University of Chinese Academy of Sciences

ICTP-AP International Centre for Theoretical Physics Asia-Pacific 国际理论物理中心-亚太地区

Topological Solitons, Phase Transitions and Gravitational Waves

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4.25, 2025

University of Science and Technology of China

Outline

- Why do we want to study solitons？
- Magnetic Monopoles
- Gravitational waves from cosmic phase transitions and Cosmic strings
- How to detect their gravitational waves?

Motivated by the desire to explore the new tool: gravitational waves

Hulse–Taylor Binary

The Nobel Prize in Physics 1993

Photo from the Nobel Foundation archive.

Russell A. Hulse

Prize share: 1/2

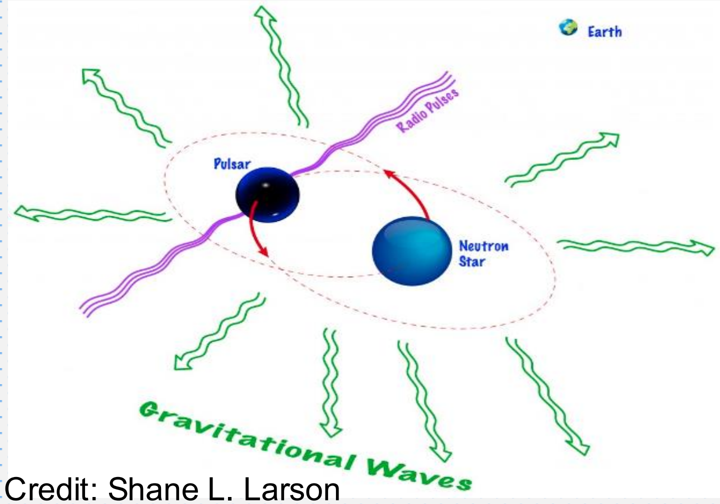
Photo from the Nobel Foundation archive.

Joseph H. Taylor Jr.

