Probing The Nanohertz GW Landscape With Pulsar Timing Arrays: *A Status Report*

Stephen R. Taylor

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Stephen Taylor
GWPAW 2017, Annecy, France, 05-31-2017

Overview

- Pulsar timing
- Searching for gravitational waves
- Supermassive black-hole binaries as sources of nanohertz gravitational waves
- Impact of binary environments on GW signals.
- *The Solar-system Ephemeris*: our new noise floor.

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Pulsar timing

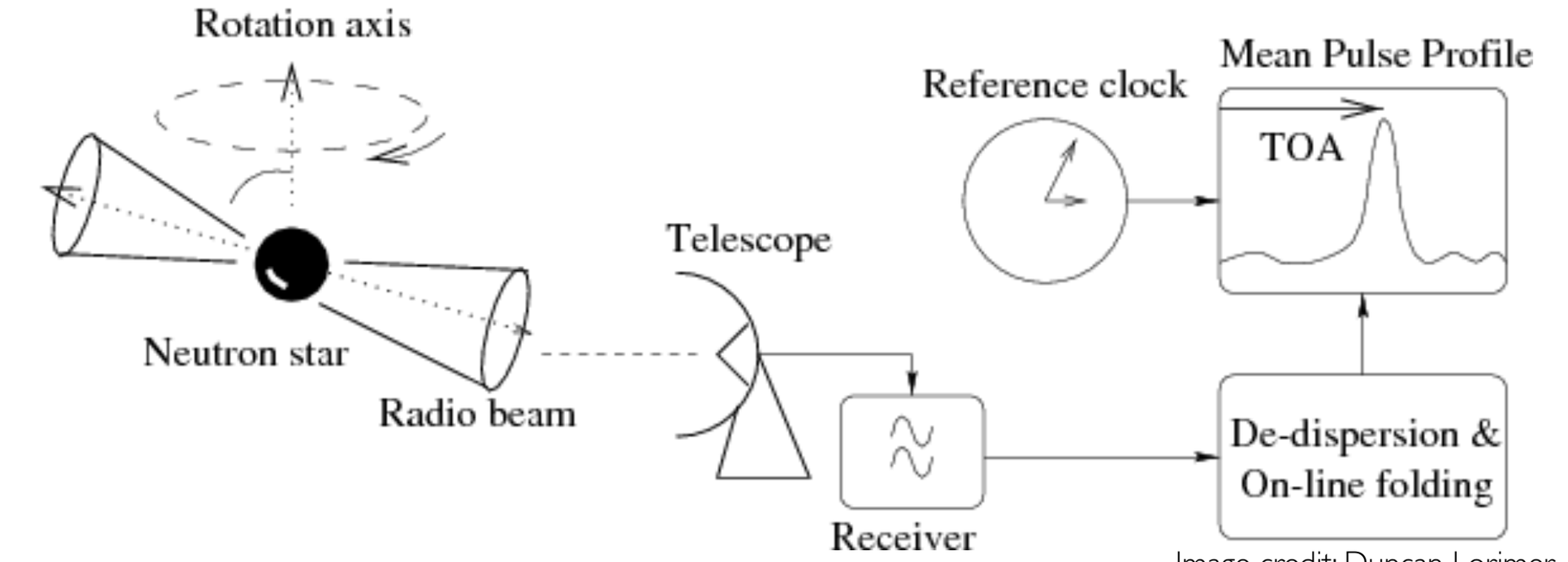
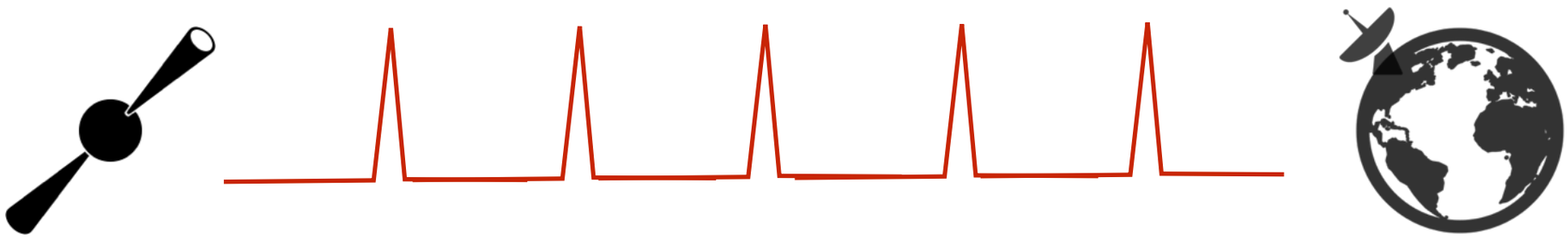


Image credit: Duncan Lorimer



Sophisticated *timing models* depend on P, Pdot, pulsar sky location, ISM properties, pulsar binary parameters etc.

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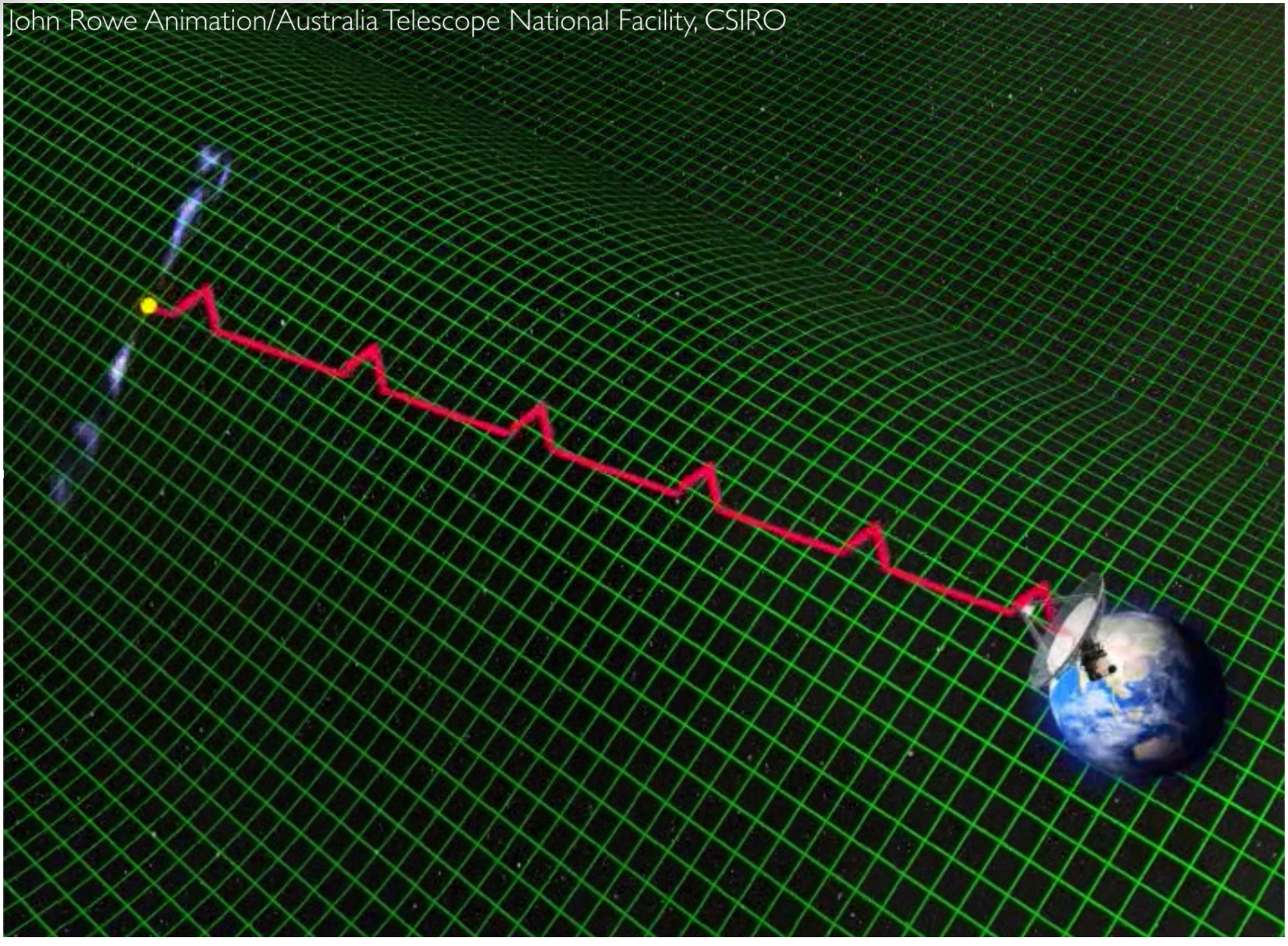

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Searching for GWs with pulsar timing

- Sensitivity band set by total observation time (1/decades) and observational cadence (1/weeks) — [~ 1- 100 nHz]
- Primary candidate is population of **supermassive black-hole binaries**

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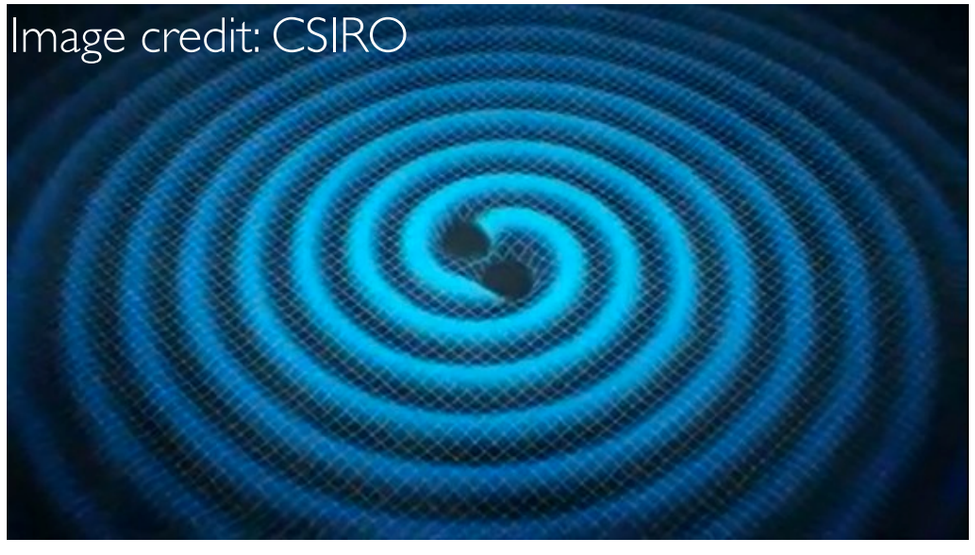

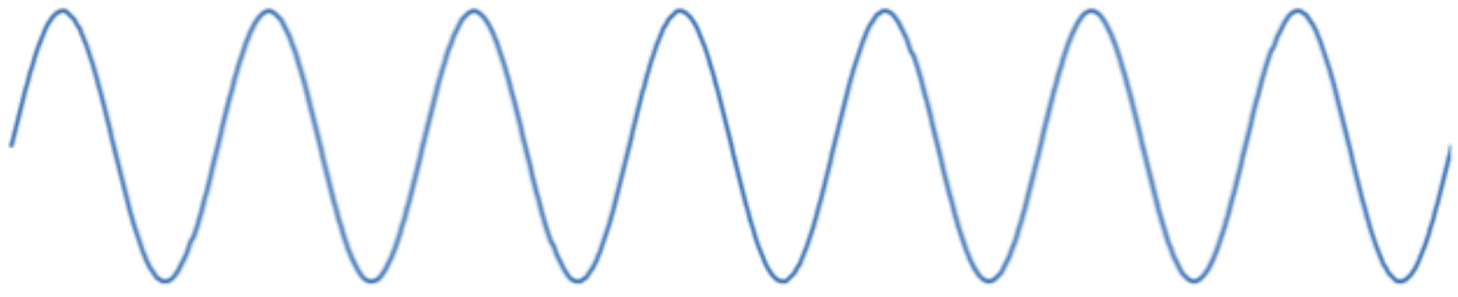

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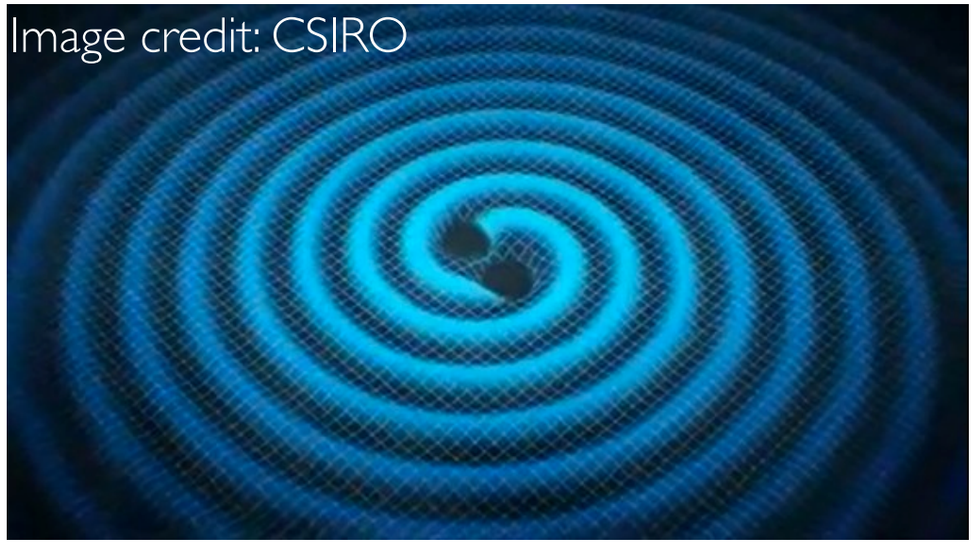

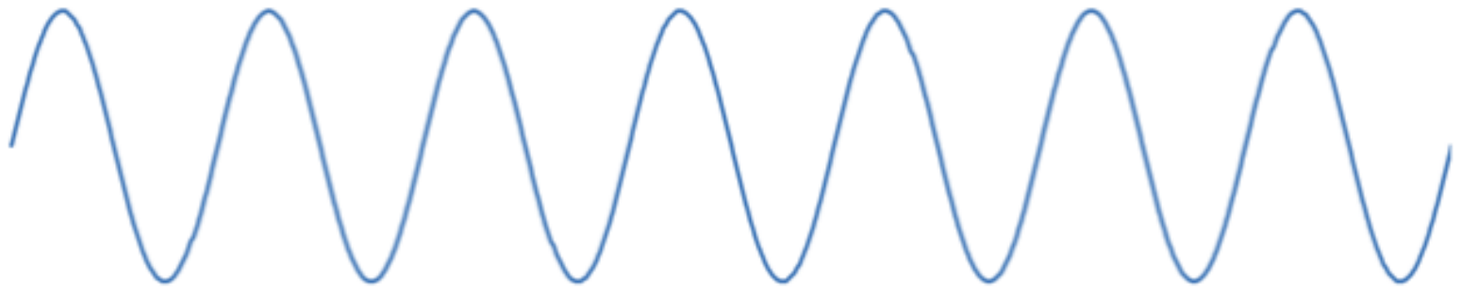

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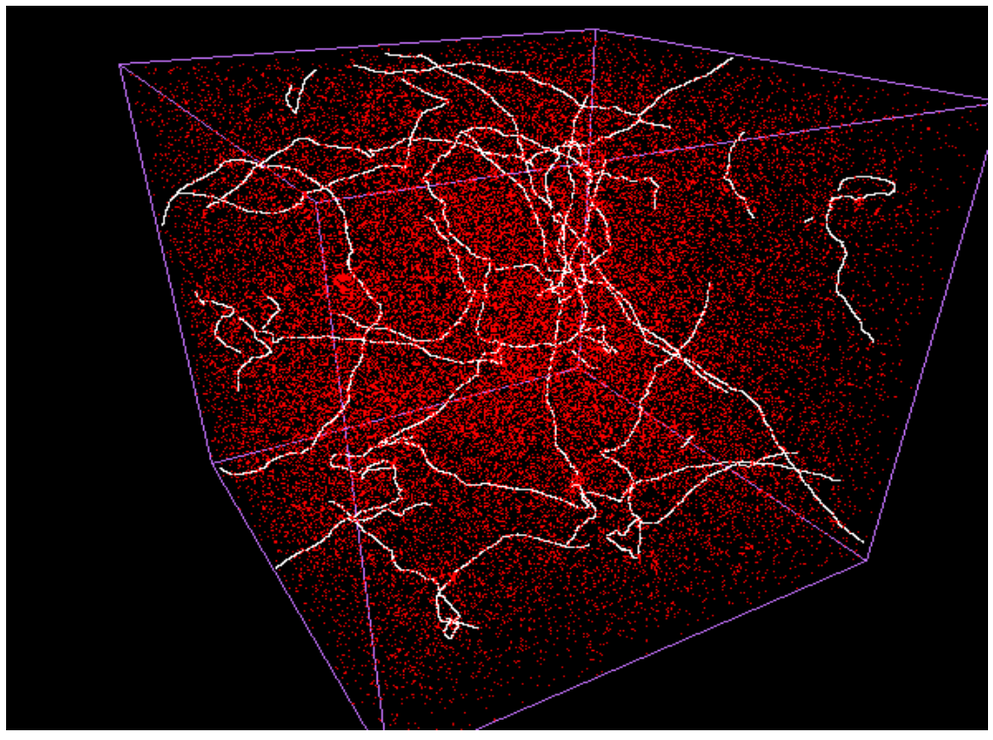

