Neutron star phase transition Probed via interfacial modes

Phys. Rev. D **107**, 083023

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Yangzhou, QCS-2023 2023-Sep-24

Outline

1: Neutron star structure and exotic dense matter phase

2: First order phase transition in NSs

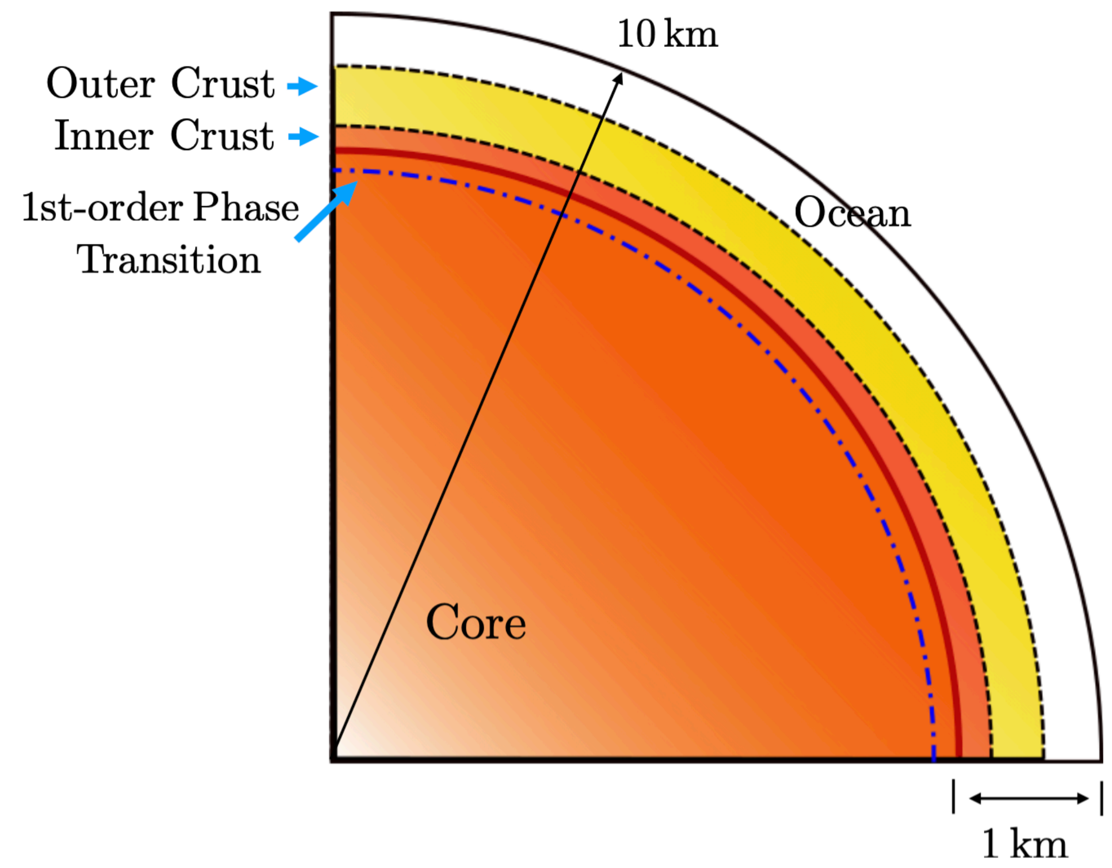
3: Neutron star seismology and Interfacial mode

4: Detectability using gravitational waves

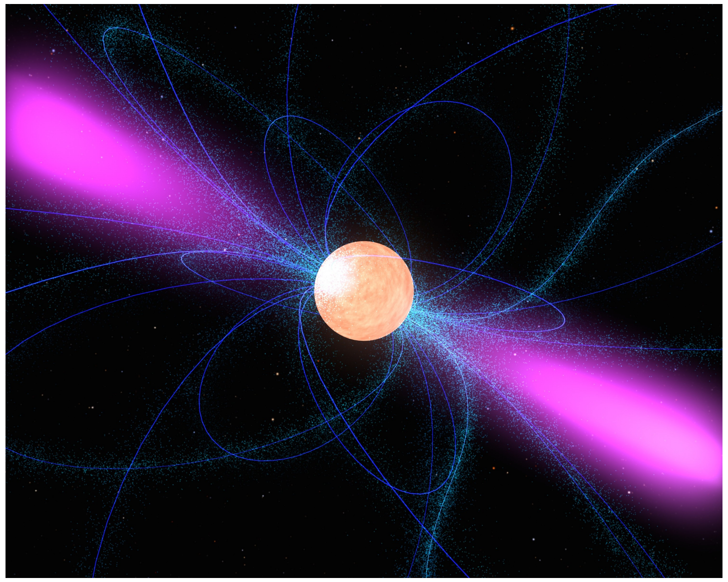
5: Discussions and Outlook

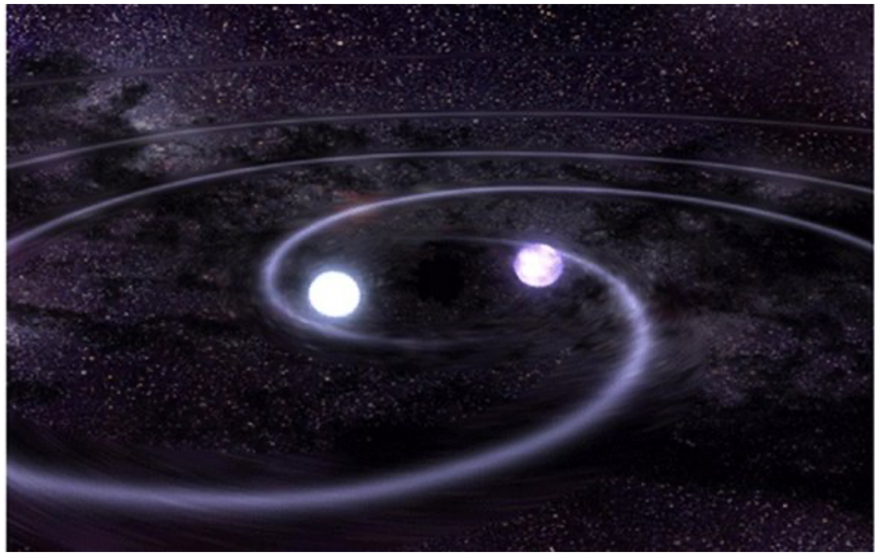
Neutron star structure

- Densest Star
- **Strong interacting matters**



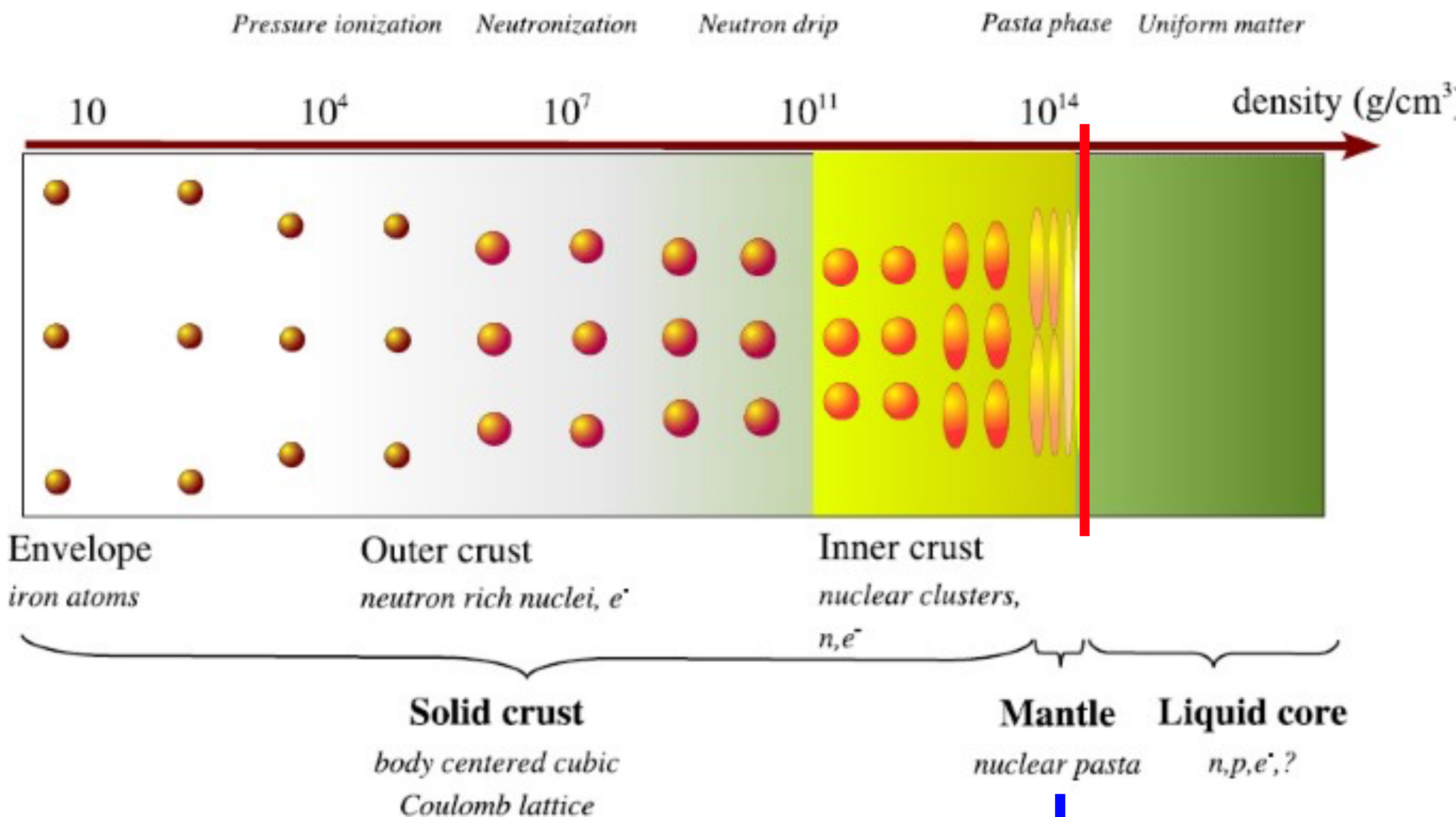
- Radio Pulsars
- Can form binary GW source





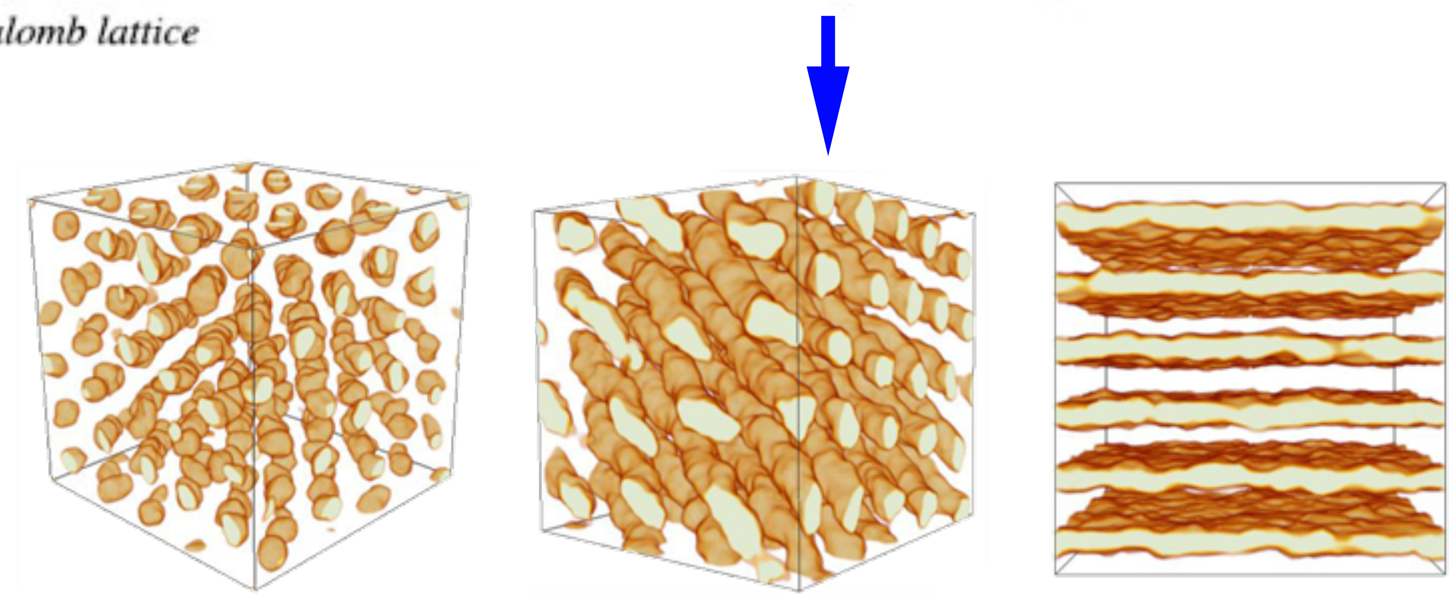
Neutron star matter: Crust+Mantle

Matter phase in an NS



Nuclear Pasta phase in an NS: crust-core transition

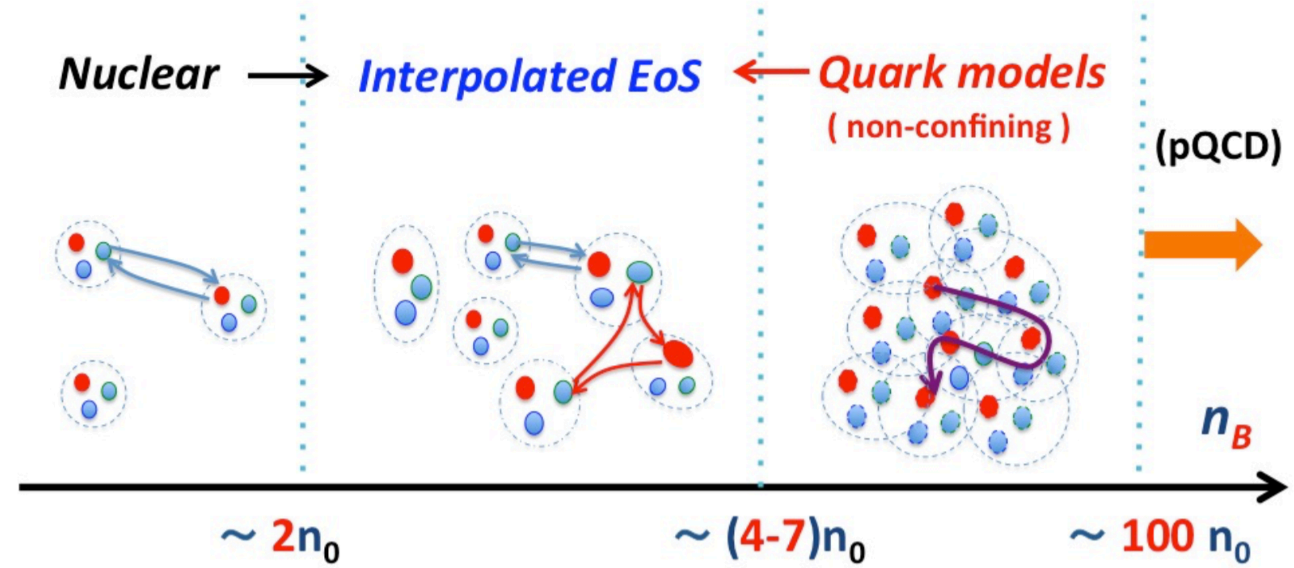
Shear modulus could jump



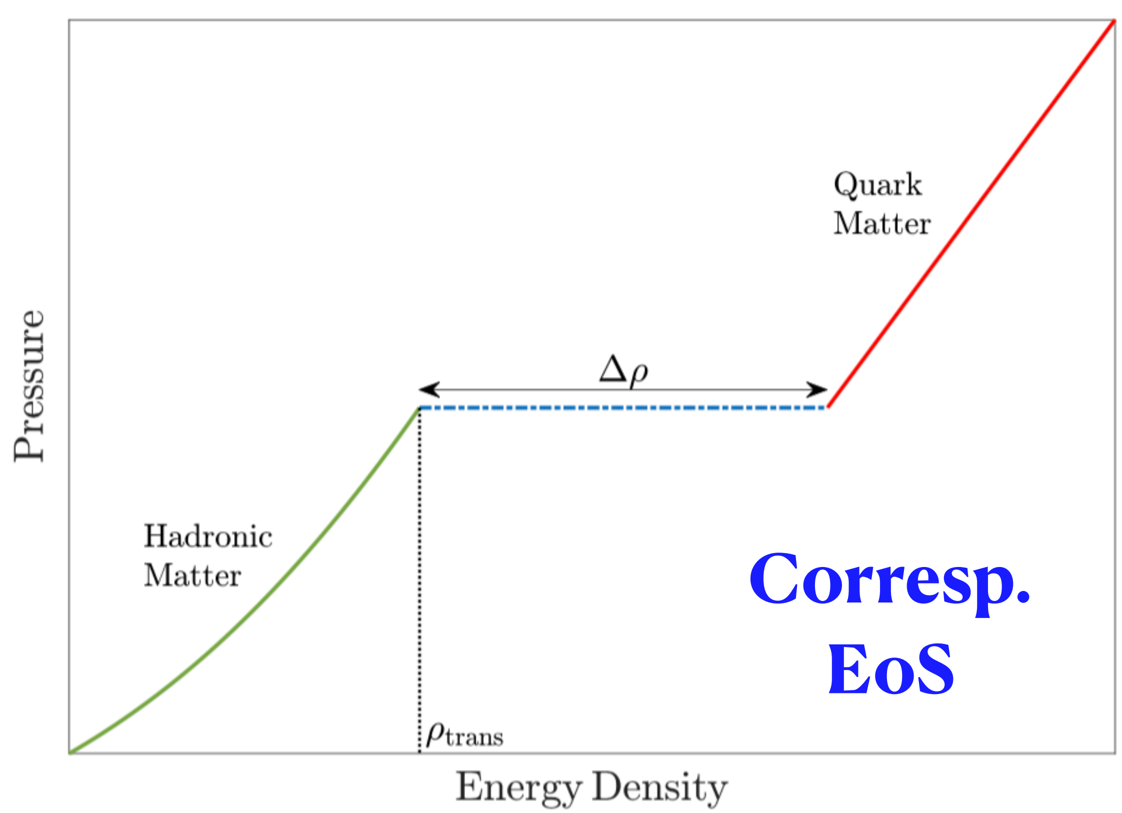
Neutron star matter: Inside the core

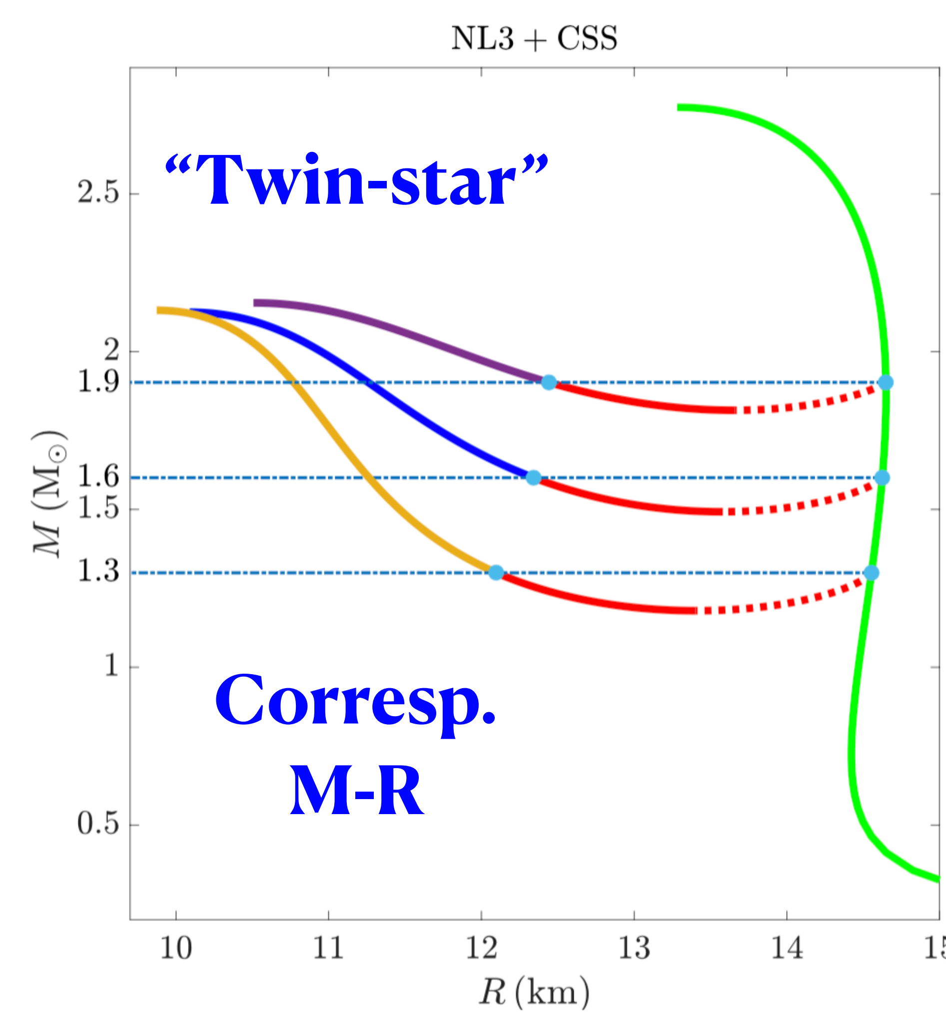
Possible
Hadron-Quark
Phase transition

1st order transition



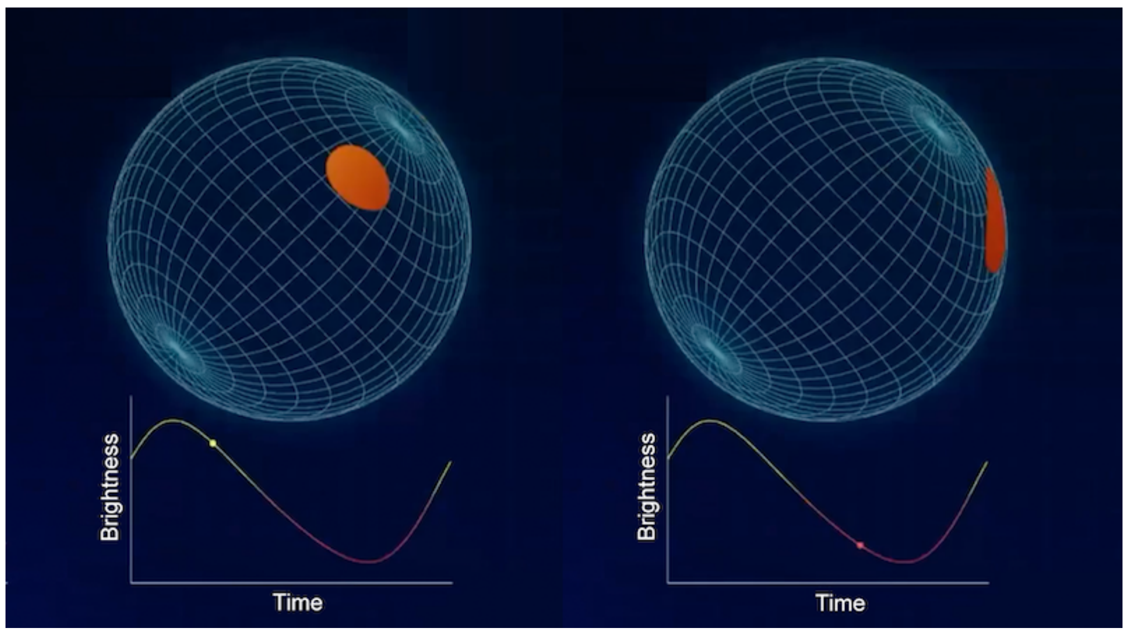
Alford, Han, and Prakash, Phys. Rev. D 88, 083013 (2013)

