Title: Nonlinear dynamical tides in white dwarf binaries

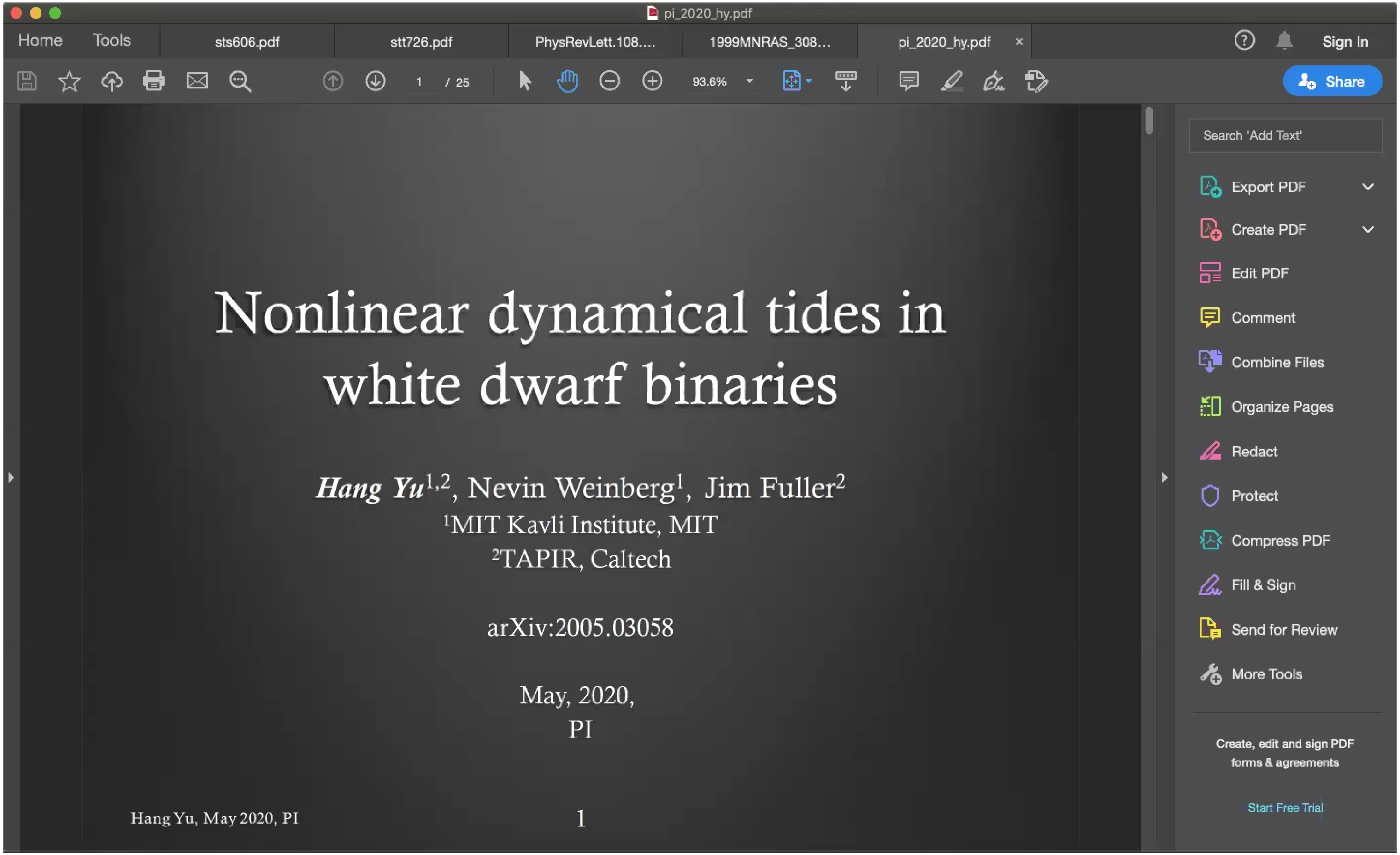
Speakers: Hang Yu

Series: Strong Gravity

Date: May 28, 2020 - 1:00 PM

URL: http://pirsa.org/20050024

Abstract: Compact white dwarf (WD) binaries are important sources for space-based gravitational-wave (GW) observatories, and an increasing number of them are being identified by surveys like ELM and ZTF. We study the effects of nonlinear dynamical tides in such binaries. We focus on the global three-mode parametric instability and show that it has a much lower threshold energy than the local wave-breaking condition studied previously. By integrating networks of coupled modes, we calculate the tidal dissipation rate as a function of orbital period. We construct phenomenological models that match these numerical results and use them to evaluate the spin and luminosity evolution of a WD binary. While in linear theory the WD's spin frequency can lock to the orbital frequency, we find that such a lock cannot be maintained when nonlinear effects are taken into account. Instead, as the orbit decays, the spin and orbit go in and out of synchronization. Each time they go out of synchronization, there is a brief but significant dip in the tidal heating rate. While most WDs in compact binaries should have luminosities that are similar to previous traveling-wave estimates, a few percent should be about ten times dimmer because they reside in heating rate dips. This offers a potential explanation for the low luminosity of the CO WD in J0651. Lastly, we consider the impact of tides on the GW signal and show that LISA and TianGO can constrain the WD's moment of inertia to better than 1% for centi-Hz systems.


