The physics and astrophysics of binary neutron stars mergers:

two birds with a stone

Luciano Rezzolla

Institute for Theoretical Physics, Frankfurt

Frankfurt Institute for Advanced Studies, Frankfurt

Plan of the talk

- ✶Our present understanding of merging binary NSs
- ✶Anatomy of GW signal: frequencies and EOS
- ✶Role of B-fields and EM counterparts
- ✶Eccentric encounters and nucleosynthesis

see Samaya's talk!

The two-body problem in GR

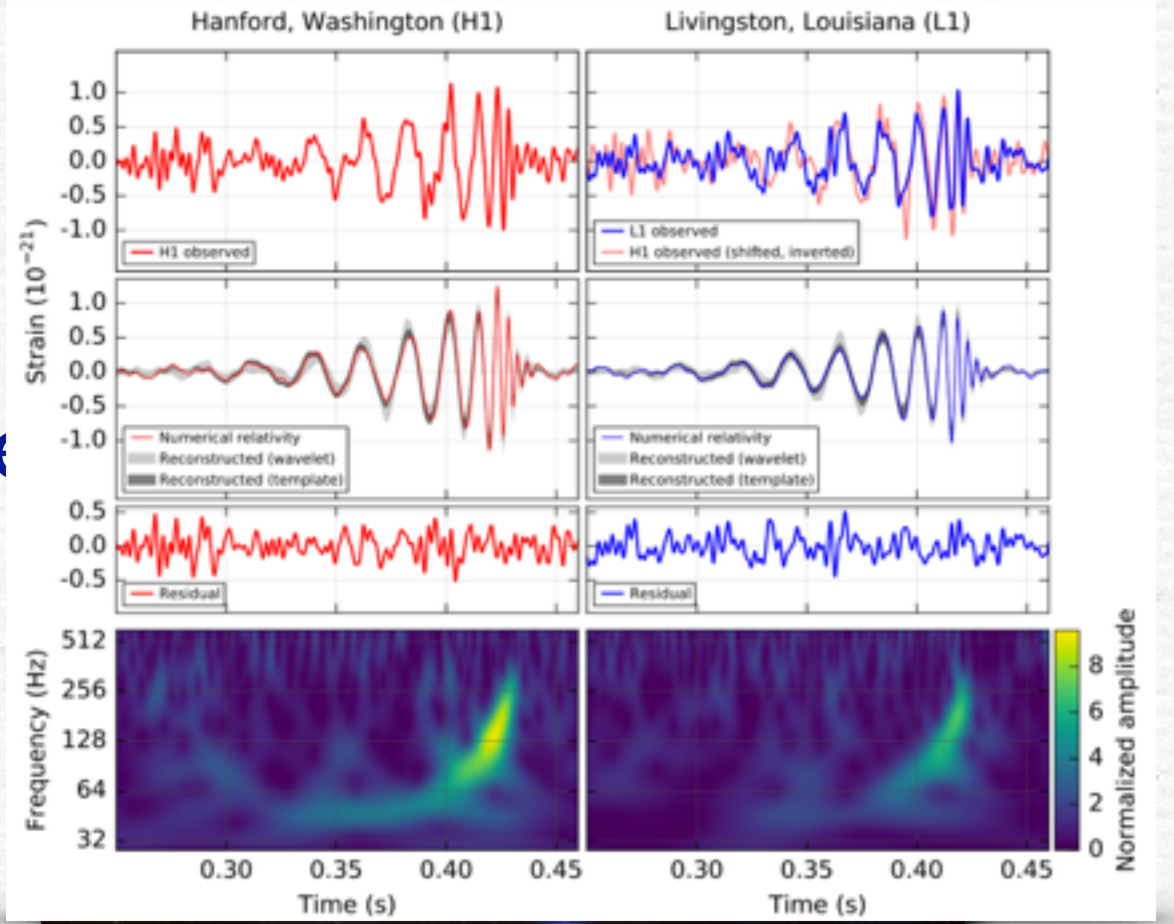
- For BHs we know what to **expect**:

BH + BH ⟶ BH + GWs

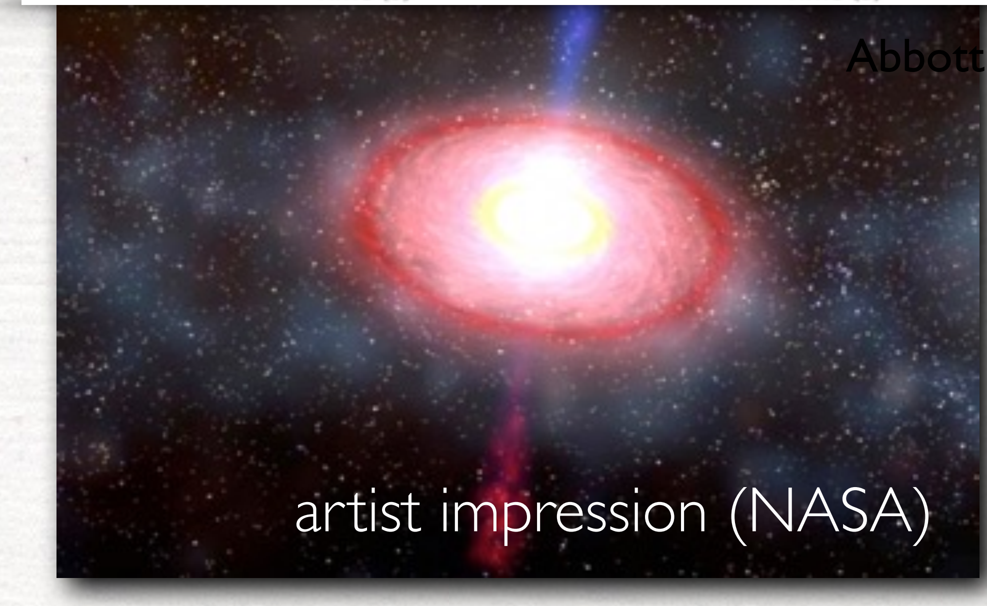
- For NSs the question is more **subtl**

hyper-massive neutron star (HMNS),

NS + NS ⟶ HMNS + **... ?** ⟶

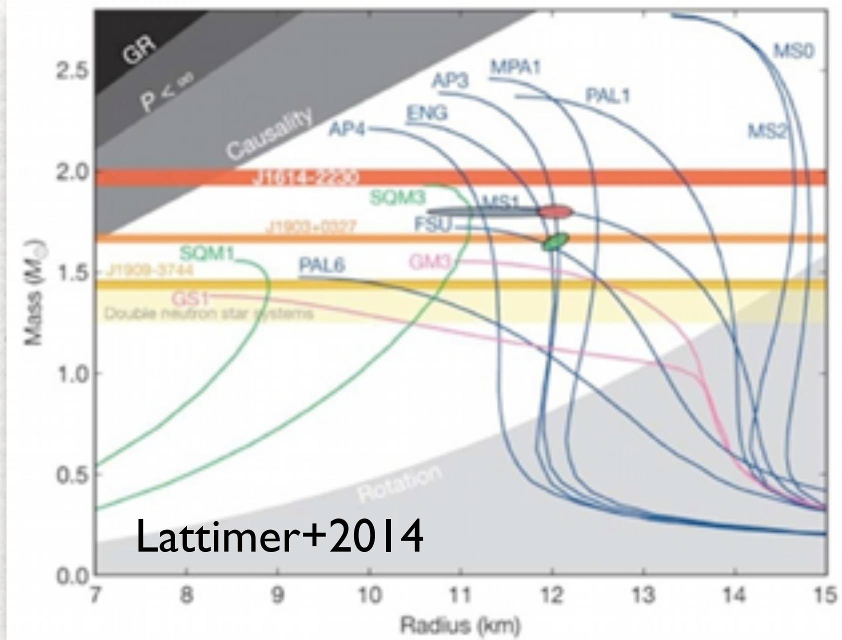


Abbott+ 2016



artist impression (NASA)

- **HMNS** phase can provide clear information on **EOS**



Lattimer+2014

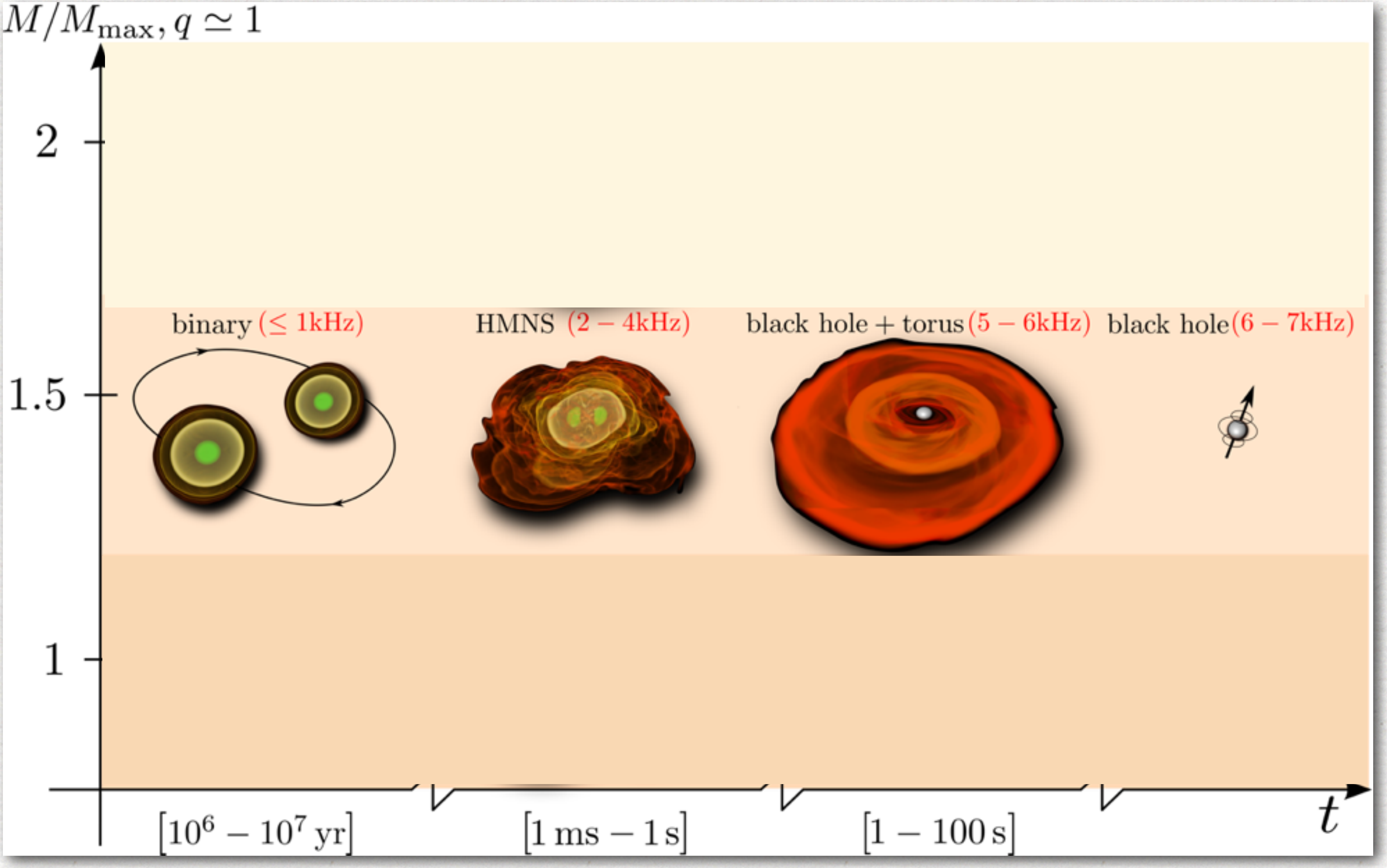
- **BH+torus** system may tell us on the central engine of **GRBs**

Animations: Breu, Radice, LR

merger → HMNS → BH + torus

LS220 EOS

Broadbrush picture

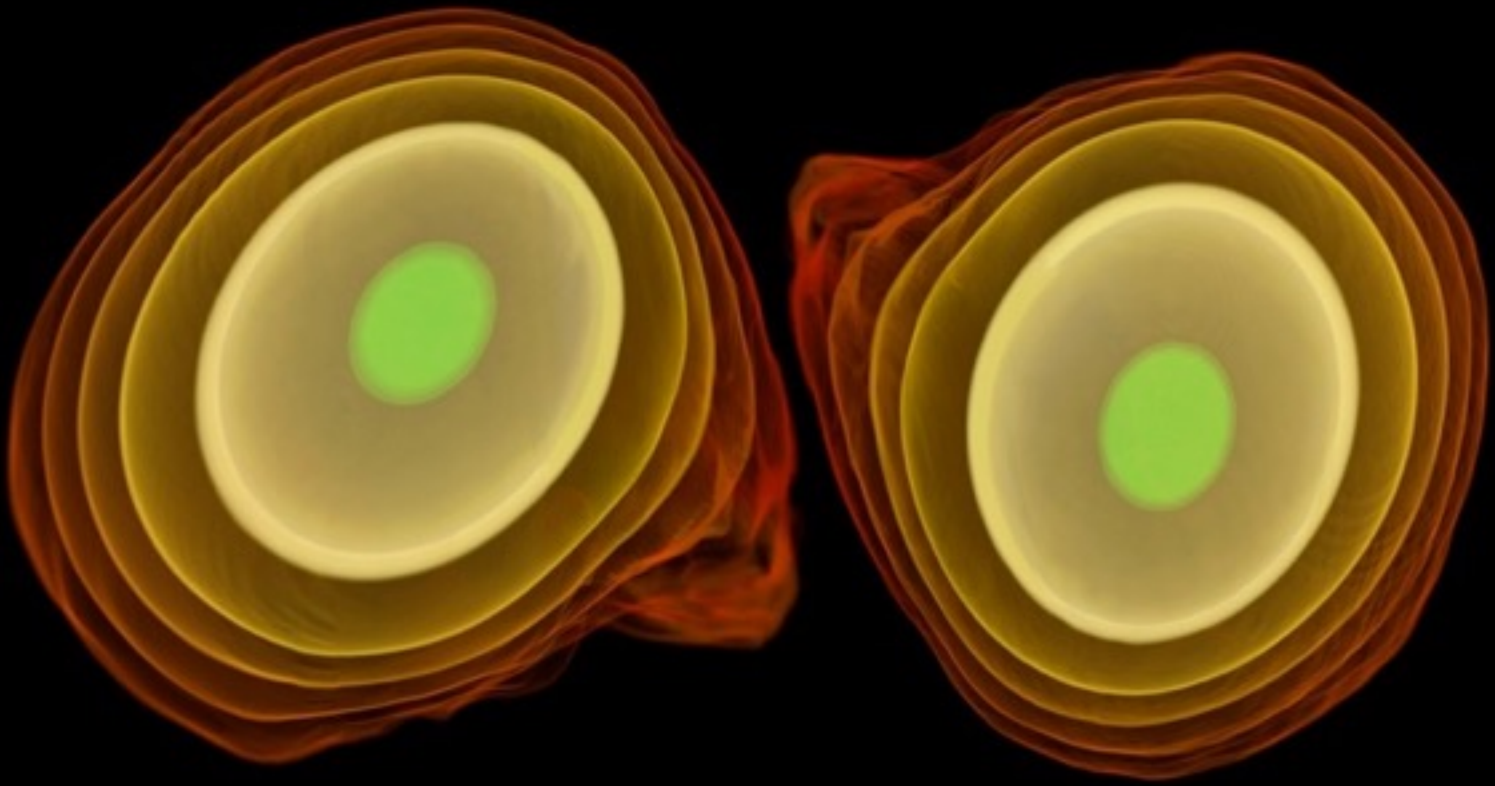


merger → HMNS → BH + torus

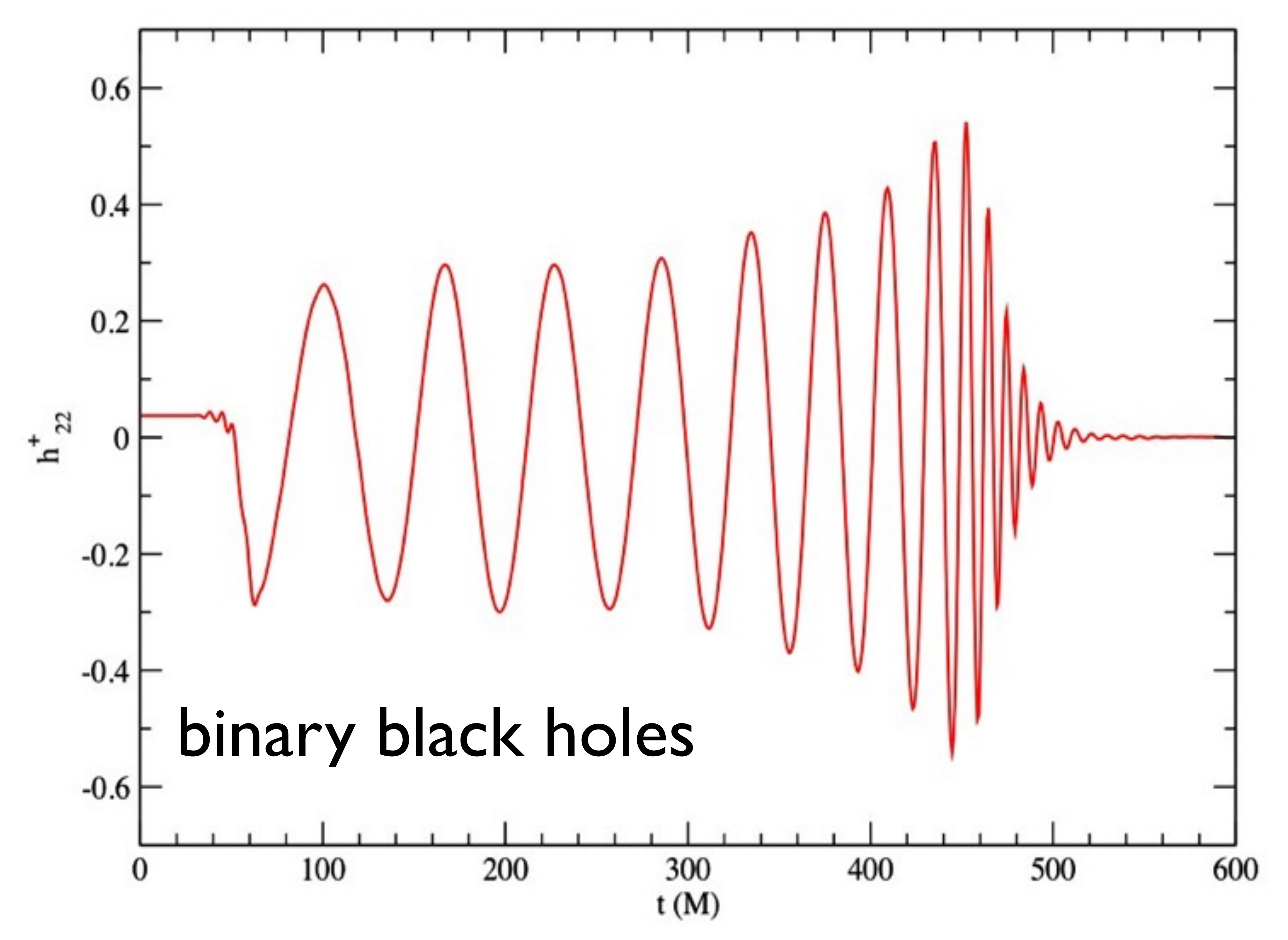
Quantitative differences are produced by:

- total mass (prompt vs delayed collapse)
- mass asymmetries (HMNS and torus)
- soft/stiff EOS (inspiral and post-merger)
- magnetic fields (equil. and EM emission)
- radiative losses (equil. and nucleosynthesis)

How to constrain the EOS

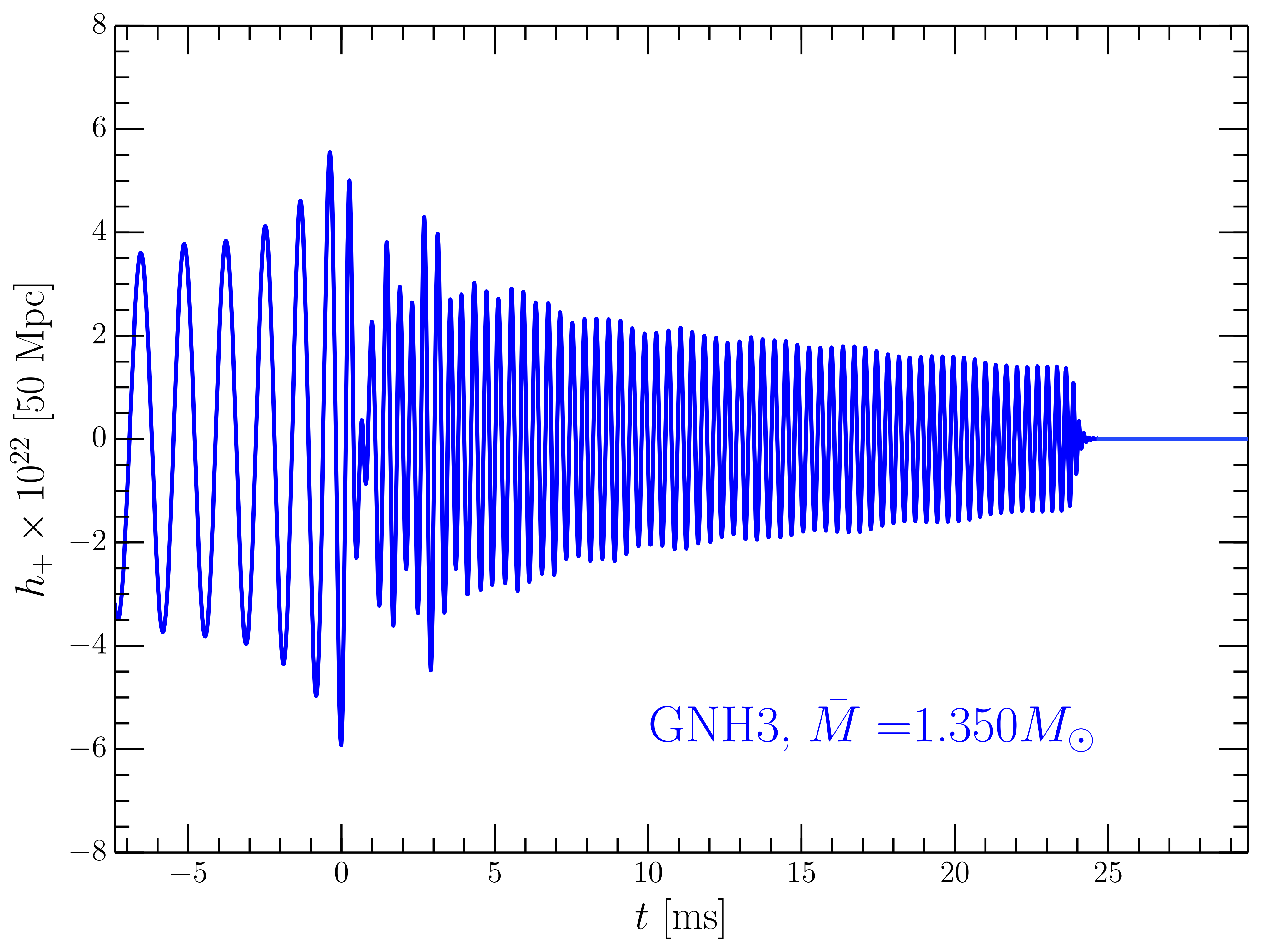


Anatomy of the GW signal



binary black holes

Anatomy of the GW signal



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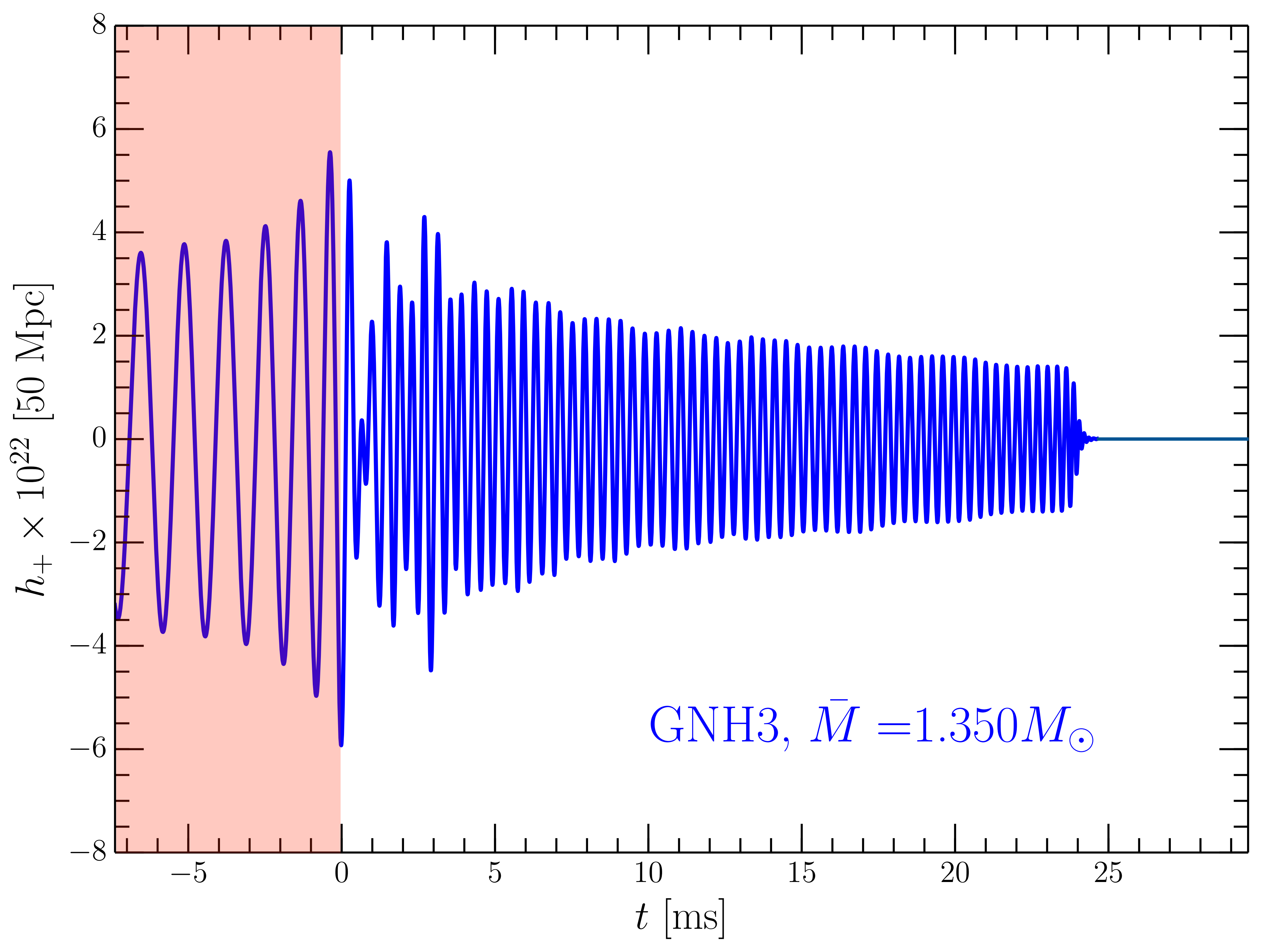
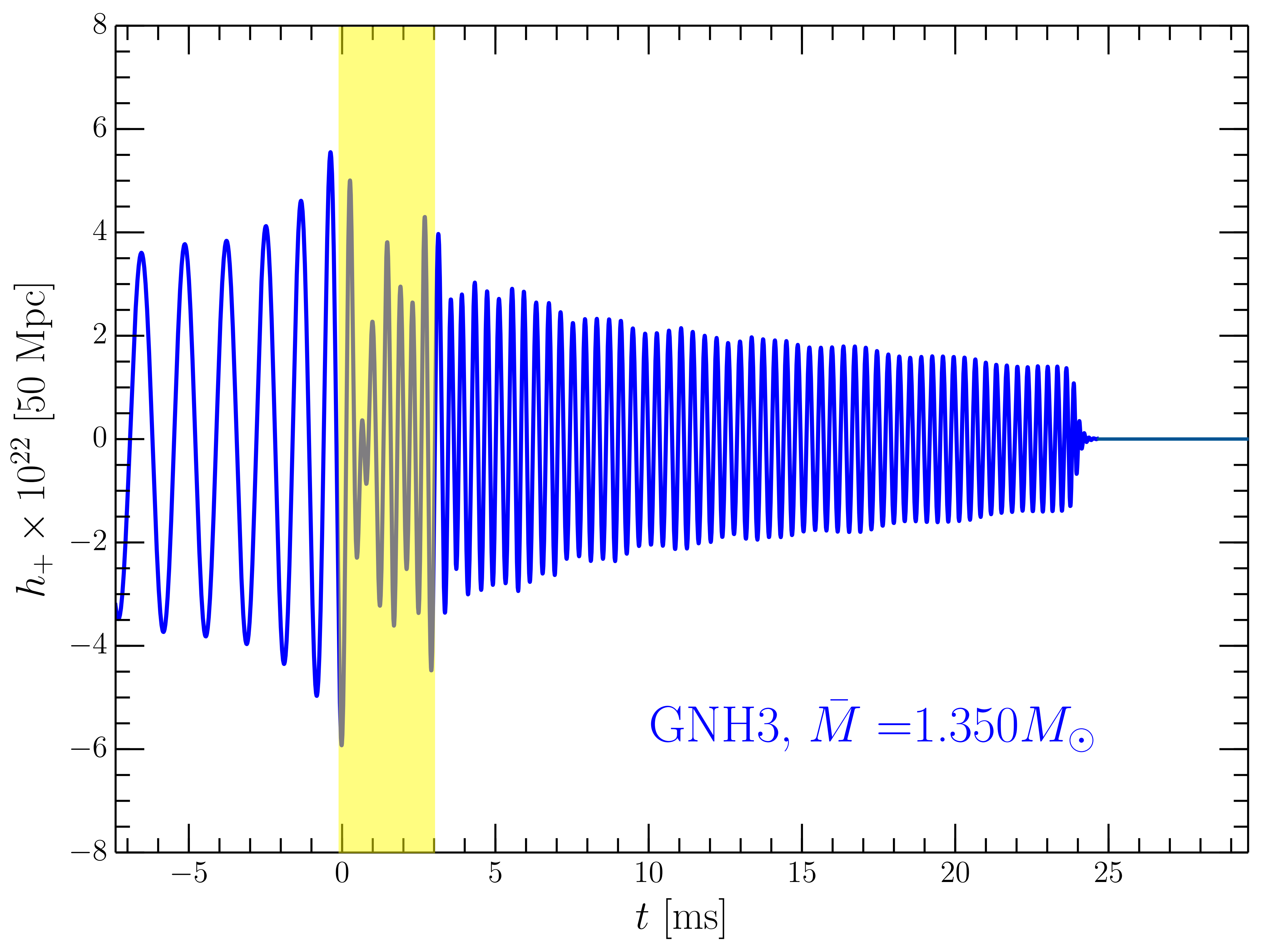


