Constraints on Physics Beyond the Standard Model with LIGO's Third Observing Run Data

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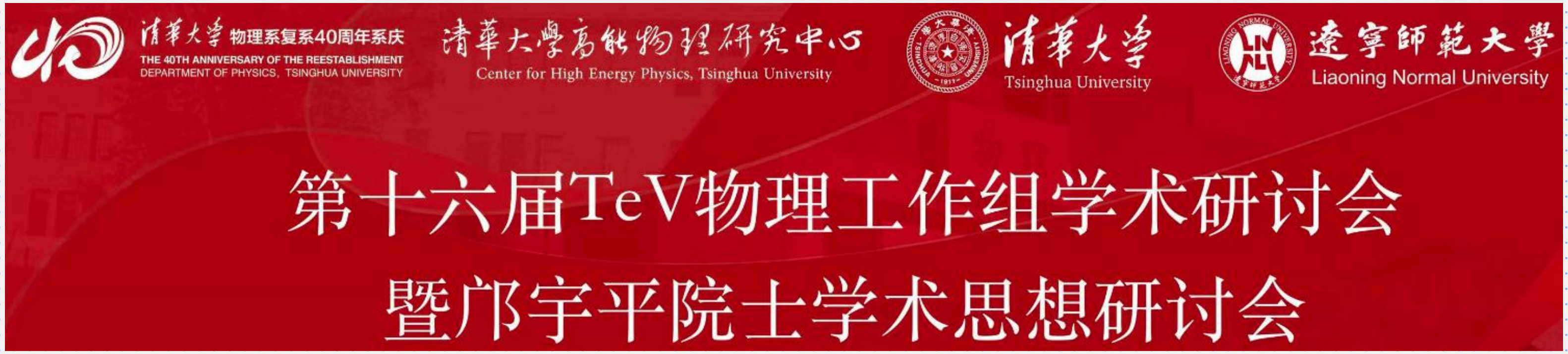
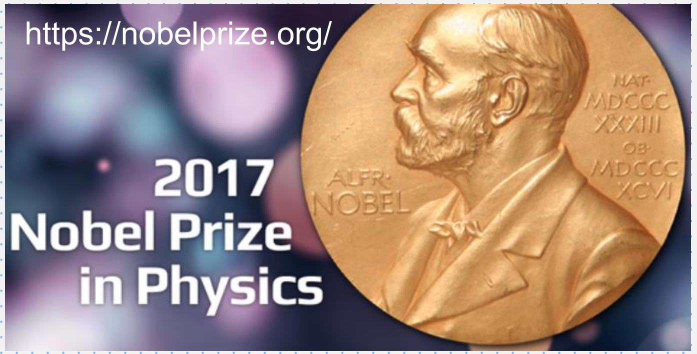
2022年11月9日

