粒子物理基于地面和空间引力波探测的一些研究

郭怀珂

国科大
国际理论物理中心（亚太地区）

2023年5月11日

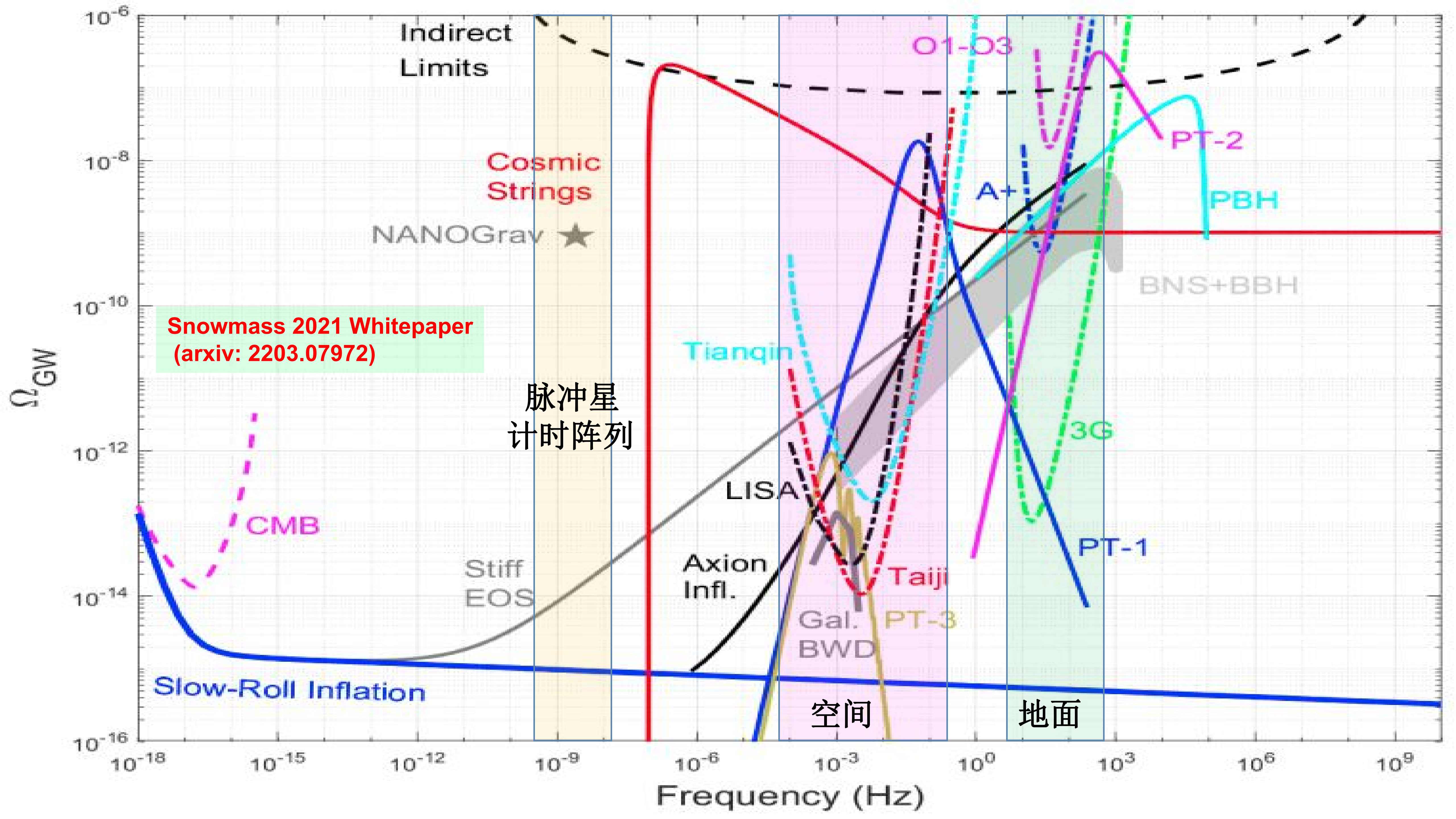
第二届地下和空间粒子物理与宇宙物理
前沿问题研讨会

Detection of early-universe gravitational-wave signatures and fundamental physics

Robert Caldwell, Yanou Cui, Huai-Ke Guo, Vuk Mandic, Alberto Mariotti, Jose Miguel No, Michael J. Ramsey-Musolf, Mairi Sakellariadou, Kuver Sinha, Lian-Tao Wang, Graham White, Yue Zhao, Haipeng An, Ligong Bian, Chiara Caprini, Sebastien Clesse, James M. Cline, Giulia Cusin, Bartosz Fornal, Ryusuke Jinno, Benoit Laurent, Noam Levi, Kun-Feng Lyu, Mario Martinez, Andrew L. Miller, Diego Redigolo, Claudia Scarlata, Alexander Sevrin, Barmak Shams Es Haghi, Jing Shu, Xavier Siemens, Danièle A. Steer, Raman Sundrum, Carlos Tamarit, David J. Weir, Ke-Pan Xie, Feng-Wei Yang & Siyi Zhou — Show fewer authors

General Relativity and Gravitation **54**, Article number: 156 (2022) | Cite this article

Snowmass 2021 White Paper

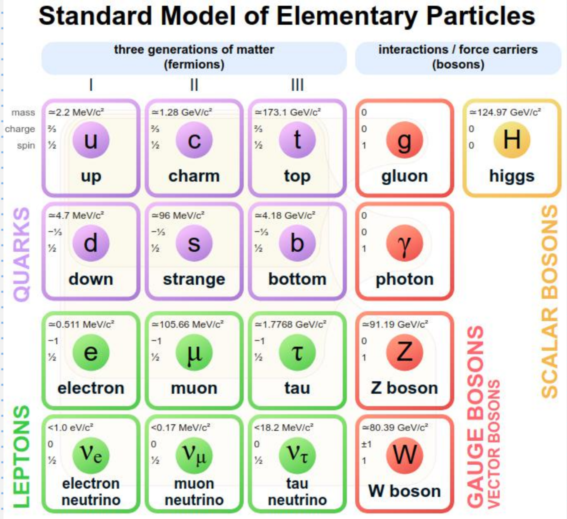


Indirect
Limits
Cosmic
Strings
NANOGrav
O1-O3
PT-2
A+
PBH
BNS+BBH
Snowmass 2021 Whitepaper
(arxiv: 2203.07972)
Tianqin
脉冲星
计时阵列
3G
LISA
CMB
PT-1
Stiff
EOS
Axion
Infl.
Taiji
Gal.
BWD
PT-3
Slow-Roll Inflation
空间
地面
Ω_{GW}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-15}
10^{-12}
10^{-9}
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
Frequency (Hz)

New Perspectives?

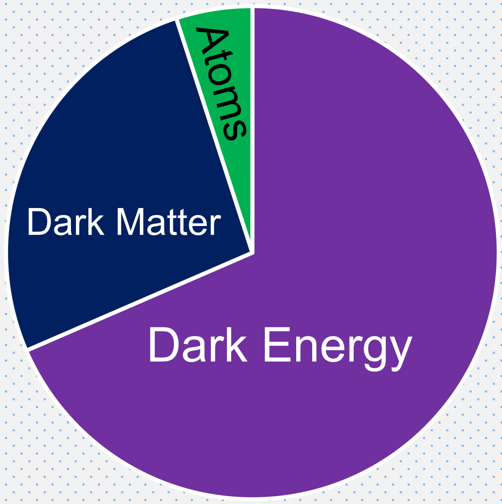
How can we reconcile the standard models of particle physics and cosmology?

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, ultralight particles)

Why more matter than anti-matter? (phase transitions)

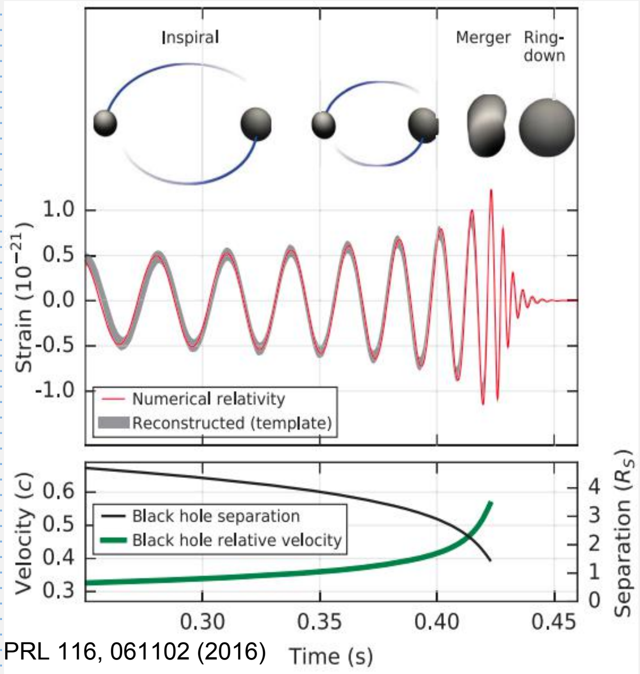
What is dark energy?

