# On gravitational collapse in astrophysics

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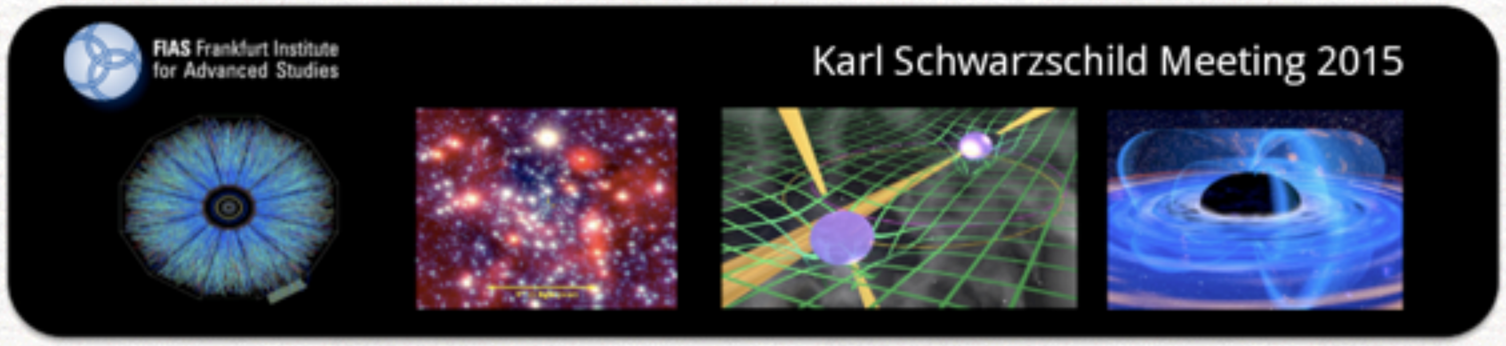


# Plan of the talk

* Role of gravitational collapse in binary neutron stars.
  - anatomy of the GW: universal frequencies and EOS
* Role of gravitational collapse in short gamma-ray bursts.
  - the riddle of the extended x-ray emission
* Role of gravitational collapse in fast radio bursts.
  - can blitzars be the explanation?

# The two-body problem in GR

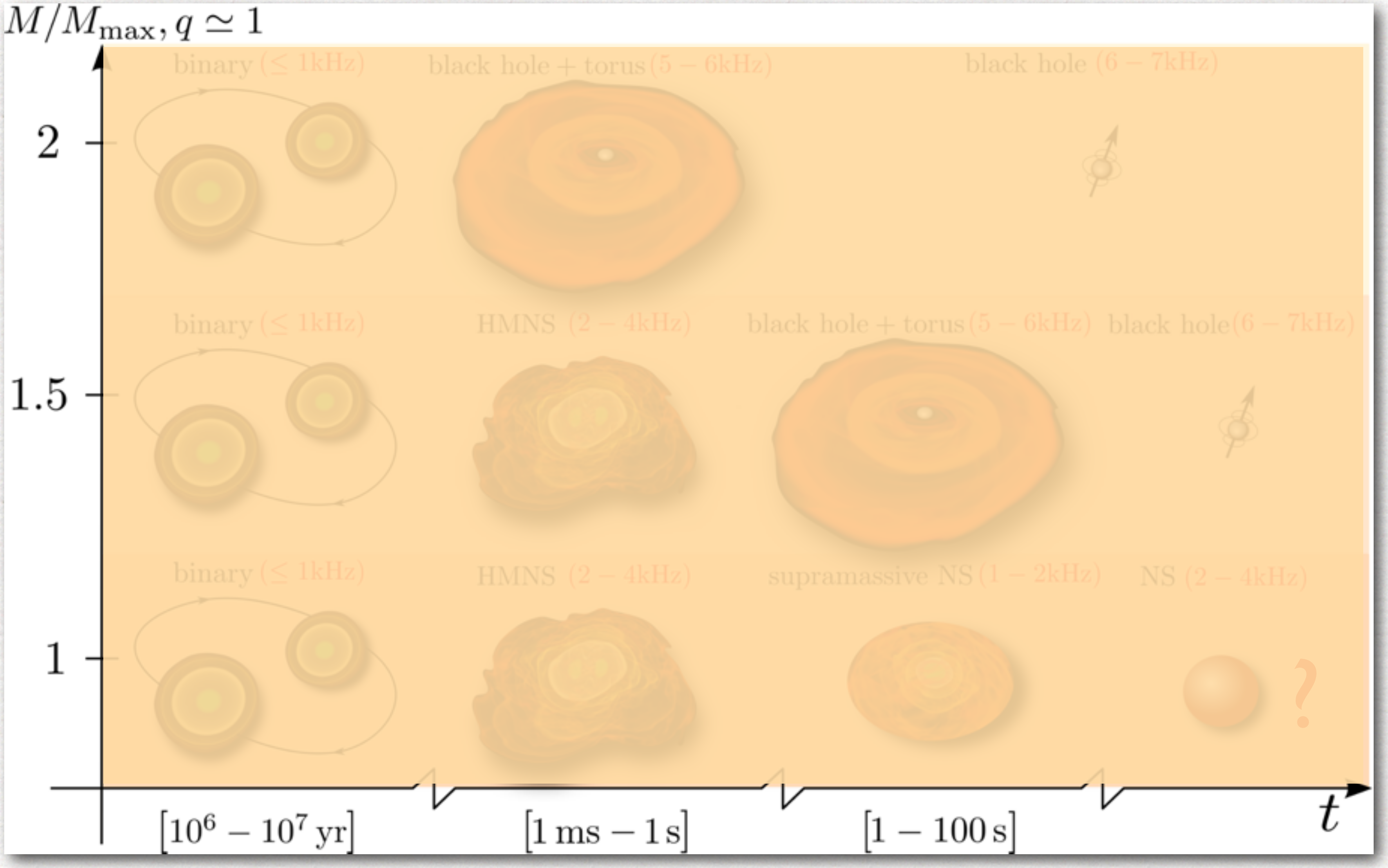
- For BHs we know what to **expect**:

BH + BH → BH + gravitational waves (GWs)

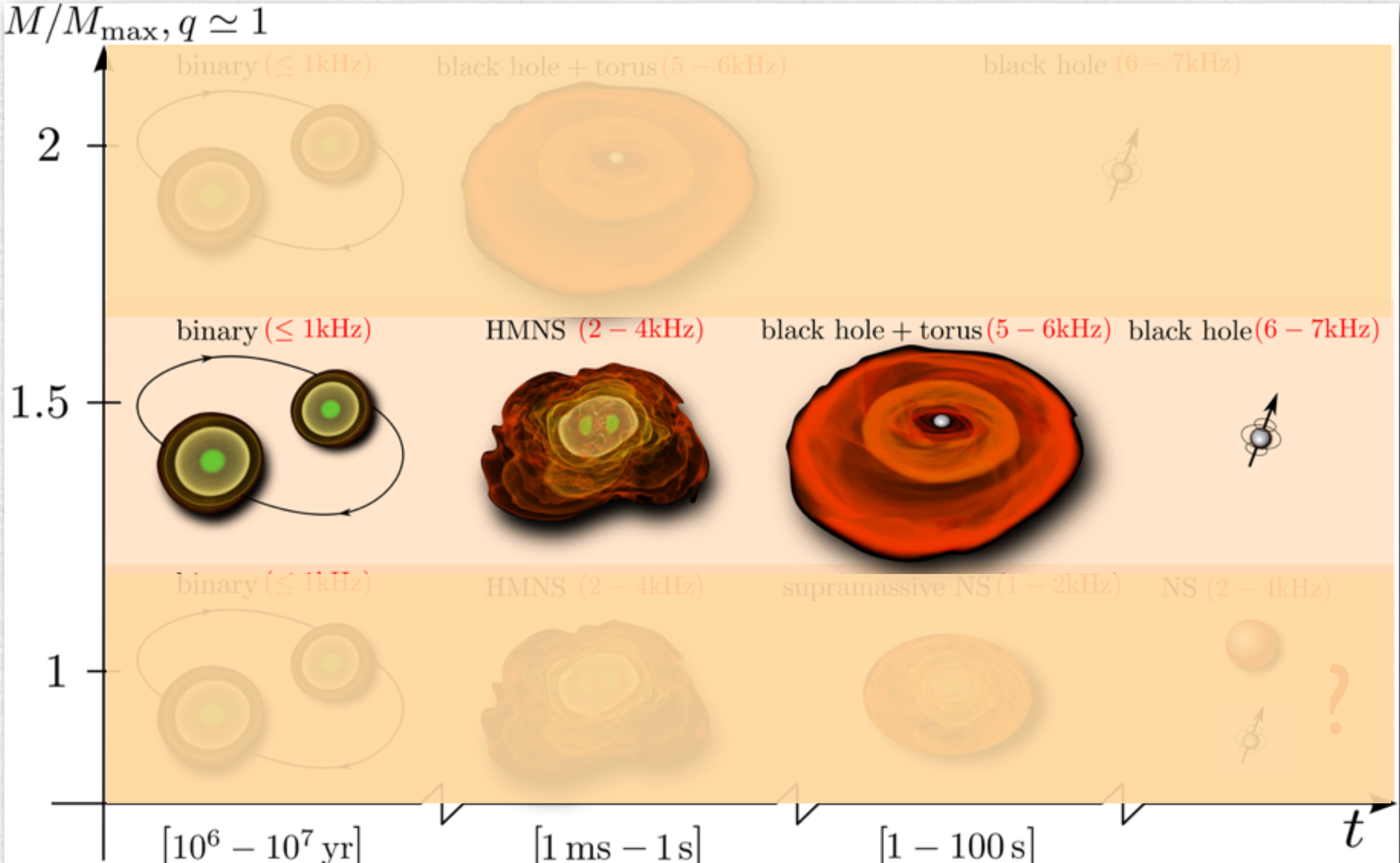
- For NSs the question is more **subtle!**

NS + NS → ... → ... → BH

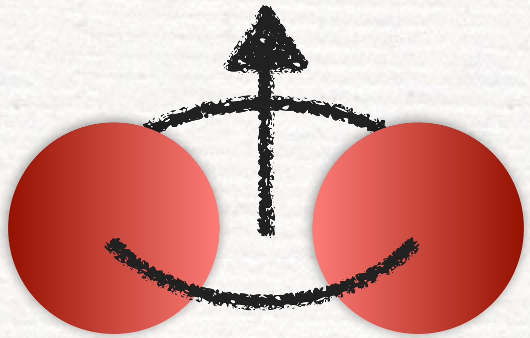
# Broadbrush picture



# Broadbrush picture

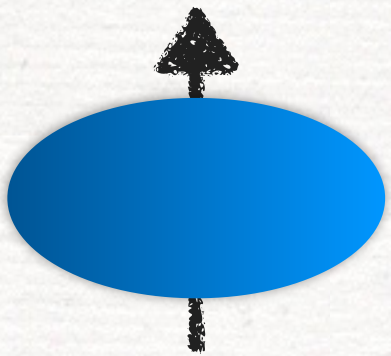


# Why should we expect a HMNS?



typical masses in binaries: $\sim 2\times 1.35 \sim \boldsymbol{2.7\ M_\odot}$

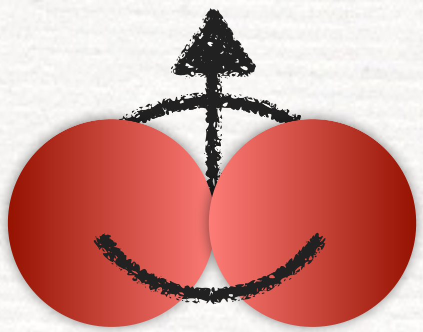
maximum observed mass: $M_{max} \sim \boldsymbol{2.0\ M_\odot}$



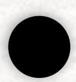
maximum rotating mass: $\sim 1.2\ M_{max} \sim \boldsymbol{2.4\ M_\odot}$

Hence, unless a black hole is produced right at the merger, the resulting object must be a ***hypermassive neutron star***.

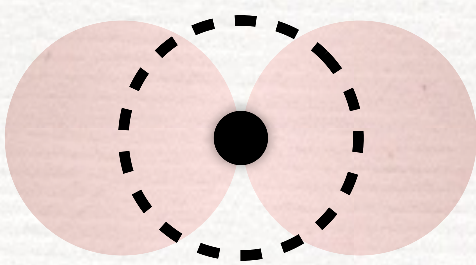
# Why should we expect a BH+torus?



size at contact: 2xR ~ ***24 km***



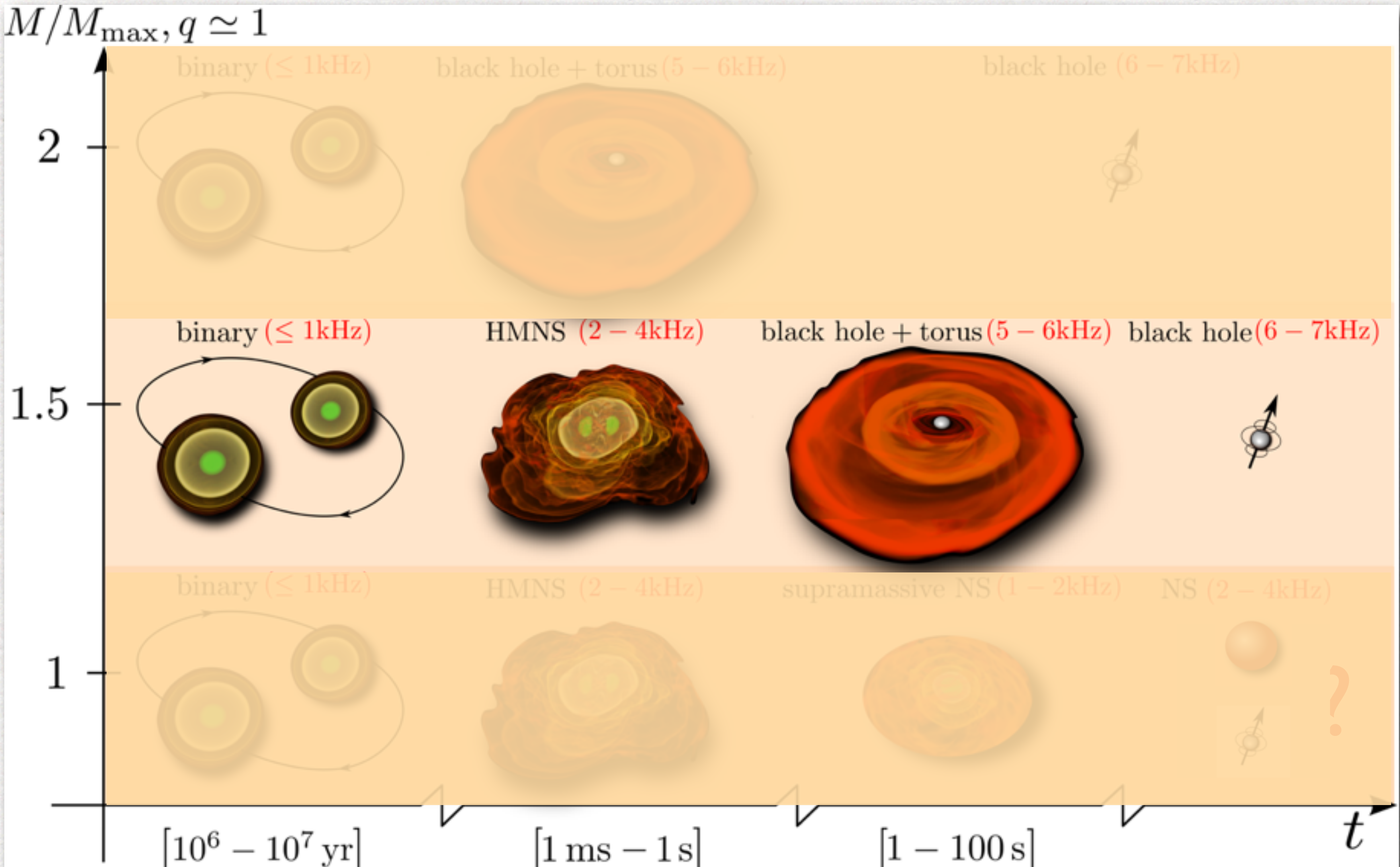
BH size ($J/M^2 \sim 0.8$): $\sim 1.2\, M_{tot} \sim 1.2 \times 2.7\, M_\odot \sim$ ***5 km***



ISCO size: $\sim 3\, M_{tot} \sim 3 \times 2.7\, M_\odot \sim$ ***12 km***

Hence, a certain amount of matter will be on orbits outside the ISCO and hence lead to a ***"stable" torus***.

# Broadbrush picture



# The two-body problem in GR

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

BH + BH → BH + gravitational waves (GWs)

- For NSs the question is more **subtle:** the merger leads to an hyper-massive neutron star (HMNS), ie a metastable equilibrium:

NS + NS → HMNS + **... ?** → BH + torus + **... ?** → BH

All complications are in the intermediate stages; the rewards high:

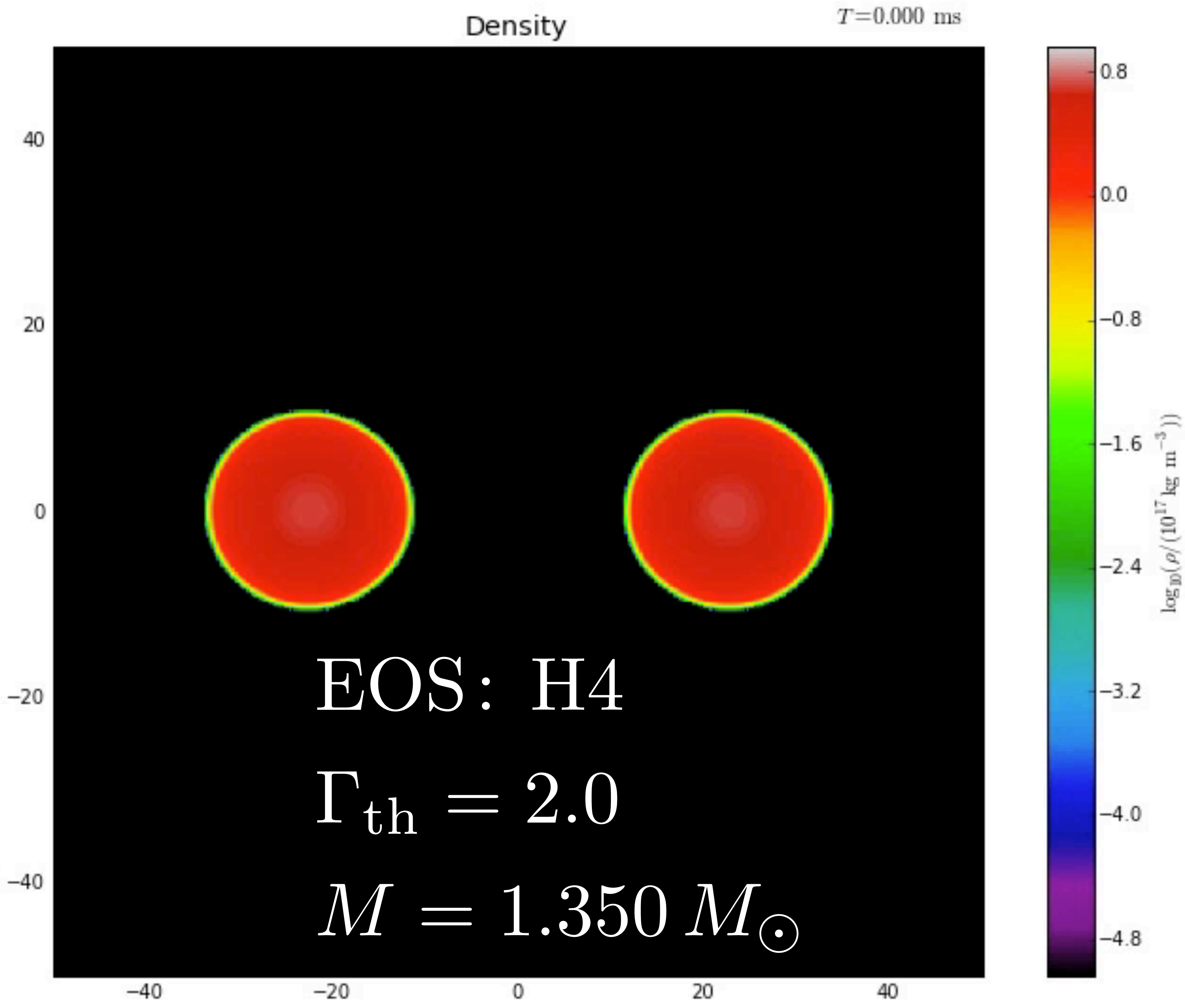
- studying the HMNS will show strong and precise imprint on the EOS
- studying the BH+torus will tell us on the central engine of GRBs

NOTE: with advanced detectors we expect to have a **realistic** rate of ~**40 BNSs** inspirals a year, ie ~ 1 a week (Abadie+ 2010) *"merger → HMNS → BH + torus"*

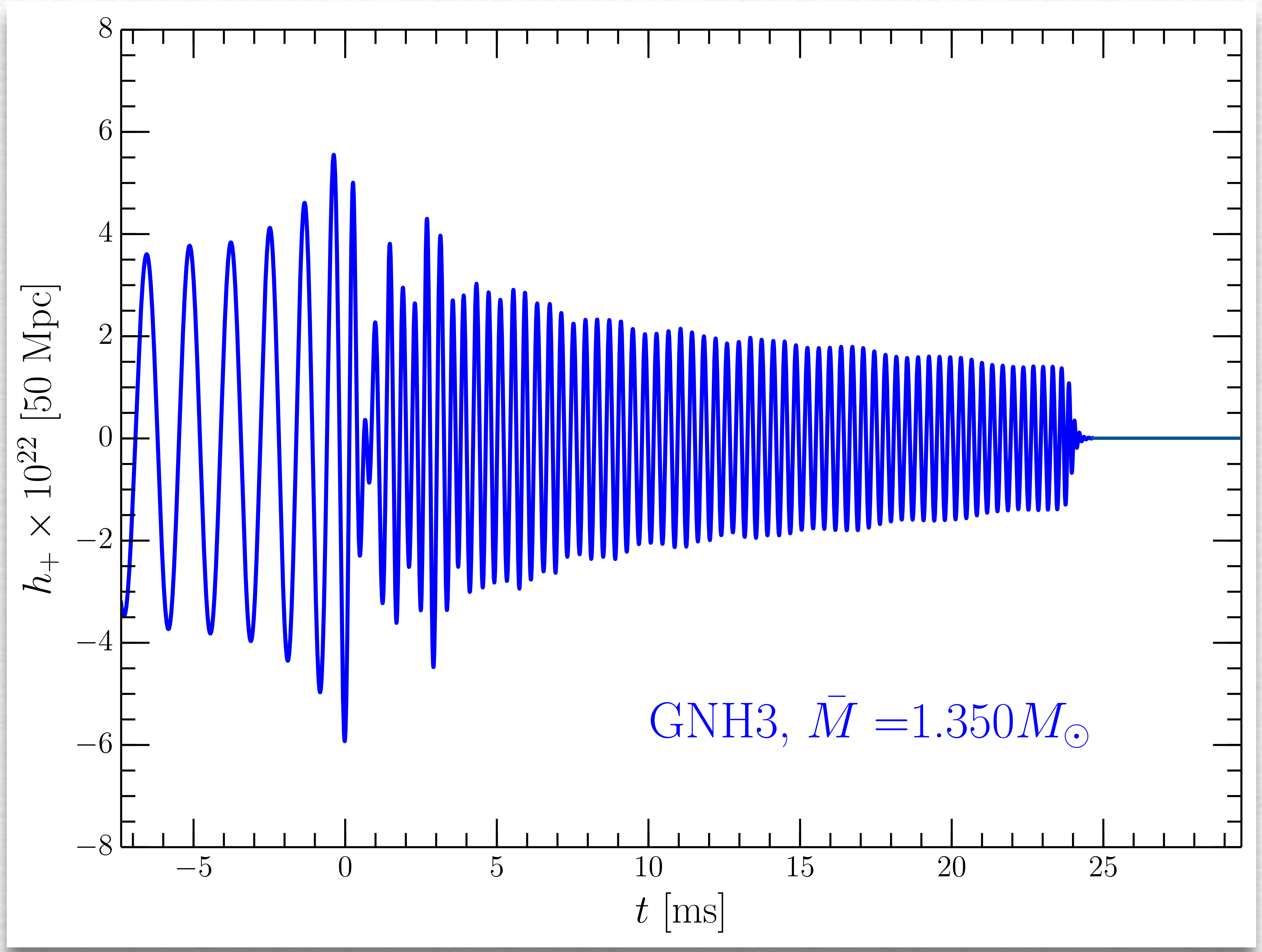
# Quantitative differences are produced by:

- **differences induced by the gravitational MASS:**
  a binary with smaller mass will produce a HMNS further away from the stability threshold and will collapse at a later time
- **differences induced by the EOS:**
  a binary with an EOS with large thermal capacity (ie hotter after merger) will have more pressure support and collapse later
- **differences induced by MASS ASYMMETRIES:**
  tidal disruption before merger; may lead to prompt BH
- **differences induced by MAGNETIC FIELDS:**
  the angular momentum redistribution via magnetic braking or MRI can increase/decrease time to collapse; EM counterparts!
- **differences induced by RADIATIVE PROCESSES:**
  radiative losses will alter the equilibrium of the HMNS

# A protypical evolution



# Anatomy of the GW signal



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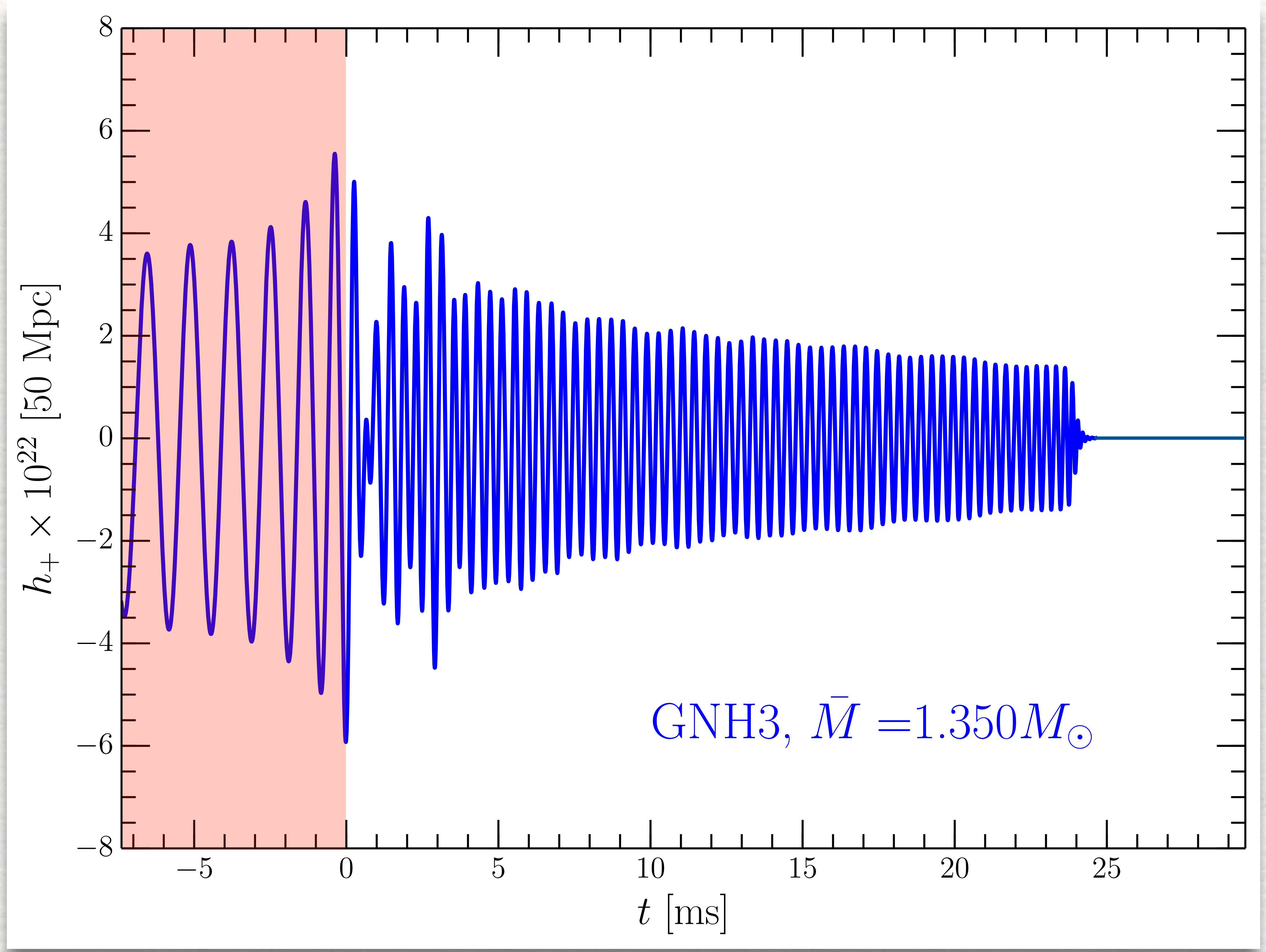
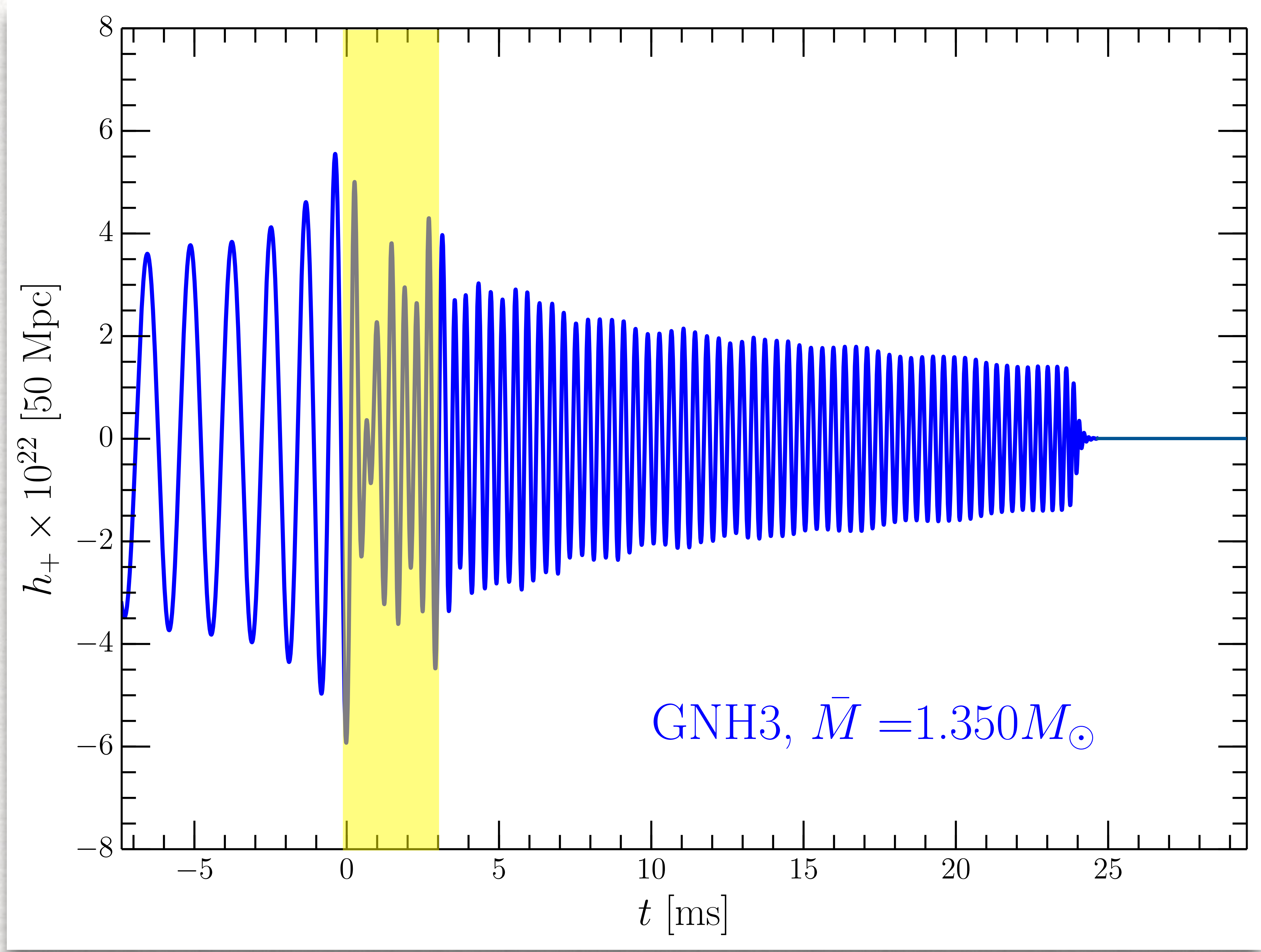