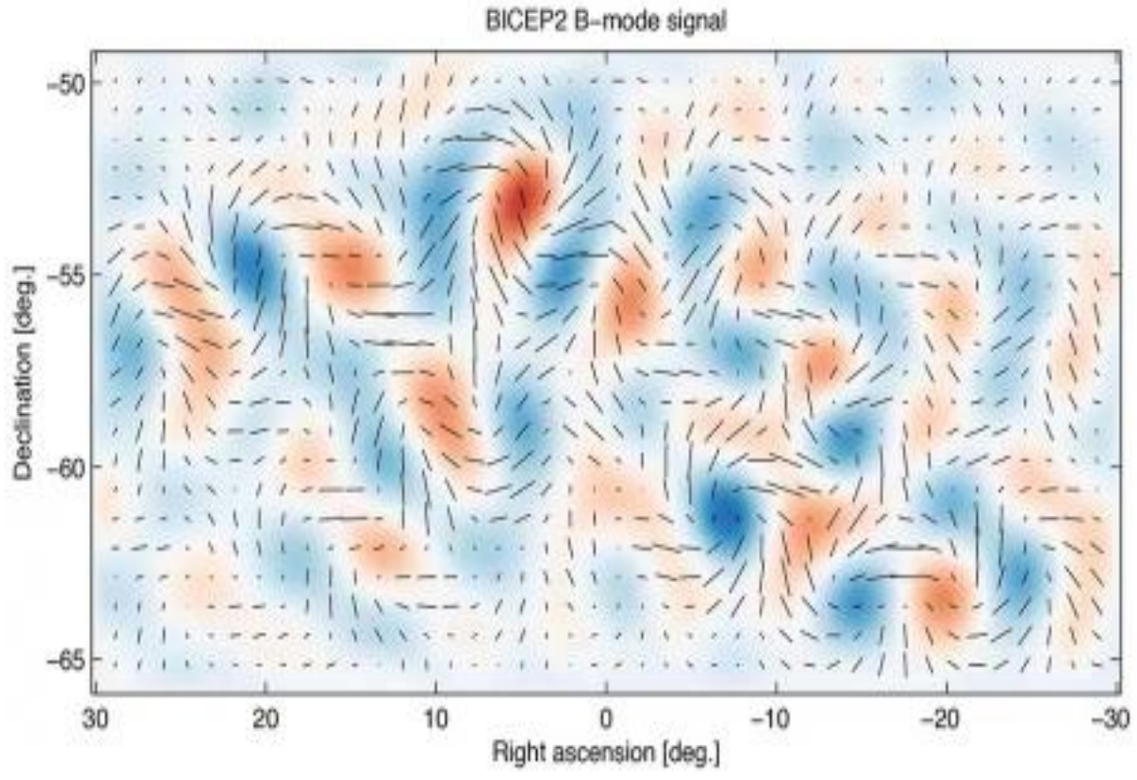

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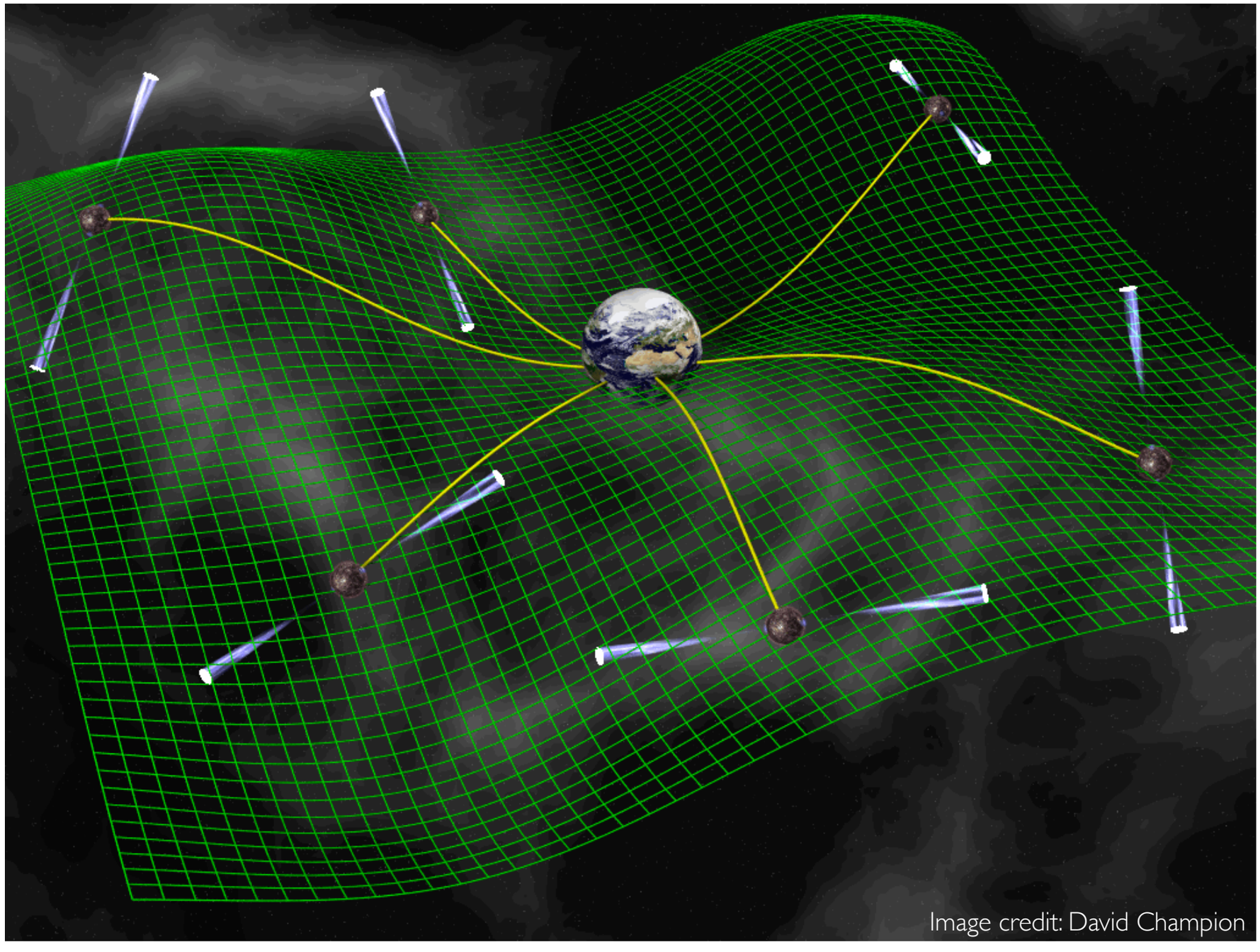

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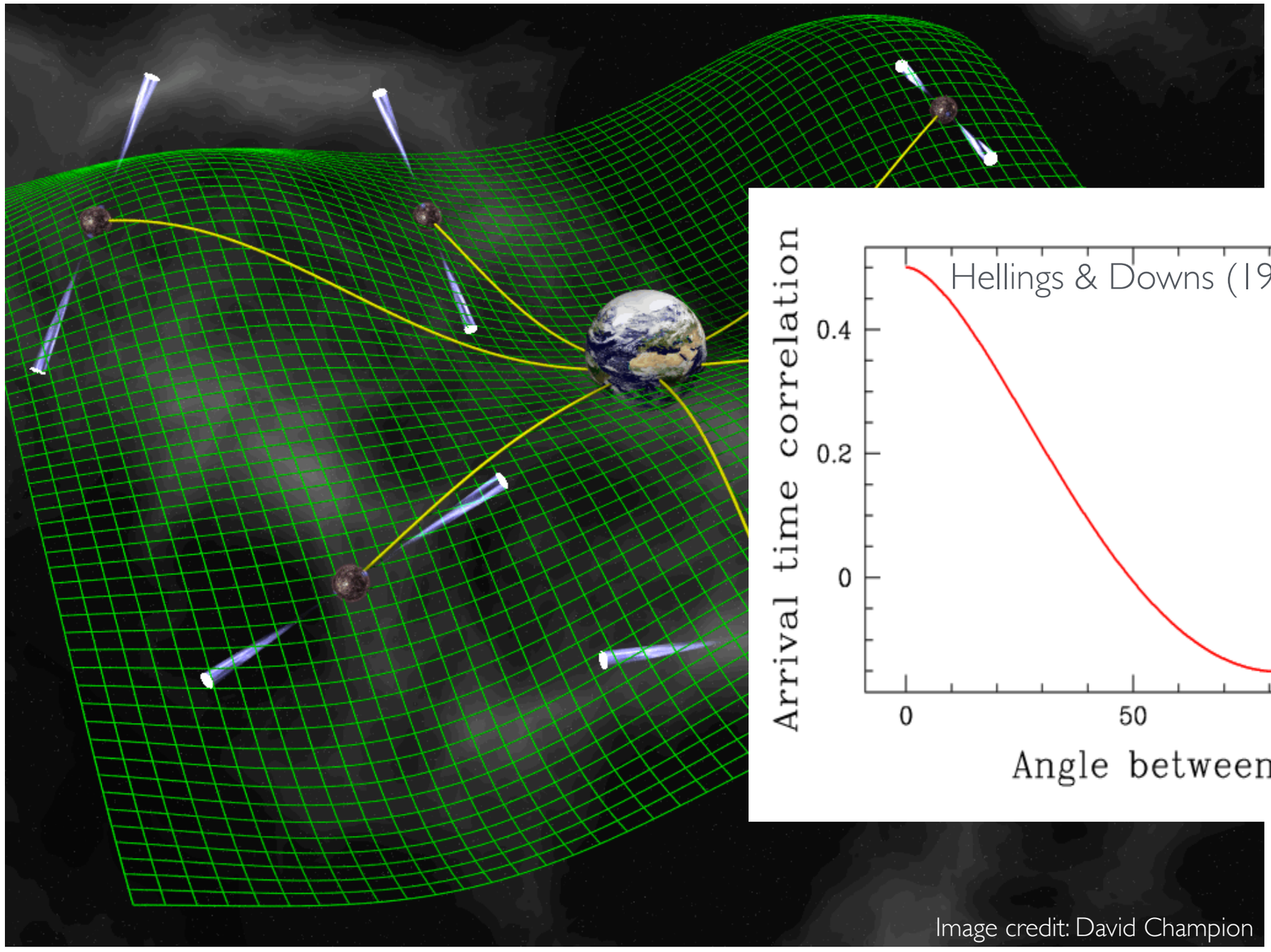

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Sources & Spectrum

How do we build a stochastic signal from these binaries, and how do the different physical processes affect the spectrum?

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$$h_c^2(f) = \int_0^\infty dz \int_0^\infty dM_1 \int_0^1 dq \frac{d^4N}{dz dM_1 dq dt_r} \frac{dt_r}{d\ln f_{K,r}}$$
$$\times h^2(f_{K,r}) \sum_{n=1}^{\infty} \frac{g[n, e(f_{K,r})]}{(n/2)^2} \delta\left[f - \frac{n f_{K,r}}{(1+z)}\right]$$

e.g. Phinney (2001), Sesana (2013)

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e.g. Phinney (2001), Sesana (2013)

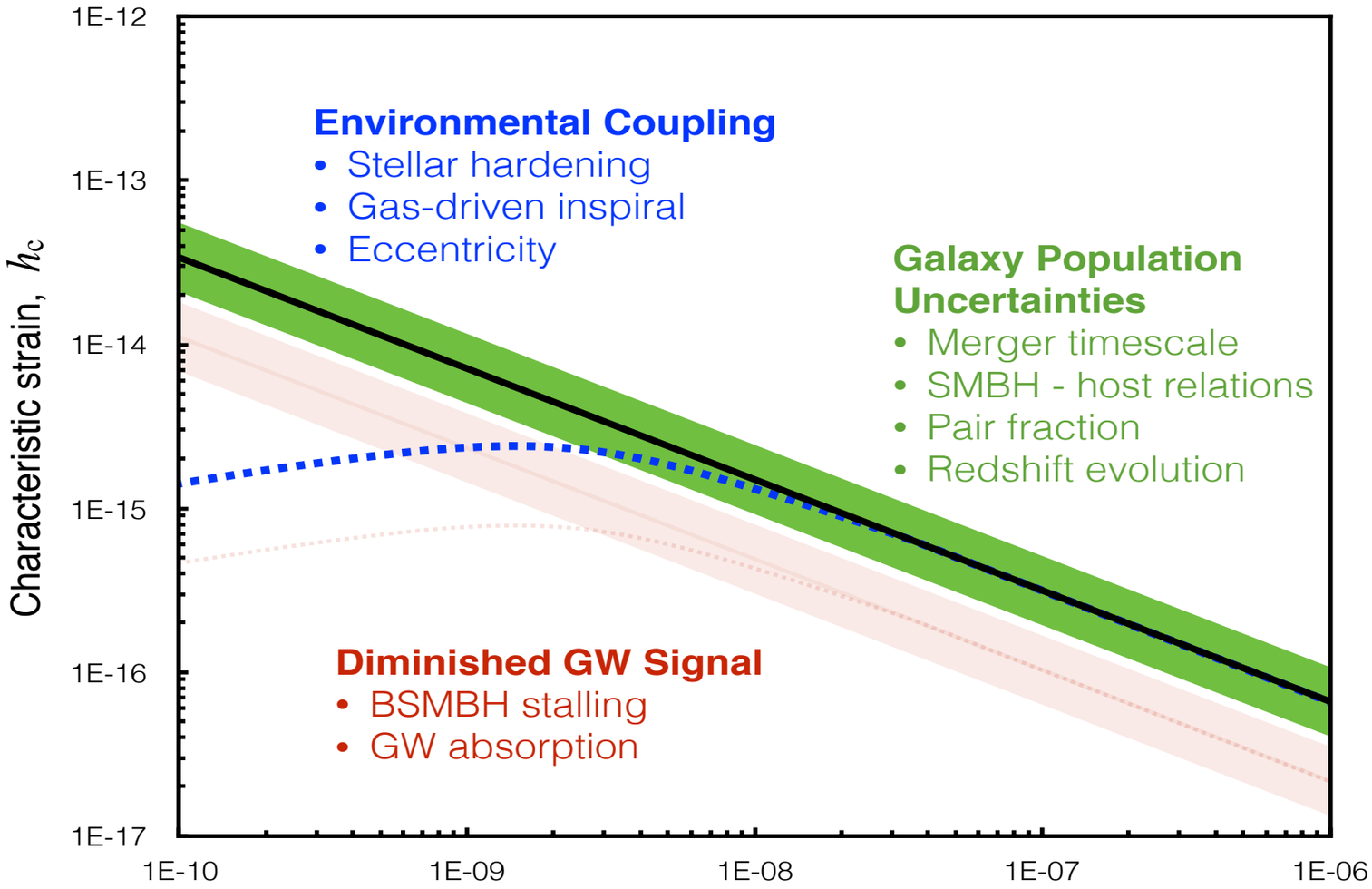
(a) Comoving merger rate — affects overall signal level

(b) Binary evolution — affects shape of spectrum through time binaries spend emitting at each frequency *(binary environmental influences enter here)*

(c) Eccentricity — affects shape of spectrum through binary orbital evolution

Sources & Spectrum

Upper limits reference the characteristic strain amplitude at a GW frequency of 1/yr (~32 nHz)



Burke-Spolaor (2015)