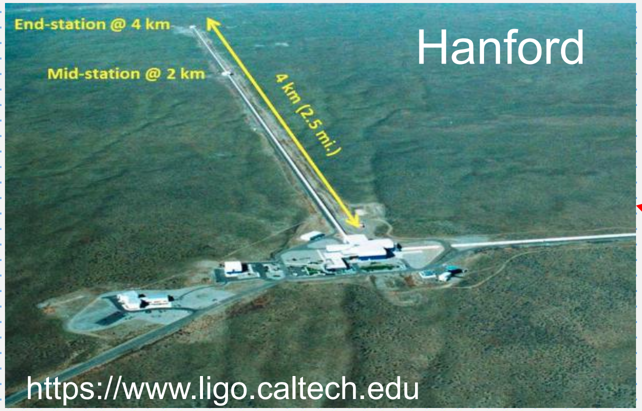


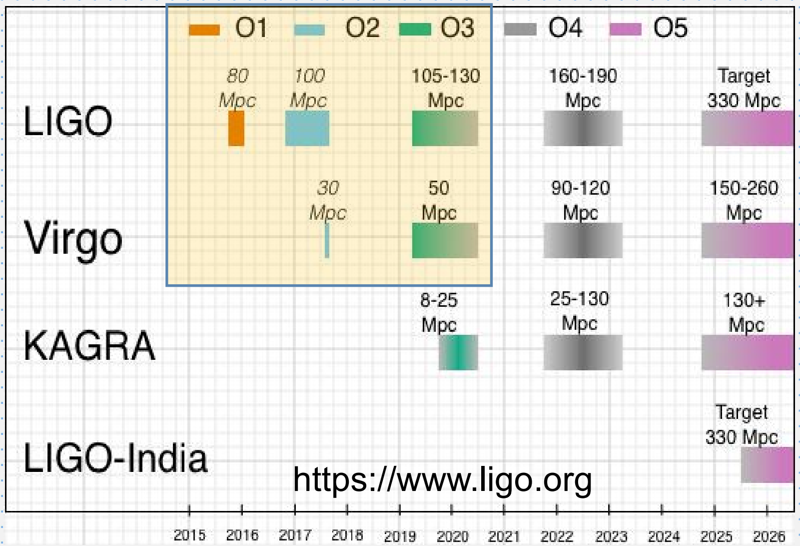
LIGO Interferometers

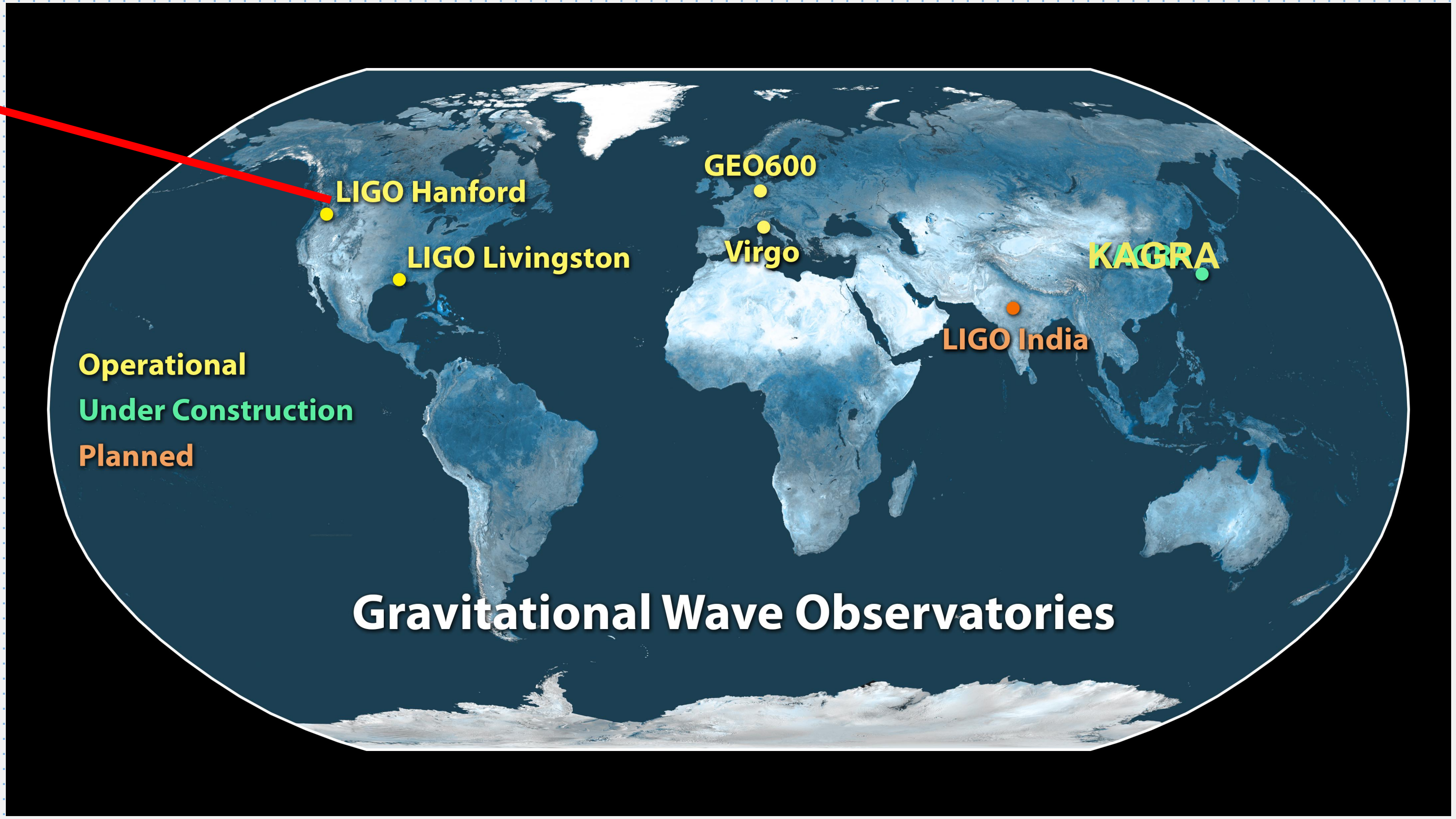


First direct detection of gravitational waves.

A new tool for astronomy, and fundamental physics







Related Publications

See also Fapeng's talk

Cosmological
First Order Phase Transitions:

PRL126 (2021) 15, 151301

Romero, Martinovic, Callister, H.G,
Martínez, Sakellariadou, Yang, Zhao

Cosmic Strings:

PRL 126,241102, LVK Collaboration Paper (key author)

Editor's Suggestion, featured in Phys.org

Dark Photon Dark Matter:

O1: (Nature) Commun.Phys. 2 (2019) 155, H.G, Riles, Yang, Zhao

O3: PRD 105 (2022) 063030, LVK Collaboration Paper (key author)

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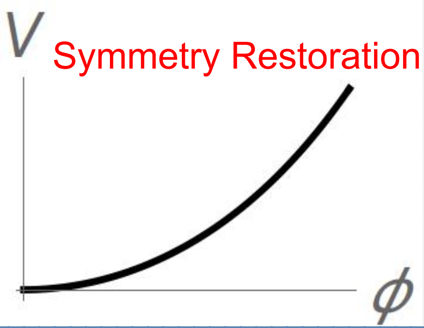
Laboratory which is a major facility fully funded by the National Science Foundation.

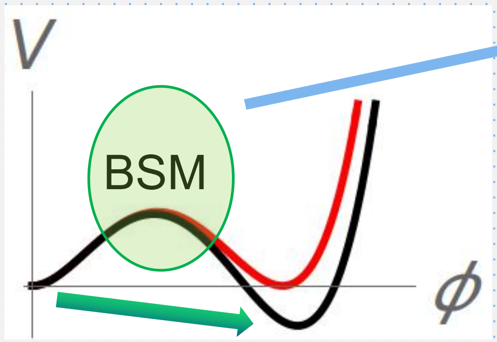
Cosmological First Order Phase Transitions