Nonlinear dynamical tides in white dwarf binaries
Hang Yu[1,2], Nevin Weinberg[1], Jim Fuller[2]
[1]MIT Kavli Institute, MIT
[2]TAPIR, Caltech
arXiv:2005.03058
May, 2020,
PI
Hang Yu, May 2020, PI
1

OUTLINE

- Introduction.
    - Motivations; previous studies on the problem.
- Local wave-breaking vs. global parametric instabilities.
- Nonlinear tidal energy dissipation.
- Tidal synchronization and heating.
- Observational signatures in EM radiation and GWs.

MOTIVATIONS

THE ASTROPHYSICAL JOURNAL LETTERS, 737:L23 (6pp), 2011 August 10 doi:10.1088/2041-8205/737/1/L23

A 12 MINUTE ORBITAL PERIOD DETACHED WHITE DWARF ECLIPSING BINARY*

WARREN R. BROWN[1], MUKREMIN KILIC[1,5], J. J. HERMES[2], CARLOS ALLENDE PRIETO[3,4], SCOTT J. KENYON[1], AND D. E. WINGET[2]
[1] Smithsonian Astrophysical Observatory, Cambridge, MA 02138, USA;
wbrown@cfa.harvard.edu, mkilic@cfa.harvard.edu, skenyon@cfa.harvard.edu
[2] Department of Astronomy, University of Texas at Austin, RLM 16.236, Austin, TX 78712, USA;
jjhermes@astro.as.utexas.edu, dew@astro.as.utexas.edu
[3] Instituto de Astrofísica de Canarias, E-38205, La Laguna, Tenerife, Spain; callende@iac.es
[4] Departamento de Astrofísica, Universidad de La Laguna, E-38205 La Laguna, Tenerife, Spain
Received 2011 June 15; accepted 2011 July 1; published 2011 July 25

- WD binaries are ubiquitous.
  - $\sim 10^8$ WD binaries in the Galaxy. (Nelemans+ 01)
- Important sources for future low-frequency GW observatories like LISA and/or TianGO.
  - $\sim 10^7$ in LISA's band; $\sim 10^3$ individually resolvable.
- Progenitors of type Ia SNe, AM CVn stars, …
- More and more such systems are being discovered by surveys like the ELM & ZTF.
- Tidal interactions are significant in such systems.
  - Spins up the WD.
  - Tidal heating.

(Fuller & Lai 11, 12a, 12b, 13, 14; Burkart+ 13)

LETTER

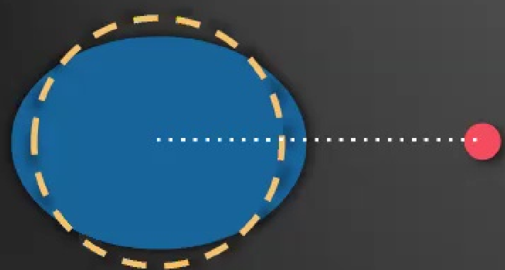
https://doi.org/10.1038/s41586-019-1403-0

General relativistic orbital decay in a seven-minute-orbital-period eclipsing binary system

Kevin B. Burdge[1*], Michael W. Coughlin[1], Jim Fuller[1], Thomas Kupfer[2], Eric C. Bellm[3], Lars Bildsten[2,4], Matthew J. Graham[1], David L. Kaplan[5], Jan van Roestel[1], Richard G. Dekany[6], Dmitry A. Duev[1], Michael Feeney[6], Matteo Giomi[7], George Helou[8], Stephen Kaye[6], Russ R. Laher[8], Ashish A. Mahabal[1], Frank J. Masci[8], Reed Riddle[6], David L. Shupe[8], Maayane T. Soumagnac[9], Roger M. Smith[6], Paula Szkody[3], Richard Walters[6], S. R. Kulkarni[1] & Thomas A. Prince[1]

LINEAR TIDE

- Equilibrium tide:



  - Fluid follows the equipotential of the companion.
  - Large-scale deformation of the star.

- Dynamical tide:

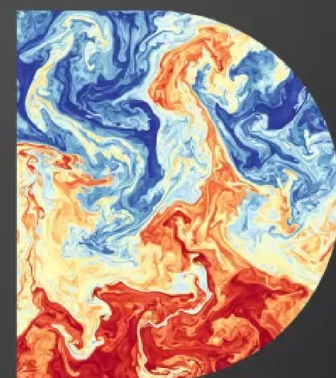


Fig. courtesy: K. Burns

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

LINEAR TIDES

- Equation of motion:

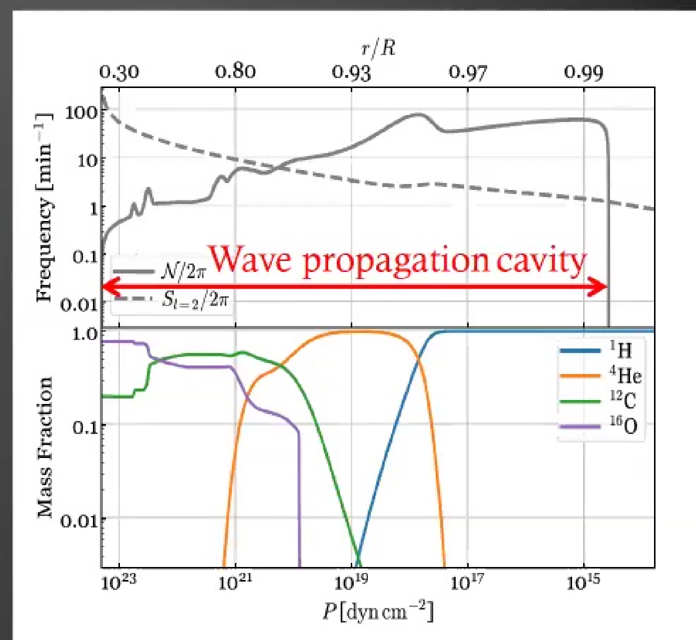
$$\rho\ddot{\xi} = \mathbf{f}_1[\xi] + \rho\mathbf{a}_{\rm tide},$$

Fluid acceleration. — Internal restoring force. — External drive.

