# 关于四面体空间引力波观测天文台的构想

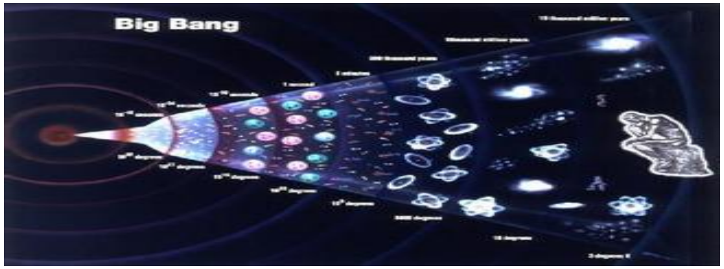
## Tetrahedron Constellation of Gravitational Wave Observatory

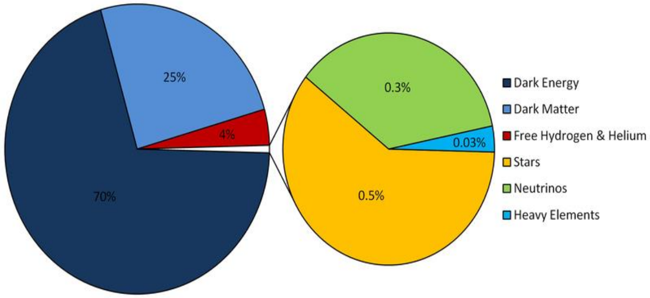
Cong Feng Qiao

In collaboration with H.B. Jin, arXiv:2405.03492
in Science China

# Understanding the Universe

## Picture of Universe: Inflation⊕DE⊕DM⊕Atomic Matter





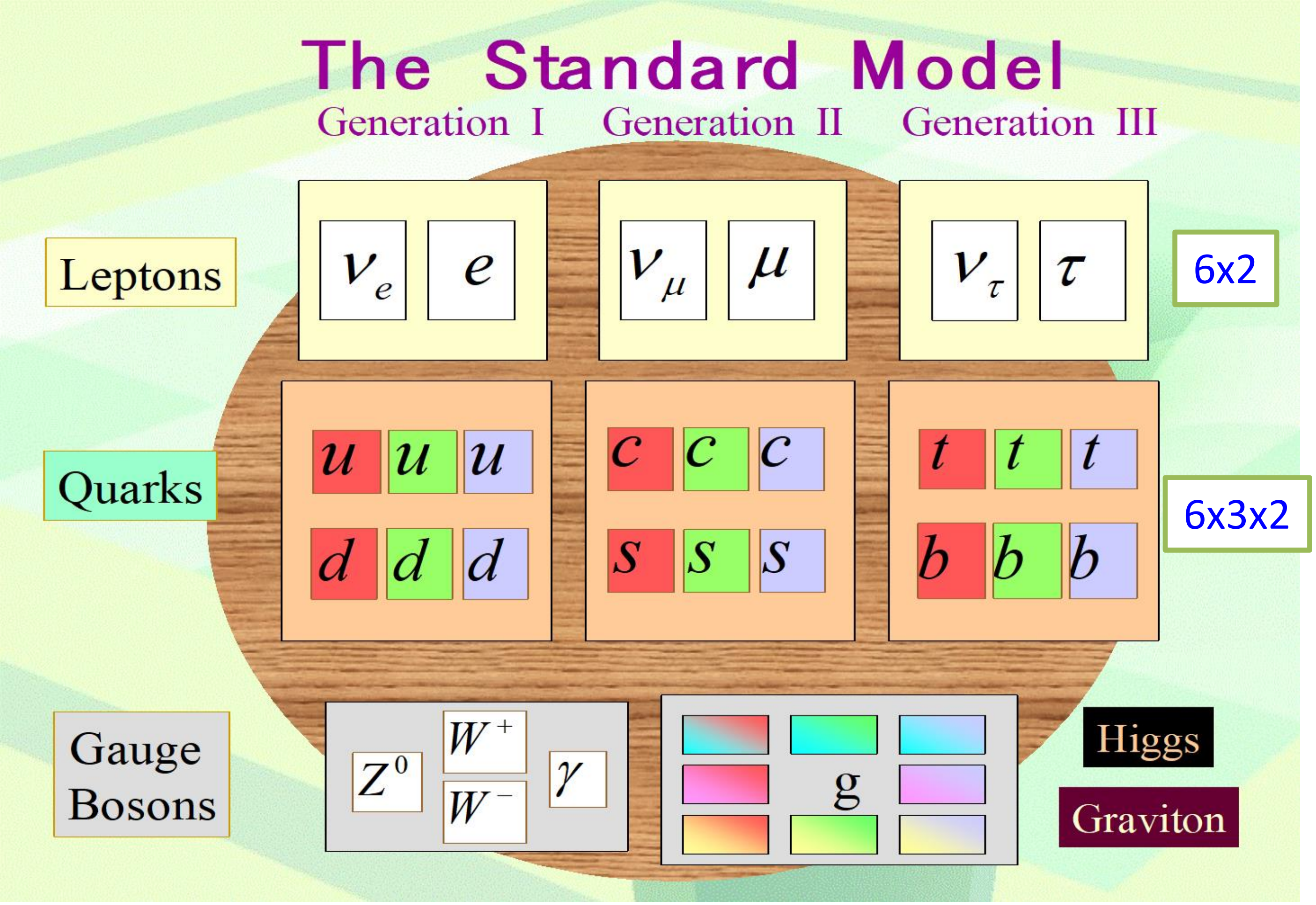
**Cosmic Components of Universe**

- **Dark Energy** ～ 70%
- **Matter** ～30%
  - **Dark Matter** ～ 85%
  - **Quark Matter** ～15% →
    - H (77%)
    - He (23%)

Our understanding of the nature of such a universe is very limited!

# Fundamental particles and interactions

- The known four basic interactions: Strong+Weak+EM+Gravity



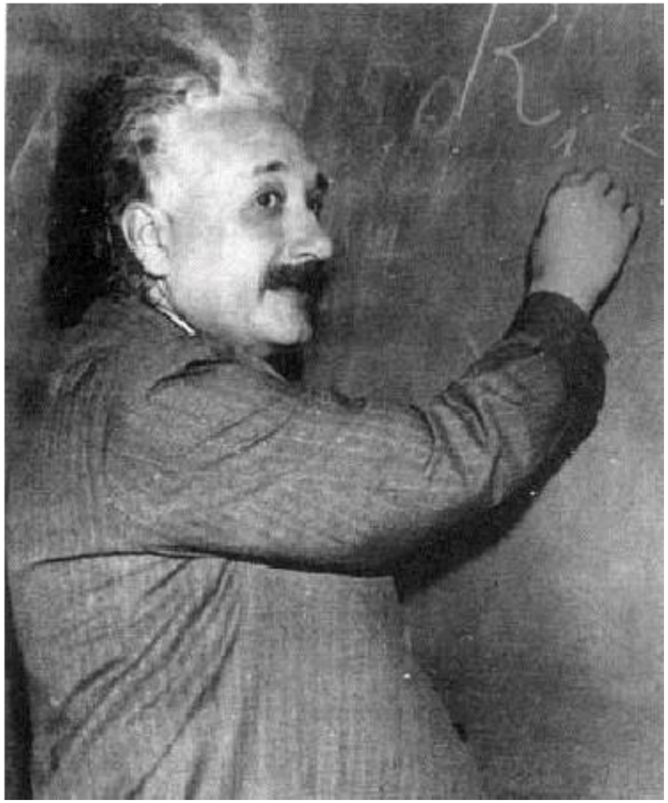
6x2

6x3x2

All 61 fundamental particles in the SM are found after the confirmation of Higgs in 2012, while the most “familiar” gravity is still nebulous

# About Gravity

- Up to now, the General Relativity, a classical theory, is still the best one for gravity, raised by Einstein one century ago

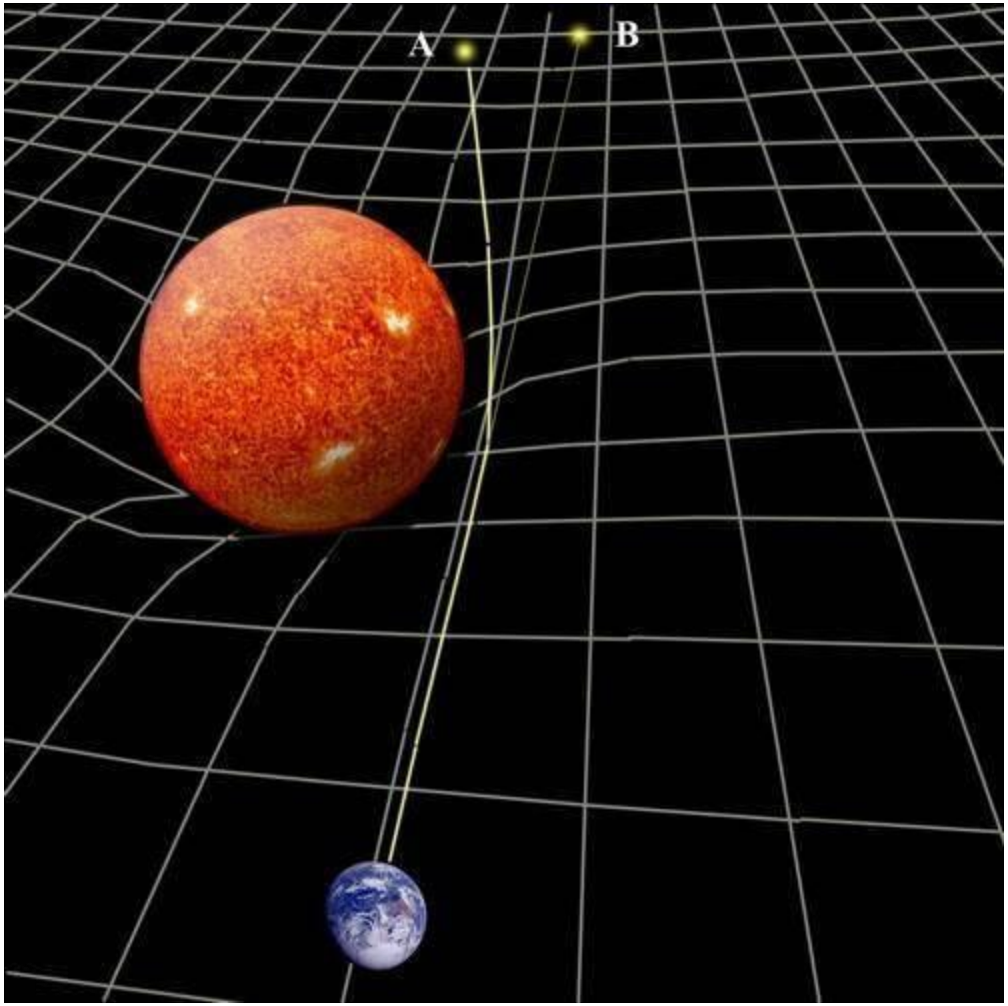


- The establishment of GR stands on the belief that the laws of physics stay the same inside any given frame of reference

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

The precession of Mercury's perihelion, Ggravitational redshift, Gravitational lensing, etc. are all triumphs of the theory of GR.

