Science with the TianQin observatory

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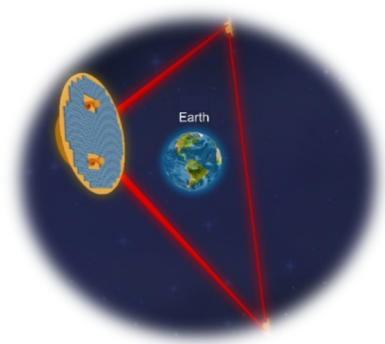
1st-3rd September, 2020

中山大學 天琴中心

TianQin Research Center for Gravitational Physics



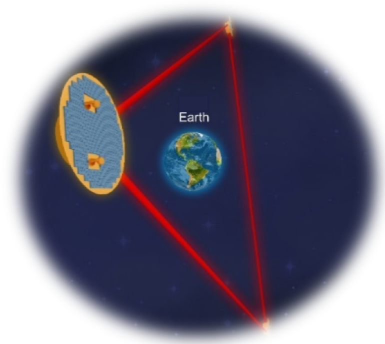
The 13th International LISA Symposium

Overview

Overview of the TianQin project

TianQin science objects

Progress of TianQin



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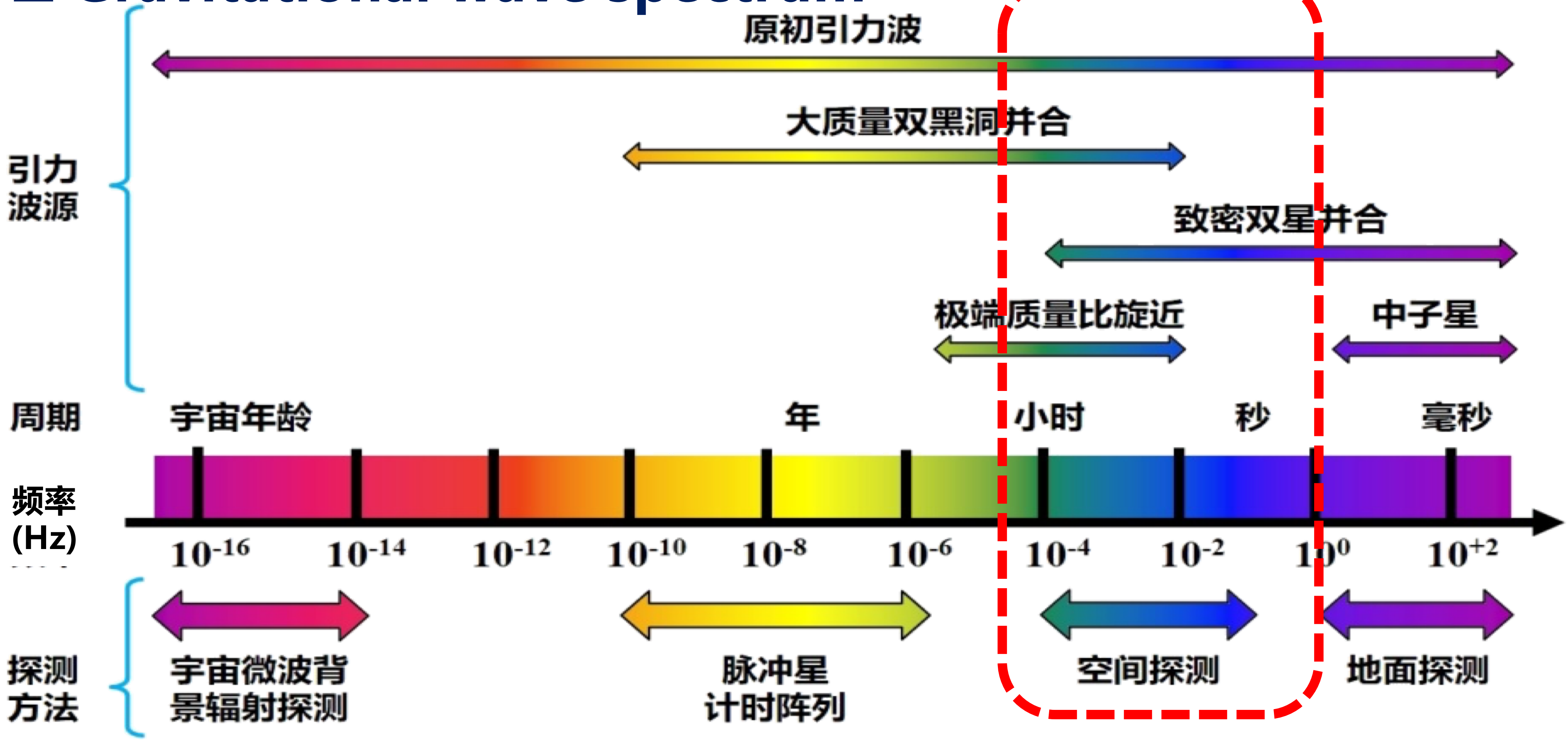
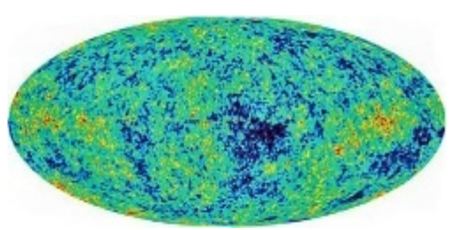
TianQin Research Center for Gravitational Physics

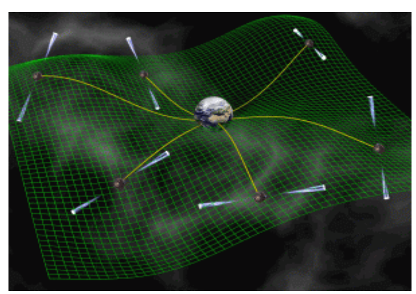
Summary

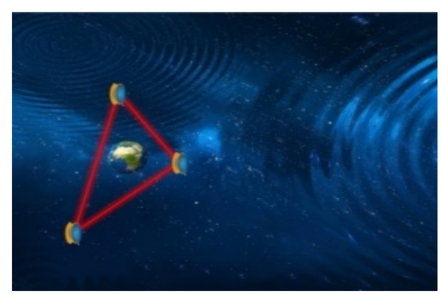
What can TianQin do

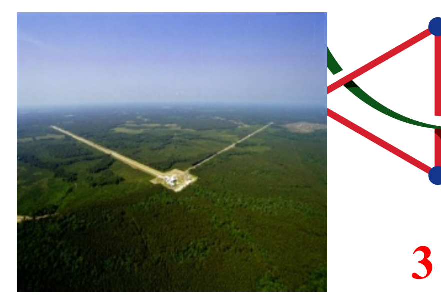
□ Gravitational wave spectrum







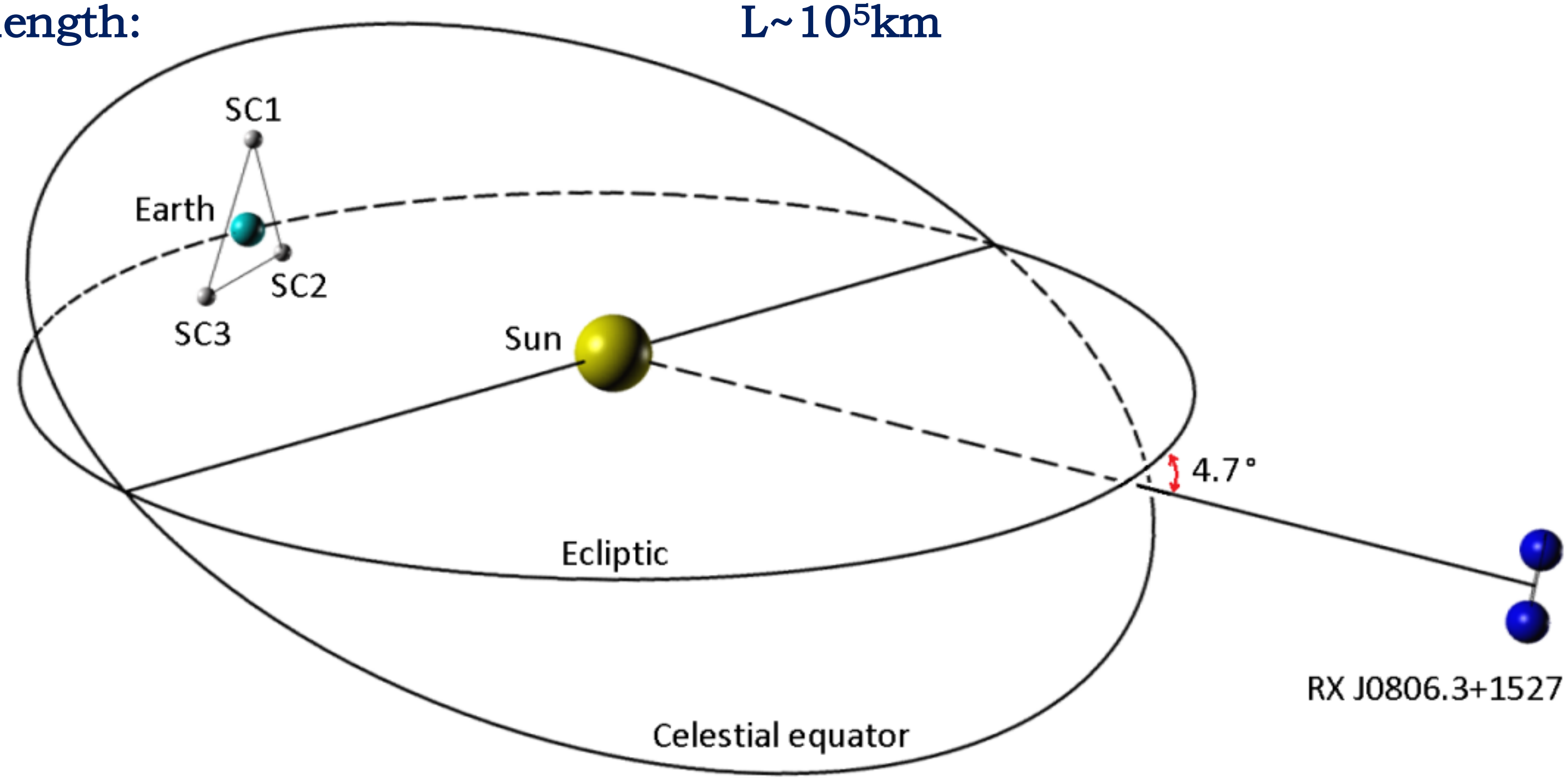




What is TianQin

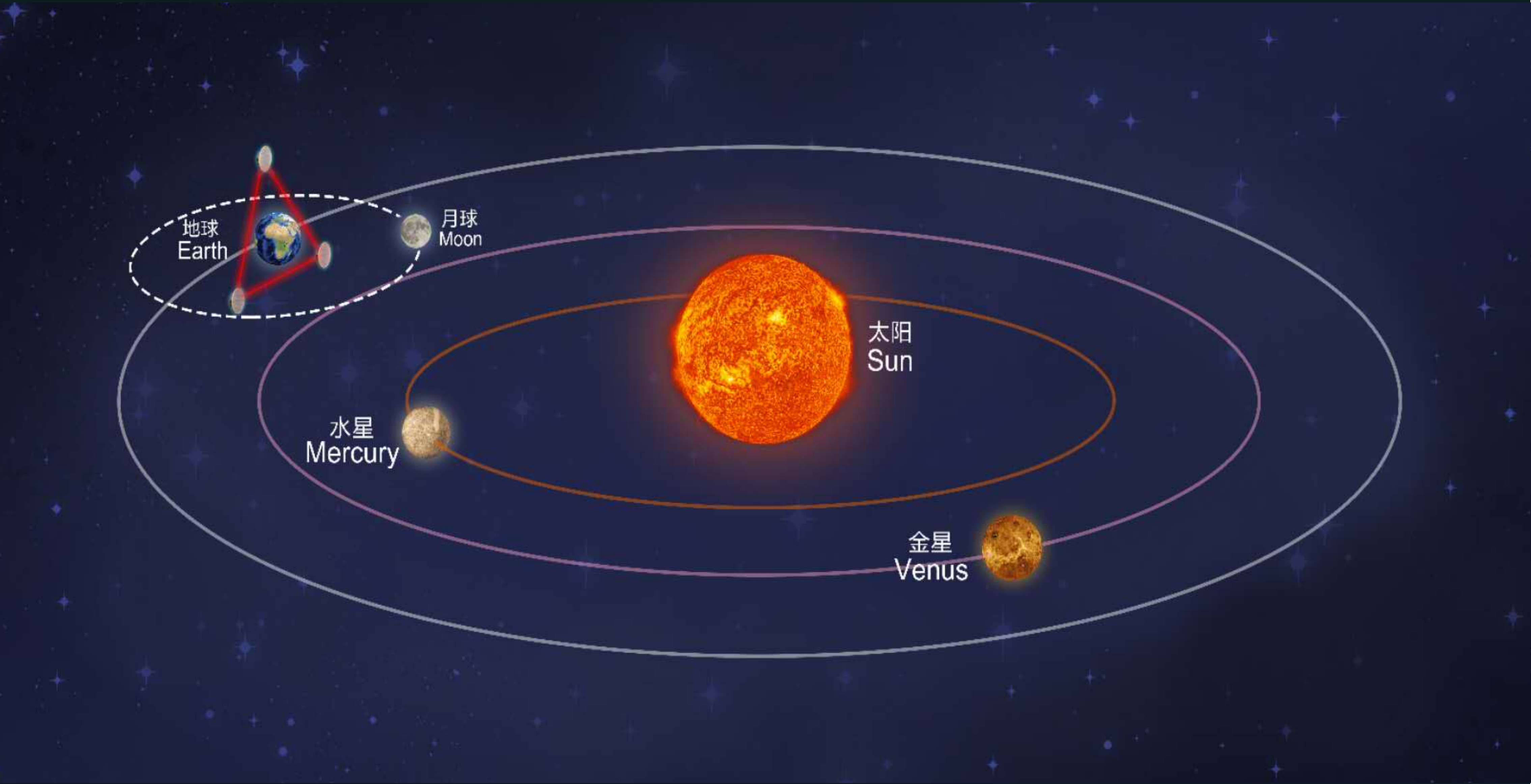
- TianQin: a space-borne gravitational wave detector

- Luo et al. 2016 CQG, Vol. 33, No. 3, 035010
- Principle: laser interferometry
- Orbit: Geocentric (Earth-orbiting)
- Arm length: $L \sim 10^5$km



LISA XIII

Artistic view of TianQin



“天琴” TianQin

Tian（天）= Heaven

Qin（琴） = Harp

TianQin (TQ):

a Harp in Heaven that awaits a cosmic pluck of GW

Overview

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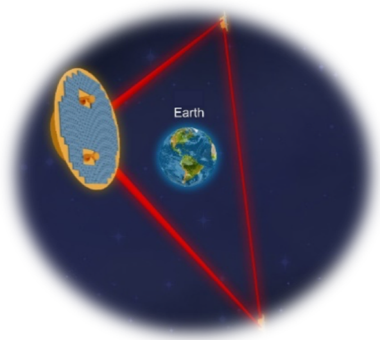
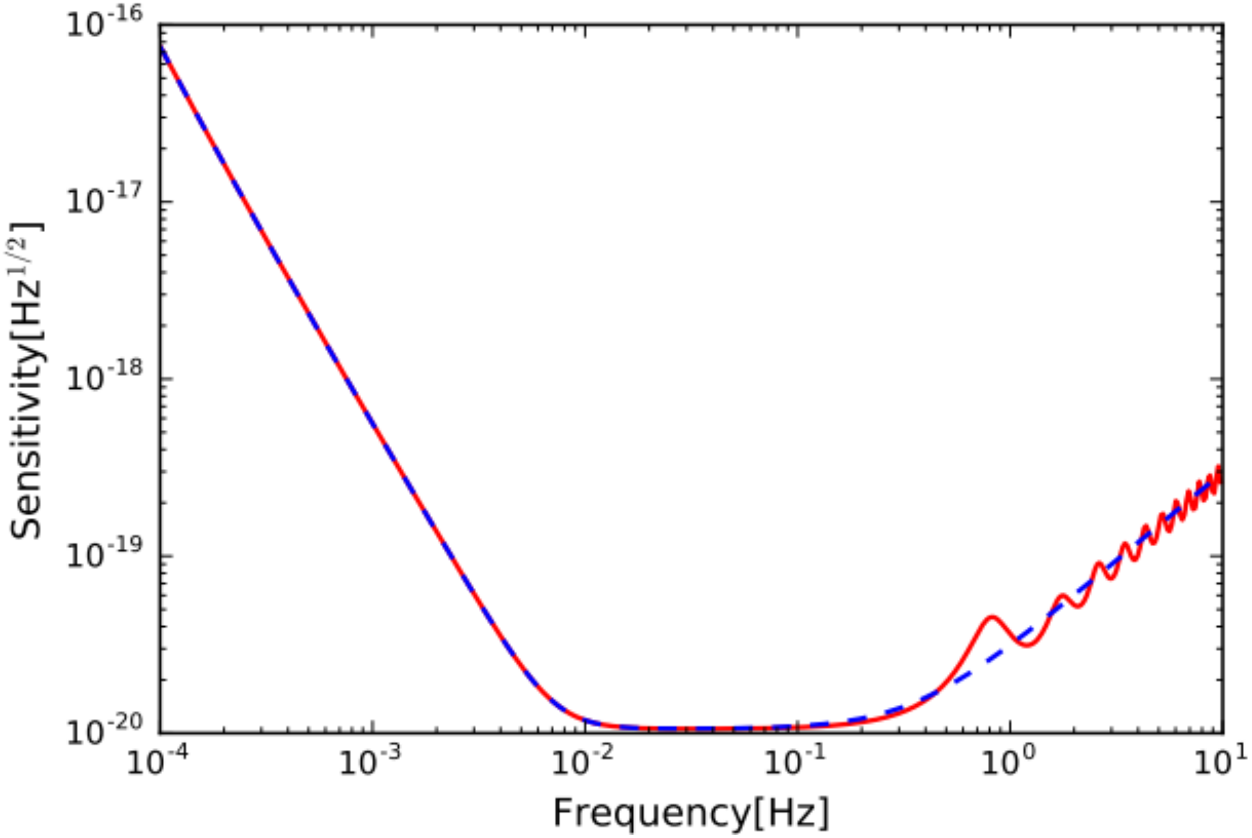
中山大學 天琴中心
TianQin Research Center for Gravitational Physics

Summary



Noise (power spectrum density)

$$S_h^{SA} = \frac{10}{3}\frac{1}{L^2}\left[\frac{4S_a}{(2\pi f)^4}\left(1+\frac{10^{-4}\mathrm{Hz}}{f}\right)+S_x\right]\times\left[1+\left(\frac{f}{0.41\frac{c}{2L}}\right)^2\right]$$



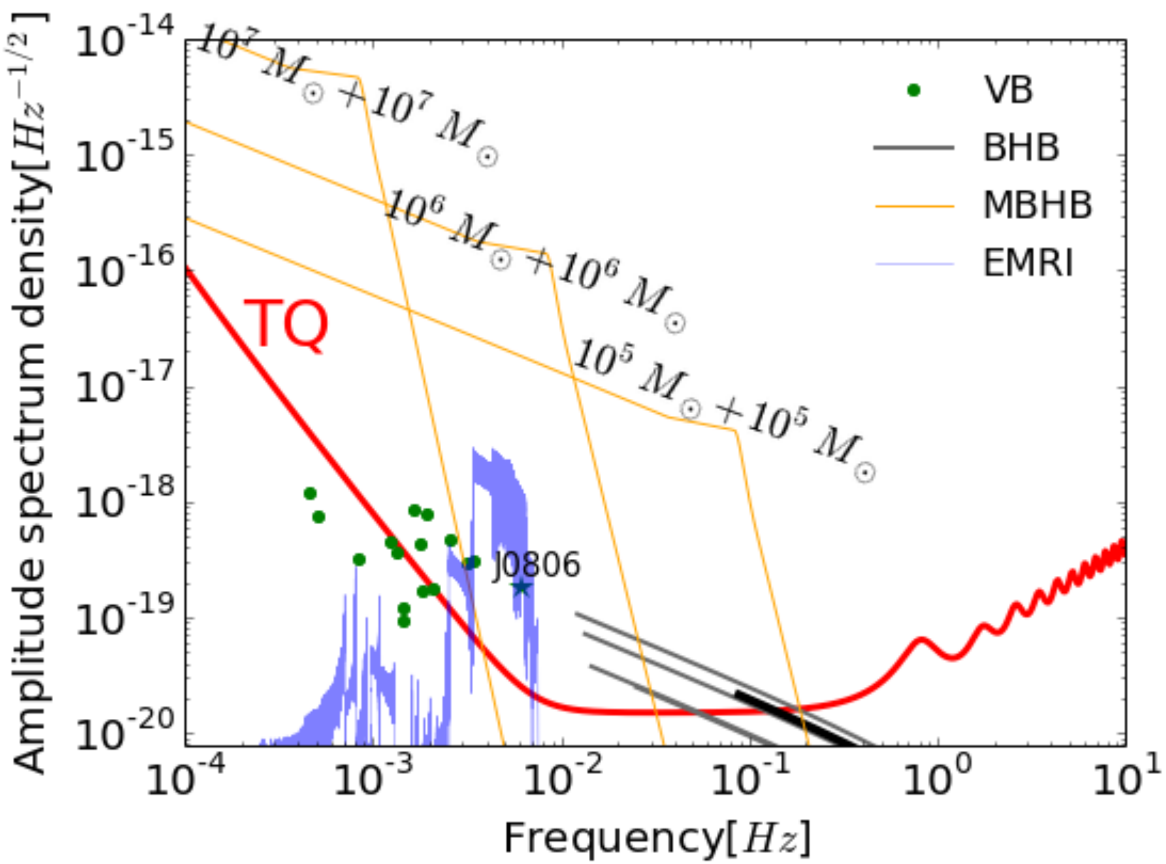
Armlength $L = \sqrt{3}\times 10^5\mathrm{km}$

