粒子物理基于引力波探测的一些研究

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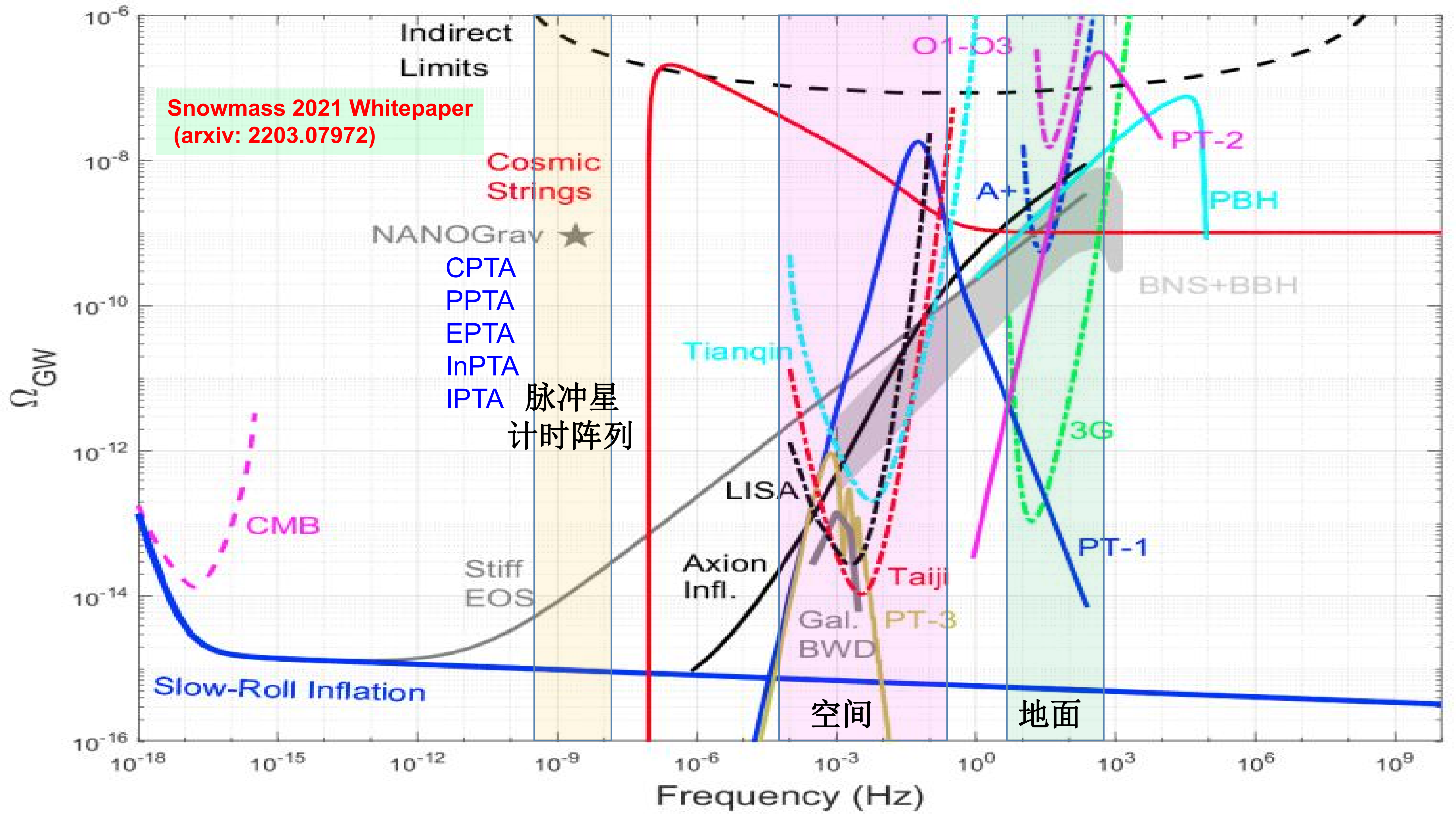
2023-7-28

第十二届“新物理研讨会”

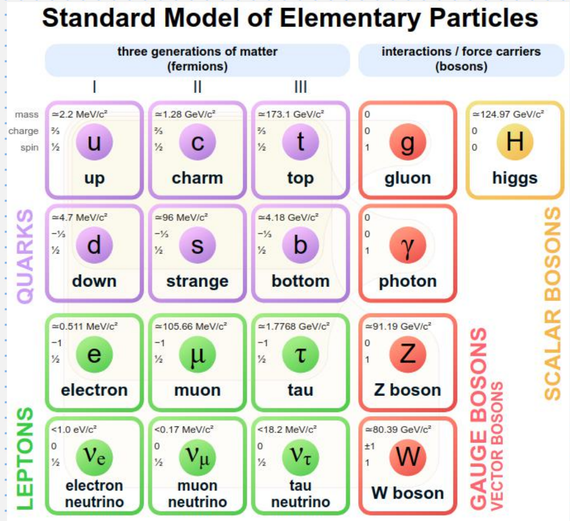


Indirect Limits
Snowmass 2021 Whitepaper
(arxiv: 2203.07972)
Cosmic Strings
NANOGrav
CPTA
PPTA
EPTA
InPTA
IPTA
脉冲星
计时阵列
O1-O3
PT-2
A+
PBH
BNS+BBH
Tianqin
3G
LISA
PT-1
CMB
Axion Infl.
Taiji
Stiff EOS
Gal. BWD
PT-3
Slow-Roll Inflation
空间
地面
Ω_{GW}
Frequency (Hz)

New Perspectives?

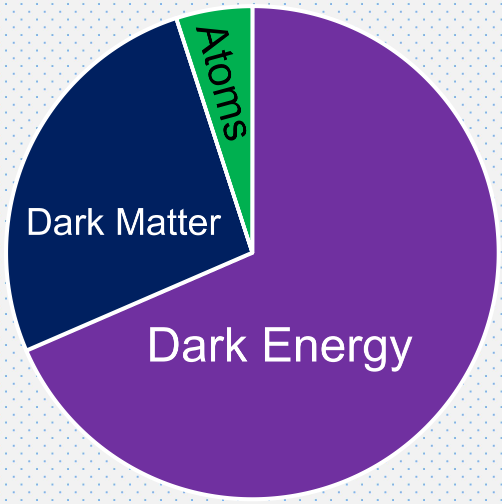
How can we reconcile the standard models of particle physics and cosmology?

Particle Physics



Physics Beyond the SM?

Cosmology



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, solitons)

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

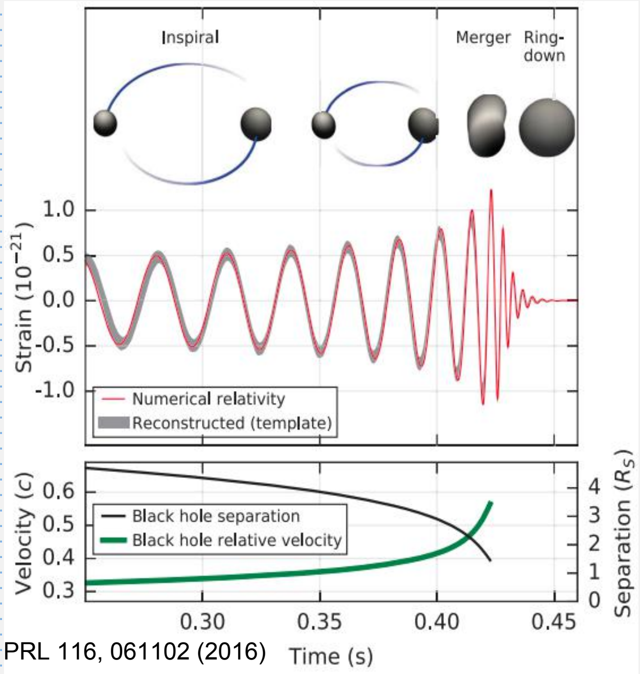
Robert Caldwell, Yanou Cui, Huai-Ke Guo, Vuk Mandic, Alberto Mariotti, Jose Miguel No, Michael J. Ramsey-Musolf, Mairi Sakellariadou, Kuver Sinha, Lian-Tao Wang, Graham White, Yue Zhao, Haipeng An, Ligong Bian, Chiara Caprini, Sebastien Clesse, James M. Cline, Giulia Cusin, Bartosz Fornal, Ryusuke Jinno, 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

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

Extreme densities

disturbances in the early universe

As Macroscopic Objects

(non-) topological solitons

Environmental Effects

Faking GW signals (dark photon)

(Only a collection of my personal works)

GWs from Particles

Extreme densities ✓

disturbances in the early universe

As Macroscopic Objects

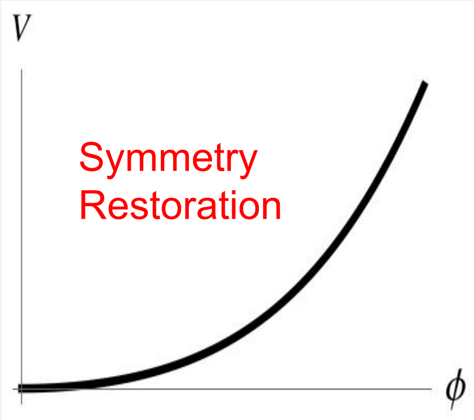
(non-) topological solitons

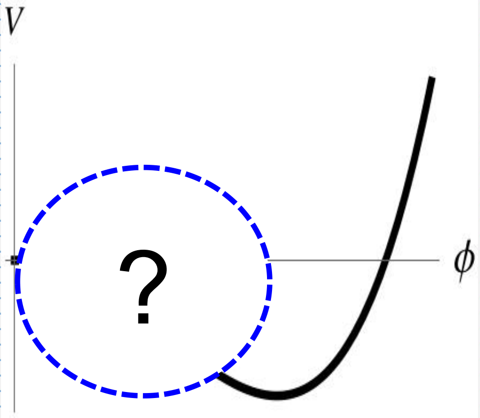
Environmental Effects

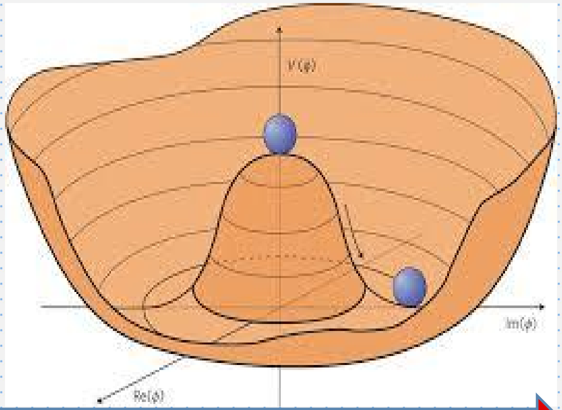
Faking GW signals (dark photon)

(Only a collection of my personal works)

