Non-vacuum spacetimes & strong gravity

Luis Lehner

Perimeter Institute for Theoretical Physics

Summary of lectures' philosophy

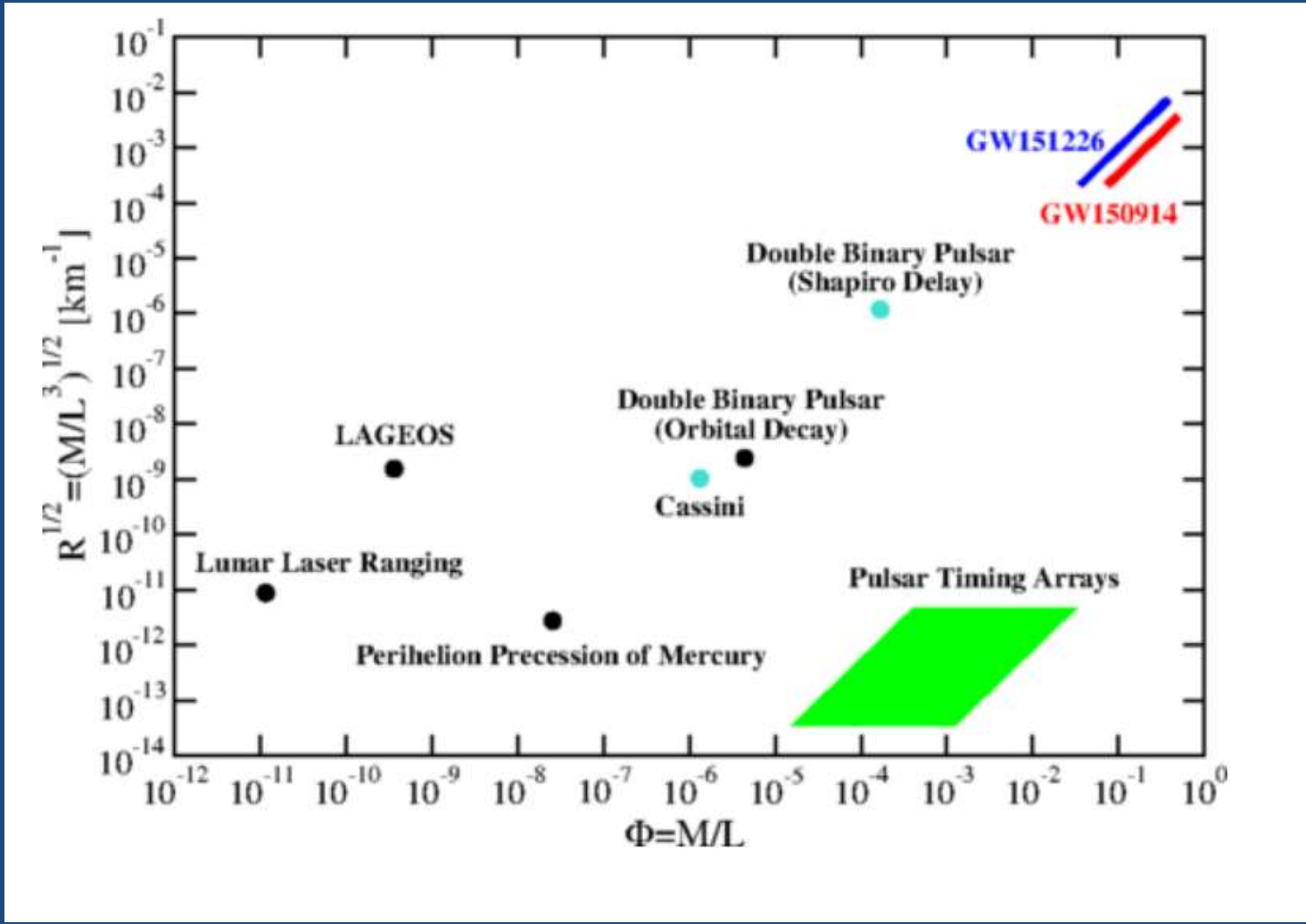
- will discuss some topics from current detections, and try to set the stage of what's coming (and what's needed!)
- Covering just a partial (limited, biased) topics. Philosophy will be to draw relevant lessons which can help you take next steps. Be them analytical or computational and wherever you might want to apply them
- Some specific examples will be mentioned, these only reflect what I know (to various degrees of depth)
- Will also reflect my personal fears, struggles and ideas of what could be done as we move forward
- Warning! I'll be jumping back and forth, do ask questions! I do not know what you know/don't know. These lectures can only be made fun by you!

General Relativity

- Theory of gravity based on fundamental principles: diffeomorphism invariance + massless spin-2 field → GR (at the linear level. e.g. Weinberg)

- Fundamental ingredients:
  - relativity: no special frame
  - equivalence: inertial effects indistinguishable from gravitational ones (e.g. equivalence between inertial and gravitational mass)
  - covariance: equations invariant under spacetime diffeomorphism
  - causality: each point admits a notion of past, present and future

Where tested ?



[figure from Yunes,Yagi,Pretorius'16]

prologue

- Specific solu al situations (various symmetries) & progress on linearized solutions
- Key role in astrophysical applications
- It should break but where & how? (what are DE/DM implying?)
- Exciting opportunities to test a still enigmatic theory and hopefully lead the way to its replacement. What/where/how test it?
- *Next few decades likely dominated by understanding dynamical solns*

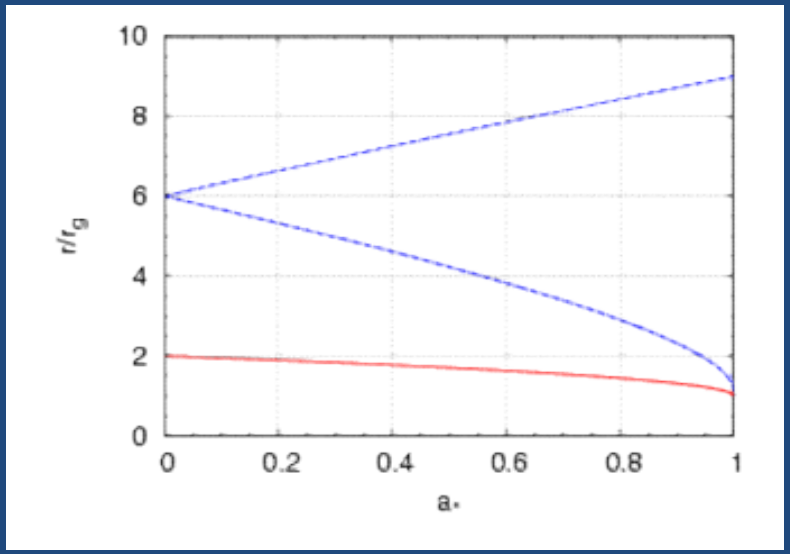
Different stages/different options

- Weak gravity?
- Weak interaction?
- Small departures from known (stable!) solutions?