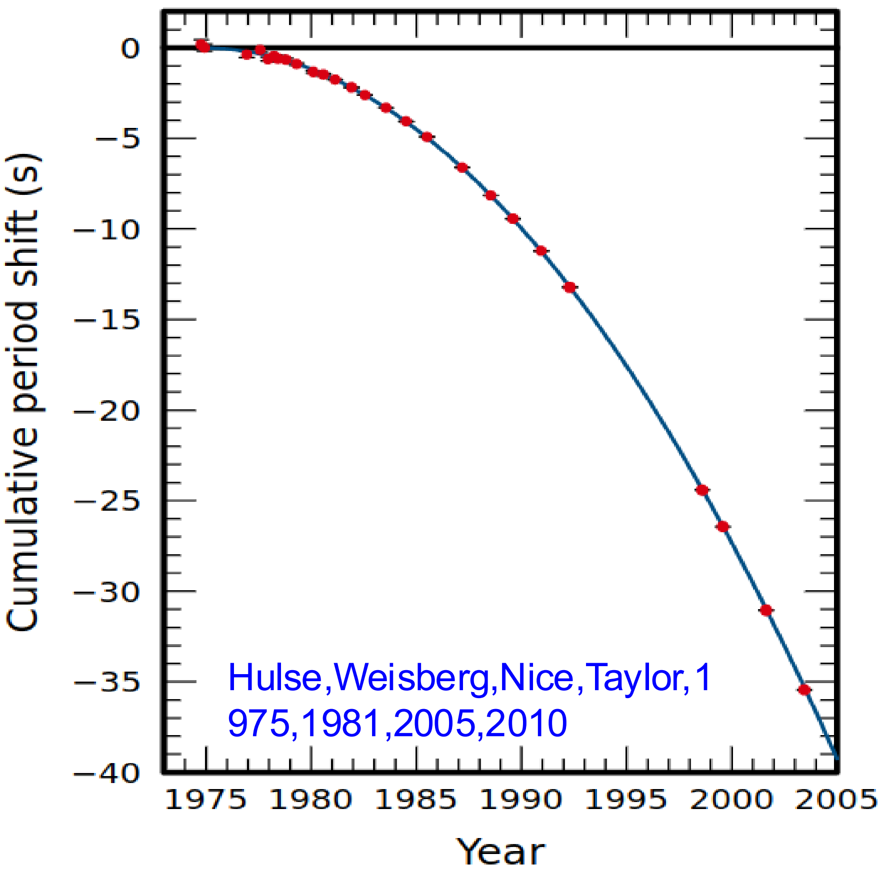
Prize share: 1/2

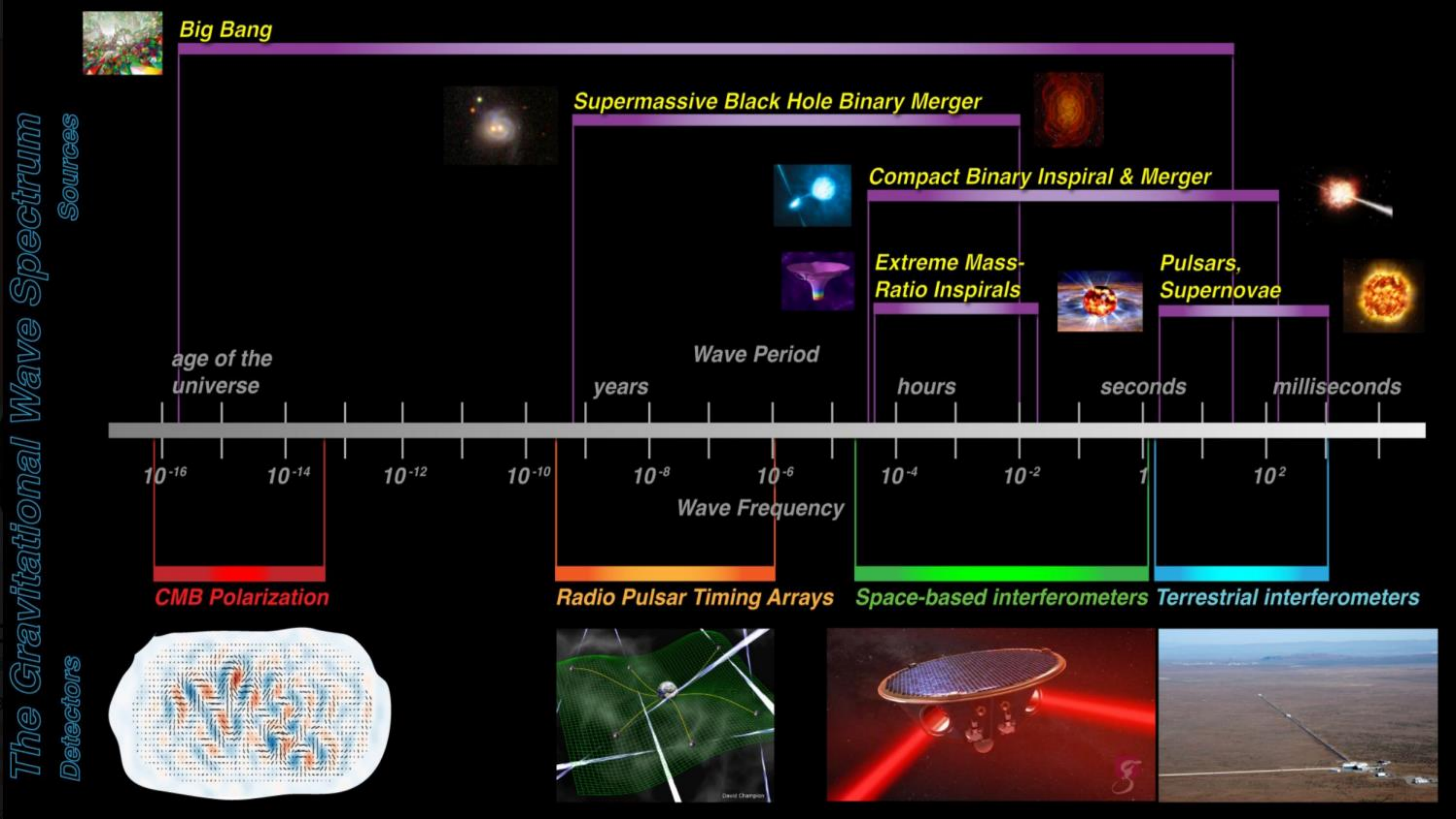
www.nobelprize.org

The Nobel Prize in Physics 1993 was awarded jointly to Russell A. Hulse and Joseph H. Taylor Jr. "for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation"



Credit: Shane L. Larson

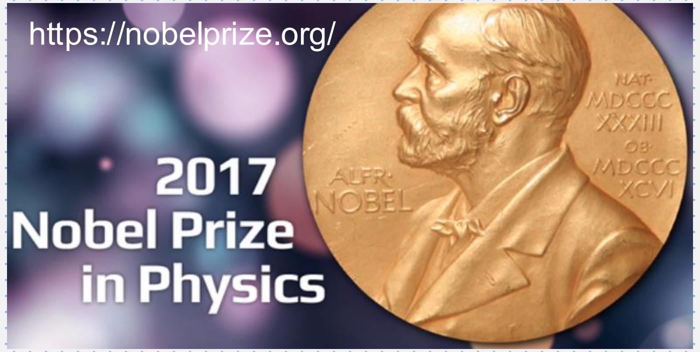


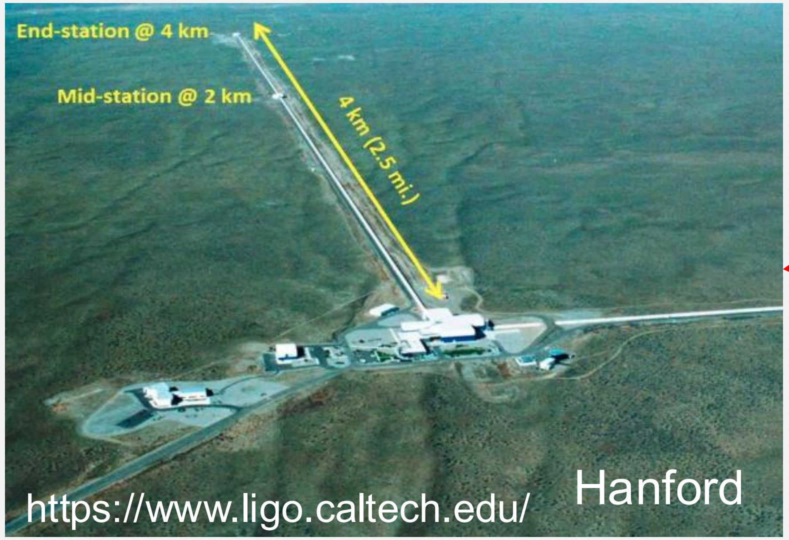

The Gravitational Wave Spectrum
Sources
Big Bang
Supermassive Black Hole Binary Merger
Compact Binary Inspiral & Merger
Extreme Mass-Ratio Inspirals
Pulsars, Supernovae
Wave Period
age of the universe
years
hours
seconds
milliseconds
10^{-16}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10^{2}
Wave Frequency
CMB Polarization
Radio Pulsar Timing Arrays
Space-based interferometers
Terrestrial interferometers
Detectors

