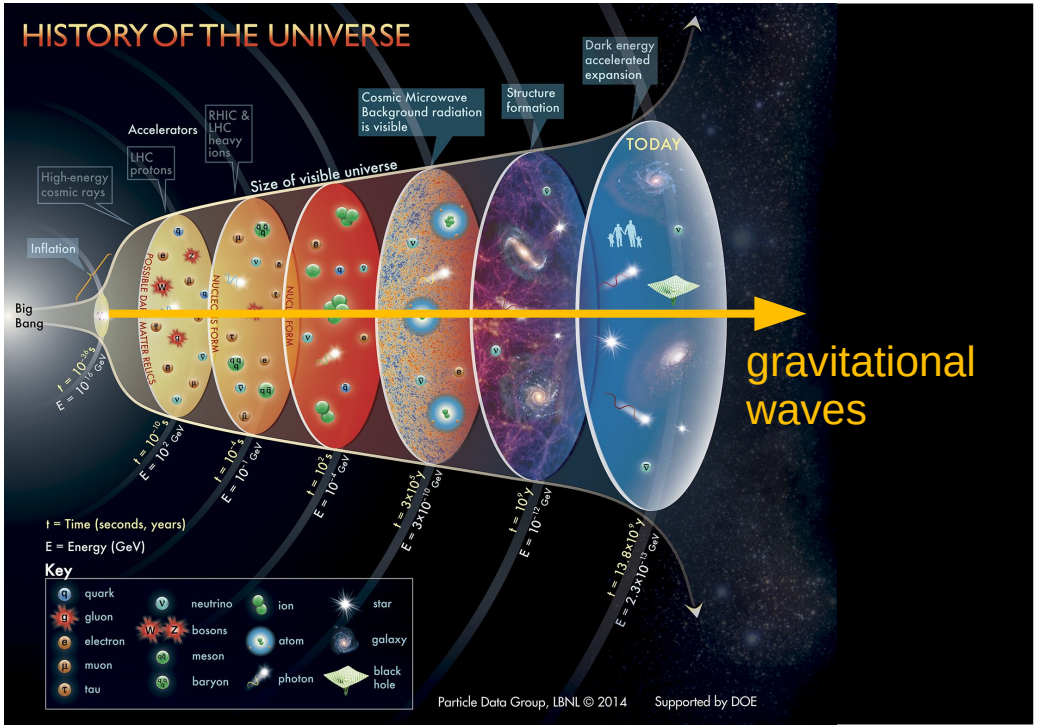
Funded by
the European Union

Searching for anisotropies with pulsar timing arrays



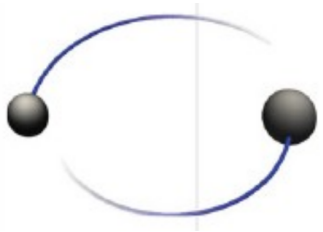
Valerie Domcke
CERN

Undark kickoff meeting, IAC, Teneriffe
October, 2024

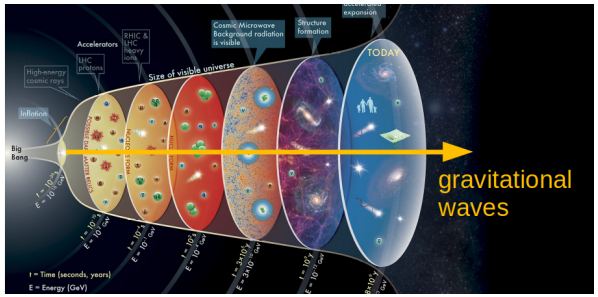
arxiv: 2407.14460
In collaboration with Frederik Depta, Gabriele Franciolini, Mauro Pieroni

Supermassive BHBs or Early Universe ?

