中国科学院大学
University of Chinese Academy of Sciences

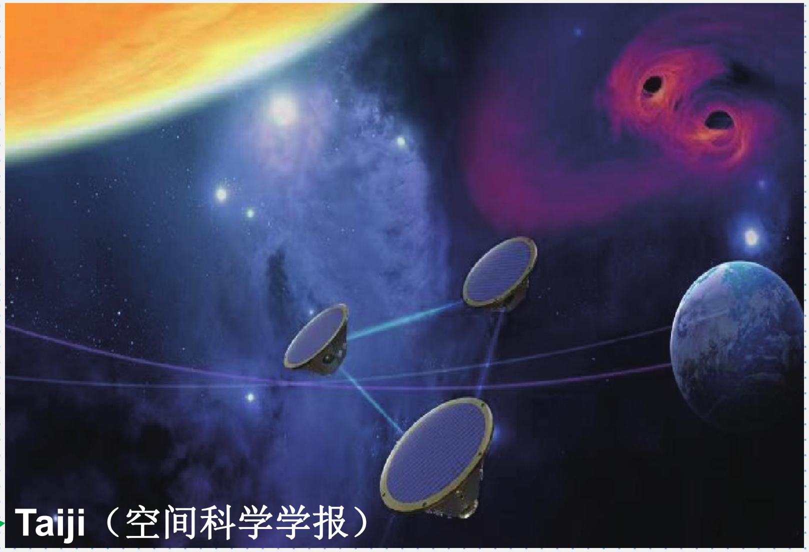
UNESCO

ICTP-AP
International Centre
for Theoretical Physics Asia-Pacific
国际理论物理中心-亚太地区

# Some (of Mine) Recent Developments on BSM Probes with Gravitational Waves

Huaike Guo

Nov. 17, 2023


LISA, Taiji, Tianqin, ...

**Gravitational Waves**

**PTA**

EPTA

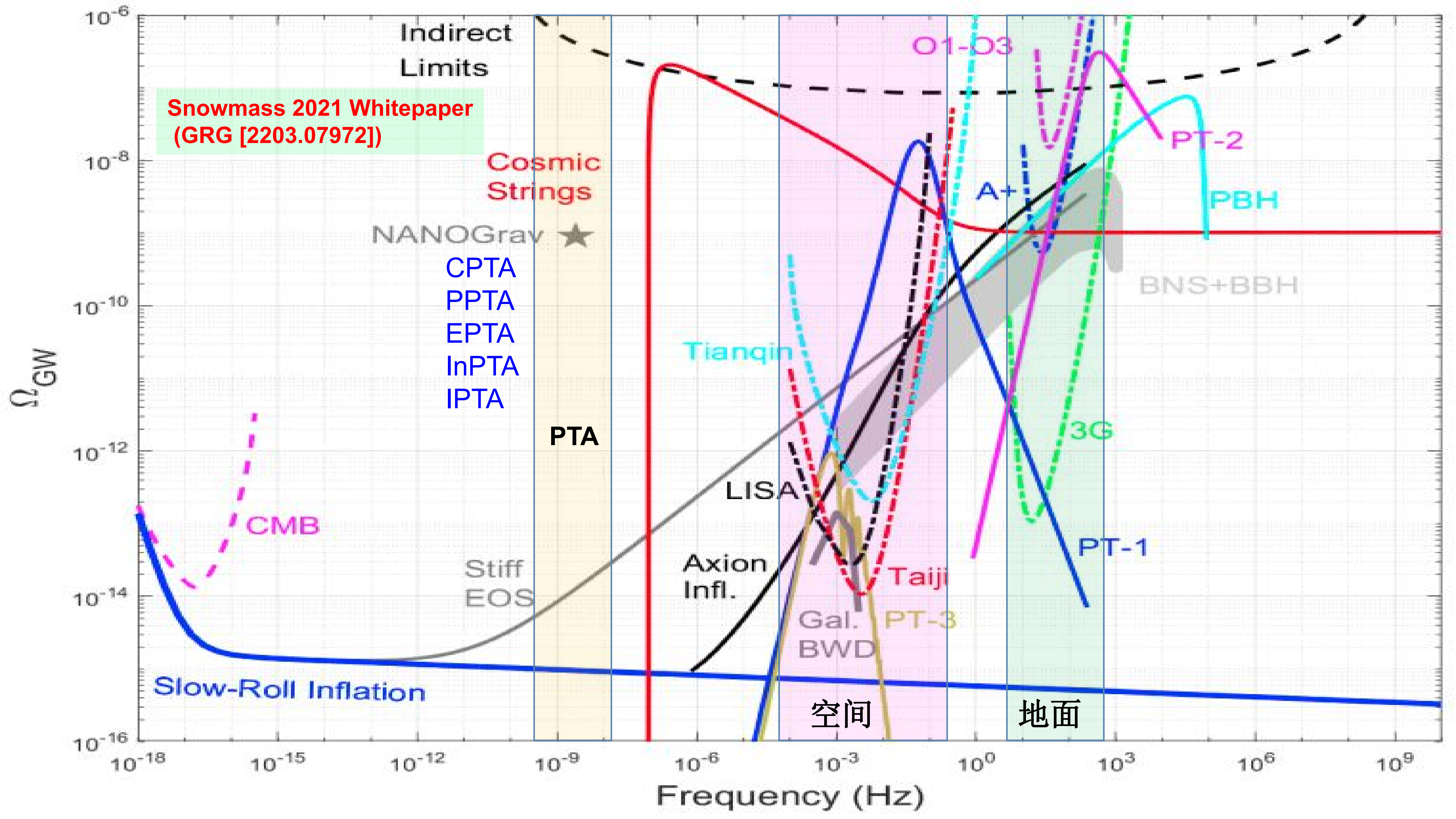
NANOGrav Physics Frontiers Center

PPTA

InPTA Indian Pulsar Timing Array

**中国脉冲星测时阵列（CPTA）**

See Asuka Ito’s talk on high frequency GW,
Qiuyue Liang’s talk on Astrometry detection
Xing-Yu Yang’s talk on PTA implications

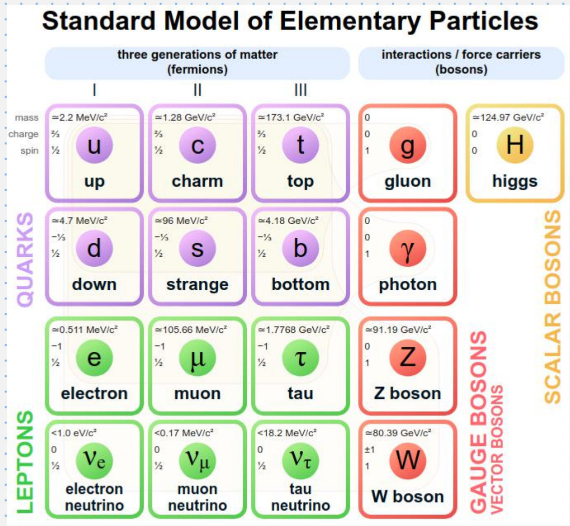


Indirect Limits
Snowmass 2021 Whitepaper
(GRG [2203.07972])
Cosmic Strings
NANOGrav
CPTA
PPTA
EPTA
InPTA
IPTA
PTA
O1-O3
PT-2
A+
PBH
BNS+BBH
Tianqin
3G
LISA
PT-1
CMB
Stiff EOS
Axion Infl.
Taiji
Gal. BWD
PT-3
Slow-Roll Inflation
空间
地面
$\Omega_{GW}$
Frequency (Hz)
$10^{-6}$
$10^{-8}$
$10^{-10}$
$10^{-12}$
$10^{-14}$
$10^{-16}$
$10^{-18}$
$10^{-15}$
$10^{-12}$
$10^{-9}$
$10^{-6}$
$10^{-3}$
$10^{0}$
$10^{3}$
$10^{6}$
$10^{9}$

# New Perspectives, with GW?

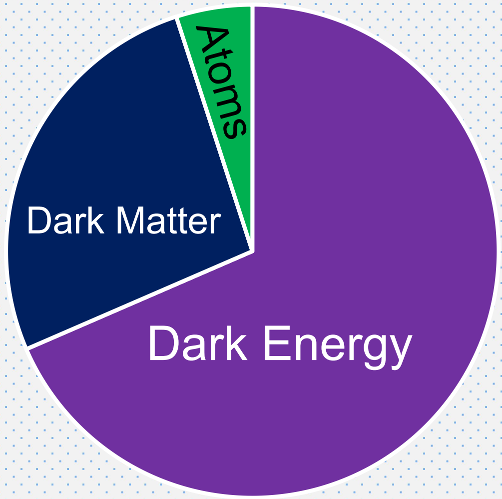
How can we reconcile the standard models of particle physics and cosmology?

**Particle Physics**




Physics Beyond the SM?

