Interpreting NANOGrav Results and its implications on primordial Cosmology

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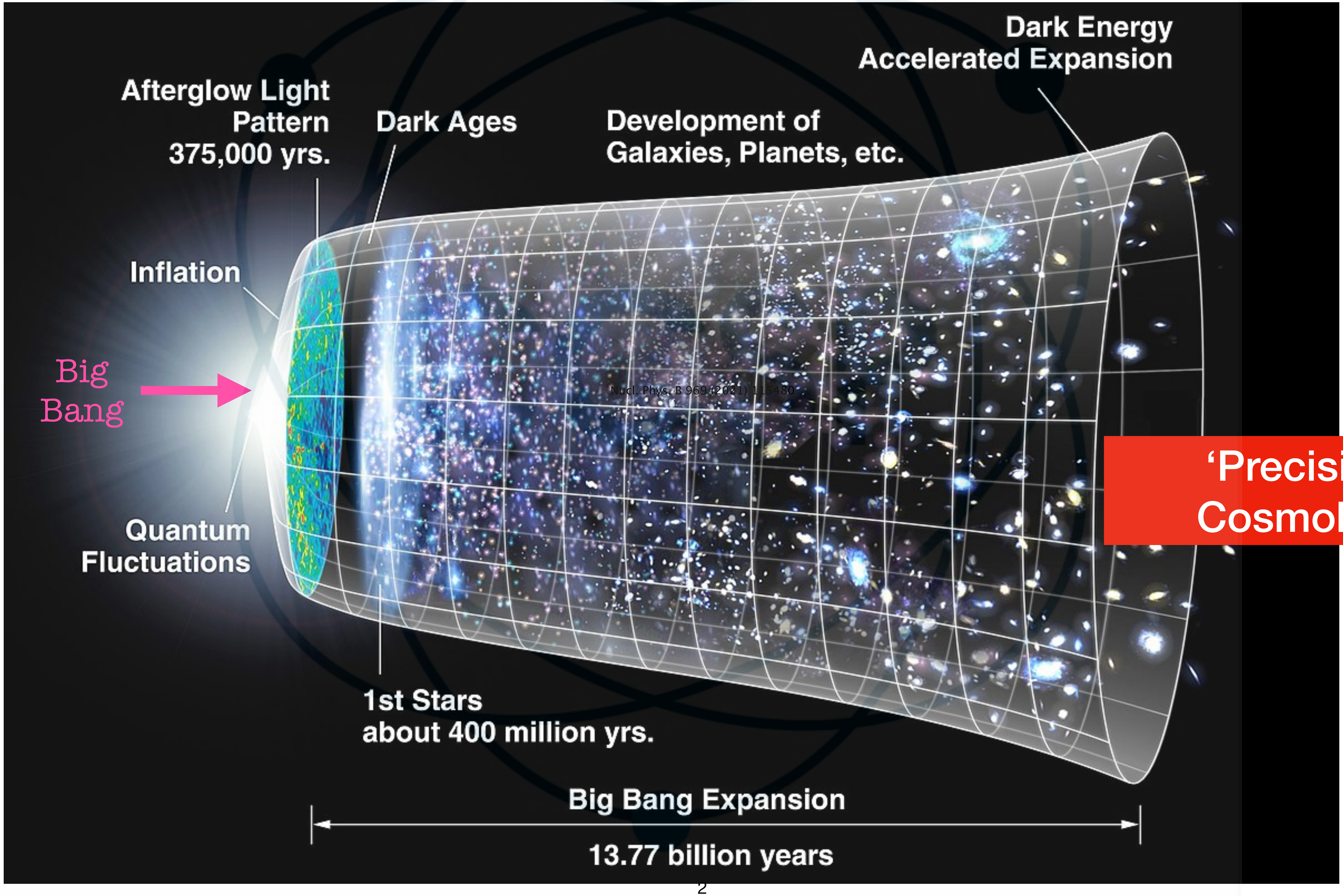
Chronology of the Universe



Big Bang

‘Precision’ Cosmology

Nucl. Phys. B 969 (2021) 115480

Courtesy: NASA library

International Pulsar Timing Array

European Pulsar Timing Array (EPTA)

Radio Telescope at Cagliari, Jordell Bank, Nancy, Westerbrock

North American Pulsar Timing Array (NANOGrav)

Arecibo and Green Bank Telescope

Parkes Pulsar Timing Array (PPTA)

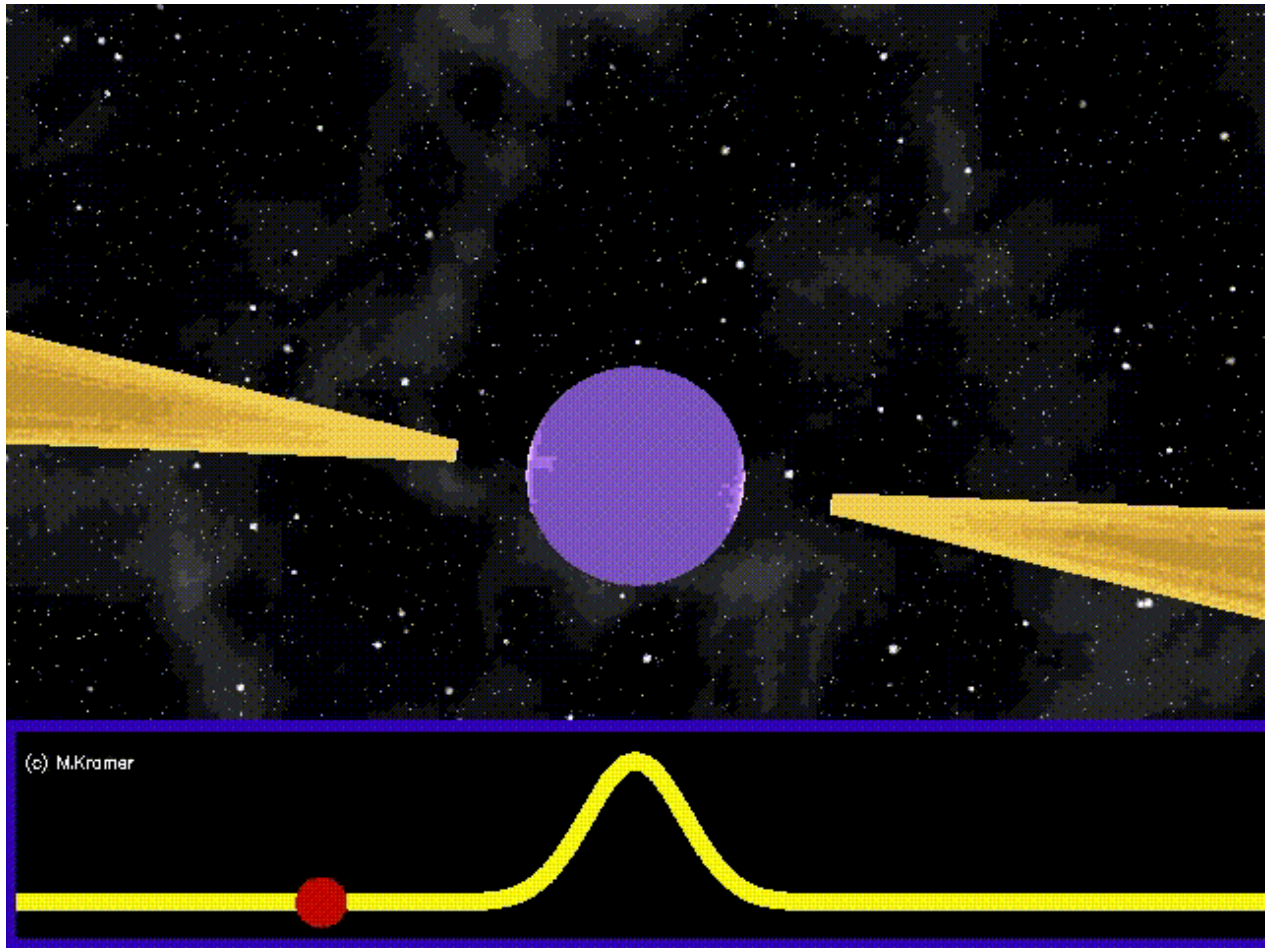
Parkes Radio Telescope, Australia

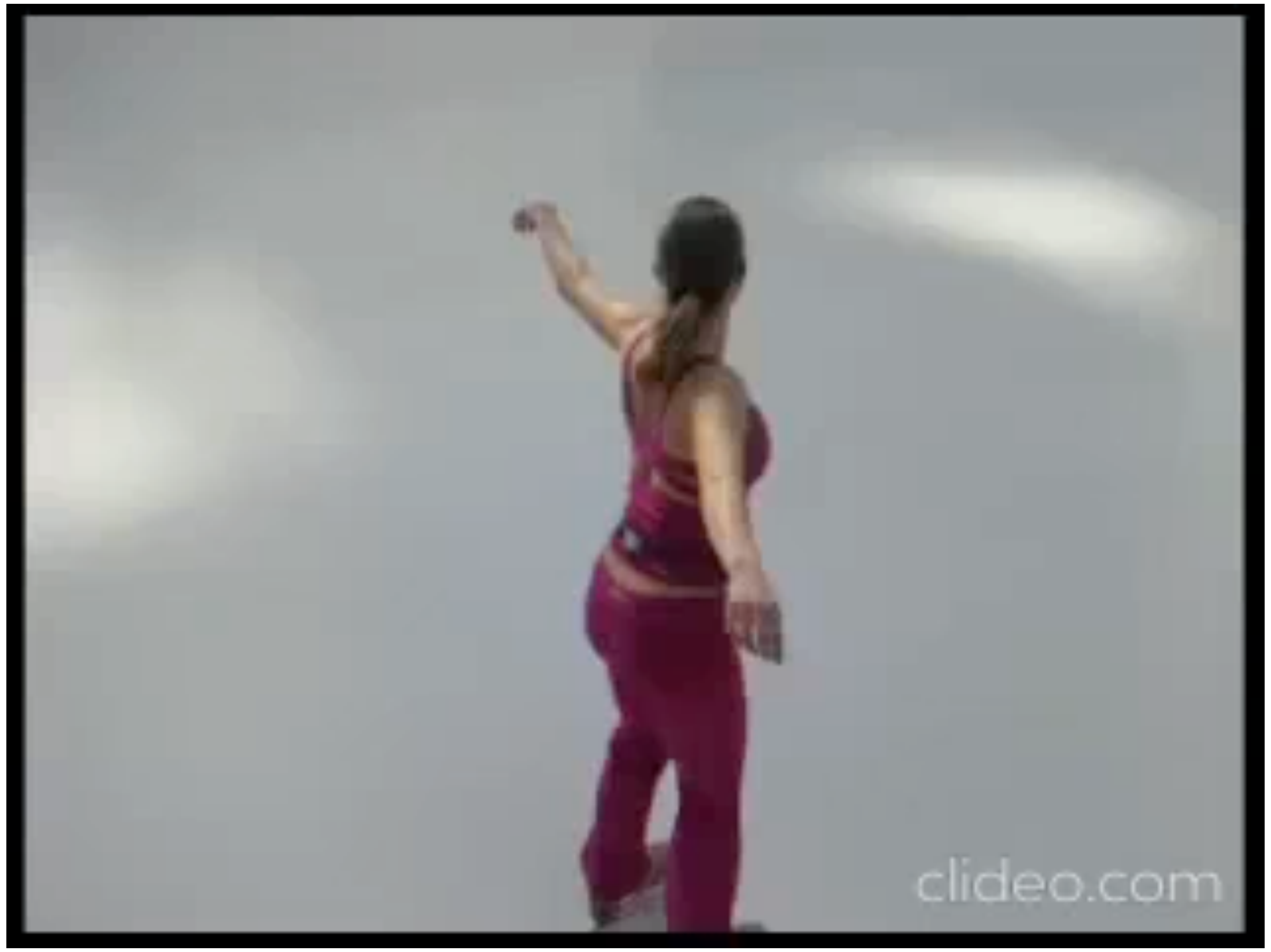
Pulsars

A pulsar is a rapidly-rotating neutron star that emits a beam of electromagnetic radiation (usually in the form of radio waves) from its magnetic poles

If the beam of radiation crosses our line of sight, we see a flash of radiation, similar to that of a lighthouse beacon.

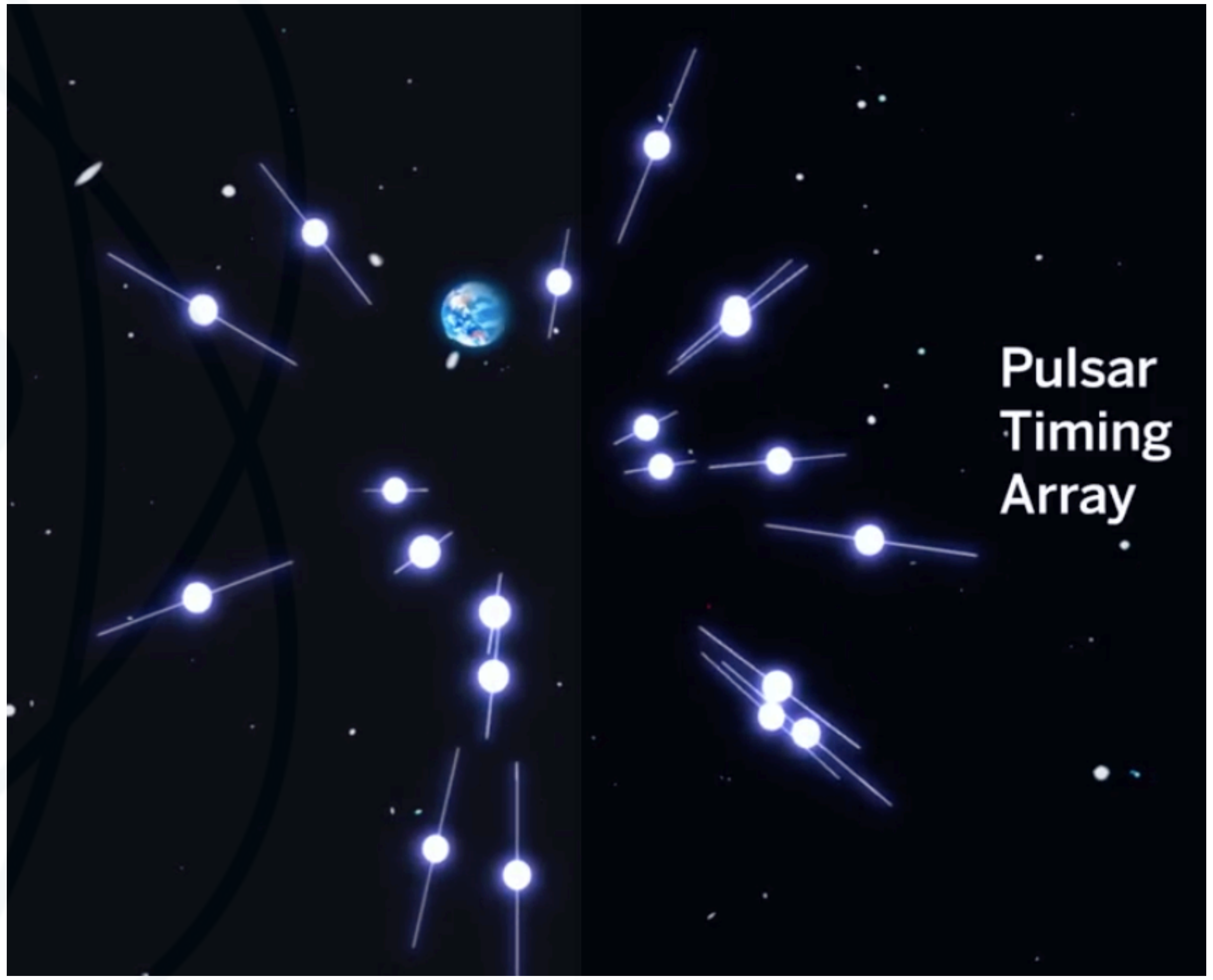
Pulses from binary pulsar PSR B1913+16 that has given us the most compelling evidence to date for the existence of gravitational waves



