Detection of Topological and Non-Topological Solitons with Gravitational Waves

Huaike Guo

University of Utah ⟶ UCAS (ICTP-AP)

12/18/2022

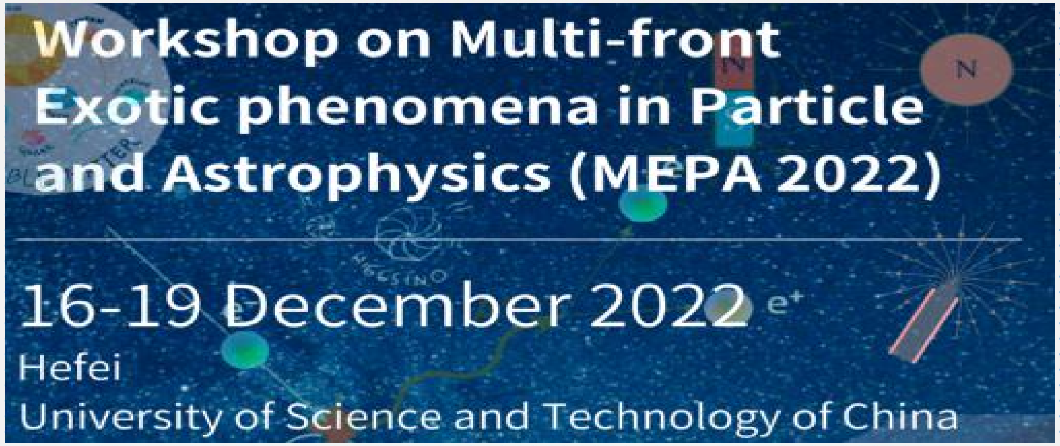
LIGO-Virgo-KAGRA collaborations, PRL 126, 241102 (2021)
(U. Utah group: Yue Zhao, HG, Fengwei Yang)

HG, Sinha, Sun, Swaim, Vagie, JCAP 10 (2021) 028

HG, Sinha, Sun, JCAP 09 (2019) 032

HG, Shu, Zhao, PRD 99 (2019) 023001

HG, Miller, arxiv:2205.10359

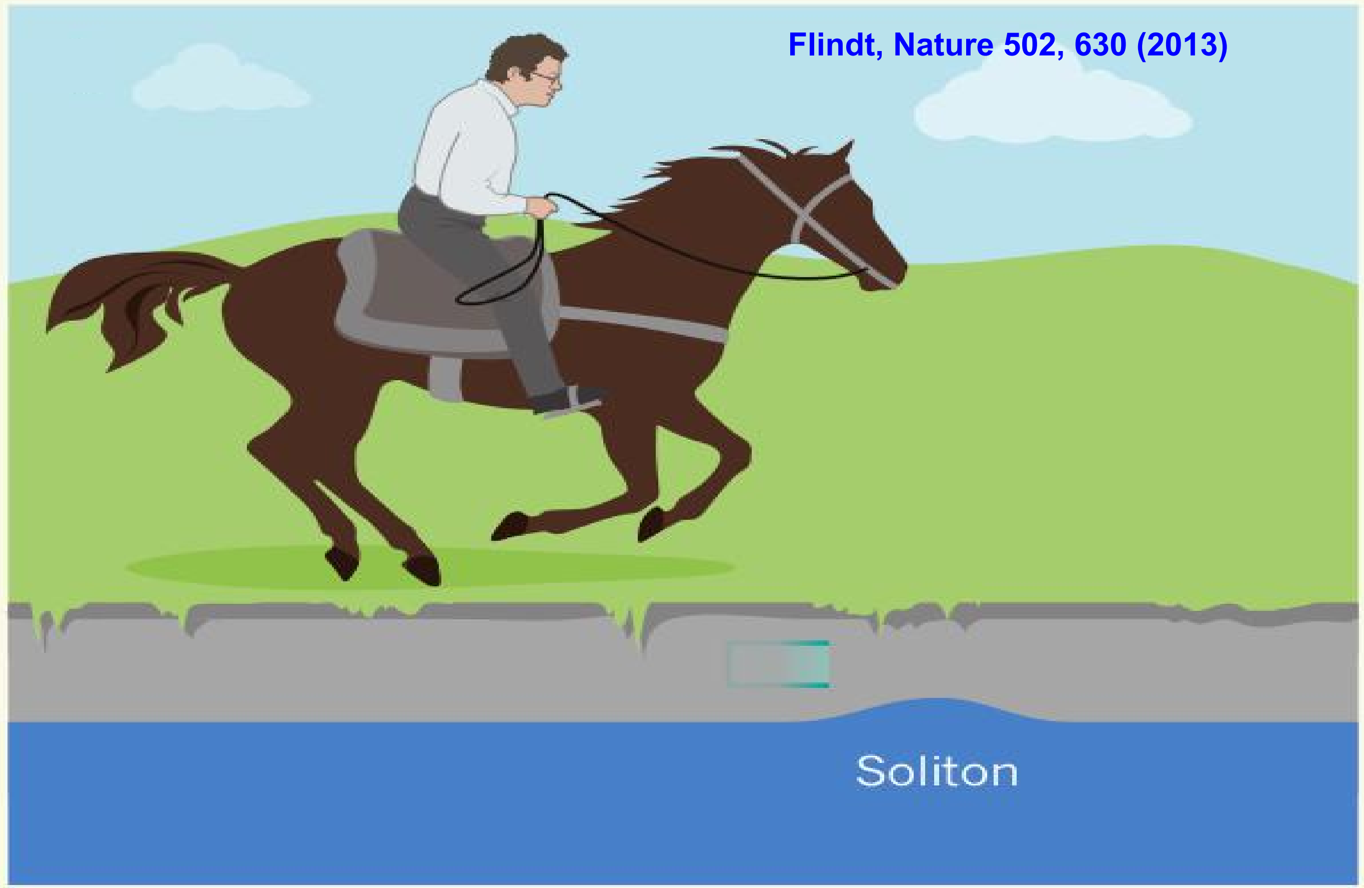


Solitons

- Localized
- Associated with nonlinear problem

Found in:

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



Why Solitons?

Appear in solutions to fundamental problems

- Topological solitons: symmetry breakings in the early universe (new physics, baryon asymmetry)
- Non-Topological solitons: as DM candidates (ultralight DM, macroscopic DM)

✓ Both are important sources of GWs (not so many from particle physics)

✓ GWs provide independent probings (very high energies, purely gravitational interactions)


REVIEW

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

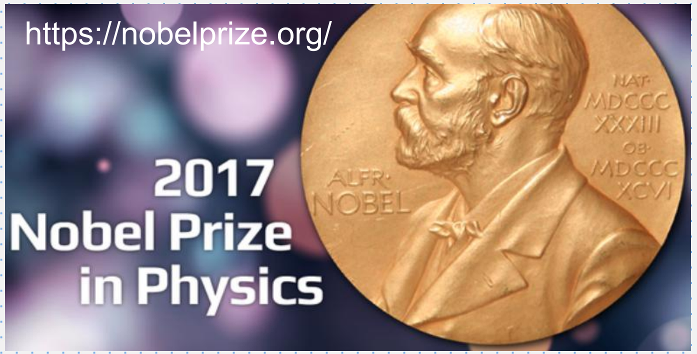
The new frontier of gravitational waves

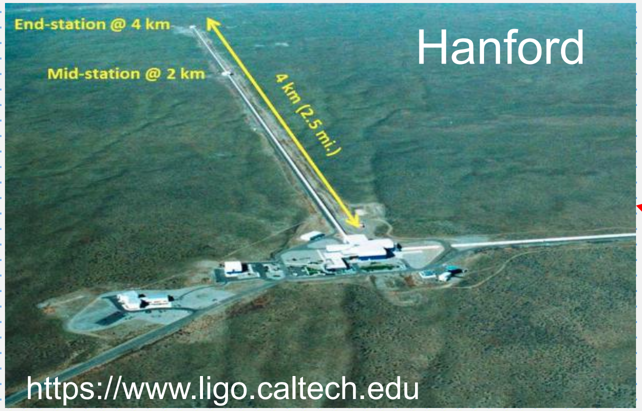
M. Coleman Miller[1,2]* & Nicolás Yunes[3]*

