Neutrinos and gravitational waves from Neutron-star mergers

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Astro-solids workshop
INT April 20th 2018

Neutrinos

During mergers and supernovae, a large fraction of the binding energy is released as neutrinos. Neutrinos are key to understand GRB and nucleosynthesis.
Can neutrinos tell us anything about the EoS?

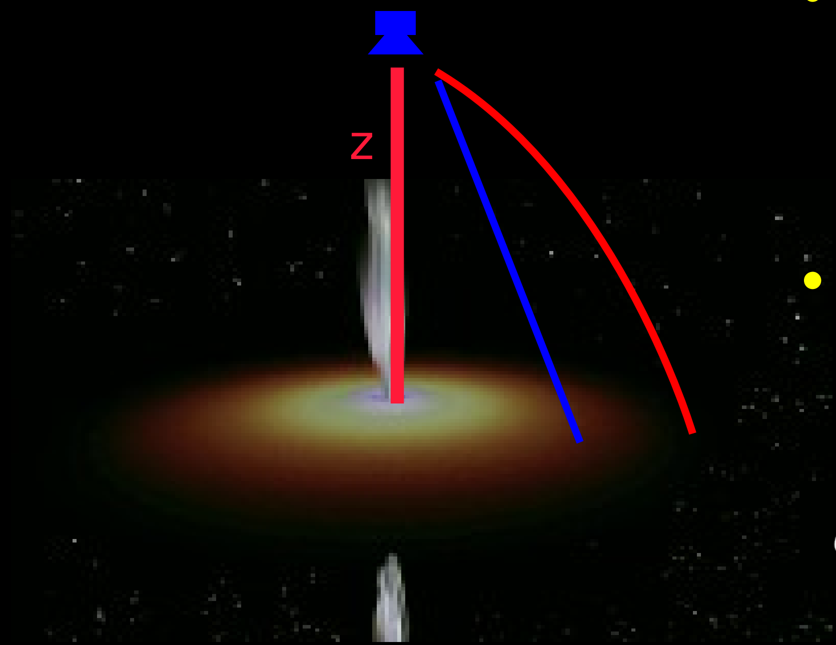
Spectra can be modified by e.g.

- Correlations within the medium (Bacca, Schwenk, Pethick, Raffelt)
- Neutrino oscillations (Balantekin, Fuller, Malkus, McLaughlin)
- General relativistic effects

Neutrinos under the influence of strong gravitational fields

$$\phi^{eff} = \frac{1}{4\pi}\int d\Omega_{ob}\,\phi_{ob}(E_{ob})$$

$$\phi_{ob}(E_{ob}) = \frac{g_\nu c}{2\pi^2(\hbar c)^3}\frac{E_{ob}^2}{\exp\left({E_{ob}}/{T_{ob}}\right)+1}$$



- Energy is red-shifted

$$E_{em} = (1+z)E_{ob}$$

- Deflection of trajectories

$$1+z = \frac{(p_t u^t + p_r u^r + p_\theta u^\theta + p_\varphi u^\varphi)_{em}}{(p_t u^t + p_r u^r + p_\theta u^\theta + p_\varphi u^\varphi)_{ob}}$$

$$d\Omega_{ob} = \sin\xi\, d\xi d\alpha$$

Neutrinos follow null geodesics in the metric imposed by the mass distribution

Neutrino Surface

At high temperatures (~ 10 MeV) matter is dissociated

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$\nu_e + n \rightarrow e + p$$

Charged Current h_ν

$$\nu + \bar{\nu} \rightarrow e + e^+$$

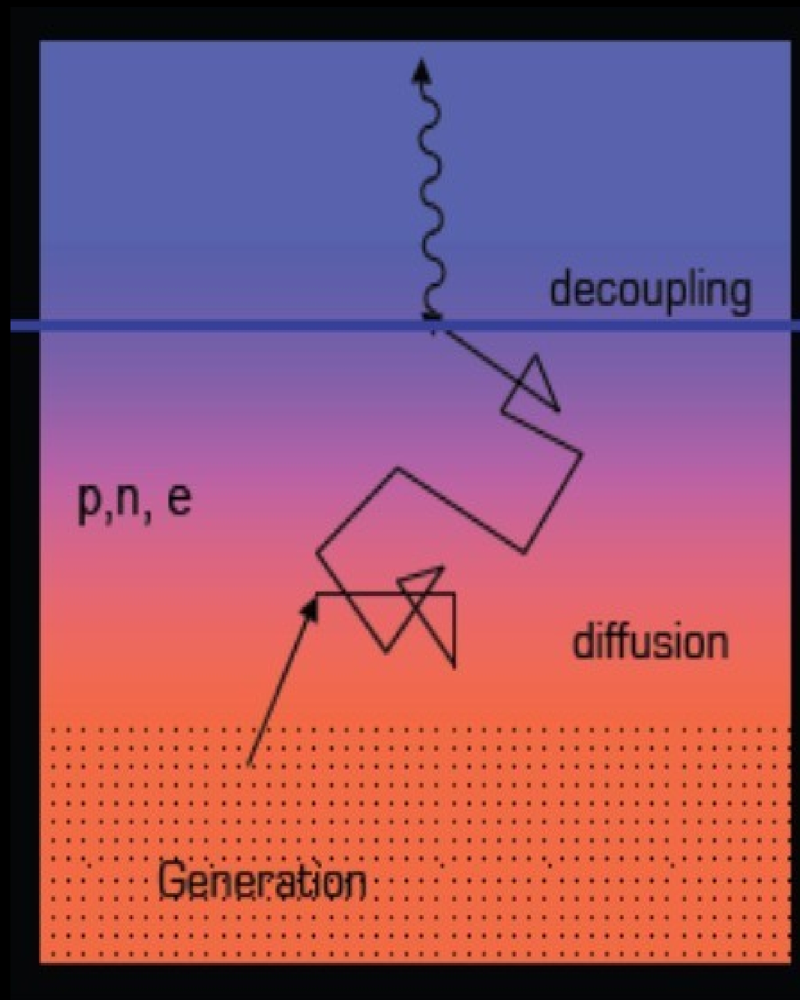
$$\nu + n \rightarrow \nu + n$$

$$\nu + p \rightarrow \nu + p$$

$$\nu + e \rightarrow \nu + e$$

Neutral Current (All flavors)

