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Searches for Inflationary GWs

in the NANOGrav 15-year dataset

Gravitational Wave Probes of
Physics Beyond Standard Model 4

23.06.2025

NANOGrav

Based on ApJL 951 L11 (2023), ApJL 978 L29 (2025)

In collaboration with the New Physics Working Group of the NANOGrav collaboration

Program

- Evidence for a GW background (GWB)

  NANOGrav 15 year dataset (2023) + EPTA & InPTA + PPTA + CPTA

  Many interpretation papers since then. Sorry if I did not cite your paper here!

- IGW I: Signals from new physics

  With the New Physics Working Group - led by **Andrea Mitridate, Kai Schmitz**

- IGW II: Running of the spectral index

  Work with **Kai Schmitz, David Esmyol, Richard von Eckardstein, Tobias Schröder**

Based on NANOGrav collaboration papers **2306.16219** and **2408.10166**. More can be found in lecture notes **2212.05594**

(Some degrees of) evidence for a GWB

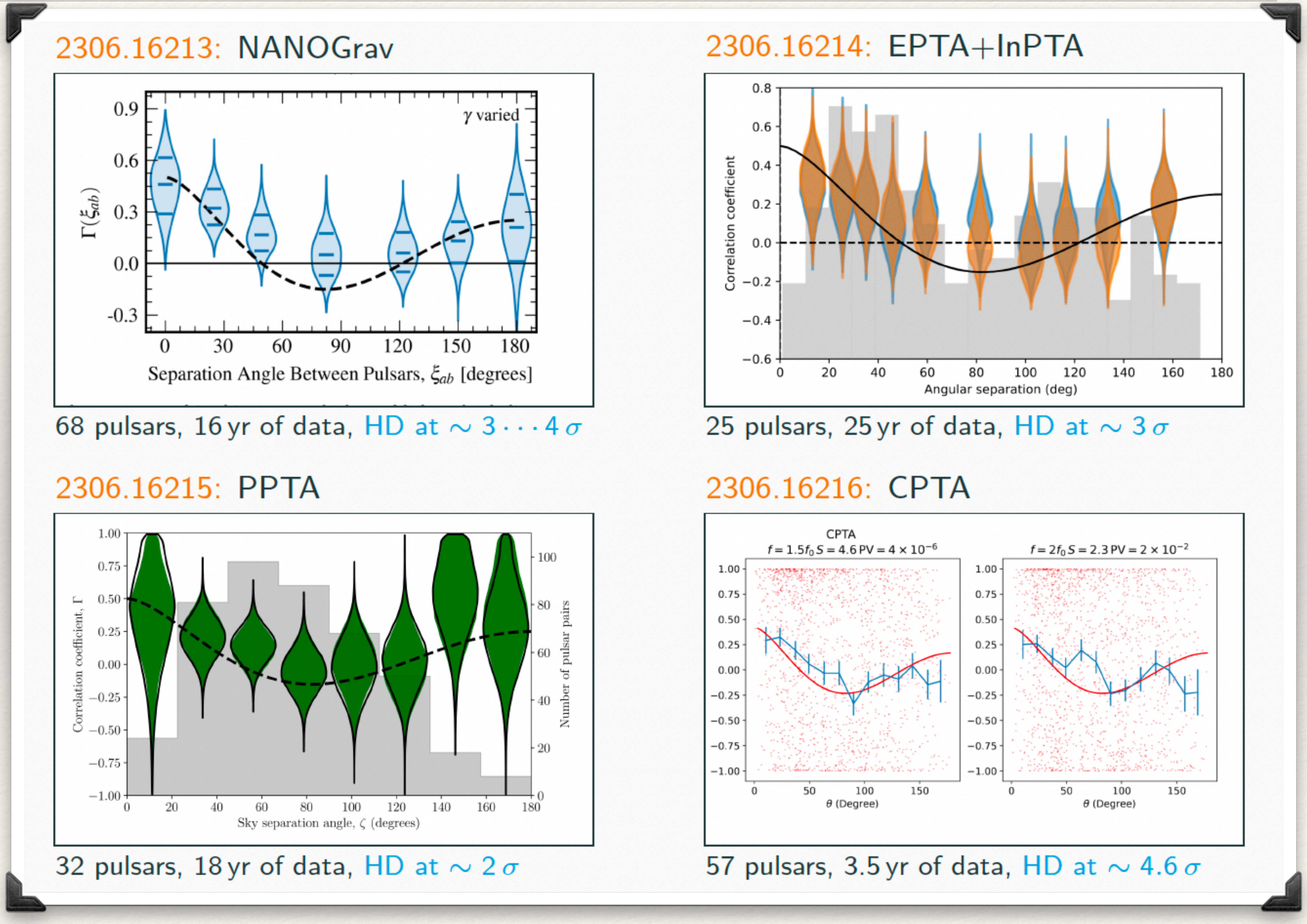
Hellings-Downs correlation
"The fingerprint" of a GWB for a set of cross-correlated timing signals from pulsars (pulsar timing arrays — PTAs)

Hellings, Downs ApJ 265(1983) L39-42

$$\langle R_a(t)R_b(t)\rangle = \int df\, P(f) \times \Gamma(\xi_{ab})$$

Read more about PTAs and nHz GWs in S.Taylor's review 2105.13270

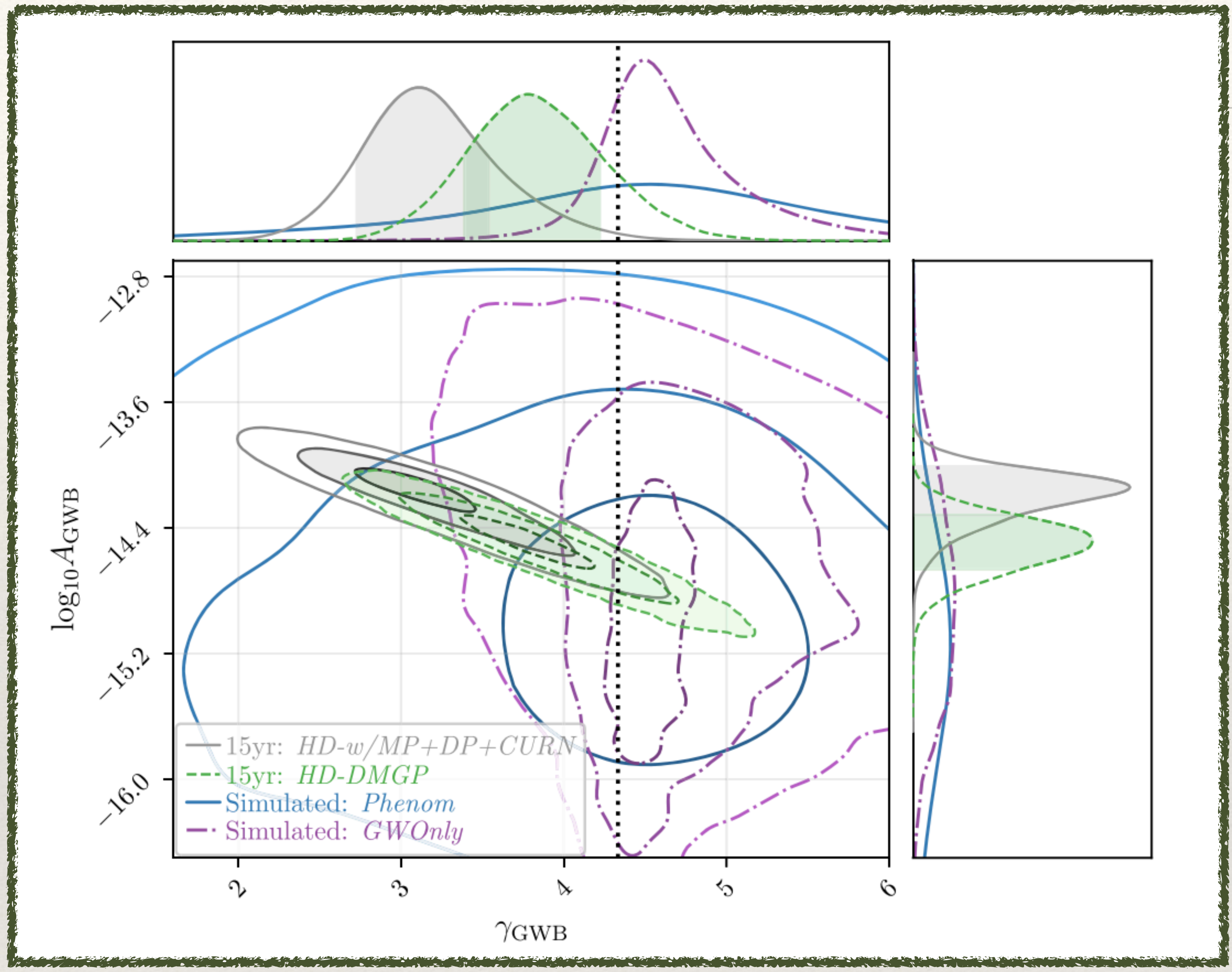
In the following, we assume the signal observed, for e.g. by NANOGrav, is a GWB. But the source is unknown.



From Kai Schmitz

Astrophysical vs Cosmological interpretations

Agazie et al. ApJL 952 L37 (2023), 2306.16220



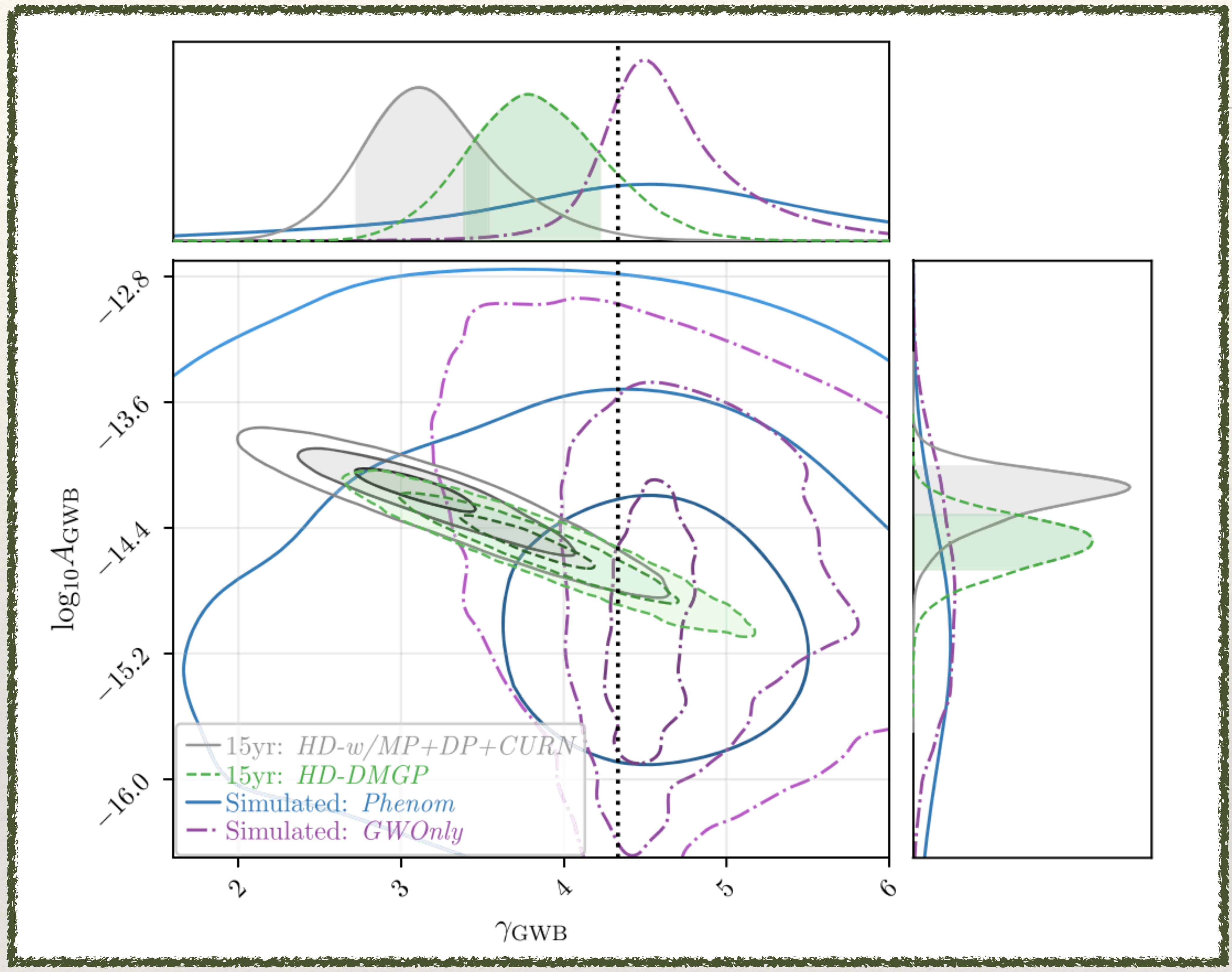
- Simpler SMBHB models (e.g. power-law with $\gamma = 13/3$) do not fit data well
- Other phenomenological models and environmental effects can fit