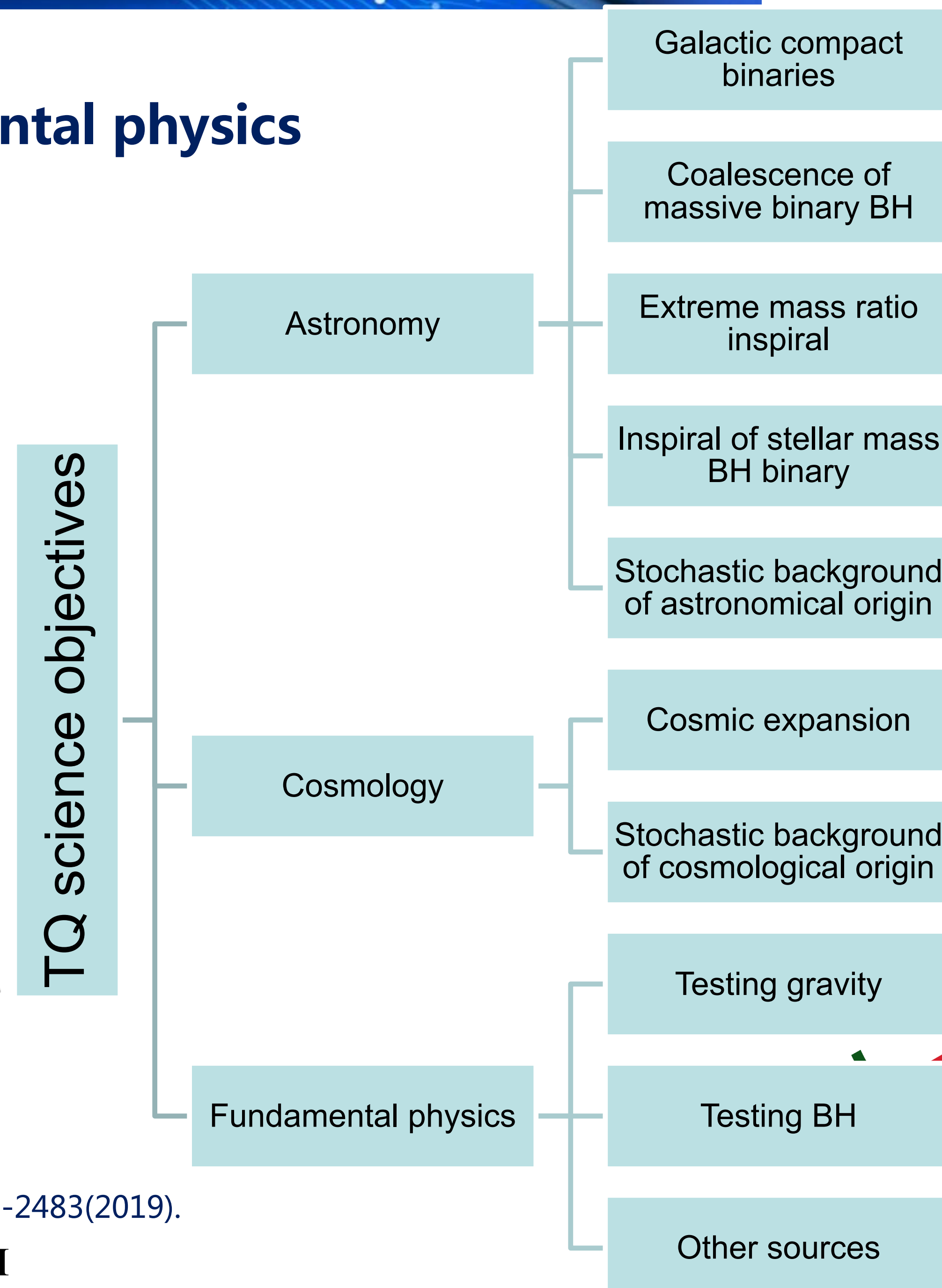
Acceleration noise $S_a = 1\times 10^{-30}\mathrm{m}^2\mathrm{S}^{-4}\mathrm{Hz}^{-1}$

Positional noise $S_x = 10^{-24}\mathrm{m}^2\mathrm{Hz}^{-1}$

Overview of TQ science objectives

- astronomy, cosmology, and fundamental physics



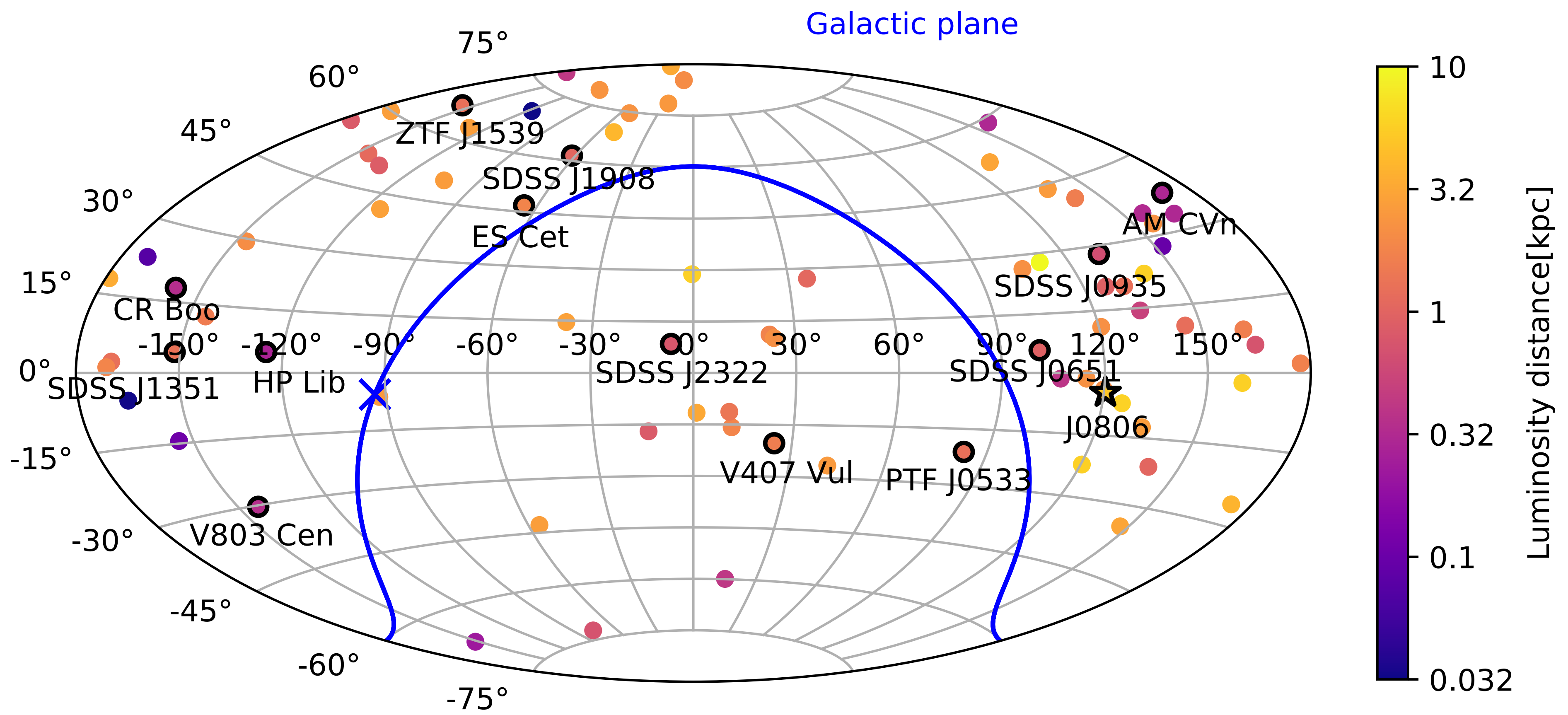


Yiming Hu, Jianwei Mei, Jun Luo*, *Chinese Science Bulletin*, 64, 24: 2475-2483(2019).

Galactic Binaries

□ Can help understand binary evolution

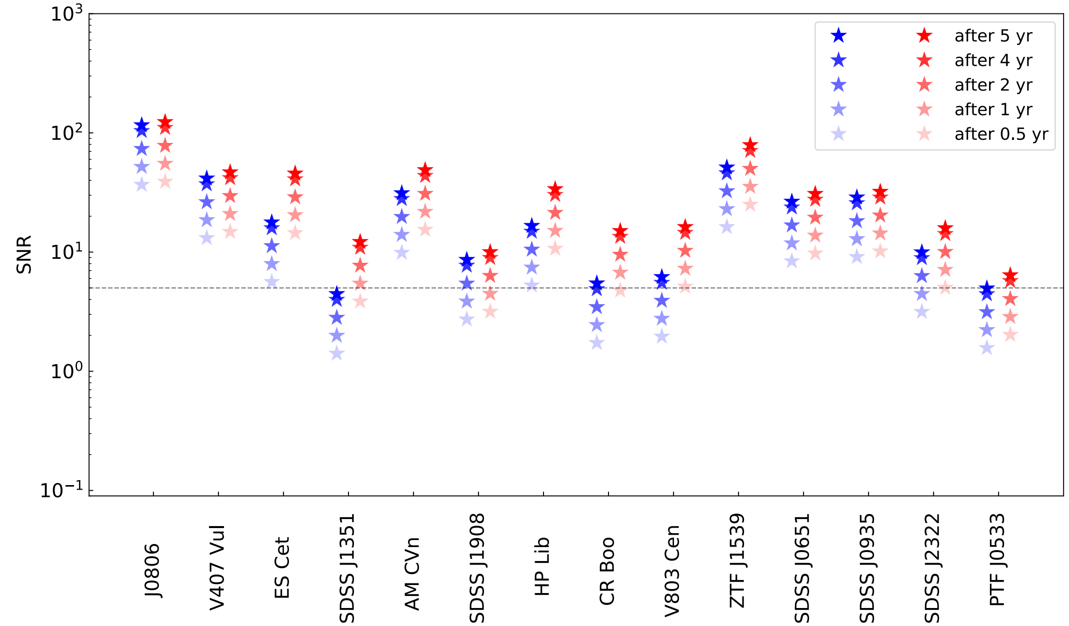
- **Different models (population synthesis) all predicts existence of large amount (~10^8) of compact binaries, dominated by binary white dwarfs**



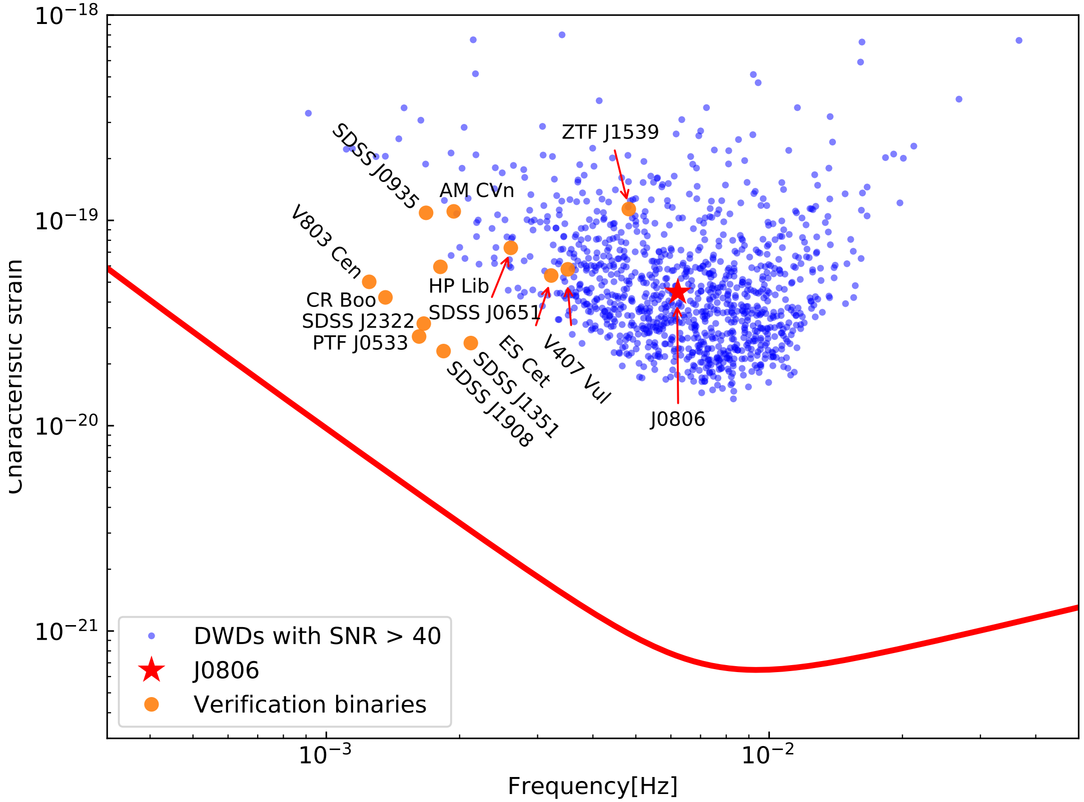
Galactic Binaries

☐ How many?

- ➢ **Observed**
- ➢ **Derived**



	0.5yr	1yr	2yr	4yr	5yr
TQ	2371	3589	5292	7735	8710
TQ II	1672	2595	3943	5782	6540
TQ I+II	3146	4716	6966	10023	11212



Galactic Binaries

□ Foreground

- Some part of LISA noise dominated by foreground
- TianQin is not influenced

Science with the TianQin Observatory: Preliminary Results on Galactic Doub
White Dwarf Binaries

Shun-Jia Huang,[1] Yi-Ming Hu,[1,*] Valeriya Korol,[2] Peng-Cheng Li,[3,4,1] Zheng-Cheng Liang,[5,1] Yang Lu,[1] Hai-Tian Wang,[6,7,1] Shenghua Yu,[8,9] and Jianwei Mei[1,†]

[1] *TianQin Research Center for Gravitational Physics and School of Physics and Astronomy, Sun Yat-sen University (Zhuhai Campus), Zhuhai 519082, P.R. China*
[2] *School of Physics and Astronomy, University of Birmingham, Birmingham B15 2TT, United Kingdom*
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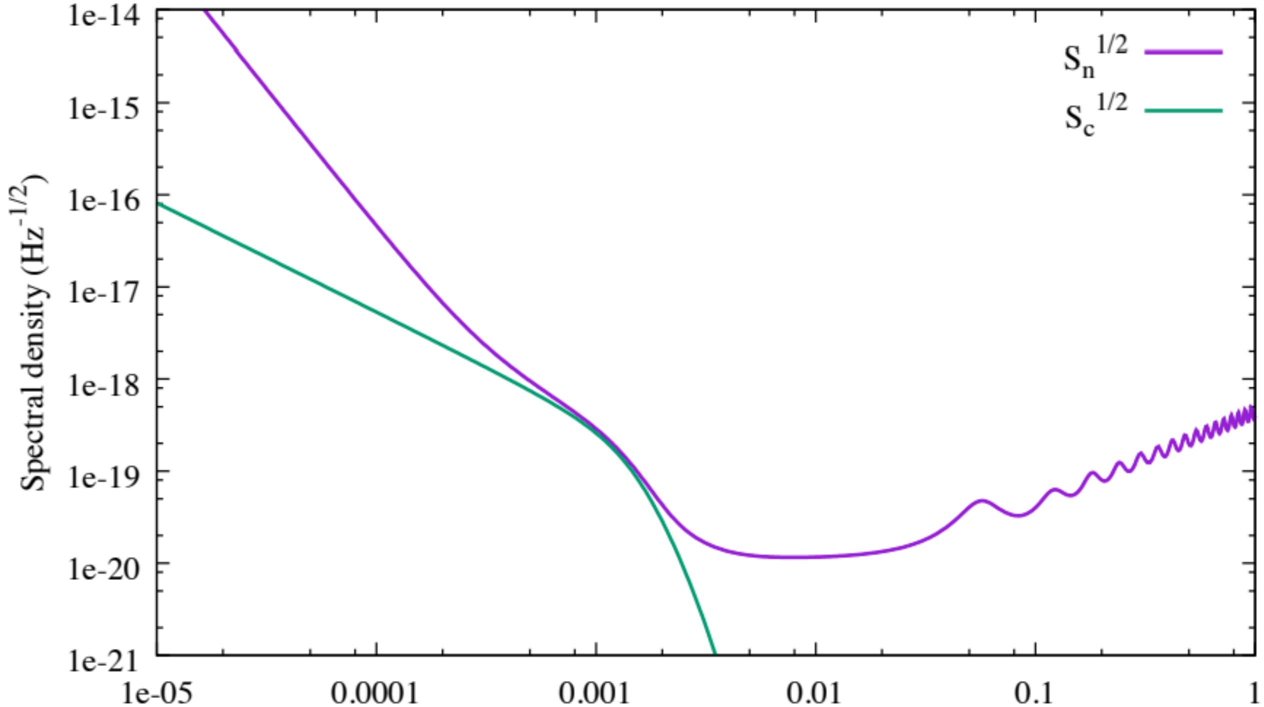
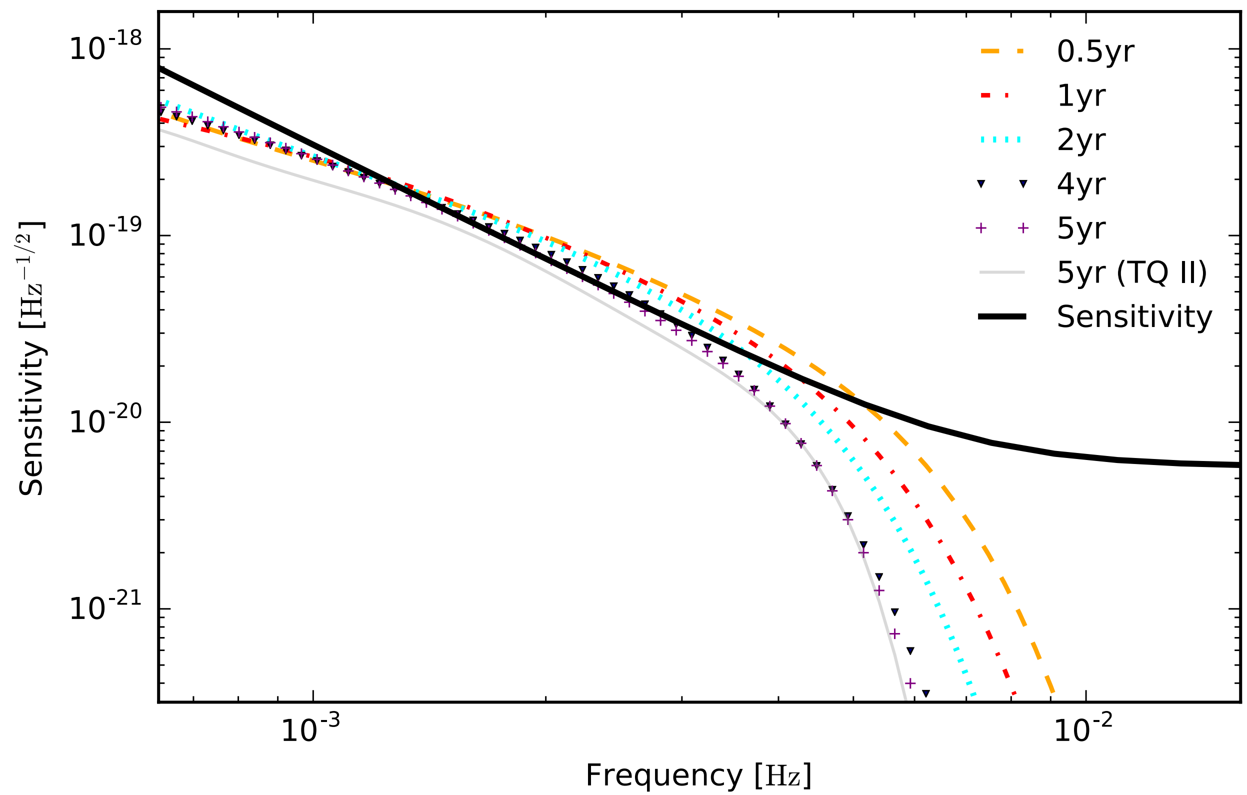
[5] *MOE Key Laboratory of Fundamental Physical Quantities Measurements, Hubei Key Laboratory of Gravitation a Quantum Physics, PGMF and School of Physics, Huazhong University of Science and Technology, Wuhan 430074, C*
[6] *Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210023, P.R. China*
[7] *School of Astronomy and Space Science, University of Science and Technology of China, Hefei, Anhui 230026, P.R.*
[8] *National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China*
[9] *The Key Laboratory of Radio Astronomy, Chinese Academy of Sciences*

