Pulsar Timing Arrays

Bruce Allen

Max Planck Institute for Gravitational Physics
Hannover, Germany

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Physics Department

Physics: 8.012 **Fall Term, 1976**

Lecture Outline

Sept.	14	General Intro to Physics, Coordinate Systems, Vectors.
	16	Kinematics Time-Length.
	21	Accelerating Motion - Linear-Circular.
	23	Nature of Forces, Torques, Force Diagrams.
	28	Statics.
	30	Elasticity, Scaling.
Oct.	5	Inertia, Newton's Law.
	7	EXAM
	14	Applications of Newton's Law.
	19	2-Dimensional Motion, Damped Motion.
	21	Simple Harmonic Motion - Seismometers.
	*26	Collisions and Conservation Laws.
	28	Conservation Laws.
Nov.	* 2	Conservation Laws and Vibrational Motion.
	4	Conservative Forces - The Potential, Newtonian Grav.
	* 9	EXAM
	11	The Eötvös Experiment, Gravational Red Shift, Principle of Equivalence.
	16	Central Forces, Angular Momentum Conservation.
	18	Non-Inertial Frames; Centrifugal - Coriolis Forces.
	23	Lense-Thirring Effect, Planetary Orbits.
	30	Planetary and Lunar Ranging Experiments.
Dec.	2	Perturbation Theory.
	7	Extended Bodies and Moment of Inertia.
	9	The Gyr
	14	EXAM
	16	Hamilton's Principle.

* Evening lecture. Special Relativity.

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Information Sheet

Lecturer: Professor R. Weiss Office 20F-006 Phone 3-3527

Recitation Instructors:	Prof. D.Barton		3-7596
	Prof. G.Brandenburg	24-511	3-7597
	Prof. C.Canizares	37-501	3-7500
	Prof. G.Clark	37-611	3-5842
	Prof. J.Friedman	24-512	3-7585
	Prof. H.Kendall	24-514	3-7584
	Prof. L.Rosenson	24-520	3-7595
Teaching Assistants:	Peter Mongeau	6-409A	3-7034
	Dana Roberts	24-612	3-7787
Course Secretary:	Susie Fennelly	4-352	3-4855

Schedule:

Lecture	TR	10-11:30	.....	26-100
Recitation Section 01	MW	9	...Barton.....	2-132
02	MW	10	...Canizares.....	24-502
03	MW	10	...Brandenburg.....	2-136
04	MW	11	...Kendall.....	8-205
05	MW	11	...Canizares.....	24-502
06	MW	12	...Kendall.....	2-132
07	MW	1	...Friedman.....	2-132
08	MW	2	...Friedman.....	2-143
09	TR	9	...Mongeau.....	2-131
10	TR	2	...Rosenson.....	26-210
11	TR	1	...Clark.....	24-407
12	TR	12	...Clark.....	2-139

Text Book: NEWTONIAN MECHANICS, A.P.French (Norton, 1971).

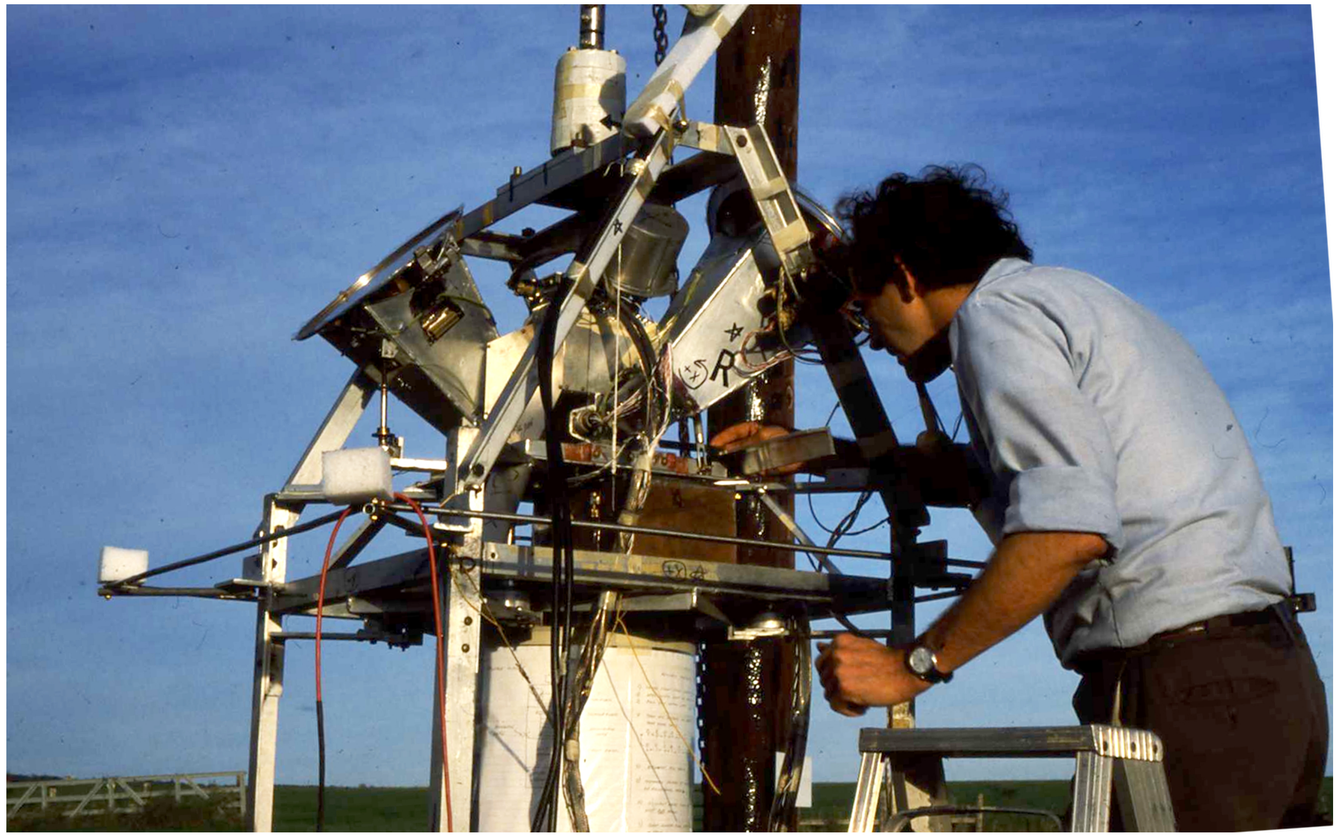
Tutoring: Dana Roberts and others. MW 1-3 p.m. Corridor Lab (4-315)