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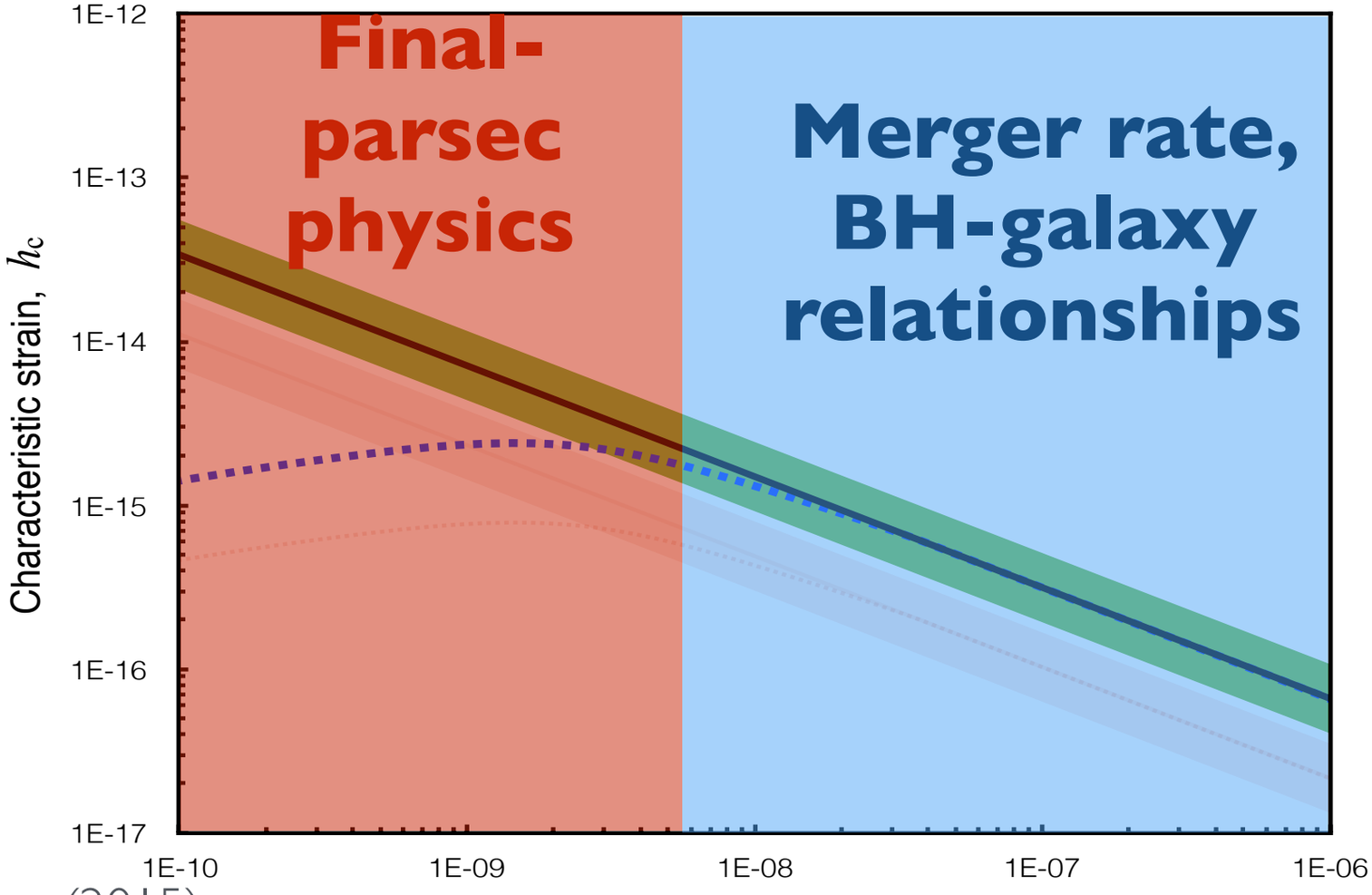

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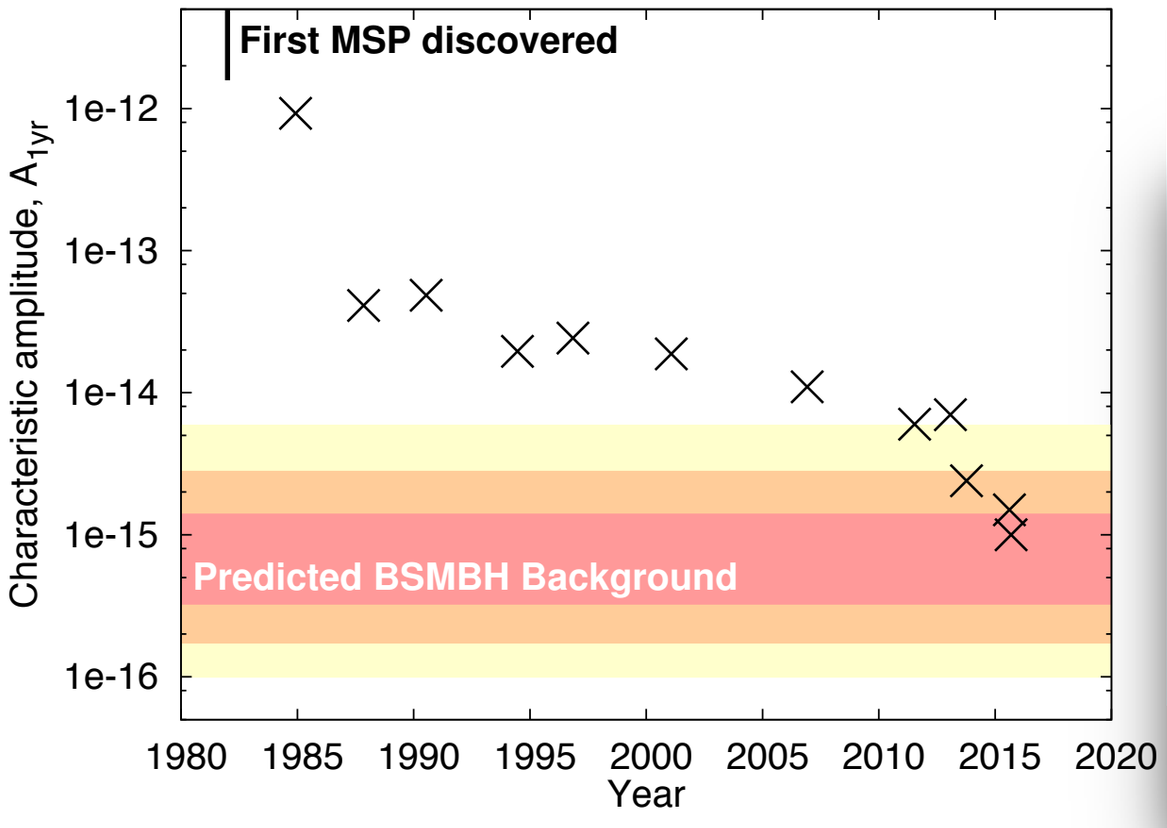
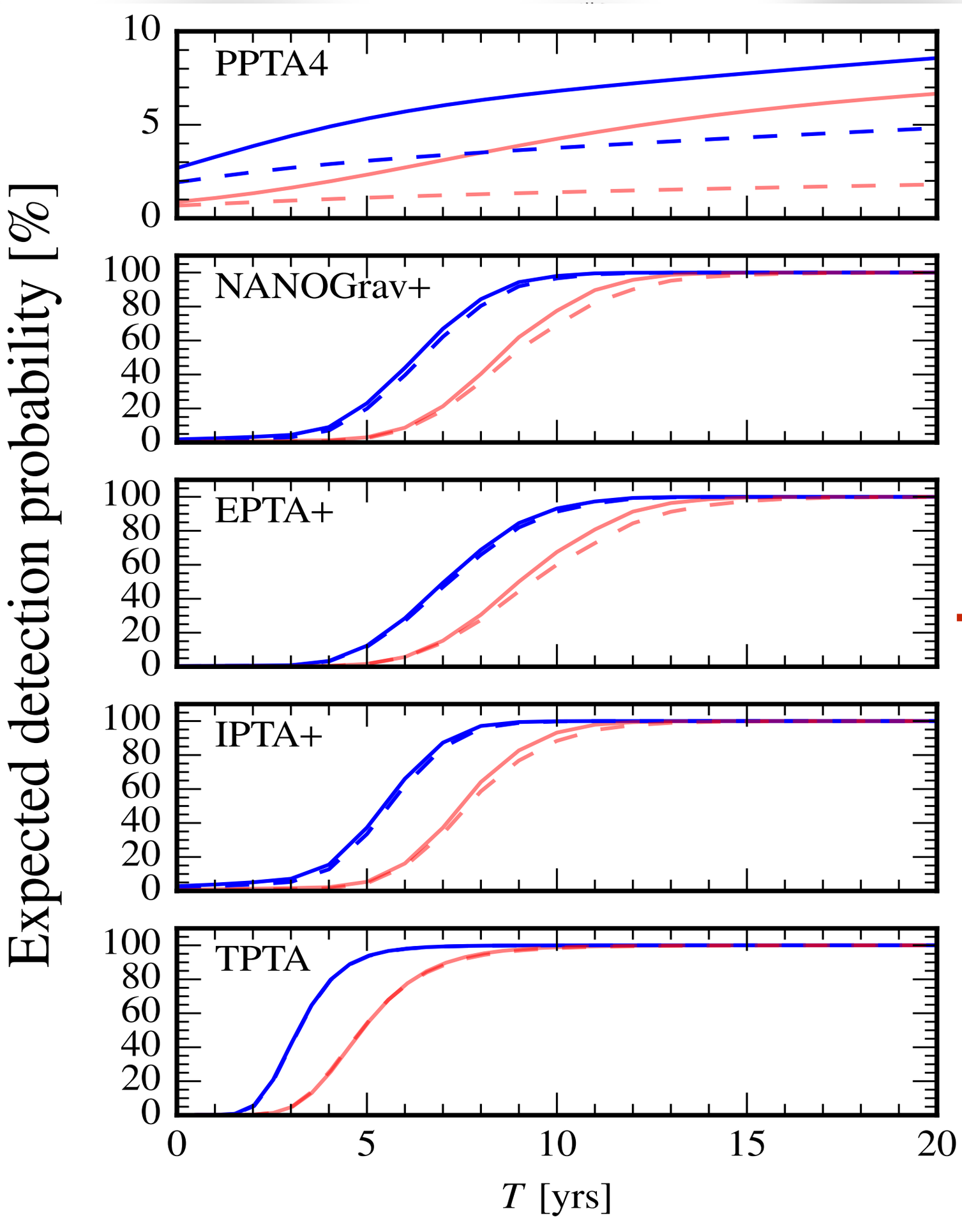


Burke-Spolaor (2015)

Lentati, **Taylor** et al. (2015) $\lesssim 3.0 \times 10^{-15}$

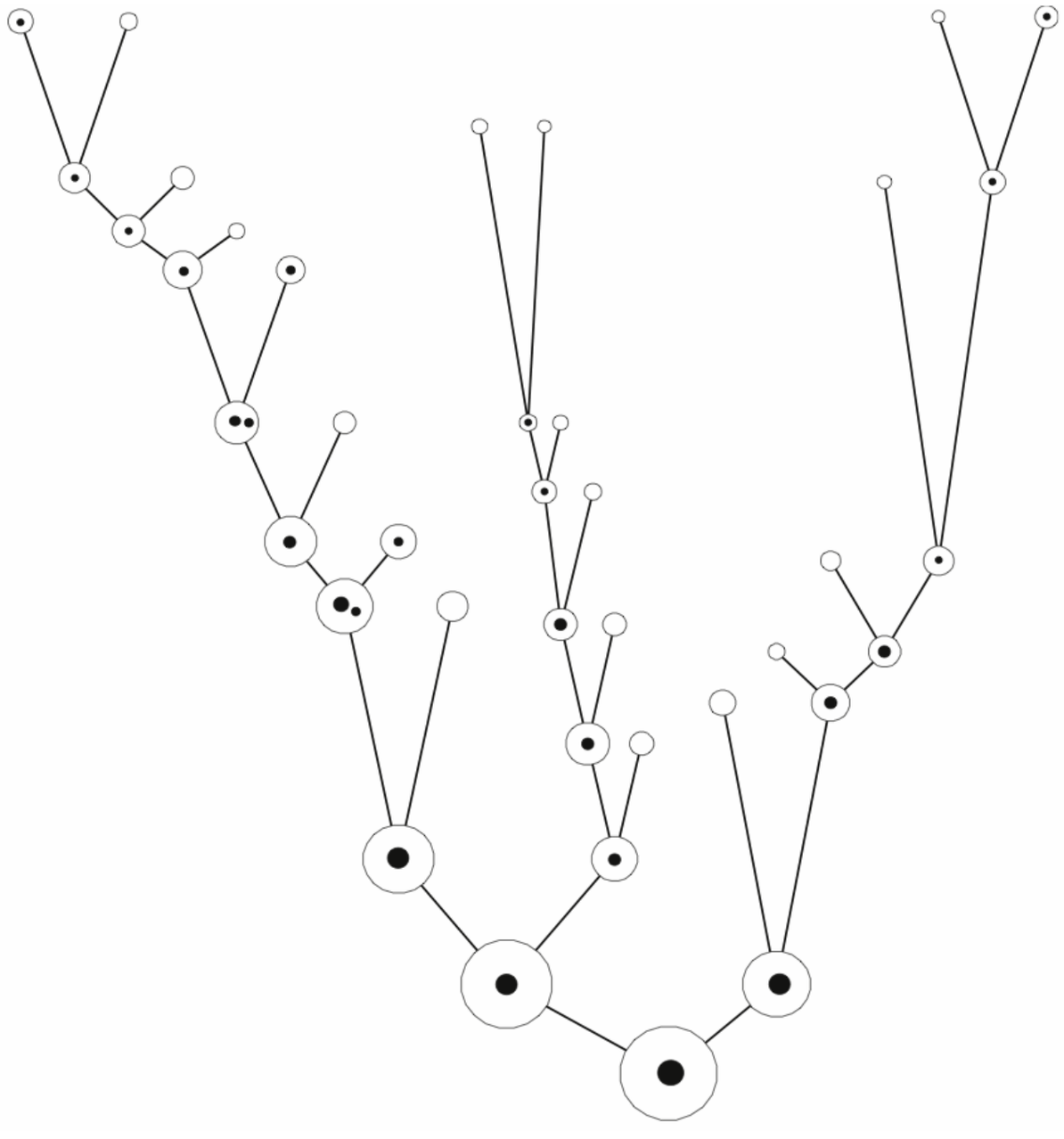
Shannon et al. (2015) $\lesssim 1.0 \times 10^{-15}$

Arzoumanian et al. (2015) $\lesssim 1.5 \times 10^{-15}$
[led by Ellis, inc. **Taylor**, Mingarelli, van Haasteren, Vallisneri, Lazio]



Taylor et al. (2016a), ApJL 819, L6

Supermassive black-hole binary evolution



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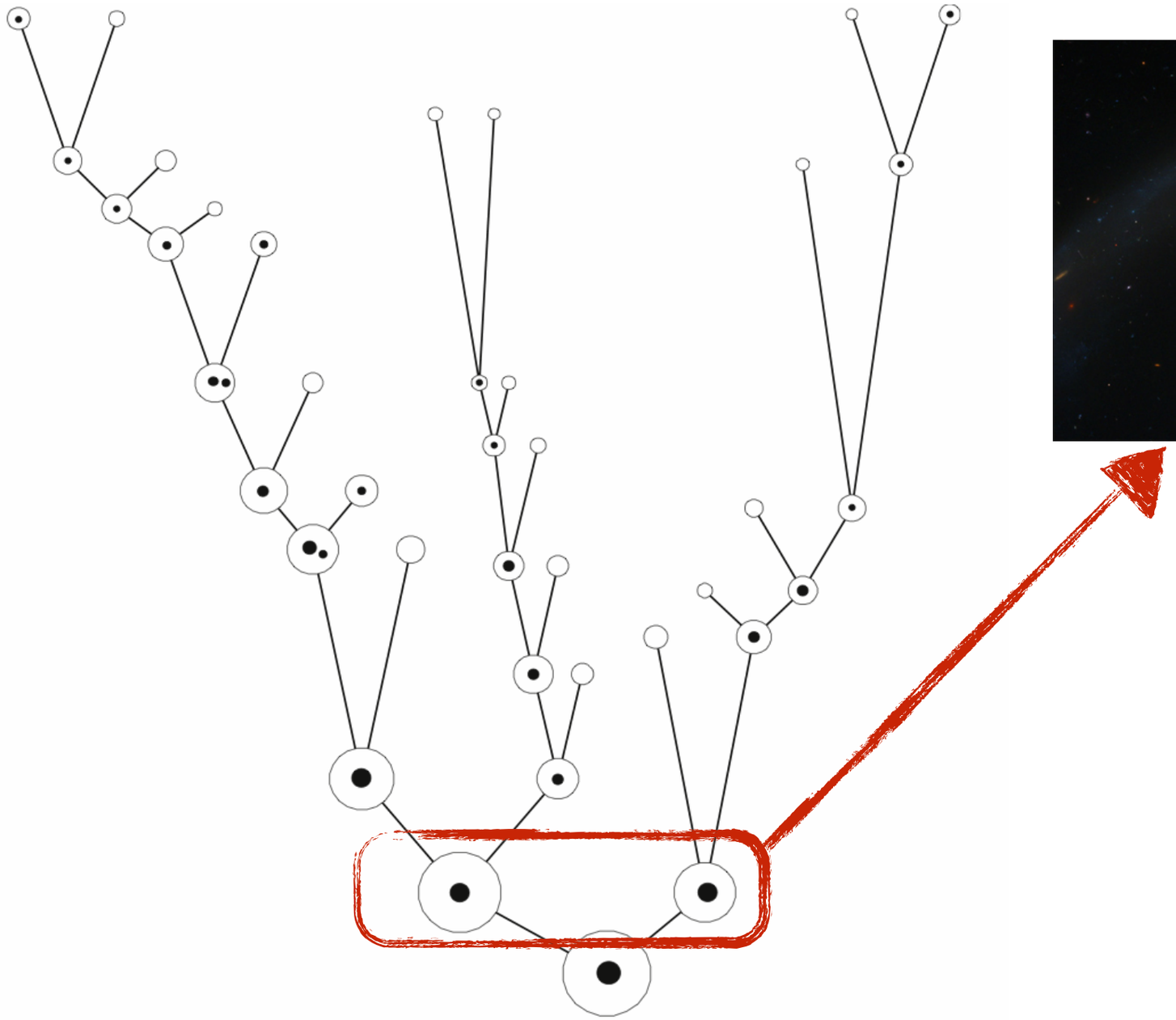

