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Phase Transition and Real Data

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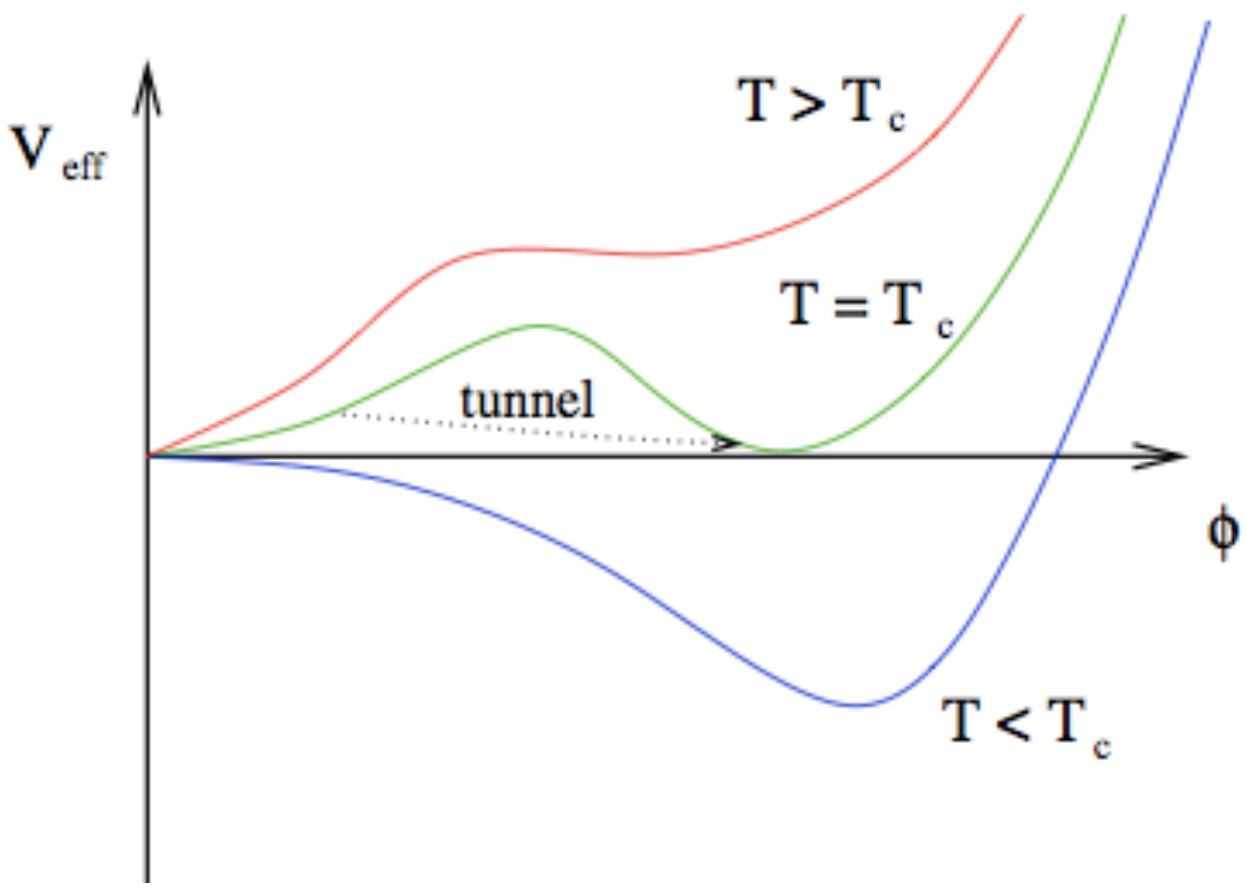
Outline

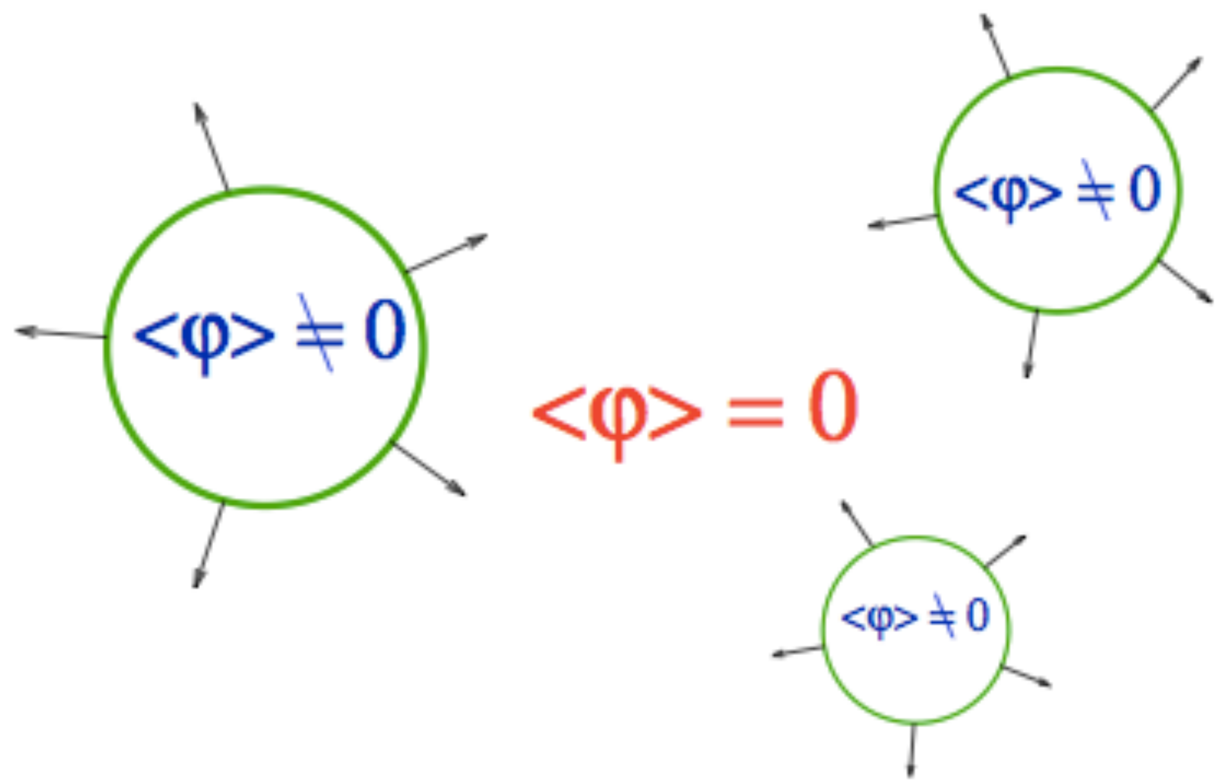
- General issue of PT and GW
- High scale PT and LIGO。
- Low scale PT and PTA。
- Some comments