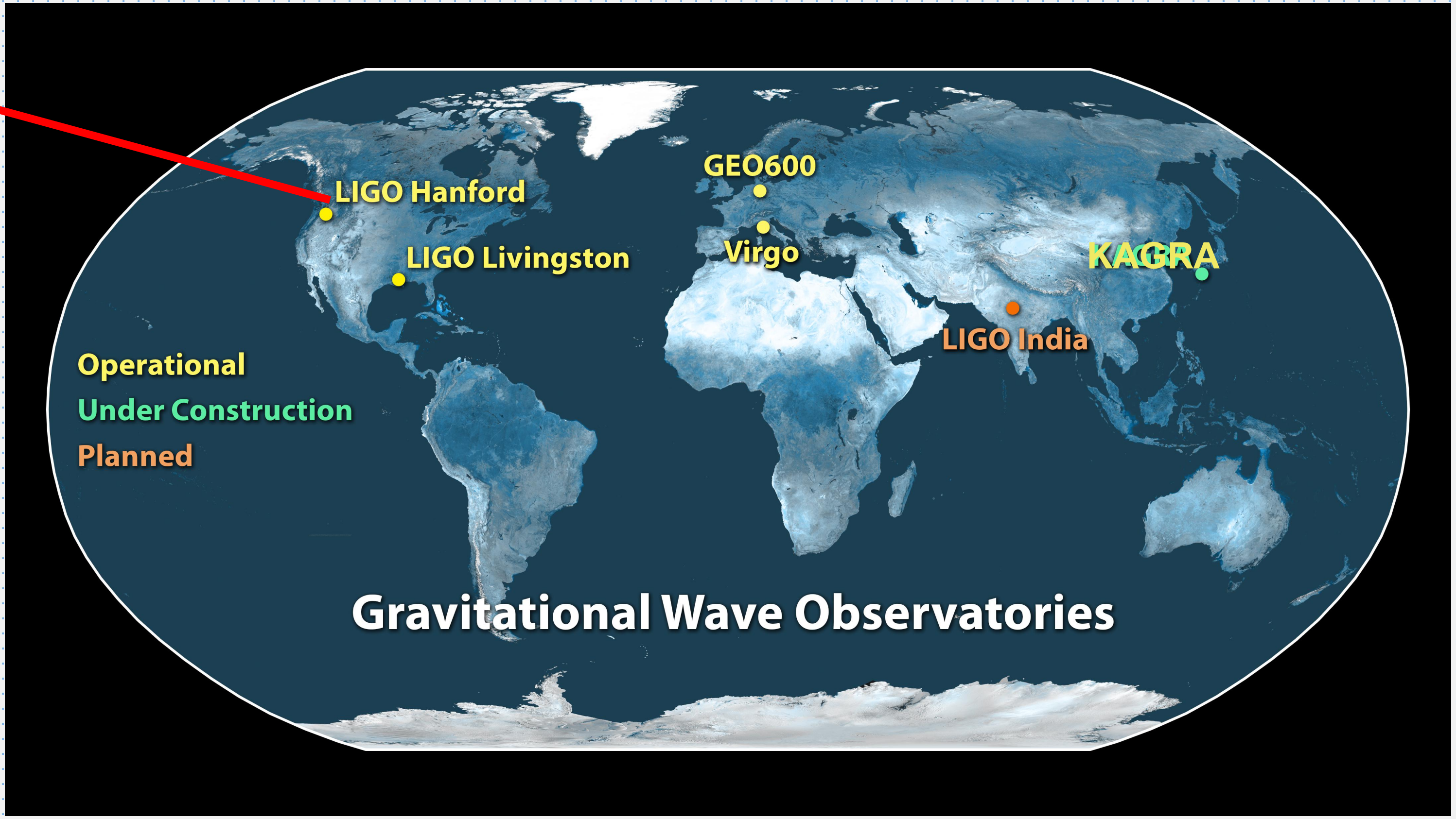
LIGO Interferometers

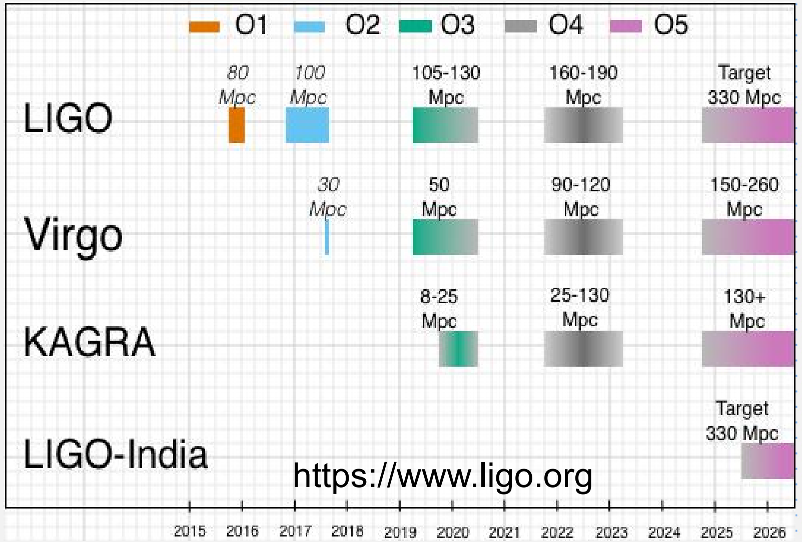
First direct detection of gravitational waves.

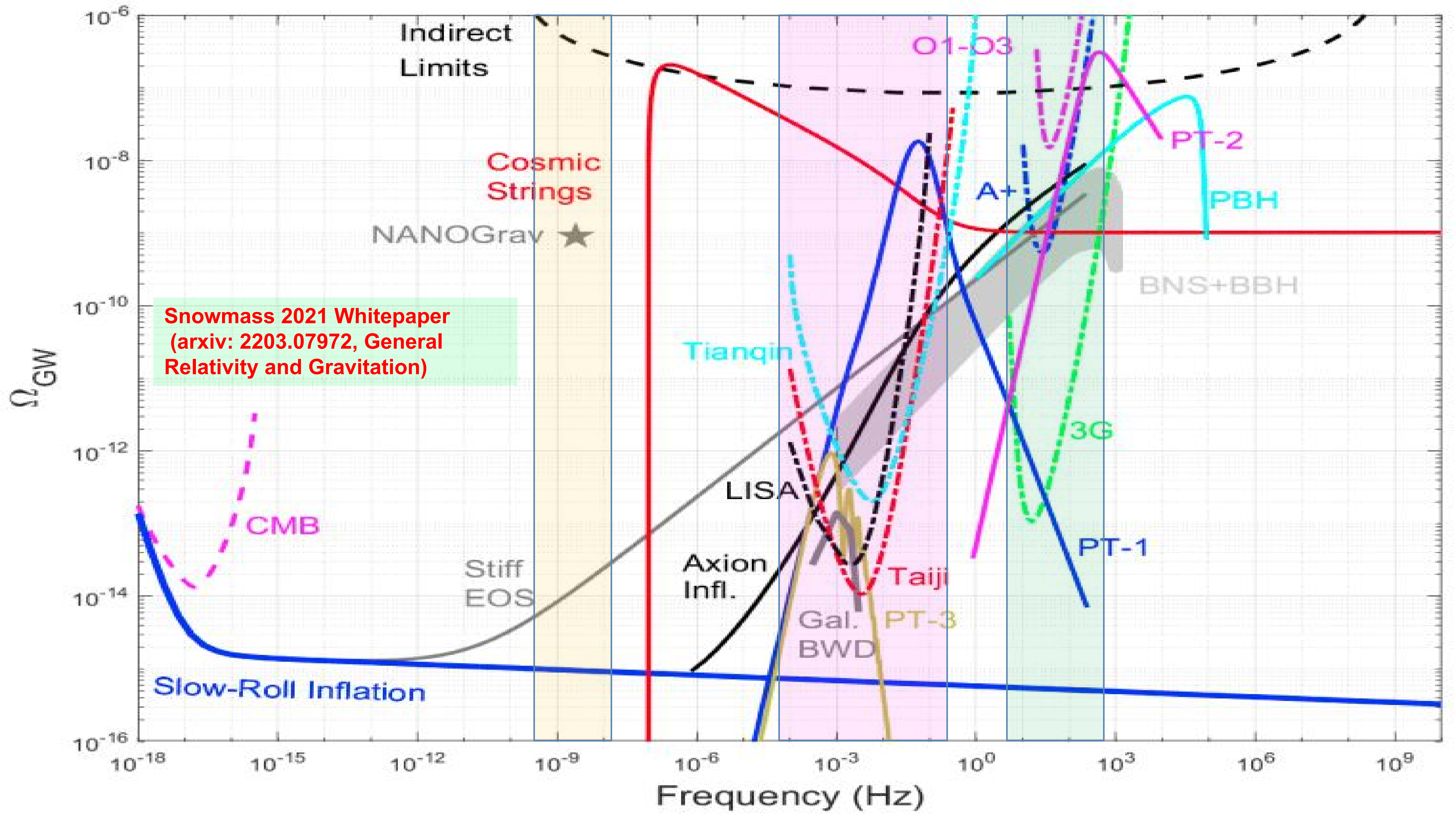
A new tool for astronomy, and fundamental physics











Indirect Limits
Cosmic Strings
NANOGrav
O1-O3
PT-2
A+
PBH
BNS+BBH
Snowmass 2021 Whitepaper
(arxiv: 2203.07972, General
Relativity and Gravitation)
Tianqin
3G
LISA
CMB
PT-1
Stiff EOS
Axion Infl.
Taiji
Gal. BWD
PT-3
Slow-Roll Inflation
Ω_{GW}
Frequency (Hz)

Solitons in Quantum Field Theory

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

See also Shuangyong's Talk

	Topological Solitons	Non-Topological Solitons
Definition	Static Solution (Theory with Spontaneously Broken Symmetry) • Global symmetry (Skyrmion) • 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) • self-interactions (or not)

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

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

Can we detect the (cosmic) topological solitons?

Topology of cosmic domains and strings

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

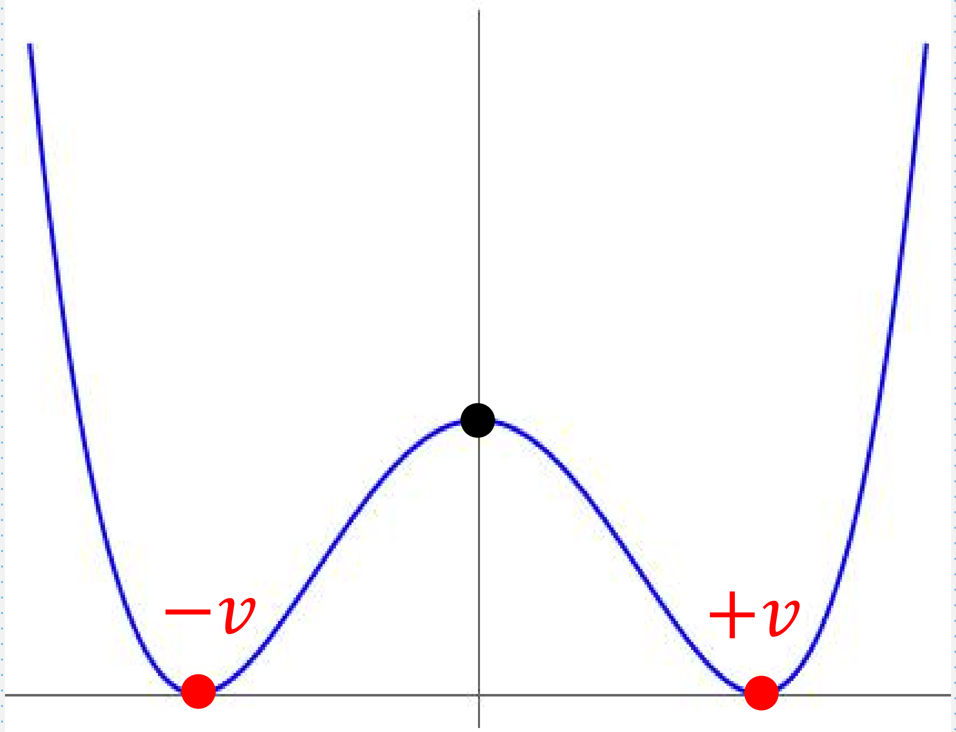
Blackett Laboratory, Imperial College, Prince Consort Road, Lor