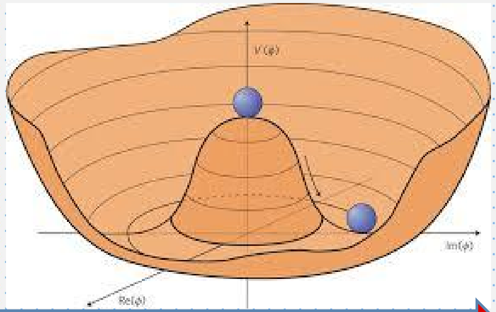
See also
Yongcheng's, Kepan's talks

Symmetry-breaking in the early universe

modification of Higgs properties







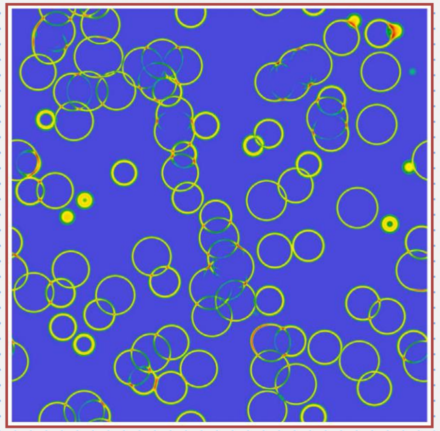
Temperature drops

Electroweak Phase Transition

Colliders CPV GW

Correlation
Complementarity

BSM

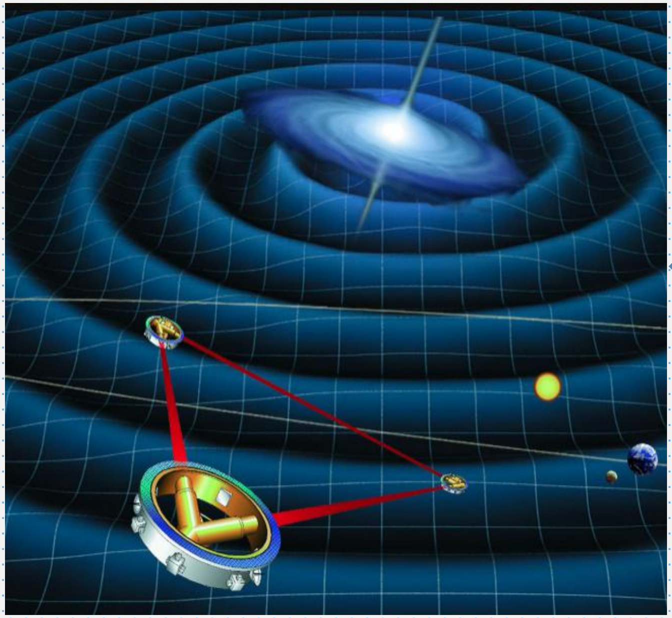


Hindmarsh, et al, 2015

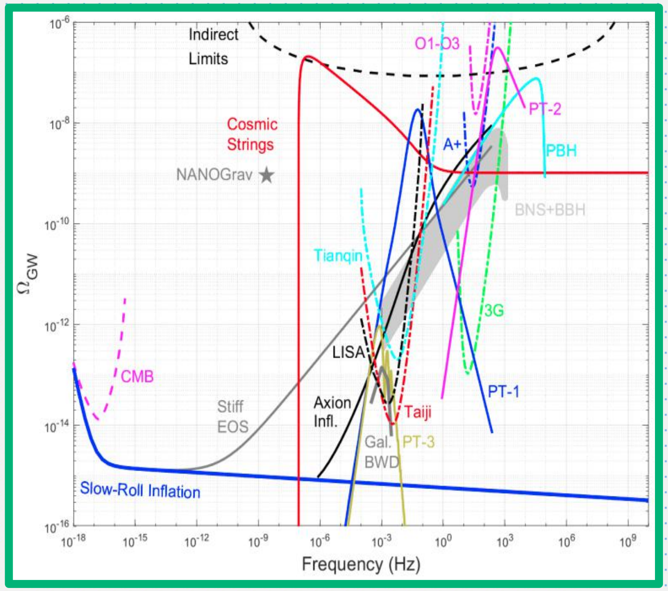
Scale of a generic PT
can be arbitrary

Flow of Studies

theoretical calculation of gravitational wave spectrum and detector simulation



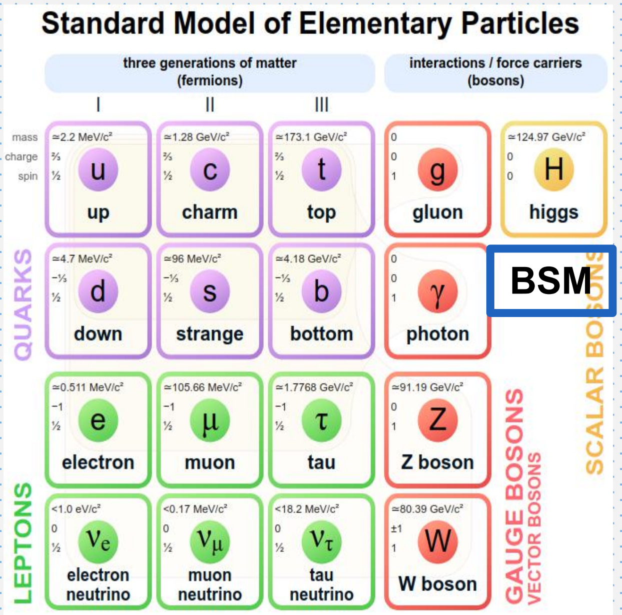
LIGO, LISA, Taiji, Tianqin...



Gravitational Wave Spectrum

α
β
v_w
T_*
g_s
...

Phase Transition Parameters



Particle Physics Model

data analysis, constraints or discovery(parameter estimation)

