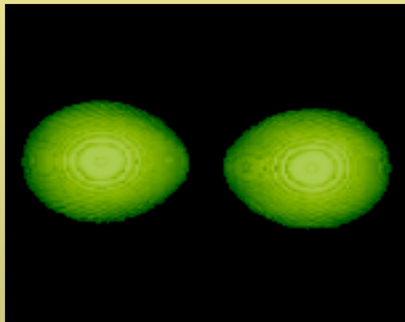
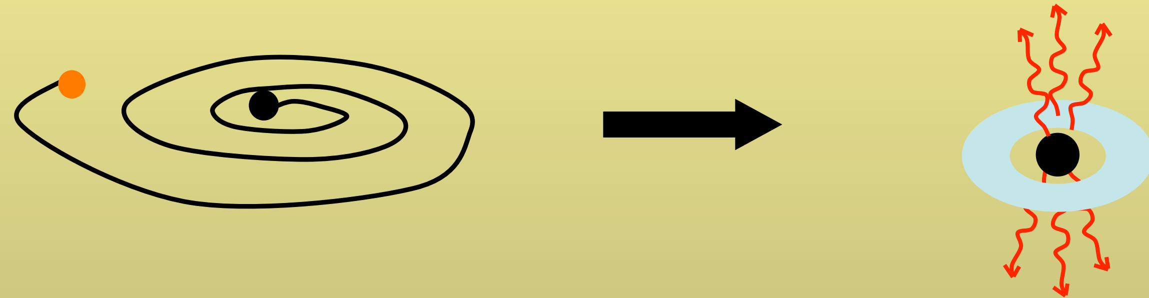
Electromagnetic Counterparts To Binary Mergers In the Gravitational Wave Era

Rosalba Perna

(Stony Brook University)

Binary (NS-NS and NS-BH) Mergers are naturally expected to be accompanied by Electromagnetic Counterparts





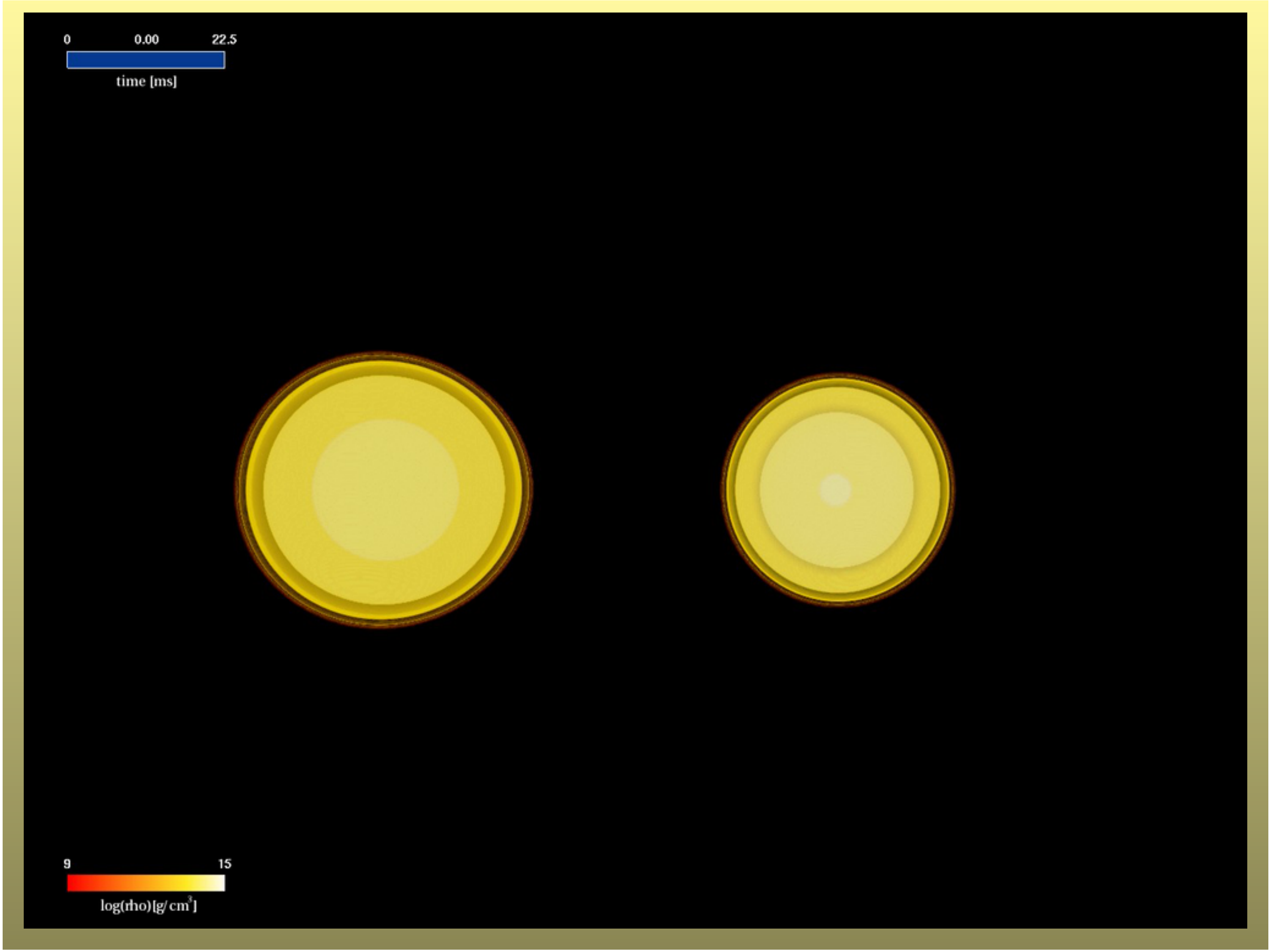
Likely already observed as Short GRBs

Corroborative pieces of evidence:

- No SN ever found associated with a short GRB
- energies a factor of 10 or more lower than for long GRBs
- generally associated with early type galaxies, with low star-formation, unlike long GRBs, associated with regions of high star formation.
- average redshift lower than for long GRBs
- Timescales!

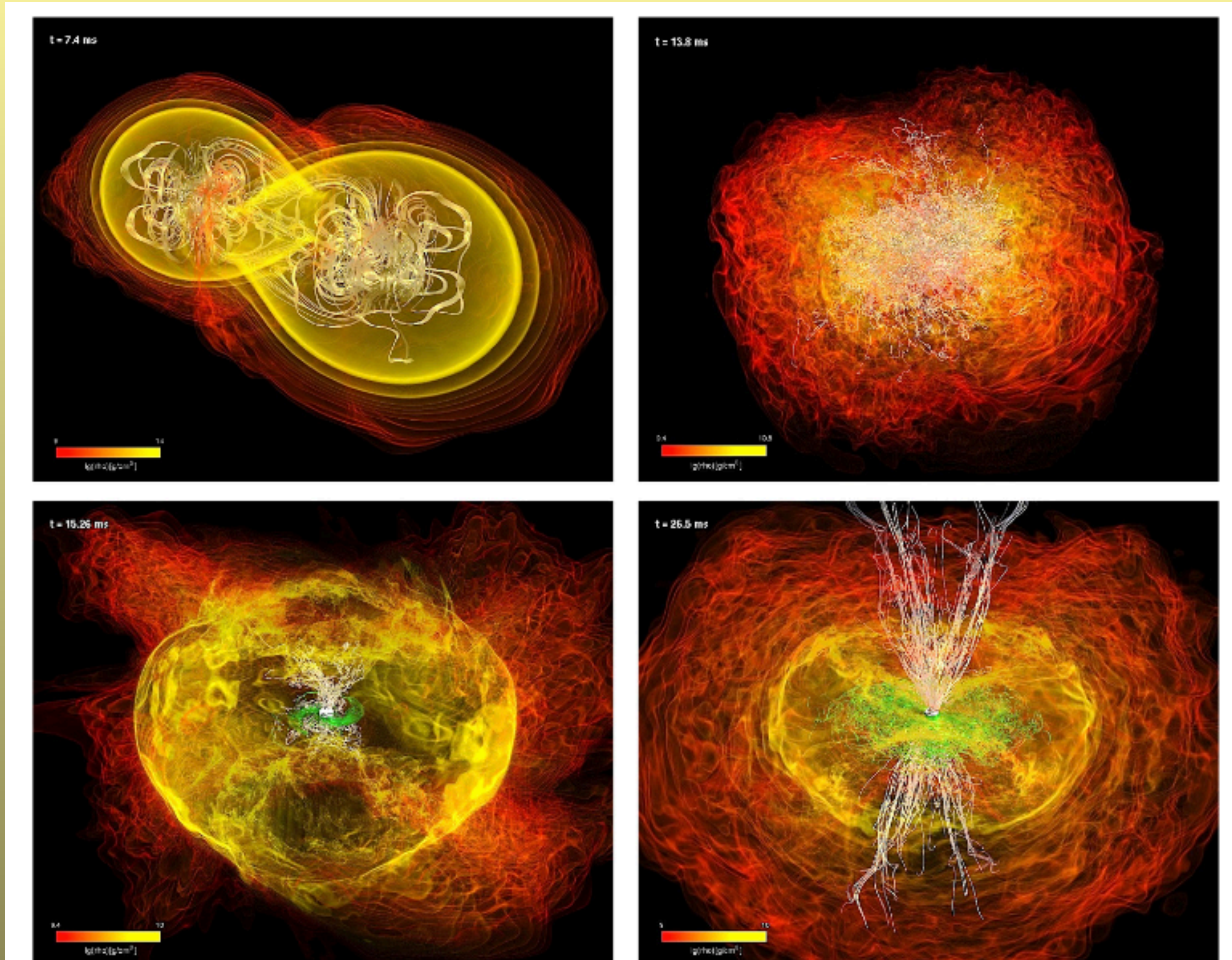
SHORT GRBs – connection with binary mergers supported by numerical simulations [e.g. Sekiguki et al 2011; Rezzolla et al 2011; Bauswein & Janka 2012; Etienne et al 2012; Palenzuela et al 2013; Deaton et al. 2013; Paschalidis et al. 2013; Read et al. 2013; Hotokezaka et al. 2013; Rosswog et al 2013; Bauswein et al 2014; ………]

