Title: The Gravitational-Wave Universe seen by Pulsar Timing Arrays

Date: Nov 03, 2016 01:00 PM

URL: http://pirsa.org/16110018

Abstract: <p>Galaxy mergers are a standard aspect of galaxy formation and evolution, and most (likely all) large galaxies contain supermassive black holes. As part of the merging process, the supermassive black holes should in-spiral together and eventually merge, generating a background of gravitational radiation in the nanohertz to microhertz regime. Processes in the early Universe such as relic gravitational waves and cosmic strings may also generate gravitational radiation in the same frequency band. An array of precisely timed pulsars spread across the sky can form a galactic-scale gravitational wave detector in the nanohertz band. I describe the current efforts to develop and extend the pulsar timing array concept, together with recent limits which have emerged from North American and international efforts to constrain astrophysical phenomena at the heart of supermassive black hole mergers.</p>

The Gravitational-Wave Universe seen by PTAs

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Max Planck Institute for Radio Astronomy / Caltech

Perimeter Institute, Waterloo
November 3rd 2016

Outline

- The gravitational-wave spectrum
- Pulsar Timing Arrays
- The gravitational-wave background
- Do supermassive black holes merge?
- Primordial gravitational wave backgrounds
- Future directions

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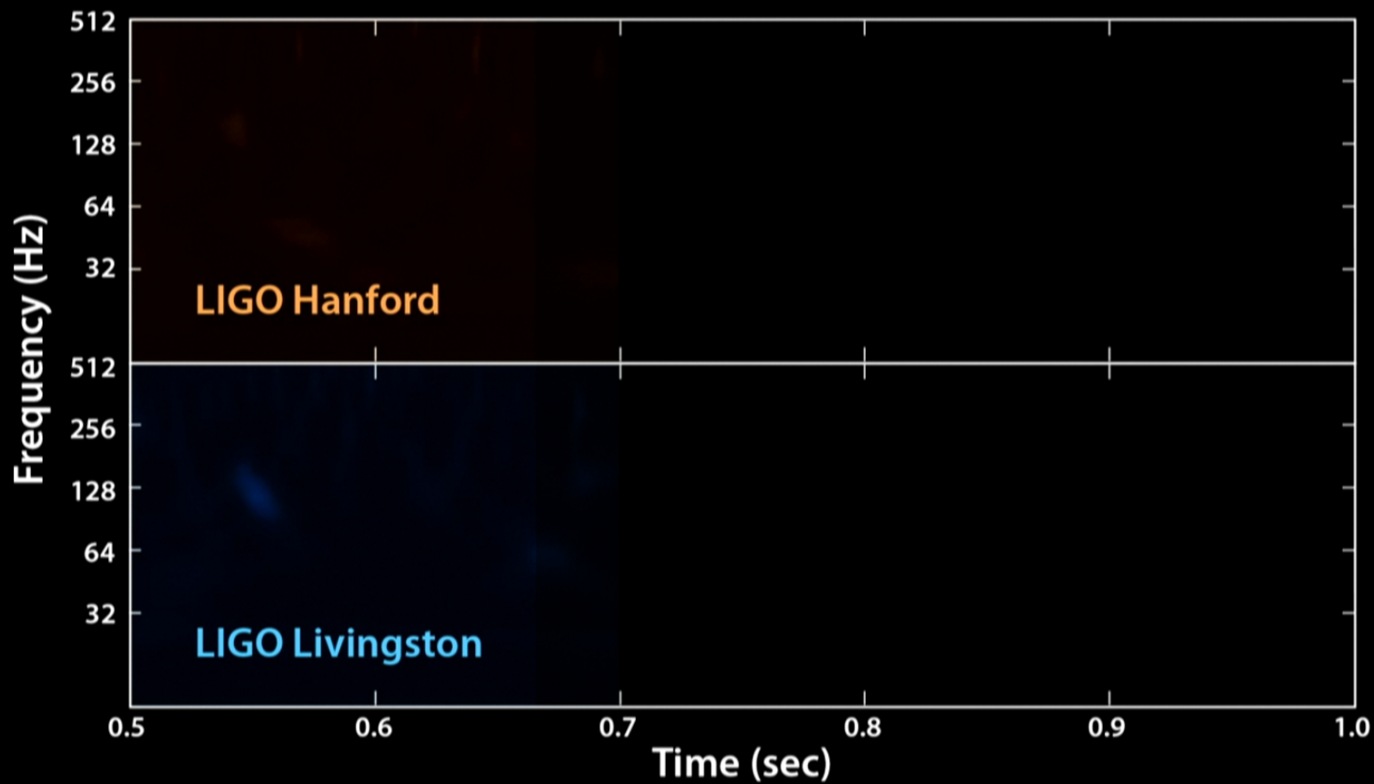
Gravitational Waves

Masses with varying quadrupole moments will emit GWs.

Image credit: The SXS (Simulating eXtreme Spacetimes) Project

Discovered Sep 14 2015



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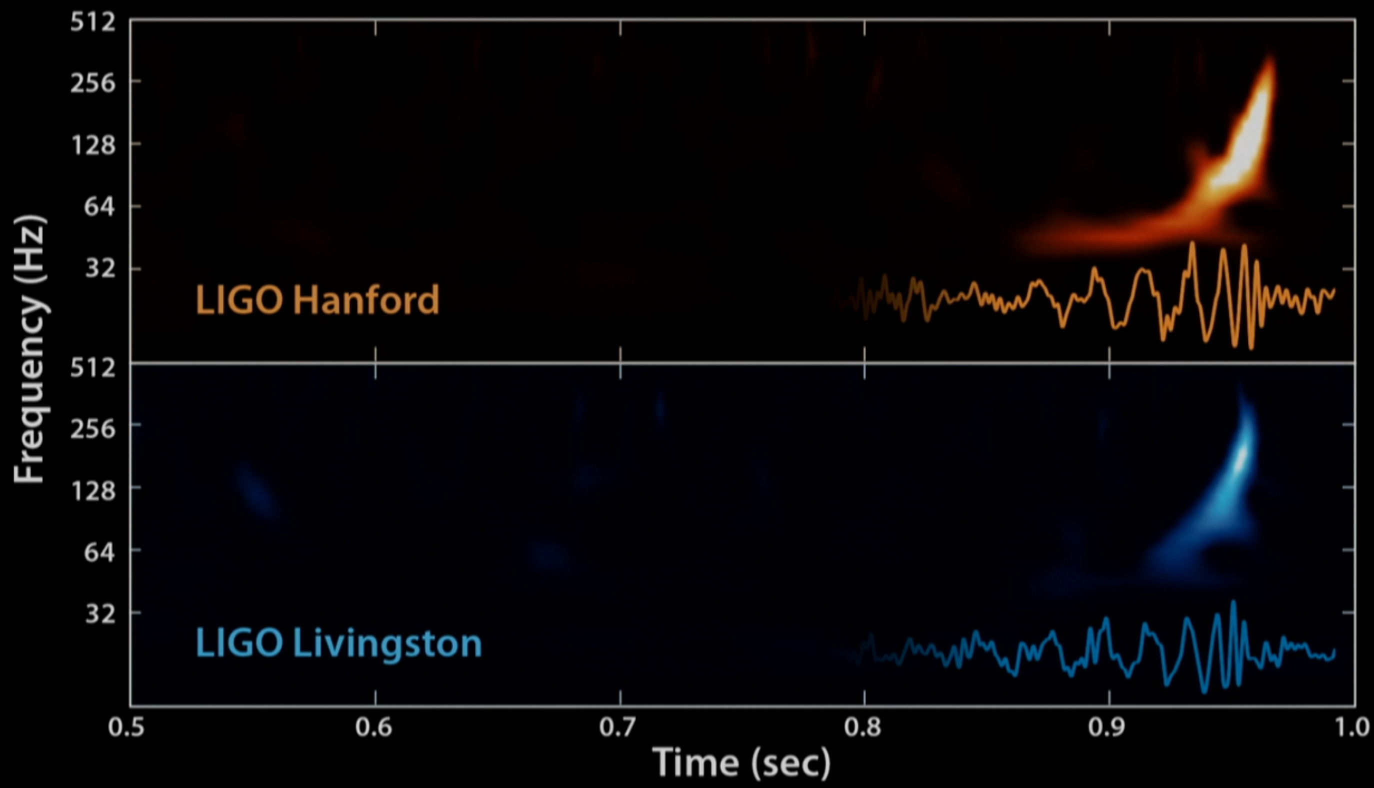

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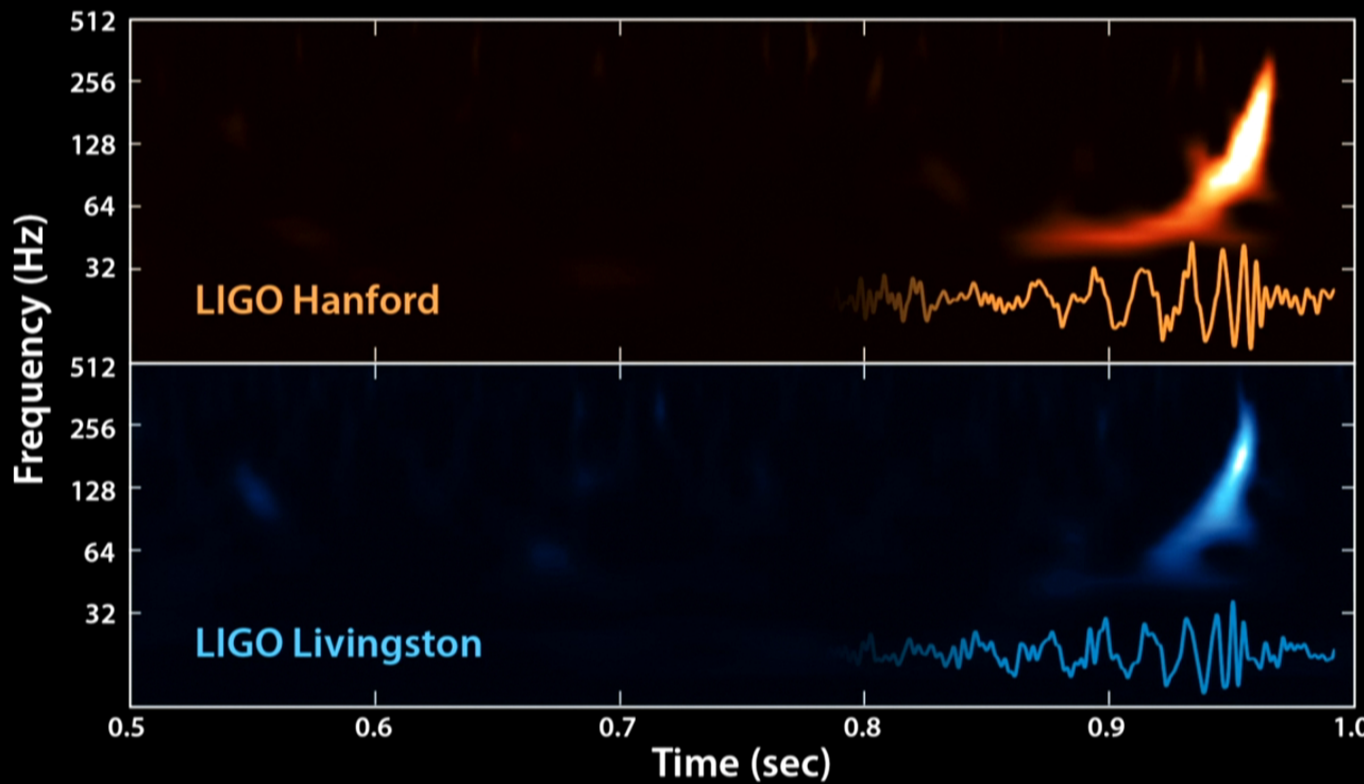
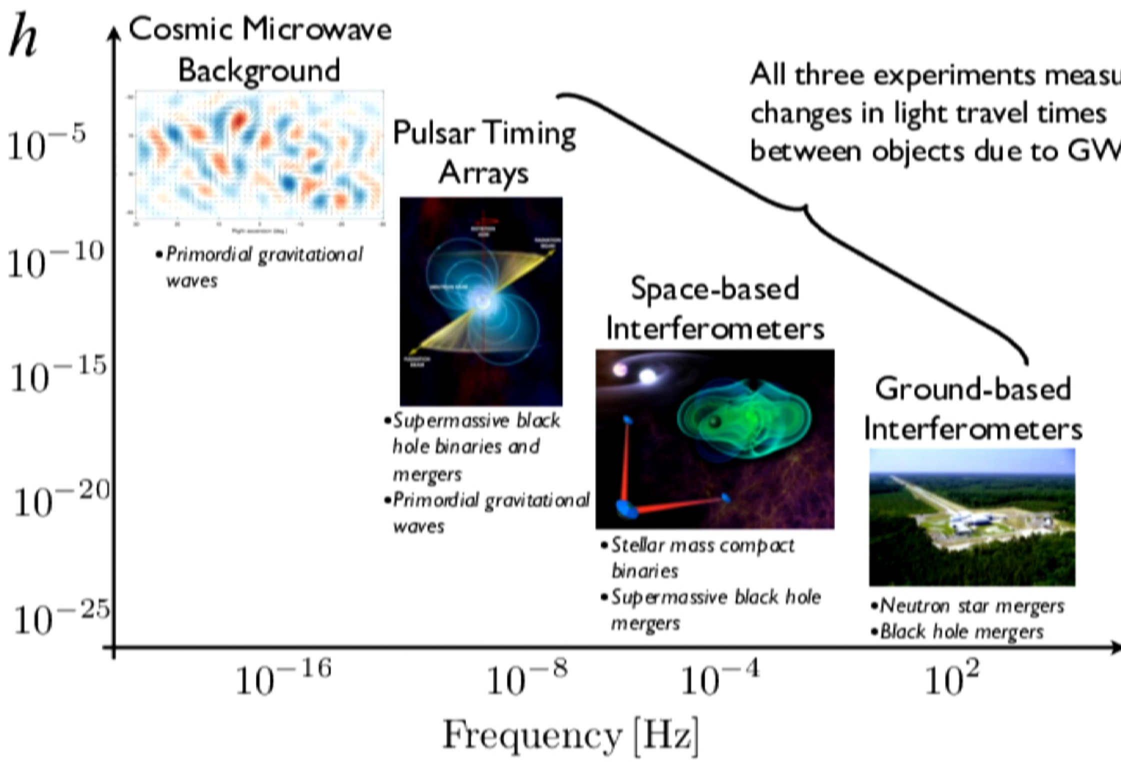


NANOGrav

The spectrum of gravitational wave astronomy



LIGO can’t see PTA sources

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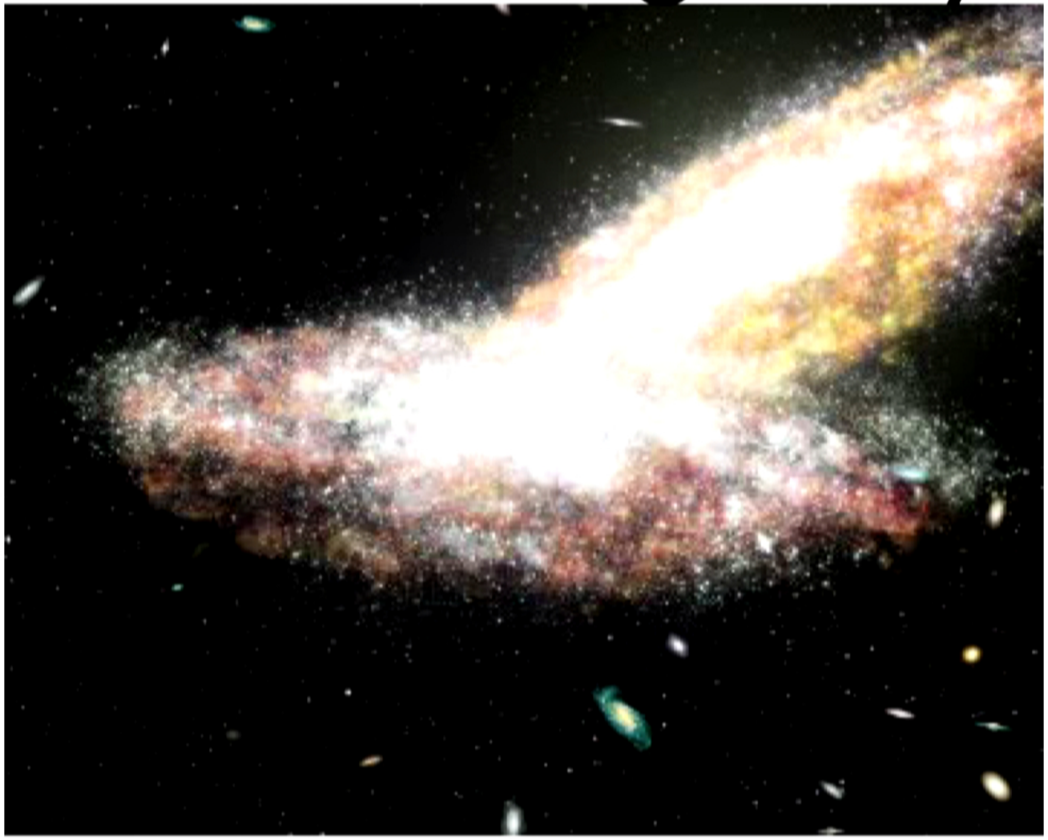
Pulsar Timing Array