General issue of PT and GW

Strong 1st PT

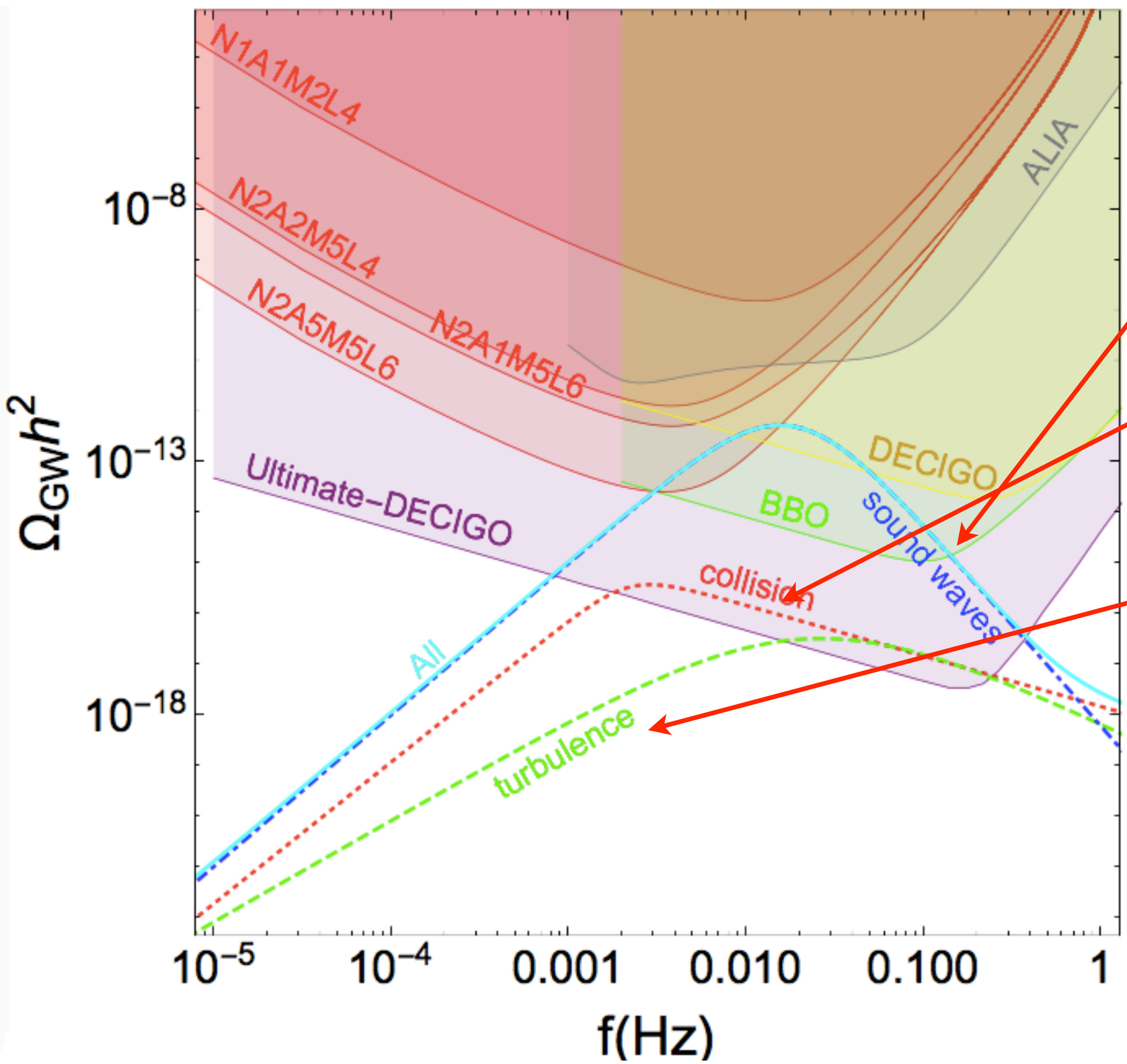


Phase transition during the cooling of the universe



Bubble nucleation during the 1st order PT.

Strong 1st PT



sound wave

None-run away potential

bubble collision

turbulence

W. Chao, H. K. Guo, J. Shu., JCAP, 1709 (2017) 09, 009

vacuum energy,
How"strong" is the 1st order PT?

$$h^2\Omega_{\rm env}(f) = 1.67\times10^{-5}\left(\frac{H_*}{\beta}\right)^2\left(\frac{\kappa\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{\frac{1}{3}}\left(\frac{0.11\,v_w^3}{0.42+v_w^2}\right)S_{\rm env}(f)\,,$$