# *The theory of General Relativity*

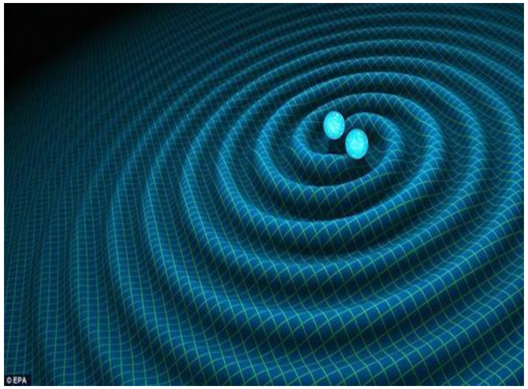


Mass tells space-time how to curve and the curvature of spacetime tells mass how to accelerate (move)

**More than one hundred years after the advent of GR, we still don’t know any solid theory superior to it**

# Gravitational Wave

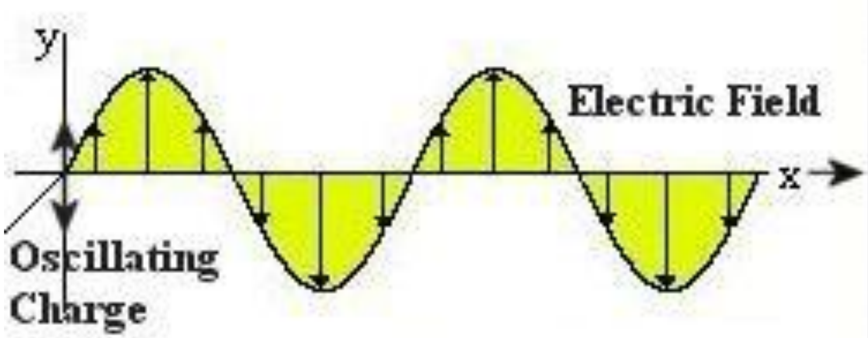
- **The gravitational wave was first predicted by Einstein in 1916, though he himself believe it will never be observed. Nevertheless, with the progress of technology, to detect GW is an everlasting dream for scientist.**



- **The leading order GW emission is Quadrupole emission, which is proportional to $G/c^5$, travelling in light speed. And hence widely believed that the GW can not be generated and detected artificially**

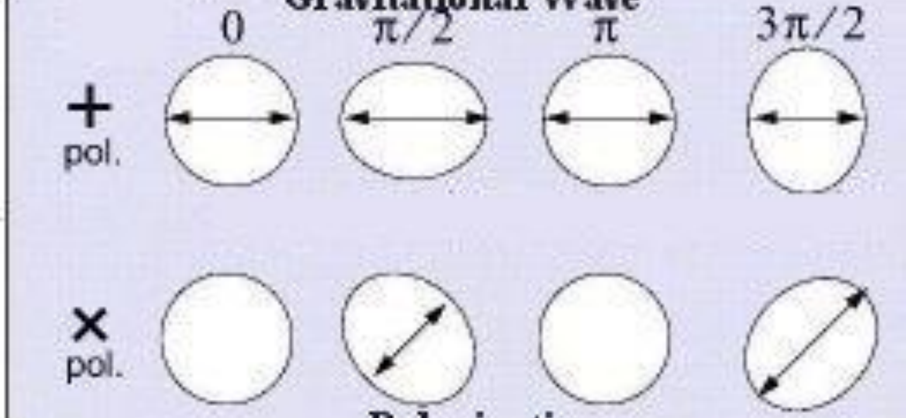
**Roughly estimation tells that spacetime strain induced by the most horrible hydrogen bomb is about $10^{-27}$**

Electromagnetic Wave

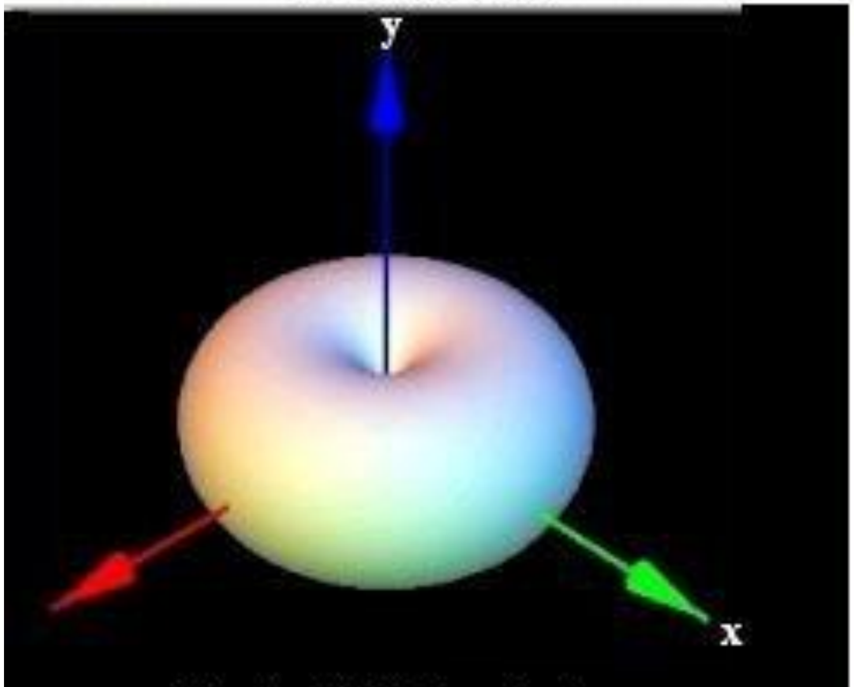


Polarization

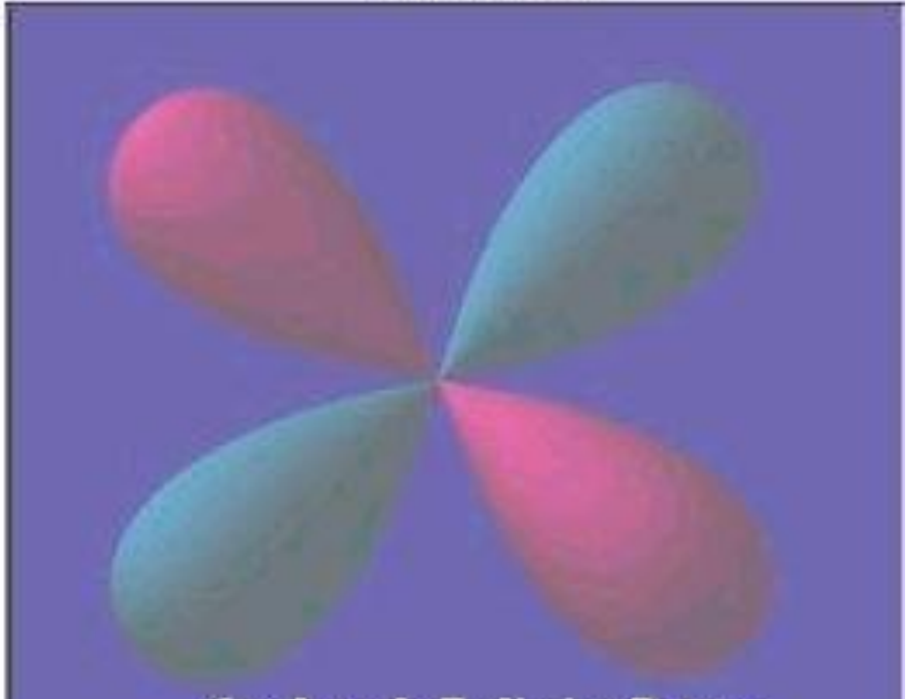
Gravitational Wave



Polarization

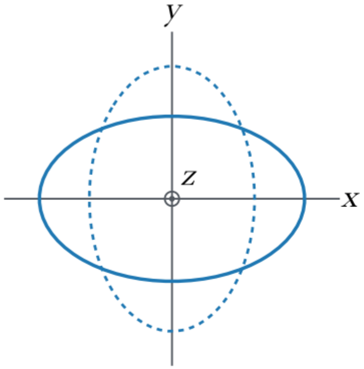


Dipole Radiation Pattern

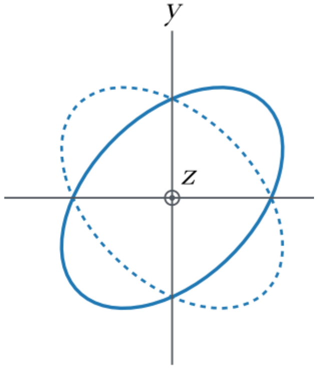


Quadrupole Radiation Pattern

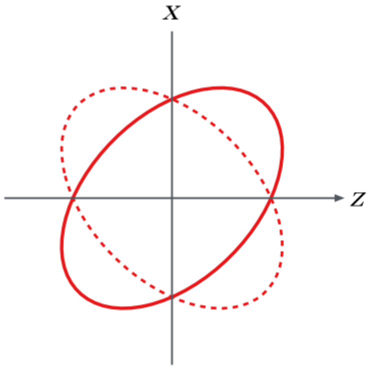
# The six possible polarization modes of various gravitational wave