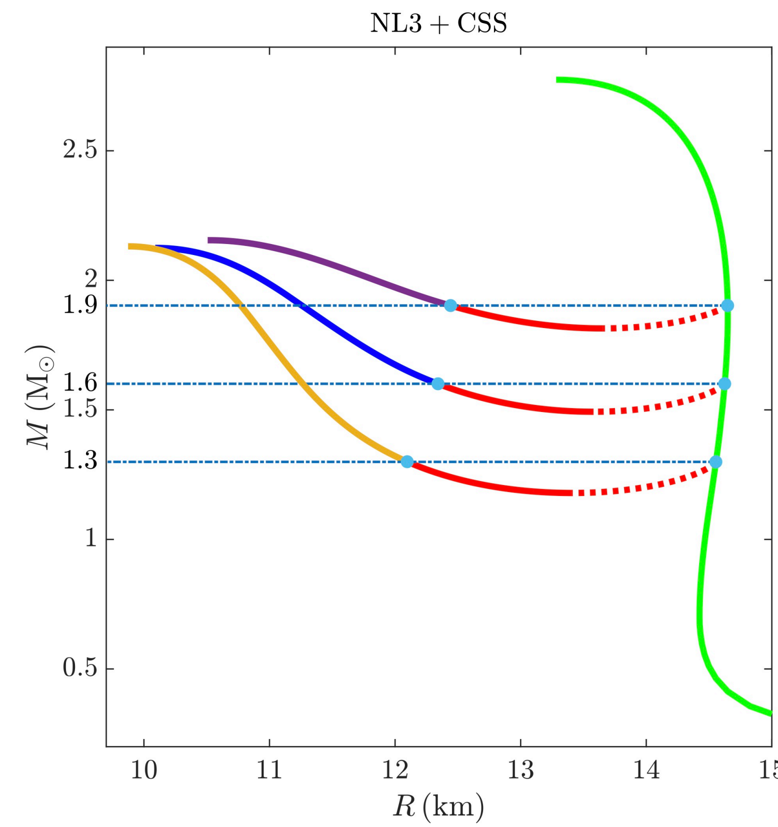




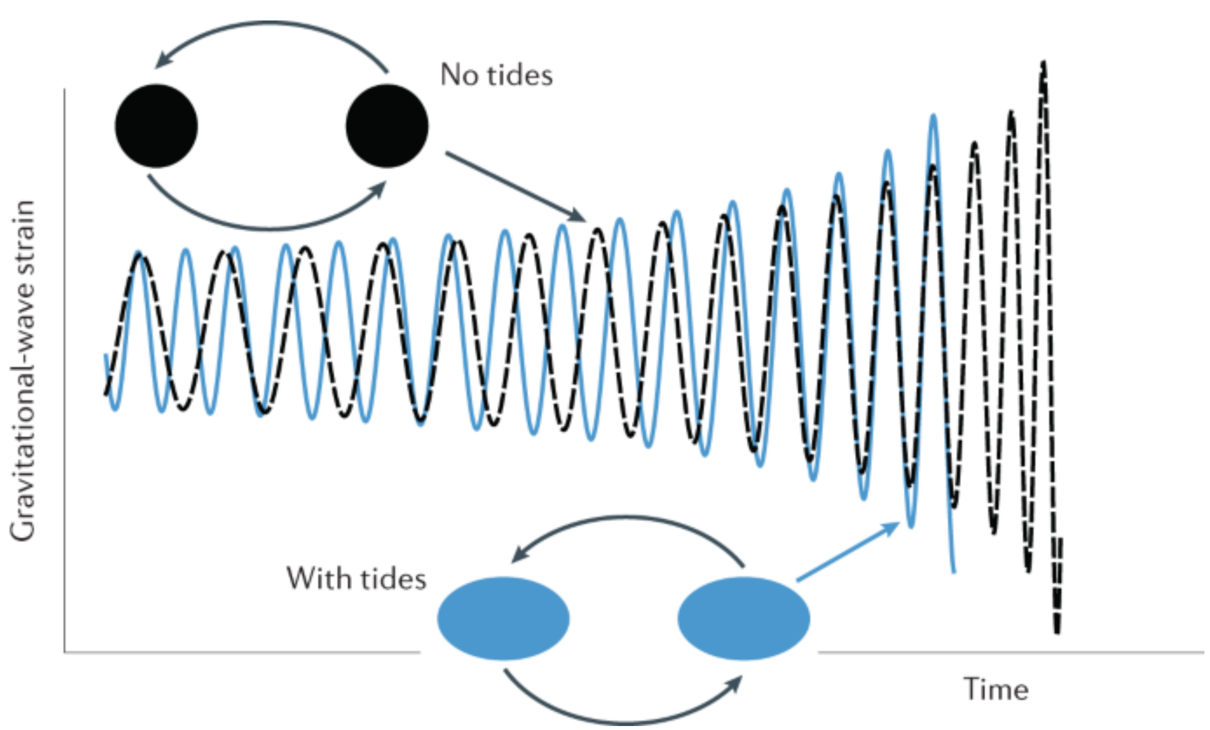
Constraint the Matter Phase

M-R relation example: NS/HS





(adiabatic) Tidal deformability



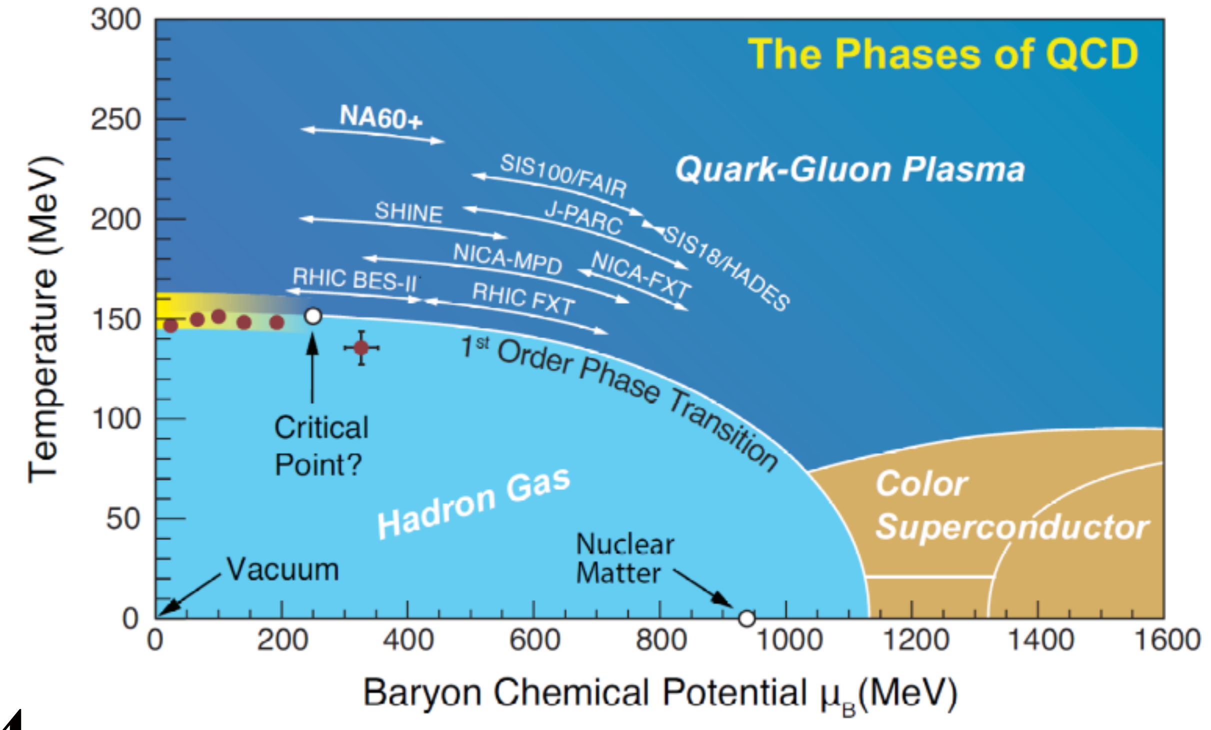
A question:

Resolve detailed Structure of EoS?

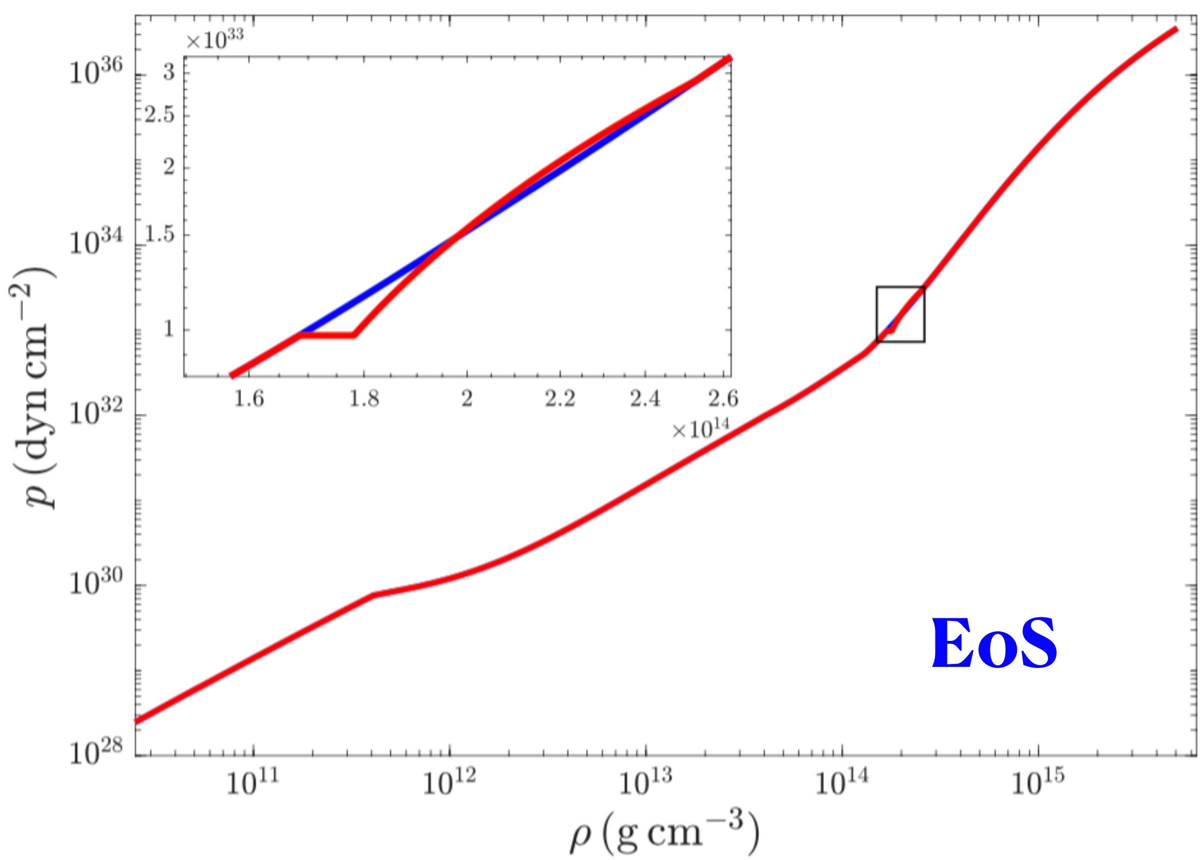
Detailed structure of EoS

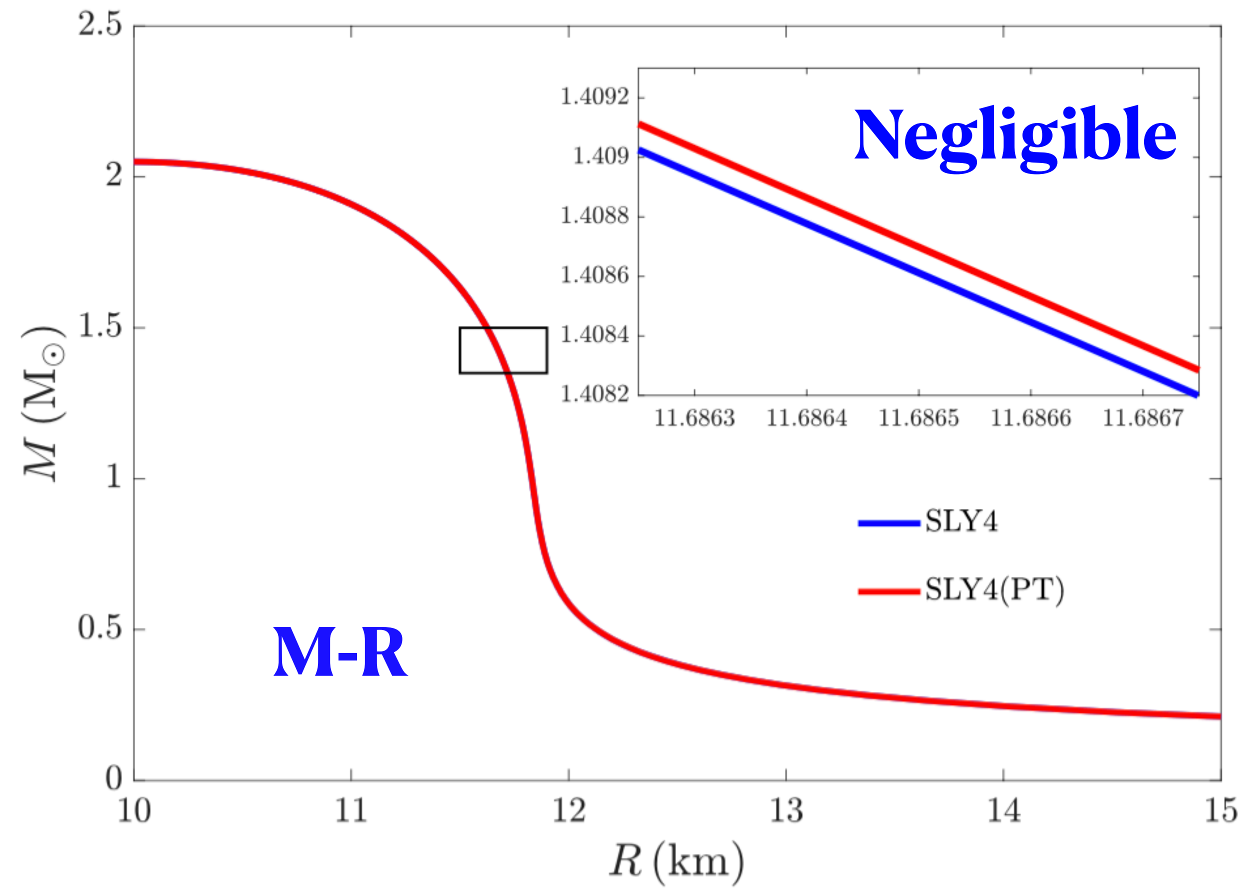
Possible "weak 1st order transition"

Emergence of new baryonic state?

