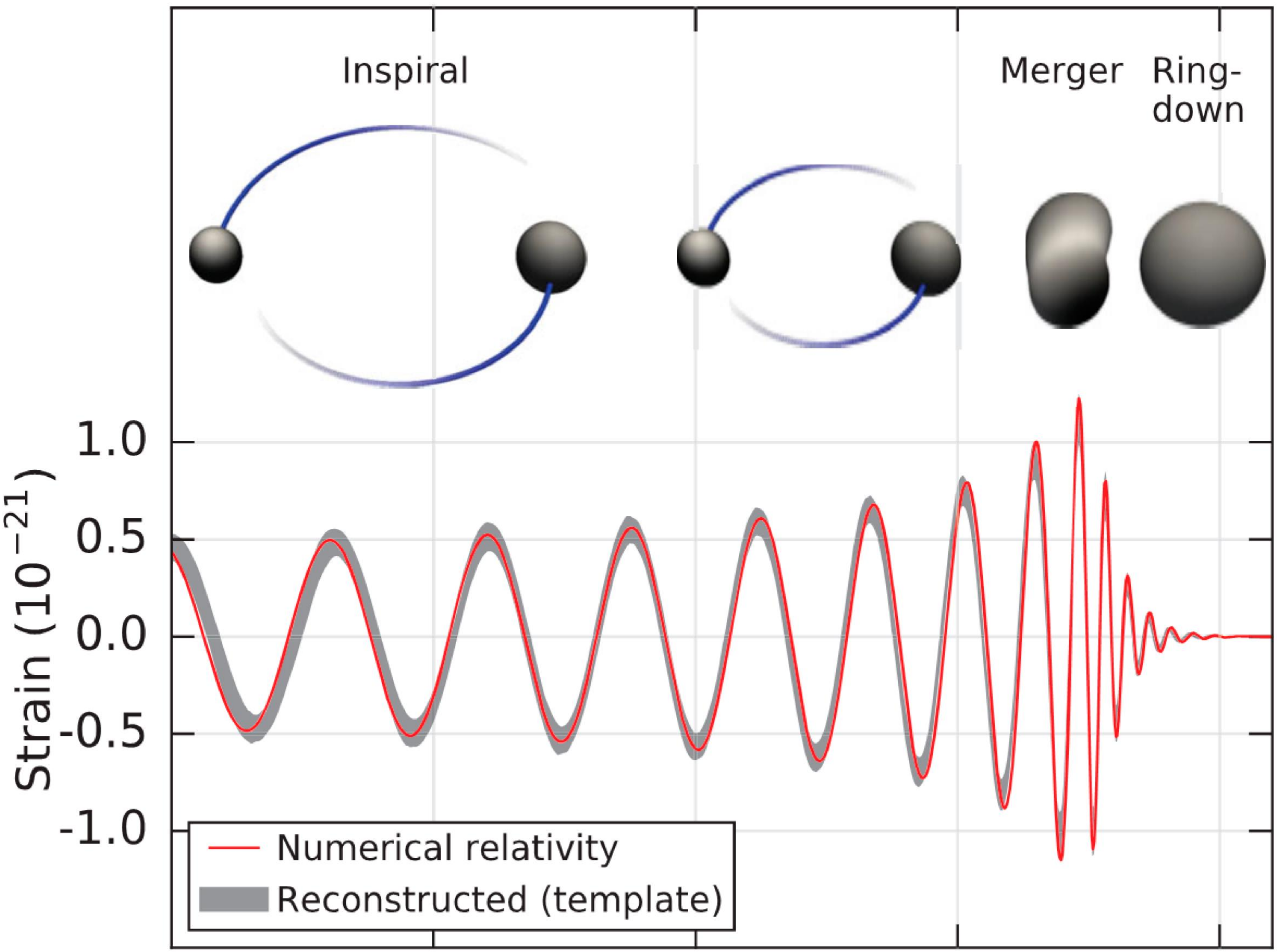
$$\gamma_1 - \gamma_2 < (\Delta t_{obs} - \Delta t_{DM}) \left(\frac{GM_{MW}}{c^3}\right)^{-1} \ln^{-1}\left(\frac{d}{b}\right)$$

比如把中微子和光子的时间差
不同频率光子的时间差
光子和引力波的时间差

或者引力波高频和低频的时间差

全部当成由弱等破坏造成

我们精确地知道引力波出发时的高频和低频时延！



WEP tests

$$u(f) \equiv A_{\mathrm{eff}}(f) e^{\mathrm{i}\Psi_{\mathrm{eff}}(f)}$$

$$\Psi_{\mathrm{eff}}(f) = 2\pi f t_0 + \varphi_0 + \sum_{k=0}^{7} \psi_k f^{(k-5)/3}$$

弱等效原理破坏导致的相位误差

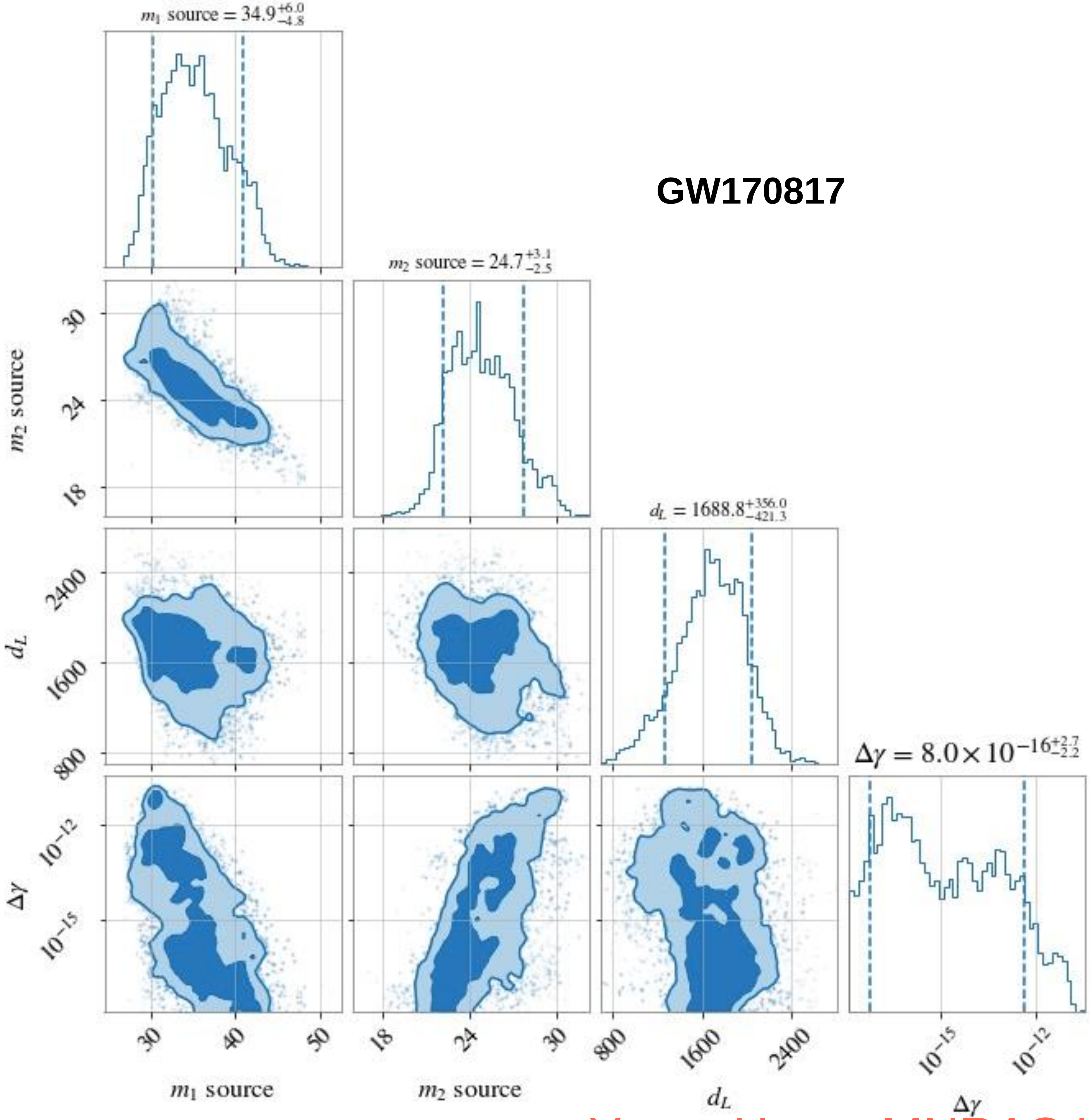
$$\delta\Psi = \pi\Delta\gamma(f_e - f_{e'})^{-1}\left(\frac{GM_{\mathrm{MW}}}{c^3}\ln\left(\frac{\left[d' + (d'^2 - b^2)^{1/2}\right]\left[r_G + s_n\left(r_G^2 - b^2\right)^{1/2}\right]}{b^2}\right)\right)(1+z)^2 f^2$$

Using 10 BBH events in the LIGO-Virgo catalog

		FAR $[\mathrm{y}^{-1}]$			
Event	UTC time	PyCBC	GstLAL	cWB	PyCBC
GW150914	09:50:45.4	$<1.53 \times 10^{-5}$	$<1.00 \times 10^{-7}$	$<1.63 \times 10^{-4}$	23.6
GW151012	09:54:43.4	0.17	7.92×10^{-3}	...	9.5
GW151226	03:38:53.6	$<1.69 \times 10^{-5}$	$<1.00 \times 10^{-7}$	0.02	13.1
GW170104	10:11:58.6	$<1.37 \times 10^{-5}$	$<1.00 \times 10^{-7}$	2.91×10^{-4}	13.0
GW170608	02:01:16.5	$<3.09 \times 10^{-4}$	$<1.00 \times 10^{-7}$	1.44×10^{-4}	15.4
GW170729	18:56:29.3	1.36	0.18	0.02	9.8
GW170809	08:28:21.8	1.45×10^{-4}	$<1.00 \times 10^{-7}$	...	12.2
GW170814	10:30:43.5	$<1.25 \times 10^{-5}$	$<1.00 \times 10^{-7}$	$<2.08 \times 10^{-4}$	16.3
GW170817	12:41:04.4	$<1.25 \times 10^{-5}$	$<1.00 \times 10^{-7}$	...	30.9
GW170818	02:25:09.1	...	4.20×10^{-5}	...	...
GW170823	13:13:58.5	$<3.29 \times 10^{-5}$	$<1.00 \times 10^{-7}$	2.14×10^{-3}	11.1

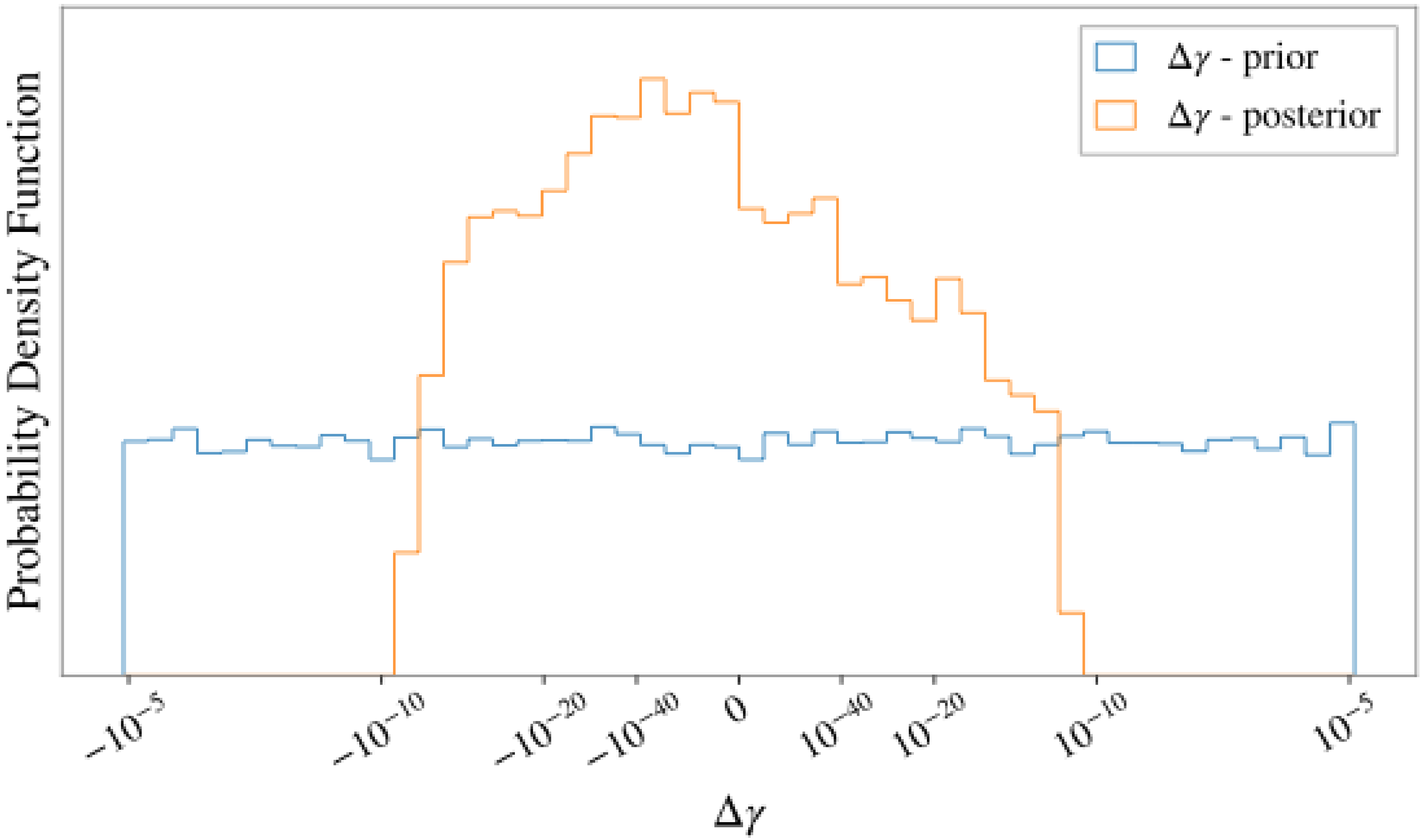
Tools: PYCBC, Bilby

GW170817



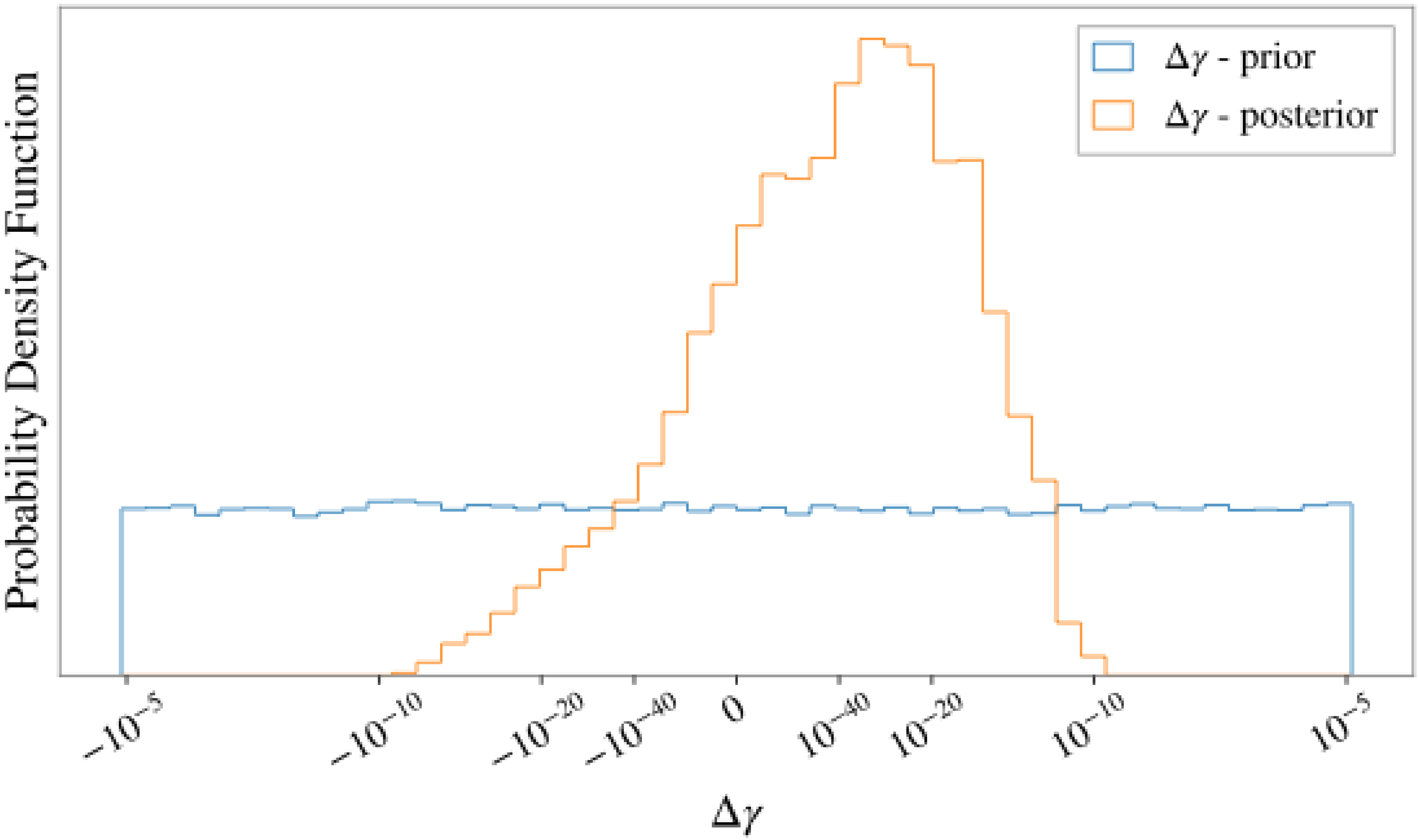
Yang, Han + MNRAS Lett. 2020

GW170823



Yang, Han & Wang MNRAS Lett. 2020

GW170104



Yang, Han & Wang MNRAS Lett. 2020

GW dispersion: propagation effect on GW phase

引力子有质量

$$E^2 = p^2 c^2 + m_g^2 c^4 + A p^{\alpha} c^{\alpha}$$

色散：不同频率引力波传播速度不同！ Mirshekari **+2012**

$$\frac{v_g^2}{c^2} = 1 - \frac{m_g^2 c^4}{E^2} - A E^{\alpha - 2} \left(\frac{v_g}{c}\right)^{\alpha}$$

