Some Particle Physics Studies with Gravitational Waves

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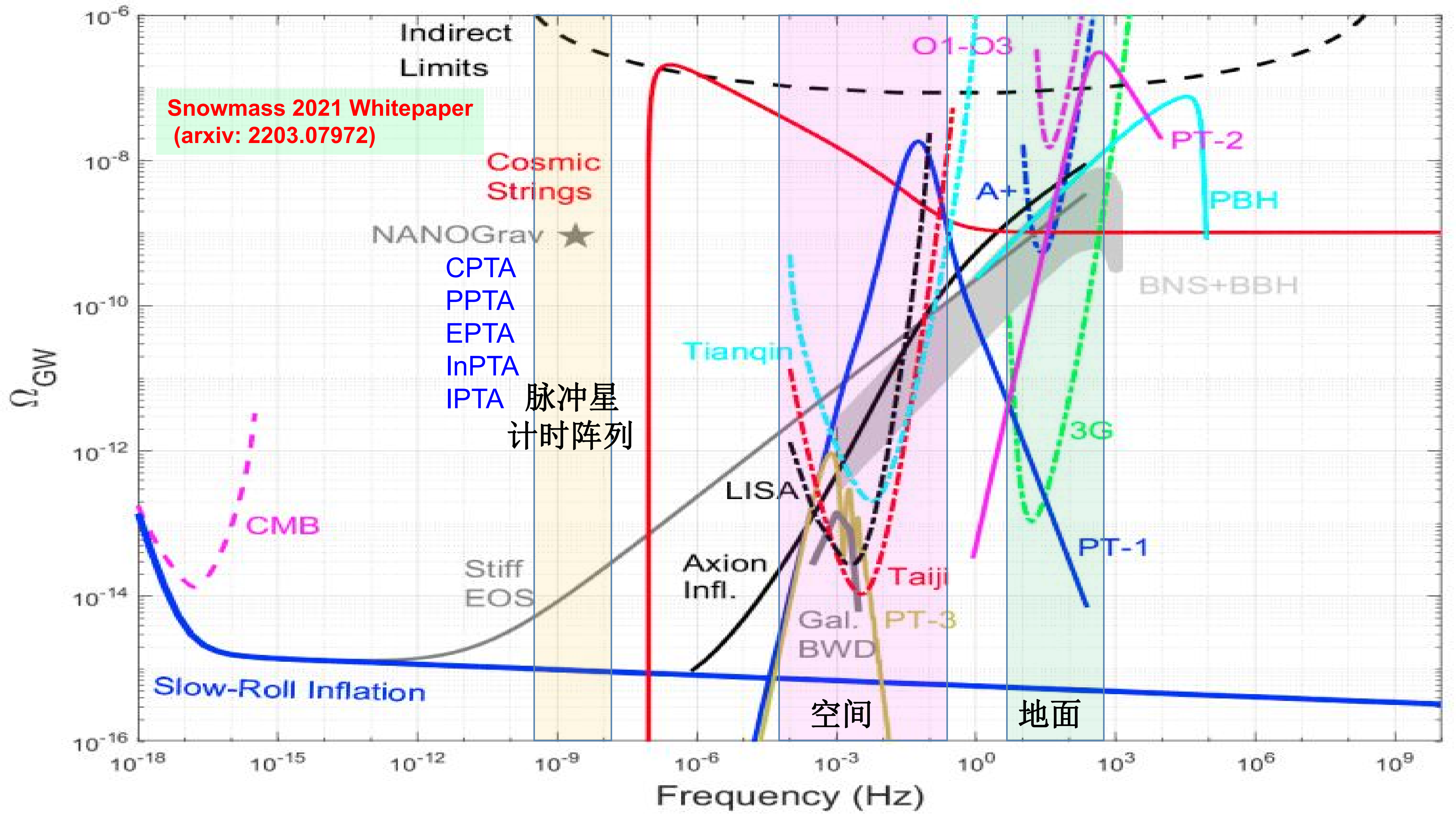
UCAS (ICTP-AP)

2023-8-8

第四届粒子物理前沿研讨会

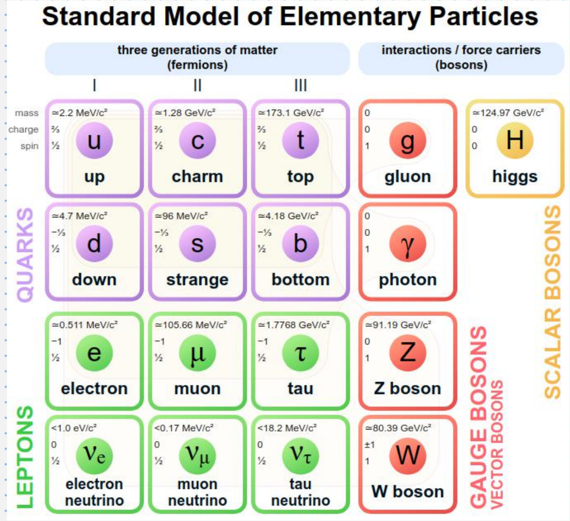


Indirect Limits
Snowmass 2021 Whitepaper
(arxiv: 2203.07972)
Cosmic Strings
NANOGrav
CPTA
PPTA
EPTA
InPTA
IPTA
脉冲星
计时阵列
O1-O3
PT-2
A+
PBH
BNS+BBH
Tianqin
3G
LISA
CMB
PT-1
Axion Infl.
Taiji
Stiff EOS
Gal. BWD
PT-3
Slow-Roll Inflation
空间
地面
Ω_{GW}
Frequency (Hz)

New Perspectives?

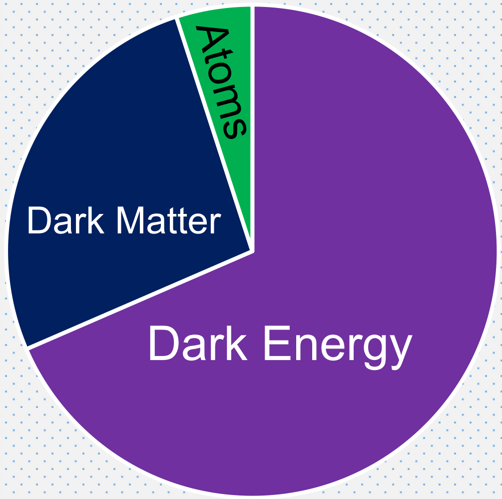
How can we reconcile the standard models of particle physics and cosmology?

Particle Physics



Physics Beyond the SM?

Cosmology

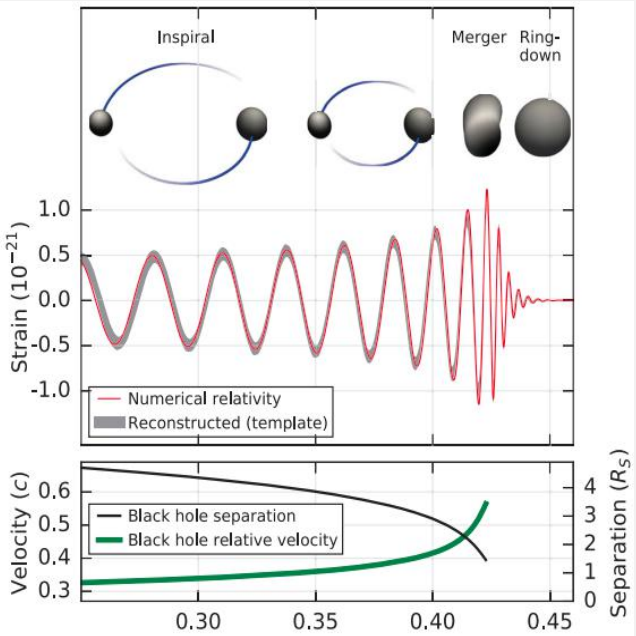


Why more matter than anti-matter? (phase transitions, solitons)

What is dark matter? (solitons, ultralight particles)

GWs from Particles?

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?