GWs from Particles?

GW generation requires macroscopic mass/energy

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

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



PRL 116, 061102 (2016)

How to study particle physics with GWs?

GWs from Particles

Extreme densities

disturbances in the early universe

Form macroscopic objects

(non-) topological solitons

Environmental Effects

Faking GW signals (dark photon)

(Only a collection of my personal works)

GWs from Particles

Extreme densities

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Environmental Effects

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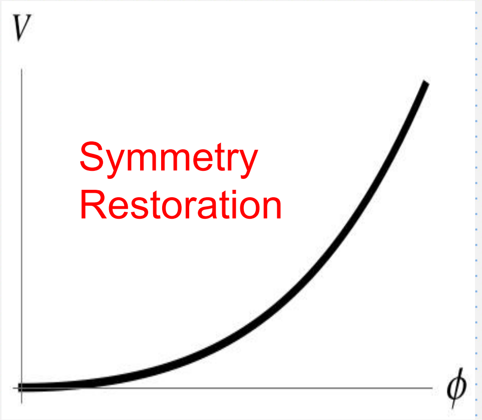
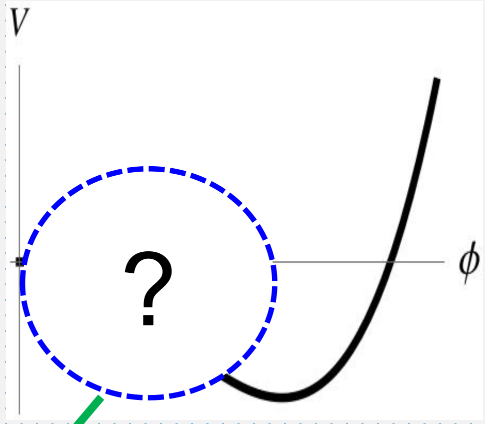
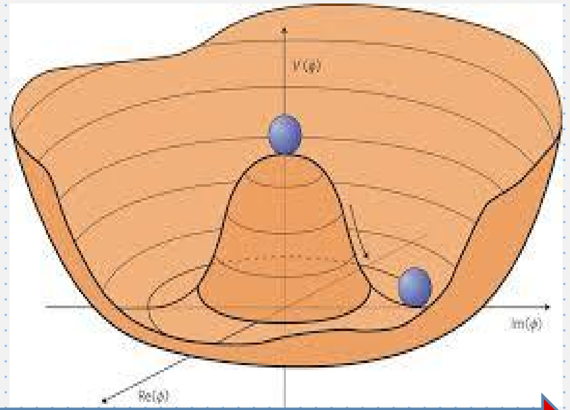
(Only a collection of my personal works)

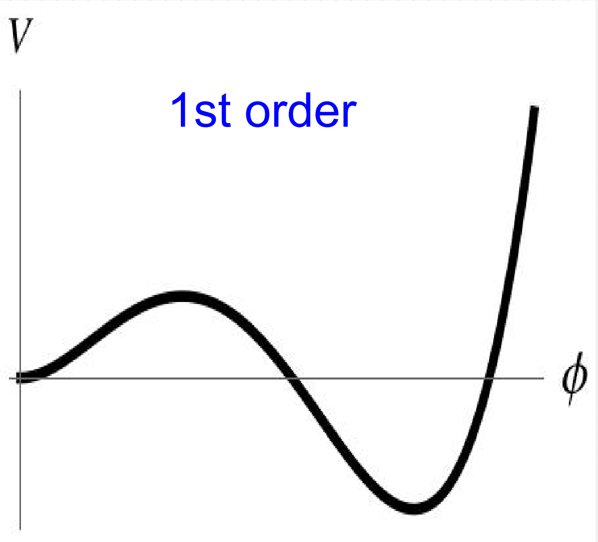
Cosmological First Order Phase Transitions

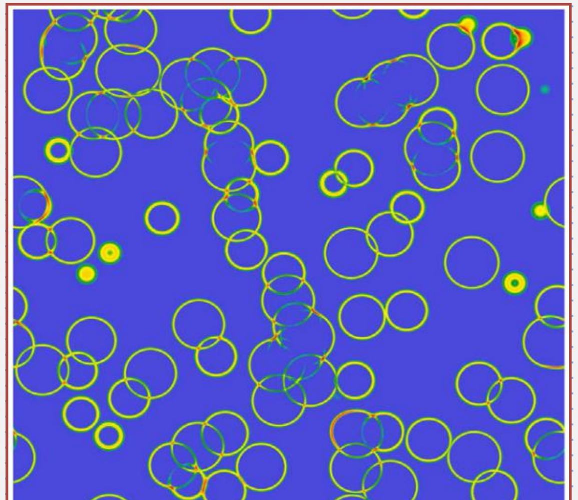






Temperature drops



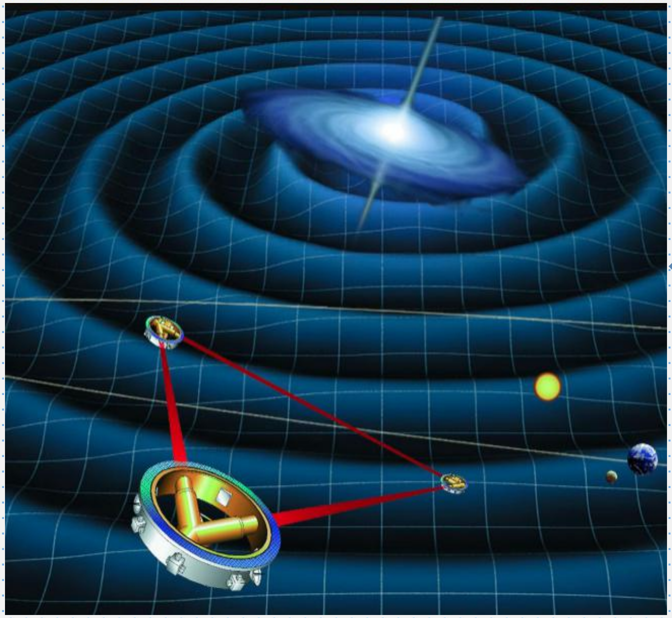

Hindmarsh, et al, 2015

Electroweak Baryogenesis

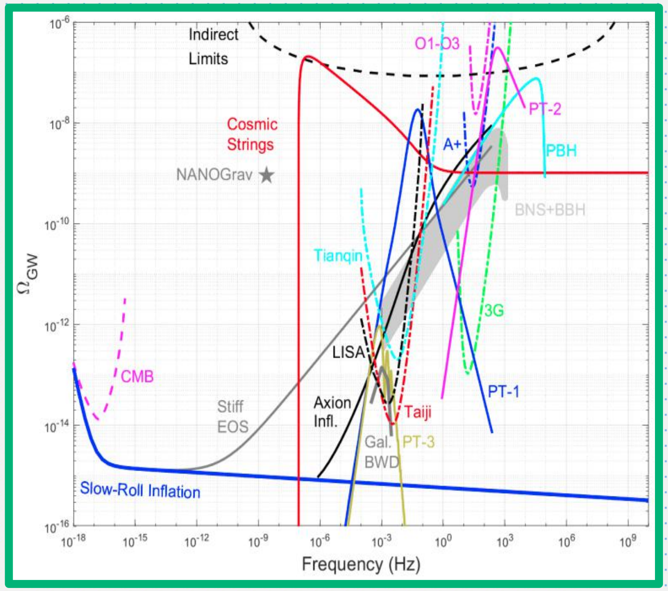
- Modified Higgs potential (Higgs physics, GW)
- Extra CP-violation (EDM, LHC)
- B-violation: Sphaleron process (LHC, GW)

Flow of Studies

theoretical calculation of gravitational wave spectrum and detector simulation



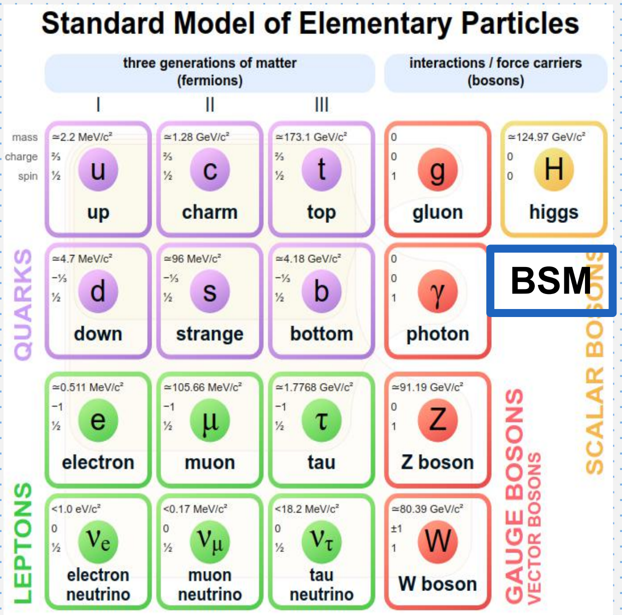
LIGO, LISA, Taiji, Tianqin...