$$\alpha = \frac{\rho_{\rm vac}}{\rho^*_{\rm rad}}\,,$$

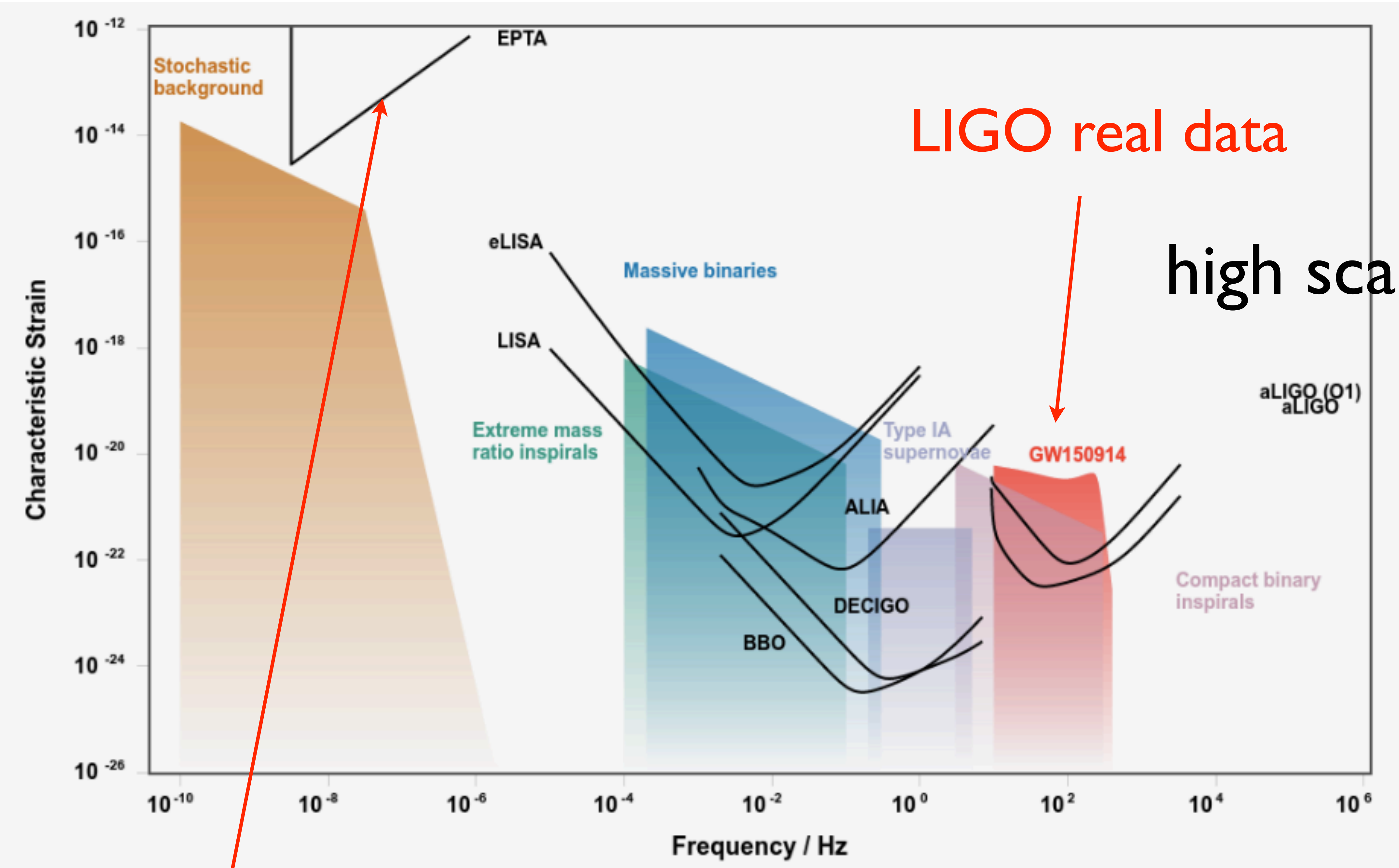
$$h^2\Omega_{\rm sw}(f) = 2.65\times10^{-6}\left(\frac{H_*}{\beta}\right)\left(\frac{\kappa_v\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{\frac{1}{3}}v_w\,S_{\rm sw}(f)\,,$$

Phase transition speed

$$\frac{\beta}{H_*} = T_*\left.\frac{dS}{dT}\right|_{T_*}$$

$$h^2\Omega_{\rm turb}(f) = 3.35\times10^{-4}\left(\frac{H_*}{\beta}\right)\left(\frac{\kappa_{\rm turb}\,\alpha}{1+\alpha}\right)^{\frac{3}{2}}\left(\frac{100}{g_*}\right)^{1/3}v_w\,S_{\rm turb}(f)\,,$$

Strong 1st PT



LIGO real data

high scale PT

low scale PT

Very roughly speaking

PTA real data

peak frequency scales with temperature

Strong 1st PT

Plank scale

GUT, Leptogenesis scale

LIGO

TeV scale

All possible spontaneous symmetry breaking corresponds to the cosmic phase transition

EW scale

sub-GeV scale

PTA

High scale PT and LIGO

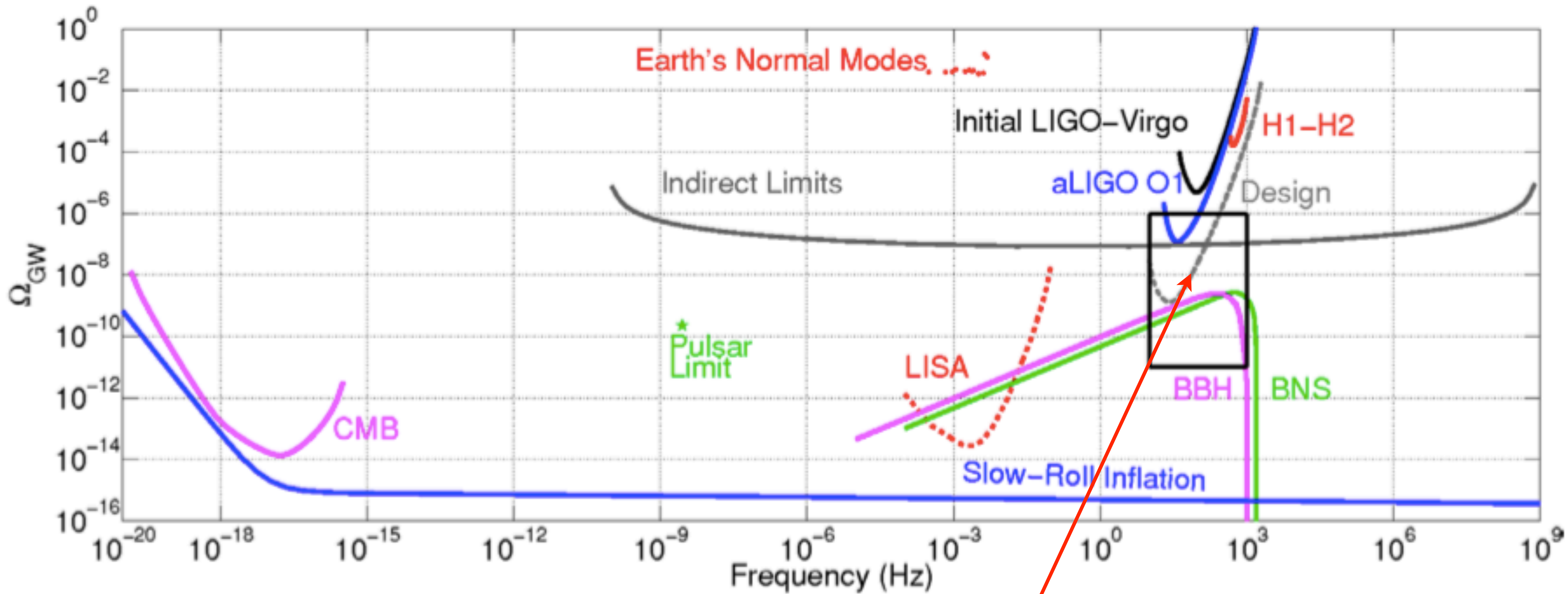
Motivation for the high scale PT

Typically the PT that LIGO is good to detect is at the PeV scale!

Some gauge extension of SM?

High scale SUSY?

Current LIGO SGWB search



Nelson Christensen 2019 *Rep. Prog. Phys.* **82** 016903

Design is roughly the O5

O1 not better than the

indirect limits from the cosmic microwave background (CMB) and Big-Bang nucleosynthesis

We can imagine O2 (open-released) & O3 (not yet) in between can probe some high-scale PT parameter space

Analysis of LIGO (SGWB)

What is the SGWB?

typically the gravitational radiation produced by an extremely large number of weak, independent, and unresolved gravitational wave sources.

