Gravitational-Wave Universe seen by Pulsar Timing Arrays

Chiara M. F. Mingarelli
Center for Computational Astrophysics,
Flatiron Institute

Séminaire Lagrange, OCA
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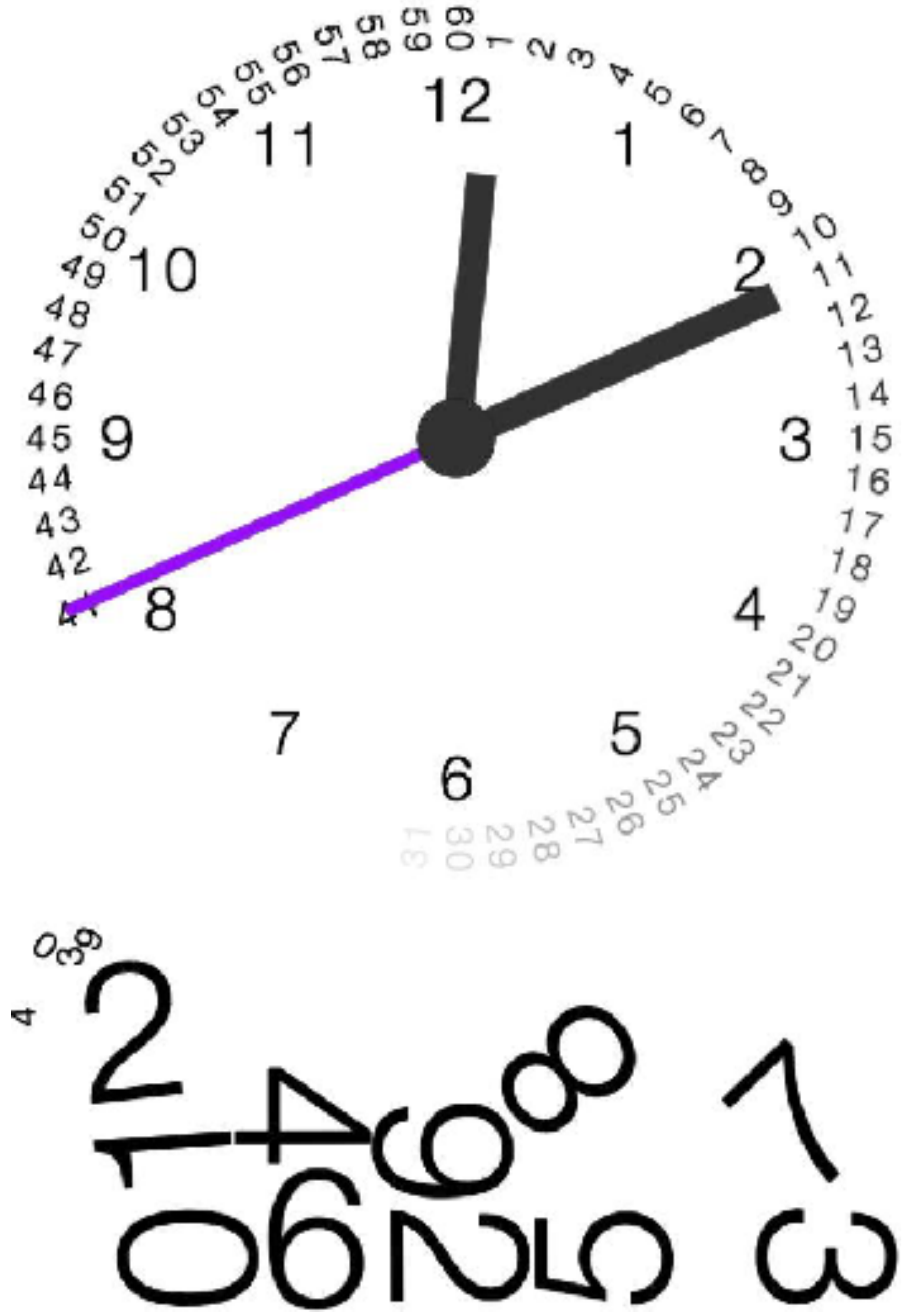
Outline

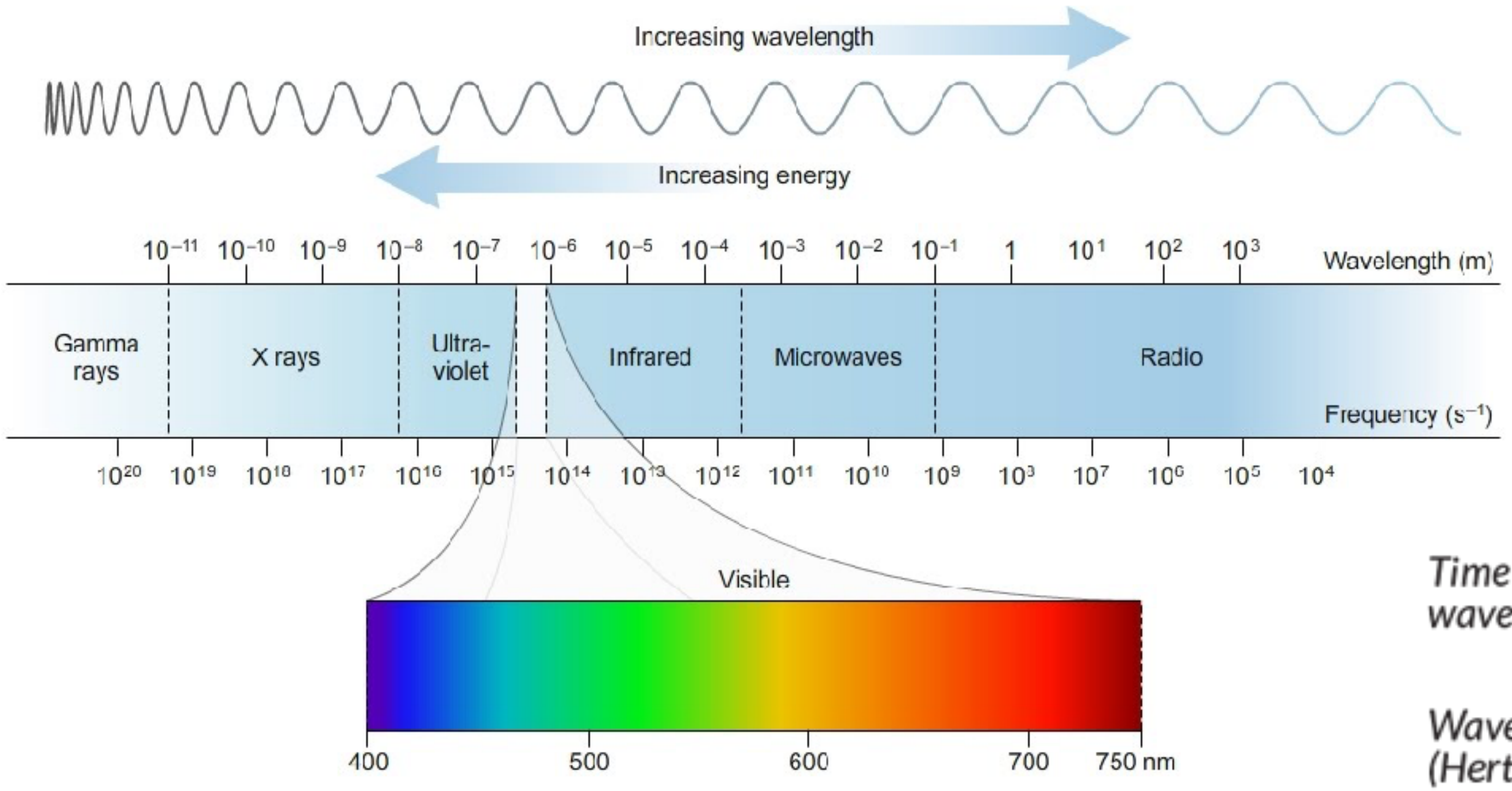
- The gravitational-wave spectrum
- **Pulsar Timing Arrays:** how they work
- Gravitational-wave background: **final parsec problem**
- Nearby *continuous* gravitational-wave sources
- How these can induce **anisotropy** in the background
- **Cutting edge**: Gaia for improved pulsar distances, Fermi targeted searches, constraining the scatter in black hole - galaxy scaling relations

I would love to talk about…

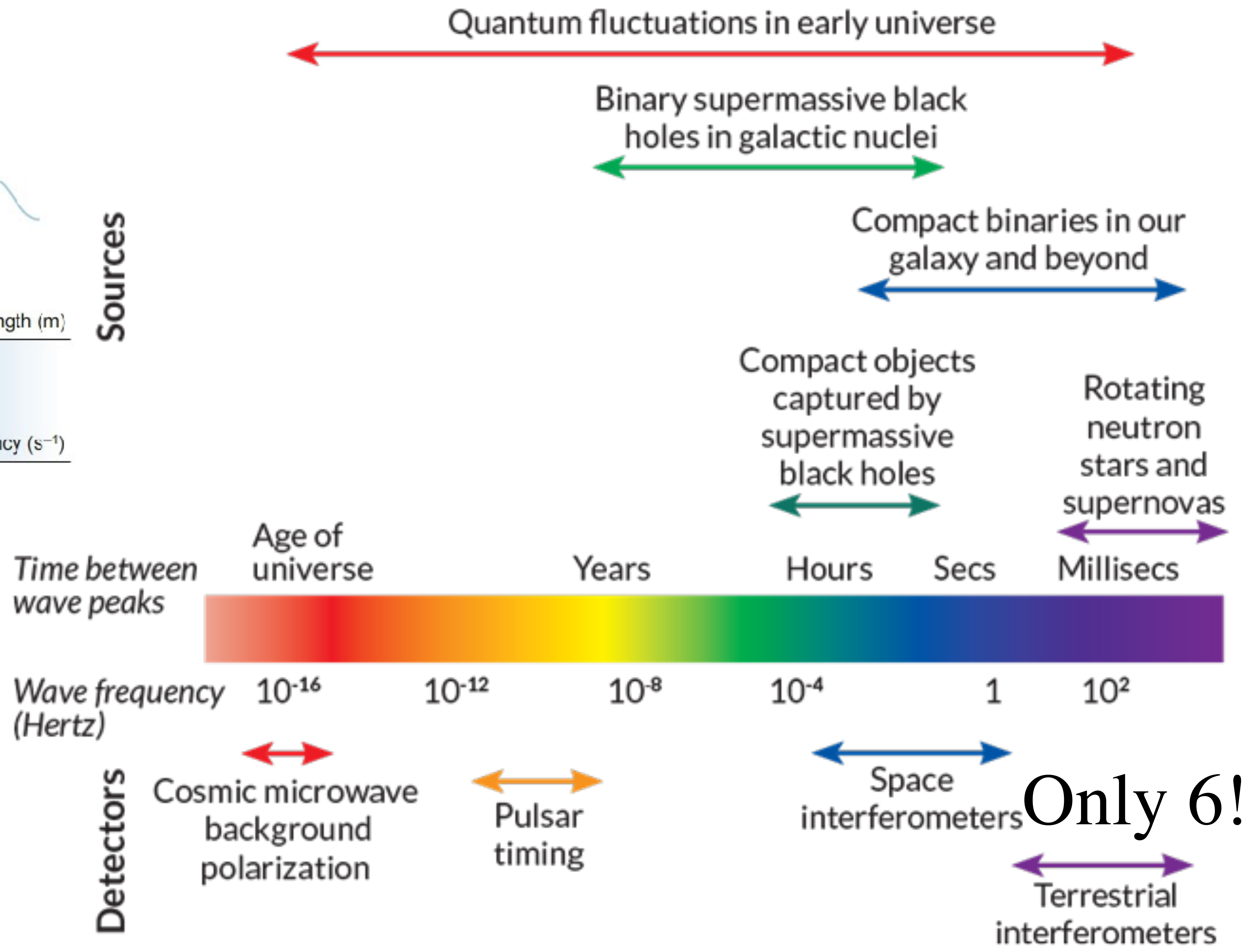
- FRBs as EM counterparts to black hole — neutron star mergers (**CMFM**, Levin, Lazio 2015)
- Constraining tensor-to-scalar ratio “r” and tensor index “n_t” in **primordial** gravitational-wave backgrounds (Lasky, **CMFM**, Smith et al. 2016)
- On the Amplitude and Stokes Parameters of a Stochastic Gravitational-Wave Background (C. Conneely, A. H. Jaffe, **CMFM**) arXiv:1808.05920
- Cosmic string tension upper limits from PTAs (all collaboration papers!)
- Strongly lensed AGN as PTA sources: lensed GWs! (Mingarelli & Barnacka, in prep)



It’s a new Universe



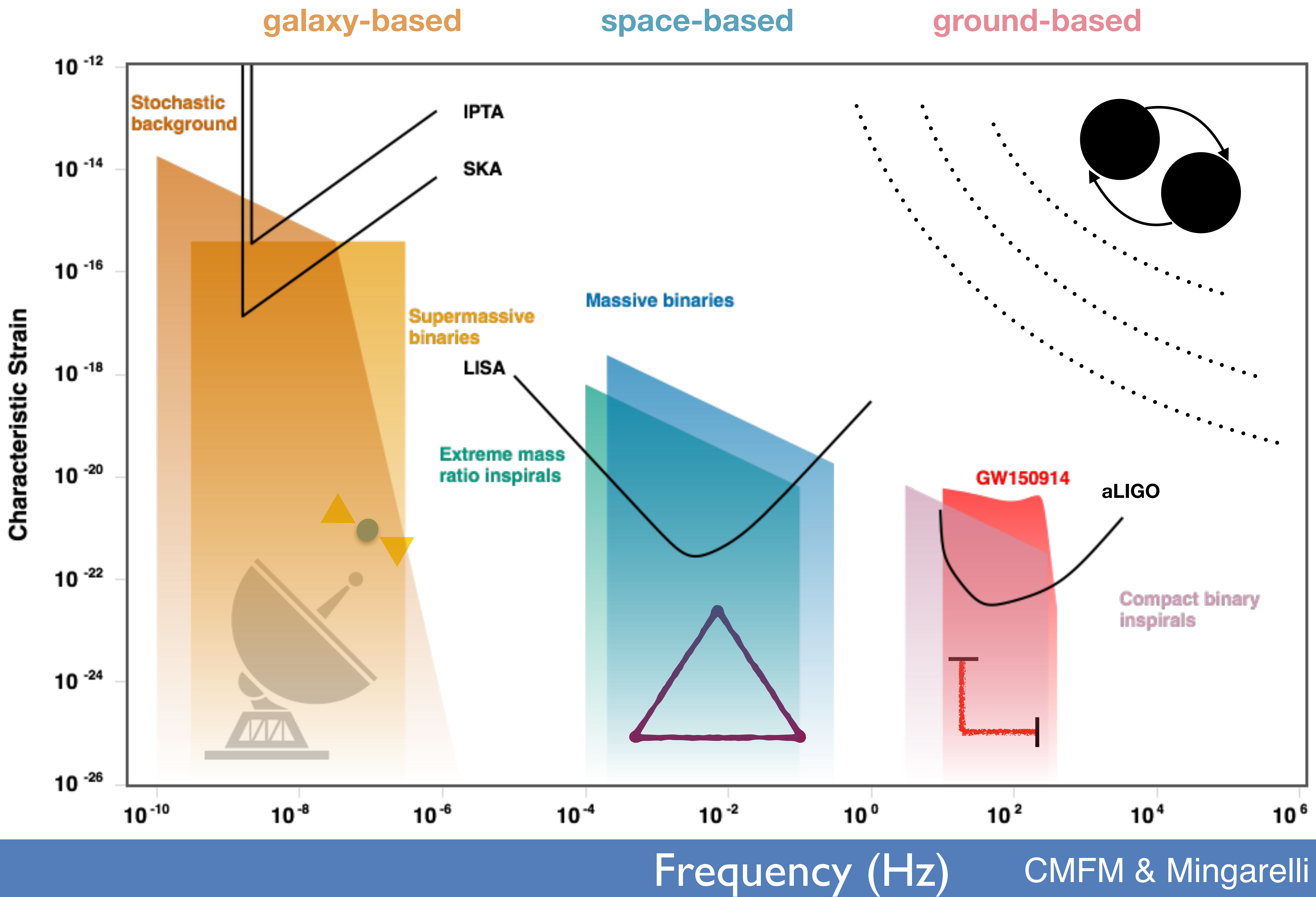
Electromagnetic spectrum



Only 6!

