The Gravitational-Wave Universe seen by Pulsar Timing Arrays

Chiara M. F. Mingarelli
Marie Curie Fellow in Theoretical Astrophysics
Caltech/MPIfR

LISA Symposium
September 8th 2016

Outline

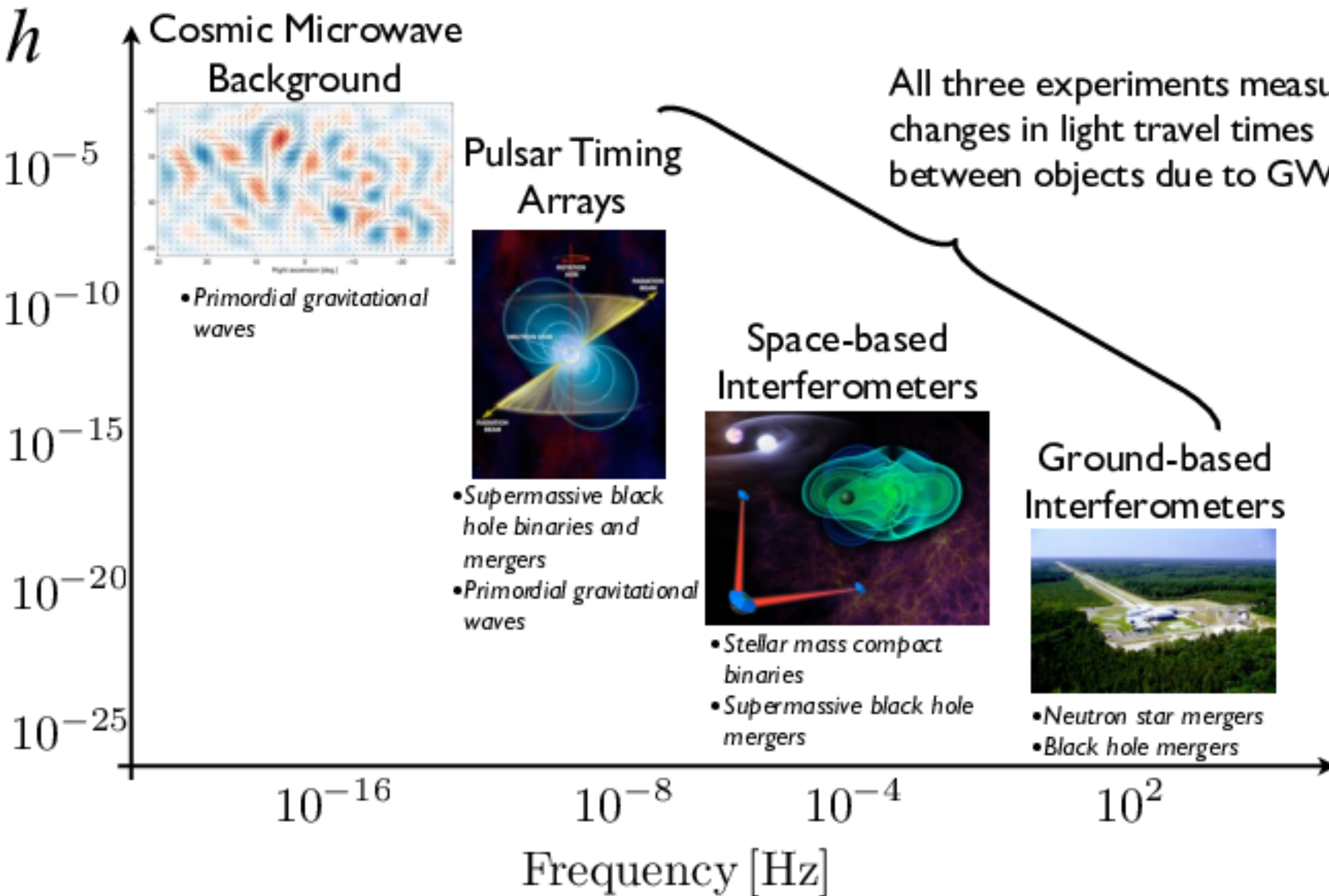
- The gravitational-wave spectrum
- Pulsar Timing Arrays
- Continuous nHz gravitational waves
- The gravitational-wave background
- New results in astrophysics and cosmology
- Future directions: anisotropy

Max-Planck-Institut für Radioastronomie

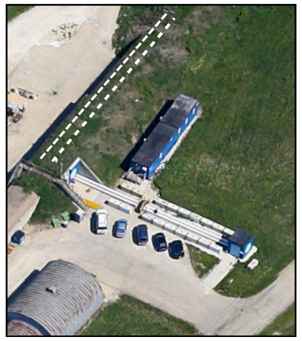
Caltech

MARIE CURIE ACTIONS

The spectrum of gravitational wave astronomy



Holometer



primordial BHs
resolvable
cosmic strings

See Brittany Kamai

LIGO can't see PTA sources

Max-Planck-Institut
für Radioastronomie

Pulsar Timing Array

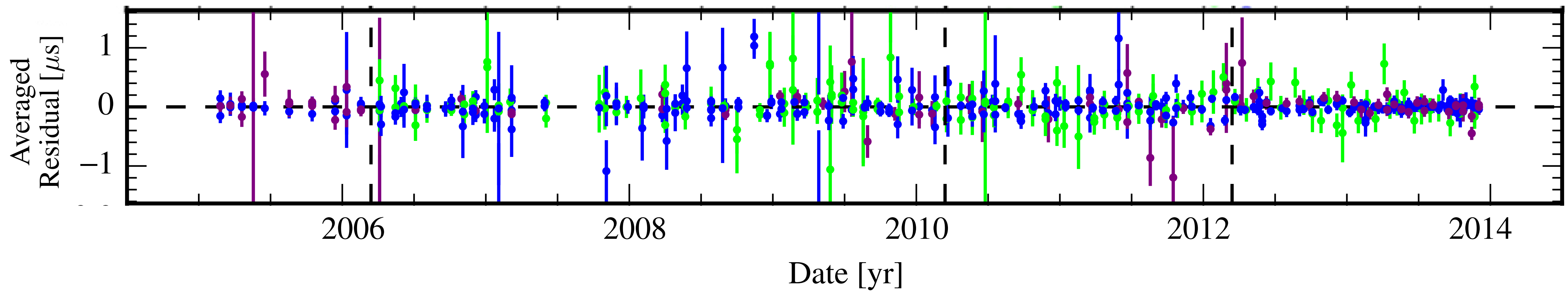
Animation from John Rowe Animation/Australia Telescope National Facility, CSIRO

Max-Planck-Institut
für Radioastronomie

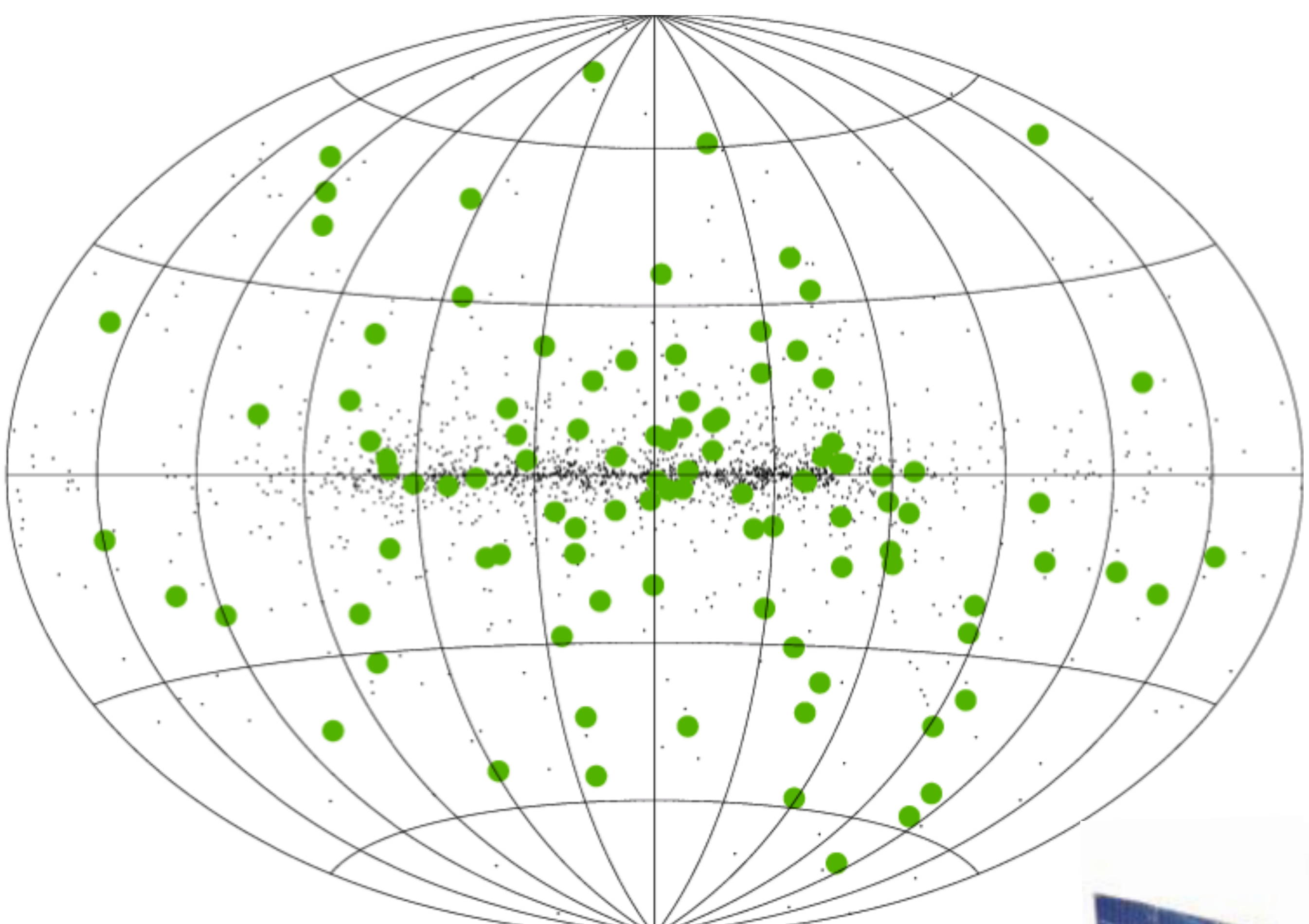
Caltech

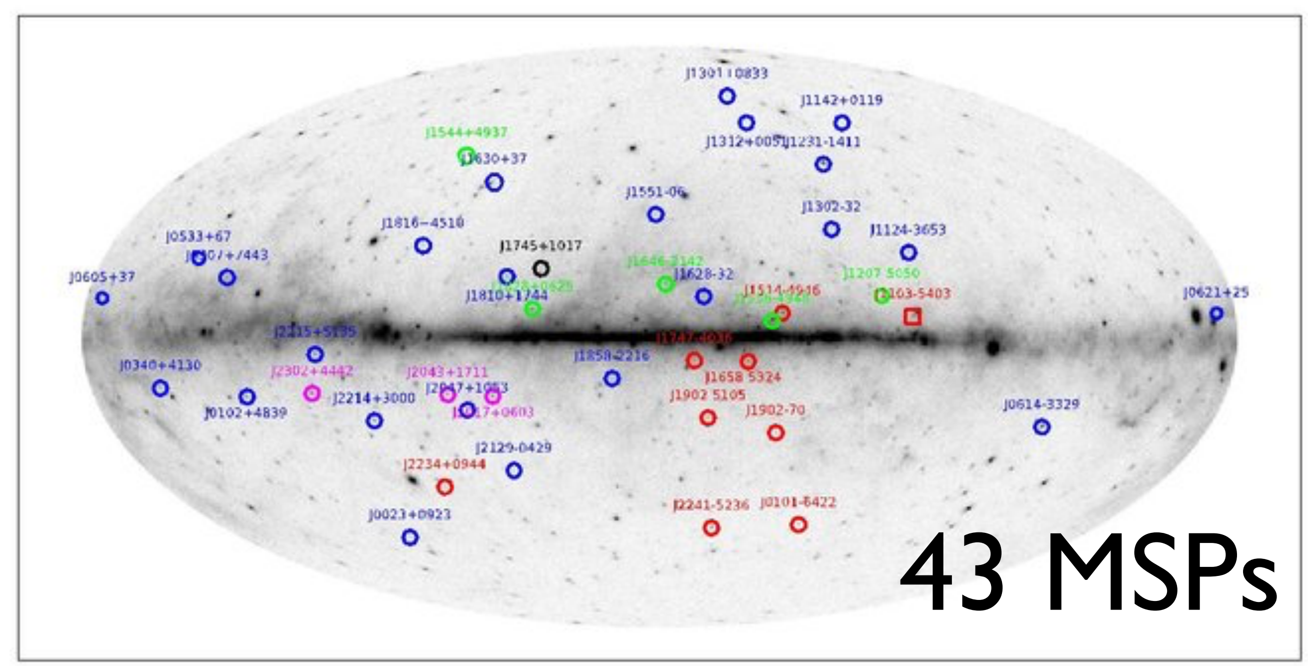
MARIE CURIE ACTIONS

Millisecond Pulsars



J1713+0747





43 MSPs

GBT, Effelsberg, Parkes, Nançay, GMRT

apted Ray et al. (2012)

