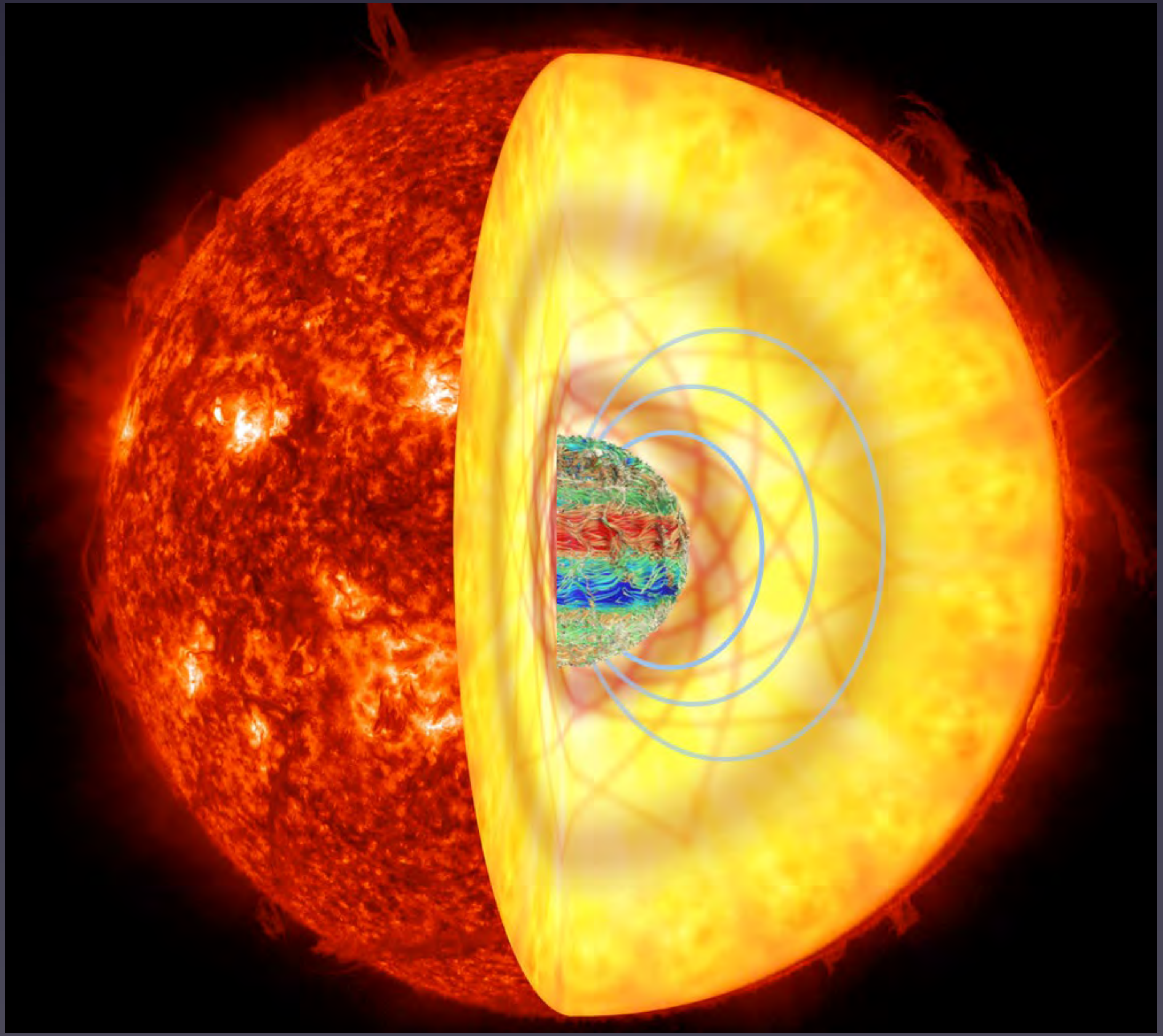
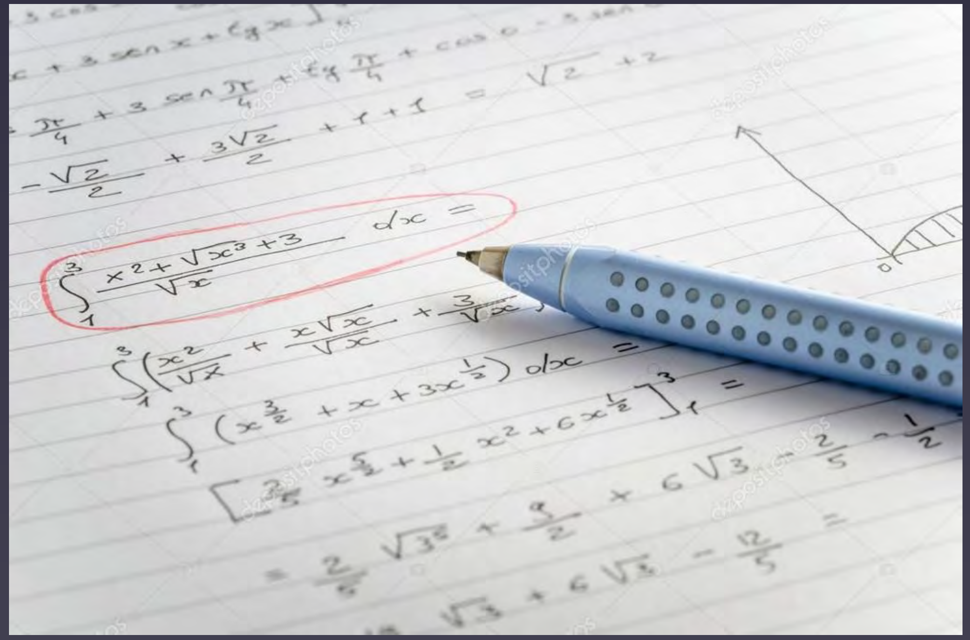
Astrophysics of Stars and Planets

Jim Fuller

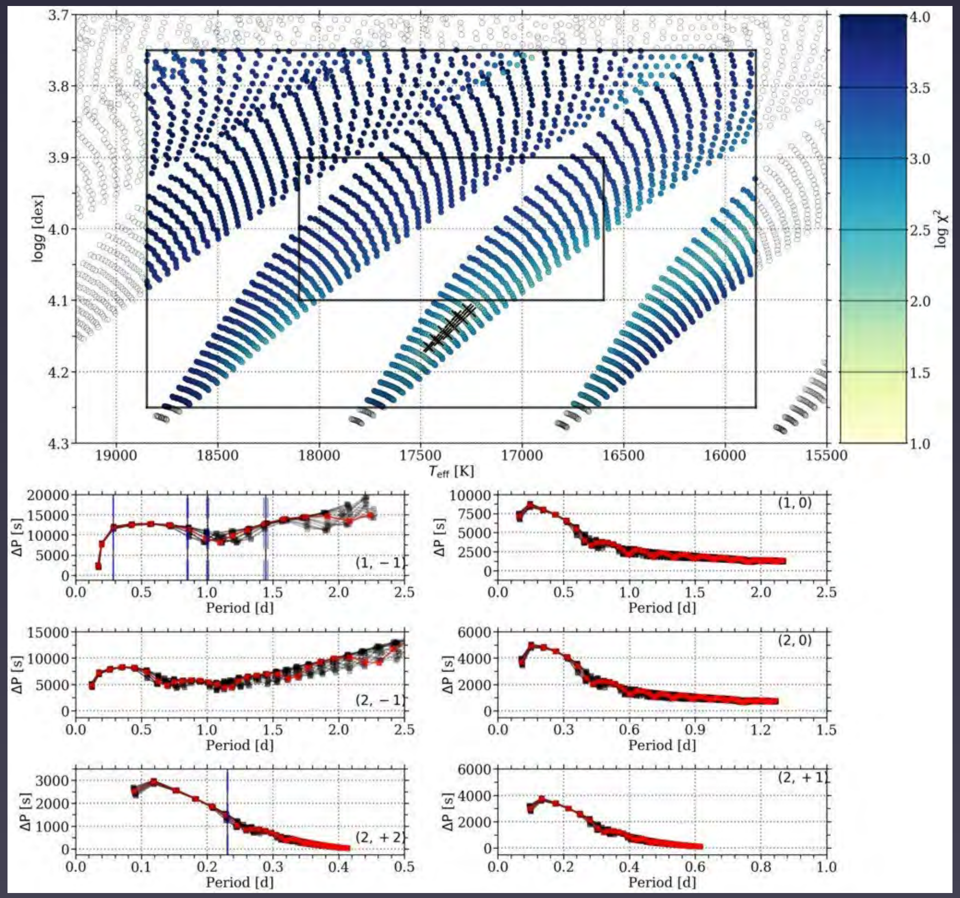
Caltech



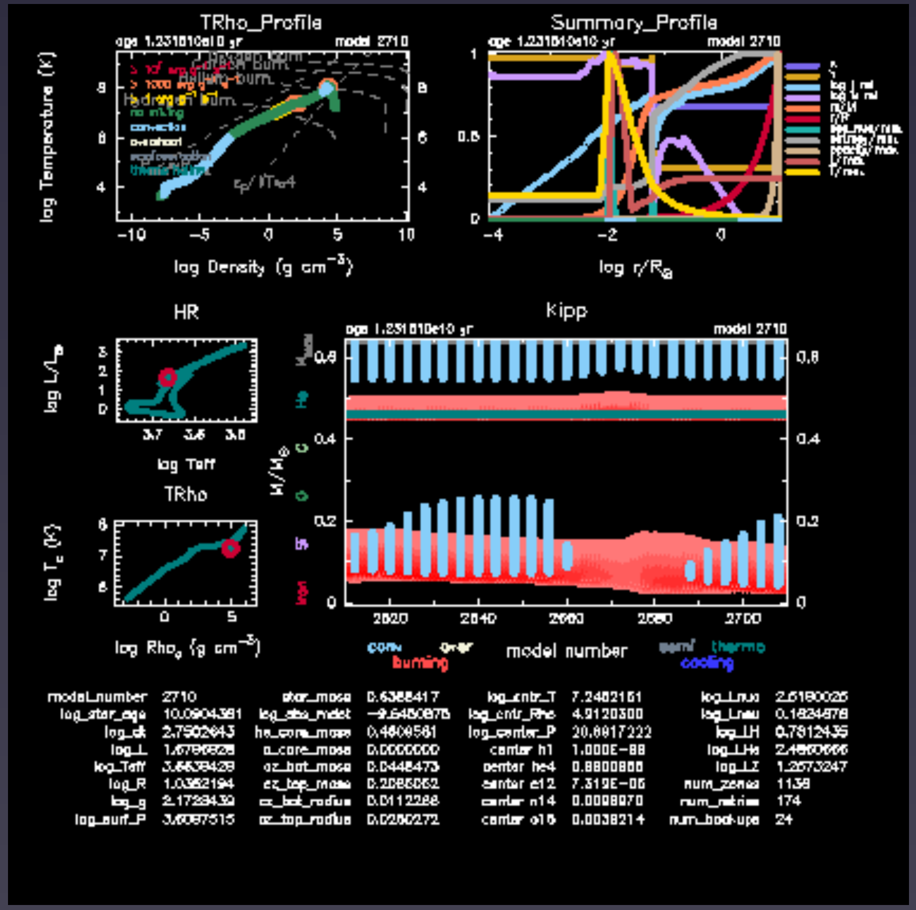
Tools



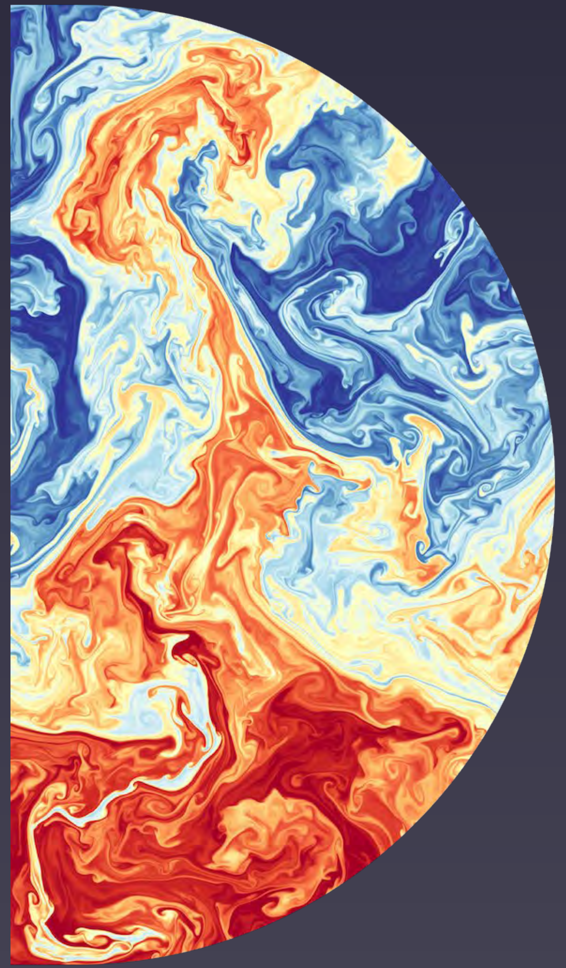
GYRE



MESA



Dedalus



Students:

Peter Scherbak

Guangyi Zhang

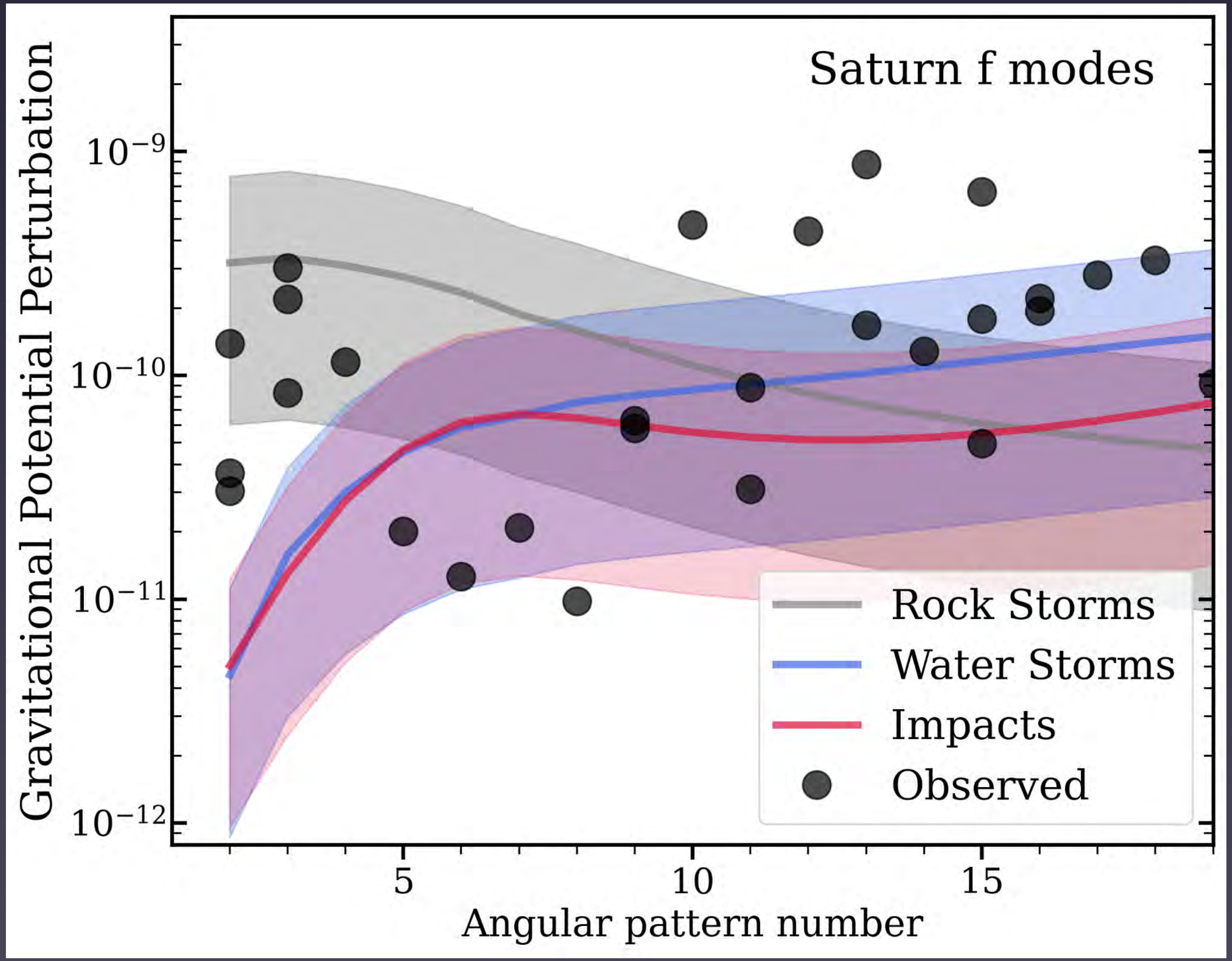
Nicolas Fernandes

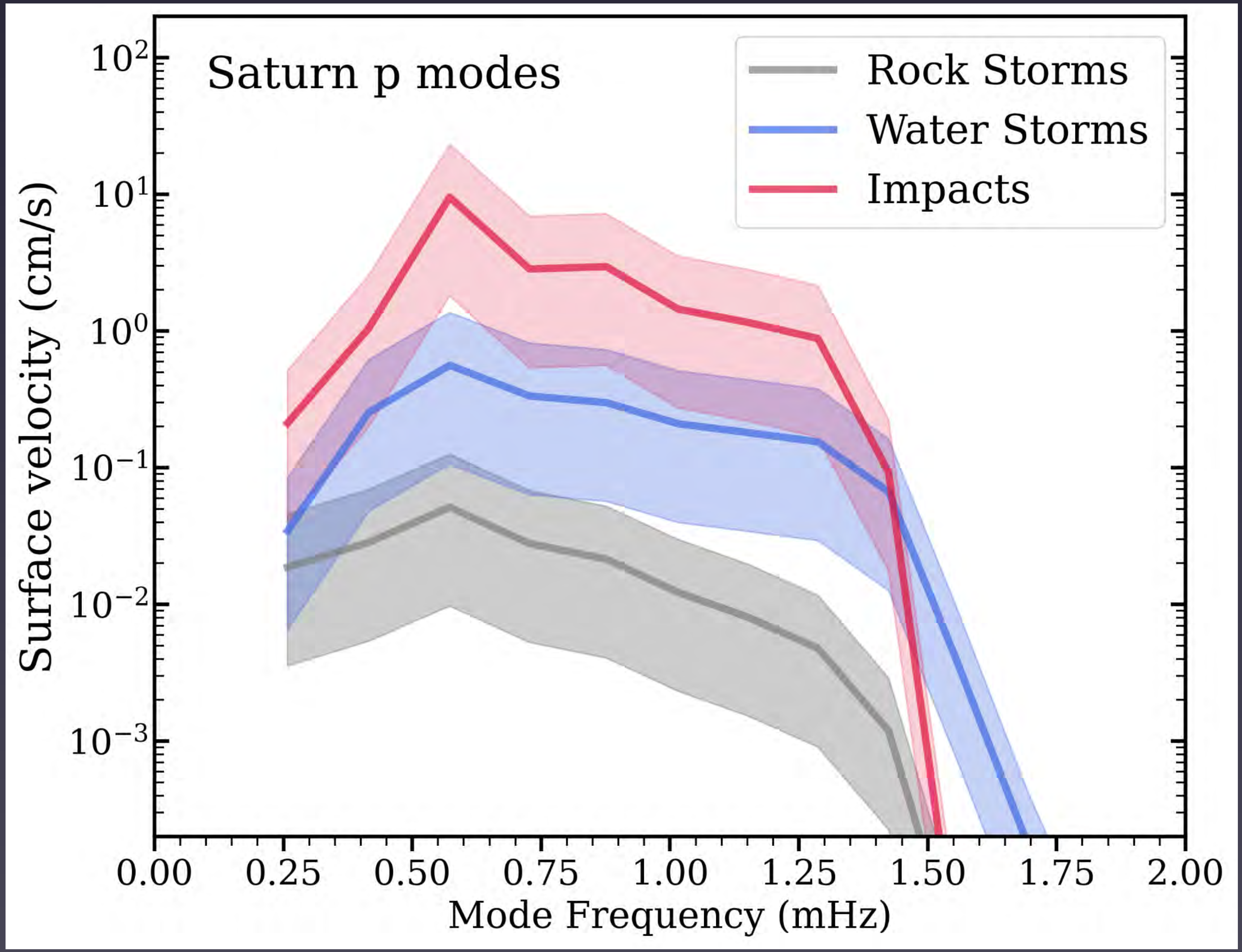
Postdocs:

Hila Glanz

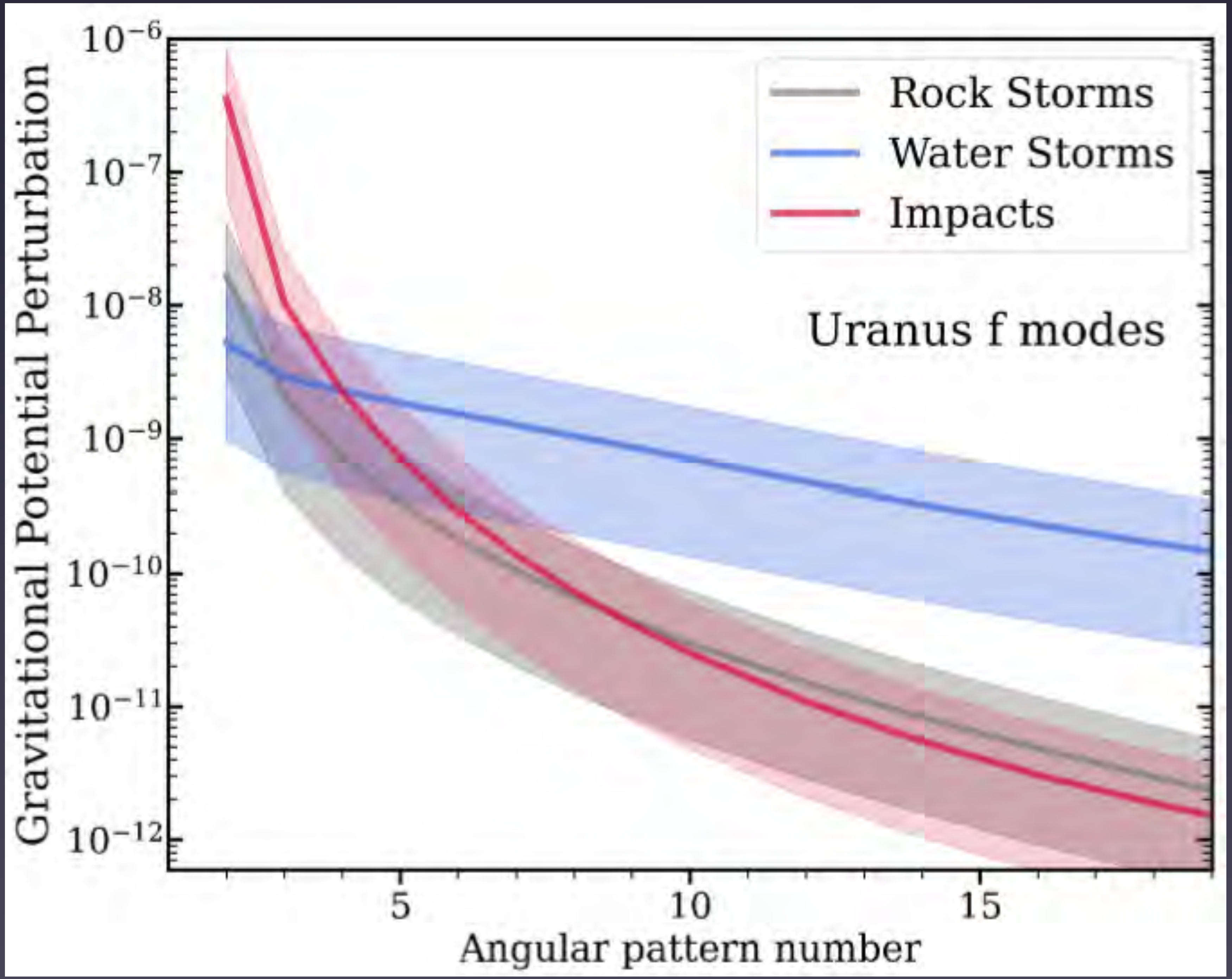
Rafa Fuentes

Mode Driving

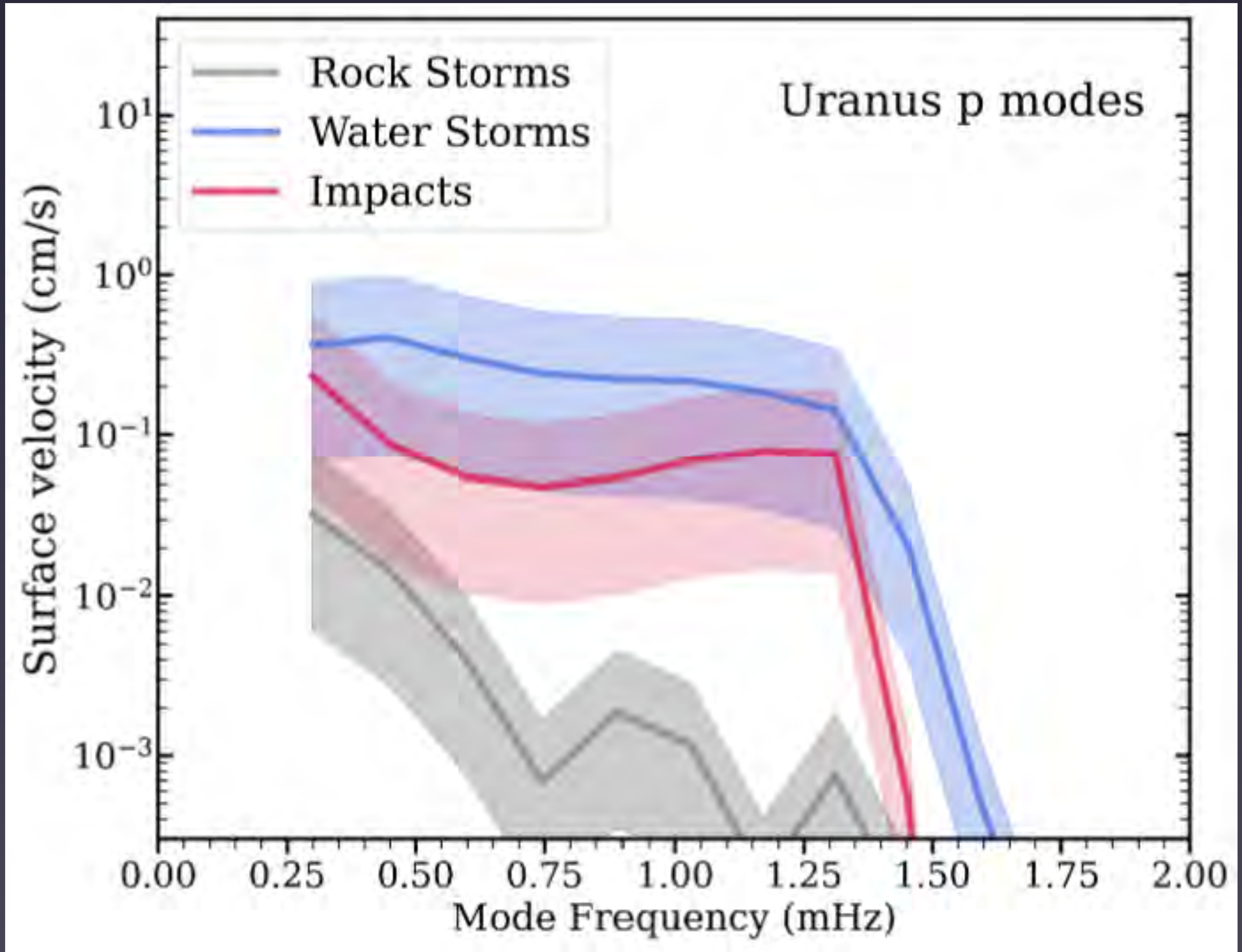




Uranus



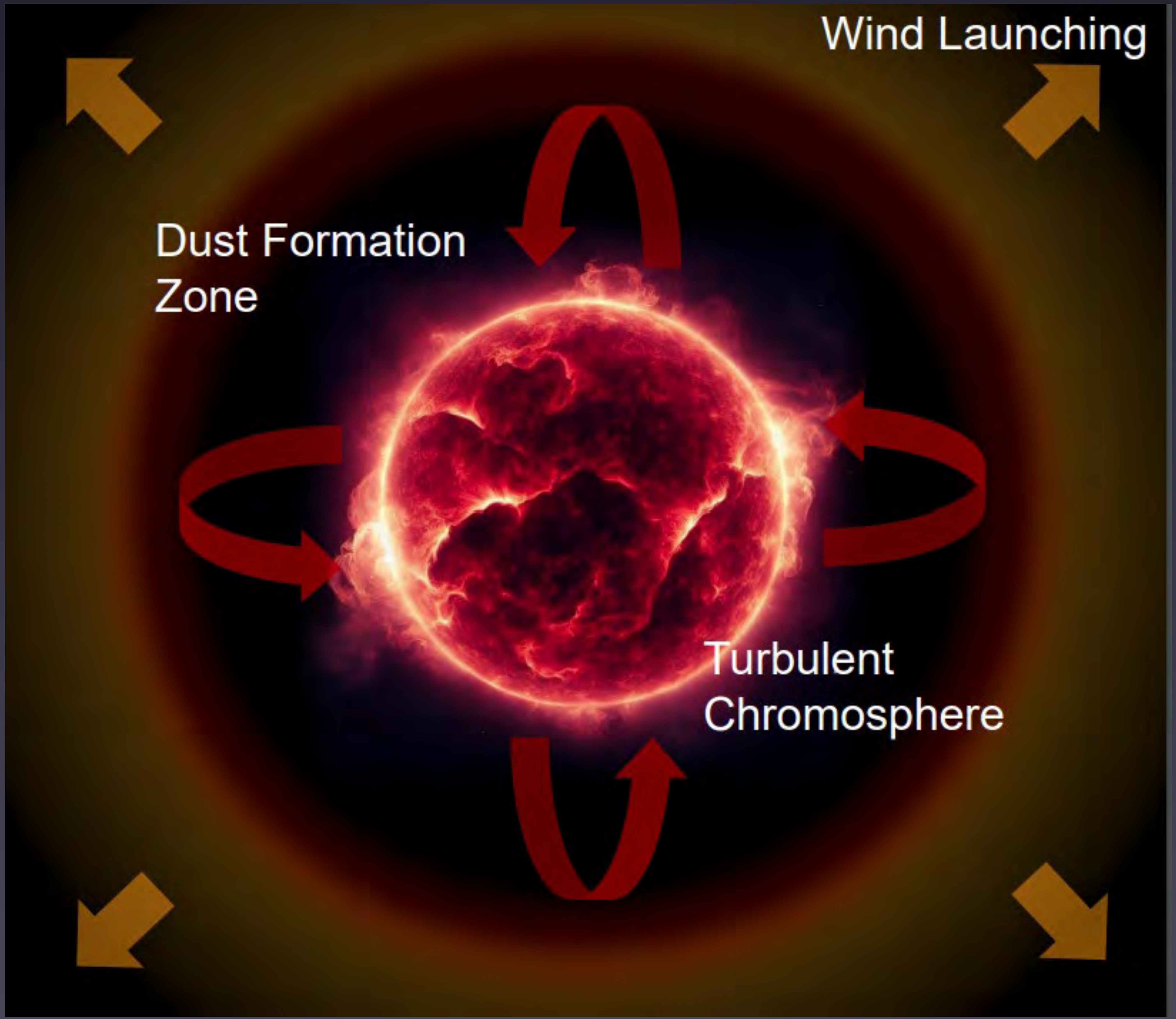
Rock Storms
Water Storms
Impacts
Uranus f modes
Gravitational Potential Perturbation
Angular pattern number
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
5
10
15

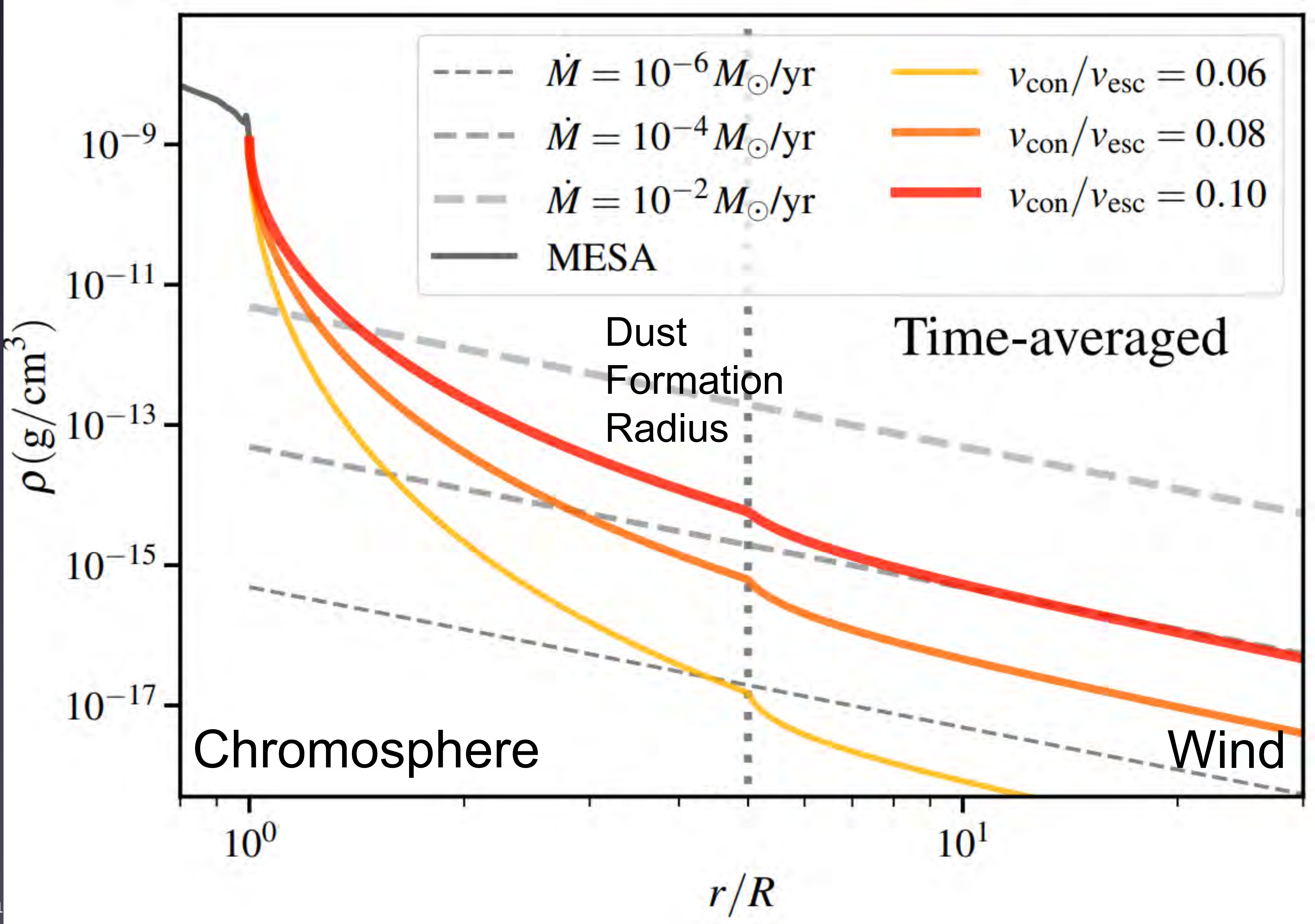


Rock Storms
Water Storms
Impacts
Uranus p modes
Surface velocity (cm/s)
Mode Frequency (mHz)
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00

Chromospheres

- Shock waves launched by ~sonic convective motions
- Waves deposit momentum, energy in chromosphere
- Dense chromospheres are able to cool (unlike Sun's corona)