和宇宙学参数耦合： Barausse+ 2020; Ezquiaga+ 2018, 2021; Creminelli+2020

$$\ddot{h}_{ij}(\mathbf{k},\mathbf{t}) + [\mathbf{3H}(\mathbf{t}) + \Gamma(\mathbf{k},\mathbf{t})]\mathbf{h_{ij}}(\mathbf{k},\mathbf{t}) + \left[\mathbf{c_T^2}(\mathbf{t})\mathbf{k^2} + \mathbf{D}(\mathbf{k},\mathbf{t})\right]\mathbf{h_{ij}}(\mathbf{k},\mathbf{t}) = \mathbf{0}$$

Habble const. **damping of amp.** **Speed of GW** **dispersion relation**

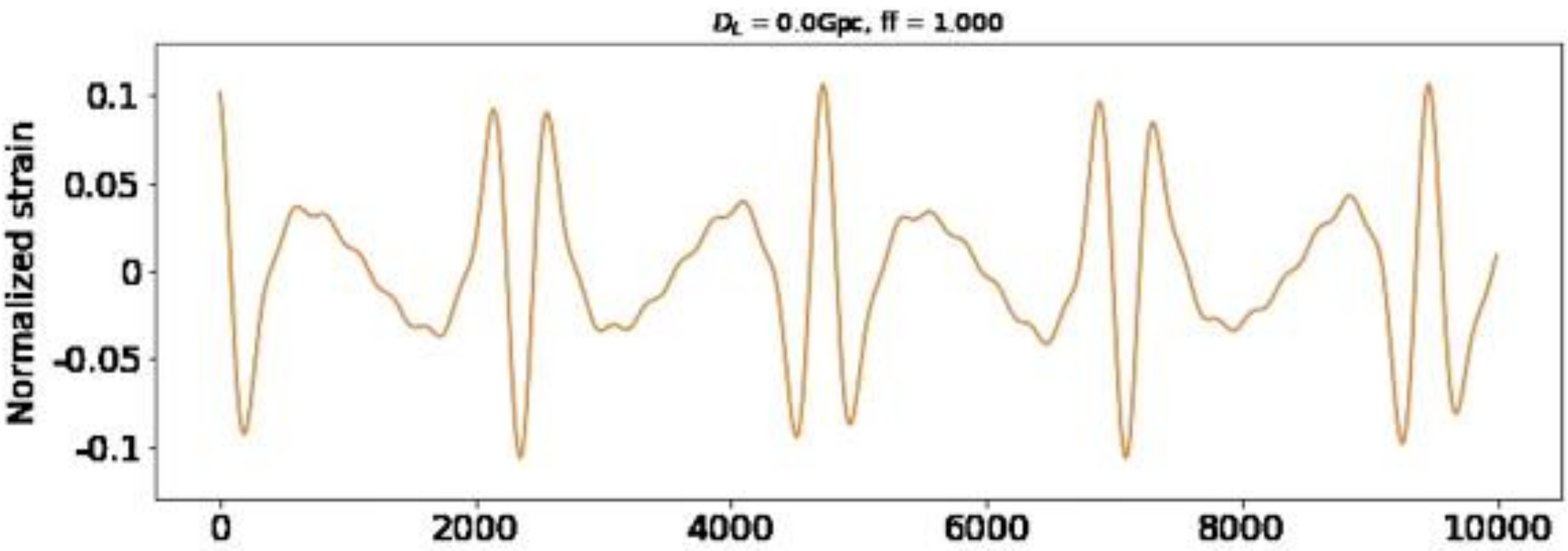
LIGO: using BBHs, for one signal, the speed of later stage than earlier

For space-borne detectors: using EMRIs

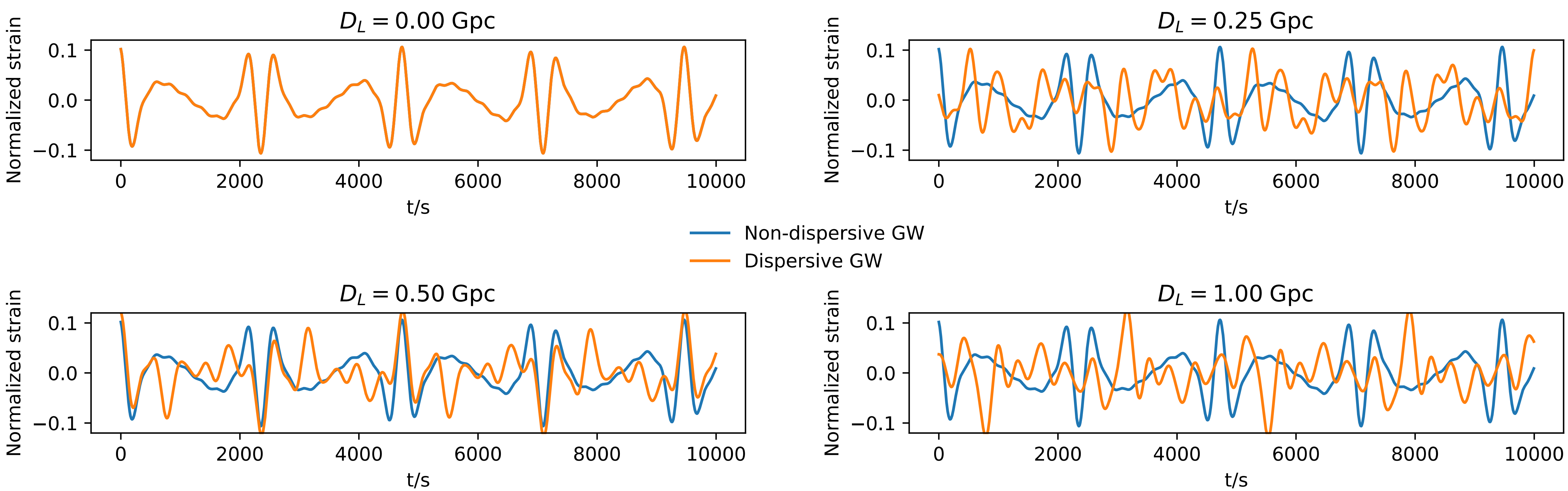
EMRIs can radiate many voices with different frequency at the same time:
If the speed of different voices are different, then

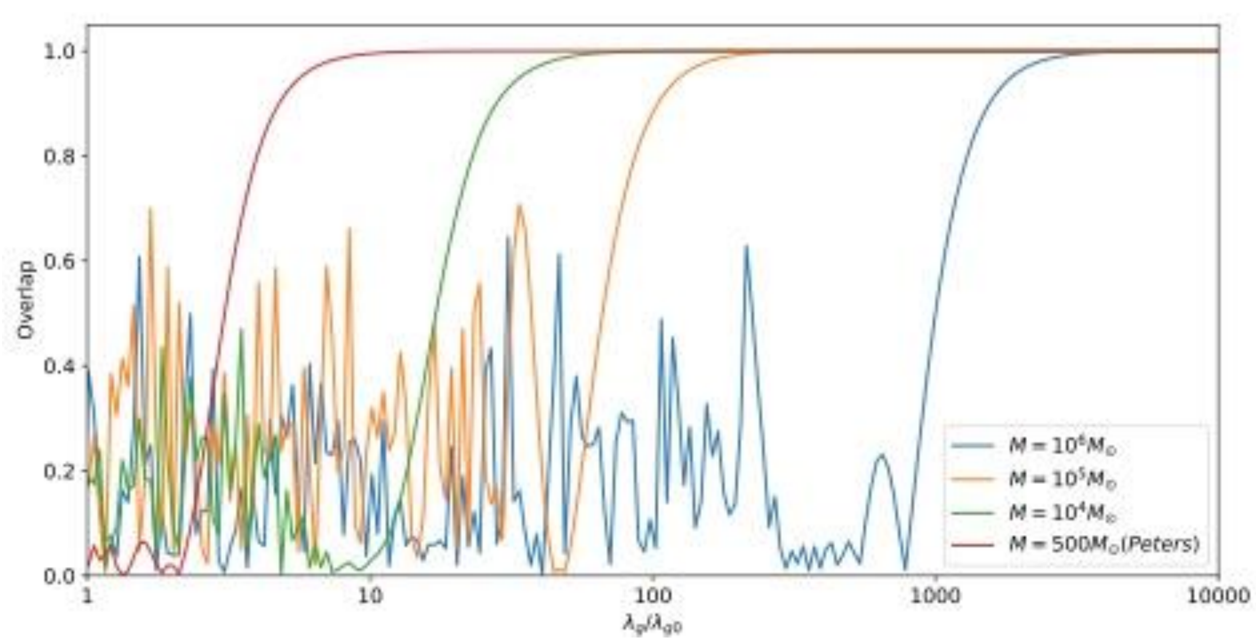
$$h_+ - i h_\times = \frac{2}{R}\sum_{lmk} \frac{Z^{H}_{lmk}}{\omega^2_{mk}} \, {}_{-2}S^{a\omega}_{lmk}(\Theta)\, e^{-i\varphi_{mk} + im\Phi + i\omega_{mk}\Delta t^{mk}_{a}}$$

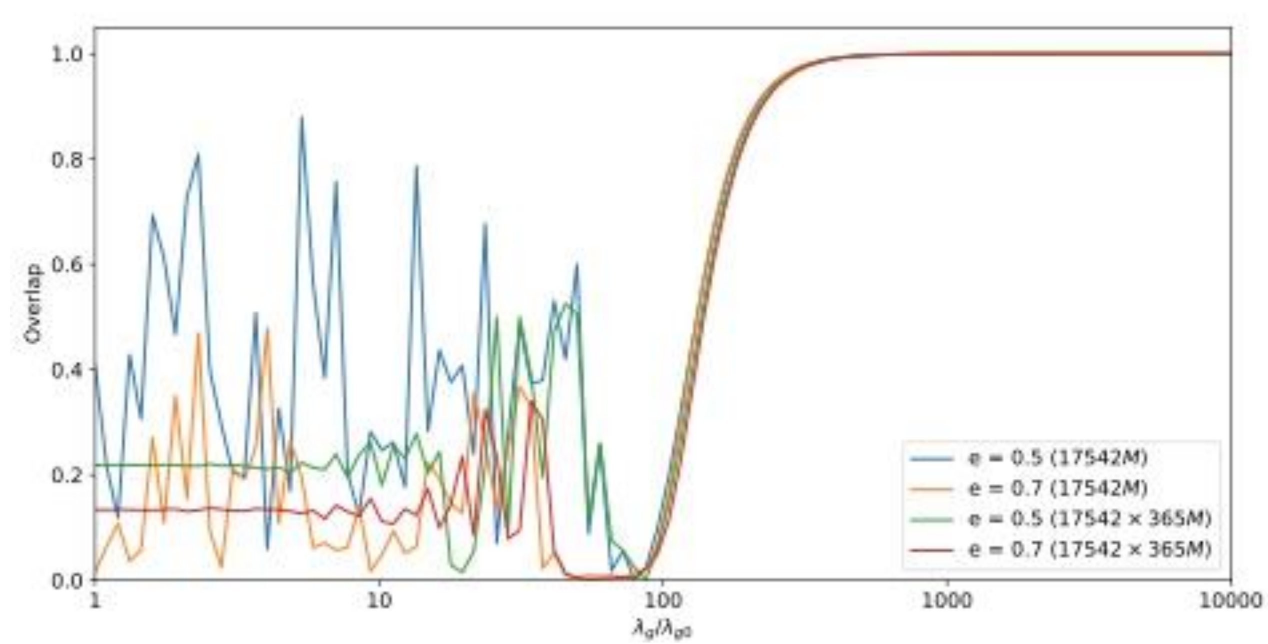
$$\Delta t_{a} = (1+Z)\frac{D_0}{2\lambda_g^2}\left(\frac{1}{f_e^2}-\frac{1}{f_e'^2}\right)$$



