Gravitational Wave Cosmology with NANOGrav

CMB-S4 Summer 2023 Collaboration Meeting

Chiara Mingarelli,
August 1st 2023
Yale University

NANOGrav
Physics Frontiers Center

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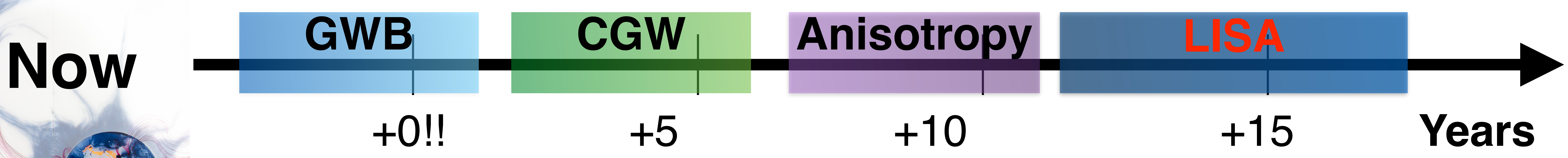
Outline

- The gravitational-wave spectrum
- **Pulsar Timing Arrays:** how they work
- Understanding new results from **NANOGrav** 15-yr data
- The future! Please send me your thoughts!



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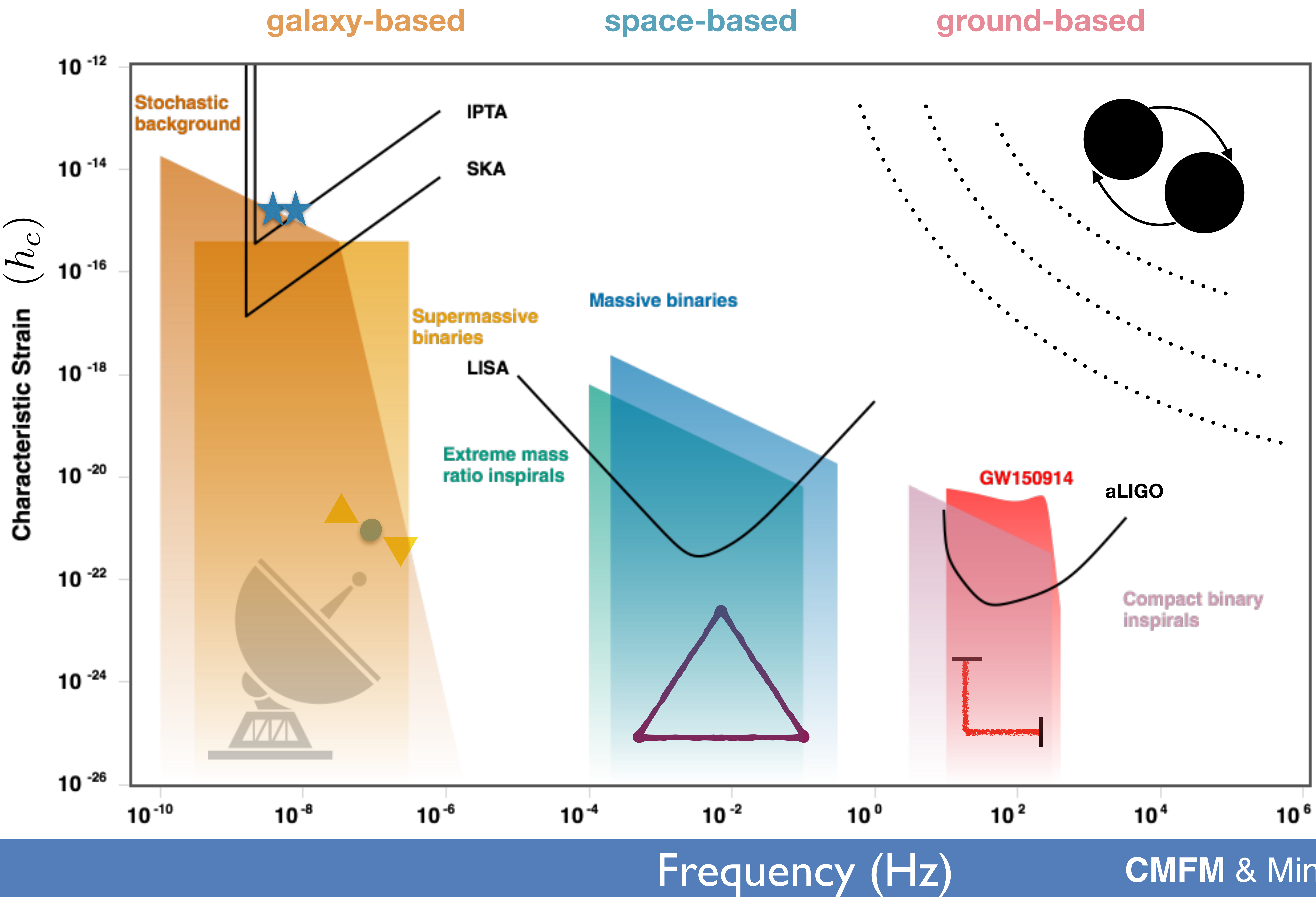
The Gravitational-Wave Spectrum



- Complementary GW detectors
- LIGO can't see PTA!
- Strain h=Δt / T
- 25 Myrs in band

CMFM & Mingarelli (2018)

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The Gravitational-Wave Spectrum

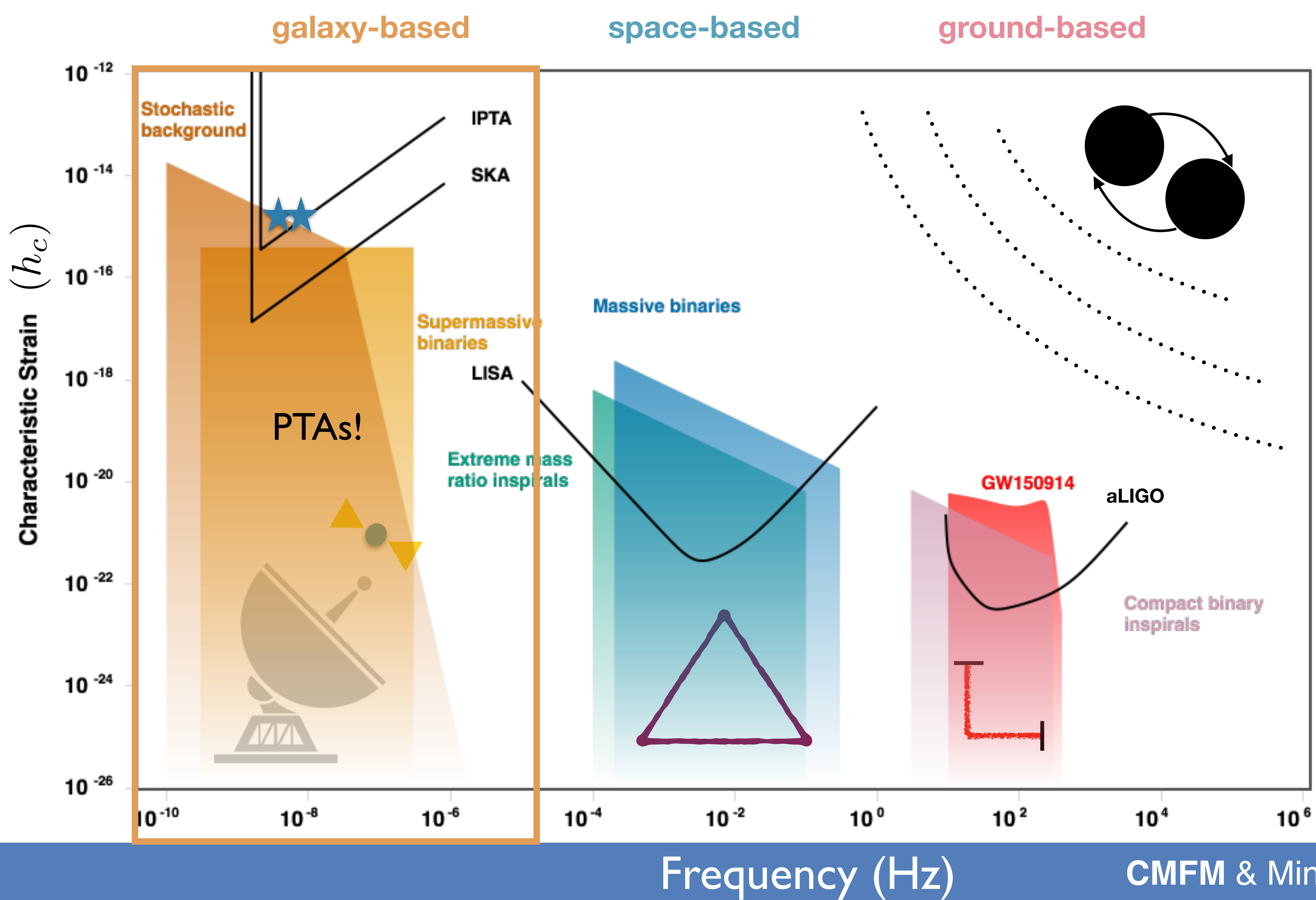

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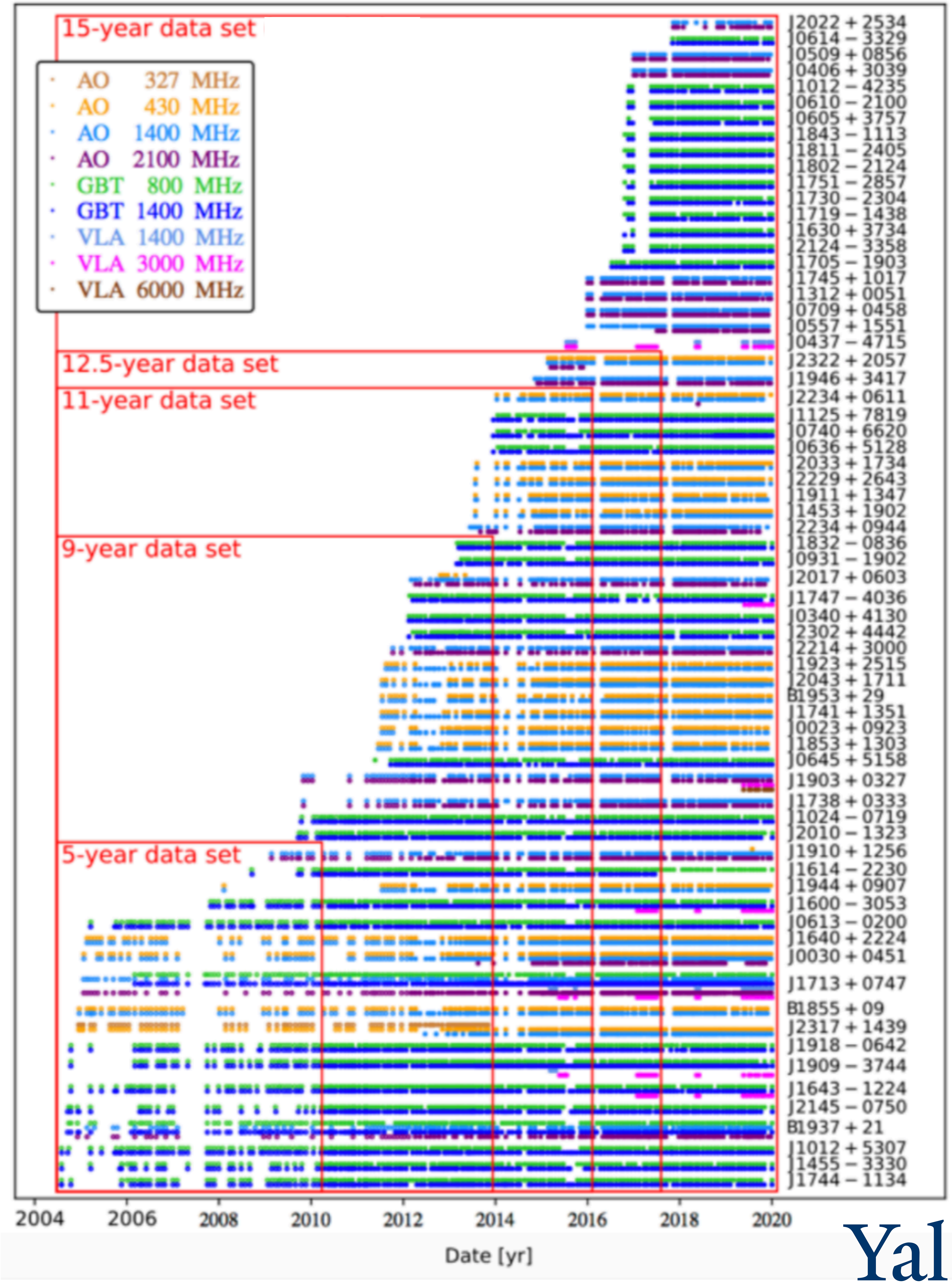
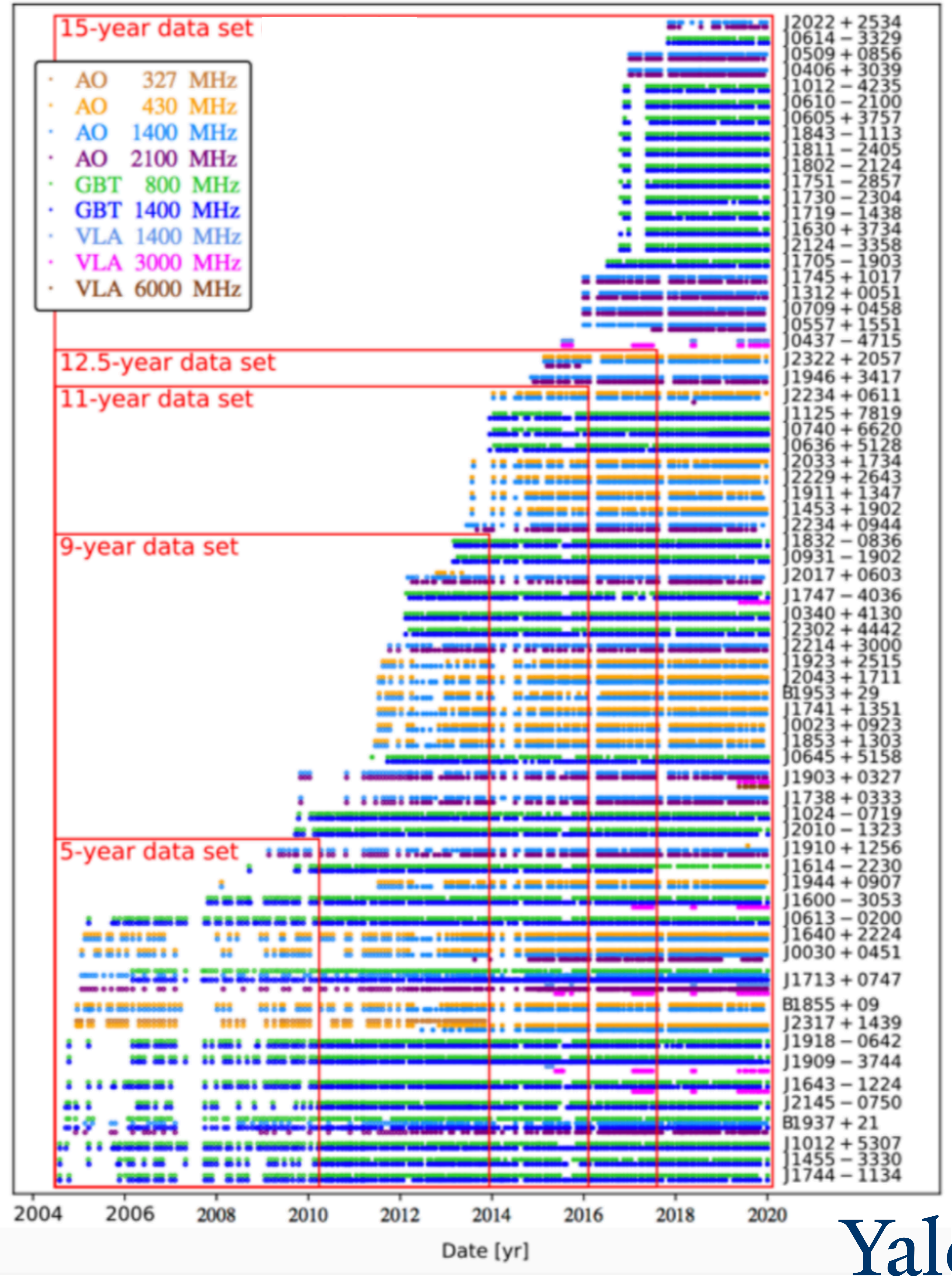
Image: Thankful Cromartie



15-yr data lead: Joe Swiggum

Figure from adapted from Agazie et al. (2023)

NANOGrav 15-yr Data Set



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NANOGrav 15-yr Data Set

- 68 MSPs

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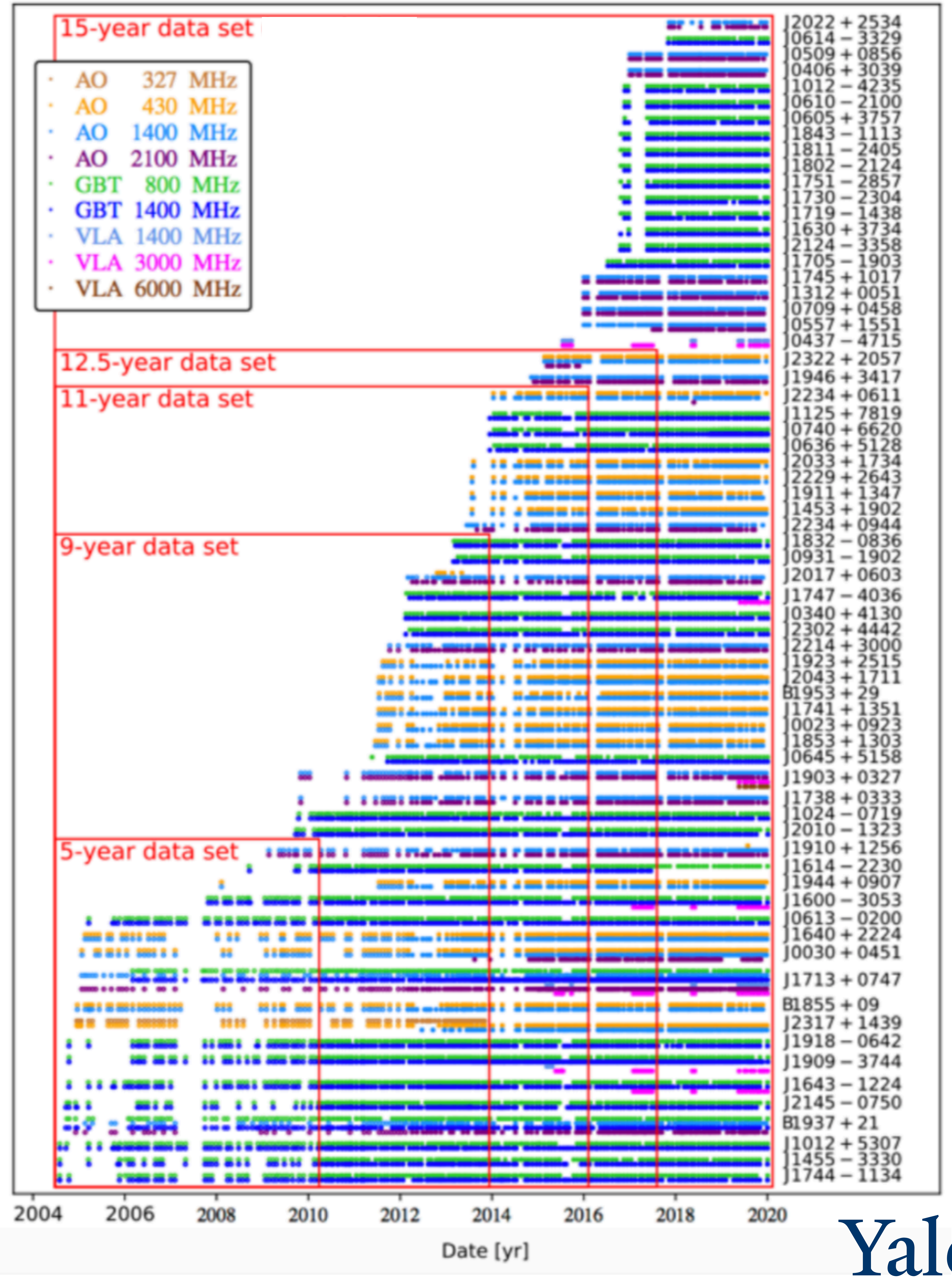

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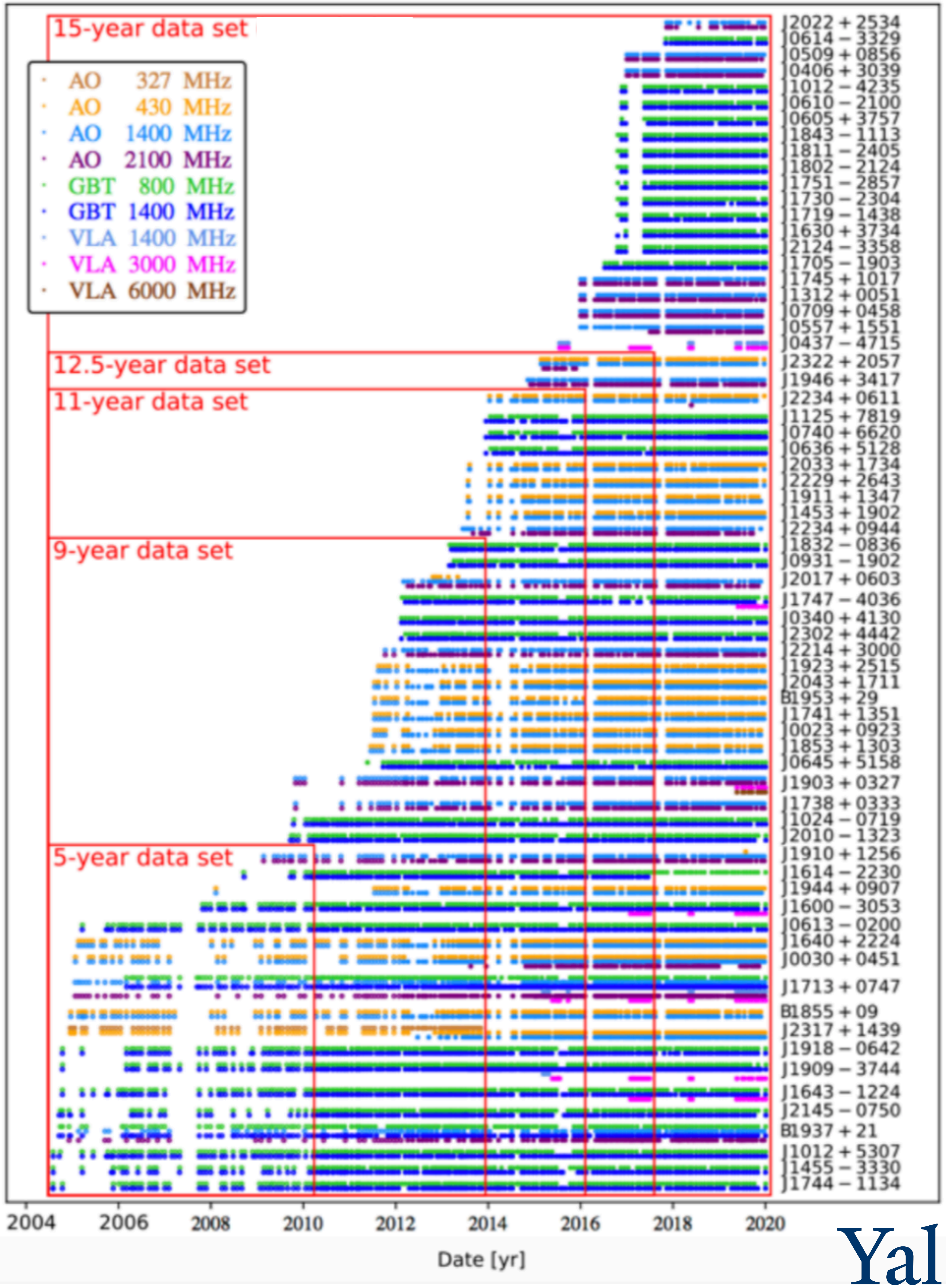
NANOGrav 15-yr Data Set

- 68 MSPs
- Timing baselines 3-15 yrs



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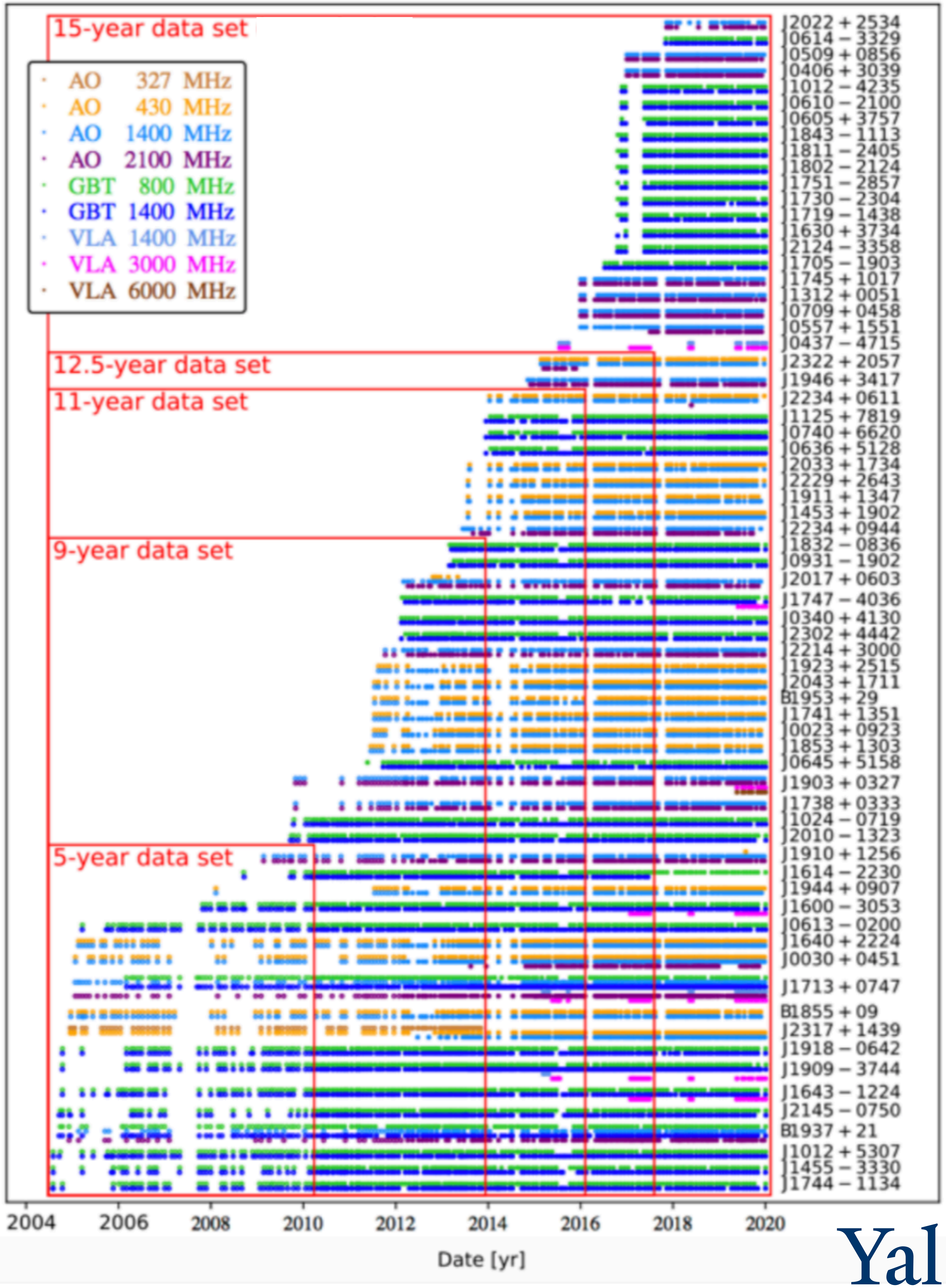

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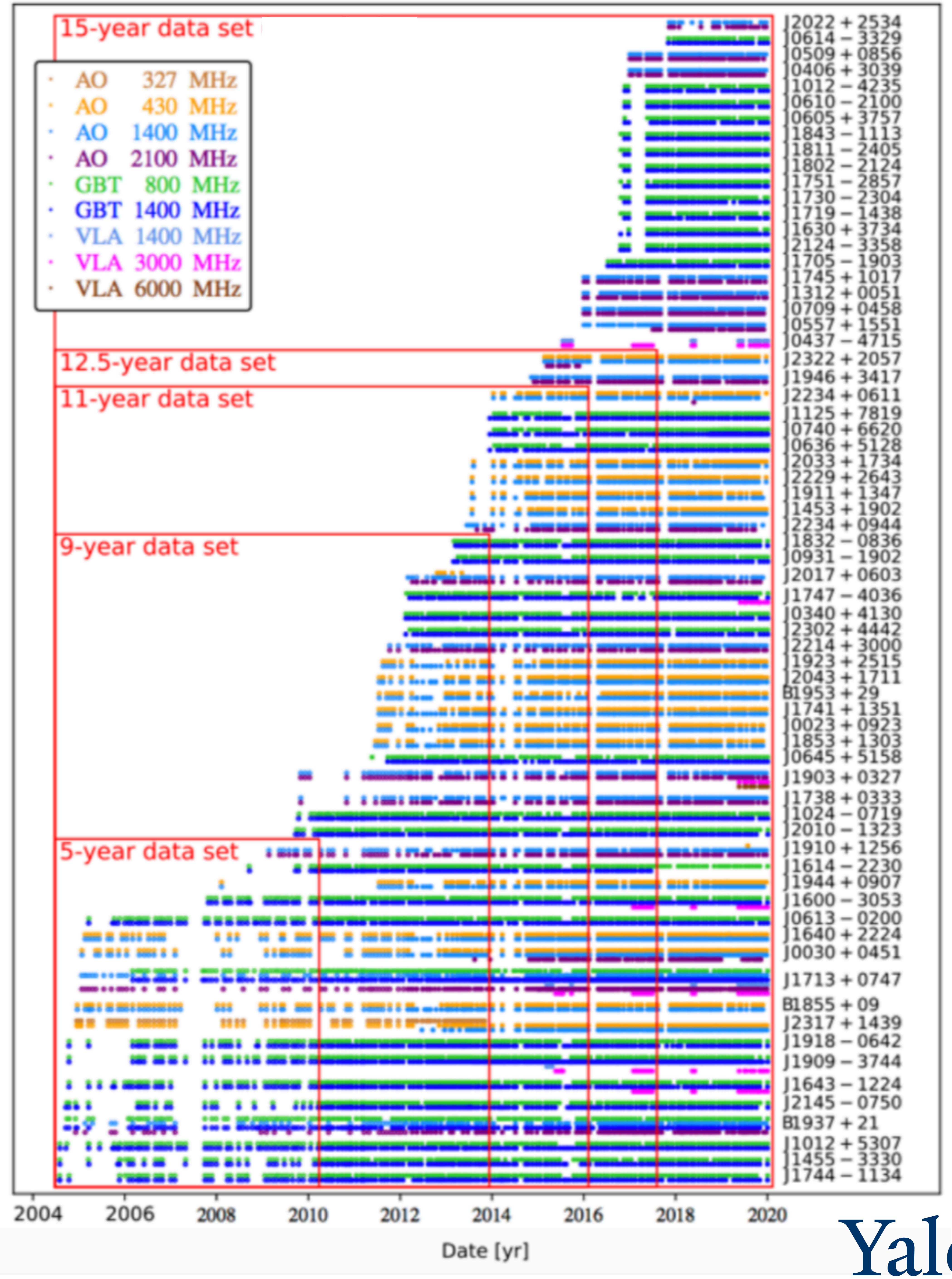

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NANOGrav 15-yr Data Set

- 68 MSPs
- Timing baselines 3-15 yrs
- Check SNR of common process increasing?
- Check HD significance increasing?
- Significant effort to automate timing pipeline with PINT (Luo+2021) for reproducibility .

