Tidal interactions during neutron star mergers: symmetry energy considerations

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NuSYM13; July 23

Outline

- Motivation: Symmetry energy at saturation density and higher

- NS-NS tidal interactions

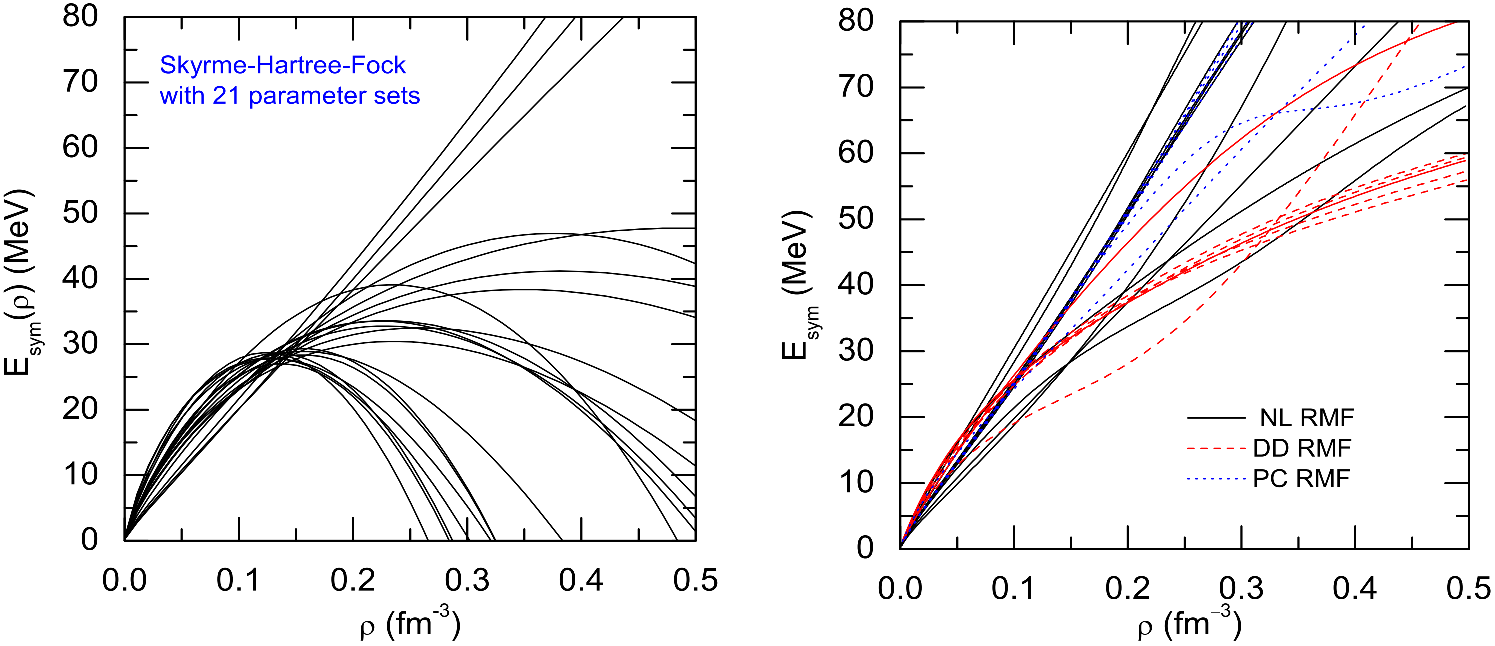
- Equilibrium tides
  - Tidal polarizability/Love number
  - Preparation of Nuclear Matter models
  - Results

- Dynamical Tides I: resonant excitation of g-modes

- Dynamical Tides II: resonant excitation of crust modes; crust shattering

- Summary

Symmetry energy



Li, Chen, Ko, Phys. Rep. 464 (2008)

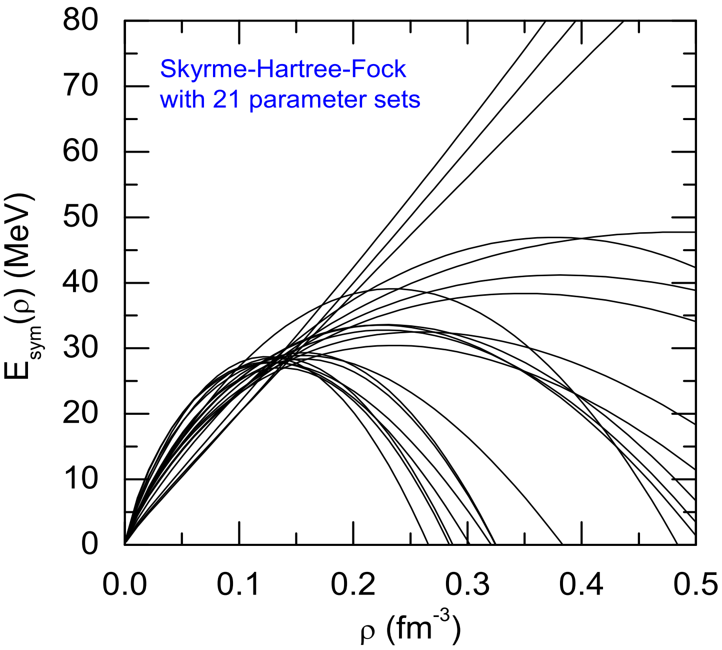
$$E(n,\delta) = E_0(n) + S(n)\delta^2 + \ldots$$