- perturbative approach (PN, PM, EOB…)
  - Recast EEs with (v/c) and (M/L) as 'smallness parameters'
  - Internal structure effects ~ k $(R/M)^5$ $(v/c)^{10}$ [Damour]
  - … BHs have k=0 *[is this 'special' ?]*
  - The above may change outside GR, e.g. ST $(v/c)^6$!
  - Not good convergence properties as (v/c)~1, (M/L)~1… resummation approaches help [Damour-Buonanno +..]
- Point-particle arguments:
  - At $m_2/m_1 \rightarrow 0$, test particle on a BH background [we know this!, E, M + Carter constant determine orbits]
  - Can 'kludge' waveforms [Hughes+], 'adiabatically' changing parameters
  - To leading order, a BH with mass m_1 , spin a_1 will have a 'merger' (or plunge) at higher freqn for higher spin!

consequences/observations…

- Light ring freqn associated to frequency of QNM [but see Price-Khanna ‘16]
- While it sounds ‘cute’… no real ‘hangup’ effect
- Different BHs (i.e. in different theories) might have different ISCO/LR properties, could be used for testing them



- Measurement of spins!

- BH shadow, structure of null geodesics and accretion physics

[D. Psaltis and A. Broderick.]

Compact binaries?

- They explore all regimes
- They involve strongest fields/fastest speeds
- Modify spacetime curvature the strongest → strongest GW signals
- Affect surrounding ‘energy forms’ in the strongest way → strongest EM/particle signals. What’s involved to study them?

Pressing to general case: Anatomy of a binary merger (in GR)

4 stages: Newtonian, inspiral, plunge/merger, after-merger

Newtonian: $t_M < t_H$: *other physics is needed to induce merger*: dynamical friction, n-body encounters, etc.

Inspiral: energy/ang. mom. Loss through GWs is the dominant mechanism.

Perturbation techniques. Rely on: separation of scales! (v/c), M/R, etc

Perturbative to nonlinear and back

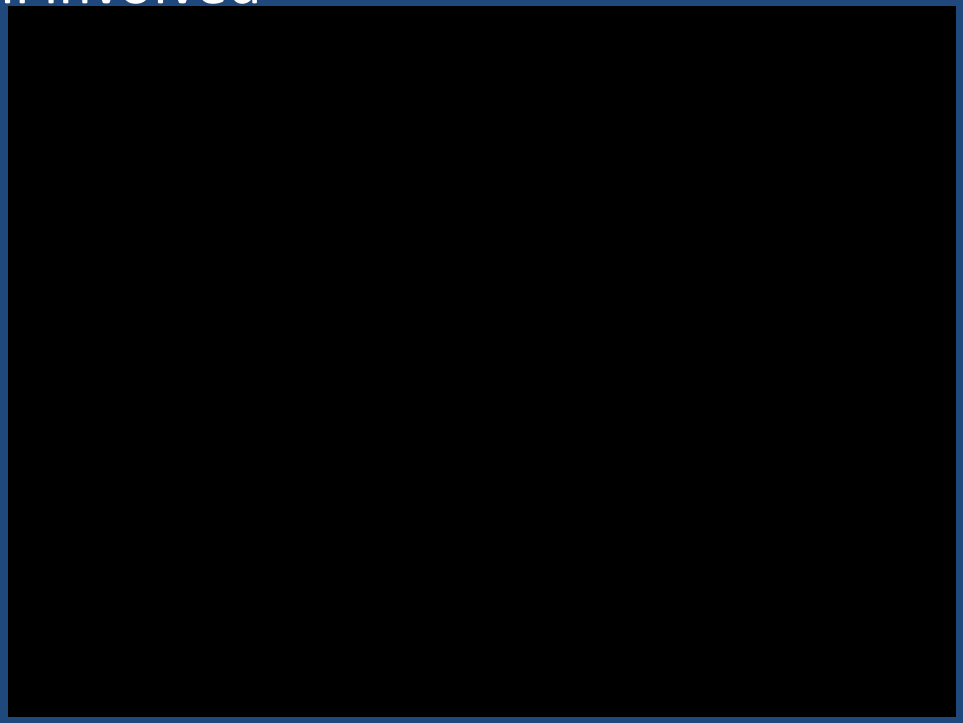
- During merger, v/c ~ 1 and objects have M/R ~ 1

→ Full solutions required, and in turn numerical simulations

- Access the truly non-linear regime of GR

"Using a term like nonlinear science is like referring to the bulk of zoology as the study of non-elephant animals." (Stanislaw Ulam)

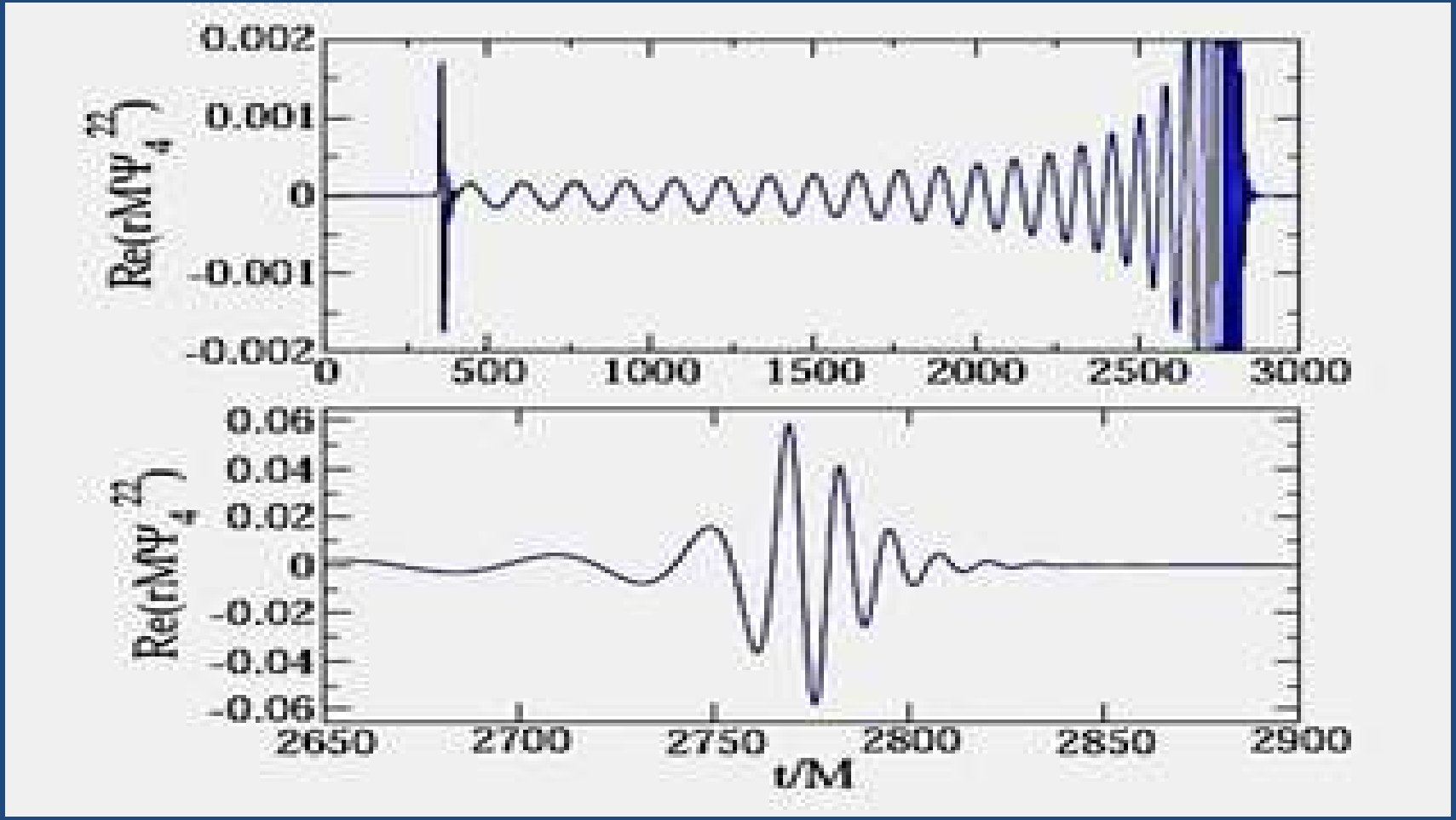
- *Merger/plunge:*
  - 2 black holes merge into one *if cosmic censorship holds.*
  - 2 NS will form another one which may collapse to a BH
  - BH-NS. The BH will disrupt or swallow the NS depending on typical radii involved