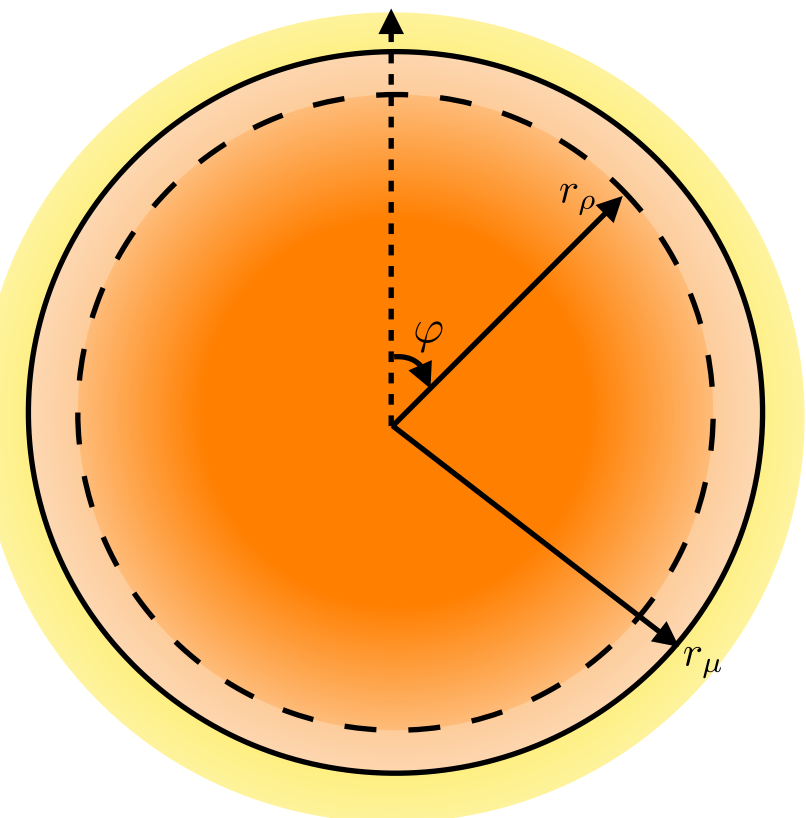


Construct a weak 1st PT on the SLy4

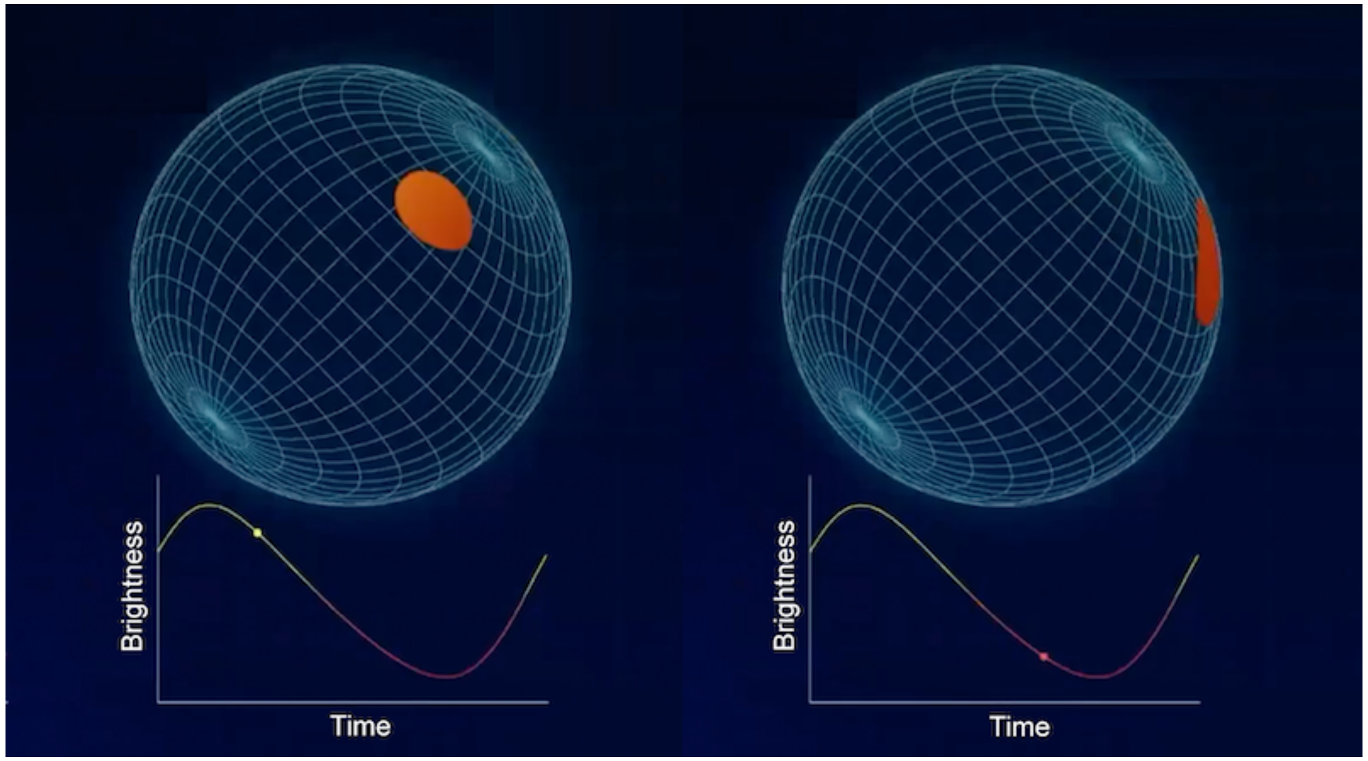




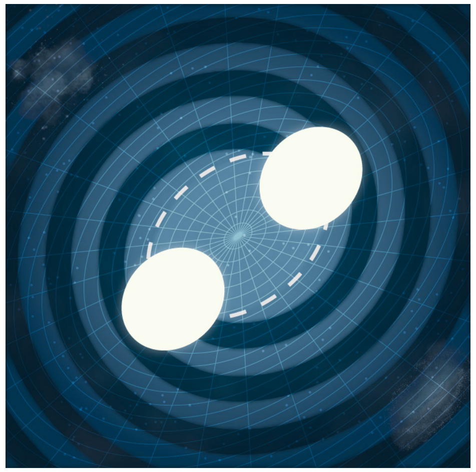
Probing weak phase transitions?



Density discontinuity effect on the M-R



Minor!



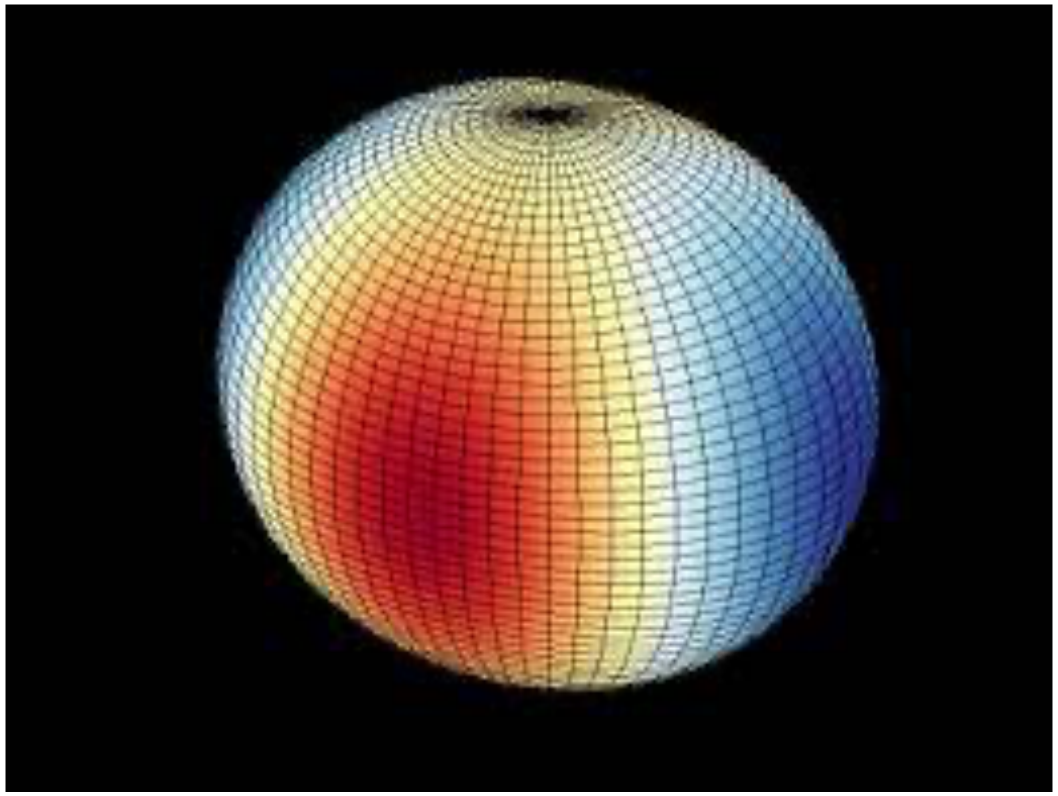
Density discontinuity effect on the tidal deformability

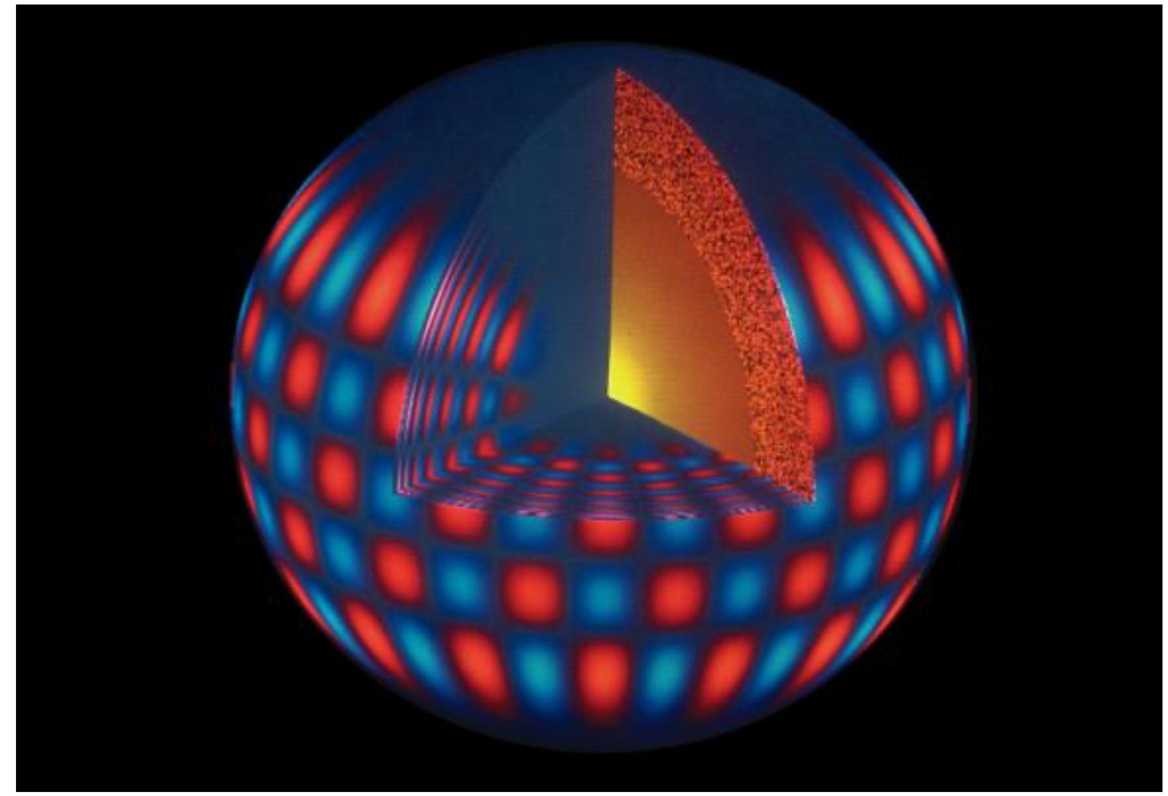
Minor!

EoS	SKI6	RS	SLY4	APR4	DD2	DDME2	TW	DD-LZ1
Λ	488	597	299	248	682	712	406	722
$\Lambda_{\rm PT}$	496	651	303	260	714	738	424	755

Only dynamical tide helps!

Neutron star seismology



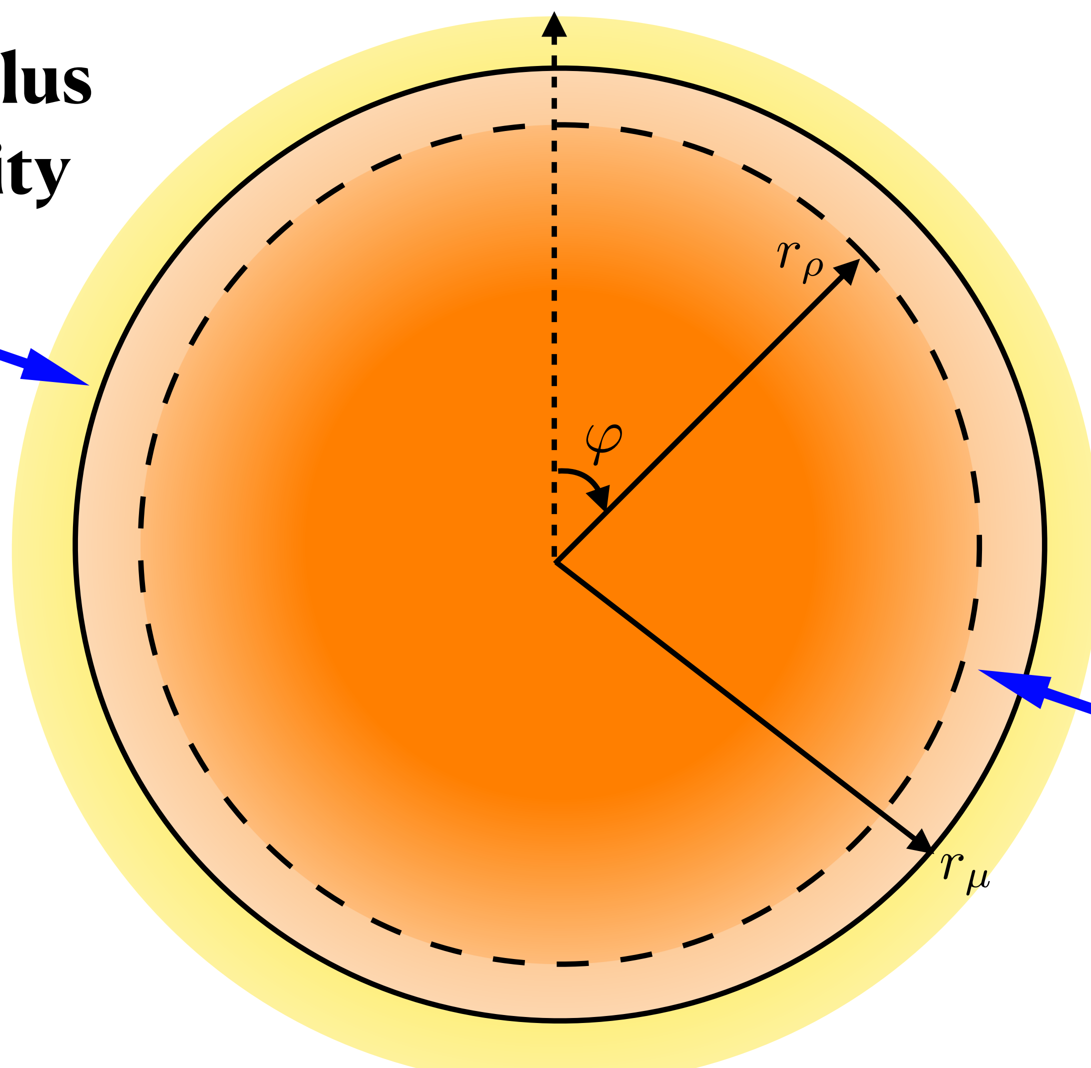


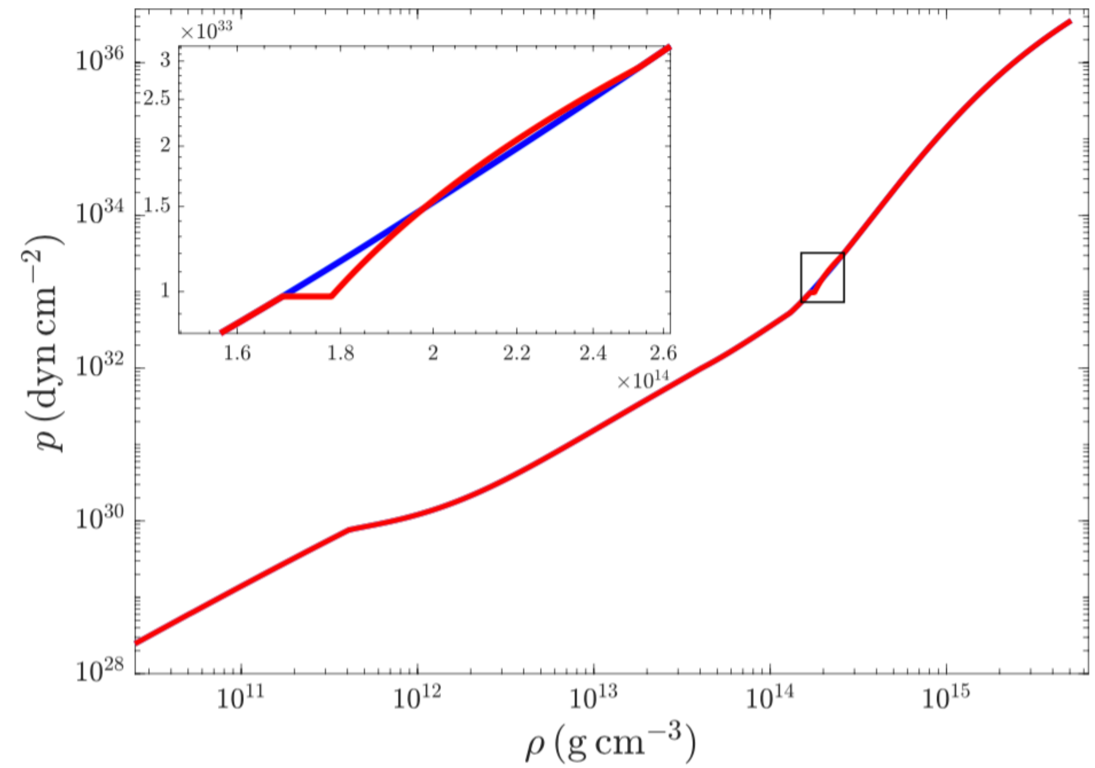
- **These oscillation modes are affected by EoS, e.g.** $$\Gamma = \frac{d\ln P}{d\ln \rho}$$
- **Can be excited by tidal motion, and NS coalescence**
- **Can couple to the orbital motion, and affect GW radiation**

Neutron star Interfacial mode

The Model

Shear Modulus Discontinuity Interface

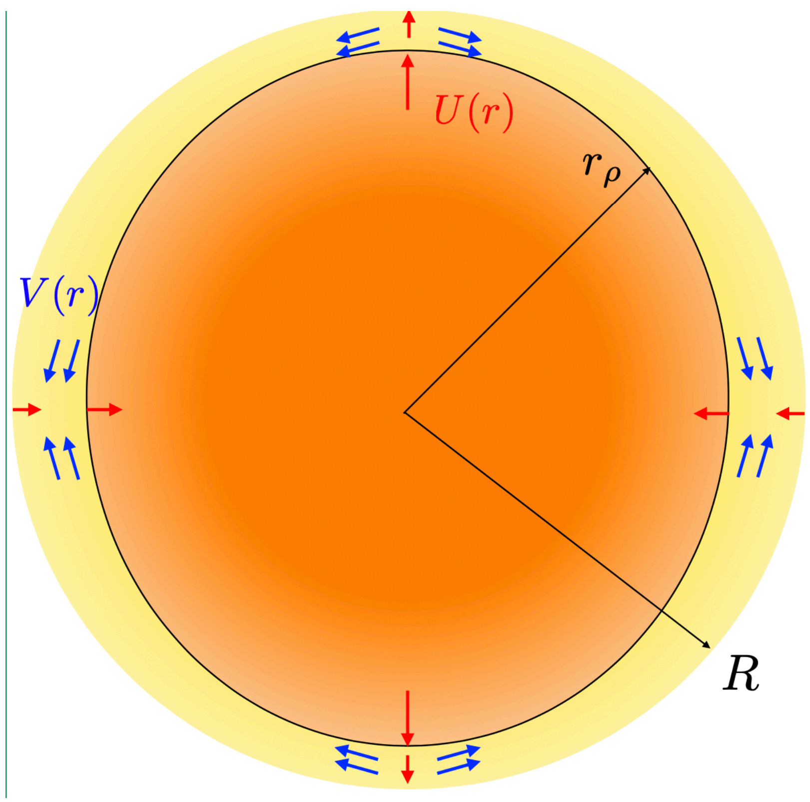




Target

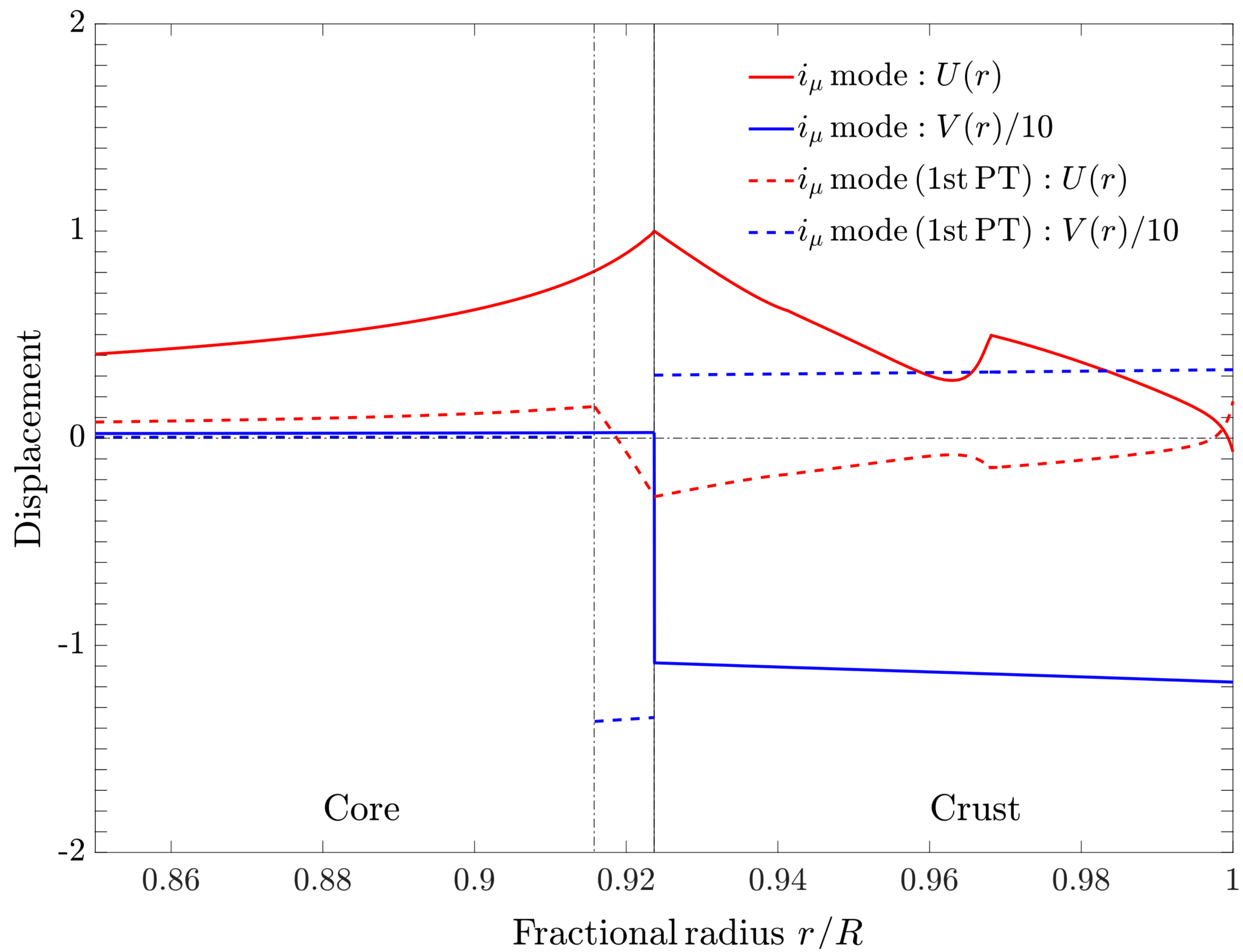
Density Discontinuity Interface

Neutron star Interfacial mode- i_μ



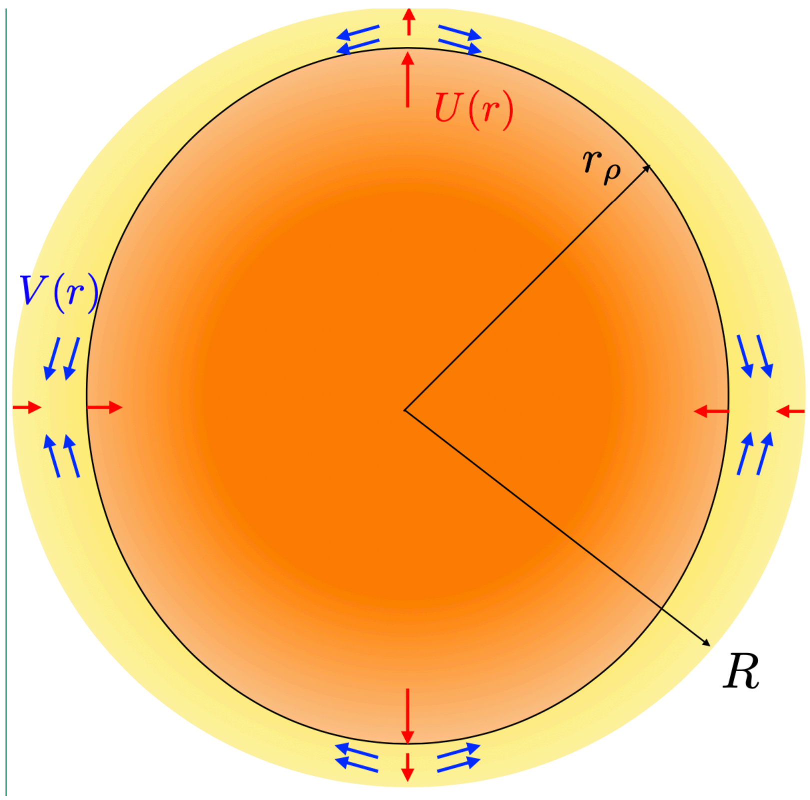
Wave function of the shear interfacial mode

