First result on cosmological first-order phase transitions with LIGO-Virgo's three observing run data

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May 25, 2021

Phys. Rev. Lett. 126, 151301 (arxiv:hep-ph/2102.01714),
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subgroup of the LIGO scientific collaboration

Probing BSM Physics with Gravitational Waves

New Physics

- High energy frontier (LHC, etc)
- Precision frontier (EDM, MDM, etc)
- Cosmic frontier (CMB, etc)
- Dark matter searches (direct, indirect, etc)
- Gravitational waves
  - ✓ cosmological FOPT (O3 done, this talk)
  - ✓ cosmic strings (O3 done)
    arxiv:gr-qc/2101.12248 (PRL accepted)
  - ✓ dark matter direct detection at LIGO (O3 done)
    O1, (Nature) Commun.Phys. 2 (2019) 155
    O3, to appear in a few days

Most primordial gravitational waves are stochastic (SGB).

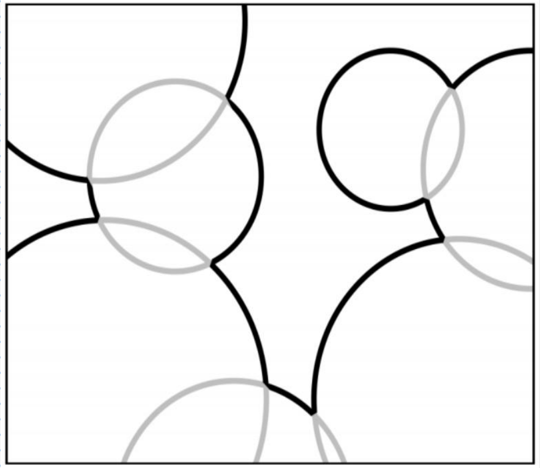
Characterizing Stochastic Gravitational Waves

For stochastic GWs that is Gaussian, stationary, isotropic and unpolarized,

$$\langle \tilde{h}^*_A(f,\hat{\mathbf{n}})\tilde{h}_{A'}(f',\hat{\mathbf{n}}')\rangle = \delta(f-f')\,\frac{\delta^2(\hat{\mathbf{n}},\hat{\mathbf{n}}')}{4\pi}\,\delta_{AA'}\,\frac{1}{2}\boxed{S_h(f)} \longrightarrow \Omega_{\rm gw}(f) = \frac{4\pi^2}{3H_0^2}\,f^3 S_h(f)$$

Cosmological First Order Phase Transition (FOPT)

Bubble Collisions



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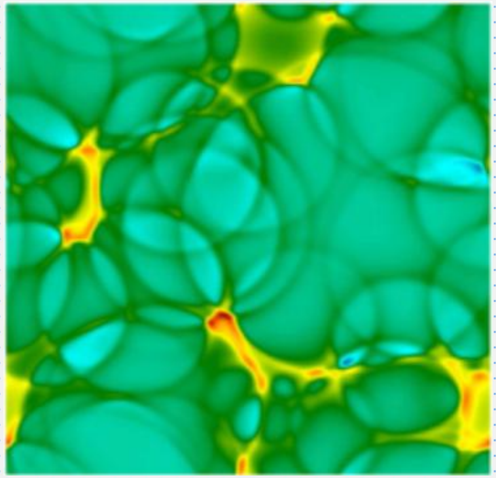
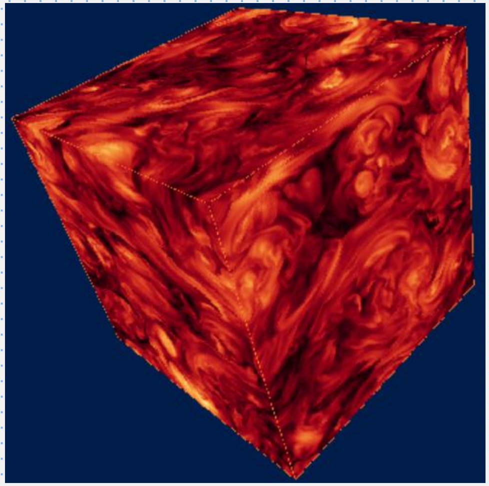
Sound Waves