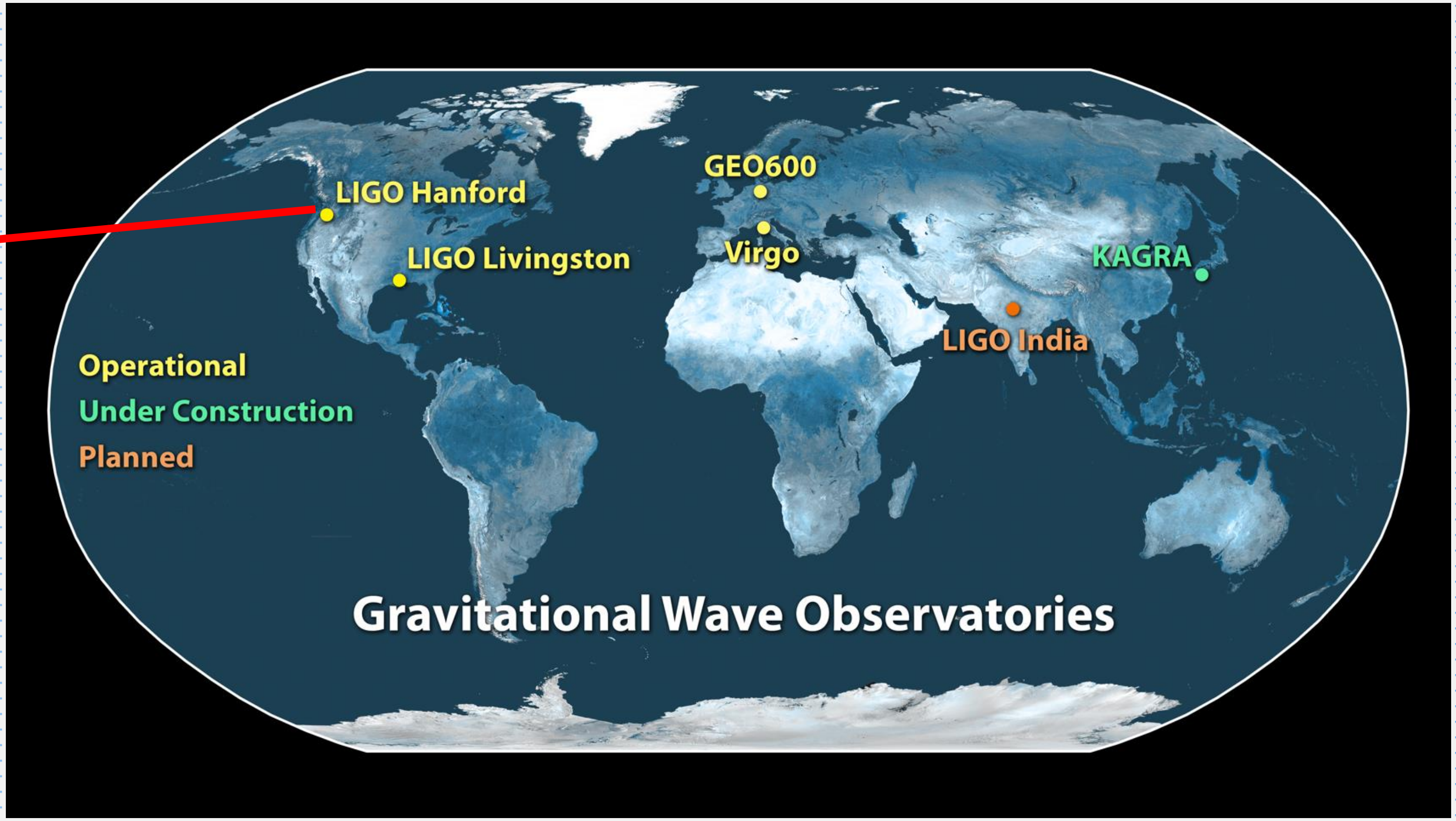
LIGO

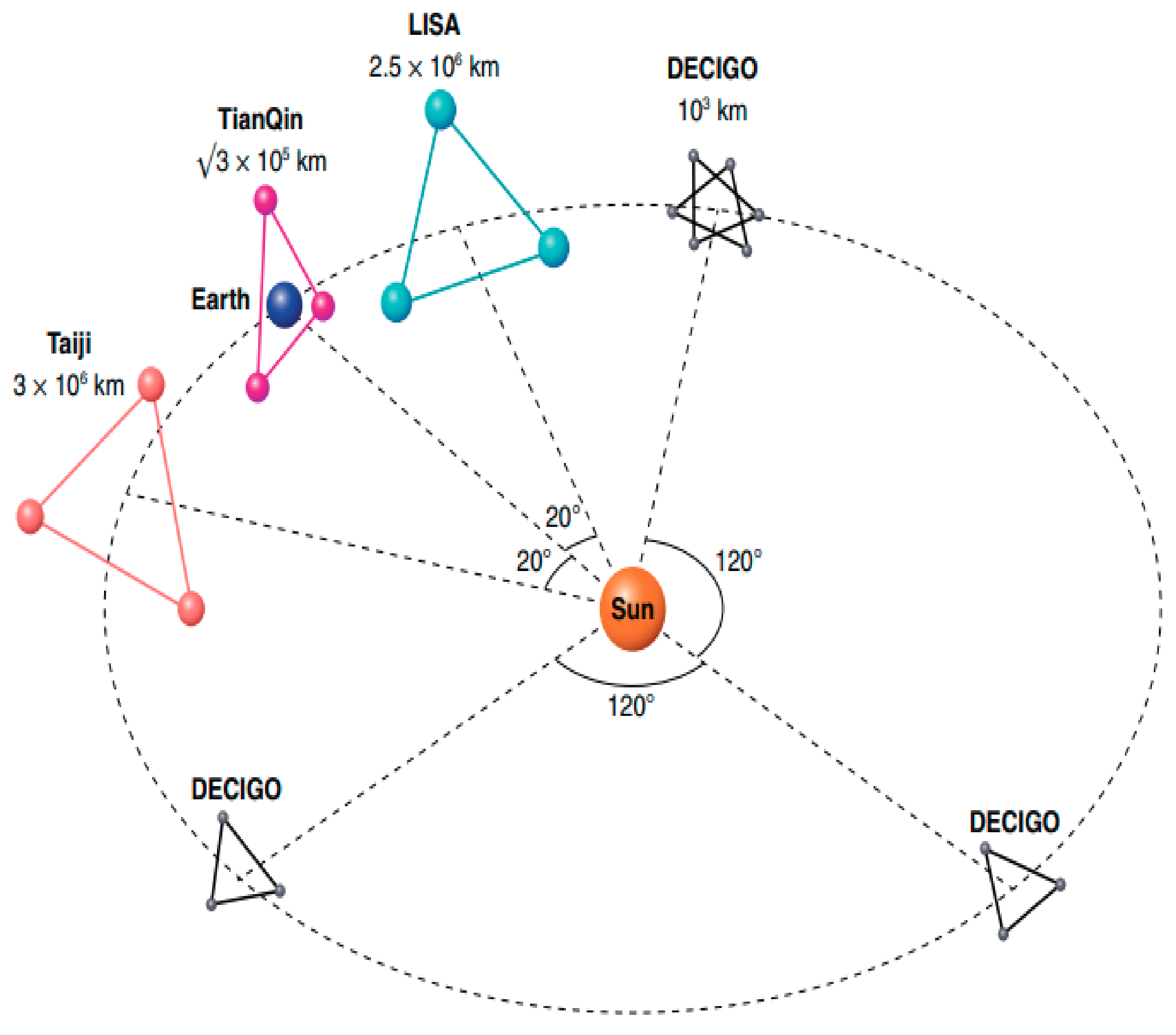
First direct detection of gravitational waves.

