Too much energy for too little noise

Dark sector phase transitions in light of PTAs, BBN, and the CMB

arXiv:230x.soon

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Theory Seminar, Department of Physics, University of Oslo
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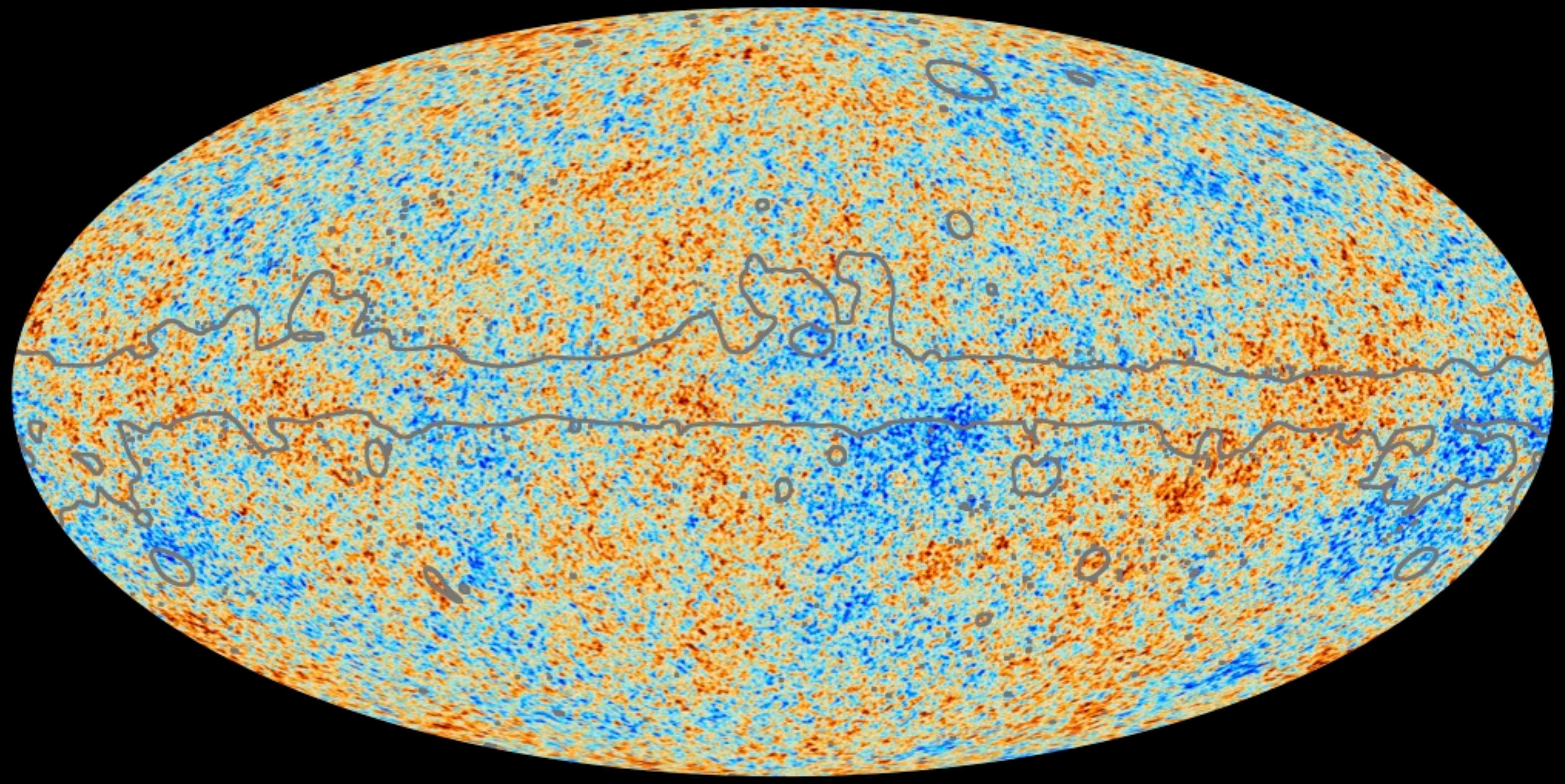
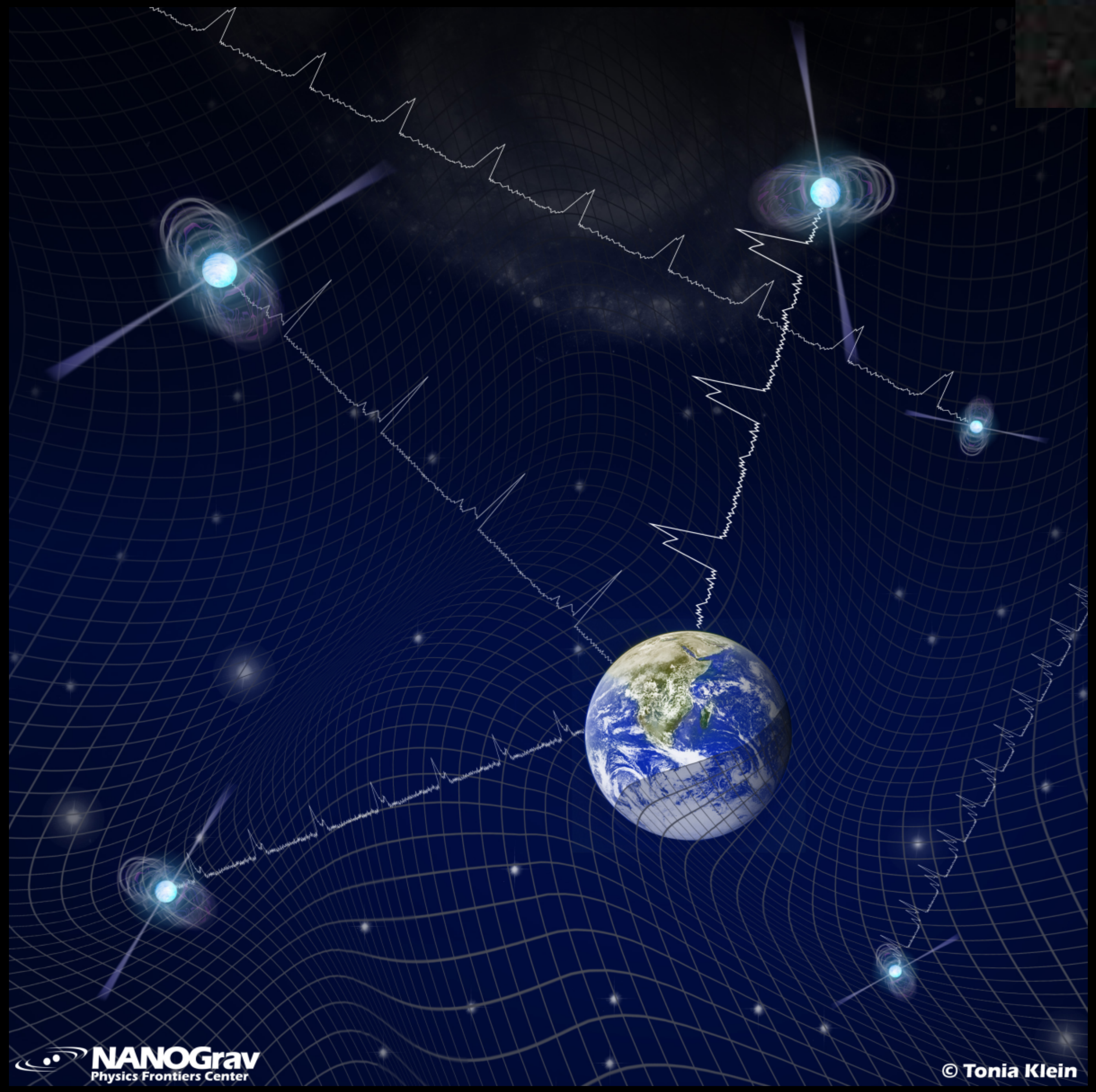
Max-Planck-Institut
für Kernphysik
Heidelberg



Planck collaboration

NASA/STSCI

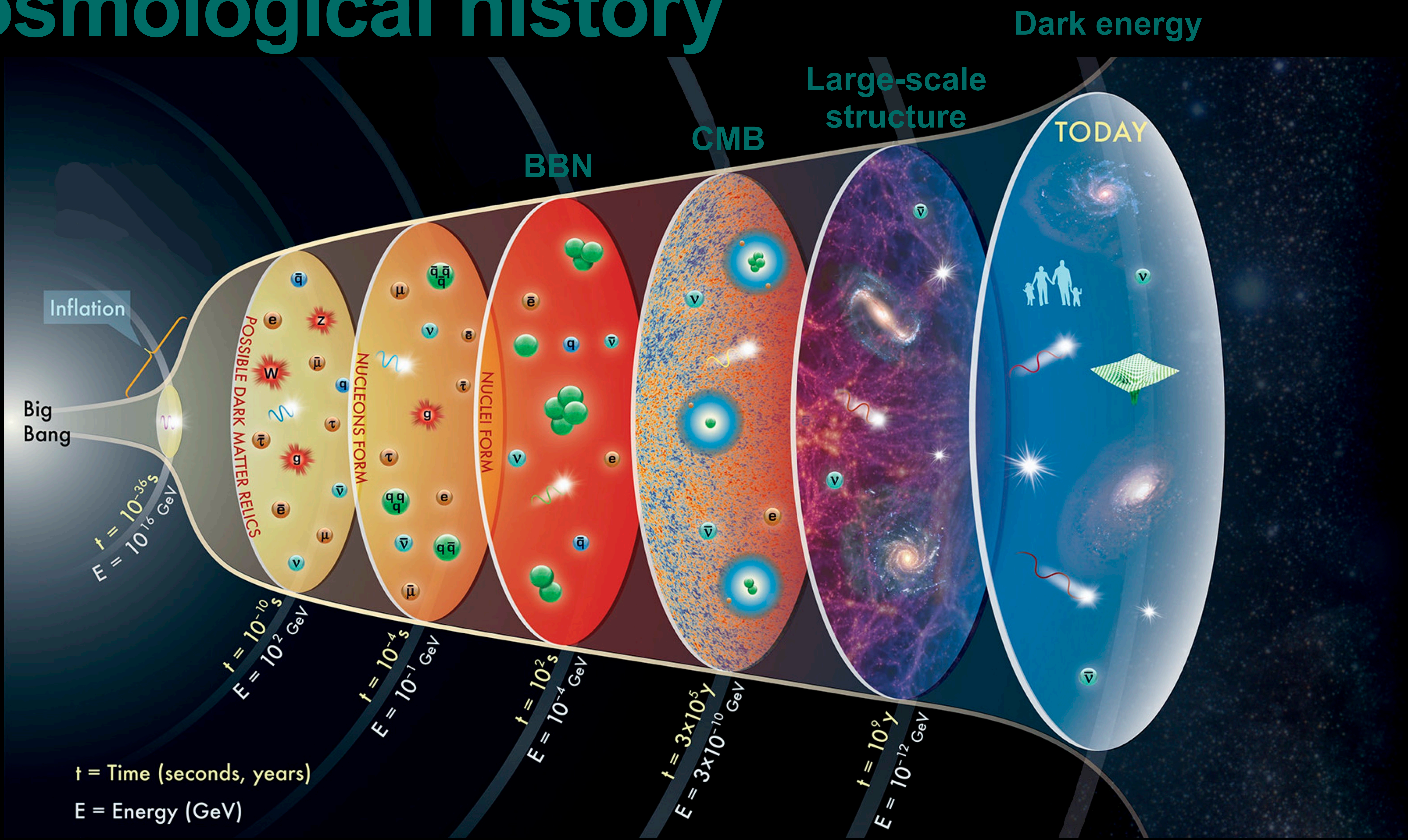


NANOGrav Collaboration

Outline

- Observational probes of the cosmological history
- Gravitational waves
- Pulsar timing arrays and the NANOGrav 12.5-year dataset
- First-order phase transitions
- Explaining the NANOGrav dataset with dark sector phase transitions
- Conclusions

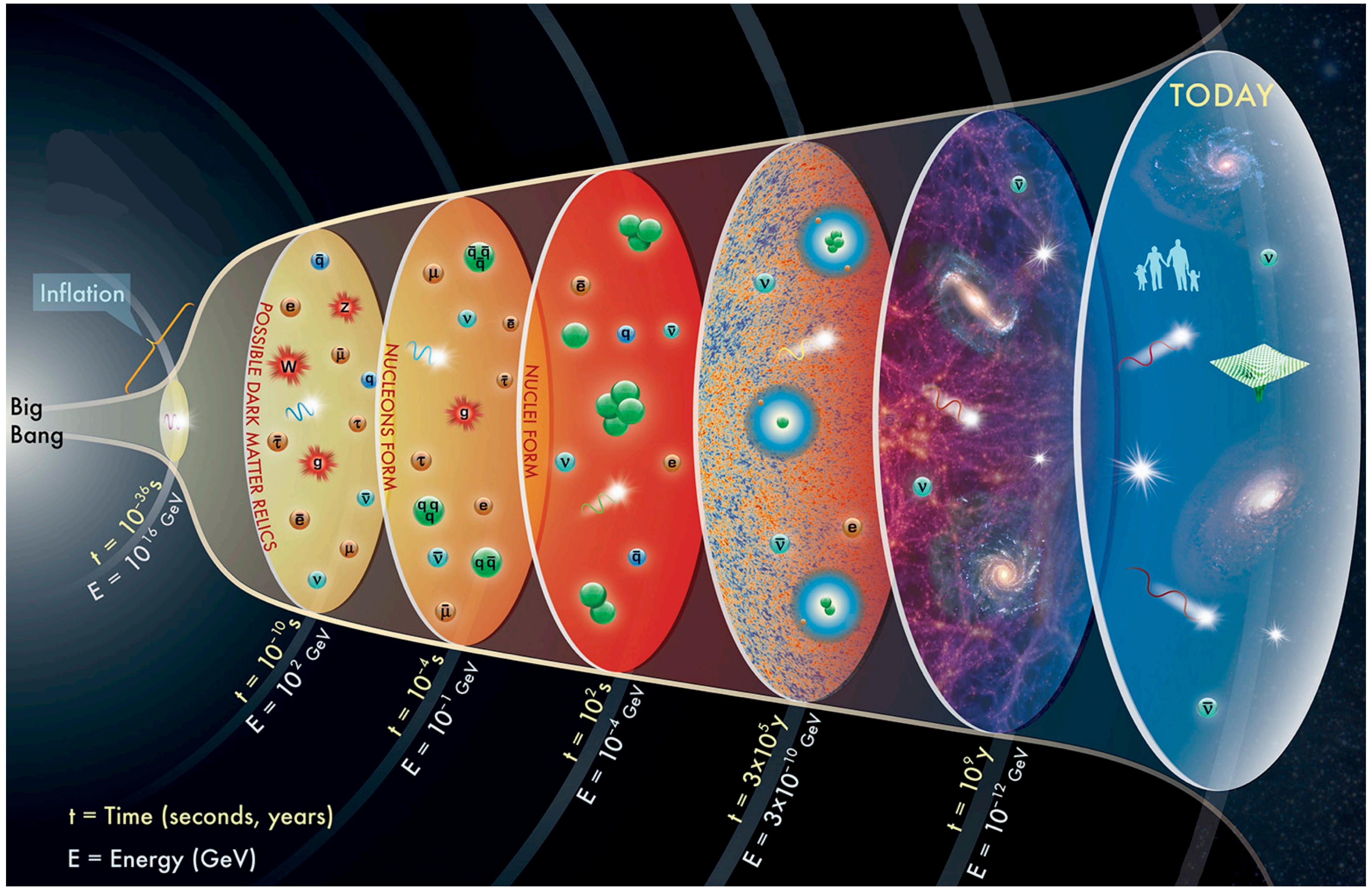
Cosmological history



Particle Data Group, LBNL

Cosmological history

- How did we arrive at this picture?
- Decades of observational cosmology
- In particular CMB missions since 90s (COBE / WMAP / Planck satellites)
- Establishment of cosmological standard model: ΛCDM
  - Λ: dark energy
  - CDM: cold dark matter
  - 6 parameters needed to explain CMB power spectrum, measured at percent-level
- Still: open questions (dark matter/dark energy/ baryogenesis/tensions/…)

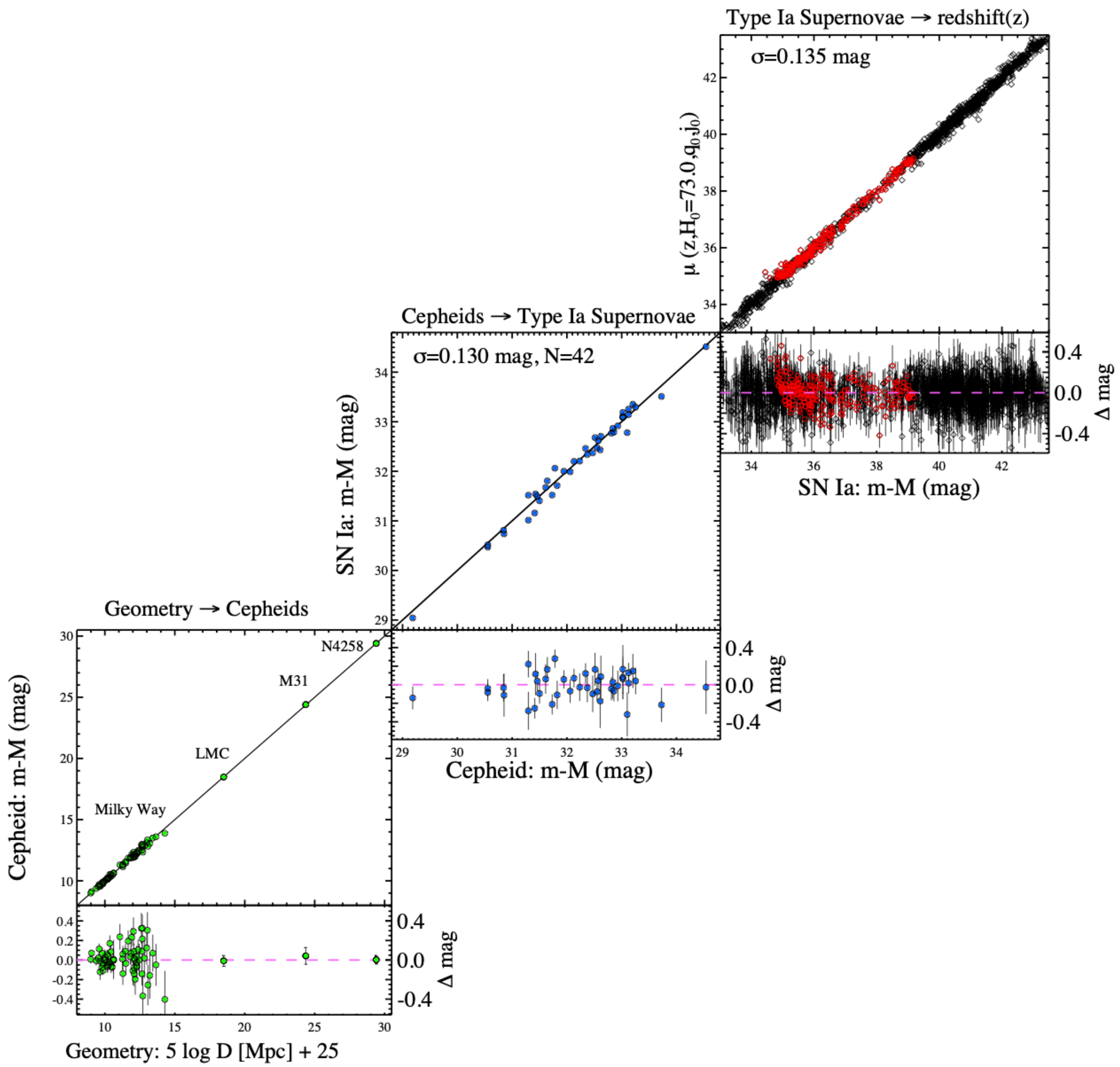


Particle Data Group, LBNL

Observational probes

Late Universe (after recombination)