Received 11 March 1976

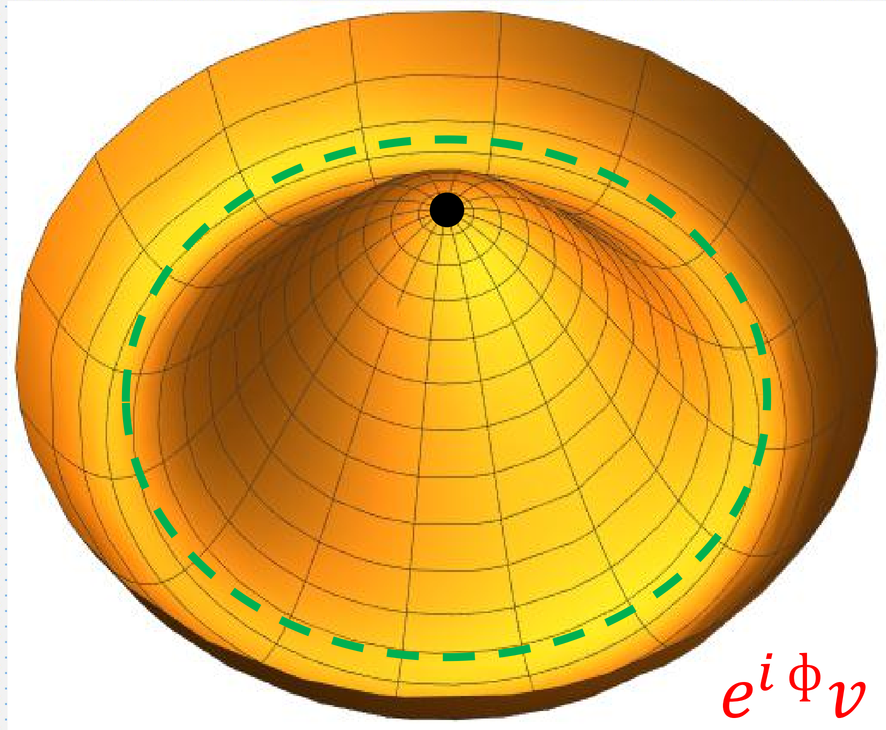
www.theguardian.com

Degenerate Vacuum States

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



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

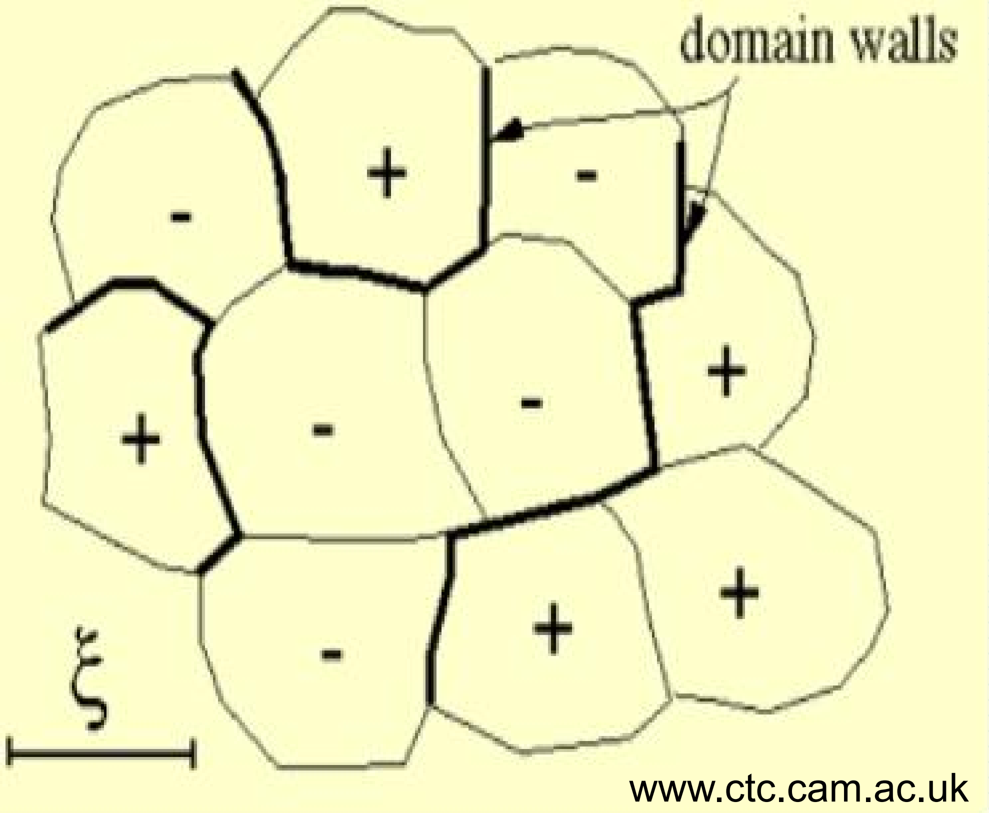


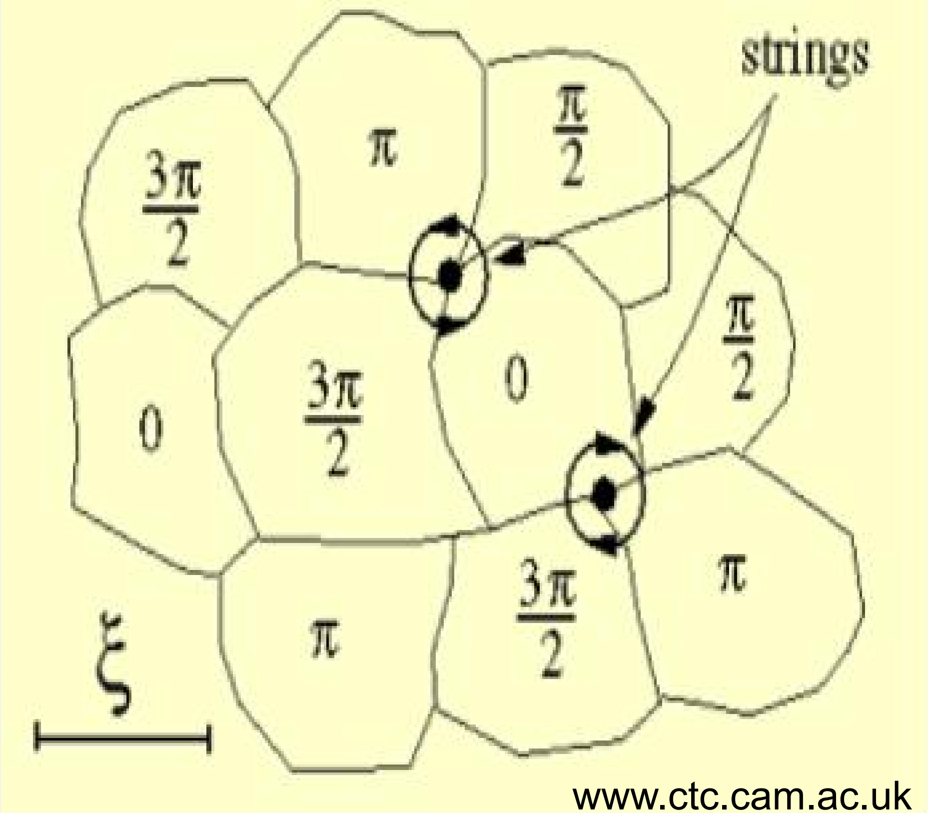
Field needs to take vacuum values at the boundary to have finite energy.

Degenerate Vacuum States

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

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





Will focus on cosmic strings.

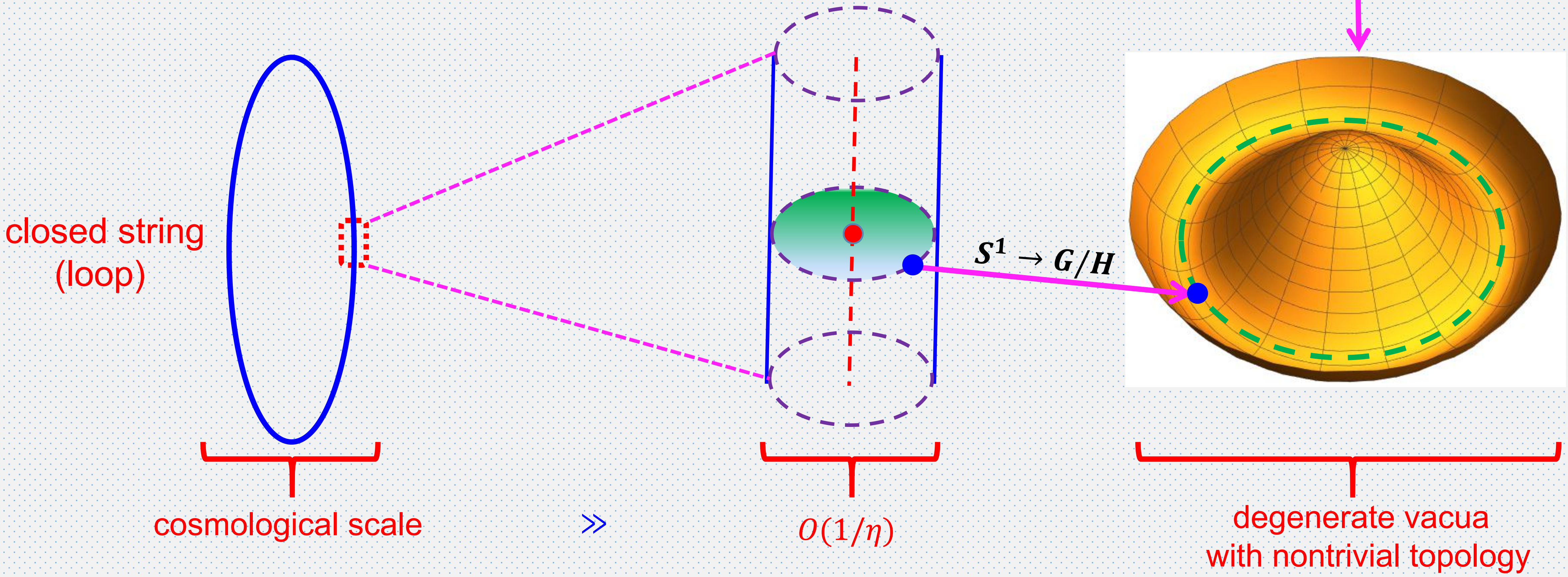
Cosmic String

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

μ: line mass density

Example: the Abelian Higgs Model

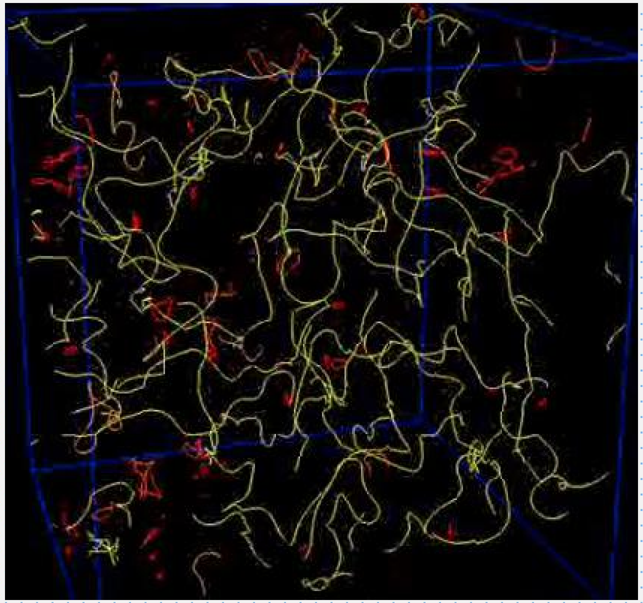
$$\mathcal{L} = |(\partial_\mu - igA_\mu)\Phi|^2 - \frac{1}{4}\lambda(|\Phi|^2 - \eta^2)^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

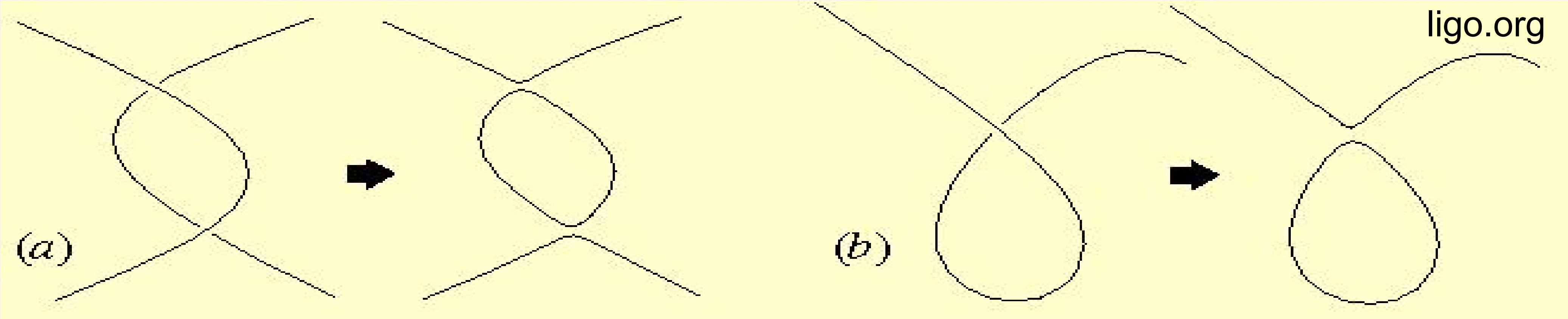


Cosmic String Network

loop distribution

- Long strings interconnect to form loops
- Loops oscillate and radiate GWs (and shrink)
- Scaling loop distributions reached in RD and MD