A new era for astronomy, and fundamental physics





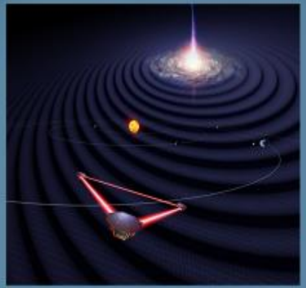




Nature Astronomy, Gong, Luo, Wang (2021)

2012年

中国科学院牵头成立了我国空间探测工作组，并首次在ELISA联盟会议上，提出了中国空间引力波探测计划



2015年

小提示

2015年9月14日，激光干涉引力波天文台（LIGO）首次直接探测到引力波

2016年

正式对外公布“太极计划”，明确了“单星、双星、三星”三步走的发展战略

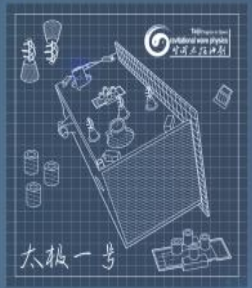
2017年

小提示

2017年10月3日，诺贝物理学奖授予三名美国科学家雷纳·韦斯（Rainer Weiss）、巴里·巴里什（Barry C. Barish）和基普·索恩（Kip S. Thorne），以表彰他们为LIGO项目和发现引力波所作的贡献

2018年

“三步走”的第一步（单星工程任务）正式启动实施

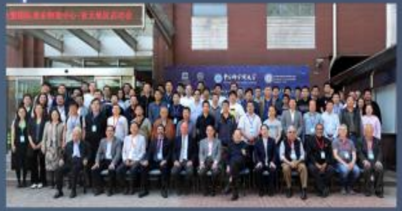


2019年

2019年8月31日，“太极一号”成功发射

白春礼院长在开学典礼上通报发射成功的喜讯

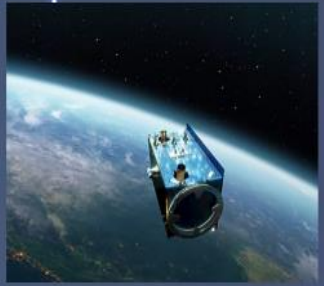
任务团队在酒泉卫星发射中心合照留念



作为太极实验室的挂靠单位，国际理论物理中心（亚太地区）正式启动运行

2020年

“太极一号”通过在轨实验，验证了关键技术路线的可行性，完成了我国空间引力波探测的第一步，成功入选2019年的“中国十大科技进展新闻”和中国科学院年度科技创新亮点成果

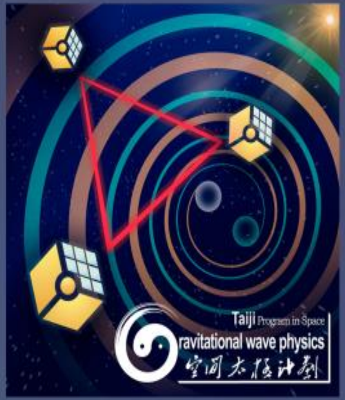


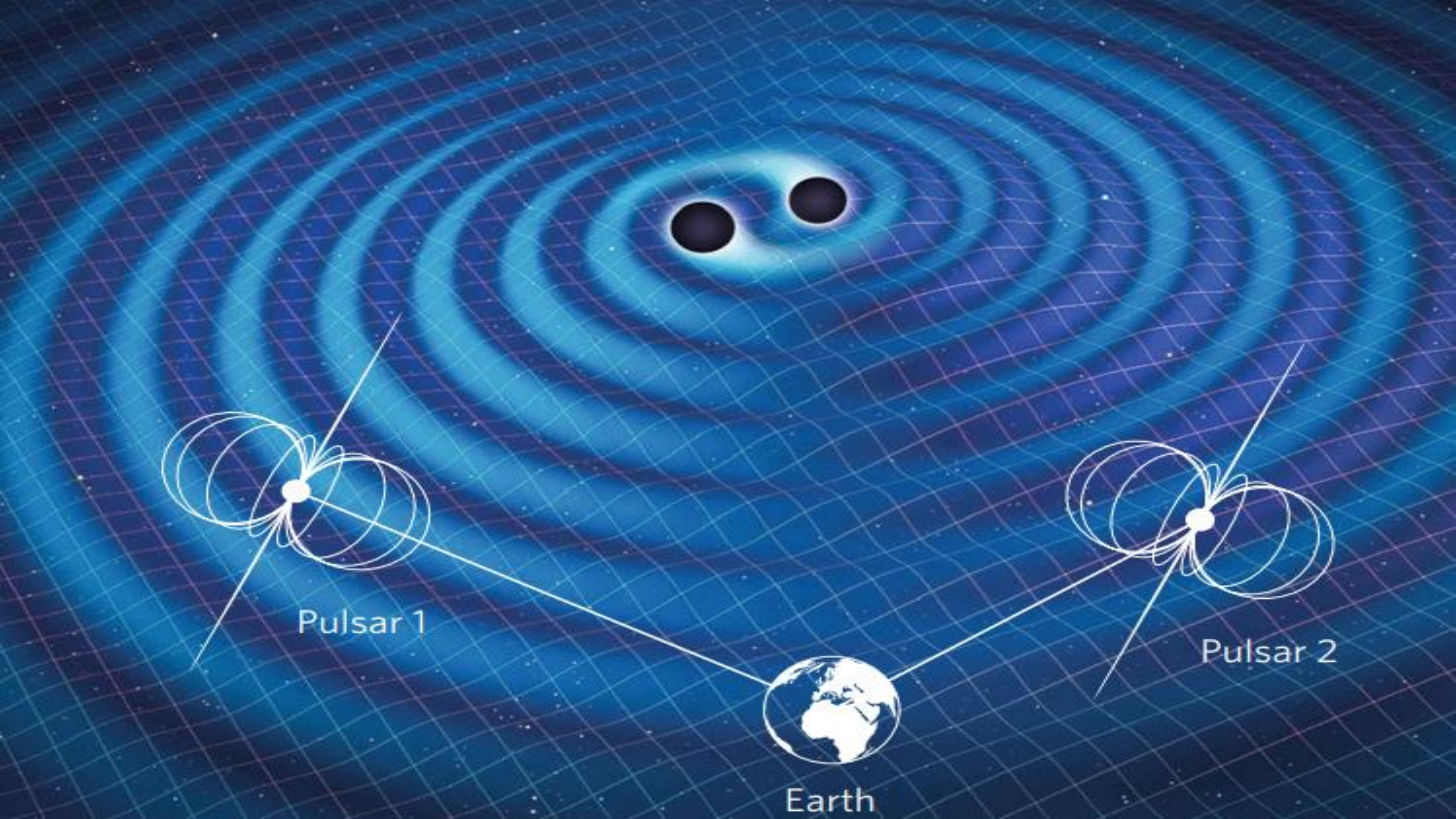
重大意义

- 中国首颗空间引力波探测技术实验卫星
- 中国首次在轨无拖曳控制技术试验
- 中国最高精度的空间激光干涉测量
- 国际上首次在轨验证微牛级射频离子和双模霍尔电推进技术

~2035年

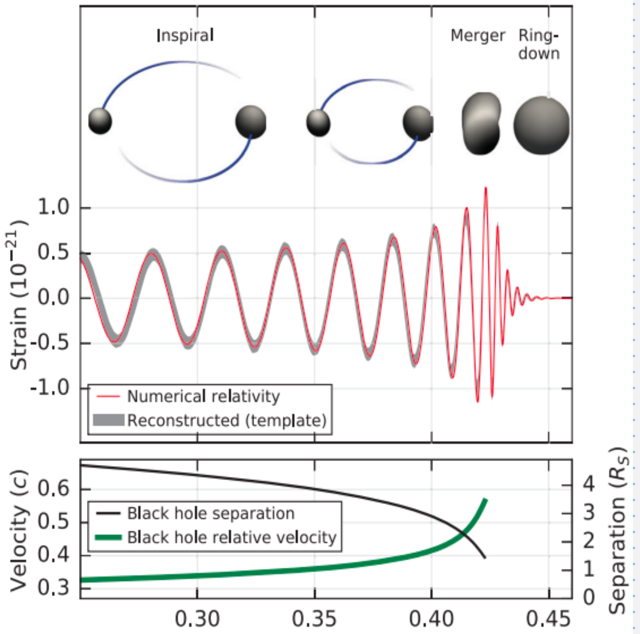
太极二号、太极三号




Pulsar 1
Pulsar 2
Earth

Why Solitons?