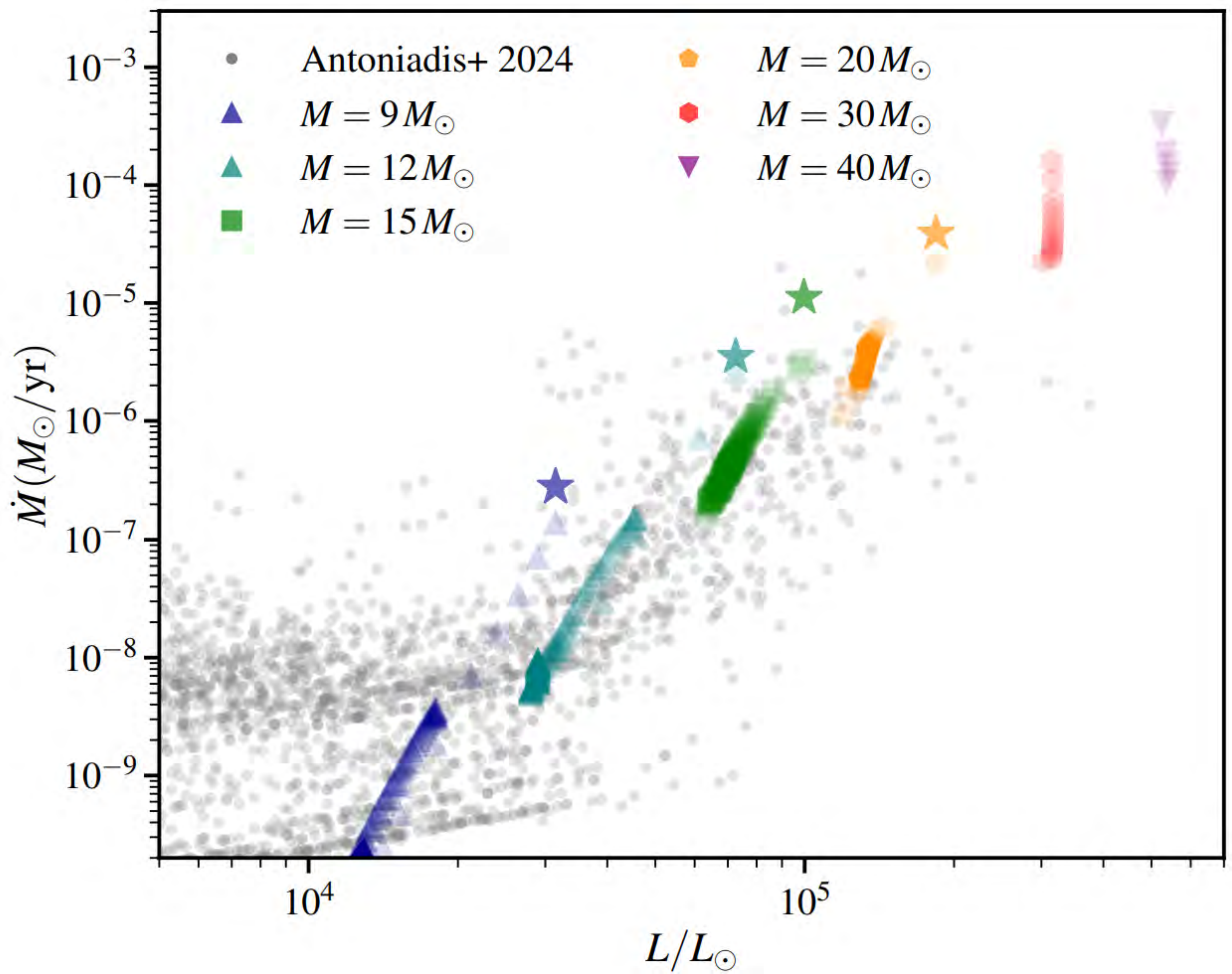
$\dot{M} = 10^{-6} M_\odot/\mathrm{yr}$
$\dot{M} = 10^{-4} M_\odot/\mathrm{yr}$
$\dot{M} = 10^{-2} M_\odot/\mathrm{yr}$
MESA
$v_{con}/v_{esc} = 0.06$
$v_{con}/v_{esc} = 0.08$
$v_{con}/v_{esc} = 0.10$
Dust Formation Radius
Time-averaged
Chromosphere
Wind
$\rho\,(\mathrm{g/cm^3})$
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-17}
10^{0}
10^{1}
r/R

Mass loss rate

- Mass loss computed by matching chromosphere to wind at dust formation radius

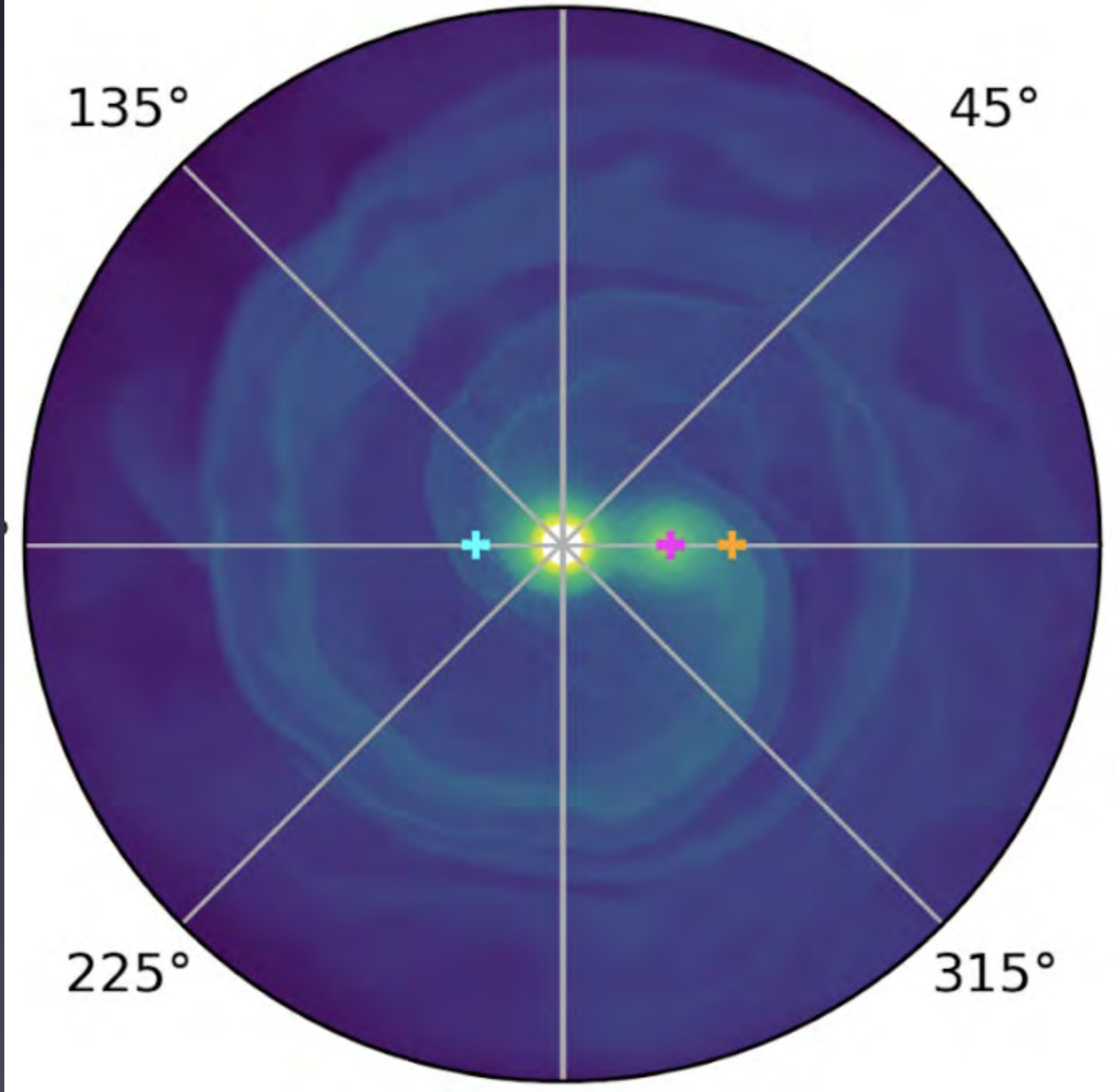
$$\dot{M} \approx 4\pi R_d^2 \rho(R_d)\, v_{\rm con}$$

$$\approx 4\pi R^2 \rho(R) v_{\rm con}\, e^{-\frac{v_{\rm esc}\sqrt{1-R/R_{\rm d}}}{v_{\rm con}}}$$



Circumbinary Flow

- Mass forms outflowing circumbinary disk
- Most mass unbound in disk with ~20 degree opening angle