Gravitational-wave spectrum

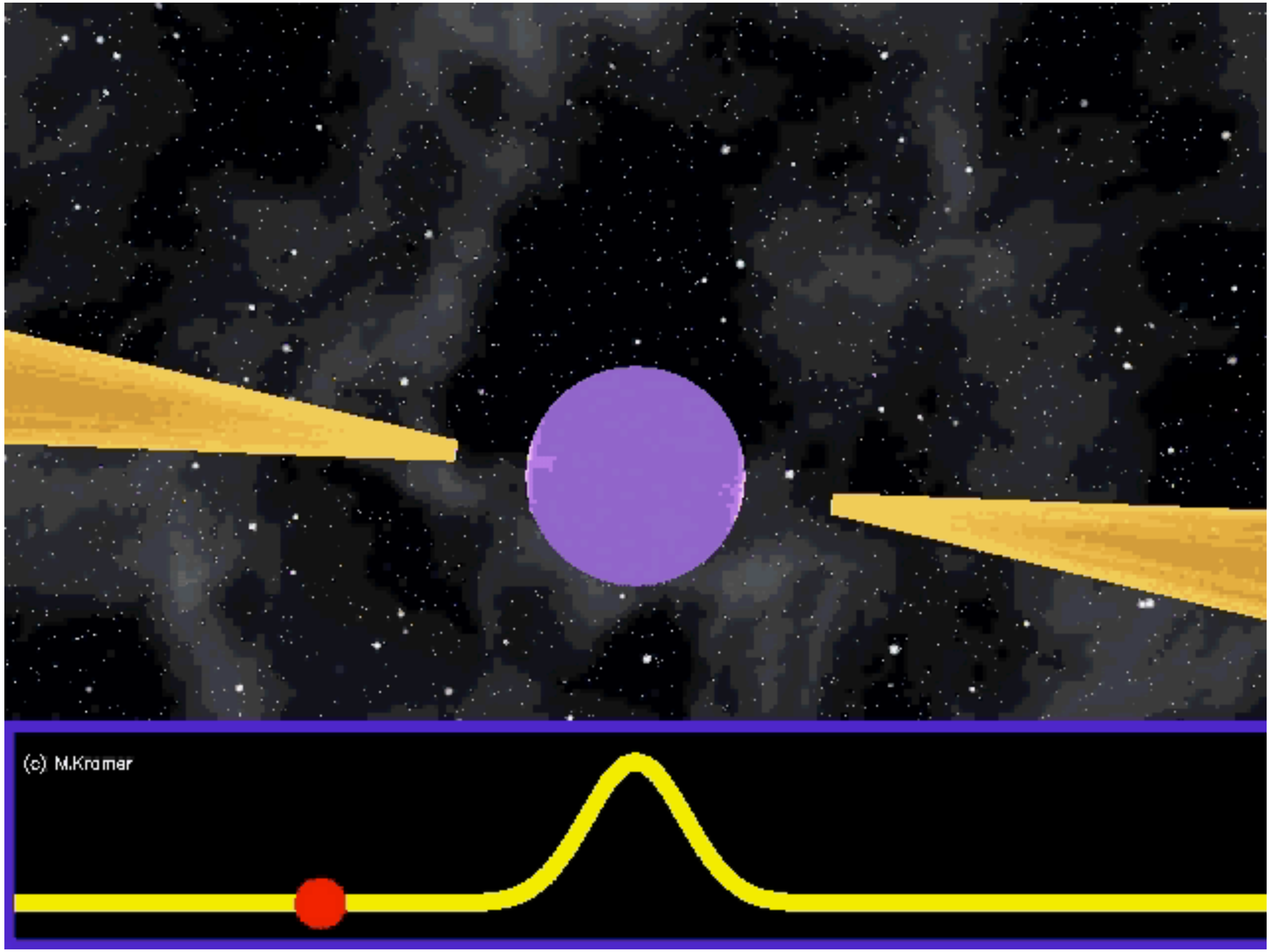
The Gravitational-Wave Spectrum



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

CMFM & Mingarelli (2018, accepted)

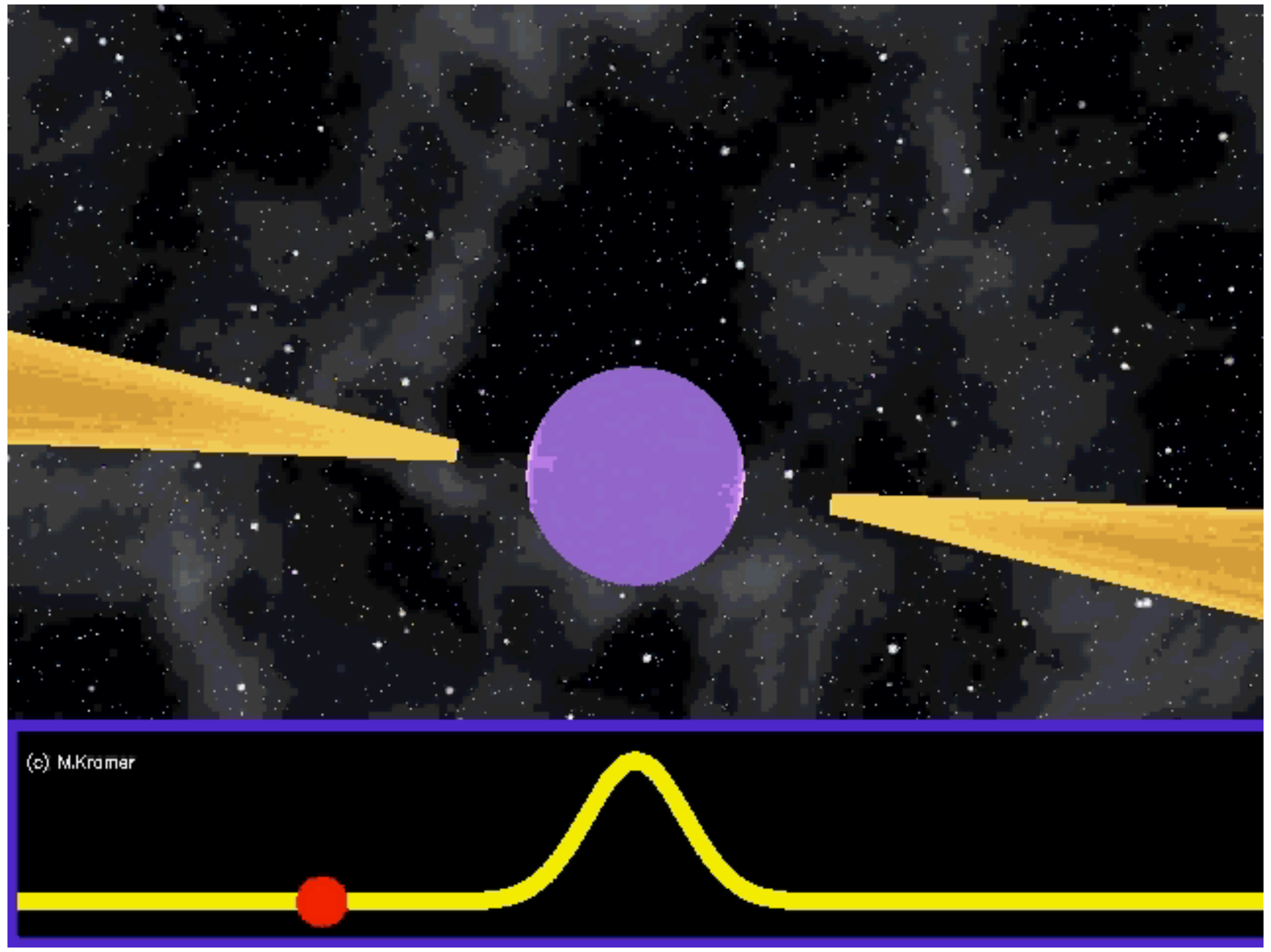
Pulsars

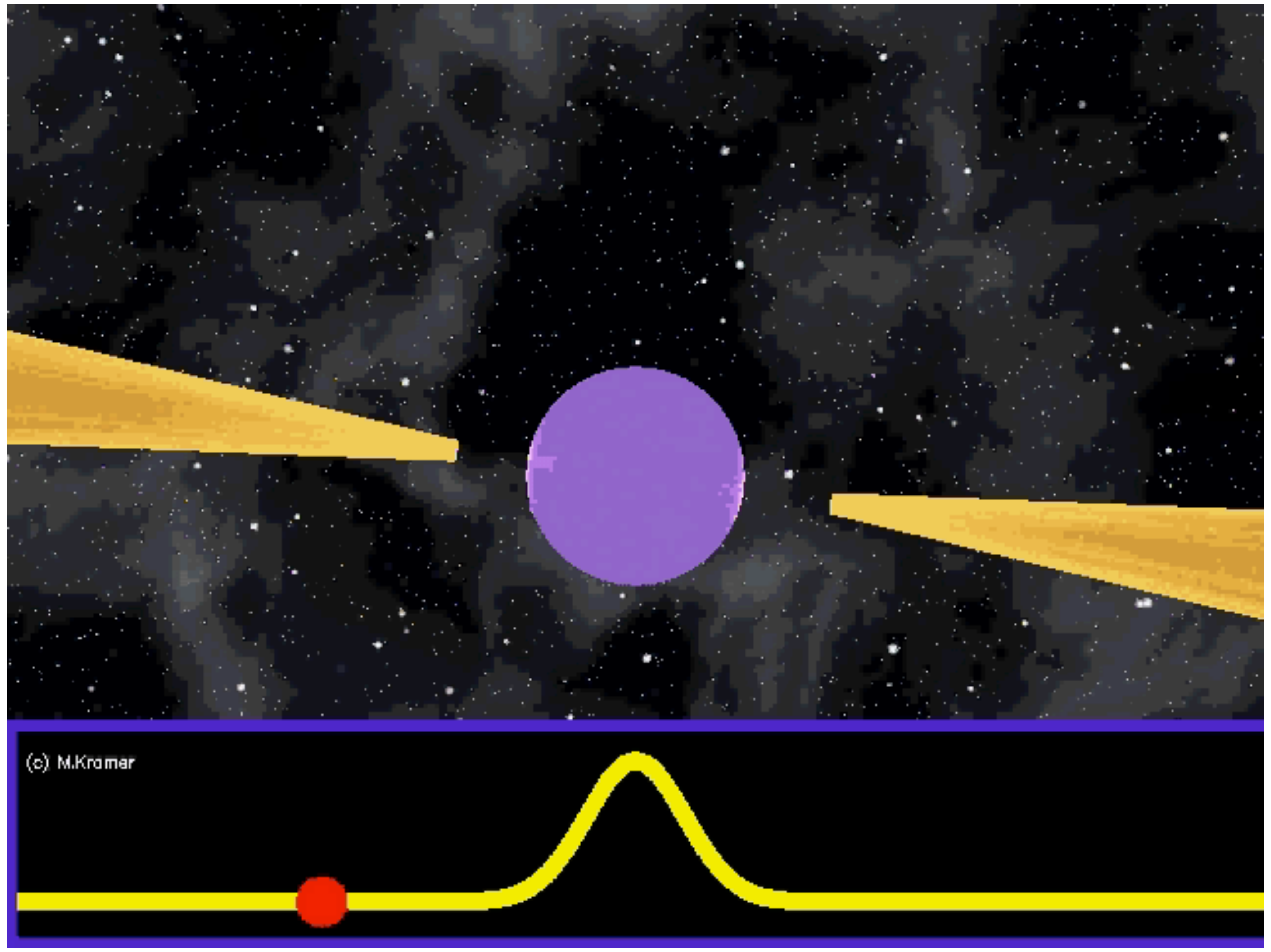


- rotating neutron stars
- compact
- rapidly rotating
- high magnetic field
- remnants of supernova explosions
- Excellent clocks!

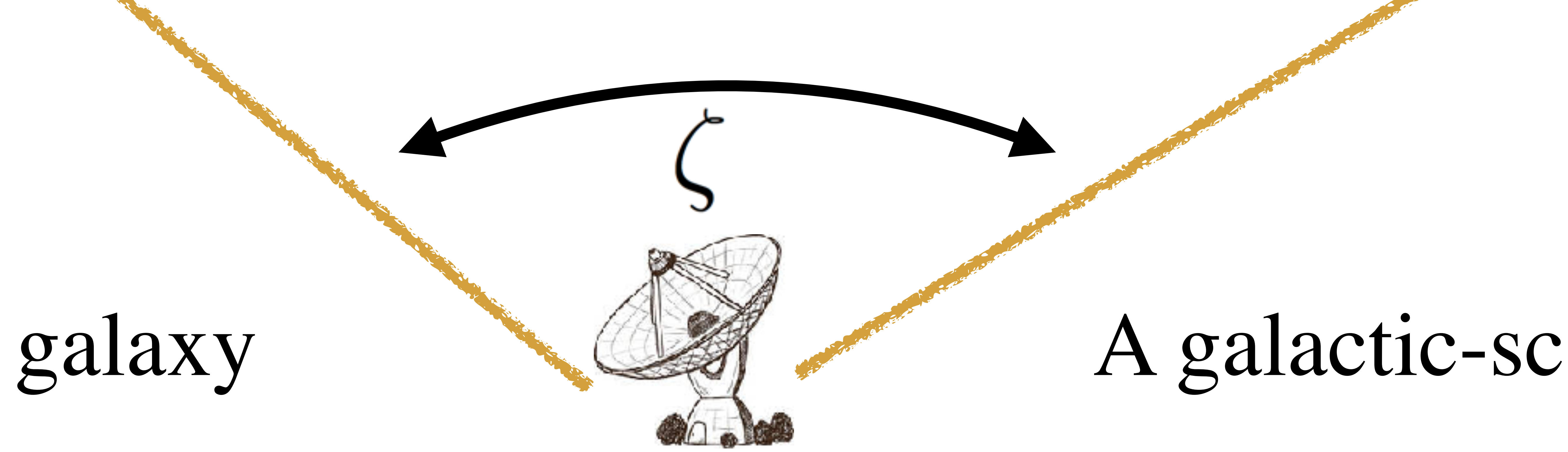
50-year anniversary!

Pulsars





GWs correlate pulsar residuals



Pulsars in our galaxy

A galactic-scale GW detector!