- If small amp & weakly damped:
  - Wave reflects at the boundary -> standing waves.
  - Orthonormal set of eigenmodes.

$$\begin{bmatrix}\xi(\mathbf{r},t)\\ \dot{\xi}(\mathbf{r},t)\end{bmatrix} = \sum q_a(t)\begin{bmatrix}\xi_a(\mathbf{r})\\ -i\omega_a\xi_a(\mathbf{r})\end{bmatrix}$$

(Schenk+ 02)

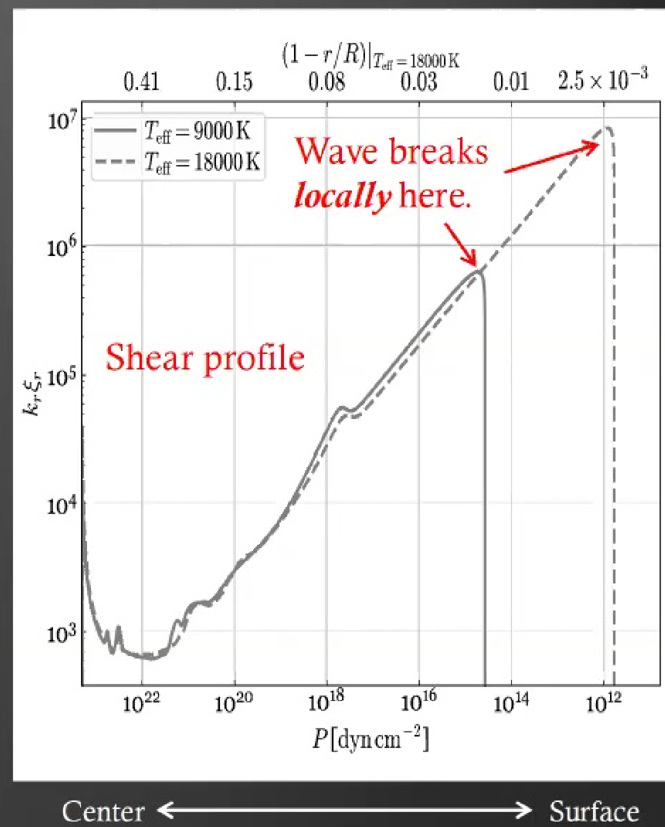


Center ⟷ Surface

(0.6 M_sun CO WD)

- Fuller & Lai:
  - modes' amplitudes too high.
  - Shear>1 -> perturbed fluid overturns the background stratification.
  - Waves break due to *local* nonlinear effects.
  - Traveling wave instead!

- Burkart et al. (2013):
  - Still using the mode expansion.
  - Wave-breaking for resonant peaks.
  - Damping term: 1/group-traveling time.



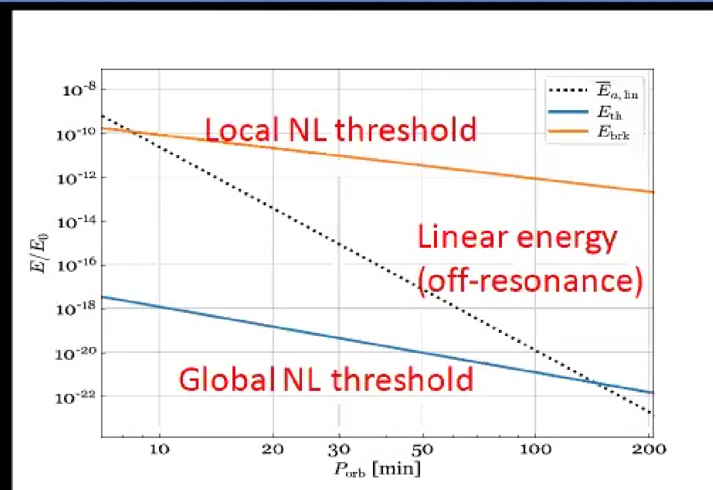
Hang Yu, May 2020, PI

Strongly nonlinear	Weakly nonlinear	Linear
Fuller & Lai 12a, b, 13, 14...	This work!	Fuller & Lai 11, Burkart et al. 13, ...
Gravity waves break at the outer boundary; One-way traveling wave.	Nonlinearly coupled mode network.	Gravity waves reflect at the boundaries; Discrete standing waves (eigenmodes).
P_orb < 10 min	10 min < P_orb < 150 min	P_orb > 150 min

- Key difference:
When do the waves become nonlinear?

