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国际理论物理中心-亚太地区

(Non-)Topological Solitons: Detection with Gravitational Waves

Huaike Guo

UCAS (ICTP-AP)

Oct. 20, 2023

LIGO-Virgo-KAGRA collaborations, PRL [2101.12248]
(U. Utah group: Yue Zhao, HG, Fengwei Yang)

HG, Sinha, Sun, Swaim, Vagie, JCAP [2010.15977]

HG, Sinha, Sun, JCAP [1904.07871]

HG, Shu, Zhao, PRD [1709.03500]

HG, Miller [2205.10359]

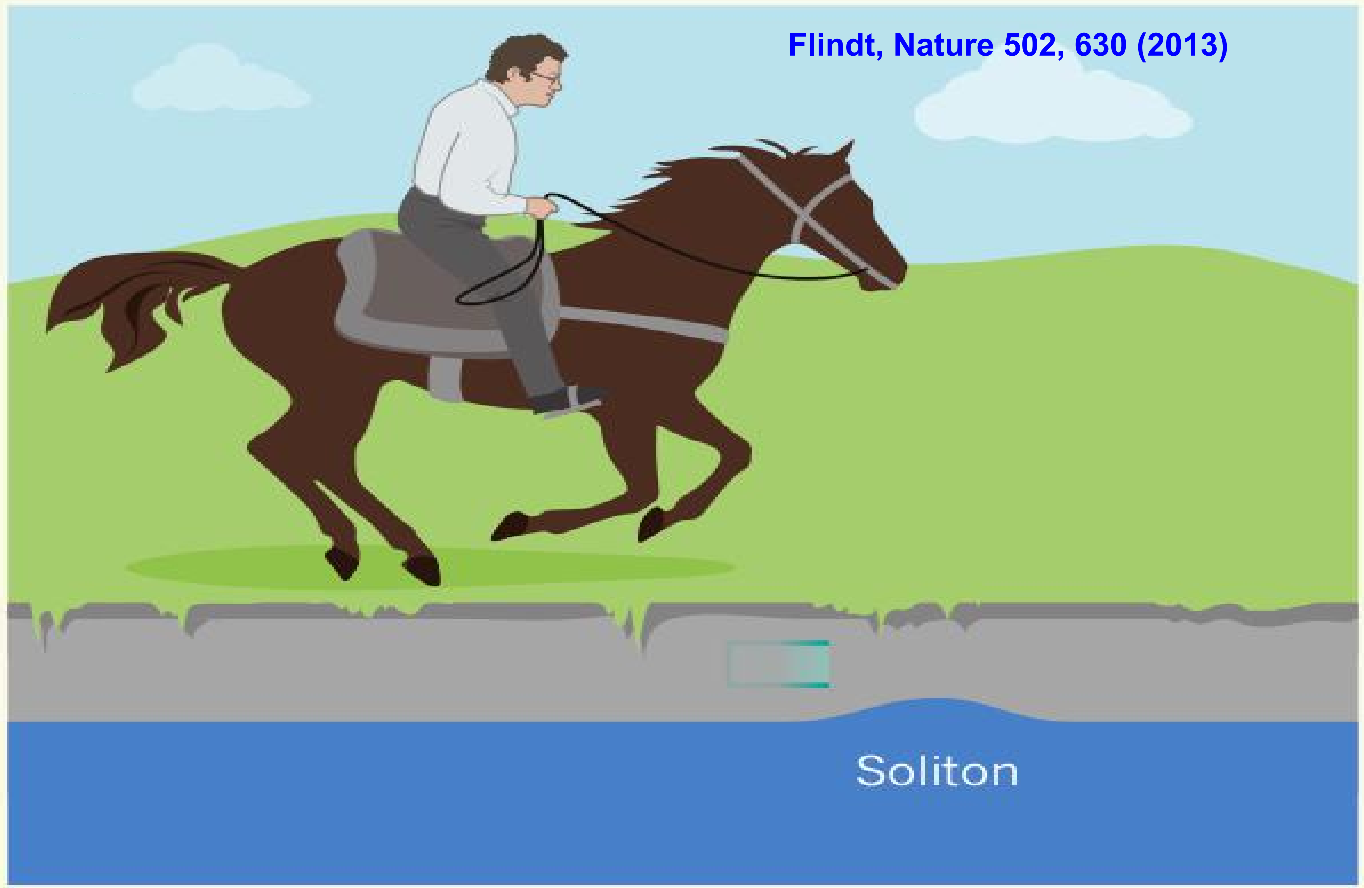
Solitons

- 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)

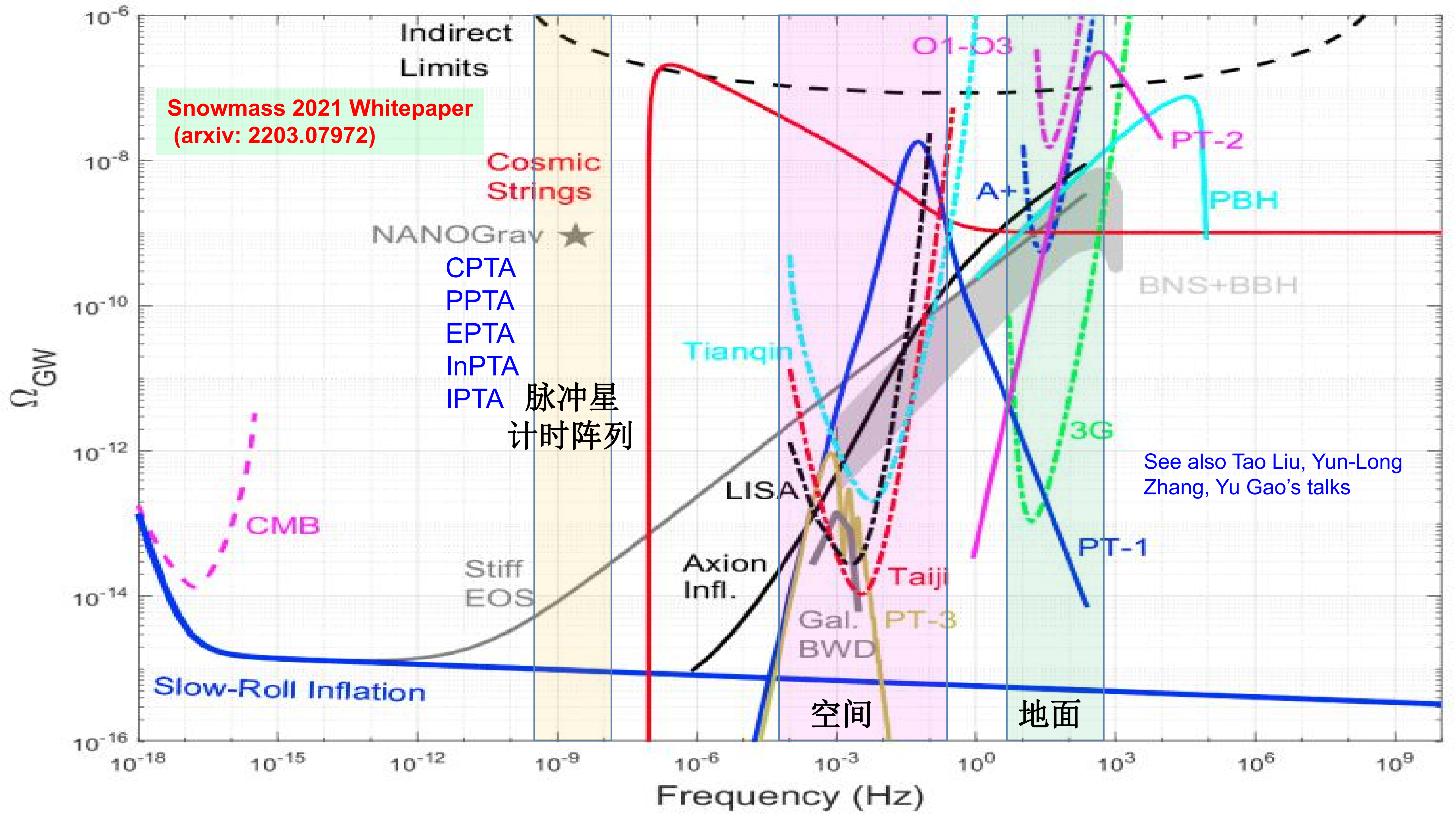
✓ GWs provide independent probings (very high energies, purely gravitational interactions)

REVIEW

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

The new frontier of gravitational waves

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



Indirect
Limits
Snowmass 2021 Whitepaper
(arxiv: 2203.07972)
Cosmic
Strings
NANOGrav
CPTA
PPTA
EPTA
InPTA
IPTA
脉冲星
计时阵列
O1-O3
PT-2
A+
PBH
BNS+BBH
Tianqin
3G
See also Tao Liu, Yun-Long Zhang, Yu Gao's talks
LISA
CMB
Stiff
EOS
Axion
Infl.
Taiji
PT-1
Gal.
BWD
PT-3
Slow-Roll Inflation
空间
地面
Ω_{GW}
Frequency (Hz)
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-15}
10^{-12}
10^{-9}
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}

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)