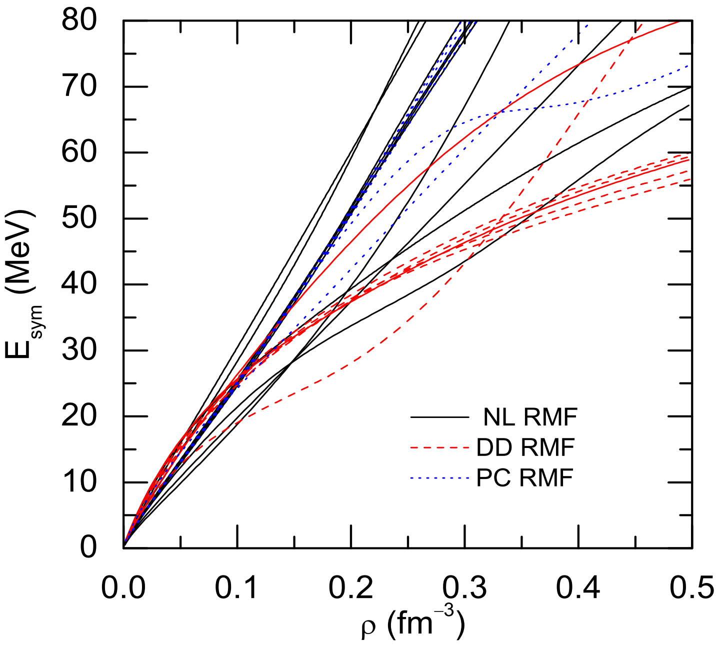
$$\delta = 1 - 2x$$

$$S(n) = J + L\chi + \frac{K_{\mathrm{sym}}}{2}\chi^2 + \ldots$$

$$\chi = \frac{n-n_0}{3n_0}$$

Symmetry energy





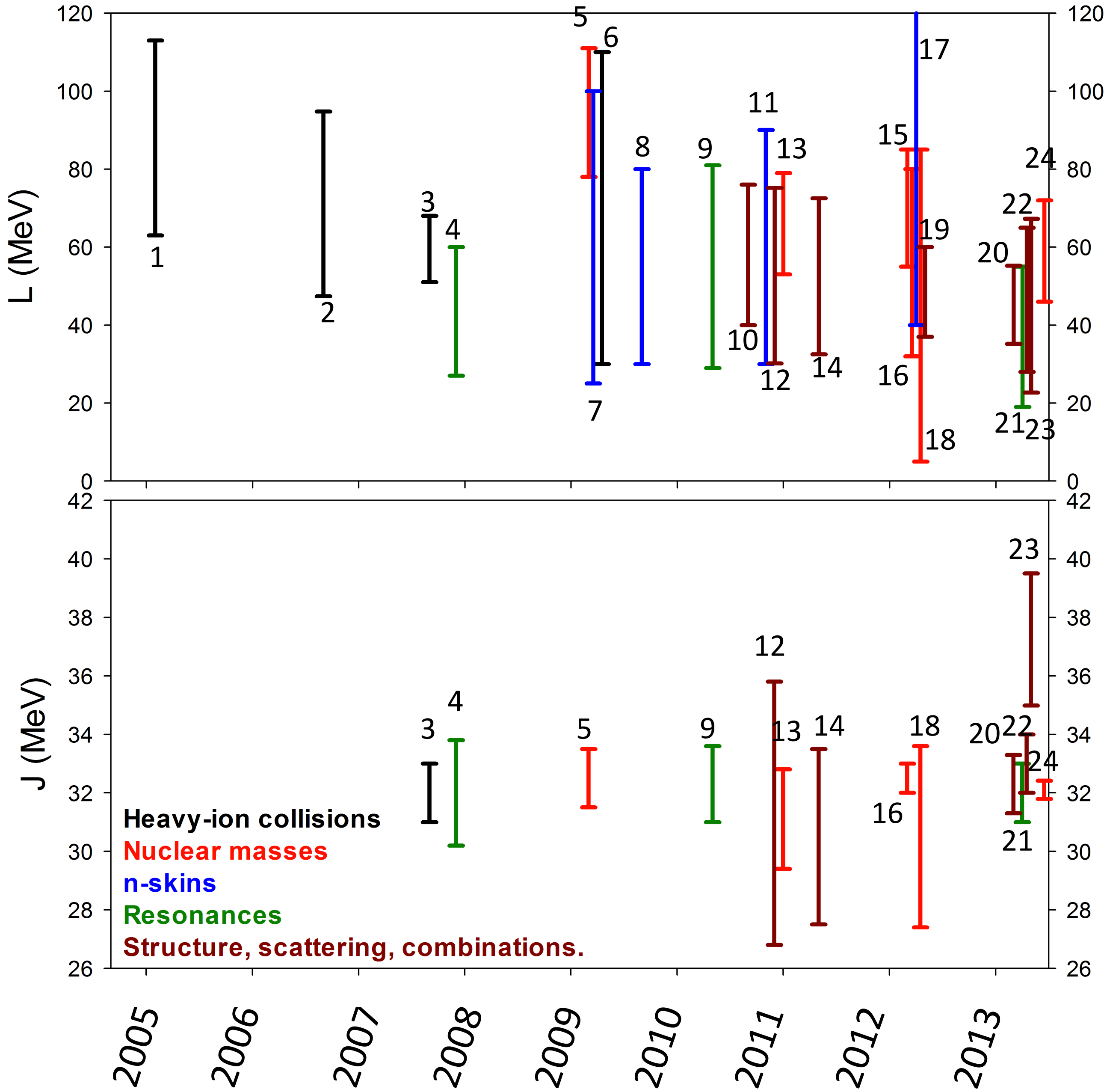
Li, Chen, Ko, Phys. Rep. 464 (2008)

$$E(n,\delta) = E_0(n) + S(n)\delta^2 + \ldots \qquad \delta = 1 - 2x$$

$$S(n) = J + L\chi + \frac{K_{\rm sym}}{2}\chi^2 + \ldots \qquad \chi = \frac{n-n_0}{3n_0}$$

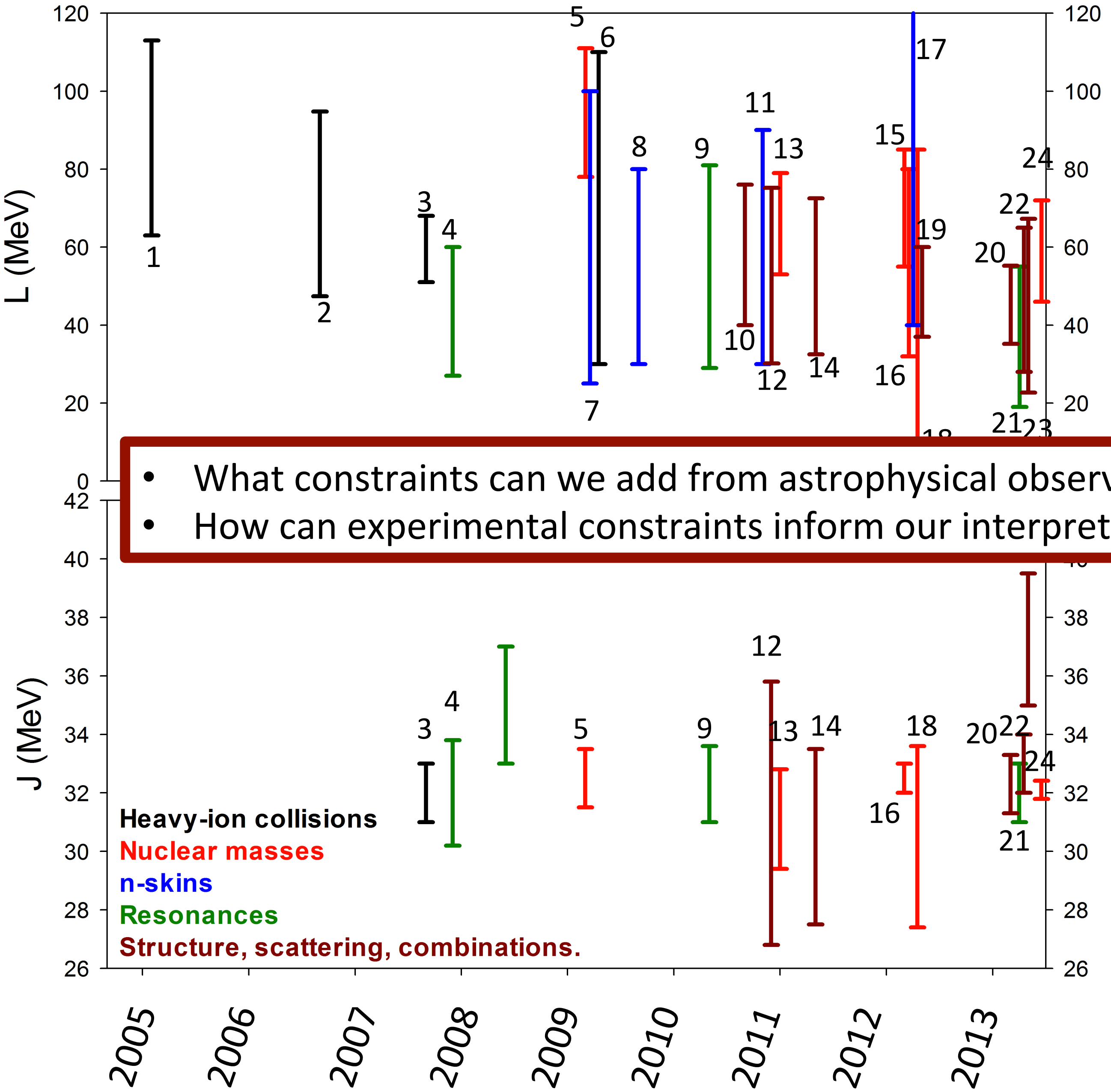
Other notations are available

Experimental Constraints: Saturation Density



1. Chen,Ko,Li; PRL94
2. Famiano et al; PRL97
3. Shetty et al; PRC76
4. Klimkiewicz et al; PRC76
5. Danielewicz, Lee; NPhys A818
6. Tsang et al; PRL102
7. Centelles et al; PRL102
8. Warda et al; PRC80
9. Carbone et al; PRC81
10. Chen, Ko, Li, Xu; PRC82
11. Zenihiro et al; PRC82
12. Xu, Li, Chen; PRC82
13. Liu et al; PRC82
14. Chen; PRC83
15. Möller et al; PRL108
16. Lattimer, Lim; arxiv:1203.4286
17. Abrahamyan et al, PRL108
18. Dong et al; PRC85
19. Piekarewicz et al; PRC85
20. Zhang, Chen; arxiv:1302.5327
21. Roca-Maza et al. PRC87
22. Wang, Ou, Liu, PRC87
23. Li et al. PLB721
24. Agrawal et al, arxiv:1305:5336

Experimental Constraints: Saturation Density



- What constraints can we add from astrophysical observation?
- How can experimental constraints inform our interpretation of observations?