Hindmarsh, et al,PRL112,041301(2013)

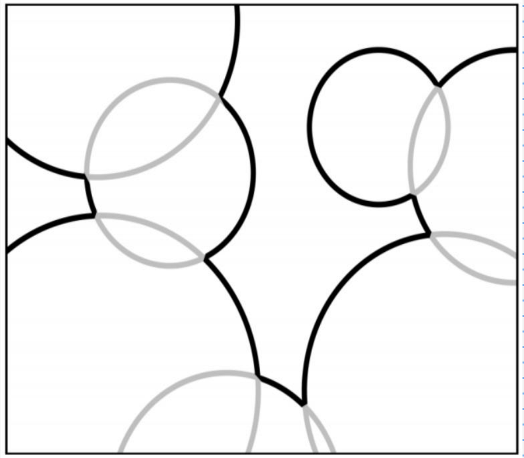
→

MagnetoHydrodynamic Turbulence



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

Bubble Collisions



Envelope Approximation

Simulations:
Kosowsky, Turner, Watkins, Kamionkowski
PRL69,2026(1992), PRD45,4514(1992), PRD47,4372(1993), PRD49,2837(1994)
Huber, Konstandin, JCAP09(2008)022
Analytical Modelling:
Jinno, Takimoto, PRD95,024009(2017)

Beyond the Envelope Approximation

Bulk flow model: Konstandin, JCAP03(2018)047, Jinno, Takimoto, JCAP01(2019)060
Direct large scalar lattice simulations: Cutting, Escartin, Hindmarsh, Weir, PRD97,123513(2018), arXiv:2005.13537:

negligible (dominant) when
other sources are present (absent)

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

Consider a scenario when BC is dominant

$$f_{\rm env} = 16.5\left(\frac{f_{\rm bc}}{\beta}\right)\left(\frac{\beta}{H_{\rm pt}}\right)\left(\frac{T_{\rm pt}}{100\ {\rm GeV}}\right)\left(\frac{g_*}{100}\right)^{1/6}\mu{\rm Hz},$$

Sound Waves

Numerical Simulations:

Hindmarsh, Huber, Rummukainen, Weir,
PRL112, 041301 (2014), PRD92, 123009 (2015), PRD96, 103520 (2017)

Analytical Modelling(sound shell model)

Minkowski: Hindmarsh, 120, 071301 (2018)
Hindmarsh, Hijazi, JCAP12(2019)062
FLRW: HG,Sinha,Vagie,White,JCAP 01 (2021) 001

- Solve the fluid velocity profile modes: detonation, deflagration, hybrid

  Espinosa, Konstandin, No, Servant (JCAP06,028)
- Reduction found for alpha~1 and small vw

  Cutting, Hindmarsh, Weir, PRL125, 021302 (2020)

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

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

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

Previous formula mistakenly enforces an infinite lifetime.

The dominant source for a FOPT in a thermal plasma.

Consider a scenario with this dominant (SW).

