Phase conversion dissipation in multi-component stars

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Alford, Han & Schwenzer,
arXiv:1404.5279

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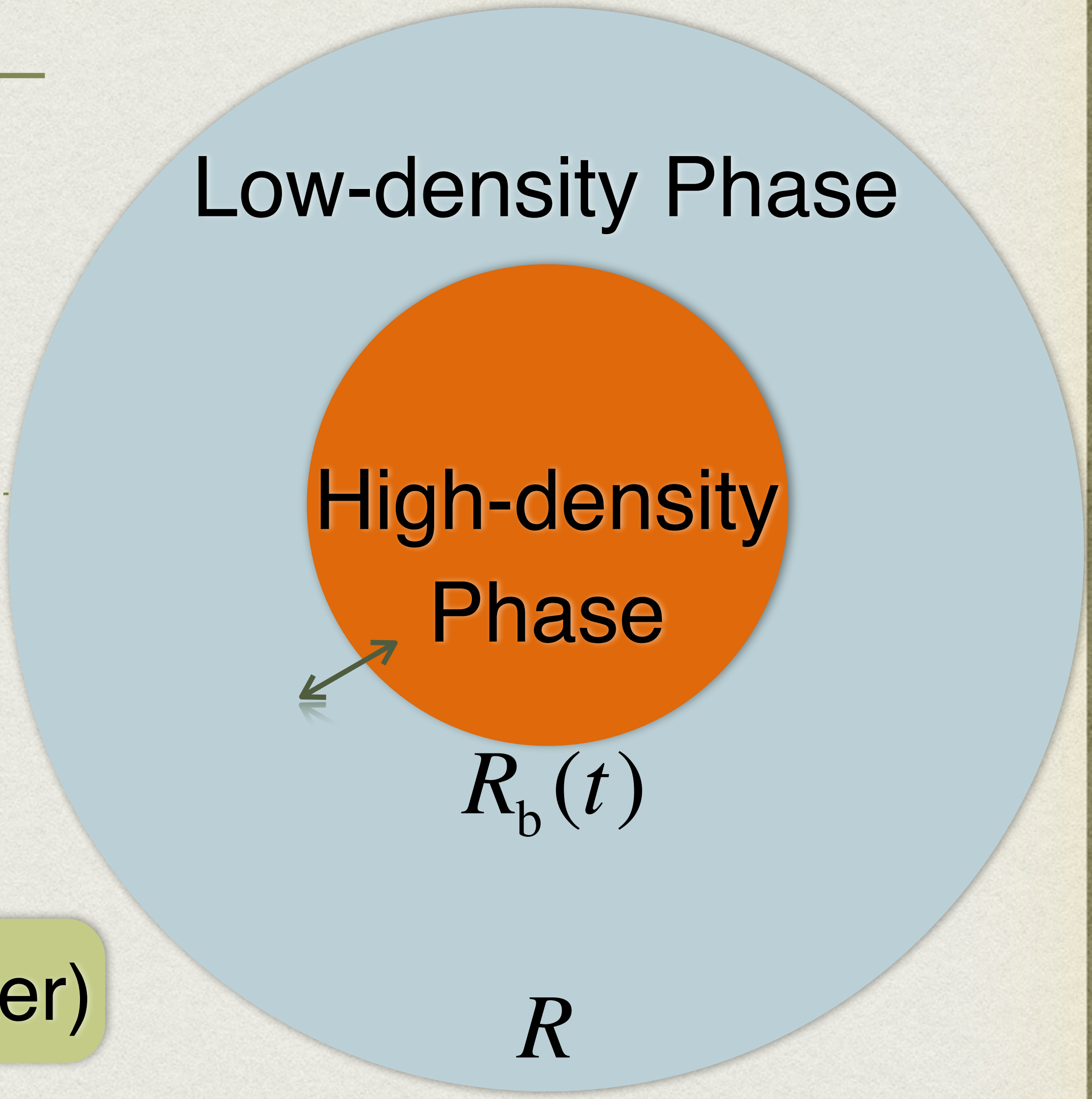
The Phases of Dense Matter

INT Program INT-16-2b Week III

Dense matter in neutron stars

properties	observables
equations of state	mass, radius, moment of inertia…
thermal & transport properties, vortex pinning	cooling, spin down, glitches, neutrinos, GW, magnetic field…

Is there quark matter in NS?



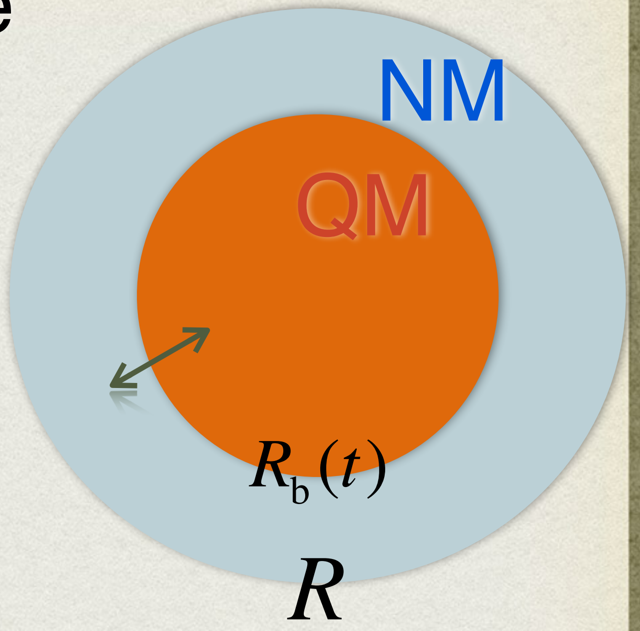
Dissipation (in uniform matter)

-Shear viscosity from particle scattering (strong/EM interaction)

-Bulk viscosity from particle transformation (weak interaction)

Dissipation at an interface

-Ekman layer damping from shear rubbing of a fluid core along a solid crust

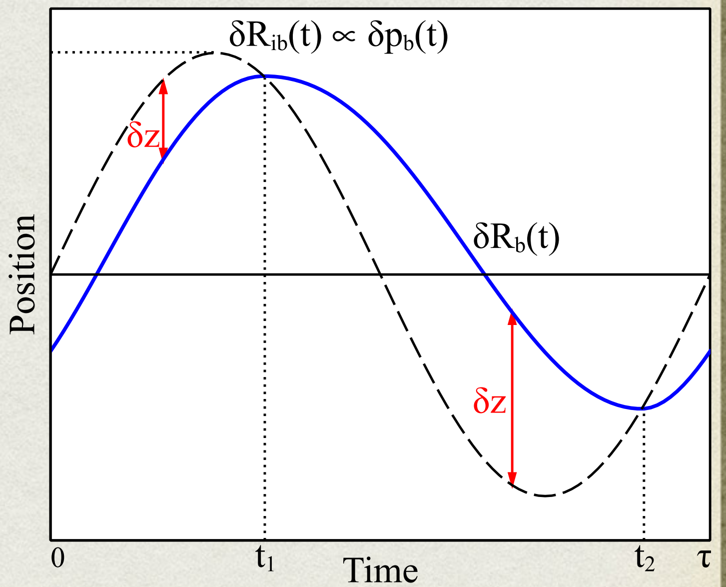


Phase conversion dissipation

-Between fluids in different phases with first-order transition separated by a sharp interface