(Dated: May 19, 2020)

https://arxiv.org/pdf/2005.07889.pdf

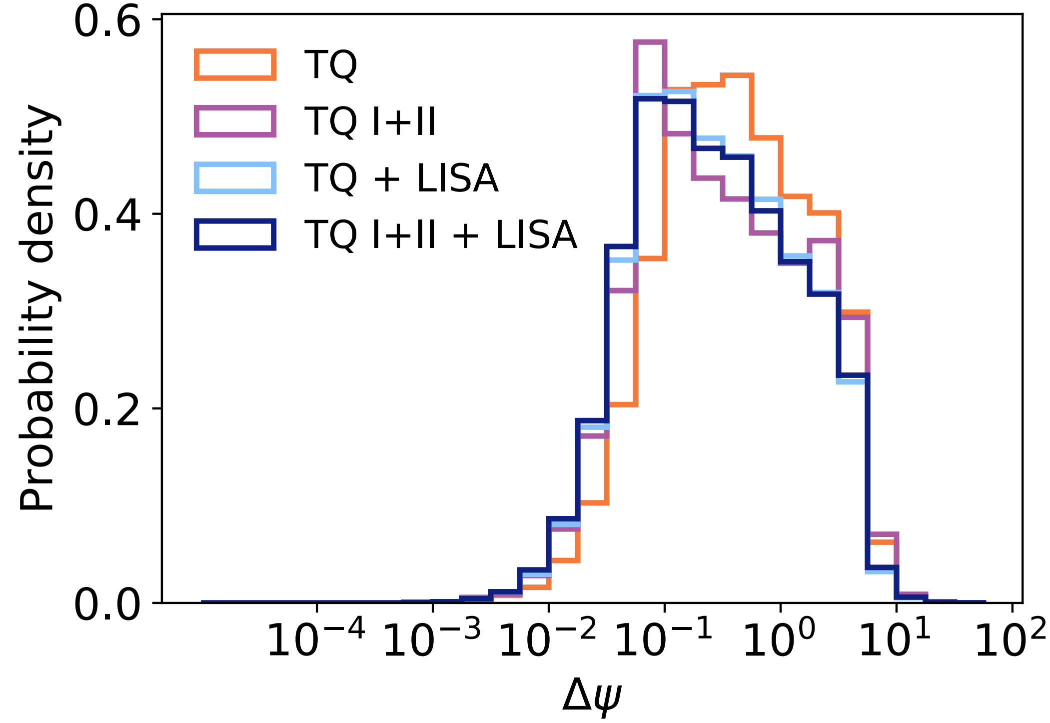


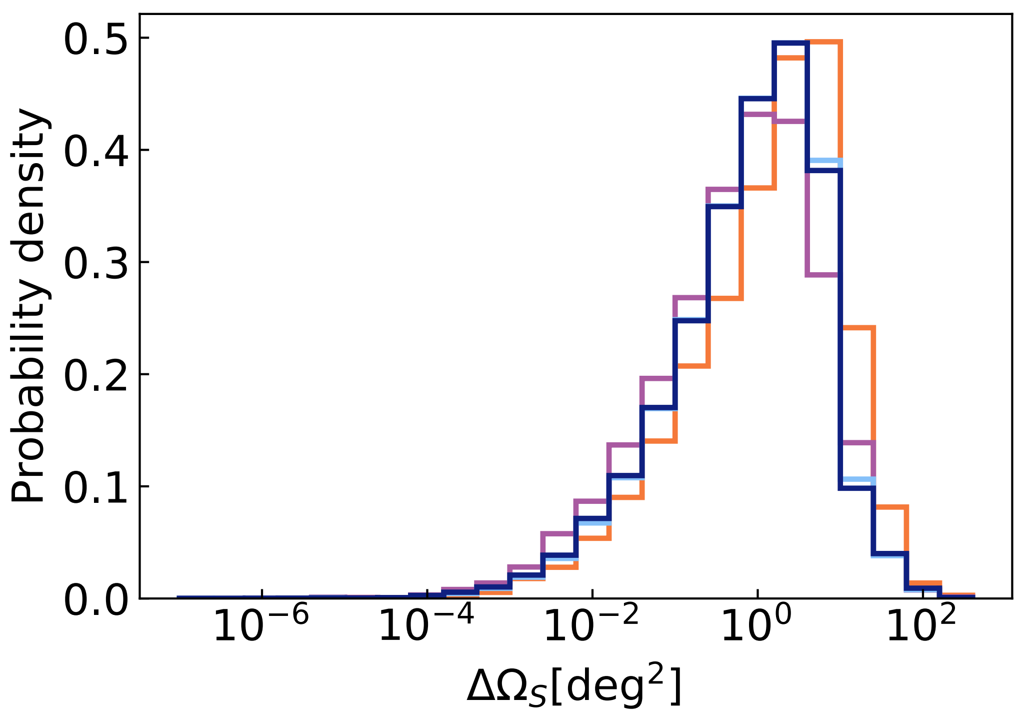


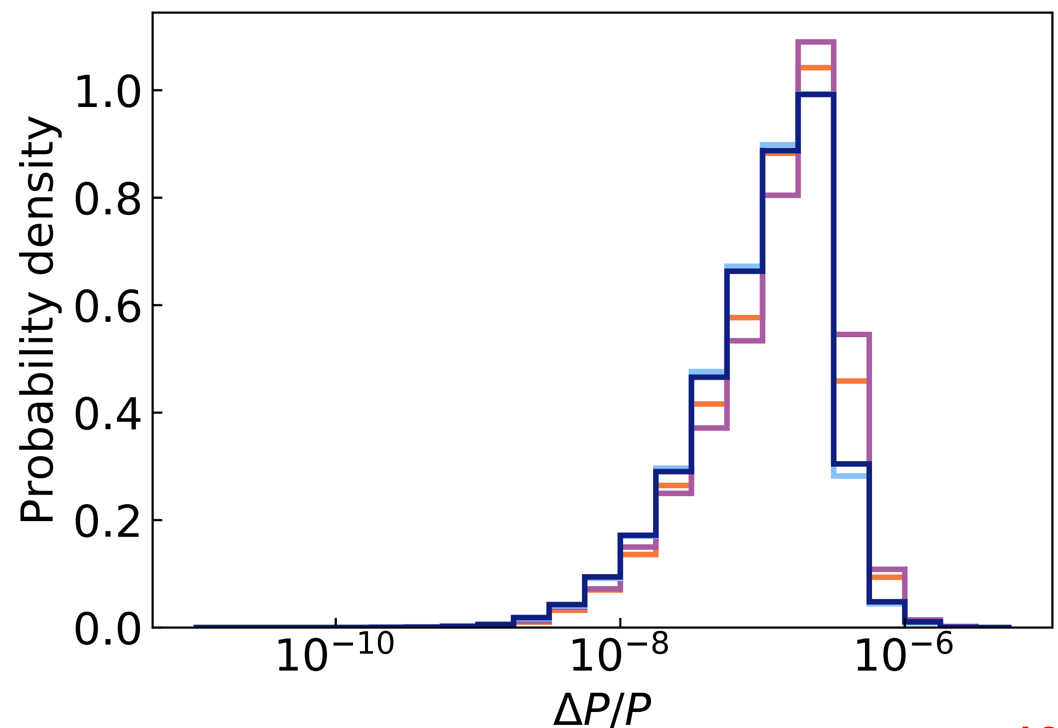
Galactic Binaries

□ Parameter estimation

- Can precisely determine parameters
- Localize within 1 sq. deg.
- Frequency determined to ~10^{-8}





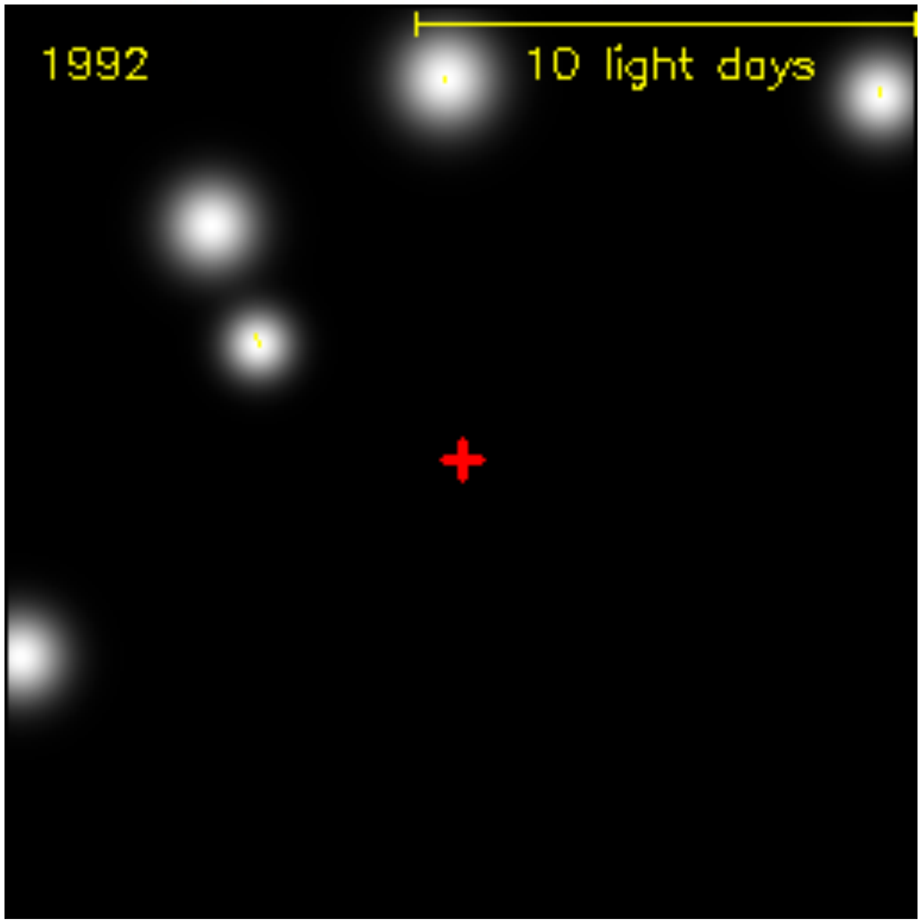


X

Massive black holes (MBH)

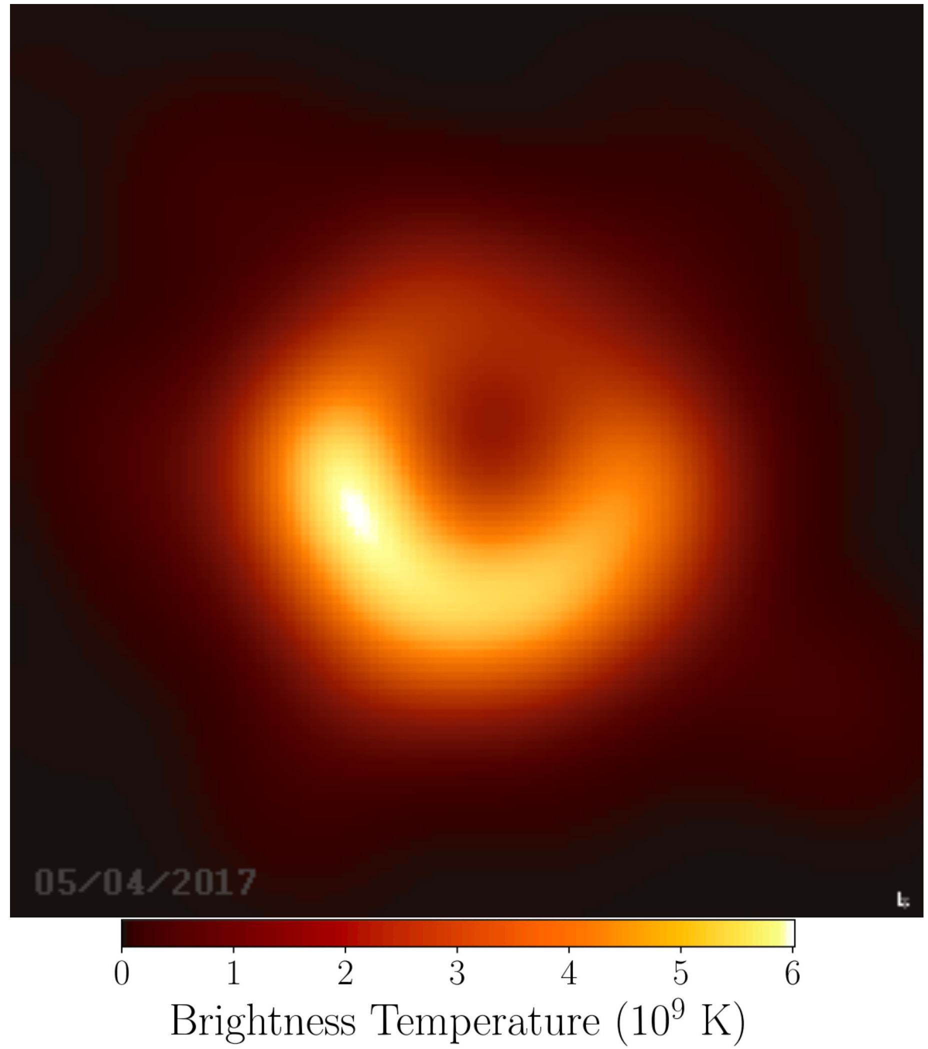
□ MBHs exist

- Sagittarius A*: MBH in the Galaxy
- About 4 million solar masses



Eisenhauer, F.; et al. (July 20, 2005). APJ 628 (1): 246–259. arXiv:astro-ph/0502129

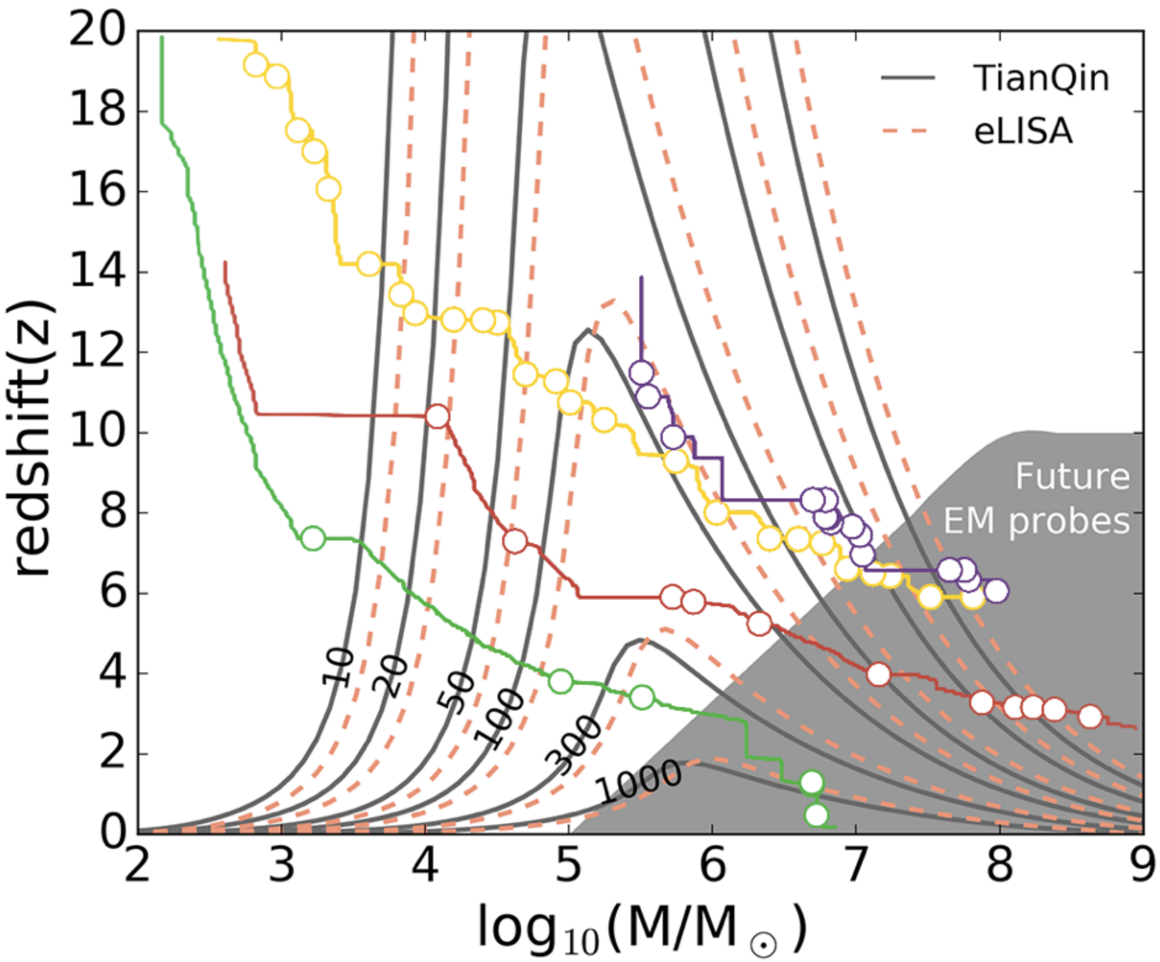
- EHT view on M87*
- 6.5 billion solar masses



The Event Horizon Telescope Collaboration, The Astrophysical Journal Letters, 875:L1

Massive black holes (MBH)

◻ MBH Mergers are deeply linked with galaxy evolution



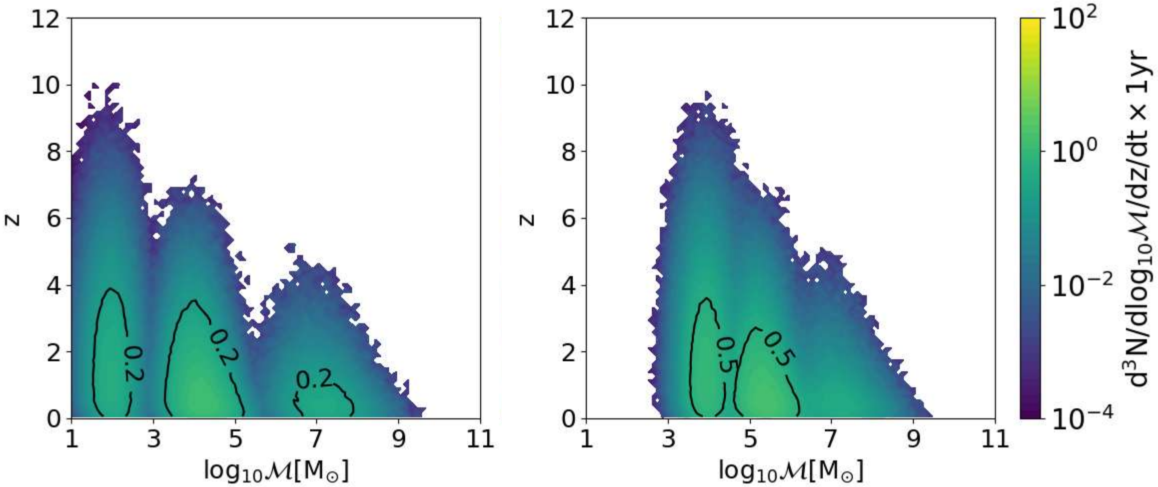
胡一鸣, 梅健伟, 罗俊, Natl. Sci. Rev. 4 (2017) no. 5, 683-684*

LISA XIII

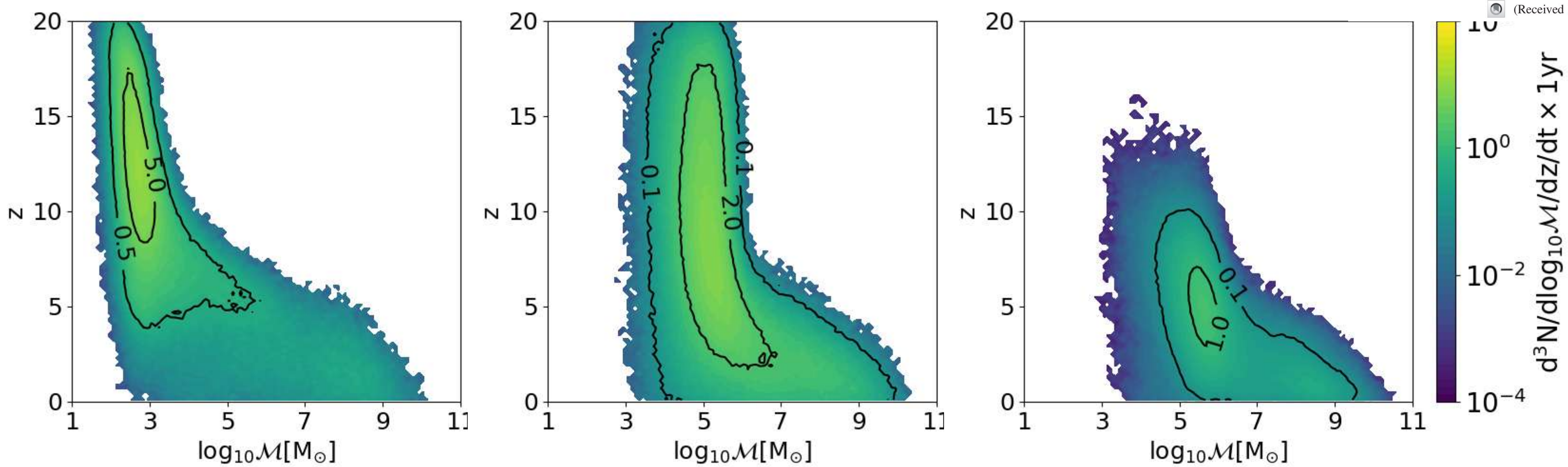
- MBH are ubiquitous in galaxy center ; MBH as massive as 10^5 solar mass observed in high redshift, questioning growth mechanism
- TQ can use GW detection to unveil the evolution of MBH and host galaxies.

