

Gravitational Waves Related to Particle Physics and Connections to Neutrino Physics

郭怀珂

国科大
国际理论物理中心（亚太地区）



2023年5月21日

第二届 无中微子双贝塔衰变及相关物理

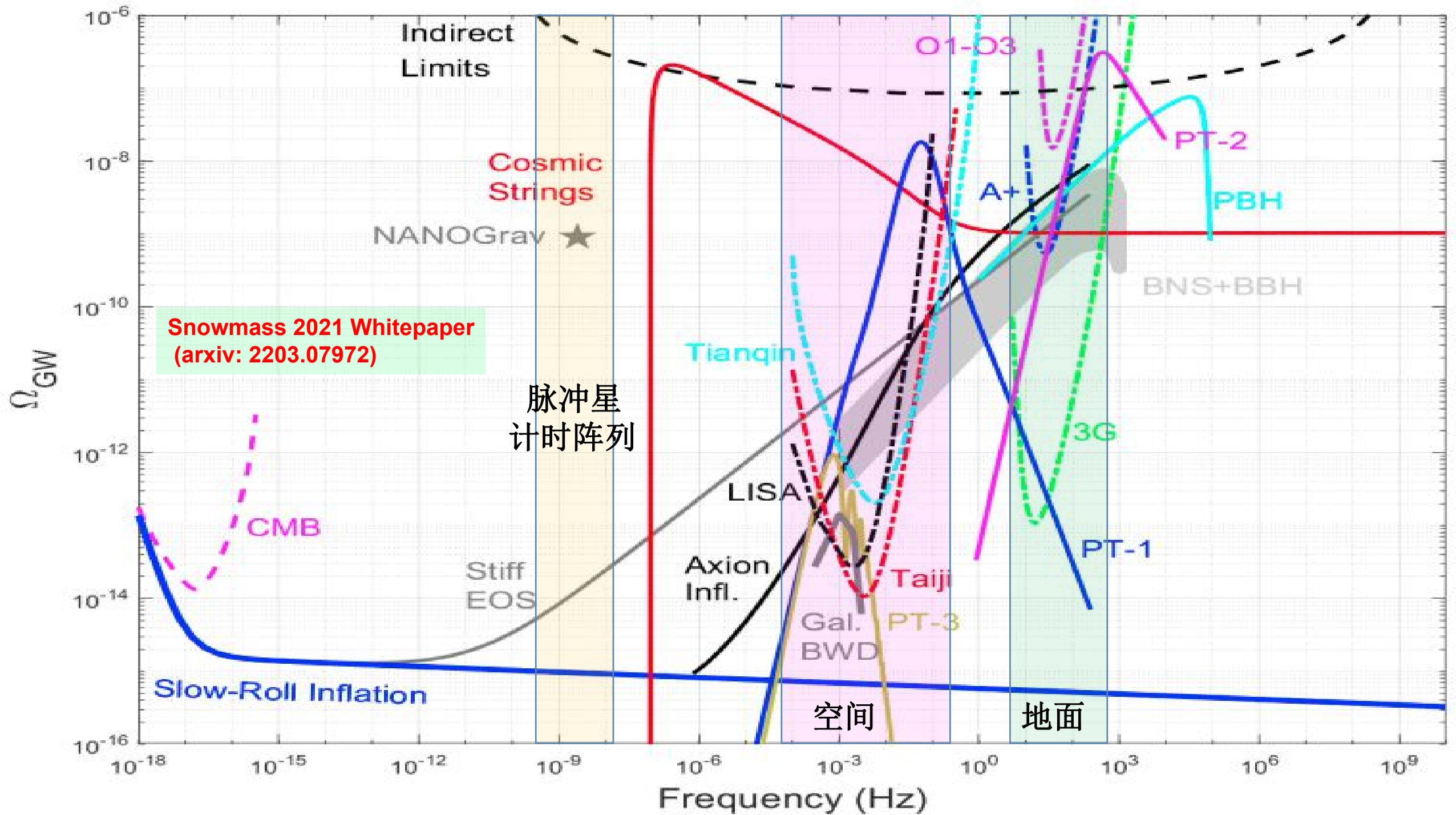
研讨会

2023.05.19 — 2023.05.23, 珠海

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

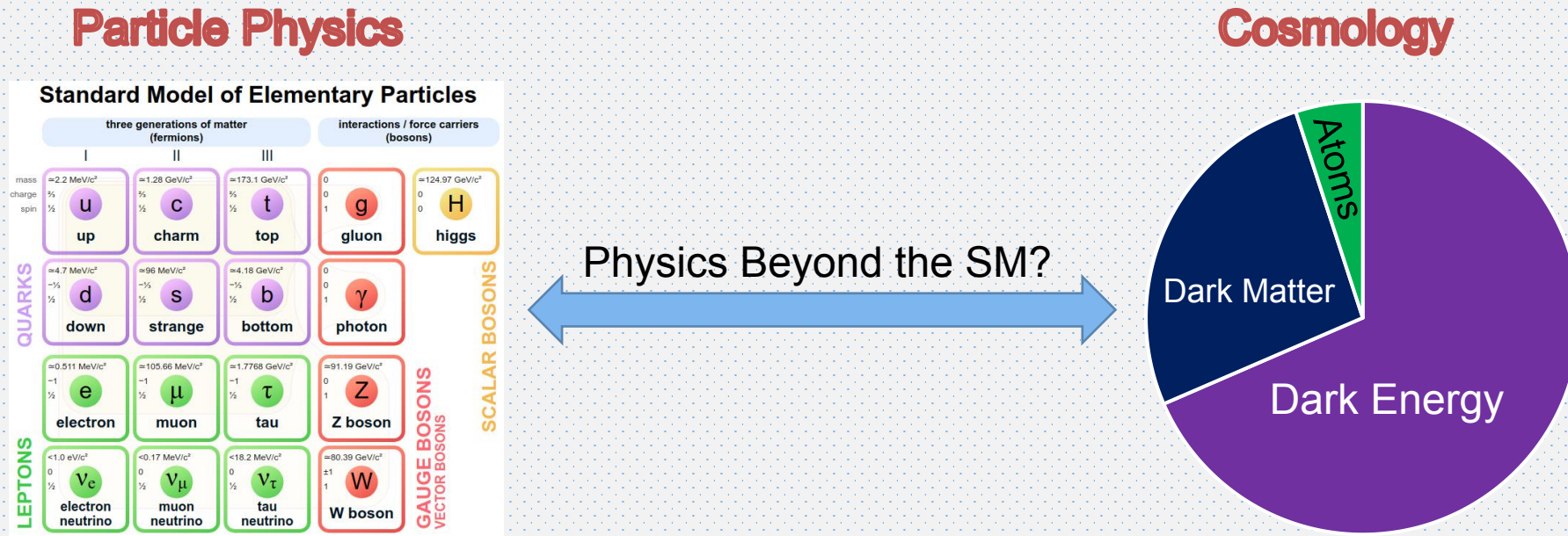
[Robert Caldwell](#), [Yanou Cui](#), [Huai-Ke Guo](#) , [Vuk Mandic](#), [Alberto Mariotti](#), [Jose Miguel No](#), [Michael J. Ramsey-Musolf](#), [Mairi Sakellariadou](#) , [Kuver Sinha](#), [Lian-Tao Wang](#), [Graham White](#), [Yue Zhao](#), [Haipeng An](#), [Ligong Bian](#), [Chiara Caprini](#), [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](#)



New Perspectives?

How can we reconcile the standard models of particle physics and 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*}

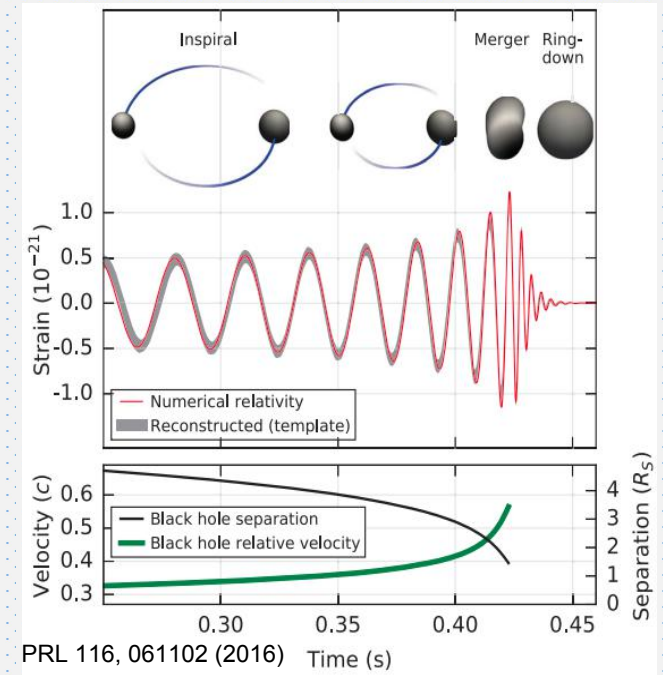
What is dark matter? (solitons, ultralight particles)
 Why more matter than anti-matter? (phase transitions)
 Neutrino physics?

GWs from Particles?

GW generation requires **macroscopic mass/energy**

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

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



How to study particle physics with GWs?

GWs from Particles

Extreme densities

disturbances in the early universe

Form macroscopic objects

(non-) topological solitons

Environmental Effects

Faking GW signals (dark photon)

GWs from Particles

Extreme densities ✓

disturbances in the early universe

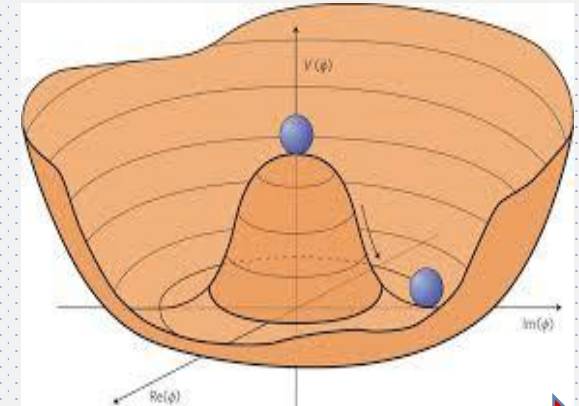
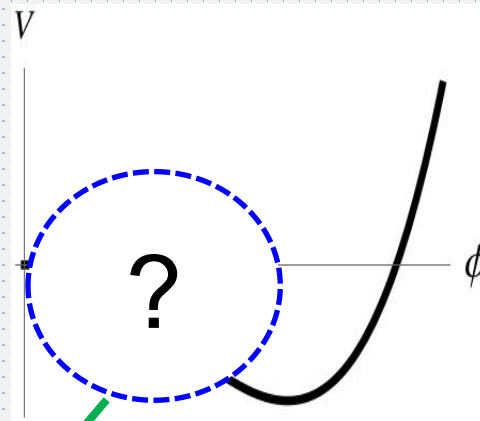
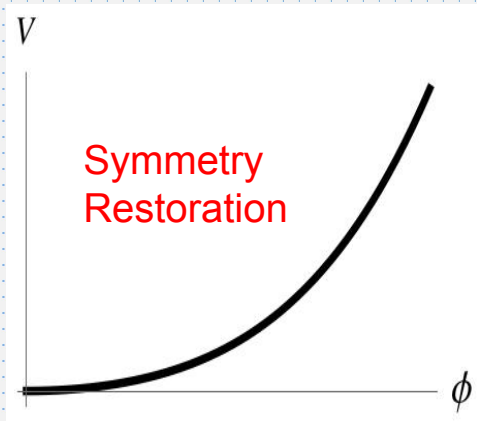
Form macroscopic objects

