Eccentric Mergers

Frans Pretorius
Princeton University

July 31, 2012
KITP, UCSB

Goal

- Motivate eccentric mergers as a potentially interesting subclass of compact object (CO) mergers from both a GW perspective and (with NS's) an EM counterpart perspective
  - could be exceptional laboratories to test GR (BHBH), and learn about NS structure and matter and nuclear densities (BH/NS)
  - instigate discussion to understand challenges for GW analysis
    - conventional CO search strategies not well adapted to this class of source; suboptimal (though robust) incoherent stacking algorithms could easily (?) be adapted; optimal cohorent stacking (i.e. templates) more challenging
  - and EM counterparts
    - distinguishable from quasi-circular inspiral?

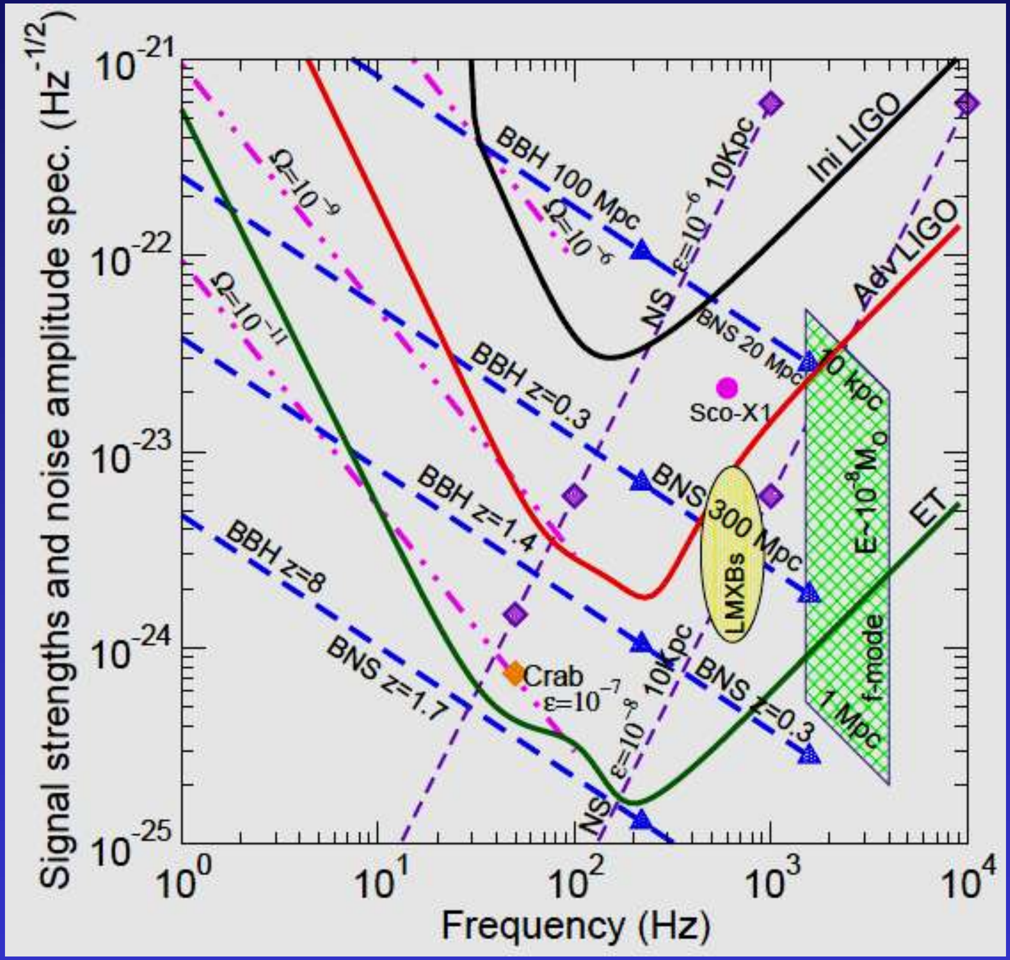
Outline

- Gravitational wave astronomy and CO mergers
  - primordial vs. dynamical capture binaries
  - merging with high eccentricity
  - mergers involving neutron stars
- Simulations of high eccentricity CO mergers
  - basic properties, outcomes, source of variability
  - GW detectability estimates
- Questions

Learning about the universe through compact object mergers

- Direct probe of the dynamical, strong field regime of gravity
  - no current observational or experimental constraints of GR in this regime, and only circumstantial evidence that observed dark compact objects are the BH's of GR
- Indirect probe of matter in extreme conditions, and binary compact object populations
  - binary BH, binary NS and BH/NS systems; primordial vs dynamical capture; NS structure and equation of state (EOS) of matter at nuclear densities
  - observing electromagnetic counterparts for events involving NS's can increase by many-fold the amount of information that can be garnered

Observing stellar mass compact object mergers with AdLIGO et al.