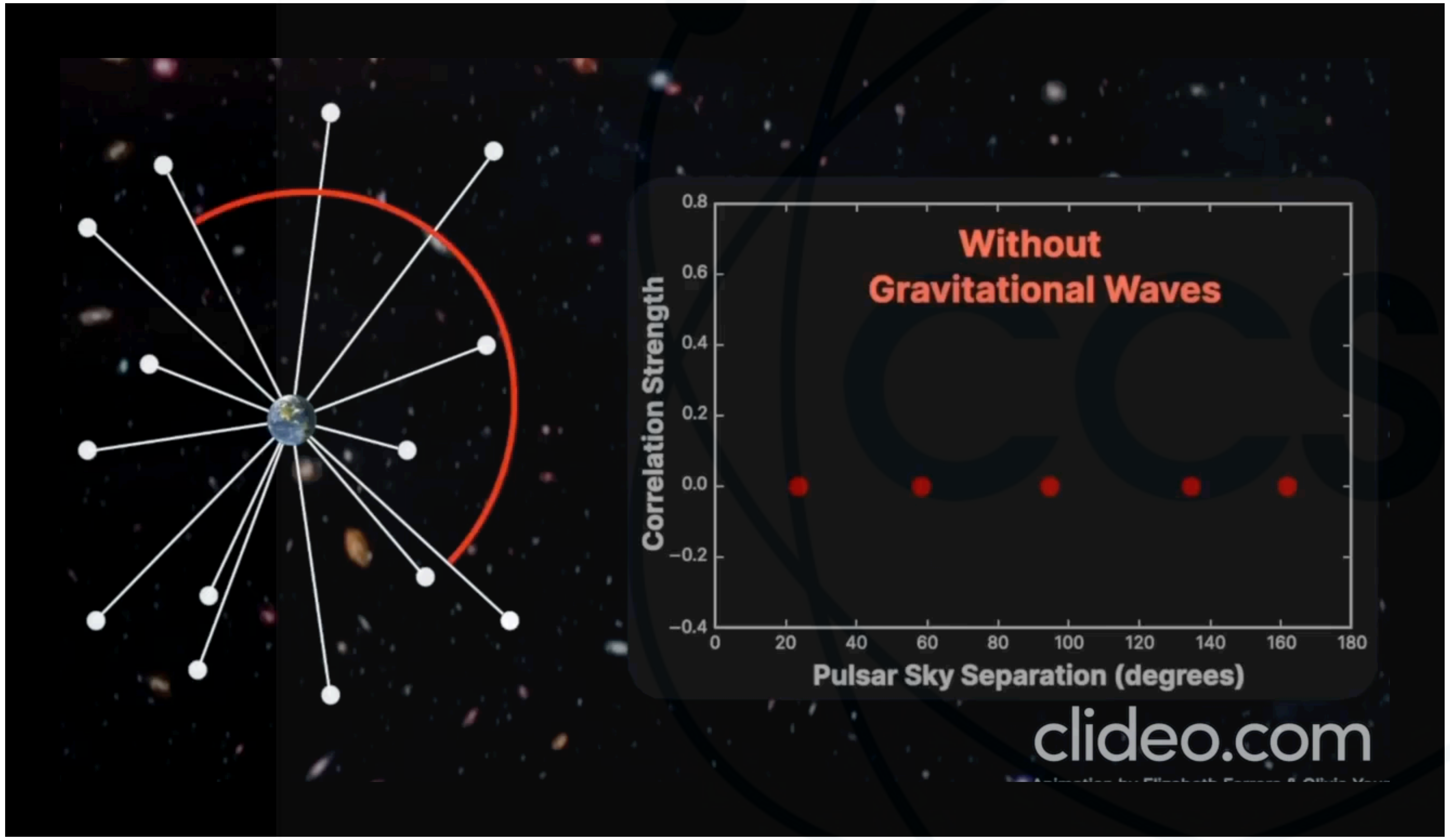


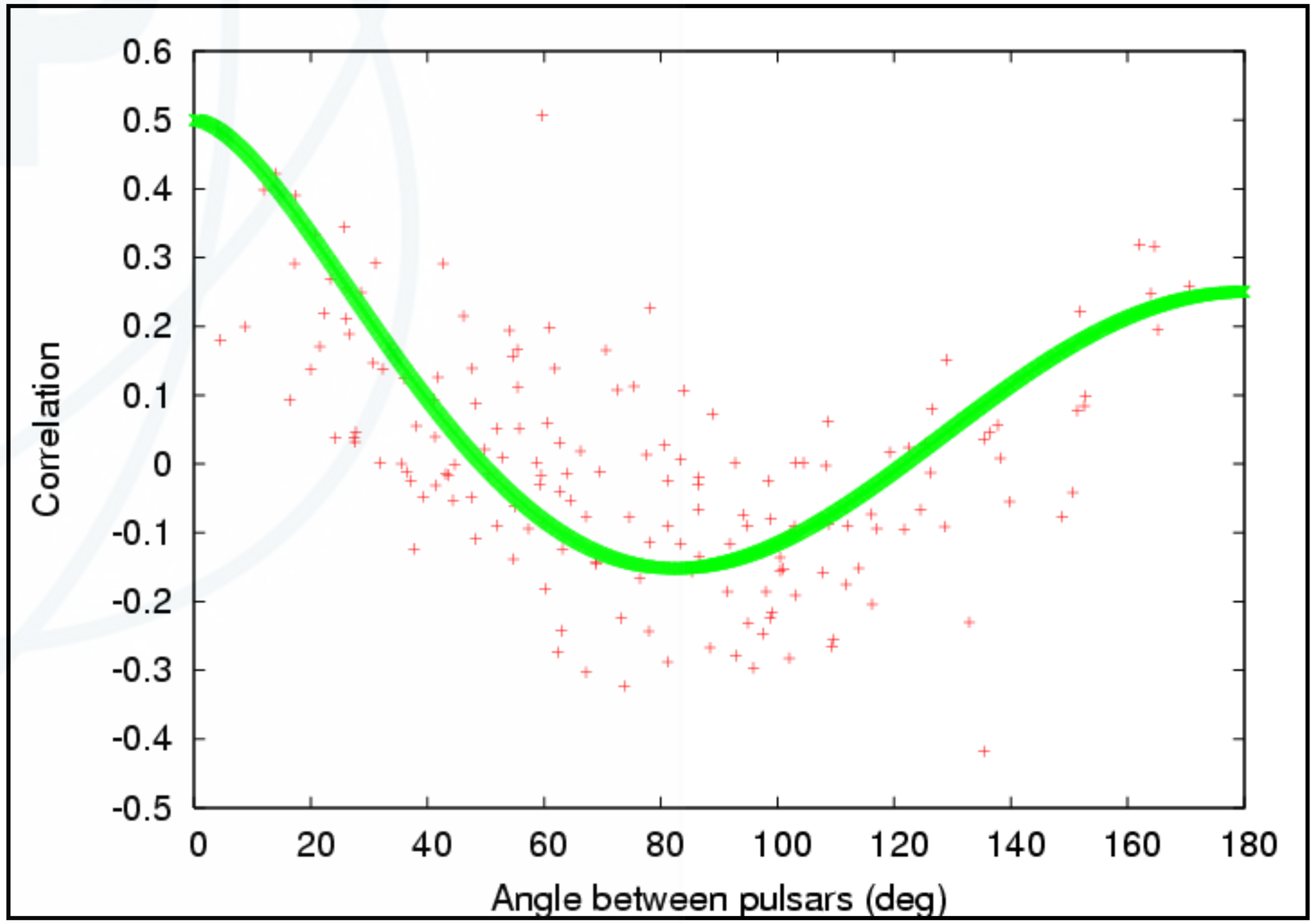
Pulsar Timing Array

- Detection of gravitational waves on the radio pulses that propagate from a pulsar to a radio antenna on Earth.
- A gravitational wave transiting the Earth-pulsar line of sight, creates a perturbation in the intervening spatial metric.
- One can then compare the measured and predicted times of arrival (TOAs) of the pulses, using timing models.
- Standard timing models factor in only deterministic influences on the arrival times of the pulses, the difference between the measured and predicted TOAs will result in a stream of timing residuals.
- Pulsar Timing Array (PTA), can correlate the residuals across pairs of Earth-pulsar baselines.
- The key property of a PTA is that the signal from a stochastic GW background will be correlated across the baselines, while that from the other noise processes will not.



Hellings Downs Correlation





The NANOGrav Buzz !!

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The NANOGrav 15-year Data Set: Evidence for a Gravitational-Wave Background

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ABSTRACT

We report multiple lines of evidence for a stochastic signal that is correlated among 67 pulsars from the 15-year pulsar-timing data set collected by the North American Nanohertz Observatory for Gravitational Waves. The correlations follow the Hellings–Downs pattern expected for a stochastic gravitational-wave background. The presence of such a gravitational-wave background with a power-law–spectrum is favored over a model with only independent pulsar noises with a Bayes factor in excess

of 10^{14}, and this same model is favored over an uncorrelated common power-law–spectrum model with Bayes factors of 200–1000, depending on spectral modeling choices. We have built a statistical background distribution for these latter Bayes factors using a method that removes inter-pulsar correlations from our data set, finding $p = 10^{-3}$ (approx. 3σ) for the observed Bayes factors in the null no-correlation scenario. A frequentist test statistic built directly as a weighted sum of inter-pulsar correlations yields $p = 5 \times 10^{-5}$–1.9×10^{-4} (approx. 3.5–4σ). Assuming a fiducial $f^{-2/3}$ characteristic-strain spectrum, as appropriate for an ensemble of binary supermassive black-hole inspirals, the strain amplitude is $2.4^{+0.7}_{-0.6} \times 10^{-15}$ (median + 90% credible interval) at a reference frequency of 1 yr^{-1}. The inferred gravitational-wave background amplitude and spectrum are consistent with astrophysical expectations for a signal from a population of supermassive black-hole binaries, although more exotic cosmological and astrophysical sources cannot be excluded. The observation of Hellings–Downs correlations points to the gravitational-wave origin of this signal.

Keywords: Gravitational waves – Black holes – Pulsars

1. INTRODUCTION

Almost a century had to elapse between Einstein's prediction of gravitational waves (GWs, Einstein 1916) and their measurement from a coalescing binary of stellar-mass black holes (Abbott et al. 2016). However, their existence had been confirmed in the late 1970s through measurements of the orbital decay of the Hulse–Taylor binary pulsar (Hulse & Taylor 1975; Taylor et al. 1979). Today, pulsars are again at the forefront of the quest to detect GWs, this time from binary systems of central galactic black holes.

Black holes with masses of 10^5–$10^{10}\,M_\odot$ exist at the center of most galaxies and are closely correlated with the global properties of the host, suggesting a symbiotic evolution (Magorrian et al. 1998; McConnell & Ma 2013). Galaxy mergers are the main drivers of hierarchical structure formation over cosmic time (Blumenthal et al. 1984) and lead to the formation of close massive–black-hole binaries long after the mergers (Begelman et al. 1980; Milosavljević & Merritt 2003). The most massive of these (supermassive black-hole binaries, SMBHBs, with masses 10^8–$10^{10}\,M_\odot$) emit GWs with slowly evolving frequencies, contributing to a noise-like broadband signal in the nHz range (the GW background, GWB; Rajagopal & Romani 1995; Jaffe & Backer 2003; Wyithe & Loeb 2003; Sesana et al. 2004; McWilliams et al. 2014; Burke-Spolaor et al. 2019). If all contributing SMBHBs evolve purely by loss of circular orbital energy to gravitational radiation, the resultant GWB spectrum is well described by a simple $f^{-2/3}$ characteristic-strain power law (Phinney 2001). However, GWB signals that are not produced by populations of inspiraling black holes may also lie within the nHz band; these include primordial GWs from inflation, scalar-induced GWs, and GW signals from multiple processes arising due to cosmological phase transitions, such as collisions of bubbles of the post-transition vacuum state, sound waves, turbulence, and the decay of any defects such as cosmic strings or domain walls that may have formed (see, e.g., Guzzetti et al. 2016; Caprini & Figueroa 2018; Domènech 2021, and references therein).

The detection of nHz GWs follows the template outlined by Pirani (1956, 2009), whereby we time the propagation of light to measure modulations in the distance between freely falling reference masses. Estabrook & Wahlquist (1975) derived the GW response of electromagnetic signals traveling between Earth and distant spacecraft, sparking interest in low-frequency GW detection. Sazhin (1978) and Detweiler (1979) described nHz GW detection using Galactic pulsars and (effectively) the solar system barycenter as references, relying on the regularity of pulsar emission and planetary motions to highlight GW effects. The fact that pulsars are such accurate clocks enables precise measurements of their rotational, astrometric, and binary parameters (and more) from the times-of-arrival of their pulses, which are used to develop ever-refining end-to-end *timing models*. Hellings & Downs (1983) made the crucial suggestion that the correlations between the time-of-arrival perturbations of multiple pulsars could reveal a GW signal buried in pulsar noise; Romani (1989) and Foster & Backer (1990) proposed that a *pulsar timing array* (PTA) of highly stable millisecond pulsars (Backer et al. 1982) could be used to search for a GWB. Nevertheless, the first multi-pulsar, long-term GWB limits were obtained by analyzing millisecond-pulsar residuals independently, rather than as an array (Stinebring et al. 1990; Kaspi et al. 1994).