No real shape, looks like noise

define background energy density spectra

$$\Omega_{\mathrm{GW}}(f) = \frac{f}{\rho_c}\frac{d\rho_{\mathrm{GW}}}{df},$$

dimensionless

energy density of GW contained in the range $(f, f + df)$

critical energy density to close the Universe

•For the LIGO and Virgo frequency bands, most theoretical models of stochastic background are characterized as a power law spectrum,

$$\Omega_{\mathrm{GW}}(f) = \Omega_\alpha \left(\frac{f}{f_{\mathrm{ref}}}\right)^\alpha$$

$\alpha = 0$ (cosmologically motivated) and

$\alpha = 3$ (astrophysically motivated)

$\alpha = 2/3$ (for compact binary coalescence)

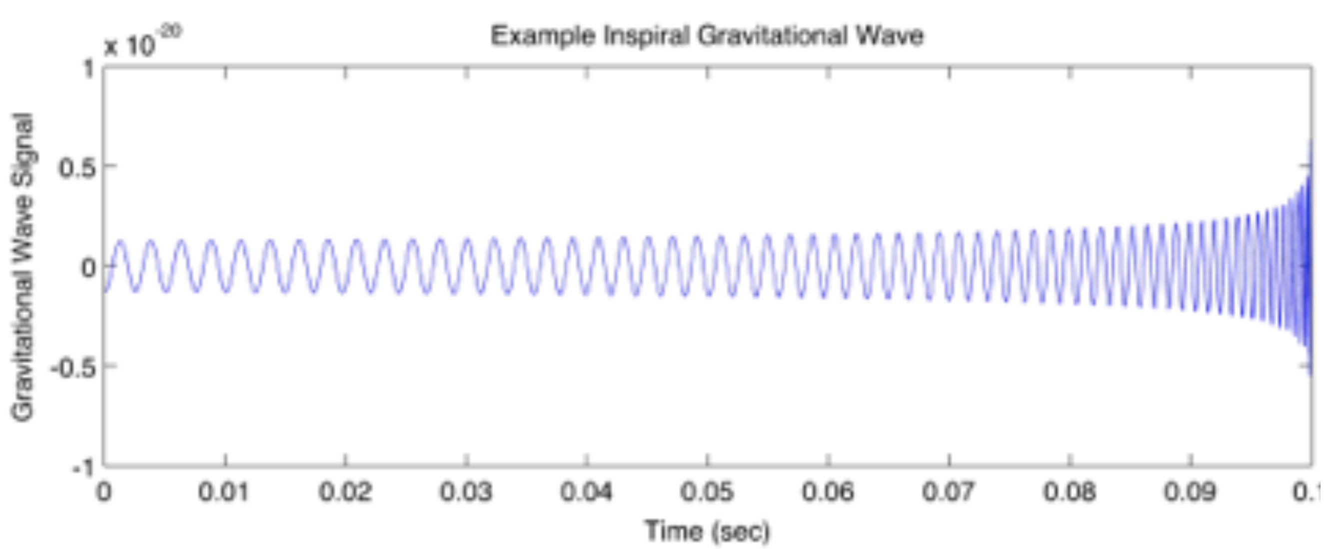
an arbitrary reference freq.

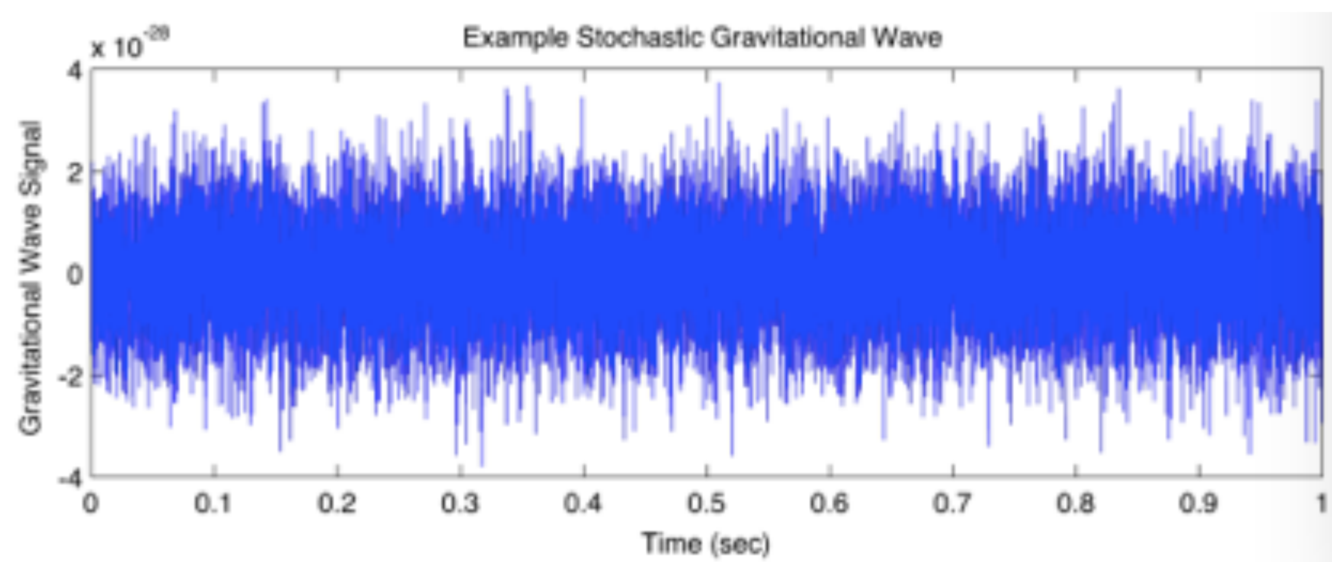
a constant characterizing the amplitude of SGWB in a given frequency band

Analysis of LIGO (SGWB)

Comparison between inspiral GW & SGWB

	Inspiral GW	Stochastic GW
Waveform	Well-predicted	Totally random
Direction	From specific location	From all directions
Search method	Template search in time domain	Cross correlation from two detector signals in frequency domain