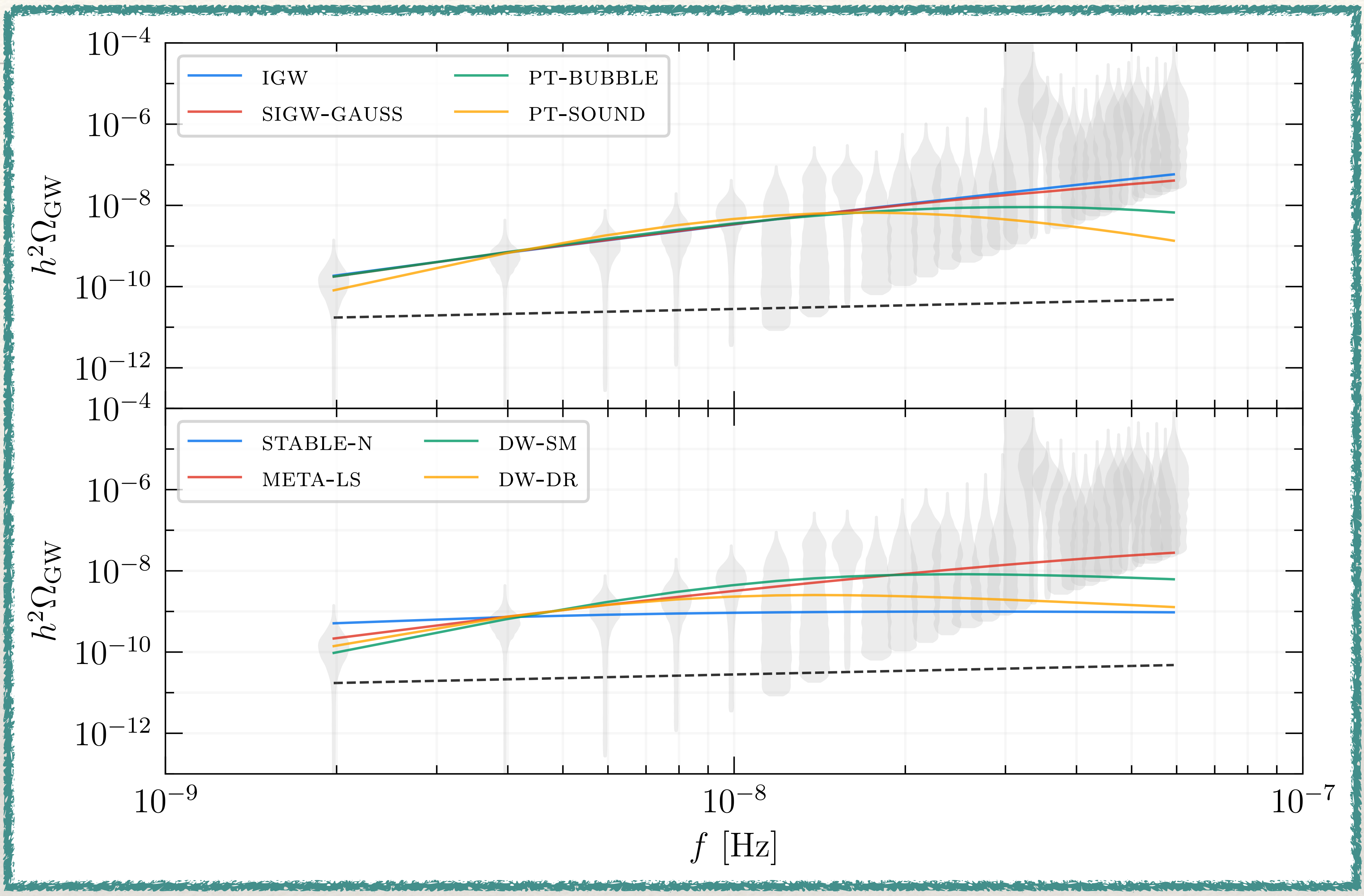
"NANOGrav paper" Agazie et al. ApJL 951 L50 (2023) 2, 2306.16222
"EPTA paper" Antoniadis et al., A&A 685 (2024) A94, 2306.16227
"PPTA paper" Reardon et al., ApJL 951 (2023) 1, L6, 2306.16215
Ellis et al., Phys.Rev.D 109 (2024) 2, 023522, 2308.08546

Astrophysical vs Cosmological interpretations

Agazie et al. ApJL 952 L37 (2023), 2306.16220

Afzal et al. ApJL 951 L11 (2023), 2306.16219





- Many cosmological models available in the literature
- Can they fit NG15 yr data? Can NG15 yr data constrain these models?

Figueroa et al., *Phys.Rev.Lett.* 132 (2024) 17, 171002, 2307.02399

Ellis et al., Phys.Rev.D 109 (2024) 2, 023522, 2308.08546

“EPTA paper” Antoniadis et al., A&A 685 (2024) A94, 2306.16227

Inflationary Gravitational waves (IGW)

- These are GWs from "first-order" tensor modes
- Focus on simple benchmark scenarios
    - What is necessary to fit PTA data?

Will not cover scalar-induced GWs.

Will not explore microphysics.

Afzal et al. ApJL 951 L11 (2023), 2306.16219

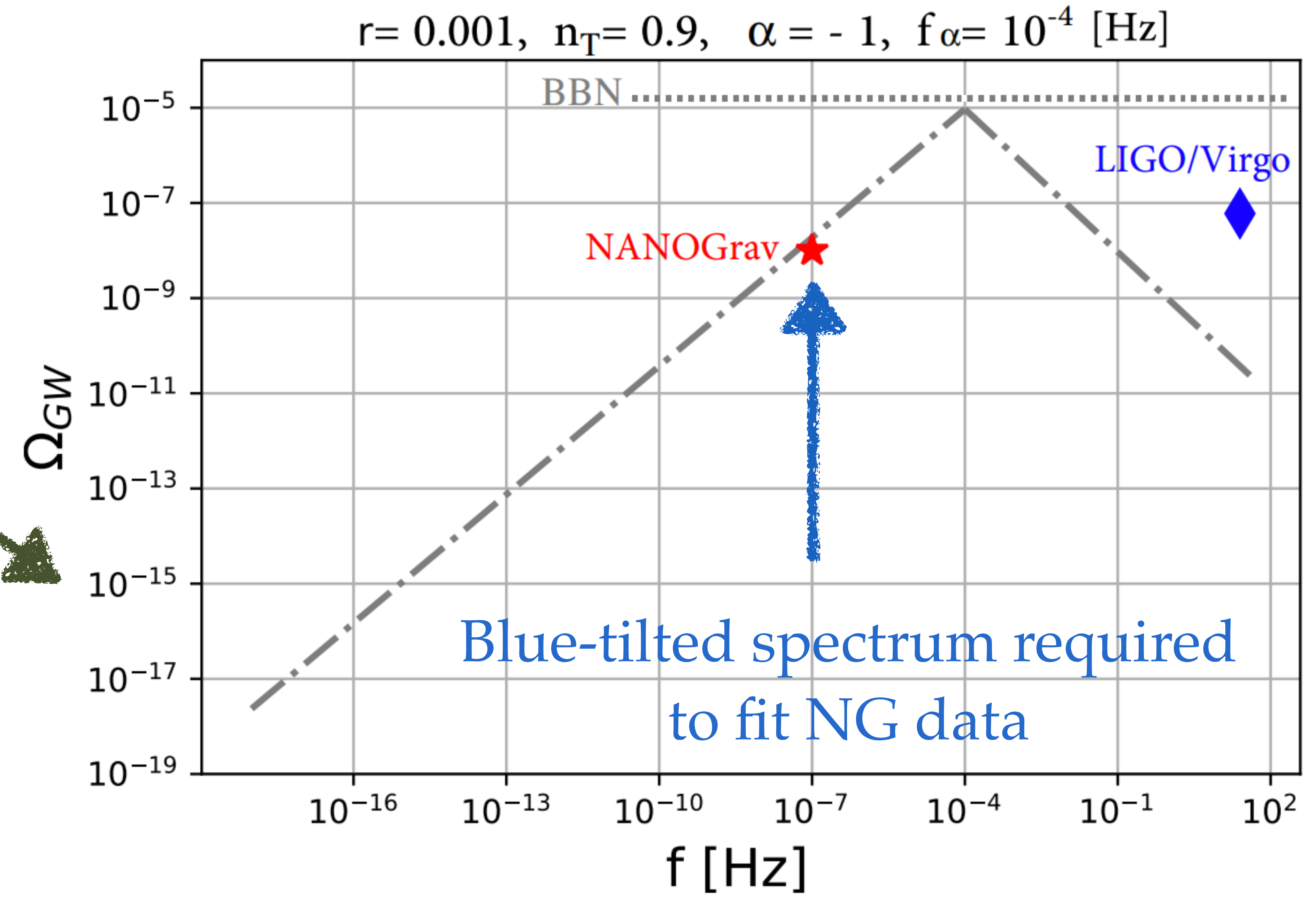
Agazie et al. ApJL 978 L29 (2025), 2408.10166

Inflationary Gravitational waves (IGW)

- One IGW interpretation: broken power-law approach

Benetti, Graef, Vagnozzi *Phys.Rev.D* 105 (2022) 4, 043520, 2111.04758

CMB: tensor perturbations
Very small at $\approx 10^{-16}$ Hz



Blue-tilted spectrum required to fit NG data

Cannot always grow …
BBN and LVK bounds

Something must change the spectral index

$$\mathcal{P}_t(f) = r\,A_s \left(\frac{f}{f_{\rm CMB}}\right)^{n_t}$$

Standard single-field slow-roll inflation spectrum is red-tilted at CMB scales!

Inflationary Gravitational waves (IGW)

- These are GWs from "first-order" tensor modes.
- As much as **model-independent** we can, let us play with
- Tensor **spectral index** (n_T) and **temperature at end of reheating** (T_{rh})
- Reheating temperature (low or high)
  - Low: (IGW I) Late reheating

    Afzal et al. ApJL 951 L11 (2023), 2306.16219
  - High: (IGW II) Running of the spectral index

    Agazie et al. ApJL 978 L29 (2025), 2408.10166
- Changing the equation of state parameter changes the spectral index

  Work in progress (Ghoshal, Graef, RRLdS, Ahmed, Pedreira, Schmitz)

S. Vagnozzi, *JHEAp* 39 (2023) 81-98, 2306.16912

Ellis et al., Phys.Rev.D 109 (2024) 2, 023522, 2308.08546

Li, Meyers, Shapiro, 2025 *ApJ* 985 117, 2503.18937

IGW I – late reheating

- **GW spectrum**

$$\Omega_{\rm GW}^{\rm inf}(f) = \frac{\Omega_{\rm r}}{24}\left(\frac{g_*(f)}{g_*^0}\right)\left(\frac{g_{*,s}^0}{g_{*,s}(f)}\right)^{4/3}\mathcal{P}_t(f)\,\mathcal{T}(f)$$

$$\mathcal{P}_t(f) = r\,A_s\left(\frac{f}{f_{\rm CMB}}\right)^{n_t}$$

CMB $A_s \sim 2 \times 10^{-9}$

Planck 2018 A&A 641 A6 (2020), 1807.06209

$r \lesssim 0.036 \quad (95\,\%\ CL)$

Ade et al. PRL 127 (2021) 151301, 2110.00483

- With **late reheating**, it is possible that T_{rh} happens at PTA frequency band
  - $T_{rh} \approx 100$ MeV
  - End of reheating (T_{rh}) - sharp transition from $w_{rh} = 0$ to $w_{rh} = 1/3$.
  - Spectral turnover (f_{rh}): $f^{n_t-2} \rightarrow f^{n_t}$
- Transfer function in the PTA band

$f_{rh} \sim 30\,\mathrm{nHz}\,(T_{rh}/1\,\mathrm{GeV})$

$$\mathcal{T}(f) \approx \frac{\Theta\left(f_{\rm end} - f\right)}{1 - 0.22\left(f/f_{\rm rh}\right)^{1.5} + 0.65\left(f/f_{\rm rh}\right)^2}$$

Kuroyanagi et al. JCAP 01 (2021) 071, 2011.03323
Kuroyanagi et al. JCAP 02 (2015) 003, 1407.4785

End of inflation $T_{end} \ggg T_{rh}$

BBN $T_{rh} > 0.1$ MeV

IGW I – late reheating

Regime I: $T_{rh} \gg 1$ **GeV**

f_{rh} is larger than f_{PTA}

Tensor modes reentered horizon during radiation era.