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

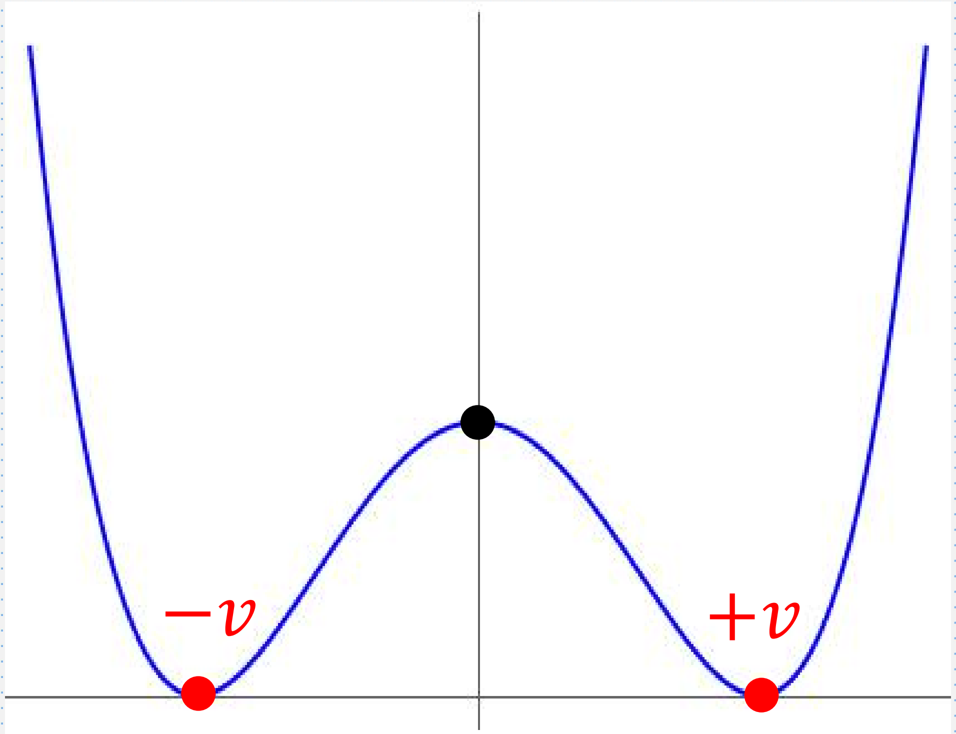
Blackett Laboratory, Imperial College, Prince Consort Road, Lo

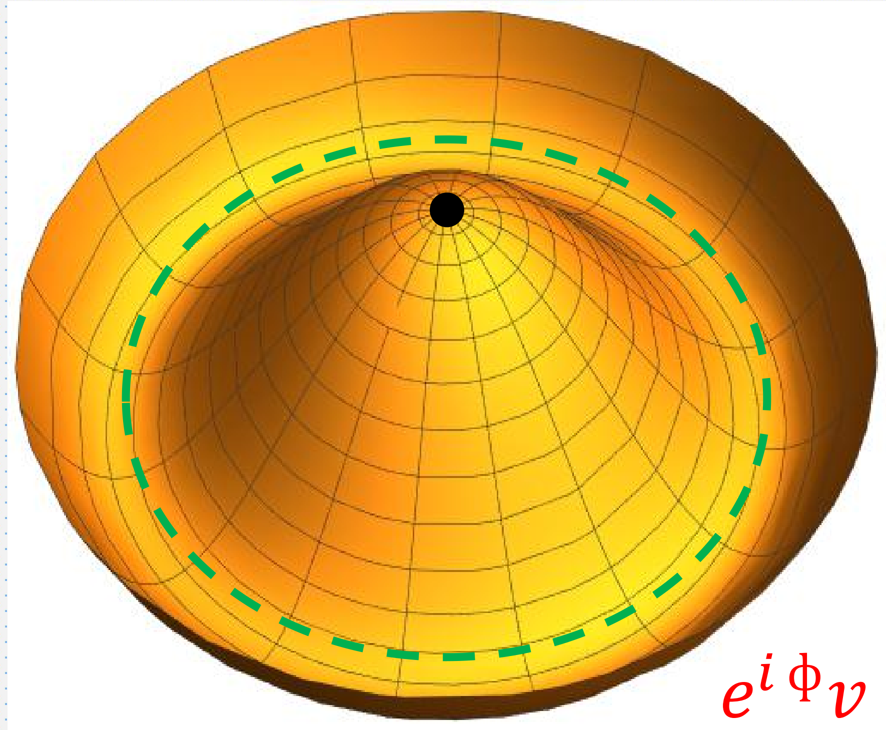
Received 11 March 1976 www.theguardian.com

Degenerate Vacuum States

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

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



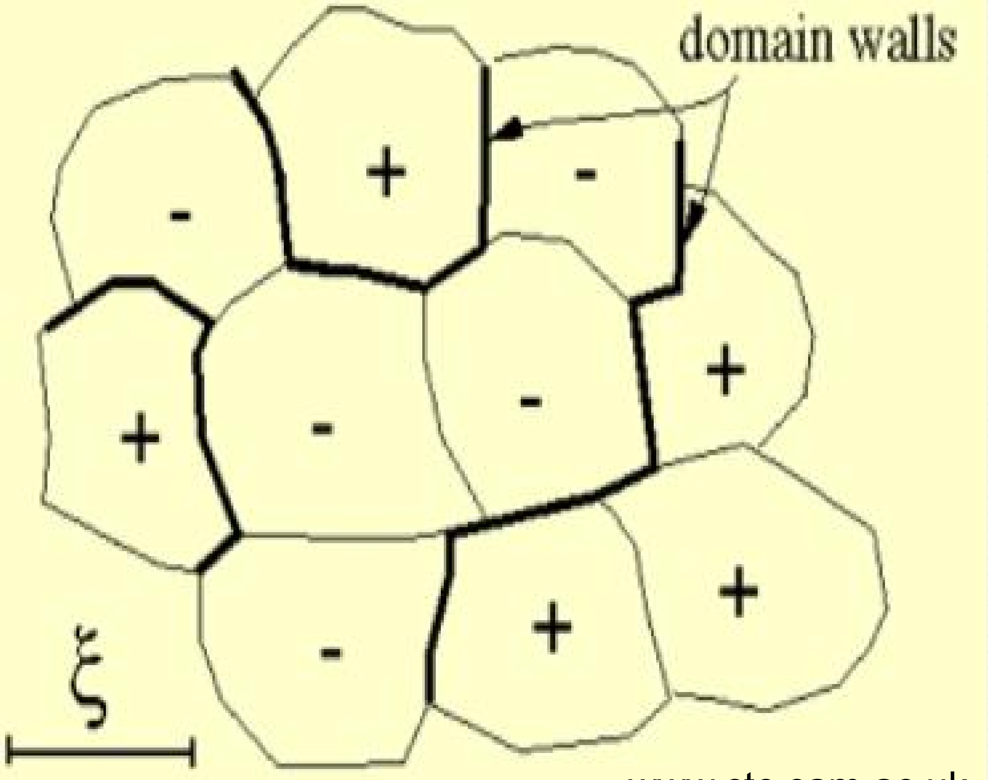


Field needs to take vacuum values at the boundary to have finite energy.

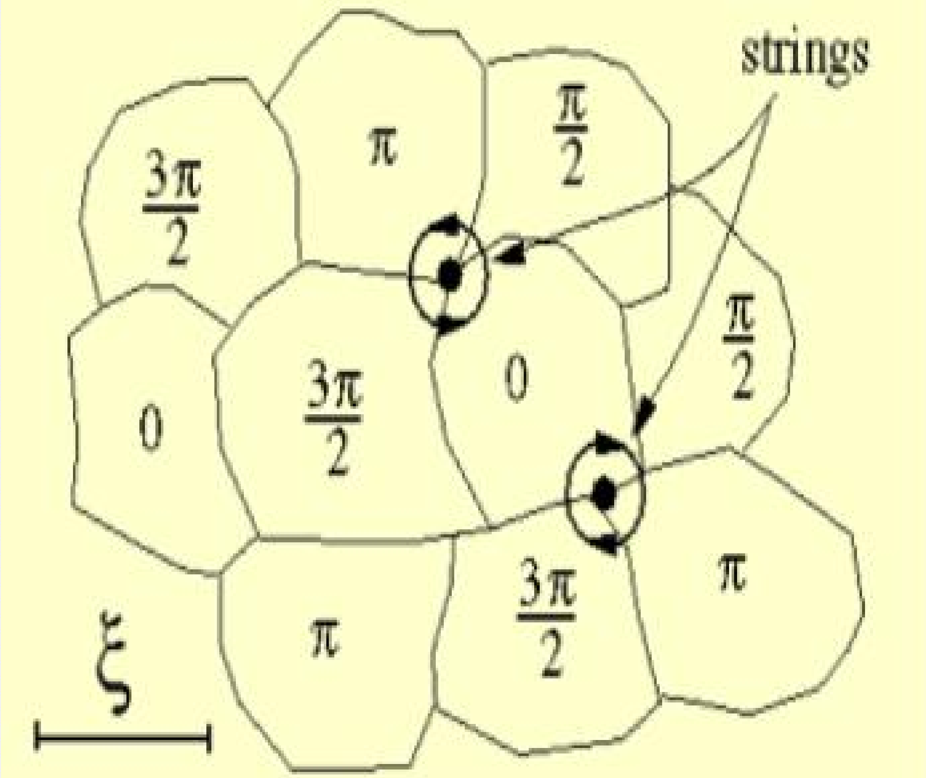
Degenerate Vacuum States

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

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



www.ctc.cam.ac.uk



www.ctc.cam.ac.uk

Will focus on cosmic strings.

