Title: Compact Objects in the Era of GW Astronomy

Date: Jun 16, 2016 11:40 AM

URL: http://pirsa.org/16060020

Abstract: I will discuss recent work modeling compact objects in an effort to extract scientific understanding from multi-messenger observations.

Motivation

To understand the Universe
through high energy astrophysical processes...

Study/model the suspected progenitors of high energy events:

- Determine observables that might confirm or reject underlying scenarios
- Assist LIGO and associated observatories to extract the most science possible (e.g. templates, search strategies, counterpart searches, etc)
- Find surprises!

High energy astrophysical events

- **sGRBs**—brightest EM events; short GRBs lasting less than 2 seconds
- **Jets**—highly collimated, energetic material; powered by BHs
- **kilonovae**—isotropic, IR or optical transients resulting from radioactive decay of heavy elements thought to arise from BNS mergers
- **FRBs**—high-energy, radio transients lasting a few milliseconds likely outside the galaxy; source unknown
- **NSs** generally: pulsars, X-ray binaries, supernovae, etc

Outline for this talk

- Binary neutron star mergers
- Using the $m = 1$ instability to extract EoS information
- Constraining the theory of gravity with compact neutron stars
- Charged black hole binaries

Our Previous Work

[Palenzuela,SLL,Neilsen,Lehner,Caballero,O'Connor,Anderson,1505.01607]
[Neilsen,SLL,Anderson,Lehner,O'Connor,Palenzuela,1403.3680]

- Barytropic, finite-temperature
- Spans sub-nuclear to supra-nuclear densities
- Largely unknown regime of matter
- Constrained by the most massive observed NSs
- Involves temperature and composition (electron fraction)
- Adapts open-source leakage code at `stellarcollapse.org`
- Novel calculation of optical depth which tracks binary NS

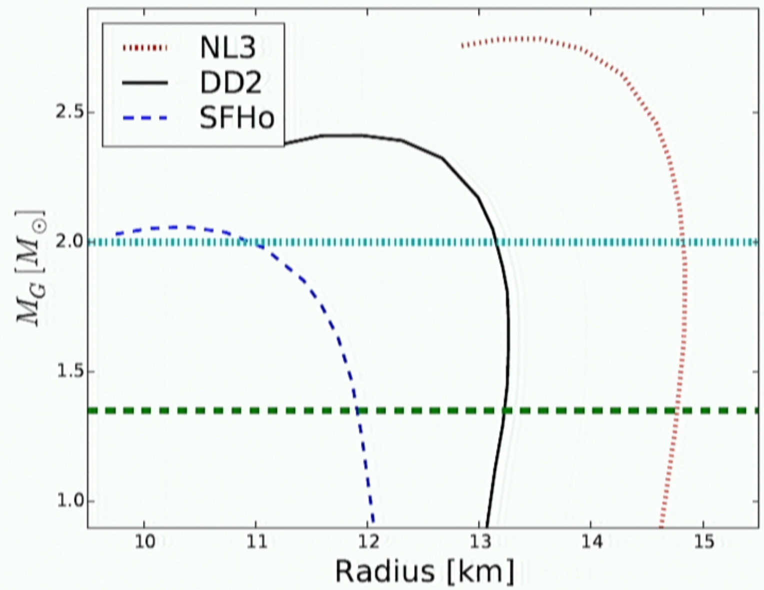
Equal mass magnetized BNS with 3 different realistic EoS:

- Soft EoS (SFHo) yields more unbound material
- Mostly equatorial outflow
- Promising for r-process IR afterglow (Y_e peaks around 0.2)
- Soft EoS more luminous in neutrinos
- High magnetization can increase amount of ejecta

Choice of Realistic, microphysical EoS

Choose range of EoS:

- NLS—stiff—large radii
- DD2—moderate—intermediate radii
- SFHo—soft—small radii



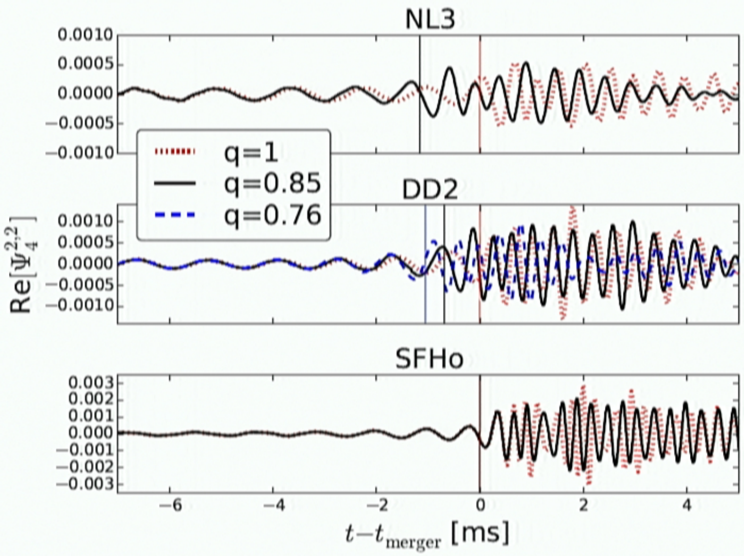
Initial Data

[Lehner,SLL,Palenzuela,Caballero,O'Connor,Anderson,Neilsen,1603.00501]

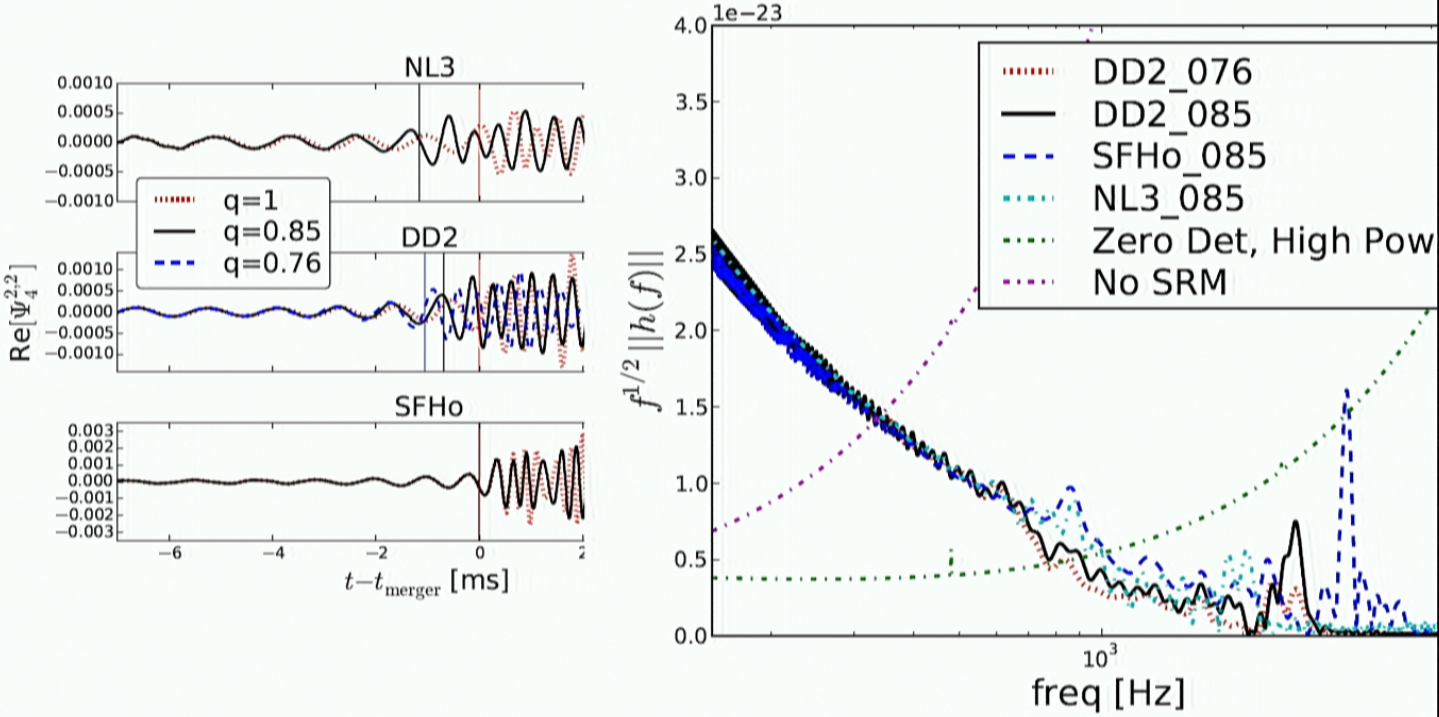
- Total mass $2.7 M_\odot$
- 45 km initial separation...4-5 orbits prior to merger
- Finest resolution: 230 meters in neighborhood of each star