Compact object tracks are ~ 1.4-1.4 M$_\odot$ binary neutron star and 7-7 M$_\odot$ binary black hole quasi-circular inspirals; from Sathyaprakash & Schutz, Living Reviews

Primordial binaries

- Denote a primordial compact object binary as one originating from a stellar binary in the field
- Event rate estimates come primarily from population synthesis studies, and for binary NS systems extrapolation of the observed population
  - many uncertainties in the models, translating to large uncertainties in event rates; summary below from LIGO topical review *[CQG 27, 2010]*

IFO	Source[a]	$\dot{N}_{low}$ yr^{-1}	$\dot{N}_{re}$ yr^{-1}	$\dot{N}_{high}$ yr^{-1}
	NS–NS	2×10^{-4}	0.02	0.2
	NS–BH	7×10^{-5}	0.004	0.1
Initial	BH–BH	2×10^{-4}	0.007	0.5
	NS–NS	0.4	40	400
	NS–BH	0.2	10	300
Advanced	BH–BH	0.4	20	1000

  - there is also a population of binaries that can form in dense cluster environments (for e.g. via exchange interactions) whose final stages of merger will resemble that of primordial binaries; these are not included in the above rates due to much larger uncertainties in the models
    - in terms of the dichotomy in the character of the final stages of the merger discussed here, also classify these as "primordial"

Dynamical capture binaries

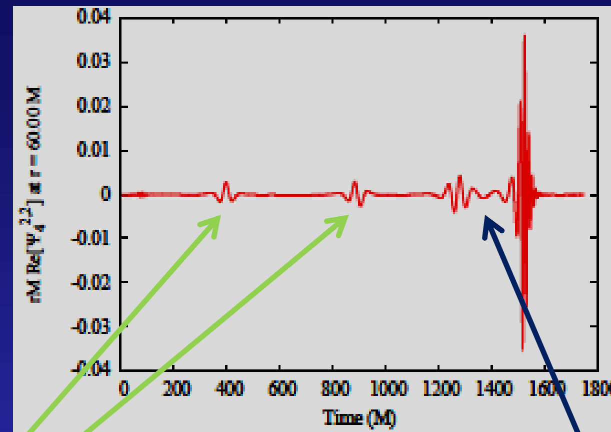
- Recently, a couple of studies have suggested close 2-body encounters in dense cluster environments resulting in a tight binary (via energy loss to GW emission or tidal interaction) could constitute a non-negligible fraction of observable events:
  - For binary BH systems, O'Leary et al. *[2009MNRAS.395.2127O]* estimate AdLIGO rates of ~ 1-10^3/year from mergers in galactic nuclei alone
  - Lee, Ramirez-Ruiz & Van de Ven *[APJ 720, 953 (2010)]* claim global event rates of NS/NS and BH/NS systems of ~1-10^2/yr/Gpc^3
    - BH/NS and/or NS/NS systems possible SGRB progenitors; estimated rate of ~ 8-30/yr/Gpc^3 for isotropic emission SGRBs *[Guetta & Piran, A&A, 453, 823 (2006)]*, several times larger if beamed; these systems could thus constitute some fraction of sGRB events
- The primary difference between primordial vs dynamical capture binaries is a significant fraction of the latter will merge with *large eccentricity*
    - due to natal kicks when the compact objects are born, some primordial binaries may merge shortly after with larger eccentricity; Kowalska et al. *[APJ 527, A70 (2011)]* estimate between 0.2% and 2% will have $e>0.01$, but still less that 0.05

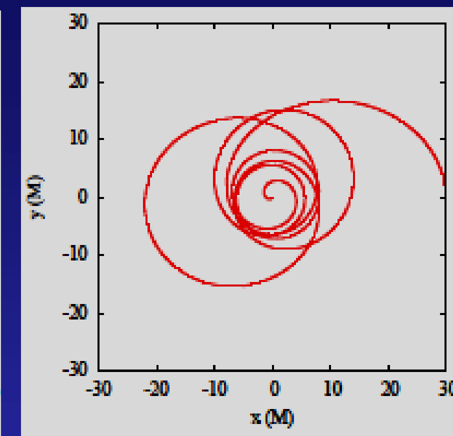
Merging with large eccentricity

- GW signal more a sequence of bursts than a chirp
  - quasi-circular templates not a good match *[Brown & Huerta, poster here]*, present burst searches do not add signals from multiple correlated bursts, and burst stacking strategies *[Kalmus et al., PRD80 (2009) 042001]* not yet adapted for these sources
  - Kocsis & Levin *[arXiv:1109.417 (2011)]* estimate the early (till separations of ~10M) repeated burst phase could be seen with AdLIGO out to 200-300Mpc for BH/NS mergers (300-600 Mpc for BBHs mergers)
    - Using Lee et al. event rates, this suggests AdLIGO detection rates of *0.3 – 10/yr* for BH/NS systems; including the last stages of the merger should increase these rates, in particular for the more massive systems
- due to the larger angular momentum more time spent in the strong field regime
  - could see some *zoom-whirl* dynamics in waveform near merger

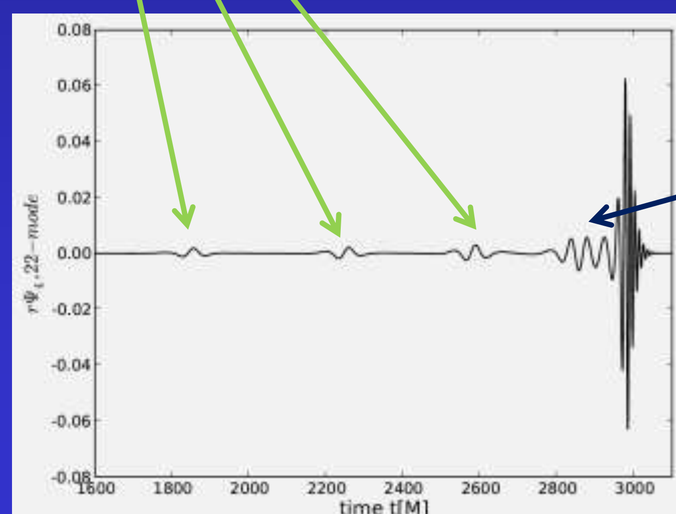
Sample BH/BH eccentric mergers

- top from *Healy, Levin & Shoemaker, PRL 103, 131101 (2009)*; $m_1/m_2=1/3$, $a_1=a_2=0.3$ anti-aligned with orbital angular momentum (L=4.10)
- bottom from *Gold & Bruegmann (to be published)*; equal mass, non-spinning, initial $e\sim.7$