GW generation requires macroscopic mass/energy



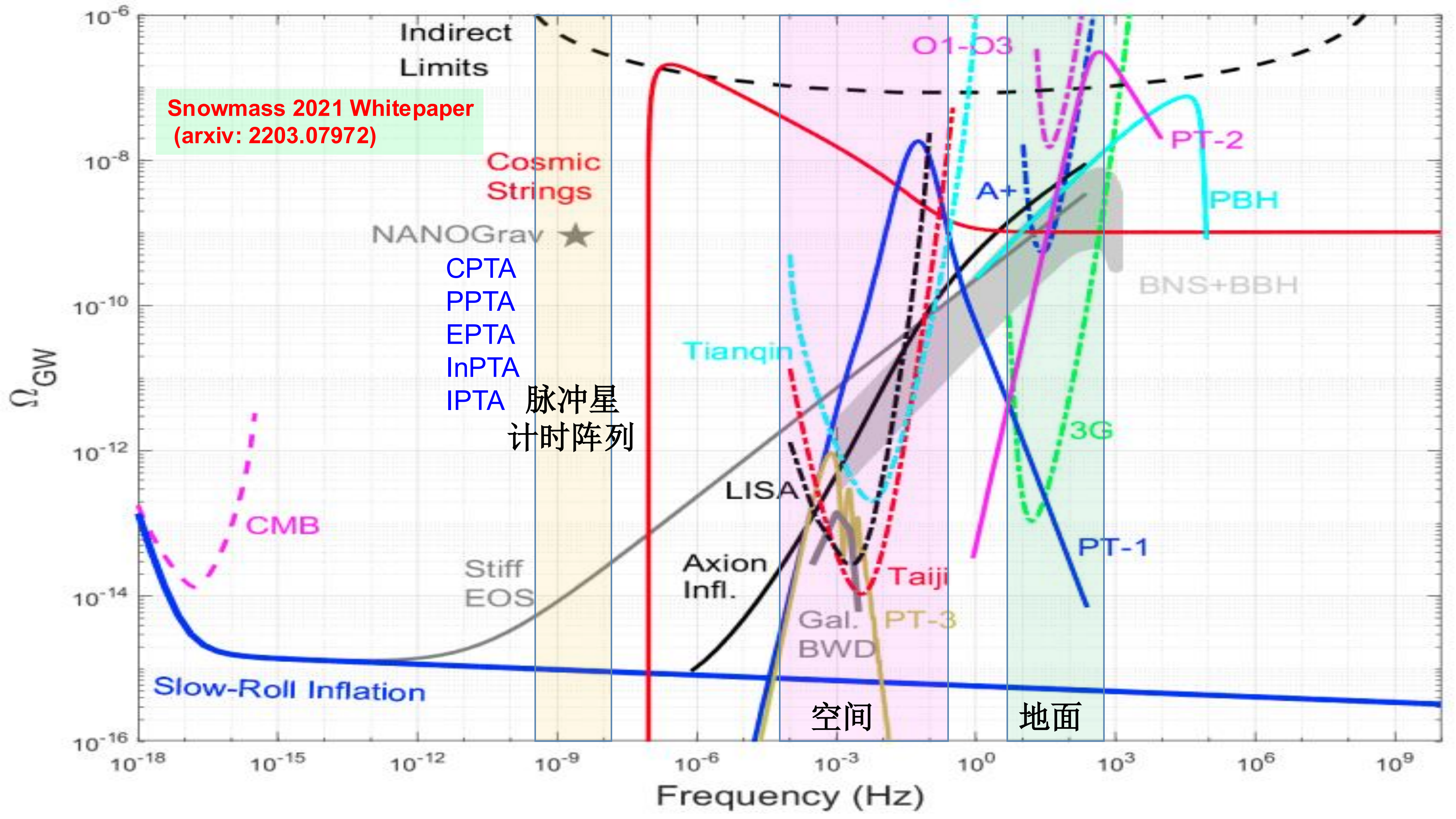
PRL 116, 061102 (2016)

$$\Box^2 h_{\mu\nu} = -16\pi G S_{\mu\nu}$$ → matter

$$h \sim 10^{-22} \frac{M/M_\odot}{r/100\mathrm{Mpc}} \left(\frac{v}{c}\right)^2$$ → huge mass/energy

How to study particle physics with GWs?

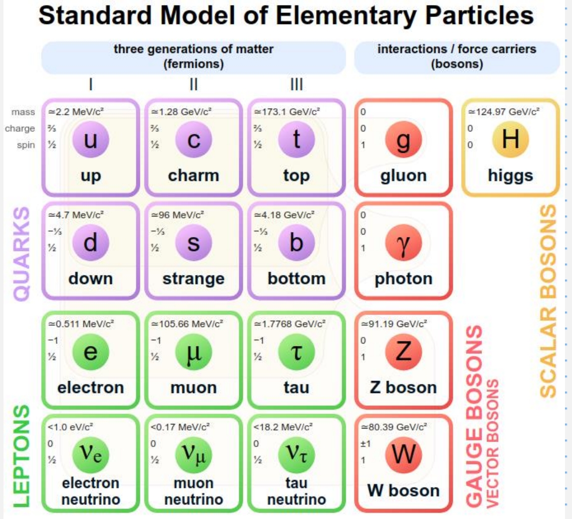
Answer: make it much bigger


Snowmass 2021 Whitepaper
(arxiv: 2203.07972)
Indirect Limits
Cosmic Strings
NANOGrav
CPTA
PPTA
EPTA
InPTA
IPTA
脉冲星
计时阵列
O1-O3
A+
PT-2
PBH
BNS+BBH
Tianqin
3G
LISA
PT-1
Axion Infl.
Taiji
Gal. BWD
PT-3
CMB
Stiff EOS
Slow-Roll Inflation
空间
地面
Ω_{GW}
Frequency (Hz)

New Perspectives?