$$Y_e = Y_p = \frac{1}{1+{}^{n}/_{p}}$$

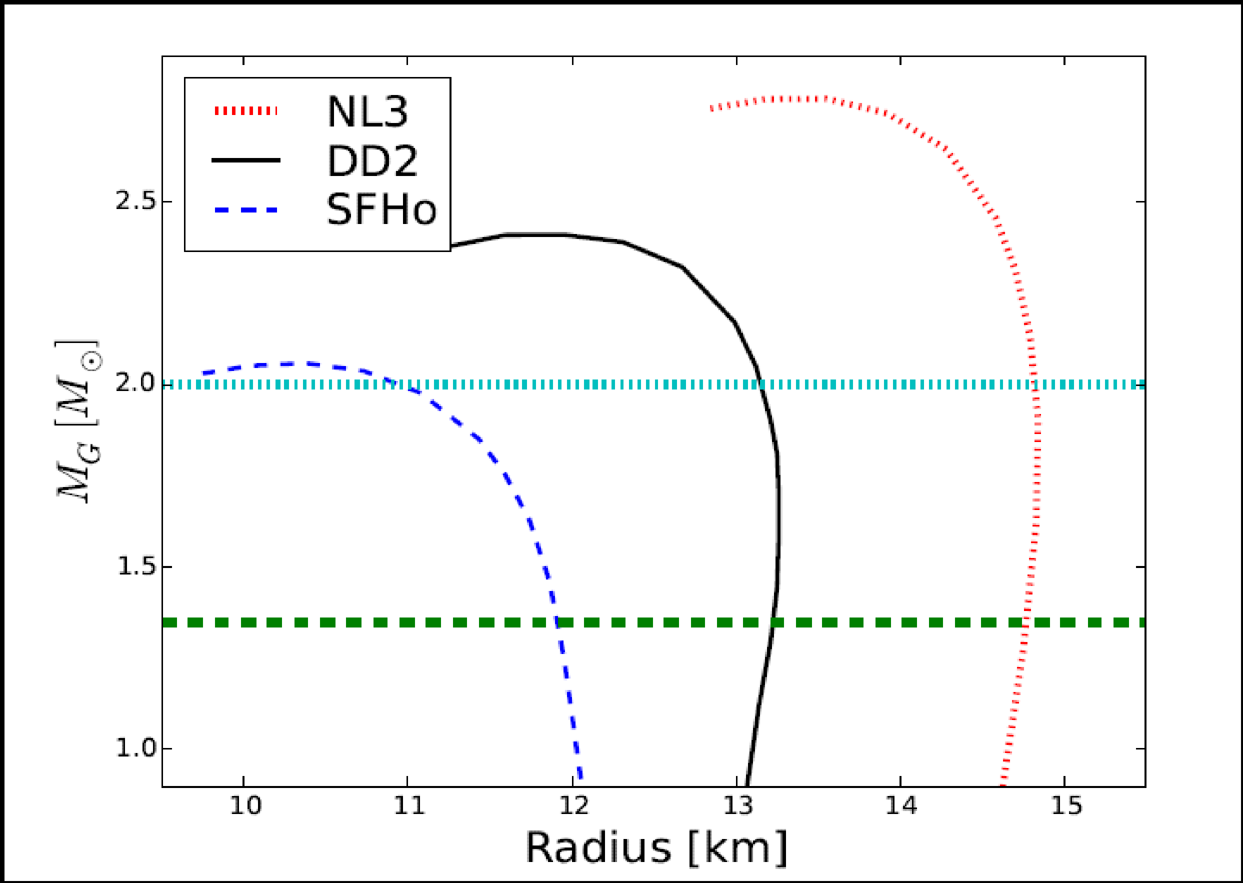


Merger of magnetized Neutron-Star (NS) mergers in general relativity with neutrino cooling and microscopical EoS

Isolated NS: Equation of State (EOS)