"usual" passage through pericenter



whirl phase; how much present sensitive to initial conditions

Mergers involving neutron stars

- There is still much unknown about the inner structure of NSs, partly due to uncertainties in models of matter at such extreme densities and pressures
  - such conditions cannot be recreated in labs on earth, and are difficult to model theoretically
- GW observation of BH/NS and NS/NS mergers could potentially reveal much information about matter in these conditions
- In the simplest hydrodynamic model of a NS, this uncertainty is quantified in the equation of state (EOS) of the fluid, which determines two important properties of a binary that could have observable consequences
  - the mass-radius relationship of individual NSs before merger
  - the dynamics of matter during and after collision for NS/NS mergers, and the details of tidal disruption in BH/NS systems

BH/NS merges with eccentricity

- An interesting coincidence for astrophysically relevant NS/BH masses : a 1.5 $M_{\odot}$ neutron star will reach it's Roche-limit *within* the range of unstable circular orbits for black holes with masses ~ 5-15 $M_{\odot}$
  - how a BH tears a NS apart could reveal much about the EOS, not only via GW emission but consequent electromagnetic and neutrino emission
  - unstable binary orbits are a distinct feature of GR, and probe the highest curvature regions outside the horizon
- A quasi-circular inspiral will only spend a fraction of an orbit within this regime
  - not much time to see interesting tidal effects, nor leave a strong imprint on the GW signal
- On the other hand, dynamical capture binaries on high eccentricity orbits could have multiple close encounters near this regime
  - much richer phenomenology of outcomes, and in many cases more GW power will be radiated at slightly lower frequencies, improving detectablity with AdLIGO *[Kocsis and Levin, arXiv:1109.4170]*

Dynamical Capture BH/NS and NS/NS simulations

- To my knowledge, only a small handful of simulations of dynamical capture BH/NS or NS/NS binaries to date
  - using Newtonian SPH, *Lee, Ramirez-Ruiz & Van de Ven [APJ 720, 953 (2010)]* and *Rosswog, Piran & Nakar [Xiv:1204.6240]* (BH/NS), incorporating some form of radiation reaction, and the latter a realistic EOS and neutrino leakage
  - using grid-based GR hydrodynamics, *Stephens et al. ApJ 737 (2011) L5 & PRD 85 (2012)* (BH/NS) and *Gold et al. [arXiv:1109.5128]* [NS/NS]
- Qualitatively similar results, namely large variability in outcome (unbound material, disk mass, GW signature) with system parameters, though for a given system details can be quite different depending on what aspects of the full problem are modeled
  - strong-field GR effects important, in particular the presence of an effective innermost stable orbit (ISO), radiation reaction, and BH spin
  - microphysics and additional matter (EM fields, radiation) essential in understanding details of EM/neutrino emission, and can also important in dynamics

A few results from our effort

B.Stephens, W. East, FP, ApJ 737 (2011) L5 & PRD 85 (2012);
and ongoing work with W. East, S. McWilliams & J. Levin

- A huge parameter space to understand and classify, much unexplored, so choosing 3 examples to highlight :
  - BH/NS mergers illustrating <u>significant variability</u> in GW signal and matter dynamics as a function of binary parameters (impact parameter, mass ratio, BH spin, NS EOS)
  - NS/NS merger illustrating the "<u>lever arm of eccentricity</u>" in being able to leave an imprint of strong-field dynamics on the GW signal
  - Simple GW template models to illustrate the <u>need for improved GW detection algorithms</u> to increase the volume of the universe that AdLIGO can listen to these events for

Variability in outcome

- As a function of input parameters see significant variability in :
  - amount of material left in accretion disk
    - larger disk masses expected to be important for powering SGRBs
  - estimated amount of unbound material
    - could be relevant for explaining late time Xray afterglows observed in some SGRBs, be sources of other EM transients and r-process elements
  - amount of zoom-whirl behavior in orbit and GW signal
- Two primary factors influencing the variability
  - *radius of NS* → function of EOS and mass of the NS
  - *pericenter distance relative to location of the innermost stable orbit (ISO)* → function of BH spin, orbital eccentricity and impact parameter
    - the closer to the ISO the longer the NS lingers in the strong field regime; if within the Roche radius more tidal stripping
    - if the pericenter is within the ISO radius then a plunge will occur, otherwise a second (or perhaps more) close encounters possible