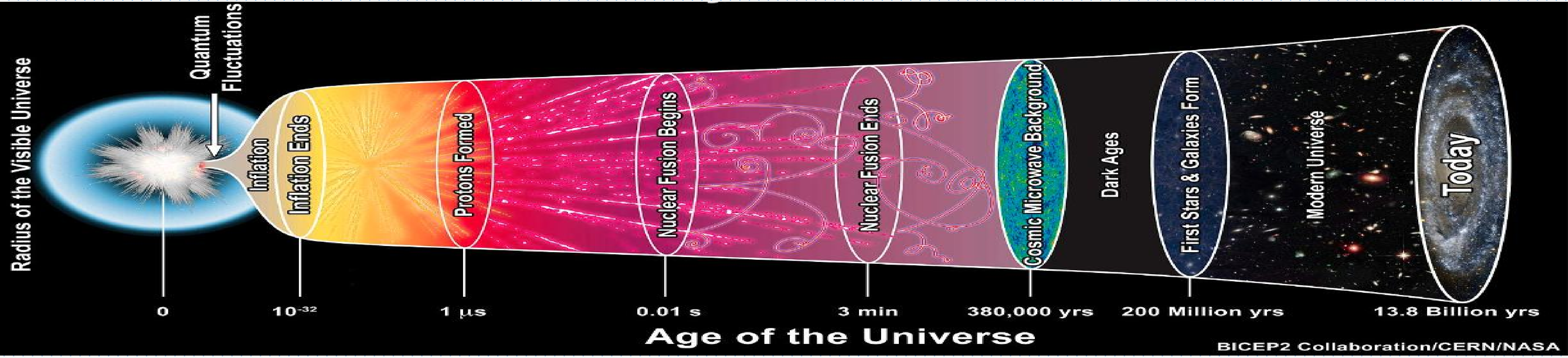
Electroweak Phase Transition



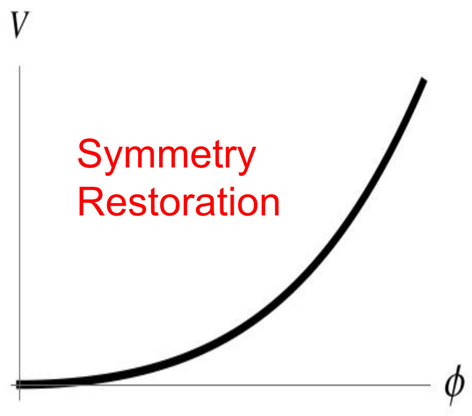


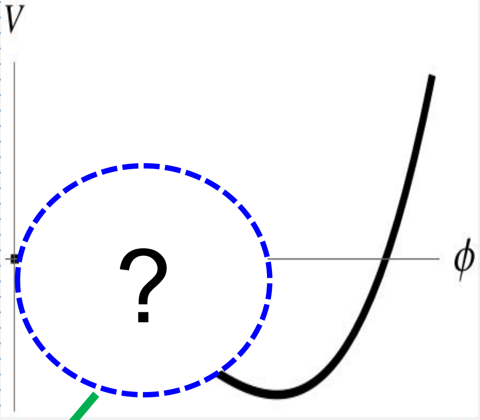


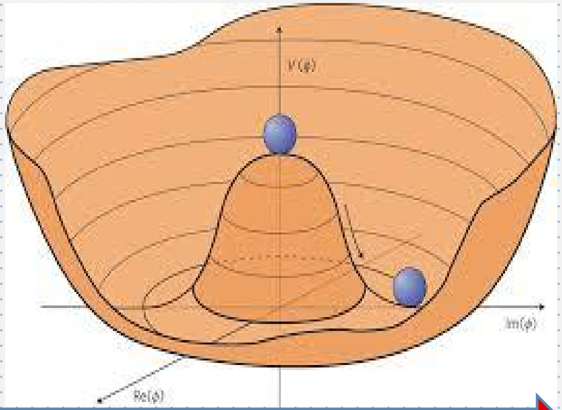
Temperature drops



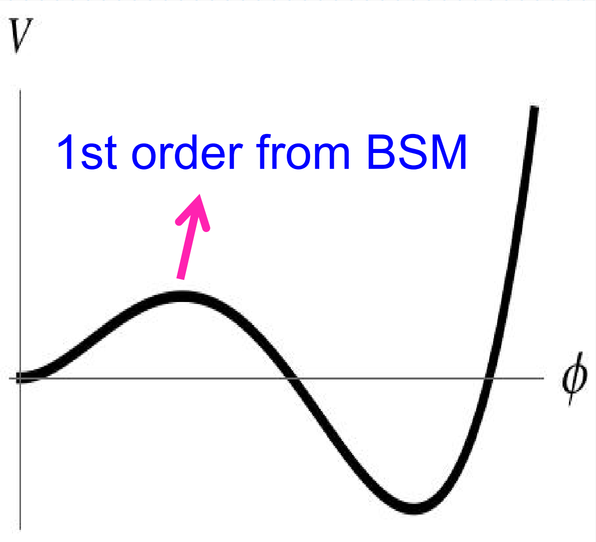
Electroweak Phase Transition



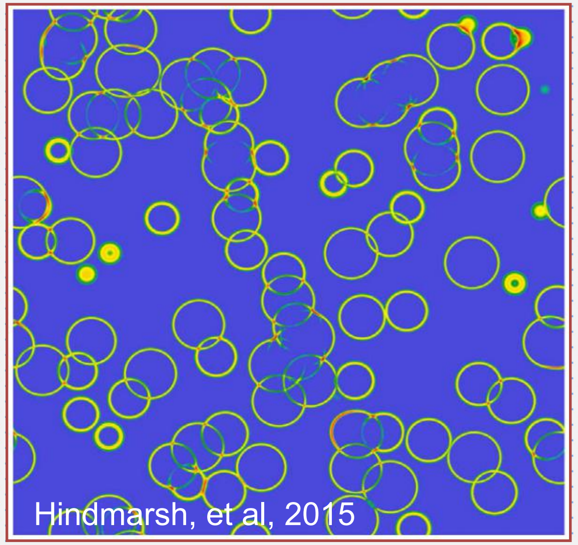




Temperature drops



bubbles, plasma, MHD



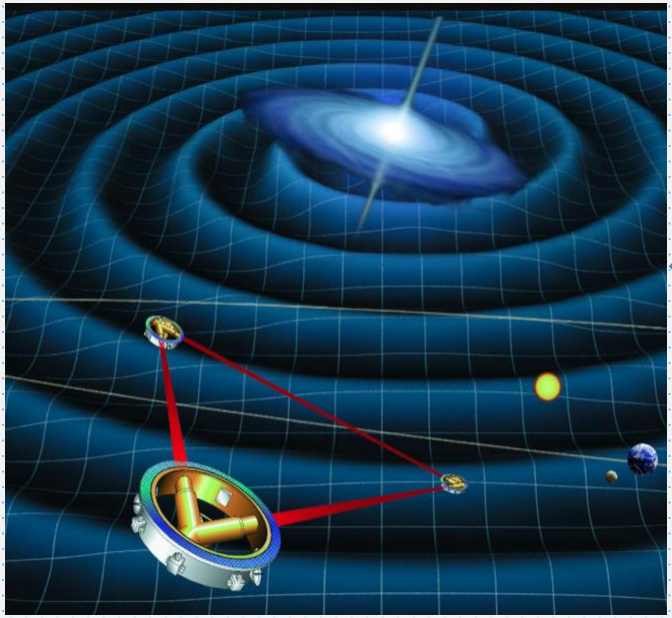
→ Electroweak Baryogenesis

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

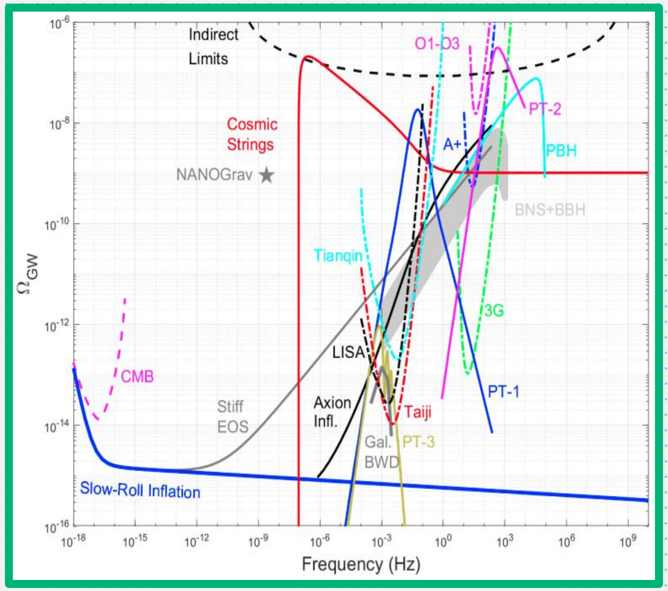
Morrissey,Ramsey-Musolf, NJP [1206.2942]

Flow of Studies

theoretical calculation of gravitational wave spectrum and detector simulation



LIGO, LISA, Taiji, Tianqin...

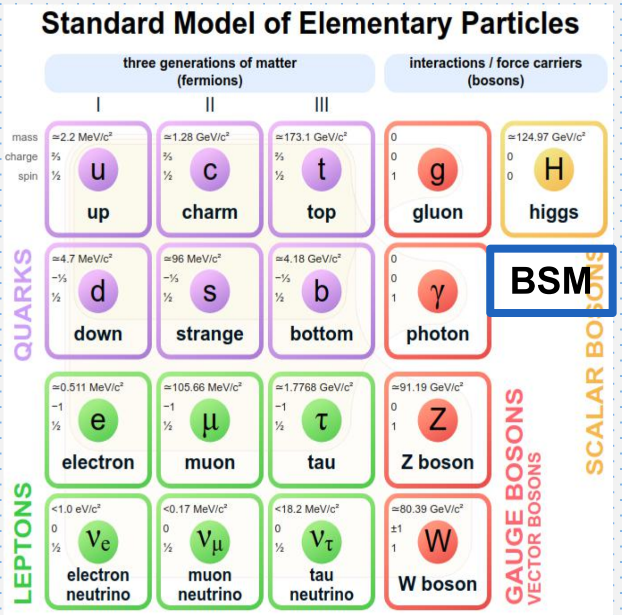


Gravitational Wave Spectrum

α
β
v_w
T_*
g_s
...

Phase Transition Parameters

EFT



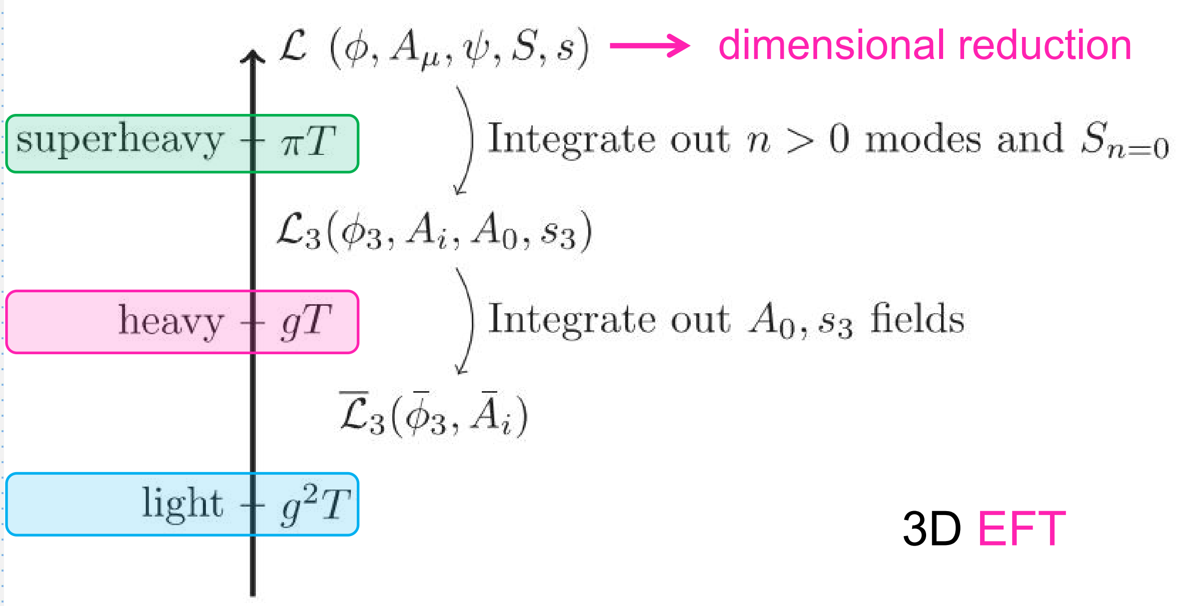
Particle Physics Model

data analysis, constraints or discovery(parameter estimation)

Effective Field Theory Approach

- Infrared problem (Linde, 1980)
- Gauge dependence
  (see, e.g., Patel,Ramsey-Musolf, JHEP [1101.4665])

- Non-perturbative method overcomes these problems
- But yet quite limited in BSM studies

