Instituto de Física
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Impacts of the Stochastic Background of Gravitational Waves in the Late Universe

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BSCG - 2022
CBPF

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Content

Introduction
- The H_0 and σ_8 tensions
- The NANOGrav Experiment
- Motivations
- Retrospective
- NANOGrav results and inflation

SBGW in light of NANOGrav + full dataset
- Stochastic gravitational waves from NANOGrav revisited
- The Model
- Observational Results
- Measuring the spectrum of primordial GW

GWs and the H_0 tension problem

Conclusions

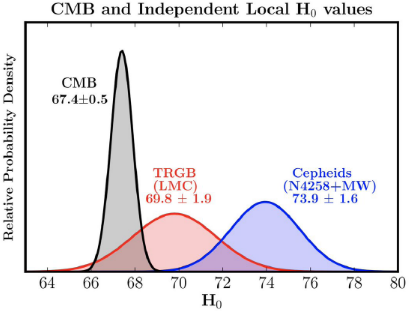
The H_0 tension

- CMB data provide the initial condition for the subsequent evolution of structure formation in the Universe.
- One can then use the standard model to make a prediction for the LSS in a late-time Universe.
- Observations of the LSS thus offer an end-to-end test of this prediction.
- We have indications that this end-to-end test can be failing.

The H_0 tension

- The discrepancy in the inferred value of H_0 between early (model dependent) and late time constraints - 4σ to 6σ.

Aghanim, N., et al., A&A 641, A6 (2020); Riess, A.G., et al., ApJL 934 L7 (2022)



Freedman, Wendy L. et al., APJ 882, No 1, (2019).

- An interesting possibility would be a signal for a new physics beyond the standard model.

However...

- The new physics that increases the current expansion rate usually suppresses the structure formation, which tend to be compensated by an increasing in the density of CDM, leading to an increase in the σ_8 tension.

Approaches to the tension

- Early dark energy, interacting neutrinos, modified gravity, $\lambda(t)$, N_{eff} ...

  - No easy extension can solve all tensions and accommodate all data
  - Adding N_{eff} can relax the tension only because the H_0 error from Planck is increased but the central value is still low.
  - Marginalysing over additional free parameters broadens the posterior of all cosmological parameters, in particular those correlated with the extra ones.
  - Free parameters result in larger uncertainties in the IR parameters.

An Alternative View

"*New Physics in light of the H_0 tension: an alternative view*",

S. Vagnozzi, Phys. Rev. D, 102, 023518, 2020.

- Are there values of w and N_{eff} which, if predicted/fixed by a physical theory, will lead to reduction in the tension while not being so disfavored against ΛCDM?
- The reduction in the tension would then be due to a genuine shift in the central value of $H0$.
- What value of w or N_{eff} would such a physical theory have to predict in order for the high-redshift estimate of H_0 match the local distance ladder estimate?
- Is there a "sweet spot" between decrease in Bayesian evidence and reduction in the H_0 tension?

- Suggests a kind of frequentist/bayesian approach.
- D.o.f. reduced with respect to the case where the parameters are free to vary.
- It was found that models with $N_{eff} = 3.95$ and $w = -1.3$ solves the tension but are strongly disfavored.
- Models with $N_{eff} = 3.45$ and $w = -1.1$ brings the tension down to 1.5σ and 2σ respectively, but are weakly and strongly disfavored by the data with respect to ΛCDM.
- There are models which predict such values.

Coming Soon

And then we extend the analysis to the parameter σ_8 using more recent data...

An empirical investigation into cosmological tensions.