Following movie:
Visualization by Giacomazzo, Koppitz, Rezzolla with data by Rezzolla et al. (2010)



0
0.00
22.5
time [ms]
9
15
log(rho)[g/cm^3]

Evidence for possible formation of a jet [Rezzolla et al. 2011]



Evidence for possible formation of a jet [Ruiz et al. 2016]

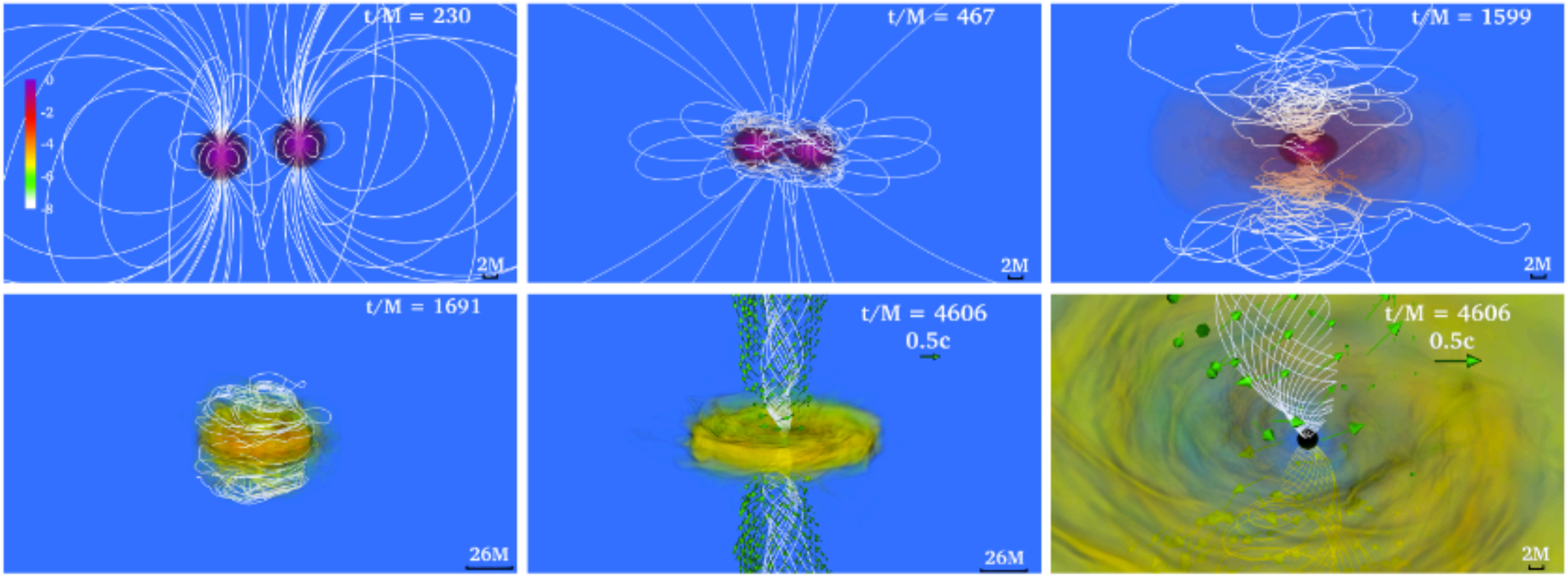


FIG. 1.— Snapshots of the rest-mass density, normalized to its initial maximum value $\rho_{0,\max} = 5.9 \times 10^{14}(1.625\,M_\odot/M_{\rm NS})^2$ g cm^{-3} (log scale), at selected times for the P case. The arrows indicate plasma velocities, and the white lines show the B-field structure. The bottom middle and right panels highlight the system after an incipient jet is launched. Here $M = 1.47 \times 10^{-2}(M_{\rm NS}/1.625M_\odot)$ ms = $4.43(M_{\rm NS}/1.625M_\odot)$ km.

Organized B-field structure also seen in GRMHD simulations by Kawamura et al (2016), independently of EOS, mass ratio, and initial magnetic field orientation

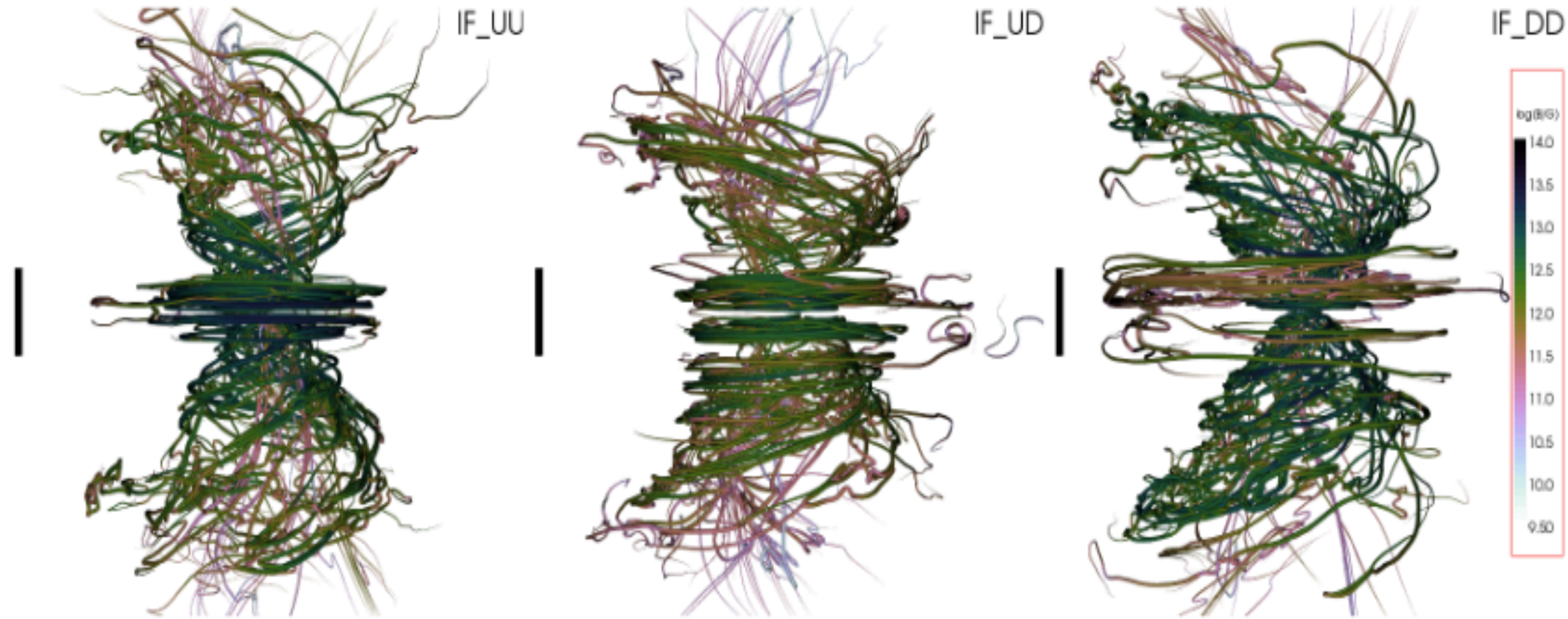
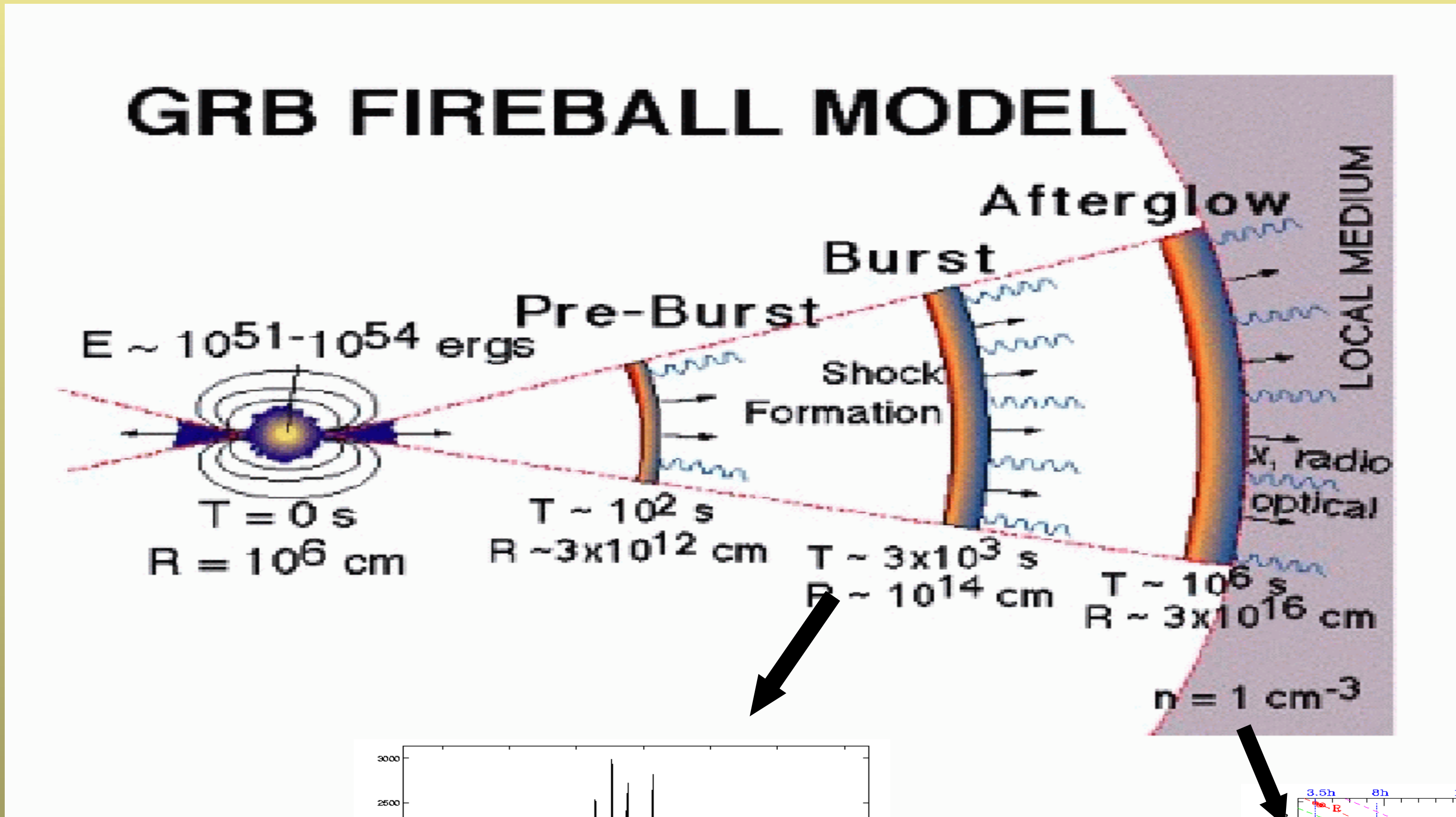
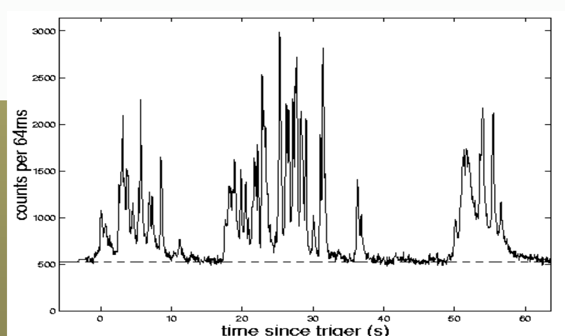
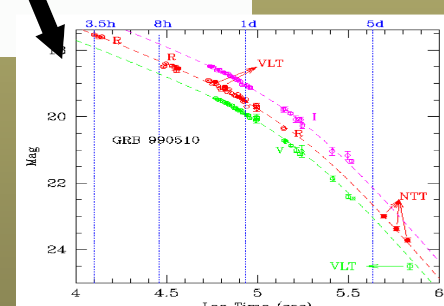