Homework: Handed out Thursday in Lectures, to be completed and given to Recitation Instructors the following Wed. or Thurs. One problem in each set to be graded by Recitation Instructor on scale 3→0. Some problems require work in the Corridor Lab.

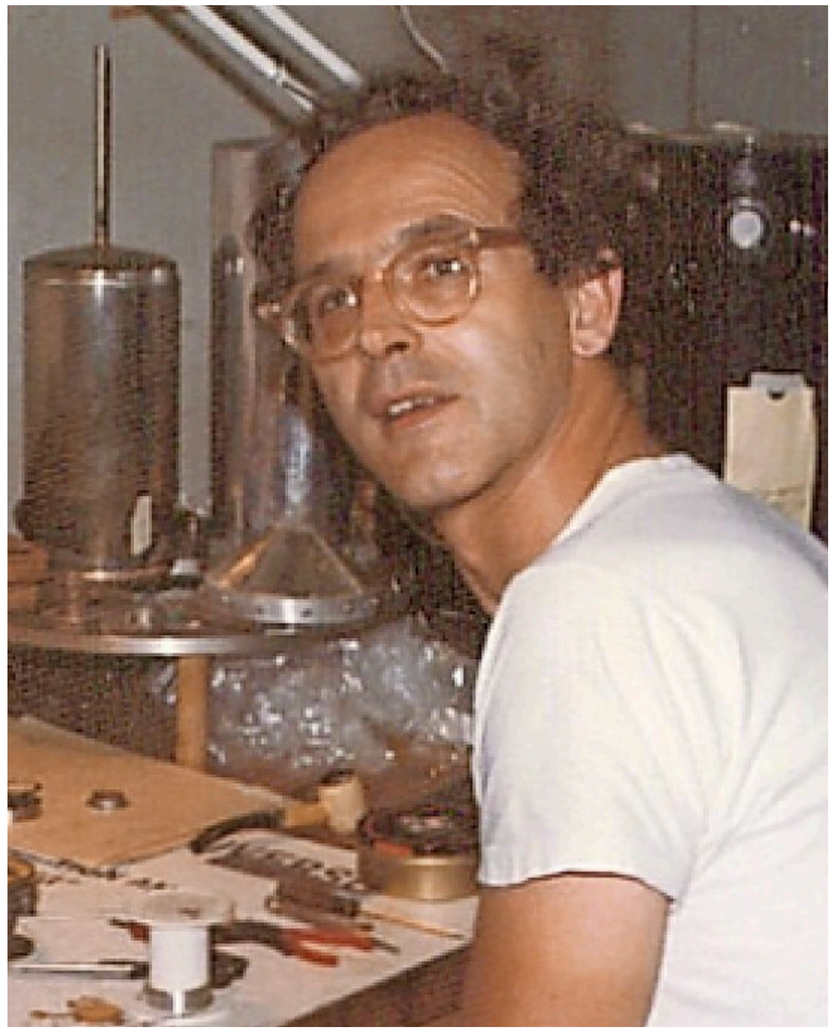
TR 11:30-1:30

Grading: PASS or FAIL. No Hidden Grades.
75% of evaluation determined by 3 1½ hour exams
25% of evaluation determined by homework.