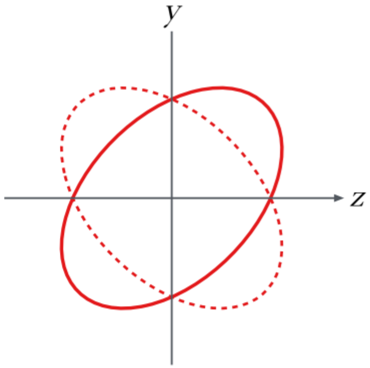
Plus



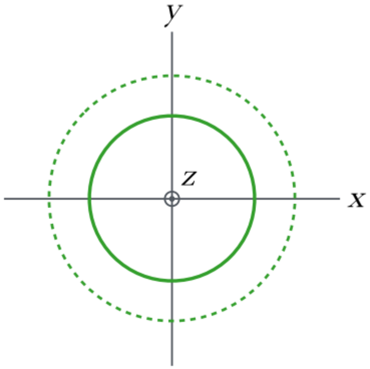
Cross



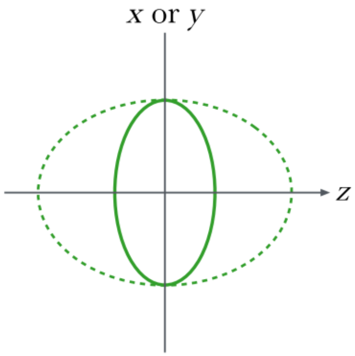
Vector $x$



Vector $y$



Breathing

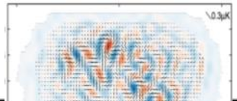


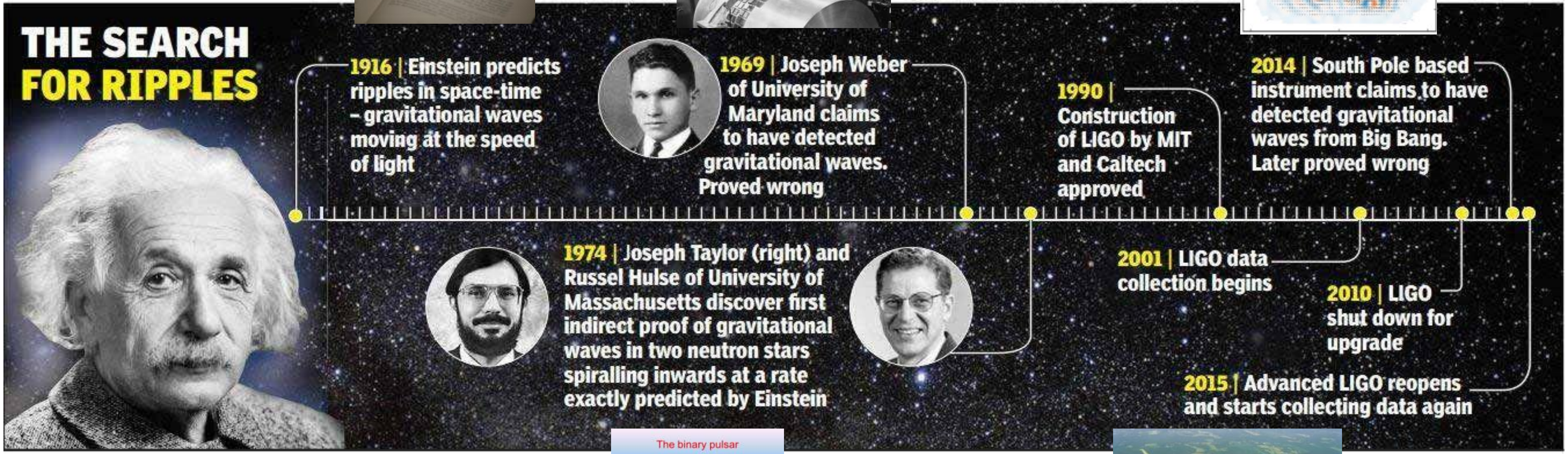
Longitudinal

**Feb. 2016, the LIGO Collaboration announced that it had made the first ever direct detection of gravitational waves. A one hundred-year-expected event, which marked the start of gravitational wave astronomy**

**The highly successful third observing run of the gravitational-wave detectors ended in spring 2020, bringing the number of known gravitational-wave detections to 90, with biggest black hole 300 times heavier than sun, which is beyond our normal expectations**

https://dcc.ligo.org/LIGO-P2000077/public





# THE SEARCH FOR RIPPLES

**1916** | Einstein predicts ripples in space-time – gravitational waves moving at the speed of light

**1969** | Joseph Weber of University of Maryland claims to have detected gravitational waves. Proved wrong

**1974** | Joseph Taylor (right) and Russel Hulse of University of Massachusetts discover first indirect proof of gravitational waves in two neutron stars spiralling inwards at a rate exactly predicted by Einstein

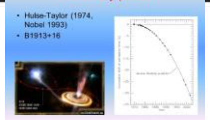
**1990** | Construction of LIGO by MIT and Caltech approved

**2001** | LIGO data collection begins

**2010** | LIGO shut down for upgrade

**2014** | South Pole based instrument claims to have detected gravitational waves from Big Bang. Later proved wrong

**2015** | Advanced LIGO reopens and starts collecting data again



The binary pulsar

- Hulse-Taylor (1974, Nobel 1993)
- B1913+16

# Types of gravitational waves

There are four categories of gravitational waves, they are:

1. **Continuous Gravitational Waves**
Produced by a single spinning massive object, like the extremely dense neutron star.

2. **Compact Binary Inspiral Gravitational Waves**
Produced by orbiting pairs of massive and dense (hence "compact") objects like white dwarf stars, black holes, and neutron stars.

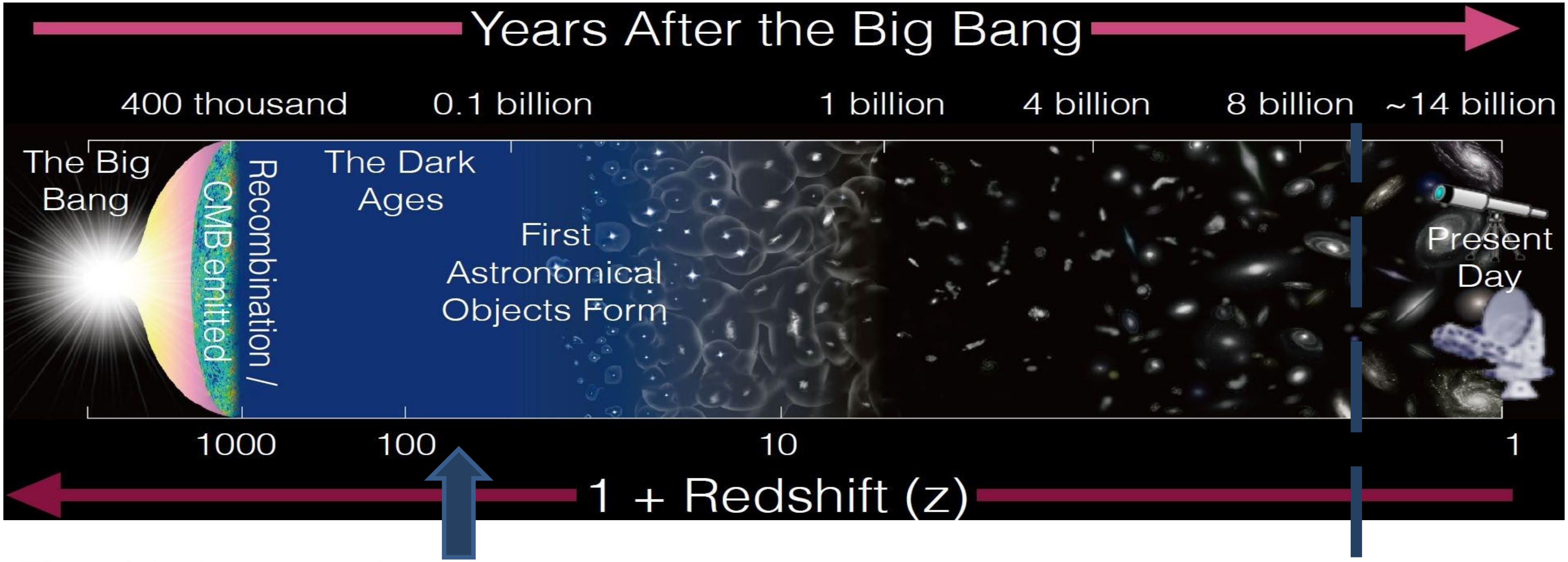
3. **Stochastic Gravitational Waves**

4. **Burst Gravitational Waves**

Gravitational waves are larger than their sources, with wave lengths starting at a few kilometers and ranging up to the size of the Universe, frequencies of $10^{-18}$Hz to$10^{4}$Hz. LIGO detects merely 10Hz more GW, a broadband of GW is waiting for exploring, beyond the capacity of LIGO experiment.

