Title: Unlocking the potential of pulsar timing arrays

Date: Mar 06, 2017 11:00 AM

URL: http://pirsa.org/17030015

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 both continuous gravitational waves and a background of gravitational radiation in the nanohertz to microhertz regime. 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 international efforts to constrain astrophysical phenomena at the heart of supermassive black hole mergers.</p>

Exciting times!

- Evolution of supermassive black hole binaries with PTAs, **Mingarelli** et al. Phys Rev Lett (2012);
- When is the pulsar term important for backgrounds? **Mingarelli** and Sidery, Phys Rev D (2014);
- Fast radio bursts from black hole batteries, **Mingarelli**, Levin, Lazio ApJ Lett (2015);
- Manifestation of final parsec physics in GWB spectrum turnover: NANOGrav (Arzoumanian et al. w **Mingarellli**, ApJ 2016);
- Primordial backgrounds: Lasky, **Mingarelli**, Smith et al. PRX (2016); Arzoumanian et al. ApJ (2016); Lentati, Taylor, **Mingarelli** et al. (2015)

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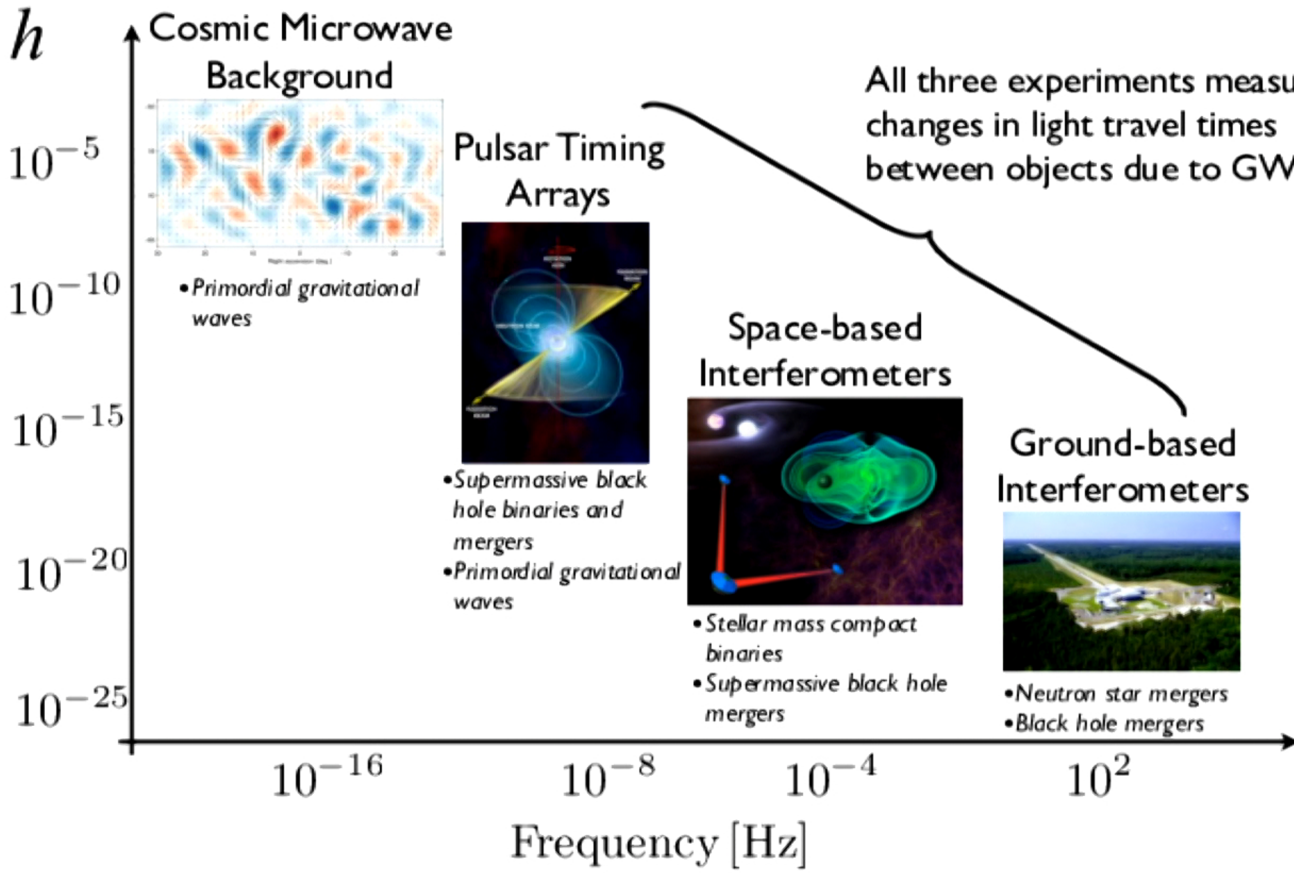
Outline

- Pulsar Timing Arrays: the gravitational-wave background
- Characterizing anisotropy in the gravitational-wave background
- Local, continuous nanoHertz gravitational-wave sources
- Future directions

The spectrum of gravitational wave astronomy



$$10^{-15} = 10\mathrm{m}/\mathrm{ly}$$

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

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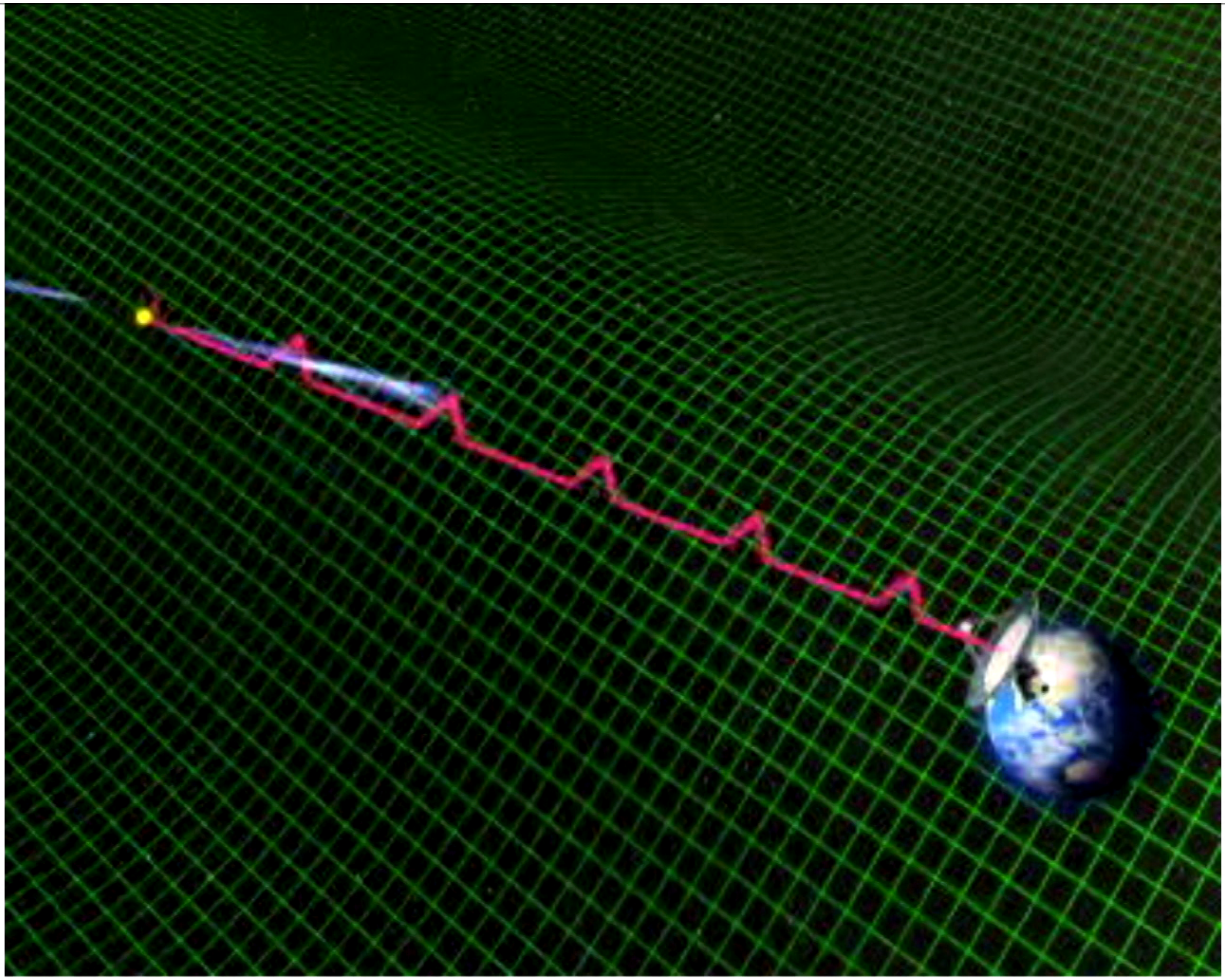

Animation from John Rowe Animation/Australia Telescope National Facility, CSIRO

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A Pulsar Timing Array

- Primary goal of PTAs is to detect nHz gravitational waves
- Currently 3 major PTAs: European PTA, Parkes PTA and NANOGrav.
- Together we form the IPTA: 49 MSPs (and counting) and 8 radio telescopes

$$h \propto \delta t / T$$

$$\delta t \sim 10^{-15} 10\mathrm{yrs} \sim 100\mathrm{ns}$$

} only MSPs can do this!

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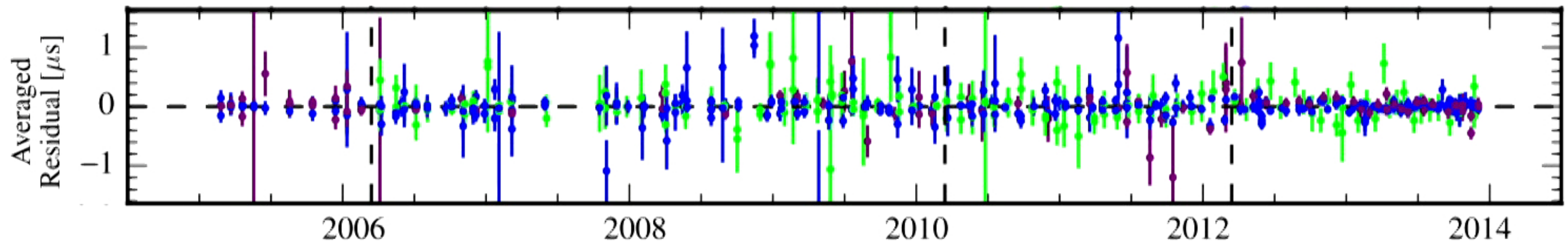
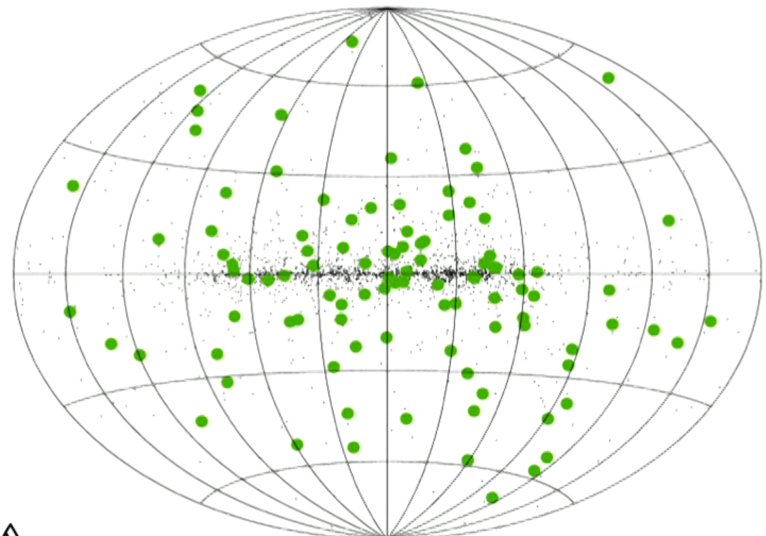
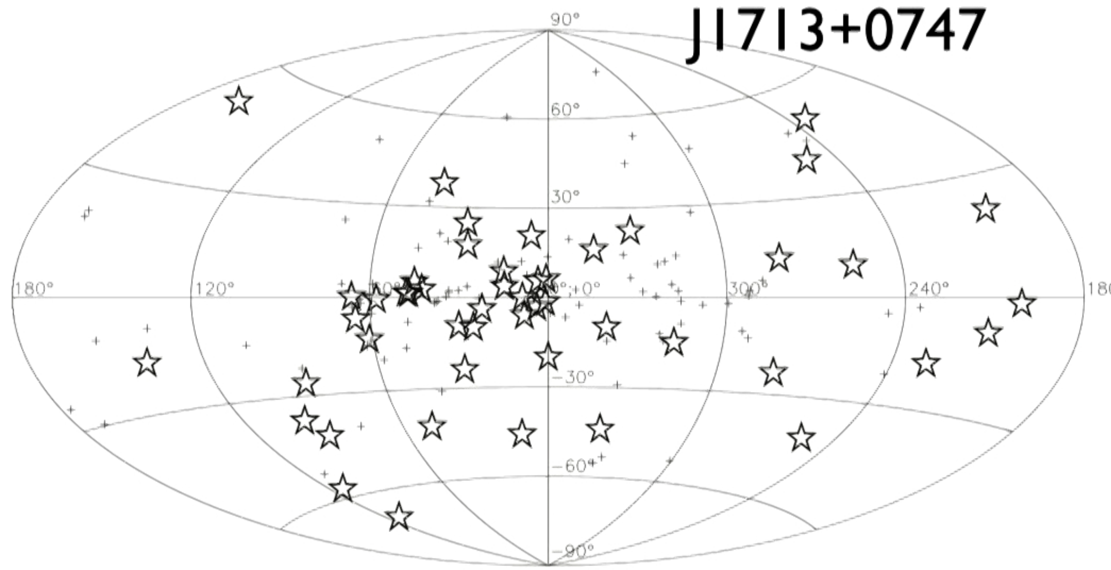
Millisecond Pulsars







