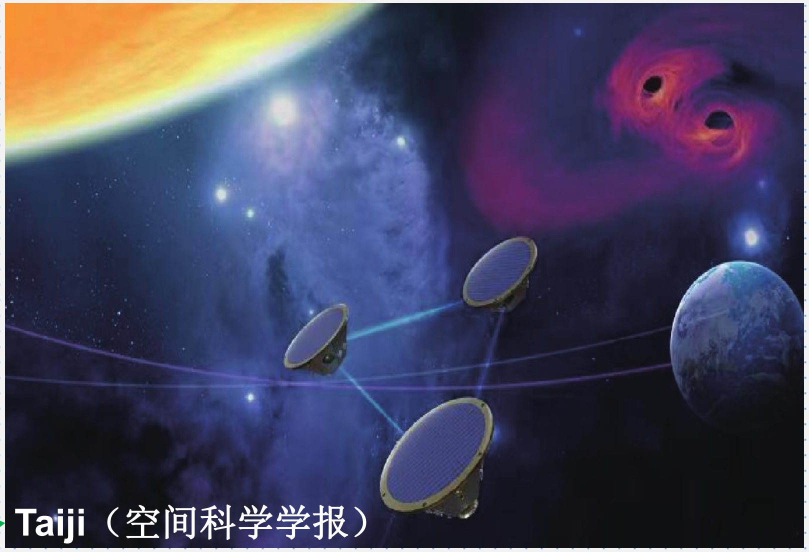
Some (of Mine) Recent Developments on BSM Probes with Gravitational Waves

Huaike Guo

Nov. 17, 2023

Gravitational Waves



LISA, Taiji, Tianqin, ...

PTA

EPTA

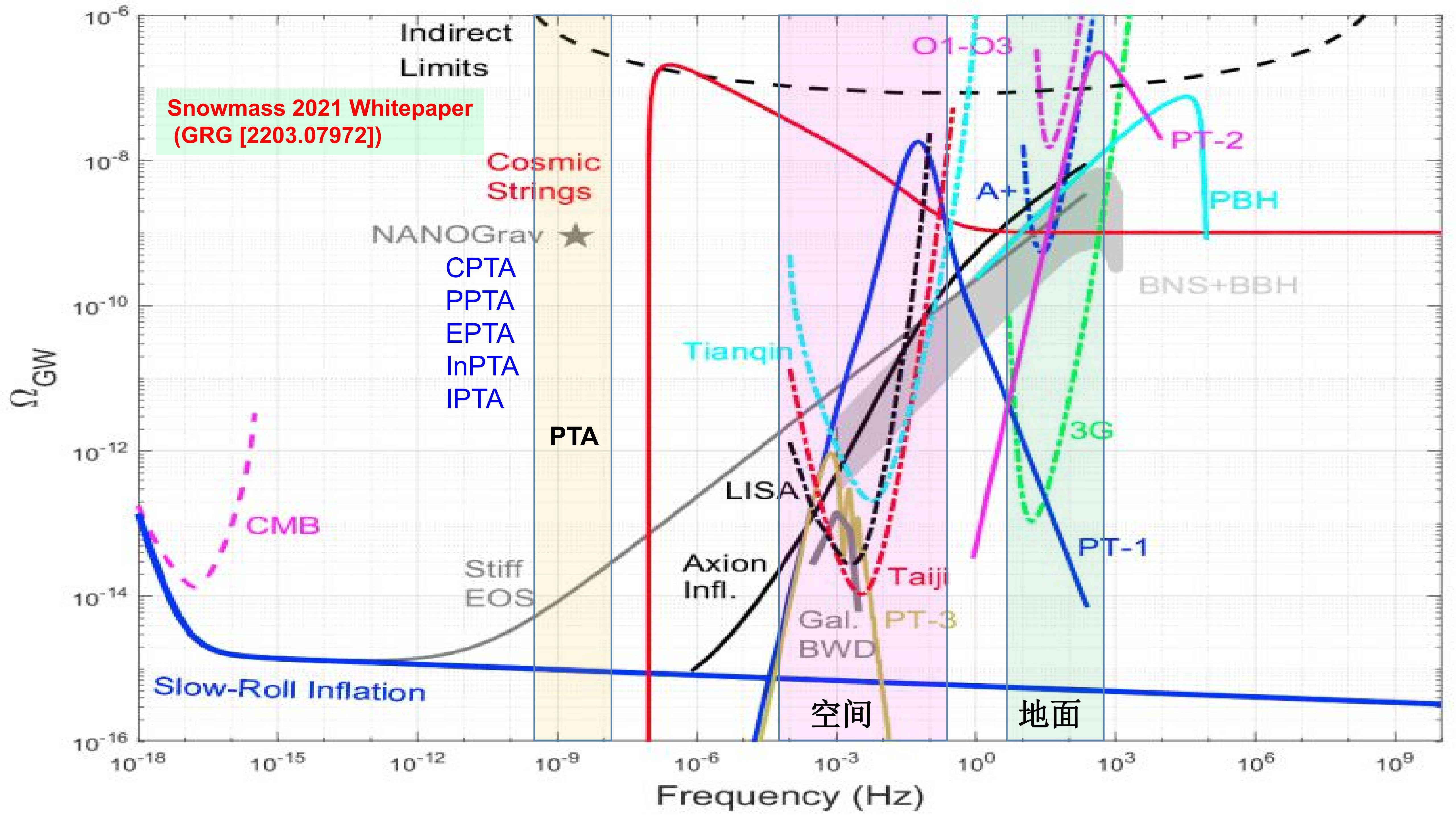
NANOGrav Physics Frontiers Center

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

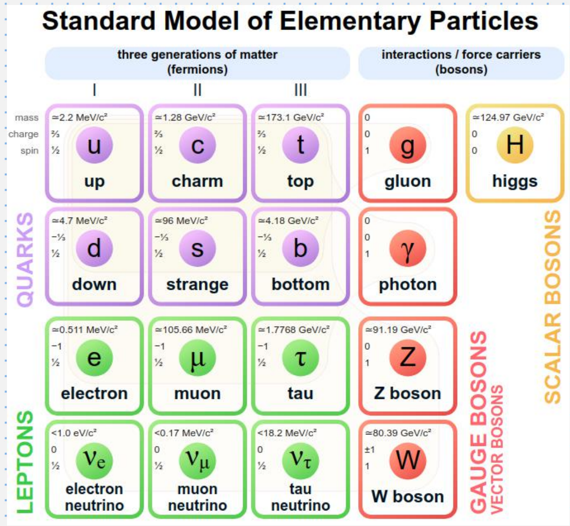


Snowmass 2021 Whitepaper
(GRG [2203.07972])
Indirect Limits
Cosmic Strings
NANOGrav
CPTA
PPTA
EPTA
InPTA
IPTA
PTA
CMB
Stiff EOS
Slow-Roll Inflation
Axion Infl.
LISA
Tianqin
Taiji
Gal. BWD
PT-3
O1-O3
A+
PT-2
PBH
BNS+BBH
3G
PT-1
空间
地面
Ω_{GW}
Frequency (Hz)

New Perspectives, with GW?

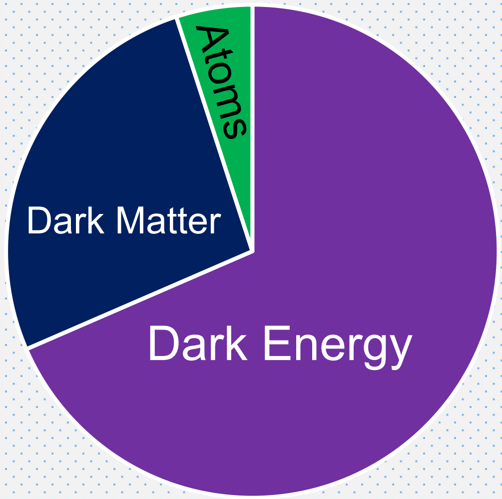
How can we reconcile the standard models of particle physics and cosmology?

Particle Physics



Physics Beyond the SM?

Cosmology

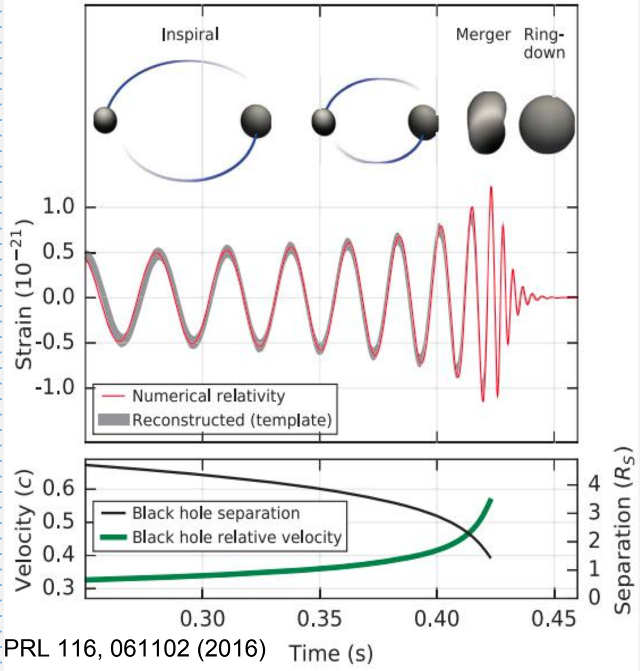


Why more matter than anti-matter? (phase transitions, solitons)

What is dark matter? (solitons, ultralight particles)

GWs from Particles?

