Tides in double white dwarfs: prospects for multi-messenger astronomy

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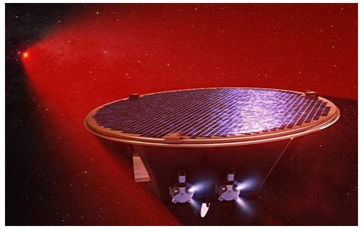
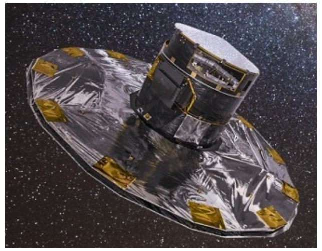
Why WD binaries?



(LISA; credit: AEI/MM/exozet)

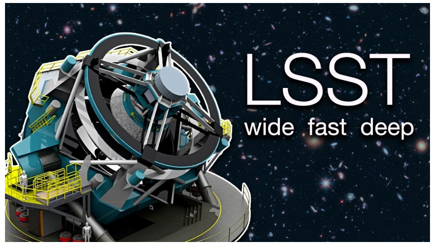
+



(Gaia; credit: ESA)

+ ZTF

+



- WD binaries are potential progenitors of type-Ia SNe (Maoz+ 14; exciting talks in this conf.;…)
- Promising sources for multi-messenger astronomy.
  - 10^4 - 10^5 by LISA/TianQin/etc in GW. (Cornish & Robson 17; Breivik+ 20; …)
  - ELM, ZTF, Gaia & LSST in optical. (Brown+ 20; Burdge+ 20; …)
  - In total, ~ 100 multi-messenger observations. (Korol+ 17; Korol+ 20; …)
- Synergy between GW & optical data. (Shah & Nelemans 14; Littenberg+ 19; Johnson+ 21; …)
- Tides (in detached binaries):
  - In GW:
    - *frequency evolution rate;*
    - *Orbital eccentricity*
  - In optical:
    - *pulsations in light curves.*

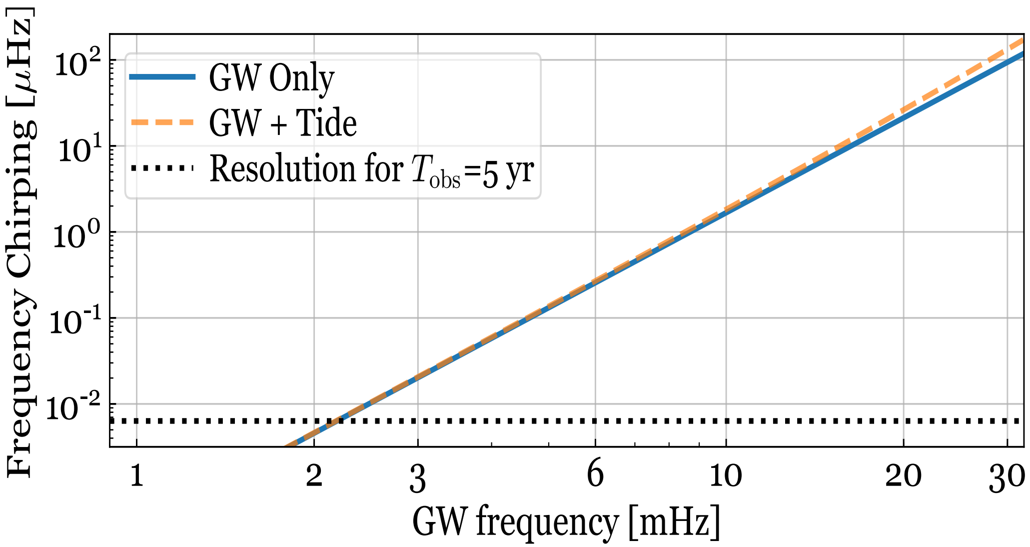
Table 4. Summary table for the number of detections with *Gaia*, LSST and LISA. We reported results for the nominal mission lifetime of 5 yr for *Gaia*, 10 yr for the LSST and 4 yr for LISA.

	Gaia	LSST	LISA
	(a) $\alpha\alpha$ CE model		
Gaia	189	93	13
LSST	93	1100	50
LISA	13	50	24 508
	(b) $\gamma\alpha$ CE model		
Gaia	246	155	25
LSST	155	1457	73
LISA	25	73	25 735

(Korol+ 17)

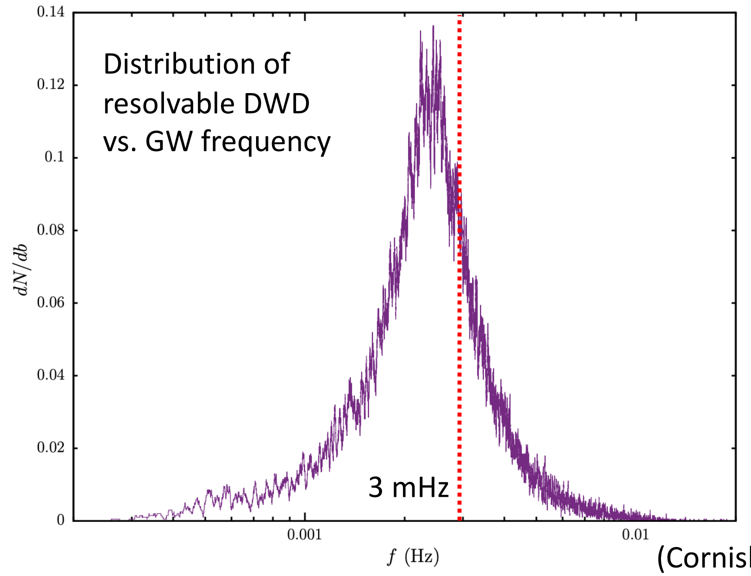
Q: what can we measure from the *orbital decay* over ~ O(1) year?