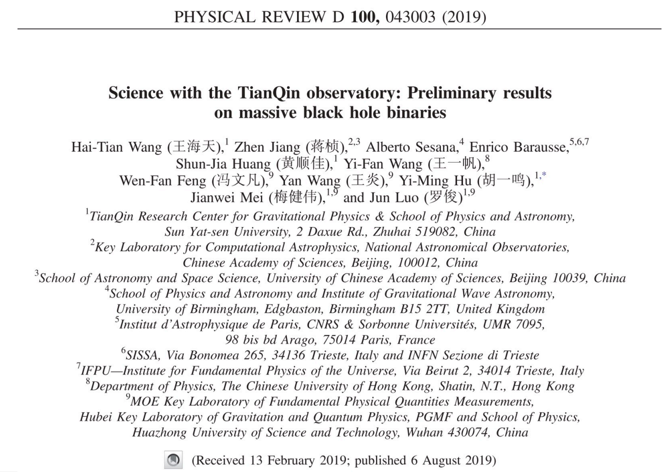
Massive black holes (MBH)

□ MBH merger history



L-seed **H-seed**





PHYSICAL REVIEW D **100**, 043003 (2019)

Science with the TianQin observatory: Preliminary results on massive black hole binaries

Hai-Tian Wang (王海天),[1] Zhen Jiang (蒋桢),[2,3] Alberto Sesana,[4] Enrico Barausse,[5,6,7] Shun-Jia Huang (黄顺佳),[1] Yi-Fan Wang (王一帆),[8] Wen-Fen Feng (冯文凡),[9] Yan Wang (王炎),[9] Yi-Ming Hu (胡一鸣),[1,*] Jianwei Mei (梅健伟),[1,9] and Jun Luo (罗俊)[1,9]

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(Received 13 February 2019; published 6 August 2019)

popIII **Q3_nod** **Q3_d**

Expected detection number

☐ Rate: per year

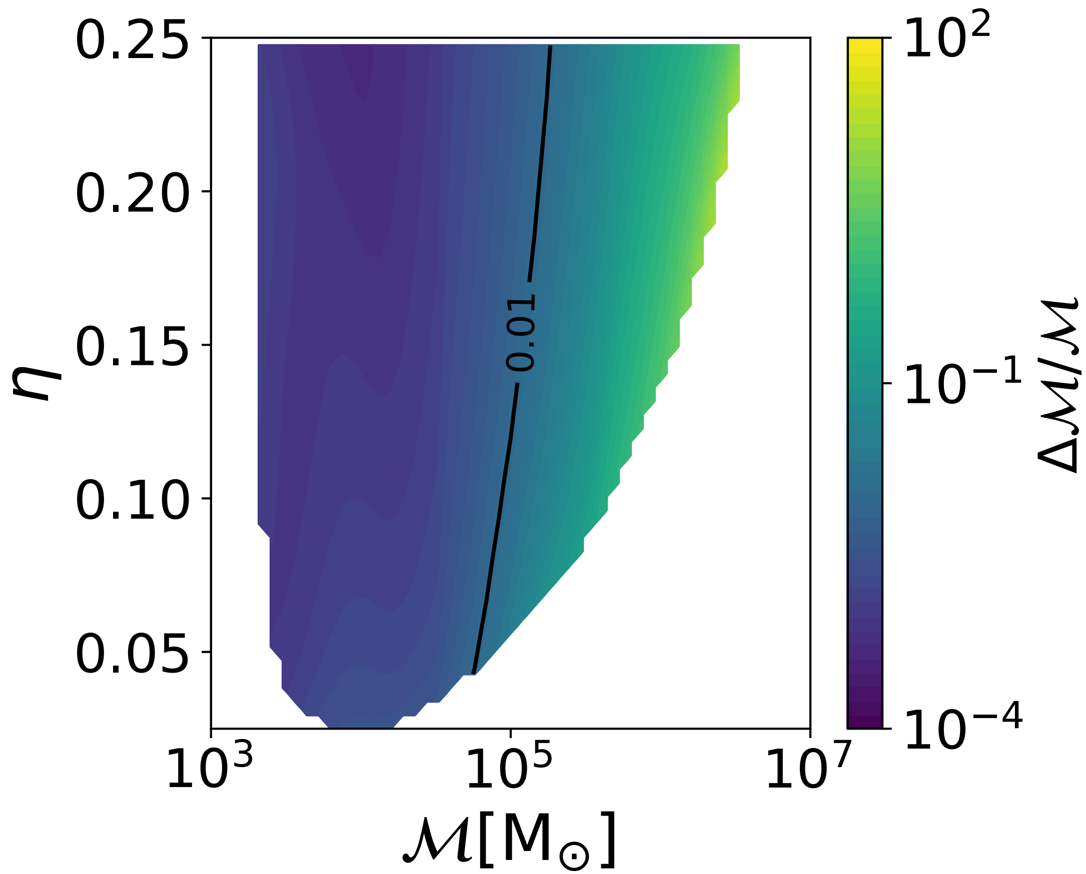
- With five years operation time

model	TQ	TQ I+II	Merger rate
L-seed	0.08	0.162	2.57
H-seed	1.055	1.642	2.57
popIII	10.58	22.60	174.70
Q3_d	4.42	8.06	8.18
Q3_nod	58.96	118.12	122.44

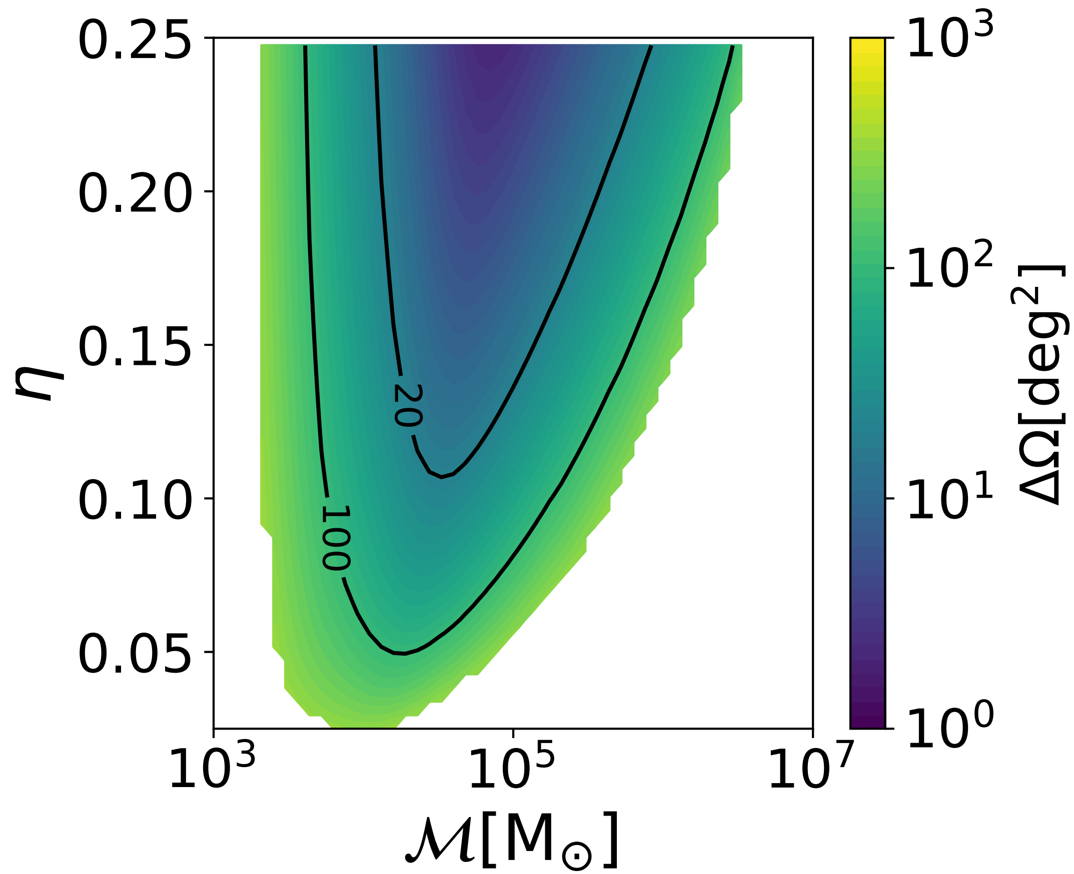
TianQin astronomy: Massive BBHs

Parameter estimation

- TQ can accurately determine parameters for far away events



Relative error of chirp mass

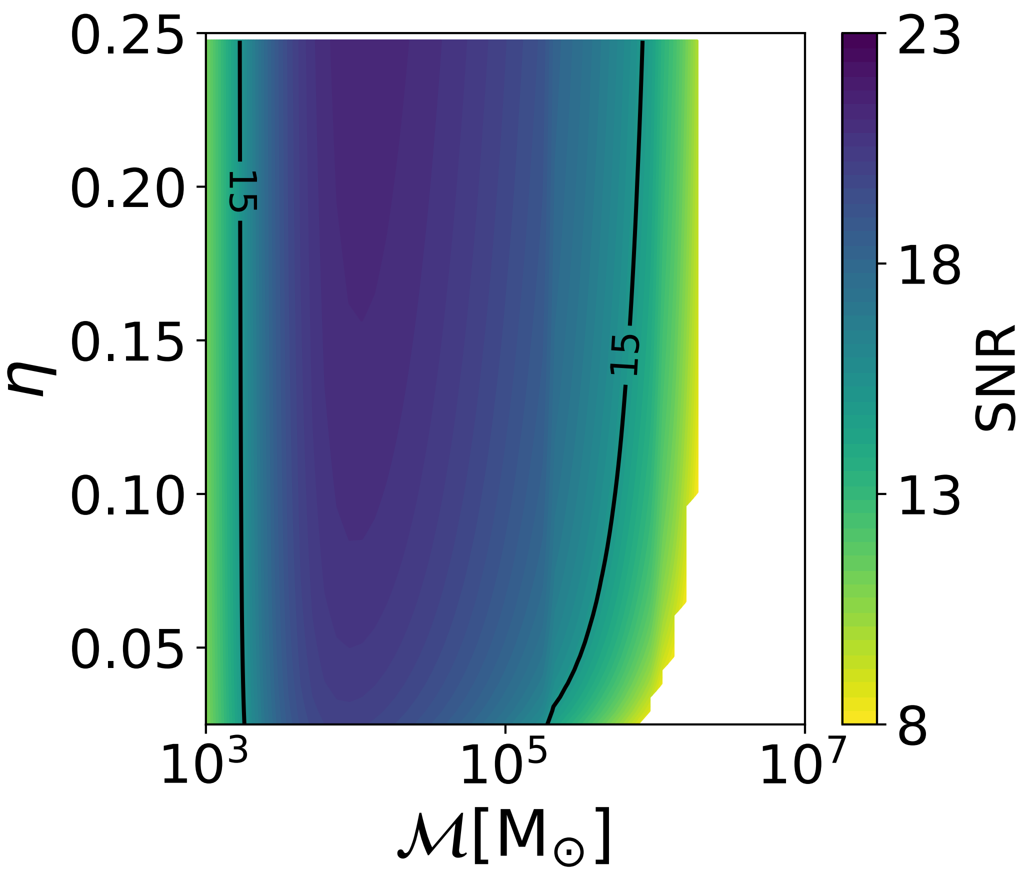


Relative error of sky localization

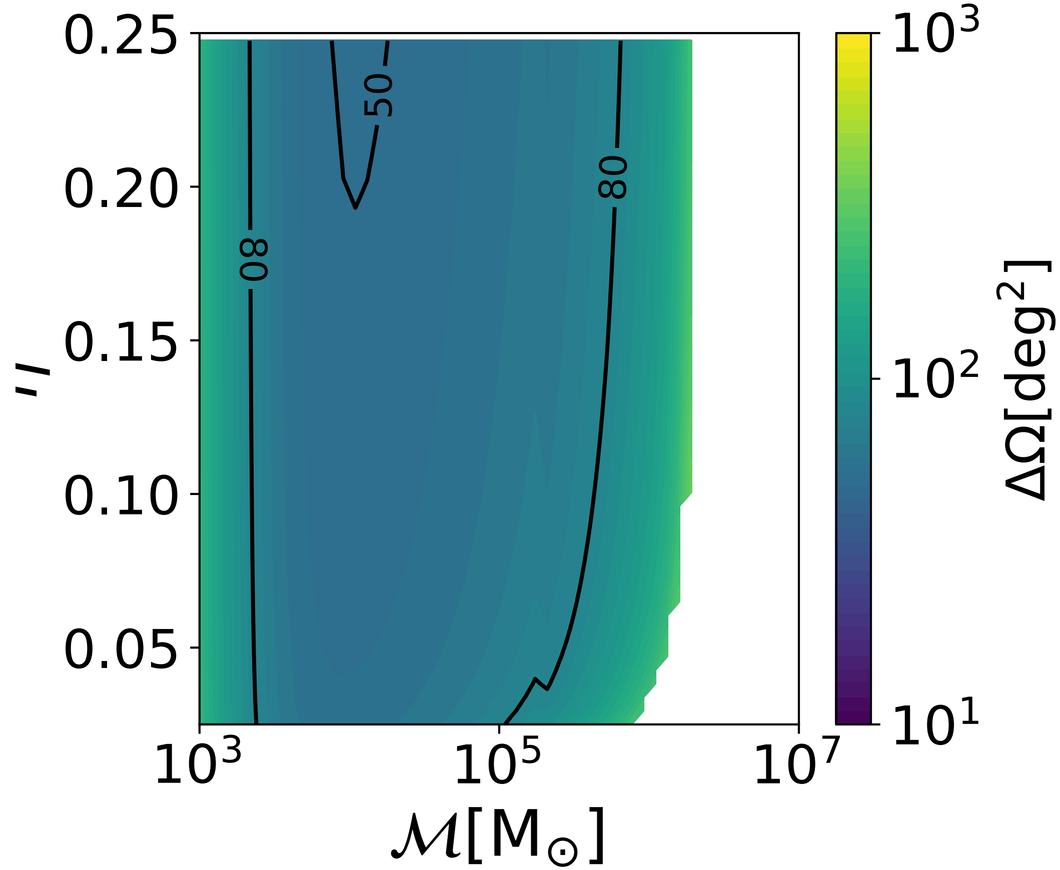
TianQin astronomy: Massive BBHs

□ Parameter estimation

- Issue early warning 24 hours before merger
- Available in arXiv:1902.04423, submitted to journal



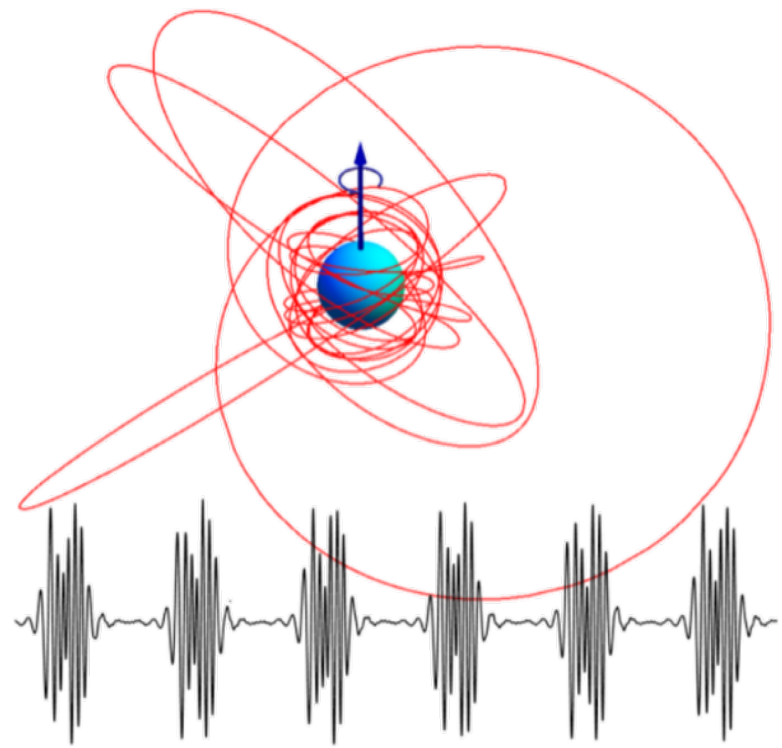
Distribution of SNR



Sky localization

Extreme mass ratio inspiral (EMRI)

- **Extreme mass ratio inspiral**
  - Capture of stellar mass compact object (black hole) with massive black holes
  - Rate highly uncertain, dependent on astronomical models
  - Waveform highly uncertain, challenging to produce accurate waveforms



V. Cardoso et al., arXiv:1908.11390

EMRI

□Astronomical models

1. MBH Mass distribution :

Barausse12

$$\frac{dn}{d\log M} = 0.005\left(\frac{M}{3\times10^{6}M_{\odot}}\right)^{-0.3} Mpc^{-3}$$

Gair10

$$\frac{dn}{d\log M} = 0.002\left(\frac{M}{3\times10^{6}M_{\odot}}\right)^{0.3} Mpc^{-3}$$

2.MBH spin :

High	a98
Flat	0<a<1
Zero	a=0

3. M-σ relation :

Gultekin09

$$t_{cusp} \sim 6Gyr$$

KormendyHo13

$$t_{cusp} \sim 10Gyr$$

GrahamScott13

$$t_{cusp} \sim 2Gyr$$

4.Capture rate of CO :

$$R_0 = 3000(1 + N_p)\left(\frac{m}{10M_{\odot}}\right)\left(\frac{M}{10^6 M_{\odot}}\right)^{-0.19} M_{\odot}Gyr^{-1}$$

S. Babak and J. Gair, Phys. Rev D 95, 103012(2017)

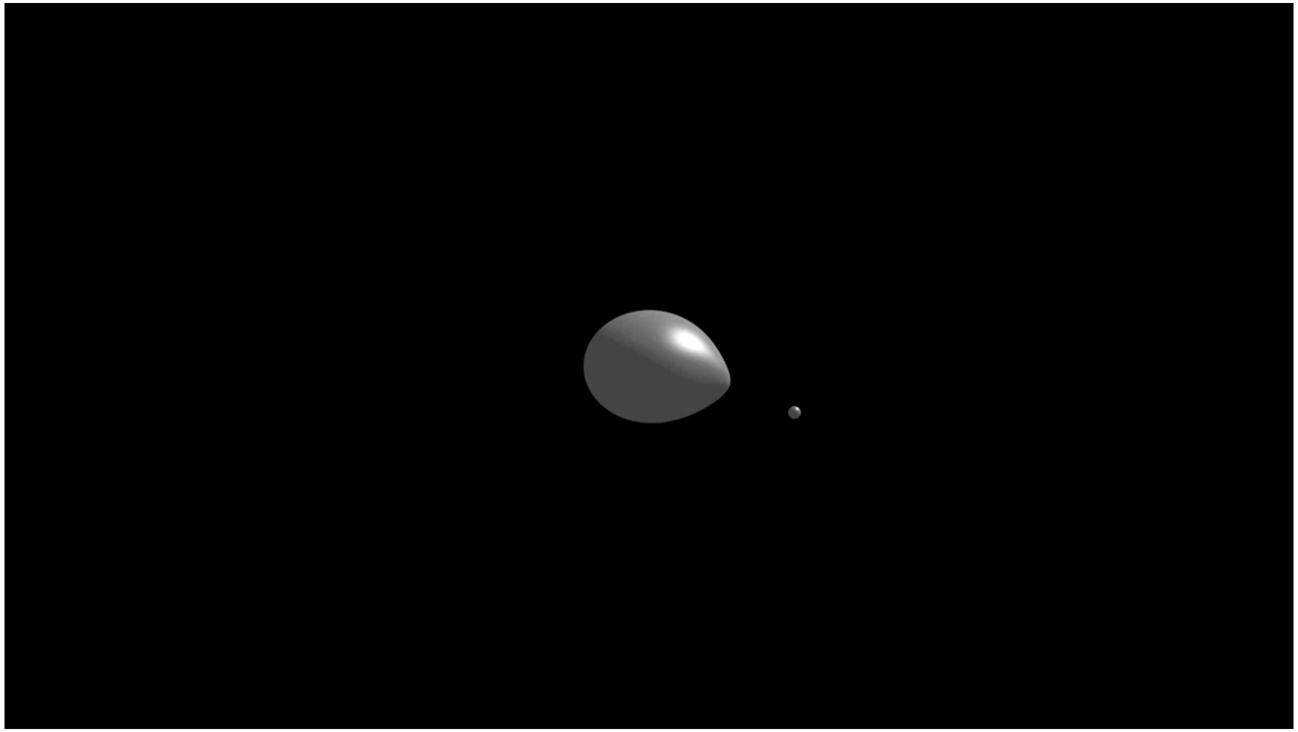
□ 12 combinations of assumptions

Model	Mass function	MBH spin	Cusp erosion	M–σ relation	N_{p}	CO mass $[M_{\odot}]$	EMRI rate $[\mathrm{yr}^{-1}]$ Total
M1	Barausse12	a98	yes	Gultekin09	10	10	1600
M2	Barausse12	a98	yes	KormendyHo13	10	10	1400
M3	Barausse12	a98	yes	GrahamScott13	10	10	2770
M4	Barausse12	a98	yes	Gultekin09	10	30	520 (620)
M5	Gair10	a98	no	Gultekin09	10	10	140
M6	Barausse12	a98	no	Gultekin09	10	10	2080
M7	Barausse12	a98	yes	Gultekin09	0	10	15800
M8	Barausse12	a98	yes	Gultekin09	100	10	180
M9	Barausse12	aflat	yes	Gultekin09	10	10	1530
M10	Barausse12	a0	yes	Gultekin09	10	10	1520
M11	Gair10	a0	no	Gultekin09	100	10	13
M12	Barausse12	a98	no	Gultekin09	0	10	20000