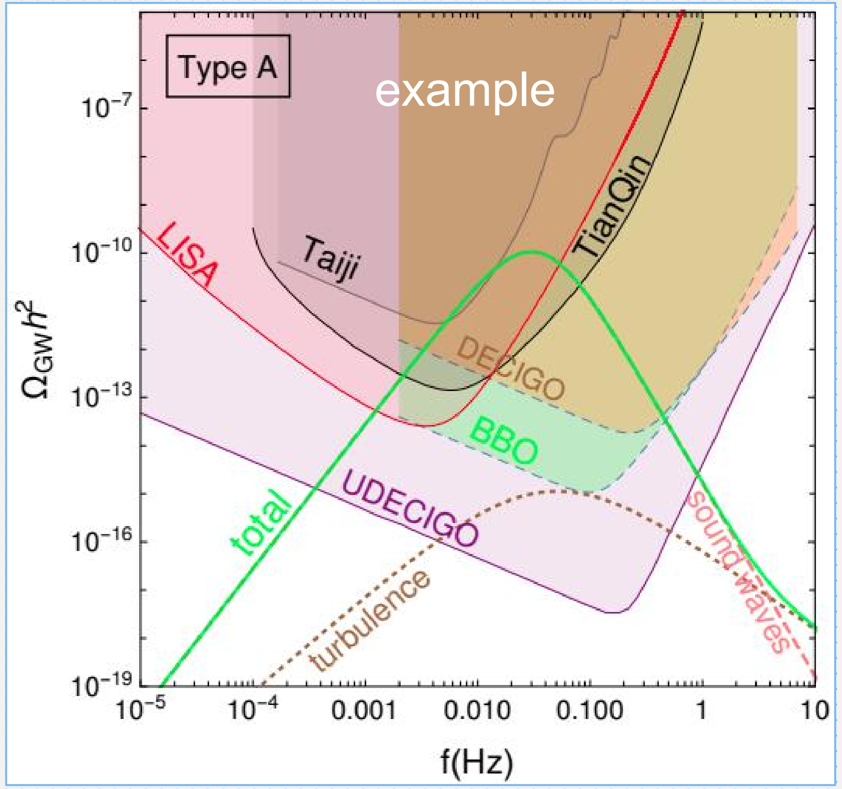
Generic Properties

Both can be approximated by a broken power law.

Peak frequency is determined by the mean bubble separation, and redshifting (Temperature).

Temperature LIGO is sensitive to

10^6 ~ 10^9GeV



Alves, Ghosh, HG, Sinha, Vagie, JHEP04,052(2019)

Broken Power Law Model

We thus also consider a generic broken power law model.

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

- n1: low f power,   fixed to be 3, (causality)
- n2: high f power, -4(SW), -1(BC), not entirely determined, will vary in the range (-8,0)
- Omega*, f*, reference amplitude and frequency.
- Δ=2 (SW), 4(BC), fixed to be 2 which gives a more conservative result

In all models (BPL, SW, BC), we also consider the non-negligible CBC contribution.

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

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

The Cross-Correlation Method

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

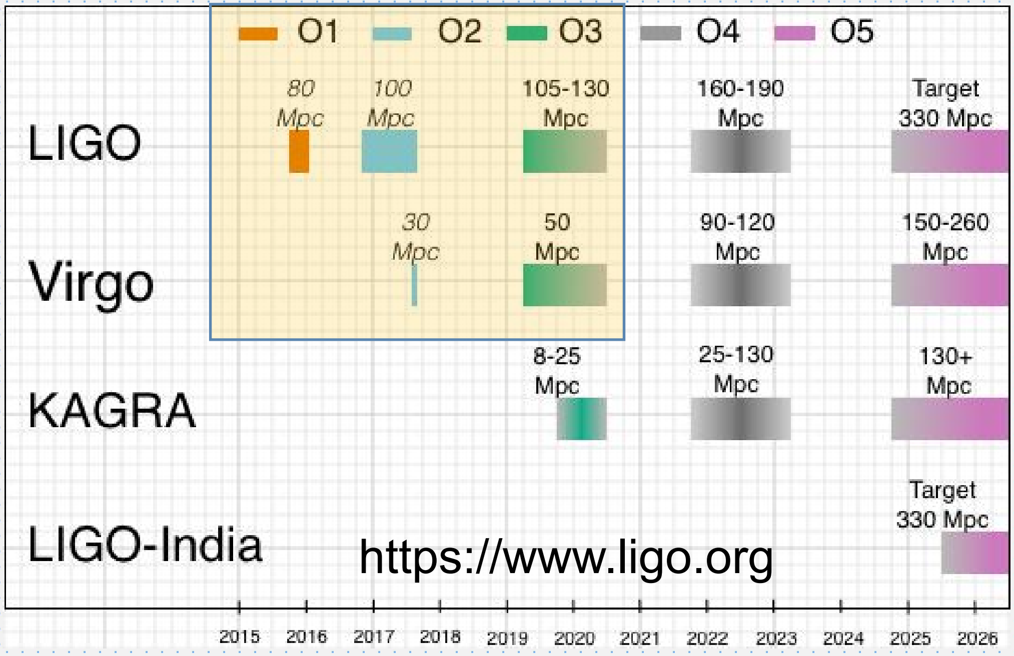
cross-correlation estimator

$$\hat{C}^{IJ}(f) = \frac{2}{T}\frac{\mathrm{Re}[\tilde{s}_I^\star(f)\tilde{s}_J(f)]}{\gamma_{IJ}(f)S_0(f)}$$

$$\langle \hat{C}^{IJ}(f) \rangle = \Omega_{\rm GW}(f)$$

O1, O2 and O3 data from interferometer I(J): (H, L, V)

overlap reduction function



https://www.ligo.org

For more details on the cross-correlation analysis, see the LIGO, Virgo and KAGRA collaboration paper arxiv:gr-qc/2101.12130