Gravitational Wave Spectrum

α
β
v_w
T_*
g_s
...

Phase Transition Parameters

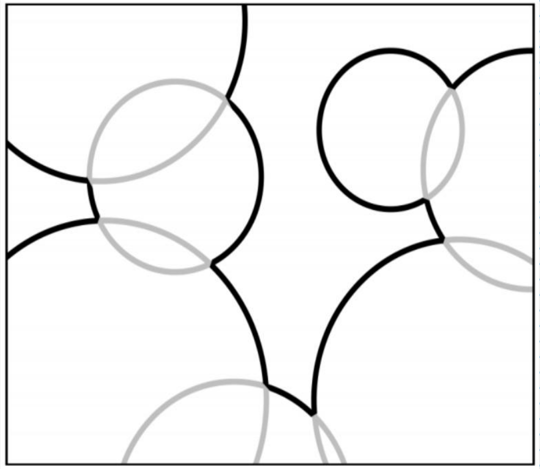


Particle Physics Model

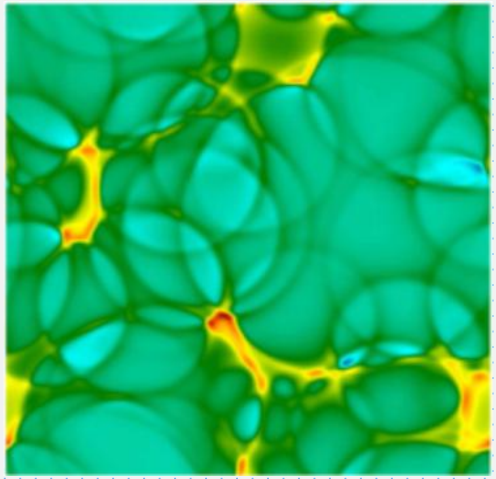
data analysis, constraints or discovery(parameter estimation)

Gravitational Wave Sources

Bubble Collisions

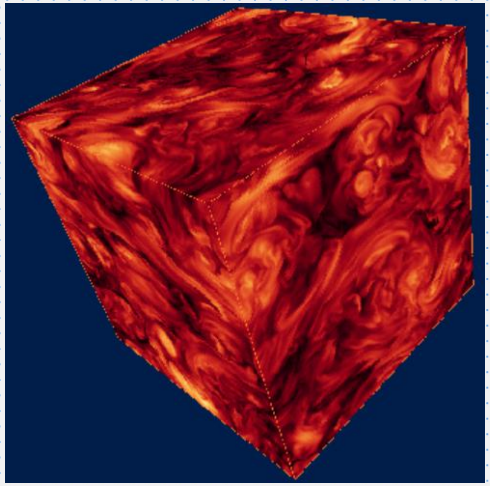


Sound Waves



Hindmarsh, et al,PRL112,041301(2013)

MagnetoHydrodynamic Turbulence



https://home.mpcdf.mpg.de/~wcm/projects/homog-mhd/mhd.html

energy concentrated at walls

acoustic production

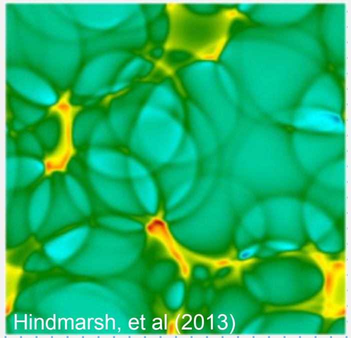
turbulent motion

New observables: primordial magnetic field, scalar perturbations, anisotropy, primordial black hole...

Di, Wang, Zhou, Bian, Cai, Liu, PRL 126 (2021) 25, 251102
Jing, Bian, Cai, Guo, Wang, PRL 130 (2023) 051001
Li, Huang, Wang, Zhang, PRD 105 (2022) 083527
Huang, Xie, PRD105 (2022) 11, 115033, JHEP 09 (2022) 052

Sound Waves

sound waves



$$\Omega_{\rm sw}(f)h^2 = 2.65\times10^{-6}\left(\frac{H_{\rm pt}}{\beta}\right)\left(\frac{\kappa_{\rm sw}\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{1/3}\times v_w\left(\frac{f}{f_{\rm sw}}\right)^3\left(\frac{7}{4+3(f/f_{\rm sw})^2}\right)^{7/2}\Upsilon(\tau_{\rm sw}),$$

Chiara Caprini et al JCAP04(2016)001

$$\Upsilon = 1-(1+2\tau_{\rm sw}H_{\rm pt})^{-1/2} \quad \text{(RD)}$$

HG,Sinha,Vagie,White,JCAP 01 (2021) 001

PHYSICAL REVIEW LETTERS 127, 251302 (2021)

Editors' Suggestion   Featured in Physics

Searching for Gravitational Waves from Cosmological Phase Transitions with the NANOGrav 12.5-Year Dataset

Zaven Arzoumanian,[1] Paul T. Baker,[2] Harsha Blumer,[3,4] Bence Bécsy,[5] Adam Brazier,[6,7] Paul R. Brook,[3,4] Sarah Burke-Spolaor,[3,4,8] Maria Charisi,[9] Shami Chatterjee,[6] Siyuan Chen,[10,11,12] James M. Cordes,[6] Neil J. Cornish,[5] Fronefield Crawford,[13] H. Thankful Cromartie,[6] Megan E. DeCesar,[14,15*] Paul B. Demorest,[16] Timothy Dolch,[17,18] Justin A. El... niels,[3,4] Peter A. Gentile... Jennings,[6] Megan L. Jones... na Laal,[30] Michael T. Lam... Lynch,[36] Dustin R. M... ry Ng,[39] David J. Nice,[14] ... o-Albert,[3,4] Xavier Siemens... Stovall,[16] Jerry P. Sun,[30] J... Vigeland,[28]

(NANOGrav Collaboration)

considered in this work. Because of the finite lifetime [54,55] of the sound waves, to derive $\Omega_{\rm SW}$ Eq. (4) needs to be multiplied by a suppression factor $\Upsilon(\tau_{\rm SW})$ given by [54]

$$\Upsilon(\tau_{\rm SW}) = 1-(1+2\tau_{\rm SW}H_*)^{-1/2} \qquad (6)$$

Phase Transitions in an Expanding Universe: Stochastic Gravitational Waves in Standard and Non-Standard Histories

Huai-Ke Guo (Oklahoma U.), Kuver Sinha (Oklahoma U.), Daniel Vagie (Oklahoma U.), Graham White (TRIUMF) (Jul 16, 2020)

Published in: JCAP 01 (2021) 001 • e-Print: 2007.08537 [hep-ph]

pdf DOI cite claim   reference search 124 citations

Experimental Searches

PHYSICAL REVIEW LETTERS **126**, 151301 (2021)

LIGO

Implications for First-Order Cosmological Phase Transitions from the Third LIGO-Virgo Observing Run

Alba Romero,[1] Katarina Martinovic,[2] Thomas A. Callister,[3] Huai-Ke Guo,[4] Mario Martínez,[1,5] Mairi Sakellariadou,[2,6] Feng-Wei Yang,[7] and Yue Zhao[7]

PHYSICAL REVIEW LETTERS **127**, 251302 (2021)

Editors' Suggestion | Featured in Physics

NANOGrav

Searching for Gravitational Waves from Cosmological Phase Transitions with the NANOGrav 12.5-Year Dataset

PHYSICAL REVIEW LETTERS **127**, 251303 (2021)