- E.g., $\dot{f}, \ddot{f}, \dddot{f}, \ldots$ to be measured by LISA in ***GW*** over a few years.
- Point-particle: $\dot{f} \propto \mathcal{M}_c^{5/3}$ → chirp mass
- How about $\ddot{f}, \dddot{f}, \ldots?$
- GW freq > 3 mHz: resolvable



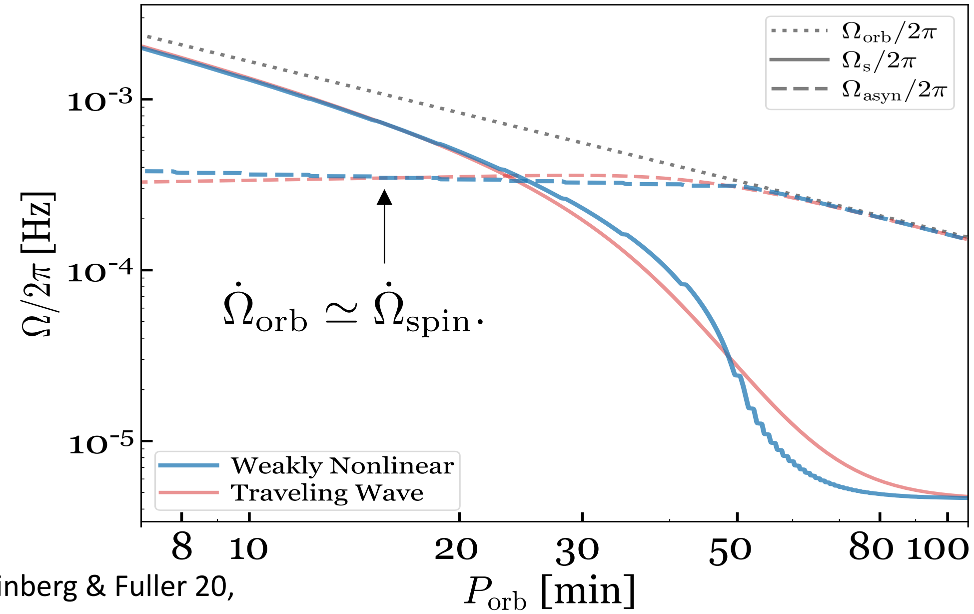
(Kuns, Yu, Adhikari & Chen 20)

Onset of Roche lobe overflow

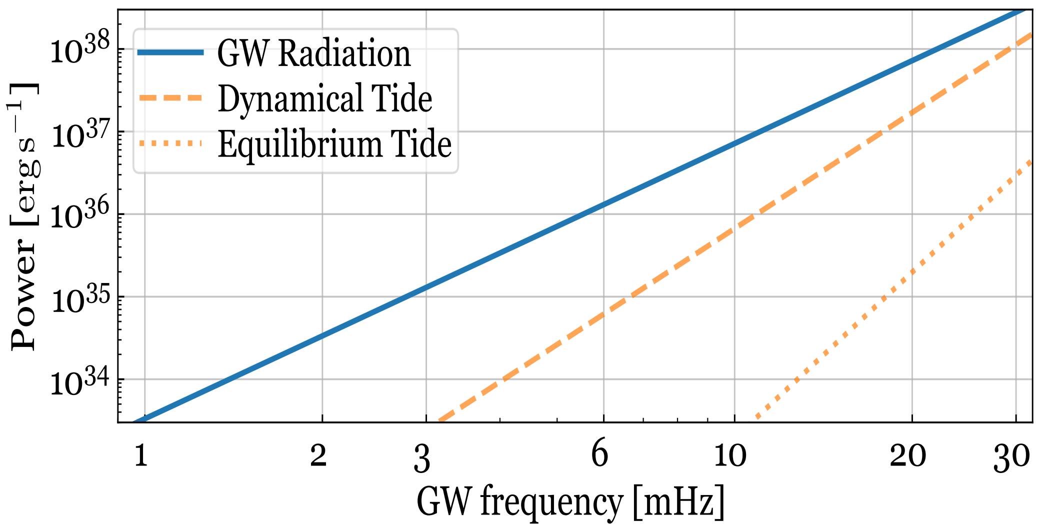


(Cornish & Robson 17)

Tidally accelerated orbital decay



(Yu, Weinberg & Fuller 20,
see also
Fuller & Lai 11, 12a, b, 13, 14, …;
Burkart+ 13; …)