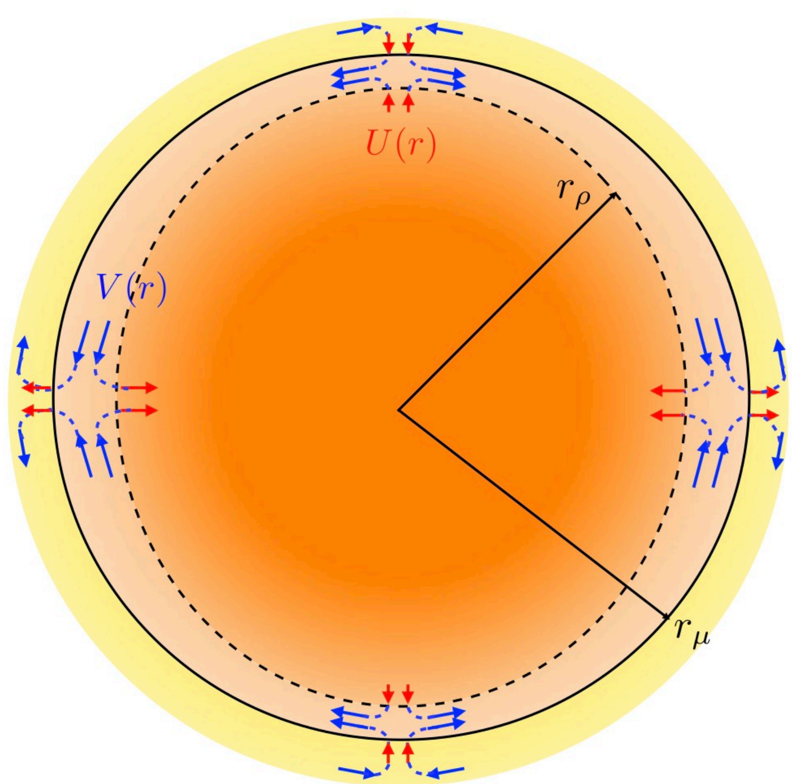
Solid line: Pure shear interfacial mode



- **Low frequency**
- **Strong interfacial Excitations**
- **Large orbital coupling**

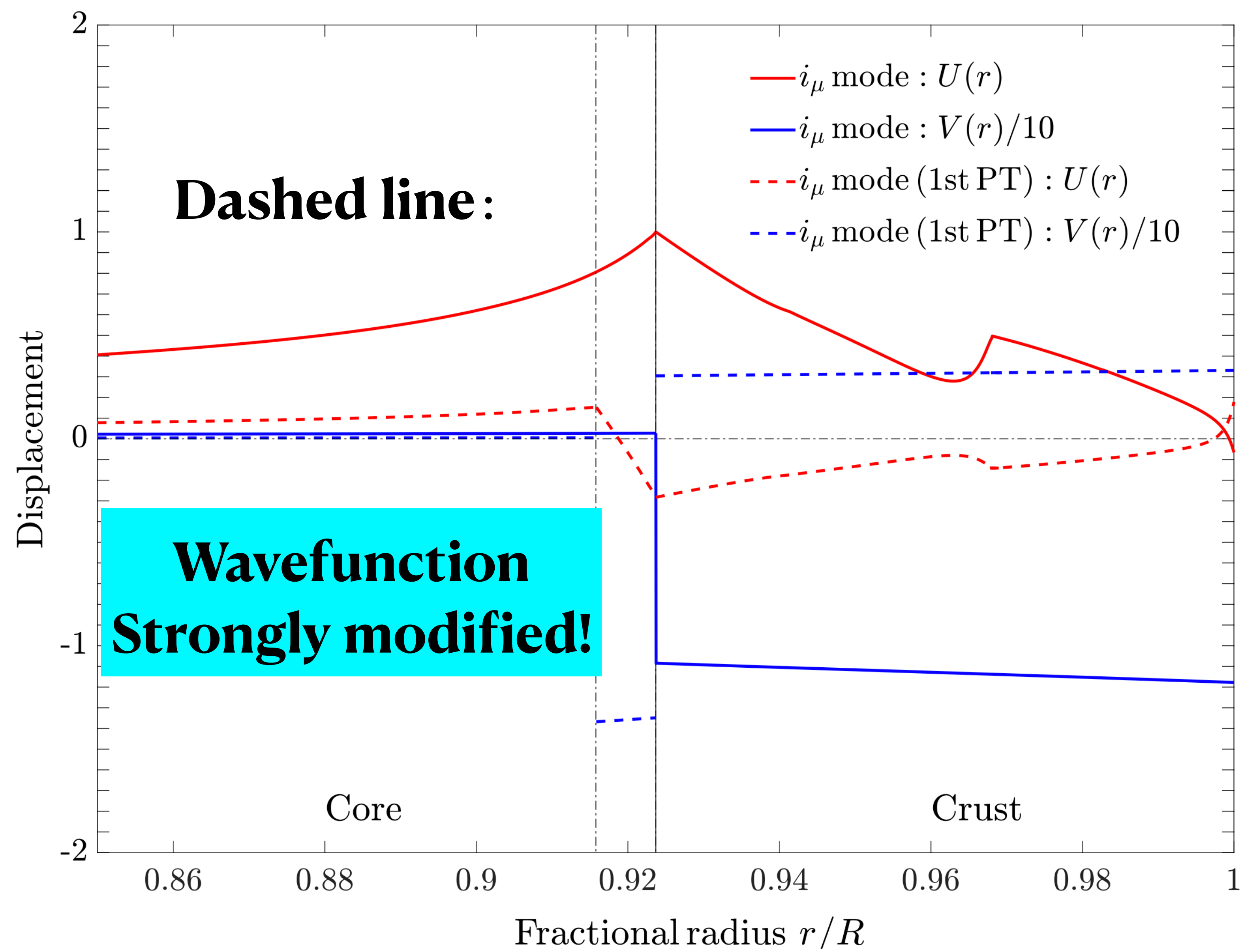
Neutron star Interfacial mode- i_μ



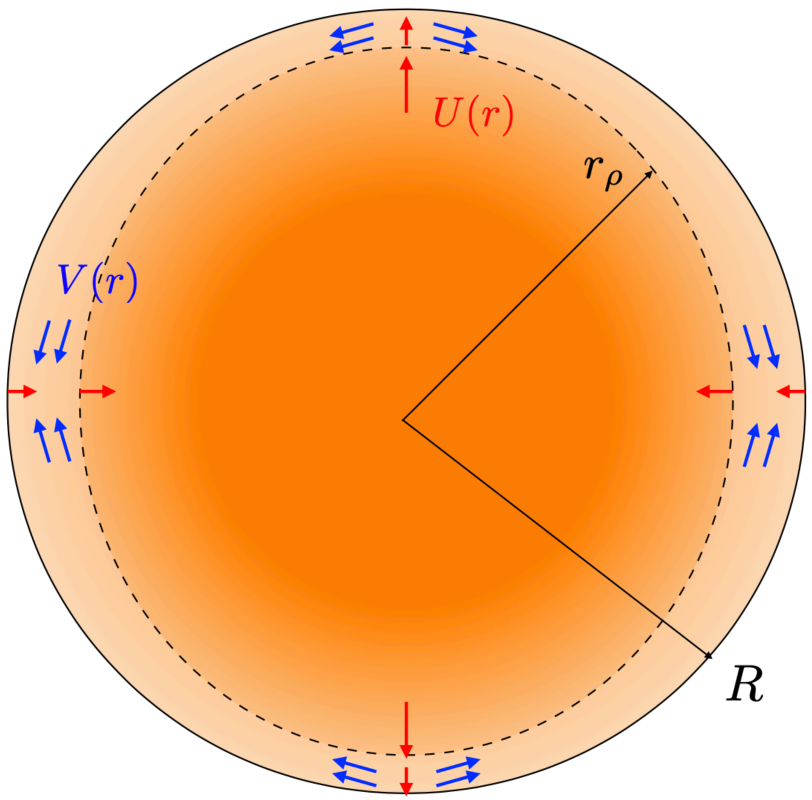


Wave function of the shear interfacial mode—Introduce PT at r_ρ

Domin: Free-slipping fluid $r_\rho < r < r_\mu$

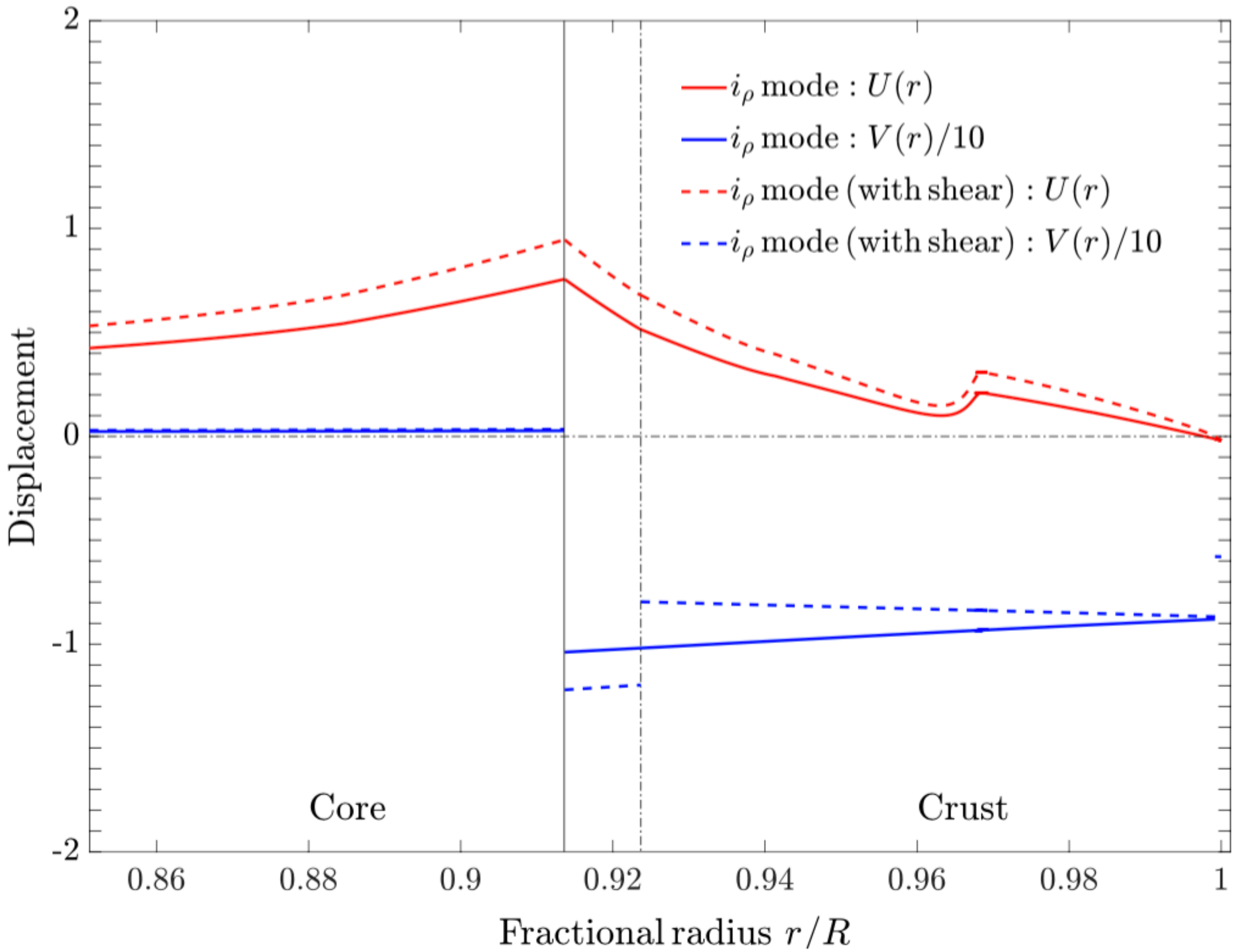


Neutron star Interfacial mode- i_ρ



Wave function of the density interfacial mode

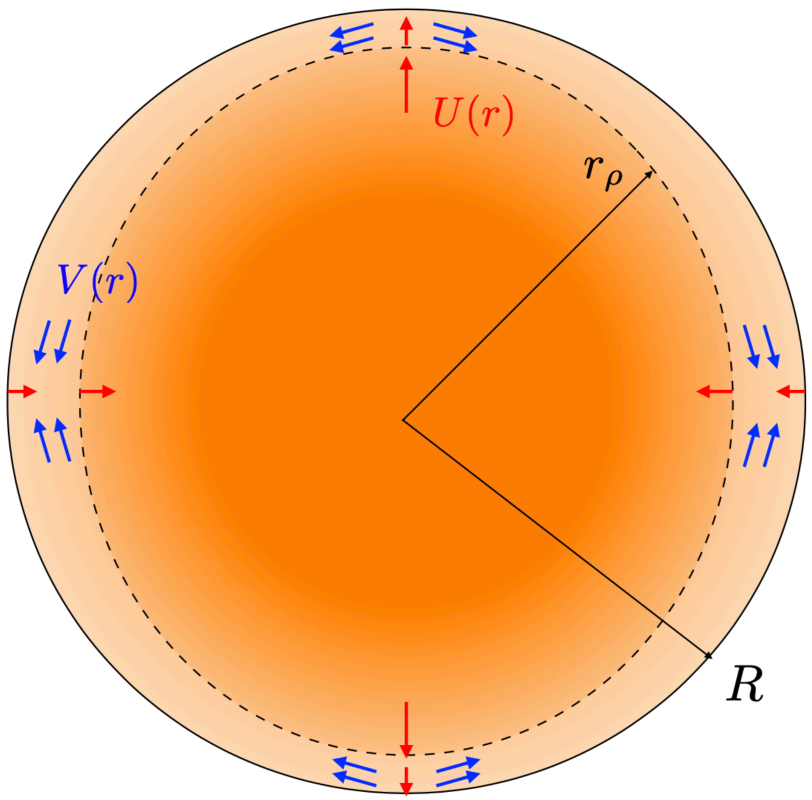
Domin: Core fluid $r > r_\rho$

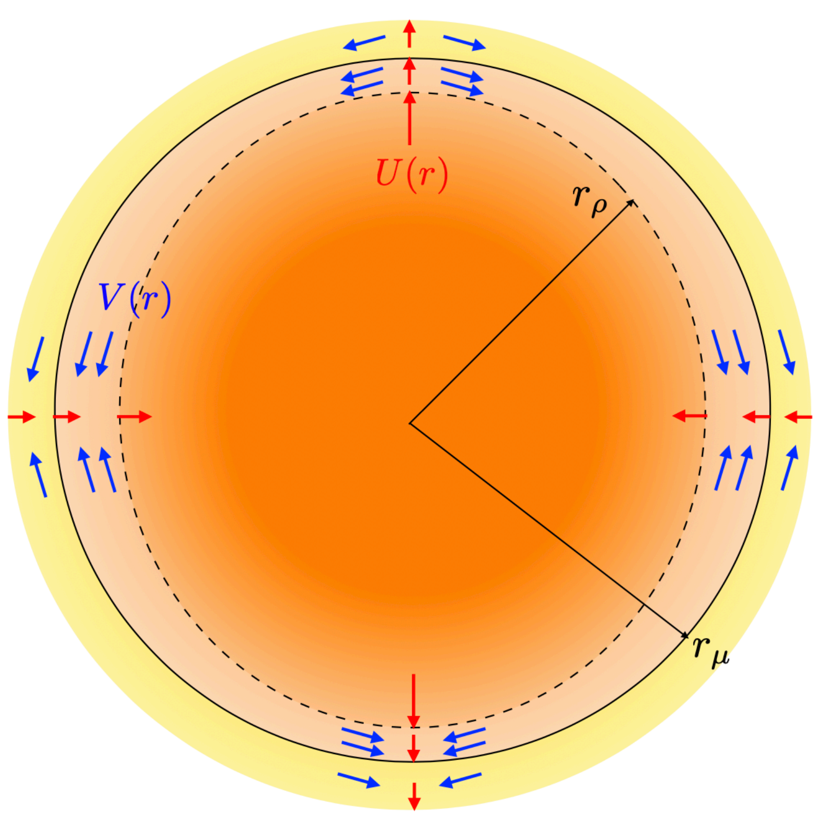


Similar to Kelvin-Helmholtz mode

- **Higher frequency**
- **Strong interfacial Excitations**
- **Large orbital coupling**

Neutron star Interfacial mode- i_ρ





Wave function of the density interfacial mode

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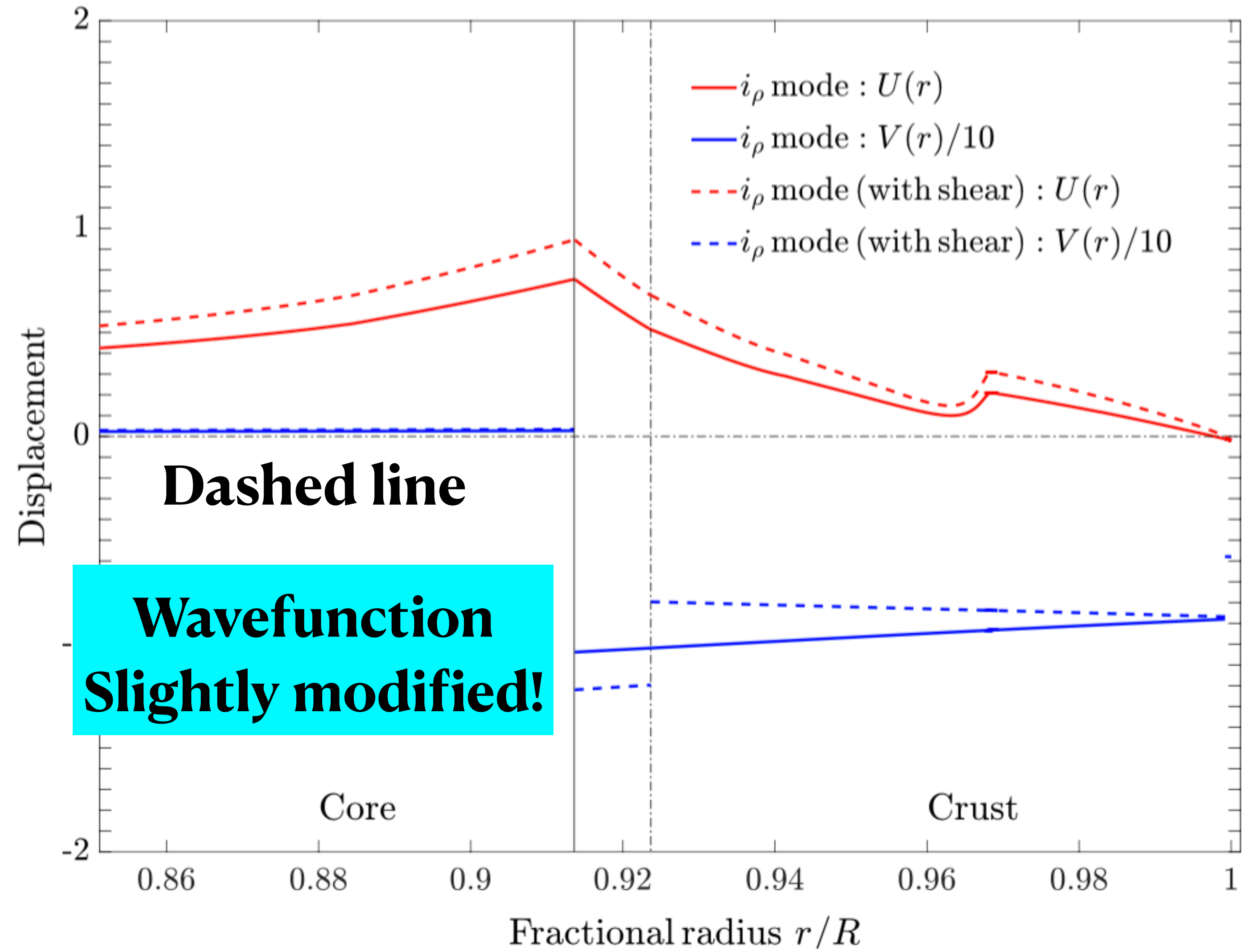


Dashed line

Wavefunction Slightly modified!