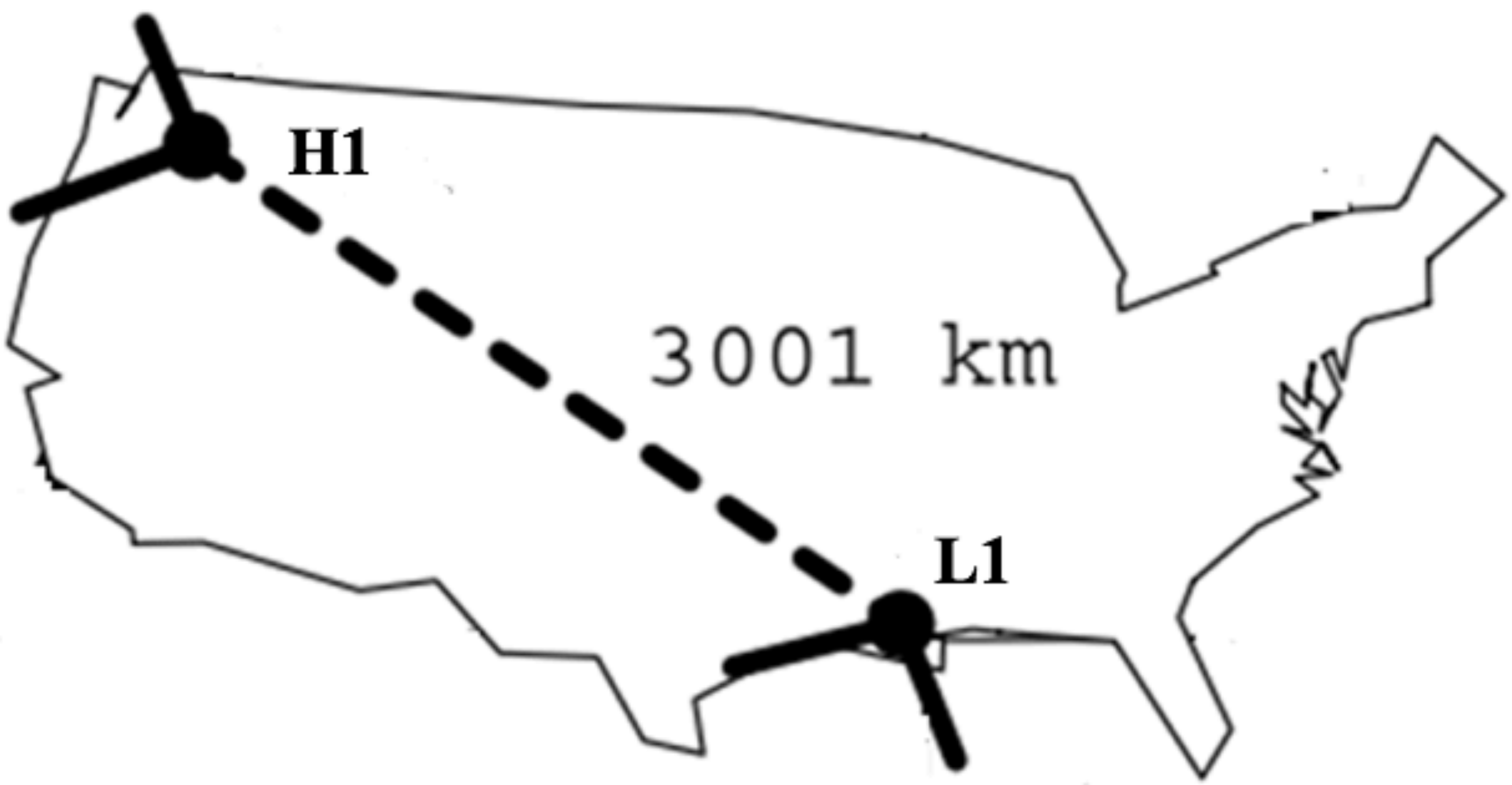
No real shape, looks like noise

Analysis of LIGO (SGWB)

How to detect the SGWB?

Looking for the correlation of the TWO (far away?) detector!

LIGO detector configuration



H1 in Hanford, L1 in Livingston.

Stable correlated signal from the SGWBs

No stable noise from the far away detector.

Detection of SGWB

- Estimator for Ω_α:

$$S = \int_{-\infty}^{\infty} df \int_{-\infty}^{\infty} df' \, \delta_T(f - f') \, \tilde{s}_1^*(f)\tilde{s}_2(f') \, \tilde{Q}(f')$$

- $\delta_T(f - f')$: finite-time approximation to delta function
- $\tilde{s}_1^*(f)\tilde{s}_2(f')$: measurement from two detectors
- $\tilde{Q}(f')$: filter function, to optimize the signal-to-noise ratio

$$\tilde{Q}(f) = \lambda \frac{\gamma(|f|)\Omega_{gw}(|f|)}{|f|^3 P_1(|f|)P_2(|f|)}$$

- $\gamma(|f|)$: overlap reduction function
- $P_1(|f|)$, $P_2(|f|)$: one-sided power spectrum density of detector
- λ: normalization constant, to make $\langle S \rangle = \Omega_\alpha$

$$\langle \tilde{n}_i^*(f)\tilde{n}_i(f')\rangle = \frac{1}{2}\delta(f - f') \; P_i(|f|)$$

Once we know the frequency dependency of stochastic background $\Omega_{gw}(f)$, $\tilde{Q}(f)$ will be also determined.