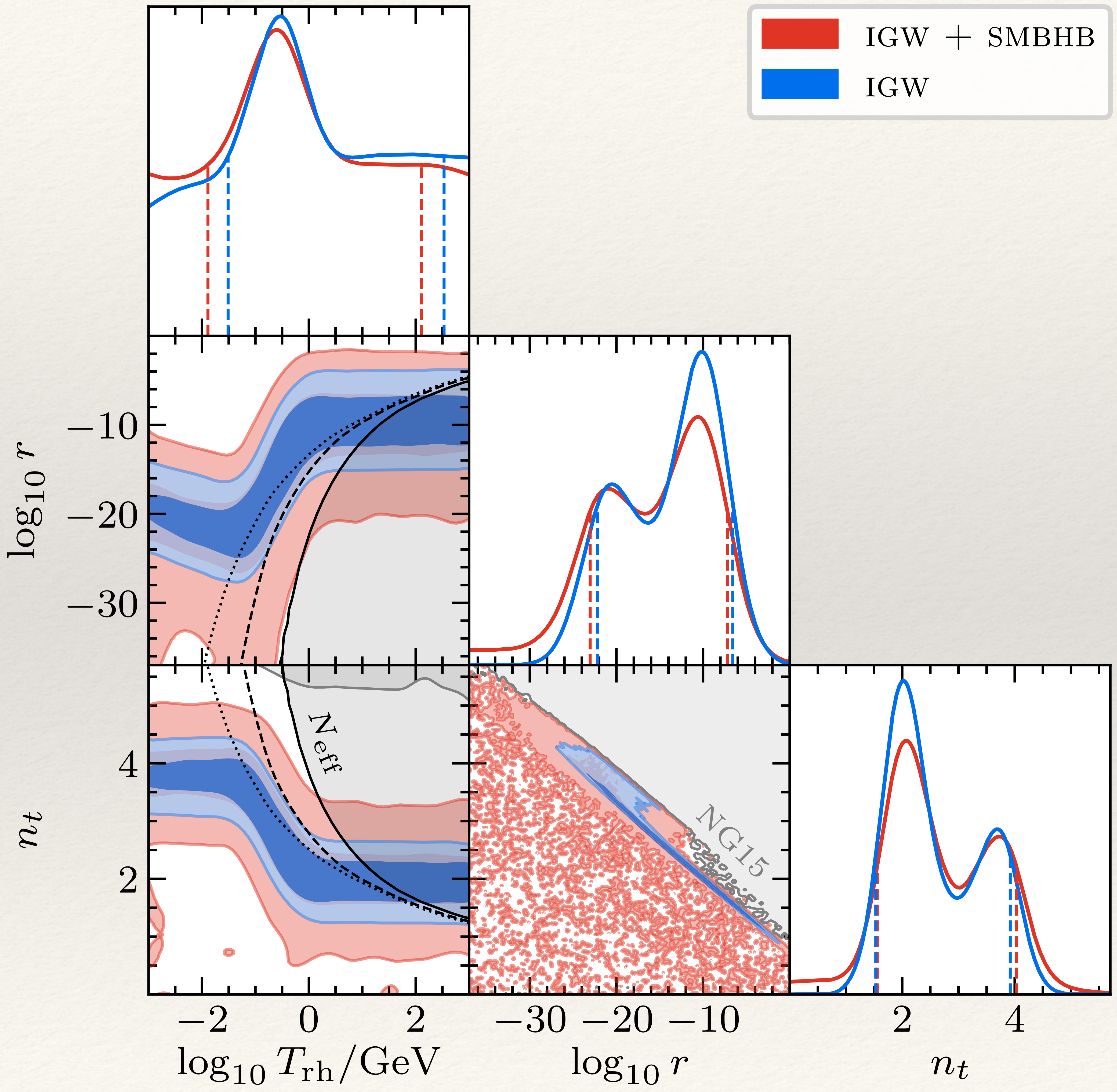
$f^{n_t} : n_t \sim 2$

Regime II: $T_{rh} \ll 1$ **GeV**

f_{rh} can be lower than f_{PTA}

Tensor modes reentered horizon during reheating time.

$f^{n_t - 2} : n_t \sim 4$



Sampled with PTArcade

Mitridate, Wright et al (2023), 2306.16377

With enterprise and enterprise_extensions

Ellis, Vallisneri, Taylor, Baker (2019)

Taylor, Baker, Hazboun, Simon, Vigeland (2021)

Strong correlation: n_t and r

$n_t = -0.14 \log_{10} r + 0.58$

Bounds: N_{eff} (see next slide)

From $N_{rh} = 0, 5, 10$

IGW I – late reheating

Bound I: N_{eff}

GW spectrum cannot exceed upper limit set by the allowed amount of extra relativistic d.o.f:

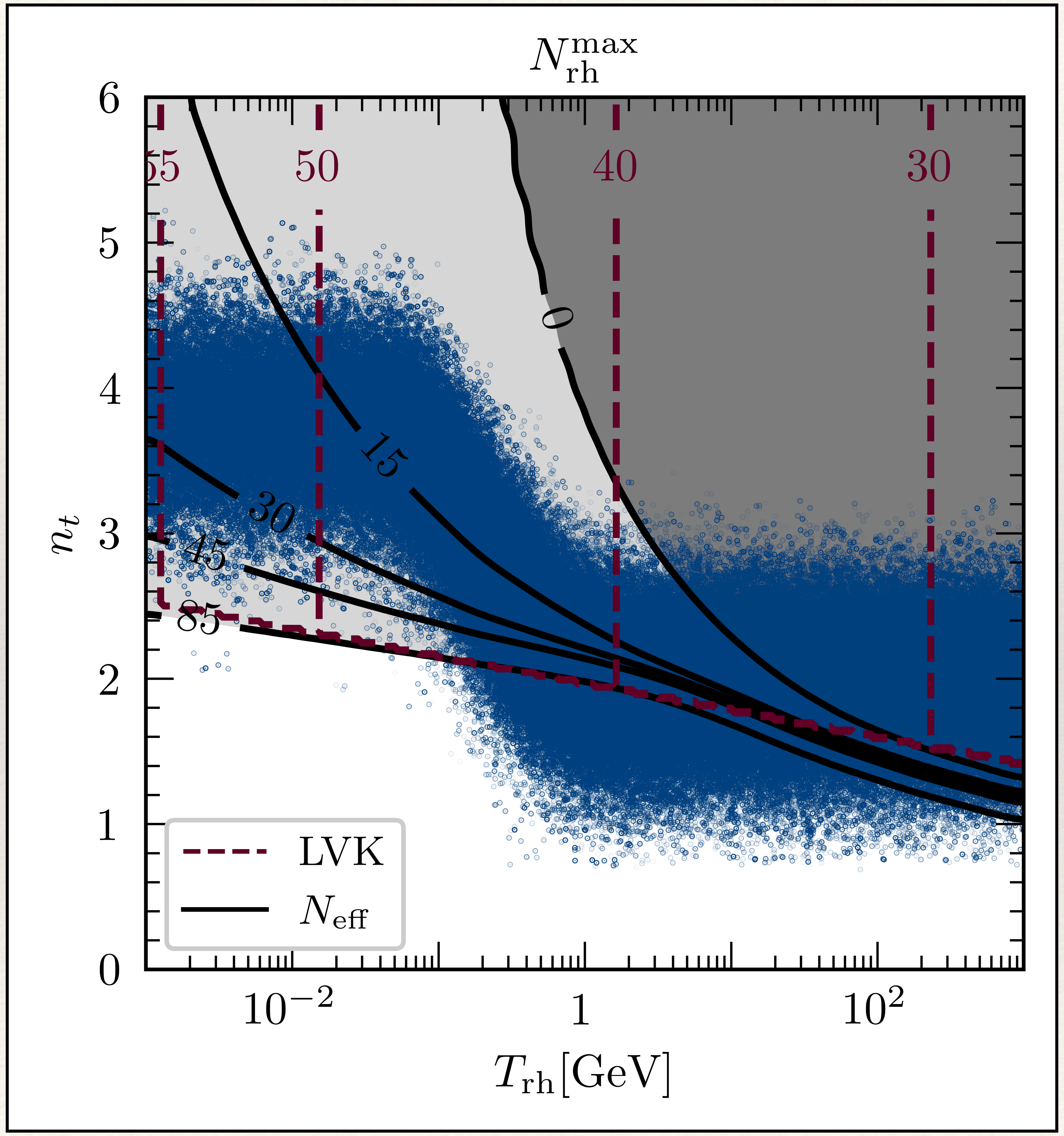
$$\int_{f_{BBN}}^{f_{end}} \frac{df}{f} h^2 \Omega_{IGW}(f) \lesssim 2.8 \times 10^{-6}$$

Caprini, Figueroa 1801.04268
Class.Quant.Grav. 35 (2018) 16, 163001

Use $f_{BBN} \sim 10^{-12}$ Hz;
Find f_{end} that saturates the integral;
Can map f_{end}^{max} into N_{rh}^{max} (number of e-folds during reheating).

If $N_{rh}^{max} < 0$, excluded.

For fixed N_{rh}, regions $N_{rh}^{max} < N_{rh}$ are excluded.



Bound II: LVK

GW spectrum, if extrapolated to LVK scale, cannot exceed their bound
$\Omega_{GW} \lesssim 1.7 \times 10^{-8}, \qquad f_{LVK} \approx 25\text{Hz}$

For a power-law spectrum

$$\Omega_{IGW}(f) \lesssim 1.7 \times 10^{-8} \left(\frac{5-2\alpha}{5}\right)^{1/2} \left(\frac{20\text{Hz}}{f_{LVK}}\right)^{-\alpha}$$

$\alpha \equiv n_t - 2, \quad f \gg f_{rh} \quad (\Omega_{GW} \sim f^{n_t-2})$

Kuroyanagi et al. JCAP 01 (2021) 071, 2011.03323
Kuroyanagi et al. JCAP 02 (2015) 003, 1407.4785

Can find N_{rh}^{max}, given (r, n_t, T_{rh}).