The Bayesian Analysis Framework

Likelihood

$$\log p(\hat{C}_{IJ}(f)|\boldsymbol{\theta}_{\rm gw},\lambda) \propto -\frac{1}{2}\sum_f \frac{\left[\hat{C}_{IJ}(f) - \lambda\Omega_{\rm gw}(f,\boldsymbol{\theta}_{\rm gw})\right]^2}{\sigma^2_{IJ}(f)}$$

calibration uncertainty

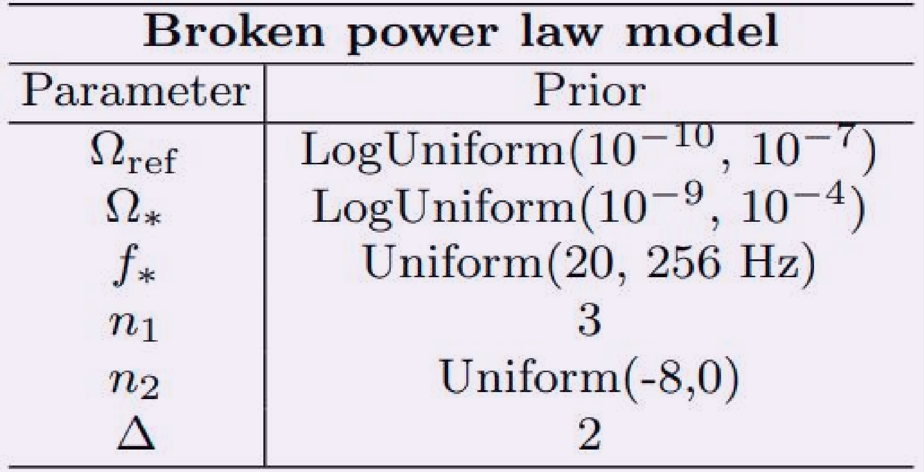
Gaussian noise

$$\sigma^2_{IJ}(f) \approx \frac{1}{2T\Delta f}\frac{P_I(f)P_J(f)}{\gamma^2_{IJ}(f)S_0^2(f)}$$

Priors for two analysis strategies:

broken power law

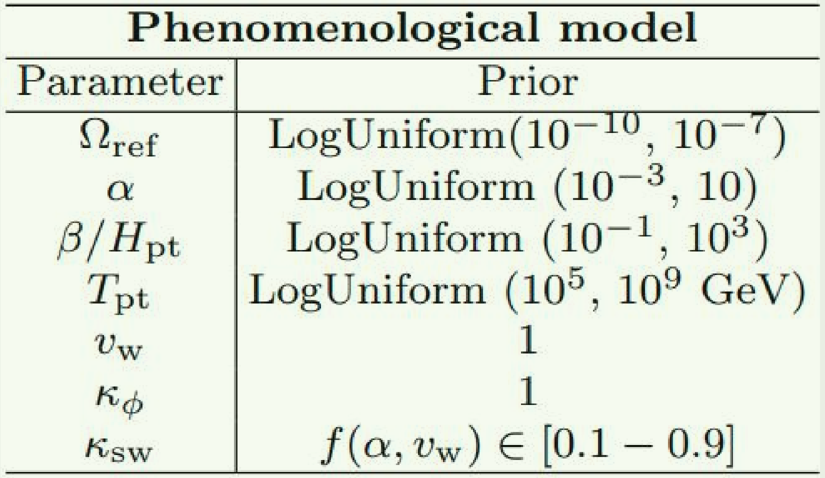
$$\Omega_{\rm bpl}(f) = \Omega_*\left(\frac{f}{f_*}\right)^{n_1}\left[1+\left(\frac{f}{f_*}\right)^{\Delta}\right]^{(n_2-n_1)/\Delta}$$