**Cosmology**

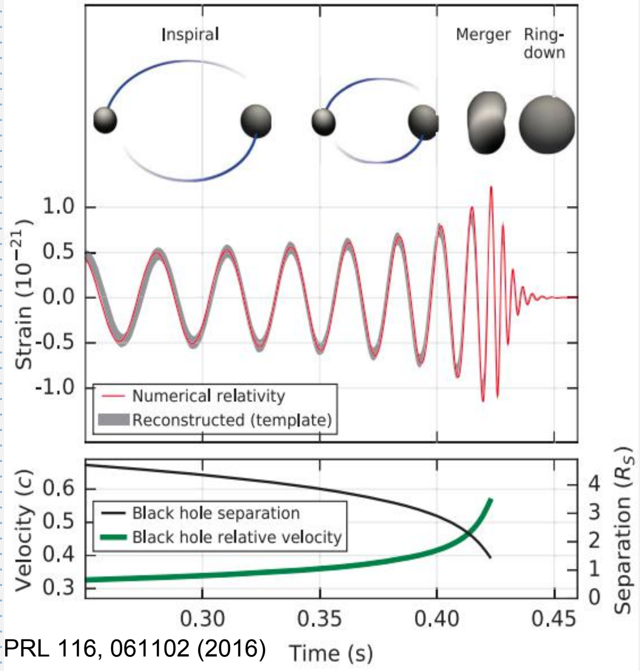



Why more matter than anti-matter? (phase transitions, solitons)

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 microscopic 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)

# GWs from Particles

Extreme densities

disturbances in the early universe

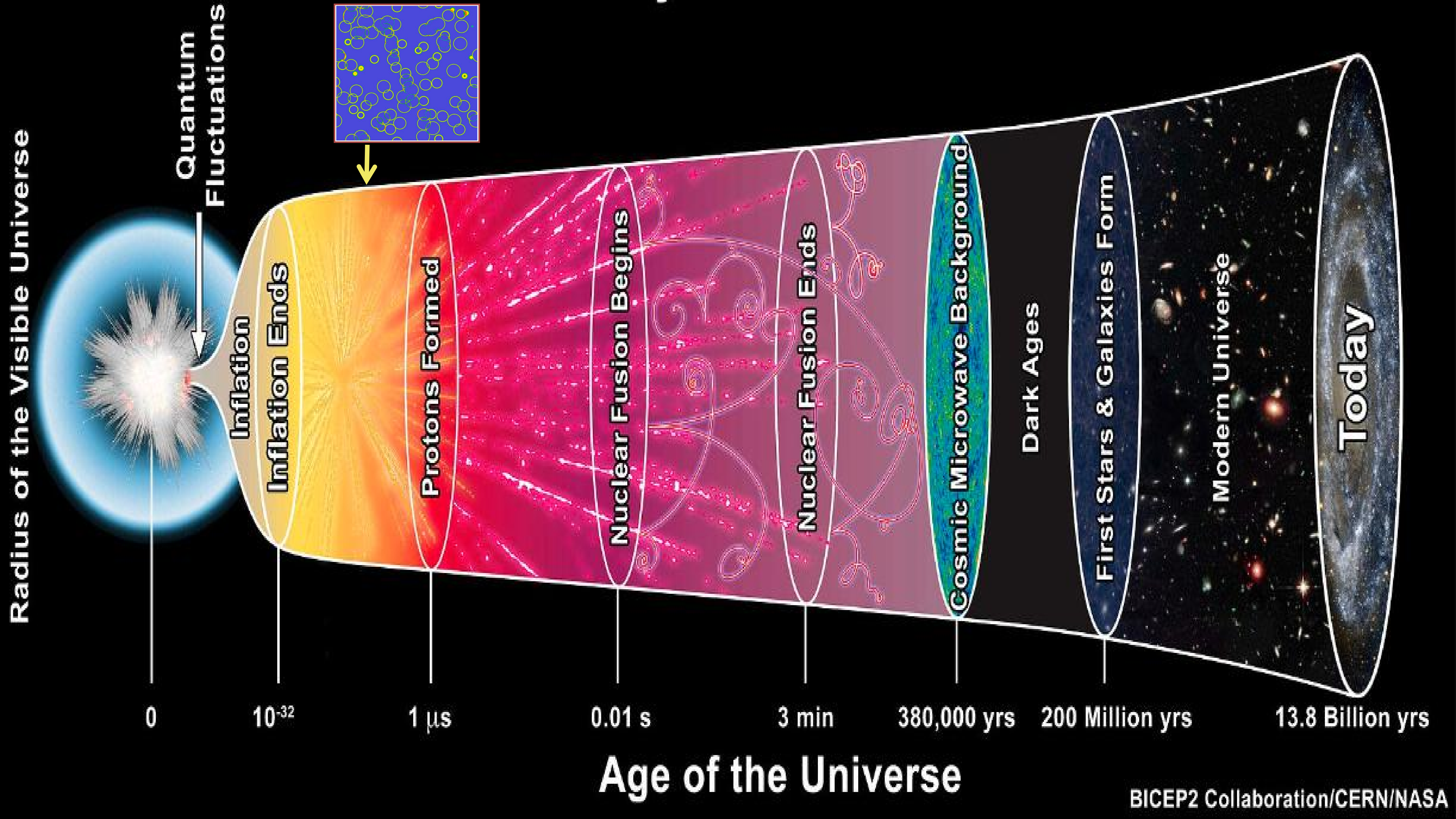
As Macroscopic Objects

(non-) topological solitons

Environmental Effects

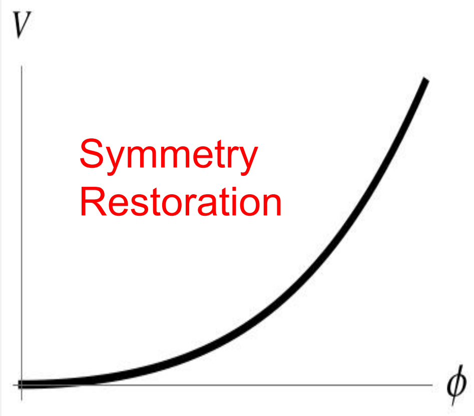
Faking GW signals (dark photon)

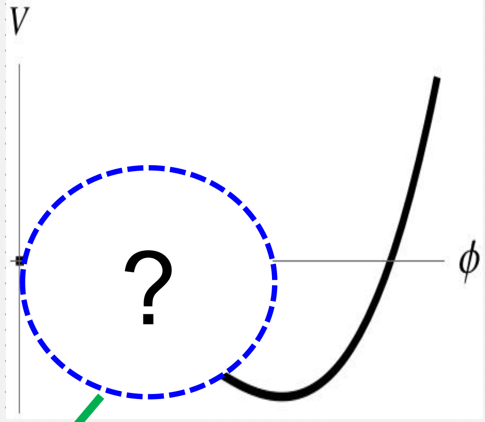
See also Jan Tristram Acuña, Ryusuke Jinno, Yue-Lin Sming Tsai's talks

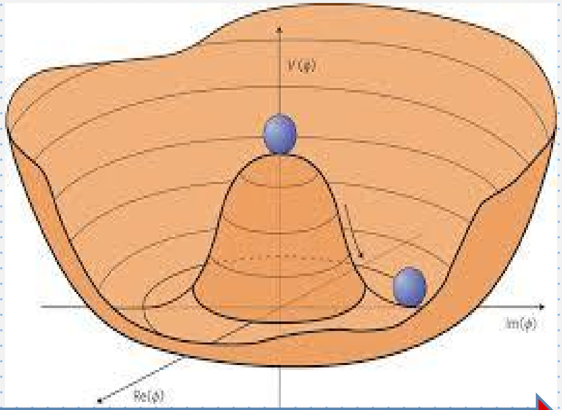


Radius of the Visible Universe
Quantum Fluctuations
Inflation
Inflation Ends
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Dark Ages
First Stars & Galaxies Form
Modern Universe
Today
0
$10^{-32}$
1 μs
0.01 s
3 min
380,000 yrs
200 Million yrs
13.8 Billion yrs
Age of the Universe
BICEP2 Collaboration/CERN/NASA

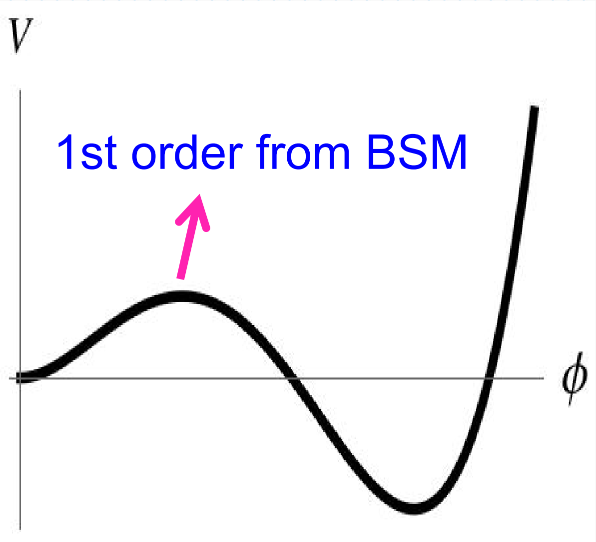
# Electroweak Phase Transition



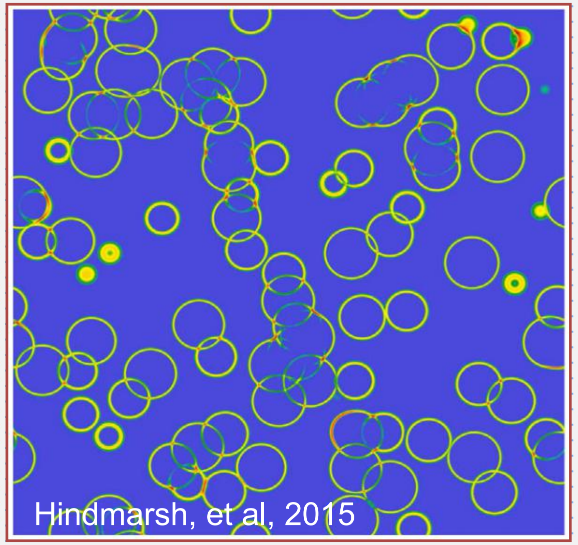



Temperature drops




bubbles, plasma, MHD




→ Electroweak Baryogenesis

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

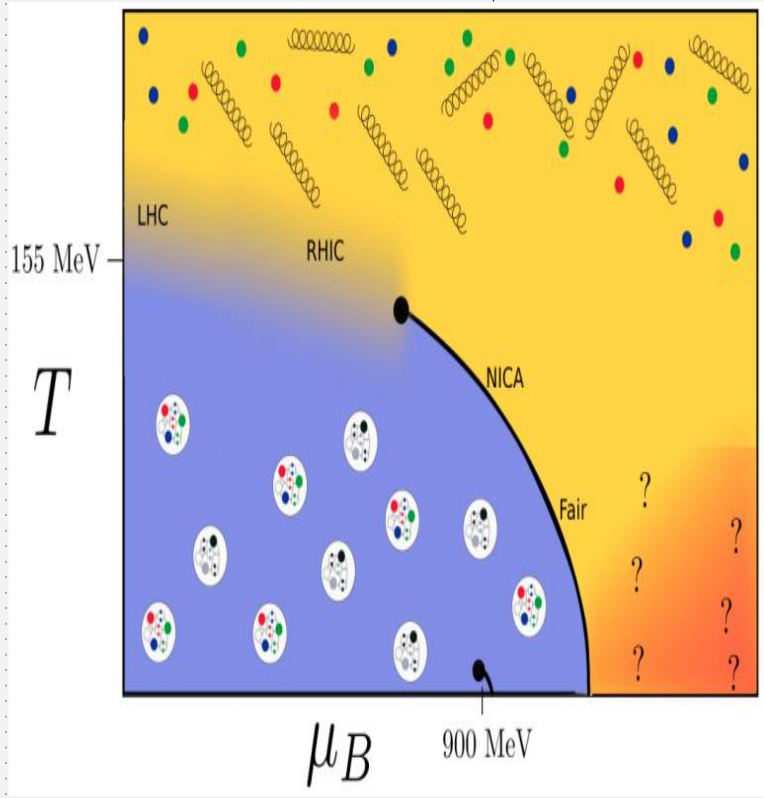
Morrissey,Ramsey-Musolf, NJP [1206.2942]