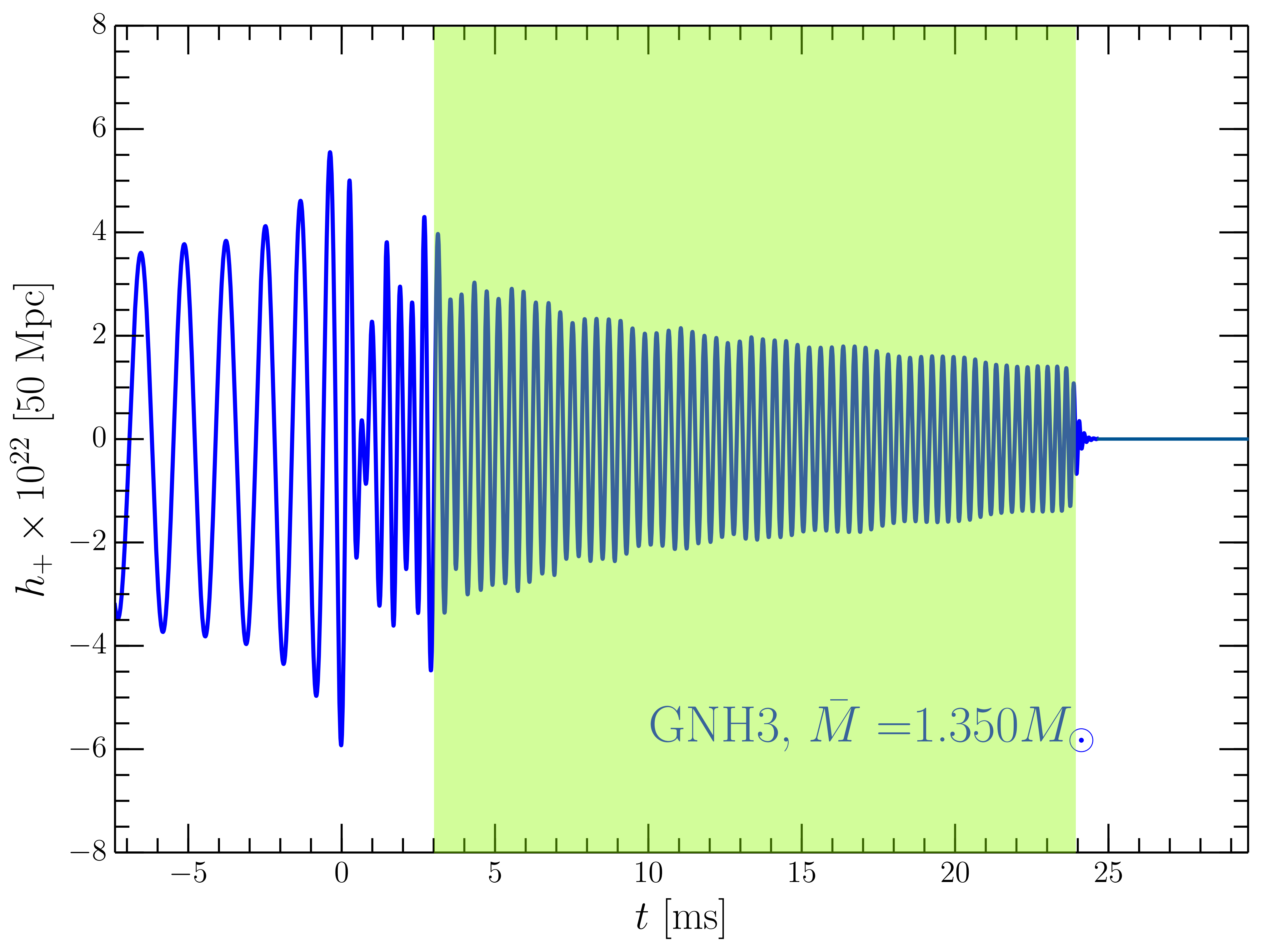
Inspiral: well approximated by PN/EOB; tidal effects important

Anatomy of the GW signal



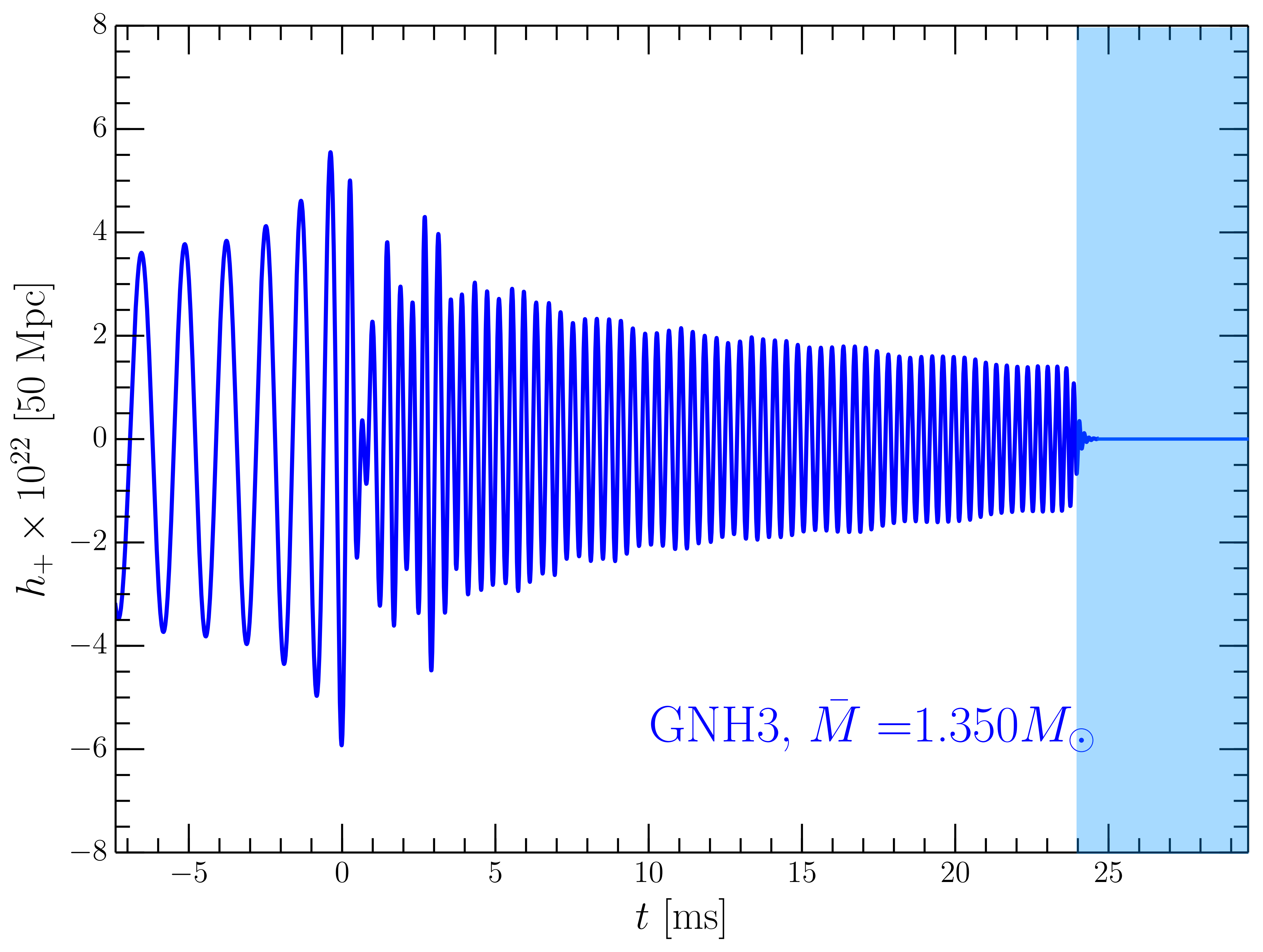
Merger: highly nonlinear but analytic description possible

Anatomy of the GW signal



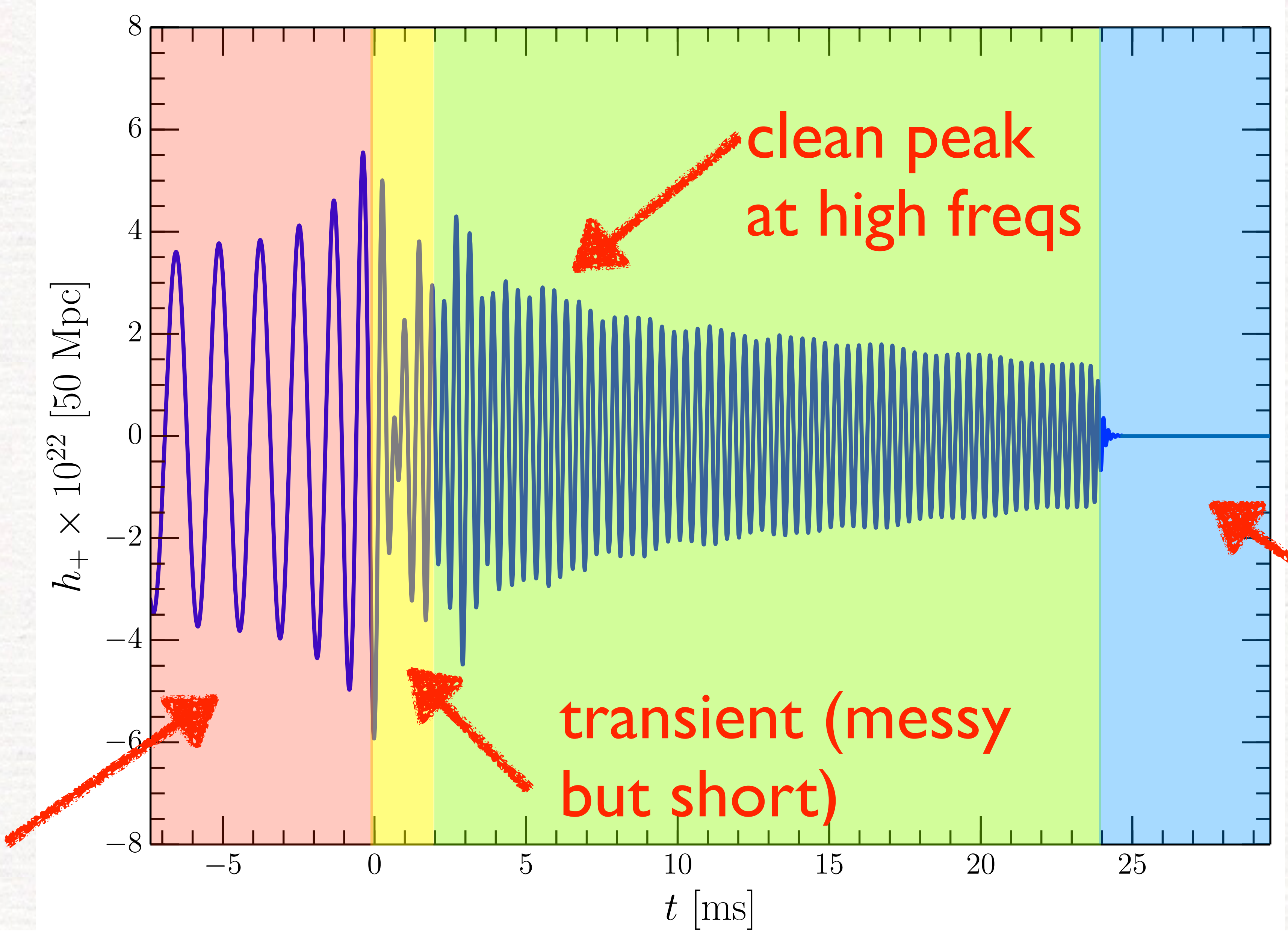
post-merger: quasi-periodic emission of bar-deformed HMNS

Anatomy of the GW signal



Collapse-ringdown: signal essentially shuts off.

Anatomy of the GW signal

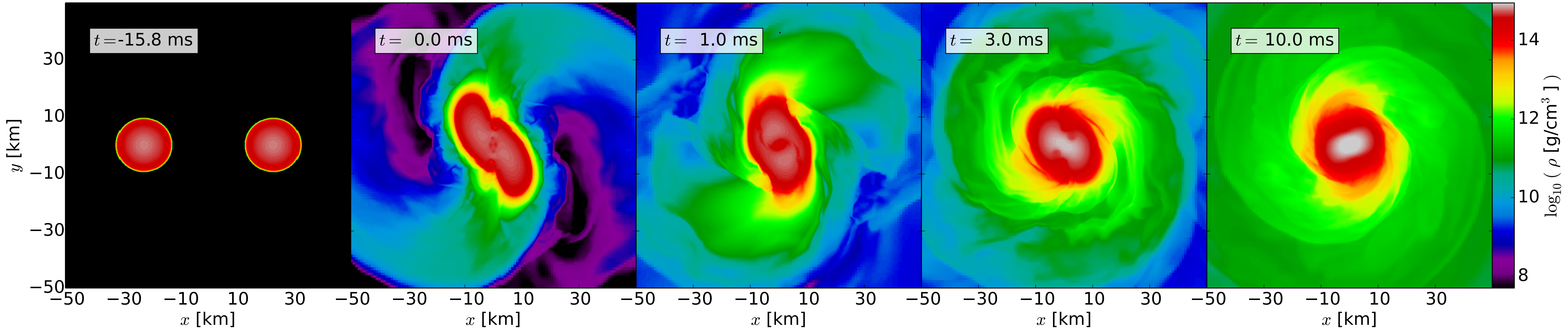


Chirp signal (track from low to high frequencies)

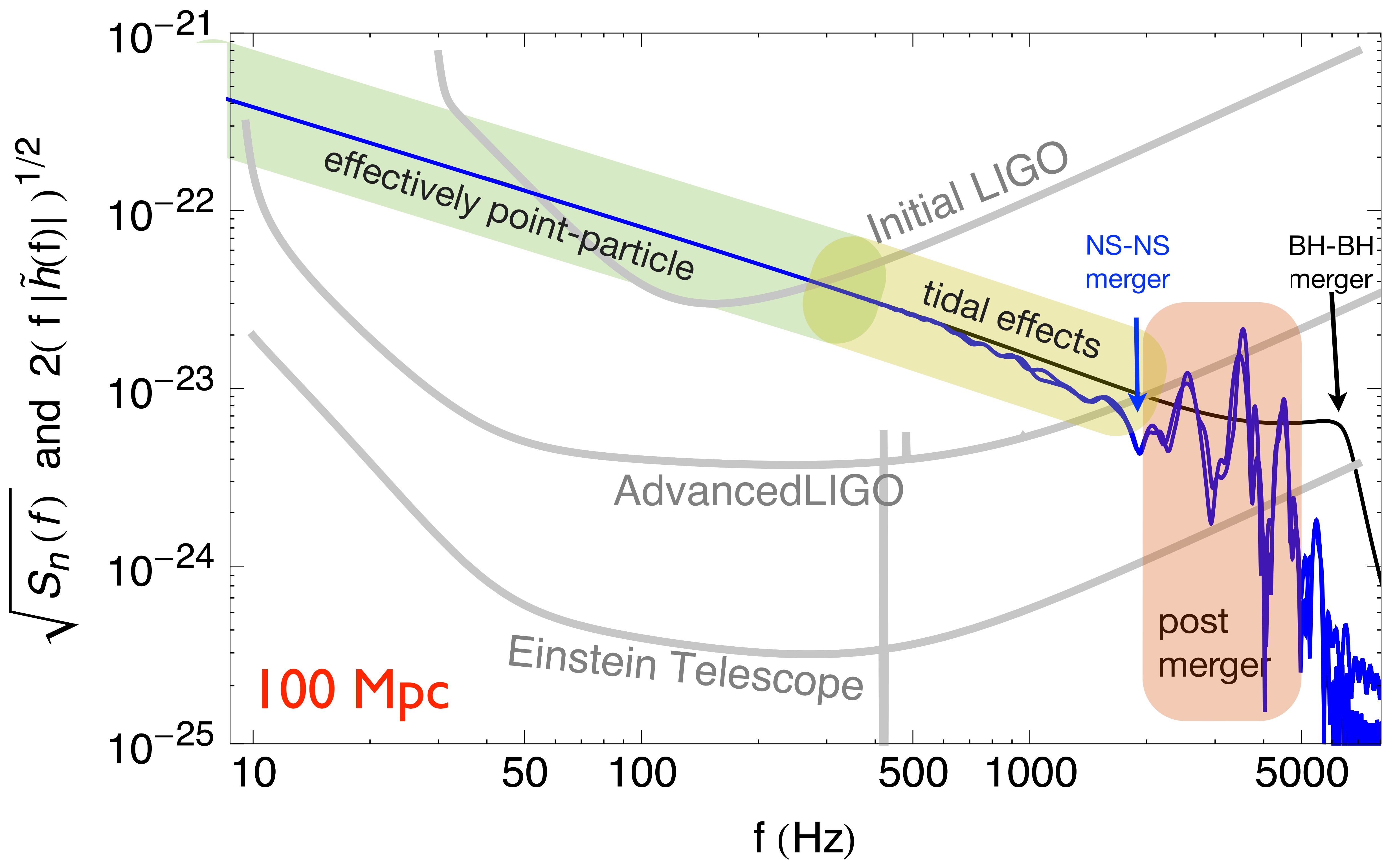
clean peak at high freqs

transient (messy but short)

Cut off (very high freqs)



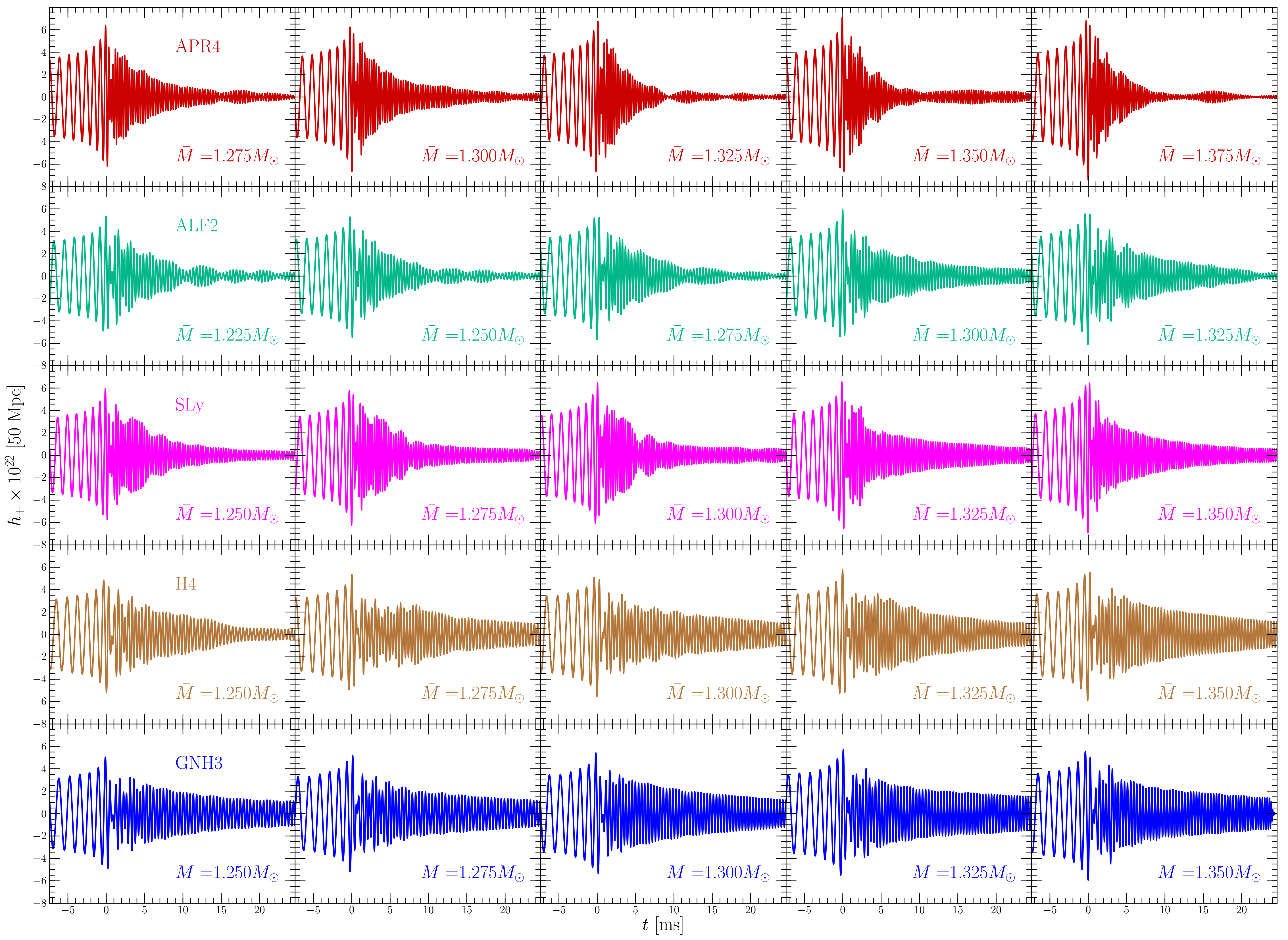
In frequency space



courtesy of Jocelyn Read

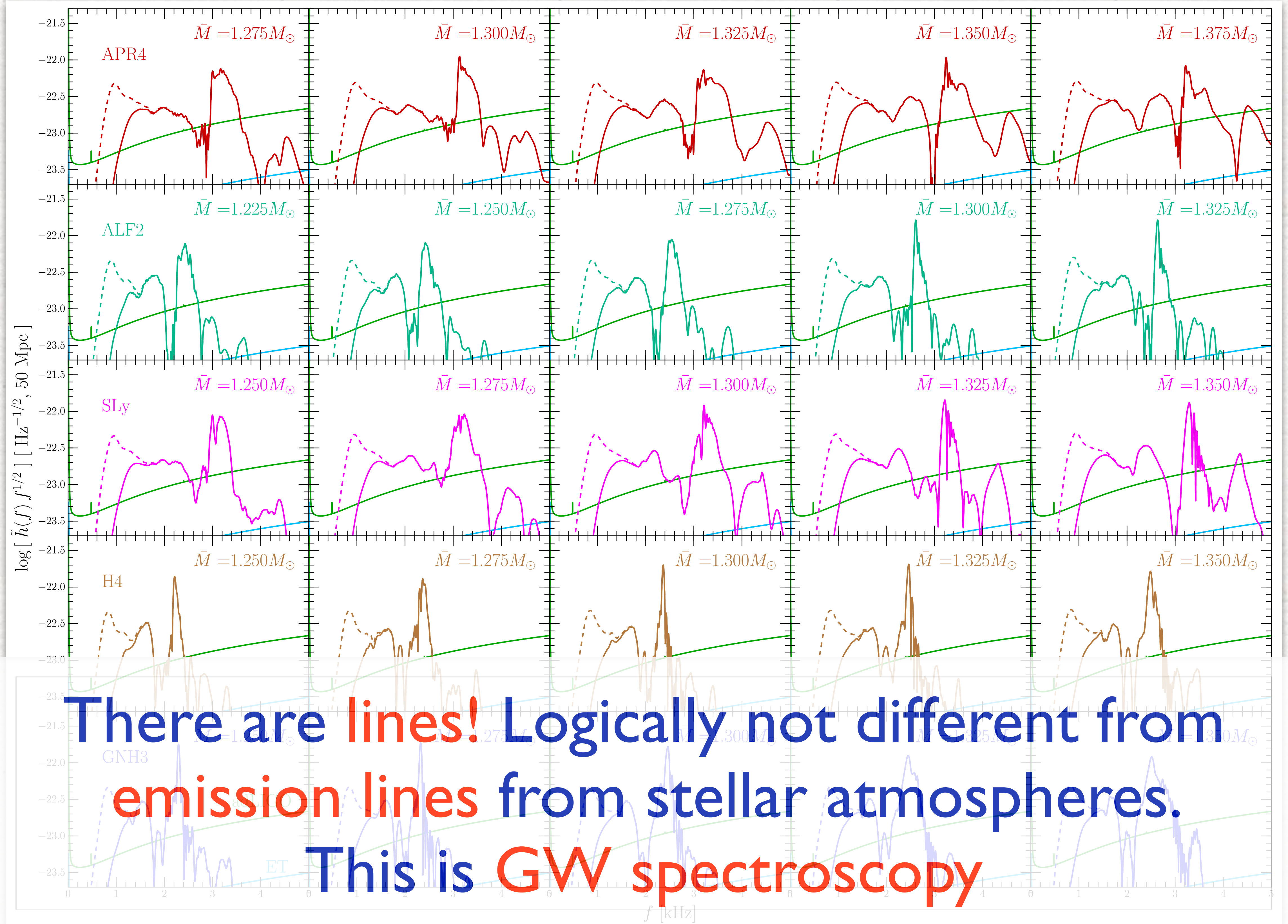
What we can do nowadays

Takami, LR, Baiotti (2014, 2015), LR+ (2016)



Extracting information from the EOS

Takami, LR, Baiotti (2014, 2015), LR+ (2016)



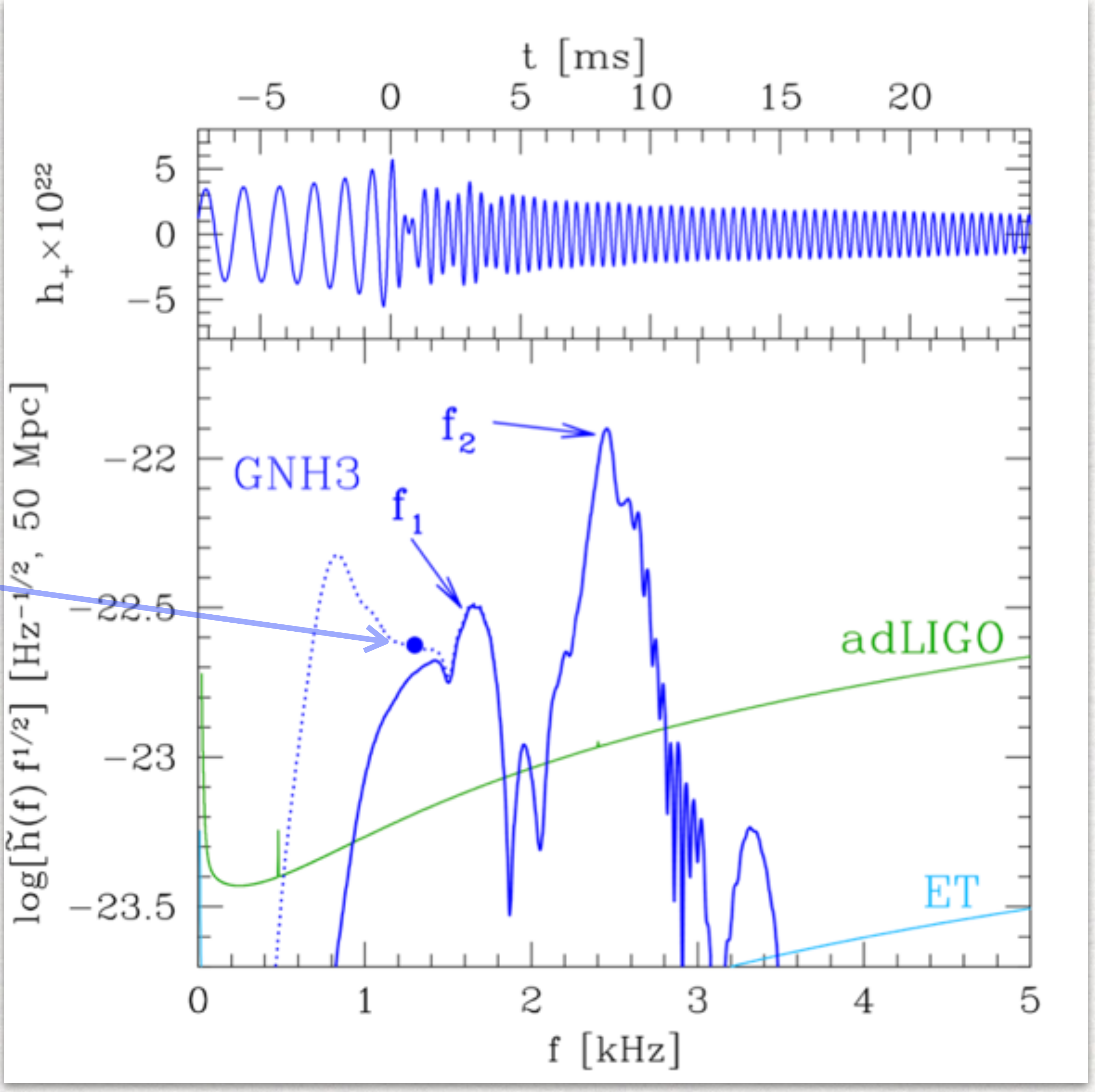
There are **lines!** Logically not different from **emission lines** from stellar atmospheres.