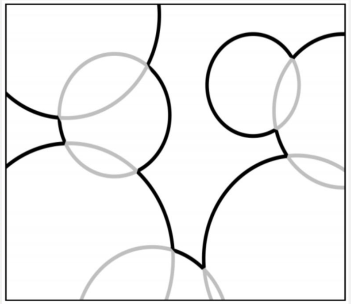
this talk

The GW Spectra

Energy density Spectrum

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

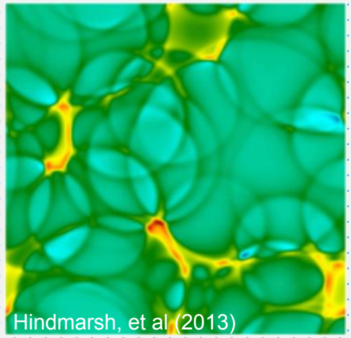
bubble collision



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

See Ligong's talk for details

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

All can be described by a broken power law model

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

Foreground

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

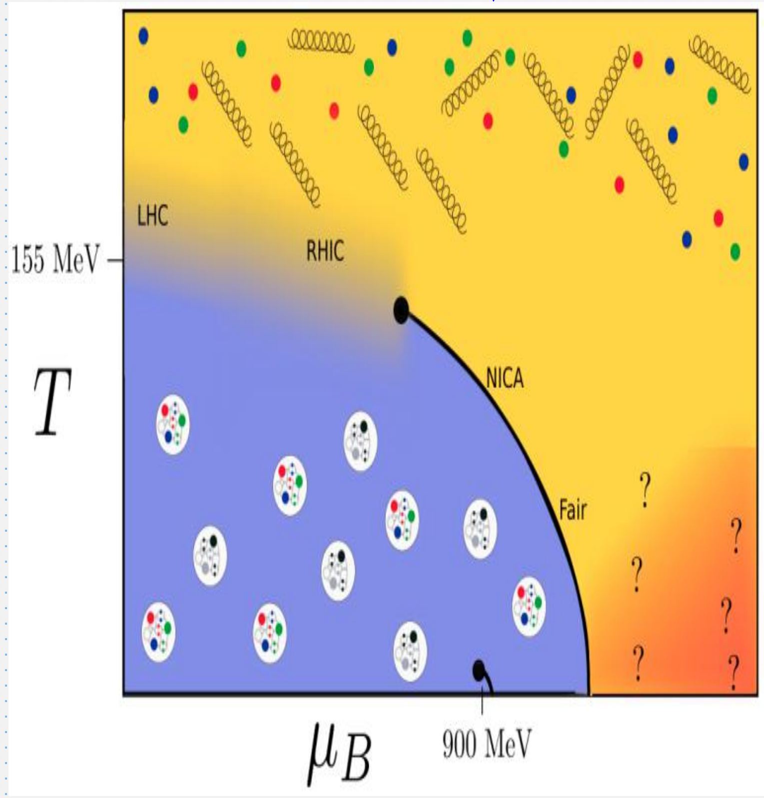
$$f_{\rm ref} = 25\ {\rm Hz}$$

Generic Features

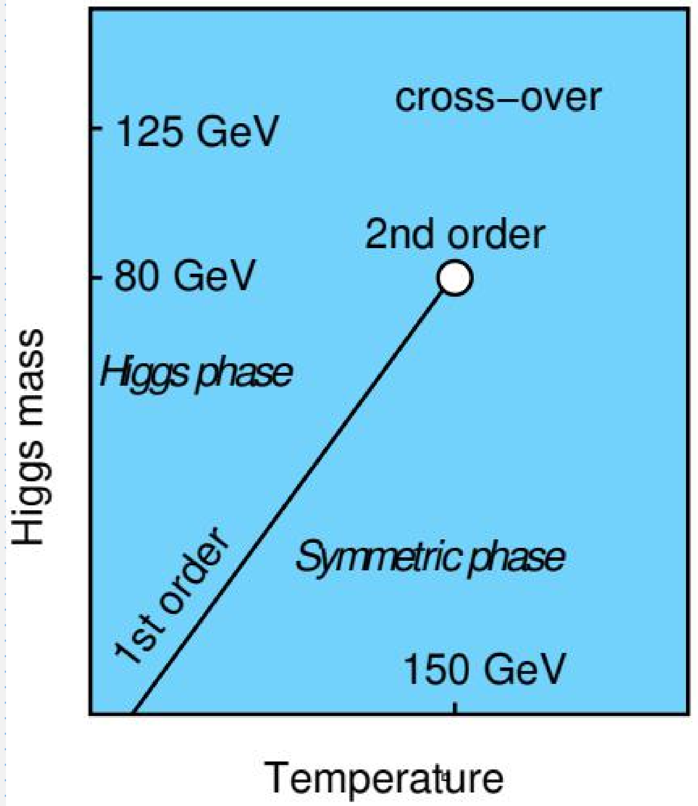
- LIGO (~100Hz) : (~PeV - EeV)
- LISA, Taiji, Tianqin: ~mHz : (~100GeV)
- PTA: nHz (~100MeV)

EWPT

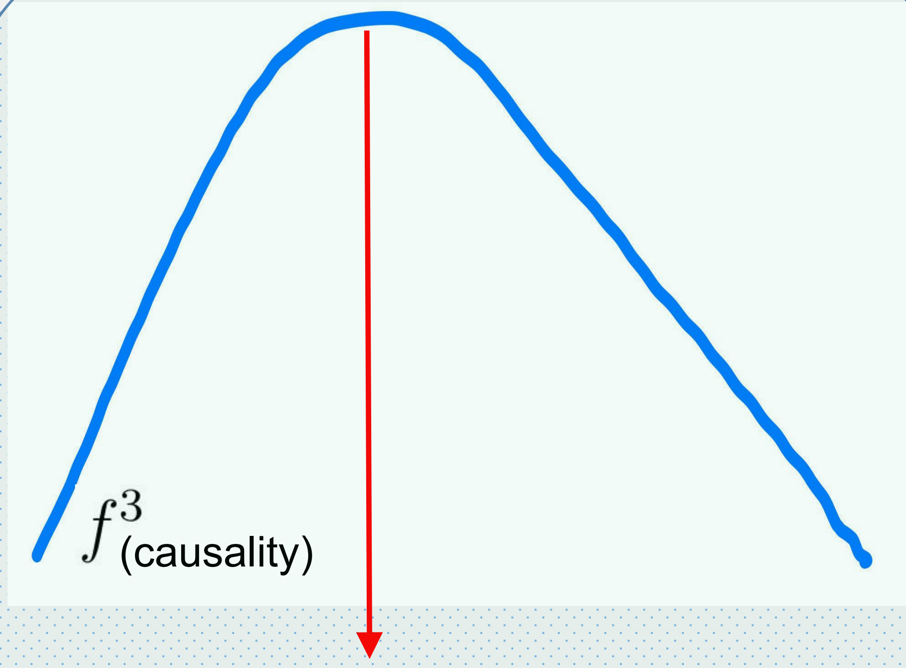
QCD PT



Guenther, arxiv: 2010.15503



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



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

typical length scale

tells PT temperature
(symmetry breaking scale)

Results

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)

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

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

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

Bubble Collision

95% CL UL with fixed Tpt and beta/Hpt

Phenomenological model (bubble collisions)				
$\Omega^{95\%}_{\mathrm{coll}}(25\ \mathrm{Hz})$				
$\beta/H_{\mathrm{pt}} \backslash T_{\mathrm{pt}}$	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 with fixed Tpt and beta/Hpt

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

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

First result from gravitational wave data!

Cosmic Strings

See also Chen’s talk

Topology of cosmic domains and strings

J.Phys.A 9 (1976) 1387-1398

T W B Kibble

Blackett Laboratory, Imperial College, Prince Consort Road, Lon

Received 11 March 1976

www.theguardian.com

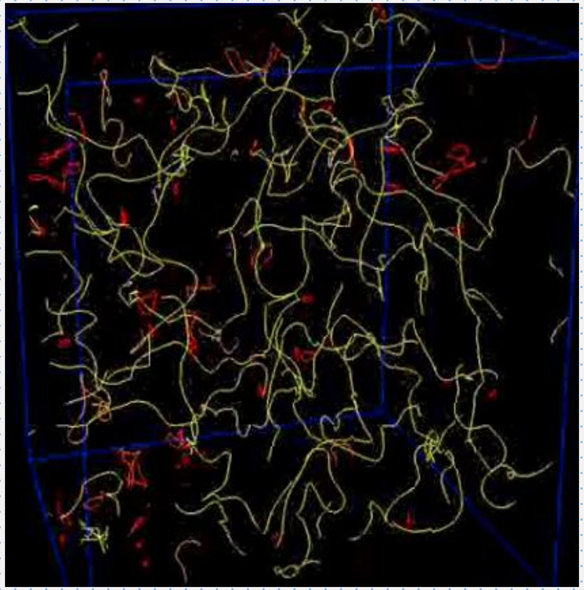
- Form irrespective of phase transition’s order
- Can be detected with gravitational waves

GW measurement tells
scale (η) of symmetry breaking ($G \to H$)