[credit SXS]

- *After merger:* use BH perturbation → decaying oscillations

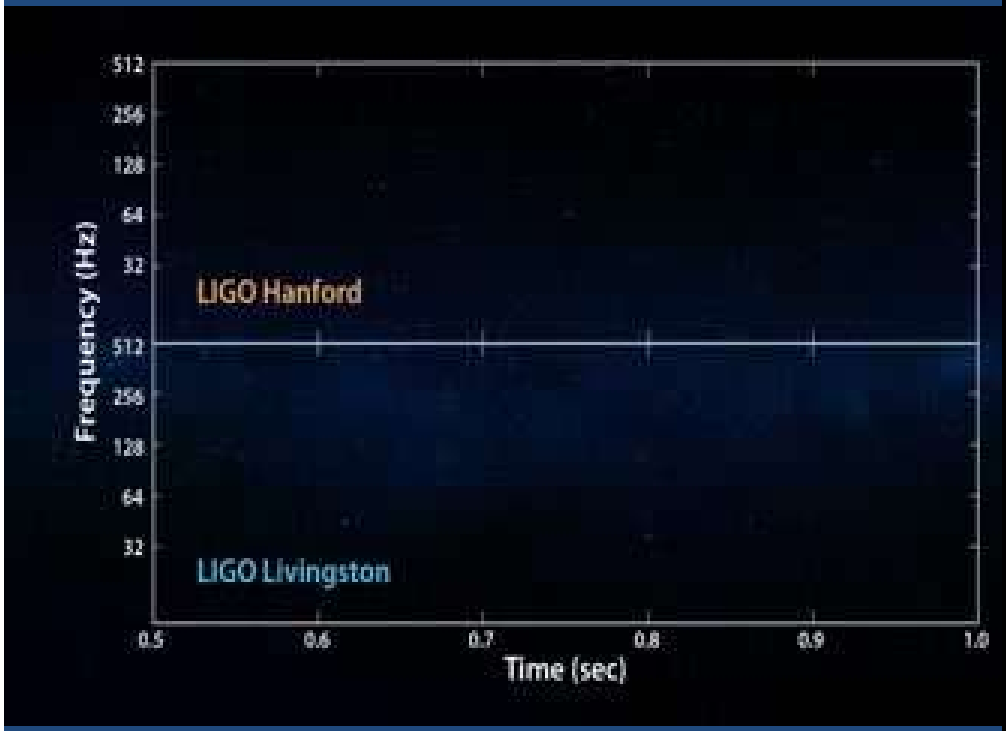
Anatomy of 'theoretical' BBH signal

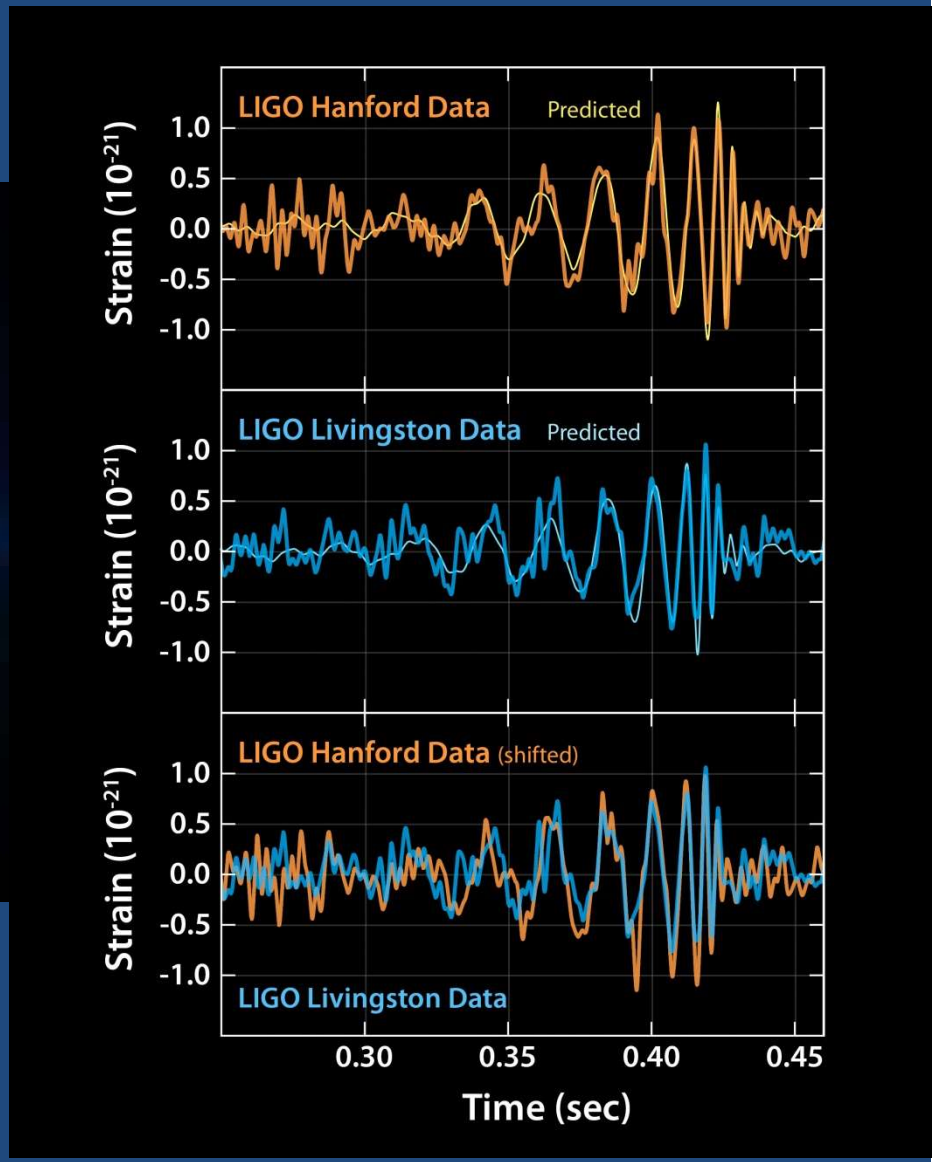


Energy radiated ~ 3- 12 % of total mass

Direct GW detections started…

September 14, 2015

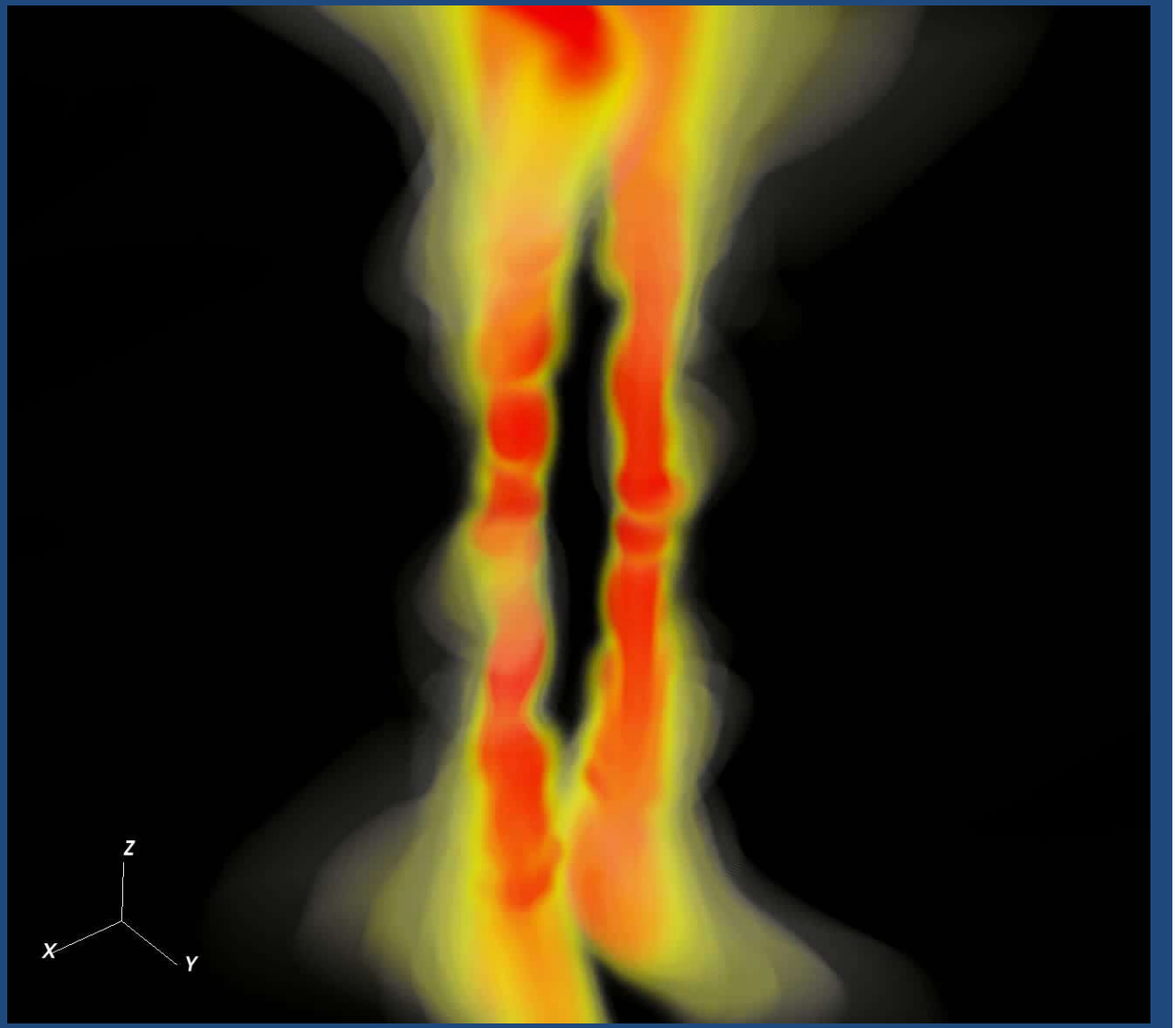




BH-BH (sims) main outcomes/surprises

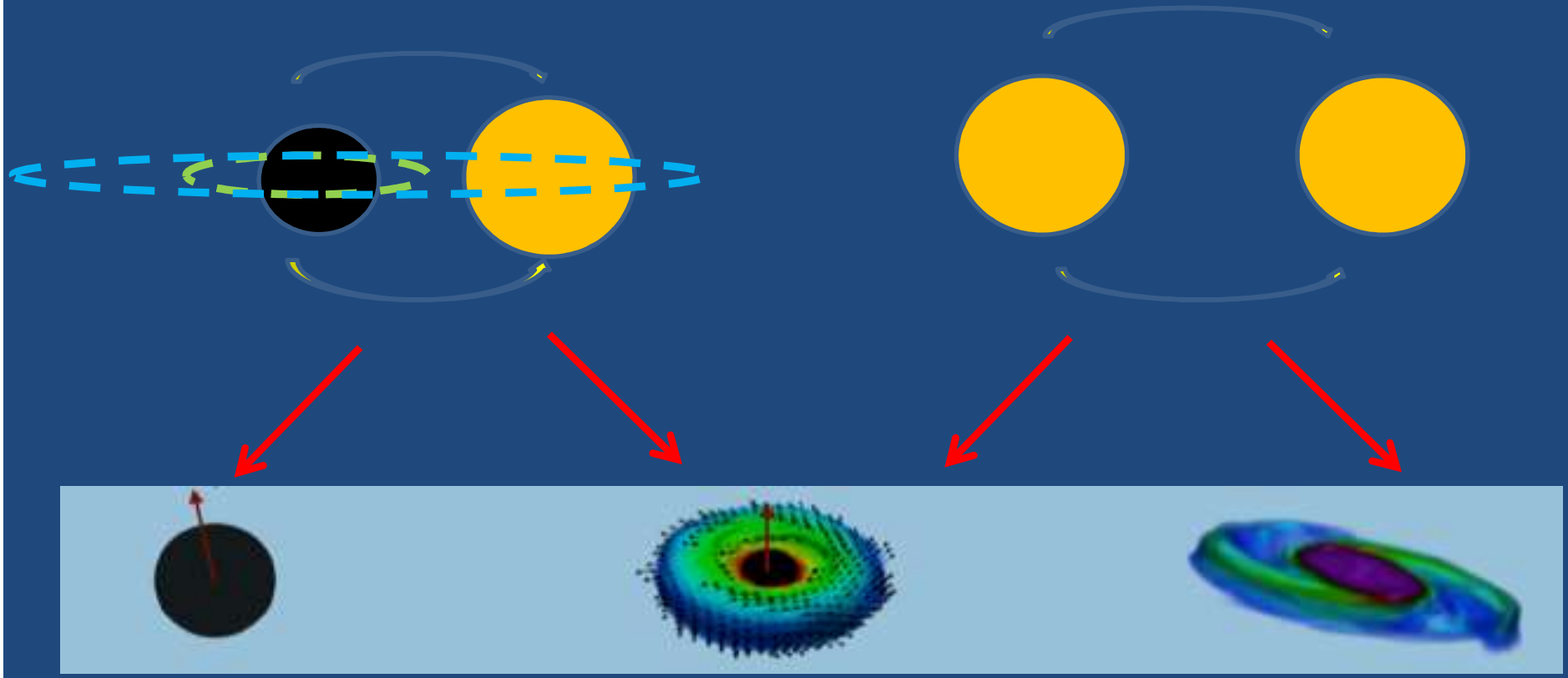
- @ largest strain! two 10 M_O BHs at 10Mpc $\Delta L/L \sim 5\ 10^{-17}$
- Peak luminosity 1/100th of Planck Lum of 10^{59} erg/s
- Very efficient mass-to-energy conversion: ~3 – 12 % M_{total}
- Very large recoils of final object possible ~ several 1000s km/s. → large enough to induce:
  - Galaxies without BHs
  - Offset AGNs
  - Off-centered TDEs….
  - (may be nature doesn't like these configurations!)