GWs from Particles

Here will focus only on a collection of my personal works:

Extreme densities

disturbances in the early universe

As Macroscopic Objects

(non-) topological solitons

Environmental Effects

Faking GW signals (dark photon)

See also 蒋赟、樊琪琪、康召丰、丁然、
谢柯盼、余钊焕、张孟超、张阳's talks

GWs from Particles

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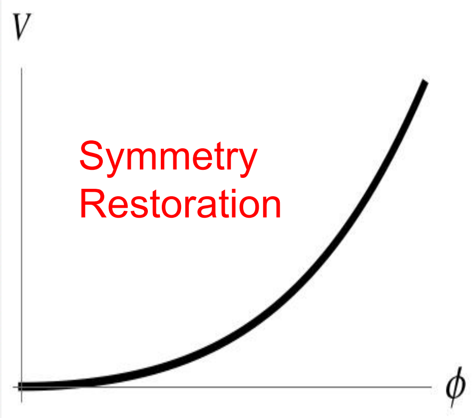
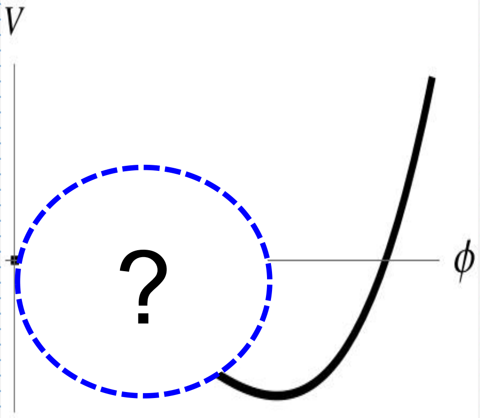
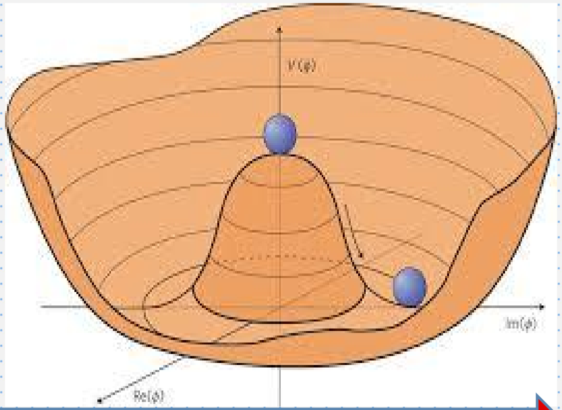
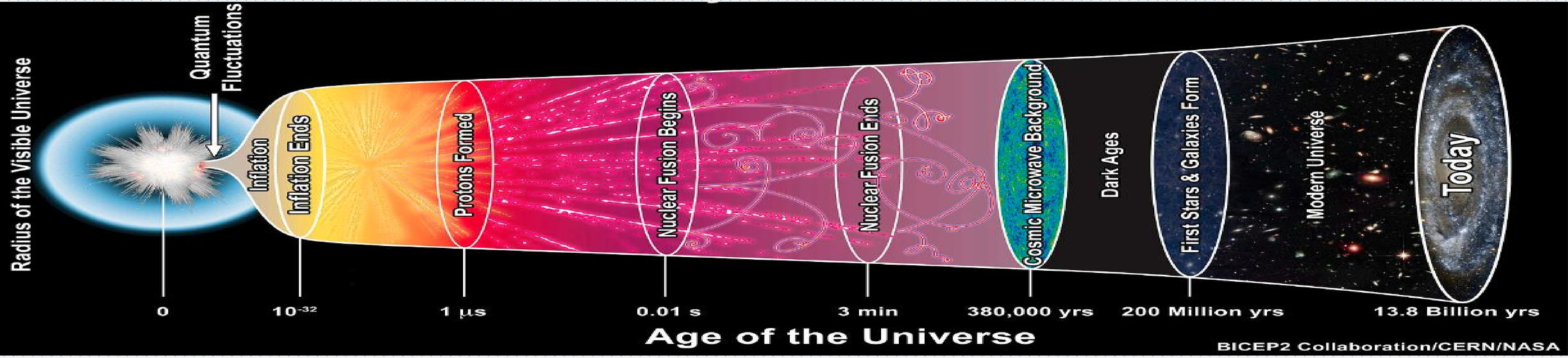
Electroweak Phase Transition



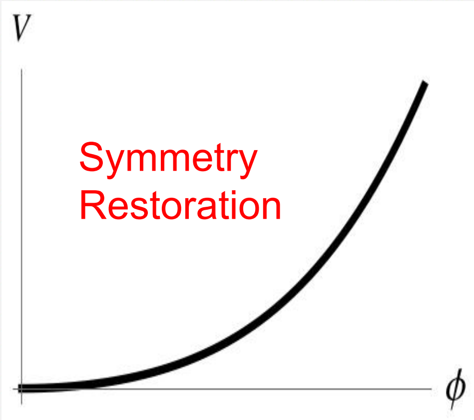


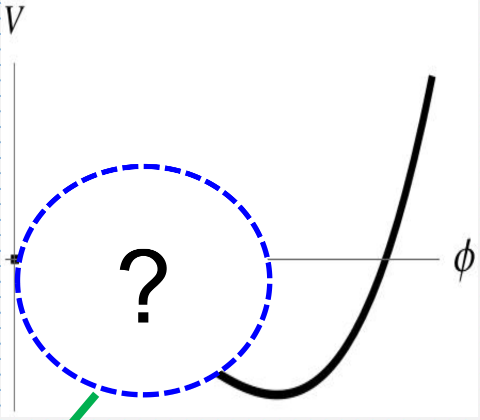


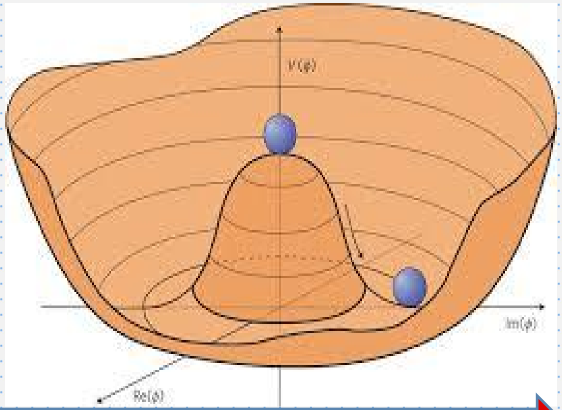
Temperature drops



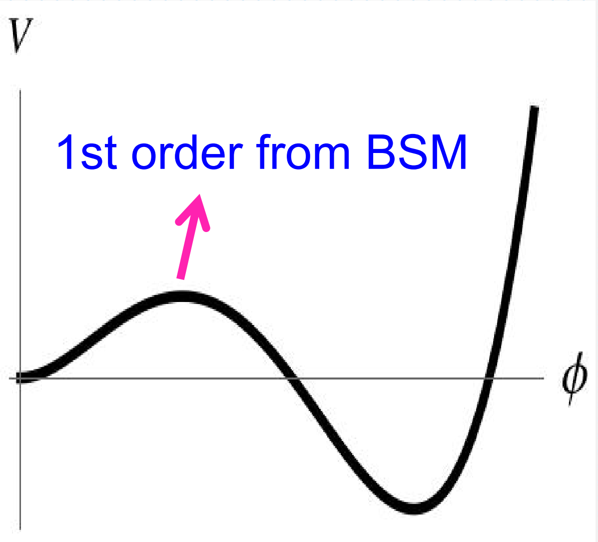
Electroweak Phase Transition



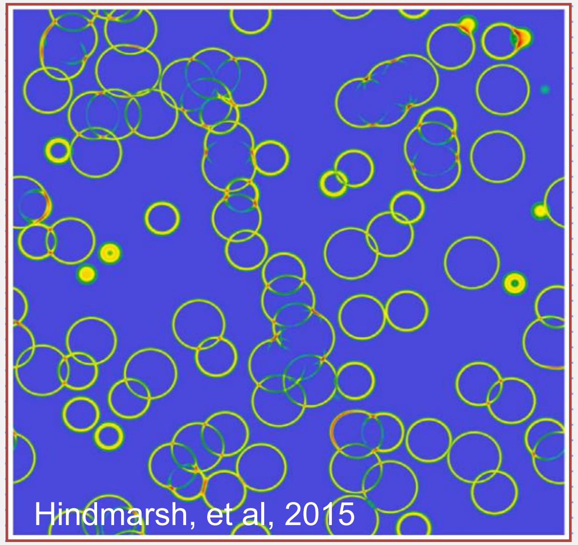




Temperature drops



bubbles, plasma, MHD



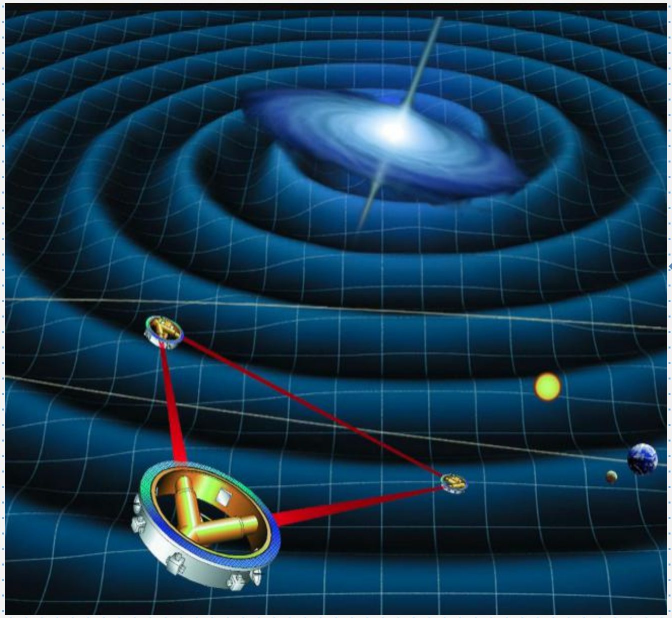
→ Electroweak Baryogenesis

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

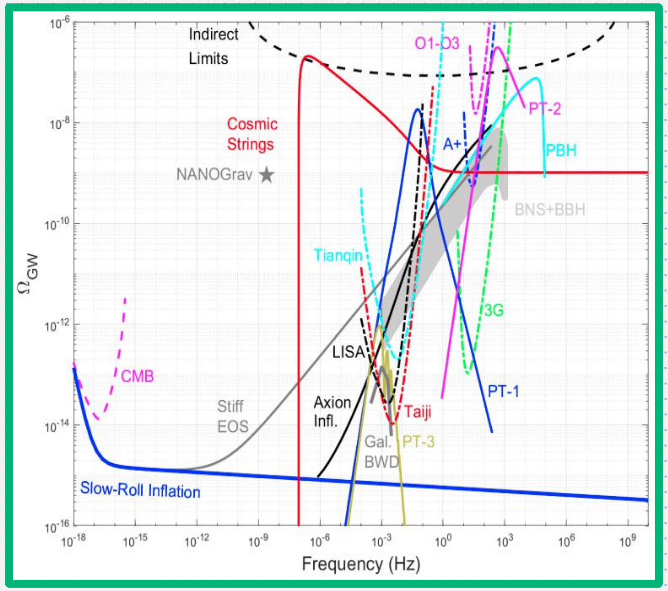
Morrissey,Ramsey-Musolf, NJP [1206.2942]