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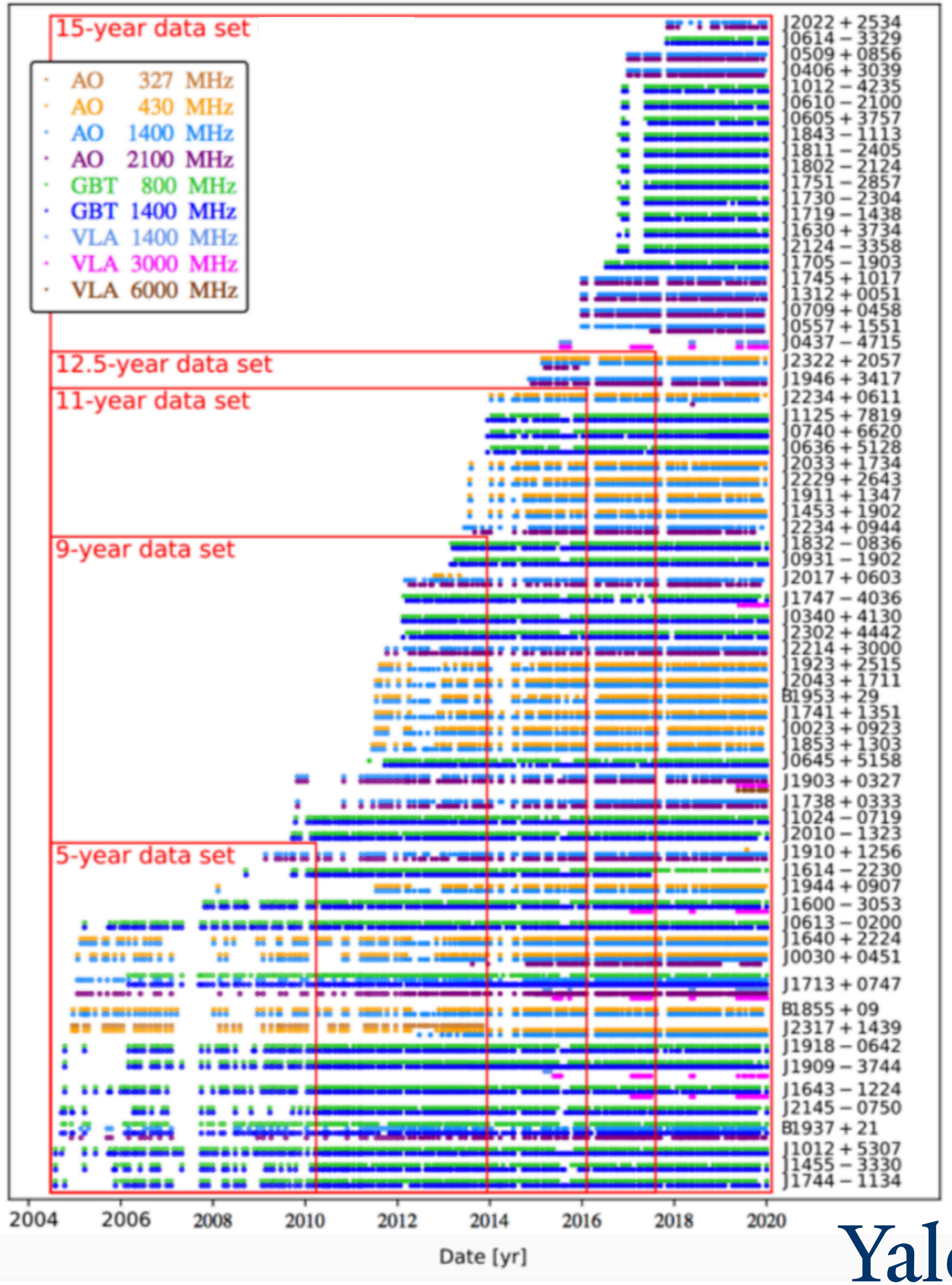

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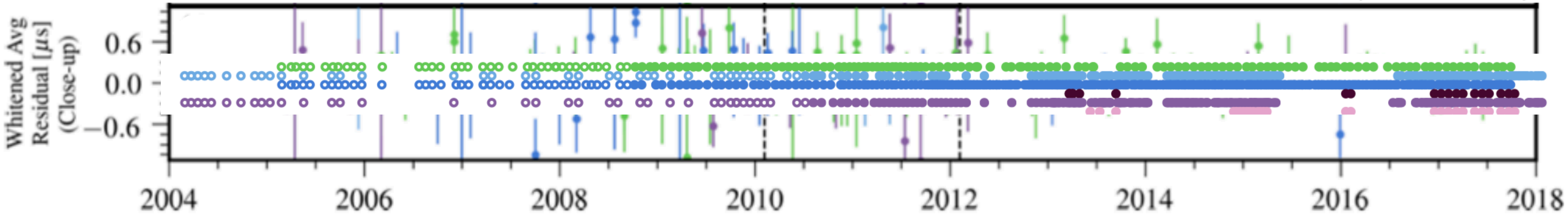
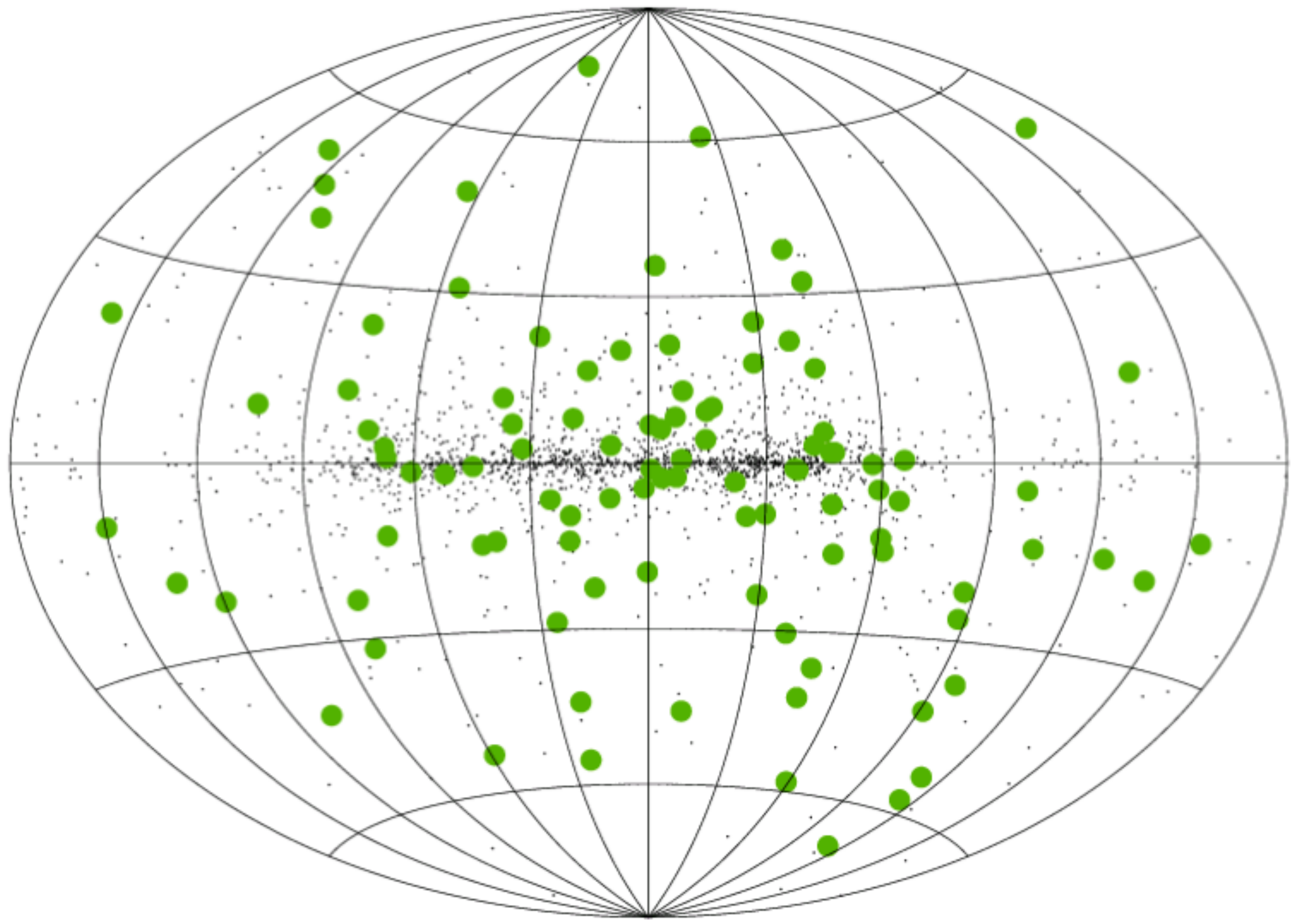
Millisecond Pulsars

Long-term Timing Campaign



Alam+ 2021a (corr. author M. DeCesar)



2300 known pulsars, 230 MSPs
Maybe 30,000 detectable!

Cross-power spectral density between pulsar a and b

$$S_{ab}(f) = \Gamma_{ab}(f)\,\frac{h_c{}^2(f)}{12\pi^2 f^3}$$

Angular correlation function

Sum of the strain emitted by e.g. SMBHBs over their cosmic merger history (Phinney 2001)

Millisecond Pulsars

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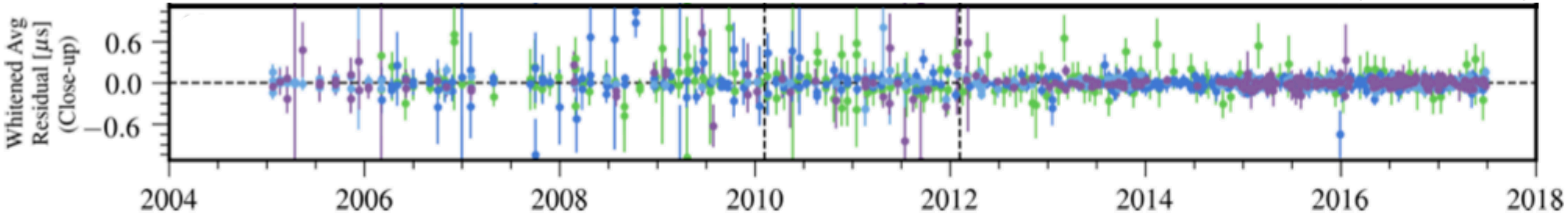

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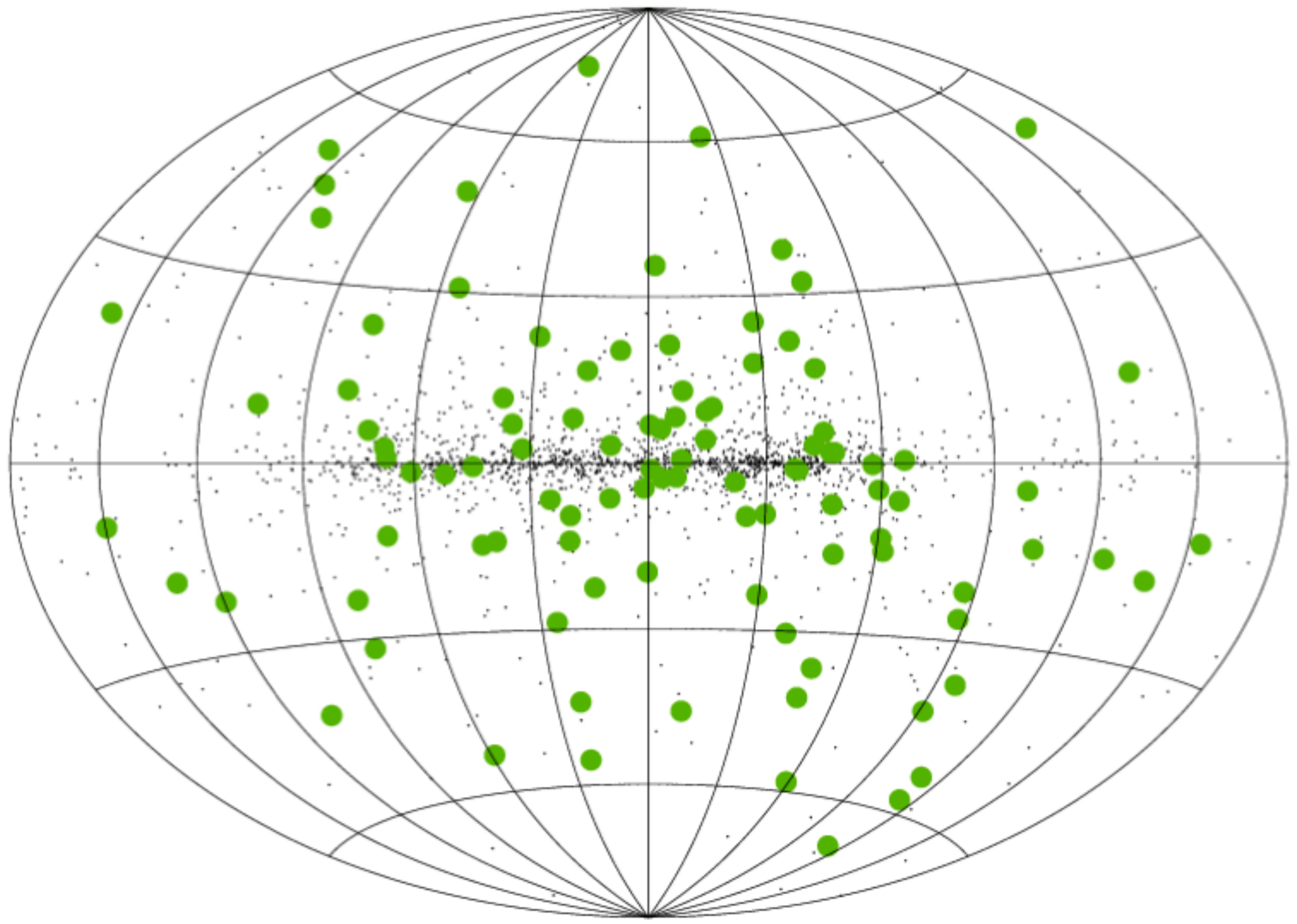

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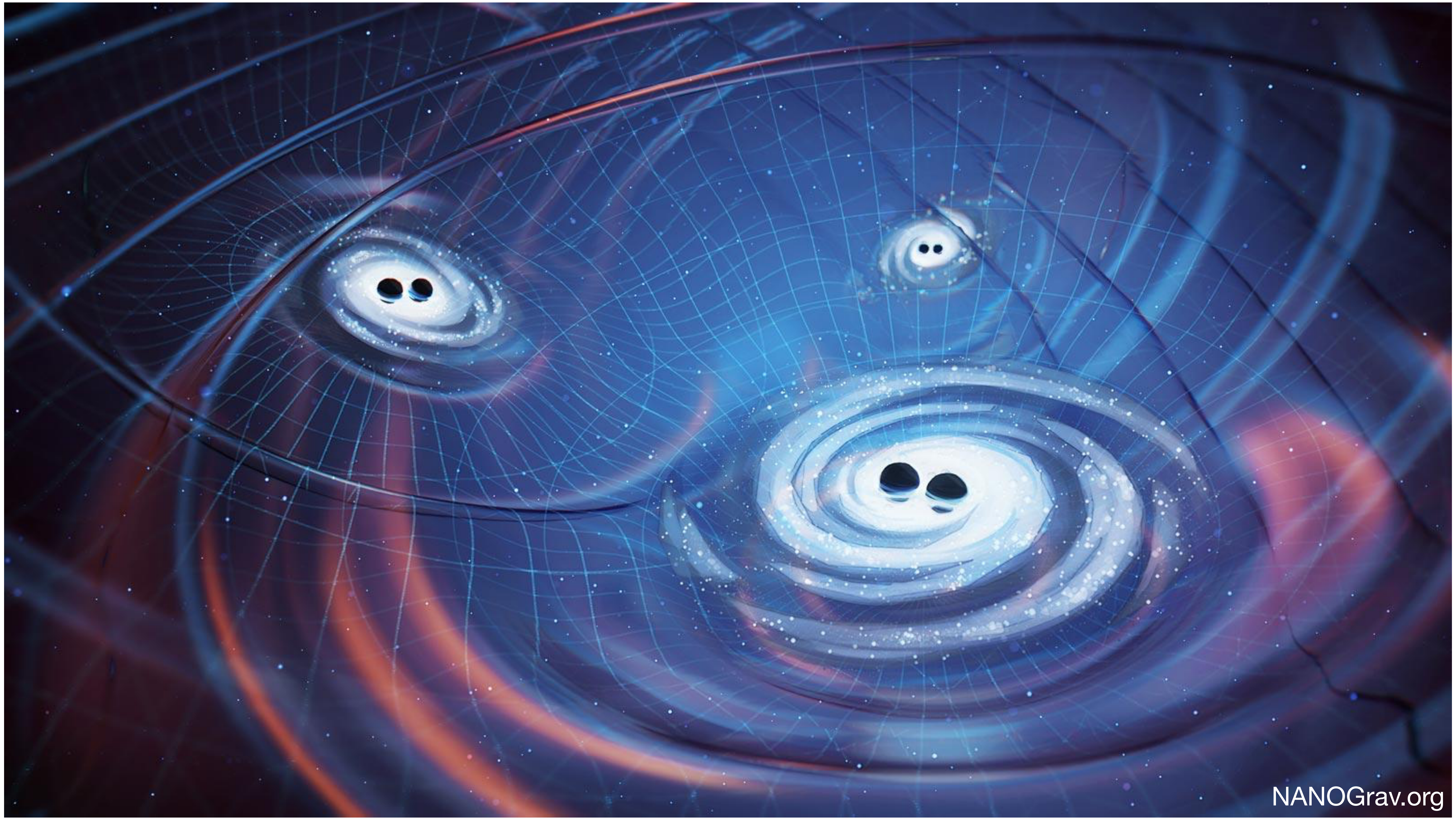
A random gravitational-wave background

- Primary Target: cosmic merger history of supermassive black holes should create a GWB

- 100,000s + SMBHBs per frequency bin — stochastic GWB

- Other GWB sources **Primordial GWs** and more?

- **Creates a signal with the same amplitude** in all pulsars with additional geometric term



Gravitational-Wave Backgrounds

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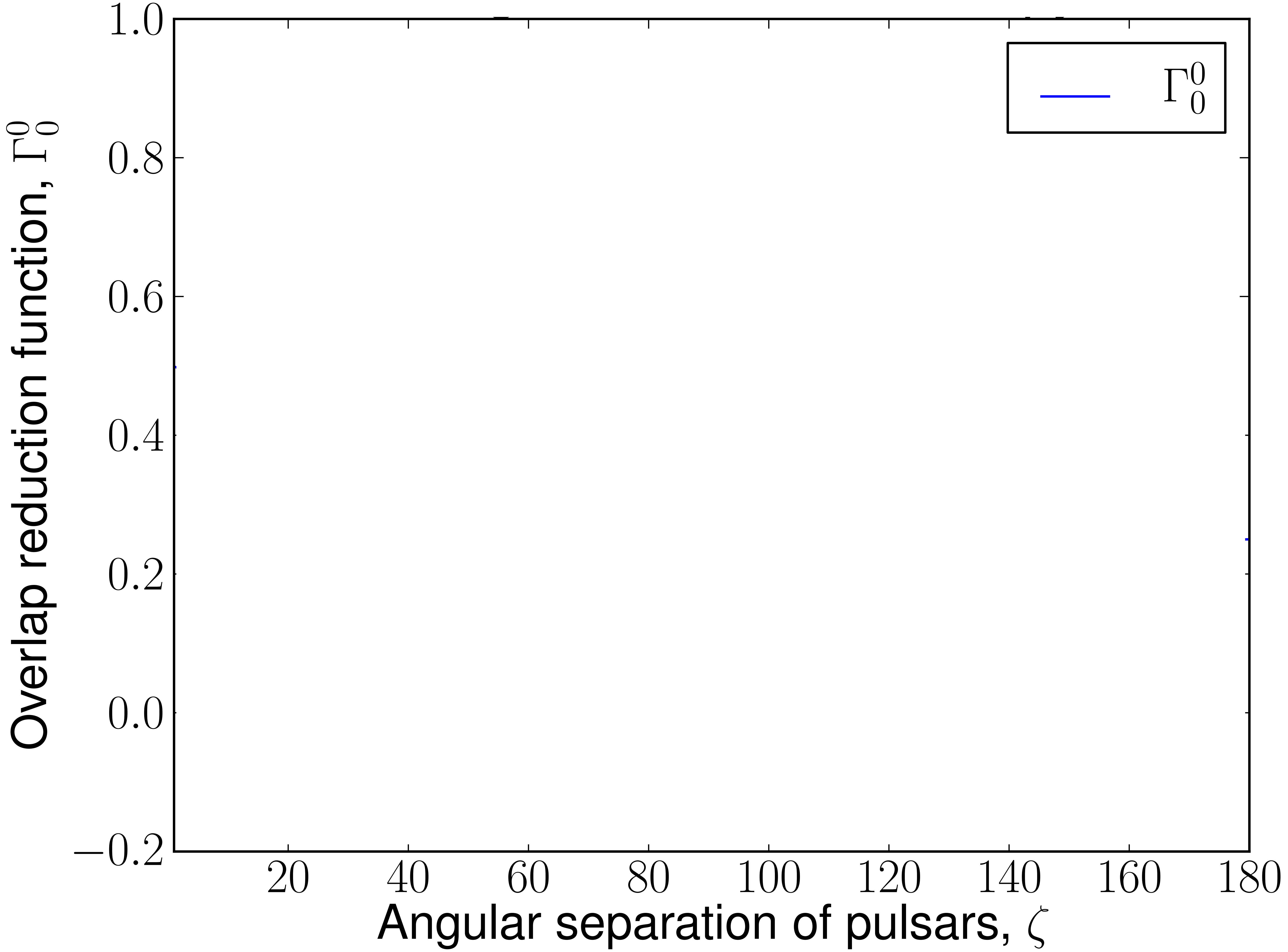

- SMBHBs, cosmic strings?
- Hellings and Downs curve
- Assumes background is isotropic (is it?)
- Pulsar correlations create “curve”
- Changes for alternative theories of gravity and anisotropic GWBs

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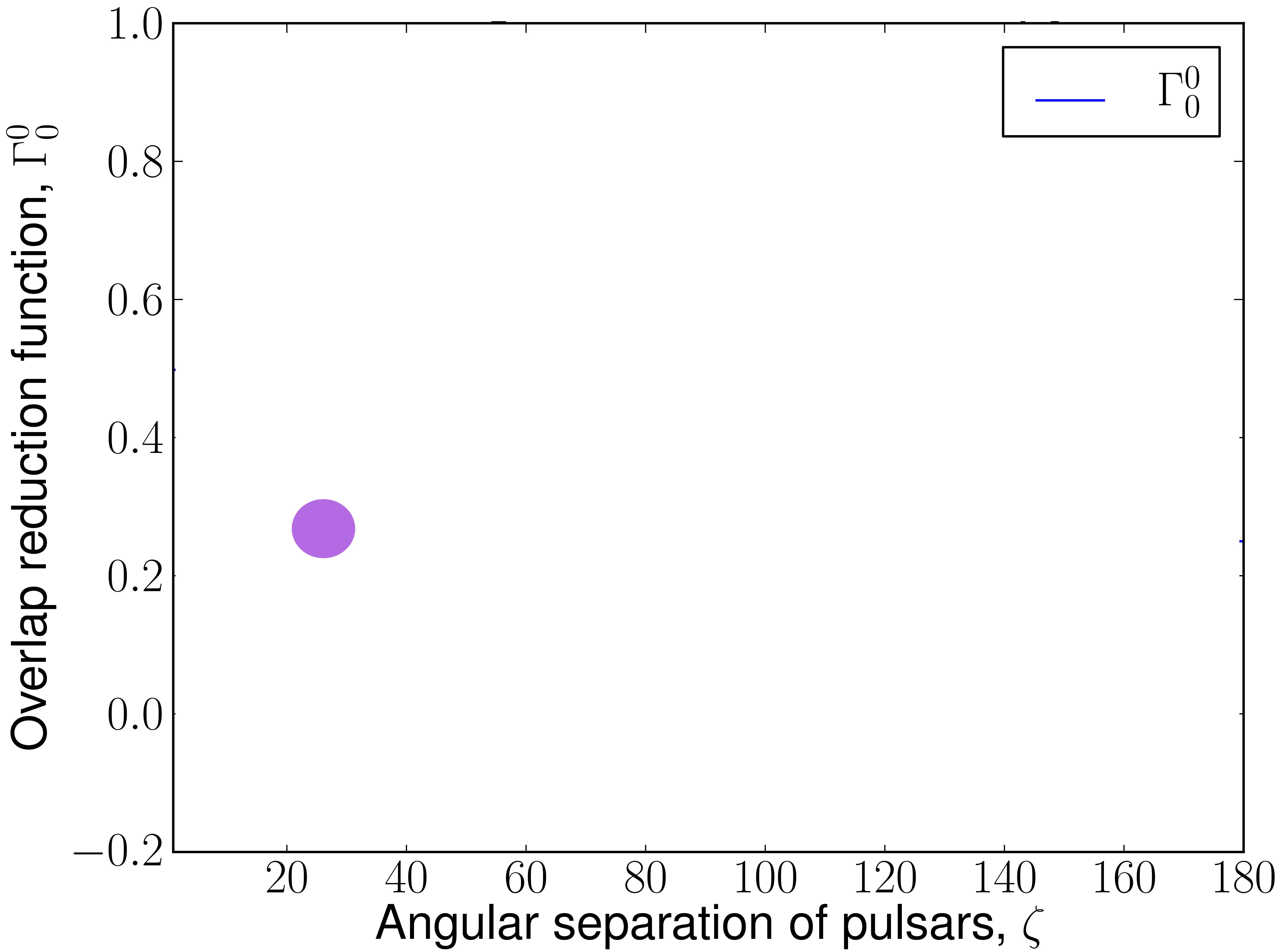