GW generation requires macroscopic mass/energy



PRL 116, 061102 (2016)

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

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

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

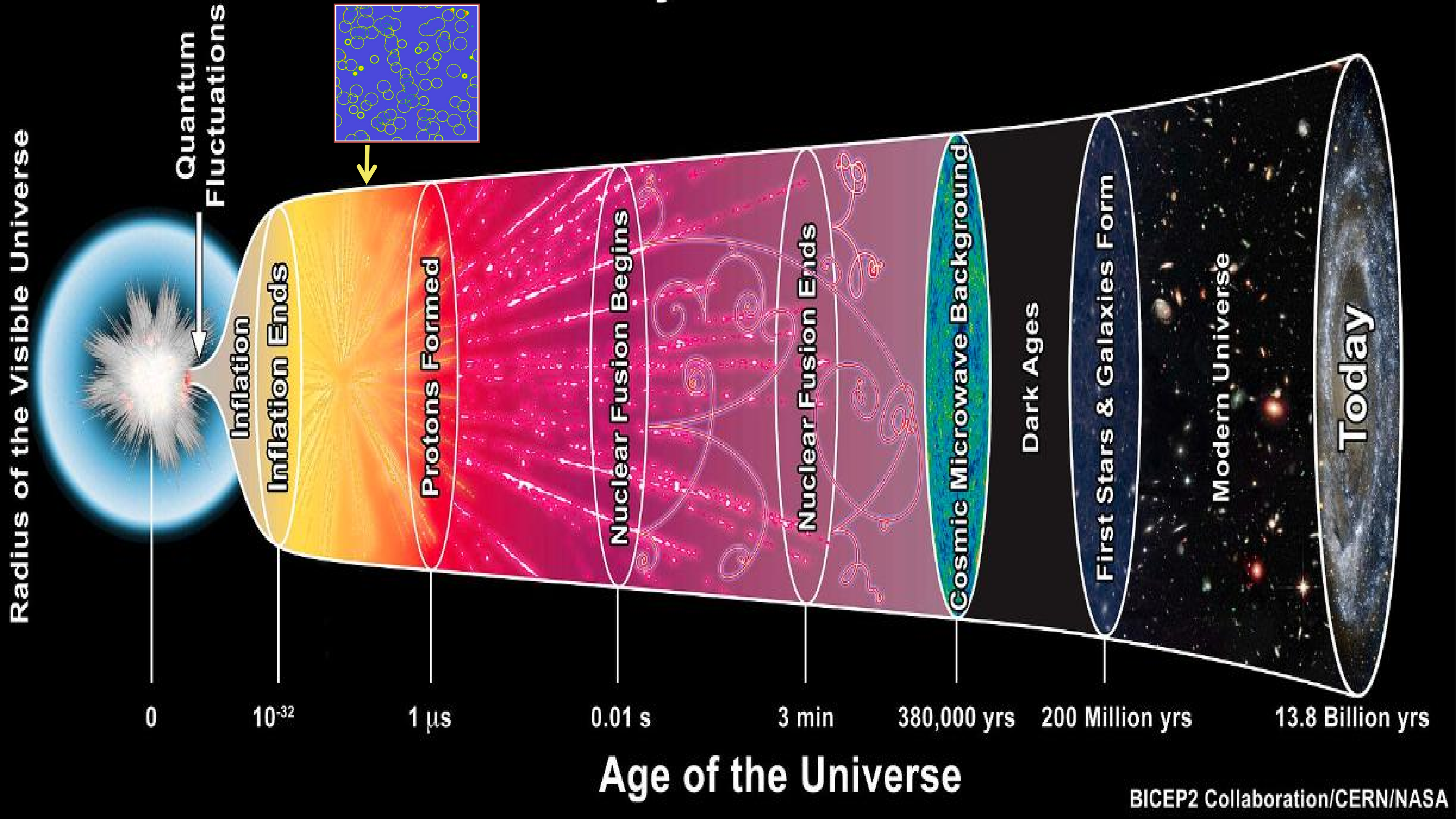
As Macroscopic Objects

(non-) topological solitons

Environmental Effects

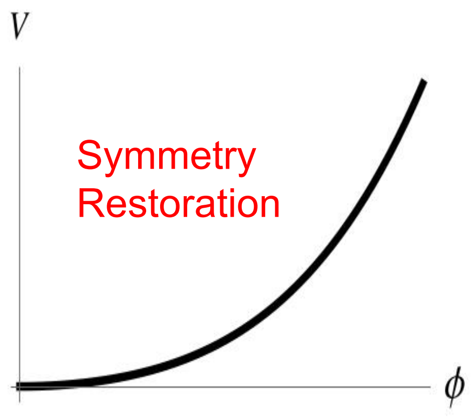
Faking GW signals (dark photon)

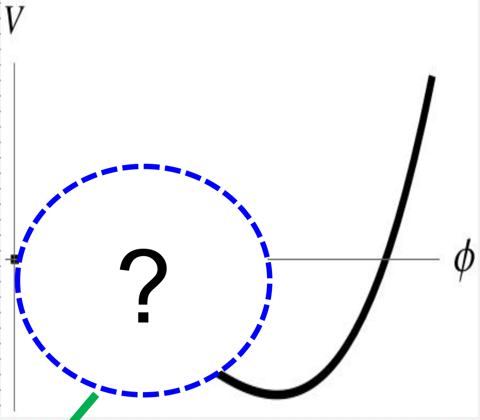
See also Jan Tristram Acuña, Ryusuke Jinno, Yue-Lin Sming Tsai’s talks

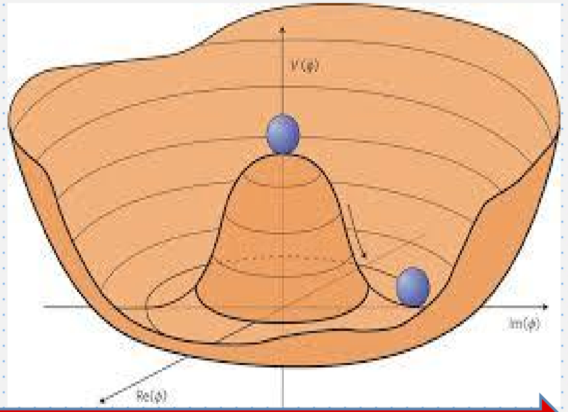


Radius of the Visible Universe
Quantum Fluctuations
Inflation
Inflation Ends
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Dark Ages
First Stars & Galaxies Form
Modern Universe
Today
0
10^{-32}
1 μs
0.01 s
3 min
380,000 yrs
200 Million yrs
13.8 Billion yrs
Age of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

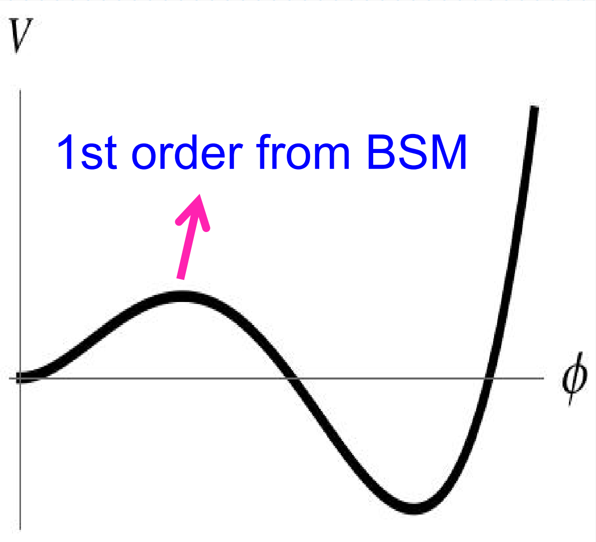
Electroweak Phase Transition



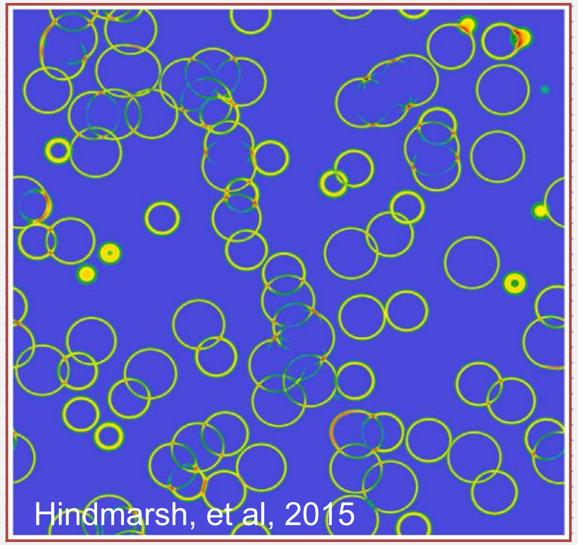




Temperature drops



bubbles, plasma, MHD



→ Electroweak Baryogenesis

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

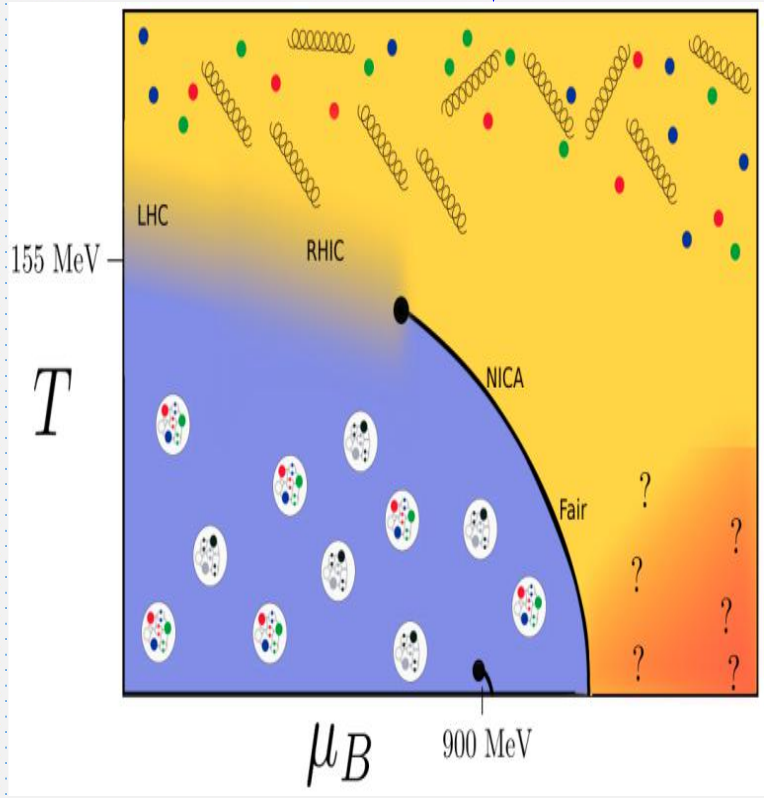
Morrissey,Ramsey-Musolf, NJP [1206.2942]