Flow of Studies

theoretical calculation of gravitational wave spectrum and detector simulation



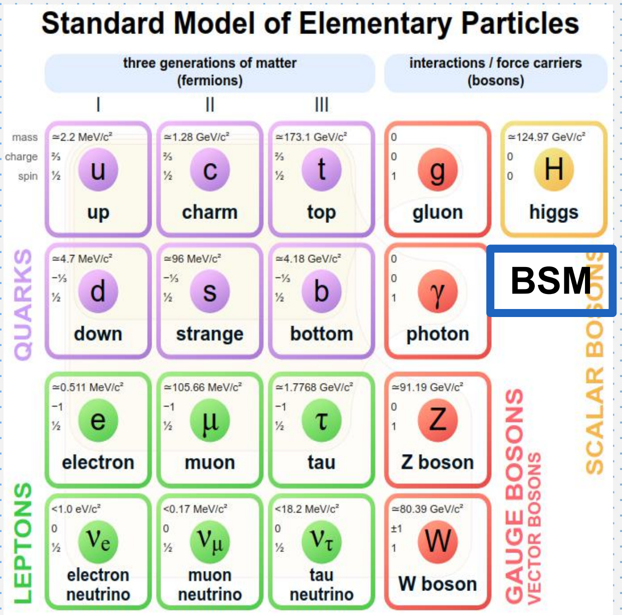
LIGO, LISA, Taiji, Tianqin...



Gravitational Wave Spectrum

α
β
v_w
T_*
g_s
...

Phase Transition Parameters

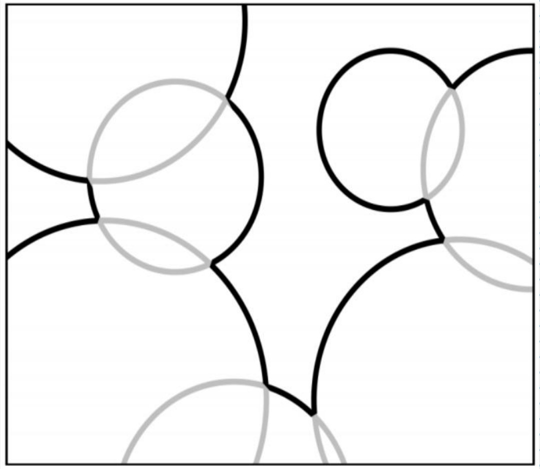


Particle Physics Model

data analysis, constraints or discovery(parameter estimation)

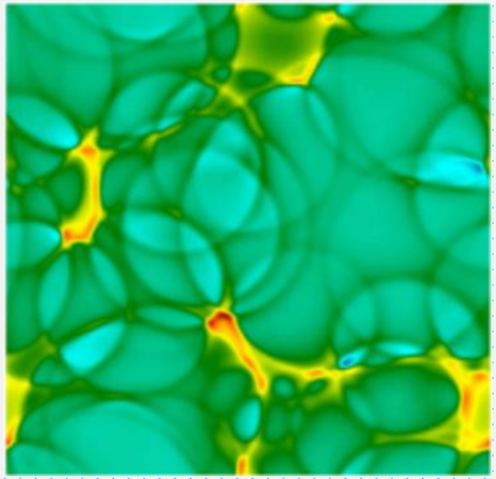
Gravitational Wave Sources

Bubble Collisions



energy concentrated at walls

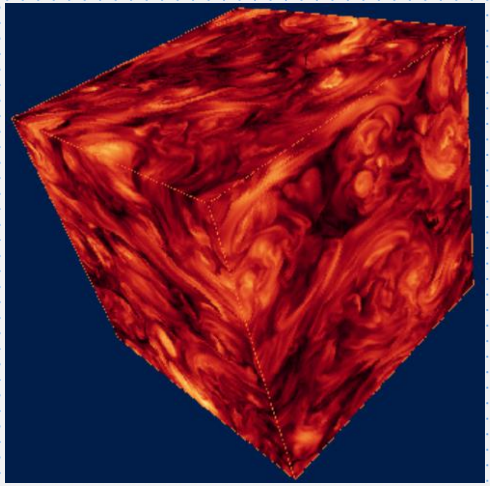
Sound Waves



Hindmarsh, et al,PRL112,041301(2013)

acoustic production

MagnetoHydrodynamic Turbulence



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

turbulent motion

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

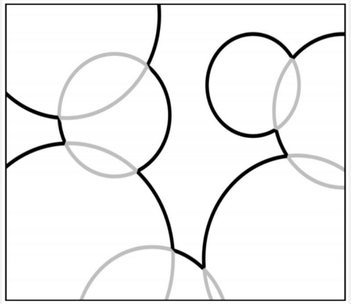
Di, Wang, Zhou, Bian, Cai, Liu, PRL 126 (2021) 25, 251102
Jing, Bian, Cai, Guo, Wang, PRL 130 (2023) 051001
Li, Huang, Wang, Zhang, PRD 105 (2022) 083527
Huang, Xie, PRD105 (2022) 11, 115033, JHEP 09 (2022) 052

The GW Observable

Energy density Spectrum

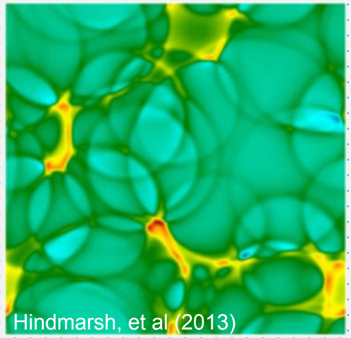
$$\Omega_{\rm GW}(f) = \frac{d\rho_{\rm GW}}{\rho_c d\log f}$$

bubble collision



$$\Omega_{\rm coll}(f)h^2 = 1.67\times10^{-5}\Delta\left(\frac{H_{\rm pt}}{\beta}\right)^2\left(\frac{\kappa_\phi\alpha}{1+\alpha}\right)^2 \times\left(\frac{100}{g_*}\right)^{1/3} S_{\rm env}(f),$$

sound waves

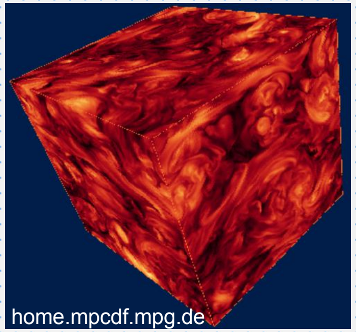


$$\Omega_{\rm sw}(f)h^2 = 2.65\times10^{-6}\left(\frac{H_{\rm pt}}{\beta}\right)\left(\frac{\kappa_{\rm sw}\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{1/3} \times v_w\left(\frac{f}{f_{\rm sw}}\right)^3\left(\frac{7}{4+3(f/f_{\rm sw})^2}\right)^{7/2}\Upsilon(\tau_{\rm sw}),$$