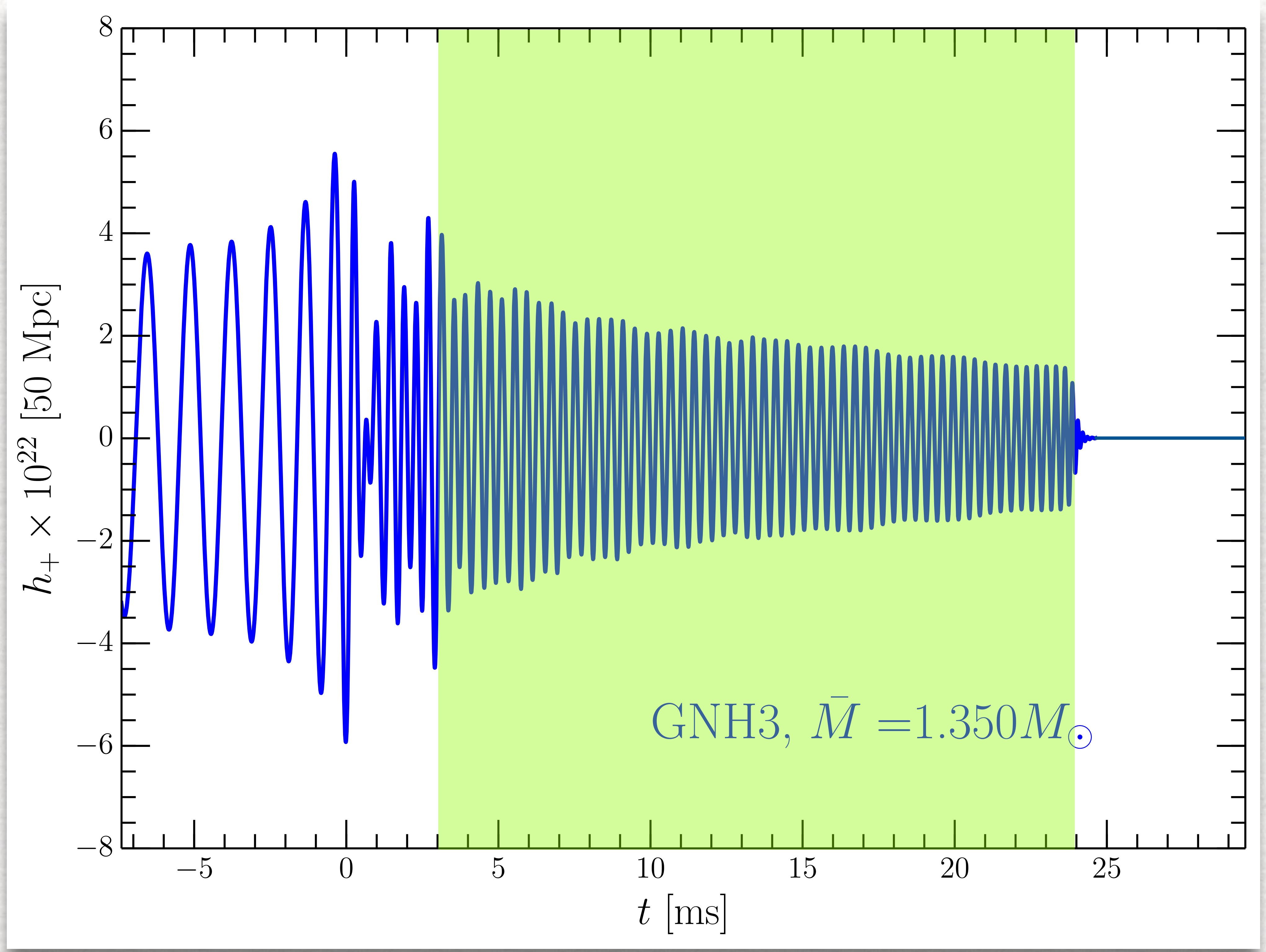

**Inspiral**: well approximated by PN/EOB; tidal effects important

# Anatomy of the GW signal



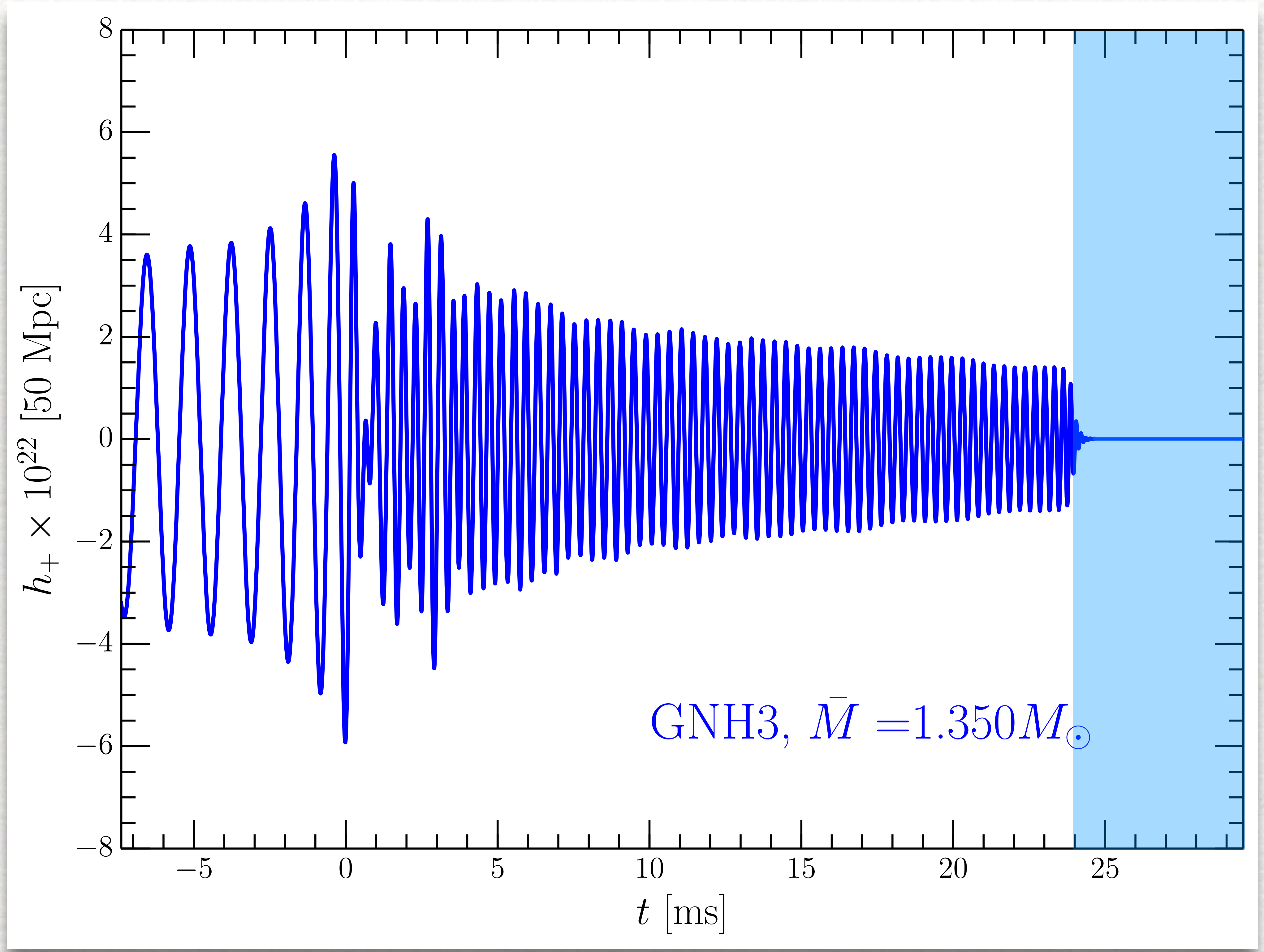

**Merger**: highly nonlinear but analytic description possible

# Anatomy of the GW signal



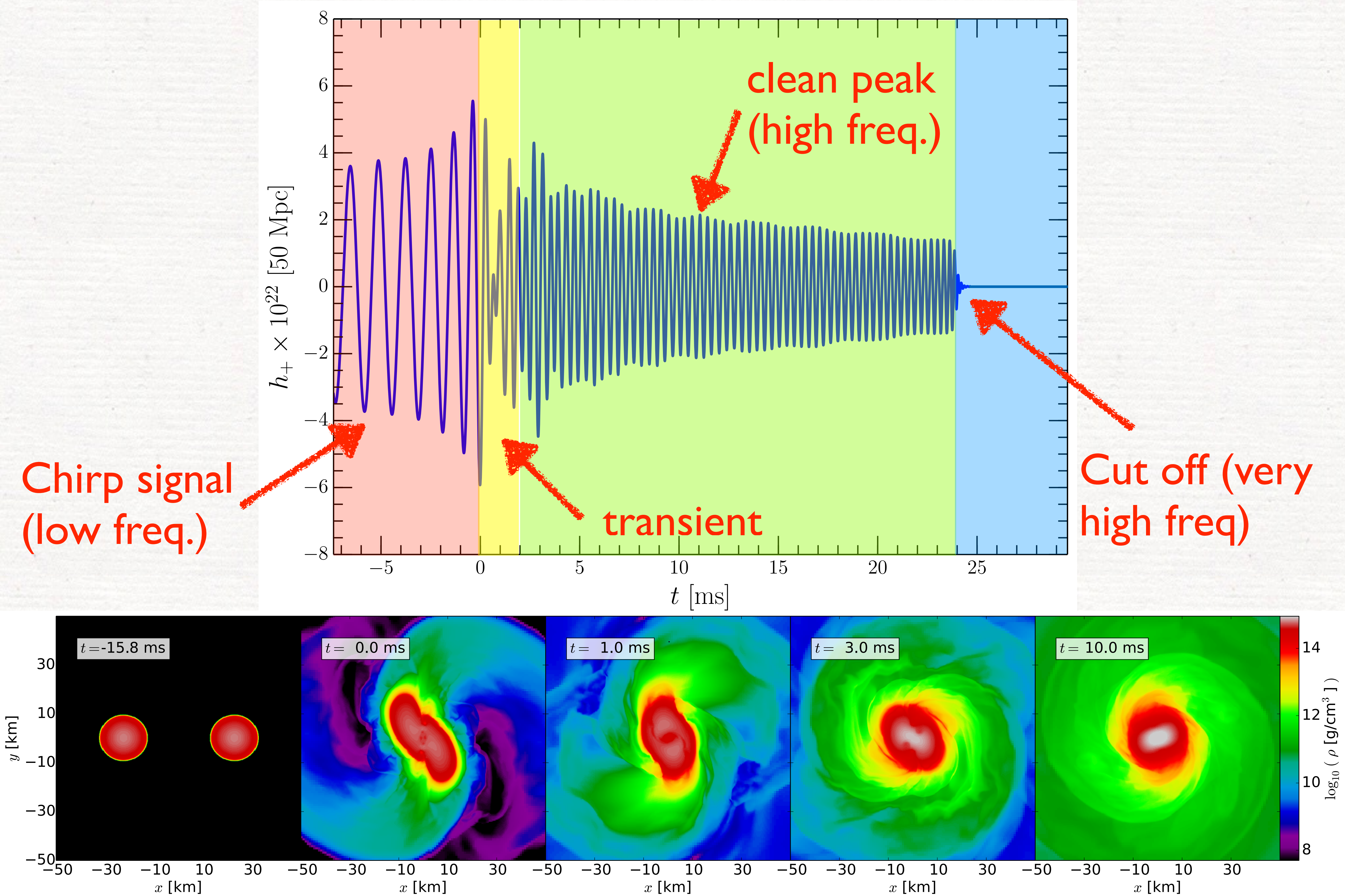

**post-merger**: quasi-periodic emission of bar-deformed HMNS

# Anatomy of the GW signal

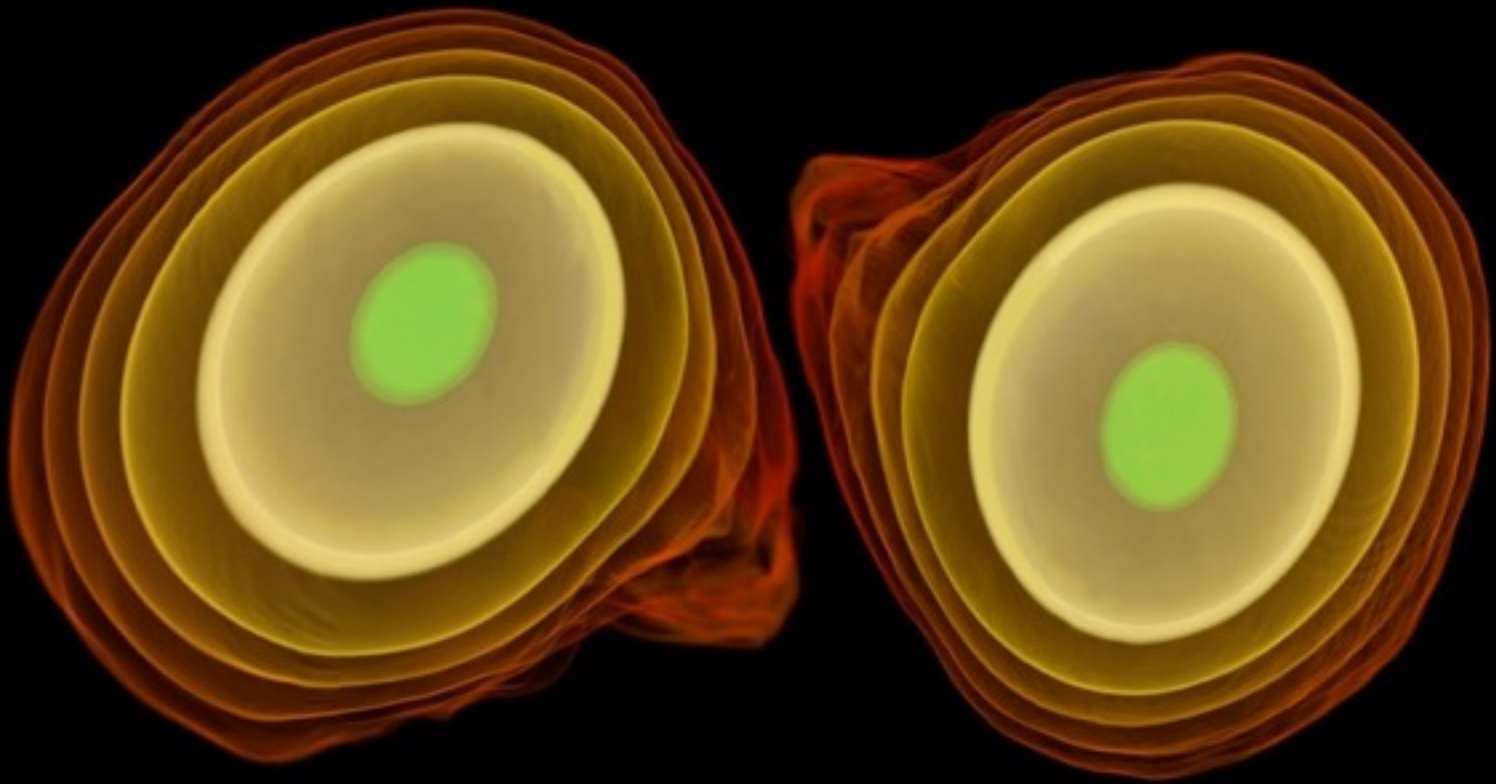



**Collapse-ringdown**: signal essentially shuts off.

# Anatomy of the GW signal

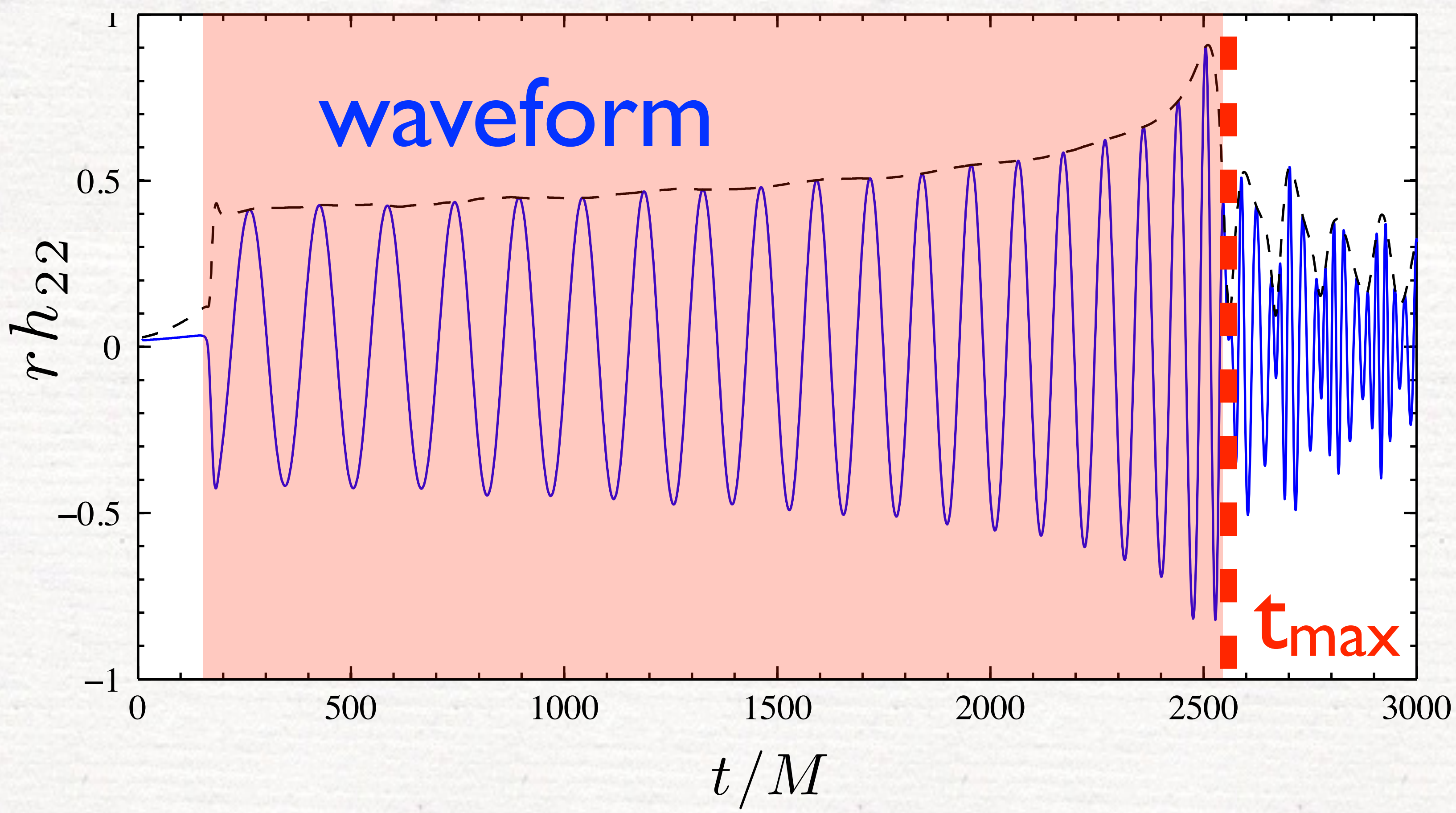


# How to constrain the EOS from the GW signal

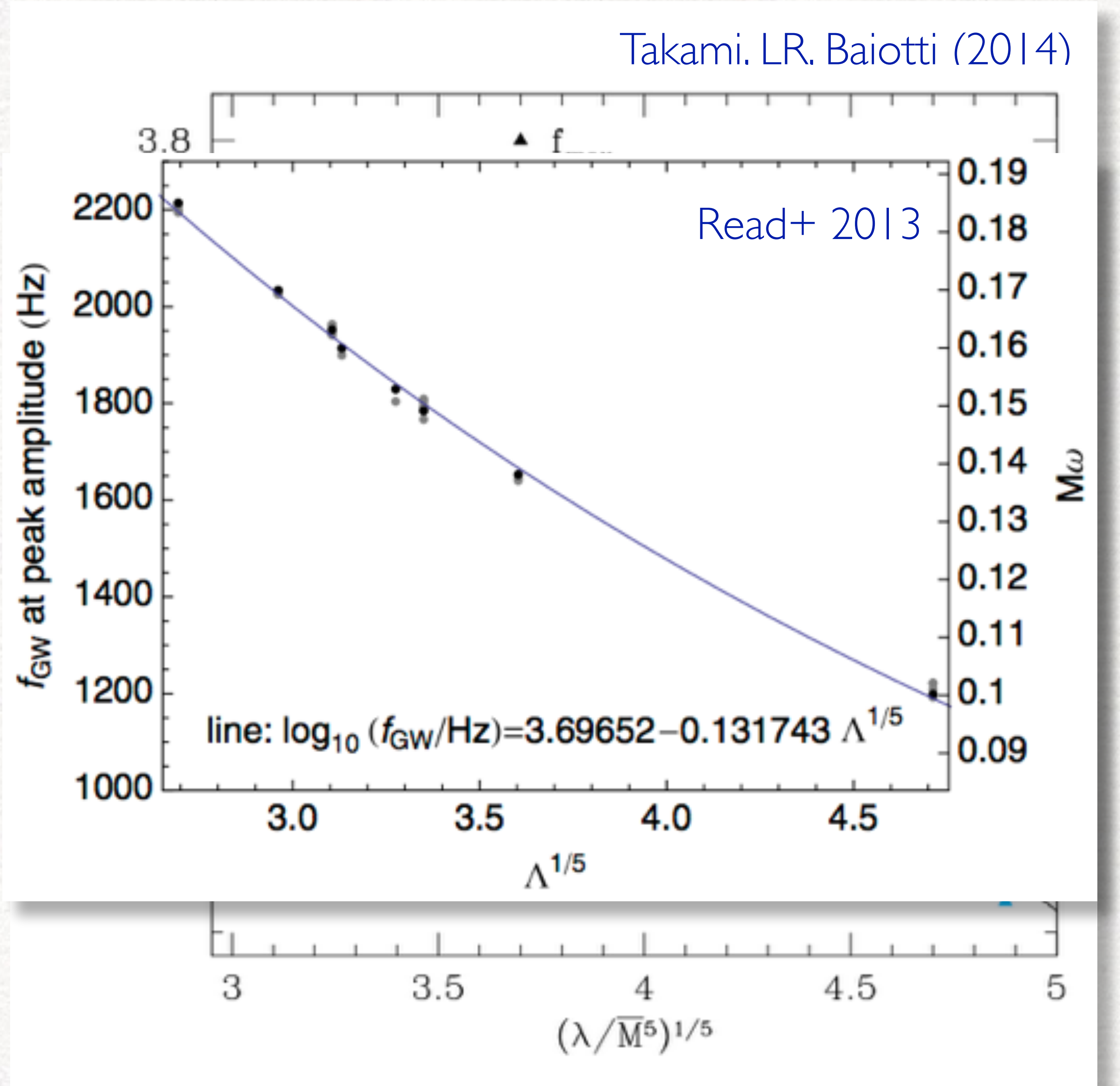


# Anatomy of the GW signal

## Inspiral



# Hints of quasi-universality



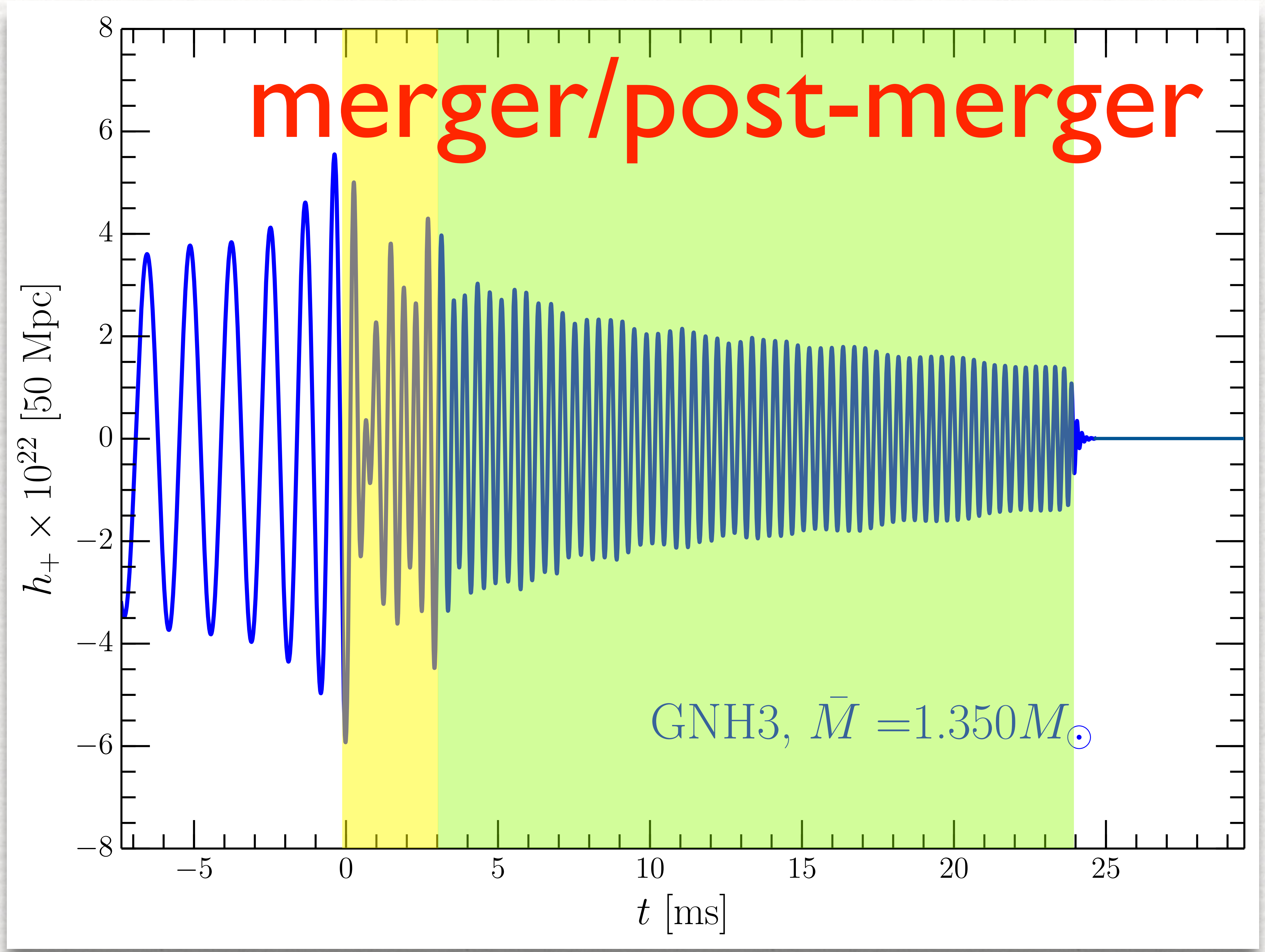

Read+, 2013, found "surprising" result: quasi-universal behaviour of GW frequency at amplitude peak

Bernuzzi+, 2014 and Takami+, 2015 confirmed with new simulations.

**Quasi-universal** properties exist in the **inspiral** of BNSs: once $\mathbf{f_{max}}$ is measured, so is tidal deformability.

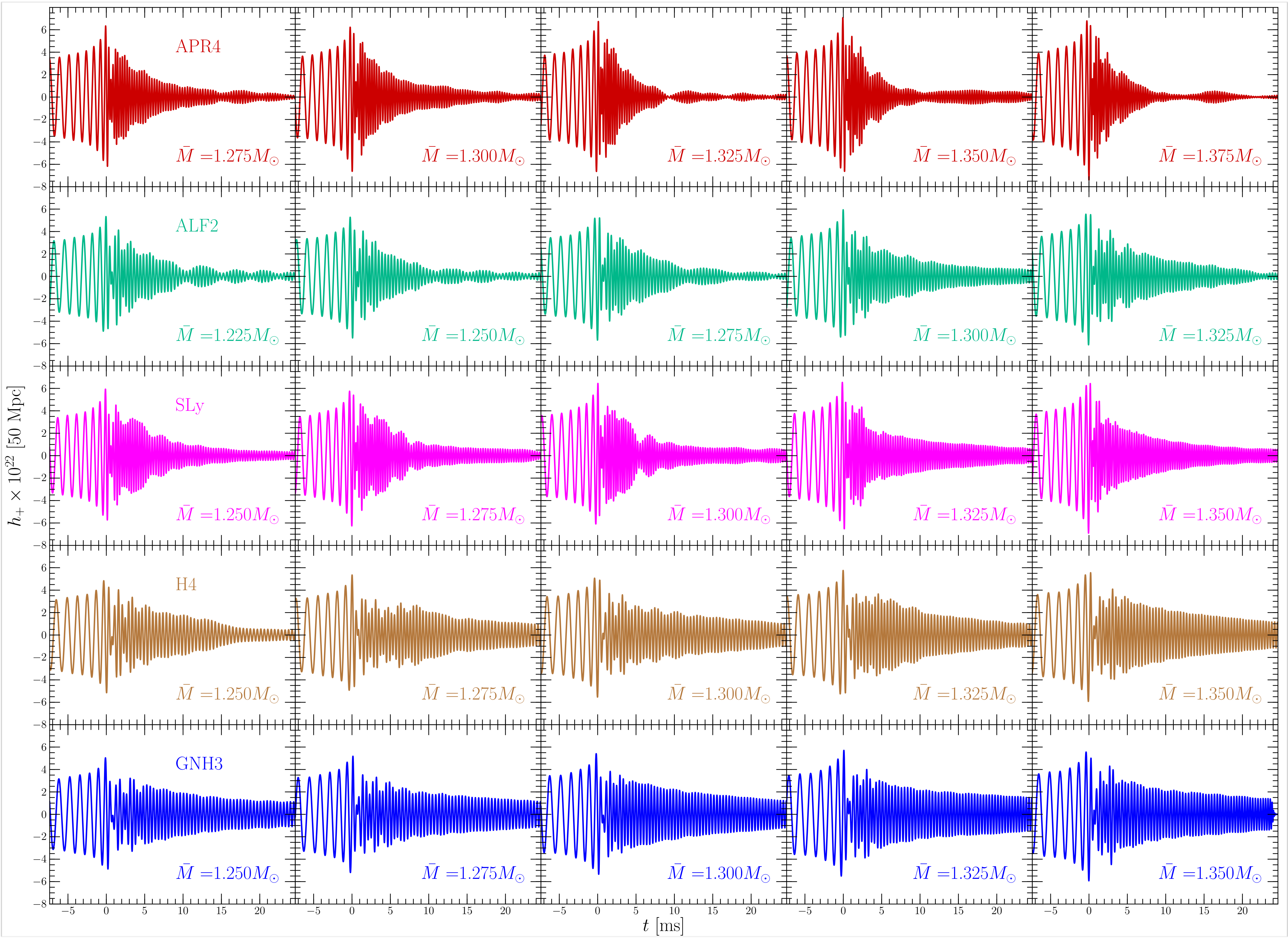
$$\Lambda = \frac{\lambda}{\bar{M}^5} = \frac{16}{3}\kappa_2^T$$ tidal deformability or Love number

# Anatomy of the GW signal



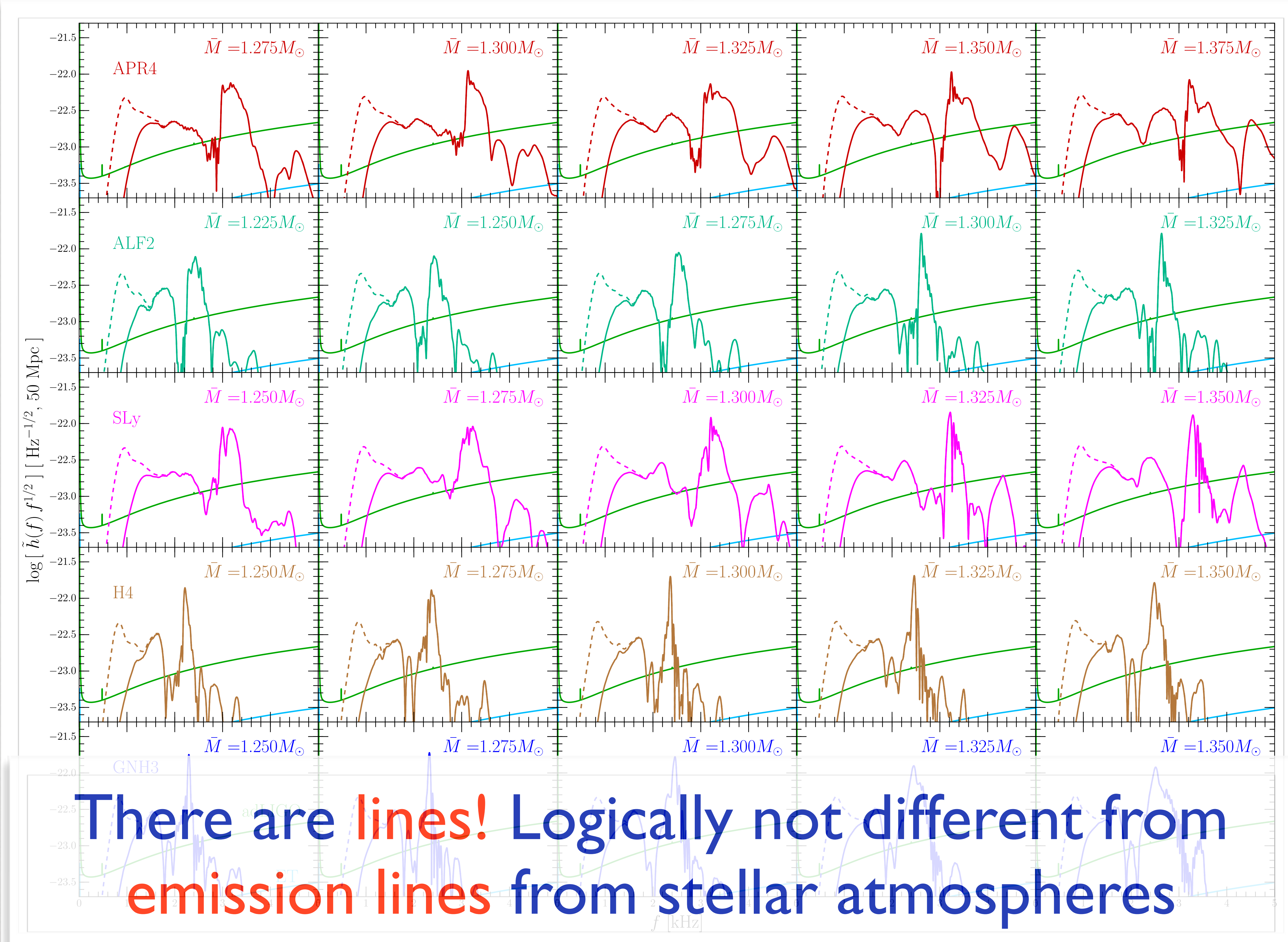
# A new approach to constrain the EOS

Takami, LR, Baiotti (2015)



# extracting information from the EOS

Takami, LR, Baiotti (2014, 2015)




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

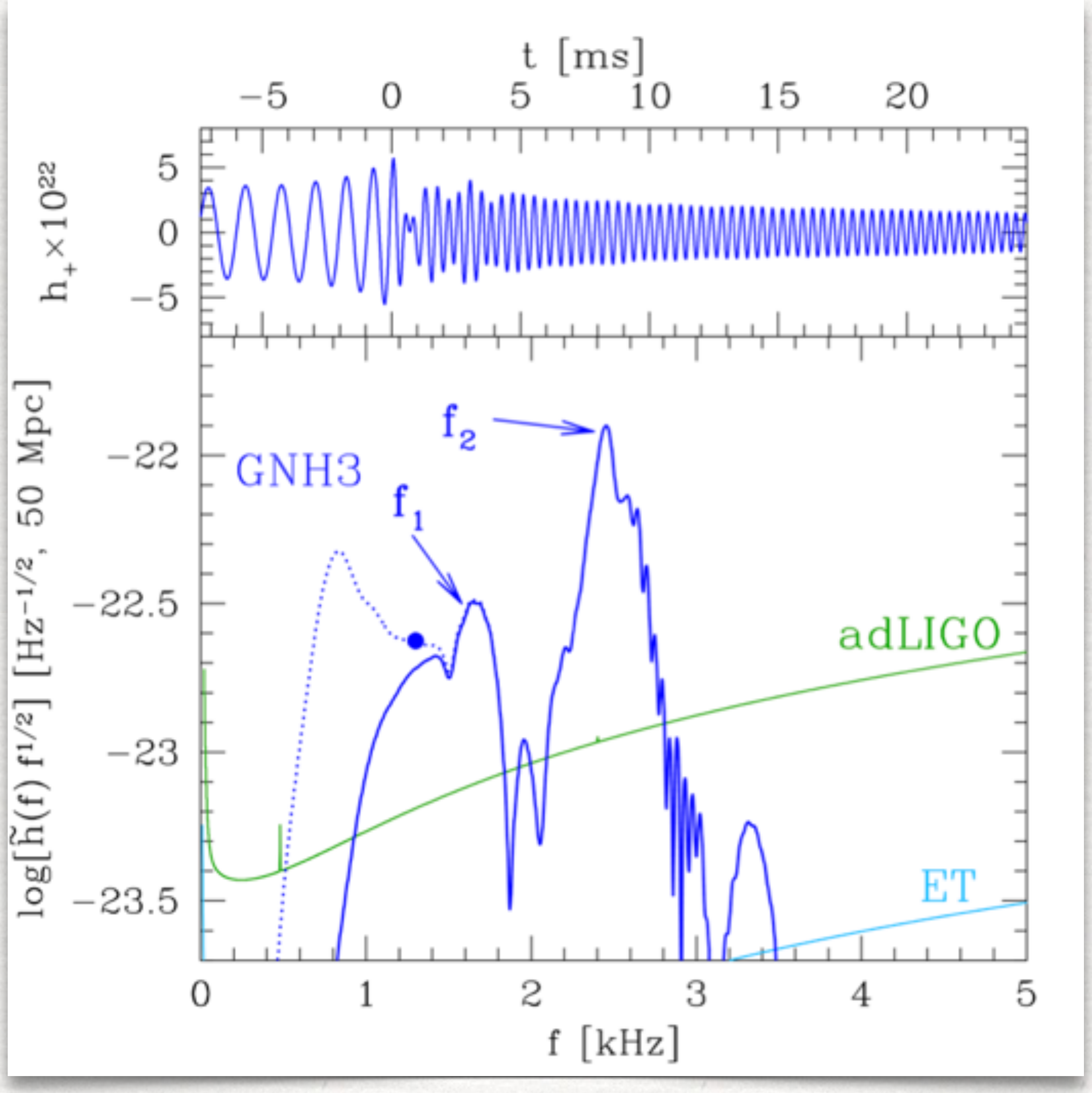
# A new approach to constrain the EOS

We have carried out numerical-relativity simulations of NS binaries with nuclear EOS and thermal contribution via ideal-fluid EOS