EoS	q	ν	$m_b^{(1)}, m_g^{(1)}$ $[M_\odot]$	$m_b^{(2)}, m_g^{(2)}$ $[M_\odot]$	$R^{(1)}$ [km]	$R^{(2)}$ [km]	$C^{(1)}$	$C^{(2)}$	$J_0^{\rm ADM}$ [G $M_\odot^2/c$]	Ω_0 [rad/s]	$f_0^{\rm GW}$ [Hz]	$M_{\rm eject}$ $[10^{-3} M_\odot]$
NL3	1.0	0.250	1.47, 1.36	1.47, 1.36	14.80	14.80	0.136	0.136	7.40	1778	566	0.015
NL3	0.85	0.248	1.34, 1.25	1.60, 1.47	14.75	14.8	0.125	0.147	7.35	1777	566	2.3
DD2	1.0	0.250	1.49, 1.36	1.49, 1.36	13.22	13.22	0.152	0.152	7.39	1776	565	0.43
DD2	0.85	0.248	1.36, 1.29	1.62, 1.47	13.20	13.25	0.144	0.164	7.34	1775	565	0.42
DD2	0.76	0.245	1.27, 1.18	1.71, 1.54	13.16	13.25	0.132	0.172	7.26	1775	565	1.3
SFHo	1.0	0.250	1.50, 1.36	1.50, 1.36	11.90	11.90	0.169	0.169	7.38	1775	565	3.4
SFHo	0.85	0.248	1.37, 1.25	1.63, 1.47	11.95	11.85	0.154	0.183	7.31	1773	564	2.2

Waveforms


NL3
DD2
SFHo
q=1
q=0.85
q=0.76
$\mathrm{Re}[\Psi_4^{2,2}]$
$t - t_{\mathrm{merger}}$ [ms]

Waveforms

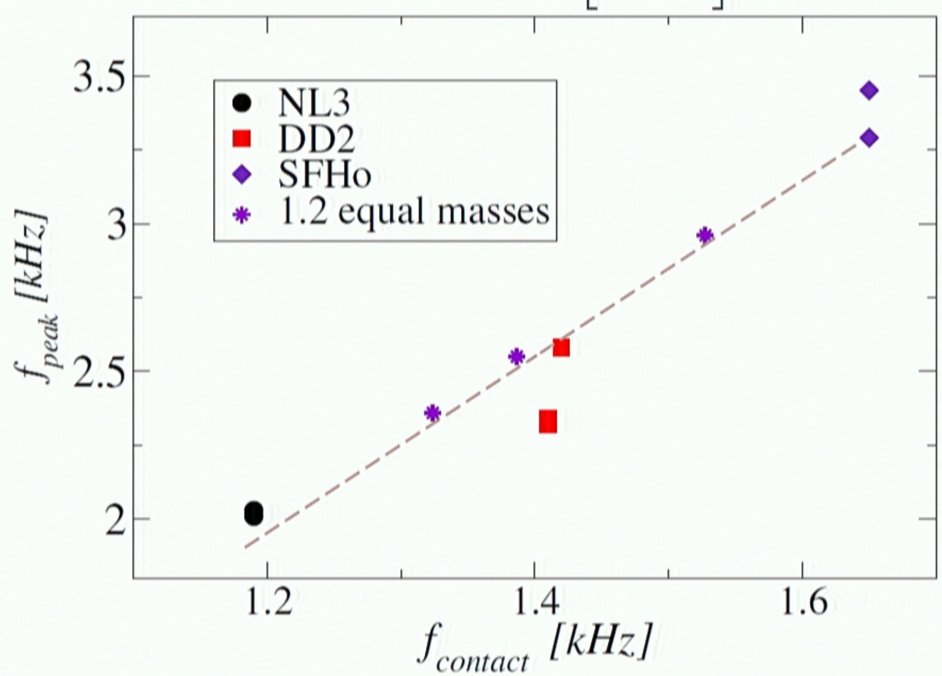


NL3
DD2
SFHo
q=1
q=0.85
q=0.76
Re[$\Psi_4^{2,2}$]
$t - t_{\rm merger}$ [ms]
1e−23
$f^{1/2}||h(f)||$
DD2_076
DD2_085
SFHo_085
NL3_085
Zero Det, High Pow
No SRM
freq [Hz]

Remnant's peak GW Frequency

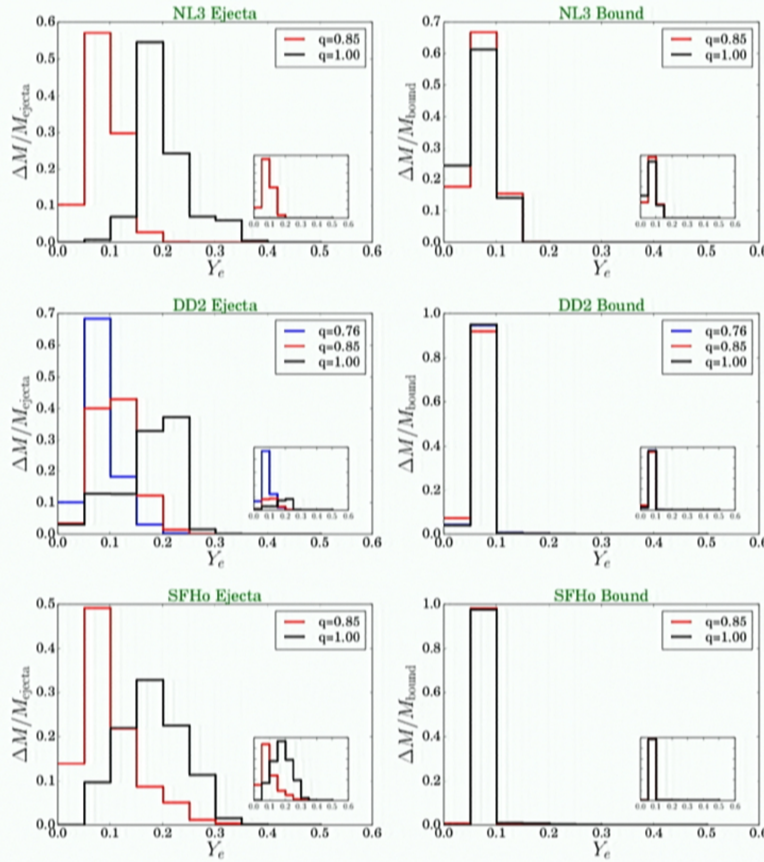
In terms of contact frequency: $f_c = \frac{1}{\pi M_g}\left(\frac{m_g^{(1)}}{M_g C_1} + \frac{m_g^{(2)}}{M_g C_2}\right)^{-3/2}$

yields fit: $f_{\rm peak}[{\rm kHz}] = -1.61 + 2.96 f_c \left[\frac{2.7 M_\odot}{M}\right] [{\rm kHz}]$