ILLUSTRIS


z=1.11
ILLUSTRIS

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

Excellent clocks = GW Detectors

- Expected pulse number *N* at an observed arrive time *t* is expressed as Taylor Series:

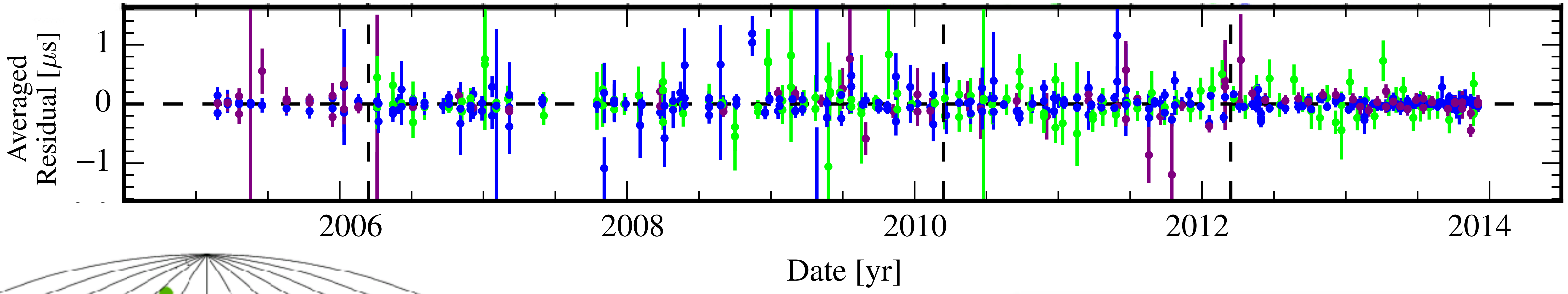
$$N = \nu_0(t - t_0) + \frac{1}{2}\dot{\nu}(t - t_0)^2 + \frac{1}{6}\ddot{\nu}(t - t_0)^3 + \cdots$$

- Residual *r(t)* = Expected - Actual arrival time

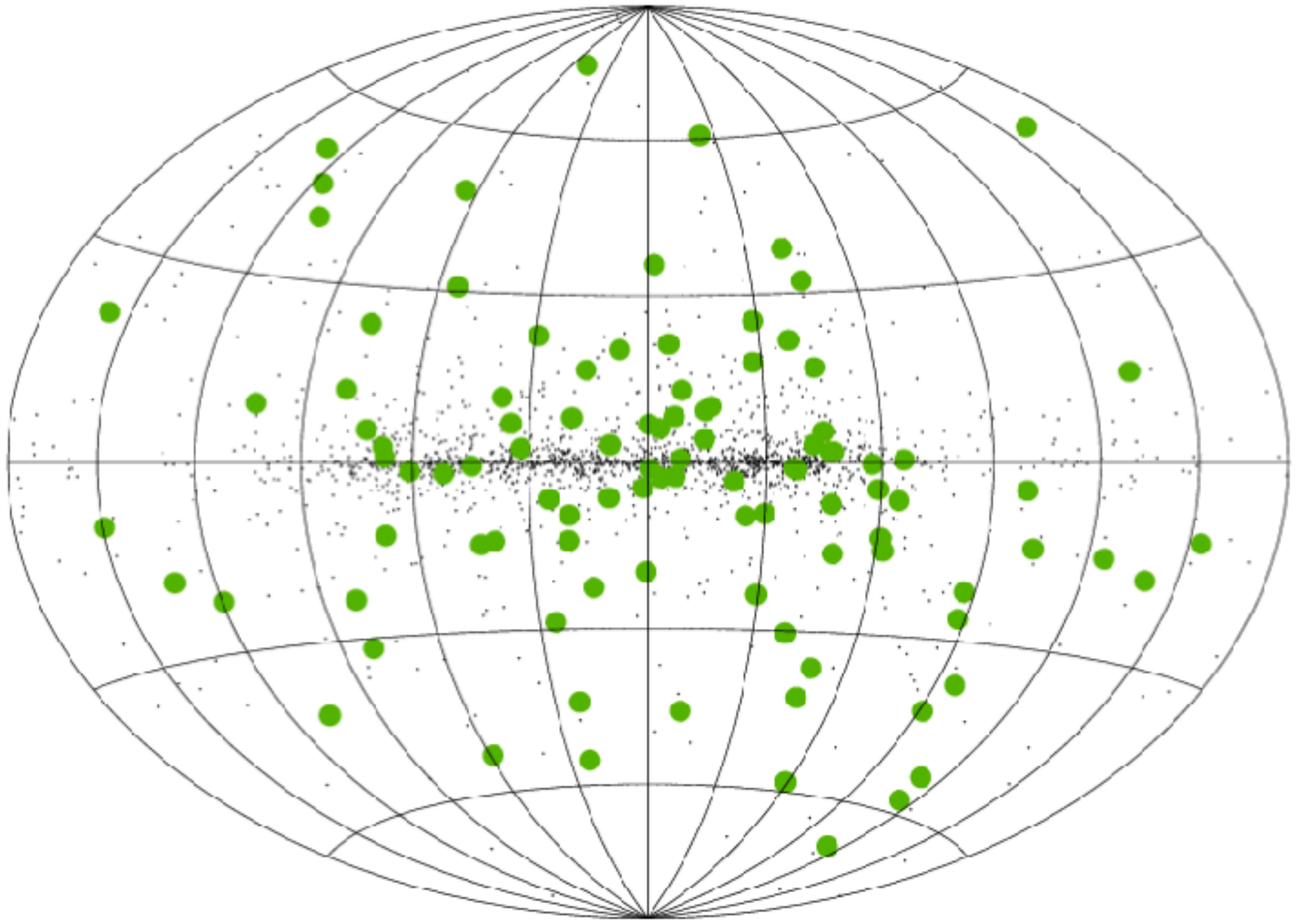
- Look for fraction frequency shift in timing residual: input into GW analysis

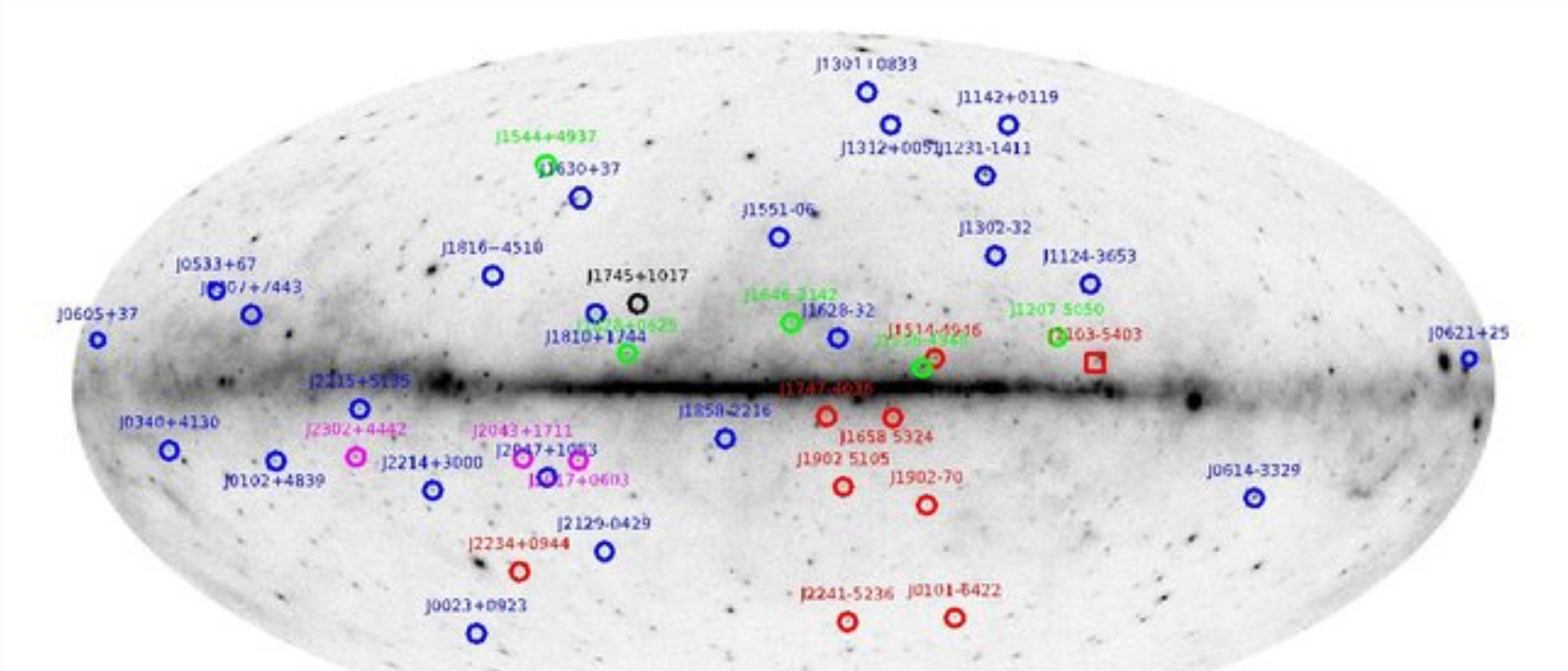
$$r(t) = \int^t \delta\nu(t')/\nu_0 dt'$$

Millisecond Pulsars



J1713+0747





86 MSPs so far, 15 added

GBT, Effelsberg, Parkes, Nançay, GMRT

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

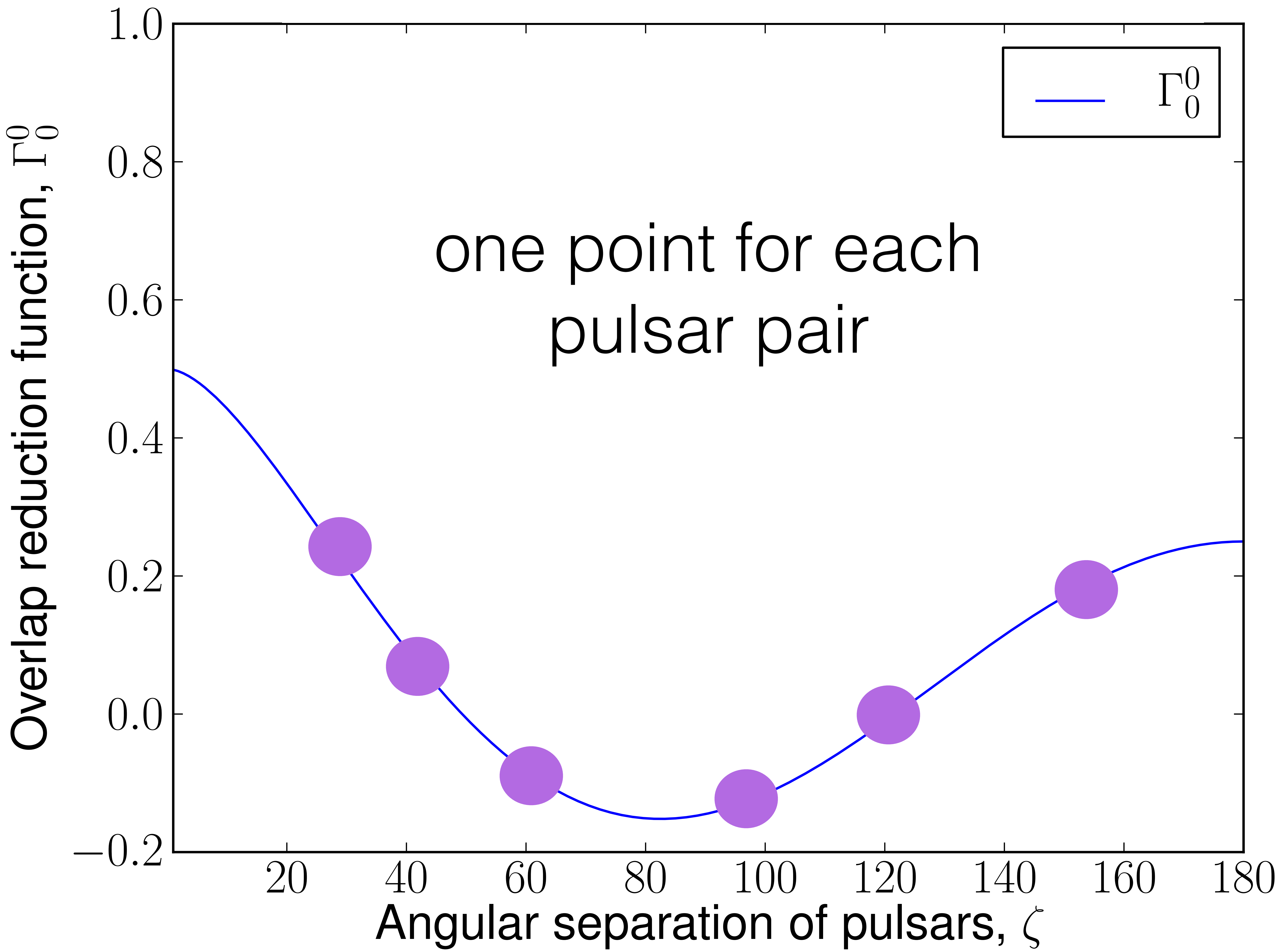
SKA x 10

Paul Ray, private communication

Key Project in Radio Astronomy

courtesy Joe Lazio

Gravitational-Wave Backgrounds



- What is “waveform” ?
- Hellings and Downs curve
- Assumes background is isotropic (but is it?)
- Pulsar correlations create “curve”
- Changes for alternative theories of gravity and anisotropic GWBs

Supermassive Black Hole Binaries

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

chirp mass

number of mergers remnants per comoving volume

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

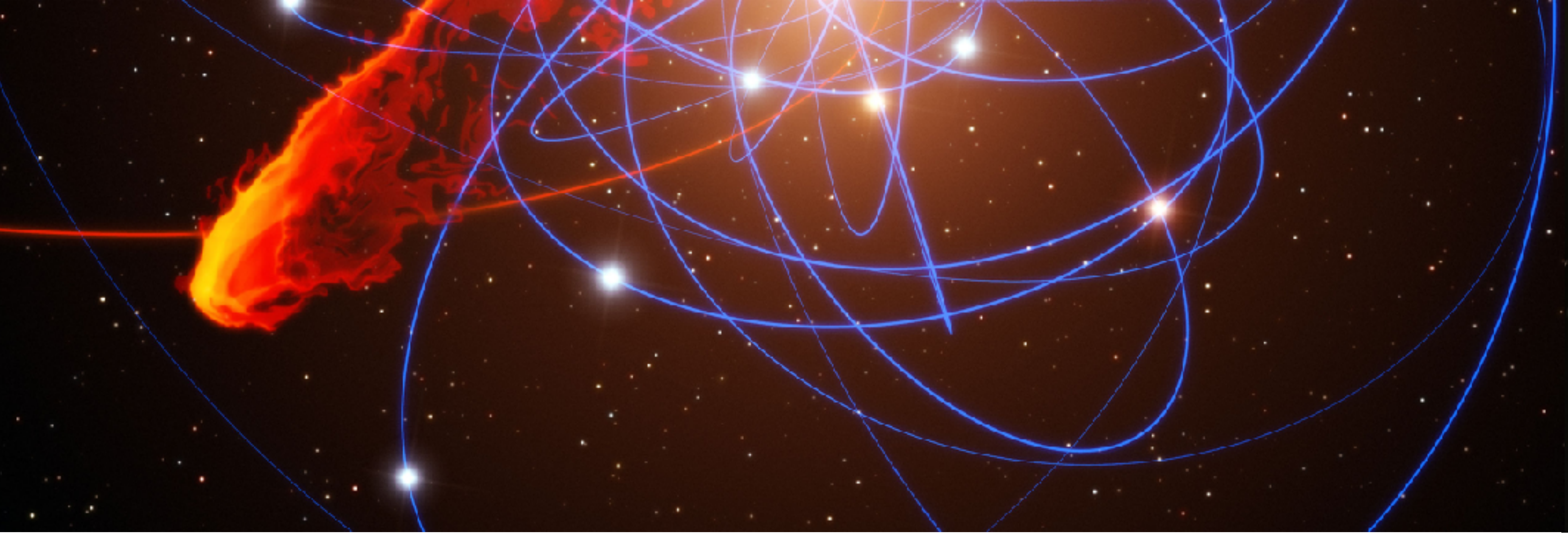
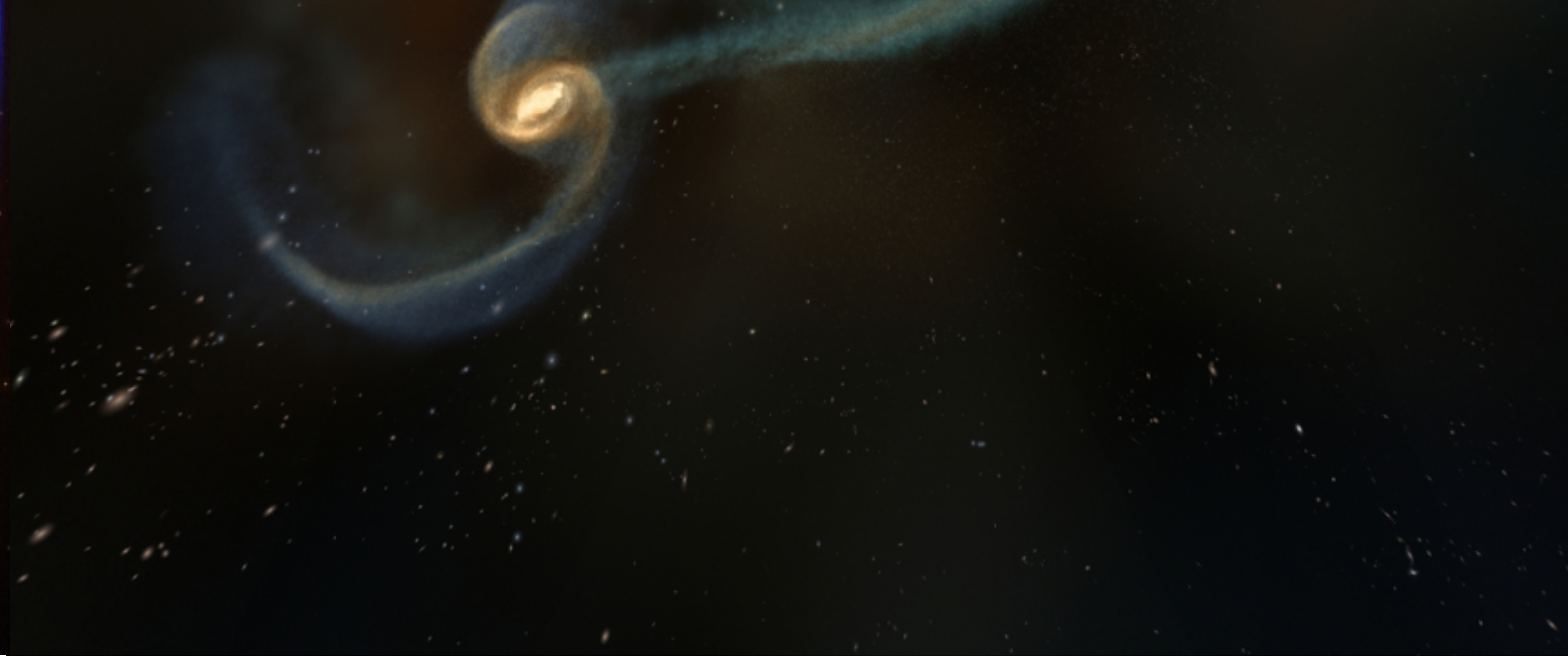
$$\Omega_{\mathrm{gw}}(f) = \frac{2\pi^2}{3H_0^2} f^2 h_c^2$$

We know a lot about *A*, can learn more

<u>Surge in the field in last 10 years</u>, here are the latest results!

