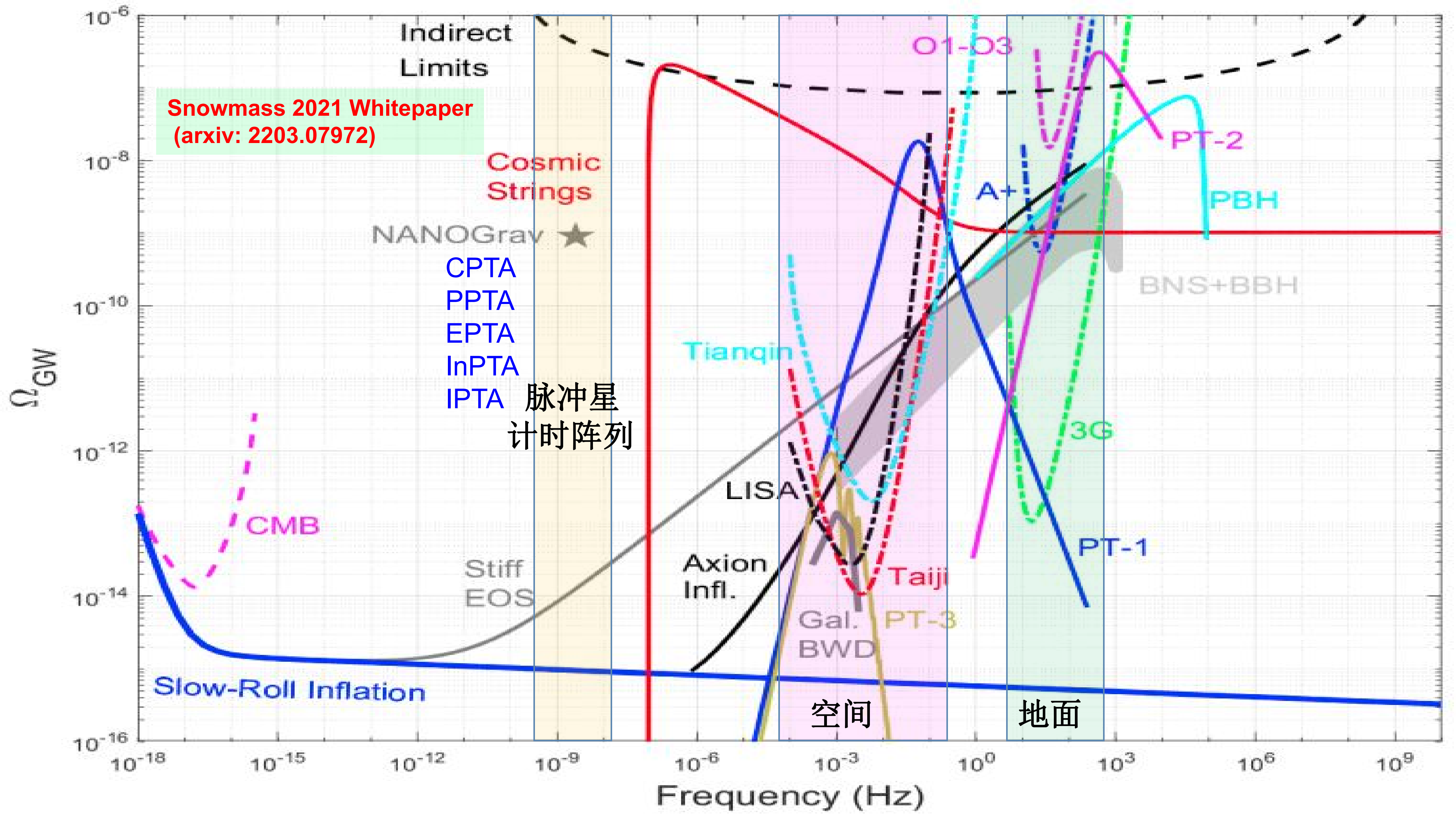
引力波与粒子物理

郭怀珂

UCAS (ICTP-AP)

Sept. 26, 2023

第三届“江门中微子实验相关的理论与唯象学”研讨会
大统一专题

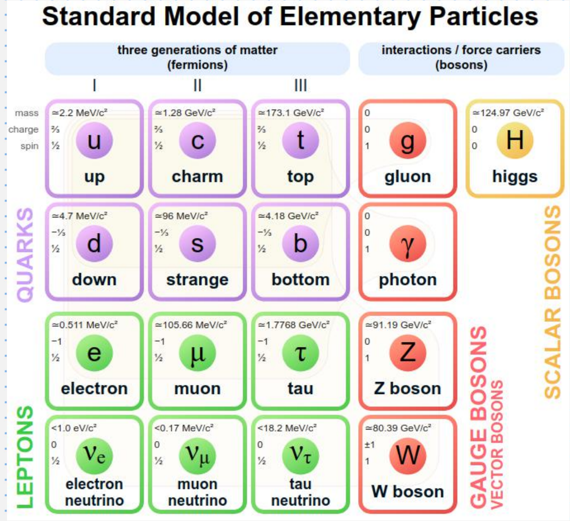


Snowmass 2021 Whitepaper
(arxiv: 2203.07972)
Indirect Limits
Cosmic Strings
NANOGrav
CPTA
PPTA
EPTA
InPTA
IPTA
脉冲星计时阵列
O1-O3
PT-2
PBH
A+
BNS+BBH
Tianqin
3G
LISA
CMB
PT-1
Stiff EOS
Axion Infl.
Taiji
Gal. BWD
PT-3
Slow-Roll Inflation
空间
地面
Ω_{GW}
Frequency (Hz)

New Perspectives?

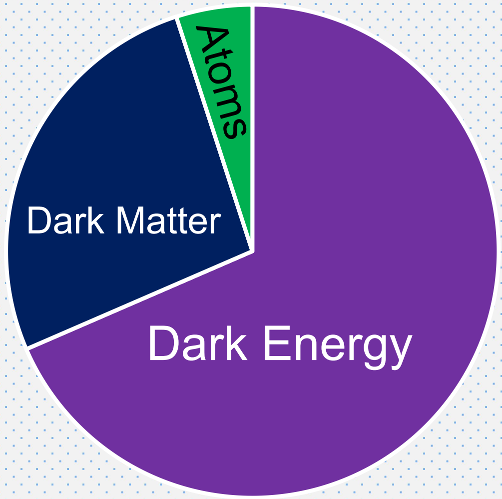
How can we reconcile the standard models of particle physics and cosmology?

Particle Physics



Physics Beyond the SM?

Cosmology

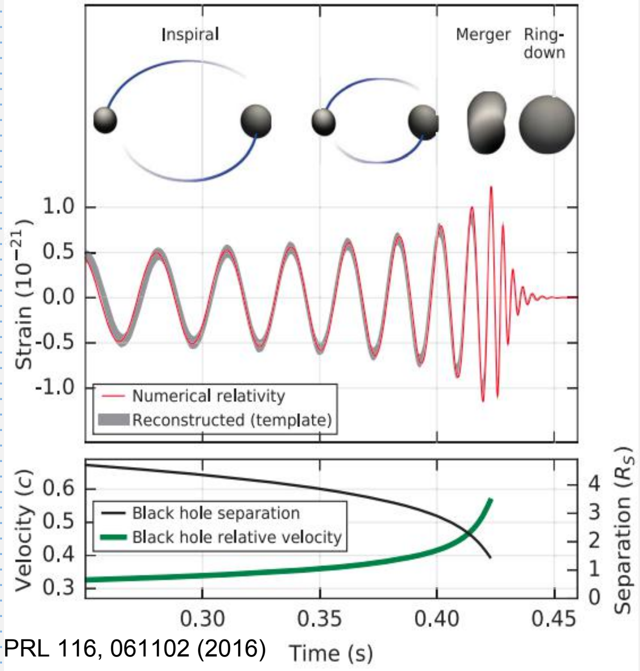


Why more matter than anti-matter (baryogenesis, leptogenesis)? (phase transitions, solitons)

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 (limited) collection:

Extreme densities

disturbances in the early universe

As Macroscopic Objects

(non-) topological solitons

Environmental Effects

Faking GW signals (dark matter)

Not covered: neutrino damping of GWs, neutron star binary, ...

GWs from Particles

Extreme densities

disturbances in the early universe

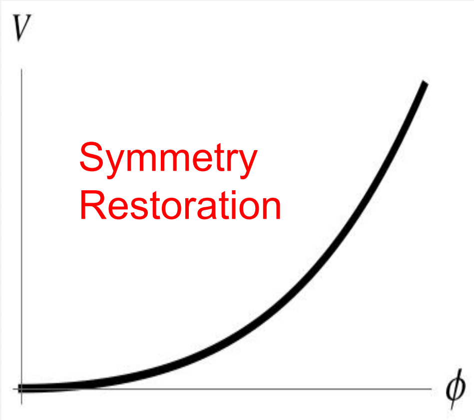
As Macroscopic Objects

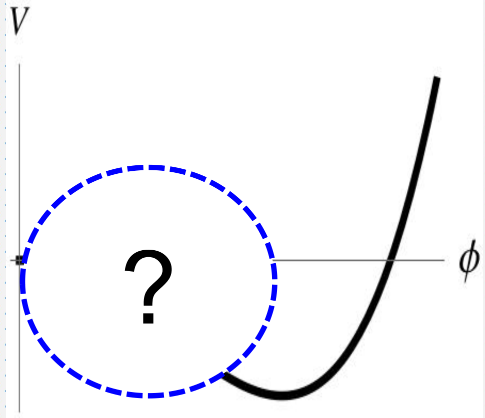
(non-) topological solitons

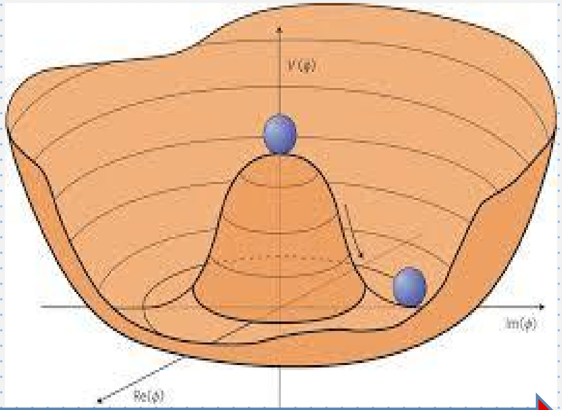
Environmental Effects

Faking GW signals (dark matter)

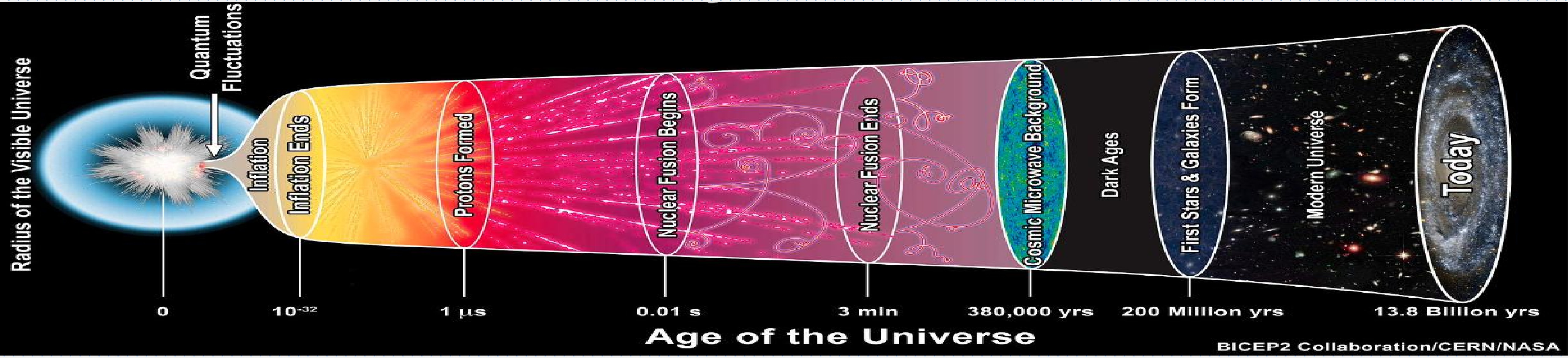
Electroweak Phase Transition



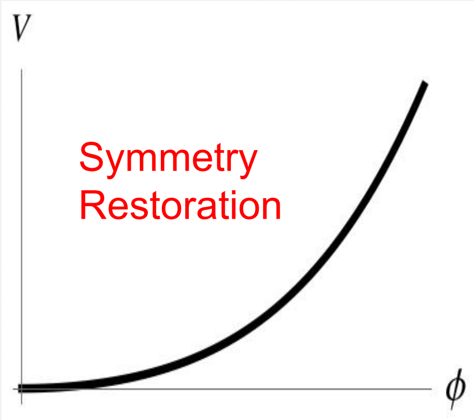


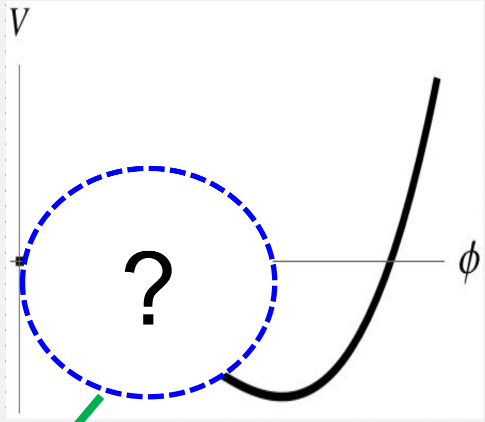


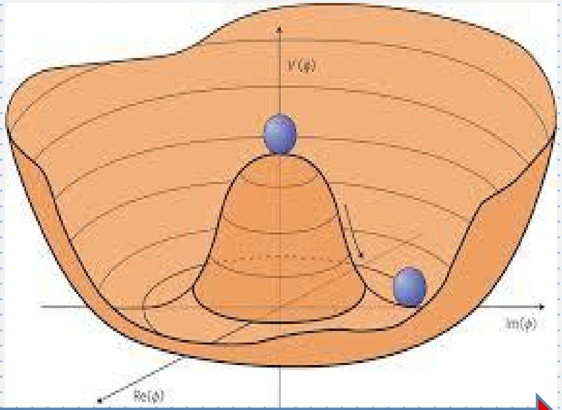
Temperature drops



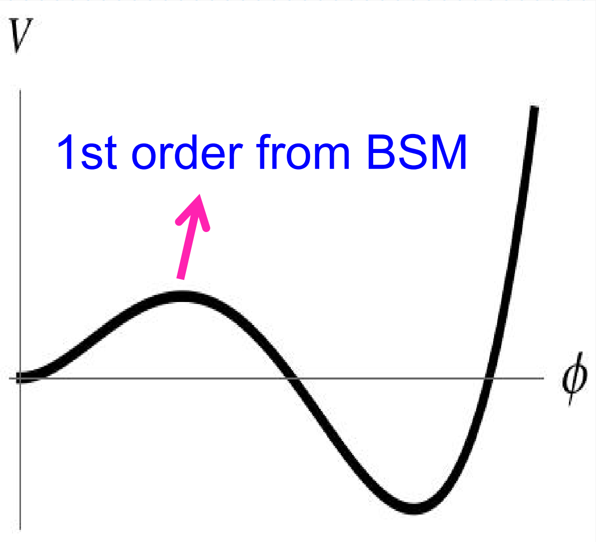
Electroweak Phase Transition



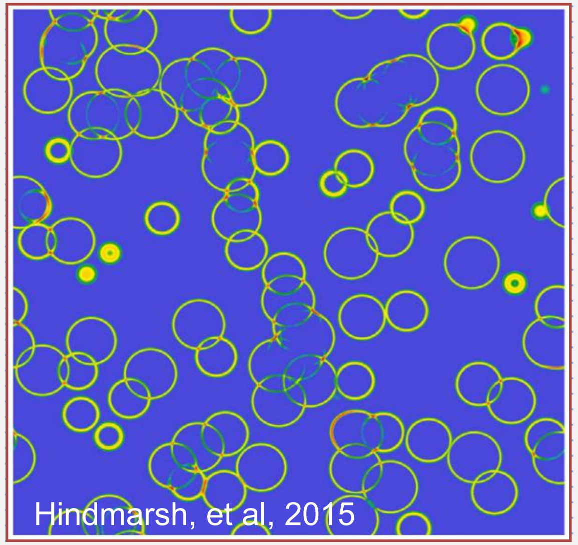




Temperature drops



bubbles, plasma, MHD



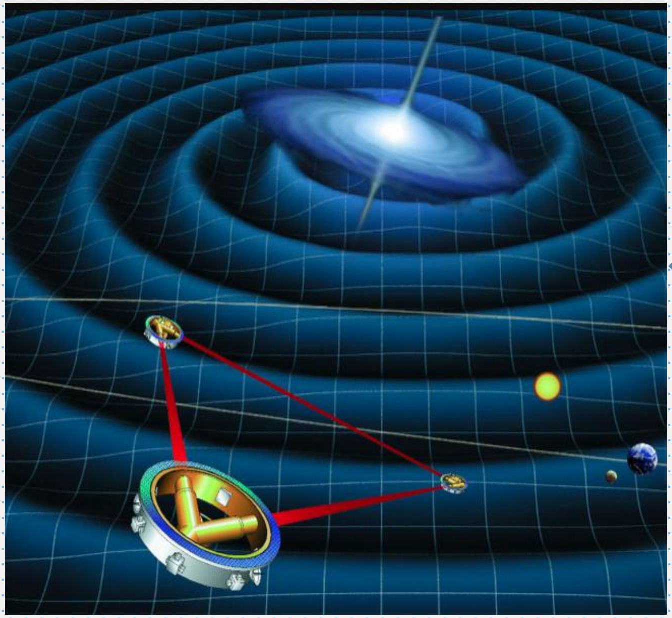
Electroweak Baryogenesis

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

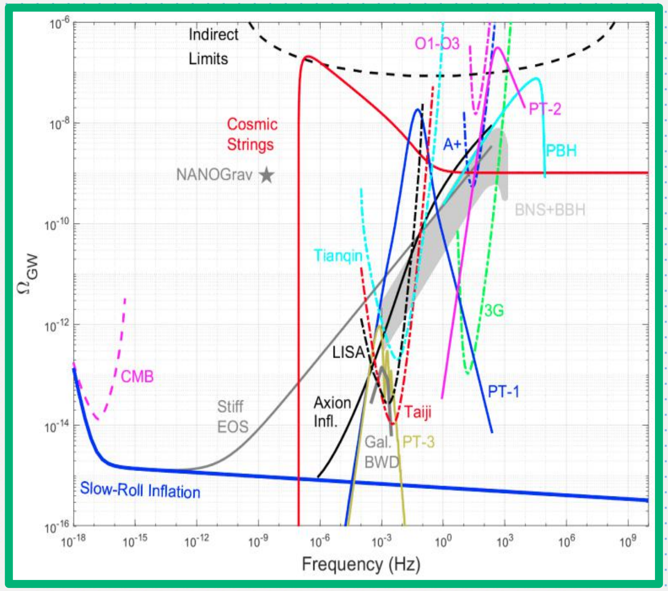
Morrissey,Ramsey-Musolf, NJP [1206.2942]

Flow of Studies

theoretical calculation of gravitational wave spectrum and detector simulation



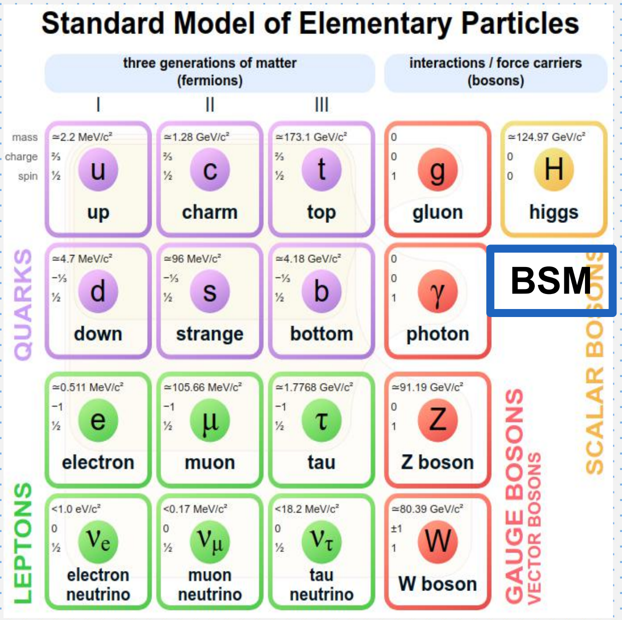
LIGO, LISA, Taiji, Tianqin...