Ejecta Properties: Electron Fraction

Electron Fraction decreases with mass ratio



Estimates of possible EM signals

Kilonova: [Barnes,Kasen,2013]

$$t^k_{\rm peak} \approx 0.25\,{\rm days}\left[\frac{M_{\rm eject}}{10^{-2}M_\odot}\right]^{1/2}\left[\frac{v}{0.3c}\right]^{-1/2}$$

$$L \approx 2\times 10^{41}{\rm erg/s}\left[\frac{M_{\rm eject}}{10^{-2}M_\odot}\right]^{1/2}\left[\frac{v}{0.3c}\right]^{1/2}$$

Radio emission from collision with ISM: [Nakar,Piran,2011]

$$t_{\rm peak} \approx 6\,{\rm yr}\left[\frac{E_{\rm kin}}{10^{51}{\rm erg}}\right]^{1/3}\left[\frac{n_0}{0.1\,{\rm cm}^{-3}}\right]^{-1/3}\left[\frac{v}{0.3c}\right]^{-5/3}$$

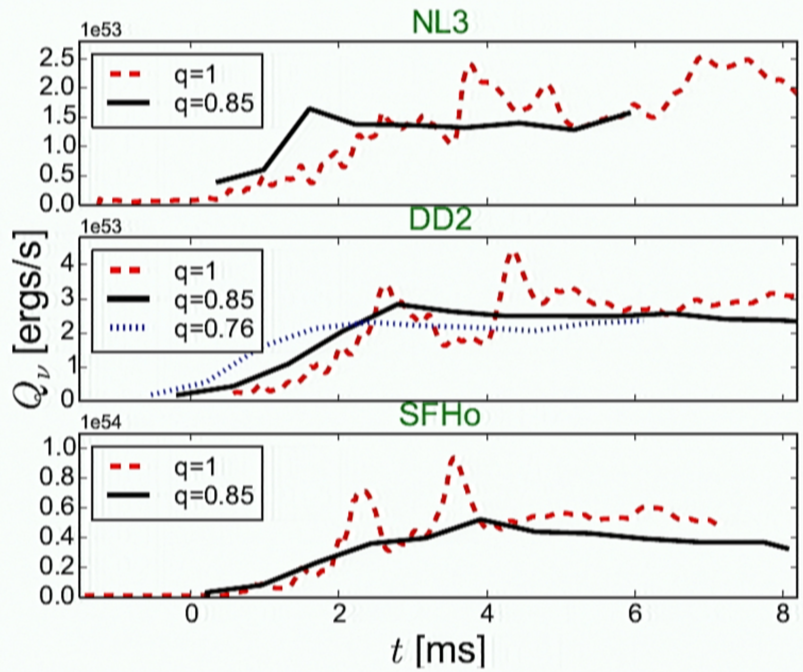
$$F(\nu_{\rm obs}) \approx$$

$$0.6\,{\rm mJy}\left[\frac{E_{\rm kin}}{10^{51}{\rm erg}}\right]\left[\frac{n_0}{0.1\,{\rm cm}^{-3}}\right]^{7/8}\left[\frac{v}{0.3c}\right]^{11/4}\left[\frac{\nu_{\rm obs}}{1\,{\rm GHz}}\right]^{-3/4}\left[\frac{d}{100\,{\rm Mpc}}\right]^{-2}$$

EoS	q	$L[10^{40}{\rm erg/s}]$	$t^k_{\rm peak}$ [days]	$M_{\rm eject}[10^{-3}M_\odot]$	v/c	$E_{\rm kin}[10^{50}{\rm ergs}]$	$t_{\rm peak}$ [yr]	$F(1\,{\rm GHz})$ [mJy]
NL3	1.0	0.9	0.008	0.015	0.45	0.01	0.31	1.8×10^{-3}
NL3	0.85	8.8	0.13	2.3	0.25	1.22	4.0	4.4×10^{-2}
DD2	1.0	4.1	0.05	0.43	0.3	0.31	1.9	1.9×10^{-2}
DD2	0.85	4.1	0.05	0.42	0.3	0.29	1.8	1.7×10^{-2}
DD2	0.76	7.2	0.09	1.3	0.3	0.76	2.5	4.6×10^{-2}
SFHo	1.0	10.6	0.16	3.4	0.25	1.8	4.6	6.5×10^{-2}
SFHo	0.85	8.6	0.13	2.2	0.25	1.8	4.6	6.5×10^{-2}

Neutrino Emission

- Softest EoS most luminous for any mass ratio because highest temperature



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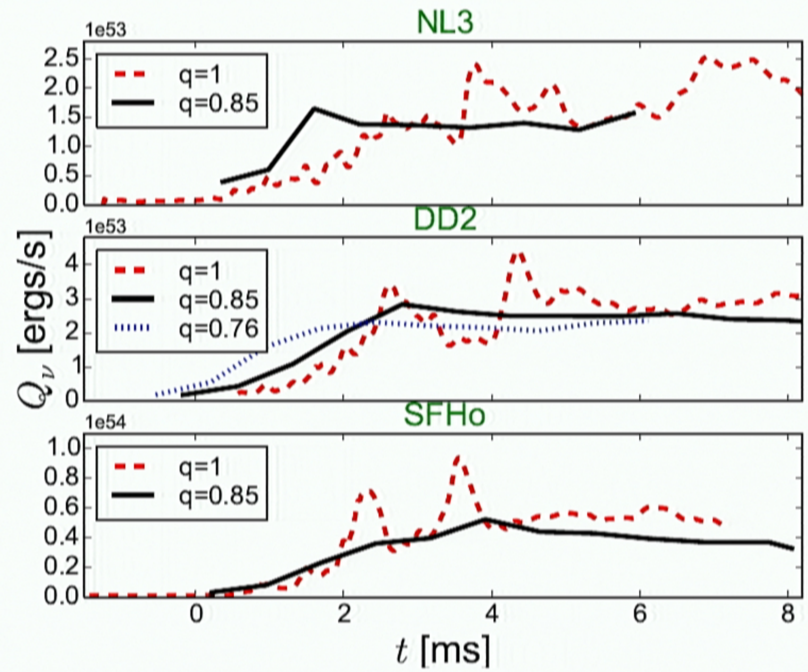

Neutrino Emission: Detectability

Assume 10kpc distant in SuperKamiokande-like water Cherenkov detector

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

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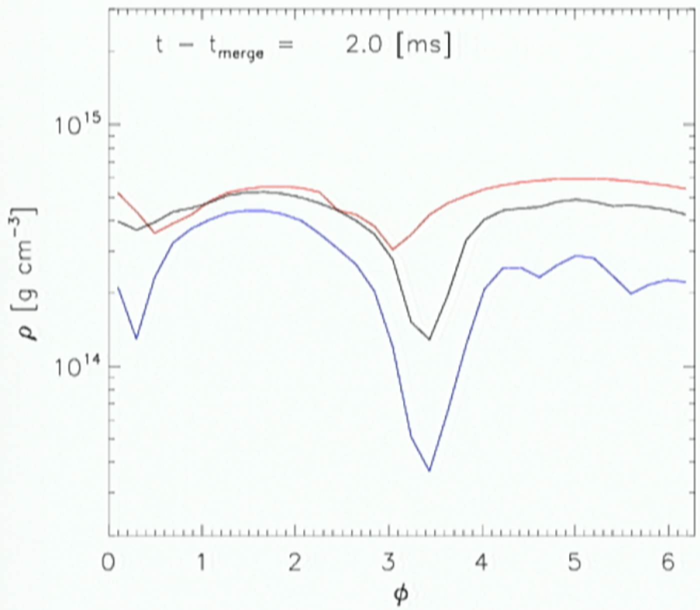
- **Using the $m = 1$ instability to extract EoS information**
- Constraining the theory of gravity with compact neutron stars
- Charged black hole binaries