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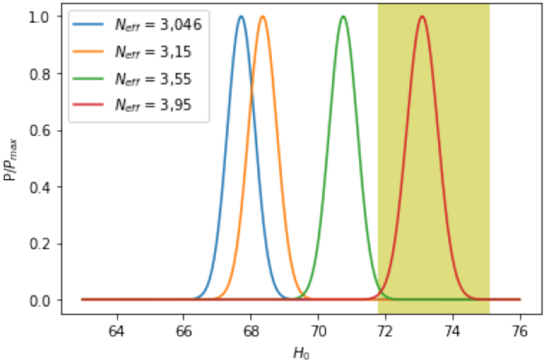
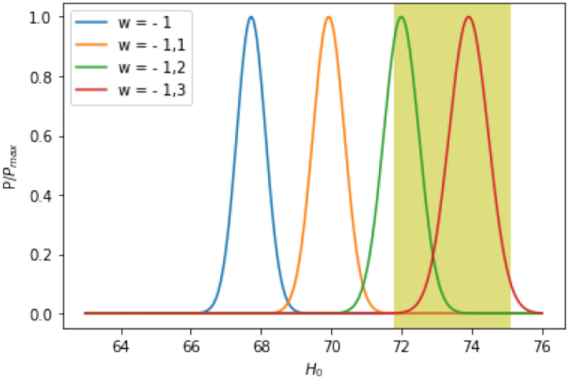
H_0 and N_{eff}

Planck 2018 + BAO + Pantheon



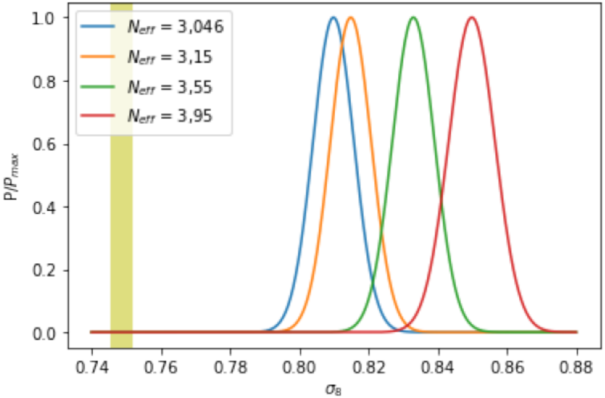
$$\Delta H_0 = H_0 - H_0|_{\Lambda CDM} \approx 5,9\Delta N_{eff} = 5,9(N_{eff} - 3,046)$$

H_0 and w



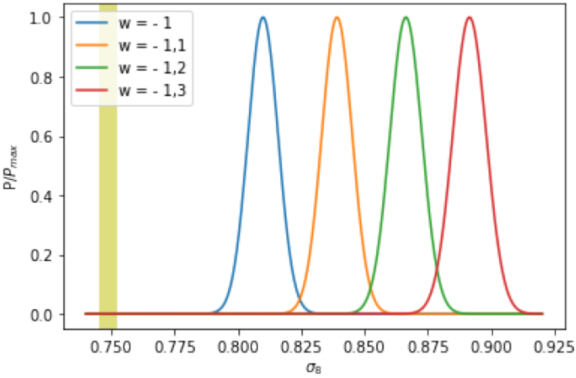
$$\Delta H_0 = H_0 - H_0|_{\Lambda CDM} \approx -20,6\Delta w = -20,6(1+w)$$

σ_8 and N_{eff}



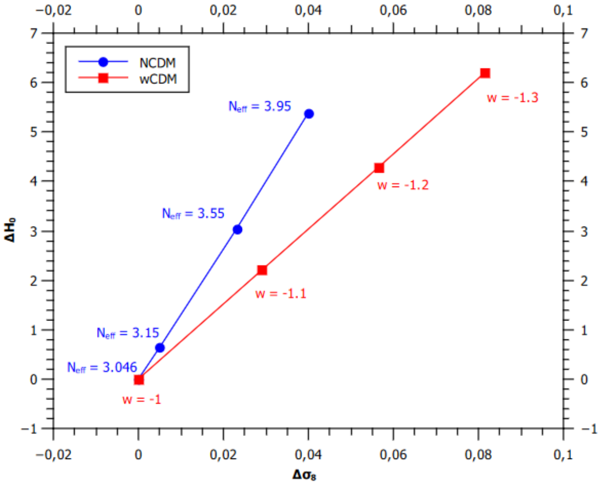
$$\Delta\sigma_8 = \sigma_8 - \sigma_8|_{\Lambda CDM} \approx 0,04\Delta N_{eff} = 0,04(N_{eff} - 3,046)$$

σ_8 and w



$$\Delta\sigma_8 = \sigma_8 - \sigma_{8|_{\Lambda CDM}} \approx -0,27\Delta w = -0,27(1+w)$$

Relating ΔH_0 and $\Delta\sigma_8$



ΔN_{eff} and Δw

- The behaviour of the interpolations suggests that models with ΔN_{eff} performs better than models with Δw regarding the two tensions.