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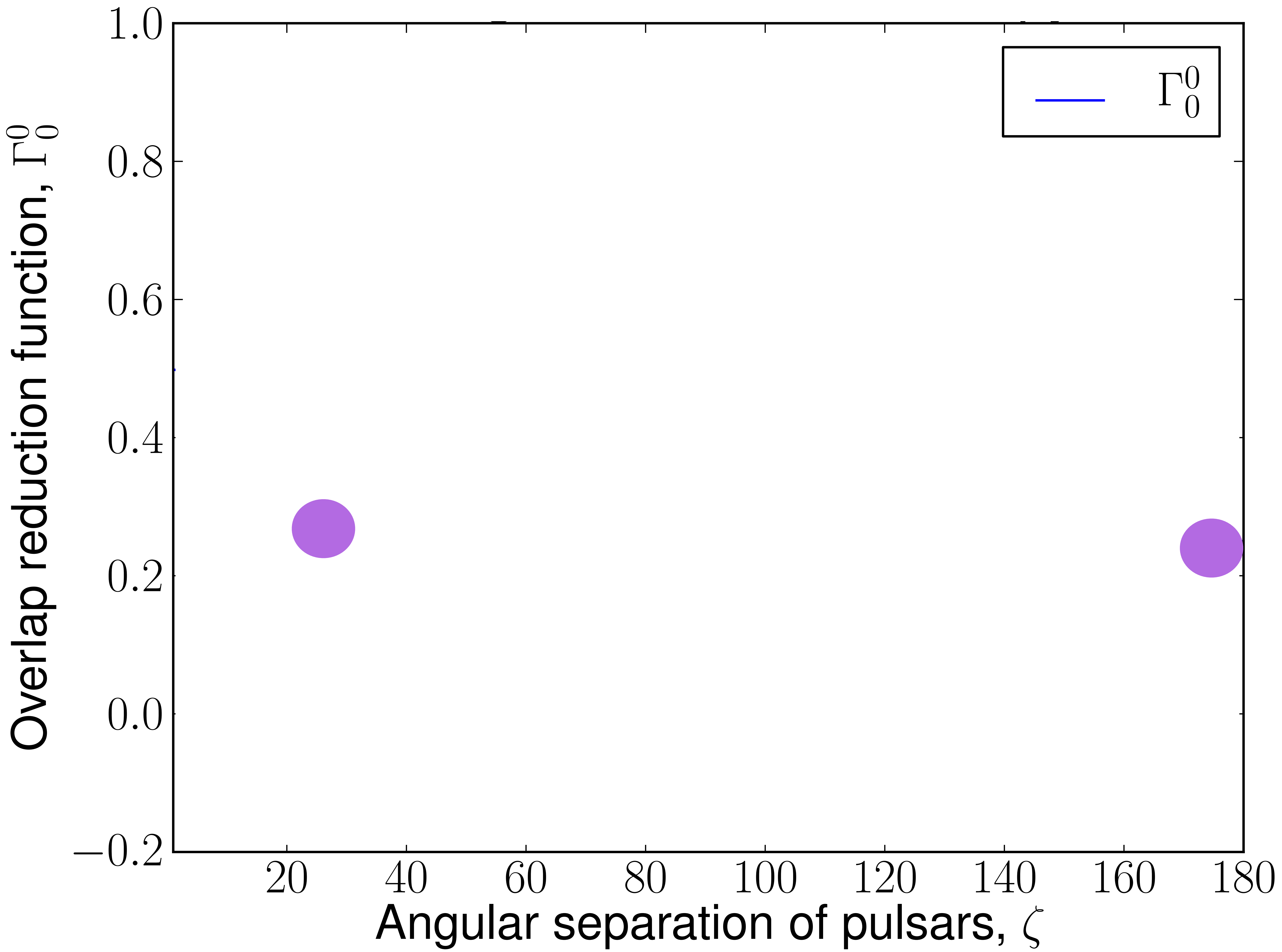

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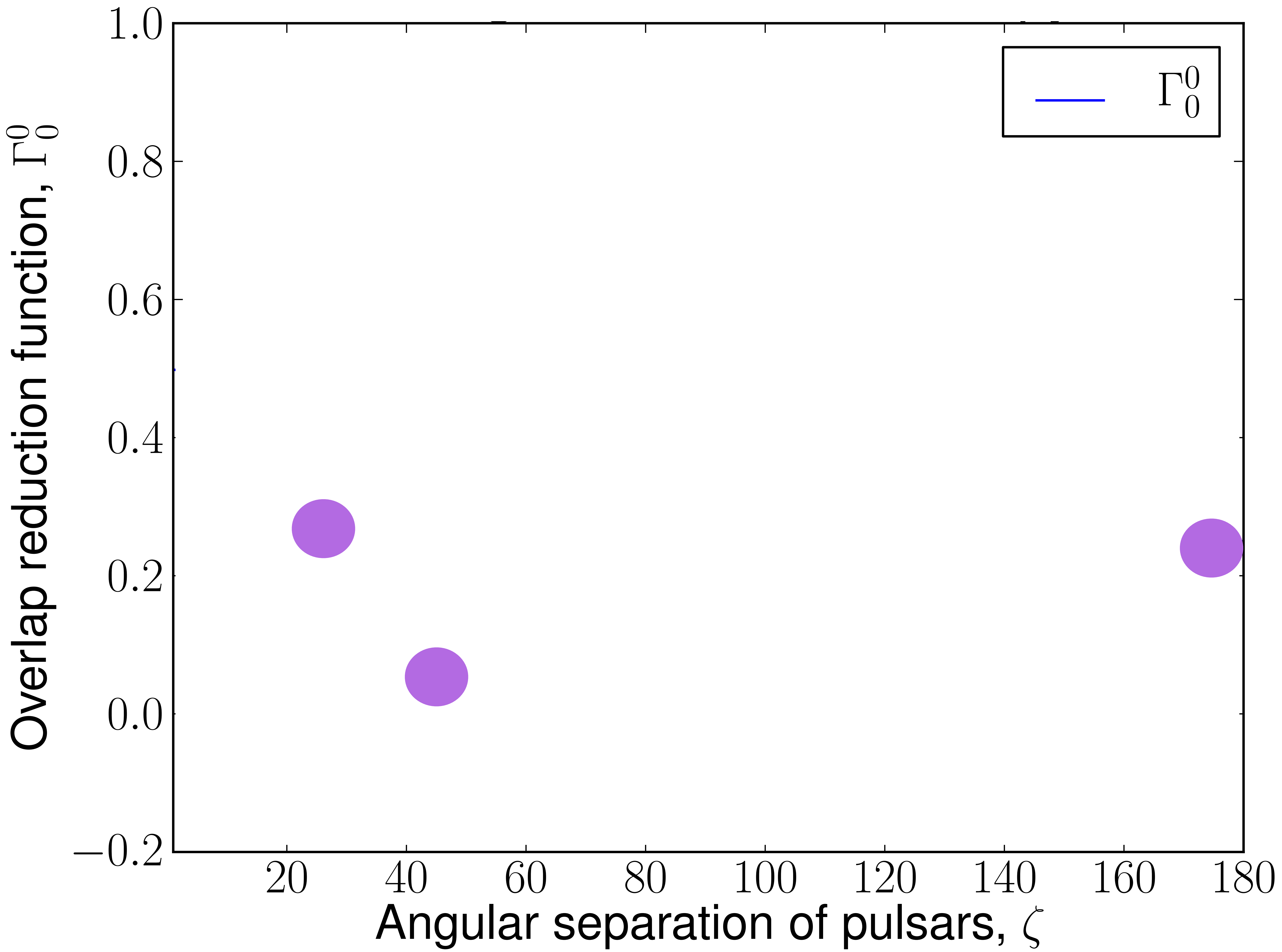

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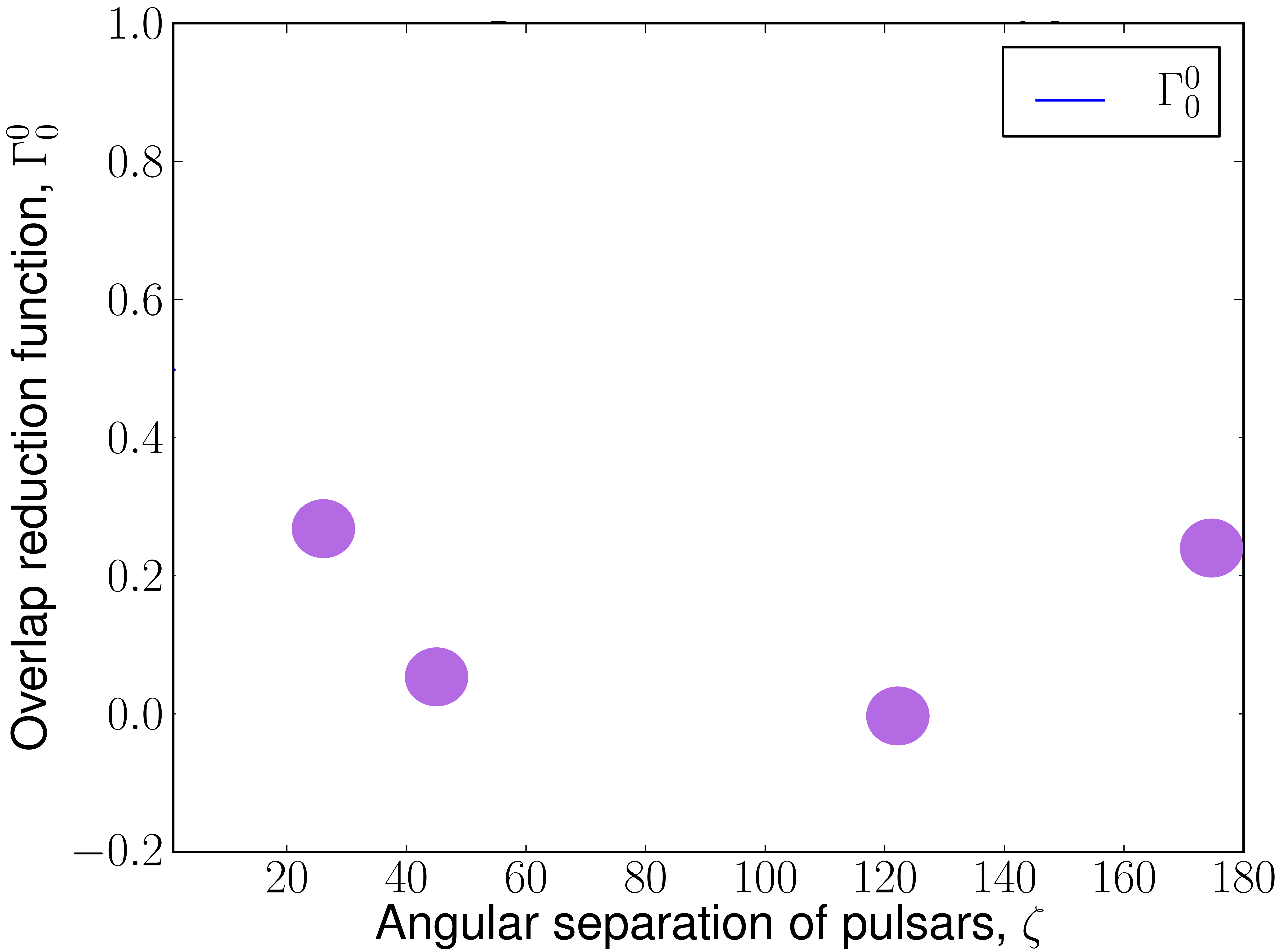

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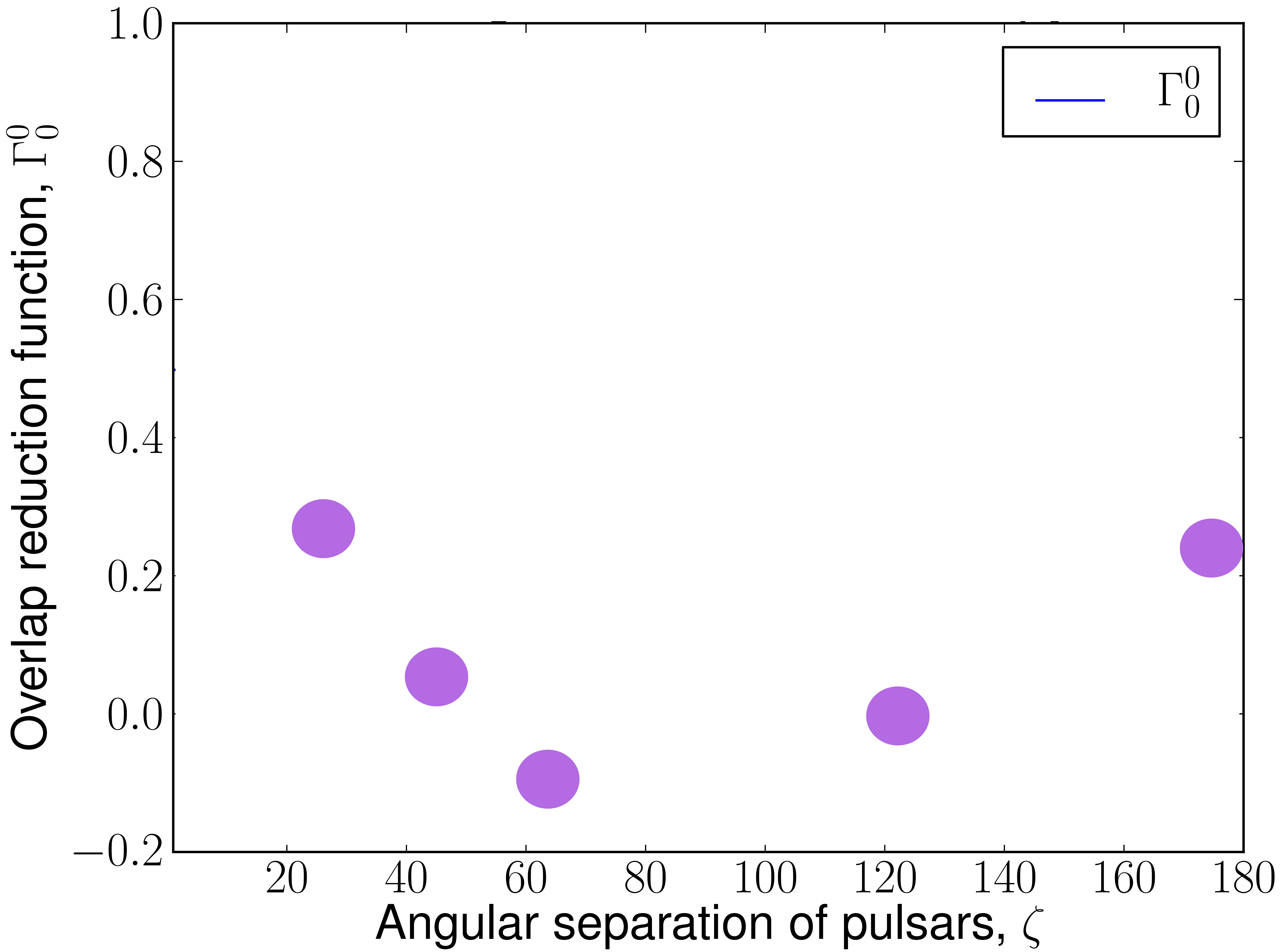

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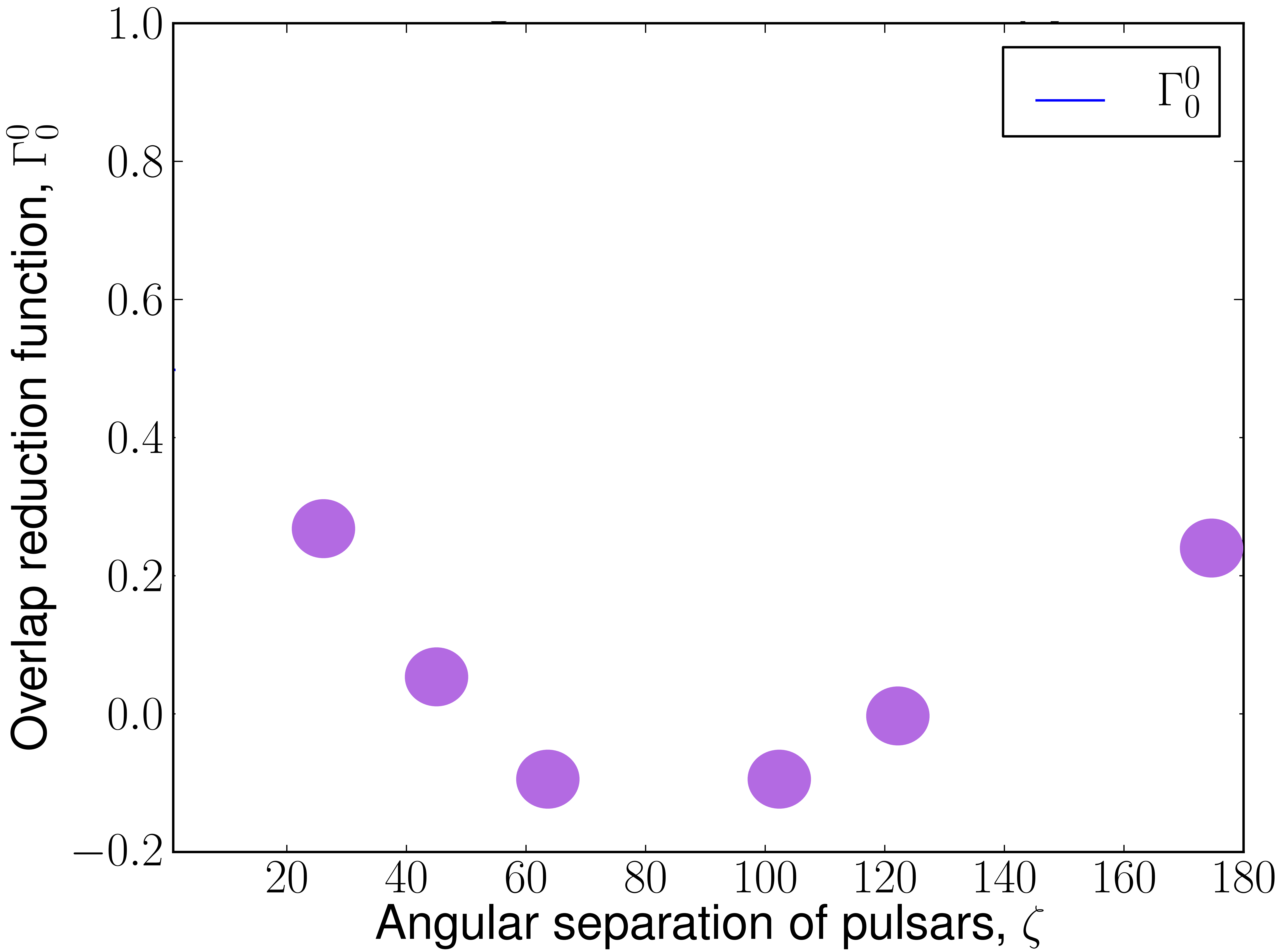

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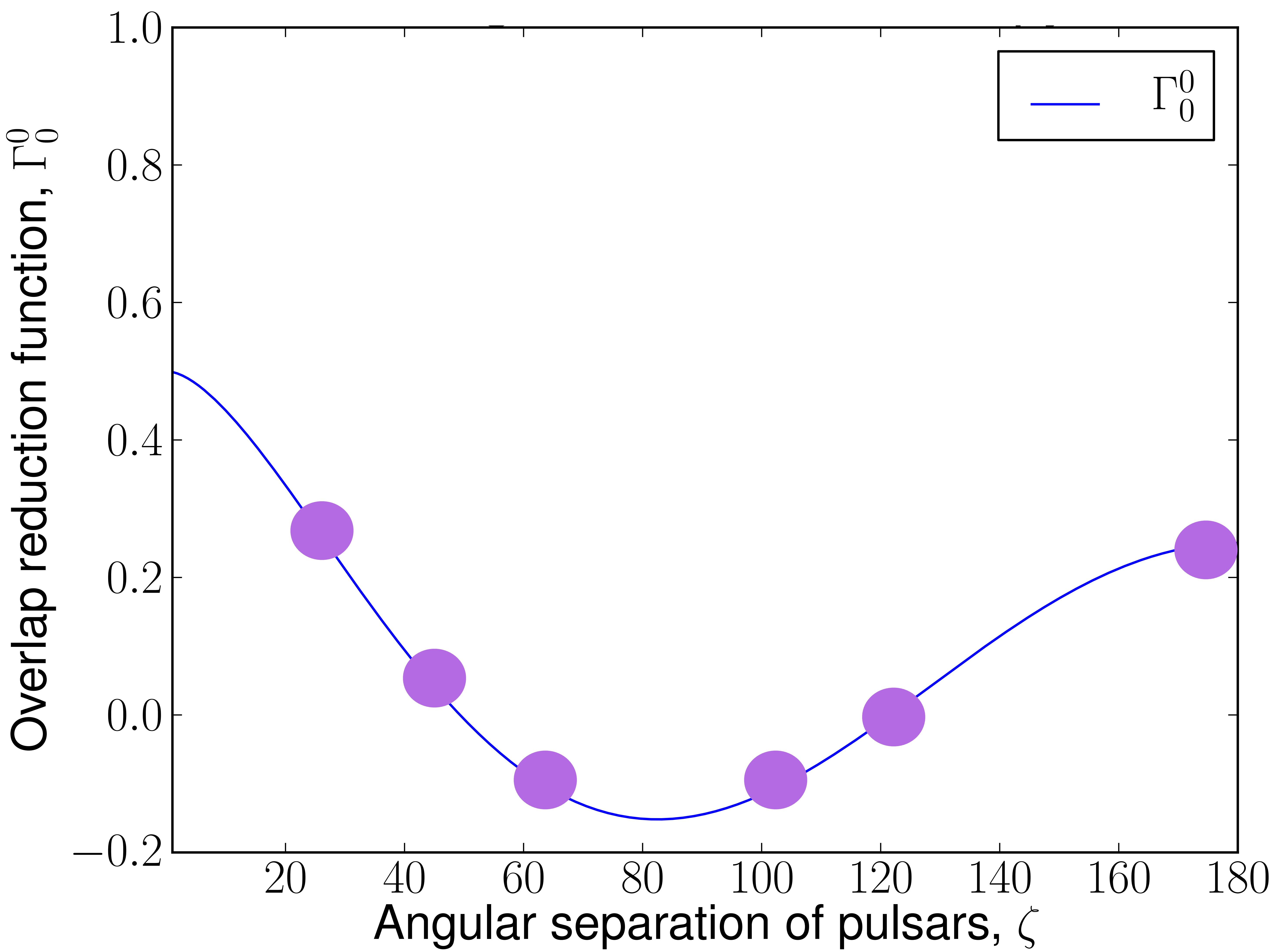

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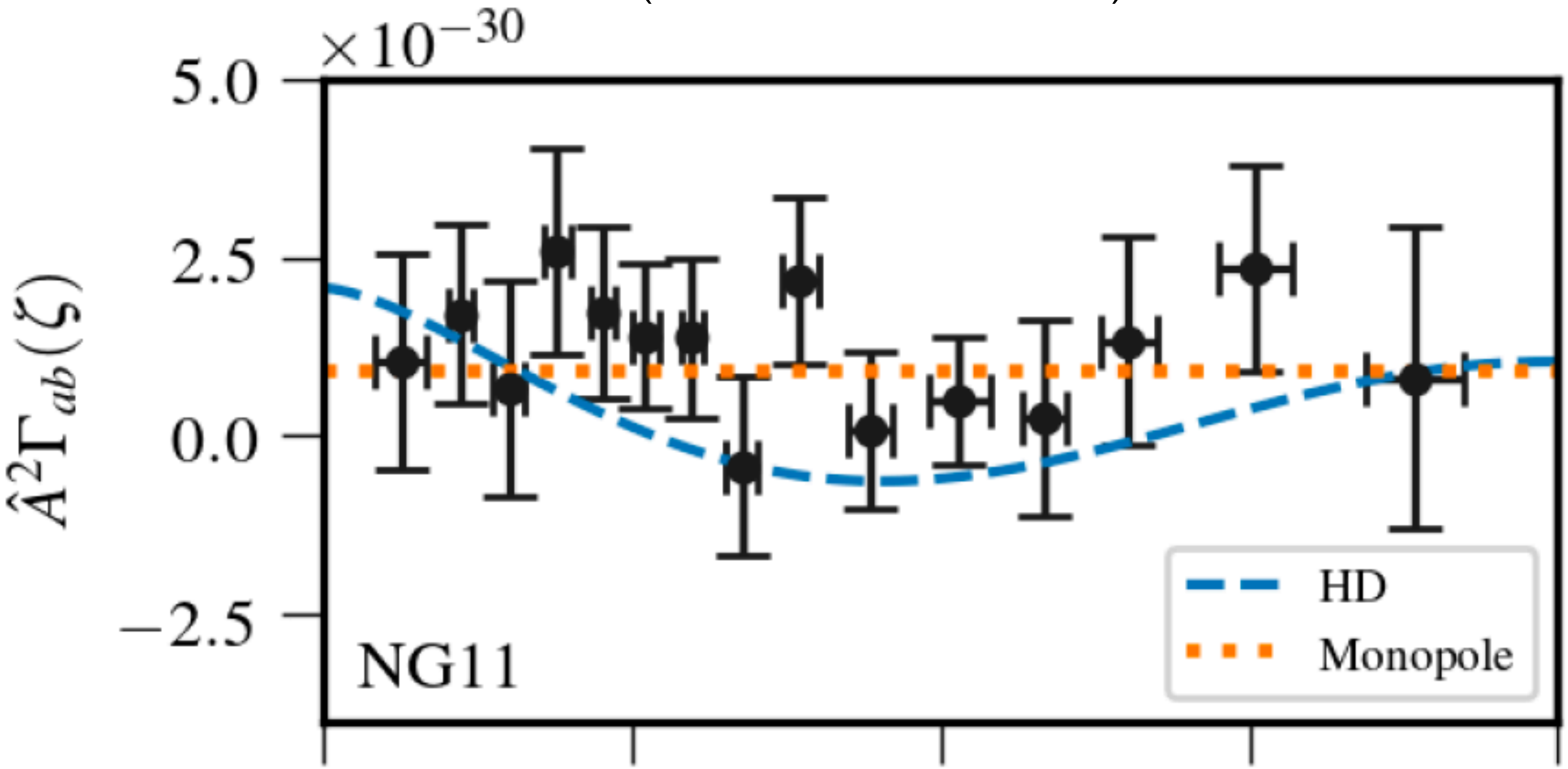
Is there a HD curve in the data?

