Compact stars and GWs: a progress report from Frankfurt

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Nuclear Physics, Compact Stars, and Compact Star Mergers 2016

NPCSM 2016, Oct.17-Nov.18, 2016, YITP, Kyoto, Japan

YIPQS

YITP Kyoto

Plan of the talk

see Takami's poster

- ✶Anatomy of GW signal: frequencies and EOS

see Nissanke's and Zhang's talks

- ✶ Role of B-fields and EM counterparts

see Lorimer's and Zhang's talks

- ✶ FRBs and "blitzars"

see Piran's, Sekiguchi's, and Tanaka's talks

- ✶ Eccentric encounters and nucleosynthesis
- ✶ A new approach to relativistic hydrodynamics

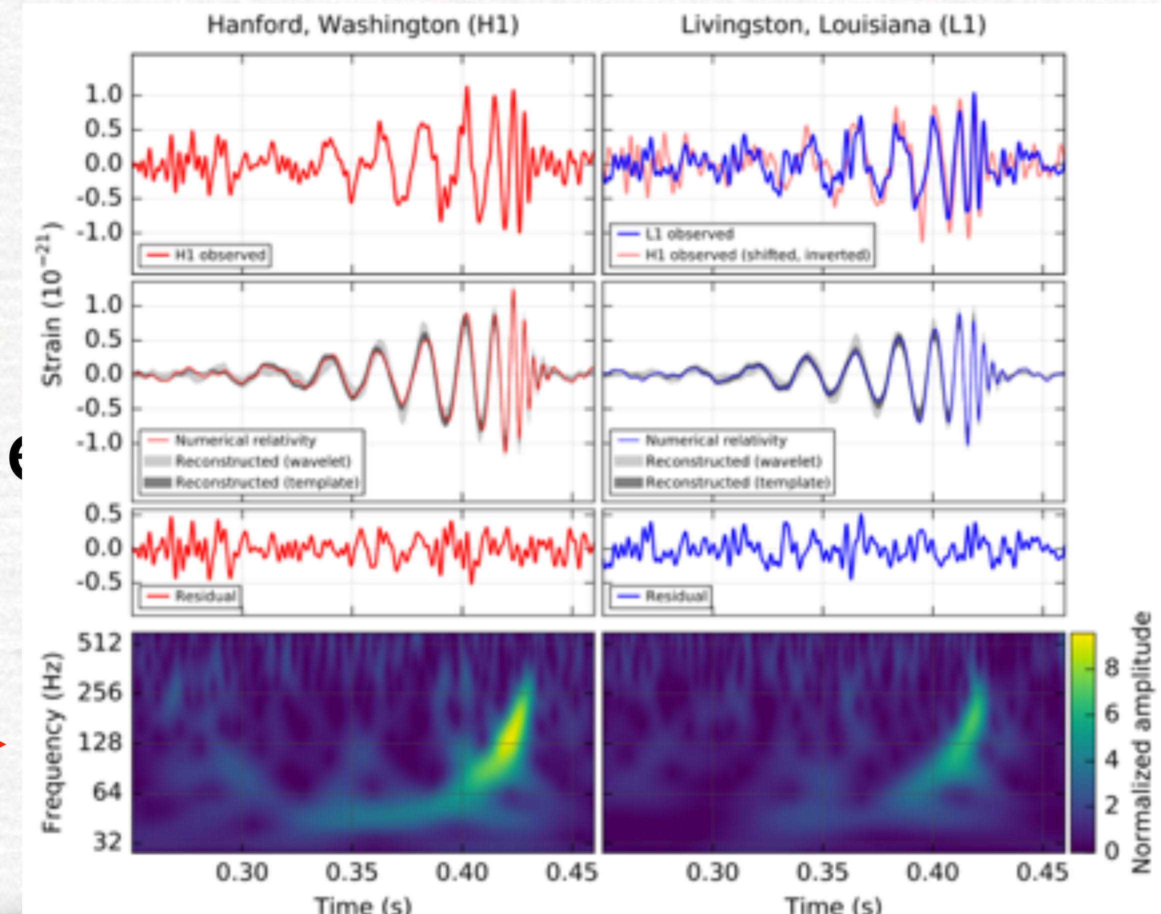