# Generic Features

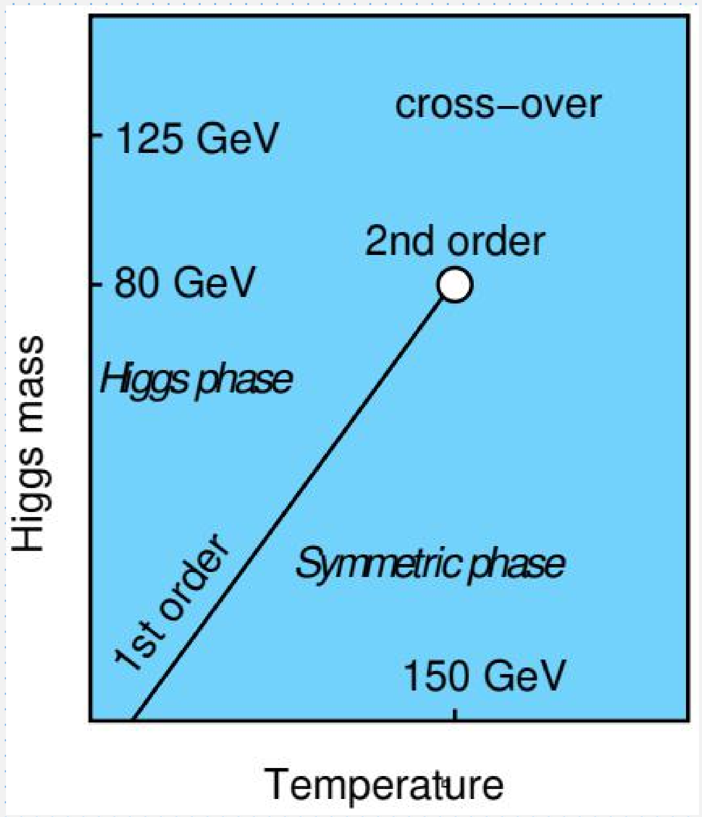
- LIGO (~100Hz) : (~PeV - EeV)
- LISA, Taiji, Tianqin: ~mHz : (~100GeV)
- PTA: nHz (~100MeV)

QCD-scale PT

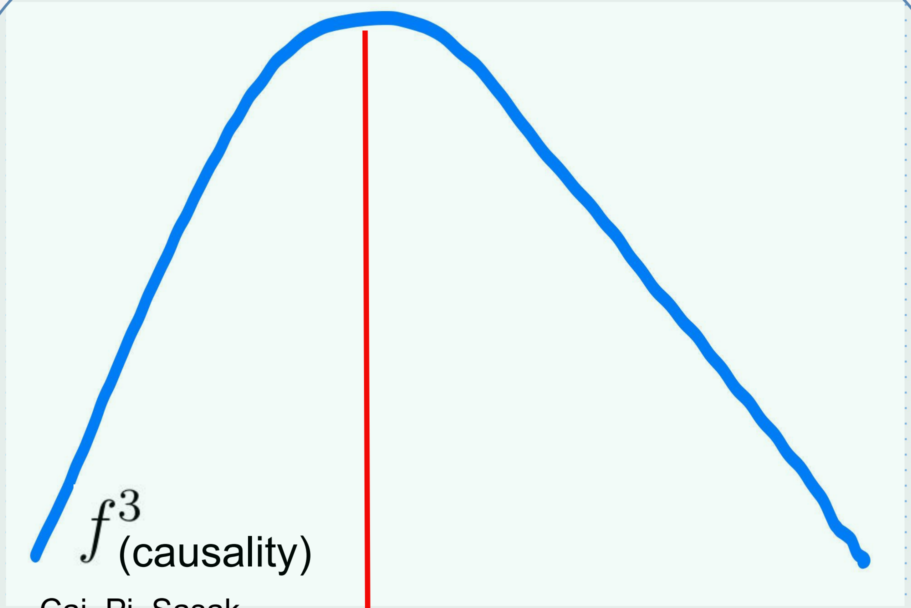
EWPT




Guenther [2010.15503]




Hindmarsh et al SciPost Phys.Lect.Notes [2008.09136]




Cai, Pi, Sasak, PRD [1909.13728]

$$f_{\rm peak} \sim 10^{-3}{\rm Hz} \left(\frac{g_s(T_*)}{100}\right)^{1/6} \left(\frac{T}{100{\rm GeV}}\right)$$

typical length scale

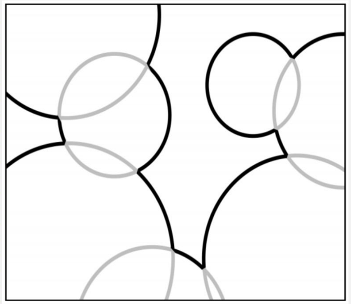
tells PT temperature
(symmetry breaking scale)

# The GW Spectra

**Energy density Spectrum**

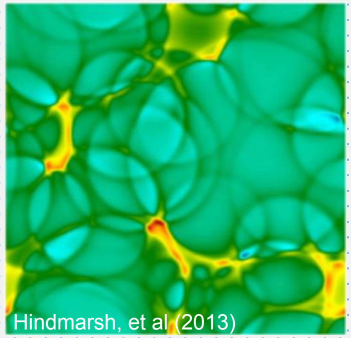
$$\Omega_{\rm GW}(f) = \frac{d\rho_{\rm GW}}{\rho_c d\log f}$$

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

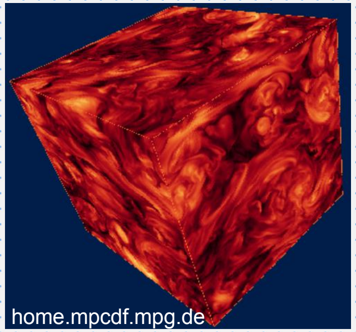



$$\Omega_{\rm sw}(f)h^2 = 2.65\times10^{-6}\left(\frac{H_{\rm pt}}{\beta}\right)\left(\frac{\kappa_{\rm sw}\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{1/3} \times v_w\left(\frac{f}{f_{\rm sw}}\right)^3\left(\frac{7}{4+3(f/f_{\rm sw})^2}\right)^{7/2}\Upsilon(\tau_{\rm sw}),$$

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

HG, Sinha, Vagie, White, JCAP [2007.08537]

MHD



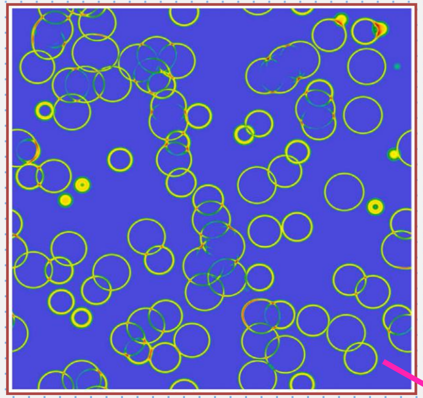

$$h^2\Omega_{\rm turb}(f) = 3.35\times10^{-4}\left(\frac{H_*}{\beta}\right)\left(\frac{\kappa_{\rm turb}\,\alpha}{1+\alpha}\right)^{\frac{3}{2}}\left(\frac{100}{g_*}\right)^{1/3} v_w\,S_{\rm turb}(f)$$

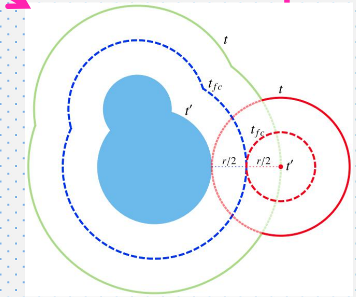
Chiara Caprini et al JCAP [1512.06239]

# Sound Waves: Modelling

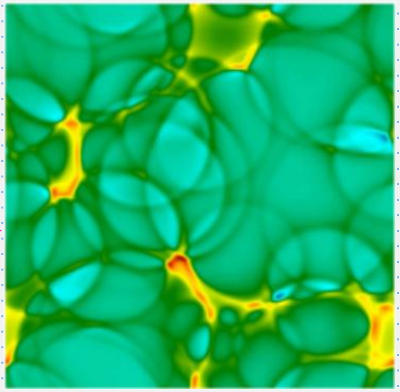
## Sound Shell Model

Hindmarsh, PRL [1608.04735]
Hindmarsh, Hijazi, JCAP [1909.10040]
HG, Sinha, Vagie, White, JCAP [2007.08537]
Cai, Wang, Yuwen, PRD Letter [2305.00074]
Pol, Procacci, Caprini [2308.12943]