(With cross-correlations)



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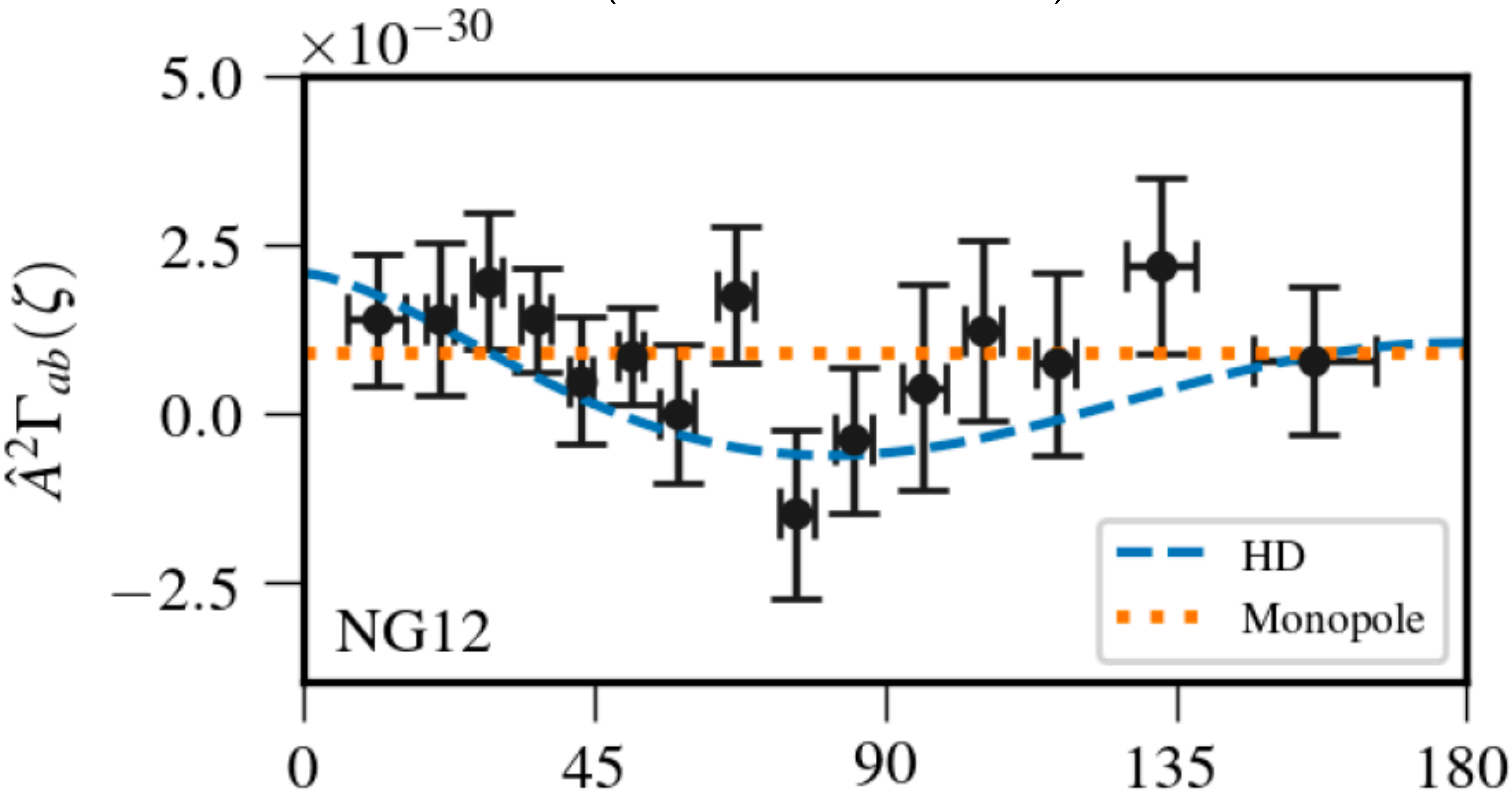

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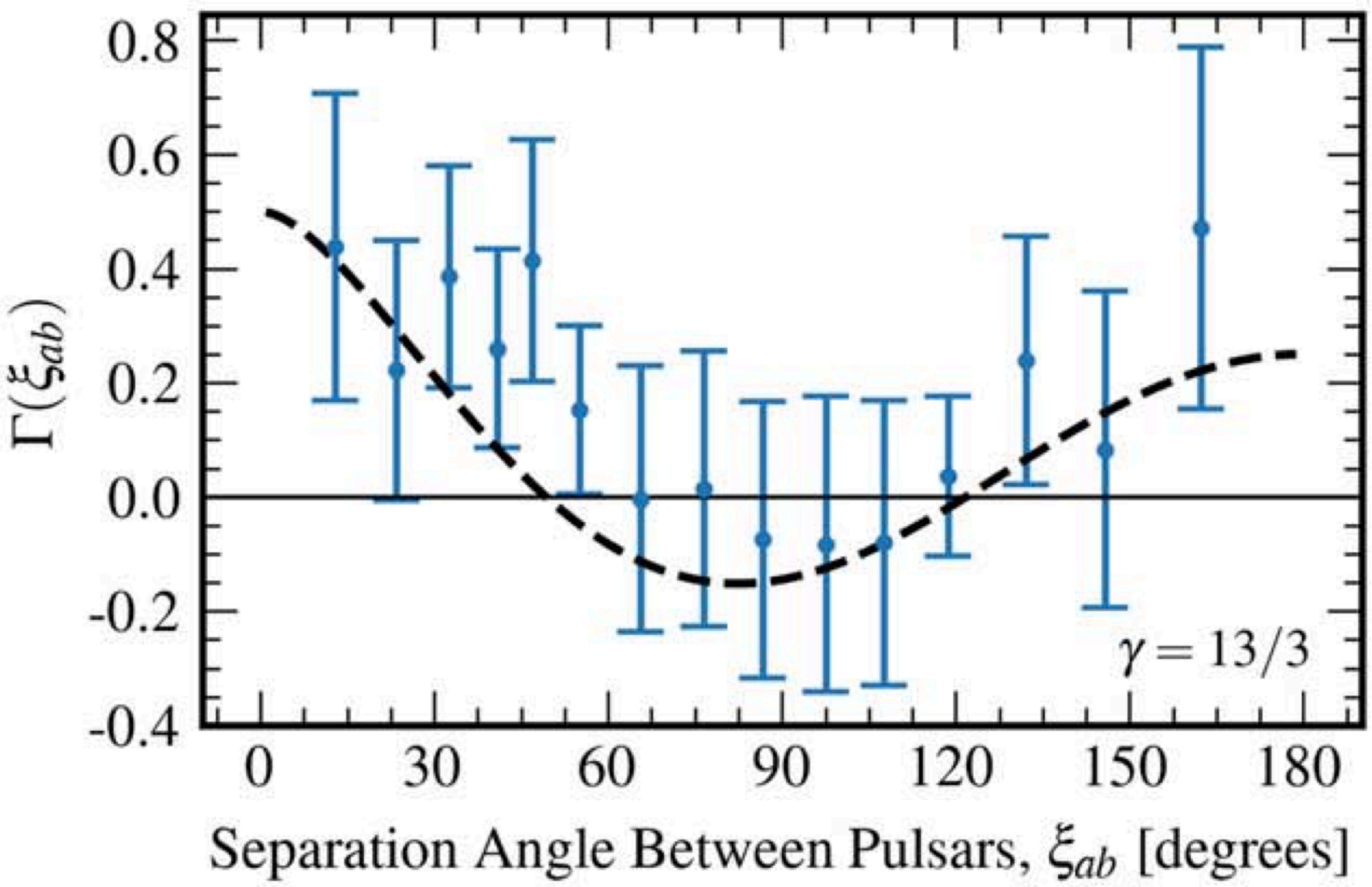

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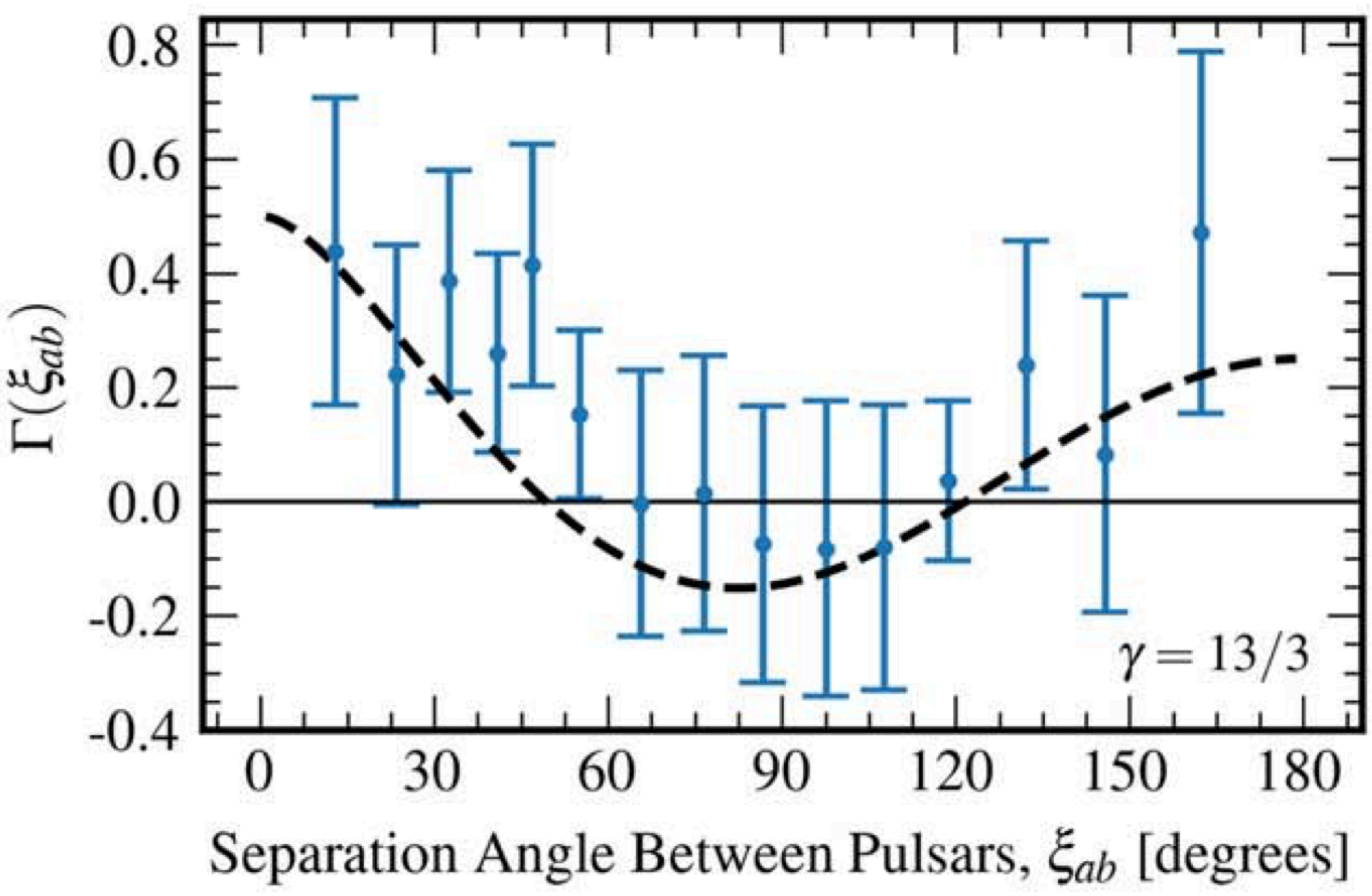

- 2211 pulsar pairs, binned

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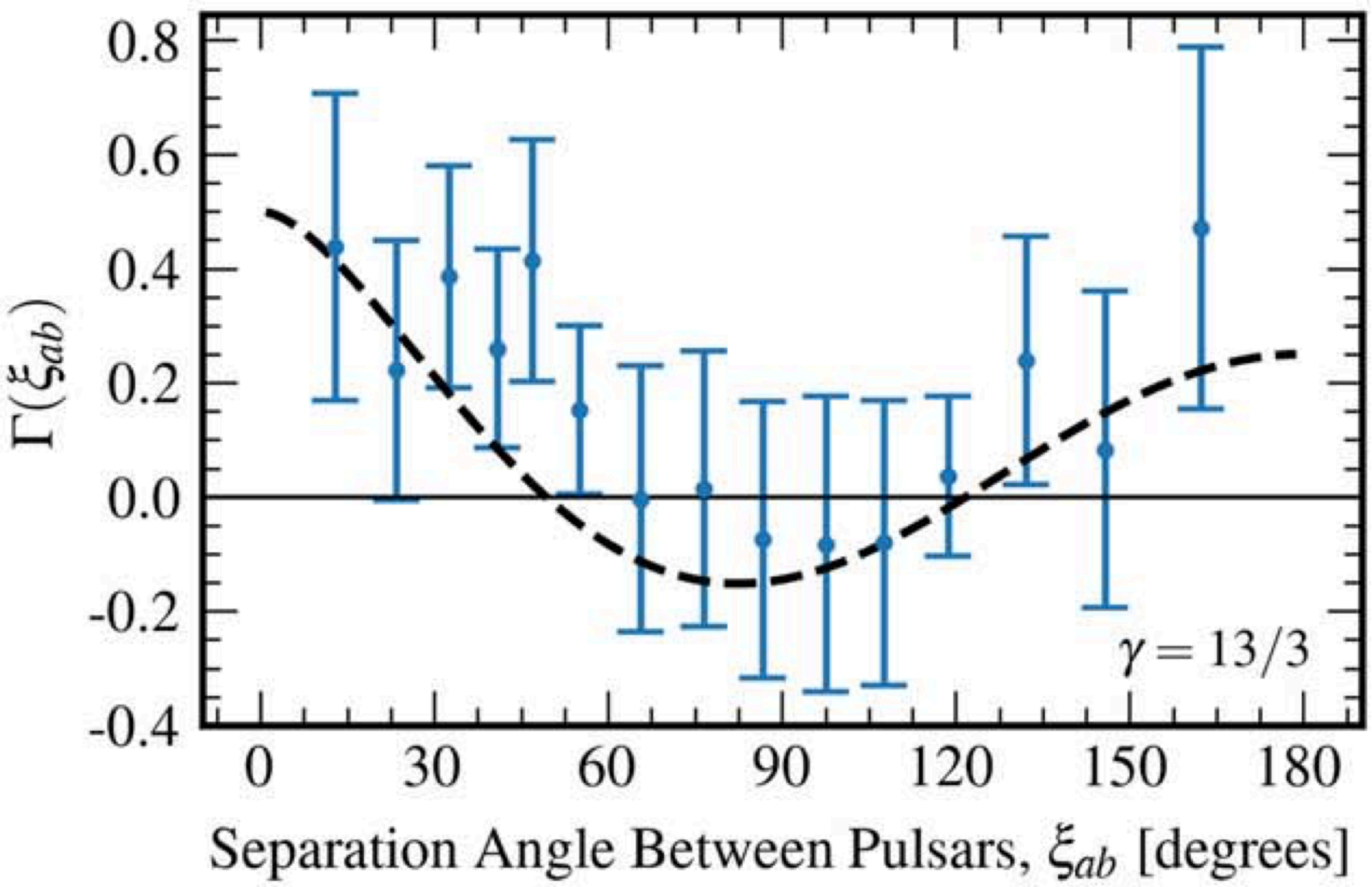

- 2211 pulsar pairs, binned
- 21 new pulsars WRT 12.5-yr

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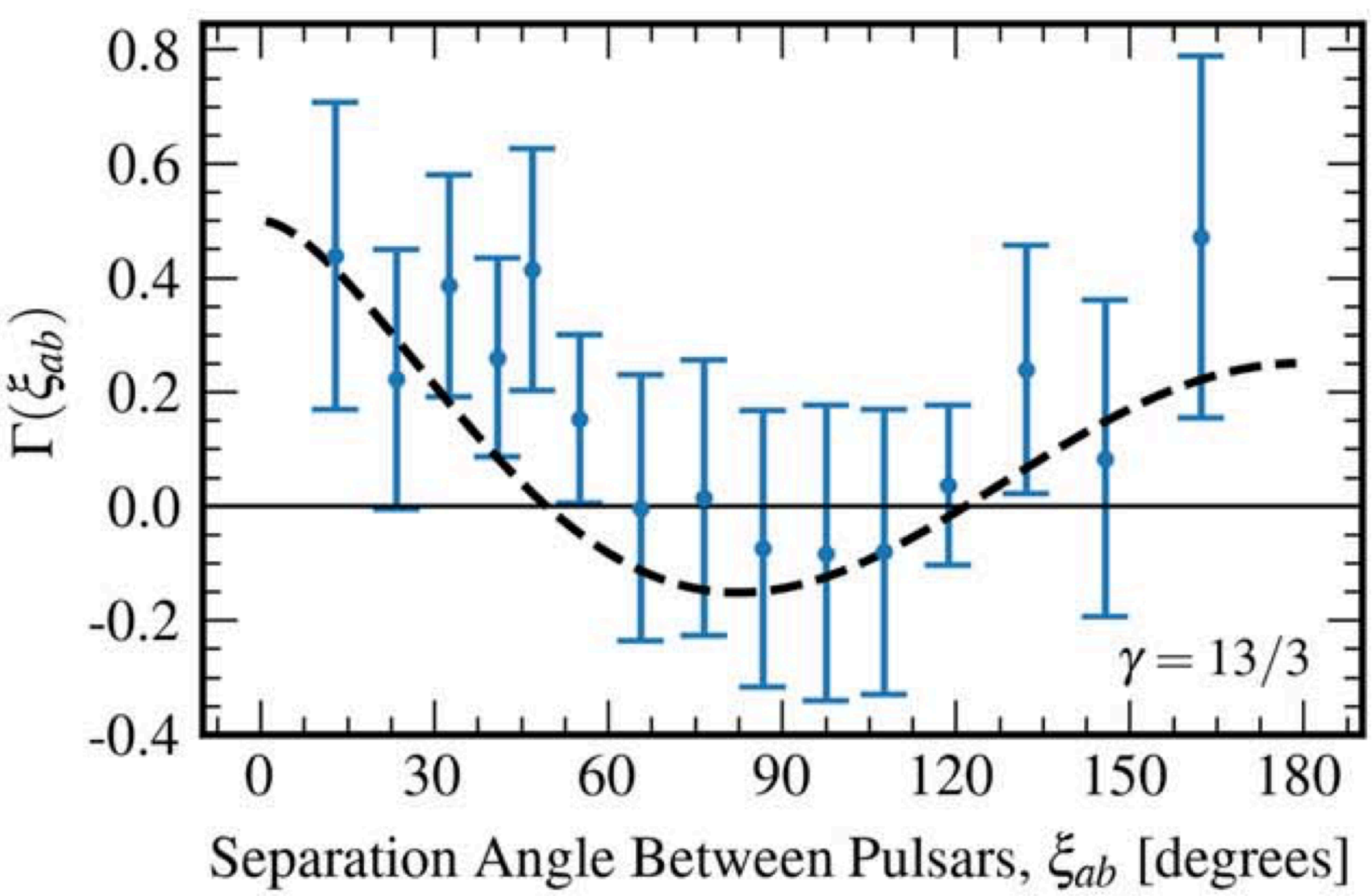

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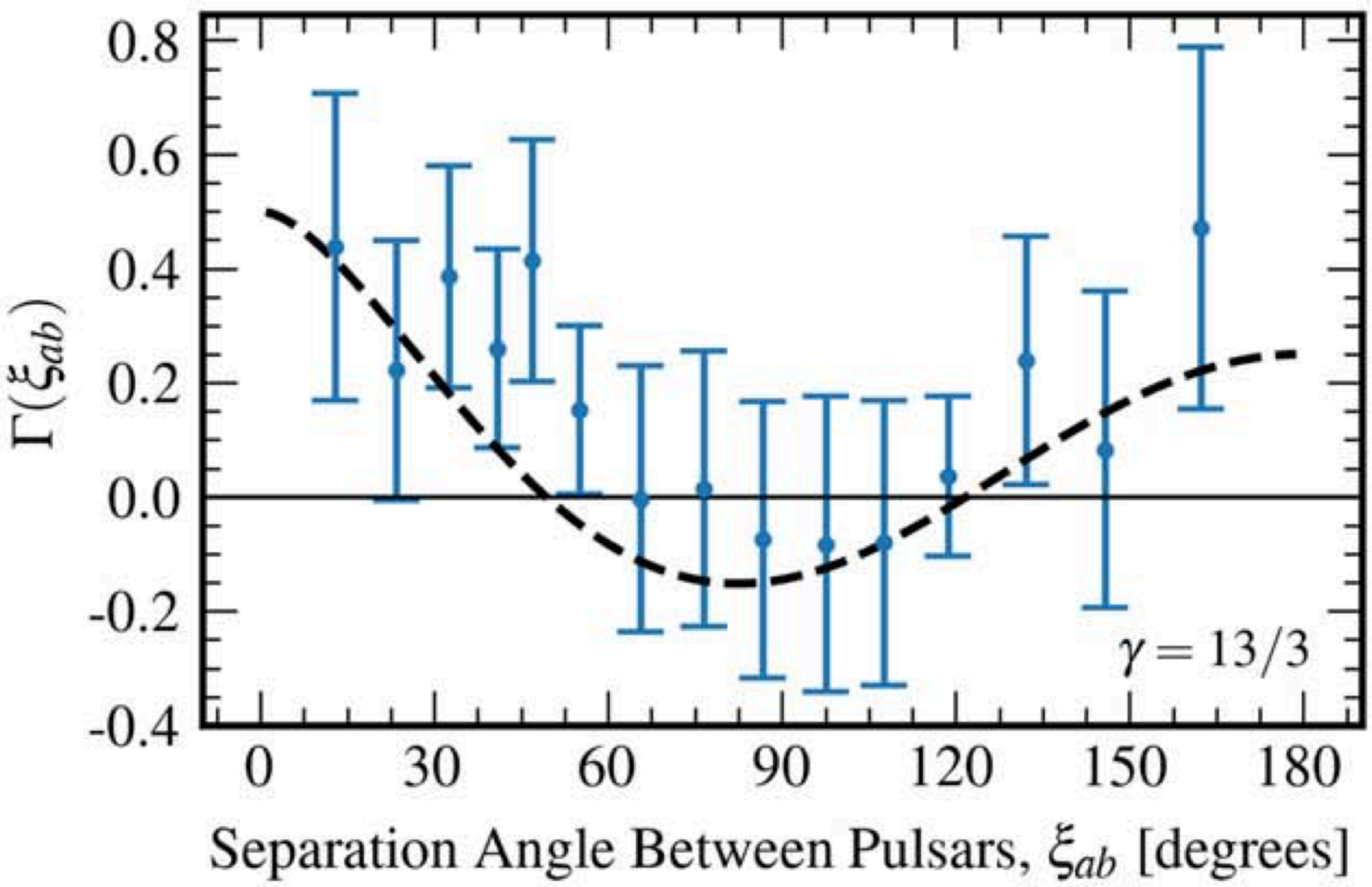

- 2211 pulsar pairs, binned
- 21 new pulsars WRT 12.5-yr
- 67 pulsars with T >3 yrs
- **Looks pretty good… but…**
  - What about Bayes Factors?
  - What about h_c, amplitude?
  - What about other PTAs?

What is the evidence for the HD curve?

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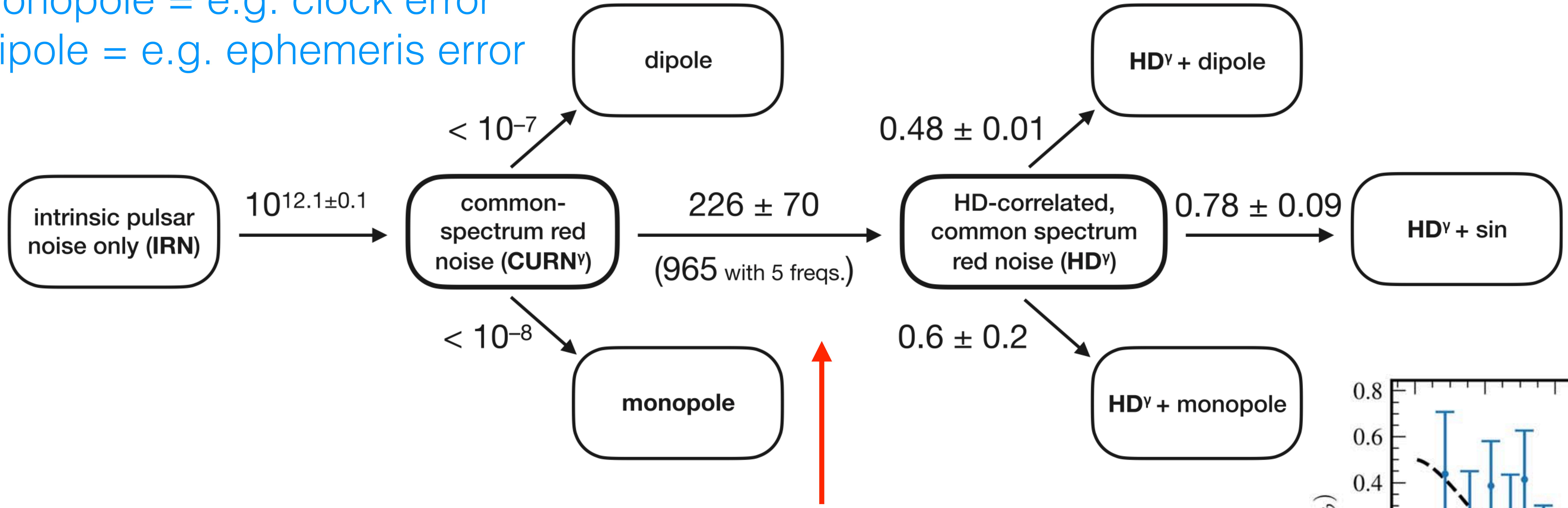
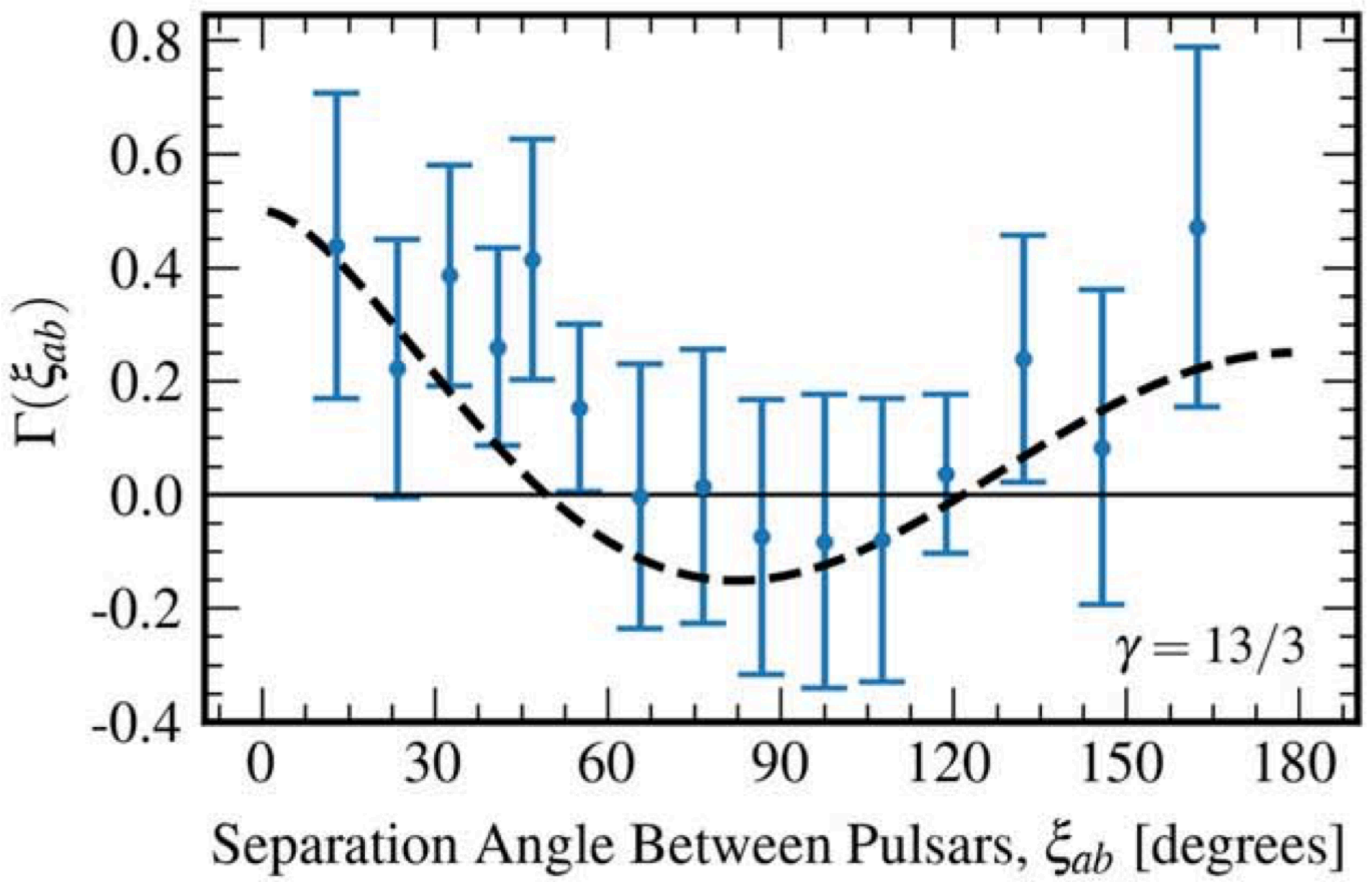
Monopole = e.g. clock error
Dipole = e.g. ephemeris error