- Type Ia supernovae
  - Use geometry (parallax information), cepheids, and type Ia supernovae to construct distance ladder
  - Combination with information on redshift $z = \Delta\lambda/\lambda$ gives Hubble constant
  - But: Hubble tension (discrepancy with CMB measurement)

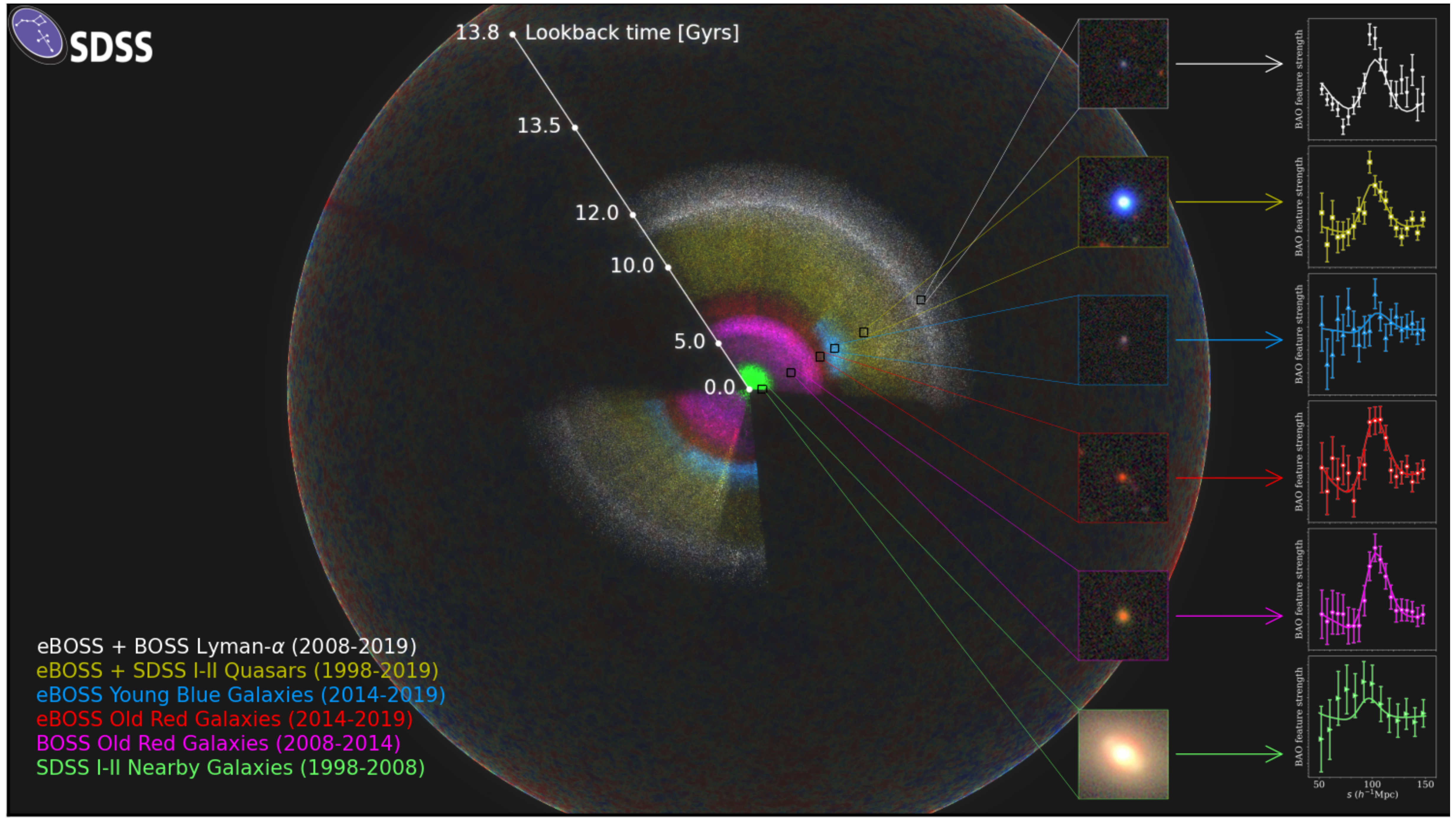


Riess et al. 2112.04510

Observational probes

Late Universe (after recombination)

- Type Ia supernovae
- Galaxy observations (redshift surveys etc.)
  - Information on matter distribution in the Universe from mapping out galaxy distribution
  - Matter power spectrum

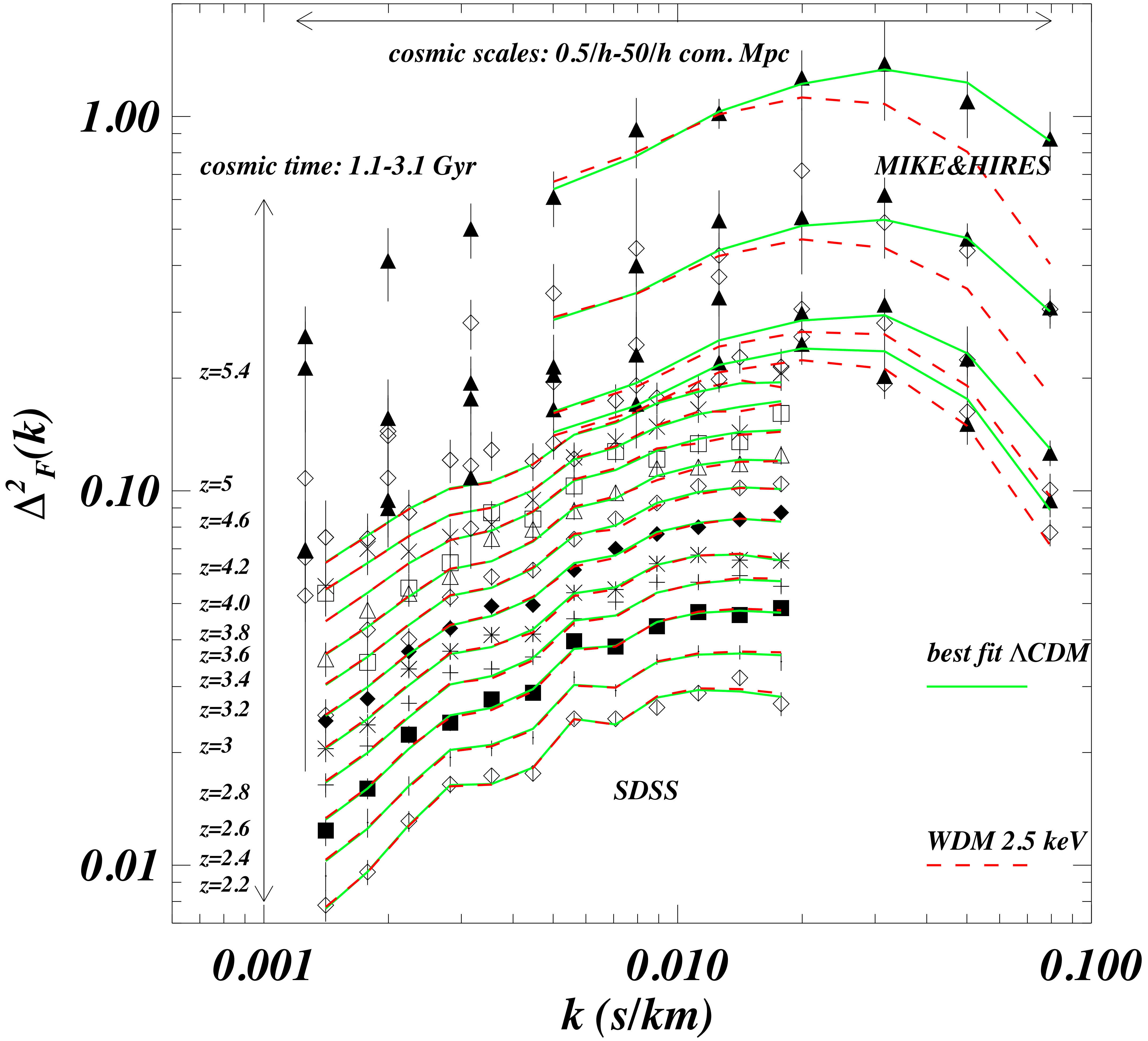


Sloan Digital Sky Survey

Observational probes

Late Universe (after recombination)

- Type Ia supernovae
- Galaxy observations (redshift surveys etc.)
- Lyman-α forest
  - Distant quasars shine light on neutral hydrogen gas clouds → absorption lines → Lyman-α forest
  - Can be used to probe matter power spectrum at small scales
  - Stringent limits on possible suppression!

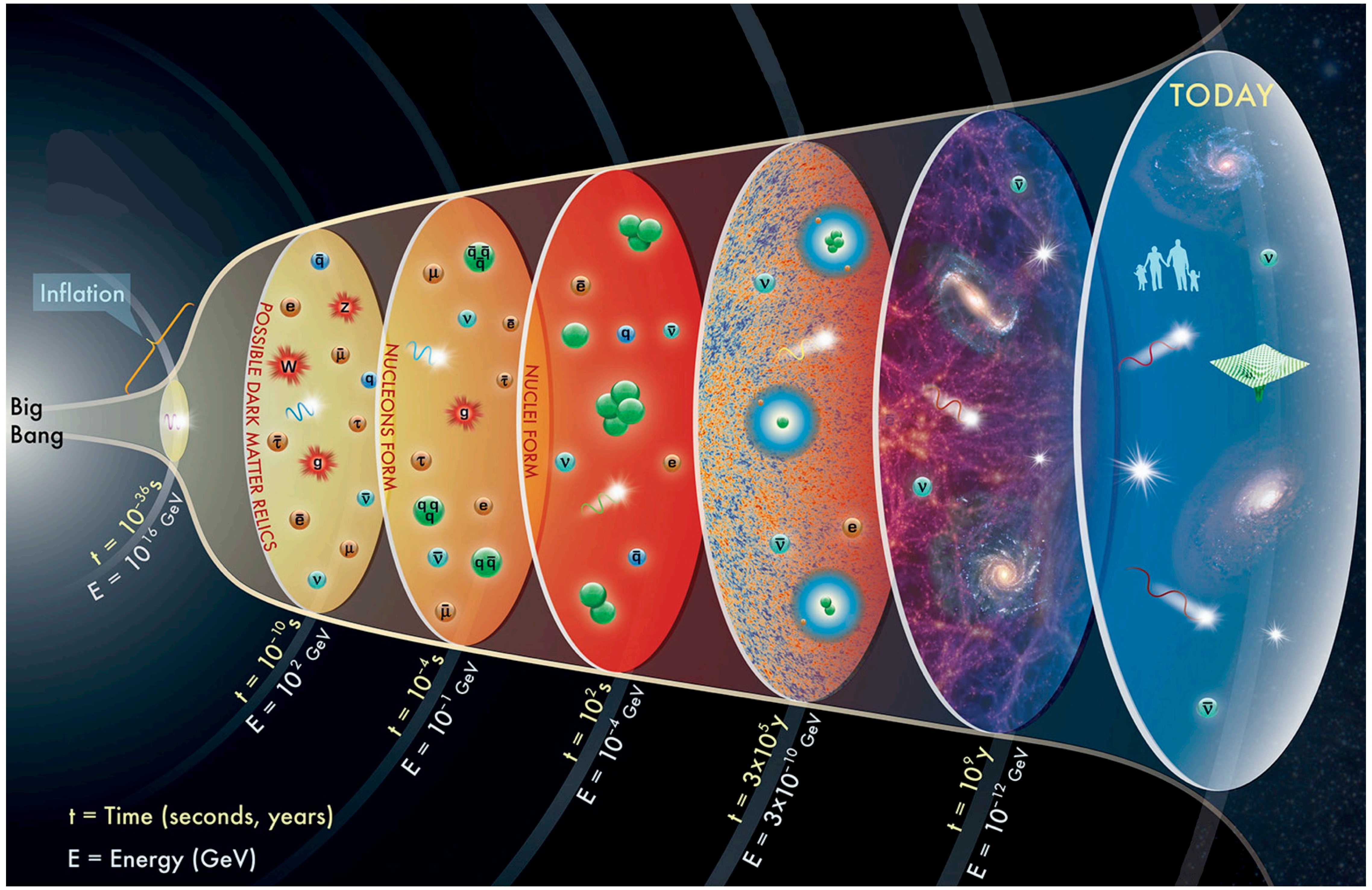


Viel et al. 1306.2314

Observational probes

Late Universe (after recombination)

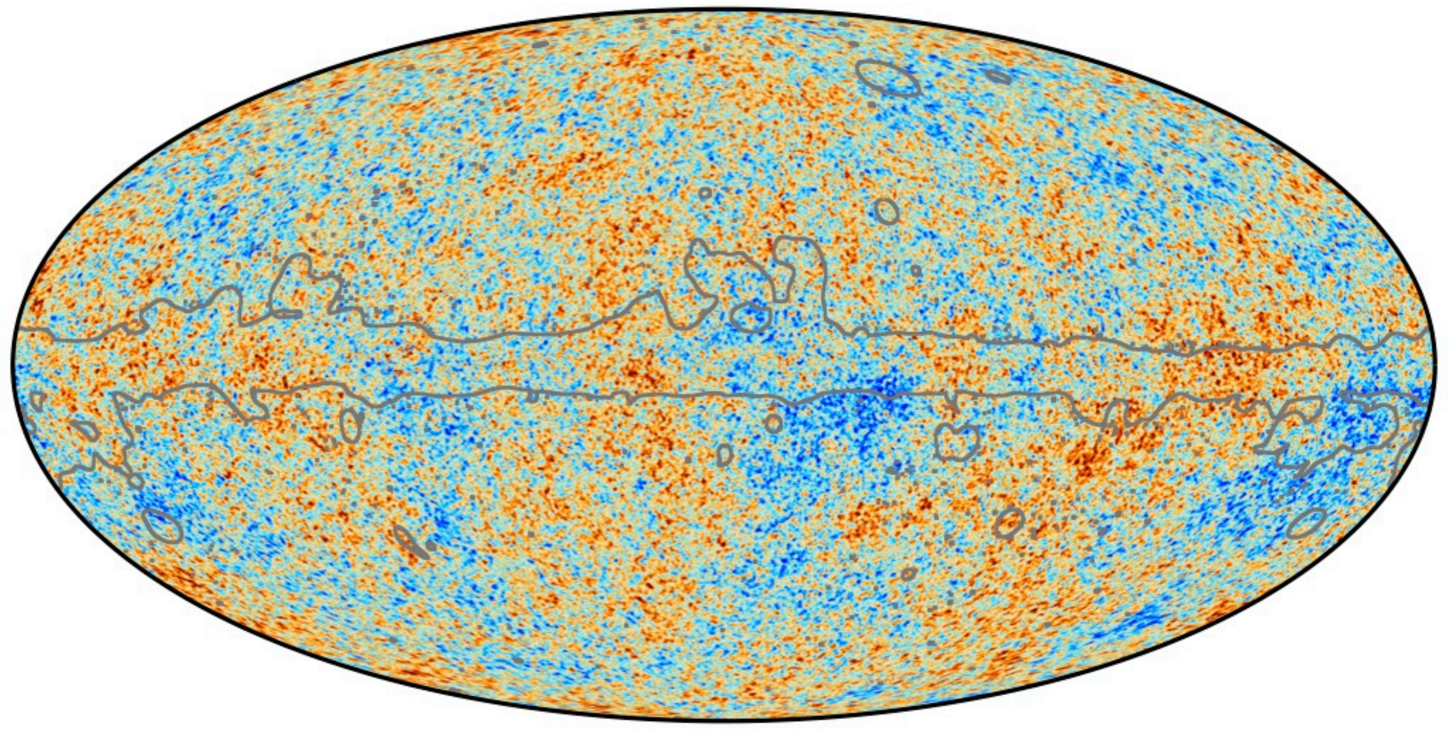
- Type Ia supernovae
- Galaxy observations (redshift surveys etc.)
- Lyman-α forest
- Future:
  - 21cm observations
    - Use 21cm spin-flip transition of neutral hydrogen to gain information at redshifts $z \gtrsim 12$
  - More generally: Intensity mapping (use other elements as well)
  - Bridges the gap to early-Universe probes



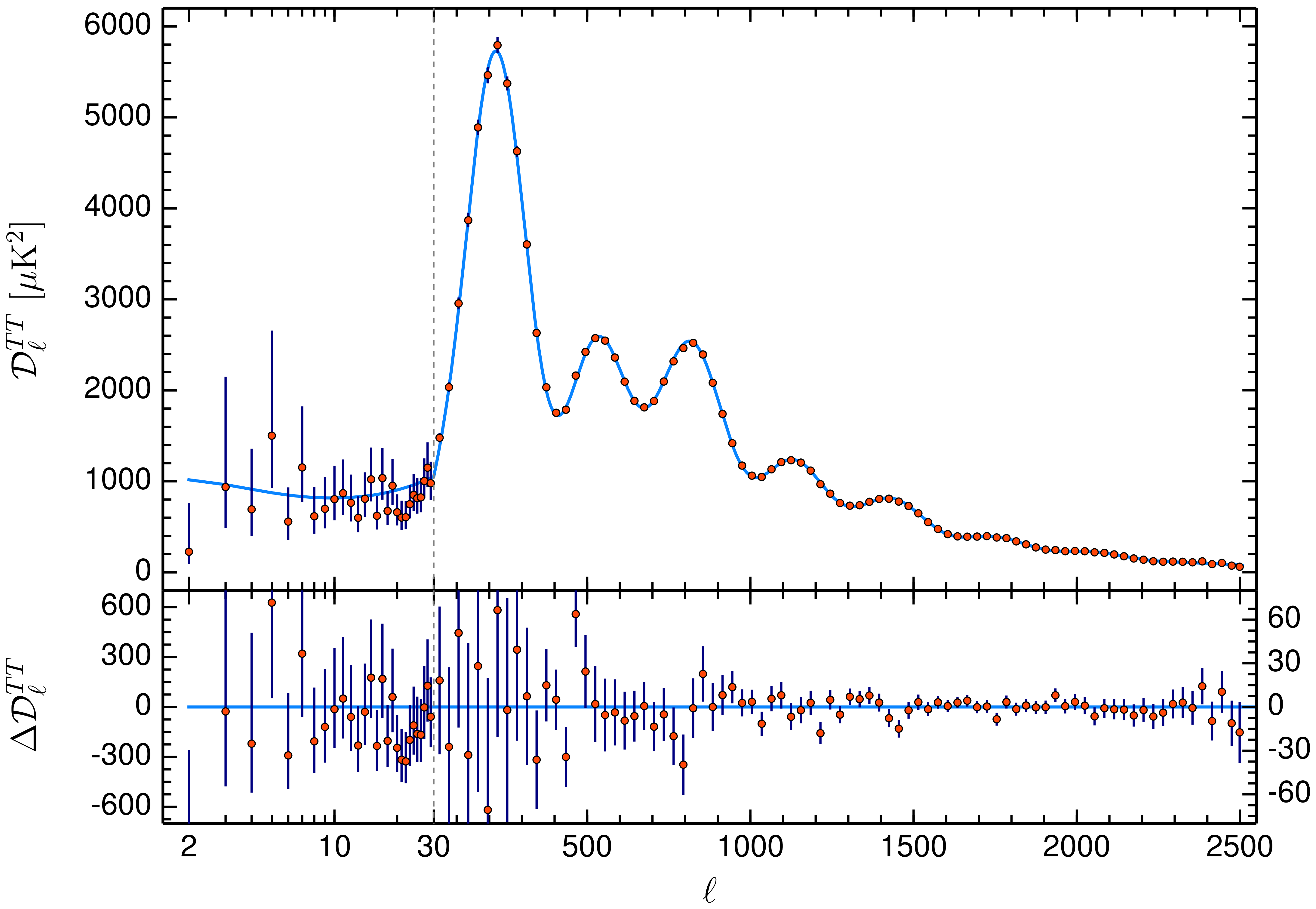
Particle Data Group, LBNL

Observational probes

Early Universe (around or before recombination)