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

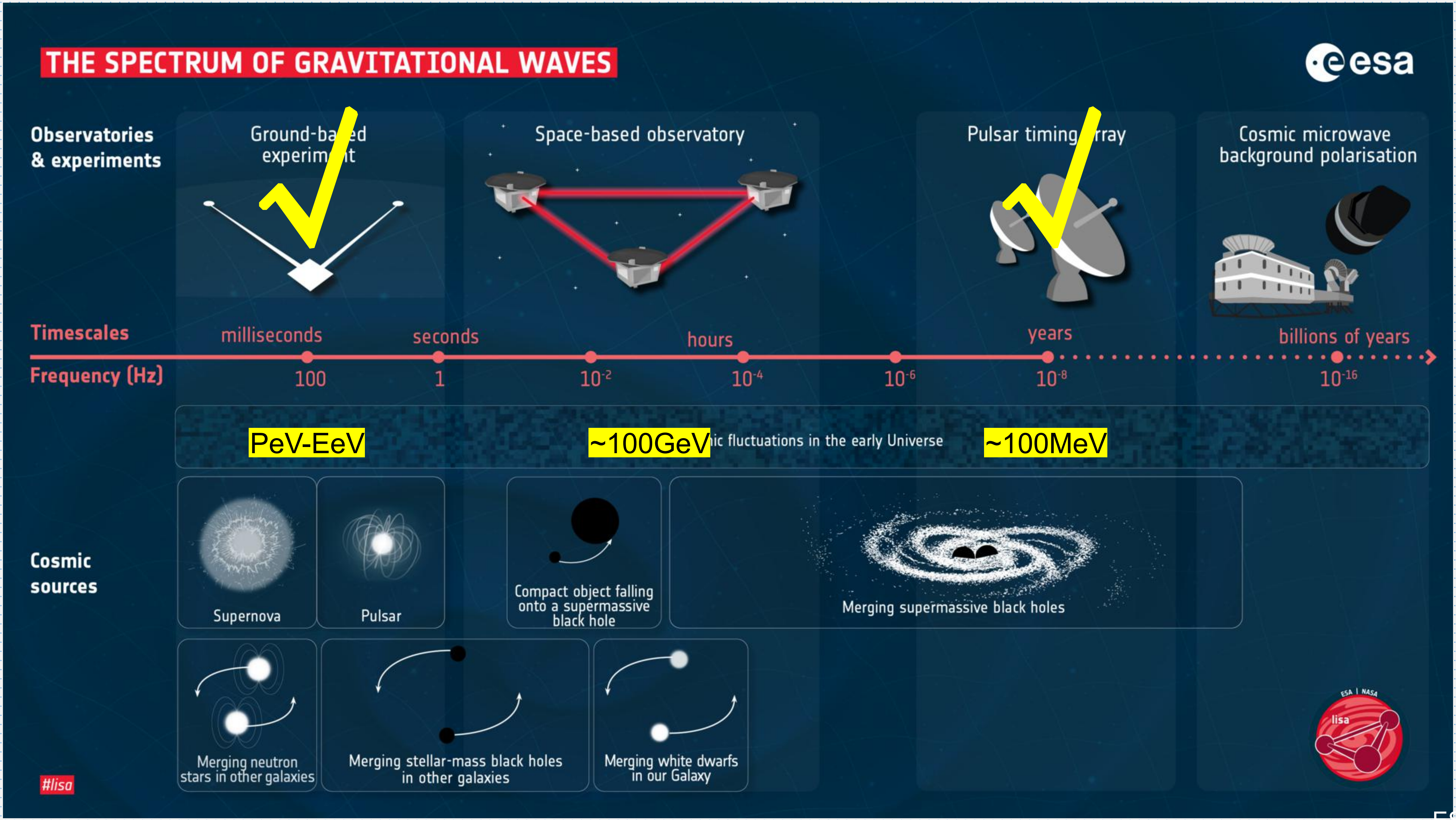
HG, Sinha, Vagie, White, JCAP 01 (2021) 001

MHD



$$h^2\Omega_{\rm turb}(f) = 3.35\times10^{-4}\left(\frac{H_*}{\beta}\right)\left(\frac{\kappa_{\rm turb}\,\alpha}{1+\alpha}\right)^{\frac{3}{2}}\left(\frac{100}{g_*}\right)^{1/3} v_w\, S_{\rm turb}(f)$$

Chiara Caprini et al JCAP04(2016)001


THE SPECTRUM OF GRAVITATIONAL WAVES
esa
Observatories & experiments
Ground-ba ed experim nt
Space-based observatory
Pulsar timing rray
Cosmic microwave background polarisation
Timescales
milliseconds
seconds
hours
years
billions of years
Frequency (Hz)
100
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-16}
PeV-EeV
~100GeV
ic fluctuations in the early Universe
~100MeV
Cosmic sources
Supernova
Pulsar
Compact object falling onto a supermassive black hole
Merging supermassive black holes
Merging neutron stars in other galaxies
Merging stellar-mass black holes in other galaxies
Merging white dwarfs in our Galaxy
ESA | NASA
lisa
#lisa

ESA

high-scale PT

LIGO 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)

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

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

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

Bubble Collision

95% CL UL with fixed Tpt and beta/Hpt

Phenomenological model (bubble collisions)

$\Omega^{95\%}_{\rm coll}(25\ {\rm Hz})$

$\beta/H_{\rm pt} \backslash T_{\rm pt}$	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

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

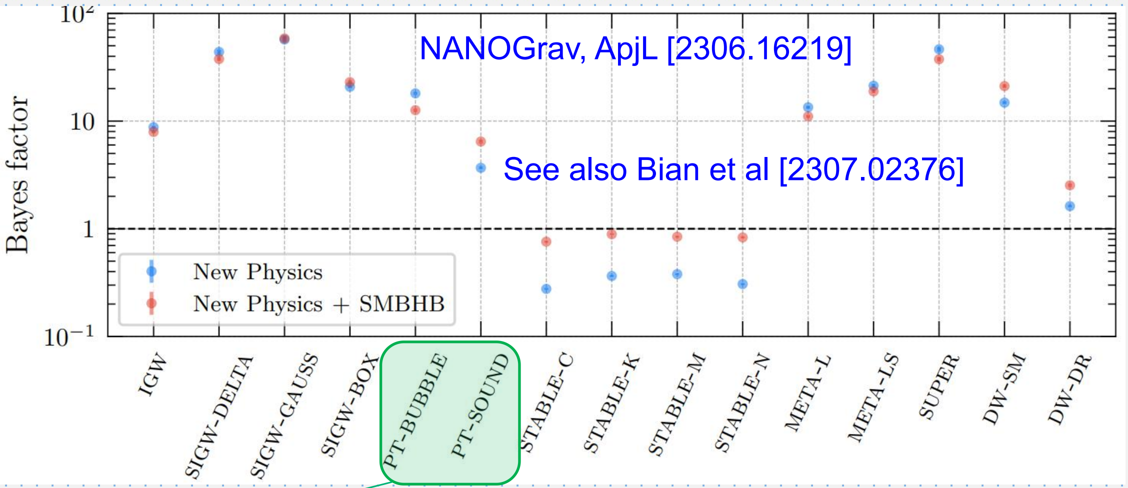
$\beta/H_{\rm pt} < 1$ and $T_{\rm pt} > 10^8$ GeV

First result from gravitational wave data!

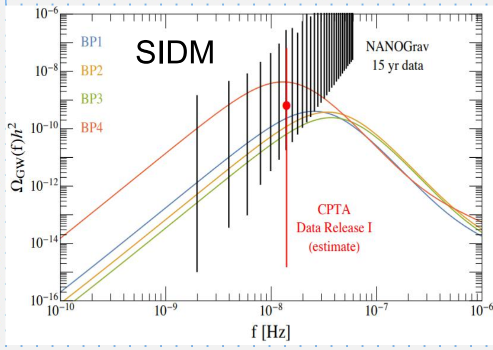
Romero,Martinovic,Callister,HG,Martínez,Sakellariadou,Yang,Zhao, PRL [2102.01714]

What possible PTA discovery implies?

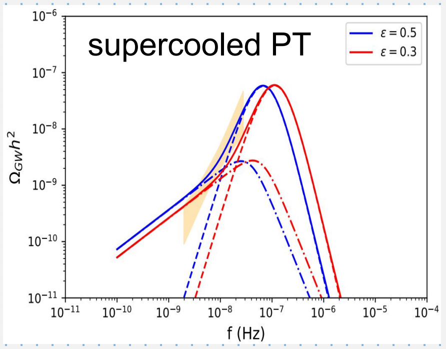
- Once discovered, firstly needs to know its origin
- Can be the next “CMB” (spectral shape, anisotropy, etc)
- Can be from first order QCD-scale PT



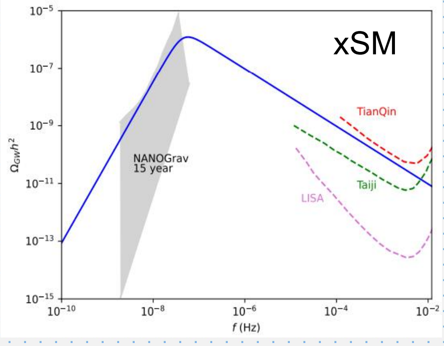
PPTA: Xue et al, PRL [2110.03096]
NANOGrav (12.5-year): Arzoumanian et al, PRL [2104.13930]
...



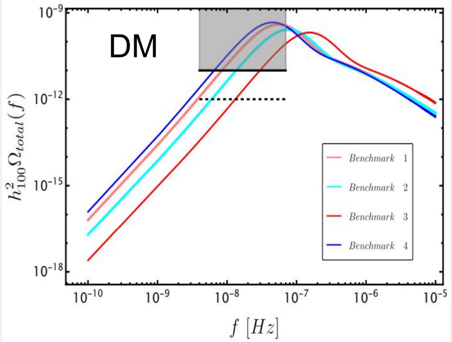
Han,Xie,Yang,Zhang [2306.16966]



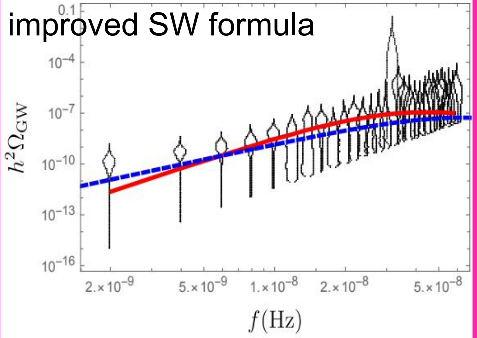
Zu,Zhang,Li,Gu,Tsai,Fan [2306.17239]



Xiao,Yang,Zhang [2307.01072]



Yang,Ma,Jiang,Huang [2306.17827]



Ghosh et al [2307.02259]

and more...