(non-) topological solitons

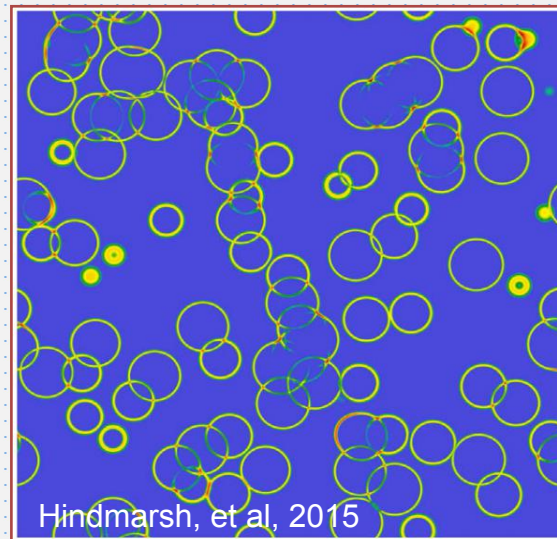
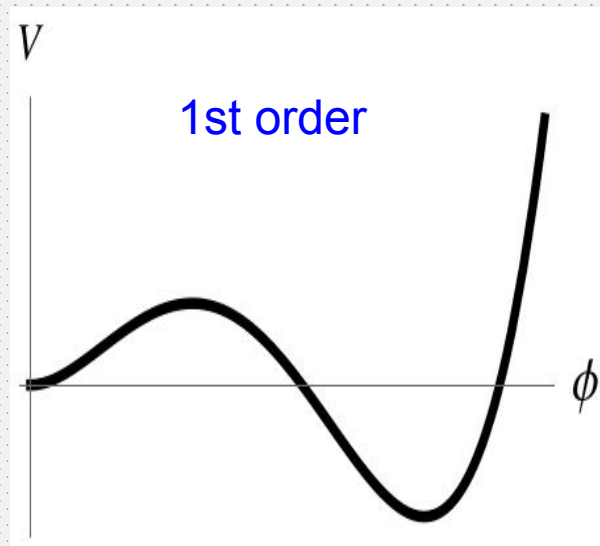
Environmental Effects

Faking GW signals (dark photon)

Cosmological First Order Phase Transitions



Temperature drops

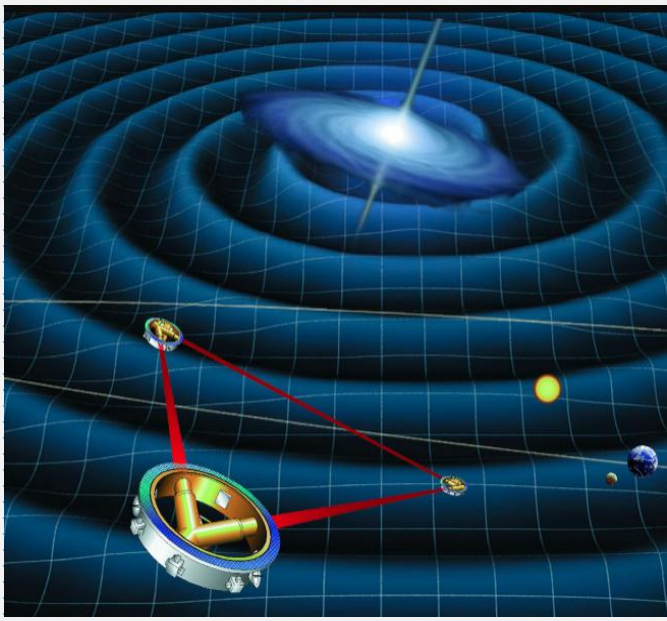


Electroweak Baryogenesis

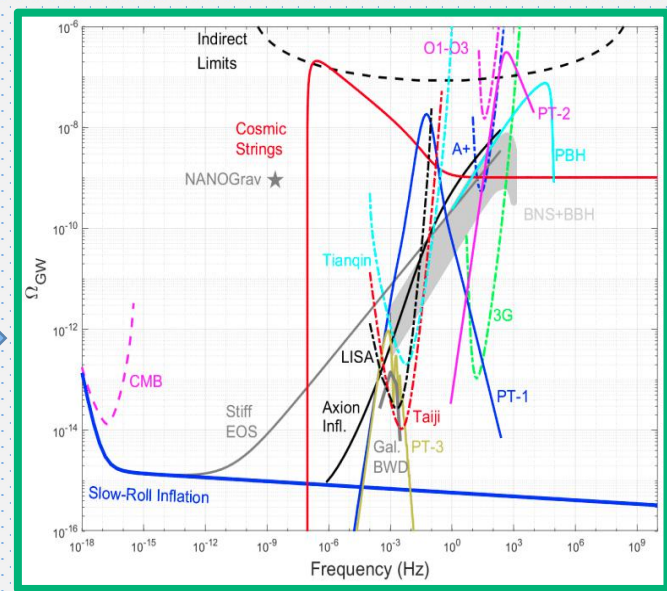
- Modified Higgs potential (Higgs physics, GW)
- Extra CP-violation (EDM, LHC)
- B-violation: Sphaleron process (LHC, GW)

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

Standard Model of Elementary Particles

	three generations of matter (fermions)			interactions / force carriers (bosons)	
	I	II	III		
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.97 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
	u up	c charm	t top	g gluon	H higgs
	d down	s strange	b bottom	γ photon	BSM
	e electron	μ muon	τ tau	Z Z boson	SCALAR BOSONS
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	GAUGE BOSONS VECTOR BOSONS
	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	$\approx 91.19 \text{ GeV}/c^2$	
	-1	-1	-1	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	$< 1.0 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	$\approx 80.39 \text{ GeV}/c^2$	
	0	0	0	± 1	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	

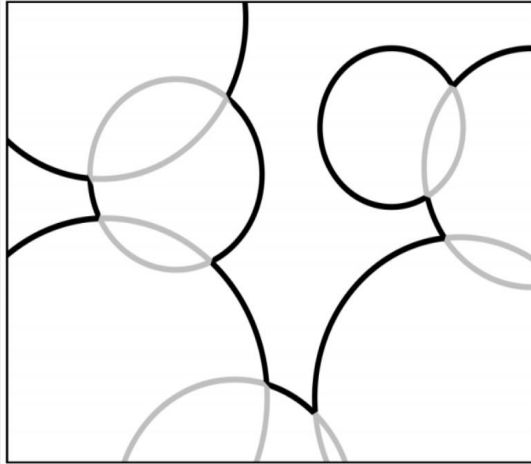
Particle Physics Model



data analysis, constraints or discovery(parameter estimation)

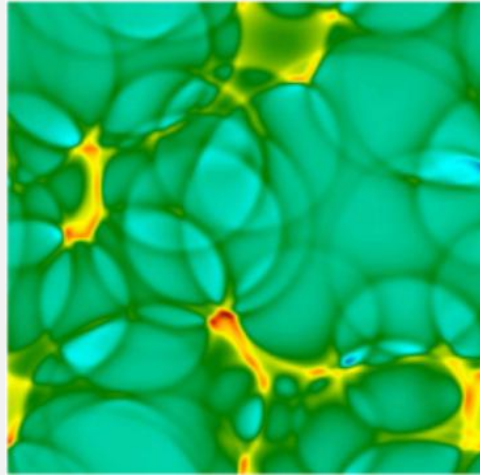
Gravitational Wave Sources

Bubble Collisions



energy concentrated at walls

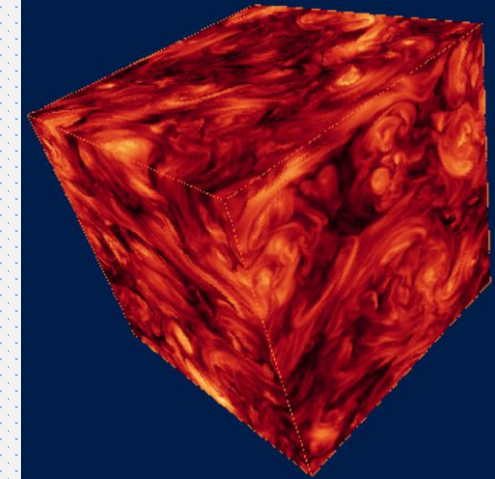
Sound Waves



Hindmarsh, et al, PRL 112, 041301 (2013)

acoustic production

MagnetoHydrodynamic Turbulence



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

turbulent motion

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

Di, Wang, Zhou, Bian, Cai, Liu, PRL 126 (2021) 25, 251102

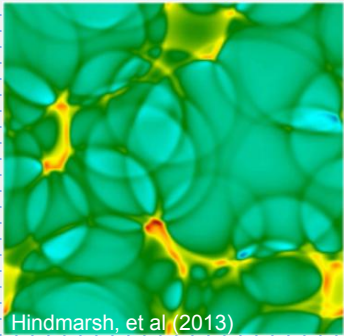
Jing, Bian, Cai, Guo, Wang, PRL 130 (2023) 051001

Li, Huang, Wang, Zhang, PRD 105 (2022) 083527

Huang, Xie, PRD 105 (2022) 11, 115033, JHEP 09 (2022) 052

Sound Waves

sound waves



Hindmarsh, et al (2013)

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

Chiara Caprini et al JCAP04(2016)001

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

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

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

Editors' Suggestion

Featured in Physics

北美纳赫兹引力波观测天文台 (NANOGrav)