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2300 known pulsars, 230 MSPs, 30,000 more?

courtesy Maura McLaughlin + Joe Lazio

Verbiest et al. (w CMFM) 2016, 1st IPTA paper

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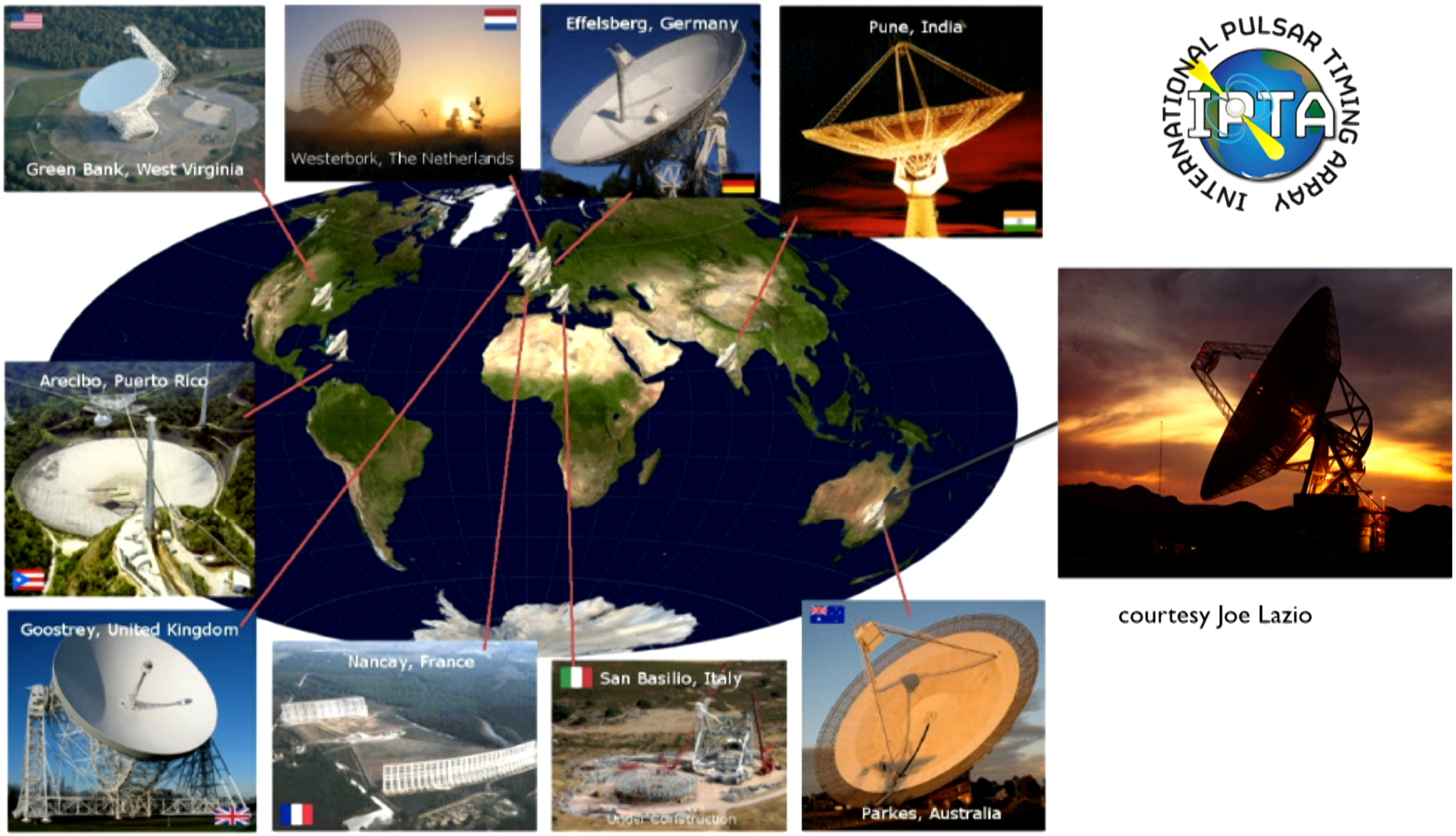


Current IPTA Radio Telescopes

8

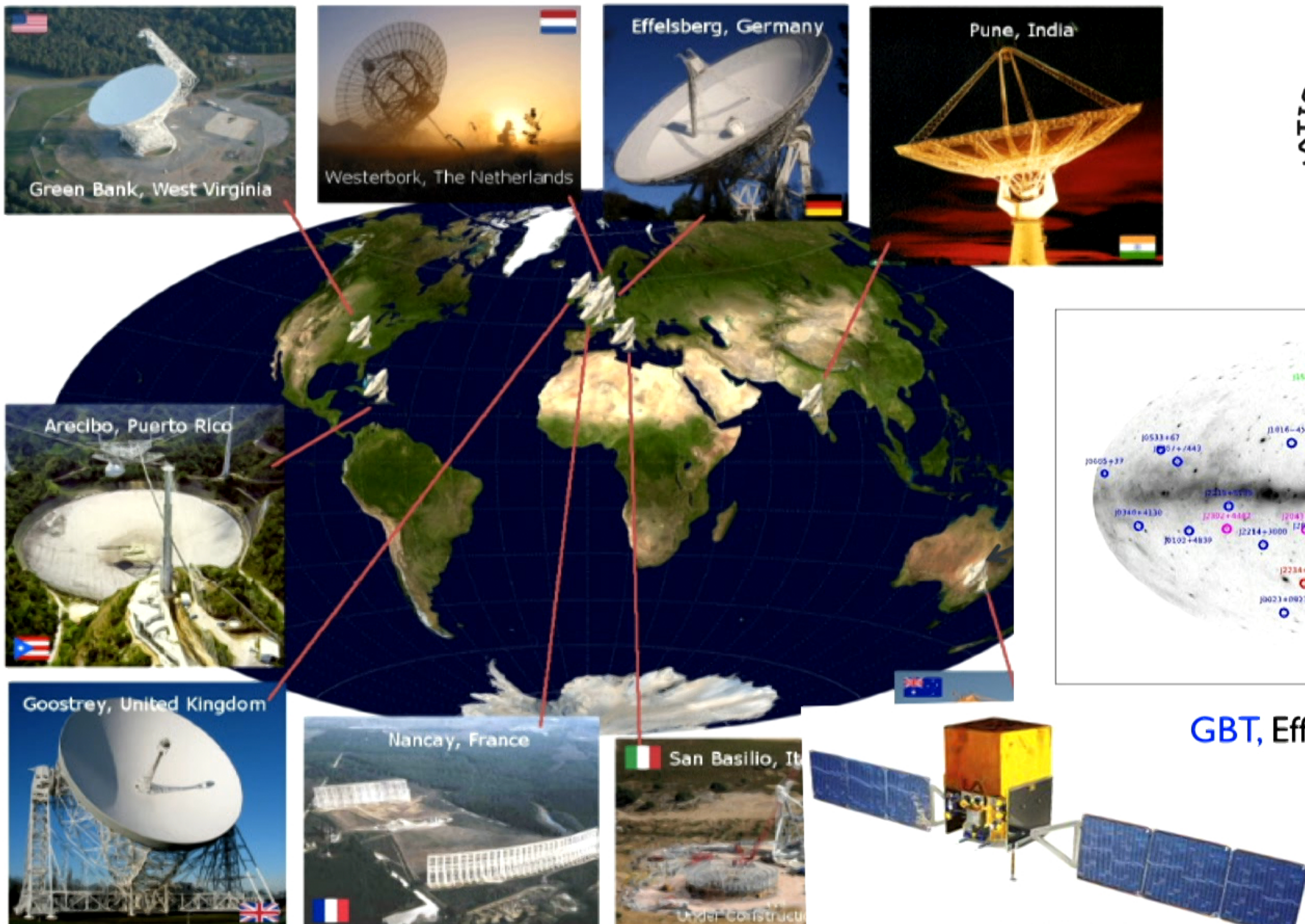
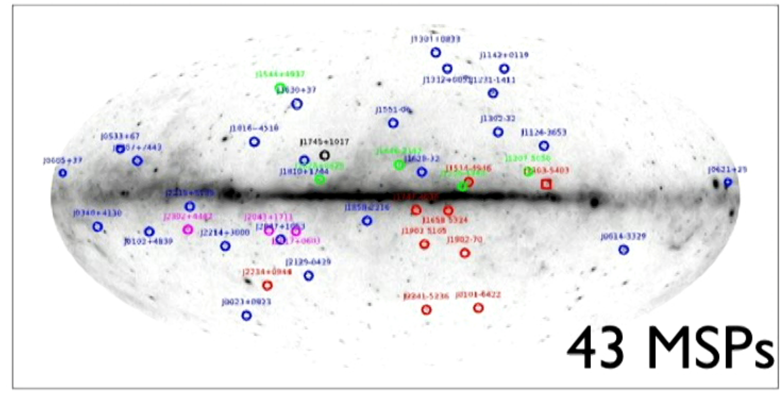


Image courtesy NASA/DOE/Fermi)



GBT, Effelsberg, Parkes, Nançay, GMRT

Adapted Ray et al. (2012)

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Current IPTA Radio Telescopes

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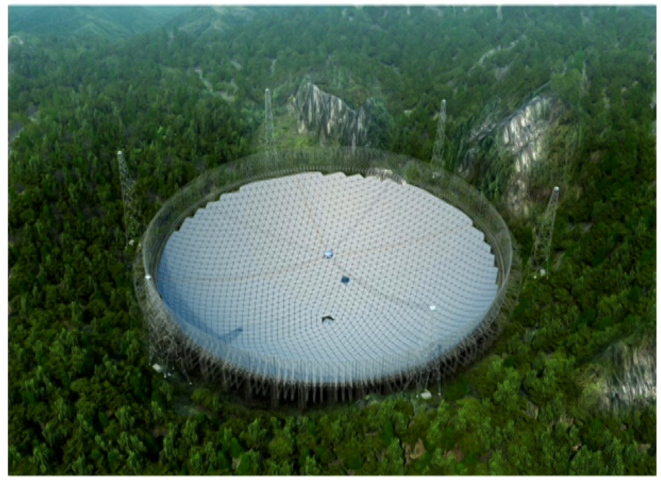
Future Telescopes: they are large.

Image: Keith Vanderlinde; Dunlap Institute

CHIME



fast.bao.ac.cn/en/

FAST

skatelescope.org

SKA

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GW Background from SMBHBs

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

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

We know a lot about A, can learn more

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Gravitational-Wave Background

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

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

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

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

Phinney (2001); Sesana(2012)

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MARIE CURIE ACTIONS

Gravitational-Wave Background

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

number of mergers remnants per comoving volume

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

Phinney (2001); Sesana(2012)

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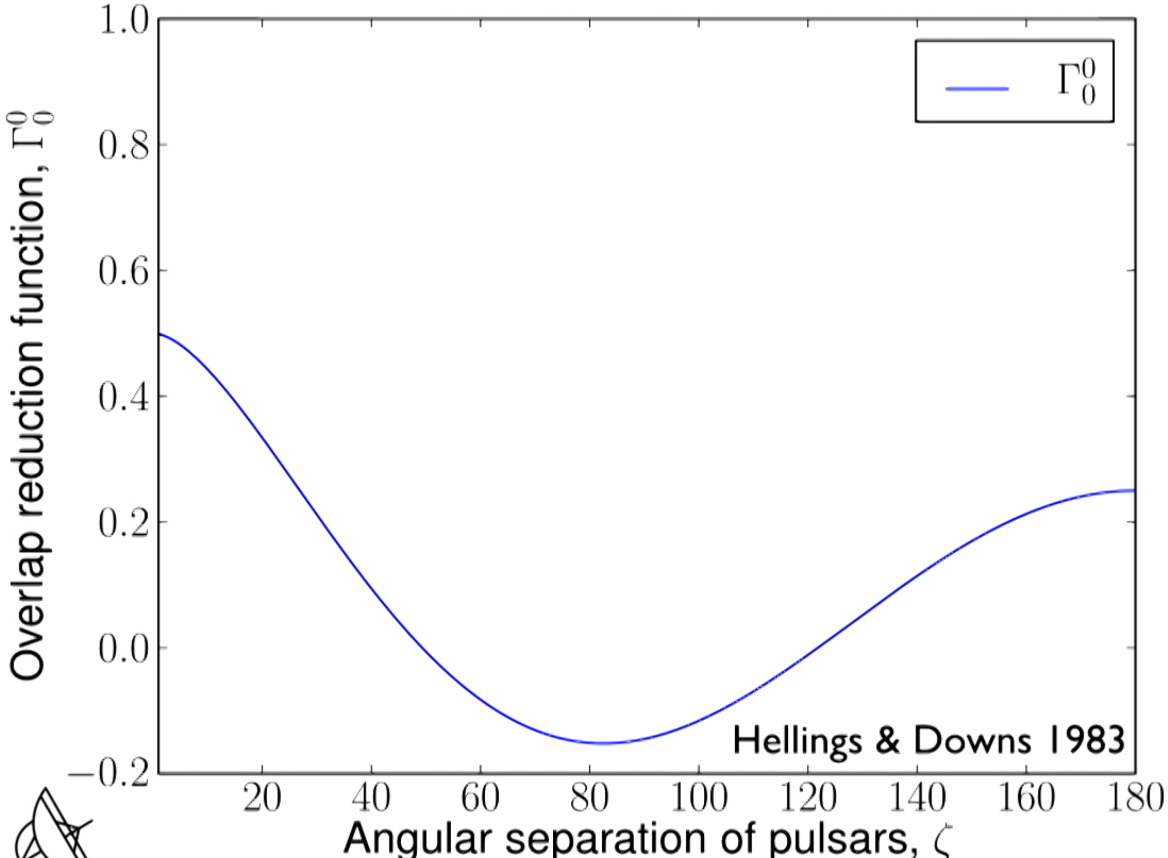
Gravitational-Wave Backgrounds