Generic Features

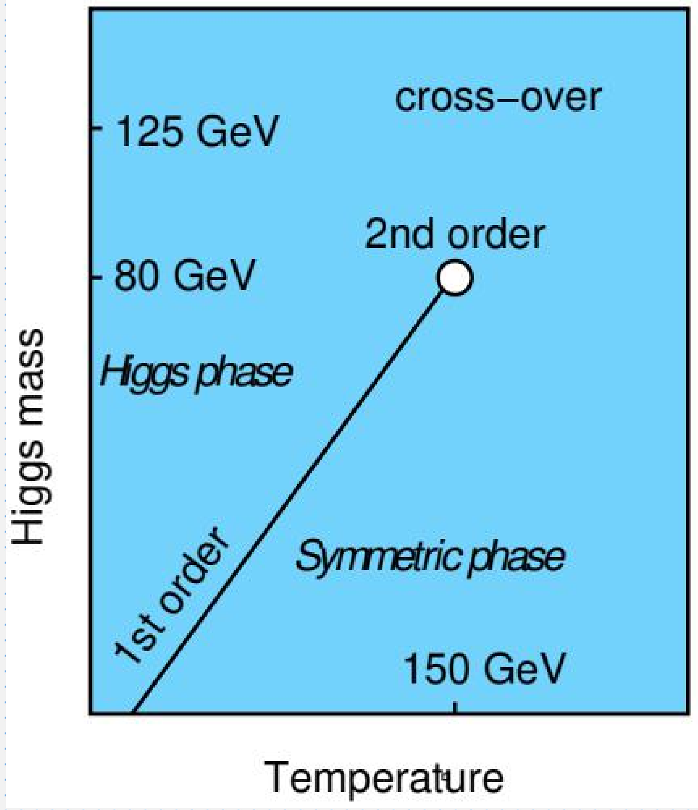
- LIGO (~100Hz) : (~PeV - EeV)
- LISA, Taiji, Tianqin: ~mHz : (~100GeV)
- PTA: nHz (~100MeV)

QCD-scale PT

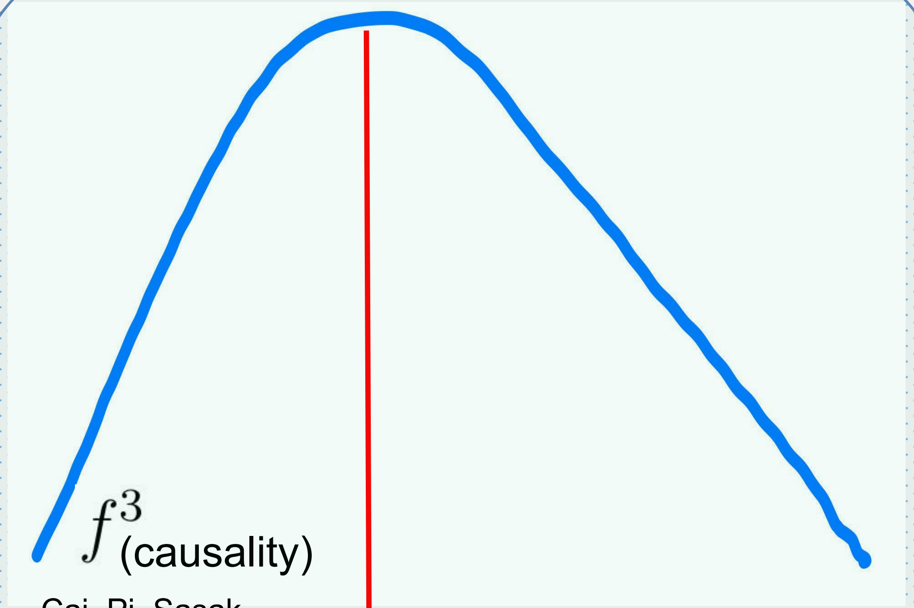
EWPT



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

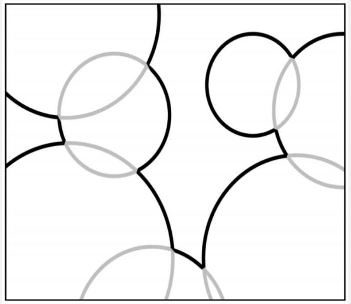
tells PT temperature (symmetry breaking scale)

The GW Spectra

Energy density Spectrum

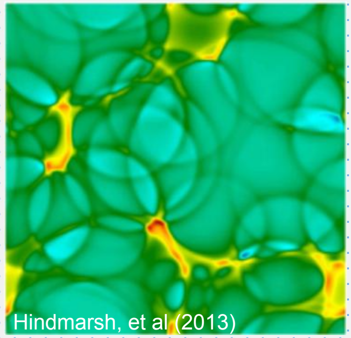
$$\Omega_{\rm GW}(f) = \frac{d\rho_{\rm GW}}{\rho_c d\log f}$$

bubble collision



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

sound waves

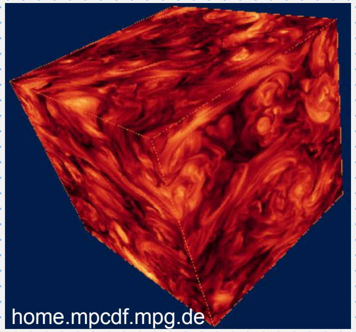


$$\Omega_{\rm sw}(f)h^2 = 2.65\times 10^{-6}\left(\frac{H_{\rm pt}}{\beta}\right)\left(\frac{\kappa_{\rm sw}\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{1/3} \times v_w\left(\frac{f}{f_{\rm sw}}\right)^3\left(\frac{7}{4+3(f/f_{\rm sw})^2}\right)^{7/2}\Upsilon(\tau_{\rm sw}),$$

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

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

MHD



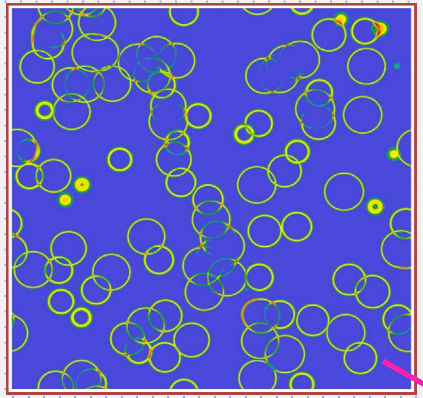
$$h^2\Omega_{\rm turb}(f) = 3.35\times 10^{-4}\left(\frac{H_*}{\beta}\right)\left(\frac{\kappa_{\rm turb}\,\alpha}{1+\alpha}\right)^{\frac{3}{2}}\left(\frac{100}{g_*}\right)^{1/3} v_w\, S_{\rm turb}(f)$$

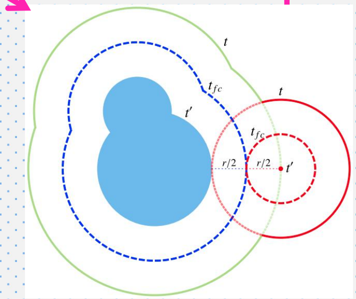
Chiara Caprini et al JCAP [1512.06239]

Sound Waves: Modelling

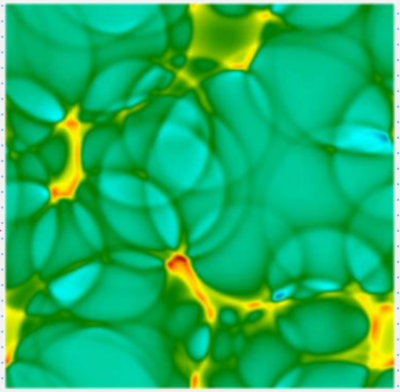
Sound Shell Model

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]