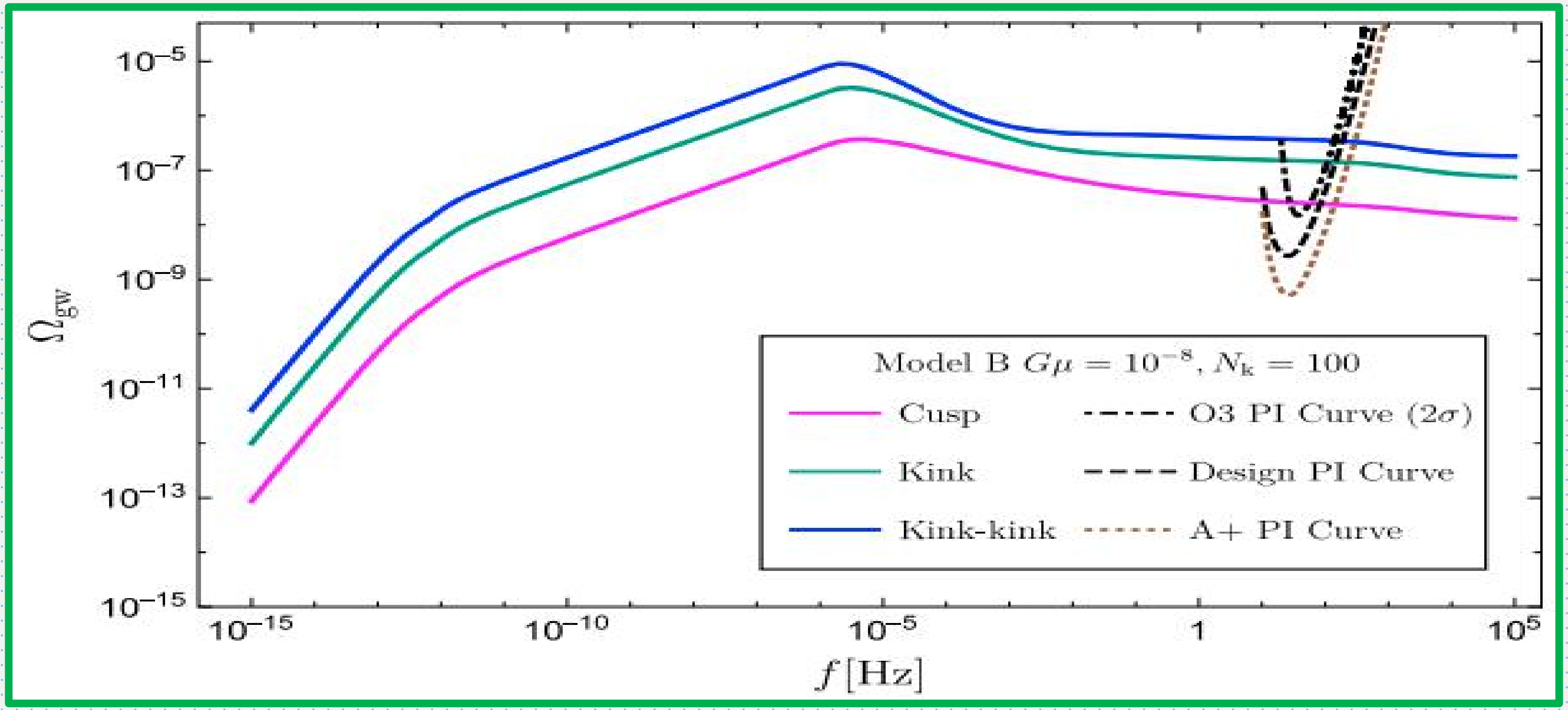


Gravitational Waves

$$\Omega_{\rm GW}(f) = \frac{4\pi^2}{3H_0^2} f^3 \sum_i \int {\rm d}z \int {\rm d}\ell \; h_i^2 \times \frac{{\rm d}^2 R_i}{{\rm d}z{\rm d}\ell}$$

cusp, kink, kink-kink collision

Damour, Vilenkin, PRL 85,3671, PRD 64, 064008



LIGO-Virgo-KAGRA collaborations, PRL 126, 241102 (2021)

String point reaching speed of light

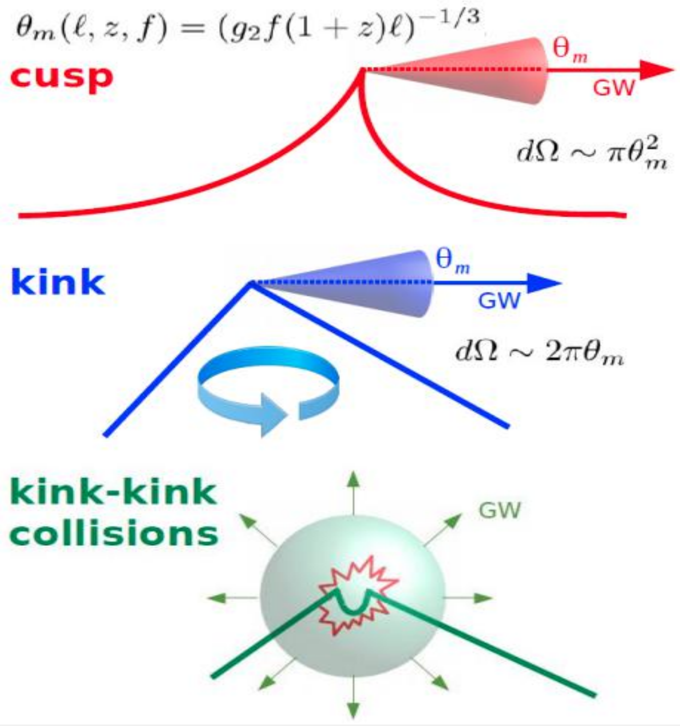


Image credit: Florent Robinet

Wide GW spectrum, detectable by different kinds of detectors

LIGO Search Result

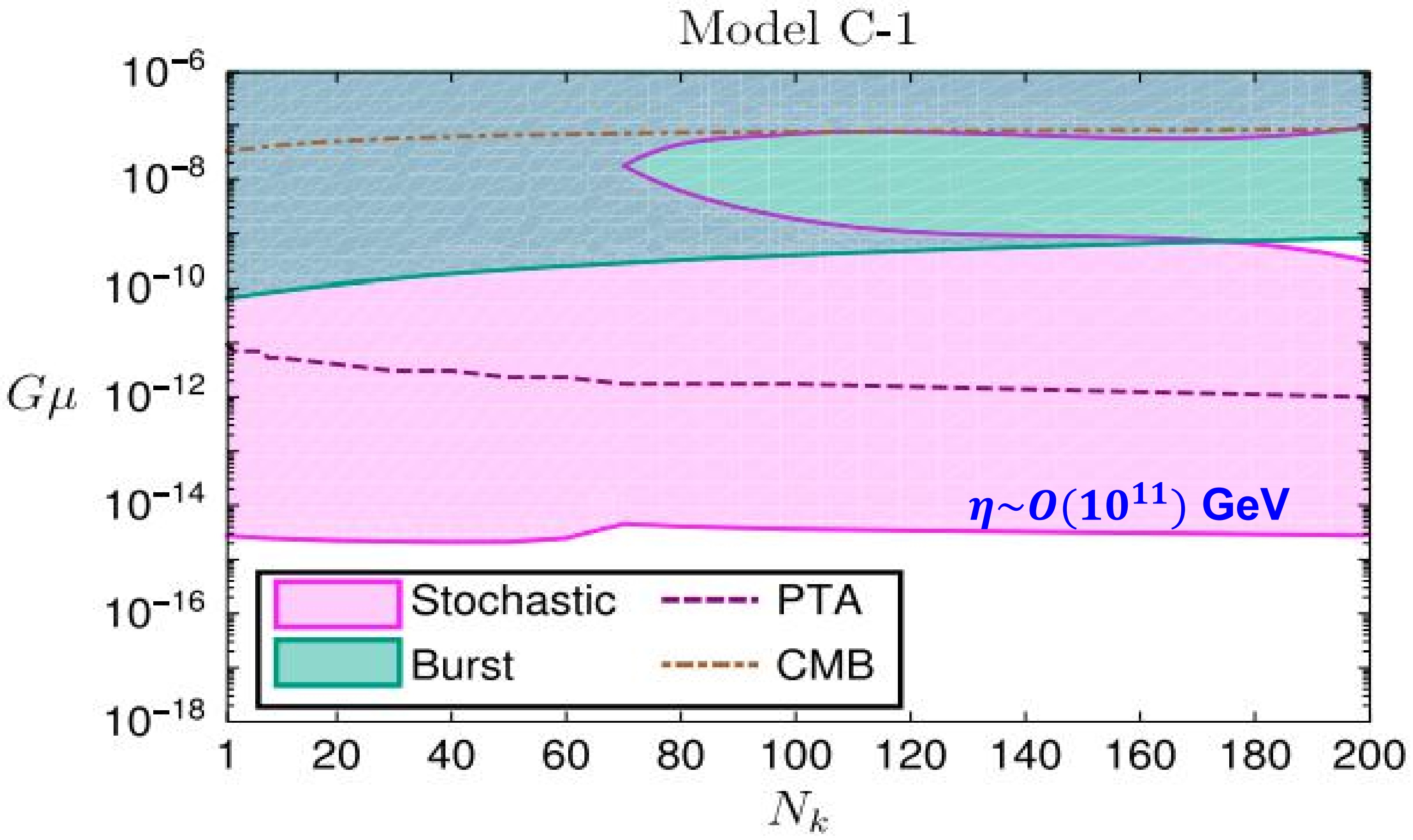
Symmetry breakings at scales higher than $O(10^{11})$ GeV with Cosmic String production are excluded

Caveat (loop distribution model)

GW measurement tells scale (η) of symmetry breaking ($G \to H$)

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

μ: line mass density



Results from PTA Measurements

Bian, Cai, Liu, Yang, Zhou, PRD (Letter) 103 (2021) 8

Blasi, Brdar, Schmitz, PRL126, 041305 (2021)

LIGO-Virgo-KAGRA collaborations, PRL 126, 241102 (2021)