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 Bécsey,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 Michael C. Johnson,²⁰ Robert W. Hellman,²¹ Michael J. Keith,²² Scott J. Kenyon,²³ David A. R. M. Lambert,²⁴ Michael L. Jones,²⁵ Michael T. Lam,²⁶ Dustin R. Marshall,²⁷ David J. Nice,¹⁴ Xavier Siemens,²⁸ Jerry P. Sun,³⁰ J. Michael *et al.*,³¹ Jennifer *et al.*,³² *et al.*,³³ *et al.*,³⁴ *et al.*,³⁵ *et al.*,³⁶ *et al.*,³⁷ *et al.*,³⁸ *et al.*,³⁹ *et al.*,⁴⁰ *et al.*,⁴¹ *et al.*,⁴² *et al.*,⁴³ *et al.*,⁴⁴ *et al.*,⁴⁵ *et al.*,⁴⁶ *et al.*,⁴⁷ *et al.*,⁴⁸ *et al.*,⁴⁹ *et al.*,⁵⁰ *et al.*,⁵¹ *et al.*,⁵² *et al.*,⁵³ *et al.*,⁵⁴ *et al.*,⁵⁵ *et al.*,⁵⁶ *et al.*,⁵⁷ *et al.*,⁵⁸ *et al.*,⁵⁹ *et al.*,⁶⁰ *et al.*,⁶¹ *et al.*,⁶² *et al.*,⁶³ *et al.*,⁶⁴ *et al.*,⁶⁵ *et al.*,⁶⁶ *et al.*,⁶⁷ *et al.*,⁶⁸ *et al.*,⁶⁹ *et al.*,⁷⁰ *et al.*,⁷¹ *et al.*,⁷² *et al.*,⁷³ *et al.*,⁷⁴ *et al.*,⁷⁵ *et al.*,⁷⁶ *et al.*,⁷⁷ *et al.*,⁷⁸ *et al.*,⁷⁹ *et al.*,⁸⁰ *et al.*,⁸¹ *et al.*,⁸² *et al.*,⁸³ *et al.*,⁸⁴ *et al.*,⁸⁵ *et al.*,⁸⁶ *et al.*,⁸⁷ *et al.*,⁸⁸ *et al.*,⁸⁹ *et al.*,⁹⁰ *et al.*,⁹¹ *et al.*,⁹² *et al.*,⁹³ *et al.*,⁹⁴ *et al.*,⁹⁵ *et al.*,⁹⁶ *et al.*,⁹⁷ *et al.*,⁹⁸ *et al.*,⁹⁹ *et al.*,¹⁰⁰ *et al.*,¹⁰¹ *et al.*,¹⁰² *et al.*,¹⁰³ *et al.*,¹⁰⁴ *et al.*,¹⁰⁵ *et al.*,¹⁰⁶ *et al.*,¹⁰⁷ *et al.*,¹⁰⁸ *et al.*,¹⁰⁹ *et al.*,¹¹⁰ *et al.*,¹¹¹ *et al.*,¹¹² *et al.*,¹¹³ *et al.*,¹¹⁴ *et al.*,¹¹⁵ *et al.*,¹¹⁶ *et al.*,¹¹⁷ *et al.*,¹¹⁸ *et al.*,¹¹⁹ *et al.*,¹²⁰ *et al.*,¹²¹ *et al.*,¹²² *et al.*,¹²³ *et al.*,¹²⁴ *et al.*,¹²⁵ *et al.*,¹²⁶ *et al.*,¹²⁷ *et al.*,¹²⁸ *et al.*,¹²⁹ *et al.*,¹³⁰ *et al.*,¹³¹ *et al.*,¹³² *et al.*,¹³³ *et al.*,¹³⁴ *et al.*,¹³⁵ *et al.*,¹³⁶ *et al.*,¹³⁷ *et al.*,¹³⁸ *et al.*,¹³⁹ *et al.*,¹⁴⁰ *et al.*,¹⁴¹ *et al.*,¹⁴² *et al.*,¹⁴³ *et al.*,¹⁴⁴ *et al.*,¹⁴⁵ *et al.*,¹⁴⁶ *et al.*,¹⁴⁷ *et al.*,¹⁴⁸ *et al.*,¹⁴⁹ *et al.*,¹⁵⁰ *et al.*,¹⁵¹ *et al.*,¹⁵² *et al.*,¹⁵³ *et al.*,¹⁵⁴ *et al.*,¹⁵⁵ *et al.*,¹⁵⁶ *et al.*,¹⁵⁷ *et al.*,¹⁵⁸ *et al.*,¹⁵⁹ *et al.*,¹⁶⁰ *et al.*,¹⁶¹ *et al.*,¹⁶² *et al.*,¹⁶³ *et al.*,¹⁶⁴ *et al.*,¹⁶⁵ *et al.*,¹⁶⁶ *et al.*,¹⁶⁷ *et al.*,¹⁶⁸ *et al.*,¹⁶⁹ *et al.*,¹⁷⁰ *et al.*,¹⁷¹ *et al.*,¹⁷² *et al.*,¹⁷³ *et al.*,¹⁷⁴ *et al.*,¹⁷⁵ *et al.*,¹⁷⁶ *et al.*,¹⁷⁷ *et al.*,¹⁷⁸ *et al.*,¹⁷⁹ *et al.*,¹⁸⁰ *et al.*,¹⁸¹ *et al.*,¹⁸² *et al.*,¹⁸³ *et al.*,¹⁸⁴ *et al.*,¹⁸⁵ *et al.*,¹⁸⁶ *et al.*,¹⁸⁷ *et al.*,¹⁸⁸ *et al.*,¹⁸⁹ *et al.*,¹⁹⁰ *et al.*,¹⁹¹ *et al.*,¹⁹² *et al.*,¹⁹³ *et al.*,¹⁹⁴ *et al.*,¹⁹⁵ *et al.*,¹⁹⁶ *et al.*,¹⁹⁷ *et al.*,¹⁹⁸ *et al.*,¹⁹⁹ *et al.*,²⁰⁰ *et al.*,²⁰¹ *et al.*,²⁰² *et al.*,²⁰³ *et al.*,²⁰⁴ *et al.*,²⁰⁵ *et al.*,²⁰⁶ *et al.*,²⁰⁷ *et al.*,²⁰⁸ *et al.*,²⁰⁹ *et al.*,²¹⁰ *et al.*,²¹¹ *et al.*,²¹² *et al.*,²¹³ *et al.*,²¹⁴ *et al.*,²¹⁵ *et al.*,²¹⁶ *et al.*,²¹⁷ *et al.*,²¹⁸ *et al.*,²¹⁹ *et al.*,²²⁰ *et al.*,²²¹ *et al.*,²²² *et al.*,²²³ *et al.*,²²⁴ *et al.*,²²⁵ *et al.*,²²⁶ *et al.*,²²⁷ *et al.*,²²⁸ *et al.*,²²⁹ *et al.*,²³⁰ *et al.*,²³¹ *et al.*,²³² *et al.*,²³³ *et al.*,²³⁴ *et al.*,²³⁵ *et al.*,²³⁶ *et al.*,²³⁷ *et al.*,²³⁸ *et al.*,²³⁹ *et al.*,²⁴⁰ *et al.*,²⁴¹ *et al.*,²⁴² *et al.*,²⁴³ *et al.*,²⁴⁴ *et al.*,²⁴⁵ *et al.*,²⁴⁶ *et al.*,²⁴⁷ *et al.*,²⁴⁸ *et al.*,²⁴⁹ *et al.*,²⁵⁰ *et al.*,²⁵¹ *et al.*,²⁵² *et al.*,²⁵³ *et al.*,²⁵⁴ *et al.*,²⁵⁵ *et al.*,²⁵⁶ *et al.*,²⁵⁷ *et al.*,²⁵⁸ *et al.*,²⁵⁹ *et al.*,²⁶⁰ *et al.*,²⁶¹ *et al.*,²⁶² *et al.*,²⁶³ *et al.*,²⁶⁴ *et al.*,²⁶⁵ *et al.*,²⁶⁶ *et al.*,²⁶⁷ *et al.*,²⁶⁸ *et al.*,²⁶⁹ *et al.*,²⁷⁰ *et al.*,²⁷¹ *et al.*,²⁷² *et al.*,²⁷³ *et al.*,²⁷⁴ *et al.*,²⁷⁵ *et al.*,²⁷⁶ *et al.*,²⁷⁷ *et al.*,²⁷⁸ *et al.*,²⁷⁹ *et al.*,²⁸⁰ *et al.*,²⁸¹ *et al.*,²⁸² *et al.*,²⁸³ *et al.*,²⁸⁴ *et al.*,²⁸⁵ *et al.*,²⁸⁶ *et al.*,²⁸⁷ *et al.*,²⁸⁸ *et al.*,²⁸⁹ *et al.*,²⁹⁰ *et al.*,²⁹¹ *et al.*,²⁹² *et al.*,²⁹³ *et al.*,²⁹⁴ *et al.*,²⁹⁵ *et al.*,²⁹⁶ *et al.*,²⁹⁷ *et al.*,²⁹⁸ *et al.*,²⁹⁹ *et al.*,³⁰⁰ *et al.*,³⁰¹ *et al.*,³⁰² *et al.*,³⁰³ *et al.*,³⁰⁴ *et al.*,³⁰⁵ *et al.*,³⁰⁶ *et al.*,³⁰⁷ *et al.*,³⁰⁸ *et al.*,³⁰⁹ *et al.*,³¹⁰ *et al.*,³¹¹ *et al.*,³¹² *et al.*,³¹³ *et al.*,³¹⁴ *et al.*,³¹⁵ *et al.*,³¹⁶ *et al.*,³¹⁷ *et al.*,³¹⁸ *et al.*,³¹⁹ *et al.*,³²⁰ *et al.*,³²¹ *et al.*,³²² *et al.*,³²³ *et al.*,³²⁴ *et al.*,³²⁵ *et al.*,³²⁶ *et al.*,³²⁷ *et al.*,³²⁸ *et al.*,³²⁹ *et al.*,³³⁰ *et al.*,³³¹ *et al.*,³³² *et al.*,³³³ *et al.*,³³⁴ *et al.*,³³⁵ *et al.*,³³⁶ *et al.*,³³⁷ *et al.*,³³⁸ *et al.*,³³⁹ *et al.*,³⁴⁰ *et al.*,³⁴¹ *et al.*,³⁴² *et al.*,³⁴³ *et al.*,³⁴⁴ *et al.*,³⁴⁵ *et al.*,³⁴⁶ *et al.*,³⁴⁷ *et al.*,³⁴⁸ *et al.*,³⁴⁹ *et al.*,³⁵⁰ *et al.*,³⁵¹ *et al.*,³⁵² *et al.*,³⁵³ *et al.*,³⁵⁴ *et al.*,³⁵⁵ *et al.*,³⁵⁶ *et al.*,³⁵⁷ *et al.*,³⁵⁸ *et al.*,³⁵⁹ *et al.*,³⁶⁰ *et al.*,³⁶¹ *et al.*,³⁶² *et al.*,³⁶³ *et al.*,³⁶⁴ *et al.*,³⁶⁵ *et al.*,³⁶⁶ *et al.*,³⁶⁷ *et al.*,³⁶⁸ *et al.*,³⁶⁹ *et al.*,³⁷⁰ *et al.*,³⁷¹ *et al.*,³⁷² *et al.*,³⁷³ *et al.*,³⁷⁴ *et al.*,³⁷⁵ *et al.*,³⁷⁶ *et al.*,³⁷⁷ *et al.*,³⁷⁸ *et al.*,³⁷⁹ *et al.*,³⁸⁰ *et al.*,³⁸¹ *et al.*,³⁸² *et al.*,³⁸³ *et al.*,³⁸⁴ *et al.*,³⁸⁵ *et al.*,³⁸⁶ *et al.*,³⁸⁷ *et al.*,³⁸⁸ *et al.*,³⁸⁹ *et al.*,³⁹⁰ *et al.*,³⁹¹ *et al.*,³⁹² *et al.*,³⁹³ *et al.*,³⁹⁴ *et al.*,³⁹⁵ *et al.*,³⁹⁶ *et al.*,³⁹⁷ *et al.*,³⁹⁸ *et al.*,³⁹⁹ *et al.*,⁴⁰⁰ *et al.*,⁴⁰¹ *et al.*,⁴⁰² *et al.*,⁴⁰³ *et al.*,⁴⁰⁴ *et al.*,⁴⁰⁵ *et al.*,⁴⁰⁶ *et al.*,⁴⁰⁷ *et al.*,⁴⁰⁸ *et al.*,⁴⁰⁹ *et al.*,⁴¹⁰ *et al.*,⁴¹¹ *et al.*,⁴¹² *et al.*,⁴¹³ *et al.*,⁴¹⁴ *et al.*,⁴¹⁵ *et al.*,⁴¹⁶ *et al.*,⁴¹⁷ *et al.*,⁴¹⁸ *et al.*,⁴¹⁹ *et al.*,⁴²⁰ *et al.*,⁴²¹ *et al.*,⁴²² *et al.*,⁴²³ *et al.*,⁴²⁴ *et al.*,⁴²⁵ *et al.*,⁴²⁶ *et al.*,⁴²⁷ *et al.*,⁴²⁸ *et al.*,⁴²⁹ *et al.*,⁴³⁰ *et al.*,⁴³¹ *et al.*,⁴³² *et al.*,⁴³³ *et al.*,⁴³⁴ *et al.*,⁴³⁵ *et al.*,⁴³⁶ *et al.*,⁴³⁷ *et al.*,⁴³⁸ *et al.*,⁴³⁹ *et al.*,⁴⁴⁰ *et al.*,⁴⁴¹ *et al.*,⁴⁴² *et al.*,⁴⁴³ *et al.*,⁴⁴⁴ *et al.*,⁴⁴⁵ *et al.*,⁴⁴⁶ *et al.*,⁴⁴⁷ *et al.*,⁴⁴⁸ *et al.*,⁴⁴⁹ *et al.*,⁴⁵⁰ *et al.*,⁴⁵¹ *et al.*,⁴⁵² *et al.*,⁴⁵³ *et al.*,⁴⁵⁴ *et al.*,⁴⁵⁵ *et al.*,⁴⁵⁶ *et al.*,⁴⁵⁷ *et al.*,⁴⁵⁸ *et al.*,⁴⁵⁹ *et al.*,⁴⁶⁰ *et al.*,⁴⁶¹ *et al.*,⁴⁶² *et al.*,⁴⁶³ *et al.*,⁴⁶⁴ *et al.*,⁴⁶⁵ *et al.*,⁴⁶⁶ *et al.*,⁴⁶⁷ *et al.*,⁴⁶⁸ *et al.*,⁴⁶⁹ *et al.*,⁴⁷⁰ *et al.*,⁴⁷¹ *et al.*,⁴⁷² *et al.*,⁴⁷³ *et al.*,⁴⁷⁴ *et al.*,⁴⁷⁵ *et al.*,⁴⁷⁶ *et al.*,⁴⁷⁷ *et al.*,⁴⁷⁸ *et al.*,⁴⁷⁹ *et al.*,⁴⁸⁰ *et al.*,⁴⁸¹ *et al.*,⁴⁸² *et al.*,⁴⁸³ *et al.*,⁴⁸⁴ *et al.*,⁴⁸⁵ *et al.*,⁴⁸⁶ *et al.*,⁴⁸⁷ *et al.*,⁴⁸⁸ *et al.*,⁴⁸⁹ *et al.*,⁴⁹⁰ *et al.*,⁴⁹¹ *et al.*,⁴⁹² *et al.*,⁴⁹³ *et al.*,⁴⁹⁴ *et al.*,⁴⁹⁵ *et al.*,⁴⁹⁶ *et al.*,⁴⁹⁷ *et al.*,⁴⁹⁸ *et al.*,⁴⁹⁹ *et al.*,⁵⁰⁰ *et al.*,⁵⁰¹ *et al.*,⁵⁰² *et al.*,⁵⁰³ *et al.*,⁵⁰⁴ *et al.*,⁵⁰⁵ *et al.*,⁵⁰⁶ *et al.*,⁵⁰⁷ *et al.*,⁵⁰⁸ *et al.*,⁵⁰⁹ *et al.*,⁵¹⁰ *et al.*,⁵¹¹ *et al.*,⁵¹² *et al.*,⁵¹³ *et al.*,⁵¹⁴ *et al.*,⁵¹⁵ *et al.*,⁵¹⁶ *et al.*,⁵¹⁷ *et al.*,⁵¹⁸ *et al.*,⁵¹⁹ *et al.*,⁵²⁰ *et al.*,⁵²¹ *et al.*,⁵²² *et al.*,⁵²³ *et al.*,⁵²⁴ *et al.*,⁵²⁵ *et al.*,⁵²⁶ *et al.*,⁵²⁷ *et al.*,⁵²⁸ *et al.*,⁵²⁹ *et al.*,⁵³⁰ *et al.*,⁵³¹ *et al.*,⁵³² *et al.*,⁵³³ *et al.*,⁵³⁴ *et al.*,⁵³⁵ *et al.*,⁵³⁶ *et al.*,⁵³⁷ *et al.*,⁵³⁸ *et al.*,⁵³⁹ *et al.*,⁵⁴⁰ *et al.*,⁵⁴¹ *et al.*,⁵⁴² *et al.*,⁵⁴³ *et al.*,⁵⁴⁴ *et al.*,⁵⁴⁵ *et al.*,⁵⁴⁶ *et al.*,⁵⁴⁷ *et al.*,⁵⁴⁸ *et al.*,⁵⁴⁹ *et al.*,⁵⁵⁰ *et al.*,⁵⁵¹ *et al.*,⁵⁵² *et al.*,⁵⁵³ *et al.*,⁵⁵⁴ *et al.*,⁵⁵⁵ *et al.*,⁵⁵⁶ *et al.*,⁵⁵⁷ *et al.*,⁵⁵⁸ *et al.*,⁵⁵⁹ *et al.*,⁵⁶⁰ *et al.*,⁵⁶¹ *et al.*,⁵⁶² *et al.*,⁵⁶³ *et al.*,⁵⁶⁴ *et al.*,⁵⁶⁵ *et al.*,⁵⁶⁶ *et al.*,⁵⁶⁷ *et al.*,⁵⁶⁸ *et al.*,⁵⁶⁹ *et al.*,⁵⁷⁰ *et al.*,⁵⁷¹ *et al.*,⁵⁷² *et al.*,⁵⁷³ *et al.*,⁵⁷⁴ *et al.*,⁵⁷⁵ *et al.*,⁵⁷⁶ *et al.*,⁵⁷⁷ *et al.*,⁵⁷⁸ *et al.*,⁵⁷⁹ *et al.*,⁵⁸⁰ *et al.*,⁵⁸¹ *et al.*,⁵⁸² *et al.*,⁵⁸³ *et al.*,⁵⁸⁴ *et al.*,⁵⁸⁵ *et al.*,⁵⁸⁶ *et al.*,⁵⁸⁷ *et al.*,⁵⁸⁸ *et al.*,⁵⁸⁹ *et al.*,⁵⁹⁰ *et al.*,⁵⁹¹ *et al.*,⁵⁹² *et al.*,⁵⁹³ *et al.*,⁵⁹⁴ *et al.*,⁵⁹⁵ *et al.*,⁵⁹⁶ *et al.*,⁵⁹⁷ *et al.*,⁵⁹⁸ *et al.*,⁵⁹⁹ *et al.*,⁶⁰⁰ *et al.*,⁶⁰¹ *et al.*,⁶⁰² *et al.*,⁶⁰³ *et al.*,⁶⁰⁴ *et al.*,⁶⁰⁵ *et al.*,⁶⁰⁶ *et al.*,⁶⁰⁷ *et al.*,⁶⁰⁸ *et al.*,⁶⁰⁹ *et al.*,⁶¹⁰ *et al.*,⁶¹¹ *et al.*,⁶¹² *et al.*,⁶¹³ *et al.*,⁶¹⁴ *et al.*,⁶¹⁵ *et al.*,⁶¹⁶ *et al.*,⁶¹⁷ *et al.*,⁶¹⁸ *et al.*,⁶¹⁹ *et al.*,⁶²⁰ *et al.*,⁶²¹ *et al.*,⁶²² *et al.*,⁶²³ *et al.*,⁶²⁴ *et al.*,⁶²⁵ *et al.*,⁶²⁶ *et al.*,⁶²⁷ *et al.*,⁶²⁸ *et al.*,⁶²⁹ *et al.*,⁶³⁰ *et al.*,⁶³¹ *et al.*,⁶³² *et al.*,⁶³³ *et al.*,⁶³⁴ *et al.*,⁶³⁵ *et al.*,⁶³⁶ *et al.*,⁶³⁷ *et al.*,⁶³⁸ *et al.*,⁶³⁹ *et al.*,⁶⁴⁰ *et al.*,⁶⁴¹ *et al.*,⁶⁴² *et al.*,⁶⁴³ *et al.*,⁶⁴⁴ *et al.*,⁶⁴⁵ *et al.*,⁶⁴⁶ *et al.*,⁶⁴⁷ *et al.*,⁶⁴⁸ *et al.*,⁶⁴⁹ *et al.*,⁶⁵⁰ *et al.*,⁶⁵¹ *et al.*,⁶⁵² *et al.*,⁶⁵³ *et al.*,⁶⁵⁴ *et al.*,⁶⁵⁵ *et al.*,⁶⁵⁶ *et al.*,⁶⁵⁷ *et al.*,⁶⁵⁸ *et al.*,⁶⁵⁹ *et al.*,⁶⁶⁰ *et al.*,⁶⁶¹ *et al.*,⁶⁶² *et al.*,⁶⁶³ *et al.*,⁶⁶⁴ *et al.*,⁶⁶⁵ *et al.*,⁶⁶⁶ *et al.*,⁶⁶⁷ *et al.*,⁶⁶⁸ *et al.*,⁶⁶⁹ *et al.*,⁶⁷⁰ *et al.*,⁶⁷¹ *et al.*,⁶⁷² *et al.*,⁶⁷³ *et al.*,⁶⁷⁴ *et al.*,⁶⁷⁵ *et al.*,⁶⁷⁶ *et al.*,⁶⁷⁷ *et al.*,⁶⁷⁸ *et al.*,⁶⁷⁹ *et al.*,⁶⁸⁰ *et al.*,⁶⁸¹ *et al.*,⁶⁸² *et al.*,⁶⁸³ *et al.*,⁶⁸⁴ *et al.*,⁶⁸⁵ *et al.*,⁶⁸⁶ *et al.*,⁶⁸⁷ *et al.*,⁶⁸⁸ *et al.*,⁶⁸⁹ *et al.*,⁶⁹⁰ *et al*