Gravitational Wave Spectrum

α
β
v_w
T_*
g_s
...

Phase Transition Parameters

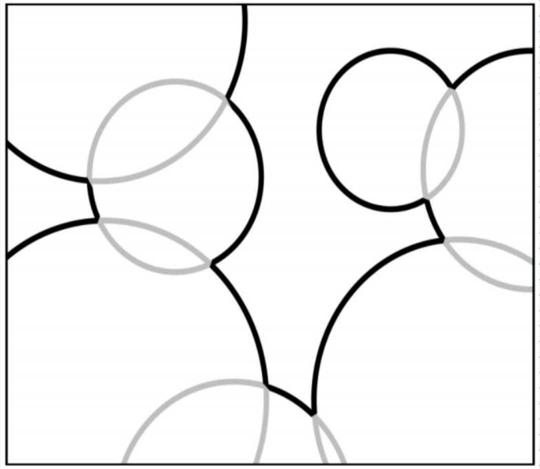


Particle Physics Model

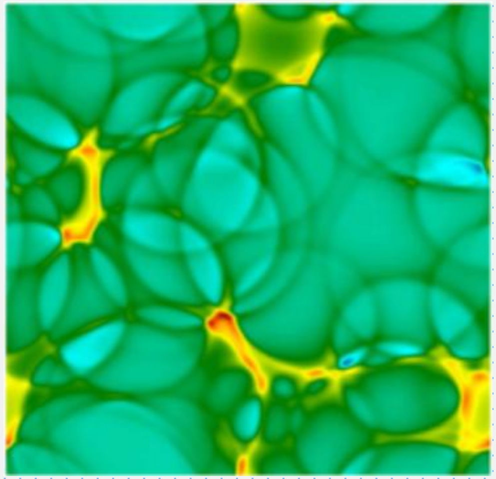
data analysis, constraints or discovery(parameter estimation)

Gravitational Wave Sources

Bubble Collisions

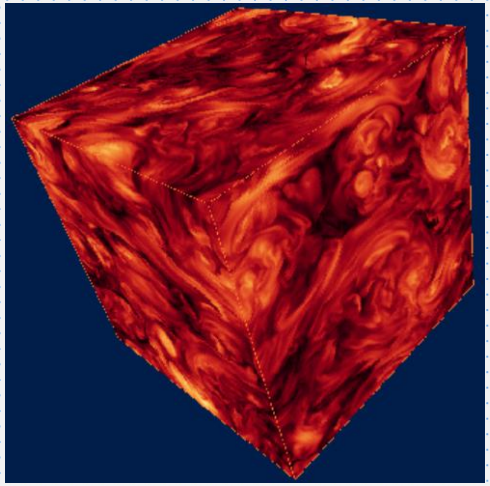


Sound Waves



Hindmarsh, et al,PRL112,041301(2013)

MagnetoHydrodynamic Turbulence



https://home.mpcdf.mpg.de

energy concentrated at walls

acoustic production

turbulent motion

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

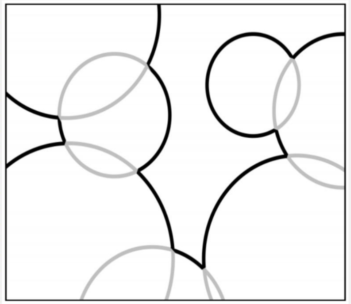
Di, Wang, Zhou, Bian, Cai, Liu, PRL 126 (2021) 25, 251102
Jing, Bian, Cai, Guo, Wang, PRL 130 (2023) 051001
Li, Huang, Wang, Zhang, PRD 105 (2022) 083527
Huang, Xie, PRD105 (2022) 11, 115033, JHEP 09 (2022) 052

The GW Observable

Energy density Spectrum

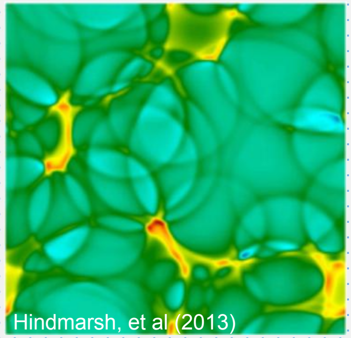
$$\Omega_{\rm GW}(f) = \frac{d\rho_{\rm GW}}{\rho_c d\log f}$$

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

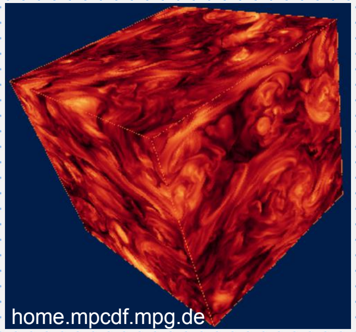


$$\Omega_{\rm sw}(f)h^2 = 2.65\times 10^{-6}\left(\frac{H_{\rm pt}}{\beta}\right)\left(\frac{\kappa_{\rm sw}\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{1/3} \times v_w\left(\frac{f}{f_{\rm sw}}\right)^3\left(\frac{7}{4+3(f/f_{\rm sw})^2}\right)^{7/2}\Upsilon(\tau_{\rm sw}),$$

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

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

MHD

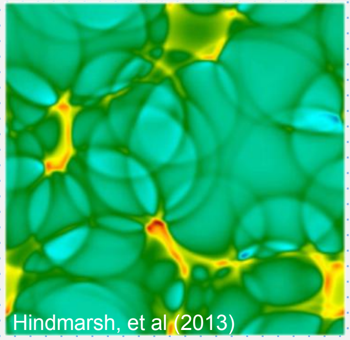


$$h^2\Omega_{\rm turb}(f) = 3.35\times 10^{-4}\left(\frac{H_*}{\beta}\right)\left(\frac{\kappa_{\rm turb}\,\alpha}{1+\alpha}\right)^{\frac{3}{2}}\left(\frac{100}{g_*}\right)^{1/3} v_w\, S_{\rm turb}(f)$$

Chiara Caprini et al JCAP04(2016)001

Sound Waves

sound waves



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

Chiara Caprini et al JCAP04(2016)001

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

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

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

Editors' Suggestion | Featured in Physics

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

Zaven Arzoumanian,[1] Paul T. Baker,[2] Harsha Blumer,[3,4] Bence Bécsy,[5] Adam Brazier,[6,7] Paul R. Brook,[3,4] Sarah Burke-Spolaor,[3,4,8] Maria Charisi,[9] Shami Chatterjee,[6] Siyuan Chen,[10,11,12] James M. Cordes,[6] Neil J. Cornish,[5] Fronefield Crawford,[13] H. Thankful Cromartie,[6] Megan E. DeCesar,[14,15*] Paul B. Demorest,[16] Timothy Dolch,[17,18] Justin A. Ellis,[19] Elizabeth C. Ferrara,[20,21,22] William Fiore,[3,4] Emmanuel Fonseca,[23] Nathan Garver-Daniels,[3,4] Peter A. Gentile,[3,4] Deborah C. Good,[24] Jeffrey S. Hazboun,[25] A. Miguel Holgado,[26,27] Kristina Islo,[28] Ross J. Jennings,[6] Megan L. Jone... Nima Laal,[30] Michael T. La... ...an S. Lynch,[36] Dustin R. M... Cherry Ng,[39] David J. Nice,[14]... ...hapiro-Albert,[3,4] Xavier Siemen... Kevin Stovall,[16] Jerry P. Sun,[30]... ...ah J. Vigeland,[28]

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

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

(NANOGrav Collaboration)

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

© 2023. The Author(s). Published by the American Astronomical Society.

OPEN ACCESS

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] Ross J. Jennings,[16,17,78] Aaron D. Johnson,[3,19] Megan L. Jones,[3] Andrew R. Kaiser,[16,17] David L. Kaplan,[3] Luke Zoltan Kelley,[39] Matthew Kerr,[40] Joey S. Key,[41] Nima Laal,[7] Michael T. Lam,[30,31] William G. Lamb,[18] T. Joseph W. Lazio,[25] Vincent S. H. Lee,[19] Natalia Lewandowska,[42] Rafael R. Lino dos Santos,[1,43] Tyson B. Littenberg,[44] Tingting Liu,[16,17] ... Alexander McEwen ... Patrick M. Meyers ... Cherry Ng,[56] ... Polina Petrov[18] ... Shashwat C. ... Levi Schult[18] ... Ingrid H. Stairs[24] ... Joseph K. Swiggum ... Michele V... Caitlin A. Witt ..., David Wright ..., Olivia Young ..., Kathryn M. Zurek ..., and The NANOGrav Collaboration

time of matter–radiation equality. The production of GWs from sound waves stops after a period τ_{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

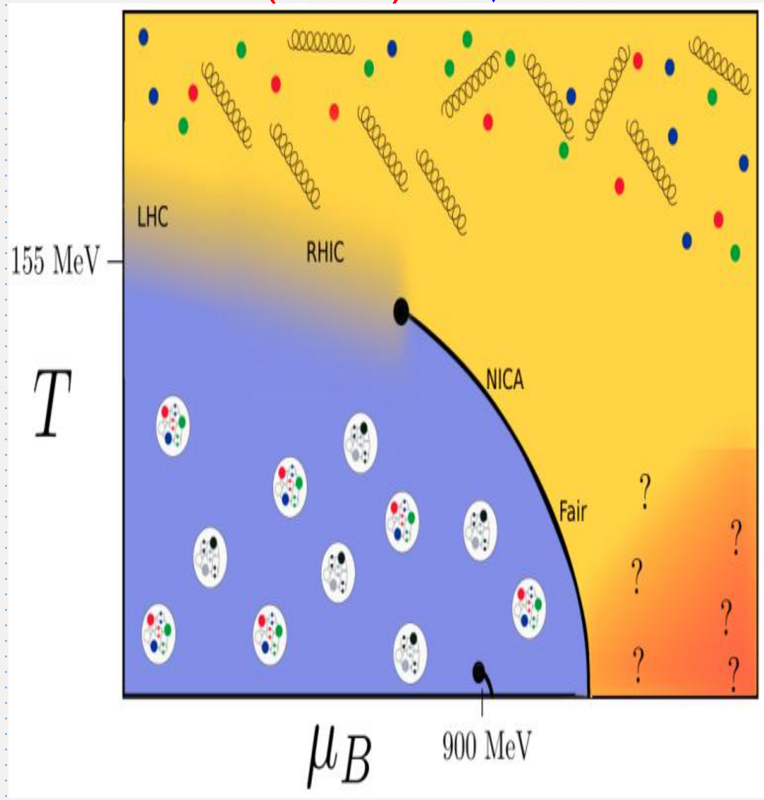
$$\Upsilon(\tau_{sw}) = 1-(1+2\tau_{sw}H_*)^{-1/2}, \qquad (36)$$

Generic Features

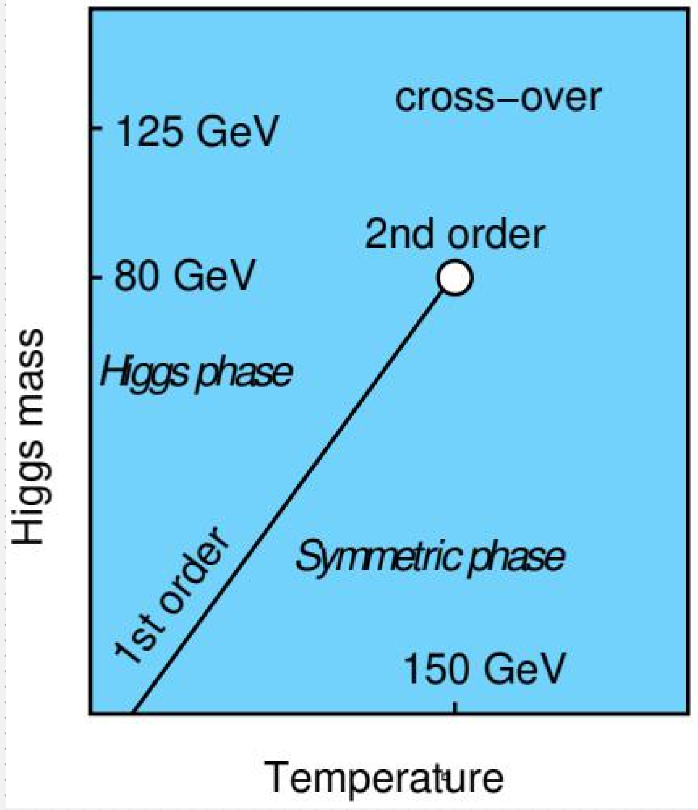
- LIGO (~100Hz) : (~PeV - EeV)
- LISA, Taiji, Tianqin: ~mHz : (~100GeV)
- PTA: nHz (~100MeV)

QCD (scale) PT

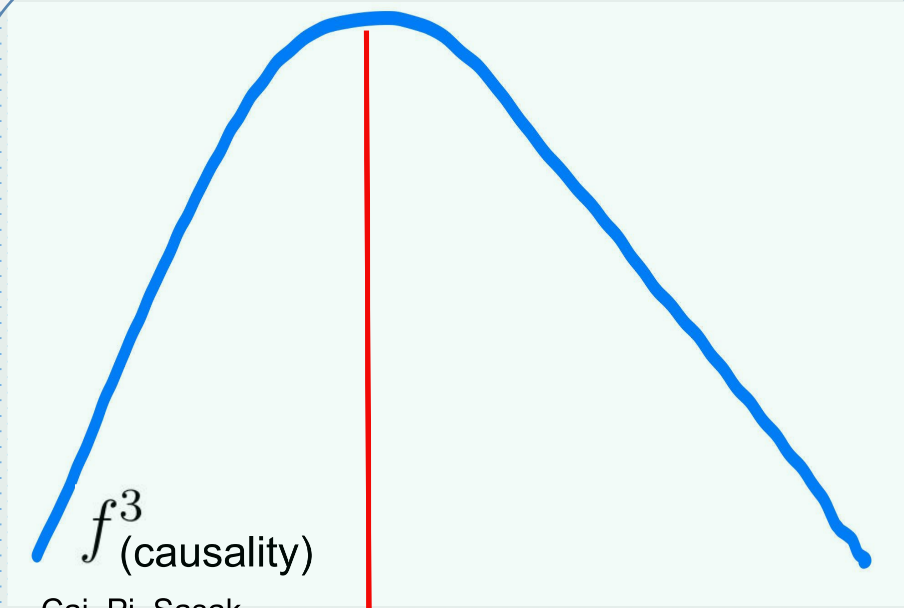
EWPT



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

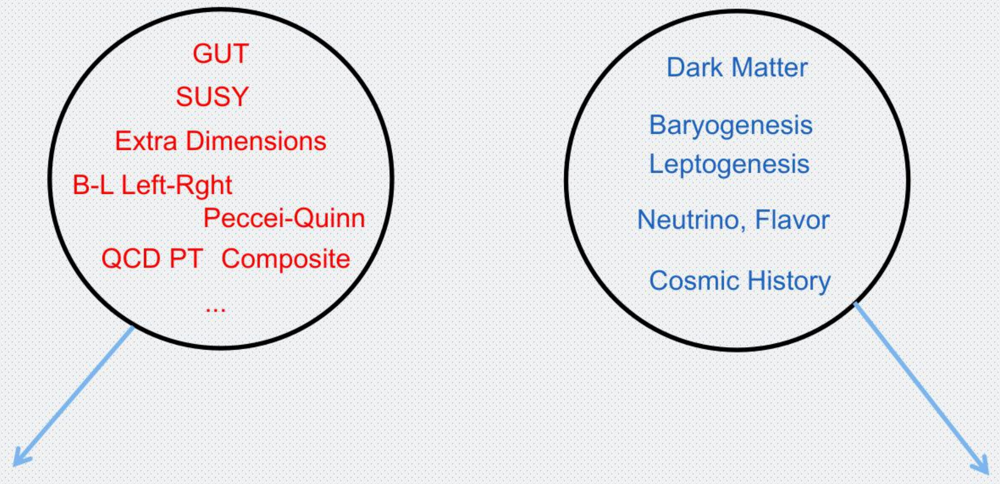
tells PT temperature (symmetry breaking scale)

BSM studies

Chung,Long,Wang, PRD [1209.1819]

- Large cubic term from thermal corrections (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]	✓	✓	✓	
$G_{\rm SM} \times G_{\rm D,SM} \times Z_2$ [74]	✓	✓	✓	
$G_{\rm SM} \times G_{\rm D,SM} \times G_{\rm D,SM} \cdots$ [75]	✓	✓	✓	
Current work				
$\mathrm{SU(2)_D} \to \mathrm{U(1)_D}$ (see the text)	✓	✓	✓	✓

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

Collider and Gravitational Wave Complementarity

- Collider and GW work towards a common goal
- Correlation and complementarity in their roles

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

Contents

Snowmass 2021 Whitepaper, GRG [2203.07972]

Session leads: Michael Ramsey-Musolf and Lian-Tao Wang

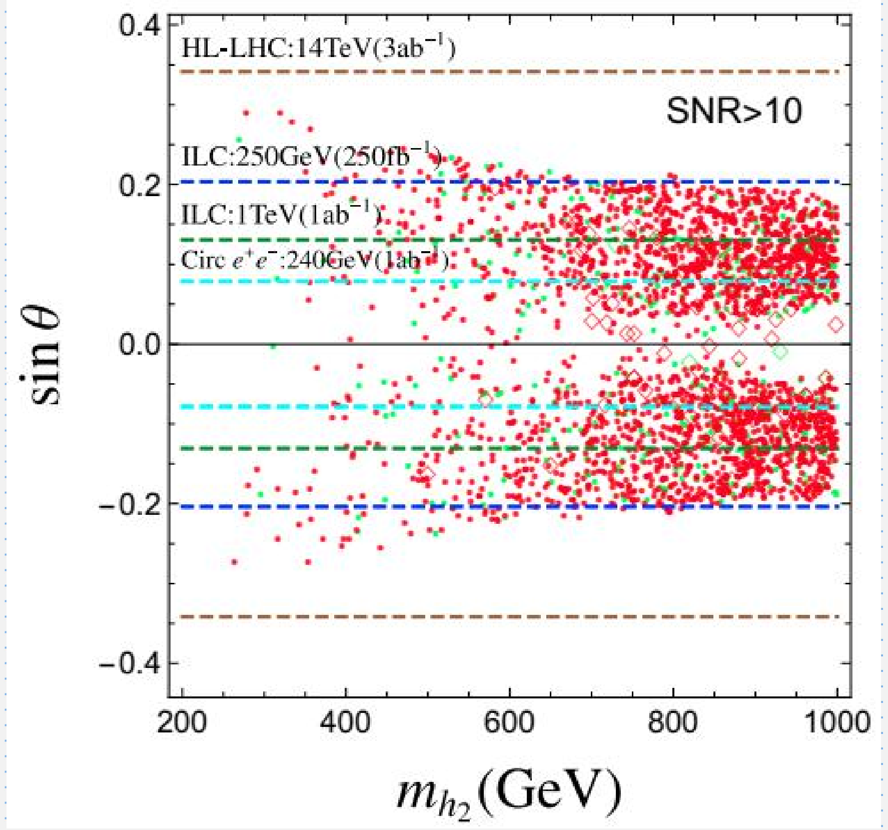
See also (Higgs exotic decay): Carena, Kozaczuk, Liu, Ou, Ramsey-Musolf, Shelton, Wang, Xie, LHEP [2203.08206]