Affecting plasma….



[Palenzuela + ‘10]

Smashing stars: What's the possible outcome?



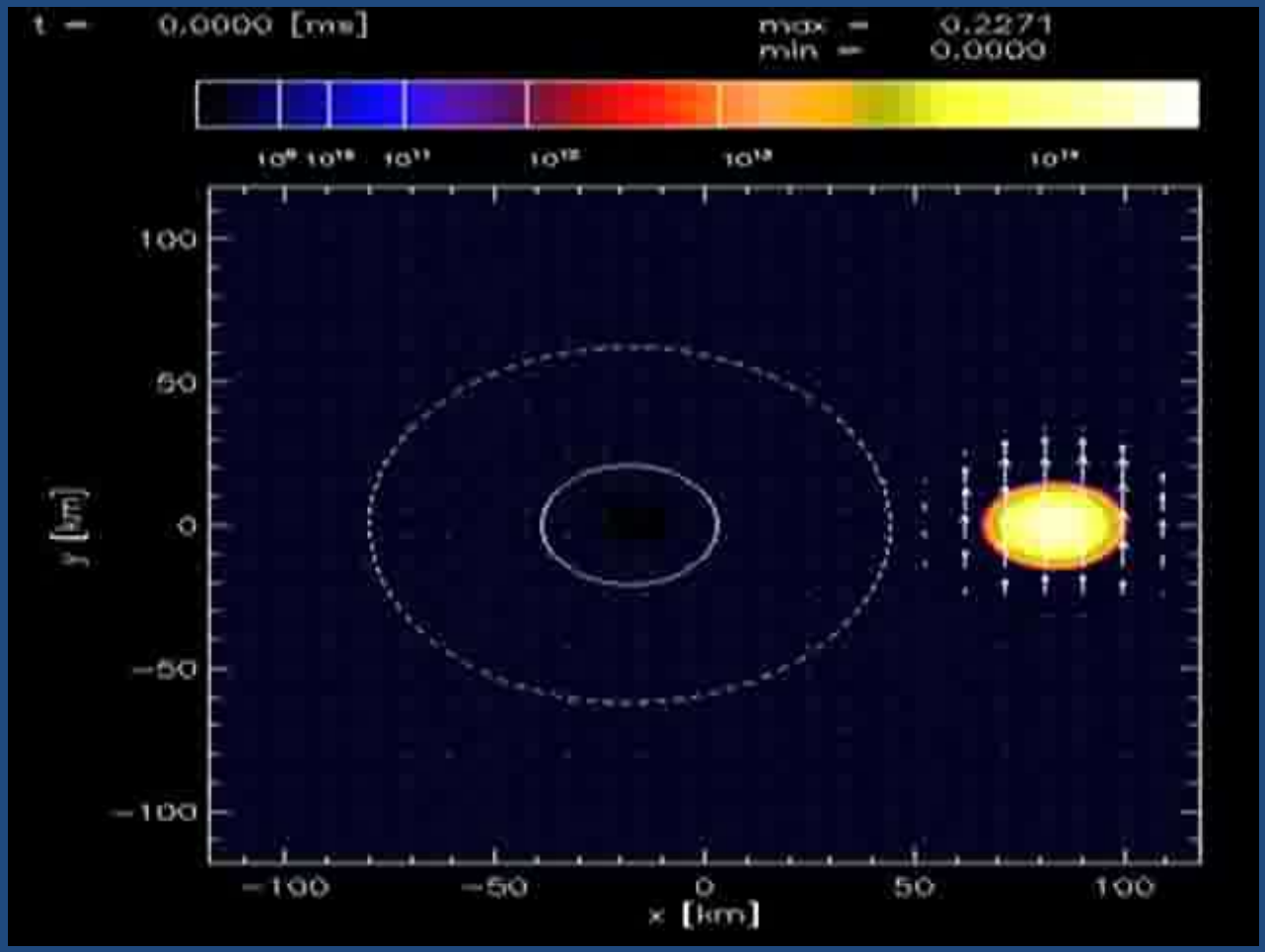
Low spin/high mass, small radius → direct plunge.
No sGRB, but could still shine?

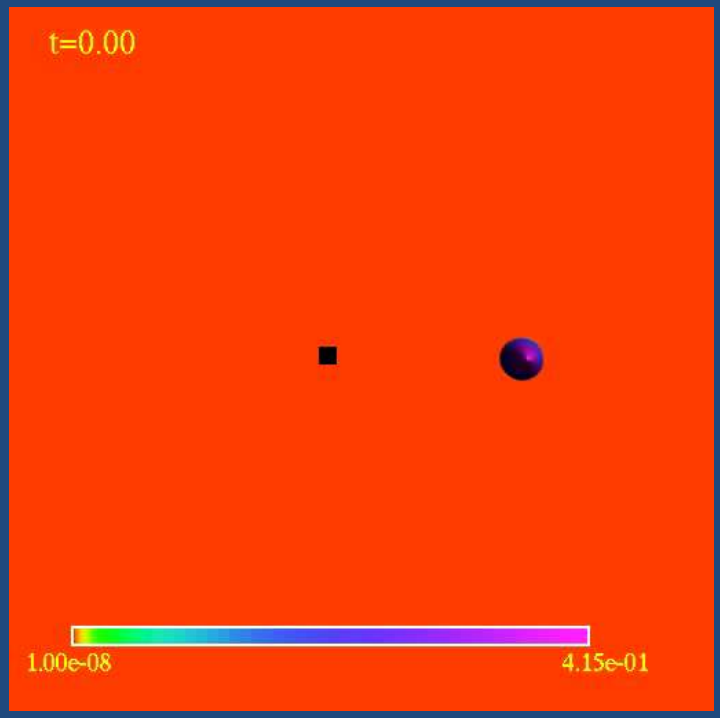
BHNS: High spin/low mass, large radius → disruption.
NSNS: $M_{tot} > 1.3\text{-}1.5\ M_{max}$
'comfortable' disk mass
GW: with a clear cutoff