- What is "waveform" ?
- Hellings and Downs curve
- Assumes background is isotropic (but is it?)
- Many pulsars create "curve"
- Changes for alternative theories of gravity and anisotropic GW backgrounds

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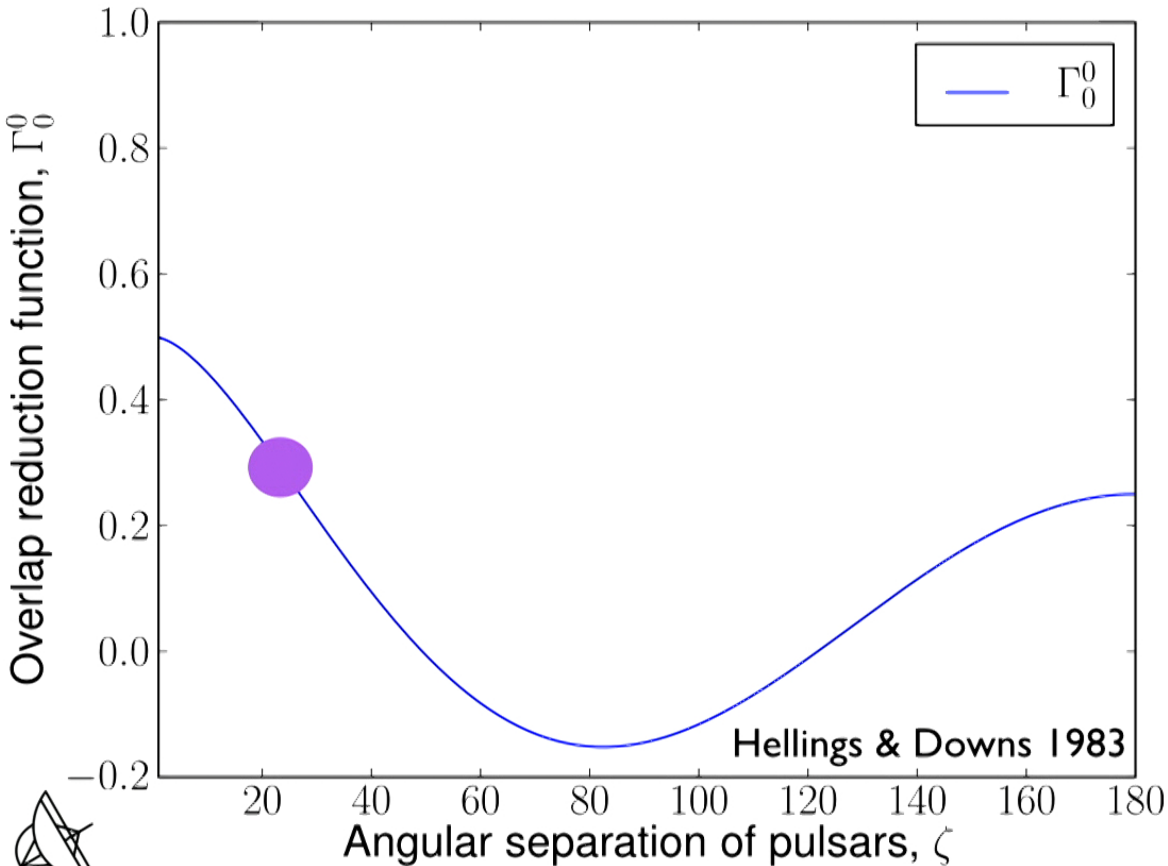
Gravitational-Wave Backgrounds



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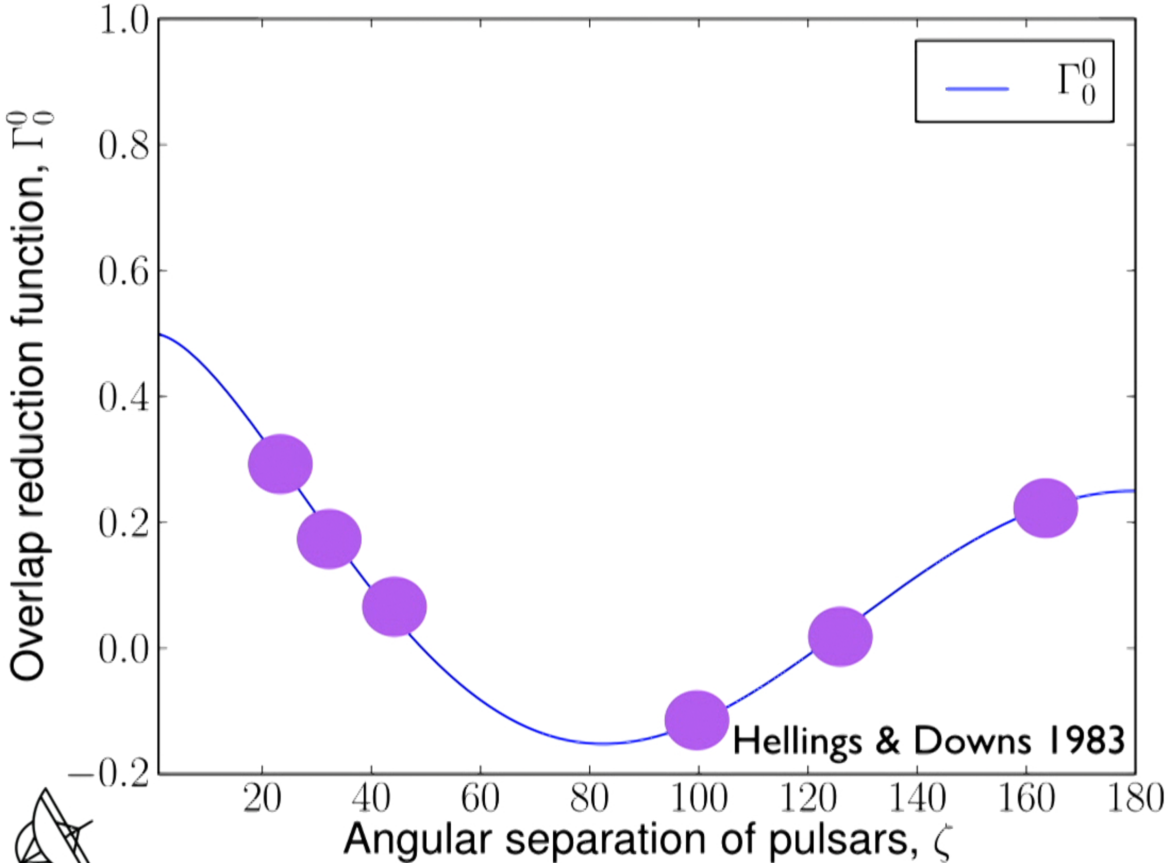
Gravitational-Wave Backgrounds



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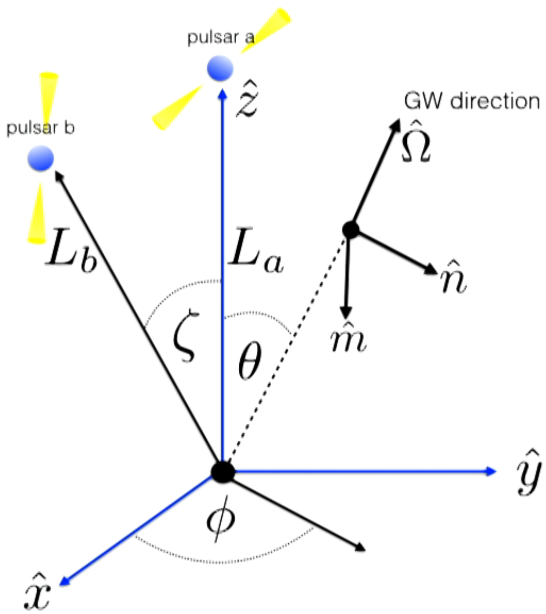
Overlap Reduction Function



$$^{(ab)}\Gamma(f,\hat{\Omega}) \equiv \int_{S^2} d\hat{\Omega} P(\hat{\Omega}) \kappa_{ab}(f,\hat{\Omega}) F_a^A F_b^A$$

$$\kappa_{ab}(f,\hat{\Omega}) \equiv \left[1 - e^{i2\pi f L_a(1+\hat{\Omega}\cdot\hat{p}_a)}\right]\left[1 - e^{-i2\pi f L_b(1+\hat{\Omega}\cdot\hat{p}_b)}\right].$$

$$F^A(\hat{\Omega}) = \left[\frac{1}{2}\frac{\hat{p}^i\hat{p}^j}{1+\hat{\Omega}\cdot\hat{p}} e_{ij}^A(\hat{\Omega})\right].$$ detector response

Short wavelength approximation, fL >>1 and $L_a=L_b$ so

$$\kappa_{ab} \approx 1 + \delta_{ab}$$

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Mingarelli and Sidery (2014)

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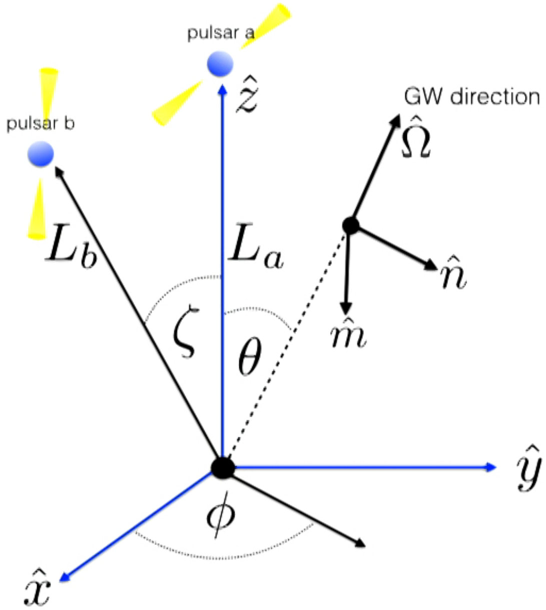
Overlap Reduction Function

$$F^A(\hat{\Omega}) = \left[\frac{1}{2}\frac{\hat{p}^i\hat{p}^j}{1+\hat{\Omega}\cdot\hat{p}}\ e^A_{ij}(\hat{\Omega})\right].$$ detector response



$$e^+_{ij}(\hat{\Omega}) = \hat{m}_i\hat{m}_j - \hat{n}_i\hat{n}_j$$

$$\hat{p}_a = (0, 0, 1),$$
$$\hat{p}_b = (\sin\zeta, 0, \cos\zeta),$$
$$\hat{\Omega} = (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta),$$
$$\hat{m} = (\sin\phi, -\cos\phi, 0),$$
$$\hat{n} = (\cos\theta\cos\phi, \cos\theta\sin\phi, -\sin\theta),$$

$$F^+_a = -\frac{1}{2}(1-\cos\theta)$$

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Mingarelli and Sidery (2014)

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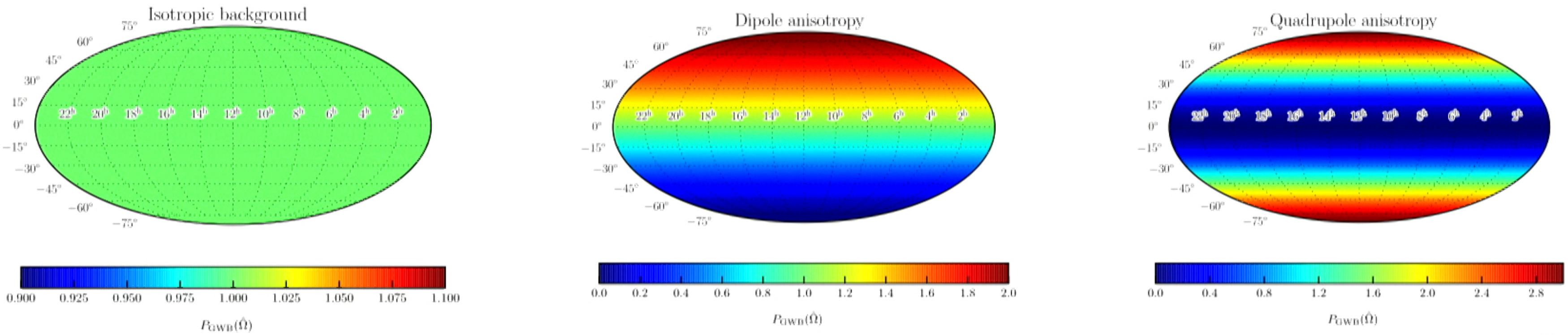
GWB Anisotropy