How much the extra parameters are allowed to vary according to the data?

- The most stringent limit of ΔN_{eff} constrained by Planck 2018 is $\Delta N_{eff} \sim 0.11$ at 68%.
- The most stringent limit on w is $w \sim -0.06$ at 68%.
- There are models which predicts the desired value of N_{eff}!

Let us analyze one of them...

Stochastic Background of Gravitational Waves

Gravitational waves must contribute to N_{eff}!

SBGW: Cosmic strings; phase transitions; PBH; merging supermassive BH binaries; primordial tensor fluctuations...

The primordial power spectrum from scalar and tensor fluctuations:

$$\mathcal{P}_{\mathcal{R}}(k) = \frac{k^3}{2\pi^2}|\mathcal{R}_k|^2$$

$$= A_\mathrm{s}\left(\frac{k}{k_*}\right)^{n_\mathrm{s}-1}$$

$$\mathcal{P}_\mathrm{t}(k) = \frac{k^3}{2\pi^2}\left(|h_k^+|^2 + |h_k^\times|^2\right) = A_\mathrm{t}\left(\frac{k}{k_*}\right)^{n_\mathrm{t}}$$

We can also write the tensor amplitude in terms of r as $A_T = r\,A_s$.

- When the tensor power increases with the frequency ($n_T > 0$) we say we have a blue tilt - high amplitude at high frequencies.

Primordial GW's contribution to ρ.

The tensor power spectrum at a given conformal time is related to its primordial counterpart as follows

$$\mathcal{P}_T(\eta, k) = \mathcal{T}_T^2(\eta, k)\mathcal{P}_T^{\rm prim}(k)\,,$$

where transfer function accounts for the evolution of tensor perturbations across the various epochs of the Universe's expansion history up to η.
The total energy density in GWs can be computed as,

$$\rho_{\rm GW} = \int_{k_{\rm IR}}^{k_{\rm UV}} d\ln k\,\frac{\mathcal{P}_T(k)}{32\pi G a^2}\left[\mathcal{T}'(k,\eta_0)\right]^2\,,$$

Primordial GW's contribution to N_{eff}

The effective number of relativistic species receives an extra contribution,

$$N_{\rm eff} \approx 3.046 + \left[3.046 + \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\right]\frac{A_s r}{24 n_T}\left(\frac{k_{\rm UV}}{k_\star}\right)^{n_T}$$

- The contribution N_{eff}^{GW} is completely negligible in models that predict a red tensor spectrum ($n_T < 0$), like standard inflation.
- The value of N_{eff}^{GW} impacts the redshift of rad/matter equality, z_{eq}, affecting the whole background expansion history.
- This affects the constraints on several cosmological parameters including H_0.

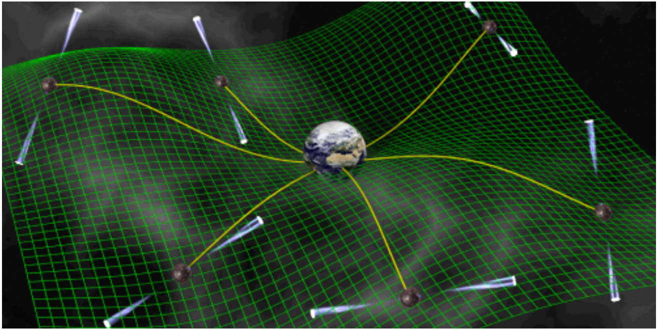
Wait a minut!

Was the Stochastic Background of Gravitational Waves ever detected at first place?

A Possible Detection

In 2020 NANOGrav reported evidence for a stochastic process affecting pulsar timing residuals in its 12.5-year dataset.

It might be the first detection of a stochastic gravitational wave background!