Mode mixing of $i_\mu - i_\rho$

Hamiltonian

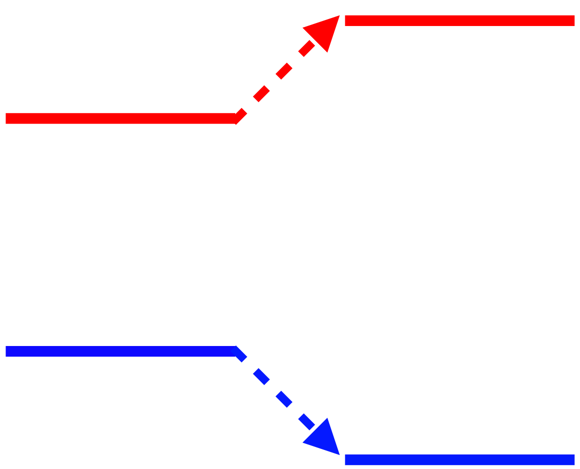
$$\mathcal{H} = \left(\xi_\mu, \xi_\rho \right) \begin{pmatrix} \omega_\mu & \epsilon \\ \epsilon & \omega_\rho \end{pmatrix} \begin{pmatrix} \xi_\mu \\ \xi_\rho \end{pmatrix}$$

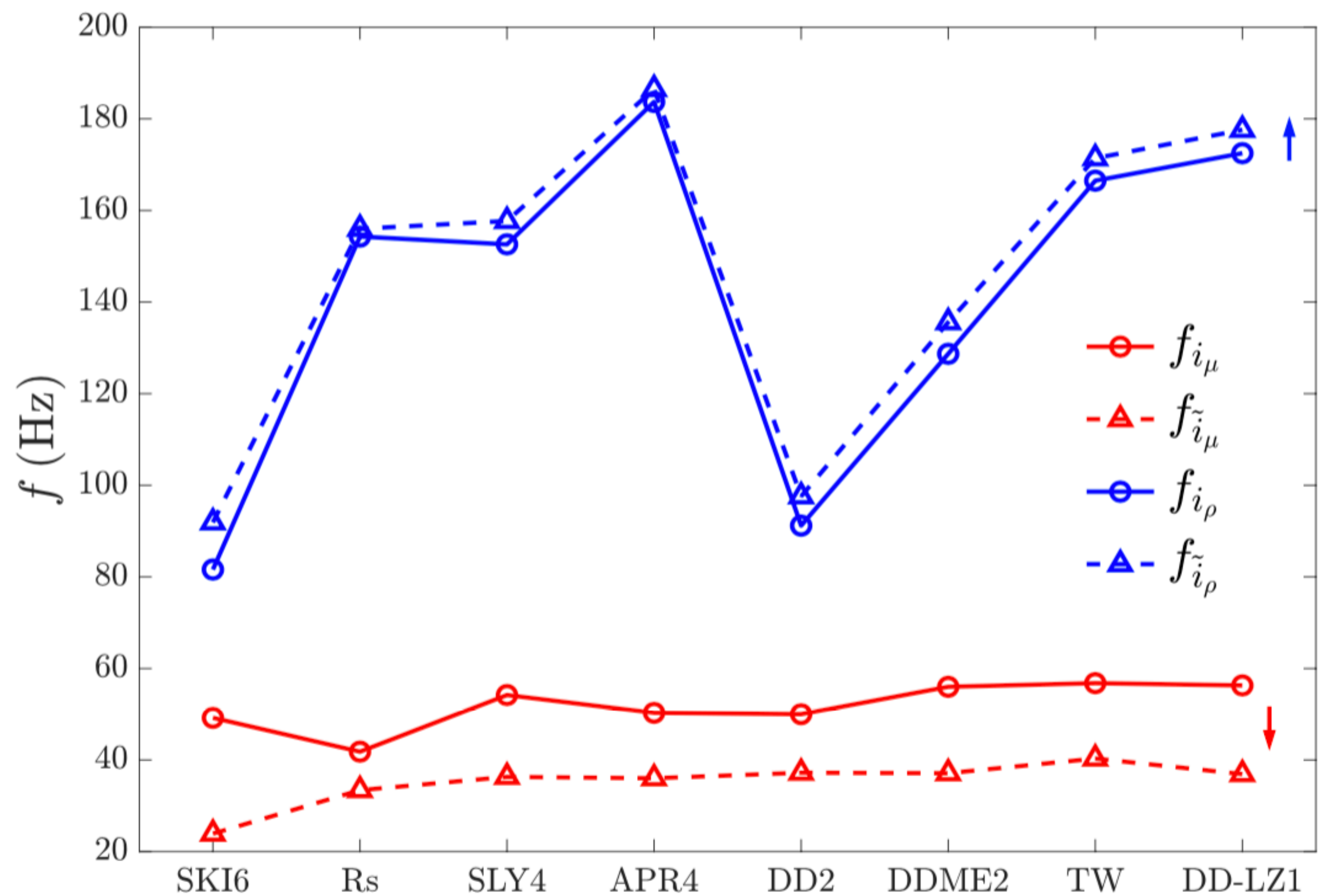
Significant Overlap

Between

$i_\mu - i_\rho$

Avoid crossing

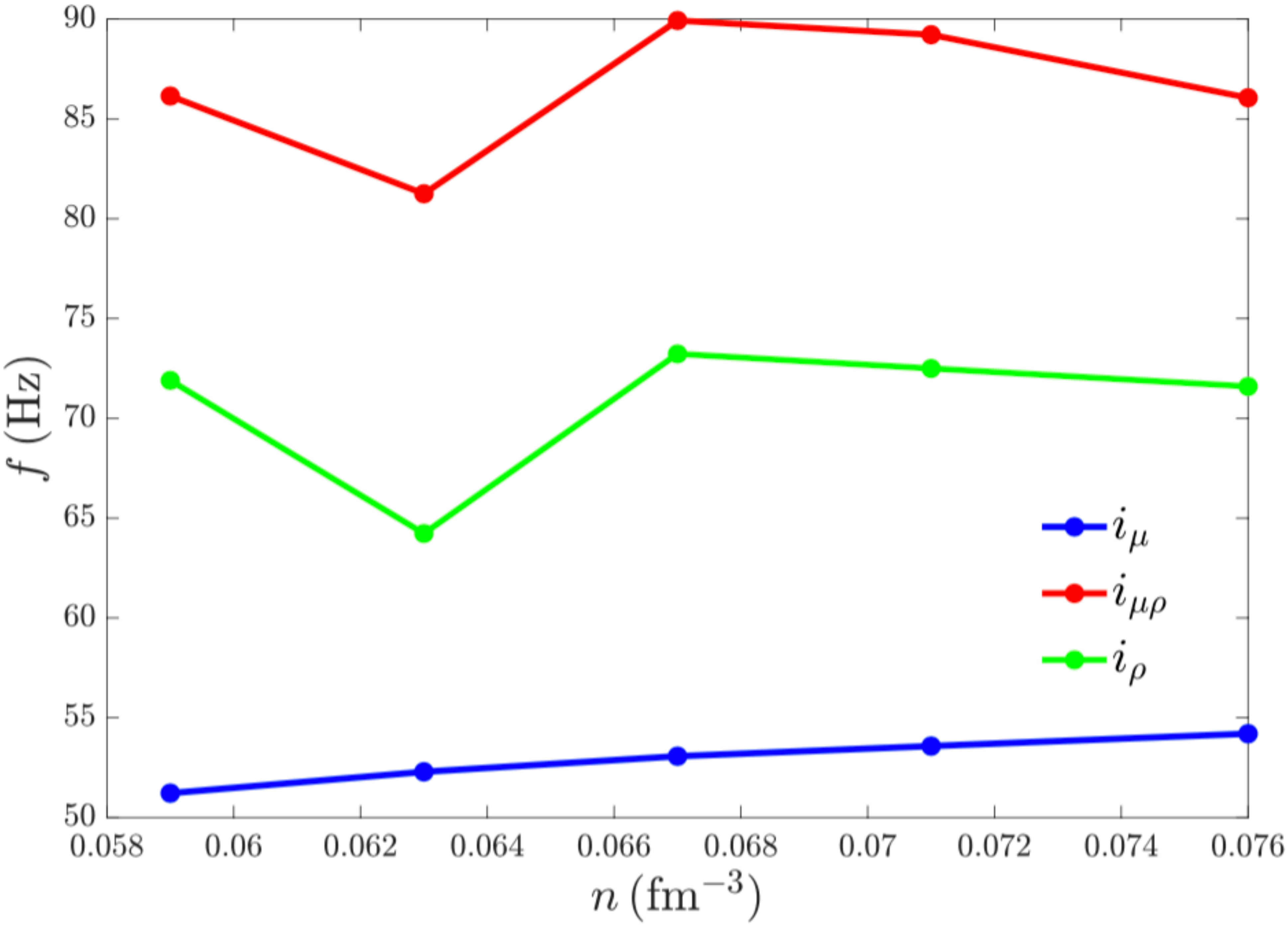




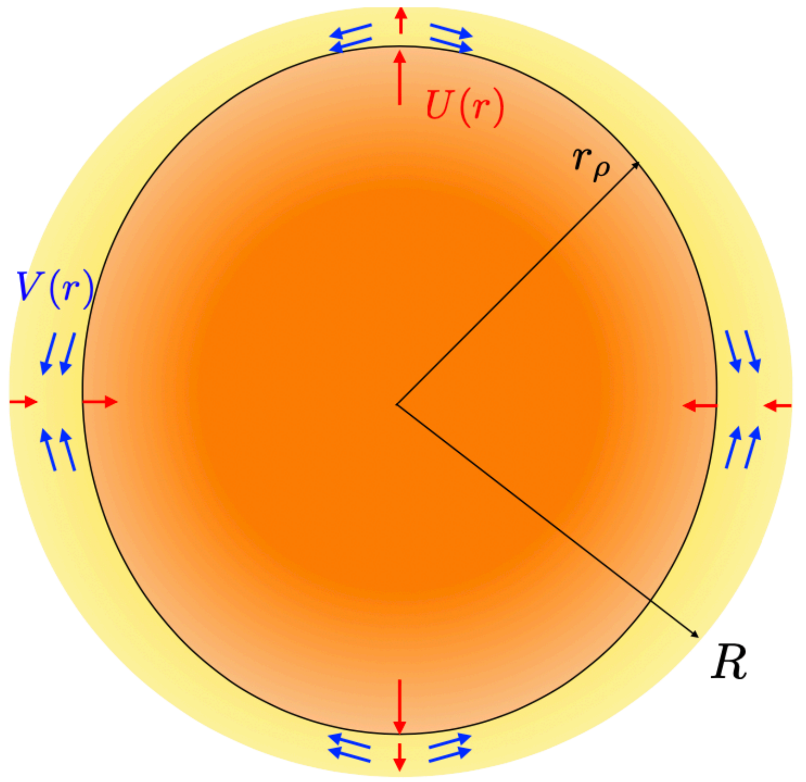
$$\tilde{\omega}_\rho = \frac{1}{2}[\omega_\mu + \omega_\rho + \sqrt{(\omega_\mu - \omega_\rho)^2 + 4\epsilon^2}] > \omega_\rho,$$

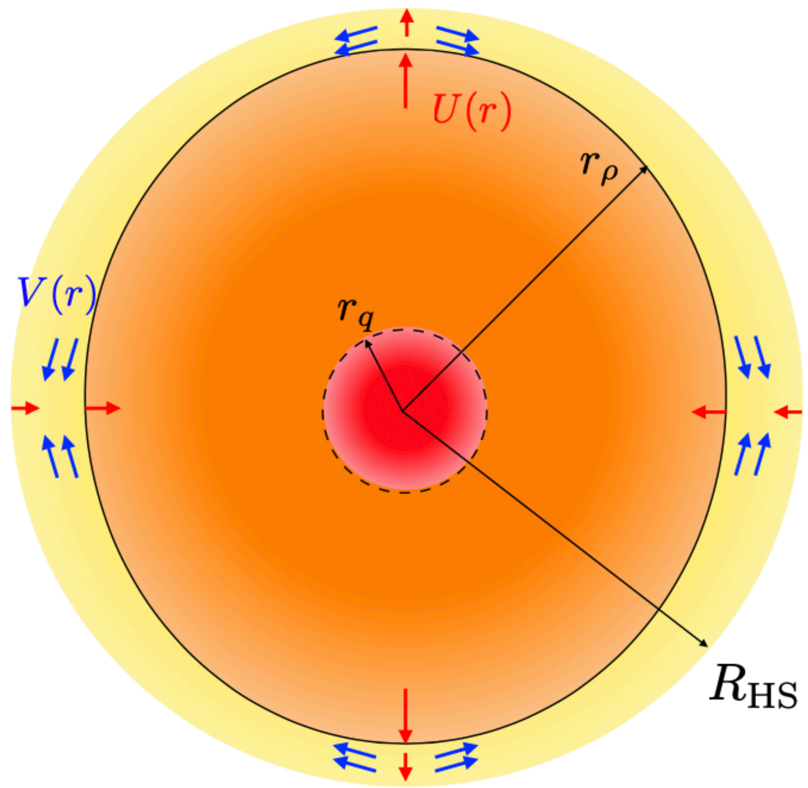
$$\tilde{\omega}_\mu = \frac{1}{2}[\omega_\mu + \omega_\rho - \sqrt{(\omega_\mu - \omega_\rho)^2 + 4\epsilon^2}] < \omega_\mu,$$