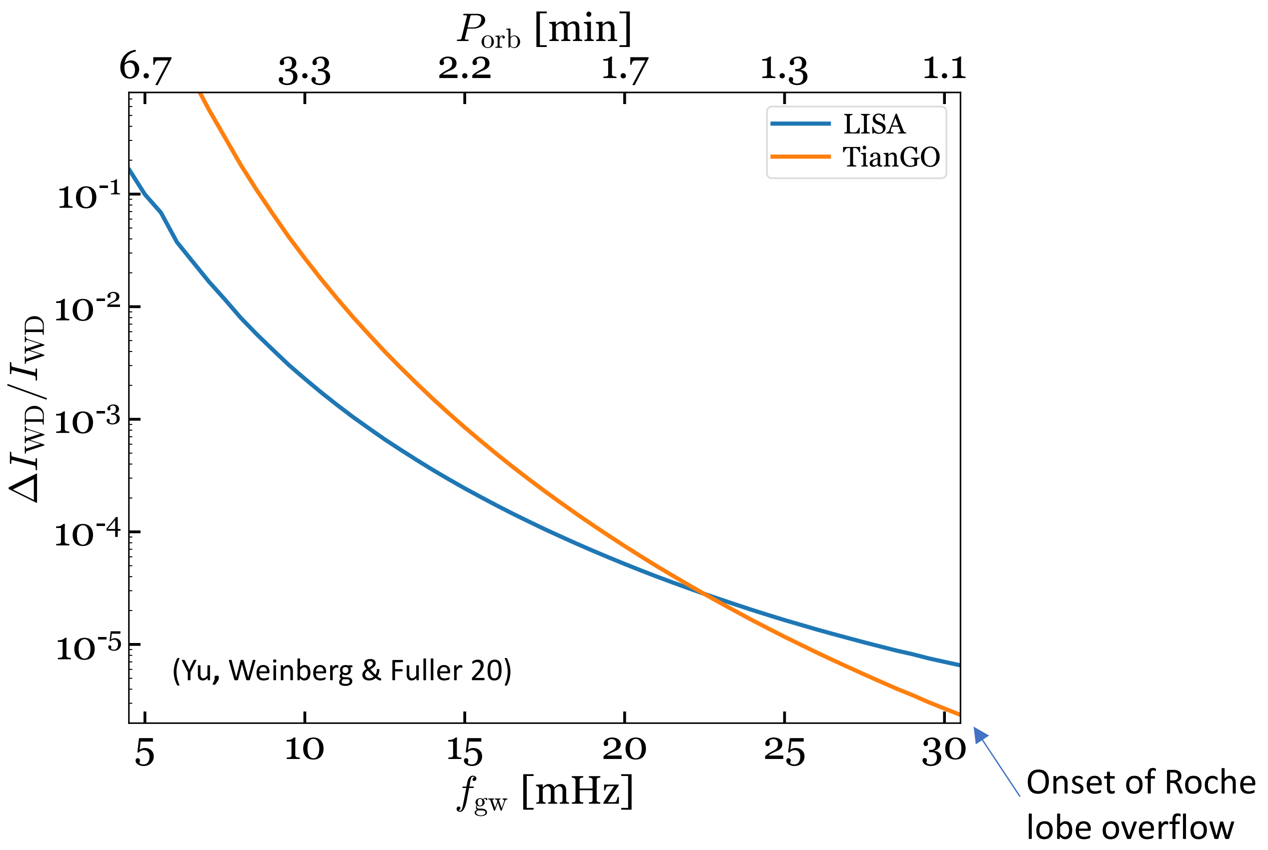


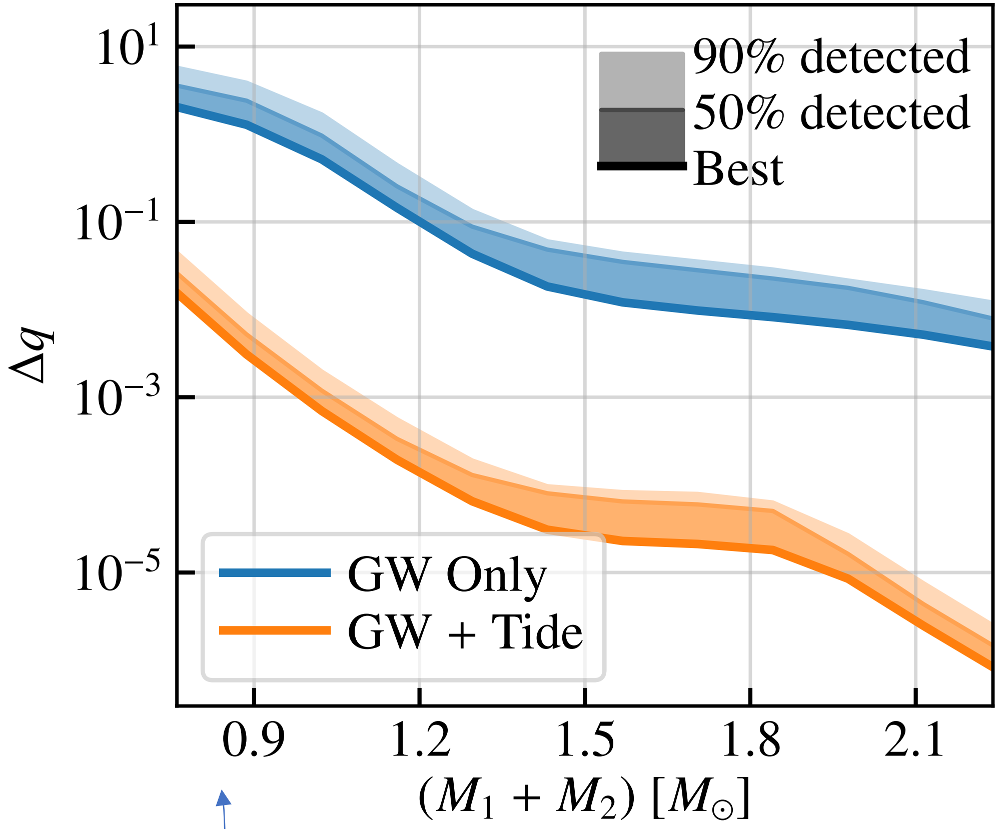
(Kuns, Yu, Adhikari & Chen 20)

- Synchronization P_orb <~ 1h
- $\dot{\Omega}_{orb} \simeq \dot{\Omega}_{spin}$.
- Orb E -> WD rotation E: accelerating orbital decay by ~10%
- Measuring I_{wd}

(see also Benacquista 11, Piro 19)

Tidally accelerated orbital decay





(Kuns, Yu, Adhikari & Chen 20; see also Wolz+ 21)

- Excess frequency evolution: moment of inertia
- $I_{wd} = I_{wd}(M)$ -> mass ratio of the system

Q: what can we measure from the *orbital equilibrium configuration*?