BF of up to <u>965 for HD correlations</u>
using 5 lowest frequencies



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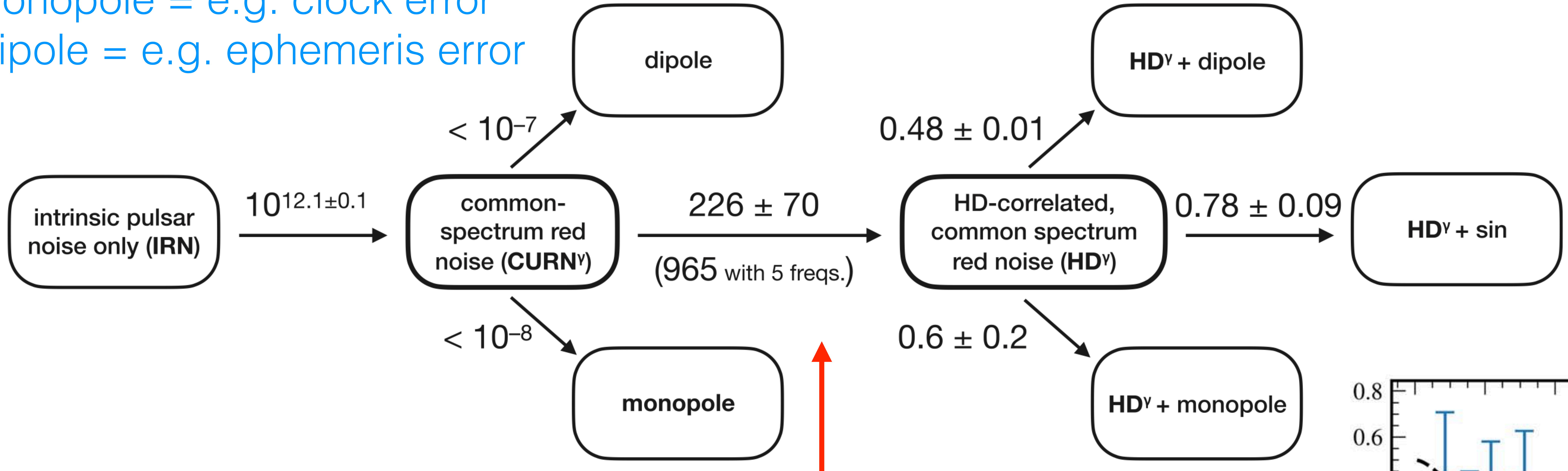

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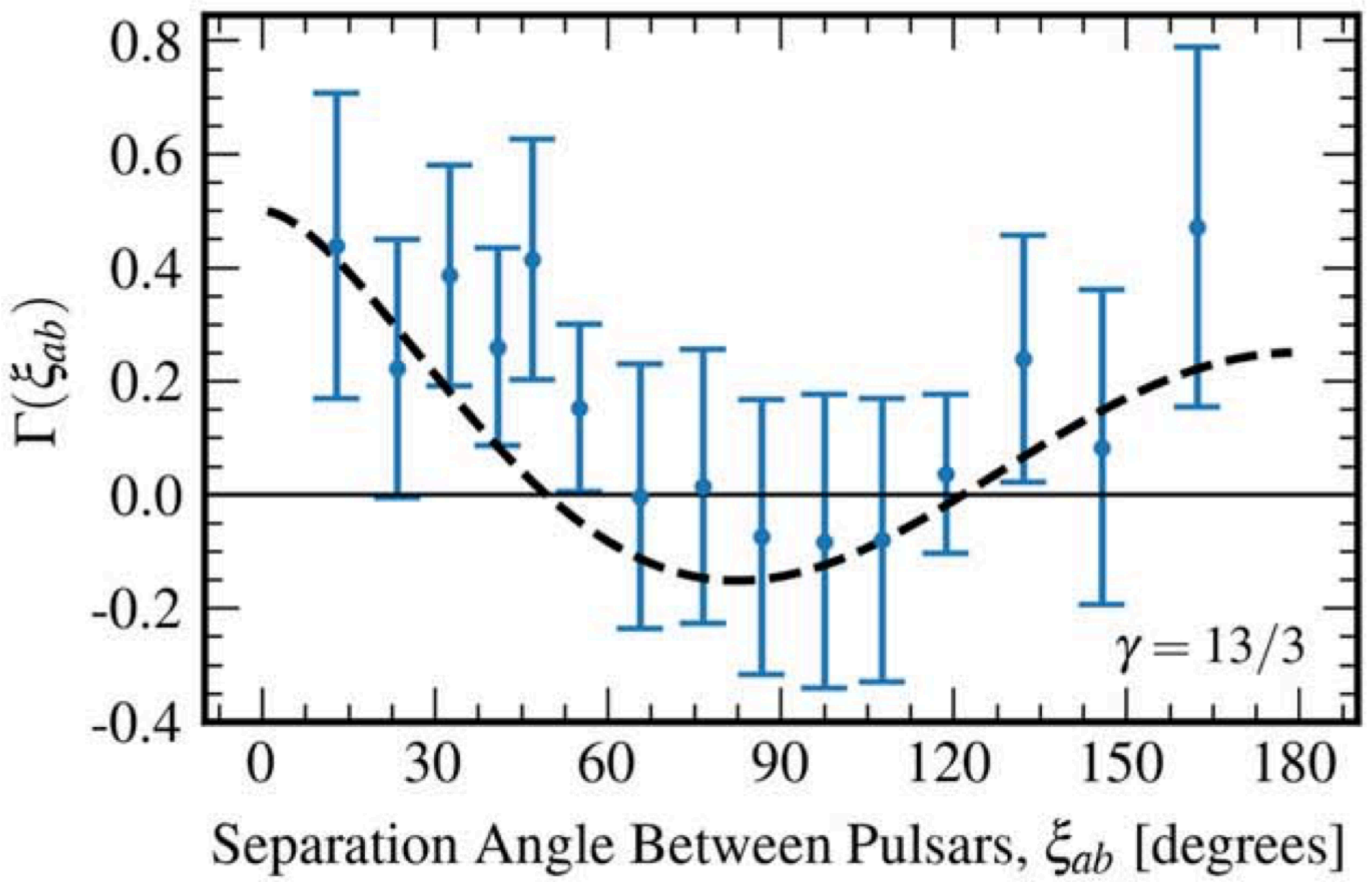
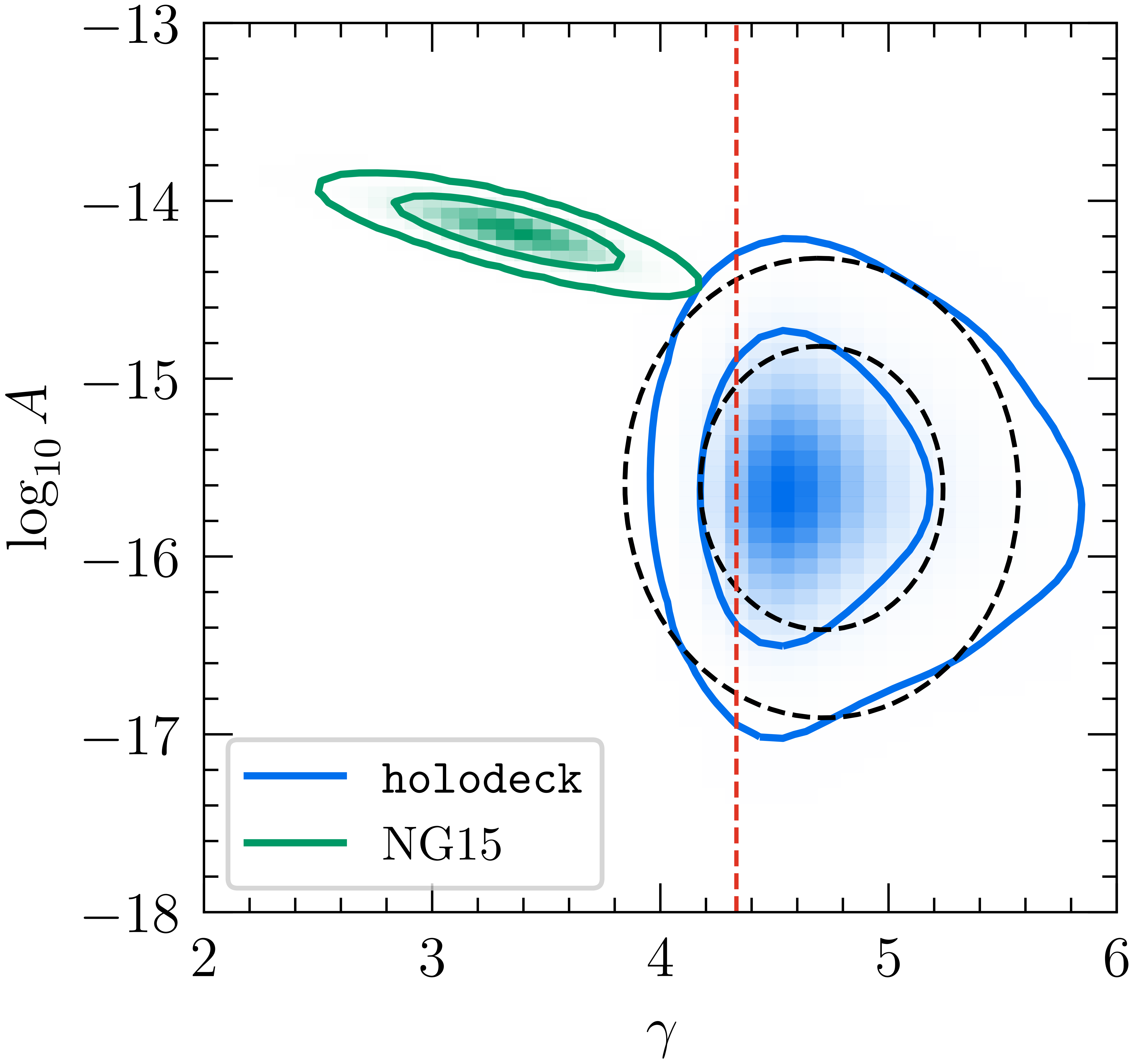
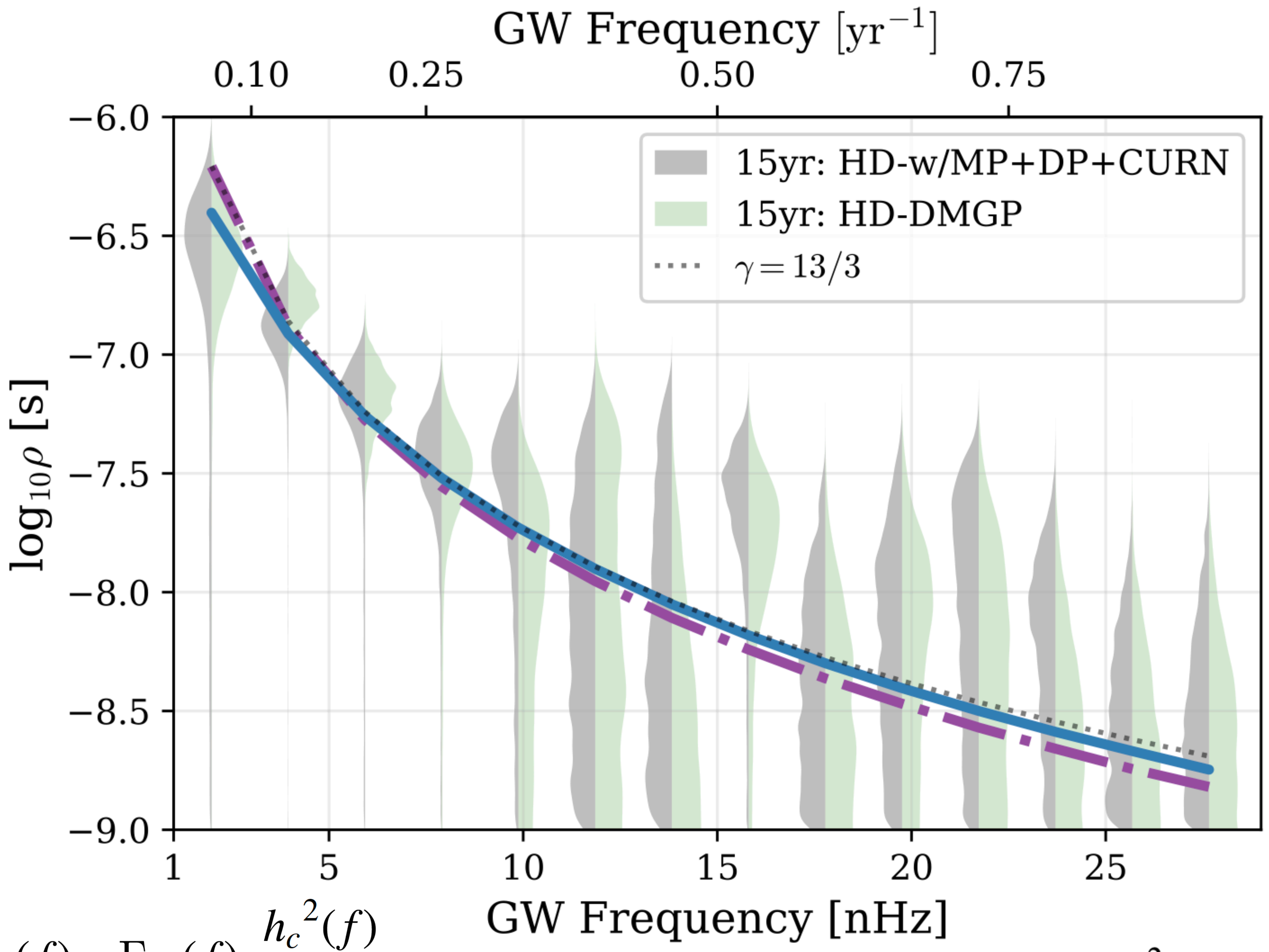


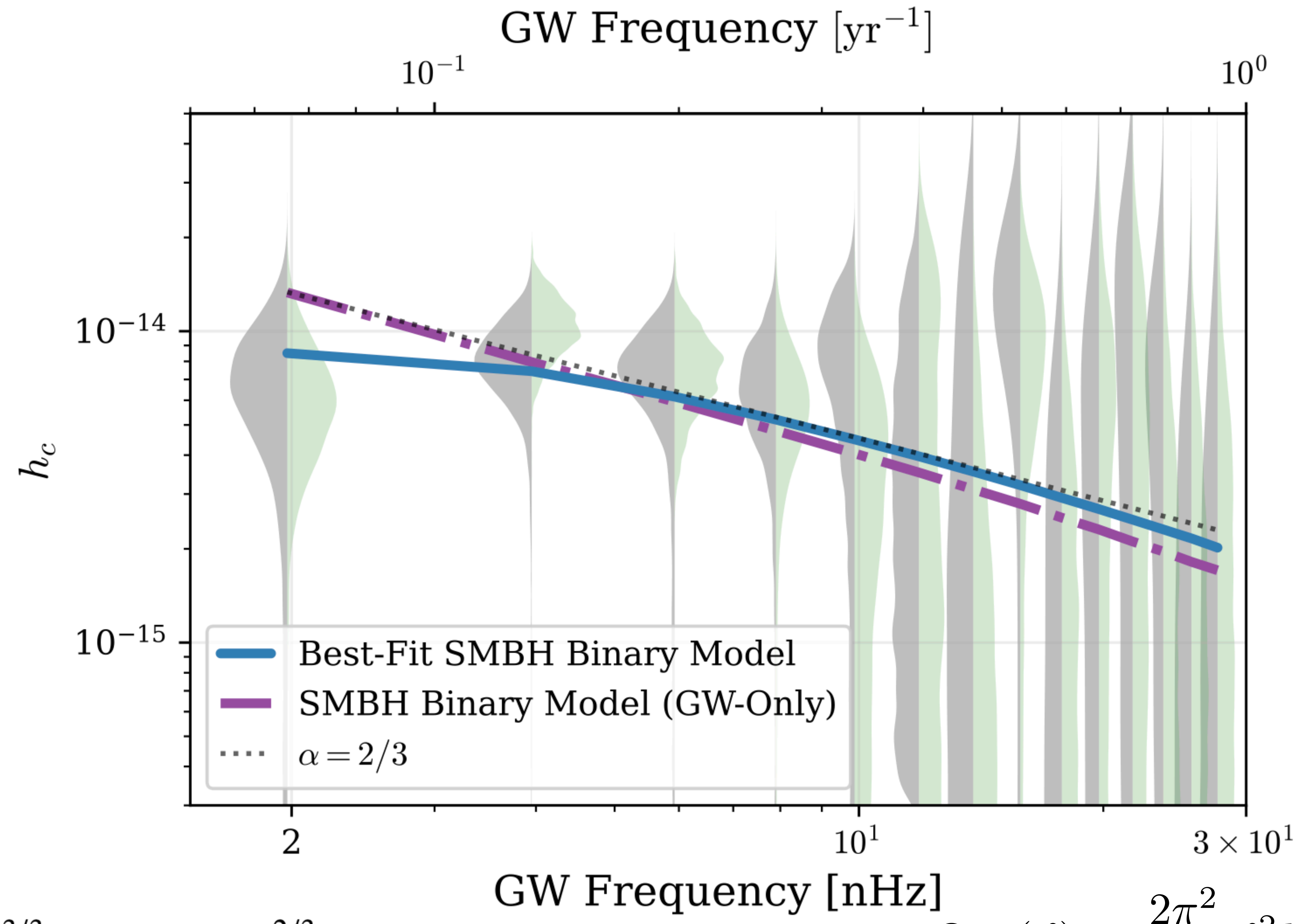
SMBHs and New Physics?

- Appears to be a tension with the spectral index, Gamma.
- For SMBHBs this is 4.33
- Still a lot of room for interpretation: caution needed
- Are we seeing more than one source of GWB?
- What else could be sourcing a nHz GWB?



What about the strain spectrum?



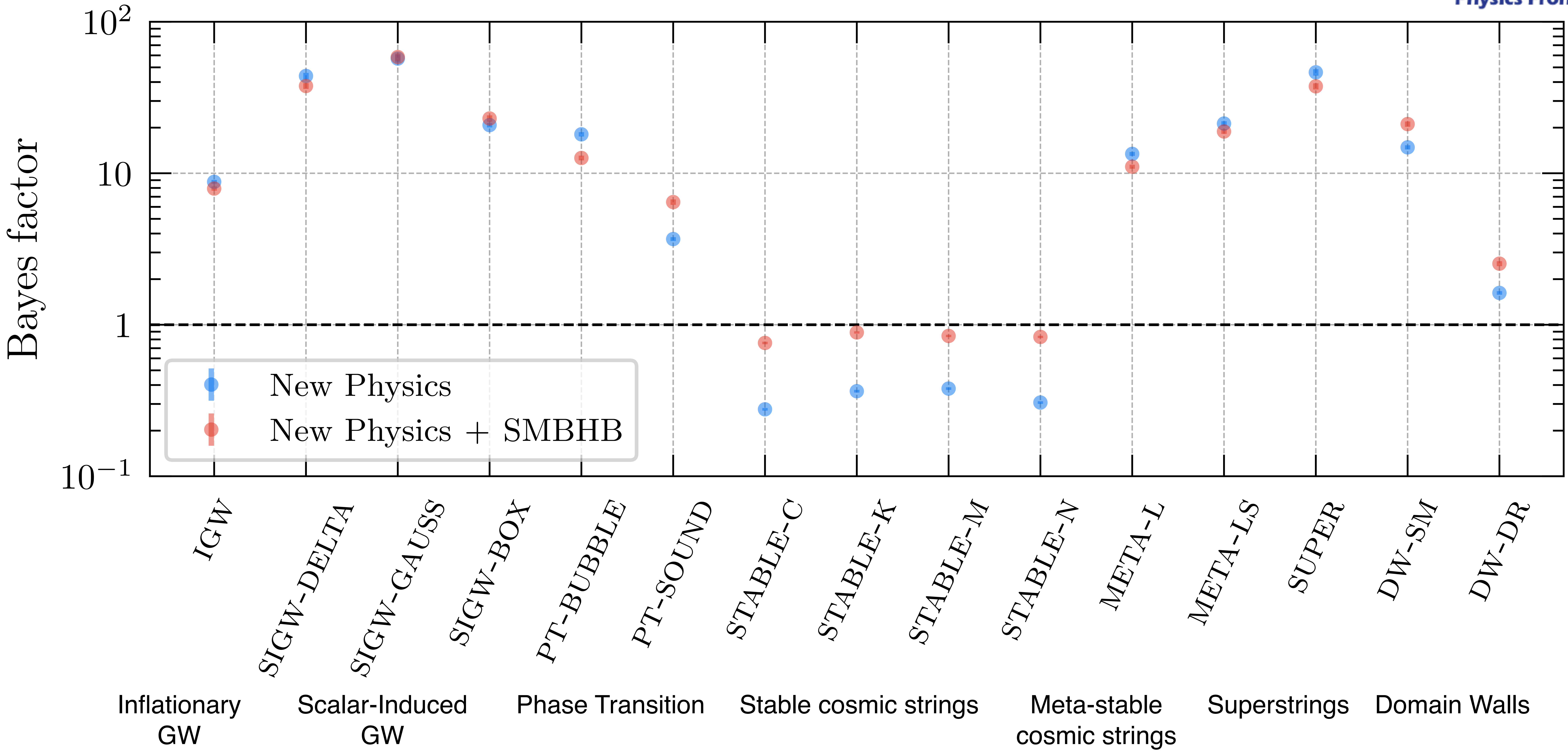


$$S_{ab}(f) = \Gamma_{ab}(f)\,\frac{{h_c}^2(f)}{12\pi^2 f^3}$$

$(\rho^2 \propto f^{-13/3}$ and $h_c \propto f^{-2/3})$

$$\Omega_{\rm gw}(f) = \frac{2\pi^2}{3H_0^2} f^2 h_c^2$$

SMBHs and New Physics?



Afzal et al (2023) corr. author Kai Schmitz 2306.16219

SMBHs and New Physics?

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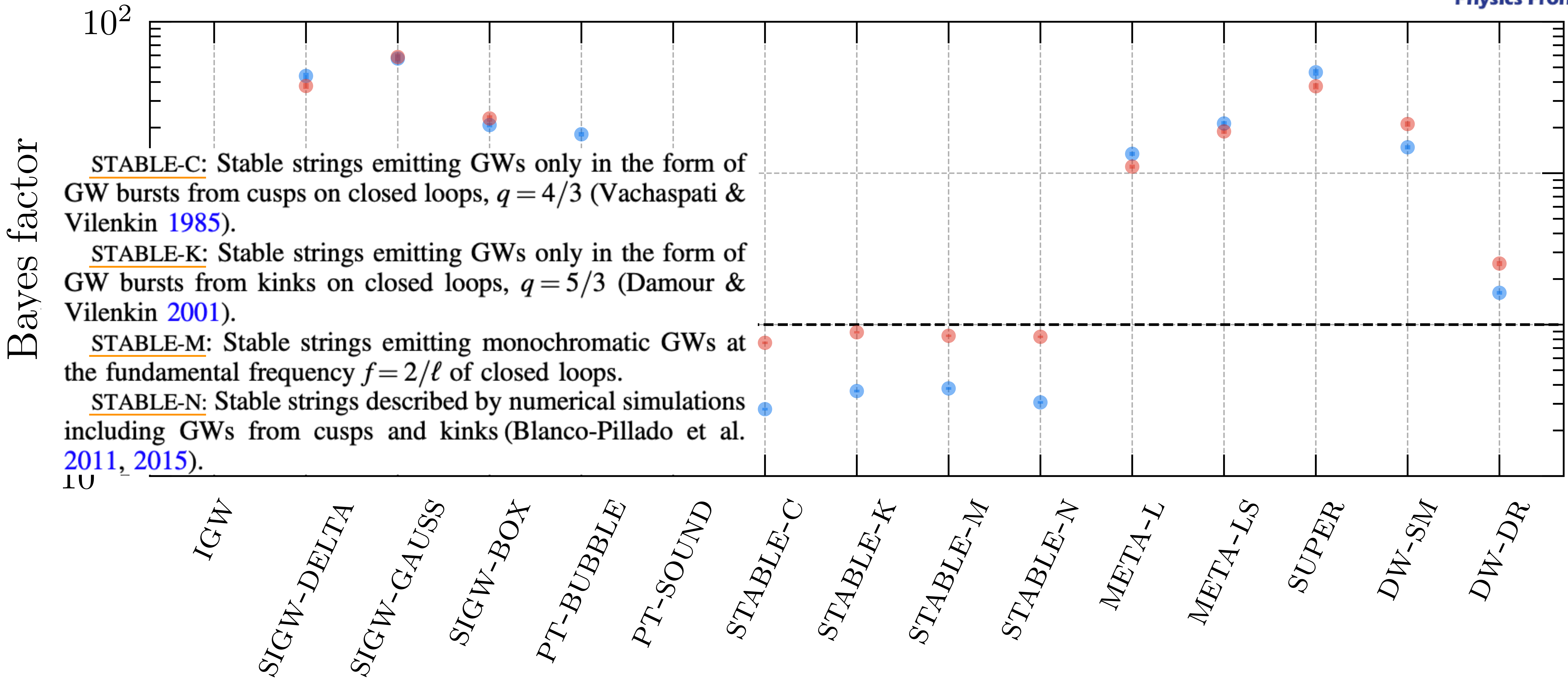


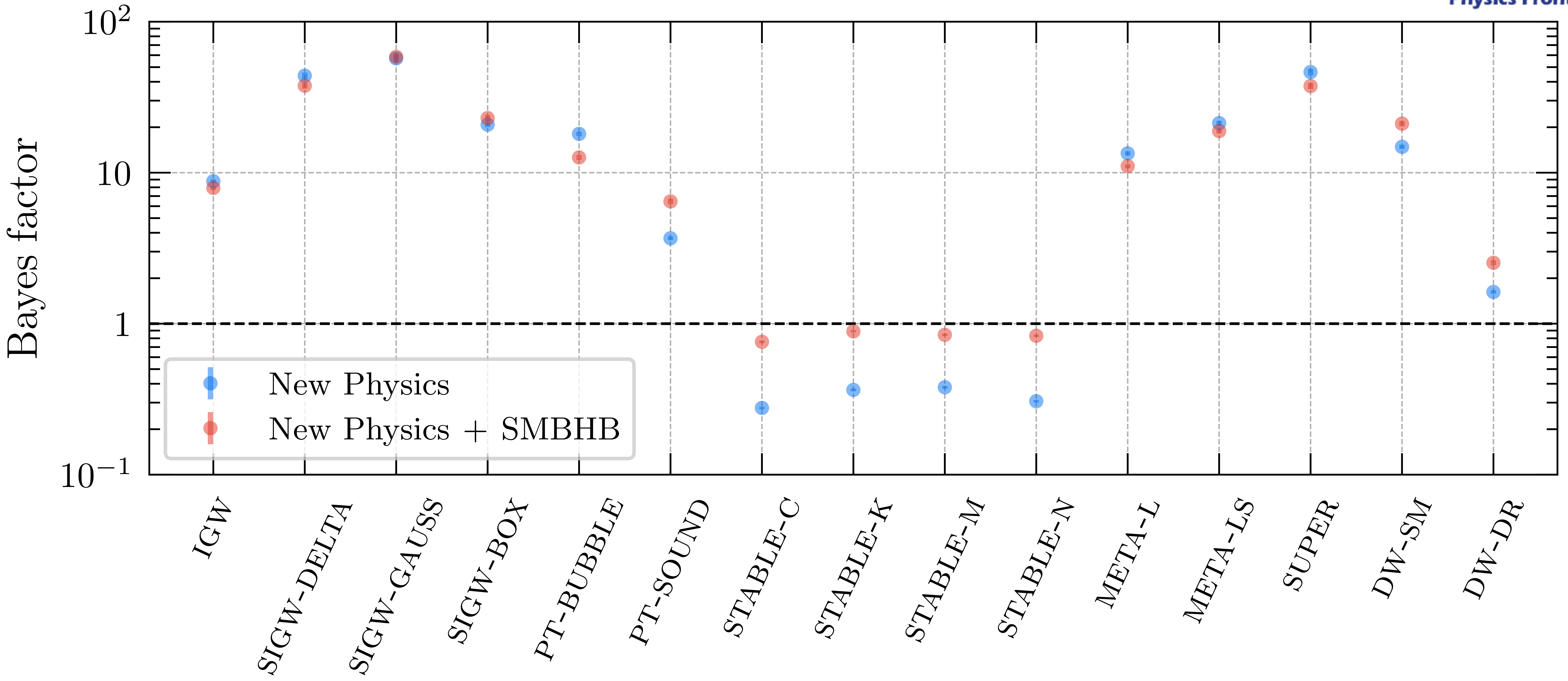
STABLE-C: Stable strings emitting GWs only in the form of GW bursts from cusps on closed loops, $q = 4/3$ (Vachaspati & Vilenkin 1985).