PSD of post-merger GW signal has a number of peaks (Oechslin+2007, Baiotti+2008)

The high-freq. peak ($f_2$) been studied carefully and produced by HMNS (Bauswein+ 2011, 2012, Stergioulas+ 2011, Hotokezaka+ 2013)

The low-freq. peak ($f_1$) is related to the early post-merger phase



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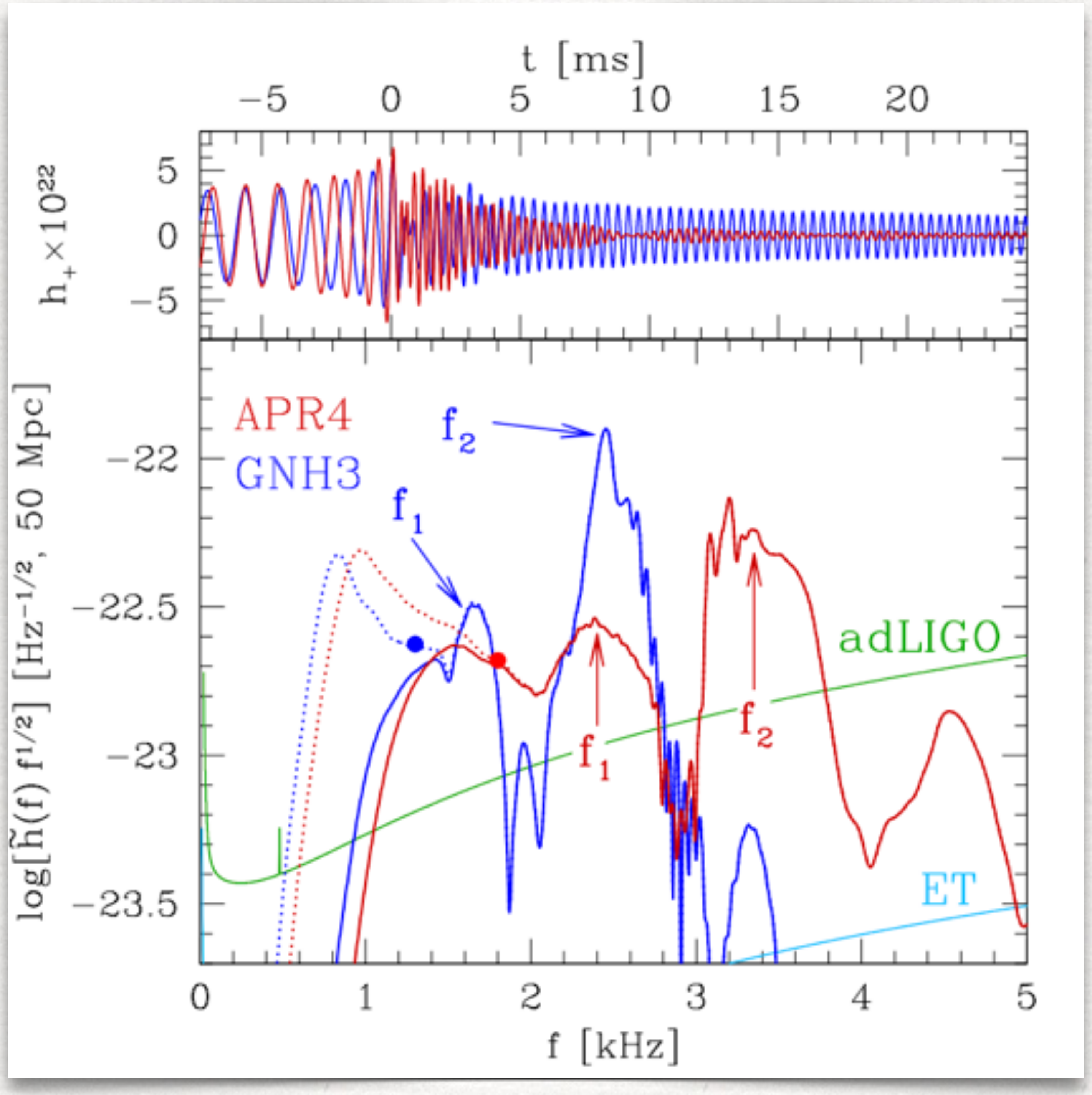
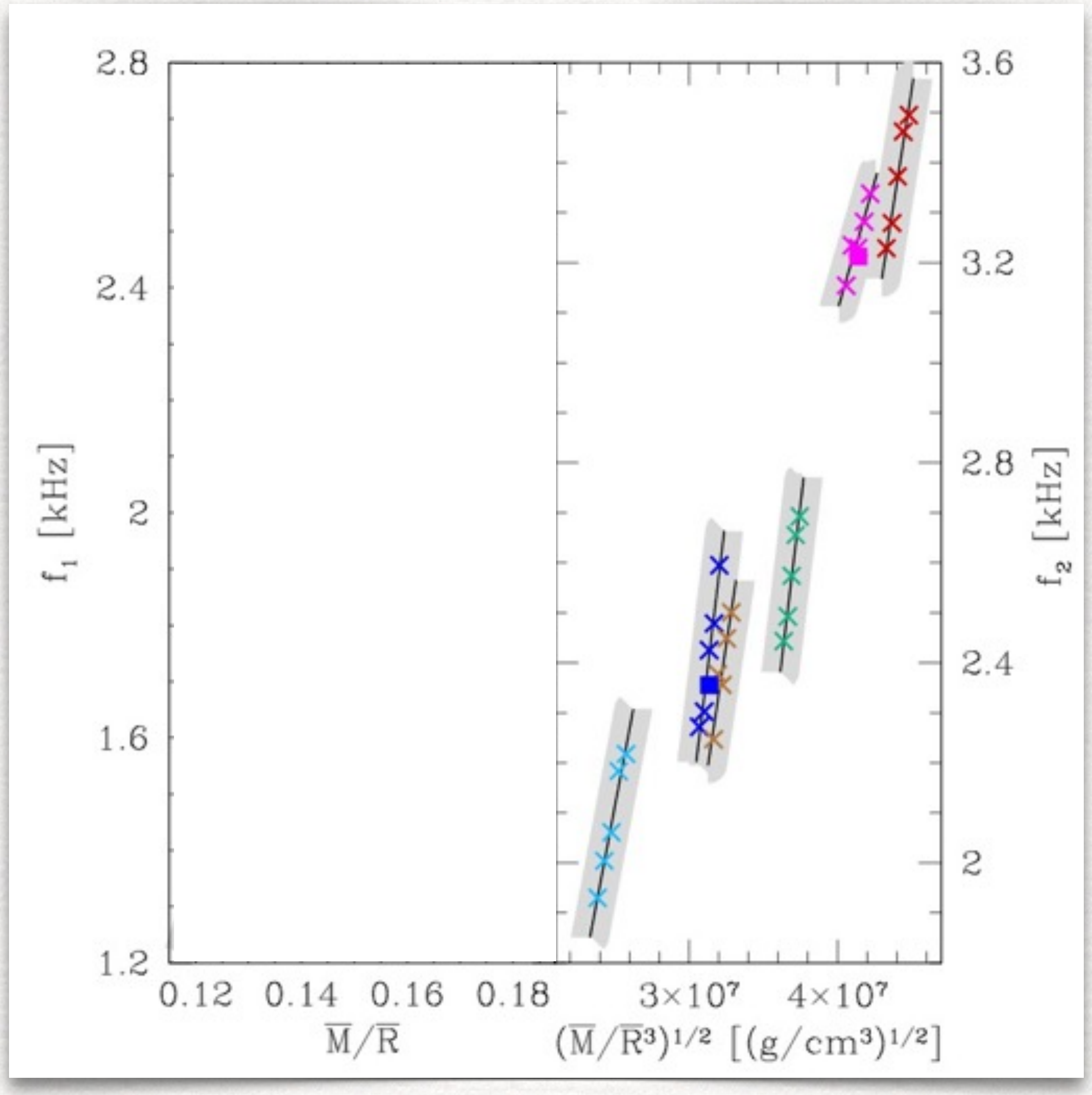


# A new approach to constrain the EOS

It is possible to correlate the values of the peaks with the properties of the progenitor stars, i.e. M, R, and combinations thereof.




Each cross refers to a given mass and crosses of the same color refer to the same EOS

The high-freq. peak $f_2$ has been shown to correlate with stellar properties, e.g., $R_{max}$, $R_{1.6}$,. etc (Bauswein+ 2011, 2012, Hotokezaka+ 2013).

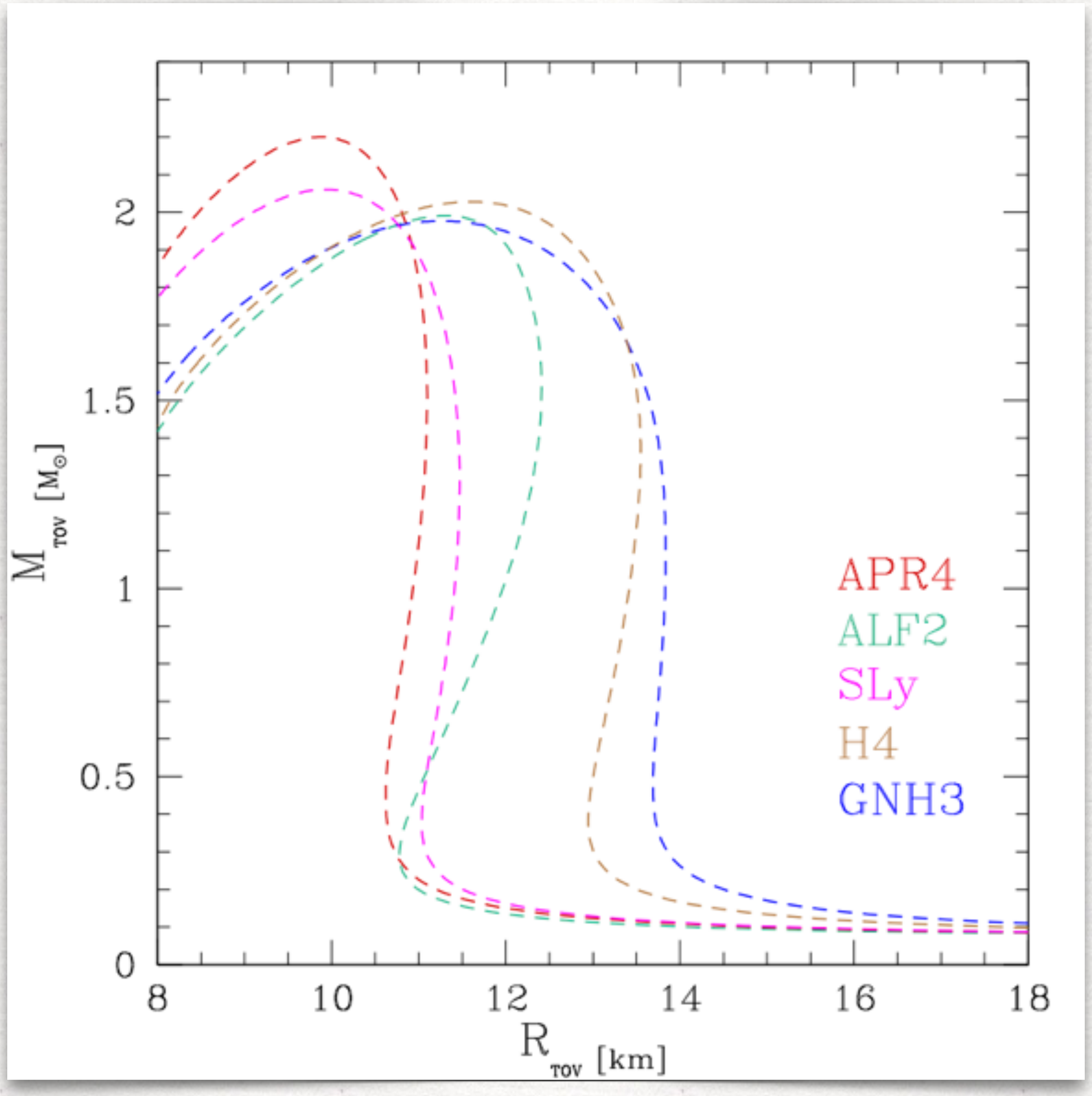
The correlation **depends** on mass

The low-freq. peak $f_1$ shows a much tighter correlation; most importantly, it **does not depend** on the EOS

# 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.

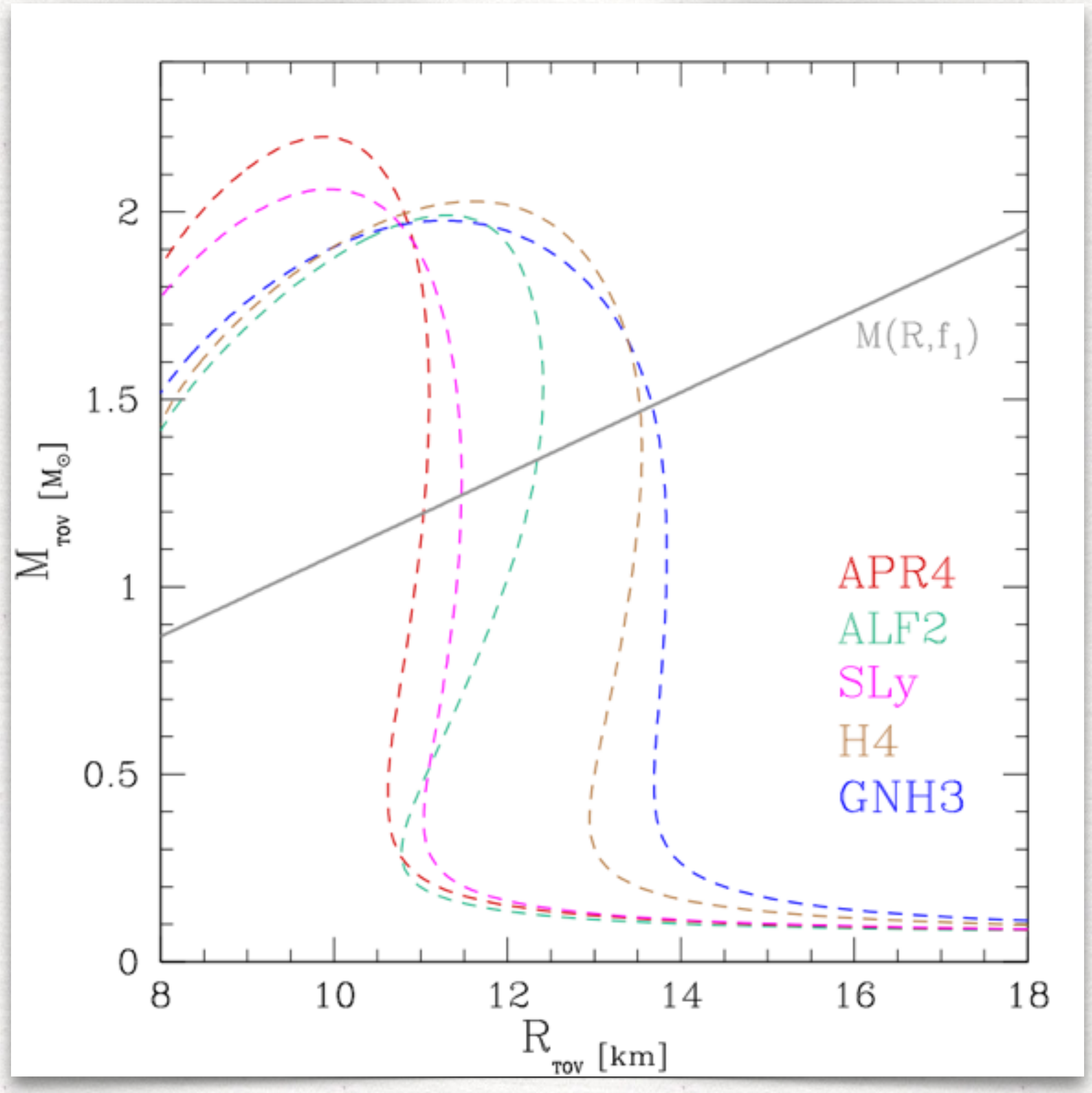
Consider your best choices as candidate EOSs



# An example: use the $M(R,f_l)$ relation

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

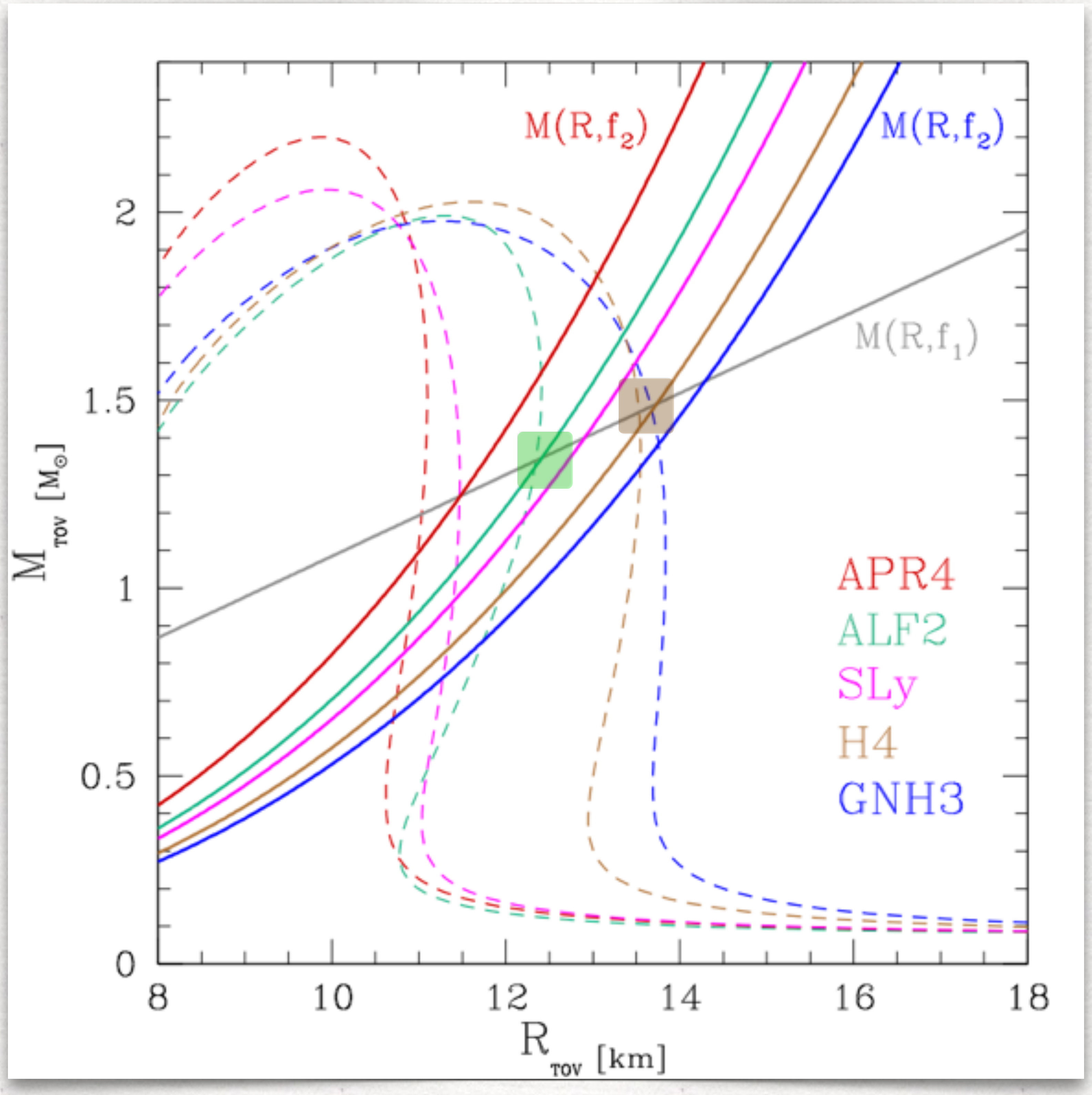
All EOSs will have **one** constraint (crossing)



# 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.

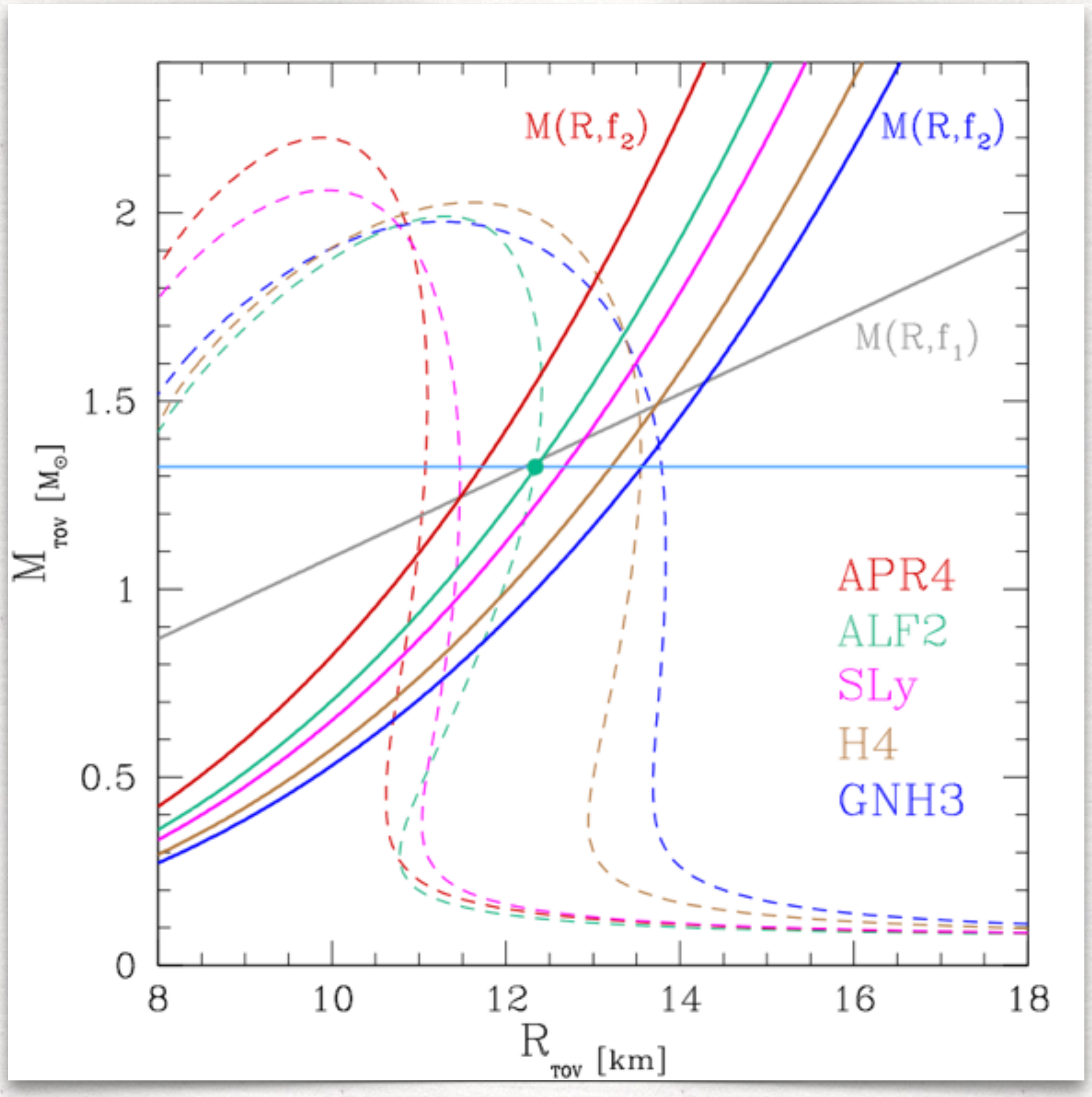
The right EOS will have **three** different constraints (APR, GNH3, SLy excluded)