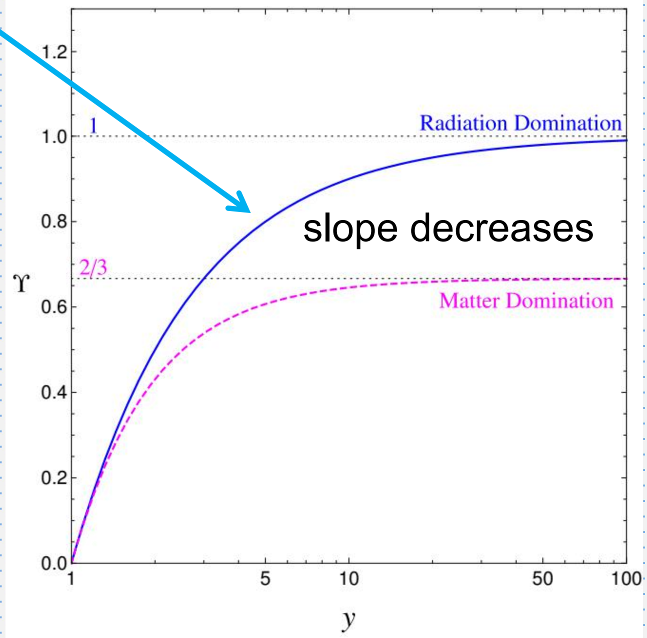


$$v^i_{\mathbf{q}} = \sum_{n=1}^{N_b} v^{i(n)}_{\mathbf{q}}$$



$$\Upsilon(\tau_{\rm sw})$$

- Less than 1 for finite lifetime of sound waves (Previous formula corresponds to infinite lifetime)
- Dependent on expansion rate
- Increasingly damped production due to expansion




HG, Sinha, Vagie, White, JCAP [2007.08537]

Reduces to Ellis, Lewicki, No, JCAP [2003.07360] for very small lifetime

# 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 | $9.2 \times 10^{-9}$ | $8.8 \times 10^{-9}$ | $1.0 \times 10^{-8}$ | $7.2 \times 10^{-9}$ |
| 1 | $1.0 \times 10^{-8}$ | $8.4 \times 10^{-9}$ | $5.0 \times 10^{-9}$ | ... |
| 10 | $4.0 \times 10^{-9}$ | $6.3 \times 10^{-9}$ | ... | ... |

no sensitivity

Sound Waves

95% CL UL

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

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

Jiang, Huang, JCAP [2203.11781]

Yu, Wang, PRD [2211.13111]



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

# 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]


Classification according to the symmetries

Classification according to the problems

| Models | Strong $1^{st}$ 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) | ✓ | ✓ | ✓ | ✓ |

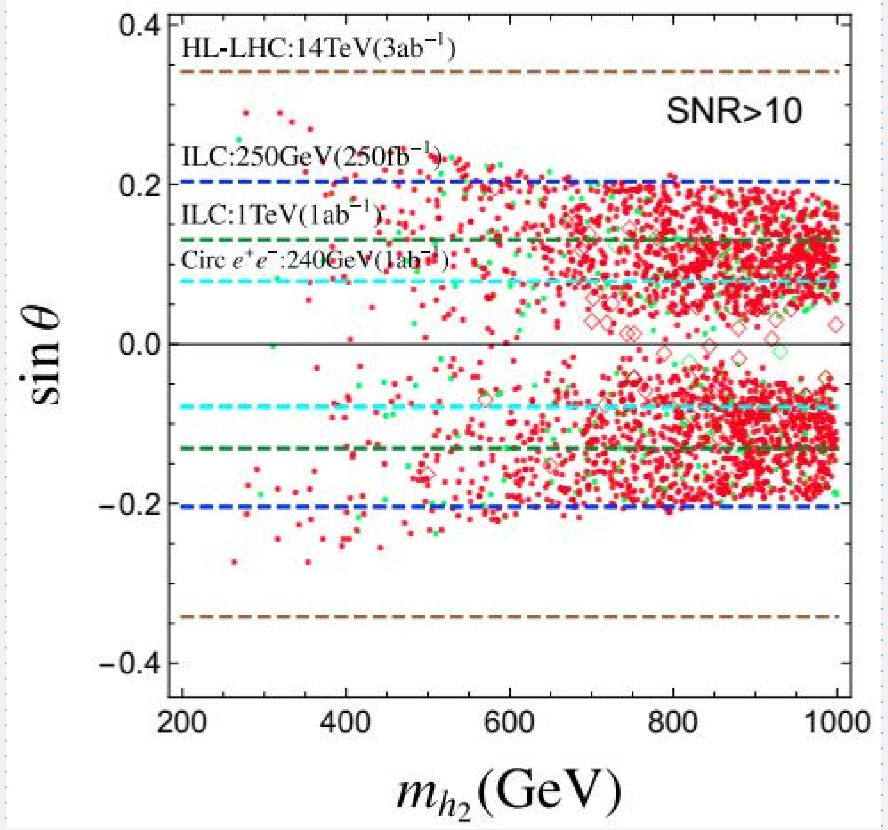
Ghosh,HG,Han,Liu, JHEP [2012.09758]

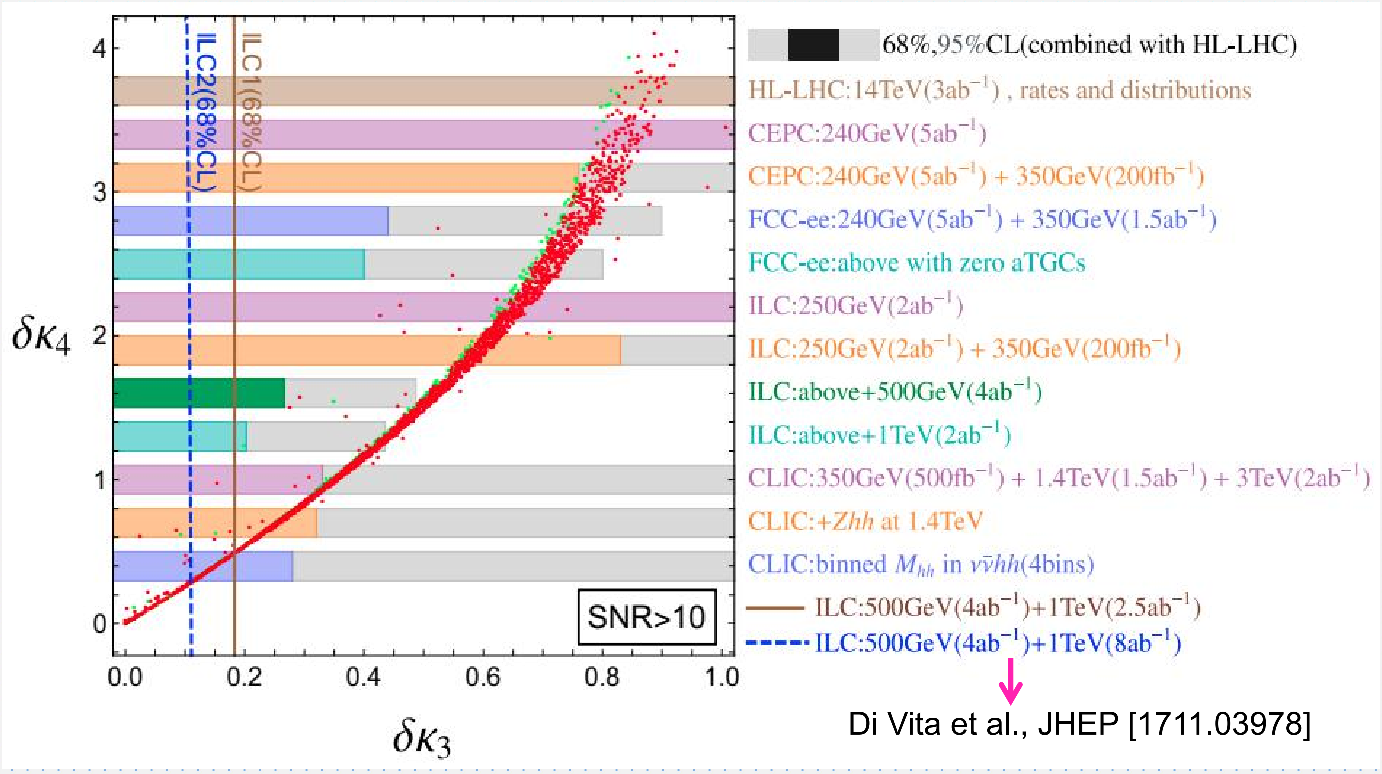
# Collider and GW Complementarity

- First order EWPT achievable in simplest SM+Singlet model
- Correlation and complementarity between collider and GW probes

h1: the Higgs
h2: heavier scalar

$$\Delta\mathcal{L} = -\frac{1}{2}\frac{m_{h_1}^2}{v}(1+\delta\kappa_3)h_1^3 - \frac{1}{8}\frac{m_{h_1}^2}{v^2}(1+\delta\kappa_4)h_1^4$$




Di Vita et al., JHEP [1711.03978]

Alves, Ghosh, HG, Sinha, Vagie, JHEP [1812.09333]

# Uncertainties

- Finite T effective potential calculations
- Phase transition parameter calculations
- GW spectra calculations (simulations, modellings)
- Possibly new phenomena

| $\Delta\Omega_{GW}/\Omega_{GW}$ | 4d approach | 3d approach |
|---|---|---|
| RG scale dependence | $\mathcal{O}(10^2 - 10^3)$ | $\mathcal{O}(10^0 - 10^1)$ |
| Gauge dependence | $\mathcal{O}(10^1)$ | $\mathcal{O}(10^{-3})$ |
| High-$T$ approximation | $\mathcal{O}(10^{-1} - 10^0)$ | $\mathcal{O}(10^0 - 10^2)$ |
| Higher loop orders | unknown | $\mathcal{O}(10^0 - 10^1)$ |
| Nucleation corrections | unknown | $\mathcal{O}(10^{-1} - 10^0)$ |
| Nonperturbative corrections | unknown | unknown |

Croon,Gould,Schicho,Tenkanen,White, JHEP [2009.10080]

| Effect(fixed wall velocity) | Range of error (medium) | Range of error (low) | Type of error |
|---|---|---|---|
| Transition temperature | $\mathcal{O}(10^{-4}\text{–}10^1)$ | $\mathcal{O}(10^{-1}\text{–}10^0)$ | Random |
| Mean bubble separation | $\mathcal{O}(0\text{–}10^{-1})$ | $\mathcal{O}(10^{-1}\text{–}10^0)$ | Suppression |
| Fluid velocity | $\mathcal{O}(10^{-2}\text{–}10^0)$ | $\mathcal{O}(10^{-2}\text{–}10^0)$ | Random |
| Finite lifetime | $\mathcal{O}(10^{-3}\text{–}10^{-1})$ | $\mathcal{O}(10^1\text{–}10^3)$ | Enhancement |
| Vorticity effects | $\mathcal{O}(10^{-1}\text{–}10^0)$ | – | Random |