2300 known pulsars, 230 MSPs

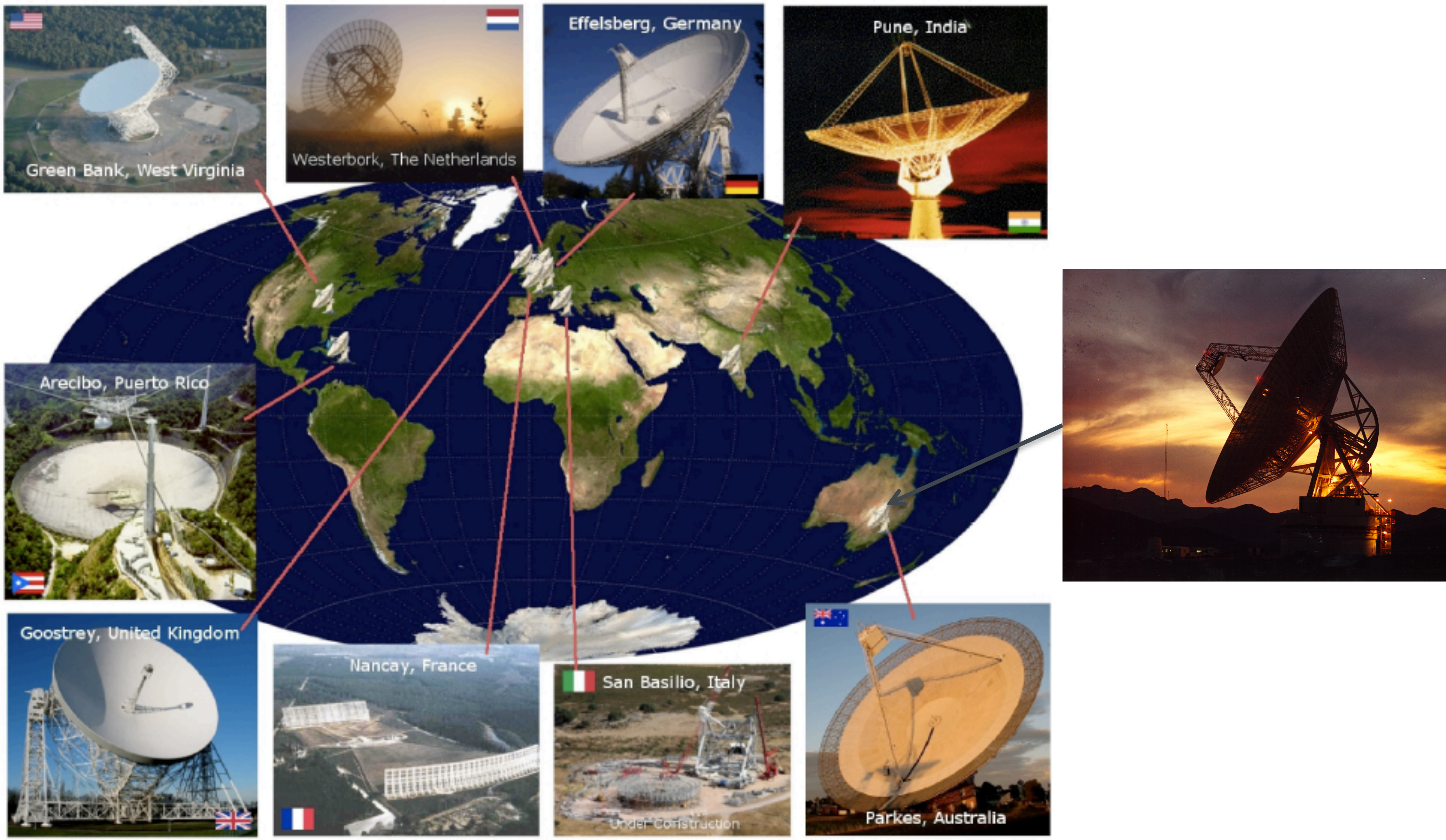
Maybe 30,000 detectable!

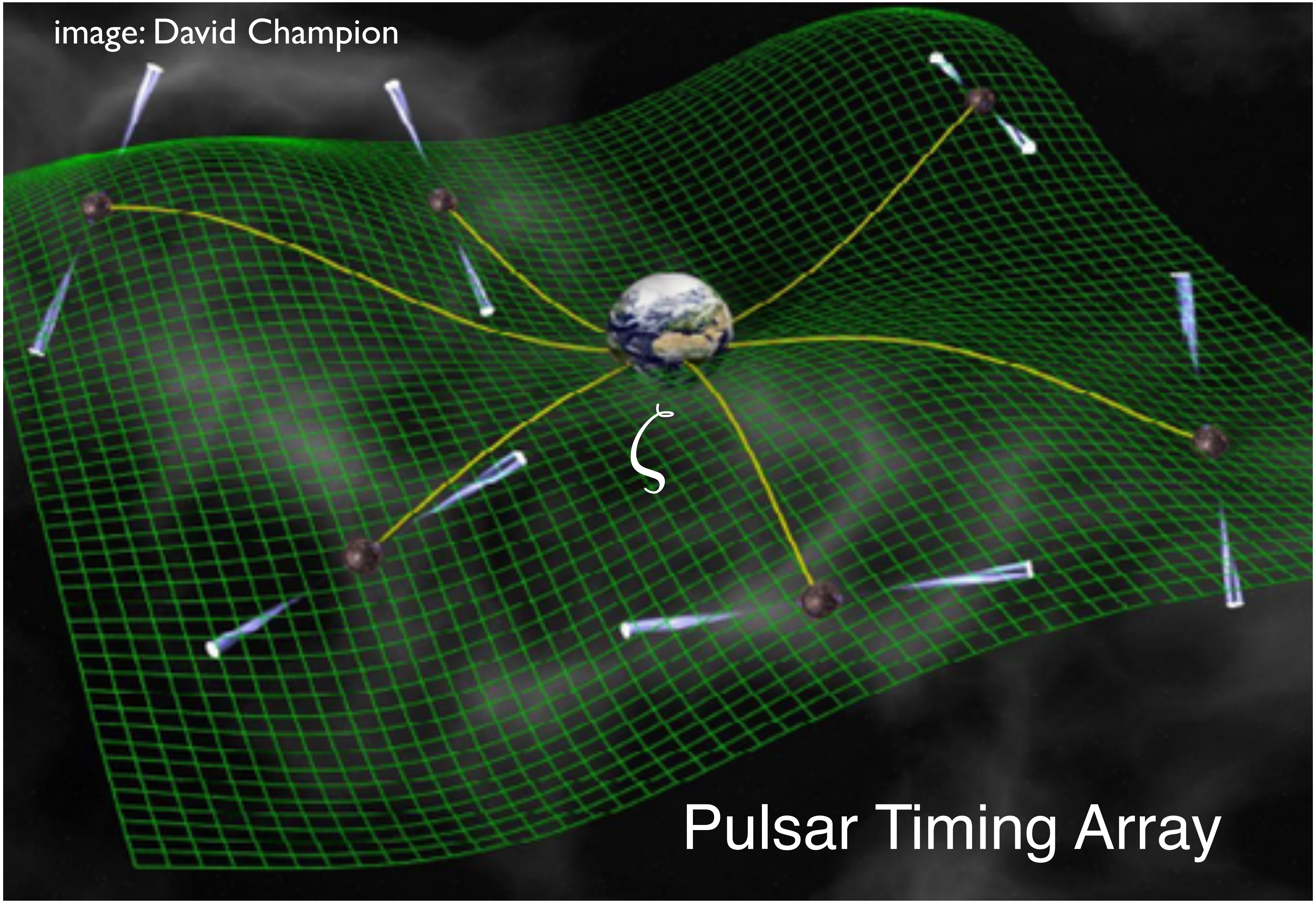
courtesy Maura McLaughlin

Image courtesy NASA/DOE/Fermi)

Caltech

Gravitational Waves, Pulsar Timing, and the Deep Space Network





Galactic GW detector! Each pulsar thousands of light years away. Signal can evolve!

Max-Planck-Institut für Radioastronomie

Caltech

MARIE CURIE ACTIONS

Continuous GW Sources

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **455,** 1665–1679 (2016) doi:10.1093/mnras/stv2092

European Pulsar Timing Array limits on continuous gravitational waves from individual supermassive black hole binaries

S. Babak,[1★] A. Petiteau,[2★] A. Sesana,[1,3★] P. Brem,[1] P. A. Rosado,[4,5] S. R. Taylor,[6,7] A. Lassus,[8,9] J. W. T. Hessels,[10,11] C. G. Bassa,[10,12] M. Burgay,[13] R. N. Caballero,[8] D. J. Champion,[8] I. Cognard,[9,14] G. Desvignes,[8] J. R. Gair,[7] L. Guillemot,[9,14] G. H. Janssen,[10,12] R. Karuppusamy,[8] M. Kramer,[8,12] P. Lazarus,[8] K. J. Lee,[15] L. Lentati,[16] K. Liu,[8] C. M. F. Mingarelli,[3,8,17] S. Osłowski,[8,18] D. Perrodin,[13] A. Possenti,[13] M. B. Purver,[12] S. Sanidas,[11,12] R. Smits,[10] B. Stappers,[12] G. Theureau,[9,14,19] C. Tiburzi,[13,20] R. van Haasteren,[17] A. Vecchio[3] and J. P. W. Verbiest[8,18]

Continuous GW Results

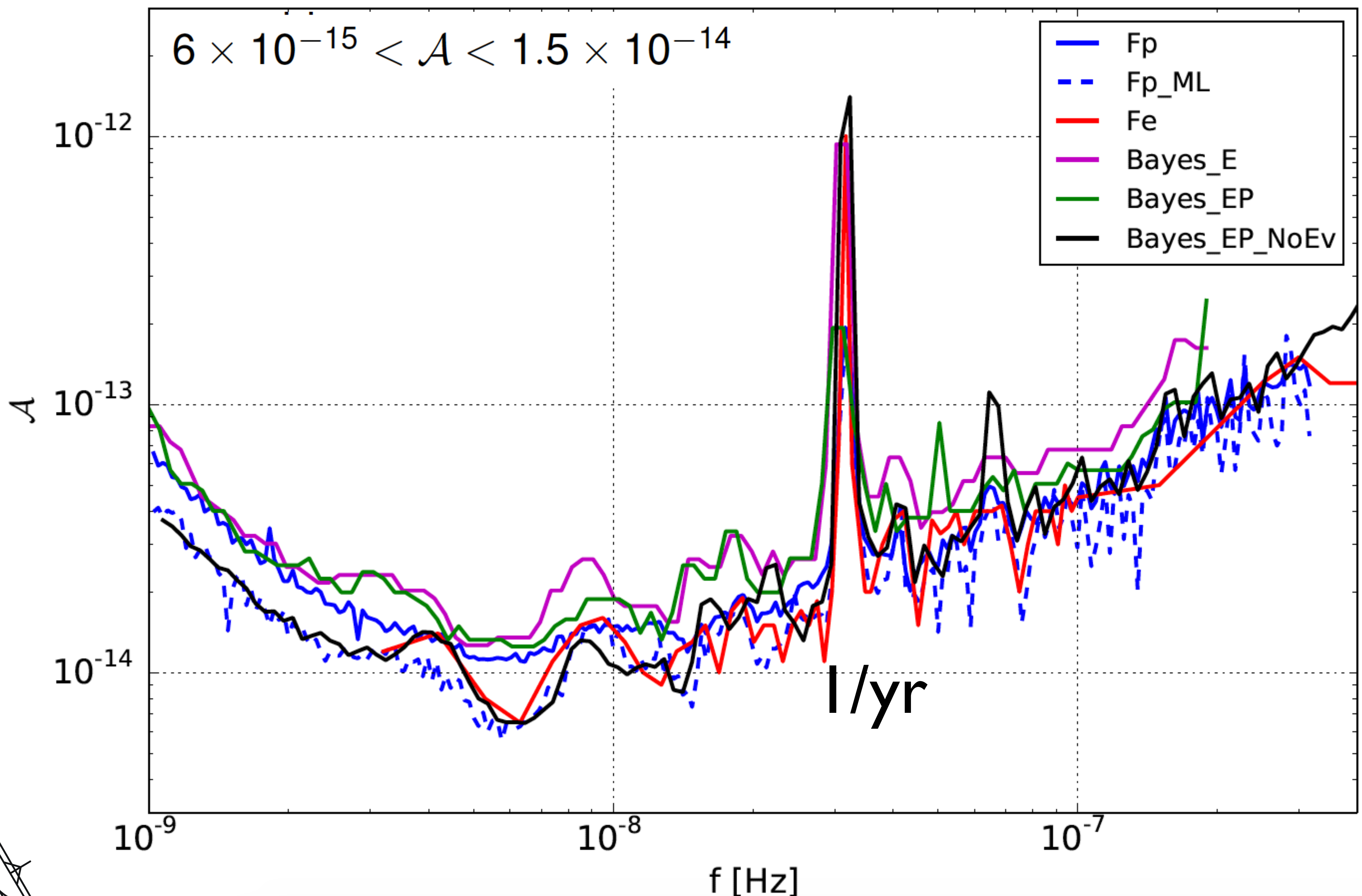
- Assume non-spinning SMBHs in circular orbit
- Model contains a single GW signal
- Separate searches: (i) using earth-term only (ii) using full non-evolving signal ($f_p = f_e$) (iii) using full evolving signal
- Methods: frequentist and Bayesian methods for setting upper limit on the strain of monochromatic GW source