STABLE-K: Stable strings emitting GWs only in the form of GW bursts from kinks on closed loops, $q = 5/3$ (Damour & Vilenkin 2001).

STABLE-M: Stable strings emitting monochromatic GWs at the fundamental frequency $f = 2/\ell$ of closed loops.

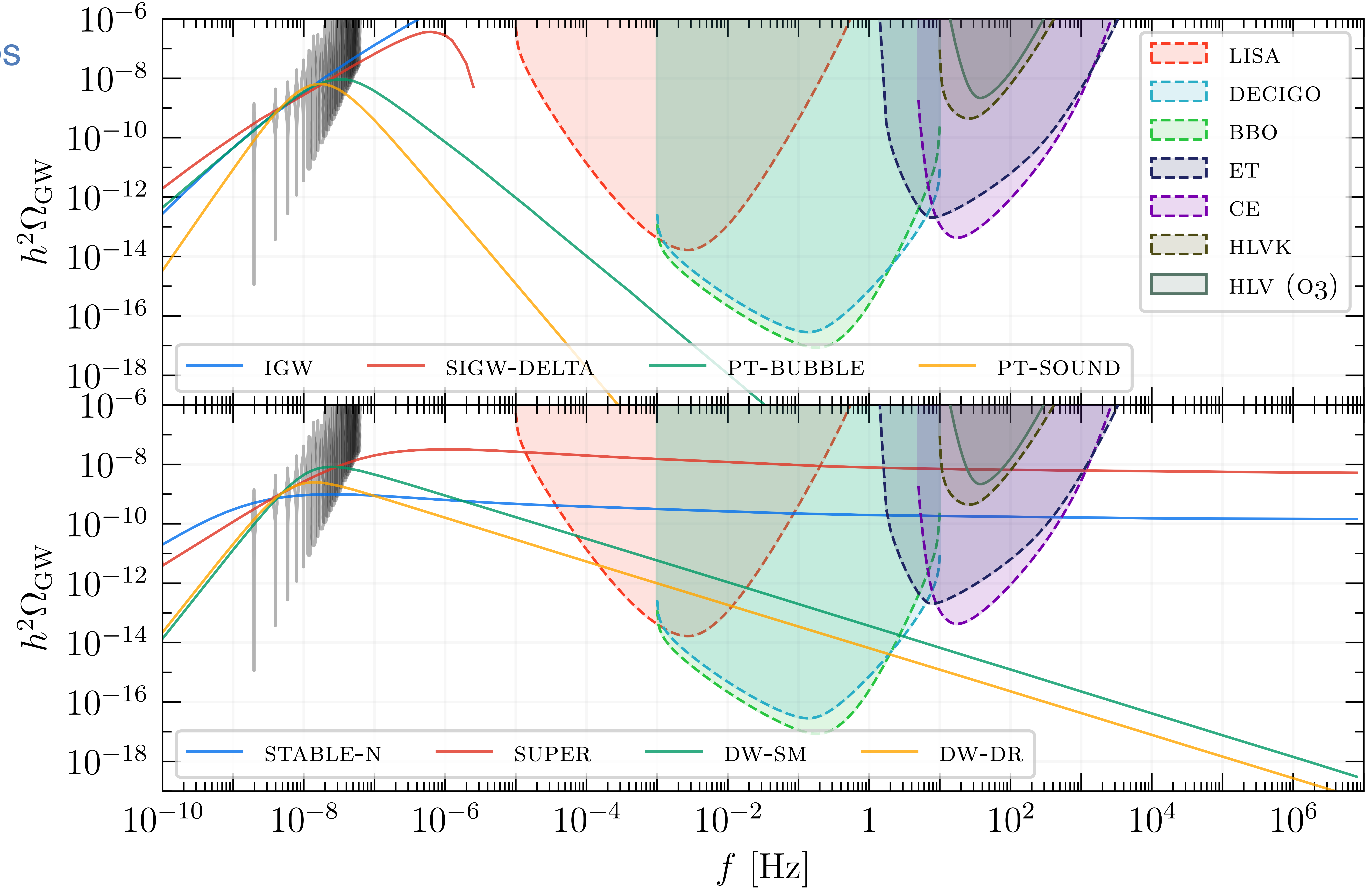
STABLE-N: Stable strings described by numerical simulations including GWs from cusps and kinks (Blanco-Pillado et al. 2011, 2015).

SMBHs and New Physics?



Inflationary GW | Scalar-Induced GW | Phase Transition | Stable cosmic strings | Meta-stable cosmic strings | Superstrings | Domain Walls

Assue 1 year Obs
Assume S/N=1



Useful Eqs

$$S_{ab}(f) = \Gamma_{ab}(f)\,\frac{h_c{}^2(f)}{12\pi^2 f^3}$$

$$\Omega_{gw}(f) = \frac{2\pi^2}{3H_0^2} f^2 h_c^2$$

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99 citations as of this morning

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1 2023arXiv230700746L 2023/07
Nano-Hertz stochastic gravitational wave background from domain wall annihilation
Lu, Bo-Qiang; Chiang, Cheng-Wei

2 2023ApJ...951L...8A 2023/07
The NANOGrav 15 yr Data Set: Evidence for a Gravitational-wave Background
Agazie, Gabriella; Anumarlapudi, Akash; Archibald, Anne M. *and 112 more*

3 2023arXiv230704691B 2023/07
Metastable cosmic strings
Buchmuller, Wilfried; Domcke, Valerie; Schmitz, Kai

4 2023arXiv230701072X 2023/07
Implications of Nano-Hertz Gravitational Waves on Electroweak Phase Transition in the Singlet Dark Matter Model
Xiao, Yang; Yang, Jin Min; Zhang, Yang

5 2023arXiv230702544A 2023/07
Falsifying Pati-Salam models with LIGO
Athron, Peter; Balázs, Csaba; Gonzalo, Tomás E. *and 1 more*

6 2023arXiv230700537B 2023/07
Inflationary origin of gravitational waves with \textit{Miracle-less WIMP} dark matter in the light of recent PTA results
Borah, Debasish; Jyoti Das, Suruj; Samanta, Rome

7 2023arXiv230701457G 2023/07
Scrutinizing the Primordial Black Holes Interpretation of PTA Gravitational Waves and JWST Early Galaxies
Gouttenoire, Yann; Trifinopoulos, Sokratis; Valogiannis, Georgios *and 1 more*

8 2023arXiv230704582B 2023/07
NANOGrav spectral index $\gamma = 3$ from melting domain walls
Babichev, E.; Gorbunov, D.; Ramazanov, S. *and 2 more*

9 2023arXiv230705455Y 2023/07
Can gravitational wave background feel wiggles in spacetime?
Ye, Gen; Silvestri, Alessandra

10 2023arXiv230702322U 2023/07
Axion-Gauge Dynamics During Inflation as the Origin of Pulsar Timing Array Signals and Primordial Black Holes
Unal, Caner; Papageorgiou, Alexandros; Obata, Ippei

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1 2023arXiv230700746L 2023/07
Nano-Her
Lu, Bo-Qia

2 2023ApJ...951
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Agazie, Ga

3 2023arXiv2307
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4 2023arXiv2307
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Xiao, Yang

5 2023arXiv2307
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Athron, Pe

6 2023arXiv2307
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Borah, Deb

7 2023arXiv2307
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8 2023arXiv2307
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Babichev, I

9 2023arXiv2307
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Ye, Gen; S

10 2023arXiv2307
Axion-Ga
Holes
Unal, Cane

11 2023arXiv230700722B 2023/07
Implications for the Supermassive Black Hole Binaries from the NANOGrav 15-year Data Set
Bi, Yan-Chen; Wu, Yu-Mei; Chen, Zu-Cheng *and 1 more*

12 2023arXiv230701086L 2023/07
A collider test of nano-Hertz gravitational waves from pulsar timing arrays
Li, Shao-Ping; Xie, Ke-Pan

13 2023arXiv230700656B 2023/07
Scale of Dirac leptogenesis and left-right symmetry in the light of recent PTA results
Barman, Basabendu; Borah, Debasish; Jyoti Das, Suruj *and 1 more*

14 2023arXiv230700572W 2023/07
Exploring the Implications of 2023 Pulsar Timing Array Datasets for Scalar-Induced Gravitational Waves and Primordial Black Holes
Wang, Sai; Zhao, Zhi-Chao; Li, Jun-Peng *and 1 more*

15 2023arXiv230701653A 2023/07
Translating nano-Hertz gravitational wave background into primordial perturbations taking account of the cosmological QCD phase transition
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- The Arecibo 305-m telescope tragically collapsed on Dec 1, 2020
- Restructured observing program: GBT (primarily 1.5 GHz), CHIME (400-800 MHz), VLA (1-4 GHz)
- GBT ultra-wideband receiver (0.7-4.2 GHz) is planned to come online in early 2022
- Future facilities
  - Next-Generation Very Large Array
  - 2000-antenna Deep Synoptic Array (DSA-2000)
  - Possible future Arecibo facility

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What is next?

Figure: NRAO/NRCC

Figure courtesy G. Hallinan

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Figure: NRAO/NRCC

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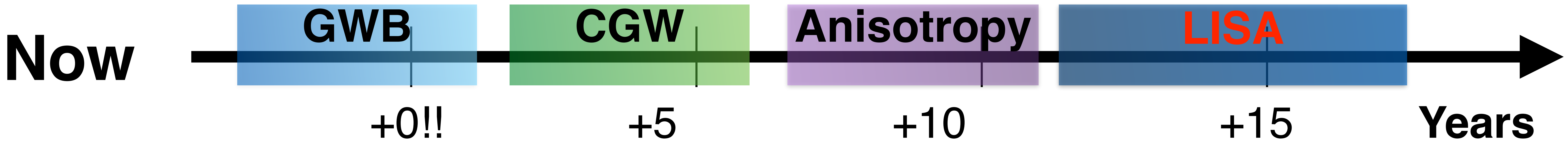
Summary

- PTA interdisciplinary and multimessenger science experiment: global radio campaigns, Gaia, fundamental physics, galaxy evolution, SMBH environments and more!

- **There is something in all the data:** common amplitude and evidence for HD correlations! Also in new EPTA and PPTA analyses (BF 60 Antoniadis et al. 2023; BF few Reardon et al. 2023; CPTA Xu et al. 2023, 4.6-sigma HD)

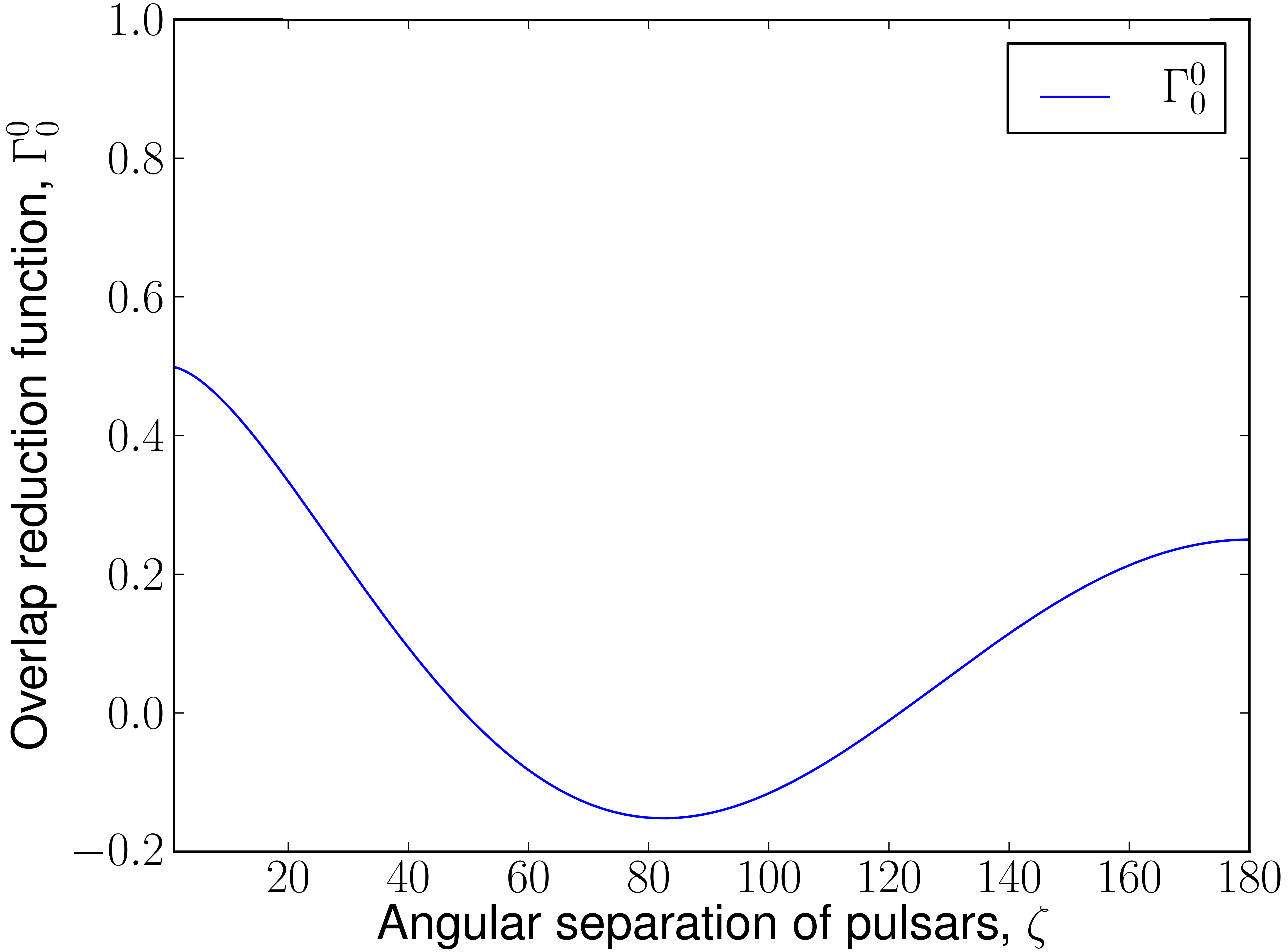
- Evidence for GWB? If so, **detection soon,** local nHz sources ~ **10 years, anisotropy to follow, and LISA!**

- **What's next? Everything!**



What is next?

Modify the correlations functions: beyond Hellings and Downs



- Decompose on a basis of spherical harmonics, new correlation functions!
- Only valid if the sky is full of pulsars (Ali-Haïmoud et al. (2020; 2021)
- More tests of GR: Lee et al. (2010); Chamberlin & Siemens (2012), O'Beirne et al. (2019)

$$S_{ab}(f) = \Gamma_{ab}(f)\,\frac{h_c{}^2(f)}{12\pi^2 f^3}$$

Arzoumanian et al. (2021), Constraints on ST & TT modes

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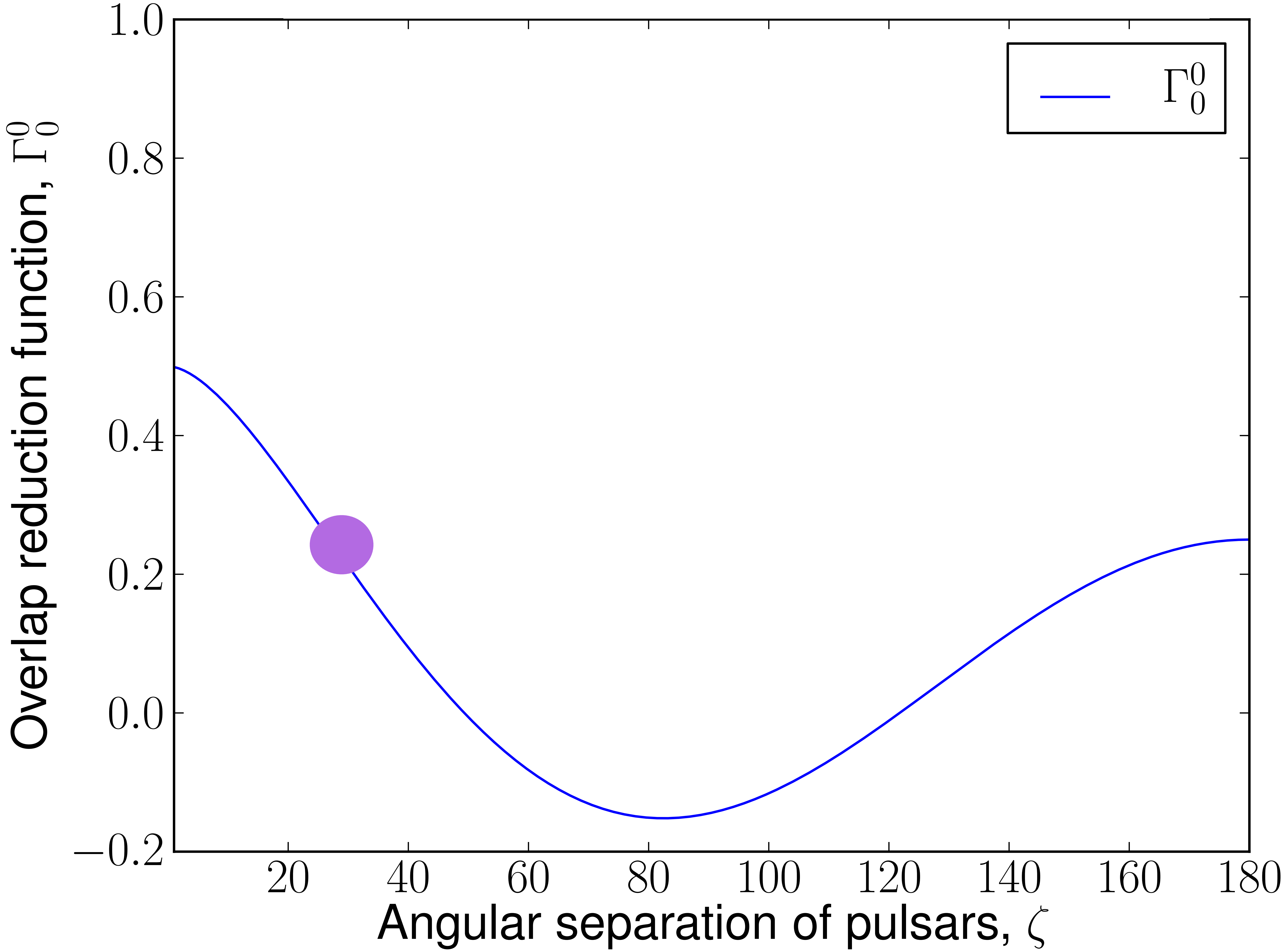

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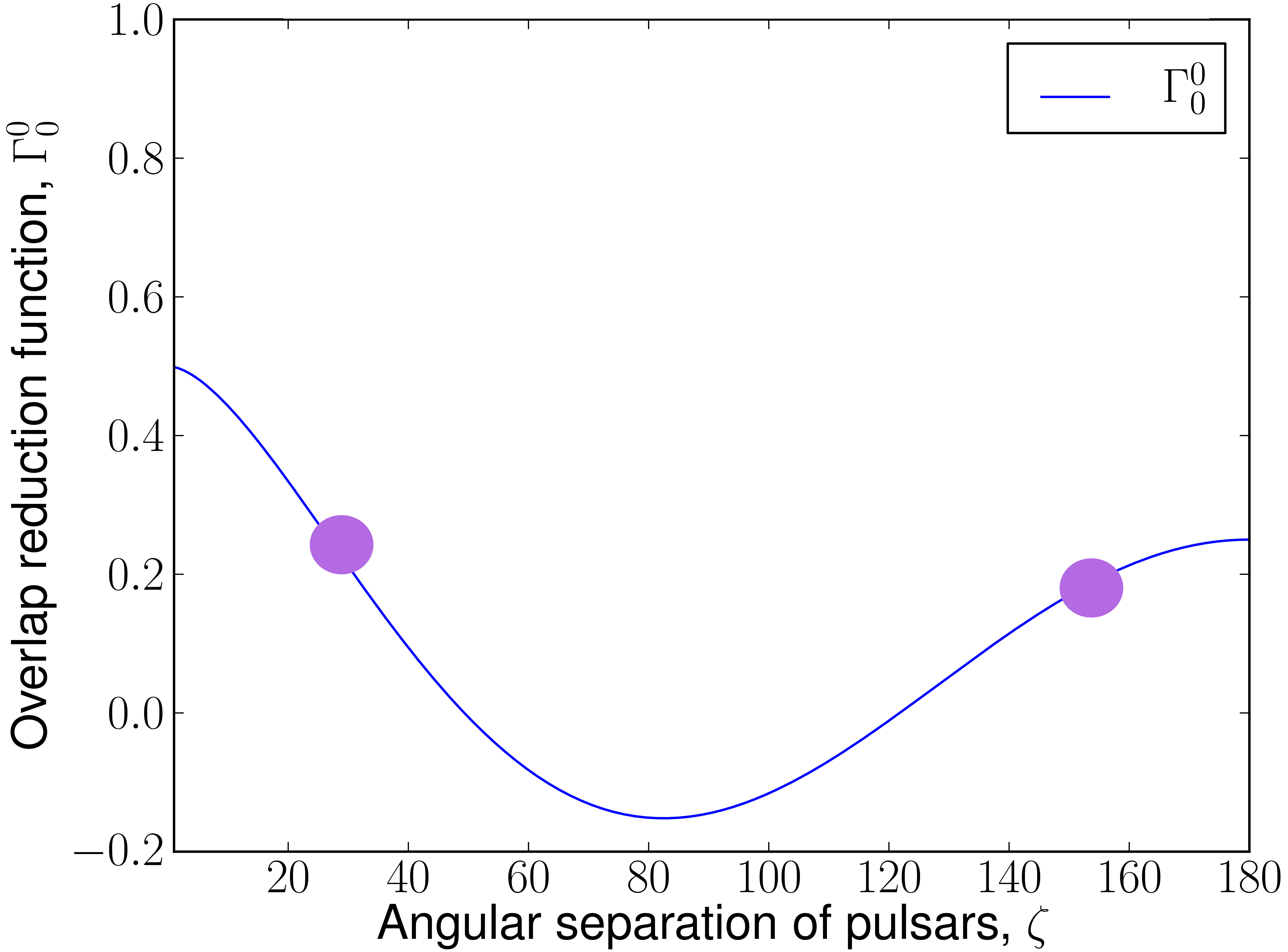

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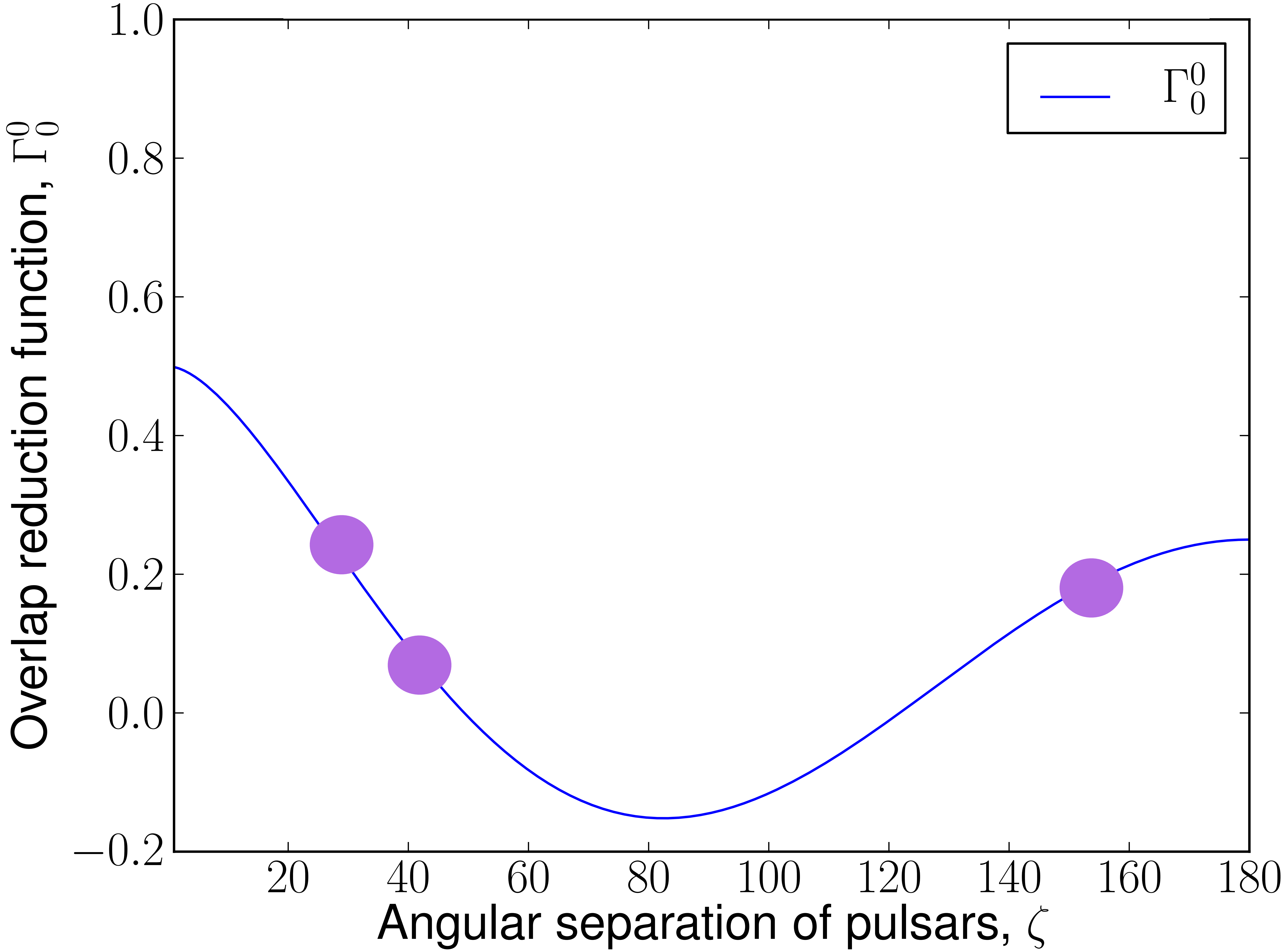
NANOGrav Physics Frontiers Center



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Arzoumanian et al. (2021), Constraints on ST & TT modes

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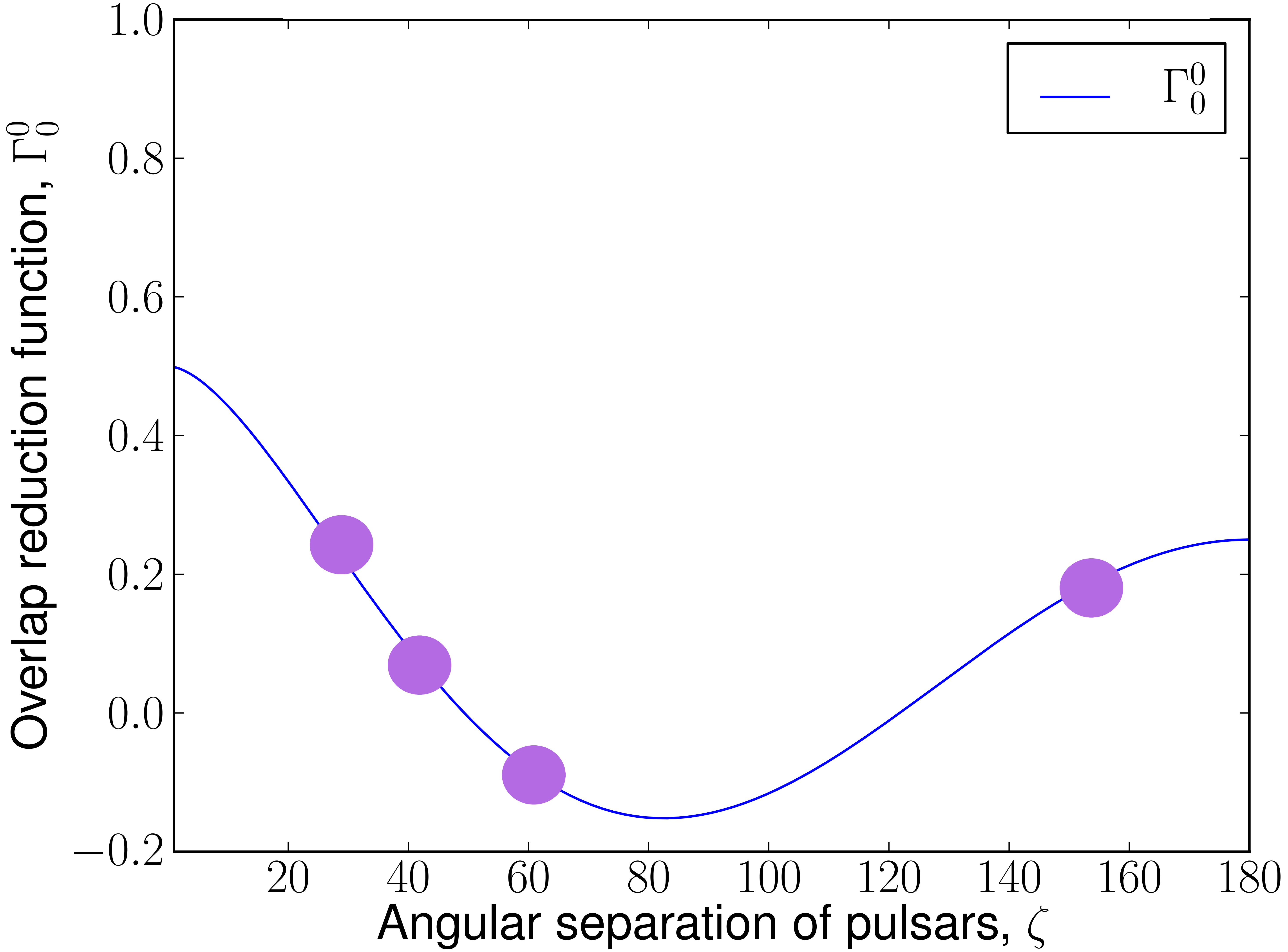