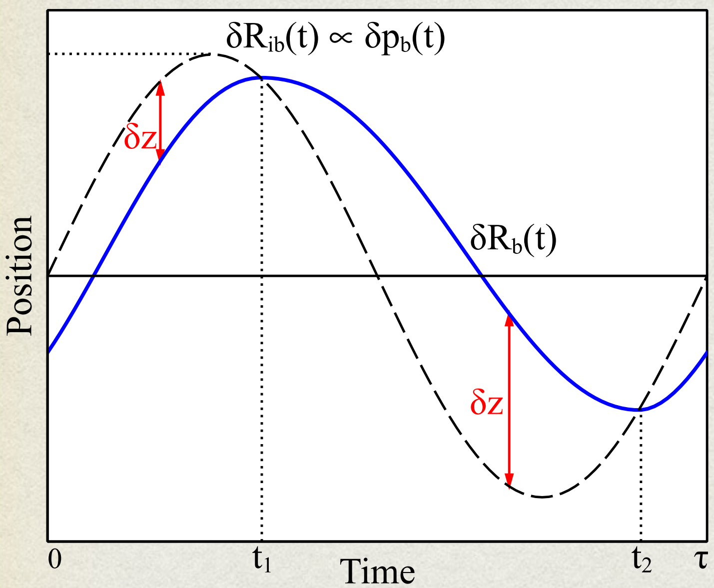
-Quark/hadron conversion

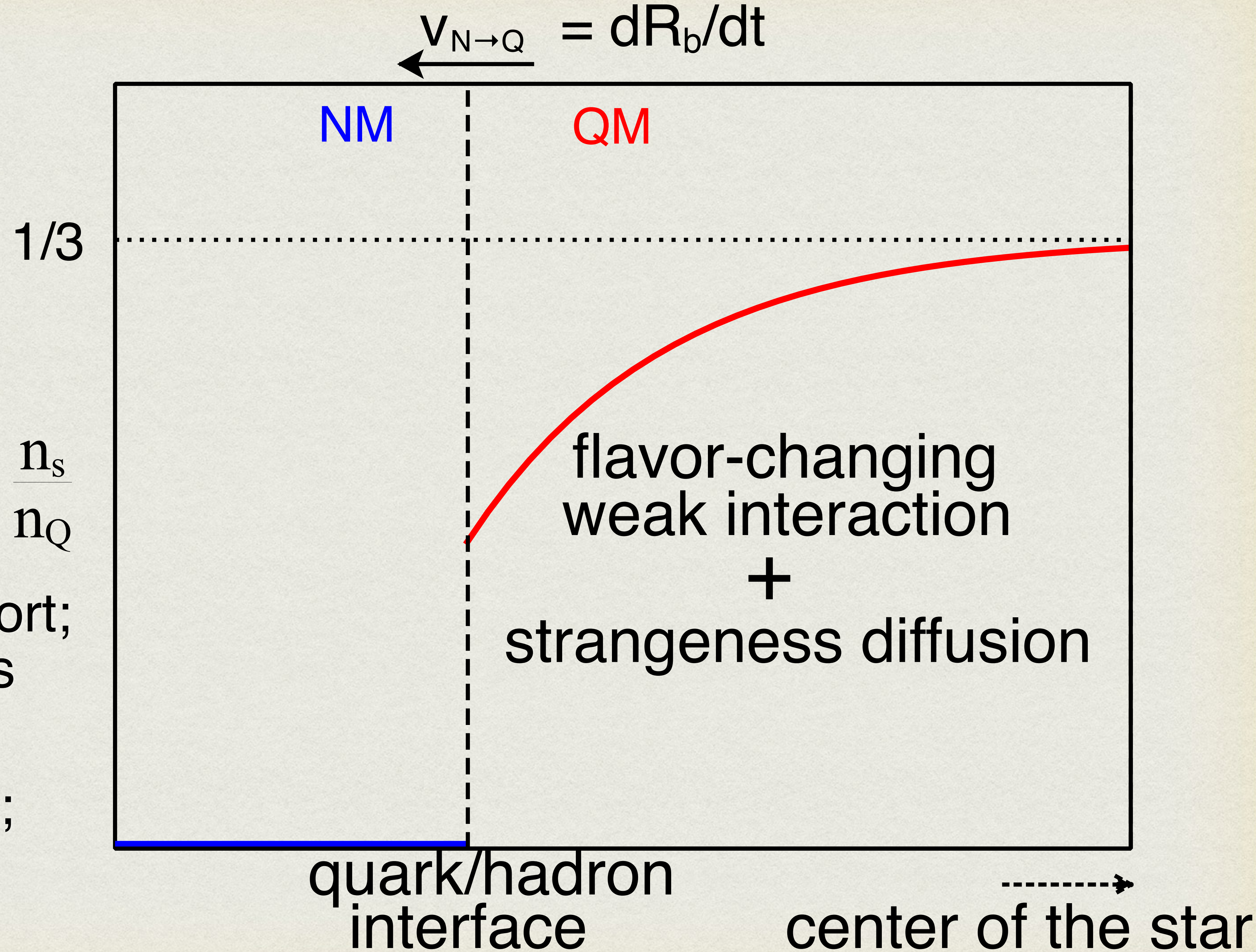
1) flavor-changing process $d \leftrightarrow s$ out of equilibrium due to global oscillations
2) instantaneous restoration $\Leftrightarrow$ phase boundary moves arbitrarily fast (no diss.)
3) finite rate of weak interaction and flavor diffusion
   $\longrightarrow$ a phase lag in system response
   $\longrightarrow$ dissipates energy