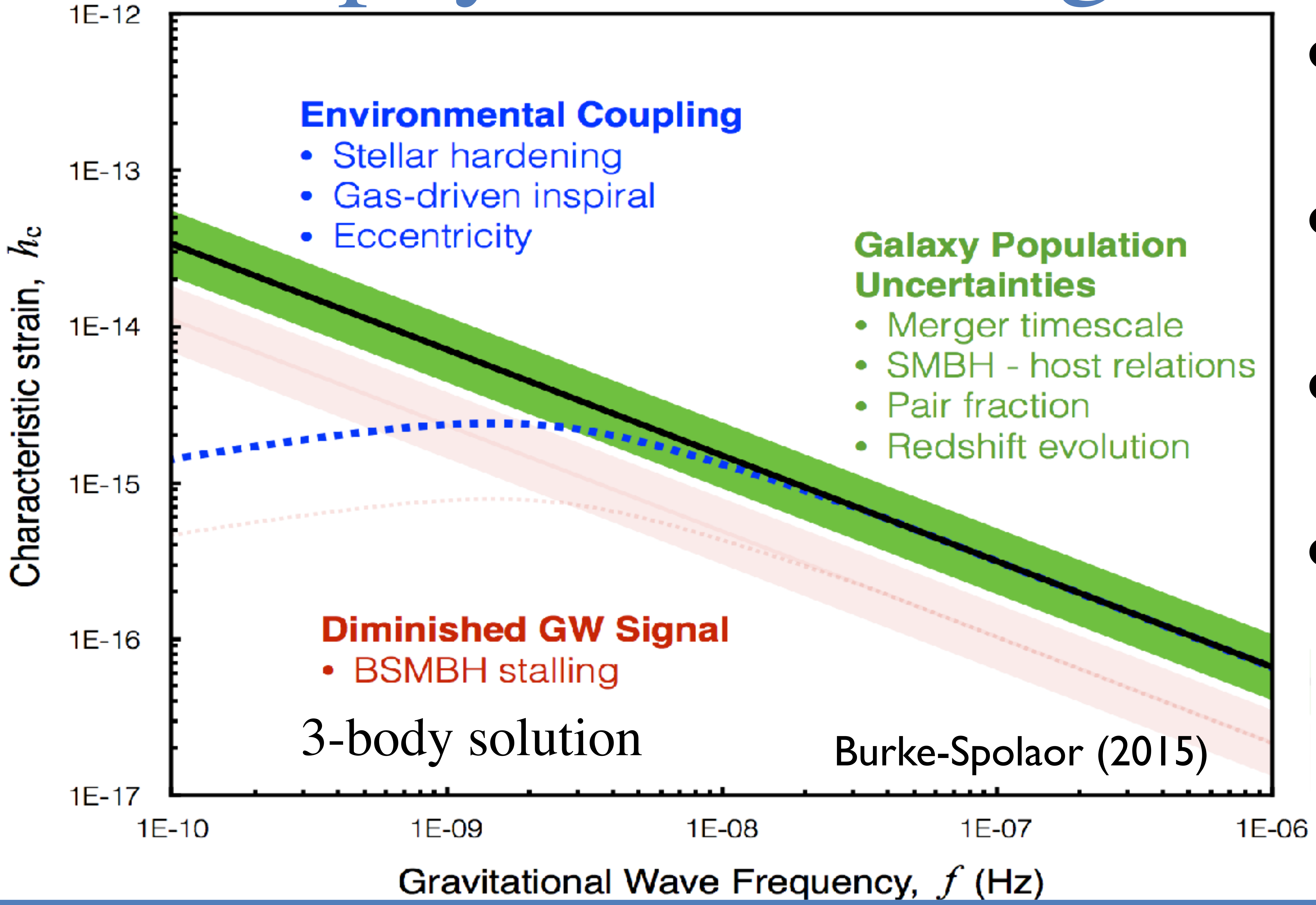
EPTA isotropic : Lentati, Taylor, CMFM + 2015; $A < 3 \times 10^{-15}$
EPTA anisotropic: Taylor, CMFM, Sesana + 2015; < 40%
18-year data in Desvignes, Caballero, Lentati + (w CMFM) 2016;

NANOGrav: Arzoumanian +(w CMFM) 2018; $A < 1.5 \times 10^{-15}$
11-yr Data: Arzoumanian +(w CMFM) 2018;
IPTA: Verbiest + (w CMFM) 2016; $A < 1.7 \times 10^{-15}$
PPTA: Shannon, Ravi, Lentati + 2015; $A < 1 \times 10^{-15}$

Final Parsec Problem?

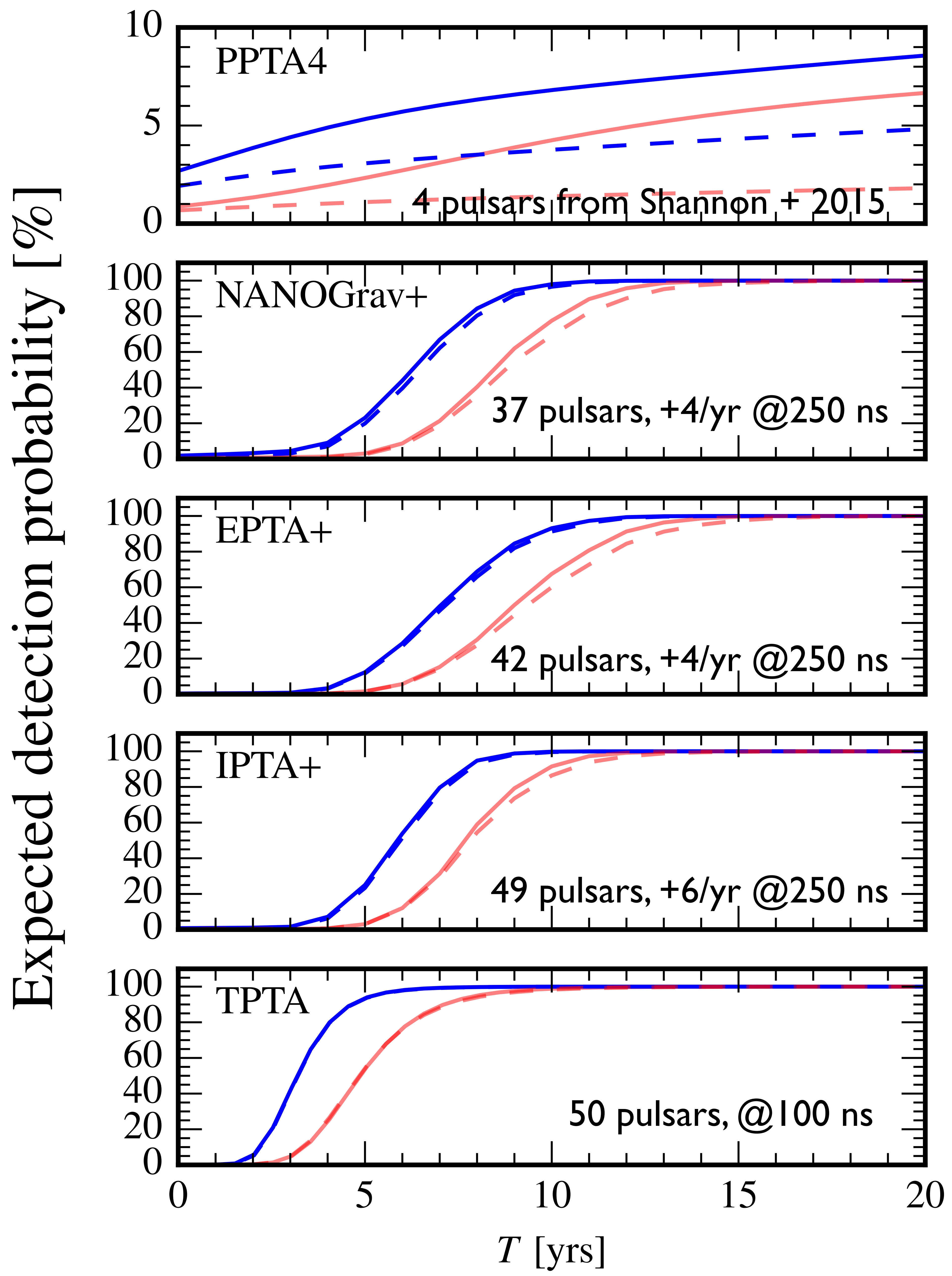
Astrophysics affecting GW spectrum



- Sampson et al. (2015)
- Arzoumanian et al. (2016, 2018)
- Middleton et al. (2018)
- Ryu et al. (2018) and Bonetti et al. (2018): 3-body interactions, floor for GWB

Time to detection?

- Given A < 1e-15, how long to detection?
- Large, expanding PTAs, e.g. NANOGRAV, will detect in < 5 yrs, first see 2-sigma hint!
- blue line = no stalling, red line = 90% stalling, dashed line = 1/11yr turnover due to stellar hardening
- More: arXiv:1602.06301



What you’ve learned so far…

- Pulsars are excellent clocks: use them to look for gravitational waves.
- Searches for GWs from supermassive black hole binaries (nHz)
- The GWB contains information about SMBHB mergers, encoded in the amplitude of the background and the shape of the strain spectrum
- Can optimize PTA sensitivity using **Fermi.**
- Detection of GWB depends on this underlying astrophysics!

Which nearby galaxies host SMBHBs?

CMFM et al.,

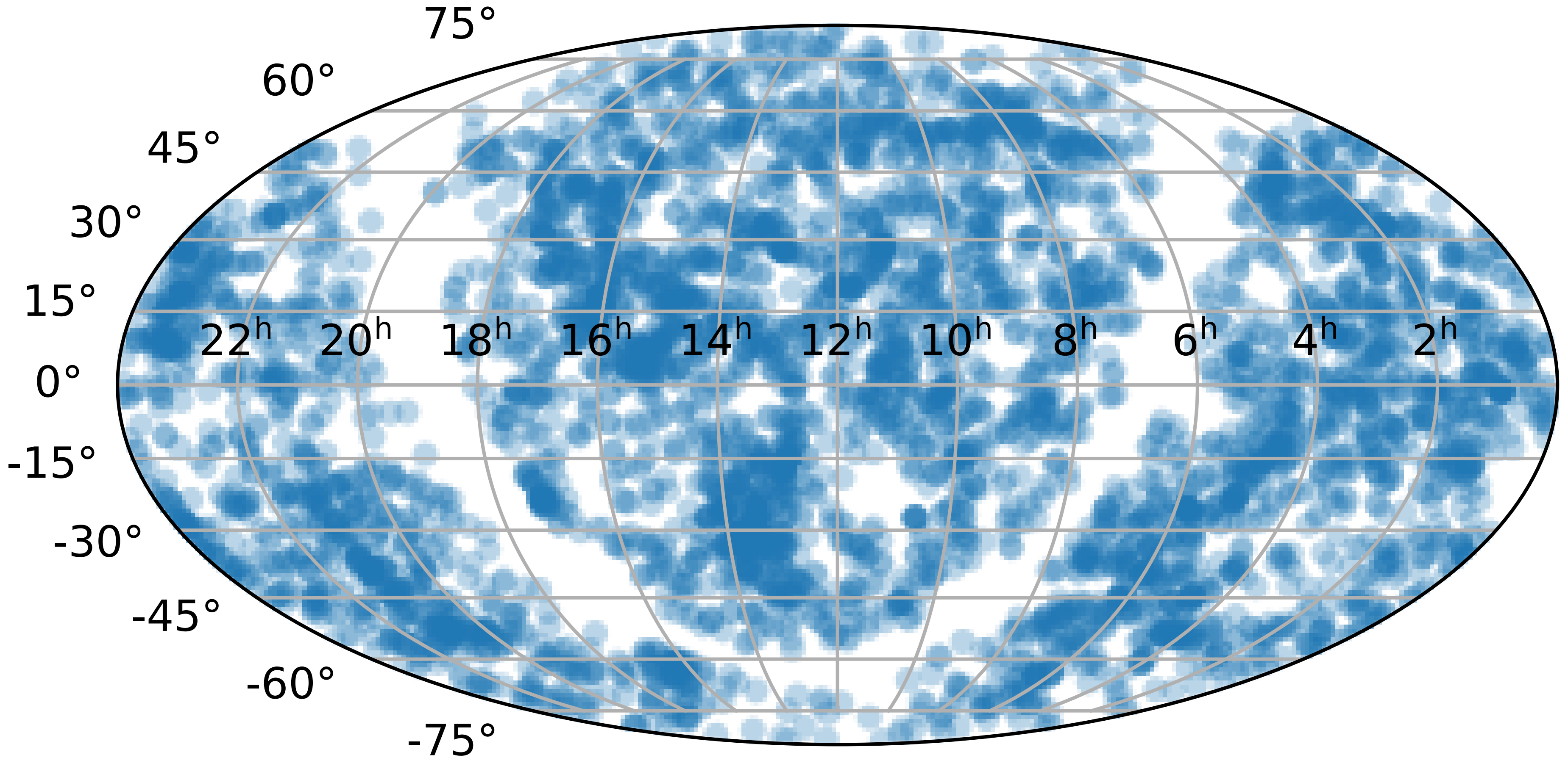
Nature Astronomy (2017)

Which galaxies host SMBHBs?
Time to Detection? Background?