Parameter space is viable $N_{rh} \sim O(1 \cdots 10)$, large n_t

IGW II – running power law

- Let us go beyond previous interpretations (constant, broken, piecewise, power laws)
- **Running power law (RPL) signal as a simplified model for IGW**

$$\Omega_{\rm GW}^{\rm inf}(f) = \frac{\Omega_{\rm r}}{24}\left(\frac{g_*(f)}{g_*^0}\right)\left(\frac{g_{*,s}^0}{g_{*,s}(f)}\right)^{4/3}\mathcal{P}_t(f)\,\mathcal{T}(f)$$

$$\mathcal{P}_t(f) = r\,A_s\left(\frac{f}{f_{\rm CMB}}\right)^{n_t + 1/2\,\beta_t \ln(f/f_{\rm CMB})}$$

- β_t : running of the spectral index n_t
- Let us assume high reheating temperature (early reheating), set $\mathcal{T} \sim 1$
- Map IGW II spectrum into RPL spectrum
    - Warning: This assumes we can extrapolate RPL spectrum all the way to $f_{inflation}$!

$$\mathcal{P}_t(f) = r\,A_s\left(\frac{f}{f_{\rm CMB}}\right)^{n_t}$$

If $\beta_t = 0$, constant power law (CPL)

IGW II – running power law

- **Running power law (RPL) signal as a simplified model for IGW**

$$\mathcal{P}_t(f) = r\, A_s \left(\frac{f}{f_{\rm CMB}}\right)^{n_t + 1/2\, \beta_t \ln(f/f_{\rm CMB})}$$

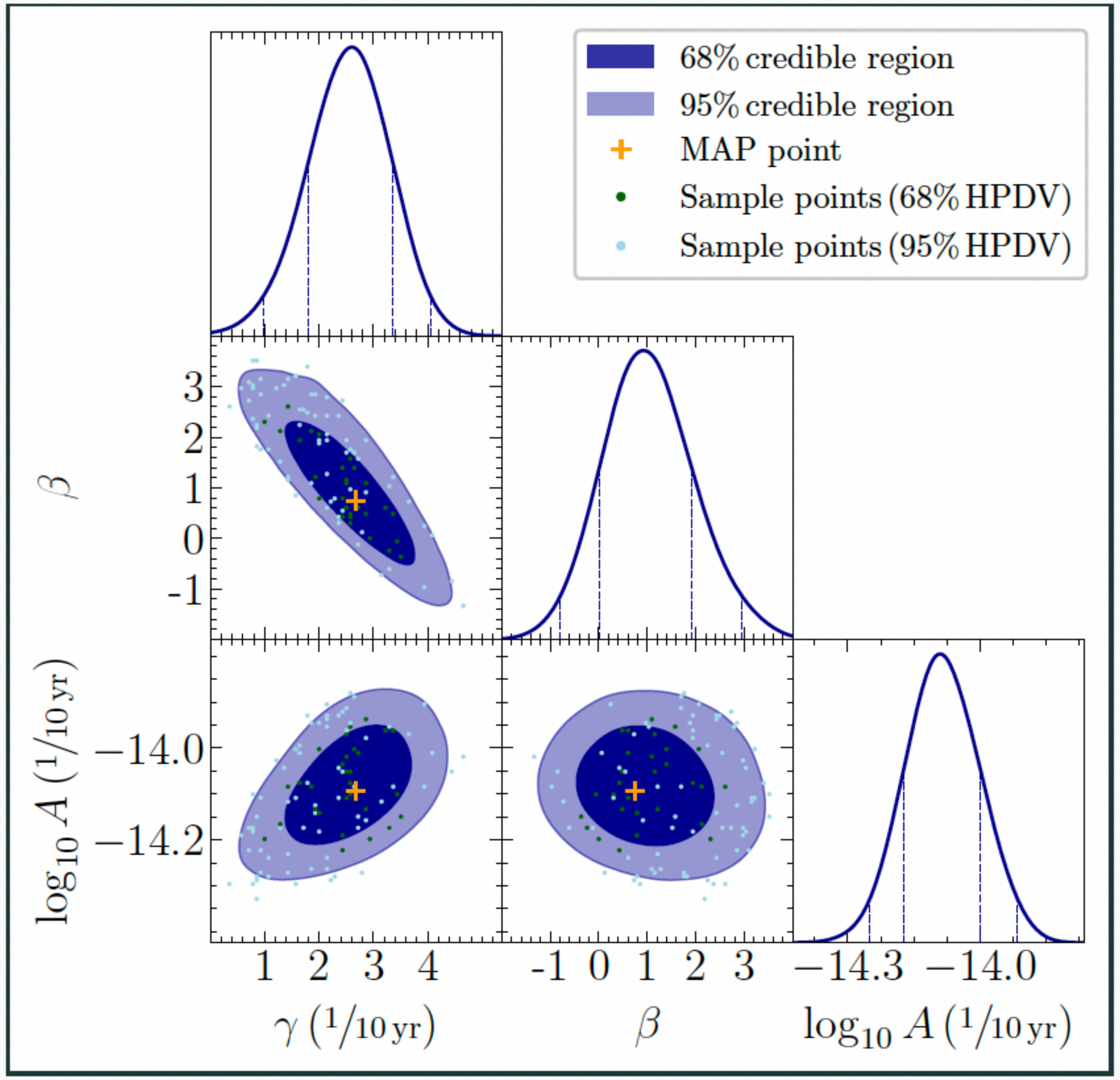
- Map IGW II spectrum into RPL spectrum

$$r = \frac{24}{\Omega^0_{\rm rad}} \frac{1}{A_s} \frac{2\pi^2}{3H_0^2} A^2 f_{\rm ref}^2 \left(\frac{f_{\rm CMB}}{f_{\rm ref}}\right)^{\tilde{n}_{\rm run}(f_{\rm CMB})},$$

$$n_t = 5 - \gamma - \beta \ln\left(\frac{f_{\rm CMB}}{f_{\rm ref}}\right), \qquad \beta_t = -\beta.$$

Sampled with PTArcade

Mitridate, Wright et al (2023), 2306.16377



IGW II – running power law

- **Running power law (RPL) signal as a simplified model for IGW**

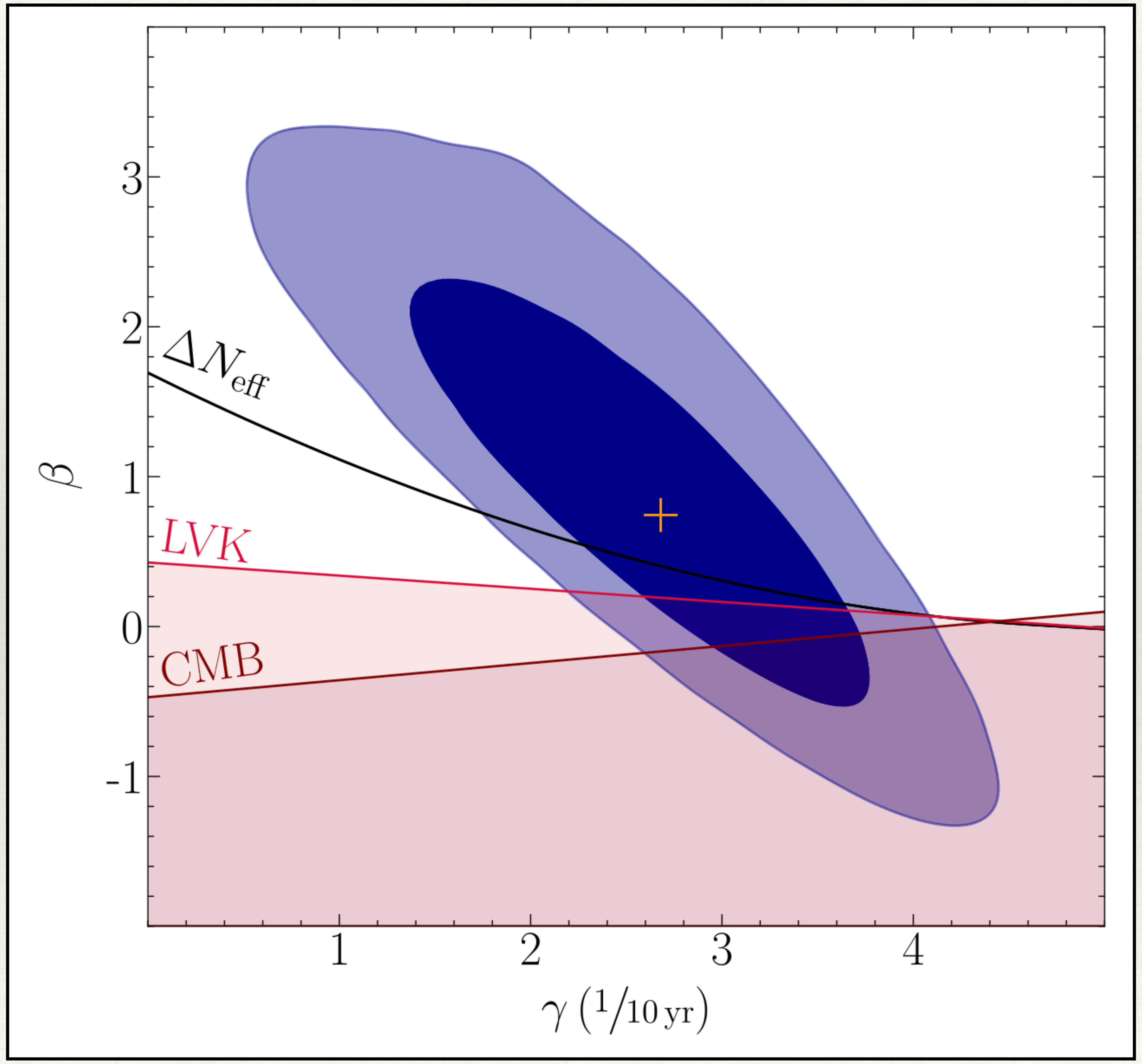
$$\mathcal{P}_t(f) = r\, A_s \left(\frac{f}{f_{\rm CMB}}\right)^{n_t + 1/2\,\beta_t \ln(f/f_{\rm CMB})}$$

- Map IGW II spectrum into RPL spectrum

$$r = \frac{24}{\Omega^0_{\rm rad}} \frac{1}{A_s} \frac{2\pi^2}{3H_0^2} A^2 f_{\rm ref}^2 \left(\frac{f_{\rm CMB}}{f_{\rm ref}}\right)^{\tilde{n}_{\rm run}(f_{\rm CMB})},$$

$$n_t = 5 - \gamma - \beta \ln\left(\frac{f_{\rm CMB}}{f_{\rm ref}}\right), \qquad \beta_t = -\beta.$$

- Derive constraints
  - Assuming spectrum extends all the way along $f_{CMB} \ll f_{ref} \ll f_{LVK}$;
  - We can compensate large variations of A with small shifts of β;
  - We need **positive** β to evade all bounds;
  - CPL does not provide viable description for such IGW.



Final remarks

- NG 15 yr data can be explained by our parametric space.
    - IGW I (late reheating = low reheating temperature)
        - $n_t \sim 3\cdots4$, $r \sim 10^{-(23\cdots16)}$, $T_{rh} \sim 10^{(-3\cdots0)}$ GeV
    - IGW II (reheating temperature high enough, above PTA scales)
        - $\beta > 0$, for e.g. MAP point (maximum of posterior)
- Can microscopic models realize such inflationary scenarios?
- We can also play with other parameters, other inflationary models.

Dziękuję za uwagę!

Thank you for attention!