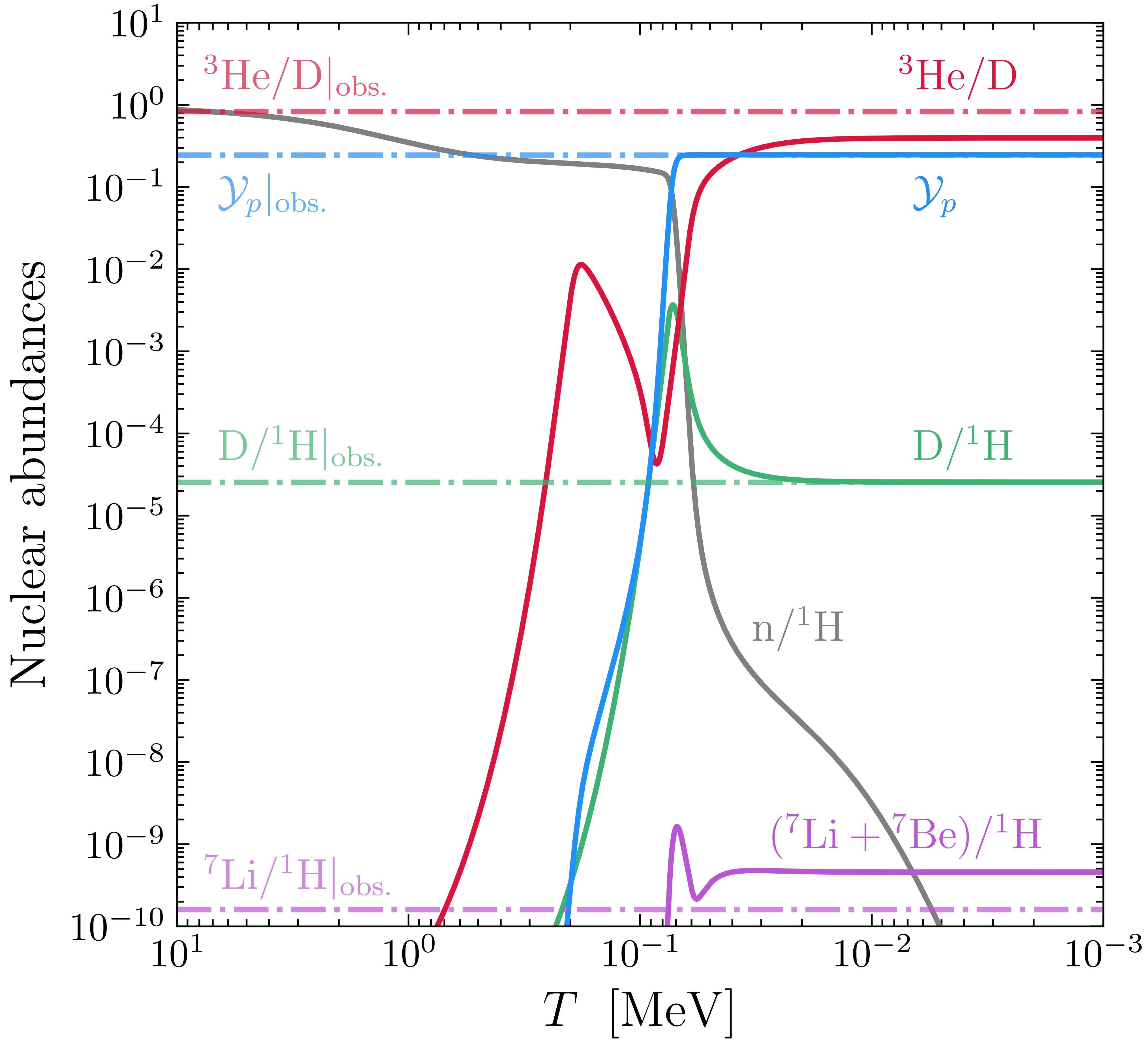
- Cosmic microwave background (CMB)
  - Anisotropies contain detailed information on cosmological history
  - Probes up to matter-radiation equality
    $z \lesssim 3400,\, T \lesssim 0.8\,\mathrm{eV}$
  - Planck: $N_{\mathrm{eff}} = 2.99 \pm 0.17$



Observational probes

Early Universe (around or before recombination)

- CMB
- Big Bang Nucleosynthesis (BBN)
  - Observations of primordial light element abundances in good agreement with prediction from standard BBN
  - Probes up to $z \lesssim 6 \times 10^9, T \lesssim 1\,\mathrm{MeV}$

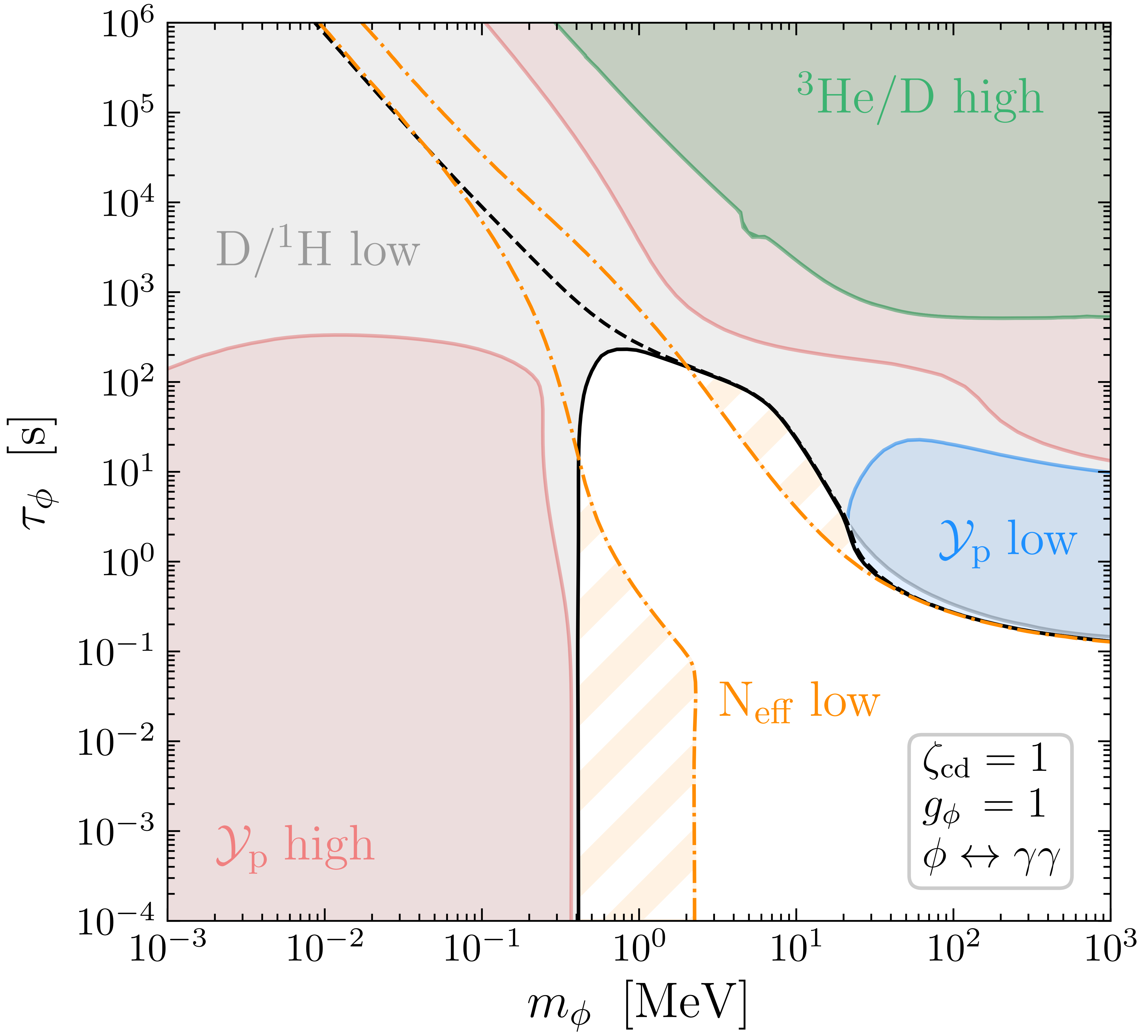


PFD, PhD thesis

Observational probes

Early Universe (around or before recombination)

- CMB
- Big Bang Nucleosynthesis (BBN)
  - Observations of primordial light element abundances in good agreement with prediction from standard BBN
  - Probes up to $z \lesssim 6 \times 10^9$, $T \lesssim 1\,\mathrm{MeV}$
  - With Planck: $N_\mathrm{eff} = 2.90 \pm 0.14$ (Yeh et al. 2207.13133)
  - Particles with $m \lesssim 1\,\mathrm{MeV}$ in equilibrium with SM or decaying with lifetimes $\tau \gtrsim 0.1\,\mathrm{s}$ severely constrained

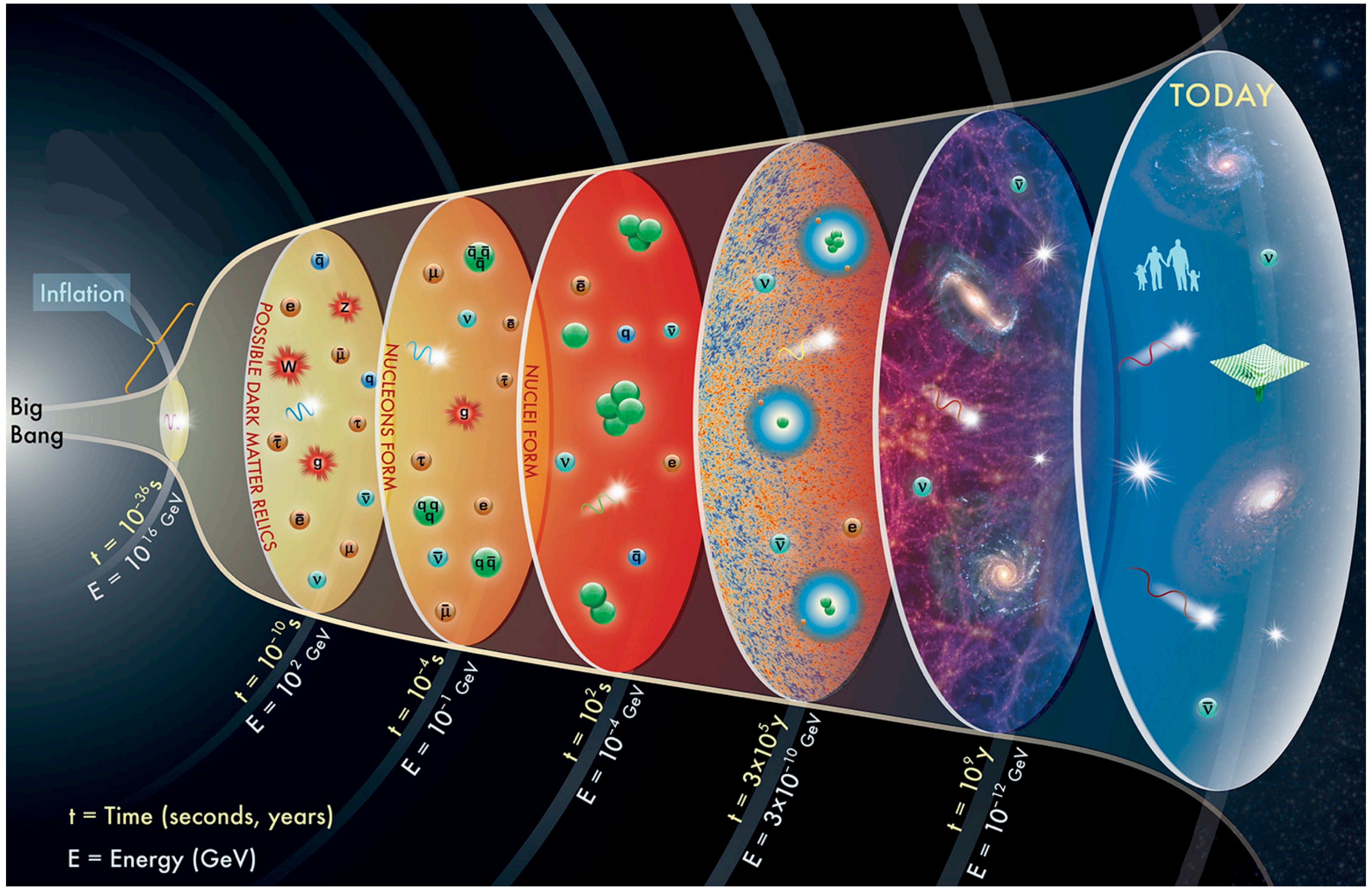


PFD et al. 2011.06519

Observational probes

Early Universe (around or before recombination)

- CMB
- BBN
- Highest temperature observationally accessible is around MeV
- How can we go to higher temperatures/earlier times?
- Gravitational waves

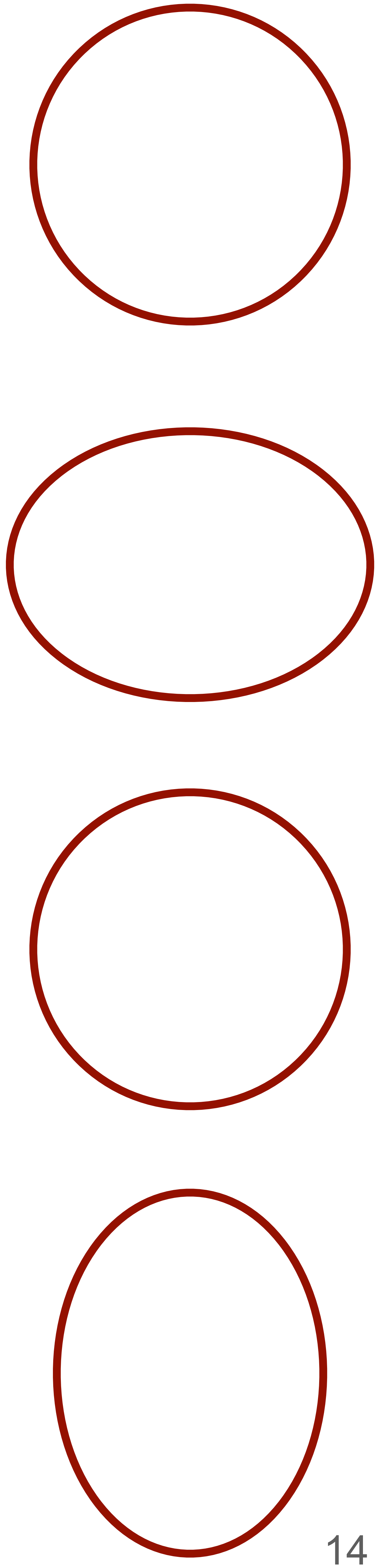


Particle Data Group, LBNL

Gravitational waves

Reminder: What are GWs?

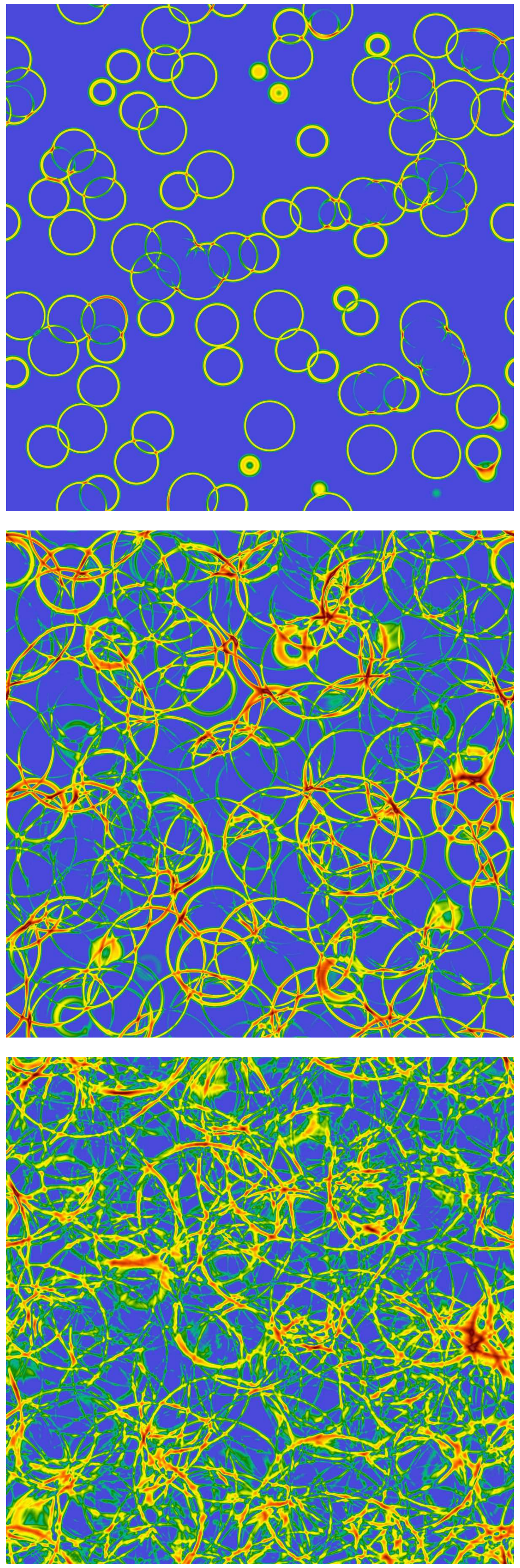
- Perturb background metric (usually flat or FLRW) $g_{\mu\nu} \rightarrow$ scalars, vectors, and tensors possible
- One can choose coordinates such that $\Box \bar{h}_{\mu\nu} = -\frac{16\pi G}{c^4} T_{\mu\nu}$ (assuming flat background)
- Wave equation with energy-momentum tensor as source
- Stretch/squeeze space perpendicular to propagation direction
- Quadrupole moment of energy-momentum tensor is lowest order for source $\bar{h}_{ij}(t, r) \propto \ddot{I}_{ij}(t - r/c)$
- $I_{ij} = \int \mathrm{d}^3 r \left(r_{ij} - 3r\delta_{ij} \right) \rho$
- Also stochastic processes can source GWs if they have non-vanishing quadrupole moment (or higher multipole orders)