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



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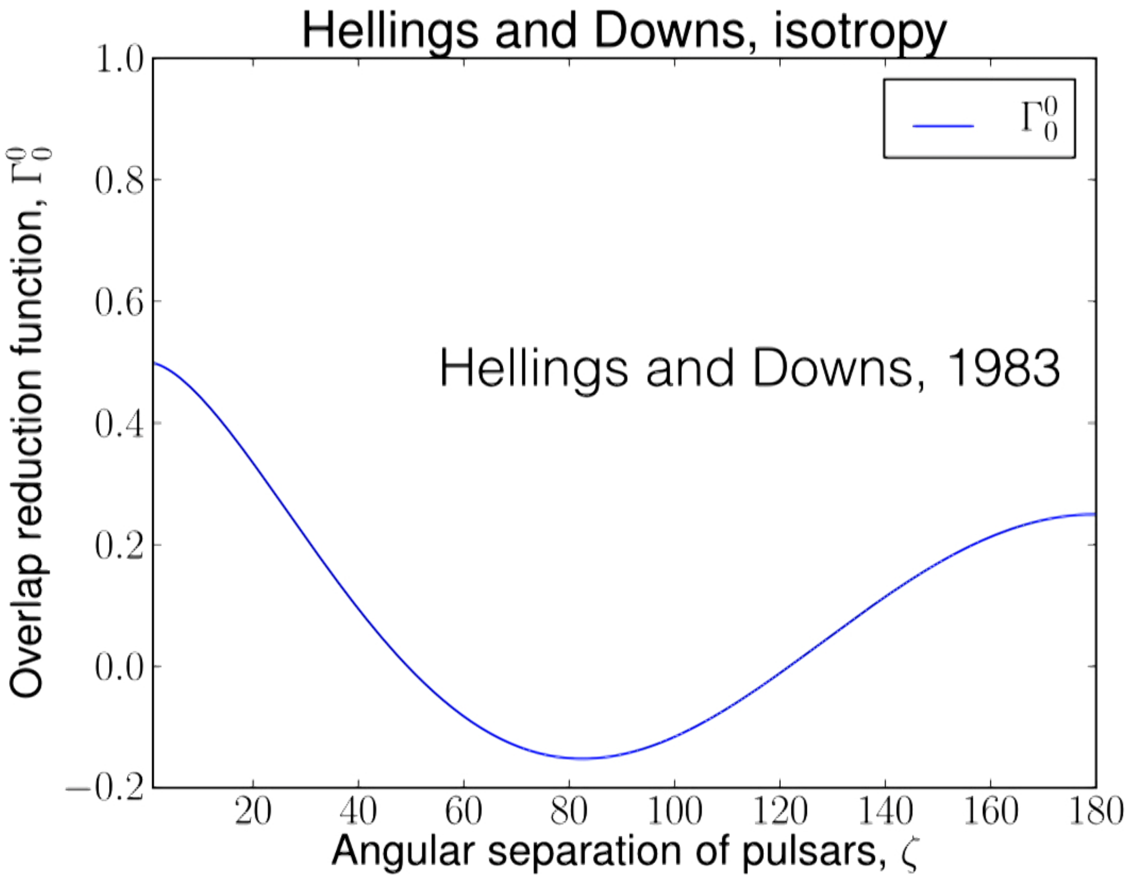
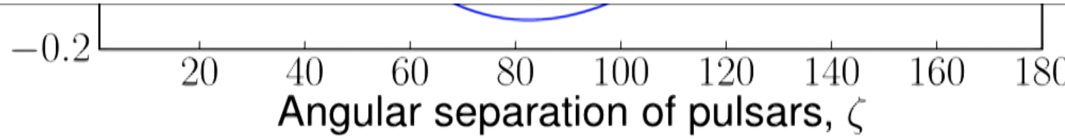
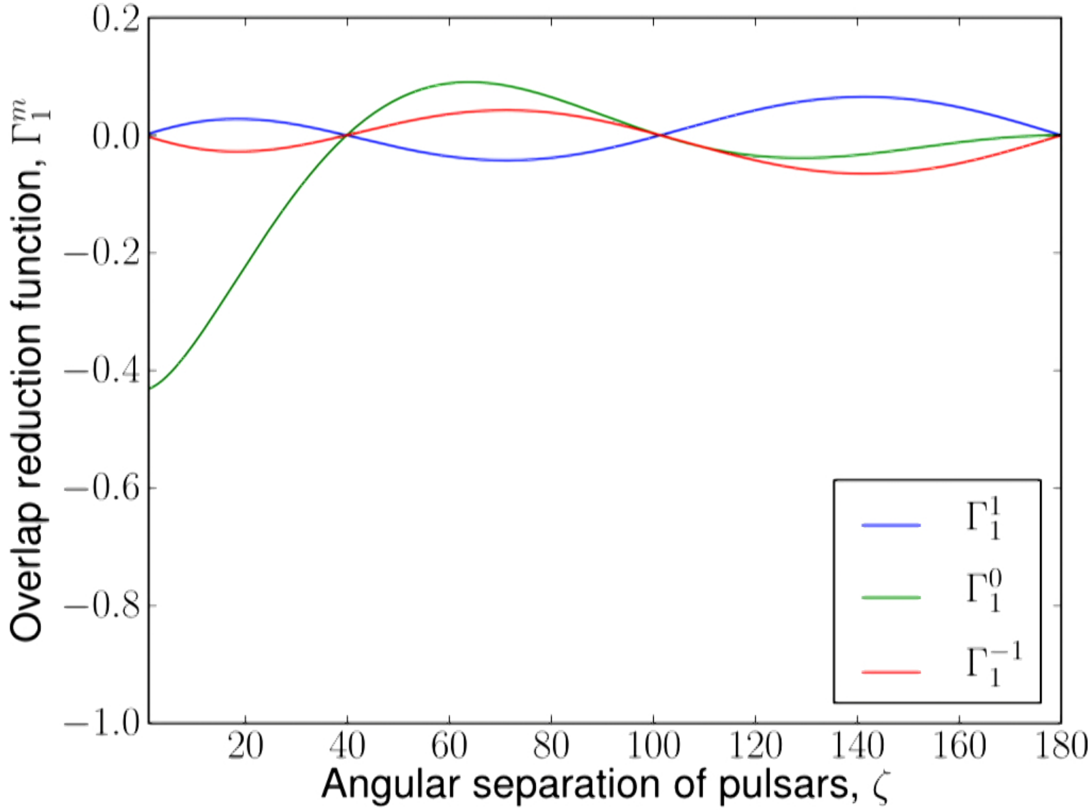
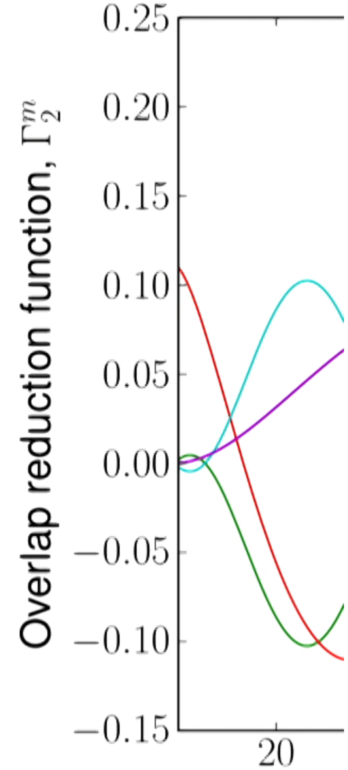


Mingarelli et al. PRD **88**, 062005 (2013)







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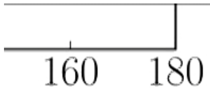

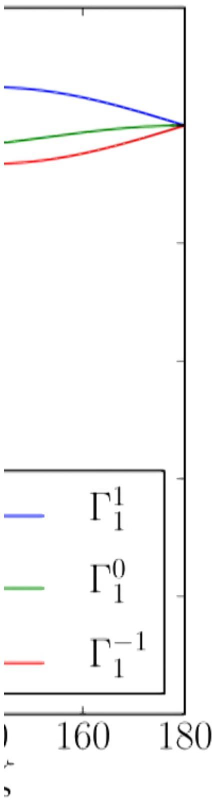

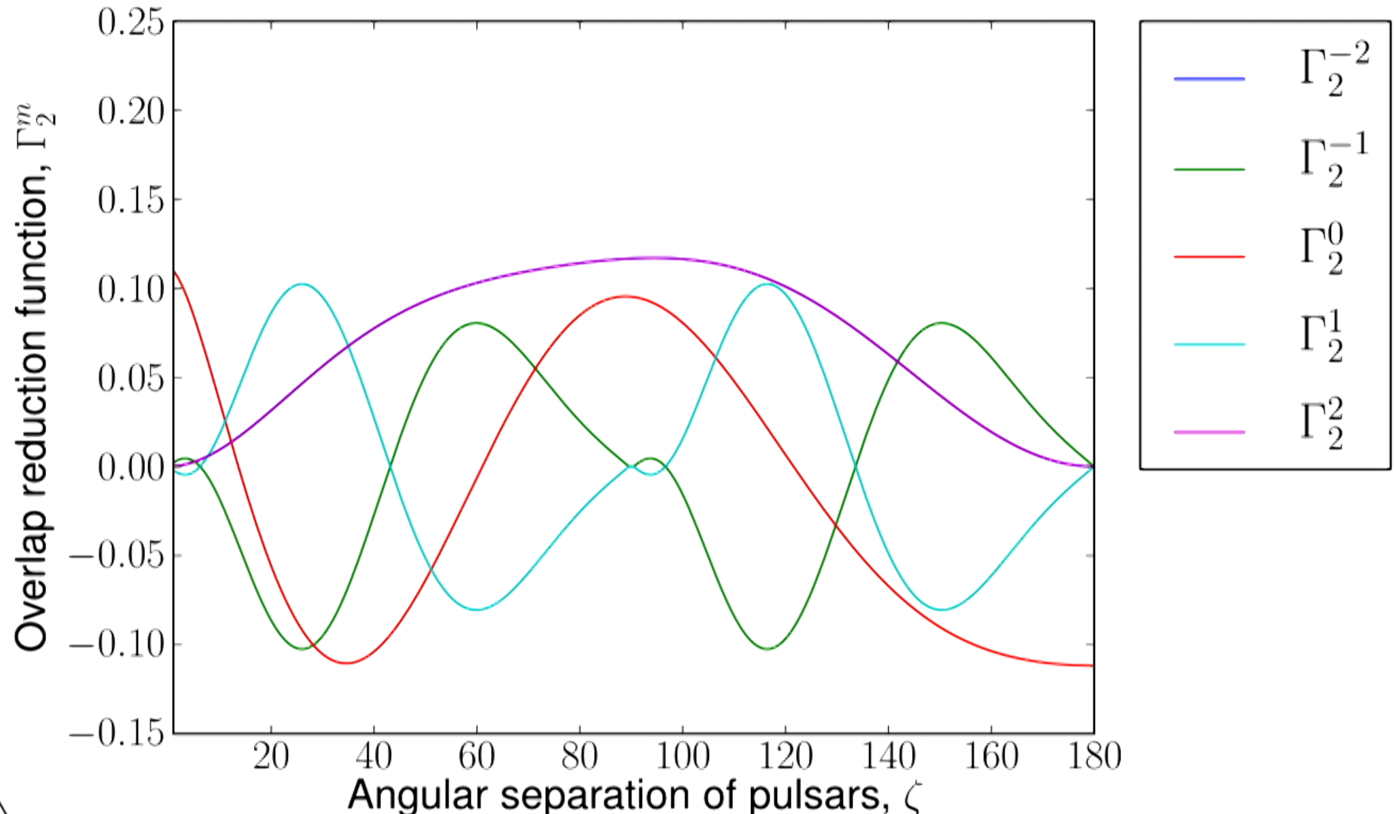

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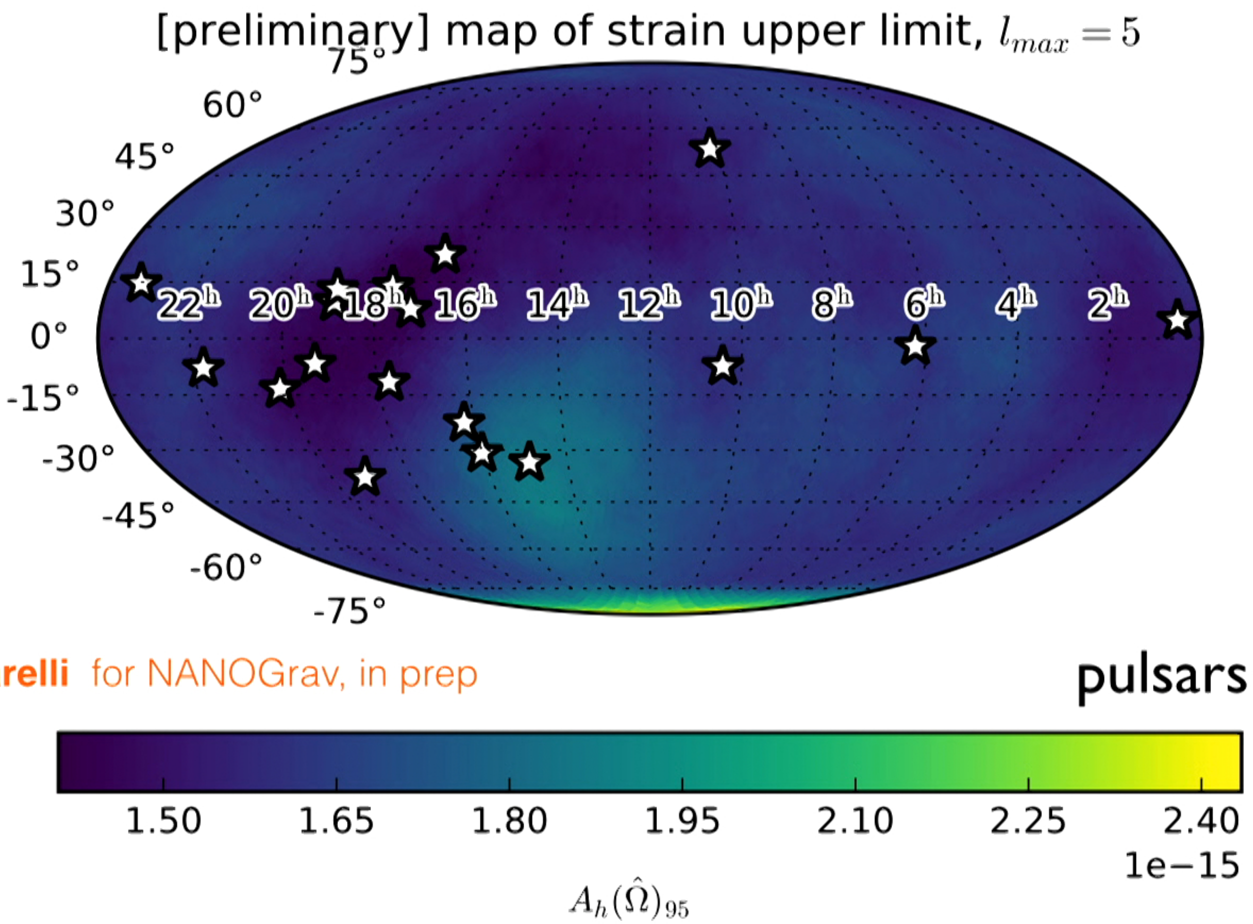