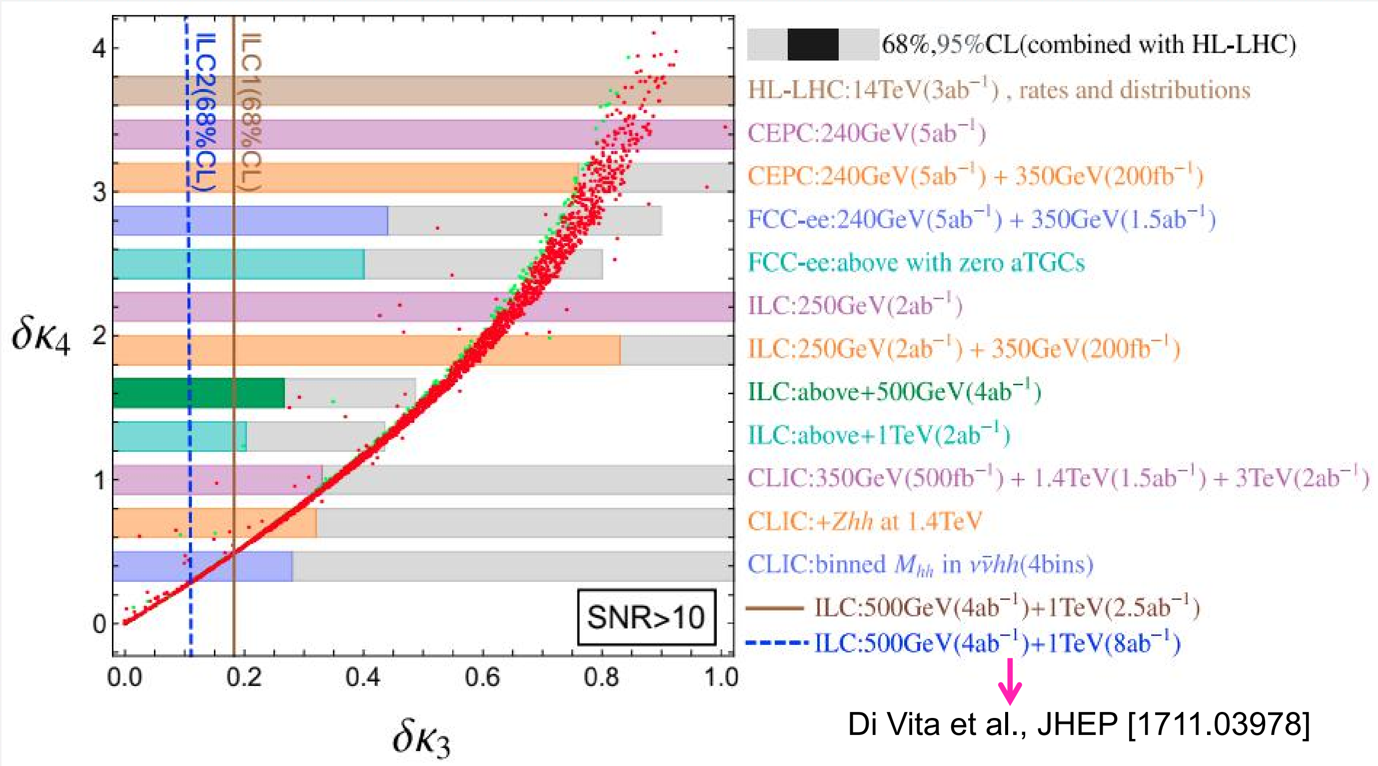
Higgs Precision Measurements

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

h1: the Higgs
h2: heavier scalar

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

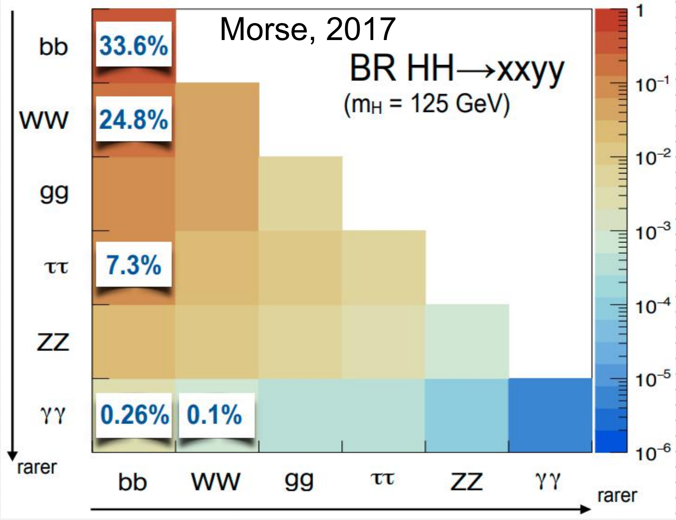




Di Vita et al., JHEP [1711.03978]

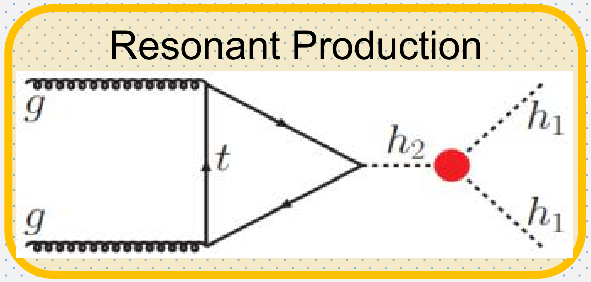
Alves, Ghosh, HG, Sinha, Vagie, JHEP [1812.09333]

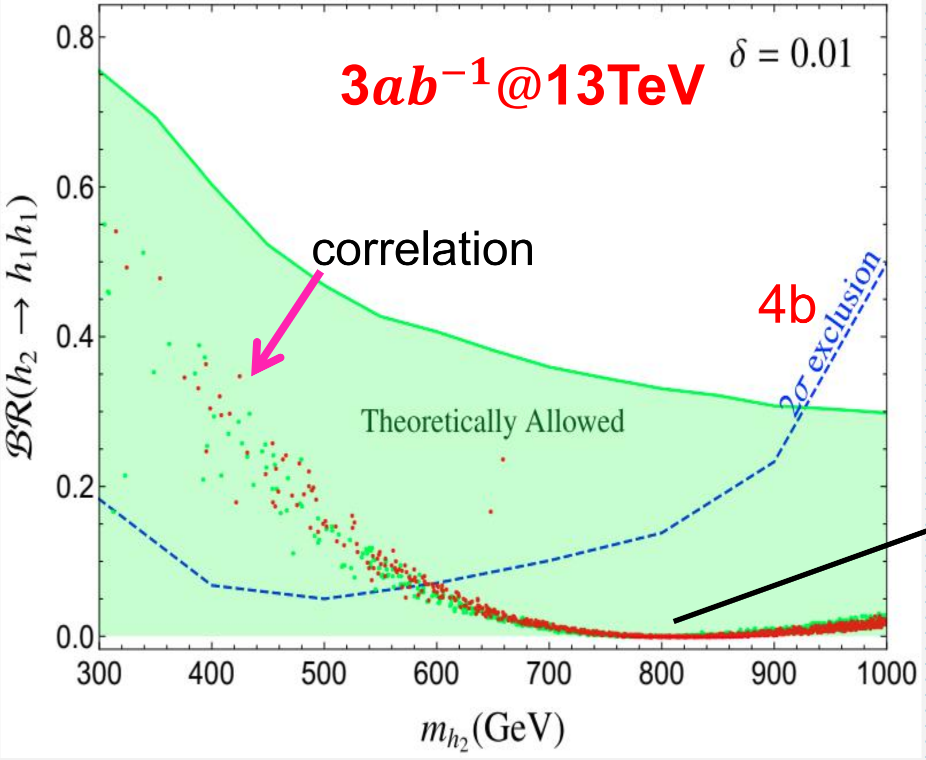
Di-Higgs Production



- Enhanced (resonant) di-Higgs production

See also:
No,Ramsey-Musolf, PRD [1310.6035]
Li,Ramsey-Musolf,Willocq, JHEP [1906.05289]
Huang,No,Pernie,Ramsey-Musolf,Safonov, PRD [1701.04442]
Zhang,Li,Liu,Ramsey-Musolf,Zeng,Arunasalam [2303.03612]
Liu,Xie,JHEP [2101.10469]
and more...

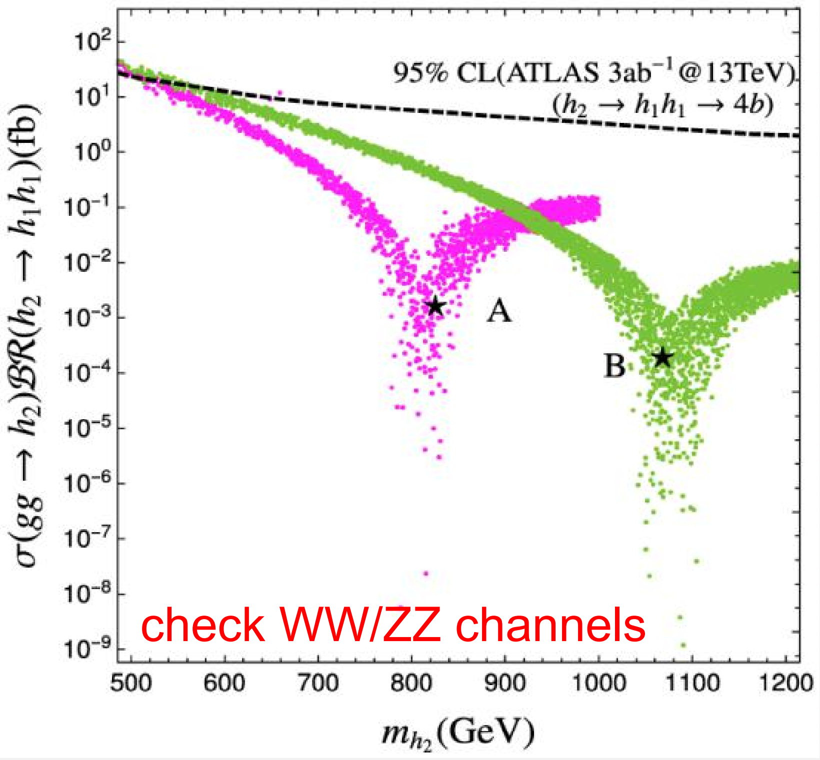




Alves,Gonçalves,Ghosh,HG,Sinha, JHEP [1909.05268]

di-Higgs "blindspot"

complementarity

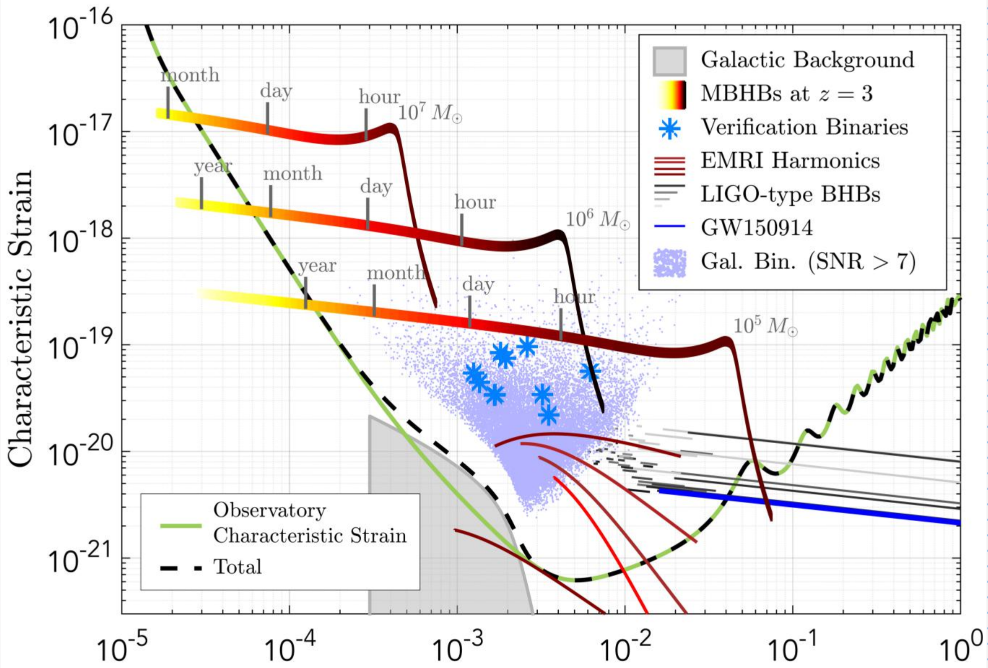


Alves,Gonçalves,Ghosh,HG,Sinha, PLB [2007.15654]

Detection at Space-based Detectors

Detection with a single detector

- Complicated, and correlated noise
- Complications from time-delay interferometry
- Solution: null channel method, or with a network



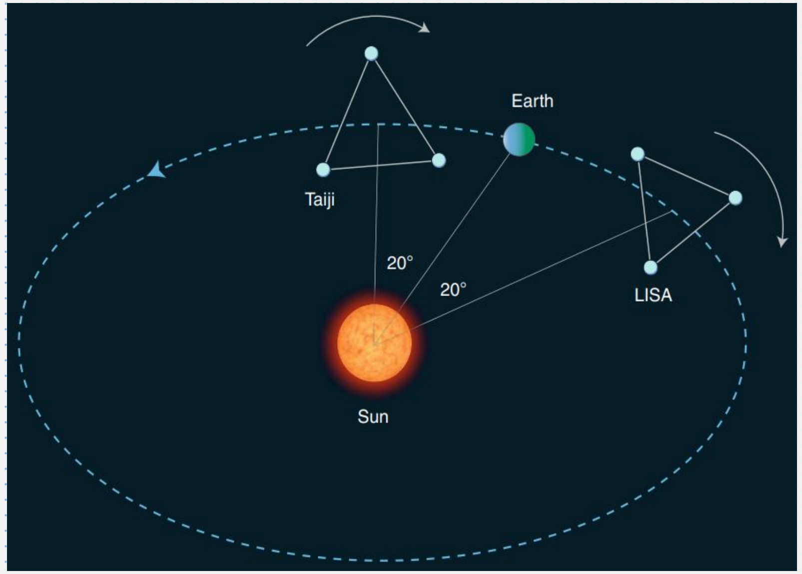
LISA [1702.00786]

galactic foreground + astro background + cosmic background

SGWB detectable down to $\Omega_{GW} \sim O(10^{-13})$

Boileau et al, MNRAS [2105.04283]

The LISA–Taiji network



Ruan, Liu, Guo, Wu, Cai, Nature Astron [2002.03603]
Cai et al [2305.04551]

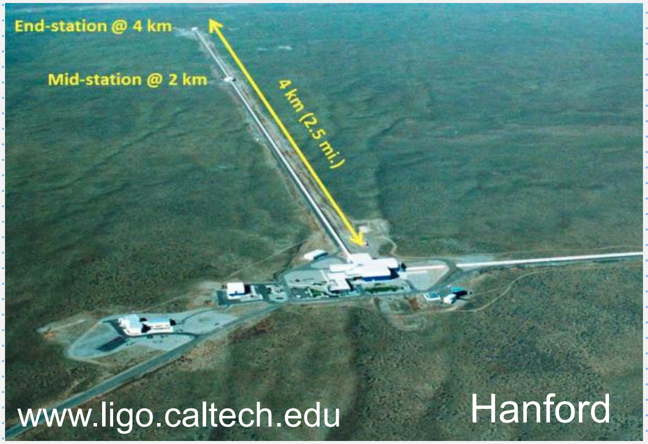
high-scale PT

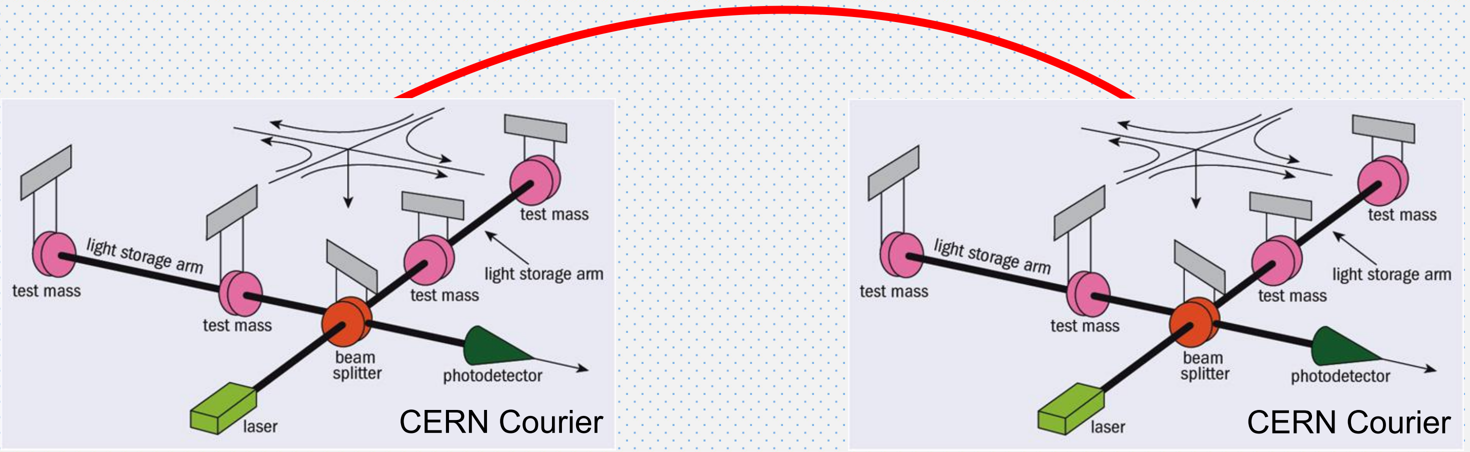
Detection at LIGO

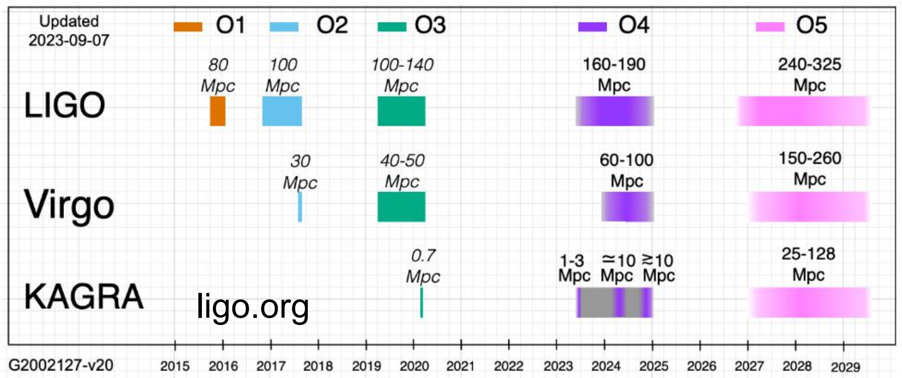
Using multiple interferometers (cross-correlation)

- So far, no discovery
- Constraints set on power laws, and relevant sources (PT etc)

LVK, PRD [2101.12130]







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)

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

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

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

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

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

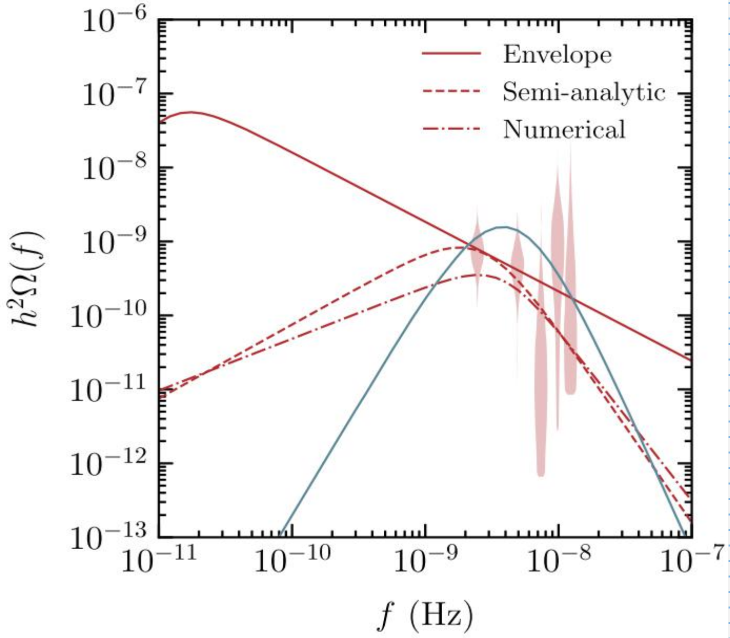
Jiang, Huang, JCAP [2203.11781]