The two-body problem in GR

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

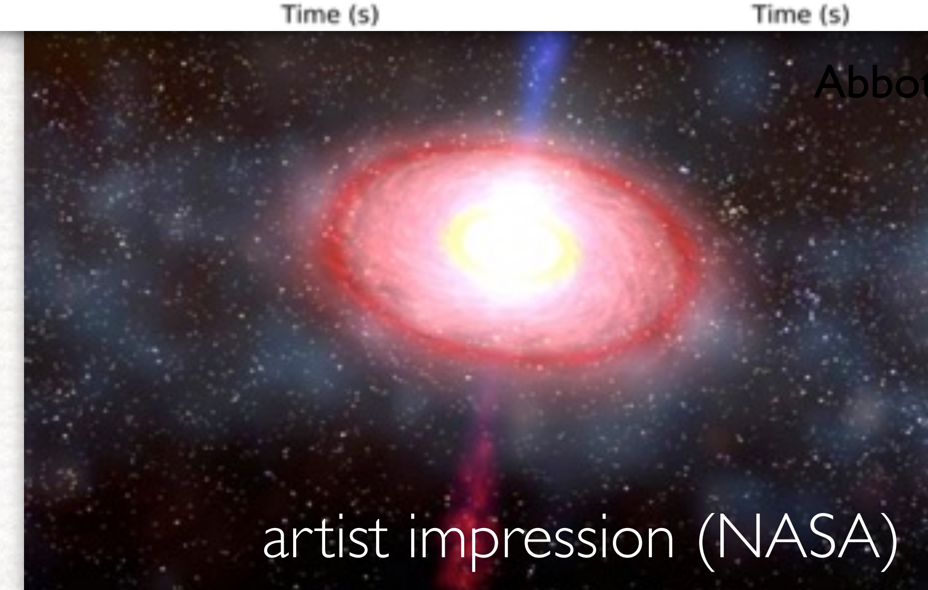
BH + BH → BH + GWs

- For NSs the question is more **subtl**
hyper-massive neutron star (HMNS),

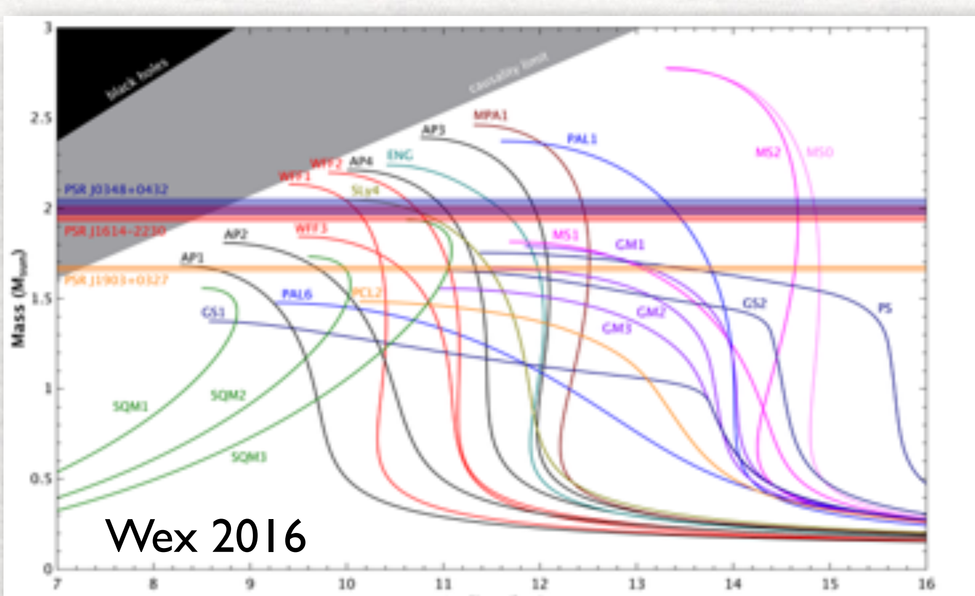
NS + NS → HMNS + ... ? →



Abbott+ 2016