Experimental Searches

PHYSICAL REVIEW LETTERS **126**, 151301 (2021)

LIGO

Implications for First-Order Cosmological Phase Transitions from the Third LIGO-Virgo Observing Run

Alba Romero ¹, Katarina Martinovic ², Thomas A. Callister³, Huai-Ke Guo⁴, Mario Martínez ^{1,5},
Mairi Sakellariadou ^{2,6}, Feng-Wei Yang ⁷, and Yue Zhao⁷

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

Editors' Suggestion

Featured in Physics

NANOGrav

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
















PHYSICAL REVIEW LETTERS **127**, 251303 (2021)

Editors' Suggestion

Featured in Physics

PPTA

Constraining Cosmological Phase Transitions with the Parkes Pulsar Timing Array

Xiao Xue ^{1,2,3}, Ligong Bian ^{4,5,*}, Jing Shu^{1,2,6,7,8,†}, Qiang Yuan ^{9,10,7,‡}, Xingjiang Zhu ^{11,12,13,§}, N. D. Ramesh Bhat,¹⁴
Shi Dai ¹⁵, Yi Feng ¹⁶, Boris Goncharov ^{11,12}, George Hobbs,¹⁷ Eric Howard ^{17,18}, Richard N. Manchester ¹⁷,
Christopher J. Russell ¹⁹, Daniel J. Reardon ^{12,20}, Ryan M. Shannon ^{12,20}, Renée Spiewak ^{21,20},
Nithyanandan Thyagarajan ²², and Jingbo Wang ²³

LIGO's 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

Bubble Collision

95% CL UL with fixed T_{pt} and β/H_{pt}

Phenomenological model (bubble collisions)				
$\Omega_{coll}^{95\%}(25 \text{ Hz})$				
$\beta/H_{pt} \backslash T_{pt}$	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

Broken Power Law

95% CL UL (CBC+BPL)

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

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

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

Sound Waves

95% CL UL

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

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

First result from gravitational wave data!