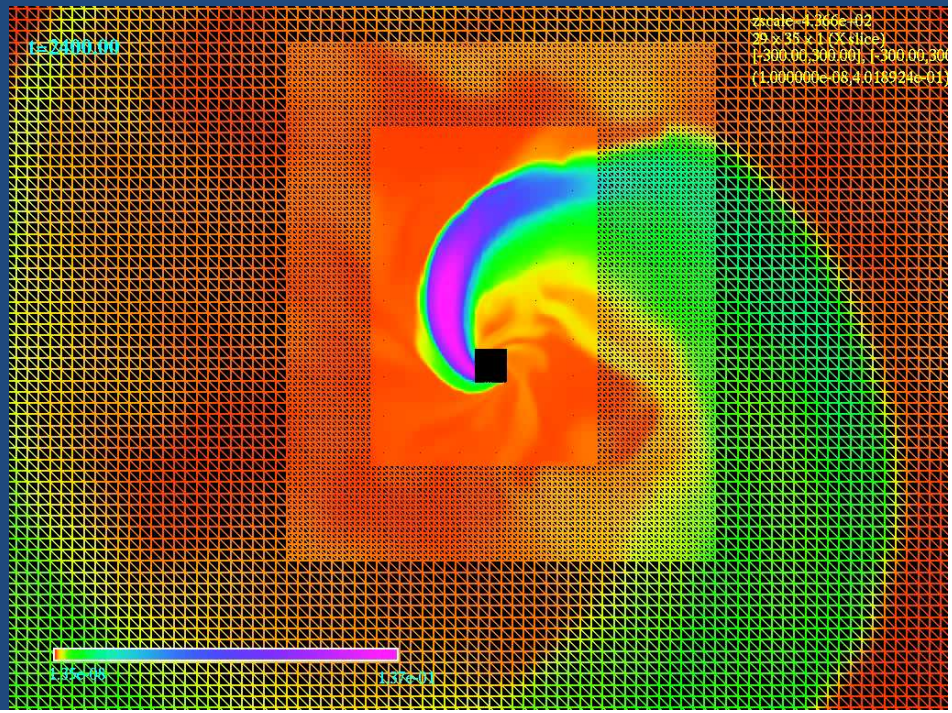
NSNS: $M_{tot} < 1.3\text{-}1.5\ M_{max}$
GW: postmerger signal
sGRB from 'sufficiently' magnetized MNS?

BH-NS

(somewhere in between…)

