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国际理论物理中心-亚太地区

电弱相变引力波的探测

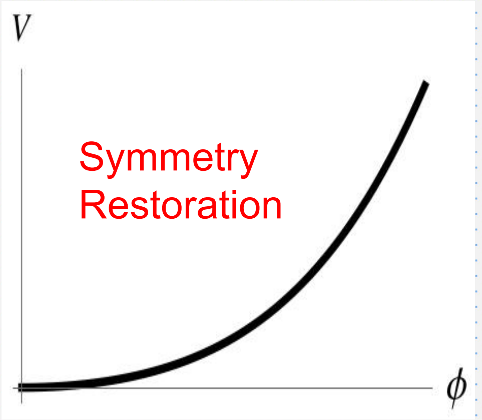
郭怀珂

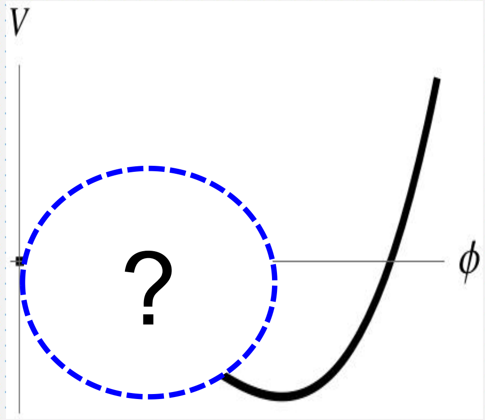
2026年7月16日

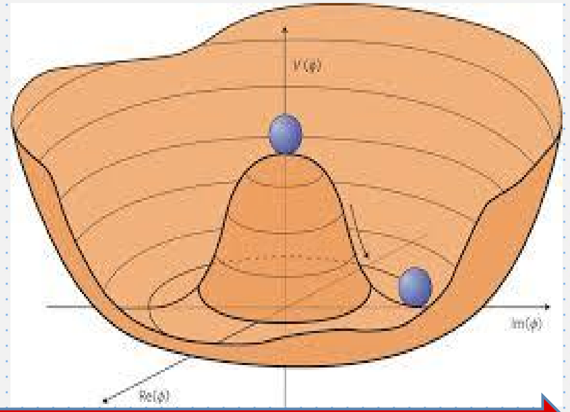
Shuo Guan, HG, Dian Jiao, Qingyuan Liang, Lei Wu, Yang Zhang, PRD [2511.00996]
Qingyuan Liang, Ligong Bian, HG, Yongcheng Wu, PRD [2511.21488]
Qingyuan Liang, Chen Yang, Haipeng An, HG, PRD [2603.21762]