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



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

Animations: Breu, Radice, LR

merger → HMNS → BH + torus

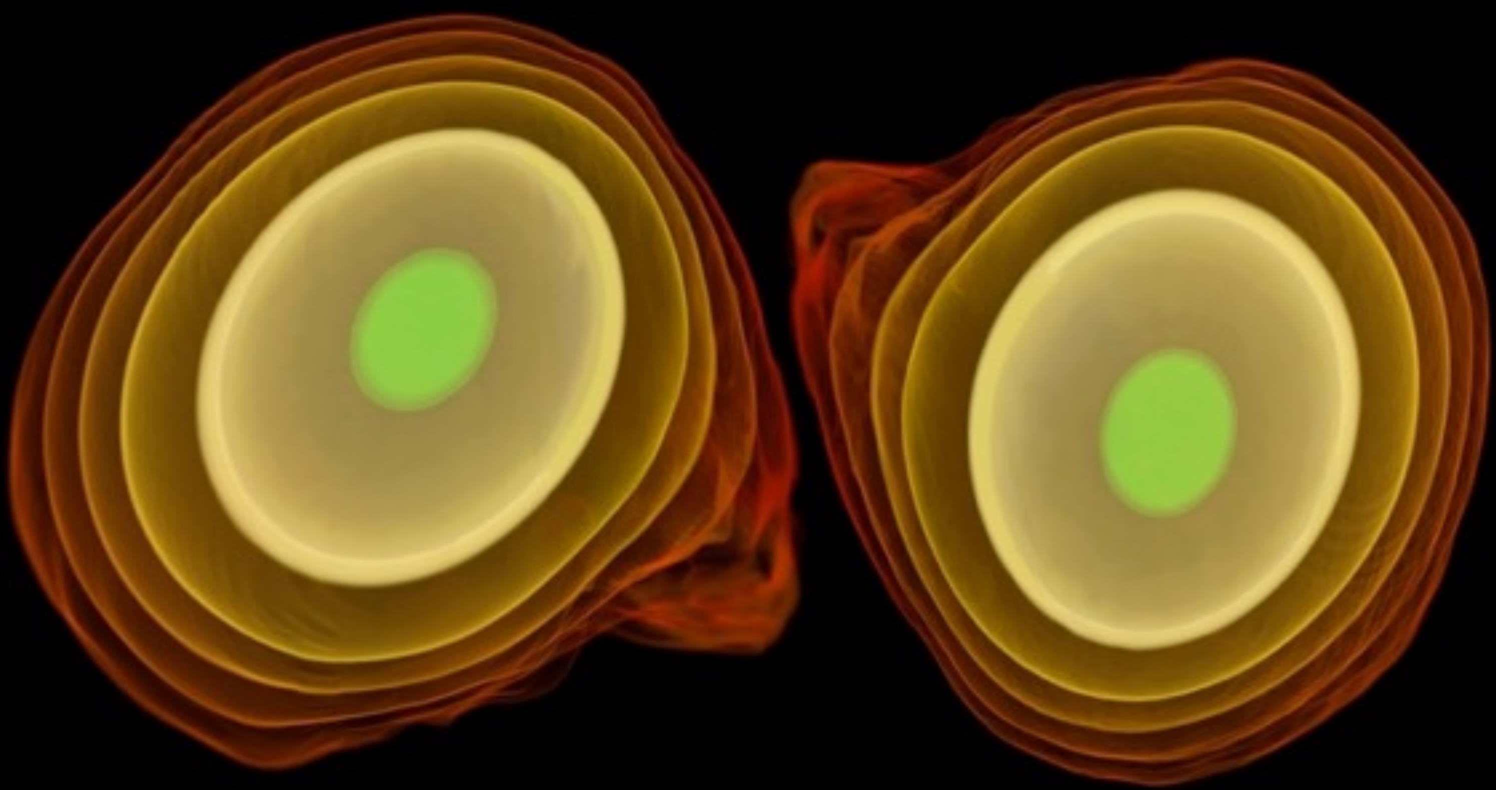
LS220 EOS

merger → HMNS → BH + torus

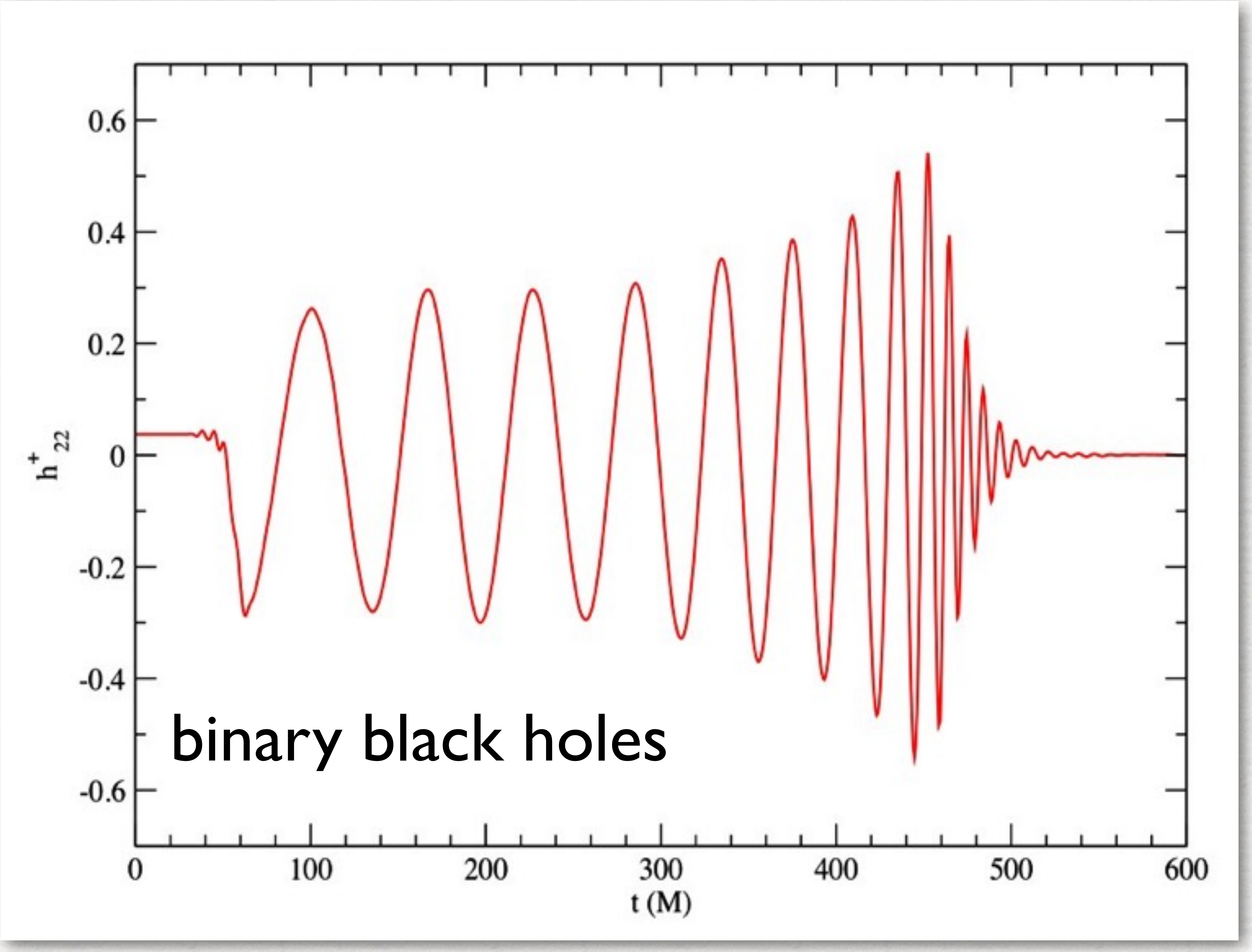
Quantitative differences are produced by:

- 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)

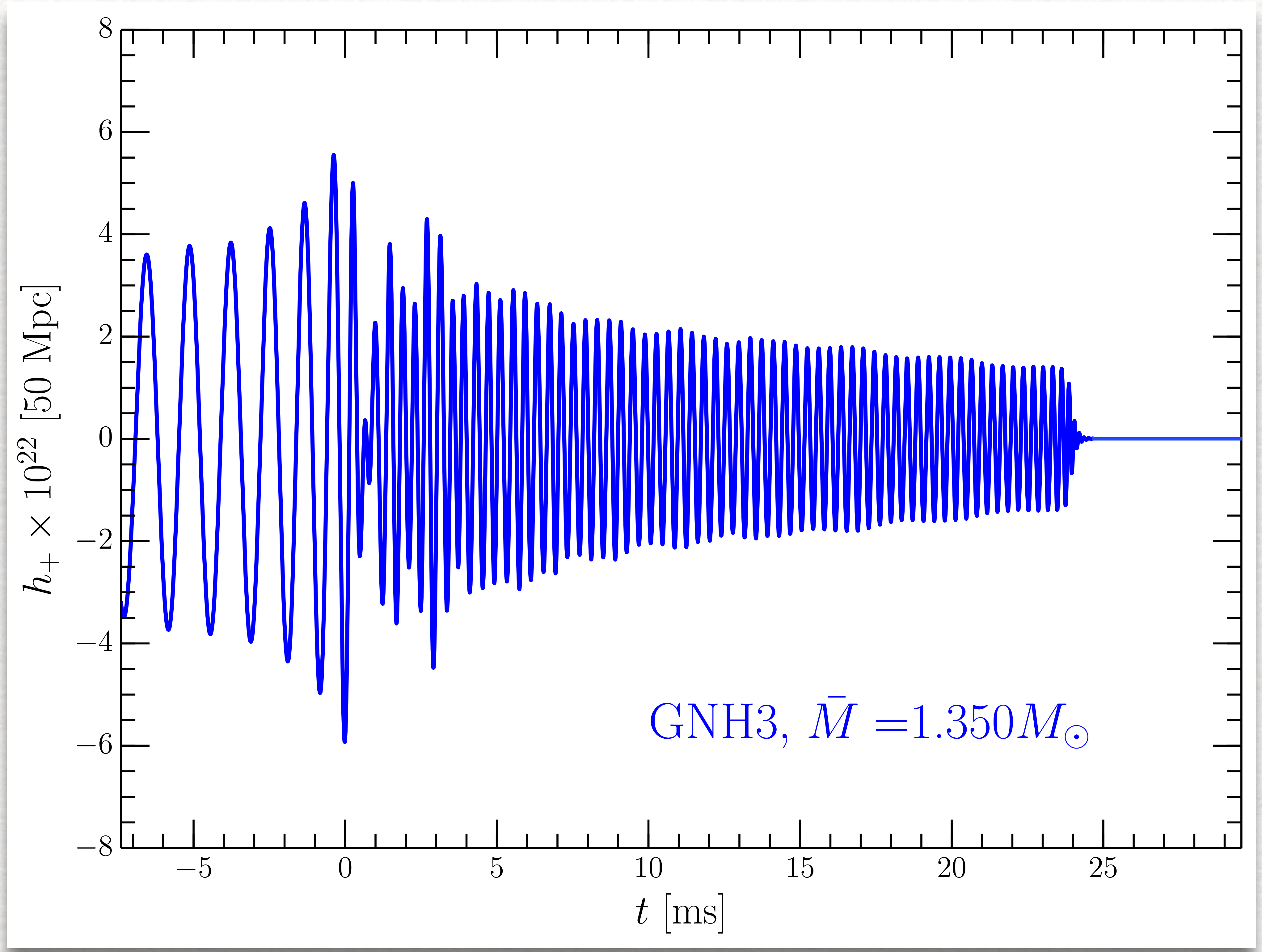