- Conservative interaction due to the (equilibrium) tide. Not from $\dot{f},\ \ddot{f},\ \dddot{f},\ \ldots$
- GW: orbital “eccentricity”
- Optical: tidally induced pulsation

Tides in GW signals

- Radial acceleration from the tide: modification to the Keplerian orbit.

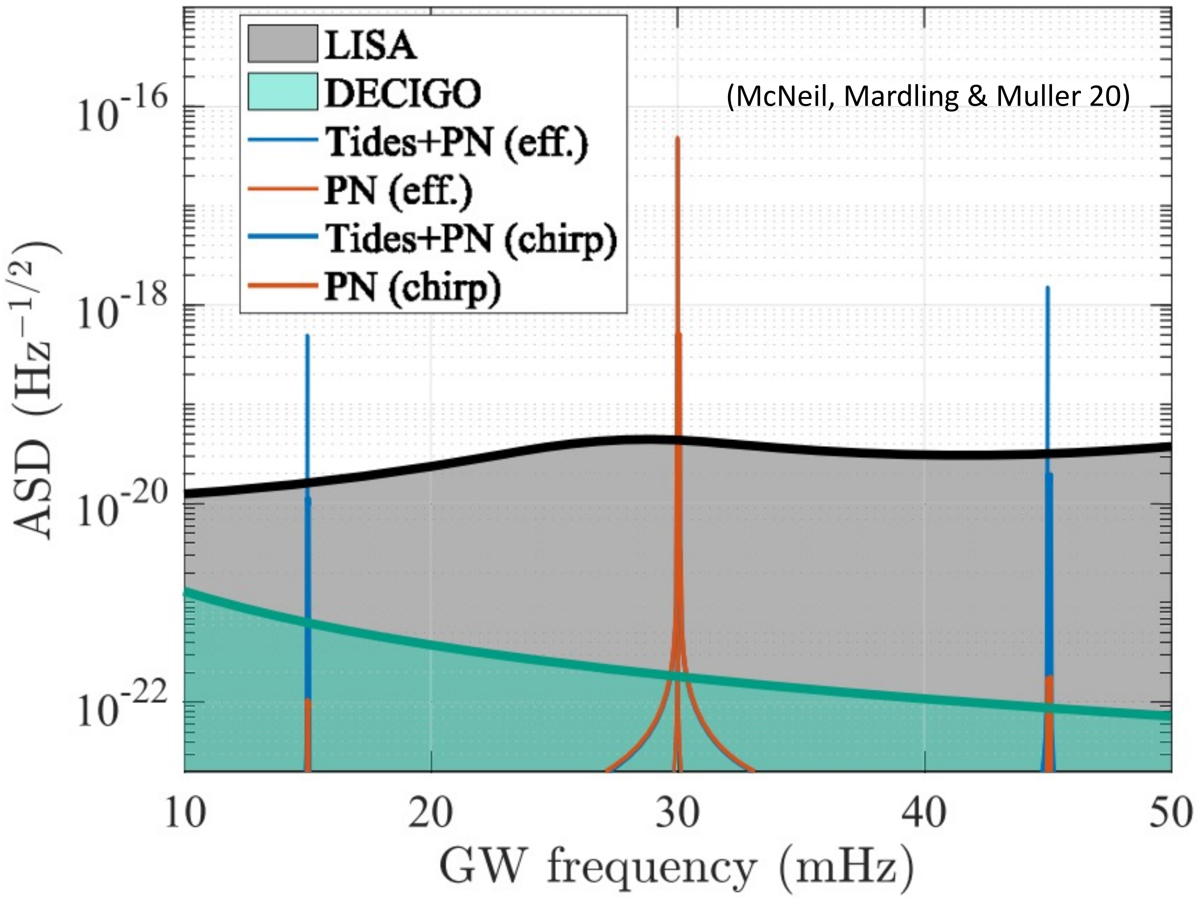
$$r^3 = \frac{GM_{\rm tot}}{\Omega^2} - \frac{r^2 g_r}{\Omega^2}$$

- Osculating orbit:

$$r^3 = \frac{GM_{\rm tot}}{\Omega^2}(1 + e\cos f)$$

- “Eccentricity” of the orbit
- Similar to tides in binary NSs
- Measure tidal deformability of a WD

$$\sim k_2 R^5$$

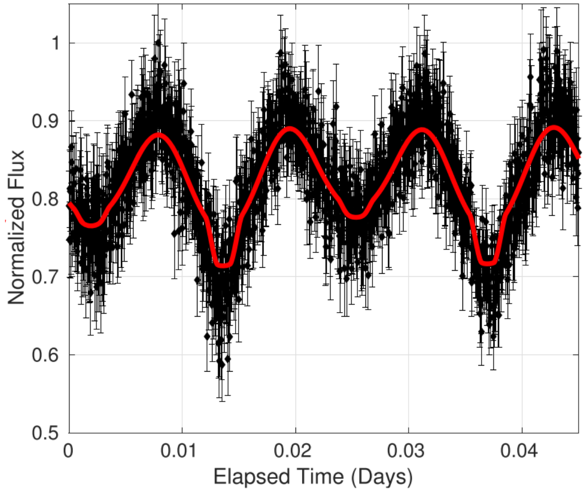


(Magnetic dipole-dipole interaction has similar effects but ~ 100x weaker; Bourgoin+ 22)