Toy model formalism

$$(udd) \leftrightarrow (uds)$$





-steady-state transport; boundary conditions

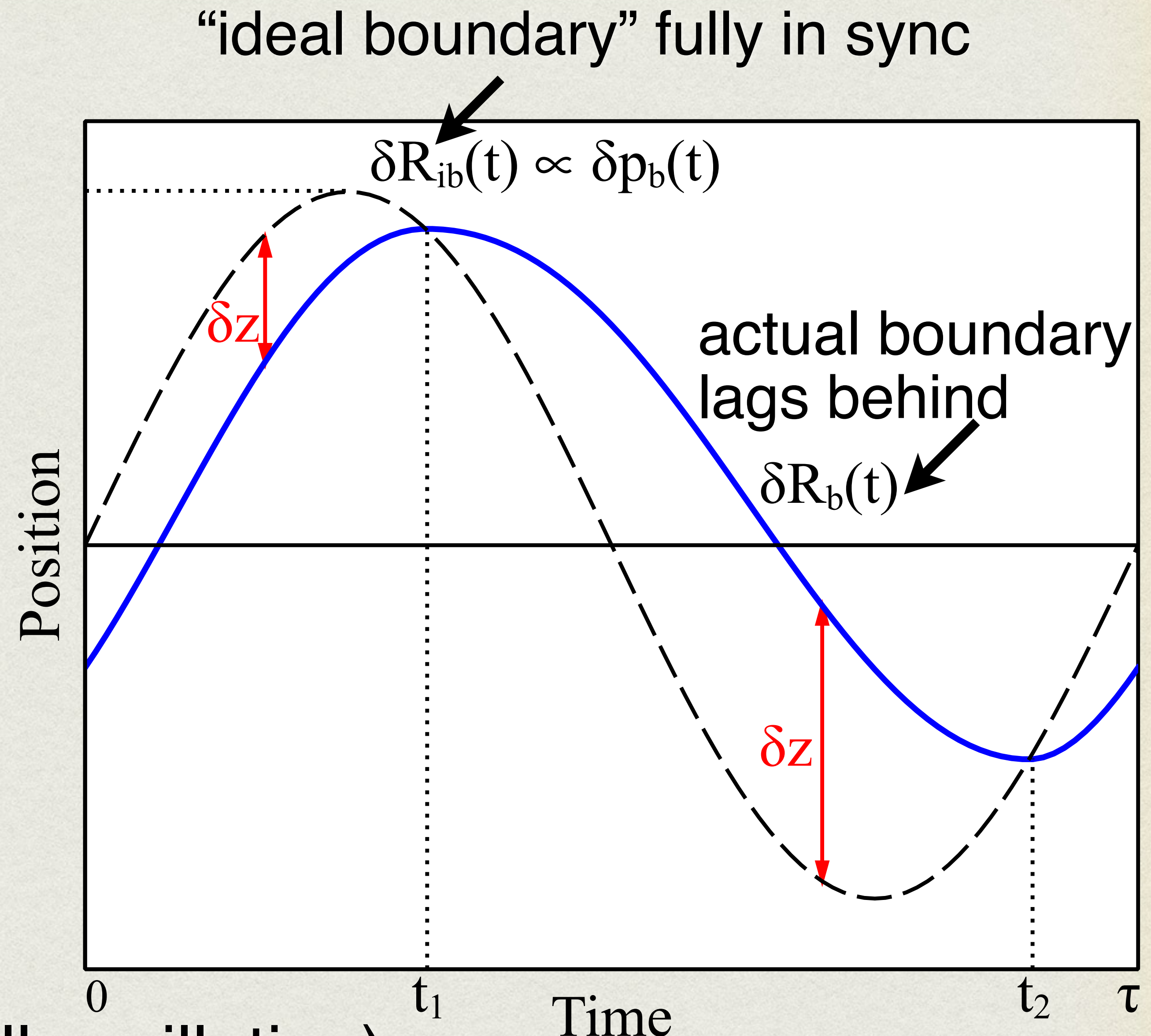
-no acceleration/ deceleration effects; no turbulence

-no leptons

Dissipated energy (pdV work)

out of phase

$$dW = -dS\left(\frac{n_N}{n_Q}-1\right)\int_0^\tau \delta p_b(t)\frac{d\delta R_b(t)}{dt}dt$$



-actual front speed $n \rightarrow q$

$$\left.\frac{d\delta R_b}{dt}\right|_{N\rightarrow Q} \propto \sqrt{D_Q/\tau_Q}$$

-similarly for the other half cycle

-two regimes

subthermal: $\Delta\mu \ll T \ll \mu$ (small oscillation)

suprathermal: $T \ll \Delta\mu \ll \mu$ (large oscillation)

R-mode saturation

-integrating over the whole star

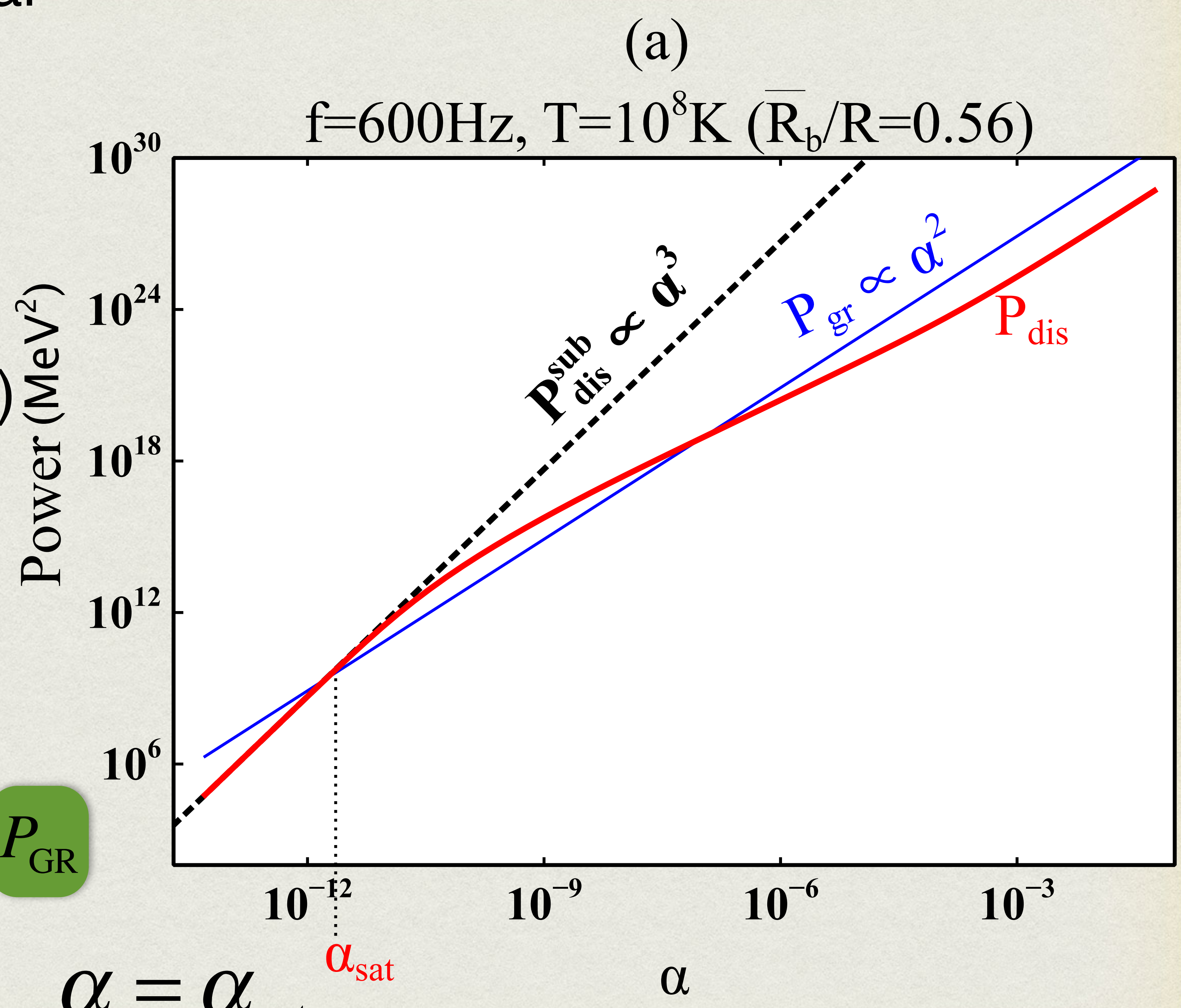
$$W \propto \begin{cases} \alpha^3, \text{subthermal} \\ \alpha^2, \text{suprathermal} \end{cases}$$

-non-linearly increasing with amplitude (resonant behavior)