中国物理学会高能物理分会
第十二届全国会员代表大会暨学术年会
高能物理战略研讨会

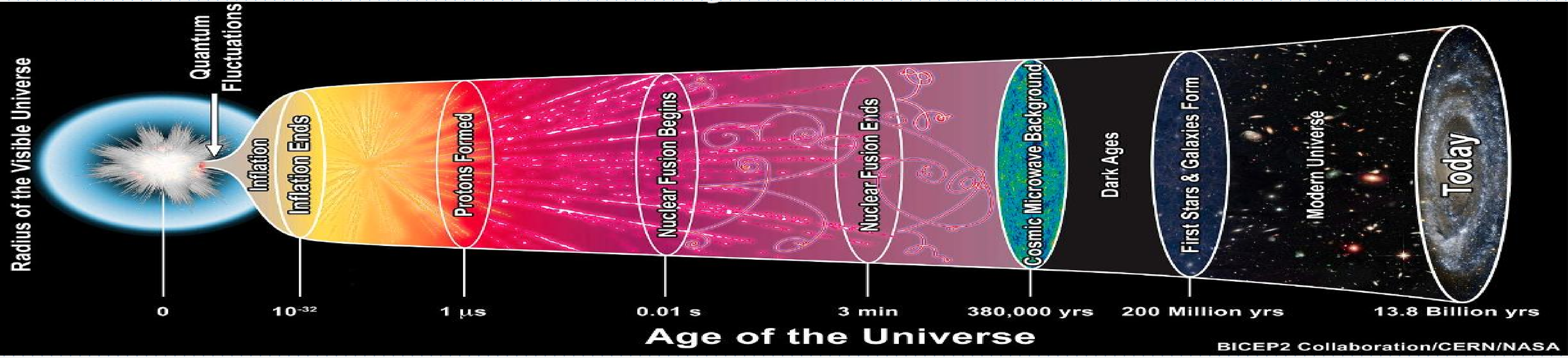
Electroweak Symmetry Breaking



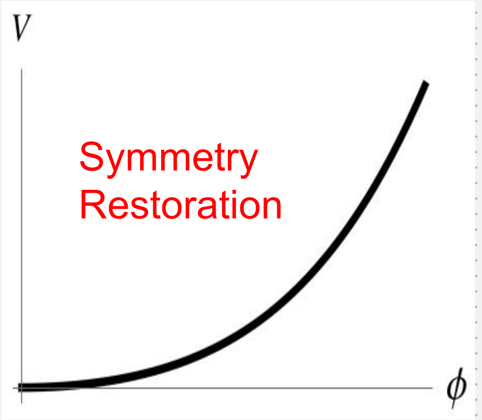


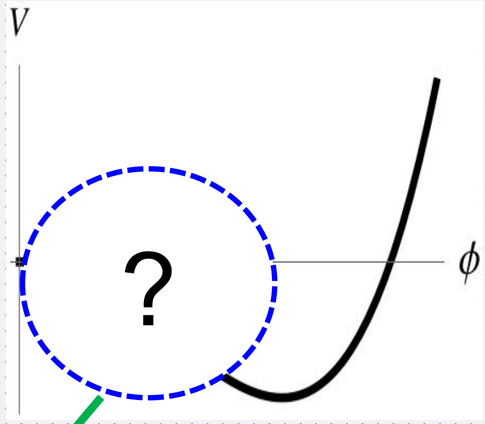


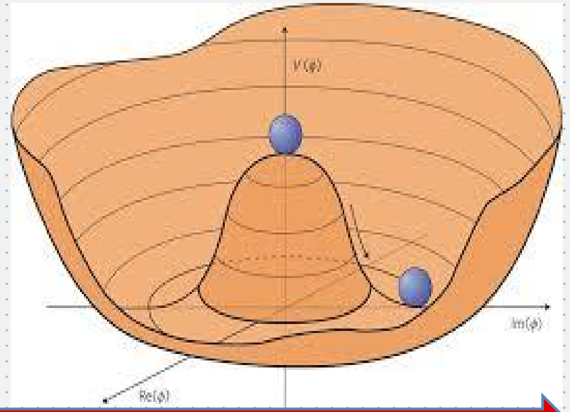
Temperature drops



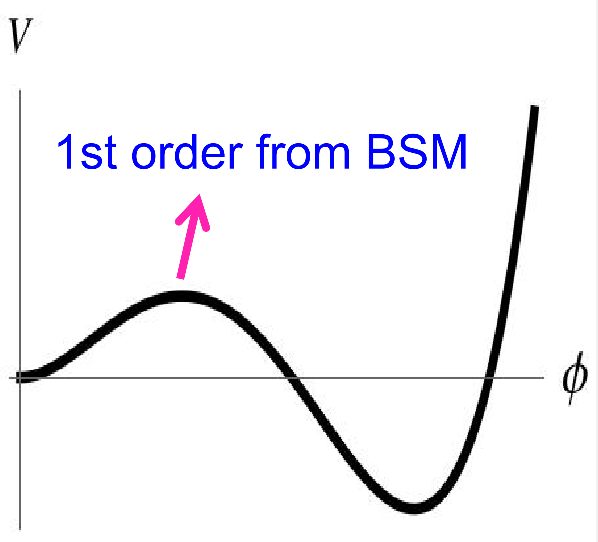
Electroweak Phase Transition

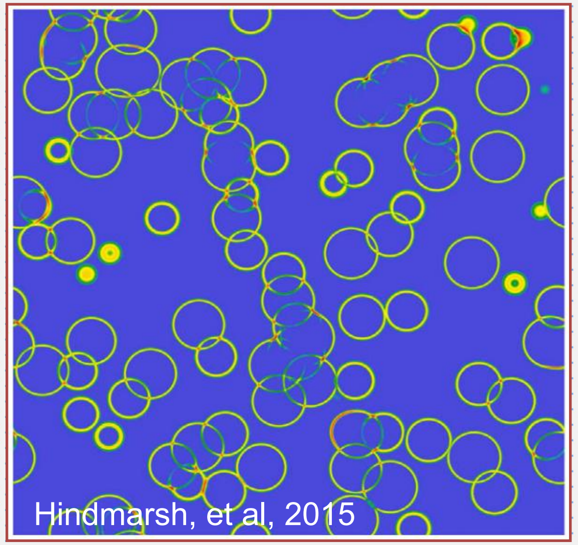






Temperature drops





→ Electroweak Baryogenesis

- Modified Higgs potential (Higgs physics, GW)
- Extra CP-violation (EDM, LHC)
- New particles, symmetries (LHC, GW)

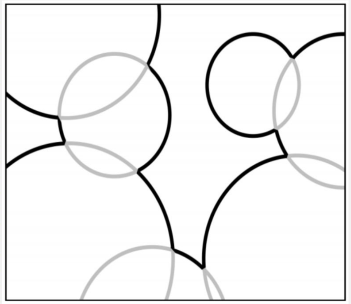
Morrissey, Ramsey-Musolf, NJP [1206.2942]

Gravitational Wave Spectra

Energy density Spectrum

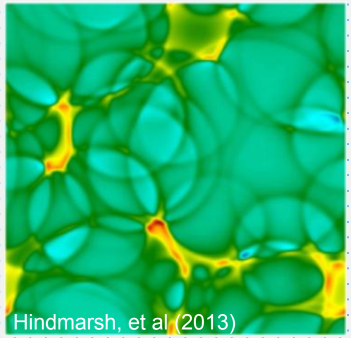
$$\Omega_{\rm GW}(f) = \frac{d\rho_{\rm GW}}{\rho_c d\log f}$$

bubble collision



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

sound waves



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

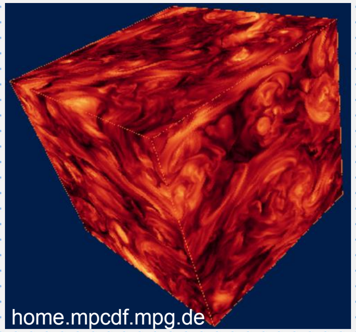
$$\Upsilon = 1-(1+2\tau_{\rm sw}H_{\rm pt})^{-1/2}$$ (RD)

HG, Sinha, Vagie, White, JCAP [2007.08537]

$$\Upsilon = \frac{2[1-y^{3(w-1)/2}]}{3(1-w)}$$

Yang Xiao, HG, Jia-Hang Hu, Jin Min Yang, Yang Zhang, PRD Letter [2410.23666]