Broken power law model

Parameter	Prior
$\Omega_{\rm ref}$	LogUniform(10^{-10}, 10^{-7})
Ω_*	LogUniform(10^{-9}, 10^{-4})
f_*	Uniform(20, 256 Hz)
n_1	3
n_2	Uniform(-8,0)
Δ	2

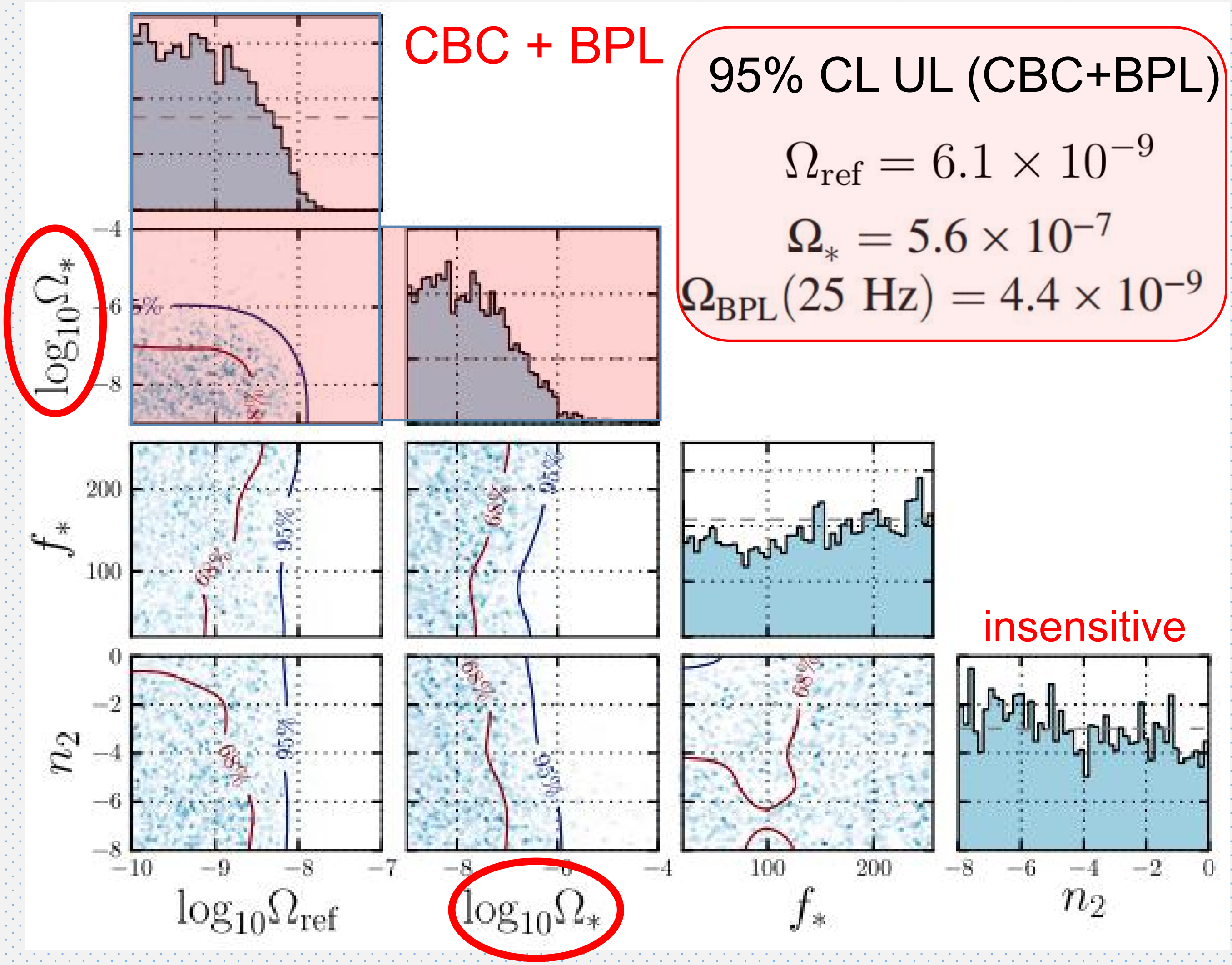
sound waves, or bubble collision



Phenomenological model

Parameter	Prior
$\Omega_{\rm ref}$	LogUniform(10^{-10}, 10^{-7})
α	LogUniform (10^{-3}, 10)
$\beta/H_{\rm pt}$	LogUniform (10^{-1}, 10^{3})
$T_{\rm pt}$	LogUniform (10^{5}, 10^{9} GeV)
$v_{\rm w}$	1
κ_ϕ	1
$\kappa_{\rm sw}$	$f(\alpha, v_{\rm w}) \in [0.1 - 0.9]$