Gravitational waves

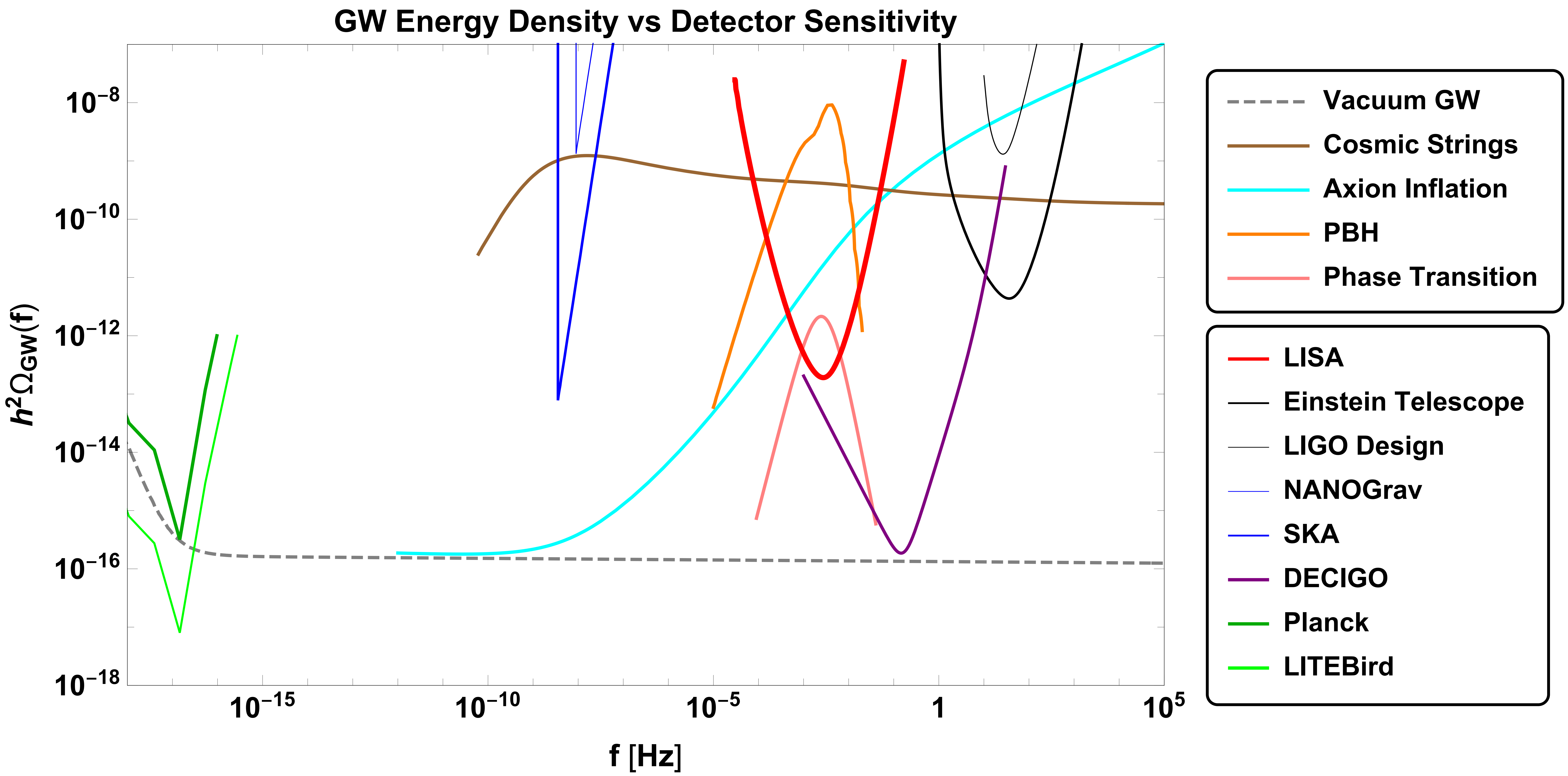
Stochastic gravitational wave background

- Why useful for early-universe cosmology?
  - Propagate freely after generation ($T \ll M_{\rm Pl}$)
  - Can probe early-Universe cosmology at much higher temperatures $T \gg \mathrm{MeV}$, earlier times $t \ll 1\,\mathrm{s}$
- GW spectrum: $\Omega_{\rm GW}(f) = \frac{1}{\rho_{\rm crit}} \frac{\mathrm{d}\rho_{\rm GW}}{\mathrm{d}\ln f} = \frac{2\pi^2}{3H^2} f^2 h_c^2(f)$
- Potential sources: first-order phase transitions, inflation, topological defects, primordial black holes, …
- Downsides:
  - Sizable GWs not in every model / all parts of parameter space
  - Distinguishing models based on GWs alone very difficult



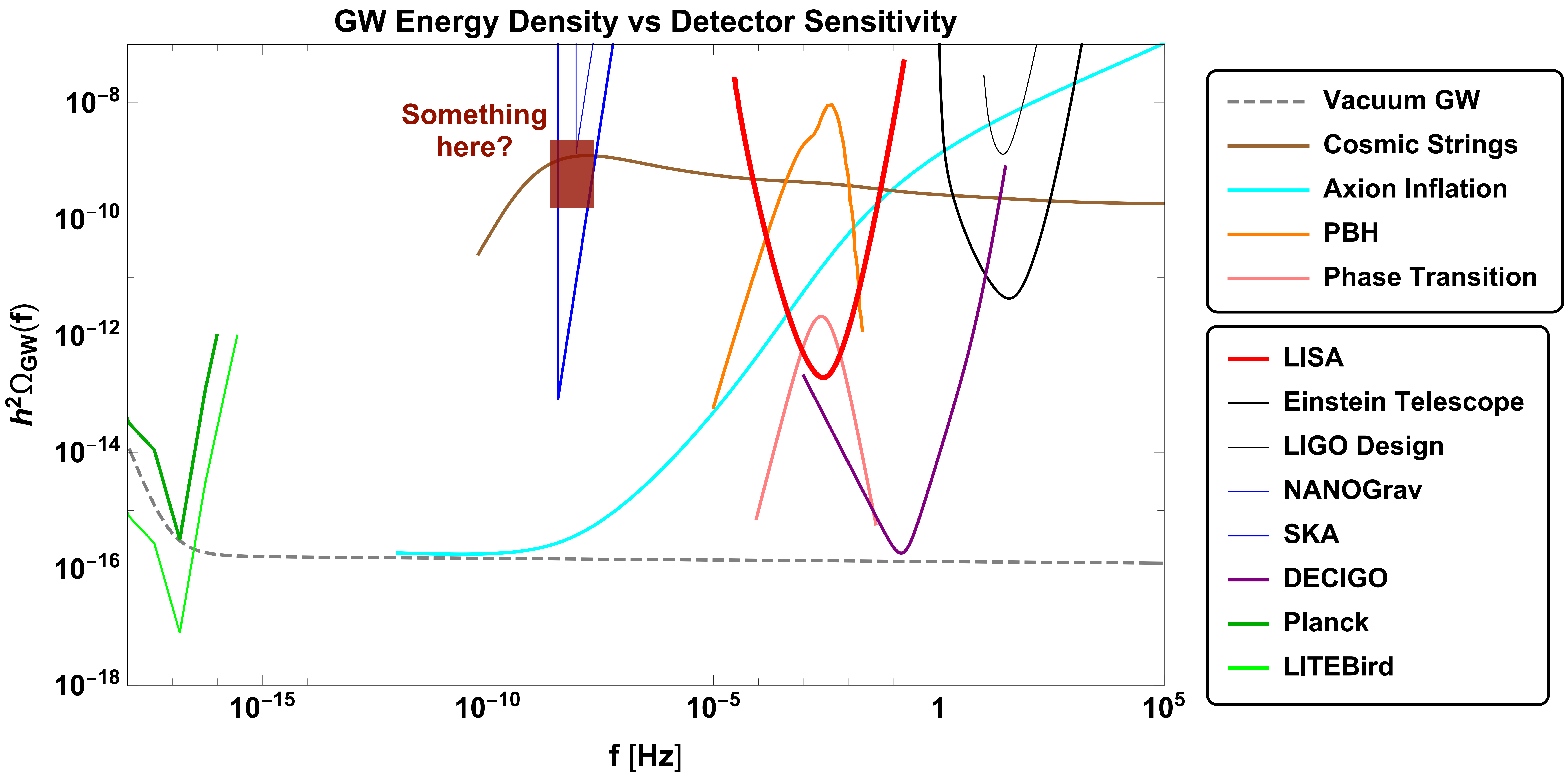
Hindmarsh et al. 1504.03291

Gravitational waves



Auclair et al. 2204.05434

Gravitational waves



Auclair et al. 2204.05434

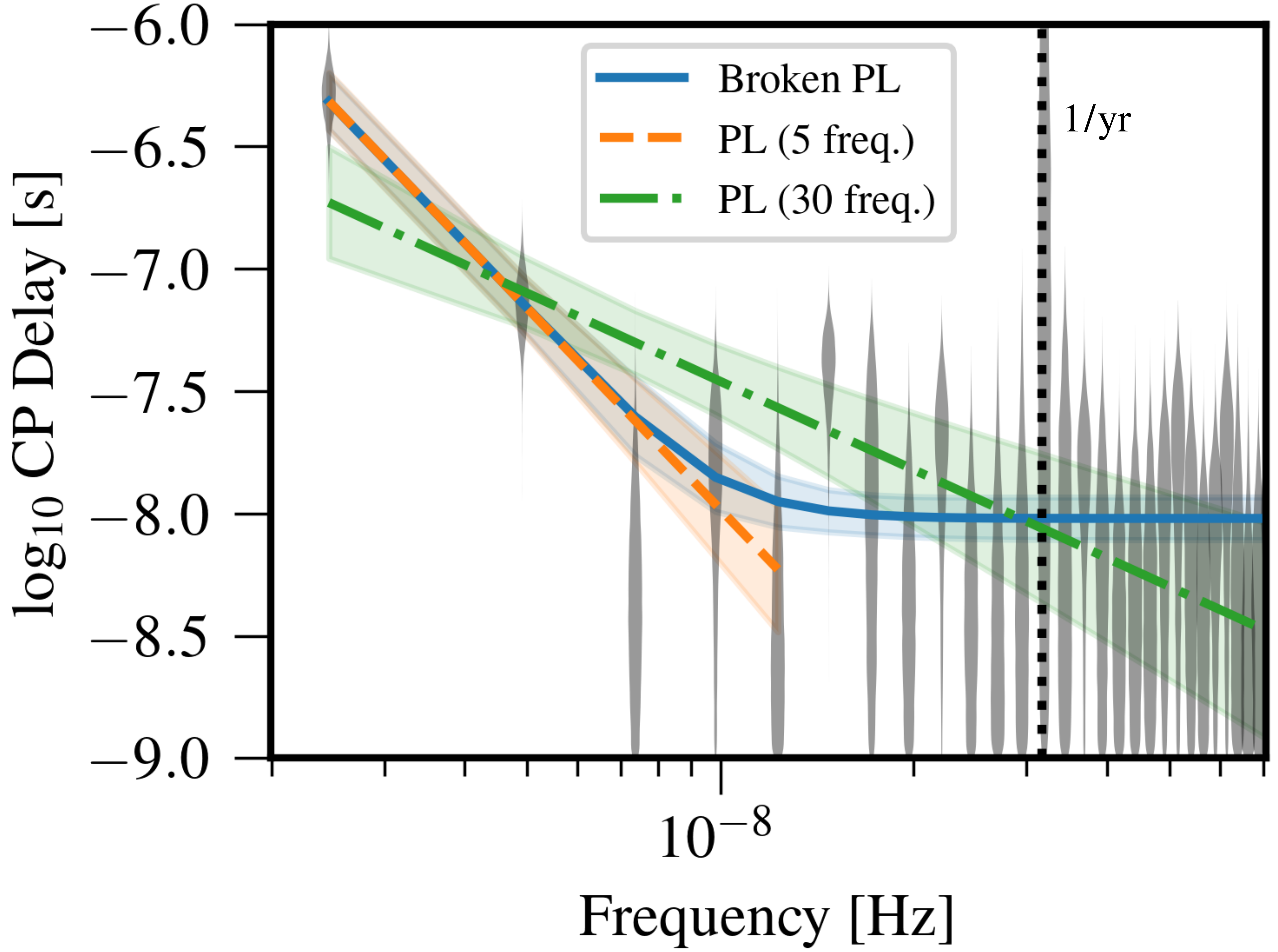
Pulsar timing arrays

- Millisecond pulsars send out radio pulses with extremely stable pulse frequency
- GWs affect propagation time → change observed pulse frequency
- PTAs regularly (~ weekly - monthly) monitor pulse frequency of pulsars with radio telescopes
- Fit time of arrival data with pulsar timing model
- Timing residuals due to
  - Pulsar-intrinsic noise
  - Common-spectrum process, e.g. GWs

NANOGrav Collaboration

NANOGrav 12.5-year data set

- Strong evidence for stochastic process!
- Common amplitude and spectral slope across pulsars if modeled as power law
- 5 lowest frequencies agree with power law
- Flattening off for higher frequencies → pulsar-intrinsic noise leaking into common-spectrum process
- Analysis performed using 5 lowest frequencies only (particularly motivated for red-tilted spectrum)
- $\log_{10} \mathrm{CP\ Delay\ [s]} = \log_{10}\left(\sqrt{\frac{H_{100}^2}{8\pi^4}\frac{h^2\Omega_{\mathrm{GW}}(f)}{f^5 t_{\mathrm{obs}} \mathrm{s}^2}}\right)$



NANOGrav collaboration 2009.04496

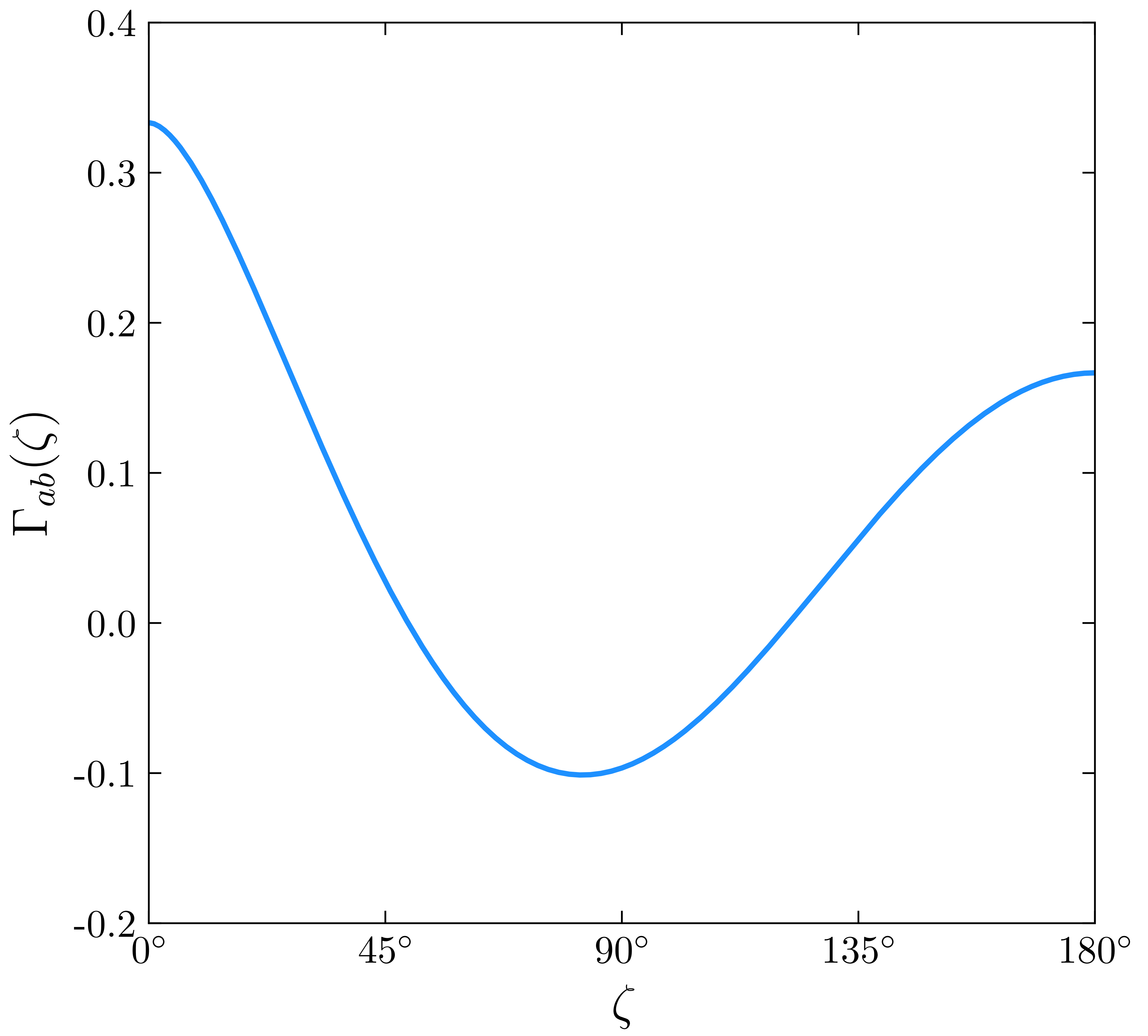
Pulsar timing arrays

How can we be sure a signal is due to GWs?

- Consider correlation Γ_{ab} between timing residuals of pulsars a and b with angle ζ between lines of sight
- Quadrupolar perturbation has specific Hellings-Downs correlation (Hellings and Downs 1983)

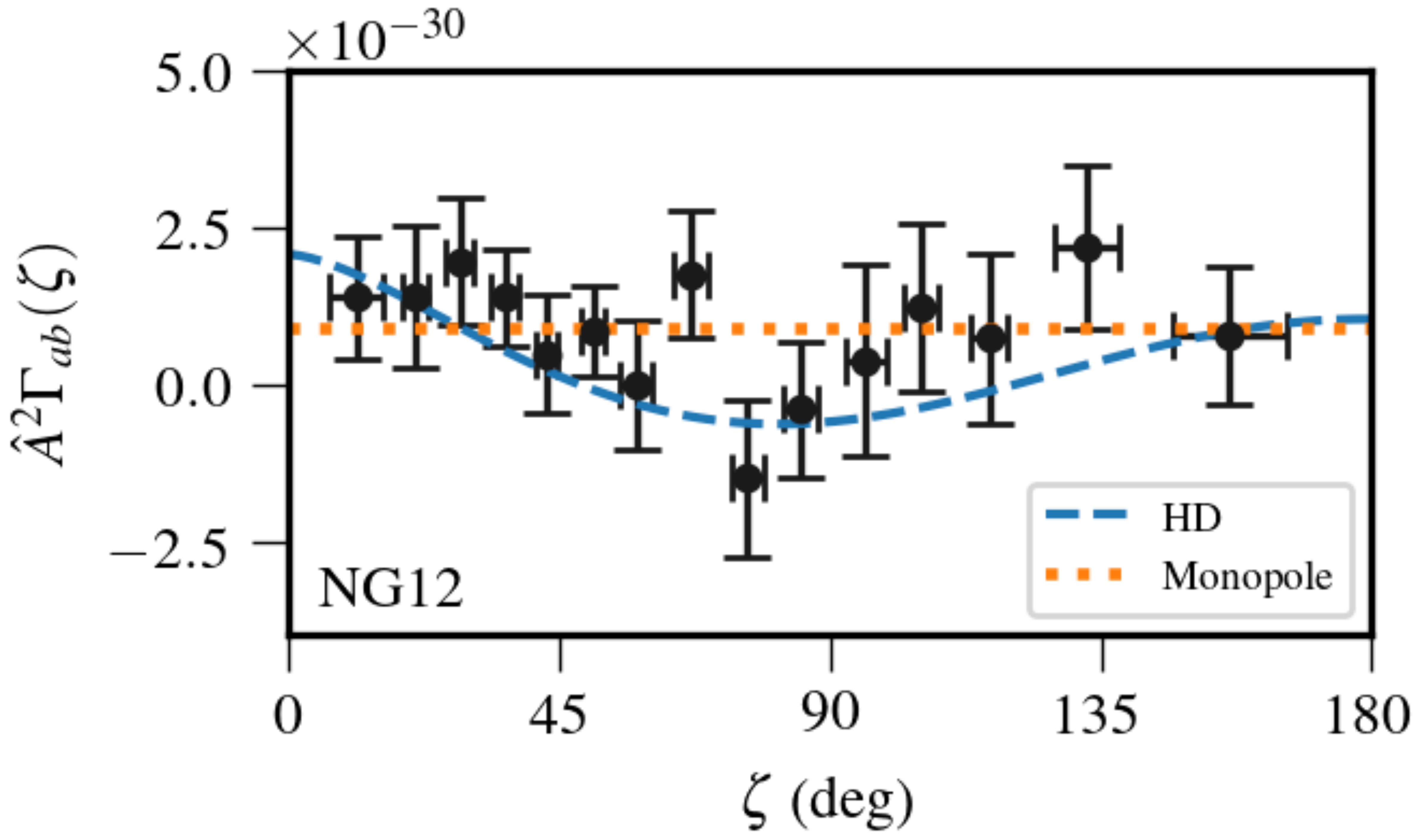
$$\Gamma_{ab}(\zeta) = \frac{1}{3} + \frac{1-\cos\zeta}{2}\left[\ln\left(\frac{1-\cos\zeta}{2}\right) - \frac{1}{6}\right]$$