FIG. 9. Magnetic field structure 35 ms after the merger, comparing models IF_q10_UU, IF_q10_UD, and IF_q10_DD. The black bars provide a length scale of 20 km. The coloring of the fieldlines indicates the magnetic field strength ($\log_{10}(B\,[\mathrm{G}])$, same colorscale for all models) along the lines. However, for quantitative results see Fig. 10.

Jet propagation → Shock Formation → Afterglows





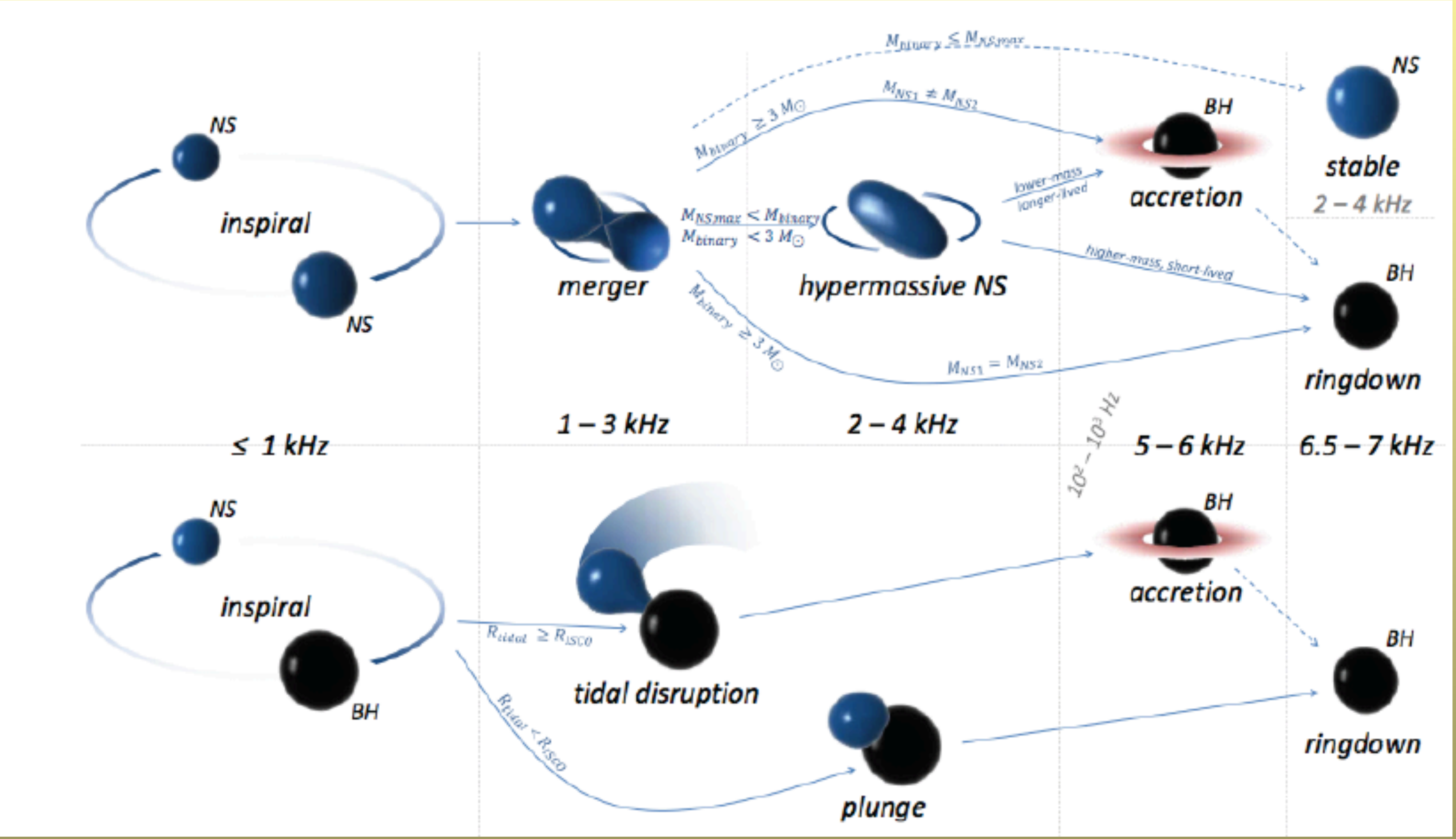


Gravitational Wave counterparts of binary mergers

(special focus on NS-NS mergers, which have a richer phenomenology of outcome products)

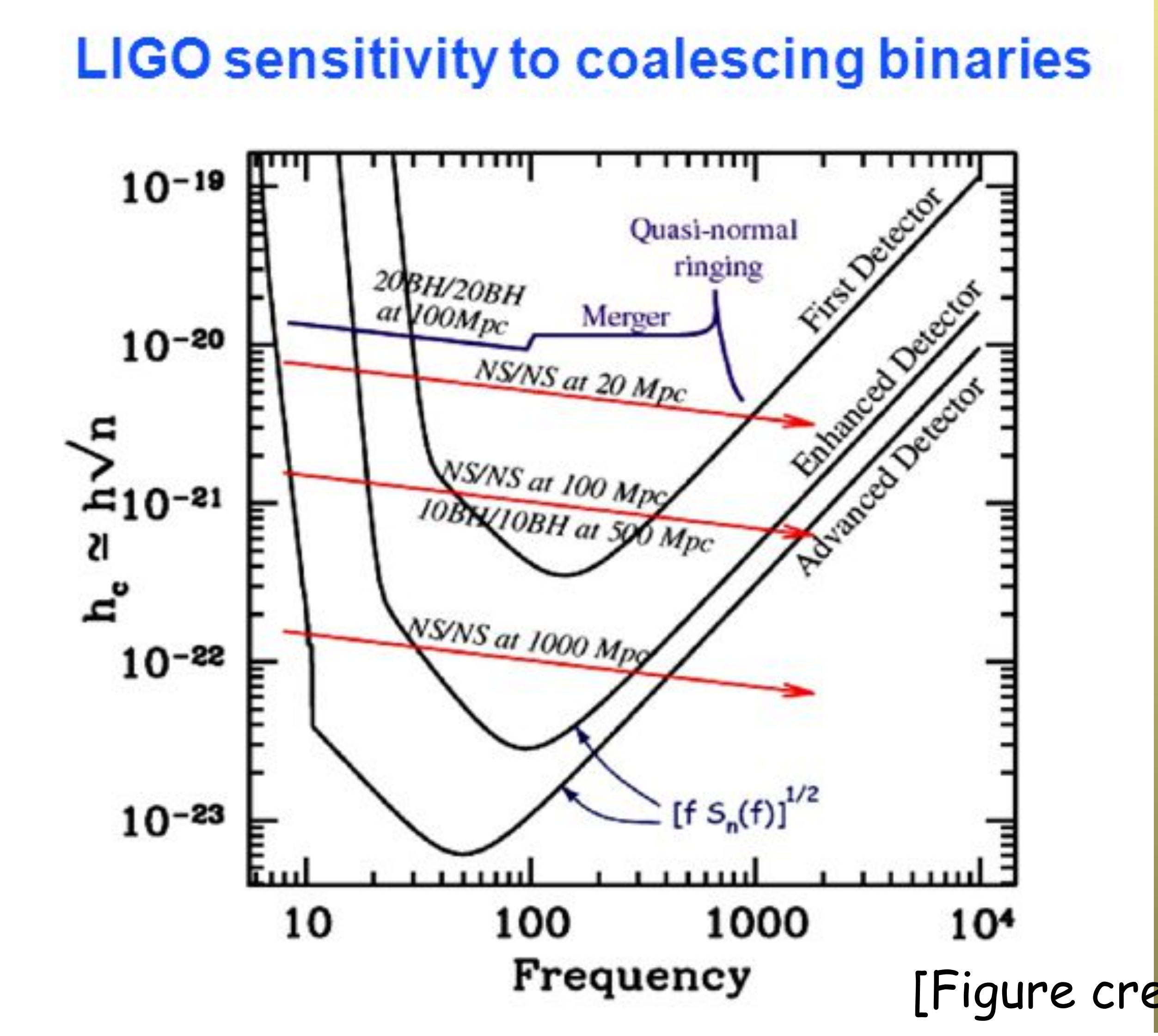
GWs from Binary Mergers

[Bartos et al. 2013]