Broken Power Law Searches



95% CL UL (CBC+BPL)

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

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

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

Posterior distributions for 2 variables (correlations)

No Evidence for BPL Signal

$$\log \mathcal{B}^{\rm CBC+BPL}_{\rm noise} = -1.4$$

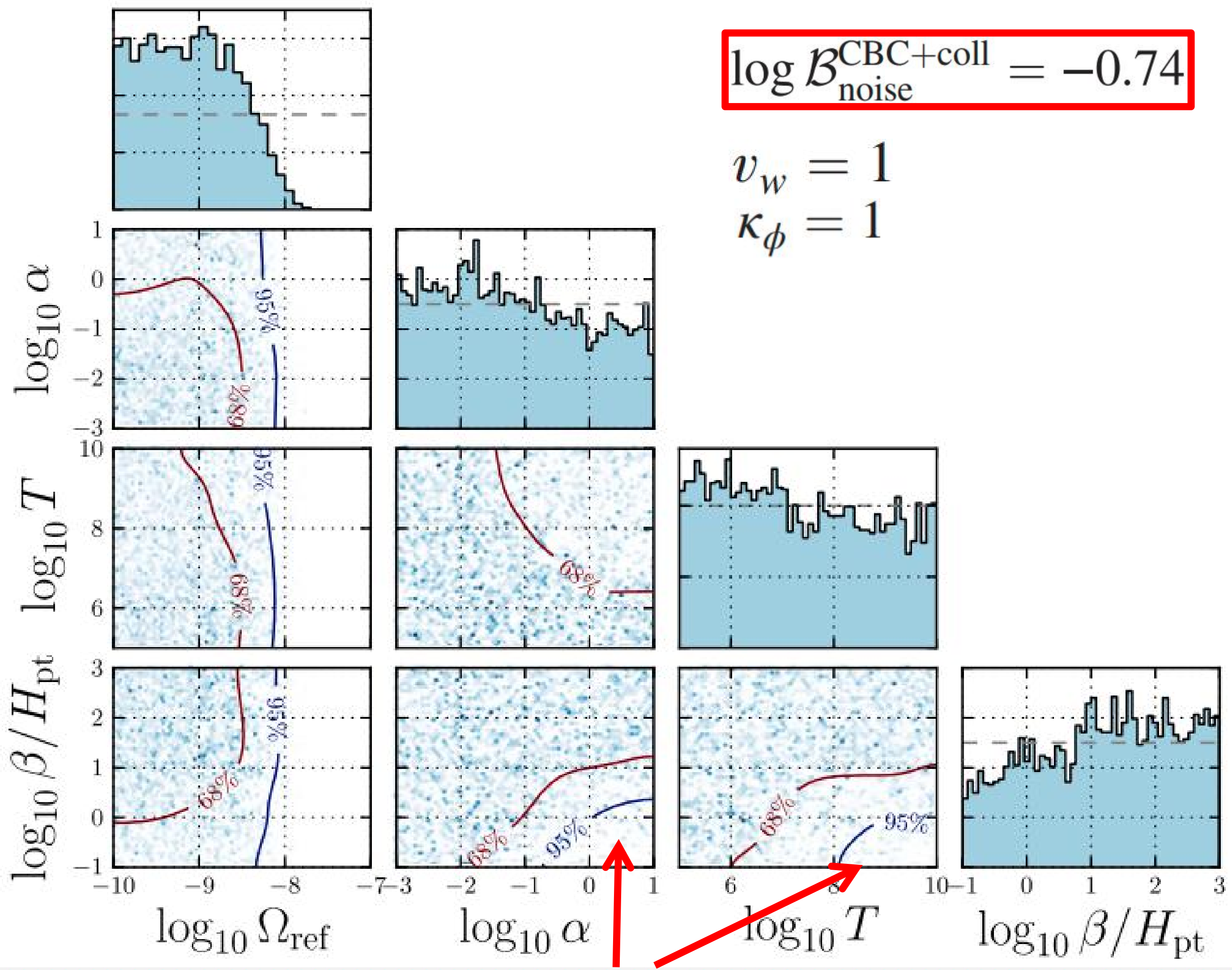
$$\log \mathcal{B}^{\rm BPL}_{\rm noise} = -0.78$$