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

μ: line mass density

Cosmological Simulation



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

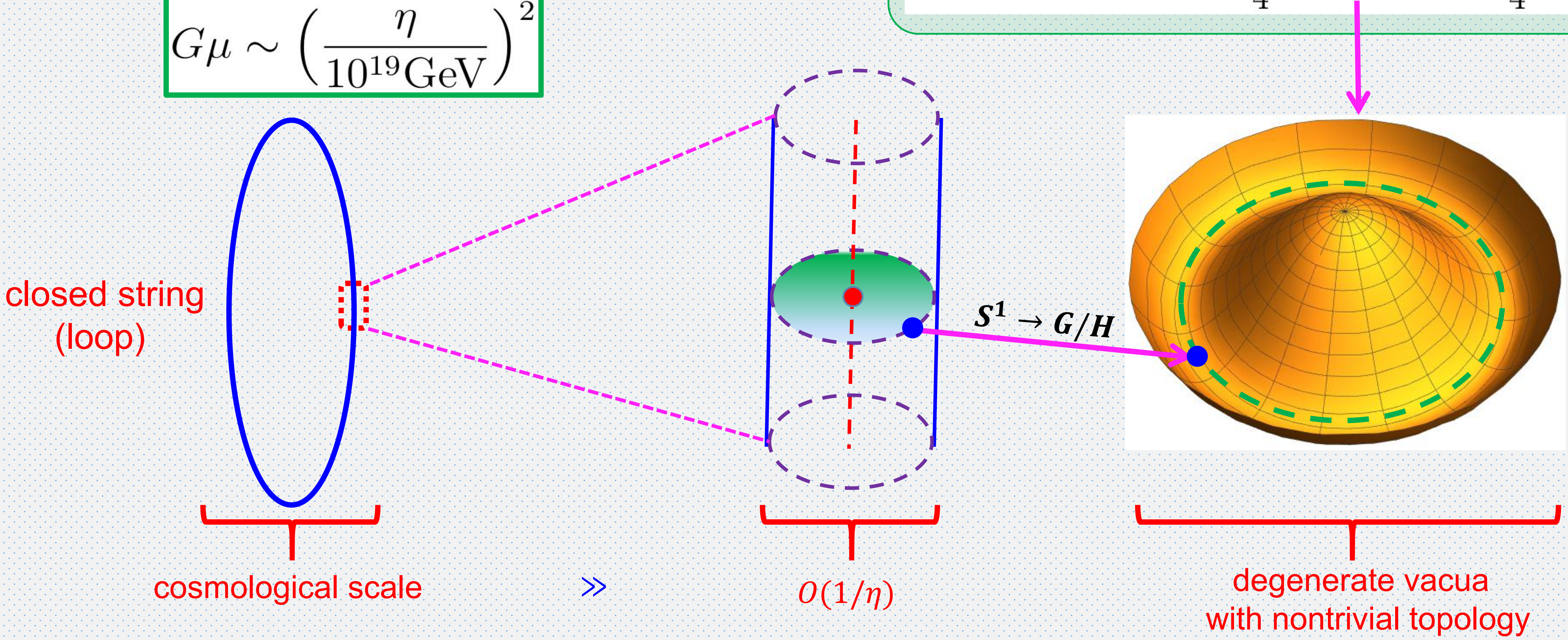
From Particle Physics Model to String

- Not sensitive to microscopic details
- GW measurement tells symmetry breaking scale

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

Example: the Abelian Higgs Model

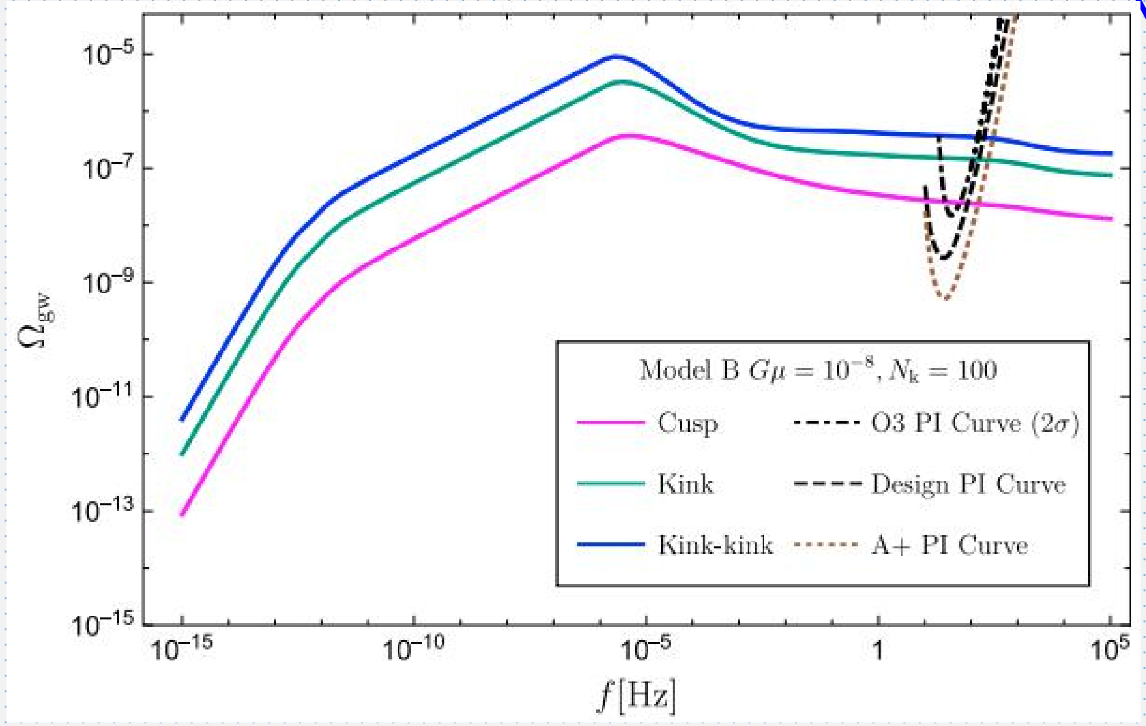
$$\mathcal{L} = |(\partial_\mu - igA_\mu)\Phi|^2 - \frac{1}{4}\lambda(|\Phi|^2 - \eta^2)^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$