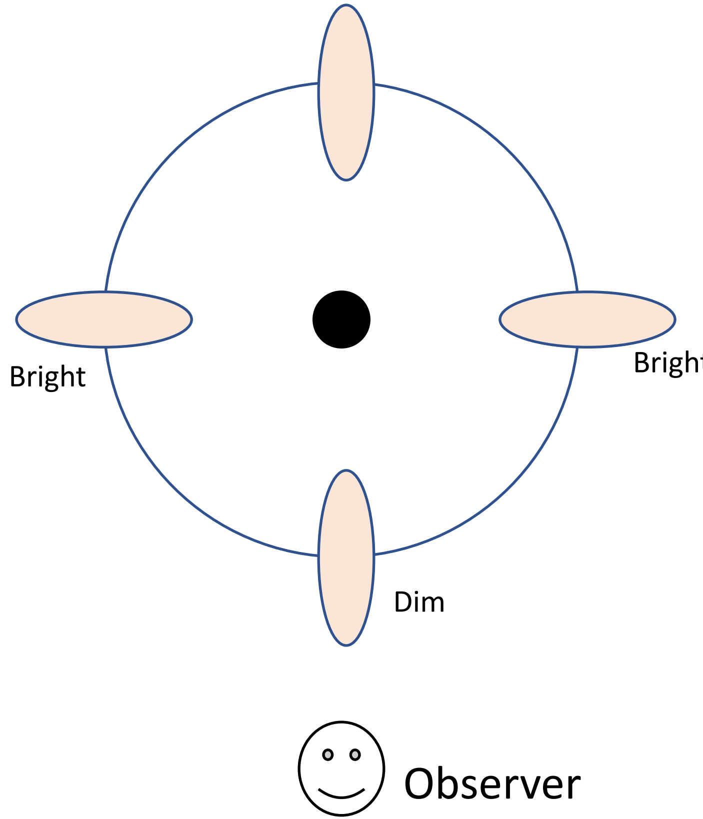
Tides in *optical* light curves

- Equilibrium tide (ellipsoidal variability):
- After removing eclipsing signal, residual brightness changes as the emitting area changes.
- Pulsating at 2f_orb, minimum when eclipsing.
- Mass ratio, etc.

$$\frac{\Delta F}{F} \sim \left(\frac{M_2}{M_1}\right)\left(\frac{R}{D}\right)^3$$



(Burdge+ 20)



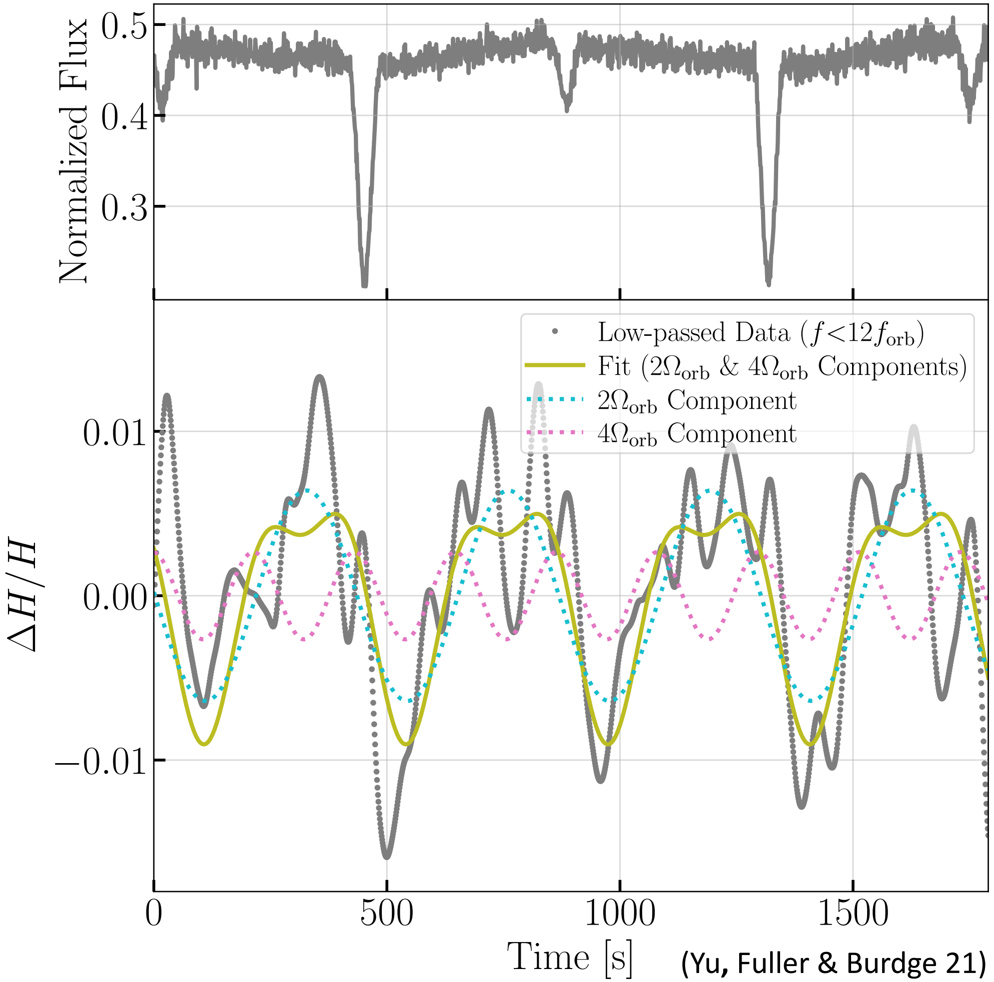
Tides in optical light curves

- Dynamical tide (also at 2f_orb):
- Non-ad perturbation to T instead of R

- If not accounted for, bias the mass ratio estimation from ellipsoidal variability.
- E.g. J0538 w/ inferred mass ratio q~ 5!