NANOGrav Results - 2020

The NANOGrav 12.5-year Data Set:
Search For An Isotropic Stochastic Gravitational-Wave Background

Zaven Arzoumanian,[1] Paul T. Baker,[2] Harsha Blumer,[3,4] Bence Bécsy,[5] Adam Brazier,[6,7] Paul R. Brook,[3,4]
Sarah Burke-Spolaor,[3,4,8] Shami Chatterjee,[6] Siyuan Chen,[9,10,11] James M. Cordes,[6] Neil J. Cornish,[5]
Fronefield Crawford,[12] H. Thankful Cromartie,[6] Megan E. DeCesar,[13,14,*] Paul B. Demorest,[15]
Timothy Dolch,[16] Justin A. Ellis,[17] Elizabeth C. Ferrara,[18] William Fiore,[3,4] Emmanuel Fonseca,[19]
Nathan Garver-Daniels,[3,4] Peter A. Gentile,[3,4] Deborah C. Good,[20] Jeffrey S. Hazboun,[21,*]
A. Miguel Holgado,[22,23] Kristina Islo,[24] Ross J. Jennings,[6] Megan L. Jones,[24] Andrew R. Kaiser,[3,4]
David L. Kaplan,[24] Luke Zoltan Kelley,[25] Joey Shapiro Key,[21] Nima Laal,[26] Michael T. Lam,[27,28]
T. Joseph W. Lazio,[29] Duncan R. Lorimer,[3,4] Jing Luo,[30] Ryan S. Lynch,[31] Dustin R. Madison,[3,4,*]
Maura A. McLaughlin,[3,4] Chiara M. F. Mingarelli,[32,33] Cherry Ng,[34] David J. Nice,[13]
Timothy T. Pennucci,[35,36,*] Nihan S. Pol,[3,4,37] Scott M. Ransom,[35] Paul S. Ray,[38] Brent J. Shapiro-Albert,[3,4]
Xavier Siemens,[26,24] Joseph Simon,[29,39] Renée Spiewak,[40] Ingrid H. Stairs,[20] Daniel R. Stinebring,[41]
Kevin Stovall,[15] Jerry P. Sun,[26] Joseph K. Swiggum,[13,*] Stephen R. Taylor,[37] Jacob E. Turner,[3,4]
Michele Vallisneri,[29] Sarah J. Vigeland,[24] Caitlin A. Witt,[3,4]

The NANOGrav Collaboration

Z. Arzoumanian et al. [NANOGrav],
``The NANOGrav 12.5 yr Data Set: Search for an Isotropic Stochastic Gravitational-wave Background,"
Astrophys. J. Lett. 905, no.2, L34 (2020)

"Strong evidence for a stochastic common-spectrum process against independent red noise process"

Caution! Detection of spatial quadrupolar correlations is required for the NANOGrav signal to be confirmed as a genuine SGWB detection

If confirmed, it will represent the first detection of SBGW!

NANOGrav - Only the first!

There is reason to be cautiously optimistic:

On the evidence for a common-spectrum process in the search for the nanohertz gravitational-wave background with the Parkes Pulsar Timing Array

Boris Goncharov,[1,2,3] R. M. Shannon,[1,2] D. J. Reardon,[1,2] G. Hobbs,[4] A. Zic,[5,4] M. Bailes,[1,2] M. Curyło,[6] S. Dai,[4,7] M. Kerr,[8] M. E. Lower,[1,4] R. N. Manchester,[4] R. Mandow,[4,1] H. Middleton,[1,9,2] M. T. Miles,[1,2] A. Parthasarathy,[10] E. Thrane,[11,2] N. Thyagarajan,[4] X. Xue,[12,13] X.-J. Zhu,[11,2] A. D. Cameron,[1,2] Y. Feng,[14] R. Luo,[4] C. J. Russell,[15] J. Sarkissian,[16] R. Spiewak,[17,1] S. Wang,[18,4] J. B. Wang,[18] L. Zhang,[19] and S. Zhang[20]

The Astrophysical Journal Letters, Volume 917, Number 2 (2021)

