New Physics Search Results from Advanced LIGO's Third Observing Run



University of Utah

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See also 一鸣's talk

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Inflation (tensor mode fluctuation)

Reheating (preheating)

- Cosmological first order phase transitions
- Topological defects (cosmic strings, domain walls, etc)
- Dark matter (primordial black holes, dark photon, axion, etc)

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See, e.g., Snowmass 2021 white paper arxiv:2203.07972 (Submitted to General Relativity and Gravitation, corresponding author)

Stochastic Gravitational Waves



The Cross-Correlation Method

- The standard method of searching for SGB
- Remove majority of noises specific to a single interferometer





Model comparison: Bayes factor

PHYSICAL REVIEW LETTERS 126, 151301 (2021)

LIGO

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

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Gravitational Wave Sources



See alo 立功's talk (new simulation result and new phenomena), 少江's talk (wall velocity calculation)

Cosmological First Order Phase Transitions

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

New Physics?

PTA: nHz (~100MeV)

See also Jiang's talk, 赟's talk



Temperature Hindmarsh et al SciPost Phys.Lect.Notes 24 (2021)

Guenther, arxiv: 2010.15503

 $f_0 = 2.65 \times 10^{-6} \text{Hz} \times \frac{1}{\epsilon} \left(\frac{g_s(T_*)}{100} \right)^{1/6} \left(\frac{T_*}{100 \text{GeV}} \right)$

Models

Broken power law model

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

Bubble collision domination

Sound waves domination

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

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

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

 $f_{\rm ref} = 25 \ {\rm Hz}$

 $\Upsilon = 1 - (1 + 2 au_{
m sw} H_{
m pt})^{-1/2}$ (RD) HG,Sinha,Vagie,White,JCAP 01 (2021) 001

Broken Power Law Searches



Results

01+02+03@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





Sound Waves

95% CL UL with fixed Tpt and beta/Hpt

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

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

First result from gravitational wave data!

Uncertainties

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

$\Delta \Omega_{ m GW}/\Omega_{ m GW}$	4d approach	3d approach
RG scale dependence	$O(10^2 - 10^3)$	$O(10^0 - 10^1)$
Gauge dependence	$\mathcal{O}(10^1)$	$\mathcal{O}(10^{-3})$
High- T approximation	$\mathcal{O}(10^{-1}-10^0)$	$O(10^0 - 10^2)$
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, JHEP04(2021)055

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

H.G, Sinha, Vagie, White, JHEP06(2021)164

See also Xiao's talk (uncertainty due to sound velocity calculation)

Cosmic String Searches

PHYSICAL REVIEW LETTERS 126, 241102 (2021)

Editors' Suggestion

Constraints on Cosmic Strings Using Data from the Third Advanced LIGO–Virgo Observing Run

R. Abbott et al.*

(LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration)



(Received 30 January 2021; revised 31 March 2021; accepted 23 May 2021; published 16 June 2021)

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Topological Defects

Solutions of classical field equations **Domain Walls** Boundaries take vacuum field values (finite energy) Degenerate vacuum (manifold) and nontrivial mapping **Cosmic Strings** + strings $\frac{3\pi}{2}$ $\frac{3\pi}{2}$ 0 π $\frac{3\pi}{2}$ π http://www.ctc.cam.ac.uk/outreach/origins/cosmic_structures_two.php Domain wa

Rotation axis

domain walls

+

+



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

LIGO Searches for Cosmic Strings

- Stochastic gravitational wave background
- Individual burst



V

scale



particle physics model dependence

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

Dark Photon Dark Matter Searches

COMMUNICATIONS PHYSICS

ARTICLE

https://doi.org/10.1038/s42005-019-0255-0 OPEN

Searching for dark photon dark matter in LIGO O1 data

Huai-Ke Guo¹, Keith Riles², Feng-Wei Yang^{3,4*} & Yue Zhao⁴

O3 Result

PHYSICAL REVIEW D 105, 063030 (2022)

Constraints on dark photon dark matter using data from LIGO's and Virgo's third observing run

R. Abbott *et al.** (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration)

Now a collaboration effort !

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The continuous wave group joined our search in O3/



All can be searched for using gravitational wave detectors.



Dark Photon Dark Matter silicon mirror a dark photon wave $U(1)_B$: 1/GeV $U(1)_{B-L}$: 1/2GeV test mass light storage arm light storage arm test mass test mass test mass beam splitter $\vec{A}_{n,0}\sin(\omega_n t - \mathbf{k}_n \cdot \mathbf{x} + \phi_n)$ photodetector laser **CERN** Courier very narrow frequency band Search method is similar $\Delta f / f = 10^{-6}$ to "continuous waves" 21

O1 Result

O3 Result



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

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

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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)





New constraint on cosmic strings with latest LIGO data

New constraint on dark photon with latest LIGO data