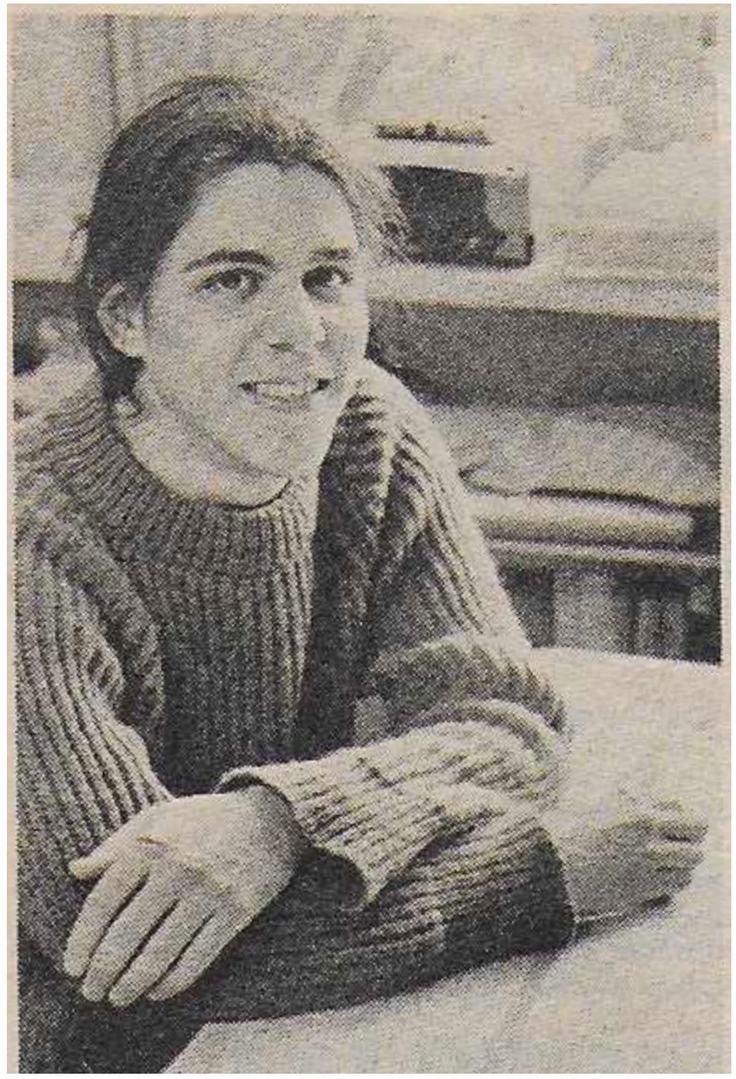
Credit: Ben Weiss



Credit: Mark Halpern



MIT, 27.2.2026



MIT, 27.2.2026

PROGRAM

EIGHTH TEXAS SYMPOSIUM ON RELATIVISTIC ASTROPHYSICS

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The National Science Foundation
The New York Academy of Sciences
The University of Texas

TO BE HELD

December 13 through 17, 1976

AT

Copley Plaza Hotel

Copley Square

Boston, Massachusetts

TUESDAY, DECEMBER 14

QUANTUM THEORY IN STRONG GRAVITATIONAL FIELDS — 9 a.m. - Noon

CHAIRMAN: B. De Witt, University of Texas

Quantum Field Theory in Curved Space-Time: an Overview (50 min.)	C. Isham, Imperial College
Fundamental Breakdown of Physics in Gravitational Collapse (40 min.)	S. W. Hawking, Cambridge University

COFFEE BREAK

Thermodynamics of Black Holes (20 min.)	D. Sciama, University of Oxford
Stress Tensor Calculations (20 min.)	P. C. W. Davies, Kings College, London
Particle Detectors and Black Holes (20 min.)	W. Unruh, University of British Columbia

X-RAY BURSTERS AND GLOBULAR CLUSTERS — 2 p.m. - 5 p.m.

CHAIRMAN: J. Bahcall, Institute for Advanced Studies

Observations of X-Ray Bursters (30 min.)	H. Gursky, Center for Astrophysics, Harvard/Smithsonian
Observations of X-Ray Bursters (30 min.)	W. Lewin, Massachusetts Institute of Technology
Physics of Accretion vs Astronomy of X-Ray Sources (30 min.)	J. Ostriker, Princeton University

COFFEE BREAK

Optical Observations of Globular Clusters (30 min.)	W. Liller, Center for Astrophysics, Harvard/Smithsonian
Neutron Star Models of X-Ray Bursters (15 min.)	D. Lamb, University of Illinois