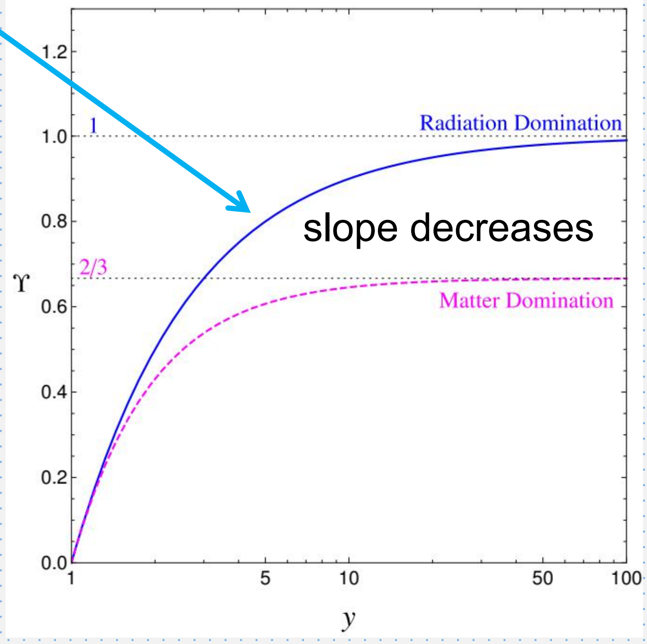


$$v^i_{\mathbf{q}} = \sum_{n=1}^{N_b} v^{i(n)}_{\mathbf{q}}$$



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

- 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

foreground: $\Omega_{\rm CBC} = \Omega_{\rm ref}(f/f_{\rm ref})^{2/3}$

$f_{\rm ref} = 25$ Hz

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

$$\Omega_{\rm BPL}(f) = \Omega_* \left(\frac{f}{f_*}\right)^{n_1}\left[1+\left(\frac{f}{f_*}\right)^{\Delta}\right]^{(n_2-n_1)/\Delta}$$

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

Jiang, Huang, JCAP [2203.11781]

Yu, Wang, PRD [2211.13111]

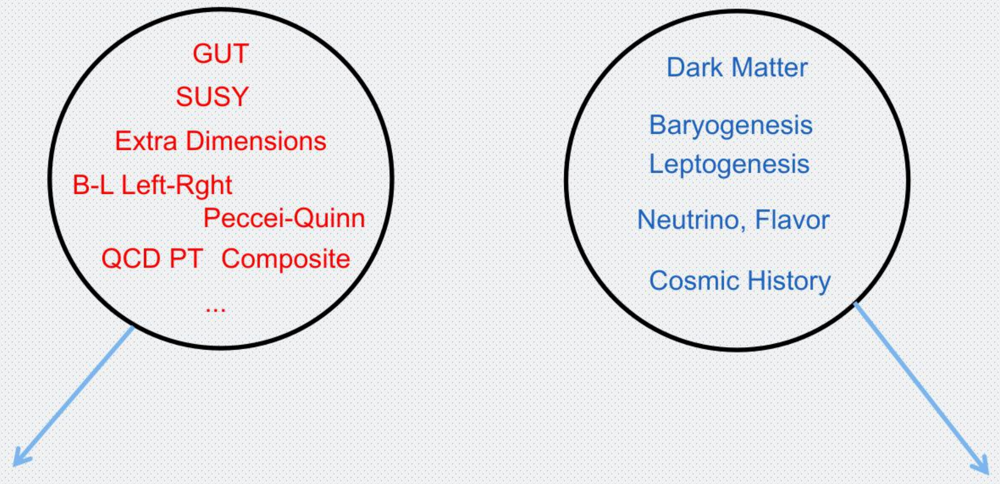
Romero,Martinovic,Callister,HG,Martínez,Sakellariadou,Yang,Zhao, PRL [2102.01714]

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 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]	✓	✓	✓	✗
$\mathrm{U(1)_D}$ (no interaction with SM) [55]	✓	✓	✓	✗
$\mathrm{U(1)_D}$ (Higgs Portal) [56]	✓	✓	✓	
$\mathrm{U(1)_D}$ (Kinetic Mixing) [57]	✓	✓	✓	
Composite SU(7)/SU(6) [58]	✓	✓	✓	
$\mathrm{U(1)_L}$ [59]	✓	✓	✓	✗
$\mathrm{SU(2)_D} \to$ global $SO(3)$ by a doublet [60–62]			✓	✗
$\mathrm{SU(2)_D} \to \mathrm{U(1)_D}$ by a triplet [63–65]			✓	✓
$\mathrm{SU(2)_D} \to Z_2$ by two triplets [66]			✓	✗
$\mathrm{SU(2)_D} \to Z_3$ by a quadruplet [67, 68]			✓	✗
$\mathrm{SU(2)_D} \times \mathrm{U(1)_{B\text{-}L}} \to Z_2 \times Z_2$ by a quintuplet and a S_c [69]			✓	✗
$\mathrm{SU(2)_D}$ with two dark Higgs doublets [70]	✓	✓	✗	✗
$\mathrm{SU(3)_D} \to Z_2 \times Z_2$ by two triplets [62, 71]			✓	✗
$\mathrm{SU(3)_D}$ (dark QCD) (Higgs Portal) [72, 73]	✓	✓	✓	
$G_{\mathrm{SM}} \times G_{\mathrm{D,SM}} \times Z_2$ [74]	✓	✓	✓	
$G_{\mathrm{SM}} \times G_{\mathrm{D,SM}} \times G_{\mathrm{D,SM}} \cdots$ [75]	✓	✓	✓	
Current work				
$\mathrm{SU(2)_D} \to \mathrm{U(1)_D}$ (see the text)	✓	✓	✓	✓

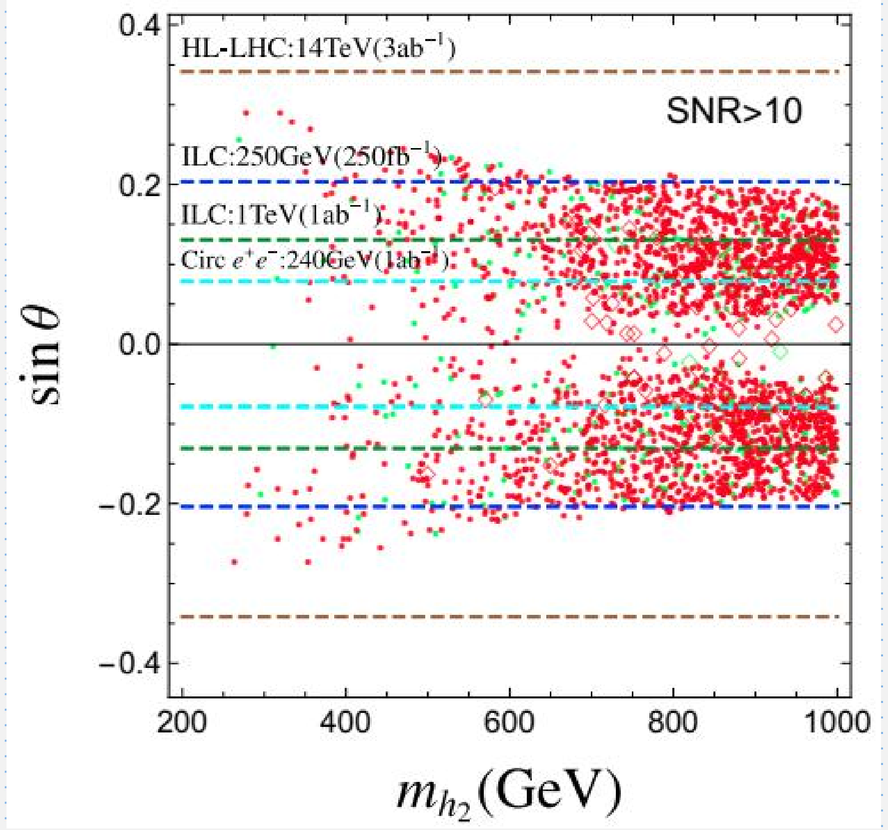
Ghosh,HG,Han,Liu, JHEP [2012.09758]