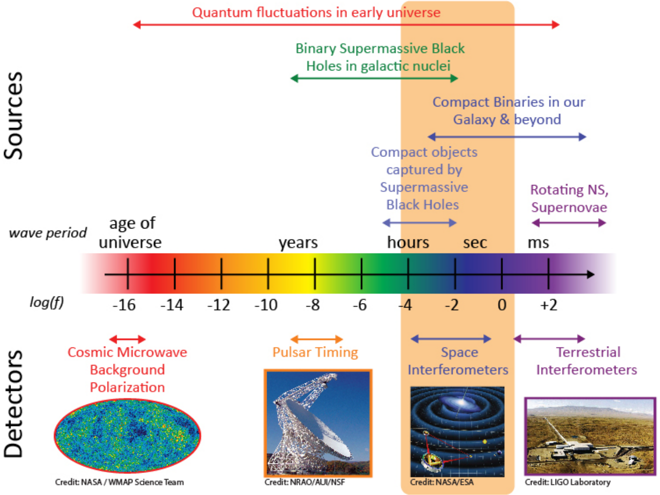
Common-red-signal analysis with 24-yr high-precision timing of the European Pulsar Timing Array: Inferences in the stochastic gravitational-wave background search

S. Chen[1,2★], R. N. Caballero[3†], Y. J. Guo[4], A. Chalumeau[5,1,2], K. Liu[4], G. Shaifullah[6,7], K. J. Lee[3,8,4], S. Babak[5,9], G. Desvignes[4,10], A. Parthasarathy[4], H. Hu[4], E. van der Wateren[11,12], J. Antoniadis[13,4,14], A.-S. Bak Nielsen[4,15], C. G. Bassa[11], A. Berthereau[1,2], M. Burgay[16], D. J. Champion[4], I. Cognard[1,2], M. Falxa[5], R. D. Ferdman[17], P. C. C. Freire[4], J. R. Gair[18], E. Graikou[4], L. Guillemot[1,2], J. Jang[4], G. H. Janssen[11,12], R. Karuppusamy[4], M. J. Keith[19], M. Kramer[4,19], X. J. Liu[20,19], A. G. Lyne[19], R. A. Main[4], J. W. McKee[21], M. B. Mickaliger[19], B. B. P. Perera[22], D. Perrodin[16], A. Petiteau[5], N. K. Porayko[4], A. Possenti[16,23], A. Samajdar[6], S. A. Sanidas[19], A. Sesana[6,7], L. Speri[18], B. W. Stappers[19], G. Theureau[1,2,24], C. Tiburzi[11], A. Vecchio[25], J. P. W. Verbiest[15,4], J. Wang[15], L. Wang[8] and H. Xu[3,26,8]

arXiv:2110.13184 [astro-ph.HE]

Things are getting more and more interesting everyday!

The Gravitational Wave Spectrum



Questions:

Can the NANOGrav signal be due to early universe SGWB?

If so, what are the implications for the primordial universe models?

Would such early universe models be in agreement with all the cosmological data we have today?

"Can the NANOGrav signal be due to an inflationary SGWB, and if so, what are the implications for inflationary parameters?"

"With a few caveats, I find that the answer to the first part of the question is Yes!"

- *Data requires* $T_{rh} < 100 GeV - 1 TeV$ *plus* $r \geq \mathcal{O}(10^{-6})$ *and* $0,7 \leq n_T \leq 1,3$.

Sunny Vagnozzi, Mon. Not. Roy. Astron. Soc. 502 (2021) L11.

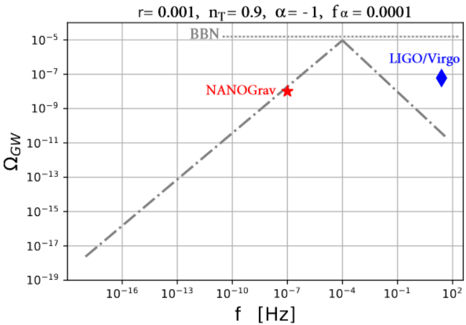
Spectral Shape

S. Kuroyanagi, T. Takahashi, S. Yokoyama

Blue-tilted inflationary tensor spectrum and reheating in the light of NANOGrav results

JCAP 01 (2021) 071.