How to constrain the EOS



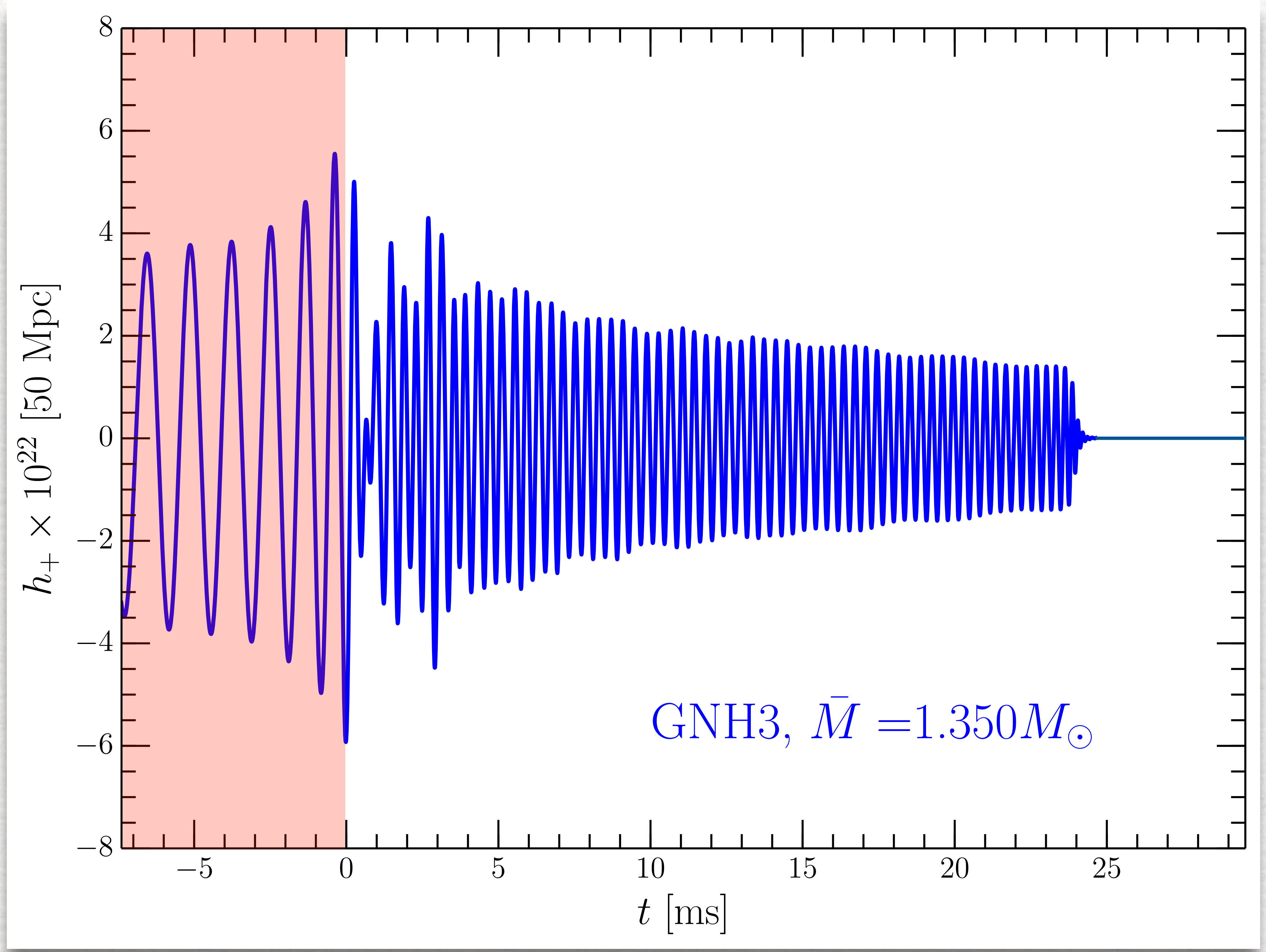
Anatomy of the GW signal



Anatomy of the GW signal