C. Palenzuela et al PRD 2015

NS mass =1.35 solar masses



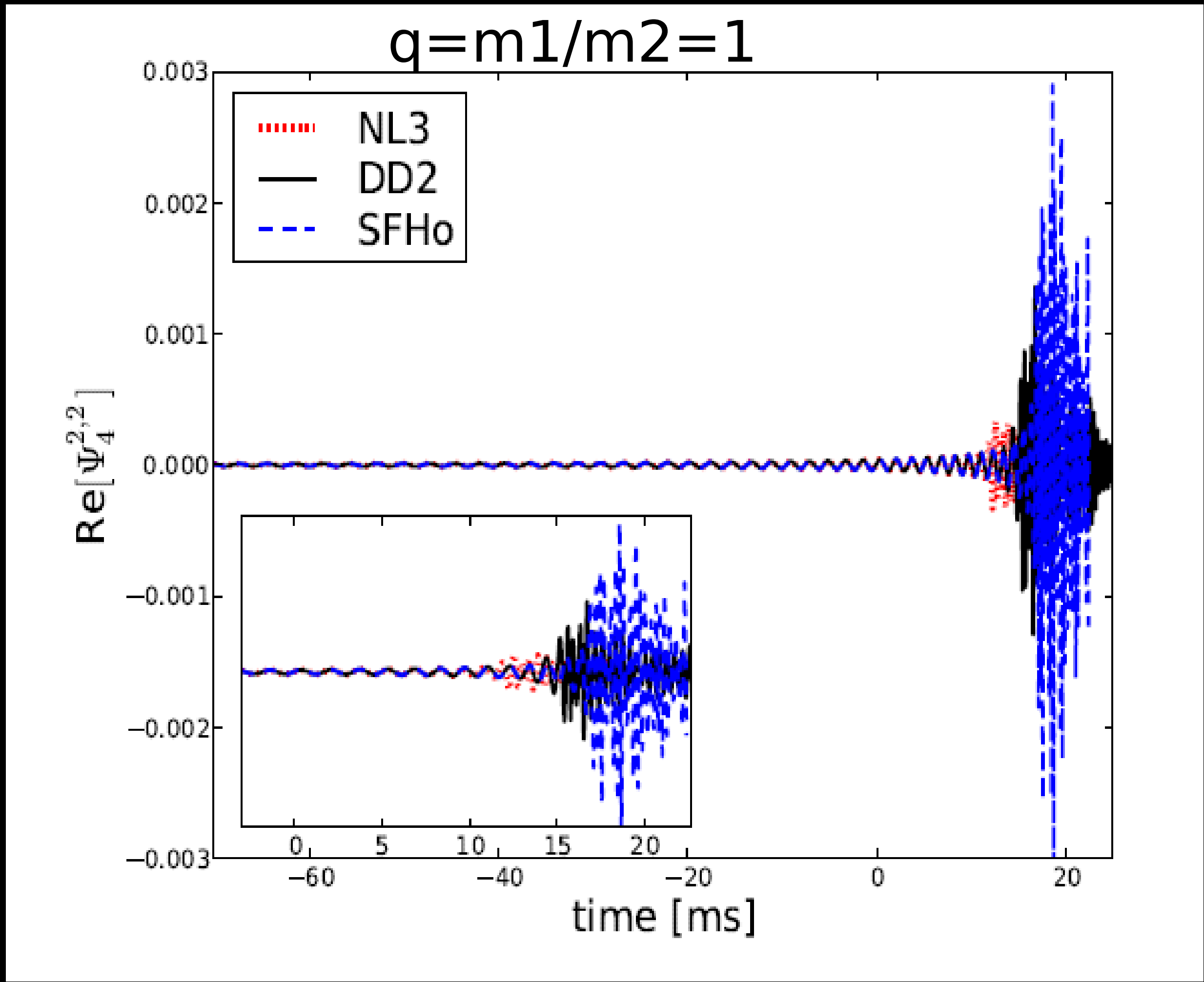
Max. mass observed by P. Demorest et al 2010
J. Antoniadis et al 2013

Statistical model (Hempel et al 2010) with the Relativistic Mean Field interactions:

NL3: Lalazissis et al (2008) , stiff
DD2: Typel et al (2012)
SFHo: Steiner et al (2012) , soft