See also

Jiang, Huang, arxiv:2203.11781

Yu, Wang, arxiv:2211.13111

GWs from Particles

Extreme densities

disturbances in the early universe

Form 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	<p>Static Solution (Theory with Spontaneously Broken Symmetry)</p> <ul style="list-style-type: none"> ● Global symmetry (Skyrmion, Cosmic String) ● Discrete symmetry (Domain wall) ● Local symmetry (Monopole, Cosmic String or Vortex line...) ● Pure gauge theory (Instanton) 	<p>Bose-Einstein Condensate (of Ultralight particles)</p> <ul style="list-style-type: none"> ● Galactic scale (DM Halo) ● Stellar scale (Boson stars)
Boundary	Non-Trivial (needs degenerate vacuum states)	Trivial vacuum state
Stabilized by	Topology (boundary field values)	<p>Conserved Charge, and Balancing</p> <ul style="list-style-type: none"> ● 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 observed)

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, London

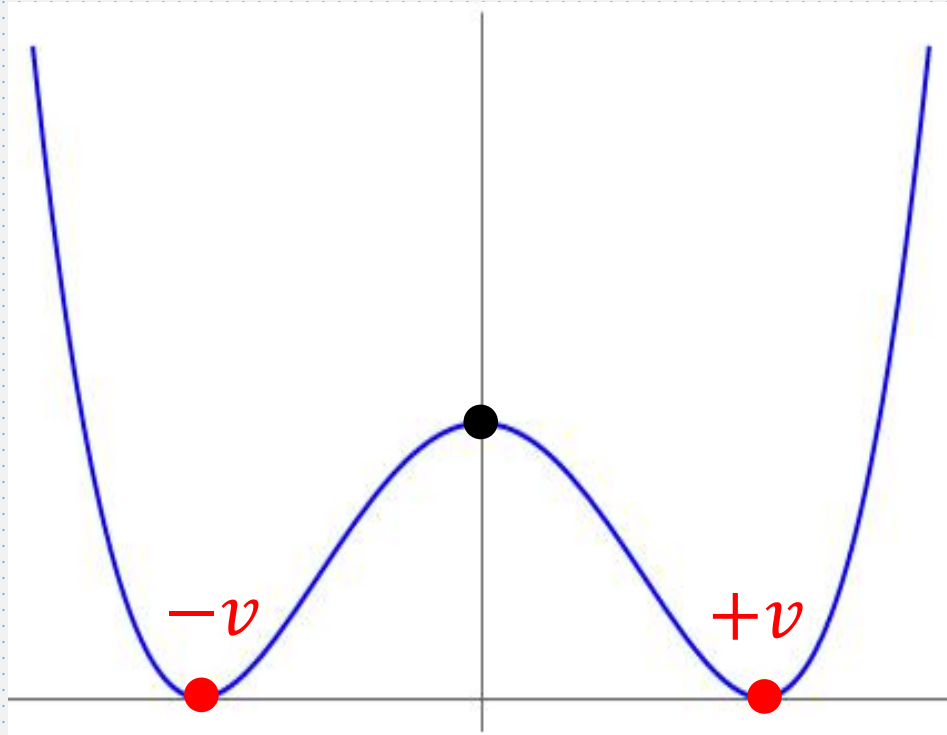
Received 11 March 1976

www.theguardian.com



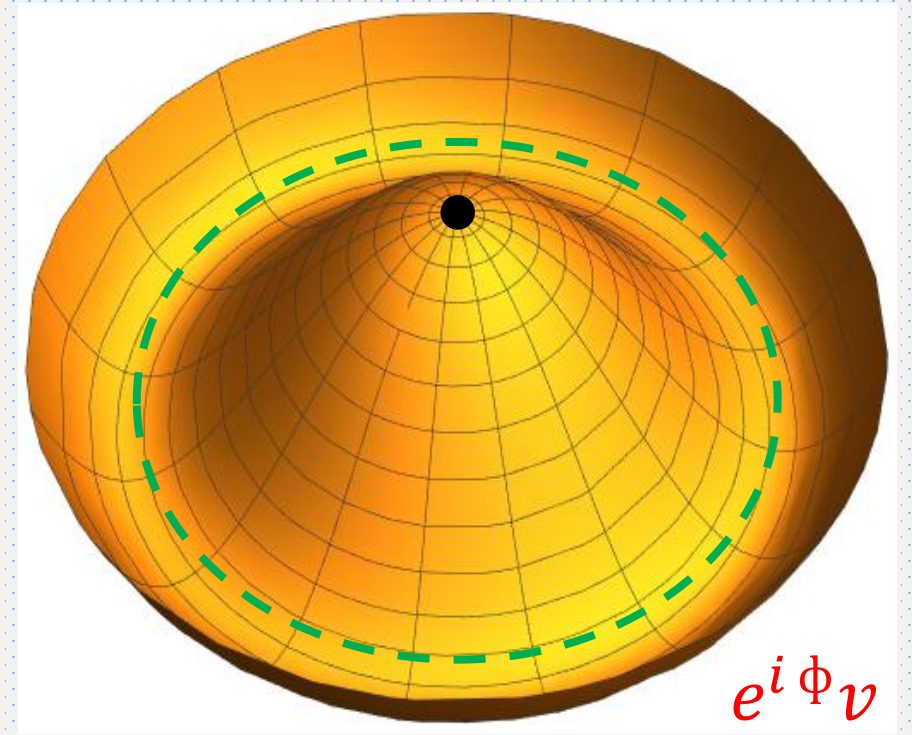
Degenerate Vacuum States

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



Domain wall

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



Cosmic String

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 ($G \rightarrow H$)

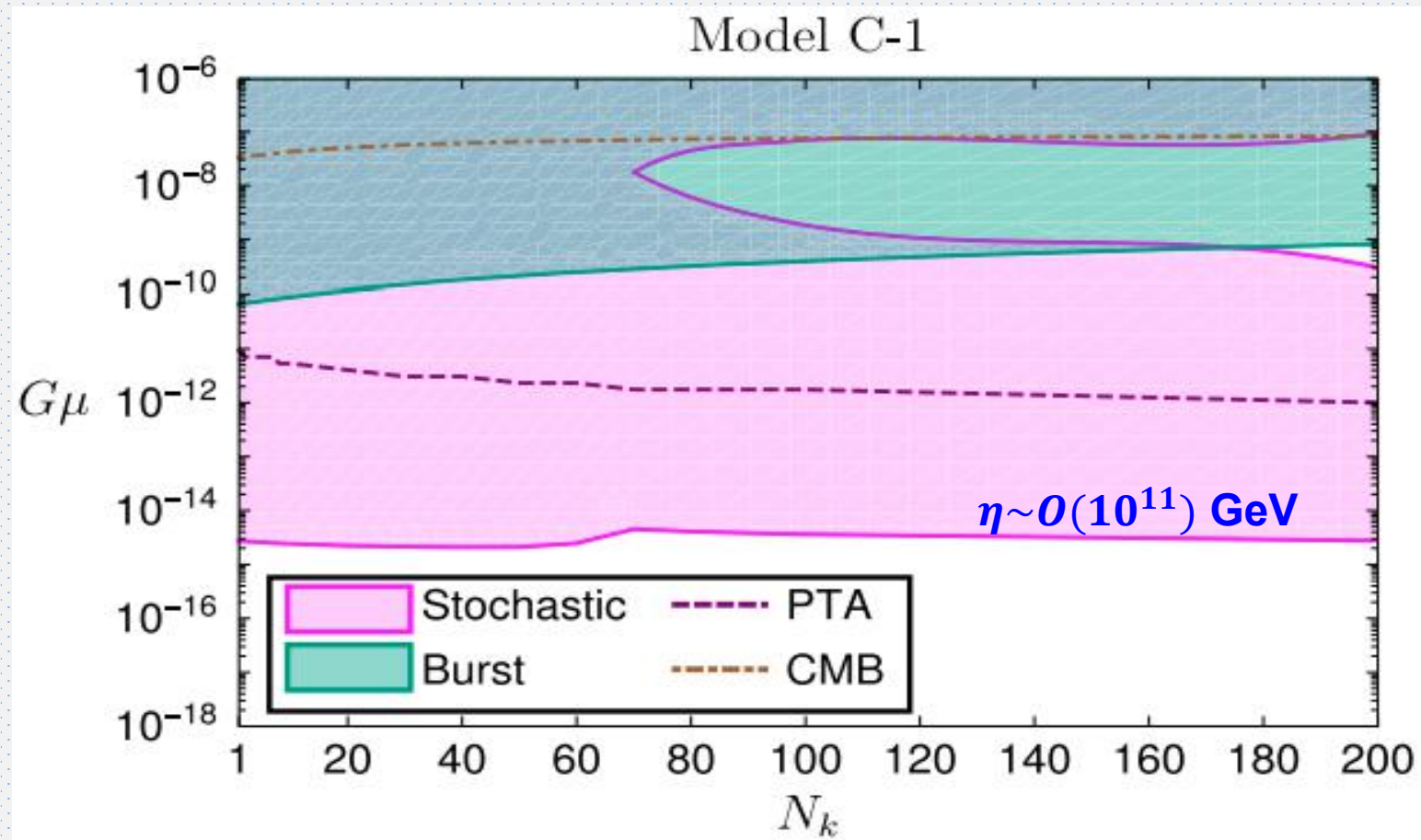
$$G\mu \sim \left(\frac{\eta}{10^{19} \text{ GeV}} \right)^2$$

μ : line mass density

Results from PTA Measurements

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

Blasi, Brdar, Schmitz, PRL 126, 041305 (2021)



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

Home / Physics / General Physics



🕒 AUGUST 27, 2021 **FEATURE**

The LIGO/Virgo Collaboration sets new constraints on cosmic strings

by Ingrid Fadell , Phys.org

f 731

🐦 42

in Share



Non-Topological Solitons

Giant Bose-Einstein condensate of ultralight particles (DM)