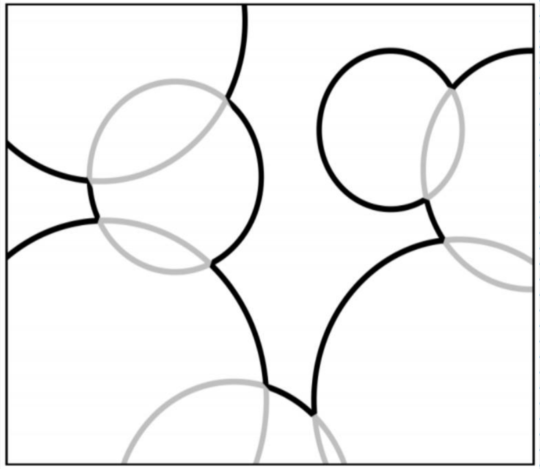


Gould,Kozaczuk,Niemi,Ramsey-Musolf,Tenkanen,Weir, PRD [1903.11604]

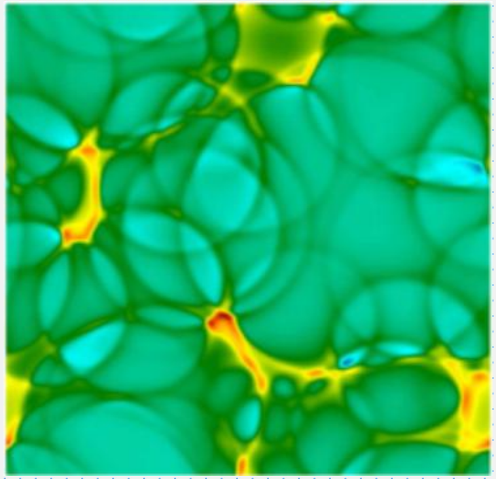
Dimensional Reduction (Status)		
SM	√	Farakos,Kajantie,Rummukainen,Shaposhnikov (1994)
MSSM	√	Cline,Kainulainen(1996), Losada(1996), Laine (1996)
xSM (SM + Singlet)	√	Brauner,Tenkanen,Tranberg,Vuorinen,Weir, JHEP [1609.06230]
ΣSM (SM + Triplet)	√	Niemi,Patel,Ramsey-Musolf,Tenkanen,Weir, PRD [1802.10500]
2HDM	√	Gorda,Helset,Niemi,Tenkanena,Weir, JHEP [1802.05056]

Gravitational Wave Sources

Bubble Collisions

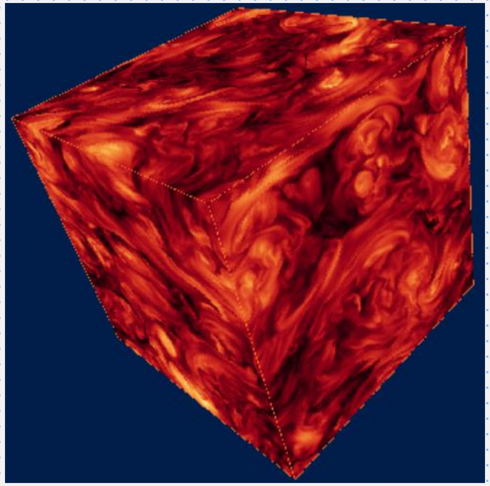


Sound Waves



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...

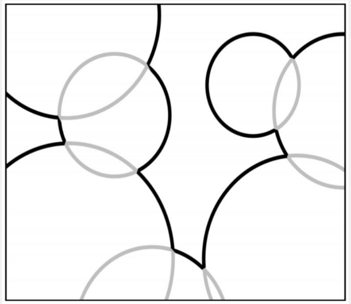
Di, Wang, Zhou, Bian, Cai, Liu, PRL 126 (2021) 25, 251102
Jing, Bian, Cai, Guo, Wang, PRL 130 (2023) 051001
Li, Huang, Wang, Zhang, PRD 105 (2022) 083527
Huang, Xie, PRD105 (2022) 11, 115033, JHEP 09 (2022) 052

The GW Observable

Energy density Spectrum

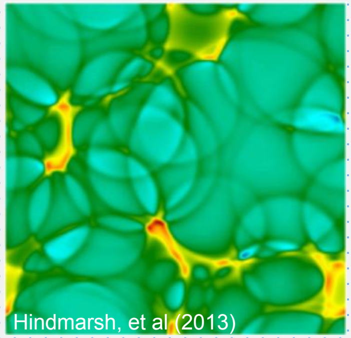
$$\Omega_{\rm GW}(f) = \frac{d\rho_{\rm GW}}{\rho_c d\log f}$$

bubble collision



$$\Omega_{\rm coll}(f)h^2 = 1.67\times 10^{-5}\Delta\left(\frac{H_{\rm pt}}{\beta}\right)^2\left(\frac{\kappa_\phi\alpha}{1+\alpha}\right)^2 \times\left(\frac{100}{g_*}\right)^{1/3} S_{\rm env}(f),$$

sound waves

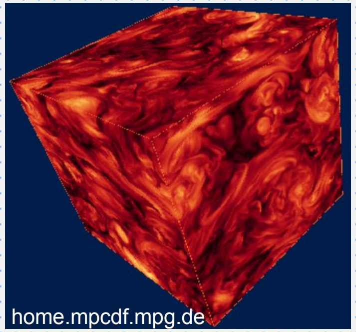


$$\Omega_{\rm sw}(f)h^2 = 2.65\times 10^{-6}\left(\frac{H_{\rm pt}}{\beta}\right)\left(\frac{\kappa_{\rm sw}\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{1/3} \times v_w\left(\frac{f}{f_{\rm sw}}\right)^3\left(\frac{7}{4+3(f/f_{\rm sw})^2}\right)^{7/2}\Upsilon(\tau_{\rm sw}),$$

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

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

MHD



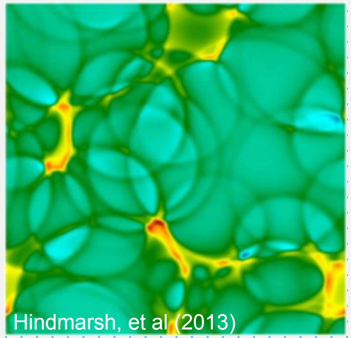
$$h^2\Omega_{\rm turb}(f) = 3.35\times 10^{-4}\left(\frac{H_*}{\beta}\right)\left(\frac{\kappa_{\rm turb}\,\alpha}{1+\alpha}\right)^{\frac{3}{2}}\left(\frac{100}{g_*}\right)^{1/3} v_w\, S_{\rm turb}(f)$$

Chiara Caprini et al JCAP04(2016)001

Sound Waves

Υ

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]
...
(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]

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

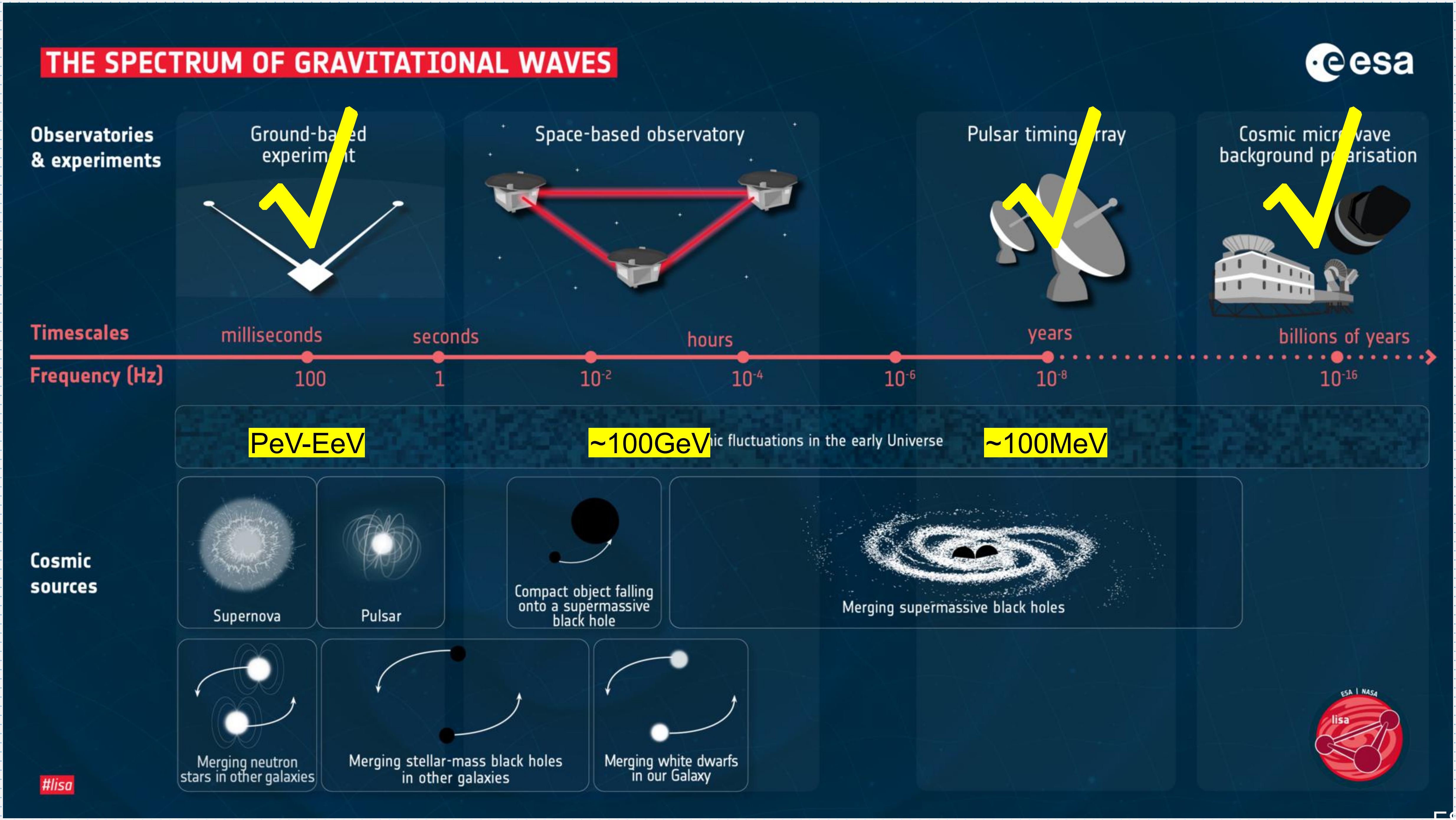
The Astrophysical Journal Letters, 951:L11 (56pp), 2023 July 1 https://doi.org/10.3847/2041-8213/acdc91

The NANOGrav 15 yr Data Set: Search for Signals from New Physics

Adeela Afzal[1,2], Gabriella Agazie[3], Akash Anumarlapudi[3], Anne M. Archibald[4], Zaven Arzoumanian[5], Paul T. Baker[6],
Bence Bécsy[7], Jose Juan Blanco-Pillado[8,9,10], Laura Blecha[11], Kimberly K. Boddy[12], Adam Brazier[13,14],
Paul R. Brook[15], Sarah Burke-Spolaor[16,17], Rand Burnette[7], Robin Case[7], Maria Charisi[18], Shami Chatterjee[13],
Katerina Chatziioannou[19], Belinda D. Cheeseboro[16,17], Siyuan Chen[20], Tyler Cohen[21], James M. Cordes[13],
Neil J. Cornish[22], Fronefield Crawford[23], H. Thankful Cromartie[13,77], Kathryn Crowter[24], Curt J. Cutler[19,25],
Megan E. DeCesar[26], Dallas DeGan[7], Paul B. Demorest[27], Heling Deng[7], Timothy Dolch[28,29], Brendan Drachler[30,31],
Richard von Eckardstein[1], Elizabeth C. Ferrara[32,33,34], William Fiore[16,17], Emmanuel Fonseca[16,17],
Gabriel E. Freedman[3], Nate Garver-Daniels[16,17], Peter A. Gentile[16,17], Kyle A. Gersbach[18], Joseph Glaser[16,17],
Deborah C. Good[35,36], Lydia Guertin[37], Kayhan Gültekin[38], Jeffrey S. Hazboun[7], Sophie Hourihane[19], Kristina Islo[3],
...
The NANOGrav Collaboration

time of matter–radiation equality. The production of GWs from sound waves stops after a period $\tau_{\rm sw}$, when the plasma motion turns turbulent (Ellis et al. 2019a, 2019b, 2020; Guo et al. 2021). In Equation (34), this effect is taken into account by the suppression factor

$$\Upsilon(\tau_{\rm sw}) = 1-(1+2\tau_{\rm sw}H_*)^{-1/2}, \quad (36)$$


THE SPECTRUM OF GRAVITATIONAL WAVES
esa
Observatories & experiments
Ground-based experiment
Space-based observatory
Pulsar timing array
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
#lisa
ESA | NASA
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)