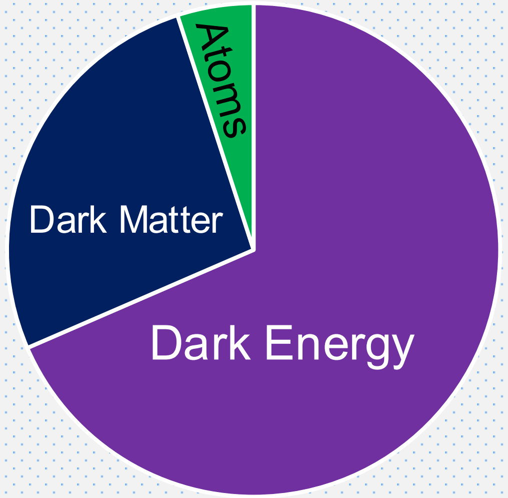
How to reconcile the two standard models?

Particle Physics



Physics Beyond the SM?

Cosmology




REVIEW

https://doi.org/10.1038/s41586-019-1129-z

The new frontier of gravitational waves

M. Coleman Miller[1,2]* & Nicolás Yunes[3]*

What is dark matter? (solitons)
Why more matter than anti-matter? (phase transitions, solitons)

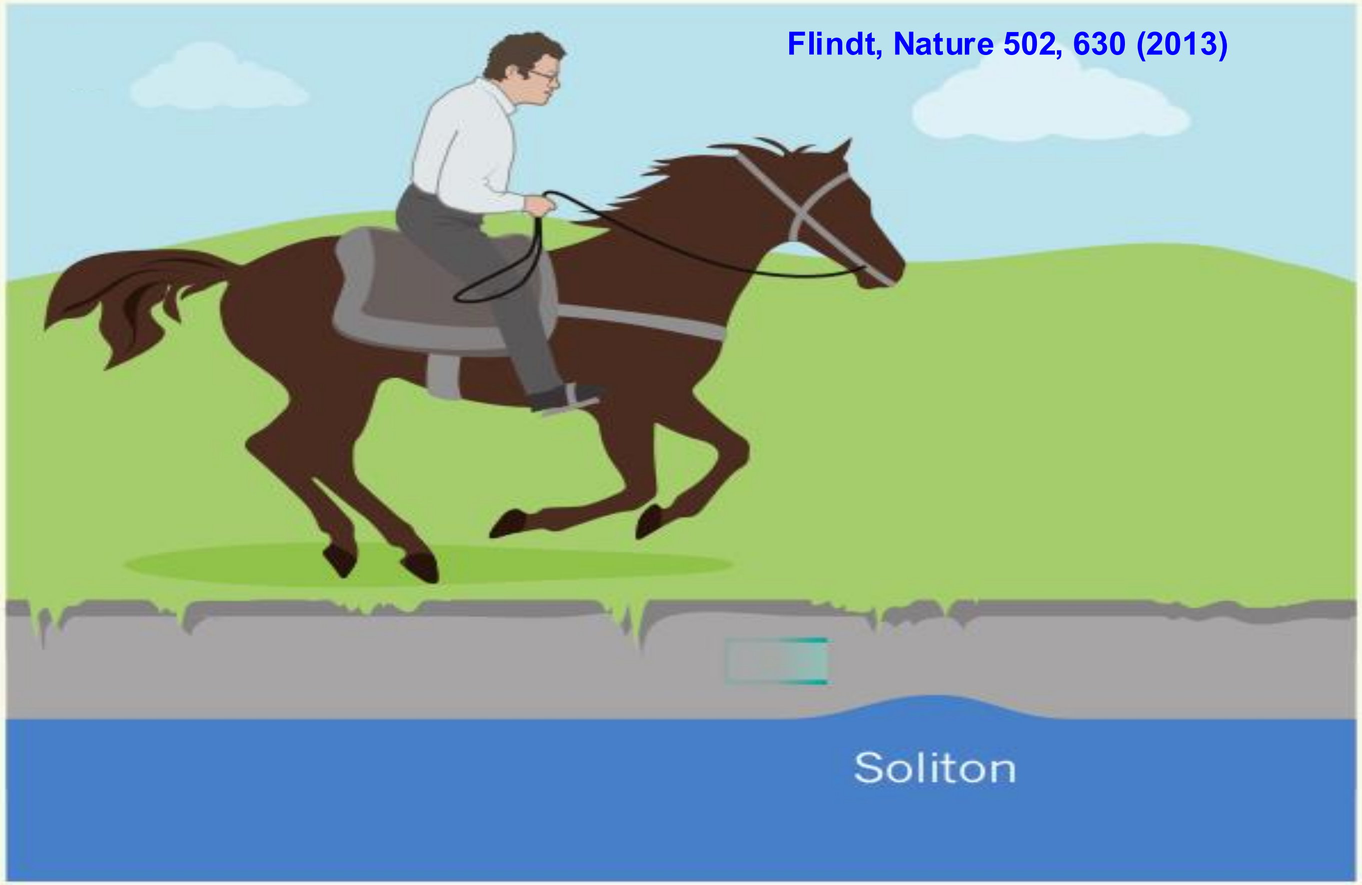
Solitons

- Localized
- Associated with nonlinear problem

Found in:

- ✓ Optics
- ✓ Hydrodynamics
- ✓ Condensed matter systems
- ✓ Quantum field theory (this talk)

...



Solitons in Quantum Field Theory

- Both are solitonic solutions to classical field equations
- Differ in the nature, context, and how they are stabilized