Editors' Suggestion | Featured in Physics

PPTA

Constraining Cosmological Phase Transitions with the Parkes Pulsar Timing Array

Xiao Xue,[1,2,3] Ligong Bian,[4,5,*] Jing Shu,[1,2,6,7,8,†] Qiang Yuan,[9,10,7,‡] Xingjiang Zhu,[11,12,13,§] N. D. Ramesh Bhat,[14] Shi Dai,[15] Yi Feng,[16] Boris Goncharov,[11,12] George Hobbs,[17] Eric Howard,[17,18] Richard N. Manchester,[17] Christopher J. Russell,[19] Daniel J. Reardon,[12,20] Ryan M. Shannon,[12,20] Renée Spiewak,[21,20] Nithyanandan Thyagarajan,[22] and Jingbo Wang[23]

LIGO's Search Result

O1+O2+O3@LIGO (H1, L1), Virgo

- No Evidence for Broken Power Law Signal
- No Evidence for Bubble Collision Domination Signal
- No Evidence for Sound Waves Domination Signal

Broken Power Law

95% CL UL (CBC+BPL)

$$\Omega_{\rm ref} = 6.1 \times 10^{-9}$$

$$\Omega_* = 5.6 \times 10^{-7}$$

$$\Omega_{\rm BPL}(25\ \text{Hz}) = 4.4 \times 10^{-9}$$

Bubble Collision

95% CL UL with fixed Tpt and beta/Hpt

Phenomenological model (bubble collisions)				
$\Omega^{95\%}_{\rm coll}(25\ \text{Hz})$				
$\beta/H_{\rm pt} \backslash T_{\rm pt}$	10^7 GeV	10^8 GeV	10^9 GeV	10^{10} GeV
0.1	9.2×10^{-9}	8.8×10^{-9}	1.0×10^{-8}	7.2×10^{-9}
1	1.0×10^{-8}	8.4×10^{-9}	5.0×10^{-9}	...
10	4.0×10^{-9}	6.3×10^{-9}	...	...

no sensitivity

Sound Waves

95% CL UL

$$\Omega_{\rm sw}(25\ \text{Hz}) \quad 5.9 \times 10^{-9}$$

$$\beta/H_{\rm pt} < 1 \text{ and } T_{\rm pt} > 10^8\ \text{GeV}$$

First result from gravitational wave data!

See also
Jiang, Huang, arxiv:2203.11781
Yu, Wang, arxiv:2211.13111

GWs from Particles

Extreme densities

disturbances in the early universe

Form macroscopic objects

(non-) topological solitons

Environmental Effects

Faking GW signals (dark photon)

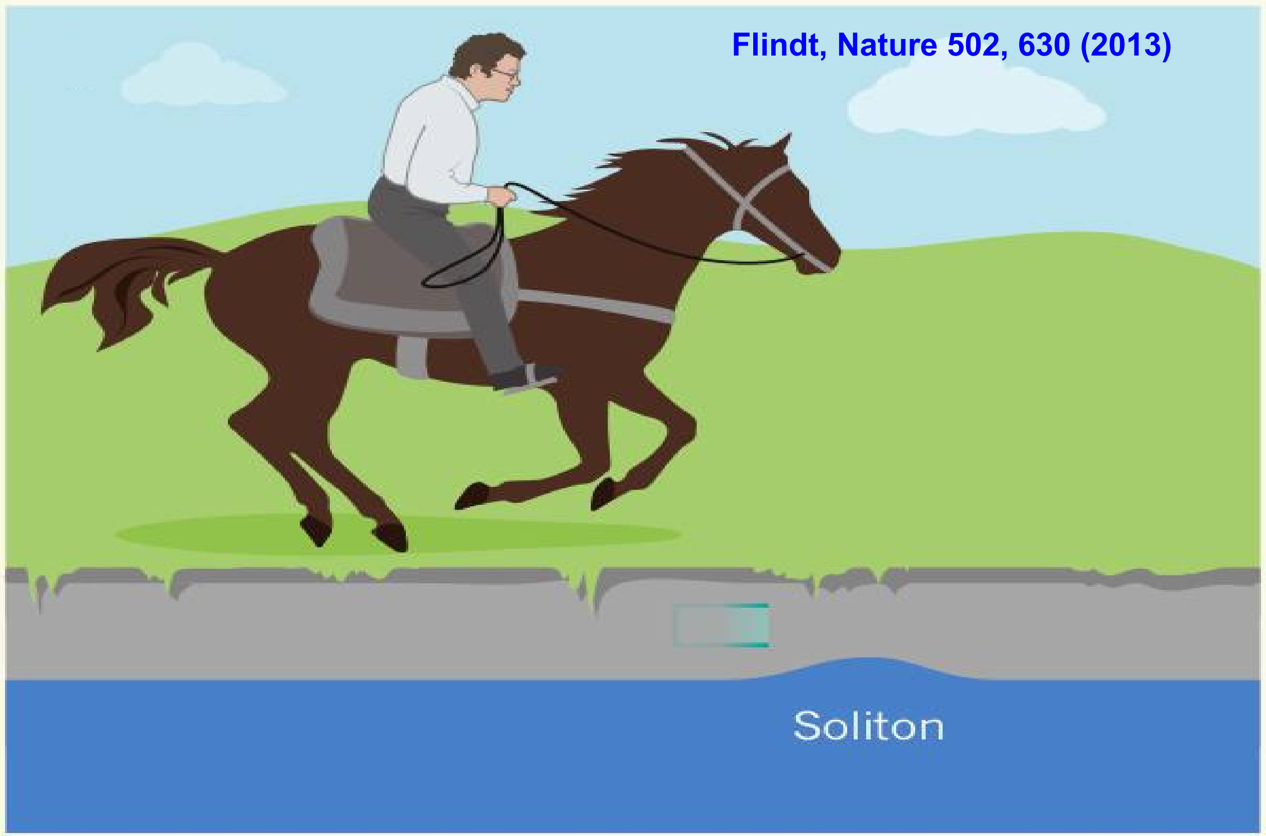
Solitons

- Localized
- Associated with nonlinear problem

Found in:

- ✓ Optics
- ✓ Hydrodynamics
- ✓ Condensed matter systems
- ✓ Quantum field theory

...



Solitons in Quantum Field Theory

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

	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) ● 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, Lon