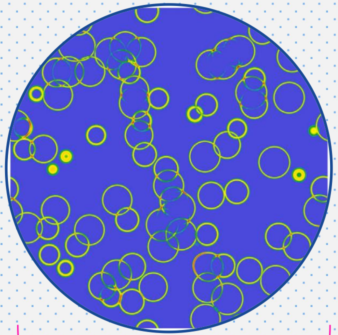
MHD



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

Chiara Caprini et al JCAP [1512.06239]

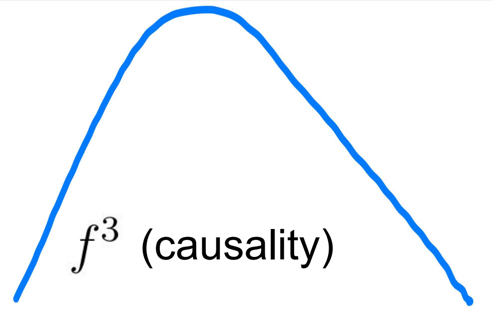
Detectors



Hubble size: 1/H*

$$f_{\rm now} = 1.65 \times 10^{-5} \left(\frac{f_{\rm PT}}{\beta}\right)\left(\frac{\beta}{H_*}\right)\left(\frac{T_*}{100{\rm GeV}}\right)\left(\frac{g_*}{100}\right)^{1/6} {\rm Hz}$$

~100-1000



Cai, Pi, Sasaki, PRD [1909.13728]