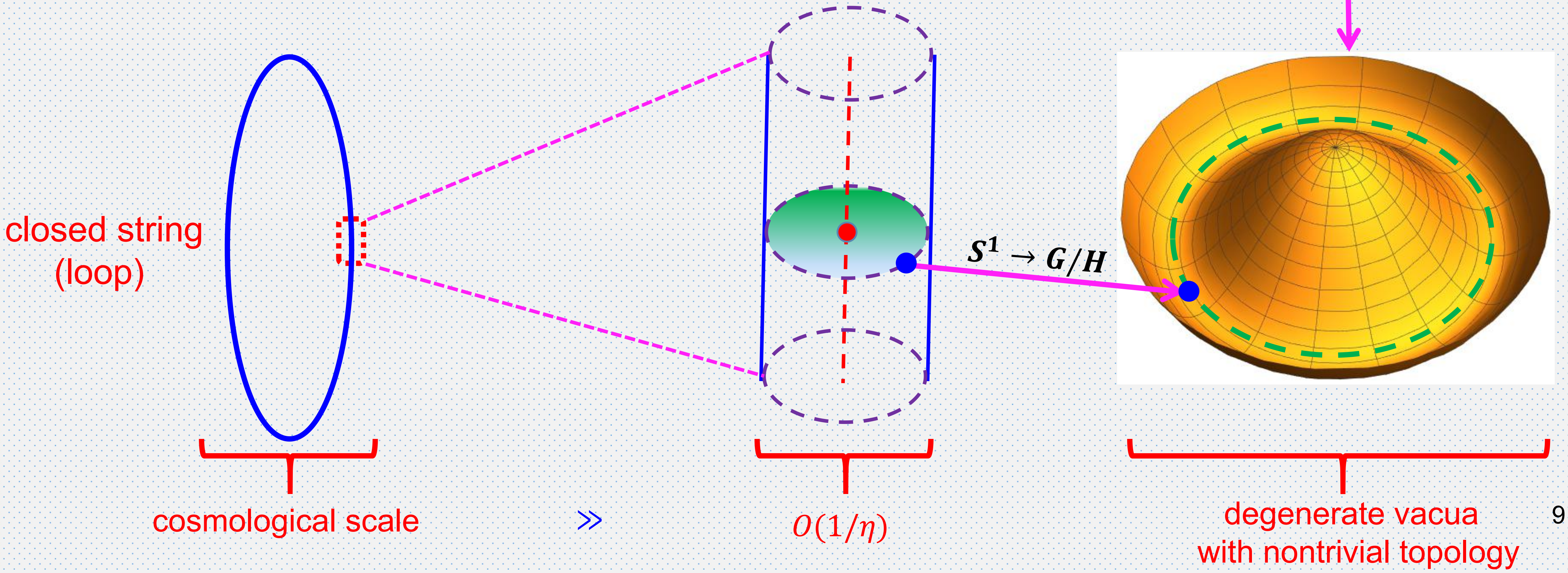
Cosmic String

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

μ: line mass density

Example: the Abelian Higgs Model

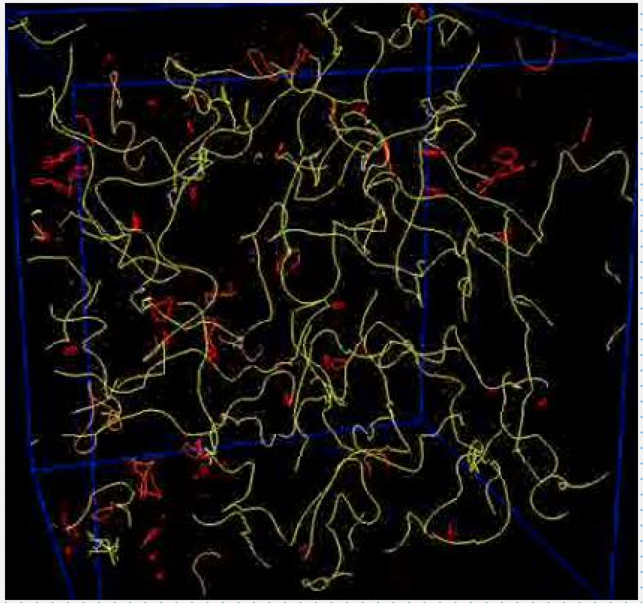
$$\mathcal{L} = |(\partial_\mu - igA_\mu)\Phi|^2 - \frac{1}{4}\lambda(|\Phi|^2 - \eta^2)^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