HG,Sinha,Vagie,White, JHEP [2103.06933]

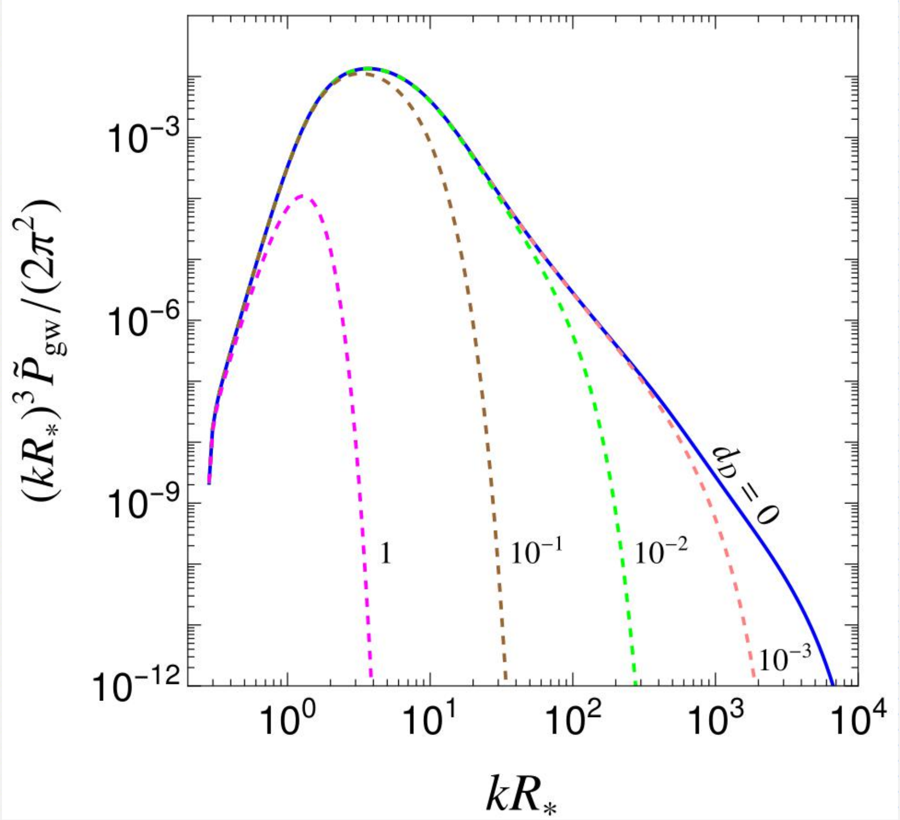
| Uncertainty | pre-factor1 | pre-factor2 | pre-factor3 |
|---|---|---|---|
| $T_p$ | 0.003% | 0.003% | 0.002% |
| $\beta R^*$ | 8.1% | 7.9% | 5.9% |
| $N_{tot}$ | 11.4% | 11.0% | 9.8% |
| $f_{\beta R^*}^{peak}$ | 11.8% | 12.0% | 14.1% |
| $\Omega_{GW}h^2_{\beta R^*}$ | 37.6% | 36.5% | 28.9% |
| $f_{sim}^{peak}$ | 36.4% | 36.4% | 35.1% |
| $\Omega_{GW}h^2_{sim}$ | 334.0% | 330.8% | 336.7% |

HG, Xiao, Yang, Zhang [2310.04654]

# Dissipative Effects as New Observables

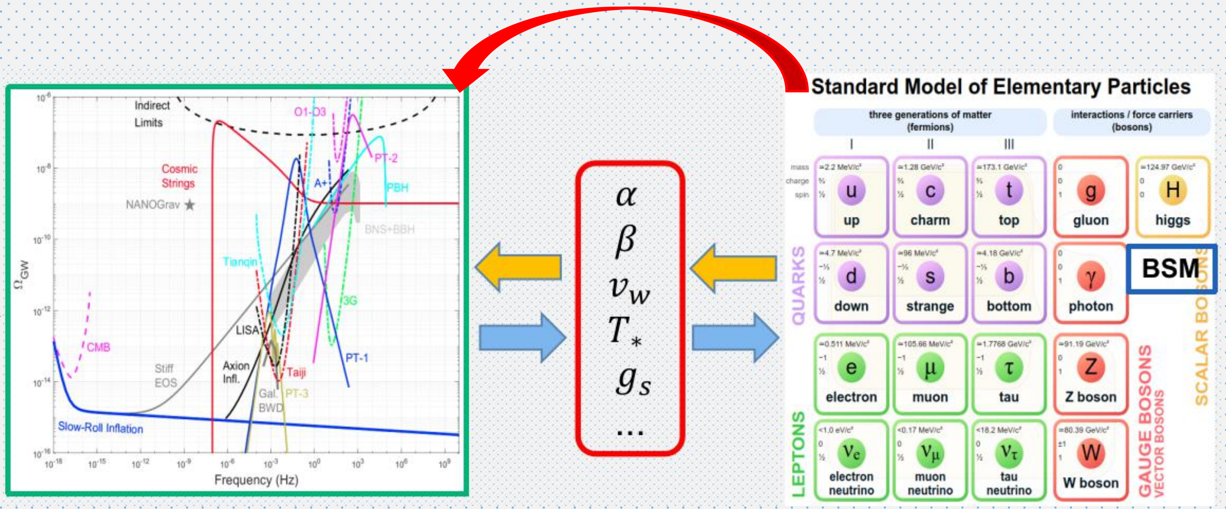
- Dissipative effects: viscosity, heat conduction
- Lead to suppression of GWs (similar to Silk damping)
- Particle physics origin of dissipations: very weak interactions
- Can be searched for at LIGO, PTA, LISA/Taiji/Tianqin ...

$$\Delta T^{ij} = -\eta\left(\frac{\partial U_i}{\partial x^j} + \frac{\partial U_j}{\partial x^i} - \frac{2}{3}\delta_{ij}\nabla\cdot\mathbf{U}\right) - \zeta\,\delta_{ij}\nabla\cdot\mathbf{U},$$
$$\Delta T^{i0} = -\chi\left(\frac{\partial T}{\partial x^i} + T\dot{U}_i\right). \quad \text{Weinberg, ApJ, 1971} \quad (1)$$




HG [2310.10927]

break the parameter degeneracy!



# GWs from Particles

**Extreme densities**

disturbances in the early universe

**As Macroscopic Objects**

(non-) topological solitons

**Environmental Effects**

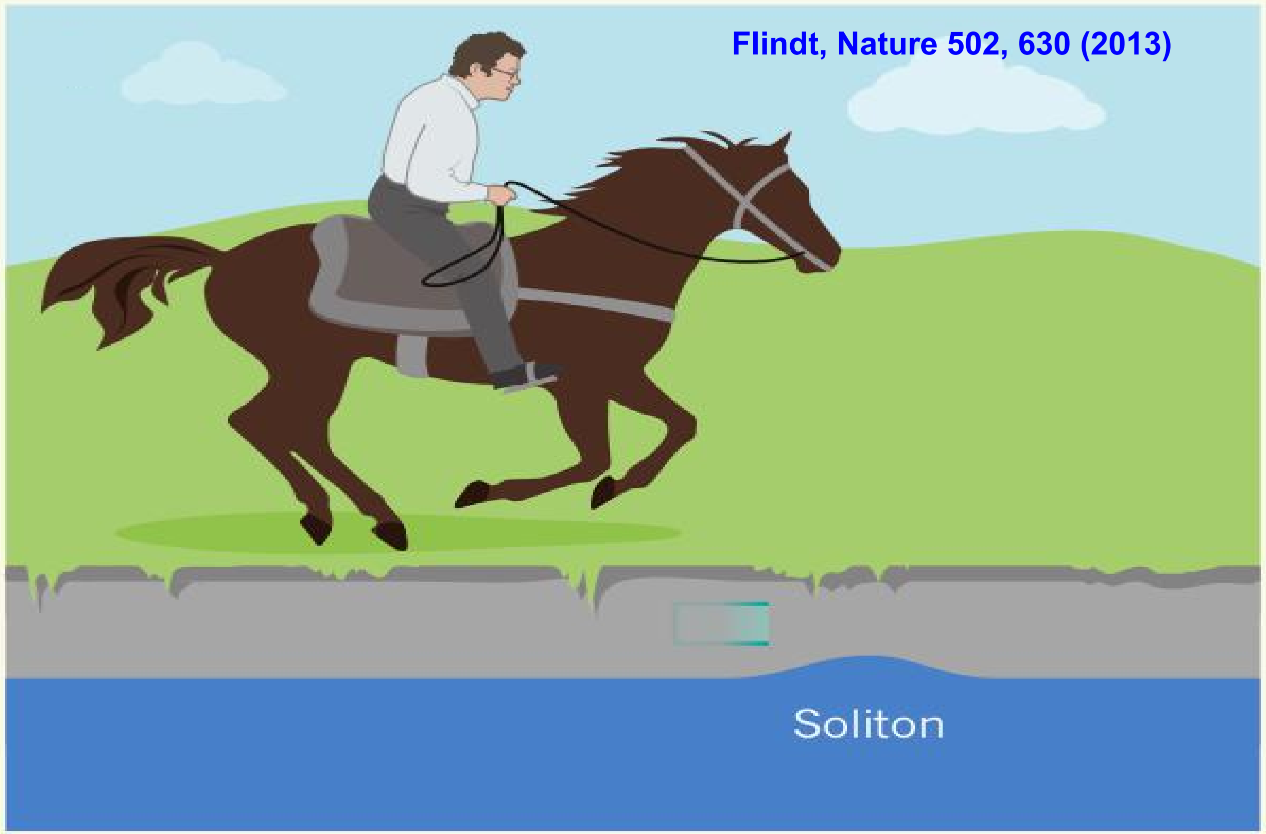
Faking GW signals (dark photon)

# 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<br>(Theory with Spontaneously Broken Symmetry)<br><br>• Global symmetry (Skyrmion, Cosmic String)<br>• Discrete symmetry (Domain wall)<br>• Local symmetry (Monopole, Cosmic String or Vortex line...)<br>• Pure gauge theory (Instanton) | Bose-Einstein Condensate<br>(of Ultralight particles)<br><br>• Galactic scale (DM Halo)<br>• Stellar scale (Boson stars) |
| Boundary | Non-Trivial (needs degenerate vacuum states) | Trivial vacuum state |
| Stabilized by | Topology (boundary field values) | Conserved Charge, and Balancing<br><br>• quantum pressure<br>• gravity (or not, Q-balls etc)<br>• 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?