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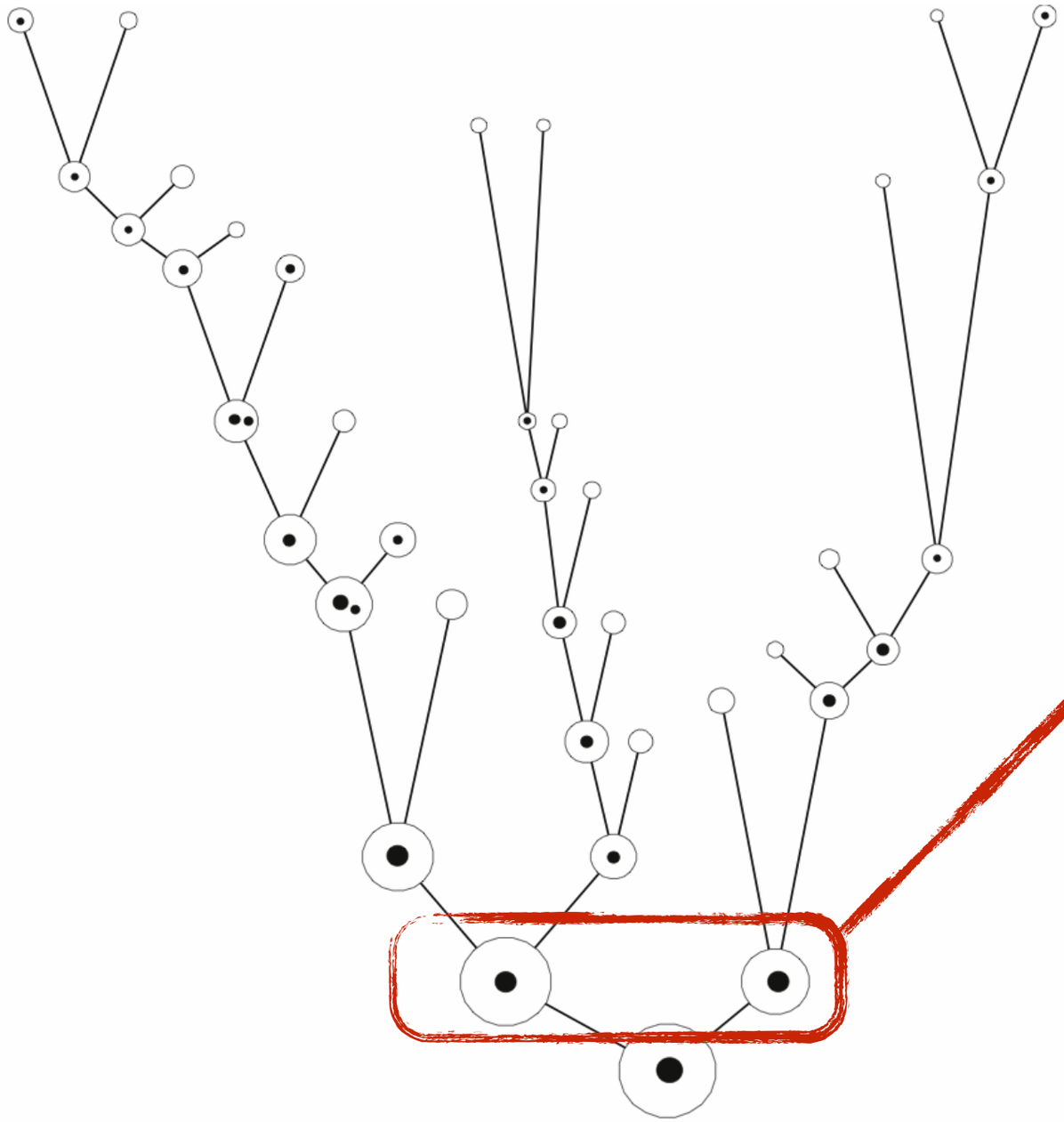

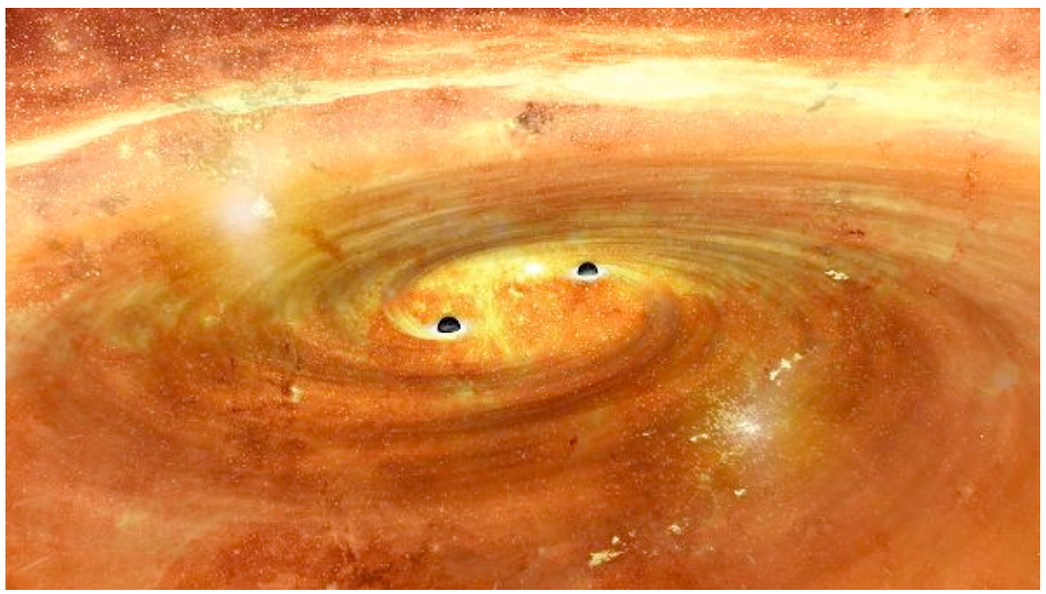

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Supermassive black-hole binary evolution

“Final parsec problem”

Dynamical friction not a sufficient driving mechanism to induce merger within a Hubble time

e.g., Milosavljevic & Merritt (2003)

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e.g., Milosavljevic & Merritt (2003)

Additional environmental couplings may extract energy and angular momentum from binary to drive it to sub-pc separations

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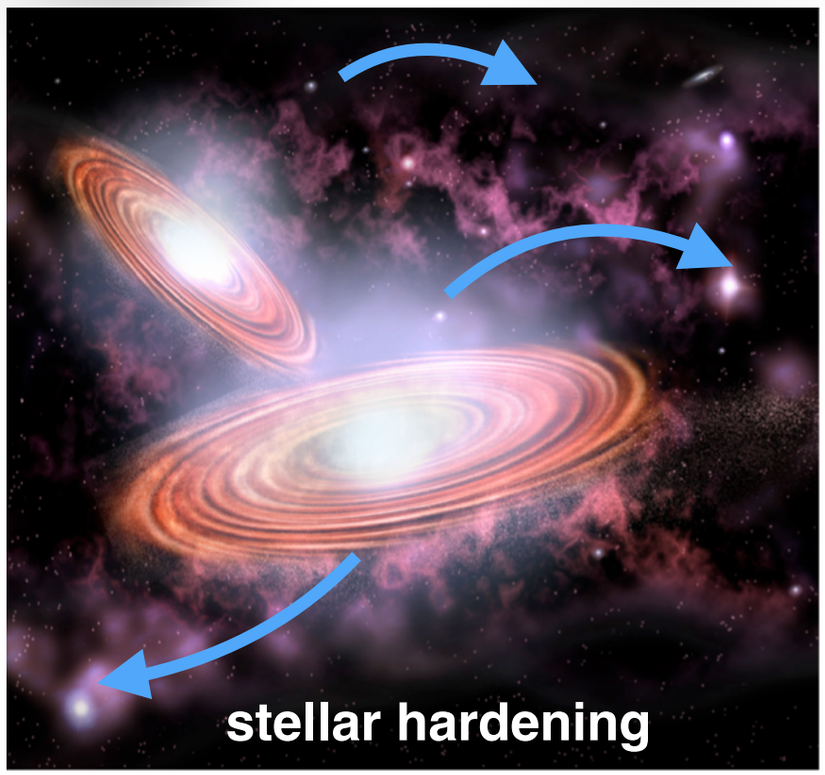