$m = 2$ develops into $m = 1$ for $q = 0.85$ DD2



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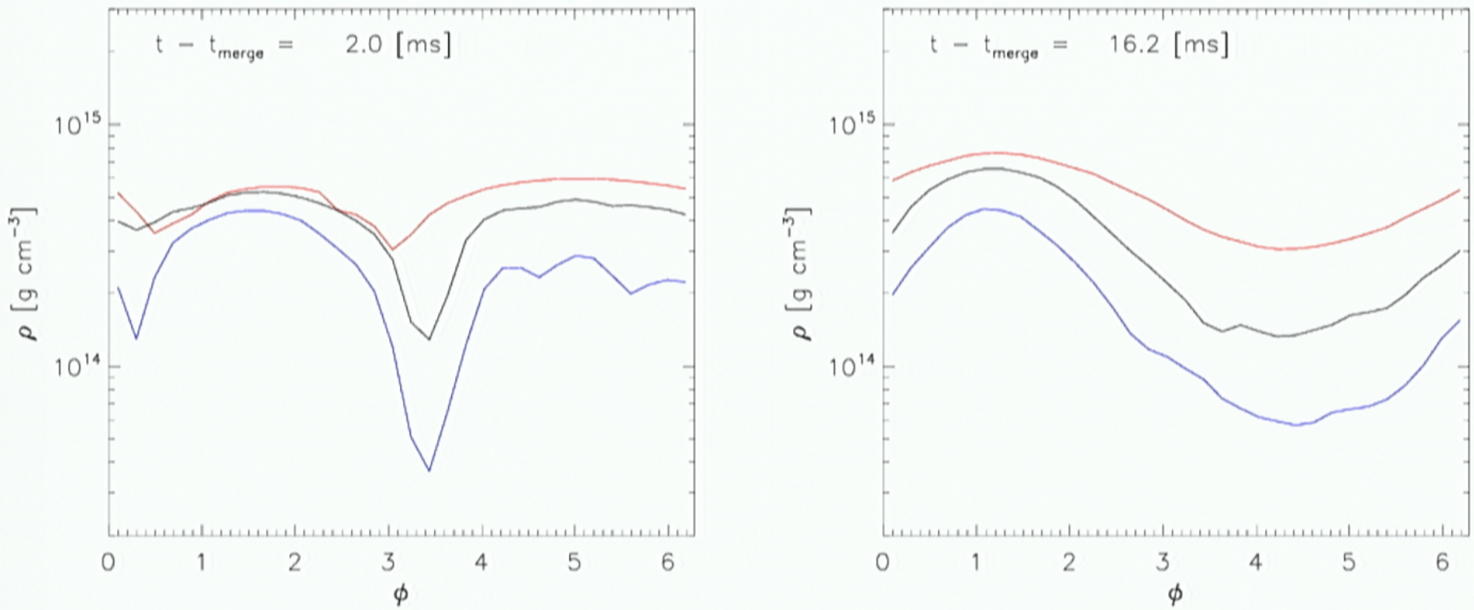
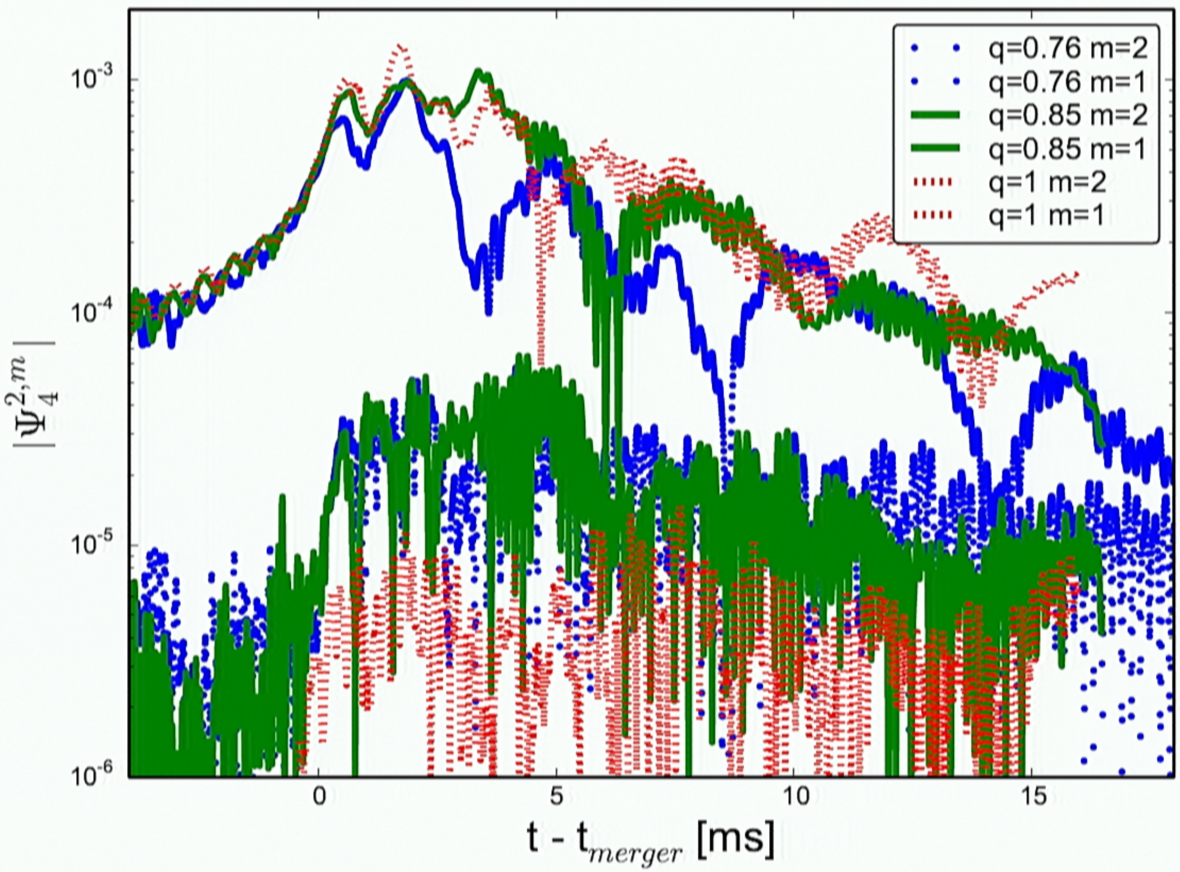
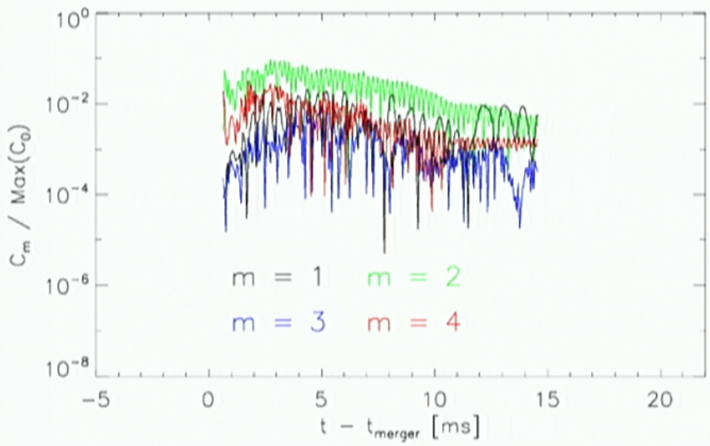


See also
[East,Paschalidis,Pretorius,Shapiro,1511.01093]
and [Radice,Bernuzzi,Ott,1603.05726]