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Backup slides

Hellings-Downs: the fingerprint

- Prediction of General Relativity: Hellings-Downs curve

Hellings, Downs ApJ 265(1983) L39-42

  - Cross correlation among timing residuals
- For a pair of pulsars,

$$\langle R_a(t) R_b(t) \rangle = \int df\, P(f) \times \Gamma(\xi_{ab})$$

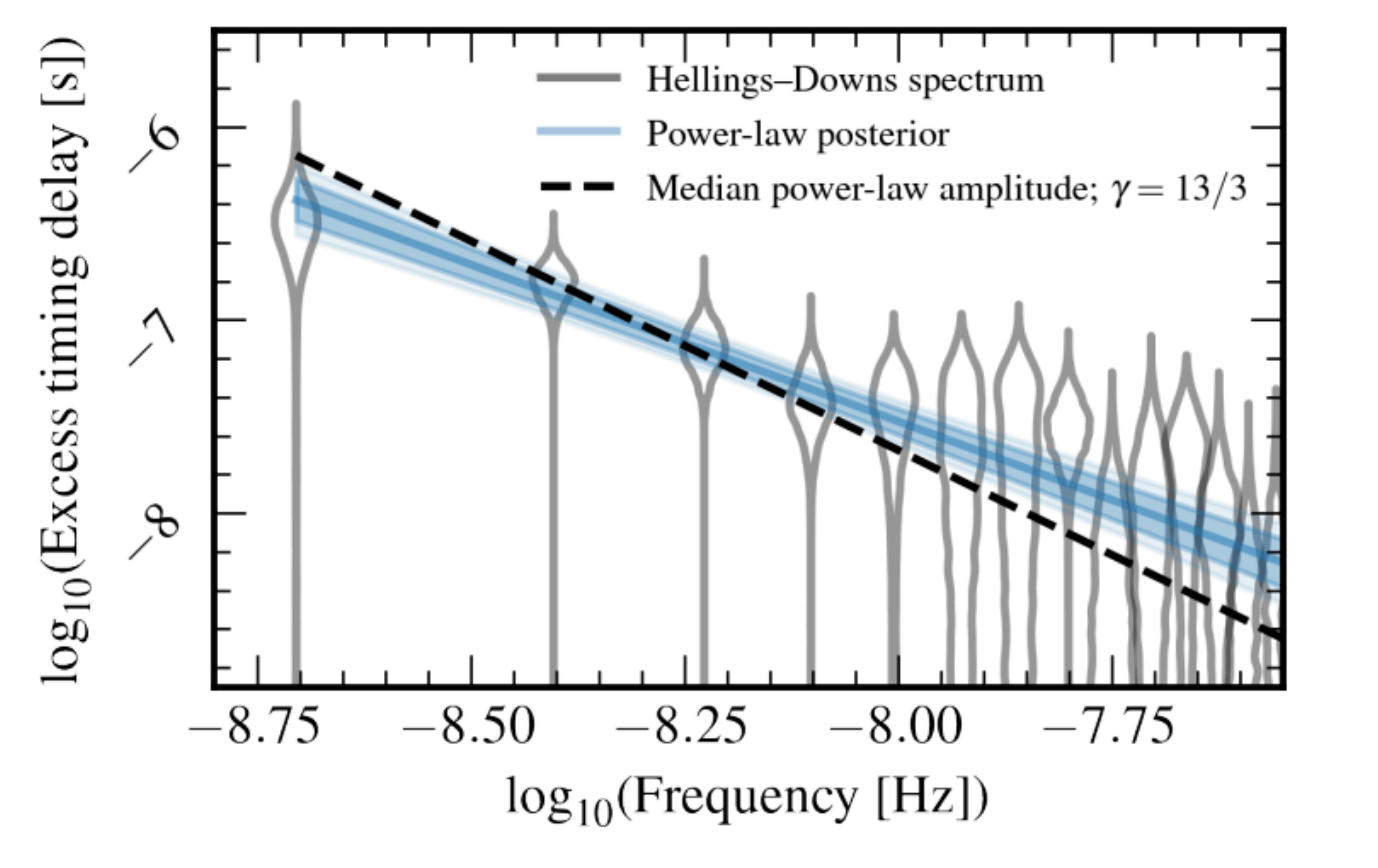
  - $P(f)$ is related to the power spectrum (GW source)
  - **$\Gamma(\xi_{ab})$ is the Hellings-Downs cross-correlation**
    - depends on the geometry of the pulsar network (not on (most of) sources)
      - ξ_{ab} is the angular separation of the pulsars
    - For laser interferometers, this function depends on the geometry of the interferometers

Evidence for a GW background

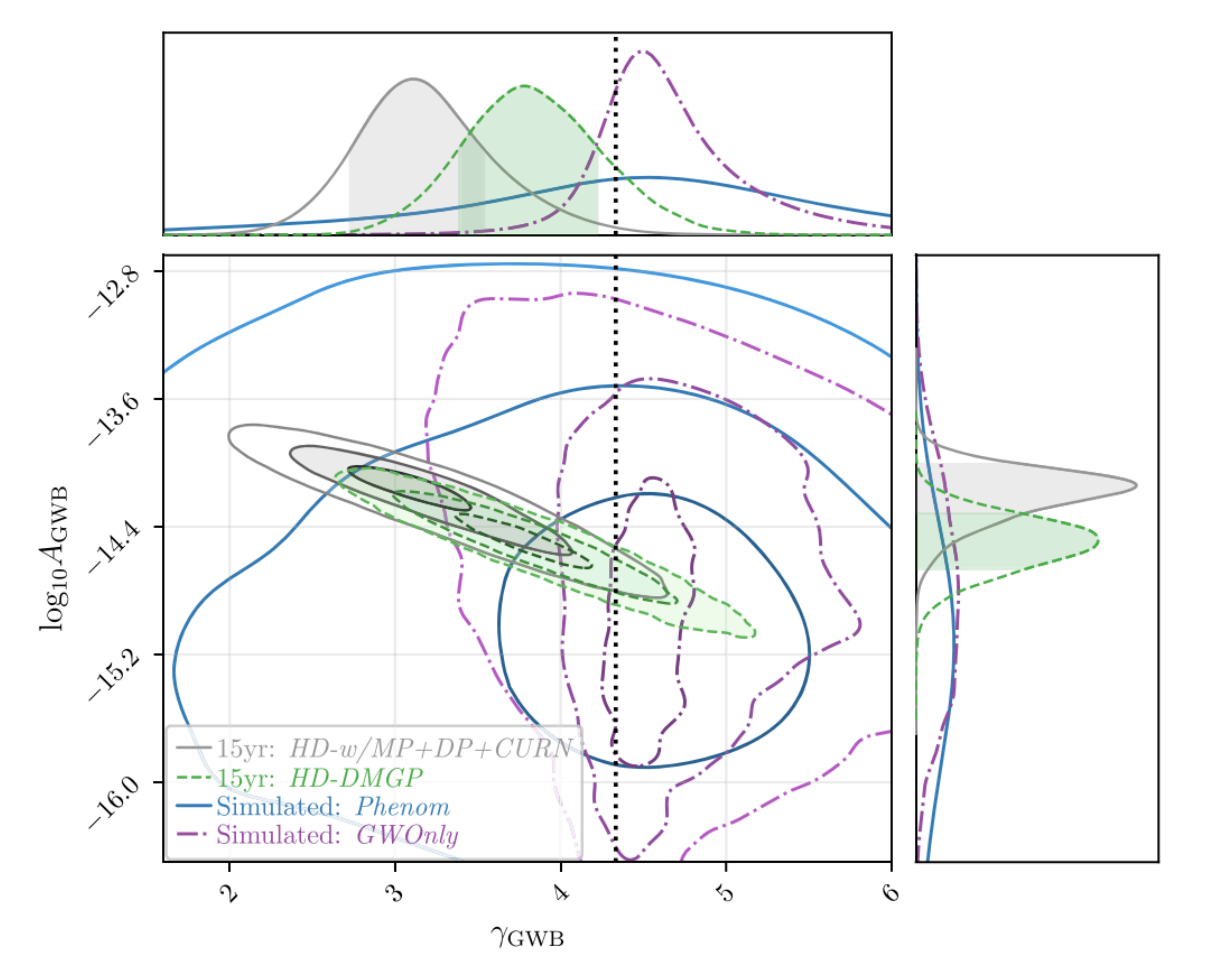
- 18 papers on arXiv 00:00 UTC June 29, 2023
  - 8 NANOGrav papers
  - 6 EPTA papers (including InPTA data)
  - 3 PPTA papers
  - 1 CPTA paper
- 4 of these papers — search for GW background (GWB)
  - (Some degree of) Evidence of Hellings-Downs correlation

Astrophysical interpretation

Agazie et al. ApJL 951 L8 (2023) 2306.16213

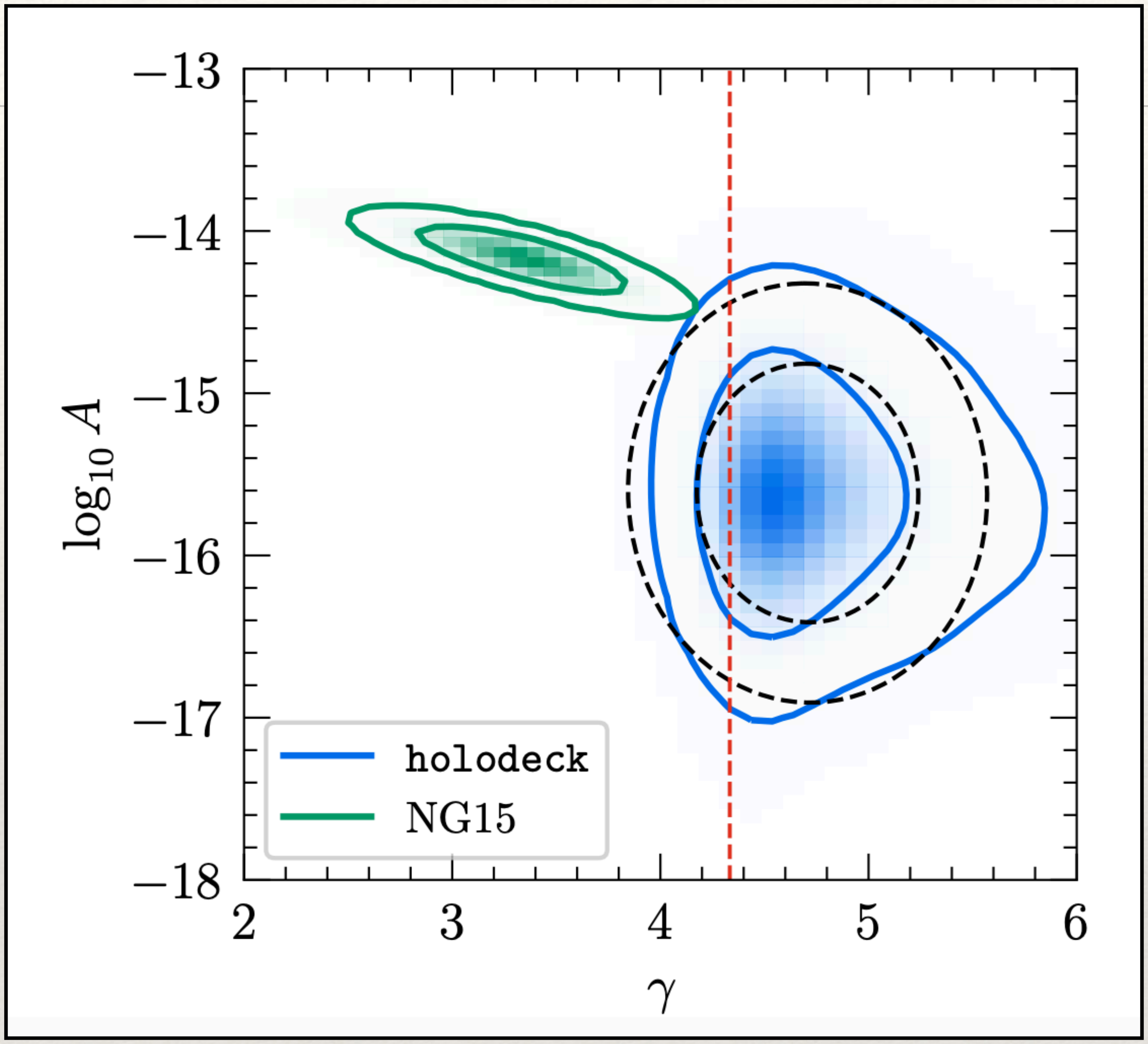


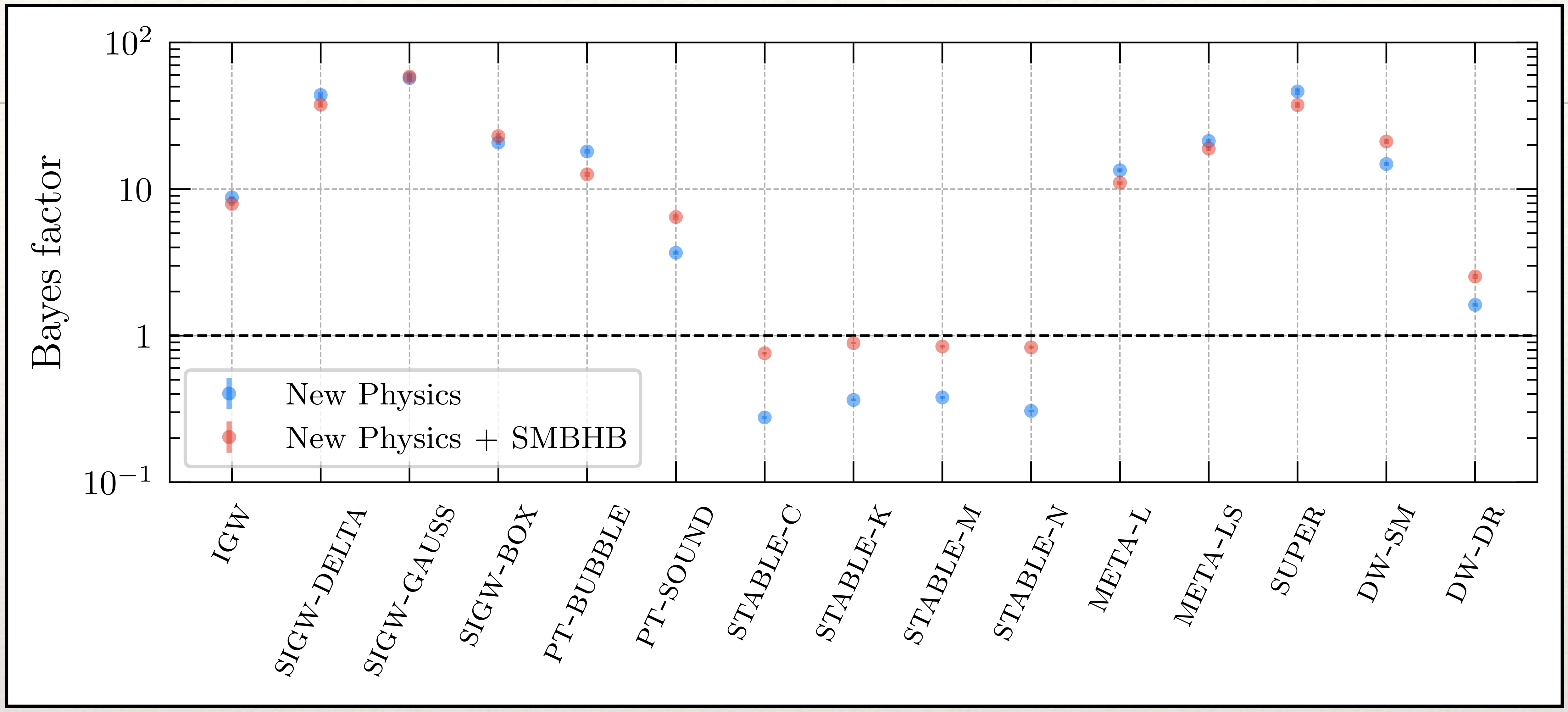
Agazie et al. ApJL 952 L37 (2023) 2306.16220