1. Chen,Ko,Li; PRL94
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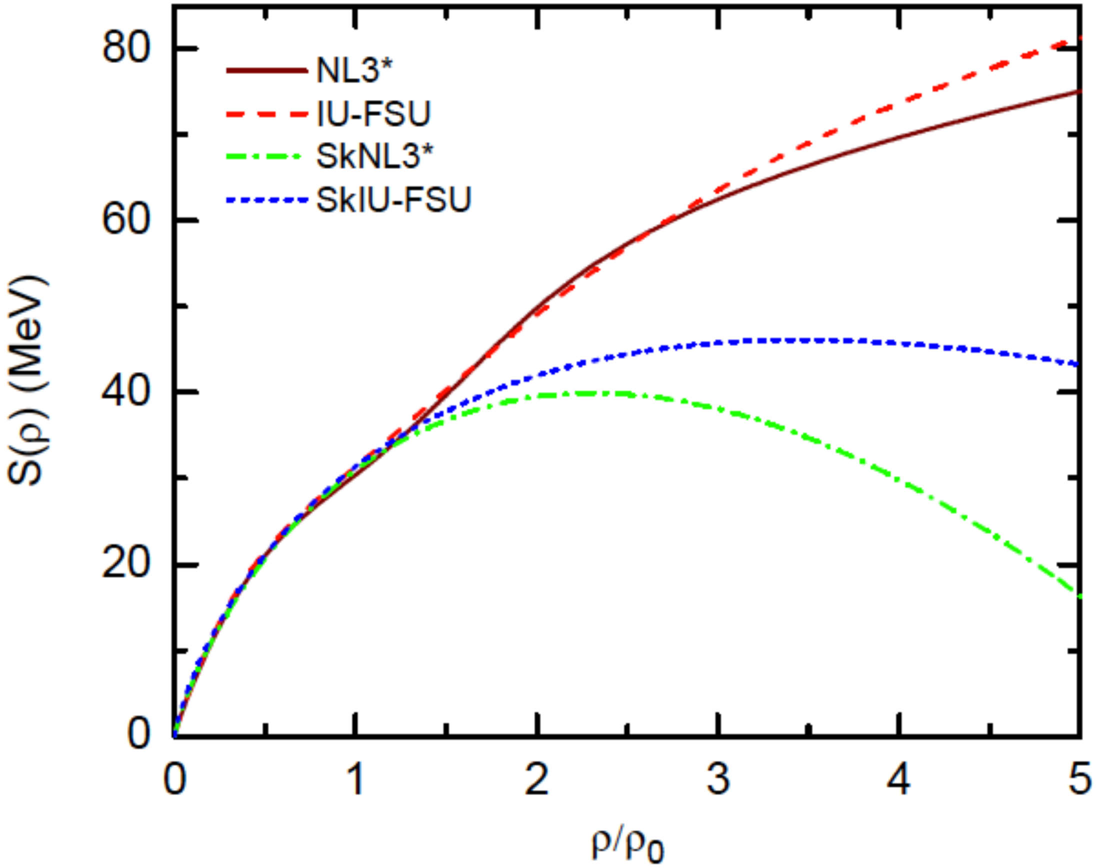
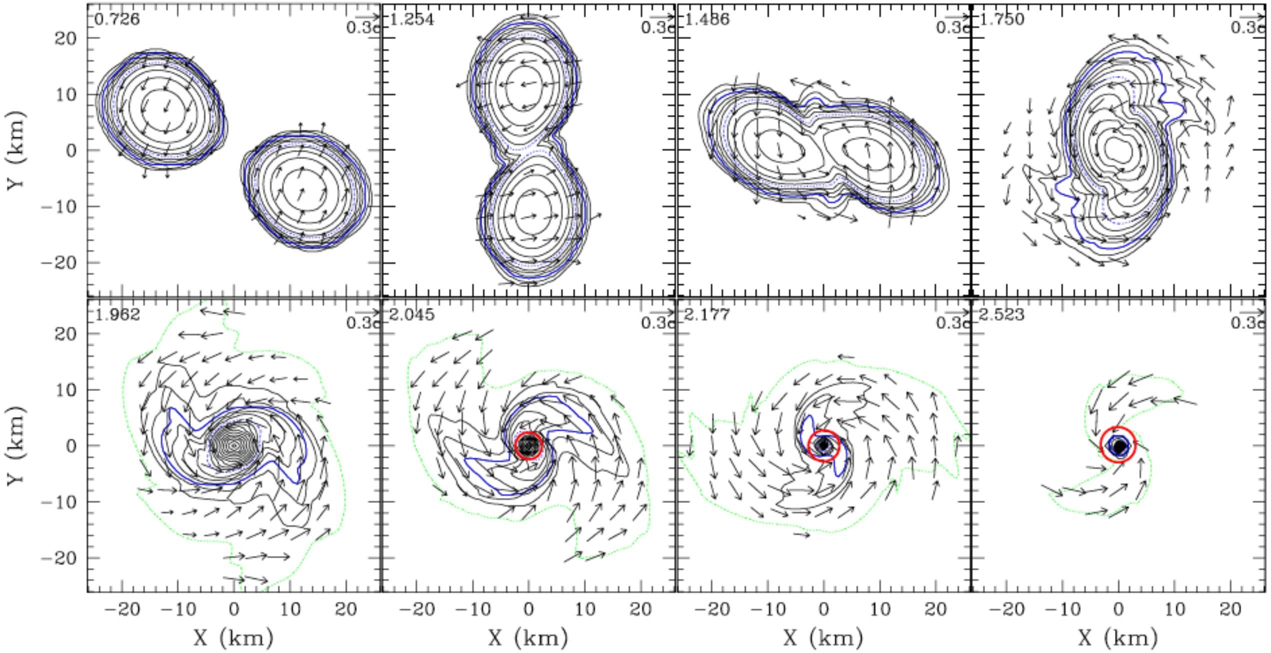
Not full story: Saturation constraints on J,L not necessarily constraining at high densities

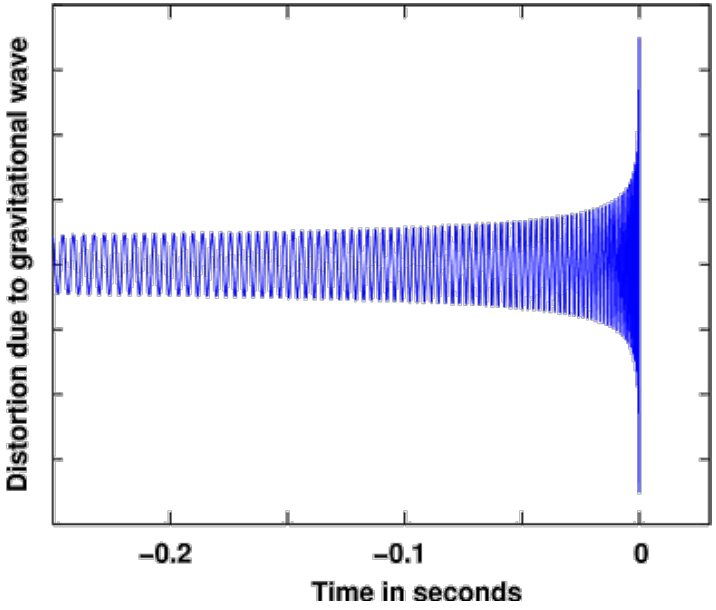


- Can we find astrophysical observables that are sensitive to high density EOS/symmetry energy? (e.g. neutrino signal from PNS - Roberts et al PRL108 (2012))

NS-NS Mergers

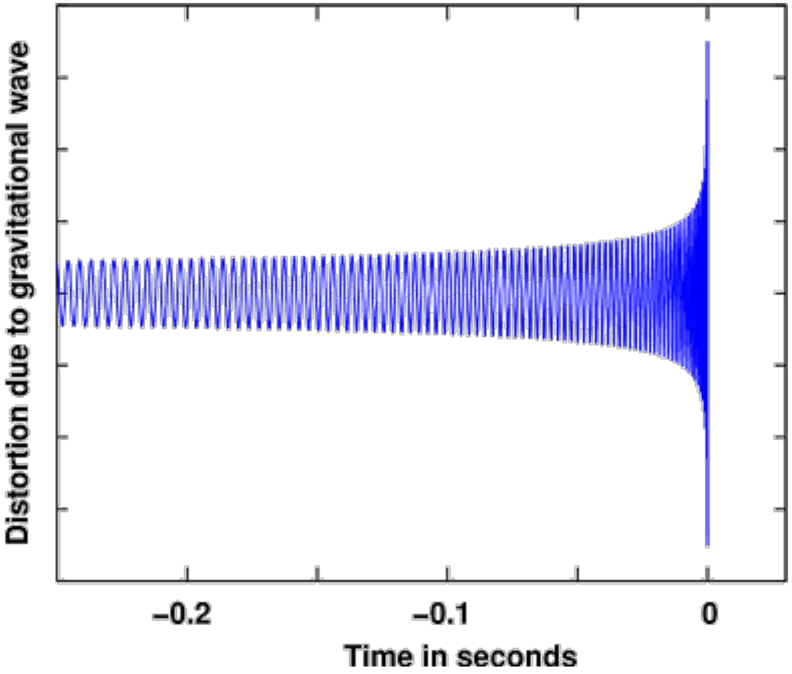


Shibata, Keisuke; PRD73, 064027 (2006)