This is **GW spectroscopy**

A new approach to constrain the EOS

Oechslin+2007, Baiotti+2008, Bauswein+ 2011, 2012, Stergioulas+ 2011, Hotokezaka+ 2013, Takami 2014, 2015, Bernuzzi 2014, 2015, Bauswein+ 2015, LR+2016…

merger frequency



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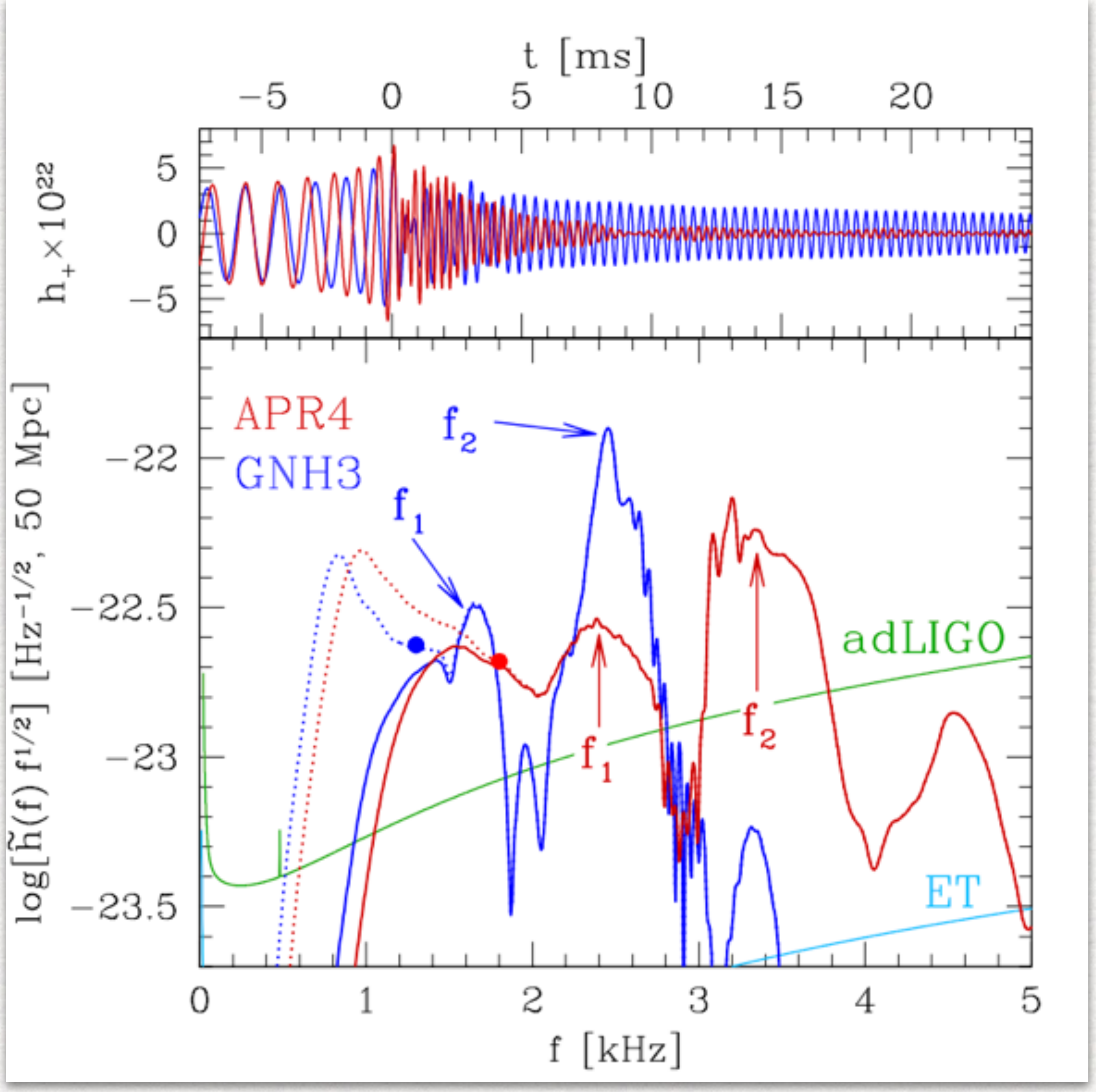
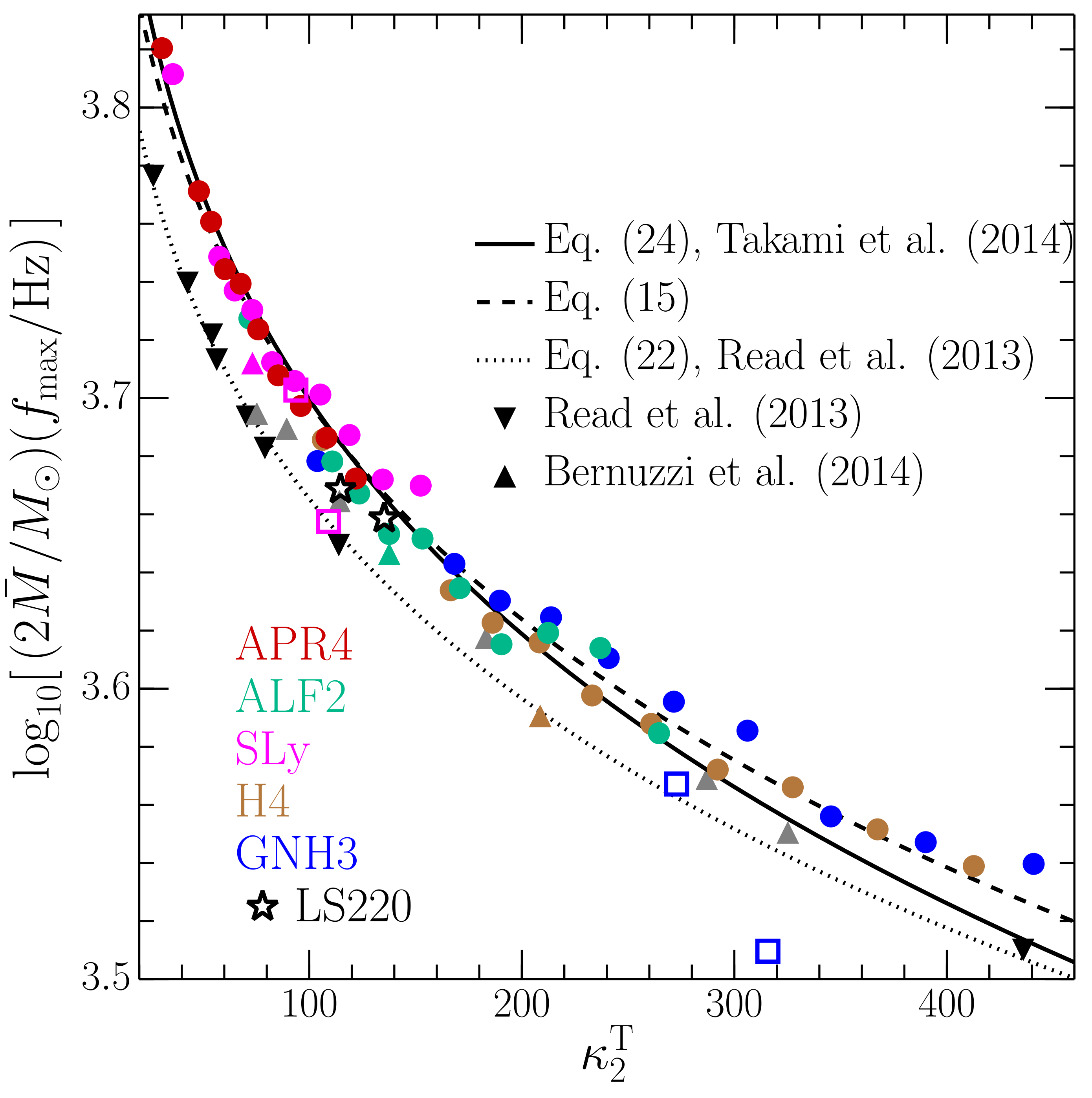


Quasi-universal behaviour: inspiral



"surprising" result: quasi-universal behaviour of GW frequency at amplitude peak (Read+2013)

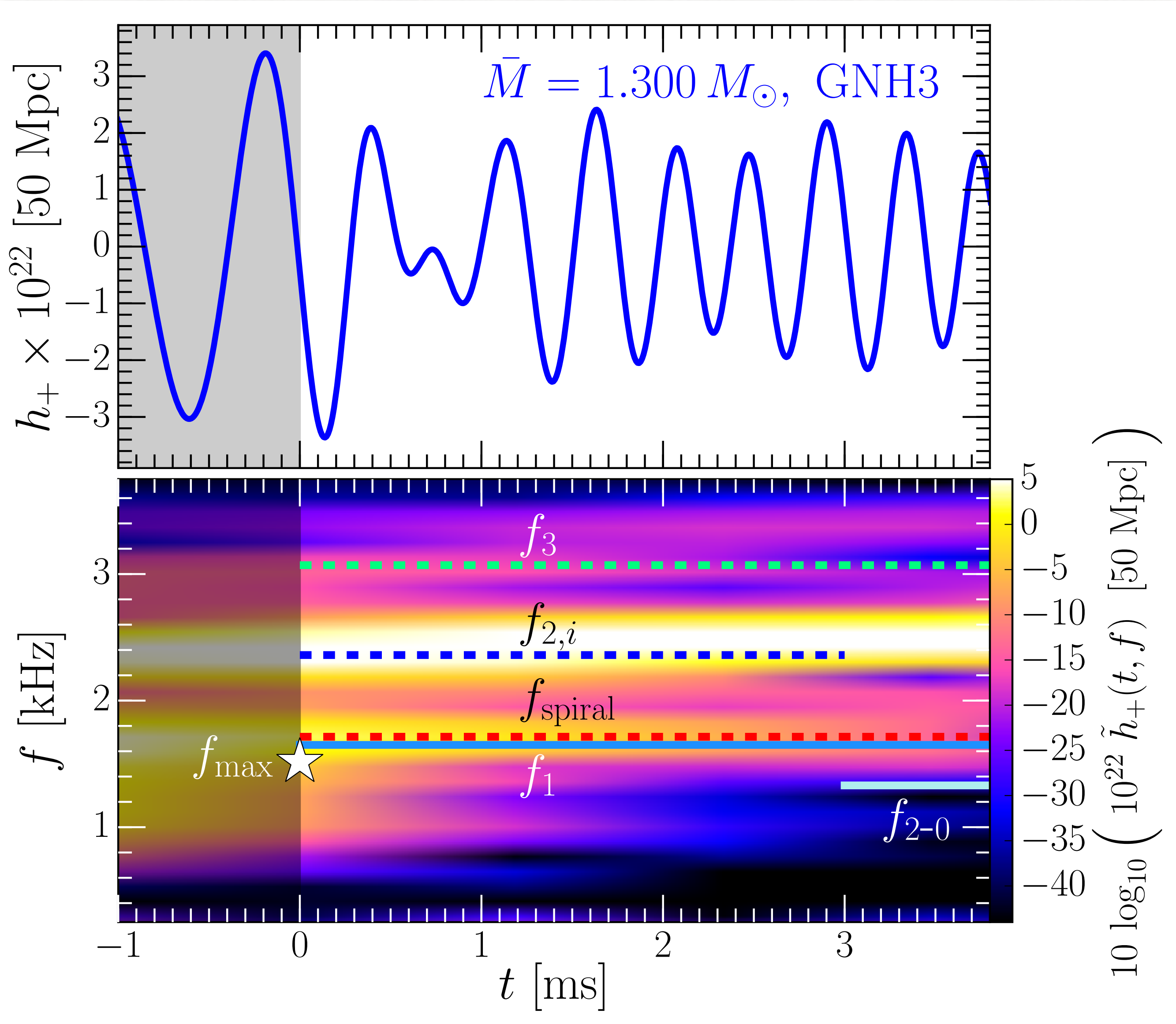
Many other simulations have confirmed this (Bernuzzi+, 2014, Takami+, 2015, LR+2016) .

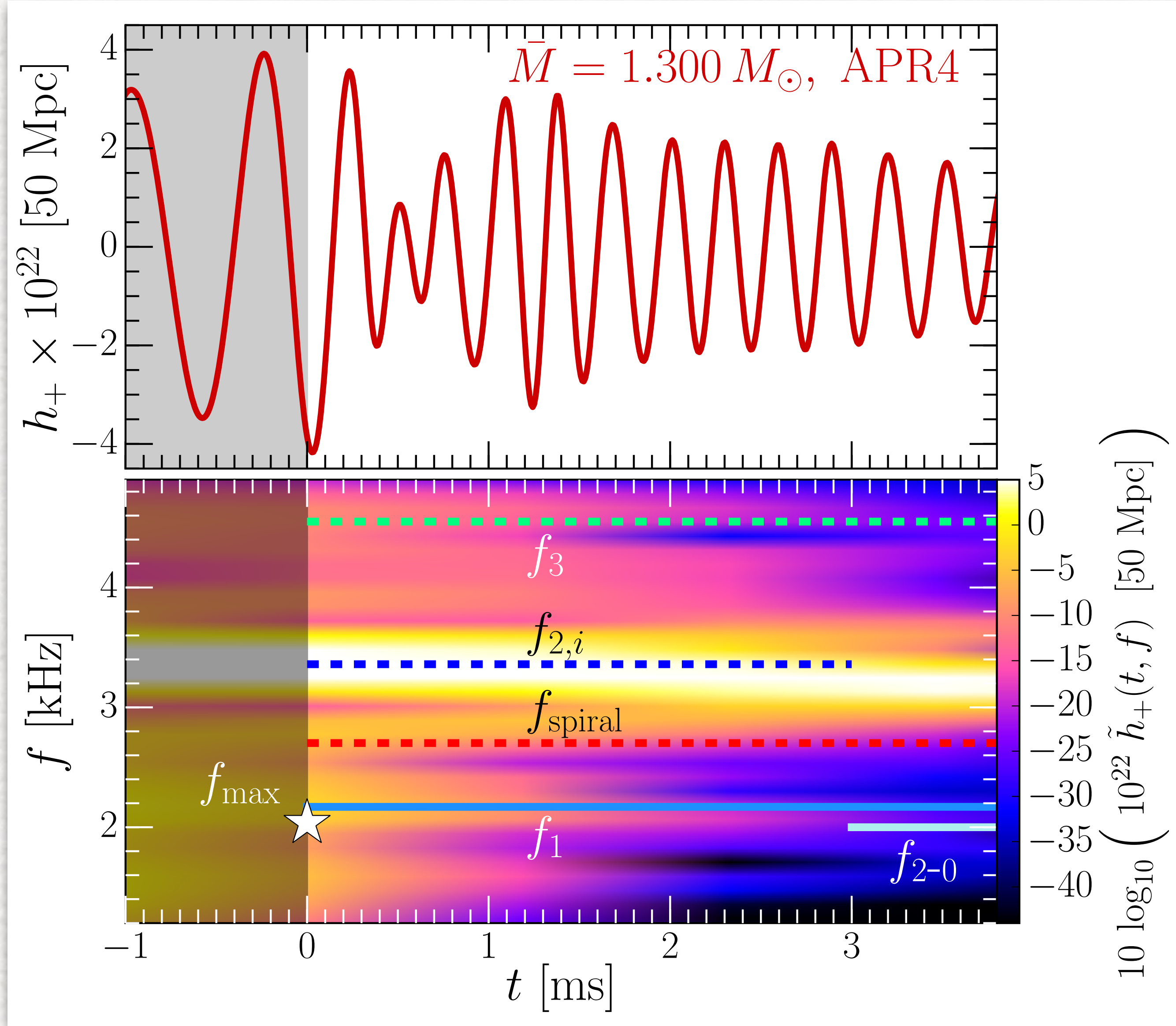
Quasi-universal behaviour in the **inspiral** implies that once **$f_{\rm max}$** is measured, so is tidal deformability, hence $I,\ Q,\ M/R$

$$\Lambda = \frac{\lambda}{\bar{M}^5} = \frac{16}{3}\kappa_2^T$$ tidal deformability or Love number

Understanding mode evolution

On a **short** timescale after the merger, it is possible to see the emergence of **f_1, f_2,** and **f_3**.

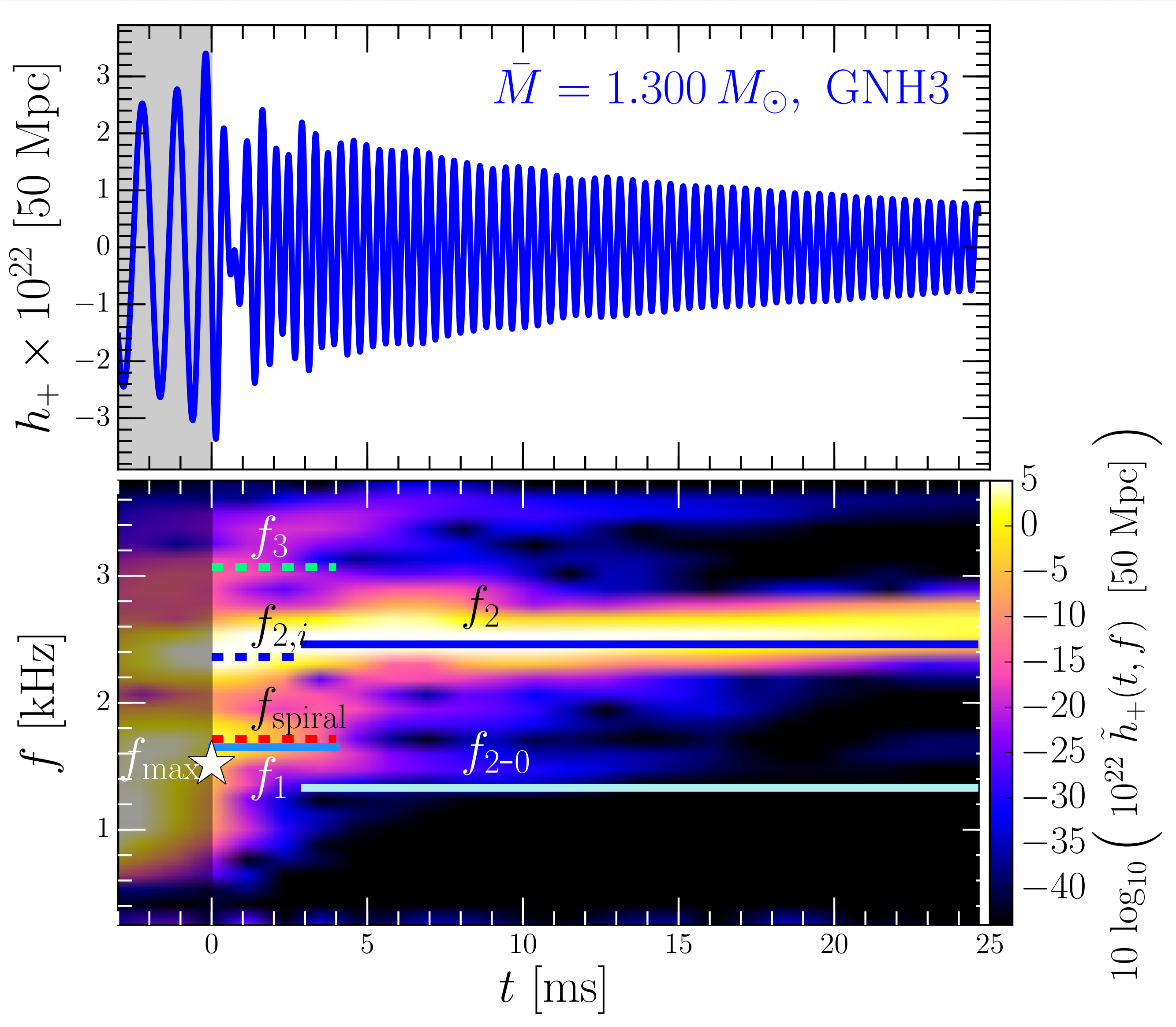


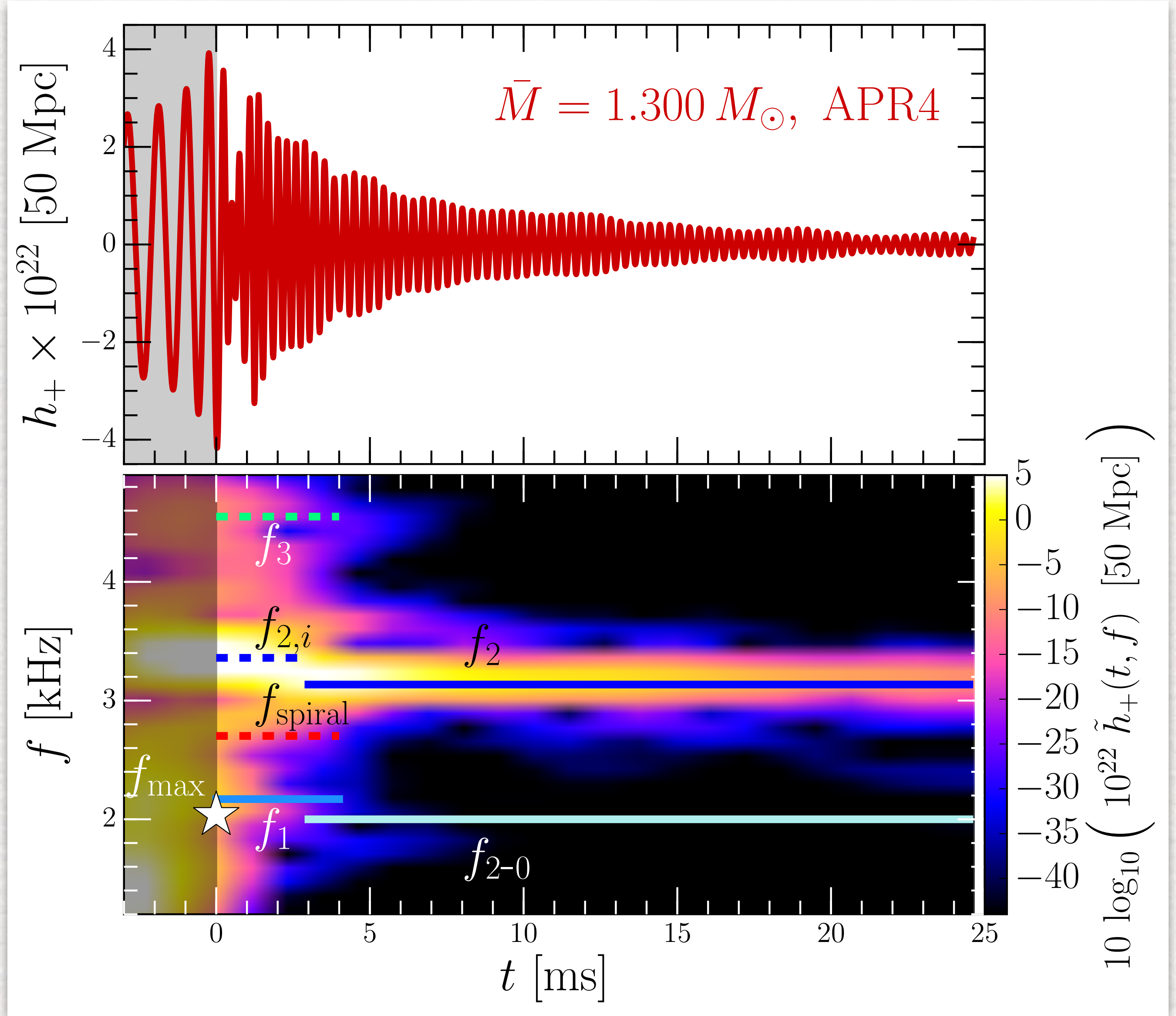


Understanding mode evolution

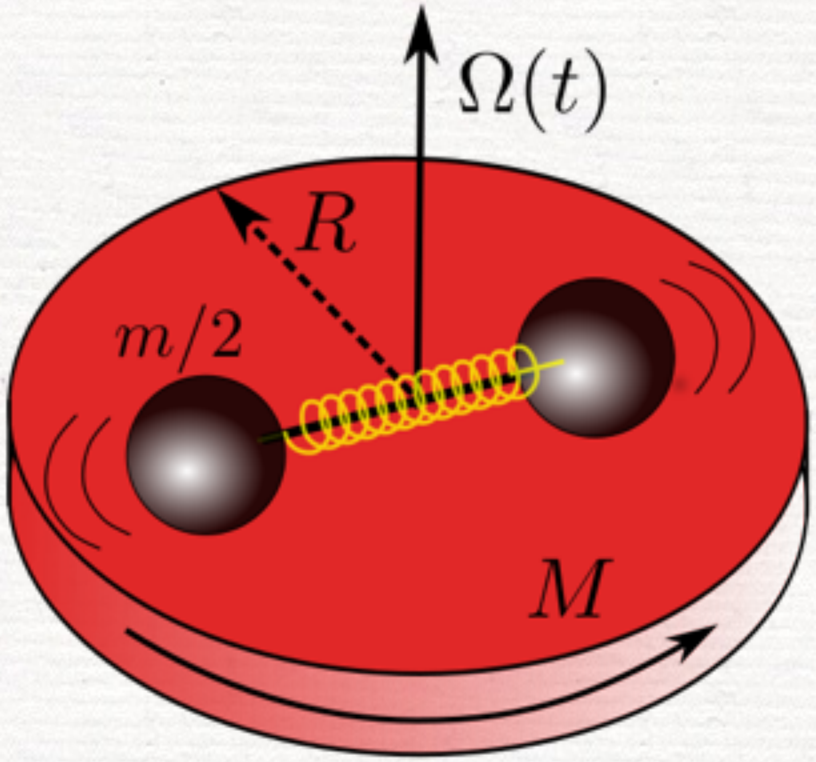
On a **long** timescale after the merger, only **f_2** survives.