- Simpler SMBHB models (e.g. power-law with $\gamma = 13/3$) do not fit data well

Search for New Physics (2023)





$$\Omega_{GW} = \frac{1}{\rho_c} \frac{d\rho_{GW}}{d\ln k}.$$

$$\Omega_{\rm gw}^{\rm observed}(k) = \frac{\Omega_{rad}^0}{24} \left(\frac{g_*(k)}{g_*^0}\right) \left(\frac{g_{*,s}^0}{g_{*,s}(k)}\right)^{4/3} \Omega_{\rm gw}^{\rm emitted}(k).$$

- How about a cosmological source instead or together?

Afzal et al. ApJL 951 L11 (2023) 2306.16219

Toward model independent approaches

- Bottom-up approach: compromise as less as possible with source
- Focus on spectral shape. First attempt: constant power law
- Cross correlation. $\langle R_a(t) R_b(t) \rangle = \int df\, P(f) \times \Gamma(\xi_{ab})$
  - $\Gamma(\xi_{ab})$ — Hellings-Downs cross-correlation
  - $P(f)$ often assumed to be a constant power law (constant γ)

$$P_{CPL}(f) = \frac{A_{GW}^2}{12\pi^2 f_{ref}^3} \left(\frac{f}{f_{ref}} \right)^{-\gamma} \quad \text{(CPL = constant power law)}$$

Vanilla SMBHB scenario predicts constant $\gamma = 13/3$

But we know this does not fit data very well!

Toward model independent approaches

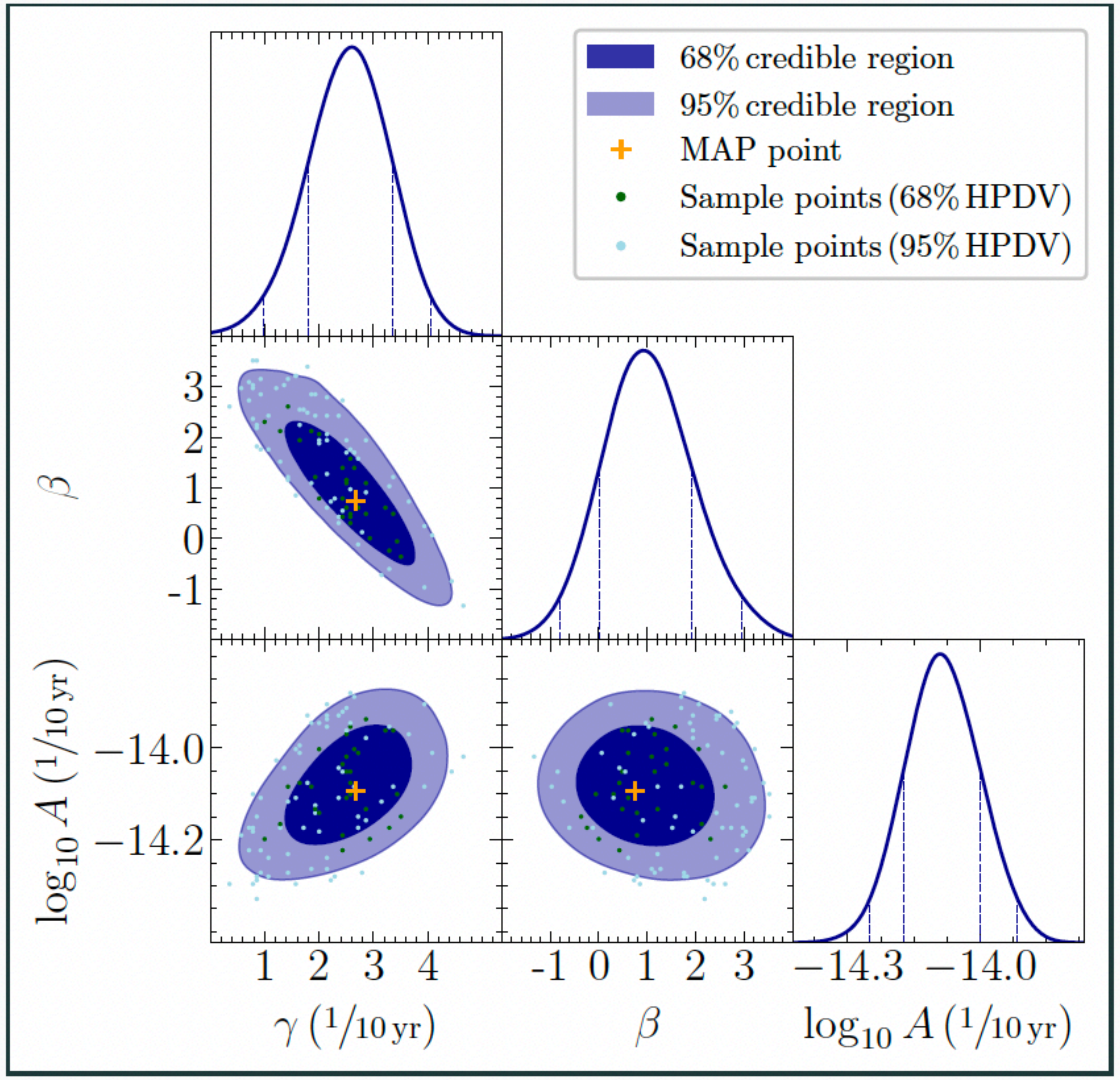
- Bottom-up approach: compromise as less as possible with source
- Focus on spectral shape. Beyond constant power law
- Cross correlation. $\langle R_a(t) R_b(t) \rangle = \int df\, P(f) \times \Gamma(\xi_{ab})$
  - $\Gamma(\xi_{ab})$ — Hellings-Downs cross-correlation
  - $\ln P(f)$ is now a parabola over $\ln(f/f_{ref})$ (effectively γ runs with the frequency)

$$P_{RPL}(f) = \frac{A_{GW}^2}{12\pi^2 f_{ref}^3} \left(\frac{f}{f_{ref}} \right)^{-\gamma - \frac{\beta}{2} \ln\left(\frac{f}{f_{ref}}\right)}$$ (RPL = running power law)

Agazie et al. ApJL 978 L29 (2025) 2408.10166

Running power law model

$$P_{RPL}(f) = \frac{A_{GW}^2}{12\pi^2 f_{ref}^3}\left(\frac{f}{f_{ref}}\right)^{-\gamma-\frac{\beta}{2}\ln\left(\frac{f}{f_{ref}}\right)}$$



- First characterization of the running of the "spectrum index" in the PTA band

$$\beta = \frac{d\gamma}{d\ln f} = 0.92^{+0.98}_{-0.91}$$ 68% credible interval

- Not conclusive, but it suggests we could compare a GWB model to a RPL template (A, γ, β), rather than a CPL

Parameter	1D MAP value	95 % HPDI credible interval
Amplitude $\log_{10} A(1/10\,\mathrm{yr})$	−14.09	[−14.25, −13.91]
Spectral index $\gamma(1/10\,\mathrm{yr})$	2.60	[0.98, 4.05]
Running of the spectral index β	0.92	[−0.80, 2.96]

BF = 0.69 (wrt to CPL — notice larger prior space for RPL)

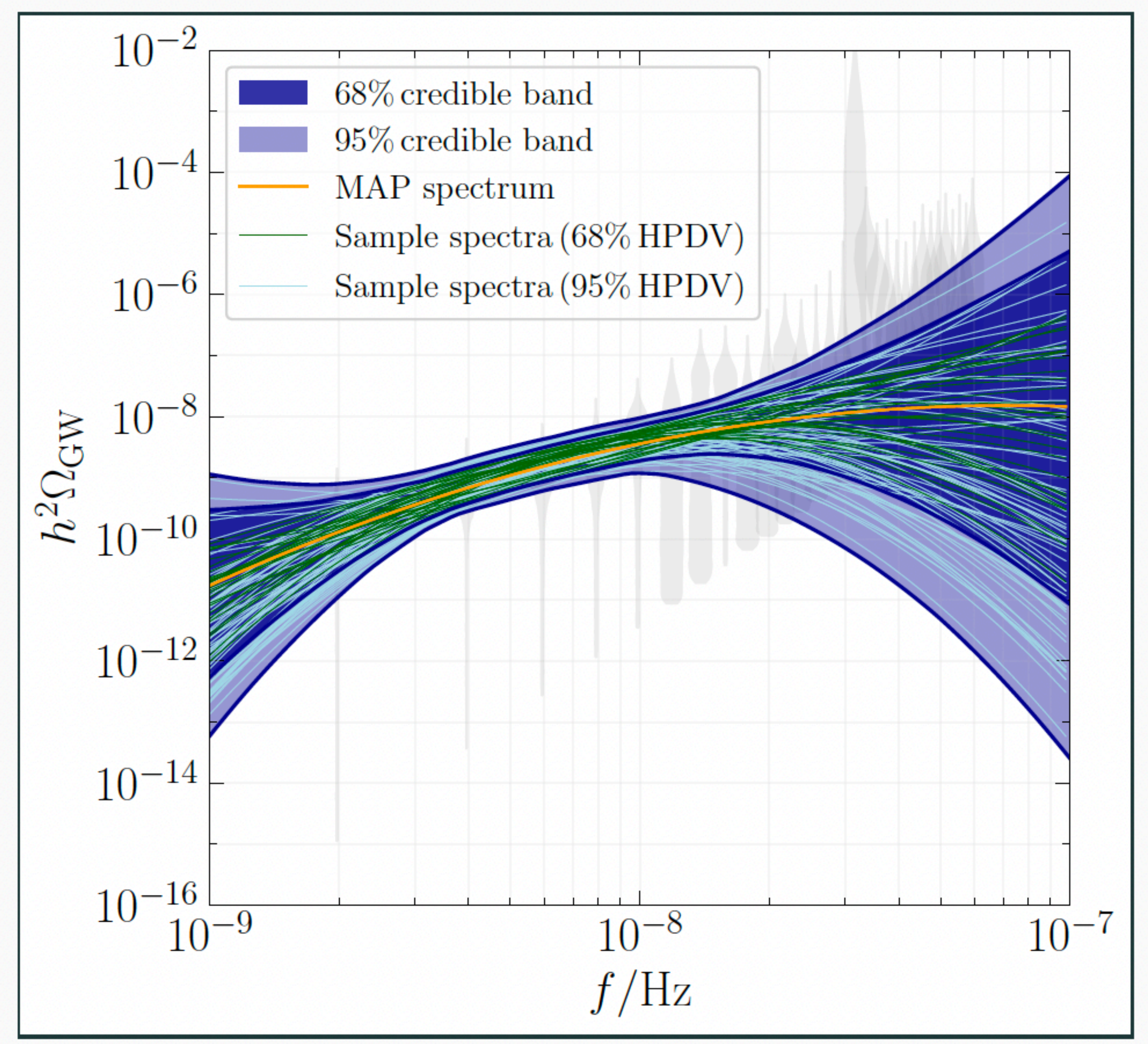
Agazie et al. ApJL 978 L29 (2025) 2408.10166