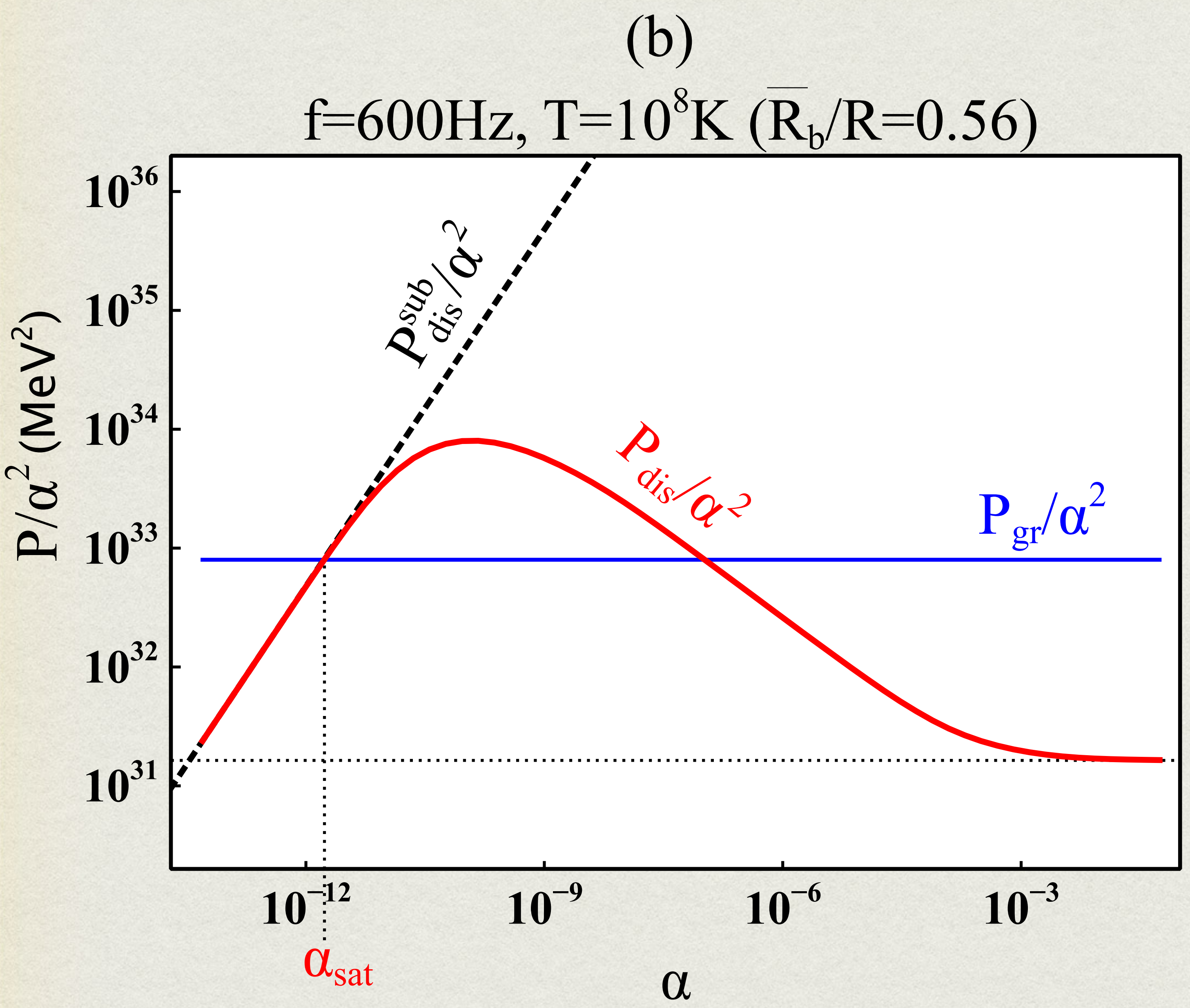
-dissipated power balances gravitational radiation power: r-mode saturated

$$P_{\rm dis} = W_{\rm dis}(\alpha) \cdot f = \left.\frac{{\rm d}\widetilde{E}(\alpha)}{{\rm d}t}\right|_{\rm GR} = P_{\rm GR}$$

$$\longrightarrow \quad \alpha = \alpha_{\rm sat}$$



Phase conversion dissipation

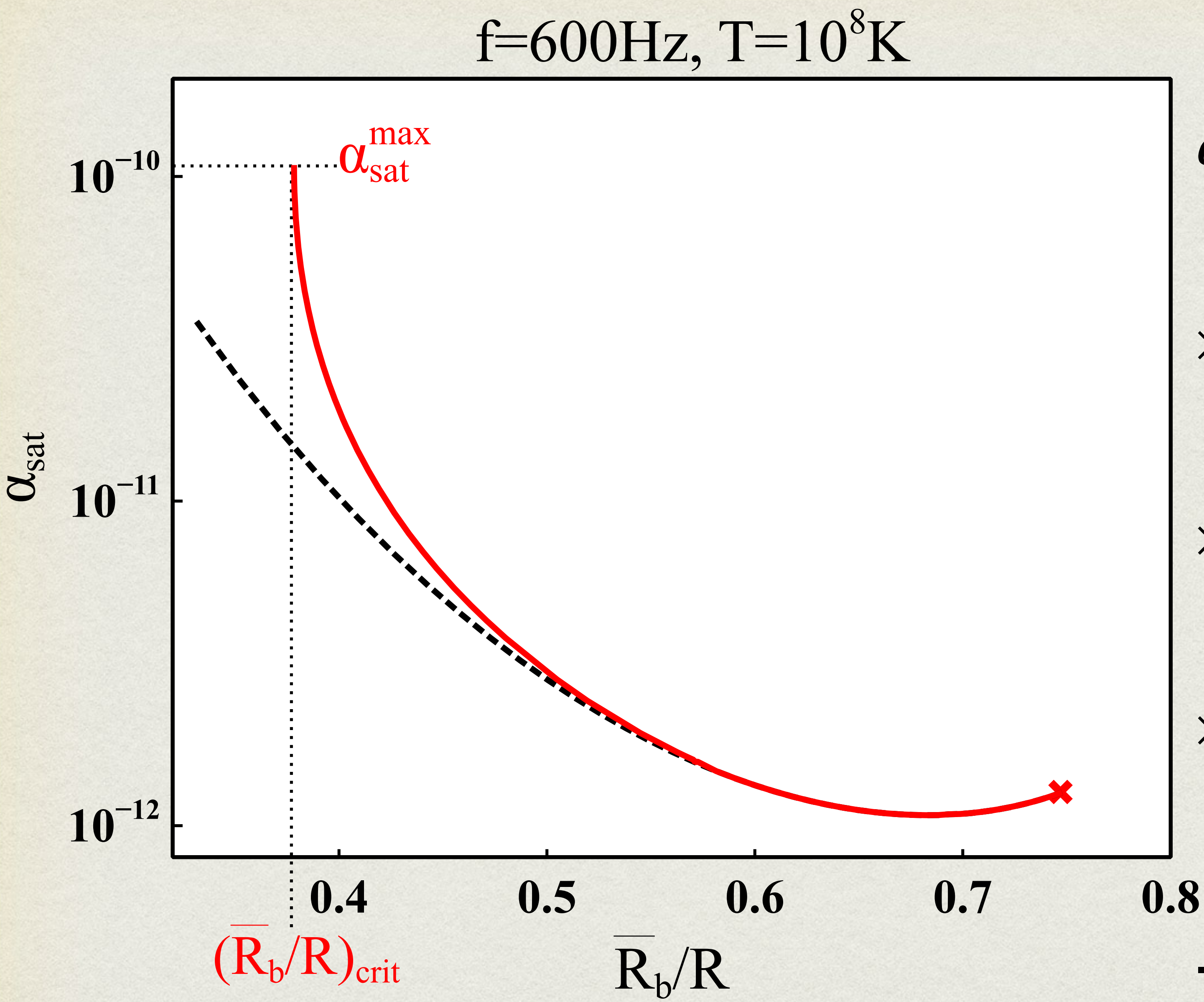


-Varying parameters e.g. the core size, rotation frequency or mass of the star will shift the curves