Testing GW dispersion with EMRI



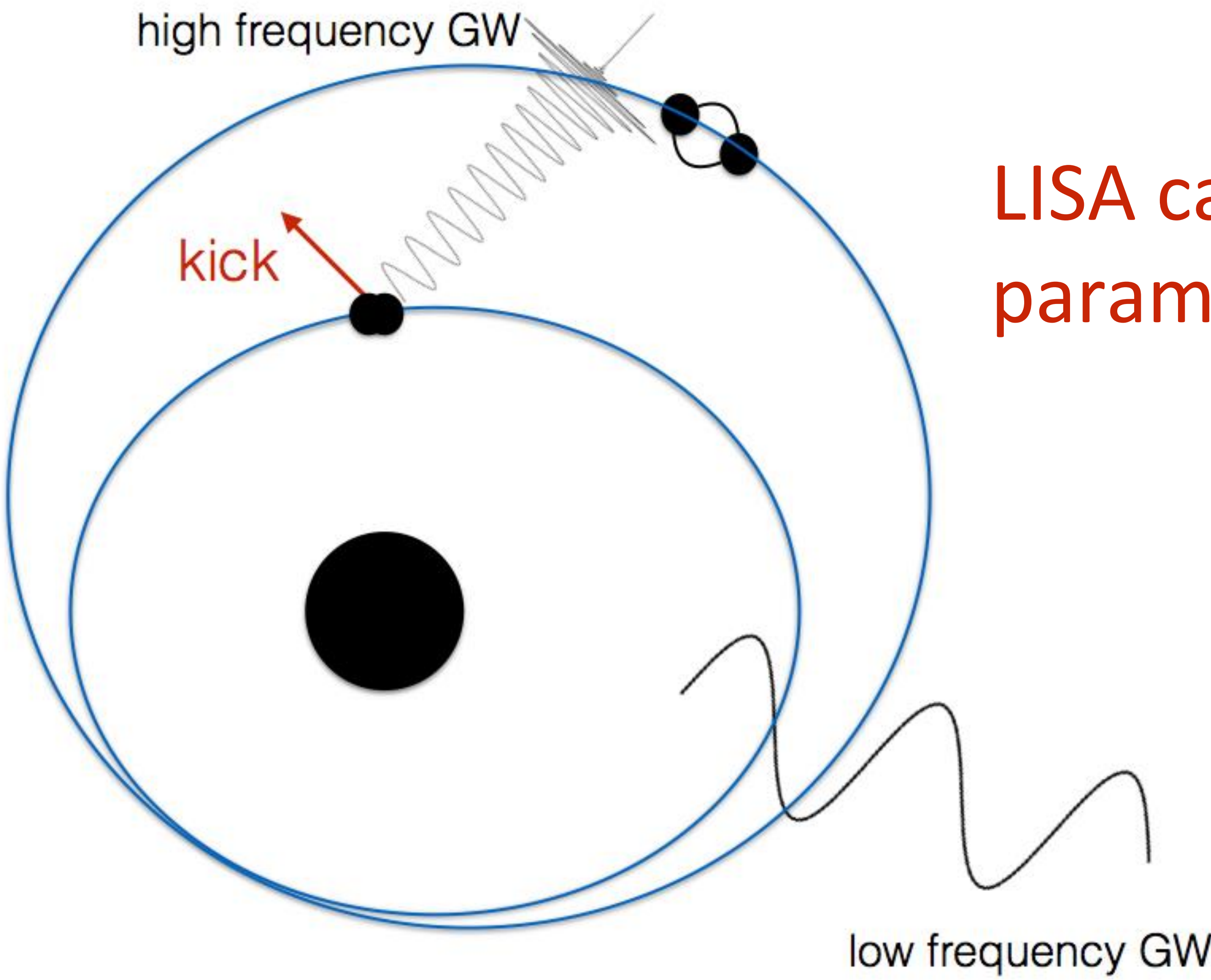




比LIGO当前结果提高2-3个量级！

Yang + 2019

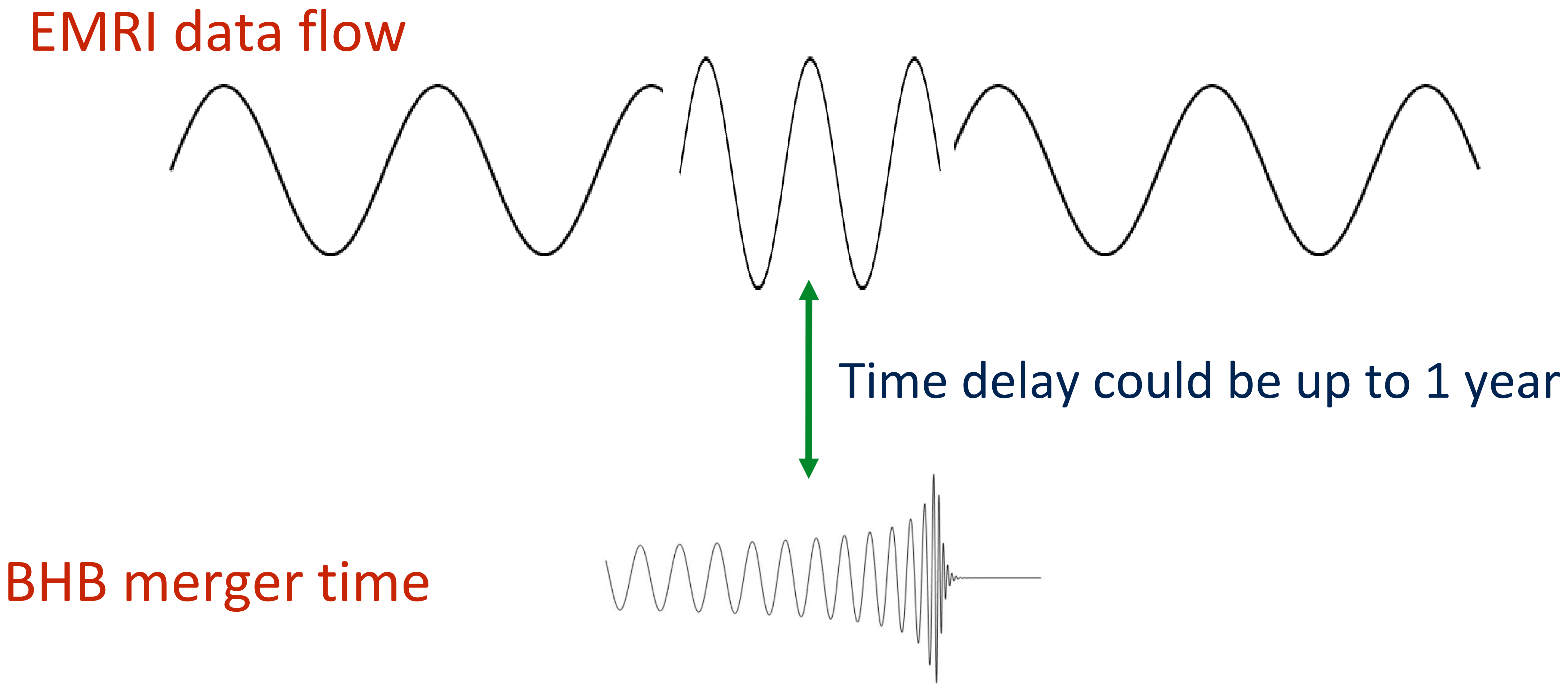
b-EMRI can confirm or rule out GW dispersion



LISA can determine the orbital parameters of EMRIs ~ 0.1%

Chen, Han, Com. Phys. 2018

Han & Chen MNRAS Lett, 2019

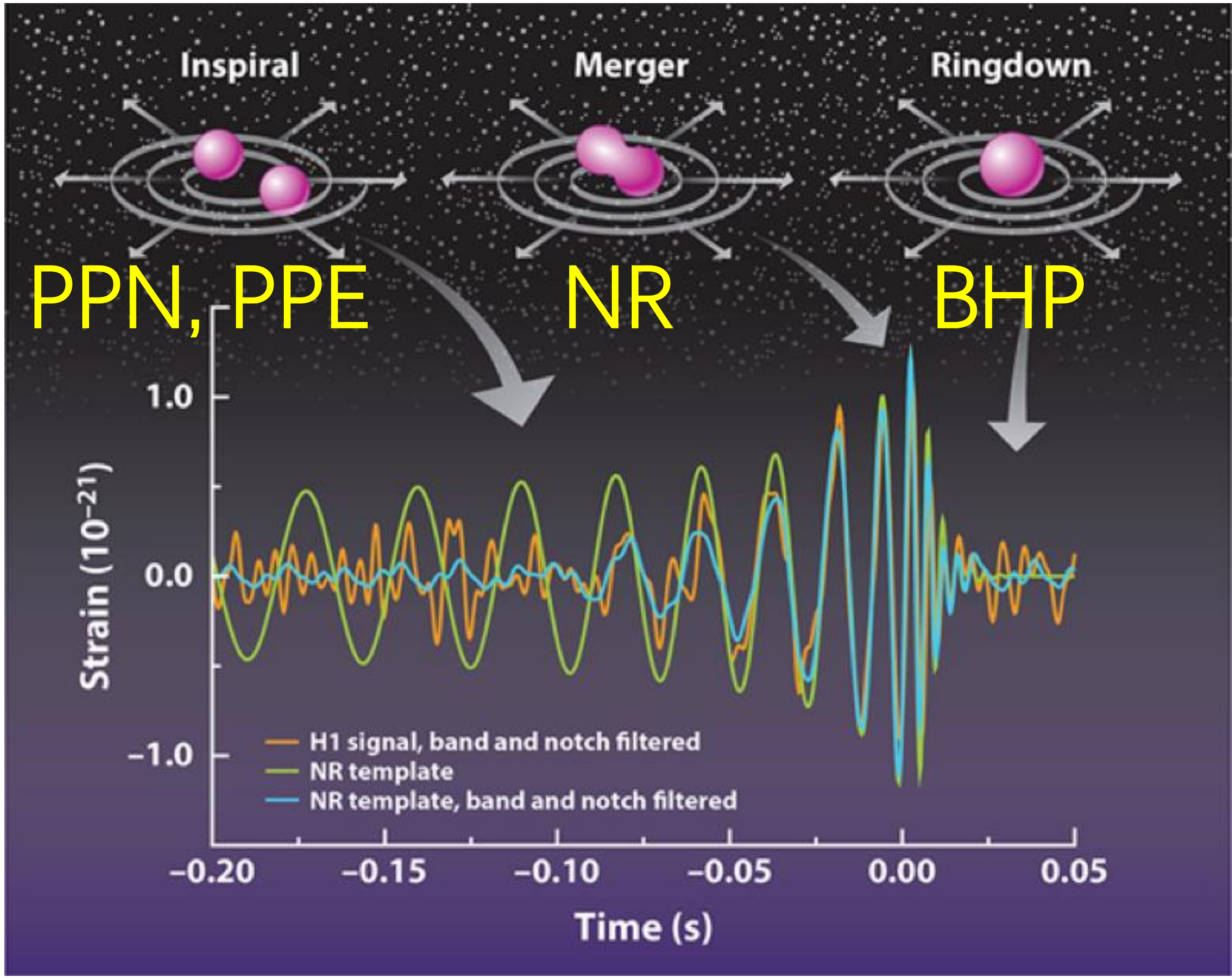


Han & Chen MNRAS Lett, 2019

Test GR with BHB GW radiation

Inspiral:
1,accurate measure PPN (Will 2014), PPE parameters (Yunes 2009);
2, scalar dipole radiation, Lorentz symmetry, gravition mass, several order better than LIGO (Chamberlain 2017)
3, combining with LIGO, Taiji can accurate predict the BHB merger time, comparing with LIGO results will have 6 order better of dipole radiation constraint (Barausse 2016)

Ringdown:
No-hair theorem tests, need parametrized waveforms! (Li, Han+ 2020, 2022)



For merge: still challenge
Highly non-linear, dynamical process
need No-GR numerical relativity

Test of GW polarizations with joint detectors

10 EARDLEY, I

ıl identities that Riem obeys. There are six
ʒebraically independent components of Riem :
.cuum (Sec. III proves this assertion and suc-
eding ones), which correspond to six modes c
larization. In a given, nearly Lorentz coord
te frame of the above type, we group these si
mponents into amplitudes of definite helicity
here $s = 0, \pm 1, \pm 2)$ under rotations about the
ıxis. There arise two real amplitudes

$$\Psi_2(u) \quad (s=0), \quad \Phi_{22}(u) \quad (s=0),$$

d two complex amplitudes

$$\Psi_3(u) \quad (s=\pm 1), \quad \Psi_4(u) \quad (s=\pm 2).$$

ɜre and throughout this paper one complex am
ıtude is equivalent to two real amplitudes. W
ll always describe a gravitational wave by its

Event	$\log_{10} \mathcal{B}_V^T$	$\log_{10} \mathcal{B}_S^T$
GW170809	0.078	0.421
GW170814	−0.032	0.740
GW170818	0.002	0.344
GW190408_181802	0.076	0.480
GW190412	0.079	0.539
GW190503_185404	−0.072	1.245
GW190512_180714	−0.024	0.346
GW190513_205428	0.139	1.380
GW190517_055101	0.008	0.730
GW190519_153544	0.067	0.799
GW190521	0.093	1.156
GW190602_175927	−0.064	0.373
GW190706_222641	0.052	0.771
GW190720_000836	0.034	0.074
GW190727_060333	0.087	1.024
GW190728_064510	−0.024	0.083
GW190828_063405	0.063	0.851
GW190828_065509	−0.034	0.084
GW190915_235702	0.020	1.238
GW190924_021846	−0.051	0.384

LVC,2020

Better test on polarization with KAGRA

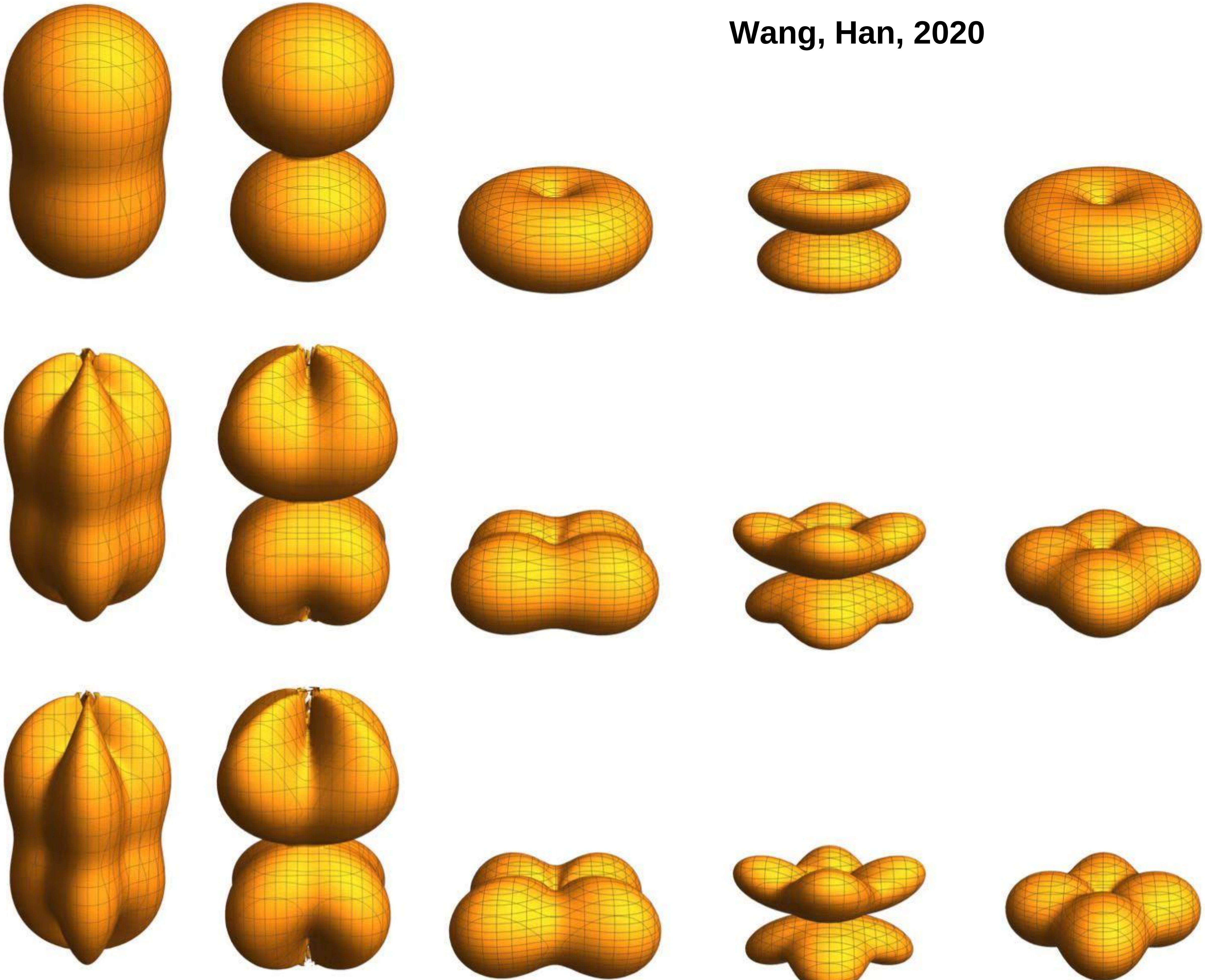
Prog. Theor. Exp. Phys. **2015**, 00000 (73 pages)
DOI: 10.1093/ptep/0000000000

KAGRA Collaboration

Overview of KAGRA : KAGRA science

T. Akutsu[1,2], M. Ando[3,4,1], K. Arai[5], Y. Arai[5], S. Araki[6], A. Araya[7], N. Aritomi[3], H. Asada[8], Y. Aso[9,10], S. Bae[11], Y. Bae[12], L. Baiotti[13], R. Bajpai[14], M. A. Barton[1], K. Cannon[4], Z. Cao[15], E. Capocasa[1], M. Chan[16], C. Chen[17,18], K. Chen[19], Y. Chen[18], C-Y Chiang[20], H. Chu[19], Y-K. Chu[20], S. Eguchi[16], Y. Enomoto[3], R. Flaminio[21,1], Y. Fujii[22], F. Fujikawa[23], M. Fukunaga[5], M. Fukushima[1], D. Gao[24], G. Ge[24], S. Ha[25], A. Hagiwara[5,26], S. Haino[20], W.-B. Han[27], K. Hasegawa[5],