Max-Planck-Institut für Radioastronomie

Caltech

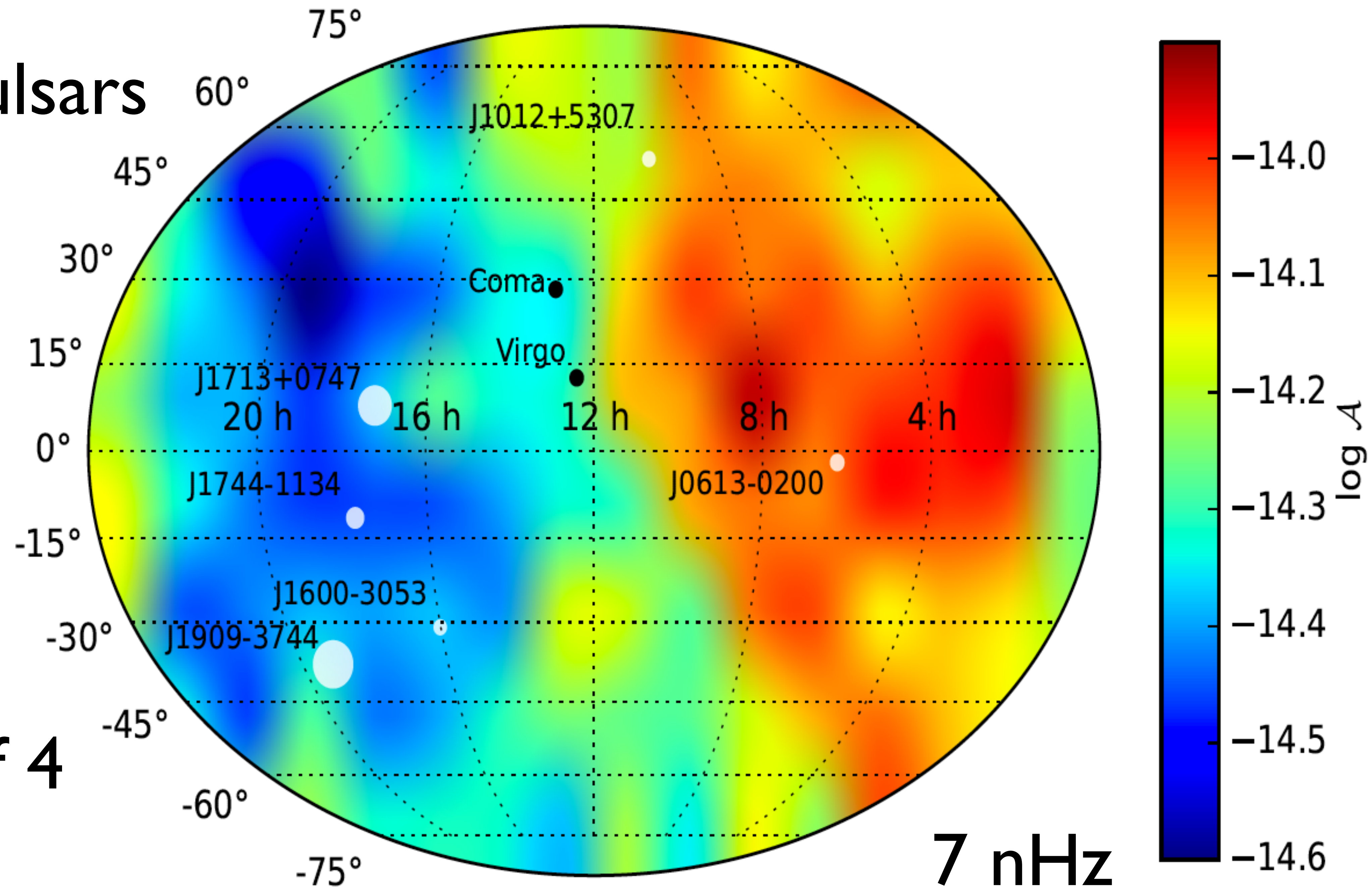
MARIE CURIE ACTIONS

Continuous GW Results



Continuous GW Results

best 6 pulsars



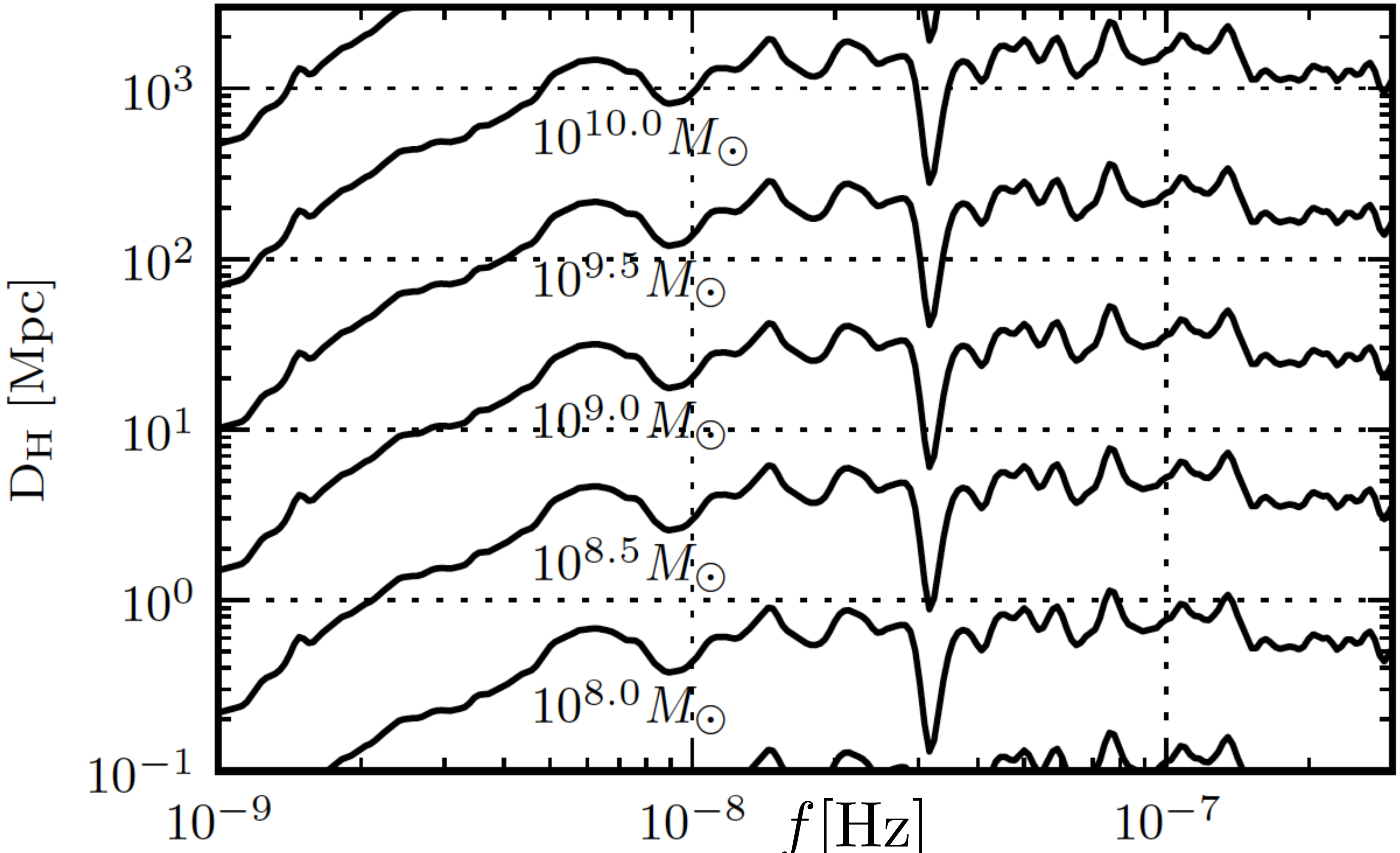
factor of 4

7 nHz

Bayesian analysis with non-evolving source

Horizon Distance

For f < 10 nHz can exclude sub-centiparsec binaries: **with $M_c >$ 10^9 M out to 25 Mpc**; **with $M_c >$ 10^{10} M: out to 1 Gpc ($z \approx$ 0.2).**



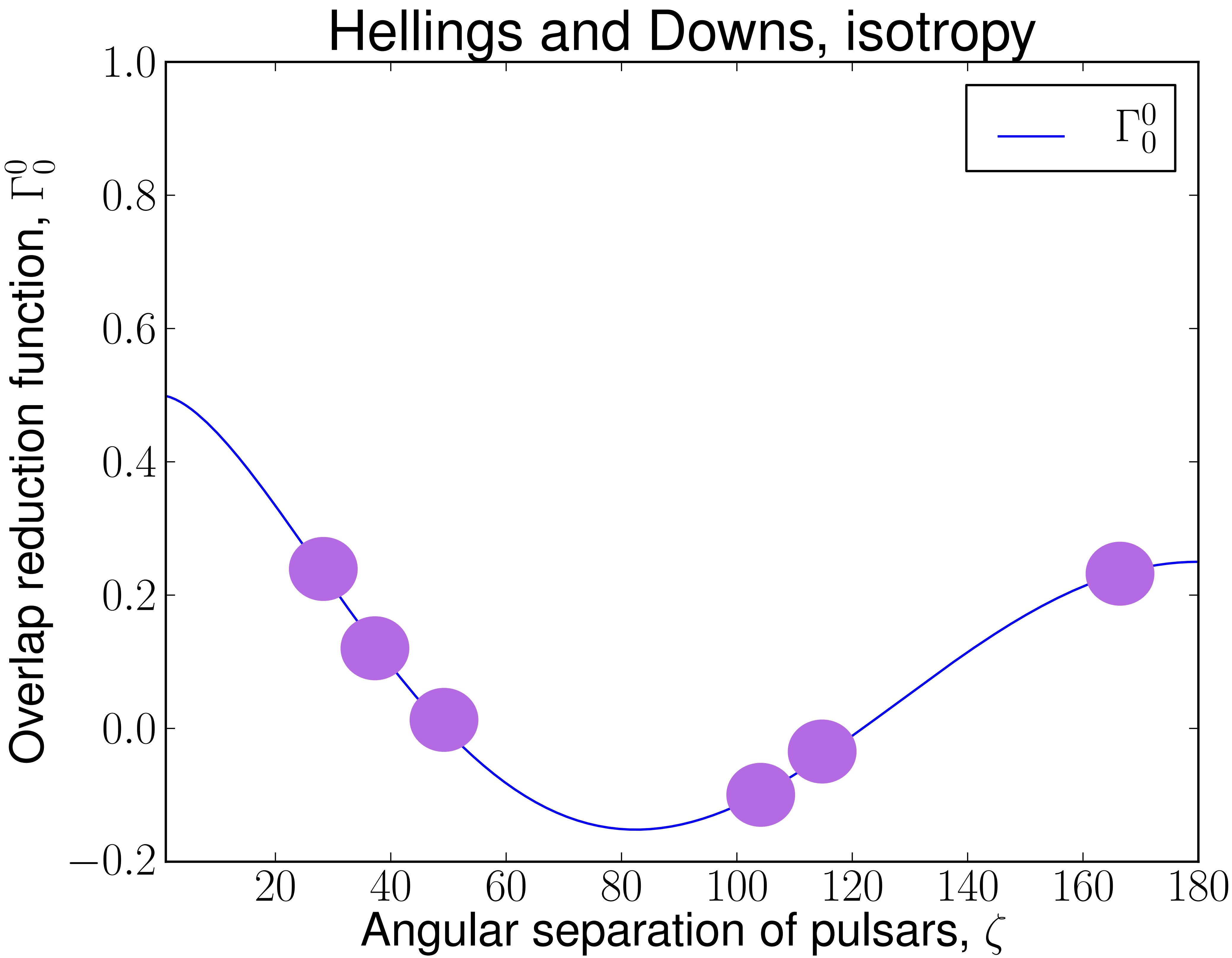
Max-Planck-Institut für Radioastronomie

Caltech

MARIE CURIE ACTIONS

the nanoHertz gravitational-wave background

$$\text{residuals} \propto \int_{S^2} d\hat{\Omega}$$ (**power distribution** x response)



Max-Planck-Institut für Radioastronomie

Caltech

MARIE CURIE ACTIONS

Stochastic Background from SMBHBs

Assuming *circular SMBH binaries* driven by GW emission only, can define a characteristic strain:

$$h_c^2 \sim f^{-4/3} \int\int dz d\mathcal{M} \frac{d^2 n}{dz d\mathcal{M}} \frac{1}{(1+z)^{1/3}} \mathcal{M}^{5/3}$$

number of mergers remnants per comoving volume

$$h_c = A \left(\frac{f}{\mathrm{yr}^{-1}} \right)^{-2/3} \qquad \Omega_{\mathrm{gw}}(f) = \frac{2\pi^2}{3H_0^2} f^2 h_c^2$$

Phinney (2001); Sesana (2012)

We know a lot about A, can learn more

Max-Planck-Institut für Radioastronomie

Caltech

MARIE CURIE ACTIONS

Surge in the field in last 10 years,
here are the latest results!