-There is no saturation if damping is insufficient to counteract driving (blue line above the maximum of red)

-If saturation occurs, most likely in the low-amplitude regime:
analytical calculation

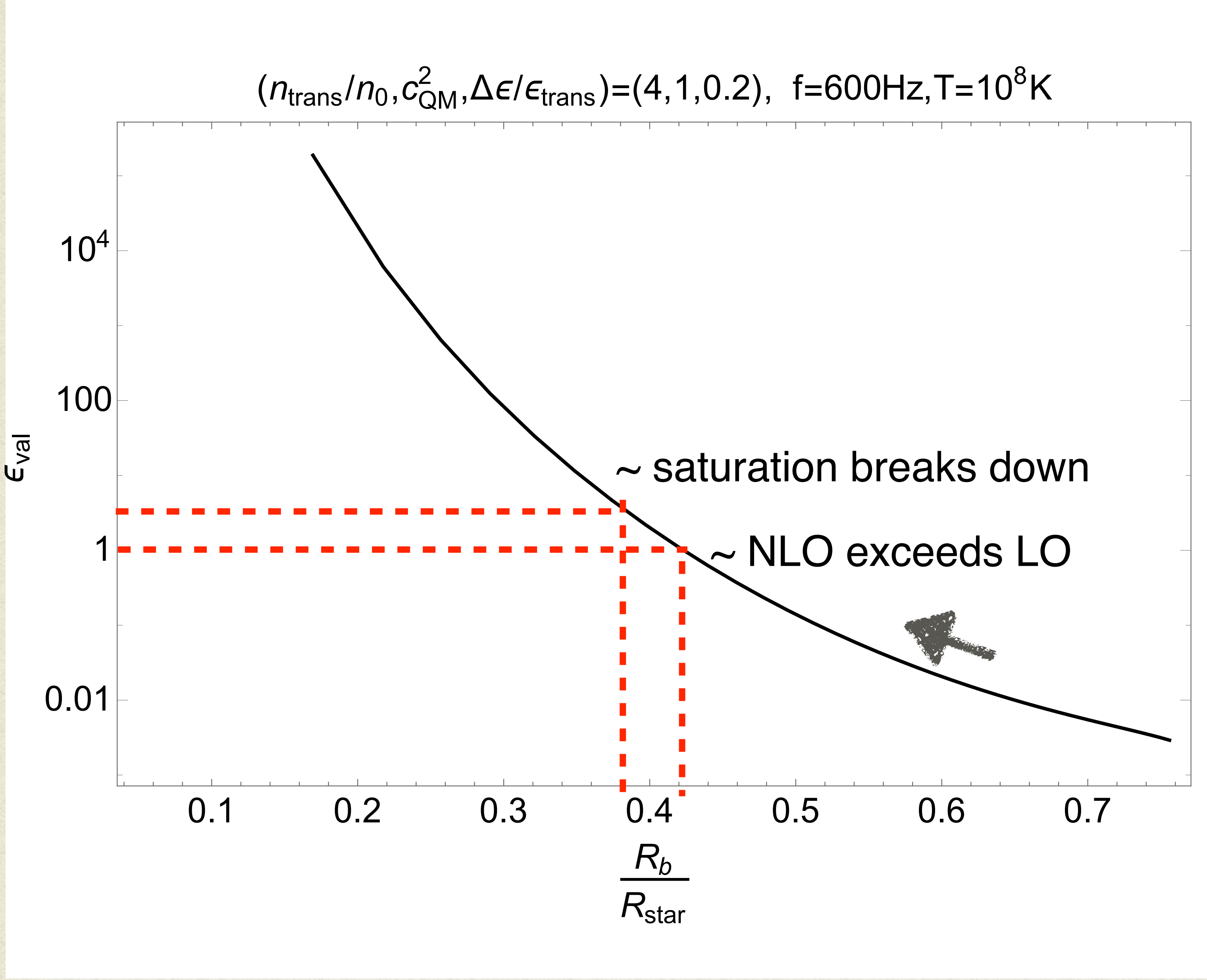
Low-amplitude approximation



$$\alpha_{sat}^{approx} \approx 4.2\times10^{-11}\gamma\left(\frac{\widetilde{D}_N}{1.5\text{MeV}}\right)\left(\frac{\tau_N}{2\times10^{-8}s}\right)^{-1}$$
$$\times\left(\frac{b_Q}{1/3}\right)^{-2}\left(\frac{n_N}{2n_0}\right)^{-4}\left(\frac{\chi_K^N}{(100\text{MeV})^2}\right)^{3}\left(\frac{g_b}{g_u}\right)^{3}$$
$$\times\left(\frac{\varepsilon_{crit}^Q}{2\varepsilon_{crit}^N}\right)^{3}\left(\frac{\varepsilon_{crit}^N}{600\text{MeV-fm}^{-3}}\right)^{3}\left(\frac{M}{1.4M_\odot}\right)^{2}$$
$$\times\left(\frac{\tilde{J}}{0.02}\right)^{2}\left(\frac{f}{1\text{kHz}}\right)^{-1}\left(\frac{R}{10\text{km}}\right)\left(\frac{\overline{R}_b/R}{0.4}\right)^{-8}$$

-Very accurate at low amplitude, but does not capture the sudden weakening at small core size