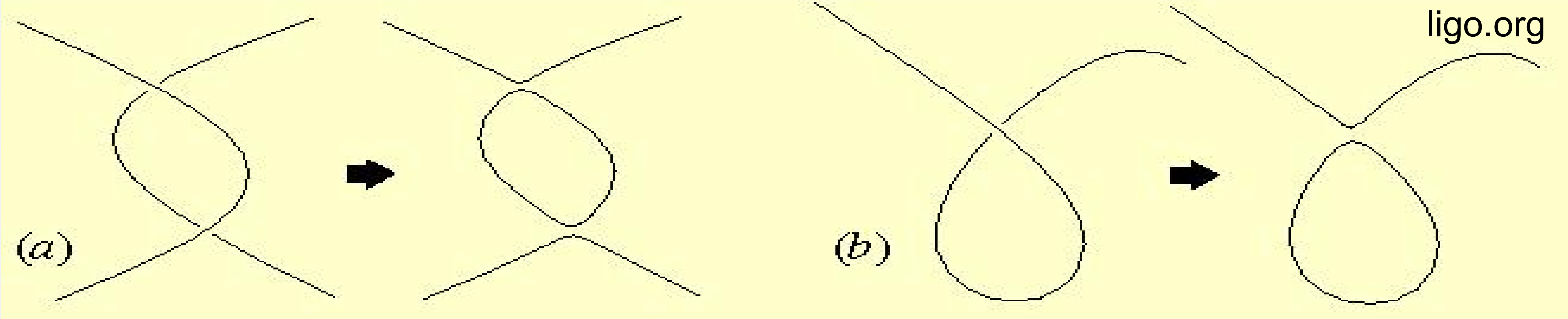


Cosmic String Network

loop distribution

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



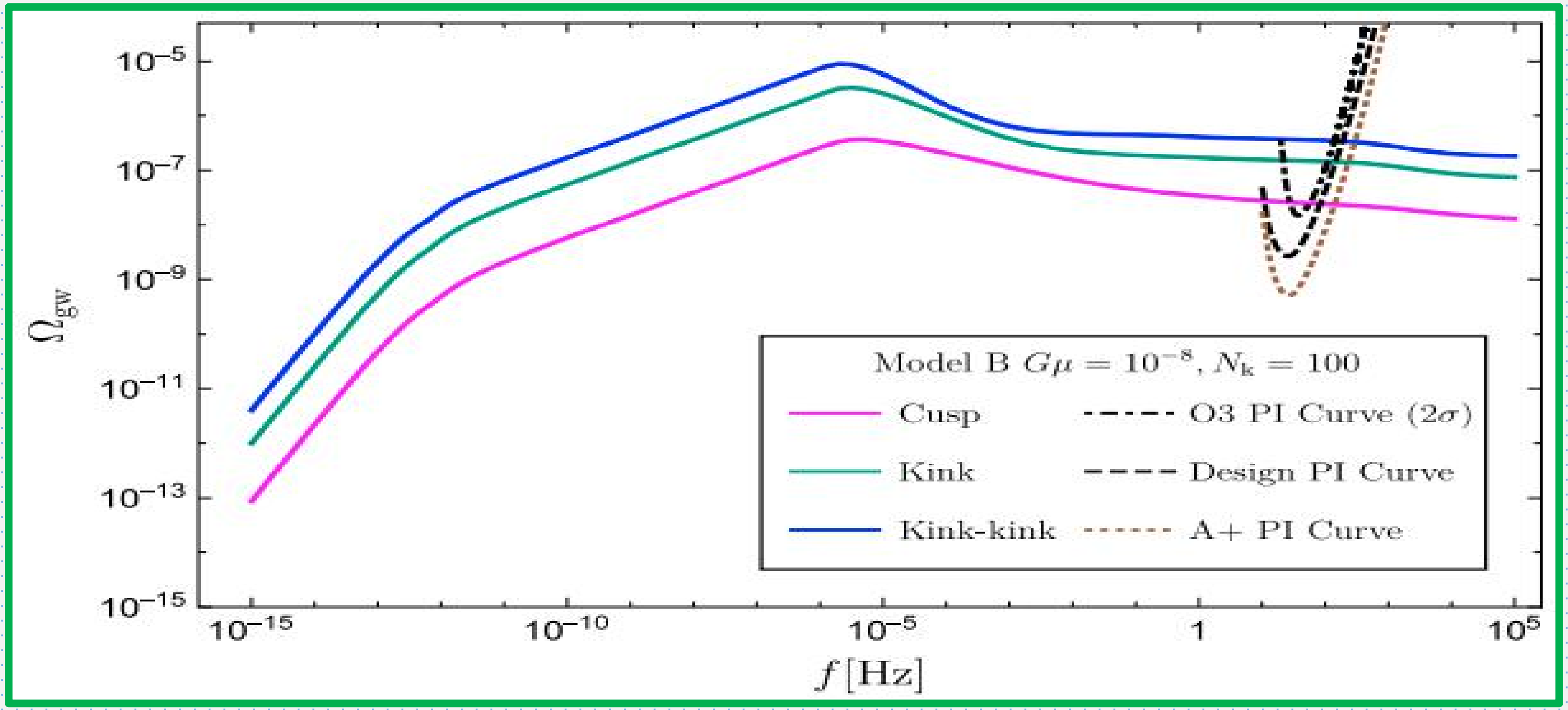


Gravitational Waves

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

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

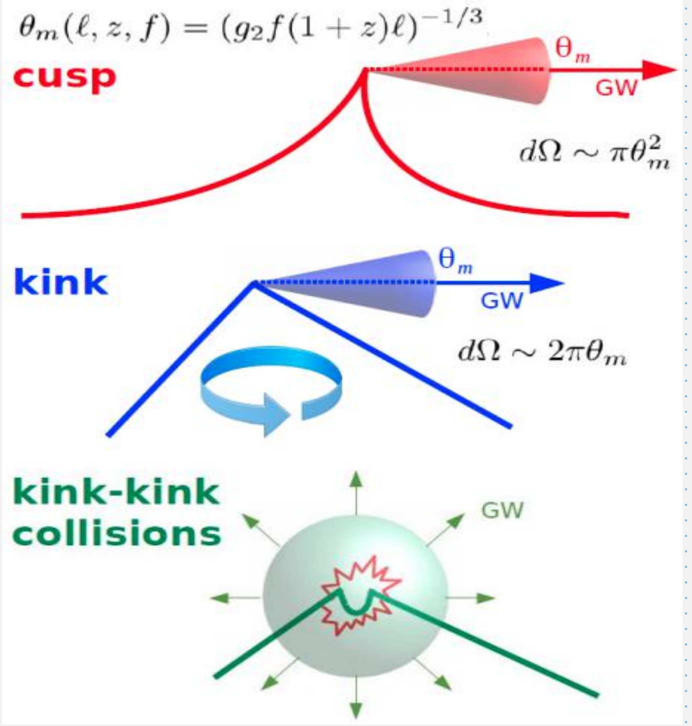


Image credit: Florent Robinet

Wide GW spectrum, detectable by different kinds of detectors

LIGO Search Result

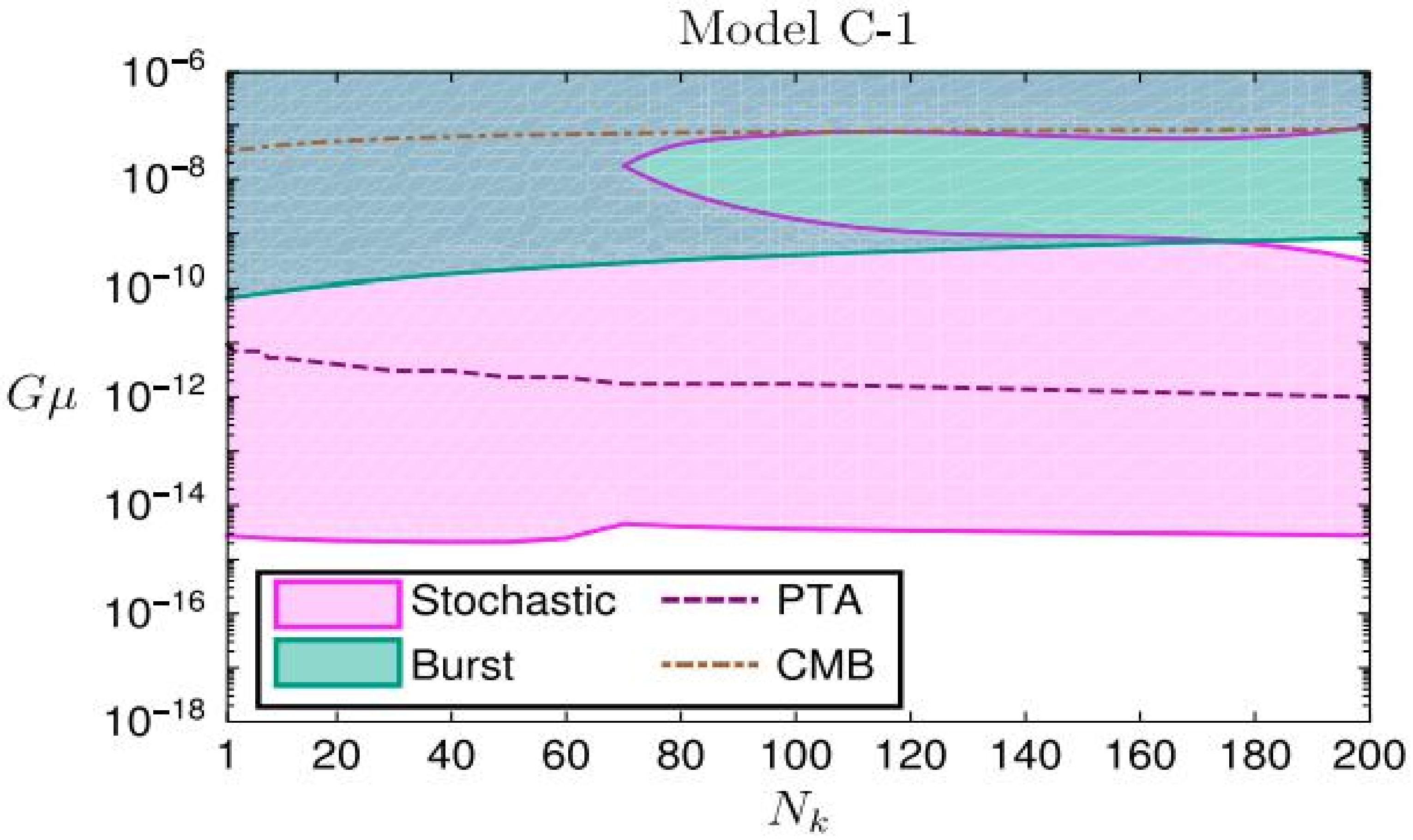
Symmetry breakings at scales higher than $O(10^{11})$ GeV with Cosmic String production are excluded

Caveat (loop distribution model)

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

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

μ: line mass density



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

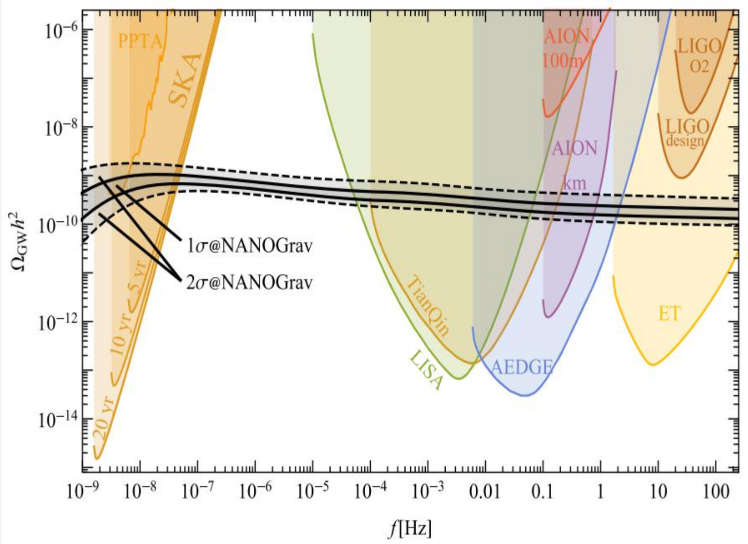
Results from PTA Measurements

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

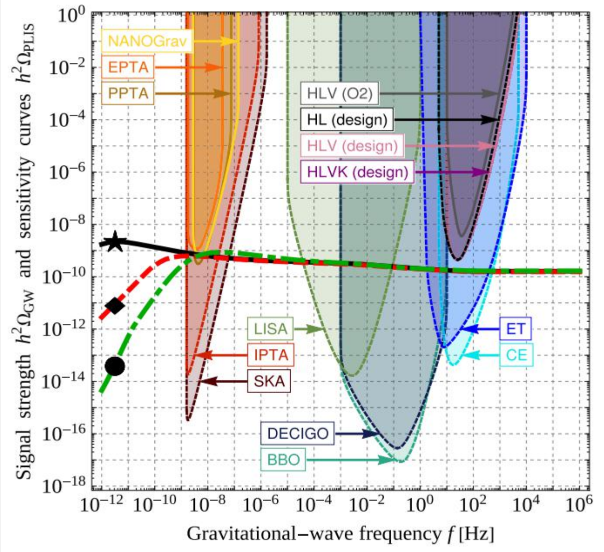
Blasi, Brdar, Schmitz, PRL126, 041305 (2021)

NANOGrav, ApjL [2306.16219]

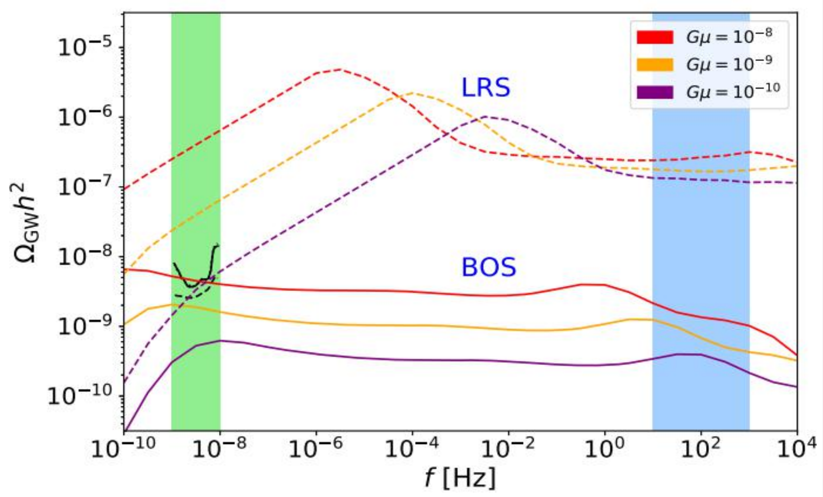
PTA Searches

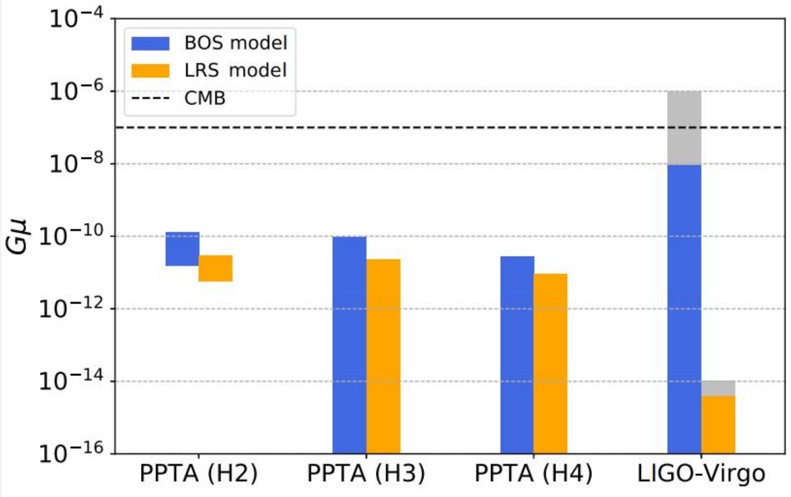


Ellis, Lewicki, PRL [2009.06555]



Blasi, Brdar, Schmitz, PRL [2009.06607]





Bian, Shu, Wang, Yuan, Zong, PRD Letter [2205.07293]

Non-Topological Solitons

Macroscopic Bose-Einstein condensate made of ultralight particles (DM)

Lee,Pang, Phys.Rept (1992)