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

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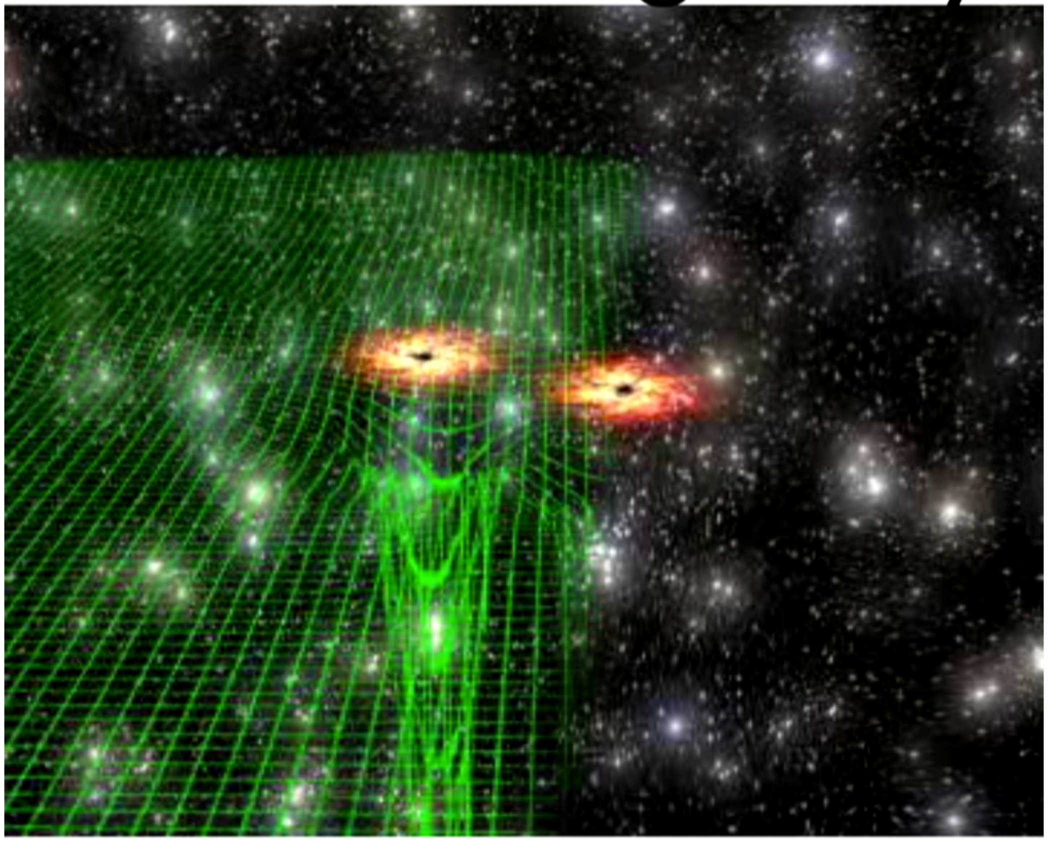
Pulsar Timing Array



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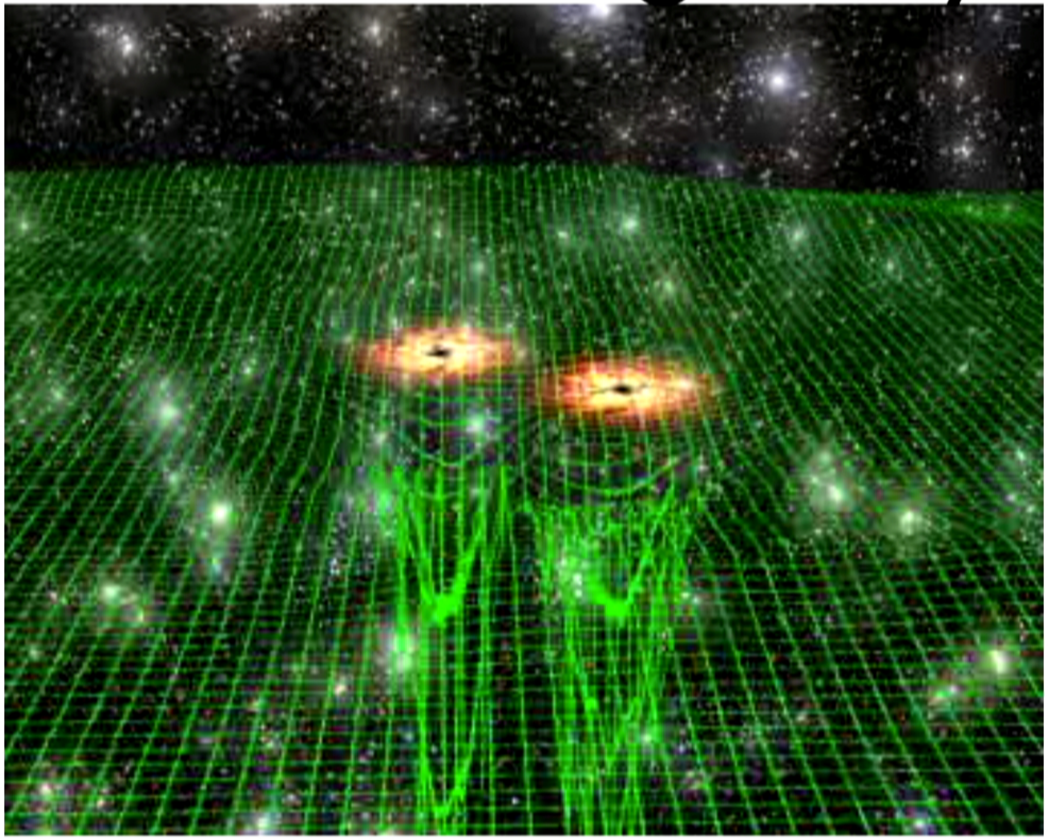

Animation from John Rowe Animation/Australia Telescope National Facility, CSIRO

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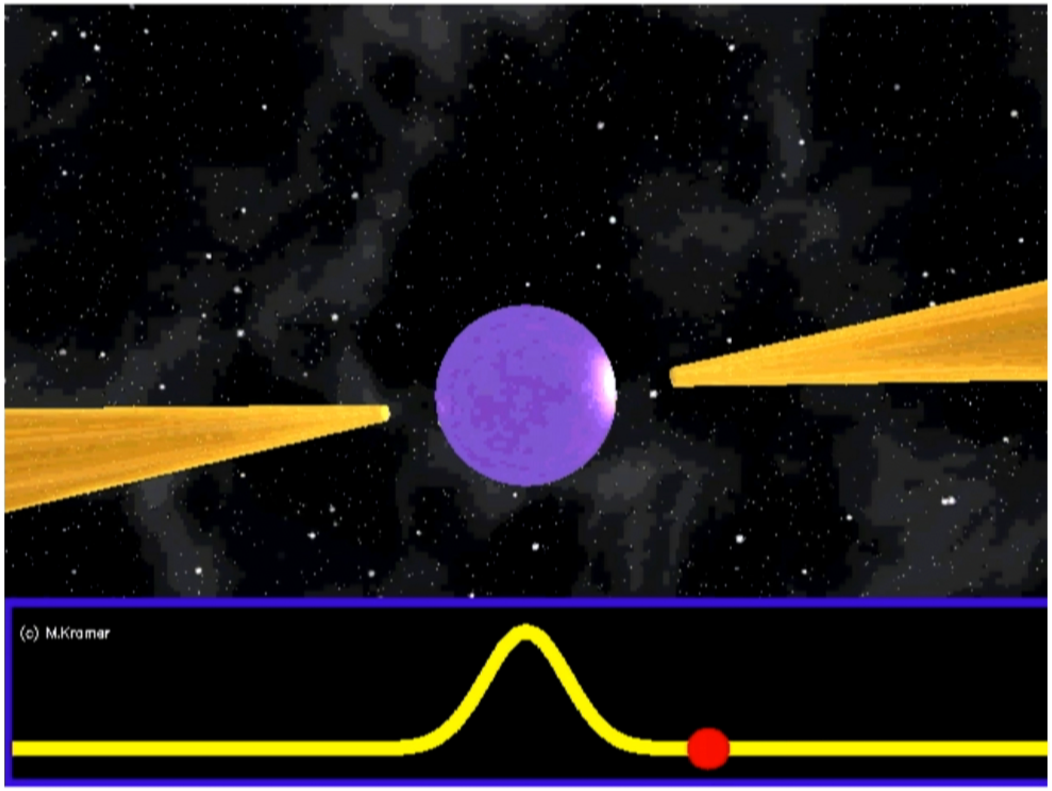
pulsars

Pulsars are rotating neutron stars. They are compact, rapidly rotating, high magnetic field remnants of supernova explosions.



Vela
11 Hz

Crab
30 Hz

B1937+21
642 Hz

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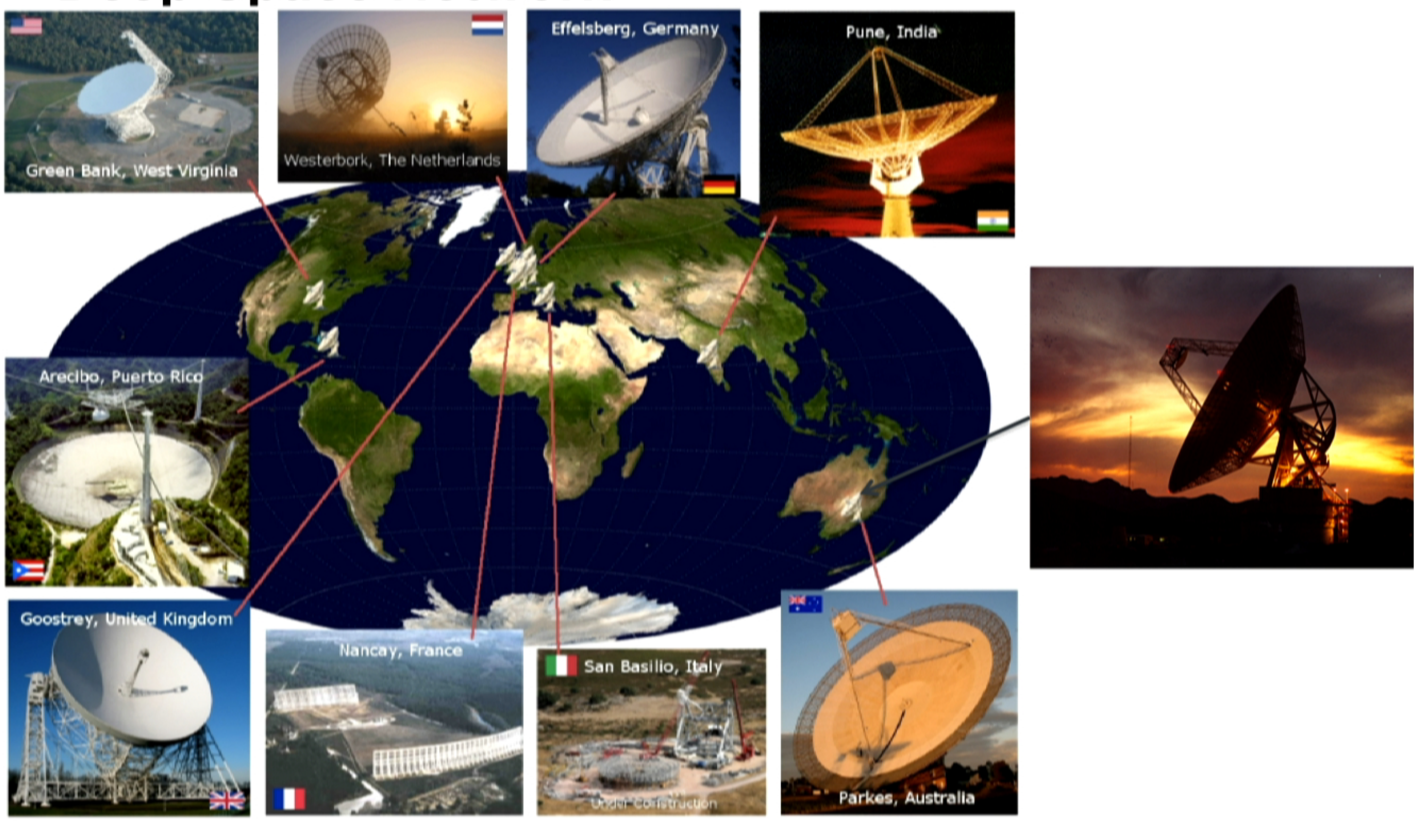
Gravitational Waves, Pulsar Timing, and the Deep Space Network



courtesy Joe Lazio

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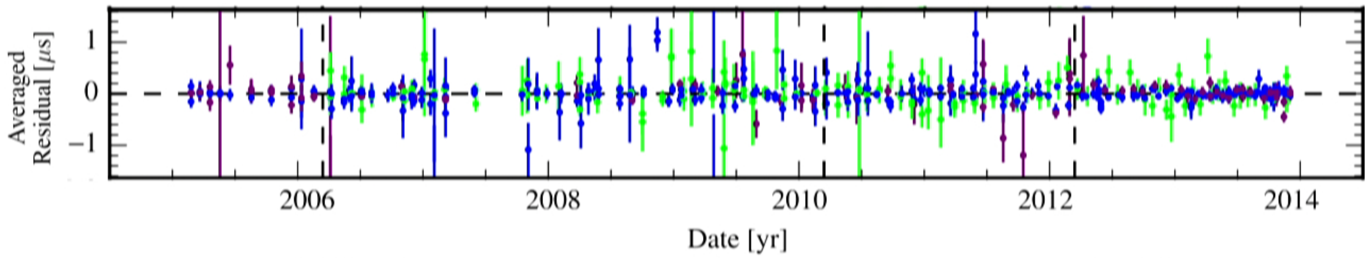
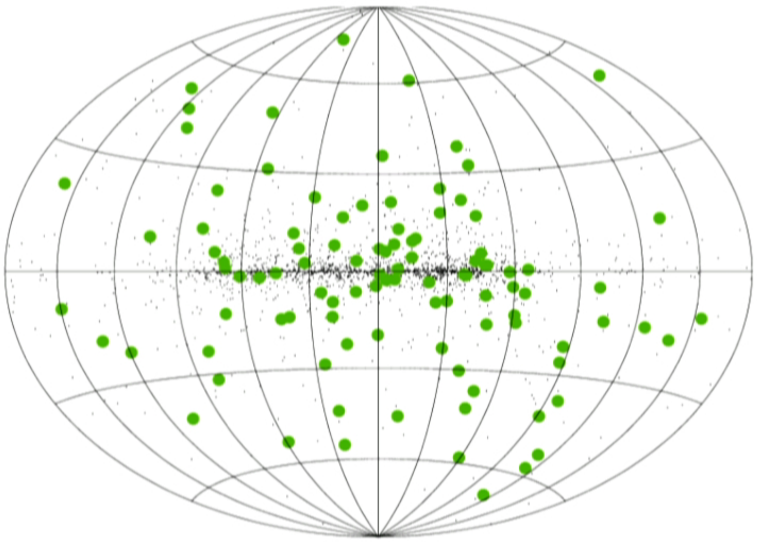
Millisecond Pulsars