Range of validity



-Compute the next-to-leading order contribution

$$P_{dis}(\alpha) = P_0(\alpha) + P_1(\alpha) + \cdots$$

$$P_0(\alpha) \propto \alpha^3, P_1(\alpha) \propto \alpha^5$$

$$P_1(\alpha_{sat}^{LO}) \leq \varepsilon P_0(\alpha_{sat}^{LO})$$

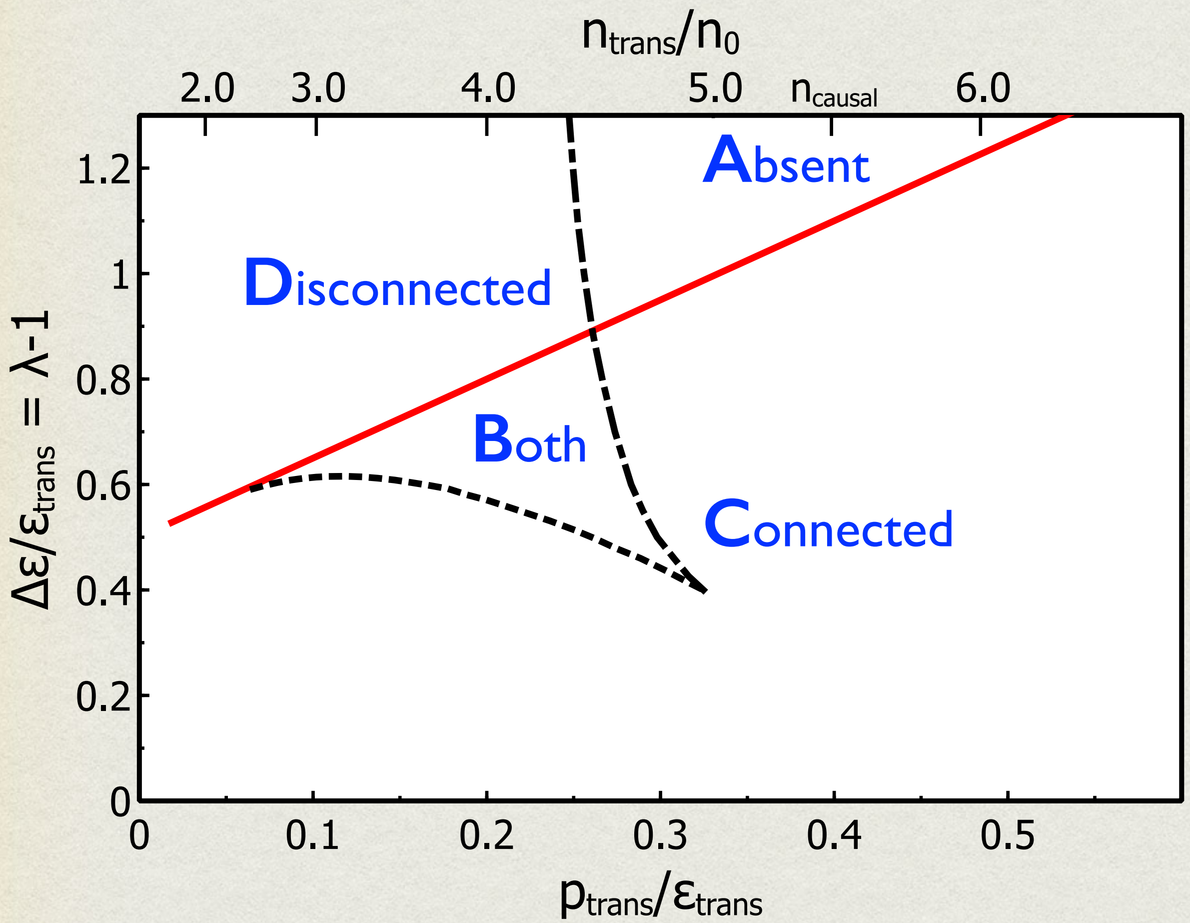
-Bound on parameter values

$$\varepsilon \geq 2.96 \left(\frac{\gamma - 1}{0.5}\right)^{-2} \left(\frac{\varepsilon_{crit}^{Q}}{2\varepsilon_{crit}^{N}}\right)^{2} \left(\frac{g_b}{g_u}\right)^{2} \left(\frac{M}{1.4 M_\odot}\right)^{4}$$

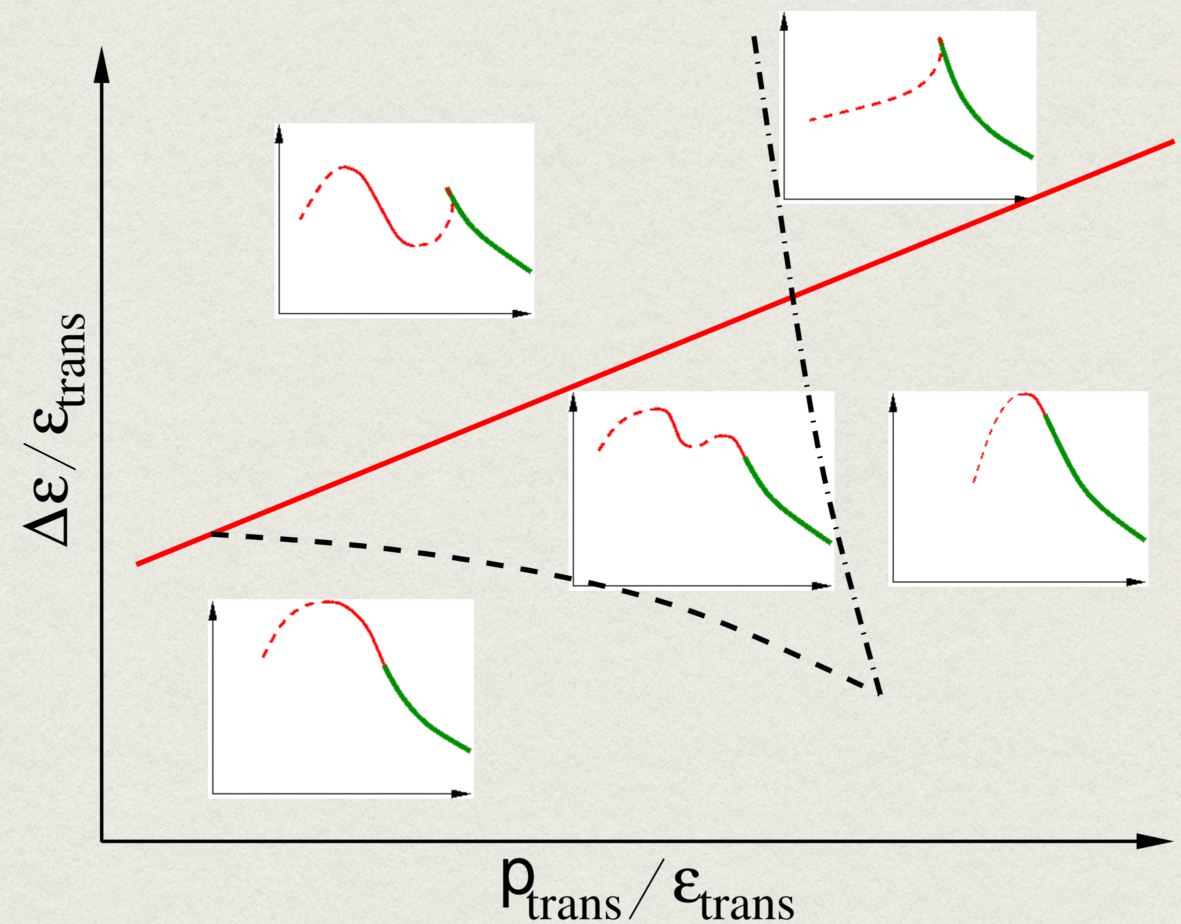
$$\times \left(\frac{\tilde{J}}{0.02}\right)^{4} \left(\frac{f}{1\mathrm{kHz}}\right)^{6} \left(\frac{R}{10\mathrm{km}}\right)^{2} \left(\frac{\bar{R}_b / R}{0.4}\right)^{-14}$$