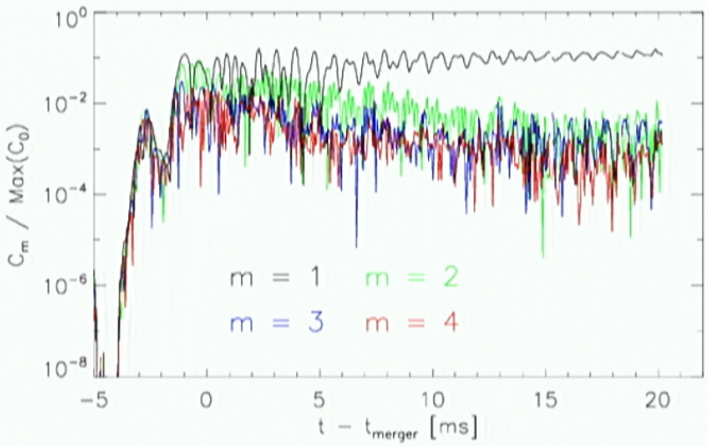
Growth of $m = 1$ Mode in GW Signal for DD2



Density Decomposition into Azimuthal Modes for DD2

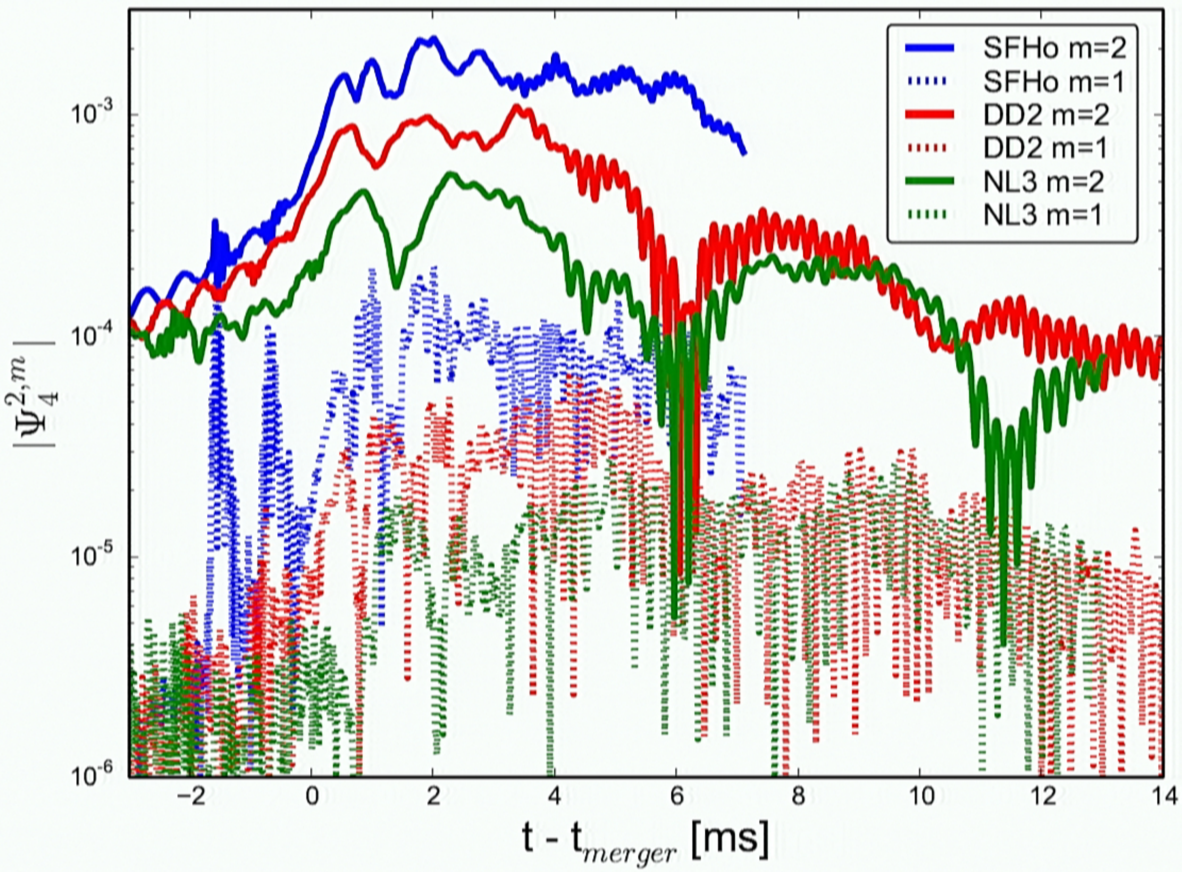


$q = 1$



$q = 0.76$

Effect of EoS on $m = 1$ mode instability



Detectability

Using:

$$\rho^2 \simeq \frac{2}{S_n(f)} \int_0^T h^2 \, dt$$

We arrive at

$$\rho_{m=1} \approx 0.6 \left[\frac{2 \times 10^{-22}\mathrm{Hz}^{-1/2}}{\sqrt{S_n(f_{\mathrm{m1}})}}\right] \left[\frac{|\Psi^0_{4_{m=1}}|}{10^{-4}}\right] \left[\frac{1.3\mathrm{kHz}}{f_{\mathrm{m1}}}\right]^2 \left[\frac{T}{10\mathrm{ms}}\right]^{1/2} \left[\frac{10\mathrm{Mpc}}{L}\right]$$

Not particularly encouraging, but...

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Not particularly encouraging, but...

Detectability

- The $m = 1$ mode **lasts longer** than the $m = 2$ mode
- Occurs at **low frequency** and hence in more sensitive region of LIGO's noise curve
- Its frequency is precisely half that of the $m = 2$ and can therefore be **explicitly targeted**

Provides another avenue for extracting information about the equation of state

- Weaker for stiff EoS than for soft EoS
- For smaller mass ratios, $m = 1$ becomes stronger and saturates earlier

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Can we constrain gravity with neutron stars?

[Palenzuela,SLL,1510.03471]

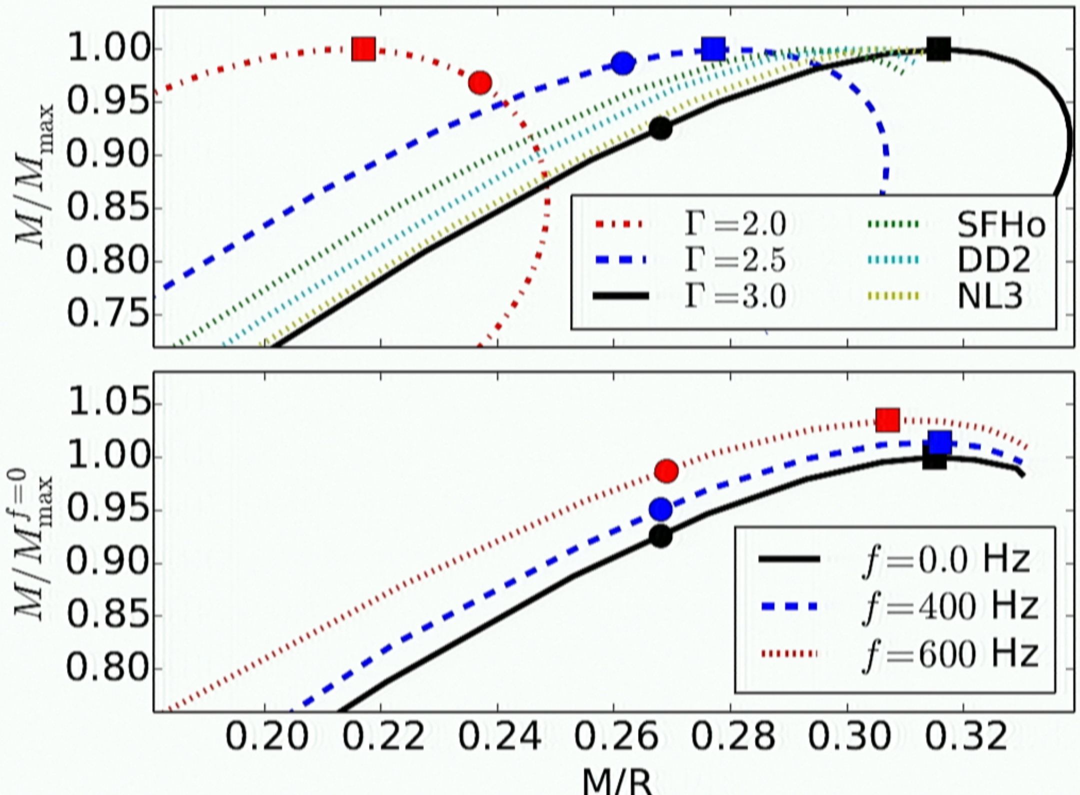
- Consider extension to GR
  - Scalar Tensor theories reduce to GR in appropriate limit, well-posed, share same causal structure
  - Particular version: Damour-Esposito-Farese model parameterized by $\{\phi_0, \beta\}$...$\phi_0 = 0 = \beta$ recovers GR
- Postive β region largely unconstrained
- Instability found for $\beta > \beta_{\rm crit}$ for very compact NS NS [Mendes,1412.6789]