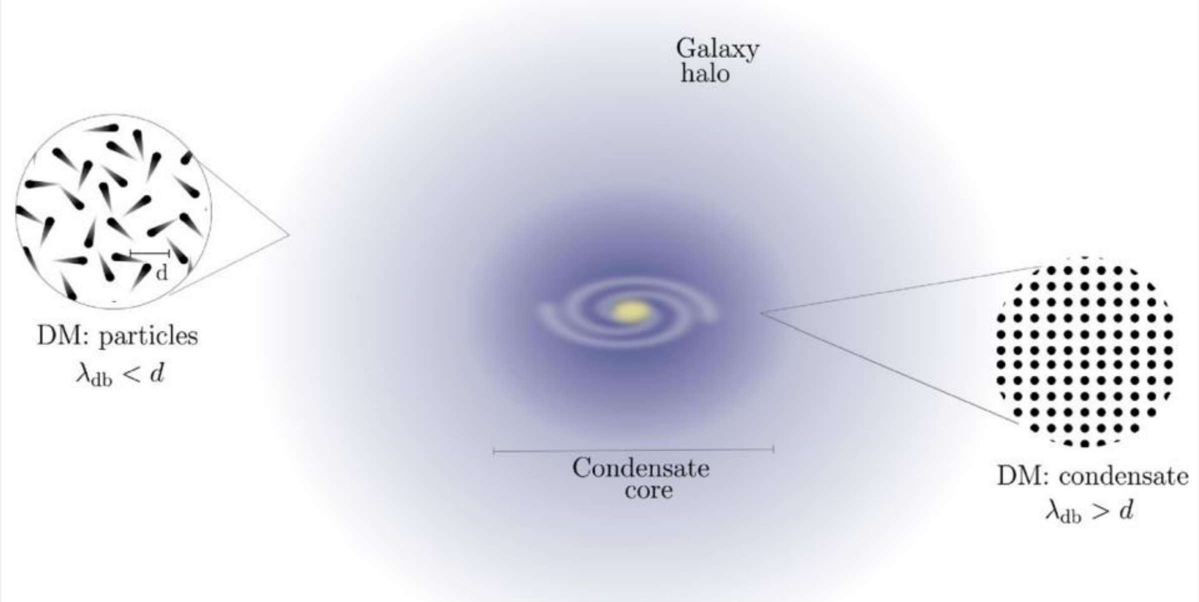
Liebling, Palenzuela, Living Rev.Rel [1202.5809]

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

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

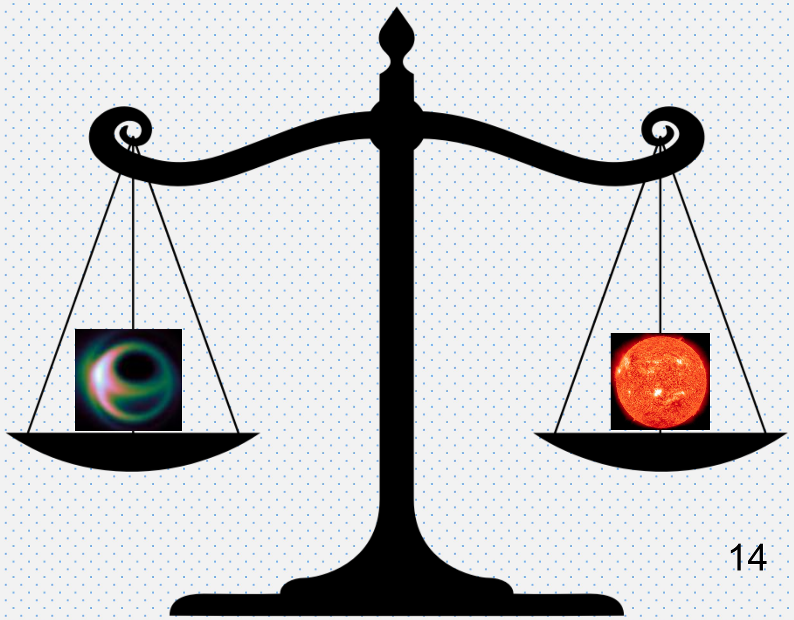
$m_{\rm ULDM} \sim 10^{-10}{\rm eV}$

Galactic Scale: solve small scale structure problems



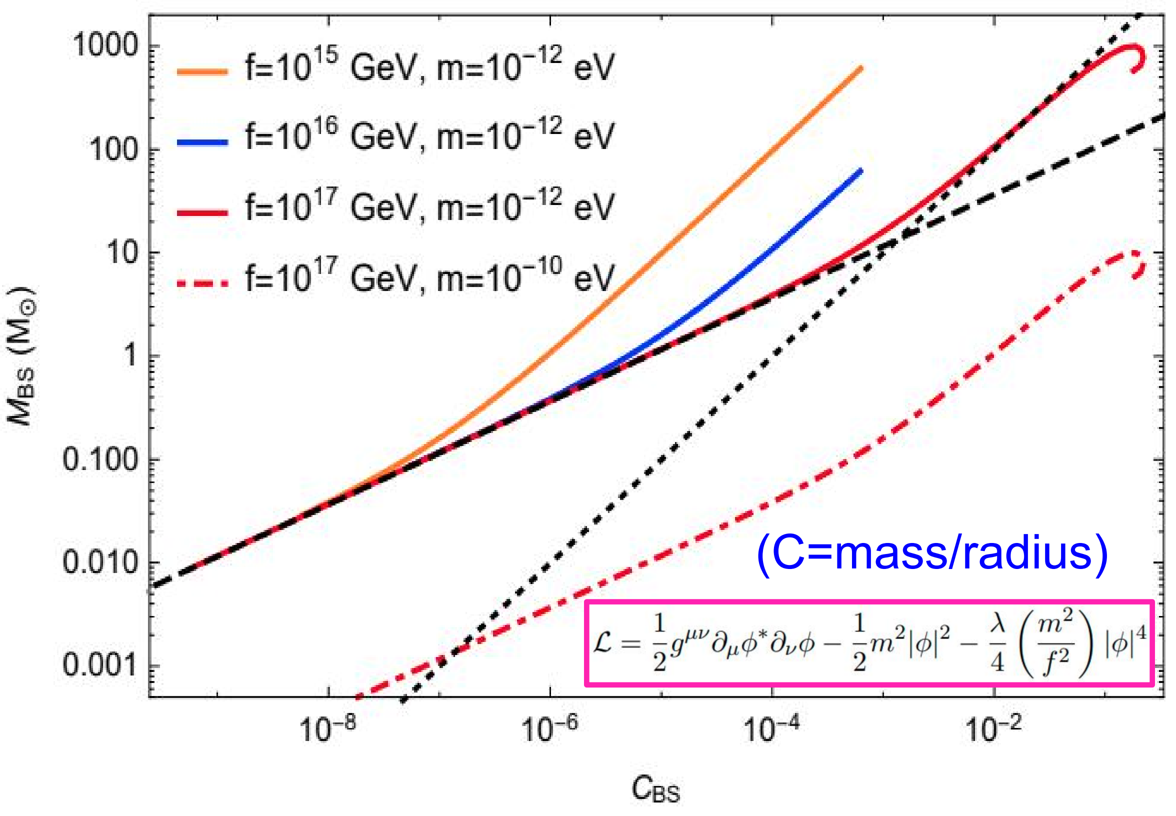
Ferreira, Astron.Astrophys.Rev. 29 (2021) 1

Stellar Scale: soliton stars

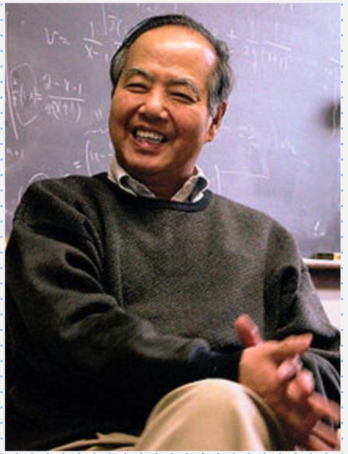


Non-Topological Solitons as Boson Stars

- Macroscopic Bose-Einstein condensate of ultralight particles
- Boson stars can be very massive and compact



HG, Sinha, Sun, JCAP [1904.07871]