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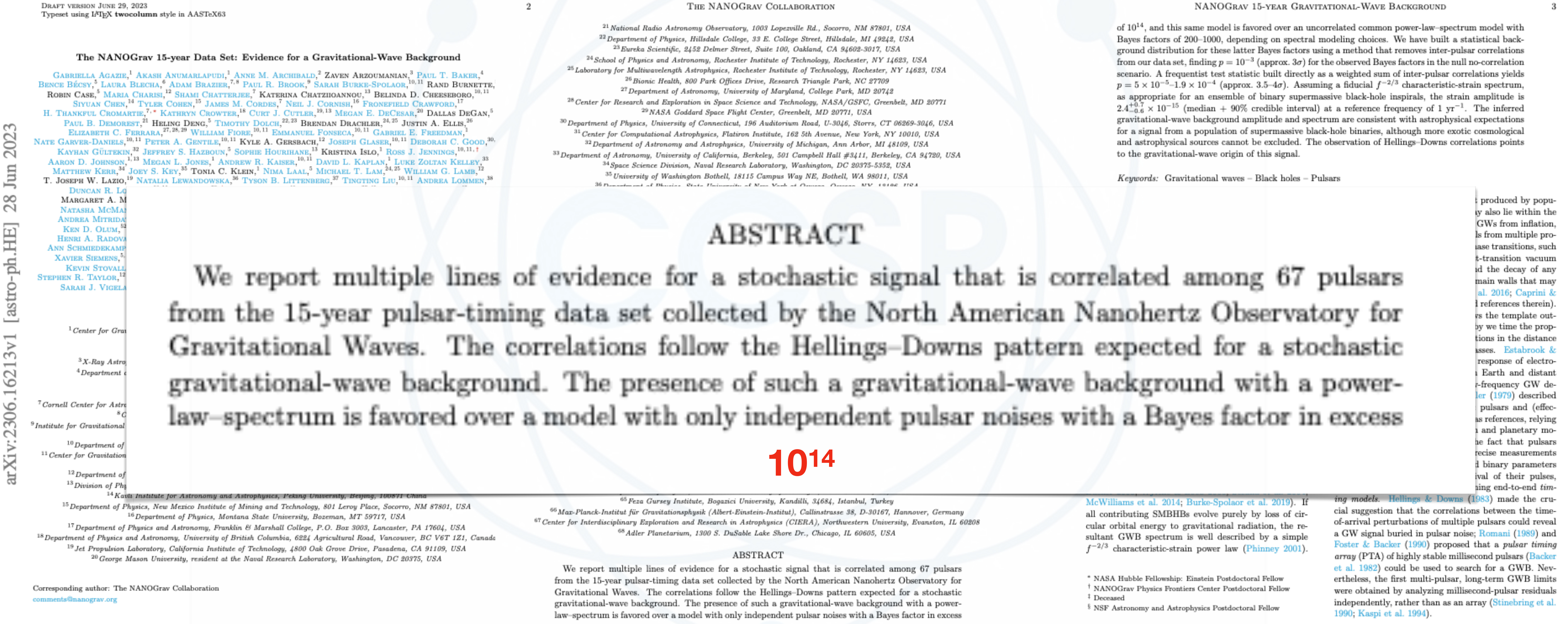

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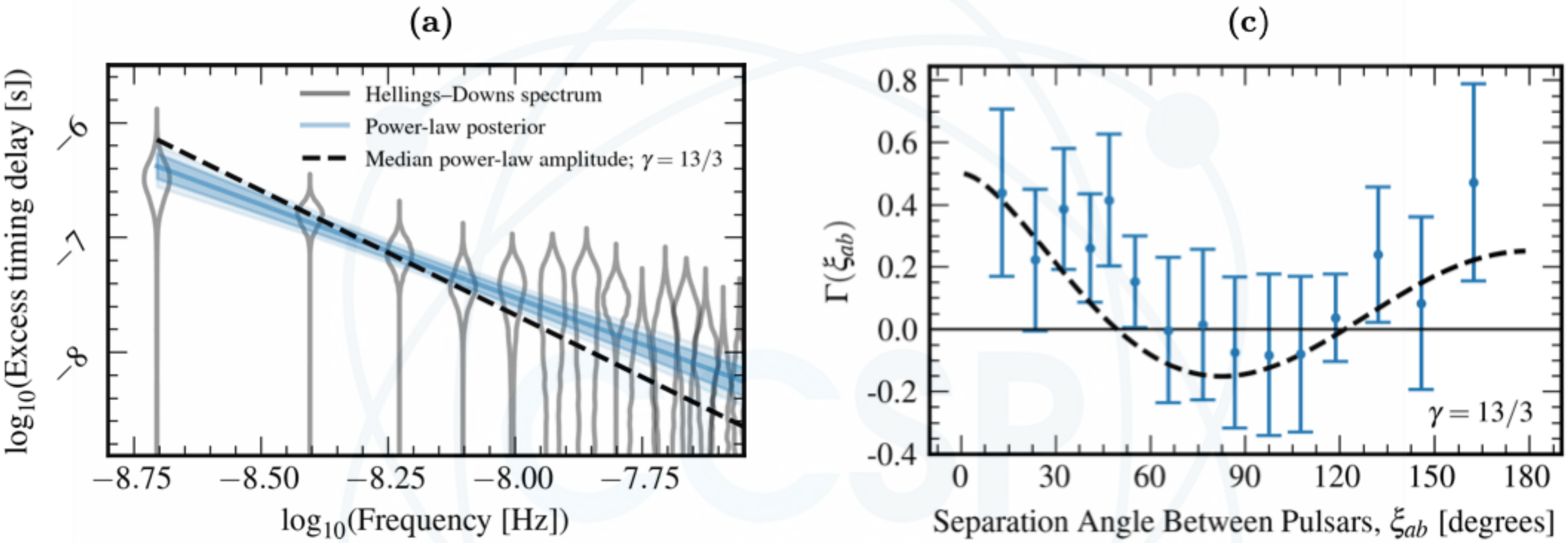
[*] NASA Hubble Fellowship: Einstein Postdoctoral Fellow
[†] NANOGrav Physics Frontiers Center Postdoctoral Fellow
[‡] Deceased
[§] NSF Astronomy and Astrophysics Postdoctoral Fellow

The NANOGrav Buzz !!



gravitational-wave background. The presence of such a gravitational-wave background with a power-law–spectrum is favored over a model with only independent pulsar noises with a Bayes factor in excess

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ABSTRACT

We report multiple lines of evidence for a stochastic signal that is correlated among 67 pulsars from the 15-year pulsar-timing data set collected by the North American Nanohertz Observatory for Gravitational Waves. The correlations follow the Hellings–Downs pattern expected for a stochastic gravitational-wave background. The presence of such a gravitational-wave background with a power-law–spectrum is favored over a model with only independent pulsar noises with a Bayes factor in excess

McWilliams et al. 2014; Burke-Spolaor et al. 2019). If all contributing SMBHBs evolve purely by loss of circular orbital energy to gravitational radiation, the resultant GWB spectrum is well described by a simple $f^{-2/3}$ characteristic-strain power law (Phinney 2001).

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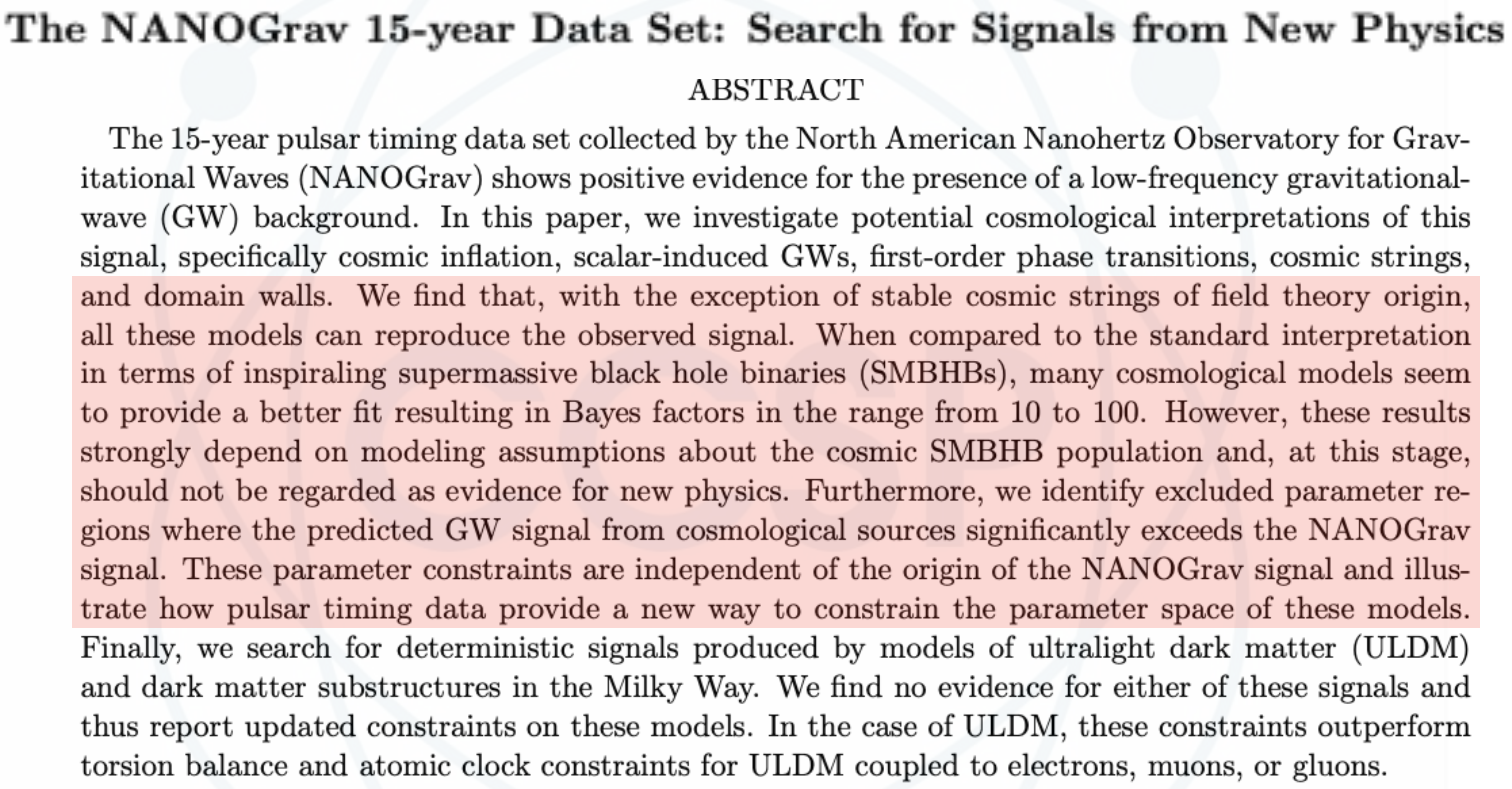
The NANOGrav Hoopla ??



The NANOGrav 15-year Data Set: Search for Signals from New Physics

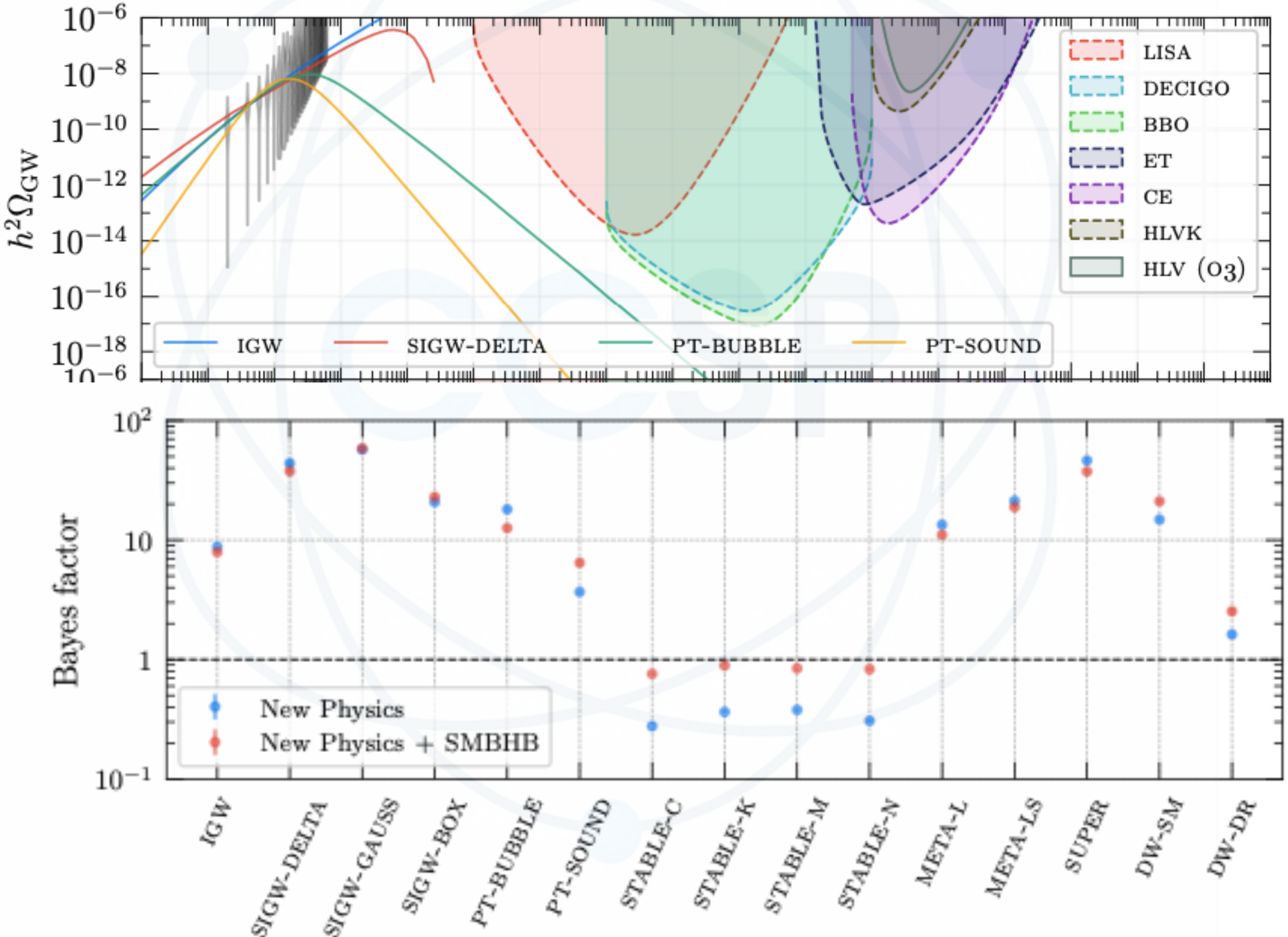
ABSTRACT

The 15-year pulsar timing data set collected by the North American Nanohertz Observatory for Gravitational Waves (NANOGrav) shows positive evidence for the presence of a low-frequency gravitational-wave (GW) background. In this paper, we investigate potential cosmological interpretations of this signal, specifically cosmic inflation, scalar-induced GWs, first-order phase transitions, cosmic strings, and domain walls. We find that, with the exception of stable cosmic strings of field theory origin, all these models can reproduce the observed signal. When compared to the standard interpretation in terms of inspiraling supermassive black hole binaries (SMBHBs), many cosmological models seem to provide a better fit resulting in Bayes factors in the range from 10 to 100. However, these results strongly depend on modeling assumptions about the cosmic SMBHB population and, at this stage, should not be regarded as evidence for new physics. Furthermore, we identify excluded parameter regions where the predicted GW signal from cosmological sources significantly exceeds the NANOGrav signal. These parameter constraints are independent of the origin of the NANOGrav signal and illustrate how pulsar timing data provide a new way to constrain the parameter space of these models. Finally, we search for deterministic signals produced by models of ultralight dark matter (ULDM) and dark matter substructures in the Milky Way. We find no evidence for either of these signals and thus report updated constraints on these models. In the case of ULDM, these constraints outperform torsion balance and atomic clock constraints for ULDM coupled to electrons, muons, or gluons.