# 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.

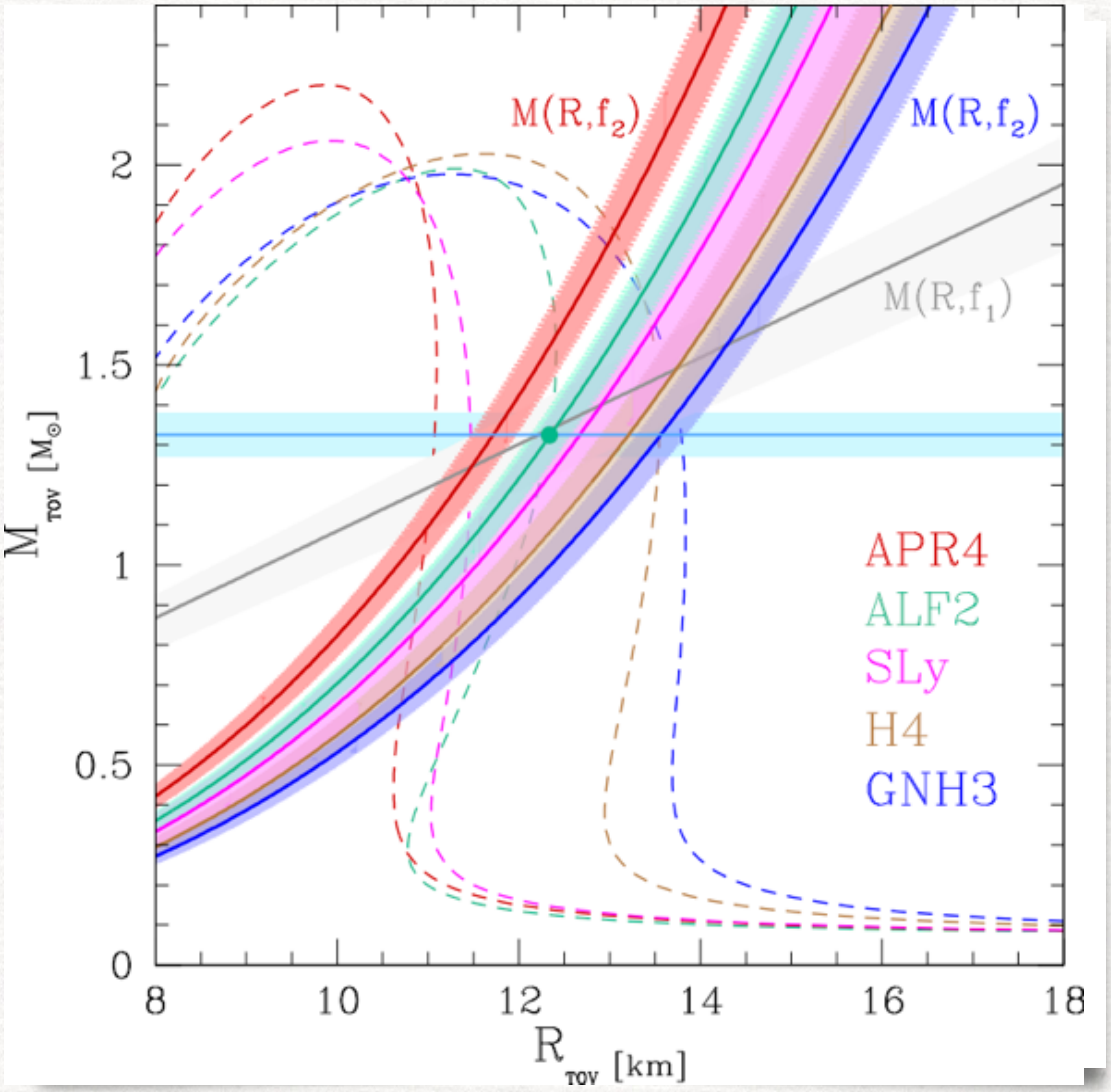


# This works for all EOSs considered

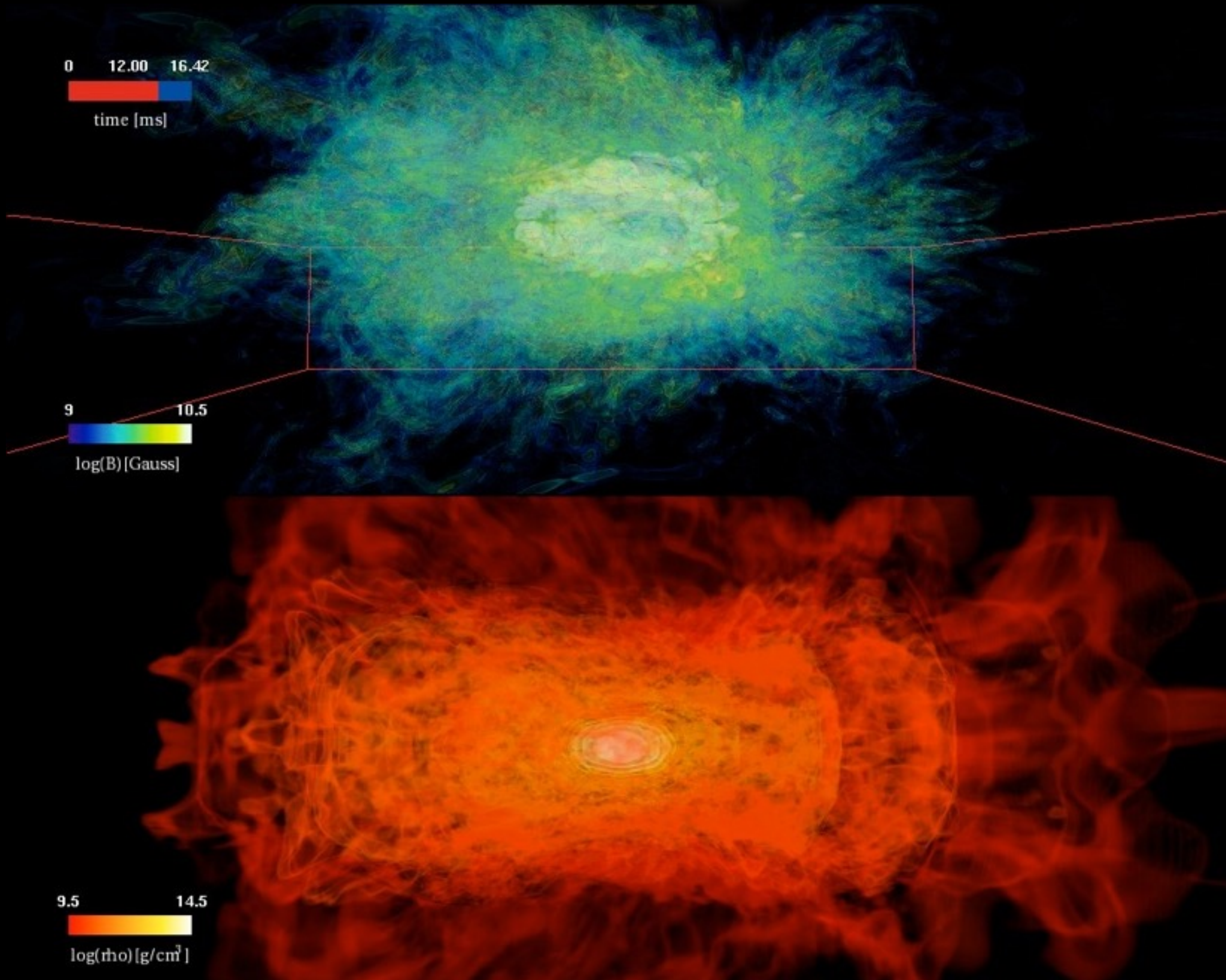
In reality things will be more complicated. The **lines** will be **stripes;** Bayesian probability to get precision on *M, R*.

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.



# The role of magnetic fields



# Ideal Magnetohydrodynamics

Most simulations to date make use of **ideal MHD**: conductivity is infinite and magnetic field simply advected.

- can B-fields be detected during the inspiral?
  - **NO**: present and future GW detectors will not be sensitive enough to measure the small differences

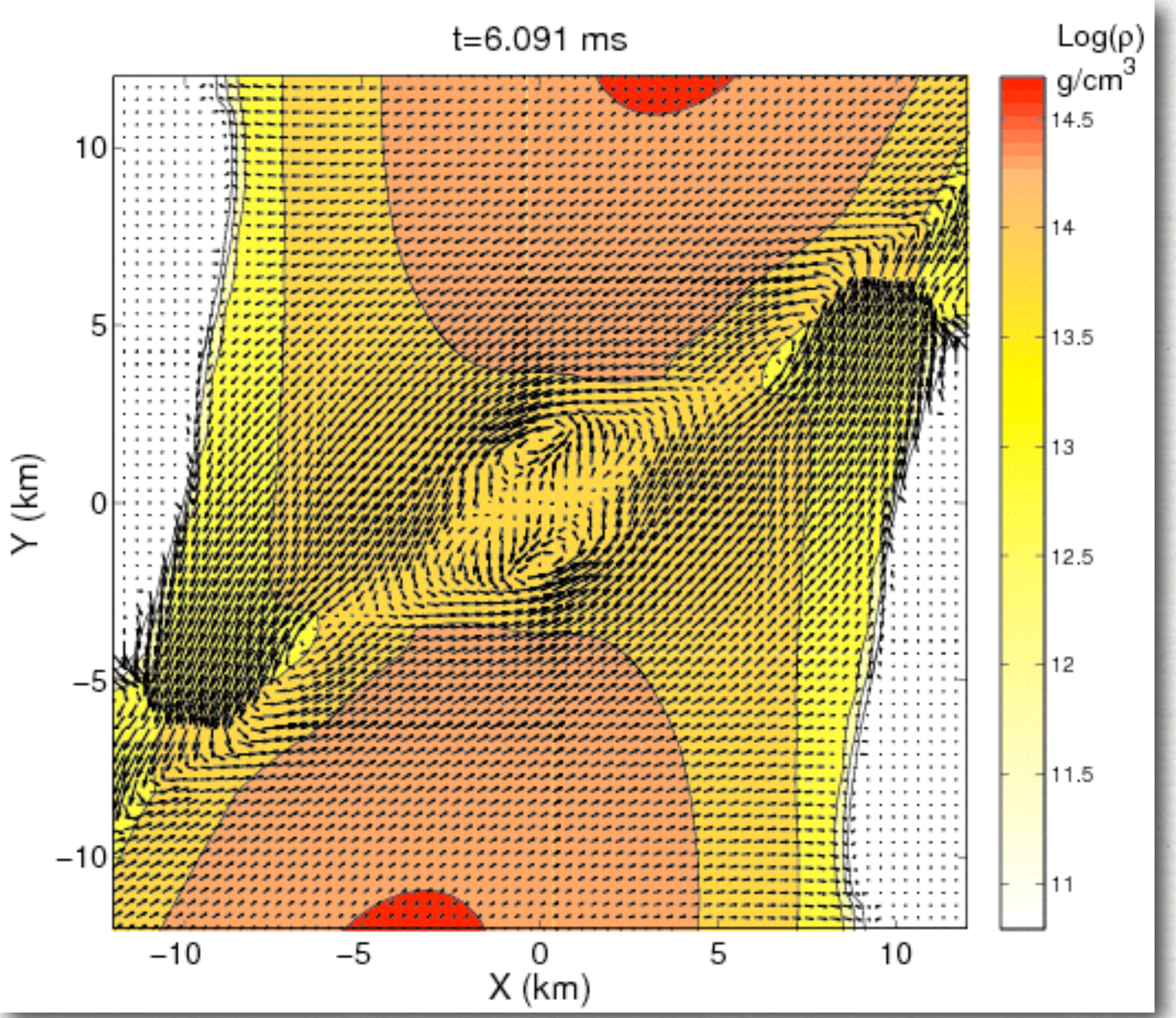
    Giacomazzo, LR, Baiotti (2009)
- can B-fields be detected in the HMNS?
  - **YES** (in principle): different B-fields change the survival time of the HMNS and can grow via MRI

    Giacomazzo, LR, Baiotti (2010), Siegel, LR+ (2013)
- can B-fields grow after BH formation?
  - **YES**: B-fields are subject to instabilities and rotation of the BH introduces preferred direction for field geometry

    LR, Giacomazzo, Baiotti, + (2011)

# MHD instabilities and B-field amplifications

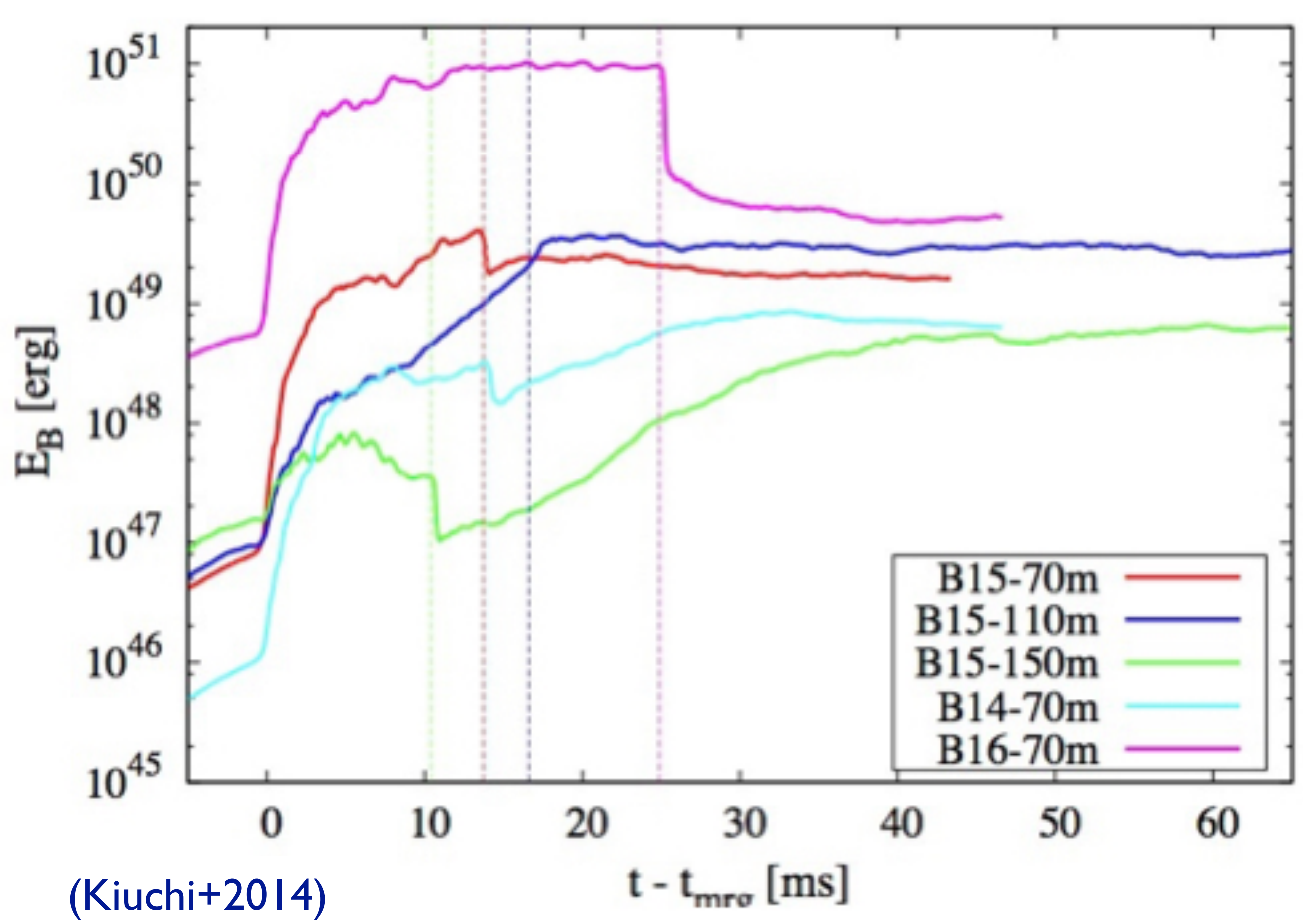
- at the merger, the NS create a strong shear layer which could lead to a **Kelvin-Helmholtz instability**; magnetic field can be amplified



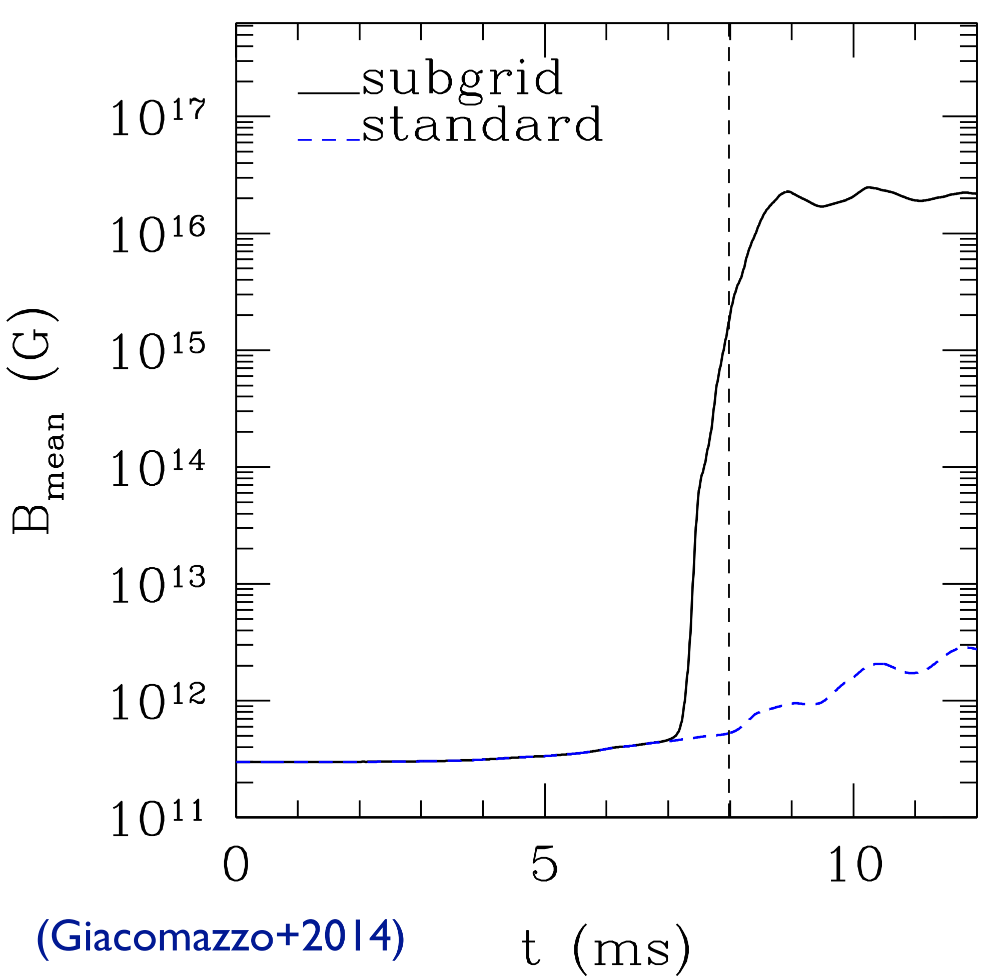

(Baiotti+2008)

# 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
- direct simulations don't show significant exponential growth (Giacomazzo+2011, Kiuchi+2014). Timescale too short? Resolution too poor?
- sub-grid models suggest B-field grows to $10^{16}$ G (Giacomazzo+2014)




(Kiuchi+2014)




(Giacomazzo+2014)

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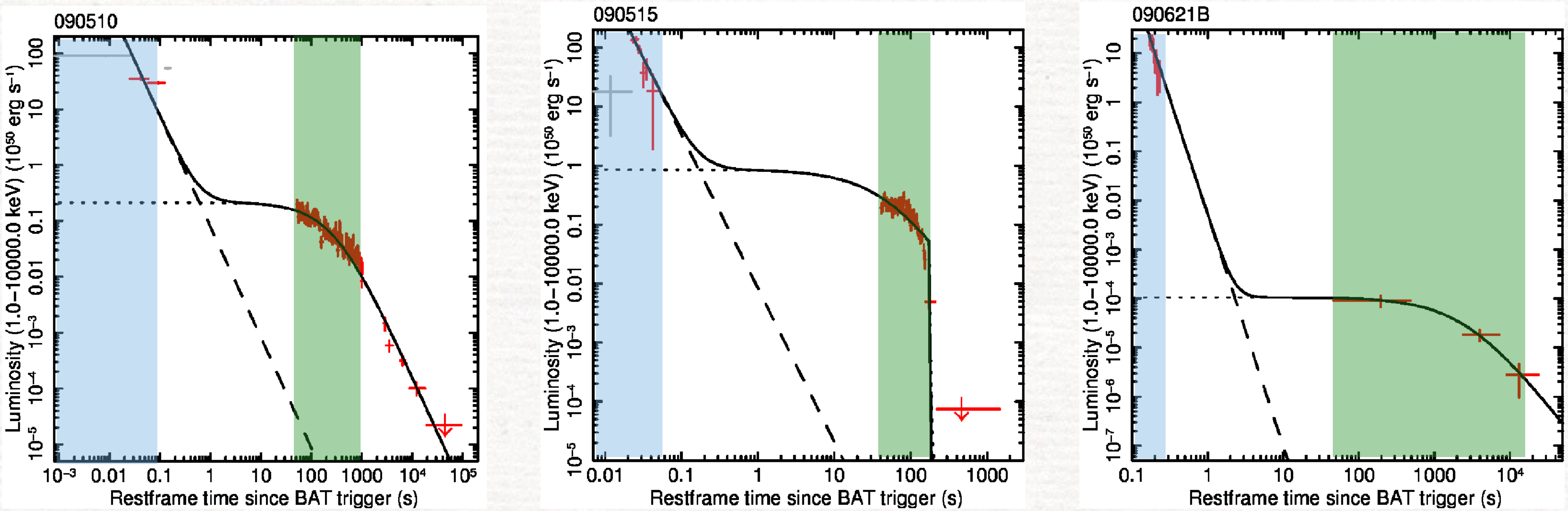
- sub-grid models suggest B-field grows to $10^{16}$ G (Giacomazzo+2014)
- differentially rotating magnetized fluids develop the **MRI (magnetorotational instability;** Velikhov 1959, Chandrasekhar 1960)
- the MRI leads to exponential growth of B-field and to an outward transfer of angular momentum: responsible for accretion in discs
- overall, consensus MRI **can develop** in HMNS (Siegel+2013,Kiuchi+2014)
- degree of amplification is unknown: are two orders of magnitude reasonable? should one expect more? what about resistivity?