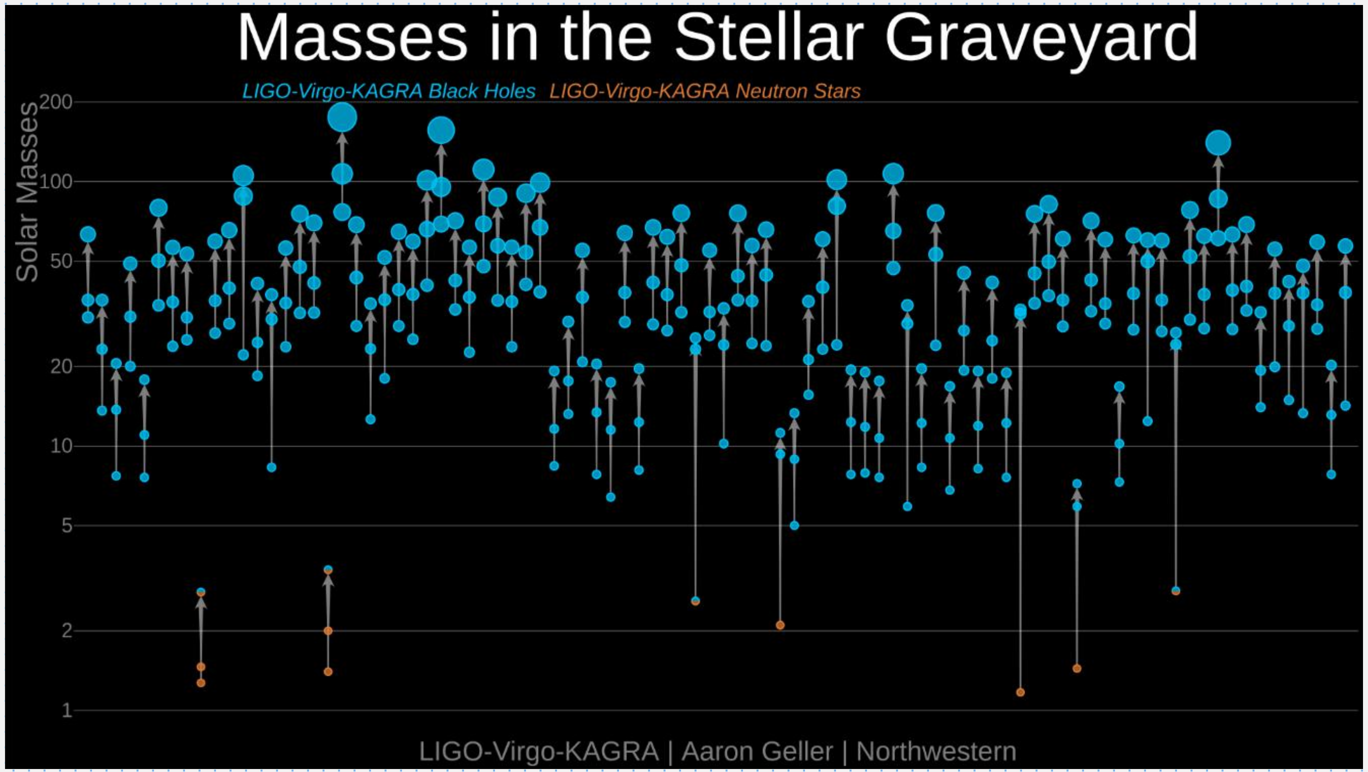


- Mini-Boson Star (without self-interaction)
- Solitonic Boson Star (specific potential)
- Oscillaton (real scalar field)
- Proca Star (massive complex vector)
- Axion Stars (dense, dilute)

Did LIGO detect Boson Stars?

- Difficult to distinguish
- Mass as discriminator

  (SBH cannot be subsolar)



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

Did LIGO Detect Dark Matter?

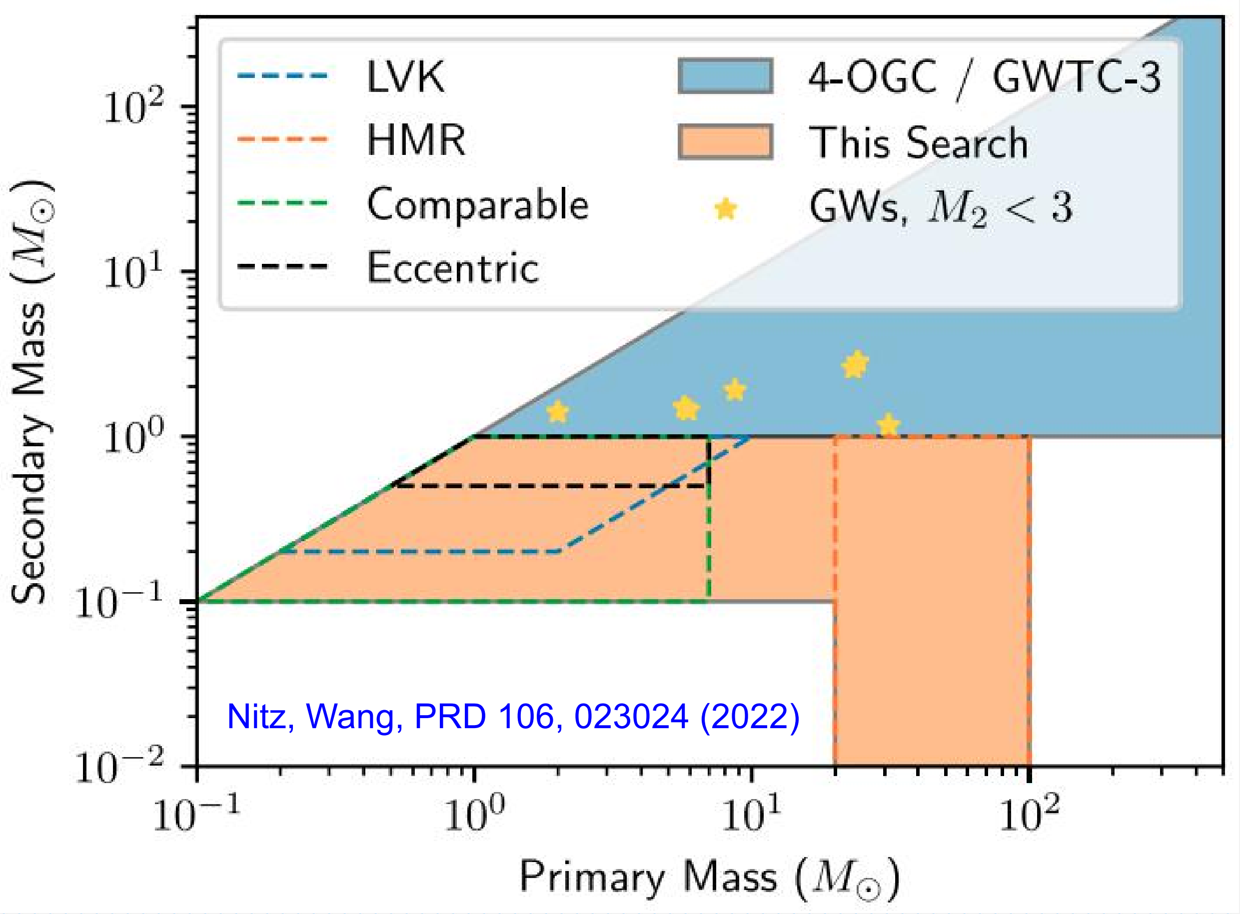
Simeon Bird,* Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, and Adam G. Riess
Department of Physics and Astronomy, Johns Hopkins University, 3400 North Charles Street, Baltimore, Maryland 21218, USA
(Received 4 March 2016; published 19 May 2016)

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

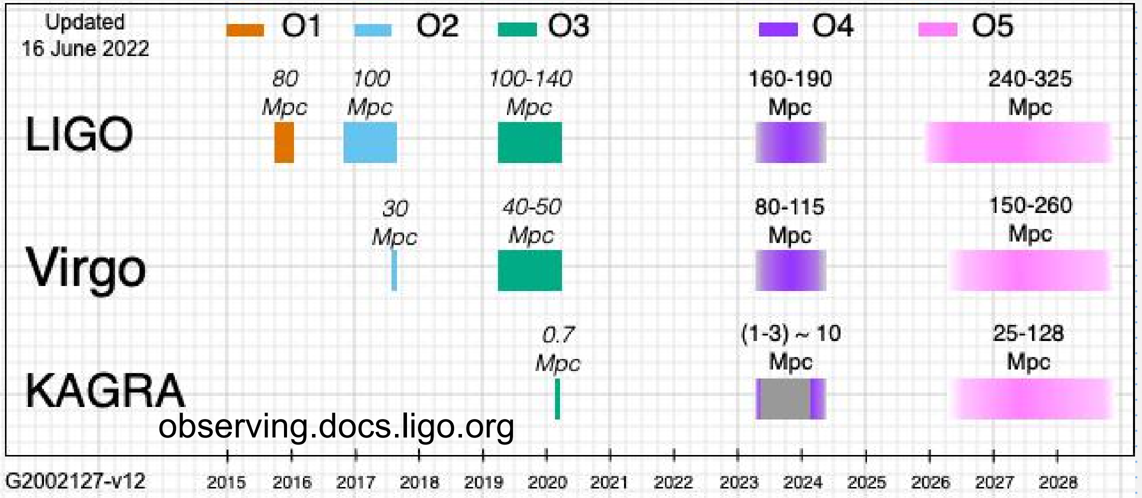
Juan Calderón Bustillo, Nicolas Sanchis-Gual, Alejandro Torres-Forné, José A. Font, Avi Vajpeyi, Rory Smith, Carlos Herdeiro, Eugen Radu, and Samson H. W. Leong
Phys. Rev. Lett. **126**, 081101 – Published 24 February 2021