- Other perturbations have different correlation:
  - Monopole (e.g. due to clock effects): $\Gamma_{ab}(\zeta) = 1$
  - Dipole (e.g. due to position of earth w.r.t. barycenter of solar system, affected by motion of other planets): $\Gamma_{ab} = \cos\zeta$



NANOGrav 12.5-year data set

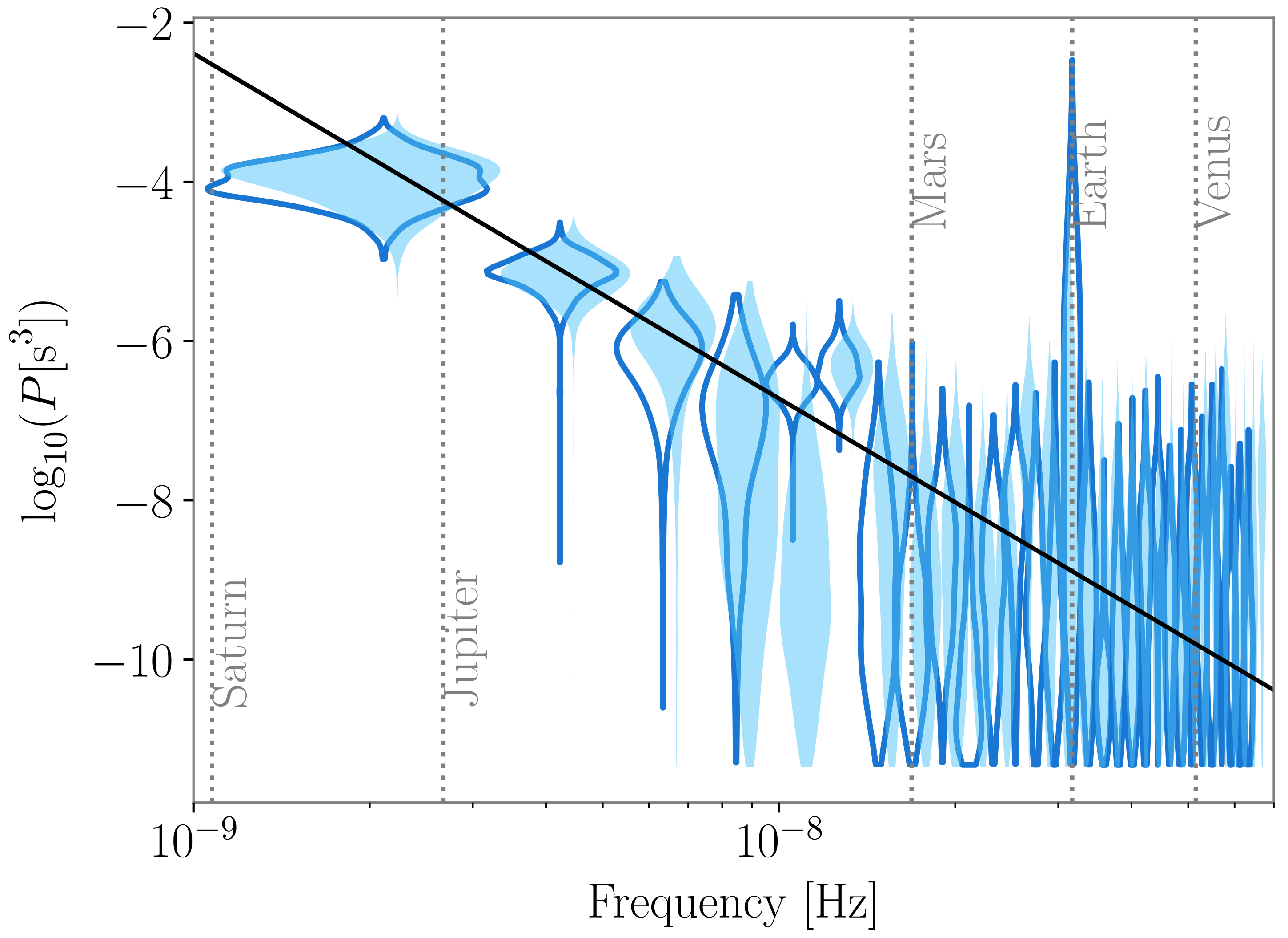
- Hellings-Downs correlation not confirmed (yet)
- Correlation consistent with monopole
- Evidence that observed signal is really due to GWs still missing

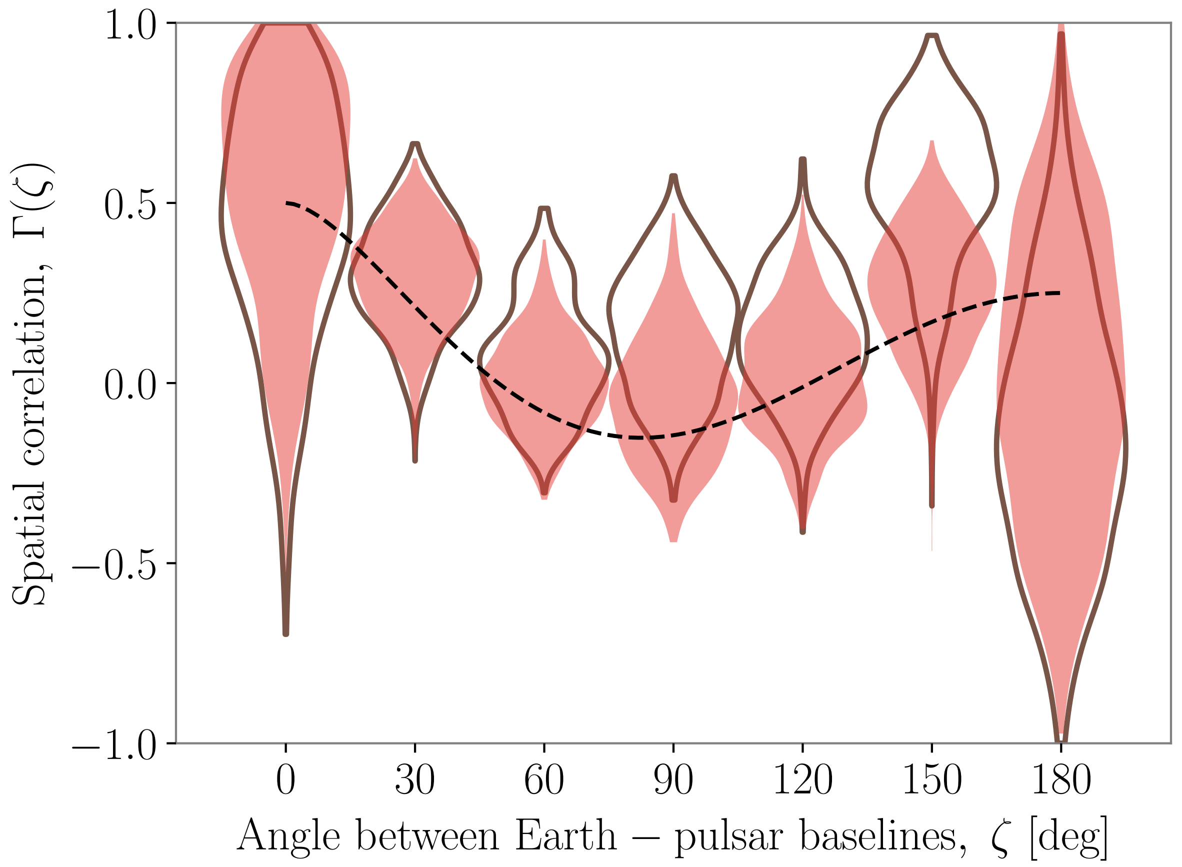


NANOGrav collaboration 2009.04496

Similar in other PTAs

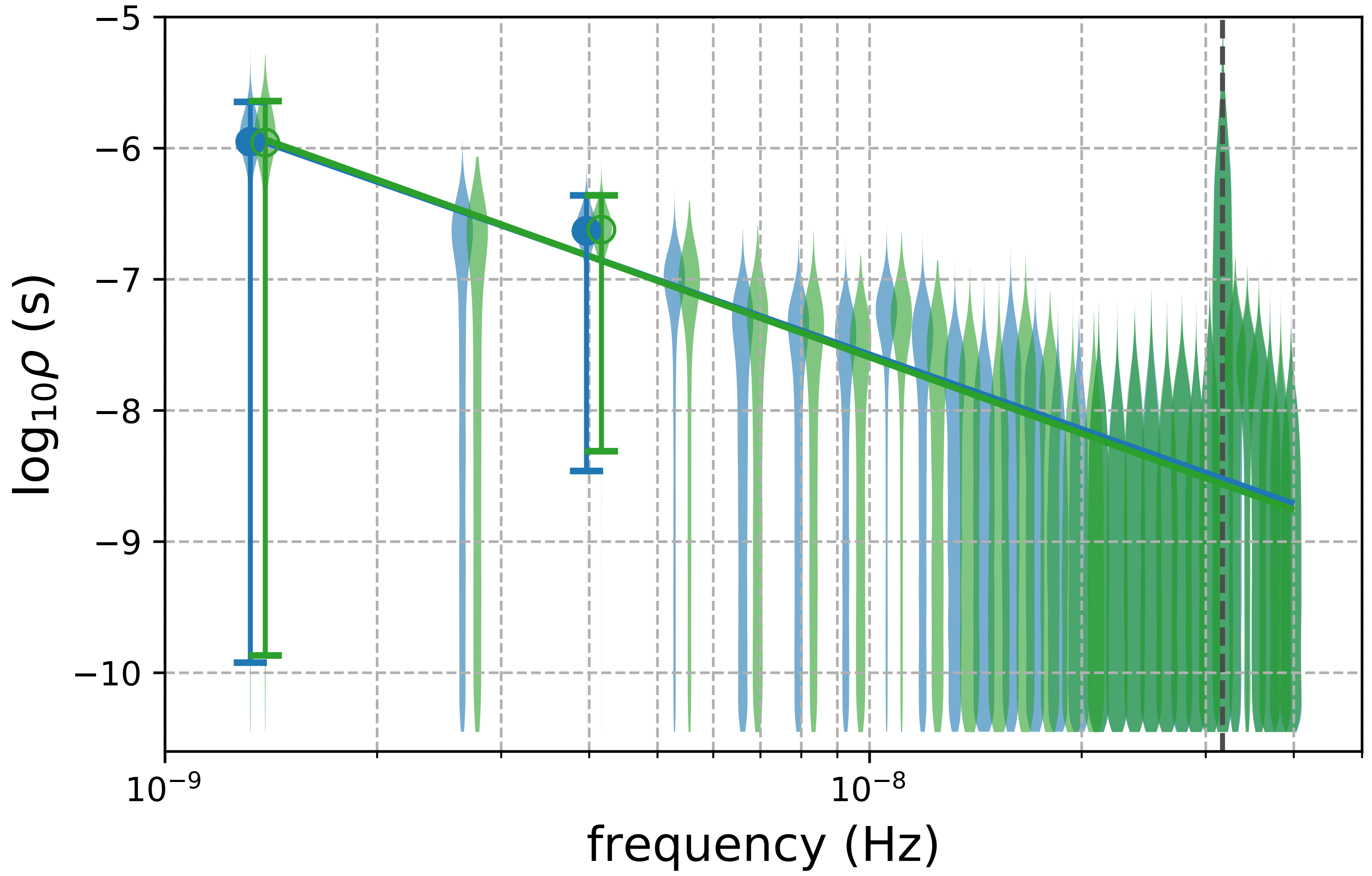
Parkes PTA

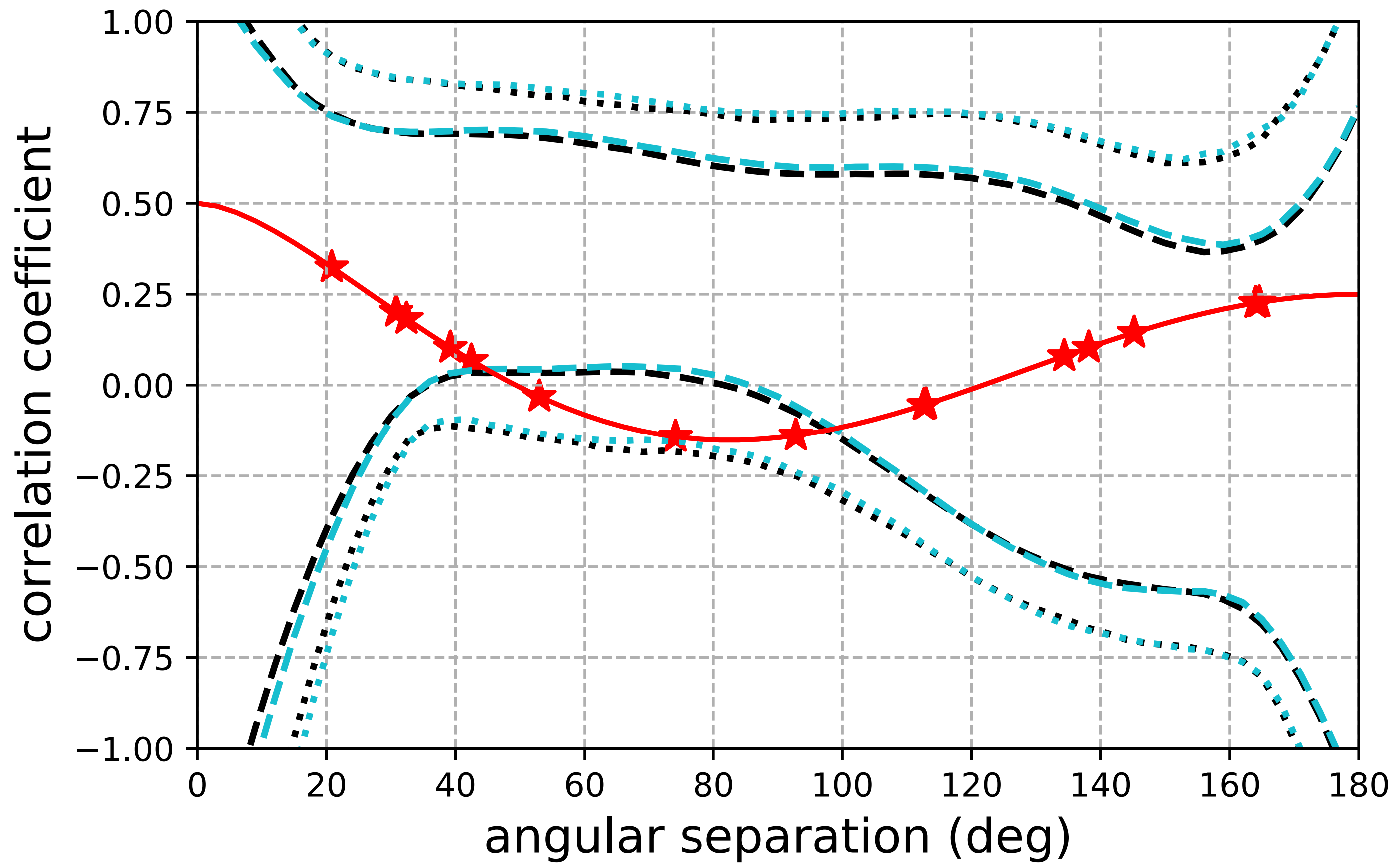




Goncharov et al. 2107.12112

European PTA

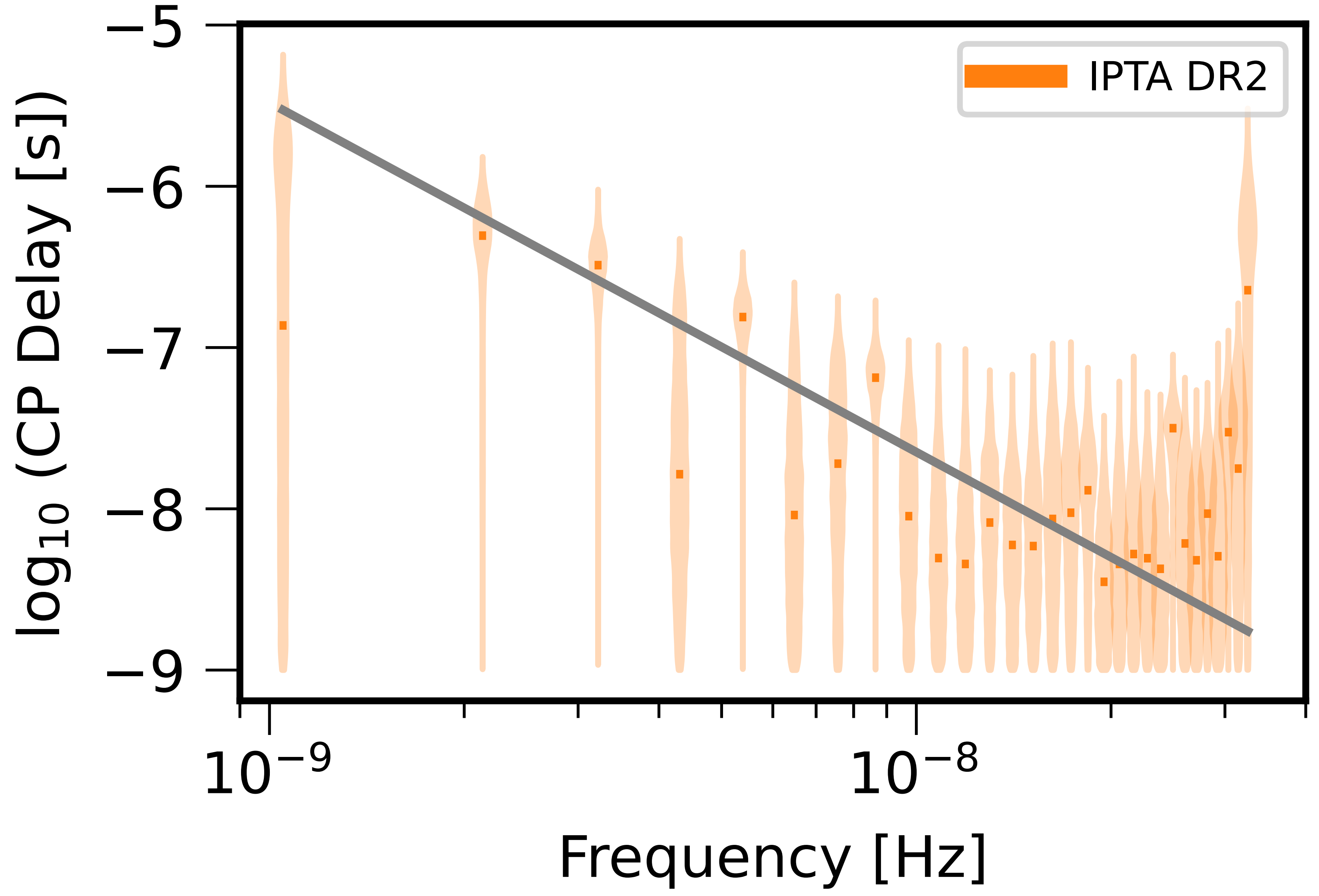


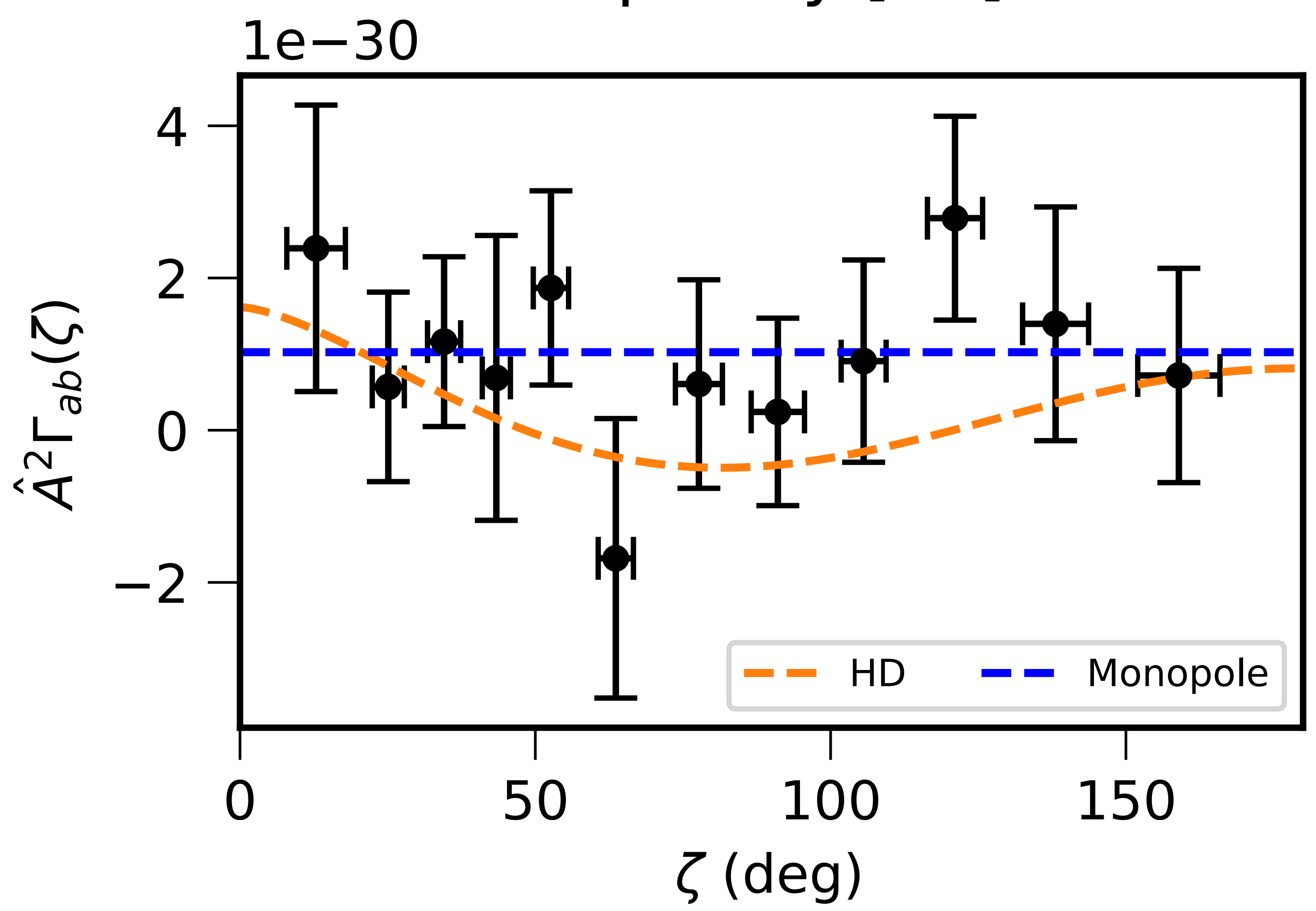


Chen et al. 2110.13184

Combination of older data from NANOGrav, PPTA, and EPTA:

International PTA



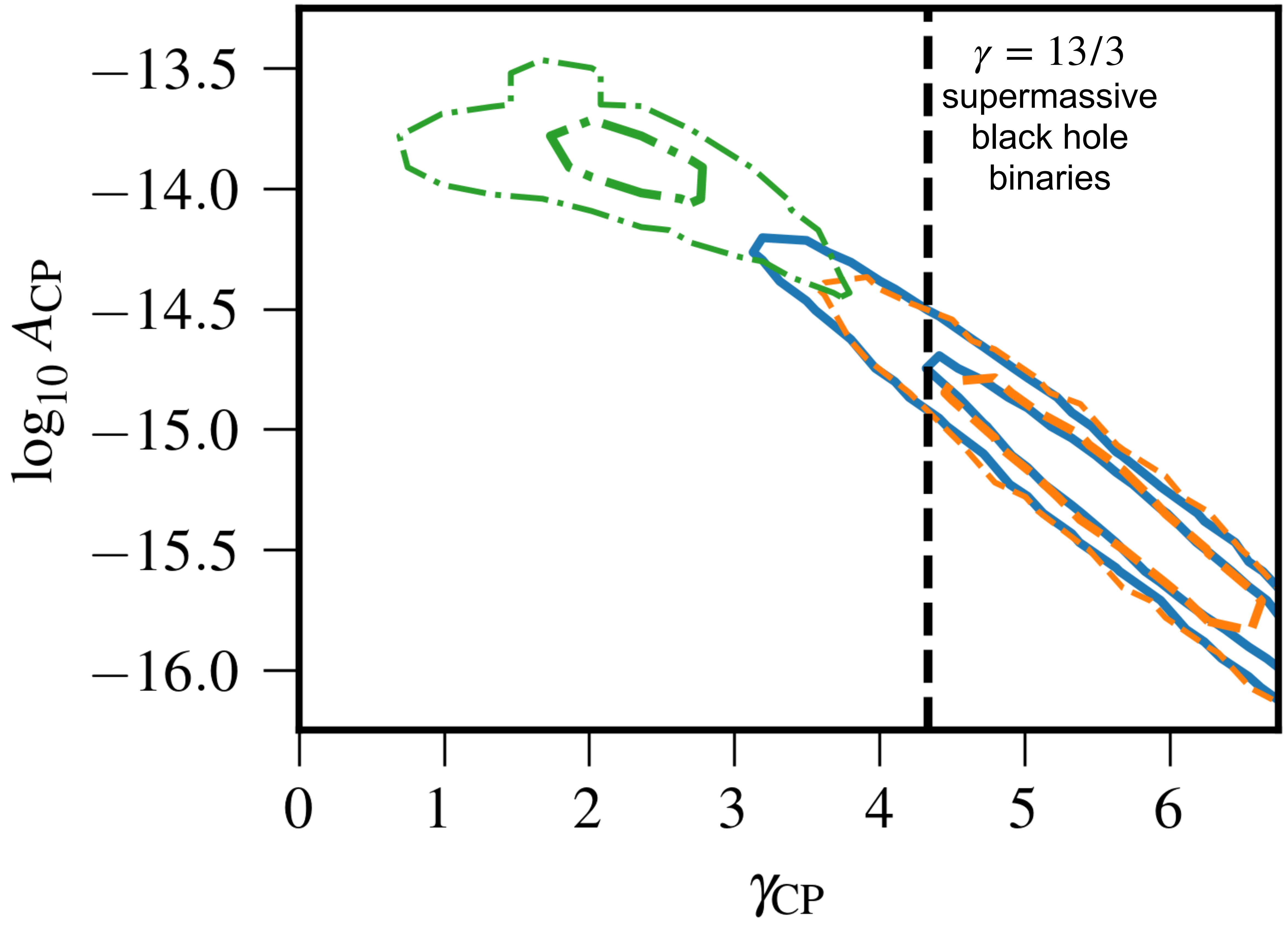


Antoniadis et al. 2201.03980

Possible explanations of signal

- Consistent with single power law
- Astrophysical
  - Supermassive black hole binaries
- Cosmological
  - Cosmic strings
  - (Formation of) primordial black holes
  - First-order phase transitions

$$\Omega_{GW}(f) = \frac{2\pi^2}{3H^2} f^2 A_{CP}^2 (f \times \mathrm{yr})^{(3-\gamma_{CP})/2}$$

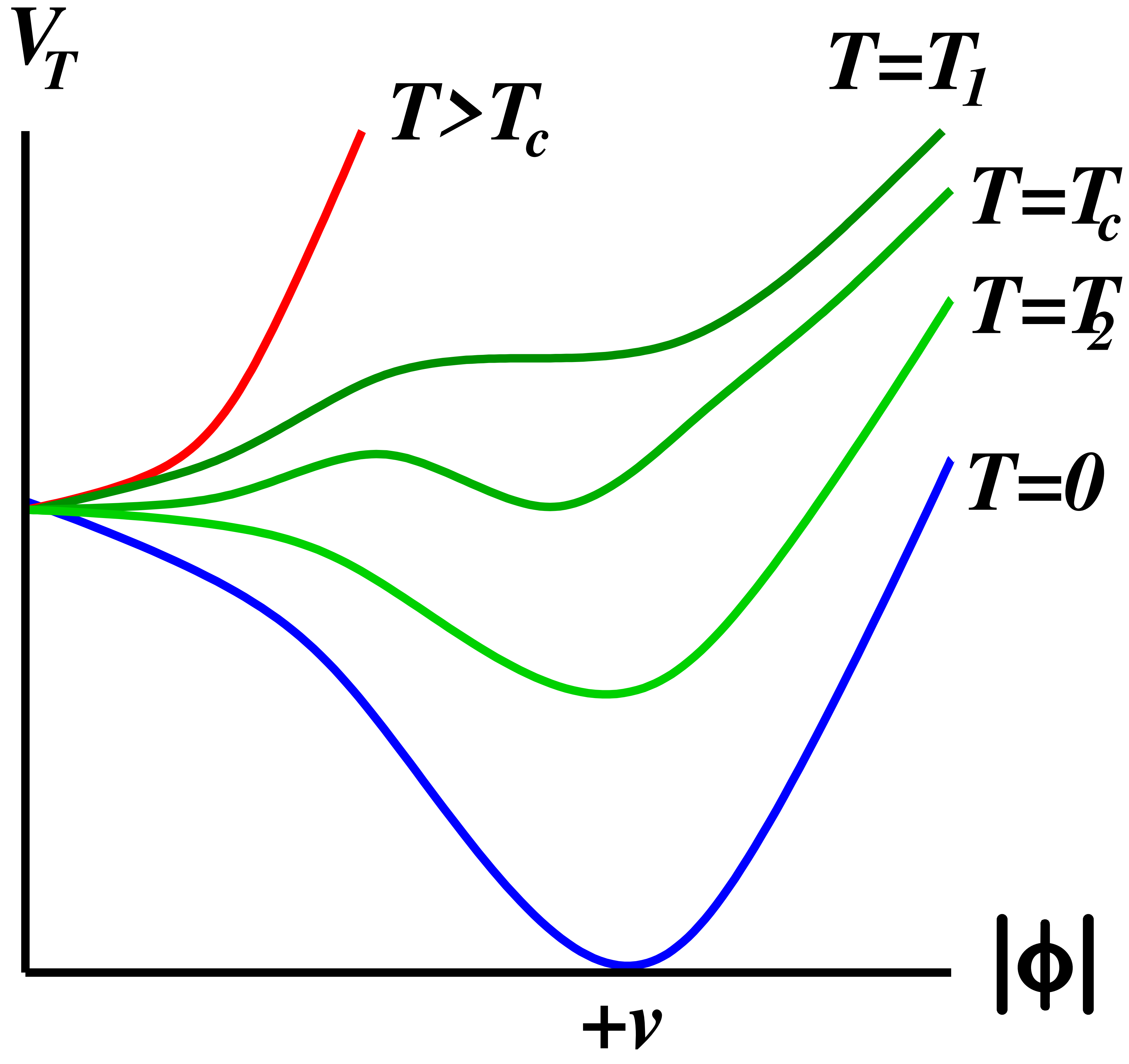


NANOGrav collaboration 2009.04496

First-order phase transitions

Thermal potential

- High-T scalar thermal potential (e.g. Higgs): (cf. Hindmarsh et al. 2008.09136)
- $V_T(\phi) = \frac{D}{2}(T^2 - T_0^2) - \frac{A}{3}T\phi^3 + \frac{\lambda_T}{4!}\phi^4 + \dots$
- Large $T \gg T_c$: only one minimum, $\phi = 0$
- T drops: second minimum forms
- T_c: minima degenerate, separated by free-energy barrier
- $T < T_c$: potential supercooling at $\phi = 0$ before transition to global minimum
- Transition leads to formation of bubbles with "true vacuum"

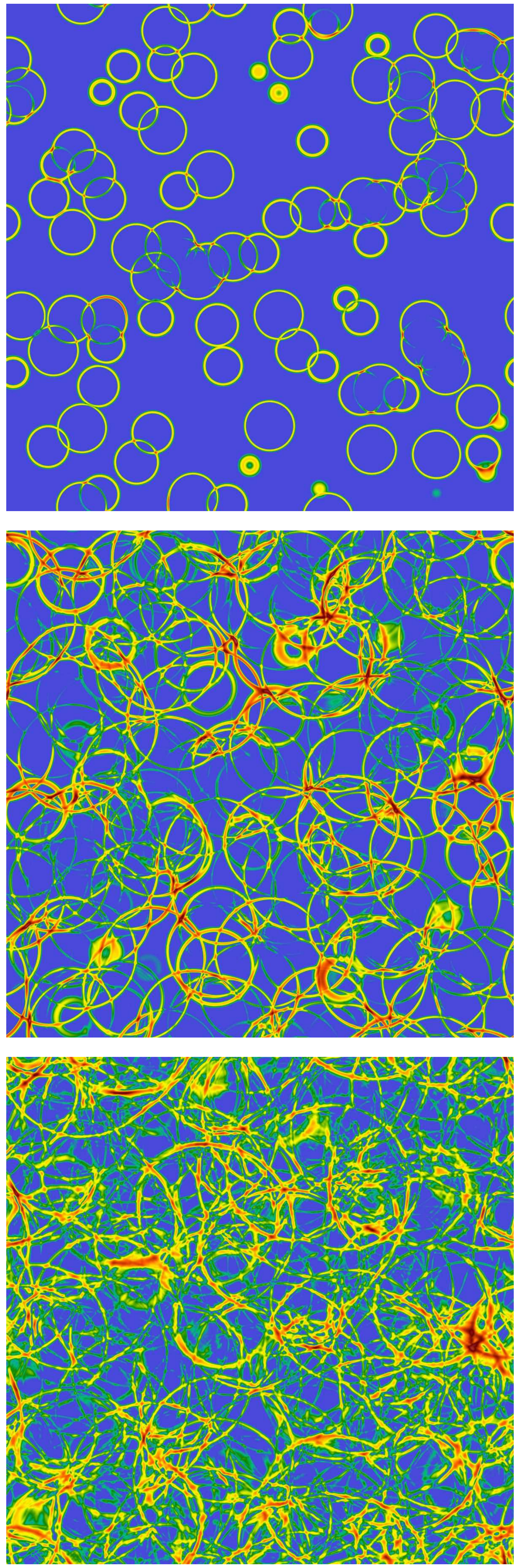


Hindmarsh et al. 2008.09136

First-order phase transitions

Bubble dynamics

- New phase ("true vacuum") is energetically favorable
- After nucleation bubbles expand, collide with other bubbles
- At some point the whole Universe is in the new phase
- Three mechanisms for GW production:
  - Bubble collisions
  - Sound waves after bubbles have merged (shells of kinetic energy)
  - Turbulences
- Complex physics, generally requires numerical simulations, but some (semi-)analytical treatments available
- Important for later: simulations neglect Hubble expansions, GW prediction for "slow" PT becomes uncertain