Merger of magnetized NSs in General Relativity with neutrino cooling

C. Palenzuela et al PRD 2015

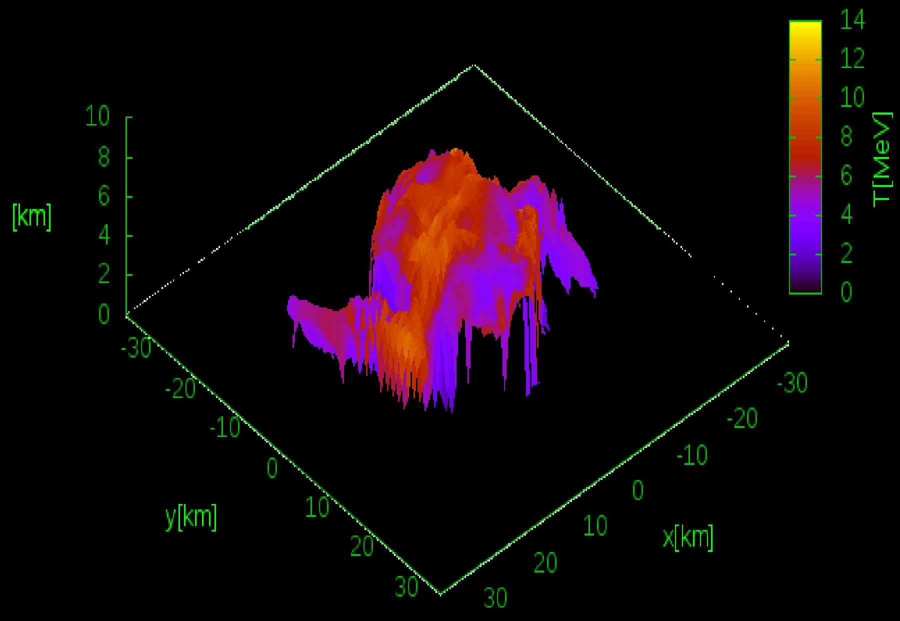


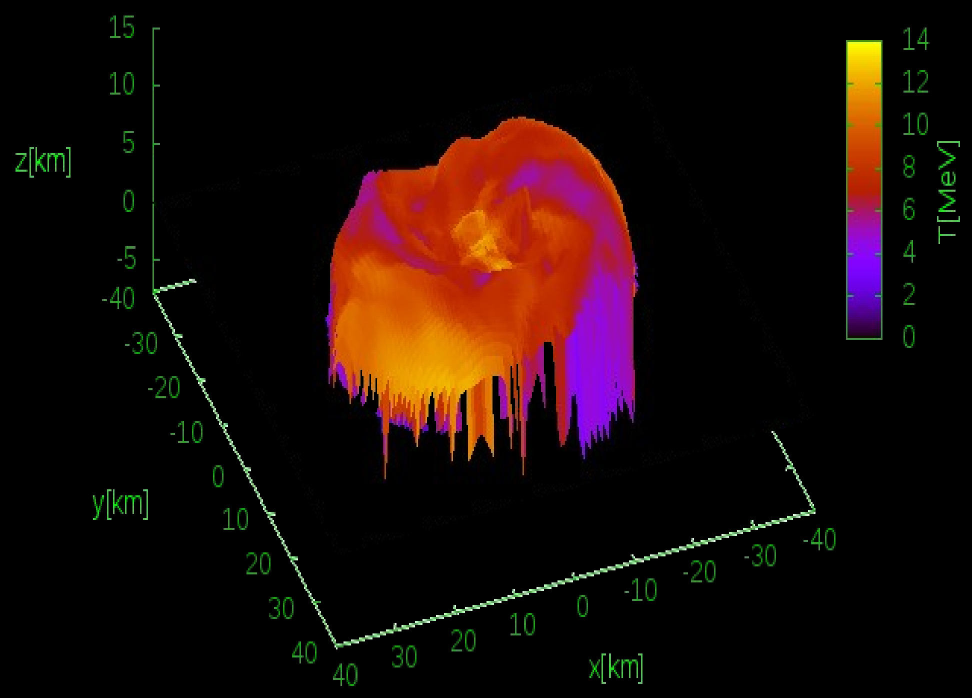
NL3: stiff
DD2: intermediate
SFHo: soft

Gravitational wave forms

Electron antineutrino surfaces

q=1





NL3

O. L. Caballero (2016)

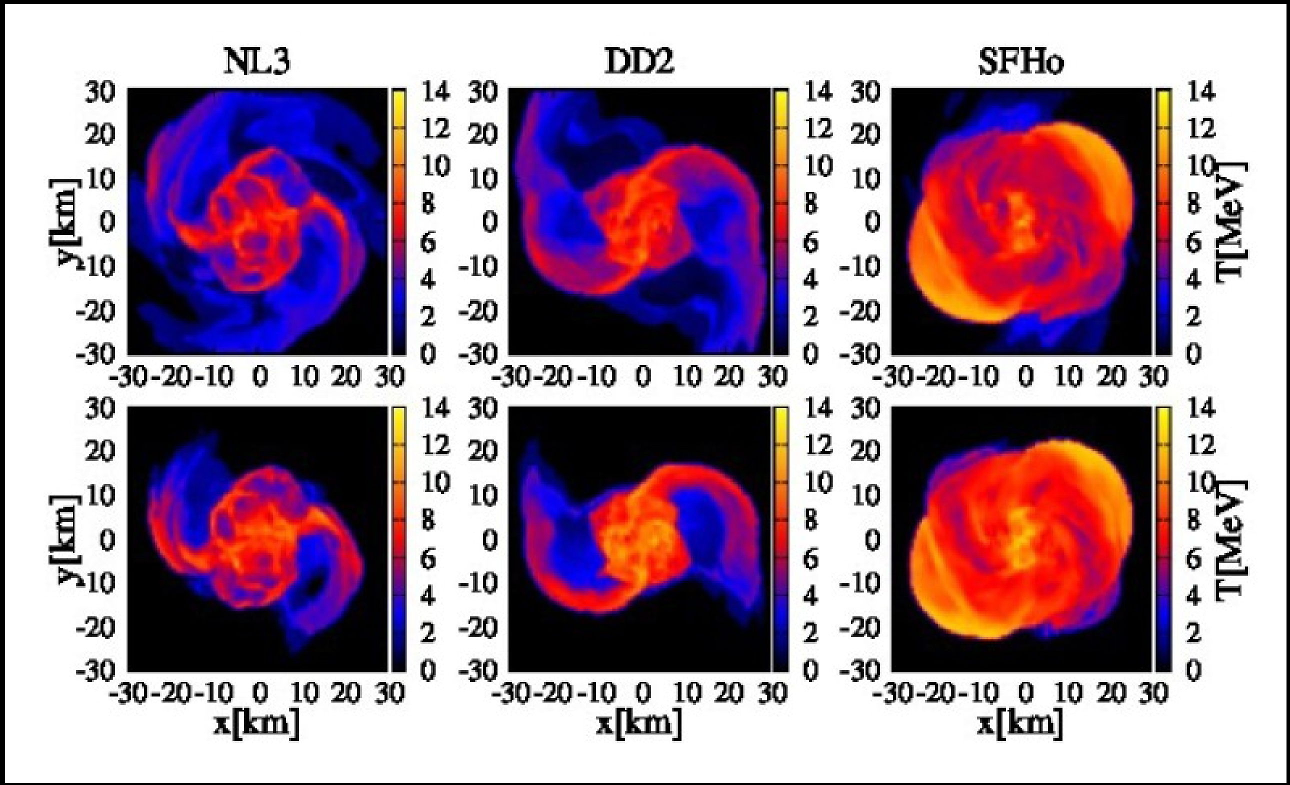
SFHo

Could we infer the EoS from the neutrino detection?

C. Palenzuela et al PRD 2015

e-neutrino

e-antineutrino



Could we infer the EoS from the neutrino detection?

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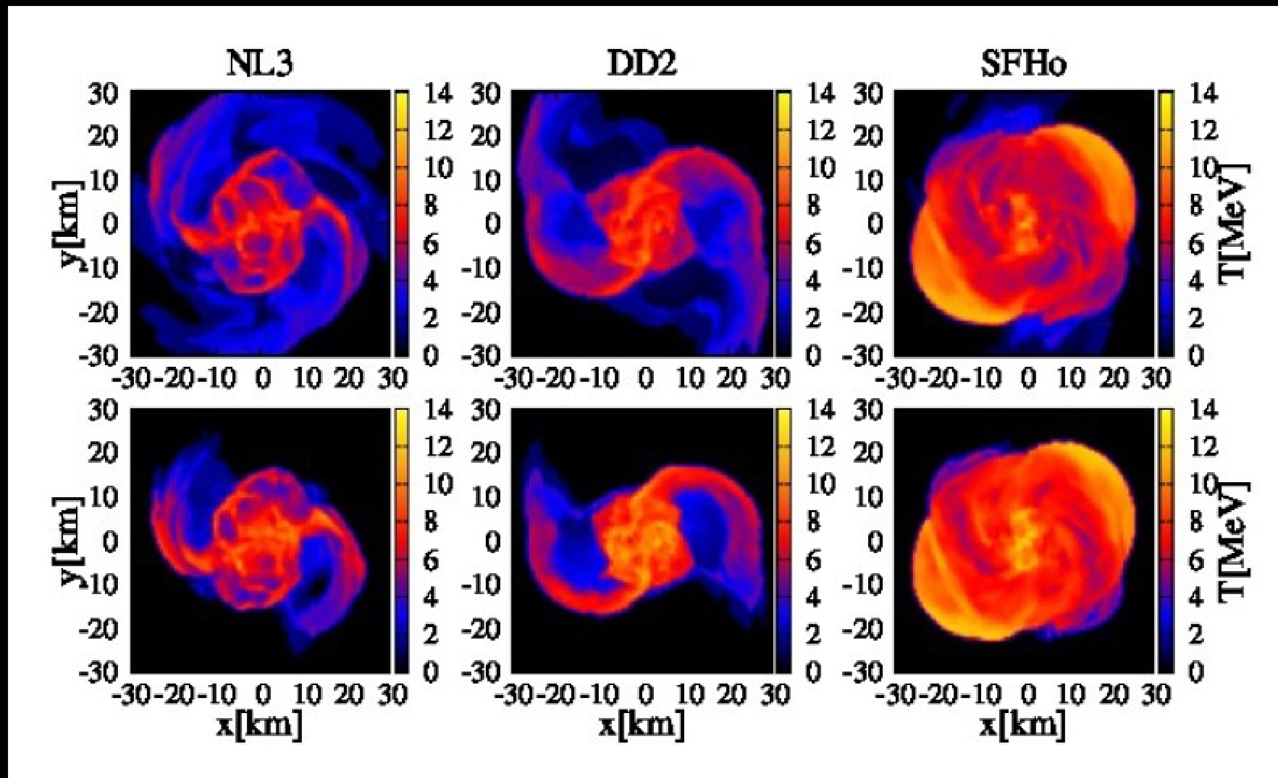