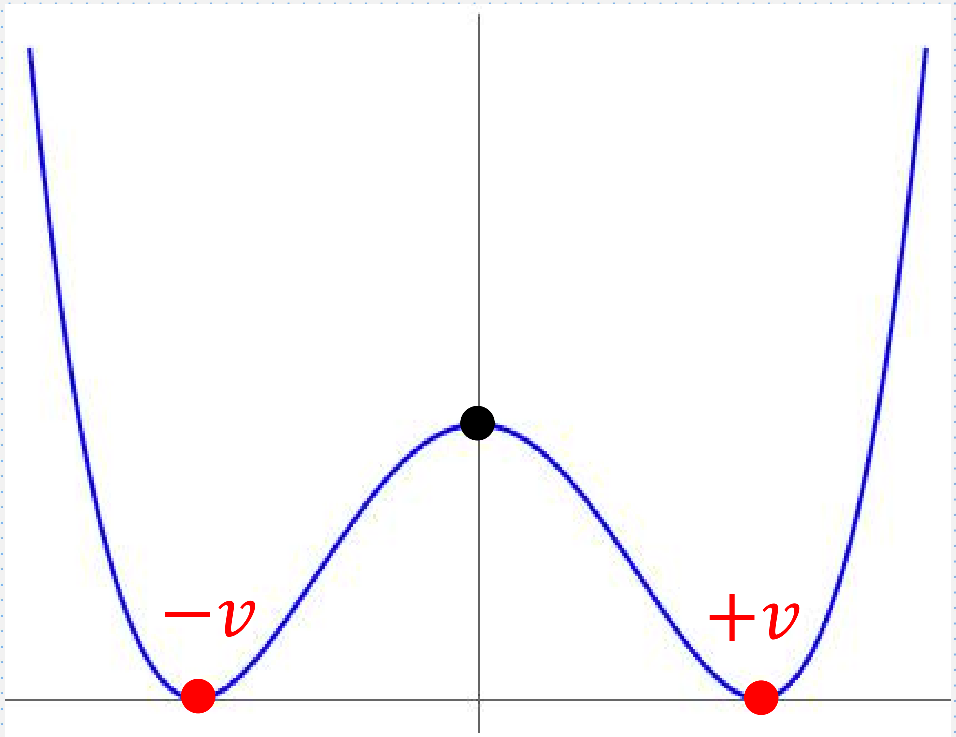
Received 11 March 1976

www.theguardian.com

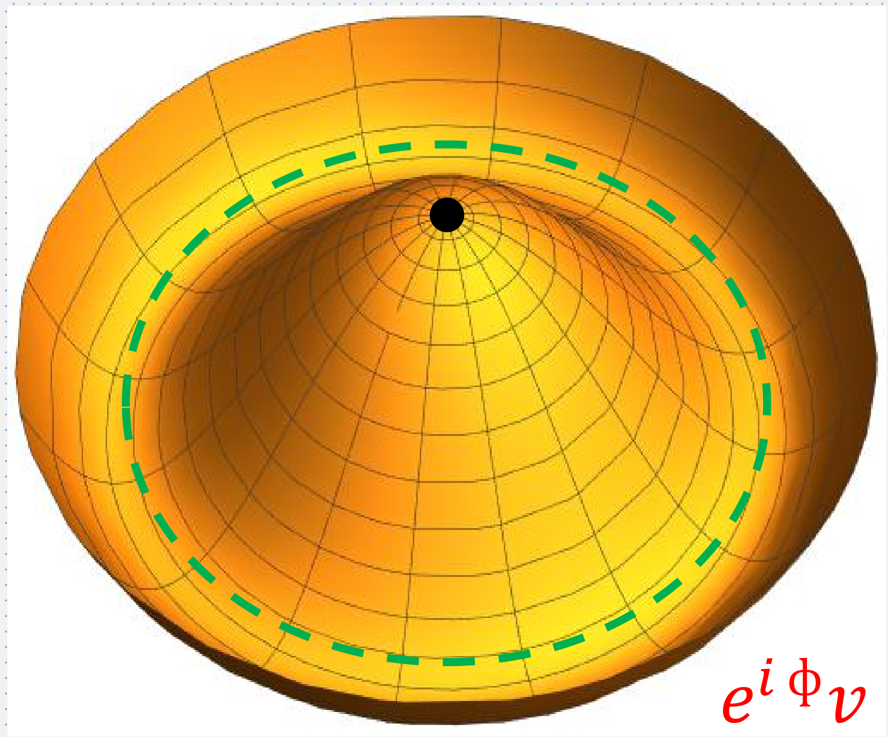
Degenerate Vacuum States

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

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



Domain wall



Cosmic String

LIGO Search Result of Cosmic Strings

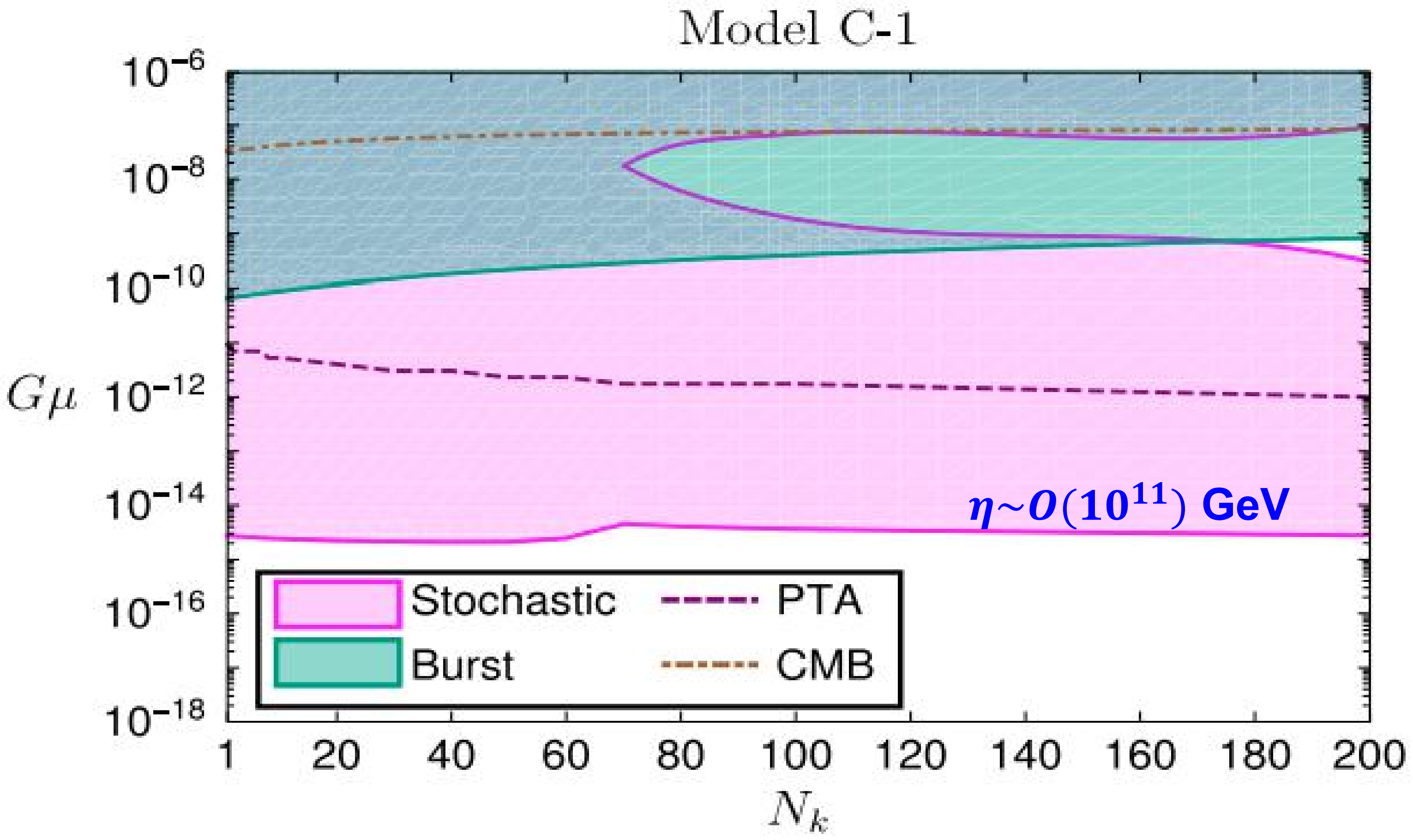
Symmetry breakings at scales higher than $O(10^{11})$ GeV with Cosmic String production are excluded

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

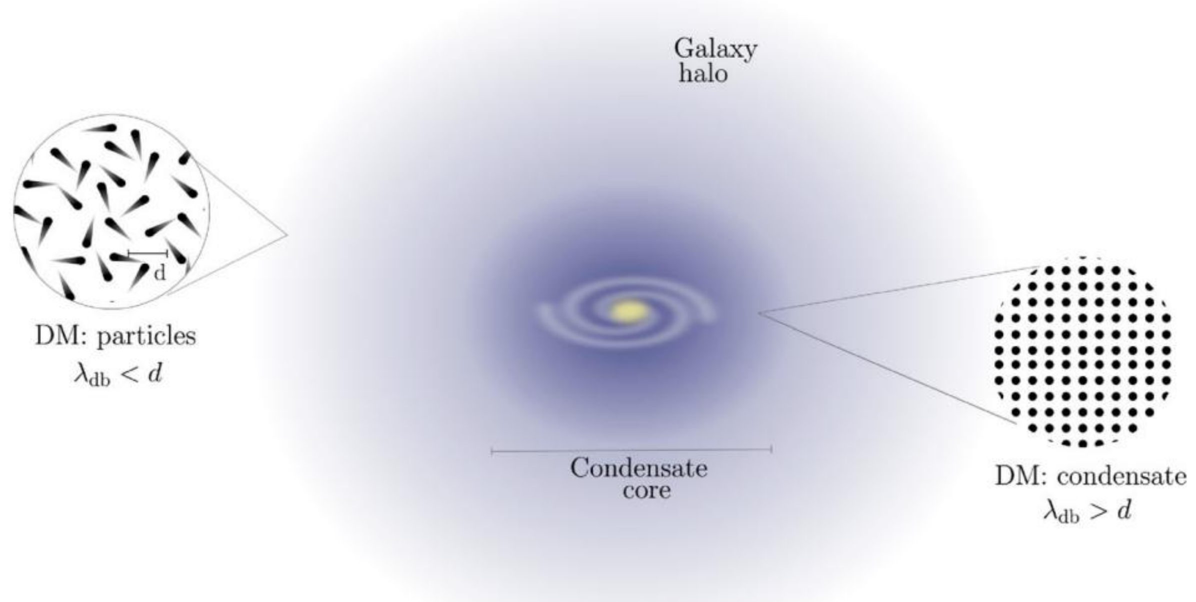
Giant Bose-Einstein condensate of ultralight particles (DM)