Yu, Wang, PRD [2211.13111]

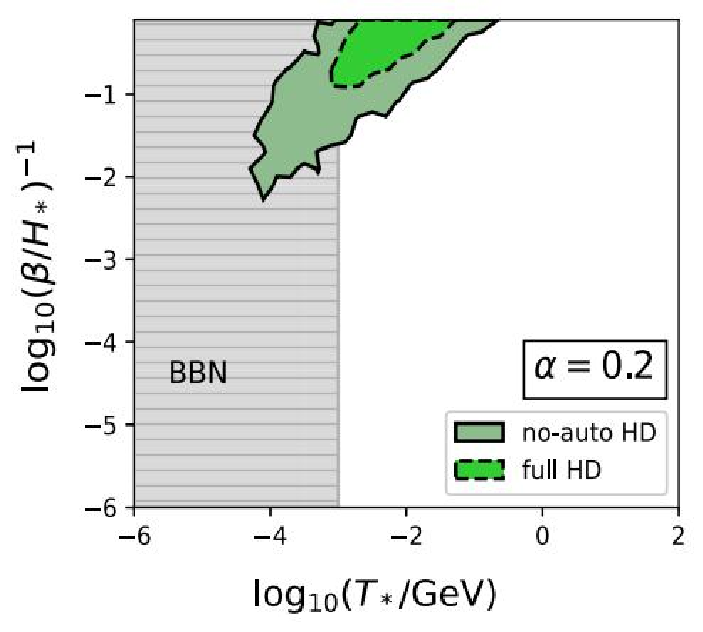
Romero,Martinovic,Callister,HG,Martínez,Sakellariadou,Yang,Zhao, PRL [2102.01714]

PTA

- No evidence for GW, constraints set



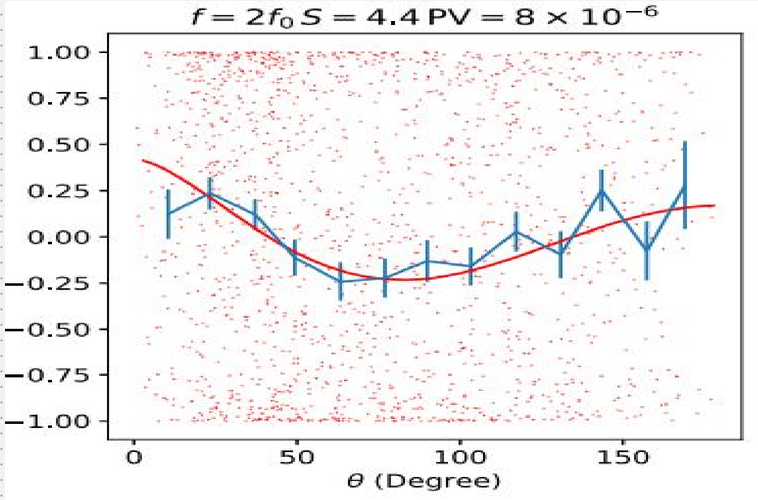
NANOGrav, PRL [2104.13930]



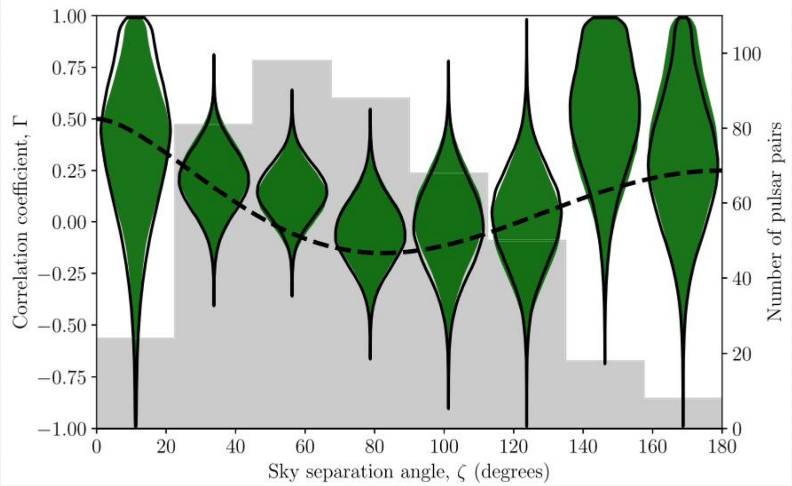
PPTA, Xue, et al, PRL [2110.03096]

QCD-scale PT

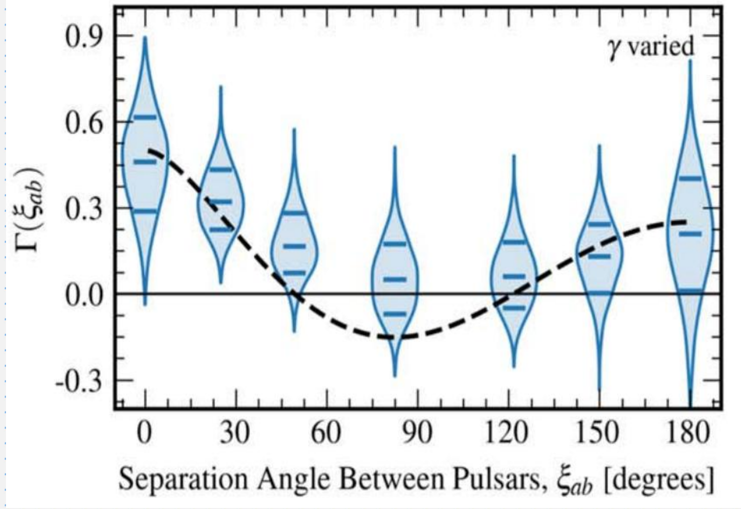
PTA: New Results with Evidence for GW



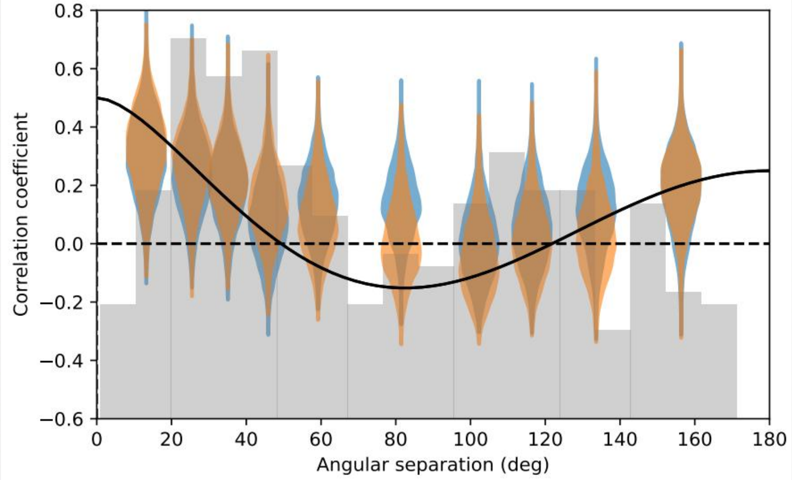
CPTA, RAA, [2306.16216]



PPTA, ApjL [2306.16215]



NANOGrav, ApjL [2306.16213]



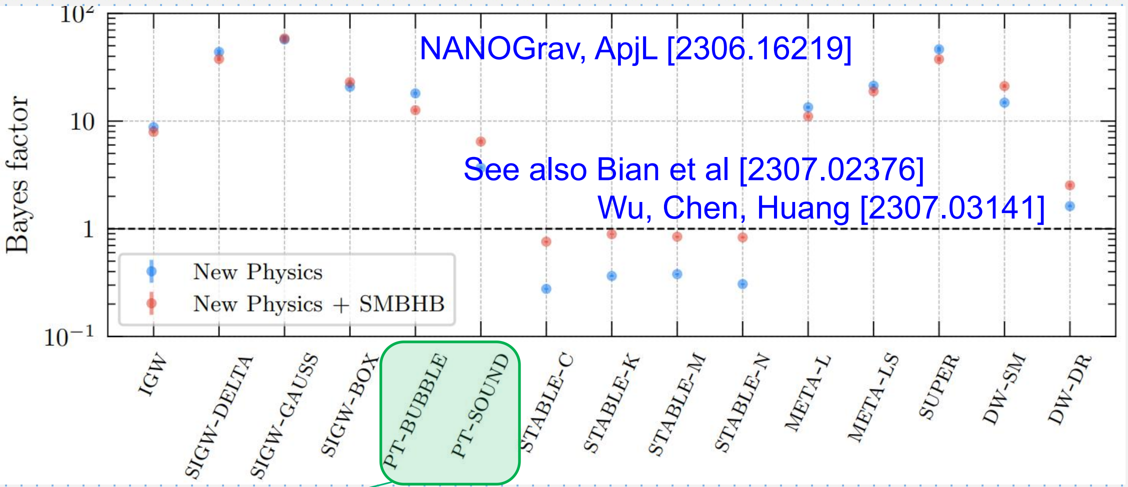
EPTA, A&A [2306.16214]

QCD-scale PT

What possible PTA discovery implies?

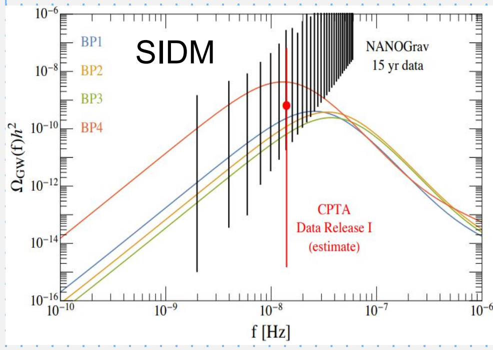
- Once discovered, firstly needs to know its origin
- Can be the next “CMB” (spectral shape, anisotropy, etc)
- Can be from first order QCD-scale PT

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

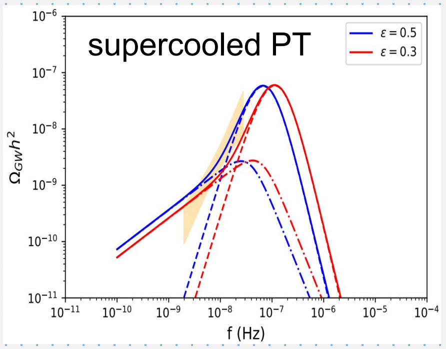


NANOGrav, ApjL [2306.16219]

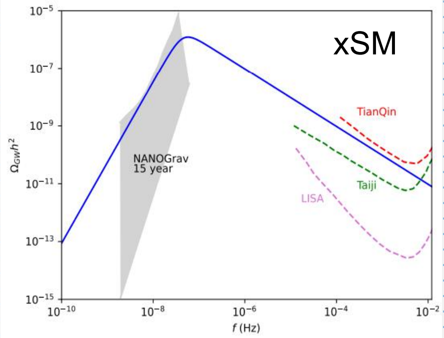
See also Bian et al [2307.02376]
Wu, Chen, Huang [2307.03141]



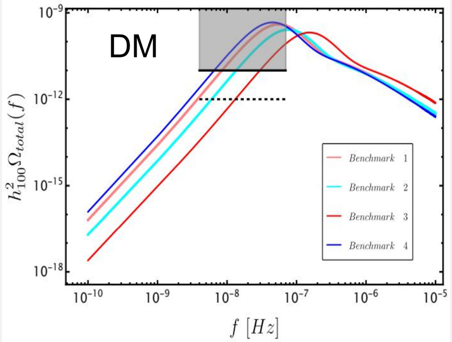
Han,Xie,Yang,Zhang [2306.16966]



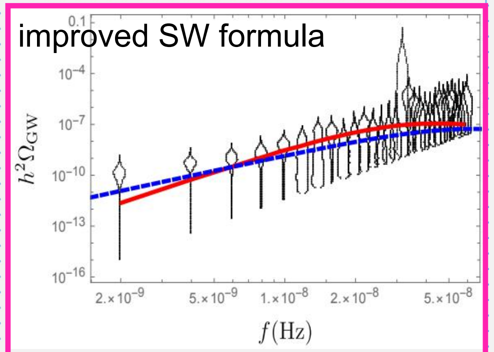
Zu,Zhang,Li,Gu,Tsai,Fan [2306.17239]



Xiao,Yang,Zhang [2307.01072]



Yang,Ma,Jiang,Huang [2306.17827]



Ghosh et al [2307.02259]

and more...

GWs from Particles

Extreme densities

disturbances in the early universe

As Macroscopic Objects

(non-) topological solitons

Environmental Effects

Faking GW signals (dark matter)

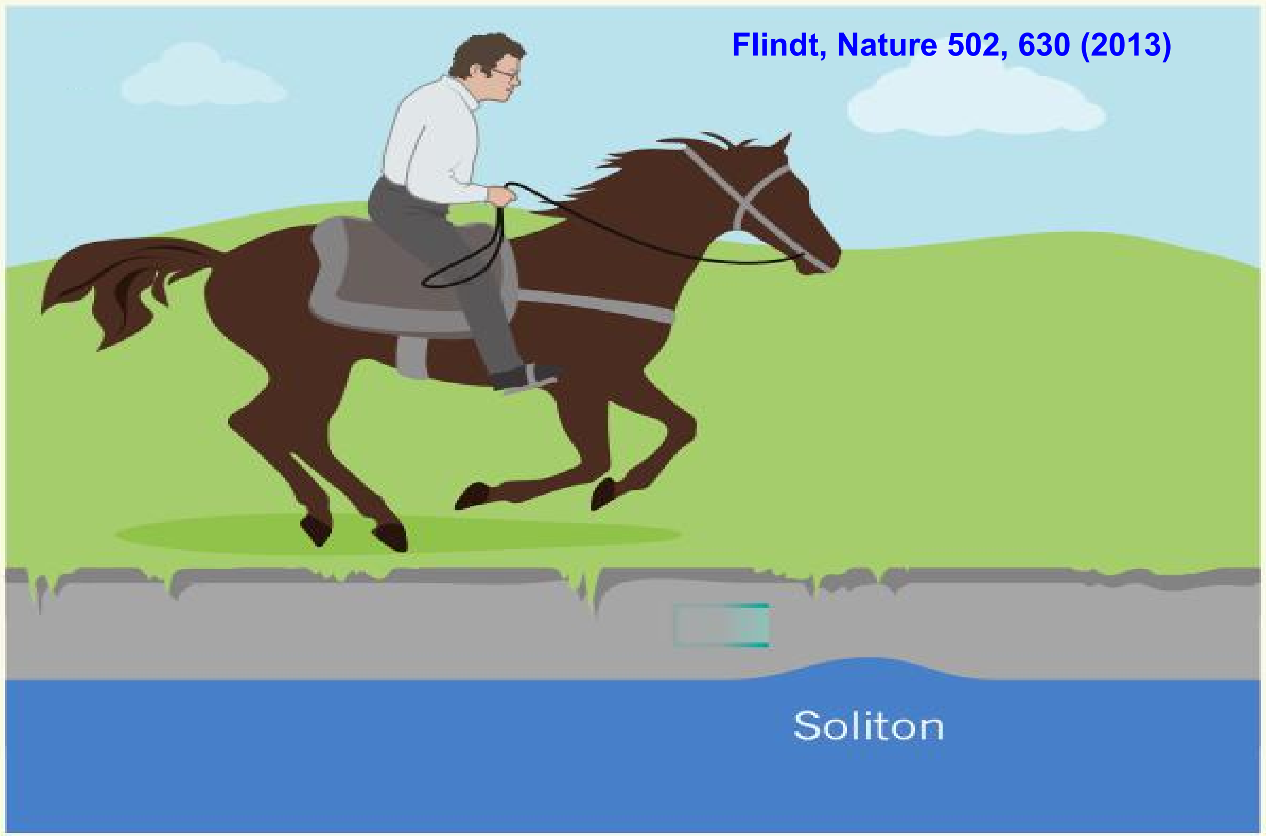
Solitons

- 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

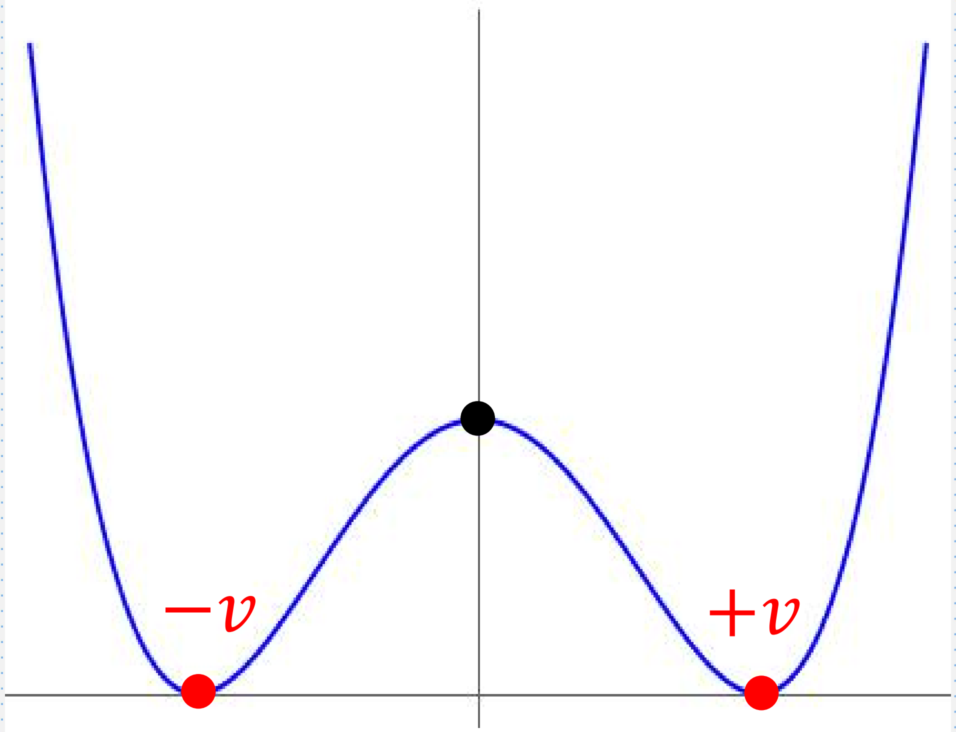
T W B Kibble   J.Phys.A 9 (1976) 1387-1398