Neutrino counts in SuperK for a NS-NS merger at 10 kpc

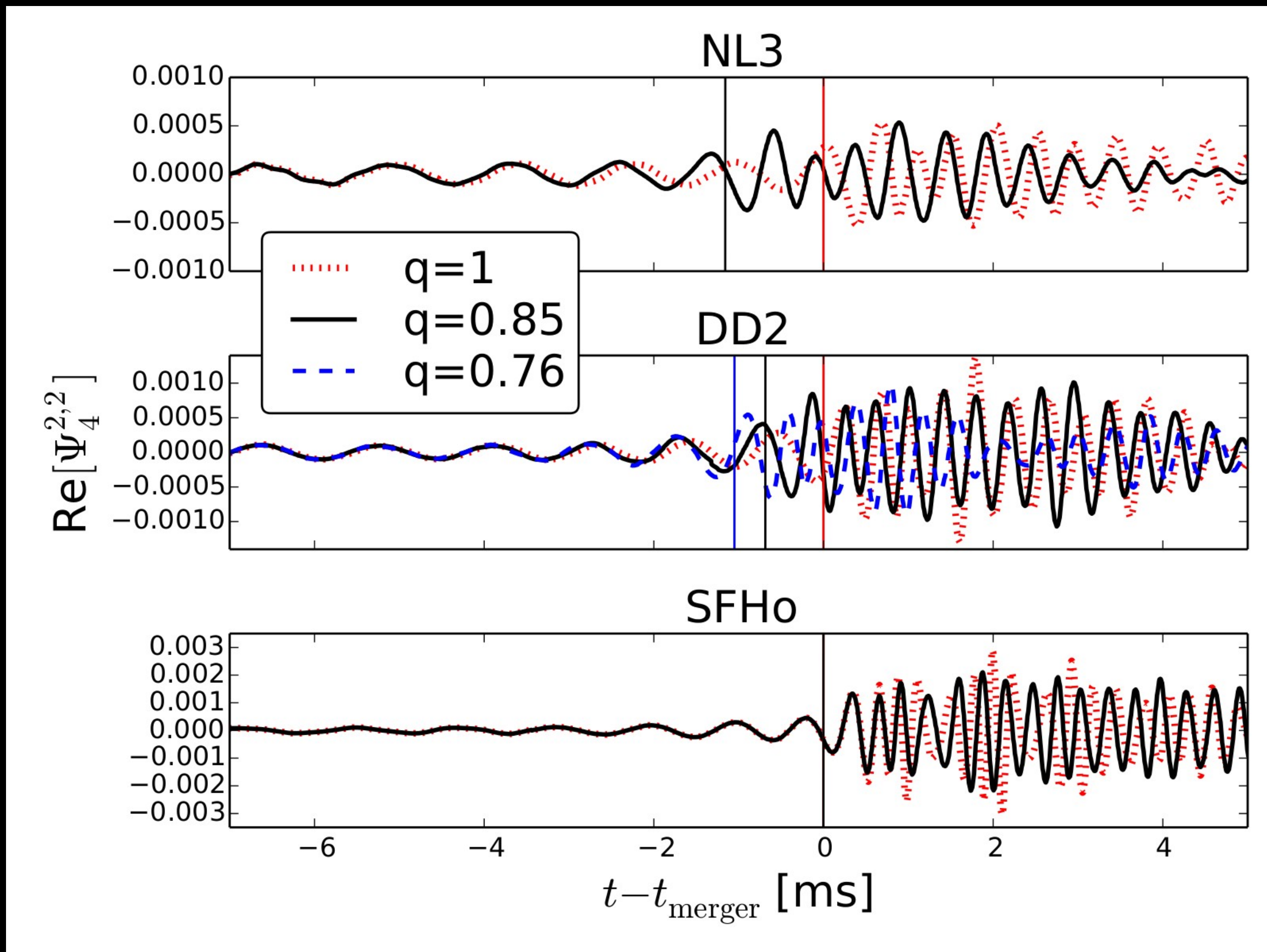
Time [ms]	$\langle E_{\bar{\nu}_e} \rangle$ [MeV]	$\langle E_{\nu_e} \rangle$ [MeV]	$L_{\bar{\nu}_e}$ [10^{53} erg/s]	R_ν [#/ms]
2.5 (NL3)	18.5 (22.4)	15.2 (18.3)	0.71	18.1
3.0 (DD2)	18.3 (22.1)	14.6 (17.4)	1.1	28.2
3.2 (SFHo)	24.6 (29.7)	23.5 (28.3)	3.5	120.8