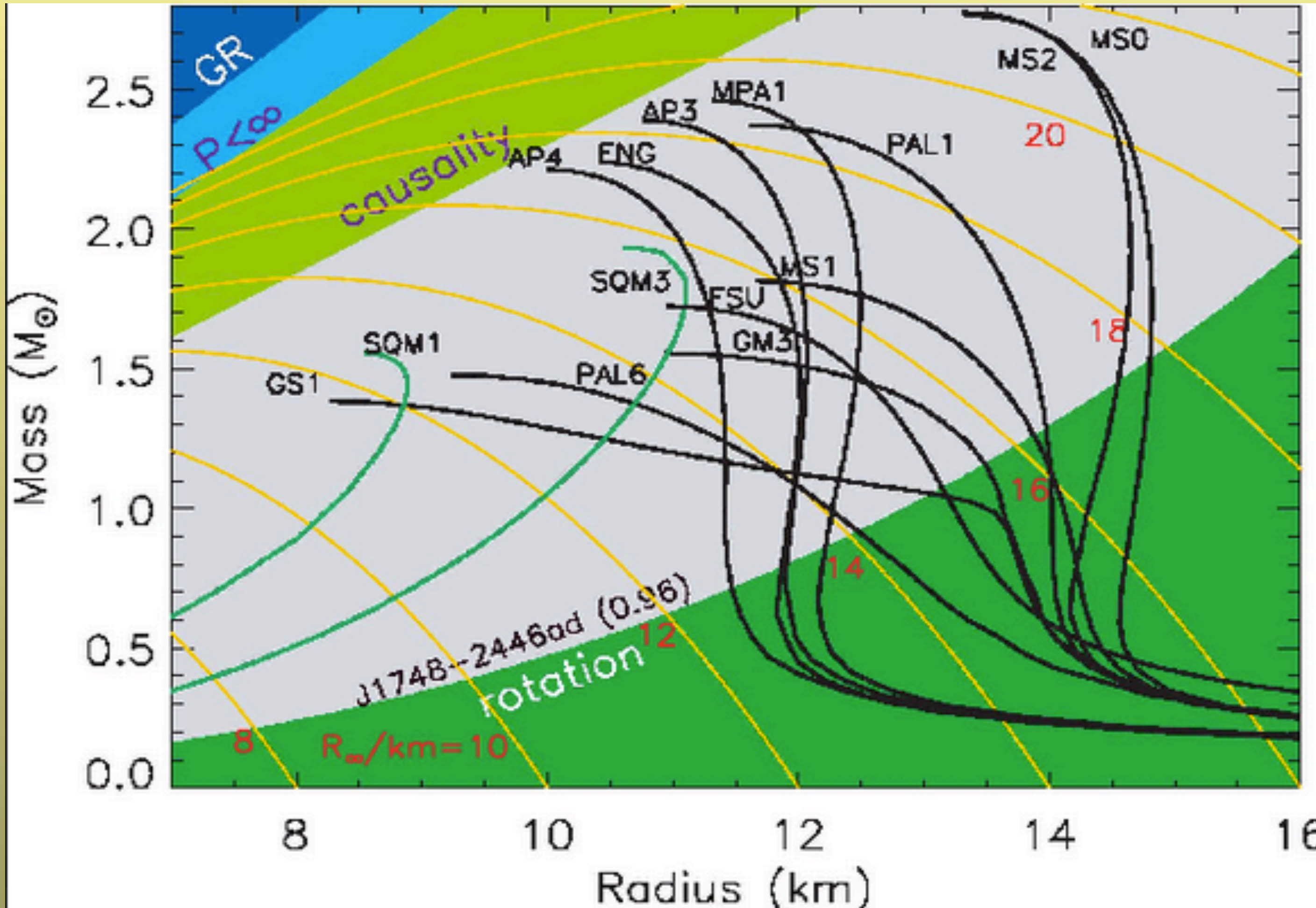
GW emission associated to various phases of the merger

Signal for NS-NS (and NS-BH) smaller than for BH-BH, but potentially *very informative*



[Figure credit: B. Barrish]

The Holy Grail of the *Equation of State (EOS) of Neutron Stars*

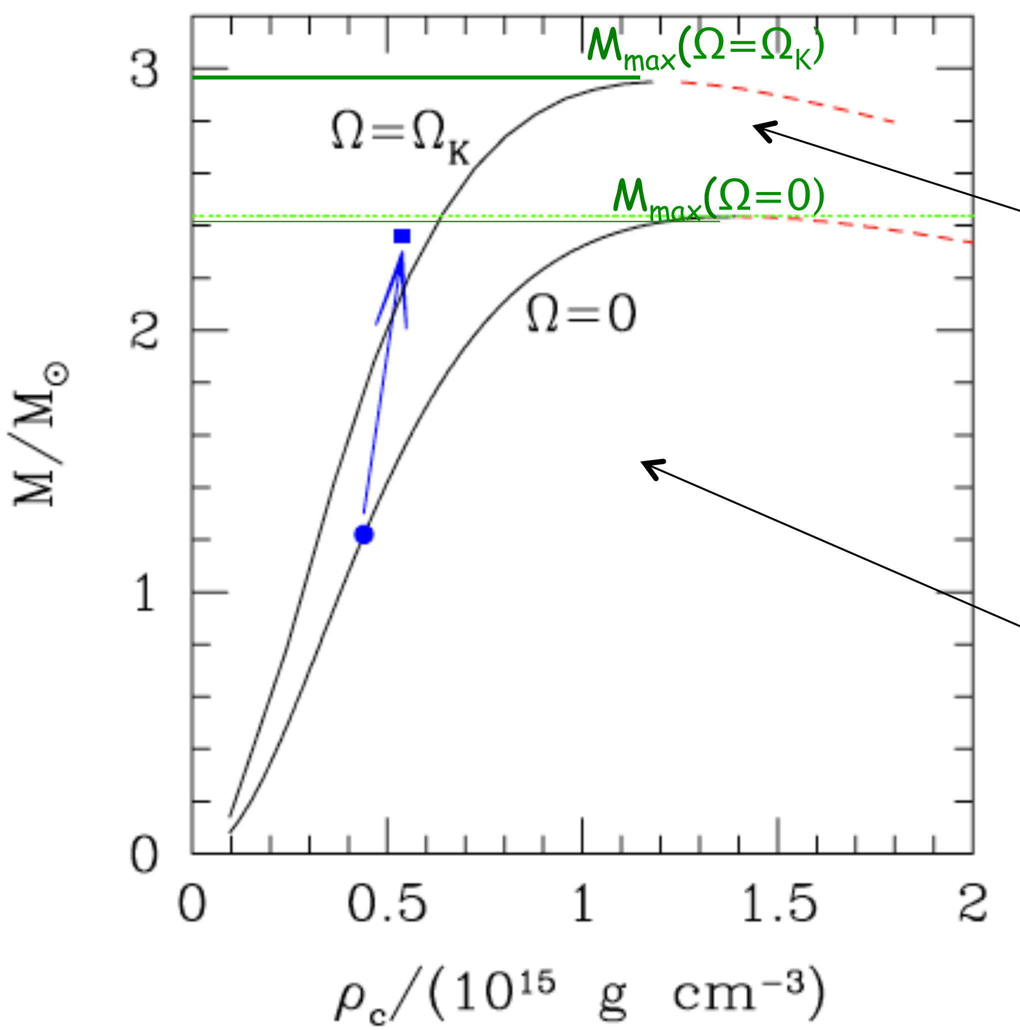


[Lattimer & Prakash 2007, 2015]

'Traditional' methods aim at direct measurements of Mass (Keplerian motion) and Radius (size of emitting region, PFs)

Gravitational waves open a new 'window' to the problem

What happens when two neutron stars merge?