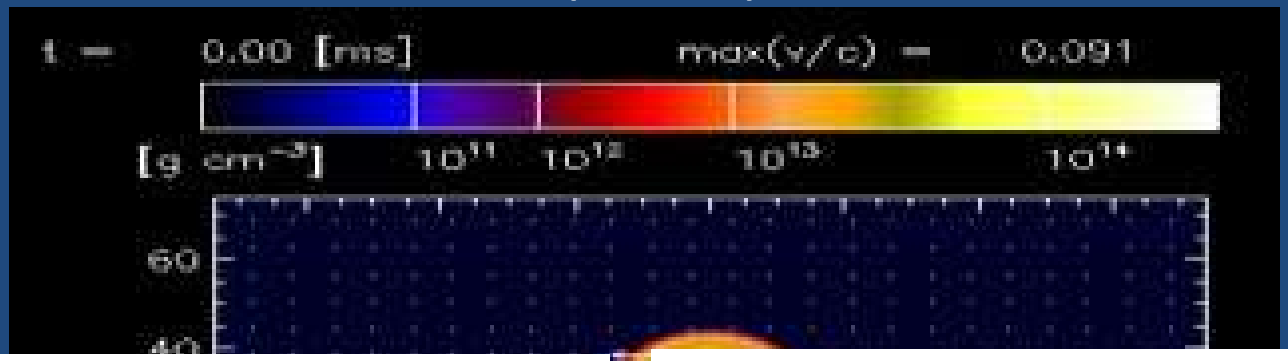


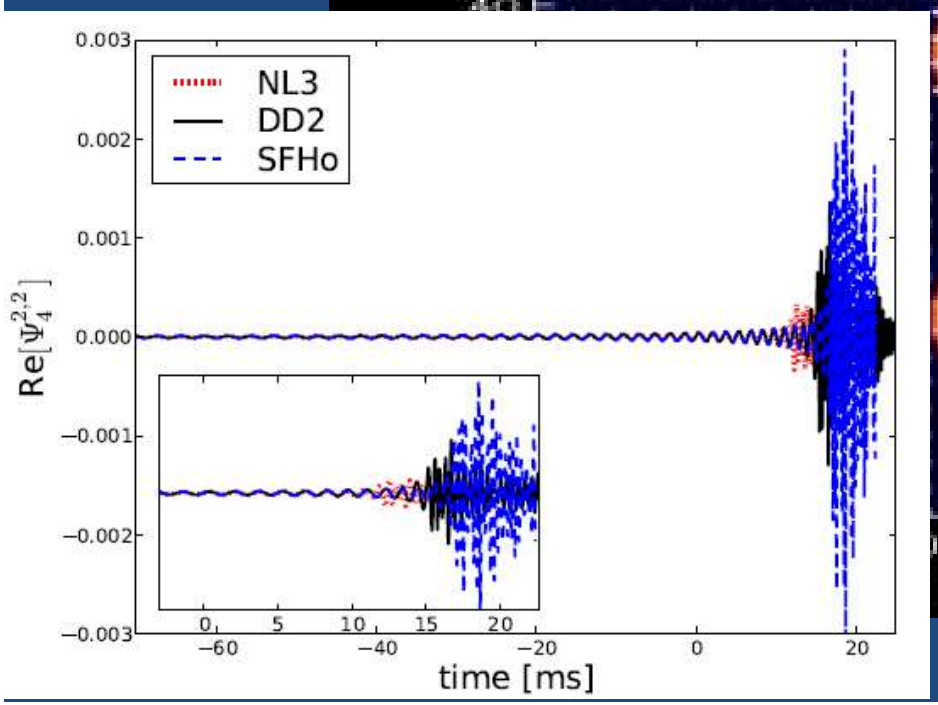

t=0.00
1.00e-08
4.15e-01

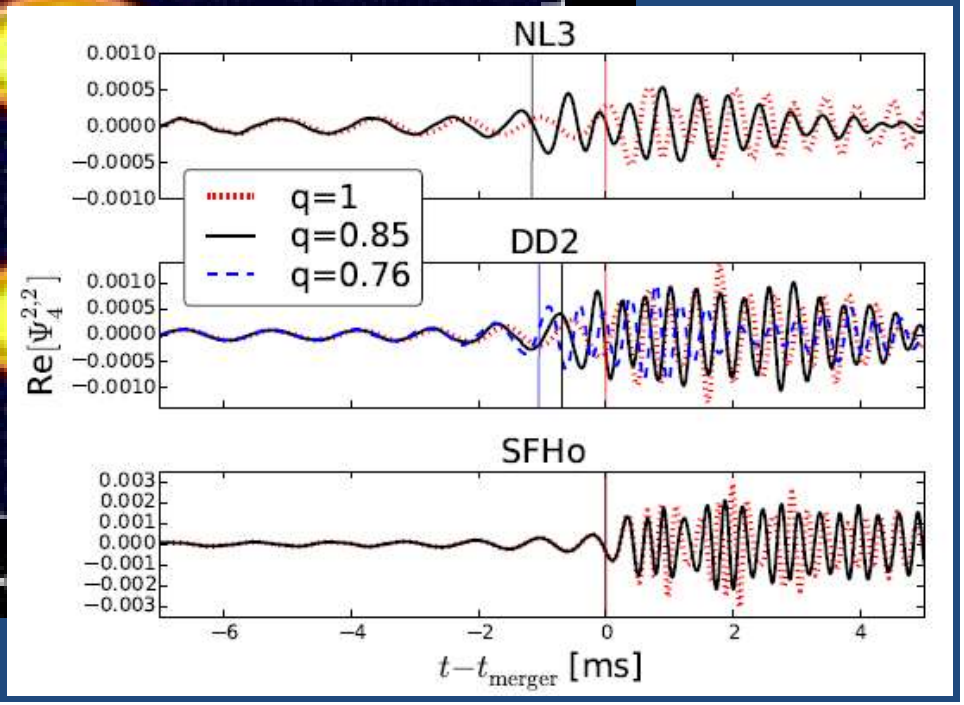


NSNS

- In principle… no-rescaling of mass possible, though constrained masses
- Recall tidal effects at 5PN (in GR)

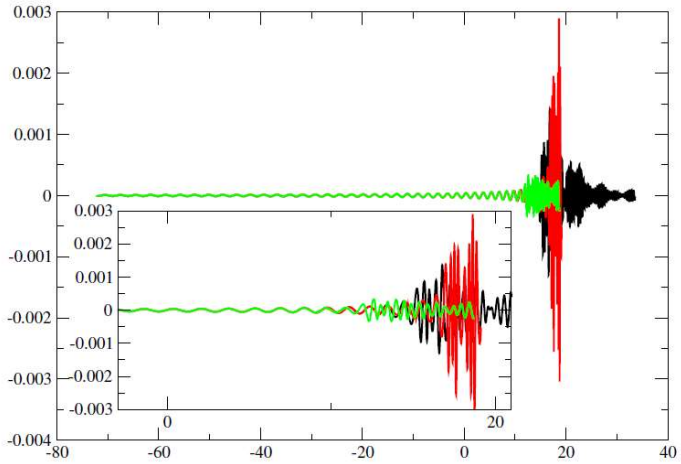


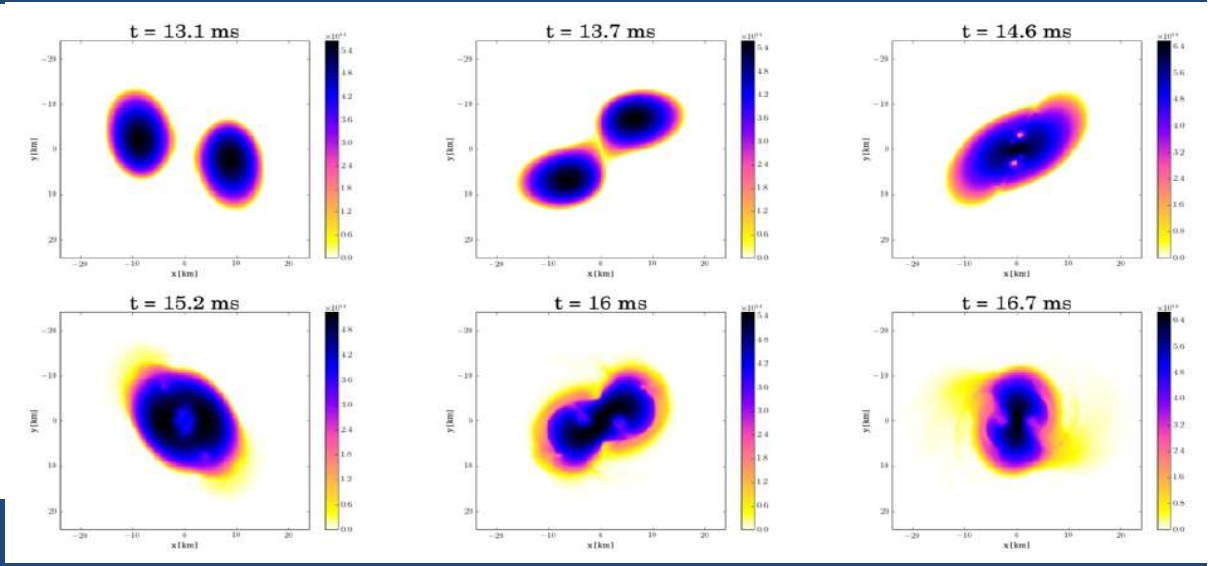


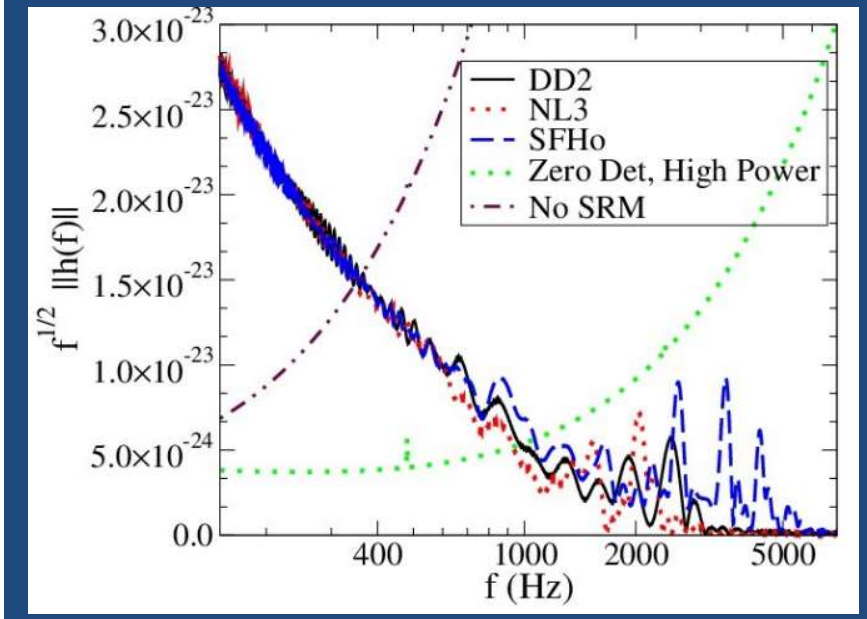


Affecting plasma….