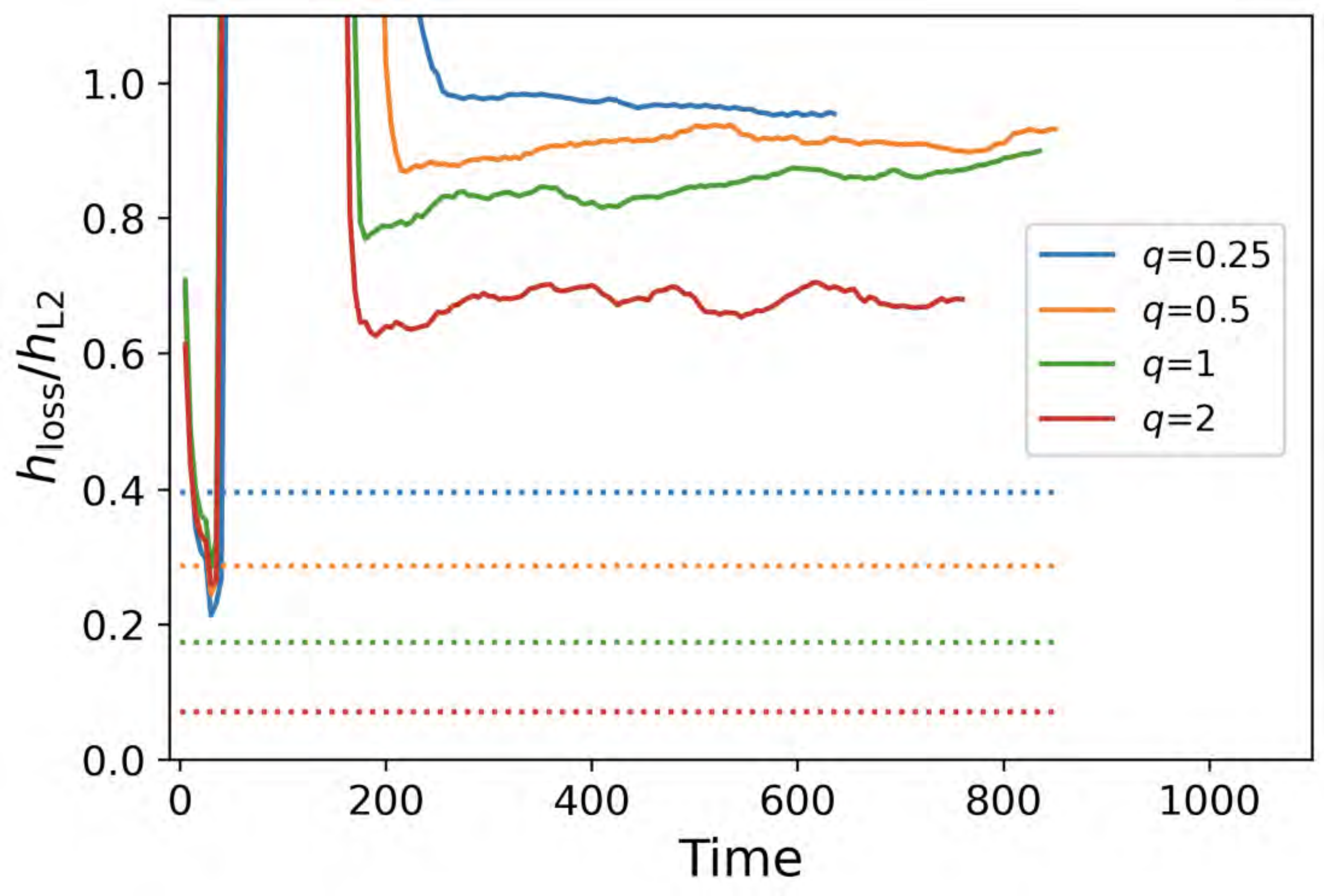


Scherbak, Lu, Fuller 2025

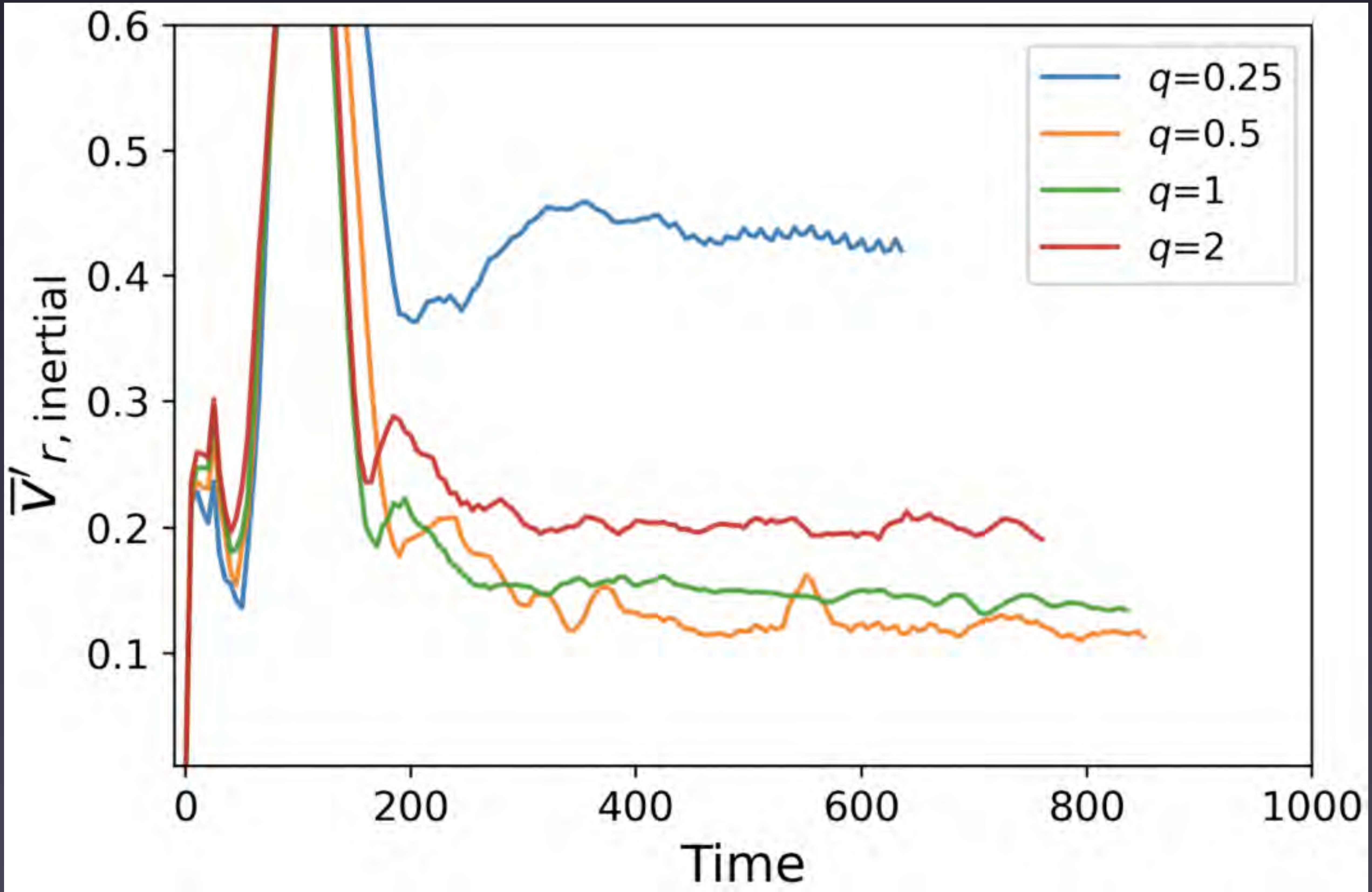
Angular Momentum Loss

- Amount of angular momentum lost determines evolution of orbit

- Major implications for forming black hole and neutron star binaries

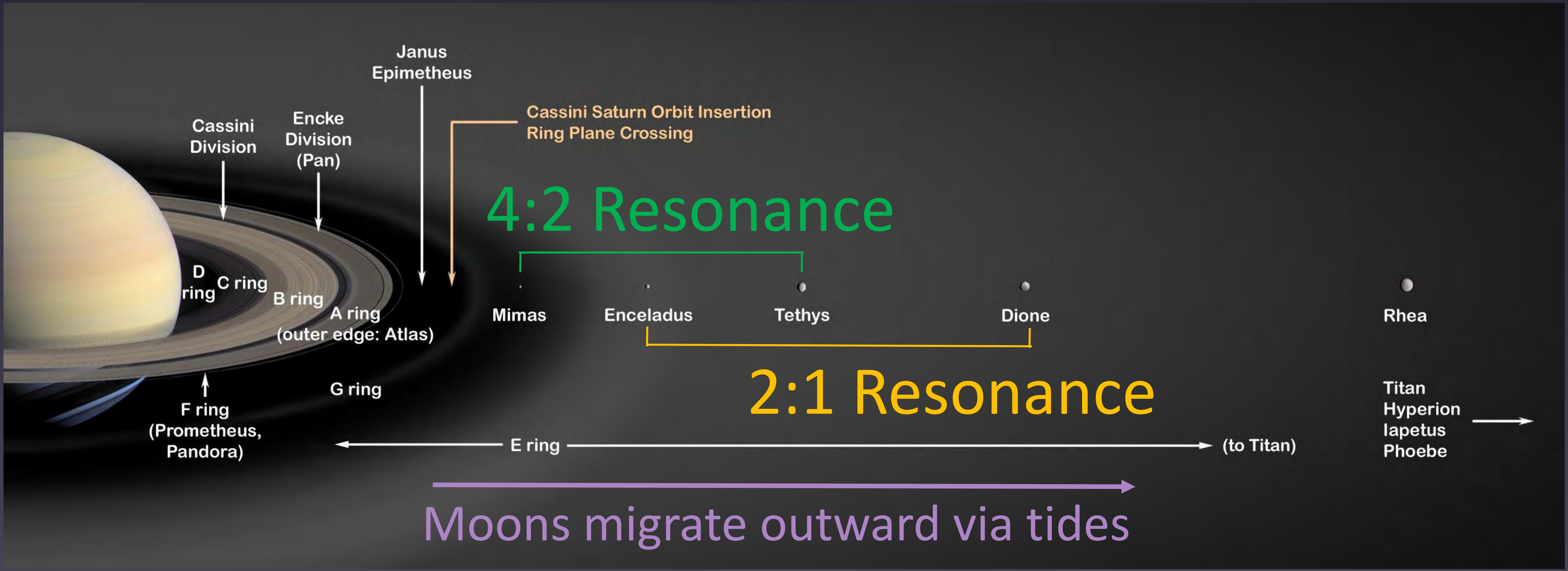


- Mass not quite unbound at outer edge of simulation domain



Scherbak, Lu, Fuller 2025

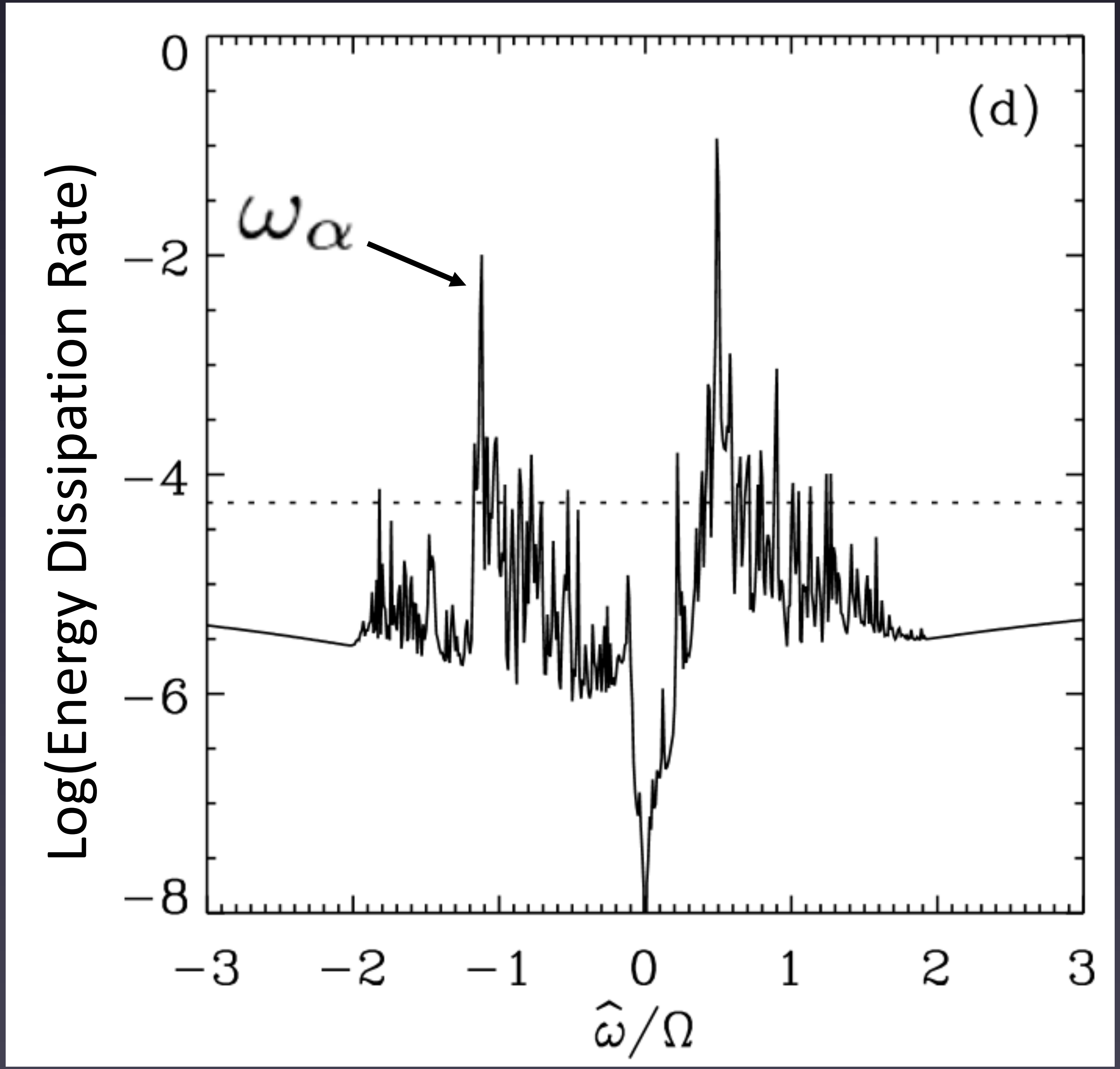
Tidal Migration of Moon Systems



Dynamical Tides

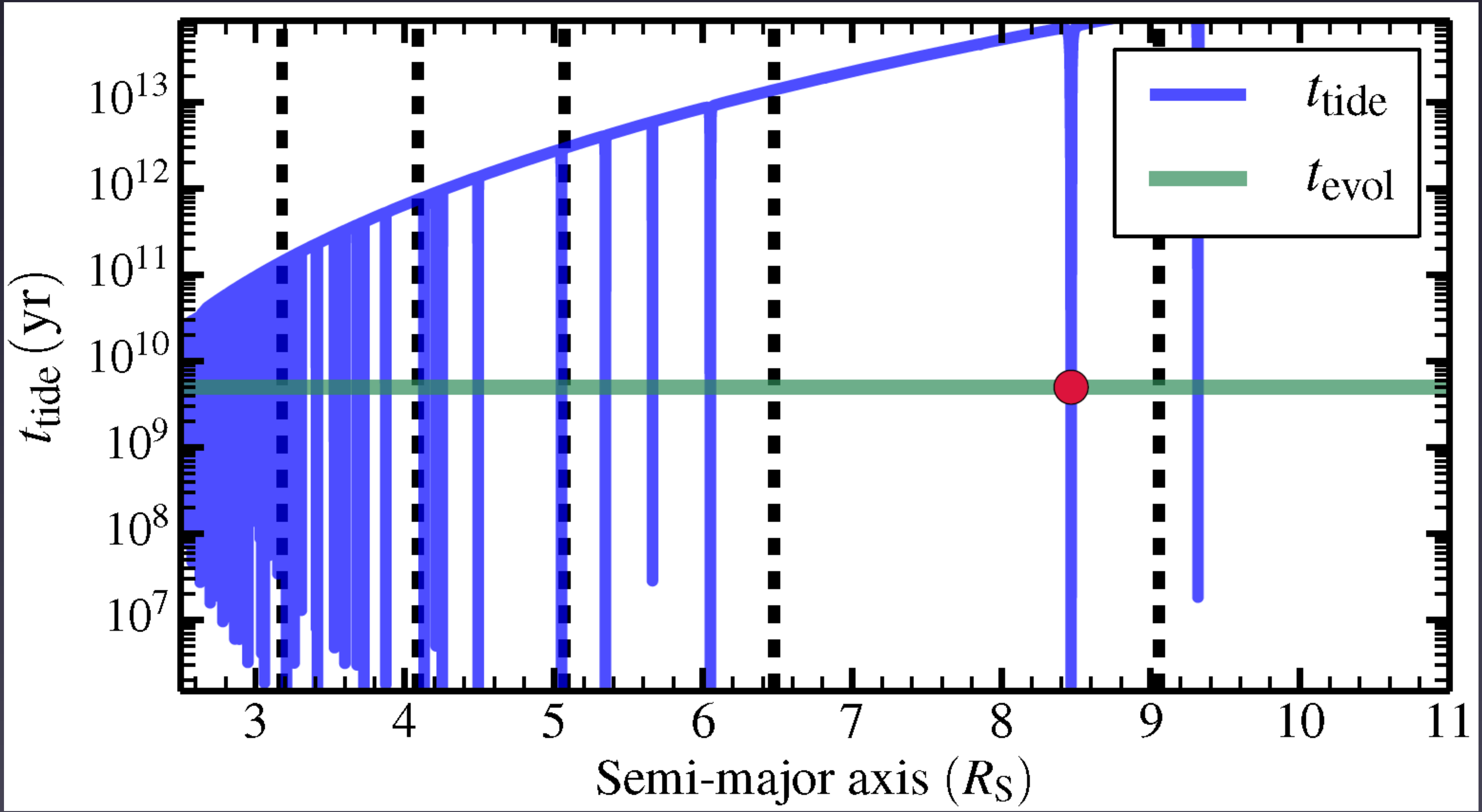
- Caused by gravity modes and inertial waves
- Energy dissipation rate varies strongly with forcing frequency
- Tidal dissipation greatly enhanced around resonant peaks where