Non-Topological Solitons

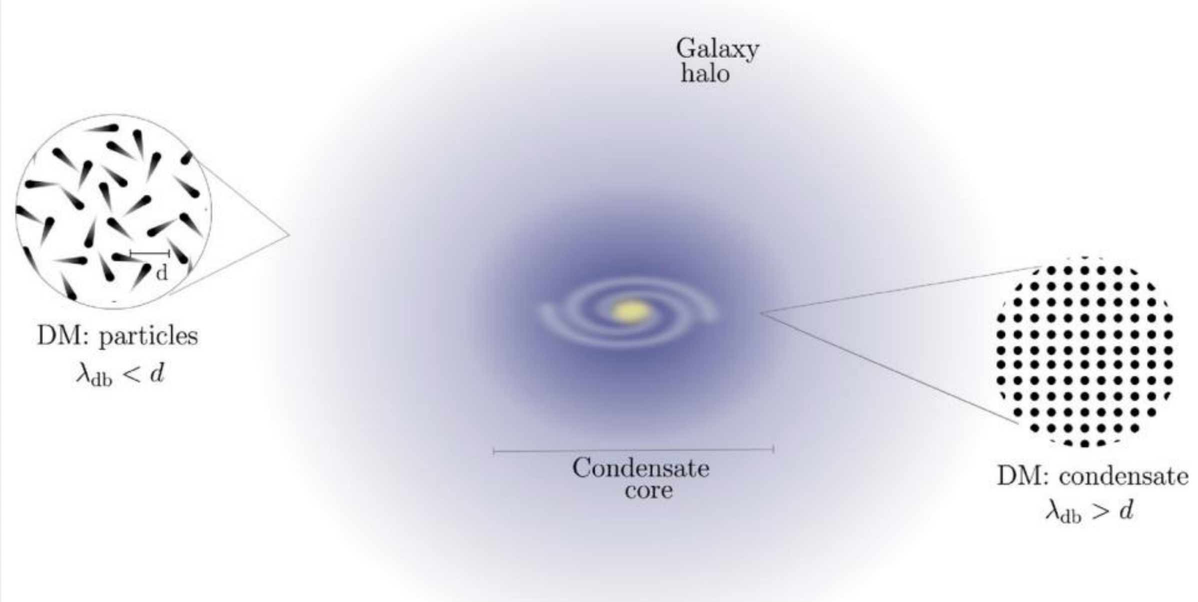
Giant Bose-Einstein condensate of some ultralight particle (DM)

$m_{\rm ULDM} \sim 10^{-22}{\rm eV}$

$$M \lesssim \frac{M_{Pl}^2}{m_{\rm ULDM}}$$

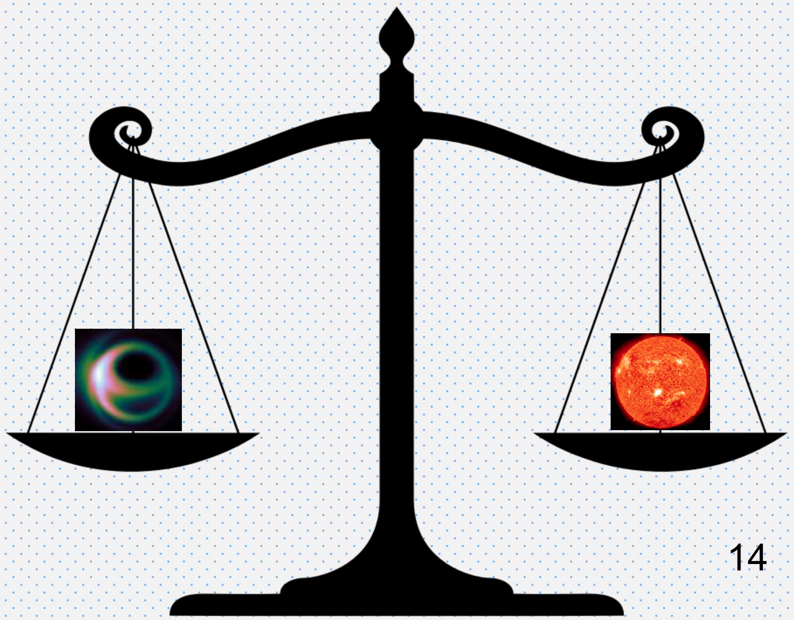
$m_{\rm ULDM} \sim 10^{-10}{\rm eV}$

Galactic Scale: solve small scale structure problems

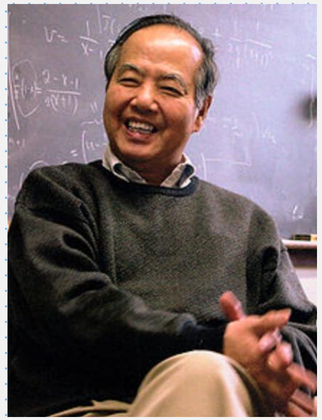


Ferreira, Astron.Astrophys.Rev. 29 (2021) 1

Stellar Scale: soliton stars



Non-Topological Solitons as Boson Stars



- Neutron Stars
- White Dwarfs
- Stellar Black Holes
- Primordial Black Holes
- Boson Stars →
- ...

Can be very compact!

(C=mass/radius)

- Mini-Boson Star (without self-interaction)
- Solitonic Boson Star (specific potential)
- Oscillaton (real scalar field)
- Proca Star (massive complex vector)
- Axion Stars (dense, dilute)

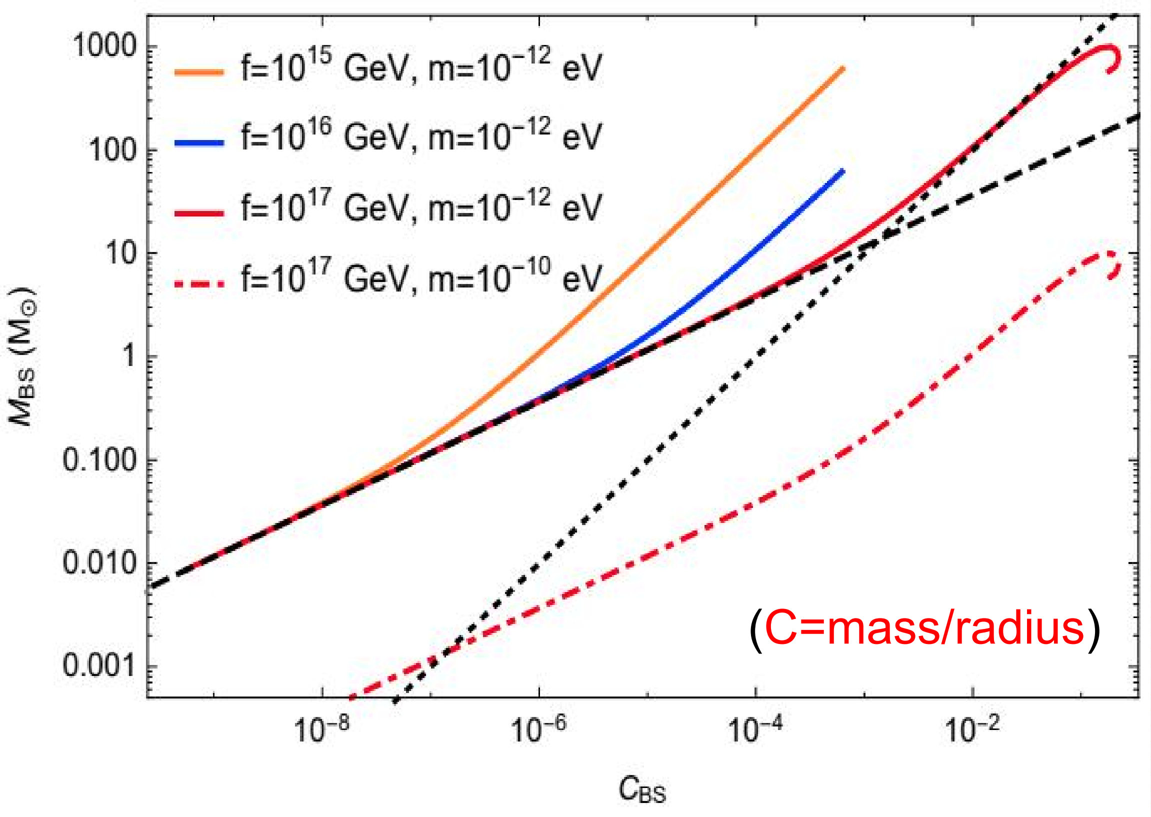
See, e.g., Liebling, Palenzuela, Living Rev Relativ (2017) 20:5

Lee,Pang, Phys.Rept (1992)

Boson Stars

1-Scalar

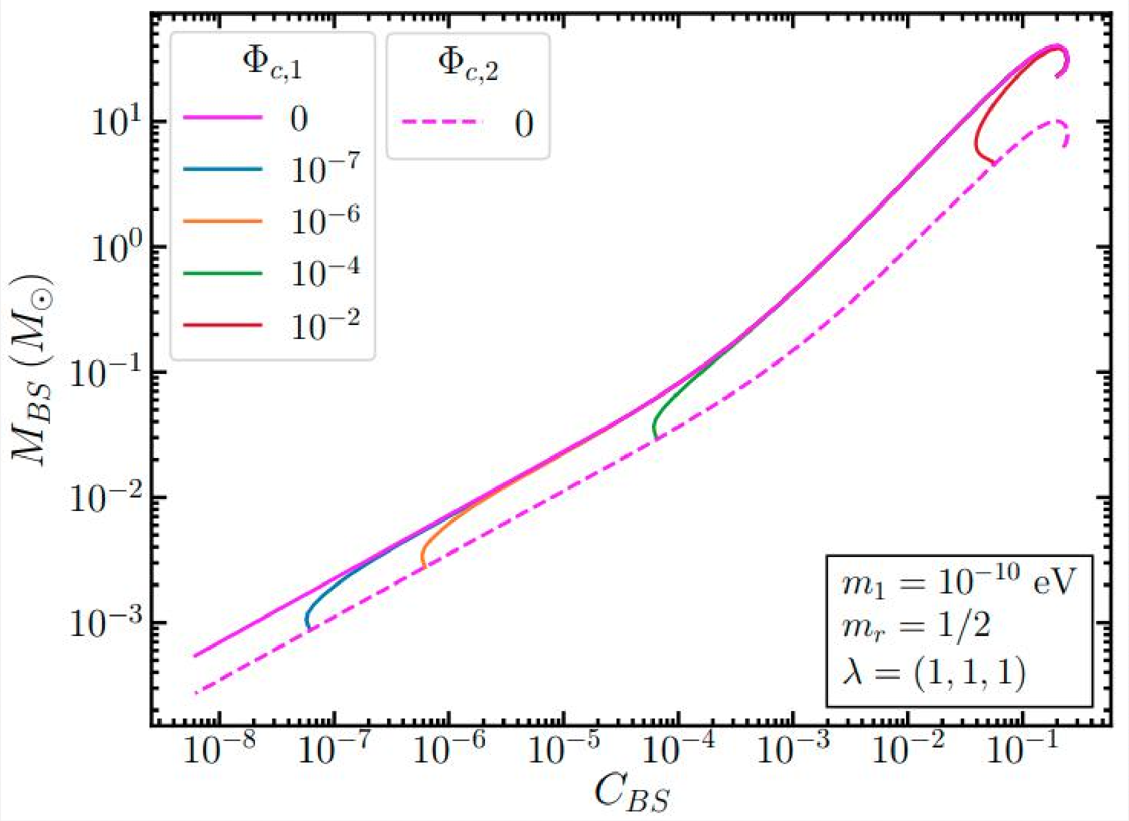
$$\mathcal{L} = \frac{1}{2} g^{\mu\nu} \partial_\mu \phi^* \partial_\nu \phi - \frac{1}{2} m^2 |\phi|^2 - \frac{\lambda}{4} \left(\frac{m^2}{f^2} \right) |\phi|^4$$