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



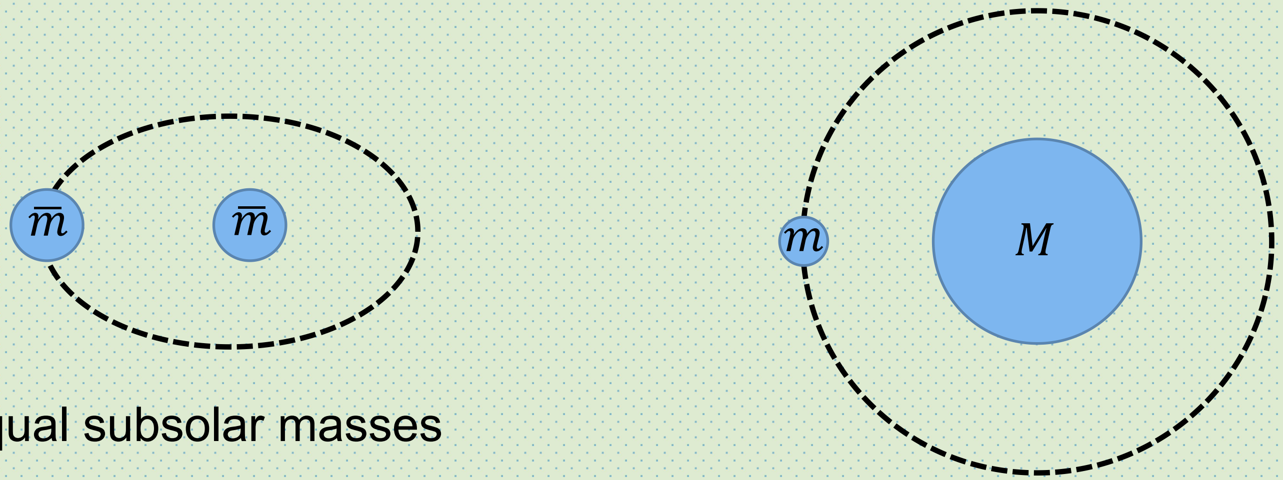
How to Search for Light Boson Stars

- 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

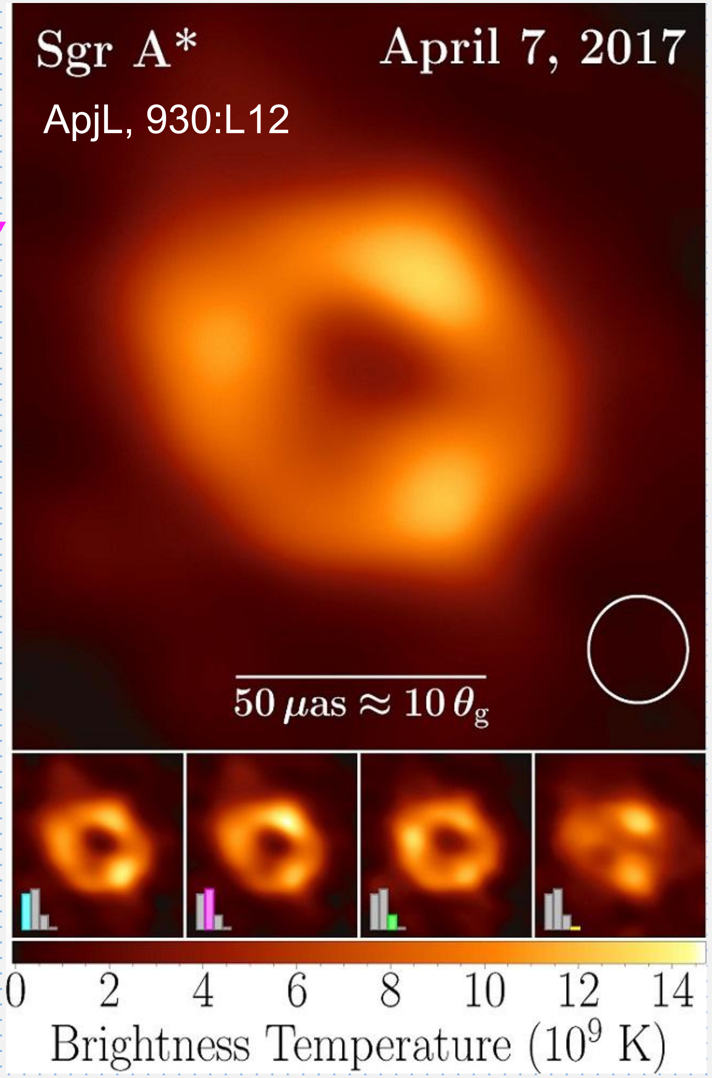
large mass ratio

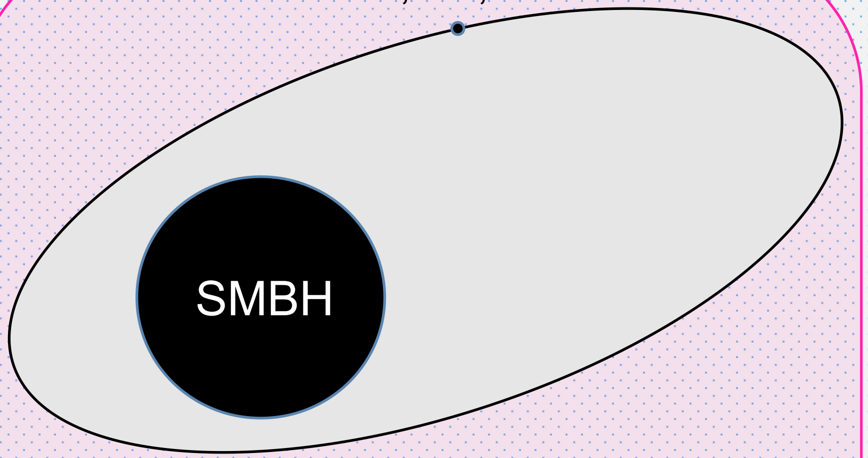
$$\frac{m}{\bar{m}} \approx 2^{-1/3} \left(\frac{\bar{m}}{M}\right)^{2/3} \Rightarrow m \ll \bar{m} \ll M$$

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

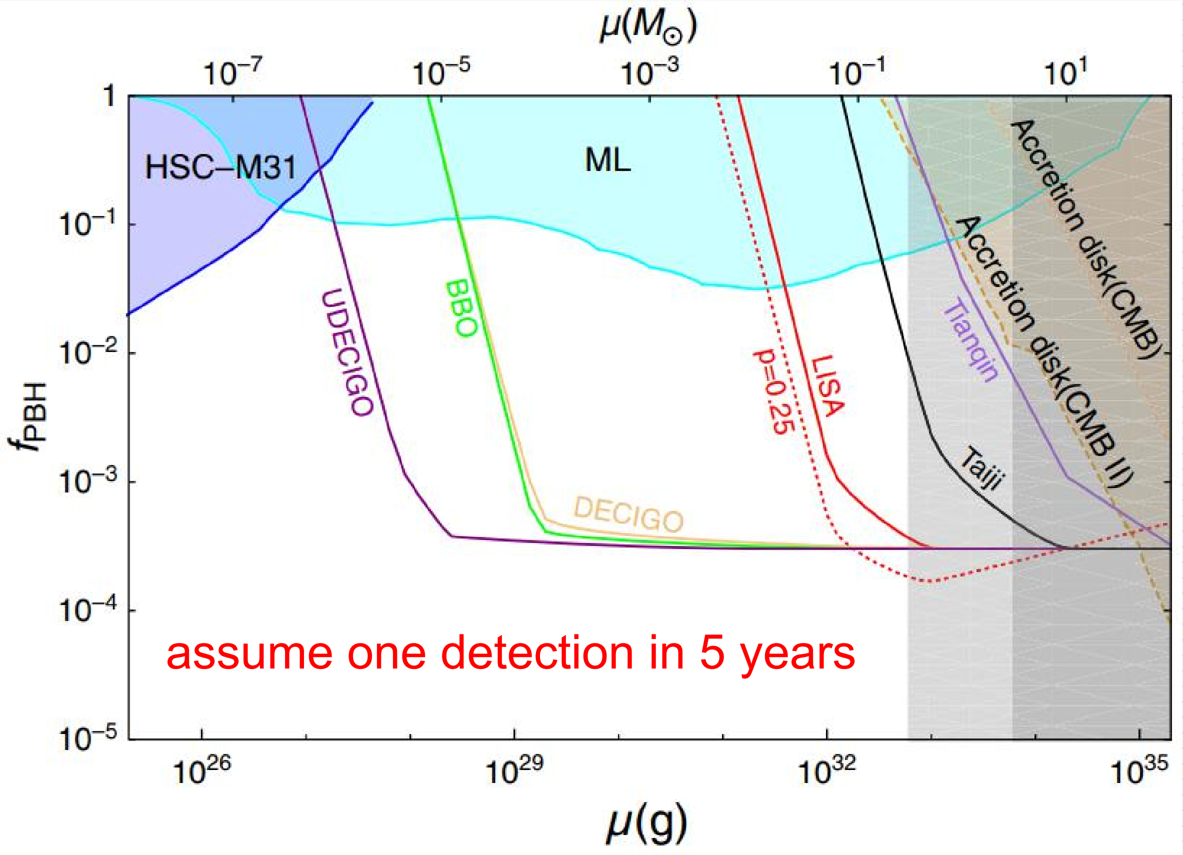
extreme mass ratio inspiral (EMRI)

important target for LISA, Taiji, Tianqin...

Sensitivity with EMRI

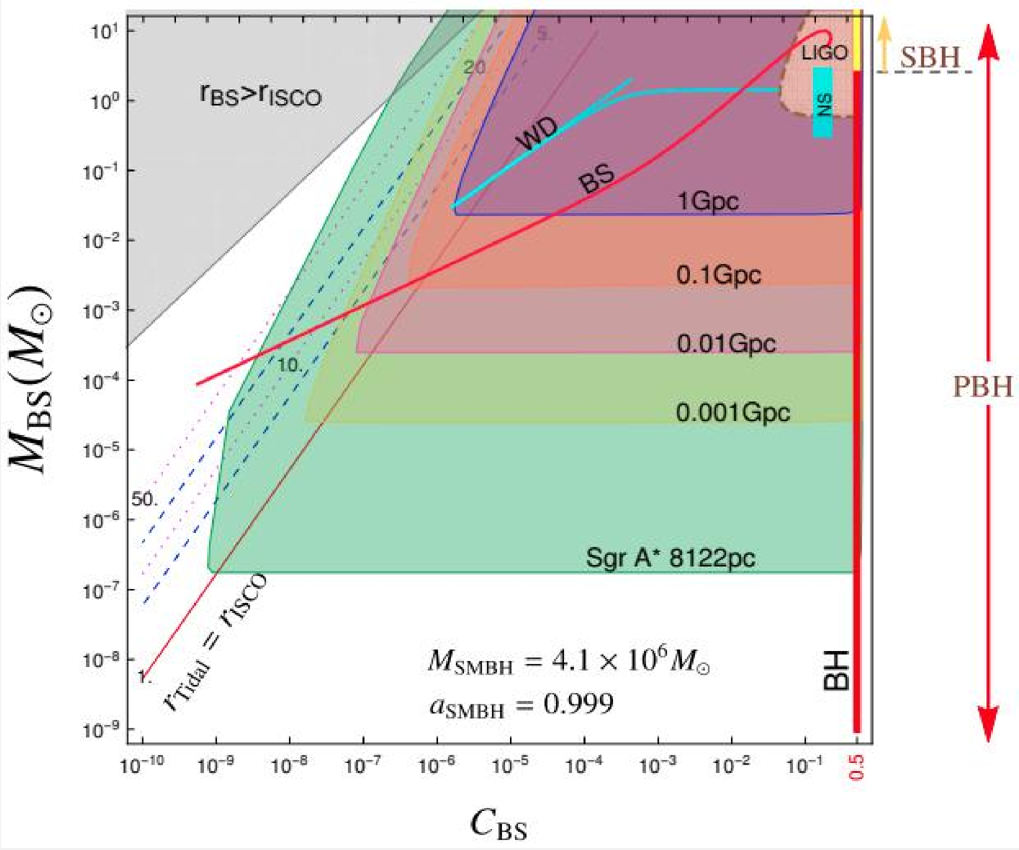
- Sensitive to a large region of parameter space