The space GW detection missions, a counterpart of LIGO, have attracted more and more attention. The space-borne GW antennae are more sensitive to 0.1 mHz to 1 Hz GW in frequency

# Gravitational Wave Detection

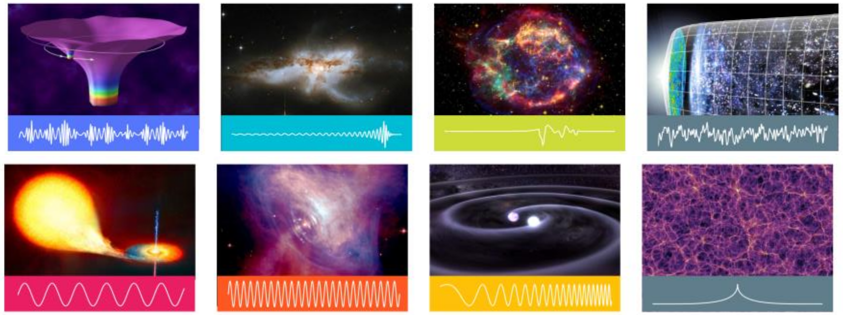


**The third generation observatory**

**Earth:** Einstein Telescope, …

**Space: LISA、Taiji、Tianqin …**

**Scientific aims**

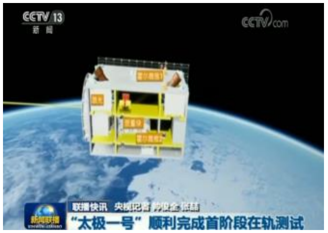


**The second generation observatory**

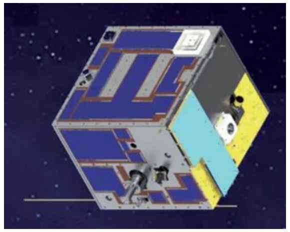
**On earth: LIGO-VIRGO-KAGRA**

**Space based: pathfinders lunched**

**LISA pathfinder**
2015年12月

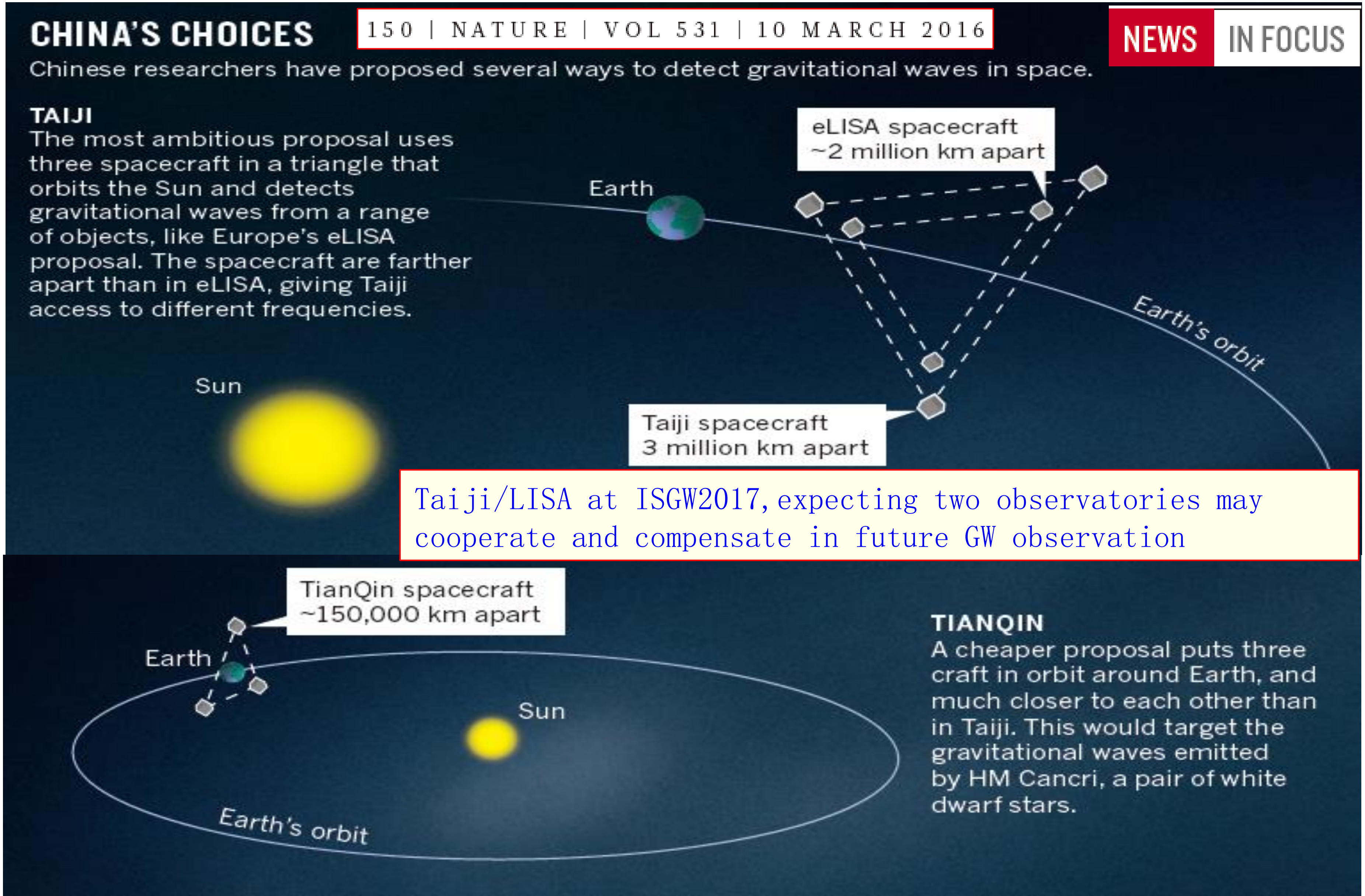


太极一号
2019年8月



天琴一号
2019年12月

# 空间引力波探测计划：LISA、太极、天琴



CHINA'S CHOICES

150 | NATURE | VOL 531 | 10 MARCH 2016

NEWS IN FOCUS

Chinese researchers have proposed several ways to detect gravitational waves in space.

**TAIJI**

The most ambitious proposal uses three spacecraft in a triangle that orbits the Sun and detects gravitational waves from a range of objects, like Europe's eLISA proposal. The spacecraft are farther apart than in eLISA, giving Taiji access to different frequencies.

**TIANQIN**

A cheaper proposal puts three craft in orbit around Earth, and much closer to each other than in Taiji. This would target the gravitational waves emitted by HM Cancri, a pair of white dwarf stars.

Taiji/LISA at ISGW2017, expecting two observatories may cooperate and compensate in future GW observation

# 国际交流

## 国科大首次主办空间引力波探测国际会议

ISGW2017

International Symposium on Gravitational Waves

May 25-29, 2017, University of Chinese Academy of Sciences, Beijing, China

**Topics**

Gravitational Wave Physics
Missions, Strategies and Plans of Gravitational Wave Detection
Frontiers of Science and Technology in Gravitational Wave Detection
International Collaboration in Gravitational Wave Detection

**International Advisory Committee (IAC)**

Chun-Li Bai (CAS), Peter Bender (CU-Boulder), Karsten Danzmann (AEI), Wen-Rui Hu (IMECH), Takaaki Kajita (Univ. Tokyo), Misao Sasaki (Univ. Kyoto), Li-Bin Xiang (CAS), Wei Yang (NSFC), He-Jun Yin (MOST), Wen-Long Zhan (CAS)

**Invited Speakers**

Masaki Ando (University of Tokyo)
David Blair (Australian International Gravitational Research Centre)
Rong-Gen Cai (Institute of Theoretical Physics, CAS)
Yanbei Chen (California Institute of Technology)
Stefan Danilishin (Institut für Theoretische Physik)
Karsten Danzmann (Albert-Einstein-Institut)
Jinn-Ouk Gong (Asia Pacific Center for Theoretical Physics)
Gerhard Heinzel (Albert-Einstein-Institut)
Gang Jin (Institute of Mechanics, CAS)
Shane L. Larson (Northwestern University)
Tjonnie G. F. LI (The Chinese University of Hong Kong)
Run-Qiu Liu (Institute of Applied Maths, CAS)
Misao Sasaki (Kyoto University)
Bangalore Sathyaprakash (Penn State University)
Bernard F. Schutz (Cardiff University)
Daniel Shaddock (The Australian National University)
Gary Shiu (University of Wisconsin / HKUST)
Shinji Tsujikawa (Tokyo Univeristy of Science)
Stefano Vitale (Università di Trento)
Suwen Wang (Stanford University)
Yue-Liang Wu (UCAS / Institute of Theoretical Physics, CAS)
William Joseph Weber (Università di Trento)
Bing Zhang (University of Nevada / Peking University)

UCAS Yan Qi Lake Campus
Photo by Zhang Qi

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Visit Website for more infomation: http://isgw2017.csp.escience.cn/

中国科学院大学
University of Chinese Academy of Sciences

2017.5.25-29 国科大举办引力波国际研讨会，此次会议的召集人为“太极计划”首席科学家国科大副校长吴岳良院士、中国科学院力学所胡文瑞院士，德国爱因斯坦研究所所长Karsten Danzmann教授和美国科罗拉多大学的著名物理学家Peter Bender教授。

# *Why GW Detection Matters*

- **GW is a astronomical messenger, a kind of new probe to the exploration of the Universe, aside from the EM signal. It is a key experiment to testing the standing gravity theory**
- **The high tech developed in the gravitational wave detection will for sure have a broad influence to society.**
- **In the past decade, there are four Nobel Prize in physics were awarded to the achievements relative to cosmology and astrophysics**

# *Why GW Detection Matters*

- **The direct observation of GW by LIGO marked the start of gravitational-wave astronomy and cosmology**

- **In the future, with more GW detection technique developed, like space gravitational observatory, our views on gravity and cosmology will definitely be improved**

- **The NRC of the States once mentioned in a report in 2007:**

*The first direct detection of low-frequency gravitational waves will be a momentous discovery, of the kind that wins Nobel Prizes*—NRC

# Various GW Detections

## 一、Direct detection

- ✓ Resonant bar
- ✓ Laser Interferometer
  - Ground based
  - Space borne
  - …
- ✓ Light clock