New Results: Astrophysics

THE ASTROPHYSICAL JOURNAL, 821:13 (23pp), 2016 April 10
doi:10.3847/0004-637X/821/1/13

CrossMark

THE NANOGRAV NINE-YEAR DATA SET: LIMITS ON THE ISOTROPIC STOCHASTIC GRAVITATIONAL WAVE BACKGROUND

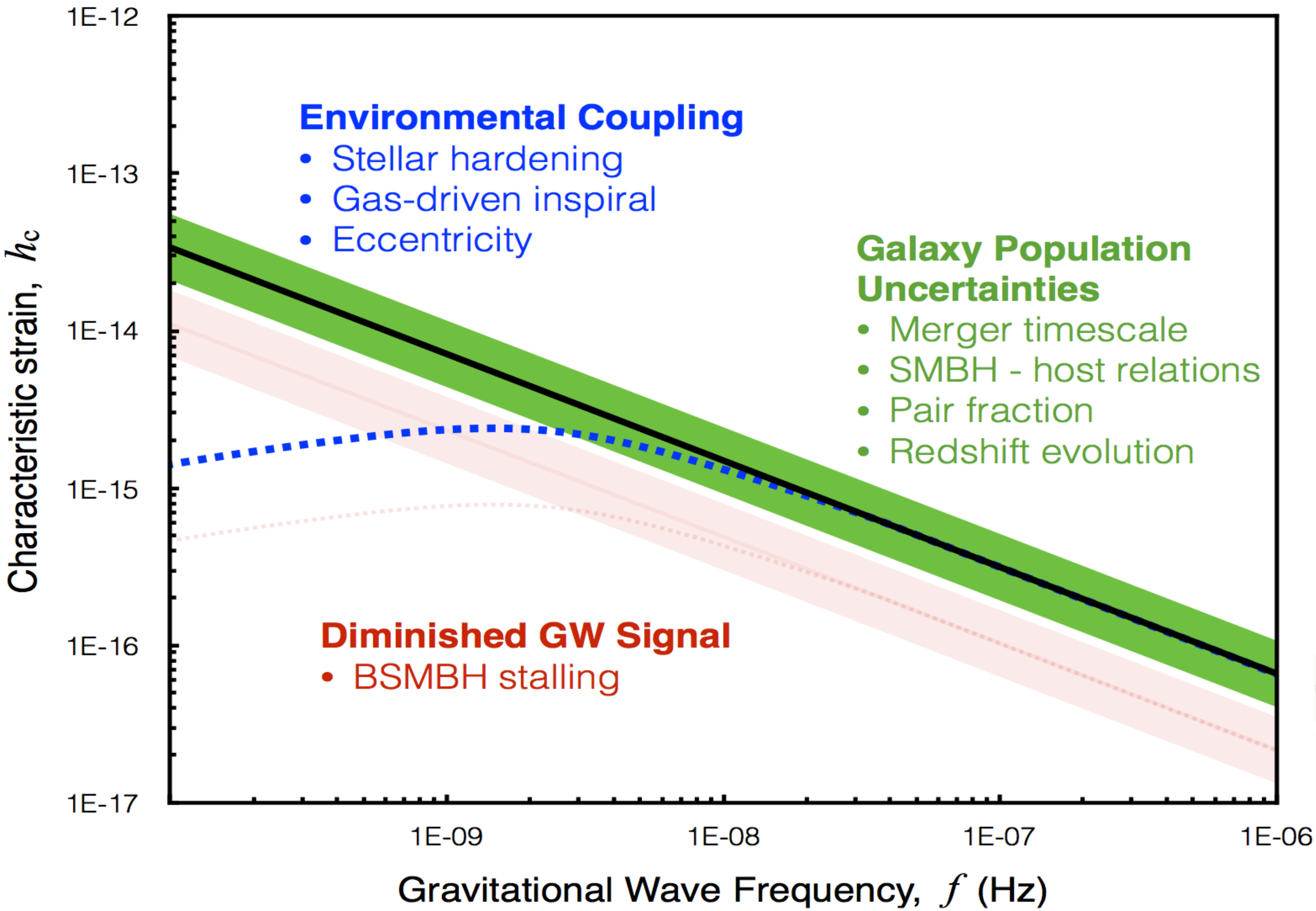
Z. ARZOUMANIAN[1], A. BRAZIER[2], S. BURKE-SPOLAOR[3,28], S. J. CHAMBERLIN[4], S. CHATTERJEE[2], B. CHRISTY[5], J. M. CORDES[2], N. J. CORNISH[6], K. CROWTER[7], P. B. DEMOREST[3], X. DENG[4], T. DOLCH[2,8], J. A. ELLIS[9,29], R. D. FERDMAN[10], E. FONSECA[7], N. GARVER-DANIELS[11], M. E. GONZALEZ[7,12], F. JENET[13], G. JONES[14], M. L. JONES[11], V. M. KASPI[10], M. KOOP[4], M. T. LAM[2], T. J. W. LAZIO[9], L. LEVIN[11], A. N. LOMMEN[5], D. R. LORIMER[11], J. LUO[13], R. S. LYNCH[15], D. R. MADISON[2,16,28], M. A. MCLAUGHLIN[11], S. T. MCWILLIAMS[11], C. M. F. MINGARELLI[17,18,30], D. J. NICE[19], N. PALLIYAGURU[11], T. T. PENNUCCI[20], S. M. RANSOM[16], L. SAMPSON[6], S. A. SANIDAS[21,22], A. SESANA[23], X. SIEMENS[24], J. SIMON[24], I. H. STAIRS[7], D. R. STINEBRING[25], K. STOVALL[26], J. SWIGGUM[11], S. R. TAYLOR[9], M. VALLISNERI[9], R. VAN HAASTEREN[9,29], Y. WANG[27], AND W. W. ZHU[7,18]
(THE NANOGRAV COLLABORATION)

Max-Planck-Institut
für Radioastronomie

Caltech

MARIE CURIE ACTIONS

recall Lucio Mayer's Talk



$$\left(\frac{da}{dt}\right)_{\rm stars} \propto a^2$$

$$\left(\frac{da}{dt}\right)_{\rm gas} \propto a^{1/2}$$

$$\left(\frac{da}{dt}\right)_{\rm gw} \propto a^{-3}$$

Max-Planck-Institut für Radioastronomie

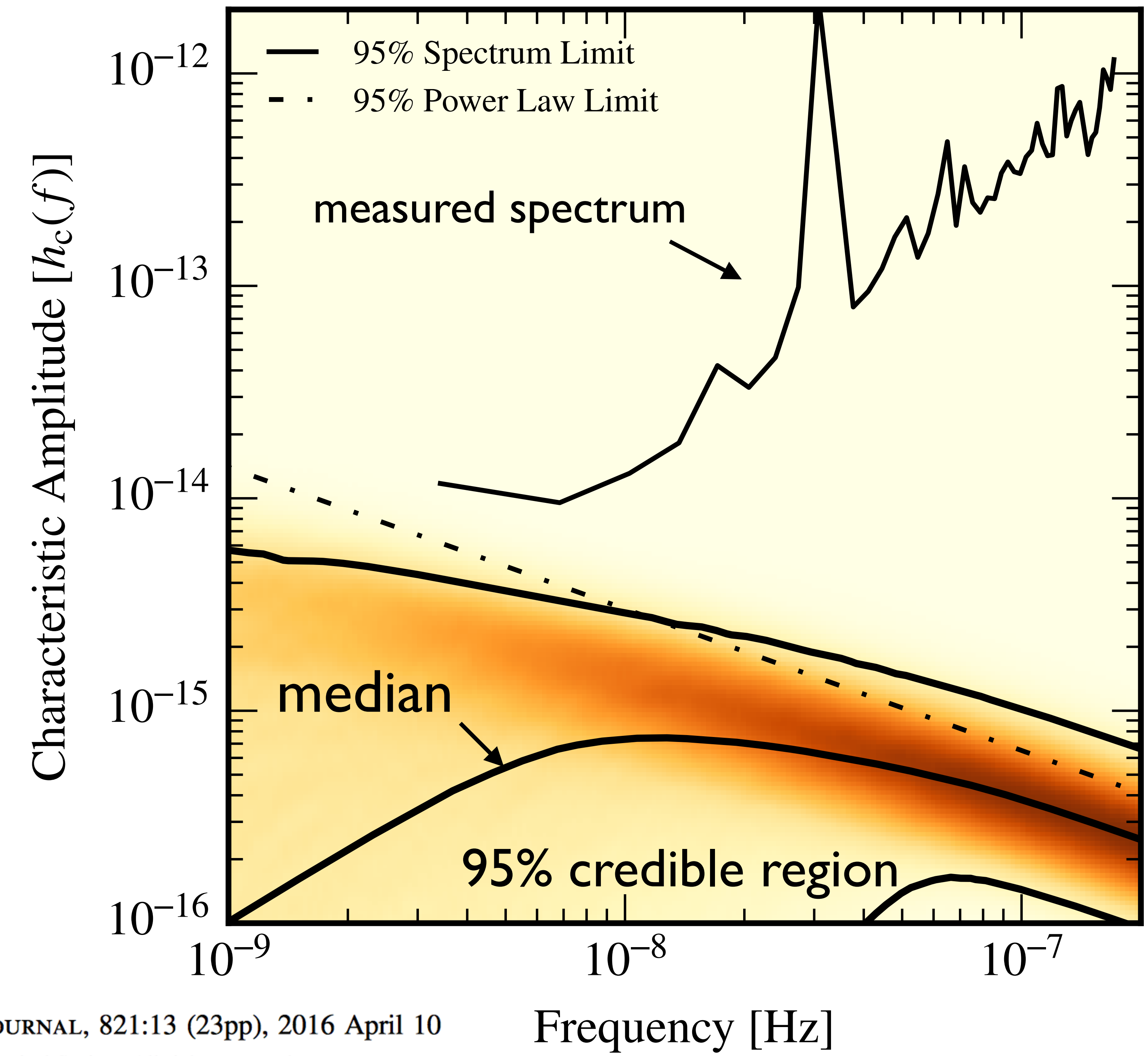
Stochastic background from SMBH mergers

[Sesana et al. 2012, Ravi et al. 2014, Burke-Spolaor 2015]