- The thermal history of the Universe, such as reheating and late-time entropy production, affects the spectral shape of GWs.



The blue tilted tensor spectrum is predicted in several early universe models, including but not limited to:

- Solid Inflation;
- Non-commutative space-times;
- Spatial or temporal diffeomorphism invariance breaking;
- General violations of the null-energy condition;
- Couplings to gauge fields and spin-2 fields;
- Modified theories of gravity (Galileon-type interaction term, Gauss-Bonnet coupling...);
- Higher order effective gravitational action corrections;
- String gas cosmology, some bouncing modes..

In summary

Results so far

- For a non-instant reheating scenario of inflation, consistency with data requires a low reheating scale, $T_{rh} < 100 GeV - 1 TeV$.
- The thermal history of the Universe, such as reheating and late-time entropy production, affects the spectral shape of IGWs at high frequencies and permits evading the upper bounds.
- An inflationary interpretation of the NANOGrav signal is not excluded.

However...

- Need for a more general tensor power spectrum.
- Consider early universe models rather than only inflation.
- Use other cosmological data and full likelihoods.

Beyond Standard Inflation

There are several motivations to go beyond ***Standard*** Inflation:

- Singularity problem, fine tunings, reheating, naturalness...

Alternatives:

D. Polarski, A. Starobinsky, Y. Verbin, JCAP 01 (2022) 052.

M. Bastero-Gil, A. Berera, Rudnei O. Ramos, Rosa J., PRL, 117, 151301 (2016).

N. Pinto-Neto, J. Fabris, J. Toniato, G. Vicente, S. Vitenti, PRD, 101,123519 (2020).

W. Hipólito-Ricaldi, R. Brandenberger, E. Ferreira, L. Graef, JCAP, 024 (2016).

R. Brandenberger, P. Peter, Found. of Phys. 47, 797 (2017).

E. Bittencourt, U. Moschella, M. Novello, J.D. Toniato, PRD 93, 124023 (2016).

R. Brandenberger; S. E. Jorás, J. Martin, PRD 66, 083514 (2002).

A. H. Chamseddine, V. Mukhanov, JCAP 03 (2017) 009.

F. Finelli, JCAP 0310 (2003) 011.

"Primordial Gravitational Waves from NANOGrav: a broken power-law approach"

M. Benetti, L. L. Graef, S. Vagnozzi, Phys. Rev. D, 105, 043520, 2022.

Beyond Single Power-Law Tensor Spectrum

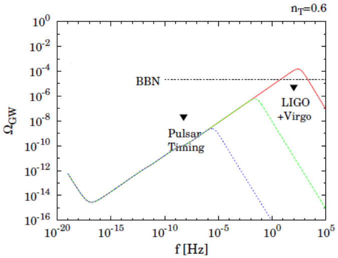
S. Kuroyanagi, T. Takahashi, S. Yokoyama, JCAP 02 (2015) 003.

The scales of CMB and LIGO differ by more than 19 orders of mag!

"We proposed a more generalized modeling of the spectrum, where the spectral power dependence changes at the characteristic frequency f_α."

"This generic modeling accommodates various models of the early Universe."

$$\Omega_{\rm GW}(k) = \begin{cases} \frac{1}{12}\left(\frac{k}{aH}\right)^2 T_T^2(k) A_T(k_{\rm ref}) \left(\frac{k}{k_{\rm ref}}\right)^{n_T} & (k < k_\alpha), \\ \frac{1}{12}\left(\frac{k}{aH}\right)^2 T_T^2(k) A_T(k_{\rm ref}) \left(\frac{k_\alpha}{k_{\rm ref}}\right)^{n_T} \left(\frac{k}{k_\alpha}\right)^{\alpha} & (k > k_\alpha) \end{cases}$$



Broken Power-Law

- We require a spectrum which is blue for frequencies below the break, and red above, with the break frequency lying between the PTA and interferometer ranges.

- The break helps:

  a) Ensuring consistency with LIGO/Virgo's upper limits;

  b) Suppressing the SGWB contribution to the radiation energy density in the early Universe (as captured by the parameter N_{eff}^{GW}) - consistency with CMB and BBN constraints.