$$\beta = \frac{d\gamma}{d\,\ln k} = 0.92^{+0.98}_{-0.91}$$

$$\frac{dn_s}{d\,\ln k} = -\,0.0045 \pm 0.0067$$

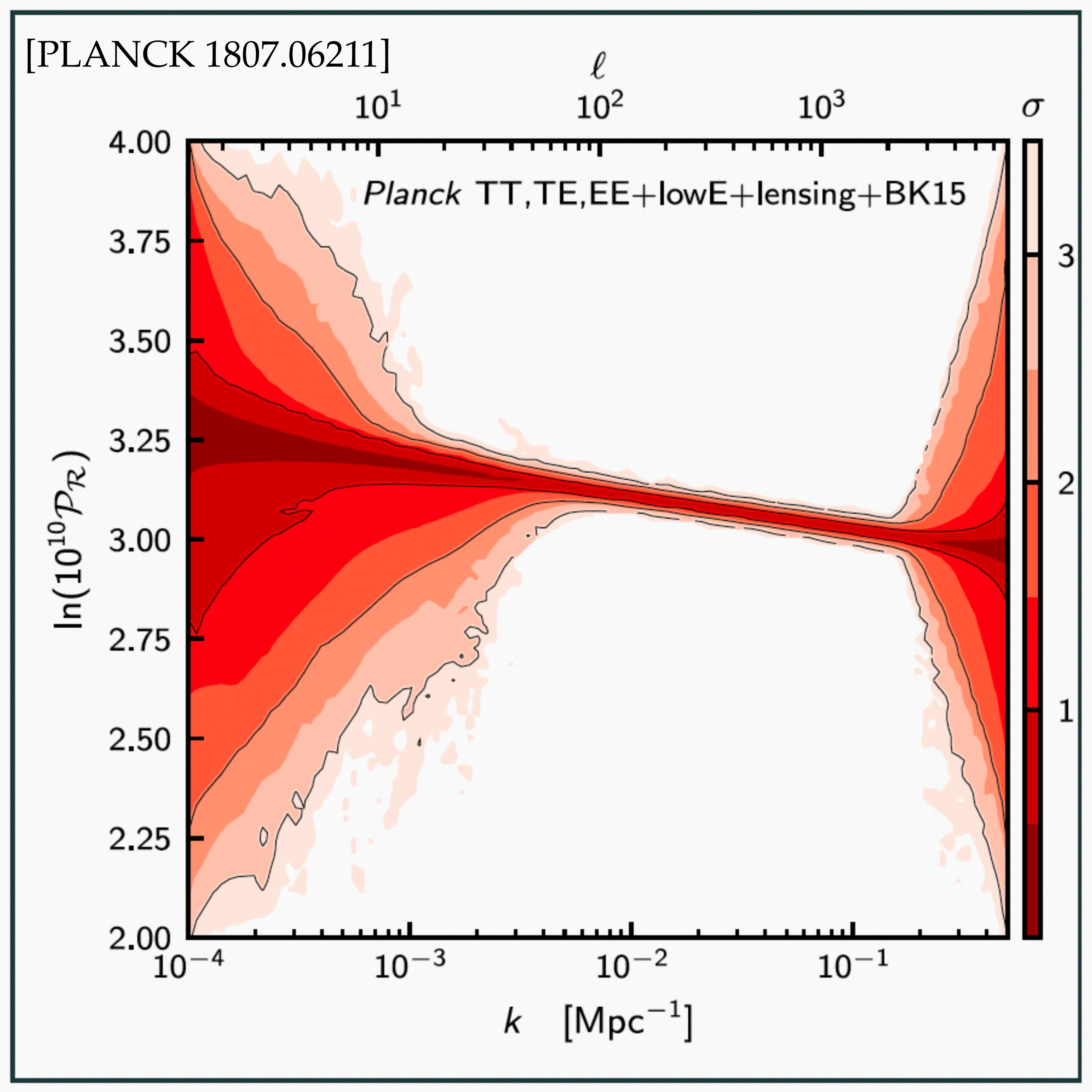
$$P_{RPL}(f) = \frac{A_{GW}^2}{12\pi^2 f_{ref}^3}\left(\frac{f}{f_{ref}}\right)^{-\gamma - \frac{\beta}{2}\ln\left(\frac{f}{f_{ref}}\right)}$$

$$P_s(k) \sim \mathscr{P}_R\left(\frac{k}{k_{ref}}\right)^{-n_s - \frac{1}{2}\frac{dn_s}{d\,\ln k}\ln\left(\frac{k}{k_{ref}}\right)}$$



Agazie et al. ApJL 978 L29 (2025) 2408.10166

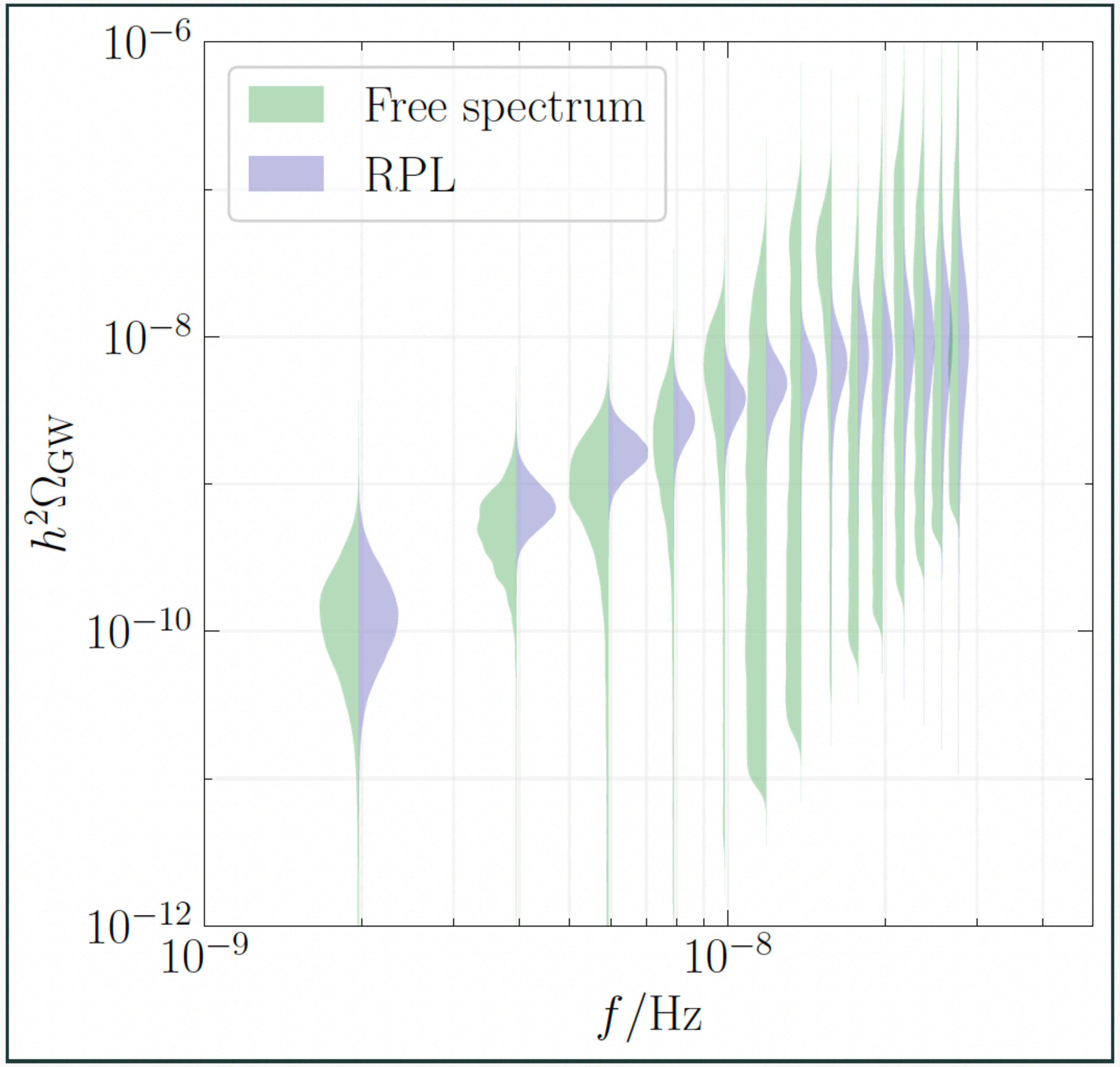
VS

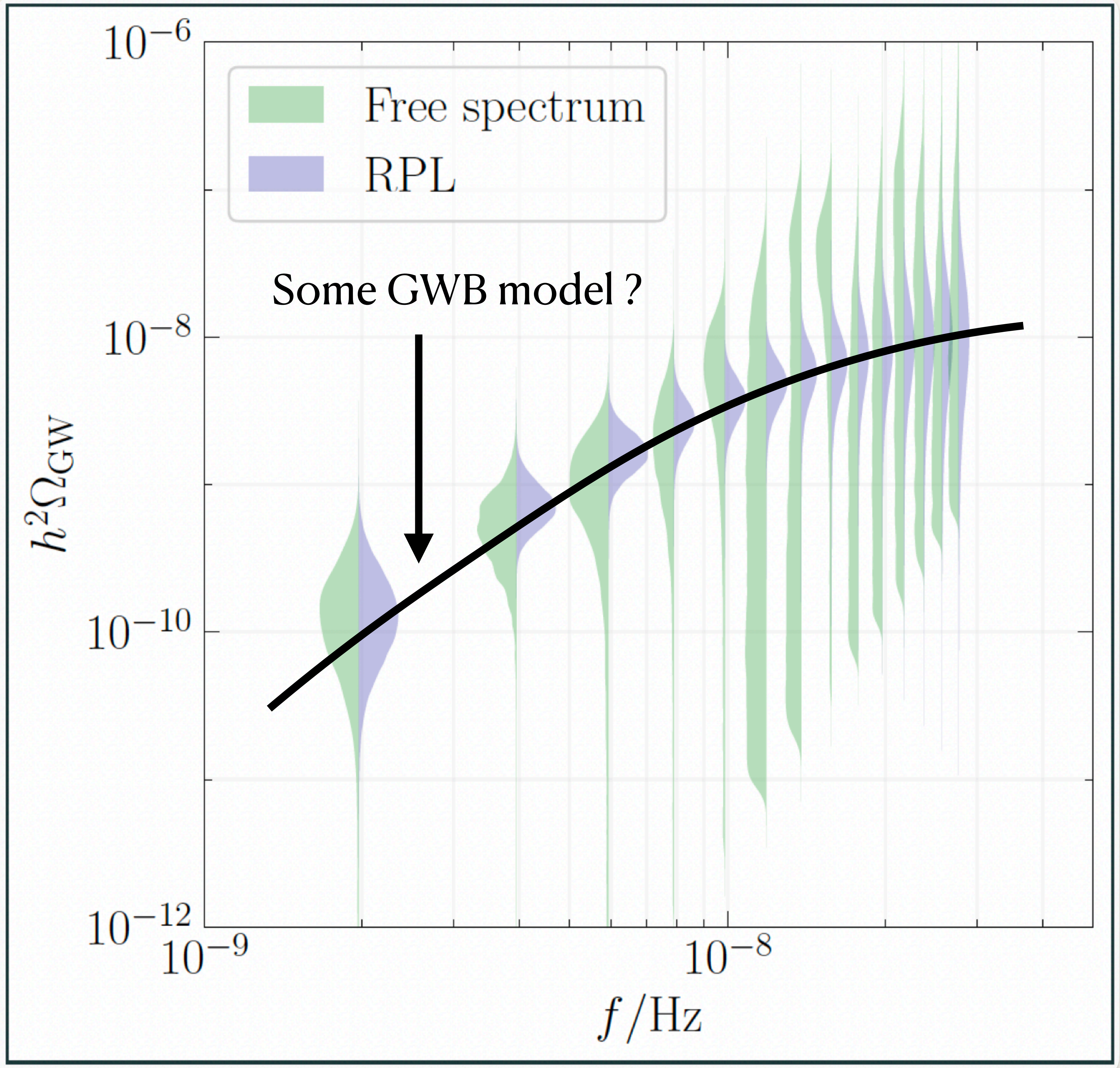


Comparison to free spectrum

Free spectrum: find the best Ω_{GW} for each data's frequency bin (not over range of frequencies, as before!)