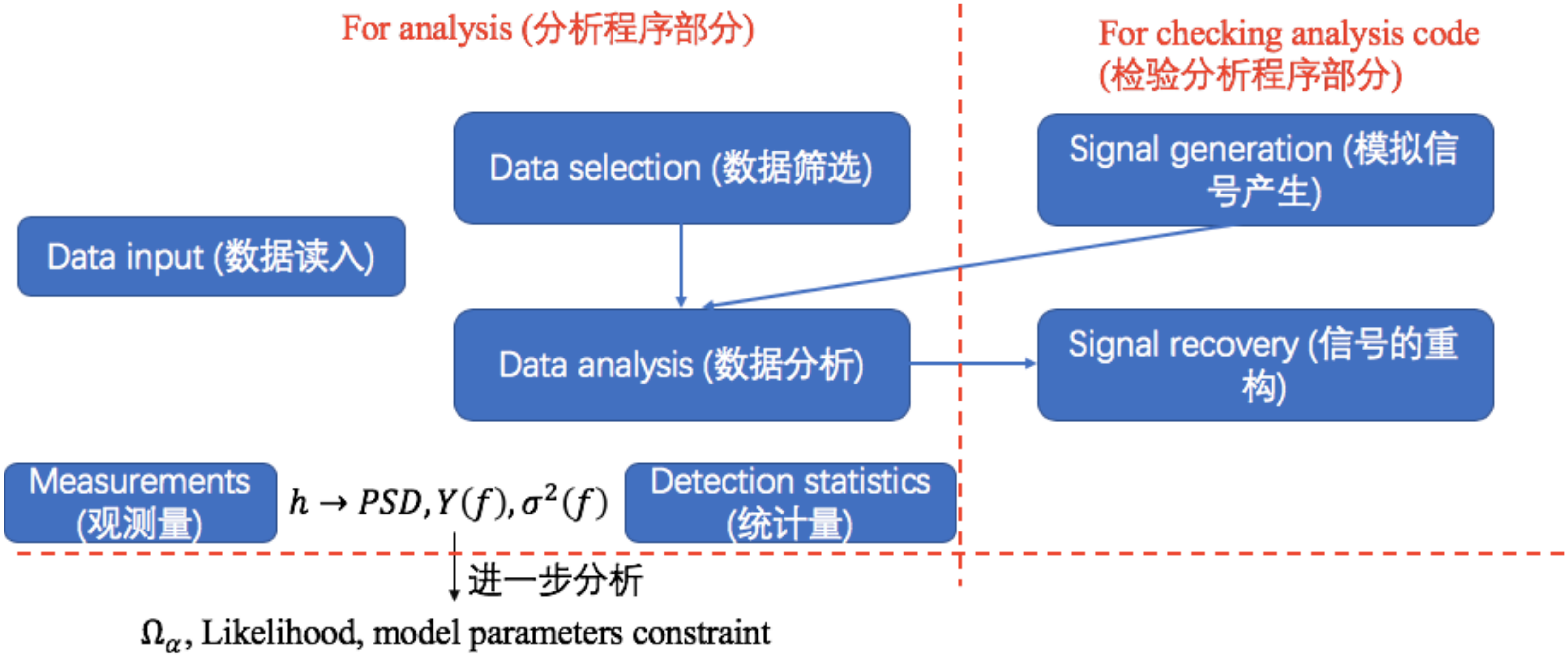
We can optimize it for PT

Detection statistics

- Expectation value:
- $\mu := \langle S \rangle = \frac{3H_0^2}{20\pi^2} T \int_{-\infty}^{\infty} df\, |f|^{-3} \Omega_{\text{gw}}(|f|)\gamma(|f|)\tilde{Q}(f)$
- Variance:
- $\sigma^2 := \langle S^2 \rangle - \langle S \rangle^2 \approx \langle S^2 \rangle \approx \frac{T}{4} \int_{-\infty}^{\infty} df\, P_1(|f|) P_2(|f|) \left|\tilde{Q}(f)\right|^2$
- Signal-to-noise ratio:
- $\text{SNR} := \frac{\mu}{\sigma}$
- Usually, set SNR = 2, to determine upper limit of Ω_{gw}.

Detection pipeline

- The composition of the pipeline, including five modules:



Low scale PT and PTA

Low scale PT for PTA

Typically the PT that PTA is good to detect is at the sub-GeV scale!

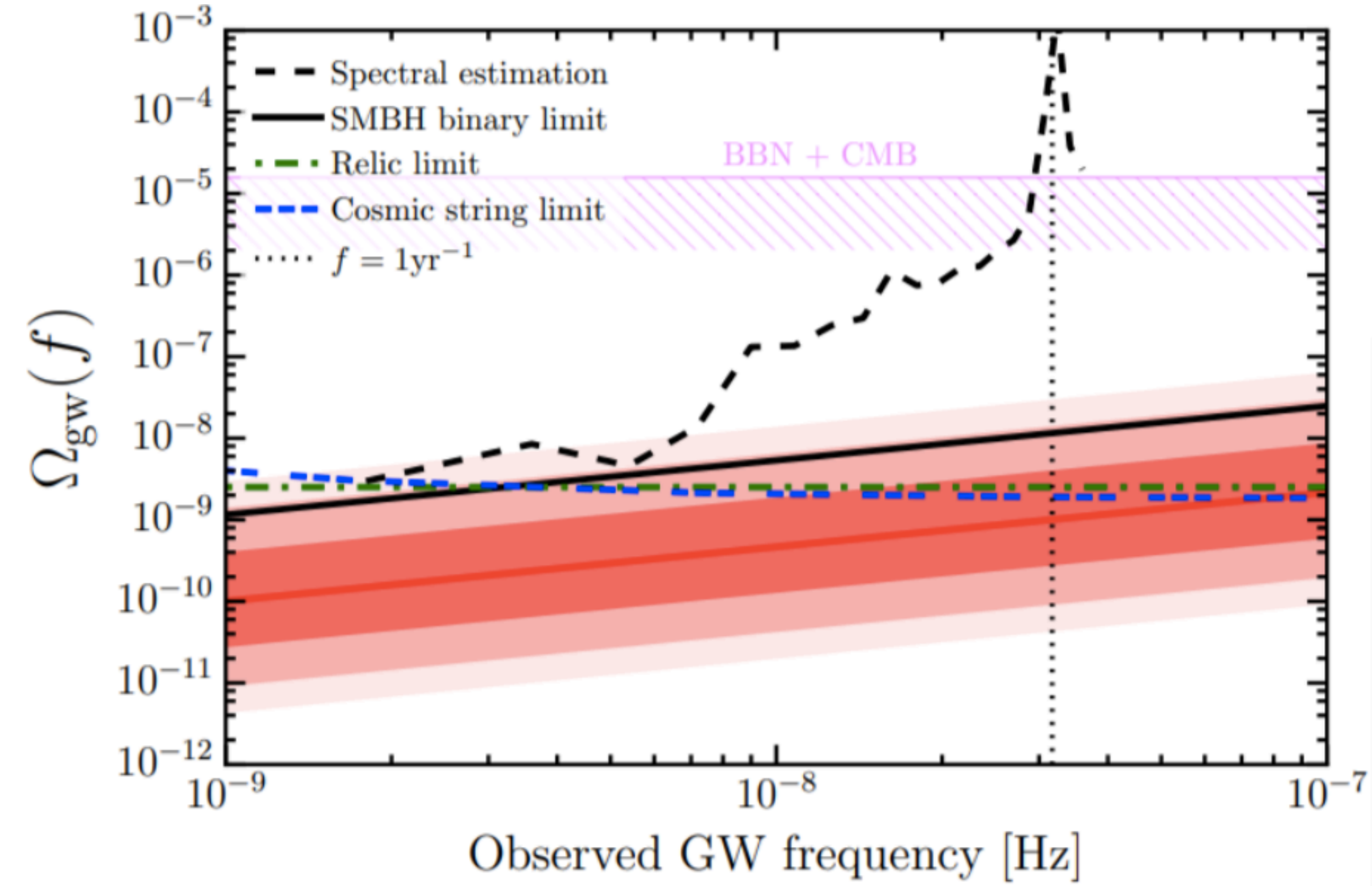
Some hidden DM model?

Hidden models of mirror QCD?