$$\log \mathcal{B}^{\rm CBC+BPL}_{\rm CBC} = -0.81$$

95% CL UL with fixed n2

Broken power law model			
	$f_* = 1$ Hz	$f_* = 25$ Hz	$f_* = 200$ Hz
$n_2 = -1$ (BC)	3.3×10^{-7}	3.5×10^{-8}	2.8×10^{-7}
$n_2 = -2$ (BC)	8.2×10^{-6}	6.0×10^{-8}	3.7×10^{-7}
$n_2 = -4$ (SW)	5.2×10^{-5}	1.8×10^{-7}	3.7×10^{-7}

Bubble Collision + CBC



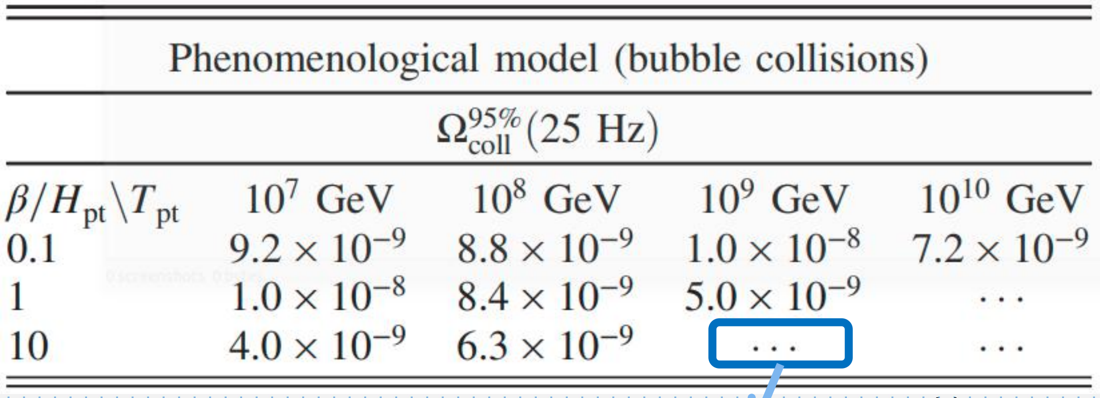
$$\boxed{\log \mathcal{B}^{\rm CBC+coll}_{\rm noise} = -0.74}$$