M. Possel, einstein-online.info

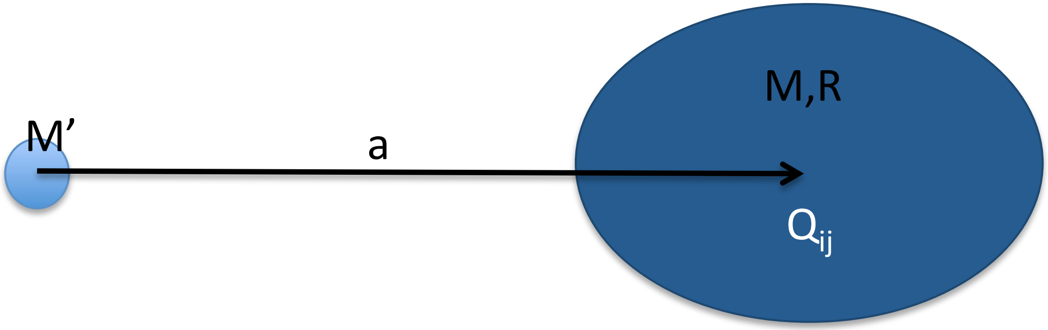
Equilibrium tides



- Tidal field E_{ij} drives f-mode (quadrupole deformation Q_{ij})
- Resulting energy transfer appears as phase shift in gravitational waveform
- Detectable cleanly f≈100-400Hz
- Phase shift depends on one parameter: tidal polarizability λ (or Love number k_2)

$$dN_{\rm GW} = dN_{\rm GW}^{(0)} \left[1 - \mathcal{O}\left(k_2 \frac{M' R^5}{M a^5} \right) \right]$$

Flanagan, Hinderer, PRD77, 021502 (2008)
Hinderer et al, PRD81, 123016 (2010)



$$Q_{ij} = -k_2 \frac{2R^5}{3G} E_{ij} \equiv -\lambda E_{ij}$$

Tidal polarizability and Love number

$$Q_{ij} = -k_2 \frac{2R^5}{3G} E_{ij} \equiv -\lambda E_{ij}$$

$$\begin{aligned}
k_2 \;=\; & \frac{1}{20}\left(\frac{R_s}{R}\right)^5 \left(1-\frac{R_s}{R}\right)^2 \left[2-y_R+(y_R-1)\frac{R_s}{R}\right] \times \\
& \times \Bigg\{ \frac{R_s}{R}\Bigg(6-3y_R+\frac{3R_s}{2R}(5y_R-8)+\frac{1}{4}\left(\frac{R_s}{R}\right)^2 \Bigg[26- \\
& - 22y_R+\left(\frac{R_s}{R}\right)(3y_R-2)+\left(\frac{R_s}{R}\right)^2(1+y_R)\Bigg]\Bigg)+ \\
& + 3\left(1-\frac{R_s}{R}\right)^2 \left[2-y_R+(y_R-1)\frac{R_s}{R}\right] \times \\
& \times \log\left(1-\frac{R_s}{R}\right)\Bigg\}^{-1} ,
\end{aligned} \tag{1}$$

$$r\frac{dy(r)}{dr} + y(r)^2 + y(r)F(r) + r^2 Q(r) = 0 \, ,$$

$$F(r) = \frac{r - 4\pi r^3 \left(\mathcal{E}(r) - P(r)\right)}{r - 2M(r)} \, ,$$

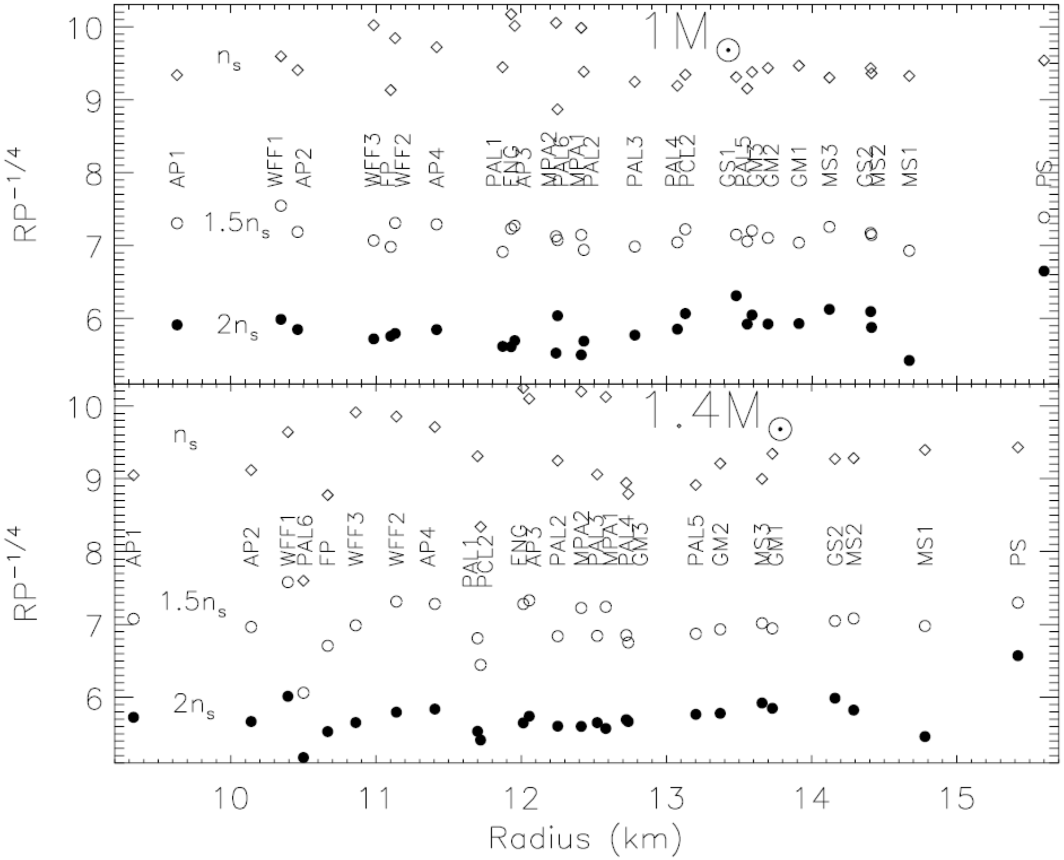
$$\begin{aligned}
Q(r) \;=\; & \frac{4\pi r\left(5\mathcal{E}(r) + 9P(r) + \frac{\mathcal{E}(r)+P(r)}{\partial P(r)/\partial \mathcal{E}(r)} - \frac{6}{4\pi r^2}\right)}{r - 2M(r)} \\
& - 4\left[\frac{M(r) + 4\pi r^3 P(r)}{r^2\left(1 - 2M(r)/r\right)}\right]^2 .
\end{aligned}$$

- Tidal polarizability λ function of global NS properties (M,R) and internal structure (function y_R obtained by integration out from center of star)
- Clearly discriminates between NSs and Strange stars

- Postnikov,Prakash,Lattimer, PRD82, 024012 (2010)

- Sensitivity to high density symmetry energy?

Preparation of Skyrme and RMF EOSs to systematically explore saturation and high density symmetry energy uncertainty



Lattimer and Prakash, ApJ 550, 426 (2001)

$$P_{\rm NS}(n_0) \approx \frac{n_0}{3}L + 0.048n_0\left(\frac{J}{30}\right)^3\left(J - \frac{4}{3}L\right)$$

- Famous correlation between fiducial pressure P and NS radius R
- Scatter of order 1km due largely to differences super saturation symmetry energy behavior
- Differences from different parameterizations within same EDF, different EDFs; would like to disentangle

Preparation of Skyrme and RMF EOSs to systematically explore saturation and high density symmetry energy uncertainty

- Skyrme-Hartree-Fock (SHF) model of nuclear matter:

$$
\begin{aligned}
\mathscr{H} = & \frac{\hbar^2}{2M}\tau + t_0\left[(2+x_0)\rho^2 - (2x_0+1)\left(\rho_{\rm n}^2+\rho_{\rm p}^2\right)\right]/4 \\
+ & \, t_3\rho^\sigma\left[(2+x_3)\rho^2 - (2x_3+1)\left(\rho_{\rm n}^2+\rho_{\rm p}^2\right)\right]/24 \\
+ & \left[t_2(2x_2+1) - t_1(2x_1+1)\right](\tau_n\rho_n + \tau_p\rho_p)/8 + \left[t_1(2+x_1) + t_2(2+x_2)\right]\tau\rho/8 \\
+ & \left[3t_1(2+x_1) - t_2(2+x_2)\right](\nabla\rho)^2/32 - \left[3t_1(2x_1+1) + t_2(2x_2+1)\right]\left[(\nabla\rho_{\rm n})^2 + (\nabla\rho_{\rm p})^2\right]/32 \\
+ & \, W_0\left[\vec{J}\cdot\nabla\rho + \vec{J}_{\rm n}\cdot\nabla\rho_{\rm n} + \vec{J}_{\rm p}\cdot\nabla\rho_{\rm p}\right]/2 + (t_1-t_2)\left[J_{\rm n}^2 + J_{\rm p}^2\right]/16 - (t_1x_1 + t_2x_2)J^2/16 \,.
\end{aligned}
$$