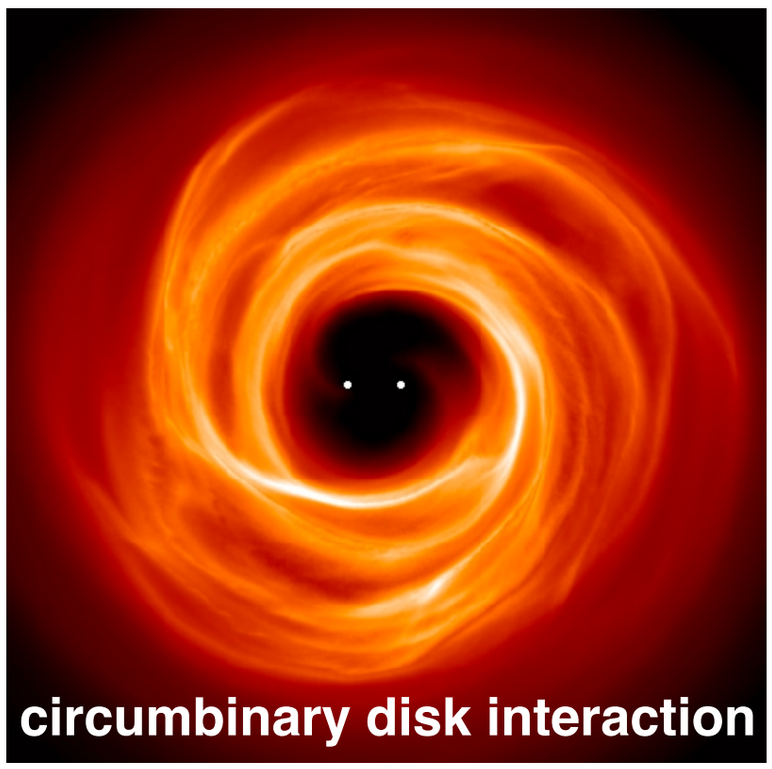

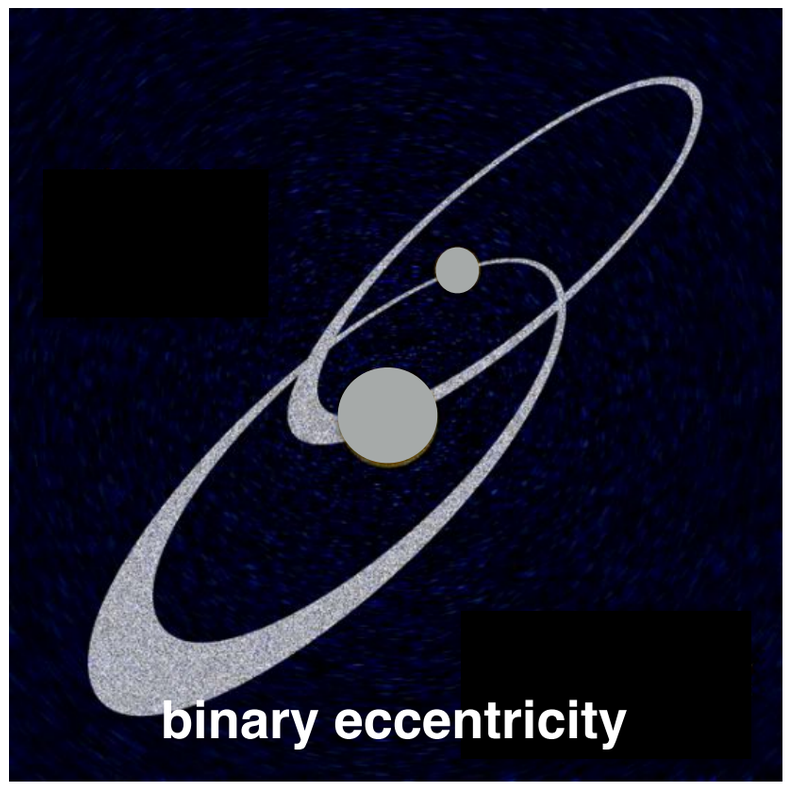

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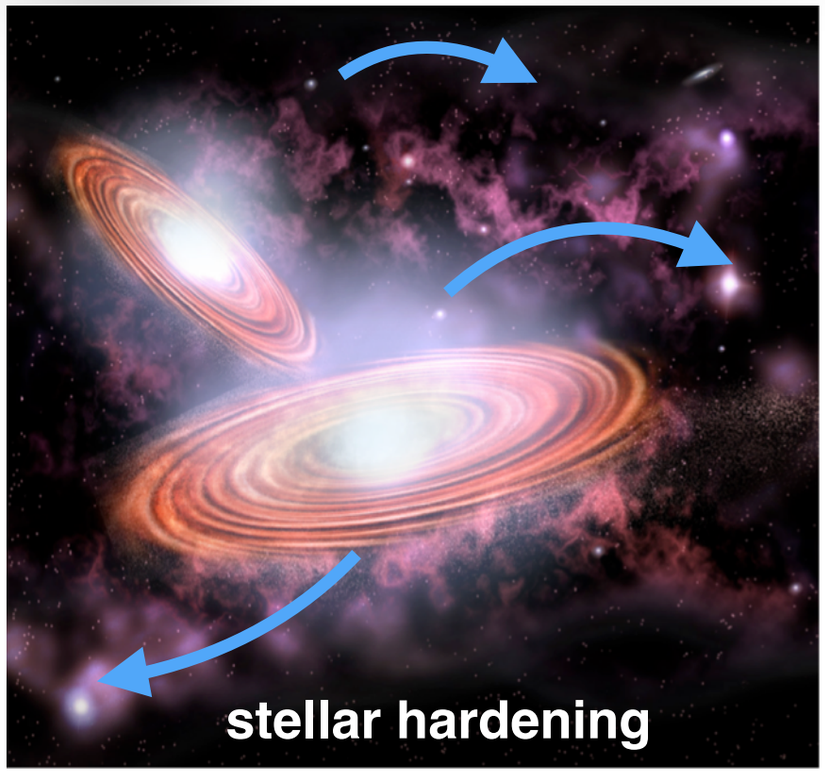
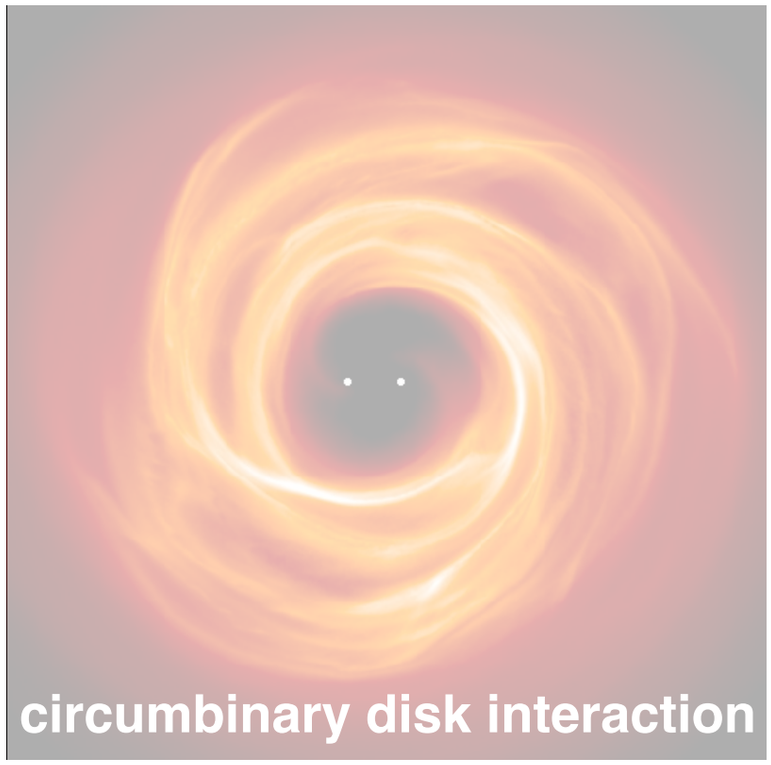
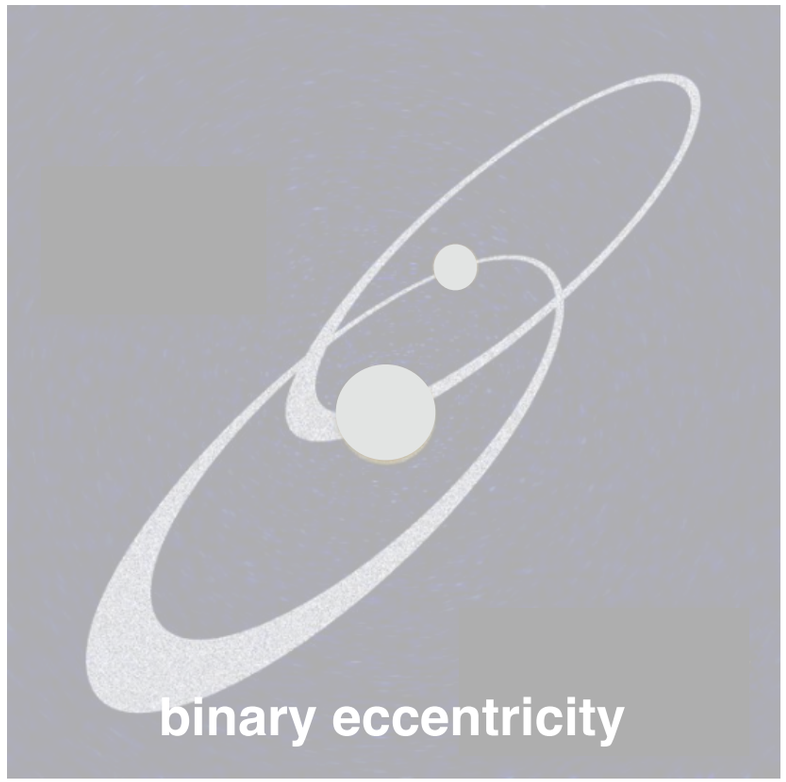
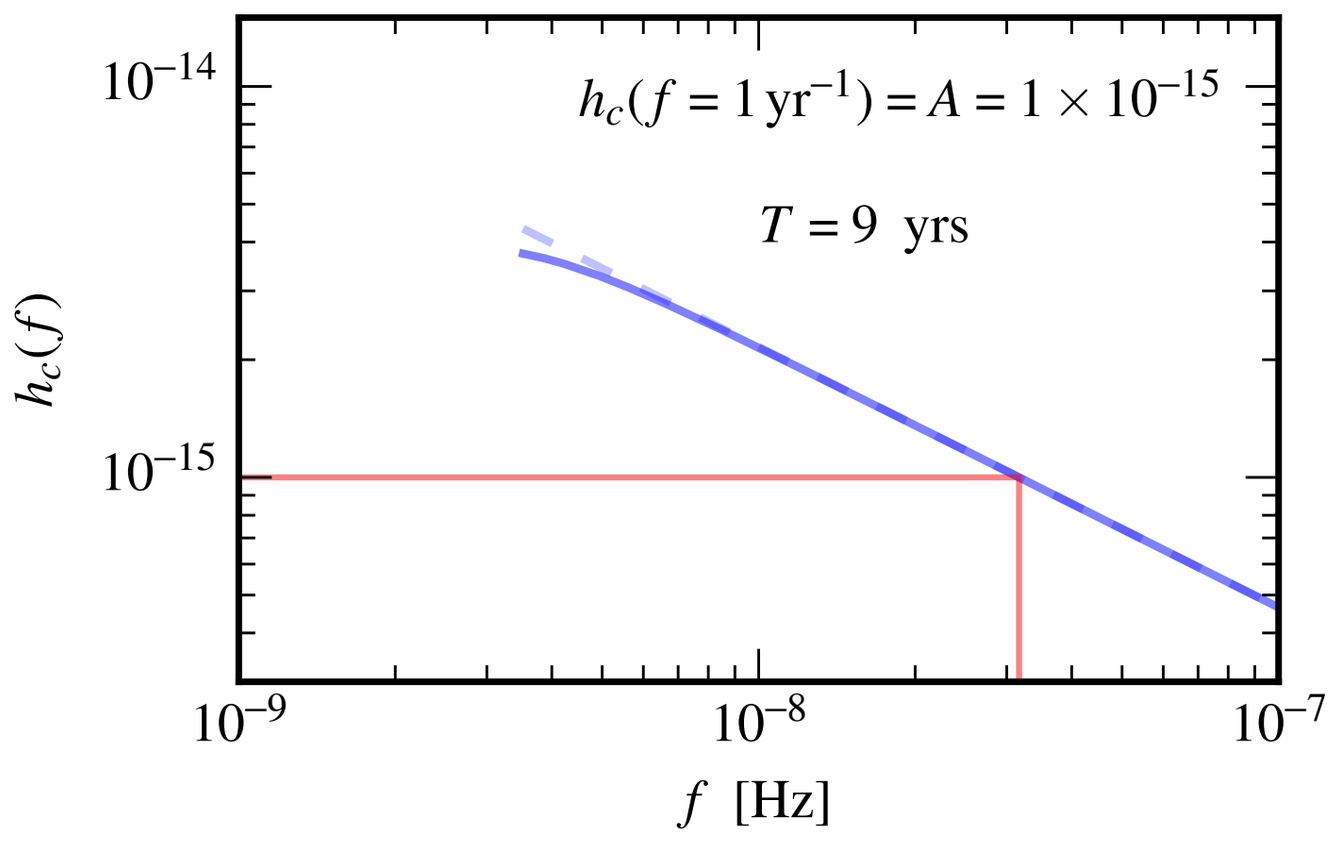
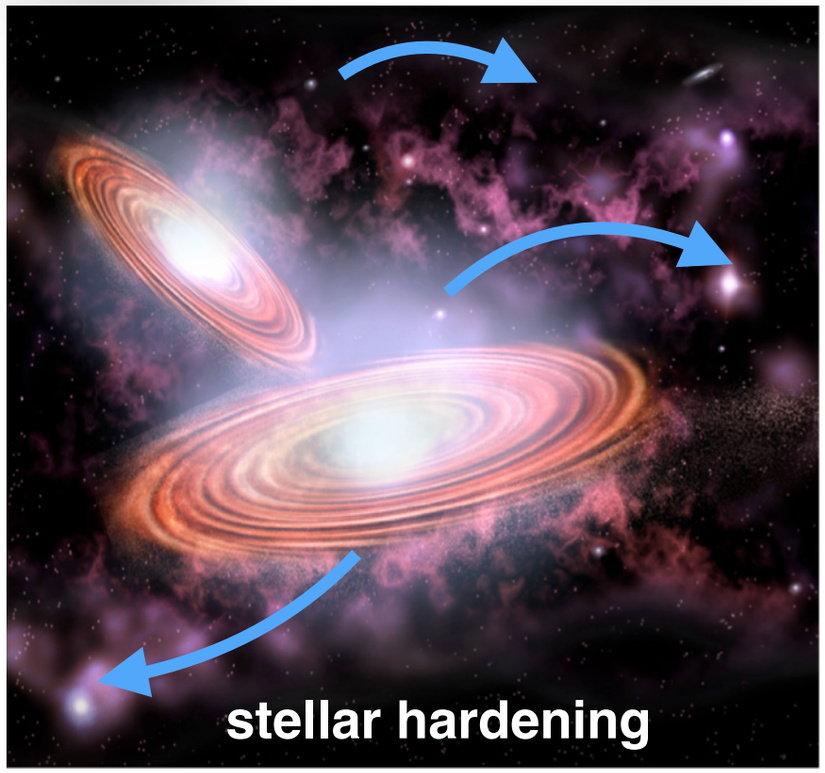