二、Indirect meaurements（**BIPULSAR、NANOGrav、FAST、BICEP、AliCPT…**）

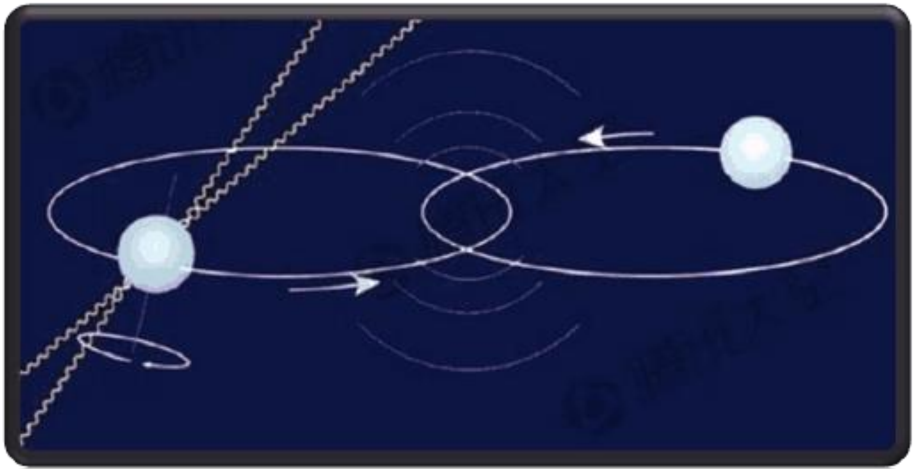
# 引力波的间接测量

## Evidence

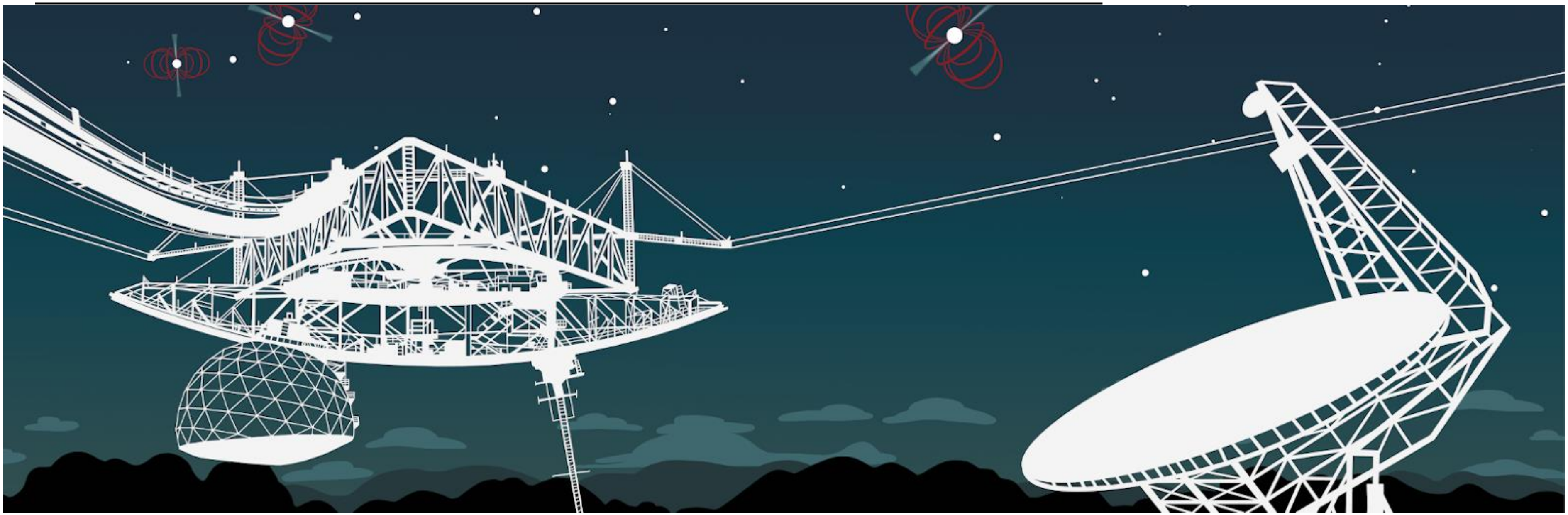
1974年Russell Hulse and Joseph Taylor发现第一个脉冲双星， Binary Pulsar 1913+16

双星系统周期的变化与引力波辐射造成的影响相吻合，简介证明了引力波的存在

为此二人获得了1993 诺贝尔物理学奖



# Indirect detection-NANOGrav



NANOGrav stands for North American Nanohertz Observatory for Gravitational Waves. NANOGrav members are drawn from across the United States and Canada and the goal is to study the Universe using gravitational waves. NANOGrav uses the Galaxy itself to detect gravitational waves with the help of objects called pulsars—exotic, dead stars that send out pulses of radio waves with extraordinary regularity. This is known as a Pulsar Timing Array, or PTA

# Indirect detection-NANOGrav

**NANOGrav was founded in October 2007 and has since grown to over 100 members at over 40 institutions.**

http://nanograv.org

# FAST(Five-hundred-meter Aperture Spherical radio Telescope

## 未来FAST组网的可能性

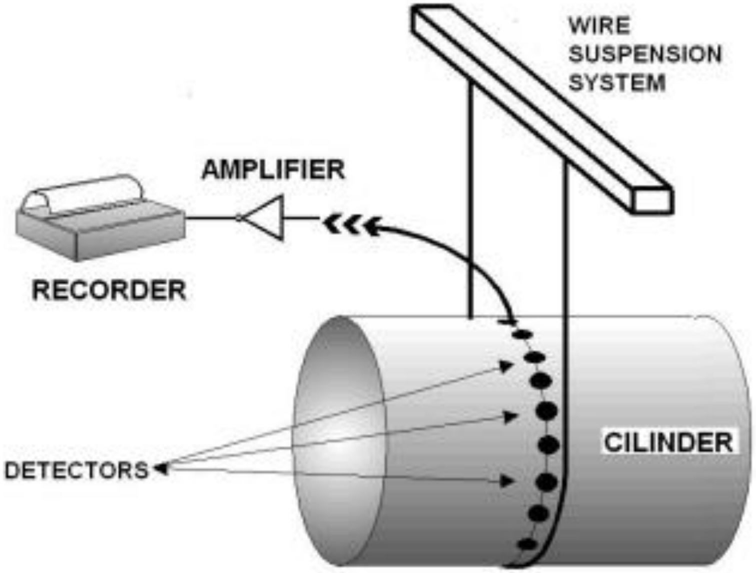
500米口径球面射电望远镜被誉为“中国天眼”，由中国天文学家南仁东先生于1994年提出构想，历时22年建成，于2016年9月25日落成启用。是由中国科学院国家天文台主导建设，具有我国自主知识产权、世界最大单口径、最灵敏的射电望远镜。综合性能是著名的射电望远镜阿雷西博的十倍。2020年1月11日，500米口径球面射电望远镜通过国家验收，投入正式运行。截至2021年3月29日，500米口径球面射电望远镜已发现300余颗脉冲星

# AliCPT primordial GW detection

阿里项目2016年正式启动；2017年3月阿里一号观测基地动工，选址于西藏阿里地区的天文观测基地，海拔5250米。建成运行后可首次实现北半球地面原初引力波观测，将与南极极点观测站、智利阿塔卡玛沙漠观测站一起，成为国际原初引力波探测的三大基地。

# Direct detection of GW

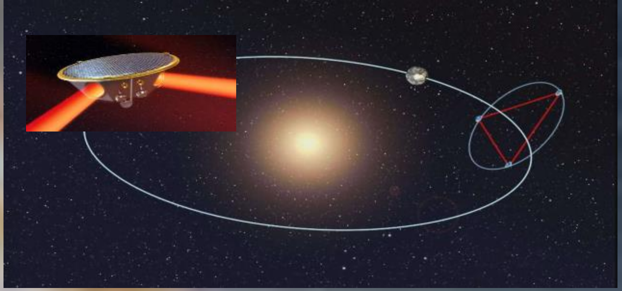
韦伯探测器和工作照



- **由于地面引力波探测装置受尺度和地球环境影响，探测更低频率，有重要宇宙学意义的引力波信号需要把探测器放到太空中**

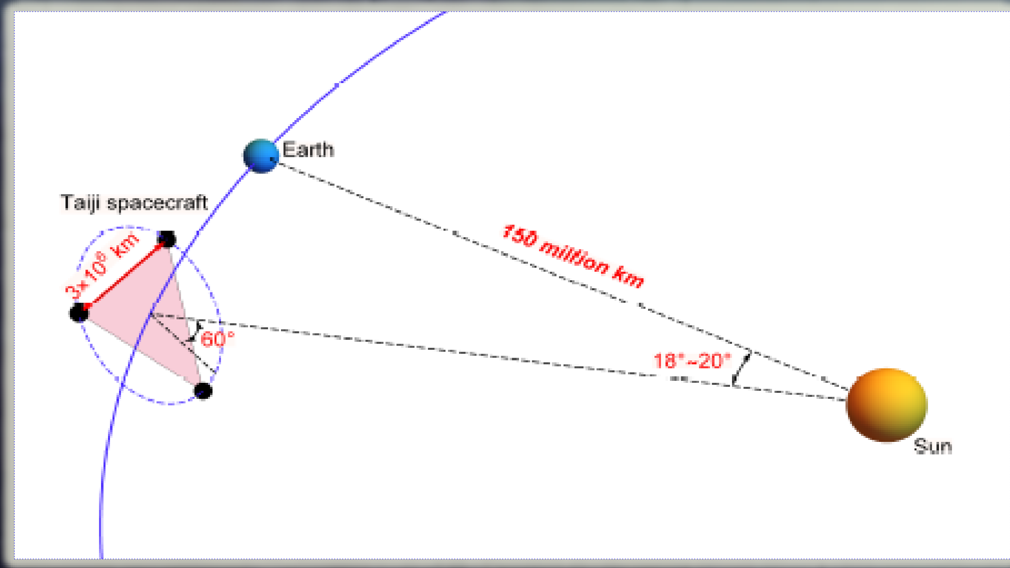
国际上，最早开始发展的空间激光干涉引力波探测计划的是20世纪70年代欧洲航天局（ESA）提出的，后与NASA合作发展的原LISA（Laser Interferometer Space Antenna）项目，后来由于NASA的退出LISA改变方案变为eLISA（evolved LISA）。2017年6月，NASA重新回归，项目也随之回到LISA，但发射时间有所提前。ESA宣布将引力波探测作为两个重大科学项目之一，列在L3阶段任务。eLISA的技术演示项目LISA-Pathfinder已于2015年12月发射，对eLISA相关技术进行了完美的演示和检验。