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

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

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

Bubble Collision

95% CL UL with fixed Tpt and beta/Hpt

Phenomenological model (bubble collisions)

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

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

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

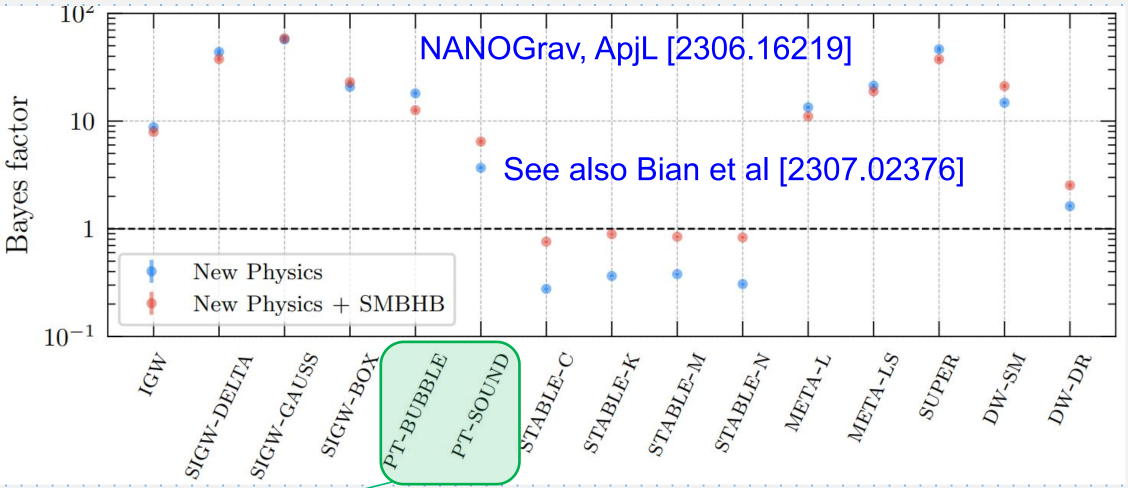
$$\beta/H_{\rm pt} < 1 \text{ and } T_{\rm pt} > 10^8\ \mathrm{GeV}$$

First result from gravitational wave data!

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

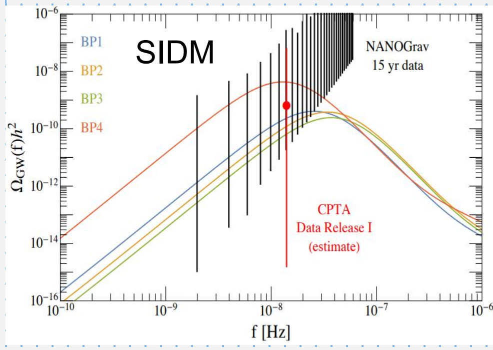
What possible PTA discovery implies?

- 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

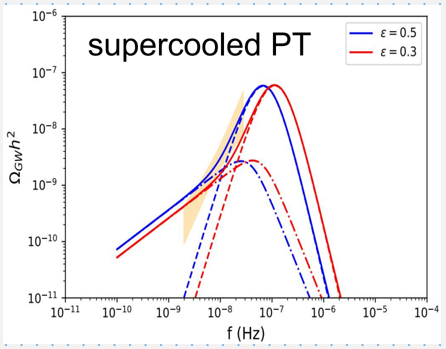


PPTA: Xue et al, PRL [2110.03096]
NANOGrav (12.5-year): Arzoumanian et al, PRL [2104.13930]
...

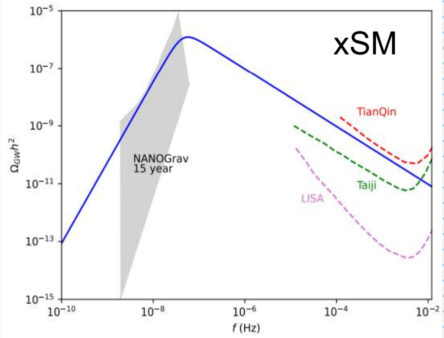
See also Kepan Xie's talk



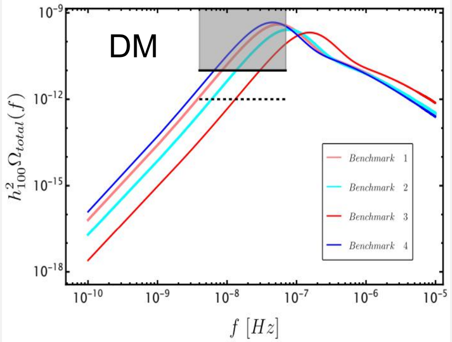
Han,Xie,Yang,Zhang [2306.16966]



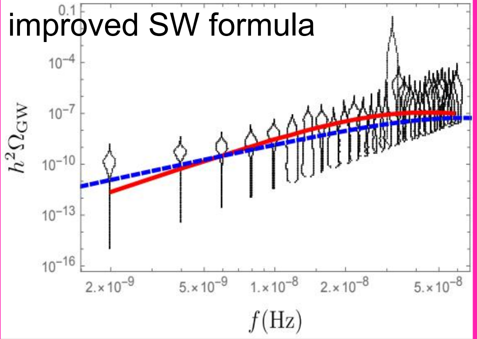
Zu,Zhang,Li,Gu,Tsai,Fan [2306.17239]



Xiao,Yang,Zhang [2307.01072]



Yang,Ma,Jiang,Huang [2306.17827]



Ghosh et al [2307.02259]

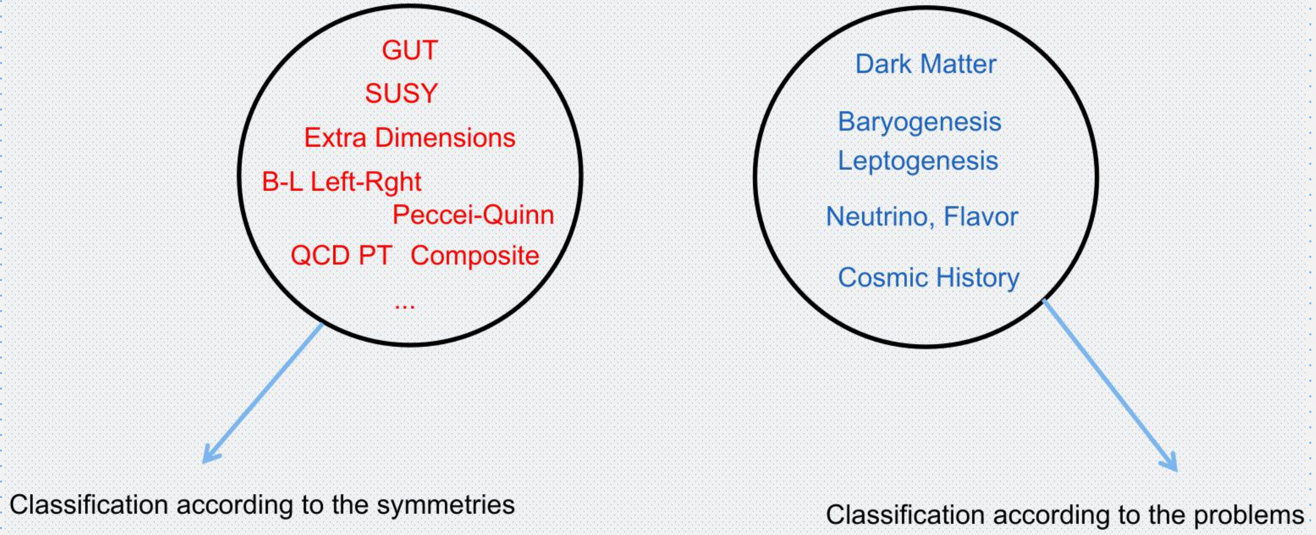
and more...

BSM studies

Chung,Long,Wang, PRD [1209.1819]

- Large cubic term from thermal correrctions (loop level)
- Add new scalars (tree level)
- Including non-renormalizable operators

  More general EFT approach: Cai,Hashino,Wang,Yu [2202.08295]



Models	Strong 1st order phase transition	GW signal	Cold DM	Dark Radiation and small scale structure
SM charged				
Triplet [20–22]	✓	✓	✓	✗
complex and real Triplet [23] (Georgi-Machacek model)	✓	✓	✓	✗
Multiplet [24]	✓	✓	✓	
2HDM [25–30]	✓	✓		✗
MLRSM [31]	✓	✓	✗	✗
NMSSM [32–36]	✓	✓	✓	✗
SM uncharged				
S_r (xSM) [37–49]	✓	✓	✗	✗
2 S_r's [50]	✓	✓	✓	✗
S_c (cxSM) [49, 51–54]	✓	✓	✓	✗
$U(1)_D$ (no interaction with SM) [55]	✓	✓	✓	✗
$U(1)_D$ (Higgs Portal) [56]	✓	✓	✓	
$U(1)_D$ (Kinetic Mixing) [57]	✓	✓	✓	
Composite SU(7)/SU(6) [58]	✓	✓	✓	
$U(1)_L$ [59]	✓	✓	✓	✗
$SU(2)_D \to$ global $SO(3)$ by a doublet [60–62]			✓	✗
$SU(2)_D \to U(1)_D$ by a triplet [63–65]			✓	✓
$SU(2)_D \to Z_2$ by two triplets [66]			✓	✗
$SU(2)_D \to Z_3$ by a quadruplet [67, 68]			✓	✗
$SU(2)_D \times U(1)_{B-L} \to Z_2 \times Z_2$ by a quintuplet and a S_c [69]			✓	✗
$SU(2)_D$ with two dark Higgs doublets [70]	✓	✓	✗	✗
$SU(3)_D \to Z_2 \times Z_2$ by two triplets [62, 71]			✓	✗
$SU(3)_D$ (dark QCD) (Higgs Portal) [72, 73]	✓	✓	✓	
$G_{SM} \times G_{D,SM} \times Z_2$ [74]	✓	✓	✓	
$G_{SM} \times G_{D,SM} \times G_{D,SM} \cdots$ [75]	✓	✓	✓	
Current work				
$SU(2)_D \to U(1)_D$ (see the text)	✓	✓	✓	✓

Ghosh,HG,Han,Liu, JHEP [2012.09758]

GWs from Particles

Extreme densities

disturbances in the early universe

As Macroscopic Objects

(non-) topological solitons

Environmental Effects

Faking GW signals (dark photon)