Blackett Laboratory, Imperial College, Prince Consort Road, Lon

Received 11 March 1976   www.theguardian.com

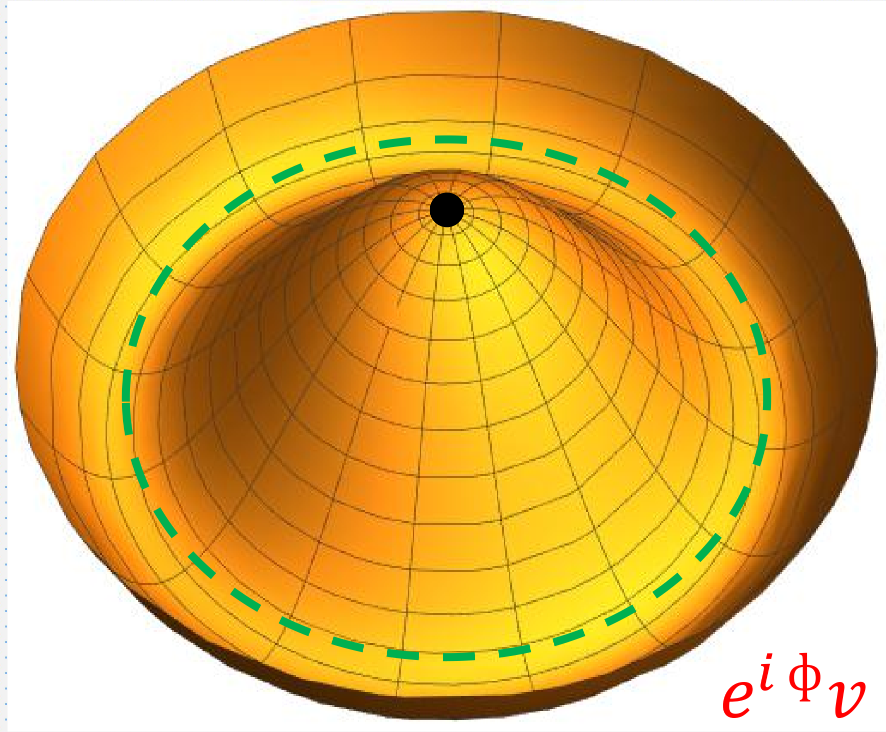
Degenerate Vacuum States

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



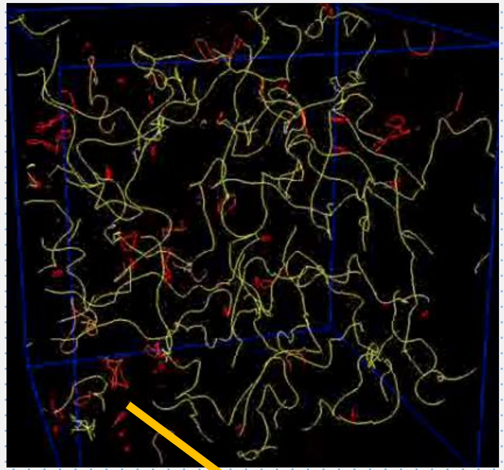
Domain wall

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



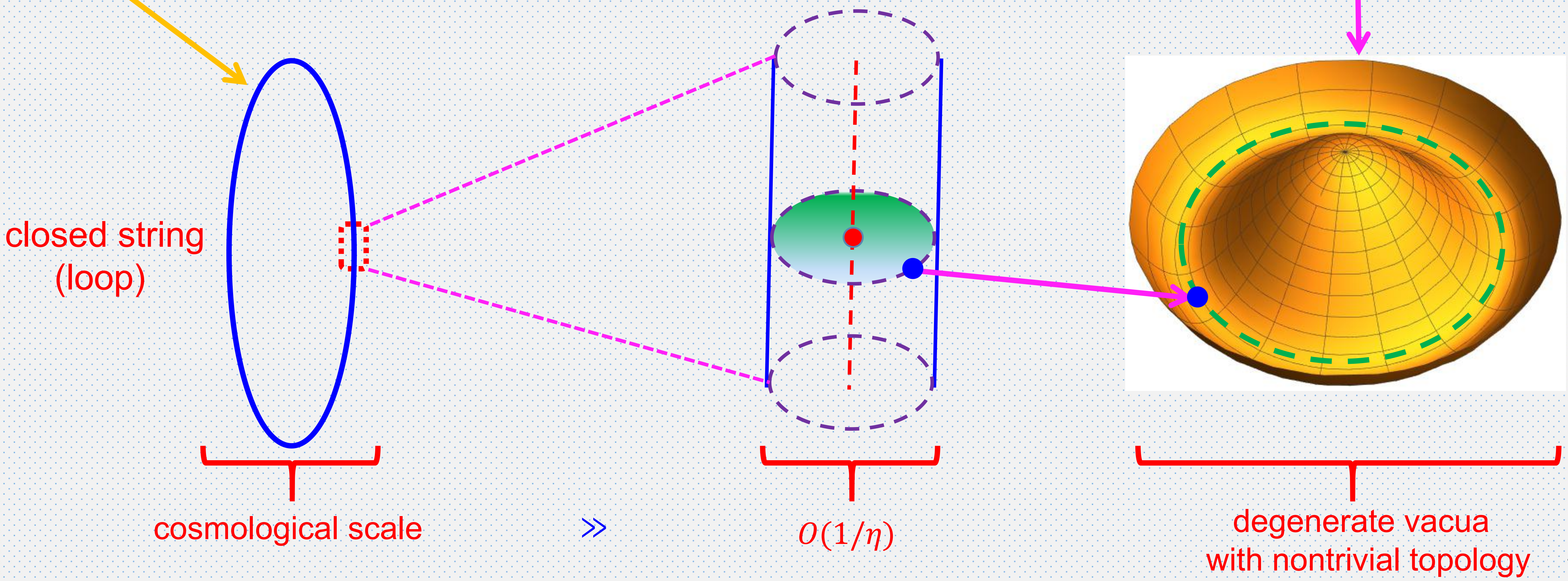
Cosmic String

Cosmic String



Example: the Abelian Higgs Model

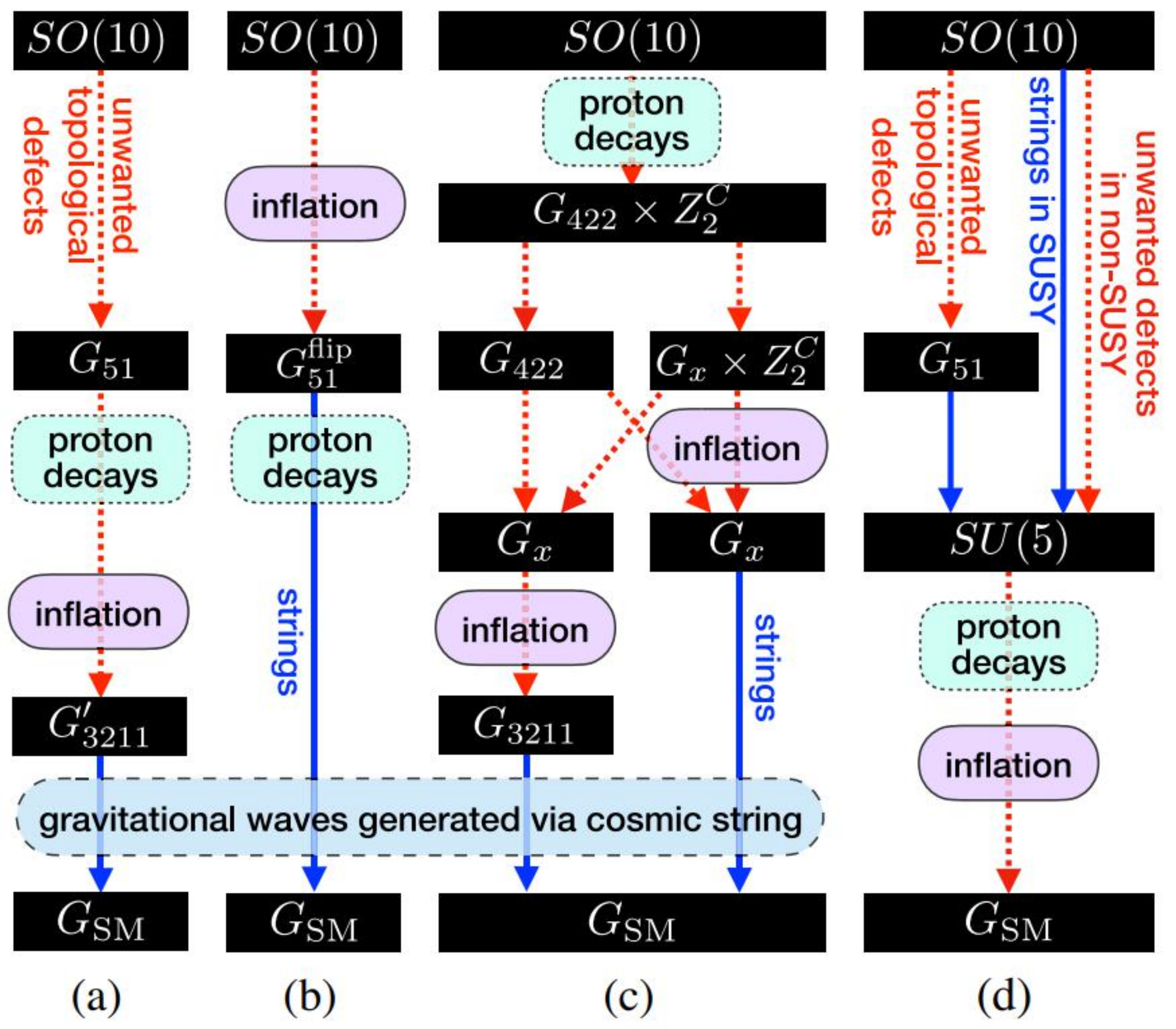
$$\mathcal{L} = |(\partial_\mu - igA_\mu)\Phi|^2 - \frac{1}{4}\lambda(|\Phi|^2 - \eta^2)^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$



GUT: Breaking Chains

King, Pascoli, Turner, Zhou, PRL [2005.13549], JHEP [2106.15634]

$$G_{51} = \mathrm{SU}(5) \times \mathrm{U}(1)_X, \qquad G_{51}^{\mathrm{flip}} = \mathrm{SU}(5)_{\mathrm{flip}} \times \mathrm{U}(1)_{\mathrm{flip}},$$
$$G_{3221} = \mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_{B-L},$$
$$G_{3211} = \mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_R \times \mathrm{U}(1)_{B-L},$$
$$G'_{3211} = \mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_X,$$
$$G_{421} = \mathrm{SU}(4)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y,$$
$$G_{422} = \mathrm{SU}(4)_C \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R. \qquad (1)$$



Gravitational Wave Production

Burst types: cusps, kinks and kink-kink collisions (Damour, Vilenkin, PRL 85,3671, PRD 64, 064008).

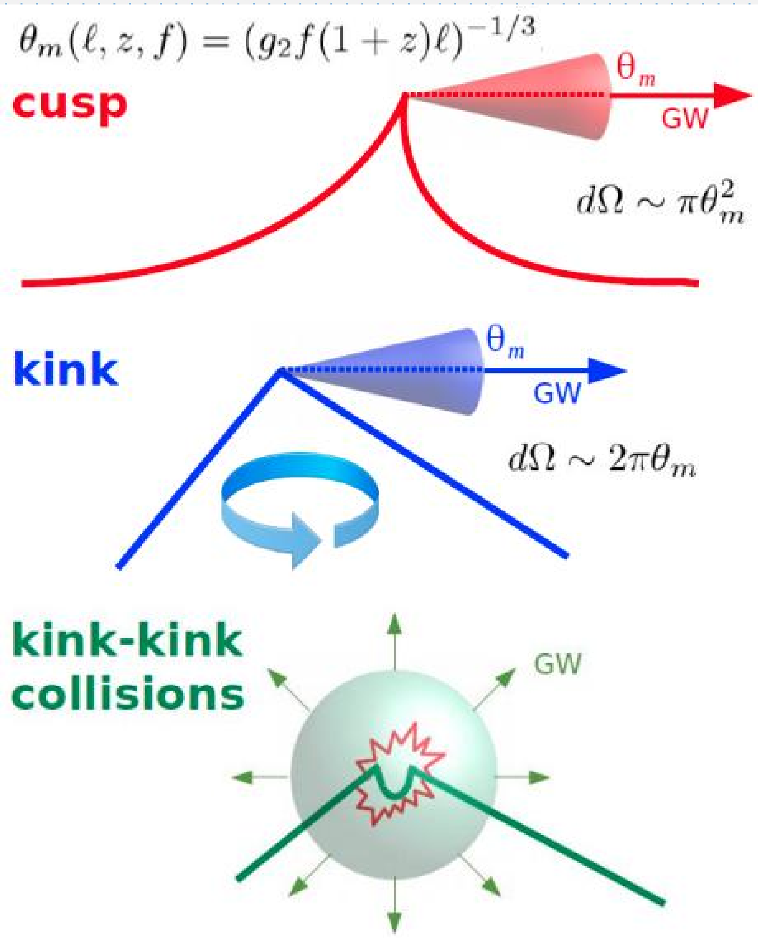


Image credit: Florent Robinet

simple waveforms in frequency domain

$$h_i(\ell, z, f) = A_i(\ell, z) f^{-q_i}$$

$$A_i(\ell, z) = g_{1,i} \frac{G\mu\, \ell^{2-q_i}}{(1+z)^{q_i-1} r(z)}$$

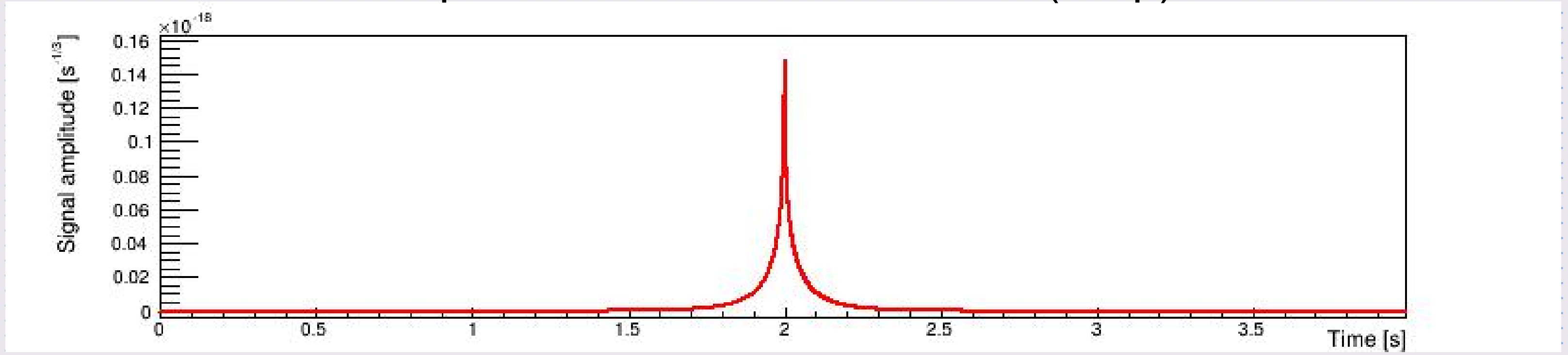
$q = 4/3, 5/3, 2$ for cusp, kink, and kk

scale

$$G\mu \sim (\eta/M_{\mathrm{Pl}})^2$$

particle physics model dependence

example waveform in time domain (cusp)

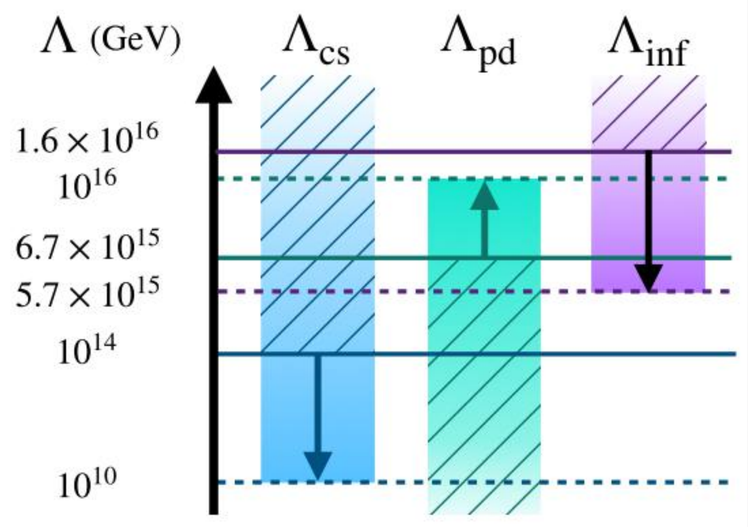


https://www.ligo.org/science/Publication-S5S6CosmicStrings

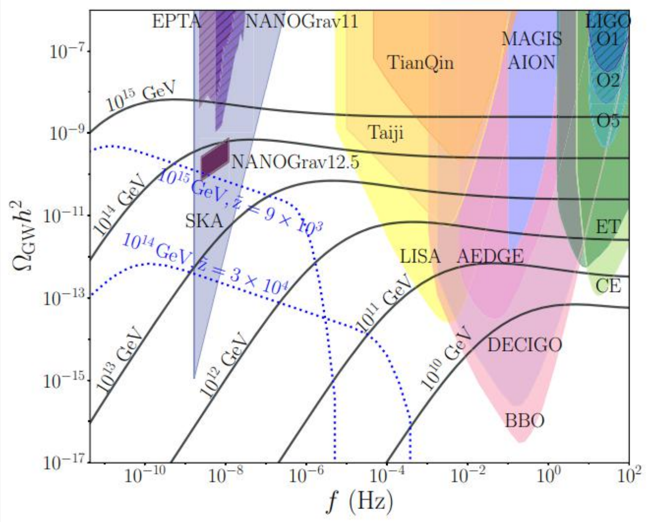
GUT: Proton Decay and GW Complementarity

King, Pascoli, Turner, Zhou, PRL [2005.13549], JHEP [2106.15634]

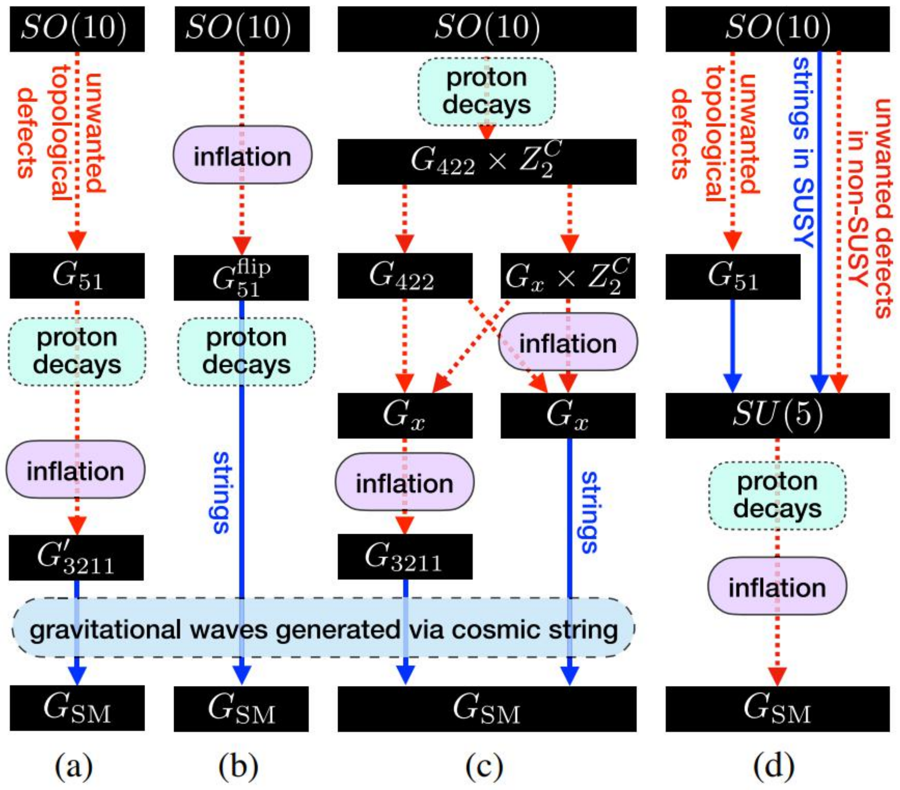
- Proton decay measurement
- GW detection
- Dangerous defects



$$\frac{\epsilon_{\alpha\beta}}{\Lambda_1^2}[(\overline{u_R^c}\gamma^\mu Q_\alpha)(\overline{d_R^c}\gamma_\mu L_\beta)+(\overline{u_R^c}\gamma^\mu Q_\alpha)(\overline{e_R^c}\gamma_\mu Q_\beta)] + \frac{\epsilon_{\alpha\beta}}{\Lambda_2^2}[(\overline{d_R^c}\gamma^\mu Q_\alpha)(\overline{u_R^c}\gamma_\mu L_\beta)+(\overline{d_R^c}\gamma^\mu Q_\alpha)(\overline{\nu_R^c}\gamma_\mu Q_\beta)],$$