$$\Box^E \varphi = -(4\pi G)\beta\varphi T_E$$

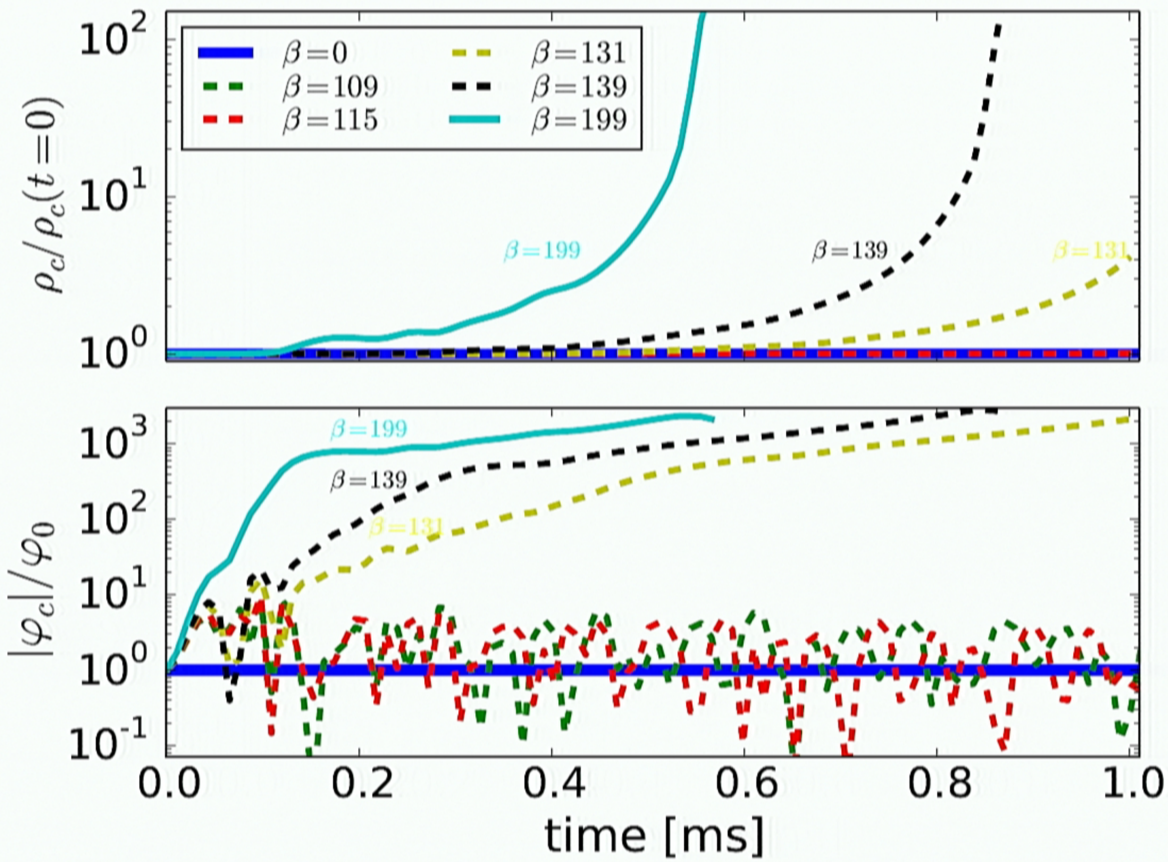
- Knowing the end state may help constrain gravity with NS observations

Space of NS Solutions

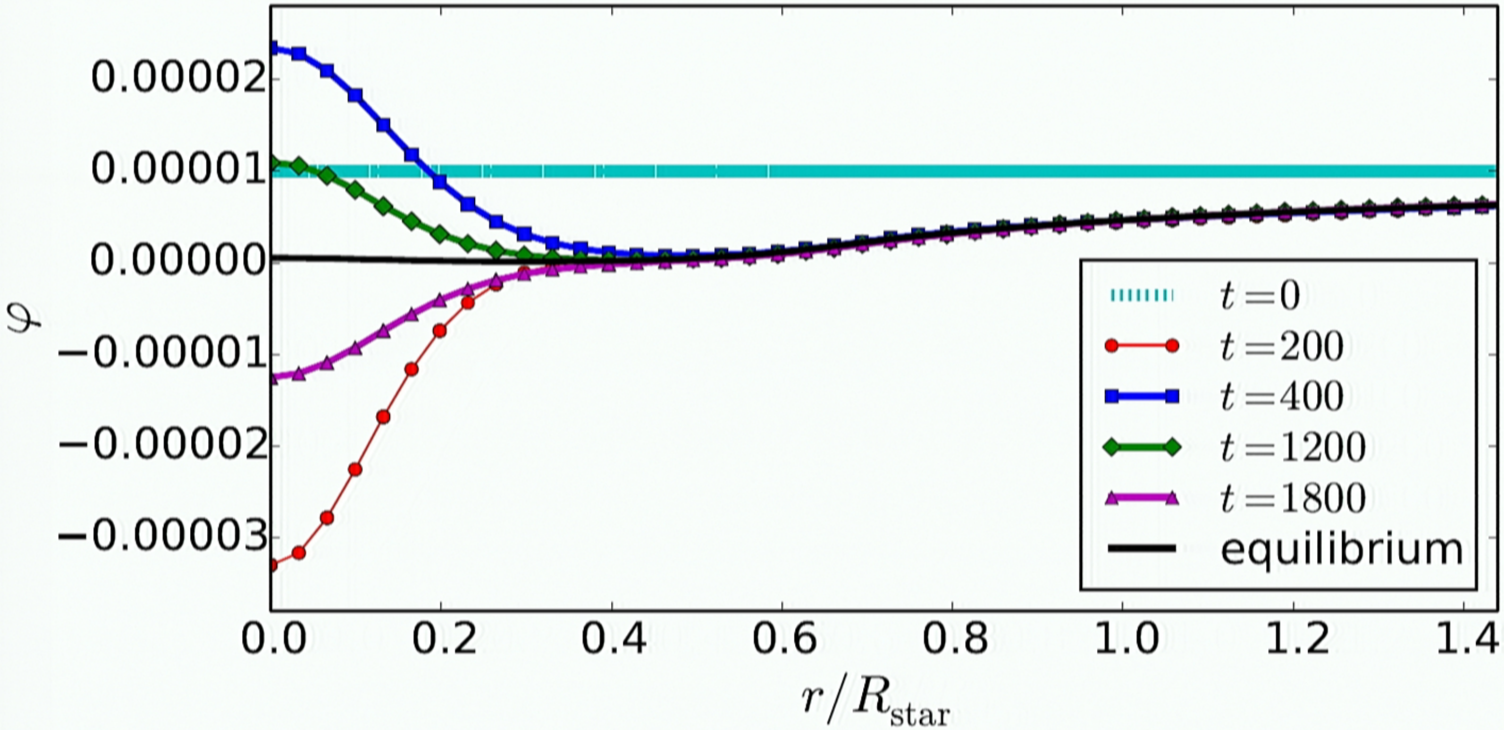
squares represent maximum mass; circles represent central T=0