S. Babak and J. Gair, Phys. Rev D 95, 103012(2017)

□ Waveform：Analytical kludge

- In analytical kludge (AK) waveform, EMRI system follow PN orbit, emitting GW following equation for elliptical orbit, and secular evolution using PN equations.
- Cutoff condition：Schwarzschild ISCO (“AKS” waveform) or Kerr ISCO (“AKK” waveform)。



Credit: Steve Drasco

EMRI

https://arxiv.org/pdf/2005.08212.pdf

Science with the TianQin observatory: Preliminary result on extreme-mas inspirals

Hui-Min Fan,[1] Yi-Ming Hu,[2,*] Enrico Barausse,[3,4,5] Alberto Sesana,[6]
Jian-Dong Zhang,[2,†] Xuefeng Zhang,[2] Tie-Guang Zi,[2] and Jianwei Mei[2,‡]
[1] *Centre for Gravitational Experiments, School of Physics, MOE Key Laboratory of Fundamental Physical Quantities Measurement & Hubei Key Laboratory of Gravitation and Quantum Physics, PGMF, Huazhong University of Science and Technology, Wuhan 430074, P. R. China*
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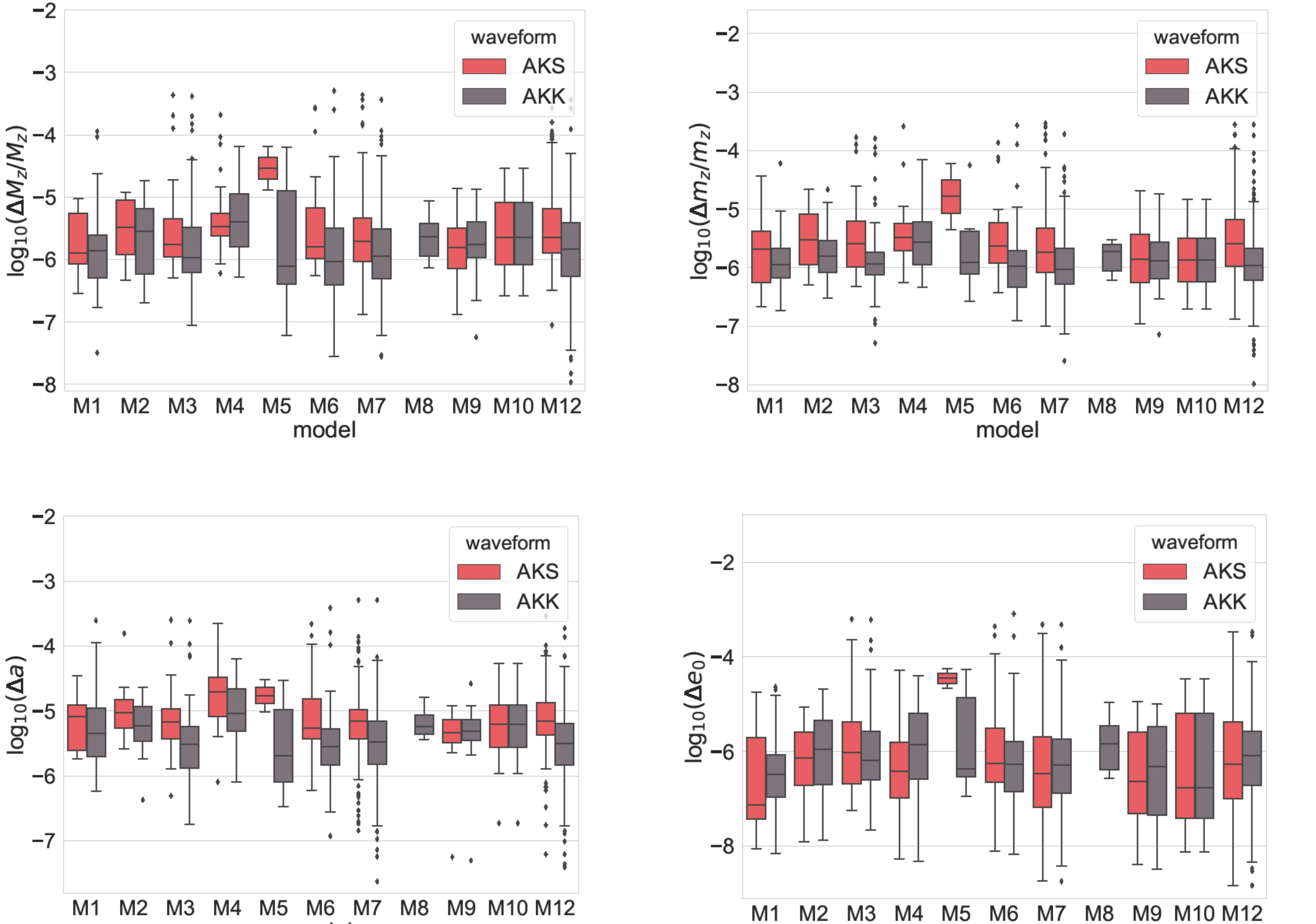
(Dated: May 19, 2020)

□AKK（AKS）rate

Model	detection rate of TianQin in mass range			Total
	$M_{10} < 5$	$5 < M_{10} < 6$	$6 < M_{10}$	
M1	1(1)	25(11)	8 (1)	34 (13)
M2	0(0)	18(12)	2(0)	20 (12)
M3	0(0)	83(28)	27 (2)	110(30)
M4	1 (0)	42(28)	7(3)	50(31)
M5	0(0)	4(2)	4(0)	8(2)
M6	1(1)	40(22)	23(0)	64(23)
M7	18(18)	187(121)	55(4)	260(143)
M8	0(0)	5(0)	1(0)	6(0)
M9	2(1)	16(14)	2(1)	20(16)
M10	0(0)	18(14)	0(0)	18(14)
M11	0(0)	0(0)	0(0)	0(0)
M12	13(11)	273(113)	150(2)	436(126)

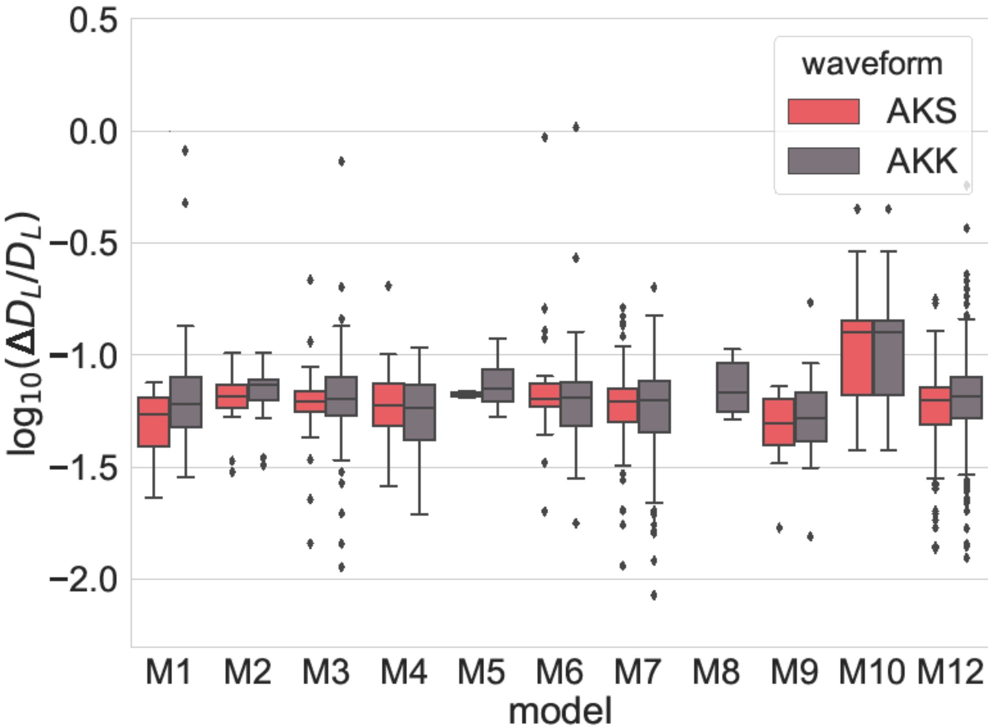
EMRI

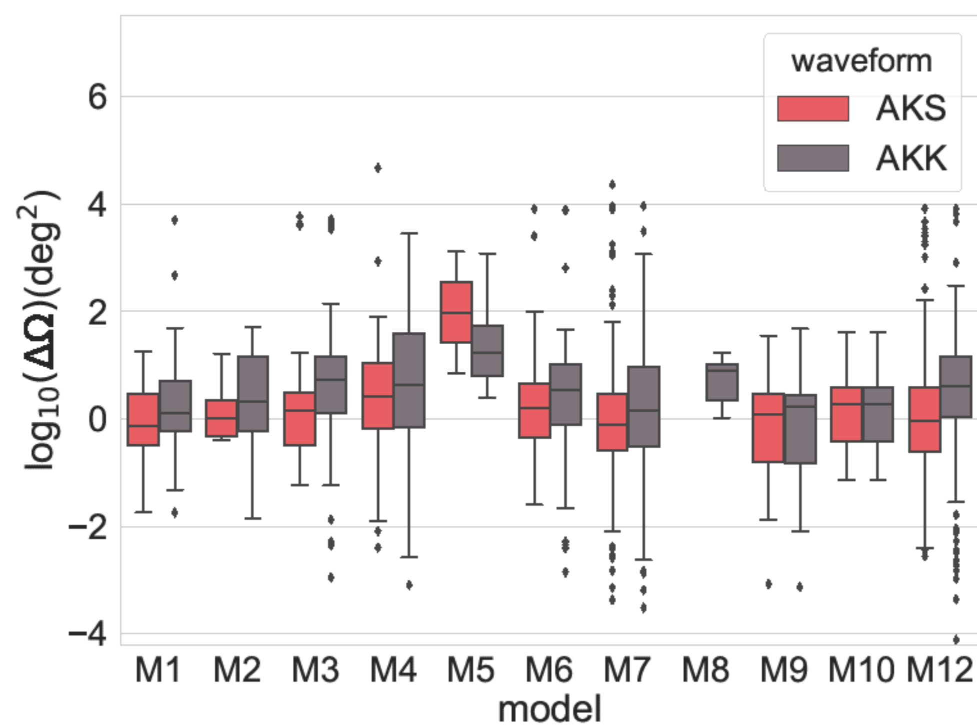
☐ PE precision for intrinsic parameters



EMRI

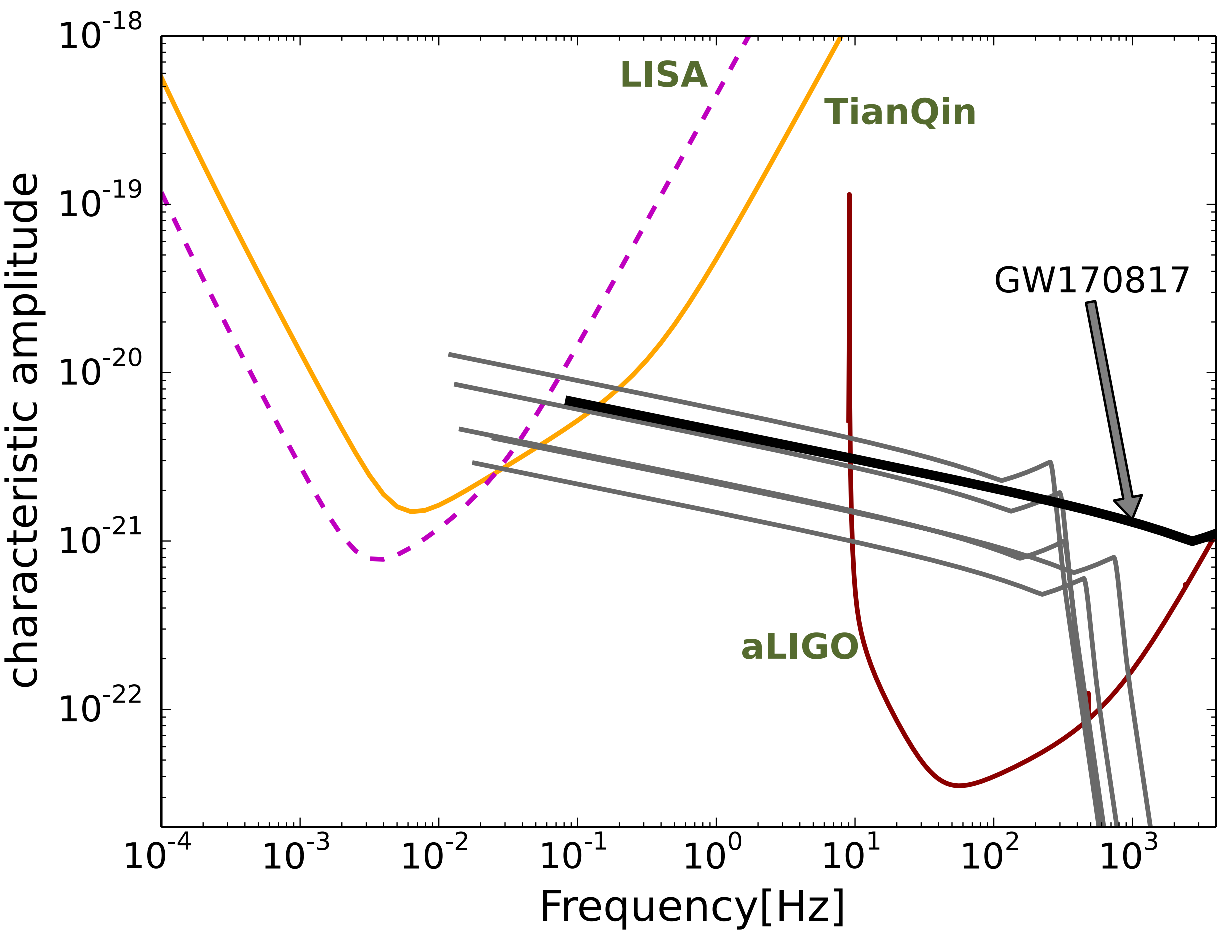
☐ PE precision for extrinsic parameters





Stellar Mass BBH

◻ Multi-band GW astronomy



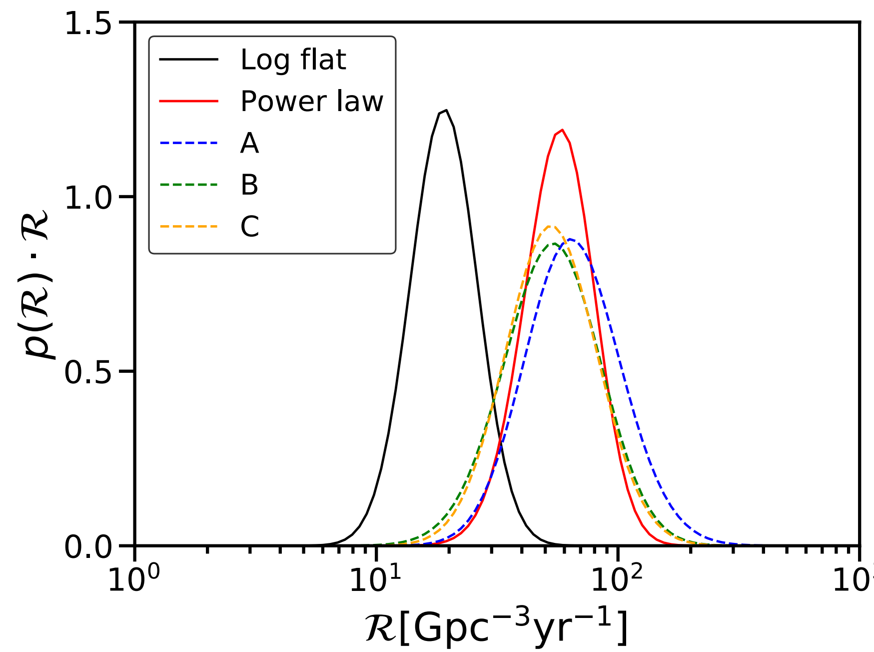
- Can observe the early inspirals of BBHs, forming early warning before merger (plotted as 10 years before merger)
- The possibility of multi-band GW observation opens a broad window of applications

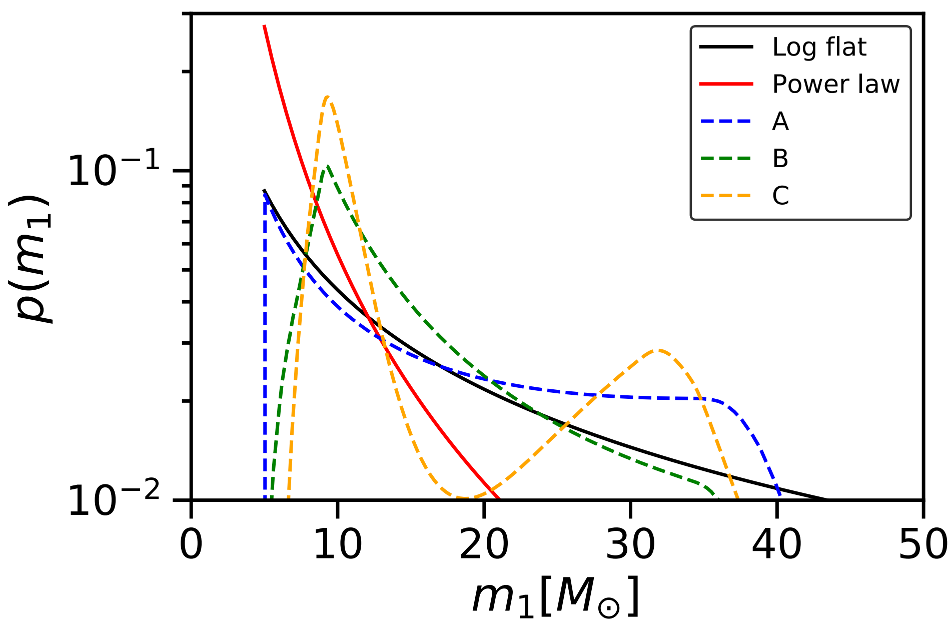
Hu, Y.-M., Mei, J. & Luo, J. NSR, 4, 683 (2017)

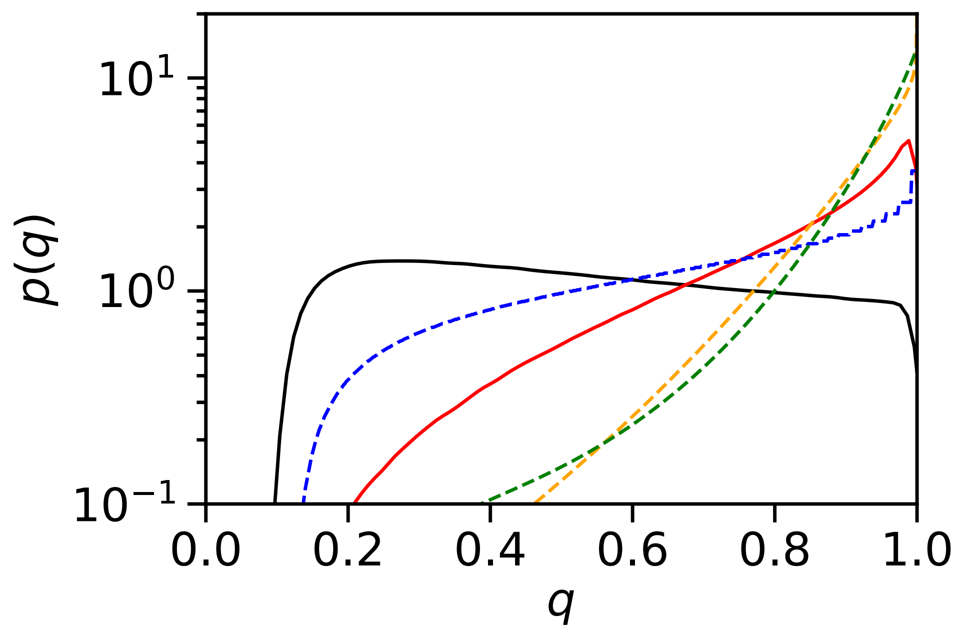
Stellar Mass BBH

□ simulated catalogue

- **Distribution of rate/mass/mass ratio derived using events detected by ground based detectors (LIGO/Virgo)**