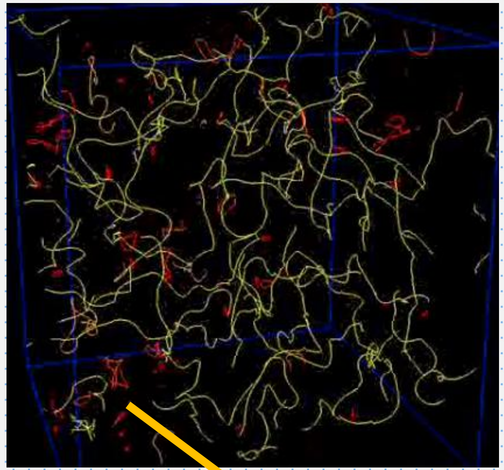
**Topology of cosmic domains and strings**

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

Blackett Laboratory, Imperial College, Prince Consort Road, Lon

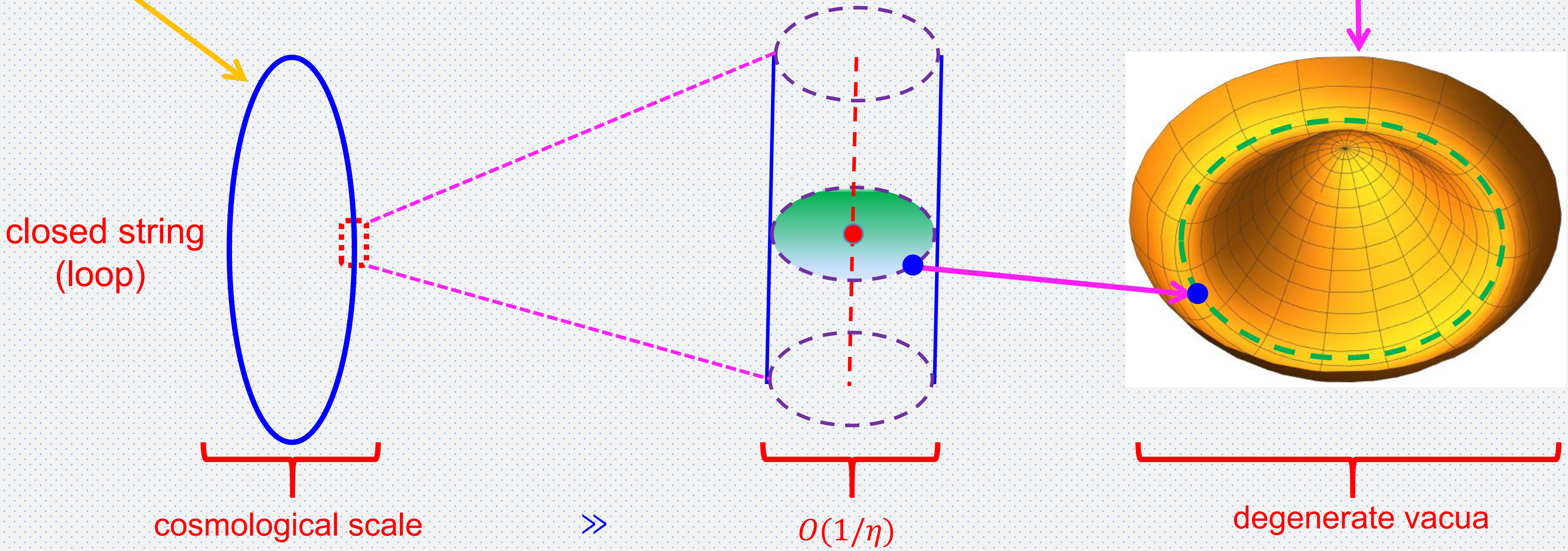
Received 11 March 1976  www.theguardian.com

# Cosmic String



**Example: the Abelian Higgs Model**

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



# 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 ($\eta$) of symmetry breaking

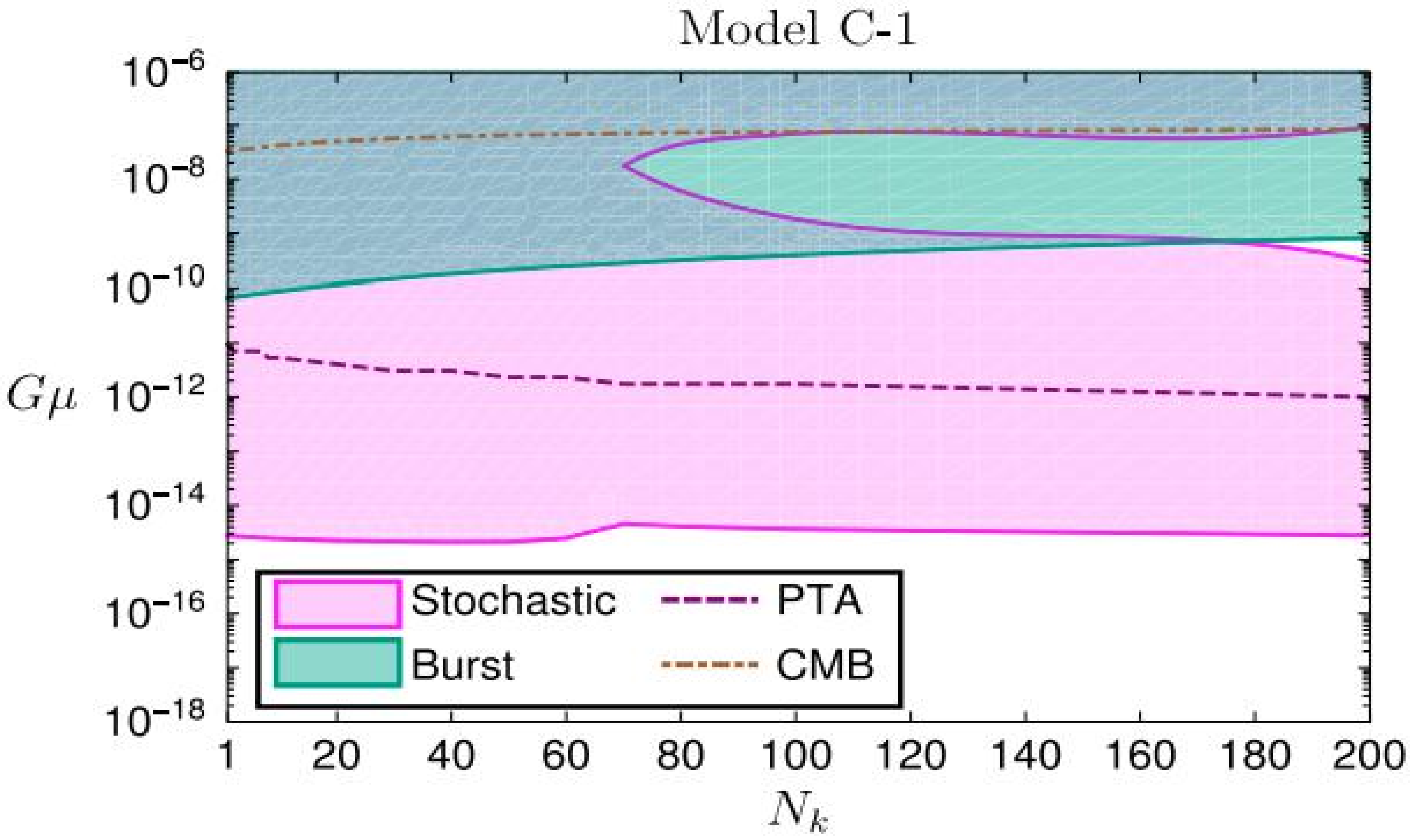
$$G\mu \sim \left(\frac{\eta}{10^{19}\mathrm{GeV}}\right)^2$$

μ: line mass density

Results from PTA Measurements

Bian, Cai, Liu, Yang, Zhou, PRD Letter [2205.07293]

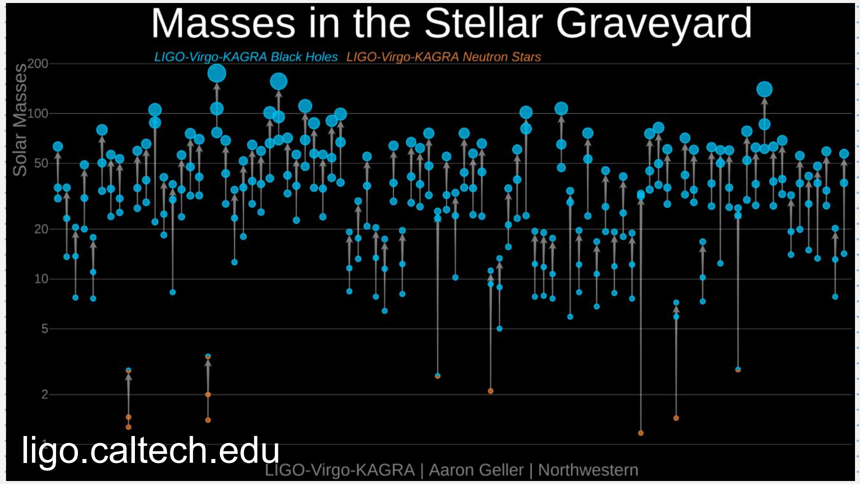
Blasi, Brdar, Schmitz, PRL [2009.06607]