What produces the short-lived **f_1** and **f_3** modes?

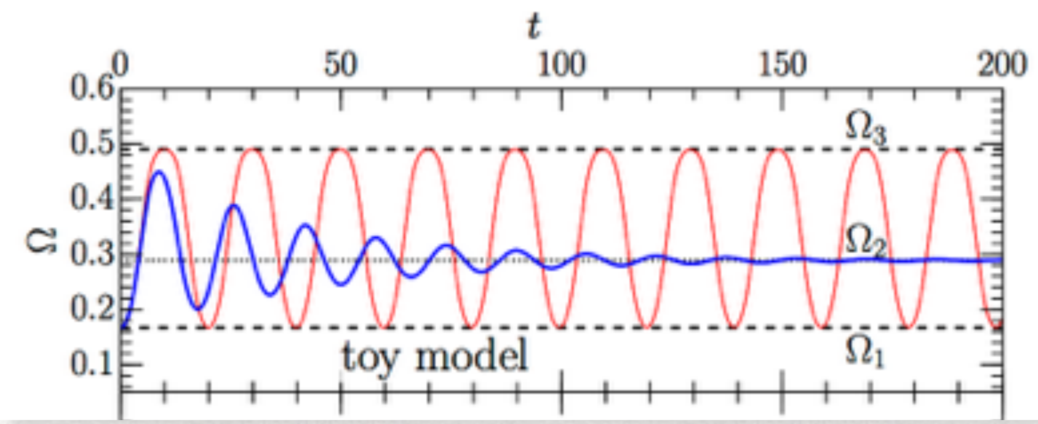




A mechanical toy model for the **f_1, f_3** peaks

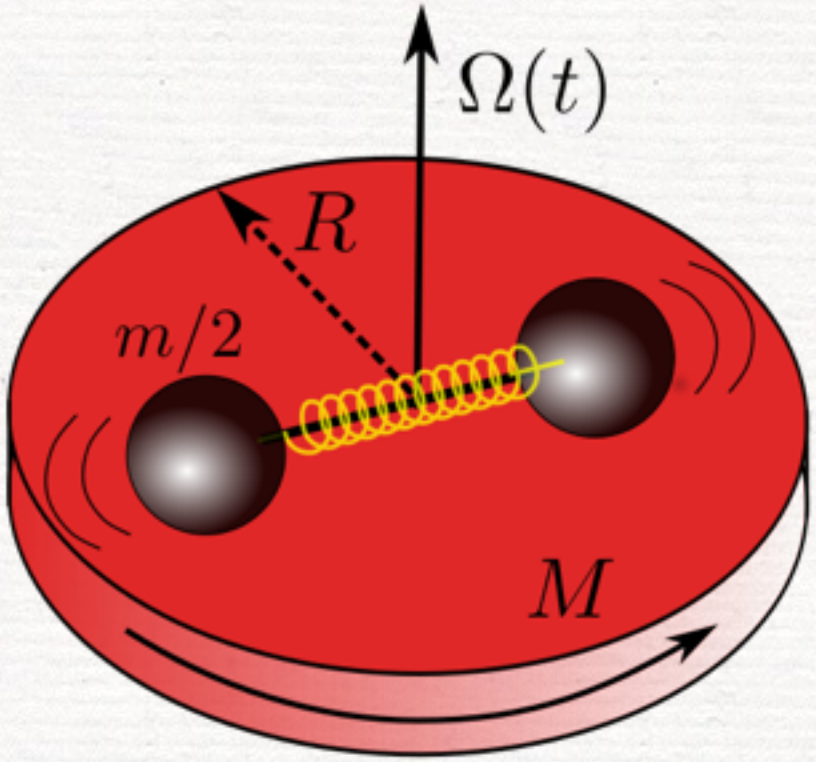


- Consider disk with 2 masses moving along a shaft and connected via a spring ~ HMNS with 2 stellar cores
- Let disk rotate and mass oscillate while conserving angular momentum



- If there is no friction, system will spin between: low freq (**f_1**, masses are far apart) and high (**f_3**, masses are close).
- If friction is present, system will spin asymptotically at **$f_2 \sim (f_1+f_3)/2$**.

A mechanical toy model for the **f_1**, **f_3** peaks



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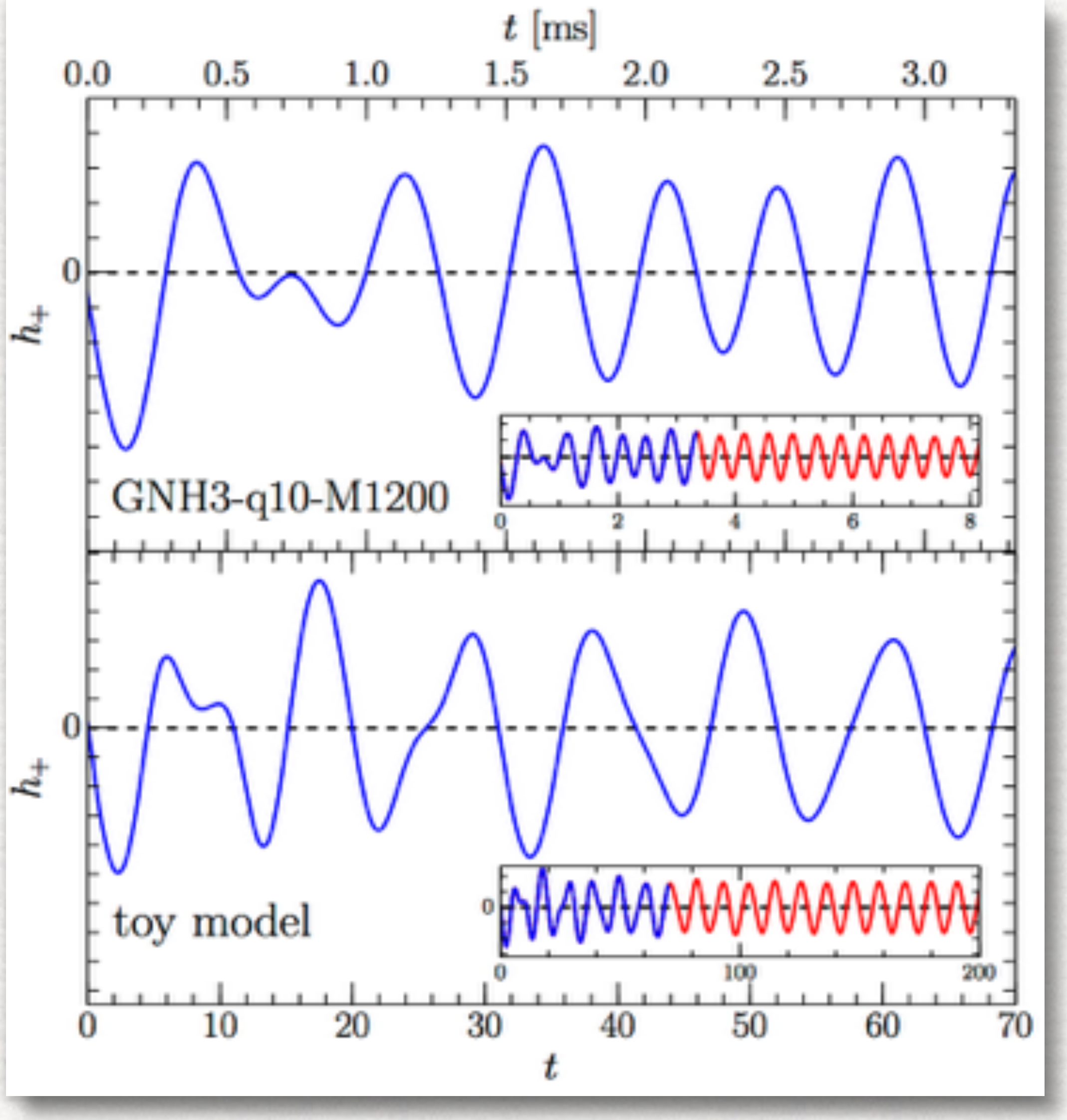
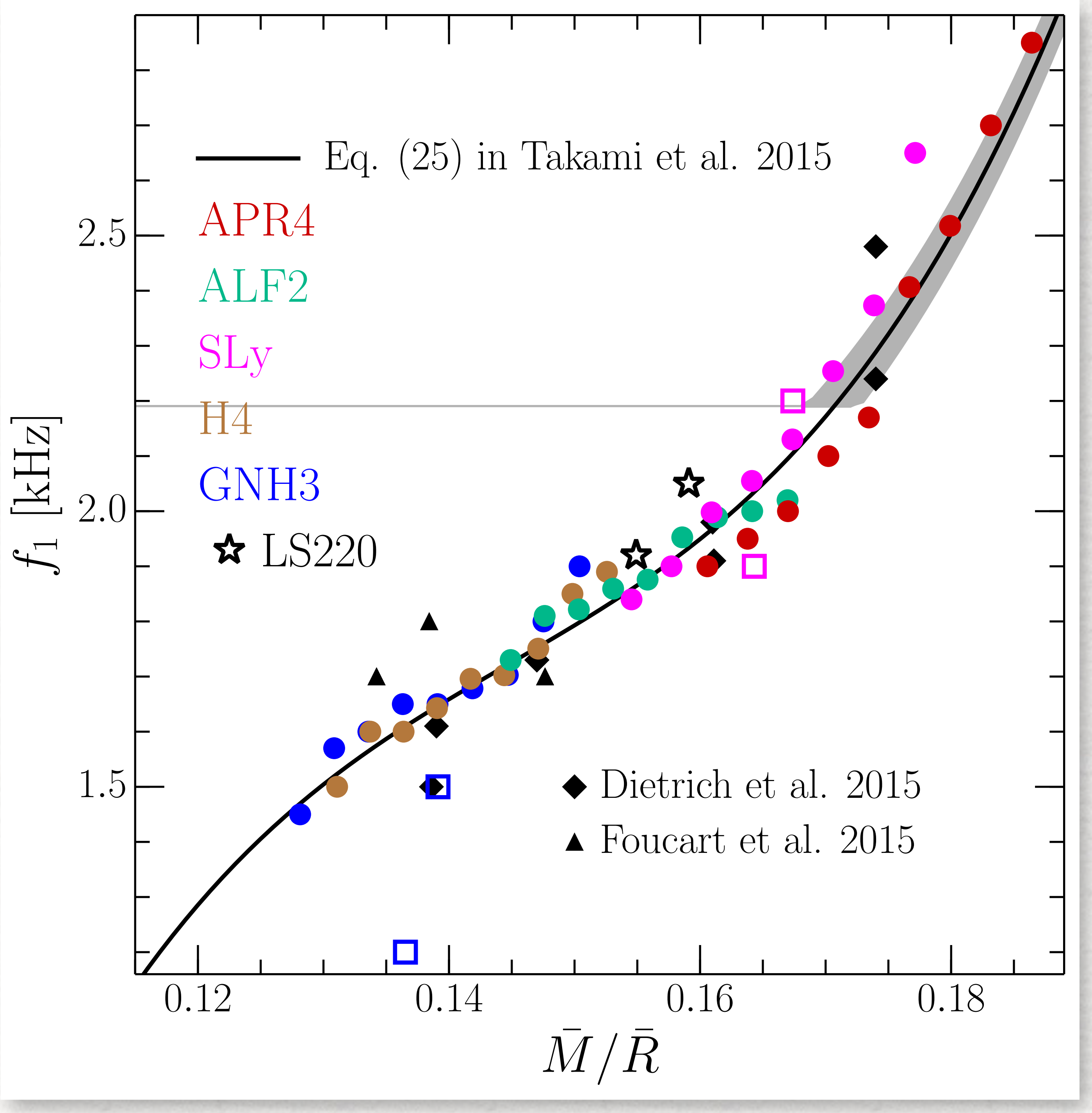
- If friction is present, system will spin asymptotically at **$f_2 \sim (f_1+f_3)/2$**.
- analytic model possible of post merger (see later).



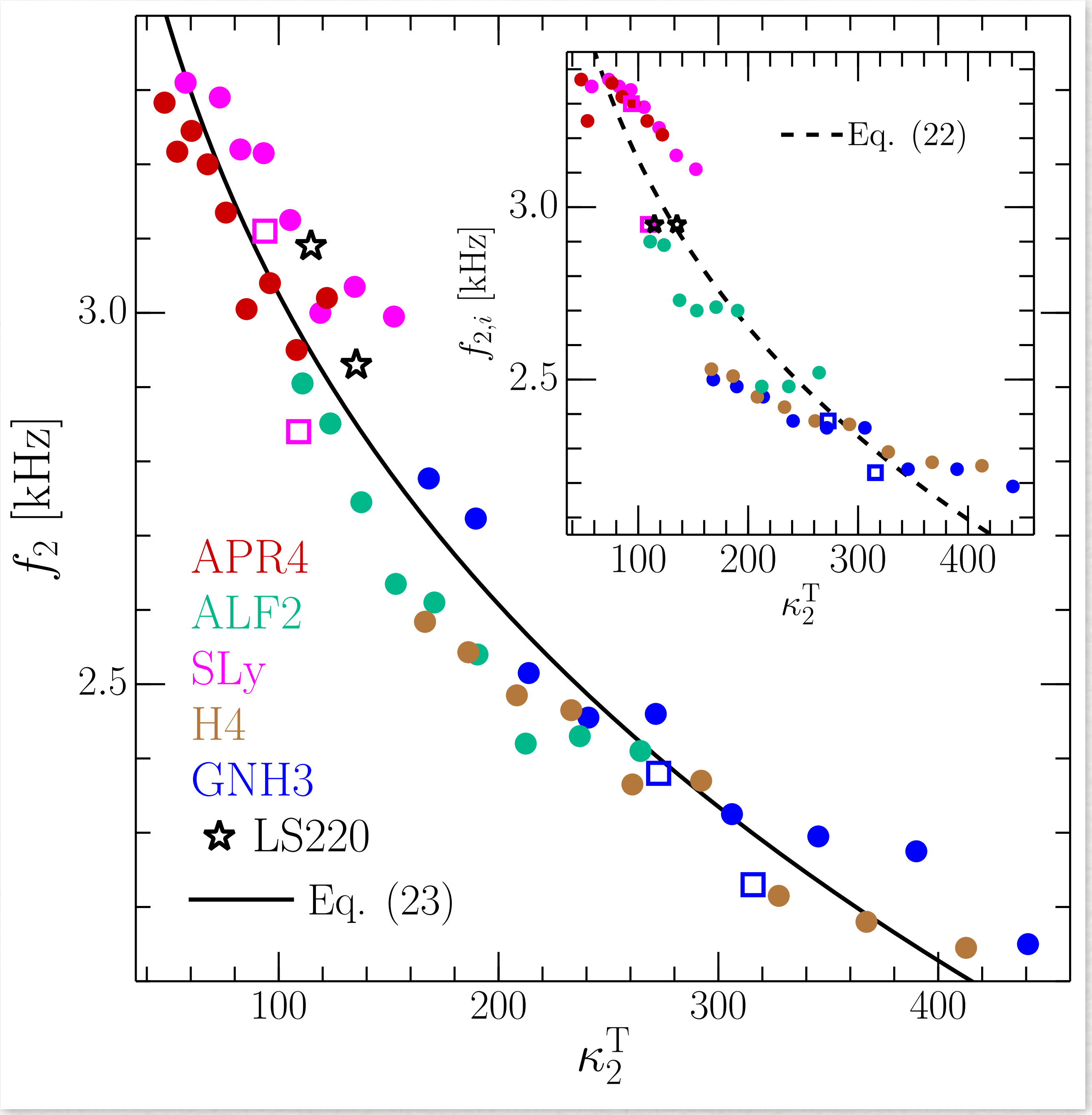
Quasi-universal behaviour: post-merger



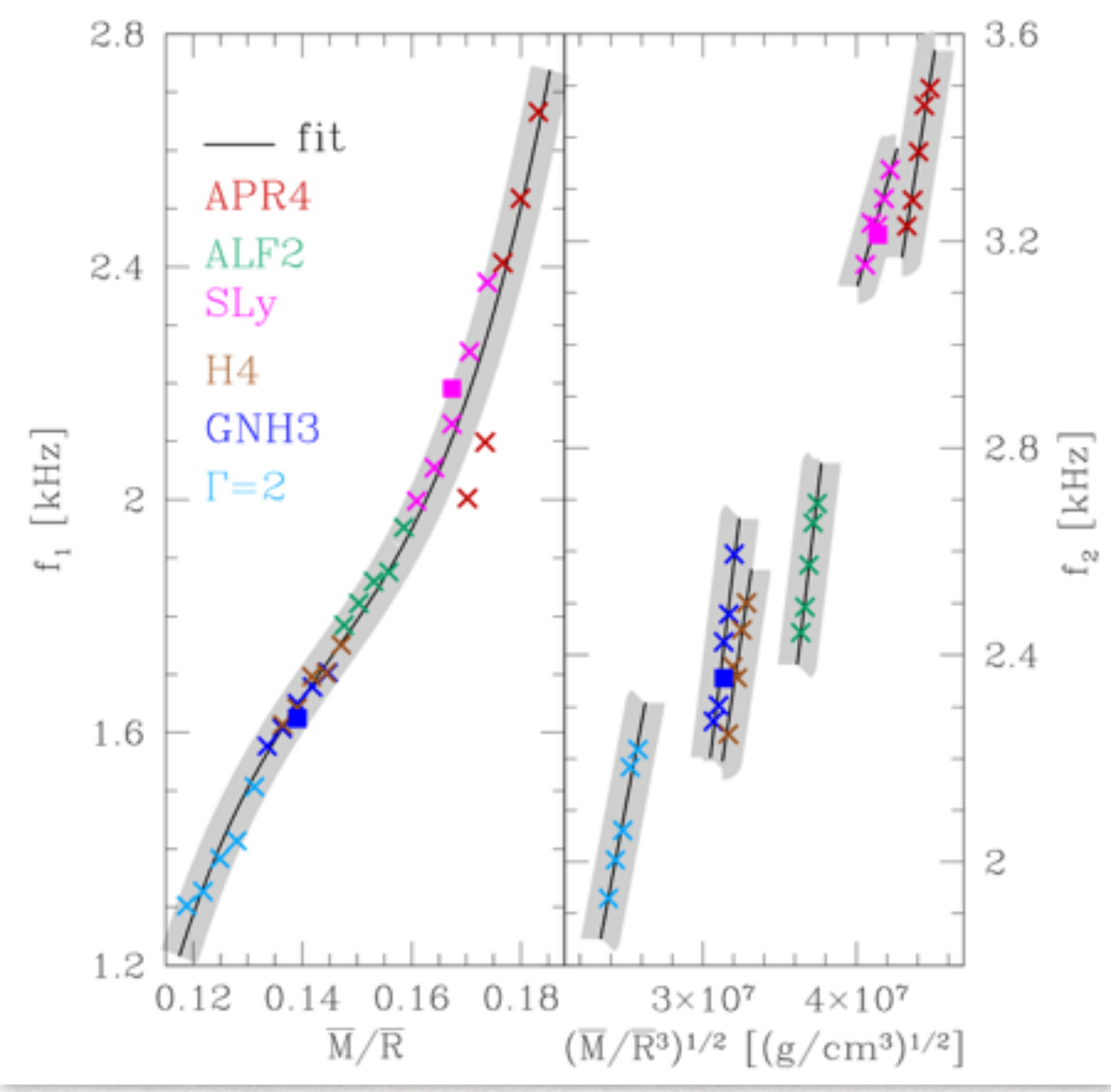
We have found **quasi-universal behaviour**: i.e., the properties of the spectra are only weakly dependent on the EOS.

This has profound implications for the analytical modelling of the GW emission: "what we do for one EOS can be extended to all EOSs."

Quasi-universal behaviour: post-merger



Correlations with Love number found also for high frequency peak **f_2**



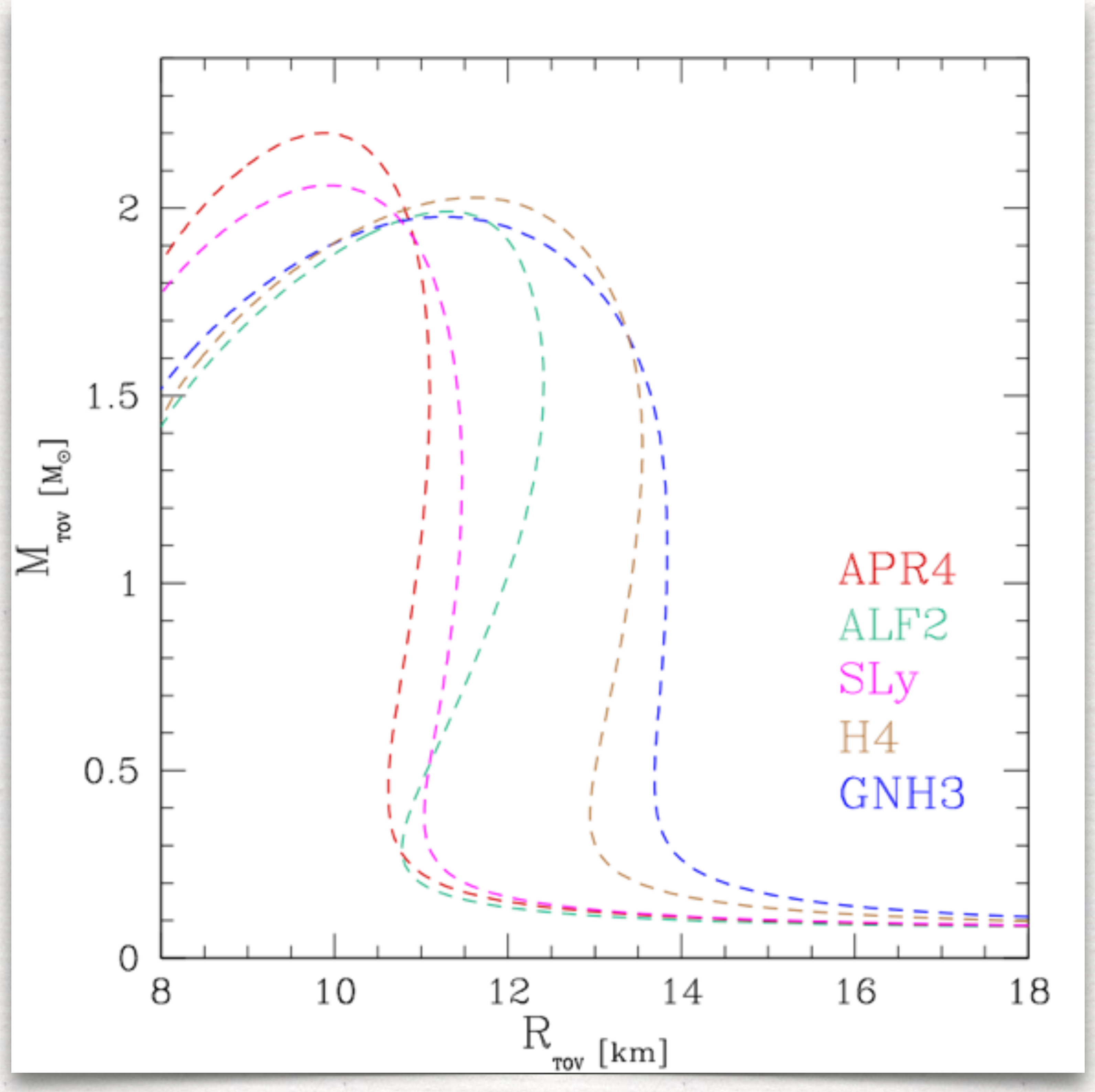
Correlations also with compactness

These other correlations are **weaker** but equally useful.

An example: start from equilibria

Assume that the GW signal from a binary NS is detected and with a SNR high enough that the two peaks are clearly measurable.

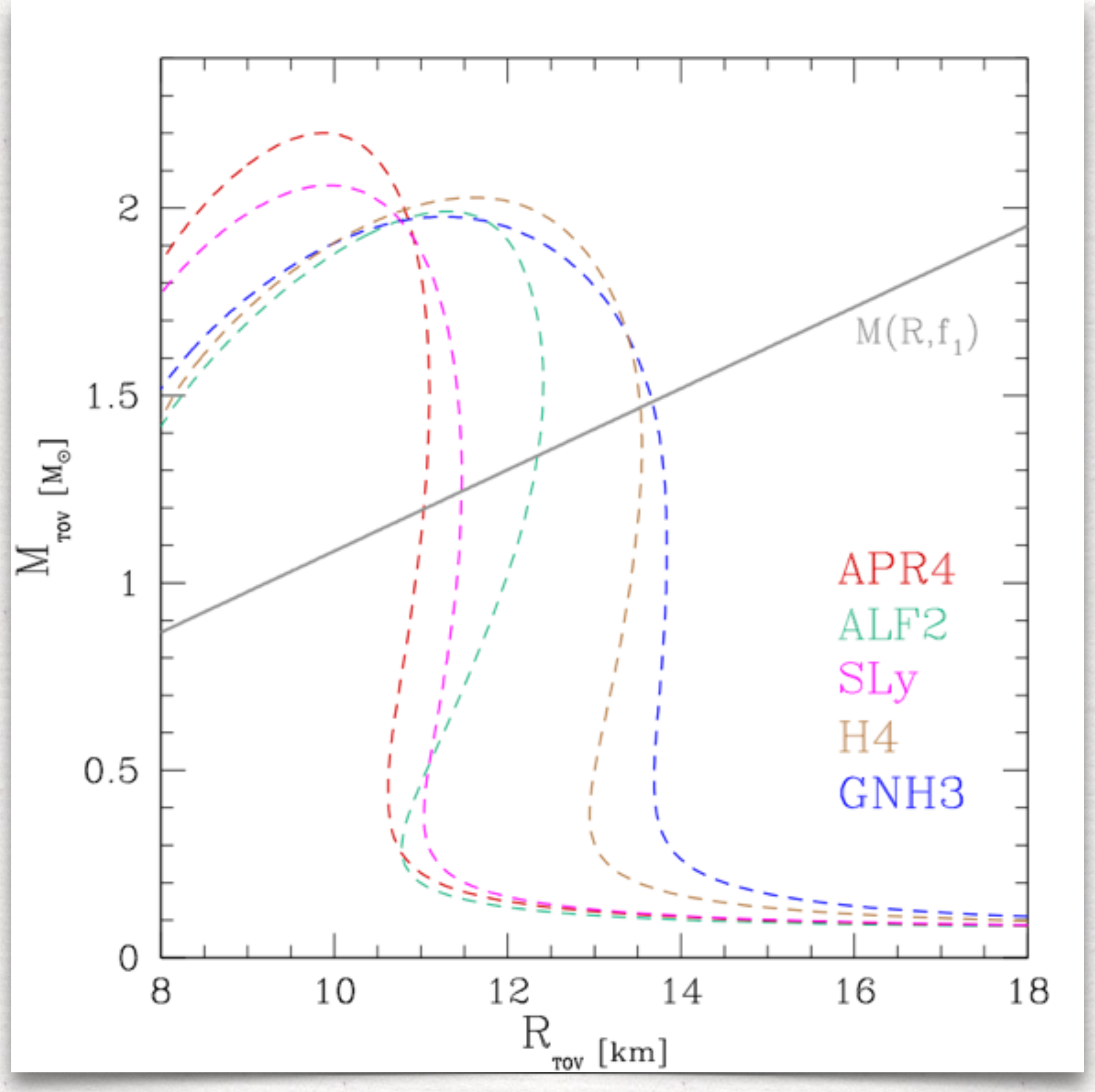
Consider your best choices as candidate EOSs



An example: use the *M(R,f$_I$)* relation

The measure of the **f$_I$** peak will fix a *M(R,f$_I$)* relation and hence a **single** line in the *(M, R)* plane.