Stellar Mass BBH

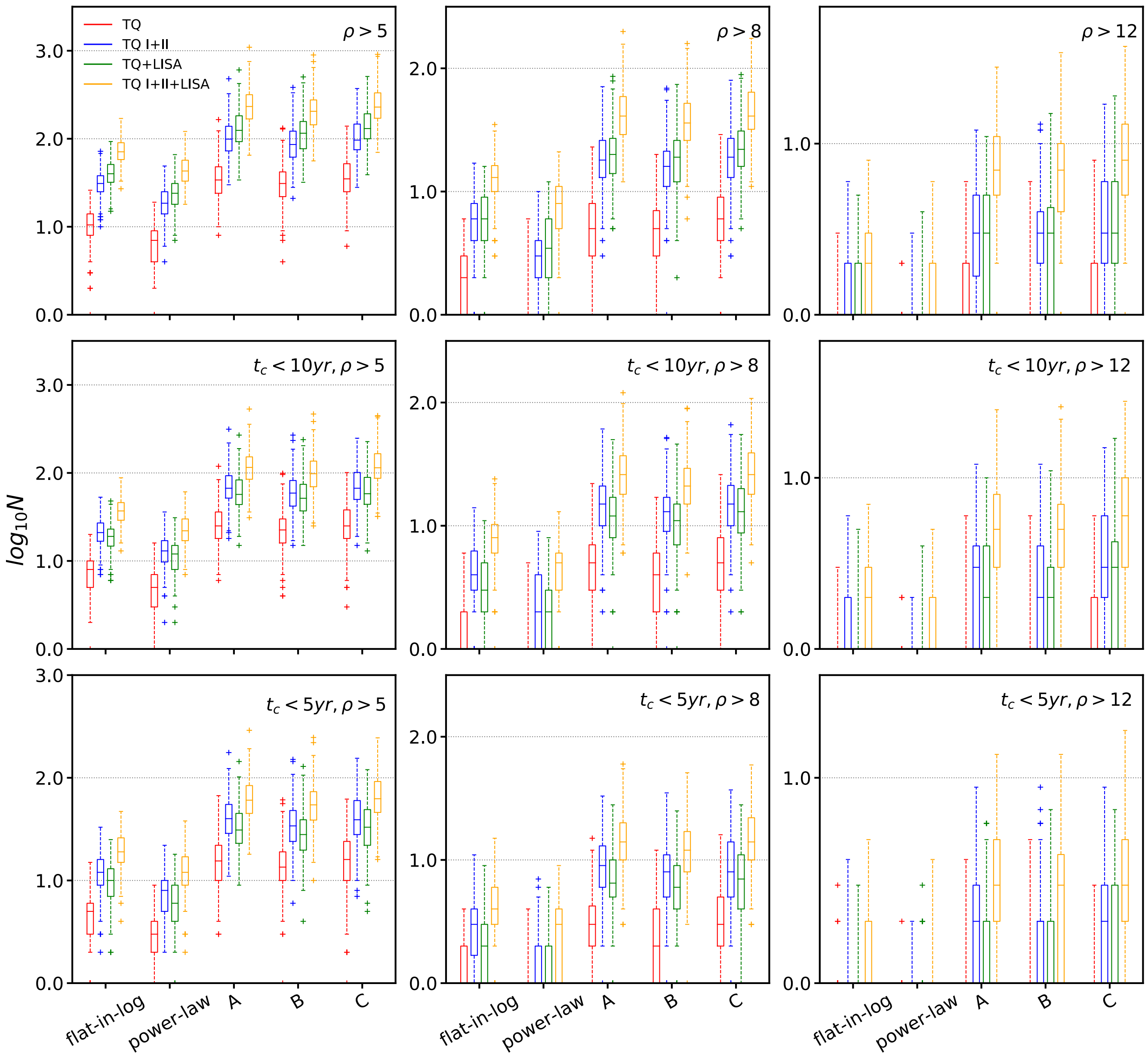
PHYSICAL REVIEW D **101,** 103027 (2020)

Science with the TianQin observatory: Preliminary results on stellar-mass binary black holes

Shuai Liu (刘帅)[1,*] Yi-Ming Hu (胡一鸣)[1,†] Jian-dong Zhang (张建东),[1,‡] and Jianwei Mei (梅健伟)[1,2,§]
[1]*TianQin Research Center for Gravitational Physics and School of Physics and Astronomy, Sun Yat-sen University (Zhuhai Campus), Zhuhai 519082, People's Republic of China*
[2]*MOE Key Laboratory of Fundamental Physical Quantities Measurements,*
ry of Gravitation and Quantum Physics, PGMF and School of Physics,
of Science and Technology, Wuhan 430074, People's Republic of China

3 February 2020; accepted 29 April 2020; published 21 May 2020)

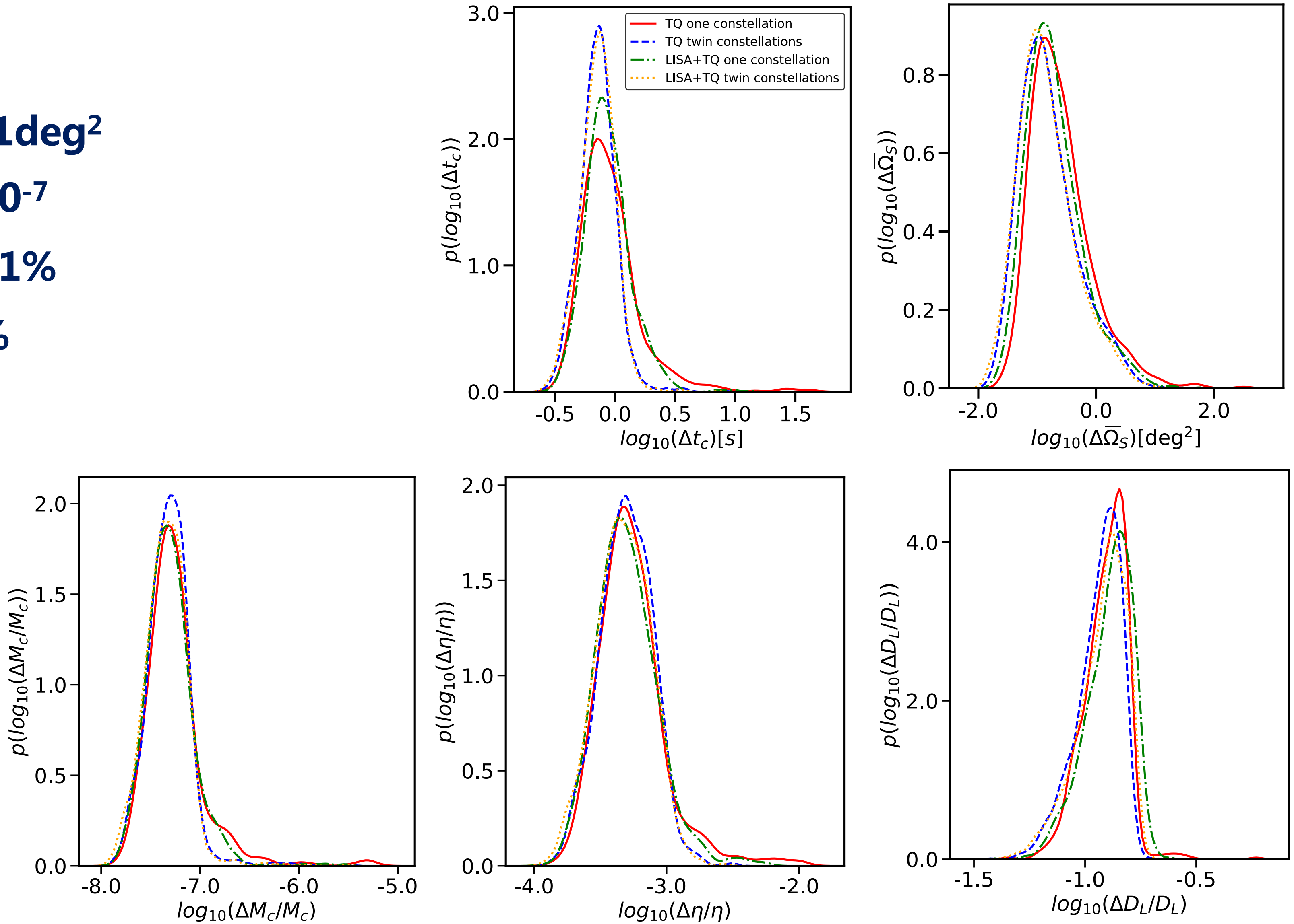
□ detection rate



Stellar Mass BBH

□ PE precision

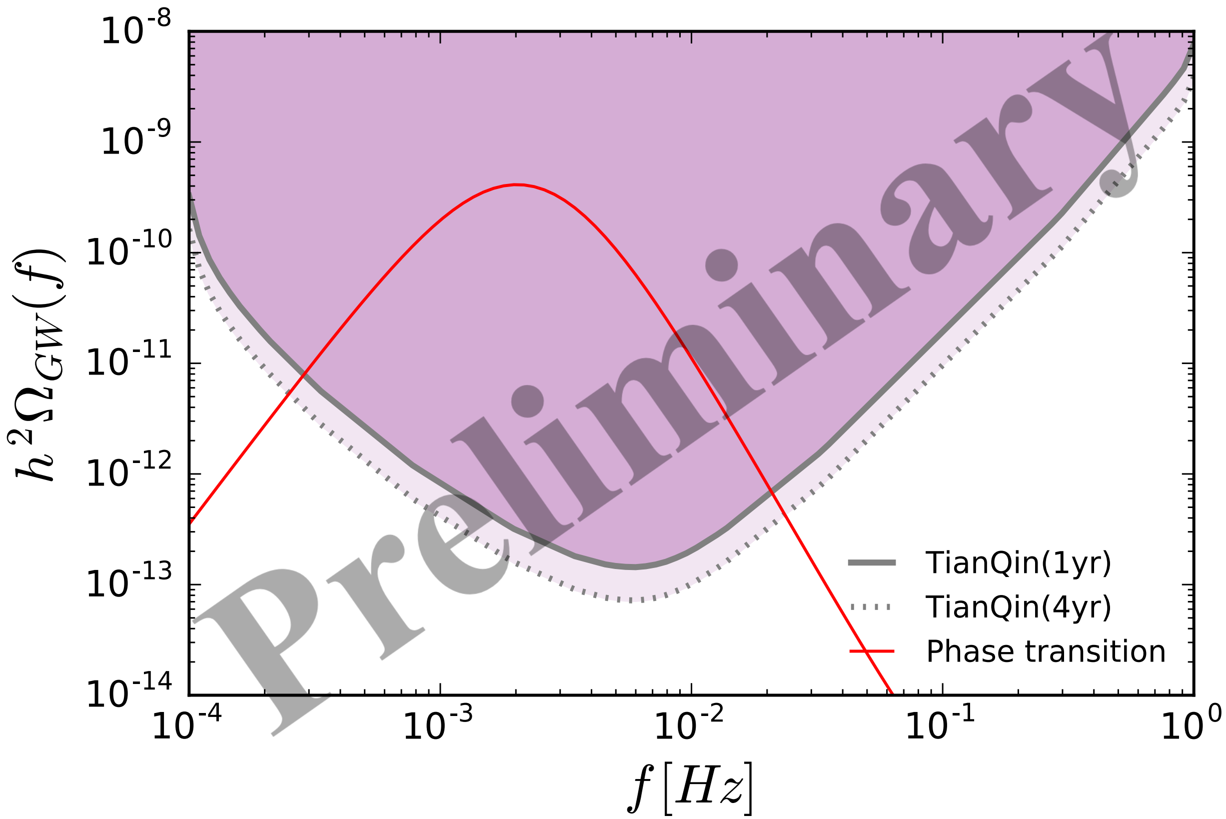
- Timing <1s
- Localisation <1deg²
- Chirp mass <10⁻⁷
- Mass ratio <0.1%
- Distance <20%



SGWB

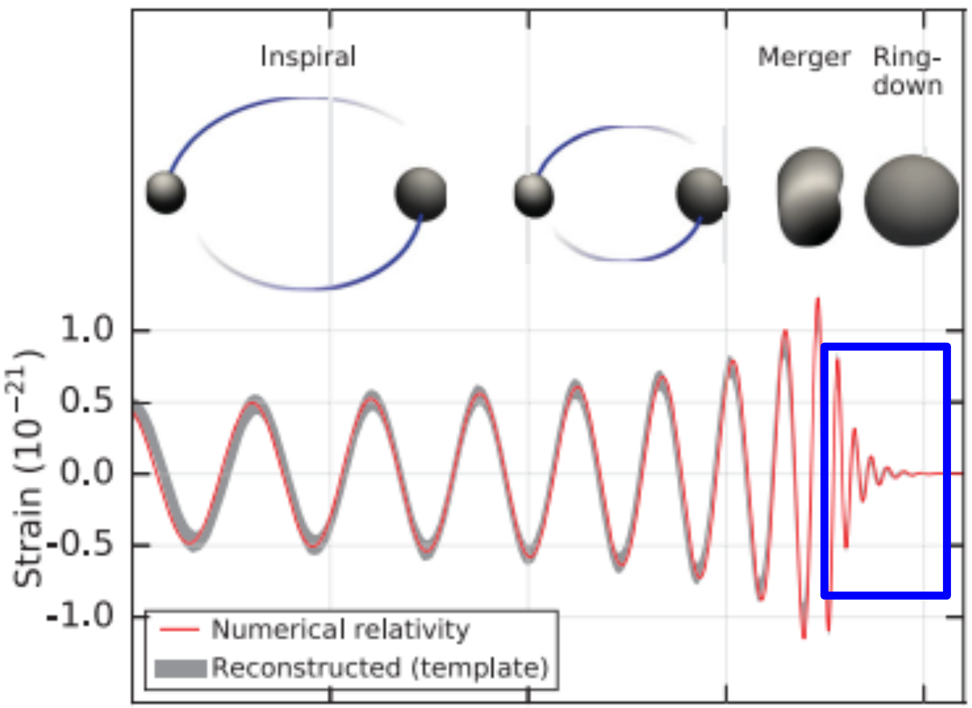
☐ Stochastic gravitational wave background (SGWB)

- **Large amount of low SNR signals exist, stacking up as SGWB**
- **SGWB is just like noise, only its origin being astronomical**
- **Can be produced by first order phase transition, vacuum bubble collision, BBH mergers etc.**



Testing GR

☐ Testing no-hair theorem with ringdown



Abbott et al. PRL.116(2016).061102

QNM

$$h_+(t) = \sum_{l,m>0} \frac{M}{D_L} A_{lm} Y_+^{lm}(\iota) \boxed{e^{\frac{-t}{\tau_{lm}}} \sin(\omega_{lm} t - m\phi)},$$

$$h_\times(t) = -\sum_{l,m>0} \frac{M}{D_L} A_{lm} Y_\times^{lm}(\iota) \boxed{e^{\frac{-t}{\boxed{\tau_{lm}}}} \cos(\boxed{\omega_{lm}} t - m\phi)}。$$

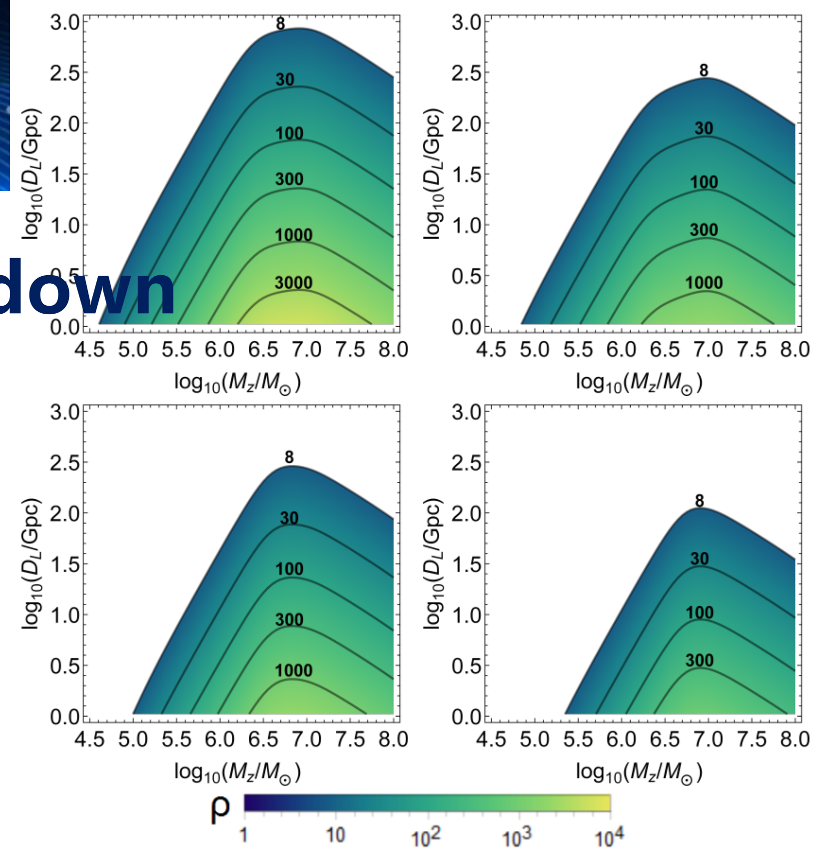
timescale frequency

- No-hair theorem : quasi-normal modes determined by BH mass/spin
- Using consistency test from multiple modes

Testing GR

☐ Testing no-hair theorem with ringdown

- ➢ Adopting 22, 21, 33, 44 modes
- ➢ Using $\delta\omega_{22}$, $\delta\tau_{22}$, $\delta\omega_{33}$ to perform consistency check

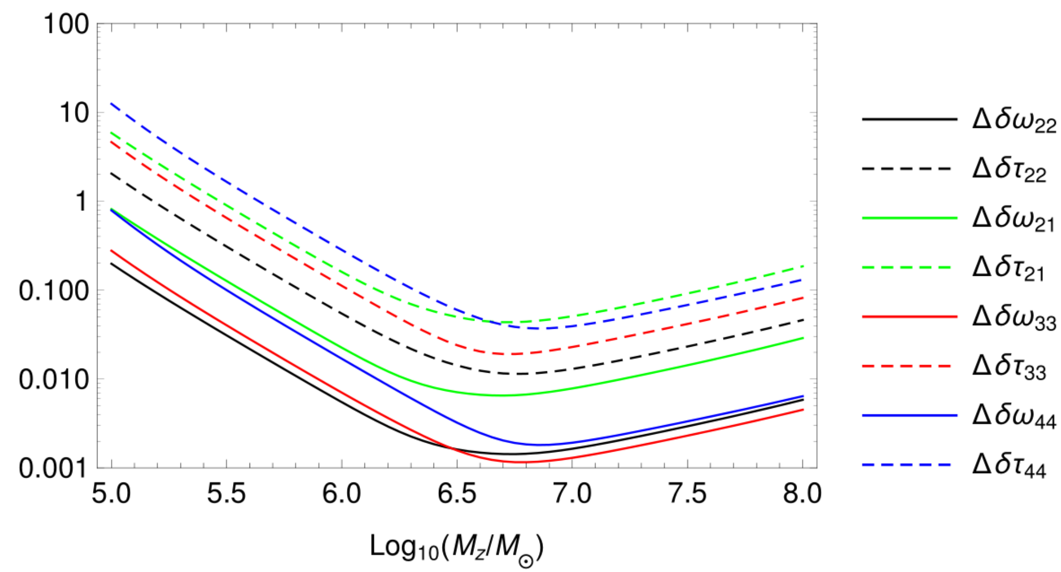


PHYSICAL REVIEW D **100,** 044036 (2019)

Science with the TianQin observatory: Preliminary results on testing the no-hair theorem with ringdown signals

Changfu Shi (石常富),[1,2] Jiahui Bao (包佳慧),[1] Hai-Tian Wang (王海天),[1] Jian-dong Zhang (张建东),[1,*]
Yi-Ming Hu (胡一鸣),[1] Alberto Sesana,[3] Enrico Barausse,[4,5,6] Jianwei Mei (梅健伟),[1,2,†] and Jun Luo (罗俊)[1,2]
[1]TianQin Research Center for Gravitational Physics and School of Physics and Astronomy,
...ampus), 2 Daxue Road, Zhuhai 519082, People's Republic of China
...mental Physical Quantities Measurement & Hubei Key Laboratory of
...ntum Physics, PGMF and School of Physics, Huazhong
...d Technology, Wuhan 430074, People's Republic of China
...Astronomy and Institute of Gravitational Wave Astronomy,
...ham, Edgbaston, Birmingham B15 2TT, United Kingdom
...physique de Paris, CNRS & Sorbonne Universités,
...095, 98 bis bd Arago, 75014 Paris, France
...a 265, 34136 Trieste, Italy and INFN Sezione di Trieste
...ntal Physics of the Universe, Via Beirut 2, 34014 Trieste, Italy