Wang, Han, 2020

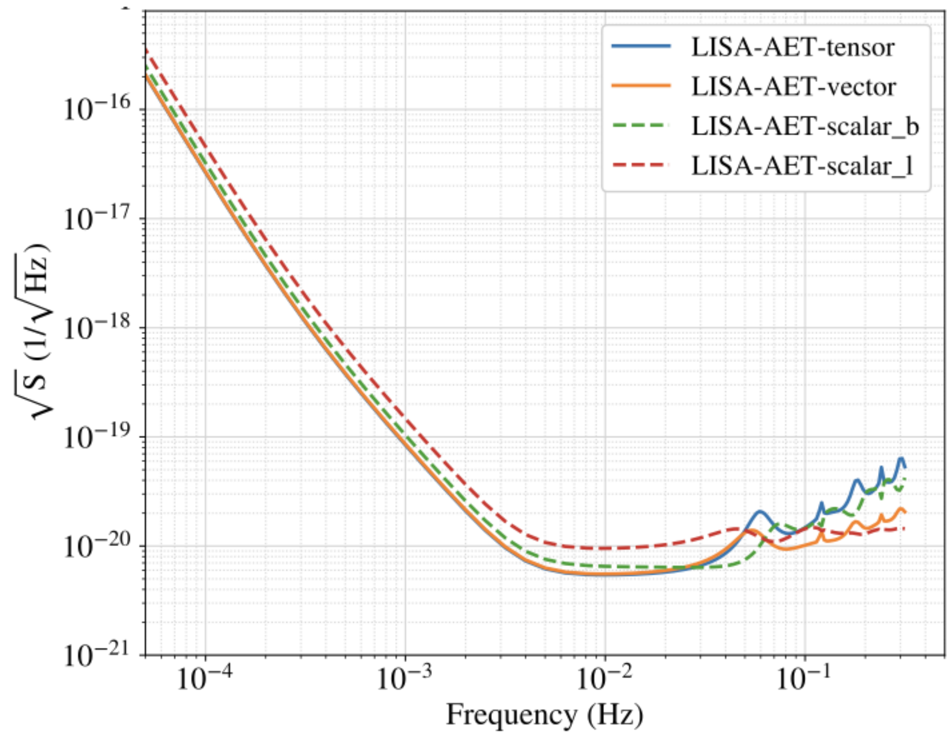


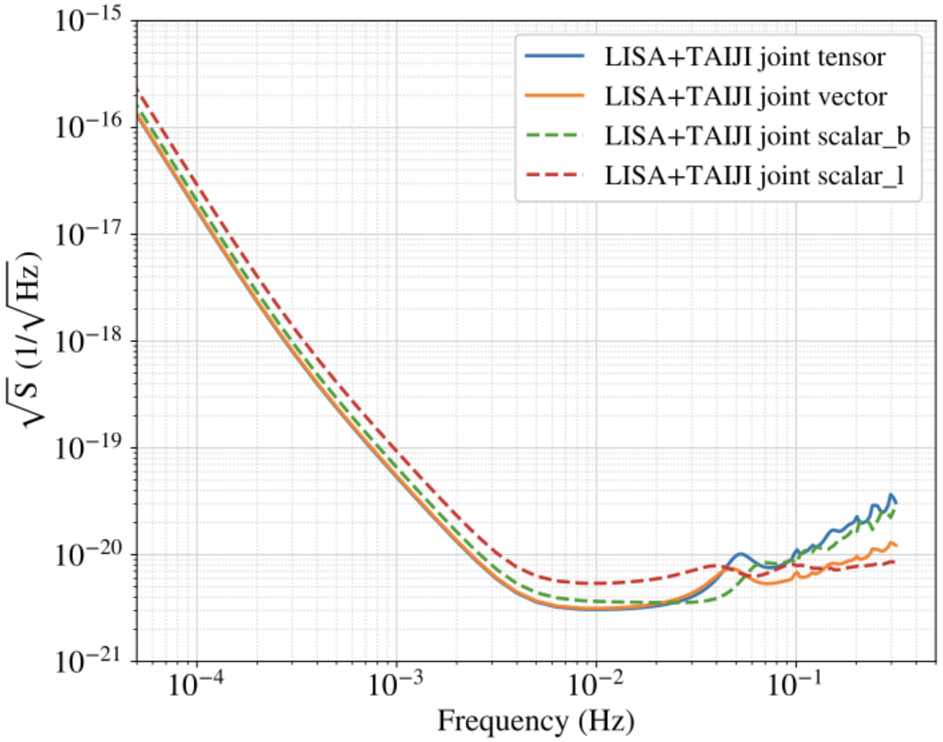
Test of GW polarizations and PPE with Taiji-Lisa

$$h(t) = F_+ h_+ + F_\times h_\times + F_{\rm x} h_{\rm x} + F_{\rm y} h_{\rm y} + F_{\rm b} h_{\rm b} + F_{\rm L} h_{\rm L}$$

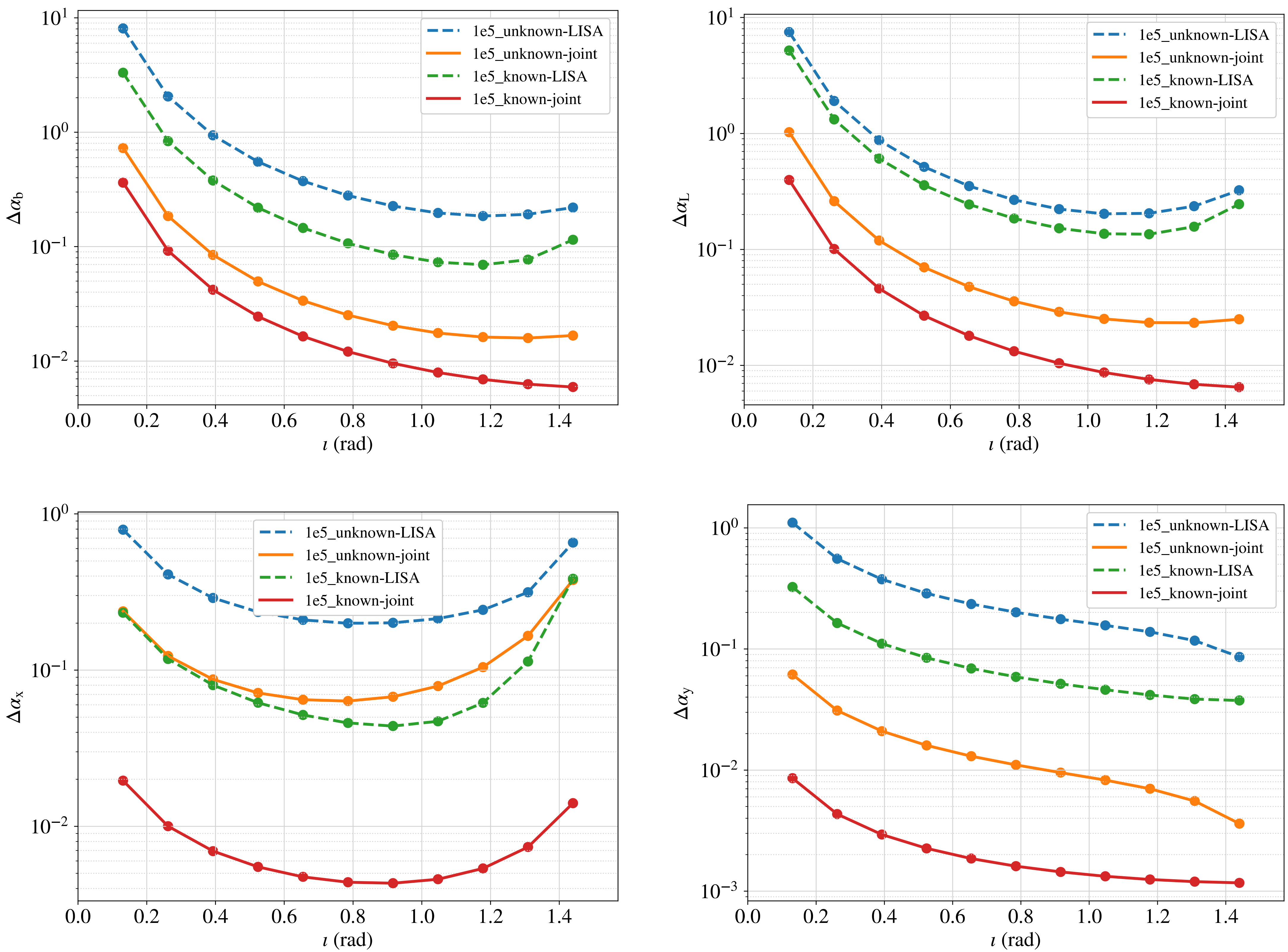
$$\begin{aligned}\tilde{h}_{\rm ppE}(f) = & \tilde{h}_{\rm GR}\left(1 + c\beta u_2^{b+5}\right) e^{2i\beta u_2^b} + \left[\alpha_{\rm b} F_{\rm b} \sin^2\iota \right. \\ & \left. + \alpha_{\rm L} F_{\rm L} \sin^2\iota + \alpha_{\rm x} F_{\rm x} \sin 2\iota + \alpha_{\rm y} F_{\rm y} \sin\iota\right] \\ & \times \frac{\mathcal{M}^2}{D} u_2^{-7/2} e^{-i\Psi_{\rm GR}^{(2)}} e^{2i\beta u_2^b},\end{aligned}$$

$$\begin{aligned}\tilde{h}_{\rm ppE,TDI}(f) = & \left[(F_+ + F_\times)(1 + c\beta u_2^{b+5}) + \alpha_{\rm b} F_{\rm b} + \alpha_{\rm L} F_{\rm L} \right. \\ & \left. + \alpha_{\rm x} F_{\rm x} + \alpha_{\rm y} F_{\rm y}\right] \tilde{h}_{\rm GR}\ e^{2i\beta u_2^b},\end{aligned}$$

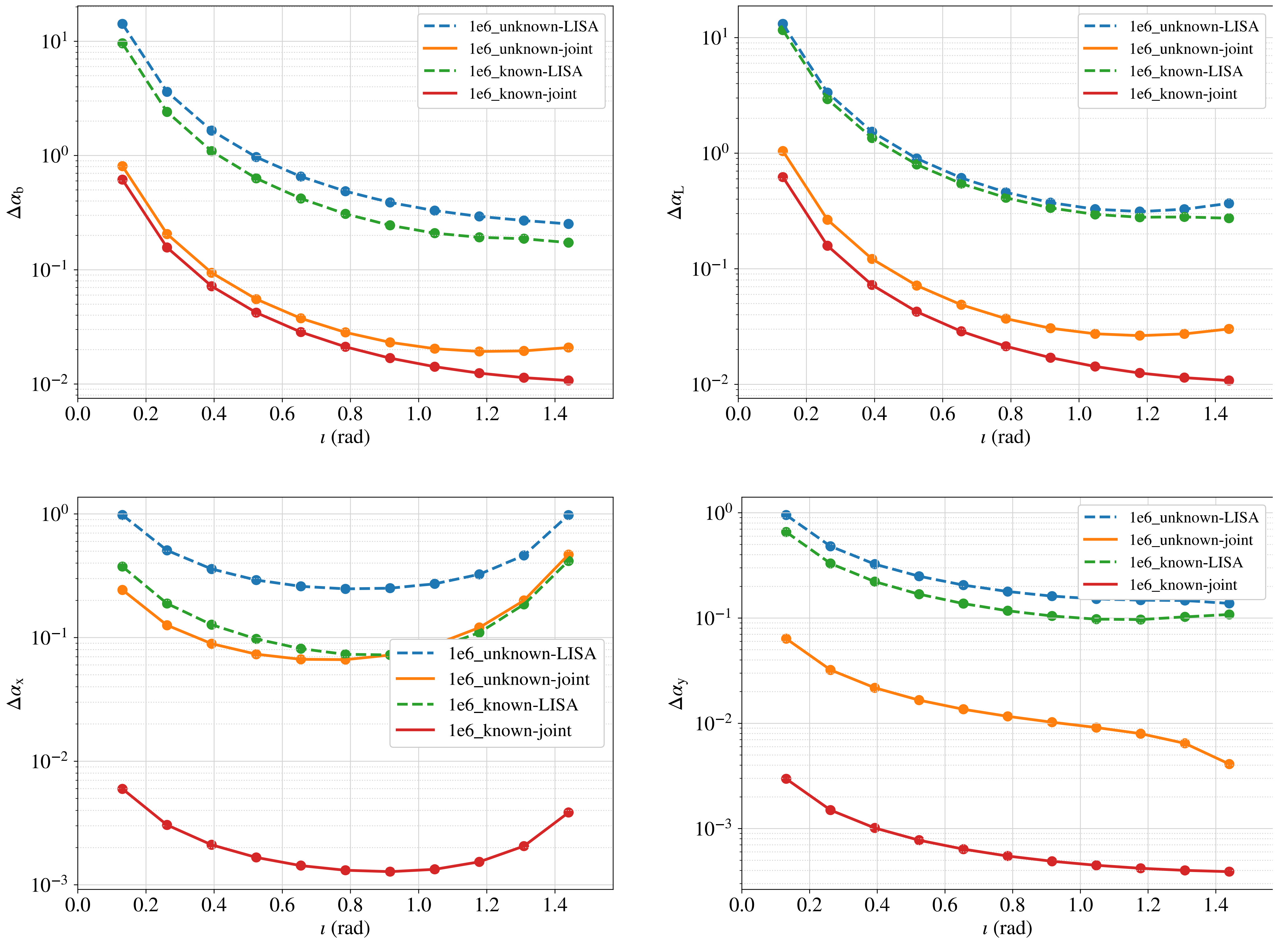




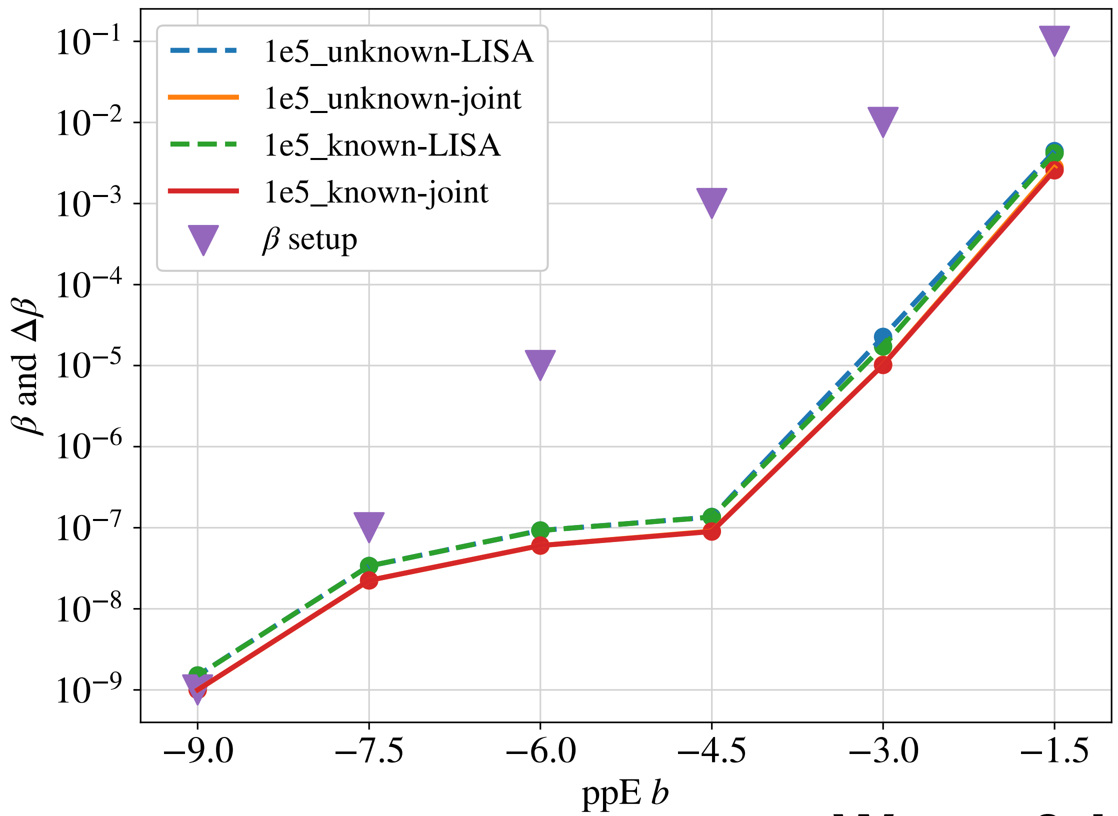
Test of GW polarizations and PPE with Taiji-Lisa