-9 parameters $\{t_0, t_1, t_2, t_3, x_0, x_1, x_2, x_3, \sigma\}$

-2 purely isovector parameters: x_0, x_3

- Relativistic Mean Field (RMF) model of nuclear matter:

$$
\begin{aligned}
\mathscr{L} = & \, \bar{\psi}\left[\gamma^\mu\left(i\partial_\mu - g_{\rm v}V_\mu - \frac{g_\rho}{2}\boldsymbol{\tau}\cdot\mathbf{b}_\mu - \frac{e}{2}(1+\tau_3)A_\mu\right) - (M - g_{\rm s}\phi)\right]\psi + \frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi - \frac{1}{2}m_{\rm s}^2\phi^2 \\
- & \frac{1}{4}V^{\mu\nu}V_{\mu\nu} + \frac{1}{2}m_{\rm v}^2V^\mu V_\mu - \frac{1}{4}\mathbf{b}^{\mu\nu}\cdot\mathbf{b}_{\mu\nu} + \frac{1}{2}m_\rho^2\,\mathbf{b}^\mu\cdot\mathbf{b}_\mu - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - U(\phi, V_\mu, \mathbf{b}_\mu)\,,
\end{aligned}
$$

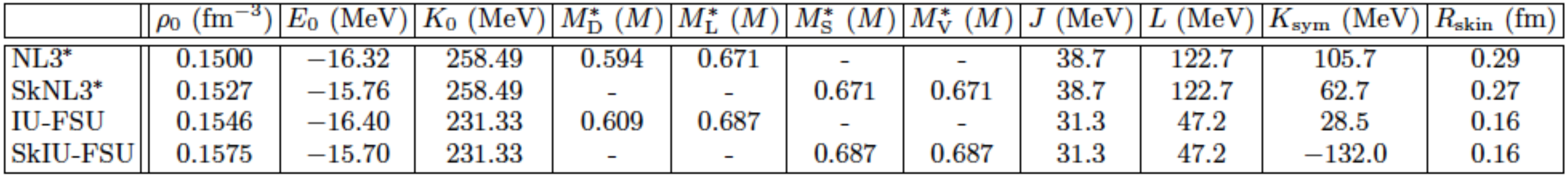
$$
U(\phi, V^\mu, \mathbf{b}^\mu) = \frac{\kappa}{3!}(g_{\rm s}\phi)^3 + \frac{\lambda}{4!}(g_{\rm s}\phi)^4 - \frac{\zeta}{4!}g_{\rm v}^4(V_\mu V^\mu)^2 - \Lambda_{\rm v}g_\rho^2\,\mathbf{b}_\mu\cdot\mathbf{b}^\mu g_{\rm v}^2V_\nu V^\nu
$$

-7 parameters $\{g_{\rm s}, g_{\rm v}, g_\rho, \kappa, \lambda, \zeta, \Lambda_{\rm v}\}$

-2 purely isovector parameters g_ρ, $\Lambda_{\rm v}$

Preparation of Skyrme and RMF EOSs to systematically explore saturation and high density symmetry energy uncertainty

- Take 2 reference RMF models: NL3, IU-FSU
- Create 2 reference Skyrme models with identical saturation NM properties: SkNL3, SkIU-FSU
  (by writing Skyrme parameters in terms of NM parameters –
  Chen et al PRC80, 014322 (2009); PRC82, 024321 (2010))
- Adjust ρ_0 and E_0 in SHF models to reproduce double magic nuclei BE, r_{ch}



	ρ_0 (fm^{-3})	E_0 (MeV)	K_0 (MeV)	M^*_{D} (M)	M^*_{L} (M)	M^*_{S} (M)	M^*_{V} (M)	J (MeV)	L (MeV)	K_{sym} (MeV)	R_{skin} (fm)
NL3*	0.1500	−16.32	258.49	0.594	0.671	-	-	38.7	122.7	105.7	0.29
SkNL3*	0.1527	−15.76	258.49	-	-	0.671	0.671	38.7	122.7	62.7	0.27
IU-FSU	0.1546	−16.40	231.33	0.609	0.687	-	-	31.3	47.2	28.5	0.16
SkIU-FSU	0.1575	−15.70	231.33	-	-	0.687	0.687	31.3	47.2	−132.0	0.16

- Re-fit the 2 purely isovector parameters in all models to the results of microscopic calculations

$$\chi^2(\mathbf{p}) \equiv \sum_{n=1}^{N} \left(\frac{\mathcal{O}_n^{(\mathrm{th})}(\mathbf{p}) - \mathcal{O}_n^{(\mathrm{exp})}}{\Delta \mathcal{O}_n} \right)^2 .$$

Model parameters: $\mathbf{p} = (p_1, \ldots, p_F)$

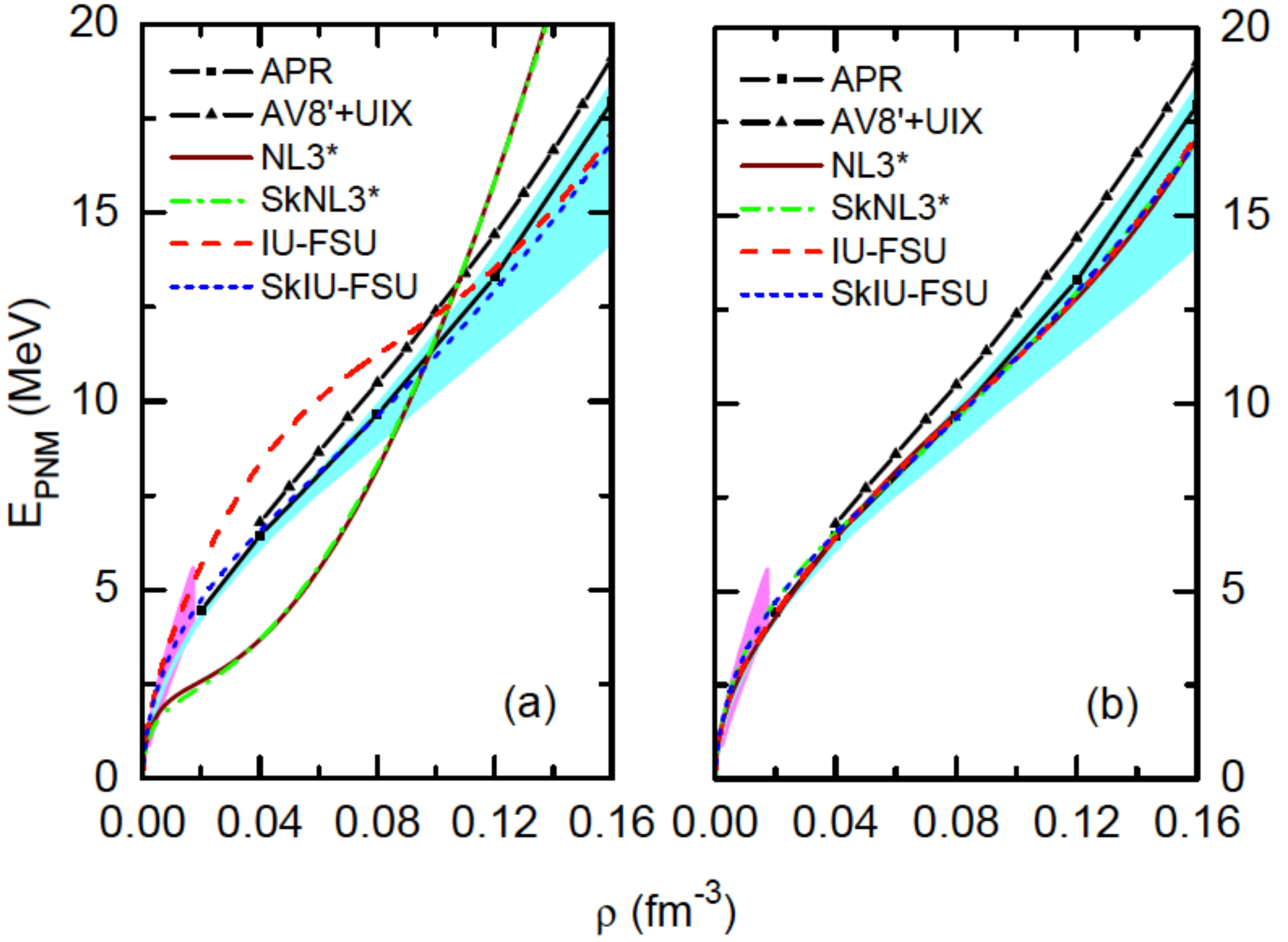
(numerical “experimental” data:

$$E_{\mathrm{PNM}}: \; 0.04 \leq \rho \leq 0.16 \ \mathrm{fm}^{-3}$$

Akmal et al PRC58, 1802 (1998)
Schwenk and Pethick PRL79, 160401 (2005)
Gandolfi et al PRC79, 054005 (2009)
Hebeler and Schwenk, PRC82, 014314 (2010))

Preparation of Skyrme and RMF EOSs to systematically explore saturation and high density symmetry energy uncertainty