Mingarelli for NANOGrav, in prep

pulsars ++

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

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

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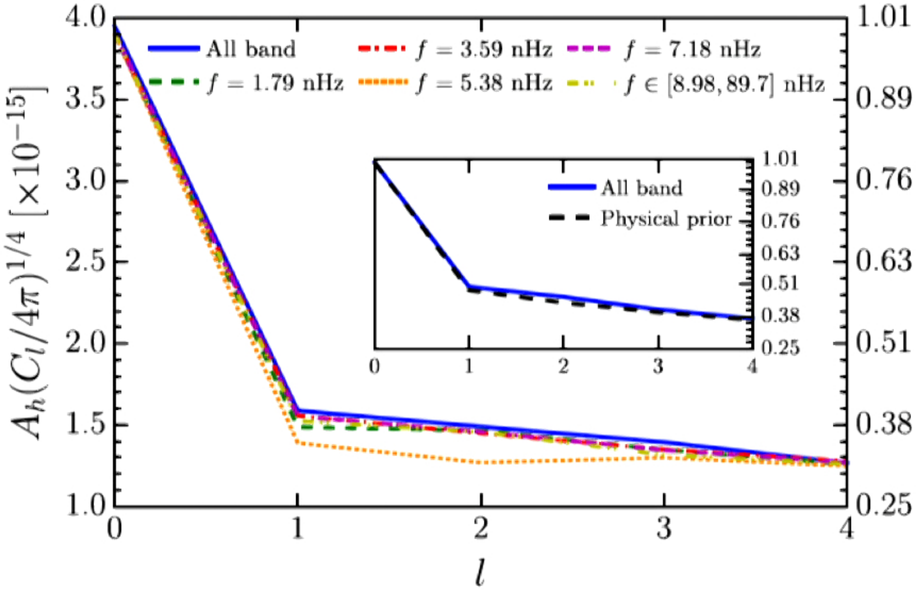
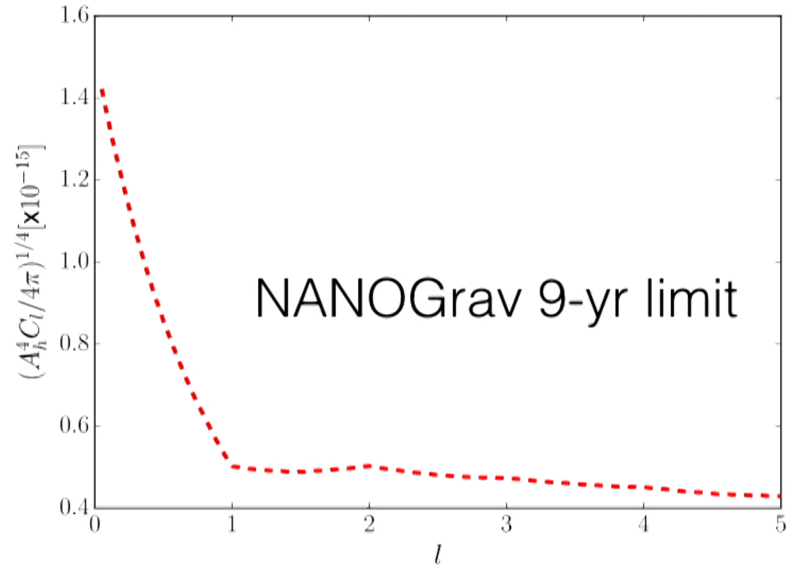
How much anisotropy?



Taylor, Mingarelli et al. Phys Rev Lett (2015)



Mingarelli + for NANOGrav, in prep

$$C_\ell = \sum_{m=-\ell}^{+\ell} |c_{\ell m}|^2/(2\ell+1)$$

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Continuous-Wave Predictions Based on Local Galaxies

Mingarelli, Lazio, Sesana, Greene, Ma, Ellis, Croft, Taylor, Burke-Spolaor (2017)

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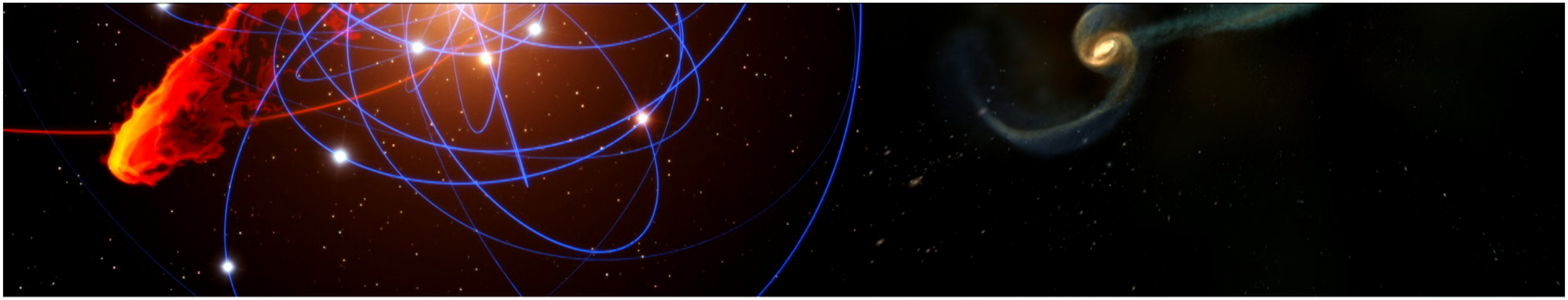
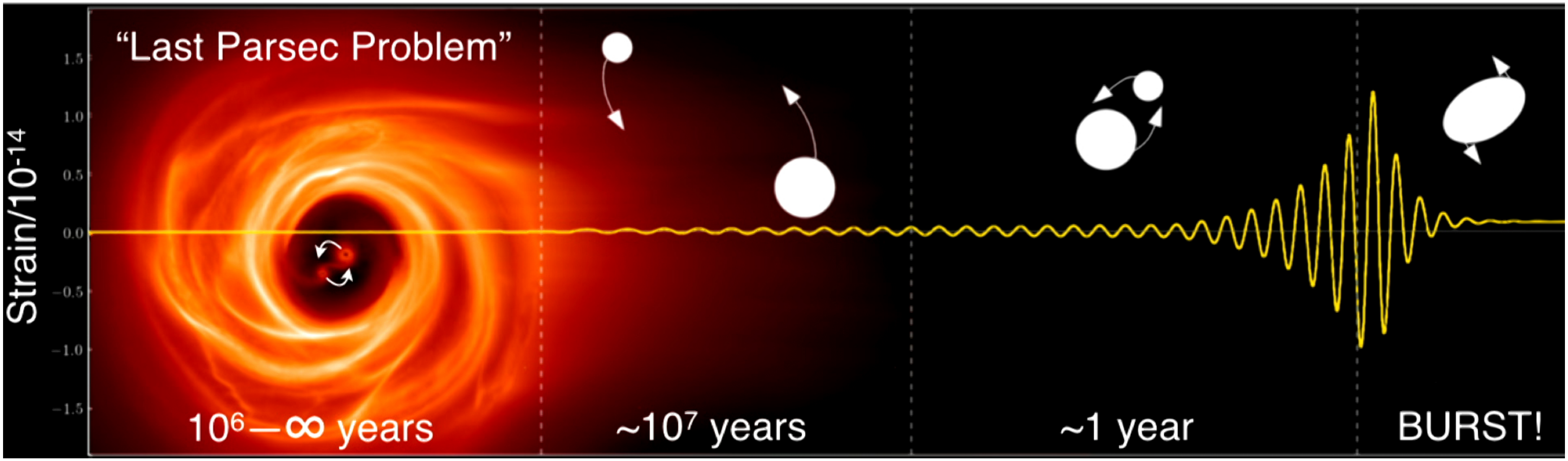


Final Parsec Problem?

gas? stars?



2MASS Catalog

- 2MASS is an all-sky galaxy catalogue; recognized standard
- near-infrared wavelength is sensitive to the dominant mass component of these galaxies
- Look for elliptical and S0 galaxies, (formed from mergers)
- Convert from k-band, Mk<-25, luminosity to galaxy's bulge mass

$$\log_{10}(M^*) = 10.58 - 0.44\,(M_K + 23)$$

- We find 5,110 galaxies out to 225 Mpc, completeness limit

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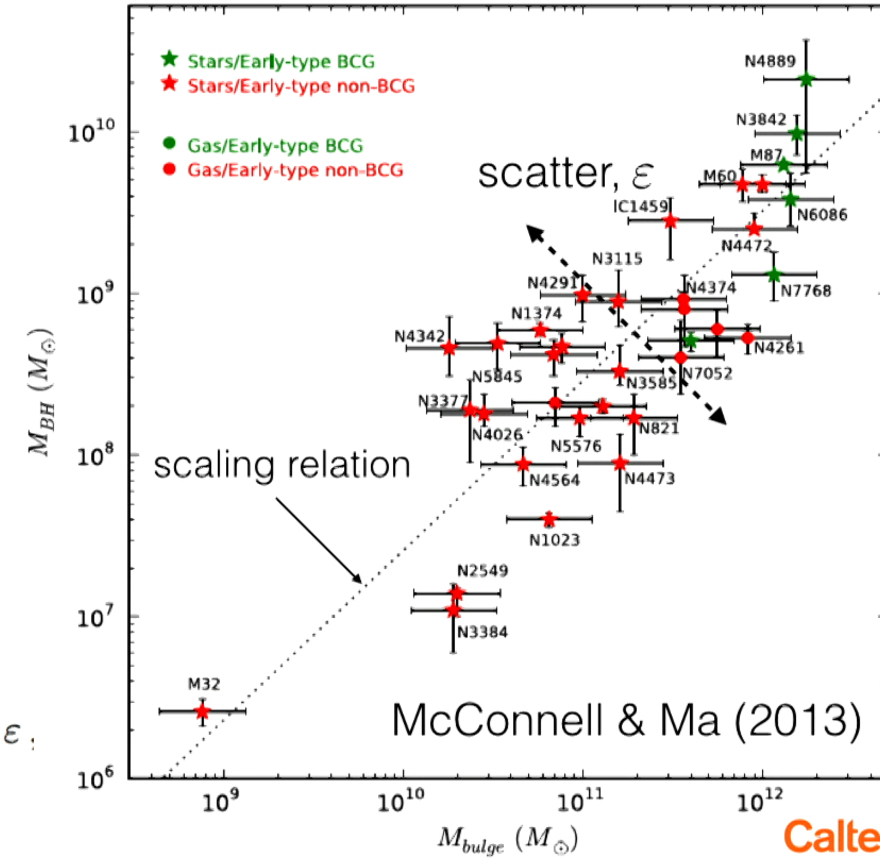
Black Hole - Host Relation

- Scaling relation between M_{BH}-M_{bulge}
- Best to include scatter parameter in draws of BH mass to be conservative
- Log-normal draws of mass, conservative
- Breaks down at extrema: **use dynamical mass estimates** for most massive galaxies

$$\log_{10}\left(\frac{M_\bullet}{M_\odot}\right) = 8.46 + 1.05 \log_{10}\left(\frac{M_{\rm bulge}}{10^{11}\,M_\odot}\right) + \varepsilon\,;$$