**Taiji** Program in Space
Gravitational wave physics
空间太极计划



# Space-Based Gravitational Wave Detection

## 空间太极计划
## Taiji Program In Space

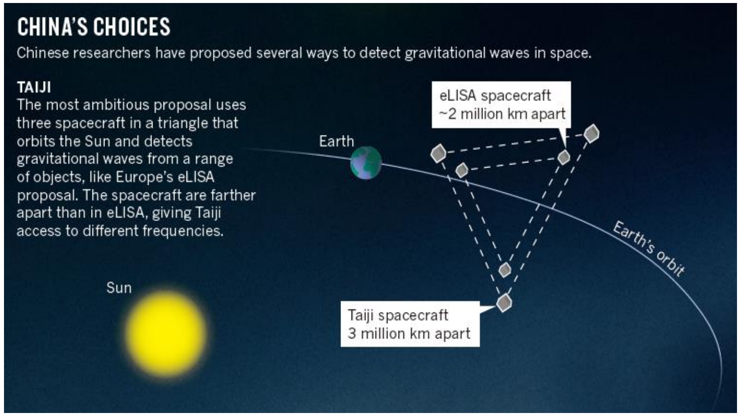


# Taiji Program in Space VS Others

**空间引力波探测涉及太阳轨道和地球轨道的选择问题：早在2011年NASA撰写的报告《Gravitational-Wave Mission Concept Study Final Report》中已有较详细的讨论。**

**地球轨道问题，其中包括：轨道噪声、温度变化、太阳阴影、科学测量时间不连续等问题**

**根据研究报告，学界认为：空间引力波探测太阳轨道应是最优方案，地球轨道方案风险性极大**



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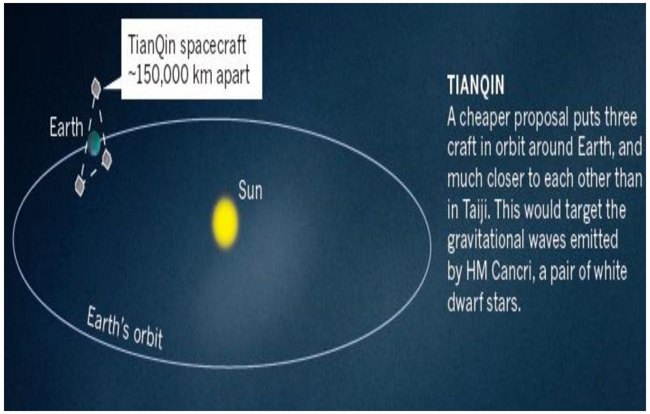
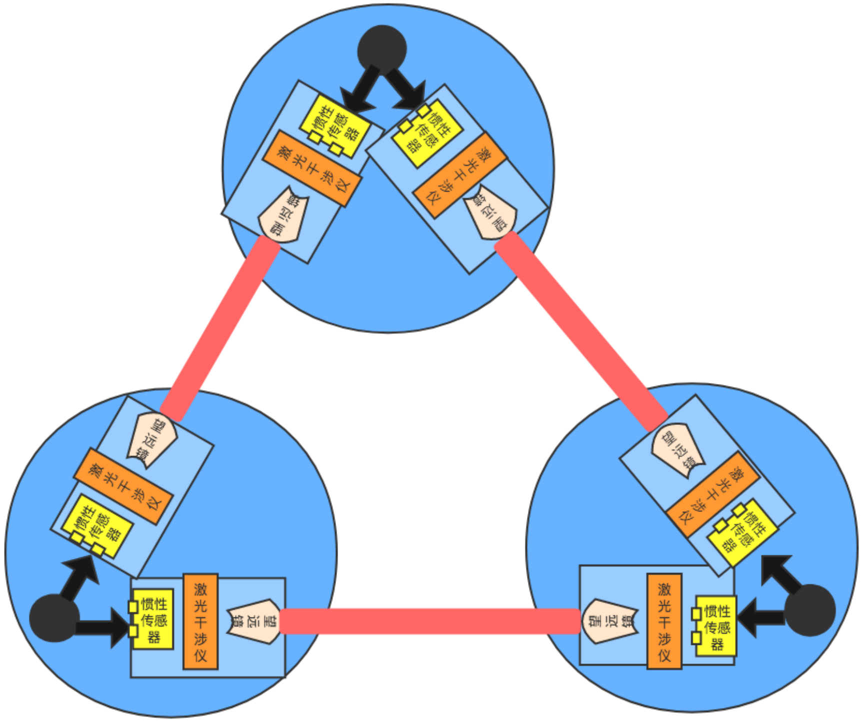


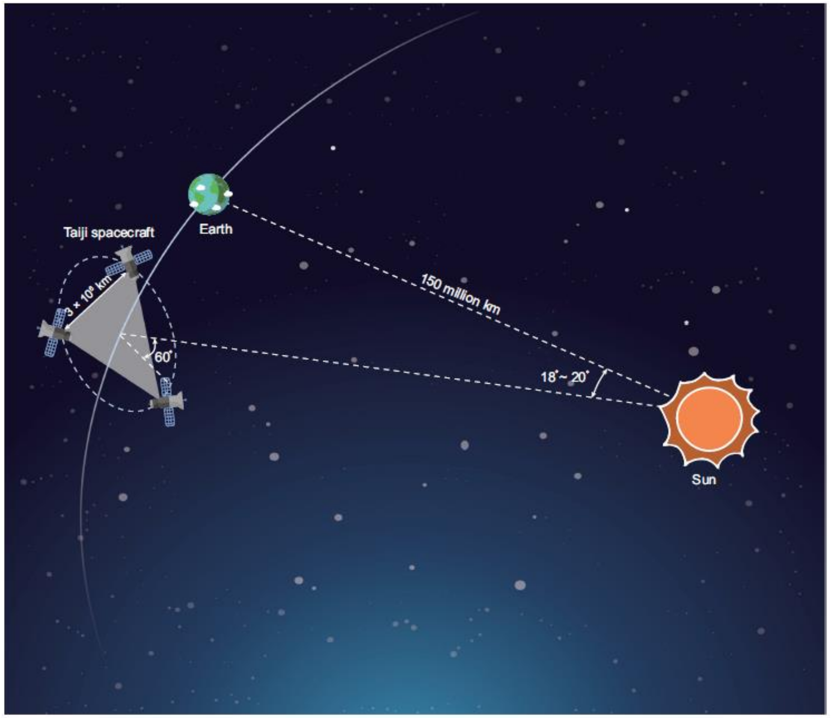
**TIANQIN**

A cheaper proposal puts three craft in orbit around Earth, and much closer to each other than in Taiji. This would target the gravitational waves emitted by HM Cancri, a pair of white dwarf stars.

| | 测距指标 Position noise | 加速度残差 Accelerate noise | 轨道 Orbit | 臂长（公里）Armlength (10km) | 频段 Frequency | Launch 发射时间 |
|---|---|---|---|---|---|---|
| **太极 Taiji** | 8pm/Hz$^{1/2}$ | 3×10$^{-15}$ms$^{-2}$/Hz$^{1/2}$ | 太阳 Sun | 300万（2012） | 0.1mHz-1Hz | 2033 |
| **LISA** | 12pm/Hz$^{1/2}$ | 3×10$^{-15}$ms$^{-2}$/Hz$^{1/2}$ | 太阳 Sun | 500万（1995）<br>100万（2011）<br>250万（2017） | 0.1mHz-1Hz | 2034 |
| **天琴 Tianqin** | 1pm/Hz$^{1/2}$ | 1×10$^{-15}$ms$^{-2}$/Hz$^{1/2}$ | 地球 Earth | 17万（2015） | 0.1mHz-1Hz | 2032-2036? |

# 空间“太极计划”结构、指标





| | 太极计划(Taiji) | LISA | eLISA |
|---|---|---|---|
| 探测器臂长 | $3\times10^{9}$m | $5\times10^{9}$m | $1\times10^{9}$m |
| 测距精度 | 5-10 pm $Hz^{-1/2}$ | 18 pm $Hz^{-1/2}$ | 11pm $Hz^{-1/2}$ |
| 激光功率 | 2W | 2W | 2W |
| 望远镜直径 | ~50cm | 40cm | 20cm |
| 无拖曳水平 | $3\times10^{-15}ms^{-2}Hz^{-1/2}$ | $3\times10^{-15}ms^{-2}Hz^{-1/2}$ | $3\times10^{-15}ms^{-2}Hz^{-1/2}$ |

- 2019年8月31日太极一号在酒泉卫星发射中心发射成功

- 同年12月天琴一号也成功发射

证 书

“‘太极一号’在轨测试成功 我国空间引力波探测迈出第一步”入选“两院院士评选2019年中国十大科技进展新闻”

中国科学院学部工作局

中国工程院办公厅

中国科学报社

二〇二〇年一月

中国科学院

“率先行动”计划第一阶段

重大科技成果及标志性进展

太极一号卫星亮相中国航天大会

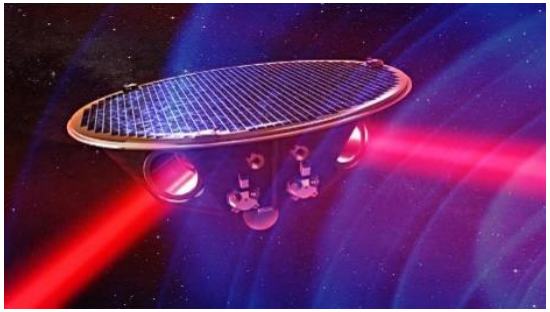
太极一号”卫星在轨测试成功，我国空间引力波探测迈出第一步，入选了由两院院士评选的2019年中国十大科技进展新闻。同时，也入选了中国科学院率先行动计划第一阶段重大科技成果及标志性进展。