Supernova:
R= 1/ms
L=10^{52} erg/s
E~ 11 MeV
t=10 sec

Merger of unequal mass magnetized NSs

L. Lehner et al CQG 2016

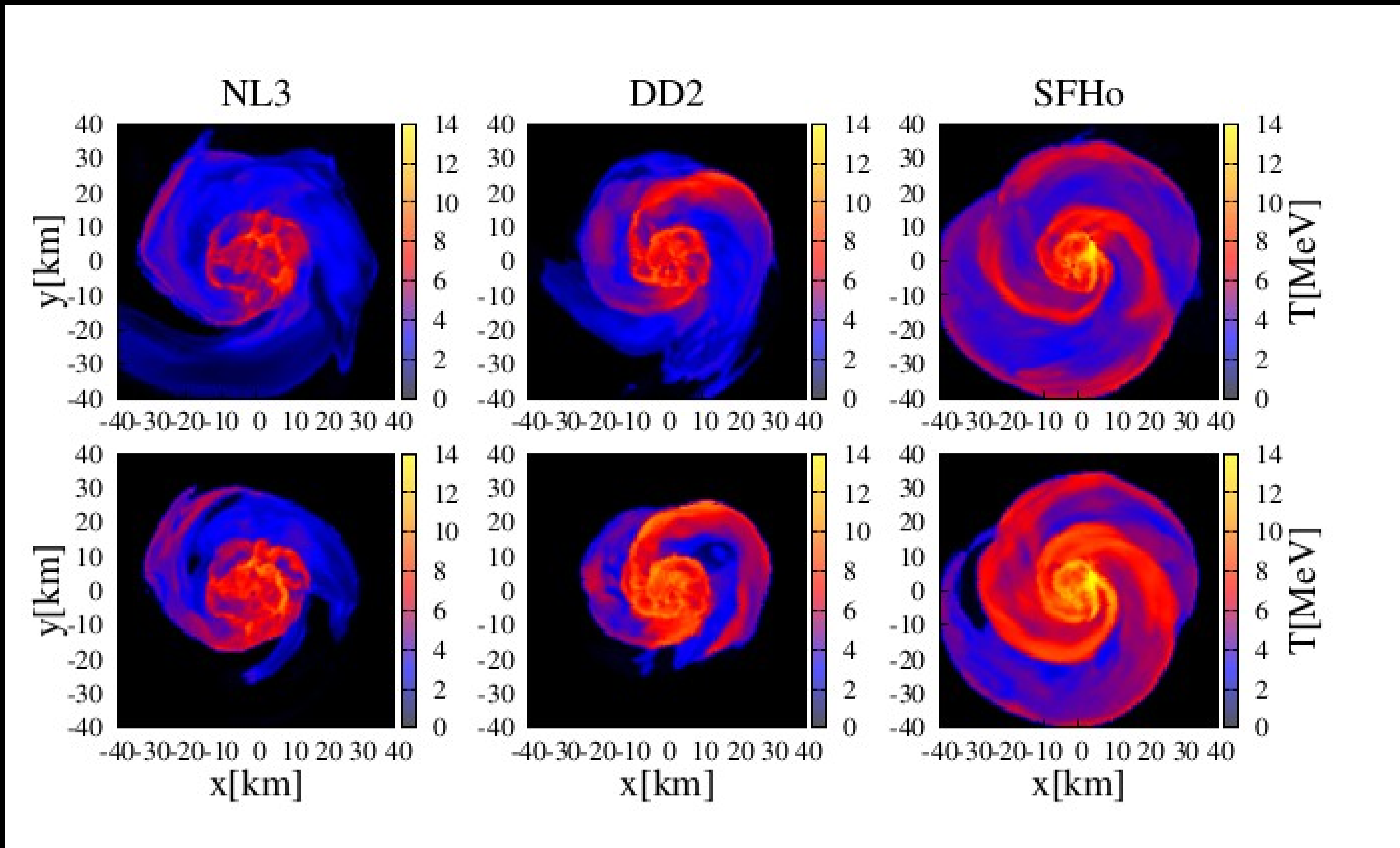
q=m1/m2



Tidal effects are more pronounced with stiffer EoS

Neutrino surface q=0.85

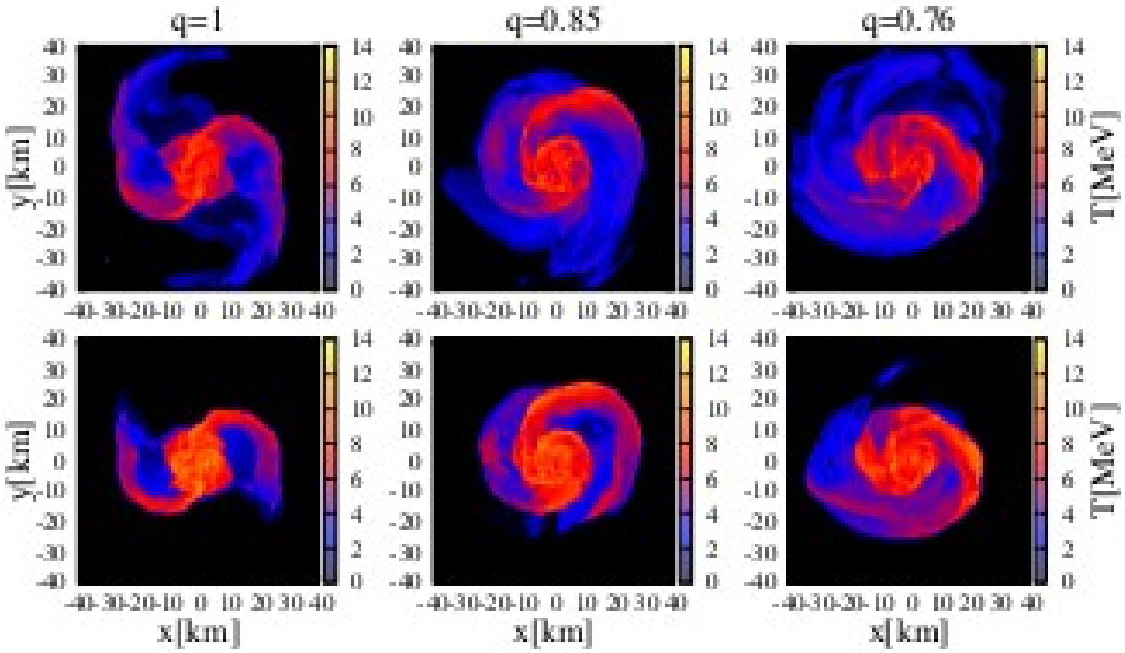
EOS effects