Also Simon et al. (2014)

2MASS + Illustris
M_{BH}-M_{bulge} McConnell & Ma 2013)
91 +/- 7 local SMBHBs
7+/- 2 stalled

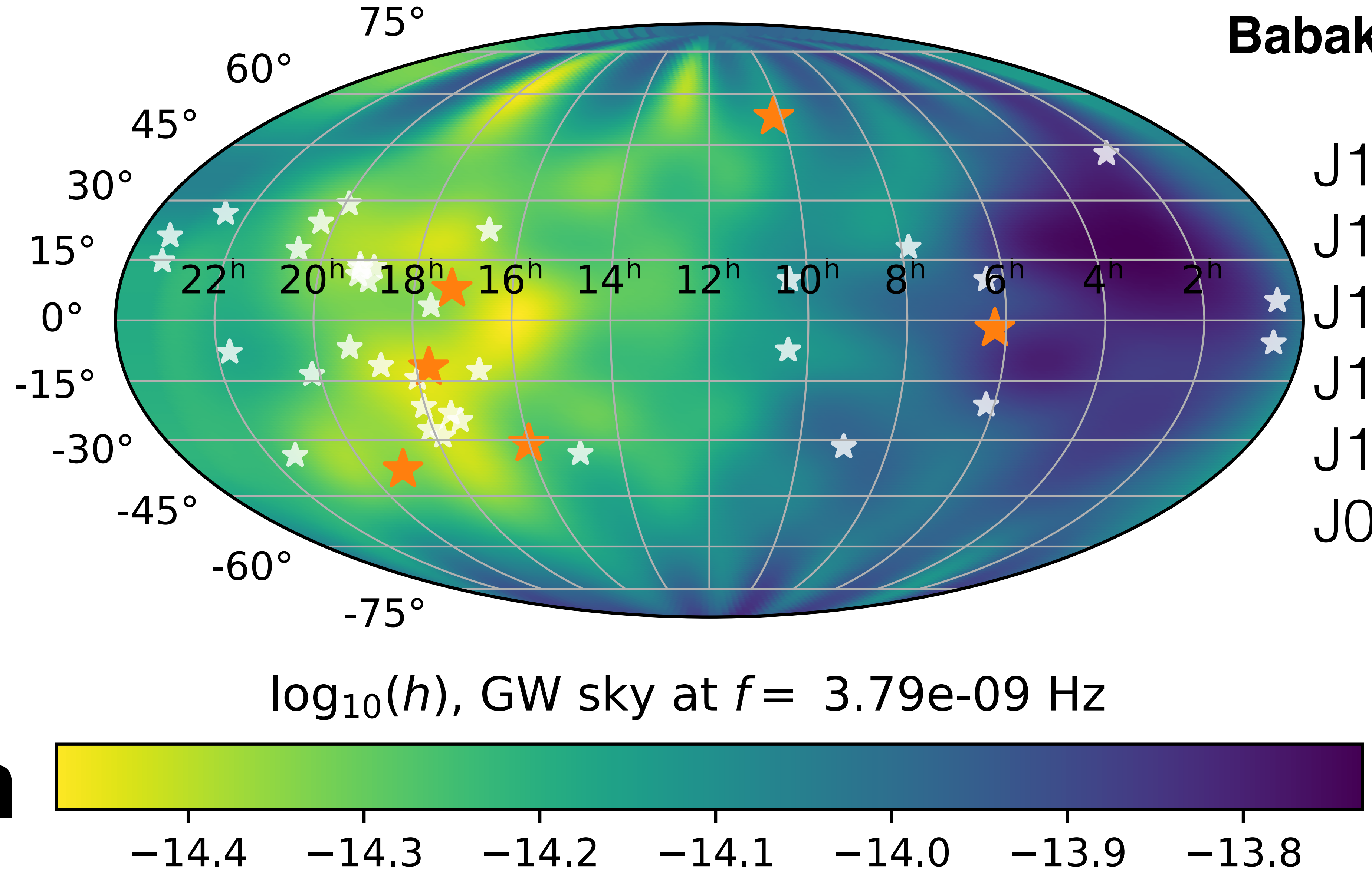
Detected with current PTA data



5,119 galaxies

2MASS galaxy distribution

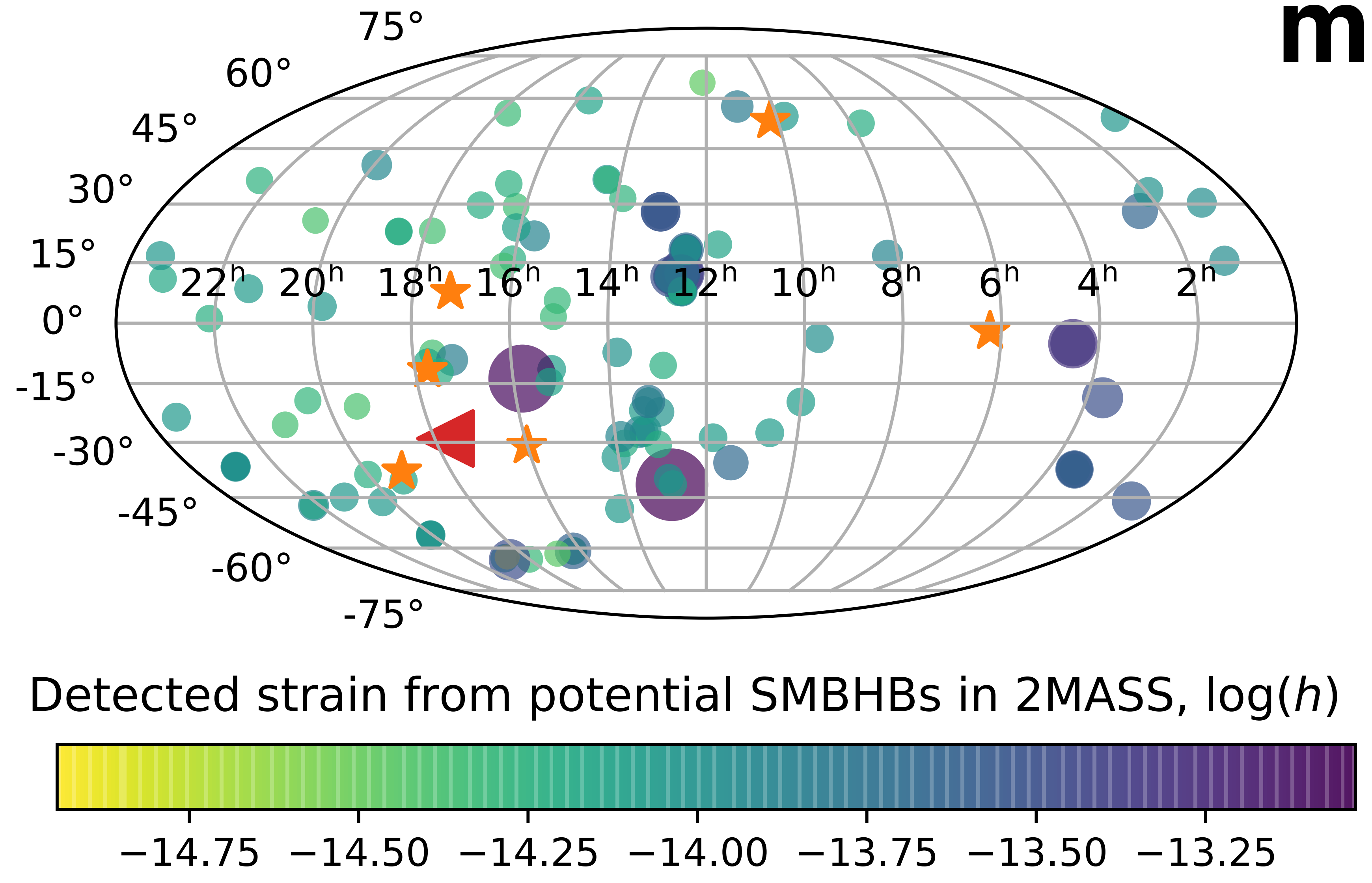
EPTA data from
Babak et al. 2016

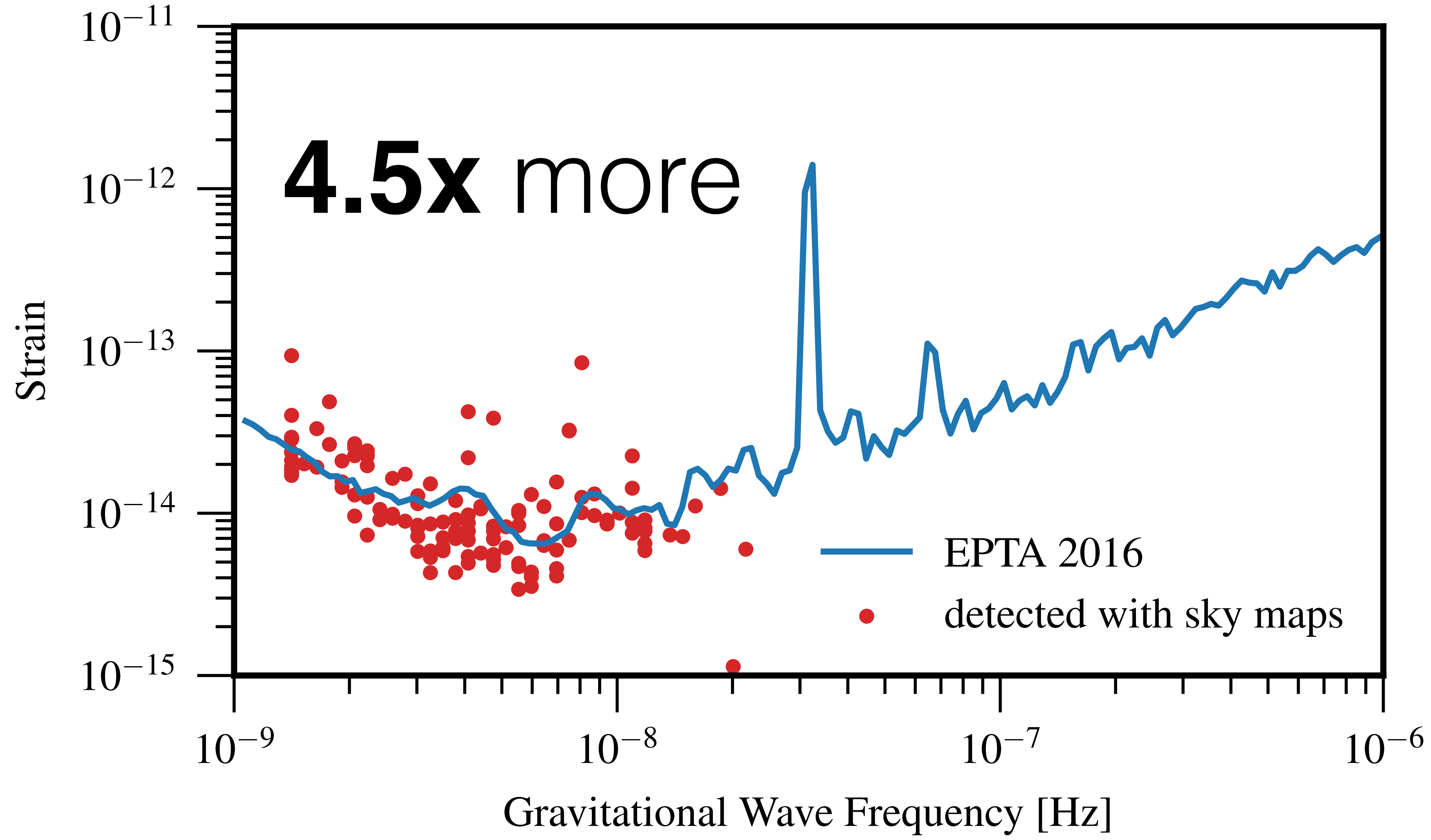


J1909-3744
J1600-3053
J1744-1134
J1713+0747
J1012+5307
J0613-0200

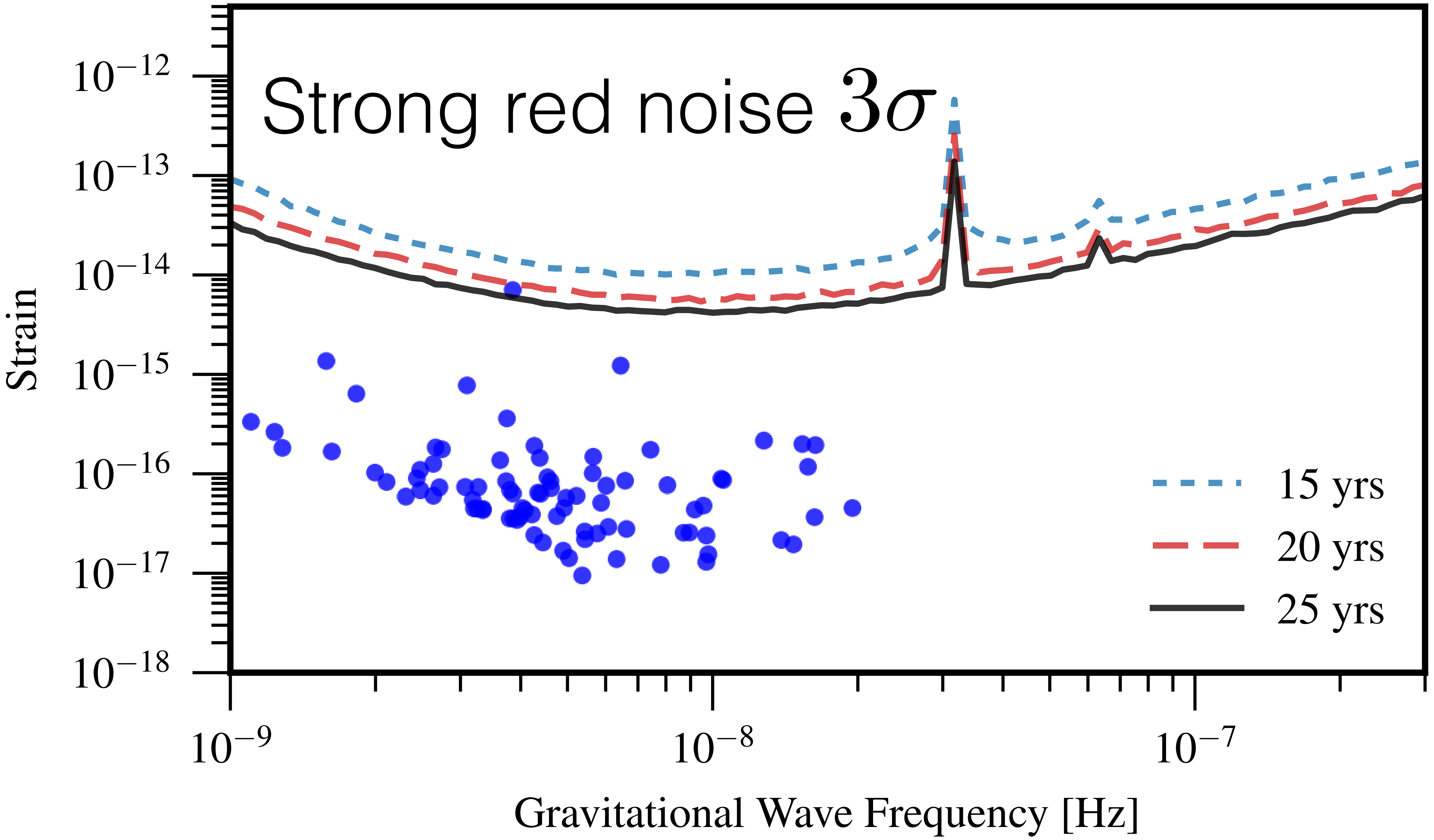
Pulsar location matters!