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

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

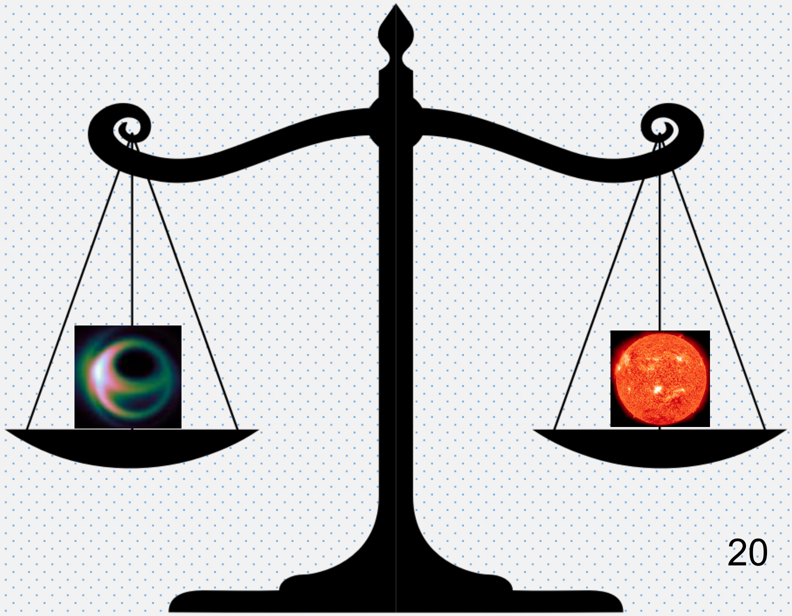
$m_{\rm ULDM} \sim 10^{-10}{\rm eV}$

Galactic Scale: solve small scale structure problems

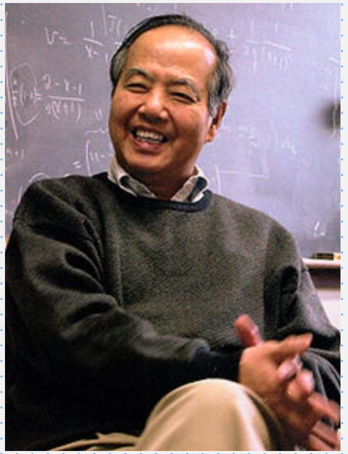


Ferreira, Astron.Astrophys.Rev. 29 (2021) 1

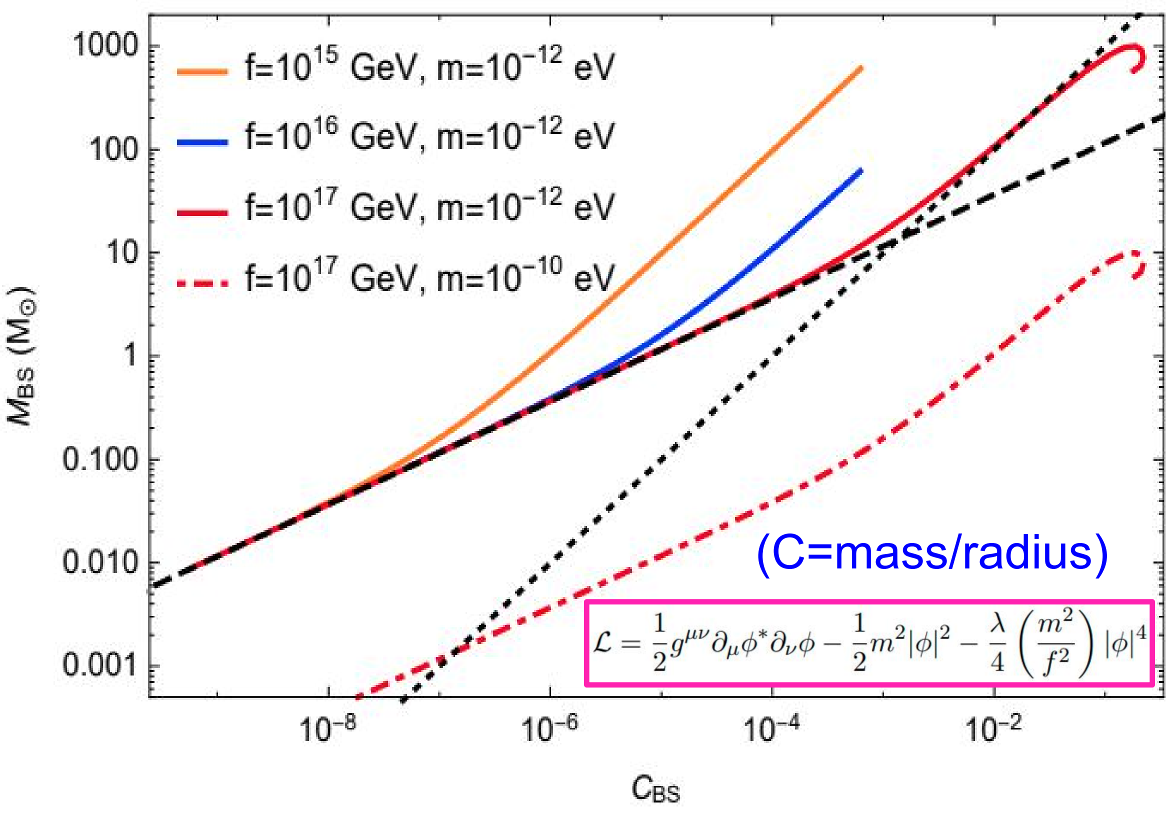
Stellar Scale: soliton stars



Non-Topological Solitons as Boson Stars



- Boson stars can be very massive and compact
- Thus can be detected just like black holes and neutron stars



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

- 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

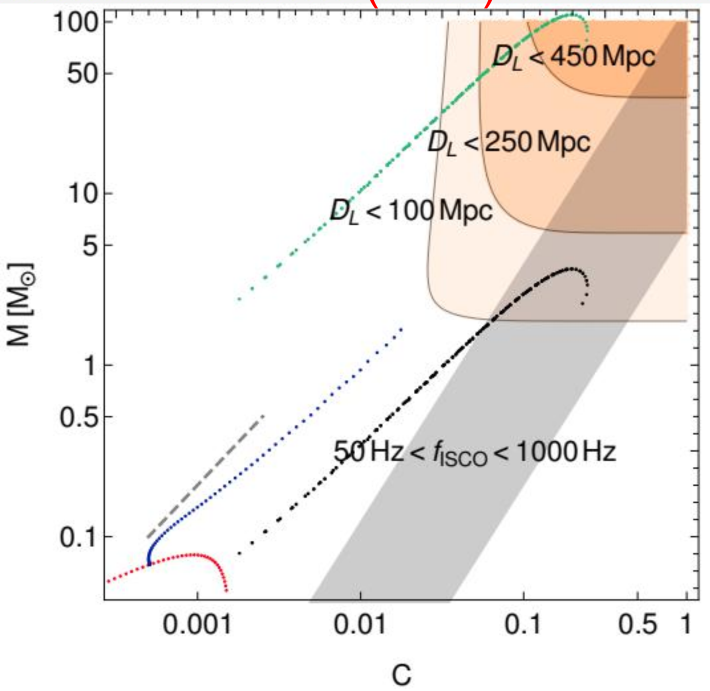
Lee,Pang, Phys.Rept (1992)

Detection with EMRIs

$$f_{\rm ISCO} = 4.4{\rm kHz}\left(\frac{1M_\odot}{M}\right)\left(\frac{n}{2}\right)g(a)$$

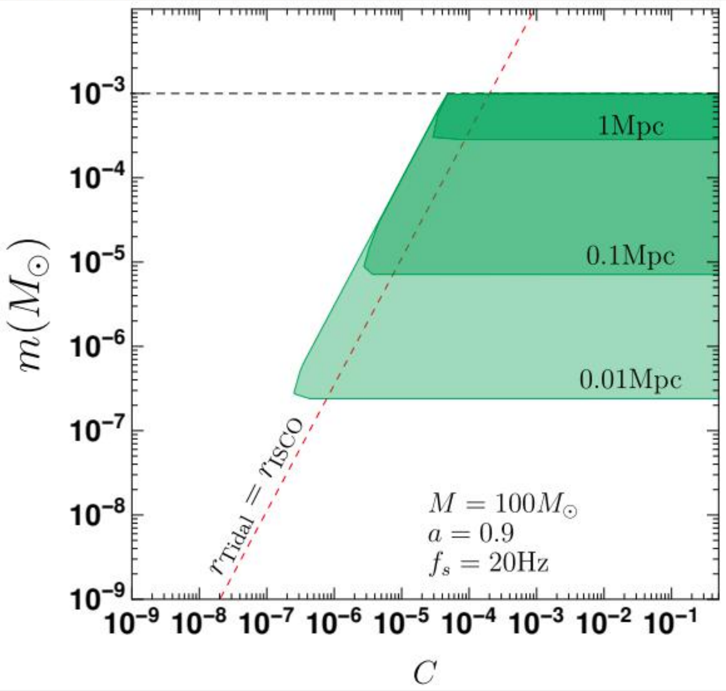
- By making one object much heavier, one can probe much ligher companion object
- Ideal systems: extreme mass ratio inspirals (EMRIs), key target of Taiji, Tianqin, LISA.
- LIGO can detect mini-EMRIs