nHz (~100MeV) QCD scale

EPTA

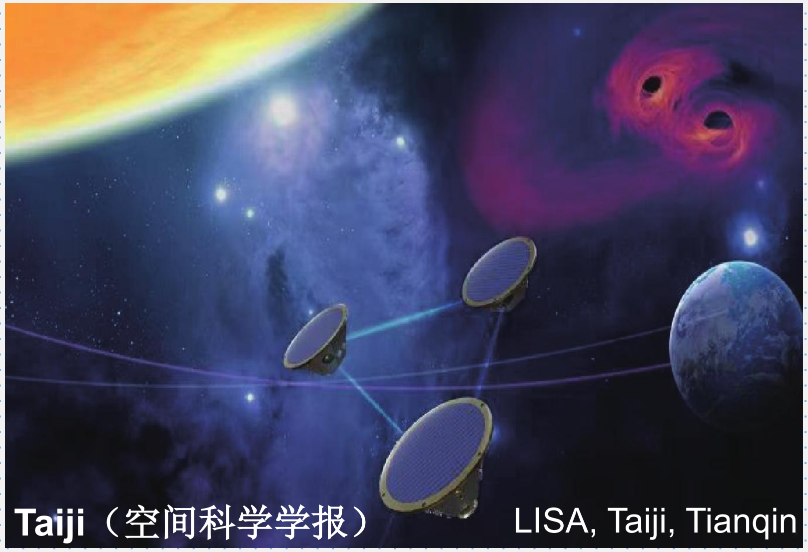
NANOGrav Physics Frontiers Center

PPTA

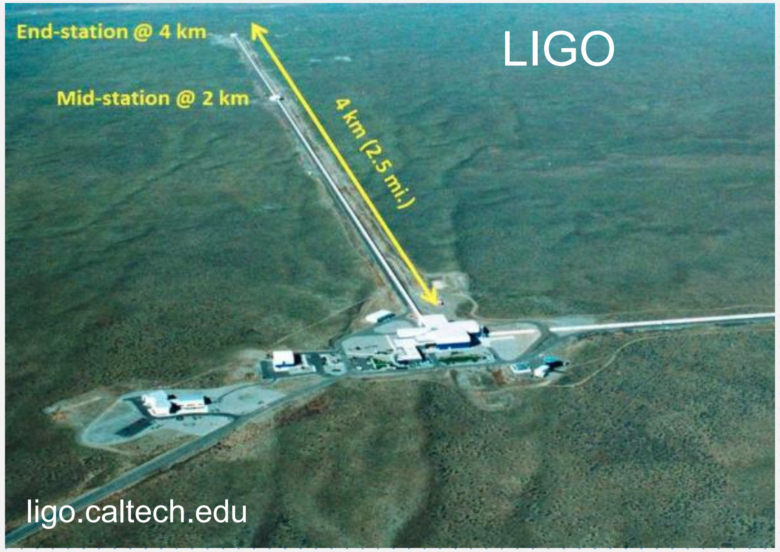
InPTA Indian Pulsar Timing Array

中国脉冲星测时阵列（CPTA）

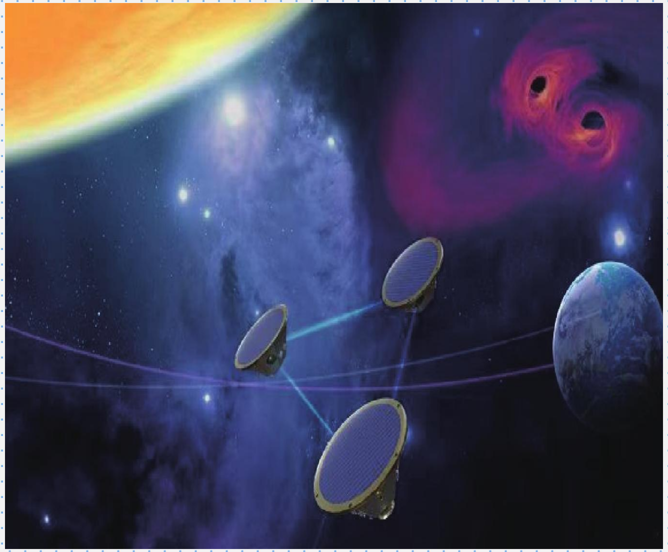
~mHz : (~100GeV) weak scale



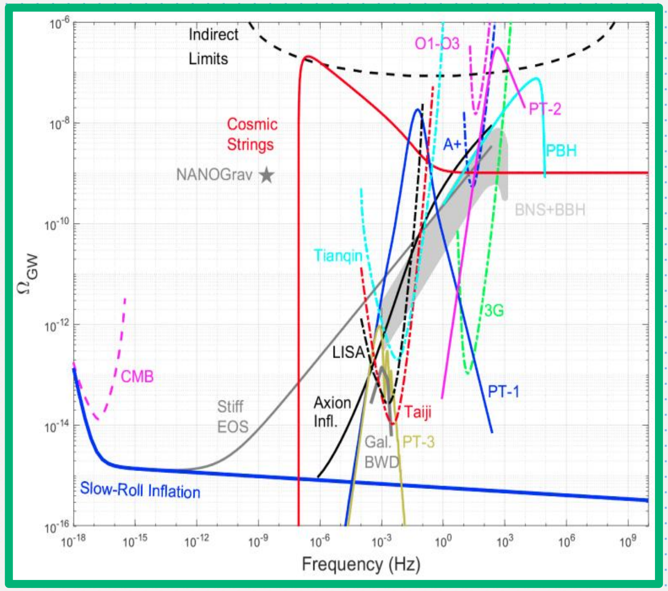
~100Hz (~PeV - EeV) high scale



Detection



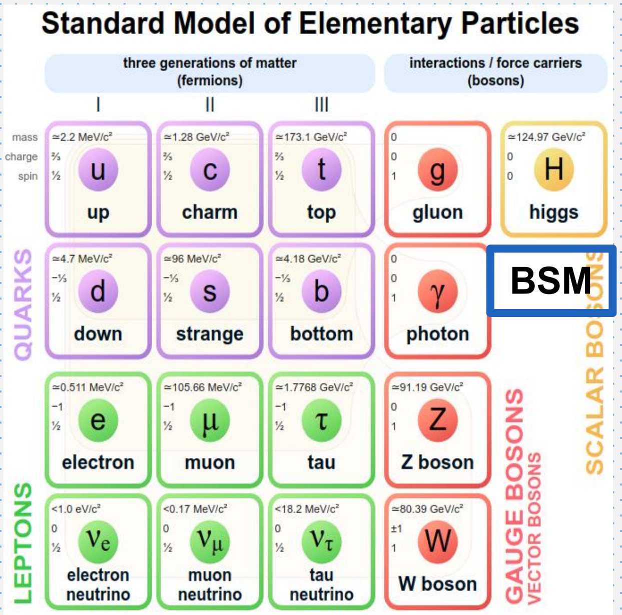
LIGO, LISA/Taiji/Tianqin, PTA, ...



Gravitational Wave Spectrum

α
β
v_w
T_*
g_s
...

Phase Transition Parameters

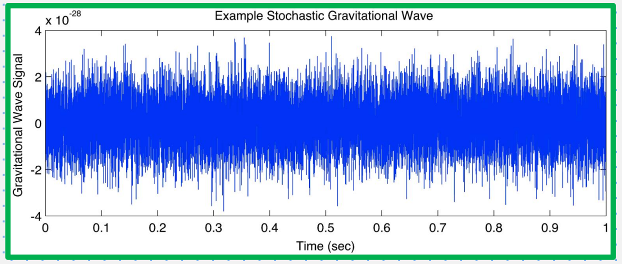


Particle Physics Model

Goal: probing the existence of BSM physics with Taiji, etc. (currently simulated data)

Detector Response and Simulation

For both ground and space based detectors:



$$\langle \tilde{n}_I^*(f)\tilde{n}_J(f')\rangle = \frac{1}{2}\delta(f-f')\delta_{IJ}P_I(f)$$

Power spectral density

$$S_h(f) = \frac{3H_0^2}{4\pi^2}\frac{\Omega_{\rm GW}(f)}{f^3}$$

Fourier component
(draw from the Gaussian distribution)

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

GW amplitude
(from all directions and frequencies)

$$h_{ij}(t,\mathbf{x}) = \sum_{A=+,\times}\int_{-\infty}^{\infty}df\int_{S^2}d^2\hat{\mathbf{n}}\;\tilde{h}_A(f,\hat{\mathbf{n}})\,e_{ij}^A(\hat{\mathbf{n}})e^{-2\pi i f(t-\hat{\mathbf{n}}\cdot\mathbf{x}/c)}$$

$F_I^A(\hat{\mathbf{n}}) = d_I^{ij}e_{ij}^A(\hat{\mathbf{n}})$ response captured in the tensor d

Detector (channel) output (time series)

$$h_I(t) = \sum_A\int df\int d^2\hat{\mathbf{n}}\;\tilde{h}_A(f,\hat{\mathbf{n}})F_I^A(\hat{\mathbf{n}})e^{-2\pi i f(t-\hat{\mathbf{n}}\cdot\mathbf{x}_I/c)}$$