Caltech

MARIE CURIE ACTIONS

Shape of the spectrum



$$\mathcal{B} = 2.23 \pm 0.15$$

$$\left(\frac{da}{dt}\right)_{\rm stars} \propto a^2$$

$$\left(\frac{da}{dt}\right)_{\rm gas} \propto a^{1/2}$$

$$\left(\frac{da}{dt}\right)_{\rm gw} \propto a^{-3}$$

THE ASTROPHYSICAL JOURNAL, 821:13 (23pp), 2016 April 10

doi:10.3847/0004-637X/821/1/13

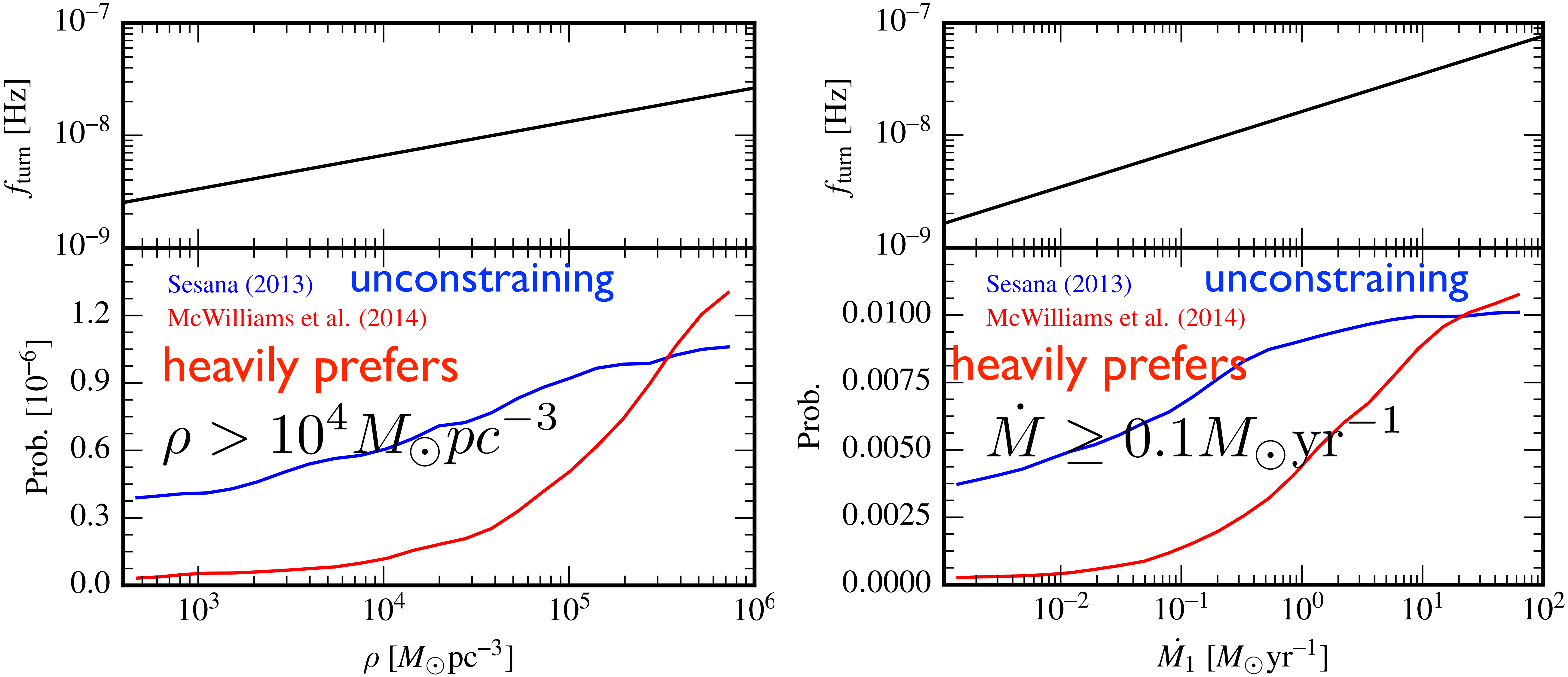
CrossMark

Max-Planck-Institut für Radioastronomie

THE NANOGRAV NINE-YEAR DATA SET: LIMITS ON THE ISOTROPIC STOCHASTIC GRAVITATIONAL WAVE BACKGROUND

Astrophysical Extraction

One or the other



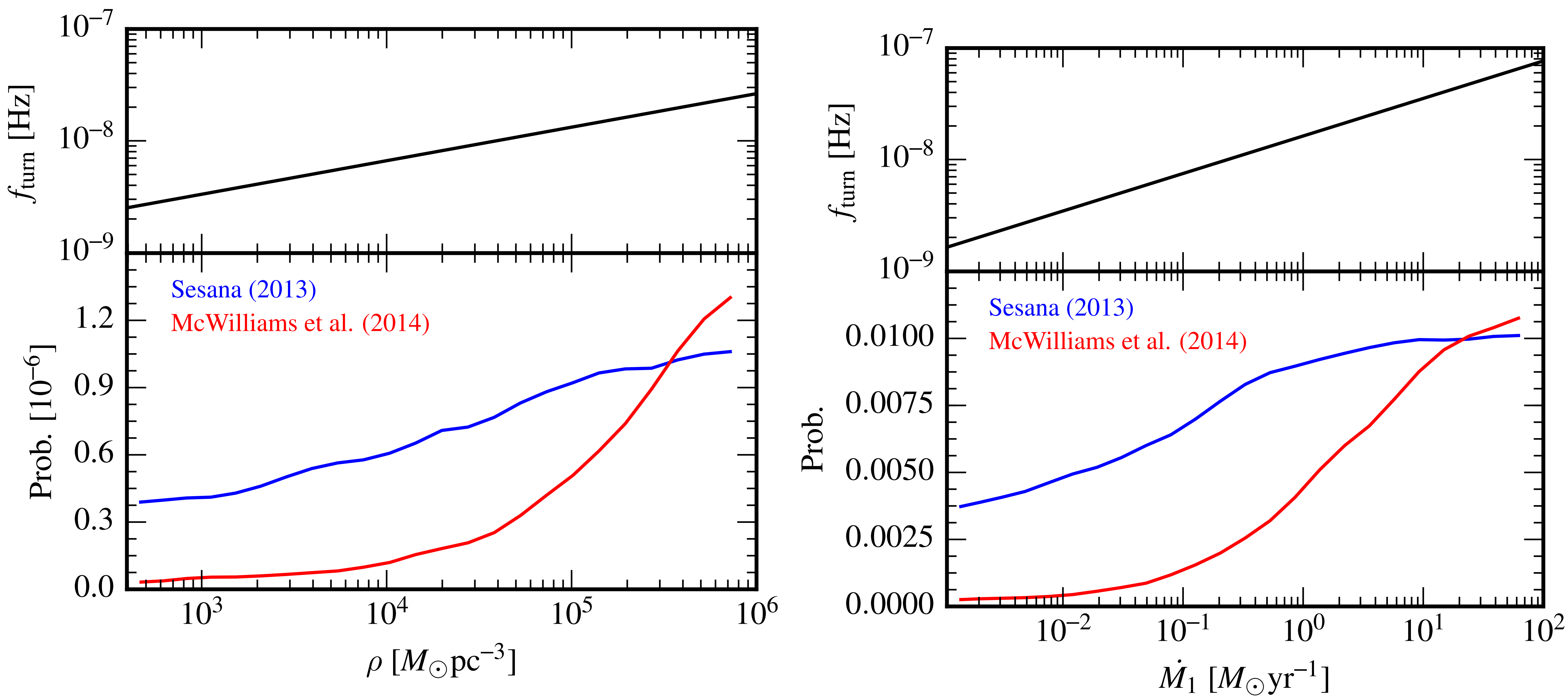
Typical densities of massive elliptical galaxies at the MBH influence radius is $10^3 M_\odot pc^{-3}$,

Max-Planck-Institut für Radioastronomie

Caltech

MARIE CURIE ACTIONS

Astrophysical Extraction



Get density of stars in SMBH environment, and accretion rate for an f_{turn} (Arzoumanian +2016)

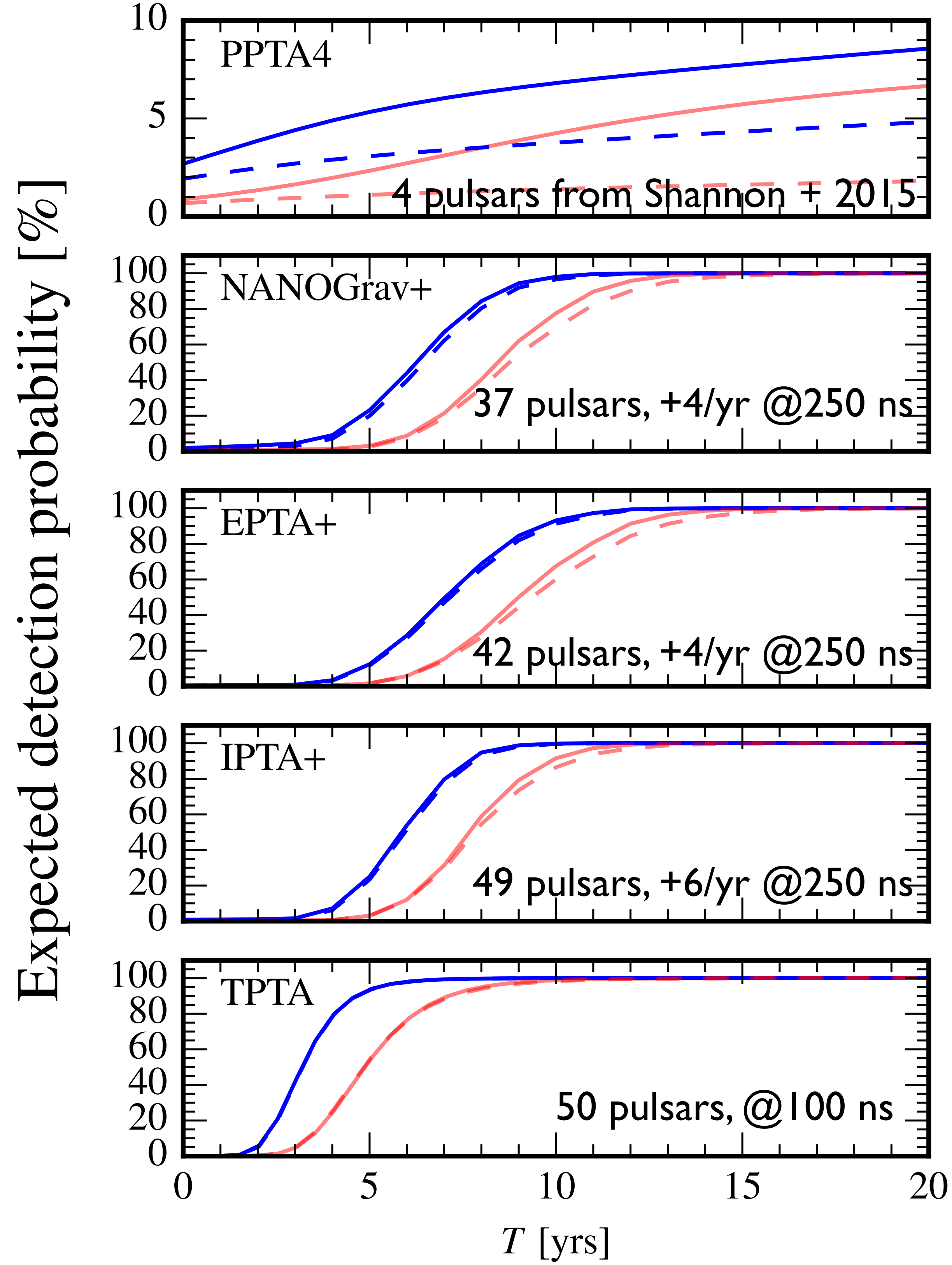
Max-Planck-Institut für Radioastronomie

Caltech

MARIE CURIE ACTIONS

Time to detection?

- Given A<1e-15, how long to detection?
- Large, expanding PTAs, e.g. NANOGrav, will detect in < 10 yrs
- blue line = no stalling, red line = 90% stalling, dashed line = 1/11yr turnover due to stellar hardening
- More: arXiv:1602.06301



Max-Planck-Institut für Radioastronomie

Taylor, Vallisneri, Ellis, **CMFM**, van Haasteren, Lazio, ApJL (2016)

Caltech

MARIE CURIE ACTIONS

New Results: cosmic strings

The Astrophysical Journal, 821:13 (23pp), 2016 April 10
doi:10.3847/0004-637X/821/1/13

CrossMark

THE NANOGRAV NINE-YEAR DATA SET: LIMITS ON THE ISOTROPIC STOCHASTIC GRAVITATIONAL WAVE BACKGROUND

Z. Arzoumanian[1], A. Brazier[2], S. Burke-Spolaor[3,28], S. J. Chamberlin[4], S. Chatterjee[2], B. Christy[5], J. M. Cordes[2], N. J. Cornish[6], K. Crowter[7], P. B. Demorest[3], X. Deng[4], T. Dolch[2,8], J. A. Ellis[9,29], R. D. Ferdman[10], E. Fonseca[7], N. Garver-Daniels[11], M. E. Gonzalez[7,12], F. Jenet[13], G. Jones[14], M. L. Jones[11], V. M. Kaspi[10], M. Koop[4], M. T. Lam[2], T. J. W. Lazio[9], L. Levin[11], A. N. Lommen[5], D. R. Lorimer[11], J. Luo[13], R. S. Lynch[15], D. R. Madison[2,16,28], M. A. McLaughlin[11], S. T. McWilliams[11], C. M. F. Mingarelli[17,18,30], D. J. Nice[19], N. Palliyaguru[11], T. T. Pennucci[20], S. M. Ransom[16], L. Sampson[6], S. A. Sanidas[21,22], A. Sesana[23], X. Siemens[24], J. Simon[24], I. H. Stairs[7], D. R. Stinebring[25], K. Stovall[26], J. Swiggum[11], S. R. Taylor[9], M. Vallisneri[9], R. van Haasteren[9,29], Y. Wang[27], and W. W. Zhu[7,18]
(The NANOGrav Collaboration)