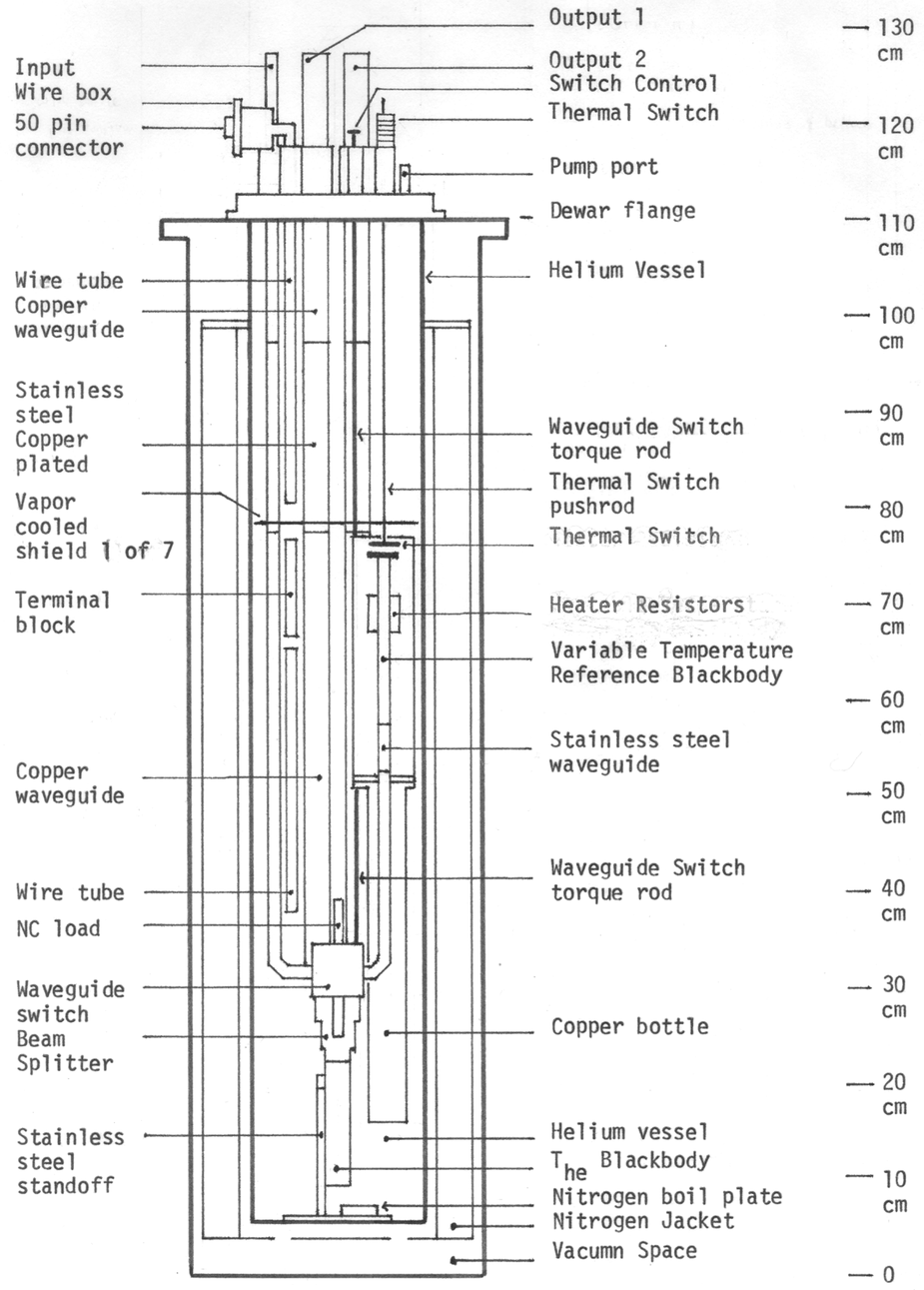
WEDNESDAY, DECEMBER 15

X-RAY ASTRONOMY — 9 a.m. - Noon

CHAIRMAN: G. Garmire, California Institute of Technology

Observations of Extragalactic X-Ray Sources (30 min.)	H. Schnopper, Center for Astrophysics, Harvard/Smithsonian

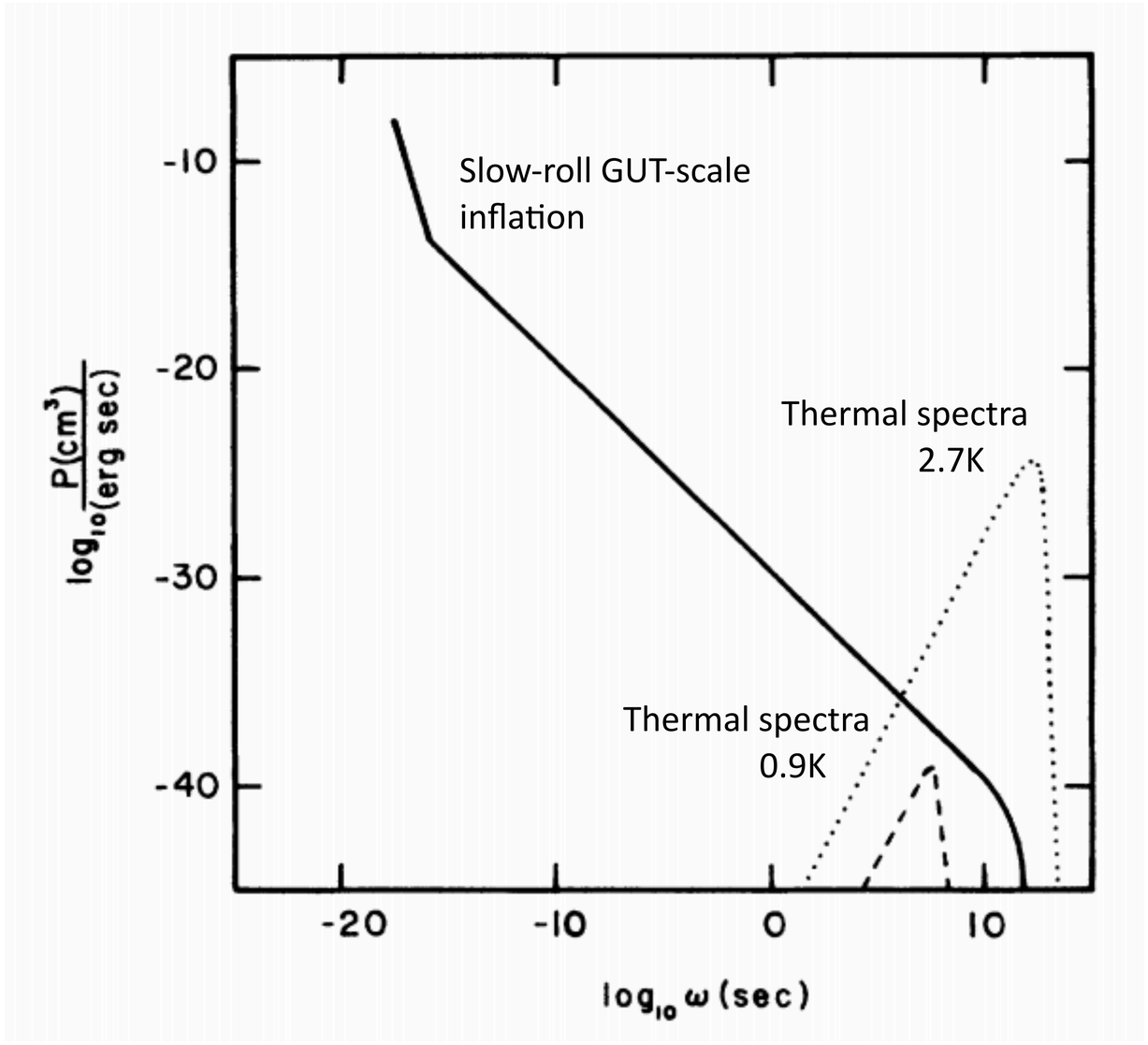
FIGURE 7. The Liquid Helium Cooled Front End



UC Santa Barbara 1984

MIT, 27.2.2026

Stochastic Background Inflation



From B. Allen, "Stochastic gravity-wave background in inflationary-universe models", PRD 37, 2078 (1988)

BA, *Vacuum states in de Sitter space*, **PRD 32** (1985) 3136

BA, Ted Jacobson, *Vector two-point functions in maximally symmetric spaces*, **Comm. Math. Phys. 103** (1986) 669