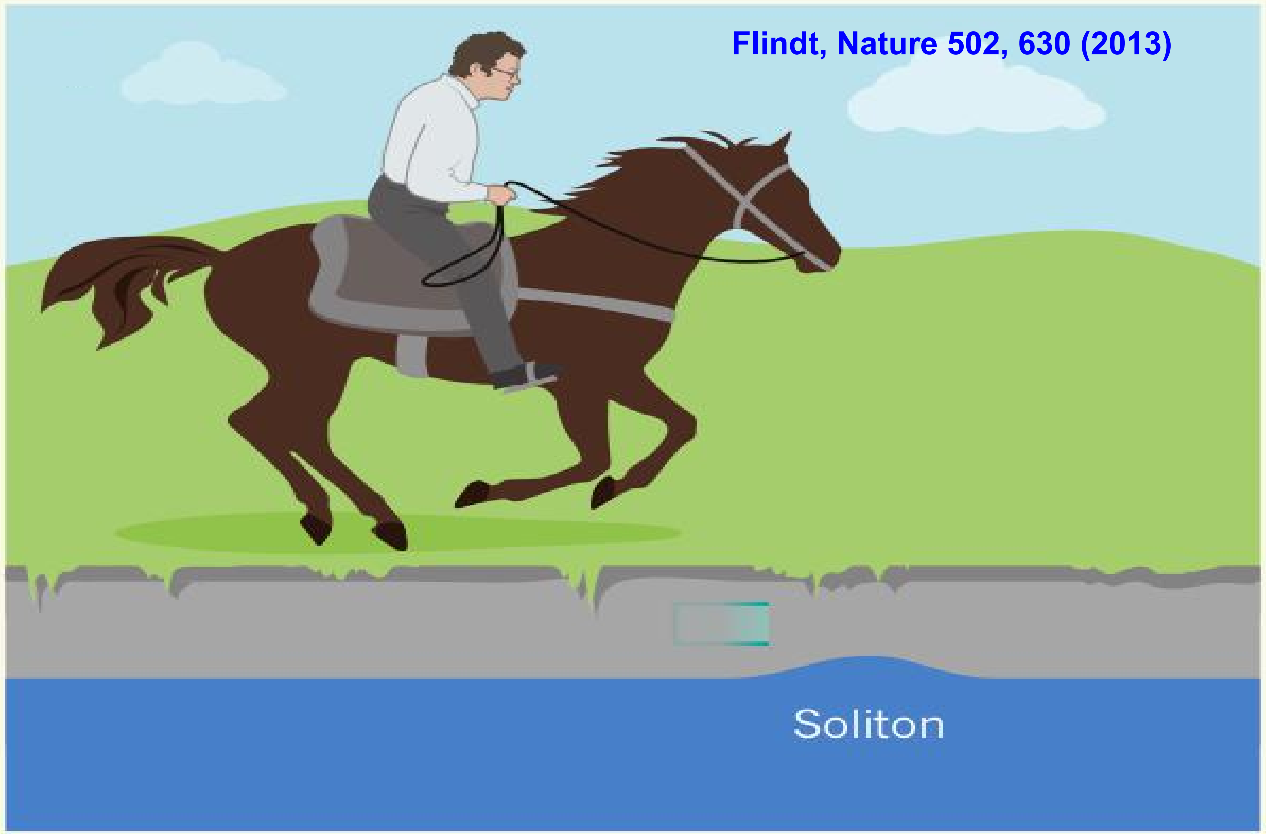
Solitons

- 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

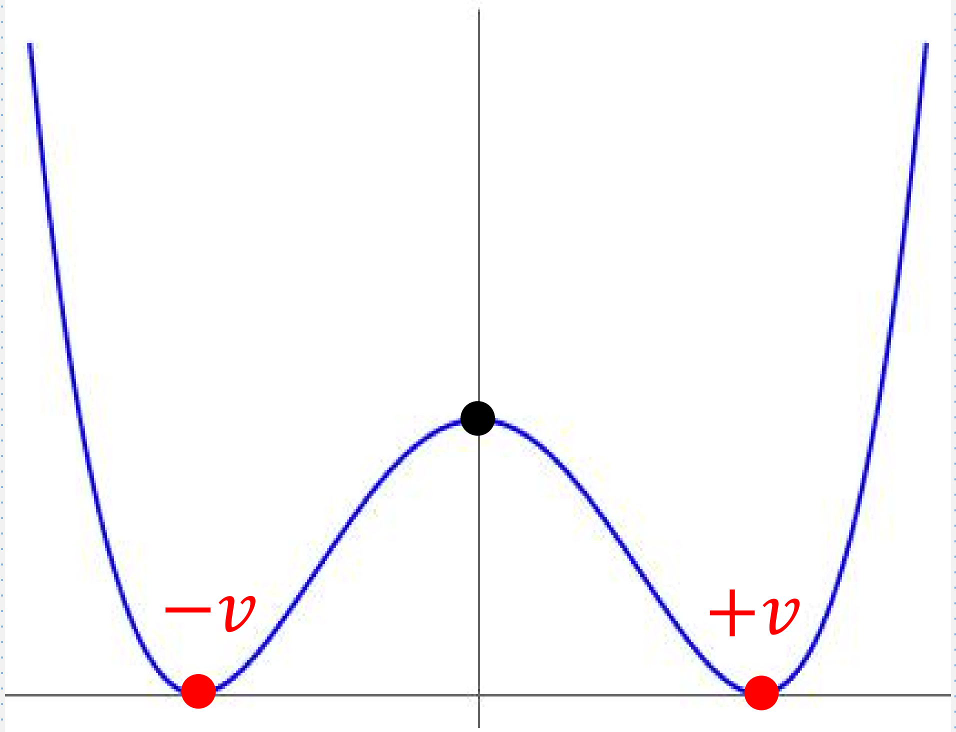
Received 11 March 1976

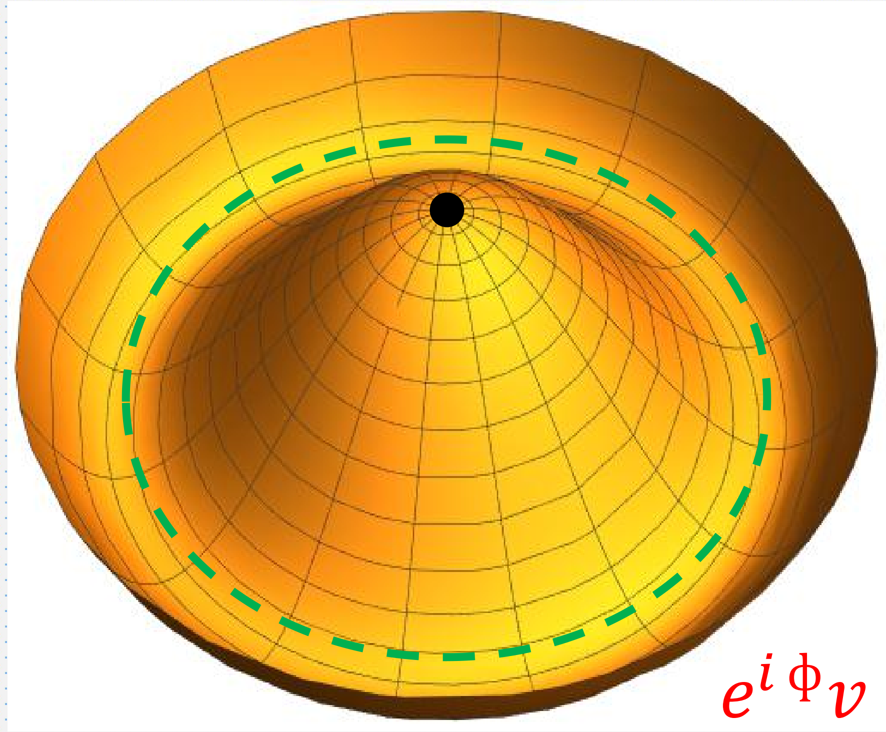
www.theguardian.com

Degenerate Vacuum States

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

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





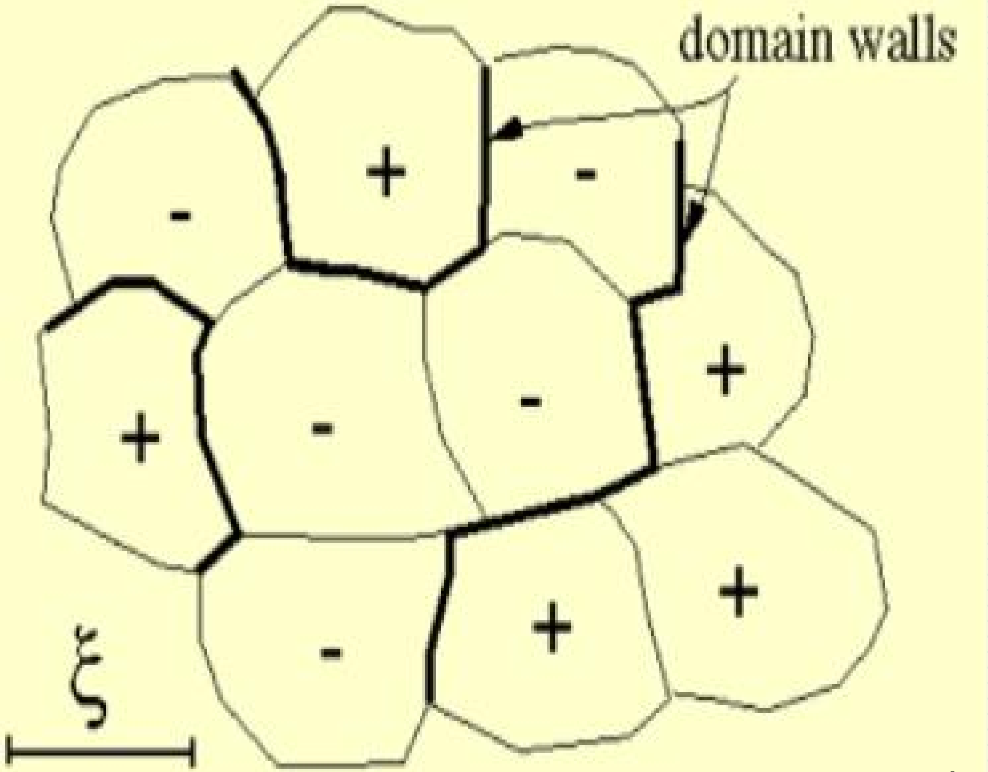
Domain wall

Cosmic String

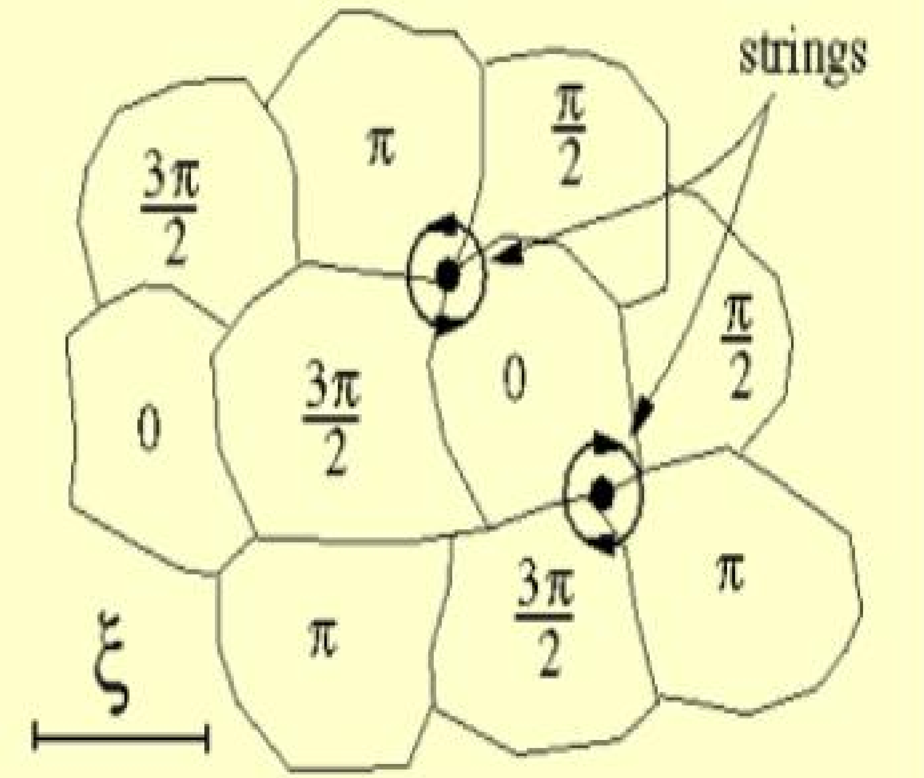
Degenerate Vacuum States

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

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