(Burdge+ 20)

- In fact, should be explained by the dynamical tide.
- Property of the atmosphere.

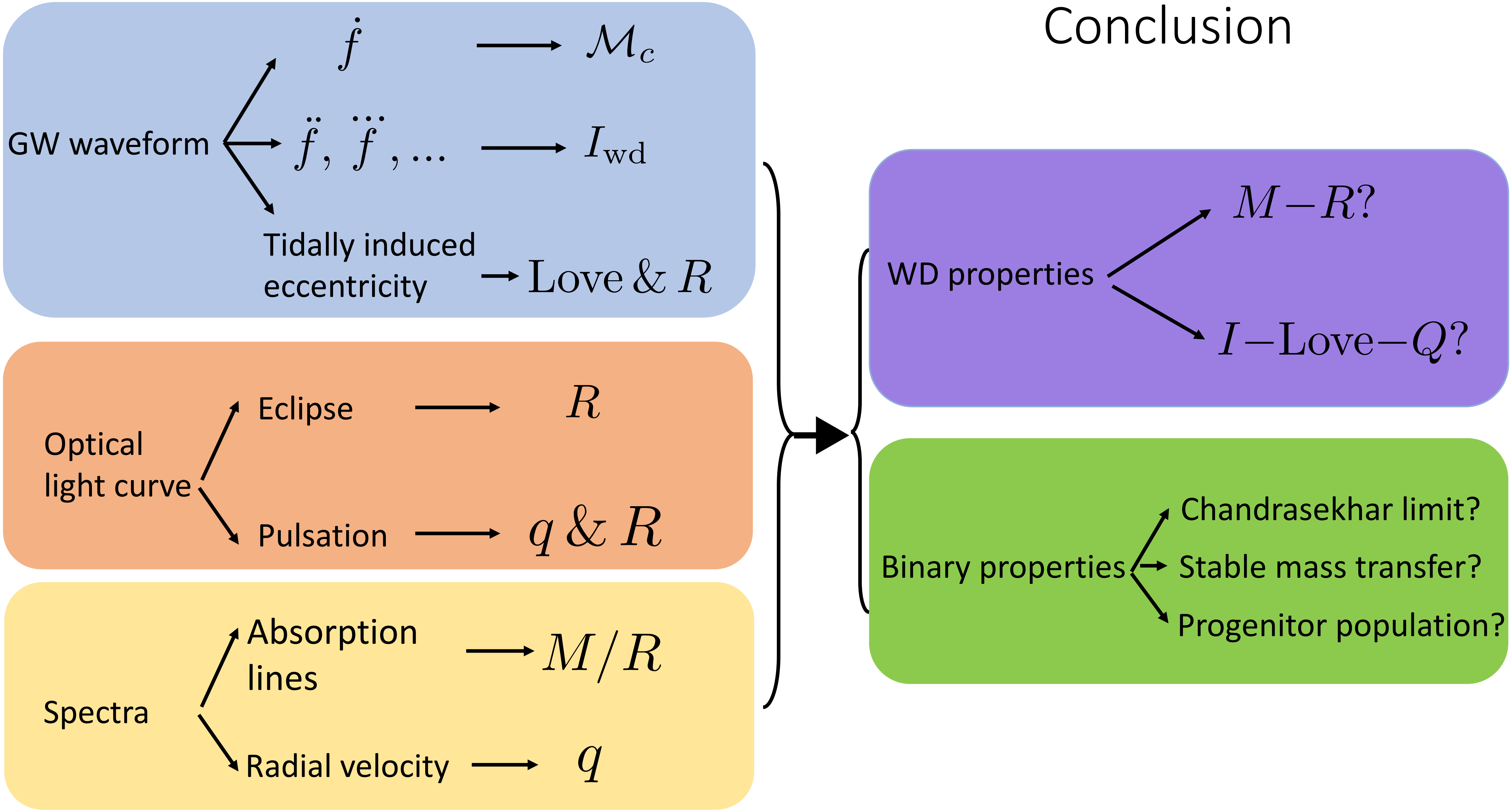


(Yu, Fuller & Burdge 21)

Full light curve.

Residual after removing eclipsing signal.

Conclusion



GW waveform
$\dot{f}$
$\mathcal{M}_c$
$\ddot{f}, \dddot{f}, \ldots$
$I_{\rm wd}$
Tidally induced eccentricity
Love & R
Optical light curve
Eclipse
R
Pulsation
q & R
Spectra
Absorption lines
M/R
Radial velocity
q
WD properties
$M - R$?
$I -$ Love $- Q$?
Binary properties
Chandrasekhar limit?
Stable mass transfer?
Progenitor population?

Thank you!