$$\omega_\alpha \simeq \omega_{\rm f} = m(\Omega_{\rm p} - \Omega_{\rm m})$$



Ogilvie & Lin 2004

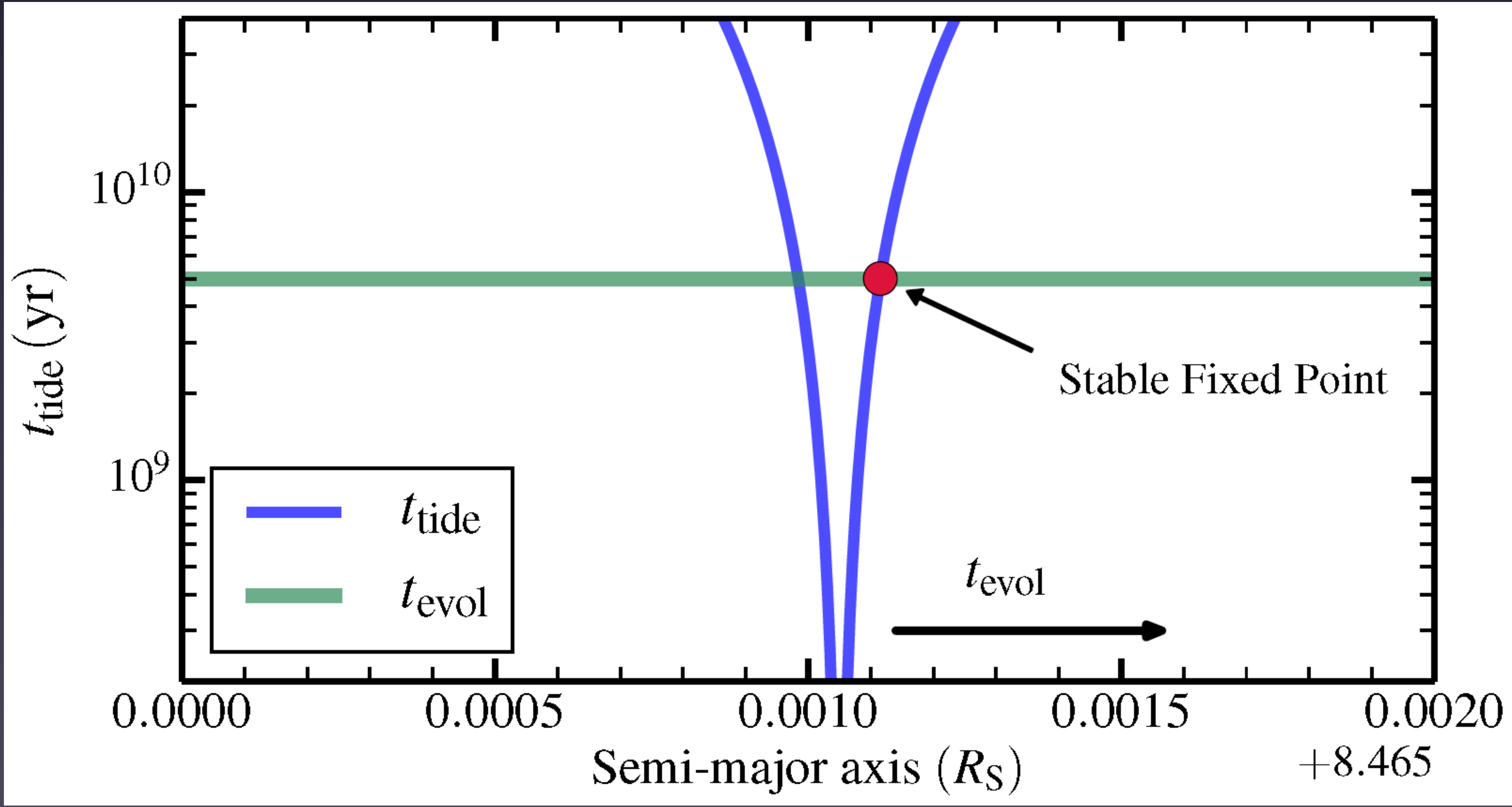
Works by Mathis, Guenel, Remus



$$t_{\rm tide} = -\frac{E_{\rm orb}}{\dot{E}_{\rm tide}} = \frac{a_{\rm m}}{\dot{a}_{\rm m,tide}}$$

Fuller, Luan, & Quataert 2016

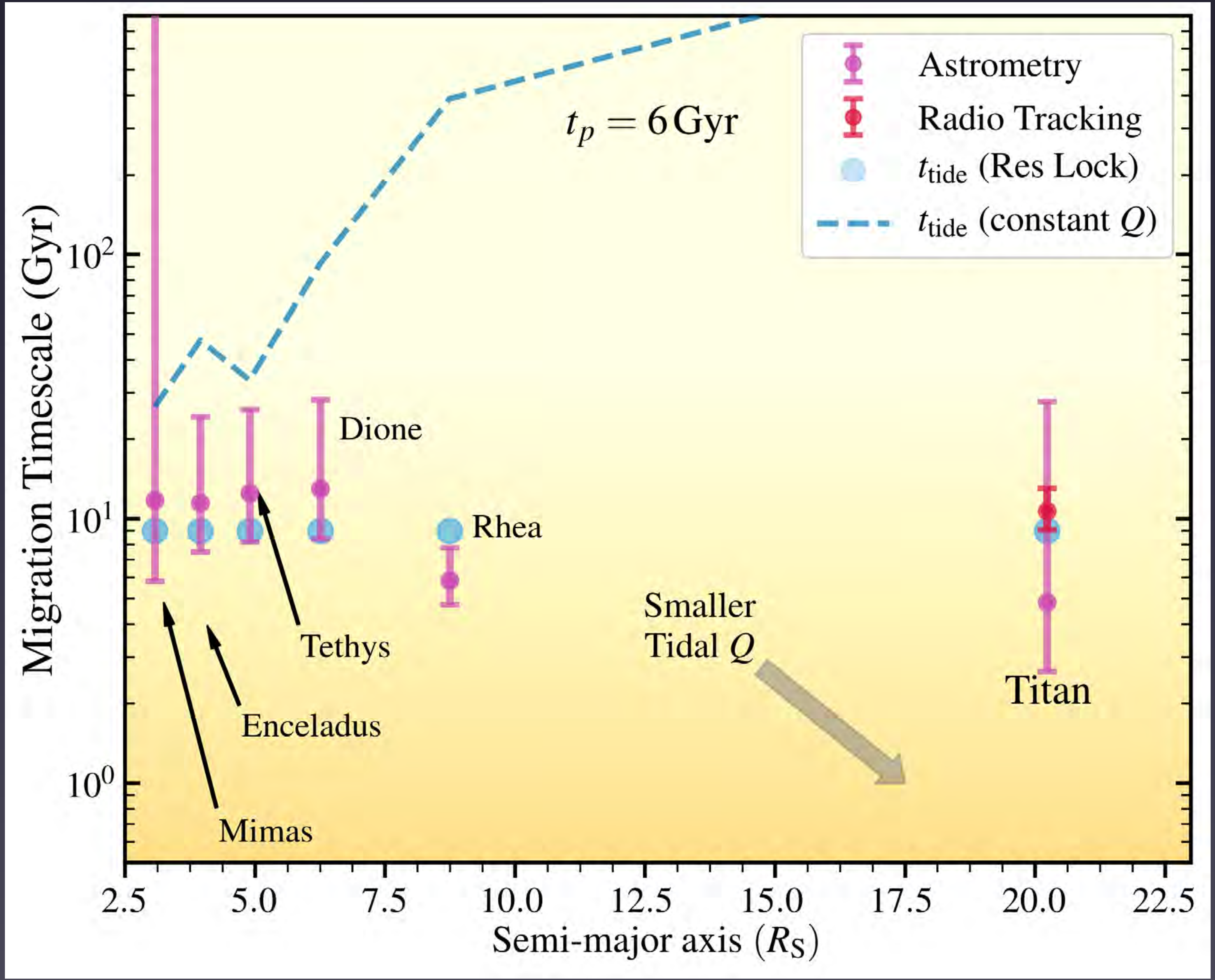
Resonance Locking of Moons



Fuller, Luan, & Quataert 2016

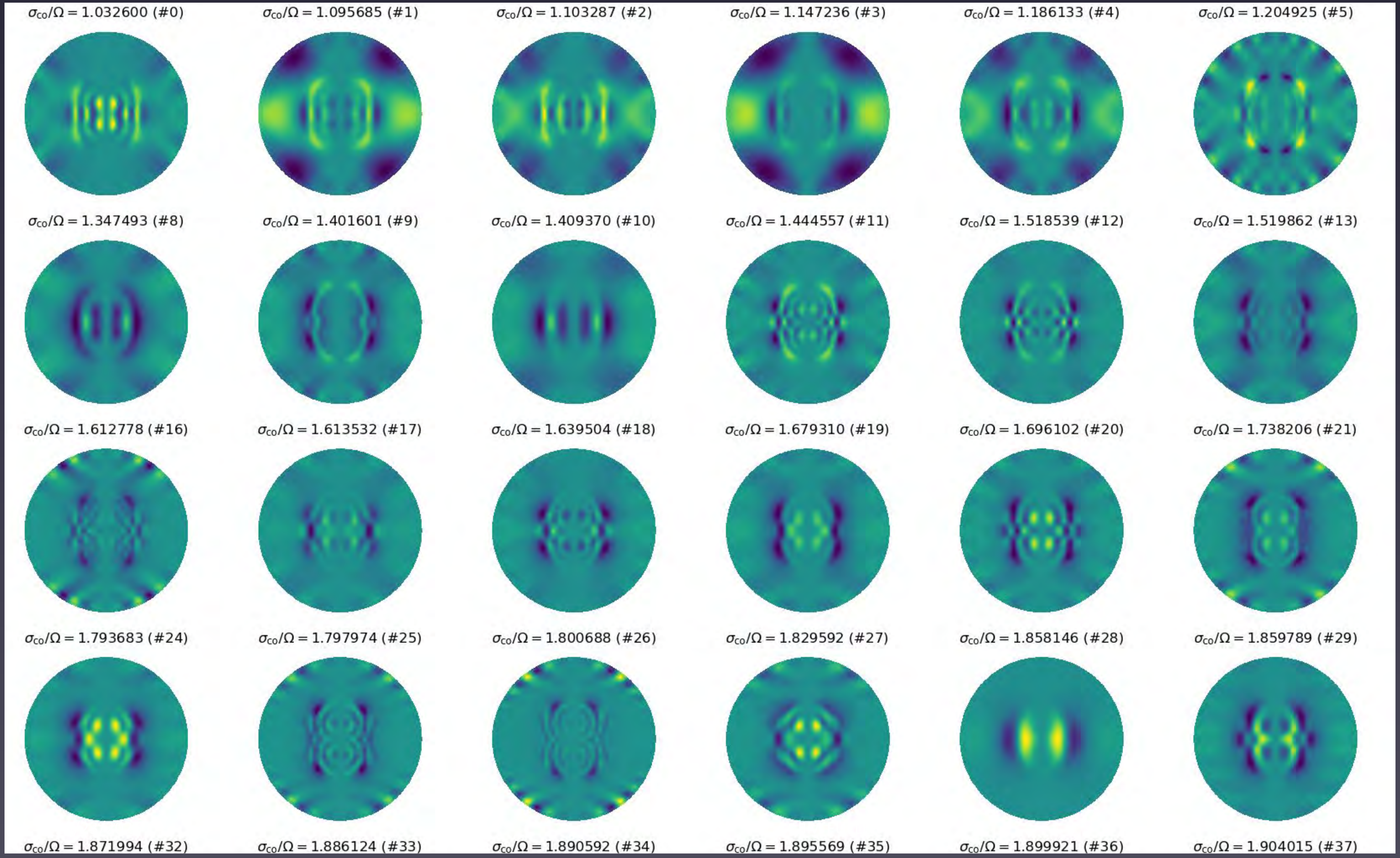
A New Paradigm

- Tidal migration time scale is nearly constant for each moon (but see Jacobson 2022)