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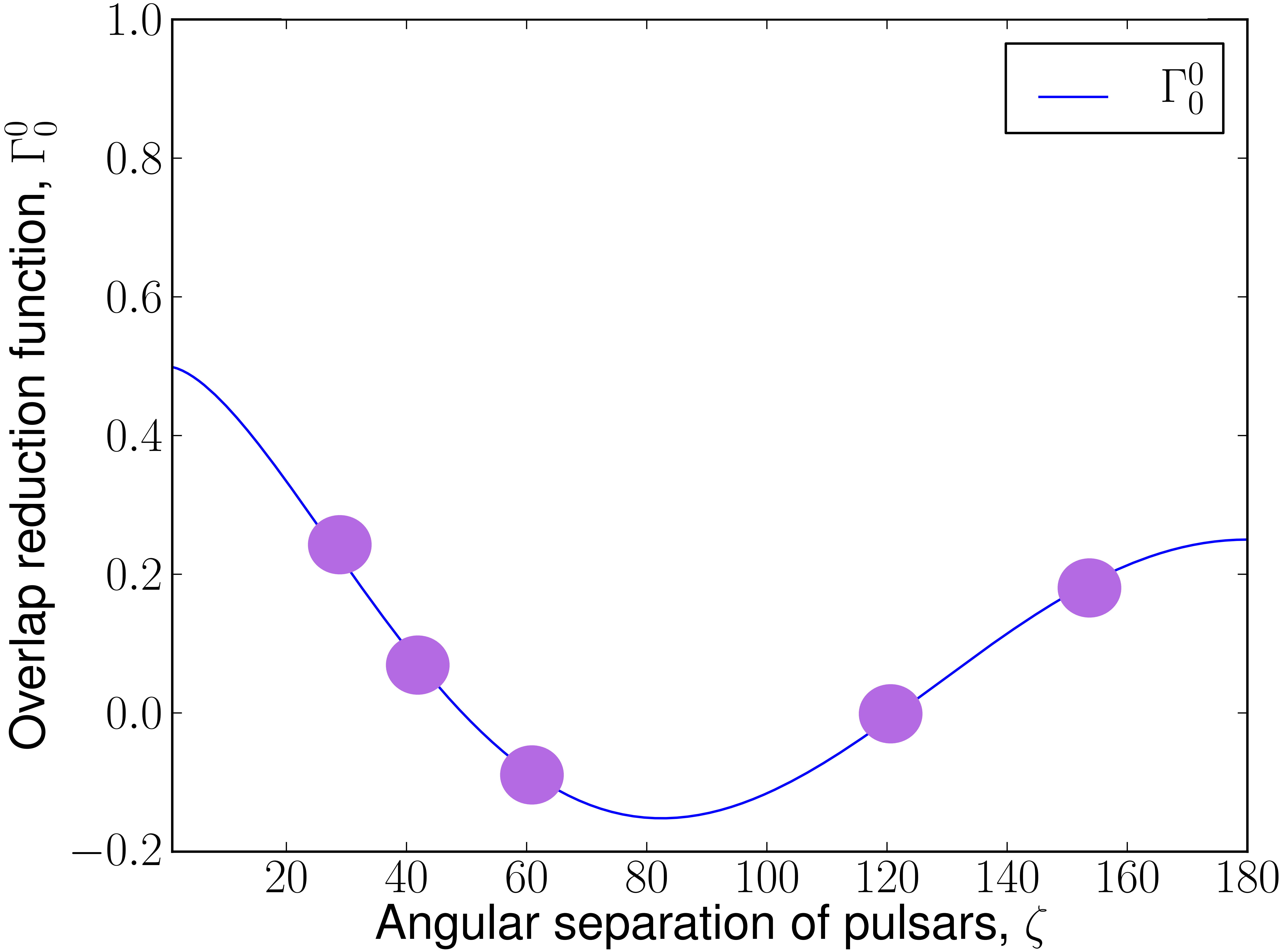

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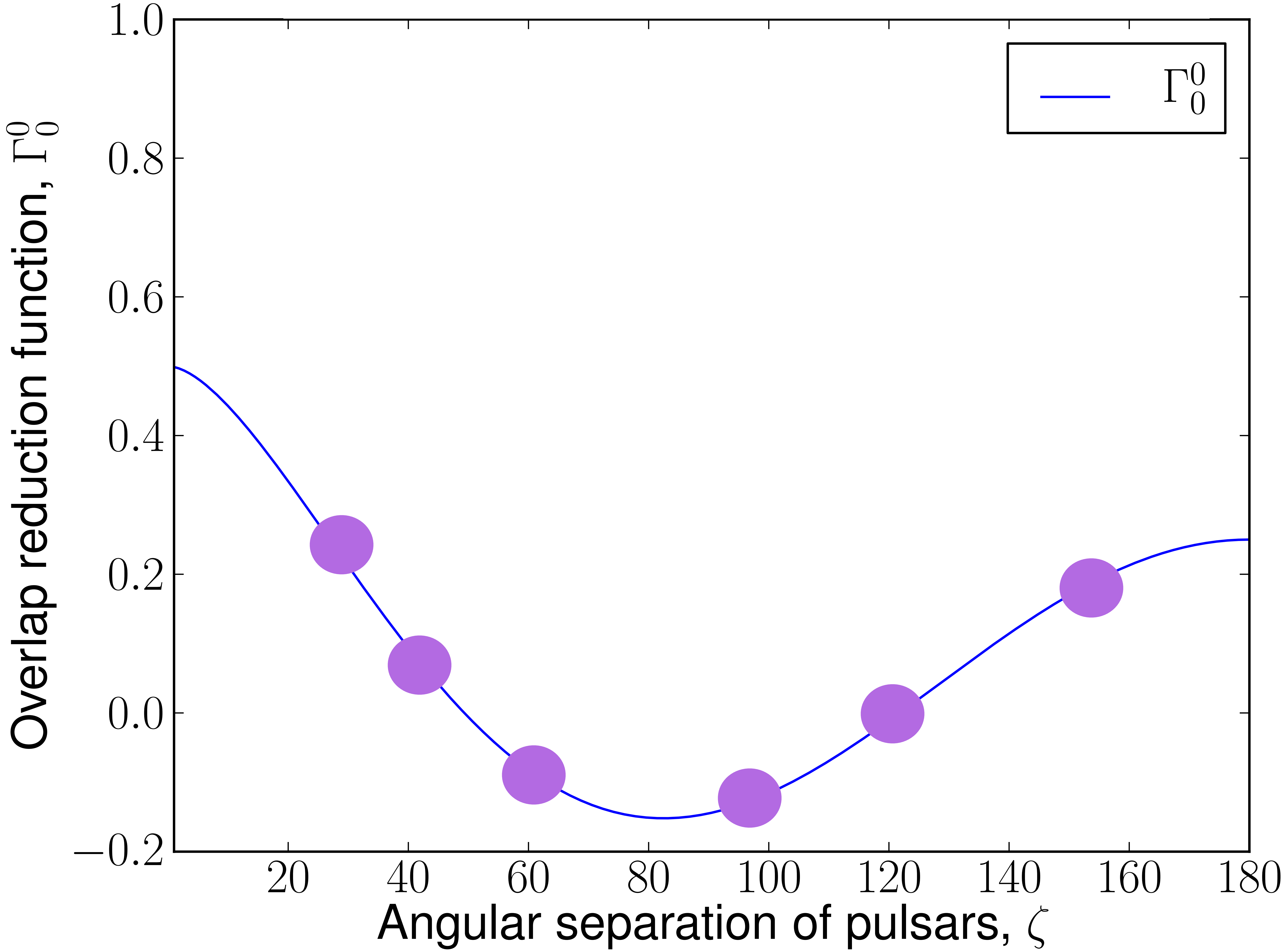

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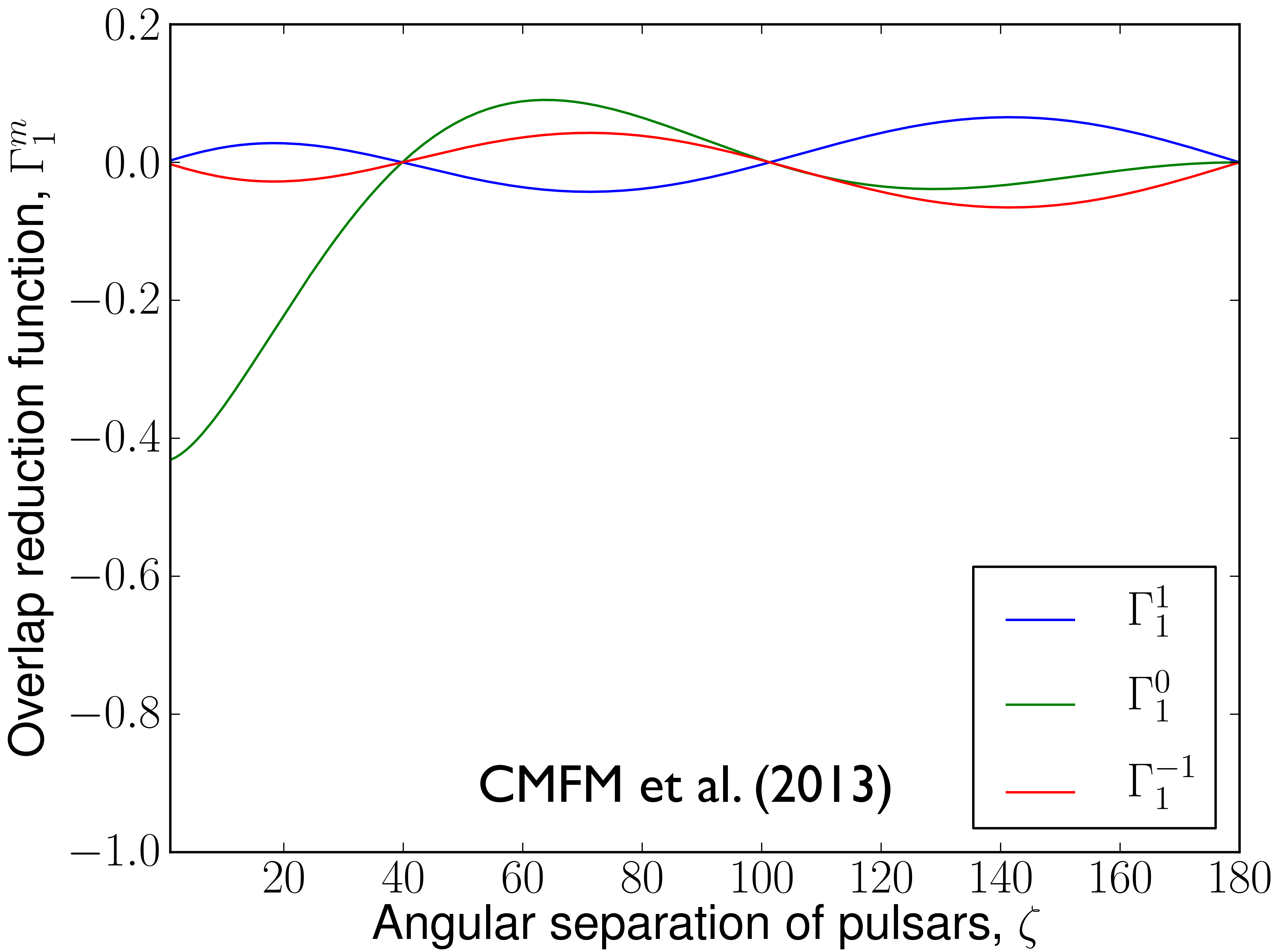

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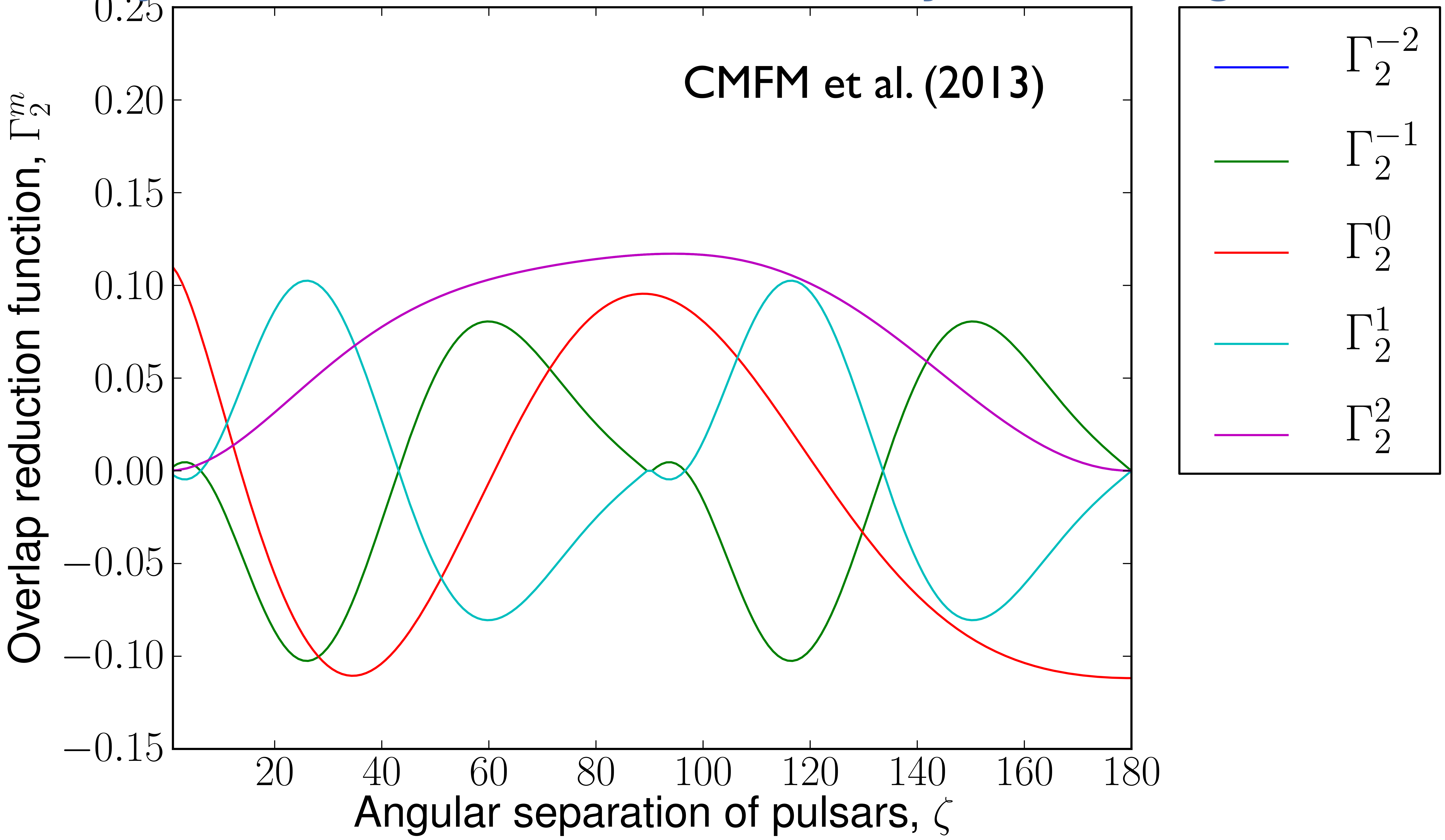

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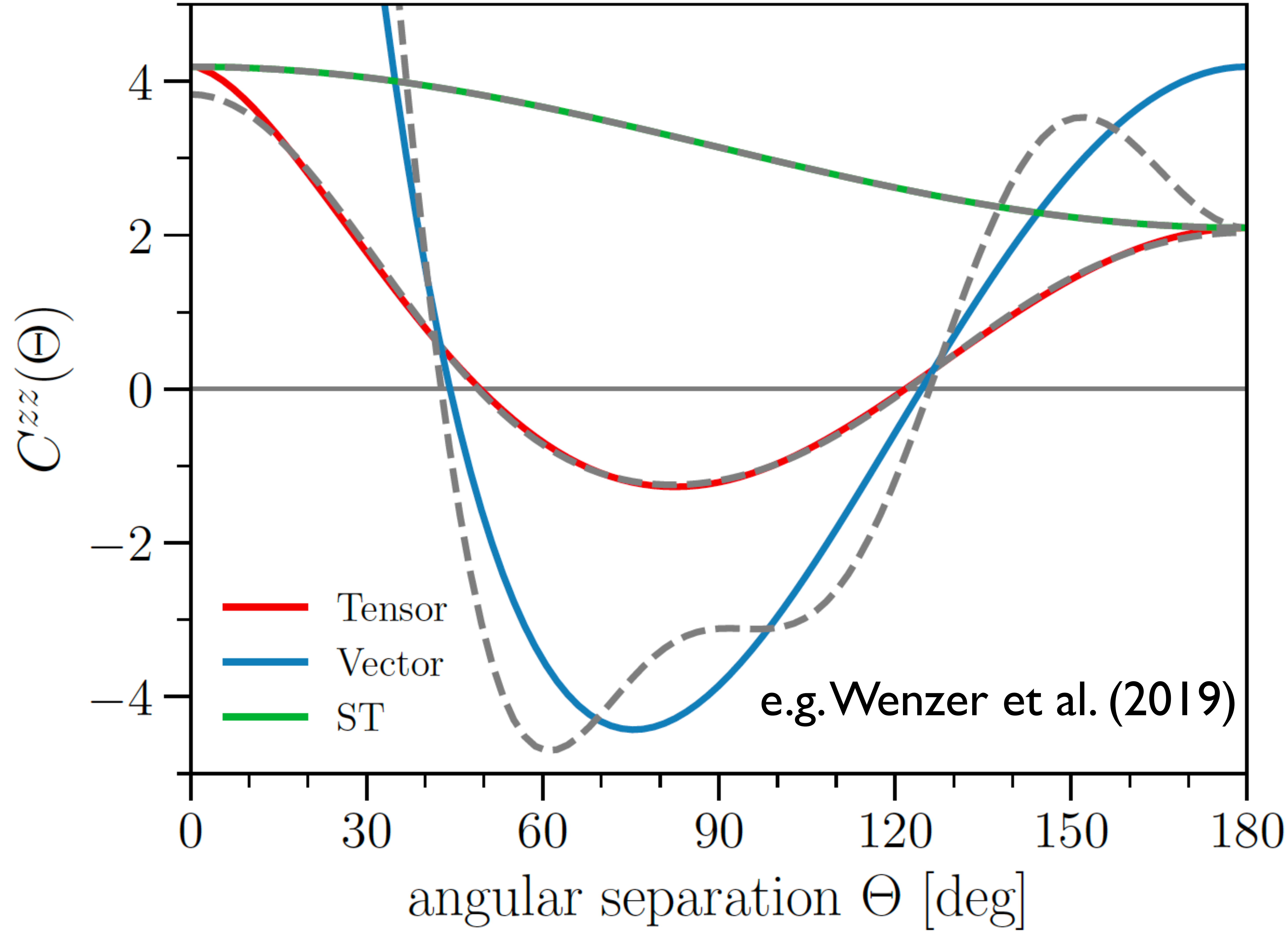

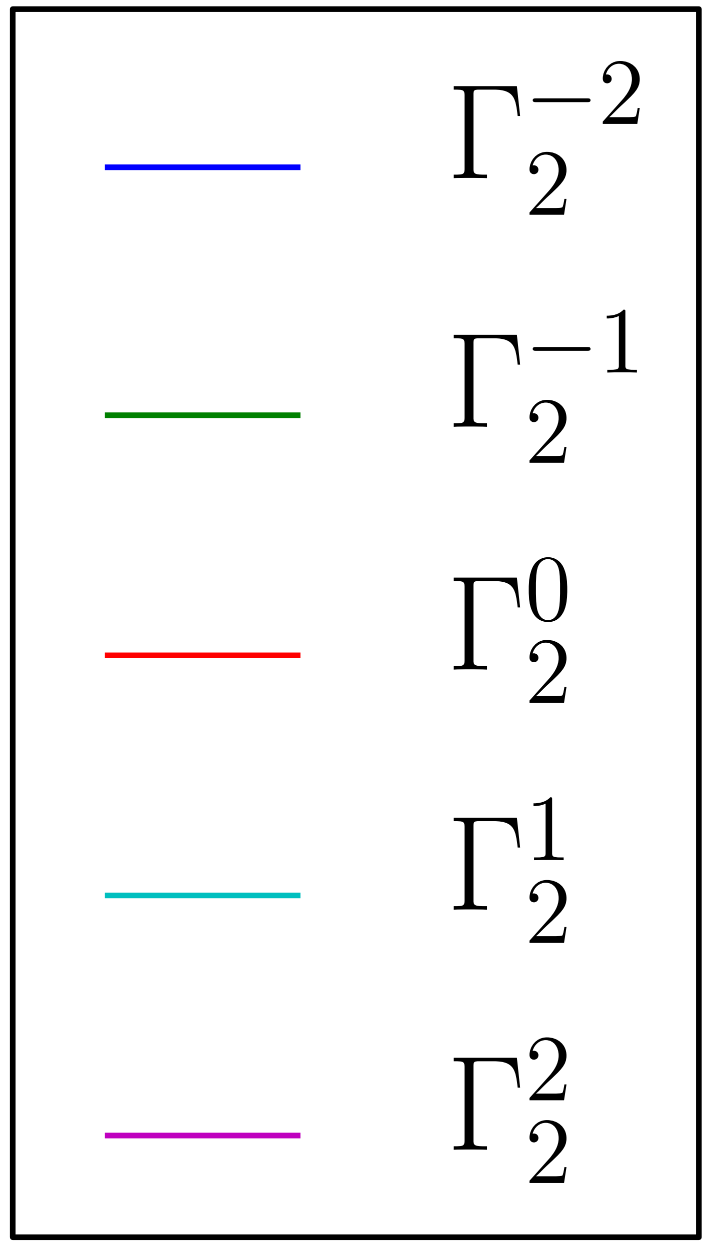

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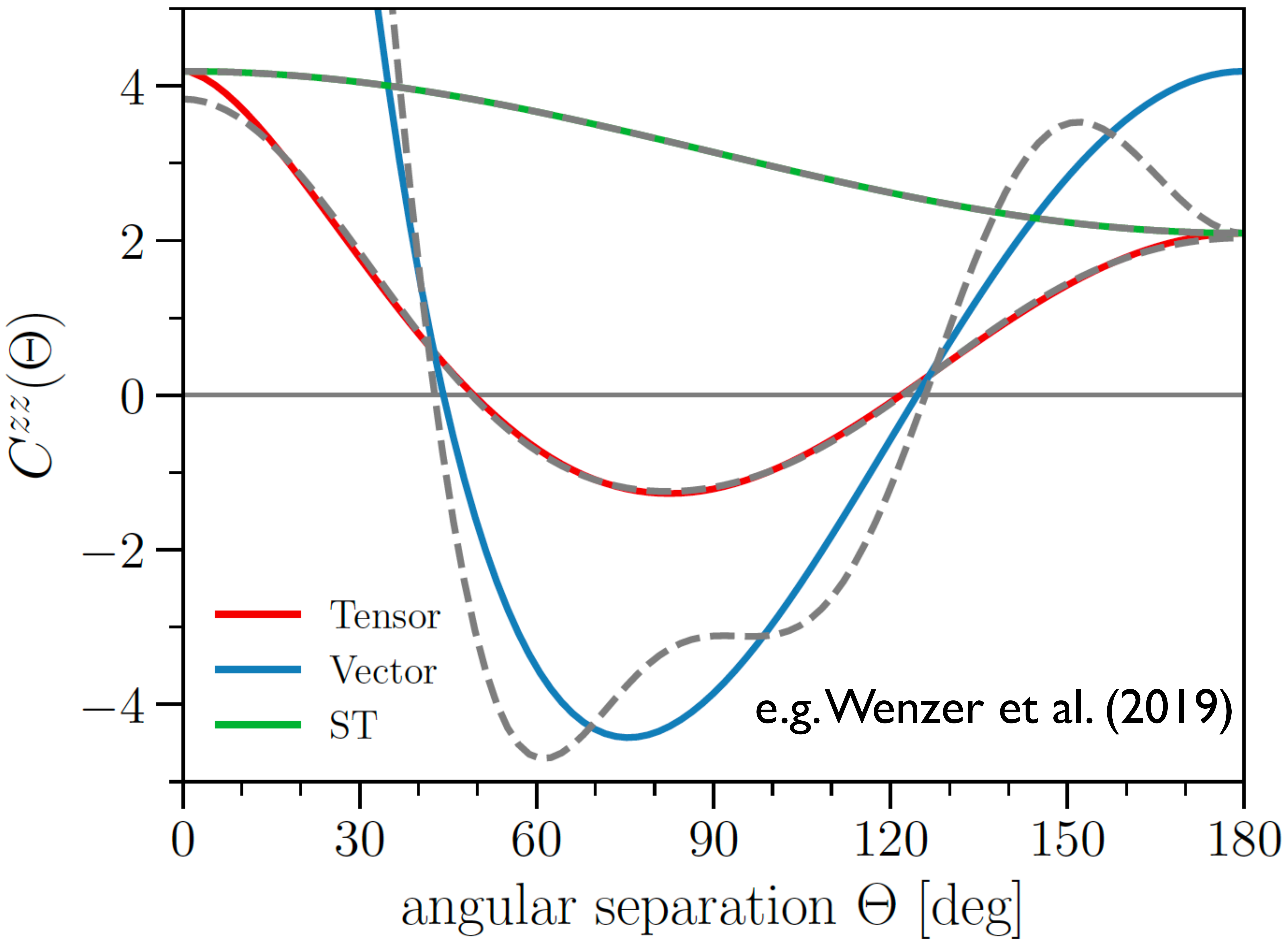