HG, Sinha, Sun, JCAP 09 (2019) 032

2-Scalars

$$\mathcal{L} = -\frac{1}{2} g^{\mu\nu} \partial_\mu \phi_1^* \partial_\nu \phi_1 - \frac{1}{2} m_1^2 |\phi_1|^2 - \frac{1}{4} c_1 |\phi_1|^4 - \frac{1}{2} g^{\mu\nu} \partial_\mu \phi_2^* \partial_\nu \phi_2 - \frac{1}{2} m_2^2 |\phi_2|^2 - \frac{1}{4} c_2 |\phi_2|^4 - \frac{1}{4} c_{12} |\phi_1|^2 |\phi_2|^2$$



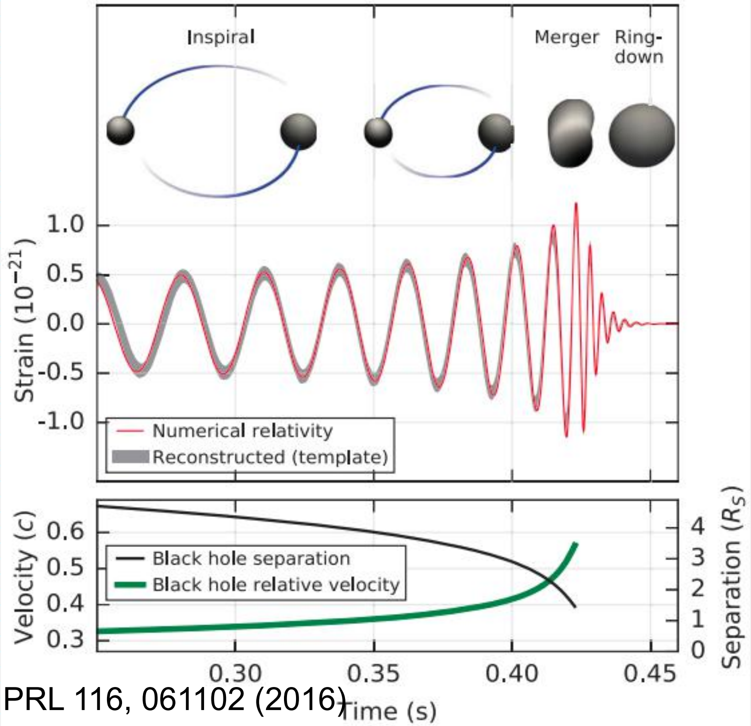
HG, Sinha, Sun, Swaim, Vagie, JCAP 10 (2021) 028

Did LIGO Detect PBH, or Boson Stars?

PRL 116, 201301 (2016) PHYSICAL REVIEW LETTERS week ending 20 MAY 2016

Did LIGO Detect Dark Matter?

Simeon Bird,* Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, and Adam G. Riess
Department of Physics and Astronomy, Johns Hopkins University, 3400 North Charles Street, Baltimore, Maryland 21218, USA
(Received 4 March 2016; published 19 May 2016)



PRL 116, 061102 (2016)

GW190521 as a Merger of Proca Stars: A Potential New Vector Boson of 8.7×10^{-13} eV

Juan Calderón Bustillo,[1,2,3,4,*] Nicolas Sanchis-Gual,[5,6,†] Alejandro Torres-Forné,[7,8,9] José A. Font,[8,9] Avi Vajpeyi,[3,4] Rory Smith,[3,4] Carlos Herdeiro,[6] Eugen Radu,[6] and Samson H. W. Leong[2]
[1]*Instituto Galego de Física de Altas Enerxías, Universidade de Santiago de Compostela, 15782 Santiago de Compostela, Galicia, Spain*
[2]*Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong*
[3]*Monash Centre for Astrophysics, School of Physics and Astronomy, Monash University, Victoria 3800, Australia*
[4]*OzGrav: The ARC Centre of Excellence for Gravitational-Wave Discovery, Clayton, Victoria 3800, Australia*
[5]*Centro de Astrofísica e Gravitação—CENTRA, Departamento de Física, Instituto Superior Técnico—IST, Universidade de Lisboa—UL, Avenida Rovisco Pais 1, 1049-001, Portugal*
[6]*Departamento de Matemática da Universidade de Aveiro and Centre for Research and Development in Mathematics and Applications (CIDMA), Campus de Santiago, 3810-183 Aveiro, Portugal*
[7]*Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Am Mühlenberg 1, Potsdam 14476, Germany*
[8]*Departamento de Astronomía y Astrofísica, Universitat de València, Dr. Moliner 50, 46100, Burjassot (València), Spain*
[9]*Observatori Astronòmic, Universitat de València, C/ Catedrático José Beltrán 2, 46980, Paterna (València), Spain*

(Received 26 September 2020; revised 20 November 2020; accepted 14 January 2021; published 24 February 2021)

Advanced LIGO-Virgo have reported a short gravitational-wave signal (GW190521) interpreted as a quasicircular merger of black holes, one at least populating the pair-instability supernova gap, that formed a remnant black hole of $M_f \sim 142\, M_\odot$ at a luminosity distance of $d_L \sim 5.3$ Gpc. With barely visible pre-merger emission, however, GW190521 merits further investigation of the pre-merger dynamics and even of the very nature of the colliding objects. We show that GW190521 is consistent with numerically simulated signals from head-on collisions of two (equal mass and spin) horizonless vector boson stars (aka Proca stars), forming a final black hole with $M_f = 231^{+13}_{-17}\, M_\odot$, located at a distance of $d_L = 571^{+348}_{-181}$ Mpc. This provides the first demonstration of close degeneracy between these two theoretical models, for a real gravitational-wave event. The favored mass for the ultralight vector boson constituent of the Proca stars is $\mu_V = 8.72^{+0.73}_{-0.82}\times10^{-13}$ eV. Confirmation of the Proca star interpretation, which we find statistically slightly preferred, would provide the first evidence for a long sought dark matter particle.

DOI: 10.1103/PhysRevLett.126.081101

- Difficult to distinguish
- Mass as discriminator!

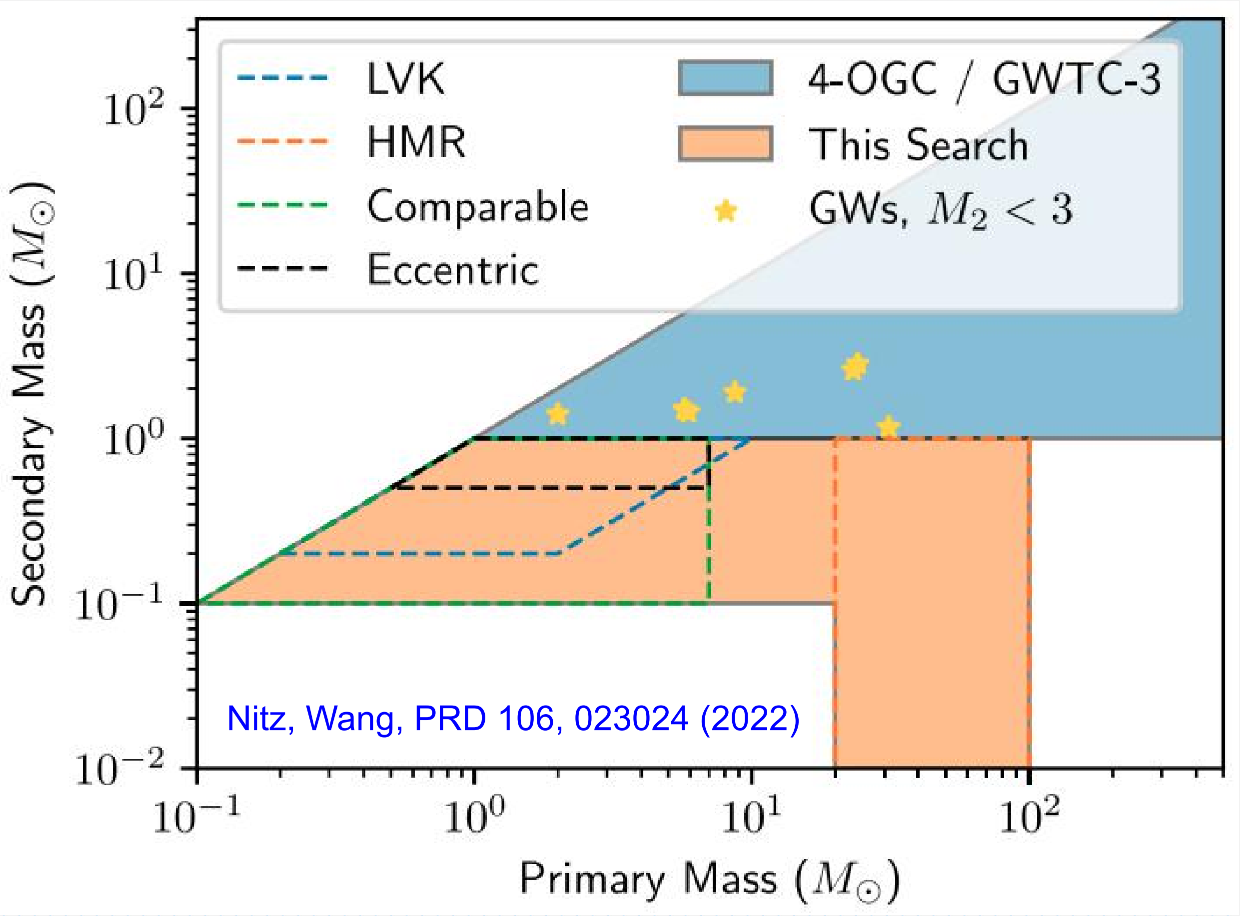
Proca star (massive complex vector field)

$$\mathcal{S} = \int d^4x\sqrt{-g}\left(\frac{R}{16\pi G} - \frac{1}{4}\mathcal{F}_{\alpha\beta}\bar{\mathcal{F}}^{\alpha\beta} - \frac{1}{2}\mu^2 \mathcal{A}_\alpha \bar{\mathcal{A}}^\alpha\right)$$

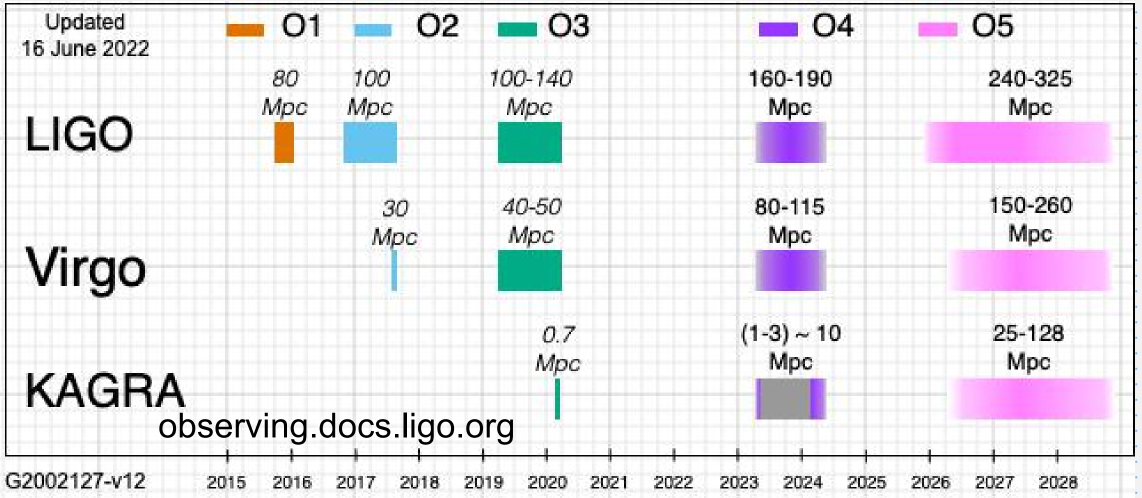
Brito et al, PLB752, 291 (2016)