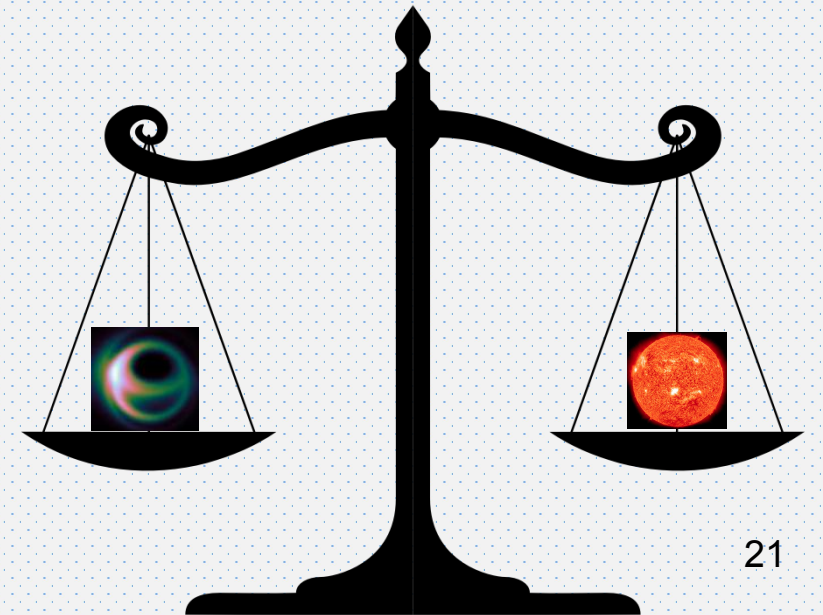
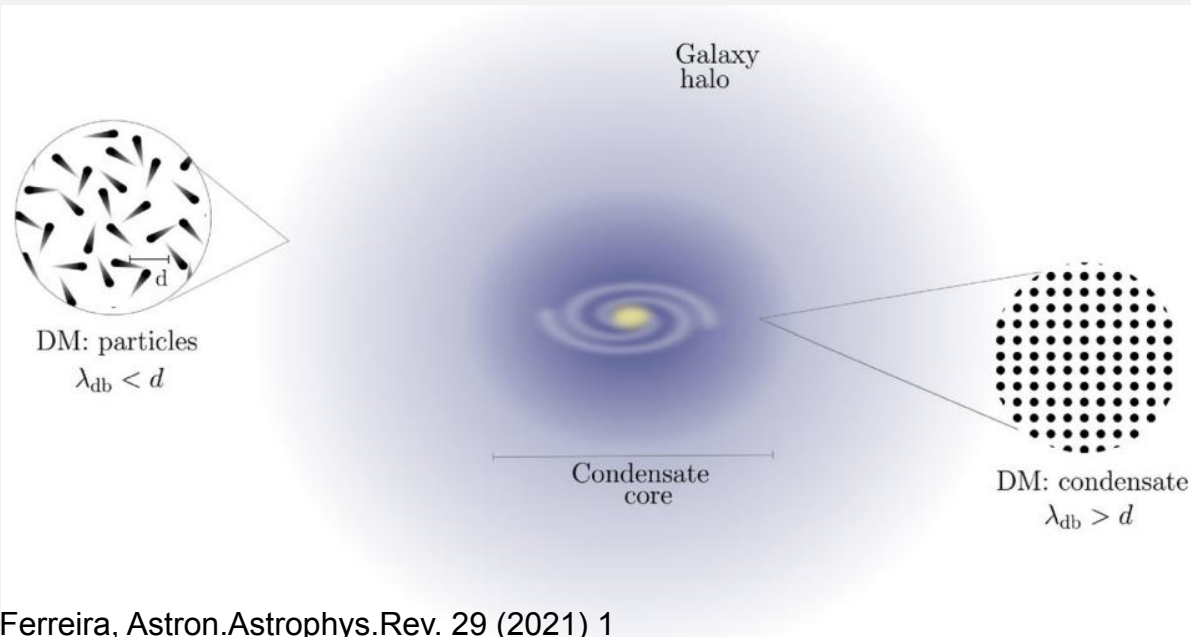
$$m_{\text{ULDM}} \sim 10^{-22} \text{ eV}$$

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

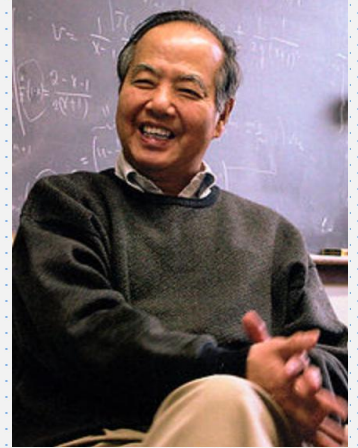
$$m_{\text{ULDM}} \sim 10^{-10} \text{ eV}$$

Galactic Scale: solve small scale structure problems

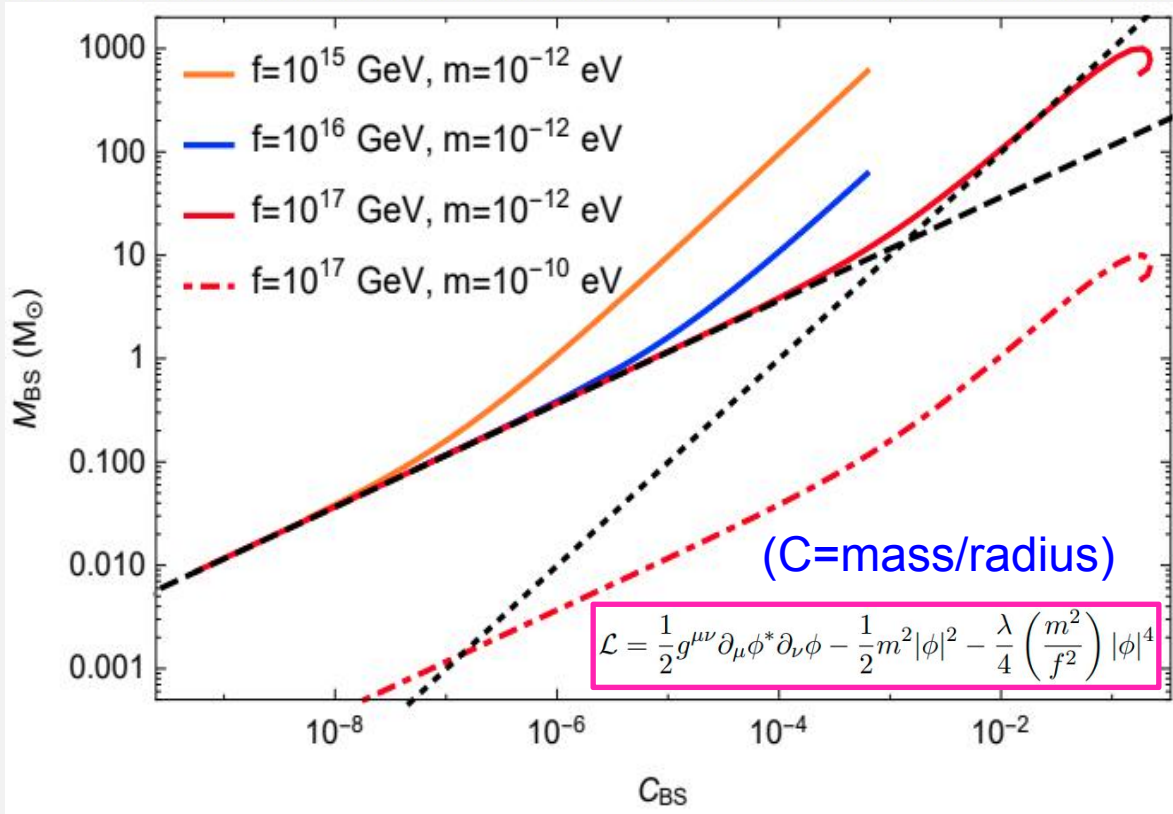
Stellar Scale: soliton stars



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

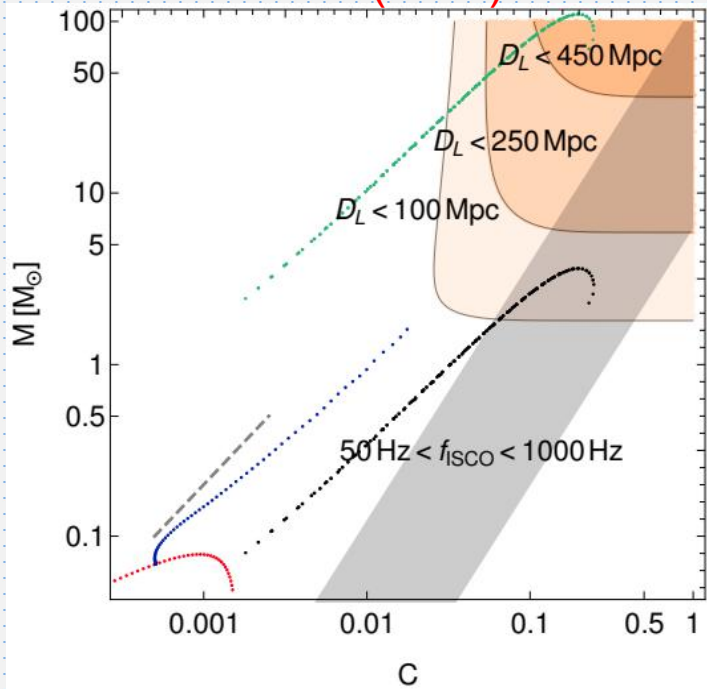
Lee, Pang, Phys.Rept (1992)

Detection with EMRIs

$$f_{\text{ISCO}} = 4.4\text{kHz} \left(\frac{1M_{\odot}}{M} \right) \left(\frac{n}{2} \right) g(a)$$

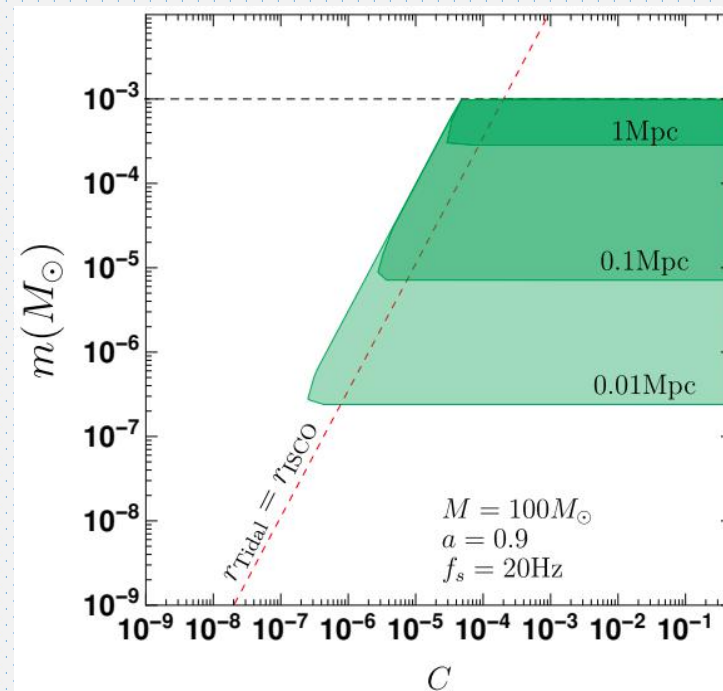
- By making one object much heavier, one can probe much lighter companion object
- Ideal systems: extreme mass ratio inspirals (EMRIs), key target of Taiji, Tianqin, LISA.
- LIGO can detect mini-EMRIs

LIGO (CBC)