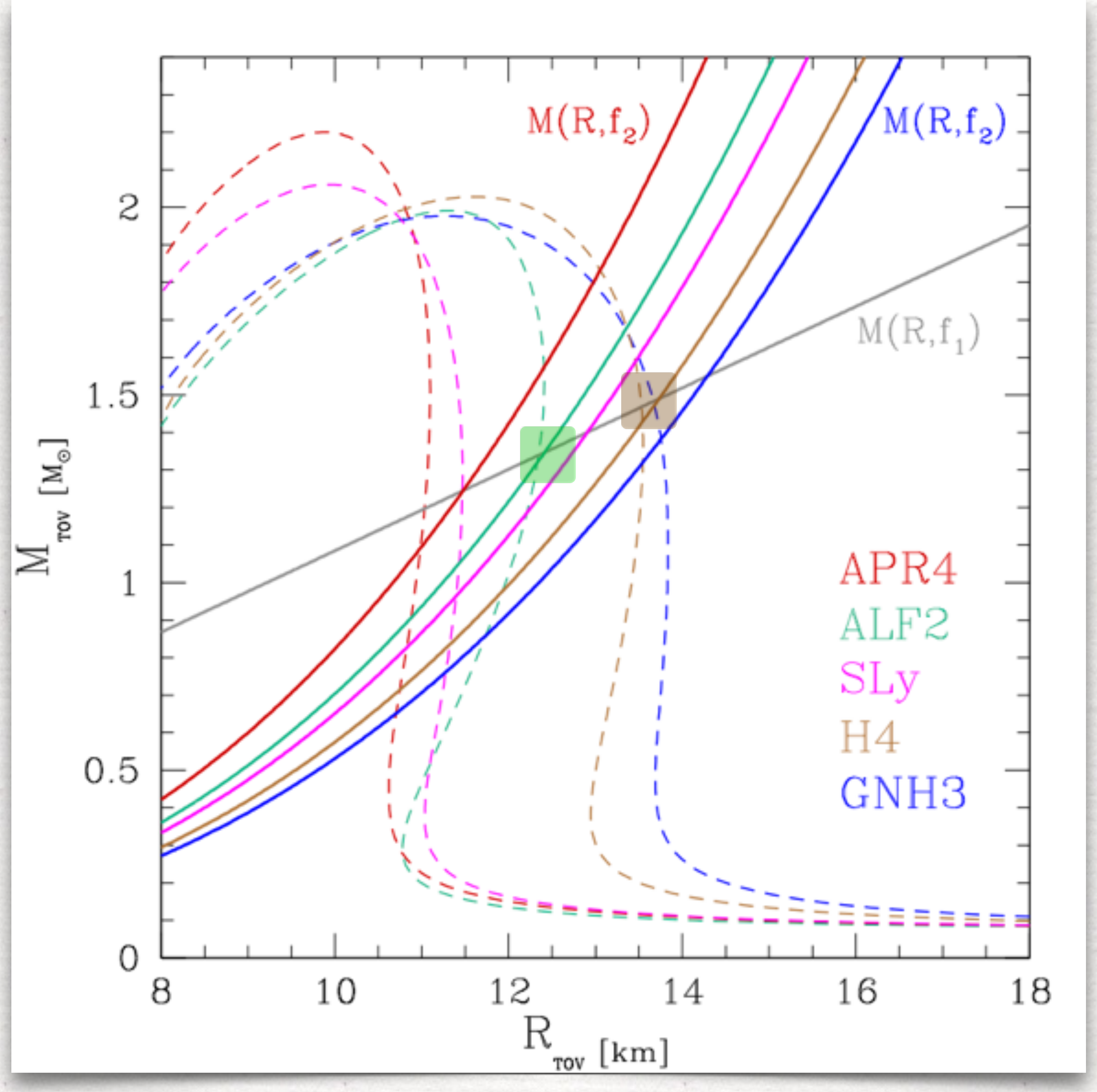
All EOSs will have **one** constraint (crossing)



An example: use the $M(R,f_2)$ relations

The measure of the **f_2** peak will fix a relation $M(R,f_2,EOS)$ for each EOS and hence a **number** of lines in the (M, R) plane.

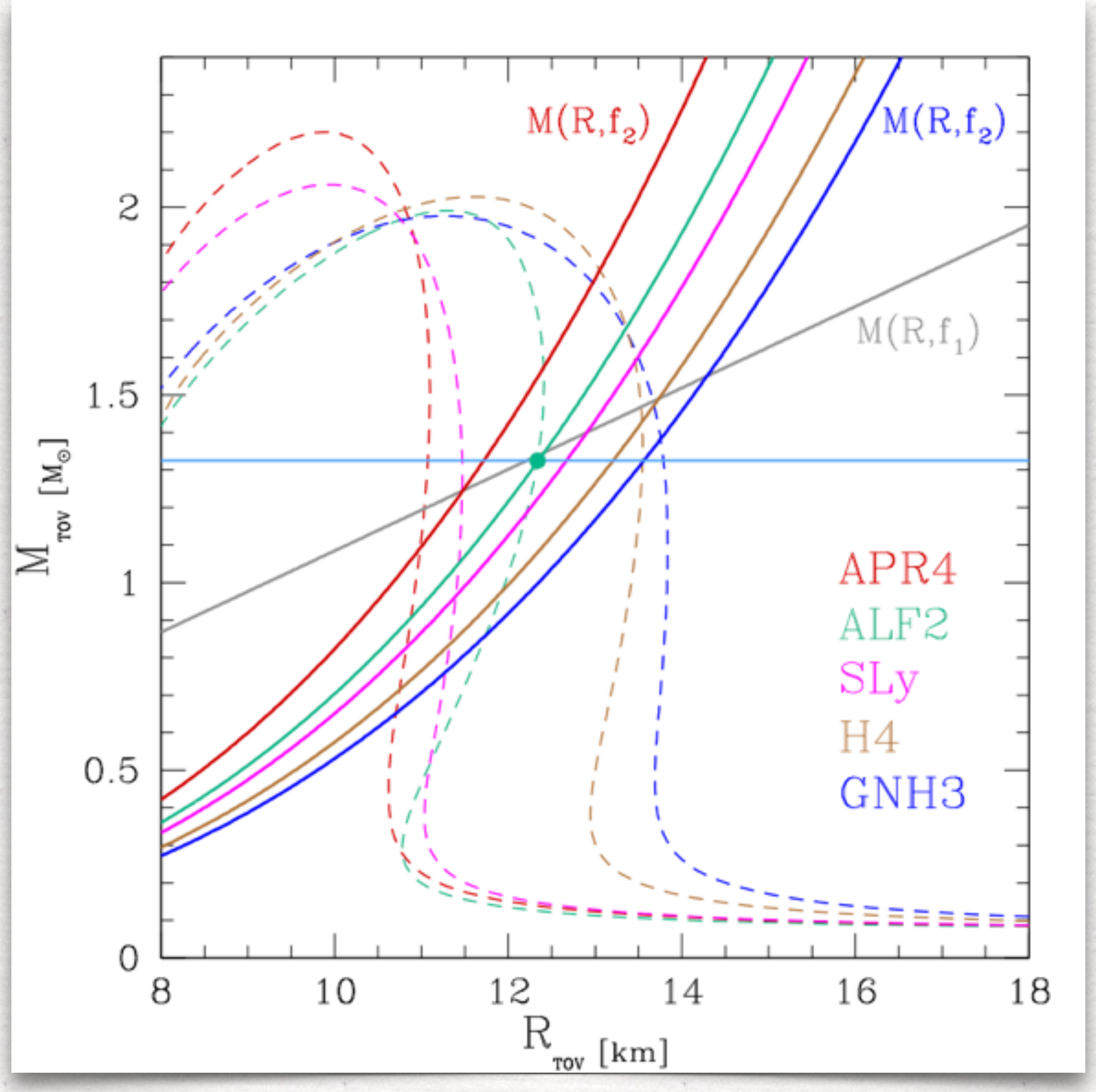
The right EOS will have **three** different constraints (APR, GNH3, SLy excluded)



An example: use measure of the mass

If the mass of the binary is measured from the inspiral, an additional constraint can be imposed.

The right EOS will have **four** different constraints. Ideally, a single detection would be sufficient.

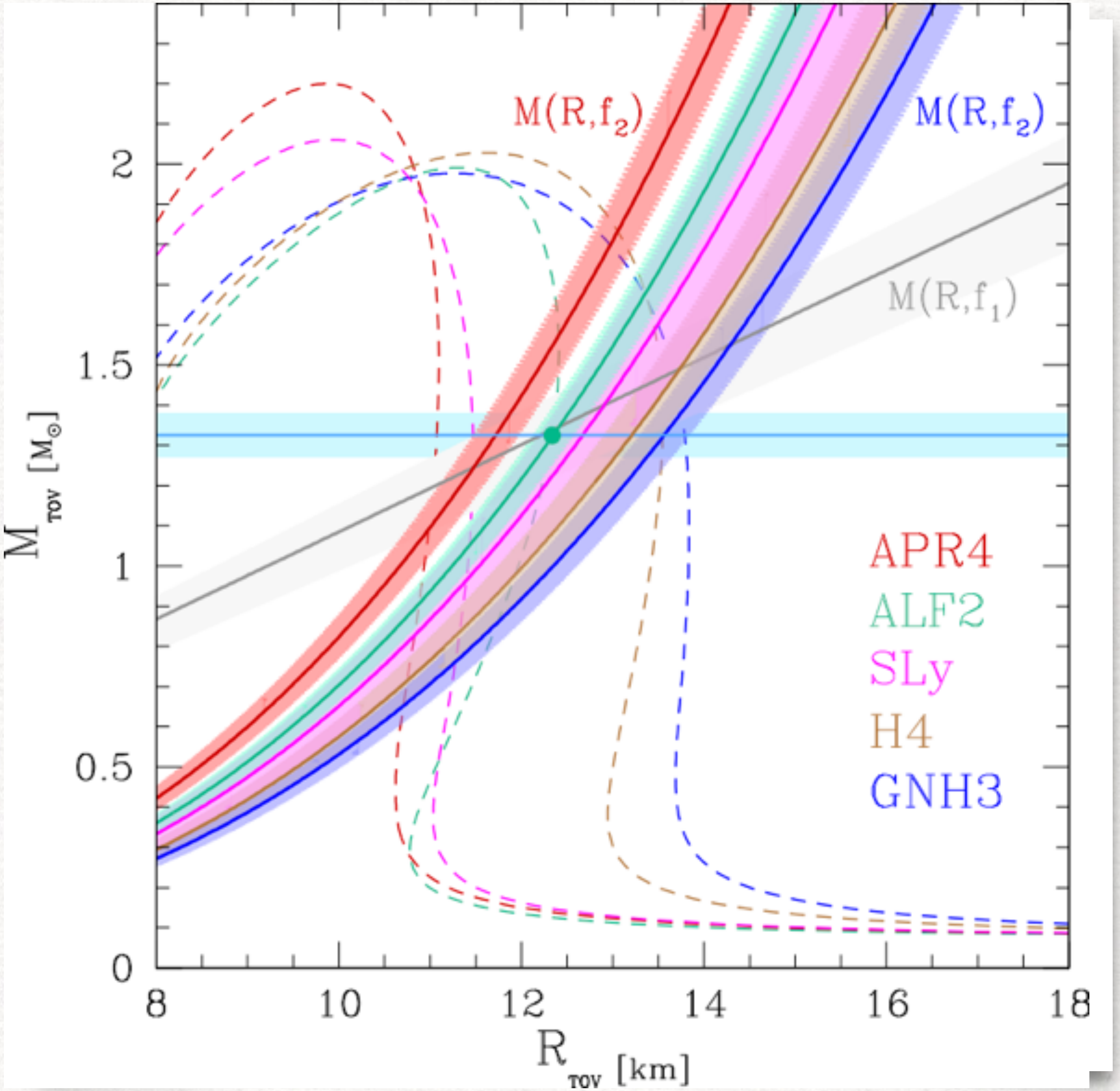


This works for all EOSs considered

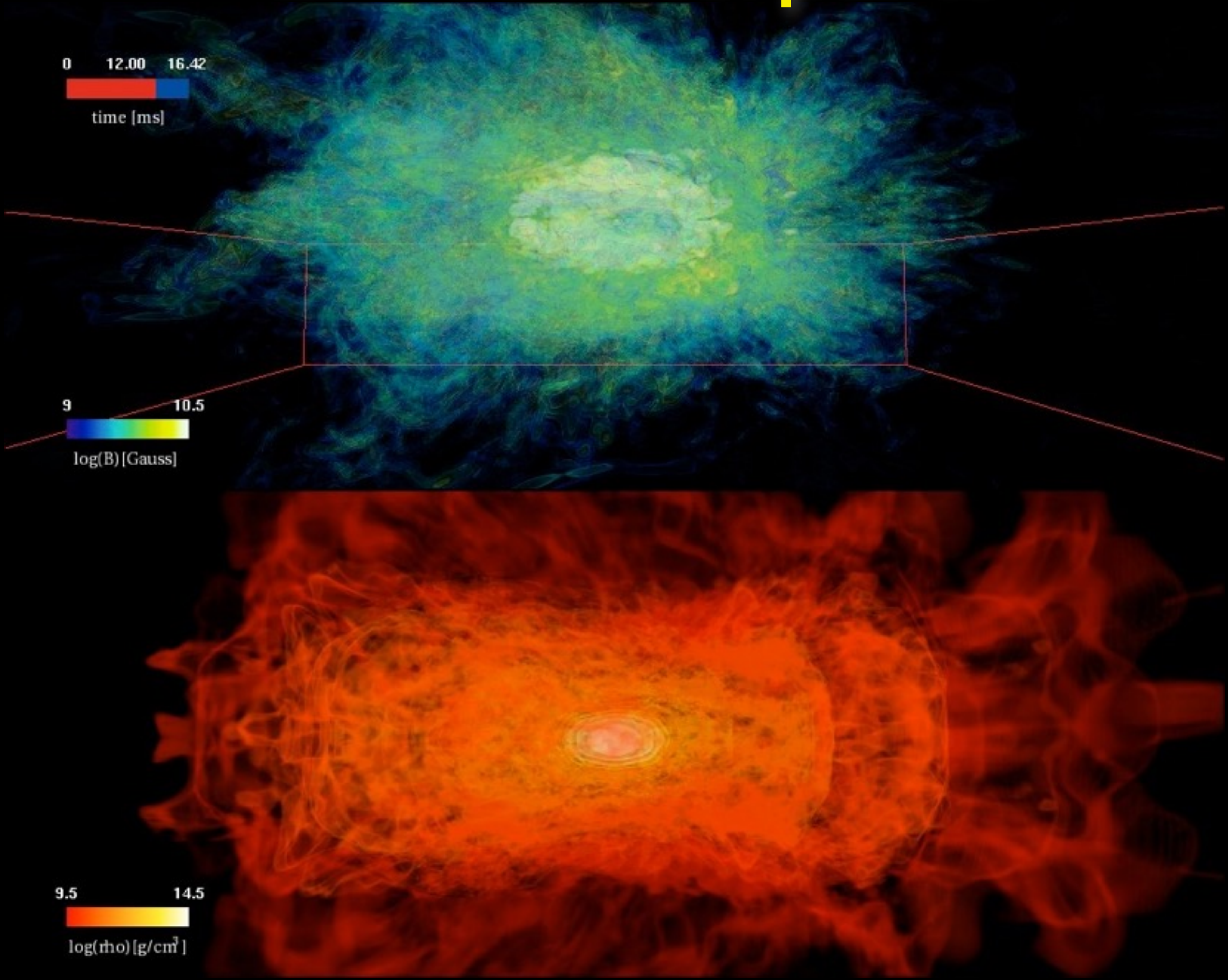
In reality things will be more complicated. The **lines** will be **stripes;** Bayesian probability to get precision on *M*, *R*.

Some numbers:

- at 50 Mpc, freq. uncertainty from Fisher matrix is 100 Hz
- at SNR=2, the event rate is 0.2-2 yr^{-1} for different EOSs.



EM counterparts



Electromagnetic counterpart (EMC)

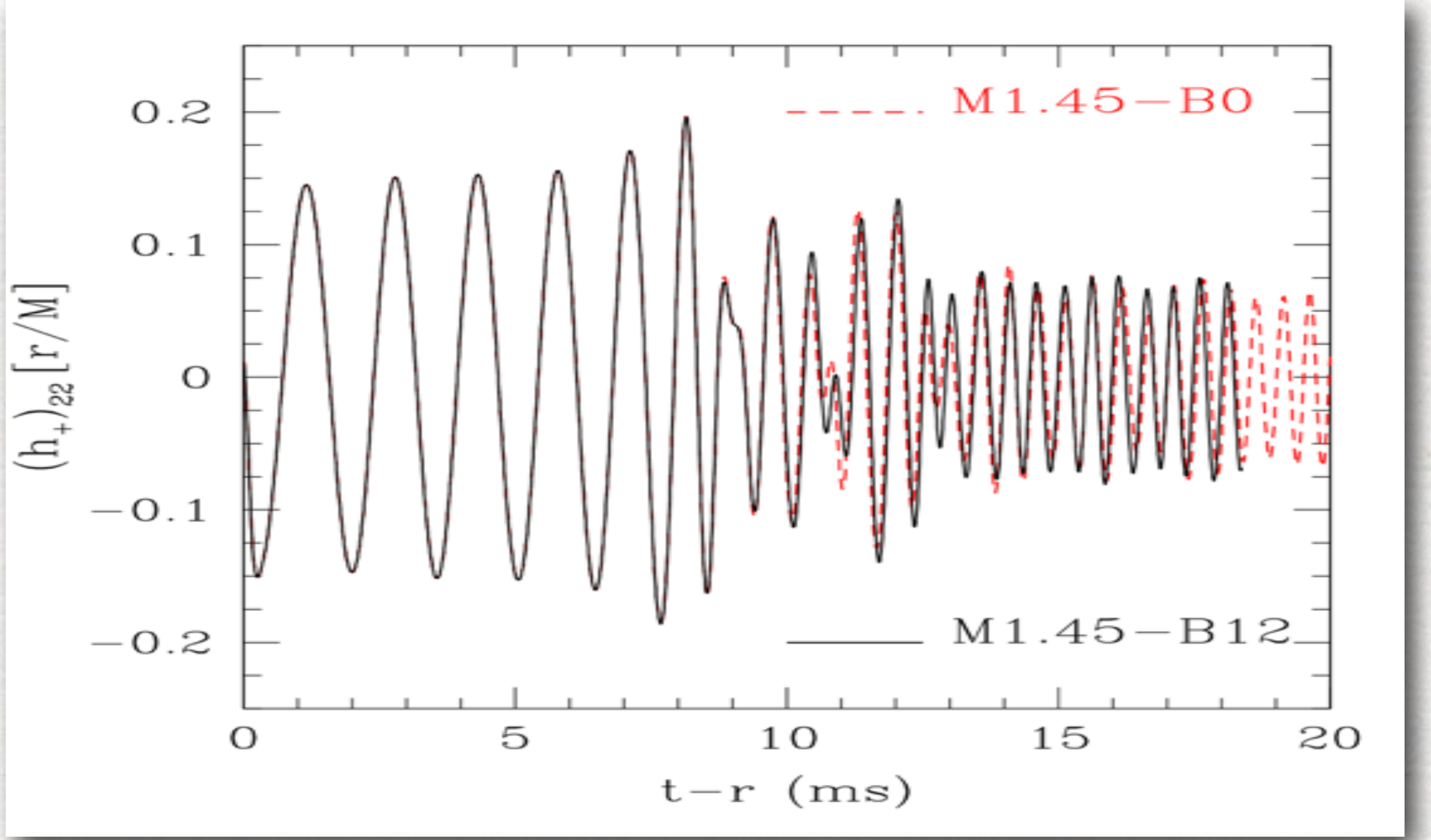
B-fields essential for EMCs. Most simulations use **ideal MHD**: infinite conductivity, magnetic field advected.

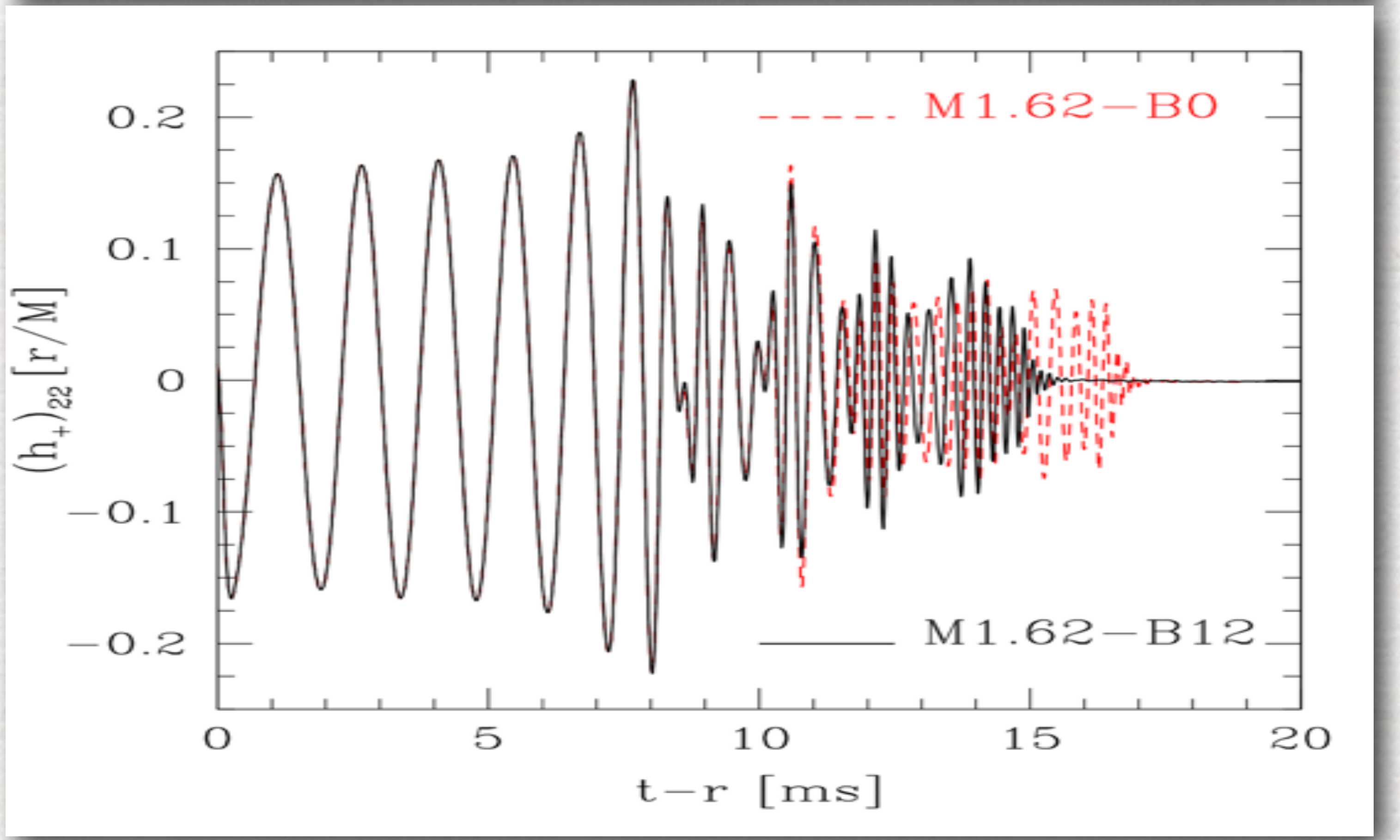
You can ask some simple questions.

- can B-fields be measured during the inspiral? ✅
- is EMC produced before merger? ❓
- do B-fields grow after merger and yield EMC? ❓
- do B-fields grow after BH formation and yield EMC? ❓

Last two questions are **incredibly hard** to answer; may require far more sophisticated numerics and microphysics

Waveforms: comparing against magnetic fields





Compare B/no-B field:

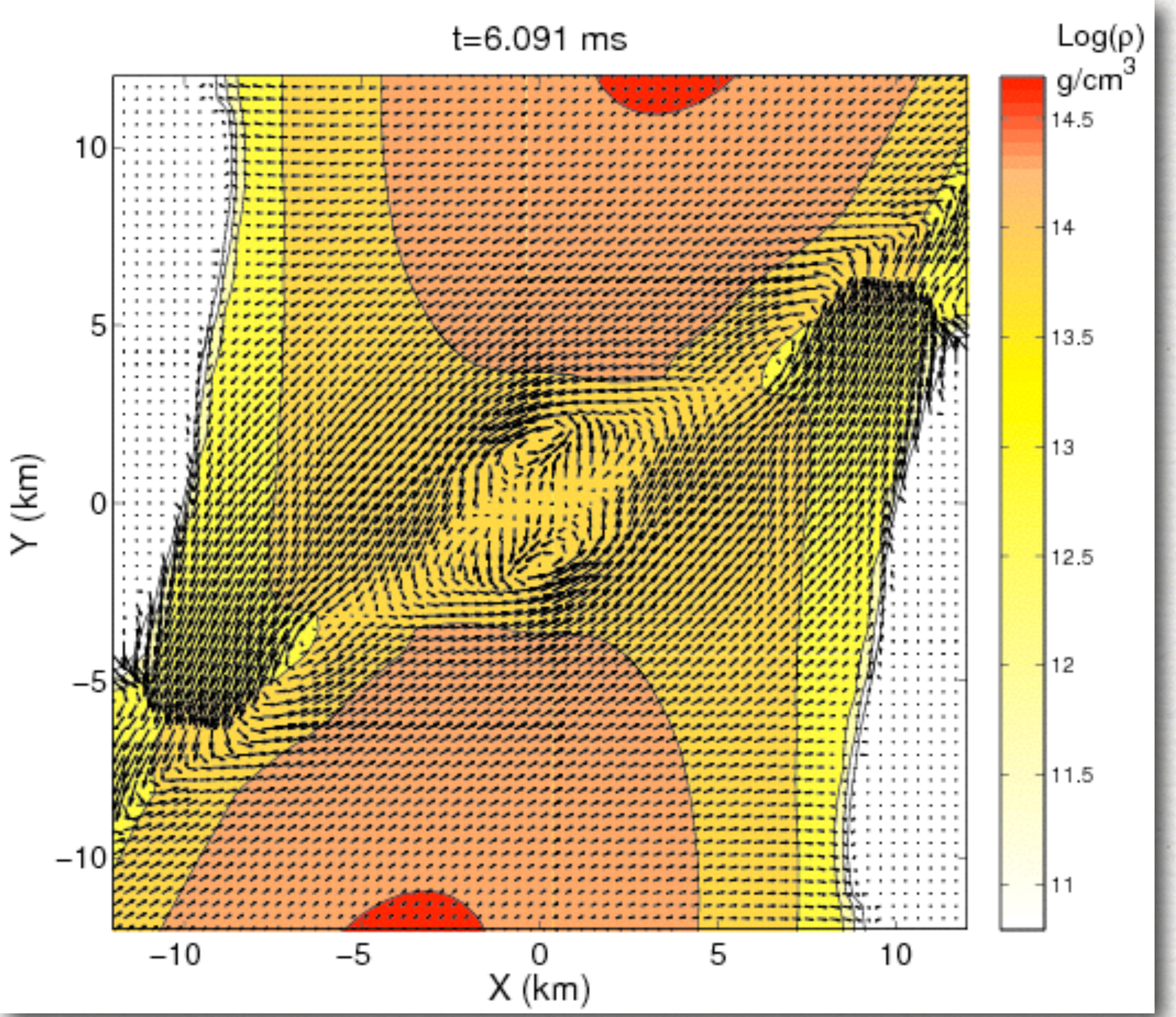
- **inspiral** waveform is different but for unrealistic B-fields (i.e. B~10^{17} G).