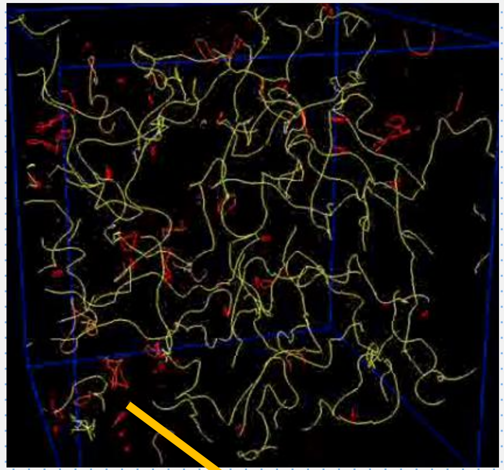
www.ctc.cam.ac.uk



www.ctc.cam.ac.uk

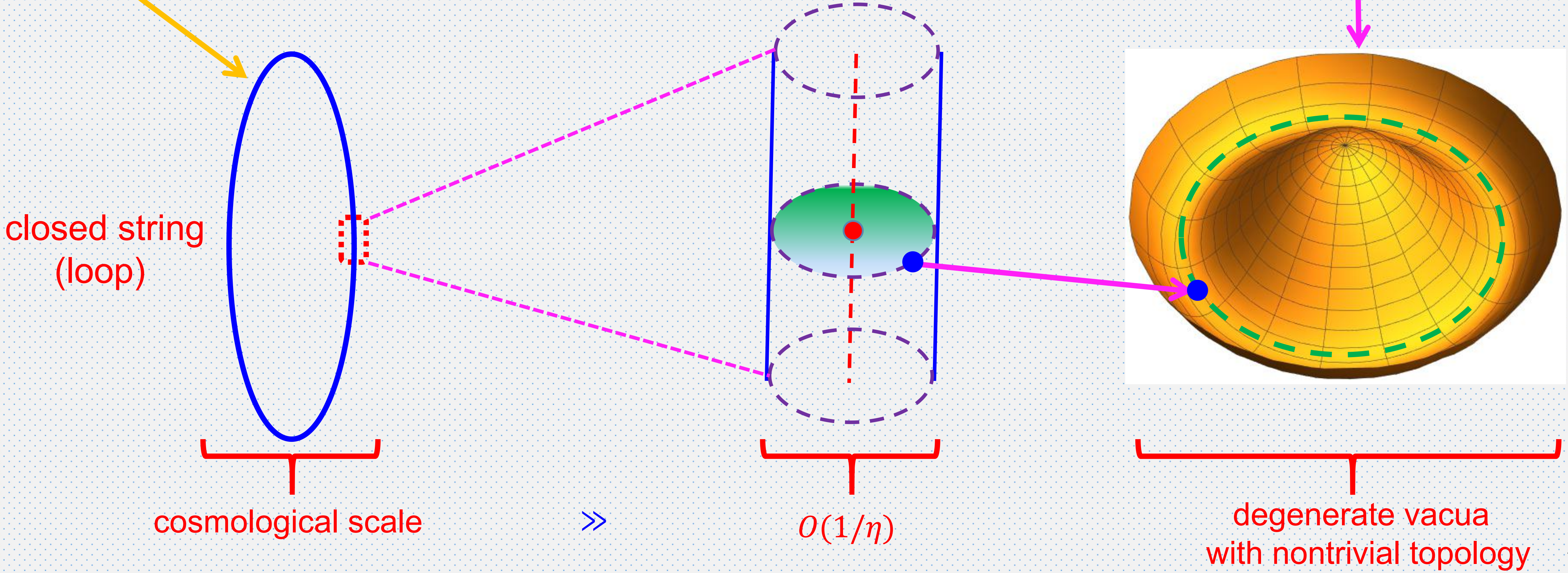
Will focus on cosmic strings.

Cosmic String



Example: the Abelian Higgs Model

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



LIGO Search Result of Cosmic Strings

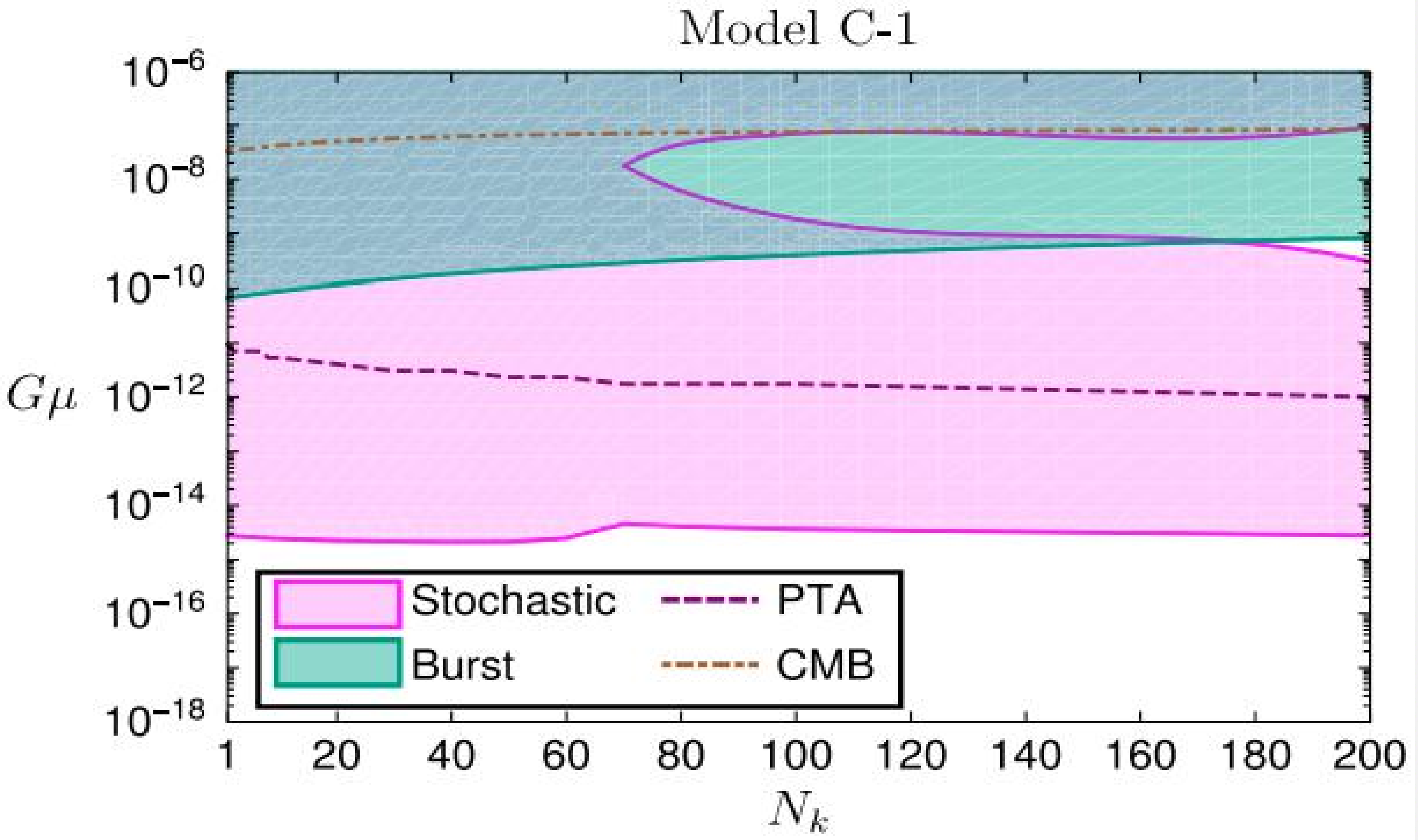
Symmetry breakings at scales higher than $O(10^{11})$ GeV with Cosmic String production are excluded

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

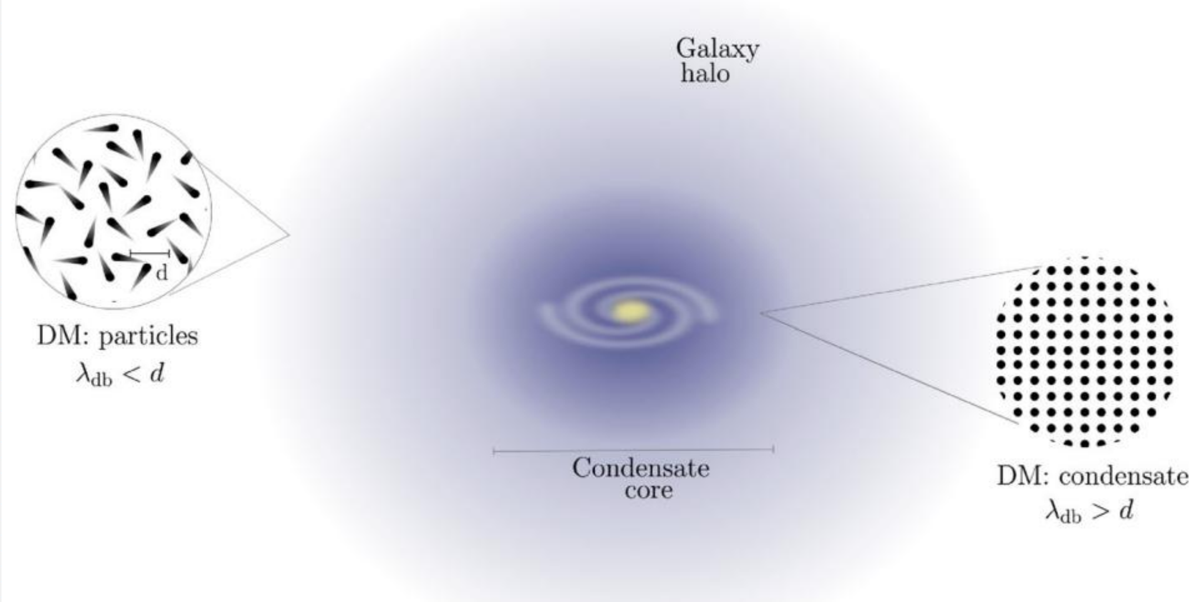
Giant Bose-Einstein condensate of ultralight particles (DM)