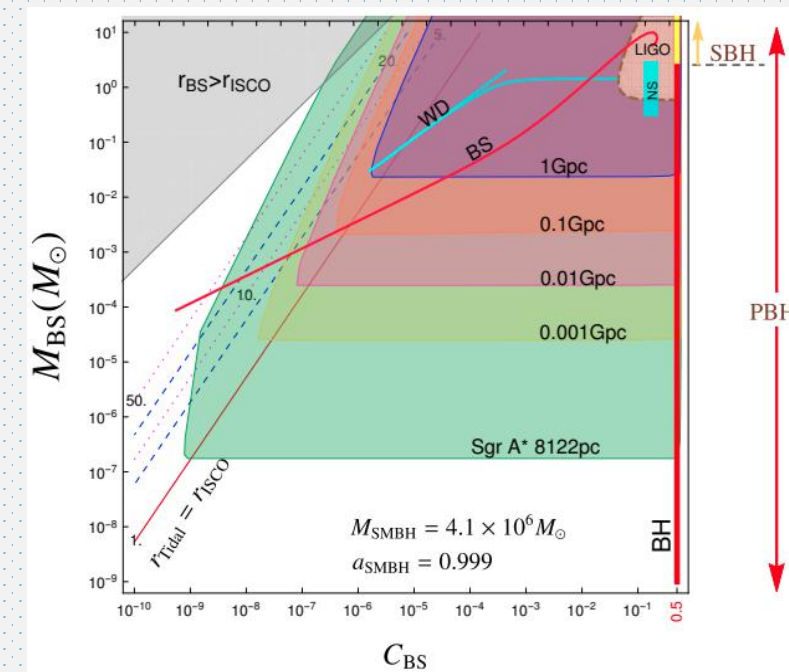
HG, Sinha, Sun, Vagie, JCAP 10 (2021) 028

LIGO (“mini-EMRI”)

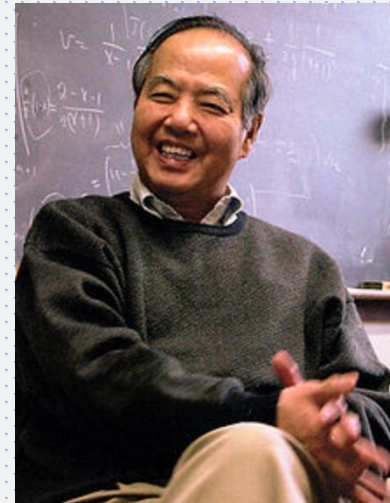


HG, A. Miller, arxiv:2205.10359

LISA, Taiji, Tianqin (EMRI)



HG, Sinha, Sun, JCAP 09 (2019) 032
 HG, Shu, Zhao, PRD 99 (2019) 023001



At present, there is no experimental evidence that soliton stars exist. Nevertheless, it seems reasonable that solutions of well-tested theories, such as Einstein's general relativity, the Dirac equation, the Klein–Gordon equation, etc. should find their proper place in nature.

Lee, Pang, Phys.Rept. 221 (1992) 251

We are aiming for their discovery

GWs from Particles

Extreme densities

disturbances in the early universe

Form macroscopic objects

(non-) topological solitons

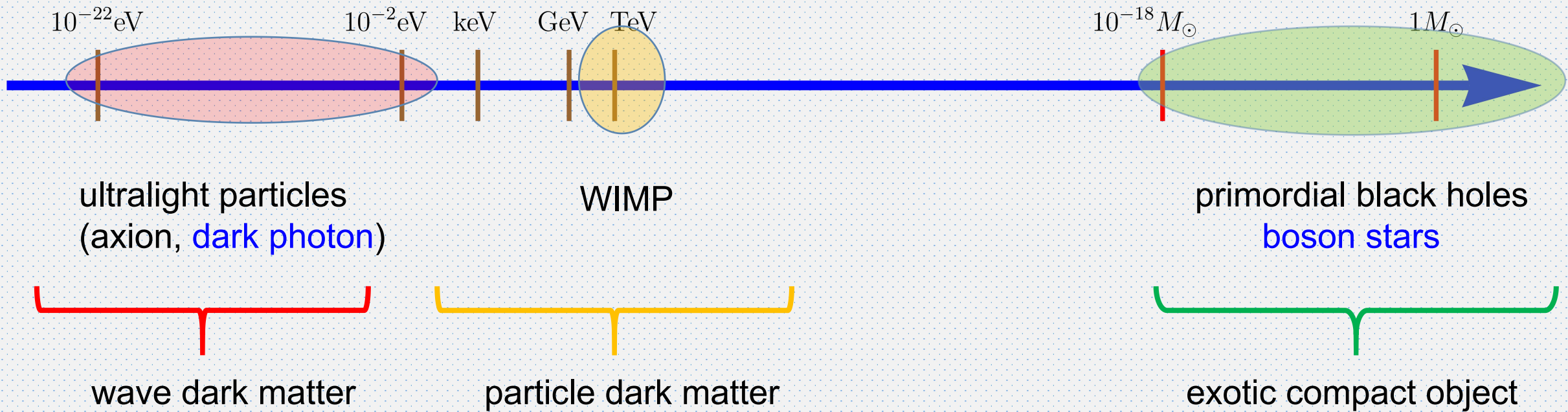
Environmental Effects

Faking GW signals (dark photon)



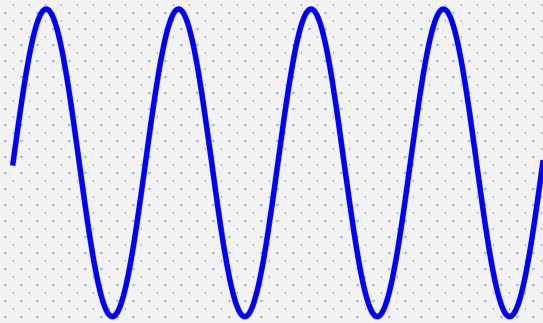
Ultralight Dark Matter

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



Dark Photon Detection at LIGO

a single dark photon



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

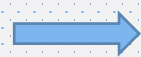


typical LIGO frequency

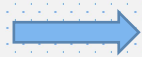
$$\omega_n = m_A \left(1 + \frac{1}{2} v_n^2\right) = 2\pi \times (100\text{Hz}) \approx 4 \times 10^{-13} \text{eV}$$