Constraining PBH (or compact Boson Star DM)



HG, Shu, Zhao, PRD [1709.03500]

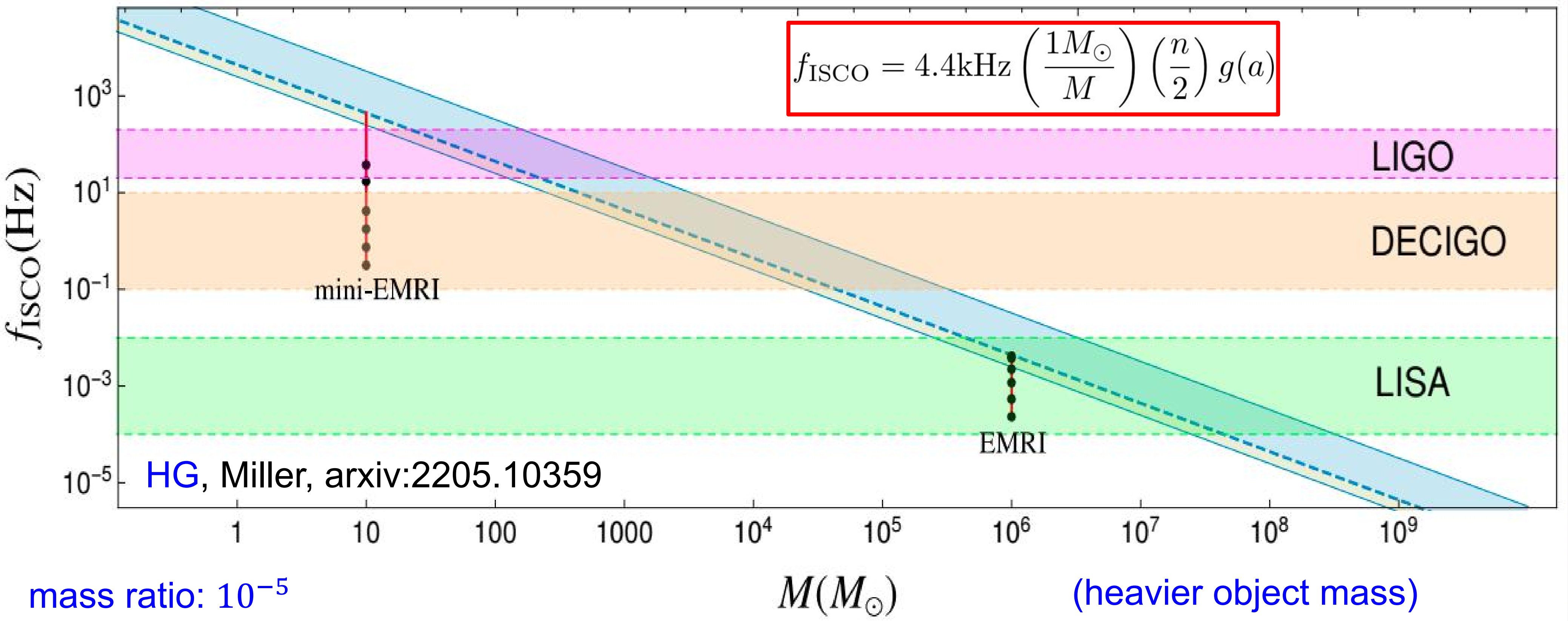
Sensitivity to Generic Exotic Compact Objects



HG, Sinha, Sun, JCAP [1904.07871]

“mini-EMRI”

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

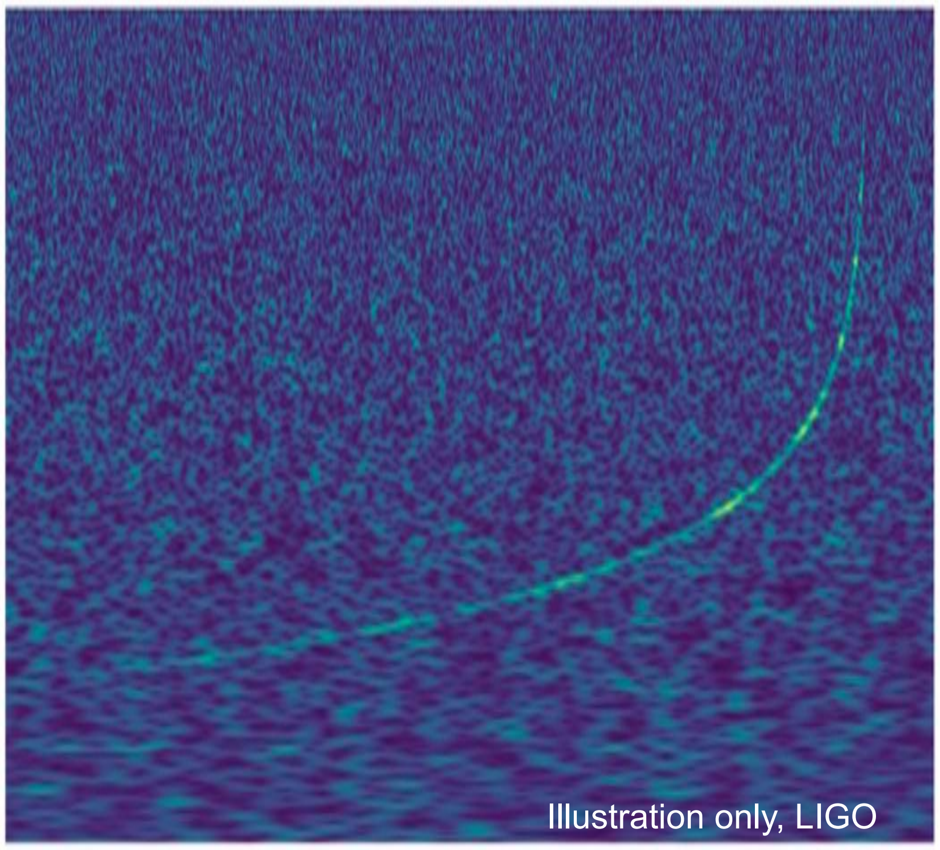


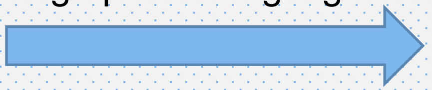
Similar systems:

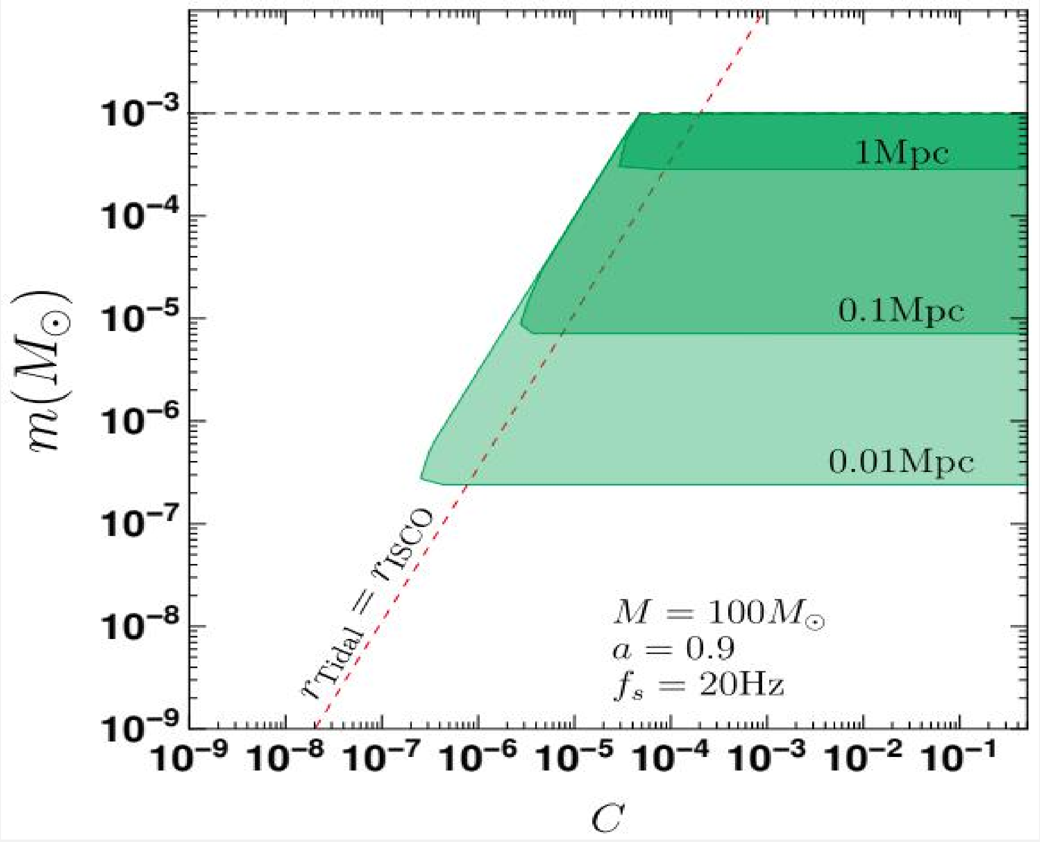
Davoudiasl, Giardino, PLB 768, 198 (2017)
Pan, Lyu, Yang, PRD 105, 083005 (2022)
Barsanti et al PRL 128, 111104 (2022)

Sensitivity to mini-EMRIs

- Matched-filtering, or techniques of continuous wave searches
- LIGO can detect mini-EMRIs!







HG, A. Miller [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)

Acknowledgement: This material is based upon work supported by NSF's LIGO Laboratory which is a major facility fully funded by the National Science Foundation.