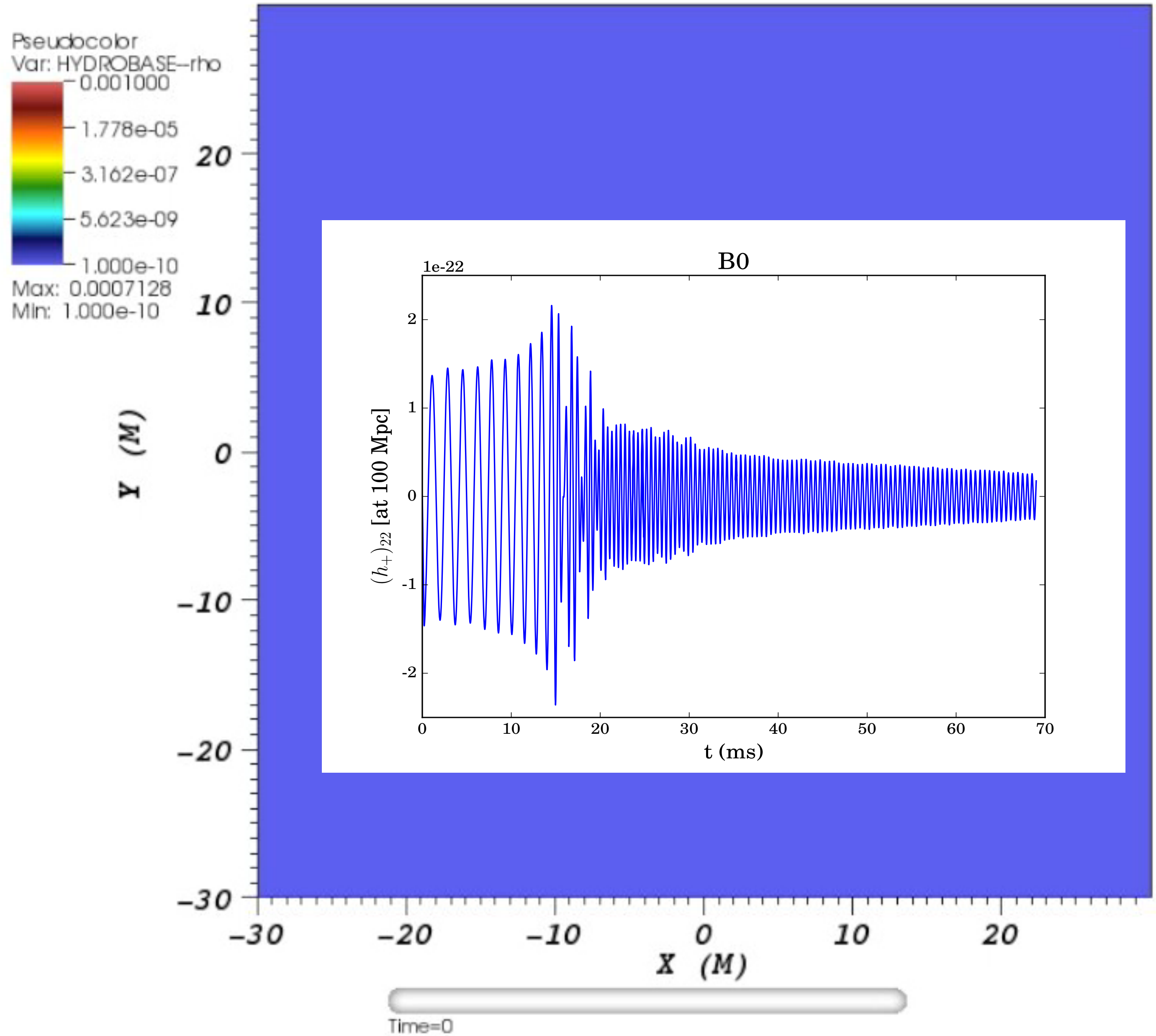
It depends…. but in a way which is sensitive to the NS EOS

Supramassive NS:
collapsing to a Black Hole after slowing down, at the point at which $M_{NS} = M_{max}(\Omega)$

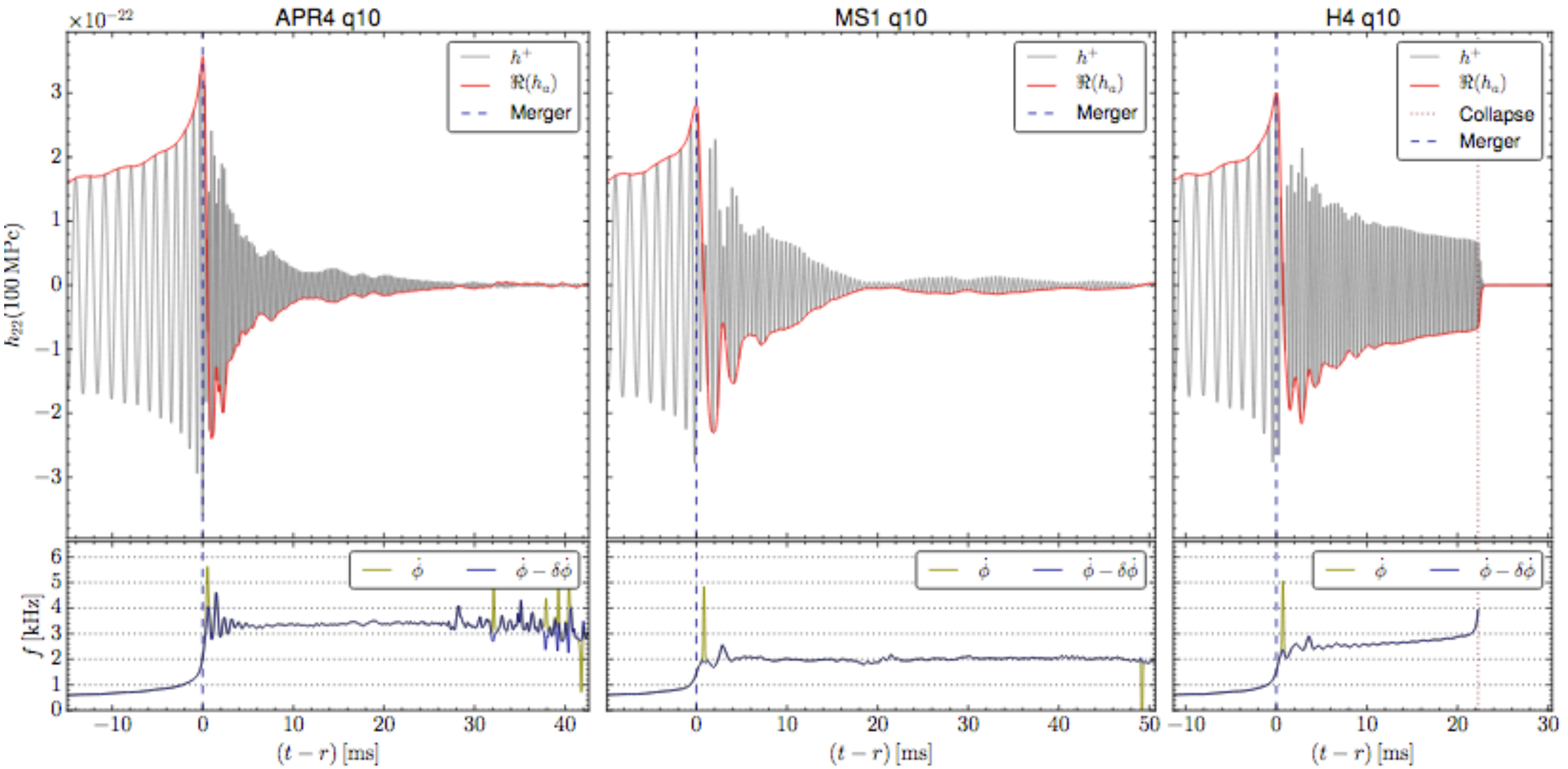
Stable NS

GWs bear imprint of NS EOS – compute with GRMHD simulations

[Giacomazzo & Perna 2013]



[Giacomazzo & Perna 2013
simulations with Whisky/MHD]



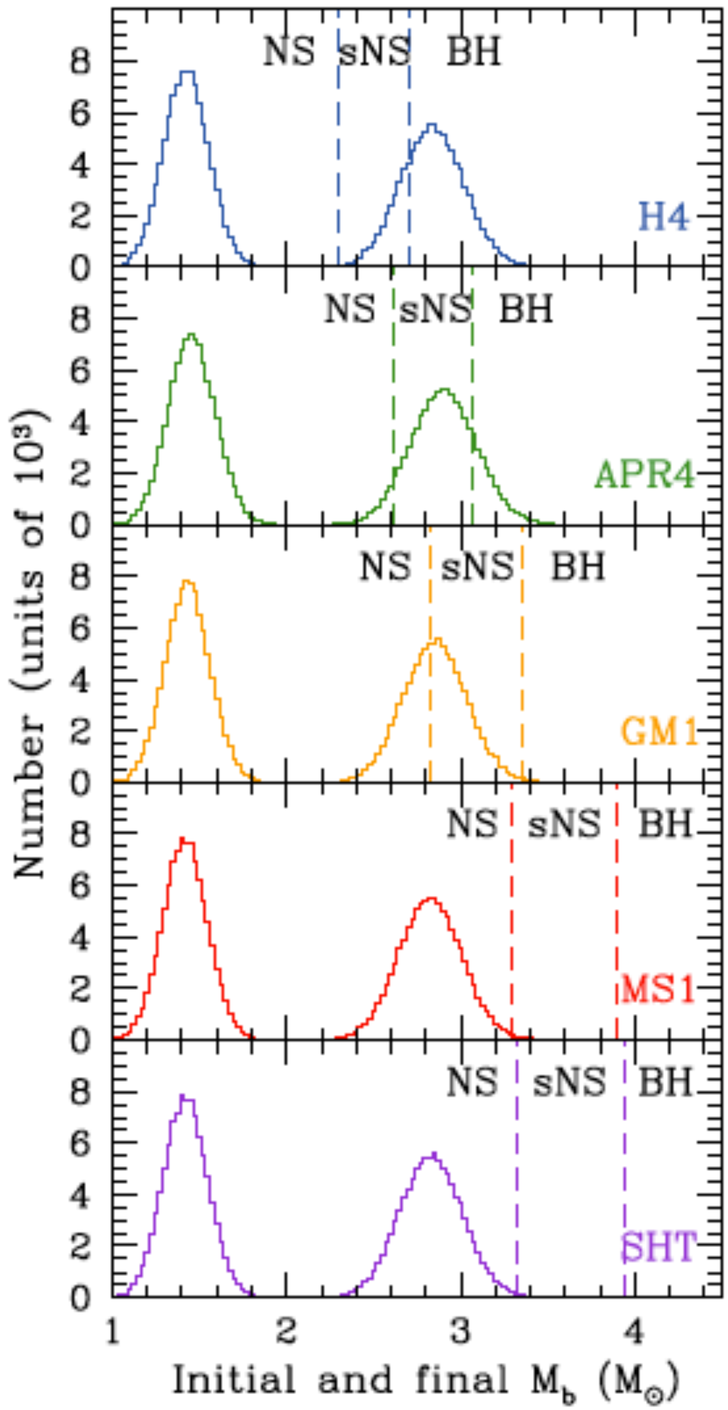
[Ciolfi et al 2017]

GW signal sensitive to equation of state of neutron stars

→ Merger of NSs probe physics of dense matter

Can we still learn something
from SGRBs + GWs
on the NS EOS without
measuring the detailed signal?