LIGO (CBC)



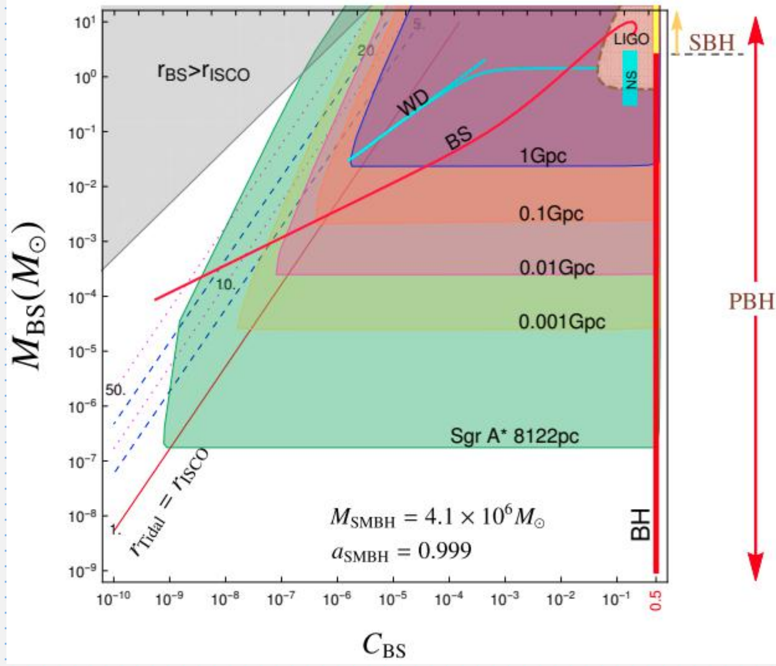
HG, Sinha, Sun, Vagie, JCAP 10 (2021) 028

LIGO ("mini-EMRI")

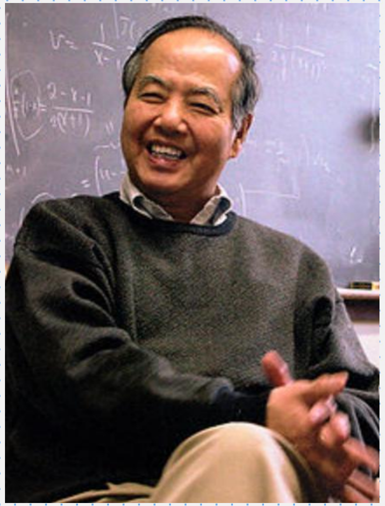


HG, A. Miller, arxiv:2205.10359

LISA, Taiji, Tianqin (EMRI)



HG, Sinha, Sun, JCAP 09 (2019) 032
HG, Shu, Zhao, PRD 99 (2019) 023001



At present, there is no experimental evidence that soliton stars exist. Nevertheless, it seems reasonable that solutions of well-tested theories, such as Einstein's general relativity, the Dirac equation, the Klein–Gordon equation, etc. should find their proper place in nature.

Lee, Pang, Phys.Rept. 221 (1992) 251

We are aiming for their discovery

GWs from Particles

Extreme densities

disturbances in the early universe

Form macroscopic objects

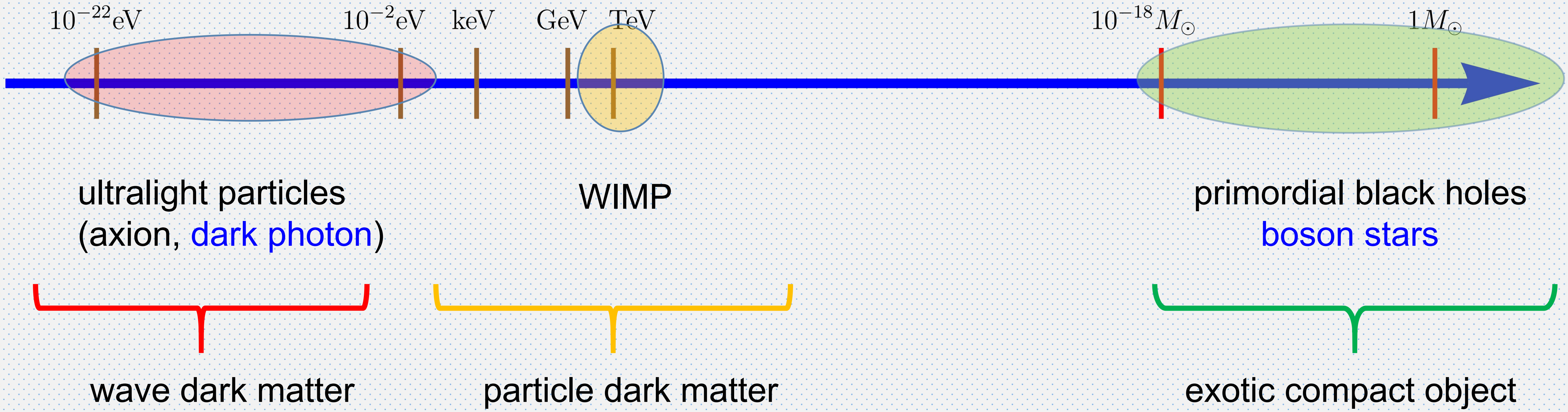
(non-) topological solitons

Environmental Effects ✓

Faking GW signals (dark photon)

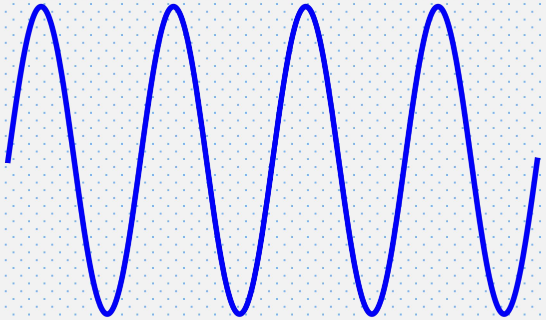
Ultralight Dark Matter

- Boson stars serve as macroscopic dark matter candidate
- So does the ultralight particle making up the boson stars

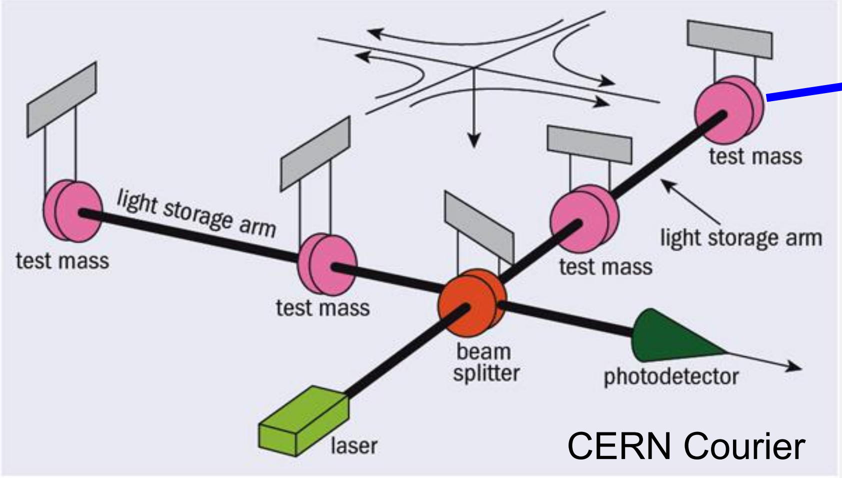


Dark Photon Detection at LIGO

a single dark photon



$\vec{A}_{n,0} \sin(\omega_n t - \mathbf{k}_n \cdot \mathbf{x} + \phi_n)$



silicon mirror

$U(1)_B$: 1/GeV

$U(1)_{B-L}$: 1/2GeV

$$\mathbf{a}_i(t, \mathbf{x}_i) \simeq \epsilon e \frac{q_{\mathrm{D},i}}{M_i} \partial_t \mathbf{A}(t, \mathbf{x}_i)$$