Sample BH/NS merger 1

Newtonian e~1, r_p = 6.95M
M_{NS0}=1.35 $M_\odot$ (R=11.6km, M/R=0.17); M_{BH0}=5.40 $M_\odot$

disk mass
~ 0.024 $M_\odot$

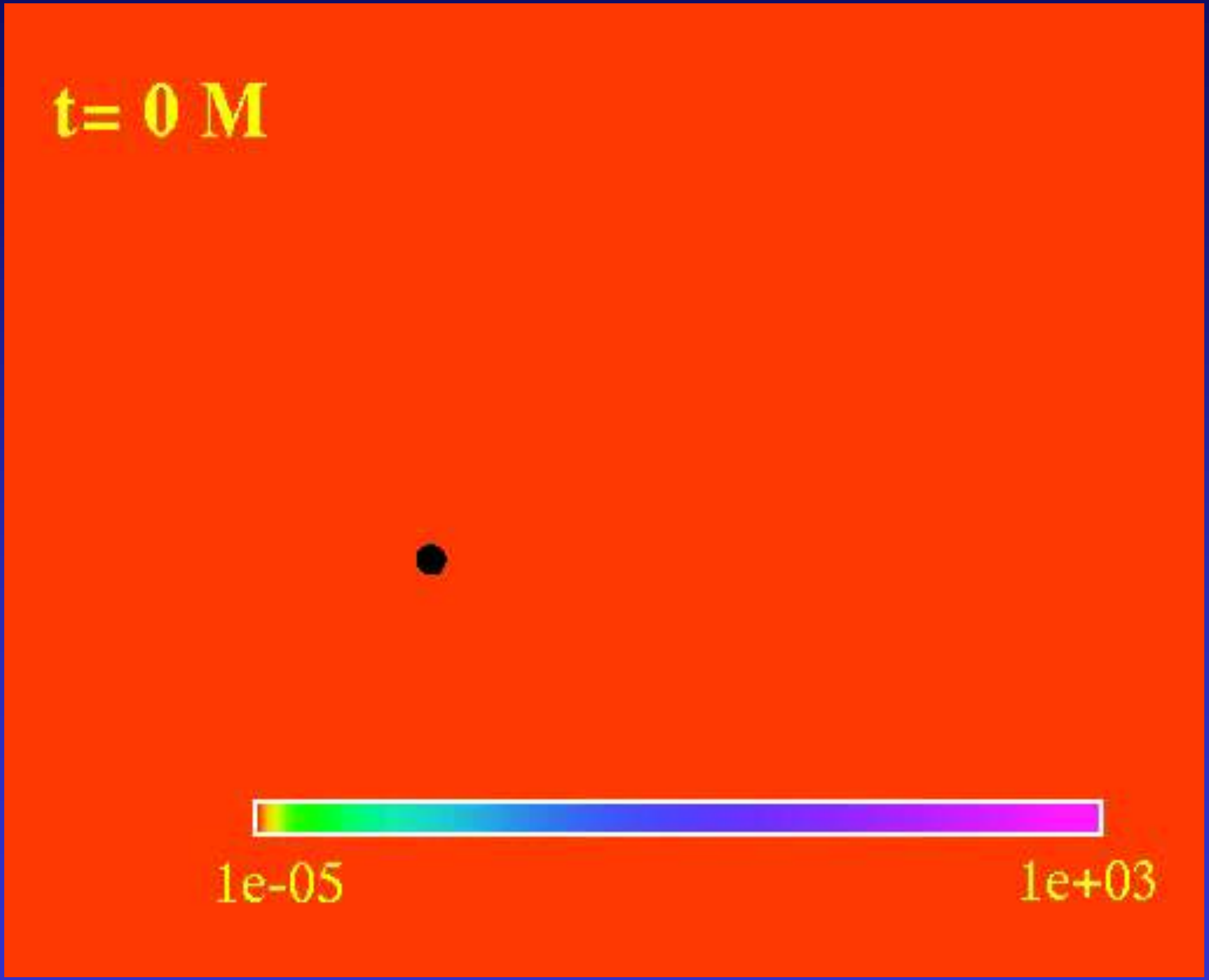
unbound material
~ 0.004 $M_\odot$

~ 0.017M energy emitted in GW's

initially non-spinning BH, final BH spin a~0.47

"HB" piece-wise polytropic EOS (M_{max}=2.12 $M_\odot$)
[Read et al. PRD 79 (2009)]