Dominant post-merger oscillation frequency can be measured only for merger events within about 20 Mpc
[Clark et al. 2014; Bauswein 2015]



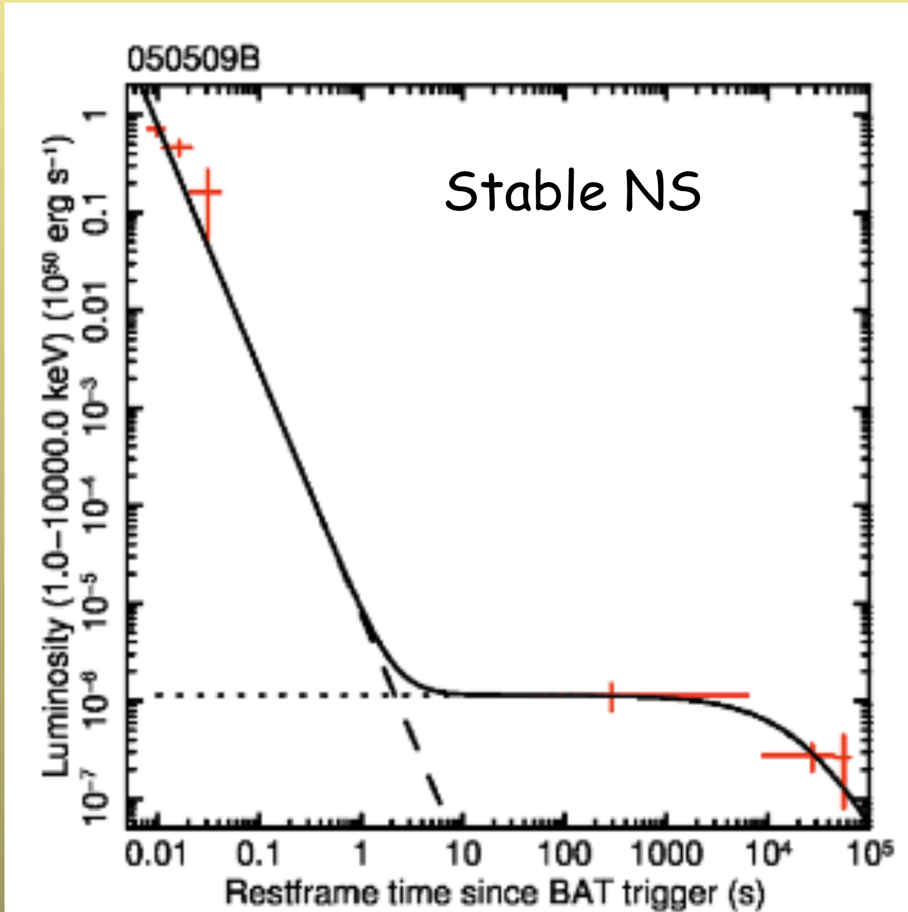
Predictions for distributions of remnants based on the observed distribution of NS in binaries

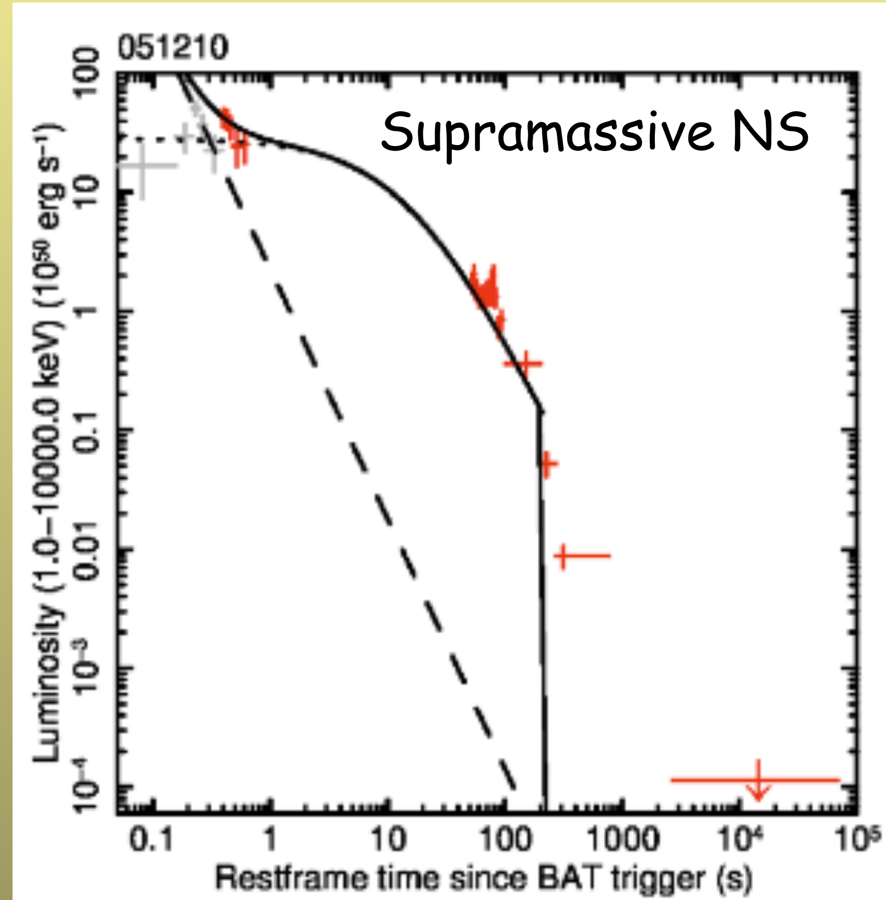
Fraction of outcome products (stable NS, supramassive NS, BH) highly dependent on the EOS of the NS

Simply identifying the remnant product in a fraction of merger events can constrain the NS EOS: both GWs and EM counterparts helpful for that.

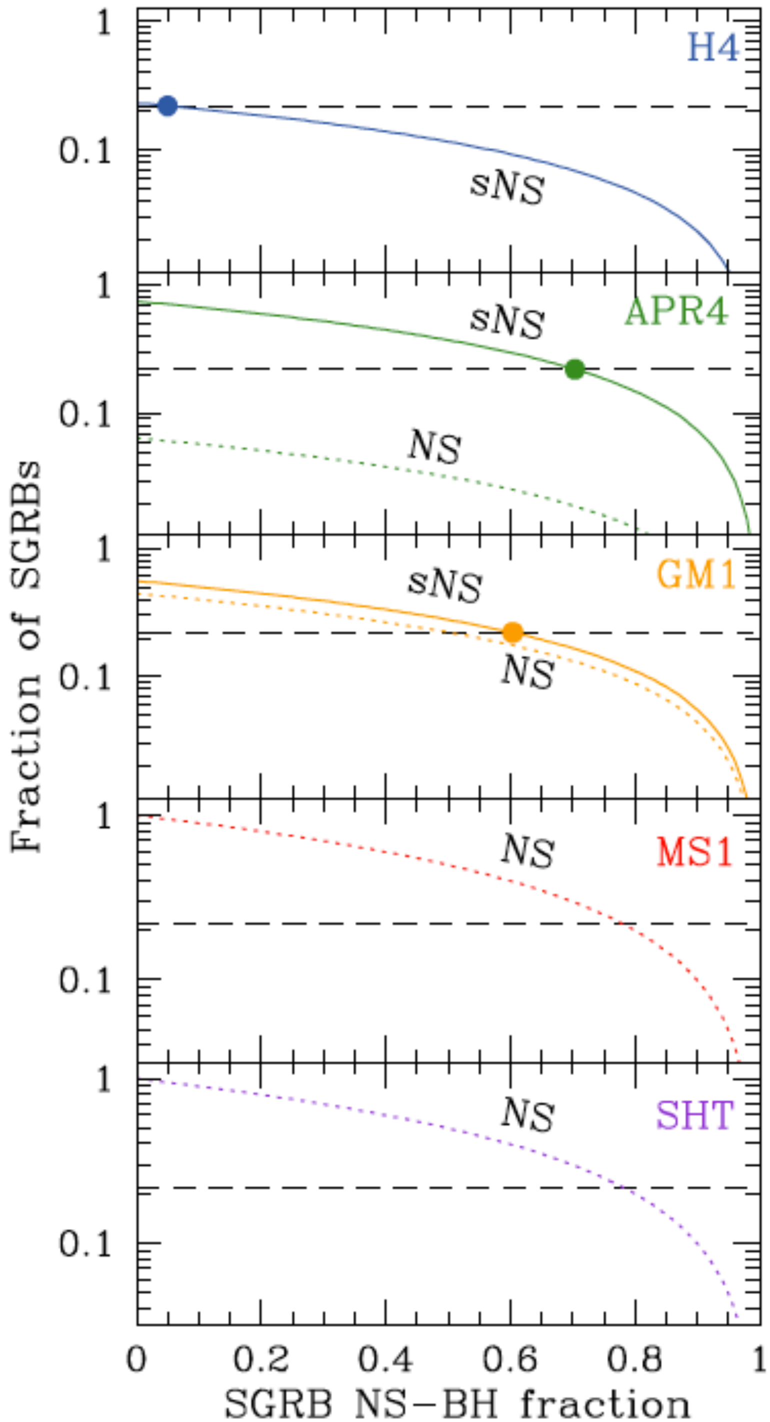
[Piro, Giacomazzo & Perna 2017]

EM counterparts may help reveal the nature of the compact object left behind after the merger





[Rowlinson et al. 2013]



Analysis of 96 SGRBs by Gao et al. (2016) argues for 22% of merger products to be sNS.