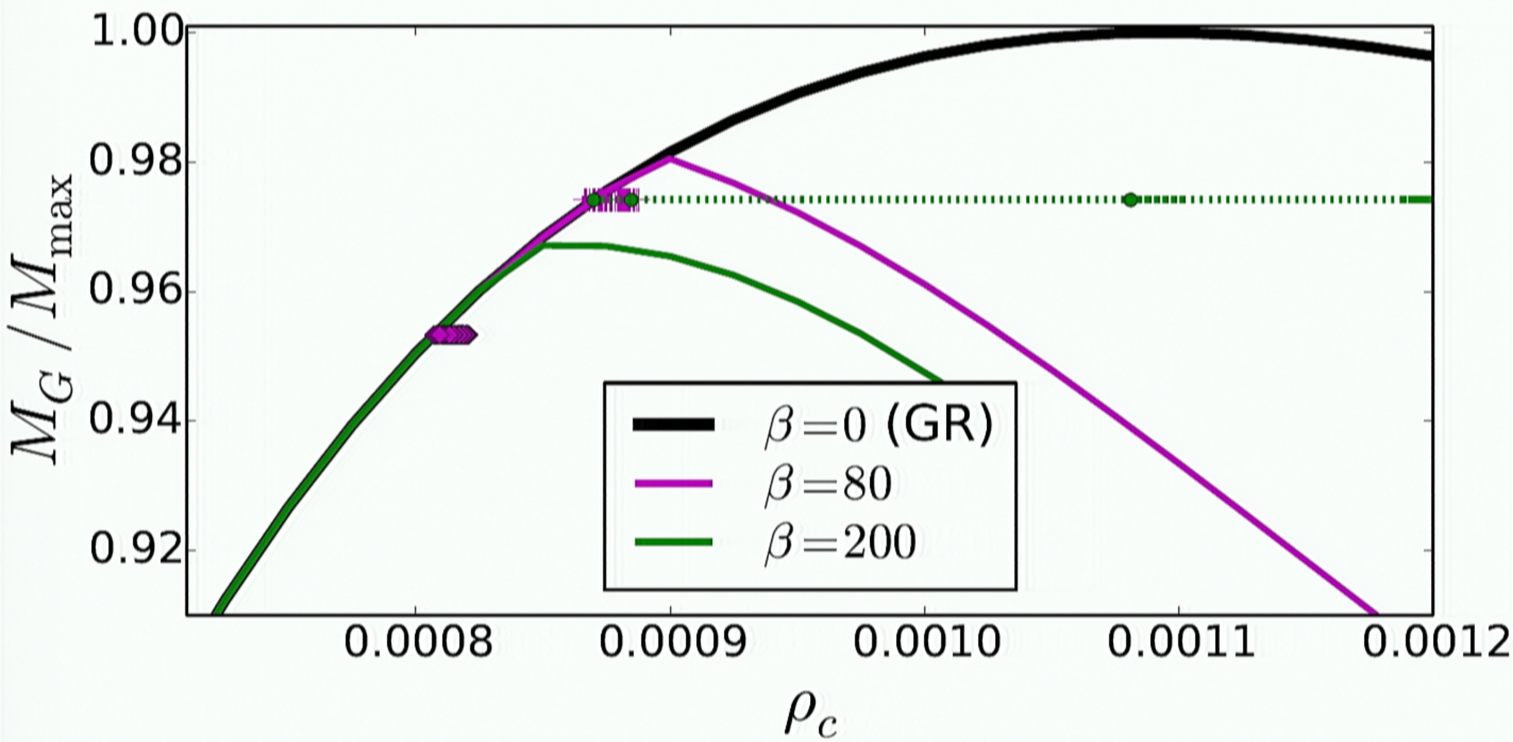
Dynamics and Critical Regime



Sub-critical oscillations about another ST Solution



Conjectured Phase Space Picture



Compact ST NS Conclusions

- Find end state of instablity: BH or other ST star
- Study the problem fully nonlinearly
- Extend the study to include rotating stars...same growth rate
- Most massive NS observed has a compactness roughly 0.28 ± 0.03 ...in the general neighborhood of this instability...
- If more compact stars are found, could bound β
- Also see [Mendes,Ortiz,1604.04175] that find dependence on details of coupling...dynamic scalarization

Fermi GBM Detection

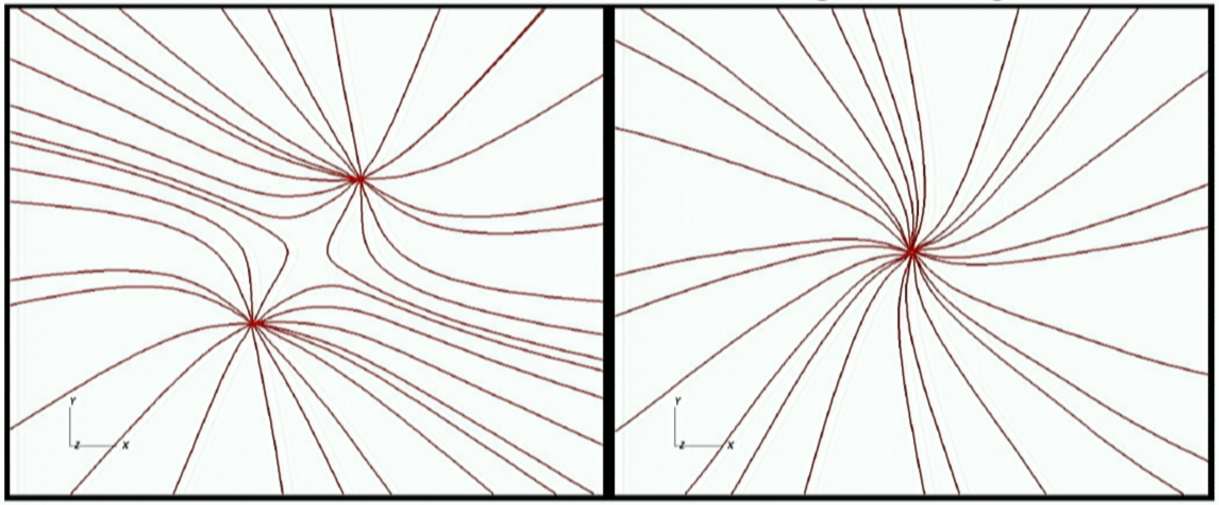
- Responding to aLIGO trigger, find sub-threshold, weak sGRB
- 0.4 s after GW peak
- Duration of 1.0s with luminosity of 10^{49} erg/s
- Satellite not ideally situated for search (only 70% FOV)
- Large swath of sky to cover ($\approx$ 600 square degrees)
- Not seen by other X-/γ-ray detectors:
  - AGILE [1604.00955]
  - INTEGRAL [1602.04180]

Could it be a charged Binary Black Hole?

[SLL,Palenzuela,In Progress...]

Either:

- the signal is **not coincident** with GW150914
- or **coincident**: somehow a BBH is producing a (weak) sGRB
  - Various possibilities w/ disks, magnetic field, etc
  - At least one of the black holes is charged [Zhang,1602.04542]



Electric field lines on the orbital plane **pre**- and **post**-merger

How could a black hole maintain a charge?