Lainey, Gomez, Fuller +, 2020

Calculating Oscillation Modes



Guangyi Zhang

Effects of Magnetic Fields on Gravity Modes

- Magnetic field exerts Lorentz forces that restrict g modes

$$\rho_0 \partial_t^2 \vec{\xi} = -\nabla \left(p' + \frac{1}{4\pi} \vec{B}_0 \cdot \vec{B}' \right) - \rho' g \hat{r} + \frac{1}{4\pi} \left(\vec{B}_0 \cdot \nabla \right) \vec{B}'$$

$$\vec{B}' = \left(\vec{B}_0 \cdot \nabla \right) \vec{\xi}$$

- Gravity modes sensitive to even weak magnetic fields

Nicholas Rui

Perturbation Theory

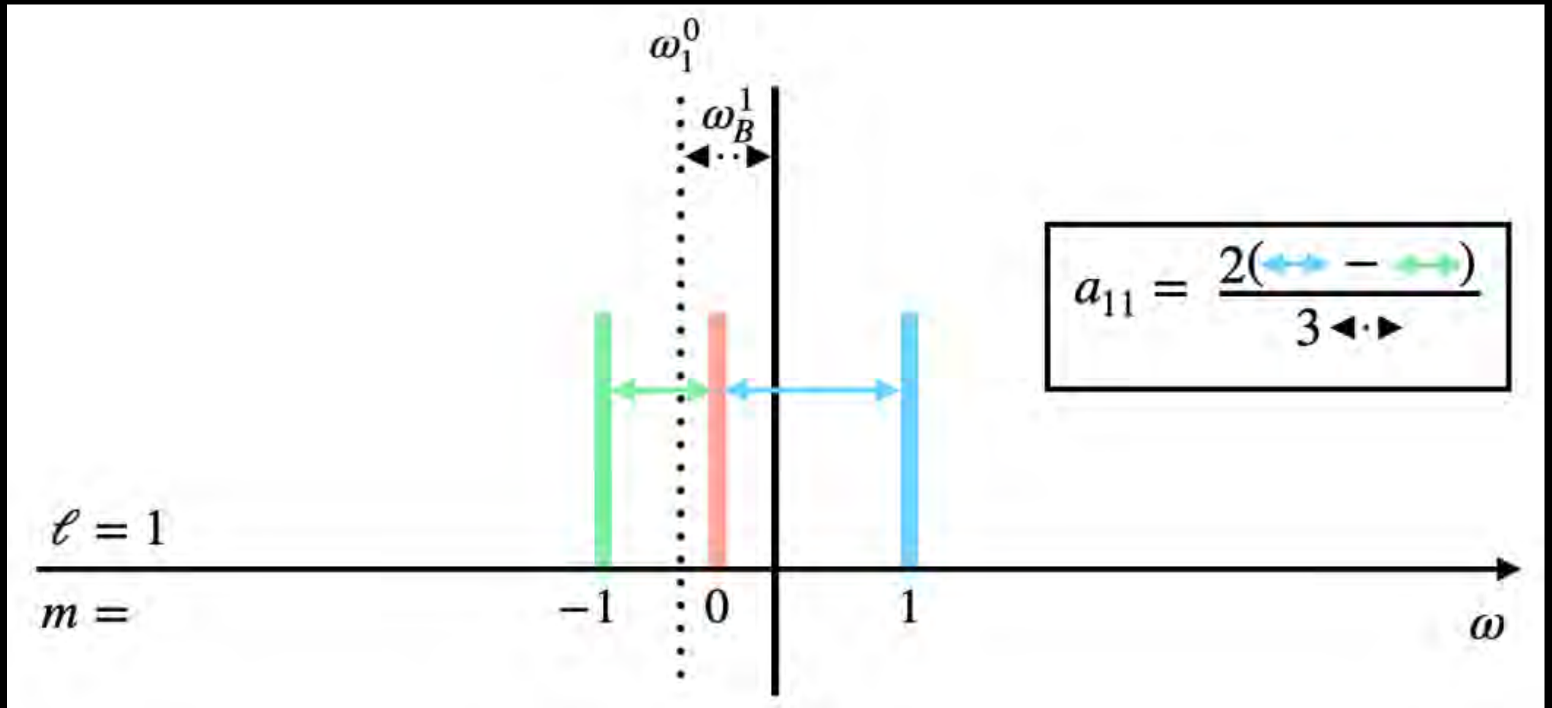
- Magnetic field perturbs mode frequencies by

$$\omega_{\rm B} = \frac{1}{\mu_0 \omega^3} \frac{\int_{r_{\rm i}}^{r_{\rm o}} \left(\frac{N}{r}\right)^3 \frac{\overline{B_r^2}}{\rho} {\rm d}r}{\int_{r_{\rm i}}^{r_{\rm o}} \frac{N}{r} {\rm d}r}$$

$$\delta\omega_g(m=0) = (1-a)\,\omega_B$$
$$\delta\omega_g(m=\pm1) = \left(1+\frac{a}{2}\right)\omega_B,$$

Deheuvels+ 2023
Hatt+ 2024

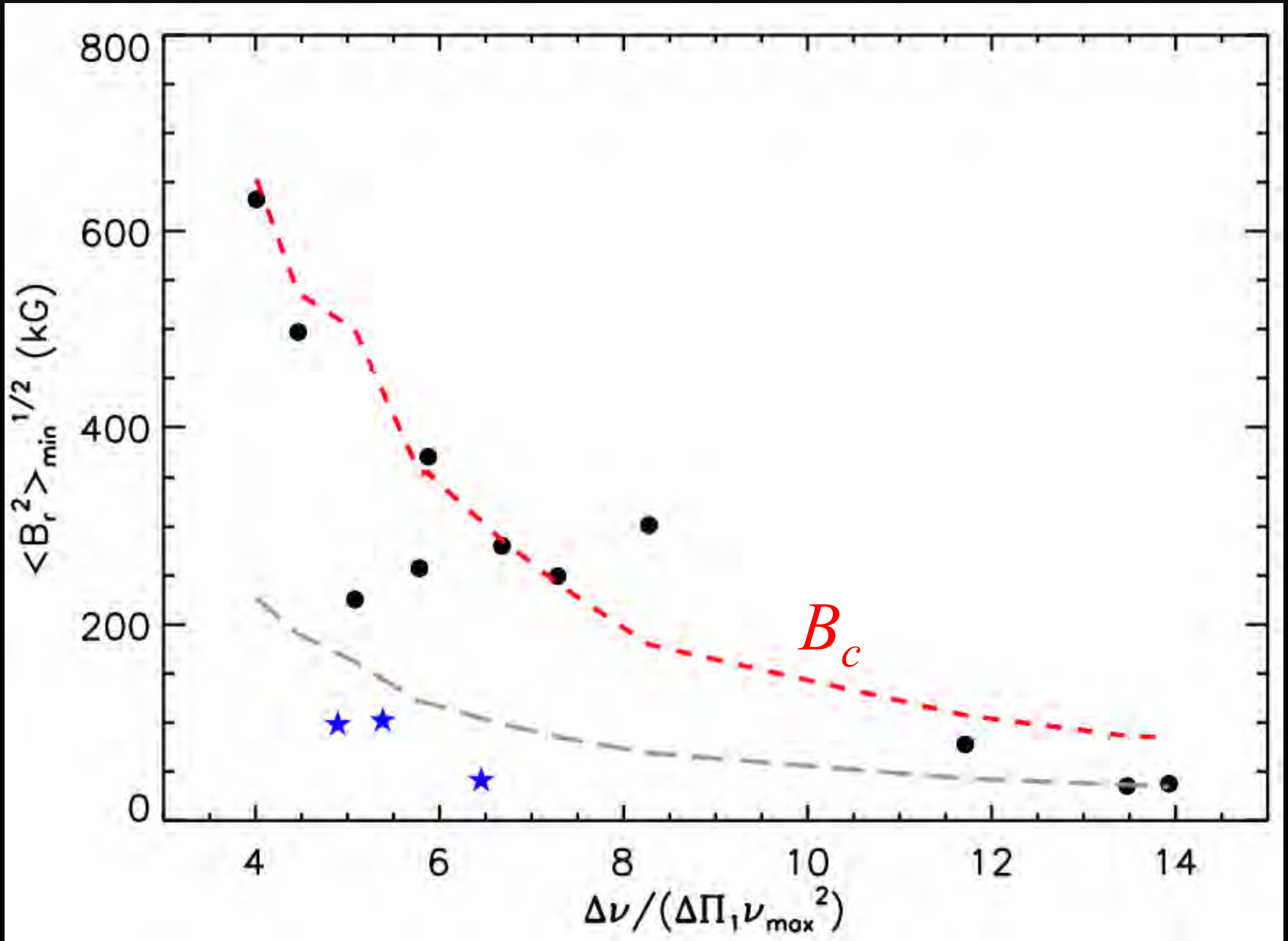
- Including both rotation and magnetic fields creates asymmetric l=1 triplets:



Das+ 2024

Magnetic fields in red giant cores

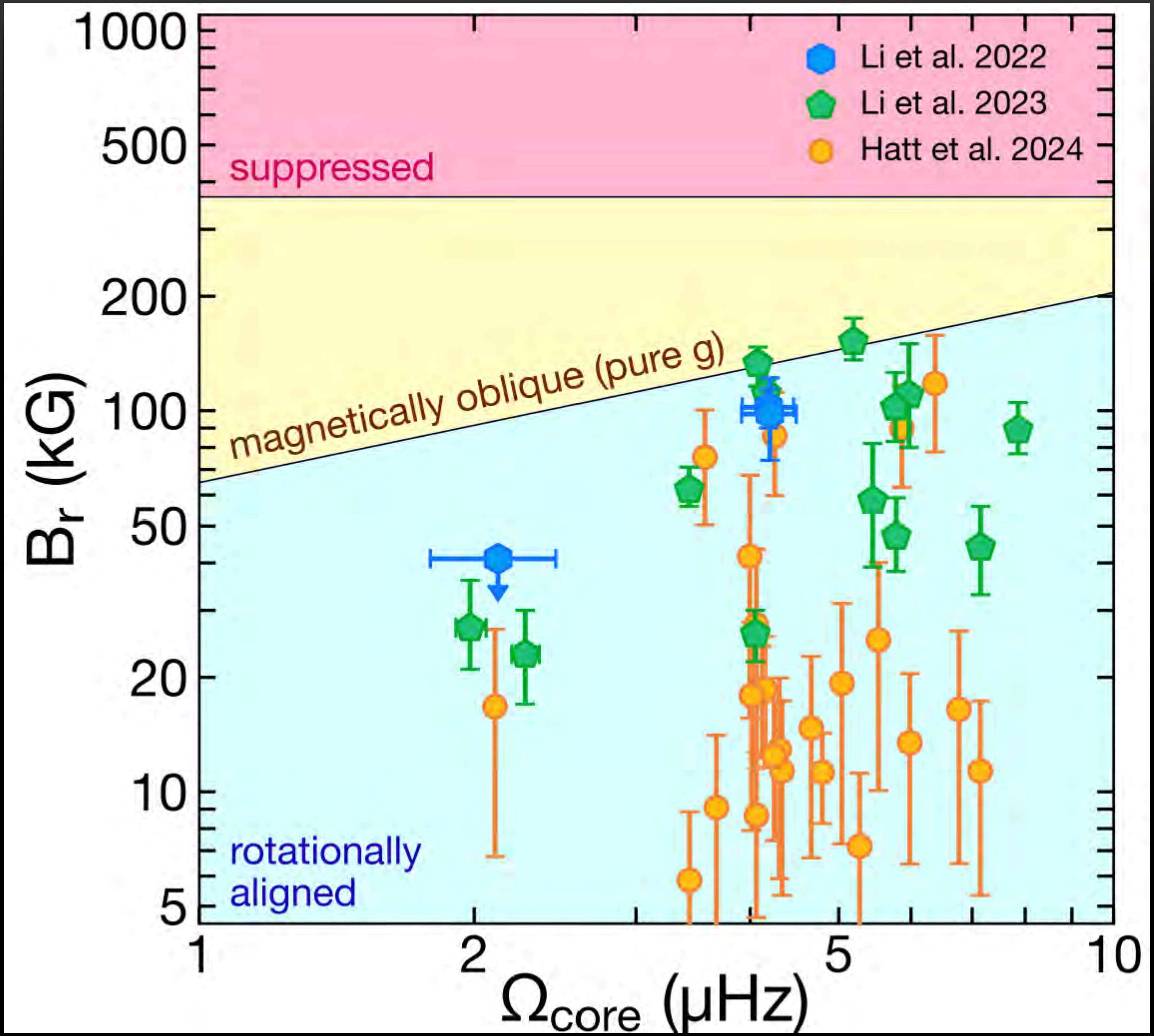
- Fields of ~10^5 G measured in a few dozen red giants
- Above a critical field strength, modes suppressed entirely