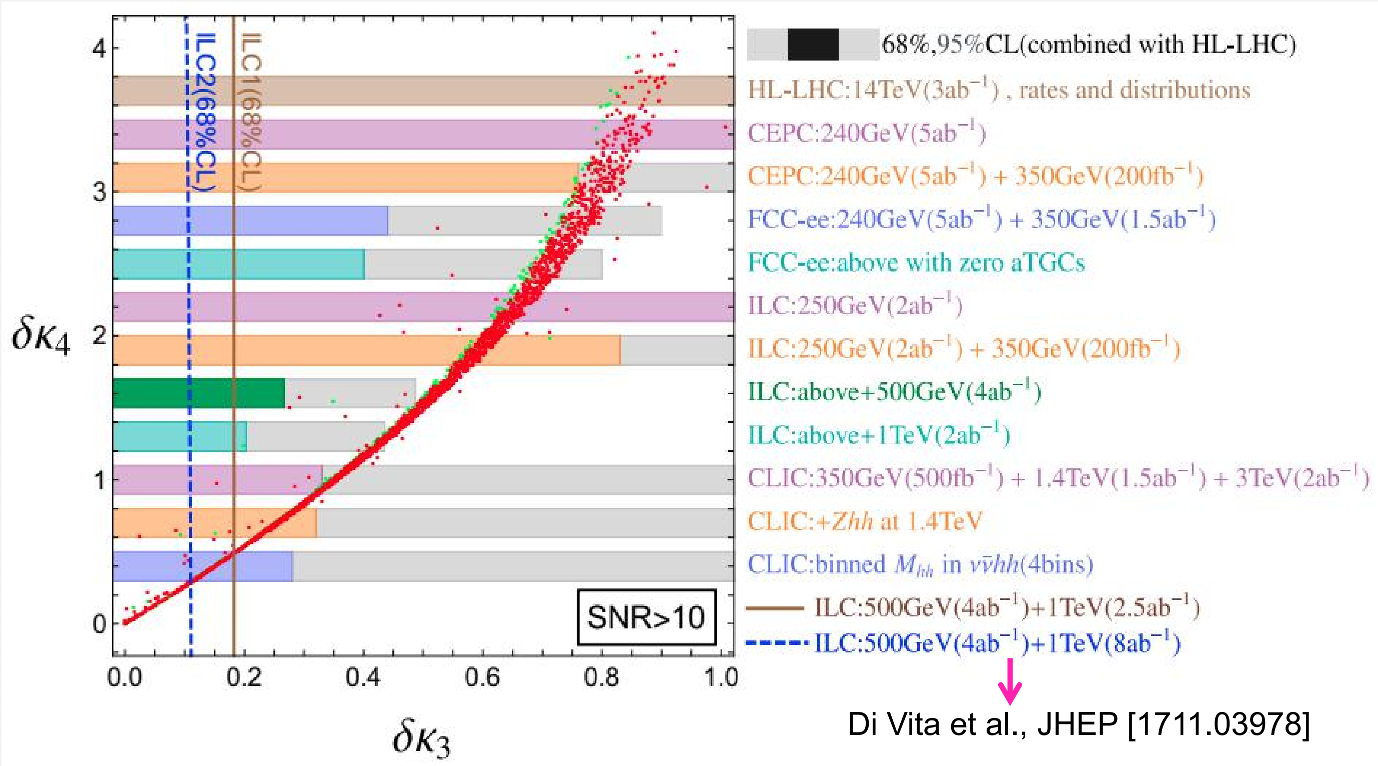
Collider and GW Complementarity

- 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

$\Delta\Omega_{\rm GW}/\Omega_{\rm GW}$	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
$T_{\rm p}$	0.003%	0.003%	0.002%
βR^*	8.1%	7.9%	5.9%
$N_{\rm tot}$	11.4%	11.0%	9.8%
$f_{\beta R^*}^{\rm peak}$	11.8%	12.0%	14.1%
$\Omega_{\rm GW}h^2_{\beta R^*}$	37.6%	36.5%	28.9%
$f_{\rm sim}^{\rm peak}$	36.4%	36.4%	35.1%
$\Omega_{\rm GW}h^2_{\rm sim}$	334.0%	330.8%	336.7%

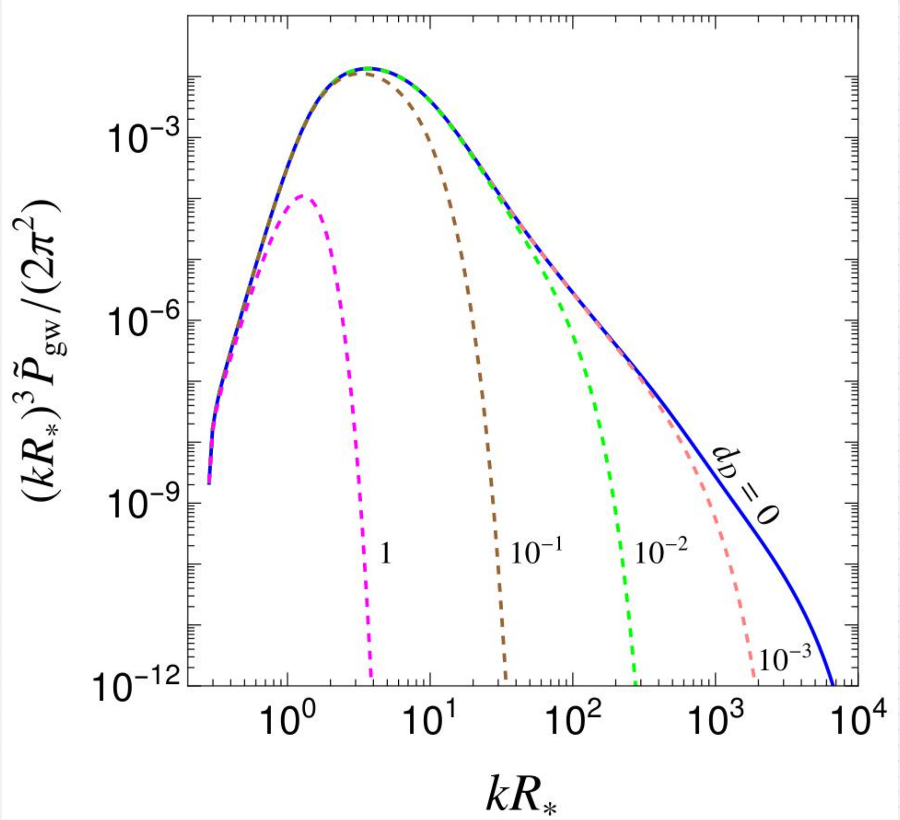
HG, Xiao, Yang, Zhang [2310.04654]

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 ...

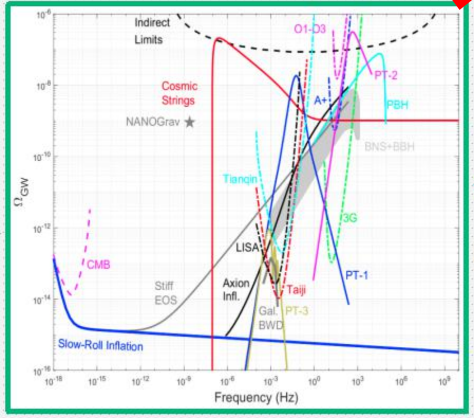
$$\Delta T^{ij} = -\eta\left(\frac{\partial U_i}{\partial x^j} + \frac{\partial U_j}{\partial x^i} - \frac{2}{3}\delta_{ij}\nabla\cdot\mathbf{U}\right) - \zeta\,\delta_{ij}\nabla\cdot\mathbf{U},$$
$$\Delta T^{i0} = -\chi\left(\frac{\partial T}{\partial x^i} + T\dot{U}_i\right). \qquad (1)$$

Weinberg, ApJ, 1971

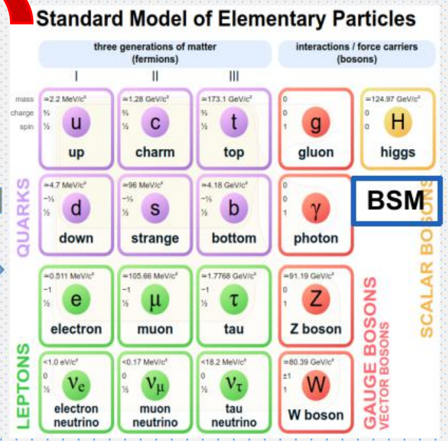


HG [2310.10927]

break the parameter degeneracy!



α
β
v_w
T_*
g_s
...



GWs from Particles

Extreme densities

disturbances in the early universe

As Macroscopic Objects

(non-) topological solitons

Environmental Effects

Faking GW signals (dark photon)

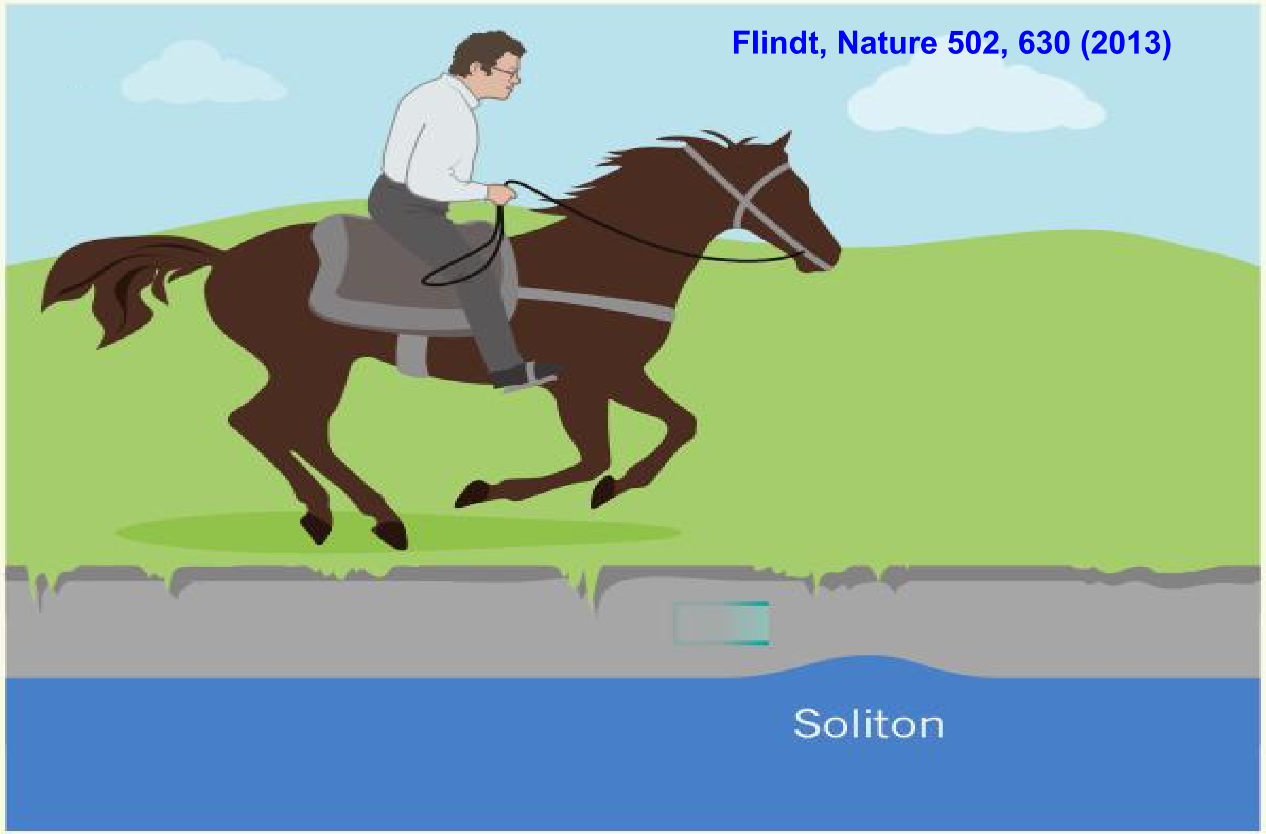
Solitons

- 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

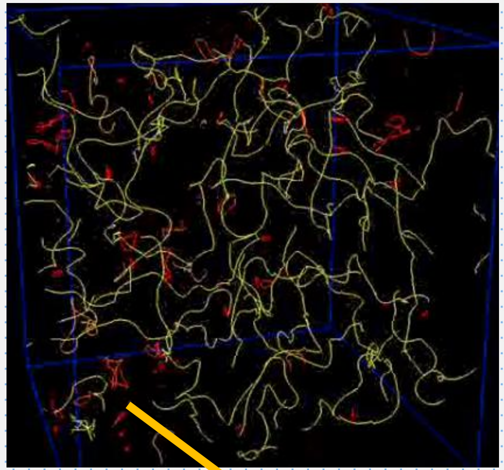
T W B Kibble J.Phys.A 9 (1976) 1387-1398