J1713+0747



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

courtesy Maura McLaughlin

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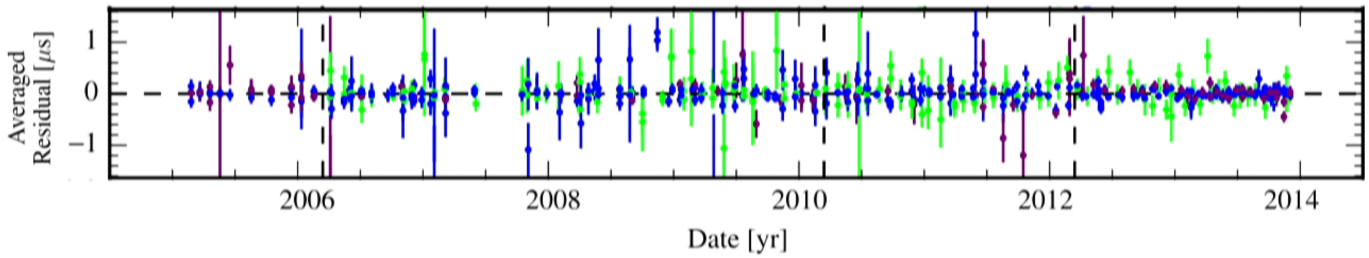
Millisecond Pulsars



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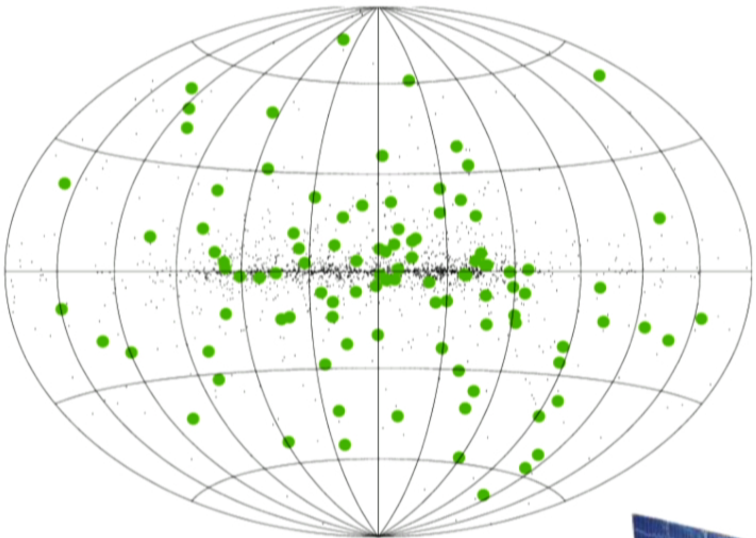

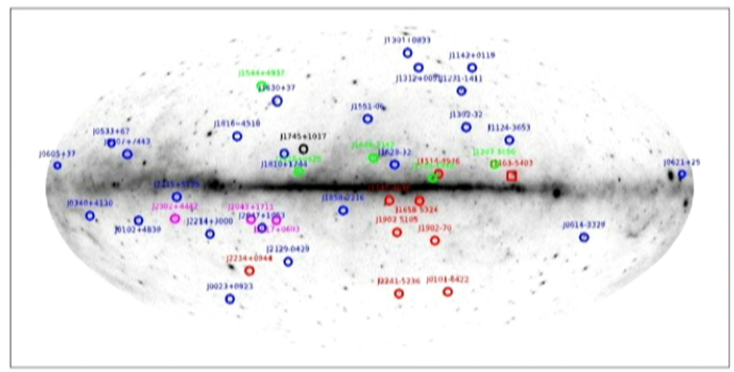

GBT, Effelsberg, Parkes, Nançay, GMRT
apted Ray et al. (2012)

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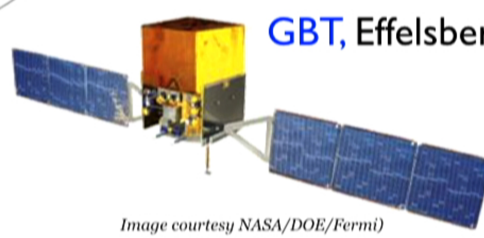

Image courtesy NASA/DOE/Fermi)

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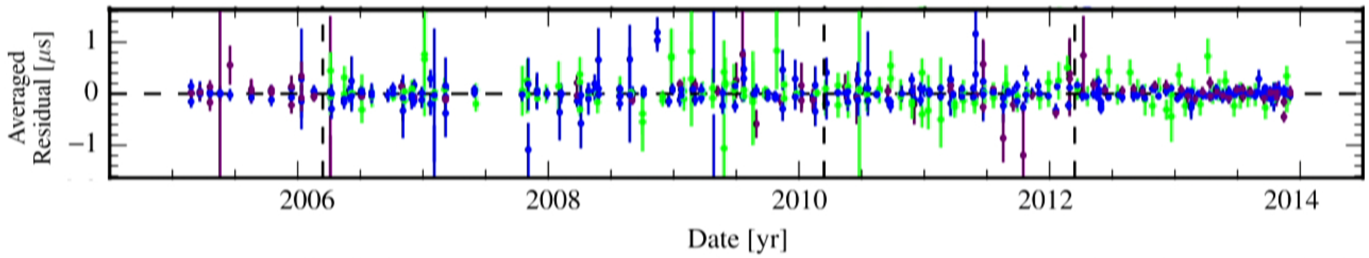
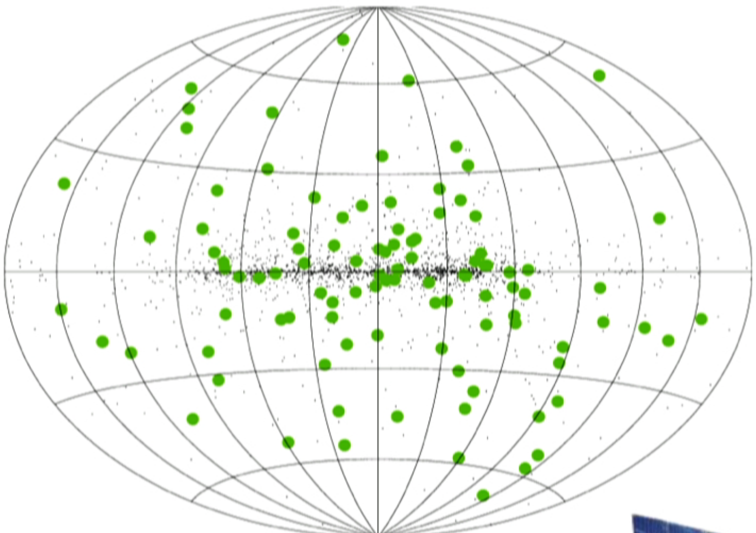
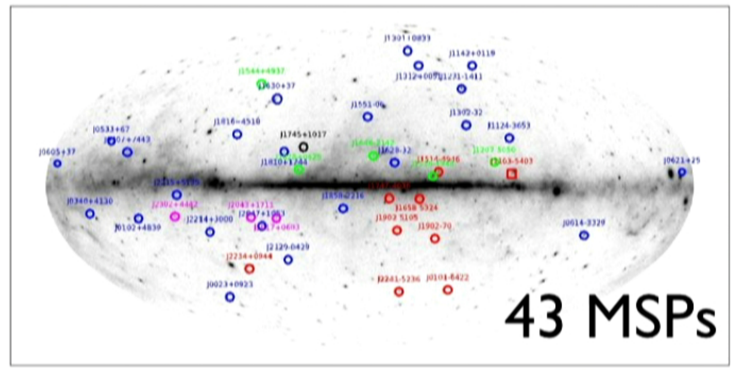
Millisecond Pulsars



J1713+0747





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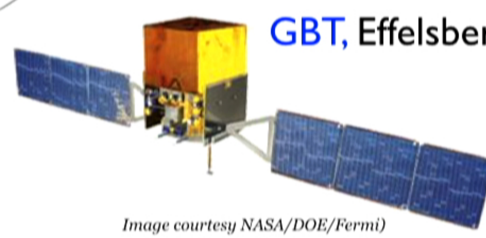

Image courtesy NASA/DOE/Fermi)

the nanoHertz gravitational-wave background

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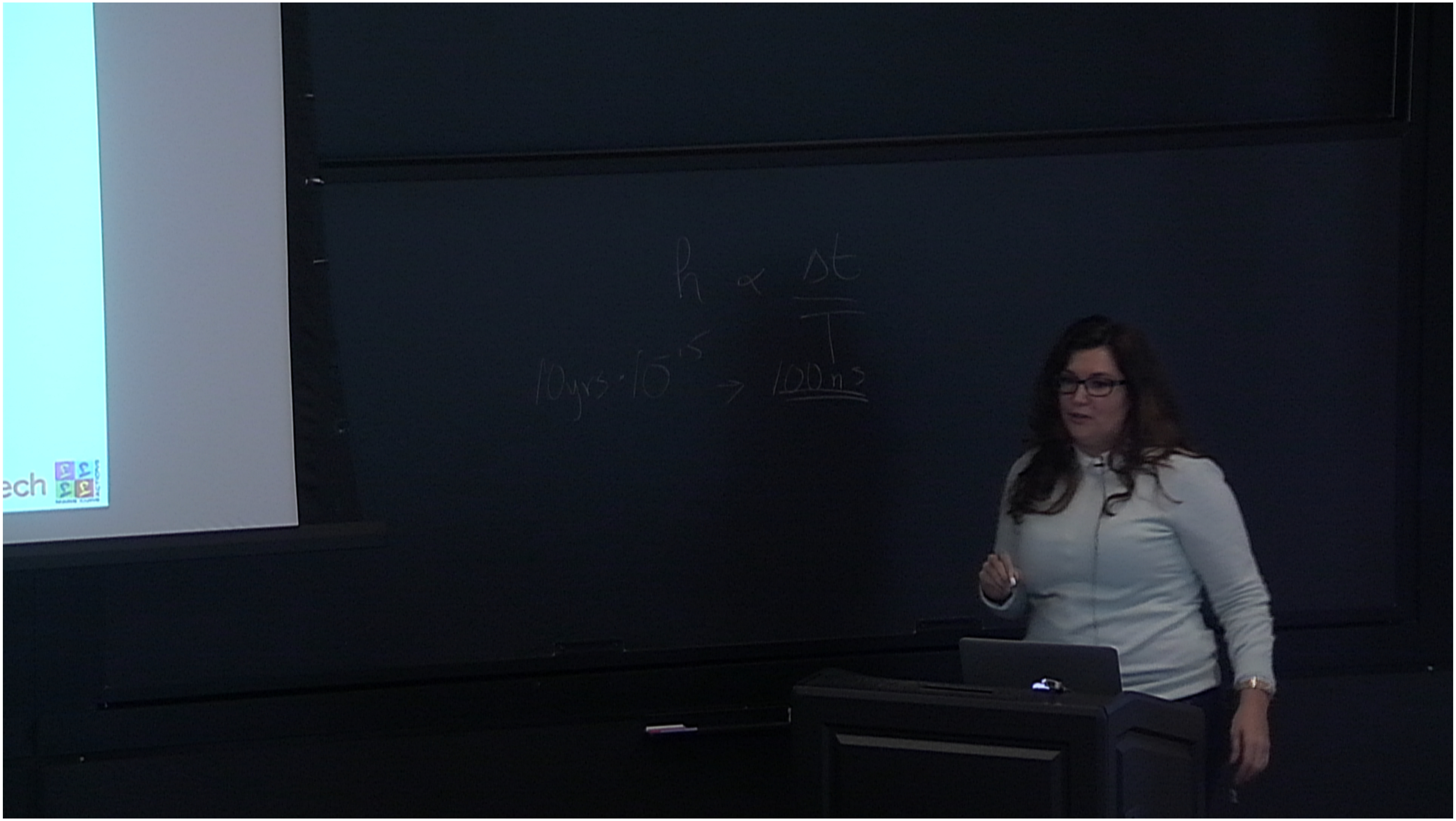
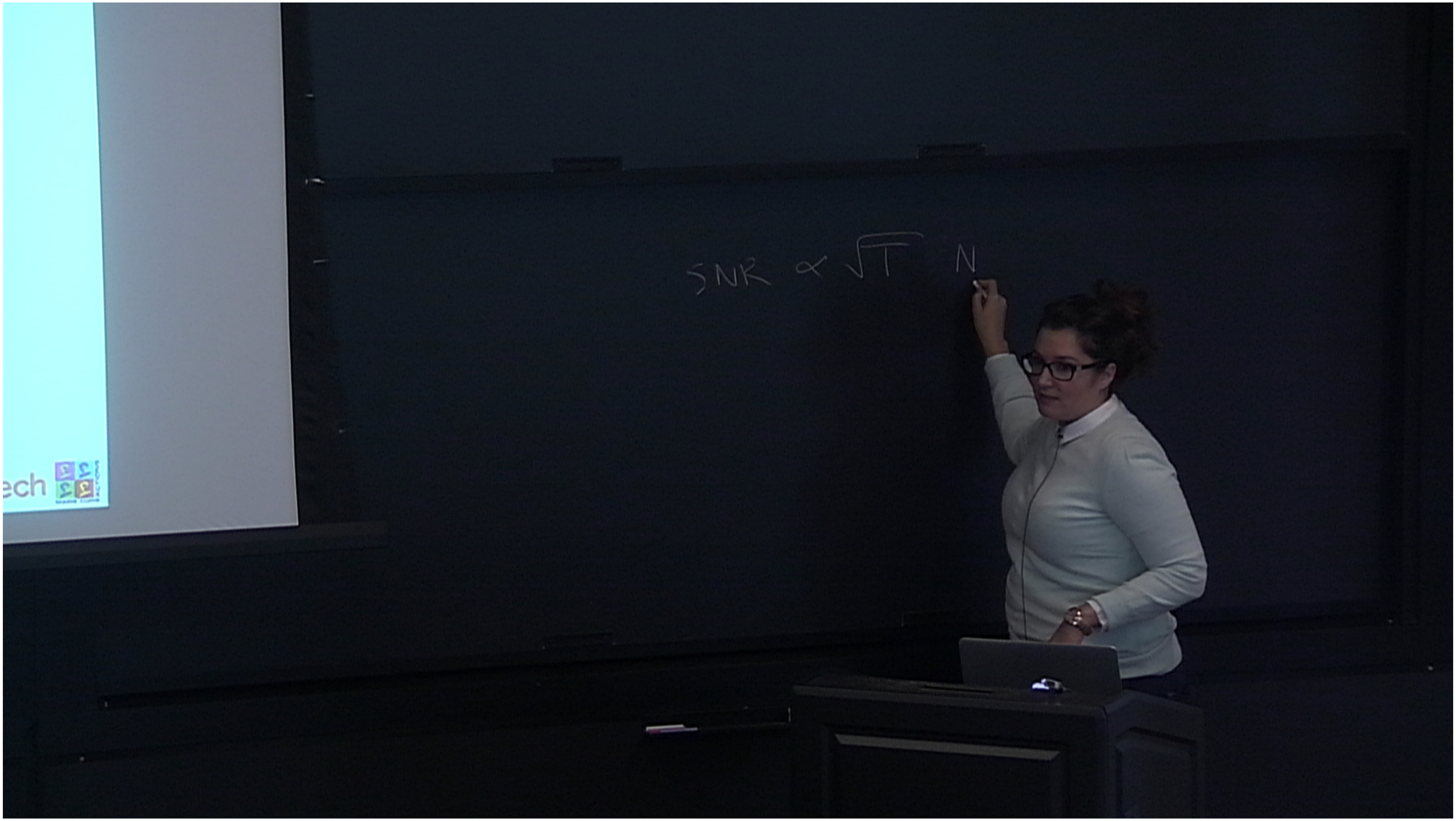
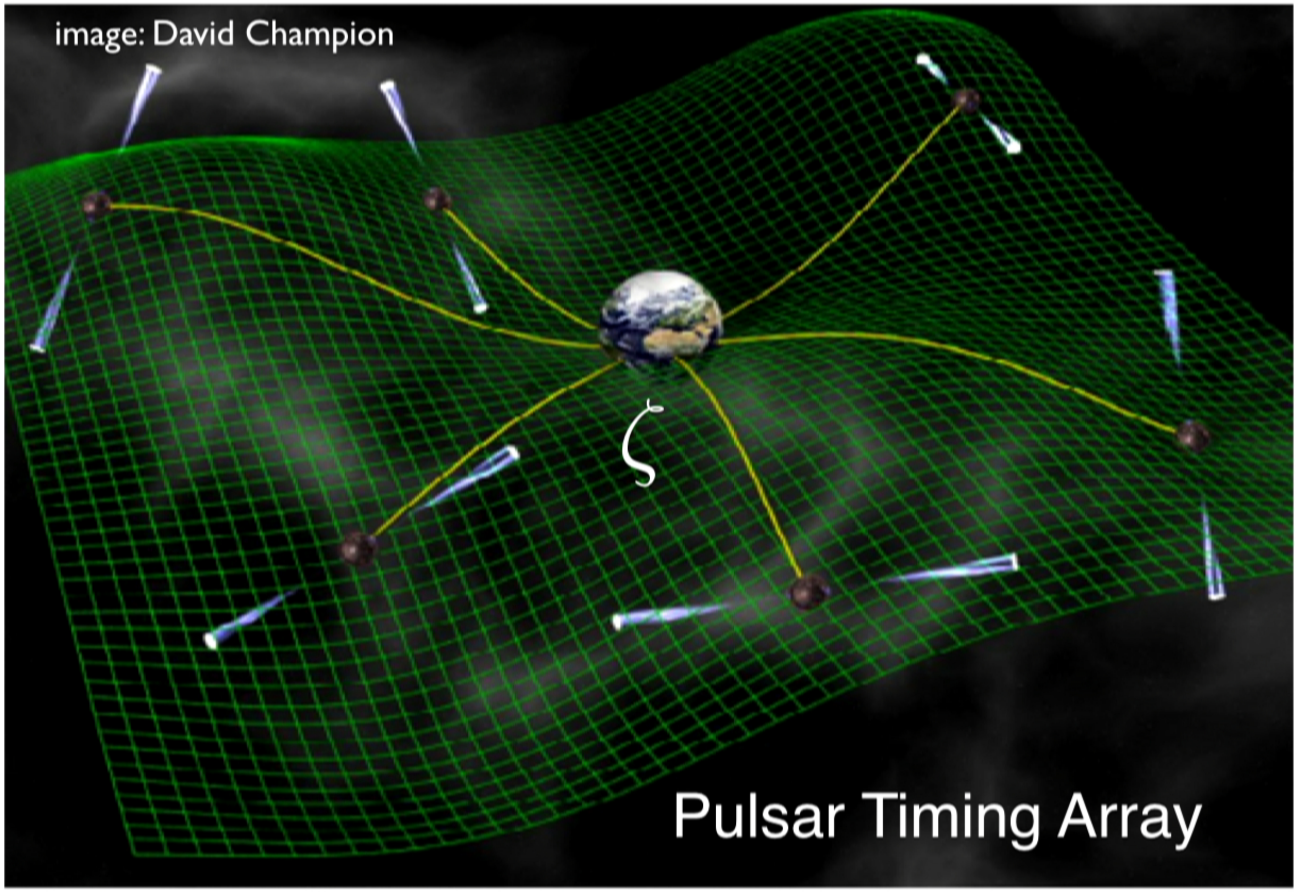