acceleration

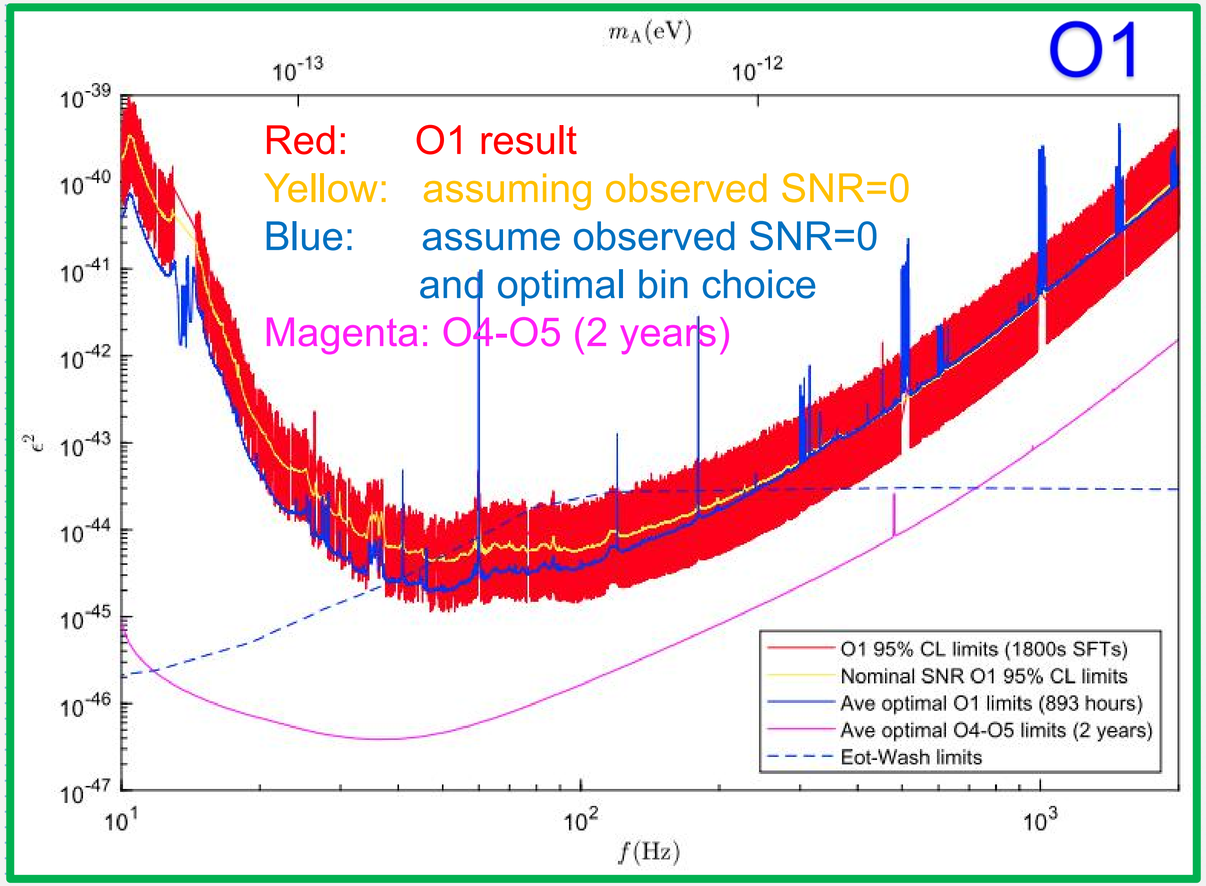
typical LIGO frequency

$$\omega_n = m_A(1 + \frac{1}{2}v_n^2) = 2\pi \times (100\mathrm{Hz}) \approx 4 \times 10^{-13}\mathrm{ev}$$

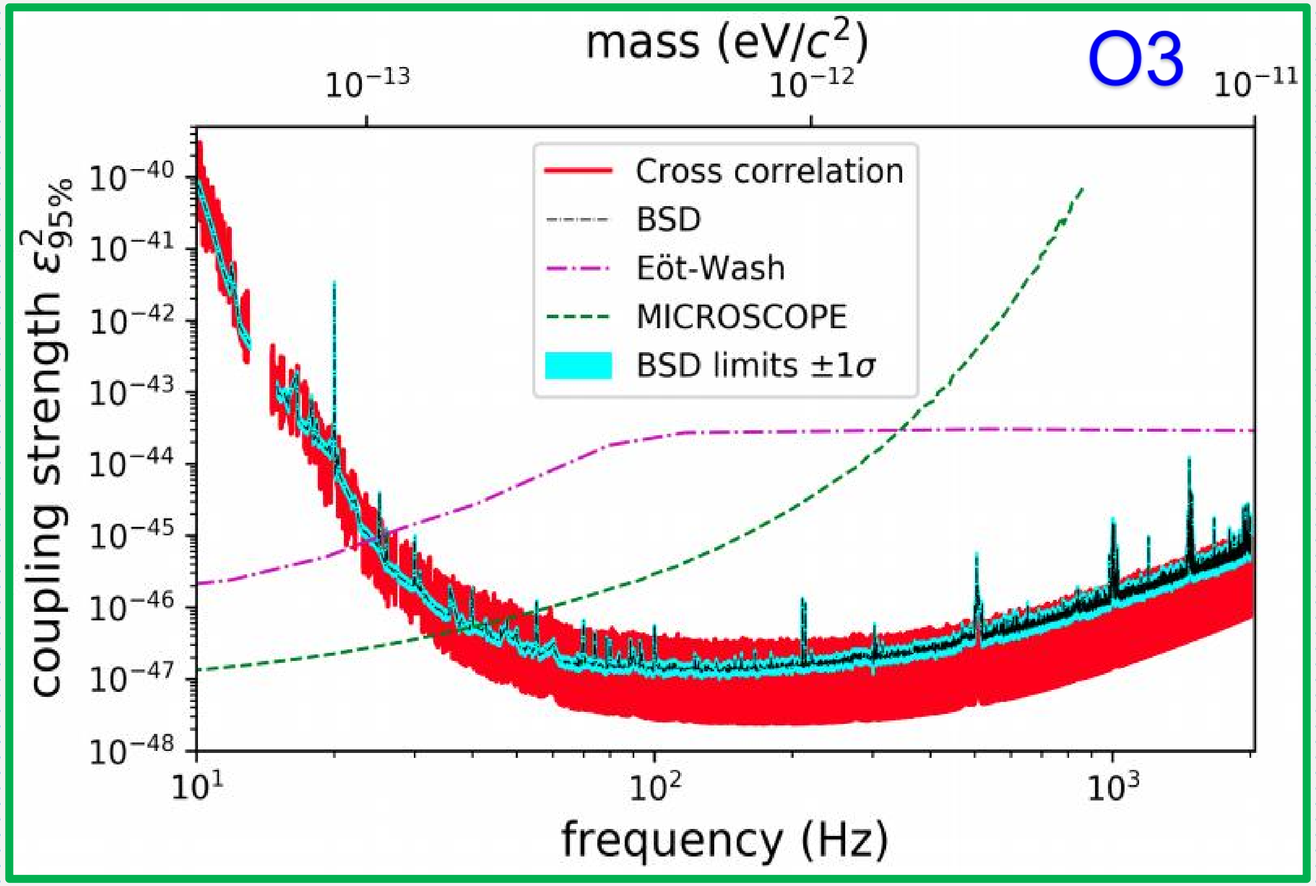
typical dark photon mass LIGO is sensitive to

$v_0 \sim \mathcal{O}(10^{-3})$ ⟹ $\Delta f / f = 10^{-6}$ ⟹ Signal: a narrow peak in frequency domain

Search Results



(Nature) Commun.Phys. 2 (2019) 155, HG, Riles, Yang, Zhao



Phys.Rev.D 105 (2022) 6, LIGO-Virgo-KAGRA Collaborations

New in O3 search:

1. Another search performed by the continuous wave group with a different method
2. An improvement factor included from finite light travel time (PRD.103.L051702, Morisaki, et al)

Summary

GWs as a new tool in particle physics studies

- Early universe symmetry breakings (phase transitions)
- Macroscopic solitons (topological and nontopological)
- Dark photon (environmental effects)

Thanks!