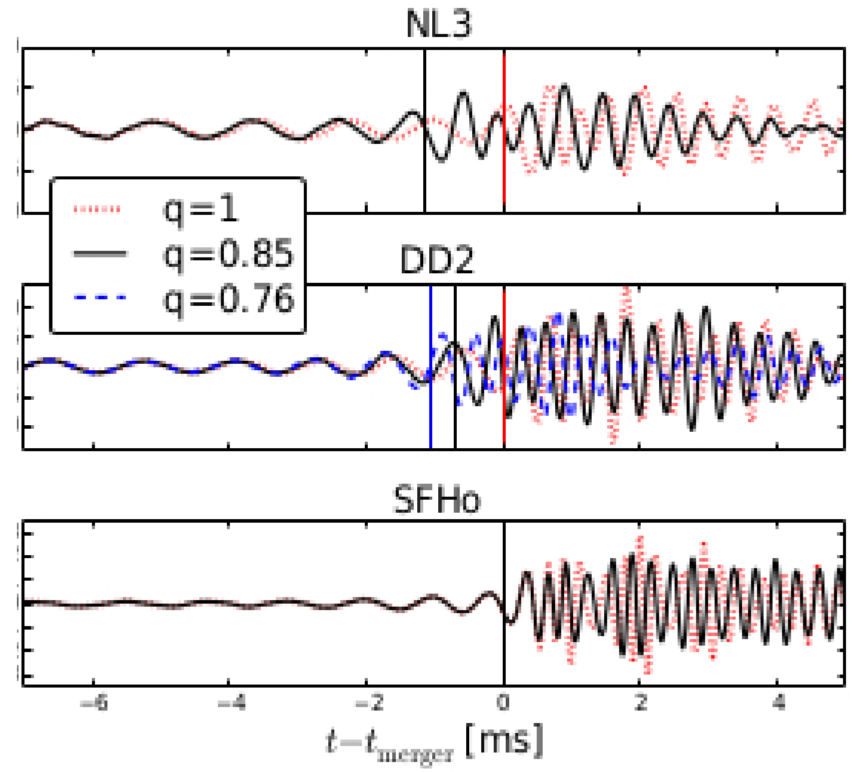


Higher peak neutrino temperatures are found with SFHo (soft) EoS

Merger of unequal mass magnetized NSs

Mass ratio q effects





DD2

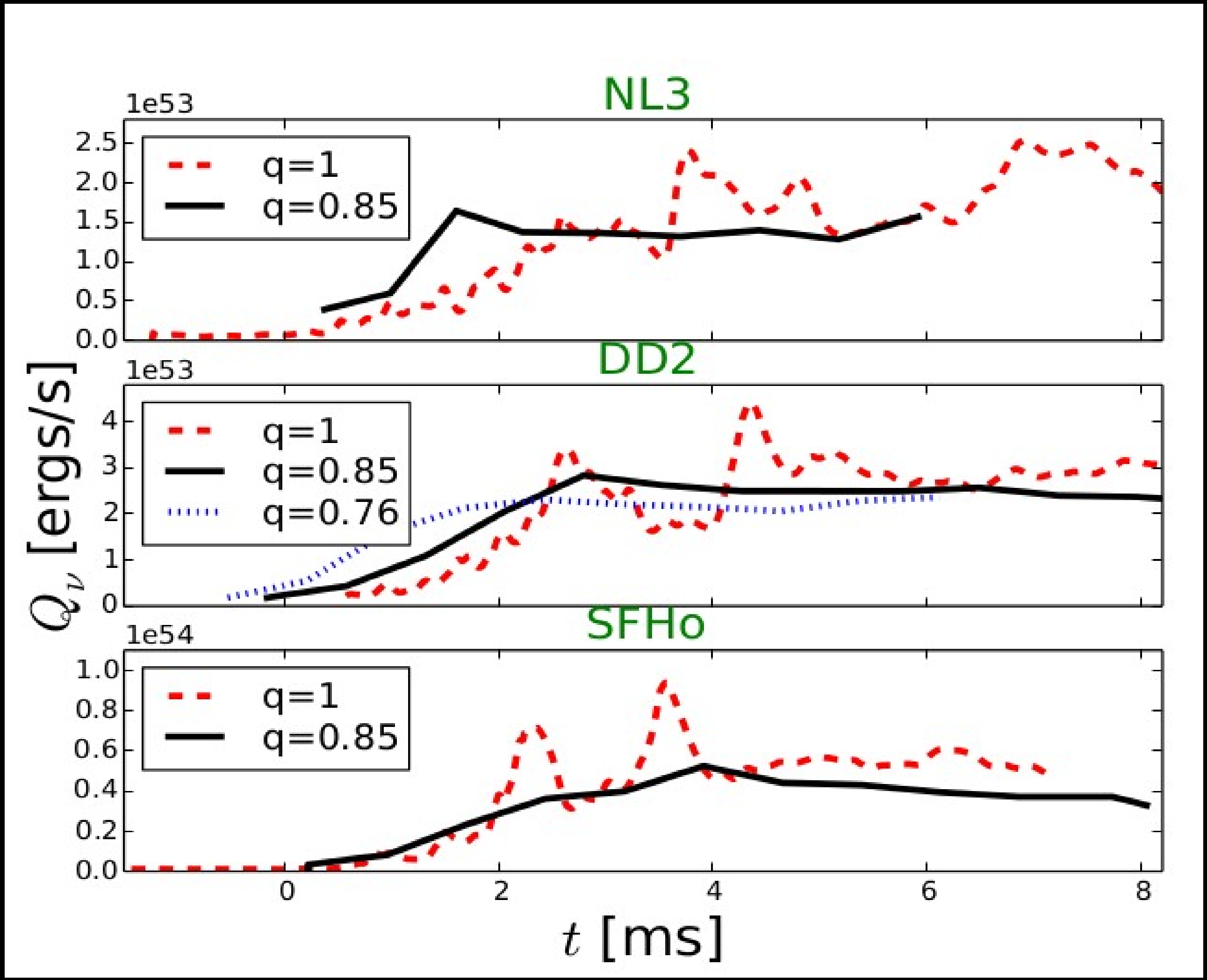
As q decreases the stronger are the tidal effects

How many neutrinos are detected in SK from a NS-NS merger at 10 kpc?