See also 丁然、谢柯盼、余钊焕、张孟超’s talks

GWs from Particles

Extreme densities

disturbances in the early universe

As Macroscopic Objects

(non-) topological solitons ✓

Environmental Effects

Faking GW signals (dark photon)

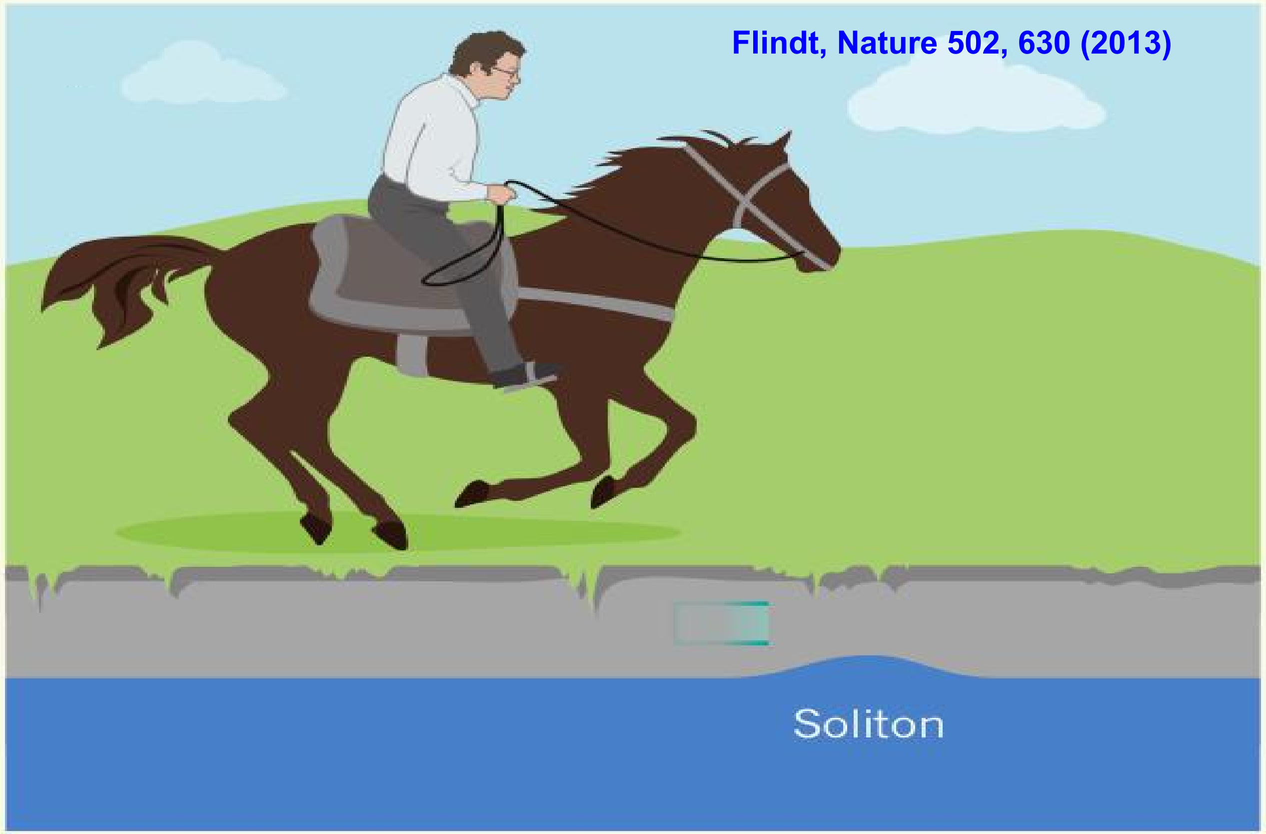
Solitons

- 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

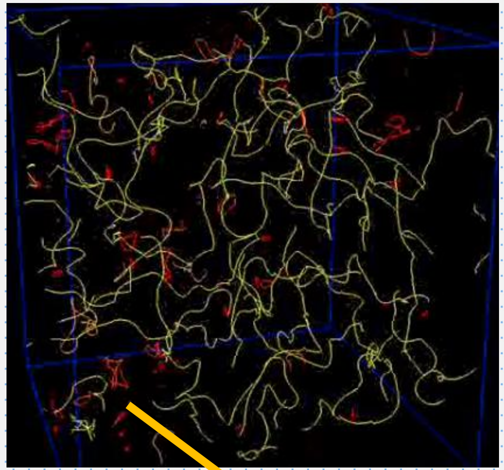
T W B Kibble J.Phys.A 9 (1976) 1387-1398

Blackett Laboratory, Imperial College, Prince Consort Road, Lon

Received 11 March 1976

www.theguardian.com

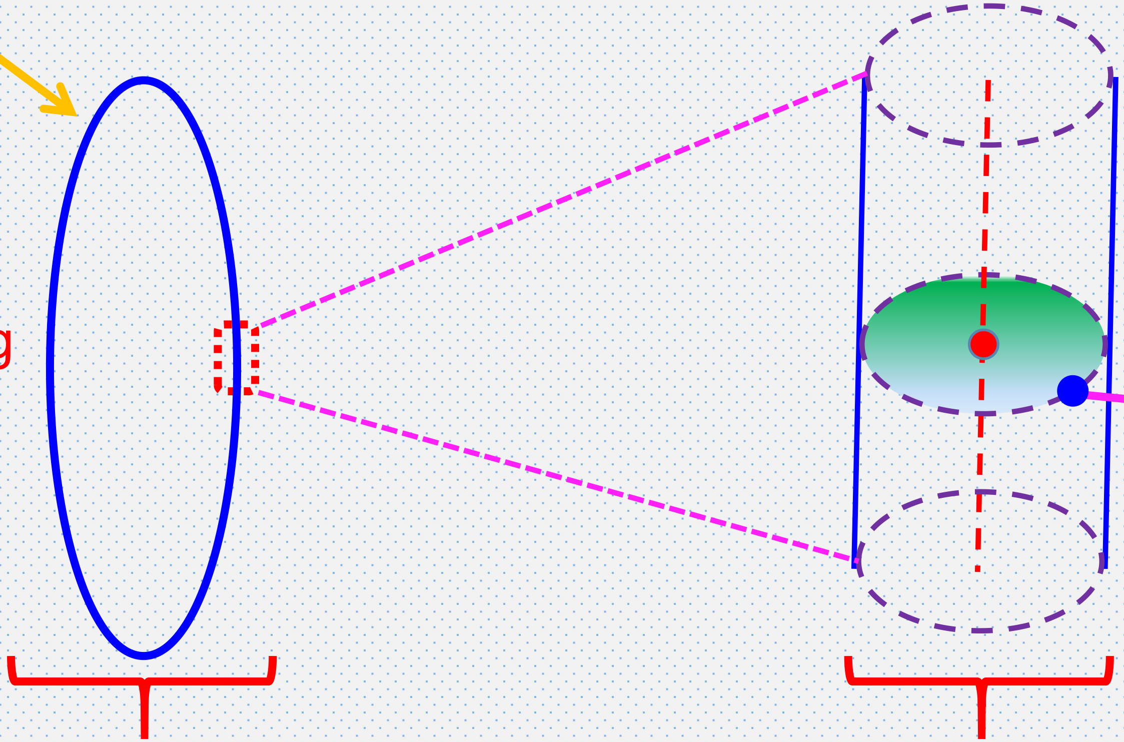
Cosmic String

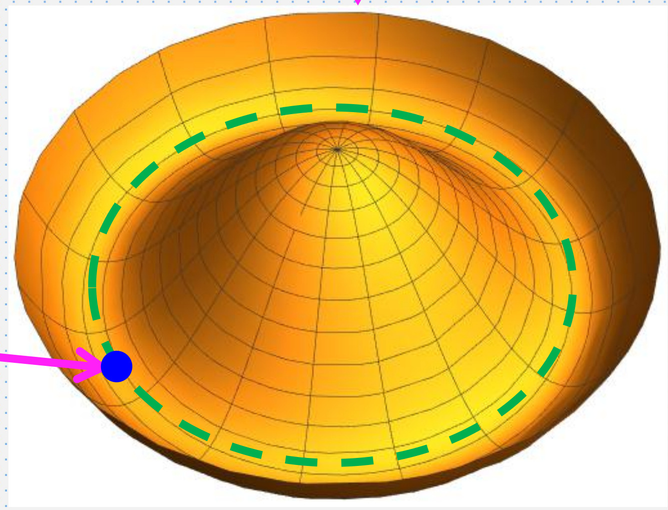


Example: the Abelian Higgs Model

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

closed string (loop)