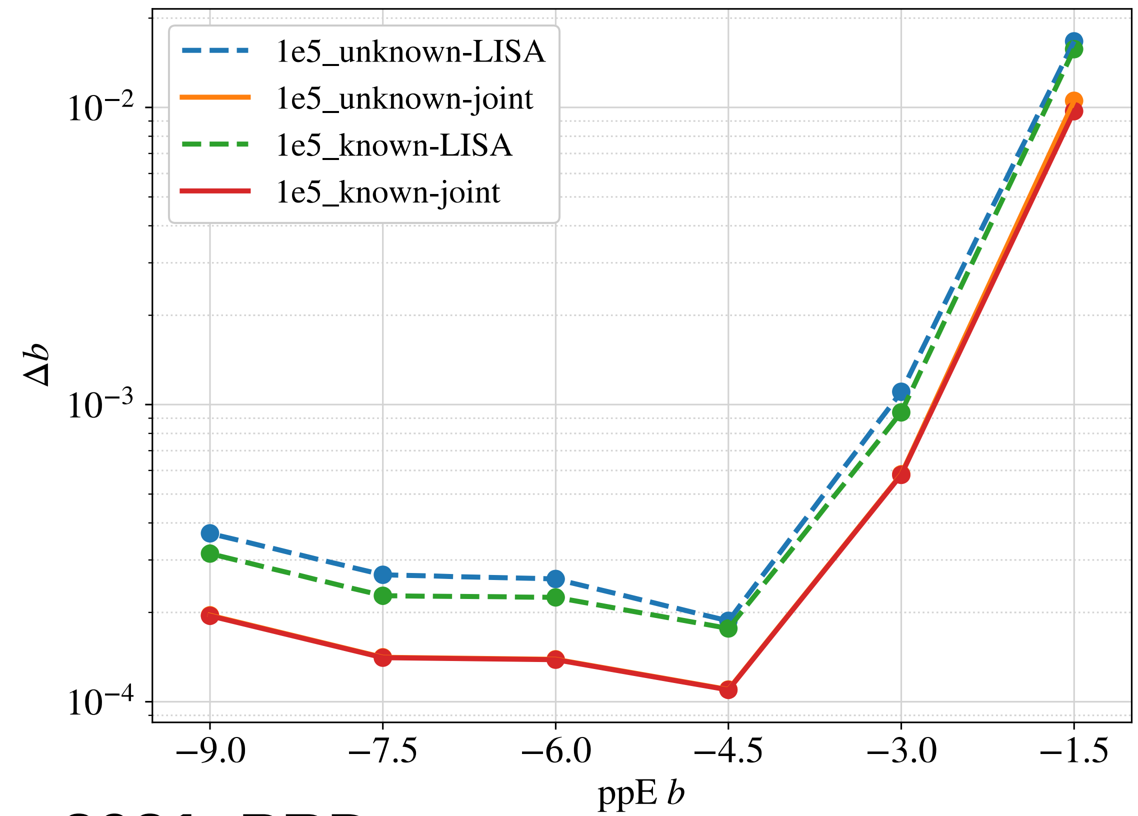


Test of GW polarizations and PPE with Taiji-Lisa

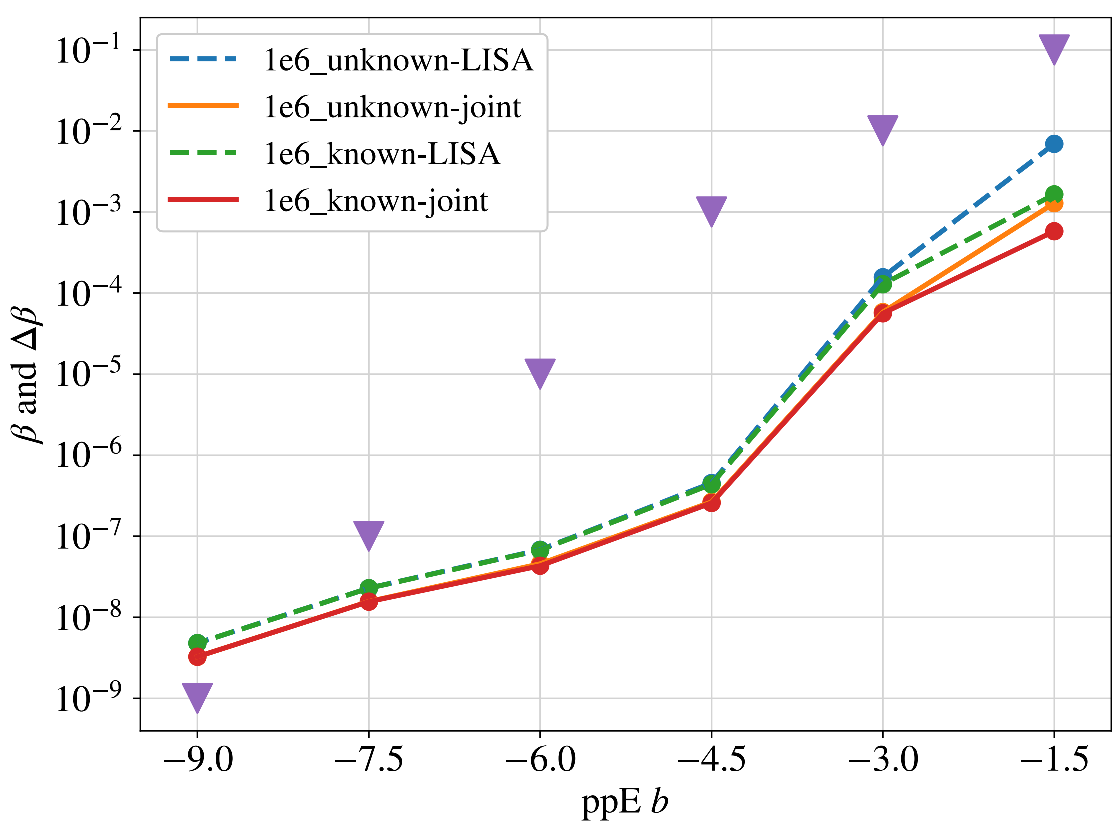


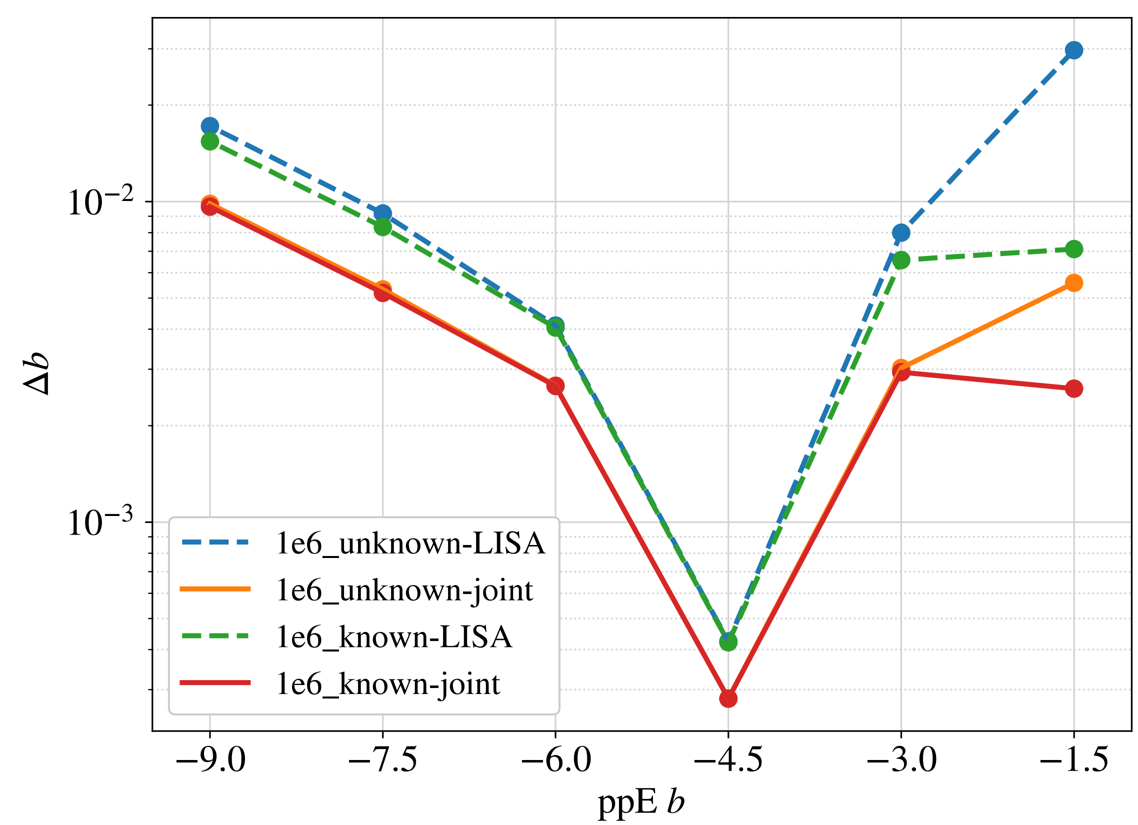
Test of GW polarizations and PPE with Taiji-Lisa





Wang & Han, 2021, PRD



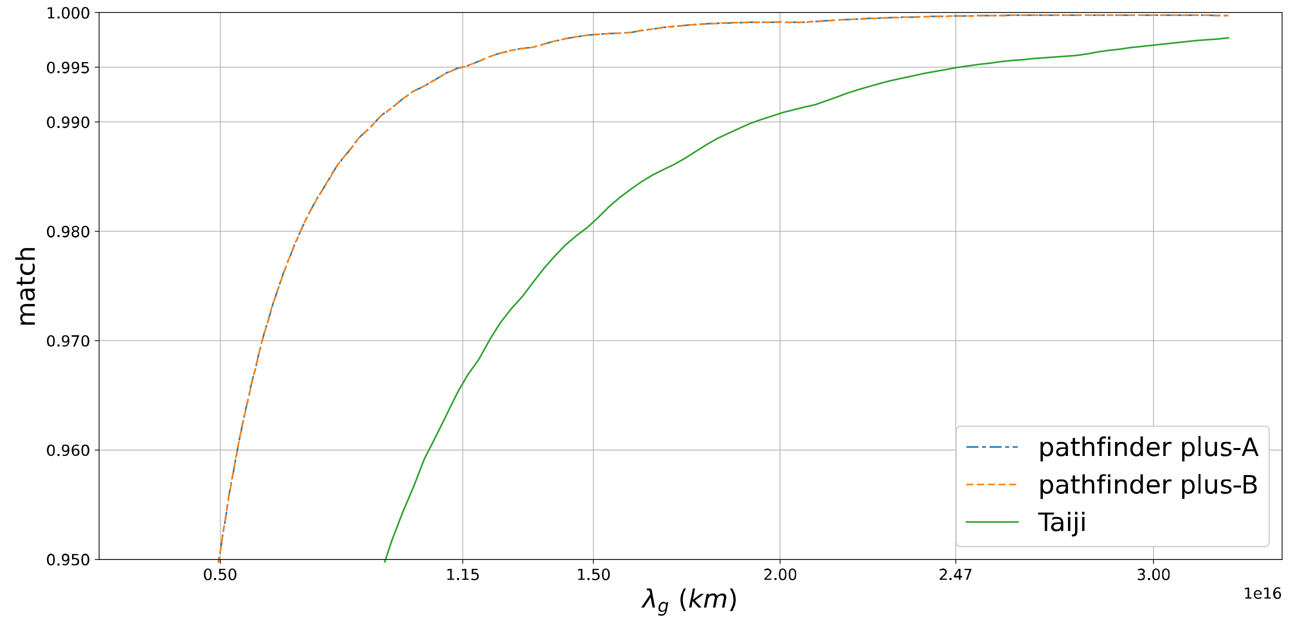


Test GR with SMBHB by Taiji/LISA

1, GW dispersion

$$\Psi(f) = \Psi_{GR}(f) + \delta\Psi(f)$$

Two orders better than
LIGO current results



2, PPE and polarization tests

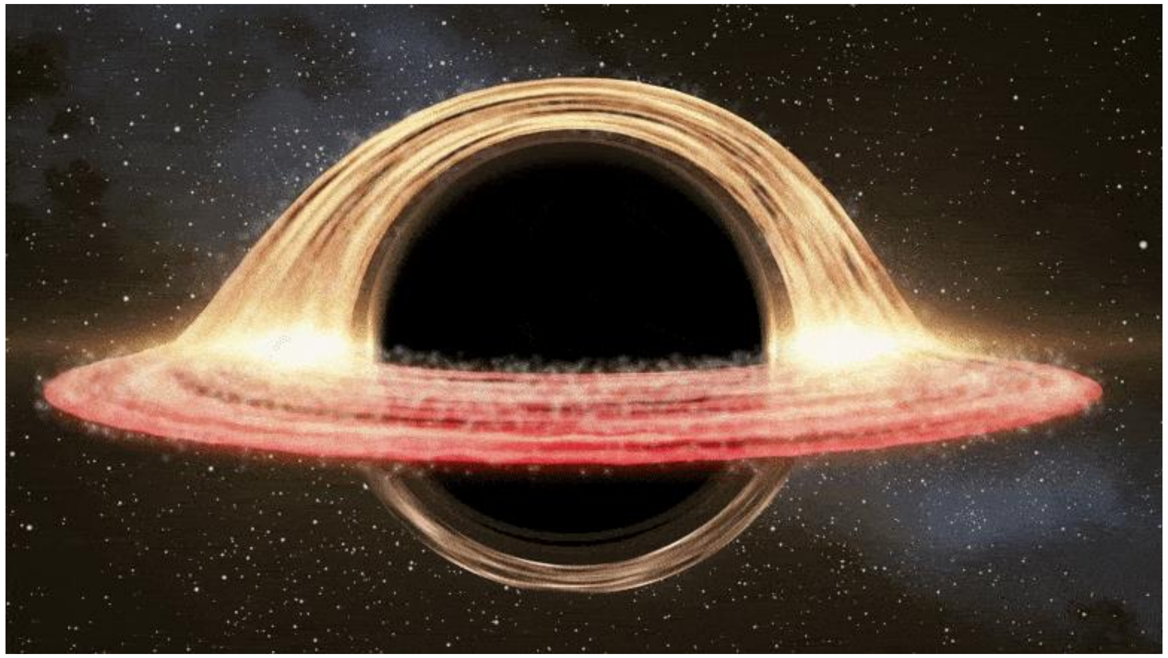
$$\tilde{h}_{\rm ppE} = \tilde{h}_{\rm GR}(1 + c\beta u_2^{b+5}) e^{2i\beta u_2^b} + [\alpha_b F_b \sin^2\iota + \alpha_L F_L \sin^2\iota + \alpha_x F_x \sin 2\iota + \alpha_y F_y \sin\iota] \times \frac{\mathcal{M}^2}{D_L} u_2^{-7/2} e^{-i\Psi^{(2)\rm GR}} e^{2i\beta u_2^b}$$