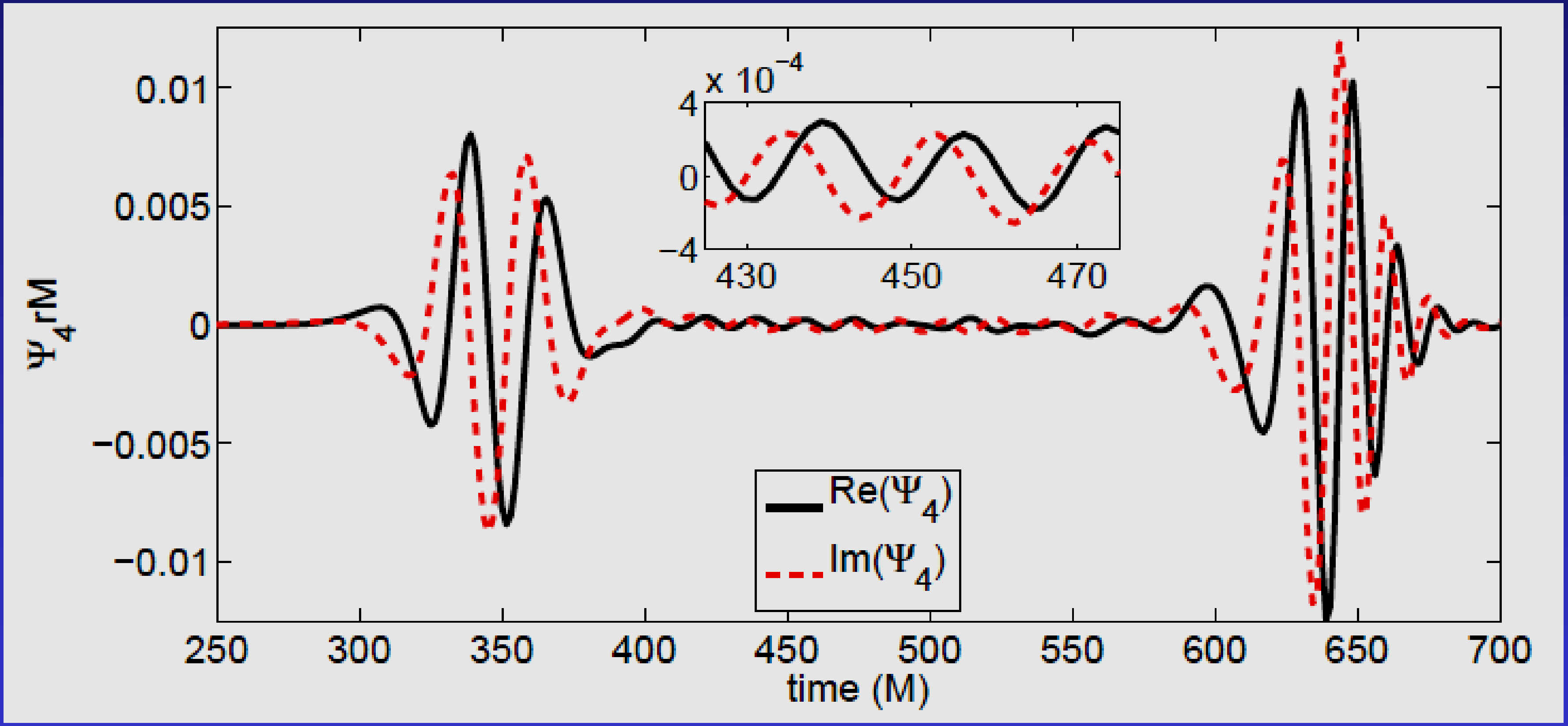
(time units in movie are wrong; total duration~ 20 ms)



rest mass density ρ

Sample BH/NS merger 1

- Gravitational wave emission from previous example



Sample BH/NS merger 2

Newtonian e~1, r_p = 7.0 M
M_{NS0}=1.35 $M_\odot$ (R=15.2km, M/R=0.13); M_{BH0}=5.40 $M_\odot$