# Do we understand X-ray afterglows?



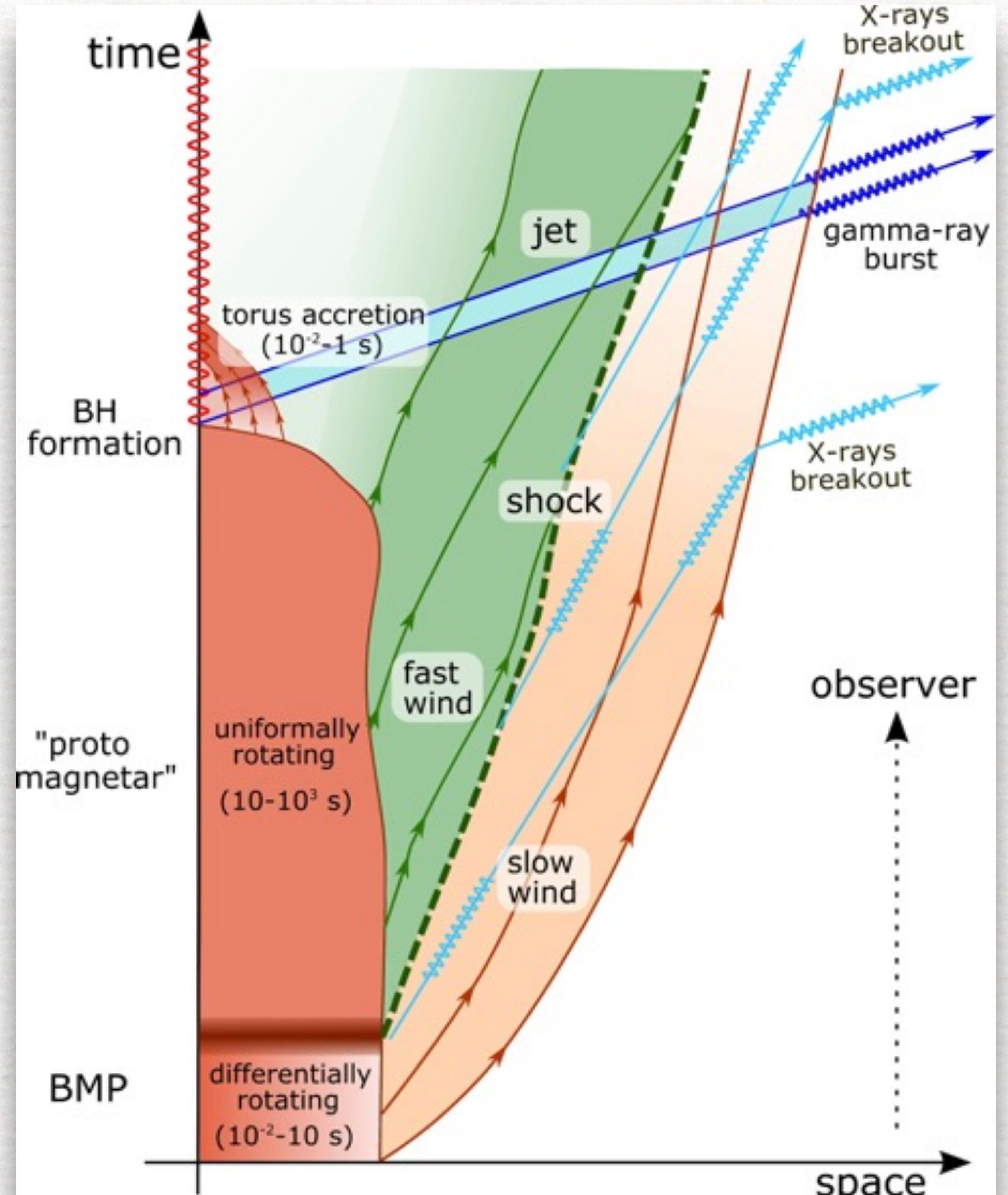

- X-ray afterglows have been observed by Swift lasting as long as $10^2$-$10^4$ s (Rowlinson+ 13; Gompertz+13)
- The x-ray afterglow could be produced by "proto-magnetar wind" with $L_x \sim 10^{49}\ \mathrm{erg\ s}^{-1}$ (Zhang & Mezsaros 01, Metzger+ 11, Zhang 13).

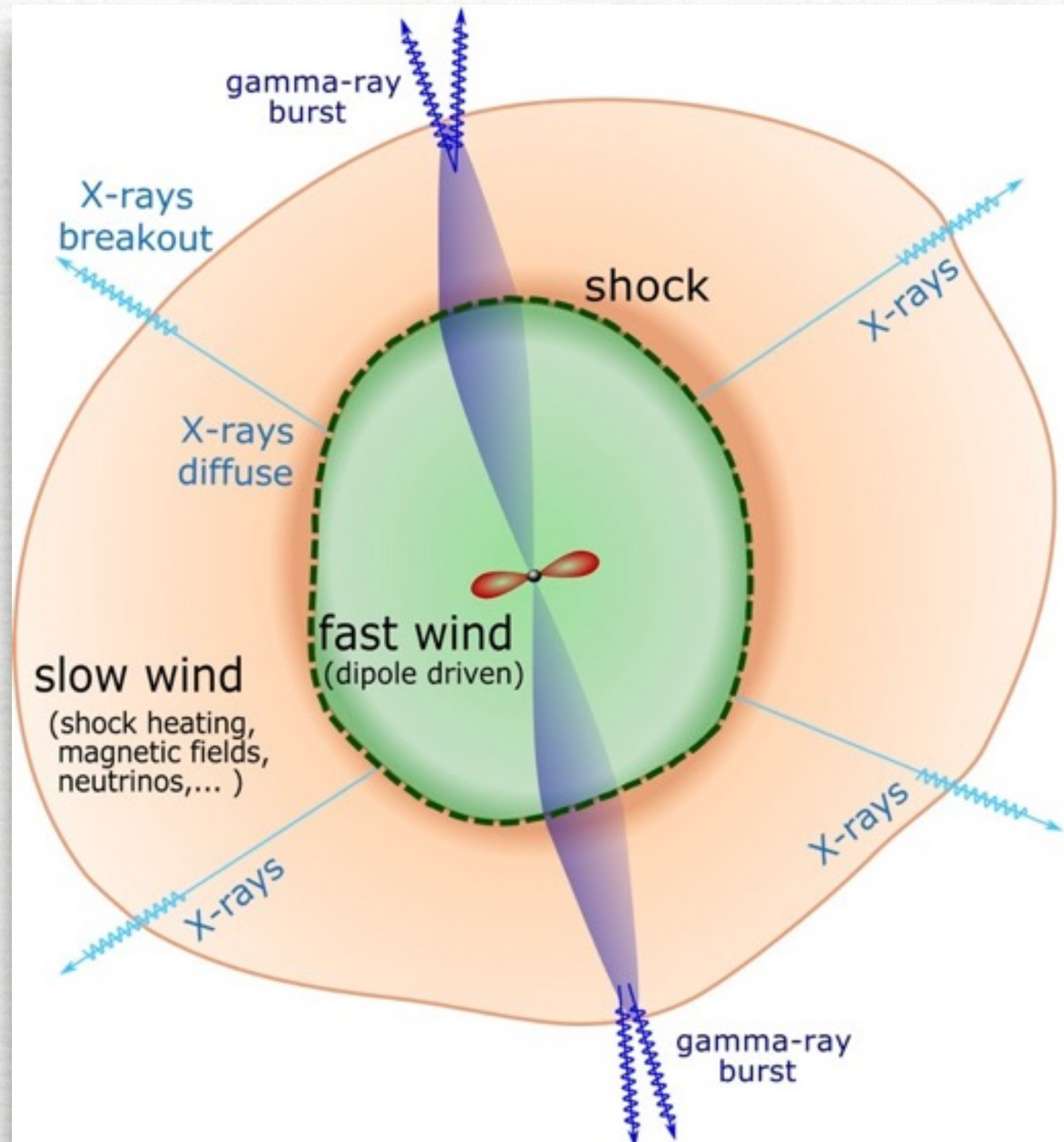
Even so, plateaus remain a **riddle**:

- differential rotation lost over 10s: what can operate for >1000s ?
- if gamma rays produced by jet, and X-rays by HMNS, how can X-rays be an afterglow? (BH formed after HMNS!)

# A novel paradigm for GRBs?

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



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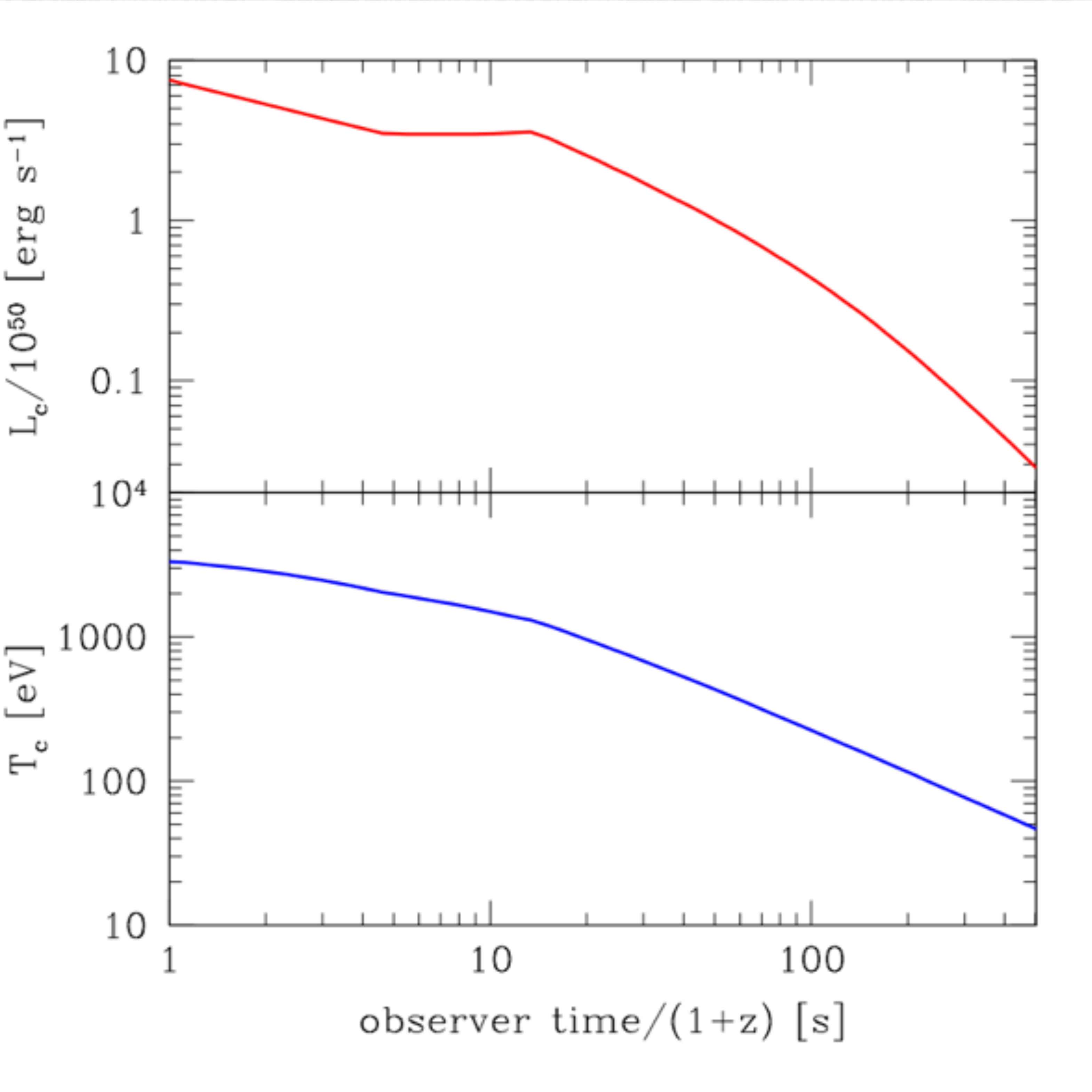


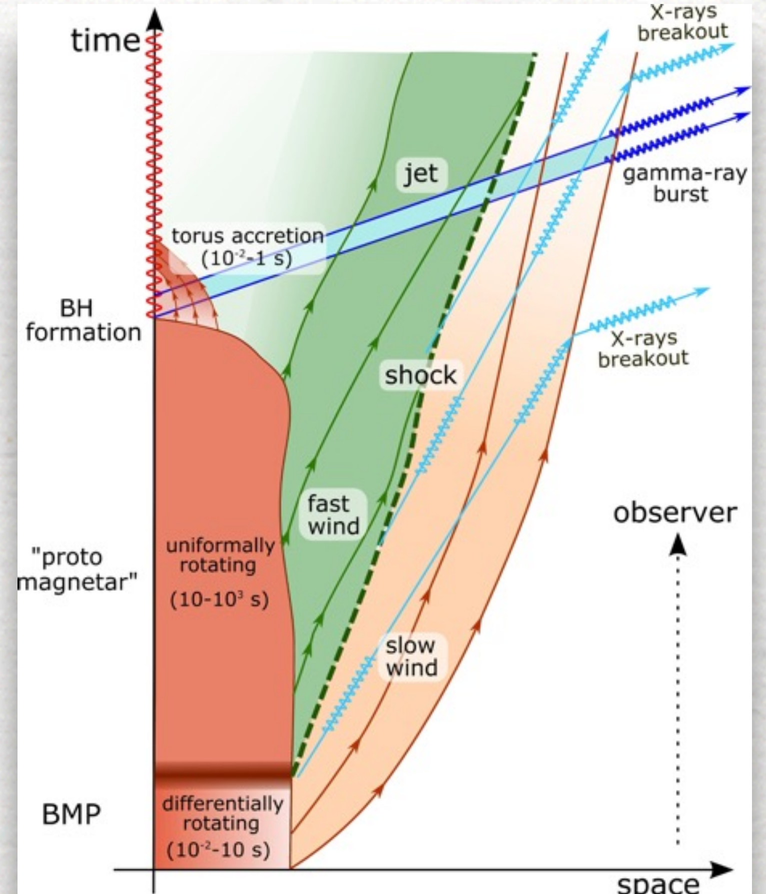

Isotropic equivalent of luminosity of cocoon in host-galaxy frame as a function of observer time (z is galaxy redshift)

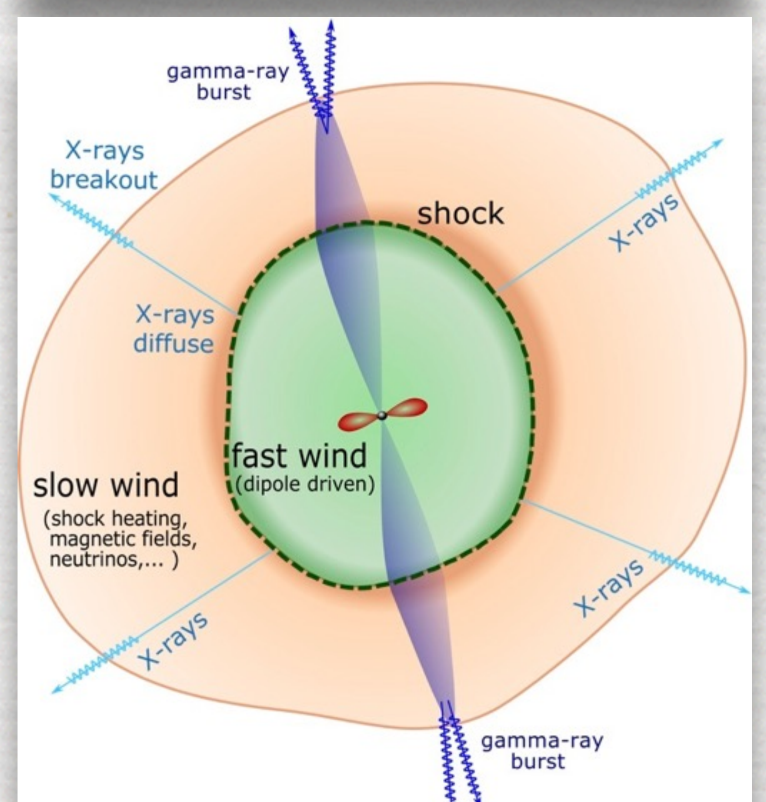
Cocoon temperature

$$\dot{M}_{sw} = 10^{-3} M_\odot \mathrm{s}^{-1}$$
$$V_{sw} = c/2$$
$$t_{sw} = 10 \ \mathrm{s}$$

# A novel paradigm for GRBs?

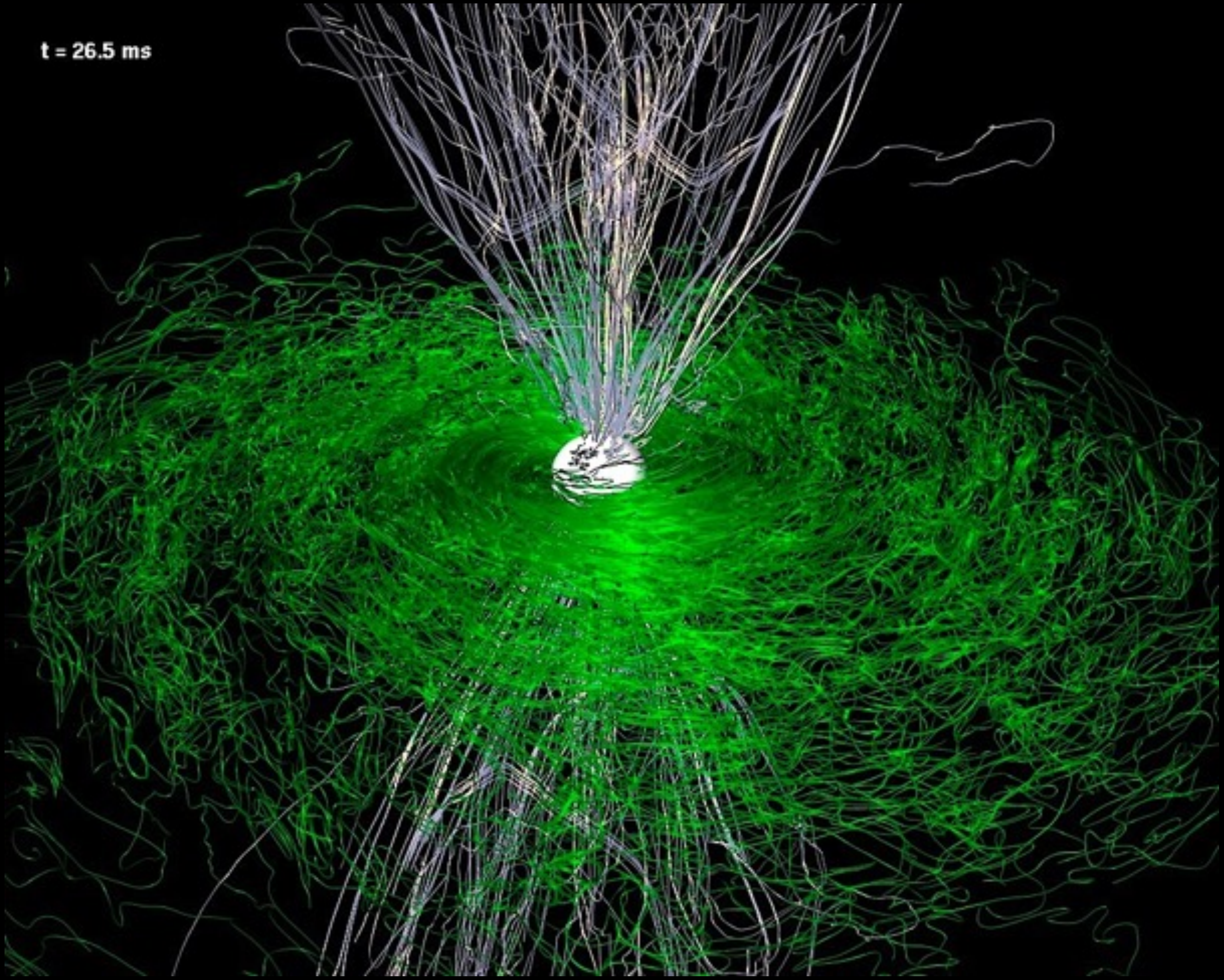
LR, Kumar (2014)




- ***solves the timescale riddle:*** X-ray luminosity is produced by BMP 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 by a number of effects.
- proposes ***unifying view with long GRBS***: a jet has to propagate in confining medium
- ***predictions***: X-ray emission possible before gamma; IC of thermal photons at break out.
- GW signal peak ***earlier*** than thought before.
- ***potential problem***: need to produce a disk at collapse and could be difficult (Margalit+15).

# Magnetic fields and black holes

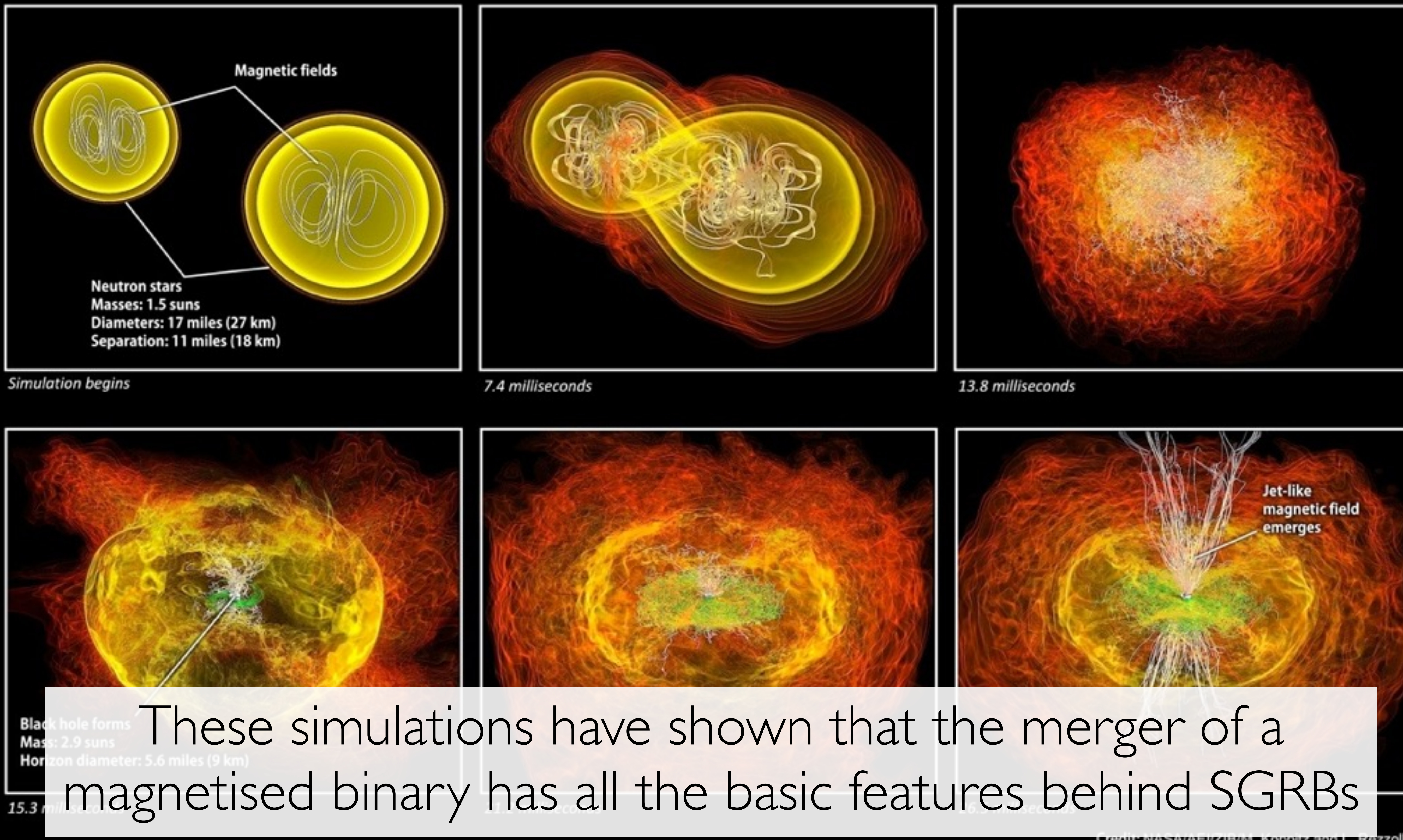


# Ideal Magnetohydrodynamics

Giacomazzo+ 2010, LR+ 2011

- Observations of short gamma-ray bursts hint to the presence of a **relativistic outflow: jet**.
- Such outflows are observed in AGNs and every time an **accretion disc** develops around a **black hole**.
- Does a neutron-star binary lead to a **relativistic jet?**
- Simulations not yet accurate enough to produce outflow but evidence is present for a **magnetic-jet structure**.