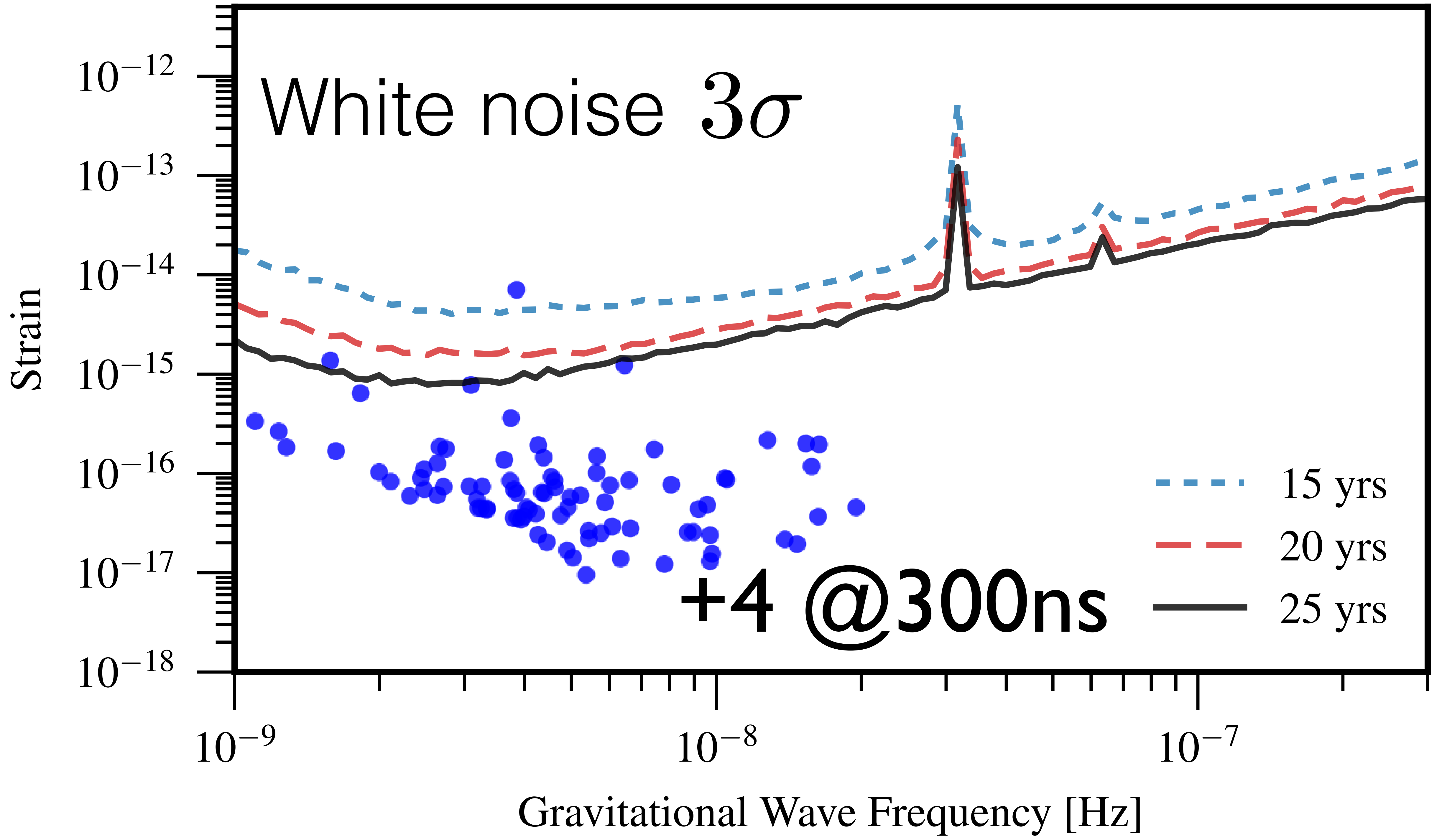
130/75k





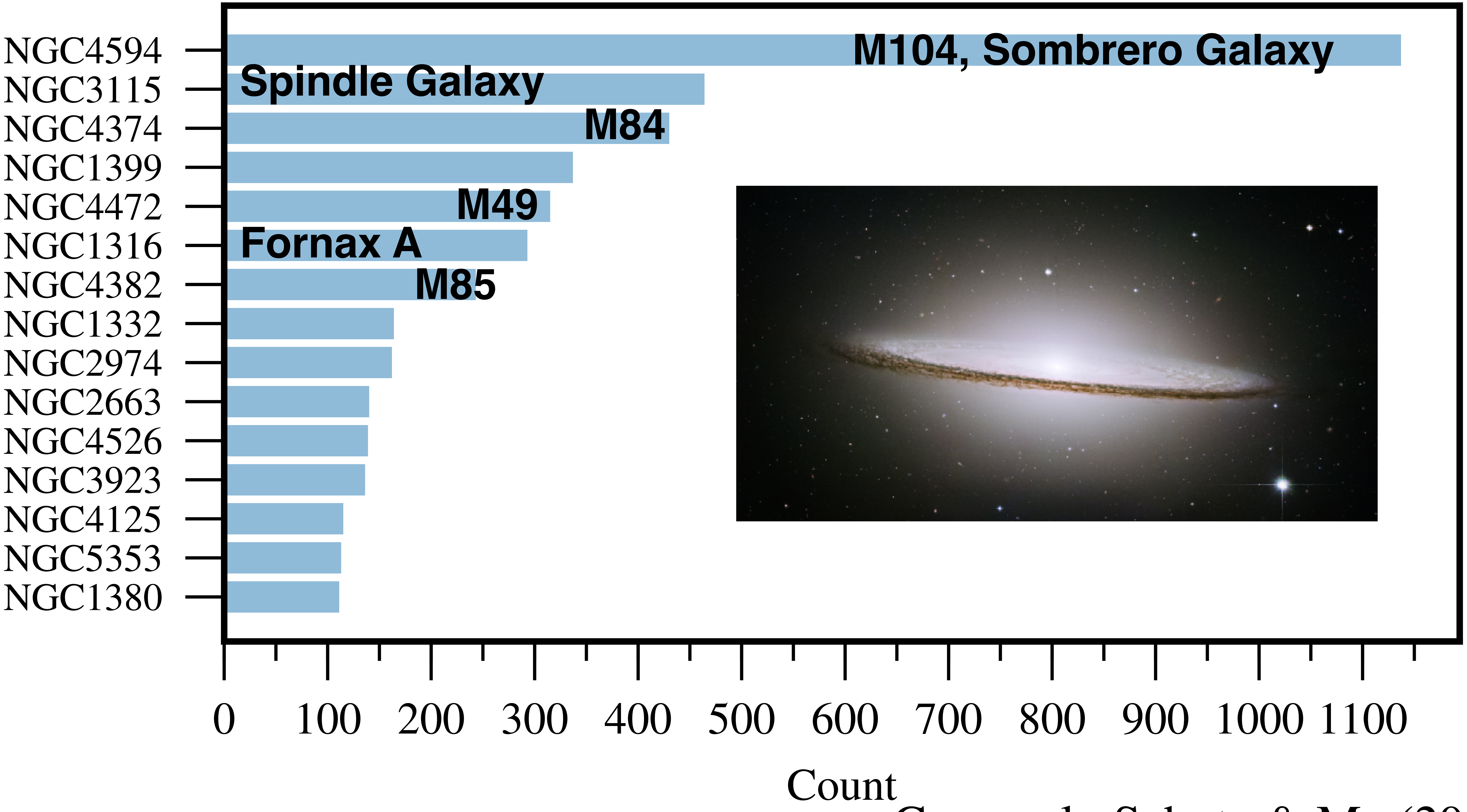
Time to detection of single sources





	FAP	now	5 yrs	10 yrs
Factor of 4!	**0.05** (2σ)	2% (0.09%)	24% (0.3%)	100% (0.8%)
sky location	**3e-3** (3σ)	0.5% (0.03%)	9% (0.2%)	48% (0.3%)
	1e-4 (4σ)	0.3% (0.01%)	4% (0.08%)	27% (0.2%)

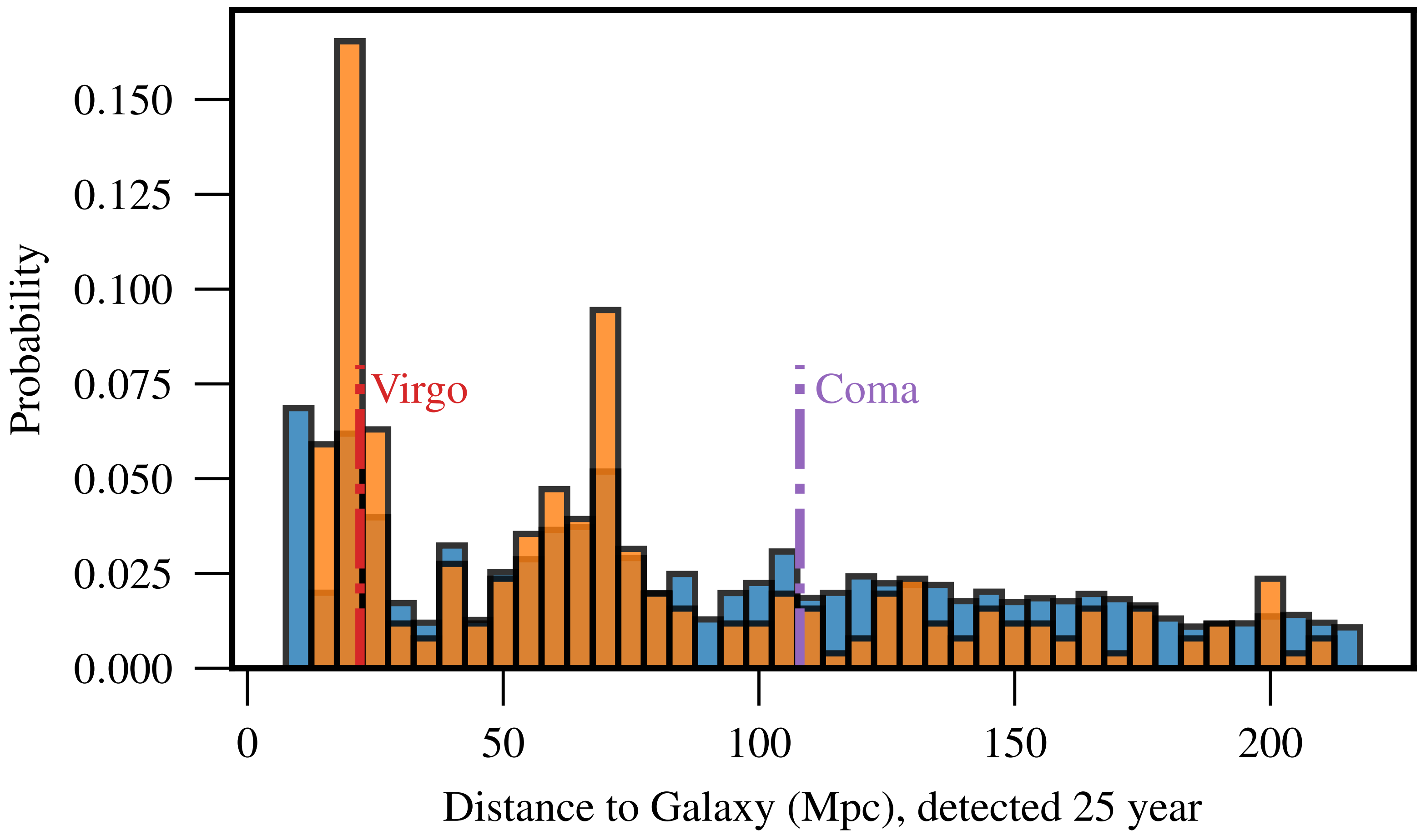
Hit List

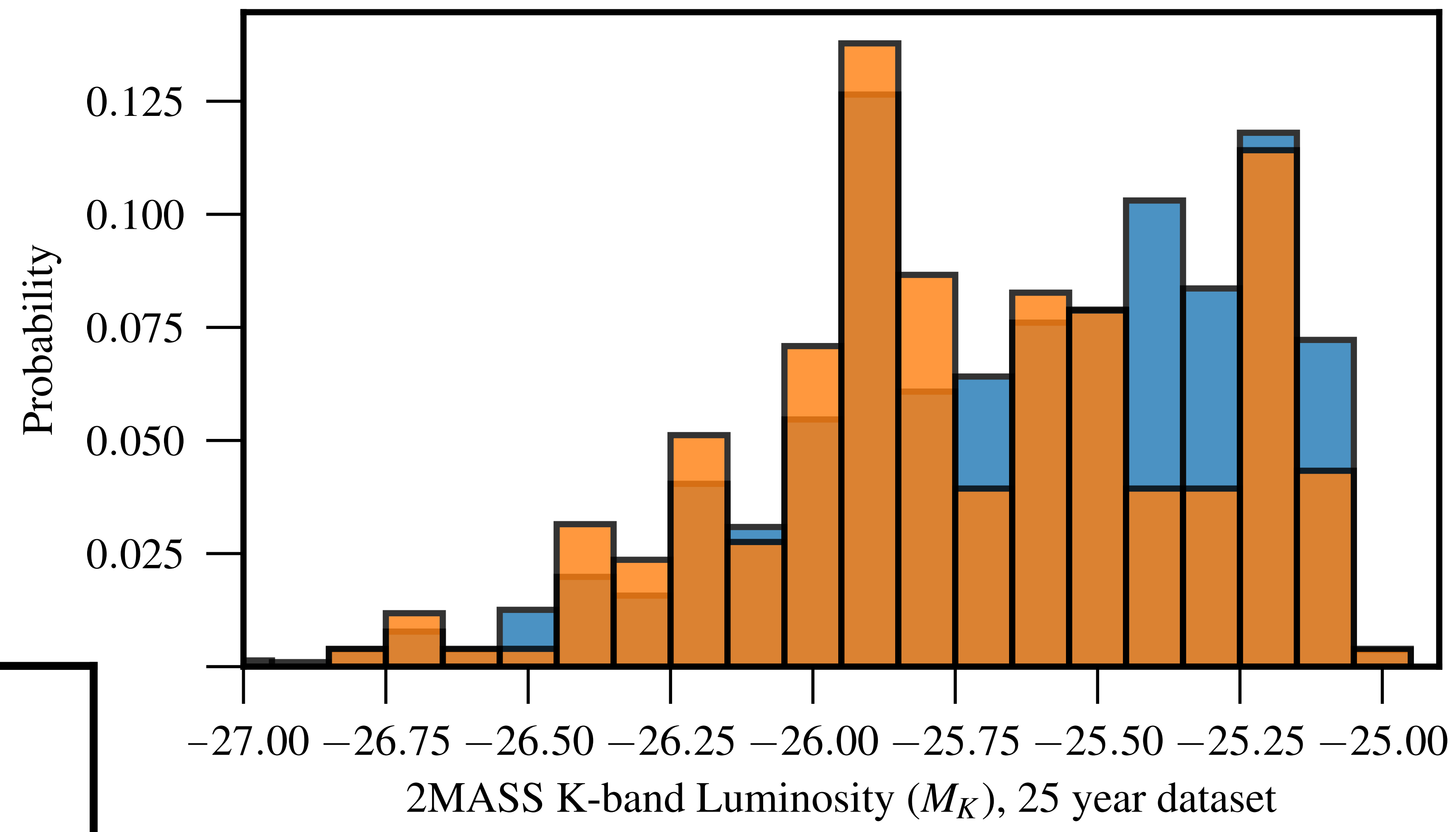


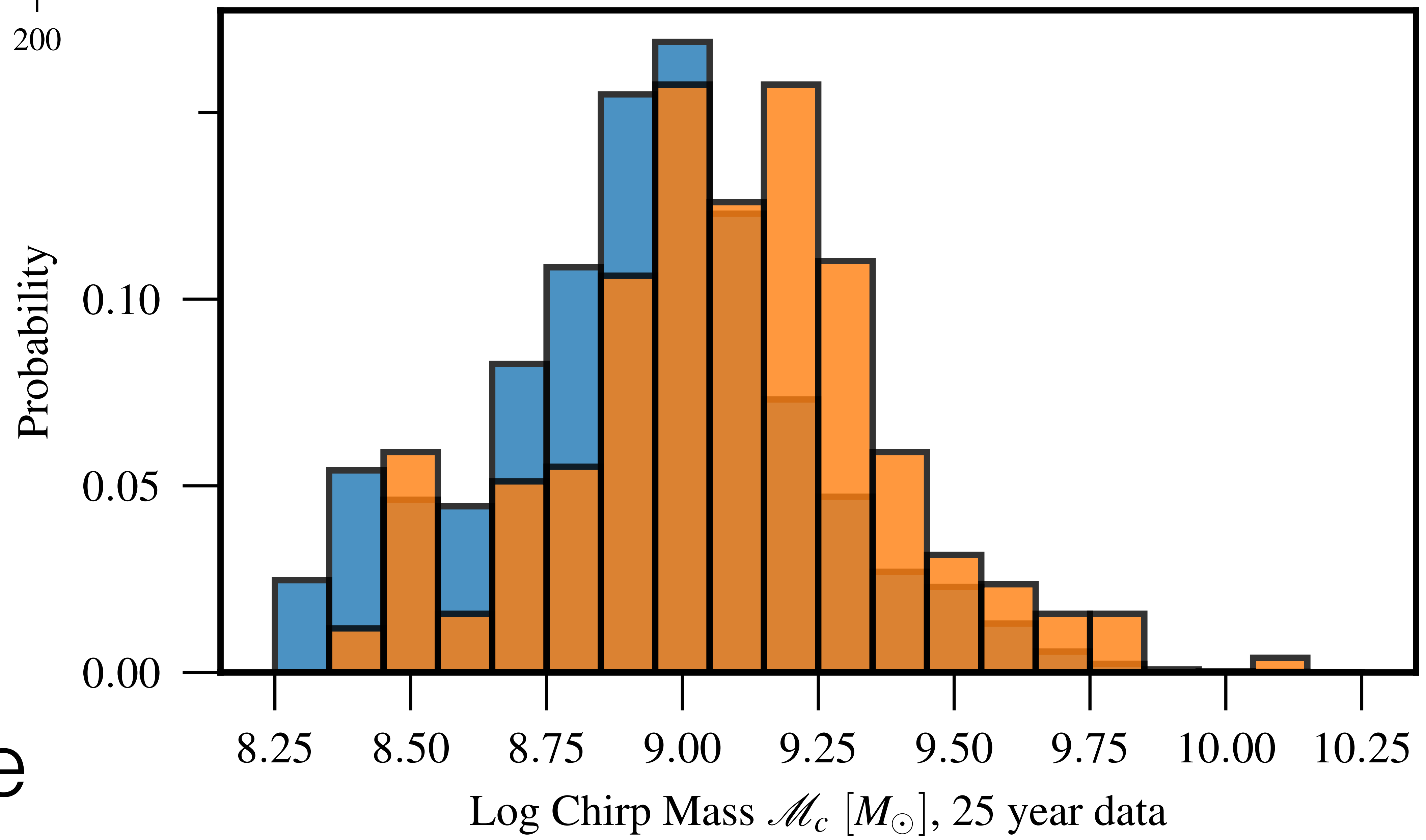
Can apply Schutz & Ma (2016), constrain q

Clues for EM counterparts

Is there an EM counterpart at all?







Gas in binary to merger?