Blackett Laboratory, Imperial College, Prince Consort Road, Lon

Received 11 March 1976

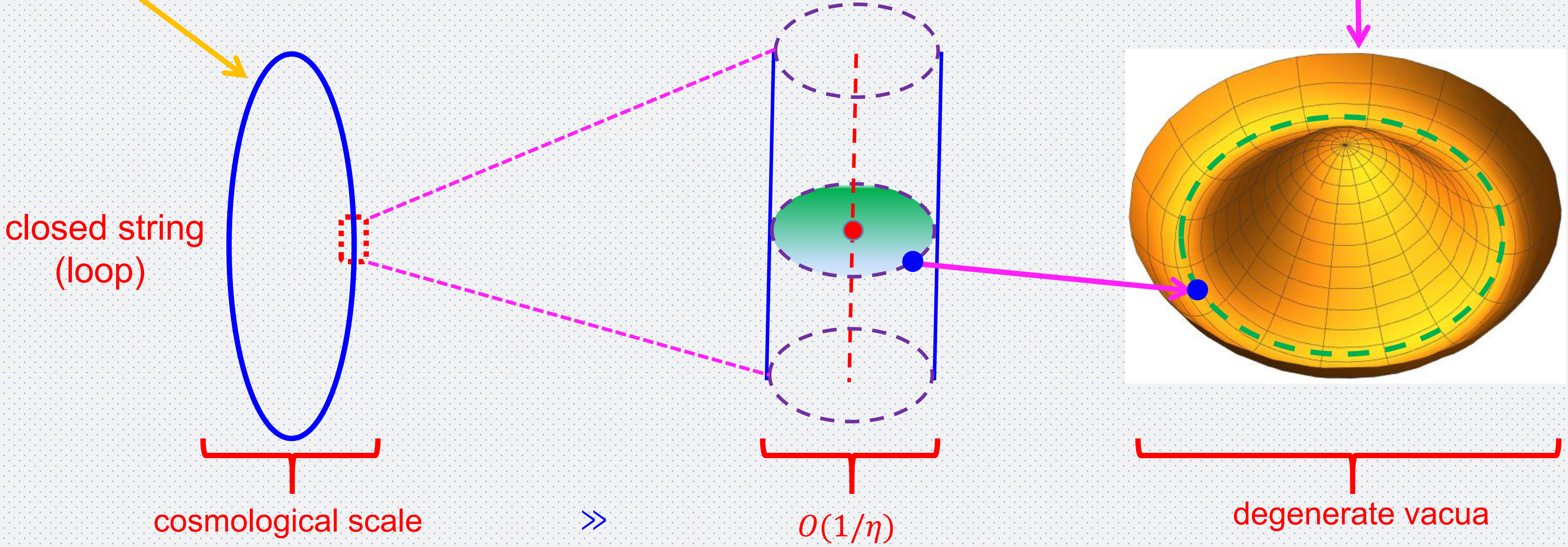
www.theguardian.com

Cosmic String



Example: the Abelian Higgs Model

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



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

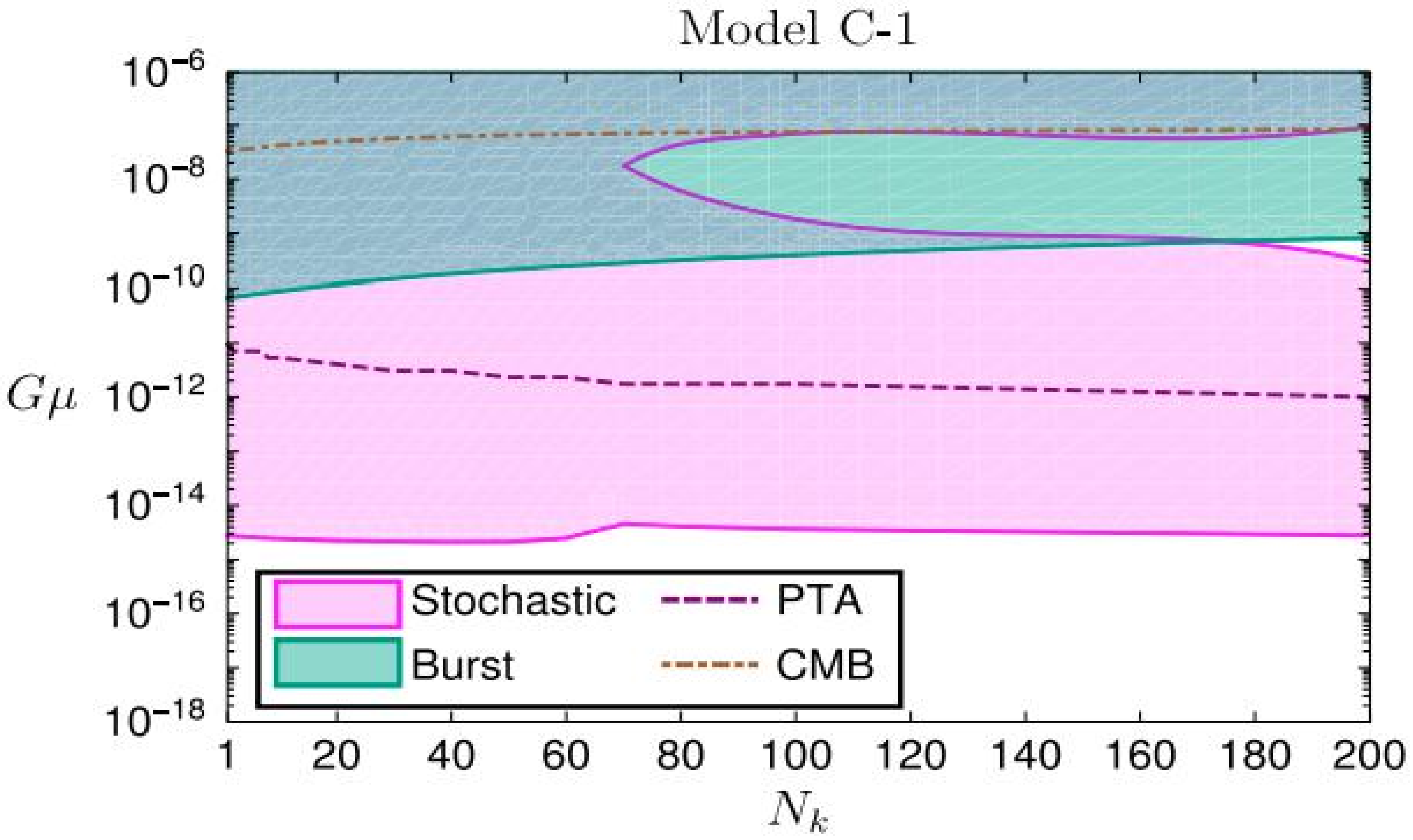
$$\boxed{G\mu \sim \left(\frac{\eta}{10^{19}\mathrm{GeV}}\right)^2}$$

μ: line mass density

Results from PTA Measurements

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

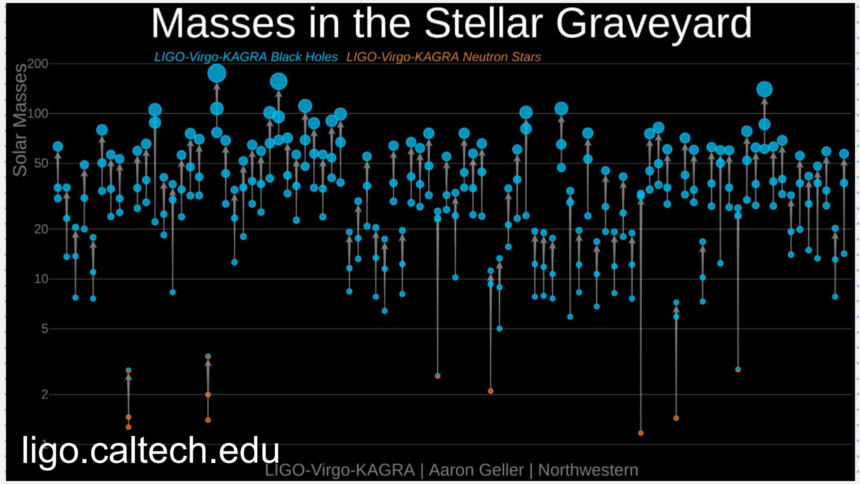
Blasi, Brdar, Schmitz, PRL [2009.06607]