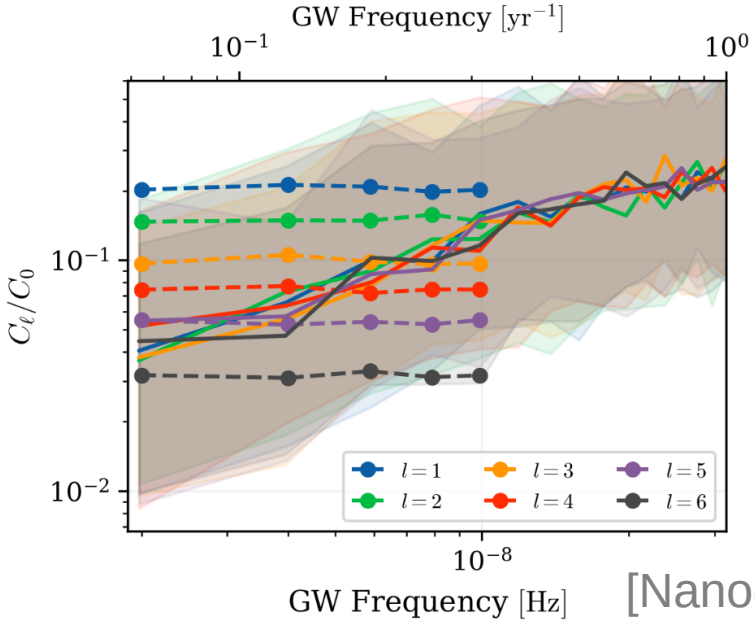
Supermassive black hole mergers



Early Universe physics

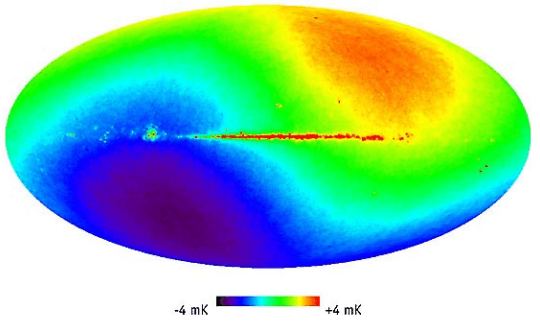


Expect ~ 2 – 20 % anisotropy from Poisson distributed SMBHBs



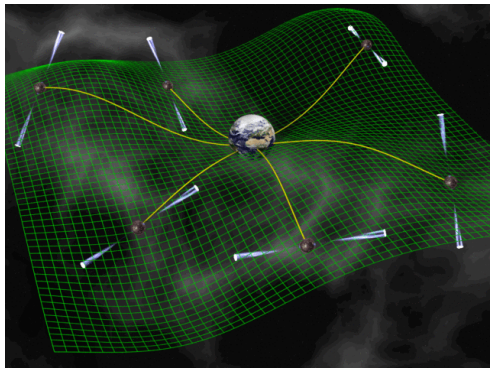
[Nanograv15]

Expect ~ 0.1 % anisotropy aligned with kinematic CMB dipole



Pulsar timing arrays

Time delay for pulse from pulsar I located at $D_I \hat{p}_I$:



$$\Delta t_I = \frac{1}{2}\hat{p}_I^a \hat{p}_I^b \int_0^{D_I} \mathrm{d}s\, h_{ab}\left(t(s), \vec{x}(s)\right)$$

$$\simeq \int_{-\infty}^{\infty} \mathrm{d}f \int \mathrm{d}^2\hat{k} \sum_P \frac{1}{2\pi i f t} F^P_{\hat{p}_I}(\hat{k})\, \tilde{h}_P(f;\hat{k})\, e^{2\pi i f t}$$

„instrument“ response

$$F^P_{\hat{p}_I}(\hat{k}) = \frac{1}{2}\frac{\hat{p}_I^a \hat{p}_I^b}{1+\hat{p}_I\cdot\hat{k}} e^P_{ab}(\hat{k})$$

Stochastic gravitational wave background (SGWB)

$\hat{p}_I$ pulsar direction

$\hat{k}$ GW direction

Pulsar timing arrays

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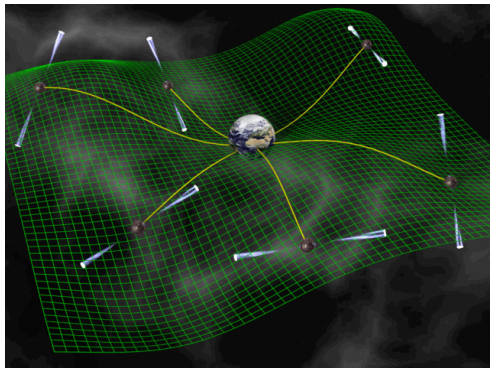