...d 25 February 2019; published 20 August 2019)



Testing GR

Constraining alternative theory with ringdown

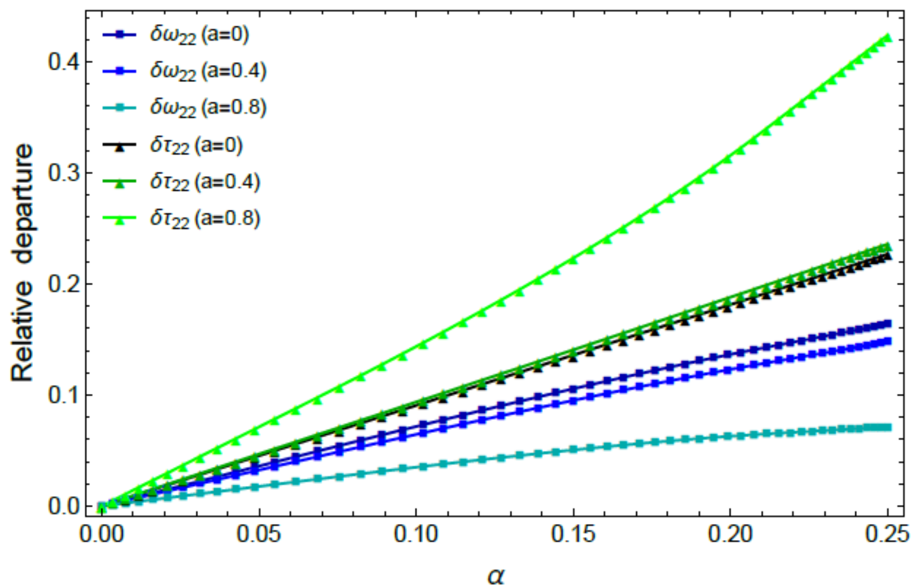
- Calculate QNM for spinning BH within STVG
- TQ can constrain α parameter
- Combining all events, can constrain up to 10^{-3}

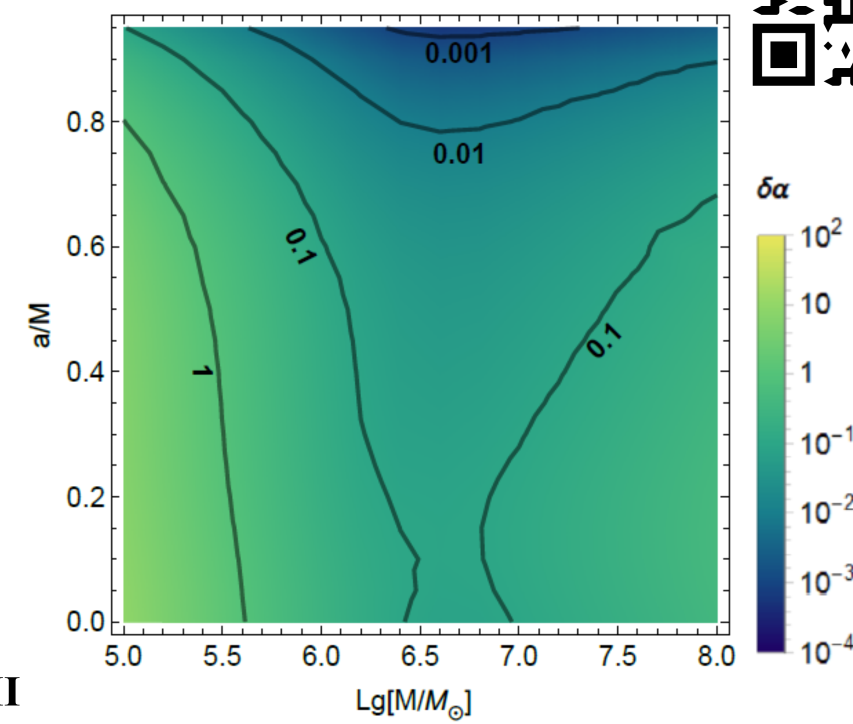
PHYSICAL REVIEW D **100**, 084024 (2019)

Constraining modified gravity with ringdown signals: An explicit example

Jiahui Bao (包佳慧),[1] Changfu Shi (石常富),[1,2] Haitian Wang (王海天),[1] Jian-dong Zhang (张建东),[1,*]
Yiming Hu (胡一鸣),[1] Jianwei Mei (梅健伟),[1,2,†] and Jun Luo (罗俊)[1,2]
[1]*TianQin Research Center for Gravitational Physics and School of Physics and Astronomy, Sun Yat-sen University (Zhuhai Campus), 2 Daxue Rd., Zhuhai 519082, People's Republic of China*
[2]*MOE Key Laboratory of Fundamental Physical Quantities Measurement & H*
Gravitation and Quantum Physics, PGMF and School of Physics, Huazhong U
Technology, Wuhan 430074, People's Republic of Chin

(Received 30 May 2019; published 14 October 201

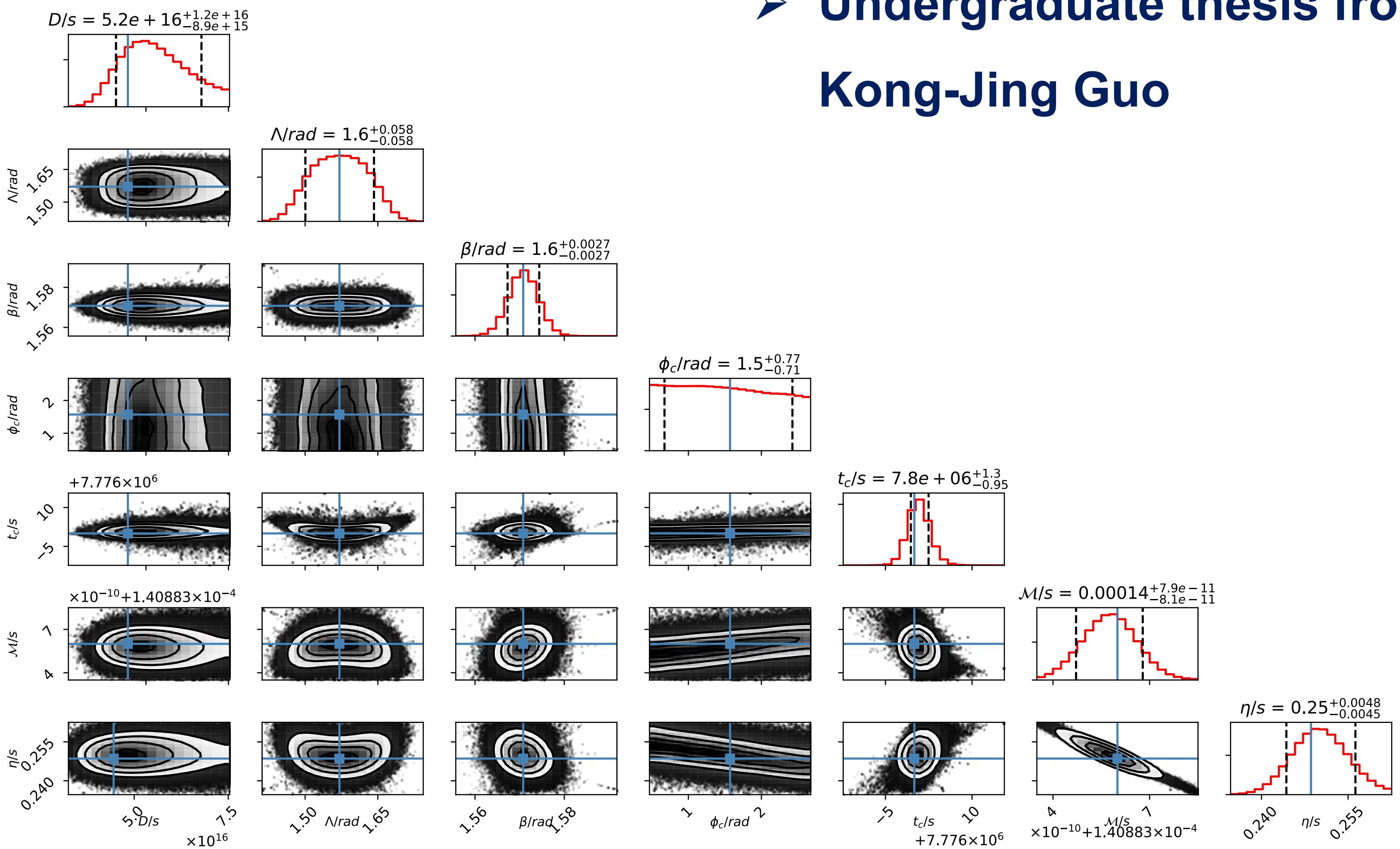




J. Bao et al. PRD 100, 084024 (2019)

Data analysis

Stellar mass BBH



- **Undergraduate thesis from Kong-Jing Guo**

Overview

Overview of the TianQin project

TianQin science objects

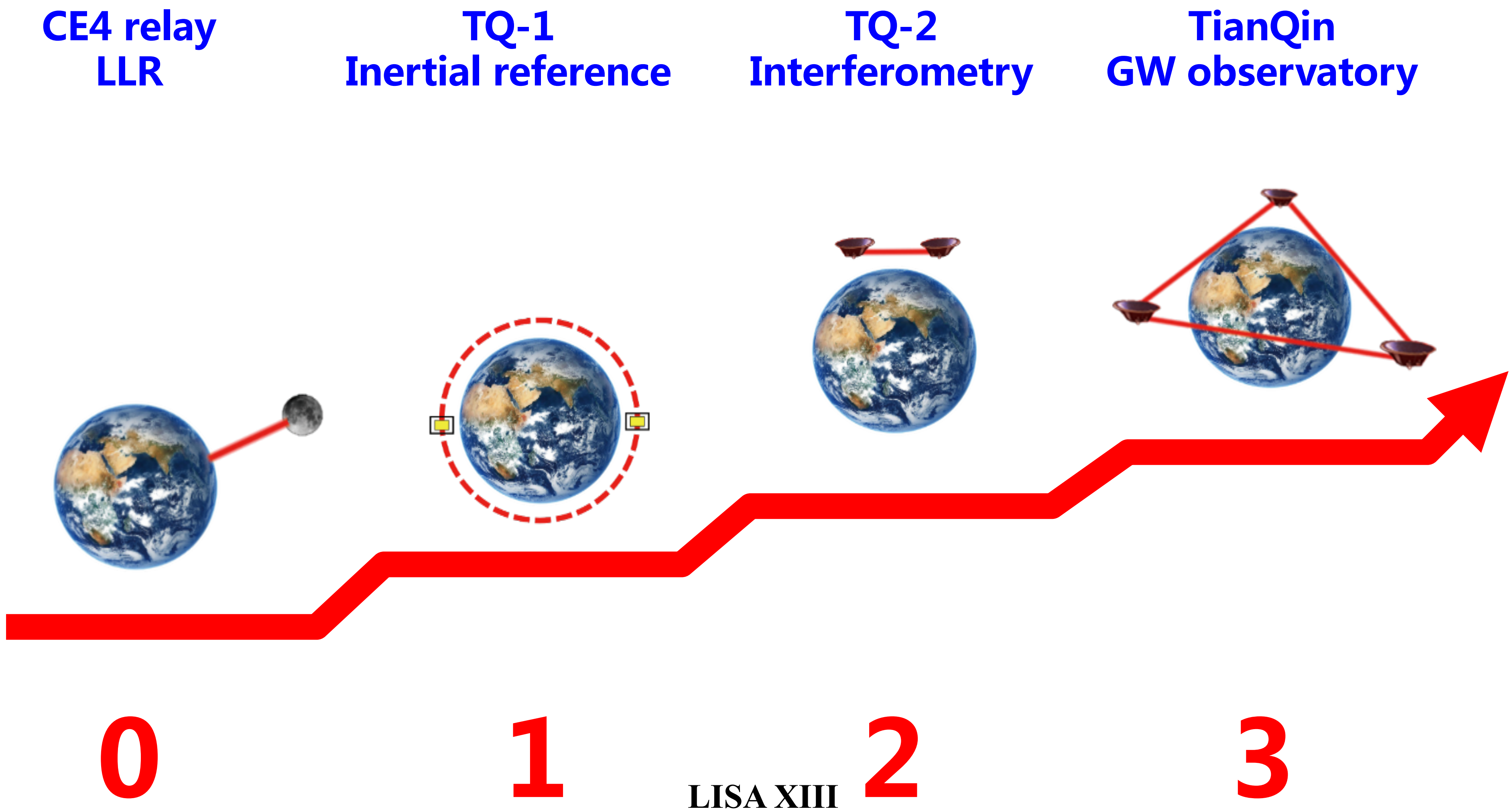
Progress of TianQin

Summary

中山大學 天琴中心
TianQin Research Center for Gravitational Physics

Roadmap of TianQin

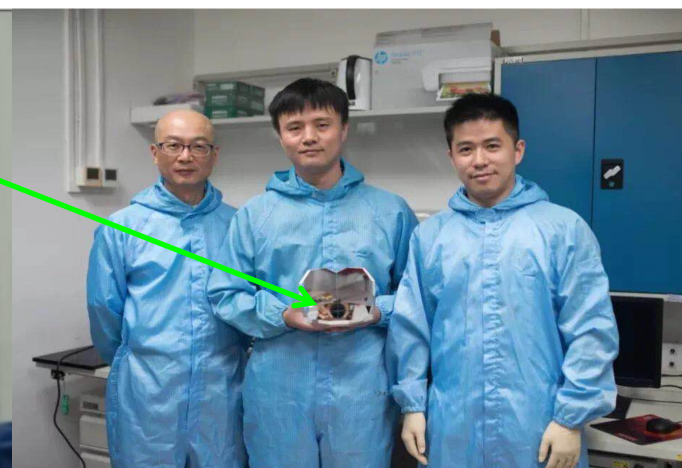
- 0123 steps

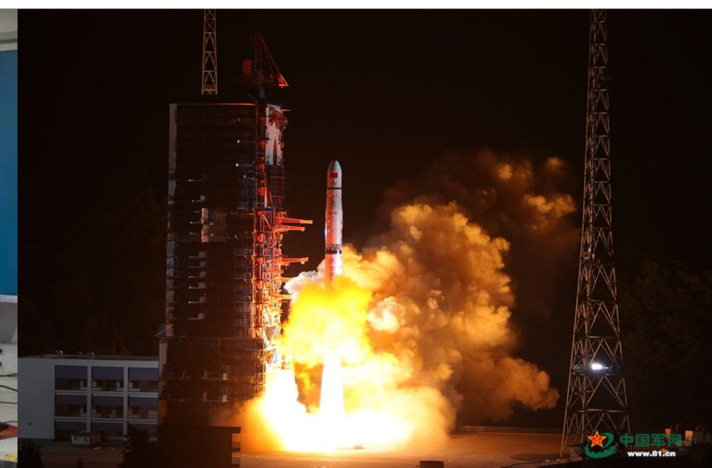


Lunar laser ranging

☐ Reflector

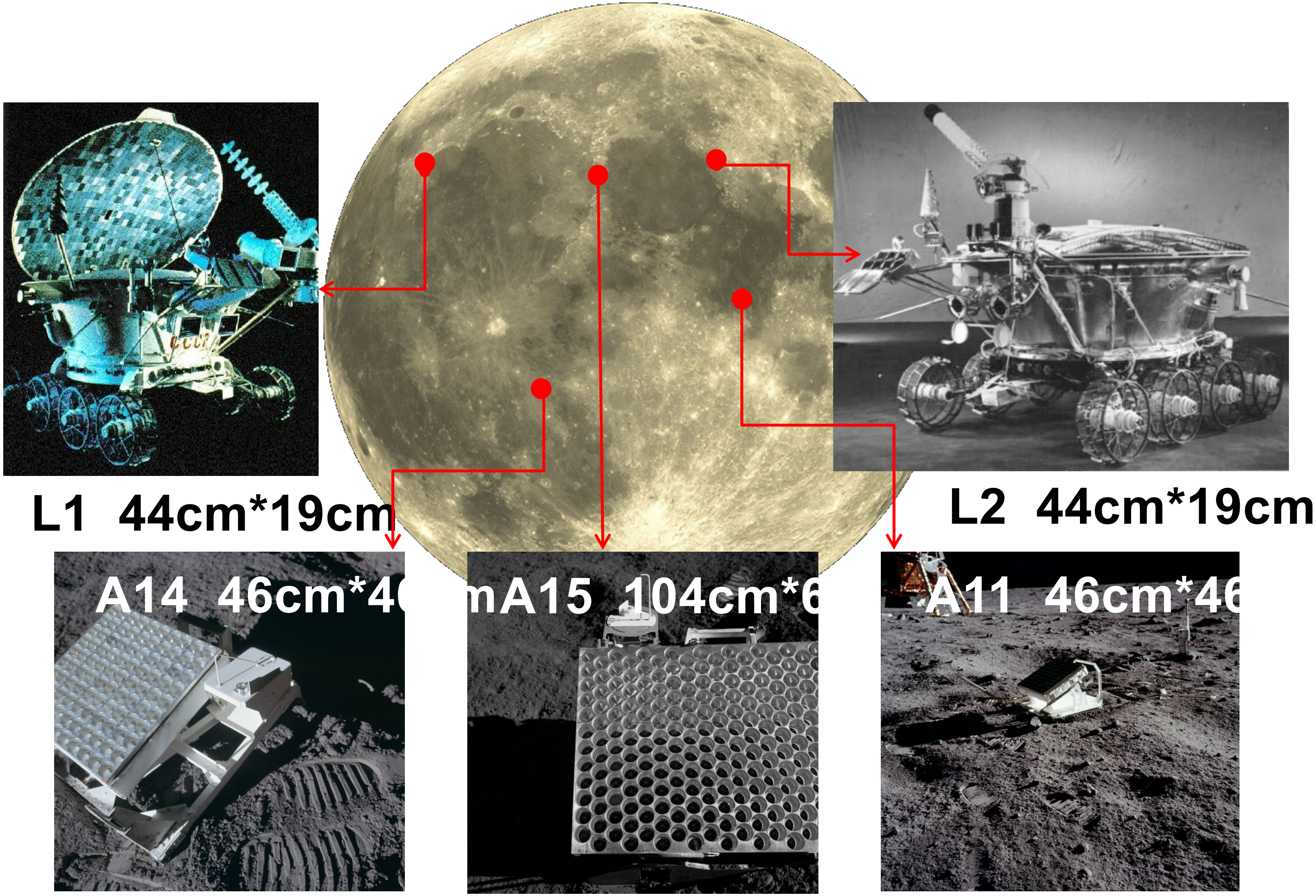
Loaded in Queqiao **17-cm corner reflector**