Hybrid star configurations

Soft NM (HLPS) + QM $c_{\mathrm{QM}}^2 = 1$



-with CSS parametrization



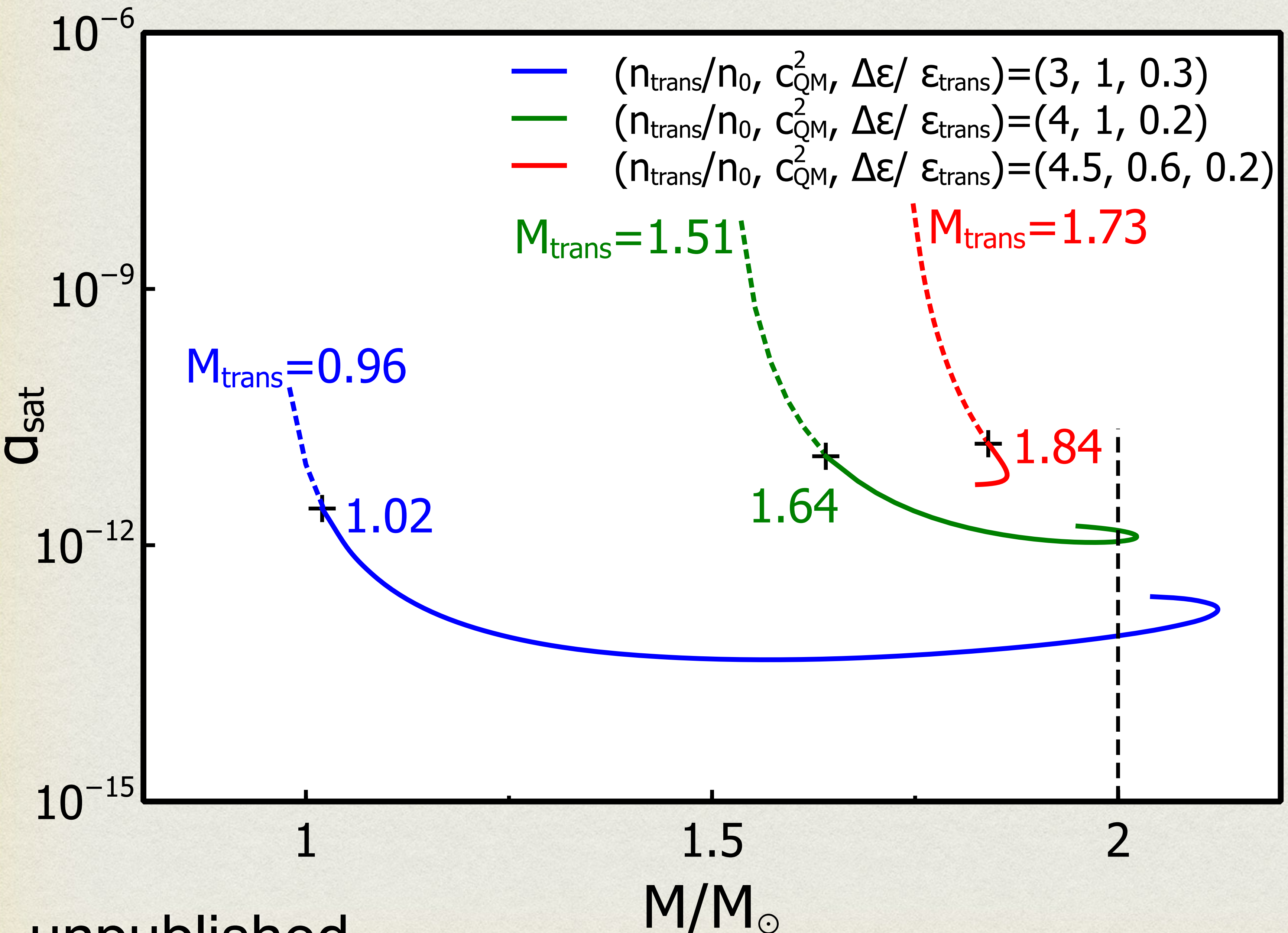
-Below the red line in regions B and C, there is a <u>connected</u> hybrid star branch

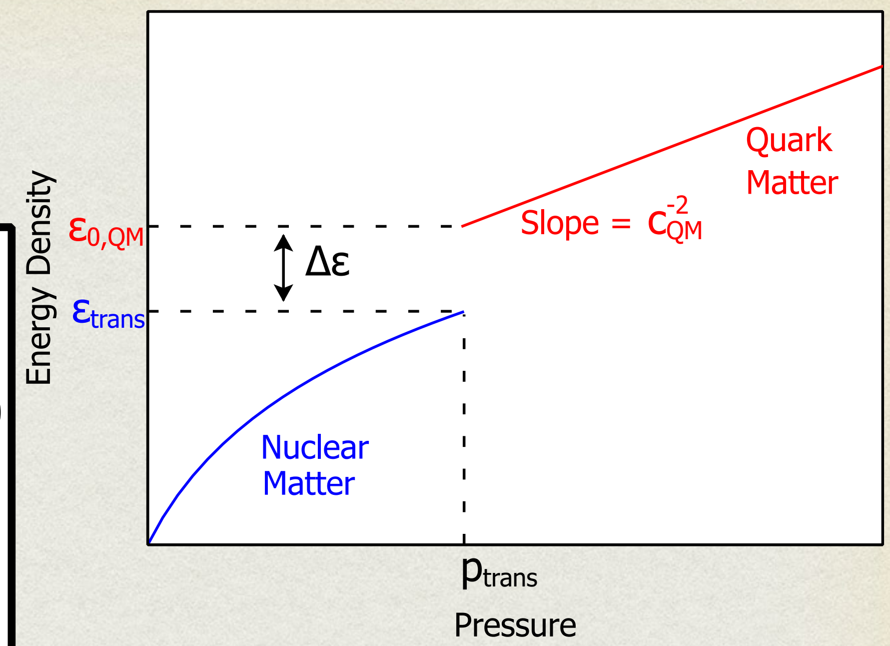
-In regions B and D, there is a <u>disconnected</u> hybrid star branch