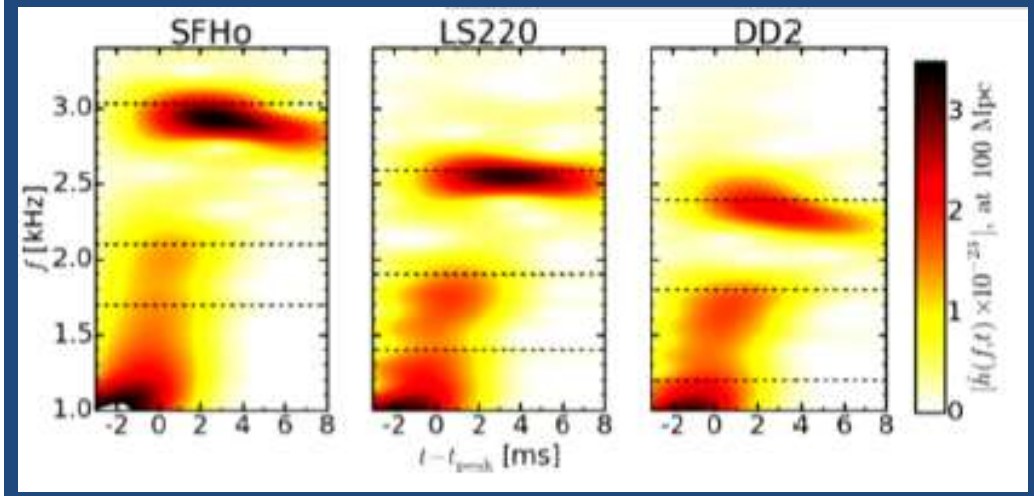
Cold matter at high densities, EoS?…





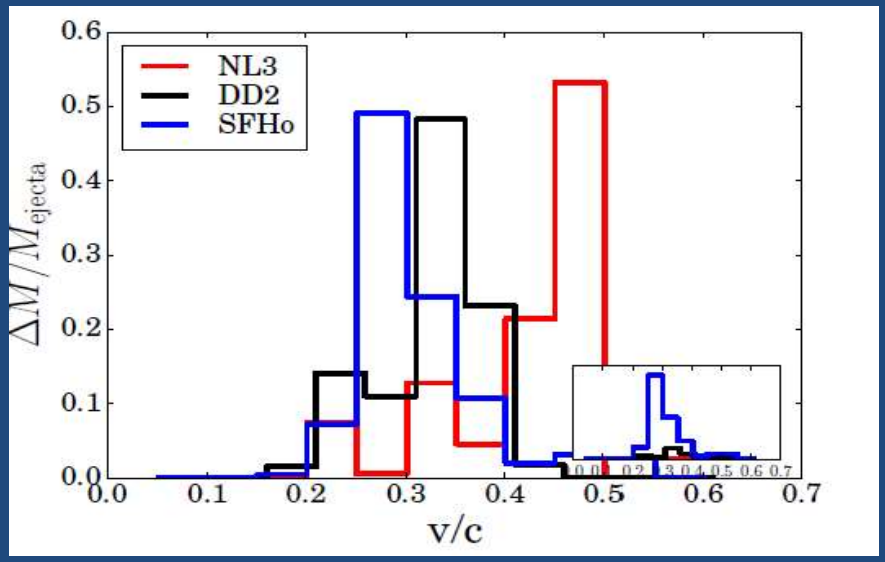


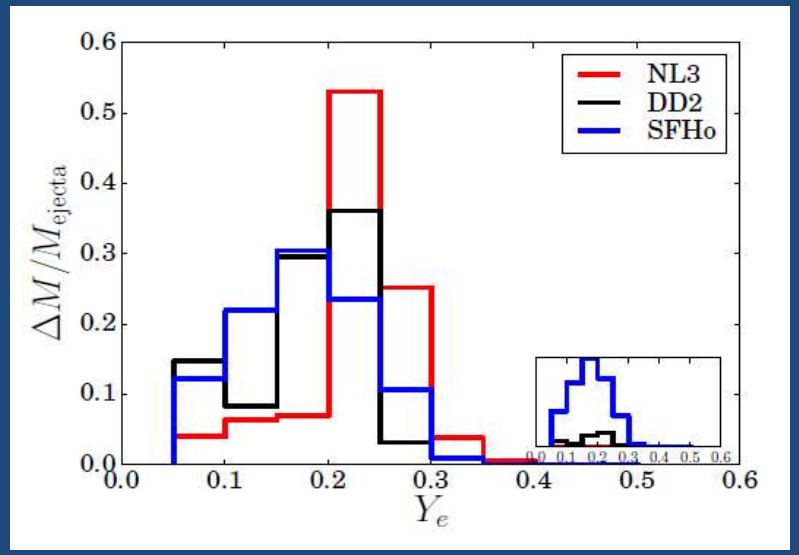
[Palenzuela,LL,Liebling,Neilsen,Caballero ‘15]

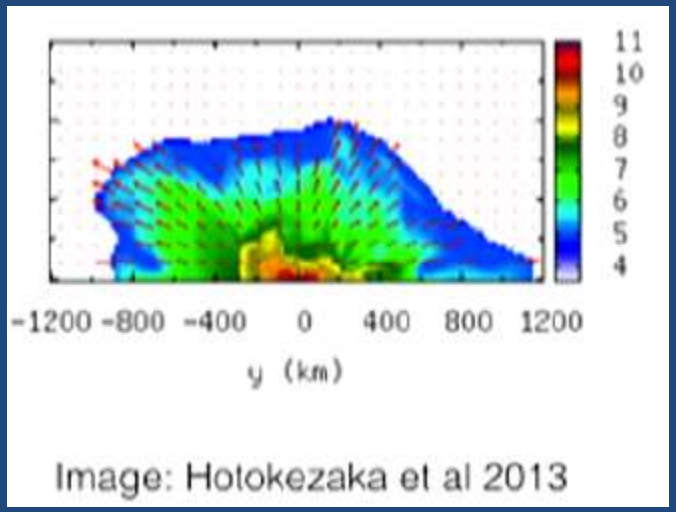


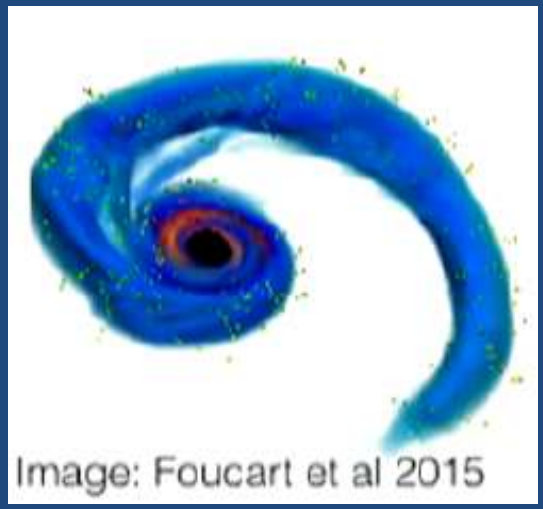
[Foucart etal ’15]

Ejecta & properties









- Also, other ejecta from winds driven by the eventual accretion disk is possible, though this is less neutron rich [Fernandez etal ‘15] and expected signal would be in the optical.

These lectures/this week…

- We will dig somewhat deep into what's involved in studying these systems and address the richer set of physics ingredients (when comparing with bbh that is) required.
- We will discuss analytical and computational issues encountered and ideas of how to face them
- We will examine 'building' blocks from a physical point of view
- We will have some exercises in the afternoon, they are open ended but try and do some of them!
- Participate! Things will be more fun if you do!