Giacomazzo+ 2010, LR+ 2011




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

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

# Resistive Magnetohydrodynamics

Dionysopoulou, Alic, LR (2015)

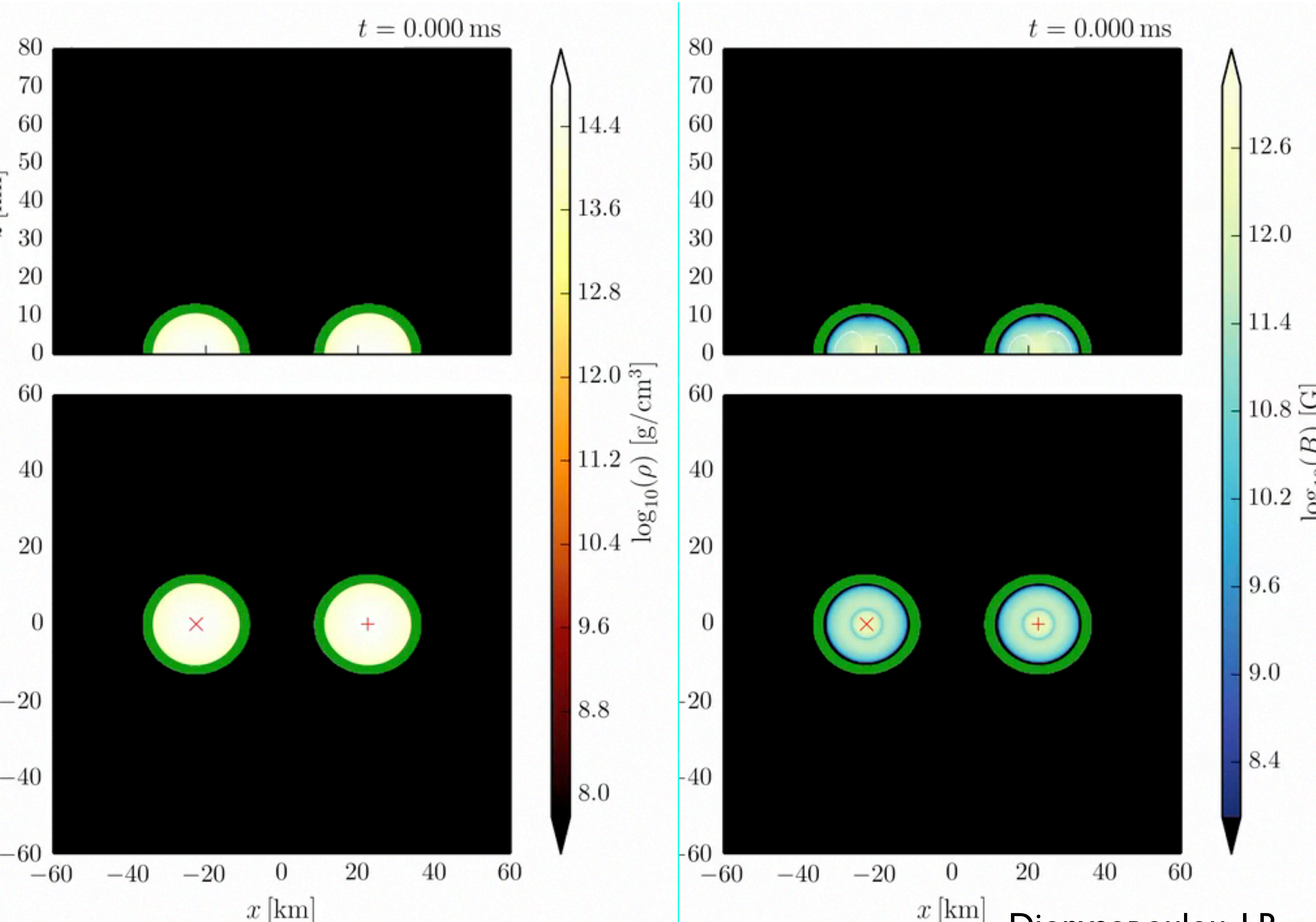
- Ideal MHD is a good approximation in the inspiral, but not after the merger (high temp, low densities).
- Main difference in resistive regime is the current, which is dictated by Ohm's law but microphysics is **poorly** known.
- We know conductivity $\sigma$ is a **tensor** and proportional to density and inversely proportional to temperature.
- A simple prescription with scalar (isotropic) conductivity:

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

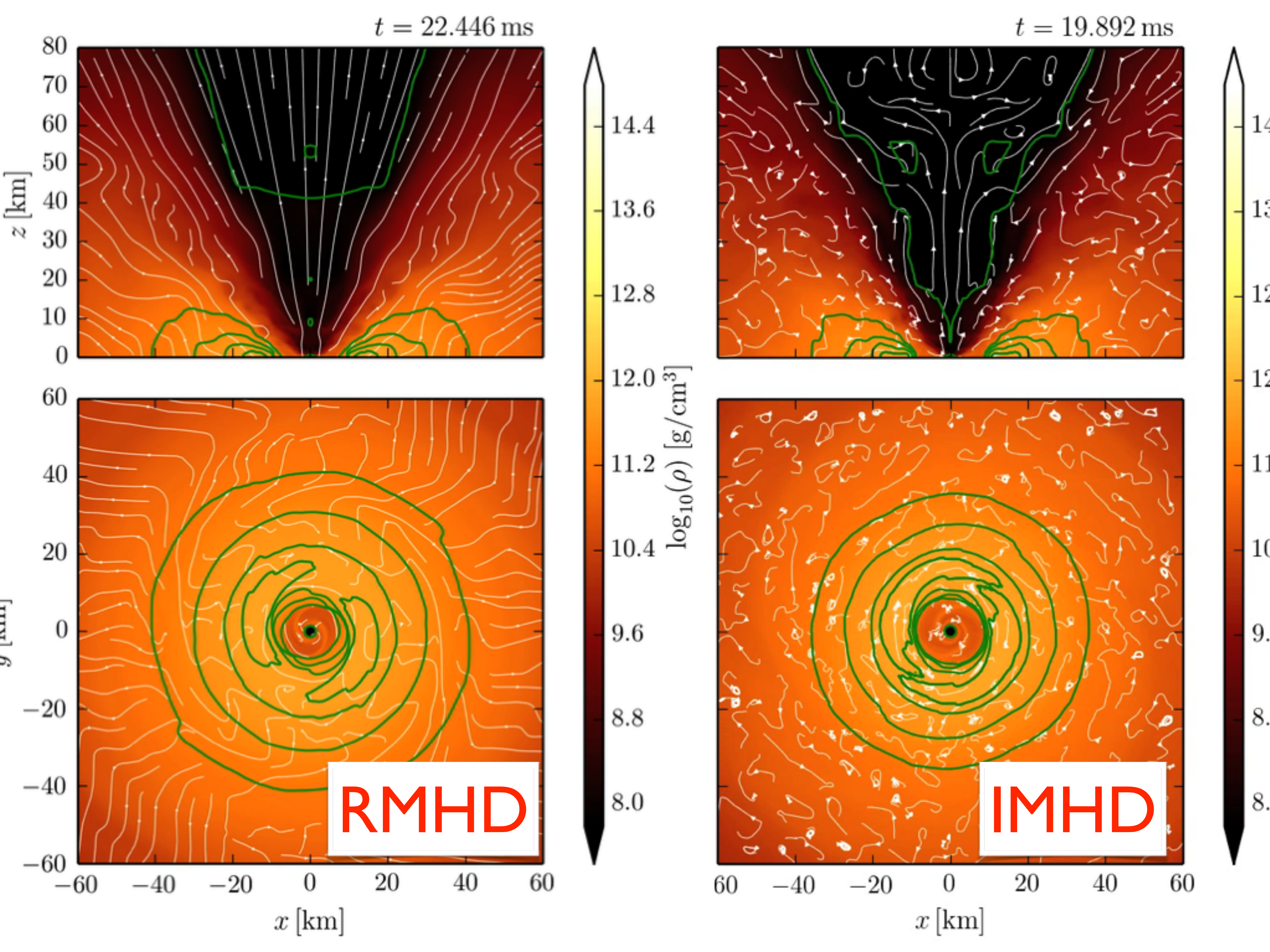
$\sigma \to \infty$ ideal-MHD (IMHD) regime

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

$\sigma \to 0$ electrovacuum



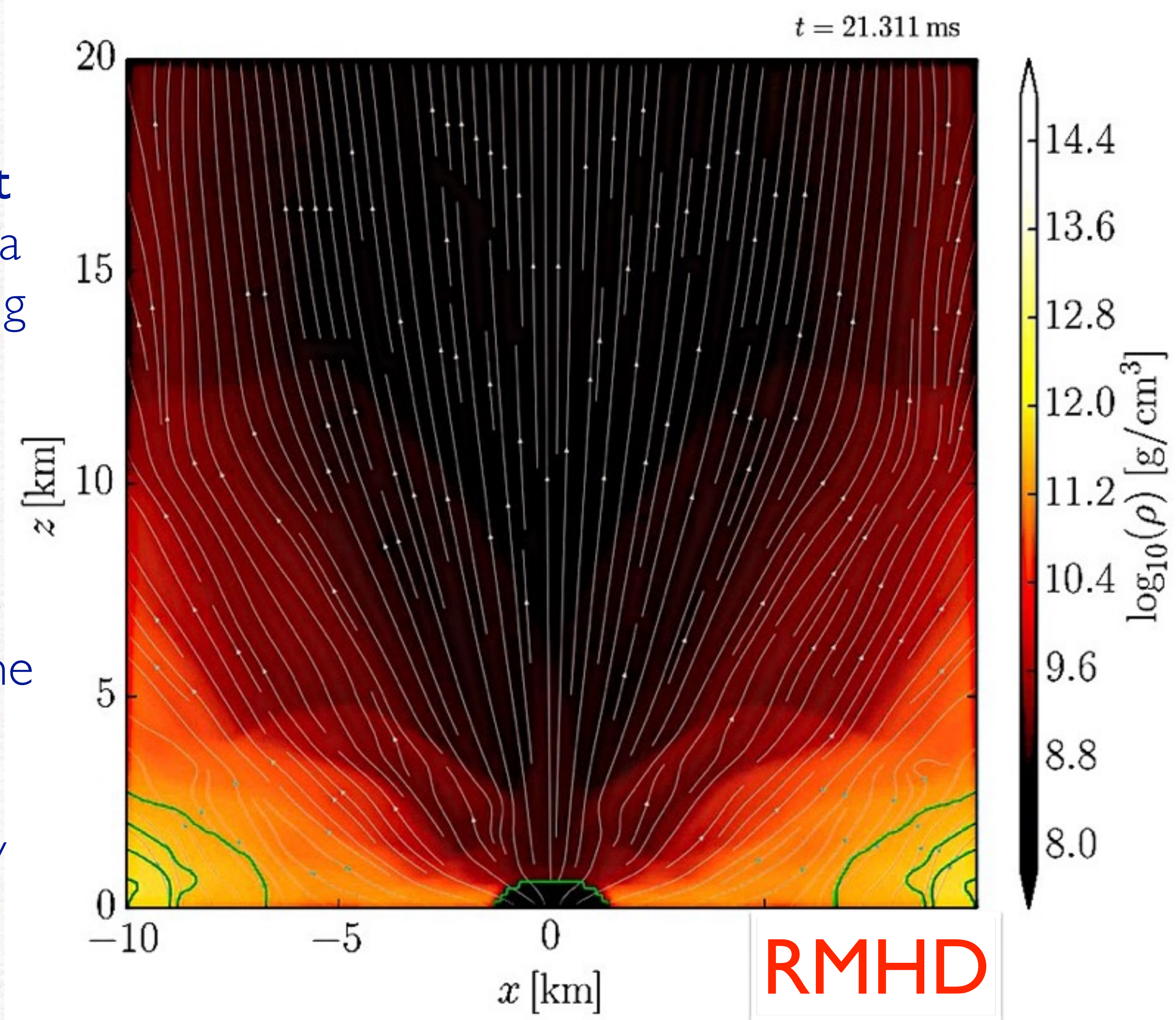

Dionysopoulou, LR



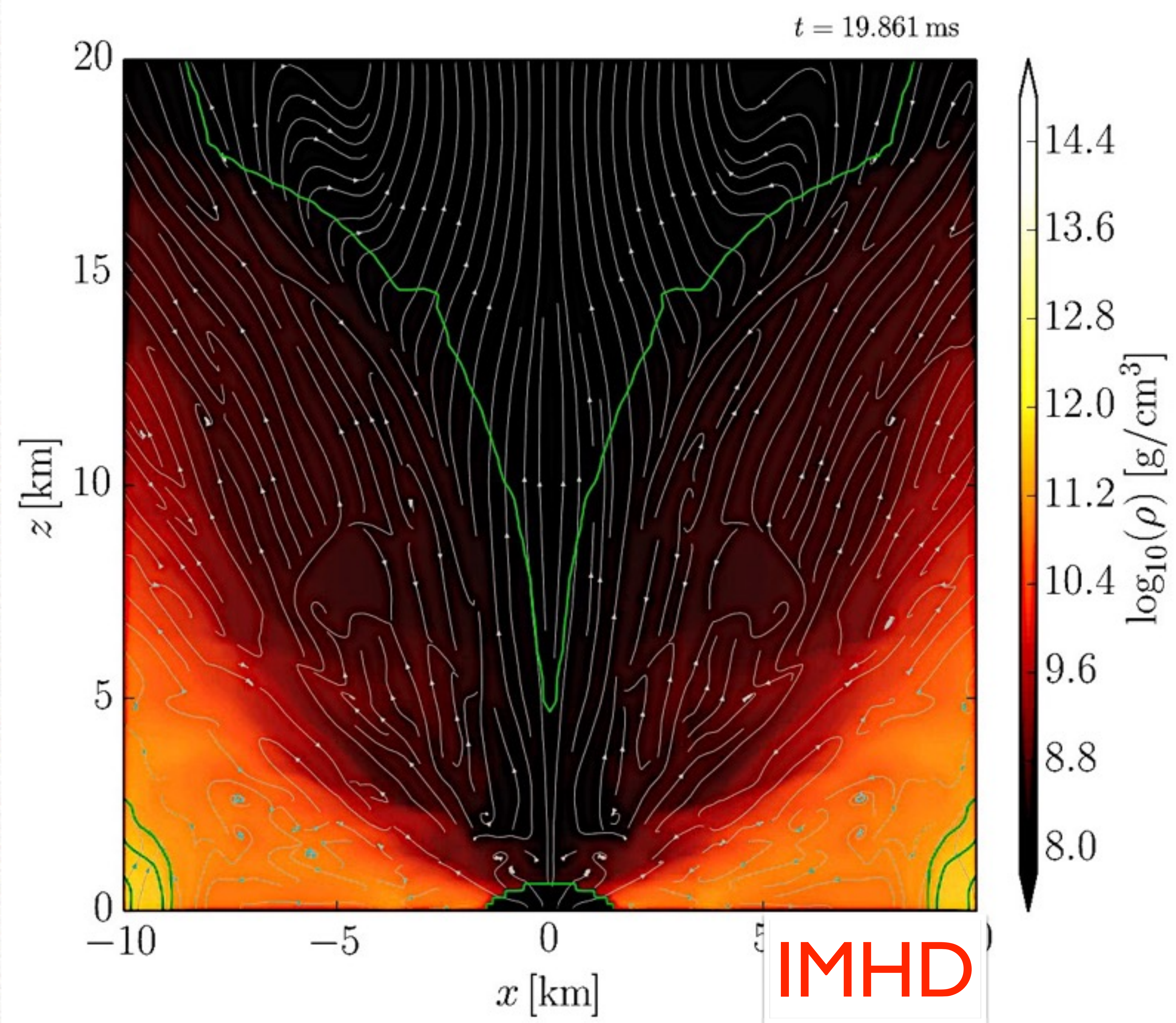
t = 22.446 ms
t = 19.892 ms
z [km]
y [km]
x [km]
x [km]
log10(ρ) [g/cm3]
14.4
13.6
12.8
12.0
11.2
10.4
9.6
8.8
8.0
RMHD
IMHD

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

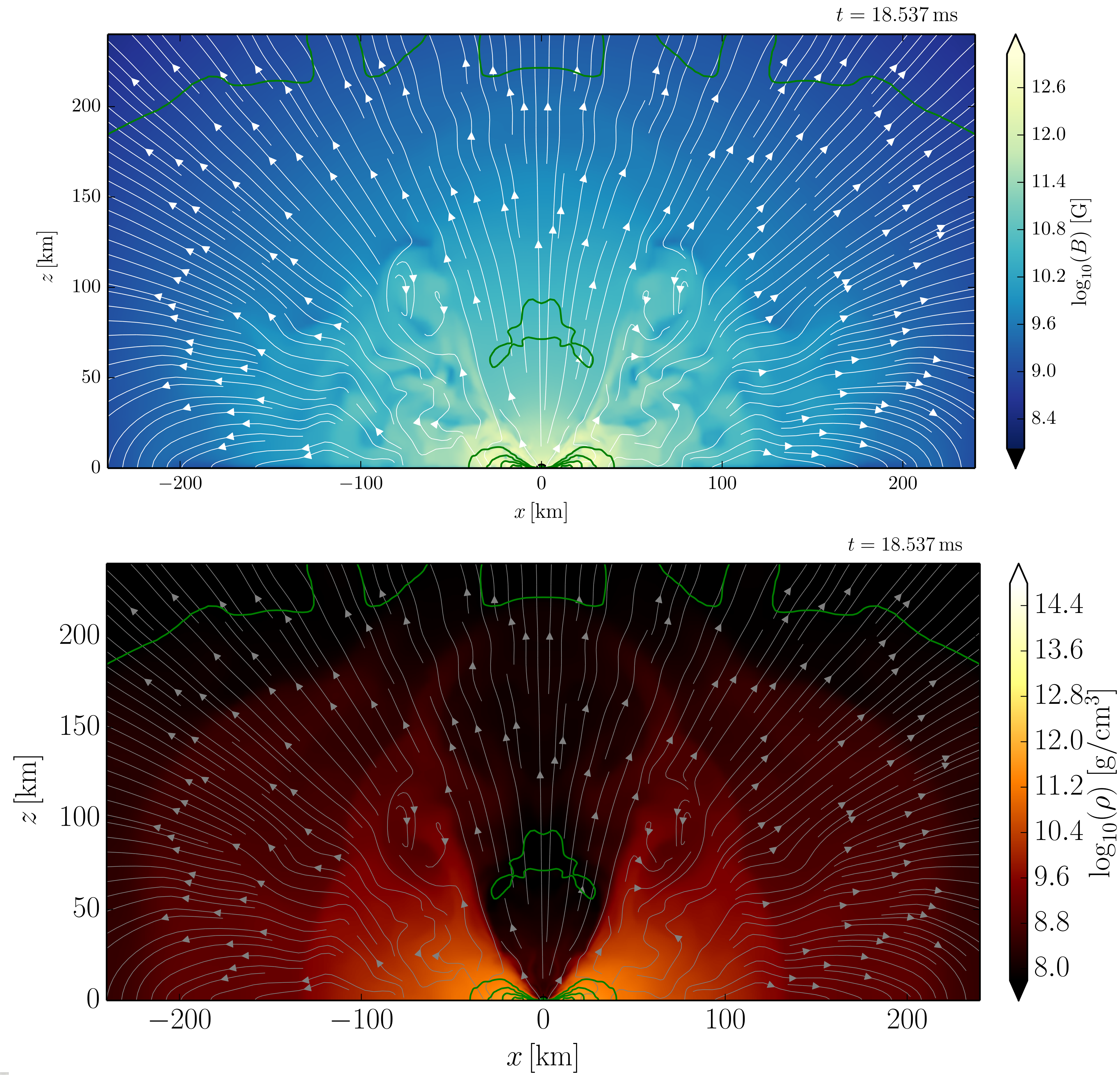
In RMHD the magnetic jet structure is present from the scale of the horizon (resolution only ~150m).



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

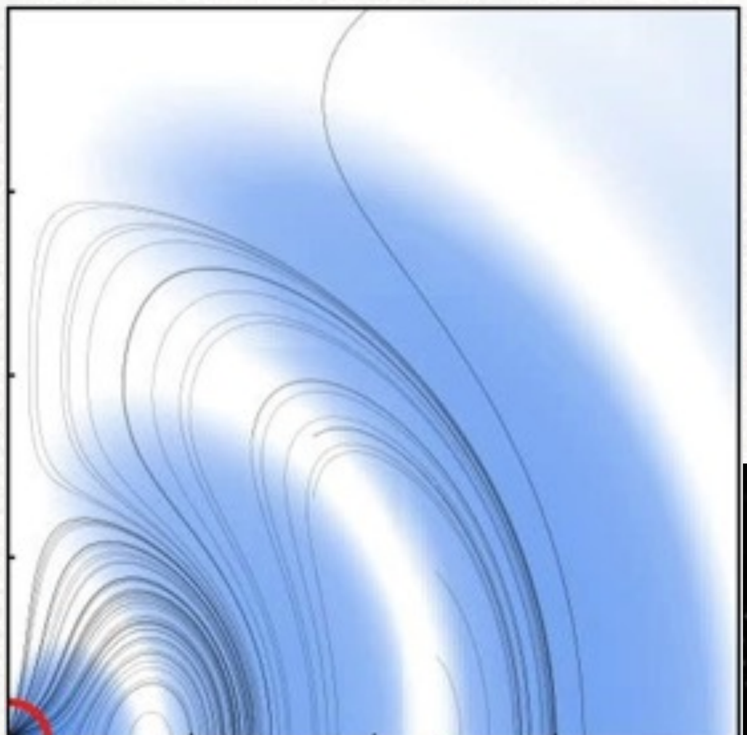


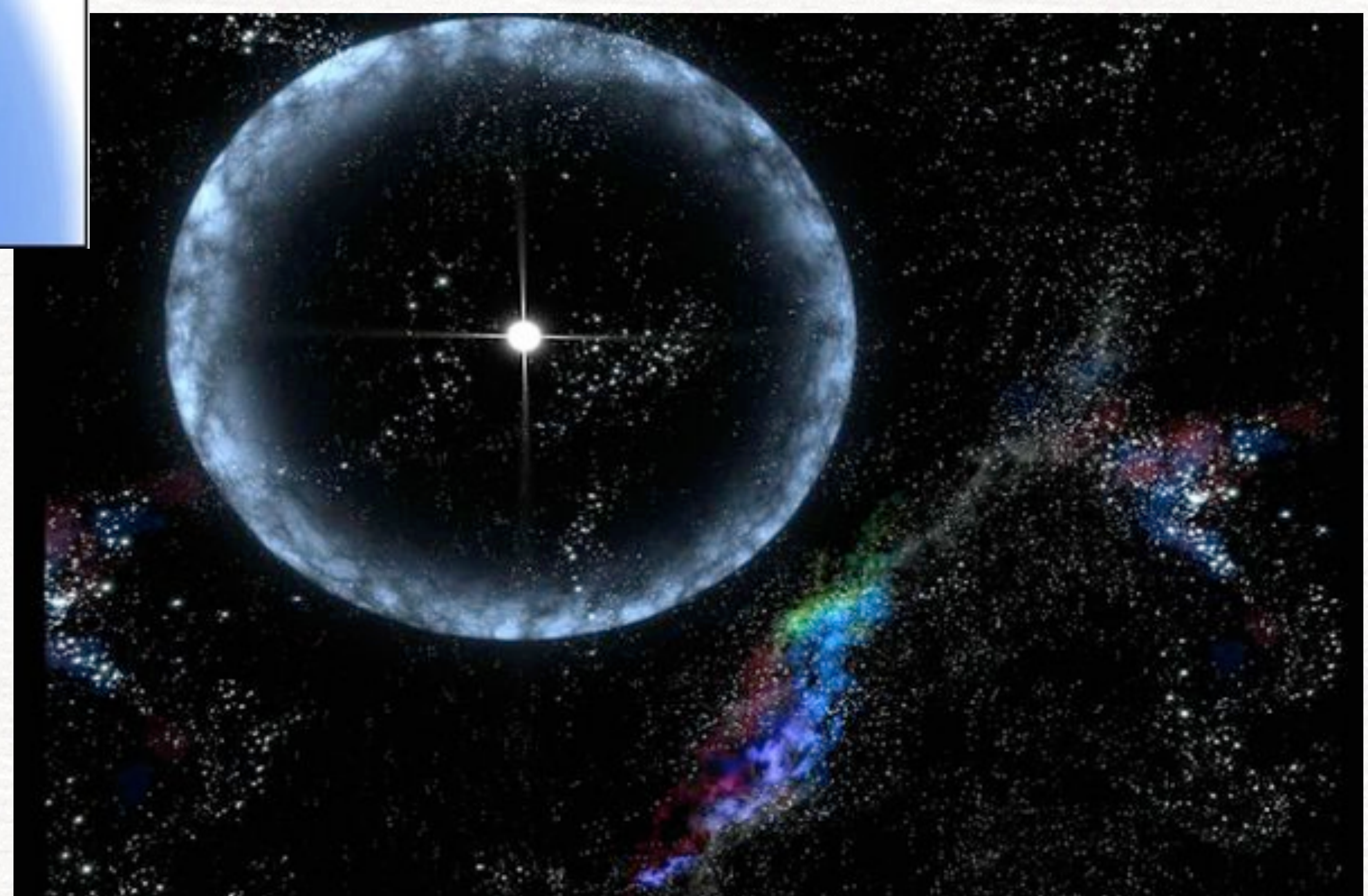
The magnetic jet structure maintains its coherence up to the largest scale of the system.