- **post-merger** waveform is different for all masses; strong B-fields delay the collapse to BH

Influence of B-fields on inspiral is **unlikely to be detected** for realistic fields

MHD instabilities and B-field amplifications

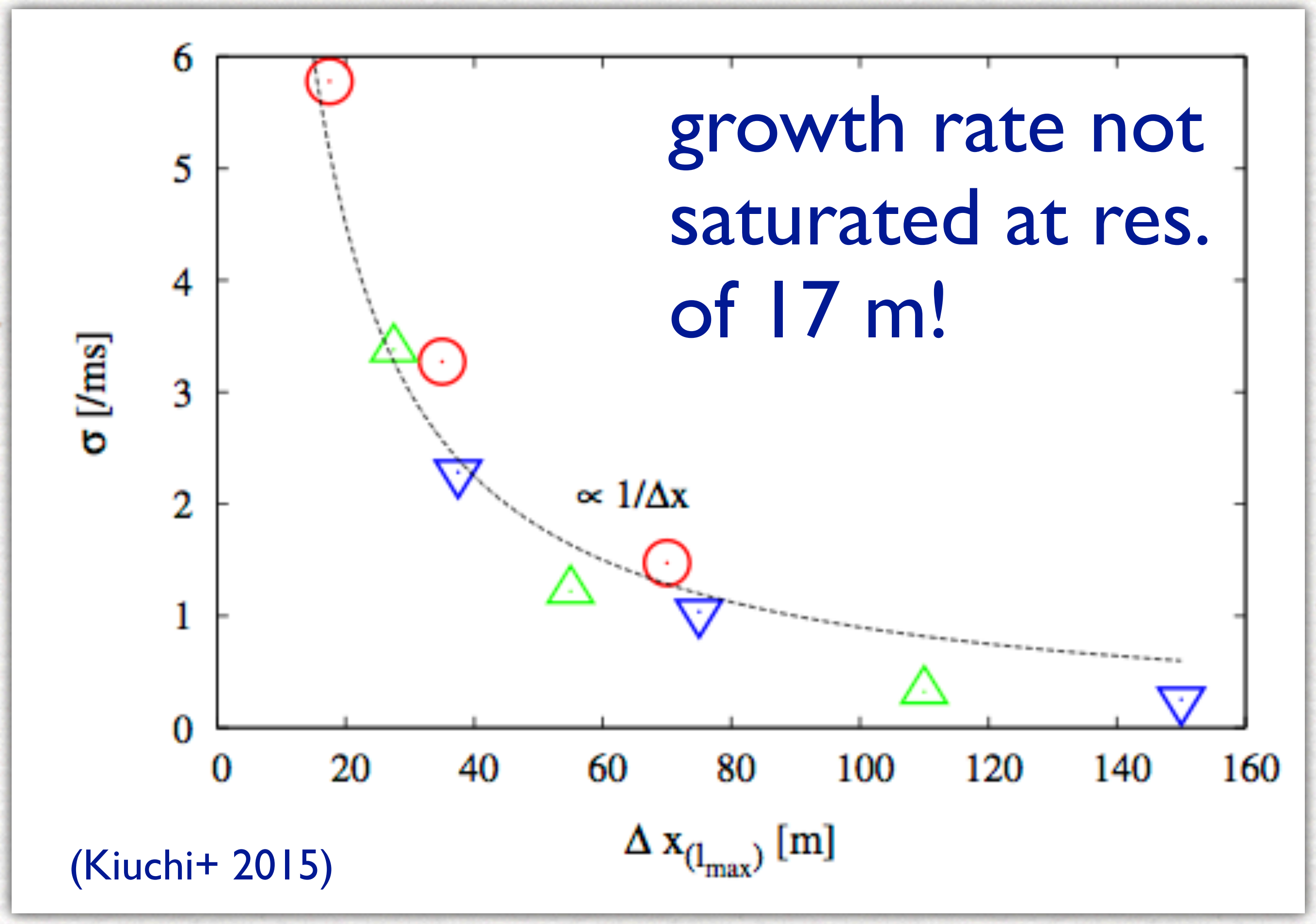
- at the merger, the NS create a strong shear layer which could lead to a **Kelvin-Helmholtz instability**; magnetic field can be amplified



(Baiotti+2008)

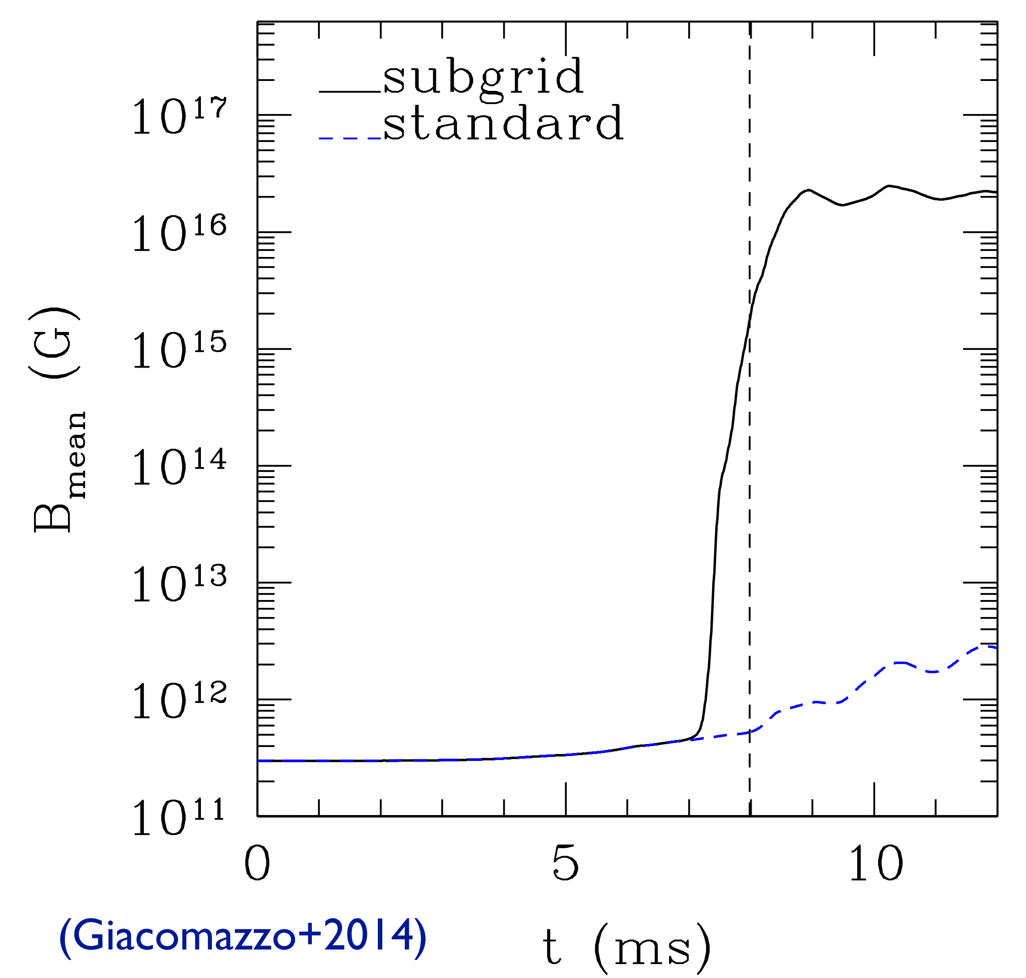
MHD instabilities and B-field amplifications

- at the merger, the NS create a strong shear layer which could lead to a **Kelvin-Helmholtz instability**; magnetic field can be amplified
- **low-res** simulations don't show exponential growth (Giacomazzo+2011) **high-res** simulations show increase of ~ 3 orders of mag (Kiuchi+2015)
- **sub-grid** models suggest B-field grows to 10^{16} G (Giacomazzo+2014)



growth rate not saturated at res. of 17 m!

(Kiuchi+ 2015)



(Giacomazzo+2014)

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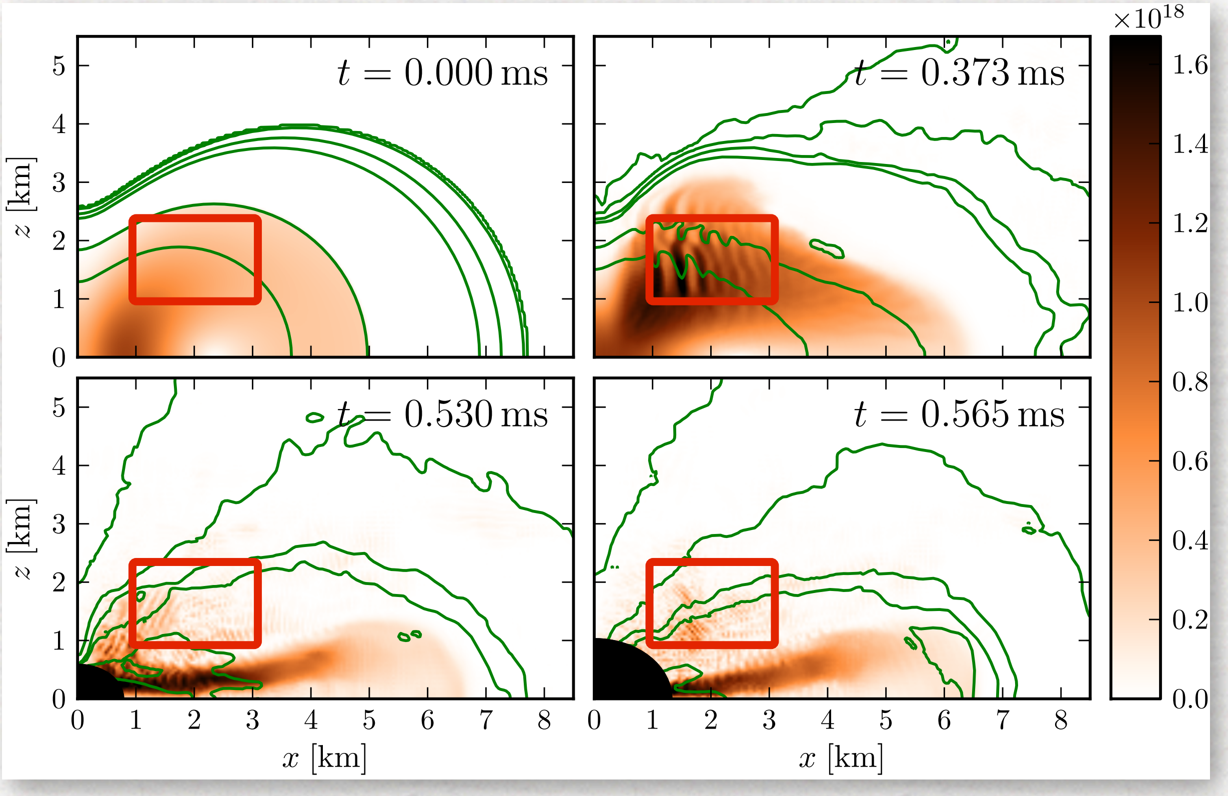
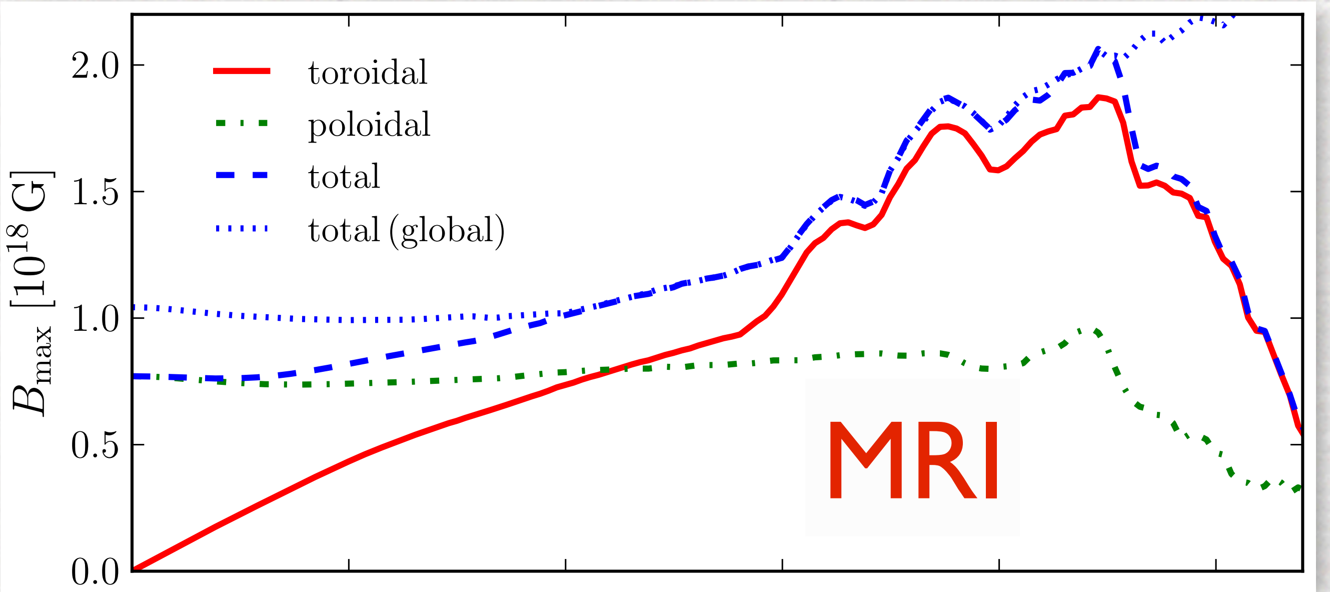
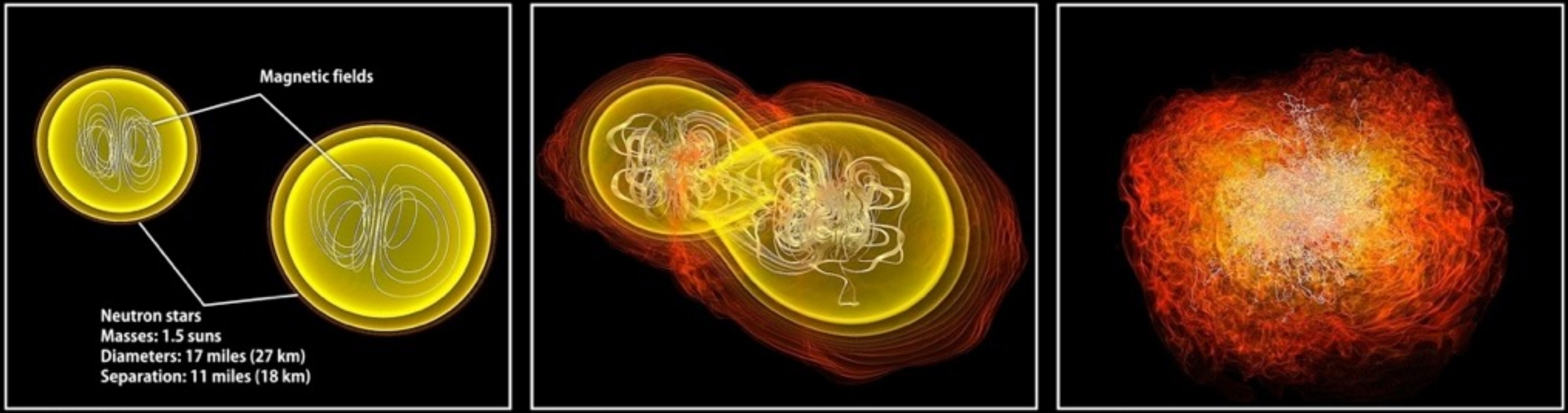




Siegel+2013

- differentially rotating magnetized fluids develop an **MRI**
- the MRI leads to exponential growth of B-field and outward transfer of ang. momentum (accretion in discs).
- consensus MRI **can develop** in HMNS (Siegel+2013,Kiuchi+2014)
- degree of amplification is **unknown**: 2-3 or 5-6 orders of magnitude? Resistivity? (Kiuchi+2015, Obergaulinger+2015)

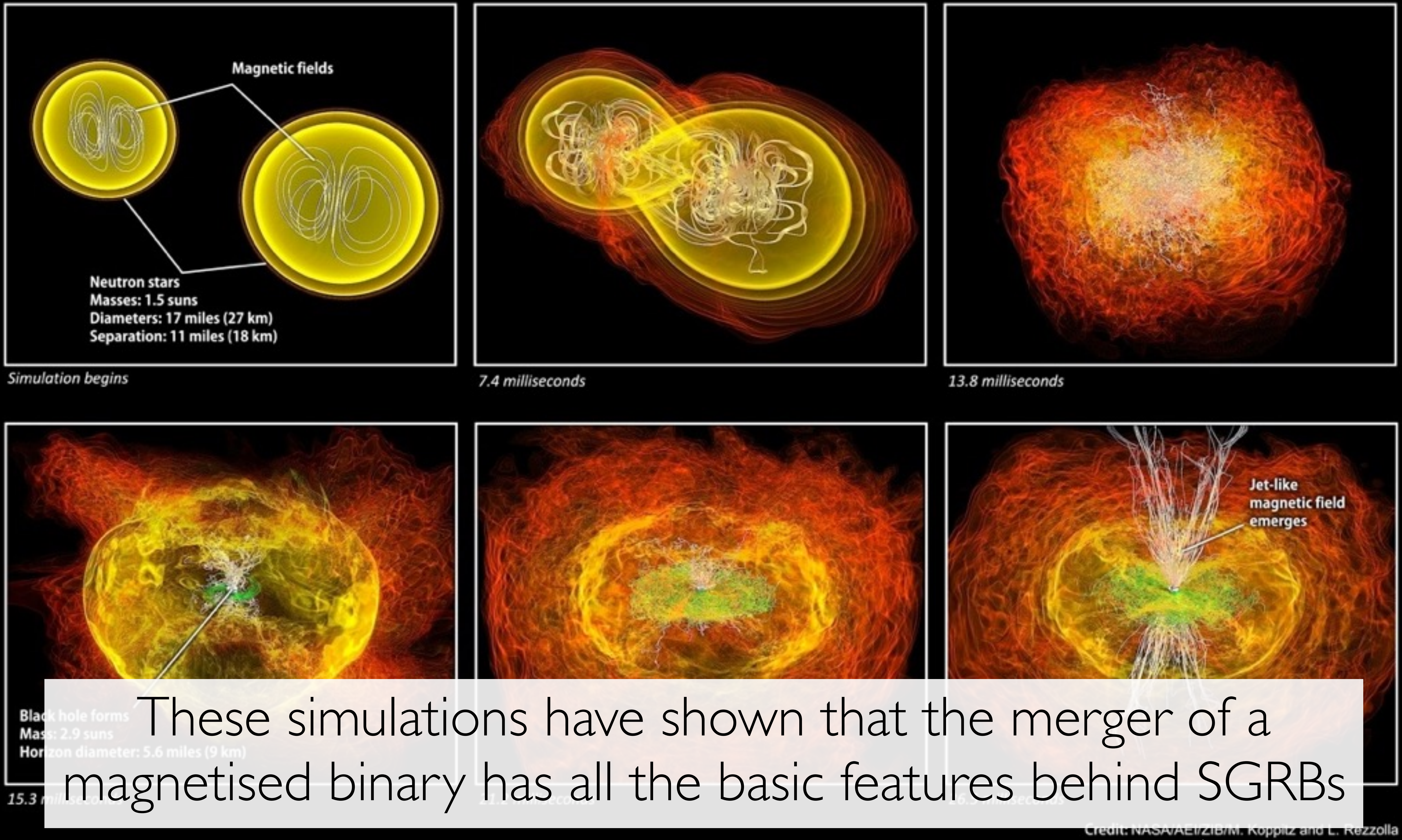
What happens when two magnetised stars collide?



Simulation begins *7.4 milliseconds* *13.8 milliseconds*

Magnetic fields in the HMNS have complex topology: dipolar fields are destroyed.

LR+ 2011



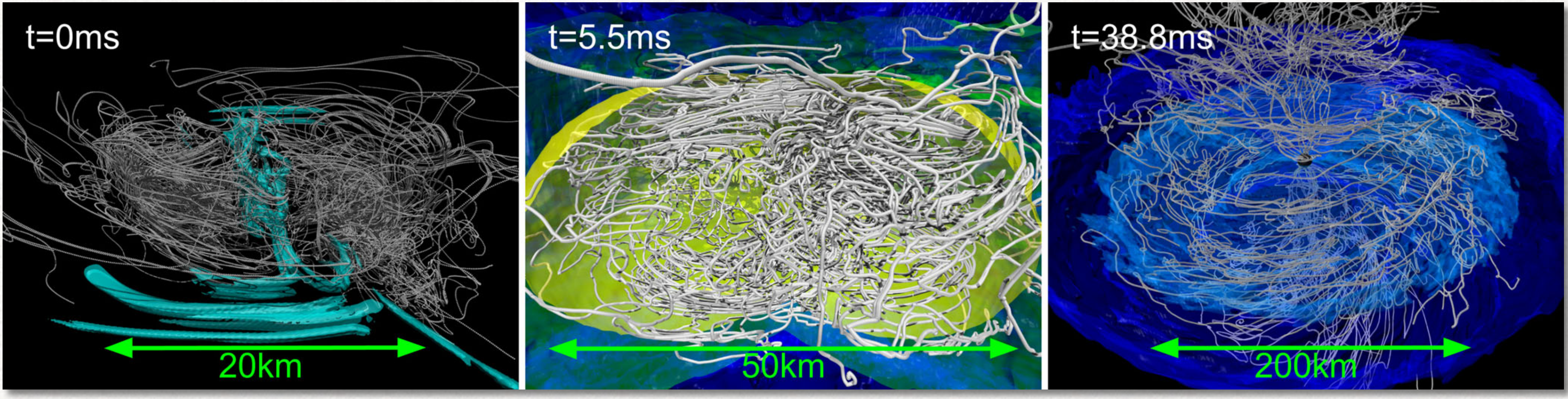
These simulations have shown that the merger of a magnetised binary has all the basic features behind SGRBs

Credit: NASA/AEI/ZIB/M. Koppitz and L. Rezzolla

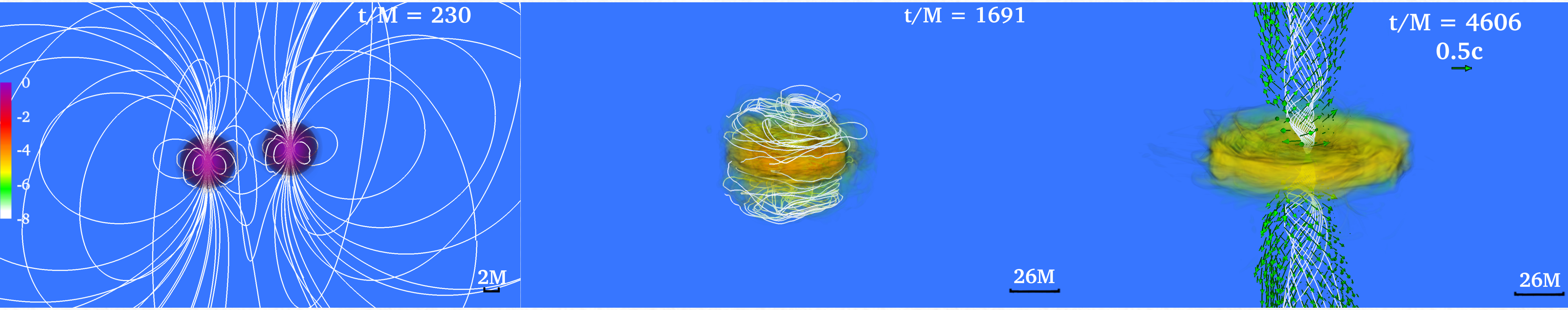
$J/M^2 = 0.83$ $\mathrm{M}_{\mathrm{tor}} = 0.063 M_{\odot}$ $\mathrm{t}_{\mathrm{accr}} \simeq M_{\mathrm{tor}}/\dot{M} \simeq 0.3\ \mathrm{s}$

Results from other groups (IMHD only)

With due differences, other groups confirm this picture.

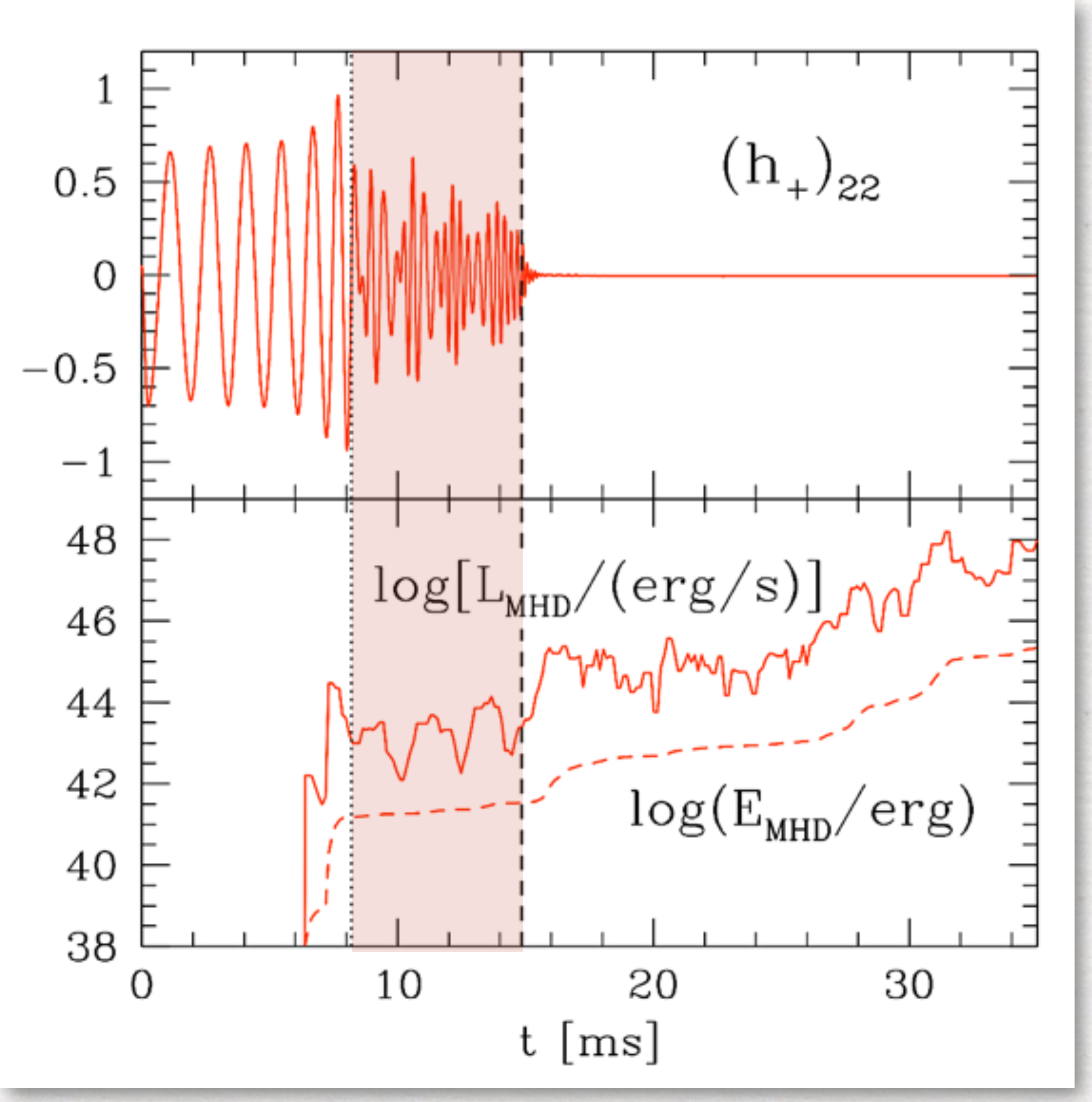


Kiuchi+ 2014



Ruiz+ 2016

A genuine multimessenger signal



- ✶GW signal shuts-off after BH formation.
- ✶EM signal roughly constant during the HMNS phase
- ✶After the BH formation, the EM grows exponentially
- ✶EM energy released ~**10^{46} erg**; luminosity ~**10^{48} erg/s**
- ✶Despite crudeness, ball-park numbers match observations.