Max-Planck-Institut für Radioastronomie

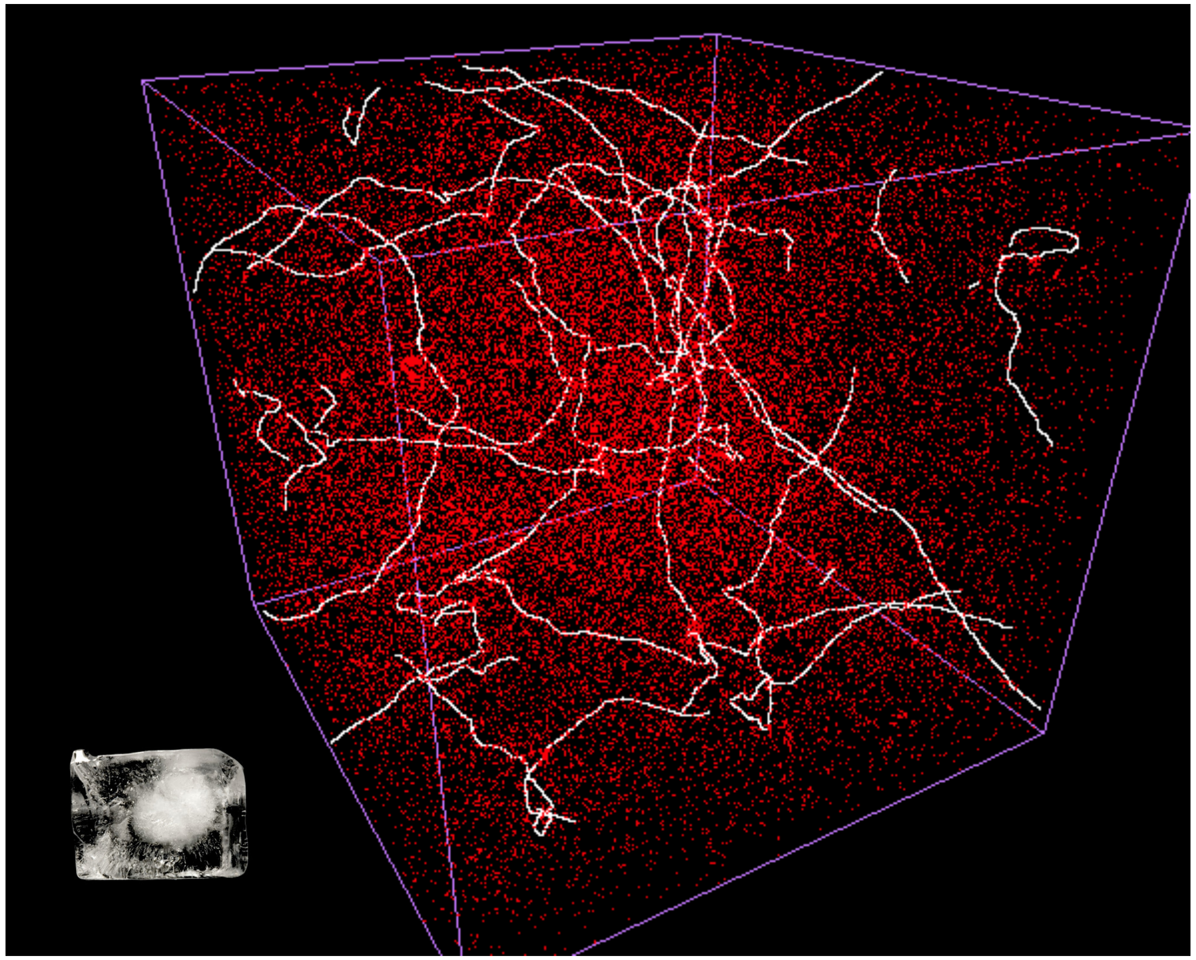
Caltech

MARIE CURIE ACTIONS

recall Sotiris Sanidas talk

Cosmic (super)Strings

- Loops decay via GW emission, creating background 10^{-16} Hz -10^{9} Hz, depending on size of loops created
- Create a background which could be detected by PTAs; place limits on string tension



C. Ringeval, F. Bouchet

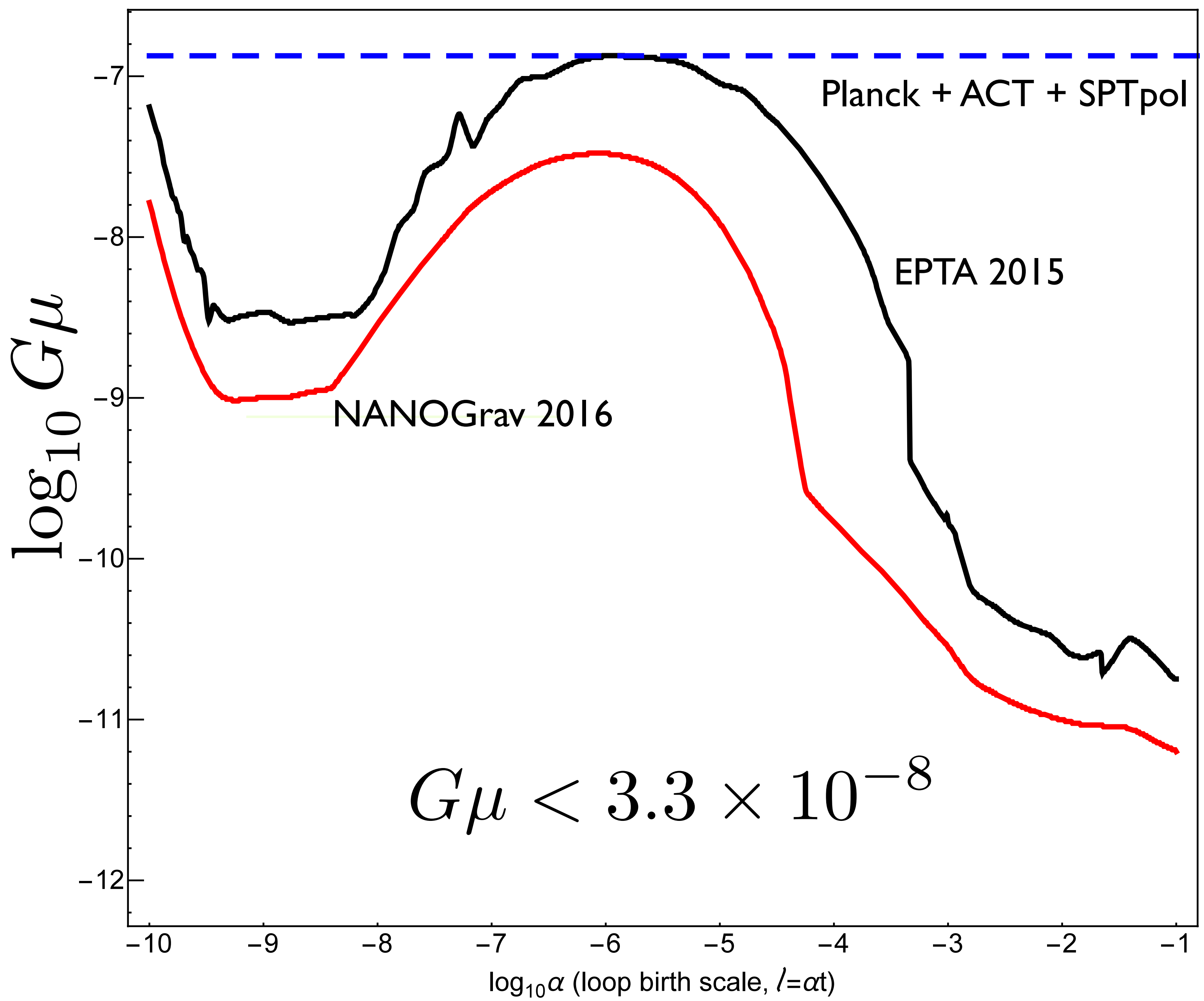
Max-Planck-Institut für Radioastronomie

Caltech

MARIE CURIE ACTIONS

NANOGrav 9-yr Results

- Both the amplitude and spectral slope information of the GWB limits were used to construct the limits.
- Nambu-Goto (field theory strings) with p=1
- 4x better than limit by *Planck* + Atacama Cosmology Telescope + SouthPoleTelescope



Arzoumanian et al. (including CMFM; 2016)

In SI units, linear density of string is 10^20 kg/m.

Max-Planck-Institut für Radioastronomie

Caltech

MARIE CURIE ACTIONS

New Results: Primordial Backgrounds

PHYSICAL REVIEW X **6,** 011035 (2016)

Gravitational-Wave Cosmology across 29 Decades in Frequency

Paul D. Lasky,[1*] Chiara M. F. Mingarelli,[2,3] Tristan L. Smith,[4] John T. Giblin, Jr.,[5,6] Eric Thrane,[1] Daniel J. Reardon,[1] Robert Caldwell,[7] Matthew Bailes,[8] N. D. Ramesh Bhat,[9] Sarah Burke-Spolaor,[10] Shi Dai,[11,12] James Dempsey,[13] George Hobbs,[11] Matthew Kerr,[11] Yuri Levin,[1] Richard N. Manchester,[11] Stefan Osłowski,[14,3] Vikram Ravi,[15] Pablo A. Rosado,[8] Ryan M. Shannon,[11,9] Renée Spiewak,[16] Willem van Straten,[8] Lawrence Toomey,[11] Jingbo Wang,[17] Linqing Wen,[18] Xiaopeng You,[19] and Xingjiang Zhu[18]

recall Angelo Ricciardone's talk

Primordial Background

- Primordial radiation can manifest as a contribution to the present day GW energy density $\Omega_{\rm gw}(f)$
- GWB spectrum directly related to the primordial tensor spectral index $n_{t,}$ tensor-to-scalar ratio "r"
- non-standard evolution of the Universe during inflation or non-standard power in GW modes when exiting horizon can produce blue spectra
- non-inflationary theories e.g. ekpyrosis + string-gas also predict blue spectra

$$\Omega_{\rm gw}(f) = \Omega_{\rm gw}^{\rm CMB}\left(\frac{f}{f_{\rm CMB}}\right)^{n_t}\left[\frac{1}{2}\left(\frac{f_{\rm eq}}{f}\right)^2 + \frac{16}{9}\right]$$

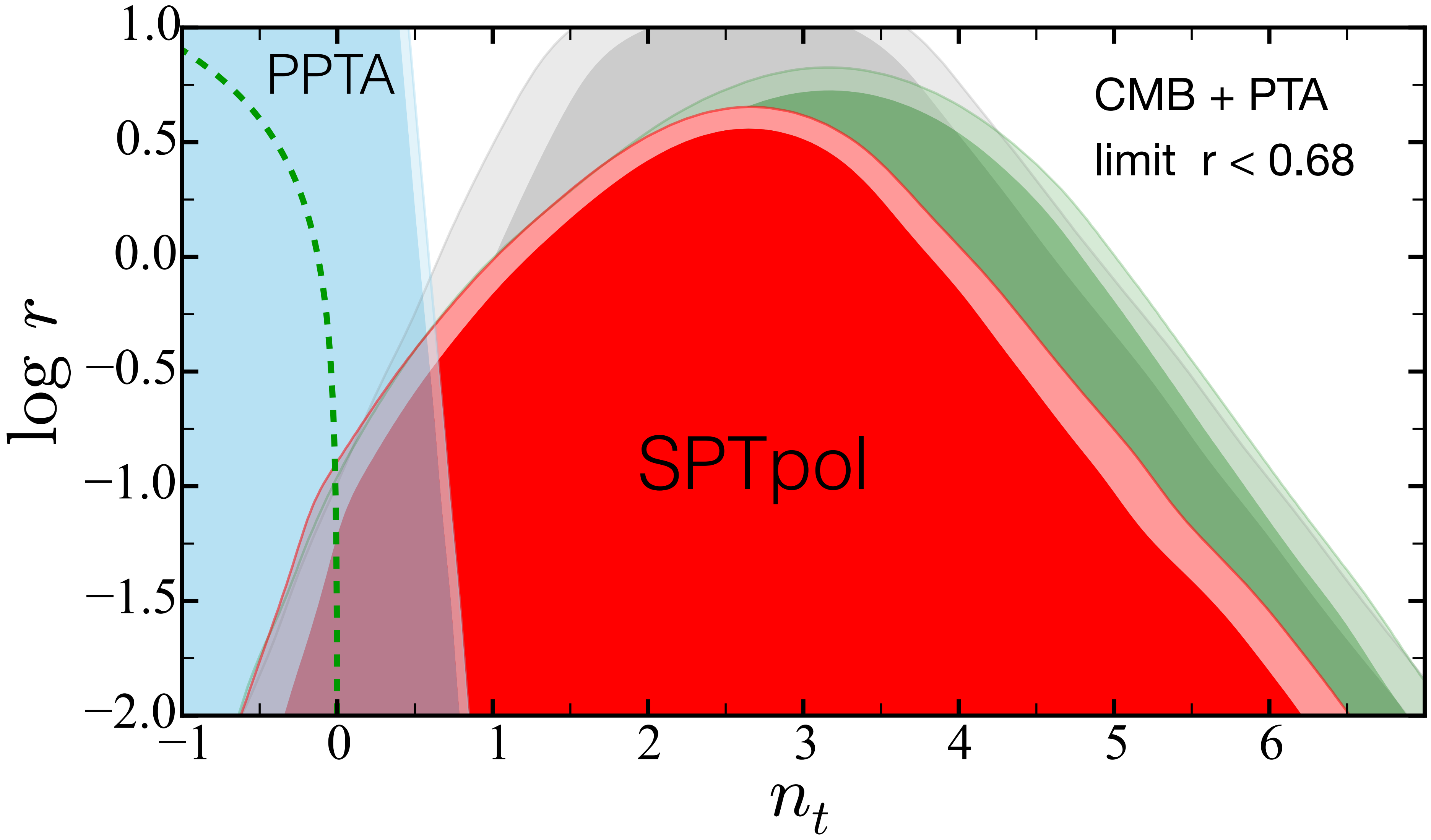
Max-Planck-Institut für Radioastronomie

e.g. Turner, White, Lindsey (1993); Smith, Kamionkowski, Cooray (2008)