PTA data from PPTA collaboration

We use the raw data from the PPTA collaboration

The Australian 64 meter Parkes telescope



EPTA-2015
1504.03692

The only last open release constrain on SGWB is from EPTA 2015, quite long time ago

Statistical correlation

We use the raw data from the PPTA collaboration

The energy density of the stochastic gravitational wave background, $\Omega_{gw}h^2$, has a relation with the the one-sided power spectral density $S(f)$:

$$S(f) = \frac{1}{12\pi^2}\frac{1}{f^5}\frac{3H_{100}^2}{2\pi^2}\Omega_{gw}h^2$$

Where,

$$H_{100} = 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

statistical correlation between the time-residuals

$$\langle \delta t_i^I \, \delta t_j^J \rangle = \int_{f_L} \mathrm{d}f \, S(f) \, \Gamma^{IJ}(\theta_{IJ}) \, \cos\left(2\pi f(t_i - t_j)\right)$$

- where t_i and t_j are pulse arrival times,
- I and I denotes different pulsars
- $\Gamma_{IJ}(\theta^{IJ})$ is known as the Hellings & Downs curve and θ^{IJ} is the angle between two pulsars

The time interval for the correlation between different time-residuals are roughly weeks or months.

Statistical correlation

The statistical analysis details

- Hellings & Downs curve:

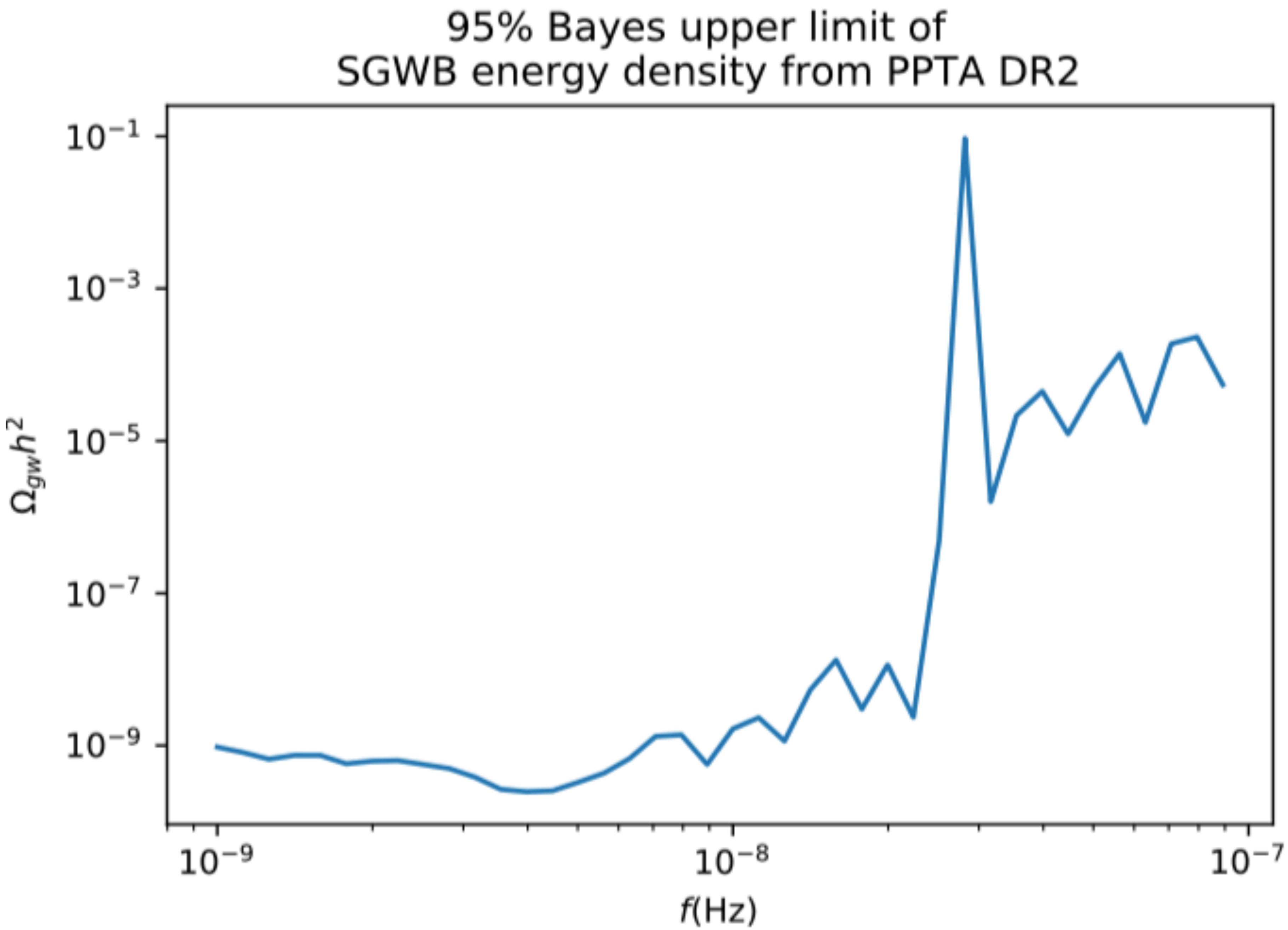
$$\Gamma(\zeta_{IJ}) = \frac{3}{8}\left[1 + \frac{\cos\zeta_{IJ}}{3} + 4(1-\cos\zeta_{IJ})\ln\left(\sin\frac{\zeta_{IJ}}{2}\right)\right](1+\delta_{IJ})$$

- Here ζ_{IJ} is the angle between the pulsars I and J on the sky and $\Gamma(\zeta_{IJ})$ is the overlap reduction function, which represents the expected correlation between the TOAs given an **isotropic** stochastic GWB, and the δ_{IJ} term accounts for the pulsar term for the autocorrelation.