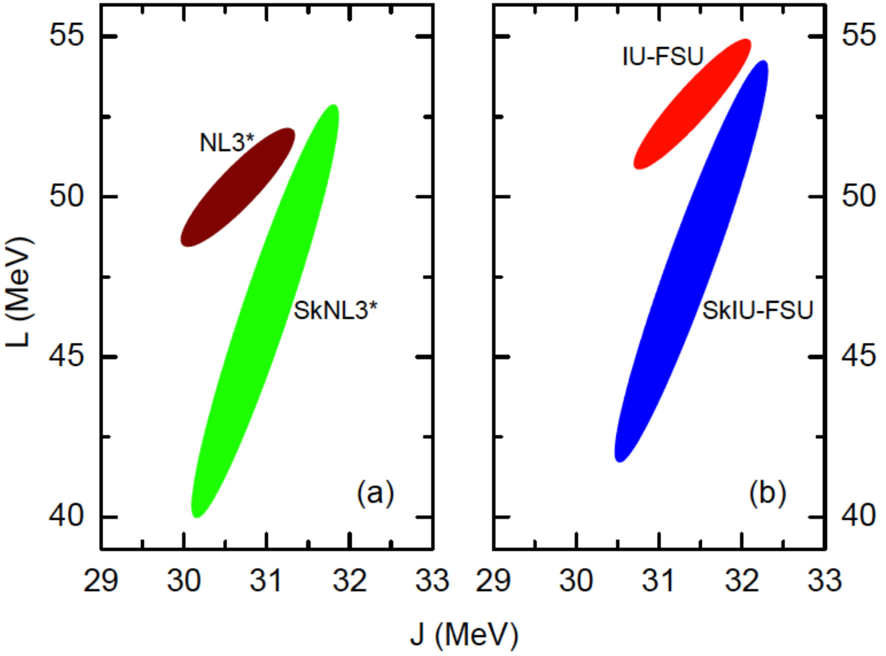
PURE NEUTRON MATTER FITS: BEFORE AND AFTER

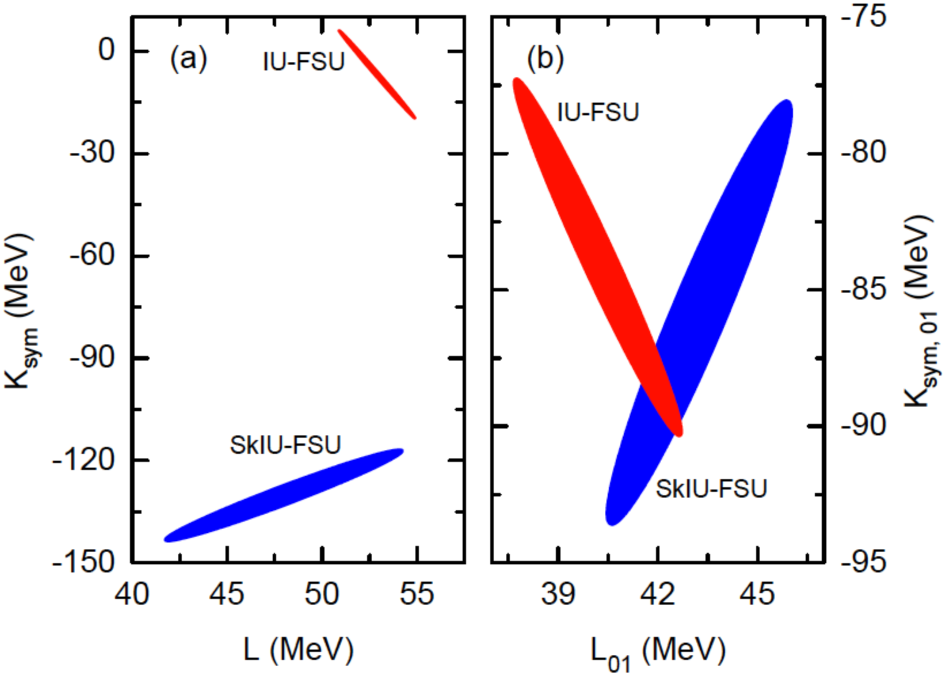


Fattoyev, Newton, Li, PRC86, 025804

Preparation of Skyrme and RMF EOSs to systematically explore saturation and high density symmetry energy uncertainty

RESULTING 1-σ CONFIDENCE ELLIPSES: SYMMETRY ENERGY PARAMETERS



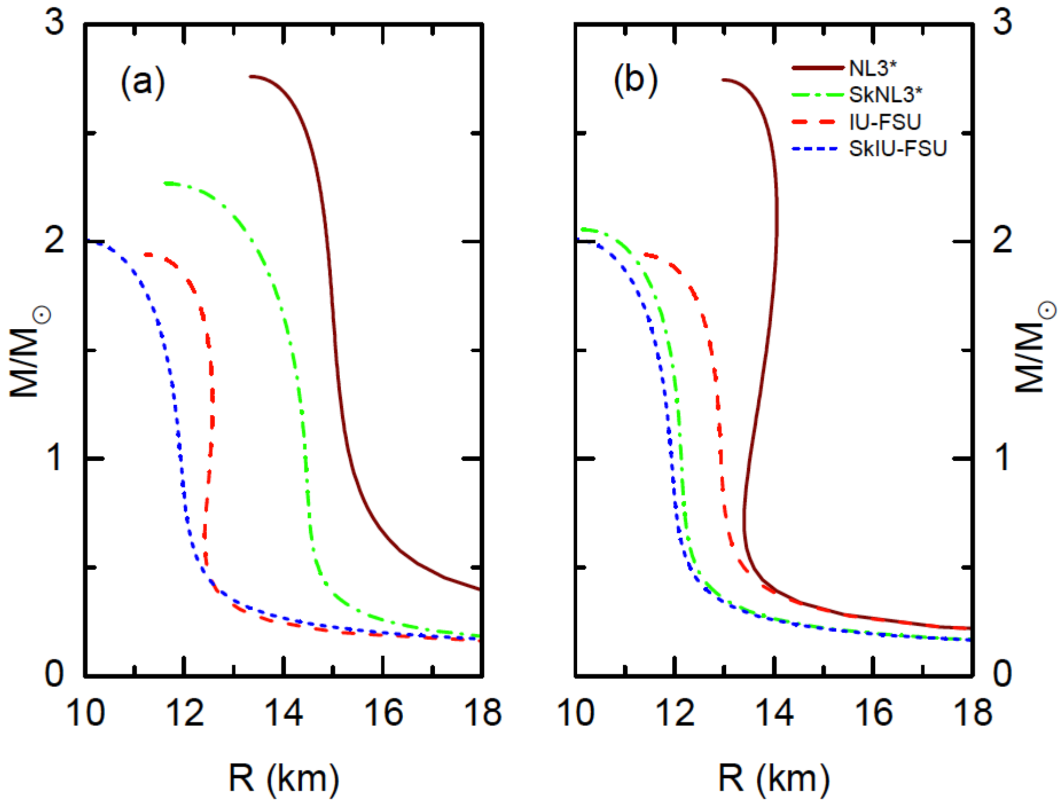


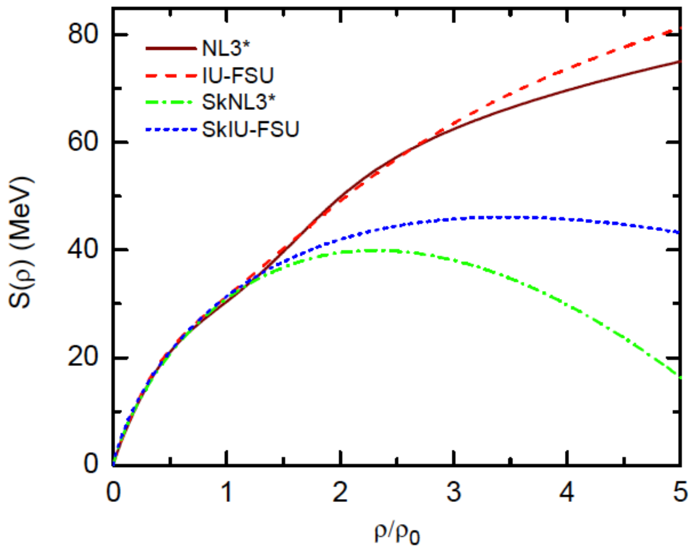
Fattoyev, Newton, Li, PRC86, 025804

	J (MeV)	L (MeV)	K_τ (MeV)
RMF	30.2 — 31.4	36.1 — 59.3	-329.7 — -215.7
SHF	30.1 — 33.2	28.5 — 64.4	-418.8 — -235.3

Experiment: $-760 < K_\tau < -372$ MeV e.g. Dutra et al, PRC85, 035201 (2012)

Preparation of Skyrme and RMF EOSs to systematically explore saturation and high density symmetry energy uncertainty