Beyond IMHD: Resistive Magnetohydrodynamics

Dionysopoulou, Alic, LR (2015)

- Ideal MHD is a good approximation in the inspiral, but not after the merger; match to **electro-vacuum** not possible.
- Main difference in resistive regime is the current, which is dictated by Ohm's law but microphysics is **poorly** known.
- We know conductivity σ is a **tensor** and proportional to density and inversely proportional to temperature.
- A simple prescription with scalar (isotropic) conductivity:

$$J^i = qv^i + W\sigma[E^i + \epsilon^{ijk}v_j B_k - (v_k E^k)v^i]\,,$$

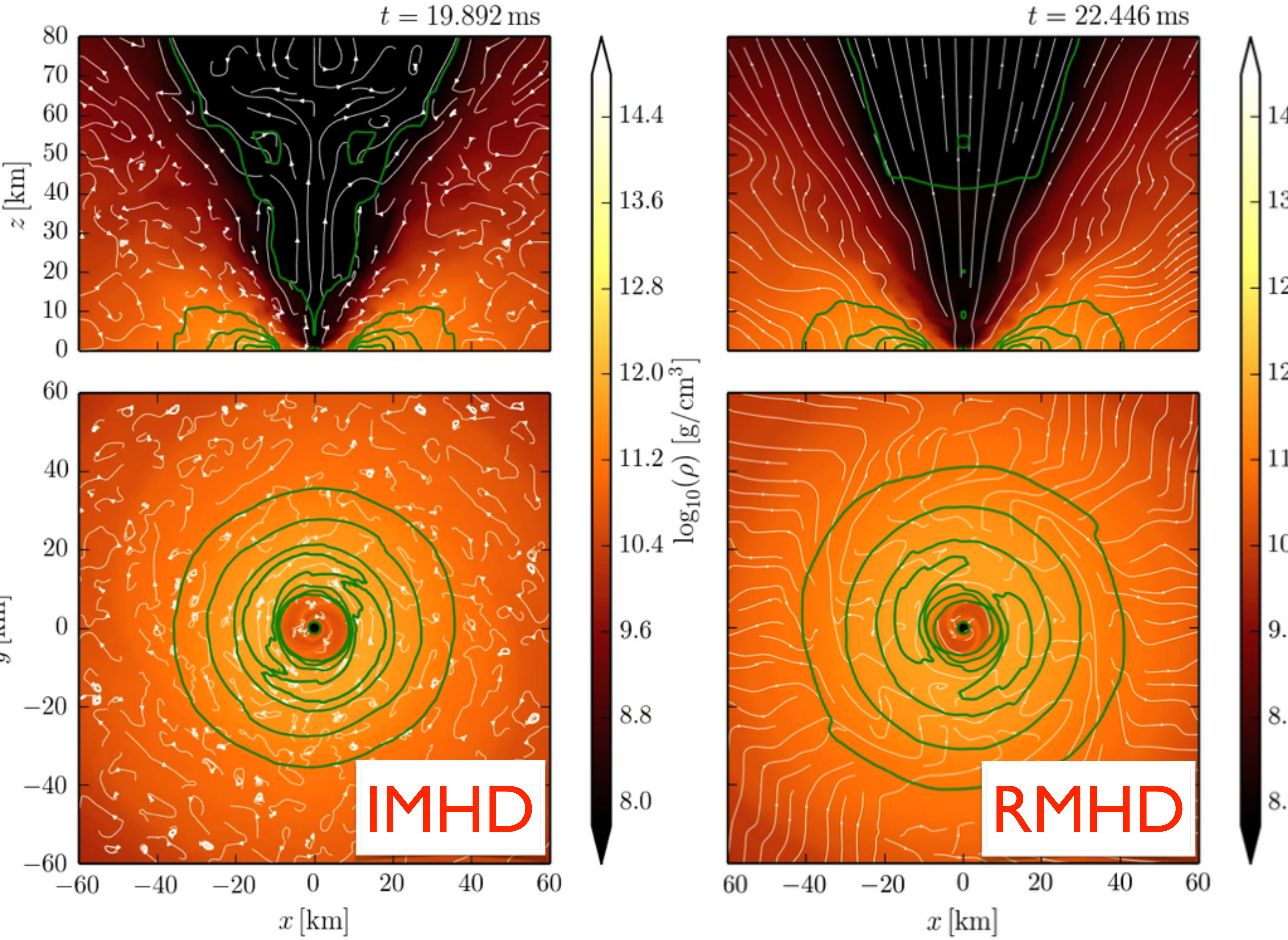
$\sigma \to \infty$ ideal-MHD (IMHD)

$\sigma \neq 0$ resistive-MHD (RMHD)

$\sigma \to 0$ electrovacuum

$$\boxed{\sigma = f(\rho, \rho_{\min})}$$

phenomenological prescription


$t = 19.892\,\mathrm{ms}$
$t = 22.446\,\mathrm{ms}$
z [km]
80
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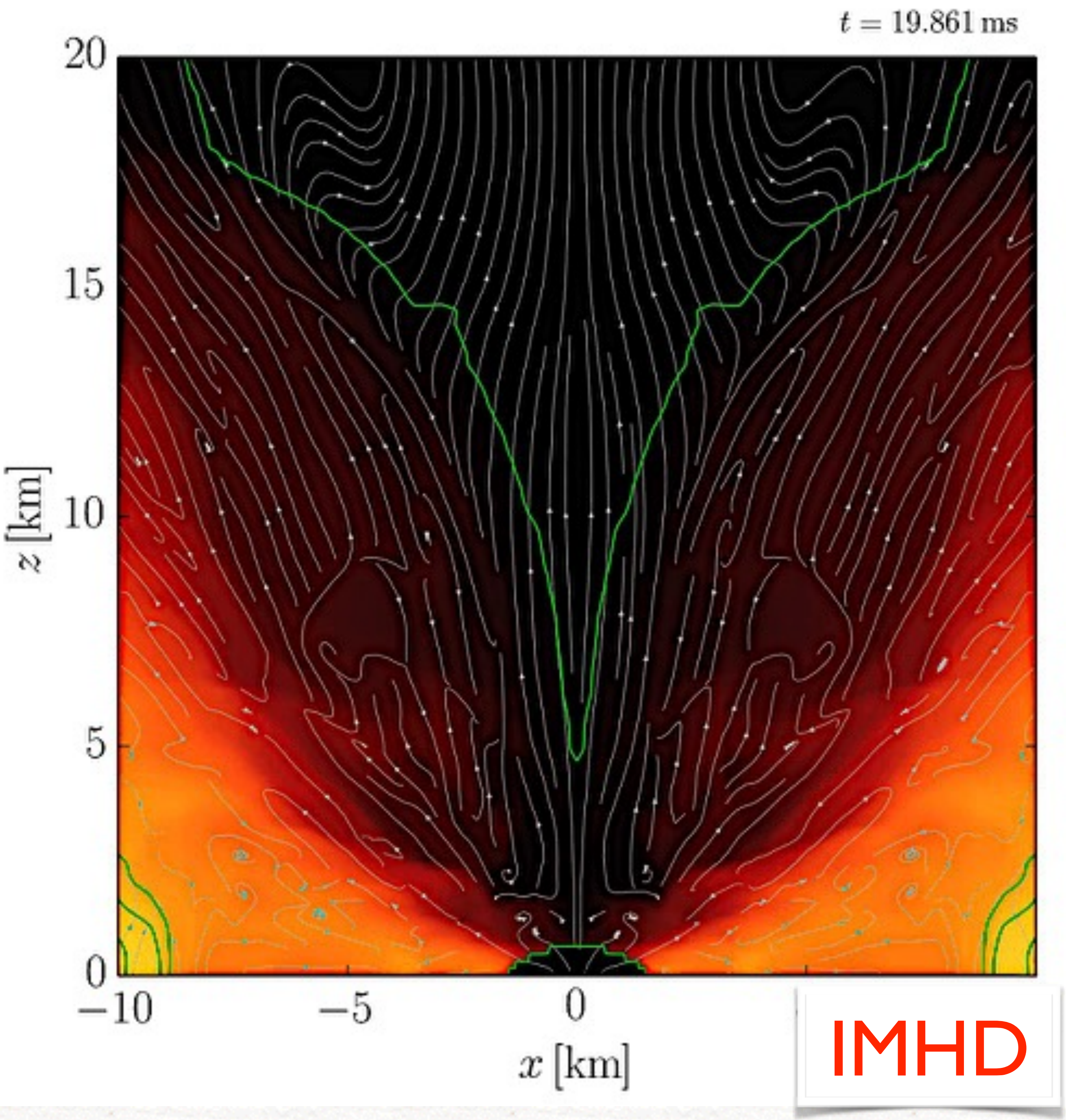
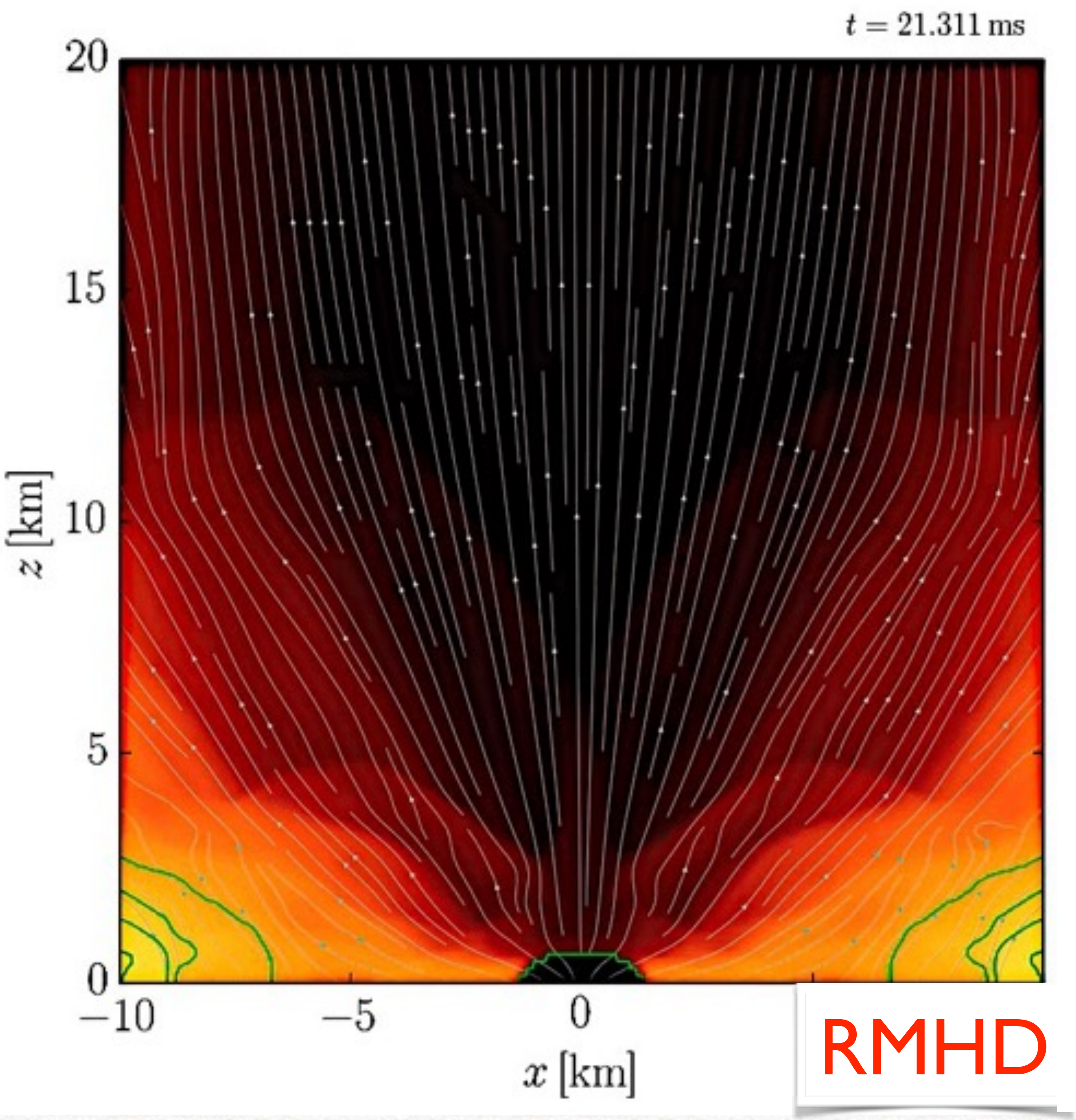
0
20
40
60
x [km]
14.4
13.6
12.8
12.0
11.2
10.4
9.6
8.8
8.0
$\log_{10}(\rho)$ [g/cm^3]
IMHD
RMHD



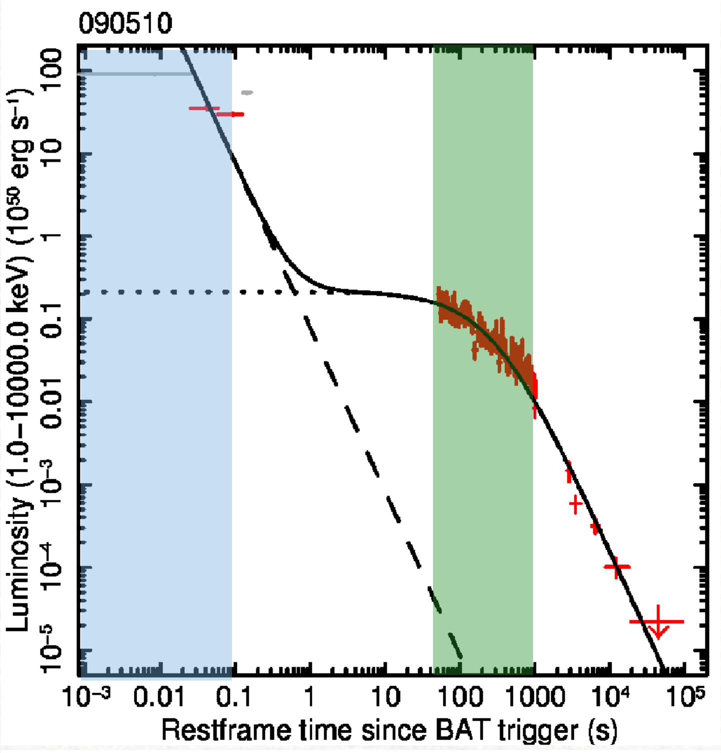


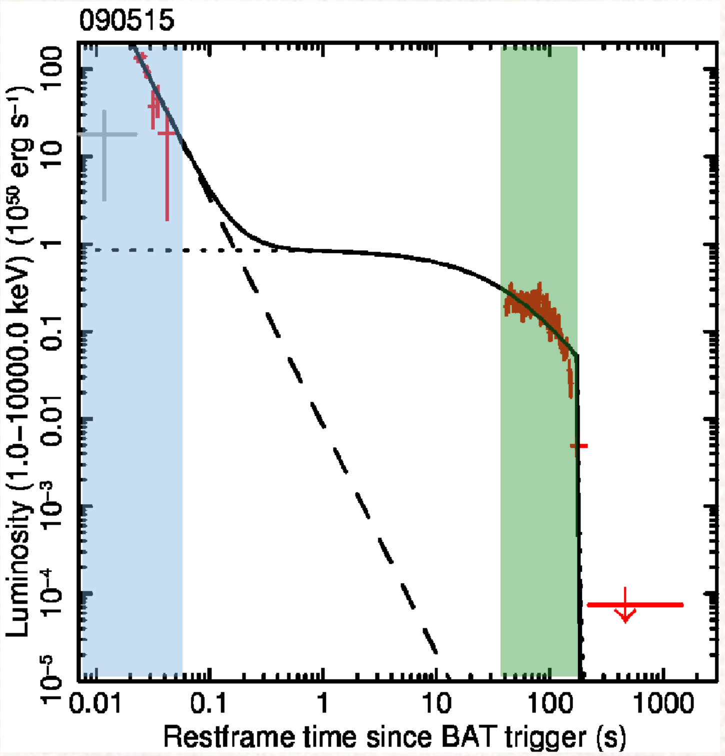
NOTE: the **magnetic jet structure** is **not** an **outflow**. It's a plasma-confining structure.

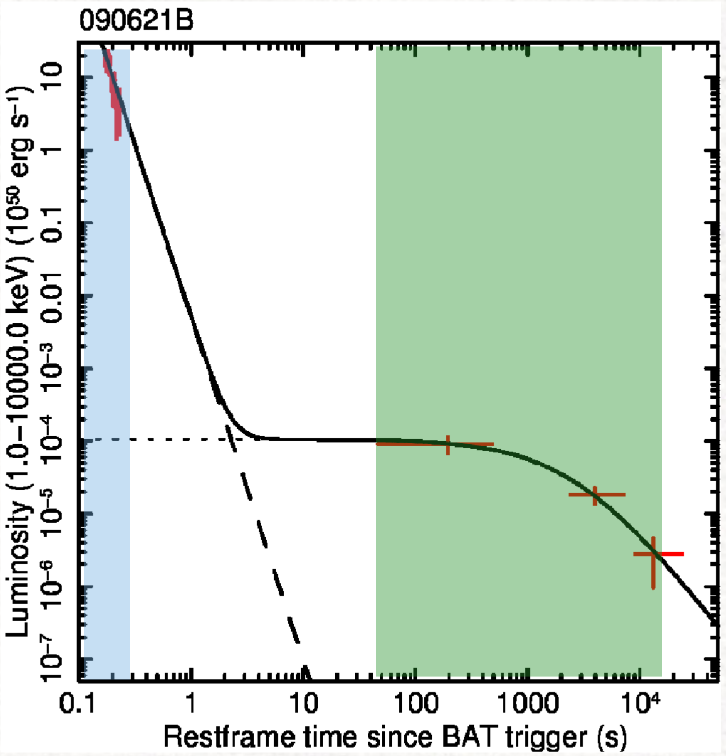
In **IMHD** the magnetic jet structure is present but less regular.

In **RMHD** it fit it is more regular at all scales.

Do we understand X-ray afterglows?



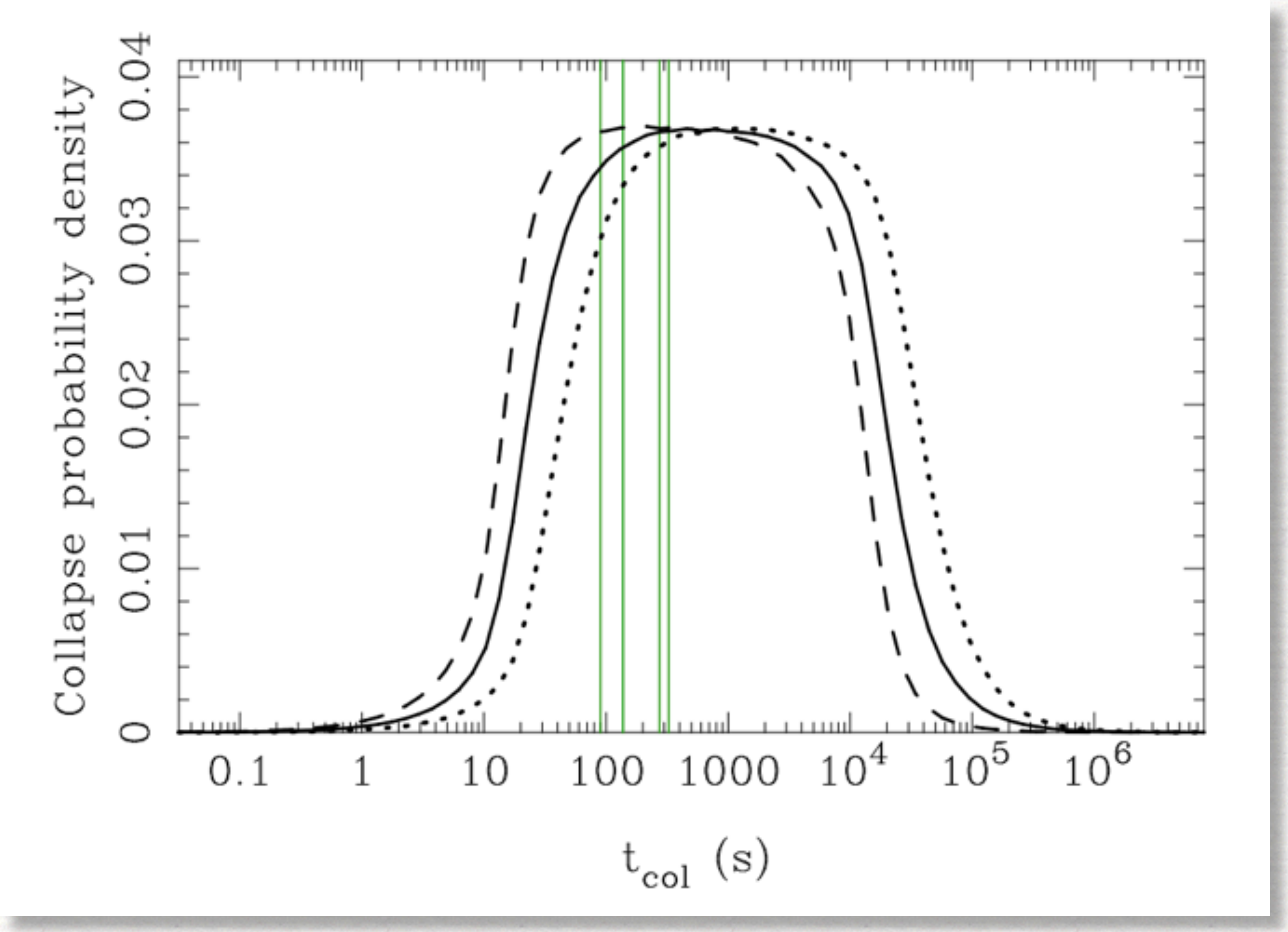




- X-ray afterglows have been observed by Swift lasting as long as 10^2-10^4 s (Rowlinson+ 13; Gompertz+13)
- The X-ray afterglow could also be produced by a "magnetically-driven" wind generated by differential rotation (Siegel+ 14)
- The X-ray afterglow could be produced by "proto-magnetar": dipolar emission with $L_x \sim 10^{49}\,\mathrm{erg\ s}^{-1}$ (Zhang & Mezsaros 01, Metzger+ 11, Zhang 13).

How long can the BMP survive?

Ravi and Lasky (2013)



PDF of the collapse time for three EOSs. The vertical lines refer to values as deduced from the observations of 4 SGRB remnants Rowlinson+ (2013).

The elephant in the room…

Magnetars are appealing for their simplicity but hardly a solution

- differential rotation lost over Alfven timescale: <~10 s; magnetically driven wind **can't explain** sustained emission for 10^3-10^4 s
- X-ray plateaus **follow** the gamma emission, yet magnetar must come **before** the BH-torus.
- simulations do not show any sign of **jet**, which emerges only when **BH-torus** is produced.

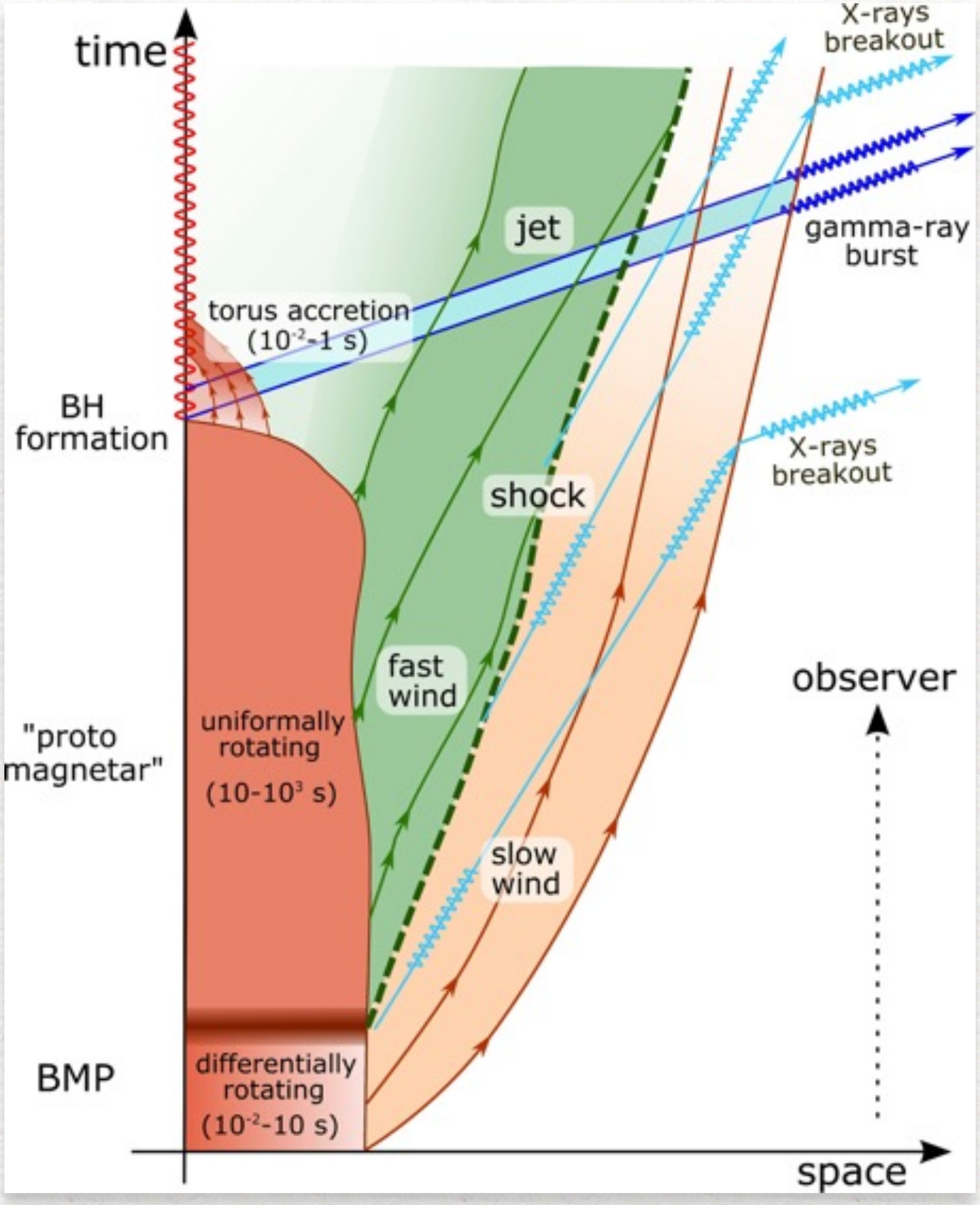
Recap:

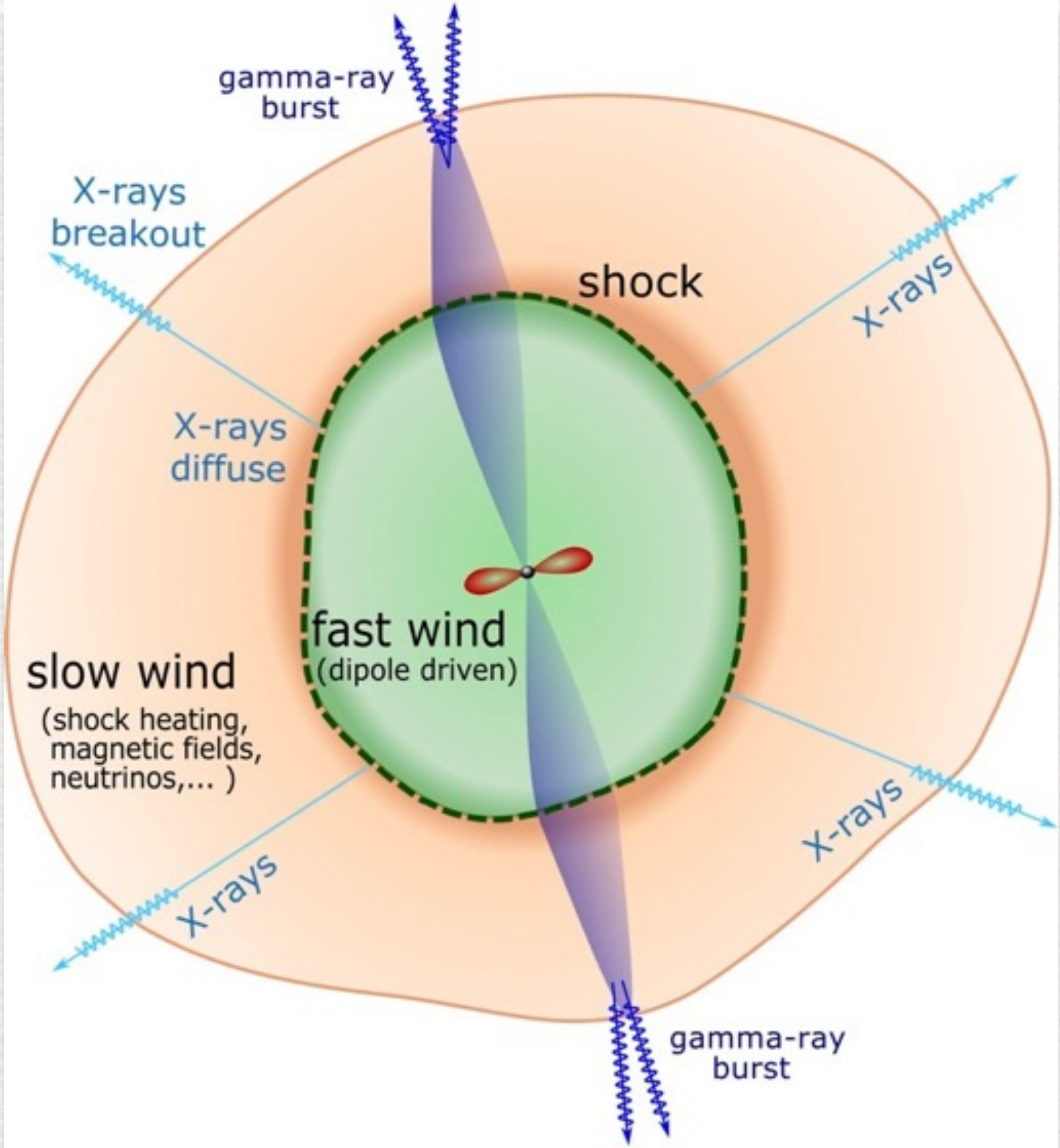
- X-rays produced by metastable magnetar
- gamma-rays produced by jet and BH-torus system

Riddle: How can the gammas arrive before the X-rays?