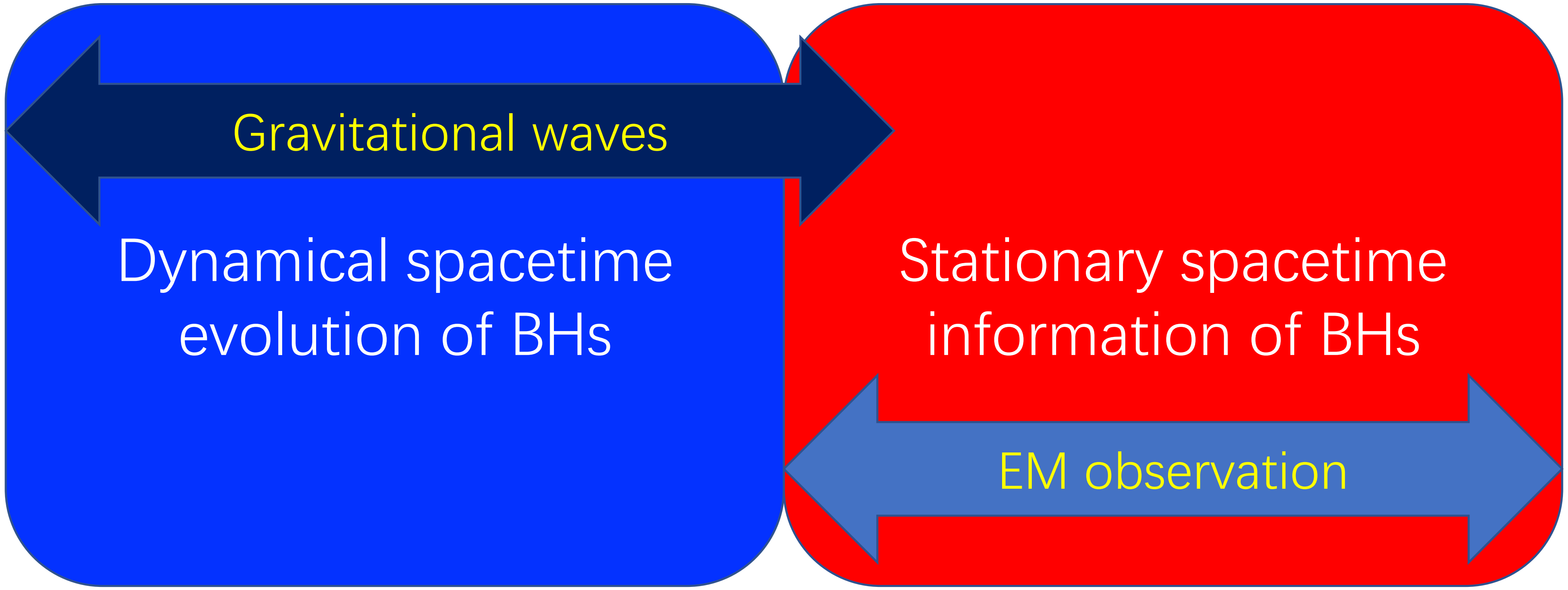
	$\Delta\beta$	Δ b	$\Delta\alpha_b$	$\Delta\alpha_L$	$\Delta\alpha_x$	$\Delta\alpha_y$
pathfinder plus-B	7×10^{-3}	5×10^{-1}	5×10^{-3}	5×10^{-3}	2×10^{-3}	4×10^{-3}
Taiji	2×10^{-5}	1×10^{-3}	7×10^{-5}	7×10^{-5}	3×10^{-5}	6×10^{-5}

Zhong, Han, Luo, Wu, SCMP, 2023

Testing Black Hole (BH)

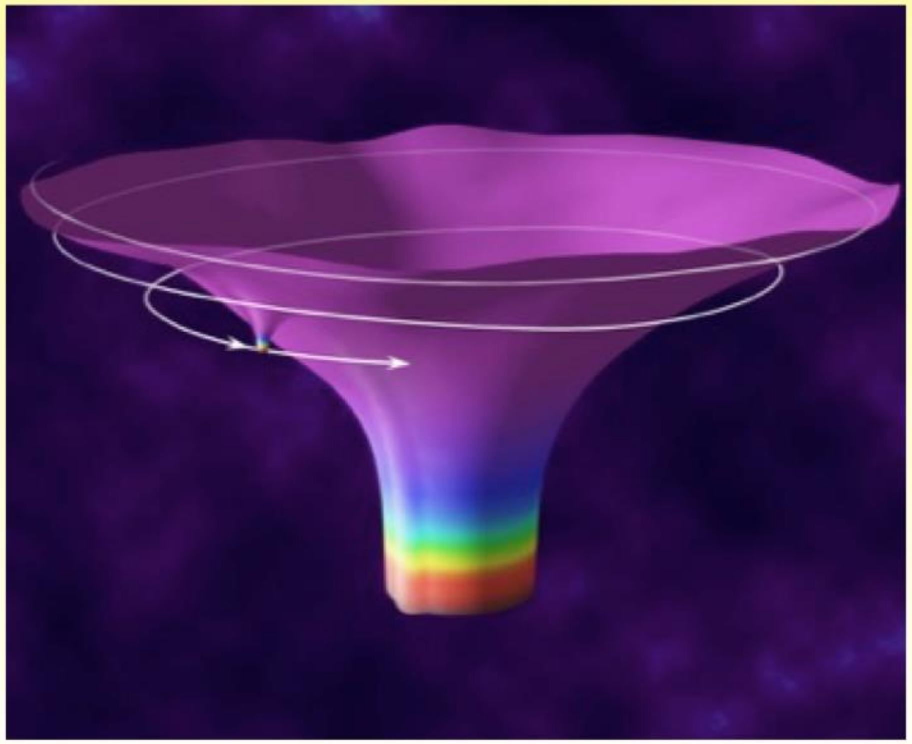
- GR: neutral BHs only have two parameters: mass and spin-----
  No-hair theorem.
- event horizon---- a surface where light can not escape;
- Singularity is covered by horizon

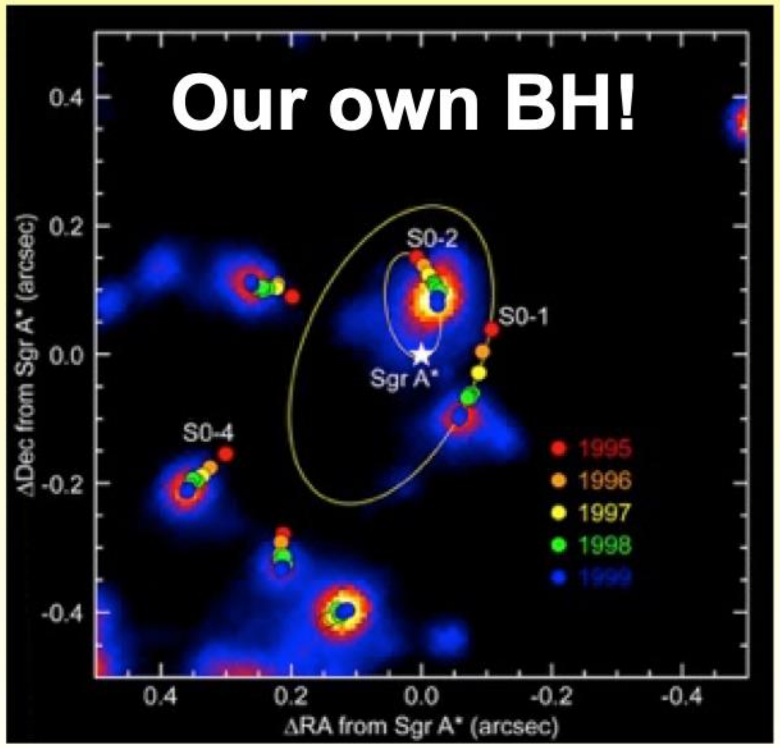




At the Edge of a Black Hole

- Capture by Massive Black Holes
  - Compact objects inspiral into massive black hole (MBH),
  - GWs map space-time geometry with superb precision
  - Allows investigation of tiny deviations from General Relativity including the “no hair” theorem



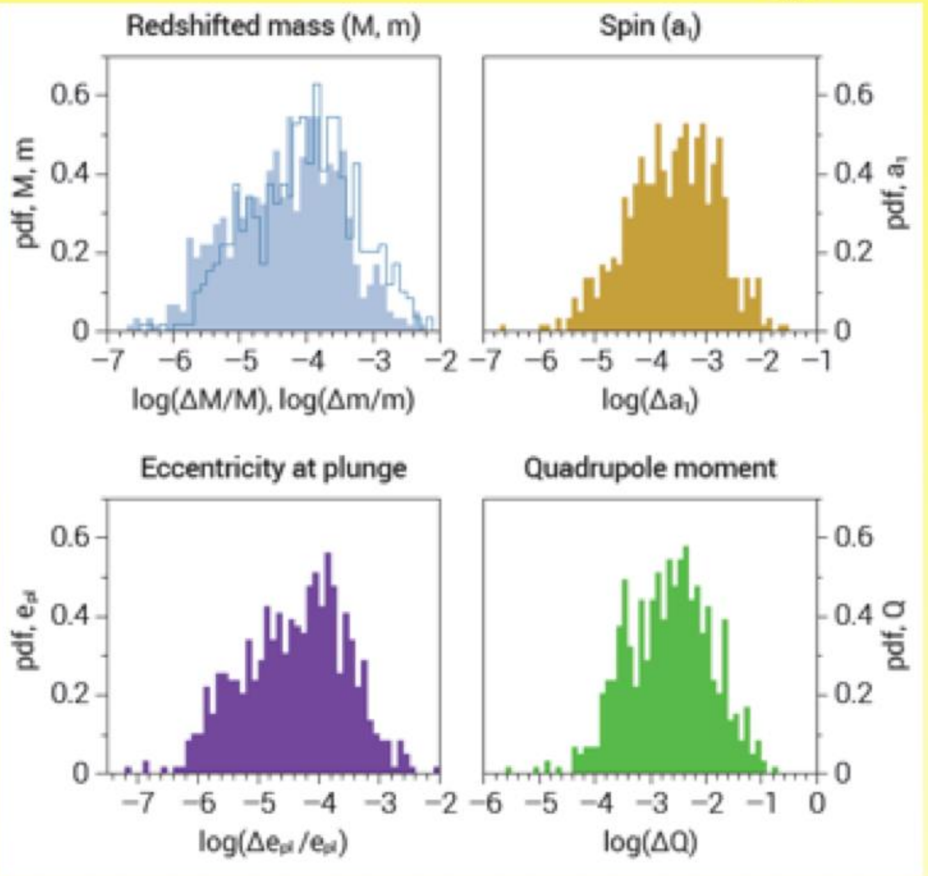


Ghez et al. 1998 ApJ 509, 678, Eckart et al. 2002 MNRAS 331, 917

From Danzmann, 2017 May 25, Beijing

Extreme Mass Ratio Inspirals

- SNR 20 up to $z \approx 0.7$ for 10^5-10^6 $M_\odot$
- Dozens of events per year
- Mass, spin to 0.1% – 0.01 %
- Quadrupole moment to < $0.001\ M_\odot^3 G^2/c^4$



- Do Black Holes have hair?
  - New objects in General Relativity
    - Boson Stars, Gravastars, non-Kerr solutions (e.g. Manko-Novikov)
  - Deviations from General Relativity
    - Chern-Simons, Scalar-Tensor, light scalar fields (axions) and black hole bomb instabilities
- Each has specific GW fingerprint!

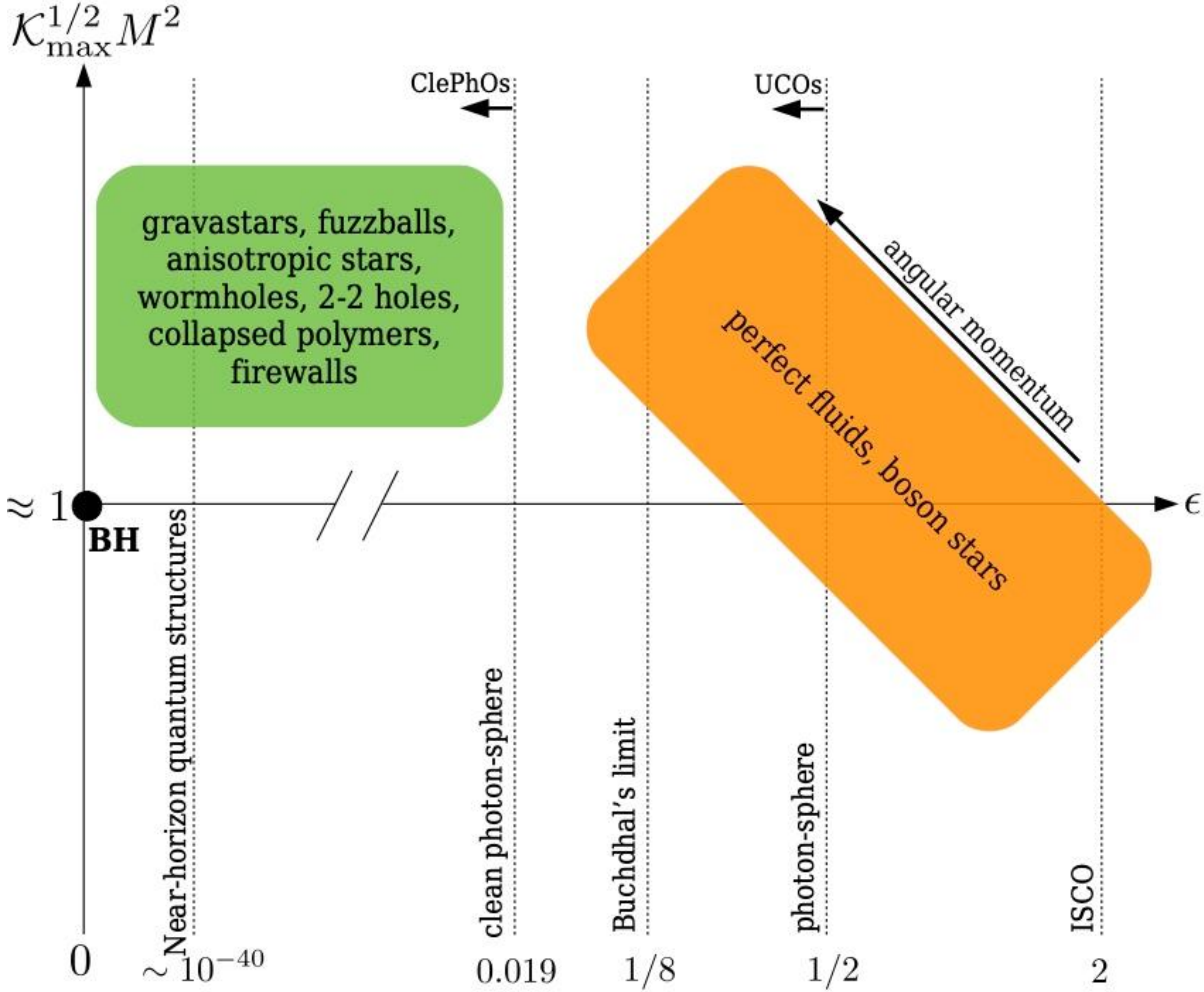
$$h(f) = A(f)e^{i(\phi_{\rm PP}+\phi_{\rm TH}+\phi_{\rm TD}+\phi_{\rm NV})}$$

Credit: Danzmann

Compact like as BH, but without horizon: exotic compact object (ECO)with hard surface at Plank scale

Model	Formation	Stability	EM signatures	GWs
Fluid stars	✓ [90]	✓ [85, 88, 109–113]	✓	✓ [85, 109, 112, 114]
Anisotropic stars	✗	✓ [115–117]	✓ [118–120]	✓ [115, 119, 120]
Boson stars & oscillatons	✓ [53, 54, 121–123]	✓ [86, 124–128]	✓ [91, 129, 130]	✓ [131–138]
Gravastars	✗	✓ [127, 139]	✓ [140–142]	∼ [112, 113, 135, 136, 138, 142–148]
AdS bubbles	✗	✓ [149]	∼ [149]	✗
Wormholes	✗	✓ [150–153]	✓ [154–157]	∼ [136, 138, 148]
Fuzzballs	✗	✗ (but see [158–161])	✗	∼ (but see [135, 148, 162])
Superspinars	✗	✓ [163, 164]	✗ (but see [165])	∼ [135, 148]
$2-2$ holes	✗	✗ (but see [166])	✗ (but see [166])	∼ [135, 148]
Collapsed polymers	✗ (but see [167, 168])	✓ [169]	✗ [168]	∼
Quantum bounces / Dark stars	✗ (but see [170, 171])	✗	✗	∼ [172]
Compact quantum objects*	✗ [73, 173, 174]	✗	✗	✓ [38]
Firewalls*	✗	✗	✗	∼ [135, 175]