stellar hardening


circumbinary disk interaction


binary eccentricity


$h_c(f = 1\,\mathrm{yr}^{-1}) = A = 1 \times 10^{-15}$
$T = 9$ yrs
10^{-14}
10^{-15}
$h_c(f)$
10^{-9}
10^{-8}
10^{-7}
f [Hz]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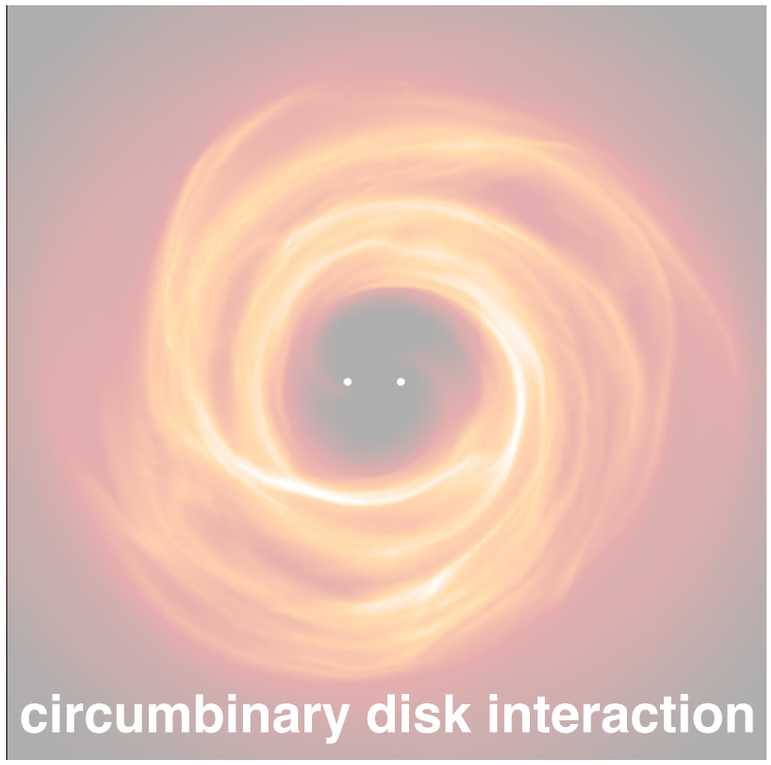
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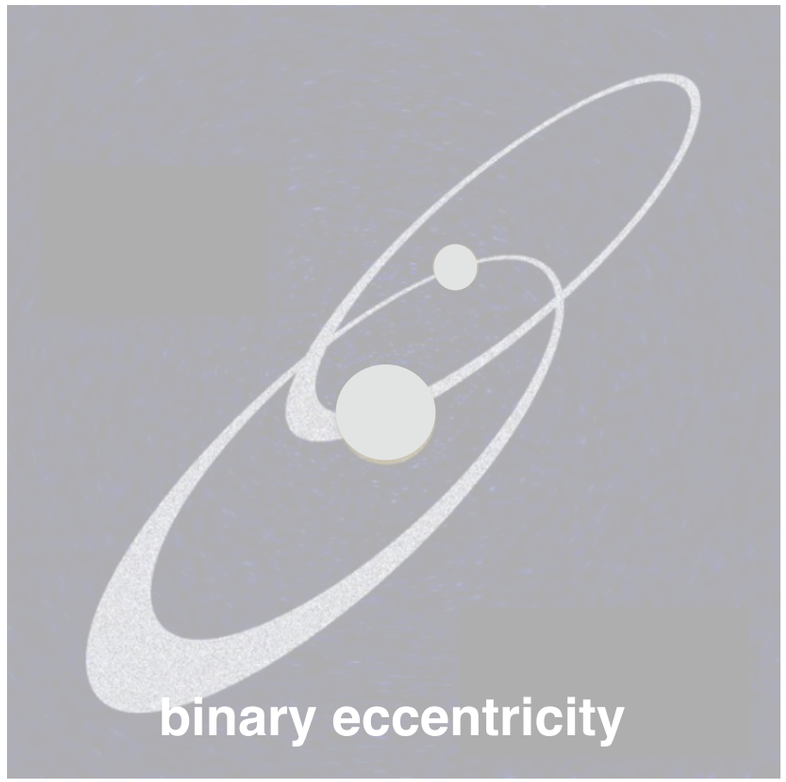
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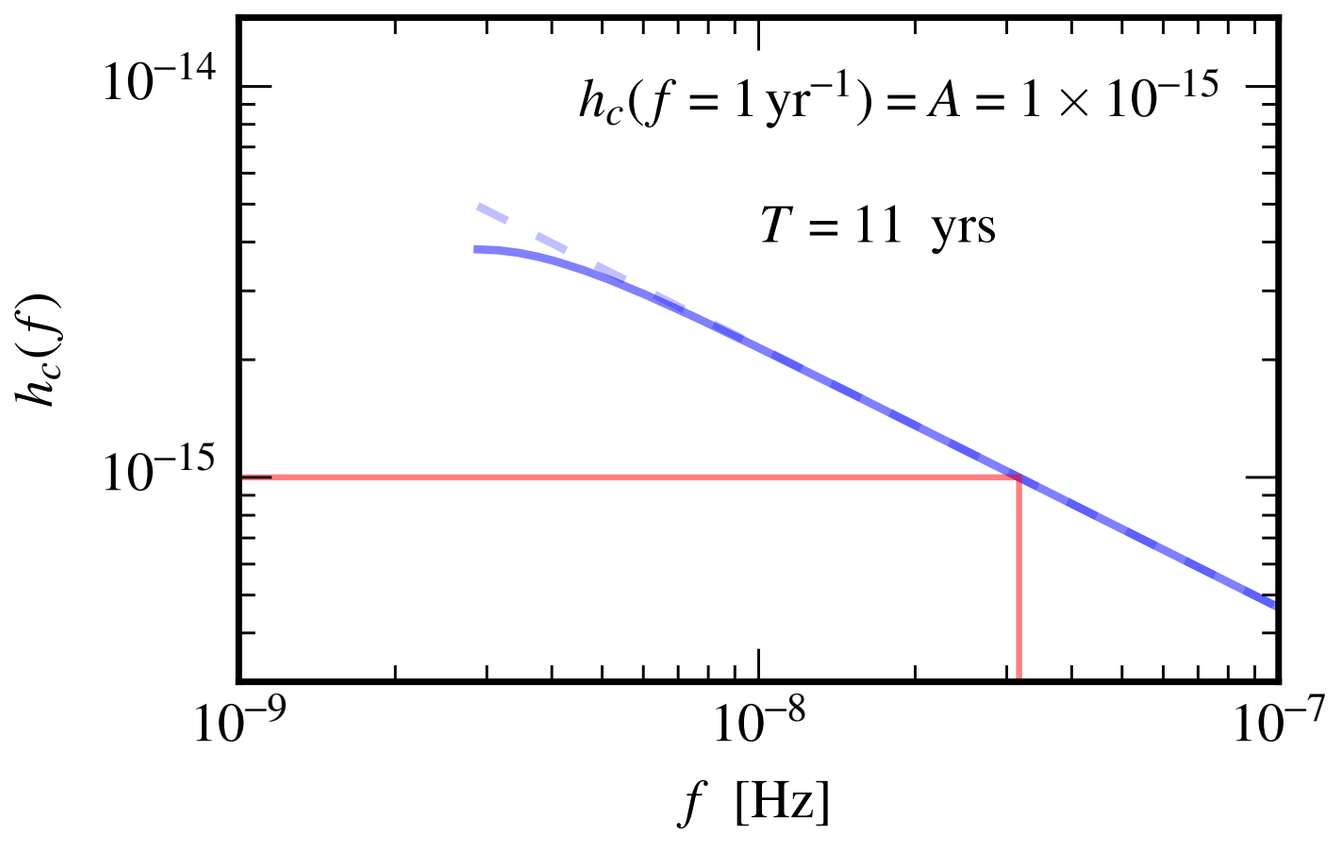
$h_c(f = 1\,\mathrm{yr}^{-1}) = A = 1 \times 10^{-15}$
$T = 11$ yrs
10^{-14}
10^{-15}
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10^{-9}
10^{-8}
10^{-7}
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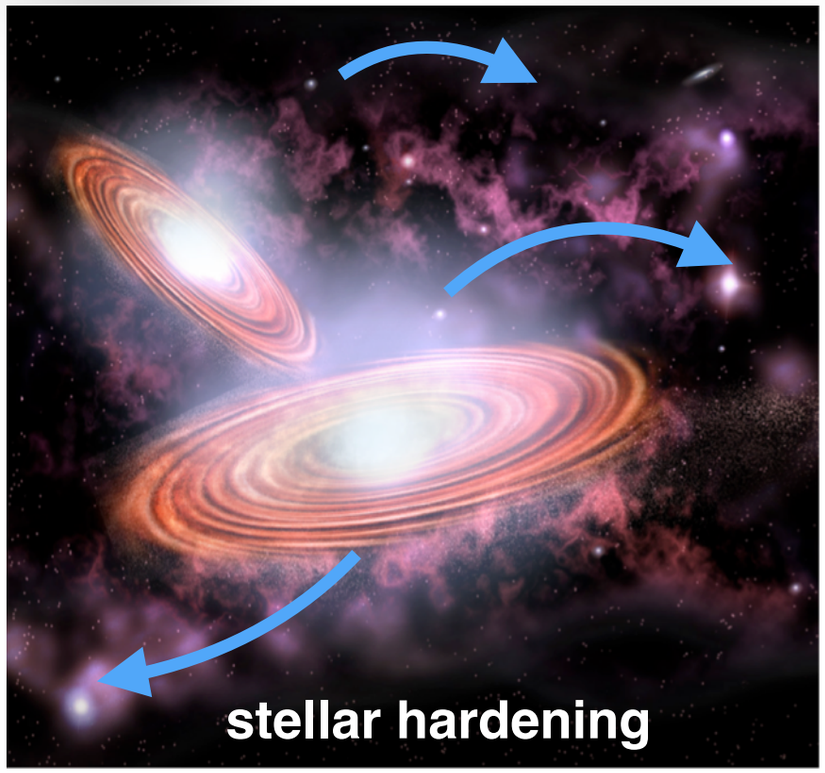
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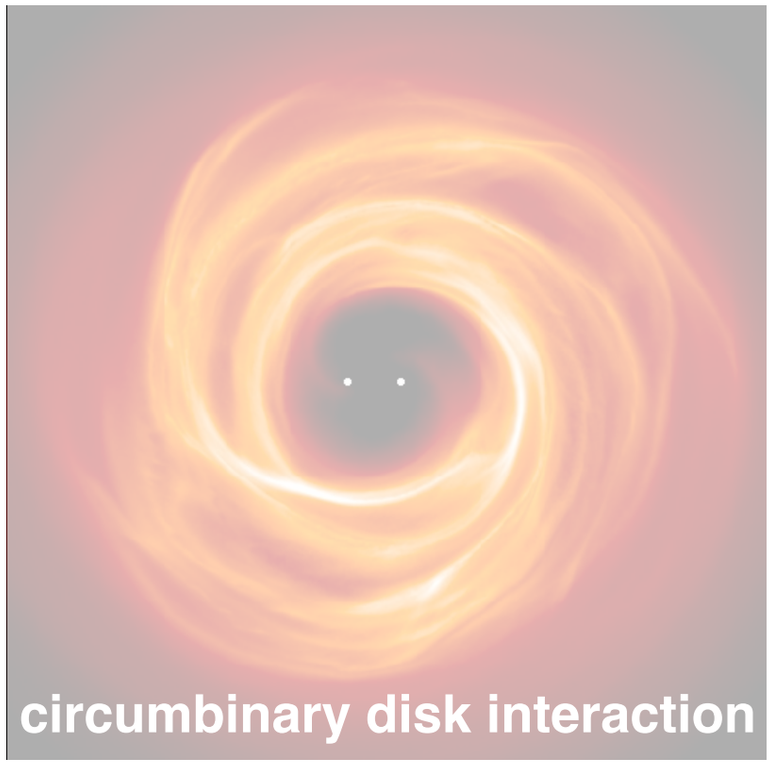
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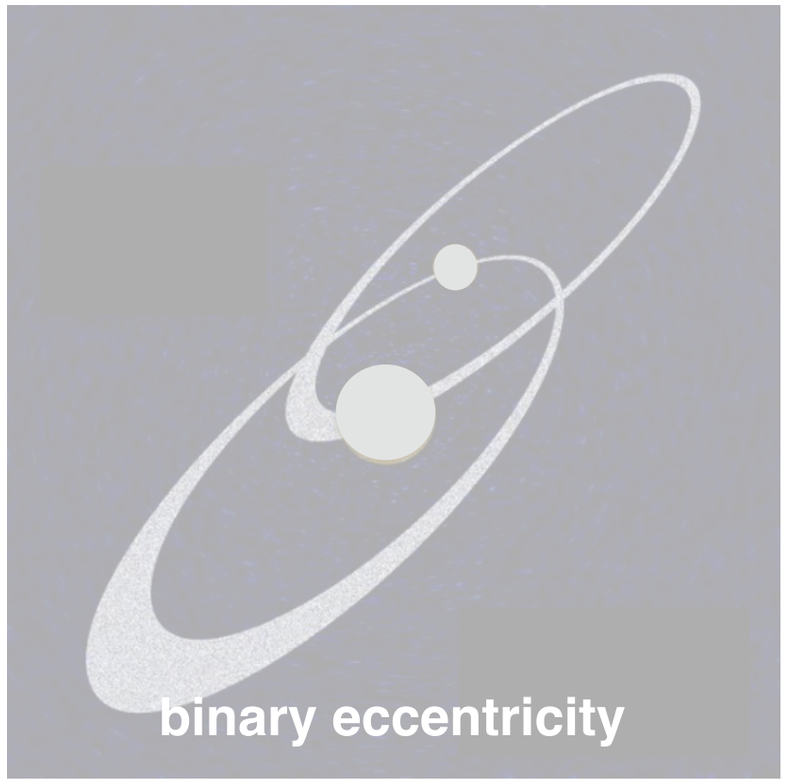
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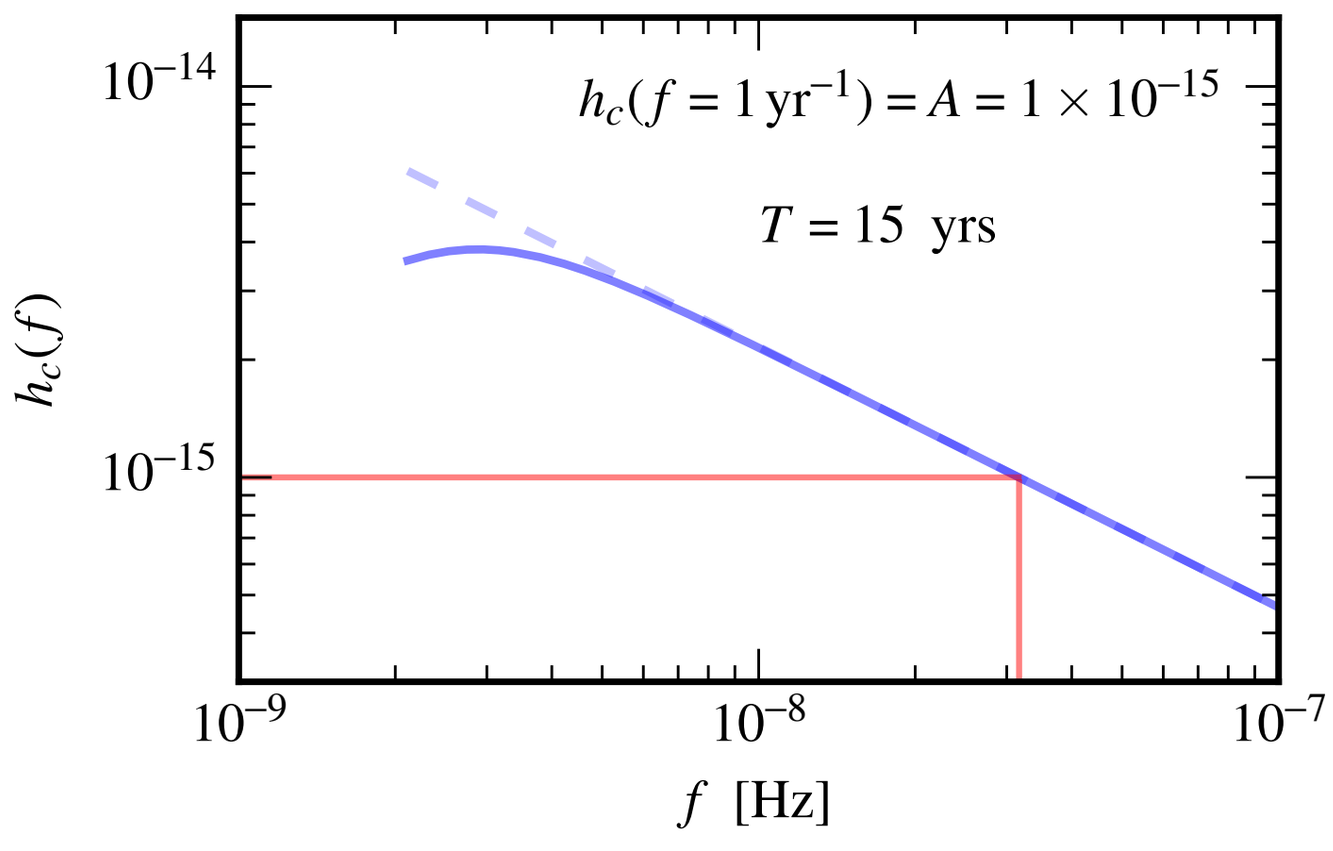
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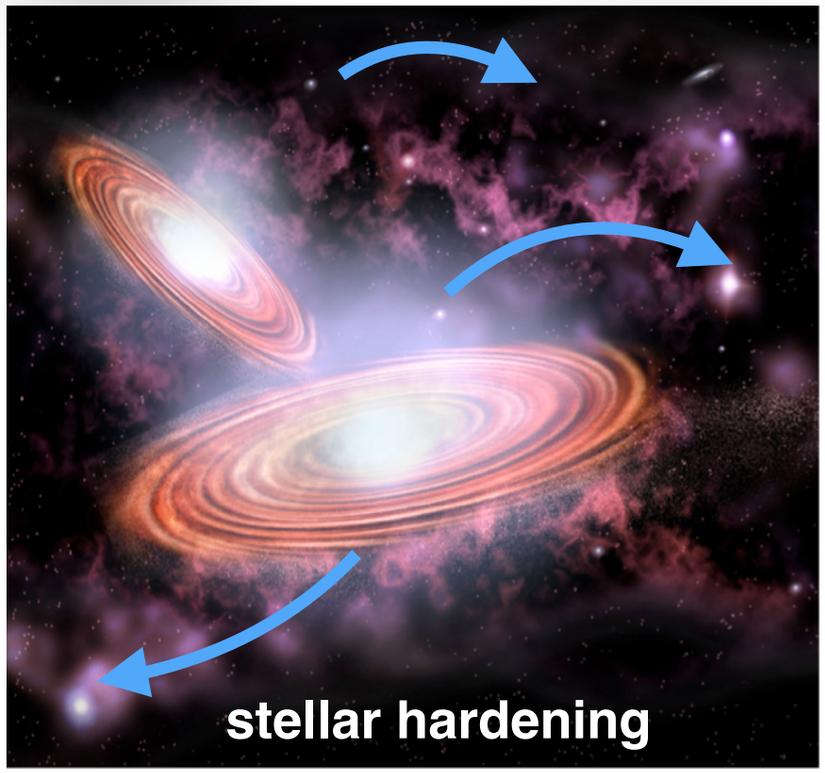
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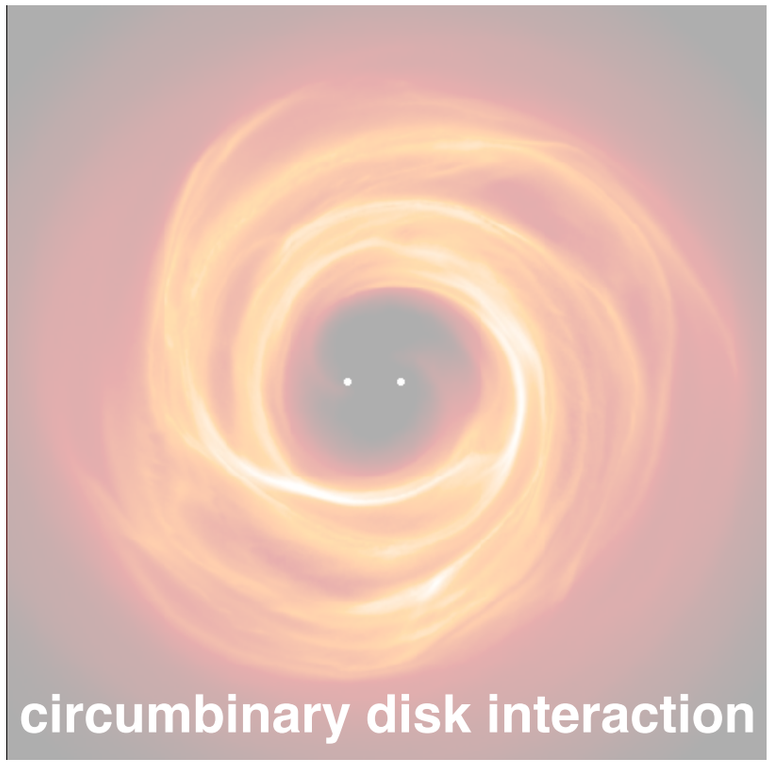
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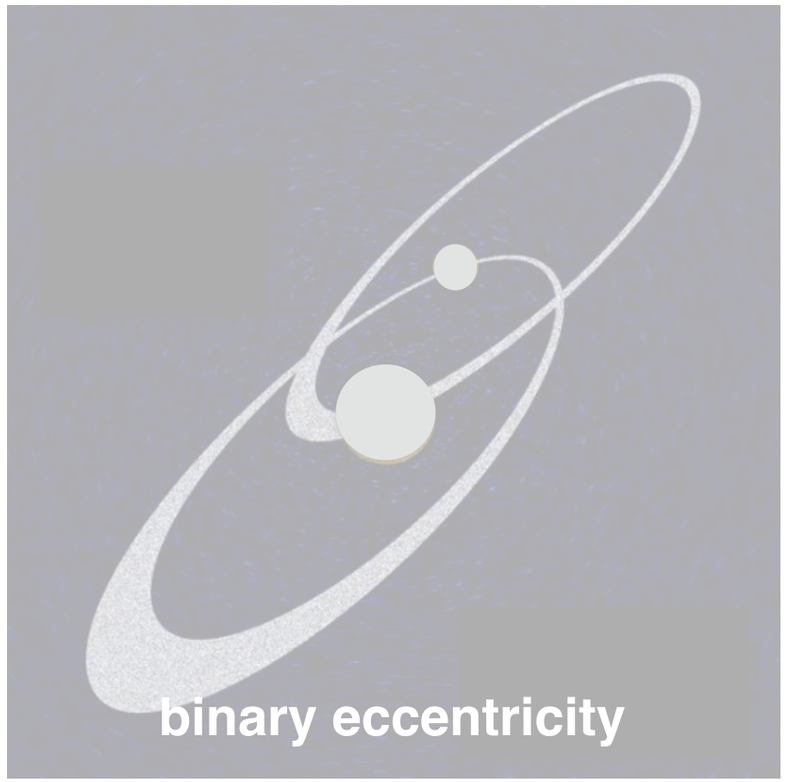
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$h_c(f)$
10^{-9}
10^{-8}
10^{-7}
f [Hz]

Probing Final-parsec Processes

$$\frac{dt}{d\ln f} = f\left[\sum_i \frac{df}{dt}\bigg|_i\right]$$

- Binary evolution will be dominated by environment at low frequencies, and radiation reaction at high frequencies