BA, *The graviton propagator in de Sitter space,* **PRD 34** (1986) 3670

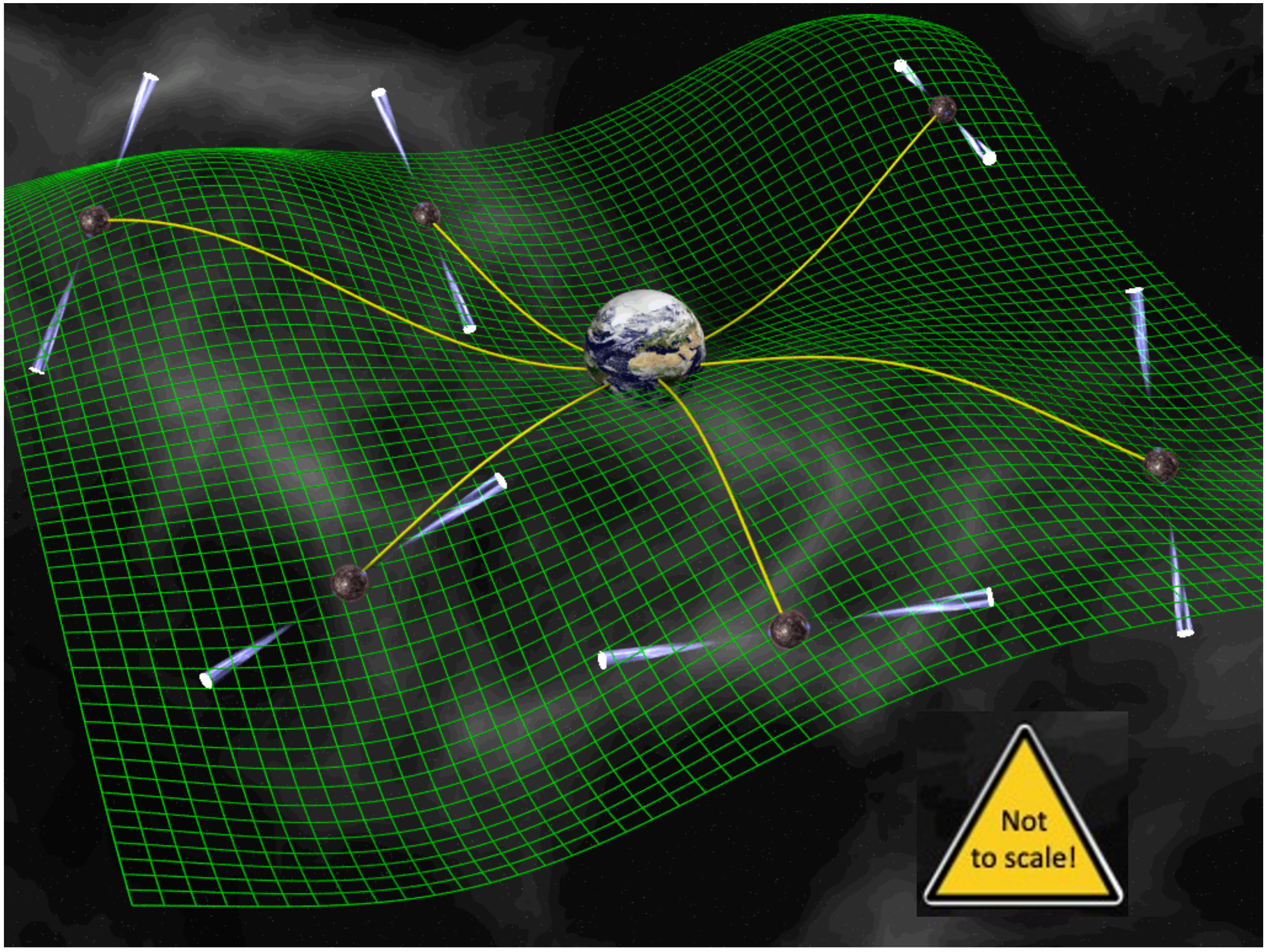
BA, *The graviton propagator in homogeneous and isotropic space-times*, **Nucl. Phys. B 287** (1987) 743-756

BA, Antoine Folacci, *The massless minimally coupled scalar field in de Sitter space*, **PRD 35** (1987) 3771

Pulsar Timing Arrays (PTAs)

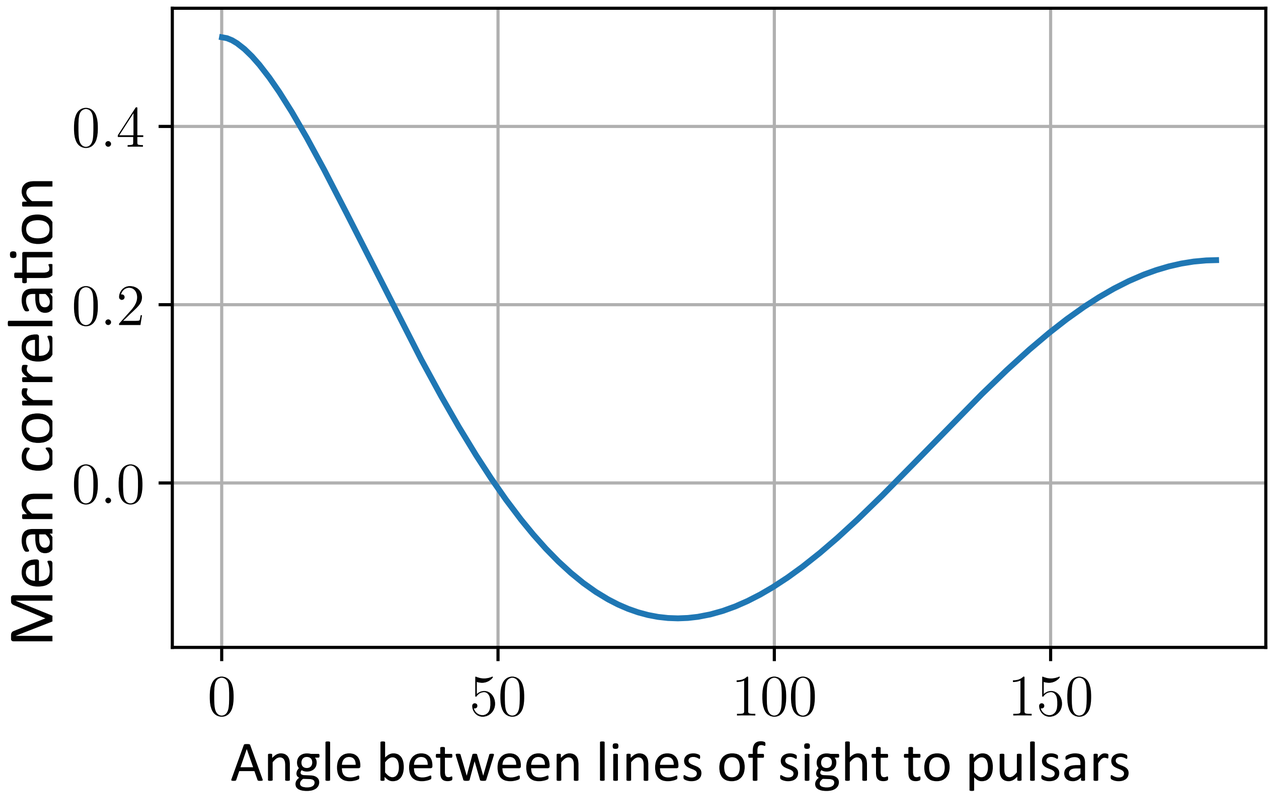
Promise: detect nano-Hz gravitational waves