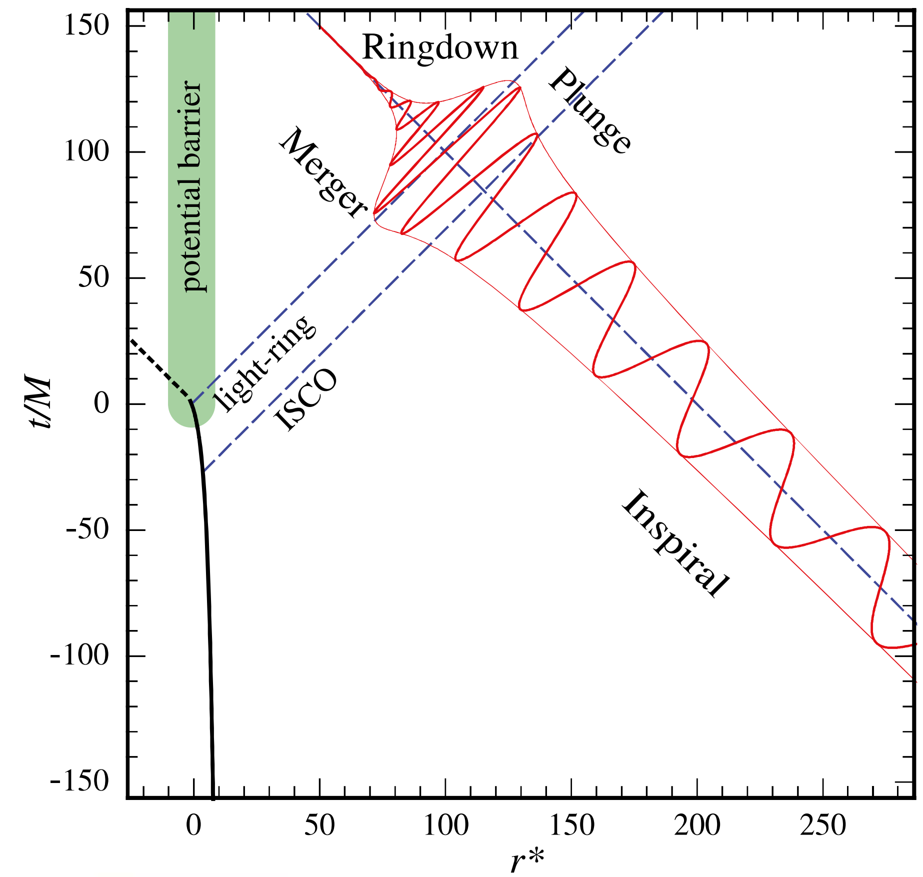
Cardoso & Pani, 2019

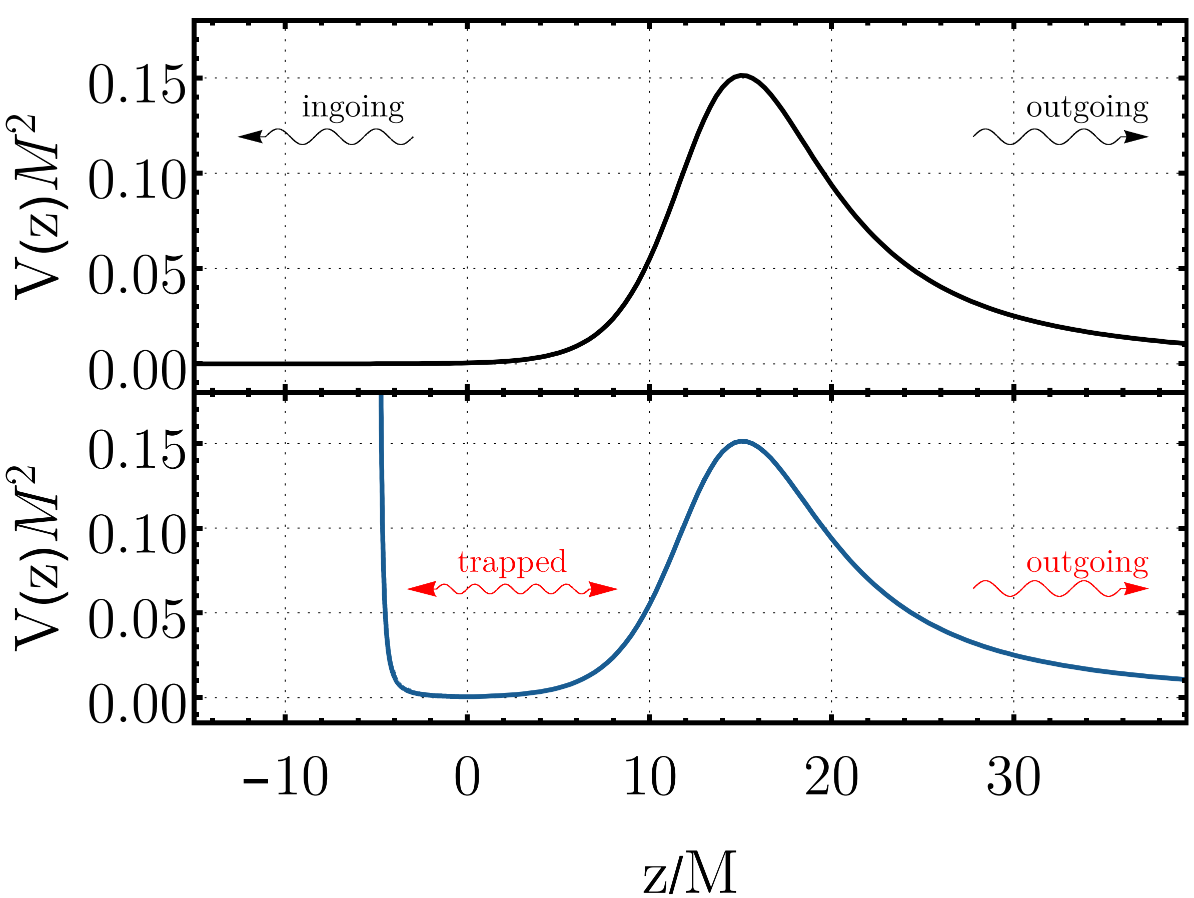


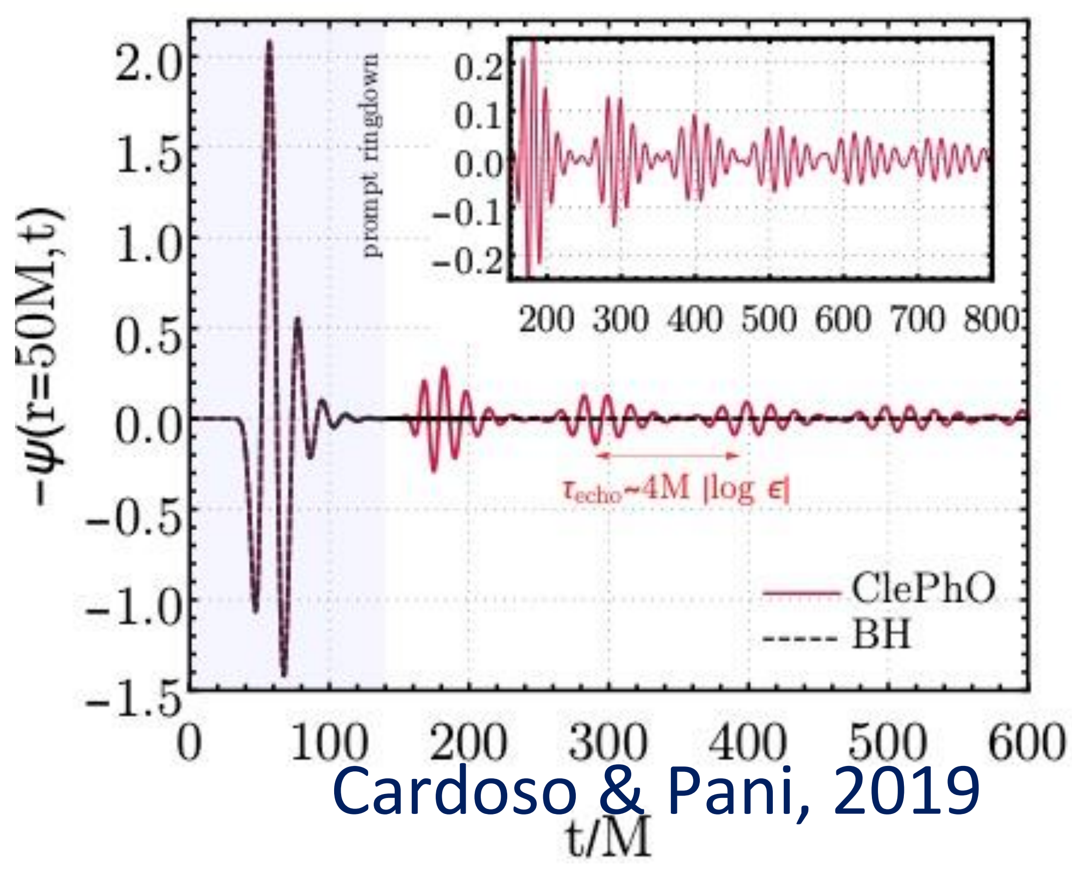
$\mathcal{K}_{\max}^{1/2} M^2$
ClePhOs
UCOs
gravastars, fuzzballs, anisotropic stars, wormholes, 2-2 holes, collapsed polymers, firewalls
perfect fluids, boson stars
angular momentum
≈ 1
BH
ϵ
Near-horizon quantum structures
clean photon-sphere
Buchdhal's limit
photon-sphere
ISCO
0
$\sim 10^{-40}$
0.019
1/8
1/2
2

Potential barrier near horizon —> GW echoes

In principle, ringdown mainly reflect the properties of light ring rather than horizon

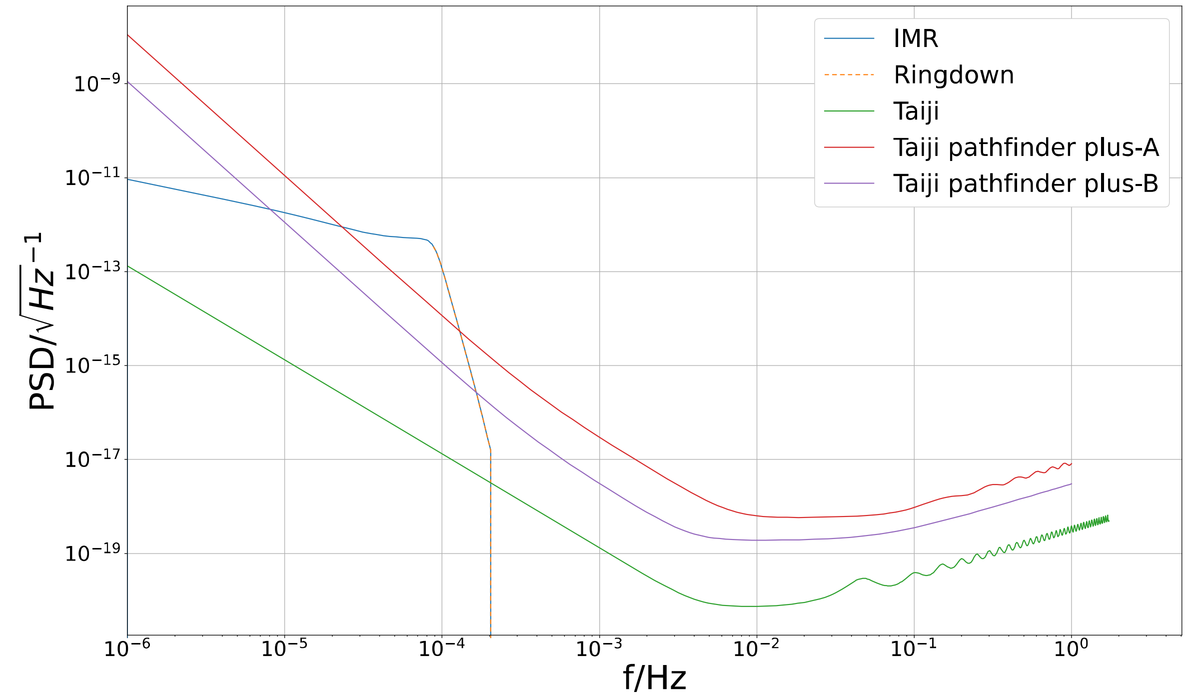






Cardoso & Pani, 2019

Test BHs with SMBHB by Taiji/LISA



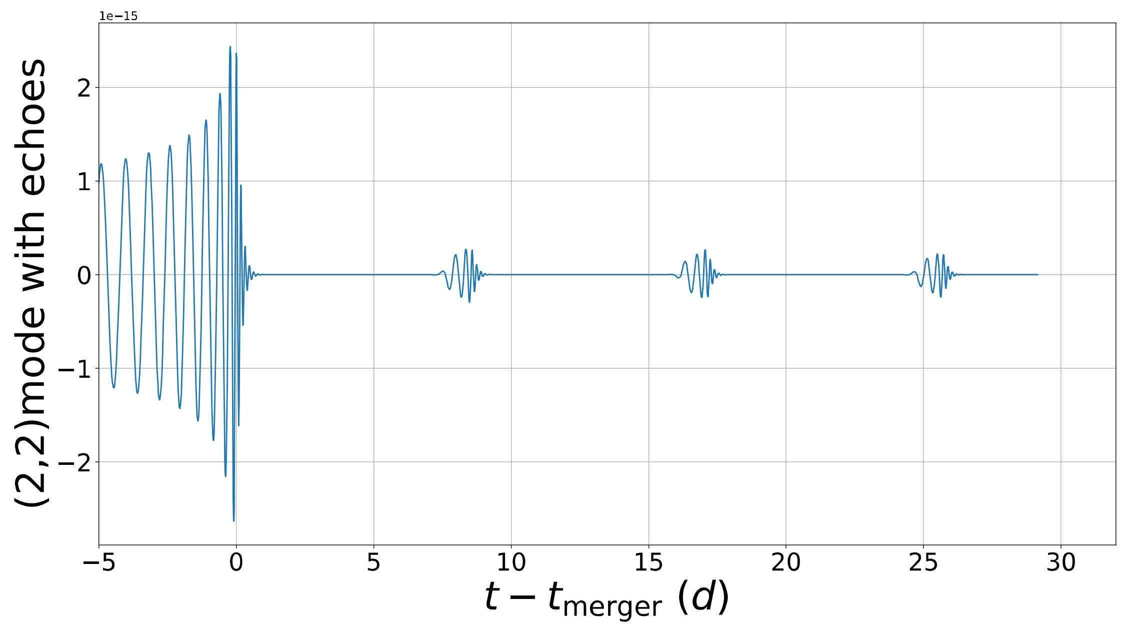
1, final BH parameter estimation

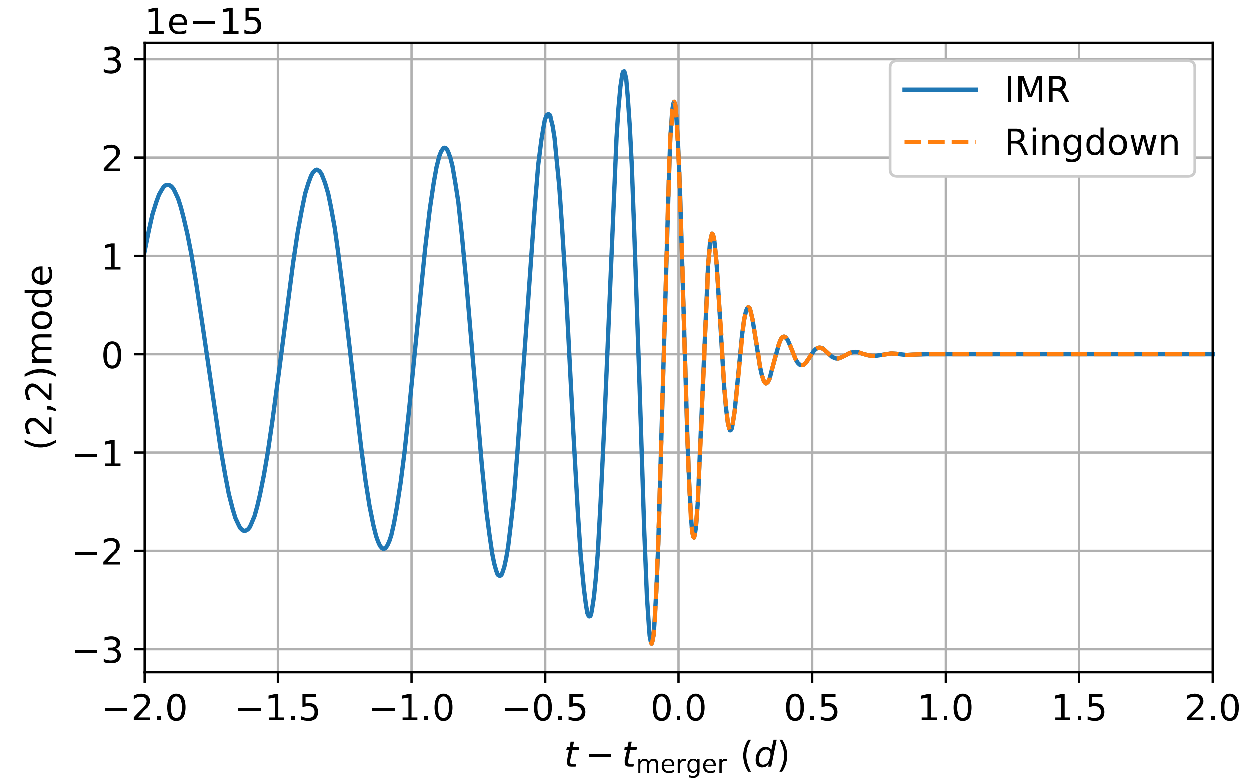
Table 3 Parameter estimation for χ_f and M_f.