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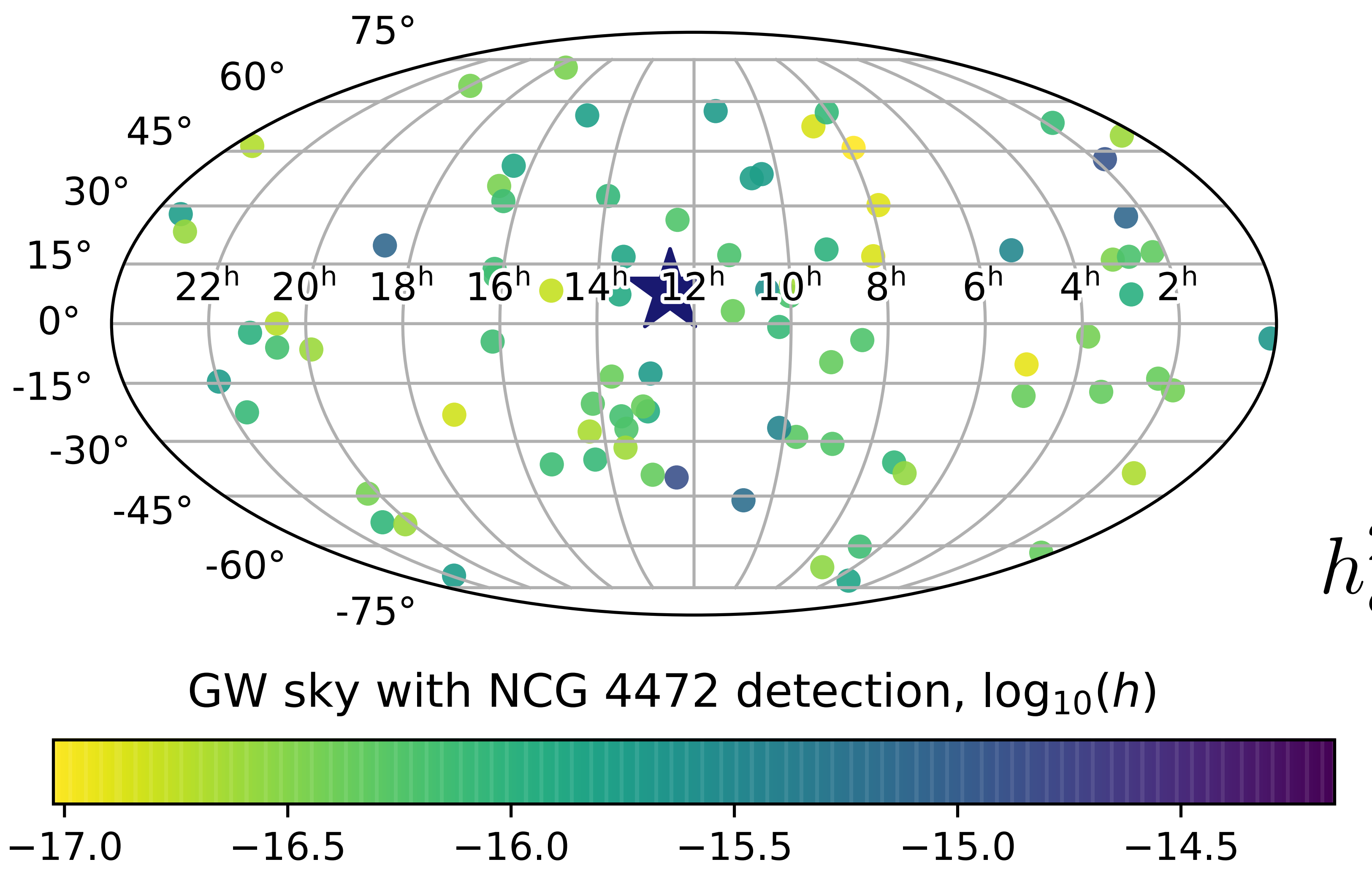
Building up the GWB and Anisotropy



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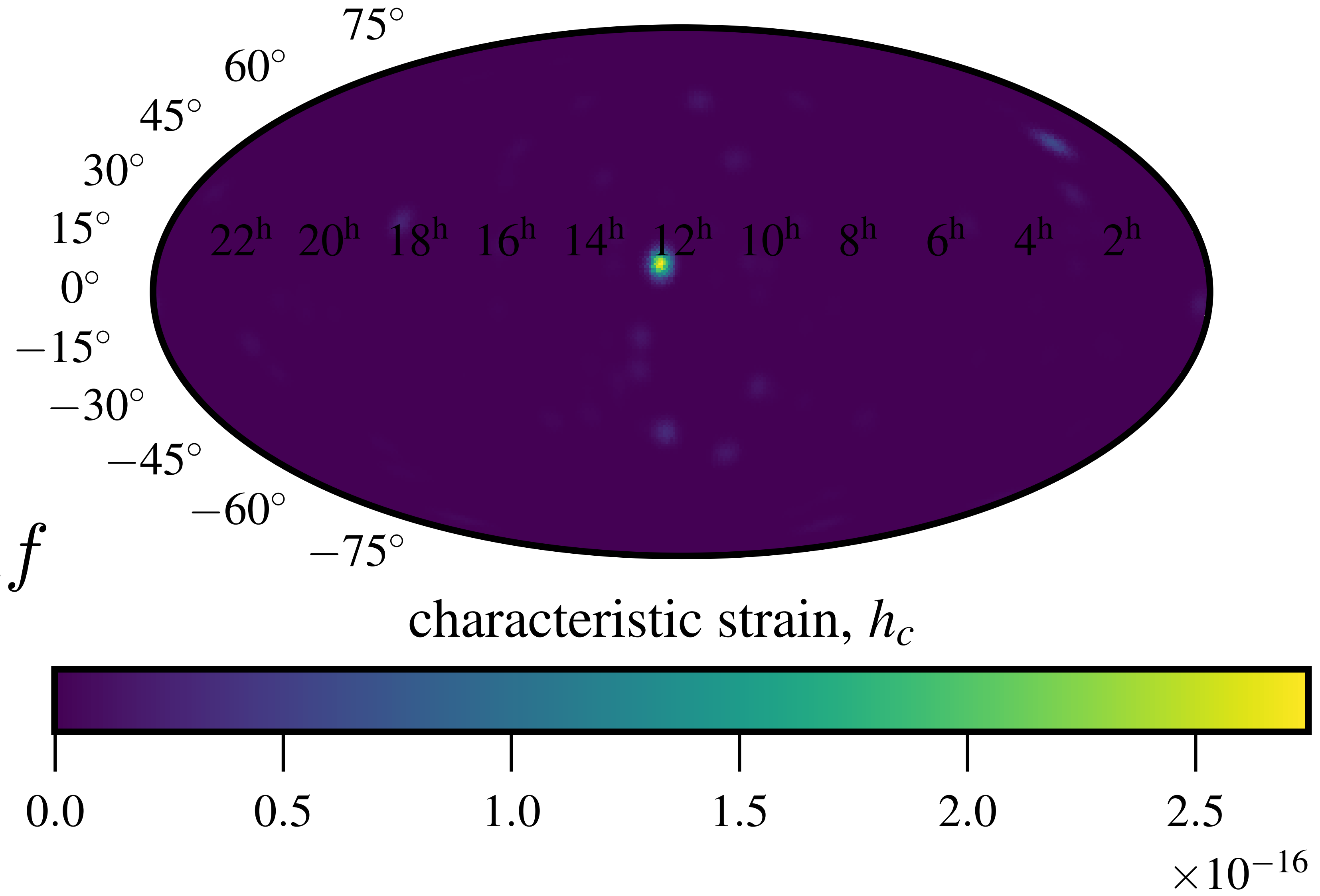
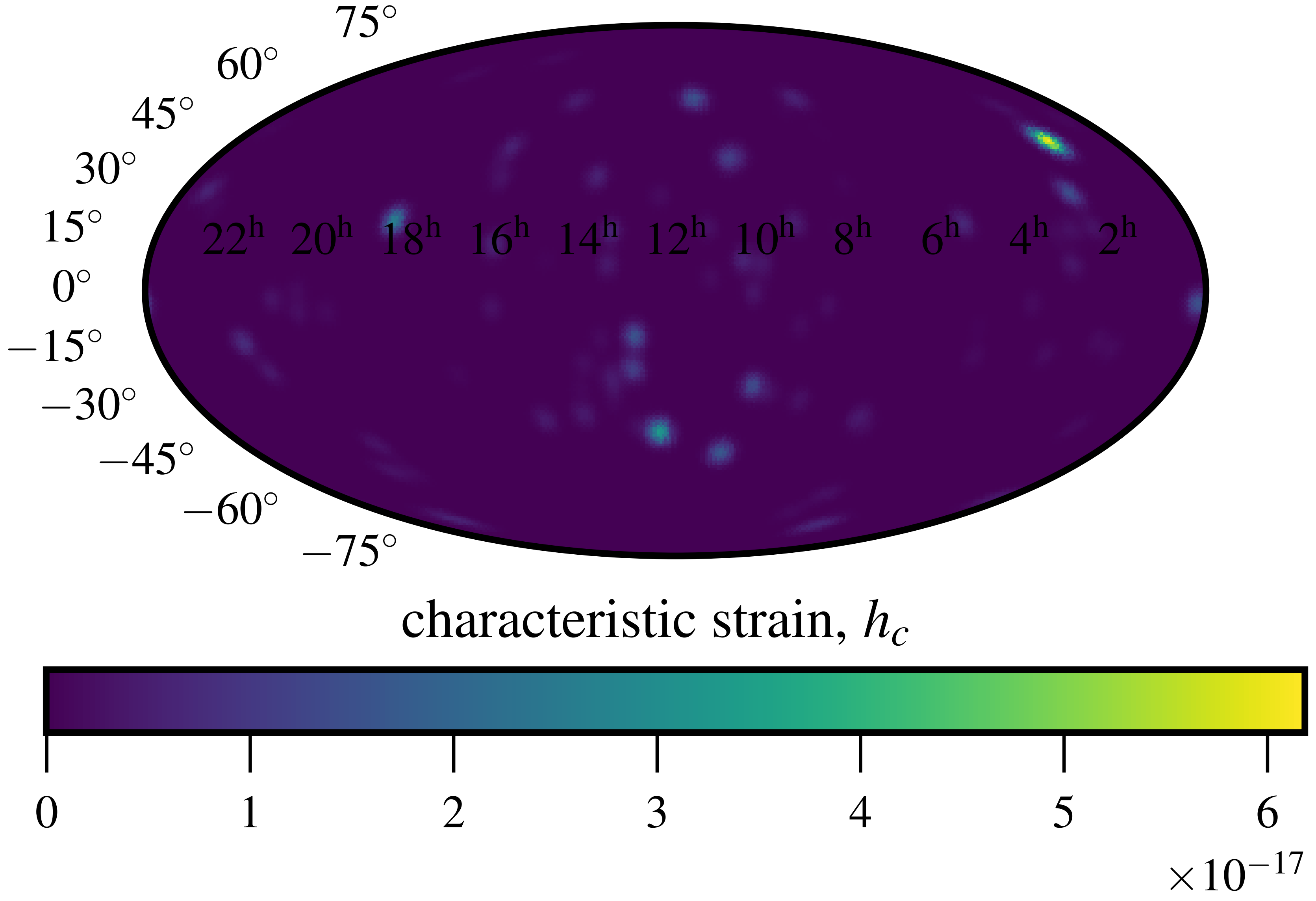
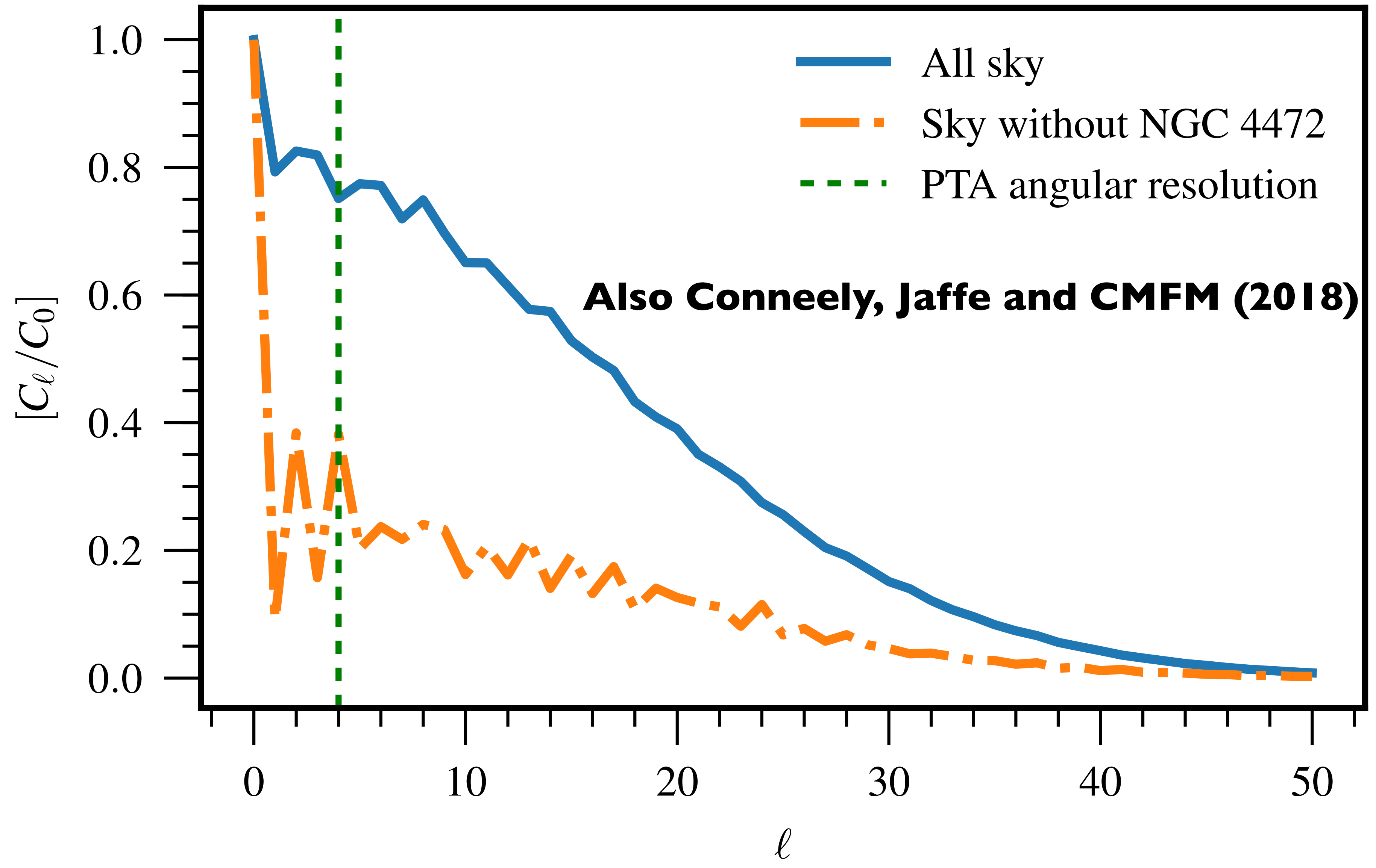


Techniques from Babak + 2016; Ali-Haïmoud, Smith, Mingarelli (2020, 2021)





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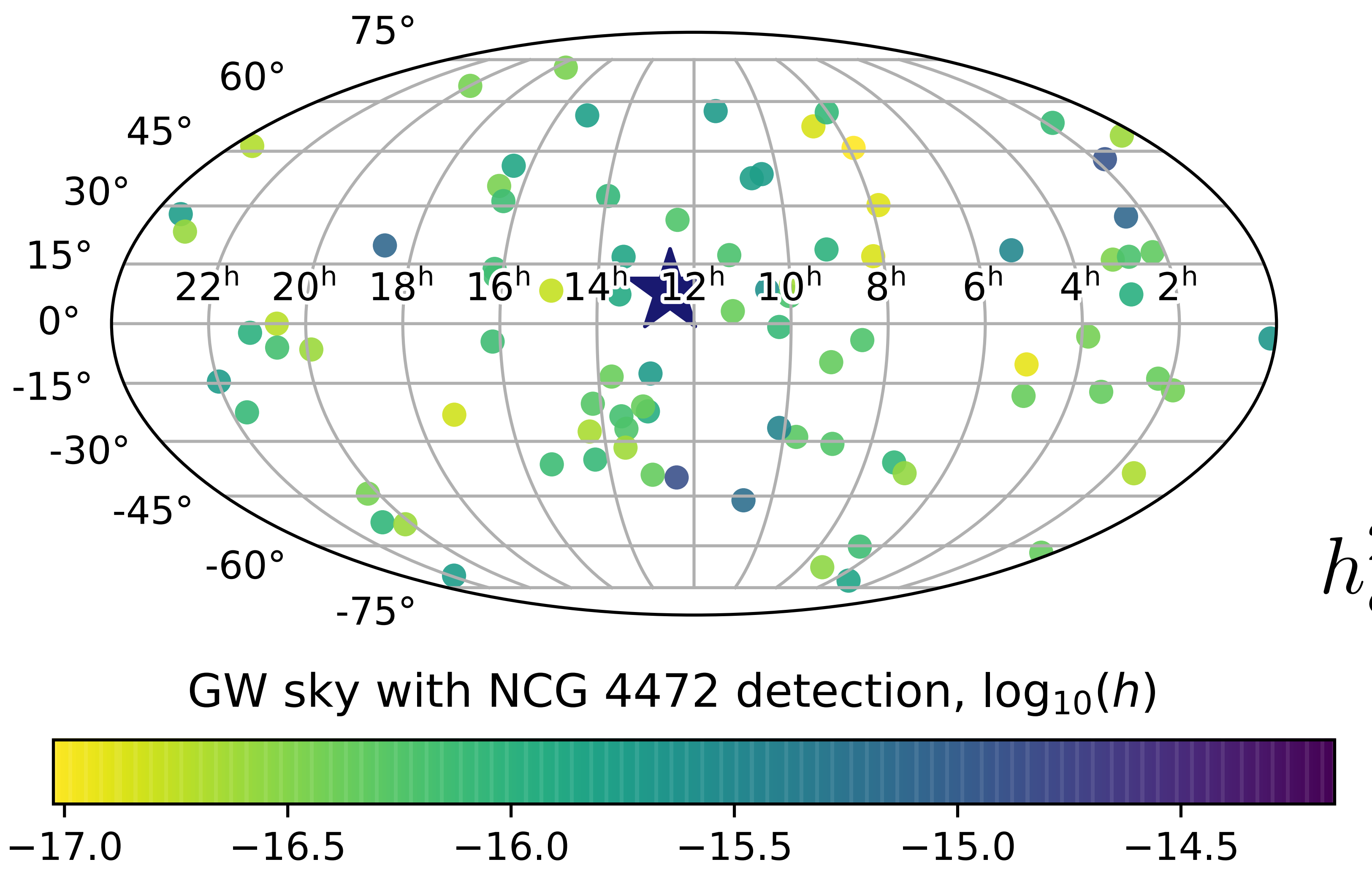

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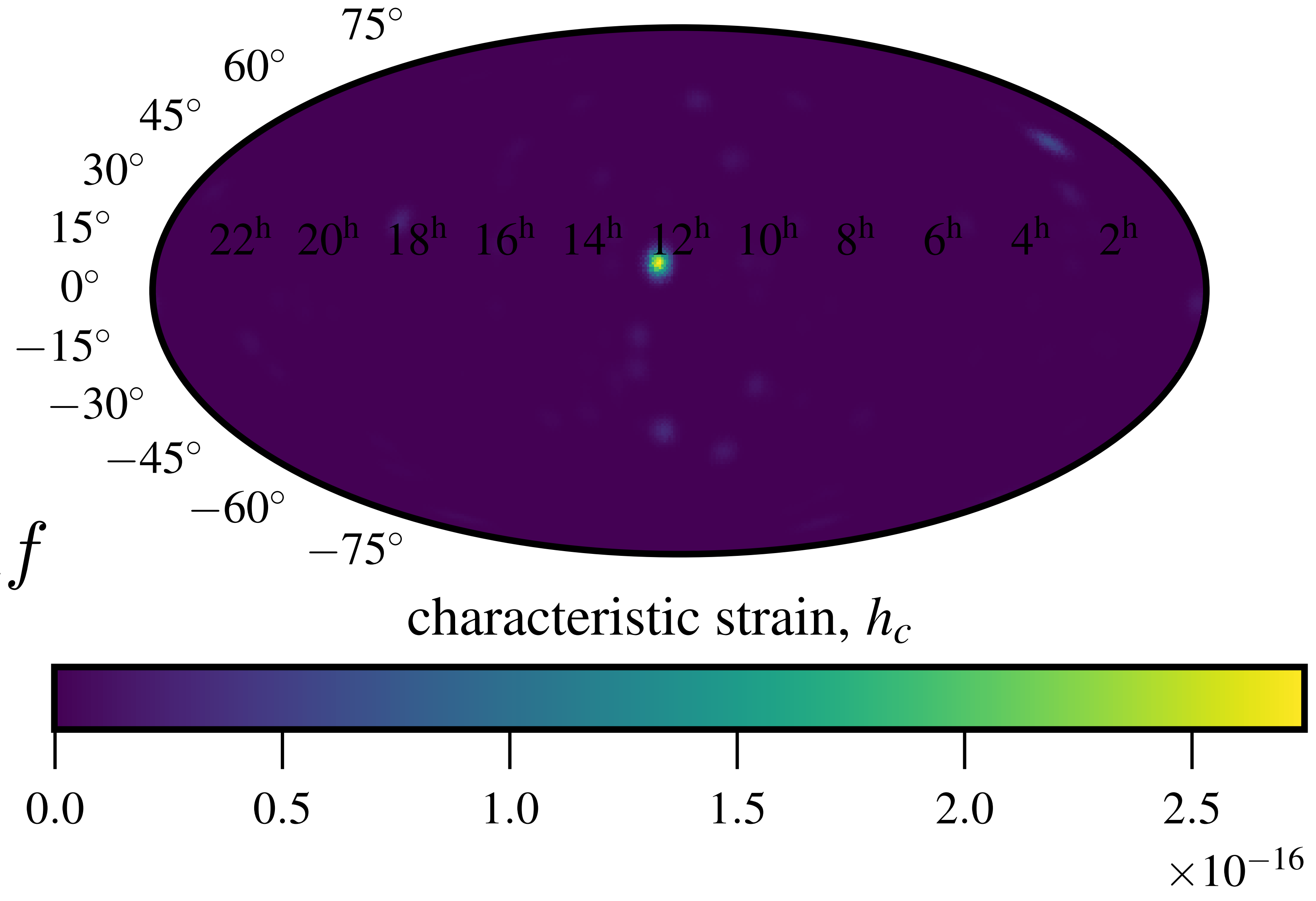

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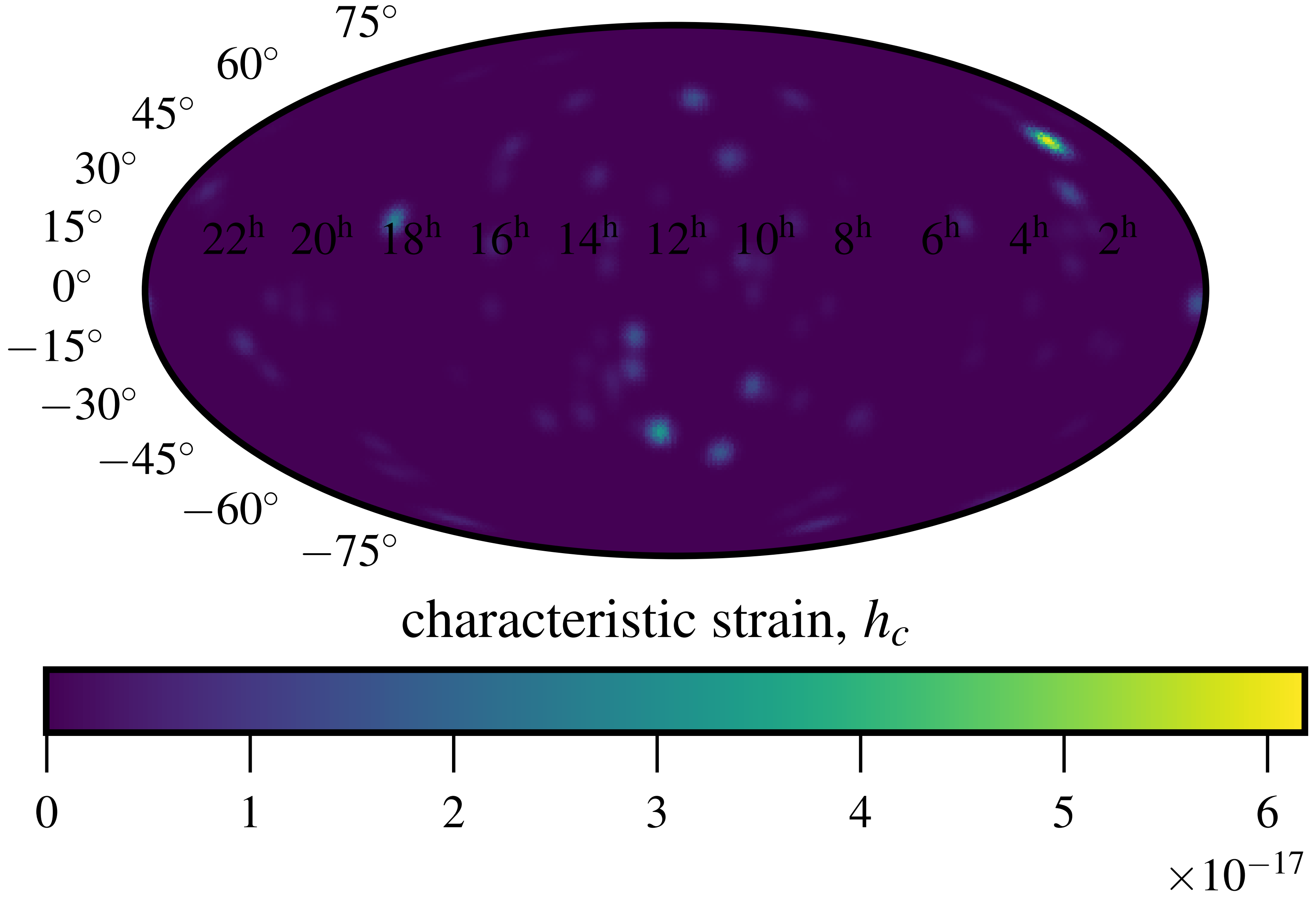

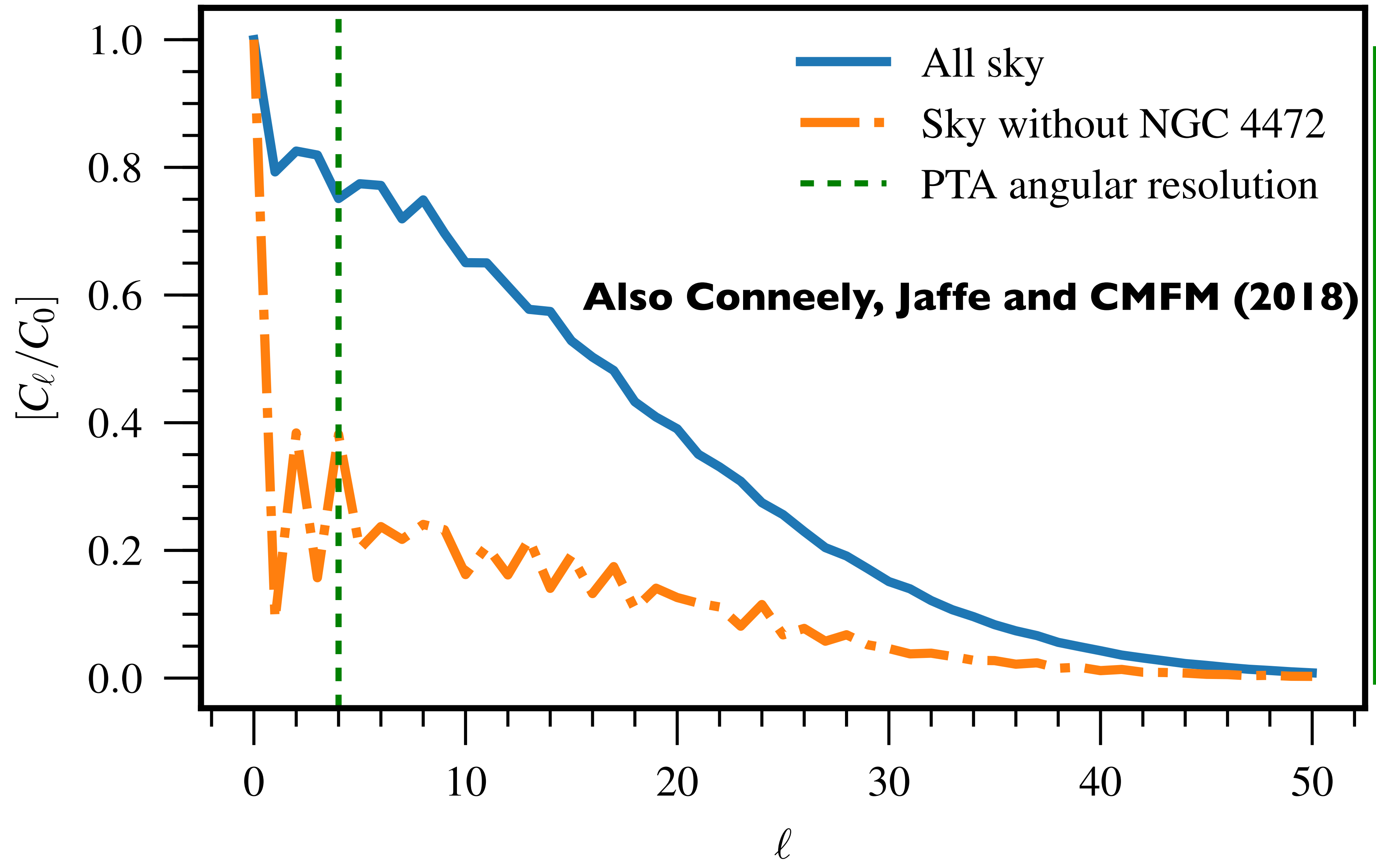

Anisotropy

$\propto 1/\sqrt{N}$

Constrain source population