But no anisotropy in the data !!

Fundamental New Physics!!

NANOGrav Collaboration, arXiv: 2306.16219



Statistical Significance

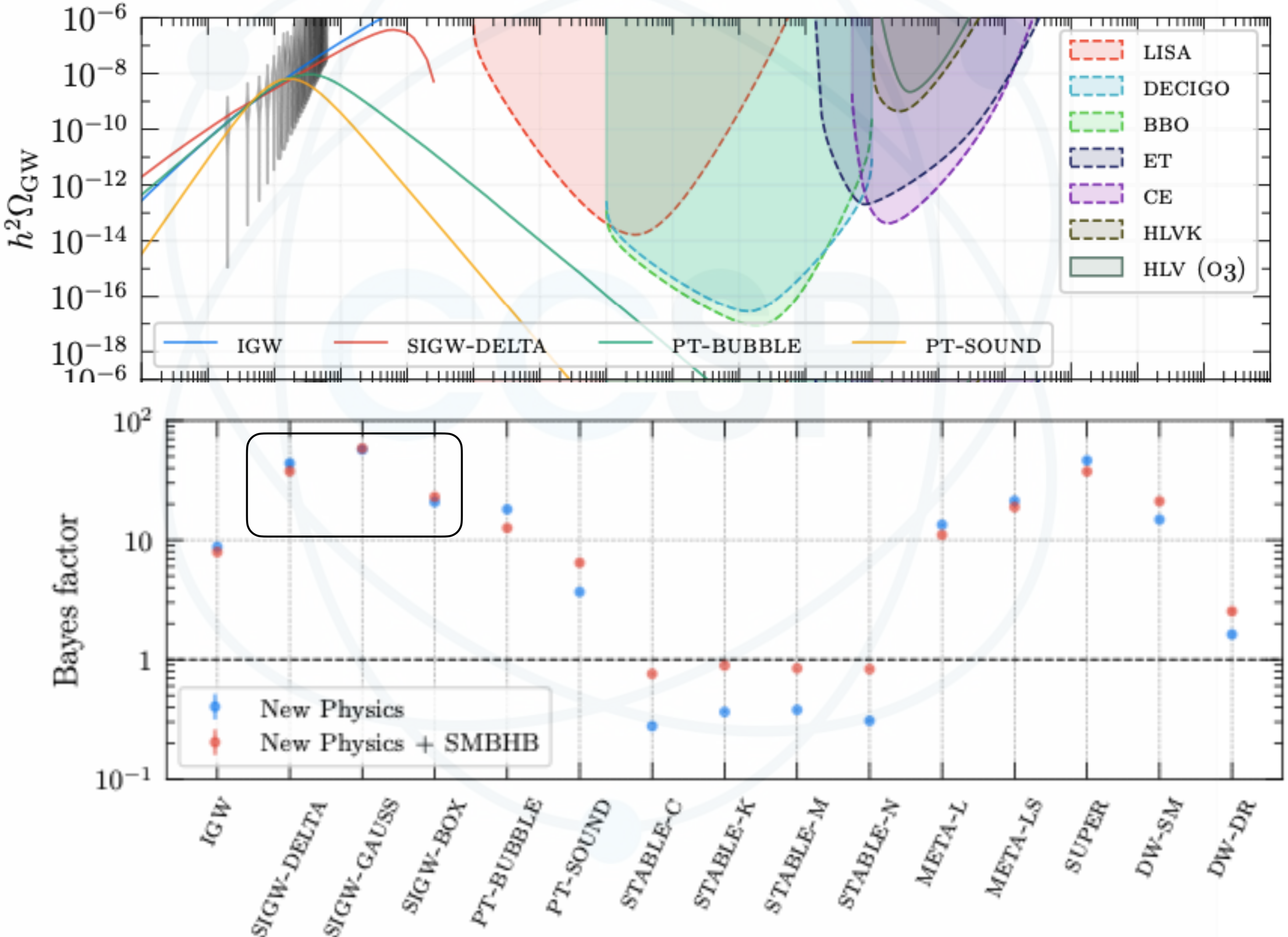
$$\mathcal{B}_{10}(\mathcal{D}) = \frac{\mathcal{Z}_1}{\mathcal{Z}_0} = \frac{P(\mathcal{D}|\mathcal{H}_1)}{P(\mathcal{D}|\mathcal{H}_0)}$$

Jeffreys Scale

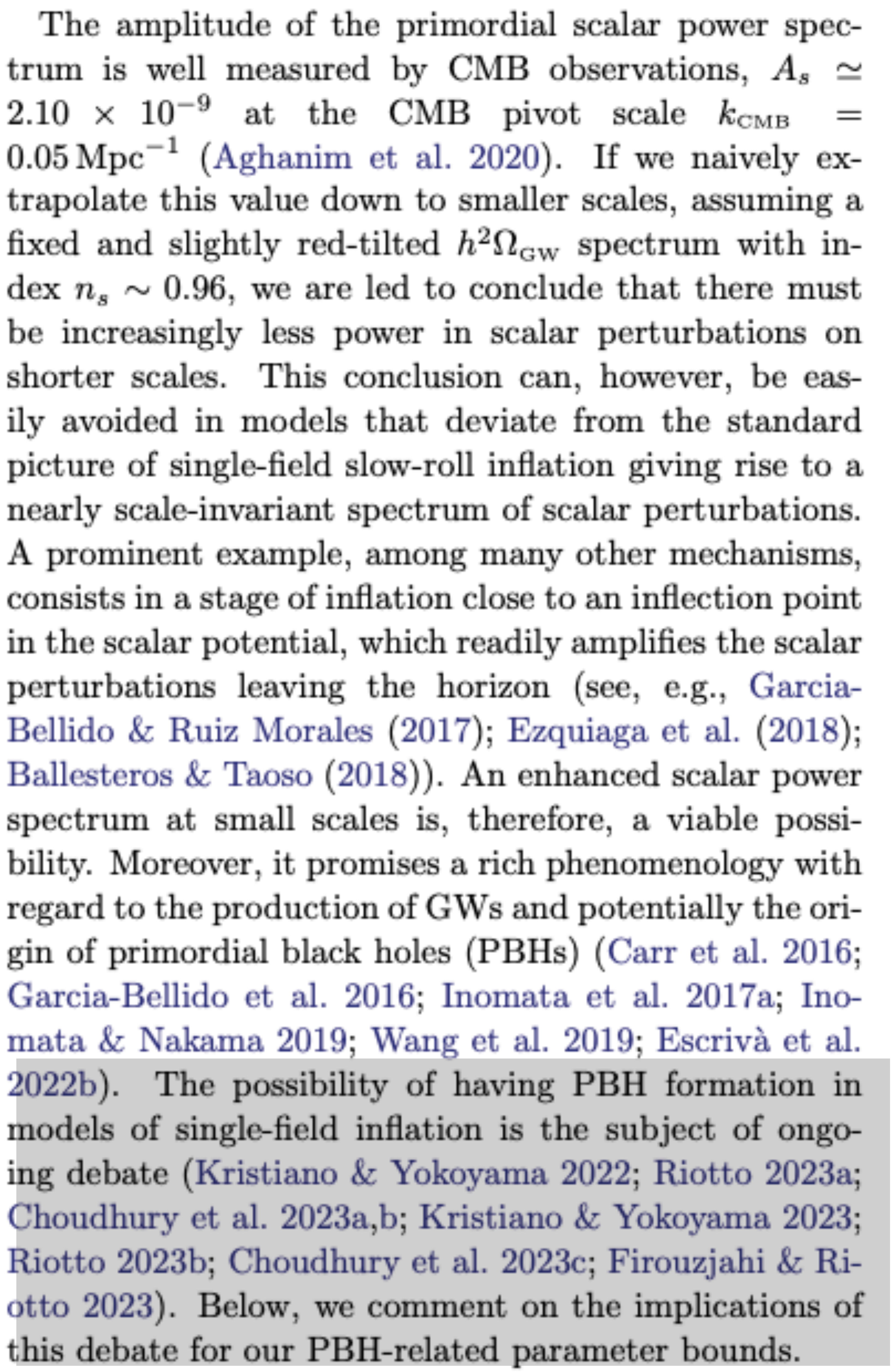
B_{10}	Interpretation
< 1	Disfavoured
10^{0} - $10^{0.5}$	Negligible
$10^{0.5}$ - $10^{1.0}$	Substantial
$10^{1.0}$ - $10^{1.5}$	Strong
$10^{1.5}$ - $10^{2.0}$	Very Strong
$10^{2.0}$ - ∞	Decisive

Fundamental New Physics!!

NANOGrav Collaboration, arXiv: 2306.16219



Scalar Induced Gravity Wave



The amplitude of the primordial scalar power spectrum is well measured by CMB observations, $A_s \simeq 2.10 \times 10^{-9}$ at the CMB pivot scale $k_{\rm CMB} = 0.05\,{\rm Mpc}^{-1}$ (Aghanim et al. 2020). If we naively extrapolate this value down to smaller scales, assuming a fixed and slightly red-tilted $h^2\Omega_{\rm GW}$ spectrum with index $n_s \sim 0.96$, we are led to conclude that there must be increasingly less power in scalar perturbations on shorter scales. This conclusion can, however, be easily avoided in models that deviate from the standard picture of single-field slow-roll inflation giving rise to a nearly scale-invariant spectrum of scalar perturbations. A prominent example, among many other mechanisms, consists in a stage of inflation close to an inflection point in the scalar potential, which readily amplifies the scalar perturbations leaving the horizon (see, e.g., Garcia-Bellido & Ruiz Morales (2017); Ezquiaga et al. (2018); Ballesteros & Taoso (2018)). An enhanced scalar power spectrum at small scales is, therefore, a viable possibility. Moreover, it promises a rich phenomenology with regard to the production of GWs and potentially the origin of primordial black holes (PBHs) (Carr et al. 2016; Garcia-Bellido et al. 2016; Inomata et al. 2017a; Inomata & Nakama 2019; Wang et al. 2019; Escrivà et al. 2022b). The possibility of having PBH formation in models of single-field inflation is the subject of ongoing debate (Kristiano & Yokoyama 2022; Riotto 2023a; Choudhury et al. 2023a,b; Kristiano & Yokoyama 2023; Riotto 2023b; Choudhury et al. 2023c; Firouzjahi & Riotto 2023). Below, we comment on the implications of this debate for our PBH-related parameter bounds.

NANOGrav Collaboration, arXiv: 2306.16219

SIGW Observed today

$$\Omega_{\rm GW}^{\rm ind}(f) = \Omega_{\rm r}\left(\frac{g_*(f)}{g_*^0}\right)\left(\frac{g_{*,s}^0}{g_{*,s}(f)}\right)^{4/3}\bar{\Omega}_{\rm GW}^{\rm ind}(f)$$

SIGW At the time of creation

$$\bar{\Omega}_{\rm GW}^{\rm ind}(f) = \int_0^\infty {\rm d}v\int_{|1-v|}^{1+v}{\rm d}u\,\mathcal{K}(u,v)\,\mathcal{P}_{\mathcal{R}}(uk)\,\mathcal{P}_{\mathcal{R}}(vk)$$

SIGW-Delta

$$\mathcal{P}_{\mathcal{R}}(k) = A\,\delta\left(\ln k - \ln k_*\right)$$

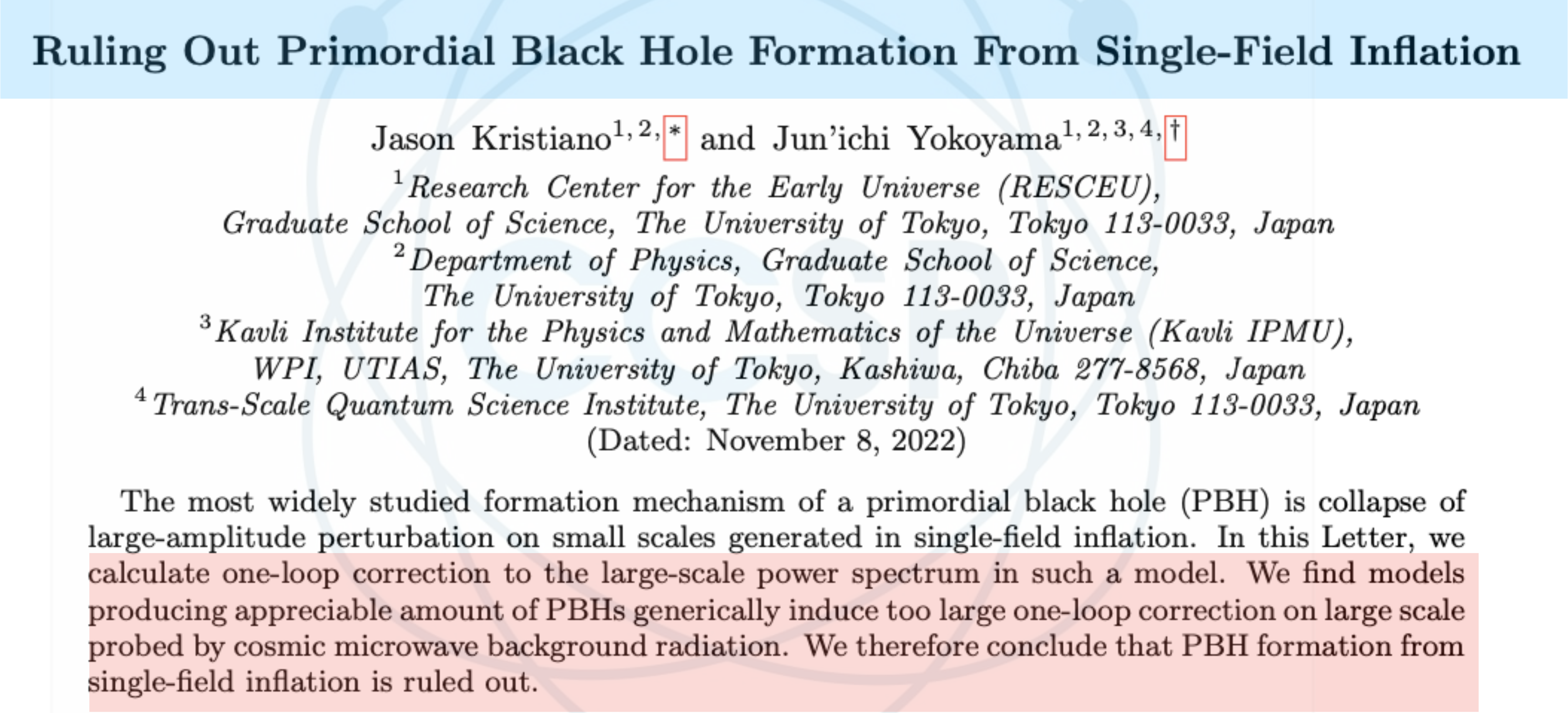
SIGW-Gauss

$$\mathcal{P}_{\mathcal{R}}(k) = \frac{A}{\sqrt{2\pi}\,\Delta}\exp\left[-\frac{1}{2}\left(\frac{\ln k - \ln k_*}{\Delta}\right)^2\right]$$

SIGW-Box

$$\mathcal{P}_{\mathcal{R}}(k) = A\,\Theta\left(\ln k_{\rm max} - \ln k\right)\Theta\left(\ln k - \ln k_{\rm min}\right).$$

Problem!!