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Stochastic gravitational wave background (SGWB)

$$\langle \tilde{h}_P(f,\hat{k}) \tilde{h}^*_{P'}(f',\hat{k}')\rangle = \frac{1}{4} S_h(f) P(\hat{k}) \delta(f-f') \delta_{PP'} \delta^2(\hat{k},\hat{k}')$$

$\hat{p}_I$ pulsar direction

$\hat{k}$ GW direction

GW power spectral density.
For isotropic SGWB:

$$\Omega_{\mathrm{GW}} h^2 = \frac{h^2}{\rho_c}\frac{\mathrm{d}\rho_{\mathrm{GW}}}{\mathrm{d}\log f} \equiv \frac{2\pi^2 f^3}{3H_0^2/h^2} S_h$$

angular distribution of GW power on the sky

$$P(\hat{k}) = \sum_{\ell,m} c_{\ell m} Y_{\ell m}(\theta,\phi)$$

Measuring anisotropies

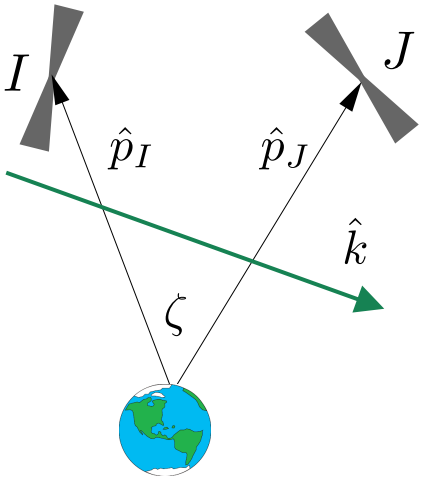
Cross-correlation:

$$\langle \Delta t_I \Delta t_J \rangle = \int_{-\infty}^{\infty} \mathrm{d}f \frac{S_h(f)}{24\pi^2 f^2} \frac{3}{2} \sum_P \int d^2\hat{k}\, F^P_{\hat{p}_I}(\hat{k}) F^P_{\hat{p}_J}(\hat{k})\, P(\hat{k})$$

instrument response
GW background

$$\equiv \Gamma_{IJ}(f) = \sum_{\ell m} c_{\ell m}\, \Gamma_{IJ,\ell m}$$

parametrizes anisotropy in SWGB



Generalized overlap reduction functions:

$$\Gamma_{IJ,\ell m} = \frac{3}{2} \sum_P \int d^2\hat{k} F^P_{\hat{p}_I}(\hat{k}) F^P_{\hat{p}_J}(\hat{k}) Y_{\ell m}(\hat{k})$$

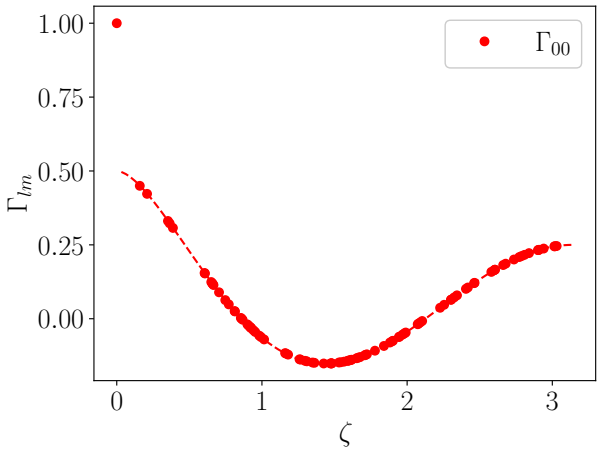
$\Gamma_{IJ,00}$ Hellings-Down correlation