Methodology and Datasets

We considered the following datasets:

- NANOGrav
- LIGO/VIRGO
- RCF - Planck (2018) / Keck Array / BICEP2.
- Barion Acoustic Oscillations - SDSS, BOSS galaxy sample...
- Pantheon Compillation - SNeIa data.
- Cosmic Chronometers – measurements of the expansion rate of the universe H(z) with galaxy data.

$\rightarrow$ We used the CAMB code in order to obtain the theoretical prediction for different models (parameters).

$\rightarrow$ The posterior distributions for the cosmological parameters are obtained by means of the CosmoMC, a code used to compare the theoretical predictions of the different models with the datasets.

Results

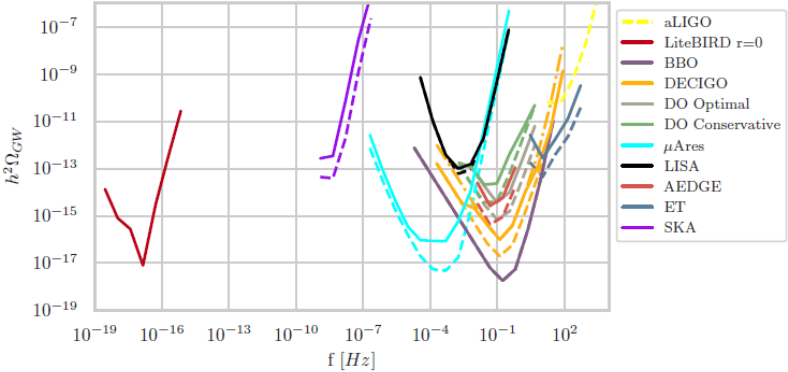
Dataset for the analysis:

CMB+BKP2+GWpriors+NANOGrav

CMB+BKP2+GWpriors+NANOGrav+BAO+Pth+CC

Analysis with f_α, r	f_α [Hz]	r	n_T
1) fixed	$10^{-6}/10^{-3}$	10^{-6}	1.31 ± 0.03
2) fixed	$10^{-6}/10^{-3}$	10^{-3}	0.98 ± 0.03
3) fixed	$10^{-6}/10^{-3}$	0.06	0.79 ± 0.03
4) free	$< 10^{-0.7}$	$> 10^{-6.6}$	0.97 ± 0.19

Detectors



P. Campeti, E. Komatsu, D. Poletti and C. Baccigalupi, ``Measuring the spectrum of primordial gravitational waves with CMB, PTA and Laser Interferometers," JCAP 01, 012 (2021).

Measuring the spectrum of primordial GW
with CMB, PTA and Laser Interferometers

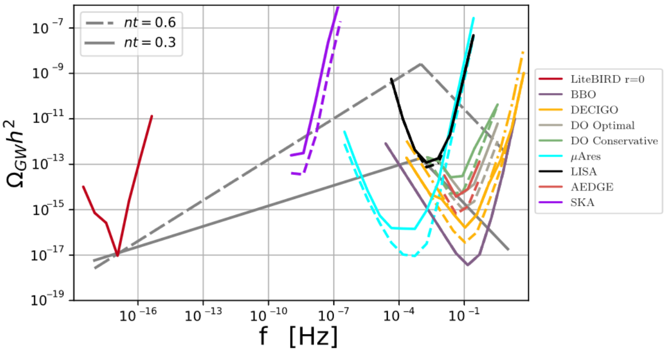
We investigate the possibility of measuring the primordial GW signal across 21 decades in frequencies, using CMB, PTA, and laser interferometers.

"We find excellent prospects for joint measurements of the GW spectrum by CMB and space-borne interferometers mission proposals."

P. Campeti, E. Komatsu, D. Poletti and C. Baccigalupi (2020)

Prospects for Detection

The double power-law model together with the predictions of the future experiments.