- Previous studies: local criterion.
Shear > 1 => overturns buoyancy => local wave-breaking

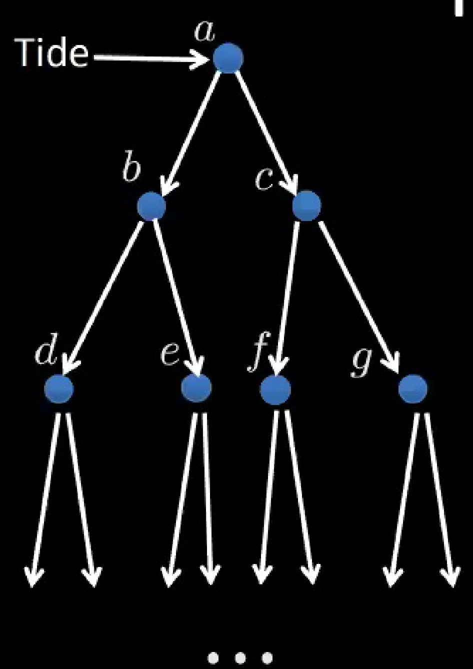
- This work: global effect.
Global parametric instability.

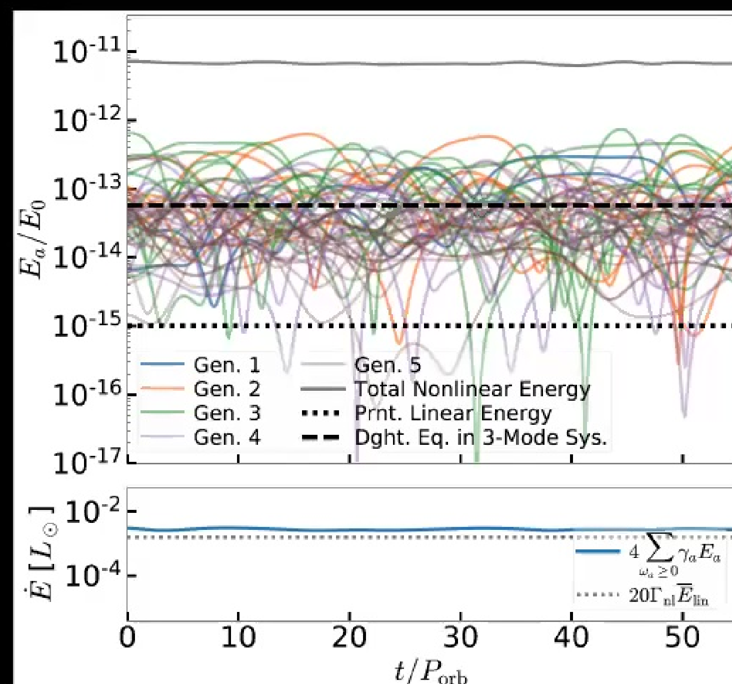


7

Orbit evolves due to GW radiation

PARAMETRIC INSTABILITY





$$\omega_a \simeq m_a(\Omega_{\rm orb} - \Omega_{\rm s})$$

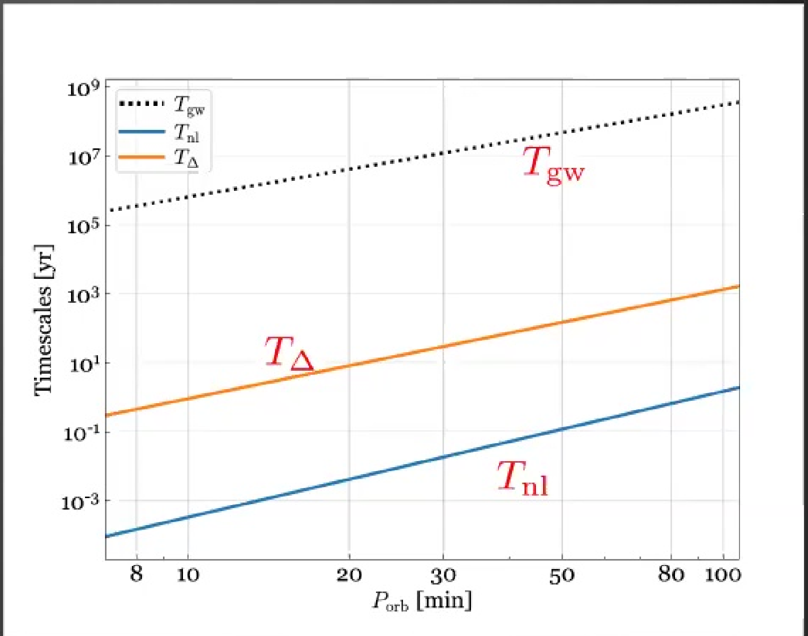
$$m_a(\Omega_{\rm orb} - \Omega_{\rm s}) + \omega_b + \omega_c \simeq 0$$

(Weinberg+ 12,
Essick & Weinberg 16)