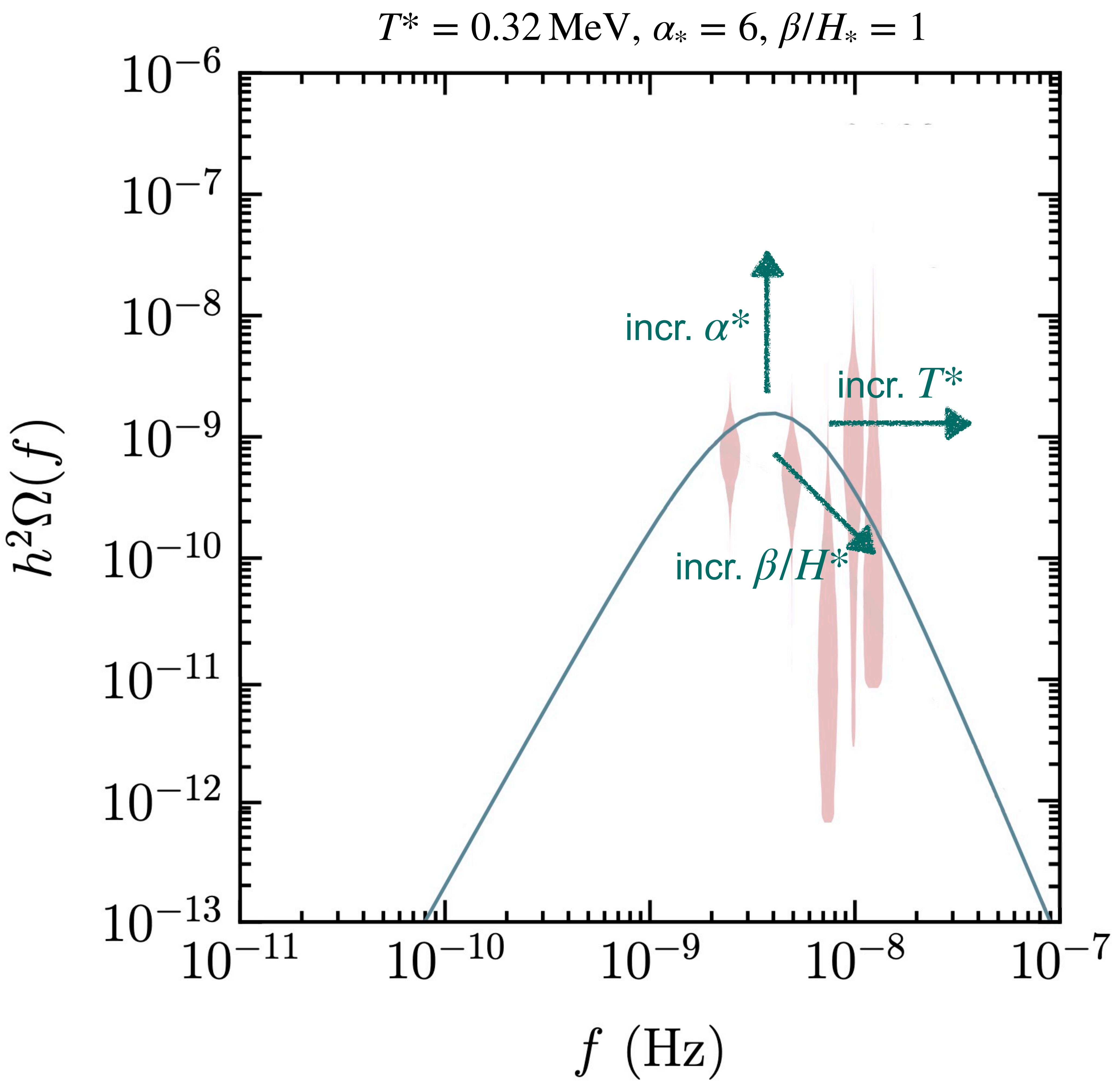


Hindmarsh et al. 1504.03291

First-order phase transitions

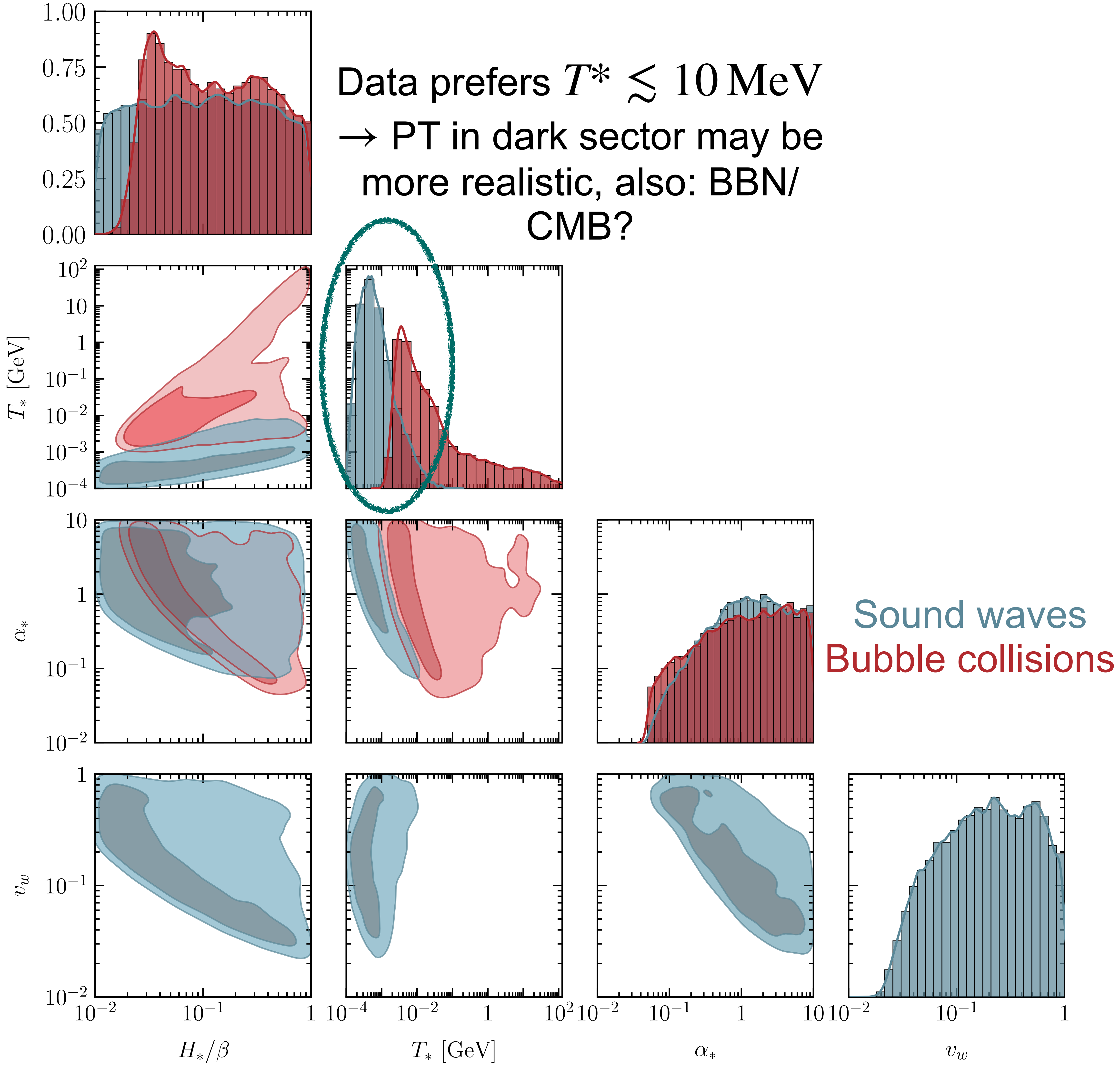
GW spectrum

- Typically depends on few parameters:
  - Type (bubble collisions, sound waves, turbulence)
    - Focus on sound waves
  - Temperature of transition T^*
  - Transition strength parameter $\alpha^* = \frac{\Delta\theta}{\rho^*_{\mathrm{tot}}}$
  - Bubble nucleation rate $\beta/H^* \rightarrow$ should be $\gg 1$
  - Bubble wall velocity v_w → set to 1
- $h^2\Omega_{\mathrm{GW,sw}}(f) \sim \mathcal{R}(T^*)\left(\frac{\alpha^*}{1+\alpha^*}\right)^2 \frac{H^*}{\beta}\, \mathcal{S}(f/f_{p,0})$
- $f_{p,0} \sim 0.1\,\mathrm{nHz}\,\frac{\beta}{H^*}\frac{T^*}{\mathrm{MeV}}\left(\frac{g^*}{10}\right)^{1/6}$



NANOGrav collaboration 2104.13930

Explaining NANOGrav with FOPTs in SM

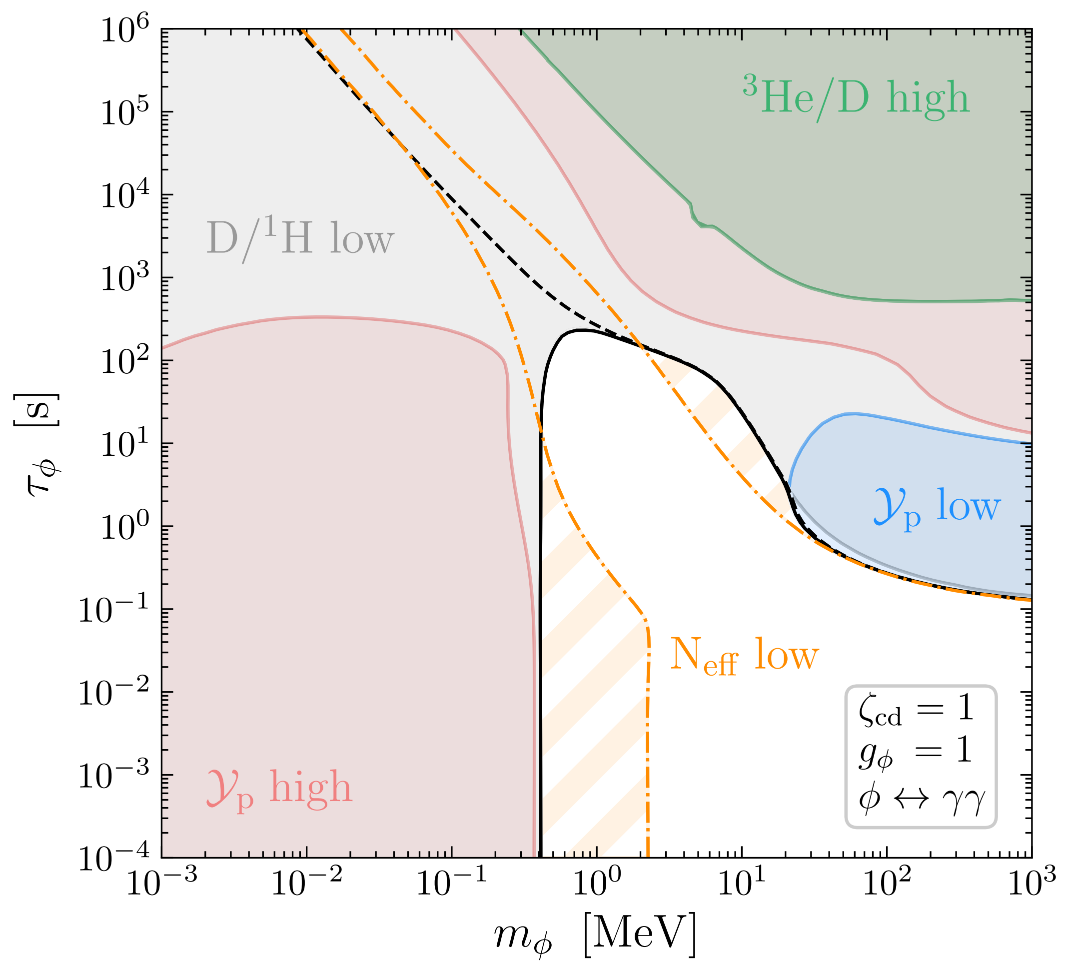


Data prefers $T^* \lesssim 10\,\mathrm{MeV}$
→ PT in dark sector may be more realistic, also: BBN/CMB?

NANOGrav collaboration 2104.13930

Dark sector phase transitions

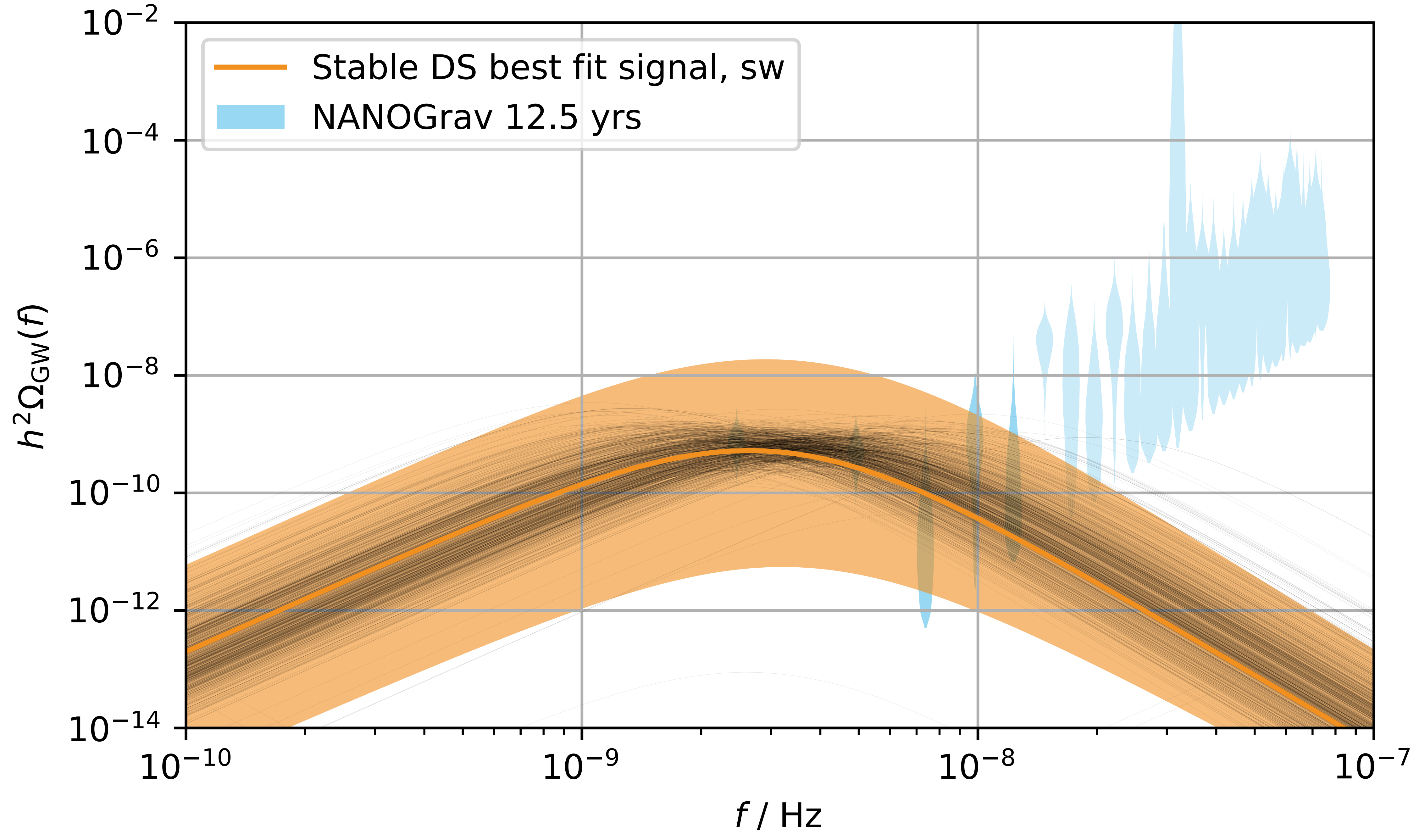
- Sector undergoing PT does not need to be in thermal contact with SM, can be dark
- GW spectrum must be adapted slightly (include DS dofs for redshifting and in energy densities)
- DS energy density after PT and (inst.) reheating: $\rho_{\mathrm{DS}}^{\mathrm{reh}} = \rho_{\mathrm{DS}}^{*} + \alpha^{*}\rho_{\mathrm{tot}}^{*}$
- If stable leads to $\Delta N_{\mathrm{eff}} \sim 6\,(\alpha^{*} + (1+\alpha^{*})(g_{\mathrm{DS}}^{*}/g_{\mathrm{SM}}^{*})\xi_{\mathrm{DS}}^{4})$, ξ_{DS}^{*} temperature ratio at PT
  - $\Delta N_{\mathrm{eff}} < 0.14\ (95\,\%$ CL) from CMB and BBN (Yeh et al. 2207.13133)
- If unstable leads to energy injection in SM plasma
  - Assume 1 bosonic dof with $m = 5\,\mathrm{MeV}$ as example