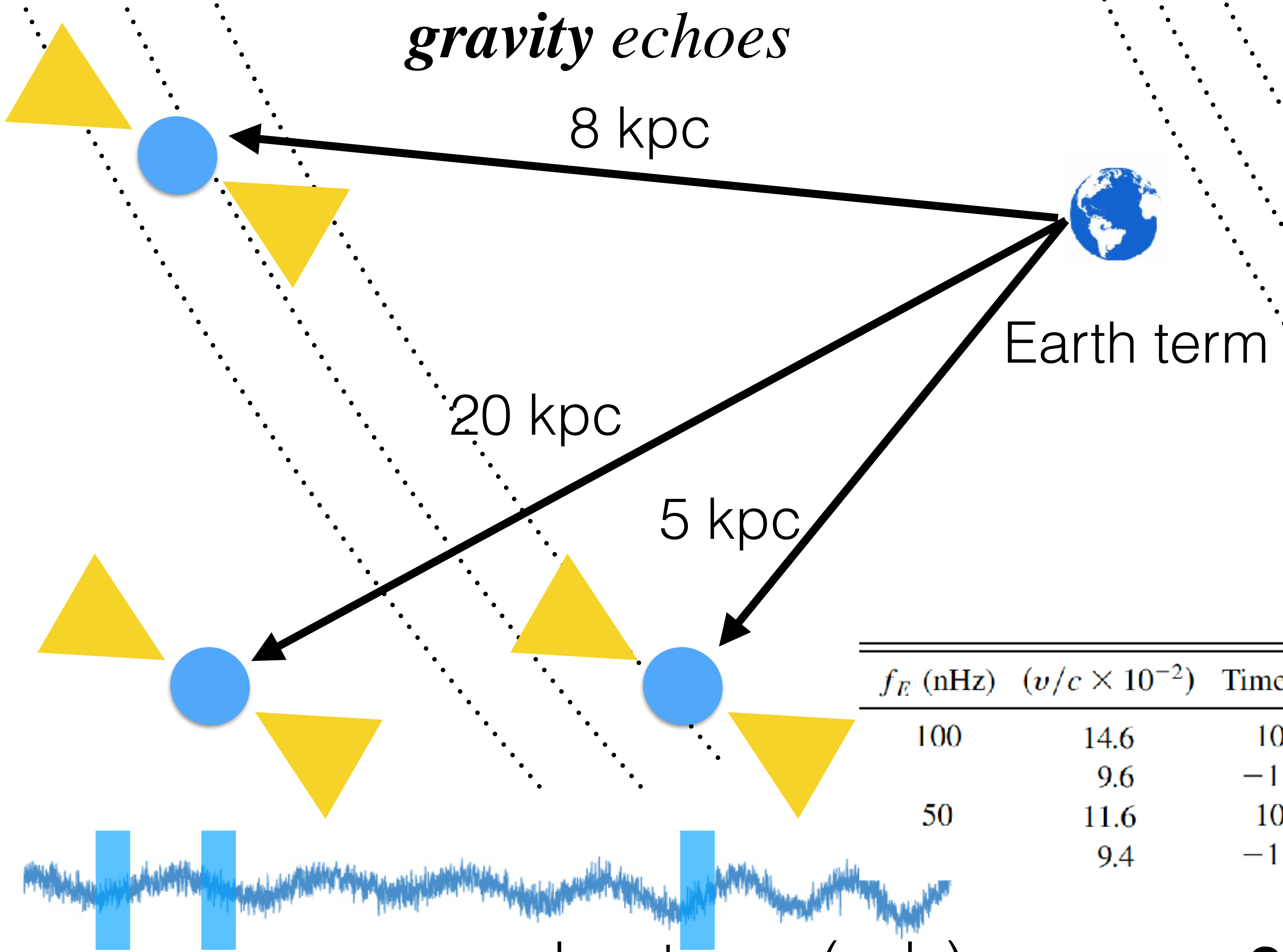
Tang, MacFadyen, Haiman (2017)

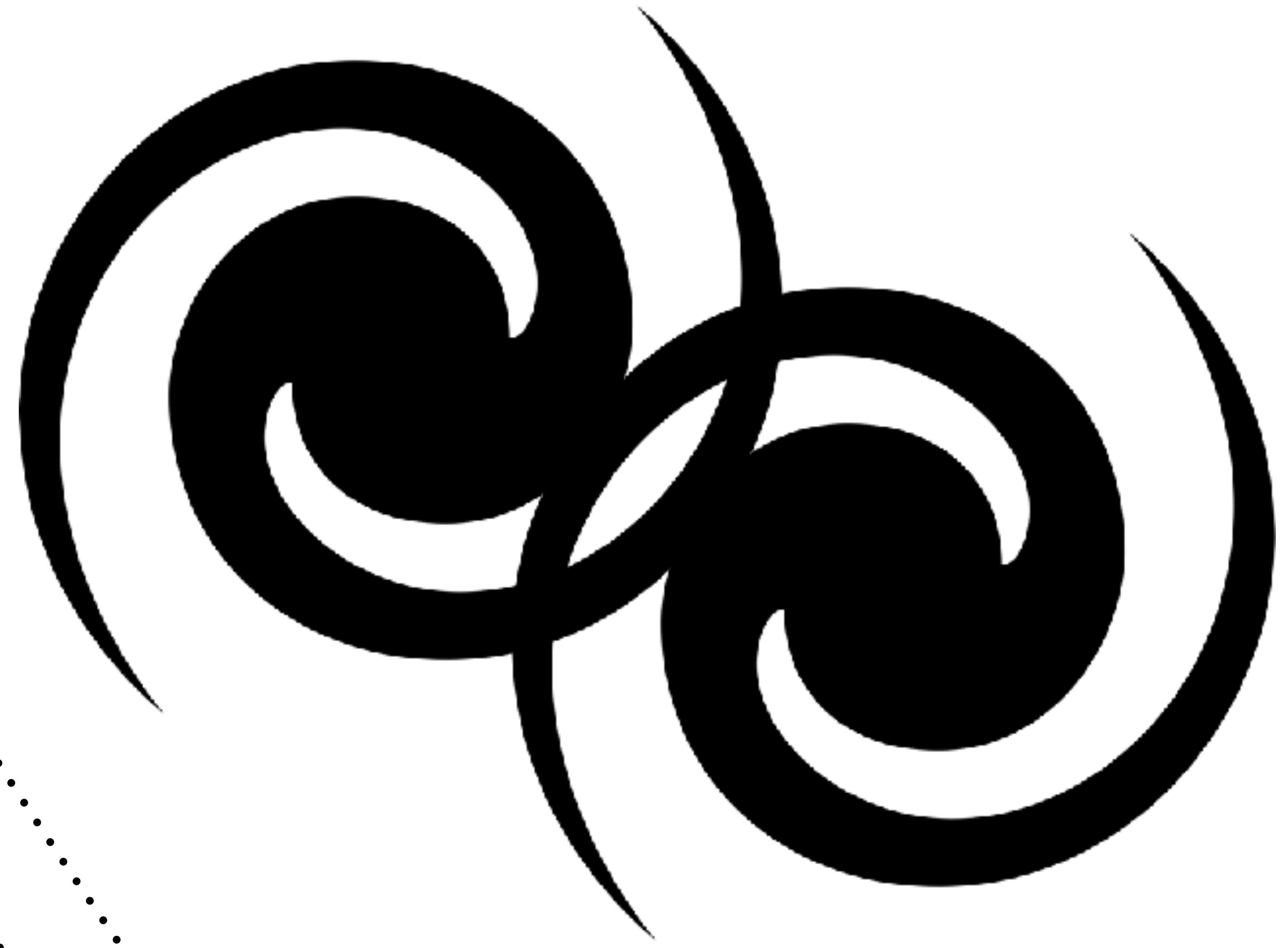
= white noise

= strong red noise

Pulsar Term Measurements

***gravity** echoes*



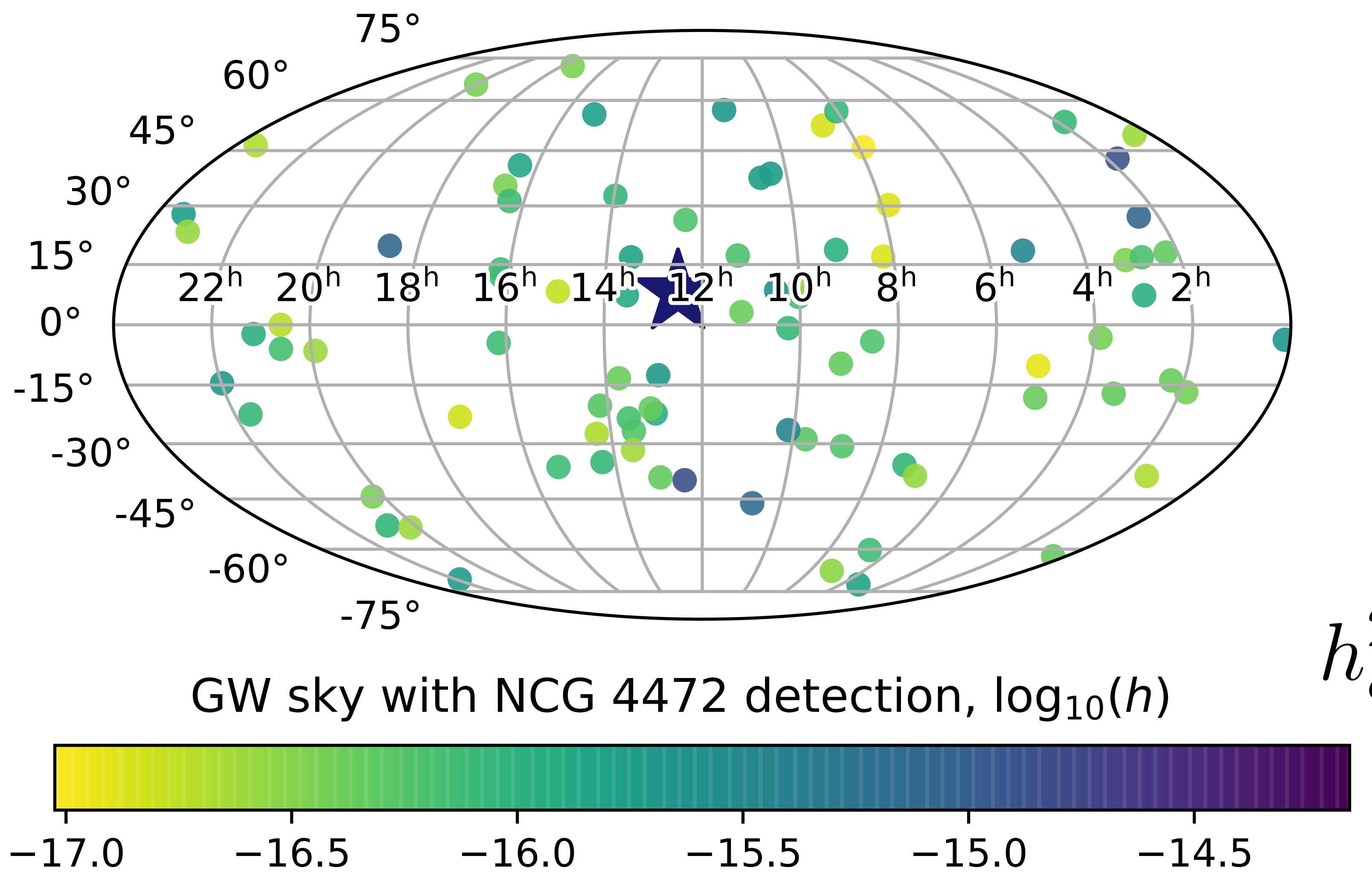


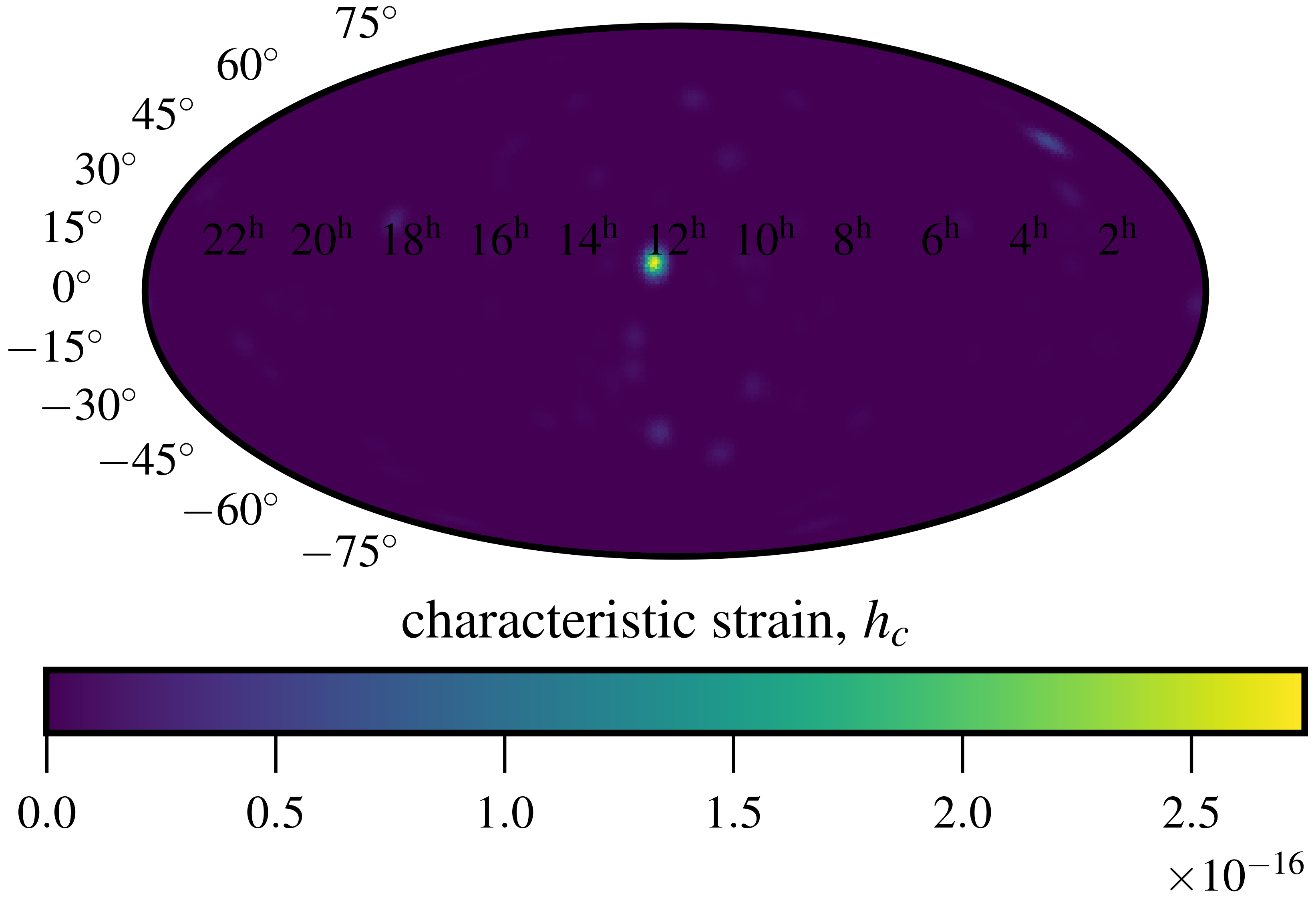
$$M = 10^9 M_\odot$$

f_E (nHz)	$(v/c \times 10^{-2})$	Time span	Δf (nHz)	Total	Newtonian	p^1N	$p^{1.5}N$	Spin orbit/β
100	14.6	10 yr	3.22	32.1	31.7	0.9	−0.7	0.06
	9.6	−1 kpc	71.2	4305.1	4267.8	77.3	−45.8	3.6
50	11.6	10 yr	0.24	15.8	15.7	0.3	−0.2	0.01
	9.4	−1 kpc	23.1	3533.1	3504.8	53.5	−28.7	2.3