typical dark photon mass
LIGO is sensitive to

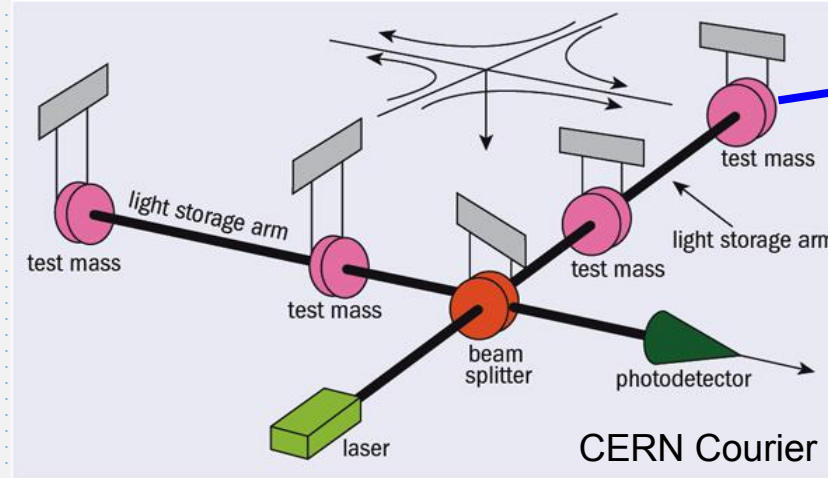
$$v_0 \sim \mathcal{O}(10^{-3})$$



$$\Delta f / f = 10^{-6}$$



Signal: a narrow peak in frequency domain

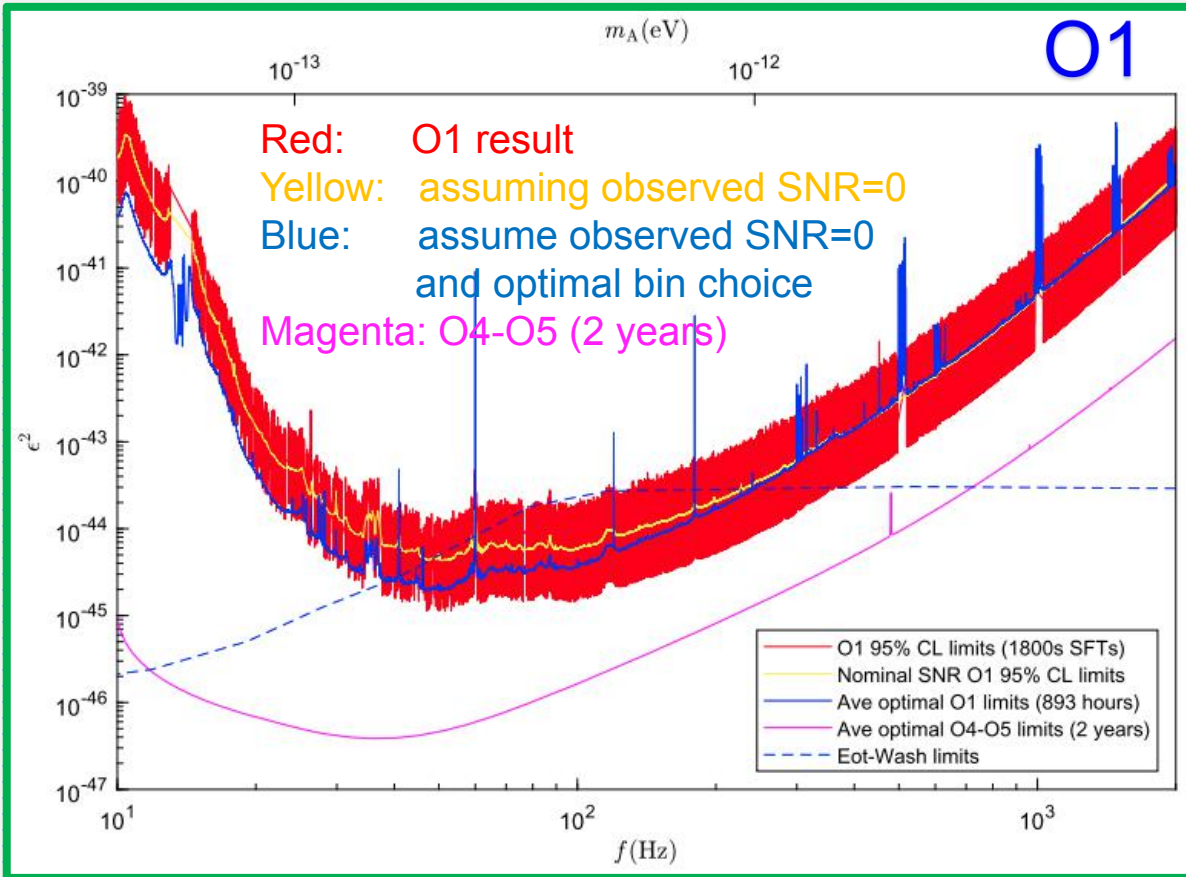


silicon mirror
 $U(1)_B: 1/\text{GeV}$
 $U(1)_{B-L}: 1/2\text{GeV}$

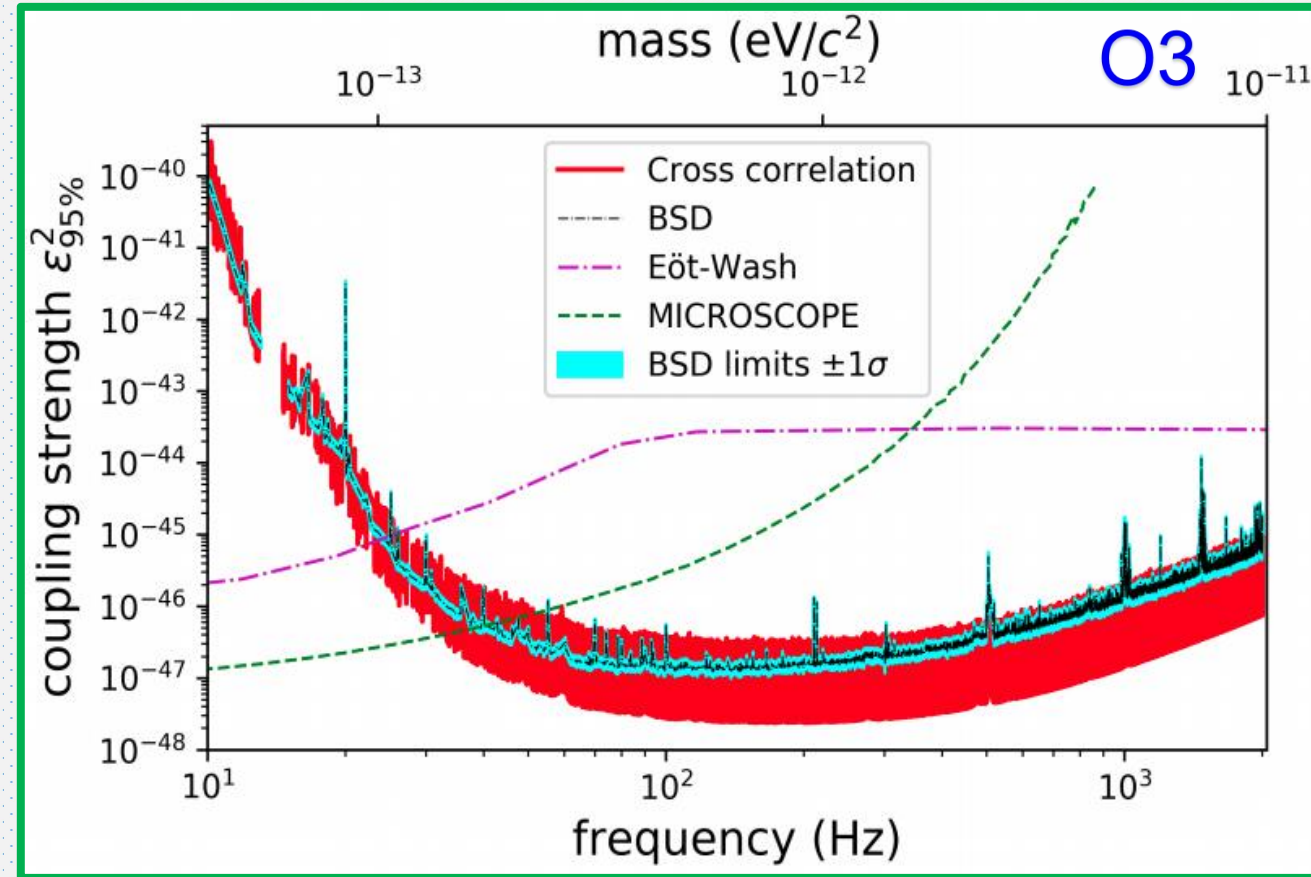
$$\mathbf{a}_i(t, \mathbf{x}_i) \simeq \epsilon e \frac{q_{D,i}}{M_i} \partial_t \mathbf{A}(t, \mathbf{x}_i)$$

acceleration

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:

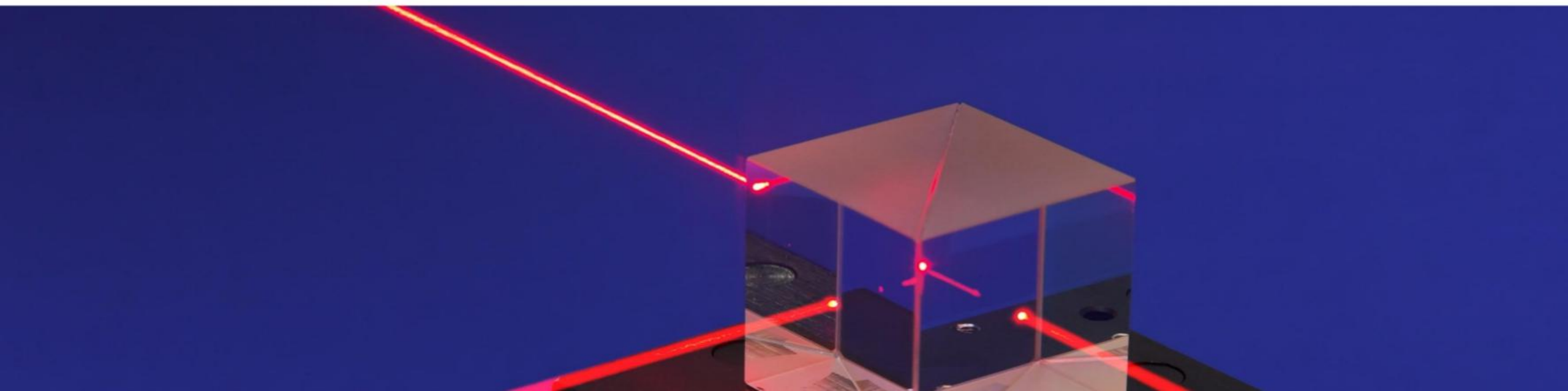
1. Another search performed by the continuous wave group with a different method
2. An improvement factor included from finite light travel time (PRD.103.L051702, Morisaki, et al)

PARTICLE PHYSICS

A New Tool for Finding Dark Matter Digs Up Nothing

 6 | 

Physicists are devising clever new ways to exploit the extreme sensitivity of gravitational wave detectors like LIGO. But so far, they've seen no signs of exotica.



Neutrinos?

See also Ligong's talk

- Can play a role in phase transitions (another degrees of freedom)
- Free streaming neutrinos affect propagation of GWs (Weinberg, 2004)
- Neutrino oscillations affected by GWs (Piriz, Roy, Wudka, PRD 54 (1996) 1587, ...)
- EM counterpart (astrophysical phenomena: supernovae, binary mergers, ...)
- ...

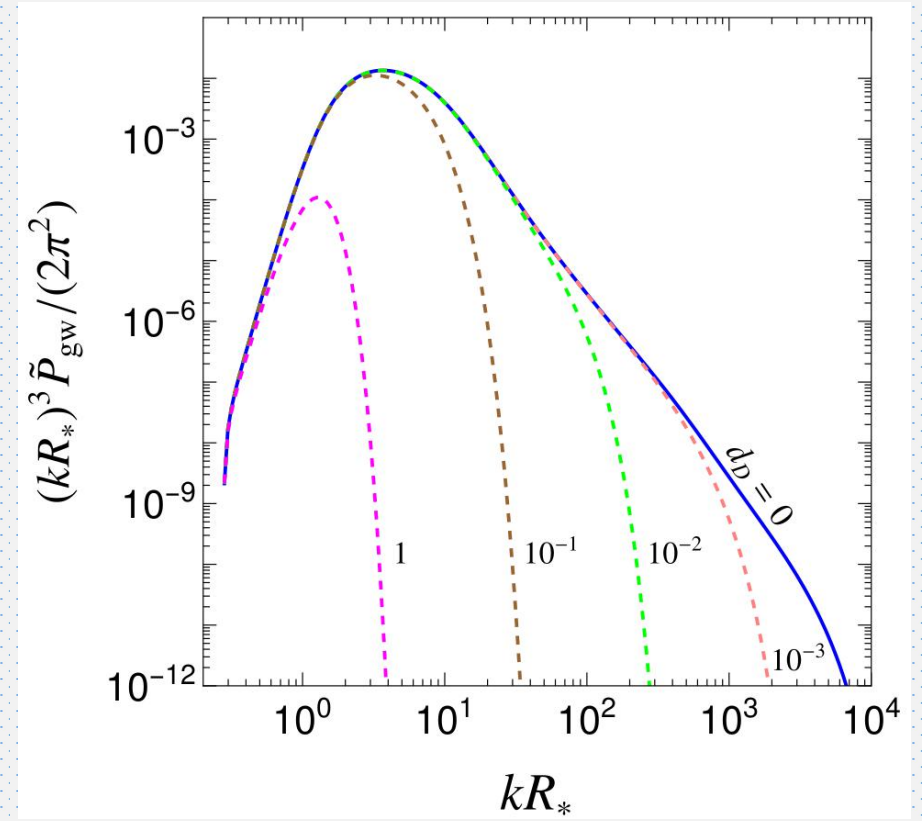
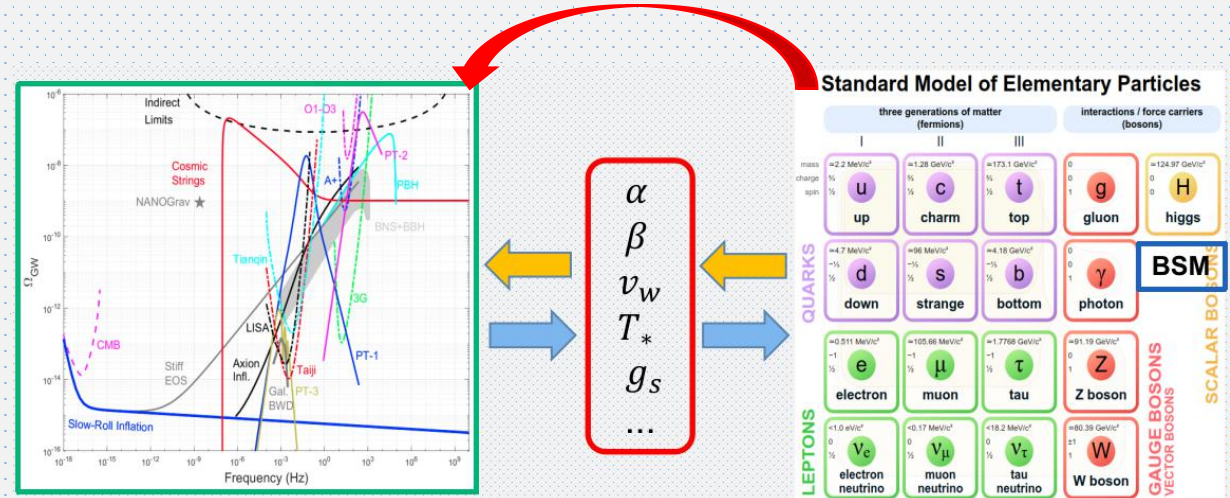
New Observables for Phase Transitions

- Going beyond the perfect fluid approximation (viscosity, heat conduction)
- Dissipative effects lead to suppression of GWs (higher frequencies) similar to Silk damping
- less so for dampings by free streaming neutrinos (Yvonne, Michael's talks)
- Particle physics origin of dissipations: rich physics dark matter, neutrino physics, etc
- Can be searched for at LIGO, Taiji, Tianqin, LISA ...

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

$$\Delta T^{i0} = -\chi \left(\frac{\partial T}{\partial x^i} + T \dot{U}_i \right). \quad (1)$$

break the parameter degeneracy!



Summary

GWs as a new tool in particle physics studies

- Early universe symmetry breakings (phase transitions)
- Macroscopic solitons (topological and nontopological)
- Dark photon (environmental effects)
- More connections to Neutrino physics

Thanks!