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

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

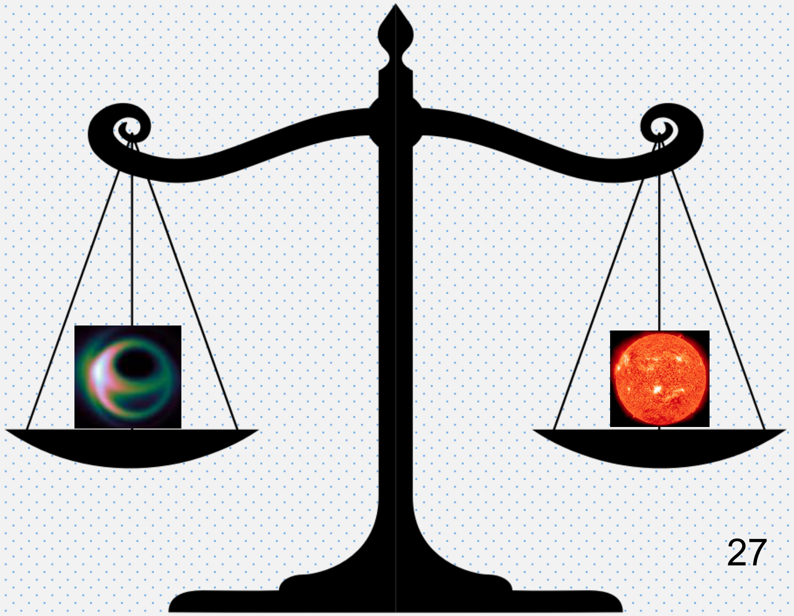
$m_{\rm ULDM} \sim 10^{-10}\text{eV}$

Galactic Scale: solve small scale structure problems

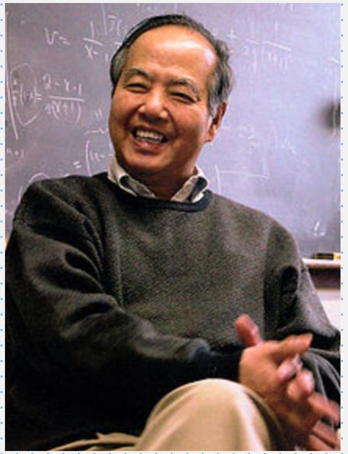


Ferreira, Astron.Astrophys.Rev. 29 (2021) 1

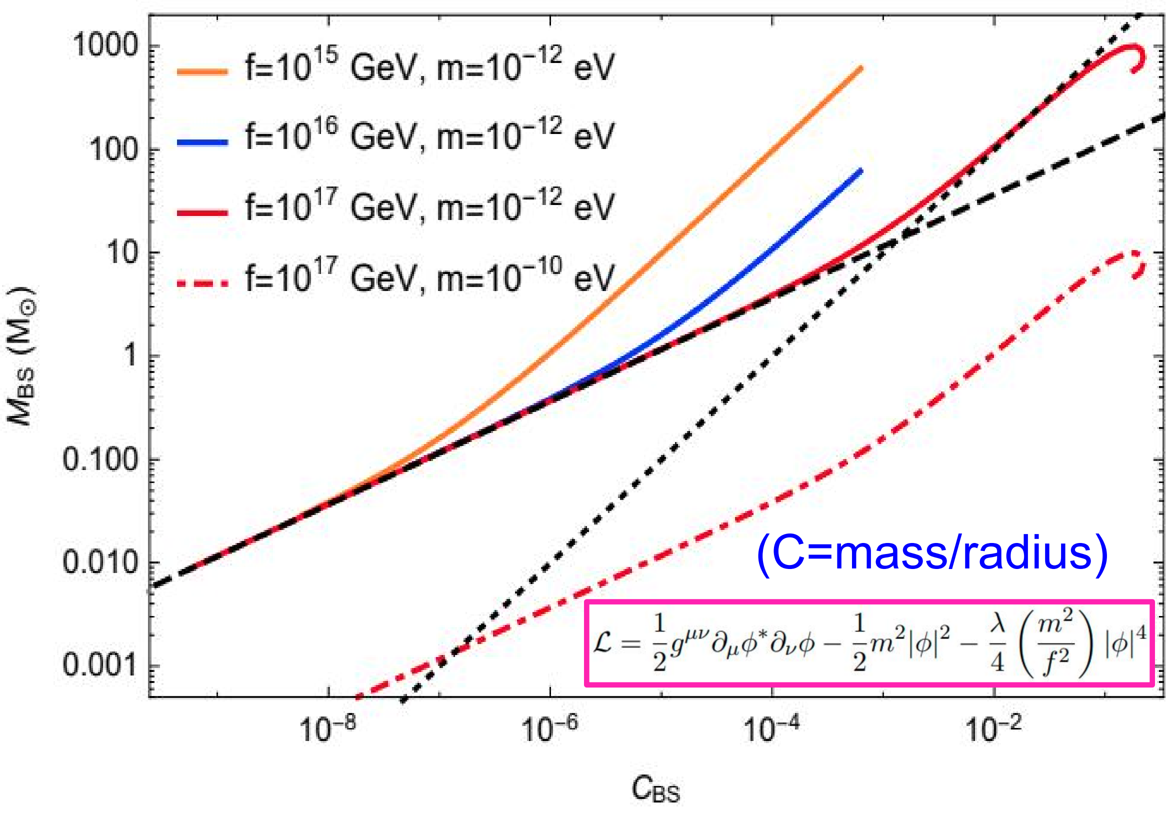
Stellar Scale: soliton stars



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)

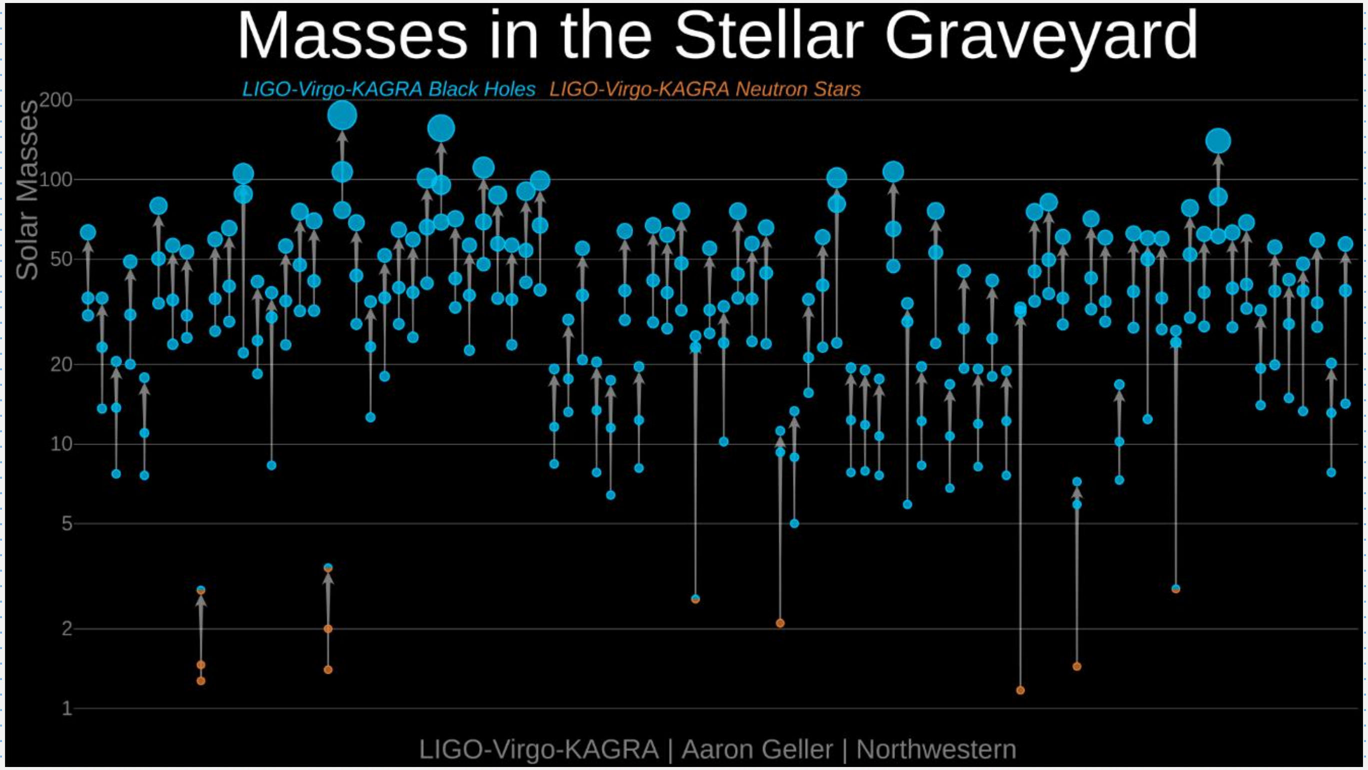
See, e.g., Liebling, Palenzuela, Living Rev Relativ (2017) 20:5

Lee,Pang, Phys.Rept (1992)

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

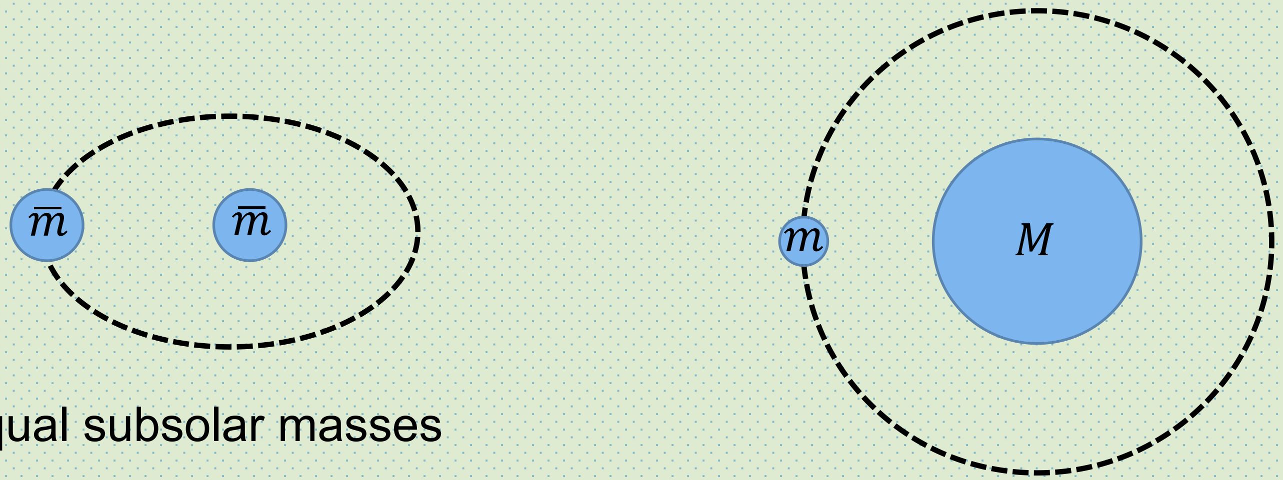
Search for Light ECOs

- 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

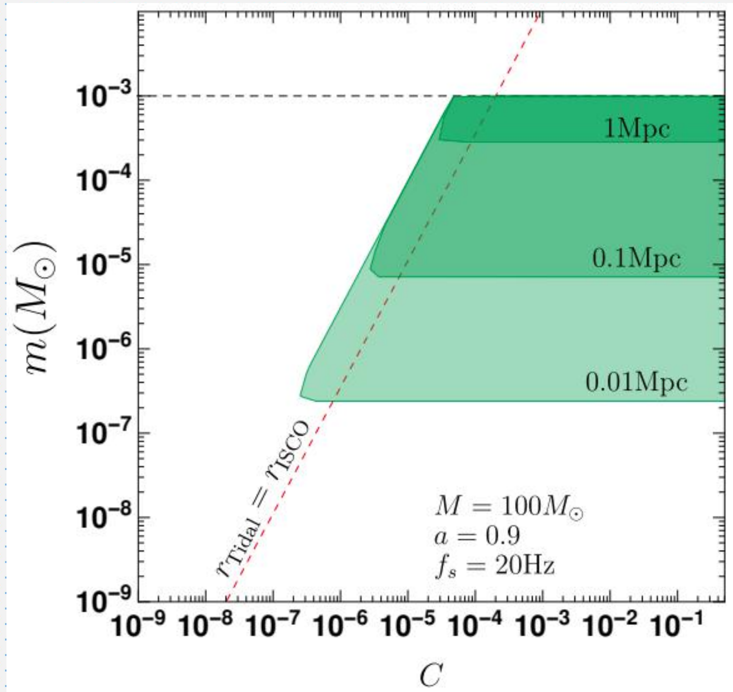
$$\frac{m}{\bar{m}} \approx 2^{-1/3} \left(\frac{\bar{m}}{M}\right)^{2/3} \Rightarrow m \ll \bar{m} \ll M$$

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

Detection with EMRI and mini-EMRI

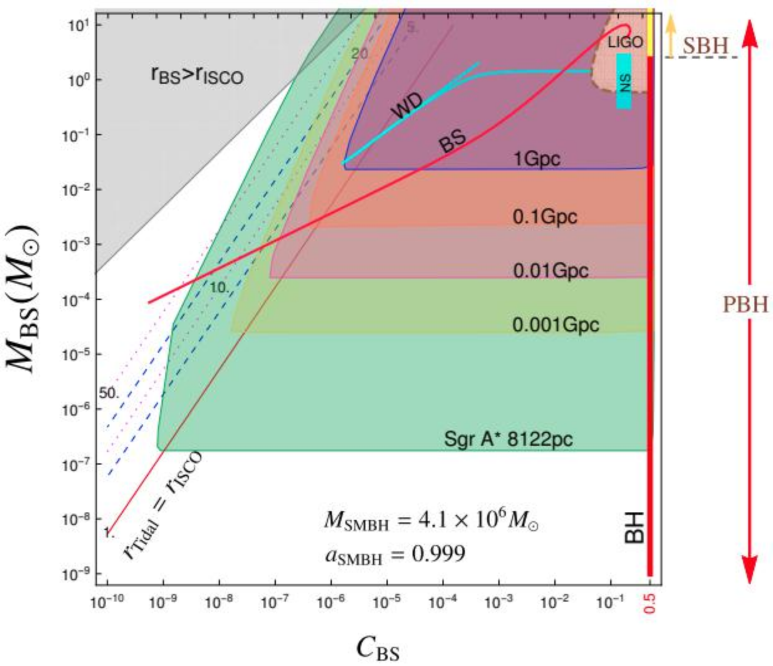
- By making one object much heavier, one can probe much ligher companion object
- Ideal systems: extreme mass ratio inspirals (EMRIs), key target of Taiji, Tianqin, LISA.
- LIGO can detect mini-EMRIs (extreme mass ratio, but lighter objects)