disk mass
~ 0.41 $M_\odot$

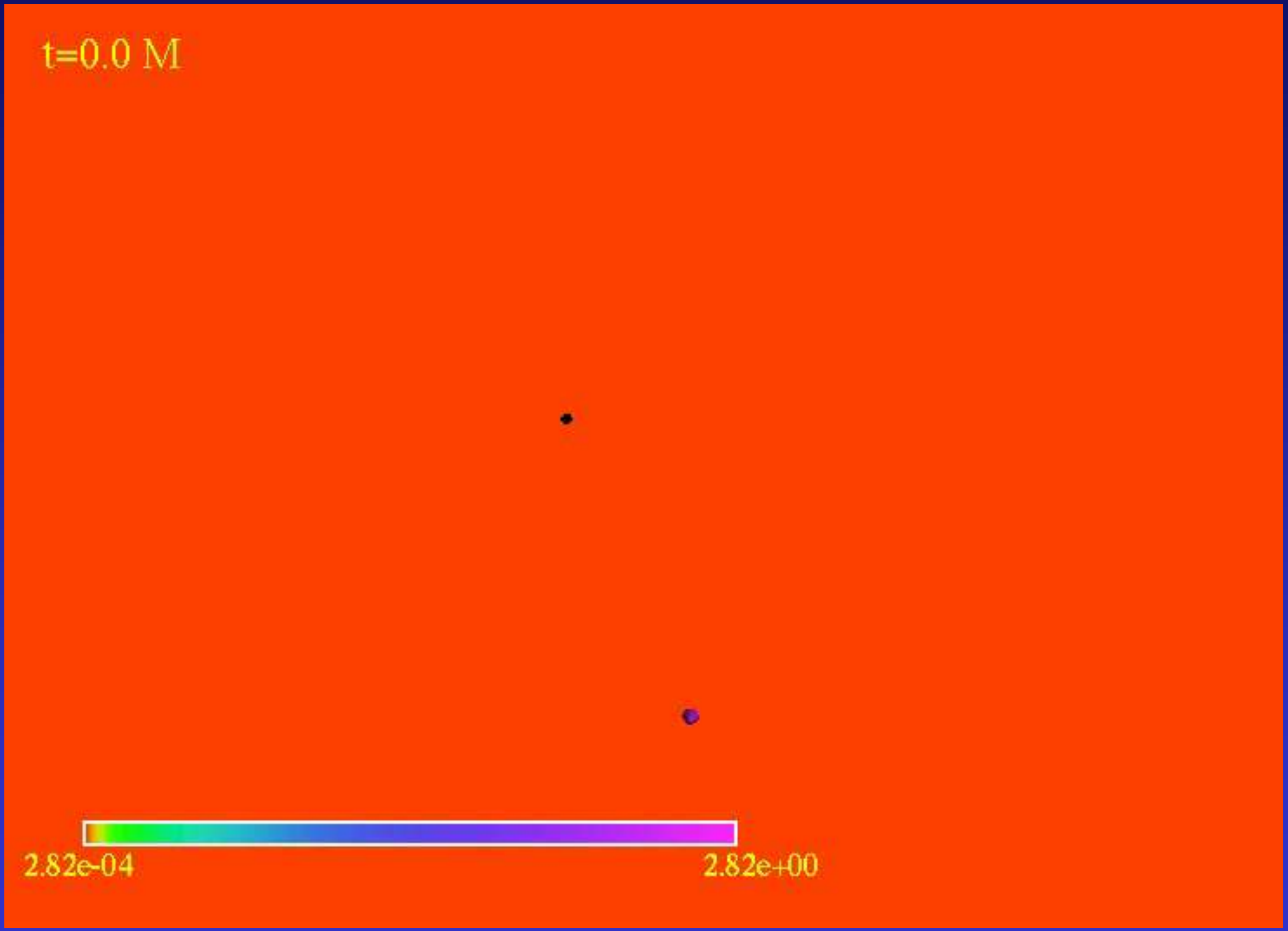
unbound material
~ 0.20 $M_\odot$

~ 0.0043M energy emitted in GW's

initially non-spinning BH, final BH spin a~0.33

2H EOS (M_{max}=2.83 $M_\odot$)

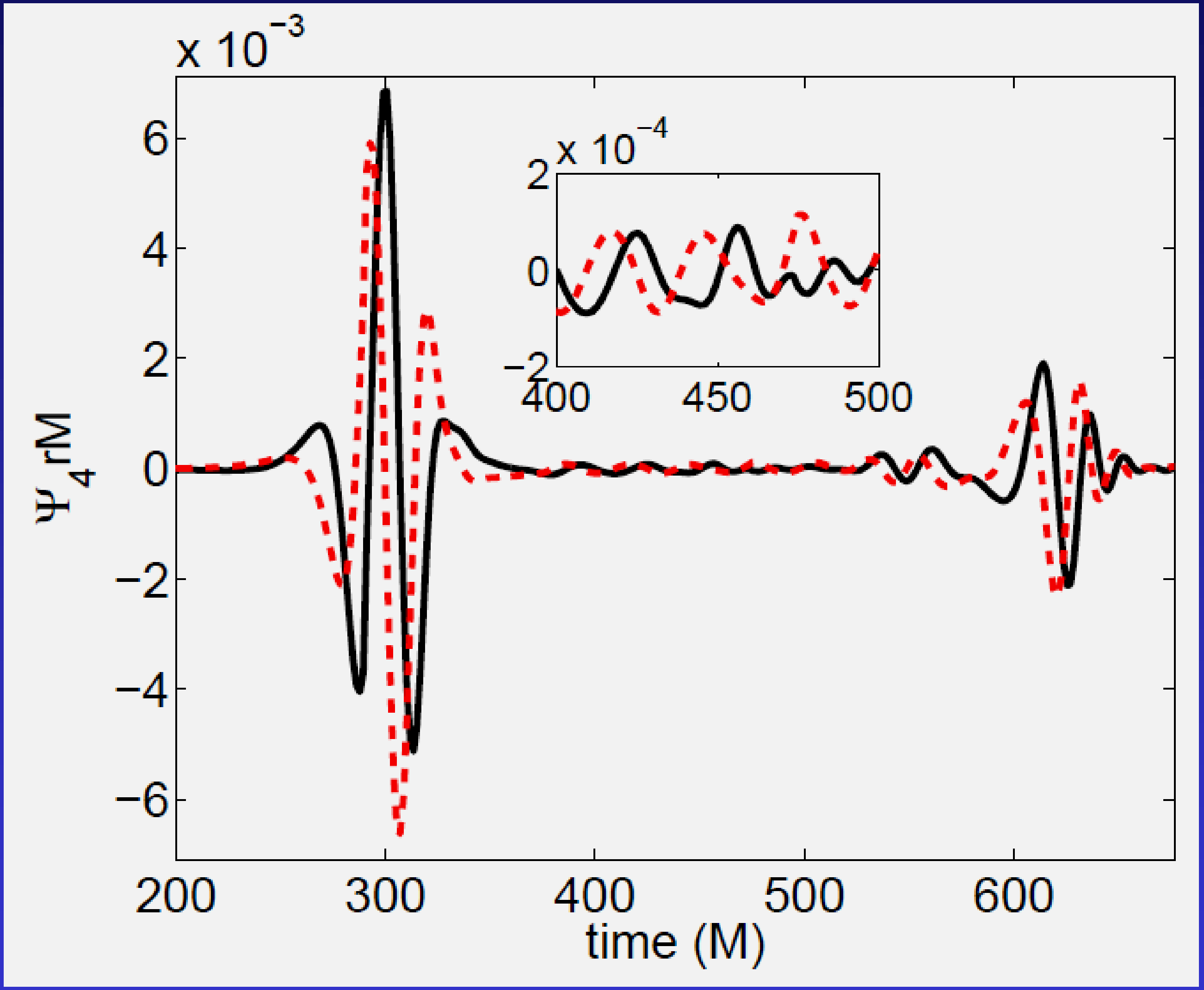
(geometric time units, again duration ~ 20 ms)



rest mass density ρ

Sample BH/NS merger 2

- Gravitational wave emission from previous example



The lever arm of eccentricity

- Because of the small capture cross section due to GW energy loss, each close encounter of the repeated burst phase occurs deep in the strong-field regime (within a few to tens of M)
  - can think of the evolving orbit as a sequence of ellipses, with the parameters of the ellipse changing quite abruptly during each pericenter passage
  - for high eccentricity, a relatively *small* deviation in the change of the parameters of the ellipse would result in a *large* dephasing of the signal at the next close encounter (thanks to Chris Thompson for emphasizing this); e.g.