Astrophysically:

- NS-BH binary might drive a current to BH, and then NS goes supernova
- Exotic scenarios of charged NSs that eventually collapse
- BH w/ angular momentum J and external magnetic field B_0 will charge to $Q = 2B_0J$ [Wald,PRD 1974]

Cosmologically:

- Dark matter might charge (via a hidden $U(1)$ symmetry) a black hole [Carodoso,et al,1604.07845]
- BHs with magnetic monopole charge
  - In absence of charges/currents, symmetry $\vec{E}$ and $\vec{B}$
  - Primordial BHs accrete cosmological magnetic monopoles [Stojkovic,Freese,hep-ph/0403248]
  - Interesting tie-ins with dark matter [Bird,et al,1603.00464]
  - Implications for PMF [Long,Vachaspati,1504.03319]

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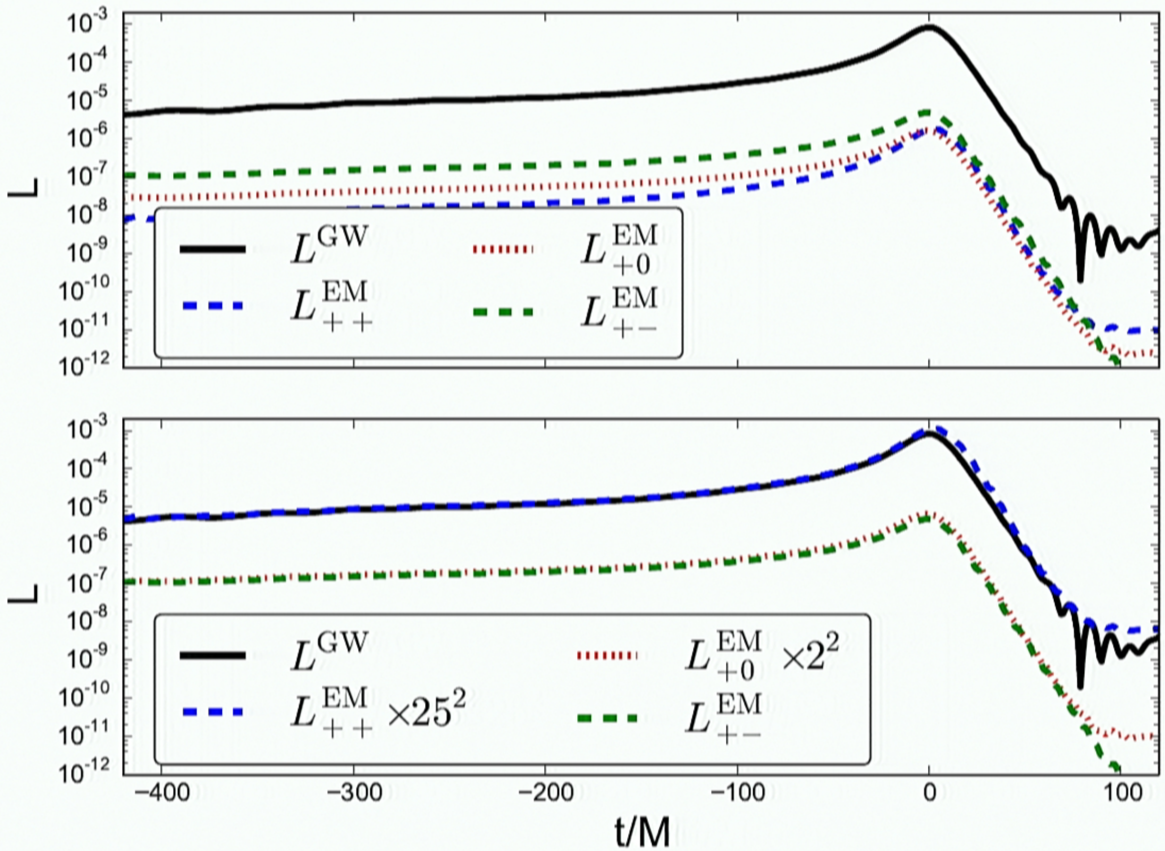
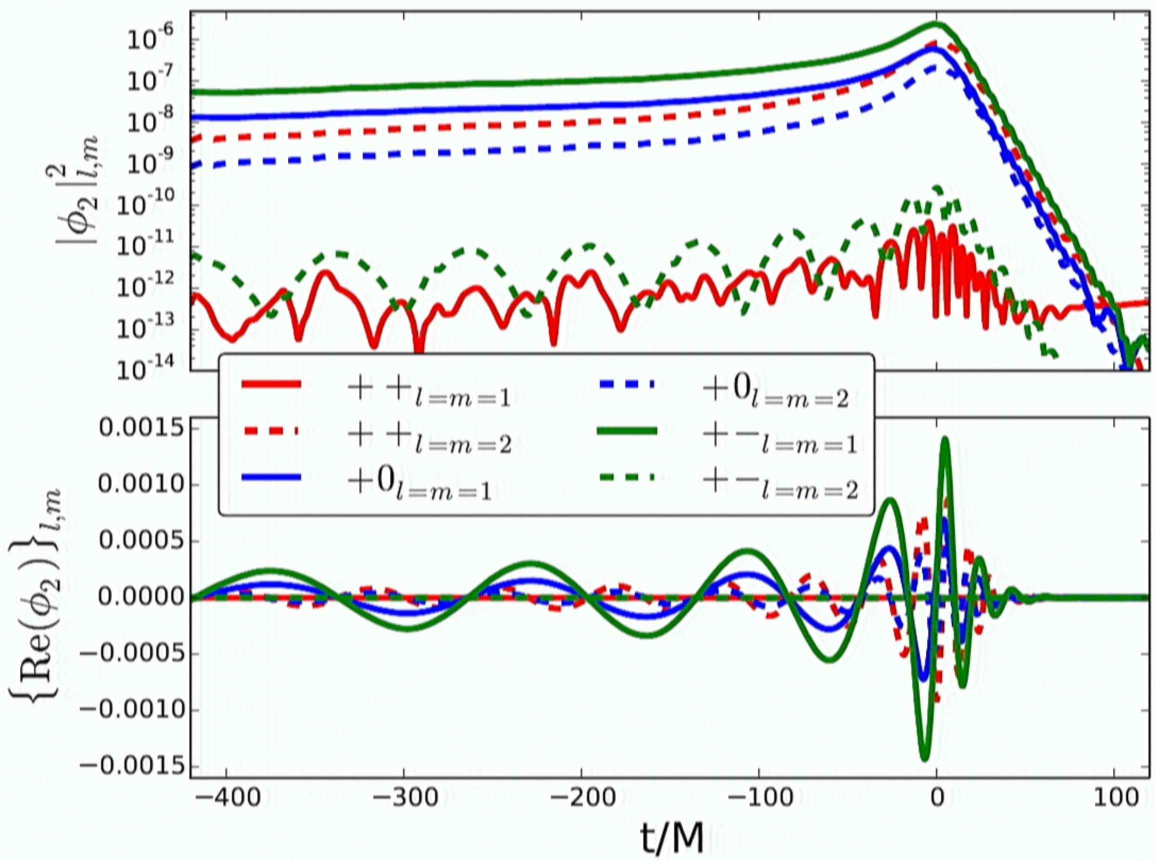
EM and GW Luminosities



Mode Structure



Results So far

Electrovacuum:

- If $q \equiv Q/M = 10^{-4}$, sufficient to power Fermi GBM event: $L_{\rm EM} \approx 10^{49}{\rm ergs/s}\left[\frac{q}{0.0001}\right]^2$ consistent with Zhang's estimate
- Only $q = 10^{-10}$ required to power (non-repeating) FRB $(10^{43}{\rm erg/s})$

Force-free:

- Past experience found interesting behavior with external magnetic field since BHS generally don't support their own magnetic field...monopolar field the exception!
- Electric charges inconsistent with force-free approach, but monopoles are!
- Early indications that force-free w/ mag. monopoles yields much more radiation!