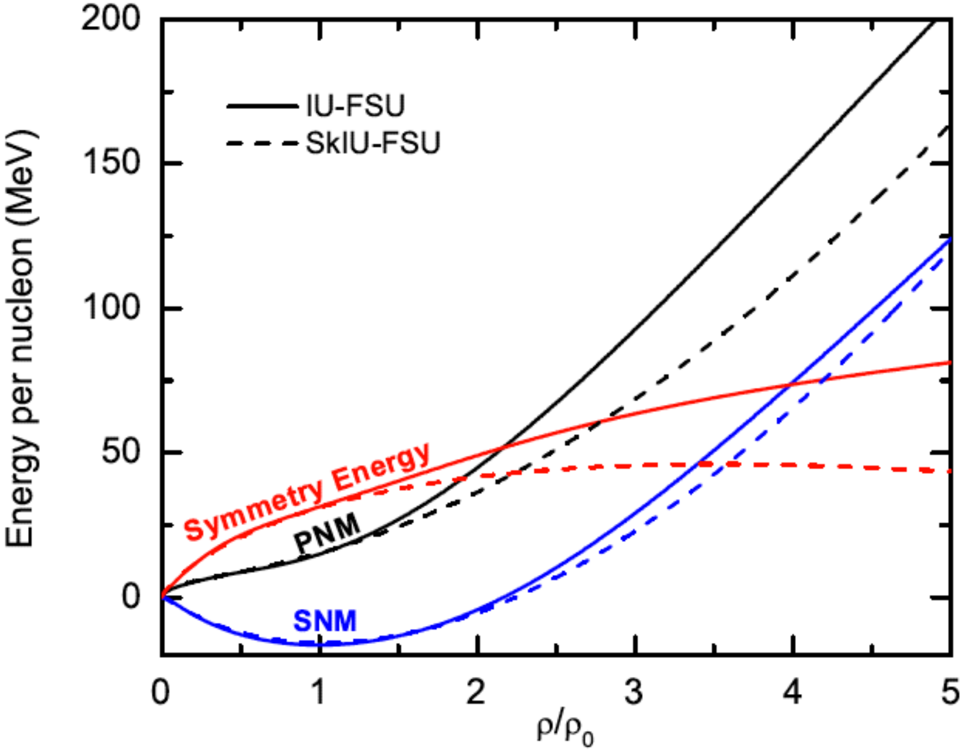
$$S_{\mathrm{RMF}}(\rho) = A(\rho)\rho^{2/3} + B(\rho)\rho\ ,$$
$$S_{\mathrm{SHF}}(\rho) = a\rho^{2/3} - b\rho - c\rho^{5/3} - d\rho^{\sigma+1}$$

Fattoyev, Newton, Li, PRC86, 025804

- When constrained by PNM calculations, RMF models are systematically stiffer at high density than SHF models.

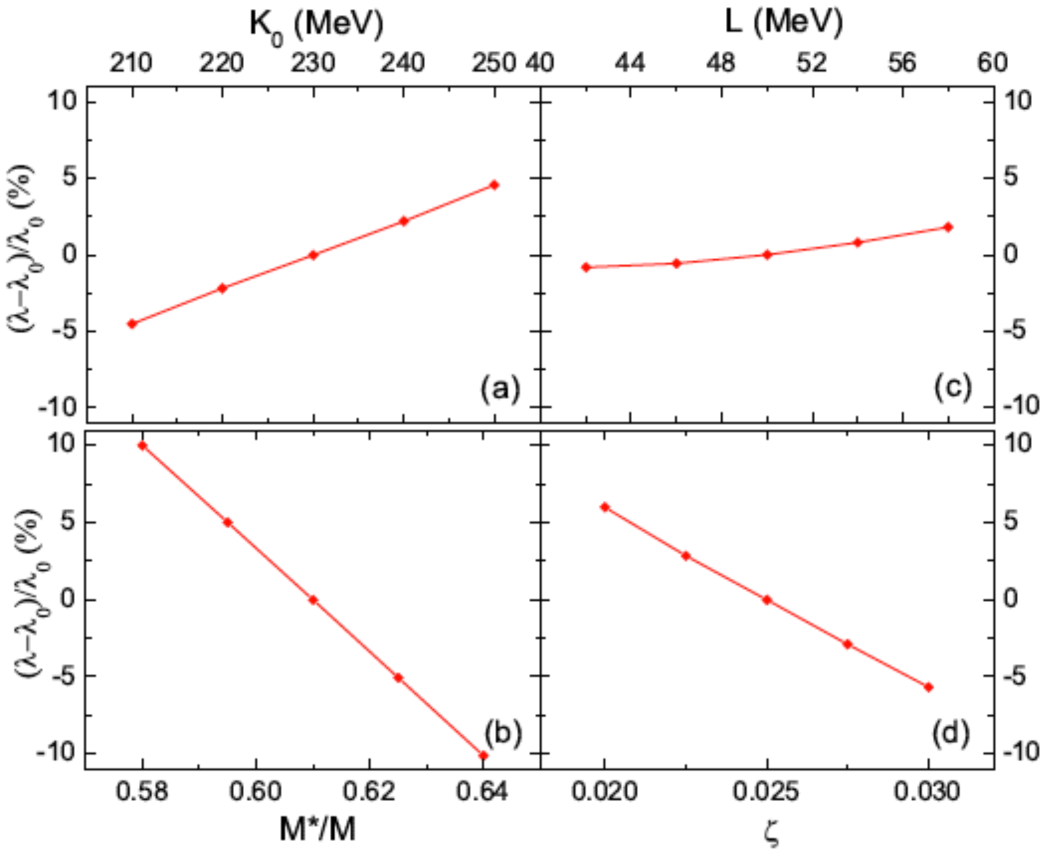
Tidal polarizability and Love number: sensitivity to high-ρ symm. energy

Reference models:



Fattoyev, Carvajal, Newton, Li, PRC87, 15806 (2013)

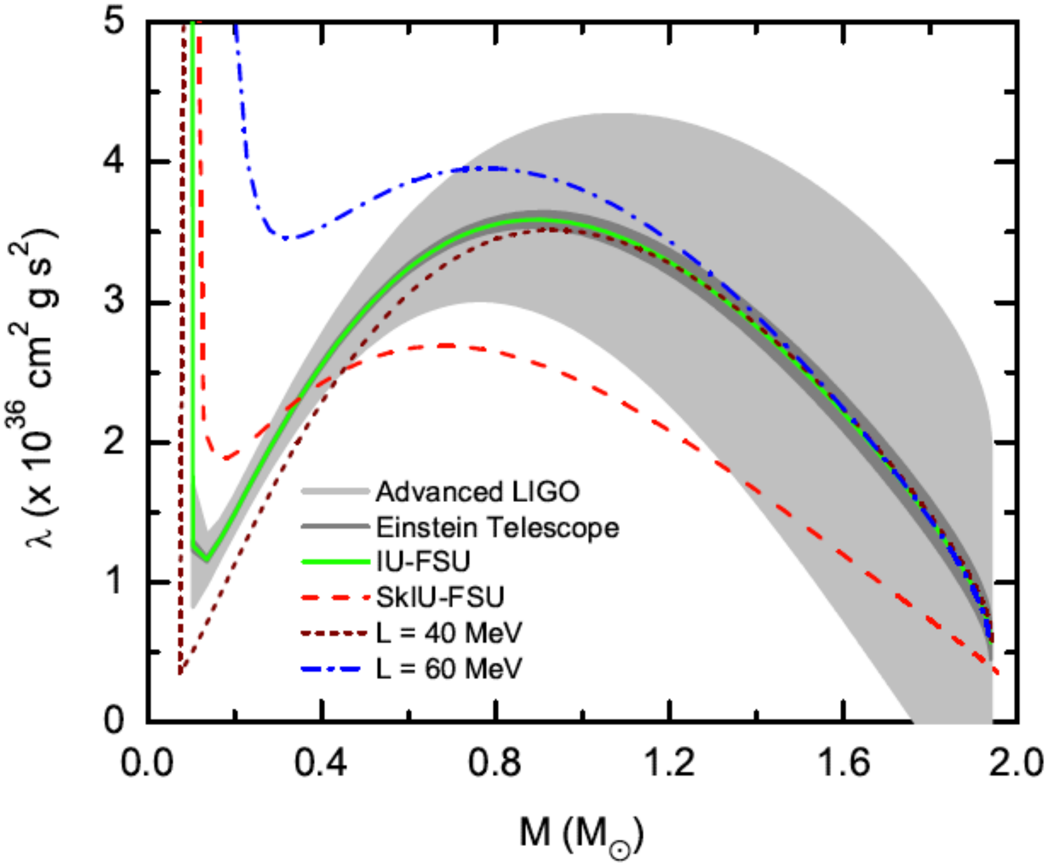
Tidal polarizability and Love number: sensitivity to high-ρ symm. energy



Fattoyev, Carvajal, Newton, Li, PRC87, 15806 (2013)