Mass as Discriminator: Subsolar ECO Searches

Rising interest in subsolar ECO searches



- One detection would point to new physics
- Boson stars differ from PBHs: tidal disruption



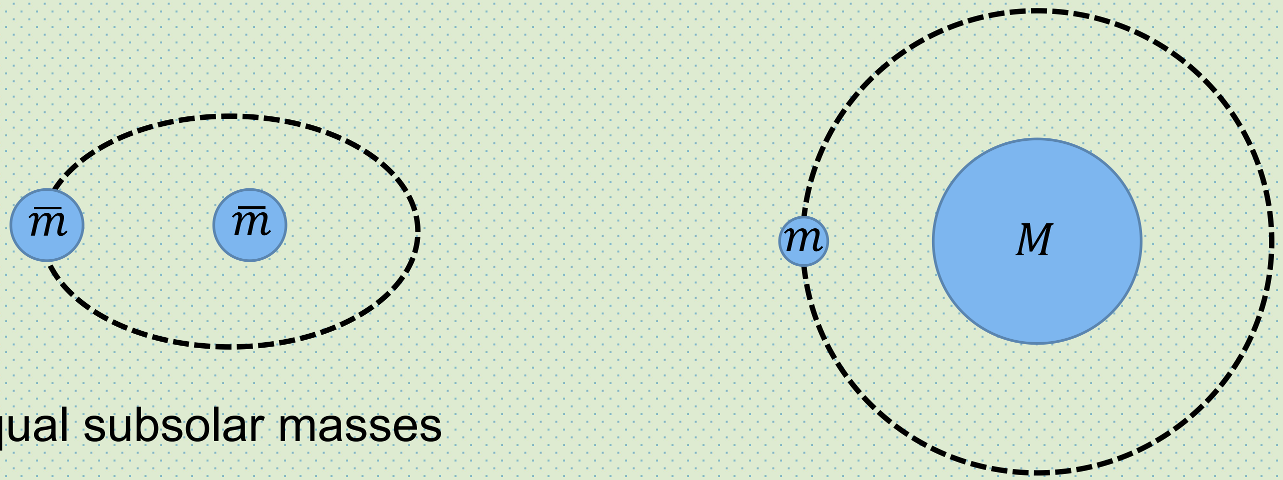
How to Search for Light Boson Stars

- Amplitude and SNR increase as the chirp mass increases

the chirp mass

$$M_c = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

Same Chirp Mass Binaries



equal subsolar masses

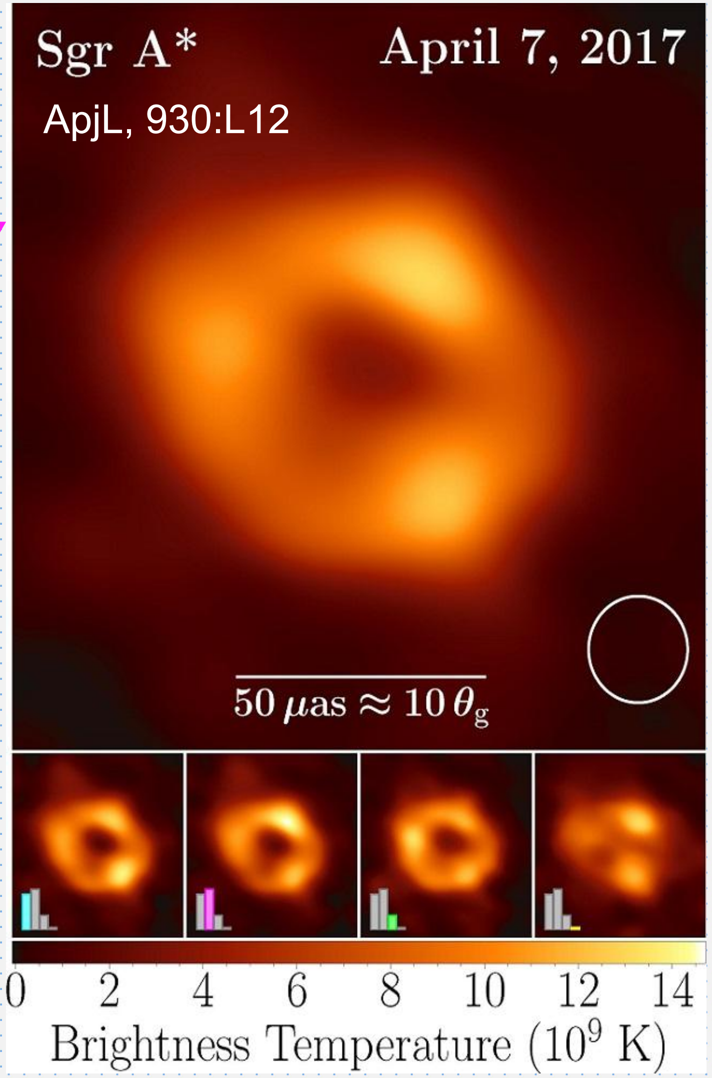
large mass ratio

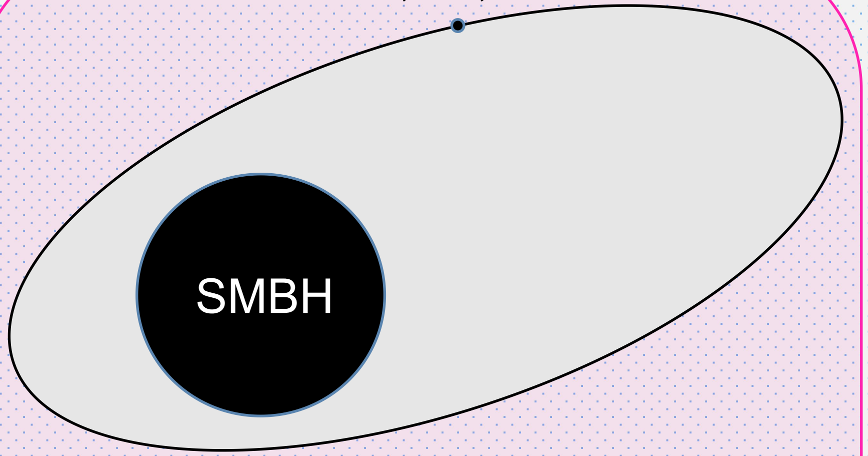
$$\frac{m}{\bar{m}} \approx 2^{-1/3} \left(\frac{\bar{m}}{M}\right)^{2/3} \Rightarrow m \ll \bar{m} \ll M$$

To probe a lighter one, make the other one heavier: larger mass ratio

The Extreme Mass Ratio Inspiral (EMRI)

Wikipedia





SMBH: $4 * 10^6$ solar mass

BH/NS/WD: O(1-10) solar mass

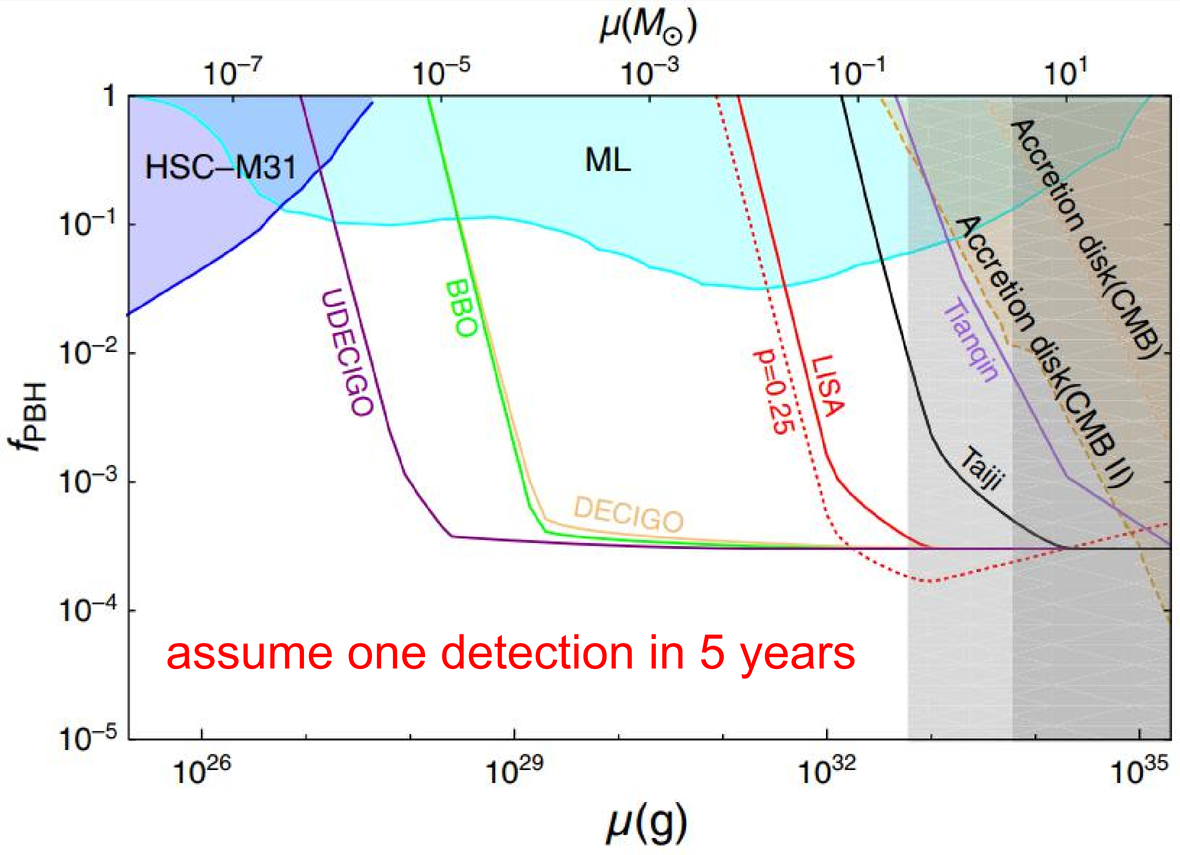
extreme mass ratio inspiral (EMRI)

important target for LISA, Taiji, Tianqin...