Gravitational Waves

$$\Omega_{\rm GW}(f) = \frac{4\pi^2}{3H_0^2} f^3 \sum_i \int \mathrm{d}z \int \mathrm{d}\ell \; h_i^2 \times \frac{\mathrm{d}^2 R_i}{\mathrm{d}z\mathrm{d}\ell}$$

cusp, kink, kink-kink collision



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

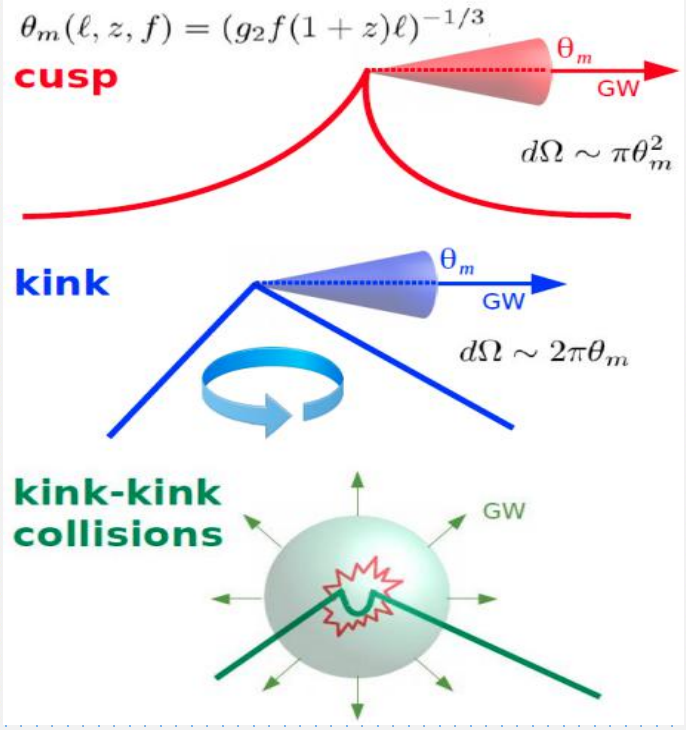
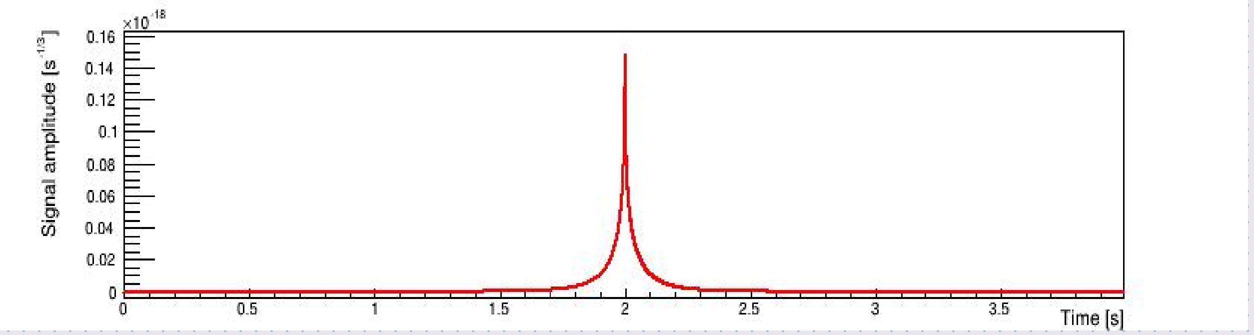


Image credit: Florent Robinet

example waveform in time domain (cusp)