Hang Yu, May 2020, PI

TIMESCALES

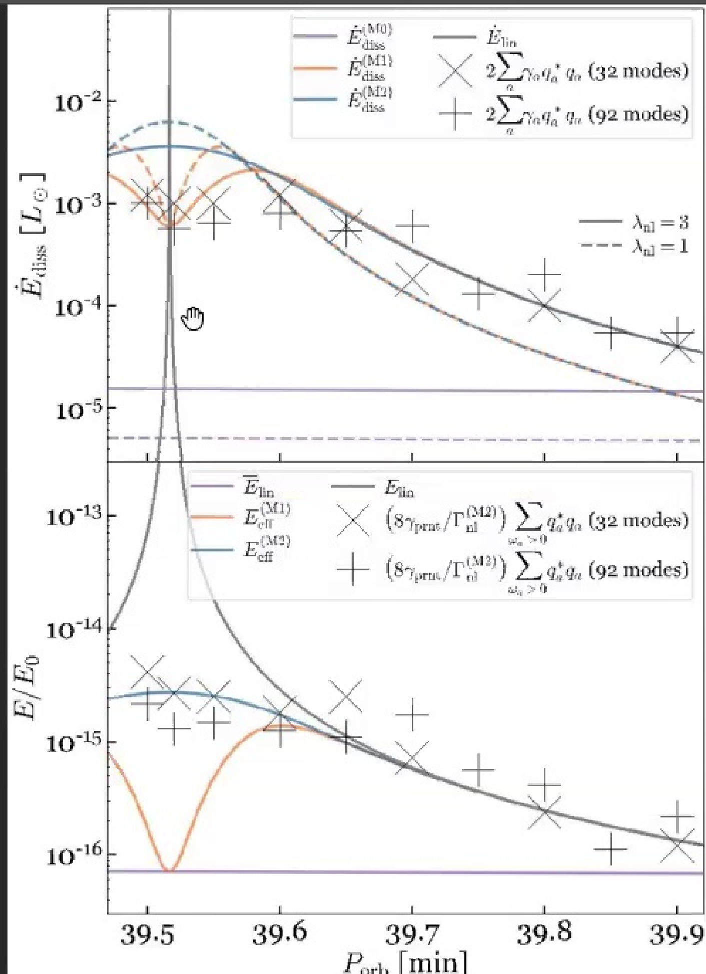
- Different timescales:
  - $T_{\rm gw} = \Omega_{\rm orb}/\dot{\Omega}_{\rm orb}$
    GW decay timescale
  - $T_{\rm nl} = 1/\Gamma_{\rm nl}$
    NL growth timescale
  - T_{Δ} :
    Time takes for an initially most resonant daughter pair to be off-resonant.



- $T_{\rm nl} \ll T_{\Delta} \ll T_{\rm gw}$.

OUR APPROACH

- Full mode-network integrations at representative orbital periods (NL growth timescale ~ days-months).
- Phenomenological models describing the nonlinear tidal dissipation rates.
- Long-term tidal synchronization and heating (GW decay timescale~ 10^7 years)
- Observational signatures in EM & GW.



⟵ Half of mode separation ⟶

- Energy dissipation rate around a resonant peak:
  - Depends on the parent mode detuning.
  - Seek a form similar to the linear theory.

$$\dot{E}_{\rm eff} = 4\gamma_{\rm eff} E_{\rm eff},$$

$$E_{\rm eff} = \frac{\omega_a^2}{\Delta_a^2 + \gamma_{\rm eff}^2(E_{\rm eff})} U_a^2,$$

$$\gamma_{\rm eff}(E_{\rm eff}) \sim \omega_a \kappa_{\rm abc} \sqrt{E_{\rm eff}}.$$

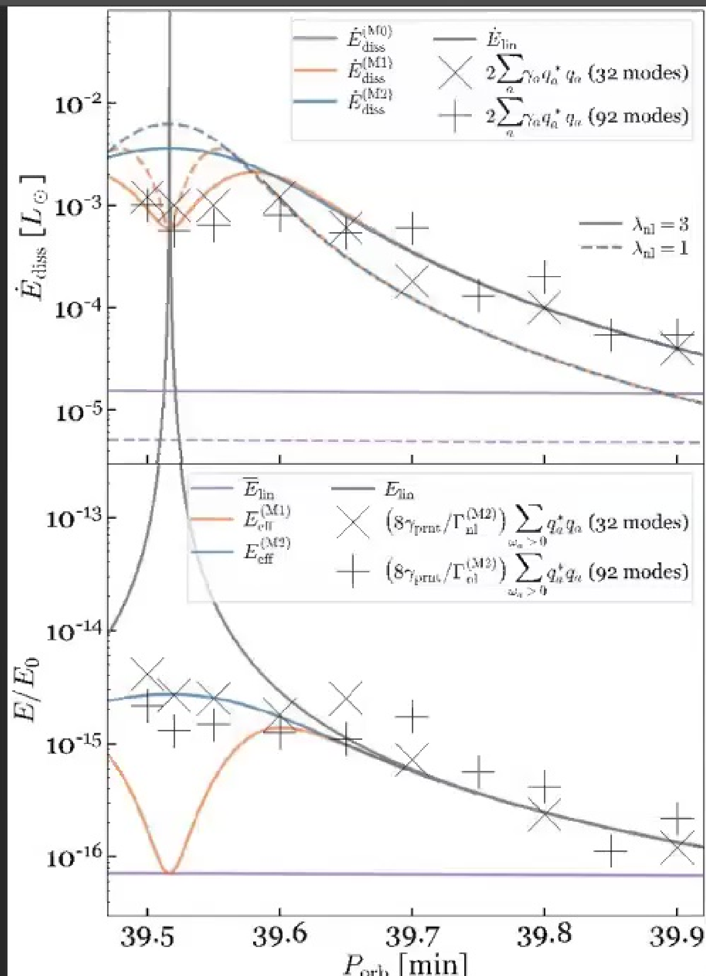
where:

ω_a = Eigenfreq of the parent,

$U_a \sim$ Tidal cpl. strength of the parent,

$\Delta_a \sim$ Freq detuning.