h ∝ Δt / T
10yrs · 10^-15 → 100ns
ech


SNR ∝ √T N
ech



Galactic GW detector composed of pulsar array!

Each pulsar thousands of light years away.

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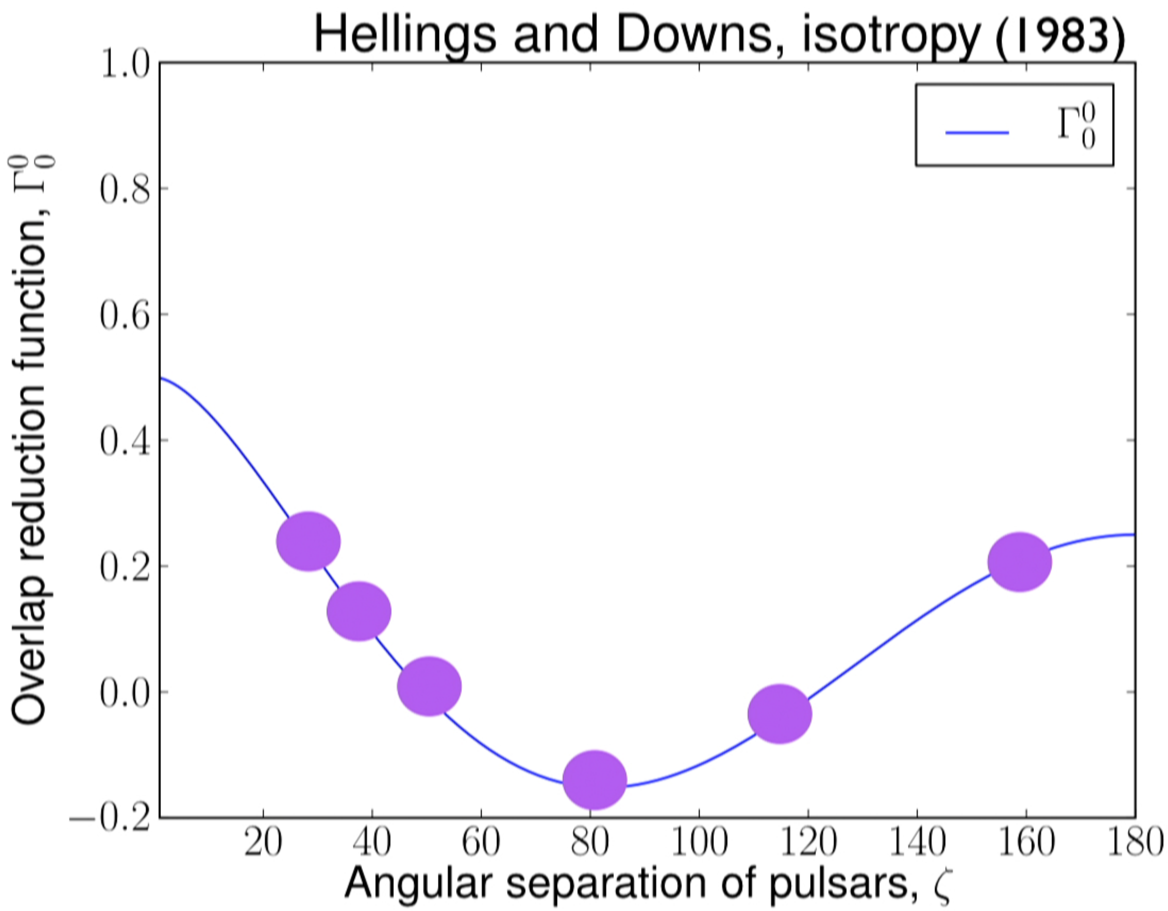
$$\text{residuals} \propto \int_{S^2} d\hat{\Omega} \; (\textbf{power distribution} \times \text{response})$$



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Stochastic Background from SMBHBs

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

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

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

Phinney (2001); Sesana (2012)

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We know a lot about A, can learn more

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Stochastic Background from SMBHBs

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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)

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We know a lot about A, can learn more

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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)

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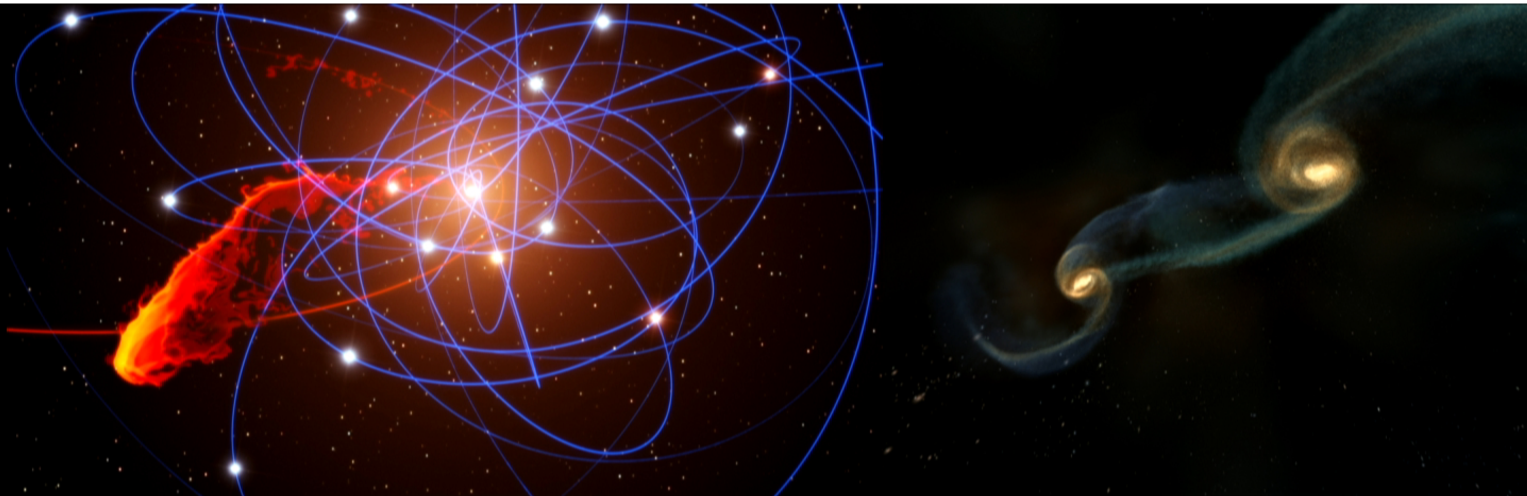
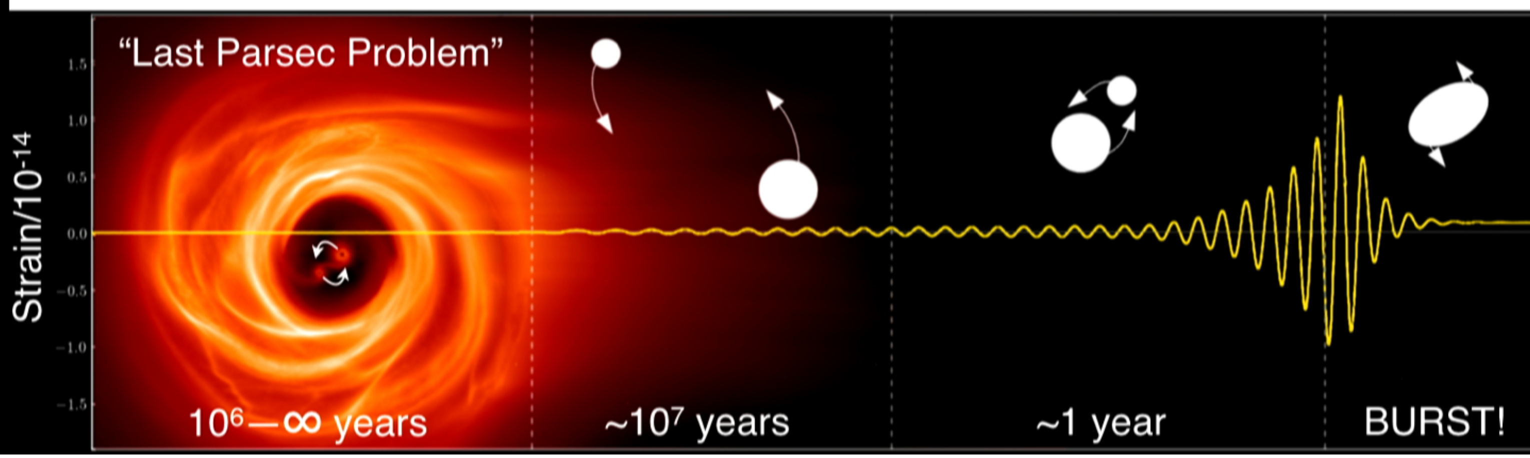
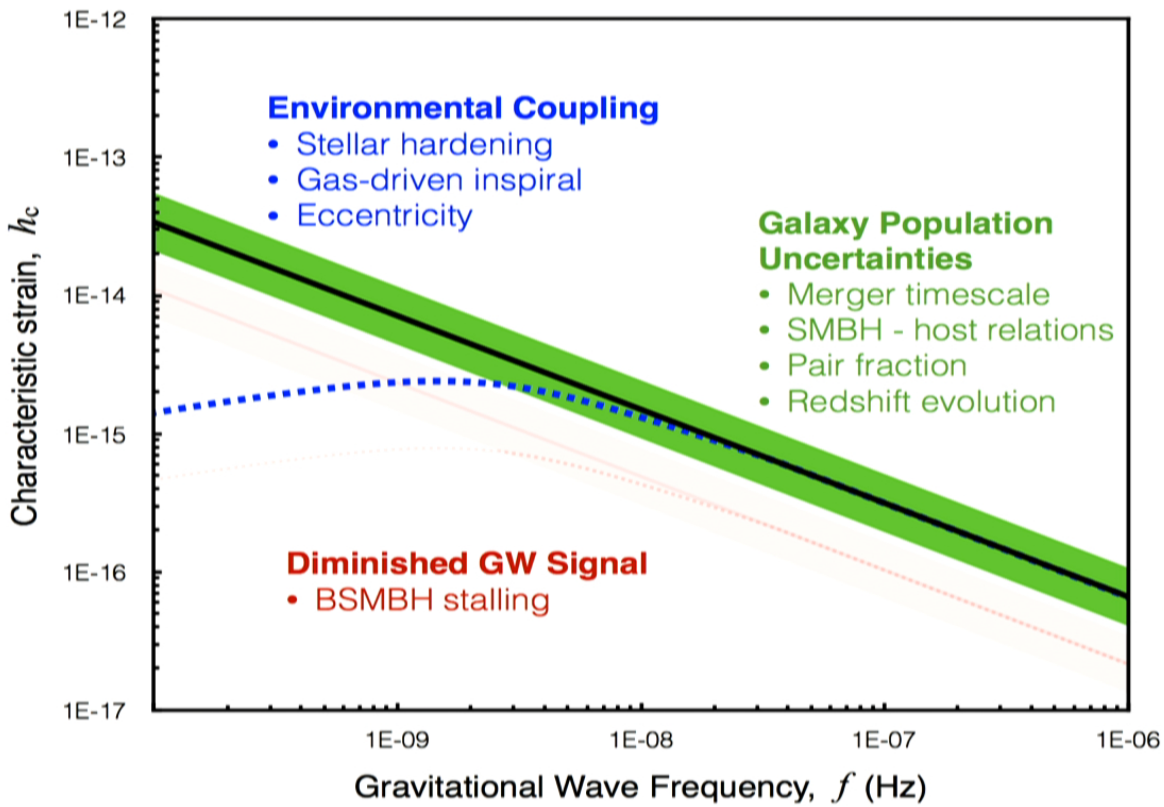


Final Parsec Problem?