RMHD

# The riddle of Fast Radio Bursts





# Fast Radio Bursts

Several **fast radio bursts** (FRBs) have been discovered recently (Keane+ 2012, Thornton+ 2013, Spitler+ 2014):

- single bright, highly dispersed millisecond radio pulses;
- pulses do not repeat and not associated with pulsar or GRB;
- the high dispersion suggests sources at cosmological distances ($z > 0.7$); expected rate: $\simeq 0.1\,\mathrm{deg}^{-2}\,\mathrm{day}^{-1}$ ~1% that of SNe;
- assuming a cosmological distance, the luminosity is

$$L = 3 \times 10^{43} \left(\frac{\nu}{1.4\,\mathrm{GHz}}\right)^{1+\alpha} \left(\frac{S_\nu}{1\,\mathrm{Jy}}\right) \left(\frac{D_\mathrm{l}}{11\,\mathrm{Gpc}}\right)^2 \mathrm{erg\,sec}^{-1} .$$

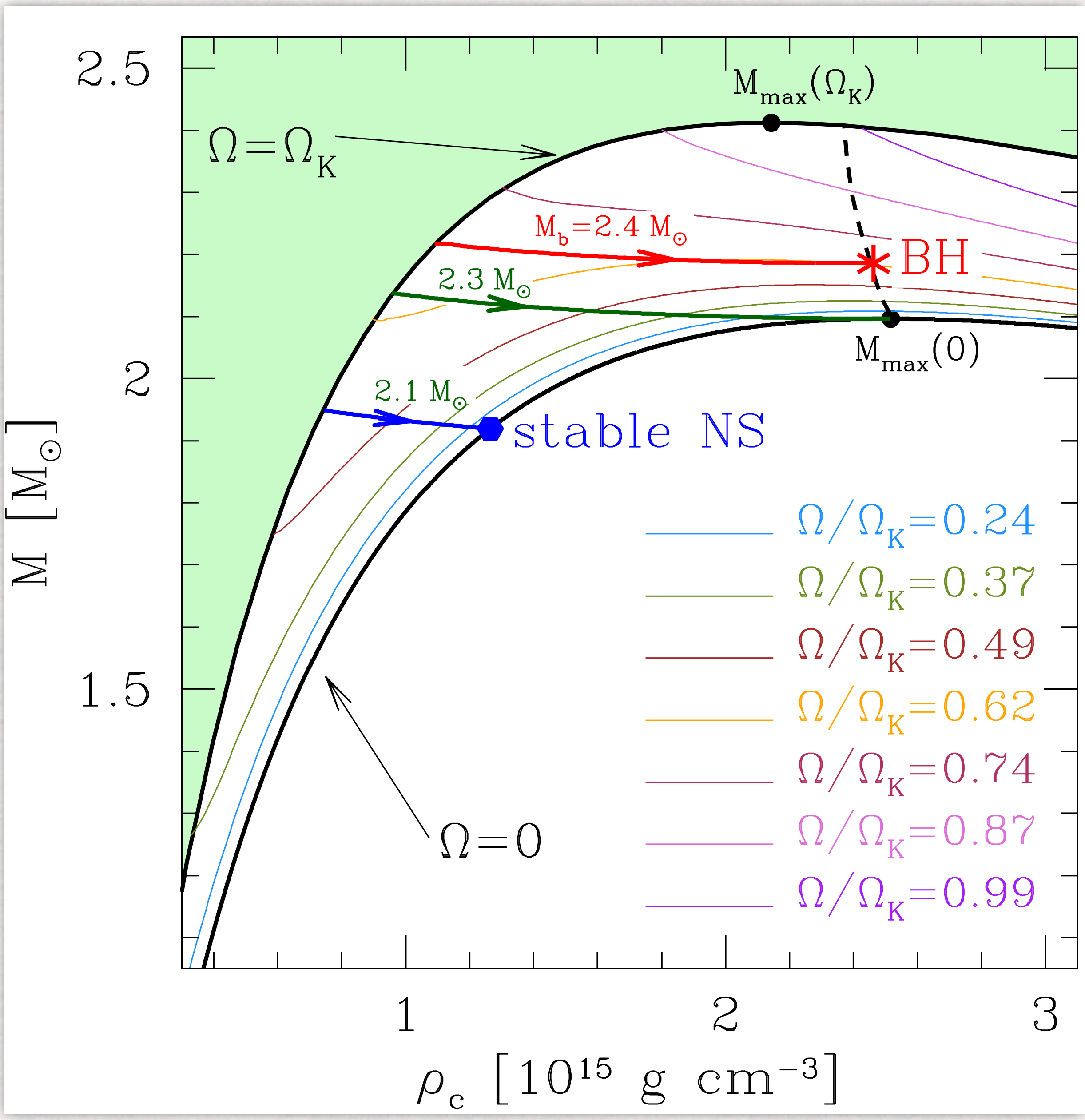
- this luminosity is nine orders of magnitude larger than a giant kJy flare from Crab; over 1ms this yields an energy which is a tiny fraction of the energy in a SN or GRB.

# FRBs and **"Blitzars"**

Falcke, LR (13)

Use these constraints: **1)** signal on timescale **~ 1ms; 2)** luminosity of $10^{43}$ erg/s; **3) absence** of other emissions beside radio.

FRBs could be result of collapse of a **supramassive NS** to a BH,

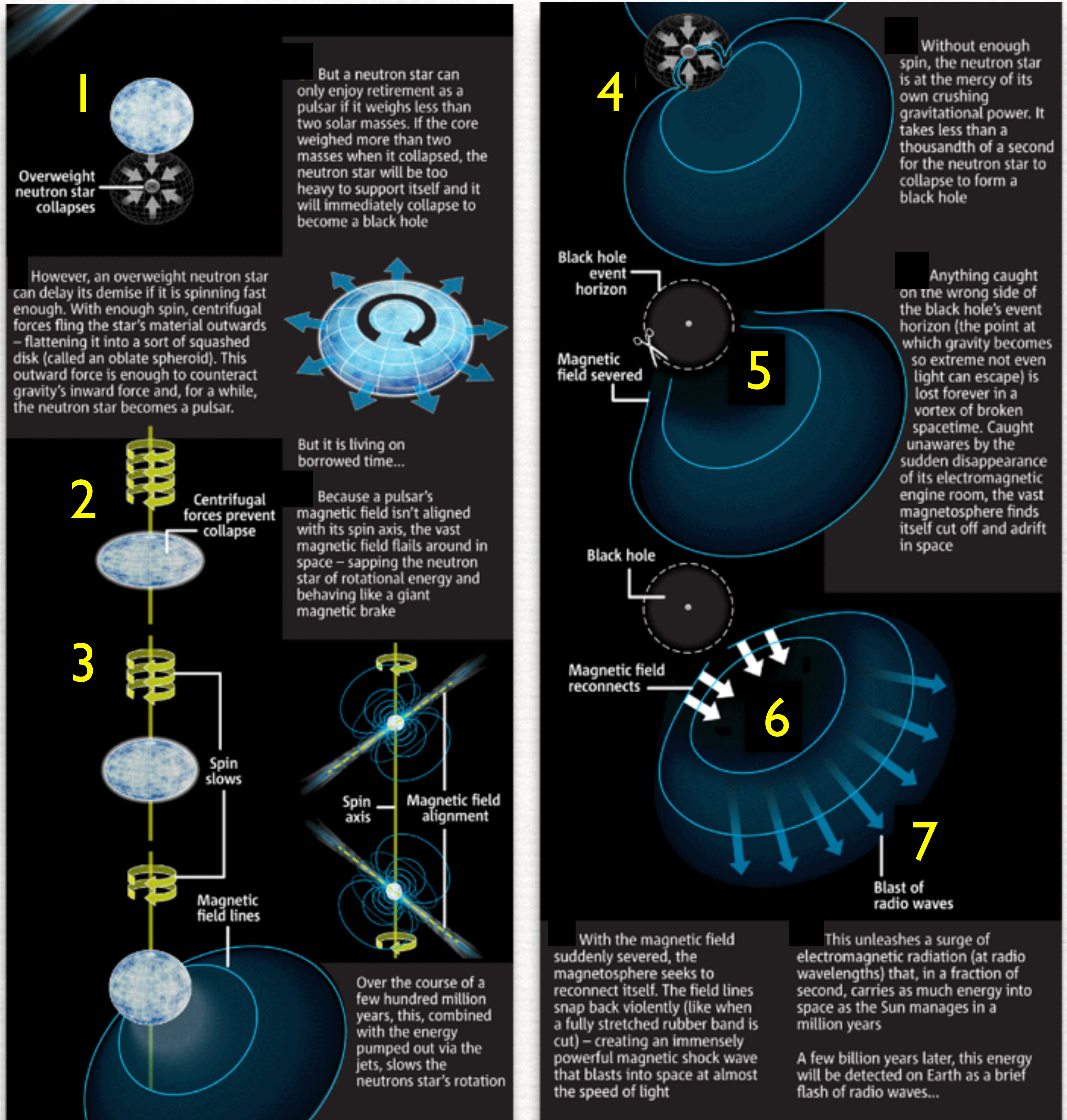



i.e., of a NS whose large mass can be supported because in rotation.

A NS with mass $M < M_{\rm max}(0)$ can support itself against collapse.

Any star with $M > M_{\rm max}(0)$ can only collapse.

# A cartoon…



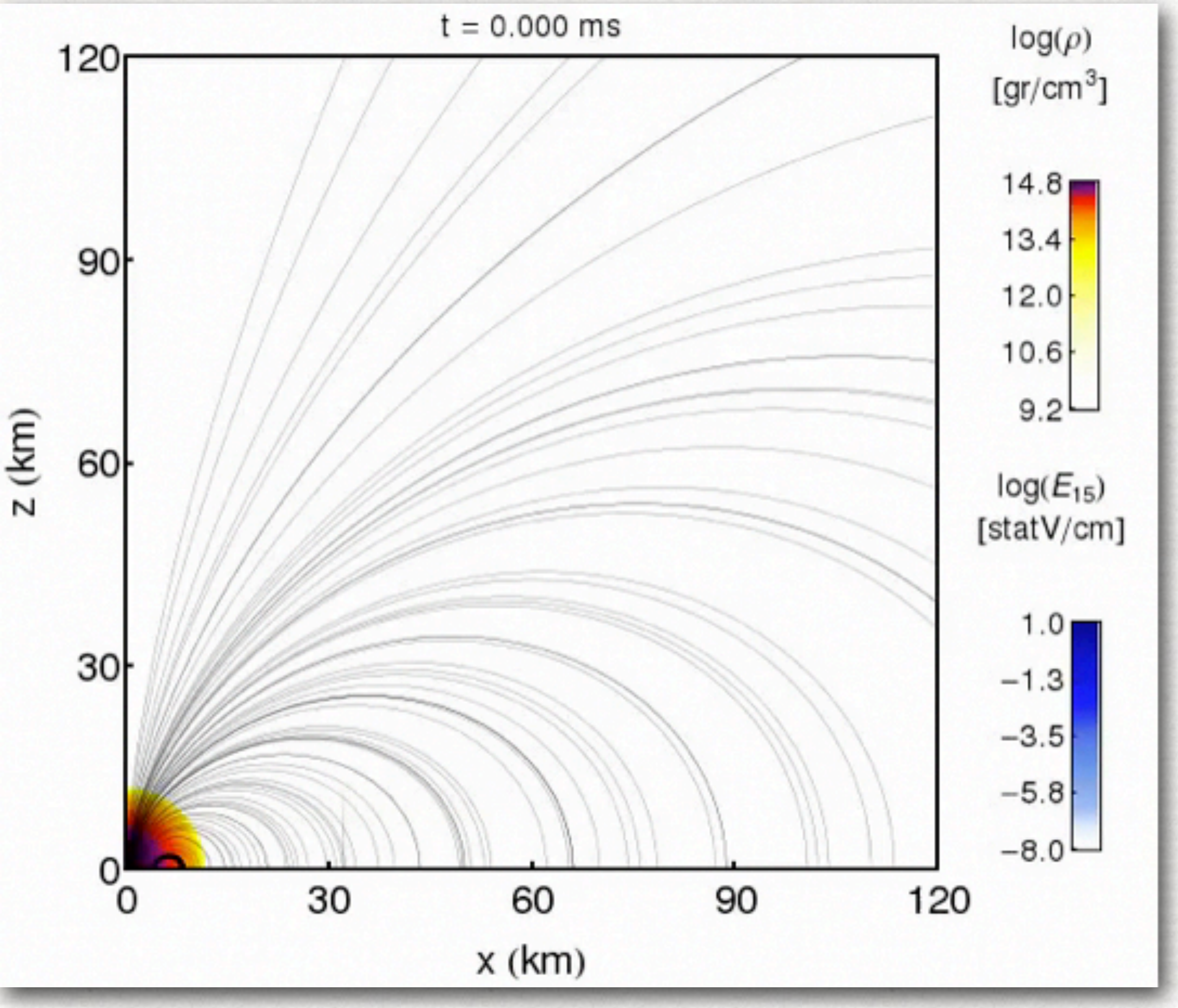

@GilliCosm on Twitter Graphic: BEN GILLILAND

www.cosmonline.co.uk

# Fast Radio Bursts and “**Blitzars**”

Falcke, LR (13)

Take a NS long after its formation ($10^3$-$10^6$ yr after SN explosion)
Magnetic braking will have slowed it down near the stability line




Dionysopoulou+13

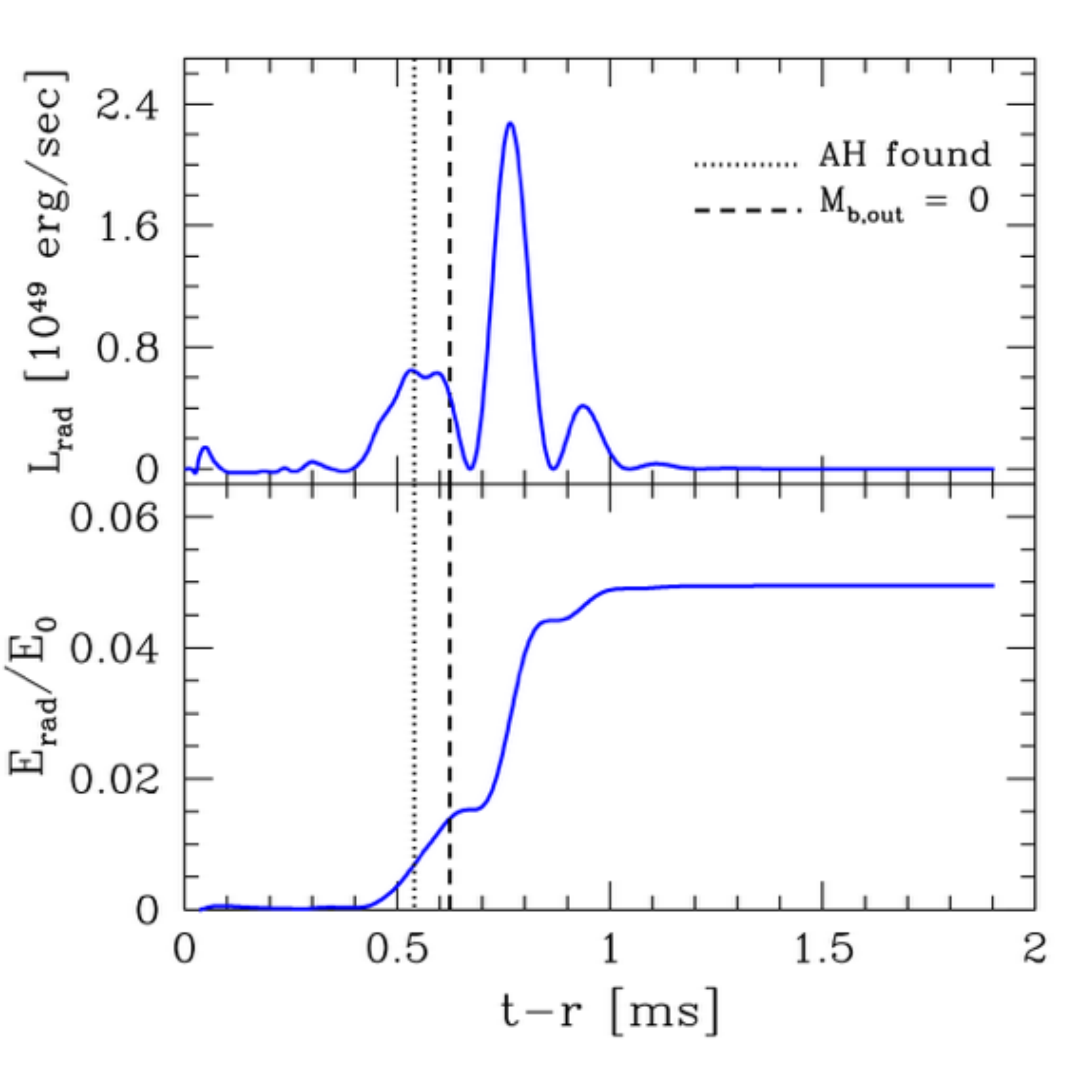
NS collapses: B-fields lines on the star surface will snap. EM shock wipes out MS

Large fraction of the energy in the MS is released over ~ 1ms radio curvature radiation

A rate of ~ 1% of NSs in SNe explosions sufficient to explain present observations.

# Light curve and emitted energy

Dionysopoulou+13



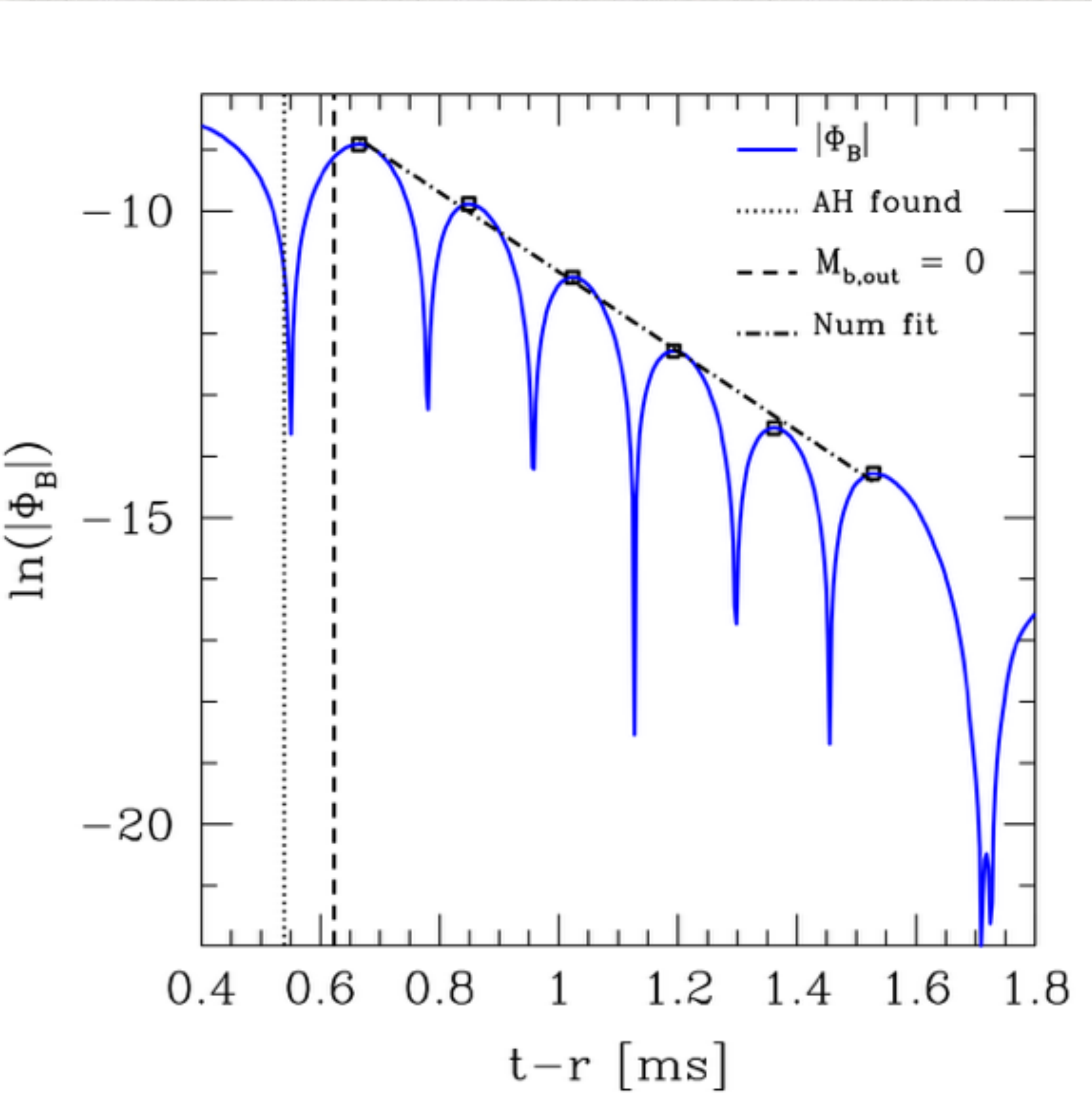

Luminosity shows series of peaks; the "snapping" of the magnetic field lines is not instantaneous.

Separation in peaks depends on mass and spin of NS: the larger the slower

About 5% of the initial energy in the magnetic field is lost in EM emission, i.e. ~ $10^{43}$ erg/s

# Light curve and emitted energy

Dionysopoulou+13




These are EM waves (i.e. vector perturbations) in a BH spacetime and will experience quasi-normal ringing.

Frequency and decay rate depend on BH mass/spin.

If observed, **ringdown would be signature of BH existence and formation.**

# Out of our rough estimates...

Falcke, LR+13

- Rate:

$1\%$ of core collapse SNe

- Luminosity for coherent curvature radiation (an upper limit ?):

$$P_{\rm t} \simeq 7.0 \times 10^{43}\ \eta_{\rm e}\, \gamma\, f_{0.1}^2\, \kappa_{\rm GJ}^2\, b_{12}^2\, m_2\, r_{10}\ \ {\rm erg\, s^{-1}}\ .$$

- Minimum frequency assuming coherent curvature radiation:

$$\nu_{\rm p} = \frac{\omega_{\rm p}}{2\pi} = \sqrt{\frac{eB\Omega}{2\pi^2 c m_{\rm e}}} \simeq 38.6\ f_{0.1}^{1/2}\ \kappa_{\rm GJ}^{1/2}\, b_{12}^{1/2}\ m_2^{1/4}\ r_{10}^{-3/4}\ \ {\rm GHz}\,.$$

- Need relativistic particles but "reasonably" relativistic:

$$\gamma_{\rm min} \gtrsim 175.3\, f_{0.1}^{1/6}\ \kappa_{\rm GJ}^{1/6}\, b_{12}^{1/6}\ m_2^{1/12}\ r_{10}^{1/12}\ .$$

# Conclusions

- ✳Modelling of binary NSs in full GR is **mature**: GWs from the inspiral can be computed with precision of binary BHs.
- ✳Spectra show characteristic freqs.; some are ”**quasi-universal**”. If observed, post-merger signal can set tight constraints on EOS.
- ✳B-fields unlikely to be detected during the inspiral but **important** after the merger: RMHD simulations show coherent jet structure.
- ✳ Extended X-ray emission is a riddle. A way out is possible in terms of a **two-wind scenario**.
- ✳FRBs are new challenge. **Blitzars** are plausible explanation.

*"For every complex natural phenomenon there is a simple, elegant, compelling, wrong explanation." T. Gold*