$L_{GW} \approx 10\,\mathrm{y}$
$L_{pulsar} \approx 1000\,\mathrm{y}$
$L_{source} \approx 10^8\,\mathrm{y}$

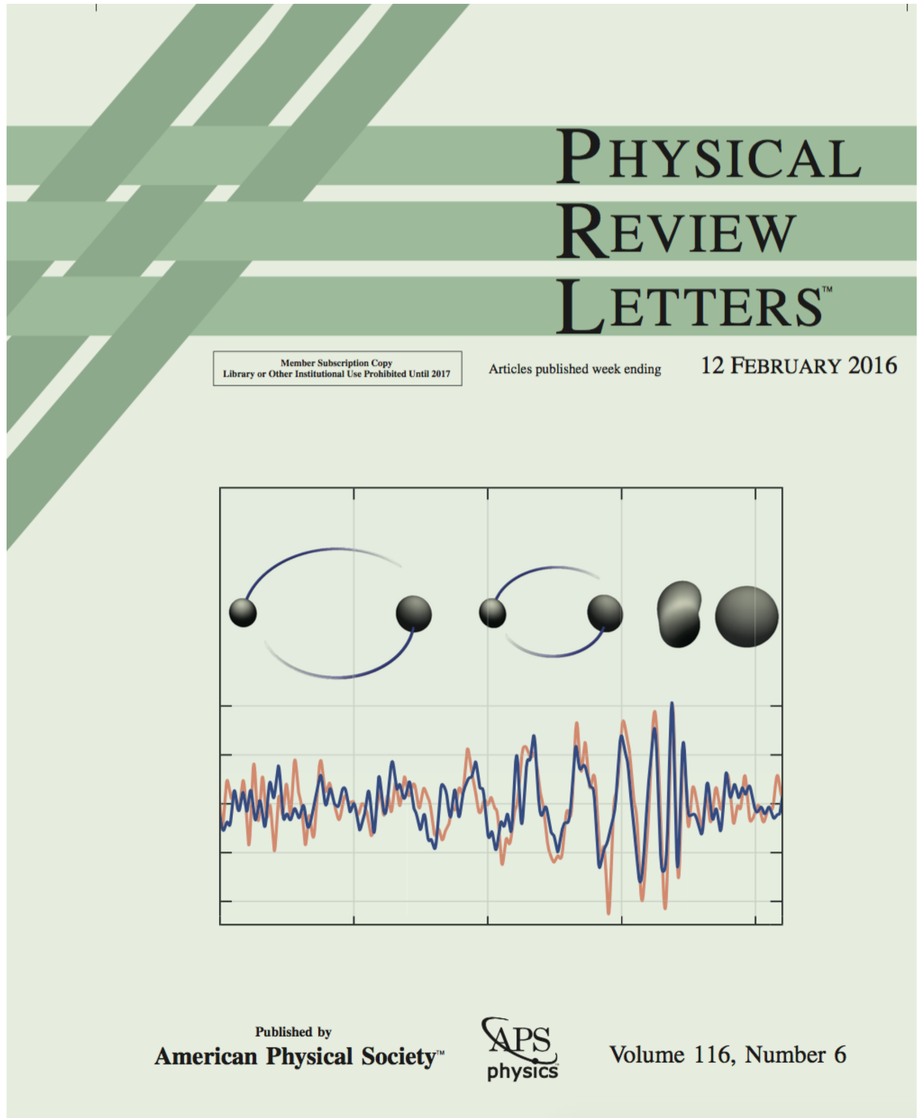


Key: Correlation Pattern in Pulsar Timing Residuals

Hellings and Downs curve



Hellings and Downs, “Upper limits on the isotropic gravitational radiation background from pulsar timing analysis”, ApJ, 265 (1983)



Current status of six PTAs

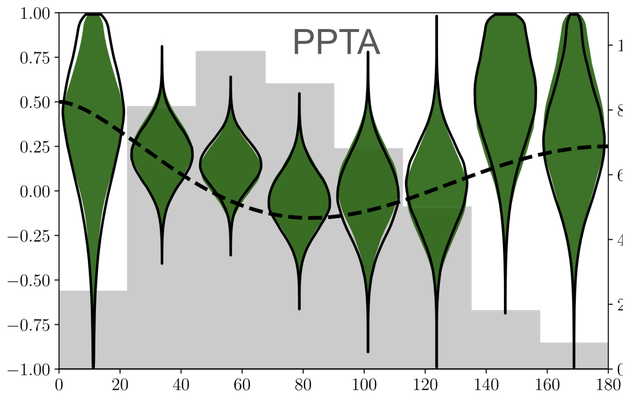
Parkes PTA (PPTA), ApJL 951 L6 (2023), 30 pulsars over 18 years, ***no support for or against***