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

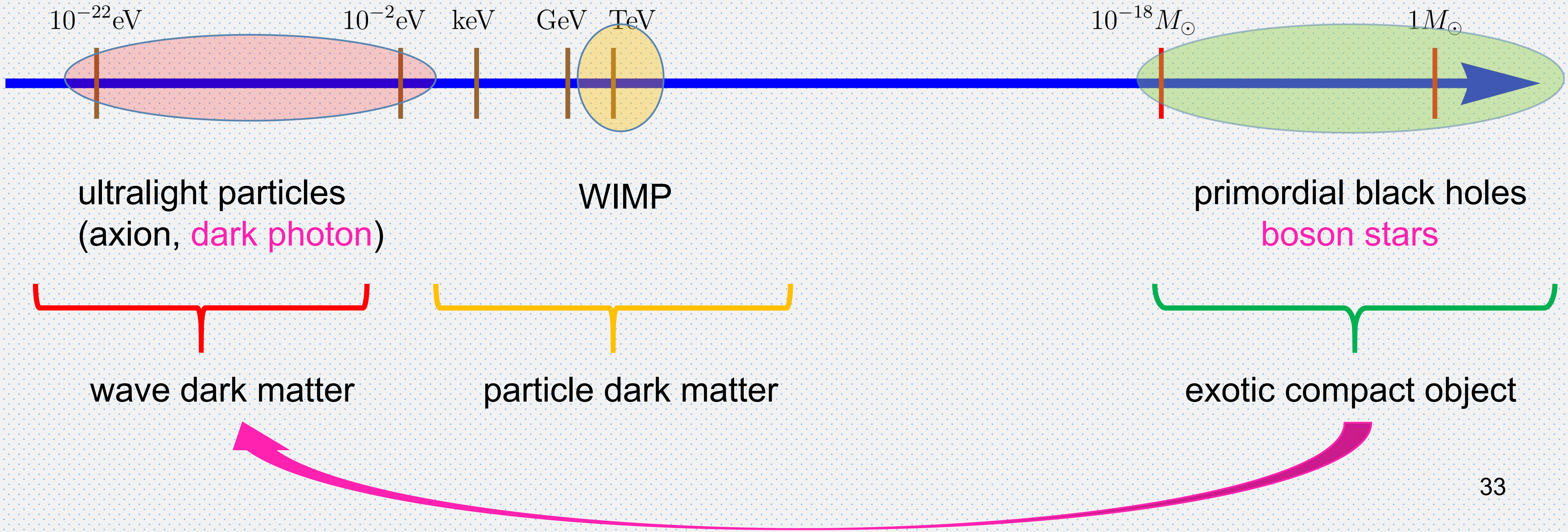
Environmental Effects

Faking GW signals (dark photon)

Ultralight Dark Matter

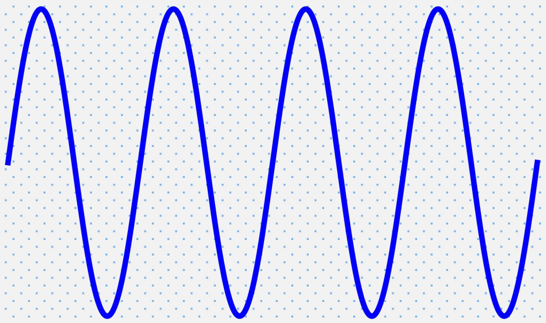
See also Xiao-Ping Wang, Jia Liu, Cheng-Cheng Han, and Yong Tang's talks

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

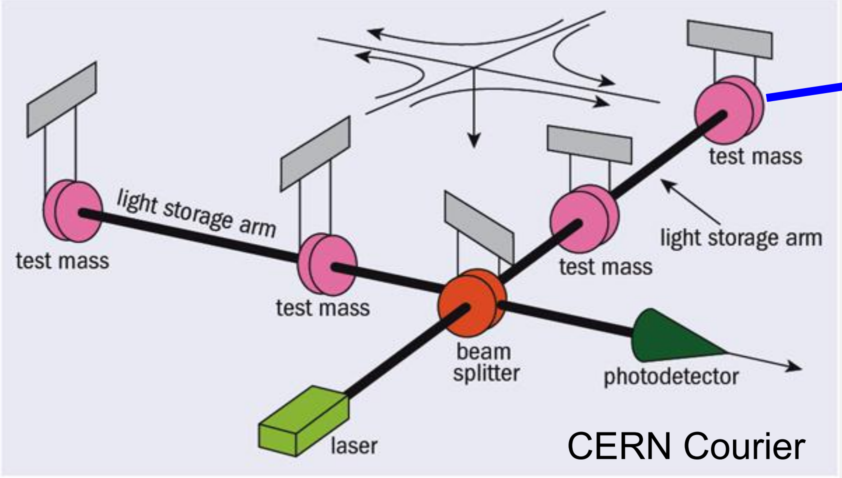


Dark Photon Detection at LIGO

a single dark photon



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



silicon mirror

$U(1)_B$: $1/\text{GeV}$

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

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

acceleration

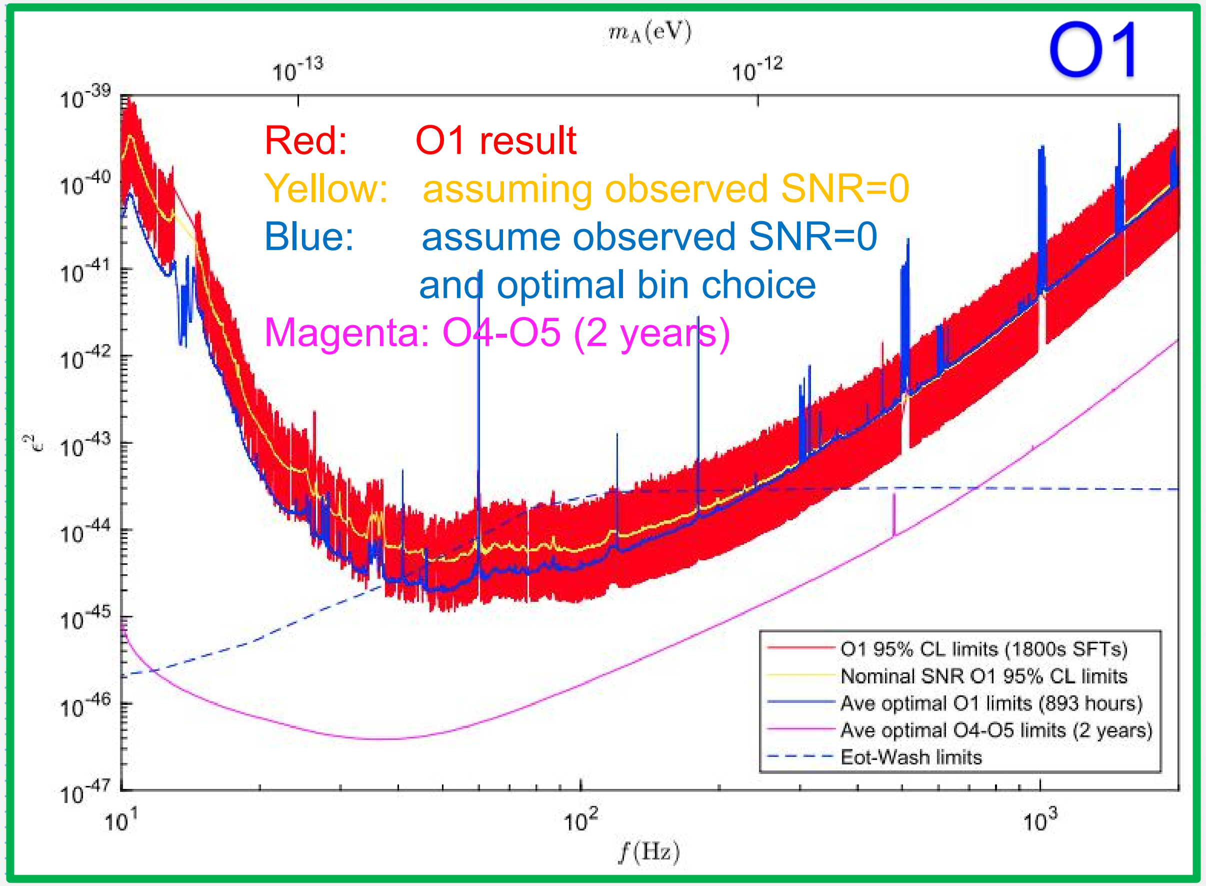
typical LIGO frequency

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

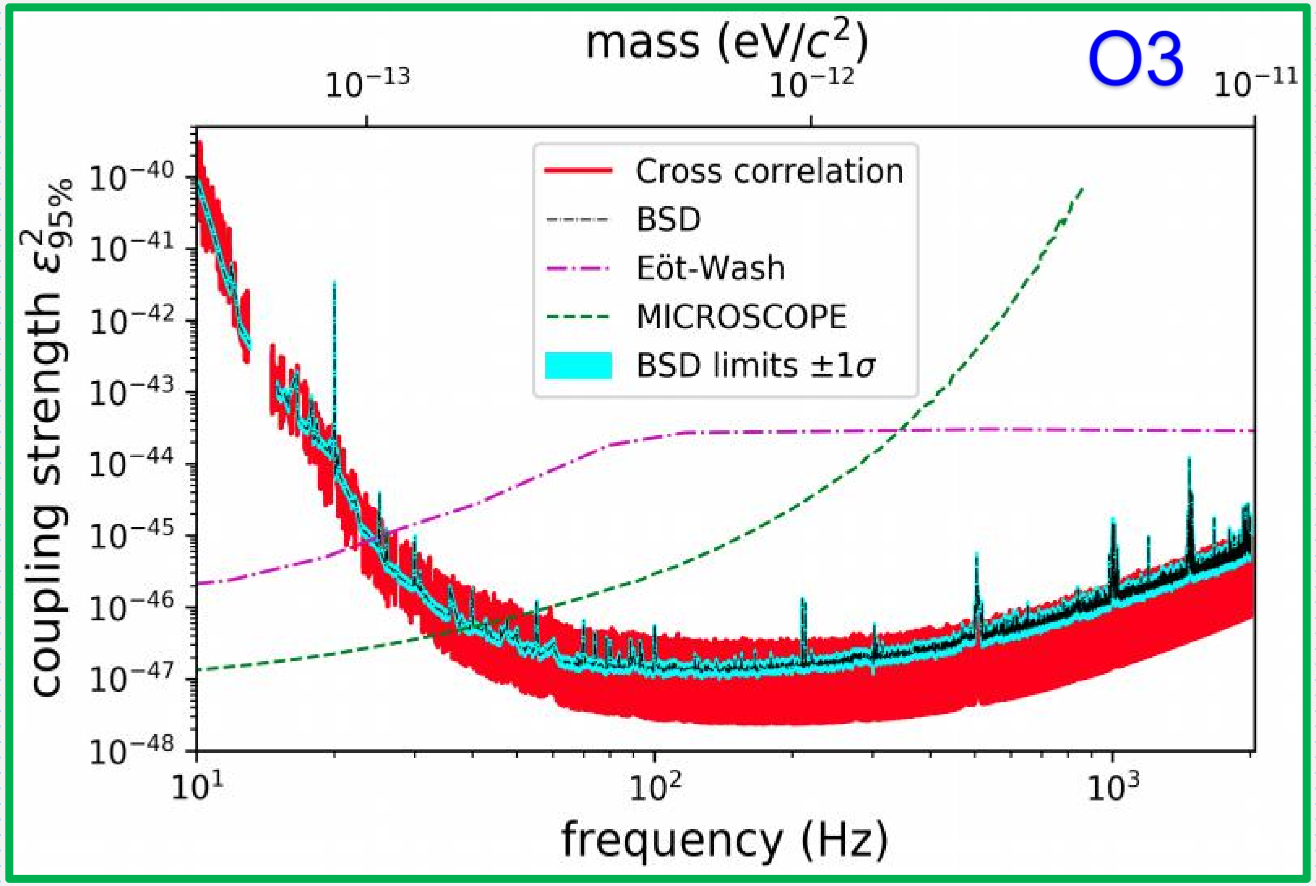
typical dark photon mass LIGO is sensitive to

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