$\kappa_{abc} \sim$ 3-mode cpl coefficient



← Half of mode separation →

- Energy dissipation rate around a resonant peak:
  - Depends on the parent mode detuning.
  - Seek a form similar to the linear theory.

$$\dot{E}_{\rm eff} = 4\gamma_{\rm eff} E_{\rm eff},$$

$$E_{\rm eff} = \frac{\omega_a^2}{\Delta_a^2 + \gamma_{\rm eff}^2(E_{\rm eff})} U_a^2,$$

$$\gamma_{\rm eff}(E_{\rm eff}) \sim \omega_a \kappa_{abc} \sqrt{E_{\rm eff}}.$$

where:

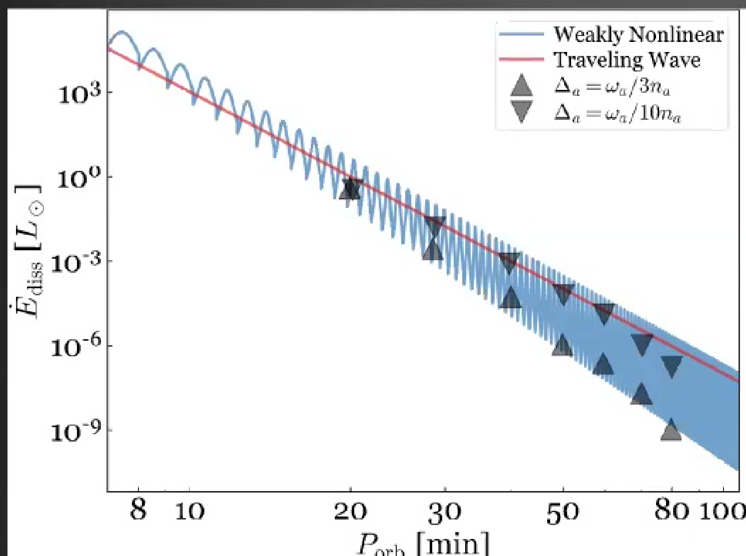
ω_a = Eigenfreq of the parent,

$U_a \sim$ Tidal cpl. strength of the parent,

$\Delta_a \sim$ Freq detuning.

$\kappa_{abc} \sim$ 3-mode cpl coefficient

11

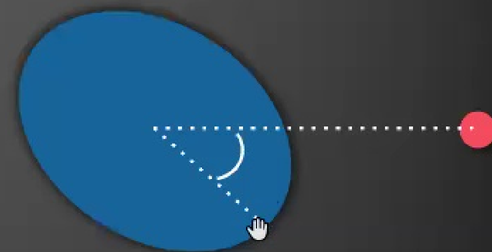


(WD is assumed non-spinning here.)

- Energy dissipation over a large range of P_orb:
  - Reduced peak-trough spread due to E-dependent damping.

TIDAL SYNCHRONIZATION

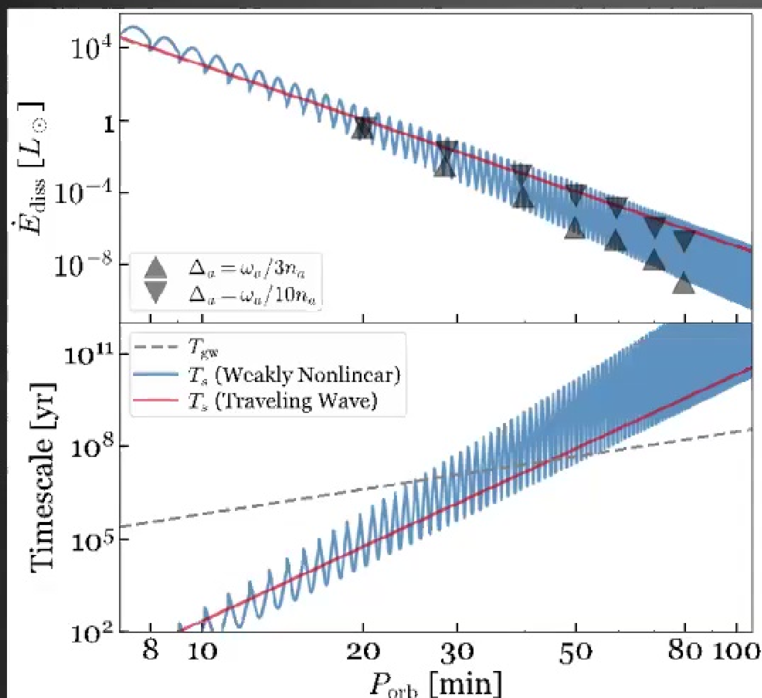
- Dissipation makes the tidal bulge lags behind the companion->Torque!



- The torque will spin up the WD.
- Synchronization:

$$\dot{\Omega}_s = \dot{\Omega}_{orb} \text{ instead of } \Omega_s = \Omega_{orb}$$

- Two questions to ask:
  - 1. For an initially non-rotating WD, when can we have $\dot{\Omega}_s \geq \dot{\Omega}_{orb}$?
  - 2. Once $\dot{\Omega}_s = \dot{\Omega}_{orb}$ is satisfied, can it be maintained?