Caltech

MARIE CURIE ACTIONS

Primordial background: Better together



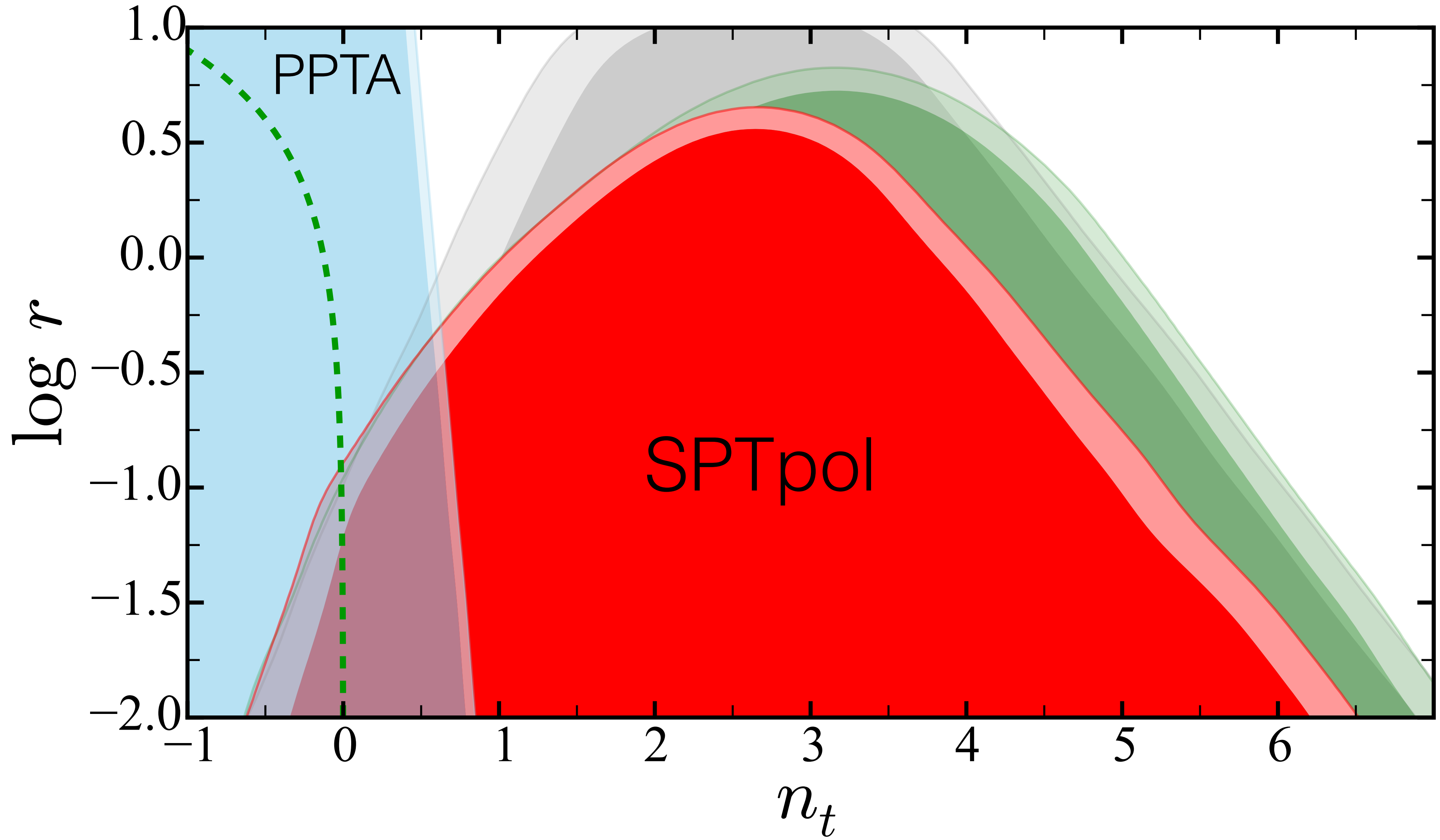
Lasky, **CMFM**, Smith, Thrane, Giblin, Caldwell + (2016)

Max-Planck-Institut
für Radioastronomie

Caltech

MARIE CURIE ACTIONS

Primordial background: Better together



Lasky, **CMFM**, Smith, Thrane, Giblin, Caldwell + (2016)

Max-Planck-Institut für Radioastronomie

Caltech

Future Directions

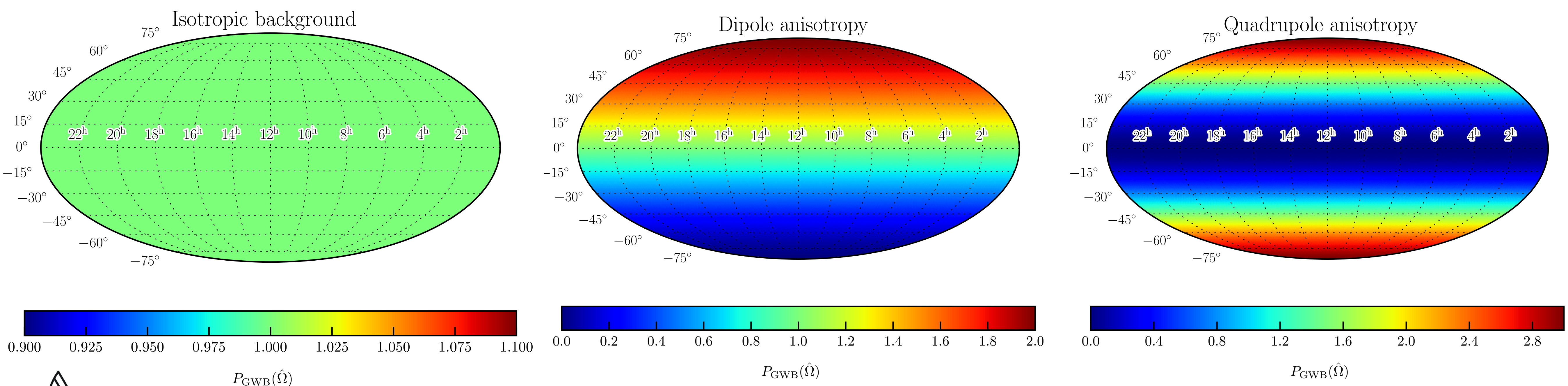
Max-Planck-Institut
für Radioastronomie

Caltech

MARIE CURIE ACTIONS

Introducing Anisotropy

- residuals $\propto \int_{S^2} d\hat{\Omega}$ (**power distribution** x response)
- Nearby and/or loud sources may introduce anisotropy
- CMB anisotropy on very small scales, GWB anisotropy large-scale (?)