Sensitivity with EMRI

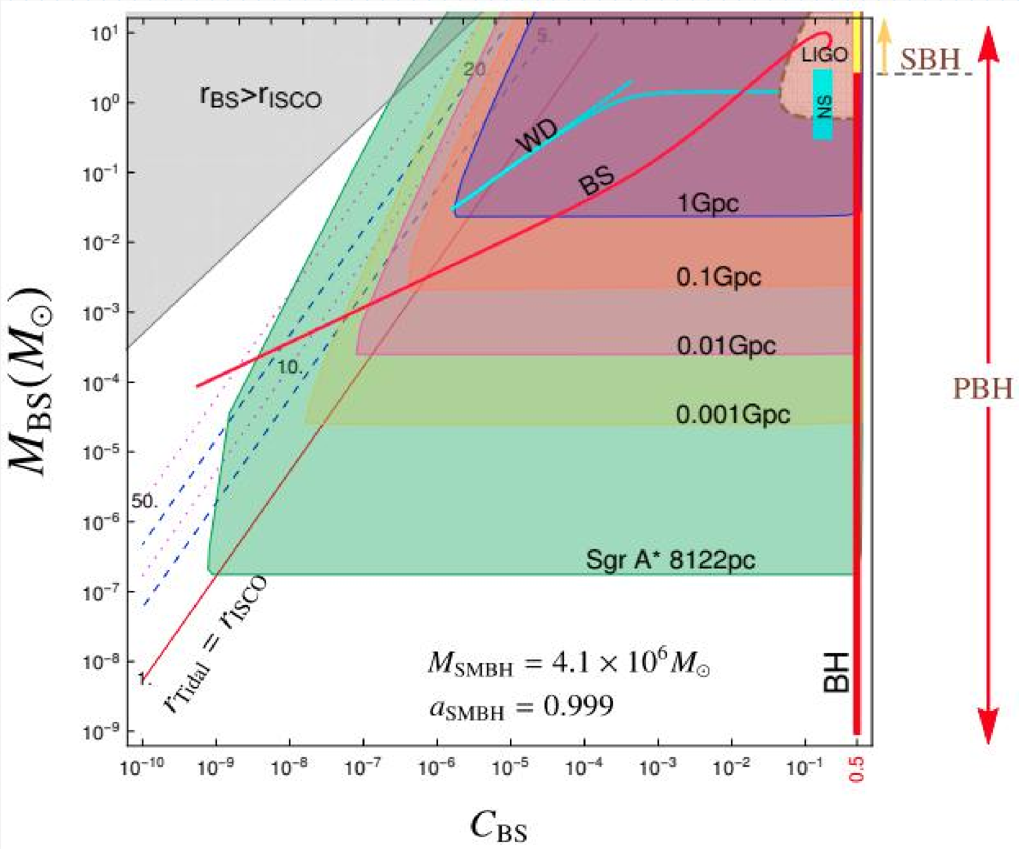
- Sensitive to a large region of parameter space

Constraining PBH (or compact Boson Star DM)



HG, Shu, Zhao, PRD 99, 023001

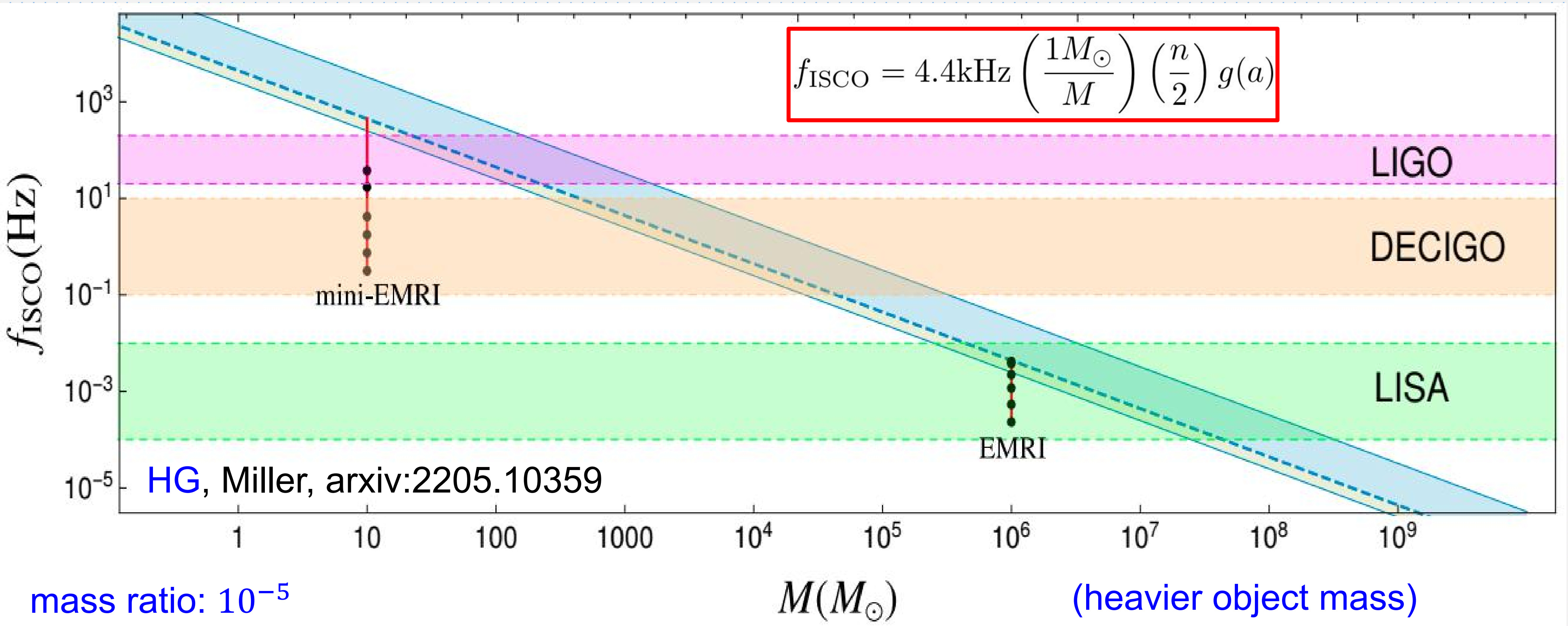
Sensitivity to Generic Exotic Compact Objects



HG, Sinha, Sun, JCAP 09 (2019) 032

“mini-EMRI”

- LIGO can detect non-standard EMRIs that we call mini-EMRIs



Similar systems:

Davoudiasl, Giardino, PLB 768, 198 (2017)
Pan, Lyu, Yang, PRD 105, 083005 (2022)
Barsanti et al PRL 128, 111104 (2022)

Sensitivity to mini-EMRIs

- Can be detected with techniques of continuous wave searches
- LIGO is able to detect a wide class of mini-EMRIs

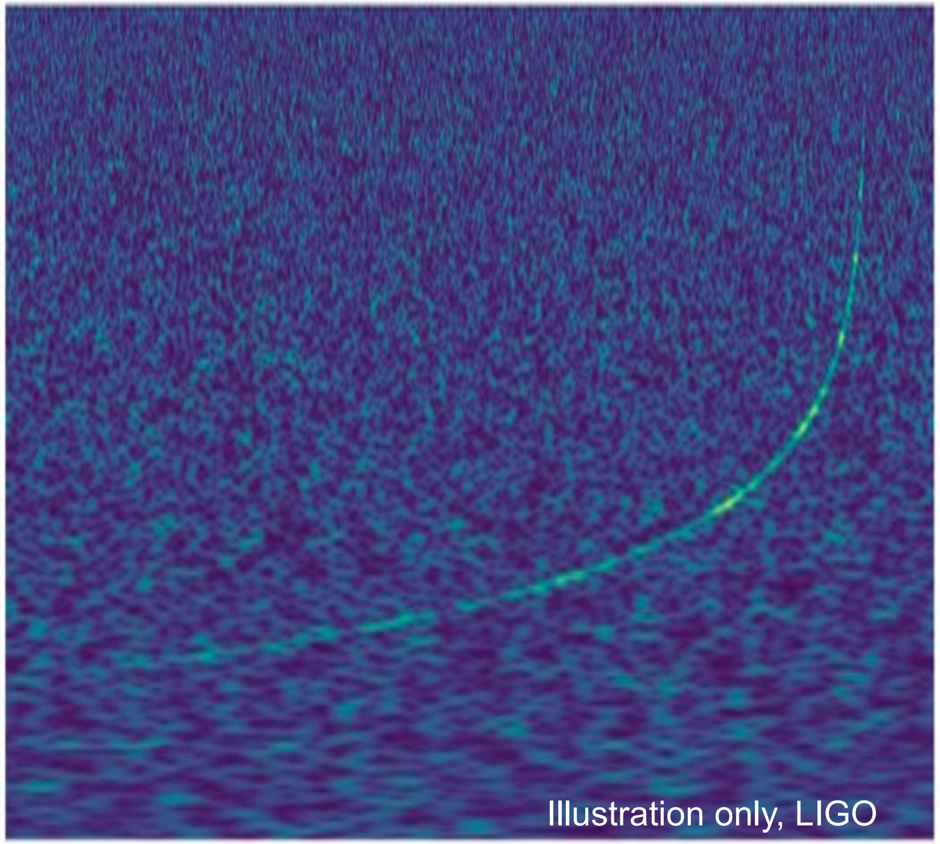
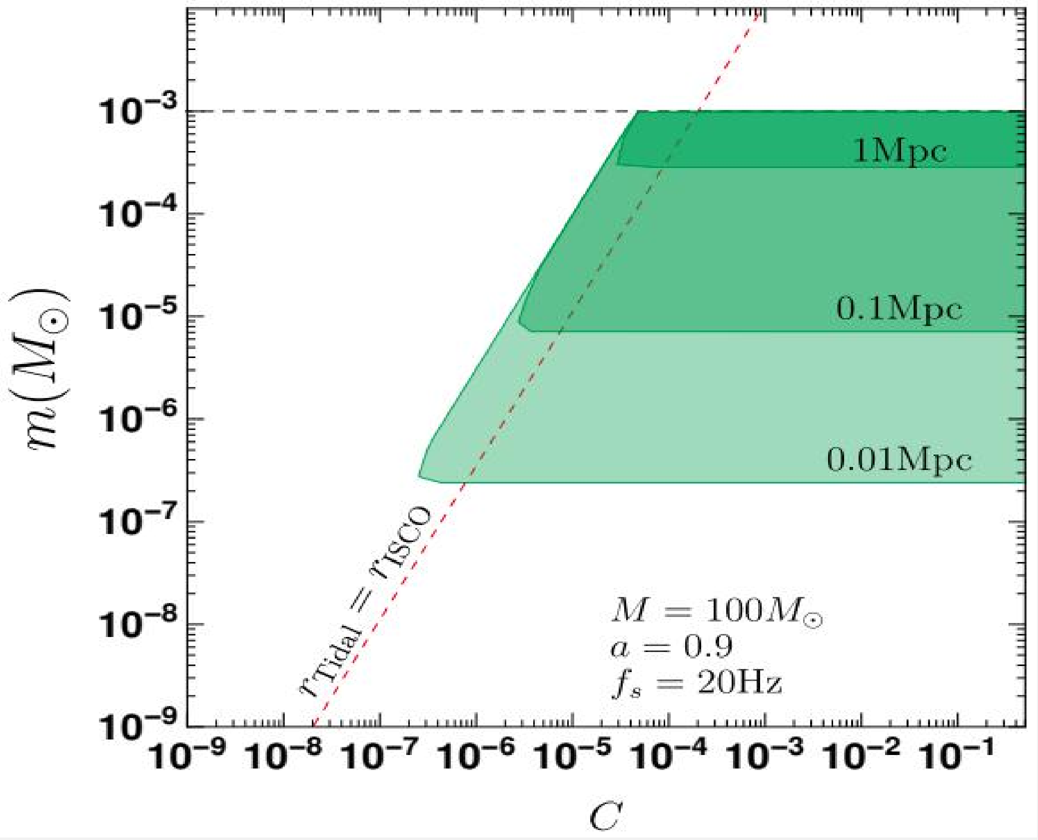


image processing algorithm



HG, A. Miller, arxiv:2205.10359

Summary

Solitons in QFT are important GW sources

- ✓ New limits on cosmic strings (topological soliton) with LIGO's new data
- ✓ New detection method for sub-solar exotic compact objects (non-topological solitons)

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