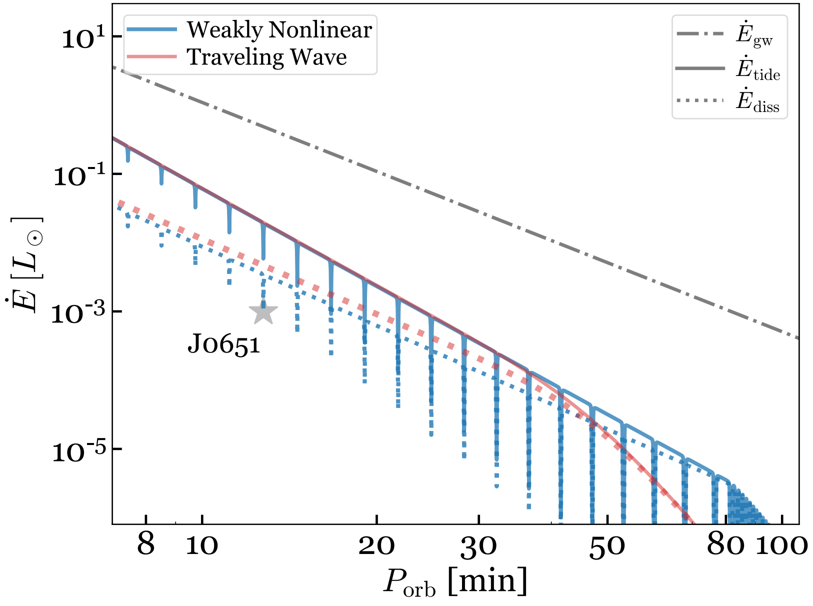
- Questions?
- Reach me at *hangyu@kitp.ucsb.edu* or *hang.yu2@montana.edu*.

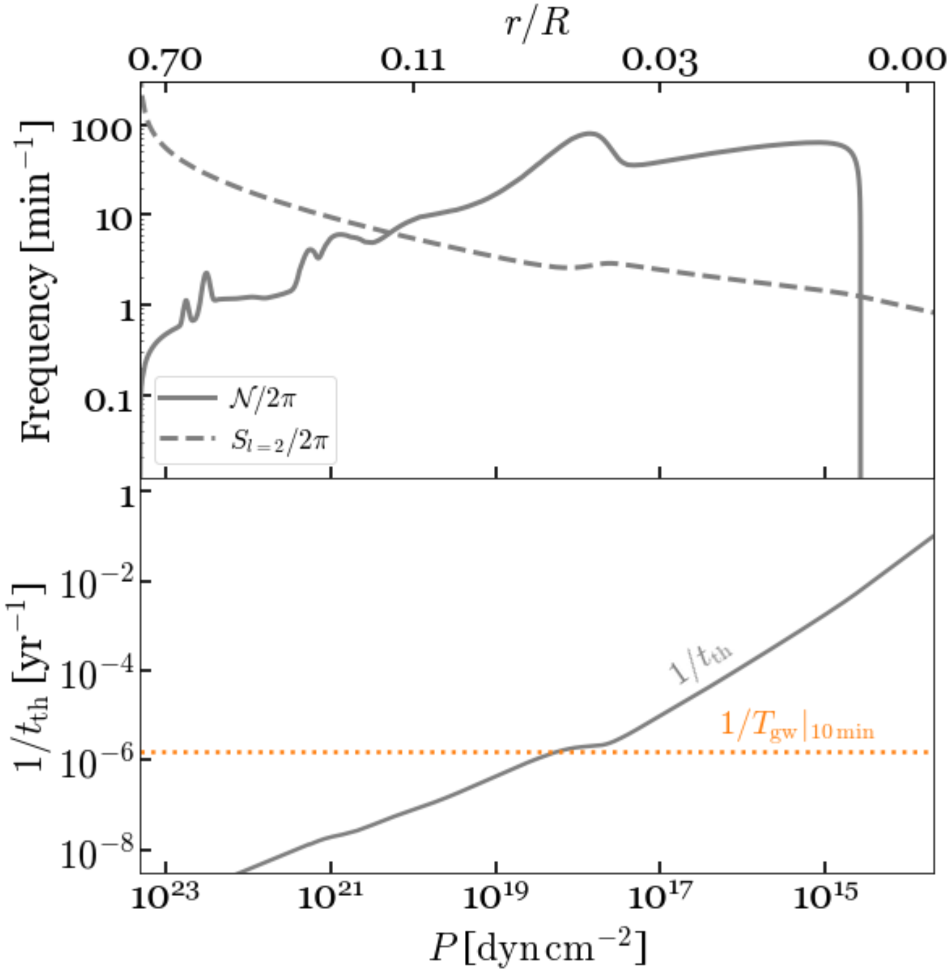
Tidal heating

- If sync:

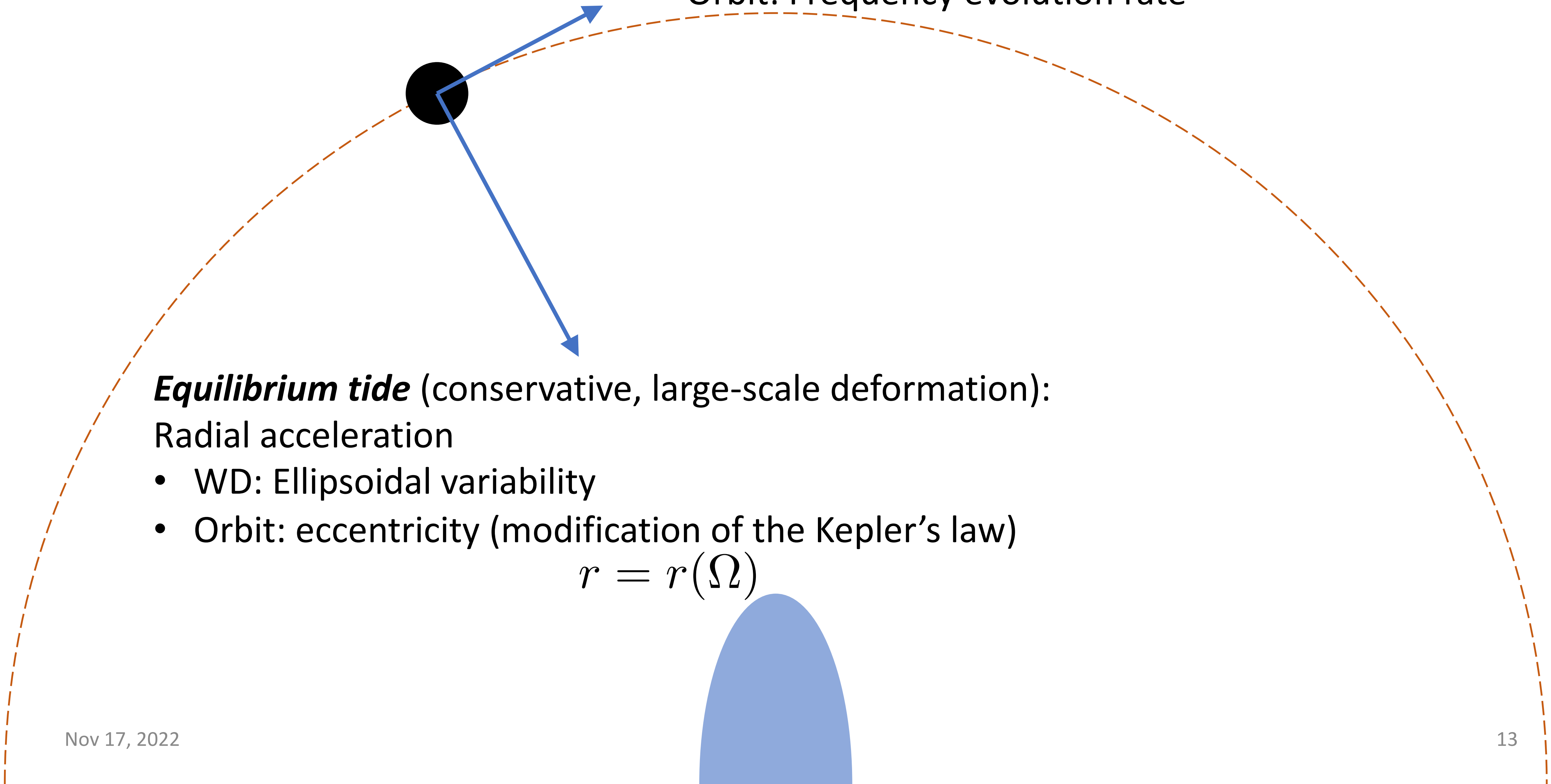
$$\dot{E}_{\rm diss} \simeq \frac{2\pi}{\Omega_{\rm orb} P_{\rm c}} \dot{E}_{\rm tide} \simeq \frac{2\pi}{P_{\rm c}} I_{\rm WD} \dot{\Omega}_{\rm orb,gw},$$

- No free knobs to tune???
- Dissipated near the surface, short diffusion timescale
- Why the CO WD in J0651 X10 dimmer than theory?





Dynamical tide (fluid dissipation):
Tangential acceleration (torque)
- WD: Tidal synchronization
- Orbit: Frequency evolution rate

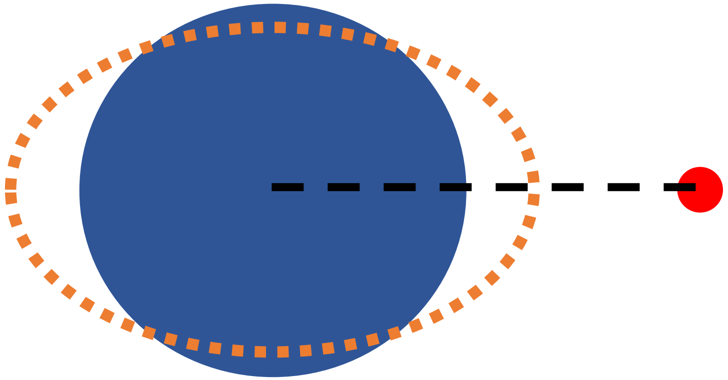


Equilibrium tide (conservative, large-scale deformation):
Radial acceleration
- WD: Ellipsoidal variability
- Orbit: eccentricity (modification of the Kepler's law)

$$r = r(\Omega)$$

Equilibrium vs. dynamical tides

- Equilibrium tide:



  - Fluid follows the equipotential of the companion.
  - Large-scale deformation of the star.
  - Conservative interaction
  - Dominant effect in BNSs.

(See, e.g., Flanagan & Hinderer 08)

- Dynamical tide:

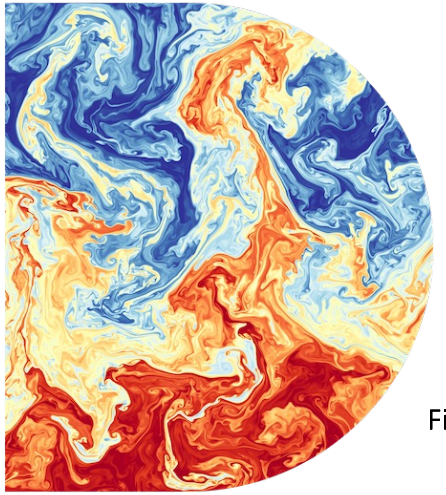


Fig. courtesy: K. Burns

  - Internal waves.
  - Supported by gravity/buoyancy.
  - Responsible for the tidal dissipation.
  - Important in BWDs!

(Fuller & Lai 11, 12a, b, 13, 14; Burkart+ 13; **Yu**, Weinberg & Fuller 20)