Deheuvels+ 2023

Oblique red giant pulsations

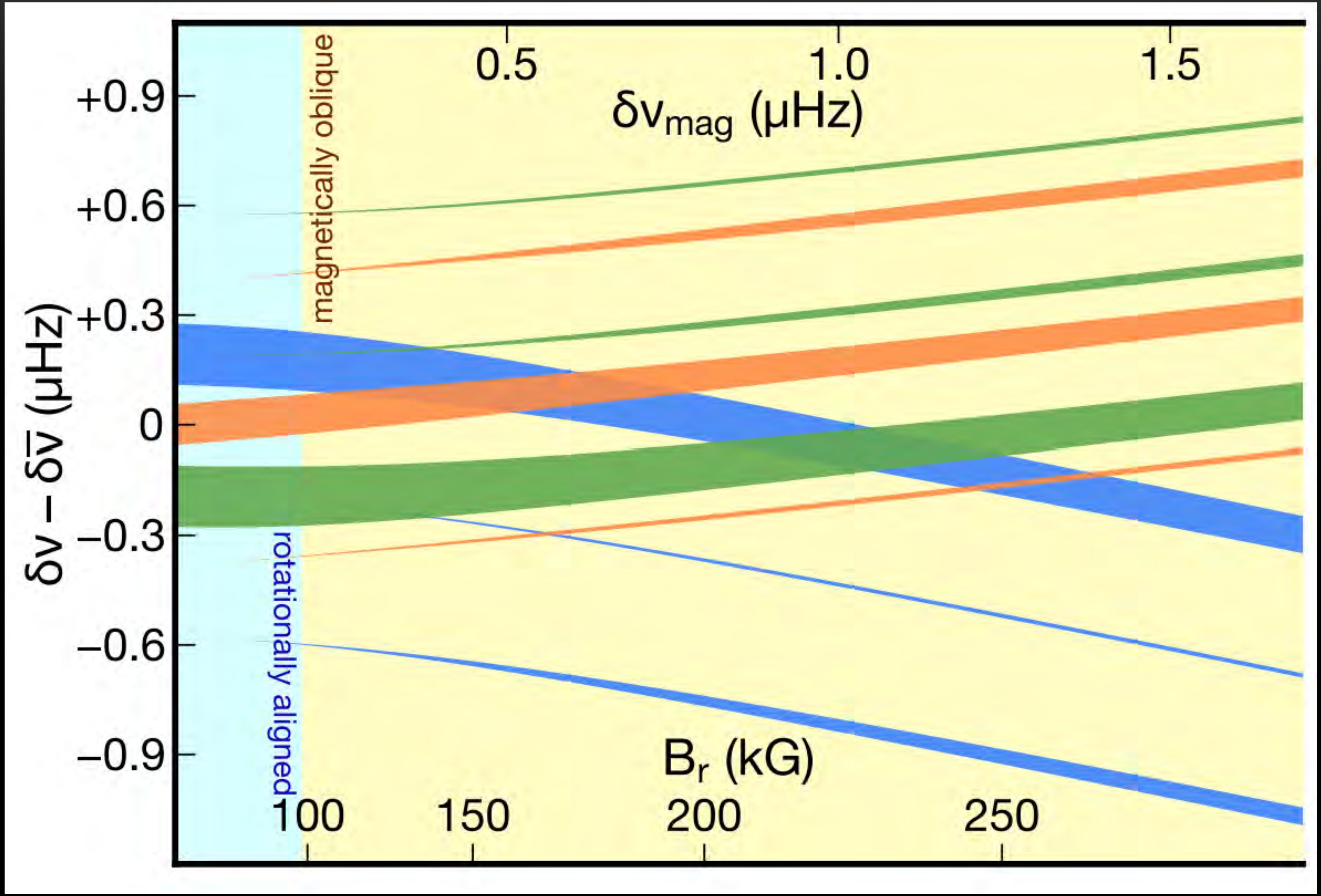
- Observed red giants are not oblique, but oblique pulsations likely exist



Rui & Fuller 2025

Magnetic and rotational perturbations

- Pulsations become oblique when magnetic frequency perturbations are larger than Coriolis perturbations

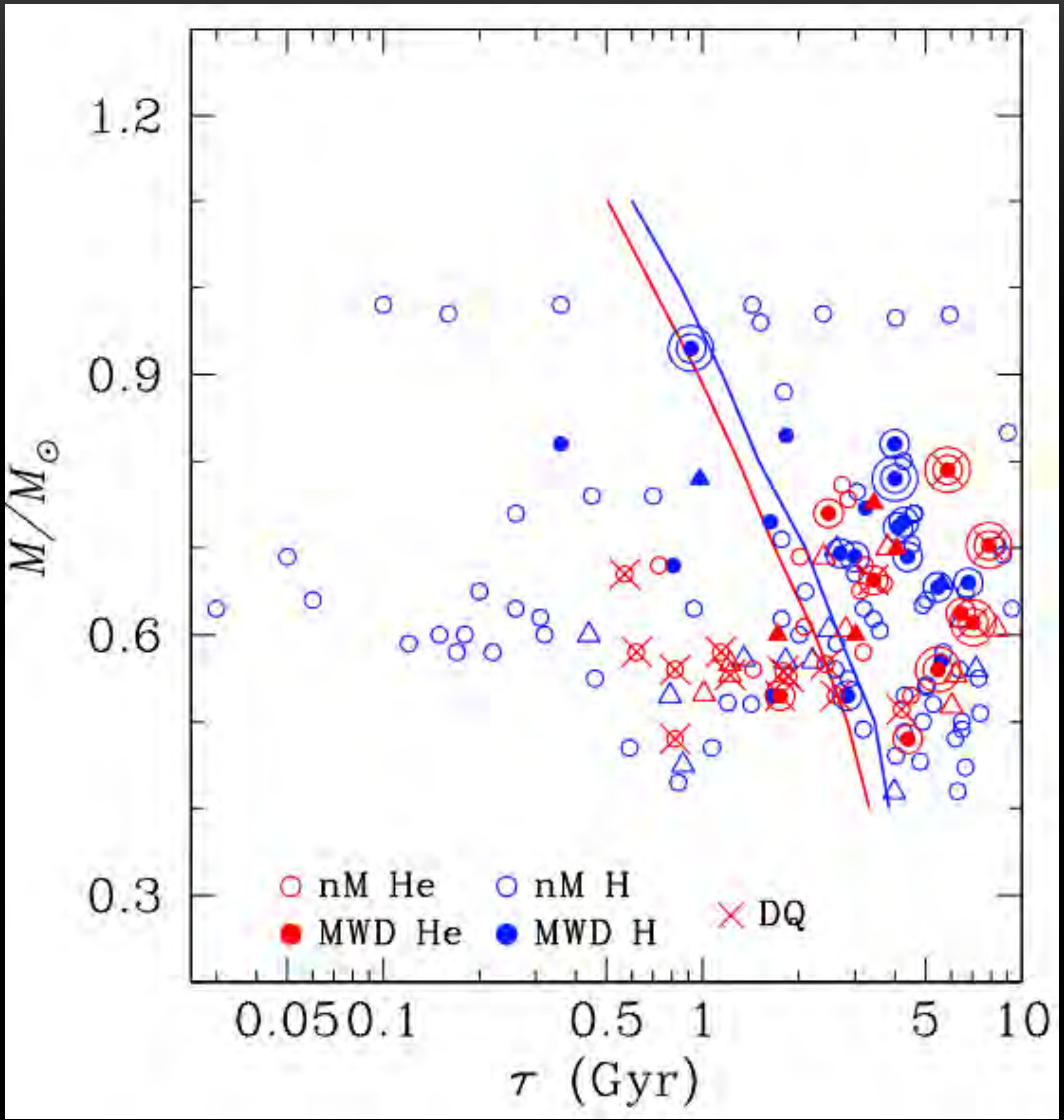


Rui & Fuller 2025

Magnetic White Dwarfs

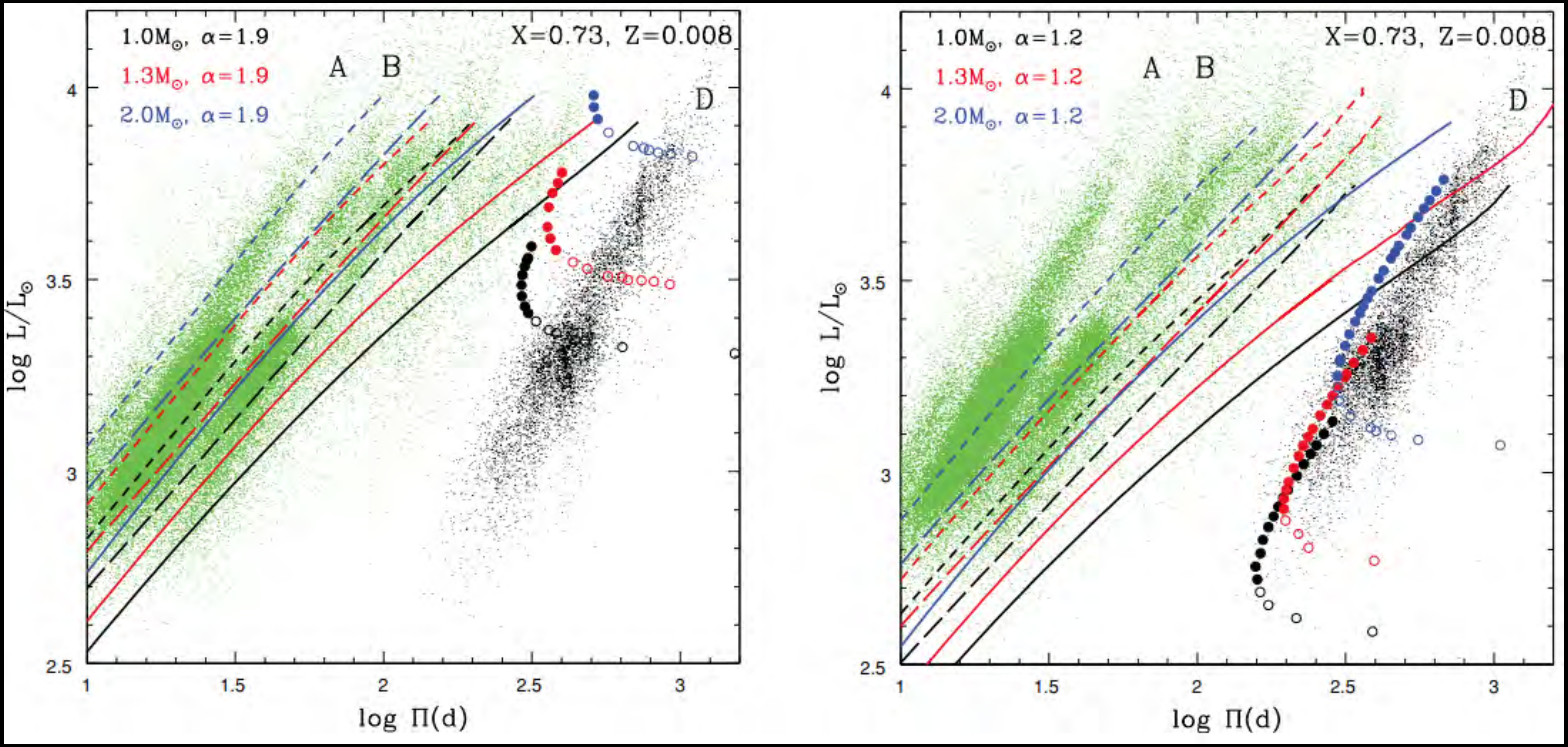
- White dwarfs become magnetic around the time they crystallize
- Crystallization-driven dynamo?

Bagnulo & Landstreet 2021



PROJECTS!

- Long secondary periods of pulsating red supergiants



Saio 2015

PROJECTS!

- Chromospheres and mass loss of red giants/supergiants
  - Perform Athena++ sims of red supergiants
  - Very computational

Projects!

- Asymmetry of crusts in moons subject to tidal heating
  - Thinner part of crust flexed more, heated more, melts and gets thinner
  - May explain why the thickness of crust varies in Moon, Enceladus, etc.
  - Analytical