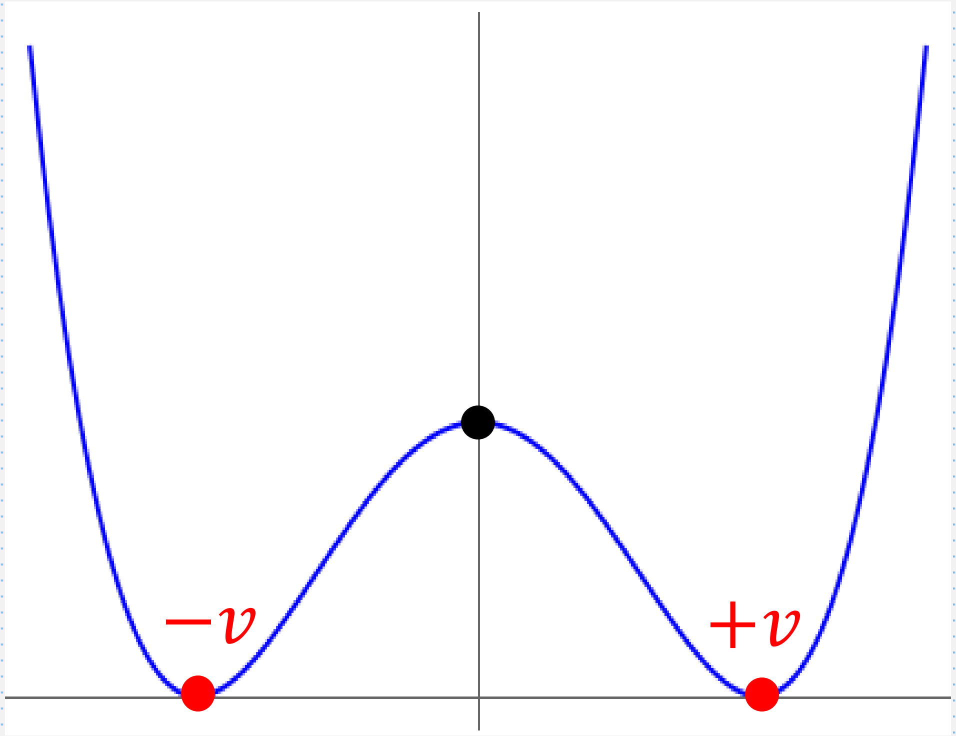
	Topological Solitons	Non-Topological Solitons
Definition	Static Solution (Theory with Spontaneously Broken Symmetry) ● Global symmetry (Skyrmion, Cosmic String) ● Discrete symmetry (Domain wall) ● Local symmetry (Monopole, Cosmic String or Vortex line...) ● Pure gauge theory (Instanton)	Bose-Einstein Condensate of Ultralight particles (DM) ● Galactic scale (DM Halo) ● Stellar scale (Boson stars)
Boundary	Non-Trivial (needs degenerate vacuum states)	Trivial vacuum state
Stabilized by	Topology (boundary field values)	Conserved Charge, and Balancing ● quantum pressure ● gravity (or not, Q-balls etc) ● self-interactions (or not)

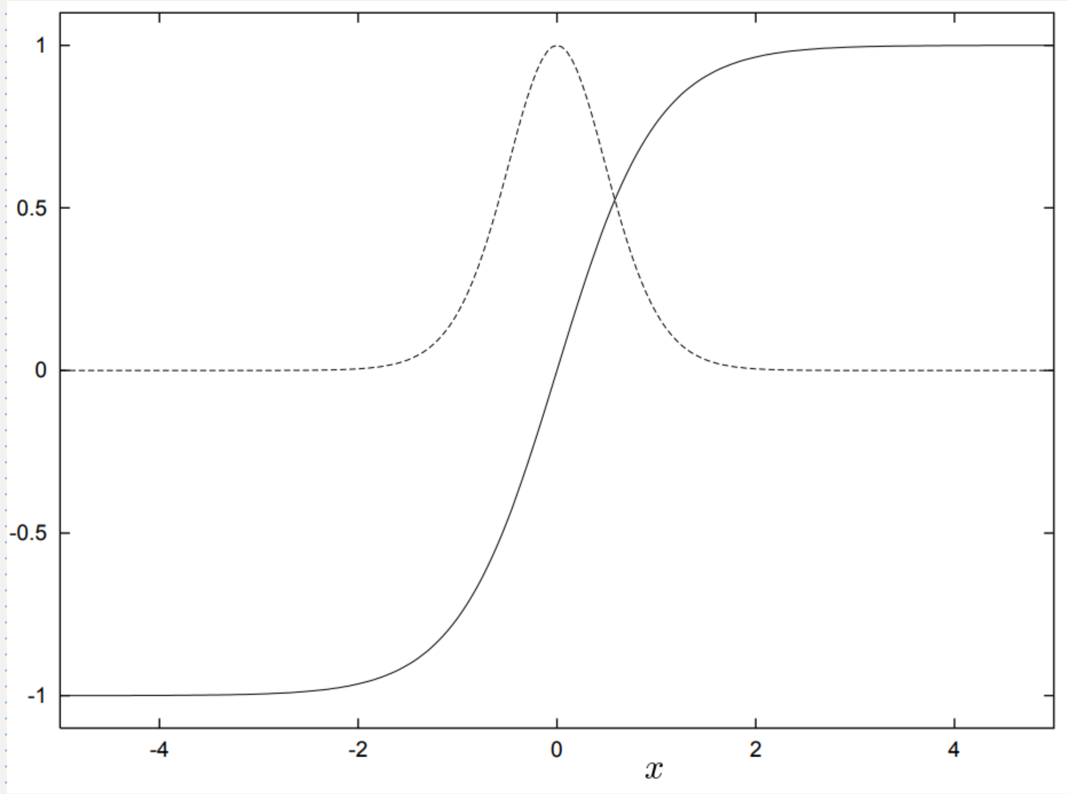
Weinberg, QFT Vol2; Topological Solitons, Manton, Sutcliffe