# Blueprint in space-borne GW detection

## ✓Key techs in Space-borne GW detection

- 高精度惯性传感器
- 激光干涉技术
- 无拖曳控制技术
- 超静超稳卫星平台技术

| | 当前水平 | 太极探路者 | 太极 | LISA |
|---|---|---|---|---|
| 星间激光干涉测距系统 | | | | |
| 臂长 | / | 0.1 x $10^{9}$ | 3 x $10^{9}$ | 5 x $10^{9}$ |
| 测距精度 | 15 pm Hz$^{-1/2}$ | 10-100 pm Hz$^{-1/2}$ | 5-8 pm Hz$^{-1/2}$ | 18 pm Hz$^{-1/2}$ |
| 角位移测量精度 | 8 nrad Hz$^{-1/2}$ | 10 nrad Hz$^{-1/2}$ | 5 nrad Hz$^{-1/2}$ | 8 nrad Hz$^{-1/2}$ |
| 激光功率 | 1 W | 1 W | 2 W | 2 W |
| 激光器频稳 | 200 Hz Hz$^{-1/2}$ | 100 Hz Hz$^{-1/2}$ | 30 Hz Hz$^{-1//2}$ | 282 Hz Hz$^{-1/2}$ |
| 激光器功率稳定性 | $10^{-1}$ Hz$^{-1/2}$ | $10^{-2}$ Hz$^{-1/2}$ | $10^{-3}$ Hz$^{-1/2}$ | $10^{-3}$ Hz$^{-1/2}$ |
| 望远镜直径 | 20 cm | 20 cm | 40 cm | 40 cm |
| 望远镜线稳定性 | 仿真结果符合要求 | 10 pm/√Hz | 1 pm/√Hz | 1 pm/√Hz |
| 望远镜角稳定性 | | 10 nrad/√Hz | 1 nrad/√Hz | 1 nrad/√Hz |
| 无拖曳航天系统 | | | | |
| 检验质量加速度噪声 | / | 3 x $10^{-14}$ ms$^{-2}$ Hz$^{-1/2}$ | 3 x $10^{-15}$ ms$^{-2}$ Hz$^{-1/2}$ | 3 x $10^{-15}$ ms$^{-2}$ Hz$^{-1/2}$ |
| 无拖曳控制位移噪声 | 仿真结果符合要求 | 10 nm/ Hz$^{1/2}$ | 2 nm/ Hz$^{1/2}$ | 2 nm/ Hz$^{1/2}$ |
| 微推力器 | 0.5 μN/ Hz$^{1/2}$ | 0.3 μN/ Hz$^{1/2}$ | 0.1 μN / Hz$^{1/2}$ | 0.1 μN / Hz$^{1/2}$ |
| 核心区域温度测控精度 | 指标未分解，未有评估结果 | 优于100 uk Hz$^{-1/2}$ | 优于ukHz$^{-1/2}$ | 优于ukHz$^{-1/2}$ |
| 重点部位及敏感方向热膨胀系数 | | 优于$10^{-6}$/K | 优于$10^{-7}$/K | 优于$10^{-7}$/K |
| 测试质量容器内的磁环境 | | 优于$10^{-7}$T/Hz$^{1/2}$ | 优于$10^{-8}$T/Hz$^{1/2}$ | 优于$10^{-8}$T/Hz$^{1/2}$ |



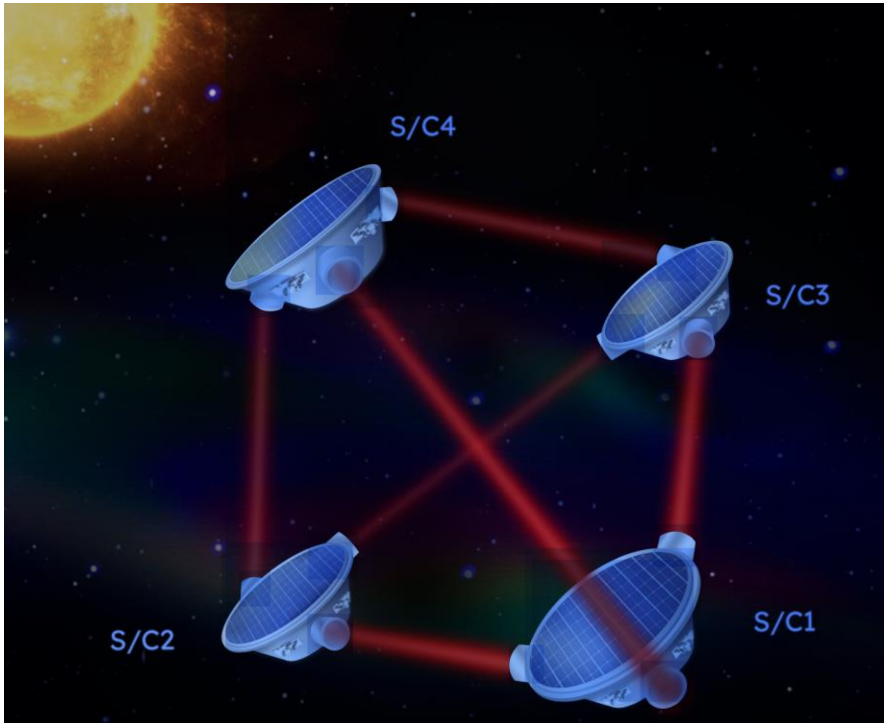
# Challenges in Space-borne Gravitational Wave Detection

- ◆ Many of technologies for the aim of GW detection are above the current technological level
- ◆ In case one of the satellites is out of order, the whole observatory will be greatly influence
- ◆ Three-spacecraft plan is almost incapable of testing the gravitation wave polarizations predicted in theories other than general relativity

✓ One of the solutions: Tetrahedron Constellation of Gravitational Wave Observatory(TEGO)

# Tetrahedron Constellation of Gravitational Wave Observatory

- ✓ **Recently, we propose a Tetrahedron Constellation of Gravitational Wave Observatory (TEGO) as a spare scenario for Taiji Project, which composed of four identical spacecrafts (S/Cs). The laser telescopes and their pointing structures are mounted on the S/C platform and are evenly distributed at three locations 120 degrees apart**



Hongbo Jin and QCF, Science China 2024

# Some Merits of TEGO

- ✓ The TEGO structures form automatically a stable mass center for the platform. The time delay interferometry (TDI) are used to suppress the frequency noise of GW detector
- ✓ The second generation time delay interferometry (TDI) would be employed to suppress the frequency noise of Gravitational Wave
- ✓ More importantly, comparing to the on-going configurations of LISA, Taiji, and Tianqin, the TEGO has more combinations of optical paths and hence more sensitive to GW signals, which implies that more GW modes beyond the predictions of General Relativity, the polarizations, might be detected

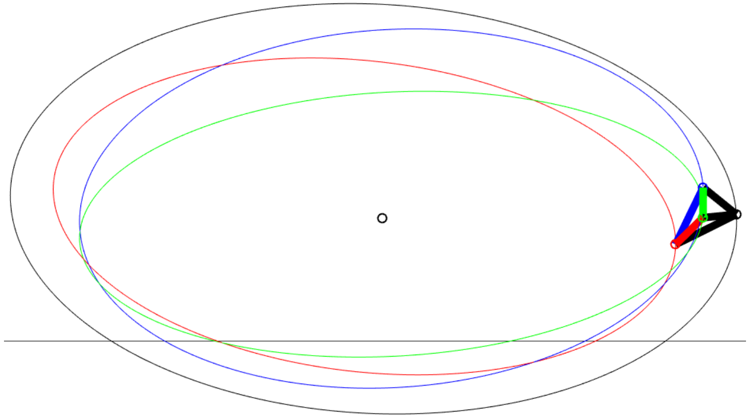
# Some Merits of TEGO

- ✓ The cost increase not much in comparison with the three-satellite project, while with rich returns.
- ✓ The extreme high technique requests may be alleviated a bit
- ✓ Much more precise in pinpointing the sources of GW
- ✓ It is even sensitive to the Dark matter and Dark Energy issues
- ✓ ……

# A few technical analyses on TEGO

$$x(t) = R\cos(\alpha) + \frac{1}{2}eR\Big(\cos(2\alpha-\beta) - 3\cos(\beta)\Big)$$
$$+\frac{1}{8}e^2R\Big(3\cos(3\alpha-2\beta) - 10\cos(\alpha) - 5\cos(\alpha-2\beta)\Big)$$
$$y(t) = R\sin(\alpha) + \frac{1}{2}eR\Big(\sin(2\alpha-\beta) - 3\sin(\beta)\Big)$$
$$+\frac{1}{8}e^2R\Big(3\sin(3\alpha-2\beta) - 10\sin(\alpha) + 5\sin(\alpha-2\beta)\Big)$$
$$z(t) = -\sqrt{3}eR\cos(\alpha-\beta) + \sqrt{3}e^2R\Big(\cos^2(\alpha-\beta)$$
$$+2\sin^2(\alpha-\beta)\Big)$$

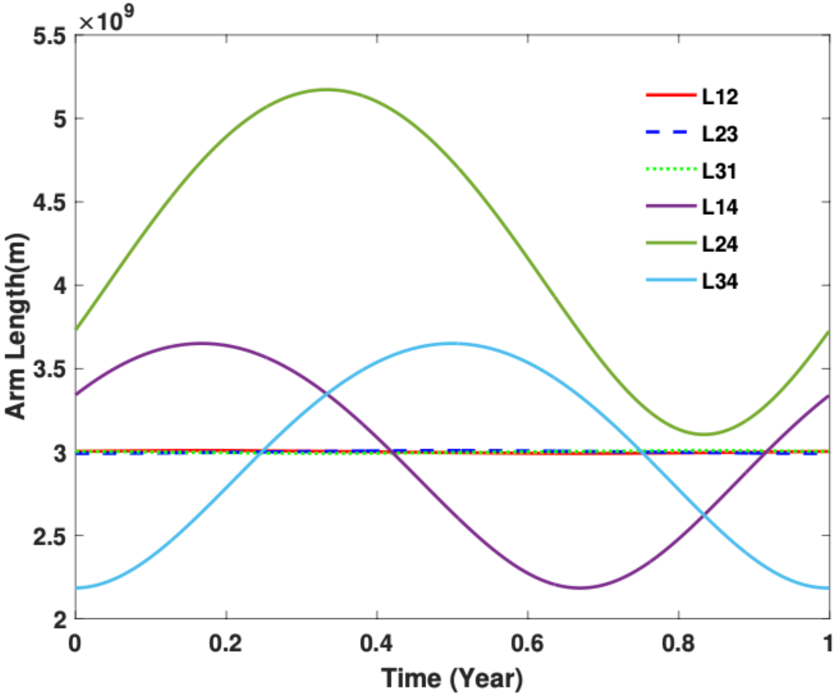
R= 1 AU for S/C1, S/C2 and S/C3；for S/C4, R = (1 + 0.0163738) AU ; α、β、γ are phases