$$\delta T \propto \frac{\delta E}{(1-e)^{5/2}}$$

δT is the change in arrival time of the next burst corresponding to a change δE in the energy at previous burst, which resulted in an orbit with effective eccentricity e

Sample NS/NS merger

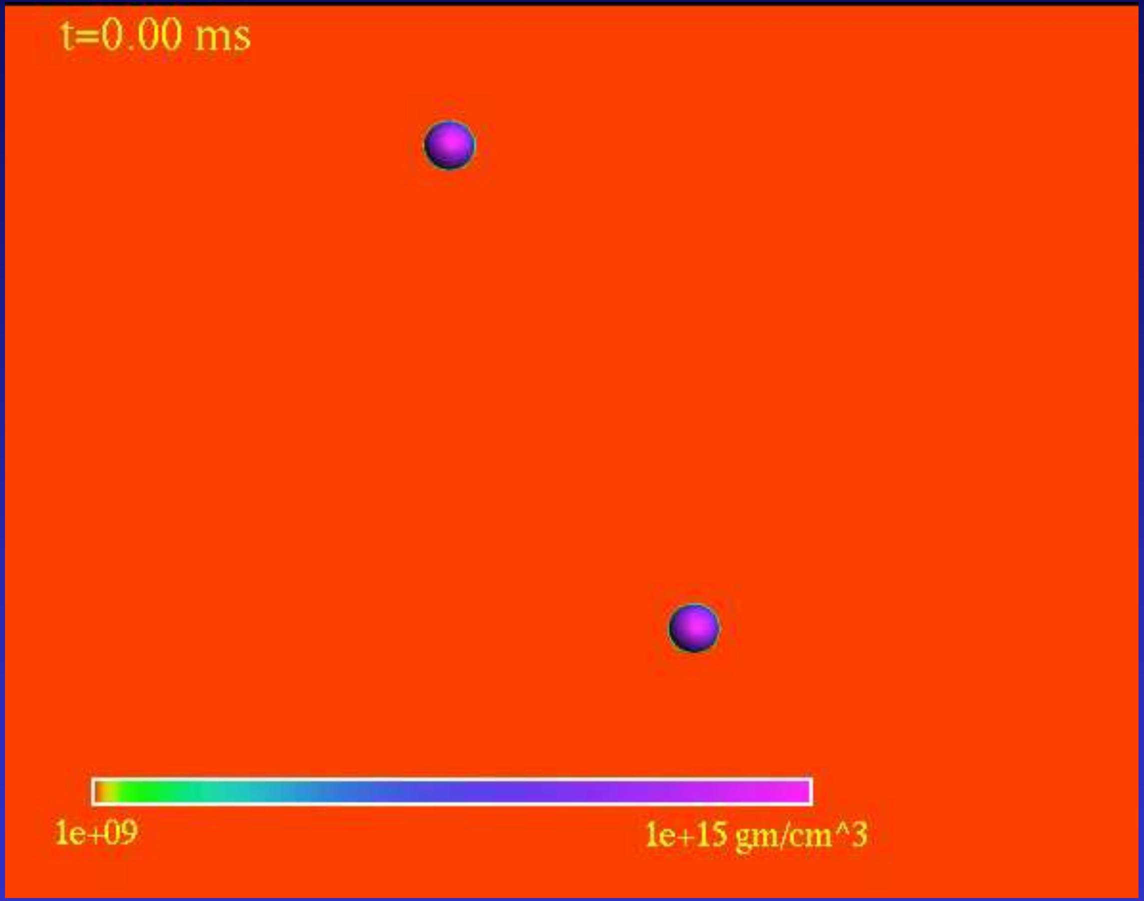
Newtonian e~1, r_p = 10.0 M
M_{NS0}=1.35 $M_\odot$ each (R=11.6km, M/R=0.17)
HB EOS, shown (M_{max}=2.12 $M_\odot$)

~ 0.00147M energy emitted in GW's during first periaps passage

Estimated period of subsequent orbit T~65ms

For the B EOS (R=10.9km, M/R=0.18, M_{max}=2.00 $M_\odot$), ~19% more energy emitted during first passage, with estimated T~50ms (energy lost to GW dominates compared to excitation of f-mode)

The 2H EOS (R=15.2km, M/R=0.13, M_{max}=2.83 $M_\odot$) NSs touch on the first encounter and consequently merge



rest mass density ρ

Detecting eccentric mergers in GW

- Several studies indicate mergers will small eccentricity will be detectable with quasi-circular/low eccentricity templates *[Martel and Poisson, PRD 60 (1999); Cokelaer and Pathak, CQG 26 (2009)]*, though not so for large eccentricities *[Brown & Heurta, poster here]*