cosmological scale $\gg$ $O(1/\eta)$

degenerate vacua
with nontrivial topology

LIGO Search Result of Cosmic Strings

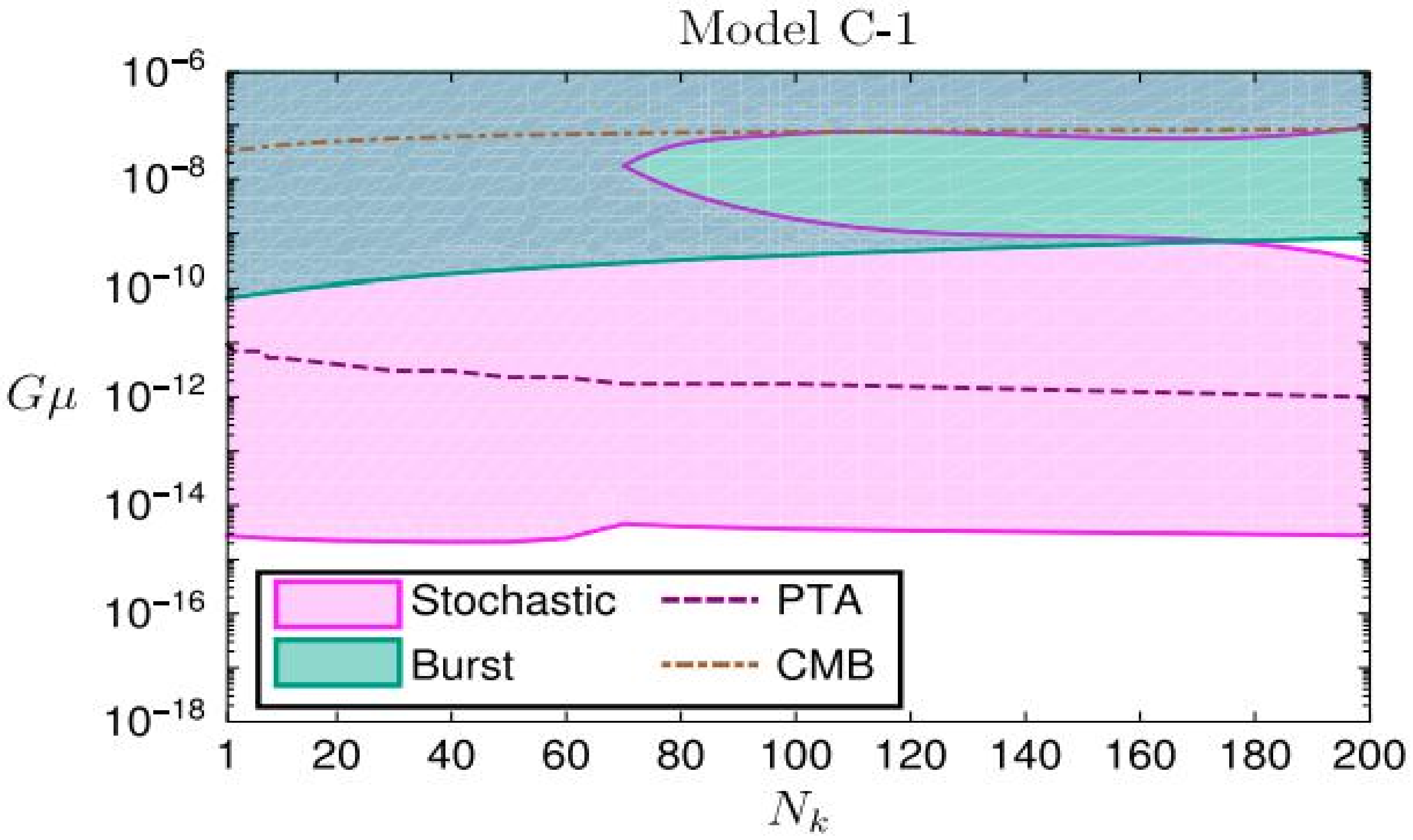
Symmetry breakings at scales higher than $O(10^{11})$ GeV with Cosmic String production are excluded

Caveat (loop distribution model)

GW measurement tells scale (η) of symmetry breaking

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

μ: line mass density



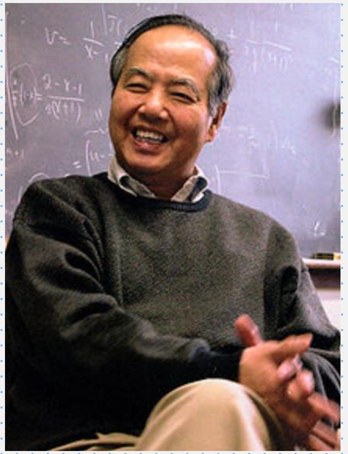
Results from PTA Measurements

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

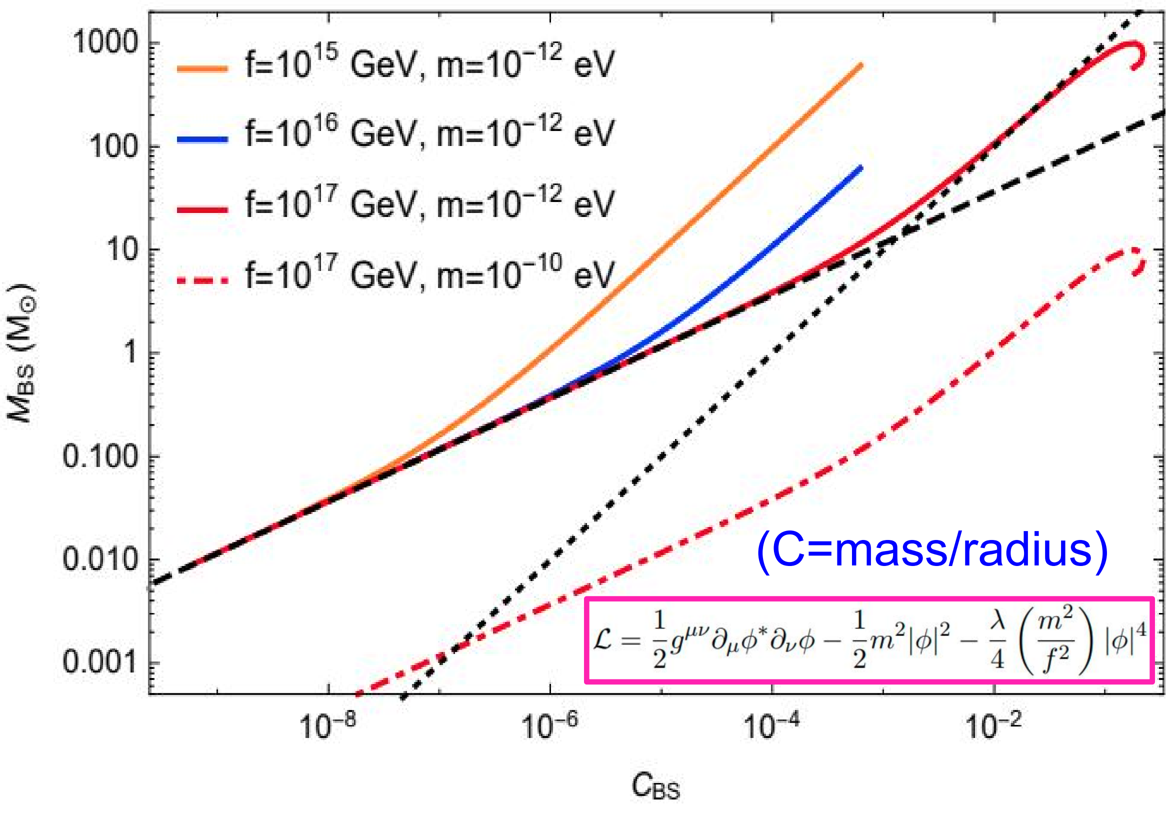
Blasi, Brdar, Schmitz, PRL126, 041305 (2021)

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

Non-Topological Solitons as Boson Stars



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



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)

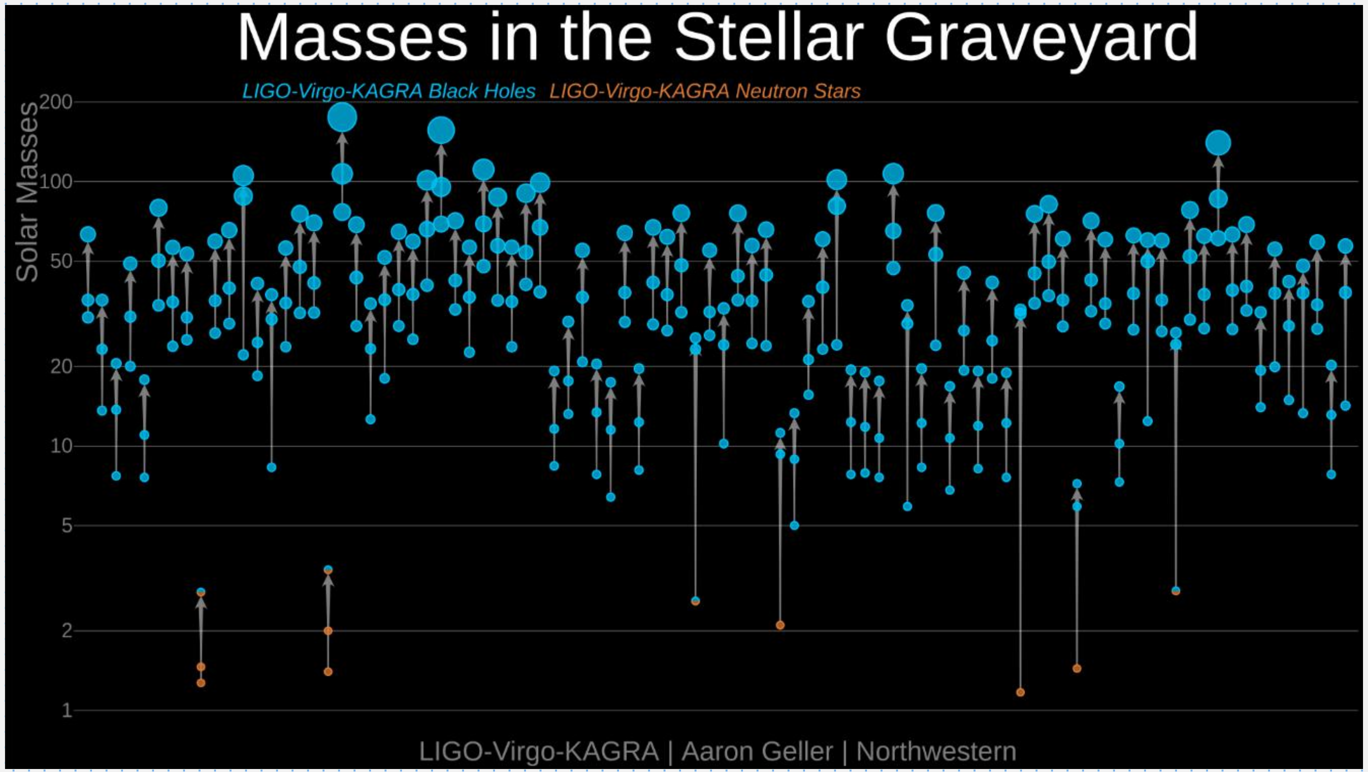
See, e.g., Liebling, Palenzuela, Living Rev Relativ (2017) 20:5