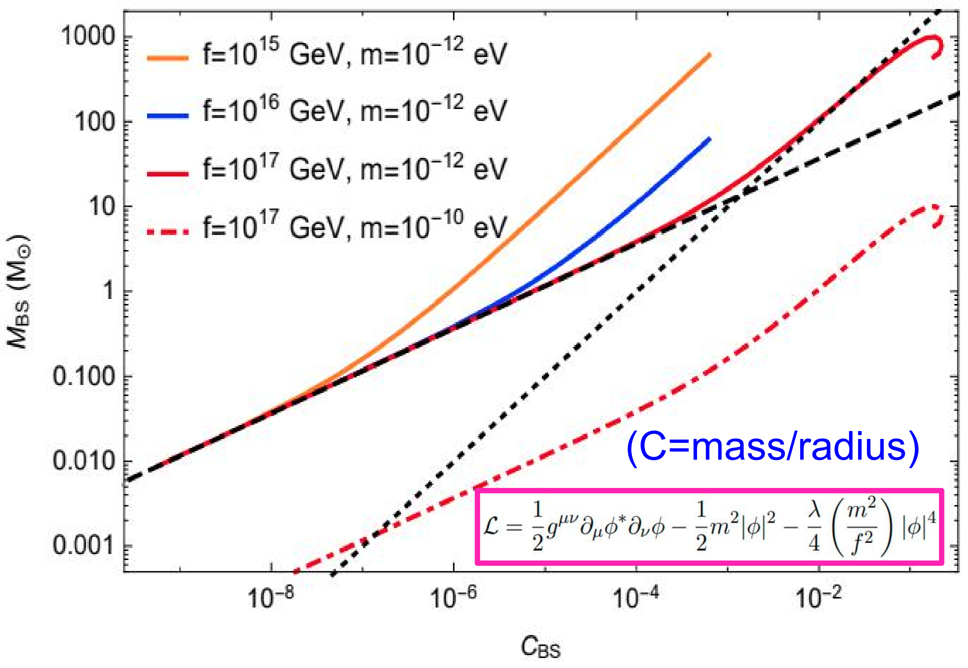


LIGO-Virgo-KAGRA collaborations, PRL [2101.12248]

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





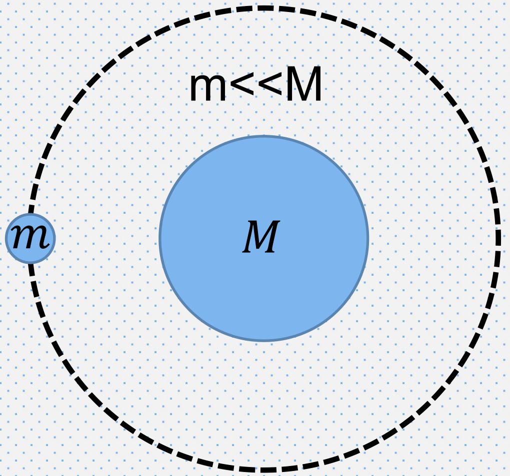
HG, Sinha, Sun, JCAP [1904.07871]

- 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)

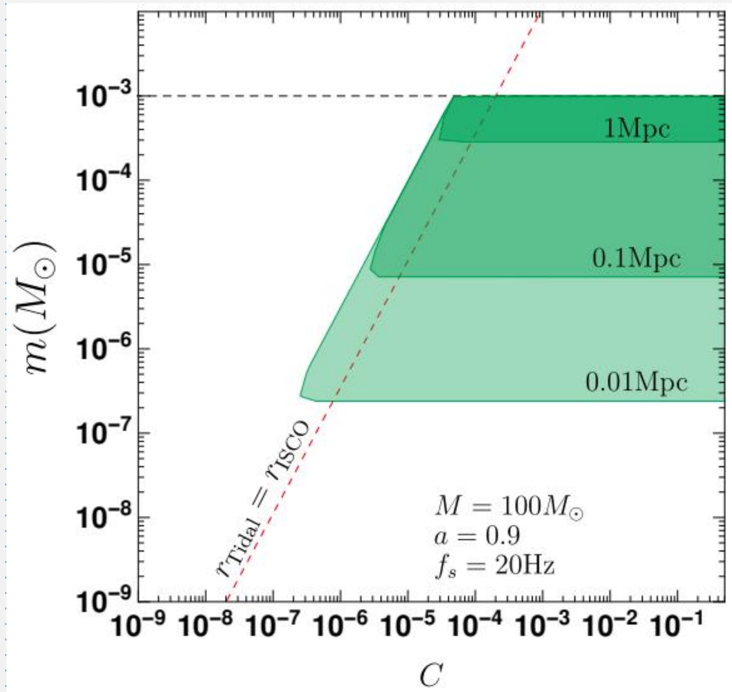
Detection with EMRI and mini-EMRI



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

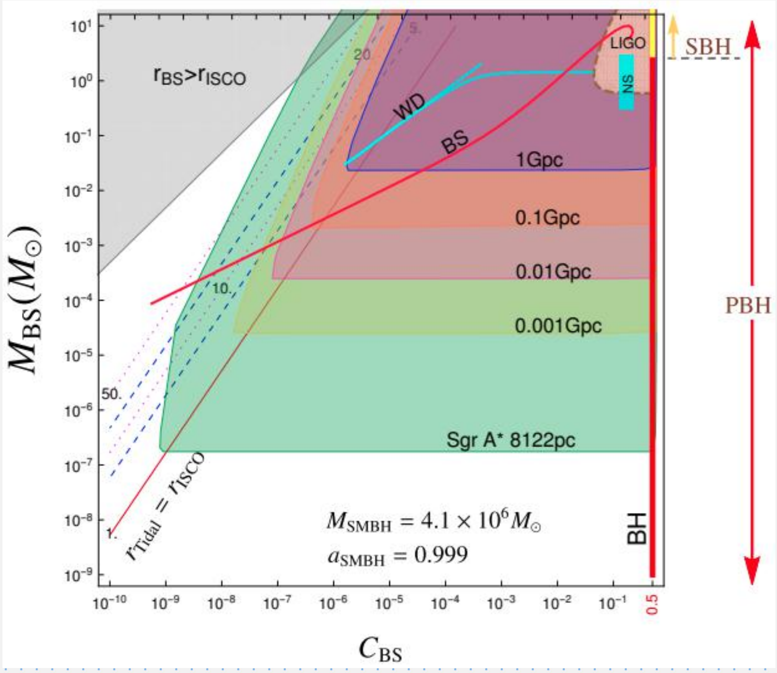
  Extreme Mass Ratio Inspirals (EMRIs), key target of LISA, Taiji, Tianqin
- LIGO can detect mini-EMRIs

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

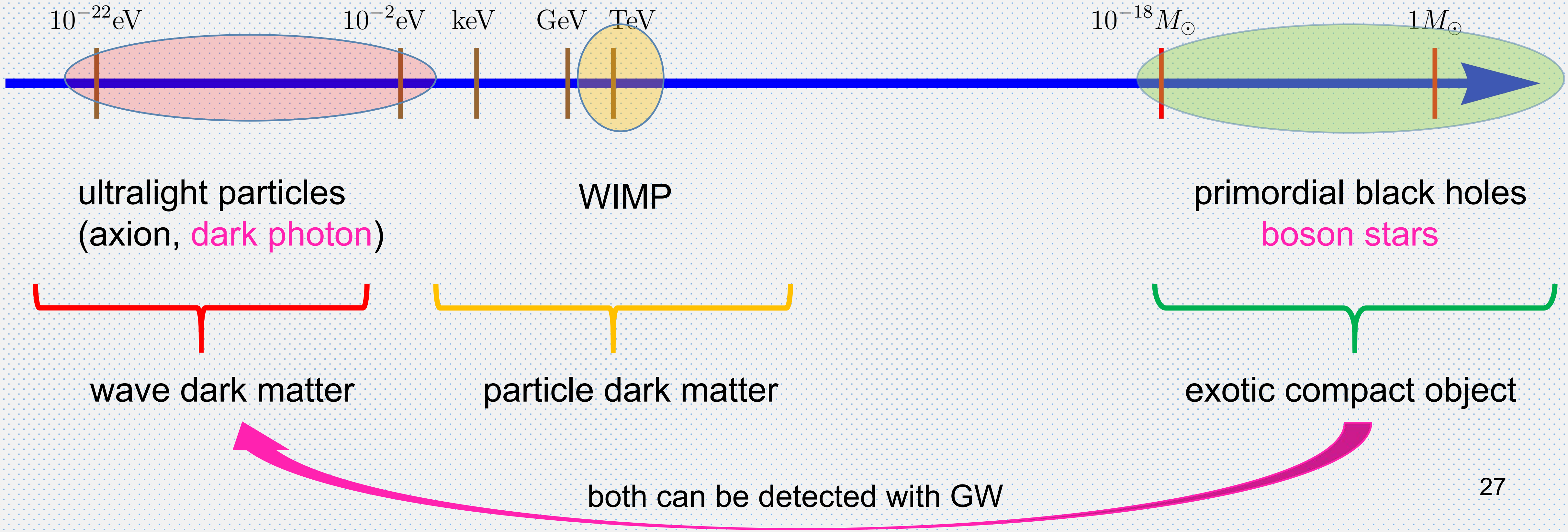
Environmental Effects

Faking GW signals (dark photon)