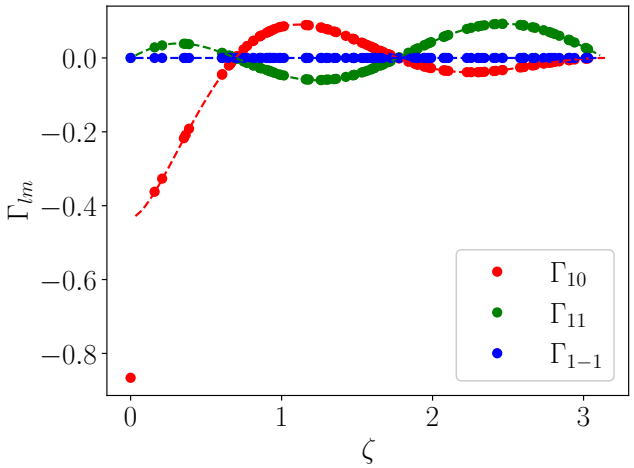
$\Gamma_{IJ,\ell m}$ instrument response to ℓ, m-multipole

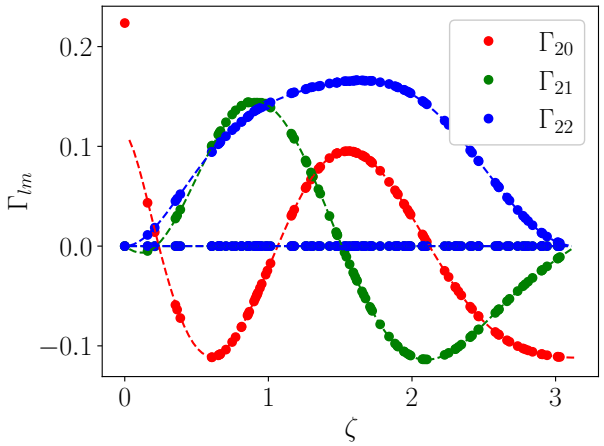
[Mingarelli et al `13]

Generalized overlap reduction functions

Generalized overlap reduction functions in computational frame (one pulsar on z axis):







Hellings-Down curve

dipole

quadrupole

Sensitivity to anisotropies

Covariance matrix

$$C_{IJ} = \langle \Delta t_I \Delta t_J \rangle \propto \sum_{\ell,m} c_{\ell m} \Gamma_{IJ,\ell m} + C_{\rm noise}$$