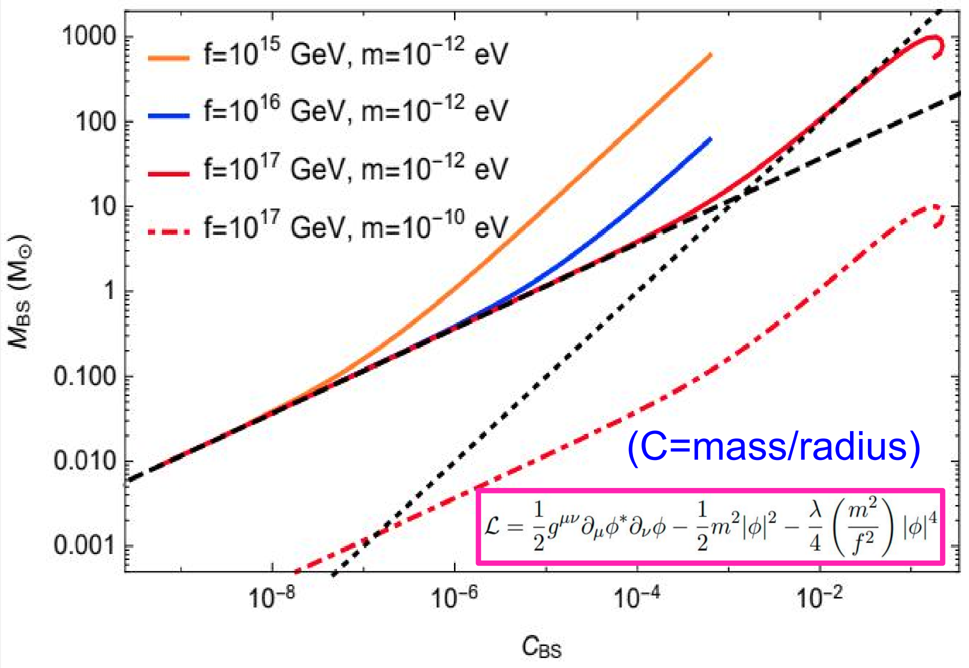



LIGO-Virgo-KAGRA collaborations, PRL [2101.12248]

# Non-Topological Solitons as Boson Stars

- Macroscopic Bose-Einstein condensate of ultralight particles
- LIGO might have detected Boson stars (Bustillo et al, PRL [2009.05376], ...)
- Difficult to distinguish between BH and BS, solution: detect a subsolar one



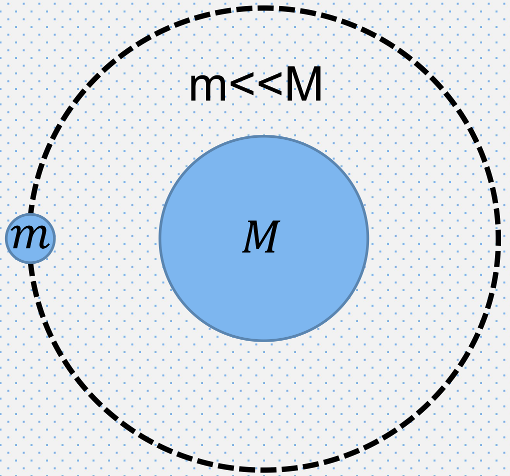

HG, Sinha, Sun, JCAP [1904.07871]

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

See, e.g., Liebling, Palenzuela, Living Rev.Rel [1202.5809]

Lee, Pang, Phys.Rept (1992)

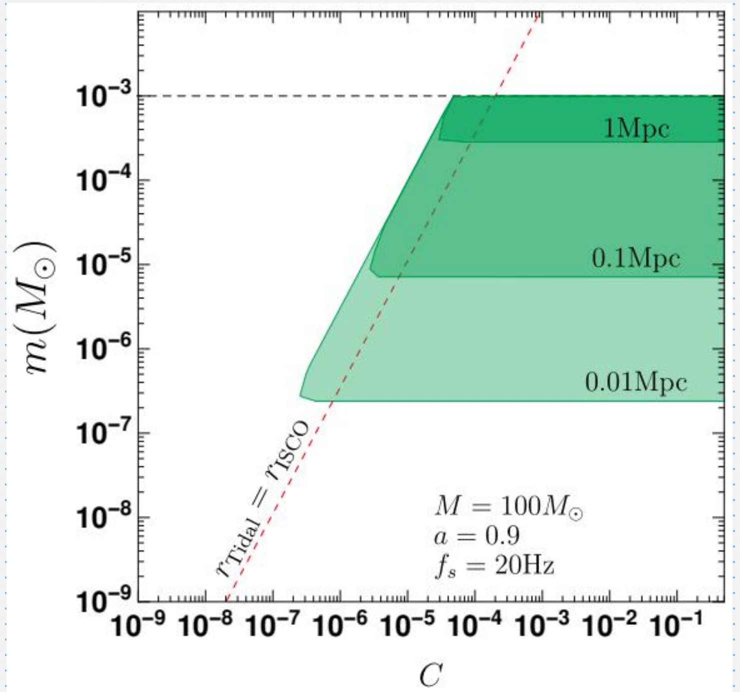
# Detection with EMRI and mini-EMRI




- Signal decreases significantly when using comparable mass binary systems
- By making one object much heavier, one can probe a much ligher companion

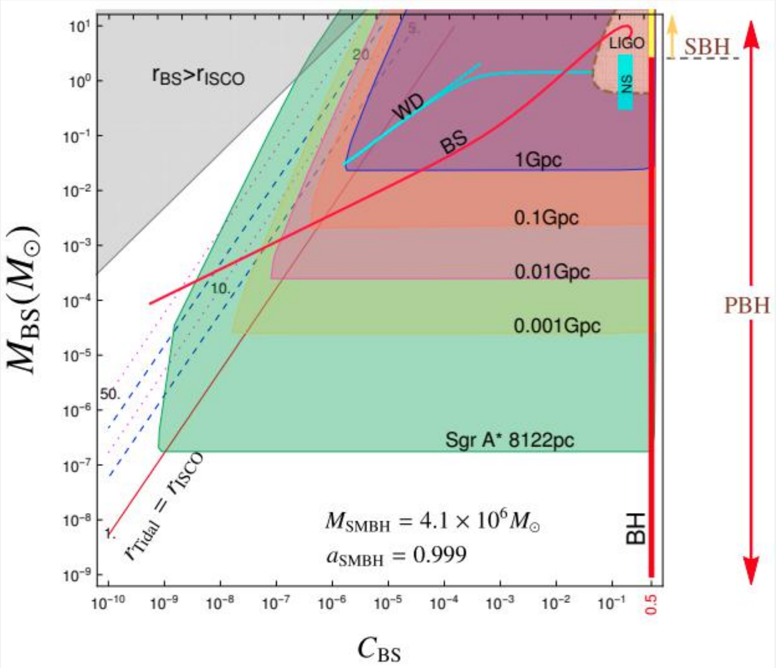
  Extreme Mass Ratio Inspirals (EMRIs), key target of LISA, Taiji, Tianqin
- LIGO can detect mini-EMRIs

LIGO ("mini-EMRI")




HG, A. Miller [2205.10359]

LISA, Taiji, Tianqin (EMRI)




HG, Sinha, Sun, JCAP [1904.07871]
HG, Shu, Zhao, PRD [1709.03500]

# GWs from Particles

**Extreme densities**

disturbances in the early universe

**As Macroscopic Objects**

(non-) topological solitons

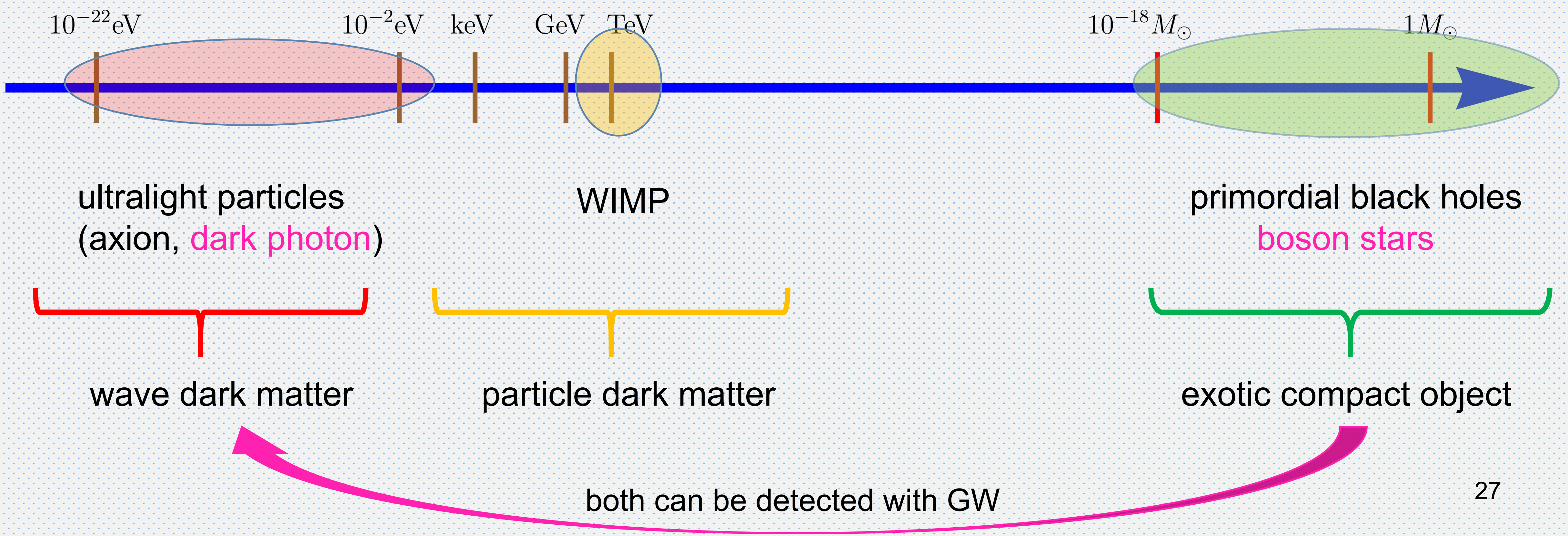
**Environmental Effects** ✓

Faking GW signals (dark photon)