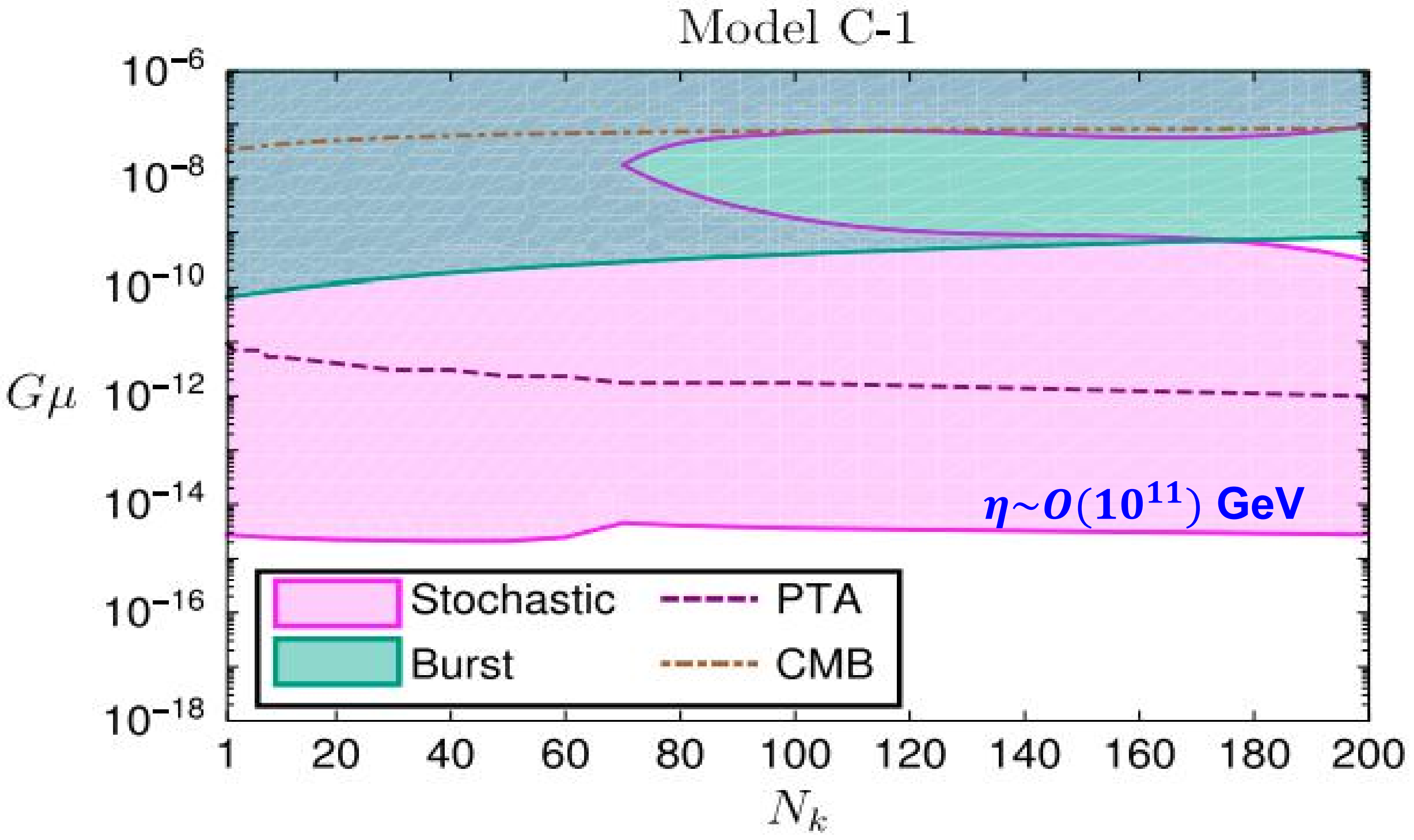


https://www.ligo.org/science/Publication-S5S6CosmicStrings

Results

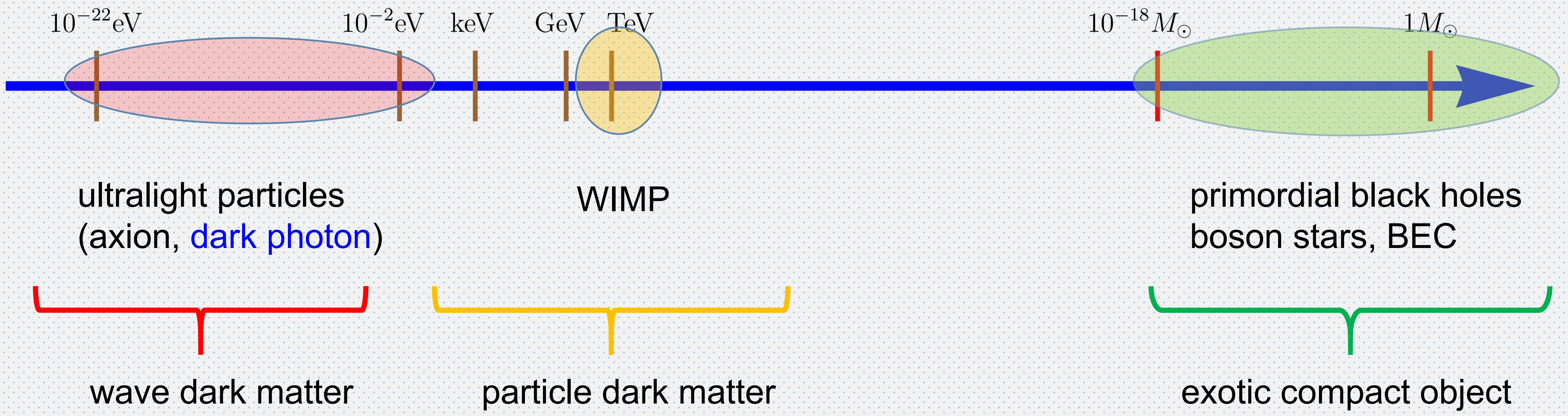
Symmetry breakings at scales higher than $O(10^{11})$ GeV
with Cosmic String production are excluded
Caveat (loop distribution model)

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



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

Dark Matter Candidates



All can be searched for using gravitational wave detectors.

Dark Photon

- Gauge boson of U(1)

$U(1)_B\ (p+n)$ $\qquad$ $U(1)_{B-L}(n)$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

dark electric field

$$E_i \sim m_A A_i$$

(affects LIGO's mirrors)

signal in LIGO's data

$$B^i \sim m_A v_j A_k \epsilon^{ijk}$$

(negligible)

$$\mathbf{A}_{\text{total}}(t,\mathbf{x}) = \sum_{i=1}^{N} \mathbf{A}_{i,0} \sin(\omega_i t - \mathbf{k}_i \cdot \mathbf{x} + \phi_i)$$

$$\rho_{\text{DM}} \approx 0.4\text{GeV}/\text{cm}^3$$

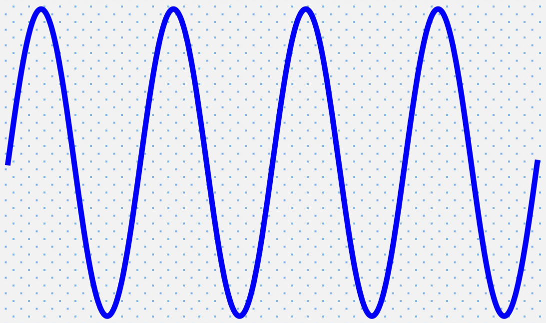
- velocity: Maxwell distribution
- polarization: Isotropic(Galaxy frame)

$$\left(\frac{1}{\sqrt{\pi} v_0}\right)^3 \exp\left(-\frac{\boldsymbol{v}'^2}{v_0^2}\right)$$