Detector (channel) output with noise

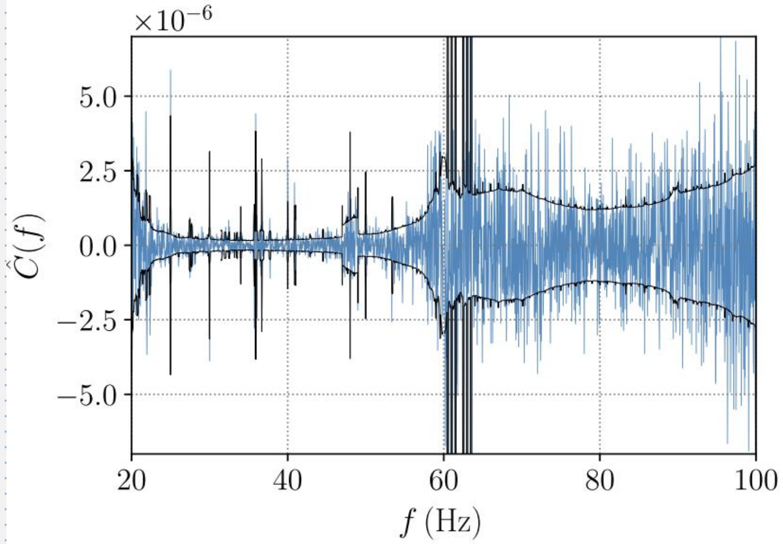
$$s_I(t) = h_I(t) + n_I(t)$$

Detection at LIGO-Virgo-KAGRA

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

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

- Glitches and gating
- Narrow spectral artifacts
- Non-Gaussian noise
- Magnetic noise
- Calibration uncertainty



LVK collaborations, PRD [2101.12130]

PT searches:

Cosmological and HEP implications [2510.26848]
Romero, ..., HG, ..., PRL [2102.01714]

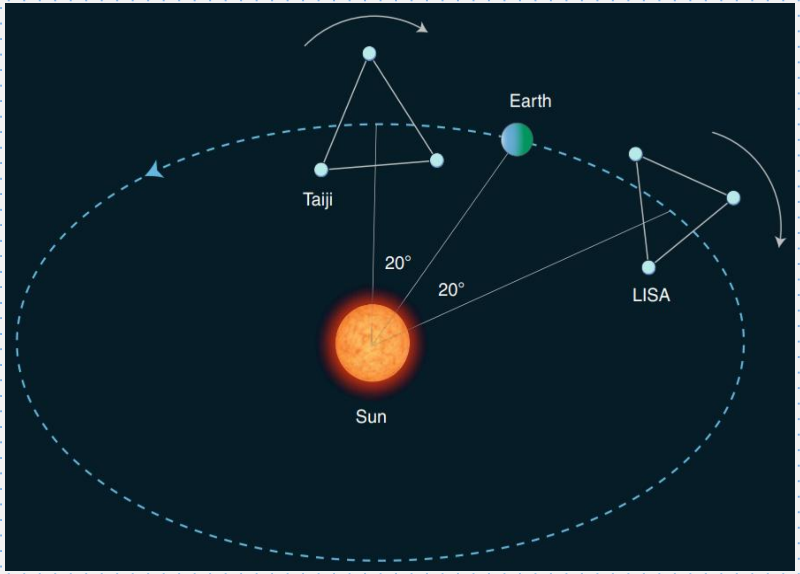
Detection in Space

Stochastic GW detection in space:

- Complicated, and correlated noise (for channels in one detector)
- Complications from time-delay interferometry

  (to cancel dominant noise from laser freq fluctuation)
- Solution: null channel method, or with a detector network

Here: with a single detector (null channel method).



Ruan, Liu, Guo, Wu, Cai, Nature Astron [2002.03603]

Studies on PT detection in space:

Gowling, Hindmarsh, Hooper, Torrado, JCAP [2209.13551]
Gowling, Hindmarsh, JCAP [2106.05984]
Boileau, et al, JCAP [2209.13277]
Huang, Bi, Cao, Huang, CPC [2309.14045]
Lewicki, et al, PRD [2403.03769]
Caprini, et al, JCAP [2403.03723]

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

Boileau et al, MNRAS [2105.04283]

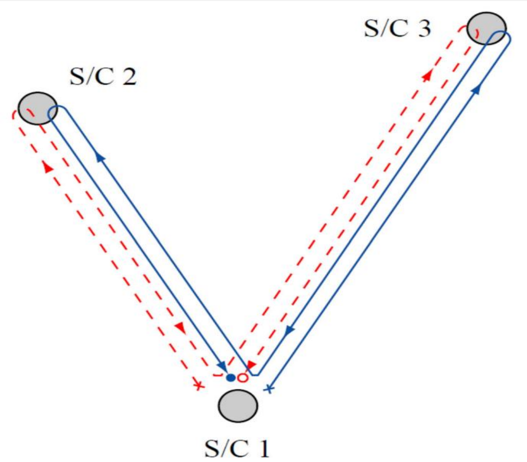
Simulation

Simulation in freq domain

(random number generation)

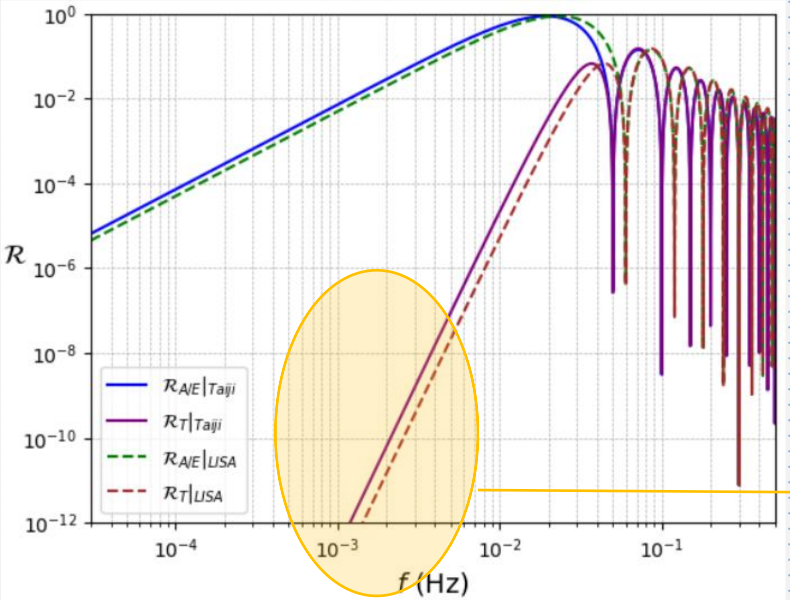
$$\langle \tilde{d}_a(f)\tilde{d}_b^\star(f')\rangle = \frac{1}{2}P_a(f)\delta_{ab}\delta(f-f')$$