Fischer information matrix

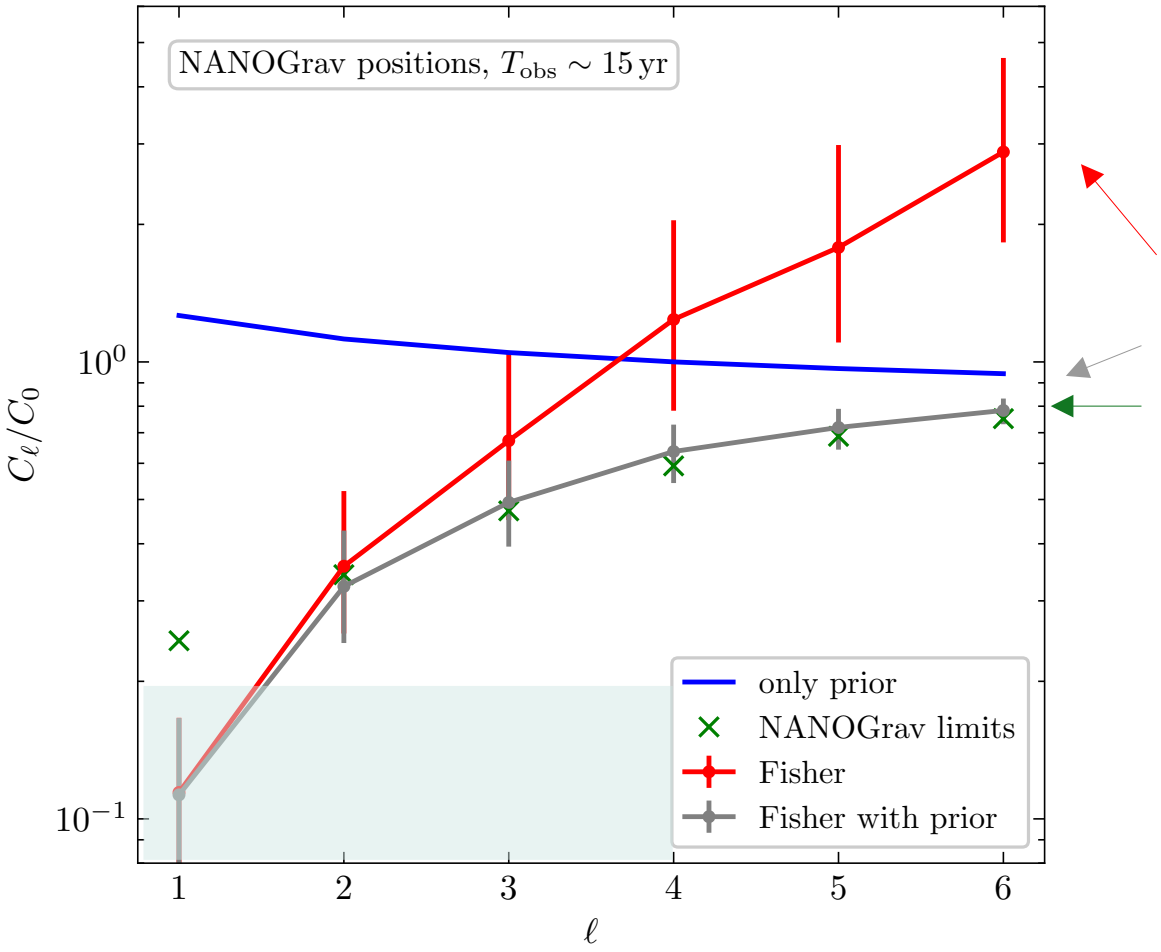
$$F_{\ell m,\ell' m'} = \sum_{f_k,IJKL} C^{-1}_{IJ} C^{-1}_{KL} \frac{\partial C_{JK}}{\partial c_{\ell m}} \frac{\partial C_{LI}}{\partial c_{\ell' m'}}$$

$$F^{-1}_{\ell m,\ell m} \quad \rightarrow \quad \text{sensitivity estimate for } c_{\ell m}$$

Assumptions:

- noise uncorrelated across pulsars, statistically isotropic
- Gaussian distributions for c_{lm}

Anisotropy searches with PTAs



[Depta, VD, Franciolini, Pieroni `24]

$$C_\ell = \frac{1}{2\ell+1}\sum_m |c_{\ell m}|^2.$$

Estimated sensitivity with 70 pulsars

Estimated reconstructed limits imposing NG prior

NG15 results

SMBHB background:

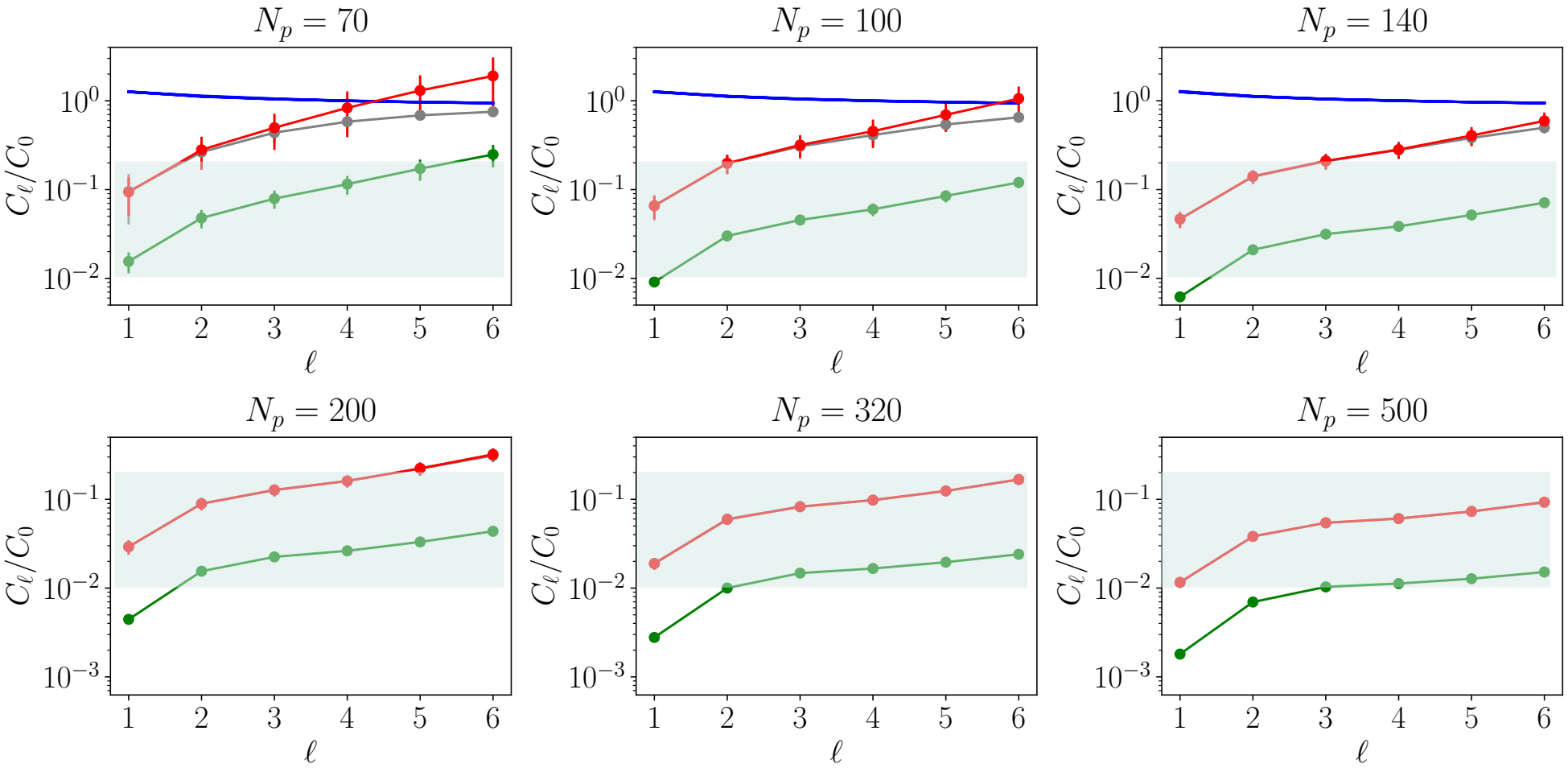
$$C_\ell/C_0 \sim 1 - 20\%$$

[Mingarelli et al `13]

Anisotropy searches with PTAs

[Depta, VD, Franciolini, Pieroni `24]

Prospects with upcoming PTAs, assuming EPTA-like and SKA-like noise:



Anisotropies of SMBHB background within reach of upcoming PTAs.

Conclusions

Anisotropies are key to distinguishing astrophysical from cosmolgical GWBs in the PTA band

With current PTA data, only constraints on dipole and possibly quadrupole are (mildly) informative

About 150 pulsars (~ current IPTA configuration) with SKA-like noise (demonstrated by Meerkat) required to probe %-level anisotropies