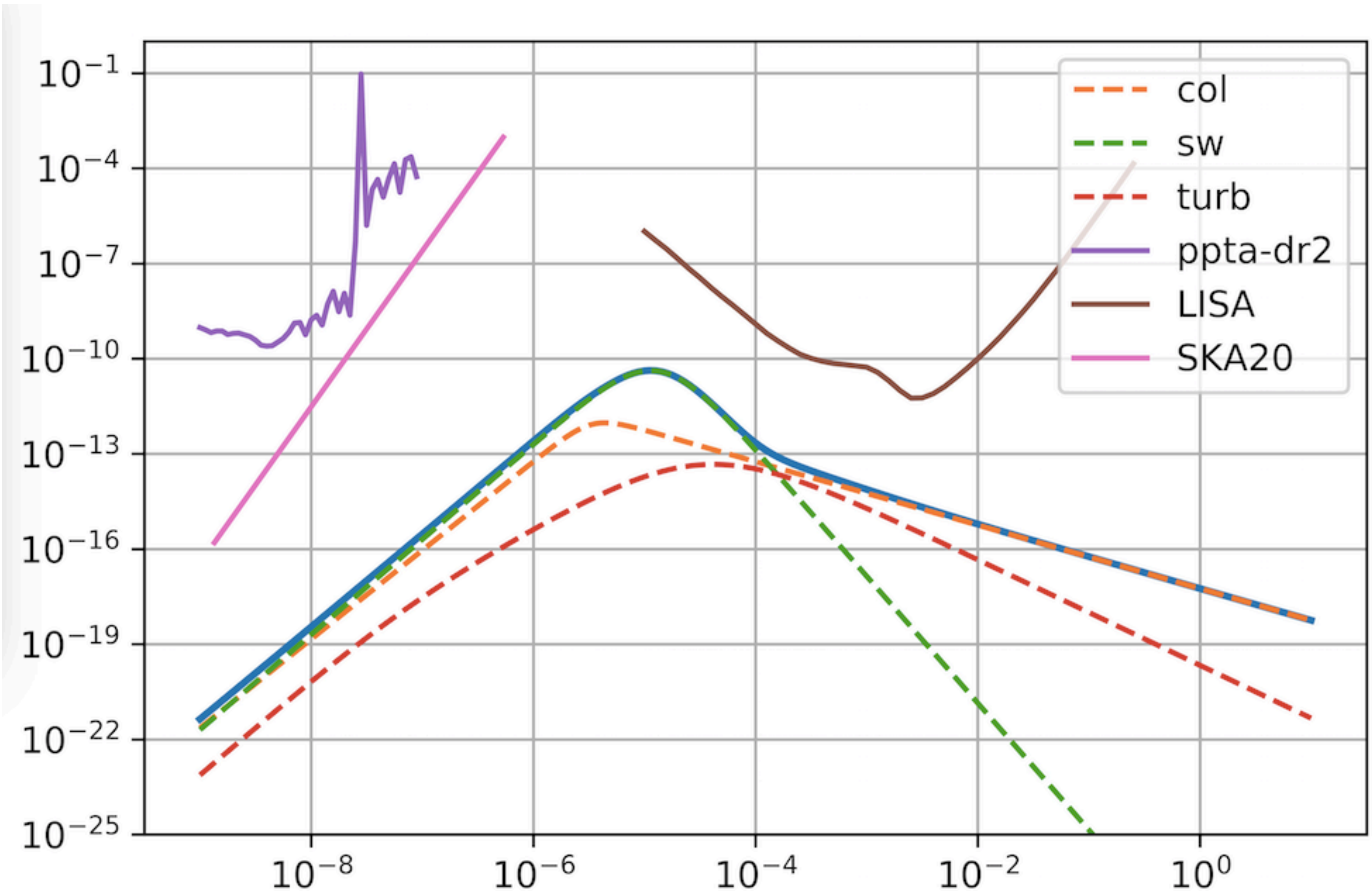
- We found the 'White noises' , 'Spin noise', 'DM-noise' parameters for each pulsar (26 in total), and fix them at their best-fit values.

- We put the free-spectrum SGWB signal into the data, and find their 95% Bayes upper limits at each frequency

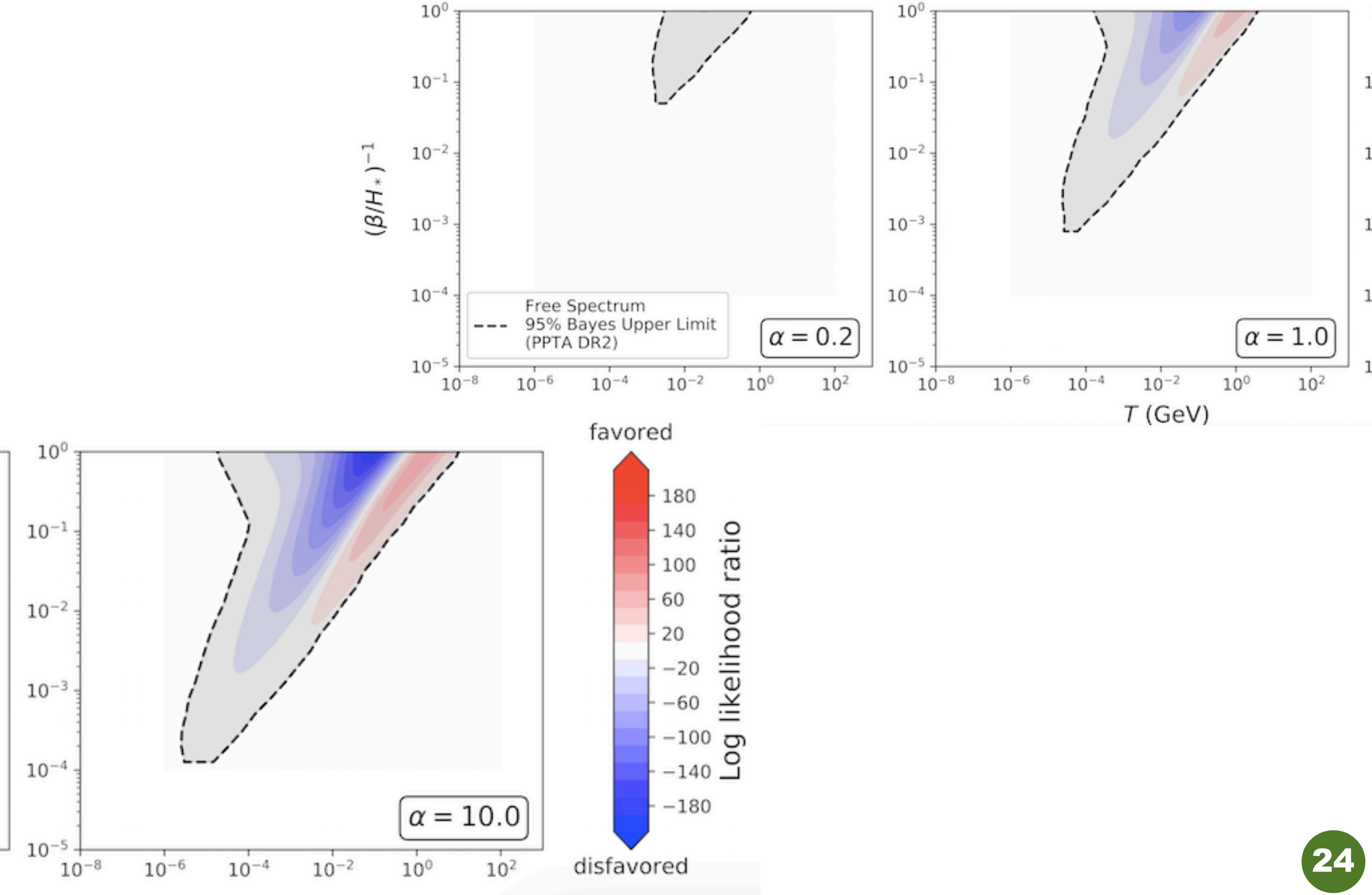
95% C.L. constrain



Full comparison



Constrain on models



Comments

Some comments

With more data, now we are approaching the cosmic phase transition using real data

- Hope the future data can tell us more on the cosmic PTs

Back up slices