$$P_a(f) = \frac{3H_0^2}{4\pi^2}\frac{\Omega_{\rm GW}}{f^3}R_a(f) + N_a(f)$$



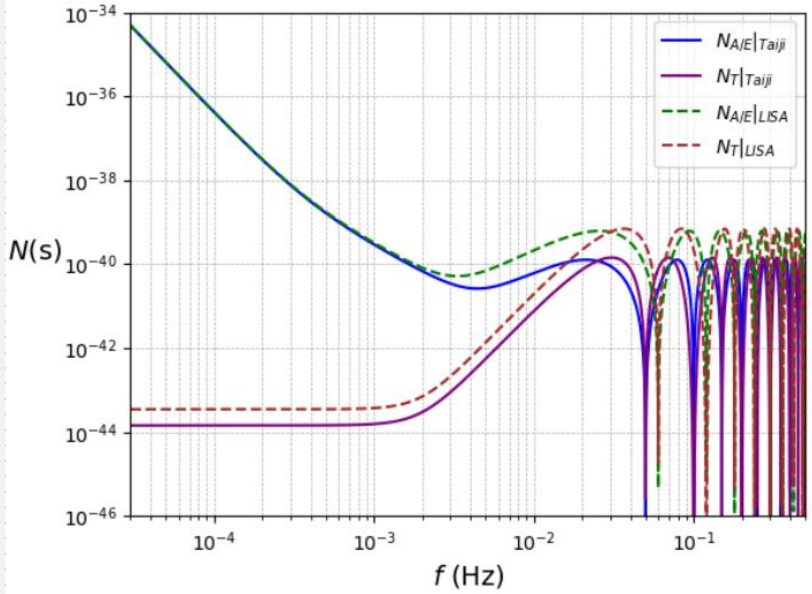
3 TDI channels of data (A, E,T)
Tinto, Dhurandhar, LRR, 2021

Response functions

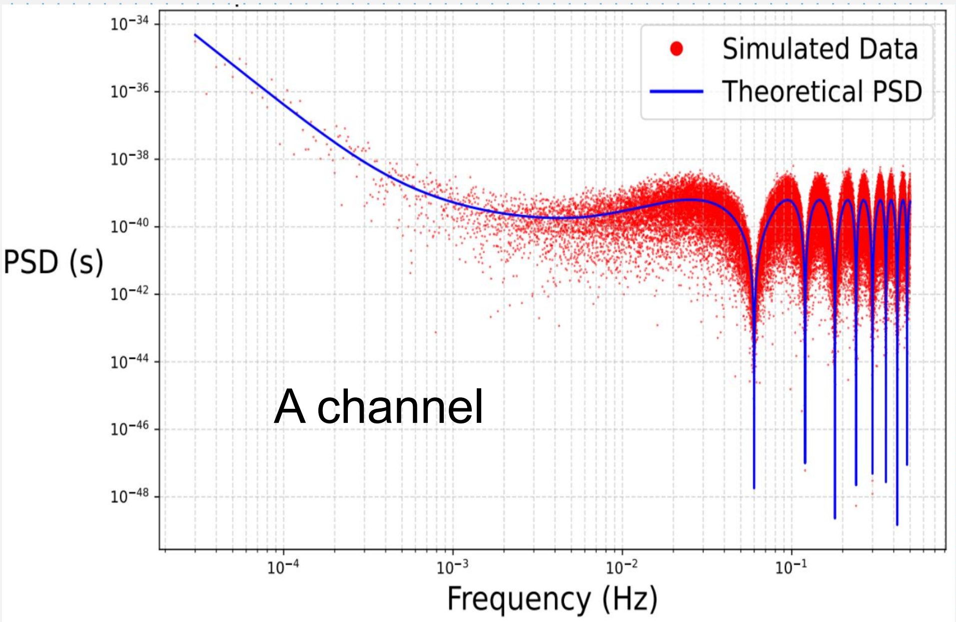


no response, null channel, to monitor noise

Noise spectra



Likelihood



The core of the statistical analysis: likelihood

both signal and noise behave as random variables

Add prior to get posterior, and do Bayesian analysis

$$\mathcal{L} = \prod_{\kappa=1}^{N_0} \prod_{k=1}^{N/2} \frac{1}{8\pi^3 \sigma_A^2 \sigma_E^2 \sigma_T^2} \exp\left[- \sum_{a=A,E,T} \frac{\left| \tilde{d}_a^\kappa(f_k) \right|^2}{2\sigma_a^2} \right]$$