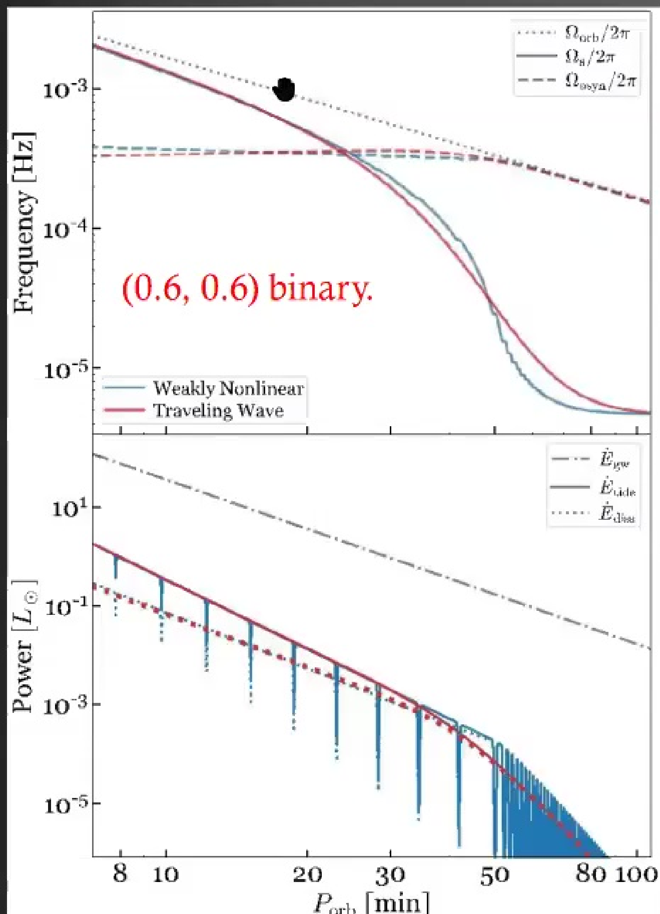
(WD is assumed non-spinning here.)

$$T_{\rm s} \equiv \frac{\Omega_{\rm orb}}{\dot{\Omega}_{\rm s}} = \text{Spin-up timescale},$$

$$T_{\rm s}^{\rm (nl)}\Big|_{\Delta_a=0} \sim \Omega_{\rm orb}^{-2}\omega_a^{-6.5},$$

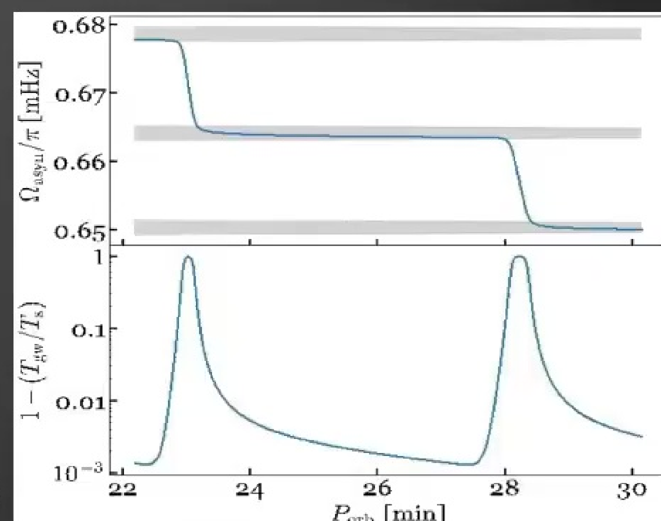
$$T_{\rm s}^{\rm (tw)} \sim \Omega_{\rm orb}^{-3}\omega_a^{-5};$$

$$T_{\rm gw} \equiv \frac{\Omega_{\rm orb}}{\dot{\Omega}_{\rm orb,gw}} \sim \Omega_{\rm orb}^{-8/3}.$$



(Solid-body rotation assumed.)

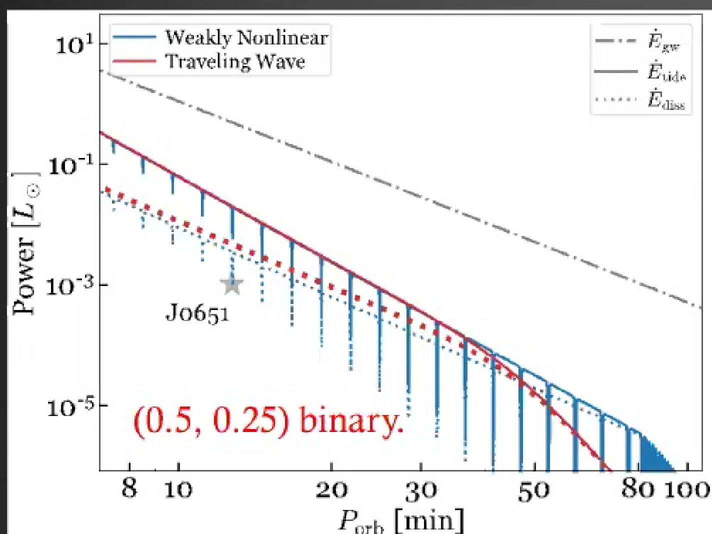
- TW: smooth heating rate dictated by GW decay.
  $\dot{\Omega}_s \simeq \dot{\Omega}_{orb} \simeq \dot{\Omega}_{orb,gw}$.
- NL: extra dips.
  Temporarily out of sync.
  $T_s^{(nl)} \sim \Omega_{orb}^{-2}$, $T_{gw} \sim \Omega_{orb}^{-8/3}$, $T_s^{(tw)} \sim \Omega_{orb}^{-3}$.
  TW can maintain sync'ed but NL cannot!