Observables		Proton decays
		$p \to \pi^0 e^+$ observed ⇒ non-SUSY contribution indicated
GWs	Observed	• types (a) and (c) favoured • types (b) and (d) excluded
	Marginal	• types (a) and (c) favoured • type (d) excluded • type (b) allowed if $p \to K^+\bar{\nu}$ not observed and $\Lambda_{\rm pd} \sim \Lambda_{\rm cs}$



Leptogenesis

Dror, Hiramatsu, Kohri, Murayama, White, PRL [1908.03227]

	$H = G_{SM}$		$H = G_{SM} \times \mathbb{Z}_2$	
G	*Defects*	*Higgs*	*Defects*	*Higgs*
G_{disc}	Domainwall*	$B - L = 1$	Domainwall*	$B - L = 2$
G_{B-L}	Abelianstring*	$B - L = 1$	$\mathbb{Z}_2$ string†	$B - L = 2$
G_{LR}	Texture*	$(\mathbf{1}, \mathbf{1}, \mathbf{2}, \frac{1}{2})$	$\mathbb{Z}_2$ string	$(\mathbf{1}, \mathbf{1}, \mathbf{3}, 1)$
G_{421}	None	$(\mathbf{10}, \mathbf{1}, 2)$	$\mathbb{Z}_2$ string	$(\mathbf{15}, \mathbf{1}, 2)$
G_{flip}	None	$(\mathbf{10}, 1)$	$\mathbb{Z}_2$ string	$(\mathbf{50}, 2)$

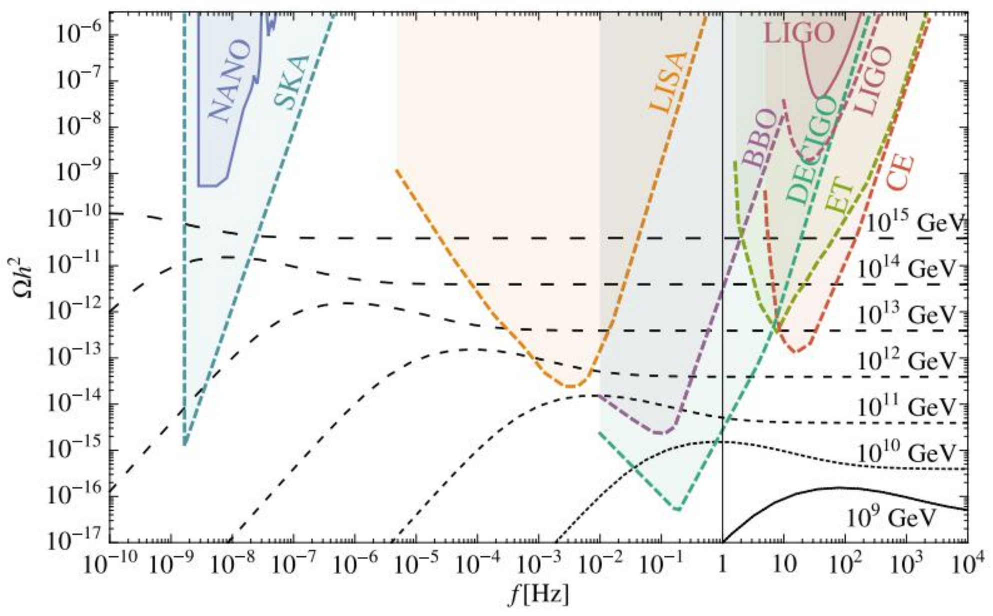
$$G_{disc} = G_{SM} \times \mathbb{Z}_N,$$

$$G_{B-L} = G_{SM} \times U(1)_{B-L},$$

$$G_{LR} = SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L},$$

$$G_{421} = SU(4)_{PS} \times SU(2)_L \times U(1)_Y,$$

$$G_{flip} = SU(5) \times U(1).$$



Loop Distribution Function

3 models considered

- Model A: (Blanco-Pillado et al., PRD 89,023512) (simulations)
- Model B: Lorentz et al., JCAP 10 (2010) 003 (analytical modelling, matched onto simulation result)
- Model C: Auclair et al., JCAP 06 (2019) 015 (interpolation between above 2)

C-1 (C-2) reproduces LDF of Model A (B) in the radiation era
and LDF of Model B (A) in the matter era

modelling loop distribution (F, dimensionless)

$$\frac{\partial}{\partial t}\left[a^3 F(l,t)\right] = a^3\mathcal{P}(l,t) + a^3\gamma_d \frac{\partial}{\partial t} F(l,t)$$

production from long strings

decay due to GW radiation

Large Nc or Nk does not necessarily lead to large signal (loops decays faster)

$$\gamma_d = \Gamma_d G\mu$$

$$\Gamma_{\rm d} \equiv \frac{P_{\rm gw}}{G\mu^2} = \sum_i \frac{P_{{\rm gw},i}}{G\mu^2}$$

dimensionless decay constant

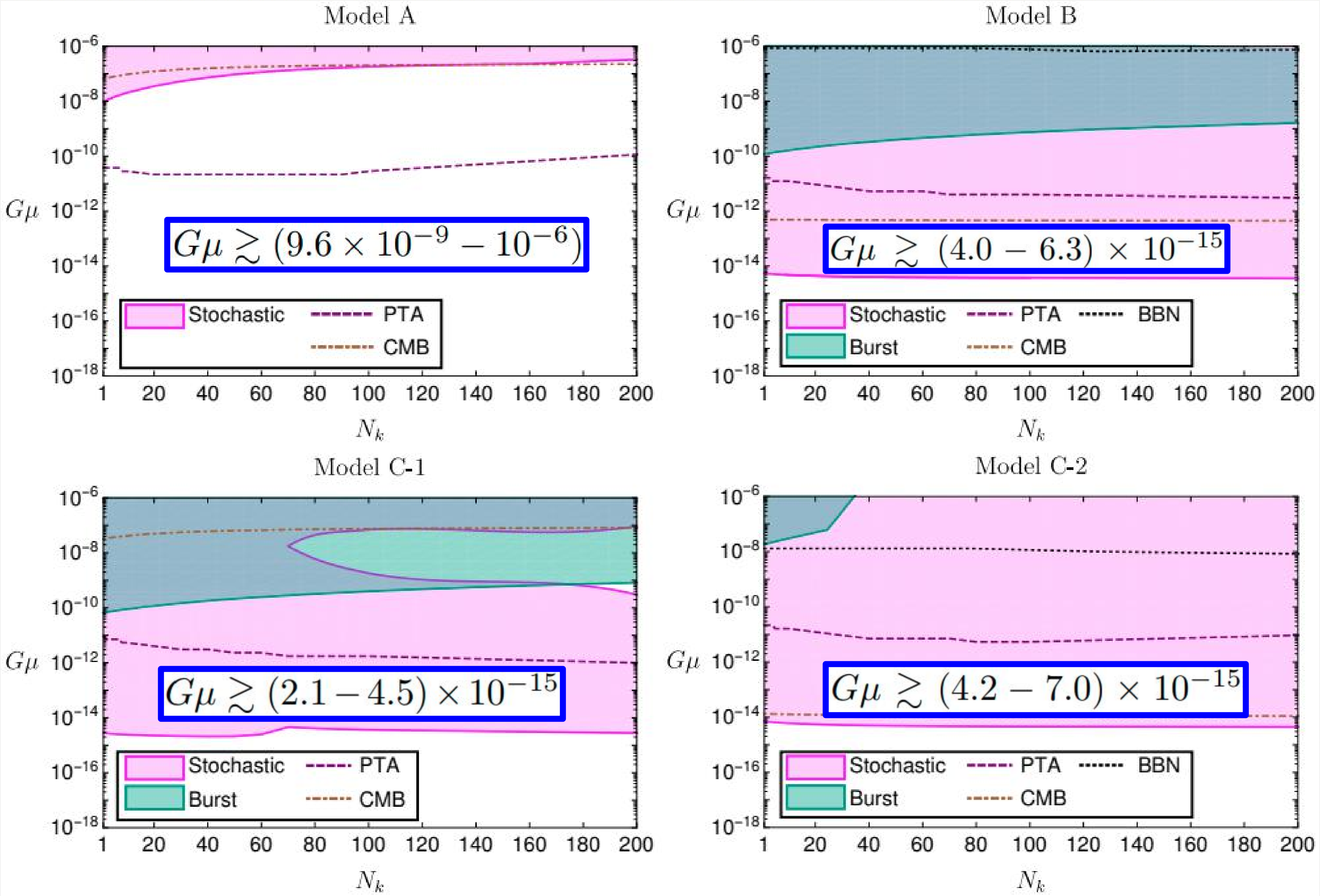
$$= N_{\rm c}\frac{3\pi^2 g_{1,{\rm c}}^2}{(2\delta)^{1/3} g_2^{2/3}} + N_{\rm k}\frac{3\pi^2 g_{1,{\rm k}}^2}{(2\delta)^{2/3} g_2^{1/3}} + N_{\rm kk} 2\pi^2 g_{1,{\rm kk}}^2$$

cusp

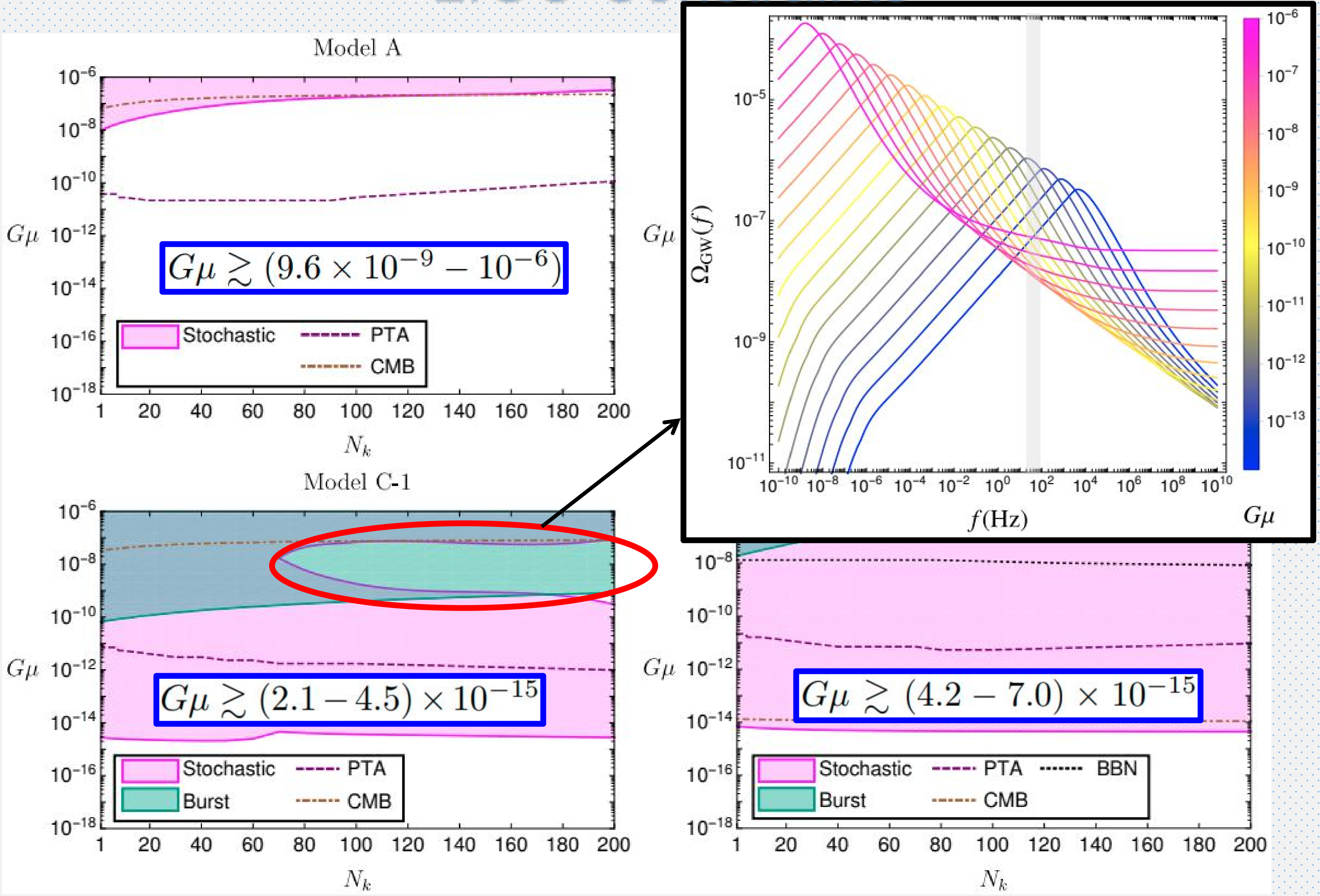
kink

kink-kink collision

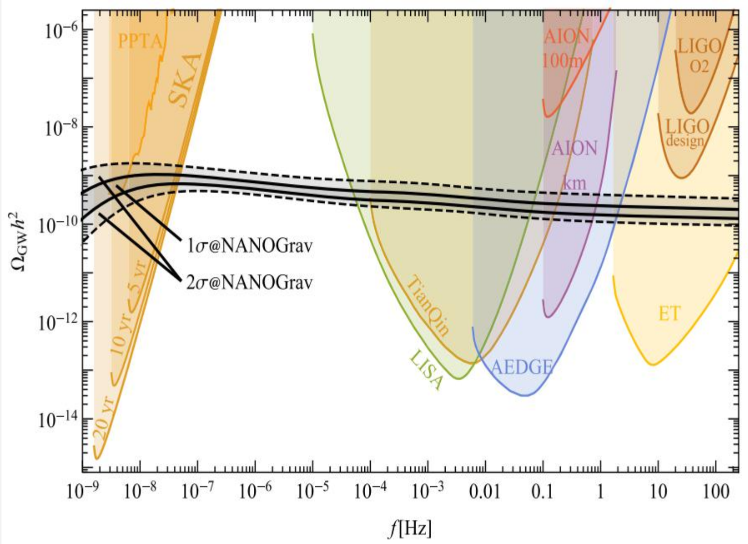
LIGO Constraints



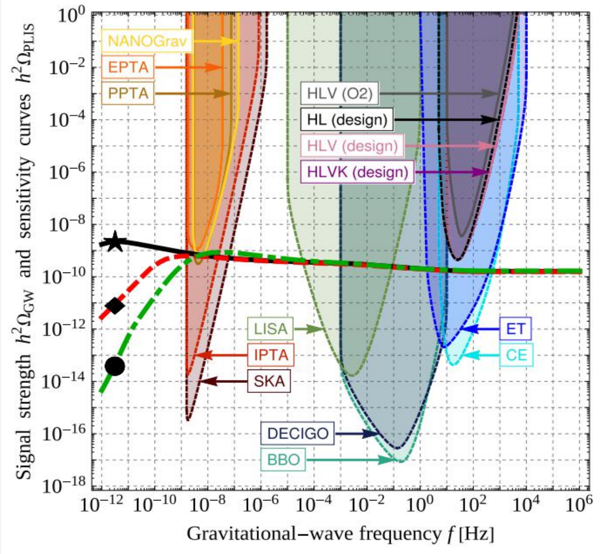
LIGO Constraints



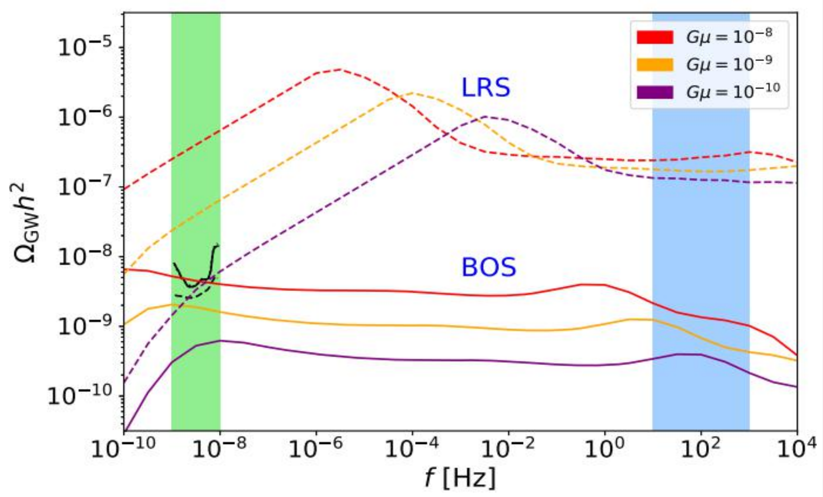
PTA

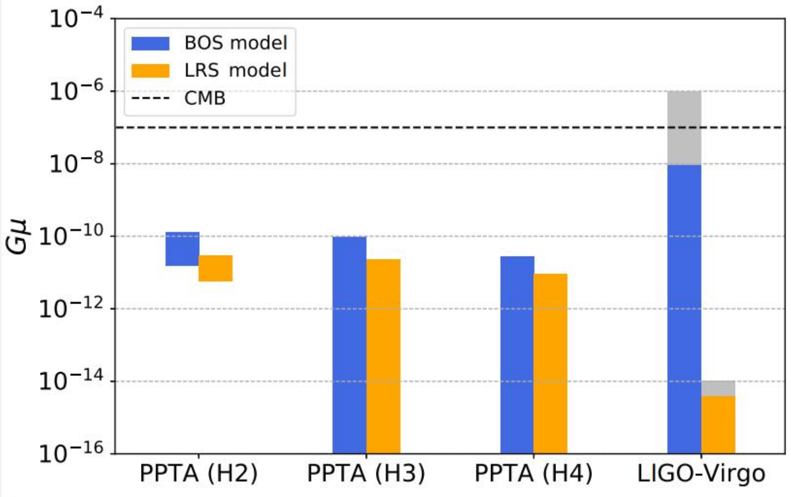


Ellis, Lewicki, PRL [2009.06555]



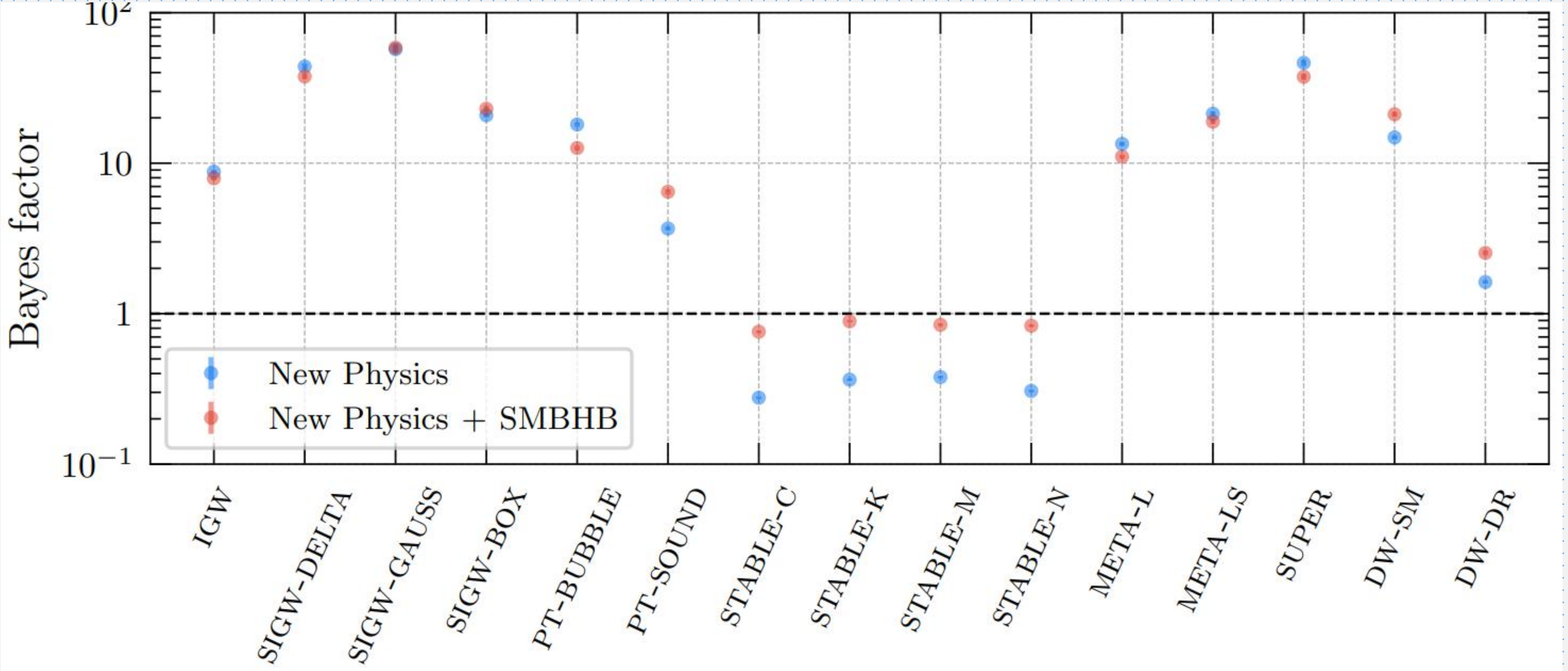
Blasi, Brdar, Schmitz, PRL [2009.06607]