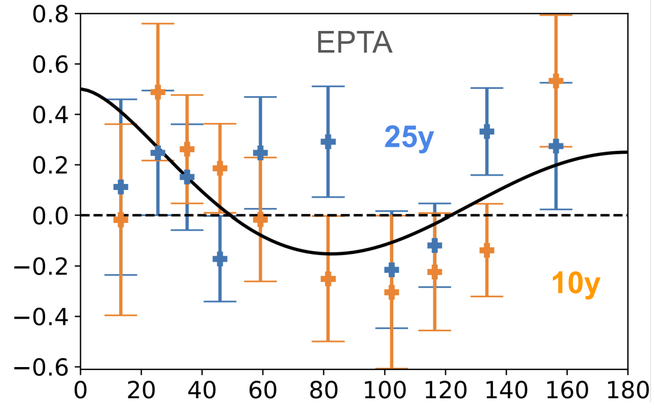
European PTA (EPTA) and Indian PTA, Astron. Astrophys. 678, A50 (2023), 25 pulsars over 25/10 years, ***"marginal evidence/evidence"***

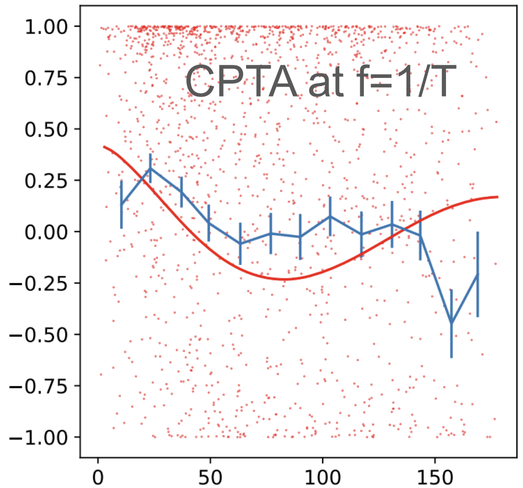
Chinese PTA (CPTA), Res. Astron. Astrophys. 23, 075024 (2023), 57 pulsars over 3 years, ***"some evidence"***

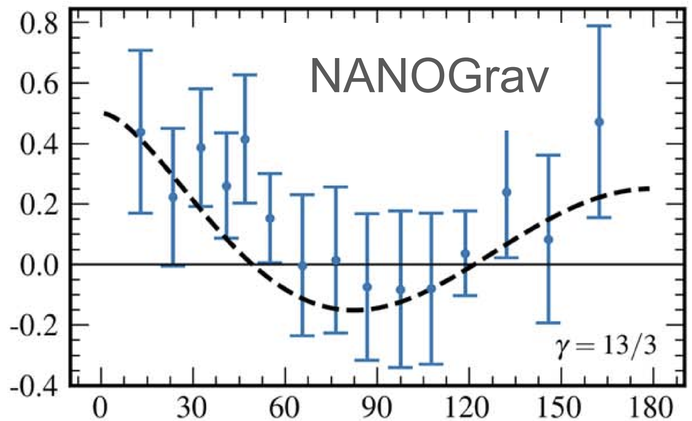
North American Nano-Hz Observatory for Gravitational Waves (NANOGrav) ApJL 951, L8 (2023), 67 pulsars over 15 years, ***"compelling evidence"*** [Publication's 3.6σ to 4.2σ later revised to 3.2σ]

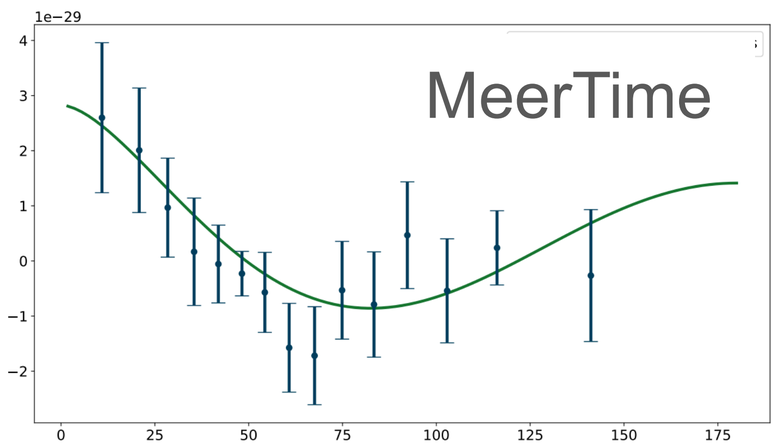
MeerTime, MNRAS 536, 1489 (2025), 83 pulsars over 4.5 years, ***"****Under different assumptions about noise processes we can produce **either** what appear to be **compelling Hellings-Downs correlations** **of high significance 3-3.4 sigma**, with a spectrum close to that which is predicted, **or** surprisingly, under slightly different assumptions, **ones that are insignificant***