Extremal case: coincide interfaces

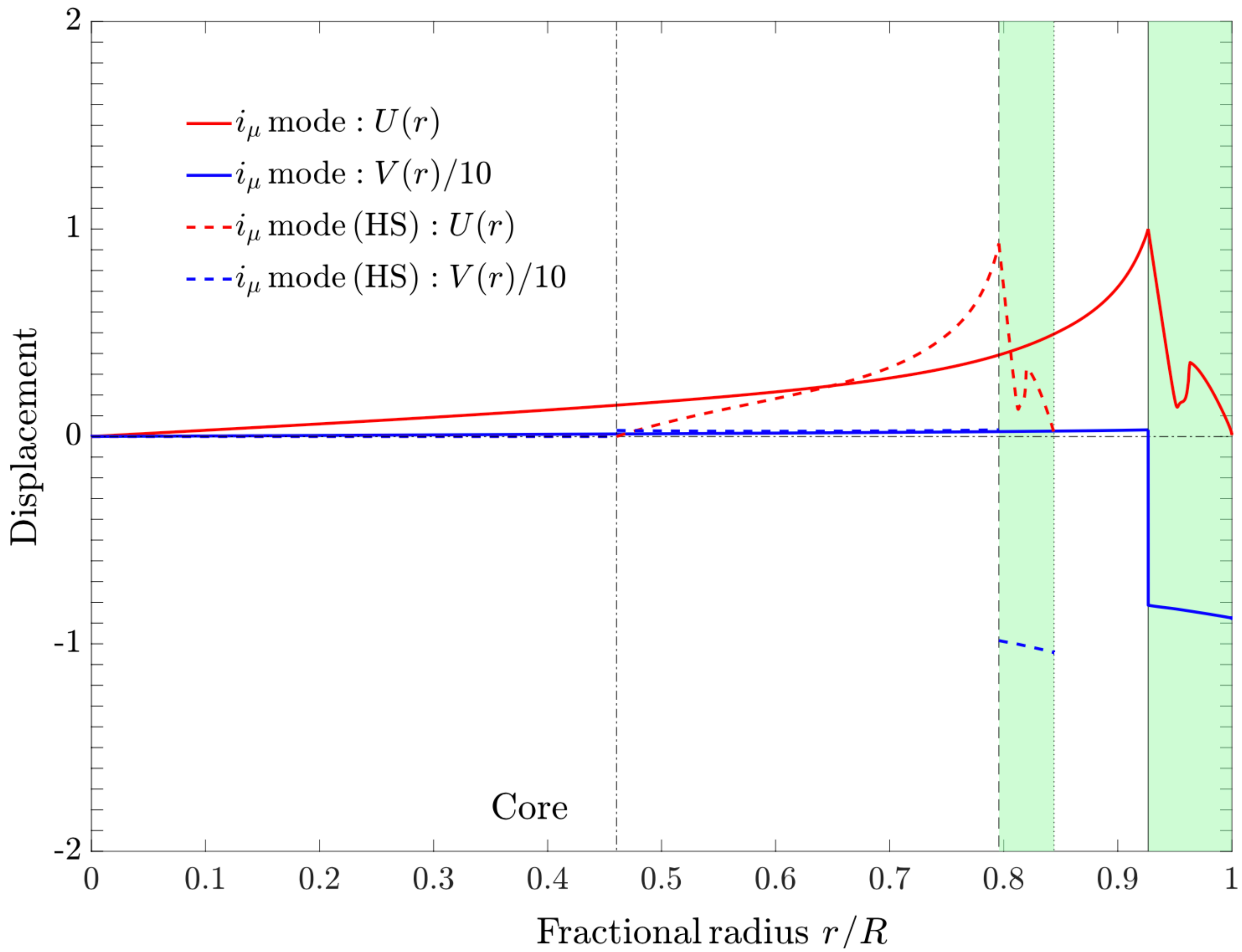


Quark-core affected Neutron star Interfacial mode- i_μ

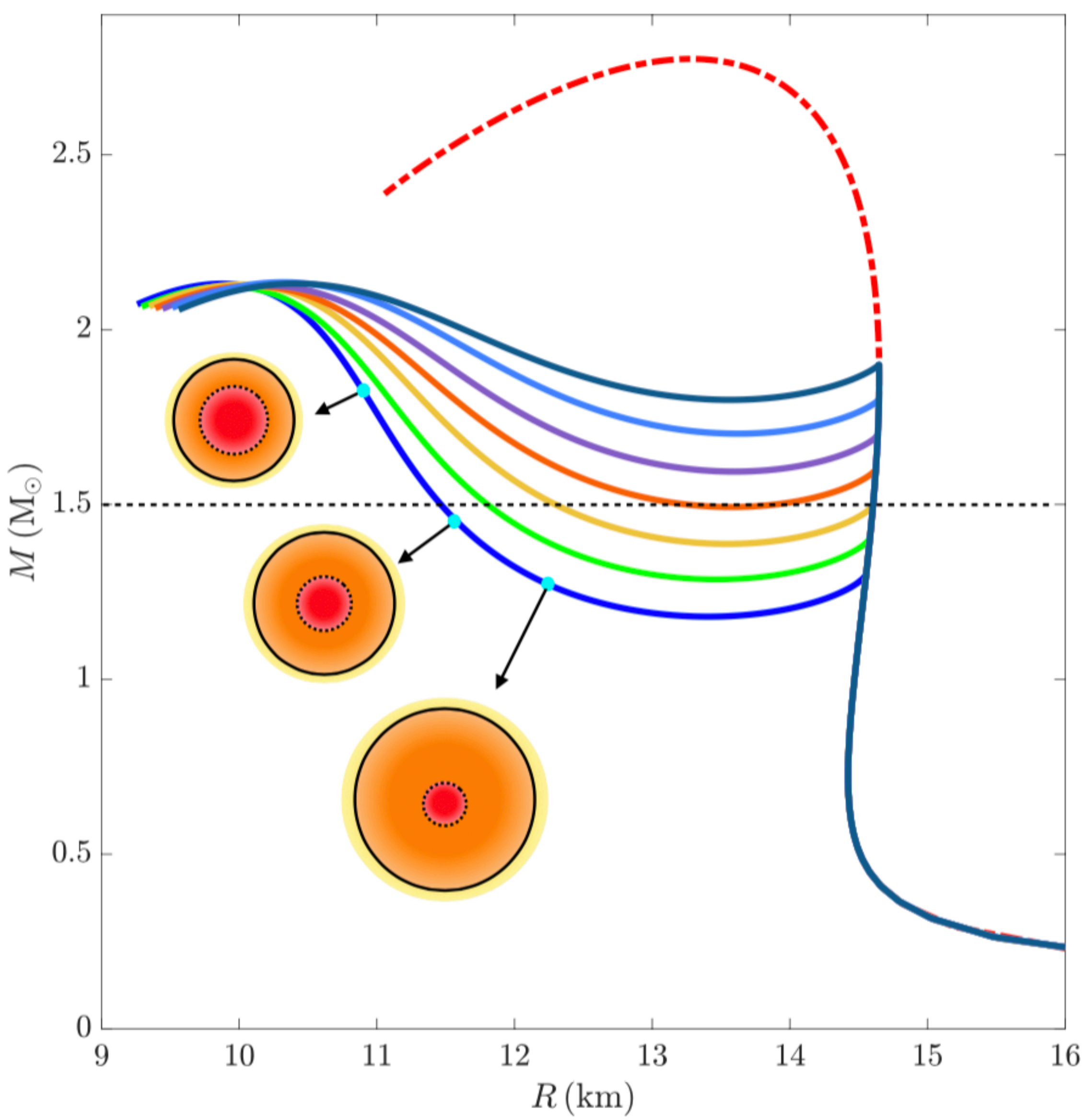


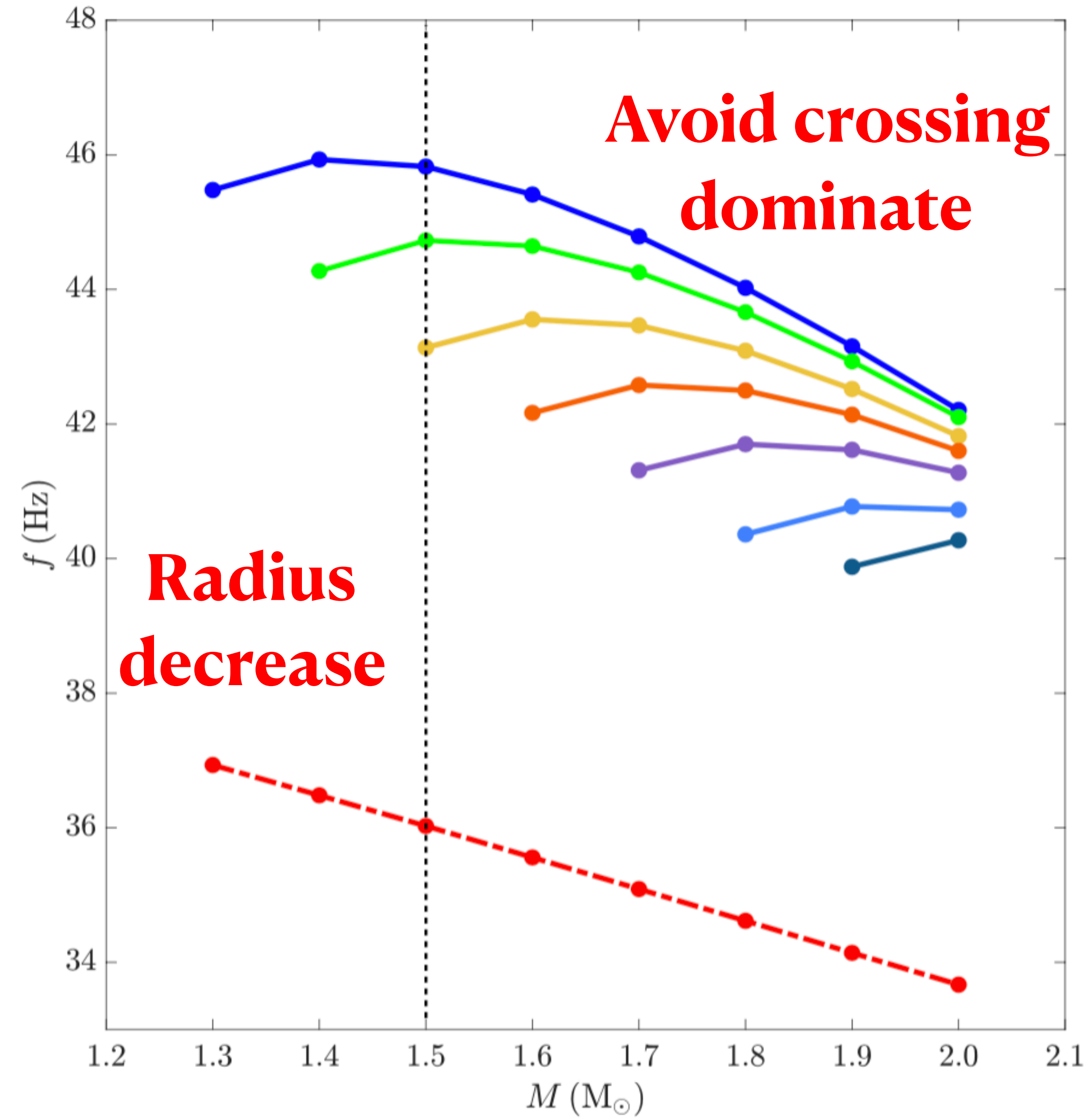


Wave function of the shear interfacial mode



Quark-core affected Neutron star Interfacial mode- i_μ

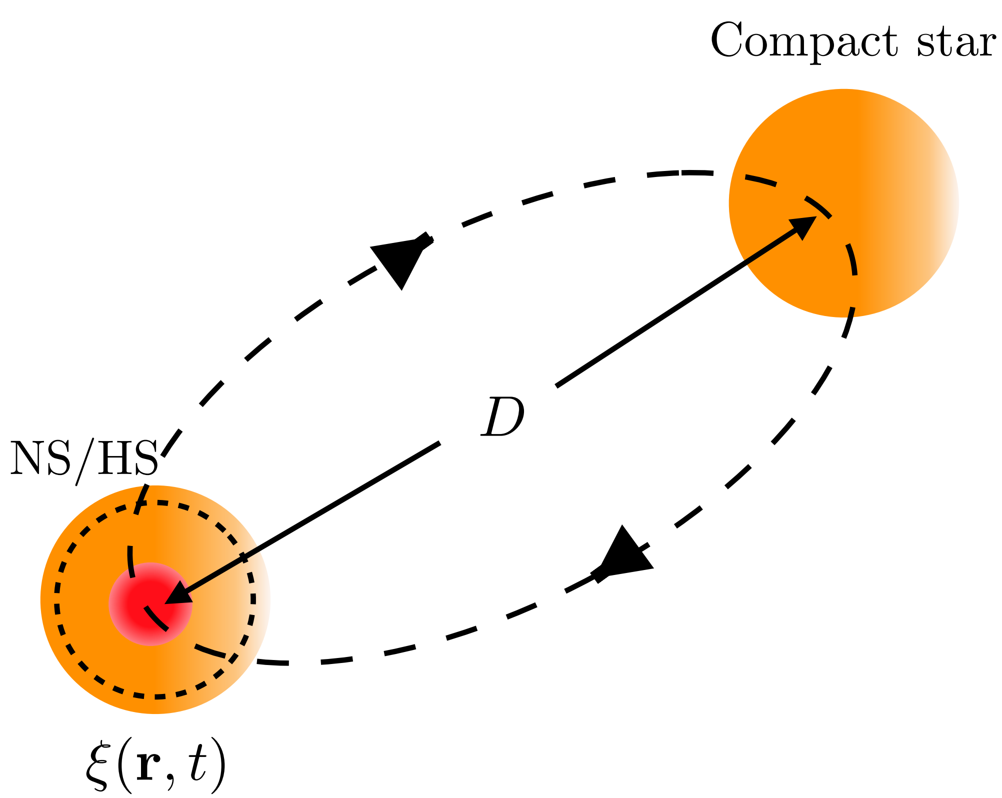


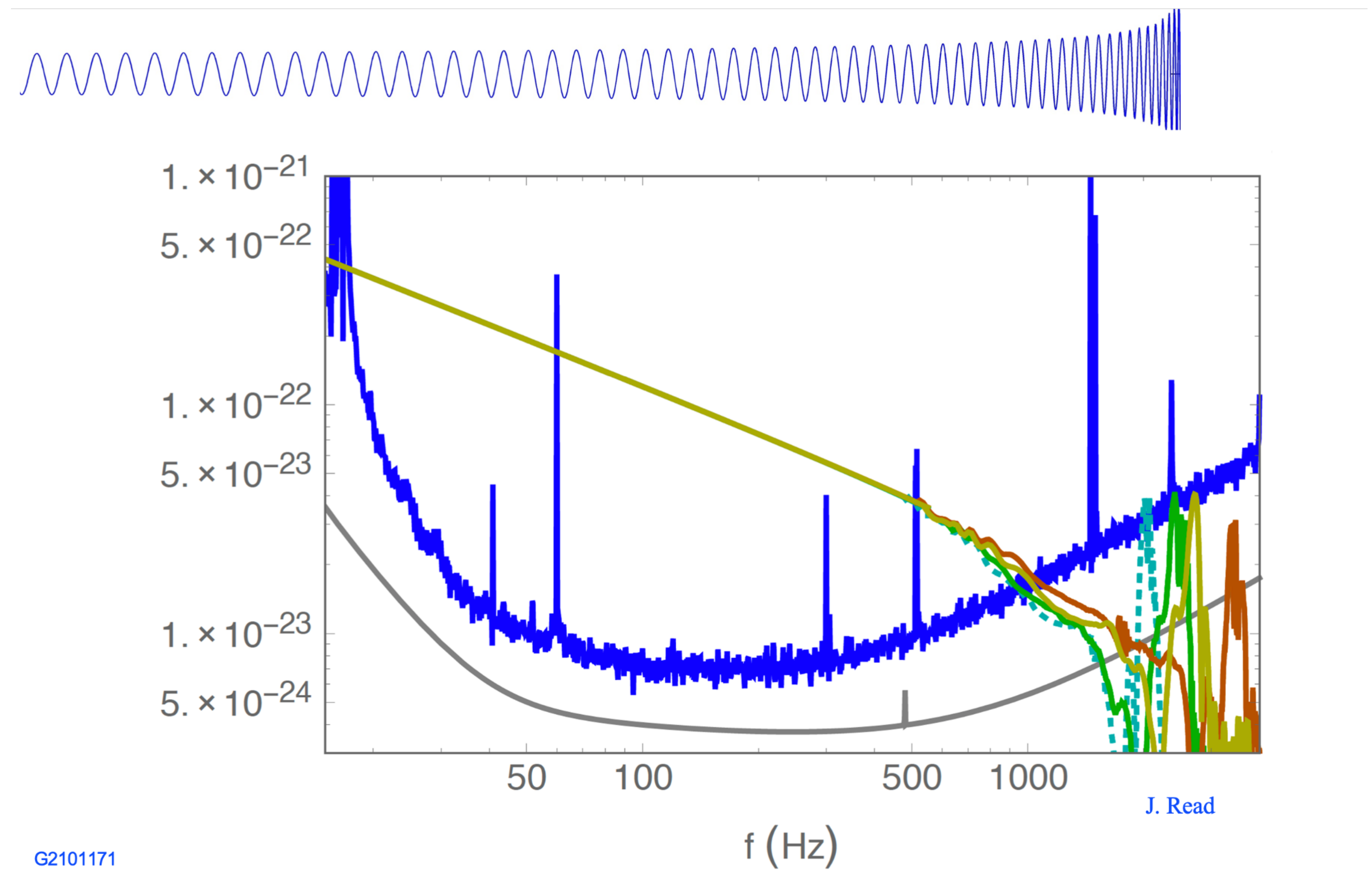


Trend of the interfacial mode frequency affected by Quark core

See Miao's talk for the i-mode related to the hadron-quark interface

Binary NS system and Gravitational waves





- **Carry information of EoS**

  Masses, Tidal deformability

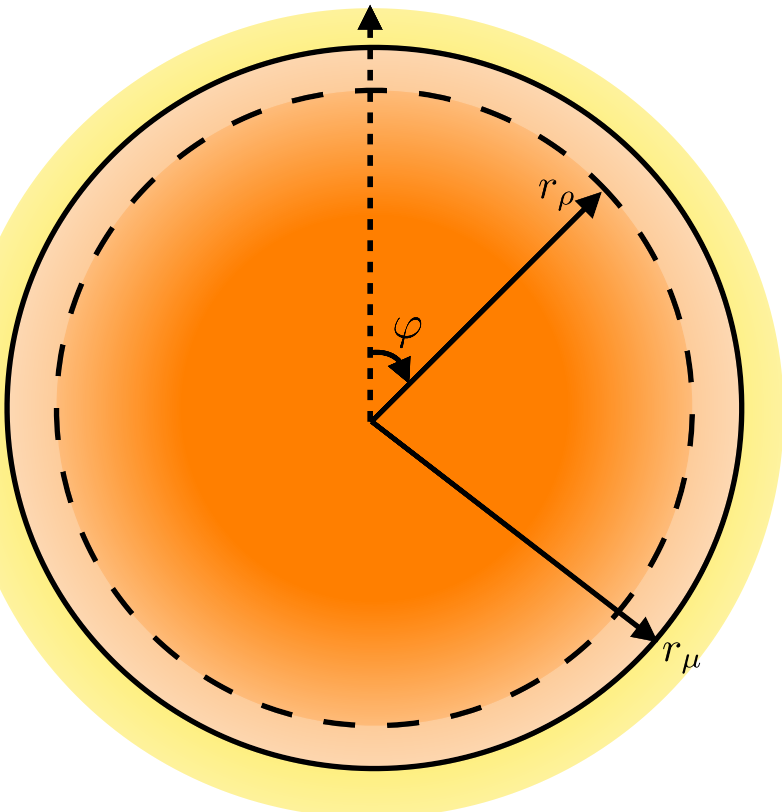
G2101171

- **Orbital-internal mode coupling**

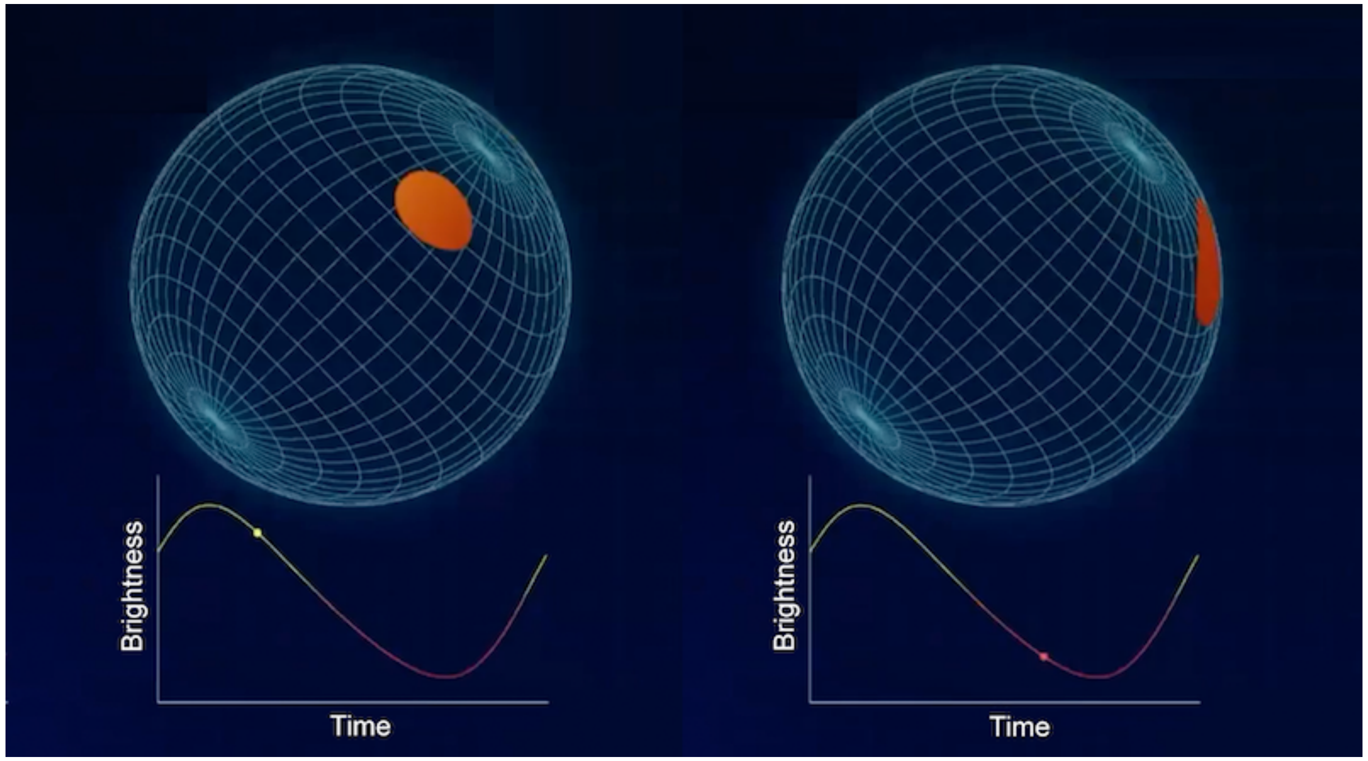
Overlap between orbital and internal mode

$$\ddot{a}_m + \omega_\alpha^2 a_m + \gamma \dot{a}_m = \frac{GMW_{2m}Q_{2m}}{D^3(t)} e^{-im\Phi(t)}.$$

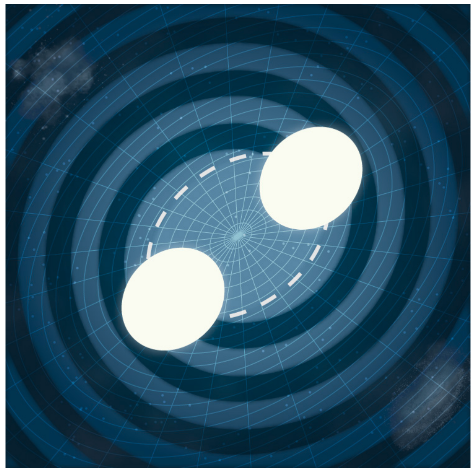
Binary NS system probing transitions?



Density discontinuity effect on the M-R



Minor!



Density discontinuity effect on the tidal deformability

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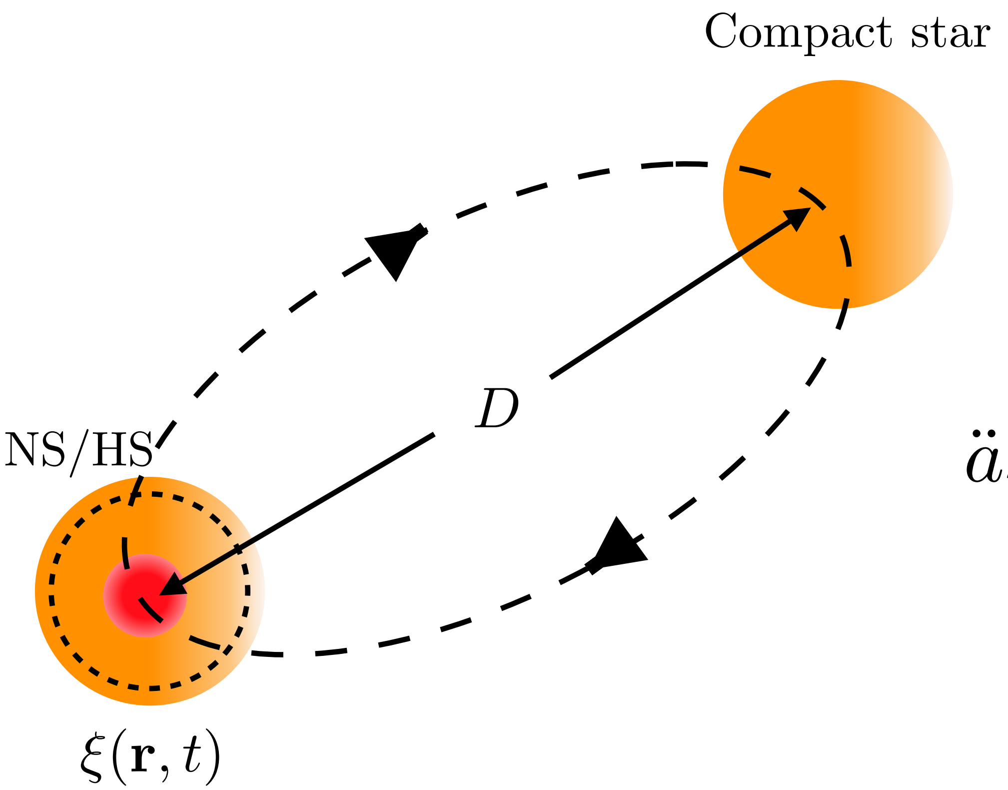
Minor!