$v_w = 1$
$\kappa_\phi = 1$

excluded at 95% CL

No Evidence for Bubble Collision Signal

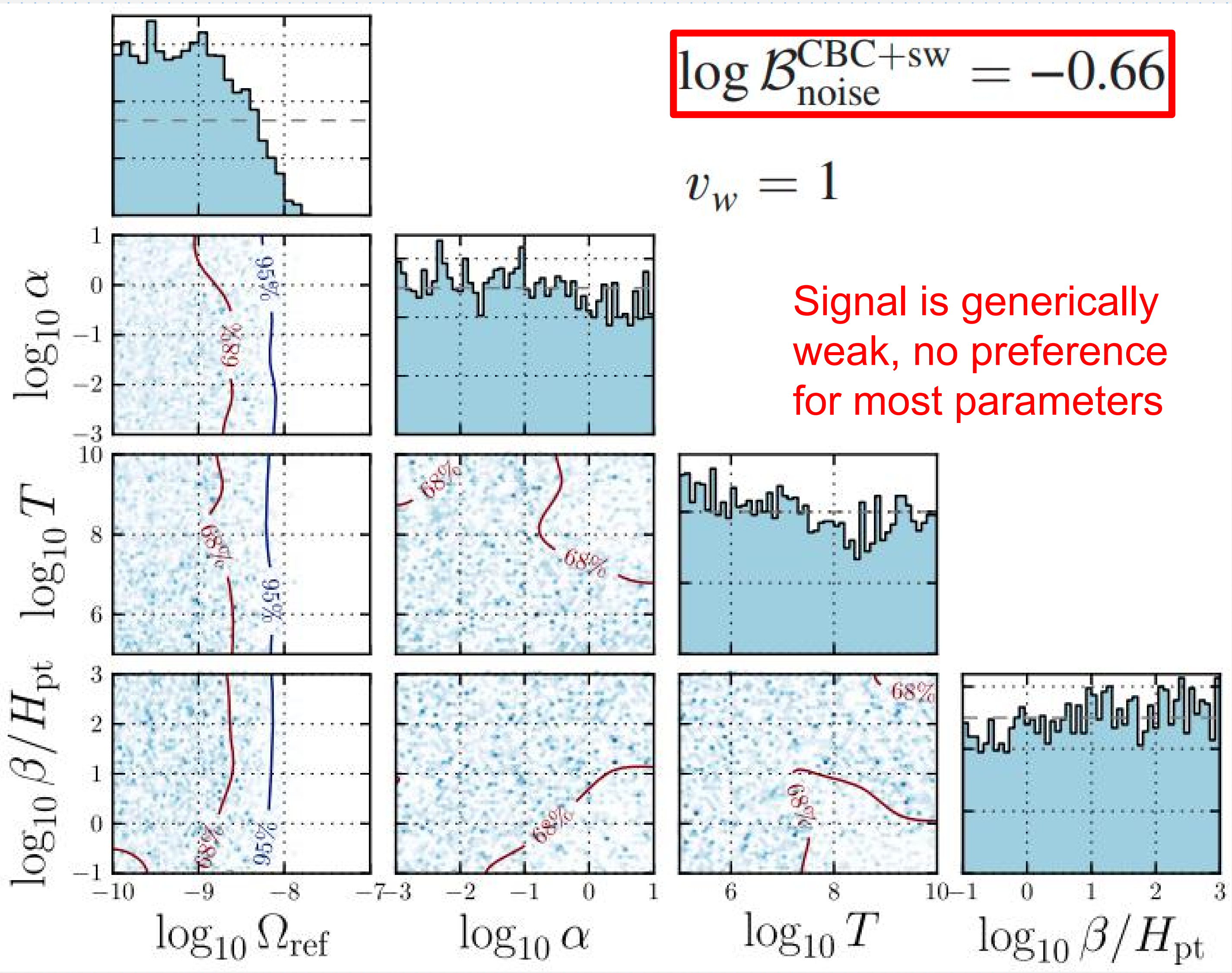
95% CL UL with fixed Tpt and beta/Hpt



Phenomenological model (bubble collisions)				
	$\Omega^{95\%}_{\rm coll}$ (25 Hz)			
$\beta/H_{\rm pt}\backslash T_{\rm pt}$	10^7 GeV	10^8 GeV	10^9 GeV	10^{10} GeV
0.1	9.2×10^{-9}	8.8×10^{-9}	1.0×10^{-8}	7.2×10^{-9}
1	1.0×10^{-8}	8.4×10^{-9}	5.0×10^{-9}	...
10	4.0×10^{-9}	6.3×10^{-9}	...	...

no sensitivity

Sound Waves + CBC



$$\log \mathcal{B}^{\mathrm{CBC+sw}}_{\mathrm{noise}} = -0.66$$

$$v_w = 1$$

Signal is generically weak, no preference for most parameters

No Evidence for Sound Waves Signal

95% CL UL with fixed Tpt and beta/Hpt

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

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

Summary

The first search for GW from cosmological FOPT with LIGO data was performed.

- (Bayesian) analysis with combined O1, O2 and O3 data.
- Searches done for 3 models: broken power law, bubble collisions, sound waves

  In all cases, CBC background are included.
- No evidence for such stochastic GWs
- Upper limits set

We would like to thank Pat Meyers for allowing us to use his code
and Alberto Mariotti for his useful comments.

Summary

Pick your favorite models and check!

The first search for GW from cosmological FOPT with LIGO data was performed.

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Thanks!