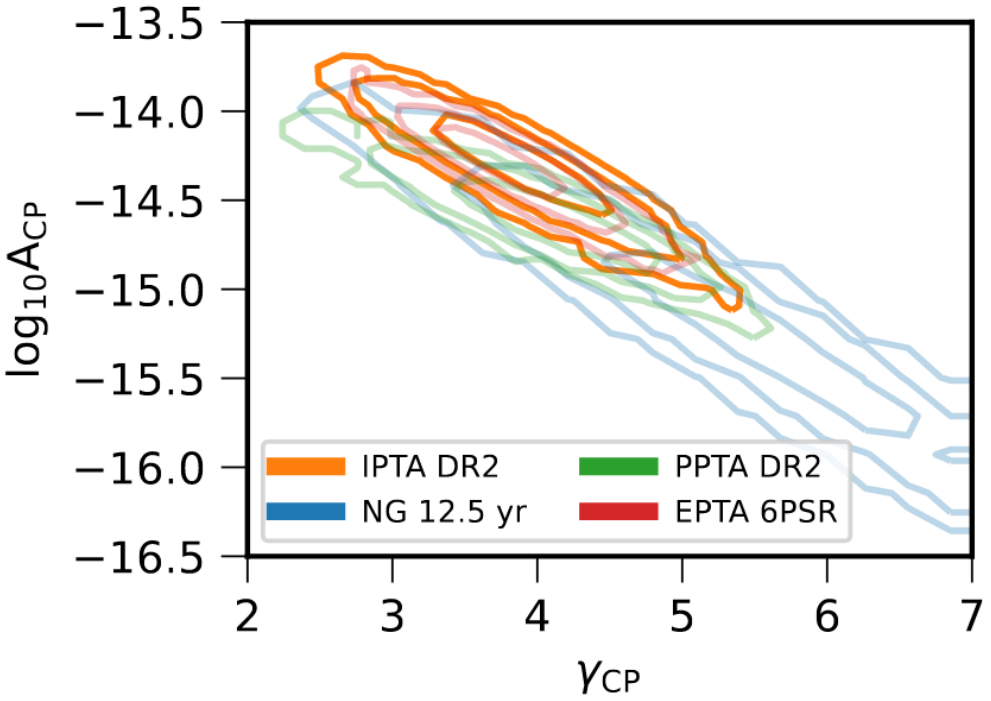
Anisotropy expected from SMBHB GWB: detection possible very soon, exclusion possible within less than 10 years.

Caution: - forecast vs real data analysis
- interpretation of local anisotropies subject to cosmic variance

Backup slides

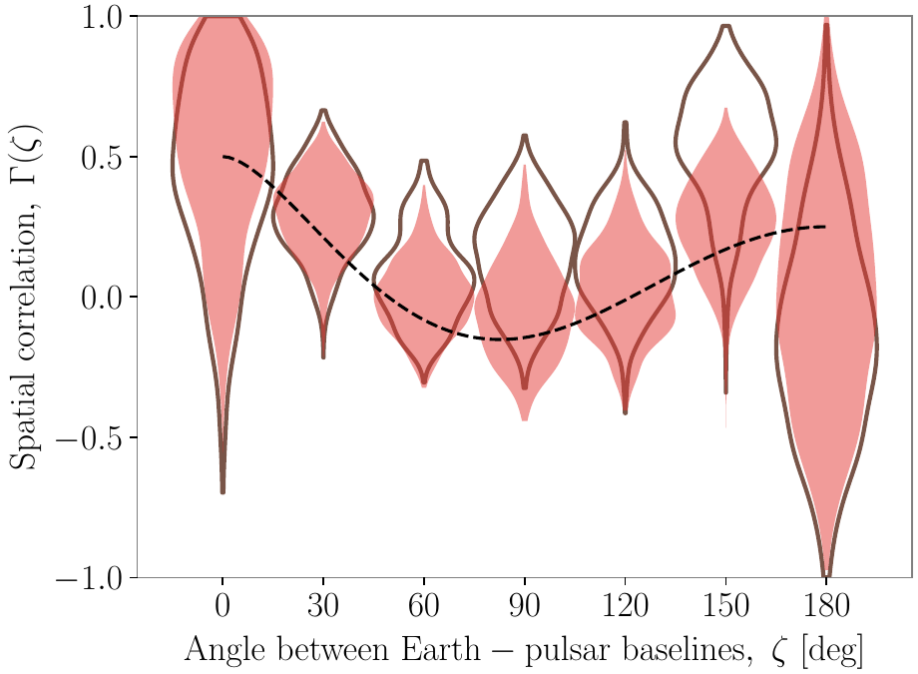
PPTA, EPTA and IPTA results

IPTA `22, 2201.03980



amplitude and spectral tilt
compatitive with NANOGrav

PPTA `21, 2107.12112



no significant detection of
quandropolar spatial correlation

Maybe. Stay tuned for more data!

NANOGrav: SMBHB interpretation