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

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

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

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Stochastic background from SMBH mergers

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

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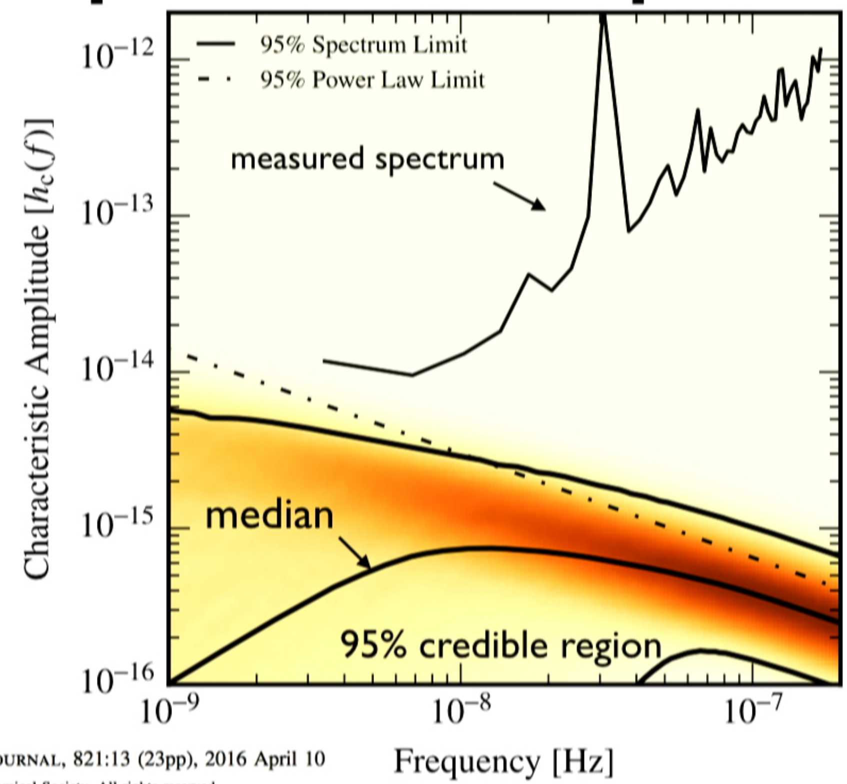
Shape of the spectrum



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

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

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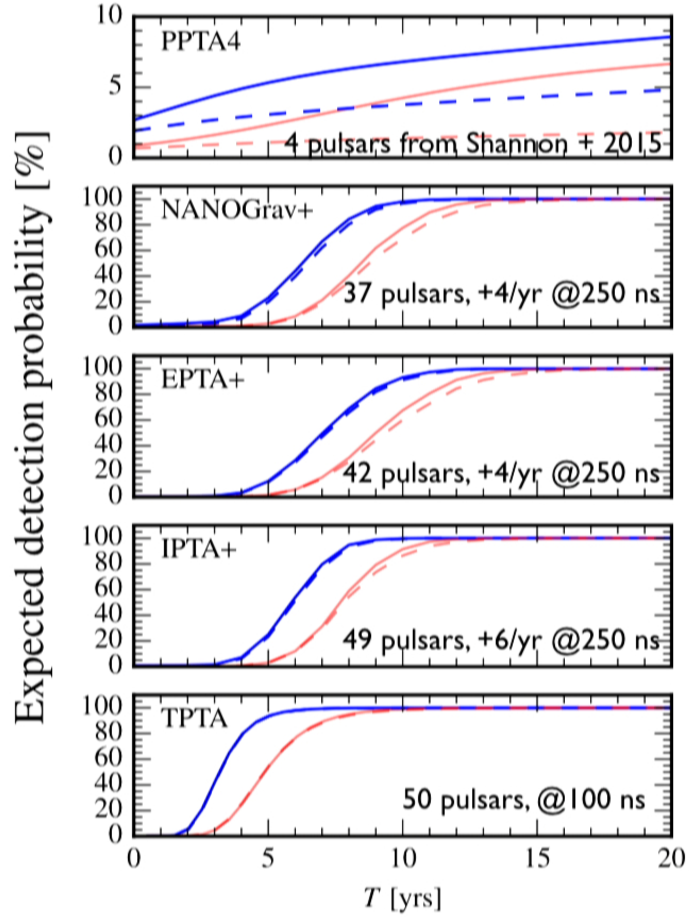
THE NANOGRAV NINE-YEAR DATA SET: LIMITS ON THE ISOTROPIC STOCHASTIC GRAVITATIONAL WAVE BACKGROUND

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



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

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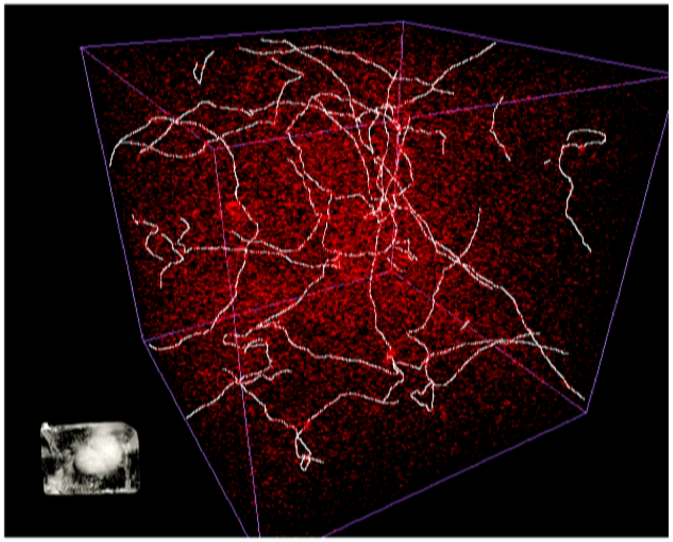
Cosmic (super)Strings

- 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

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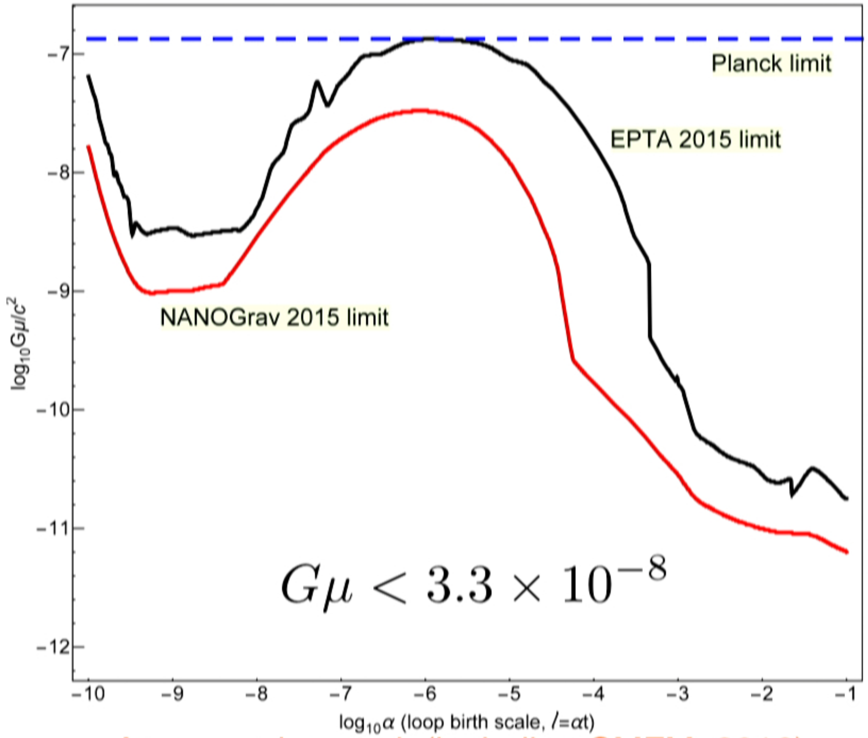
NANOGrav 9-yr Results

- 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.

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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 spectra
- **non-inflationary** theories such as ekpyrosis (e.g. Boyle, Steinhardt, Turok 2004) + string-gas (Brandenberger + Vafa 1989) also predict blue spectra

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

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

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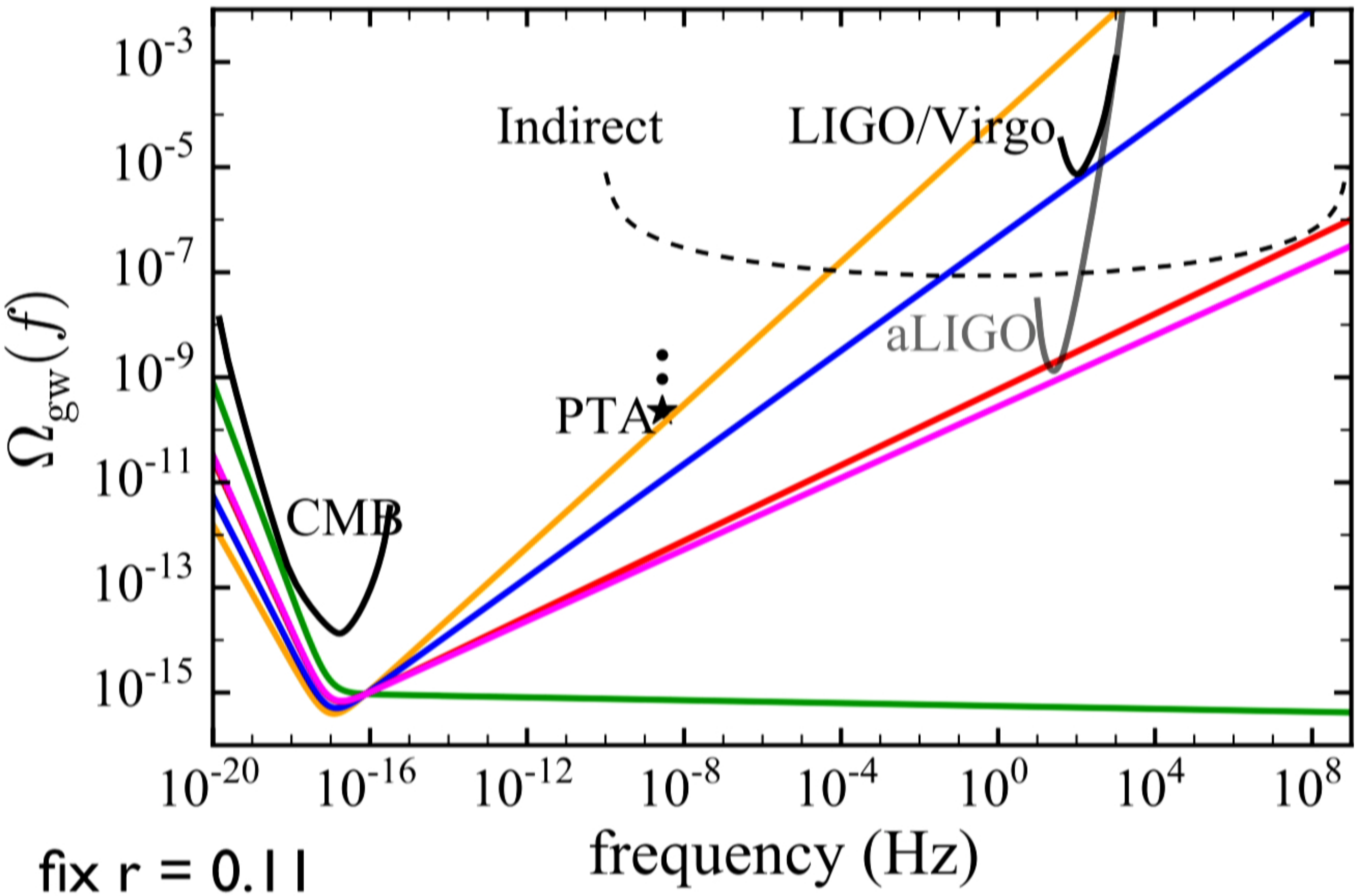
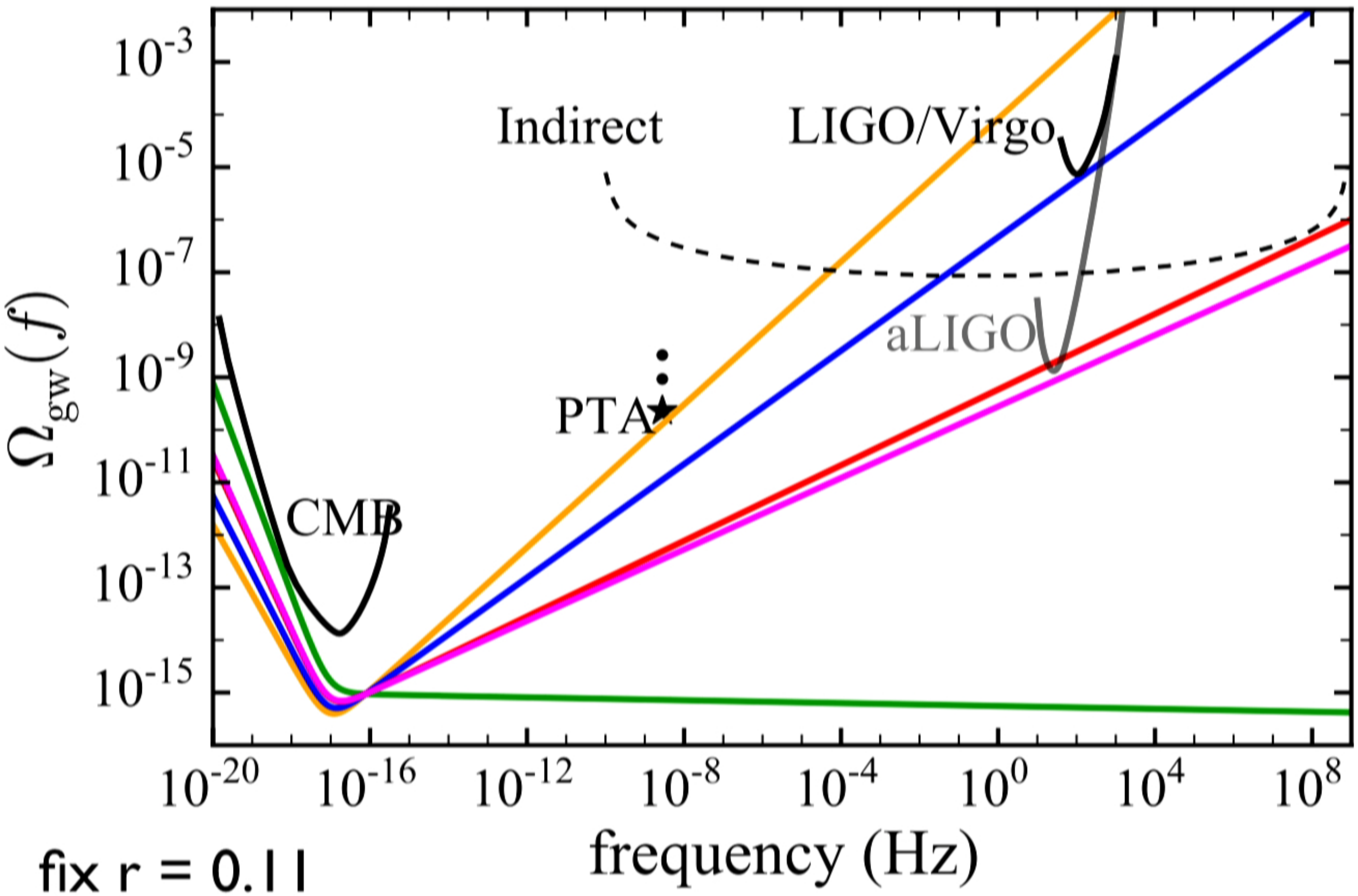


fix r = 0.11

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



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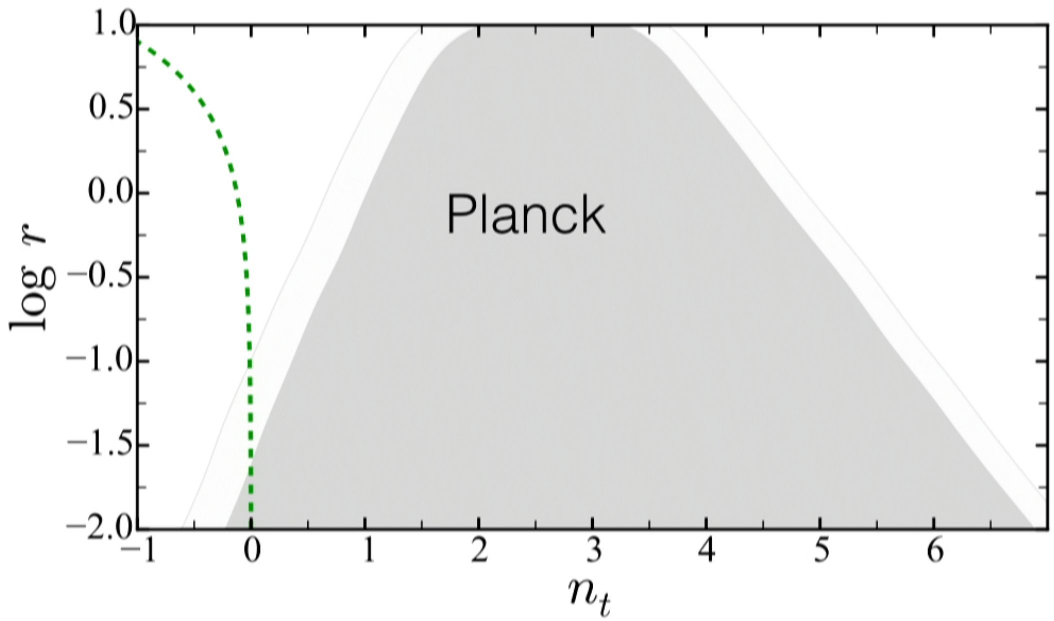
Lasky, **CMFM**, Smith, Thrane, Giblin, Caldwell + (2016)