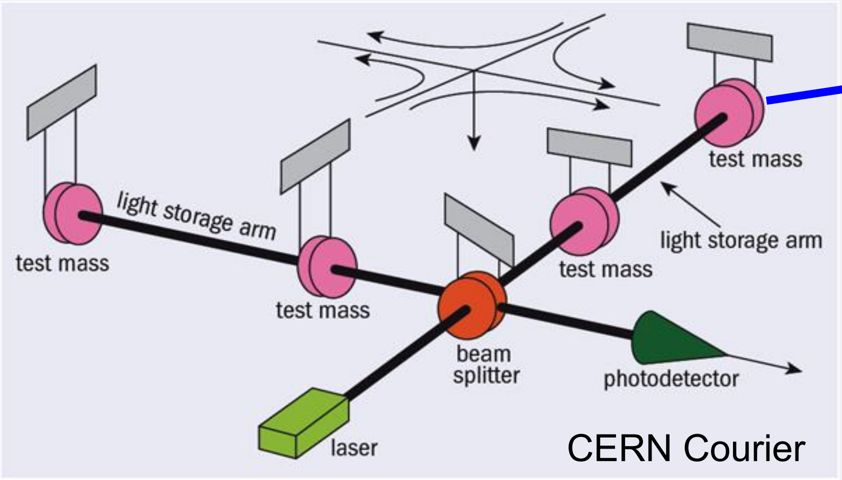
$$v_0 \sim \mathcal{O}(10^{-3})$$

Signal Properties

a dark photon wave



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



CERN Courier

silicon mirror

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

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

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

acceleration

typical LIGO frequency

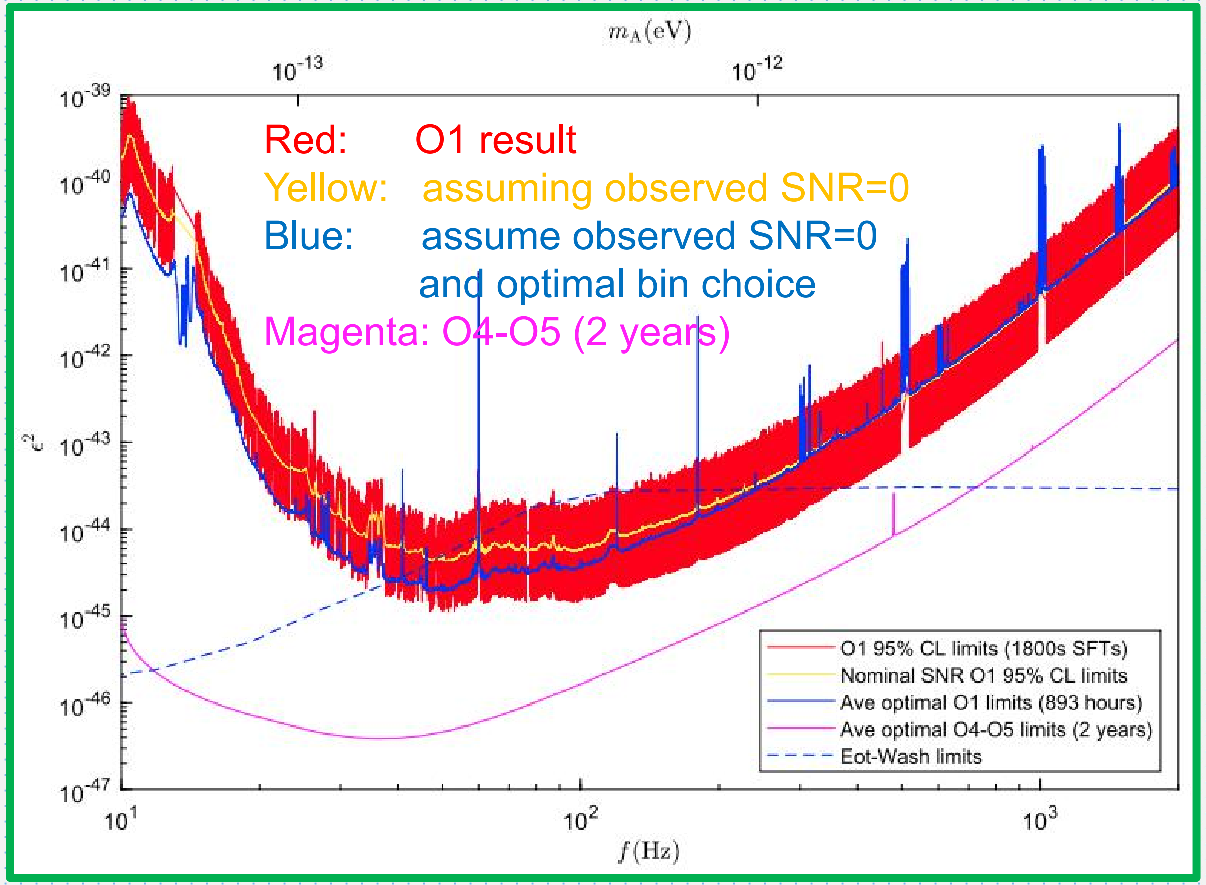
$$\omega_n = m_A(1 + \frac{1}{2}v_n^2) = 2\pi \times (100\mathrm{Hz}) \approx \boxed{4 \times 10^{-13}\mathrm{ev}}$$

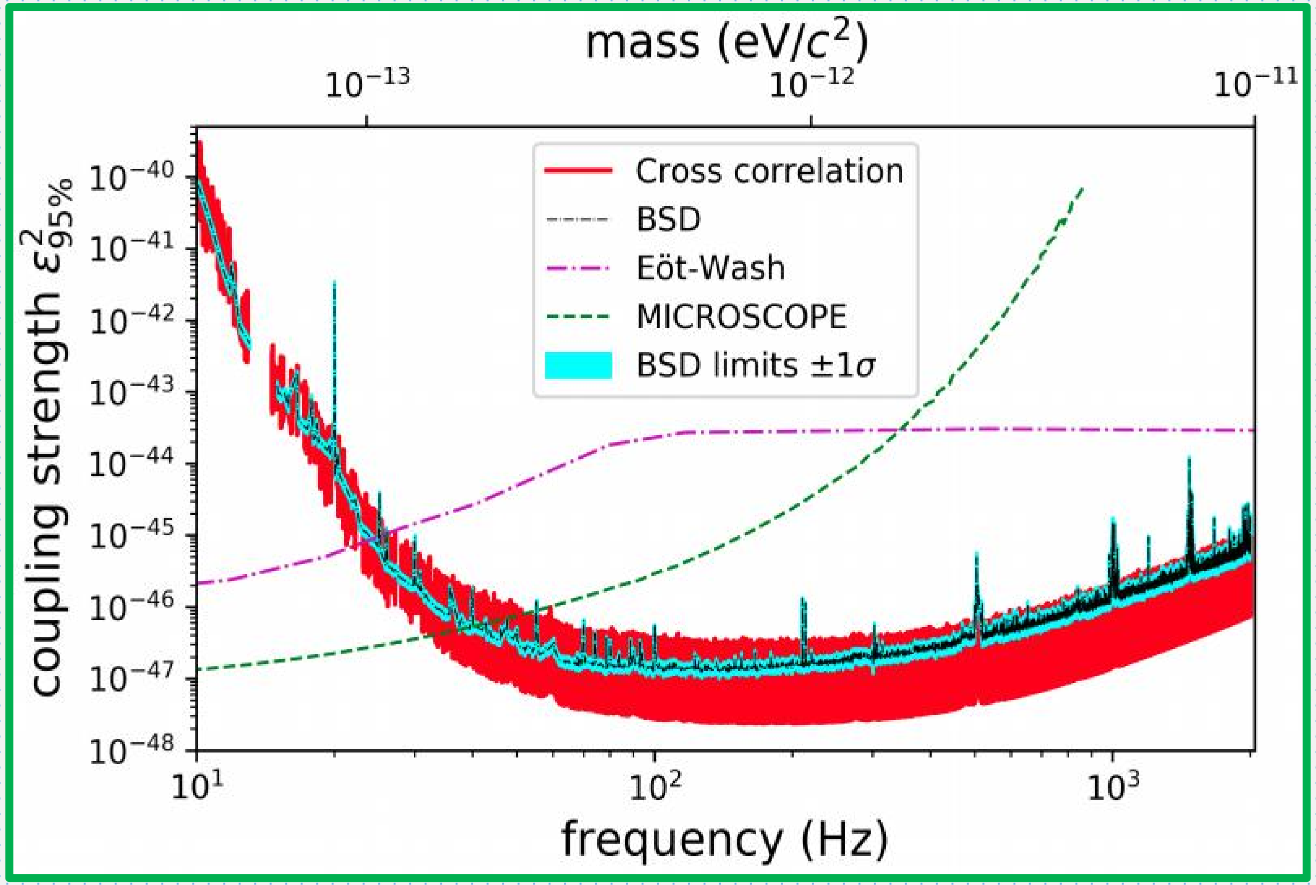
typical dark photon mass LIGO is sensitive to

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

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

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)

Summary

- First search for cosmological first order phase transitions with LIGO’s data
- New constraint on cosmic strings with latest LIGO data
- New constraint on dark photon with latest LIGO data

Thanks!