- Variation of saturation density properties/high density SNM

Tidal polarizability and Love number: sensitivity to high-ρ symm. energy



Fattoyev, Carvajal, Newton, Li, PRC87, 15806 (2013)

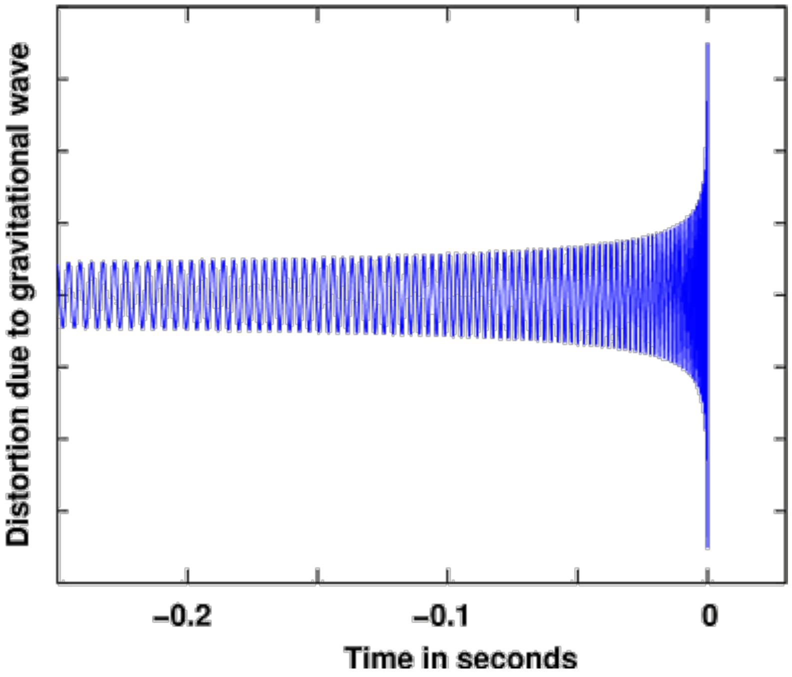
- Detector sensitivities assuming Optimally oriented, equal mass binary at D=100 Mpc
  - Damour, Nagar, PRD81, 084016 (2010)
  - Damour, Nagar, Villain, PRD85, 123007 (2012)

$$\Delta\tilde{\lambda} \approx \alpha \left(\frac{M}{M_\odot}\right)^{2.5} \left(\frac{m_2}{m_1}\right)^{0.1} \left(\frac{f_{\rm end}}{\rm Hz}\right)^{-2.2} \left(\frac{D}{100{\rm Mpc}}\right)$$

Hinderer et al, PRD 81, 123016 (2010)

- At $1.4M_{SUN}$, high density behavior of symmetry energy at limit of AdvLIGOs ability to constrain

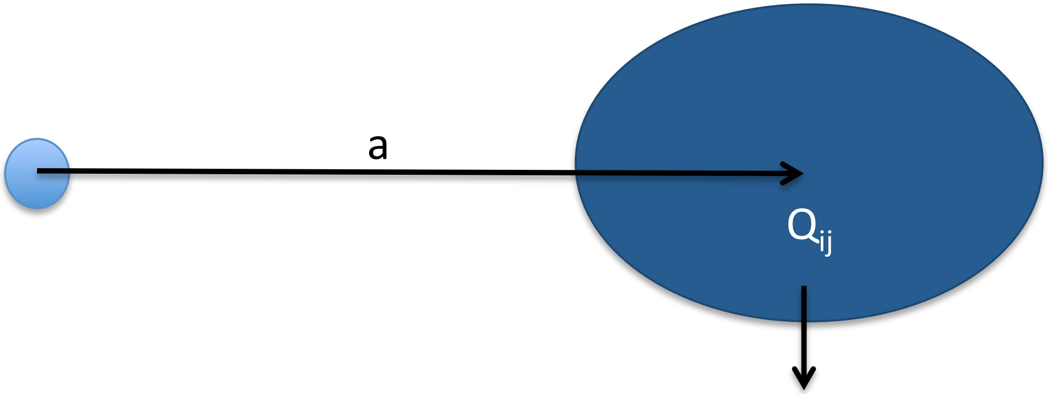
Dynamical tides I



- Tidal field E_{ij} resonates low frequency g-modes, inertial modes ≈100Hz

$$\omega_\alpha = m\Omega_{\rm orb}, \quad m = 2, 3, \cdots$$

- Resulting energy transfer appears as phase shift in gravitational waveform
- Estimated to produce negligible phase shift dN < 0.1, but only estimated for R=10km
- But… $\Delta N \propto R^4$
- Radius/symmetry energy measurements determine whether we should worry

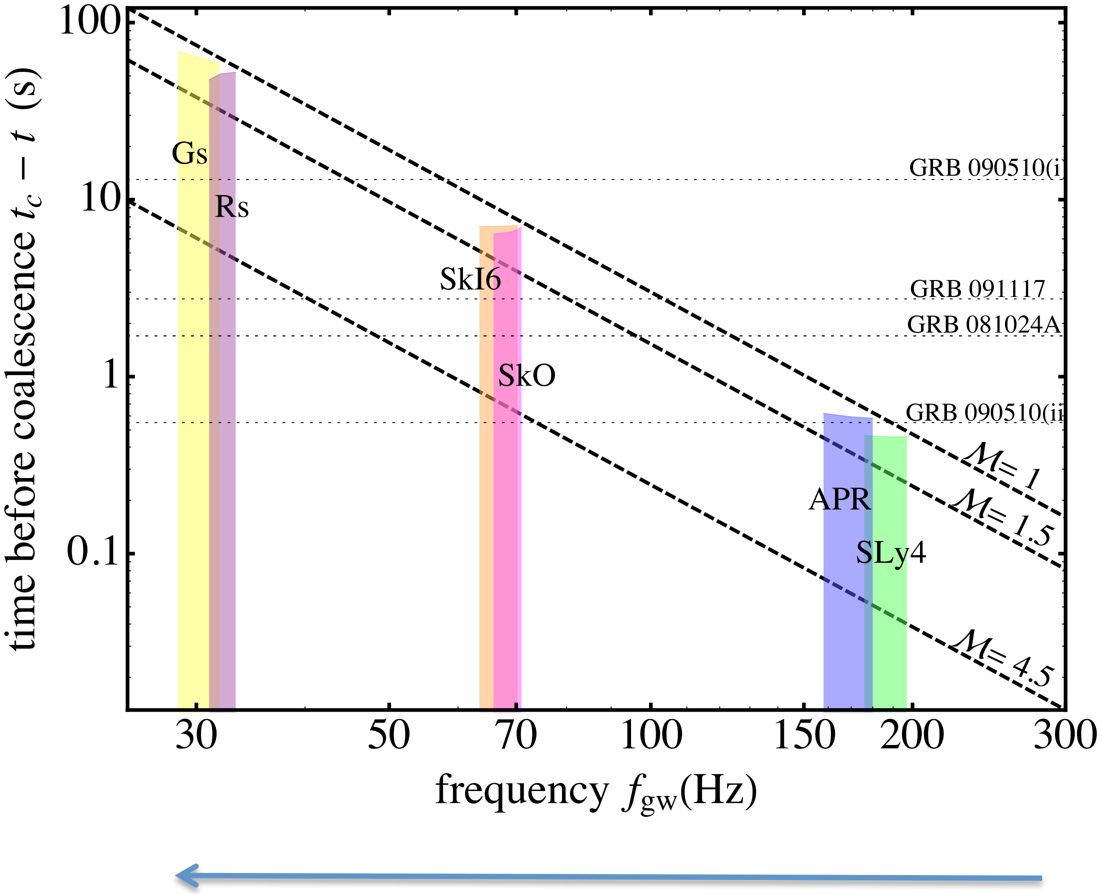


Lai, D., MNRAS 270, (1994)
Ho, W.C.G., Lai, D., MNRAS 308 (1999)
Lai, D., Wu, Y., PRD 74, 024007 (2006)

Dynamical tides II: Crust shattering - symmetry energy constraints?

- NS-NS mergers strong candidates for sGRBs
- Precursor flares observed 1-10s before 4 GRBs
- Possible interpretation: crust shattering by tidal excitation of crustal interface mode

≈100Hz (Tsang et al PRL108, 2012)



L=95 MeV L = 45 MeV

Summary

- Explored sensitivity of tidal polarizability to high density symmetry energy
    - Sample models: RMFs/Skyrmes with same saturation properties, fit to PNM
    - RMFs give systematically stiffer symmetry energy at high density
- High density symmetry energy behavior of models can be distinguished (just) by Adv. LIGO
- Tidal field/g-mode resonance: change in GW waveform assumed negligible, but symmetry energy/radius measurements needed to bolster confidence
- Tidal field/crustal interface mode resonance could shatter crust
    - EM signature: precursor flares to sGRBs?
    - If so, favors mid-high saturation stiffness