Primordial background: Better together



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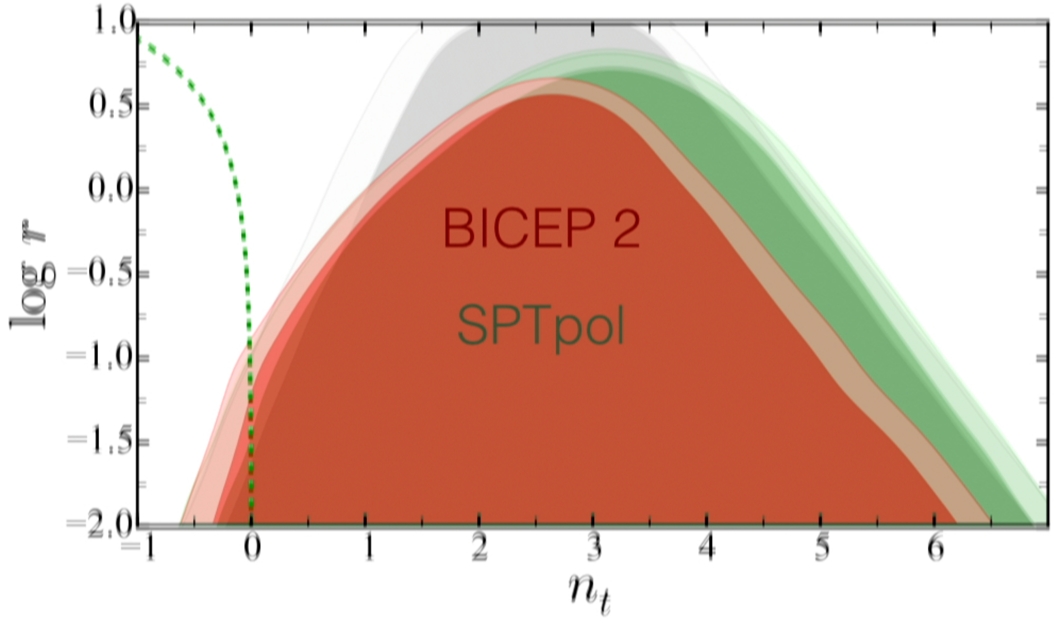

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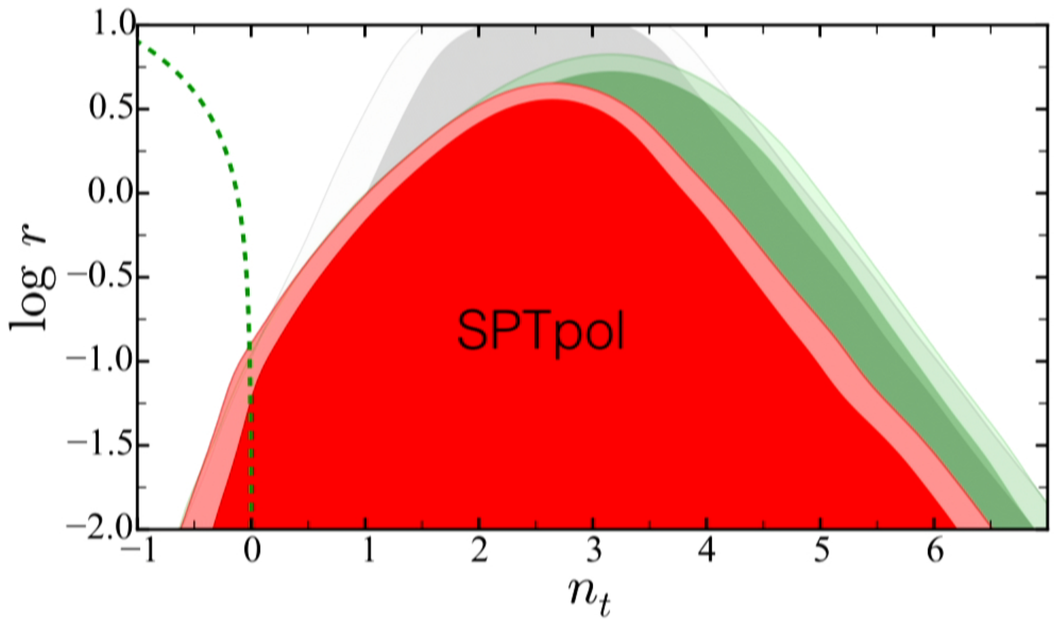

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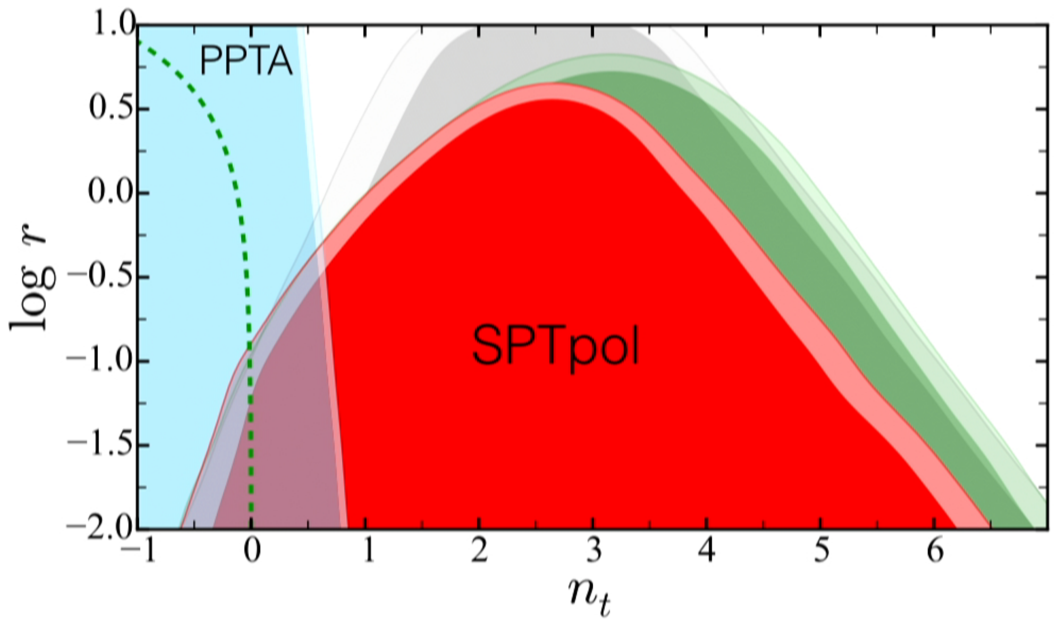

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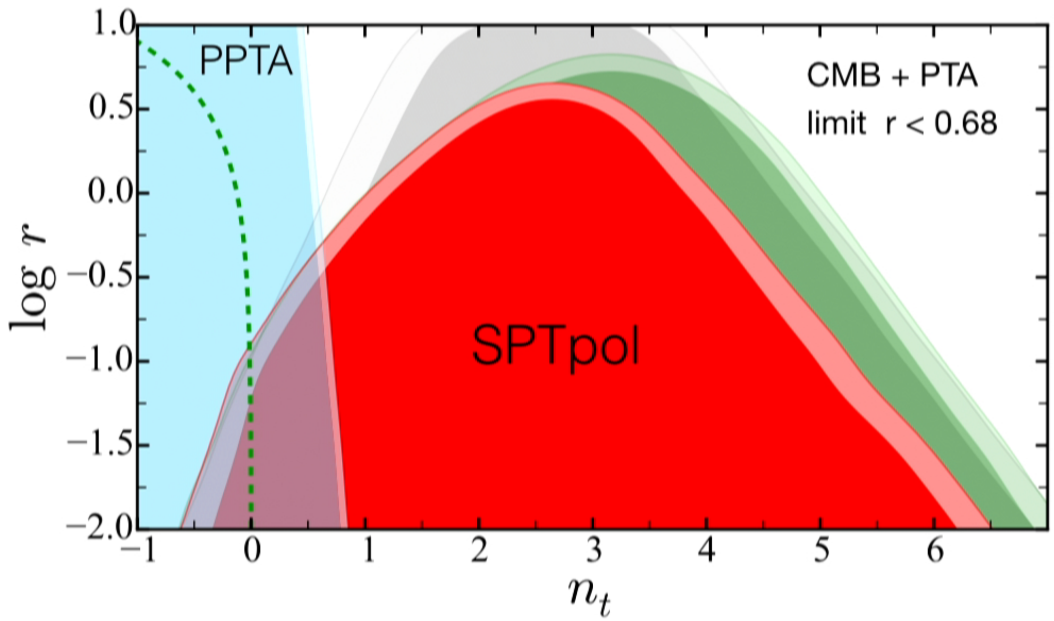

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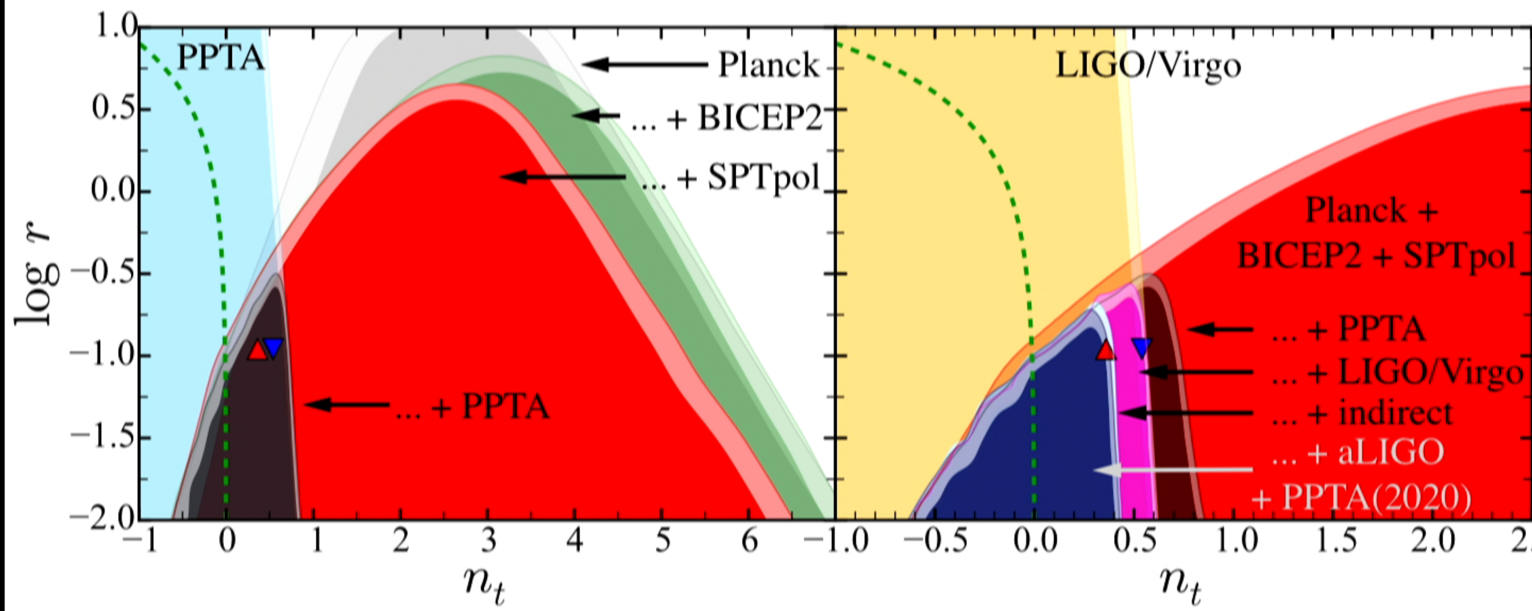

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Future Directions

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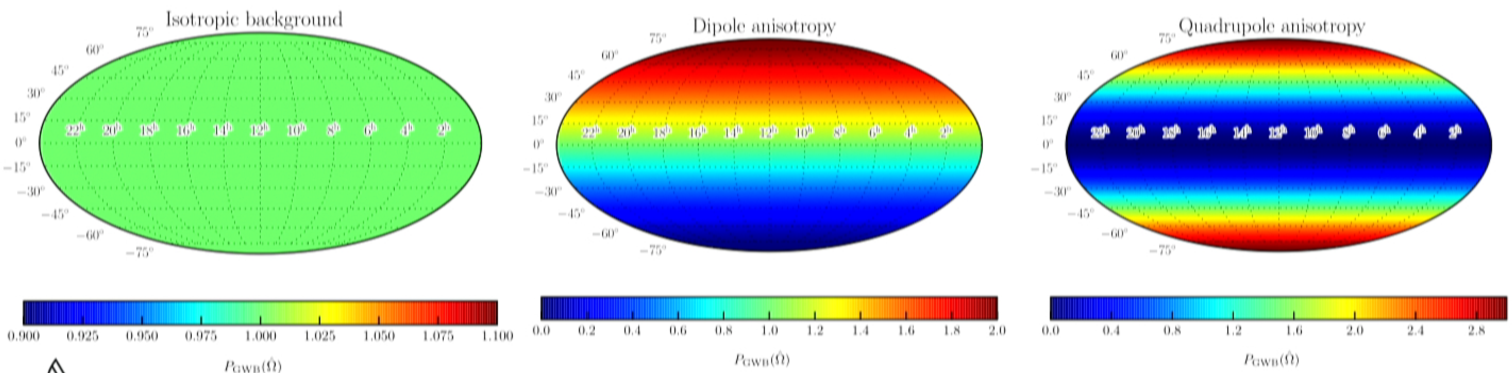
Introducing Anisotropy

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



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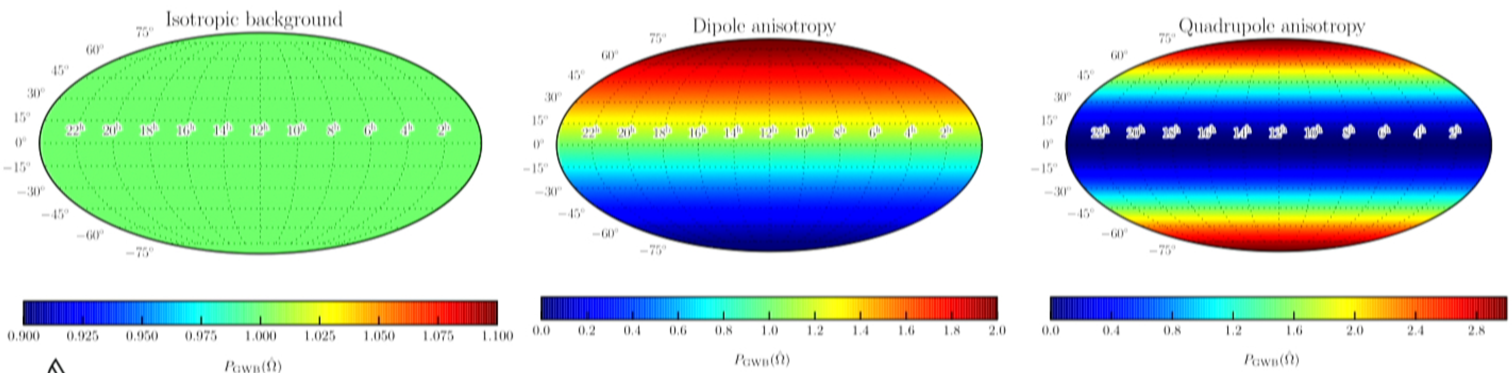

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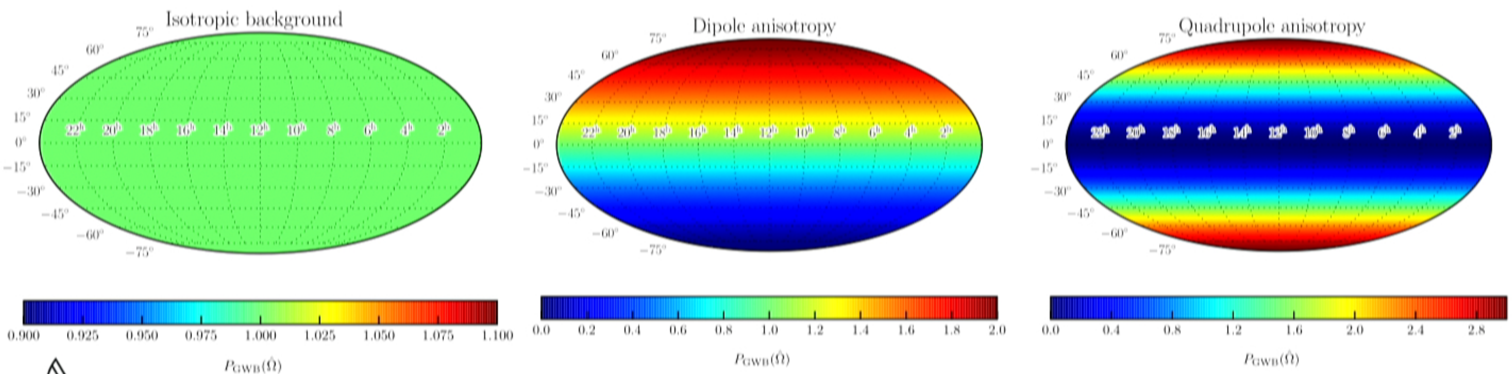
Introducing Anisotropy

- 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 (?)