Bian, Shu, Wang, Yuan, Zong, PRD Letter [2205.07293]

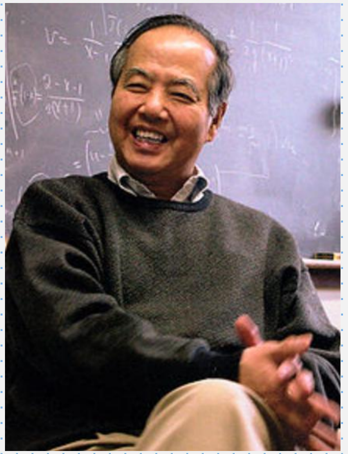
PTA: New



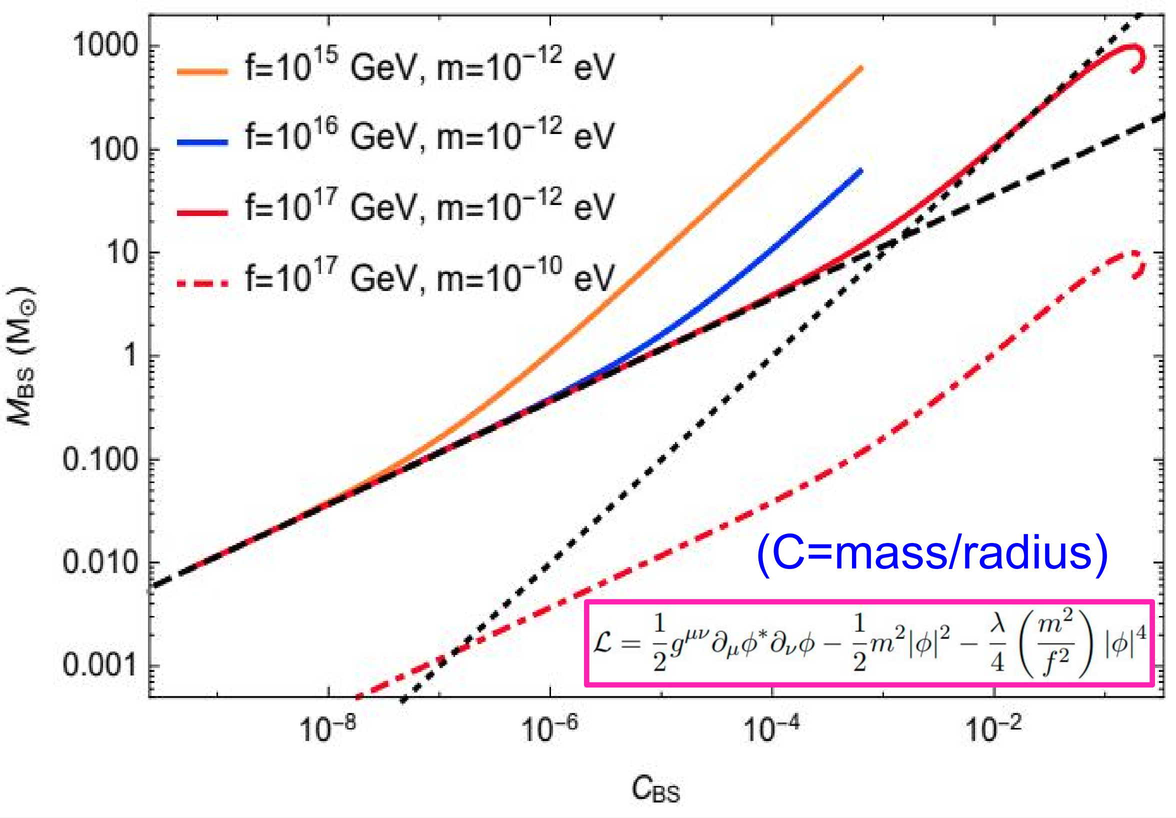
NANOGrav, ApjL [2306.16219]

See also Bian et al [2307.02376], Wu, Chen, Huang [2307.03141]

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)

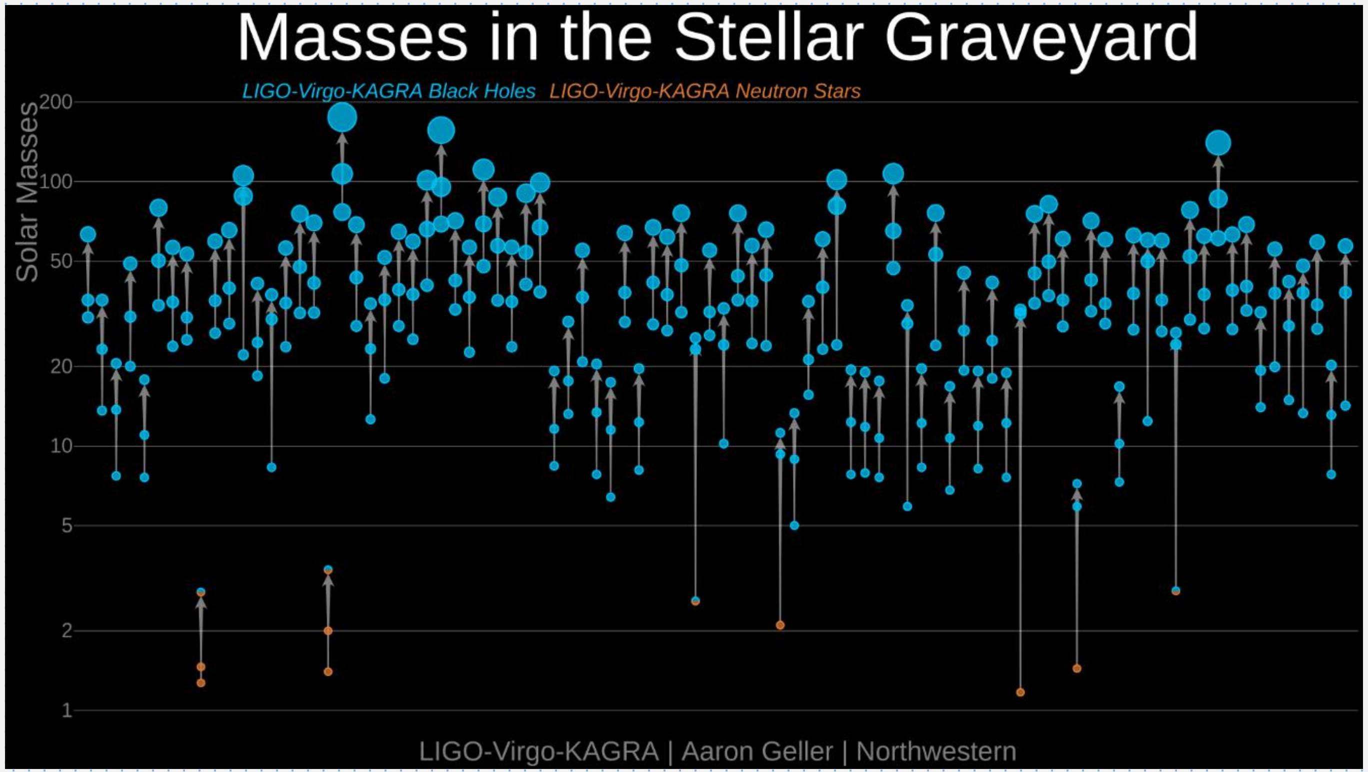
See, e.g., Liebling, Palenzuela, Living Rev Relativ (2017) 20:5

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

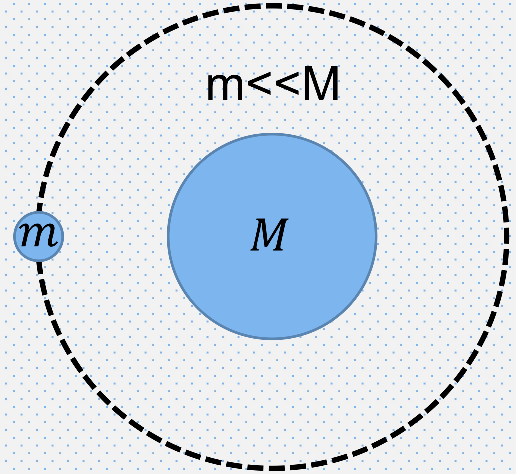
(Received 4 March 2016; published 19 May 2016)

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

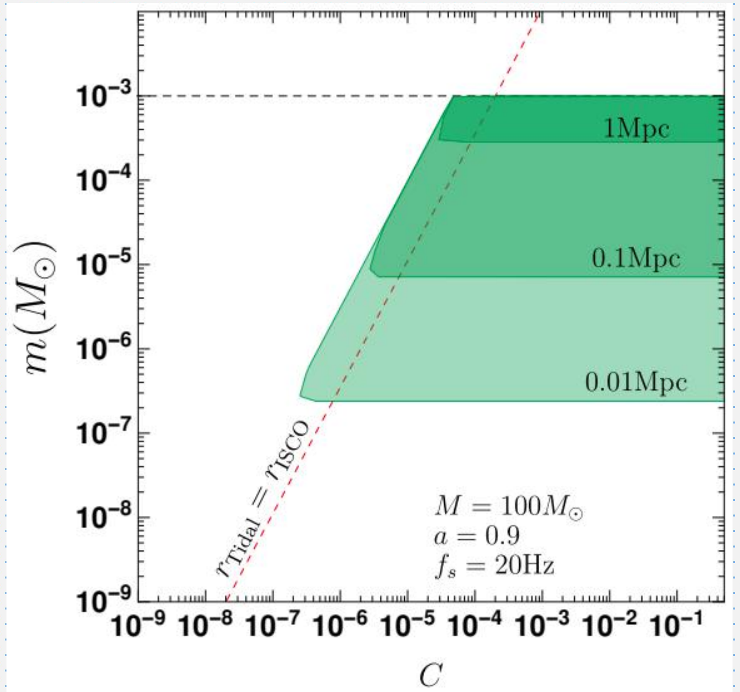
Phys. Rev. Lett. **126**, 081101 – Published 24 February 2021

Detection with EMRI and mini-EMRI



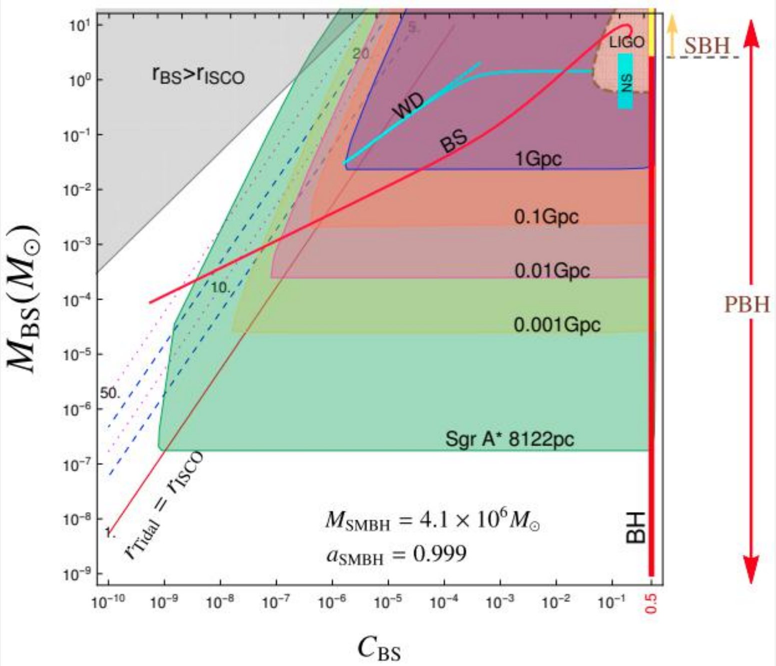
- By making one object much heavier, one can probe much ligher companion object
- Ideal systems: extreme mass ratio inspirals (EMRIs), key target of Taiji, Tianqin, LISA.
- LIGO can detect mini-EMRIs (extreme mass ratio, but lighter objects)

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

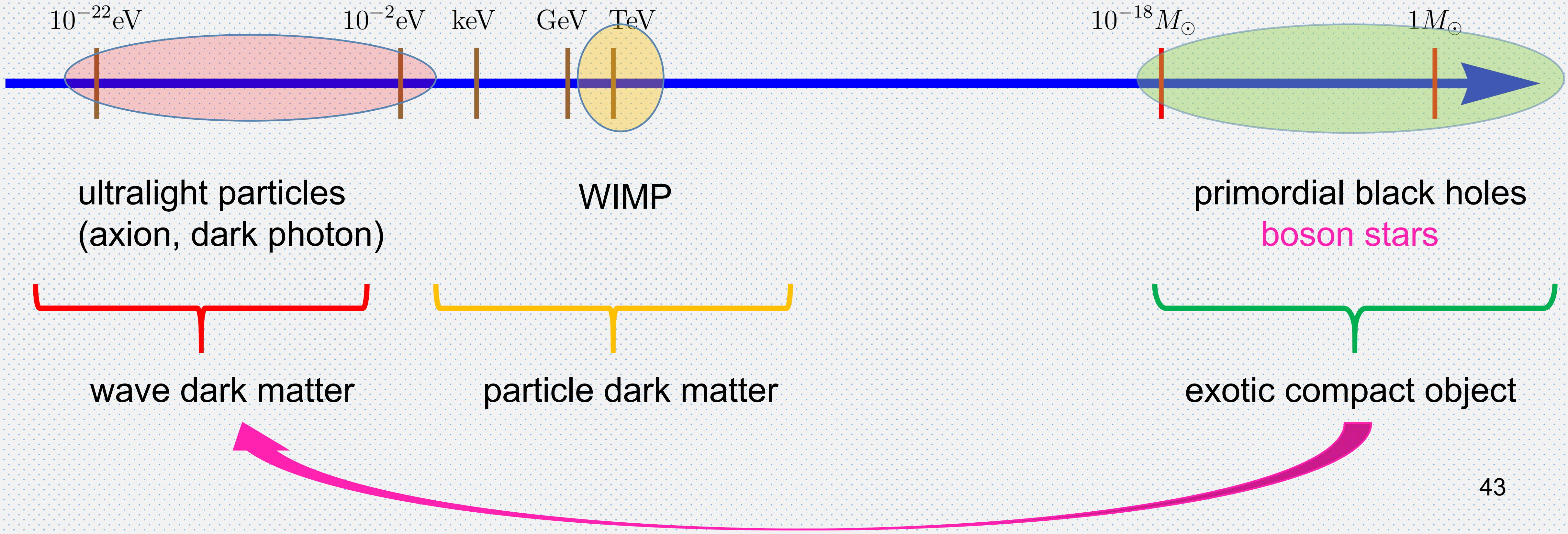
(non-) topological solitons

Environmental Effects ✓

Faking GW signals (dark matter)

Ultralight Dark Matter

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



Dark Matter

Vector

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}m^2 A^\mu A_\mu - \epsilon e J^\mu A_\mu$$

- Dark photon dark matter
- U(1) B or B-L
- Induces differential arm-length change for LIGO

Scalar

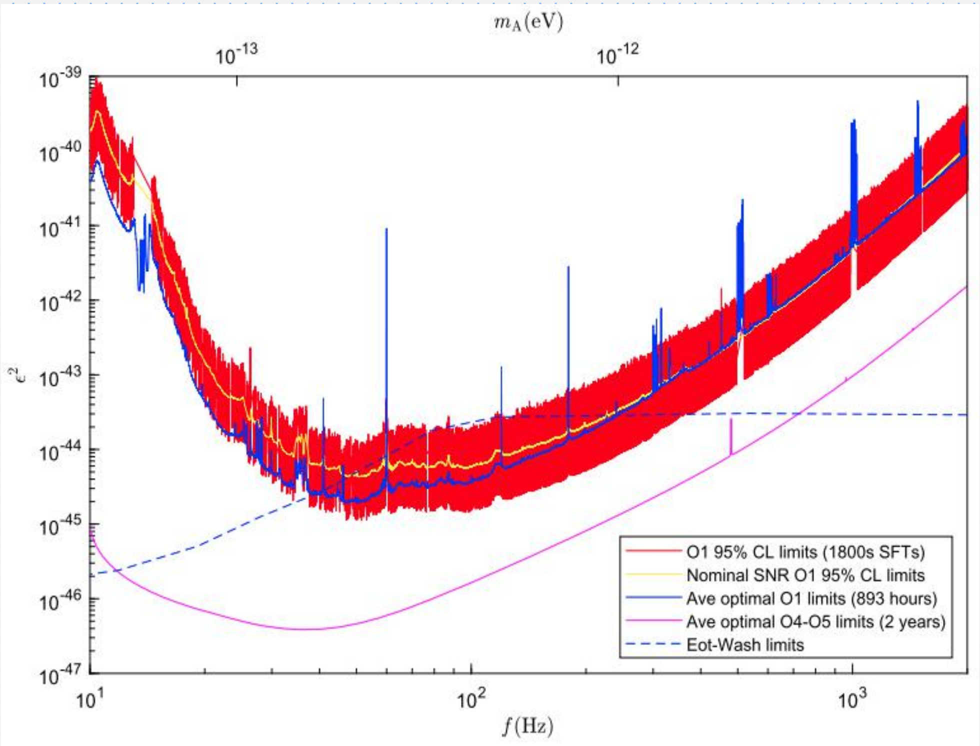
Damour, Donoghue, PRD [1007.2792]

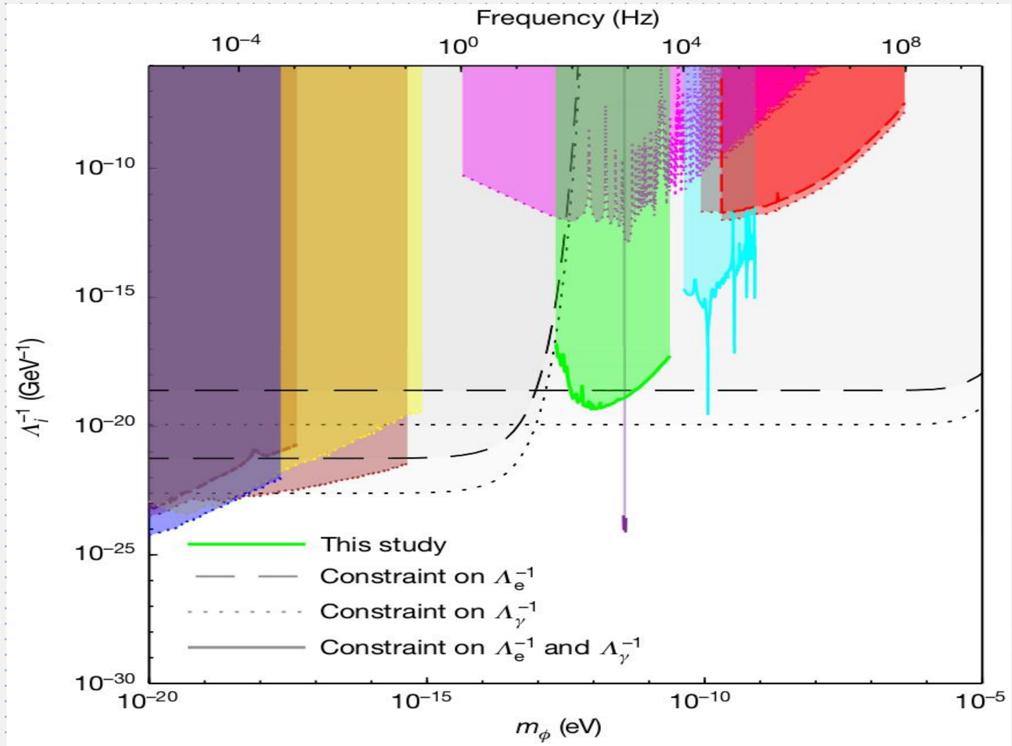
$$\mathcal{L}_{\text{int}\phi} = \kappa\phi\Big[+\frac{d_e}{4e^2}F_{\mu\nu}F^{\mu\nu} - \frac{d_g\beta_3}{2g_3}F^A_{\mu\nu}F^{A\mu\nu} - \sum_{i=e,u,d}(d_{m_i} + \gamma_{m_i}d_g)m_i\bar{\psi}_i\psi_i\Big].$$