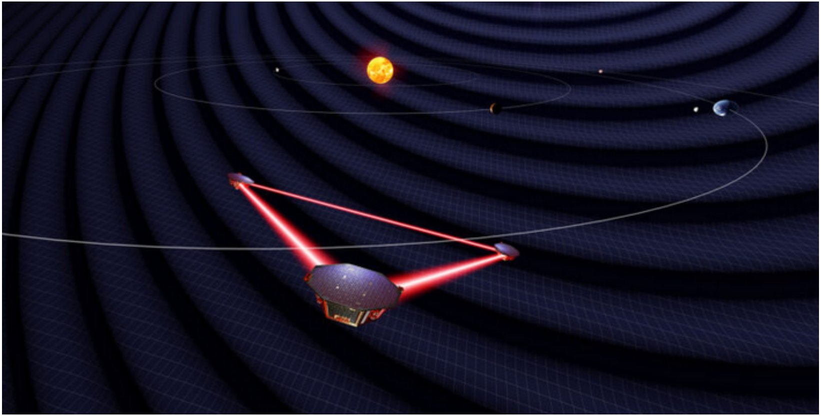


Conclusions and Prospects

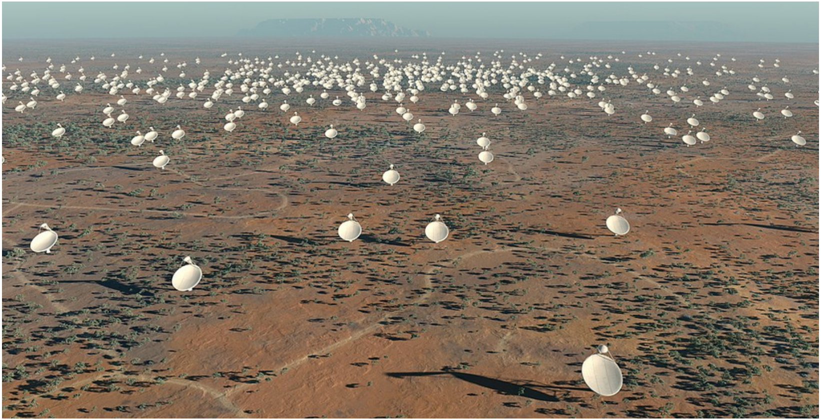
- We consider a model able to describe the whole frequency range between the CMB and LIGO, by means of two power laws of different inclination, which meet at a characteristic frequency f_α.
- This provides a way to reconcile the NANOGrav detection with LIGO being also in agreement with the other cosmological data. Fitting a wide range of precision cosmological and astrophysical datasets within a SGWB spectrum, requires several deviations from the standard picture.
- This model can explain the NANOGrav signal with a value of $n_T \sim 1$ and f_α lower than $0.2Hz$, contributing to the value of N_{eff} at most for ~ 0.11.
- The expected sensitivities of the future experiments are 100 times better than the first generation.
- Testing the spectral shape of SBGWs through complementary measurements should bring some light about physical origin of the signal.

Great expectation for big news in the near future!

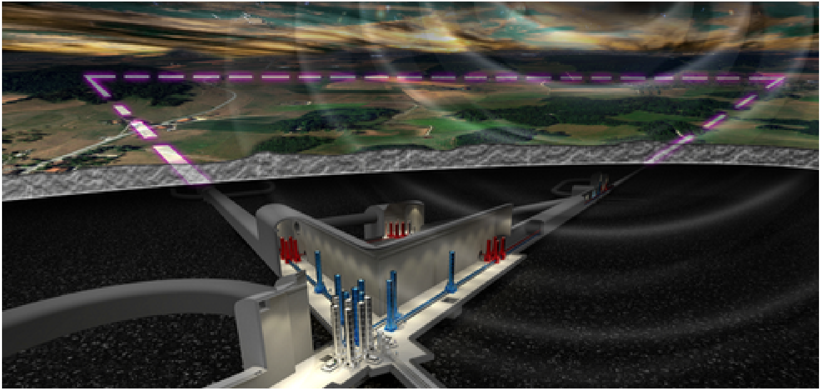
LISA - 2034



SKA - Starting Construction



Einstein Telescope - 2035



LiteBIRD - 2028

Thank you!