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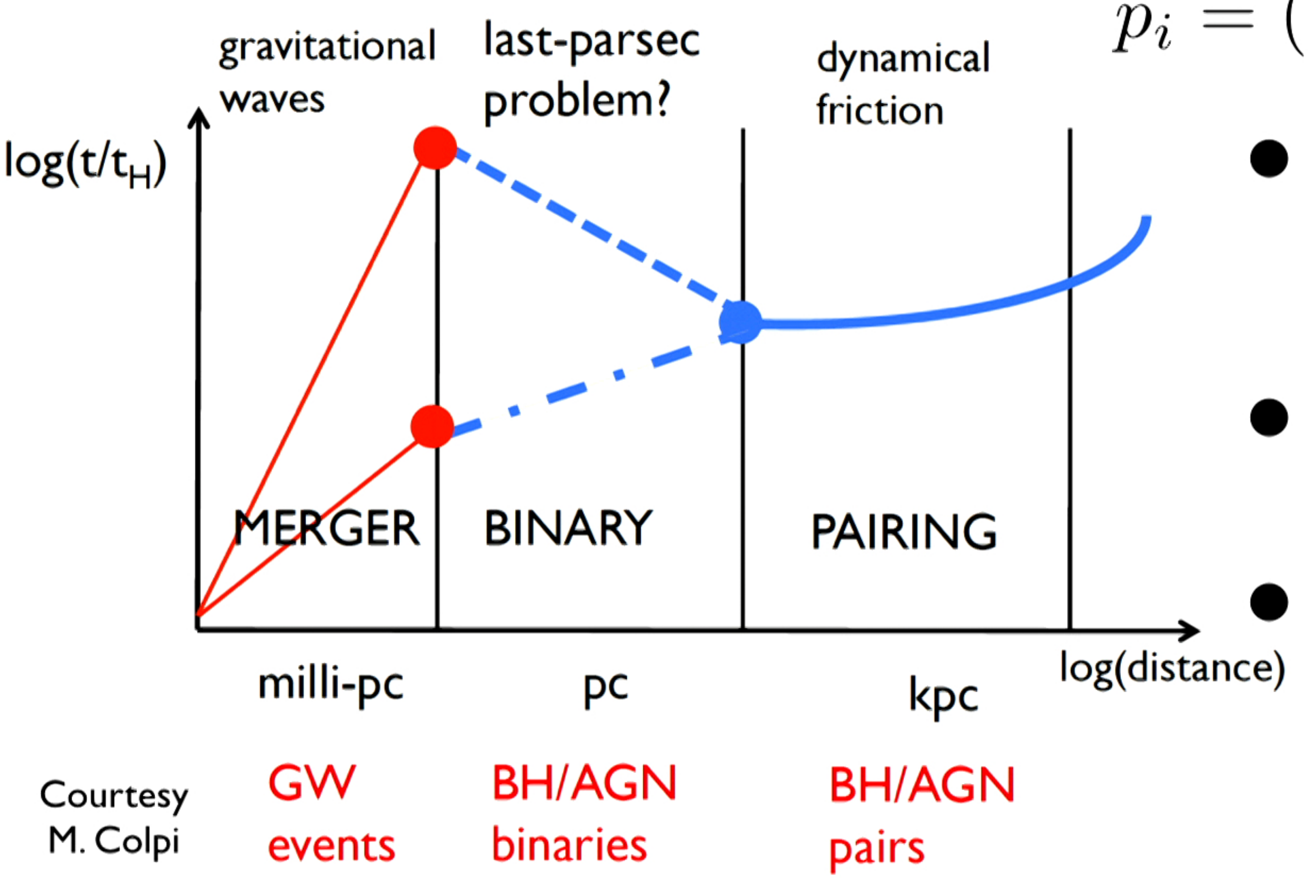
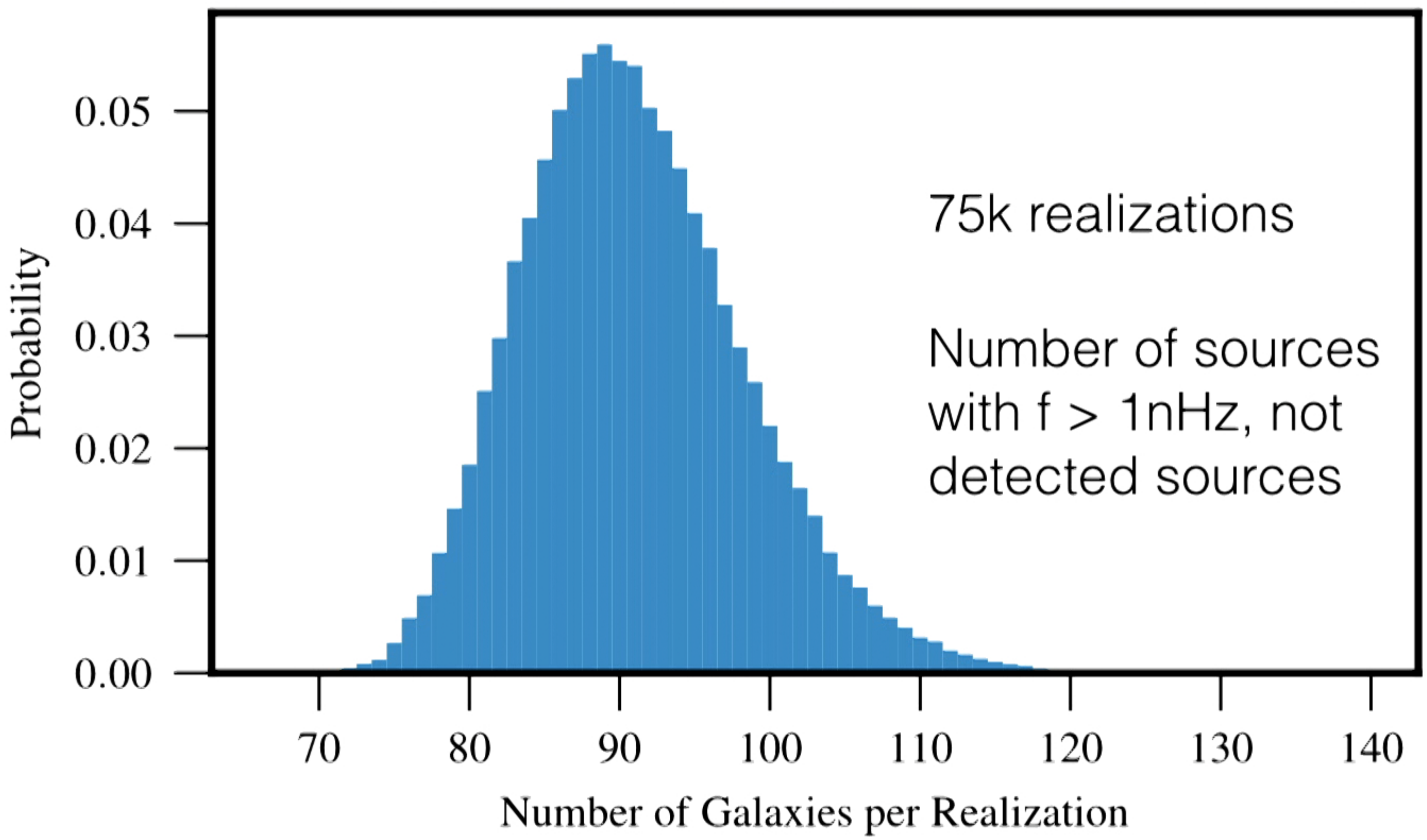
Simulating a GW sky: choosing host galaxies



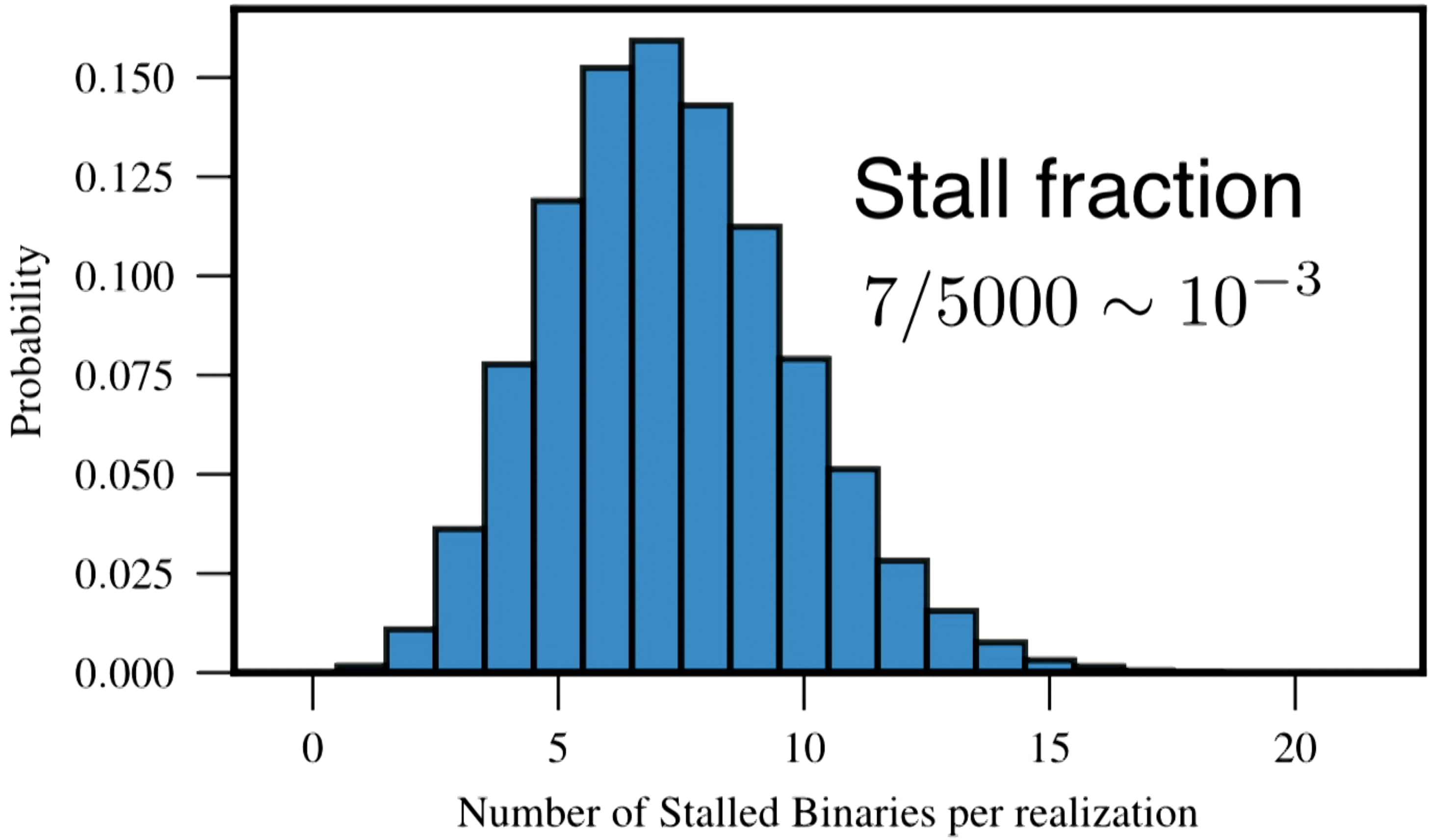
$$p_i = (t_{c,i}/T_z) \times (dN/dt \cdot T_z)$$

- Merger rate from Illustris (Rodriguez-Gomez et al. 2015) at that z;
- Total galaxies w PTA binary is sum of all p_i's
- If $T_z > 12.5$ Gyr, stalled

Result: GW sources per realization



Result: GW sources per realization



Which sources can be detected?

- Have BH masses and distances, need GW frequency and mass ratio, q, to compute strain:

$$h = \sqrt{\frac{32}{5}} \frac{(\pi f)^{2/3}}{D_L} \mathcal{M}_c^{5/3}$$

- Sample log-normal distribution of q [0.25,1.0]

- Uniform sample in t_c [100 yr, 26 Myr] and use above q, to compute GW frequency:

$$f = \pi^{-1} \mathcal{M}^{-5/8} \left[\frac{256}{5} (t_c - t) \right]^{-3/8}$$

- t_c limit corresponds to a minimum GW frequency of 1 nHz.

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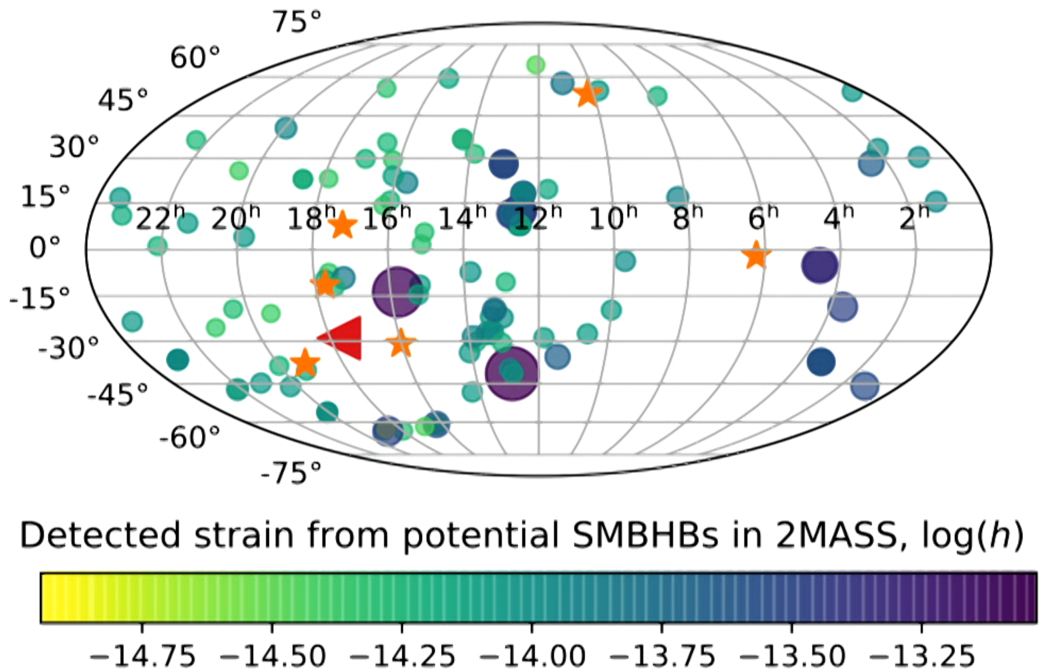
Detected with EPTA



- Is non-detection surprising?
- Use sky maps vs sky-averaged h
- Six top EPTA pulsars (Babak et al. 2016)
- Triangle: Sag A*
- circles: sources detected with current EPTA
- Detector response!