Lee,Pang, Phys.Rept (1992)

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

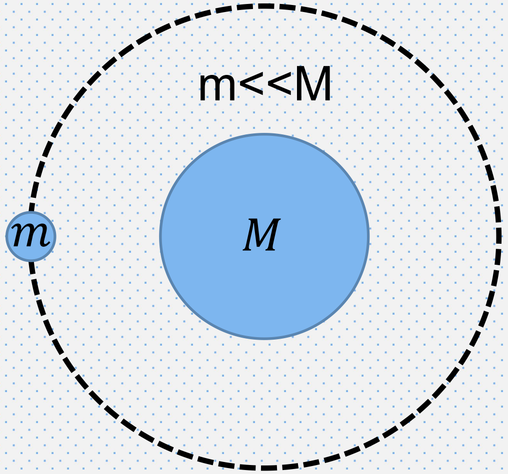
Did LIGO Detect Dark Matter?

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

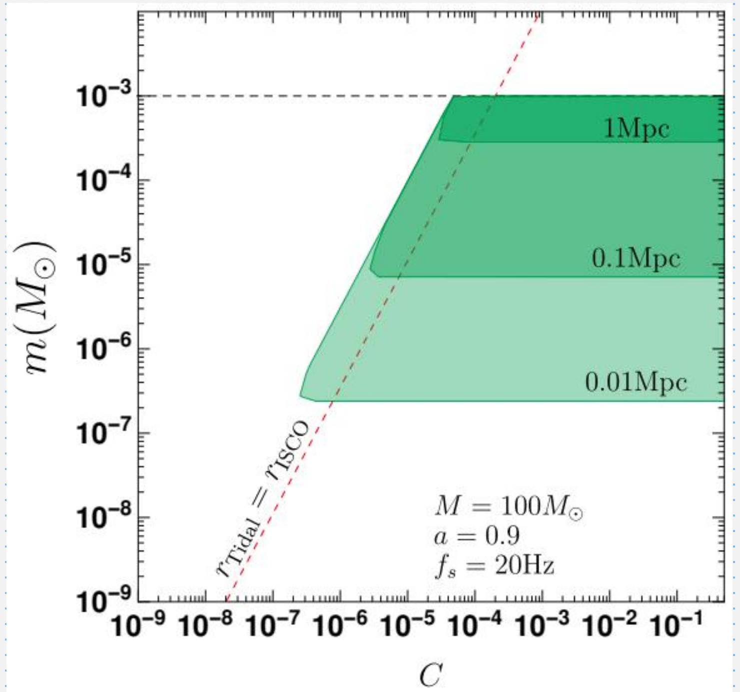
Juan Calderón Bustillo, Nicolas Sanchis-Gual, Alejandro Torres-Forné, José A. Font, Avi Vajpeyi, Rory Smith, Carlos Herdeiro, Eugen Radu, and Samson H. W. Leong
Phys. Rev. Lett. **126**, 081101 – Published 24 February 2021

Detection with EMRI and mini-EMRI



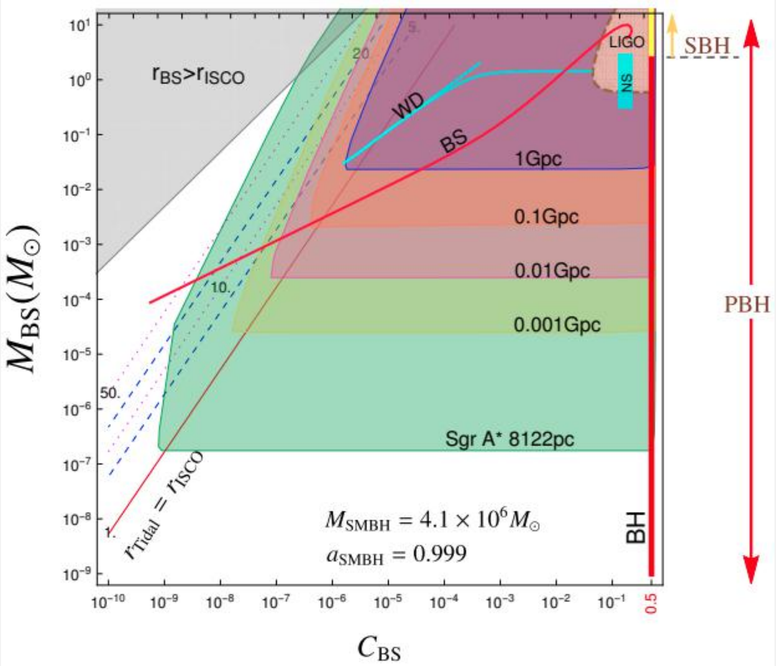
- By making one object much heavier, one can probe much ligher companion object
- Ideal systems: extreme mass ratio inspirals (EMRIs), key target of Taiji, Tianqin, LISA.
- LIGO can detect mini-EMRIs (extreme mass ratio, but lighter objects)

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

GWs from Particles

Extreme densities

disturbances in the early universe

As Macroscopic Objects

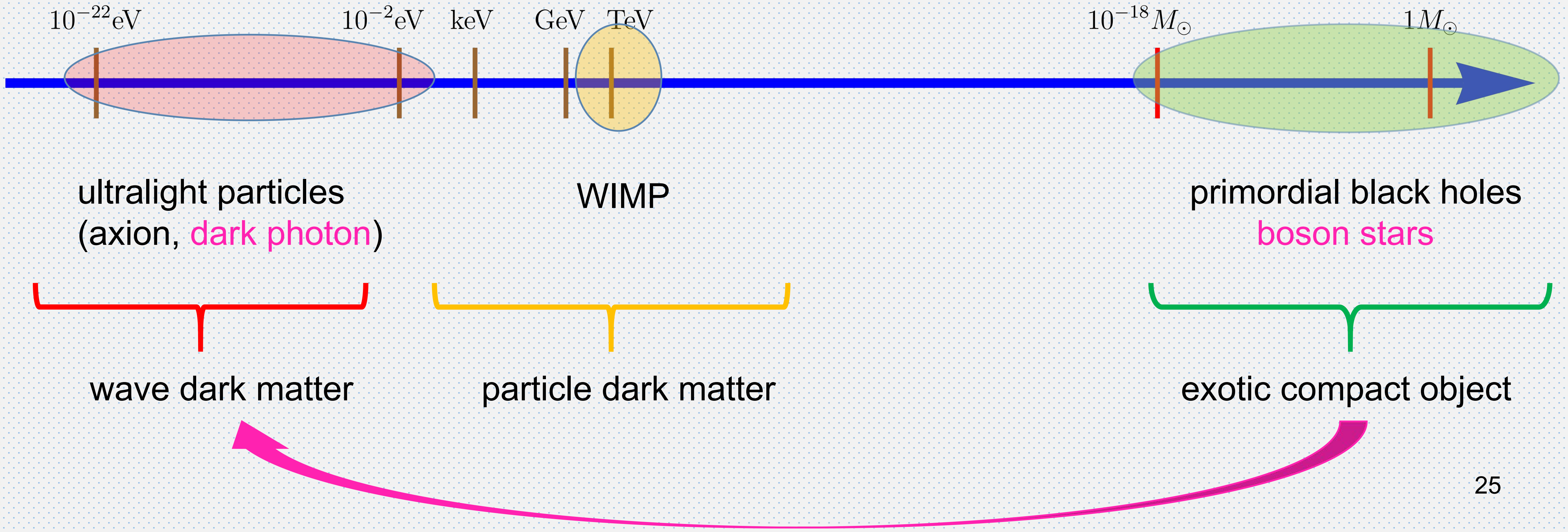
(non-) topological solitons

Environmental Effects ✓

Faking GW signals (dark photon)