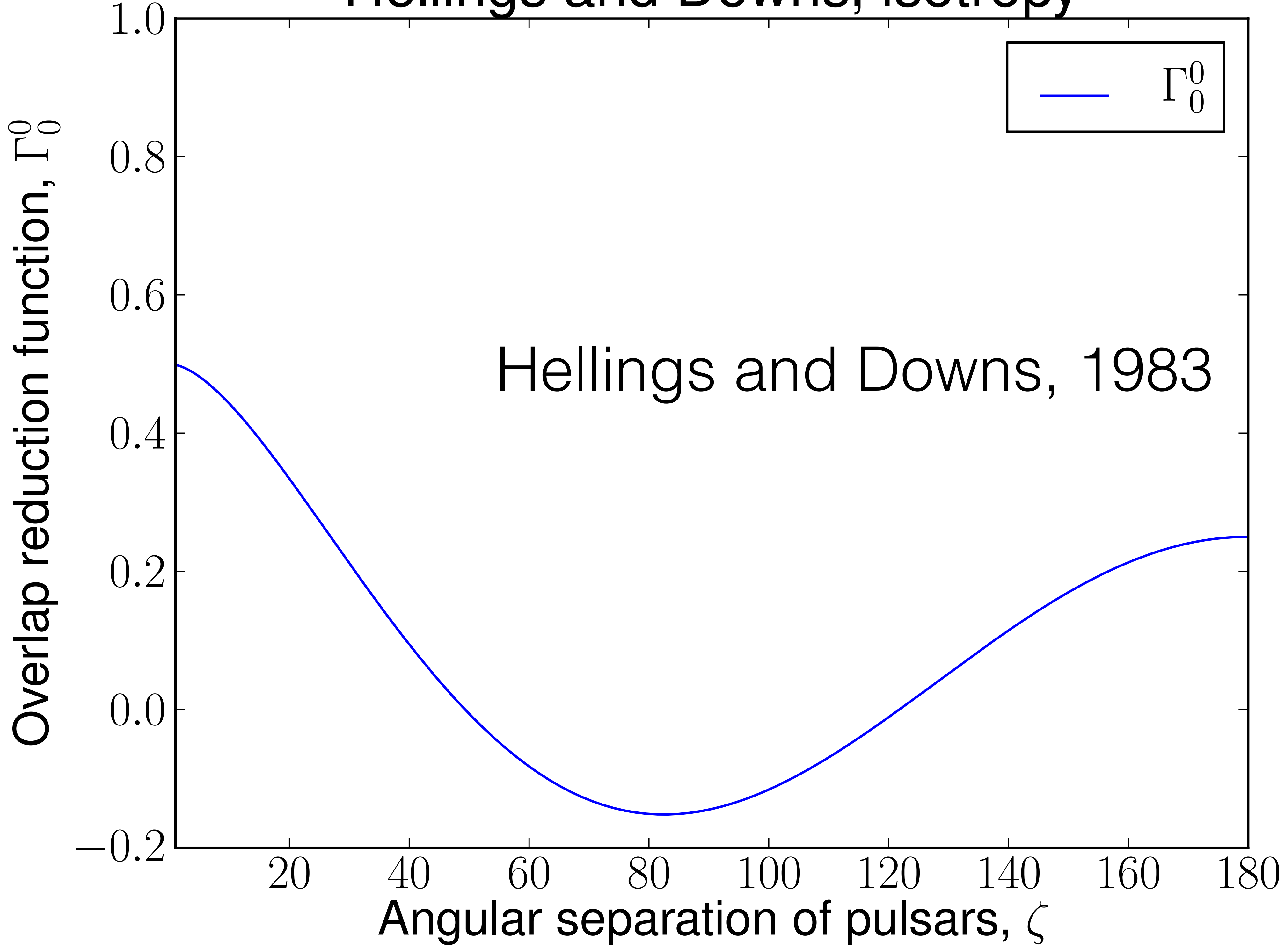


Max-Planck-Institut für Radioastronomie

Caltech

MARIE CURIE ACTIONS

Hellings and Downs, isotropy

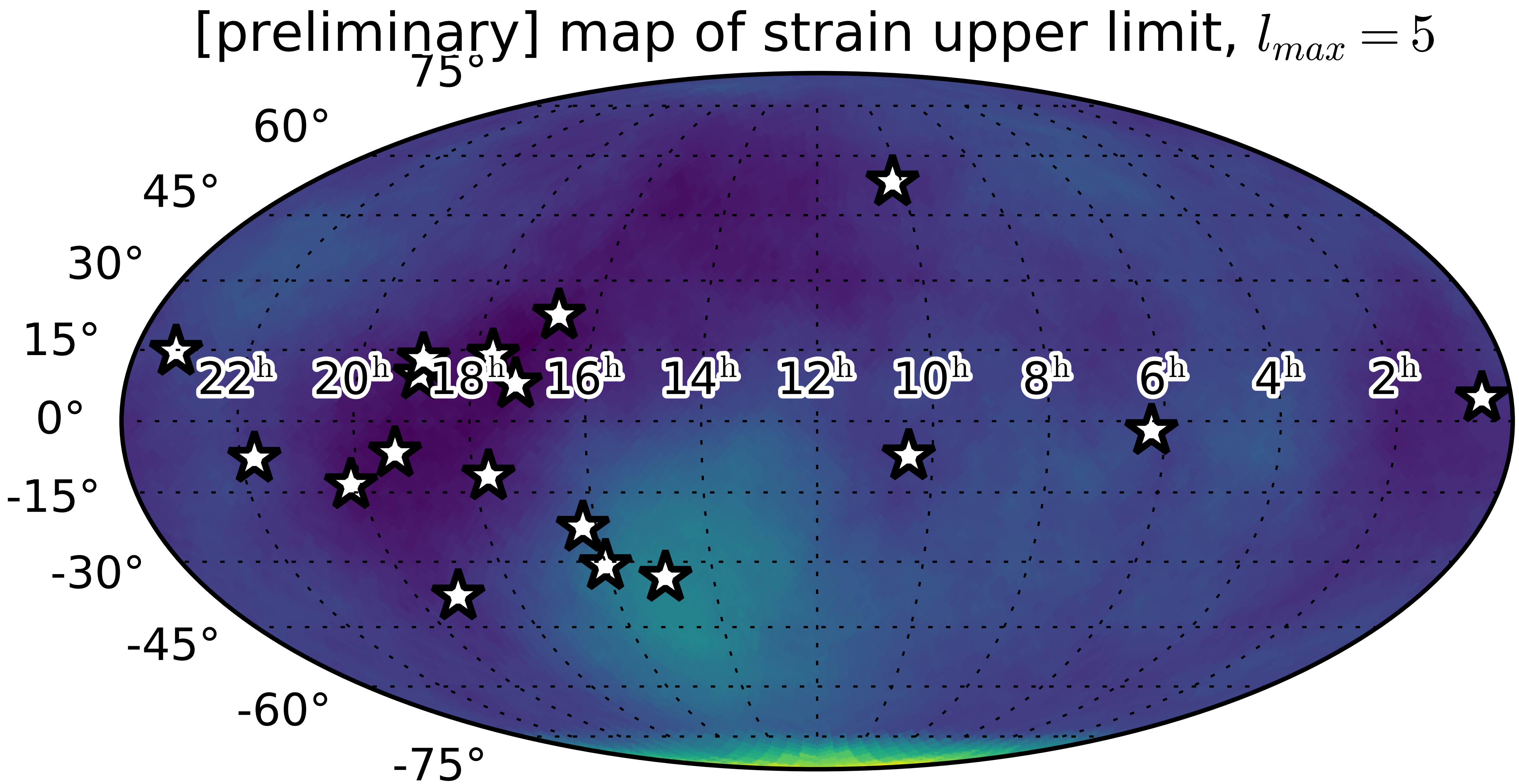


CMFM et al. PRD **88**, 062005 (2013)

Max-Planck-Institut für Radioastronomie

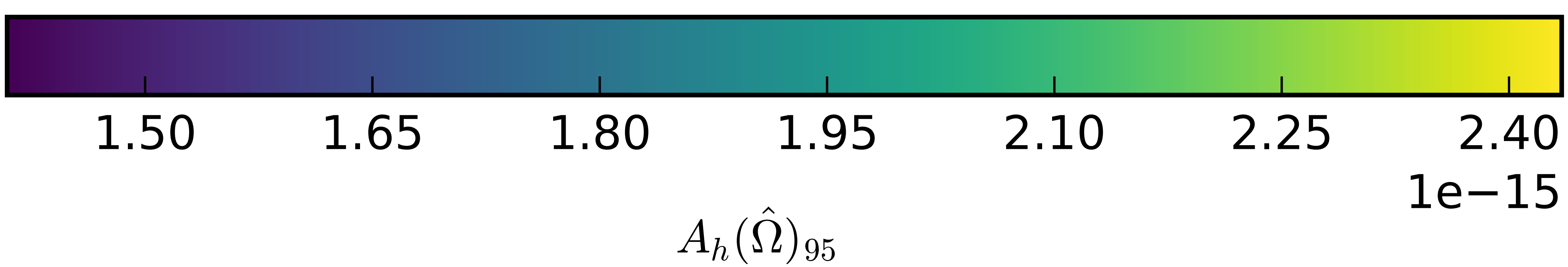
Caltech

MARIE CURIE ACTIONS



CMFM + for NANOGrav, in prep

pulsars ++

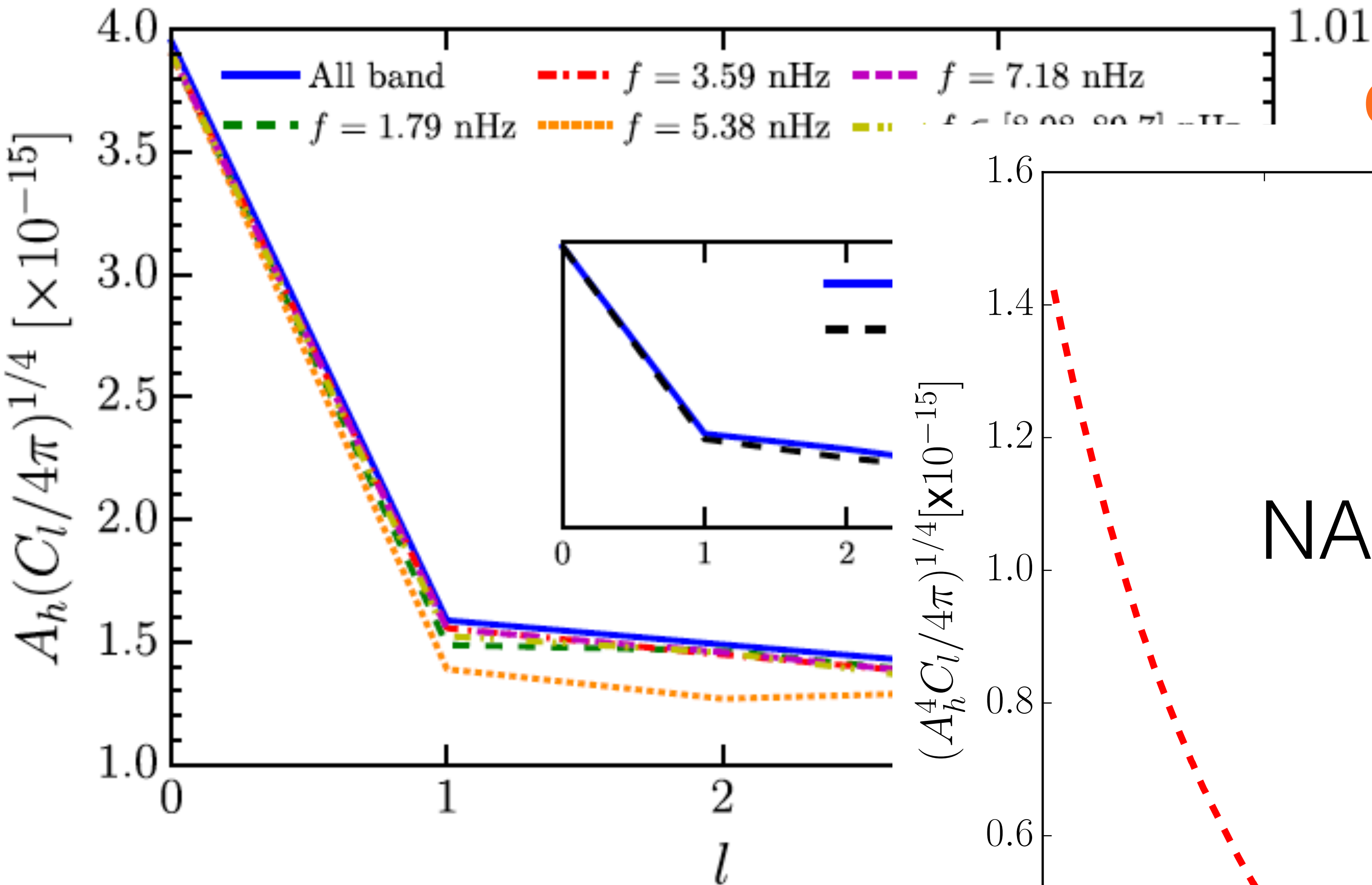


Max-Planck-Institut für Radioastronomie

Isotropic limit A < 1.5 x 10^{-15}

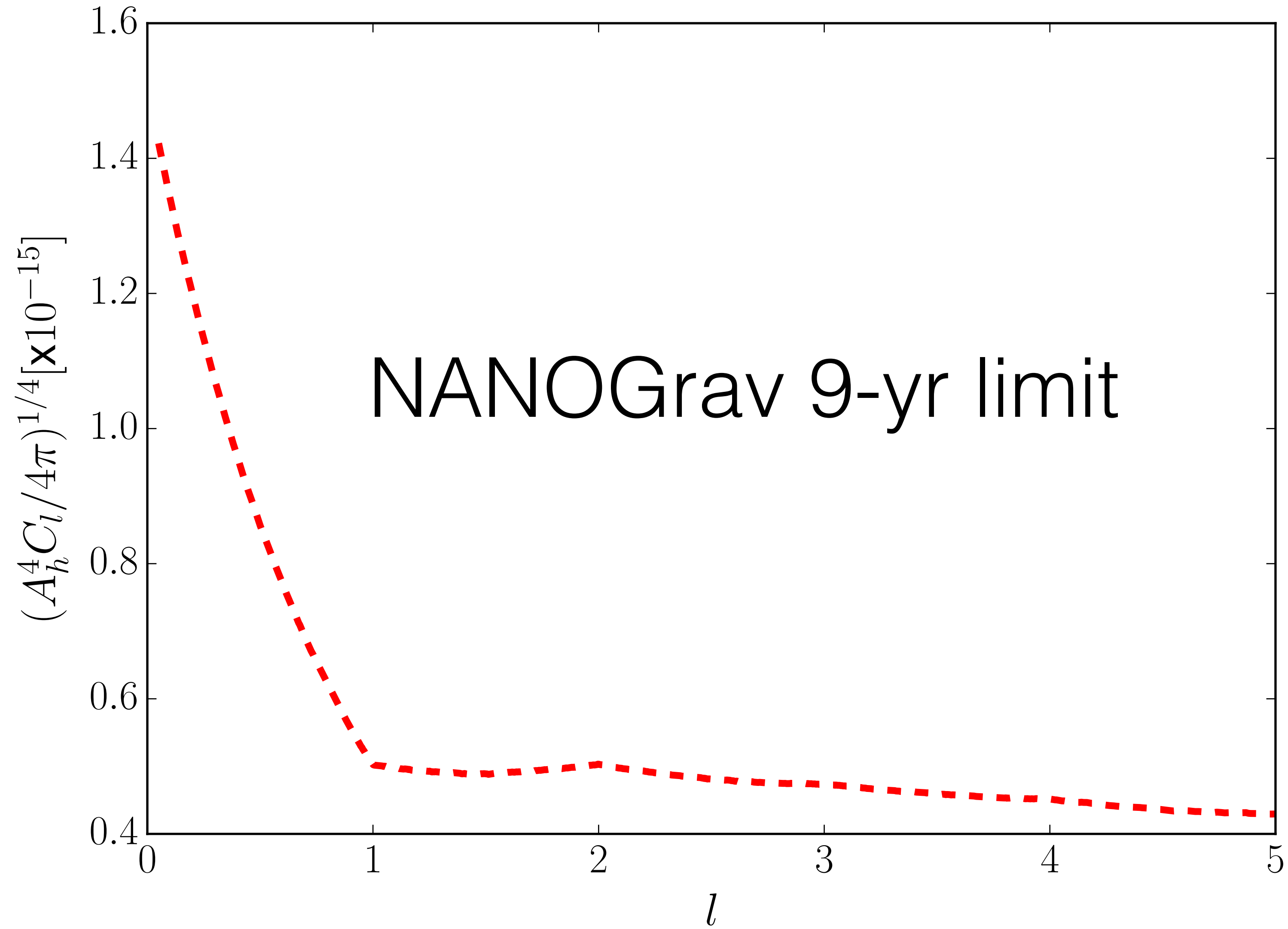
$$l = 180/\sqrt{\Delta\Omega/\mathrm{deg}^2}$$

How much anisotropy?



Taylor, CMFM + (PRL, 2015

CMFM + for NANOGrav, in prep



- Red dashed line shows 95% upper limit on strain amplitude
- **32% GW power contained in higher multipoles,** EPTA 40%.

Max-Planck-Institut für Radioastronomie

Caltech

MARIE CURIE ACTIONS

Detection: Bayes Factors

- To make us credible, we need to show how our signal improves over time
- Preliminary Bayes factor results using the Savage-Dickey ratio
  - ratio of the marginal posterior density and the prior density evaluated in noise regime

Description	Bayes Factor
anisotropy: (signal + noise) vs noise only	0.6
anisotropic vs isotropic	0.8
(isotropic + noise) vs noise only	0.5

CMFM + for NANOGrav, in prep

Summary

- PTA **interdisciplinary** science experiment: radio astronomy, GWB +anisotropy+CW, galaxy evolution, SMBH env, ISM, cosmology
- Rule out sub-centiparsec binaries **with $M_c >$ 10^9 M out to 25 Mpc**; **with $M_c >$ 10^{10} M: out to 1 Gpc ($z \approx$ 0.2) for $f <$ 10 nHz**
- Already **placing astrophysical constraints** on SMBHB environments
- **Best** cosmic string tension limits, **4x more constraining** that combined CMB+ ACT + SPTpol measurements
- **New:** first NANOGrav limit for stochastic background anisotropy, in preparation
- **Detection** expected in 7-10 years, evidence for GWB soon

Max-Planck-Institut
für Radioastronomie

Thank You!

Caltech

MARIE CURIE ACTIONS