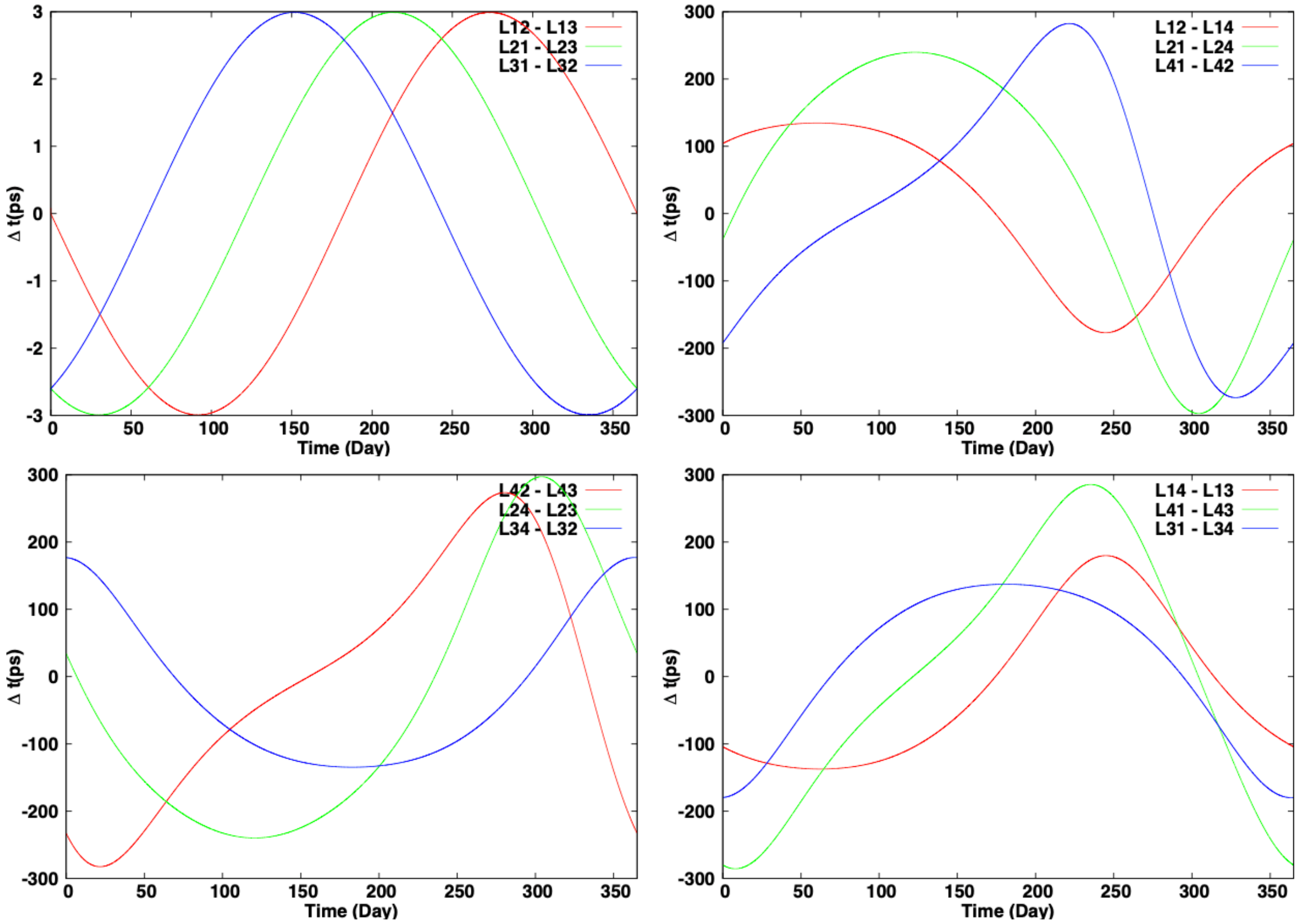
# A few technical analyses on TEGO

- ☐ Variations of the arm lengths, Laser path distance between S/Cs, within a year

- ☐ In the space-borne observatories with three spacecrafts in triangle, the laser frequency noise are the dominant one, which is also the case for TEGO

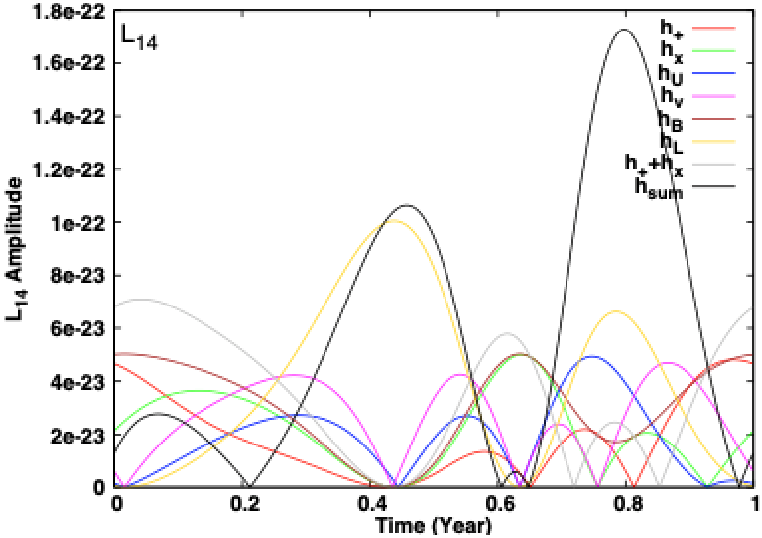


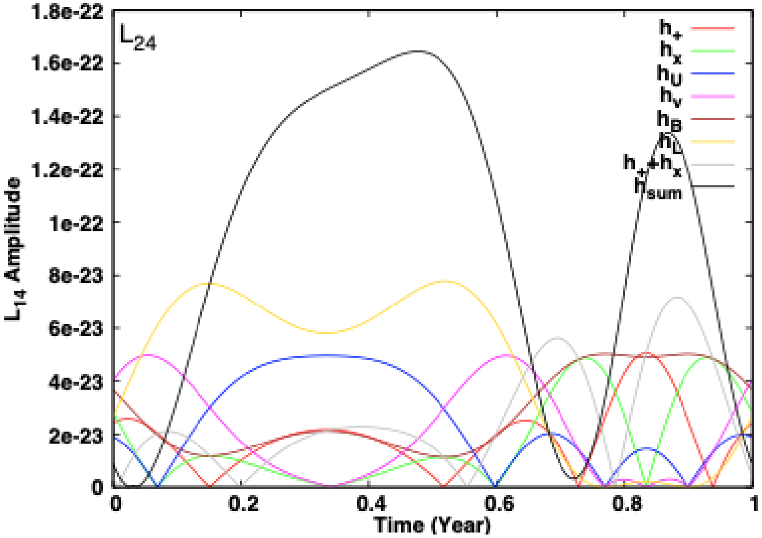
# A few technical analyses on TEGO

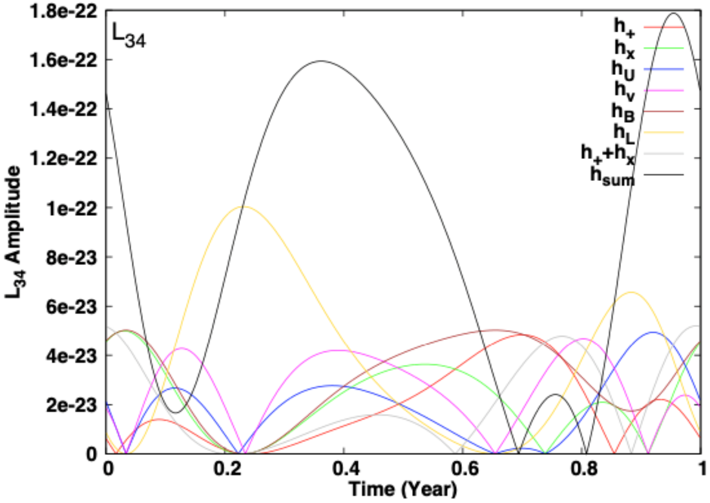


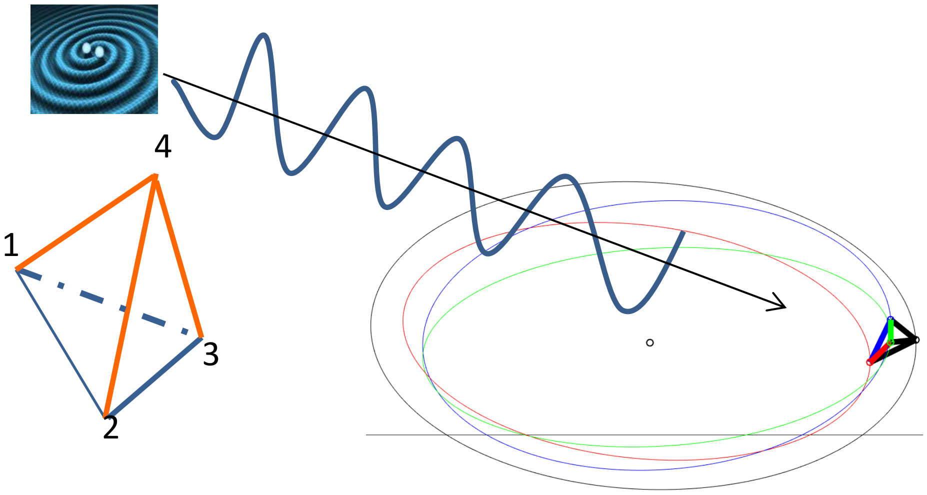
Michelson TDI configuration from the optical path combination of two arms.
Note, the optical path differences are below the limits of noise canceling

# Amplitude of six polarization modes in TEGO









# Summary and Comments

I. TEGO系统通过增加一个航天器和相应的光学路径组合，能够同时对六种引力波极化模式进行高灵敏度探测。这为研究引力波的极化特性提供了更多的自由度和更高的灵敏度。

II. TEGO采用多种时间延迟干涉仪（TDI）配置，有效抑制激光频率噪声。这种改进使得TEGO在探测引力波信号时具有更高的信噪比。

III. 通过在航天器平台上均匀分布的激光望远镜和指向结构，TEGO形成了一个稳定的质量中心。与传统的三航天器配置相比，增加的第四个航天器和望远镜提供了安全备份，增强了系统的可靠性。

# Summary and Comments

IV. TEGO的设计允许直接探测广义相对论之外的引力波模式，如标量纵向模式。这为验证和扩展现有的引力理论提供了新的实验平台 。

V. TEGO成本相对于三星计划并没有增加多少，但收益倍增。

VI. TEGO是我们最近提出的一个空间引力波探测天文台方案。初步分析发现TEGO存在稳定的卫星轨道，可以开展引力波探测实验。未来还需要更多的人员参与。

# Summary and Comments

VII. 可以预期，未来十余年将是引力波天文学大发展的年代，人类有望对全波段引力波进行观察，从而对引力理论、宇宙演化有新的认识。

# THANKS

# Backups

# 649次香山科学会议——中国空间引力波探测计划和国际协作联盟

**2019.4.17-18 北京香山饭店**