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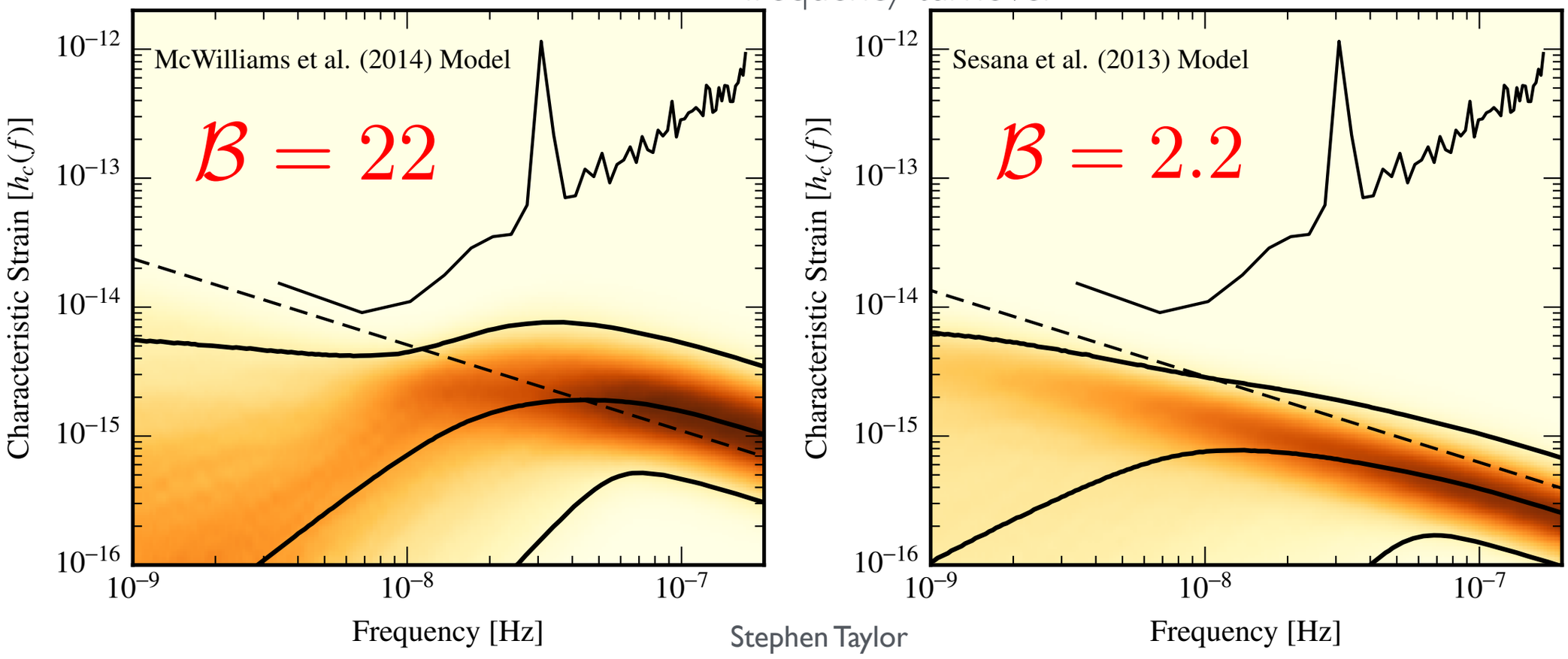

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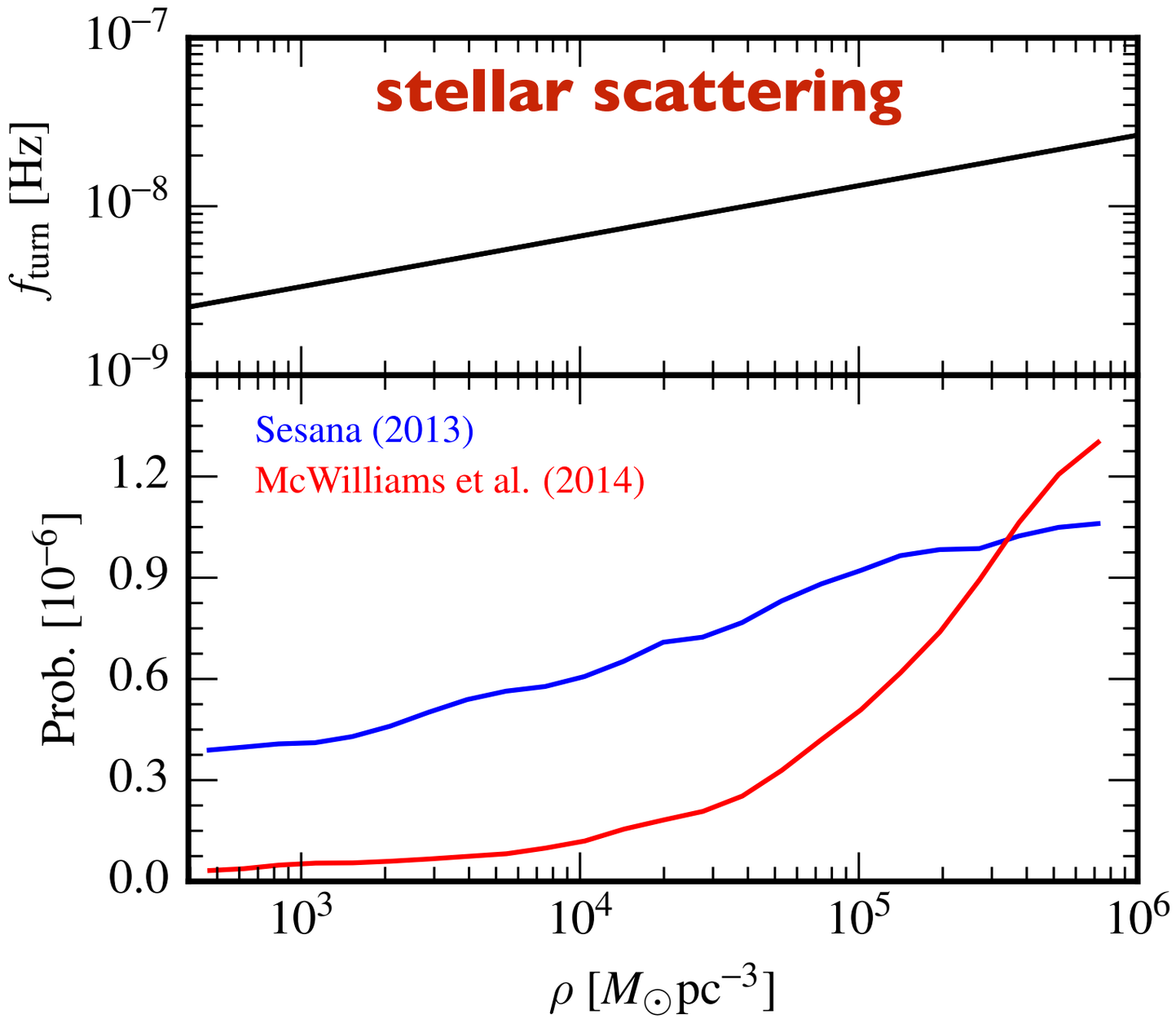

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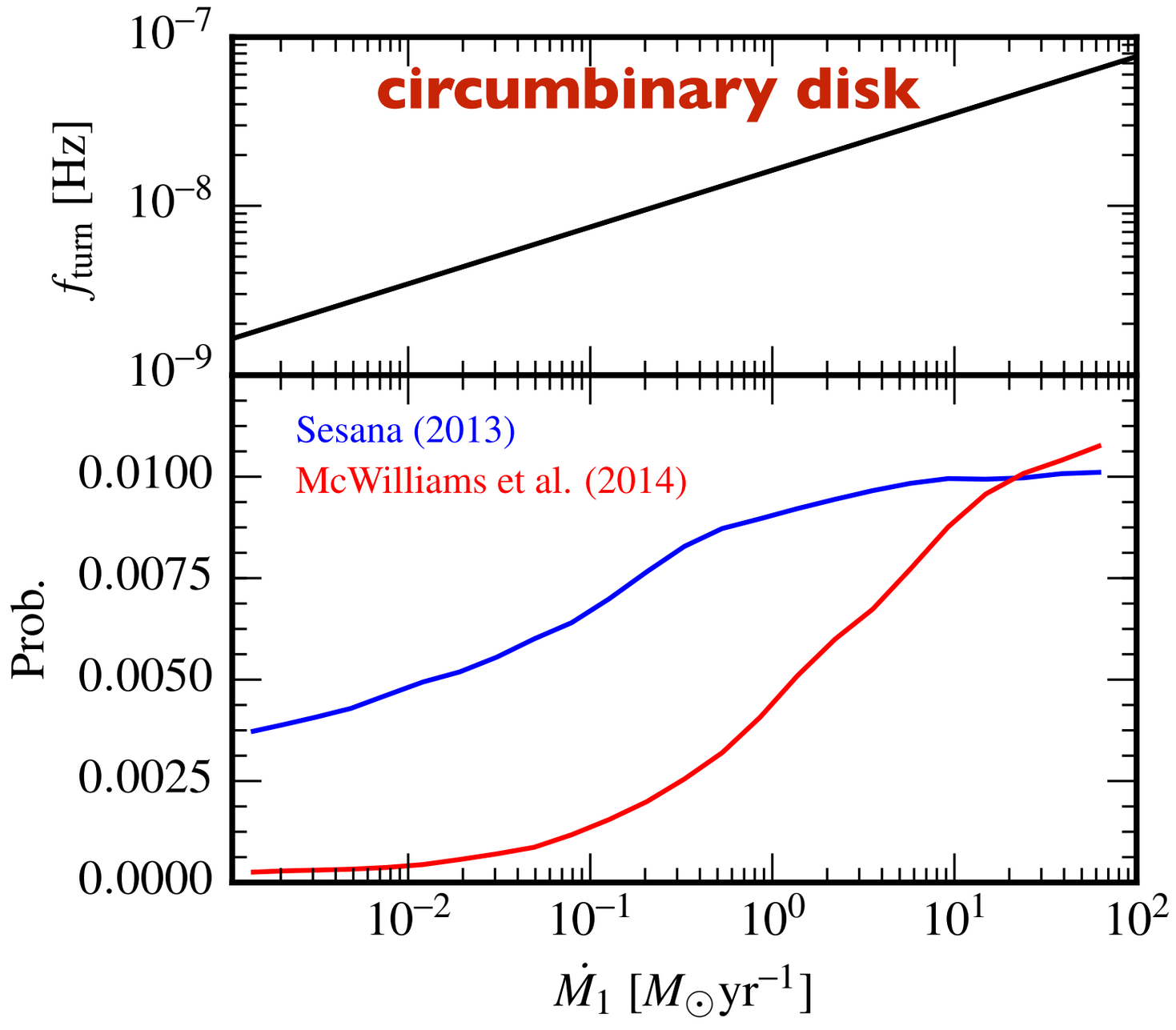

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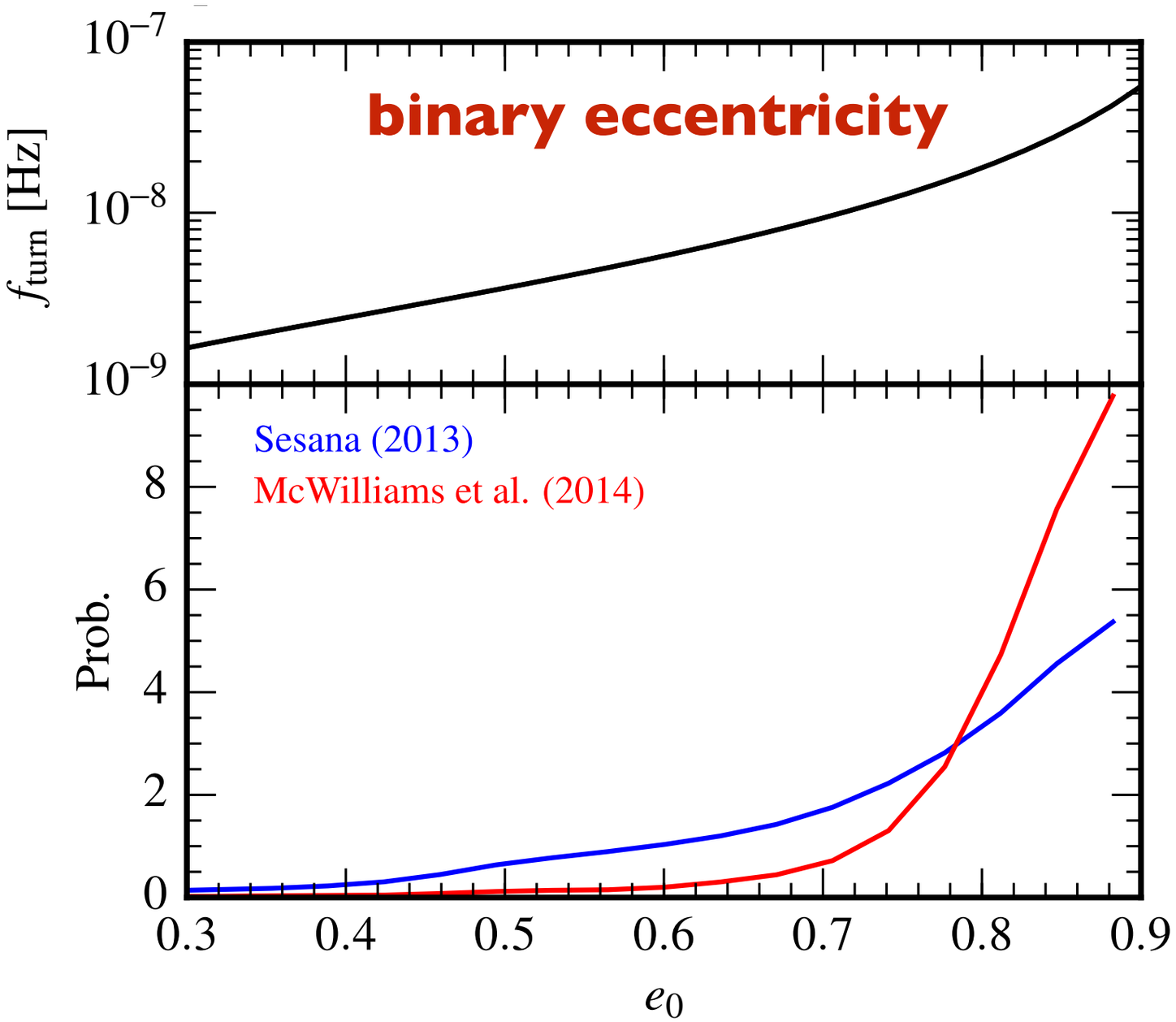
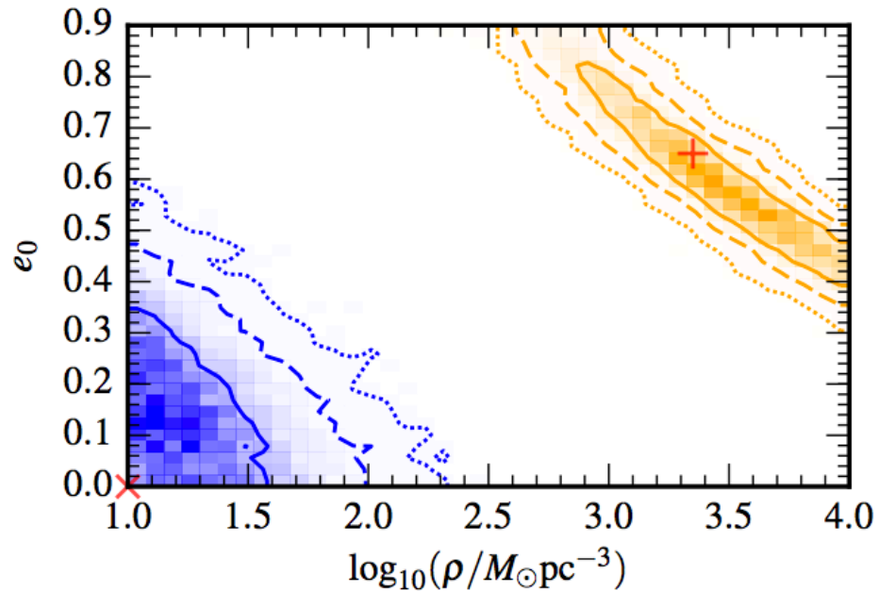


Latest techniques

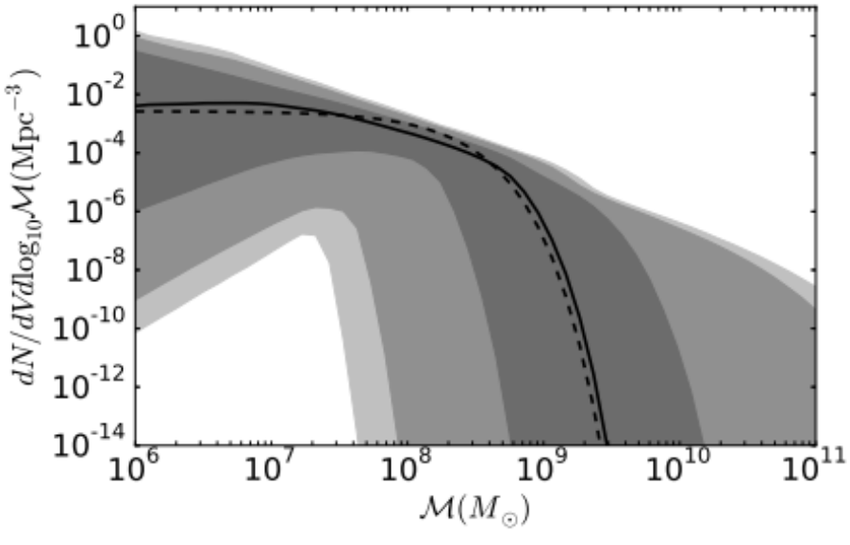
- Build a bank of spectral shapes from **population simulations** (including all physics).
- **Train a Gaussian Process to learn the spectral properties.**
- Provides a **fast physically-trained model**.
- Can be trivially expanded.