Alford, Han and Prakash, arXiv:1302.4702

Dependence on QM EoS

f=600Hz, T=10^{8}K





unpublished

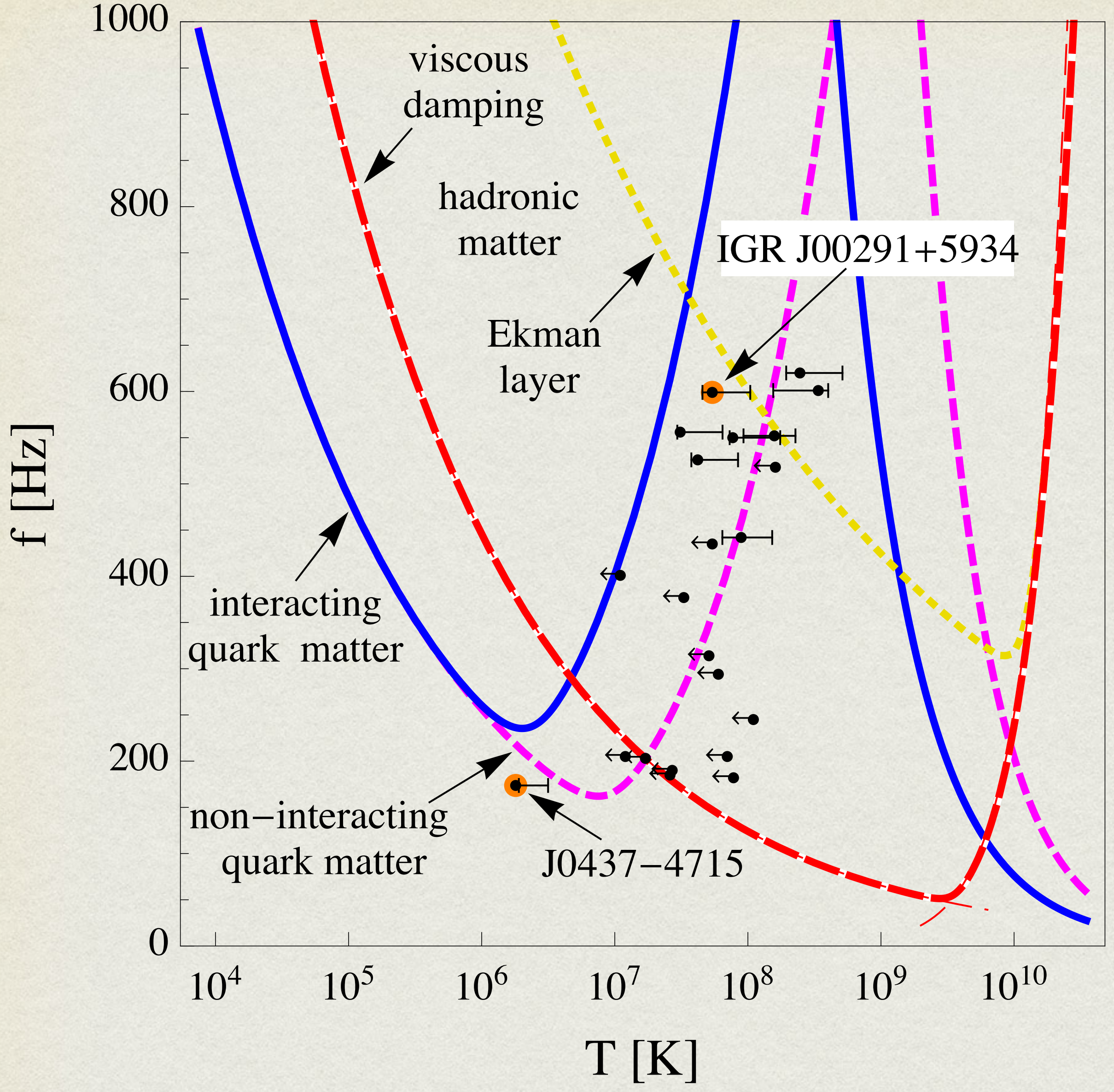
QM EoS parameters

$p_{\rm trans} / \varepsilon_{\rm trans}$

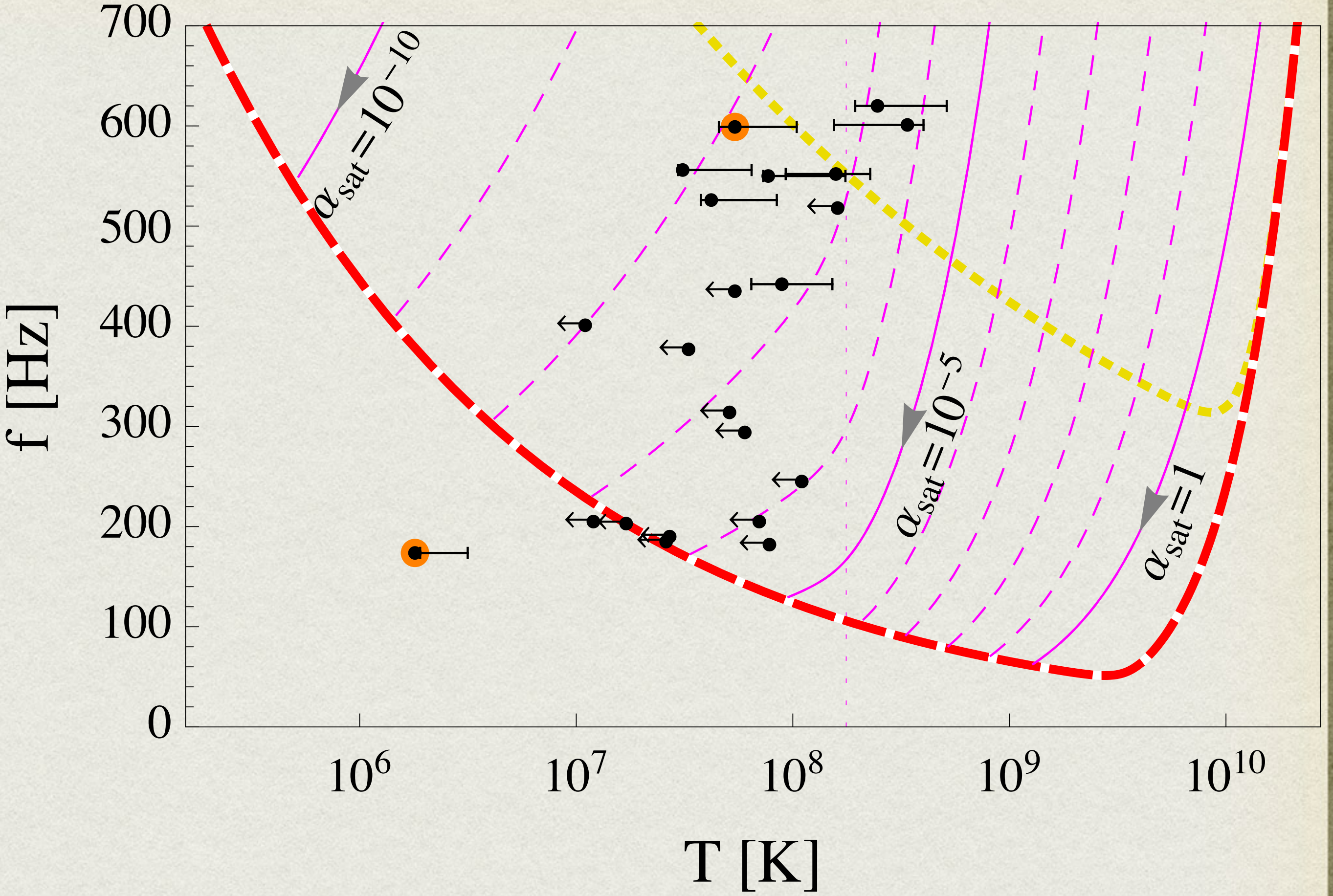
$\Delta\varepsilon / \varepsilon_{\rm trans}$

$c^2_{\rm QM}$

Astrophysical interpretation



Alford & Schwenzer, Phys. Rev. Lett. 113, 251102



Alford & Schwenzer, MNRAS 446.4 (2015)

- Damping vs. saturation
  (no r-mode) (tiny r-mode)
- Thermal & spin evolution

Discussion

Toy model simplifications

-EoS parametrization

-(steady-state) laminar approach

-diffusion coefficient estimates in nuclear/quark matter

-density oscillations due to r-mode in non-uniform matter

Outlook

-vary nuclear EoSs; more quark matter EoS parameter space

-other 1st-order phase transitions with sharp interface

-mixed phases:
 1) domains of charged hadronic and quark matter coexist
 2) nuclear pasta in the inner crust

-hydrodynamic instability

Summary

A new saturation mechanism for oscillations in hybrid stars

-Phase conversion dissipation: a reasonable first estimate of the damping through a sharp boundary moving periodically in a steady state

Extremely low saturation amplitude can be achieved

-$\alpha_{\mathrm{sat}} \simeq O(10^{-12} \sim 10^{-10})$: consistent with millisecond pulsar frequency data

-At low amplitude analytic prediction is given

-Saturation amplitude relies on multiple parameters, among which the quark core size is the most sensitive one

Interpretation of observations

arXiv:1404.5279

-MSRPs could form a separate population of very cold sources and would not show *detectable* r-mode GW emission

THANK YOU!

Q & A