$N_0 = 126$: number of segments

$N = 10^6$: frequency bins in one segment

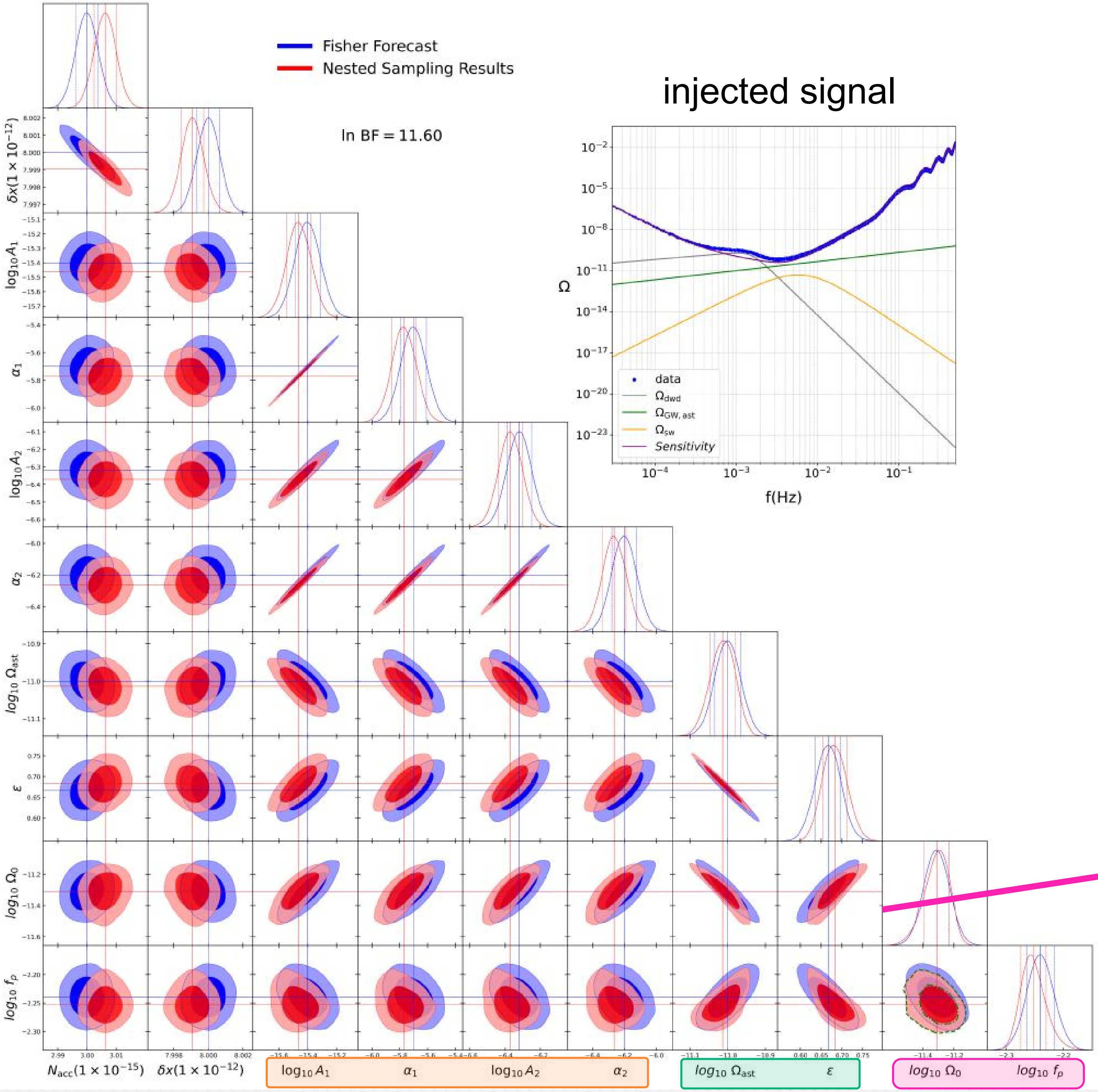
$T = 1.26 \times 10^8\,\mathrm{s}$: observation time

$f_s = 1\,\mathrm{Hz}$: sampling frequency

$$\sigma_a^2 = \frac{T f_s^2}{4} \left[\frac{3H_0^2}{4\pi^2} \frac{\Omega_{\mathrm{GW}}}{f^3} R_a(f) + N_a(f) \right]$$

2 noise parameters: dx, Nacc

astrophysical background (extra-galactic BBH, BNS)
astrophysical foreground (double white dwarf)
cosmological background (PT)

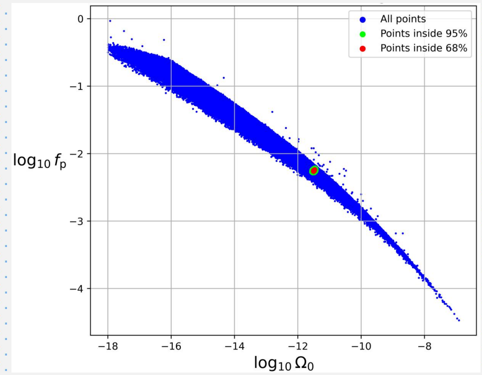


SW spectrum with no parameter degeneracy

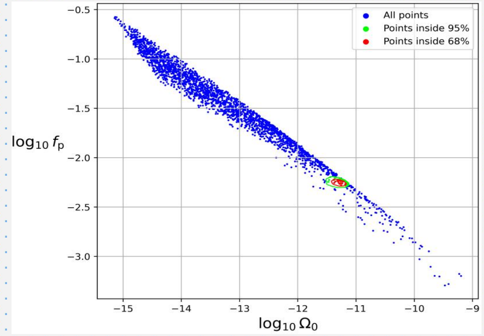
$$\Omega_{sw}(f) = \Omega_0 \left(\frac{f}{f_p}\right)^3 \left(\frac{7}{4+3\,(f/f_p)^2}\right)^{7/2}$$

$$\Omega_{astro}(f) = \Omega_{ast} \left(\frac{f}{f_{ref}}\right)^{\varepsilon}$$

$$\Omega_{dwd}(f) = \frac{A_1\,(f/f_*)^{\alpha_1}}{1 + A_2\,(f/f_*)^{\alpha_2}}$$



xSM (SM + singlet)