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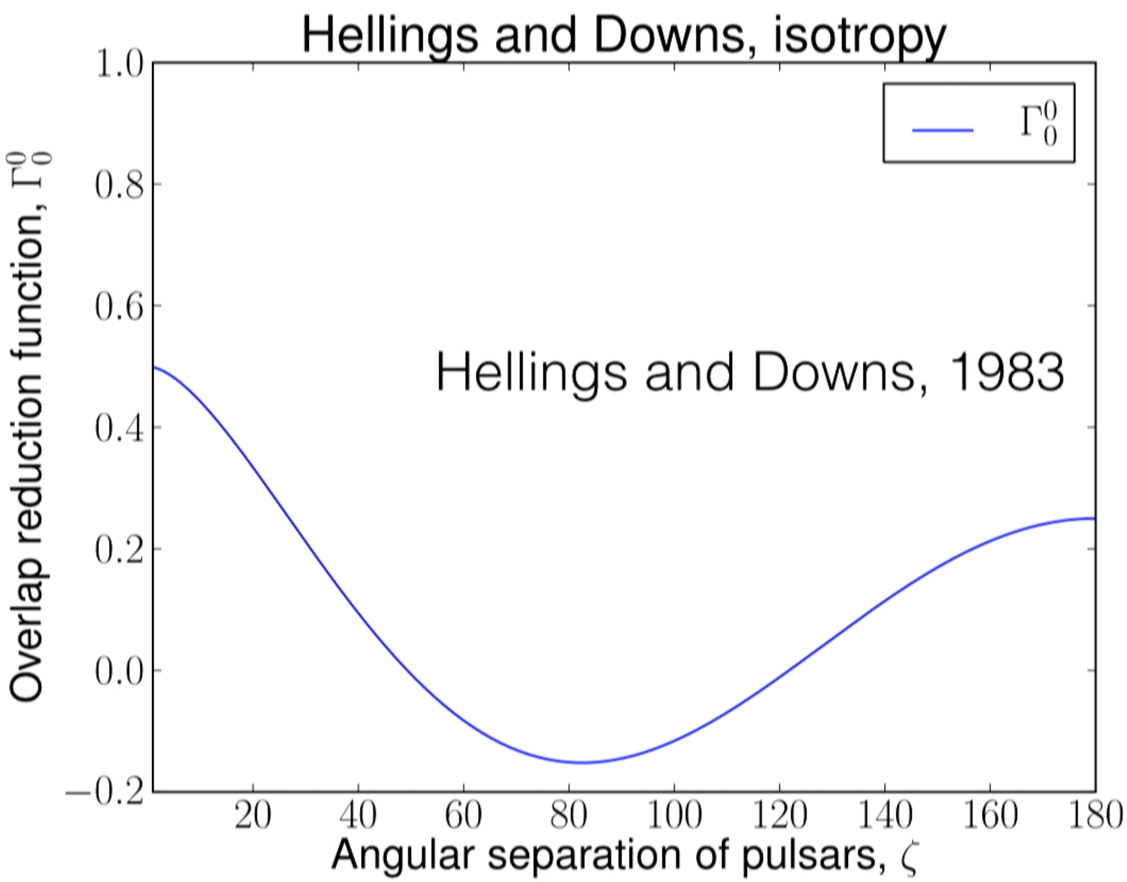
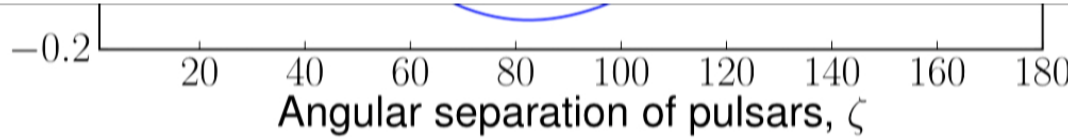
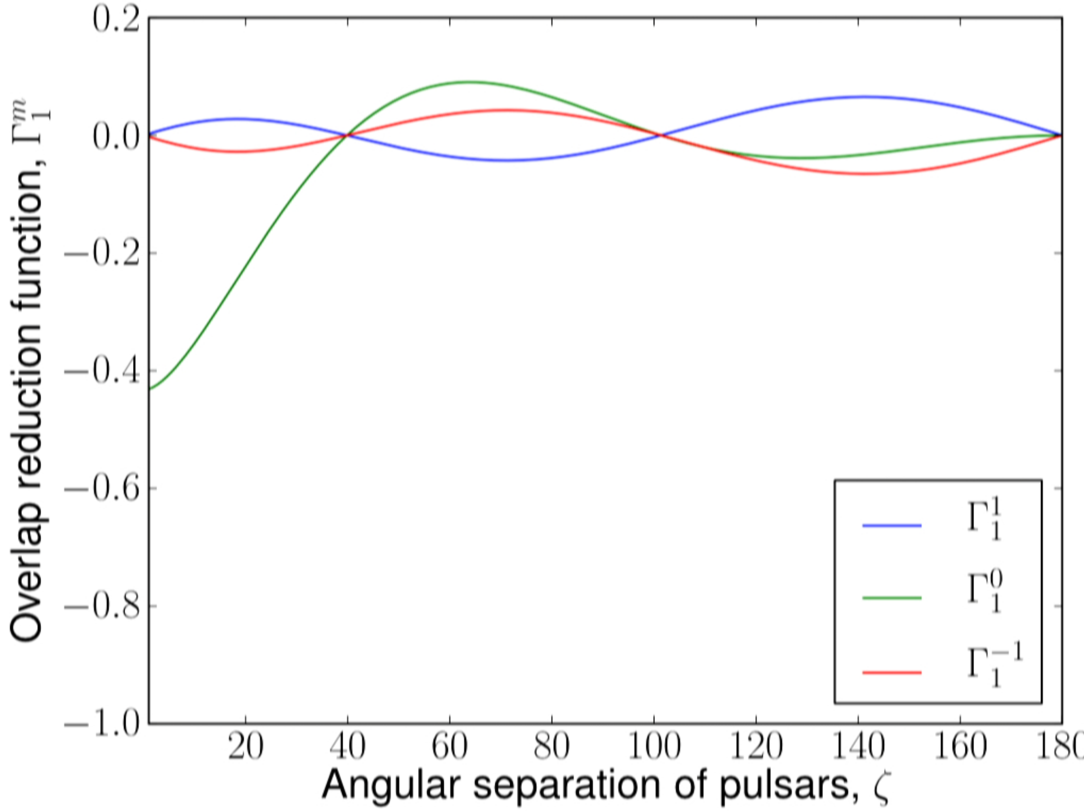


CMFM et al. PRD **88**, 062005 (2013)





Overlap reduction function, Γ_2^m

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

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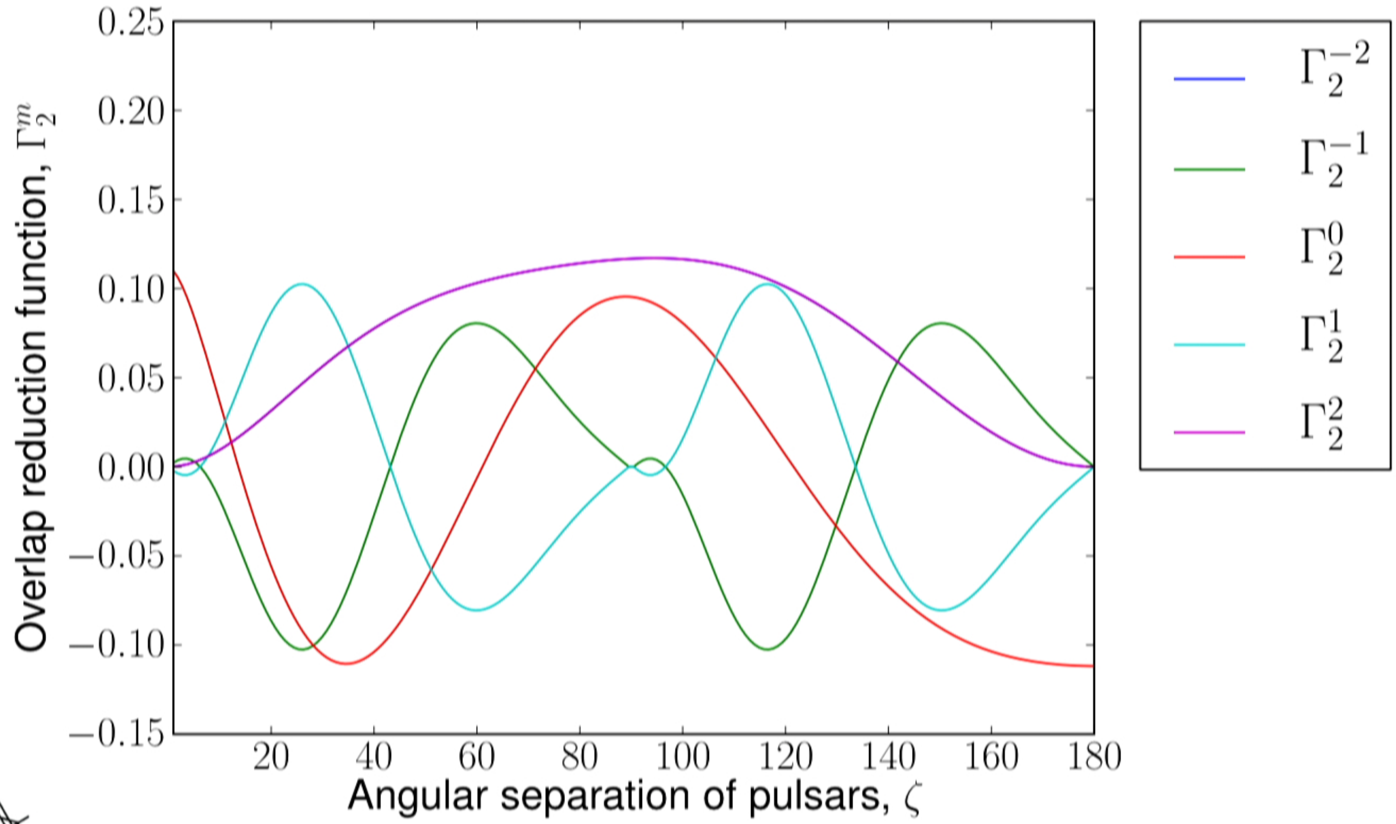

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CMFM et al. PRD **88**, 062005 (2013)

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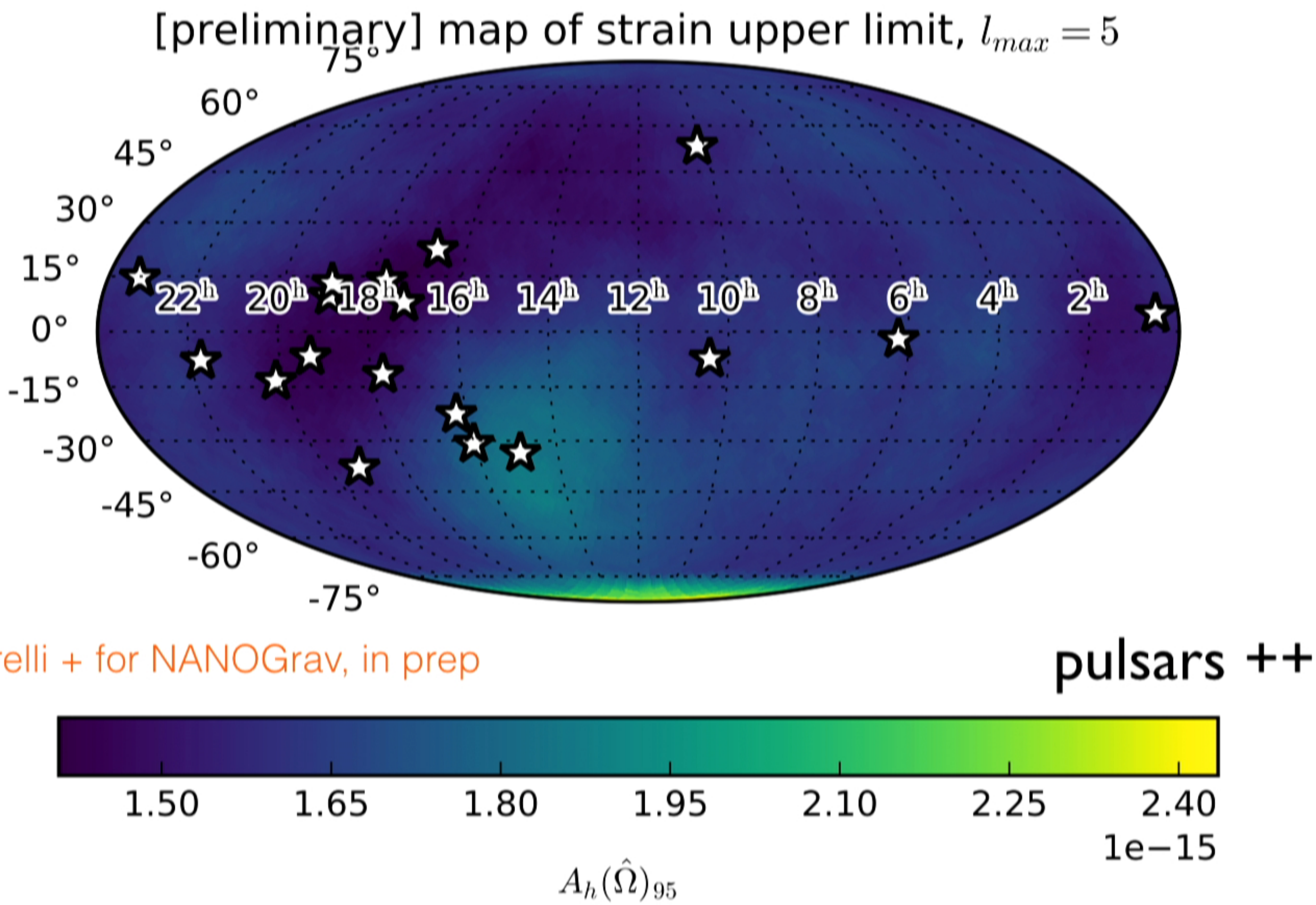

Mingarelli + for NANOGrav, in prep

pulsars ++

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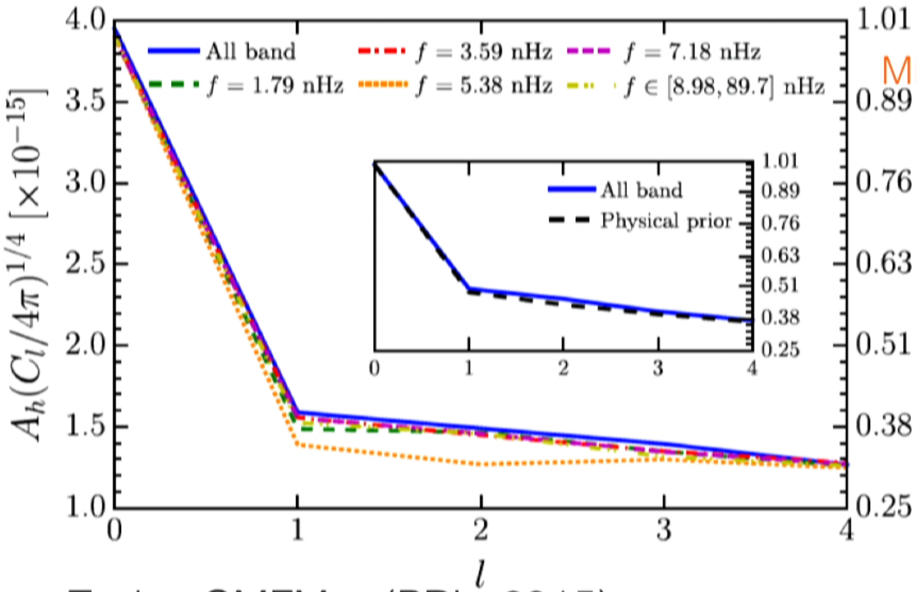
Isotropic limit A<1.5e-15