$$F^A(\hat{\Omega}) = \left[\frac{1}{2}\frac{\hat{p}^i\hat{p}^j}{1+\hat{\Omega}\cdot\hat{p}}\; e_{ij}^A(\hat{\Omega})\right].$$

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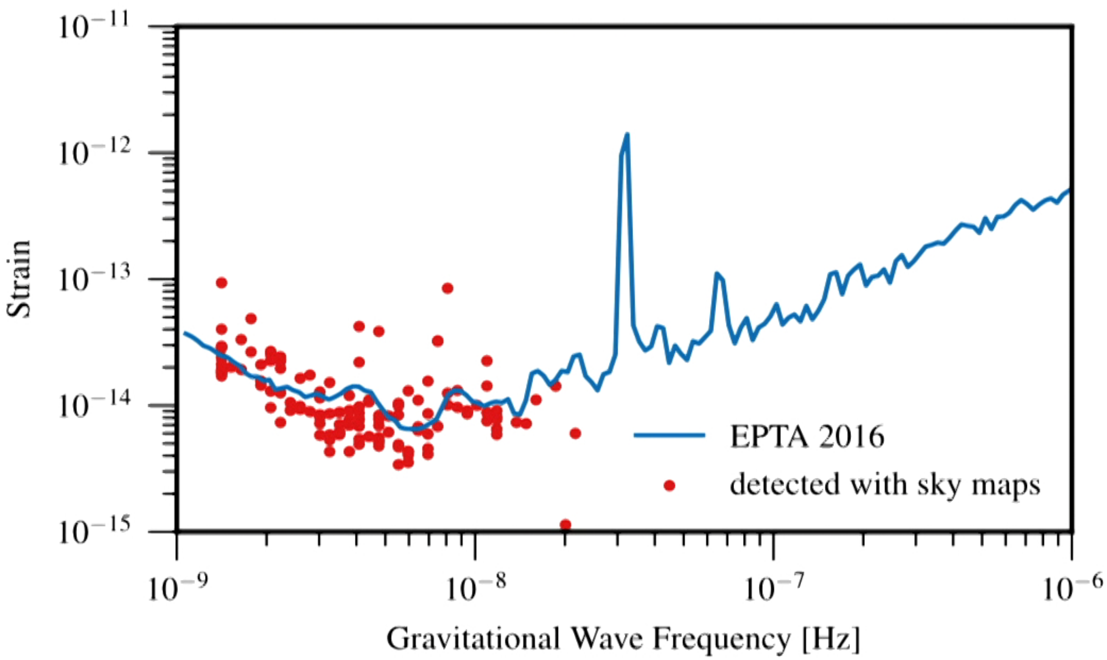
Detected with EPTA



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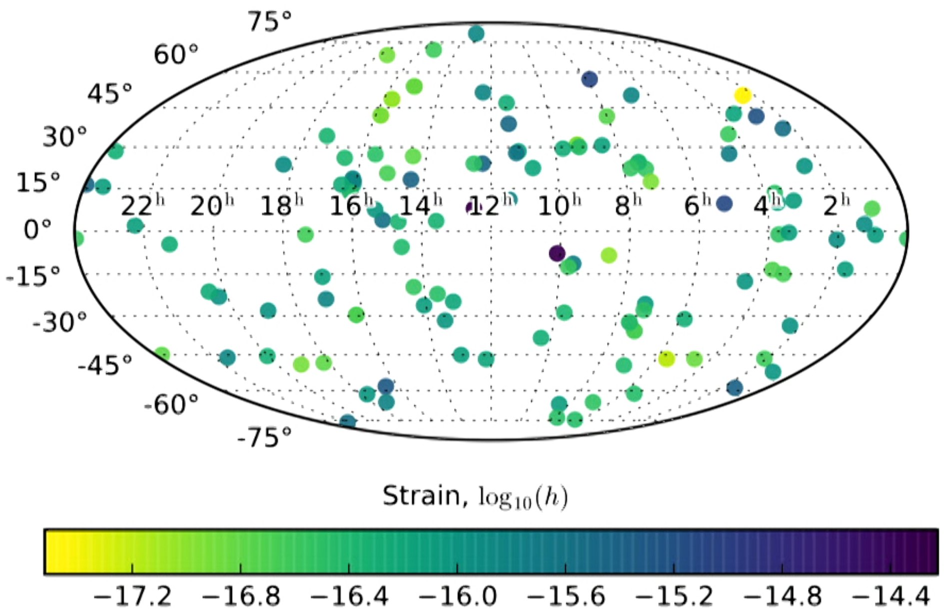
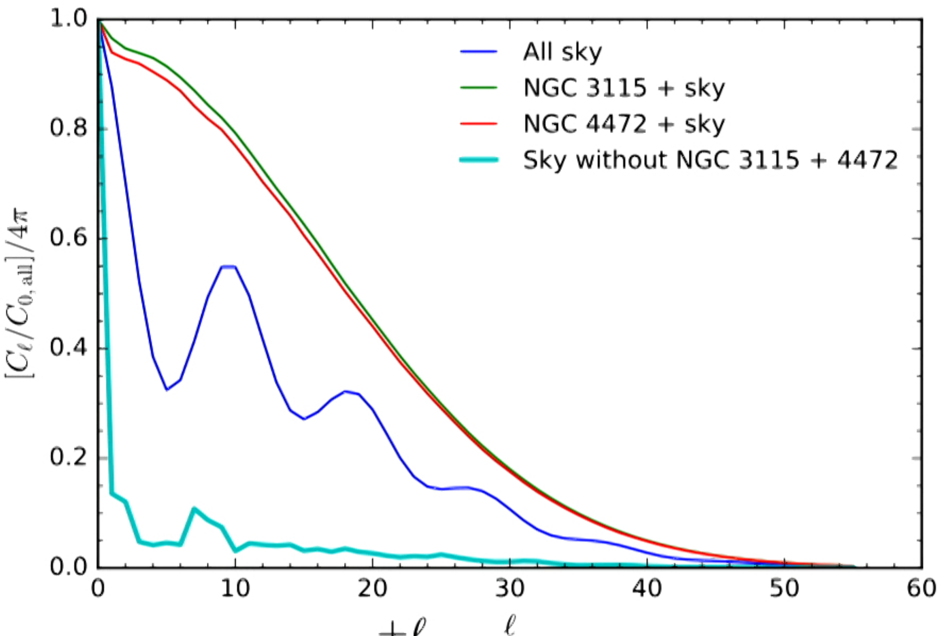
Contributions to GWB





$$h_c^2 = \sum_k h_k^2 f_k / \Delta f$$

$$C_\ell = \sum_{m=-\ell}^{+\ell} |c_{\ell m}|^2 / (2\ell + 1)$$

Contribution to isotropic GWB < 1%

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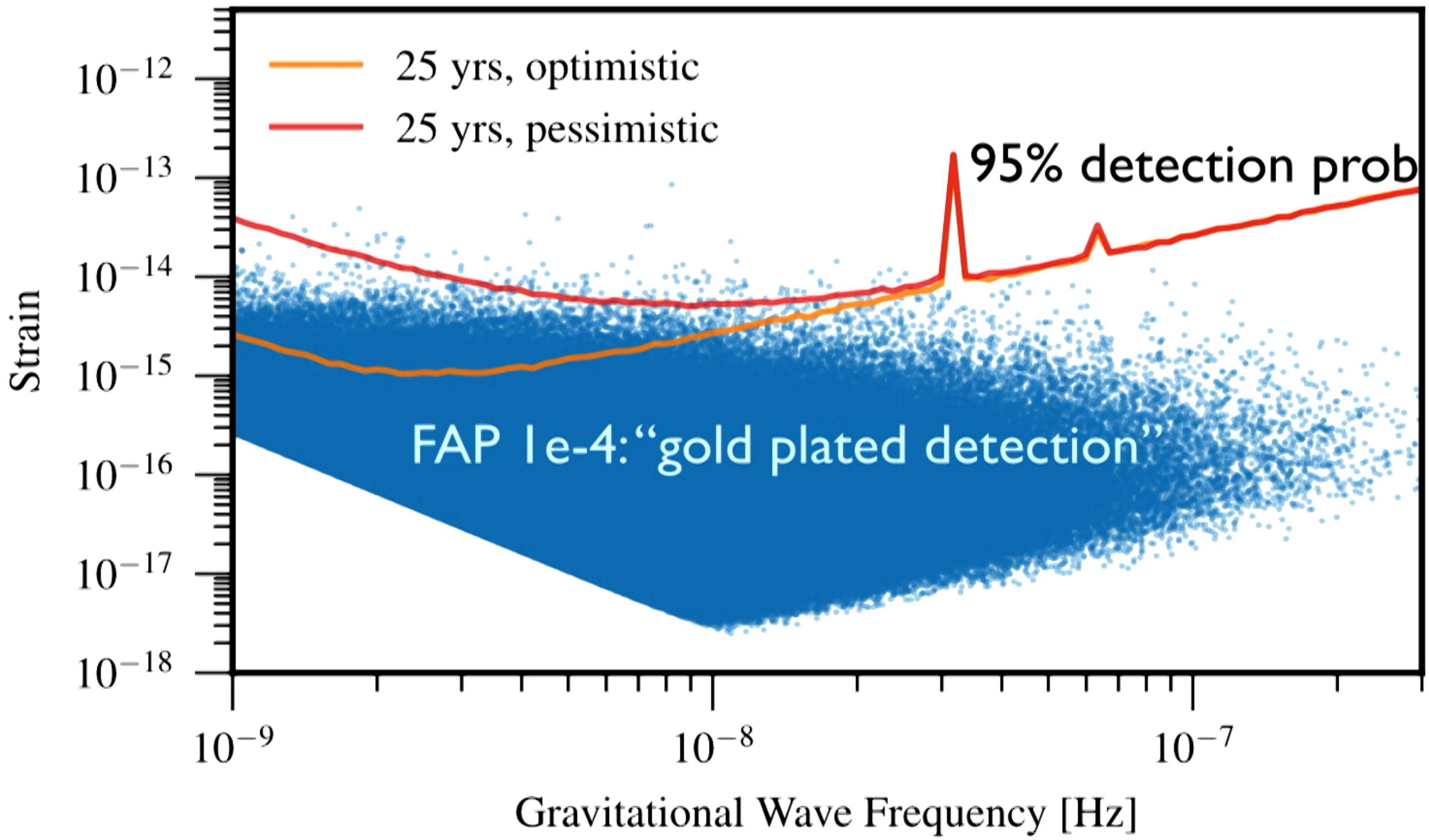
Time to detection



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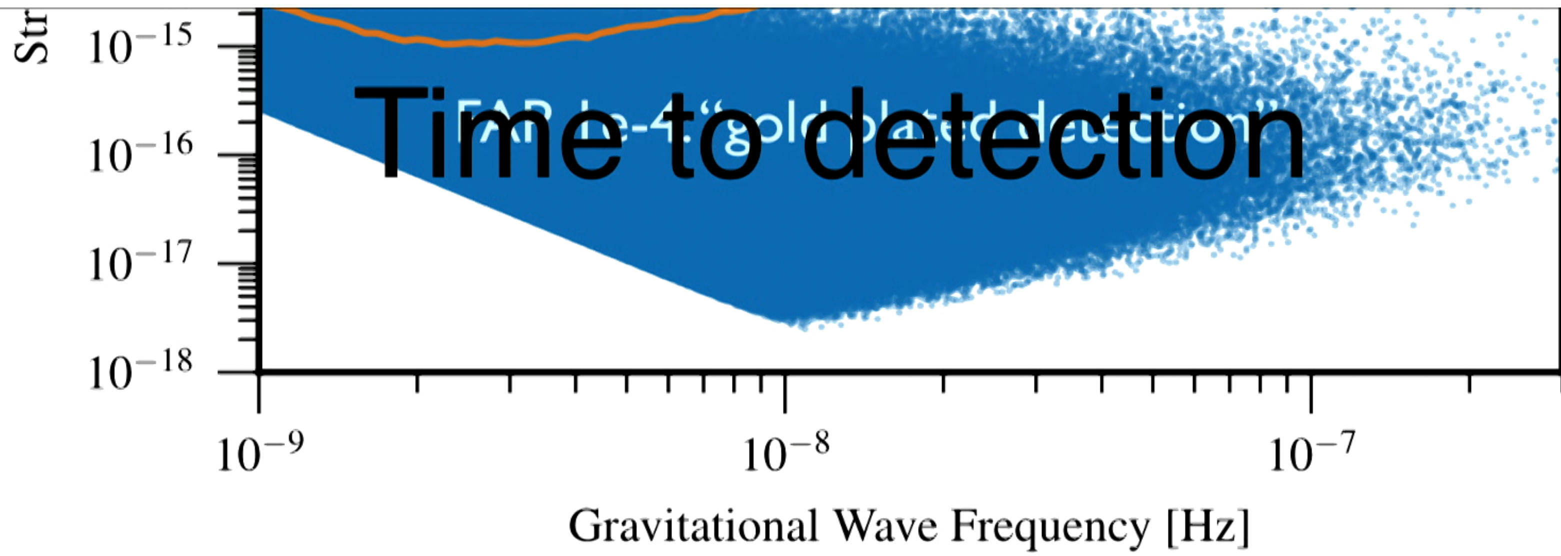
Time to detection



Factor of 4!
sky location

FAP	15 yrs	20yrs	25 yrs
0.05 (2σ)	2% (0.09%)	24% (0.3%)	123% (0.8%)
3e-3 (3σ)	0.5% (0.03%)	9% (0.2%)	48% (0.3%)
1e-4	0.3% (0.01%)	4% (0.08%)	27% (0.2%)