Ruling Out Primordial Black Hole Formation From Single-Field Inflation

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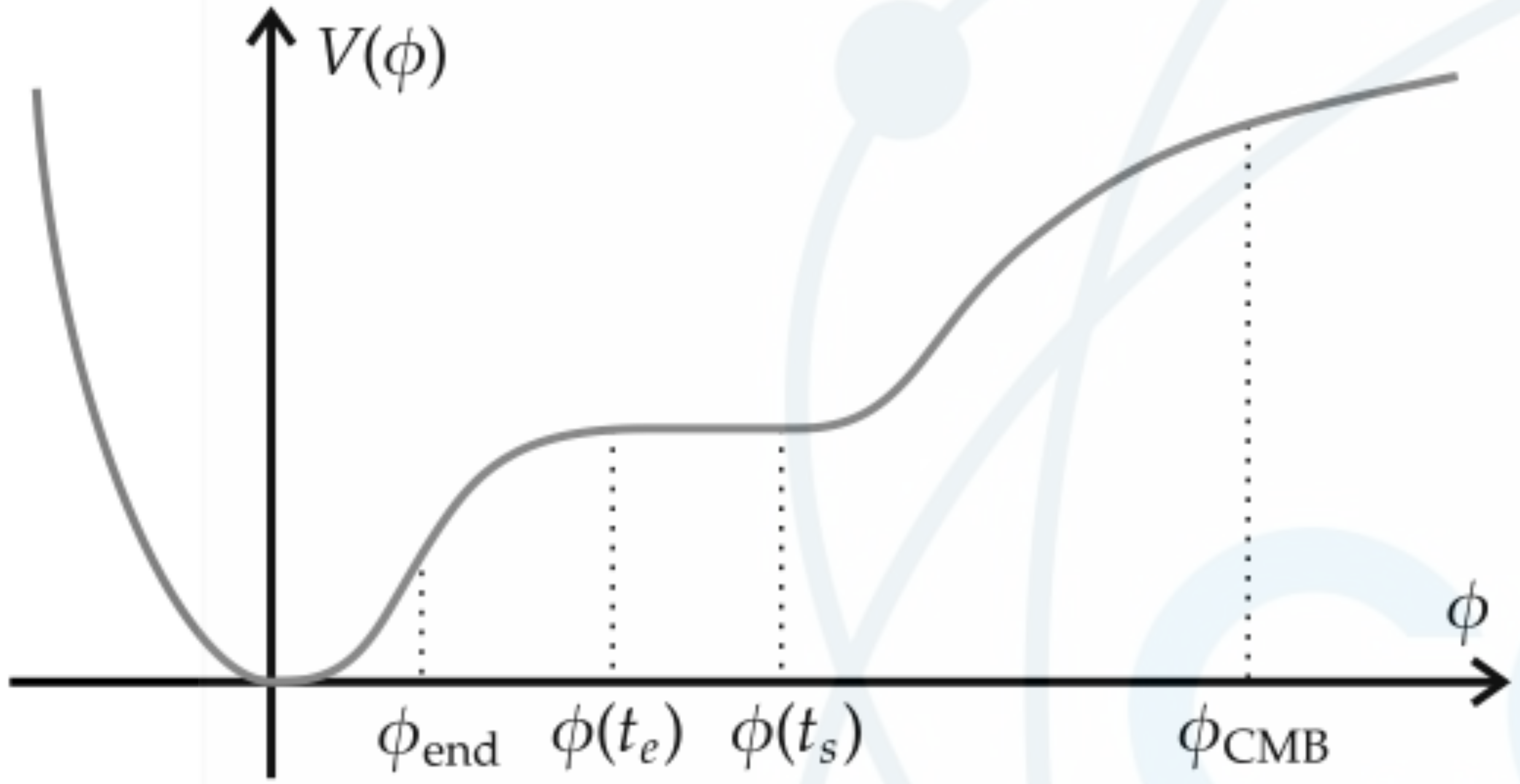
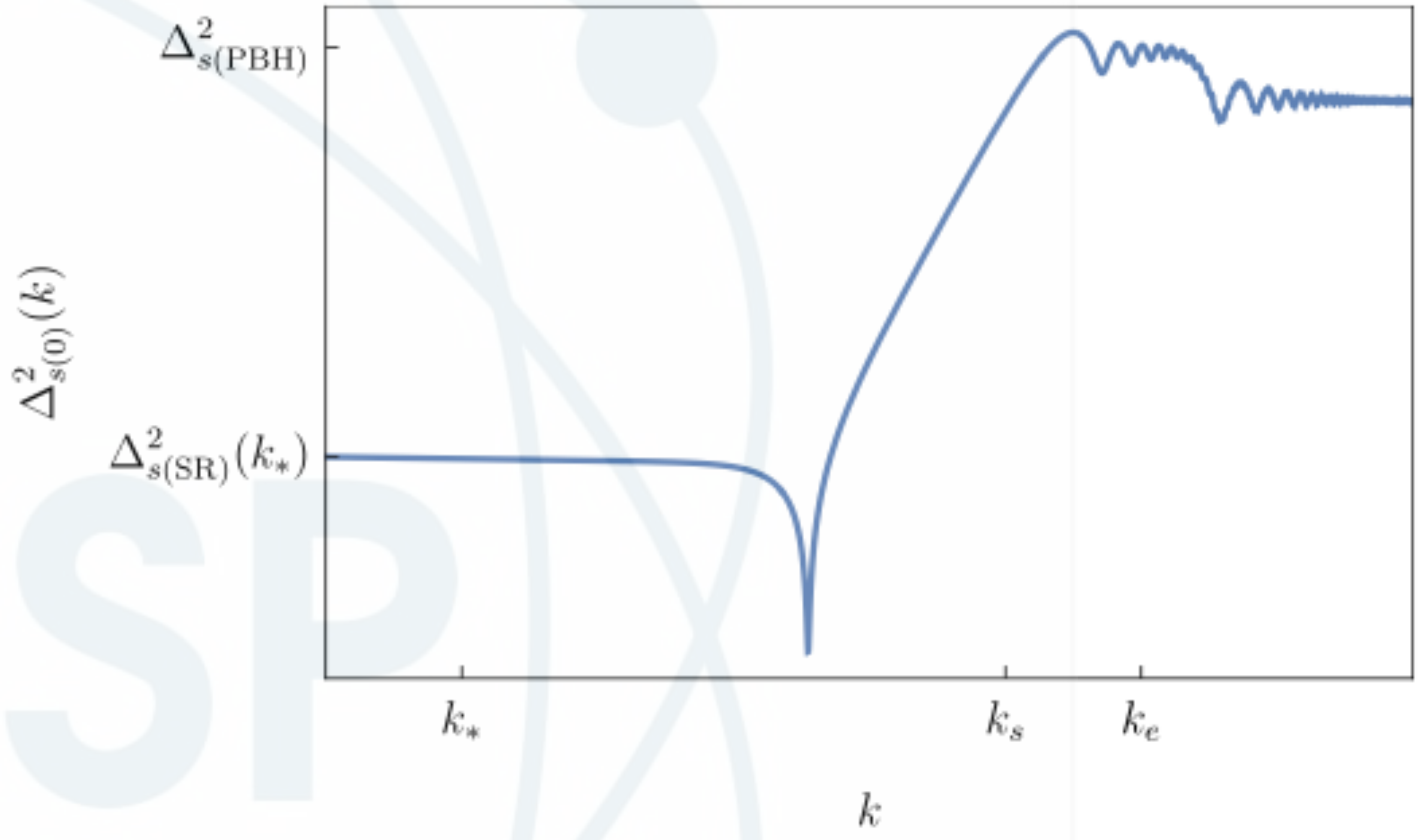
(Dated: November 8, 2022)

The most widely studied formation mechanism of a primordial black hole (PBH) is collapse of large-amplitude perturbation on small scales generated in single-field inflation. In this Letter, we calculate one-loop correction to the large-scale power spectrum in such a model. We find models producing appreciable amount of PBHs generically induce too large one-loop correction on large scale probed by cosmic microwave background radiation. We therefore conclude that PBH formation from single-field inflation is ruled out.

arXiv:2211.03395 [hep-th]

Problem!!

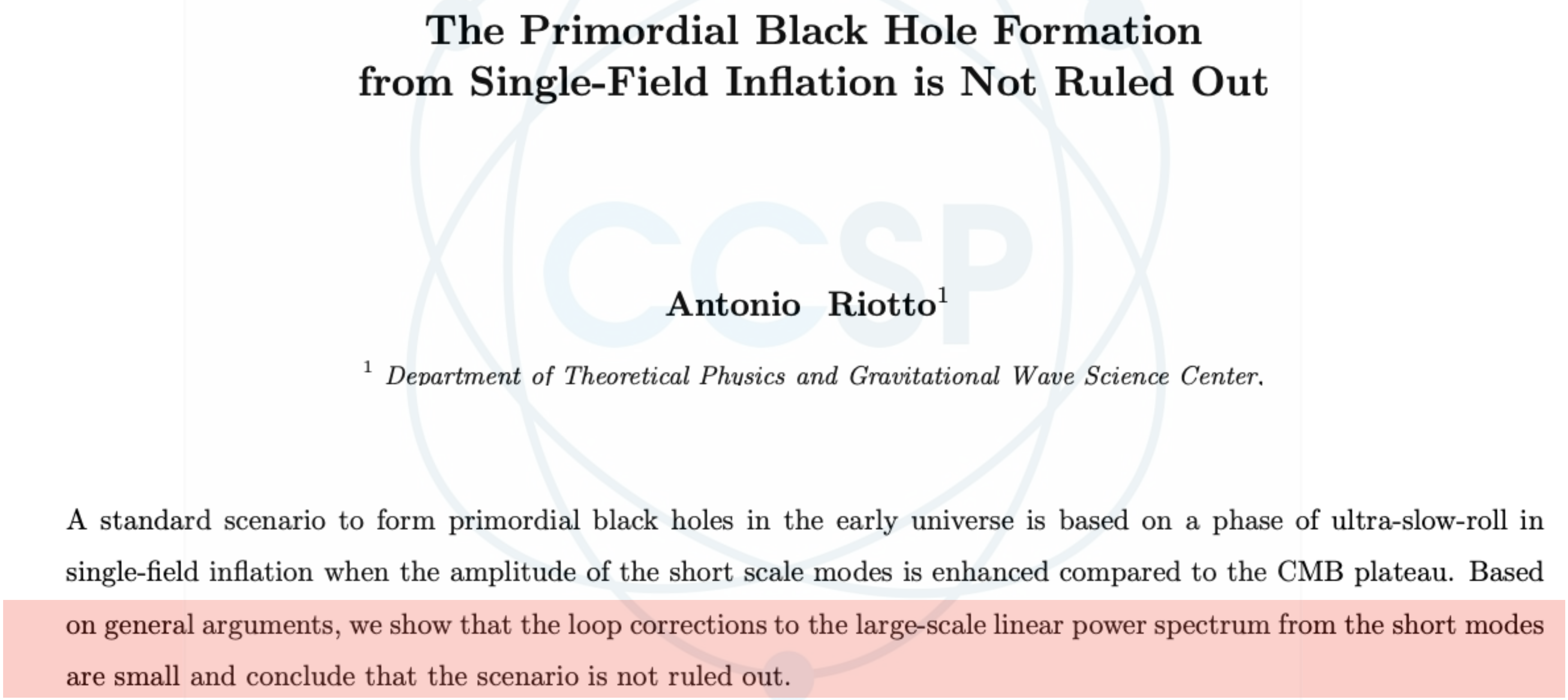




$$\Delta^2_{s(1)}(p) = \frac{1}{4}(\Delta\eta(\tau_e))^2 \left[\Delta^2_{s(\rm SR)}(p)\right]^2 \times \left(\frac{k_e}{k_s}\right)^6 \left[1.1 + \log\frac{k_e}{k_s} + \mathcal{D}(\Lambda)\right]$$

$$\mathcal{D}(\Lambda) \propto \Lambda^2$$

Problem??



The Primordial Black Hole Formation from Single-Field Inflation is Not Ruled Out

Antonio Riotto[1]

[1] *Department of Theoretical Physics and Gravitational Wave Science Center,*

A standard scenario to form primordial black holes in the early universe is based on a phase of ultra-slow-roll in single-field inflation when the amplitude of the short scale modes is enhanced compared to the CMB plateau. Based on general arguments, we show that the loop corrections to the large-scale linear power spectrum from the short modes are small and conclude that the scenario is not ruled out.