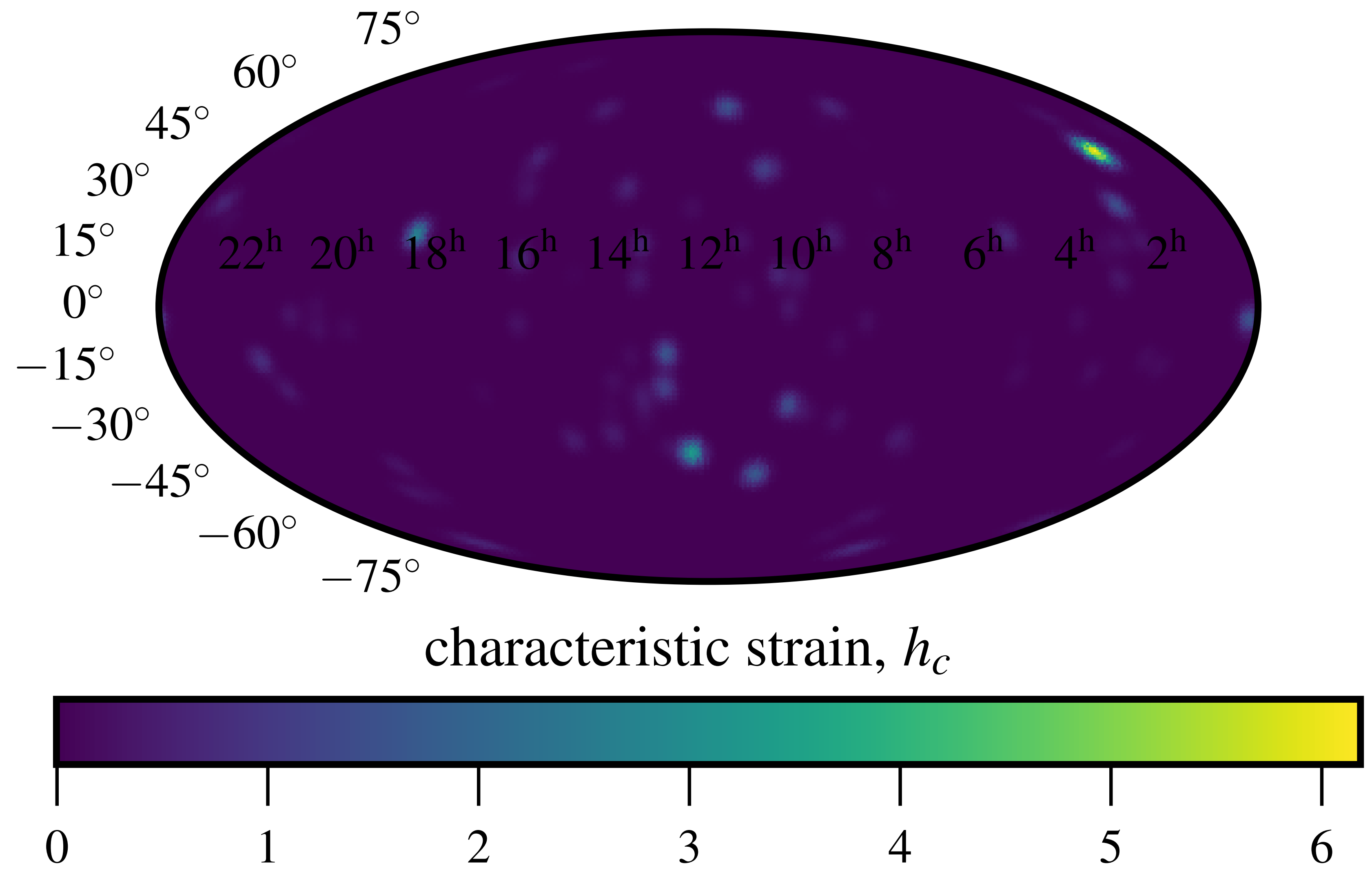
CMFM et al. (2012), Phys. Rev. Lett

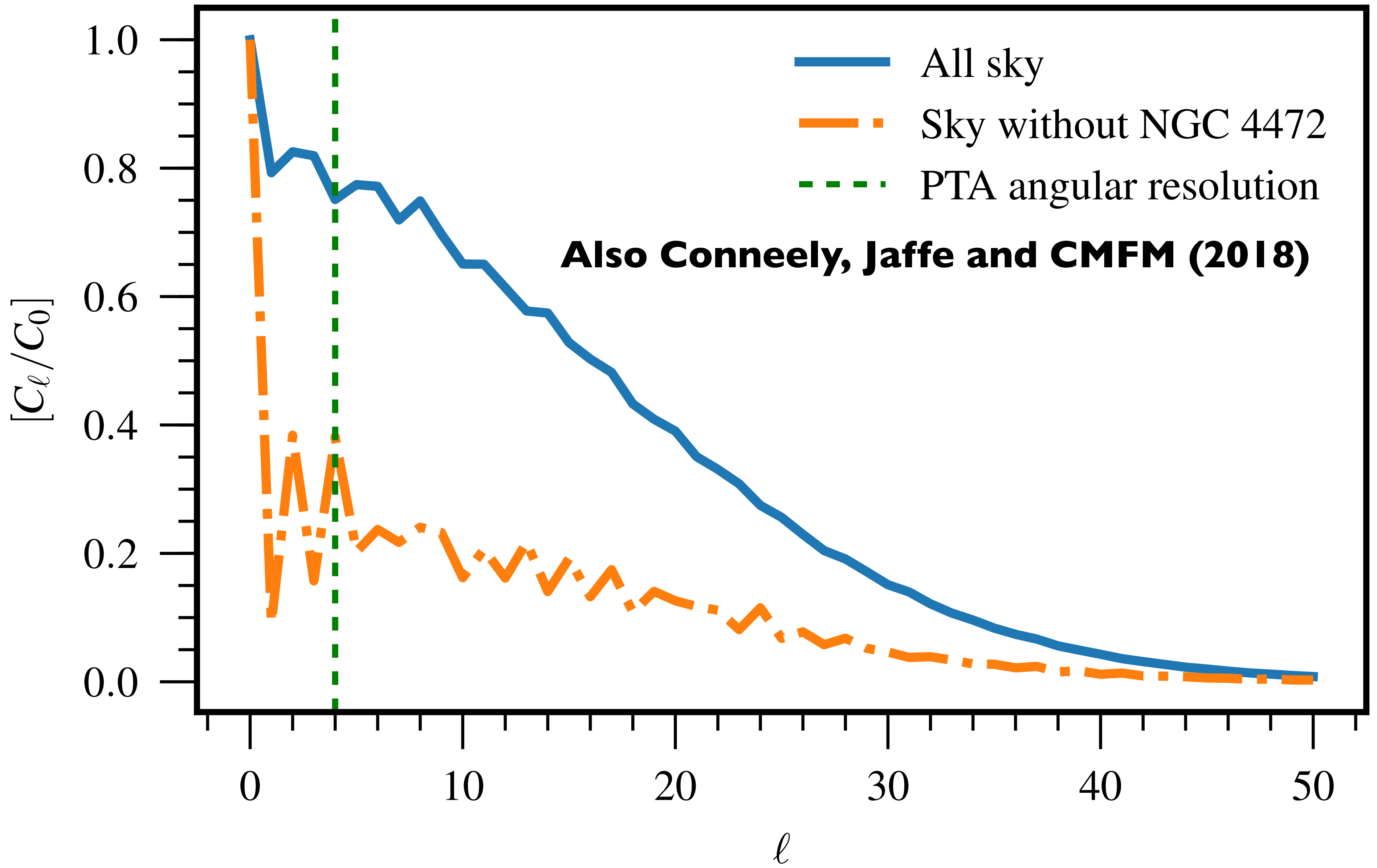
Future: GWBs and Anisotropy





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





CMFM et al. (2017), Nature Astronomy

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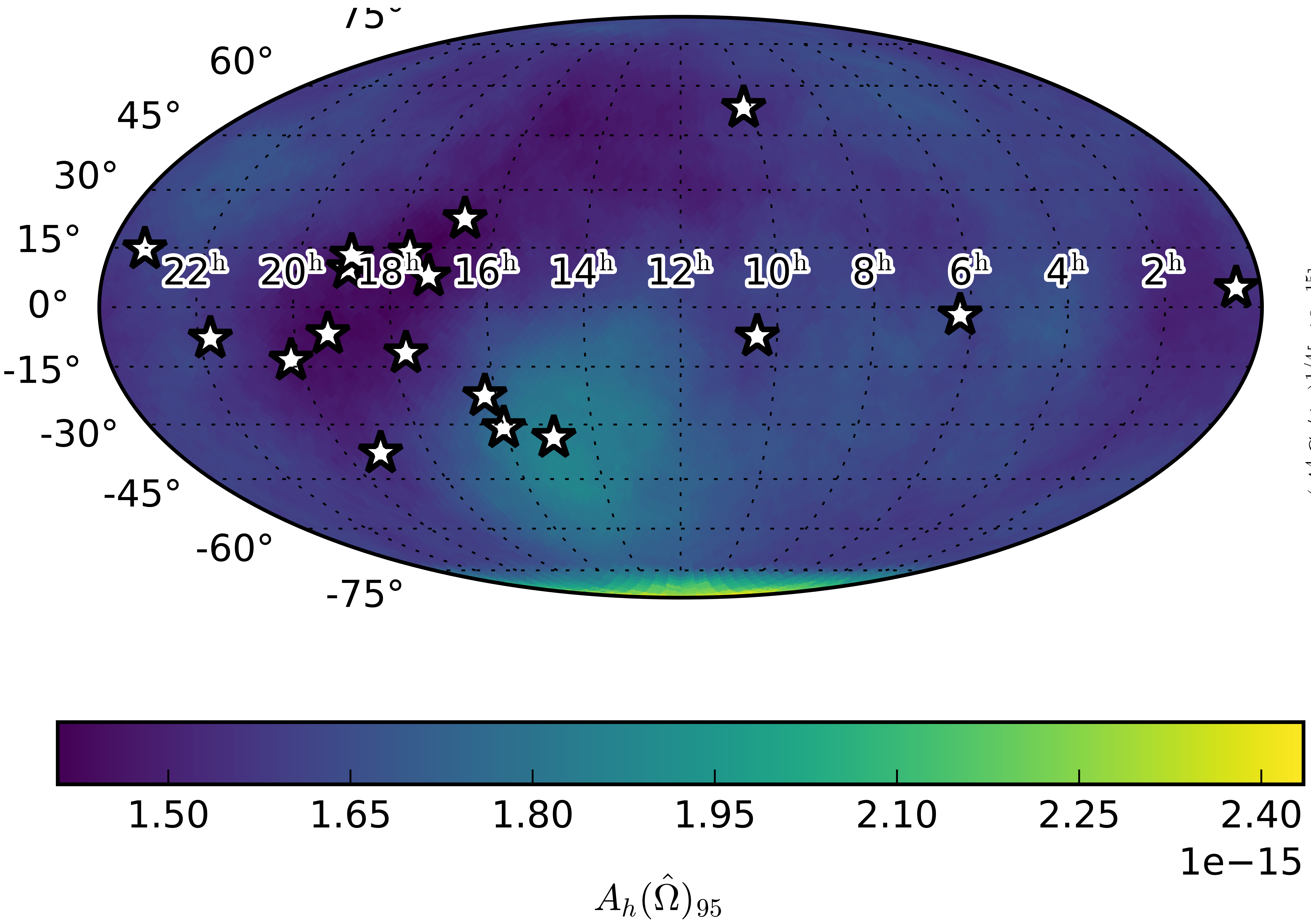
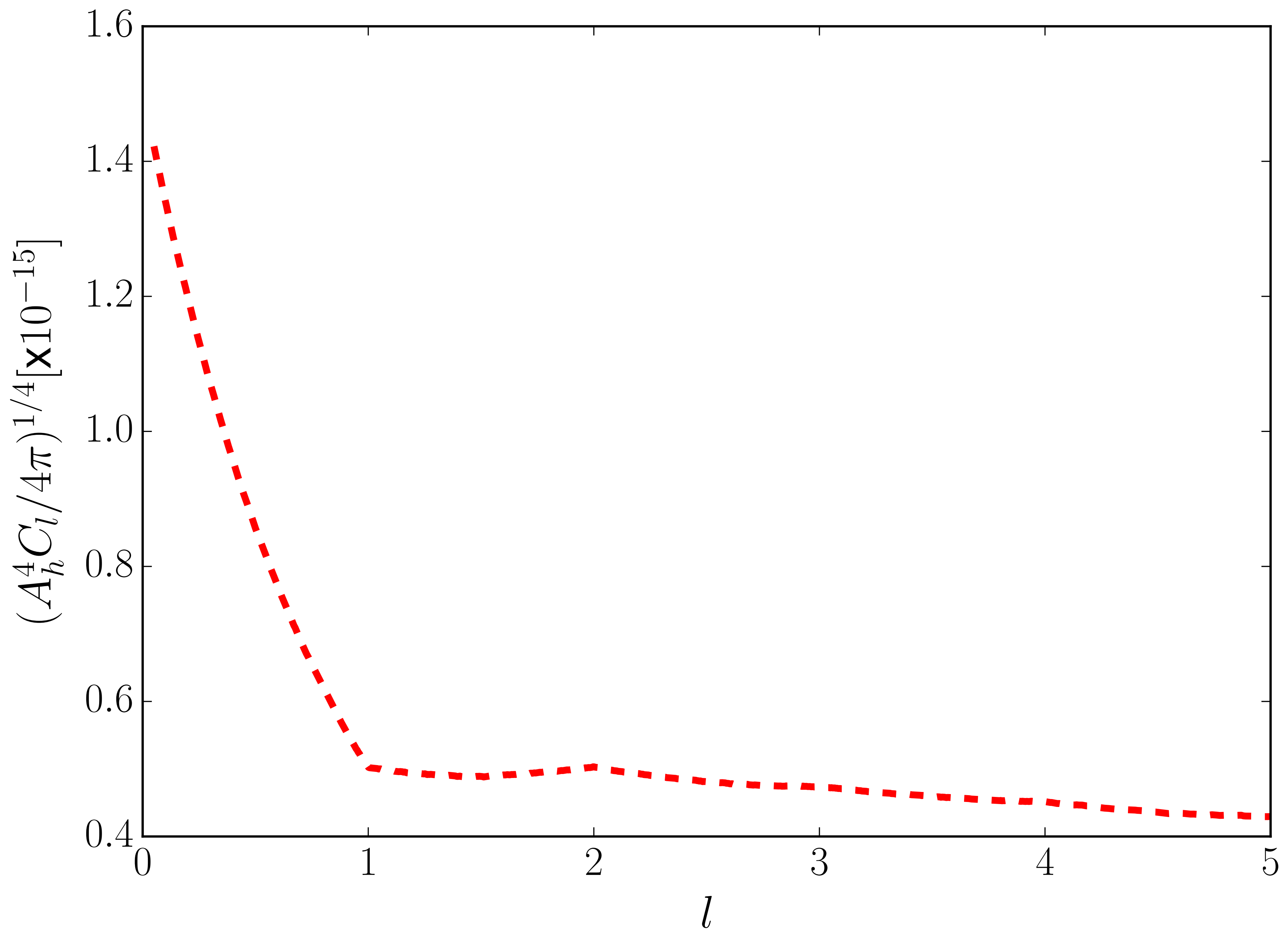
Limits on GWB Anisotropy





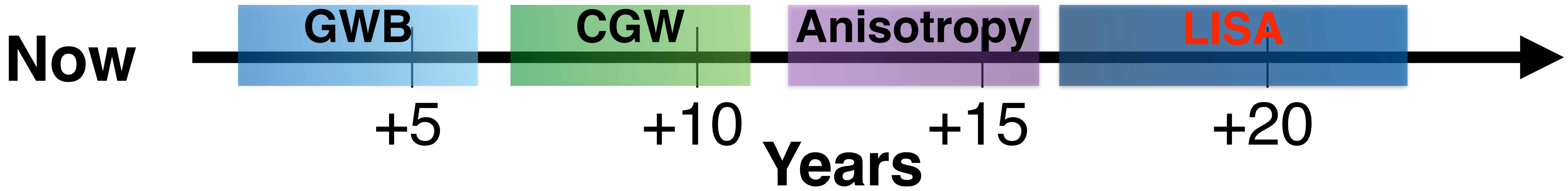
$$l = 180/\sqrt{\Delta\Omega/\mathrm{deg}^2}$$

CMFM et al. for NANOGrav, in prep

Methods from CMFM et al. (2013 & 2014)

Summary

- PTA interdisciplinary science experiment: radio, optical, and gamma ray astronomy, fundamental physics, galaxy evolution, SMBH environments and more!
- Already placing **astrophysical constraints** on SMBHB environments via GW spectrum
- New: EPTA and NANOGrav (in prep) limit stochastic background anisotropy
- Evidence for GWB appearing soon, **detection in ~ 5 years,** local sources ~ **10 years**
- **Can now build GW skies from galaxy surveys:** create GW backgrounds to learn about underlying astrophysics: final parsec problem, binary eccentricity, more!



The orchestra is warming up… and we've only heard the violin