Binary NS system and Gravitational waves

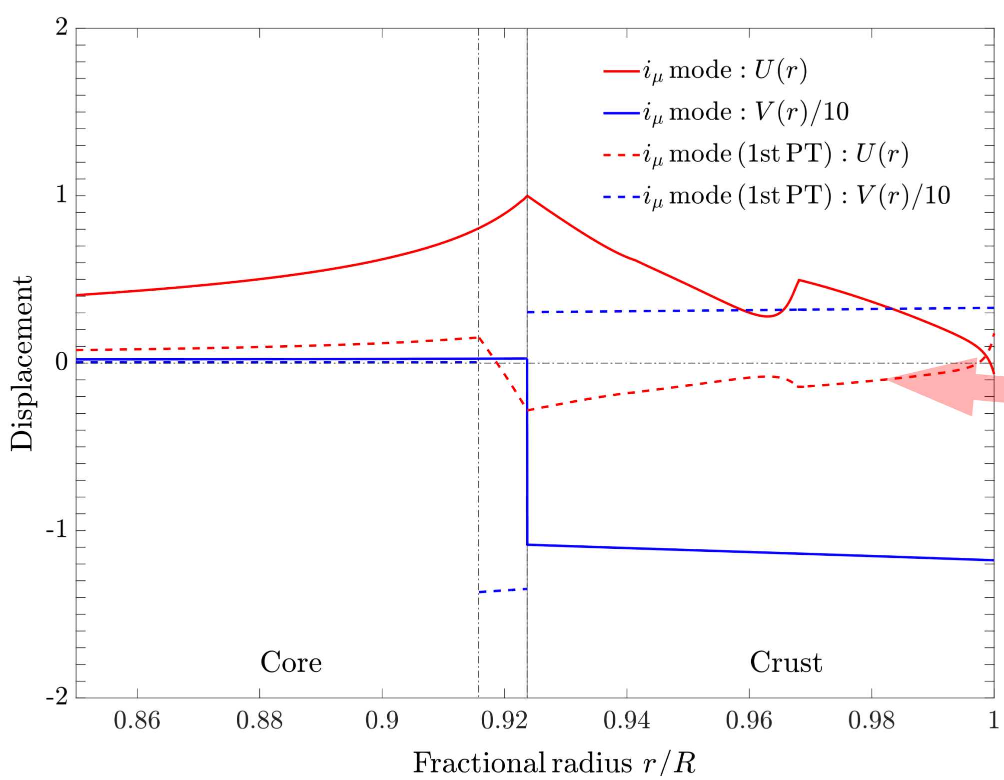


Density discontinuity effect on
Orbital-internal mode coupling

$$\ddot{a}_m + \omega_\alpha^2 a_m + \gamma \dot{a}_m = \frac{GMW_{2m}Q_{2m}}{D^3(t)} e^{-im\Phi(t)}.$$

Overlap between orbital and internal mode

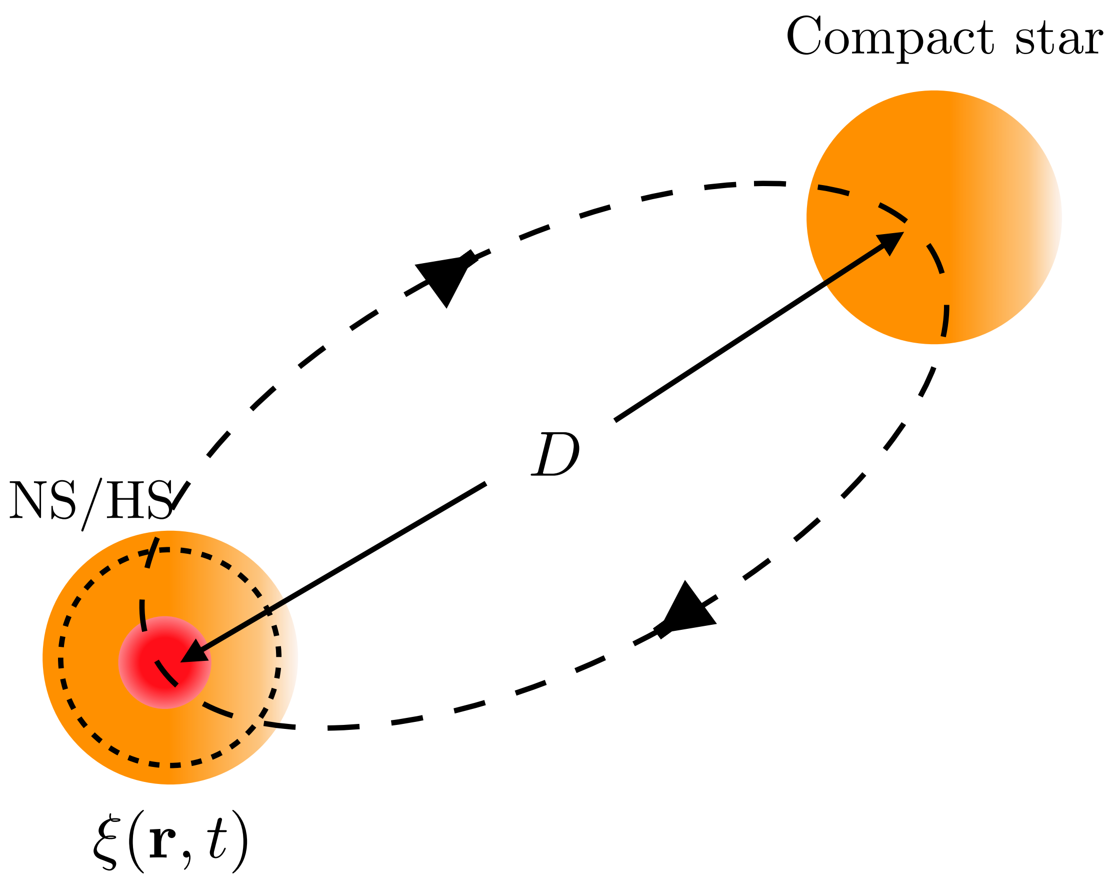
Remind: Wave function

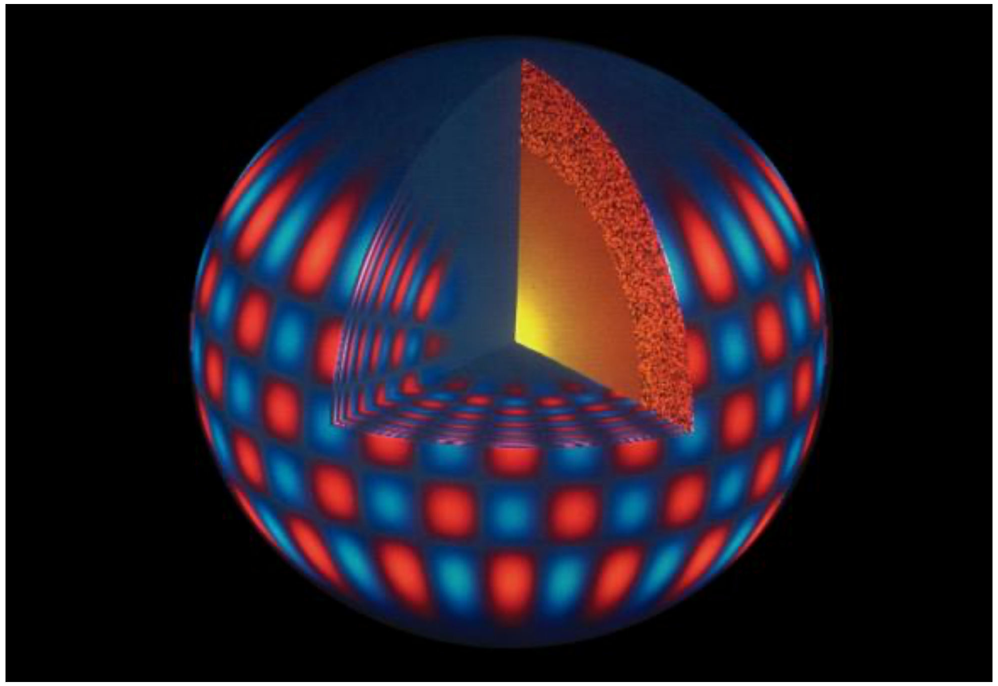


Mode	Q	Q^U	Q^V
i_μ	0.026	0.041	−0.015
i_ρ	−0.019	0.035	−0.054
i_μ (1st PT)	−0.0227	0.00001	−0.00228
i_ρ (with shear)	0.007	0.043	−0.036

Density discontinuity also affects frequency!

Binary NS system and Gravitational waves





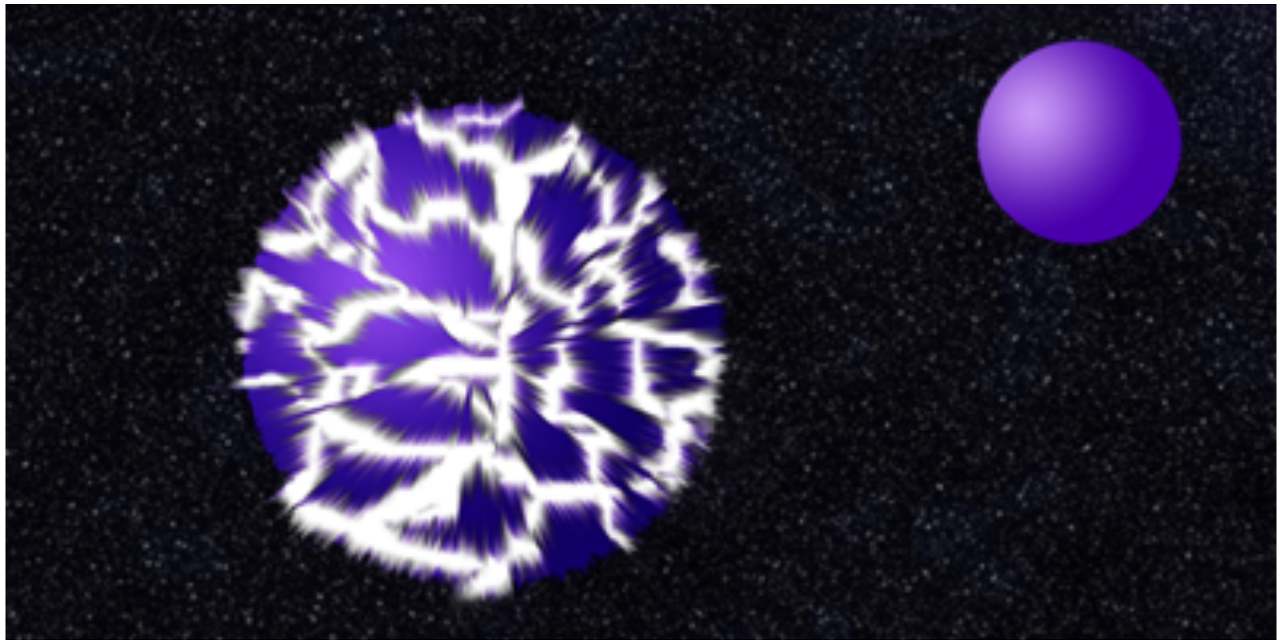
Full-elastic case

Inelastic case:

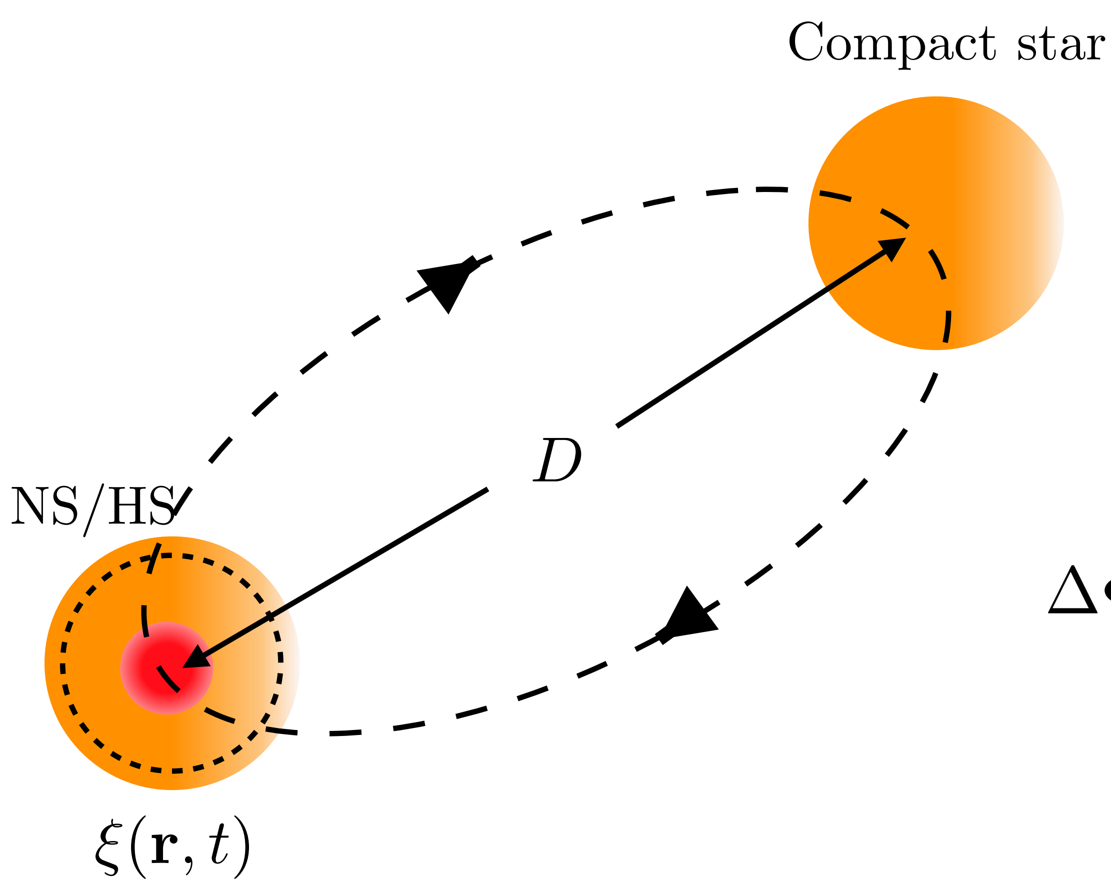
Crust Shattering
Crust Melting

Tsang et al, Phys. Rev. Lett. **108**, 011102

Pan, et al, Phys. Rev. Lett. **125**, 201102



Binary NS system and Gravitational waves



Modification to the gravitational wave Waveform

$$h(f) = A(f)\exp[-i\Phi(f)]$$

$$\Delta\Phi(f) = -\sum_j \sum_{A=1,2} \delta\phi_{j\mathrm{GW}}^{(A)} \left(1 - \frac{f}{f_j^{(A)}}\right) \Theta(f - f_j^{(A)})$$

$$\Delta\phi_{j\mathrm{GW}} = -\frac{5\pi^2}{1024}\left(\frac{Rc^2}{GM}\right)^5 \frac{2q}{1+q} |Q_{2,2}^j|^2 (2\pi\tilde{f}_j)^{-2}$$

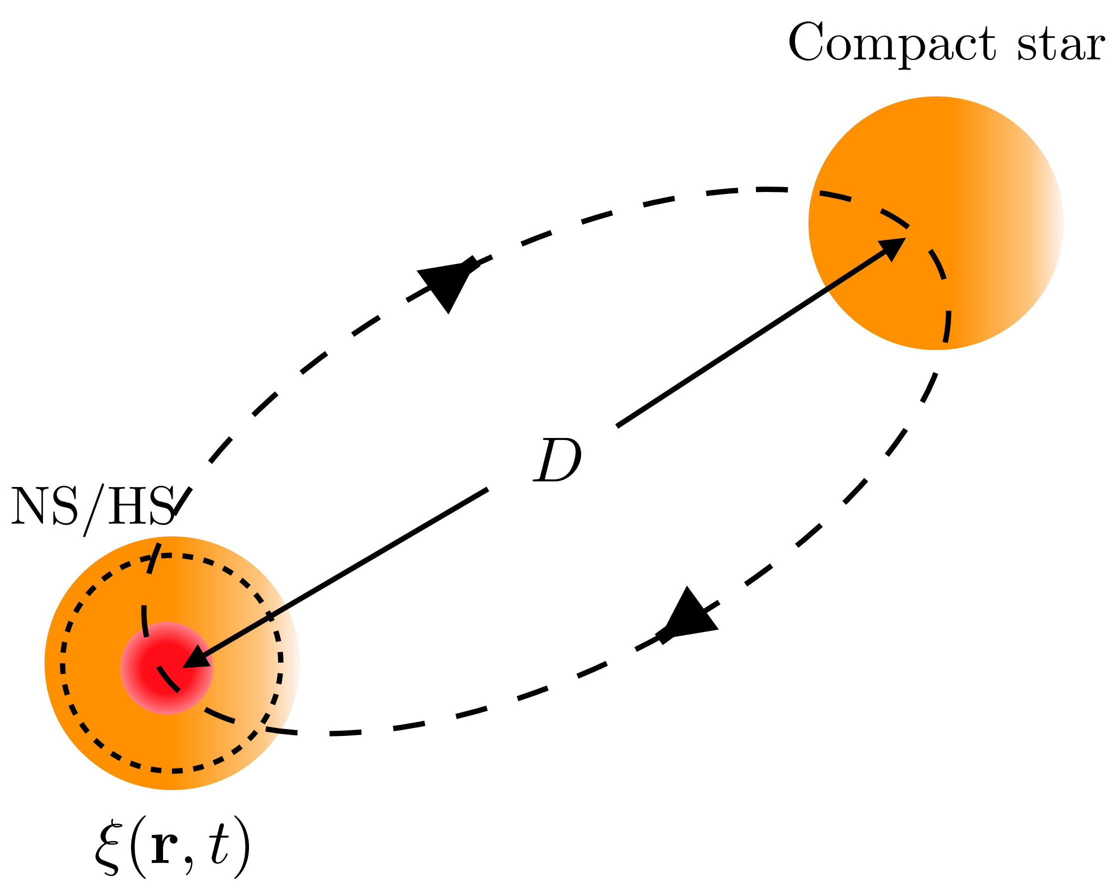
$$\approx 54 \left(\frac{100\,\mathrm{Hz}}{f_j}\right)^2 \left(\frac{Q_{2,2}^j}{0.03}\right)^2 \left(\frac{1.4\,M_\odot}{M}\right)^4 \left(\frac{R}{10\,\mathrm{km}}\right)^2 \frac{2q}{1+q},$$

Energy stored in NS oscillation:

- **A earlier merger time**
- **Resonance induced phase shift**

New parameters: NS oscillation frequency & phase shift

Detectability of phase transition from GW signals



Fisher information analysis (assuming no prior)

$$\Gamma_{mn} = \left(\frac{\partial h}{\partial \theta_m} \middle| \frac{\partial h}{\partial \theta_n} \right),$$

$$(a|b) = 2\int_0^\infty \frac{a^*(f)b(f) + a(f)b^*(f)}{S_{hh}(f)}$$

Energy stored in NS oscillation:

- **A earlier merger time**
- **Resonance induced phase shift**

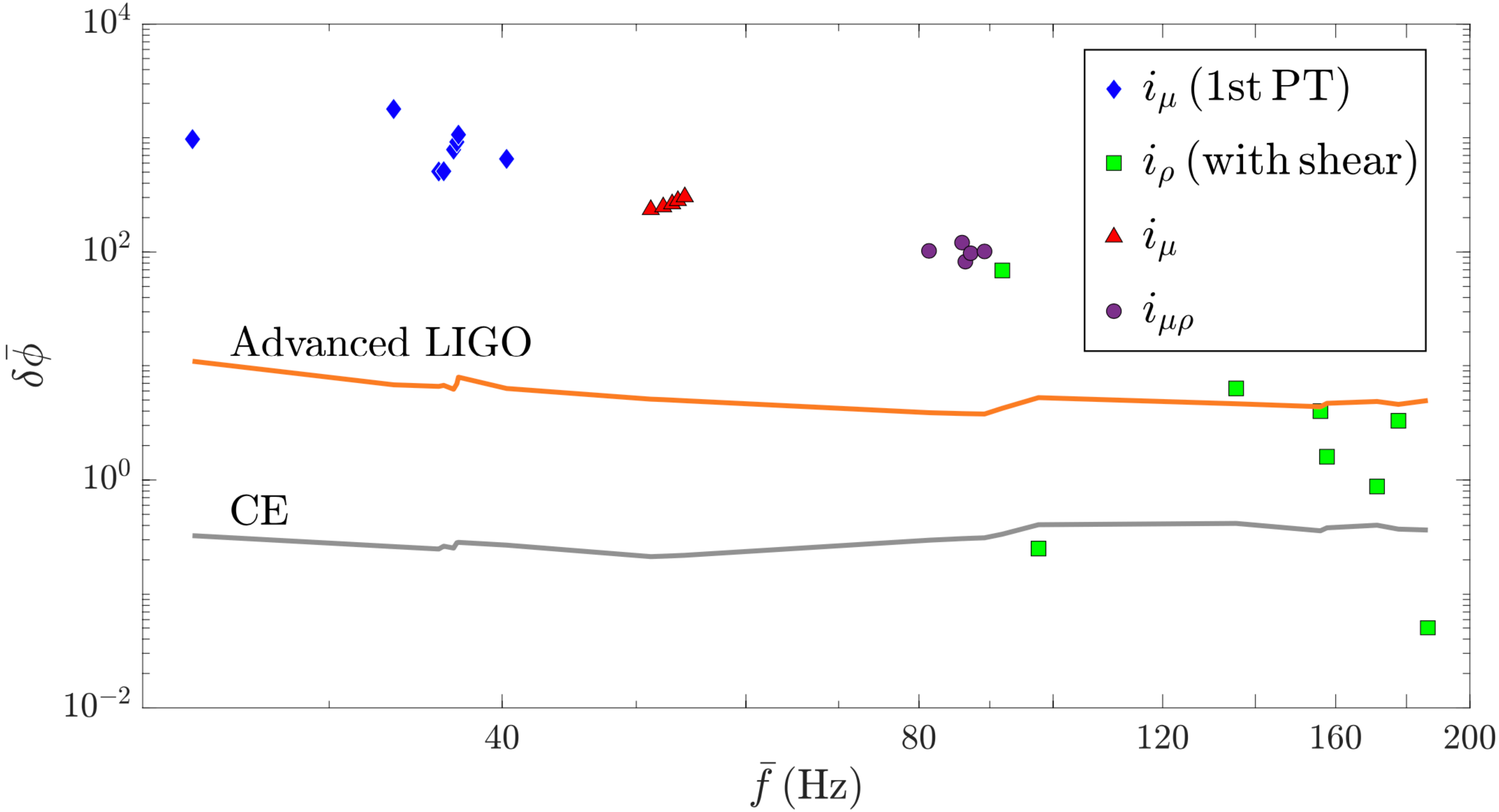
Detector strain sensitivity

$$\Delta\theta_m = \sqrt{(\mathbf{\Gamma}^{-1})_{mm}}$$

New parameters: NS oscillation frequency & phase shift

Detectability of phase transition from GW signals

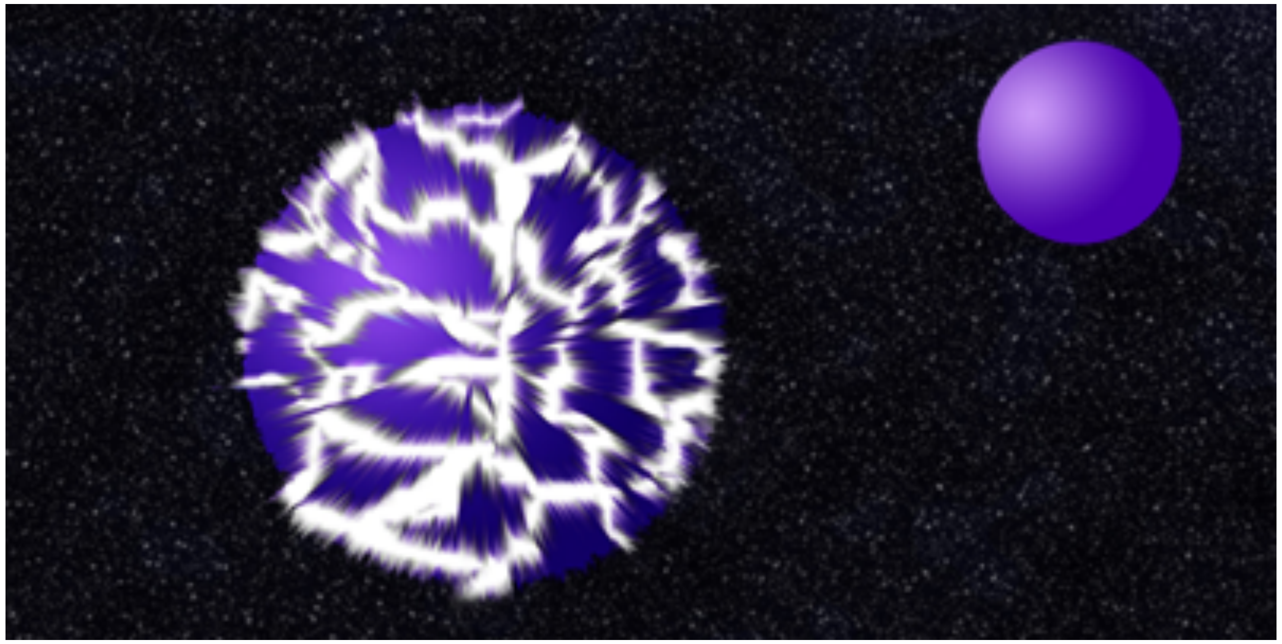
Detectability in the full elastic case

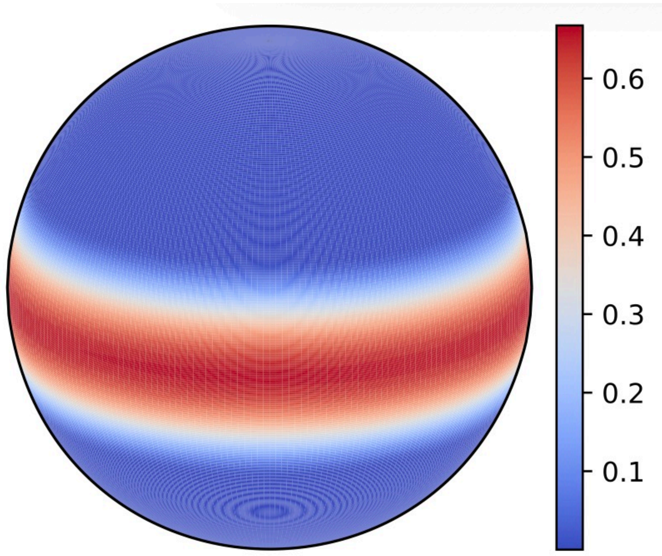


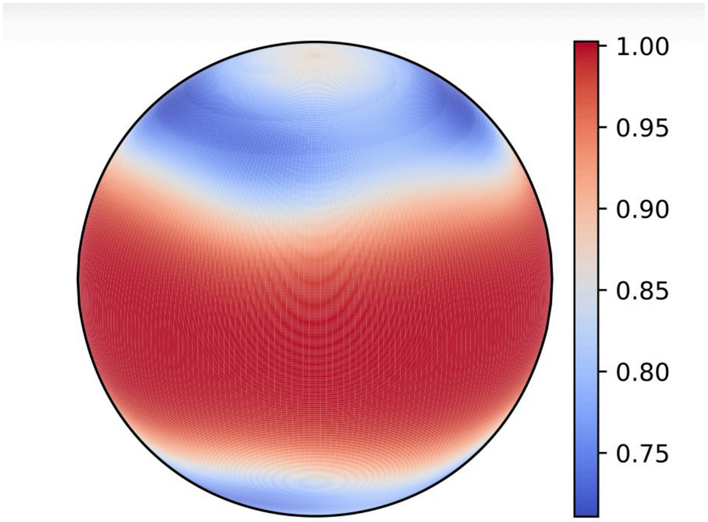
Detectability of phase transition from GW signals

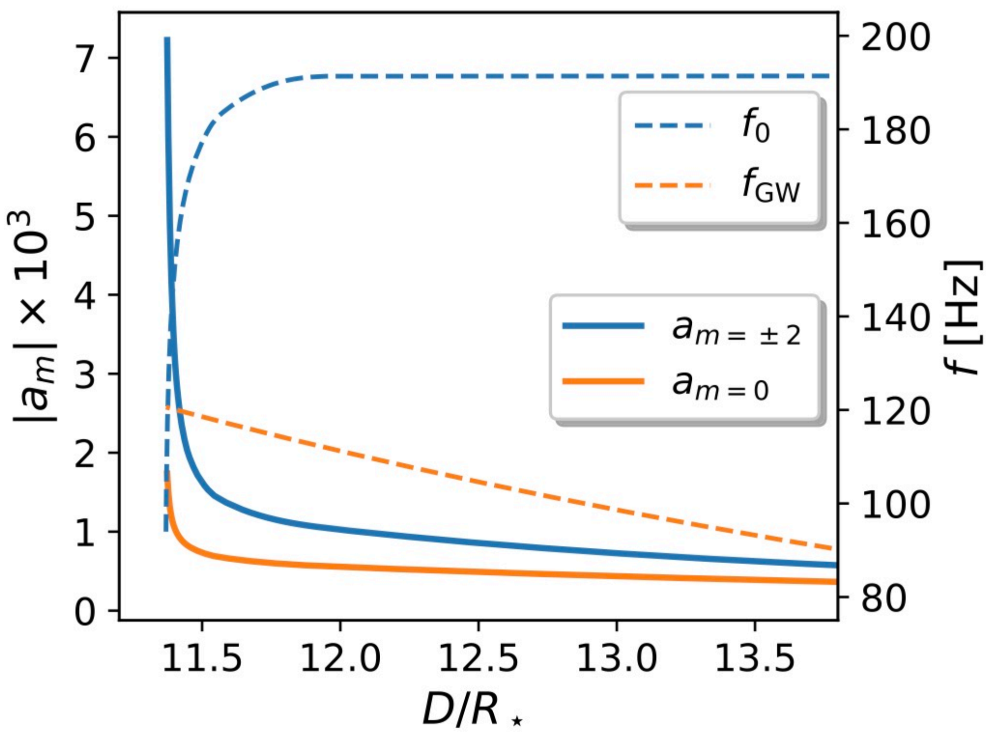
Inelastic case:

Crust Shattering





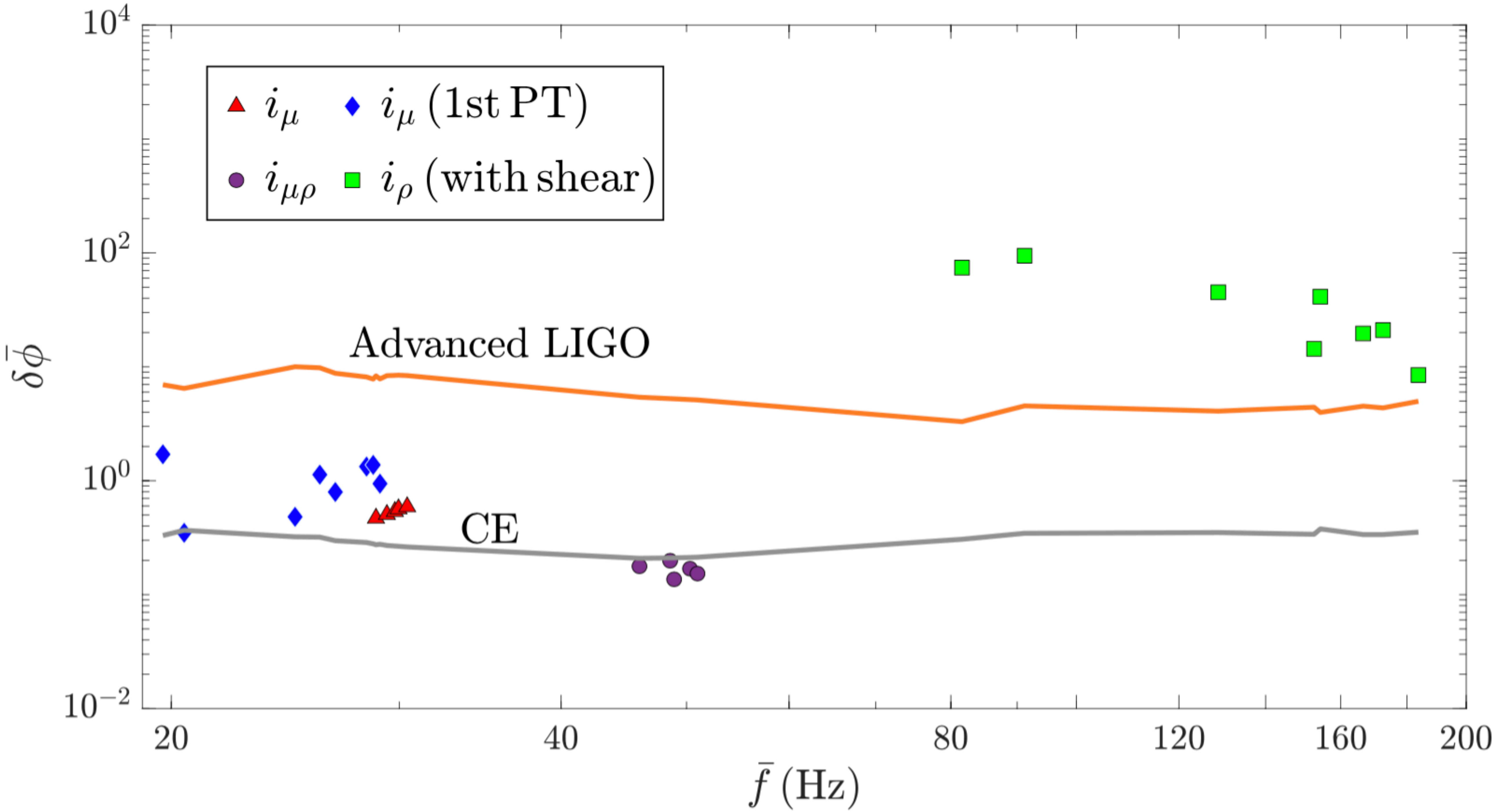




Crust Melting, from Pan et. al. PRL, 125,201102,2020

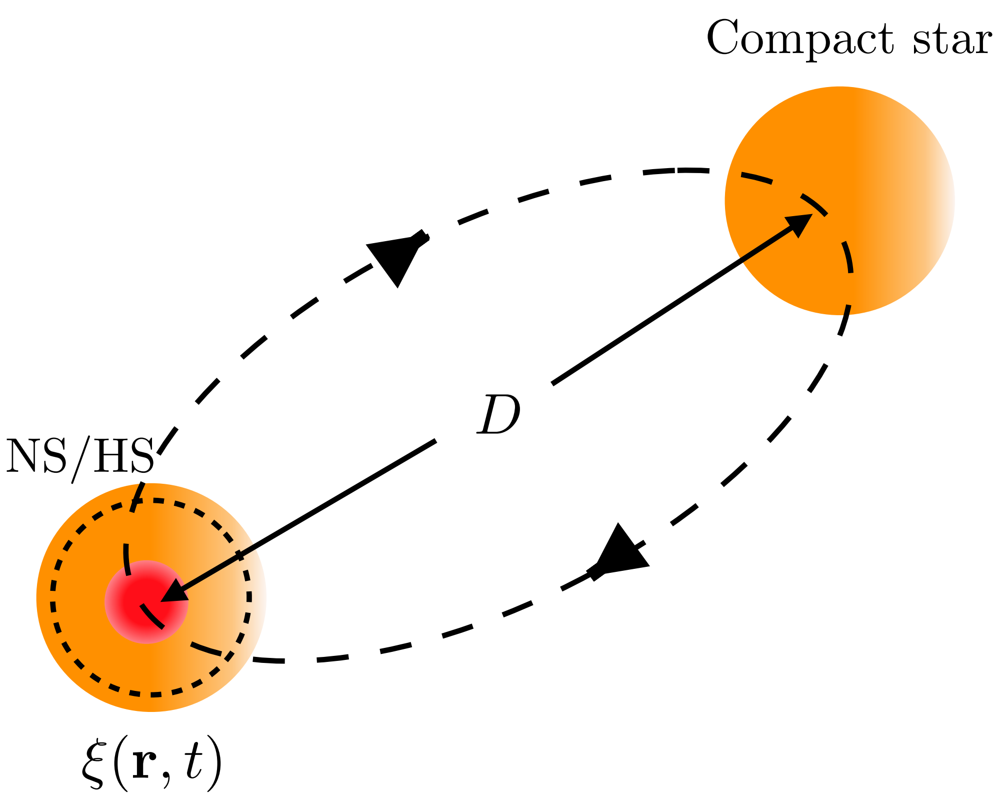
Detectability of phase transition from GW signals

Detectability in the inelastic case



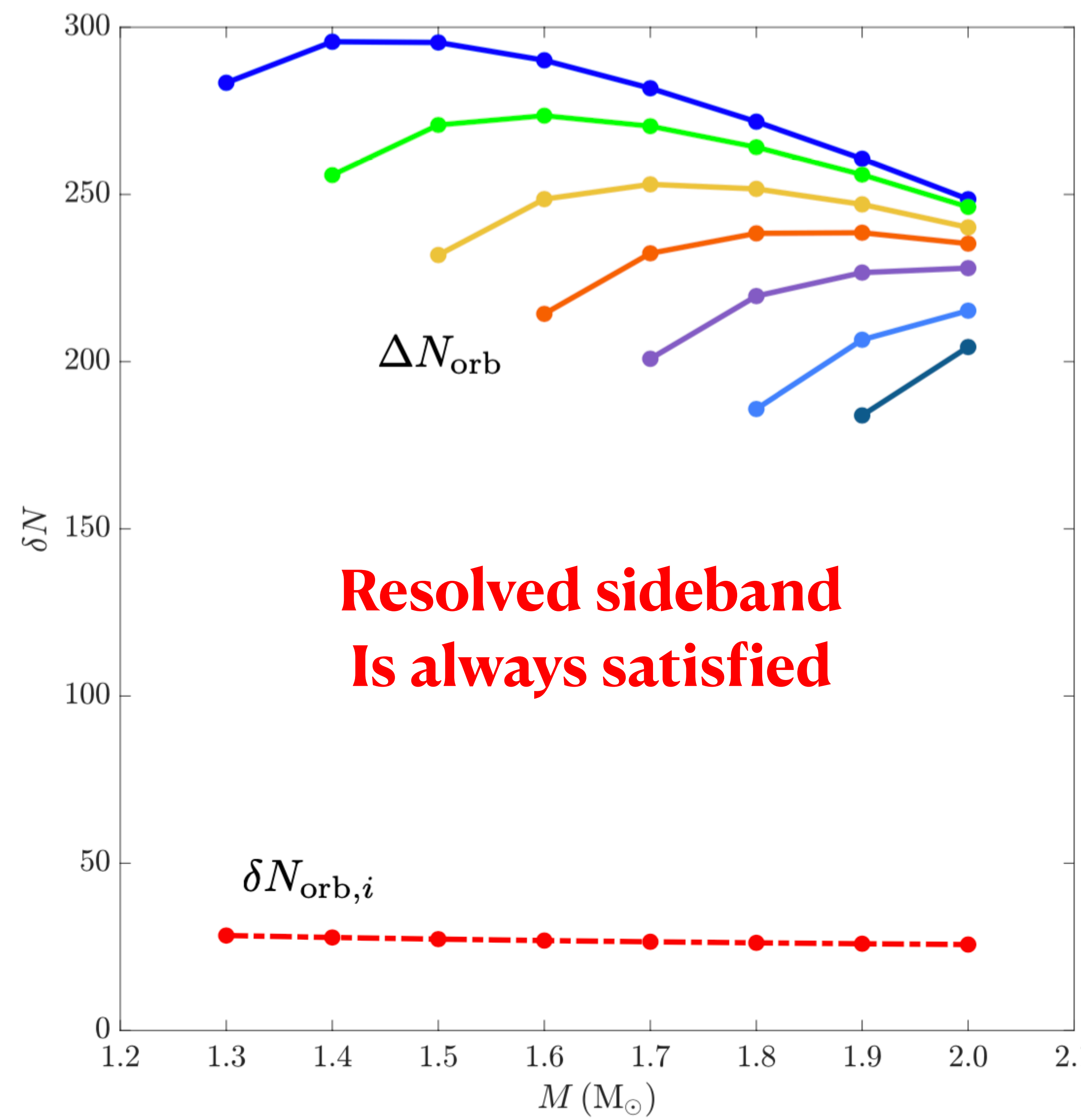
Detectability of phase transition from GW signals

Distinguishing the twin-star



The on-resonance bandwidth Must be smaller than the NS-HS I-mode Frequency difference!

Resolved sideband limit!



Outlook and Summary

1st order Phase transition could have a minor effect on M-R and deformability

1st order Phase transition can significantly affect Interfacial Mode

These effects are promising to be detected using GWs from BNS

A Complete and consistent GR treatment still lack

Inelastic process is still not very clear

Coupling with other modes is yet to be analysed

Acknowledgement

Jiaxiang Zhu

Chuming Wang

Chengjun Xia
(From Yangzhou University)

Enping Zhou

Micala Oertel, Paris Observatory

and ComPOSE team

Thank you!

Questions?