Current PTAs : 10-15 years

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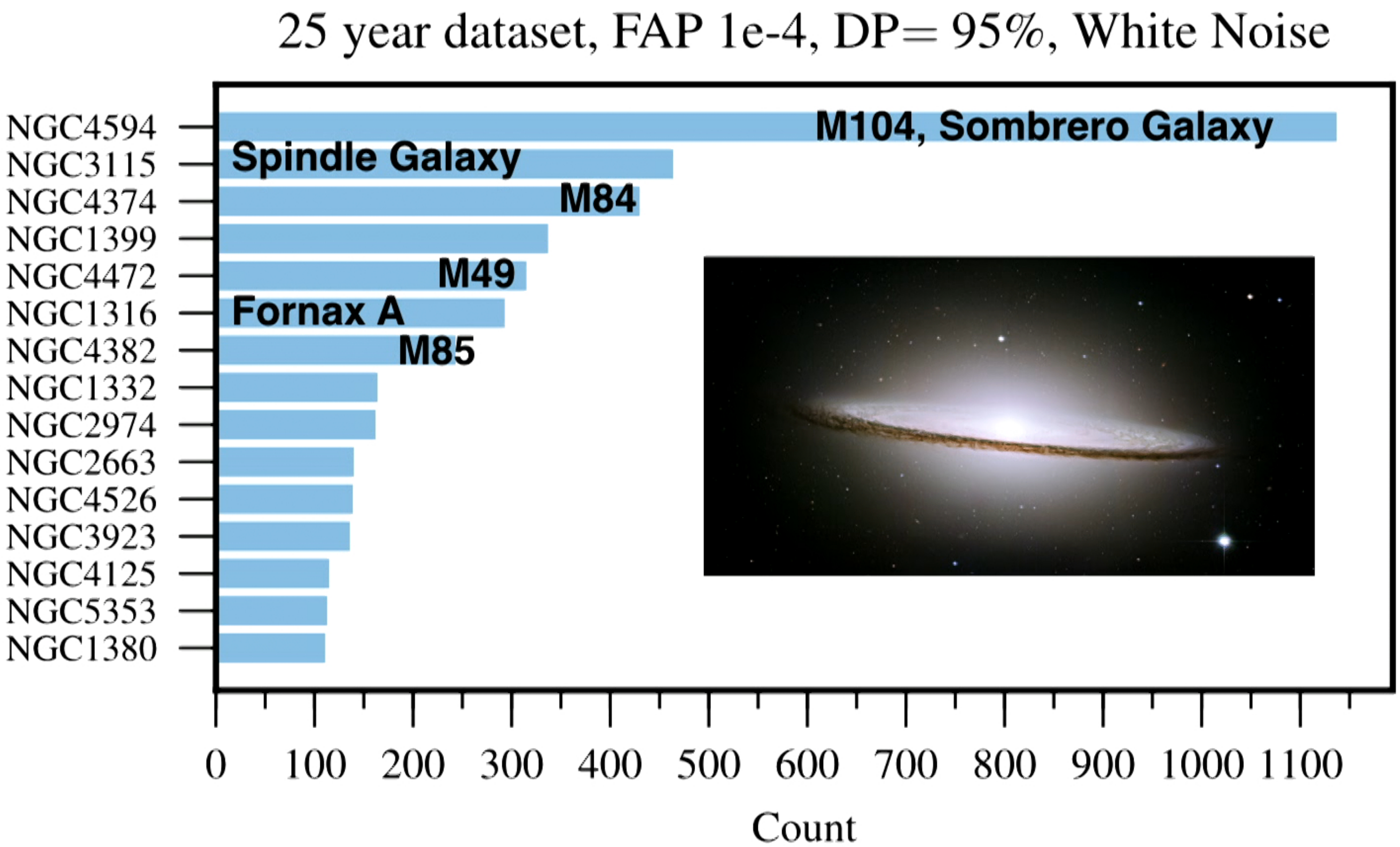
Hit List



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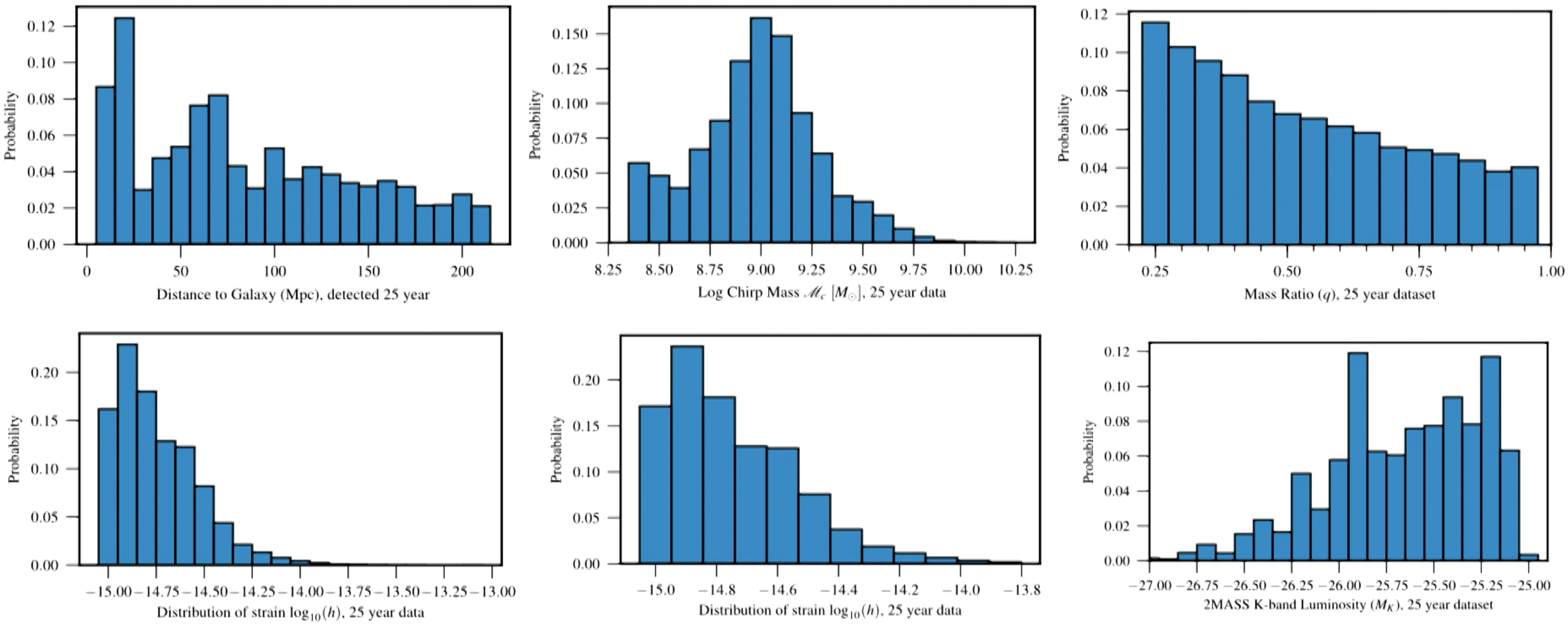
Clues for EM counterparts



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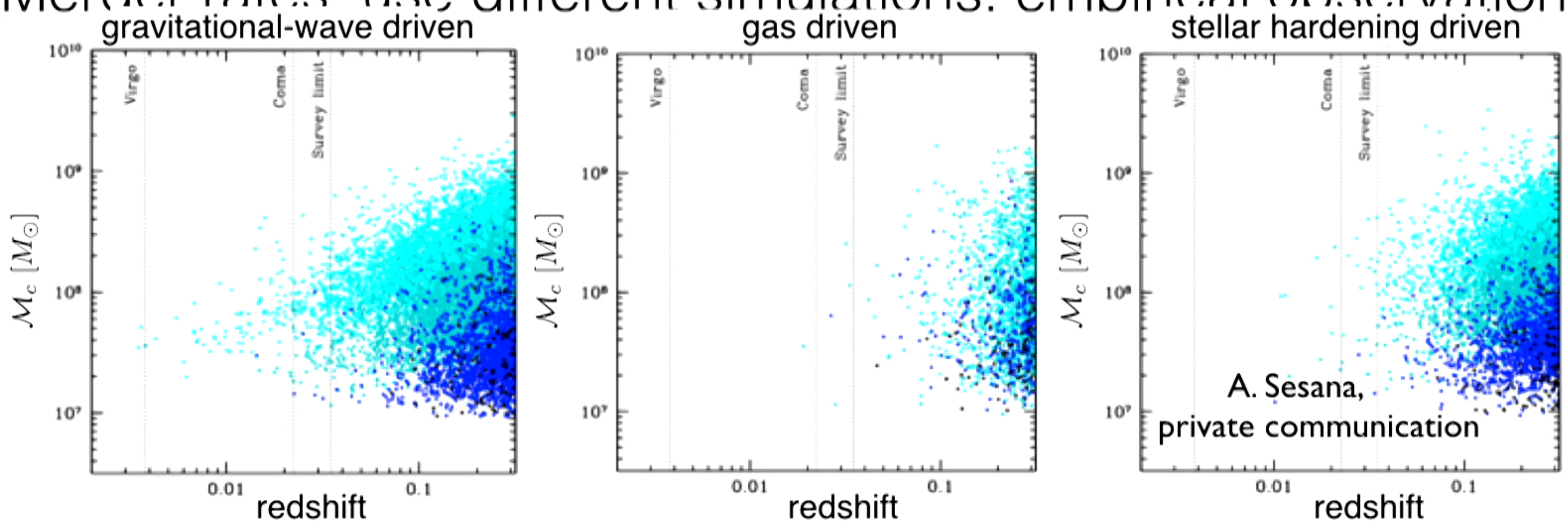
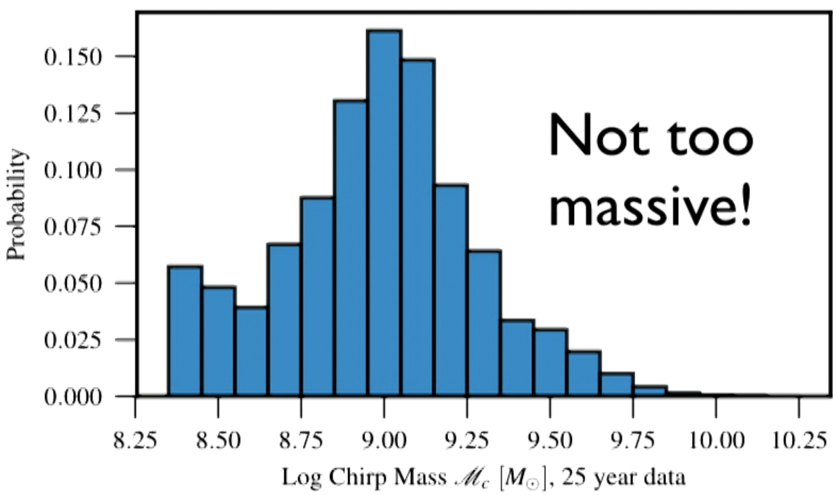
Future Directions

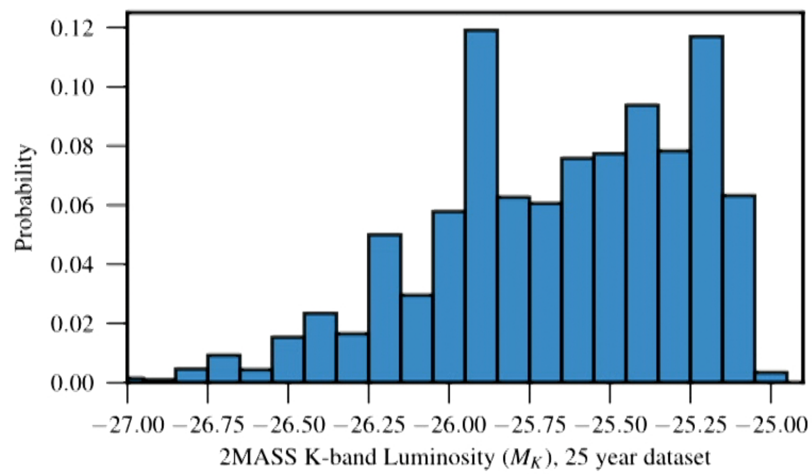
- Use SDSS to create background, compare to claims by Kelley et al. (2016) that GWB dominated by z<0.3
- Add complexity: eccentricity, gas, stellar hardening interplay
- Merger rates: use different simulations, empirical observations



Future Directions

- EM Followups: What to look for? Clues in this work
- New x-ray data from e-ROSITA soon may contain SMBHB signatures
- Build your own PTA: likely SMBHB host galaxies + Fermi candidates
- Extra-galactic PTAs: add pulsars in LMC (48.5 kpc)





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Future Directions

LISA (not supposed to call eLISA anymore)

- SMBHBs in LISA band will suffer same final parsec problems: PTAs can inform what one will see in LISA data
- Methods developed to constrain anisotropy can be used to characterize the white-dwarf foreground
- More!

Primordial Backgrounds

- Search for evidence of anisotropic inflation via dipole in GWB

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Summary

- PTA **interdisciplinary** science experiment: radio astronomy, GWB+anisotropy +CW, galaxy evolution, SMBH environments and more
- **Backgrounds**: EPTA and NANOGrav (soon IPTA) to limit stochastic background anisotropy
- On average, ~90 **galaxies per sky** with SMBHBs emitting GWs with f > 1 nHz out to 225 Mpc
- **Continuous Wave Detection?** Current non-detection unsurprising, <1 % chance for nearby sources, local source likely in 10 years
- Depends on **relative sky position of pulsars and galaxies,** and on pulsar red noise: x4 more detections using sky maps
- Future directions: **tremendous.**

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