See also Yong Tang's talk

# Ultralight Dark Matter

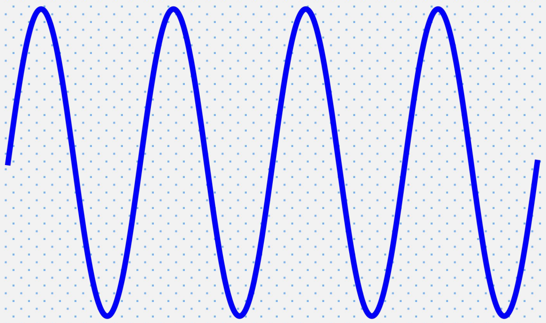
- Boson stars serve as macroscopic dark matter candidate
- So does the ultralight particle making up the boson stars



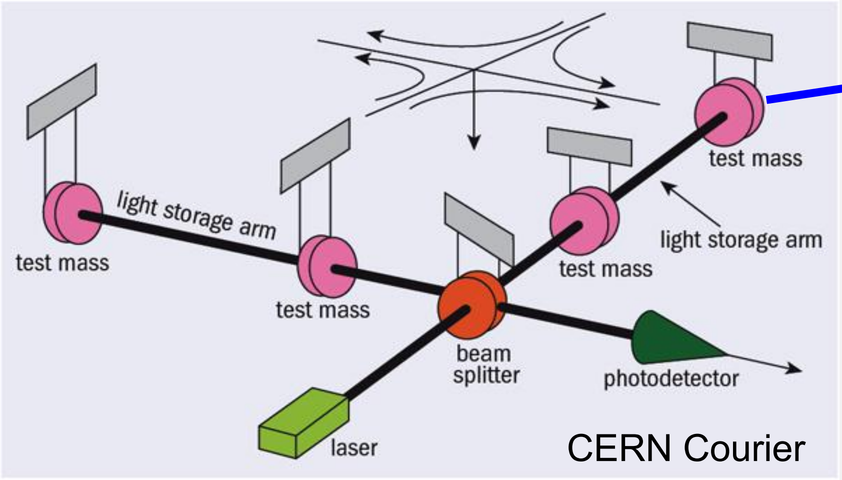
# Dark Photon Detection at LIGO

Pierce, Riles, Zhao, PRL [1504.07237]

a single dark photon



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




silicon mirror

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

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

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

acceleration

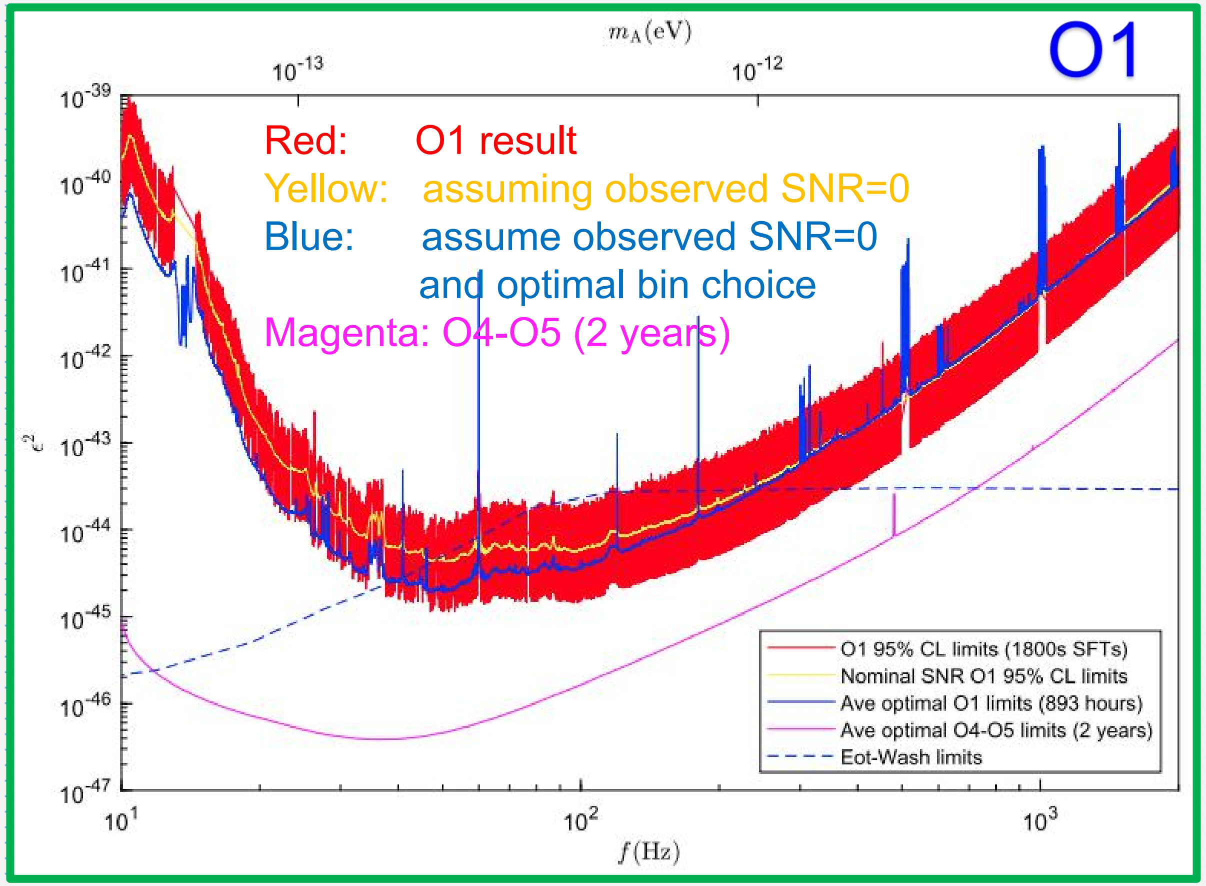
typical LIGO frequency

$$\omega_n = m_A(1+\frac{1}{2}v_n^2) = 2\pi\times(100\mathrm{Hz}) \approx 4\times10^{-13}\mathrm{ev}$$

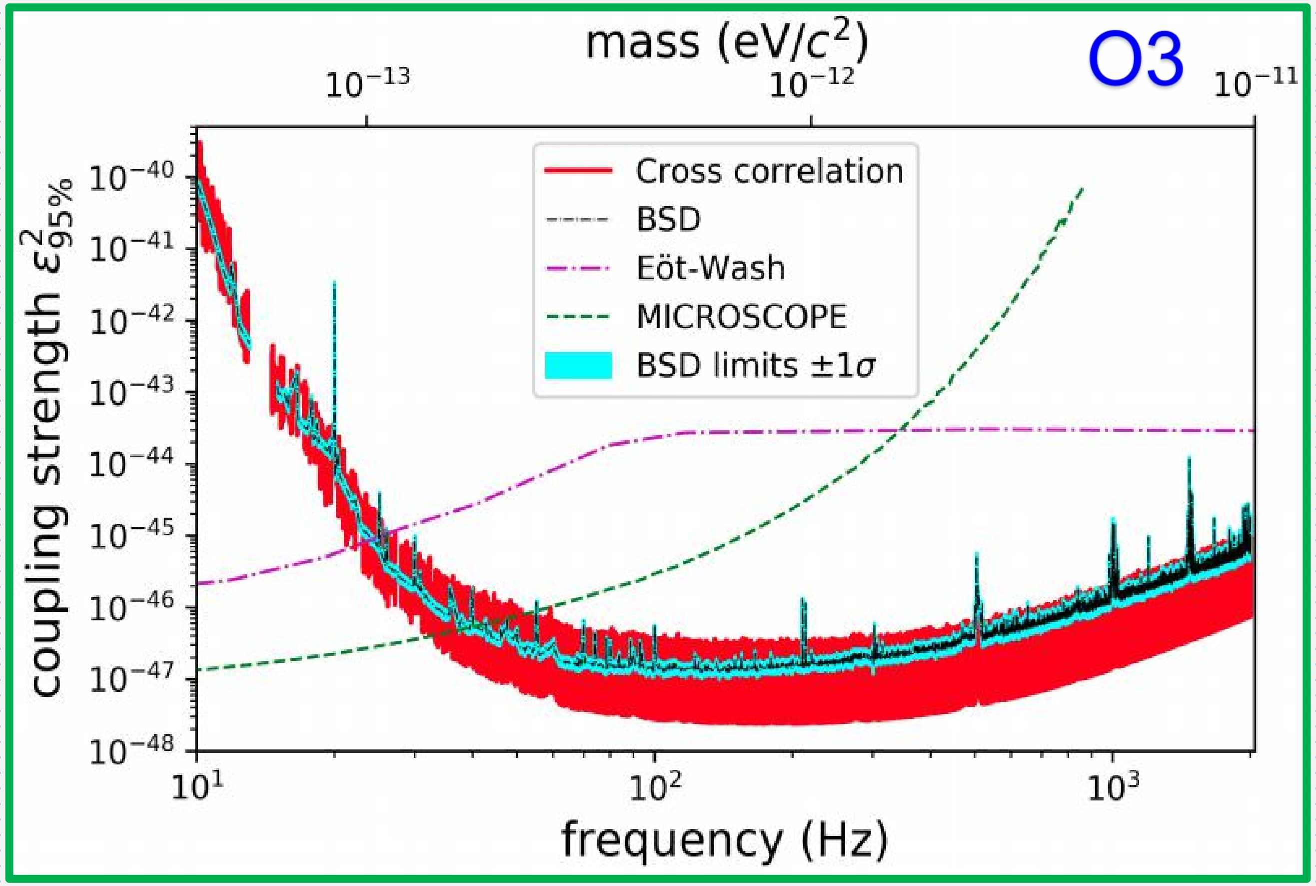
typical dark photon mass LIGO is sensitive to

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

# LIGO Search Results




HG, Riles, Yang, Zhao, (Nature) Commun.Phys, [1905.04316]




LIGO-Virgo-KAGRA Collaborations, PRD [2105.13085]

GEO600: Vermeulen, et al, Nature [2103.03783]

LISA/Taiji/Tianqin: Yuan,Jiang,Huang, PRD [2204.03482], Yu,Yao,Tang,Wu, PRD [2307.09197], Miller, Mendes, PRD [2301.08736]

# Summary

GW provides new perspectives in BSM searches

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

# Thanks!