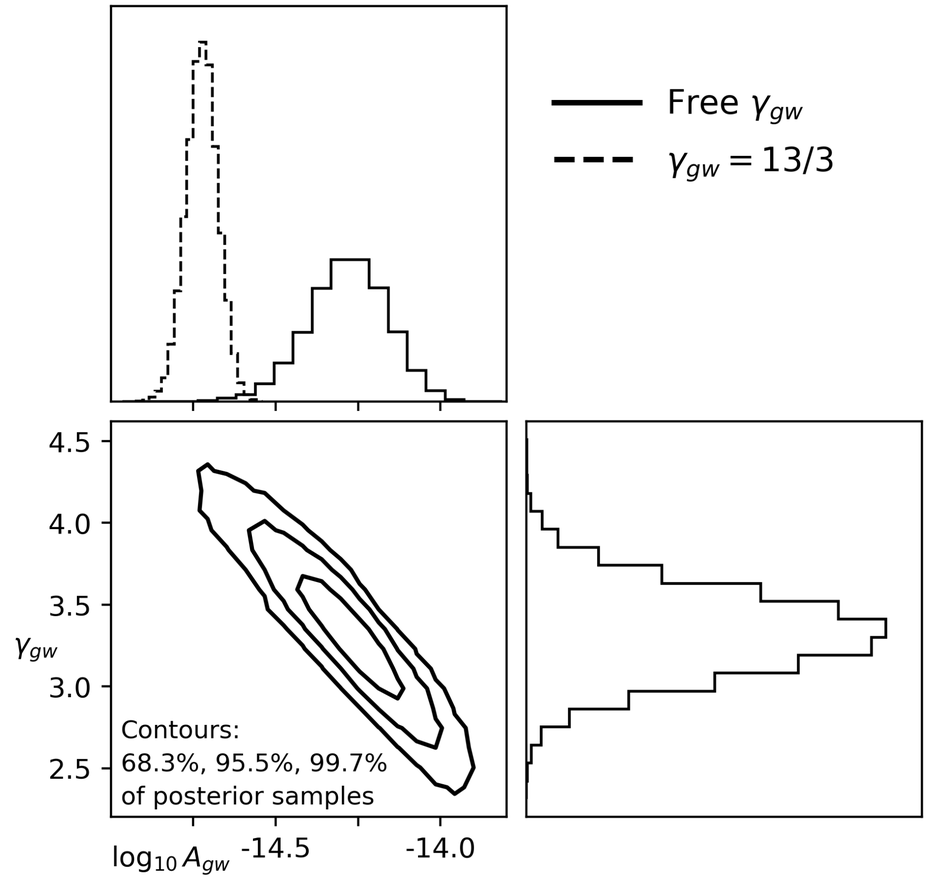
First Analysis of five-PTA Data Set

- June 2023 data from 5 of 6 PTAs is public: 121 pulsars in total
- New “direct combination” method from van Haasteren, otherwise vanilla analysis
- Search for a stochastic gravitational wave background which is:
  - isotropic, unpolarized, Gaussian, stationary
  - power-law spectrum:

$$\Omega_{gw}(f) \equiv \frac{f}{\rho_{cr}}\frac{d\rho_{gw}}{df} = \frac{2\pi^2}{3H_0^2}A_{gw}^2 f_r^2 \left(\frac{f}{f_r}\right)^{-\gamma_{gw}+5}$$

$$f_r \equiv 1/\text{year}$$

Yu and Allen, *Stochastic gravitational-wave background search using data from five pulsar timing arrays*, **arXiv2512.08666**



Posteriors on the slope and amplitude

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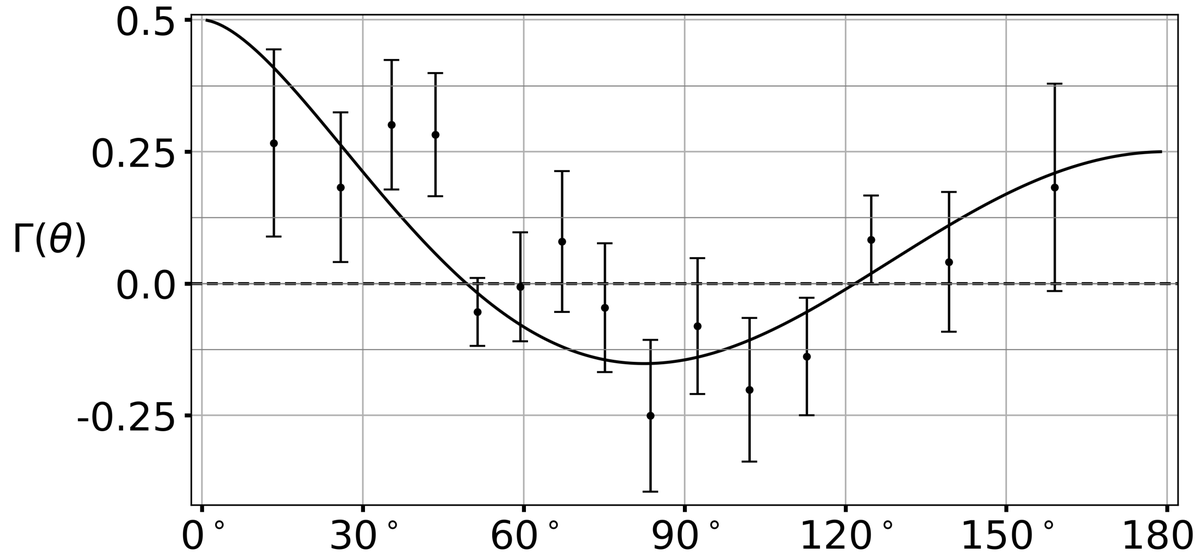
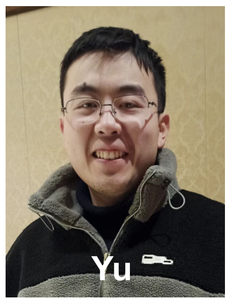


Reconstruction of the Hellings and Downs curve (reduced $\chi^2 = 0.84$, a good fit)



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False alarm probability and detection significance

statistic	significance	mean	median	68% range	95% range
OS	σ-units:	**4.0**	4.5	(4.0, 5.1)	(3.4, 5.6)
	$-\log_{10} p$:	4.4	5.5	(4.4, 6.7)	(3.5, 8.0)

Bayes factor = E_{HD}/E_0 = 4400 $\approx 4.1\sigma$ significance