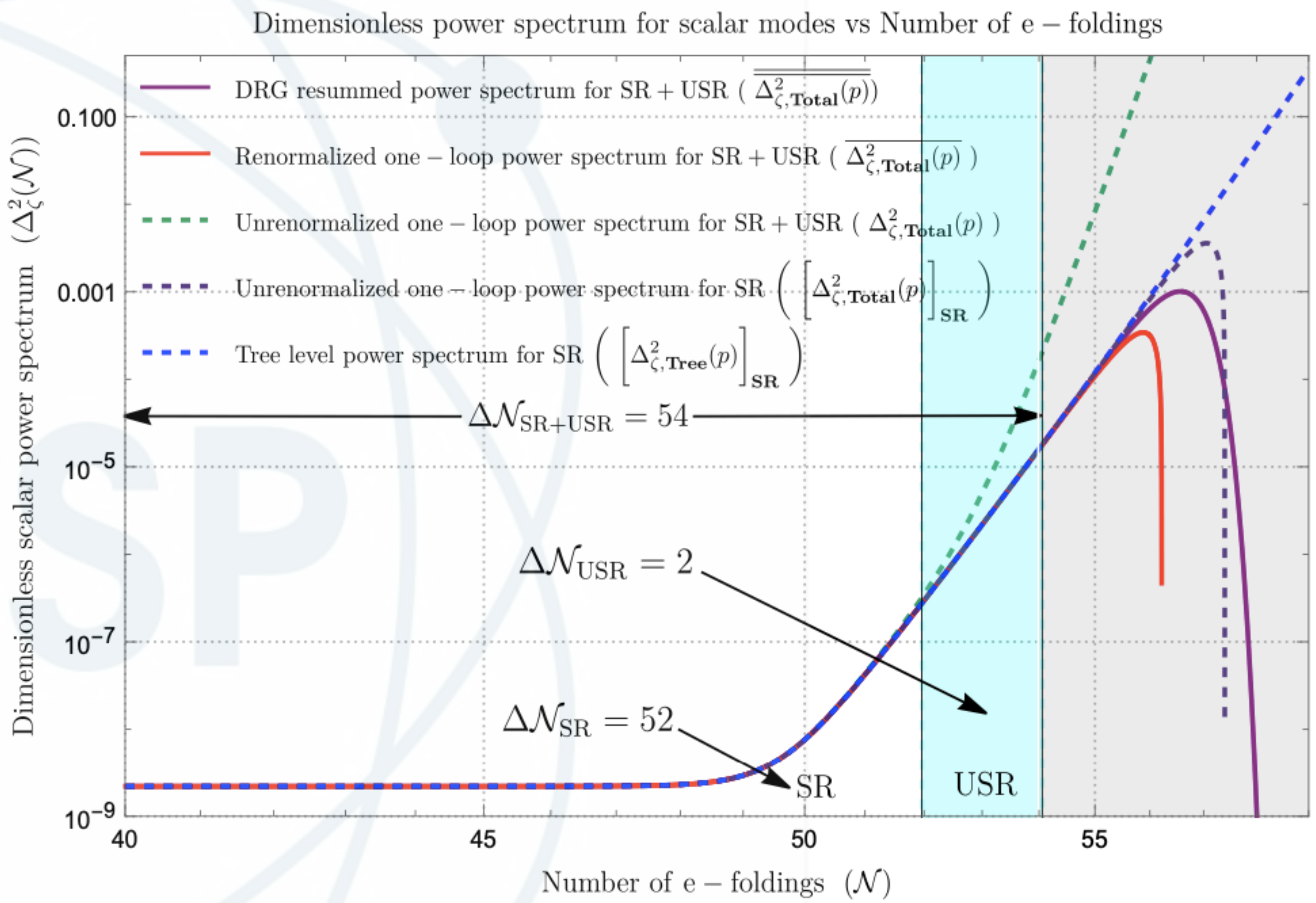
arXiv:2301.00599 **[astro-ph.CO]**

What was the Problem of the Problem??

No quadratic divergence term is present !!

Choudhury, MRG, Sami 2301.10000 [astro-ph.CO]

$$
\begin{aligned}
\Delta^2_{\zeta,\textbf{Total}}(p) &= \Delta^2_{\zeta,\textbf{Tree}}(p) + \Delta^2_{\zeta,\textbf{One-loop}}(p)\\
&= \Bigg\{ \underbrace{\left[\Delta^2_{\zeta,\textbf{Tree}}(p)\right]_{\textbf{SR}}}_{\textbf{SR contribution for inflation}}\\
&\quad + \underbrace{\left[\Delta^2_{\zeta,\textbf{One-loop}}(p)\right]_{\textbf{SR}}}_{\textbf{Sub-leading one-loop correction due to SR}}\\
&\quad + \underbrace{\left[\Delta^2_{\zeta,\textbf{One-loop}}(p)\right]^2_{\textbf{USR on SR}}}_{\textbf{Sub-leading one-loop correction due to USR on SR}} \Bigg\}.\\
&= \left[\Delta^2_{\zeta,\textbf{Tree}}(p)\right]_{\textbf{SR}} \Bigg\{ 1 + \left[\Delta^2_{\zeta,\textbf{Tree}}(p)\right]_{\textbf{SR}} \left(c_{\textbf{SR}} - \frac{4}{3}\ln\left(\frac{k_e}{p_*}\right)\right)\\
&\quad + \frac{1}{4}\left[\Delta^2_{\zeta,\textbf{Tree}}(p)\right]_{\textbf{SR}} \left((\Delta\eta(\tau_e))^2 \left(\frac{k_e}{k_s}\right)^6 - (\Delta\eta(\tau_s))^2 \right) \ln\left(\frac{k_e}{k_s}\right) \Bigg\}
\end{aligned}
$$



$$\boxed{\Delta\mathcal{N}_{\rm USR} = \mathcal{N}_e - \mathcal{N}_s = \ln(k_e/k_s) \approx \ln(10) \approx 2}$$

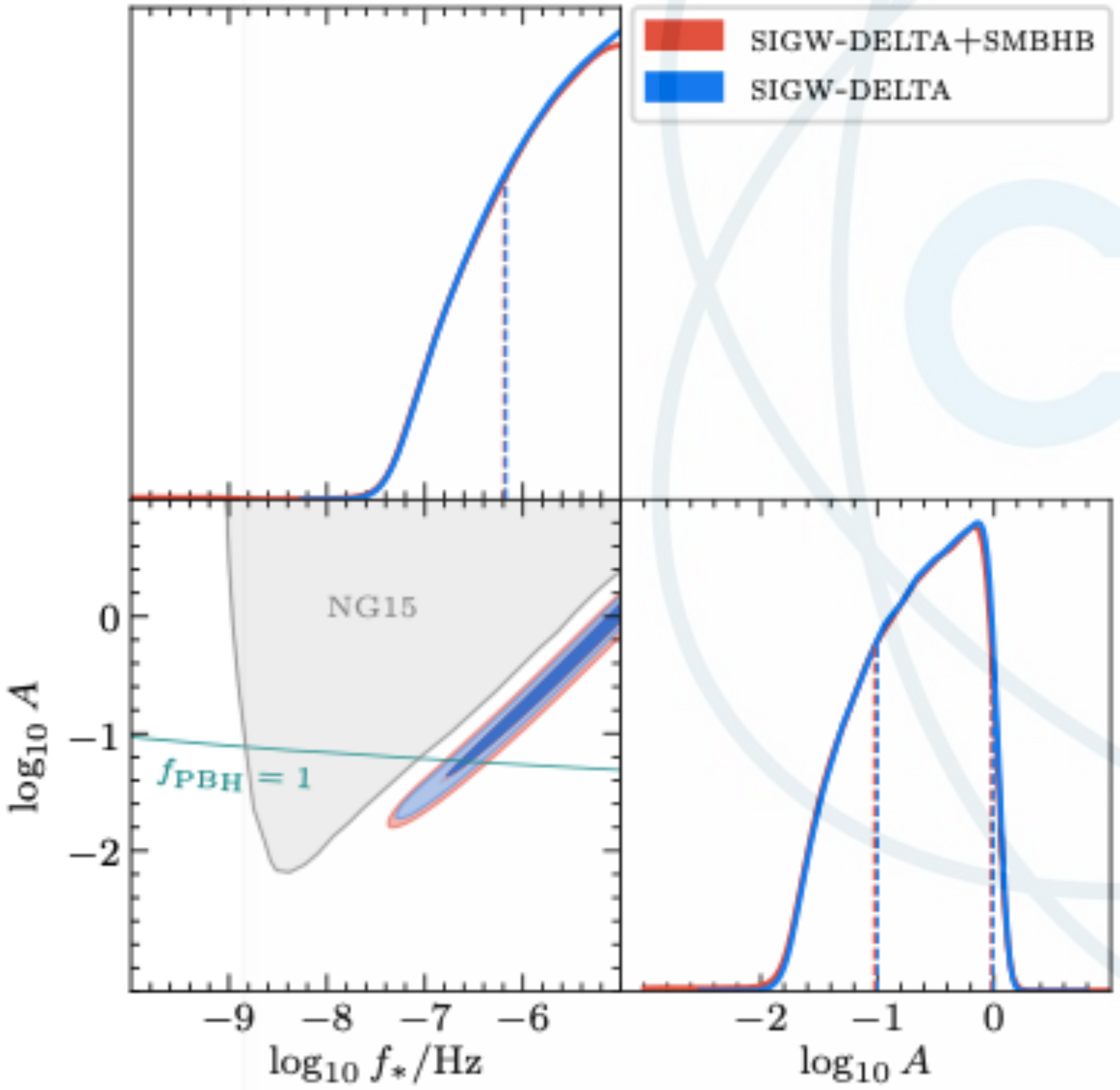
Consequence:

$$\boxed{M_{\rm PBH} \sim 10^2 \text{gm}}$$

Then No DM explanation possible!!

SIGW- Delta

$$\mathcal{P}_{\mathcal{R}}\left(k\right) = A\,\delta\left(\ln k - \ln k_*\right)$$

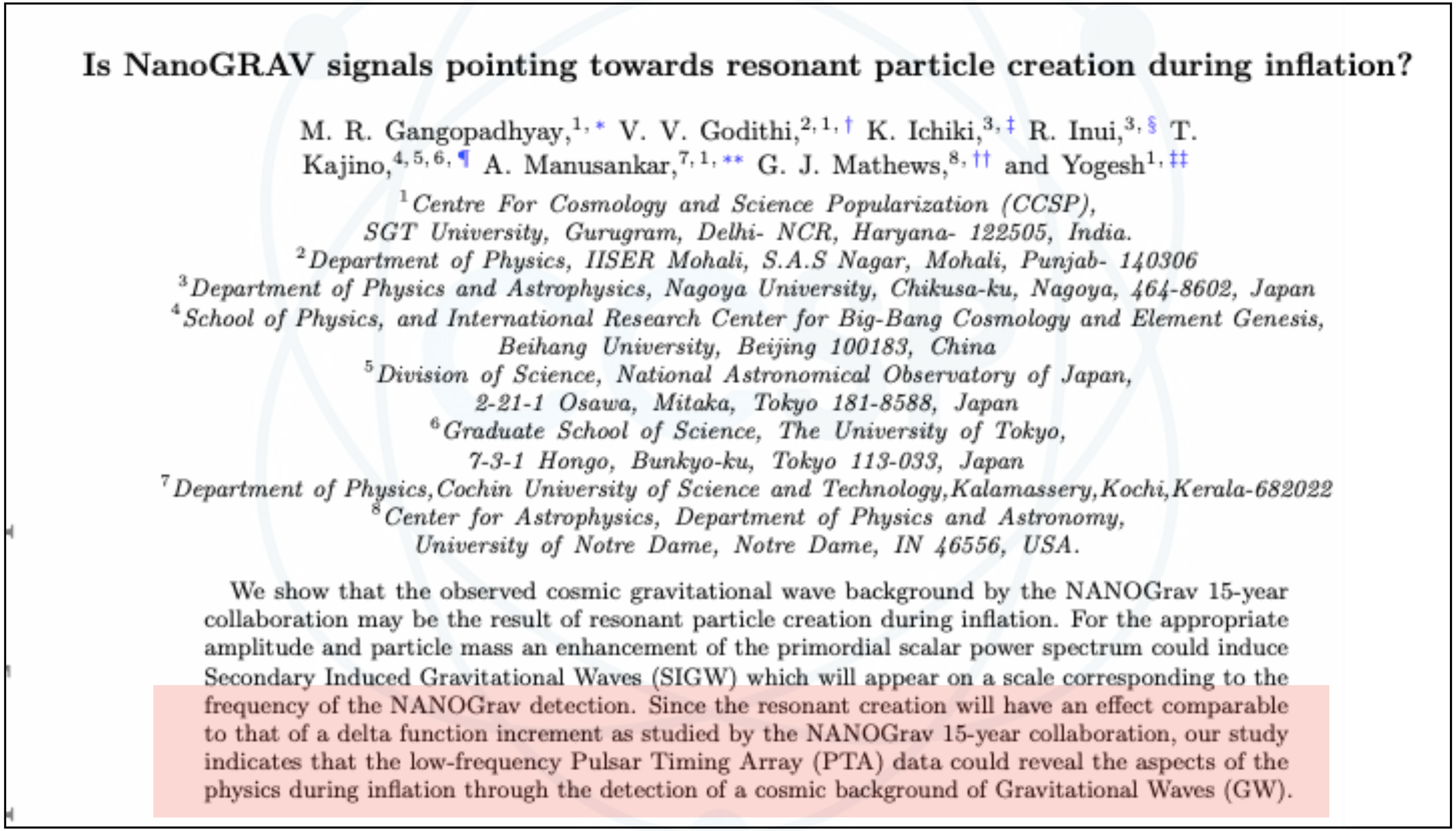


$$f = \frac{k}{2\pi} = 1.5 \times 10^{-15} \left(\frac{k}{1\ \mathrm{Mpc}^{-1}}\right) \mathrm{Hz}$$

$$\Omega_G W \;=\; fn(A_{GW}, f)$$

NANOGrav Collaboration, arXiv: 2306.16219

Is it possible to get SIGW-Delta from theory??



Is NanoGRAV signals pointing towards resonant particle creation during inflation?

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We show that the observed cosmic gravitational wave background by the NANOGrav 15-year collaboration may be the result of resonant particle creation during inflation. For the appropriate amplitude and particle mass an enhancement of the primordial scalar power spectrum could induce Secondary Induced Gravitational Waves (SIGW) which will appear on a scale corresponding to the frequency of the NANOGrav detection. Since the resonant creation will have an effect comparable to that of a delta function increment as studied by the NANOGrav 15-year collaboration, our study indicates that the low-frequency Pulsar Timing Array (PTA) data could reveal the aspects of the physics during inflation through the detection of a cosmic background of Gravitational Waves (GW).

Theoretical Background

The amplitude of the density perturbation of amplitude $\delta_H(k)$ when it crosses the Hubble radius

$$\delta_H(k) \approx \frac{H^2}{5\pi\dot{\phi}}$$

where H is the Hubble parameter and $\dot{\phi}$ is the inflaton field time derivative when the comoving wavenumber k crosses the Hubble radius during inflation.

If the inflaton field has a simple Yukawa coupling (λ) to a fermion field ψ of mass m, then the interaction Lagrangian density is given by

$$\mathscr{L}_Y = -N\,\lambda\phi\bar{\psi}\psi$$

In this case the equation of motion for the inflaton field can be written as

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} - N\lambda\langle\bar{\psi}\psi\rangle = 0$$

for N fermions of mass m coupled to the inflaton.