EoS	q	t [ms]	$\langle E_{\bar{\nu}_e} \rangle$ [MeV]	$\langle E_{\nu_e} \rangle$ [MeV]	$L_{\bar{\nu}_e}$ [10^{53} erg/s]	R_ν [#/ms]
NL3	1.0	3.4	18.5 (22.4)	15.2 (18.3)	0.7	18
NL3	0.85	3.0	15.6 (18.7)	12.6 (15.1)	0.8	18
DD2	1.0	3.3	18.3 (22.1)	14.6 (17.4)	1.1	28
DD2	0.85	2.8	18.1 (21.7)	15.1 (18.0)	1.0	25
DD2	0.76	2.4	19.7 (23.9)	14.8 (17.9)	1.3	36
SFHo	1.0	3.5	24.6 (29.7)	23.5 (28.3)	3.5	121
SFHo	0.85	3.9	17.8 (21.3)	15.3 (17.9)	2.0	50

The mass ratio affects neutrino mean energies more strongly for the soft EOS

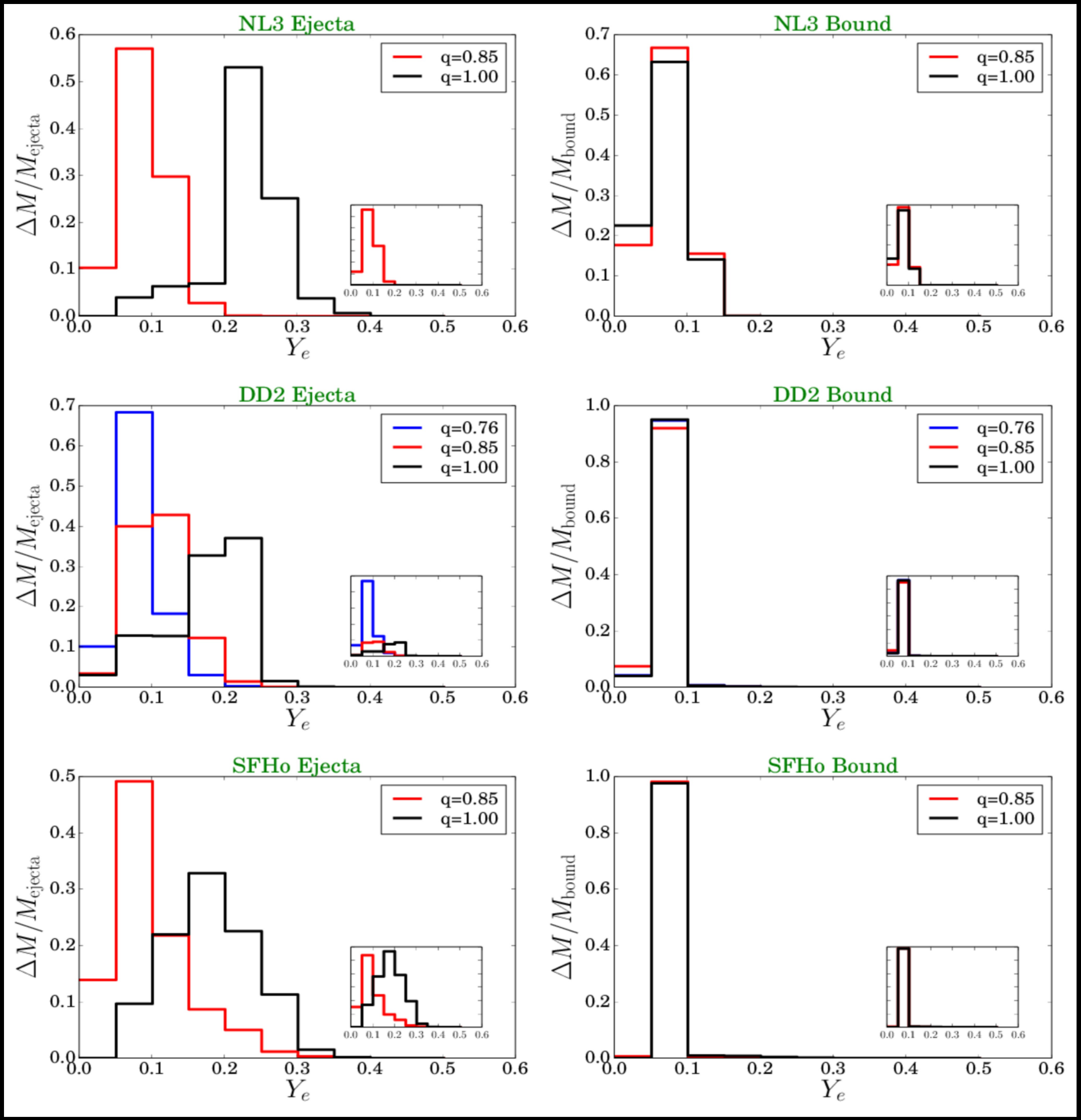
Neutrino luminosity evolution



Luminosity oscillates for q=1

Electron fraction distribution for unbound and bound material

Electron fraction decreases as q decreases, compatible with r-process nuclosynthesis and kilonova



Summary

- We could detect neutrinos from binary NS mergers coming from the Milky Way and satellite galaxies in SuperK
- And from Andromeda (780 kpc) in HyperK
- Soft EOS result in larger neutrino luminosities and average energies
- For q <1 the neutrino signal is affected more strongly for a soft EoS
- Ejecta with Ye < 0.2 could be produced regardless of the EoS
- Given several observations of q and GW neutrinos we could decipher the EoS

Collaborators

- Luis Lehner (Perimeter Institute), Carlos Palenzuela (University of the Balearic Islands), David Neilsen (Bringham Young U.), Steve Liebling (Long Island U.), Evan O’Connor (Stockholm University)