Kinks/Domain Wall

$\pi_0(\mathcal{M})$

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \lambda(v^2 - \phi^2)^2$$





Topological Solitons, Manton, Sutcliffe

Cosmic String/Vortex Line

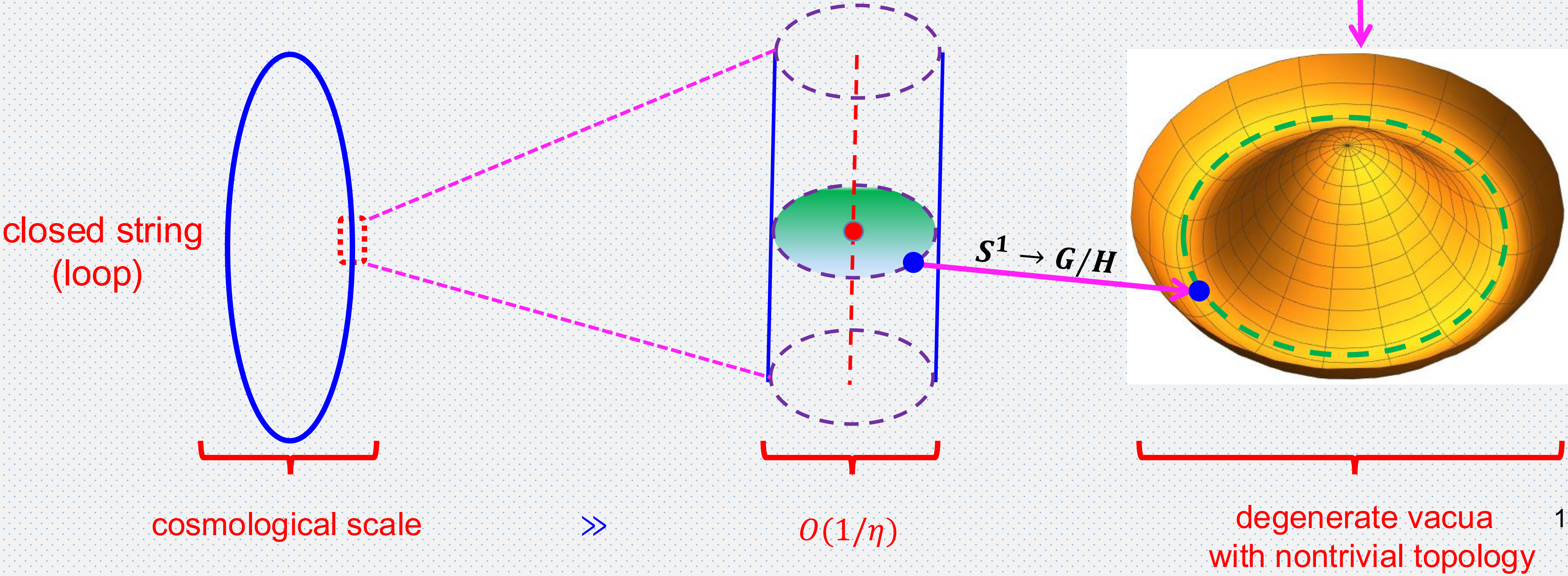
$\pi_1(\mathcal{M})$

$$G\mu \sim \left(\frac{\eta}{10^{19}\mathrm{GeV}}\right)^2$$

μ: line mass density

Example: the Abelian Higgs Model

$$\mathcal{L} = |(\partial_\mu - igA_\mu)\Phi|^2 - \frac{1}{4}\lambda(|\Phi|^2 - \eta^2)^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$



Topological Solitons in the Early Universe

- Firstly proposed to form in the early universe (Kibble,1976)
  (None observed)
- Later proposed to form in condensed matter systems (Zurek, 1985)
  (already oberved)

Name variant:
Topological Defects

Topology of cosmic domains and strings

T W B Kibble J.Phys.A 9 (1976) 1387-1398

Blackett Laboratory, Imperial College, Prince Consort Road, Lor

Received 11 March 1976

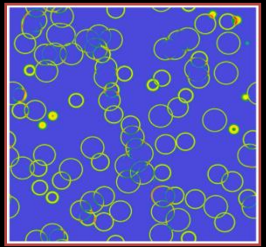
www.theguardian.com

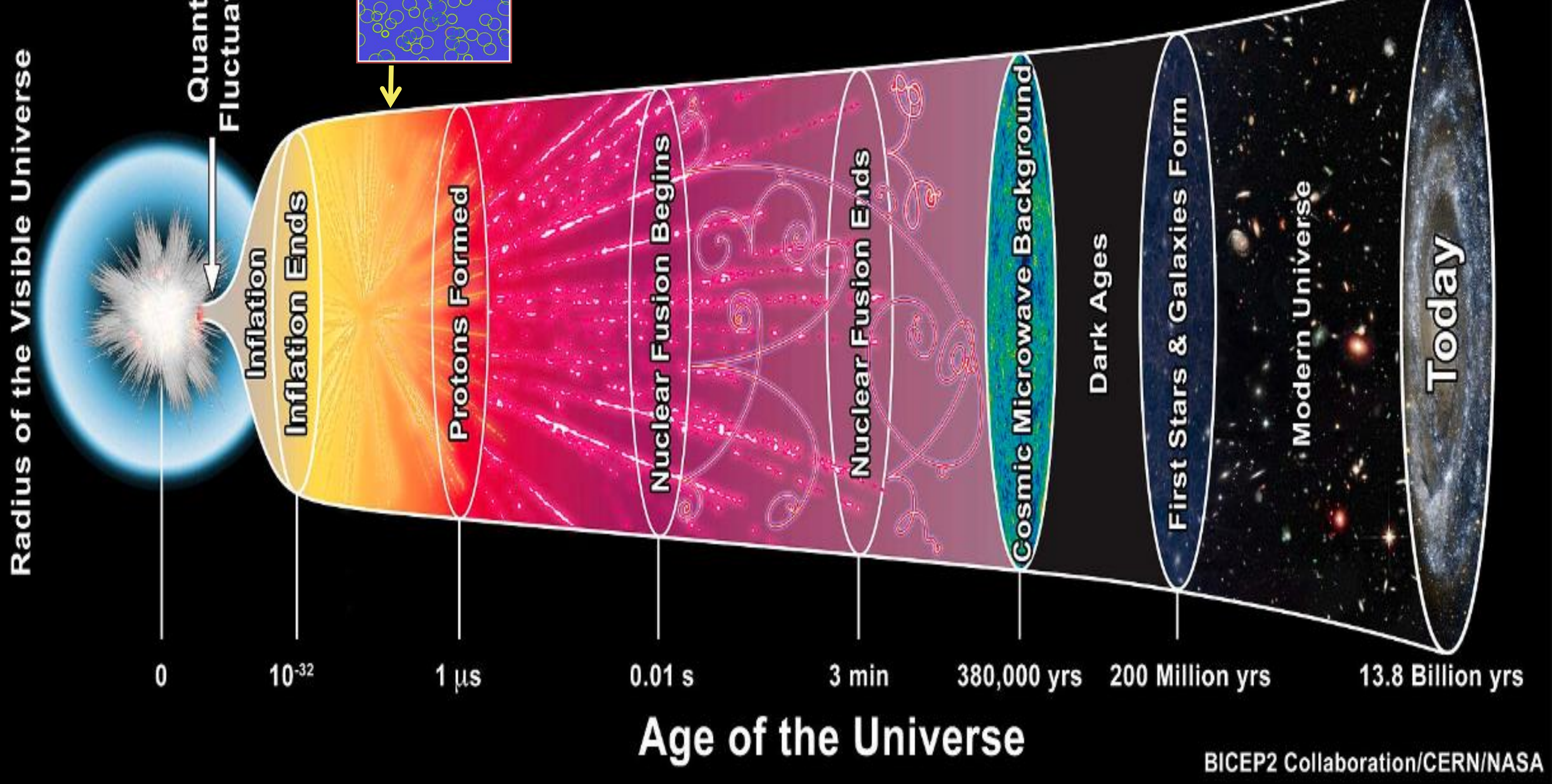
The Cosmological Kibble Mechanism in the Laboratory: String Formation in Liquid Crystals

Science, 263 (1994)

Mark J. Bowick,* L. Chandar, E. A. Schiff, Ajit M. Srivastava

first order PT, cosmological defects (cosmic string)





Topological Solitons in the Early Universe

$$V(\phi) = \frac{1}{4}(\phi^2 - v^2)^2$$

$$V(\Phi) = \frac{1}{4}(|\Phi|^2 - \eta^2)^2$$