Hang Yu, May 2020, PI

15

EM OBSERVATION



- The NL model might reproduce the luminosity of the CO WD in J0651 if it resides in a dip.
- Only ~ 1% chance...
- (Also ignored adjustment to the background structure due to tidal heating.)

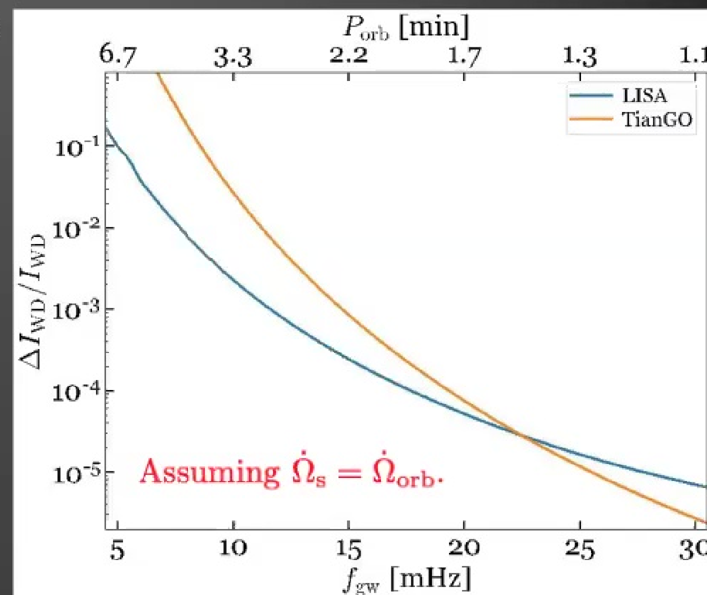
Hang Yu, May 2020, PI 16

GW OBSERVATION

- Focusing on sys' w/ P_orb <~ 5 min.
  - TW regime; sync'ed.
- Tidal effects accelerate the orbital decay.

$$\dot{E}_{\rm tide}/\dot{E}_{\rm pp} \propto I_{\rm WD} f_{\rm gw}^{4/3}.$$

- Allows us to measure the WD's moment of inertia.



Freq resolution $\sim 6\,$nHz;
Freq evolution $\sim 1-100\,\mu$Hz.

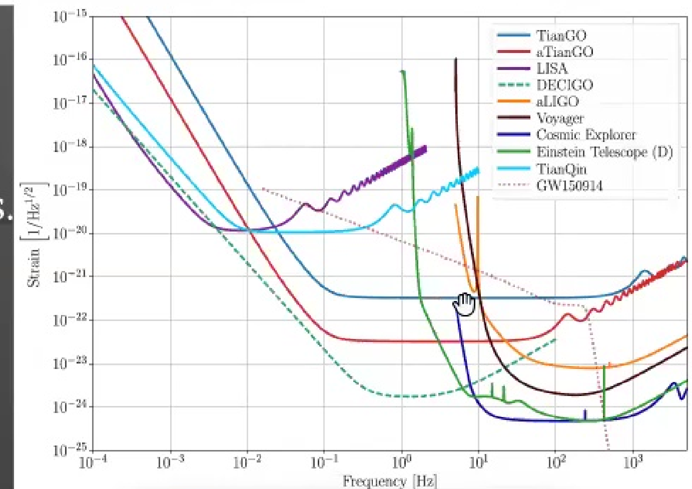
TianGO

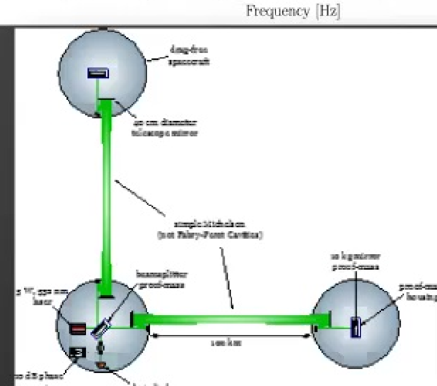
arXiv:1908.06004

Astrophysics and cosmology with a deci-hertz gravitational-wave detector: TianGO

Kevin A. Kuns,[1,2,*] Hang Yu,[3,*] Yanbei Chen,[3] and Rana X Adhikari[1]
[1] LIGO Laboratory, California Institute of Technology, Pasadena, California 91125, USA
[2] LIGO Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
[3] Theoretical Astrophysics 350-17, California Institute of Technology, Pasadena, California 91125, USA

- Sensitive from 10 mHz to 10 Hz.
- Real-time Michelson w/ 100 km arms.
  - Much simpler/cheaper than LISA.
  - Adopts LIGO technologies.
- For WDs, comparable to LISA.
- Multi-band ob. of LIGO sources.
- Great for localization:
  - Long baseline b/t TianGO & ground.
  - Doppler shift (as in band for ~ yrs).





CONCLUSIONS

- Tide is weakly nonlinear for WDs w/ P_orb ~ 10-150 min.
- Nonlinearity captured by an effective NL damping $\gamma_{\rm eff} \sim \sqrt{E_{\rm eff}}$.
  (linear damping is independent of energy.)
- Evolution track similar to the TW model overall.
  (consequence of tidal synchronization.)
- Extra dips in the tidal heating because
  synchronization cannot be maintained in the NL model.
- Luminosity at a dip consistent w/ J0651; only ~1% chance.
- WD moment of inertia can be well measured by a centihertz detector.

Hang Yu, May 2020, PI 19