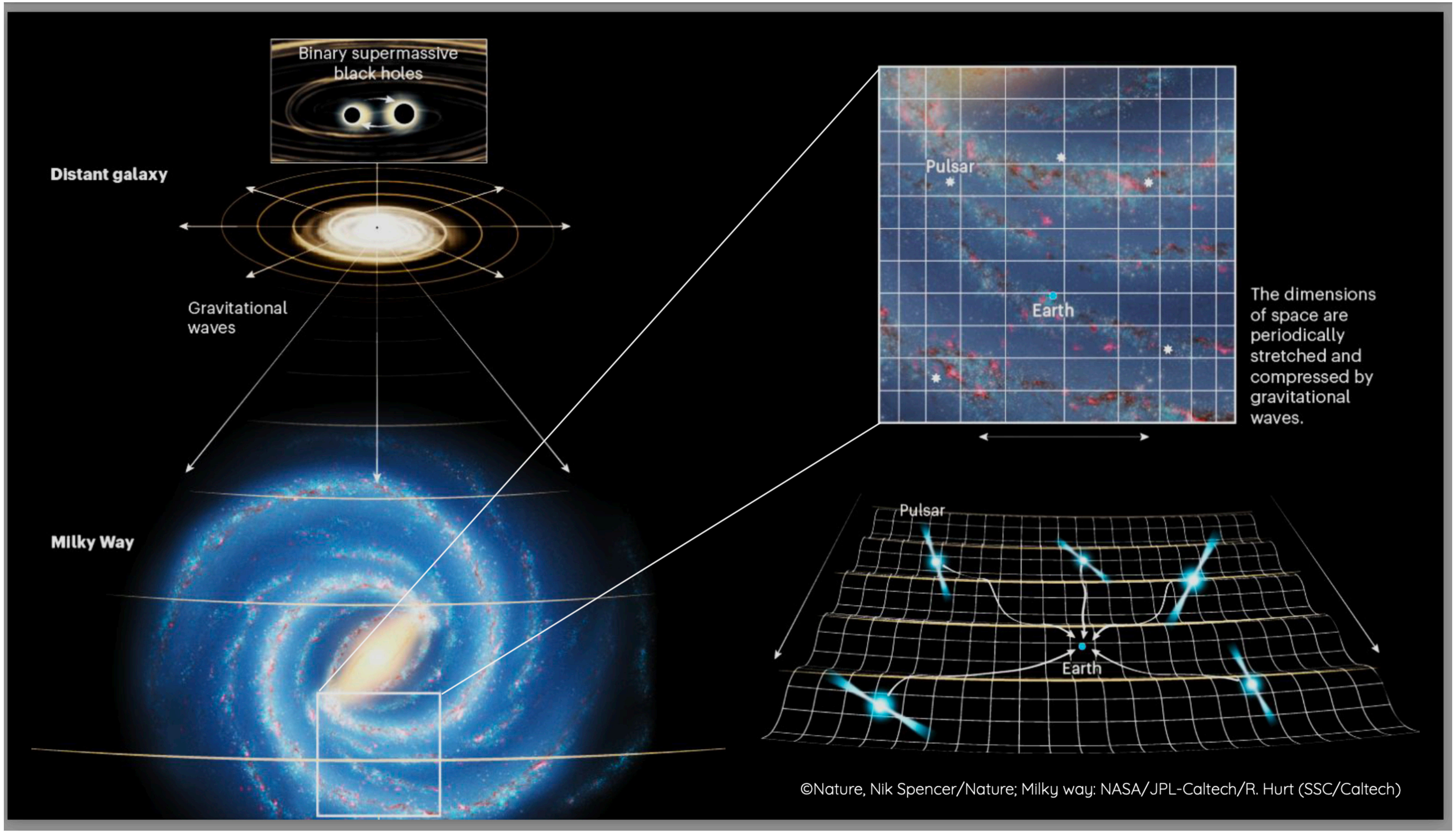
Bayesian periodograms (the "violins")





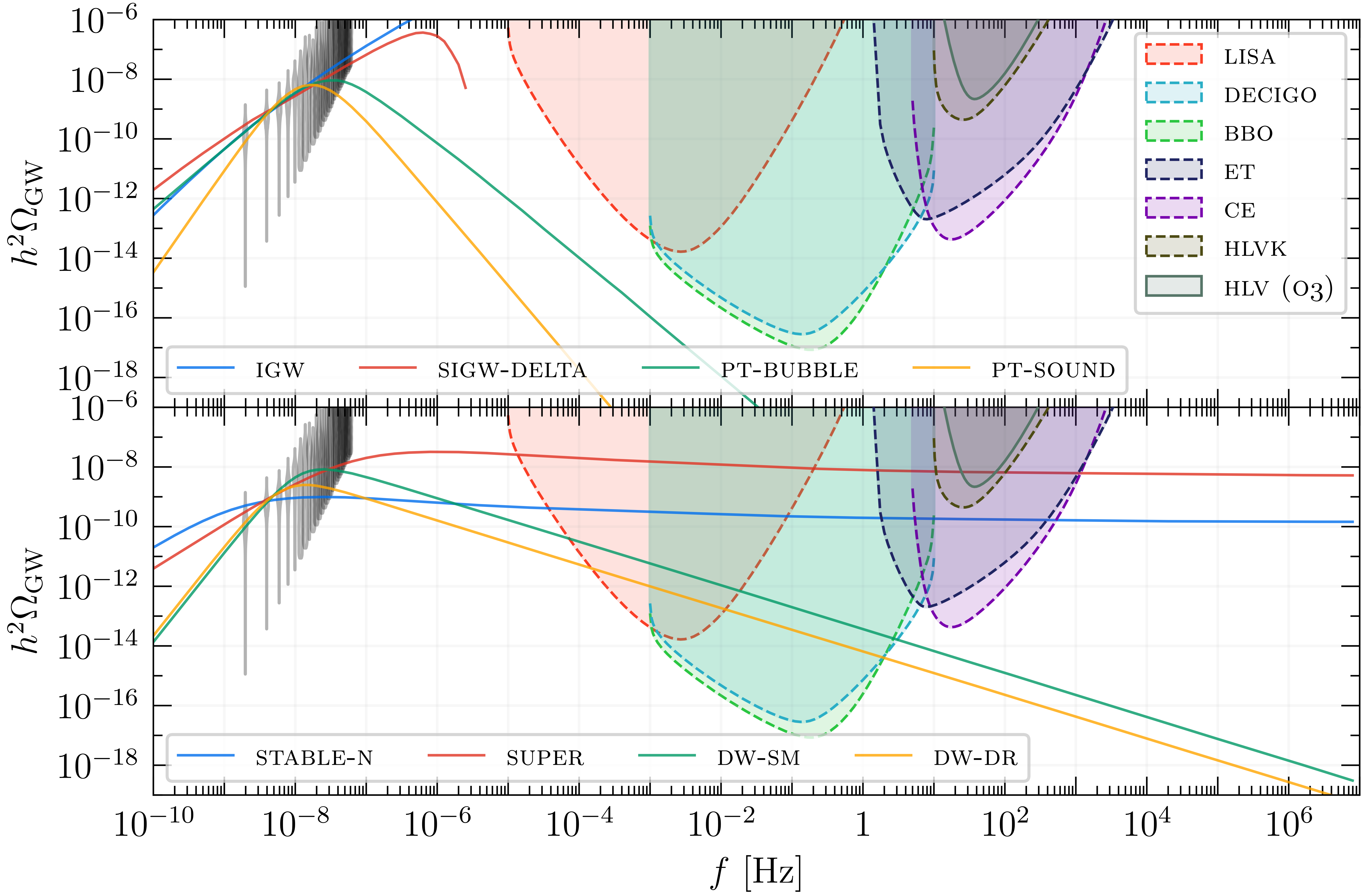
Pulsar timing arrays

- Strategy: timing a galactic-sized network of millisecond pulsars



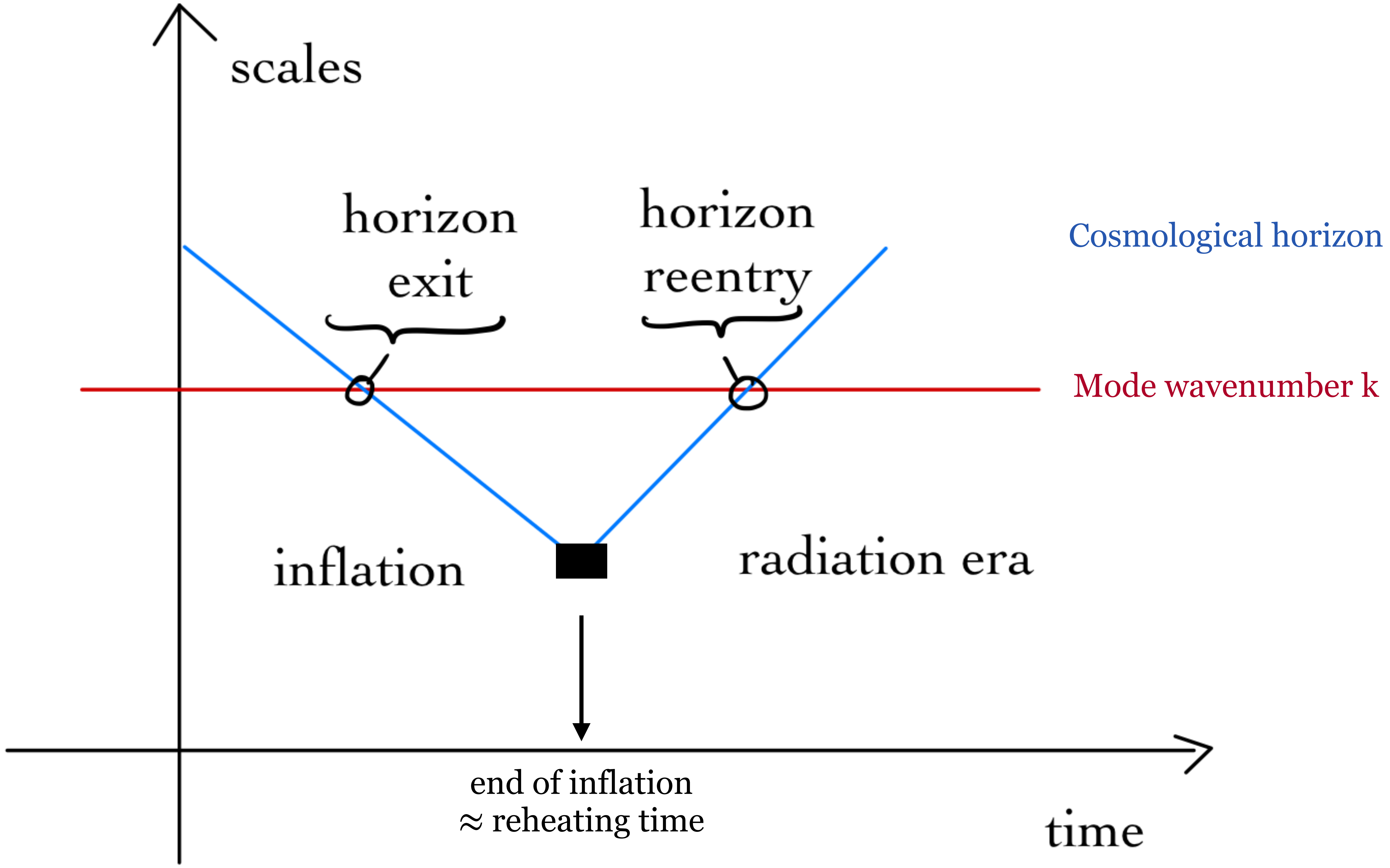
Afzal et al. ApJL 951 L11 (2023) 2306.16219

Complementary probes



Inflation

- Very fast early expansion
- Quantum fluctuation modes could grow inside the Hubble horizon, leave the horizon, and enter again.



Inflation

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