Any EOS which predicts a fraction of sNS larger than 22% requires that a fraction of SGRBs is due to NS-BH mergers instead of NS-NS mergers.

Dots indicate the required fraction for H4, APR4, GM1, while MS1 and SHT are incompatible with the data, since they predict a negligible fraction of sNS.

[Piro, Giacomazzo & Perna 2017]

GW+EM: Measure cosmological parameters

[Schutz 1986]

- Detection of GW signal from binary merger →

  Distance to the source

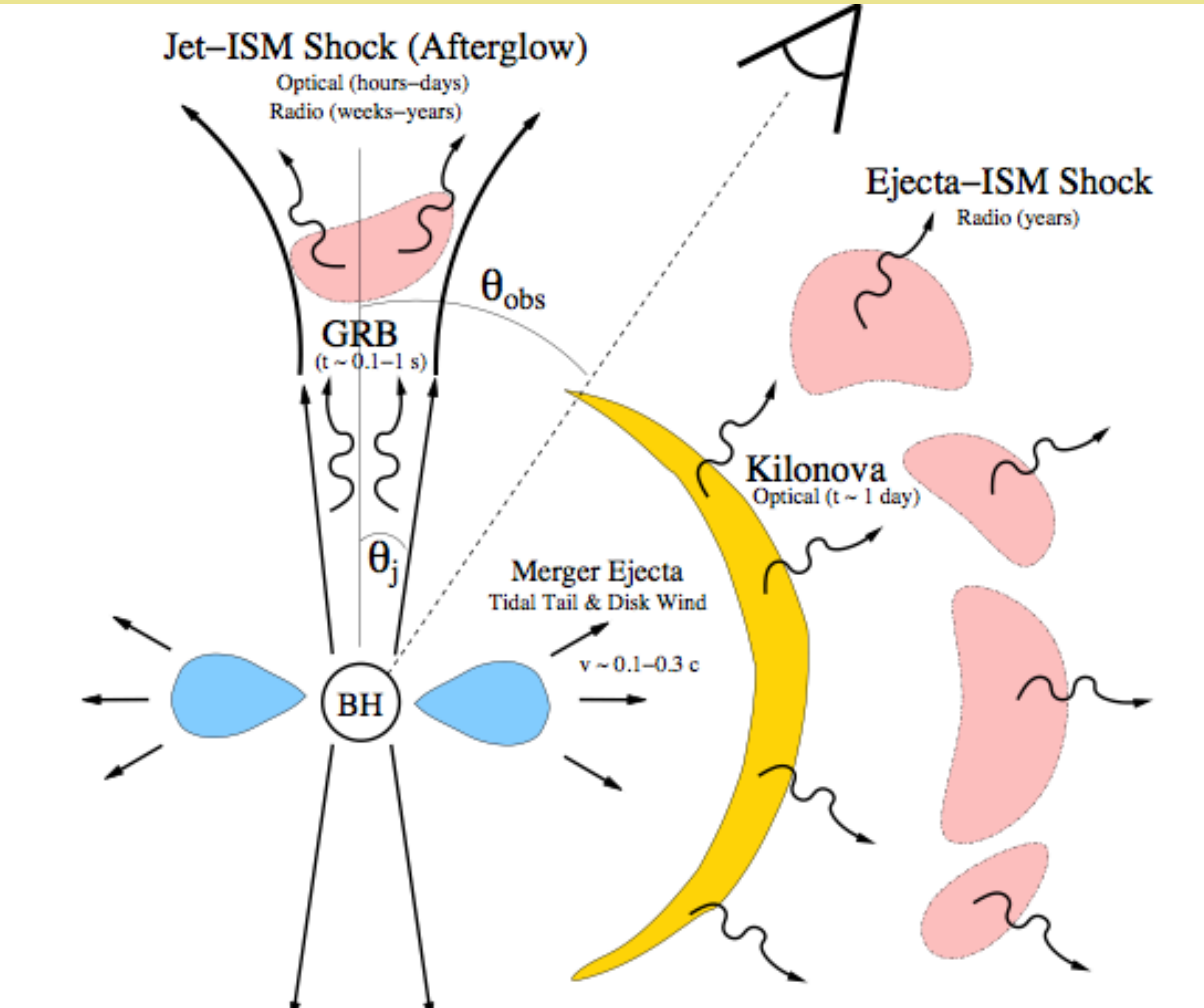
  Distances: up to ~ 10-30% precision for
  <~ 500 Mpc for NS-NS
  <~ 1.5 Gpc for NS-BH
  with Advanced Ligo & Virgo [e.g. Nissanke et al. 2010]

- Detection of associated short GRB and afterglow observation →

  Redshift of the source (up to z ~ a few)

→ Measure Hubble constant to 2% precision [Dalal et al 2006]

Probe Jet angular structure



[Metzger & Berger 2012]

- Angular structure of GRB jet is largely unknown

→ Rate of binary mergers detected through GWs, together with the rate of short GRBs with confirmed association with those binaries, can be used to constrain the opening angle of GRB jets

Electromagnetic Counterparts to Binary ***Black Hole*** Mergers?

- Not *expected* on theoretical grounds (unlike the NS-NS & NS-BH cases)

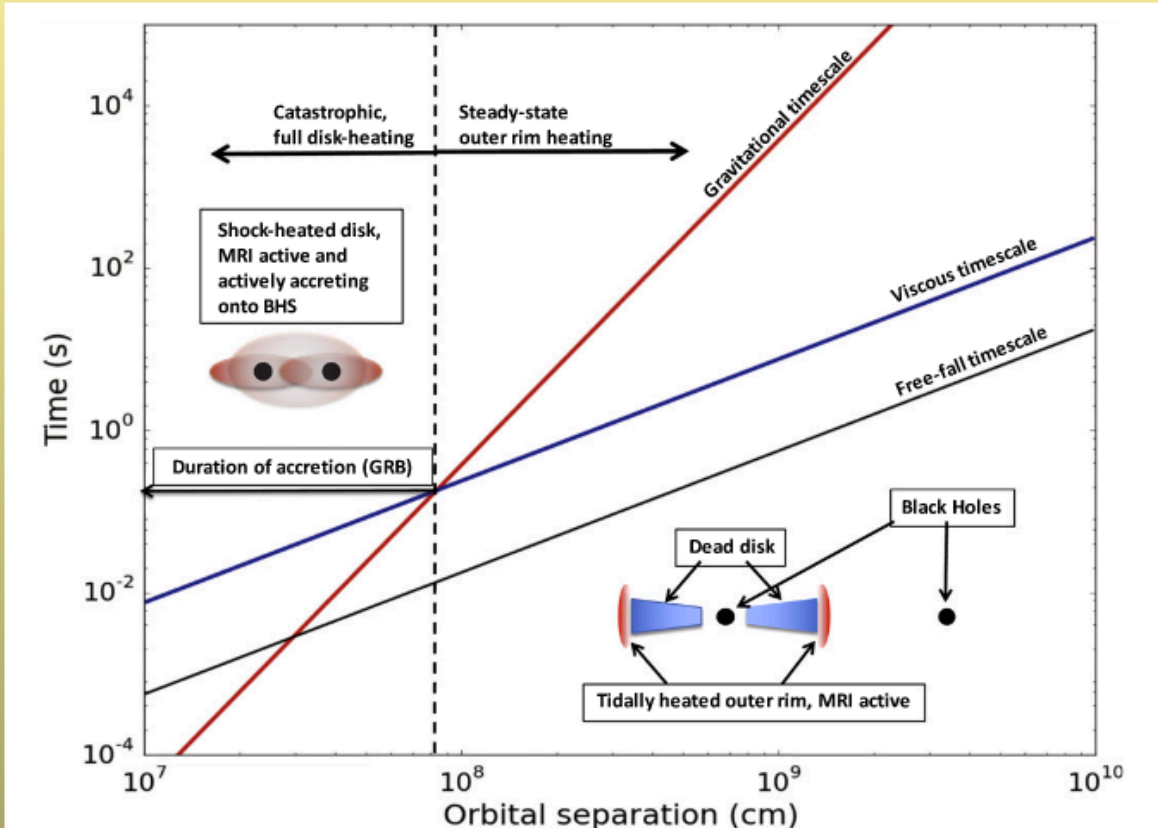
- Observationally: tentative detection of gamma-ray counterpart by Fermi (Connaughton et al. 2016) and by Agile (Stalder et al. 2017)

- Theoretically (after the facts): some ideas have been proposed

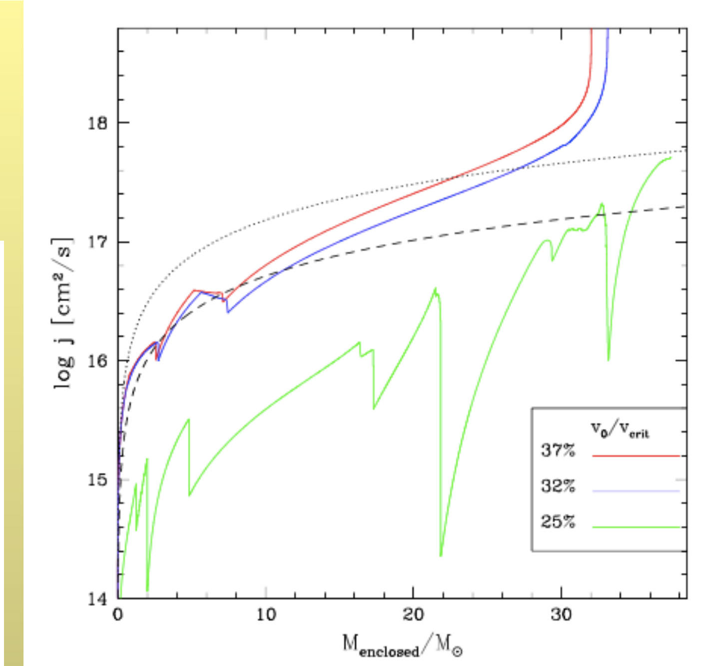
An (incomplete) list of some of the proposed ideas:

- Formation of a binary BH inside a massive star [Loeb 2016, but ruled implausible by Dai et al. 2016 & Woosley 2016]
- BH-BH merger with at least one charged BH generating evolving magnetic dipole and driving Pointing flux [Zhang 2017; see also Fraschetti 2016]
- Binary system of massive star+ BH ; star collapses forming a second BH; BH-BH merger (with mass accretion from the star envelope; [Janiuk et al. 2017]
- Heating of a circumbinary disk by shocks [De Mink & King 2017]
- Remnant disk from evolution of low-metallicity, high mass stars [Perna et al. 2016]

- Fallback Disk formed after SN explosion



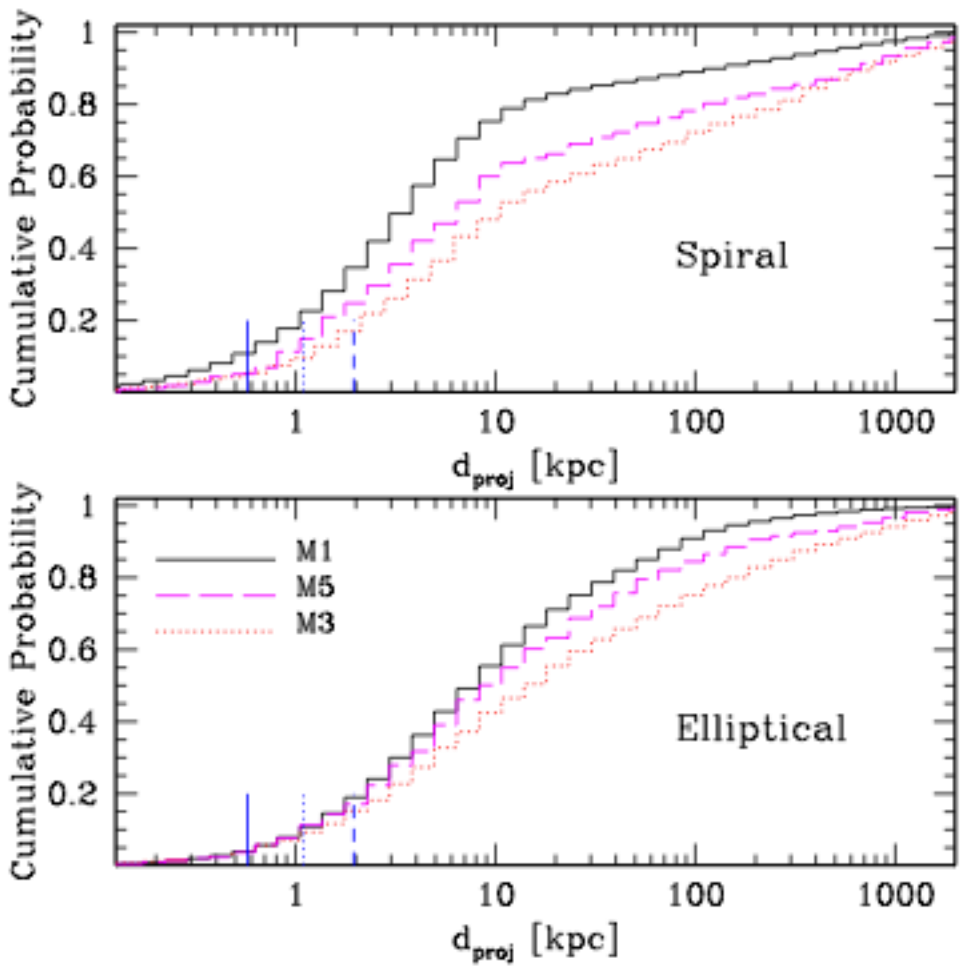
[Perna, Lazzati & Giacomazzo 2016]



- Disk cools and eventually MRI shuts down → 'dead disk' can then survive for very long time

- During the final phases of merger the disk is reheated, the MRI operates again, and accretion operates on the usual dynamical scale – timescales just work out…

What are the prospects for EM counterpart detections to BH-BH Binary mergers *if* the Energetics were comparable to the Fermi candidate counterpart?

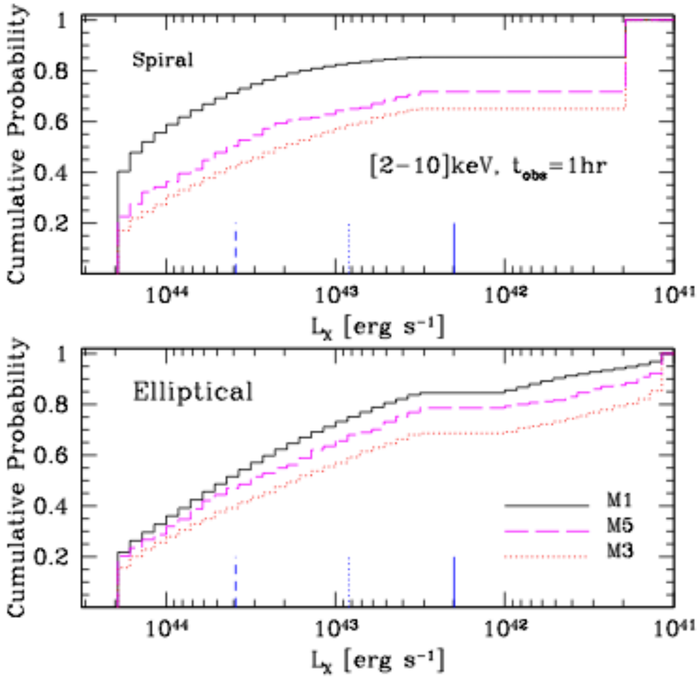


Study in progress [Perna et al. 2017]:

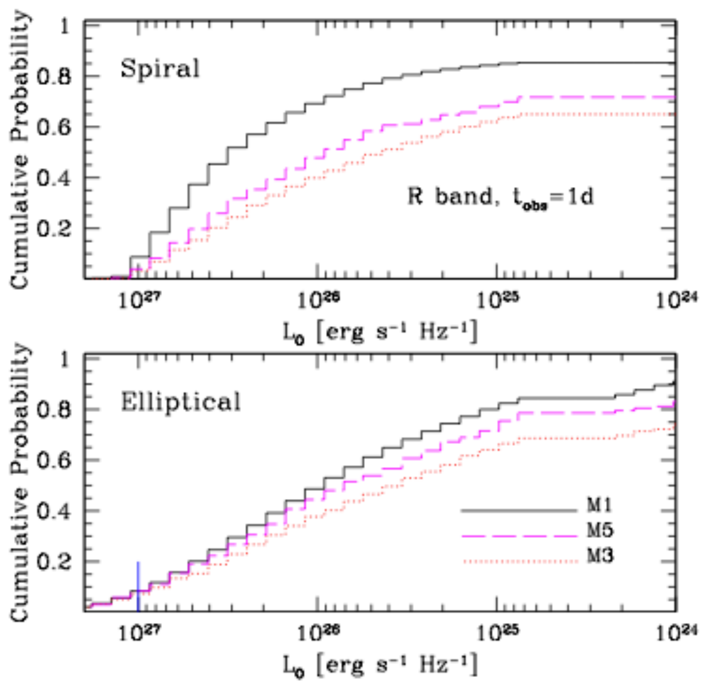
Using the population Synthesis code *StarTrack* [Belczynski et al. 2008], the Statistical properties of the BH-BH population are computed.

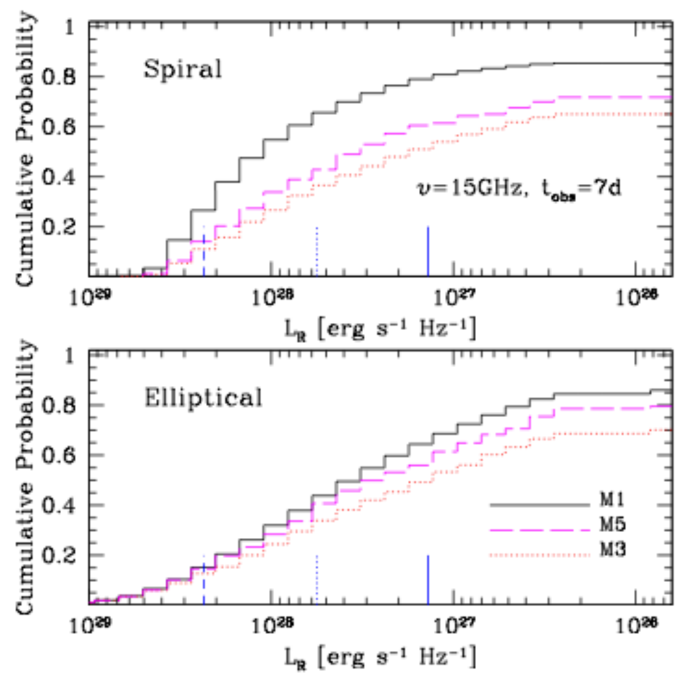
Merger locations within host galaxies are important since determine density of ISM, on which afterglow magnitude depend

Predicted Afterglow intensities at different wavelengths [Perna et al. 2017, in prep.]



A sizeable fraction of afterglows should be detectable, especially in X-rays, if EM counterparts are present and energetics are comparable to that of the Fermi possible counterpart to GW





SUMMARY

- **NS-NS and NS-BH mergers:**
  EM radiation has been detected –
  now awaiting for GW counterparts

- **BH-BH mergers:**
  GW radiation has been detected –
  now awaiting for EM counterparts

LOTS to learn with both together…