Chung, Kolb, Risotto, Thackchev, PRD 62, 043508

Theoretical Background

The effective mass of the fermion is then given by :

$$M(\phi) = m - N\lambda\phi$$

The effective mass term thus vanishes as the inflaton field value reaches $\phi_* = m/N\lambda$. Hence, a resonant creation of this fermion field will take place as $\phi \to \phi_*$. Which leads to:

The fermion VEV:

$$\boxed{\langle\bar{\psi}\psi\rangle = n_* \Theta(t - t_*) \exp\left[-3H_*(t - t_*)\right]}$$

E.O.M.

$$\boxed{\ddot{\phi} + 3H\dot{\phi} = -V'(\phi) + N\lambda\langle\bar{\psi}\psi\rangle}$$

MRG, Ichiki, Mathews, Kajino, PRD 92, 1235192

Theoretical Background

Solution to the equation of Motion

$$\dot{\phi}(t > t_*) = \phi(t > t_*)_{\lambda=0} \\ + N\lambda n_* \theta(t - t_*) \exp\left[-3H_*(t - t_*)\right]$$

Primordial Power spectrum as it exits the horizon

$$\delta_H(k) = \frac{[\delta_H(k)]_{\lambda=0}}{1 - \theta(a - a_*)\,|\,\dot{\phi}_*\,|^{-1} N\lambda n_* H_*^{-1}(a_*/a)^3 \ln(a/a_*)}$$

The perturbation spectrum becomes:

$$\delta_H(k) = \frac{\left[\delta_H(k)\right]_{\lambda=0}}{1 - \theta(k - k_*) A (k_*/k)^3 \ln(k/k_*)}$$

Theoretical Background

The coefficient A can be directly related to the coupling constant λ using for the particle production Bogolyubov coefficient

$$|\beta_k|^2 = \exp\left(\frac{-\pi k^2}{a_*^2\lambda\,|\dot{\phi}_*|}\right)$$

Then the number density of fermions (n_*) can be calculated as:

$$n_* = \frac{2}{\pi^2}\int_0^\infty dk_p\, k_p^2\, |\beta_k|^2 = \frac{\lambda^{3/2}}{2\pi^3}|\dot{\phi}_*|^{3/2}$$

This gives:

$$A = \frac{N\lambda^{5/2}}{2\pi^3}\frac{\sqrt{|\dot{\phi}_*|}}{H_*} \approx \frac{N\lambda^{5/2}}{2\sqrt{5}\pi^{7/2}}\frac{1}{\sqrt{\delta_H(k_*)|_{\lambda=0}}}$$

Theoretical Background

Given that the CMB normalization requires $\delta_H(k)\,|_{\lambda=0} \sim 10^{-5}$, we then have $A \sim 1.3N\lambda^{5/2}$

One can deduce that $\lambda \leq 1$ requires $N > 1$as expected for the given values of A.

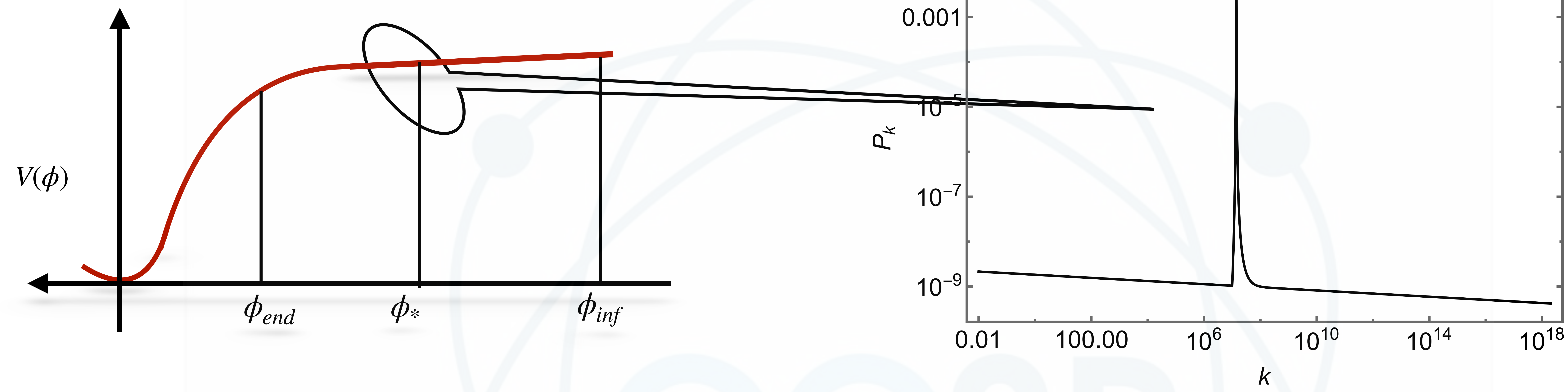
Finally we can write the power spectrum

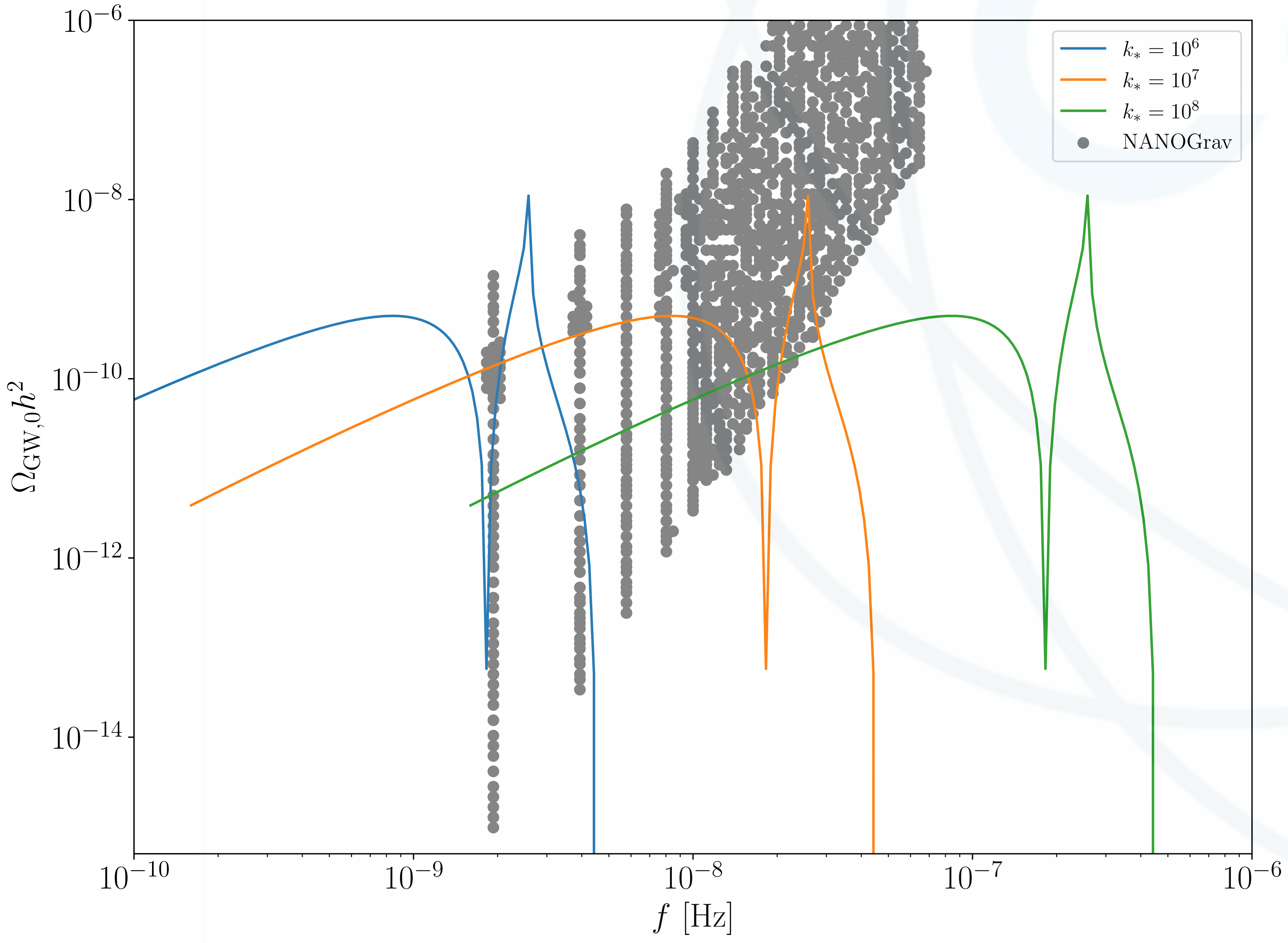
$$P(k) \sim \delta_H^2(k)$$

Allowing the contribution from the scale dependence of the scalar spectral index, n_s, modelled by a running $\alpha(= d\ln n_s / d\ln k)$, and running of the running, $\beta(= d^2 \ln n_s / d(\ln k)^2)$. The scalar power spectrum, can be re-written in a more familiar form:

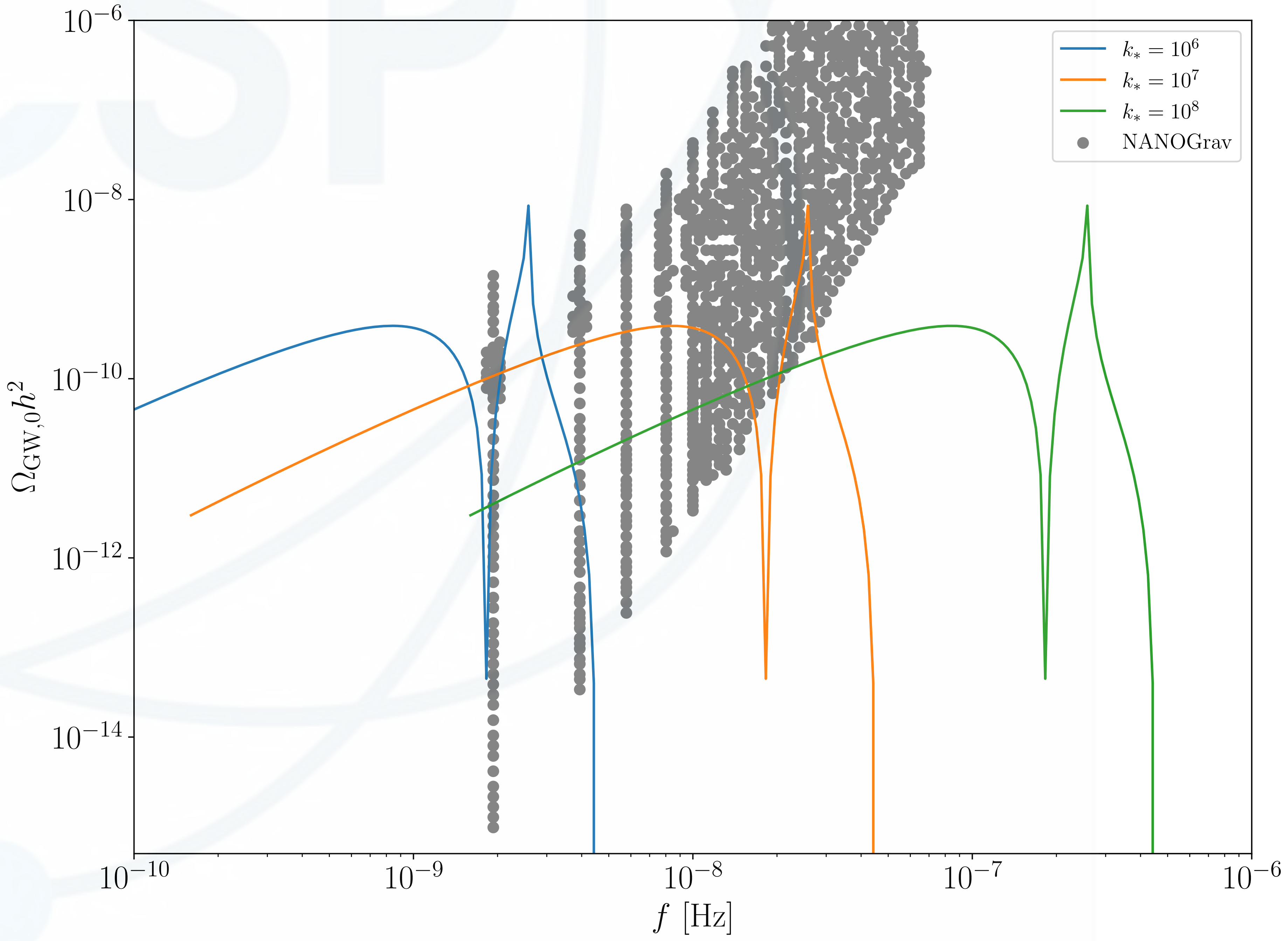
$$P_k = A_s \left(\frac{k}{k_p}\right)^{n_s - 1 + \frac{\alpha_s}{2}\ln\left(\frac{k}{k_p}\right) + \frac{\beta_s}{6}\left(\ln\left(\frac{k}{k_p}\right)\right)^2}$$