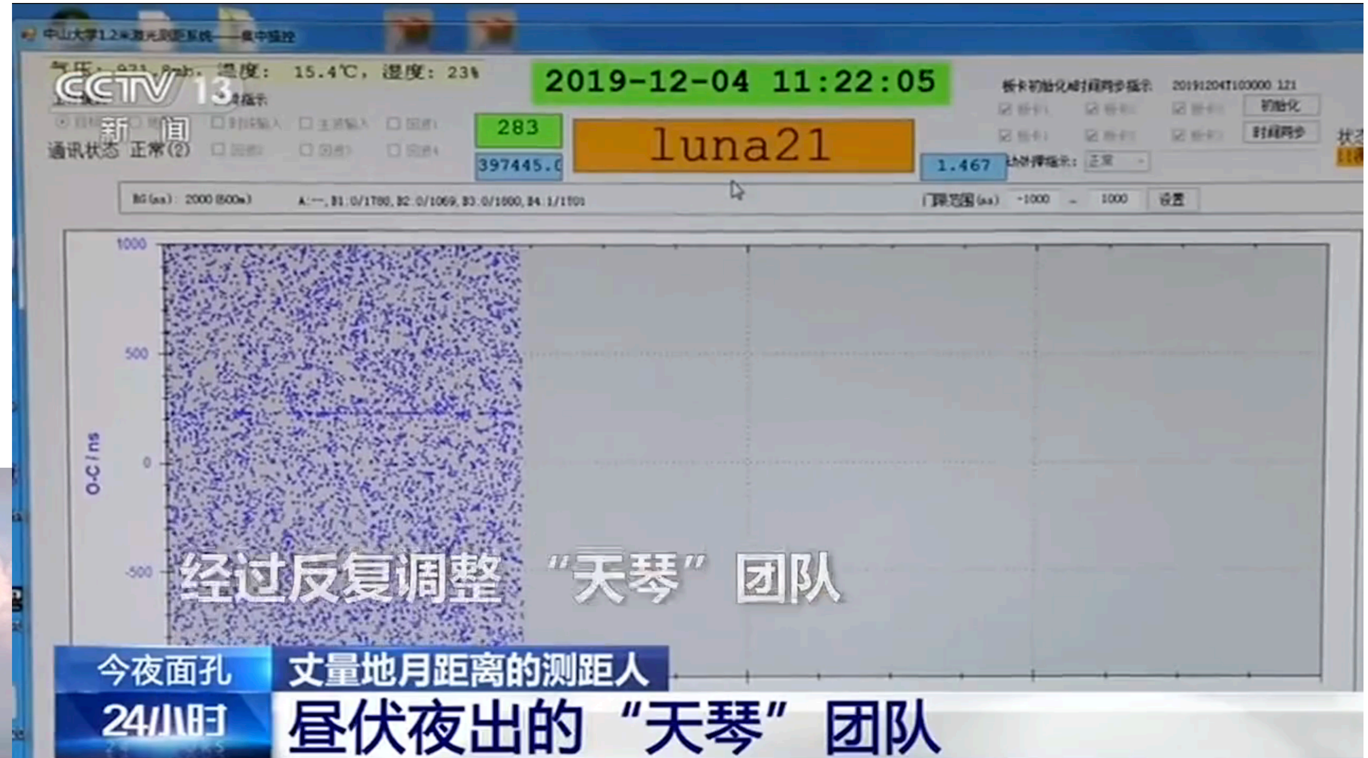
LLR progress

□ Reflectors location



LLR progress

□LLR



TQ-1 progress

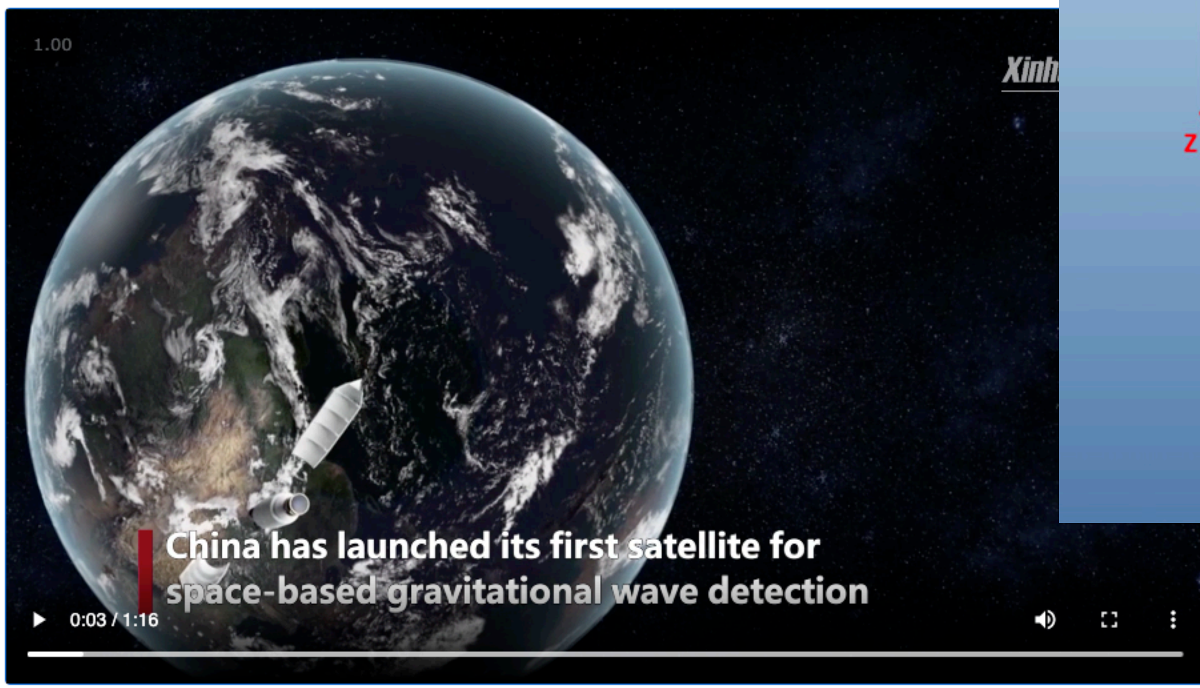
新华网 NEWS www.xinhuanet.com XINHUANET

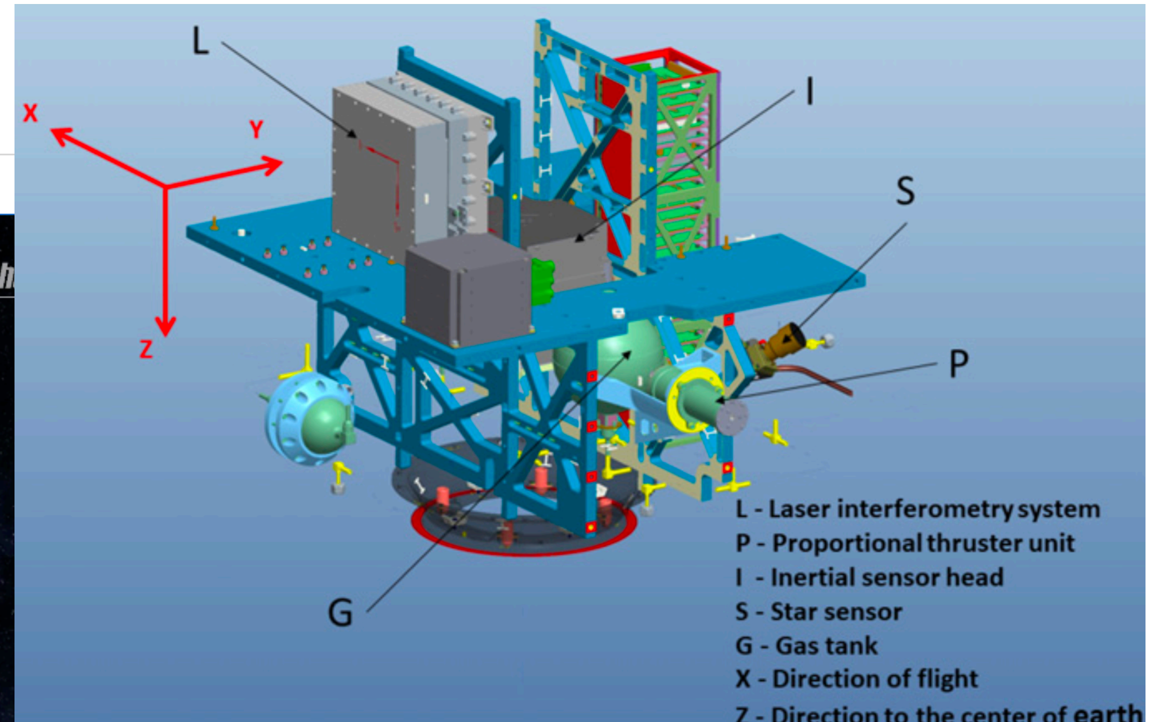
Sunday, June 28, 2020

Editions

China launches first satellite for space-based gravitational wave detection

Source: Xinhua | 2019-12-21 18:19:16 | Editor: huaxia





A new milestone: China launches Tianqin-1, its first satellite for space-based gravitational wave detection.

TQ-1 progress

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Classical and Quantum Gravity

PAPER

The first round result from the TianQin-1 satellite

Jun Luo[1,2], Yan-Zheng Bai[2], Lin Cai[2], Bin Cao[1], Wei-Ming Chen[1], Yu Chen[1], De-Cong Cheng[2], Yan-Wei Ding[1], Hui-Zong Duan[1], Xingyu Gou[3] + Show full author list

Published 19 August 2020 • © 2020 IOP Publishing Ltd

Classical and Quantum Gravity, Volume 37, Number 18

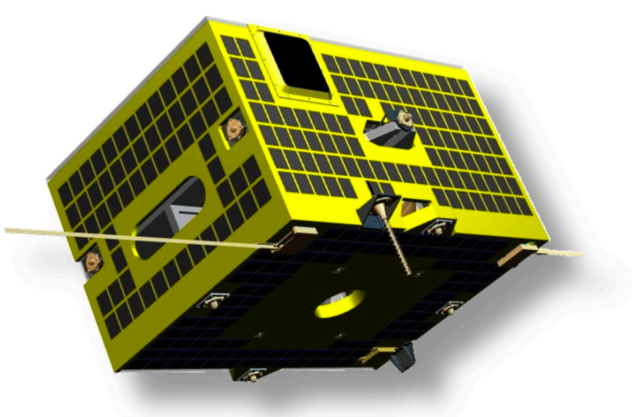
Article PDF

Figures | References

+ Article information

Abstract

The TianQin-1 satellite (TQ-1), which is the first technology demonstration satellite for the TianQin project, was launched on 20 December 2019. The first round of experiment had been carried out from 21 December 2019 until 1 April 2020. The residual acceleration of the satellite is found to be about 1×10^{-10} m/s^2/Hz$^{1/2}$ at 0.1 Hz and about 5×10^{-11} m/s^2/Hz$^{1/2}$ at 0.05 Hz, measured by an inertial sensor with a sensitivity of 5×10^{-12} m/s^2/Hz$^{1/2}$ at 0.1 Hz. The micro-Newton thrusters has demonstrated a thrust resolution of 0.1 μN and a thrust noise of 0.3 μN/Hz$^{1/2}$ at 0.1 Hz. The residual noise of the satellite with drag-free control is 3×10^{-9} m/s^2/Hz$^{1/2}$ at 0.1 Hz. The noise level of the optical readout system is about 30 pm/Hz$^{1/2}$ at 0.1 Hz. The temperature stability at temperature monitoring position is controlled to be about ±3 mK per orbit, and the mismatch between the center-of-mass of the satellite and that of the test mass is measured with a precision of better than 0.1 mm.



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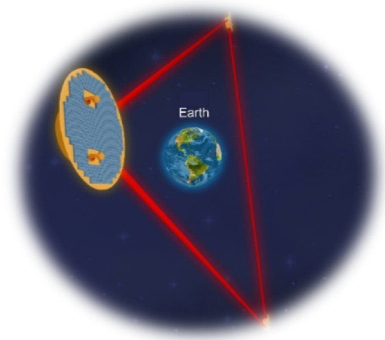
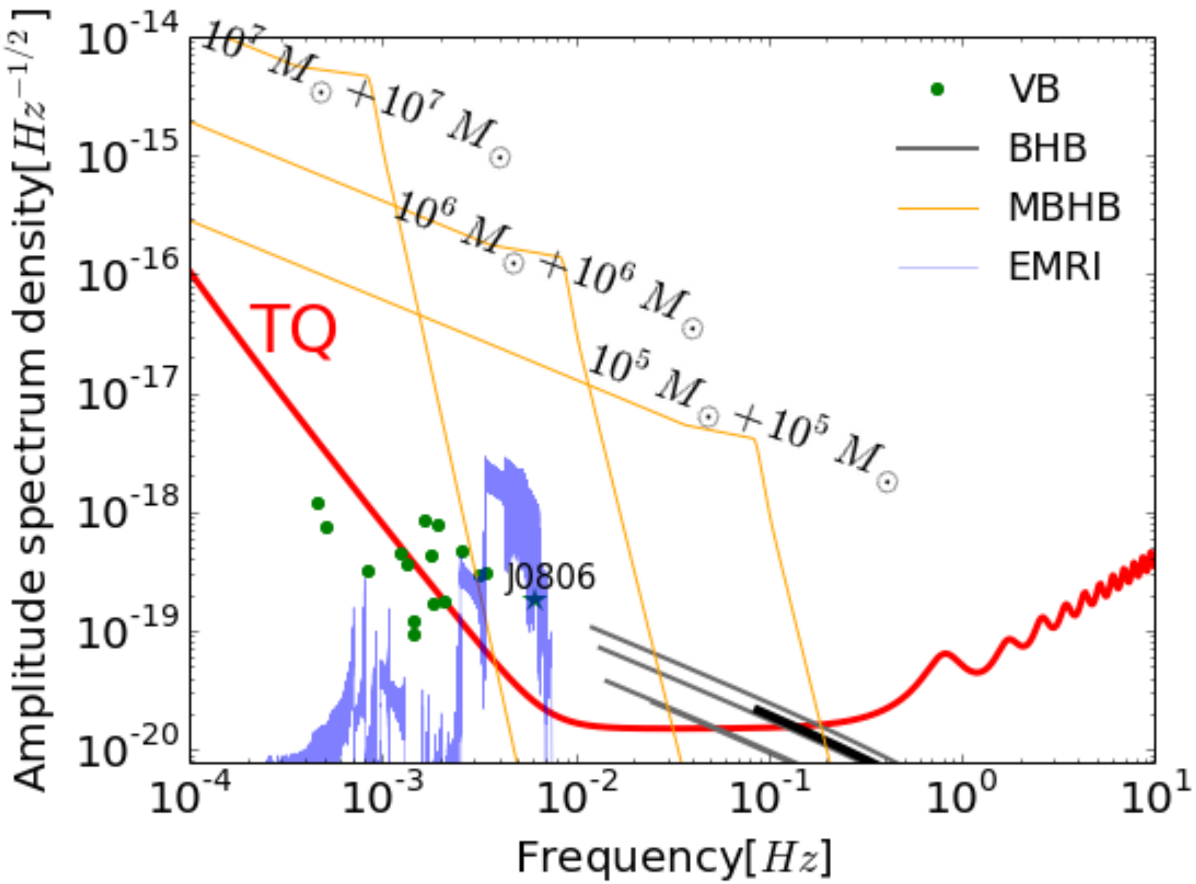


Summary

- **TQ science objectives includes: astronomy; cosmology; fundamental physics**



TQ science objectives

- Astronomy
  - Galactic compact binaries
  - Coalescence of massive binary BH
  - Extreme mass ratio inspiral
  - Inspiral of stellar mass BH binary
  - Stochastic background of astronomical origin
- Cosmology
  - Cosmic expansion
  - Stochastic background of cosmological origin
- Fundamental physics
  - Testing gravity
  - Testing BH
  - Other sources

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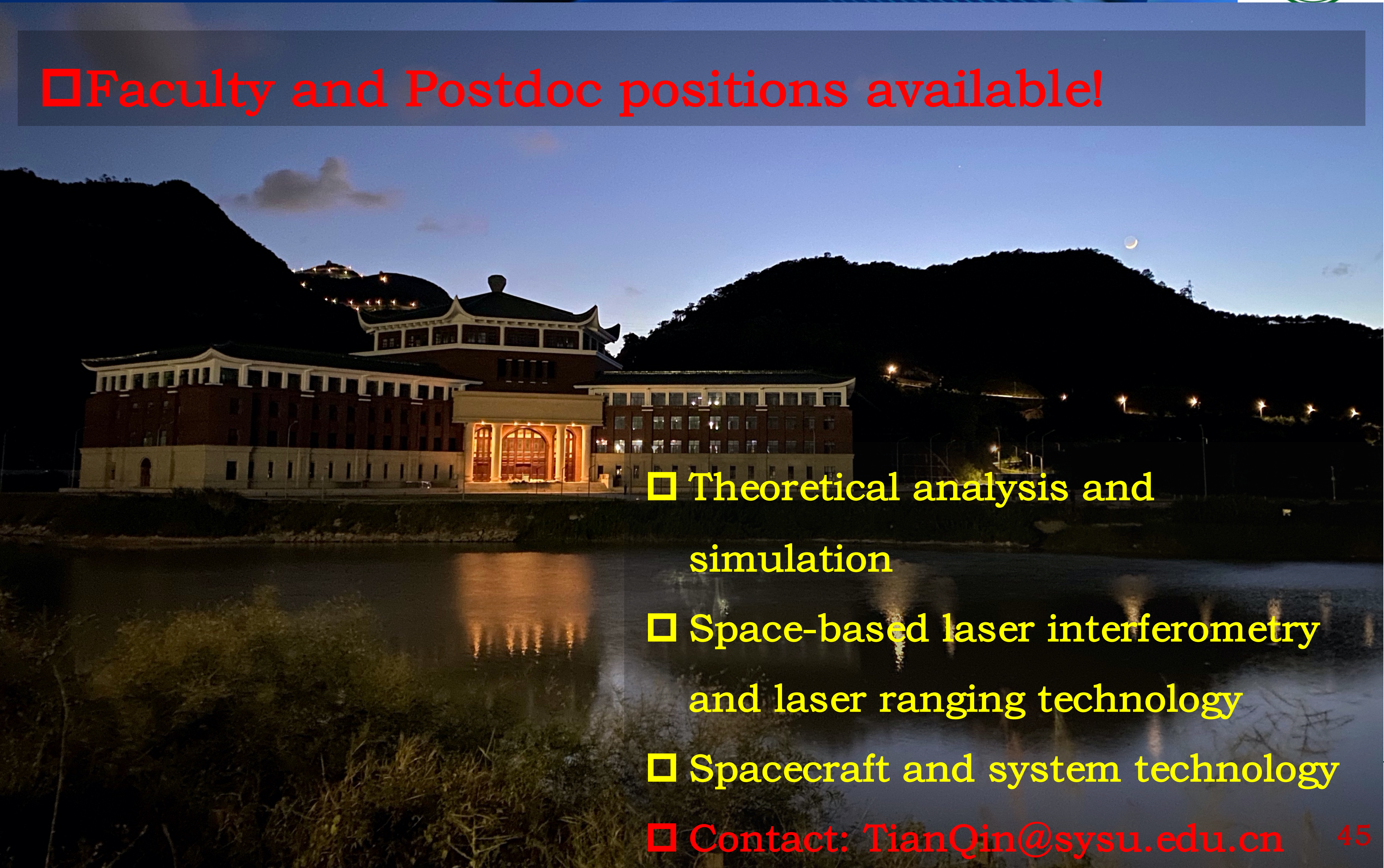

□ Faculty and Postdoc positions available!

- □ Theoretical analysis and simulation
- □ Space-based laser interferometry and laser ranging technology
- □ Spacecraft and system technology
- □ Contact: TianQin@sysu.edu.cn

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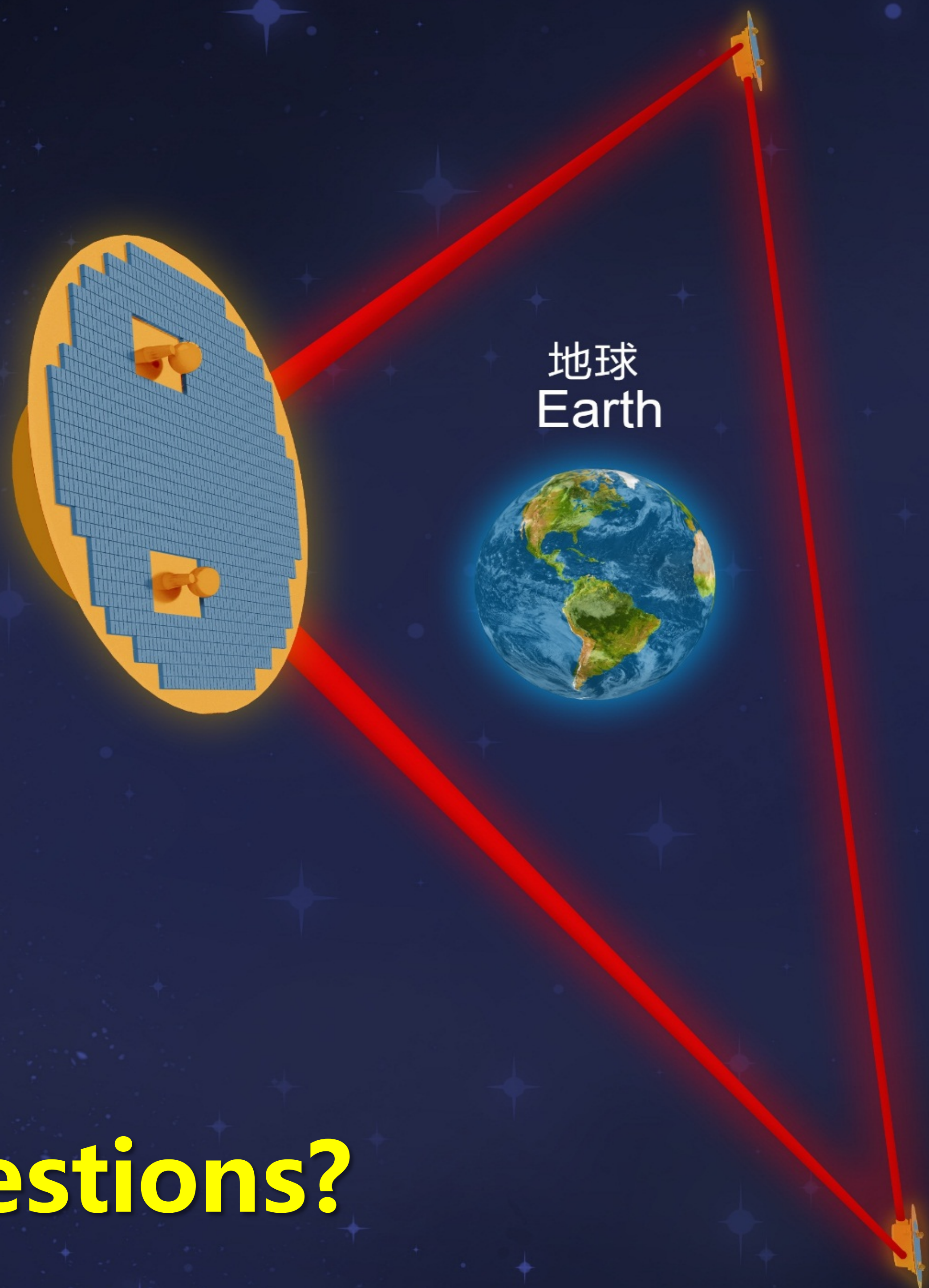

Questions?