Taylor et al., PRL 118, 181102 (2017)

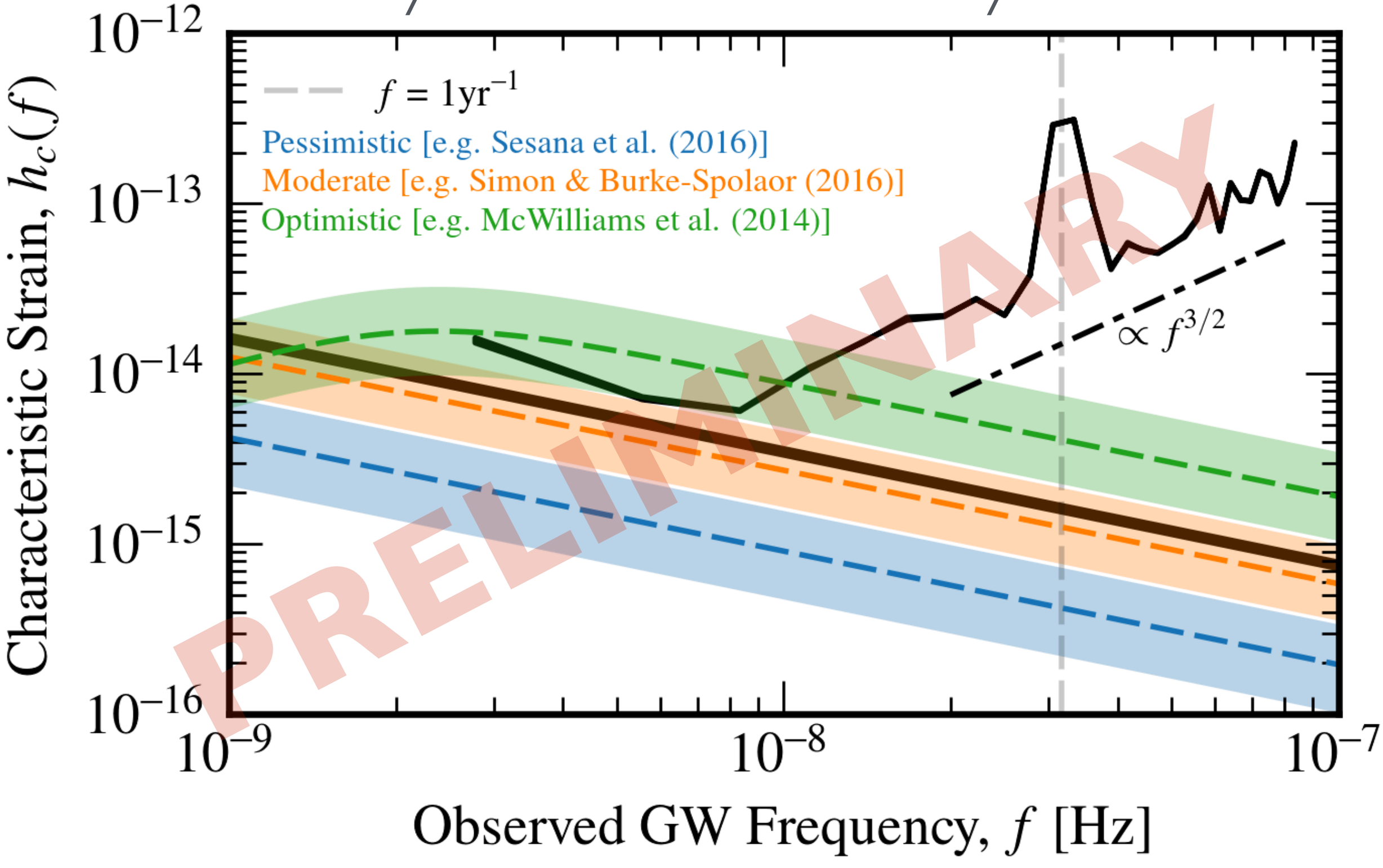


- Build a **semi-analytic model** to probe loss-cone scattering.
- Also expand merger-rate density with simplified prescription.

Chen et al., arXiv:1612.02826



Preliminary NANOGrav 11yr Results

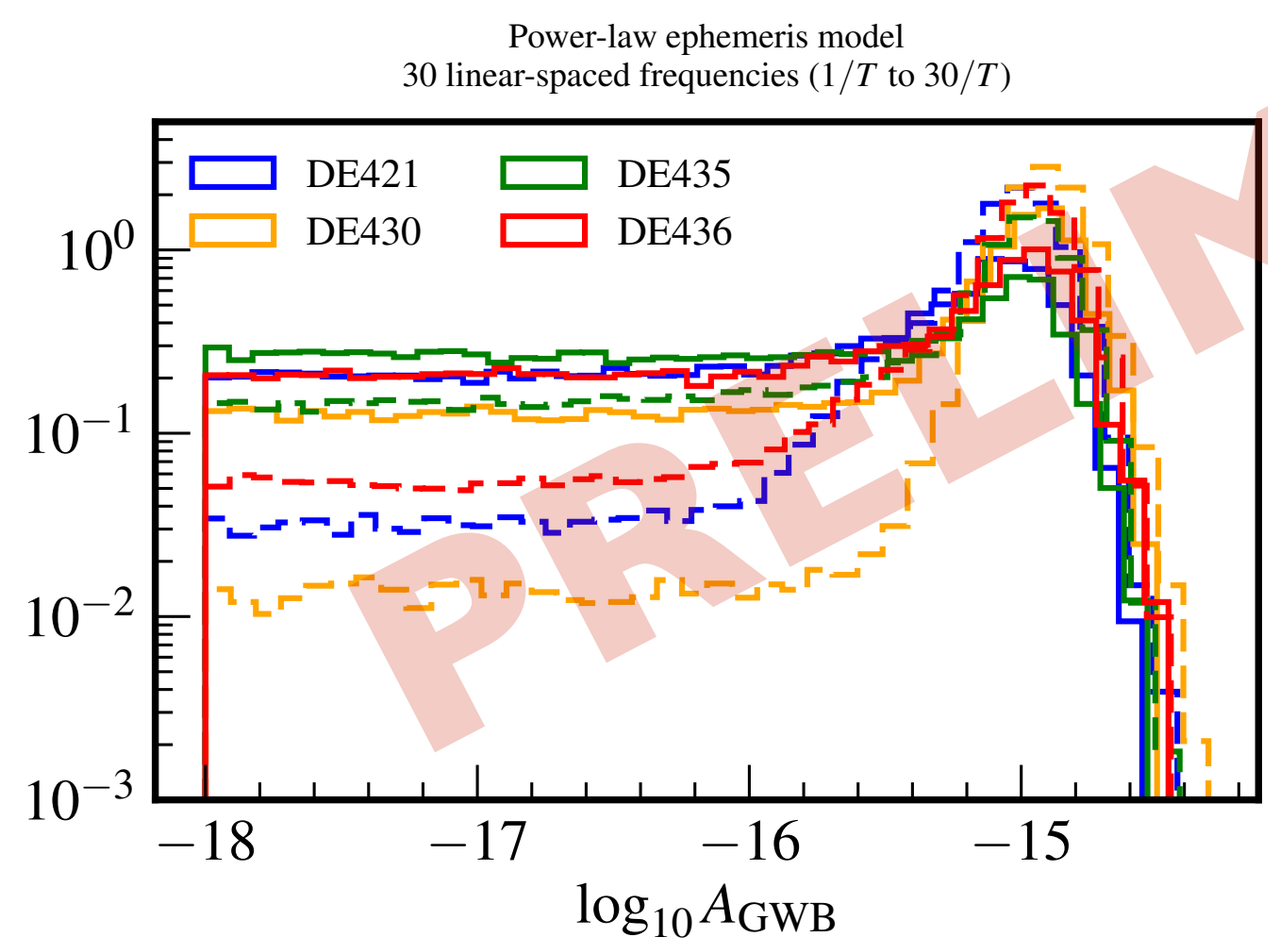


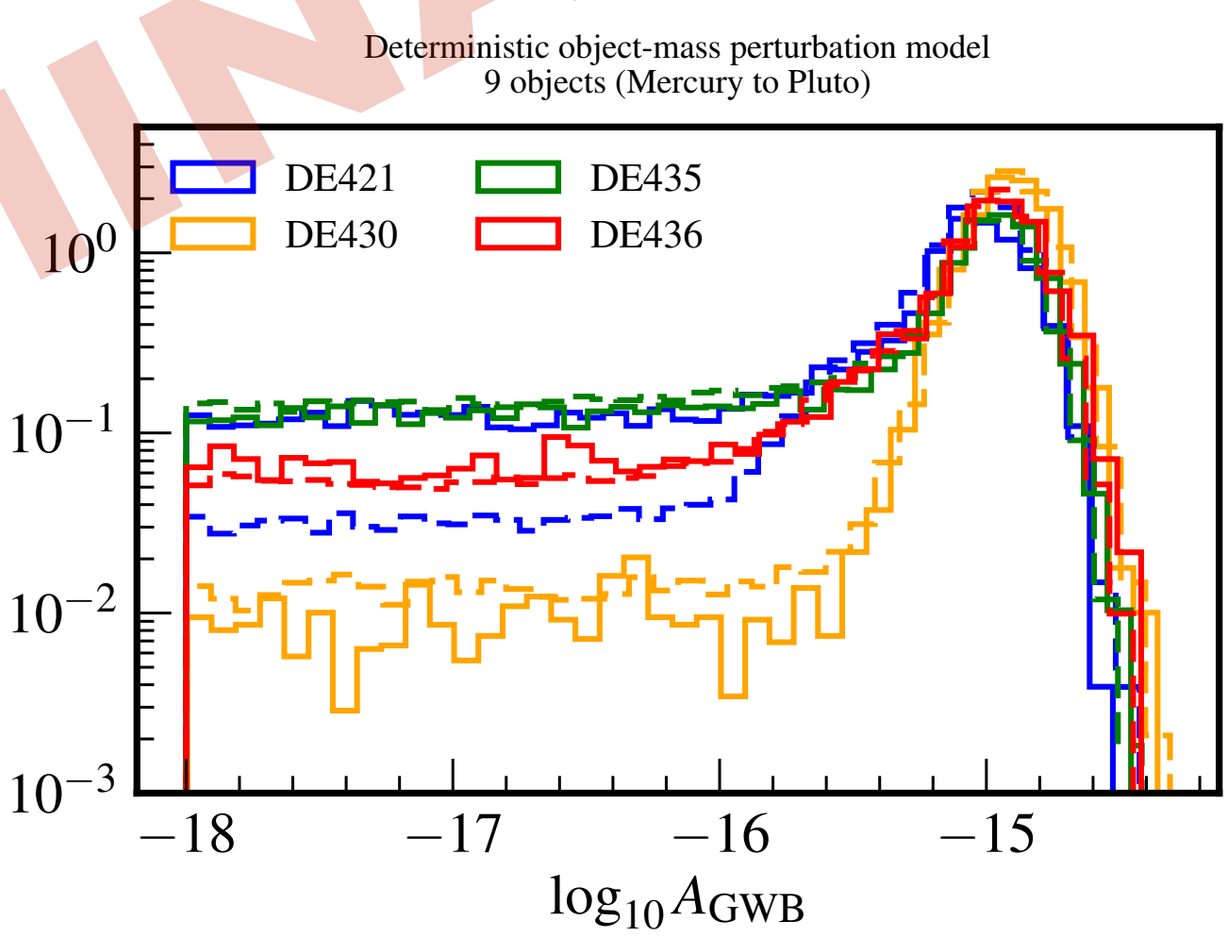
The Solar System Ephemeris

- All TOAs referenced to the SSB.
- Location of SSB requires the masses and trajectories of all objects in solar-system.
- JPL do not really care about the position of the SSB. *They care about navigating probes to planets.*
- The ephemeris time-series has not usually been fit for in our PTA analysis. It has been subtracted.

Preliminary NANOGrav 11yr Results

- Bayes factor for a common red process (i.e. leaving out H&D correlations) versus noise range from ~1 (DE435) to ~10 (DE430).
- It is **crucial to marginalize** over the difference in the ephemeris uncertainties for **robust GW statistics**.





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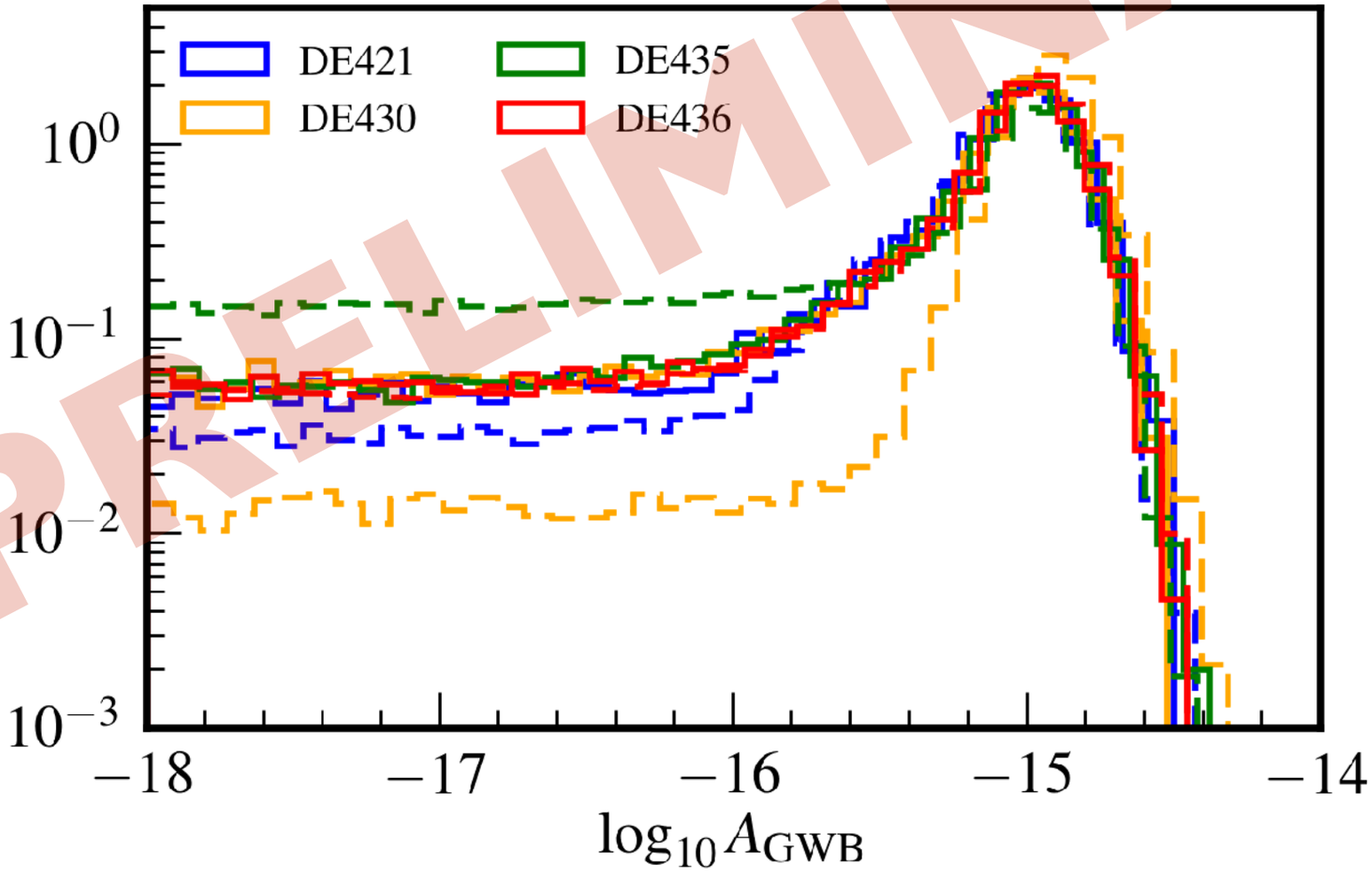
NANOGrav 11yr dataset – Roemer mixture model



Summary

- PTAs are expected to make a GW detection within ~5-10 years.
- The GW strain spectrum encodes information about SMBHB dynamical evolution.
- Constraining the spectral shape can tell us about disc accretion, and loss-scone scattering.
- PTAs are now sensitive to the solar-system ephemeris. A huge milestone for us!