Resonance and GW



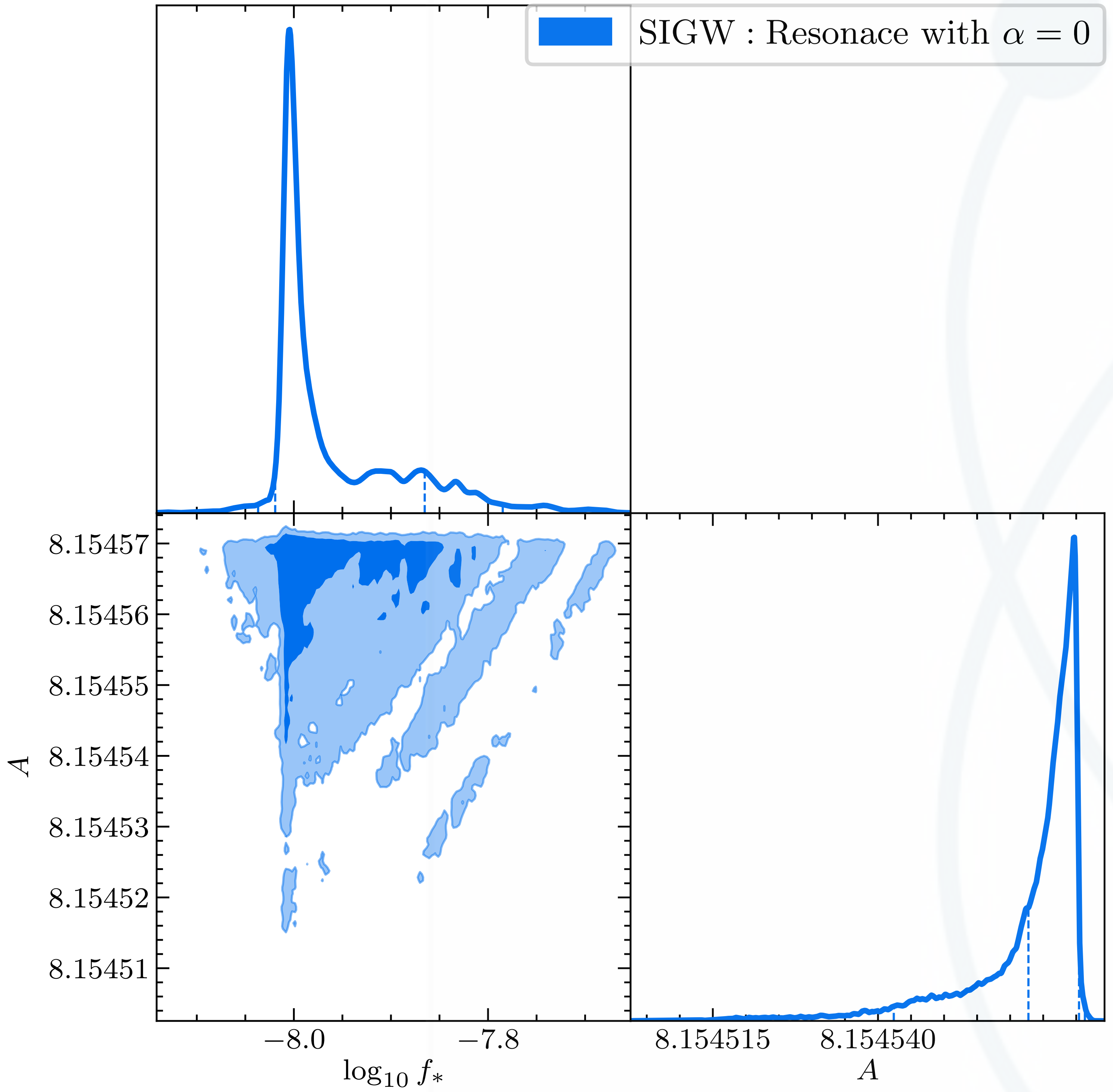


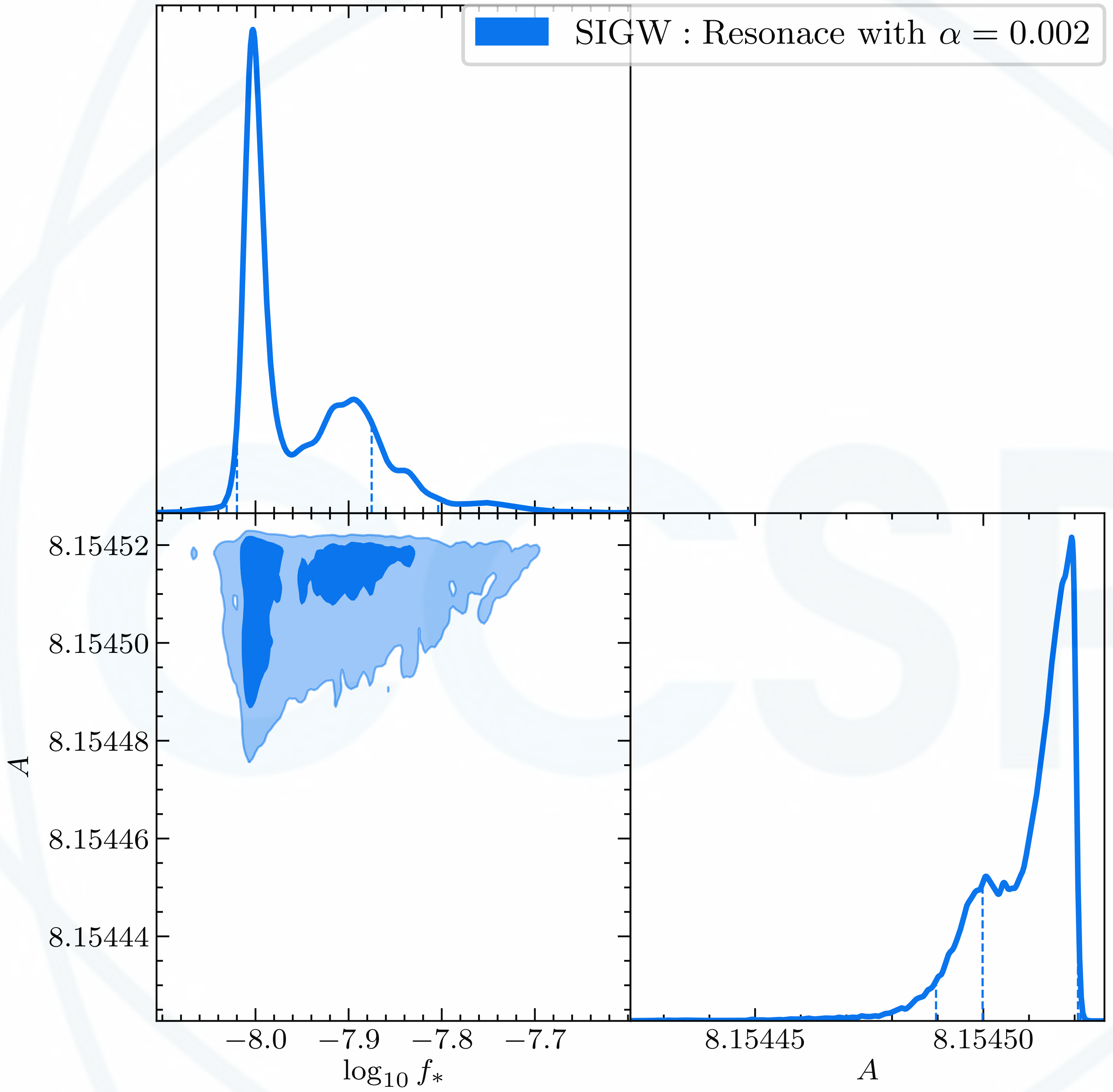
$\alpha = 0.0, \beta = 0.0$

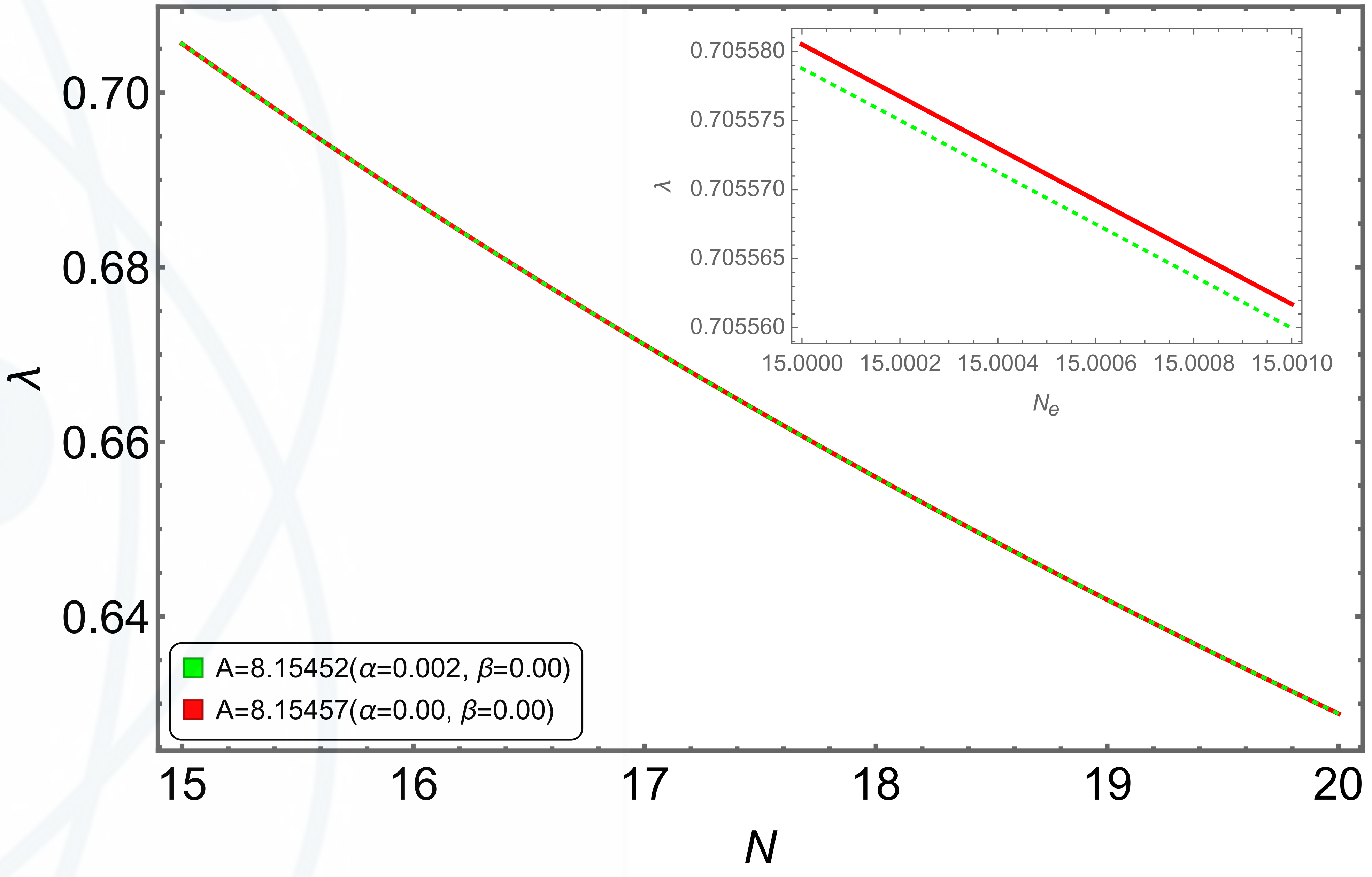


$\alpha = 0.002, \beta = 0$

MCMC Analysis

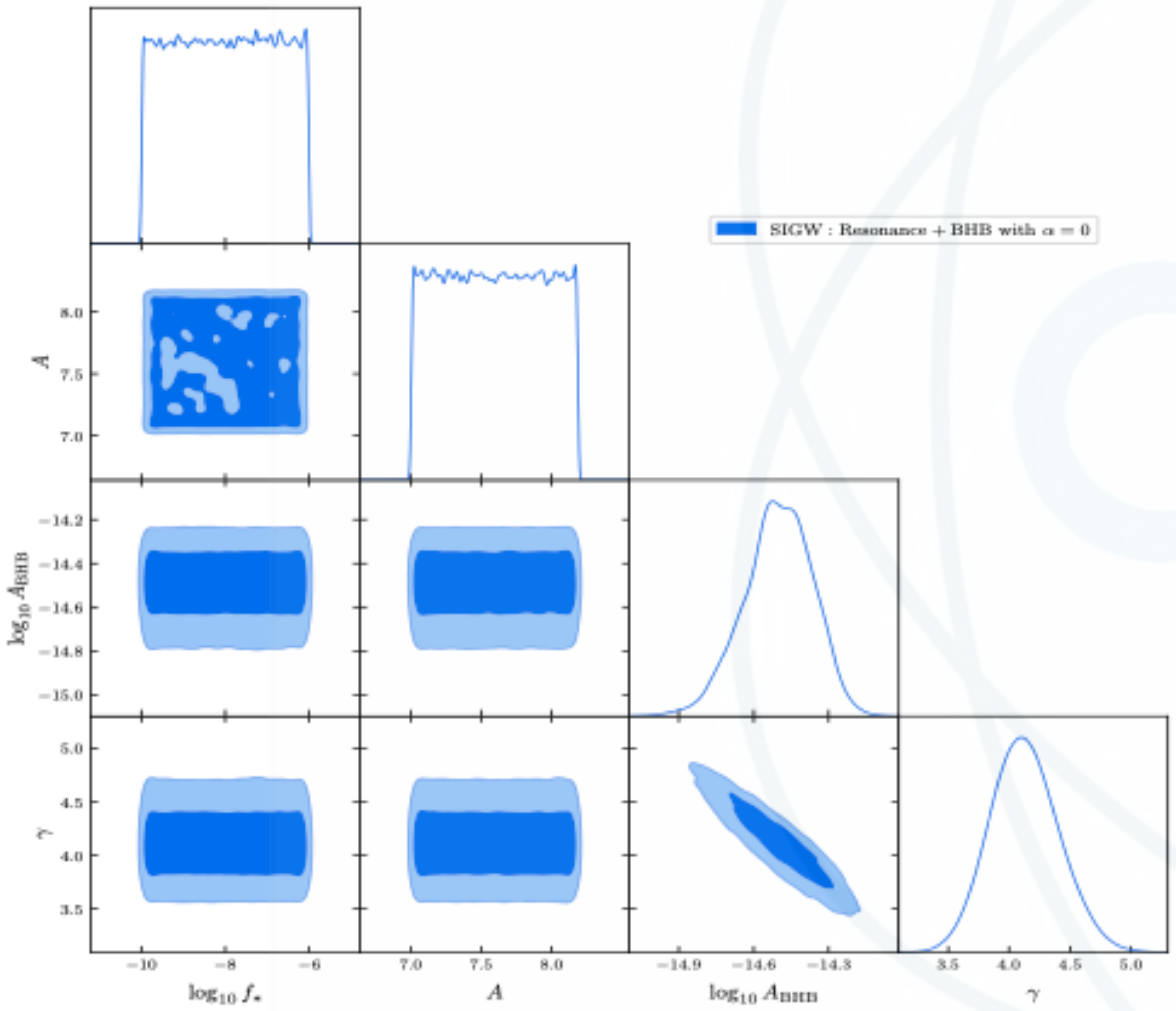






Bayes Factor ~ 65

MCMC Analysis



Parameters	Prior
A	Uniform $[7.0,\ 8.19]$
f_* /[Hz]	Uniform $[10^{-10},\ 10^{-6}]$
N	Uniform $[10,\ 30]$
λ	Uniform $[0.30,\ 1.0]$
$(\log_{10} A_{\rm BHB},\ \gamma)$	Normal $[\boldsymbol{\mu}_{\rm BHB}, \boldsymbol{\sigma}_{\rm BHB}]$

Bayes Factor ~ 60

What's The Future

A. Constraining the theoretical model required to realise the production of SIGW and PBHs through the early Universe litmus tests such as BBN.

B. PBHs with mass less than 10^9 g have evaporated before the commencement of BBN however the study of these, can unravel the mysteries related to Dark Matter, Baryogenesis etc.

C. Since, GW signals are very clean, the detection of a GW signal of non-astrophysical origin, could have highest of impact on the understanding of evolution of our Universe.

D. Please wait for next releases by the PTA collaborations, remember NanoHertz => Crest to Crest 20-30 years!!

Thank You