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

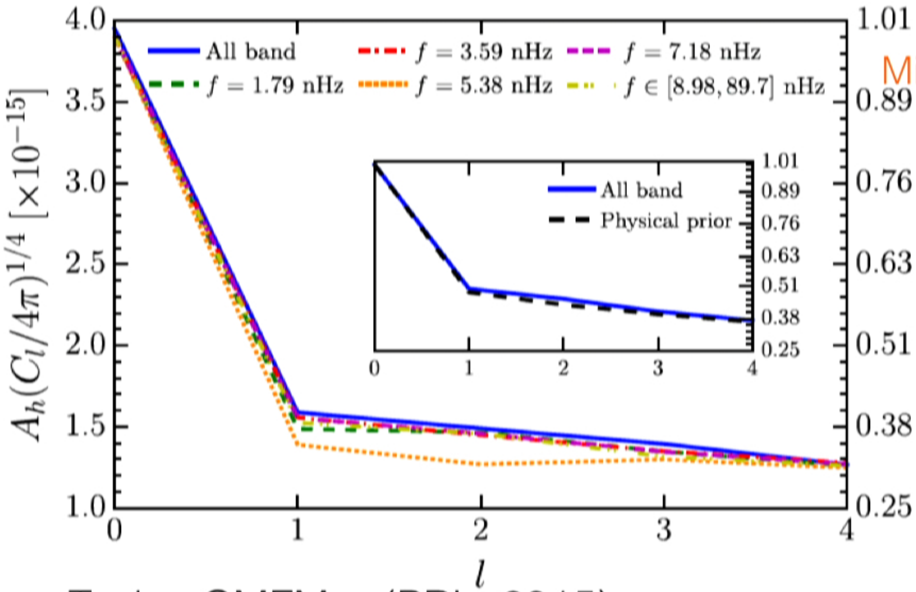
How much anisotropy?



Mingarelli + for NANOGrav, in prep

Taylor, CMFM + (PRL, 2015)

How much anisotropy?



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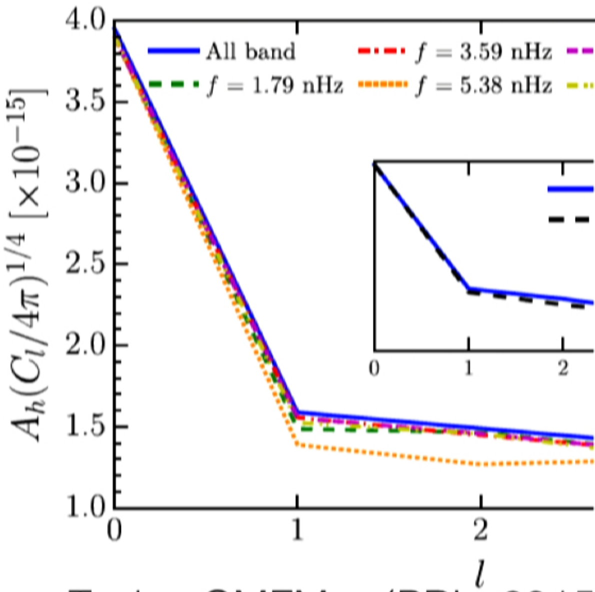
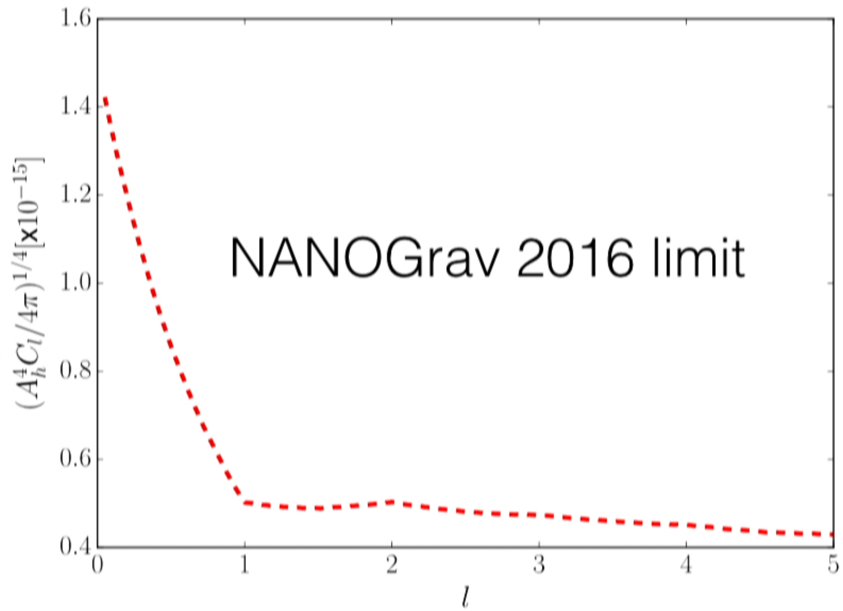


Taylor, CMFM + (PRL, 2015

Mingarelli + for NANOGrav, in prep



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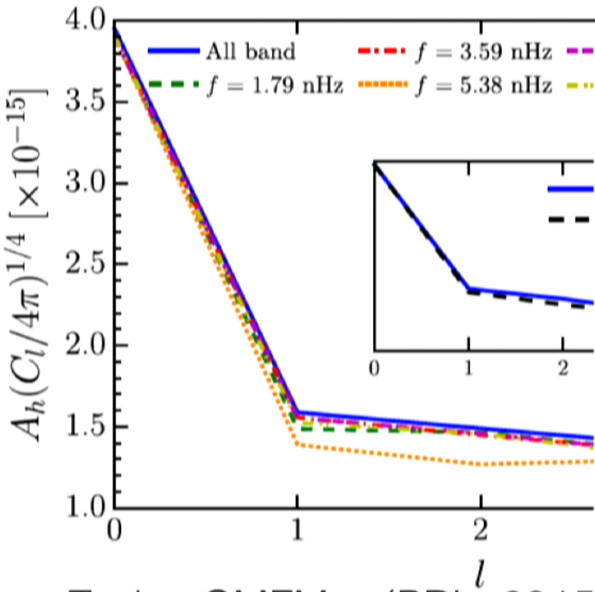

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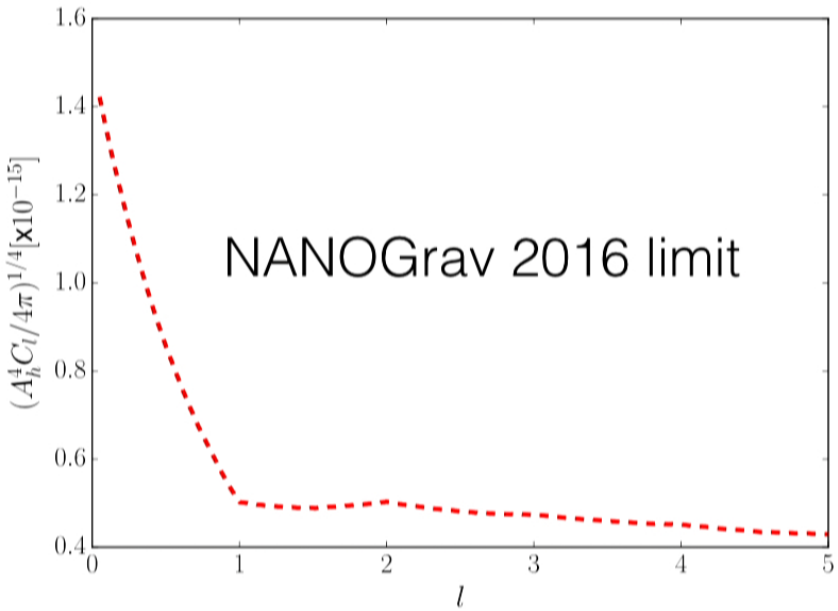

- Red dashed line shows 95% upper limit on strain amplitude
- 32% GW power contained in higher multipoles, EPTA 40%.

Summary

- PTA **interdisciplinary** science experiment: radio astronomy, GWB +anisotropy+CW, galaxy evolution, SMBH env, ISM, cosmology
- 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

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Thank You!

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Summary

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Thank You!

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Big Open Questions

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

- Do supermassive black hole binaries merge?
- If so, how much help to supermassive black hole binaries get from environmental effects (gas/stars) to overcome the final parsec problem?
- Do cosmic (super)strings exist?
- How long will it take to distinguish between GW backgrounds?
- Are SMBHBs really the dominant contributors to the nanohertz GW background?

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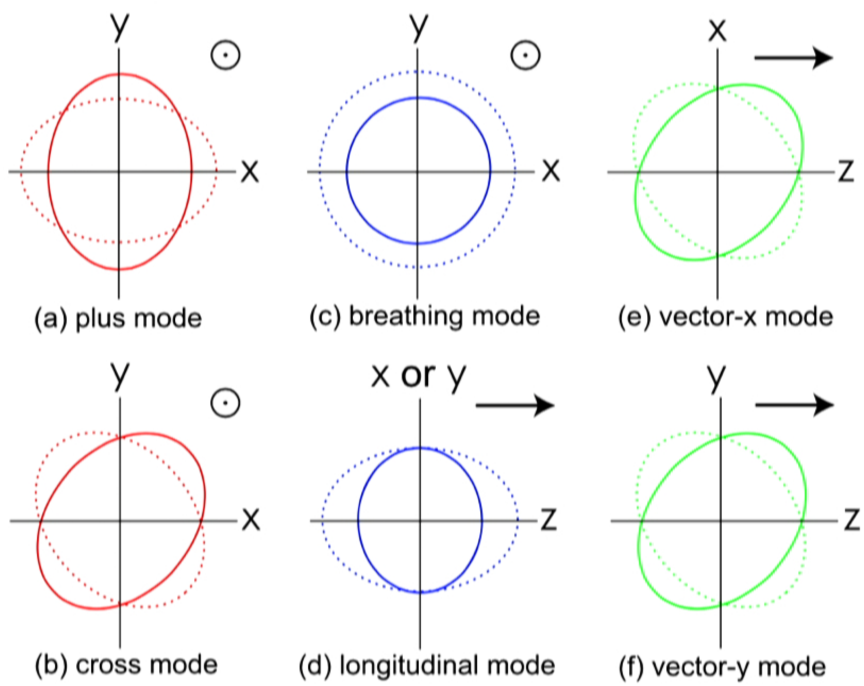
Caltech MARIE CURIE ACTIONS

Alternative GW Polarizations

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



Chamberlin & Siemens, PRD 2012

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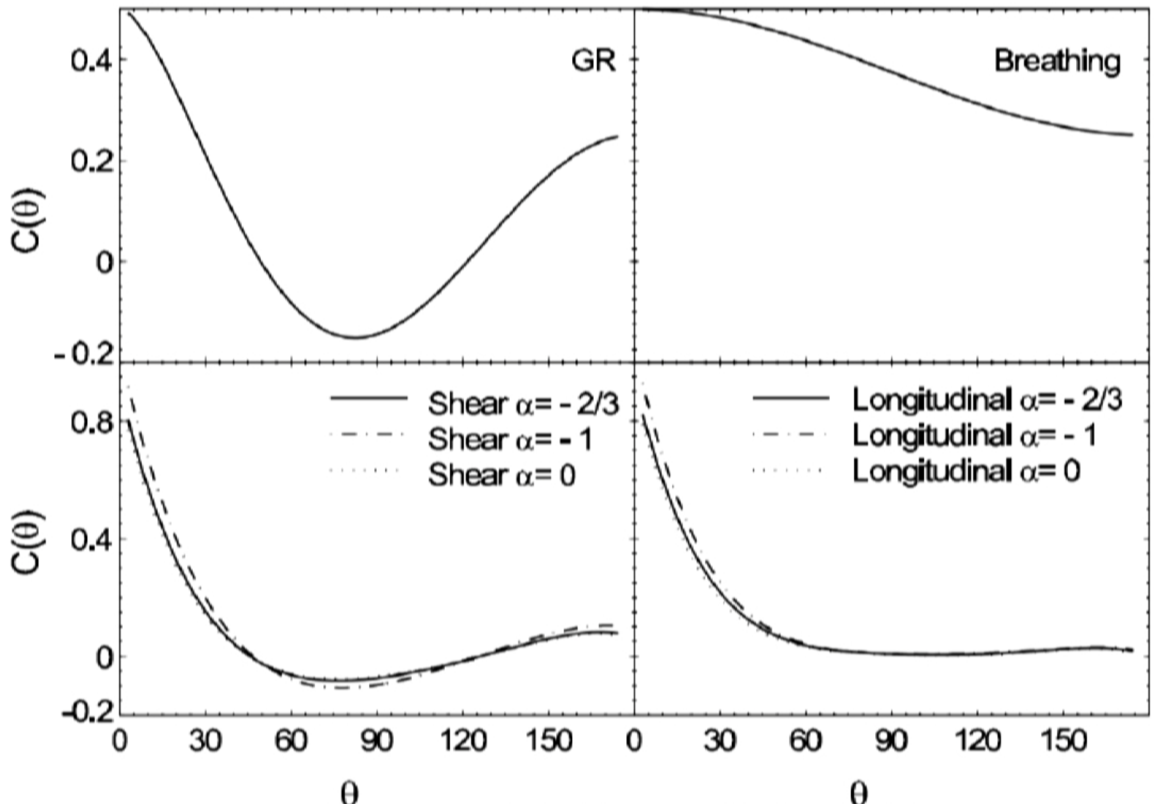
New correlation functions

Lee et al. (2008)



anisotropy by Gair, Romano, Taylor (2015)

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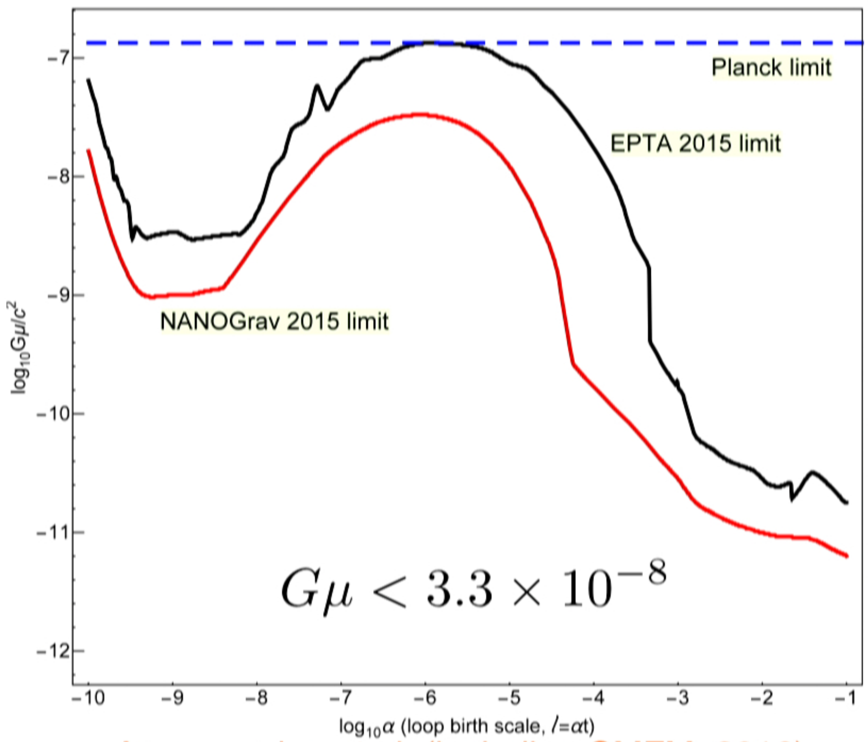
NANOGrav 9-yr Results

- 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.

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