- Dilaton
- Cause variation in fundamental constants
- Changes mirror size and refractive index for LIGO

Ground-based GW Detectors

- Ground-based GW detector: LIGO-Virgo-KAGRA, GEO600
- LIGO O1 data first analyzed in 2019



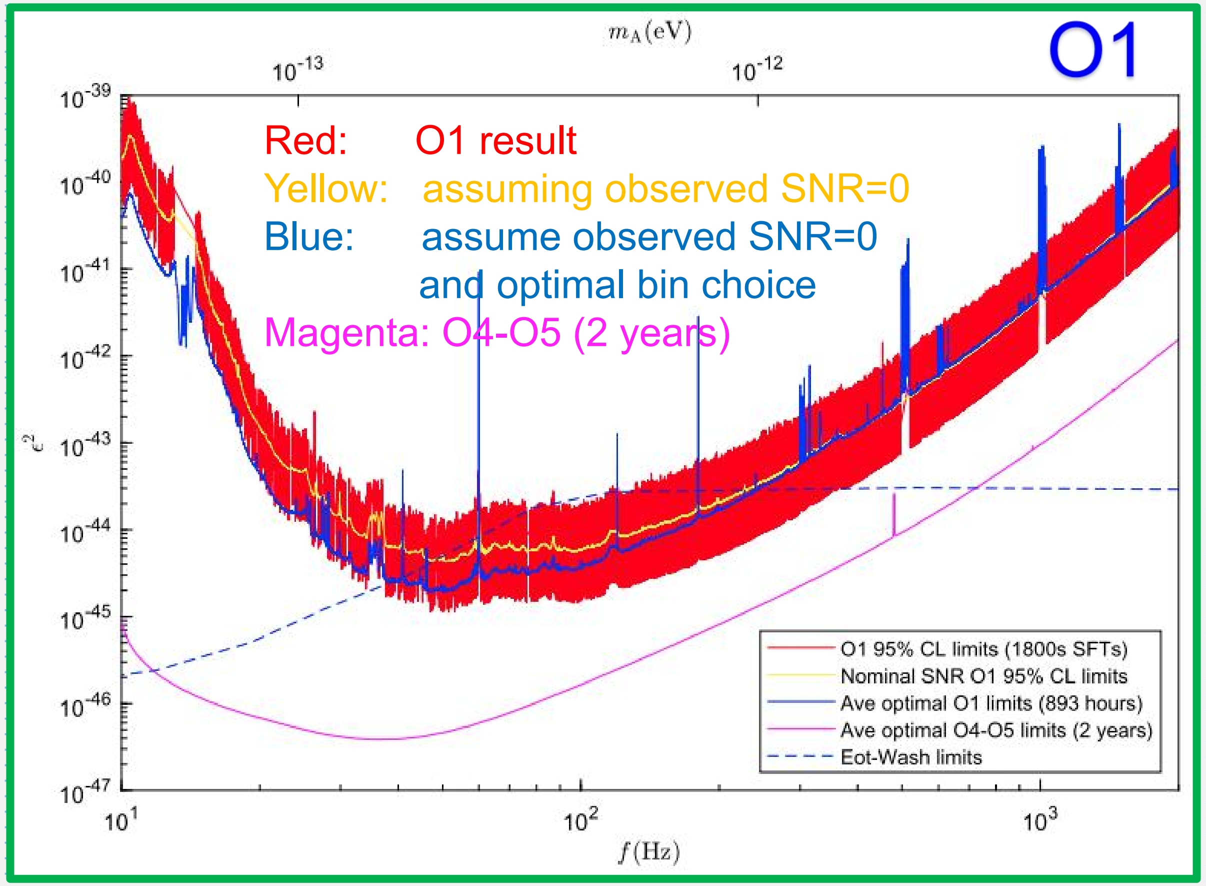


HG, Riles, Yang, Zhao, Communications Physics [1905.04316]

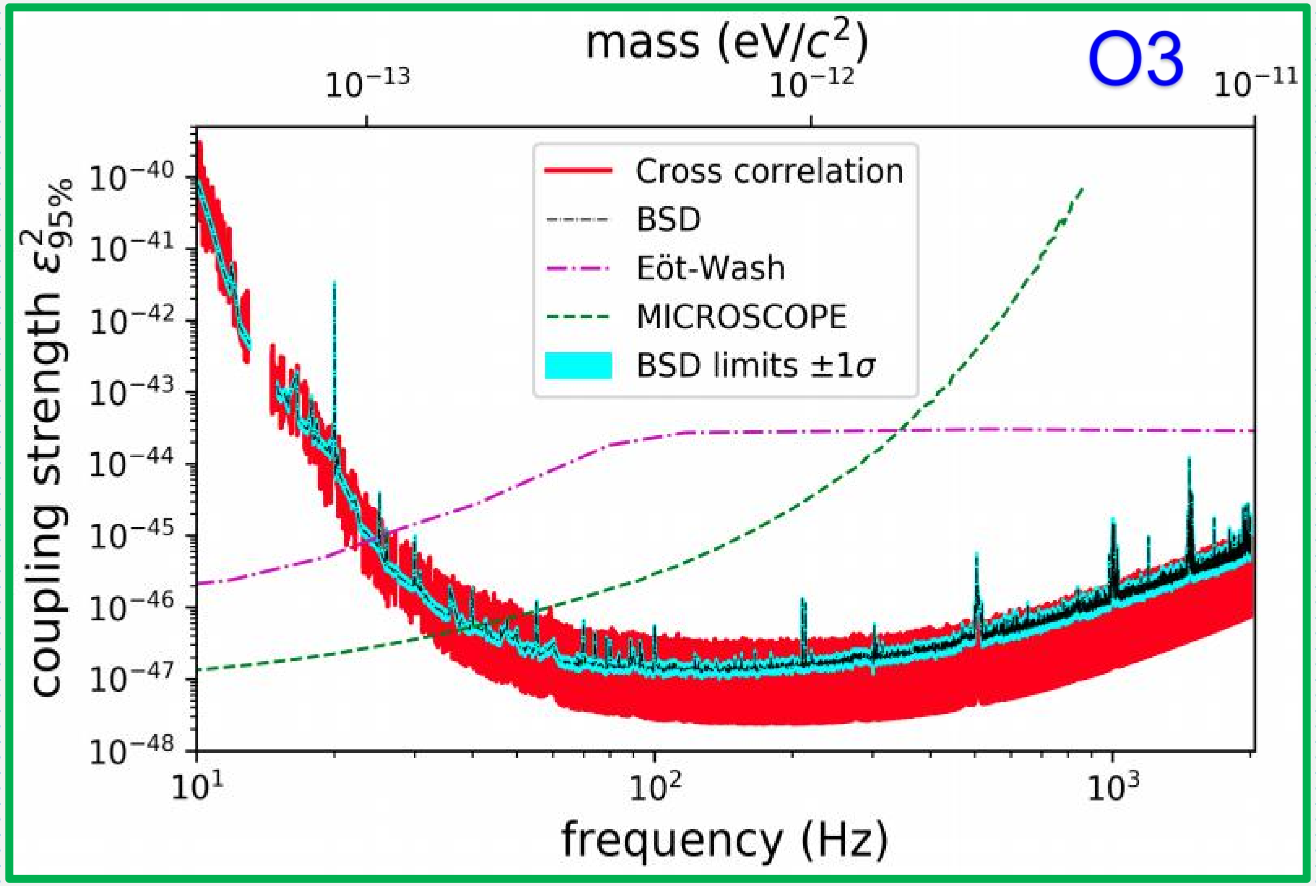
Vermeulen, et al, Nature [2103.03783]

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

LIGO Search Results



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

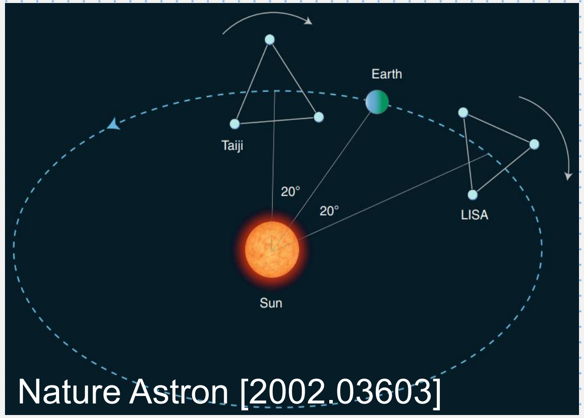


Phys.Rev.D 105 (2022) 6, LIGO-Virgo-KAGRA Collaborations

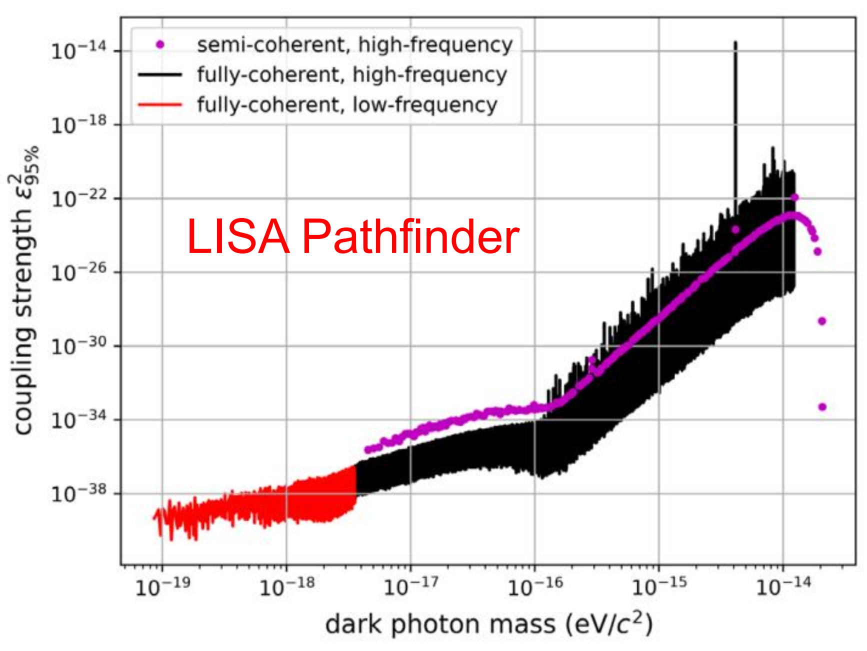
New in O3 search:

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

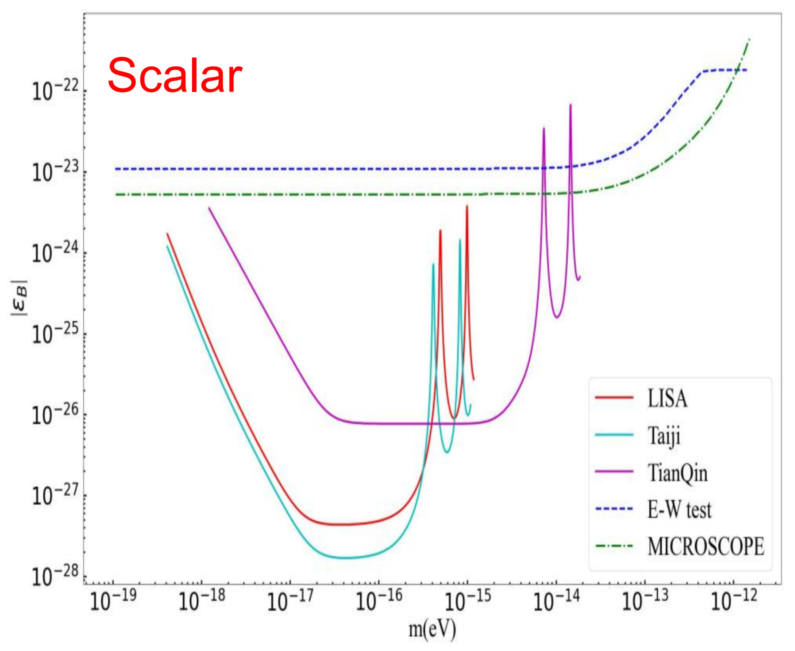
Space-based GW Detectors

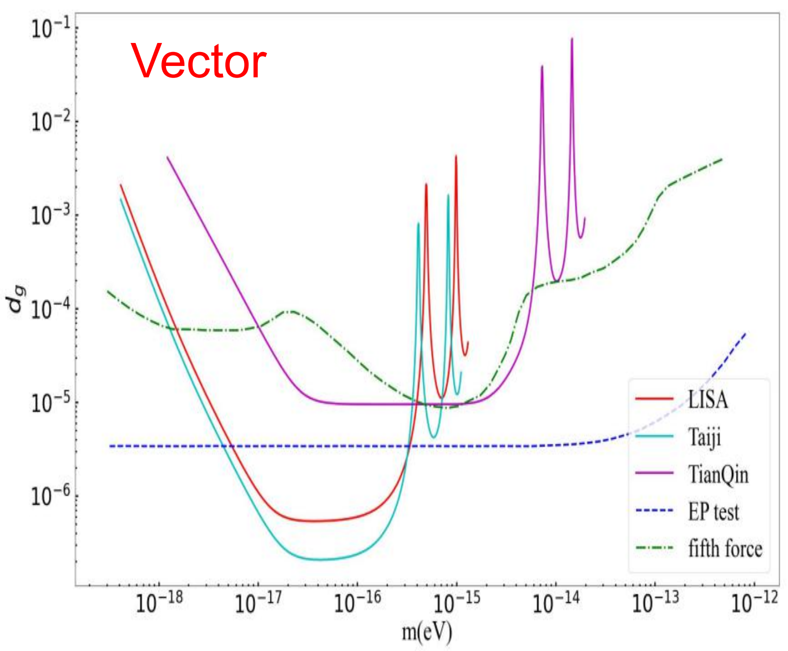


- Space-based GW detector: LISA, Taiji, Tianqin
- Lower frequency -> Lower mass
- Time delay interferometry: non-trivial detector response



Miller, Mendes, PRD [2301.08736]

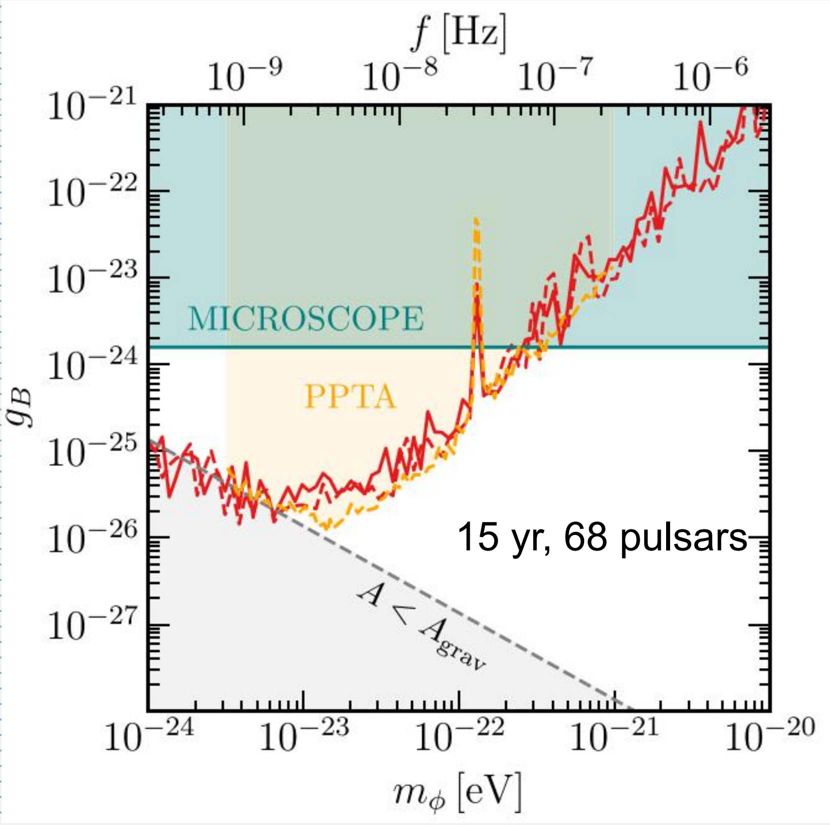




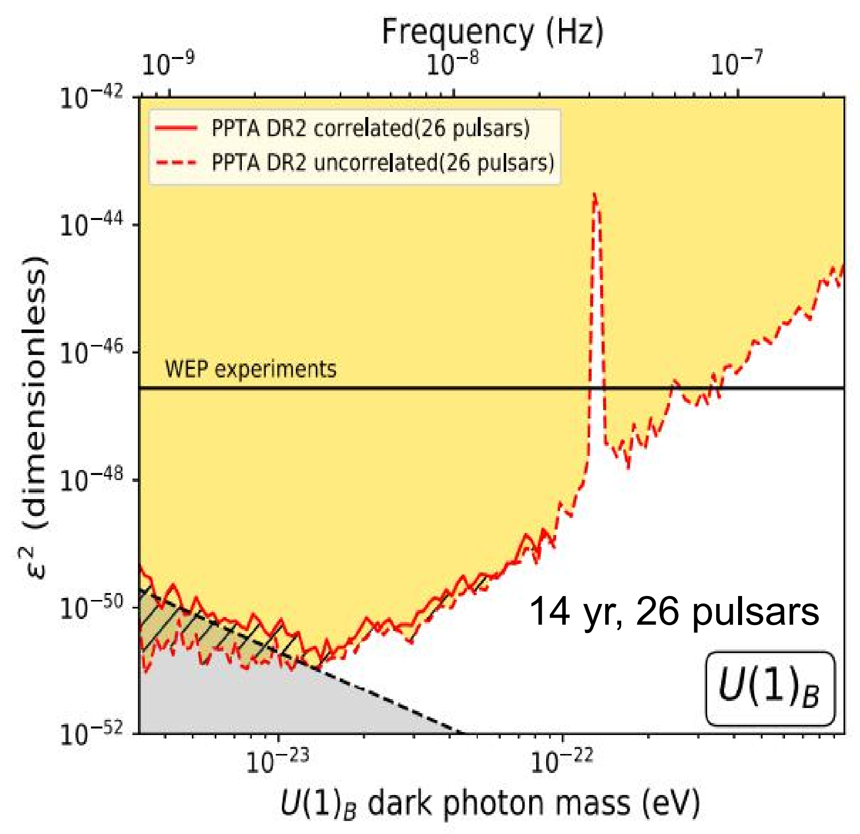
Yu, Yao, Tang, Wu [2307.09197]

PTA Limits

- Even lower frequency -> even lower mass



NANOGrav, ApjL [2306.16219]



PPTA, Xue, et al, PRR [2112.07687]

Summary

GW is a new tool in particle physics studies

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

Thanks!