	pathfinder plus-B	Taiji
$\Delta M_f/M_f$	8×10^{-4}	9×10^{-6}
$\Delta\chi_f/\chi_f$	5×10^{-3}	6×10^{-5}

, GW echos

Xin+, 2021





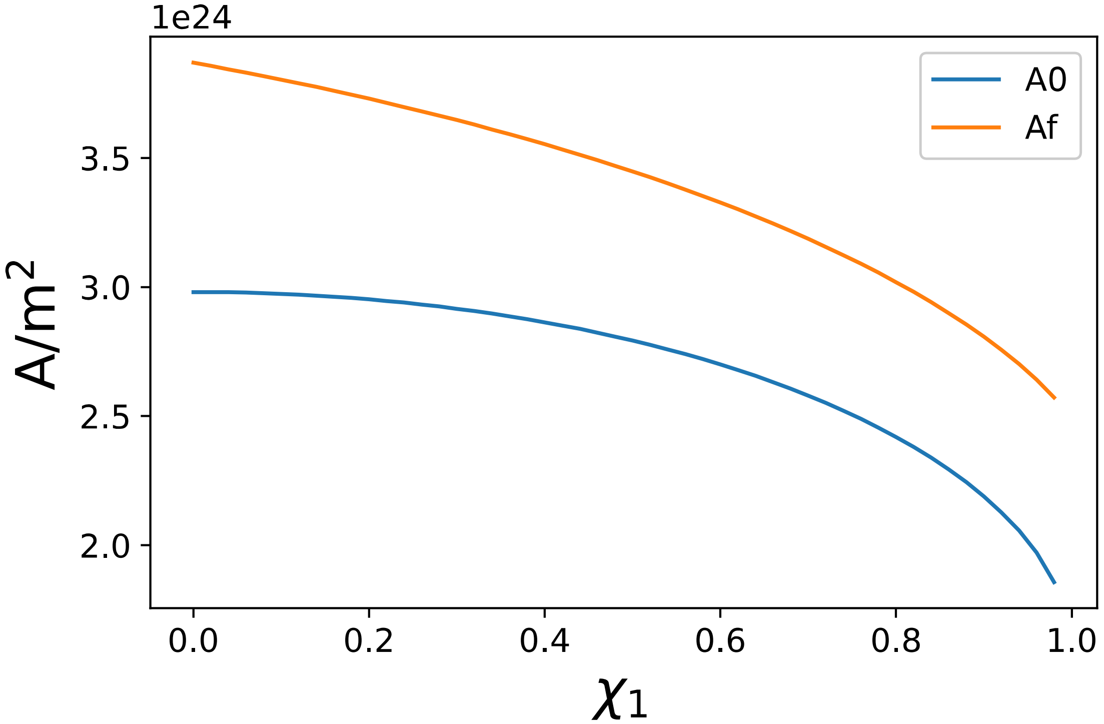
	pathfinder plus-B	Taiji
$\Delta\gamma/\gamma$	6×10^{-2}	5×10^{-4}

Zhong, Han, Luo, Wu, SCMP, 2023

Test BHs with SMBHB by Taiji/LISA

1, BH area theorem

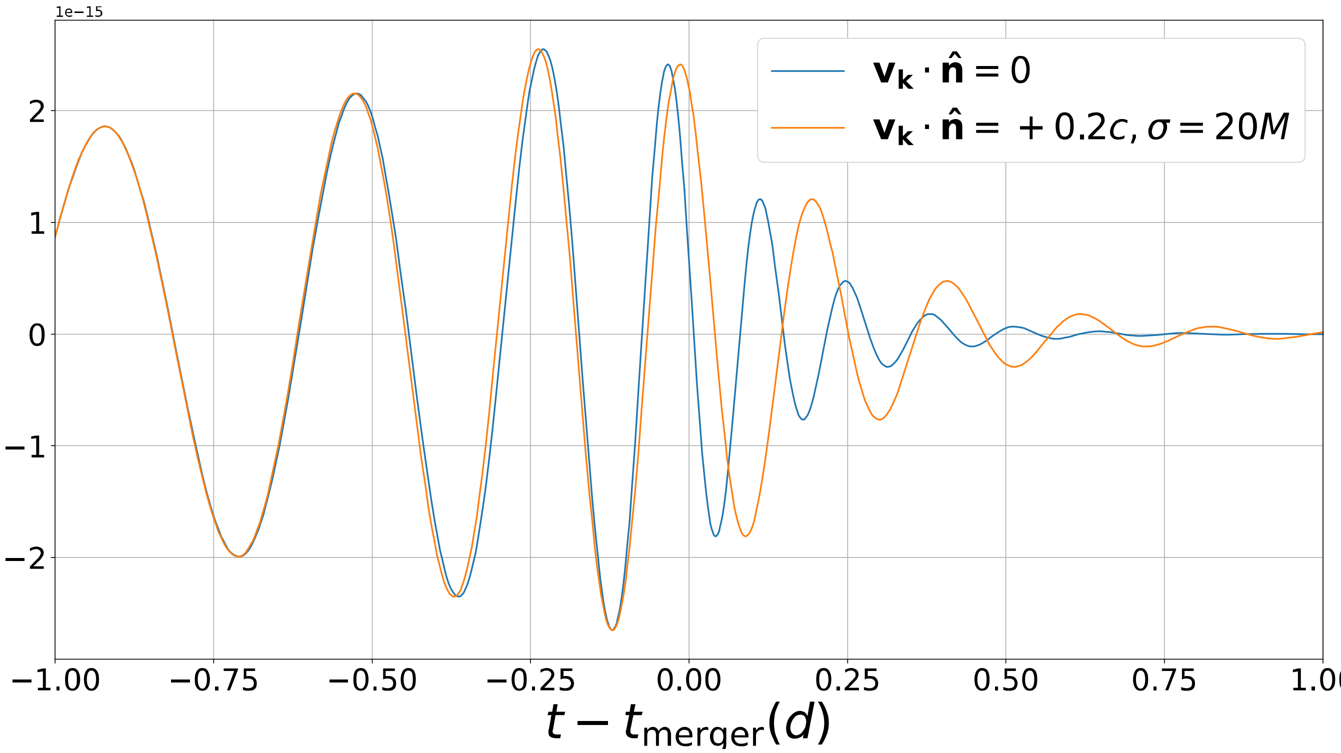
$$\mathcal{A}(m,\chi) = 8\pi m^2(1 + \sqrt{1-\chi^2})$$



2, Gravitational recoil: > 900 km/s

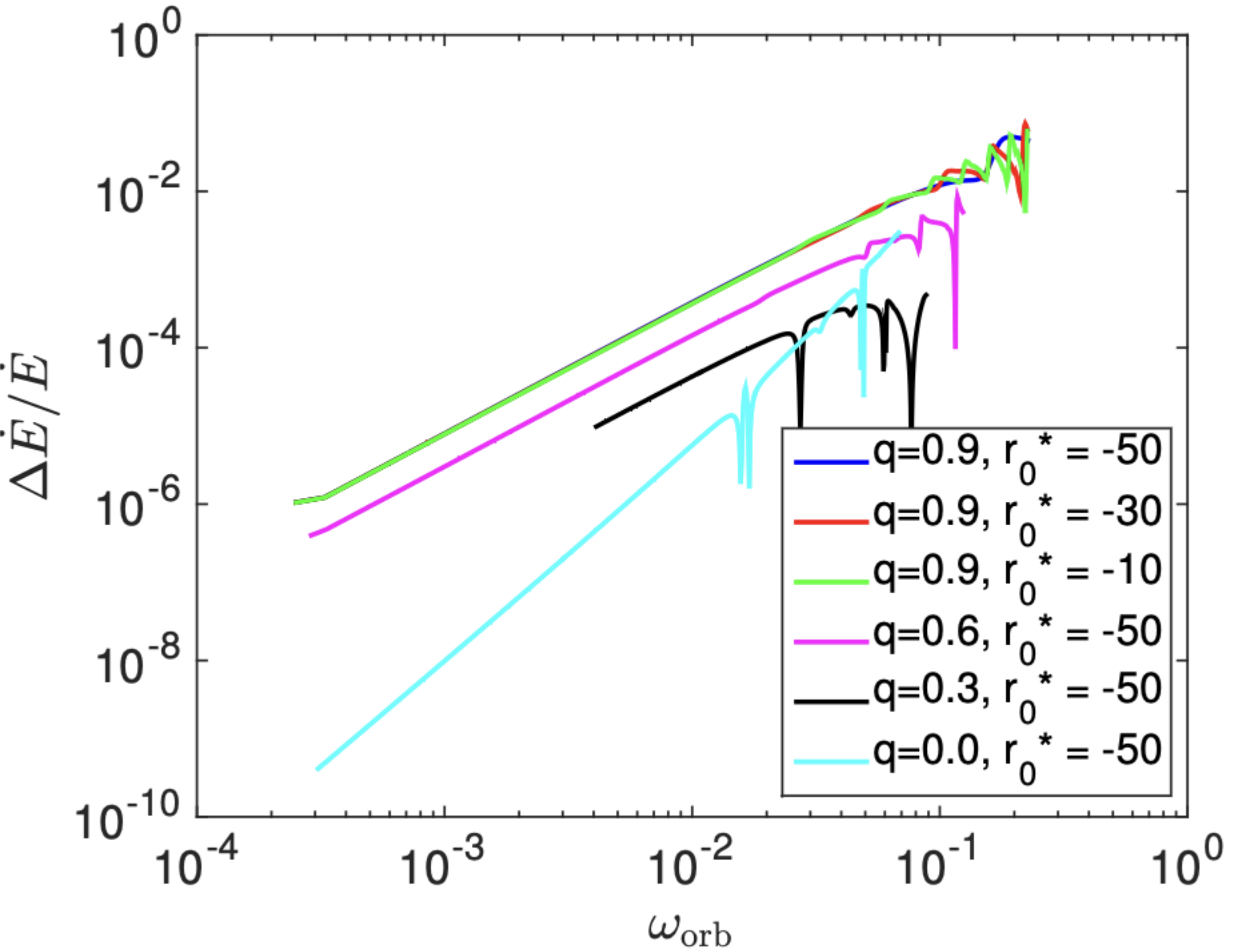
$$\frac{d}{dt}v_k(t) = \mathbf{V_k}\cdot\mathbf{n}\frac{\sum_n \alpha_n\phi_n(t)}{\int_{-\infty}^{\infty}\sum_n \alpha_n\phi_n(t)dt}$$

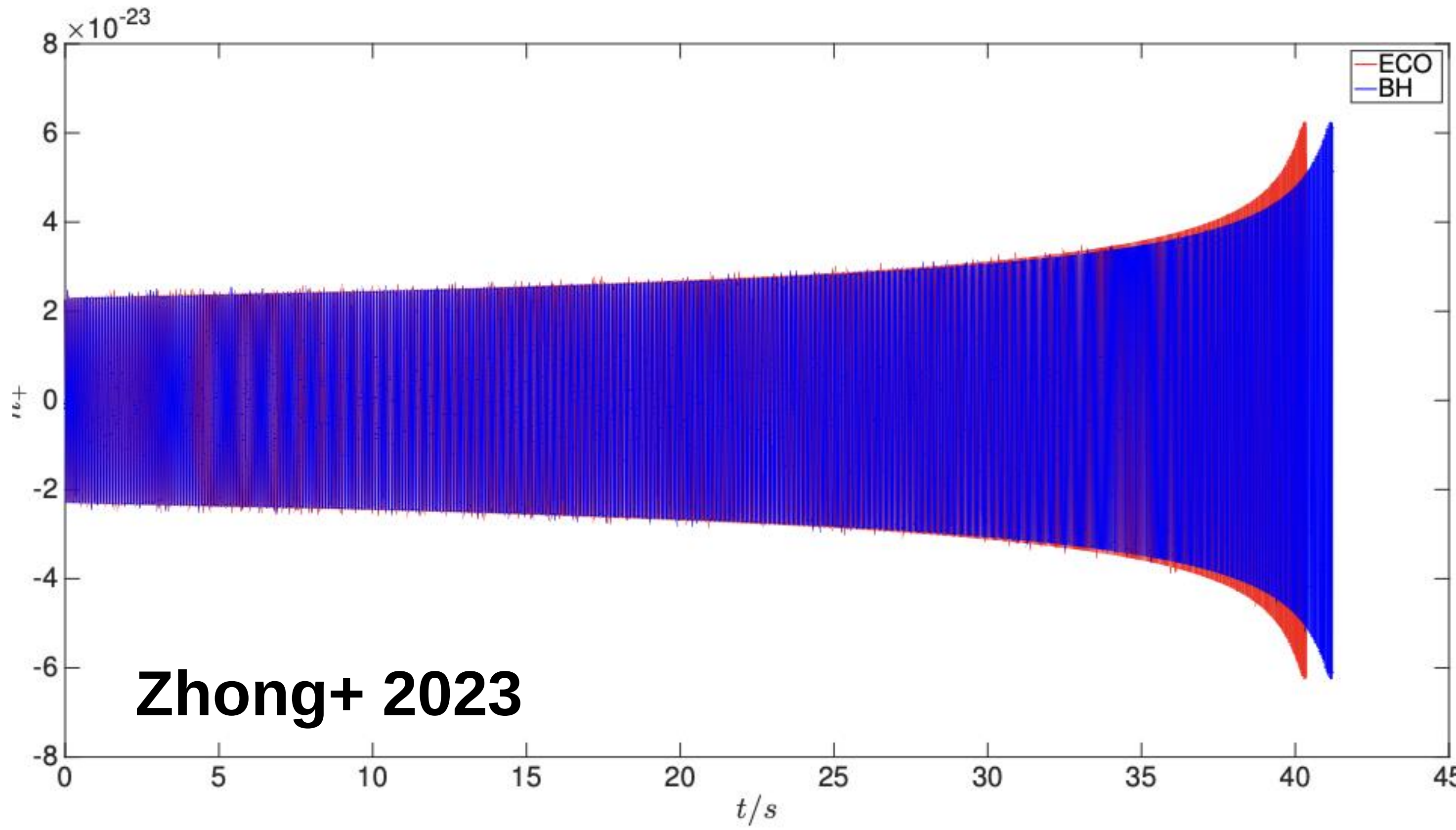
$$\phi_n(t) = \frac{1}{\sigma\sqrt{2^n n!\sqrt{\pi}}}\exp\left(-\frac{(t-t_c)^2}{2\sigma^2}\right)H_n\left(\frac{t-t_c}{\sigma}\right)$$



Zhong, Han, Luo, Wu, SCMP, 2023

EMRI: distinguish BH/ECO not from echo but from inspiral!





Surface produce different flux. → EMRI/IMRI waveform dephase

EMRI can measure the tidal love number at $q^{1/2}$ (Pani, 2019)

$$h(f) = A(f)e^{i(\phi_{\rm PP}+\phi_{\rm TH}+\phi_{\rm TD}+\phi_{\rm NV})}$$

Conclusions

- 空间引力波探测器可以极高精度地测量黑洞稳态和动态形状 (Measure BH accurately both for stationary and dynamical spacetime)；

- 检验广义相对论 (test GR): 引力波的传播规律、偏振、黑洞性质, 非真空GR…

- 新物理？(New Physics):量子引力、大统一场论（Wu）

- 需要一个系统的理论来统一各种no-GR效应

- 需要精确的模板和数据分析: 简并和混淆

Thanks!

wbhan@shao.ac.cn