A solution to the riddle?

LR, Kumar (2014) (also Ciolfi, Siegel 2014)





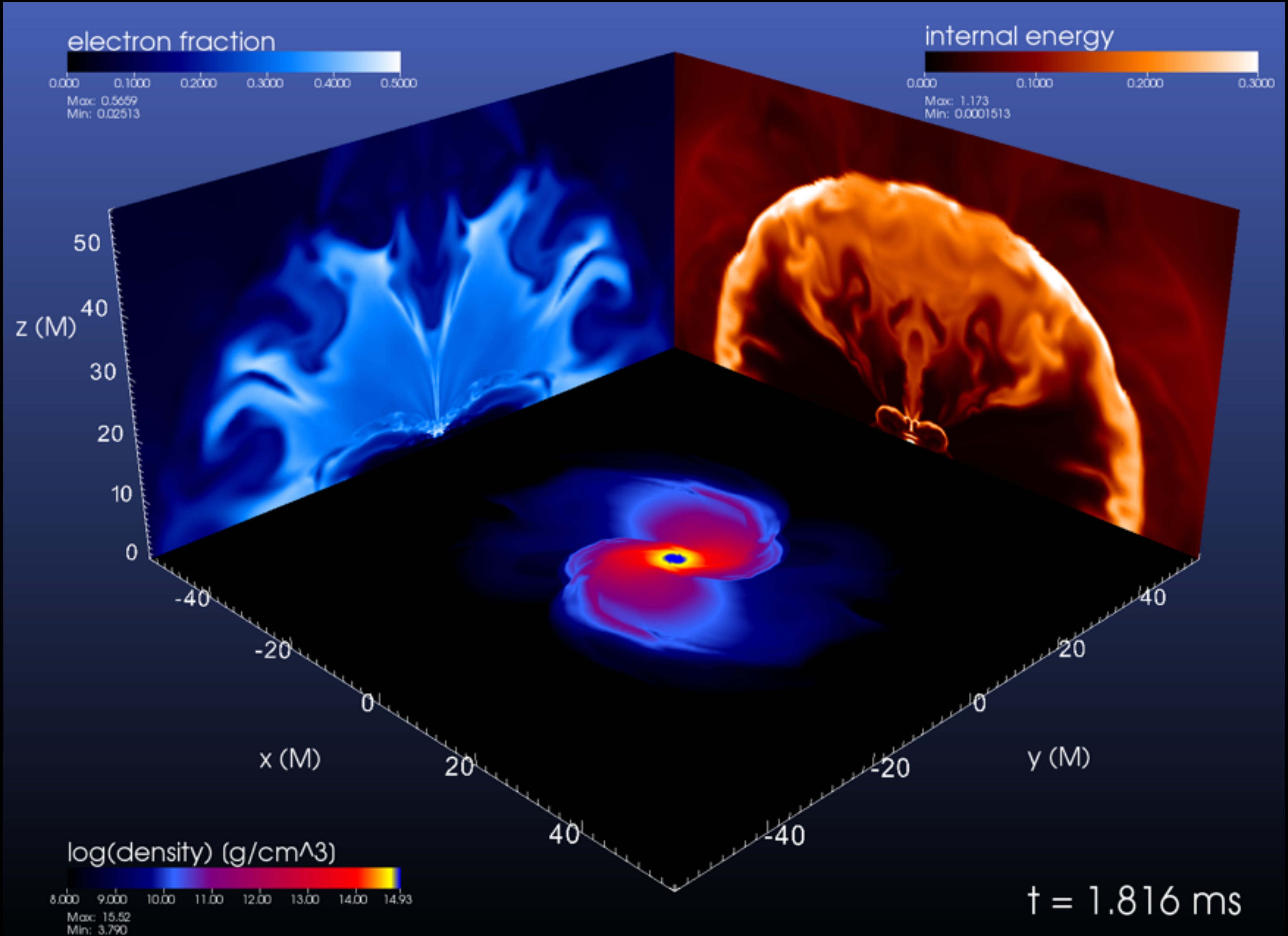
A novel paradigm for GRBs?

LR, Kumar (2014)

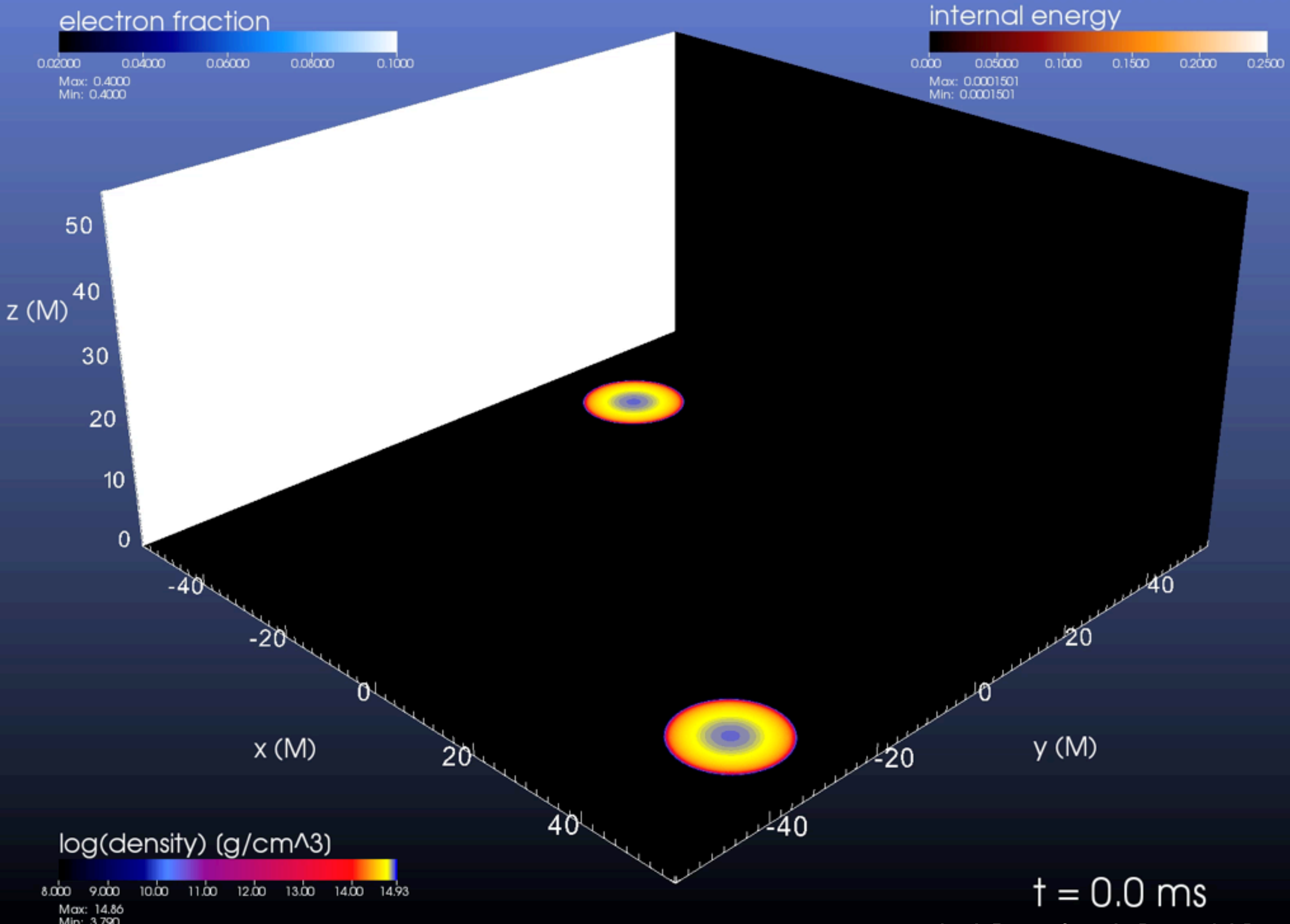
- ***solves the timescale riddle:*** X-ray luminosity is produced by HMNS and can last up to 10^4 s
- ***solves the timing riddle****:* X-ray emission is produced before gamma emission but propagates more slowly.
- ***consistent with simulations****:* slow wind is produced in many ways.
- ***unifying view with long GRBS****:* jet propagates in confining medium.
- ***predictions****:* X-ray emission possible before gamma; IC of thermal photons at break out.
- GW signal peak could be much ***earlier*** than gamma emission.
- ***potential problem***: need a disk at collapse and this could be difficult (Margalit+15).

Dynamically captured binaries

Radice+ (2016)

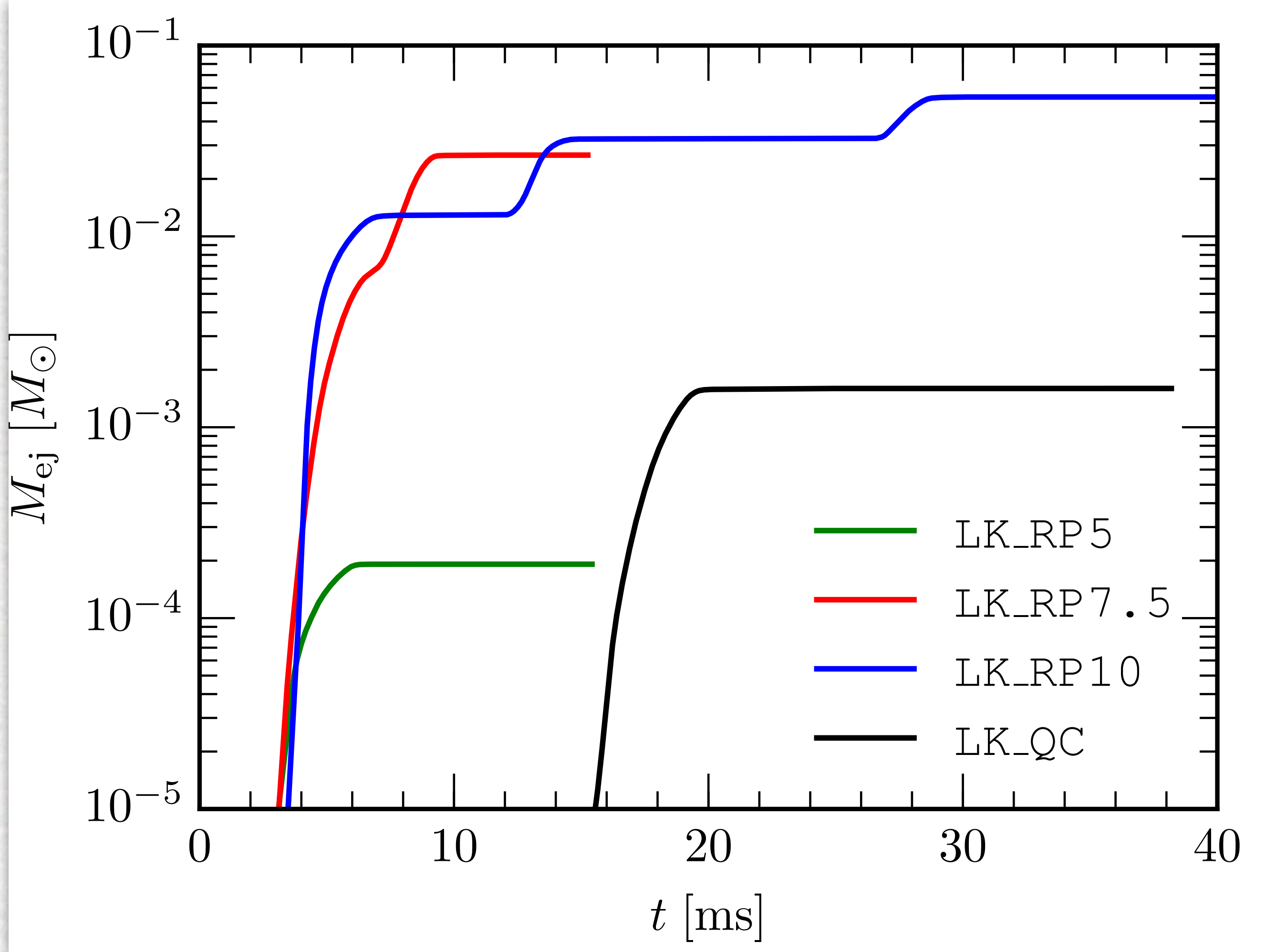


- High-eccentricity mergers can occur in dense stellar environments, e.g., globular clusters (GCs).
- About 10% of all SGRBs show significant offsets from the bulge of their host galaxies.
- Offsets could be due to kicks imparted to the binaries, or to binaries being in GCs around host galaxy.



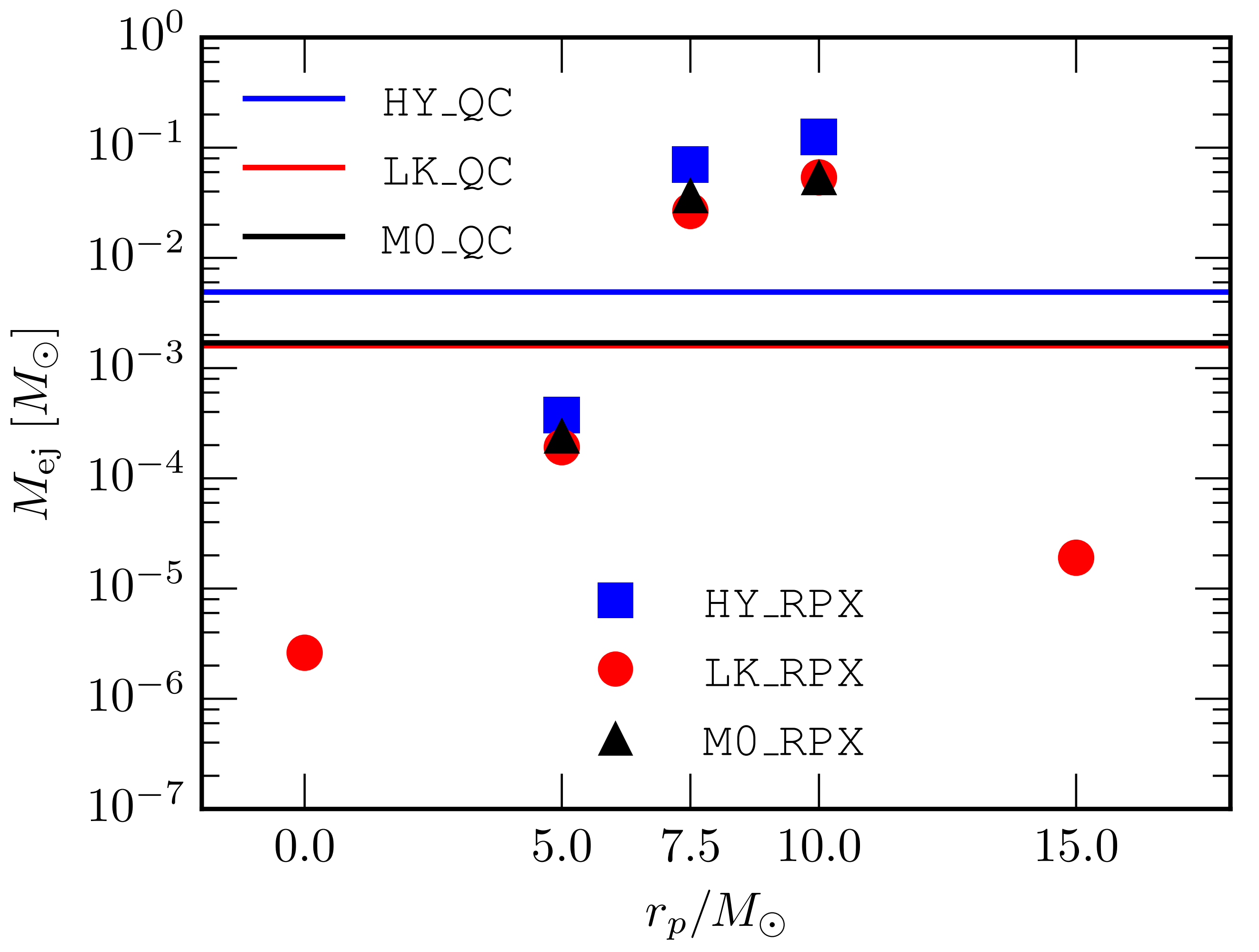
animations by J. Papenfort, L. Bovard, LR

Mass ejection

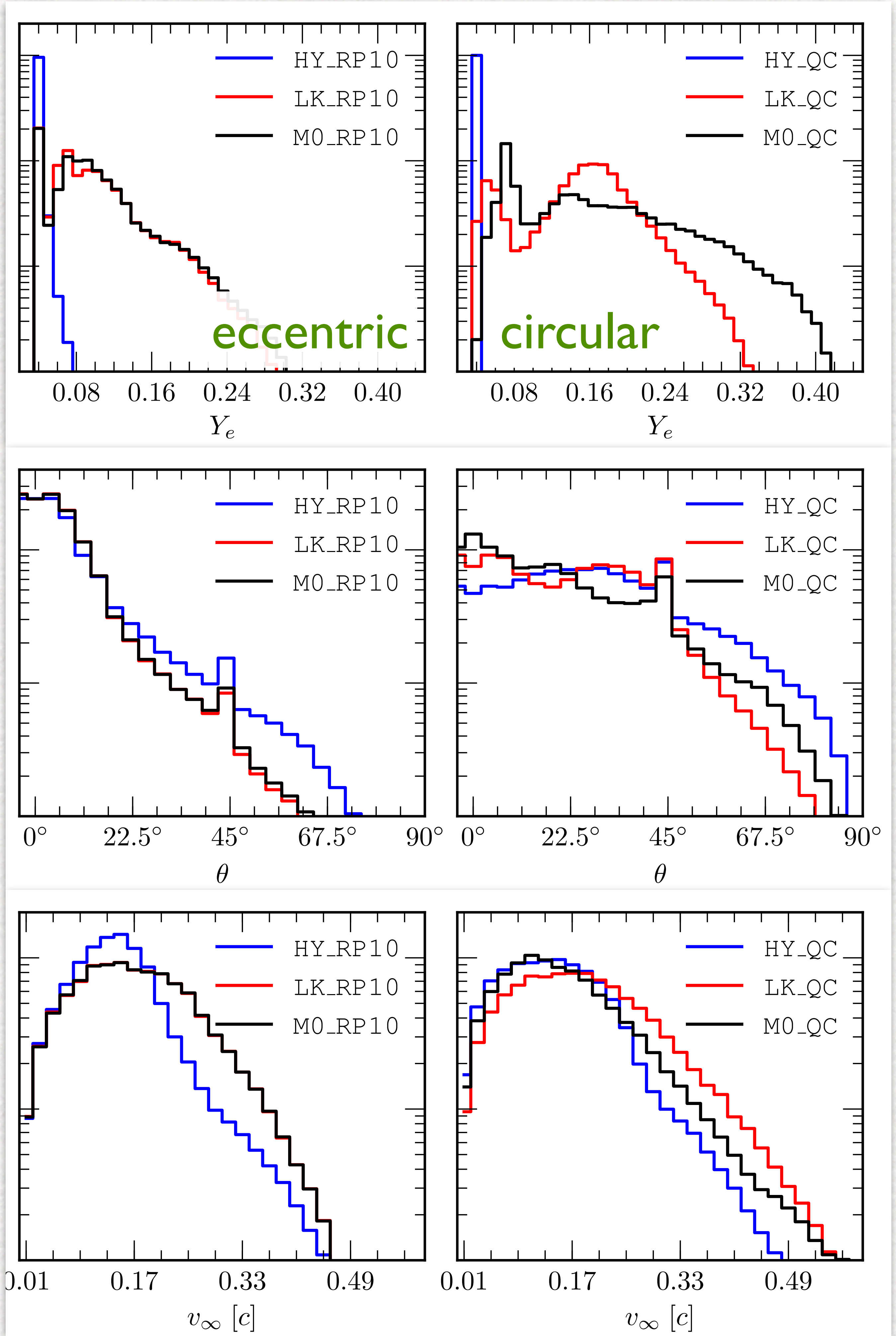


- Mass ejected depends on impact parameter and takes place at each encounter.
- Quasi-circular binaries have smaller ejected masses (1-2 orders of magnitude)

- Mass ejected depends on whether neutrino losses are taken into account (less ejected mass if neutrinos are taken into account)



Distributions in electron fraction, entropy, velocity



Broader distribution in *Ye* when neutrino losses are taken into account

Mass ejected at all latitudes but predominantly at **low elevations** (orbital plane)

Broad distribution in *asymptotic* velocities **independent** of initial conditions

Macronova emission

Energy via radioactive decay of r-process nuclei powers transients in optical/near-infrared with peak emission after (Grossman+ 14)

$$t_{\rm peak} = 4.9 \left(\frac{M_{\rm ej}}{10^{-2}\ M_\odot}\right)^{1/2} \times \left(\frac{\kappa}{10\ {\rm cm}^2\ {\rm g}^{-1}}\right)^{1/2} \left(\frac{\langle v_\infty\rangle}{0.1\ c}\right)^{-1/2} {\rm days}\,,$$

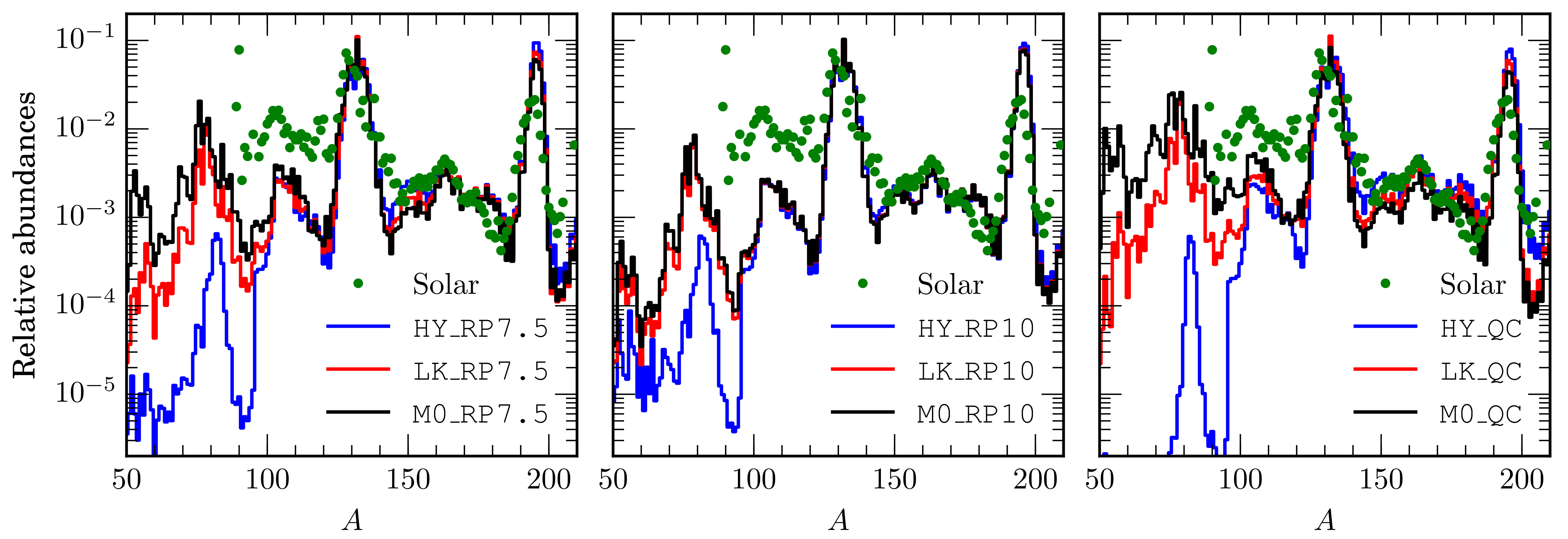
The peak bolometric luminosity is estimated to be ("ectonova")

$$L = 2.5\times 10^{40} \left(\frac{M_{\rm ej}}{10^{-2}\ M_\odot}\right)^{1-\alpha/2} \times \left(\frac{\kappa}{10\ {\rm cm}^2\ {\rm g}^{-1}}\right)^{-\alpha/2} \left(\frac{\langle v_\infty\rangle}{0.1\ c}\right)^{\alpha/2} {\rm erg\ s}^{-1}\,.$$

with radioactive energy release a power law $\dot\epsilon = \dot\epsilon_0 (t/t_0)^{-\alpha},\ \alpha \simeq 1.3$

Eccentric binaries: ~ **4 times more luminous** than quasi-circular;
delayed peak emission: ~ 8 days (cf. 1.5)

Nucleosynthesis



- Ejected matter undergoes **nucleosynthesis** as expands and cools.
- Abundance pattern for ***A>120*** is robust and good agreement with solar (2nd and 3rd peak well reproduced)
- Abundances very **robust**: essentially the same for eccentric or quasi-circular binaries

Conclusions

- ✳Modelling of binary NSs in full GR is **mature**: GWs from the inspiral can be computed with precision of binary BHs

- ✳Spectra of post-merger shows clear peaks, some of which are **"quasi-universal"**. If observed, will set tight constraints on EOS

- ✳Magnetic fields unlikely to be detected during the inspiral but **important** after the merger: instabilities and EM counterparts

- ✳ **Eccentric** binaries are rare but with larger ejected matter and macronova emission. "high-*A*" nucleosynthesis very robust

Detection of waveforms from BNSs has potential to solve two fundamental problems: EOS, GRBs. We can't wait…