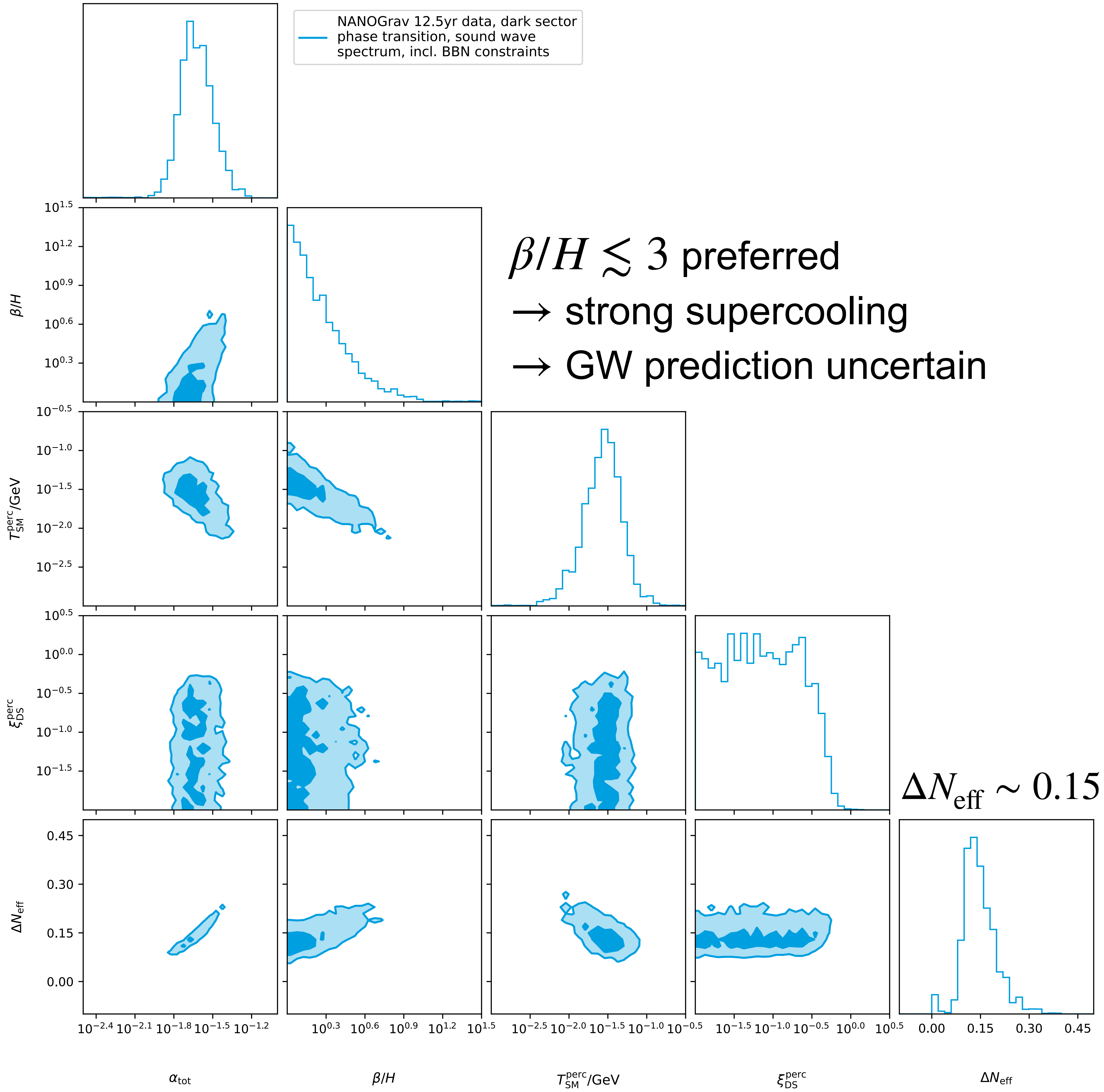


PFD et al. 2011.06519

Explaining NANOGrav with dark sector PTs

Stable dark sector $\beta/H \geq 1$



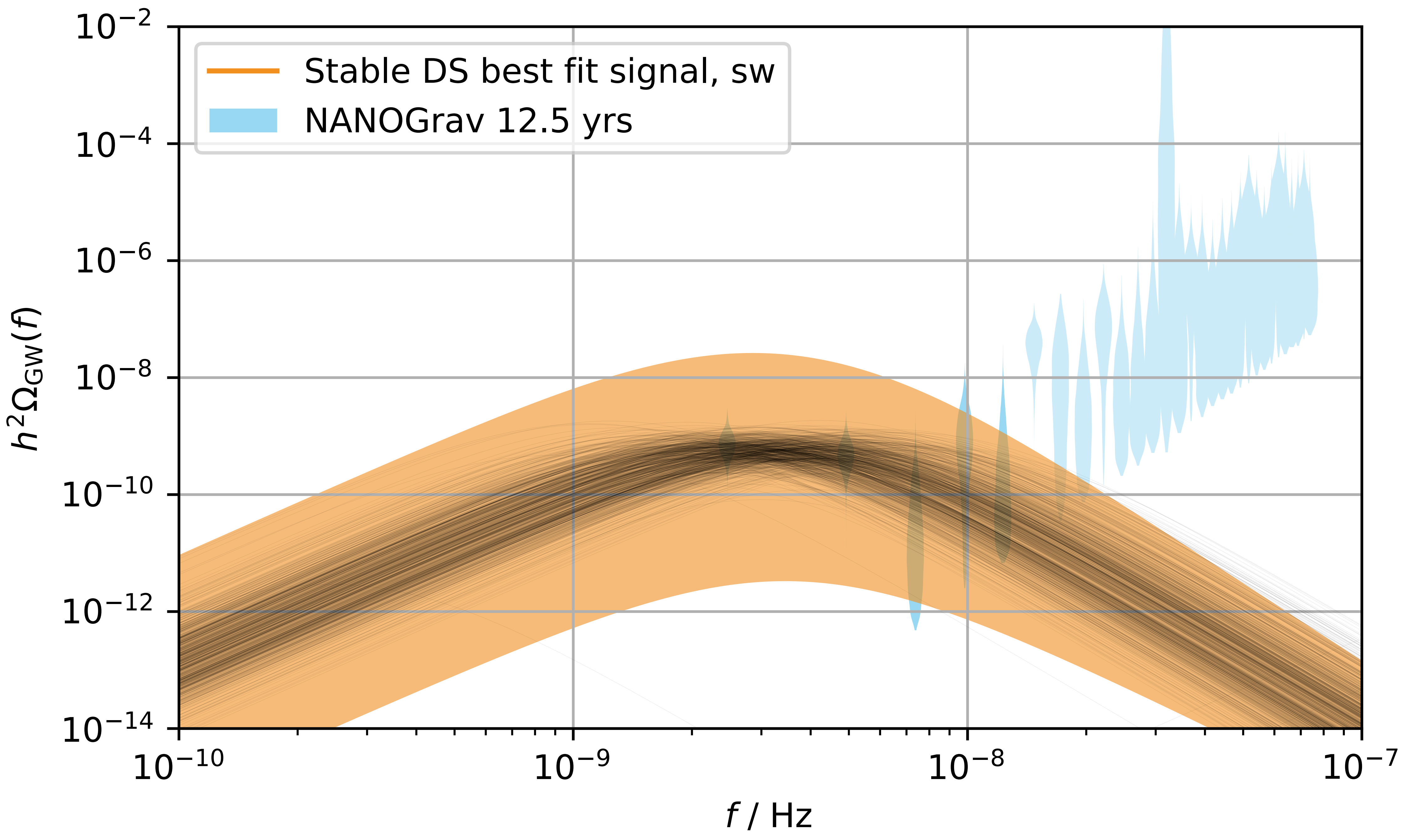


$\beta/H \lesssim 3$ preferred
→ strong supercooling
→ GW prediction uncertain

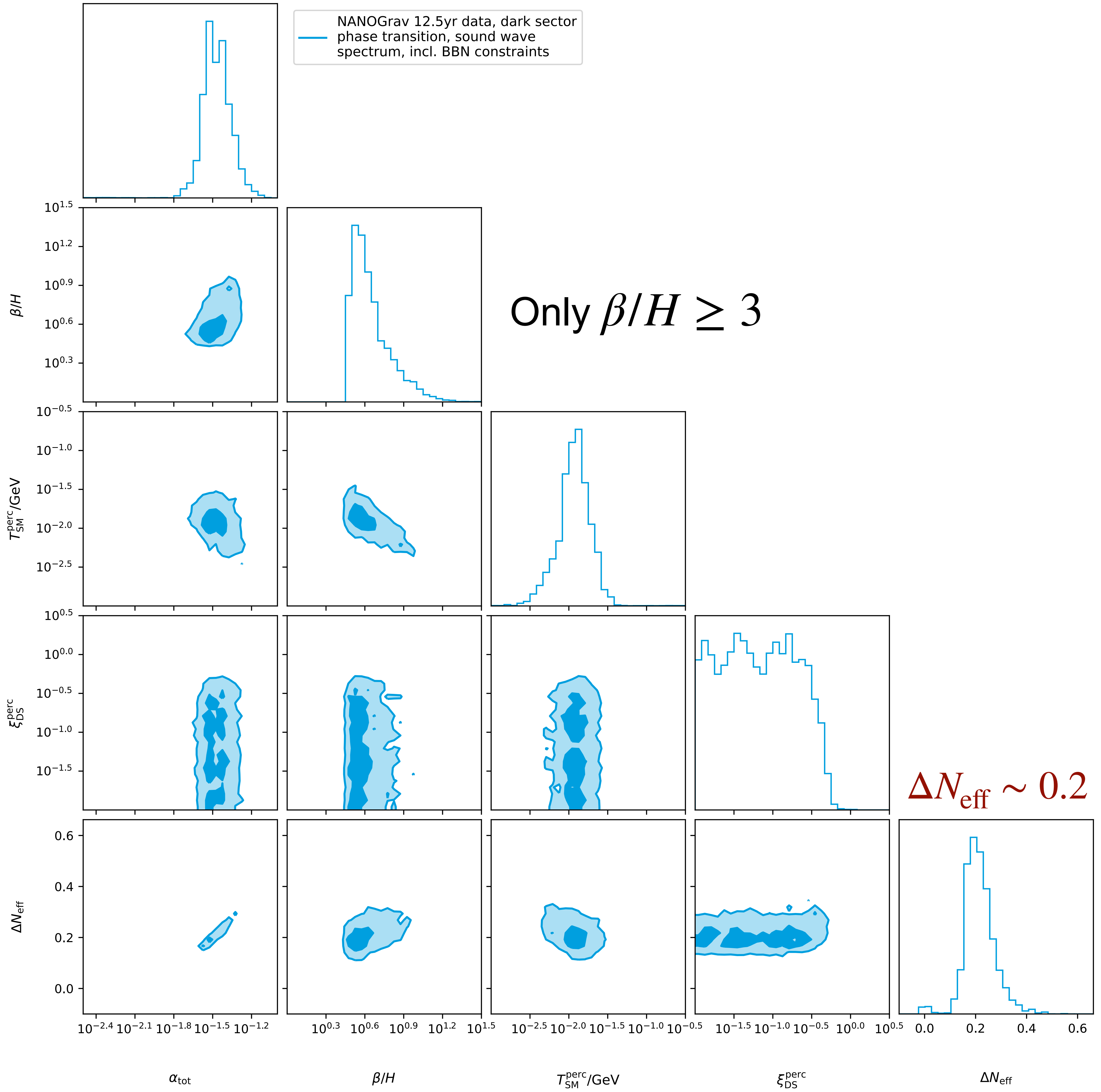
$\Delta N_{\rm eff} \sim 0.15$

Explaining NANOGrav with dark sector PTs

Stable dark sector $\beta/H \geq 3$



Best-fit not in plot!

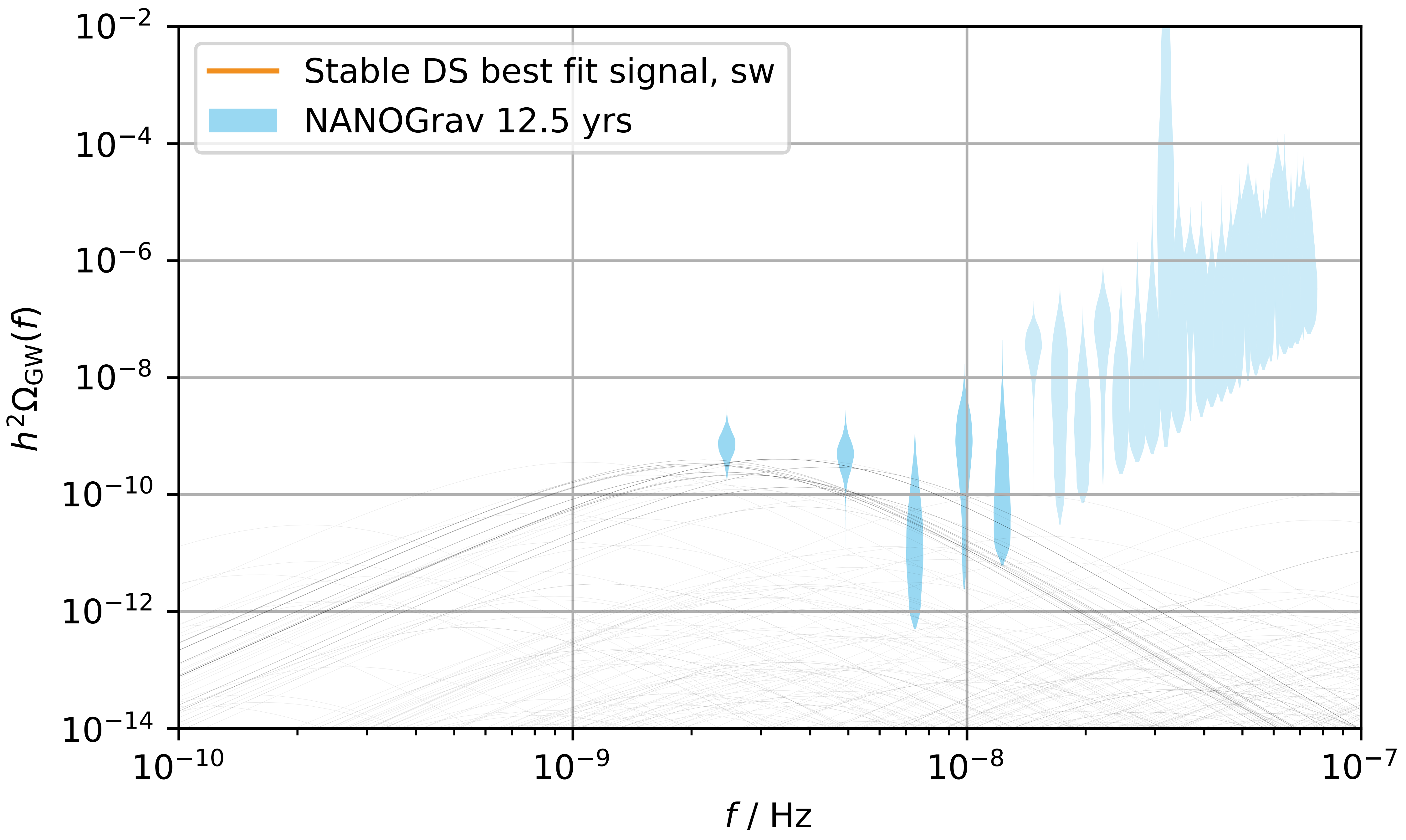


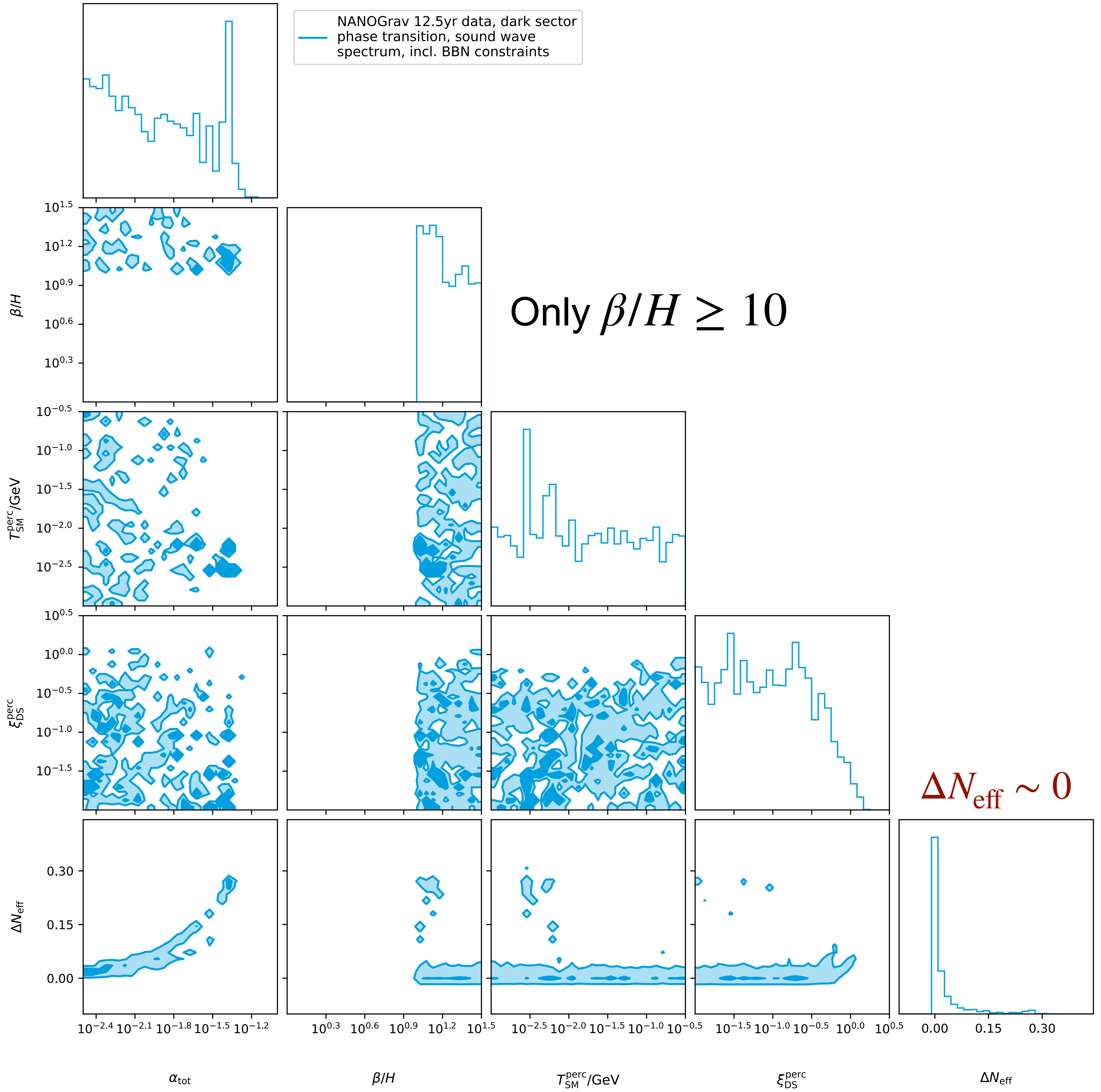
Only $\beta/H \geq 3$

$\Delta N_{\text{eff}} \sim 0.2$

Explaining NANOGrav with dark sector PTs

Stable dark sector $\beta/H \geq 10$





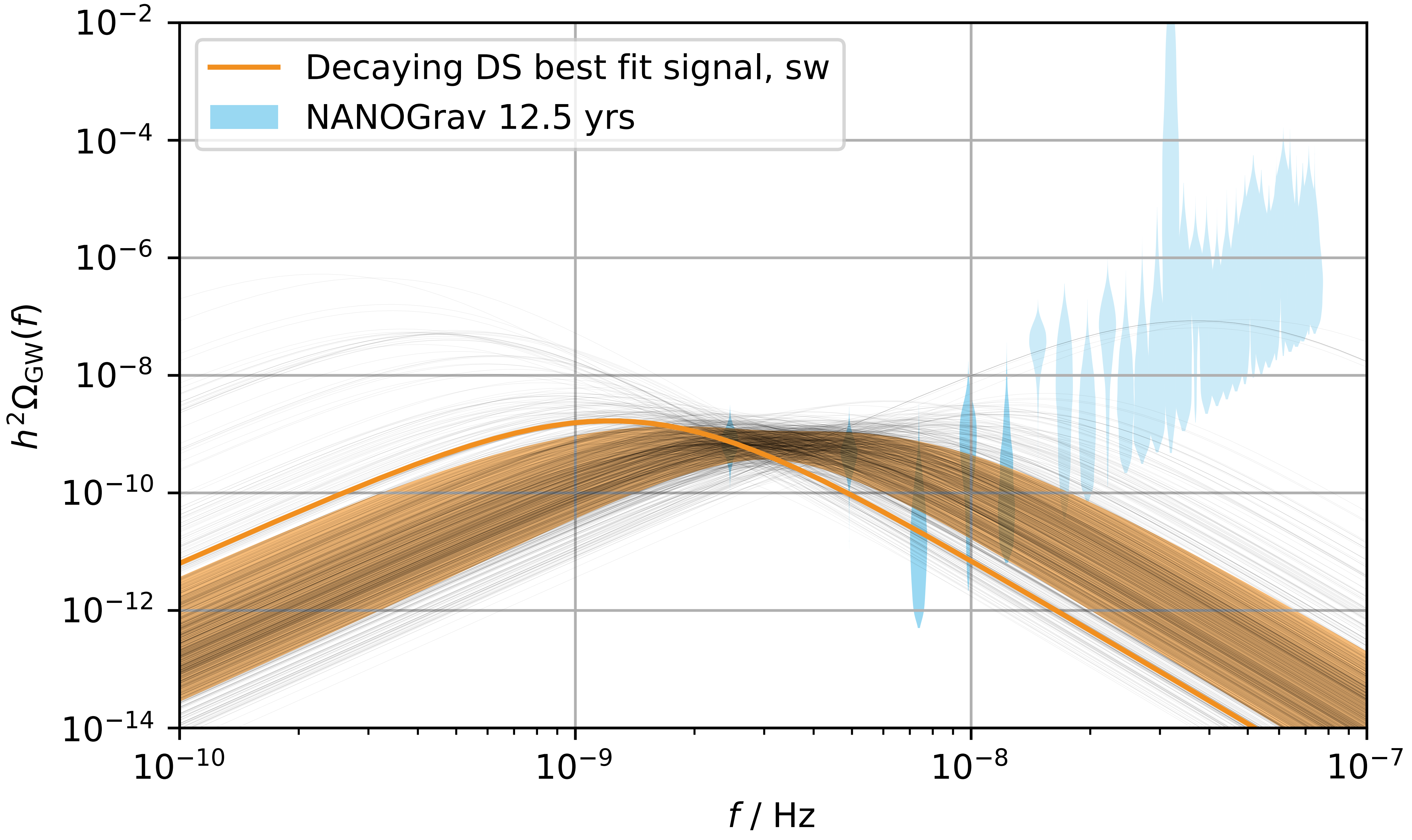
Cannot explain NANOGrav anymore

→ whole "signal" in pulsar-intrinsic noise!

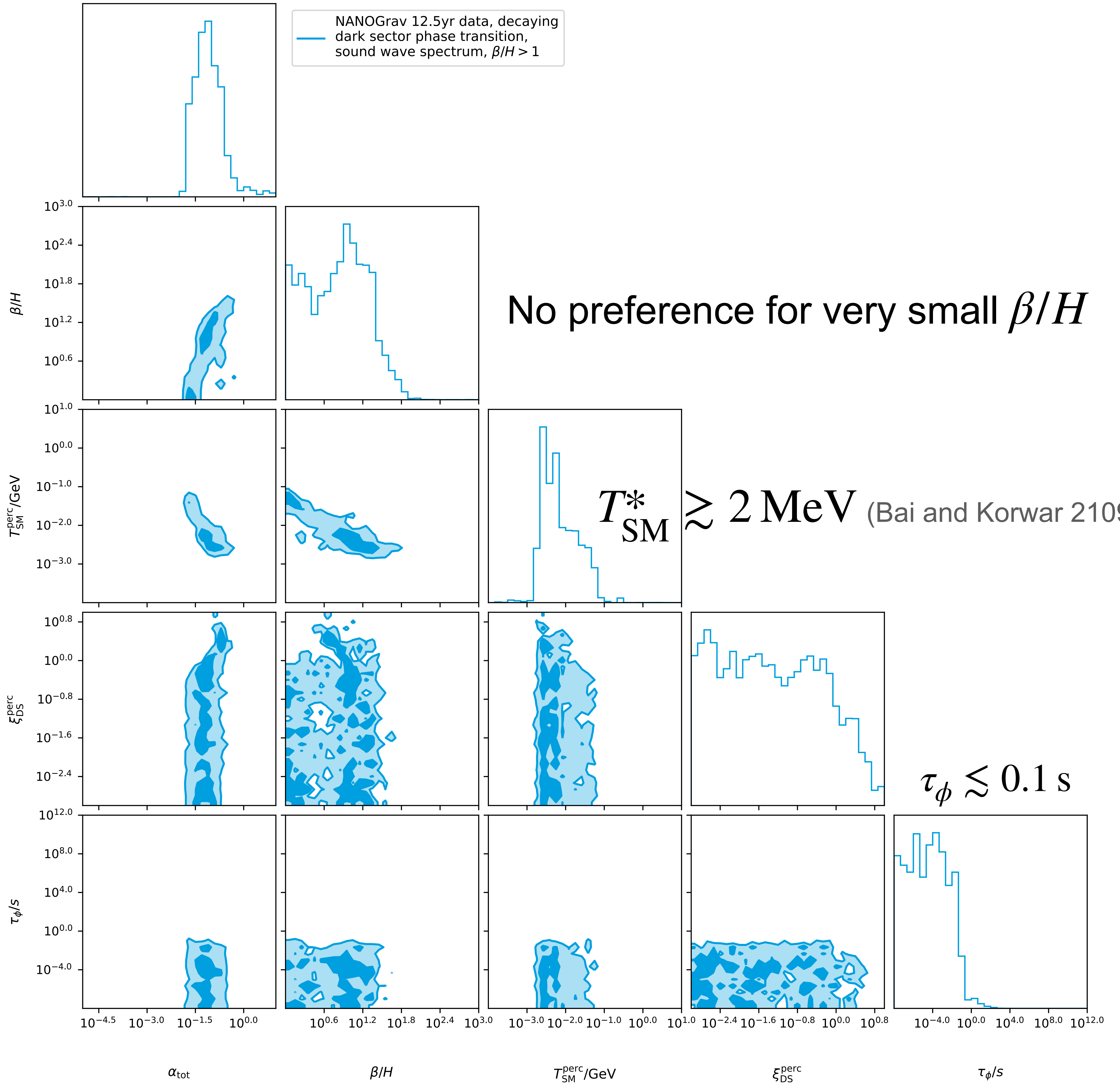
→ stable DS PTs for NANOGrav imply small β/H

Explaining NANOGrav with dark sector PTs

Decaying dark sector



Bayes factor $10^2 - 10^4$ compared to only pulsar-intrinsic noise, statistically preferred over stable DS ($10^0 - 10^1$)



No preference for very small β/H

$T^*_{SM} \gtrsim 2\,\text{MeV}$ (Bai and Korwar 2109.14765)

$\tau_\phi \lesssim 0.1\,\text{s}$

Conclusions

- Consistent picture of our Universe's evolution up to MeV-scale temperatures established by observational cosmology
- Gravitational waves have the potential to probe even higher temperatures / earlier times
- NANOGrav collaboration found evidence of common-spectrum process
- If signal due to phase transition $T \lesssim 10\,\mathrm{MeV}$ preferred → dark sector more likely?
- Stable dark sector problematic due to small β/H
- Decaying dark sector well possible, requires decays before BBN

Tusen takk!