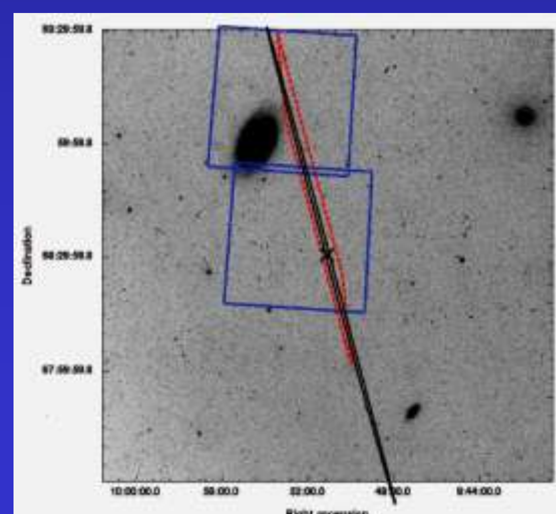
- A common lore is that burst or excess power searches will *detect* a good fraction of eccentric mergers with modest loss of SNR, though (to my knowledge) no studies have shown this

- Using a simple template bank of high eccentricity merges, motivated & calibrated by the numerical results, we are starting to address the above, namely, how well existing searches would be at detecting events compared to an optimal (matched filter) search
  - answer depends very much on the parameters of the system, but early results suggest there is a large swath of parameter space where burst searches before poorly (miss > 90% of otherwise detectable events)
  - will give one example

Detecting eccentric mergers in GW

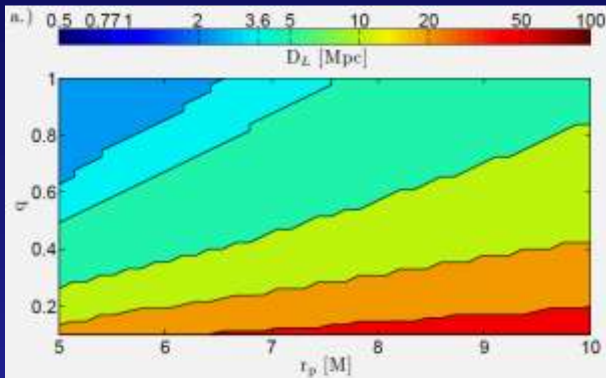
- Consider a 1.35 $M_\odot$ NS merger with a second (non-spinning) CO, with mass ratio q, initial (Newtonian) periaps distance r_p and eccentricity $e{\sim}1$, and model initial LIGO noise curve

- Will show distance to which an SNR 8 event can be seen using optimal, burst and excess power searches, to ask :
  - *if a small r_p eccentric merger was the progenitor for either GRB 070201, possibly originating in M31 at a distance ~770Kpc, or GRB 051103, possibly originating in M81 (3.6Mpc), would they have been detected with the methods employed in either search [LSC, APJ 681 (2008) LSC & APJ 755 (2012)]?*

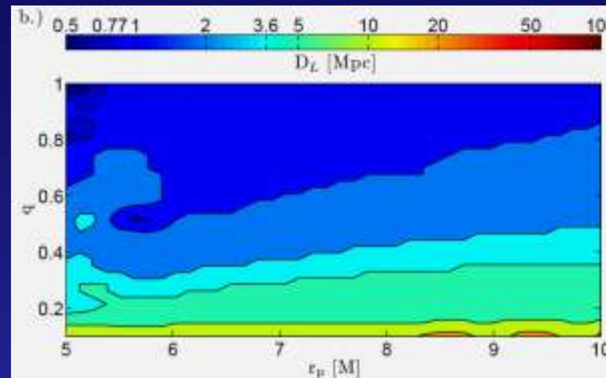


Adelman-McCarthy, et al. 2006[left]; Hurely et al., 2010 [right]

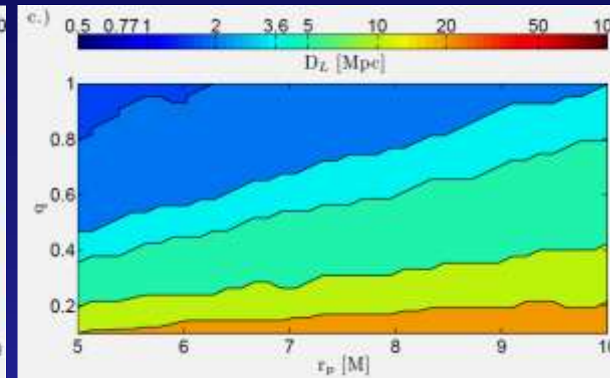
Initial LIGO horizon distance for SNR 8 NS/CO merger



(optimal) matched filter



sine-Gaussian burst



(incoherently) stacked excess power

- optimal search : for M31 event would have been detected for all parameters included, the M81 event for most except small r_p NS/NS mergers
- burst search : for M31, all BH/NS candidates, and marginally NS/NS events; for M81, only the moderate-high mass ratio BH/NS mergers
- stacked excess power : for M31, all events, for M81, only the moderate-high mass ratio BH/NS mergers

Questions

- Variability :
  - GW templates : how to construct sufficiently accurate models of the events, in particular to include tidal effects with NSs?
  - counterparts : different characteristics (EM transients, r-process yields) to QC inspiral? If high eccentricity NS/NS mergers are a sub-class of GRB progenitor, expect for the nearest (10's Mpc) events will not have an AdLIGO GW counterpart.
- Lever arm of eccentricity :
  - how much better (if any) would high eccentricity mergers be at
    - constraining NS properties (BH/NS or NS/NS)?
    - testing GR (BH/BH)?
- GW detection & parameter estimation:
  - are coherent methods (templates) viable for multiple (>>1) burst searches?
  - If not, can they still be used post-detection (via burst or stacked excess power) for parameter estimation? How well can parameters be extracted using alternative methods?