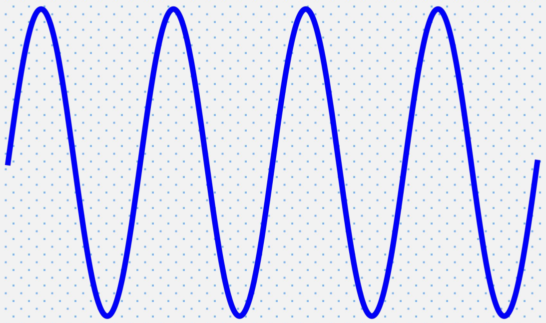
Ultralight Dark Matter

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

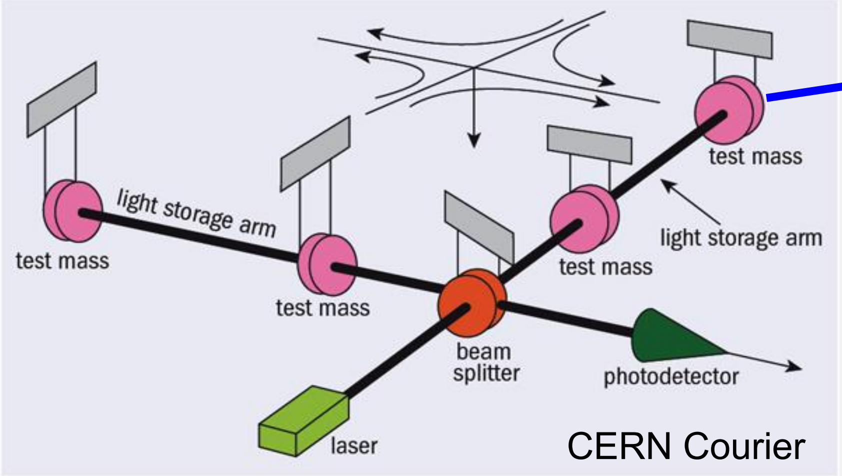


Dark Photon Detection at LIGO

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

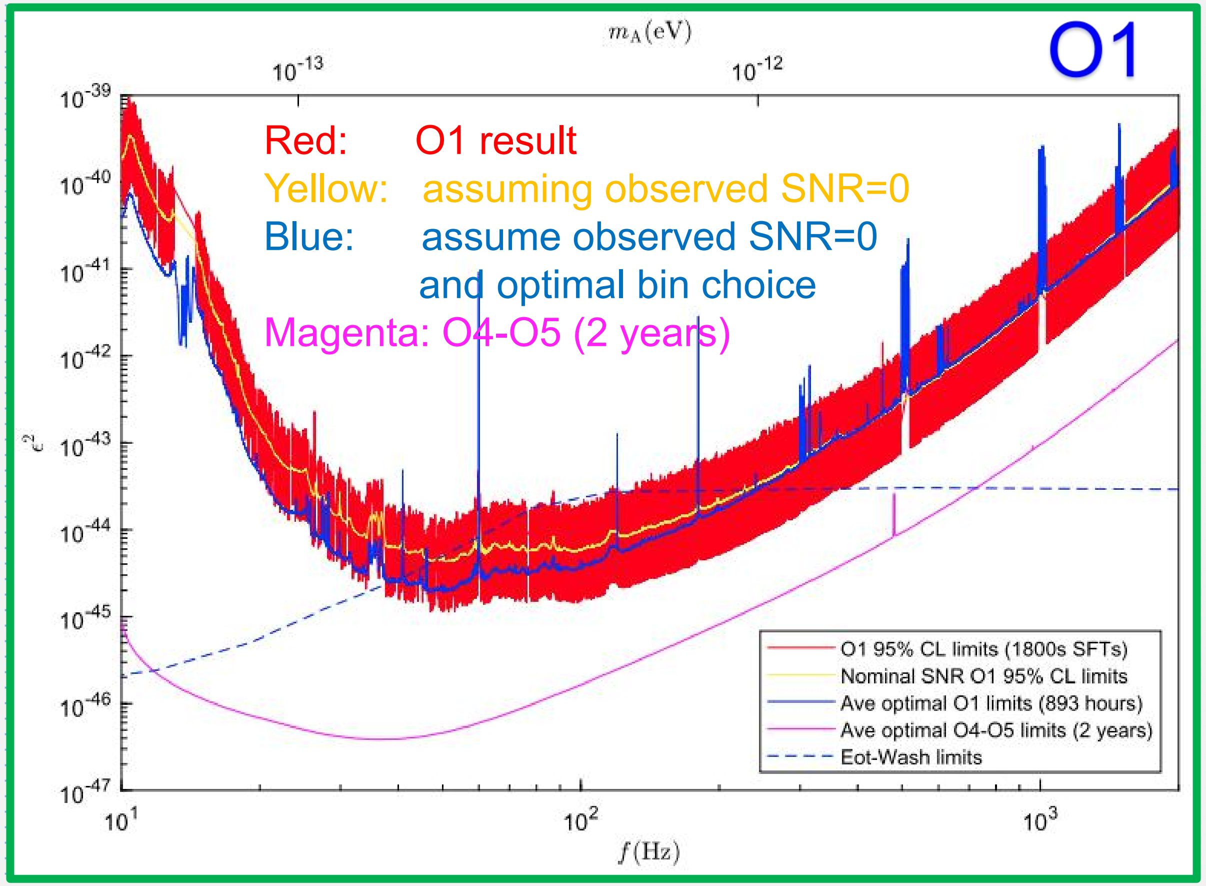
typical LIGO frequency

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

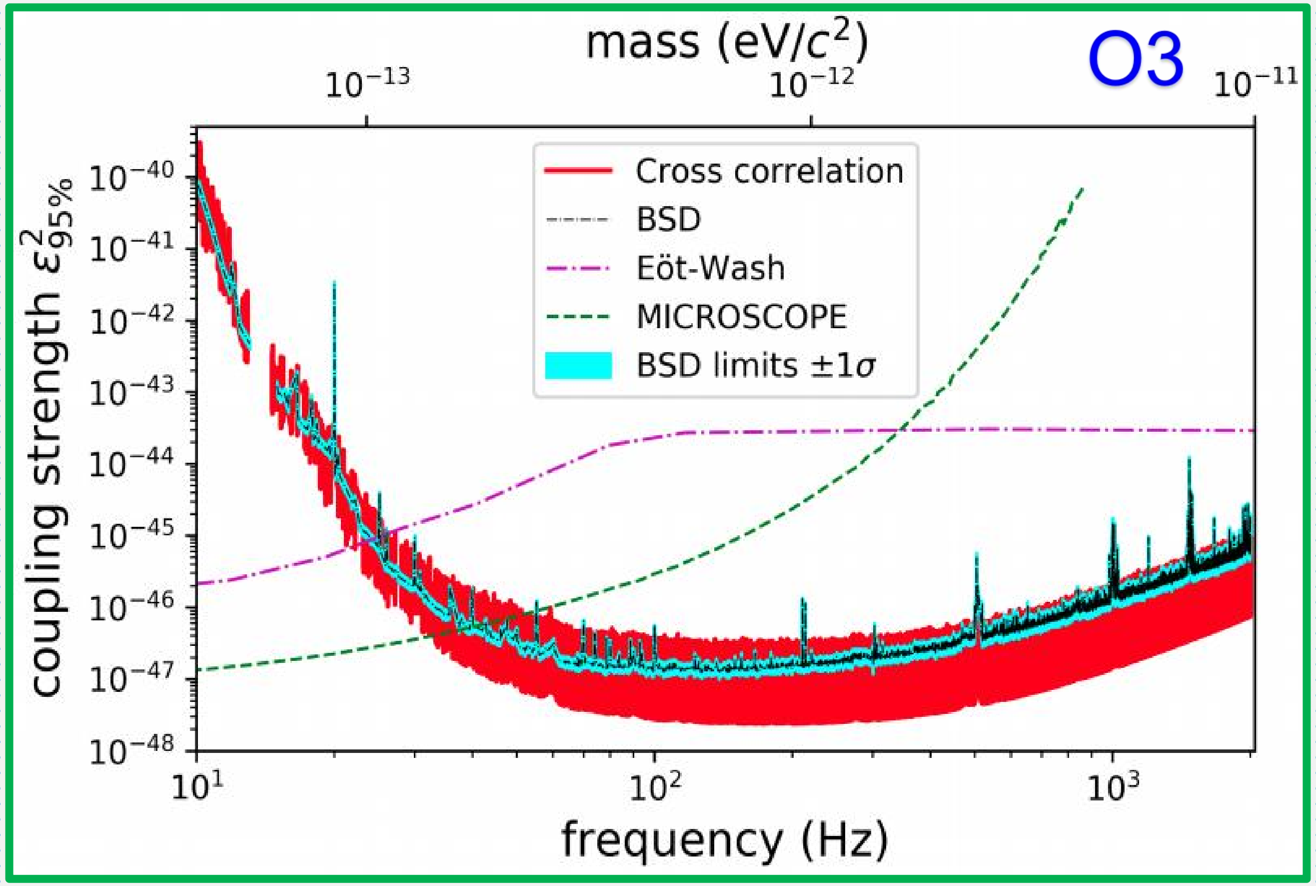
typical dark photon mass LIGO is sensitive to

$v_0 \sim \mathcal{O}(10^{-3})$ ⇨ $\Delta f / f = 10^{-6}$ ⇨ 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

See also Yuan,Jiang,Huang, PRD [2204.03482], Yu,Yao,Tang,Wu [2307.09197]

Summary

GWs as a new important tool in particle physics studies

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

Thanks!