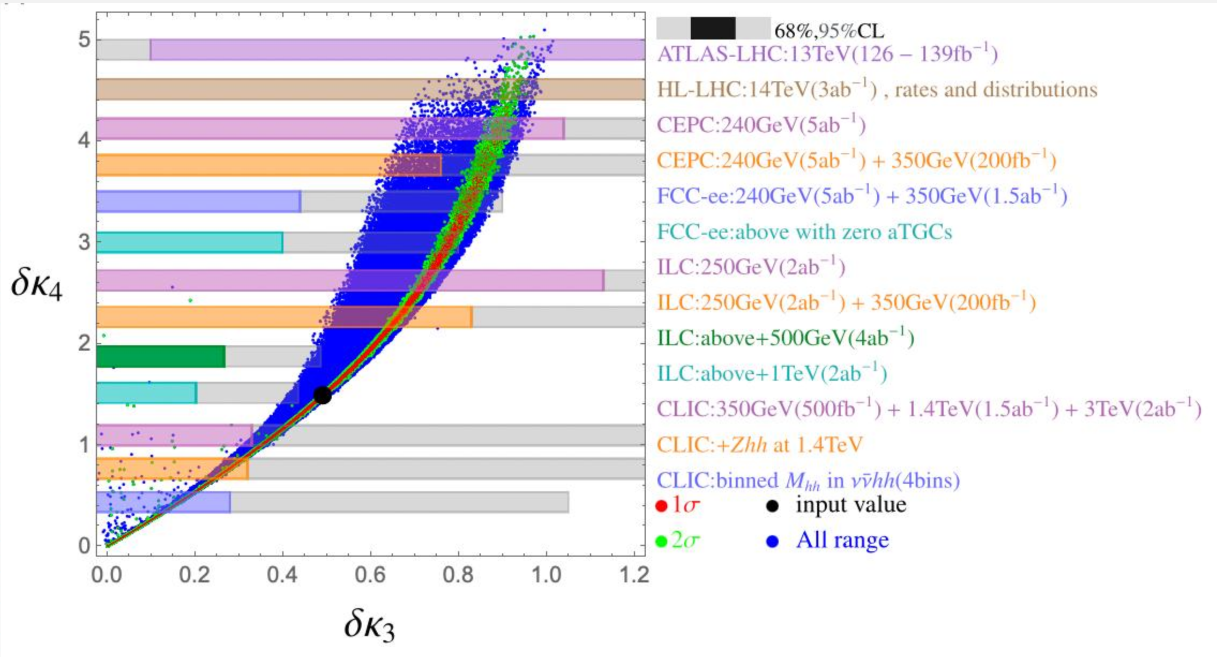


CxSM (SM + complex singlet)

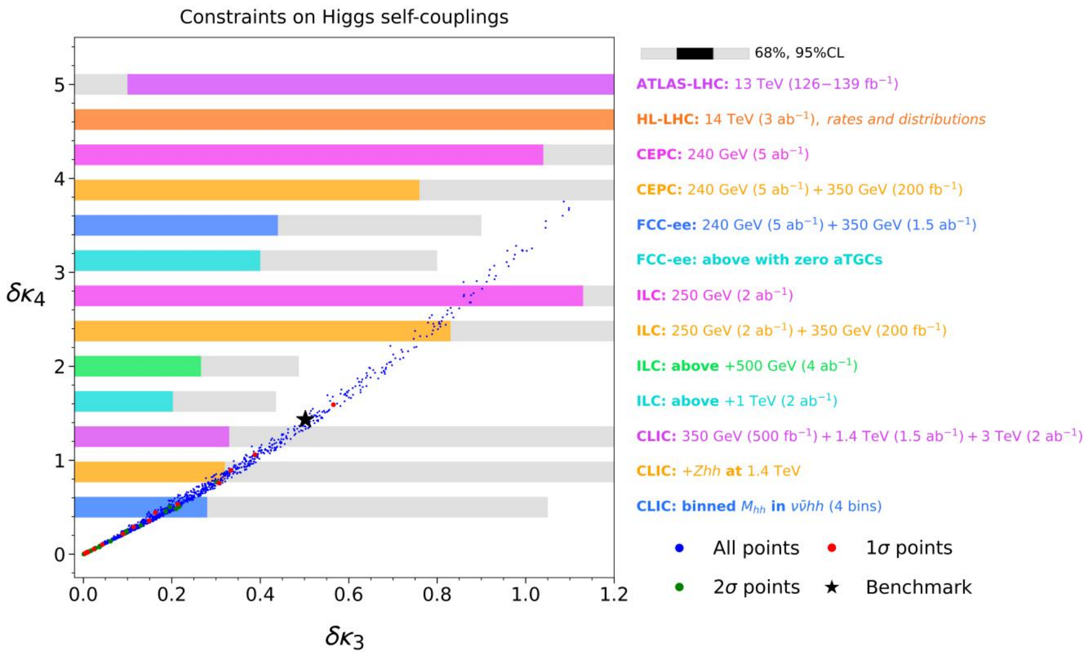
Higgs Self-Couplings

- Translate spectral measurement to model parameters
- Constrain Higgs self-couplings, etc

xSM (SM + singlet)



CxSM (SM + complex singlet)



GW measurement can constrain both cubic and quartic couplings.

Summary

- ❑ Demonstrated a pipeline of measuring EWPT and making predictions for Taiji
- ❑ Taiji is able to probe Higgs self-couplings, and other observables
- ❑ Future directions: time-domain simulation (to appear), more realistic noises, ...

Thanks!