See also Yong Tang's talk

Ultralight Dark Matter

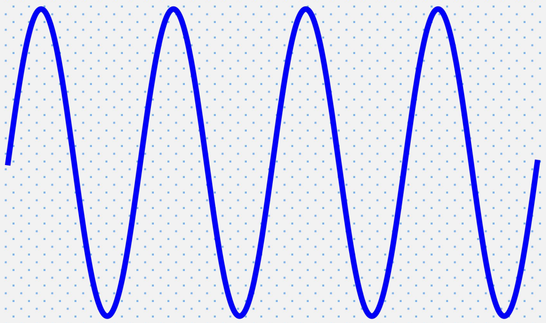
- Boson stars serve as macroscopic dark matter candidate
- So does the ultralight particle making up the boson stars



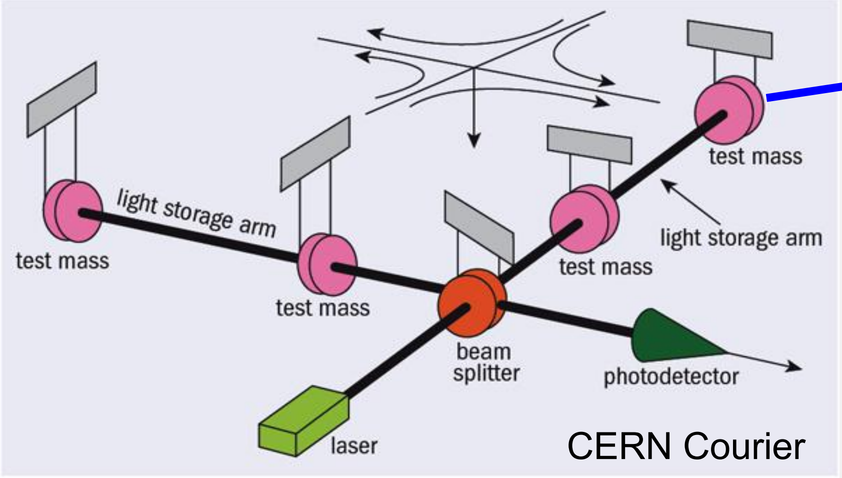
Dark Photon Detection at LIGO

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

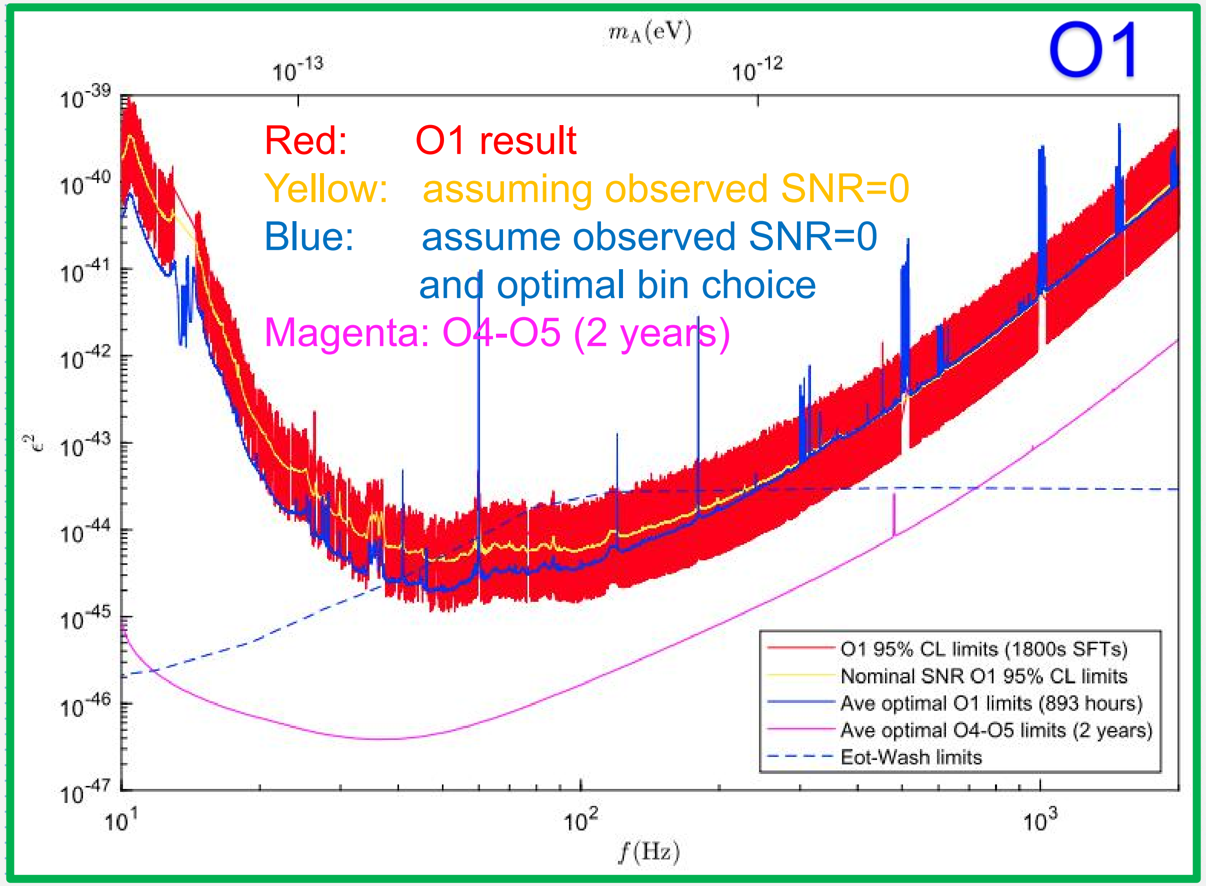
typical LIGO frequency

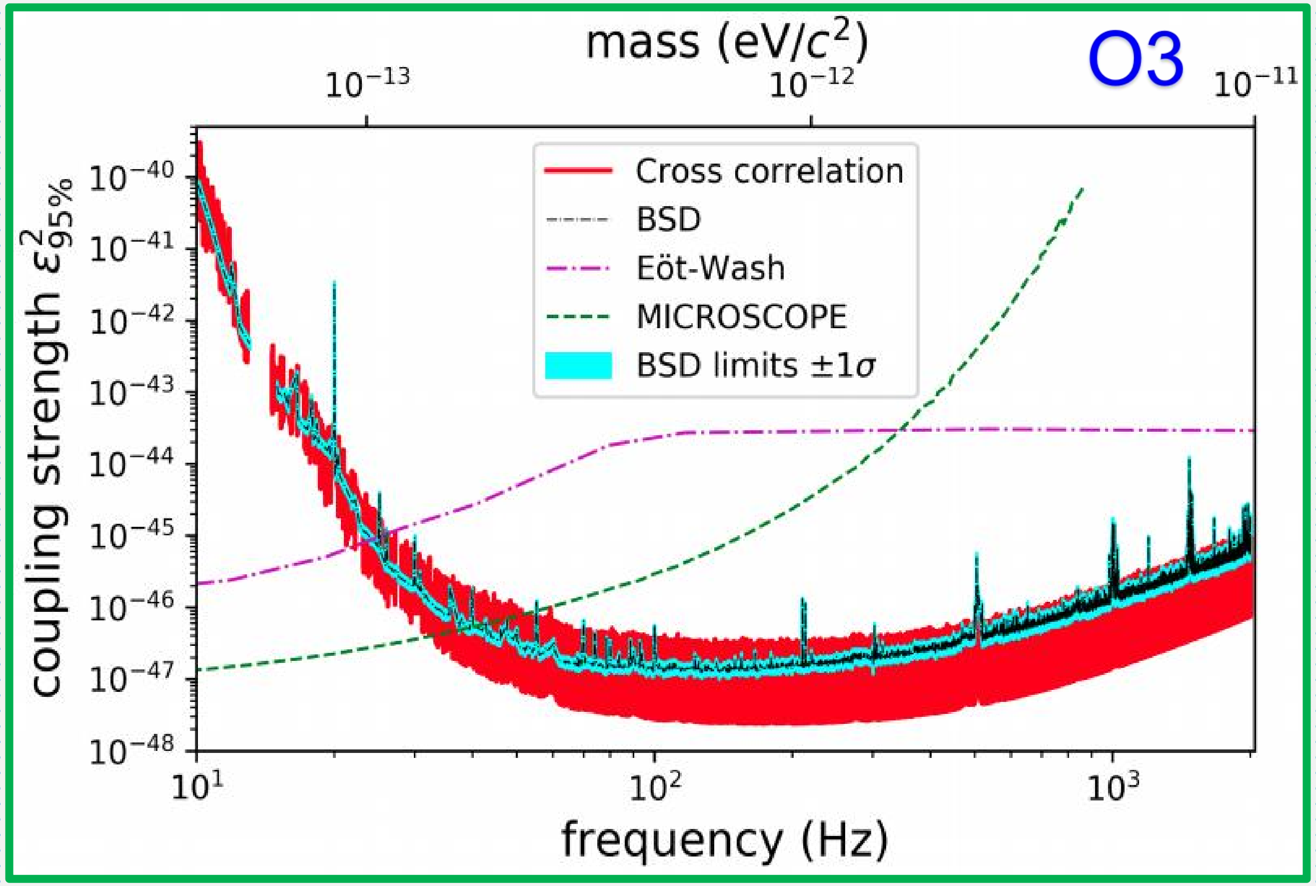
$$\omega_n = m_A(1 + \frac{1}{2}v_n^2) = 2\pi \times (100\mathrm{Hz}) \approx \boxed{4 \times 10^{-13}\mathrm{ev}}$$

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

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)

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Thanks!