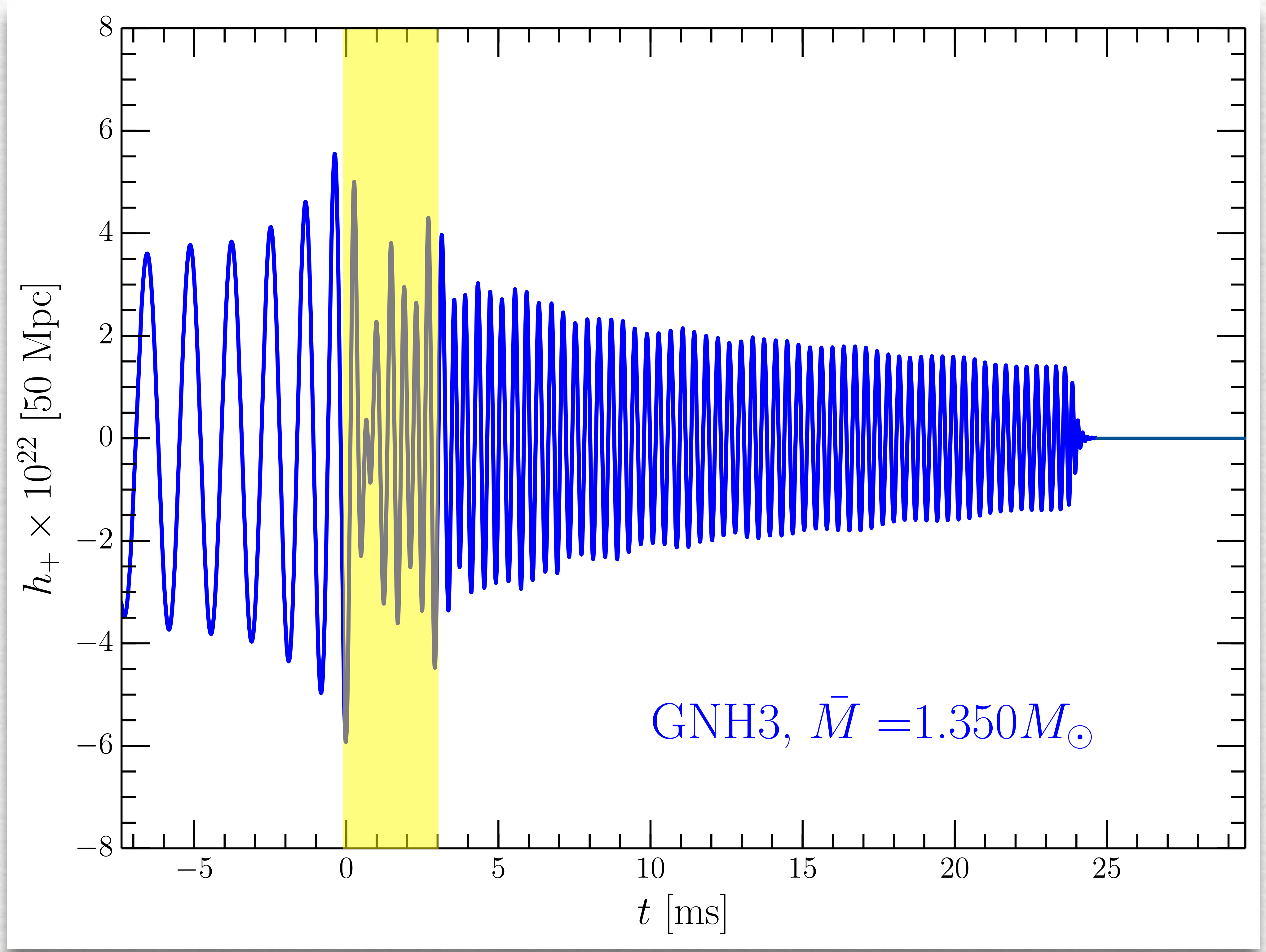


Anatomy of the GW signal



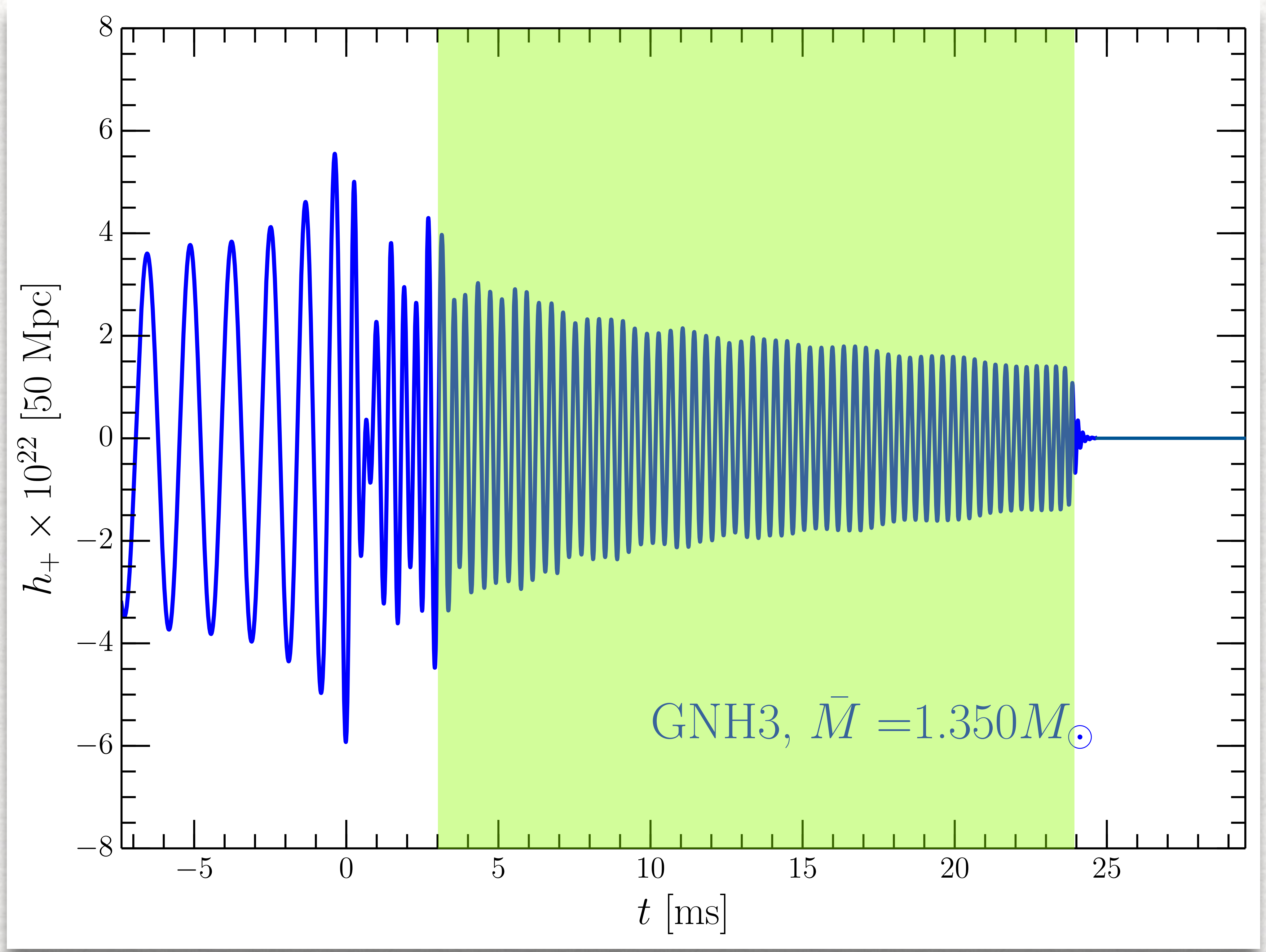
Inspiral: well approximated by PN/EOB; tidal effects important

Anatomy of the GW signal



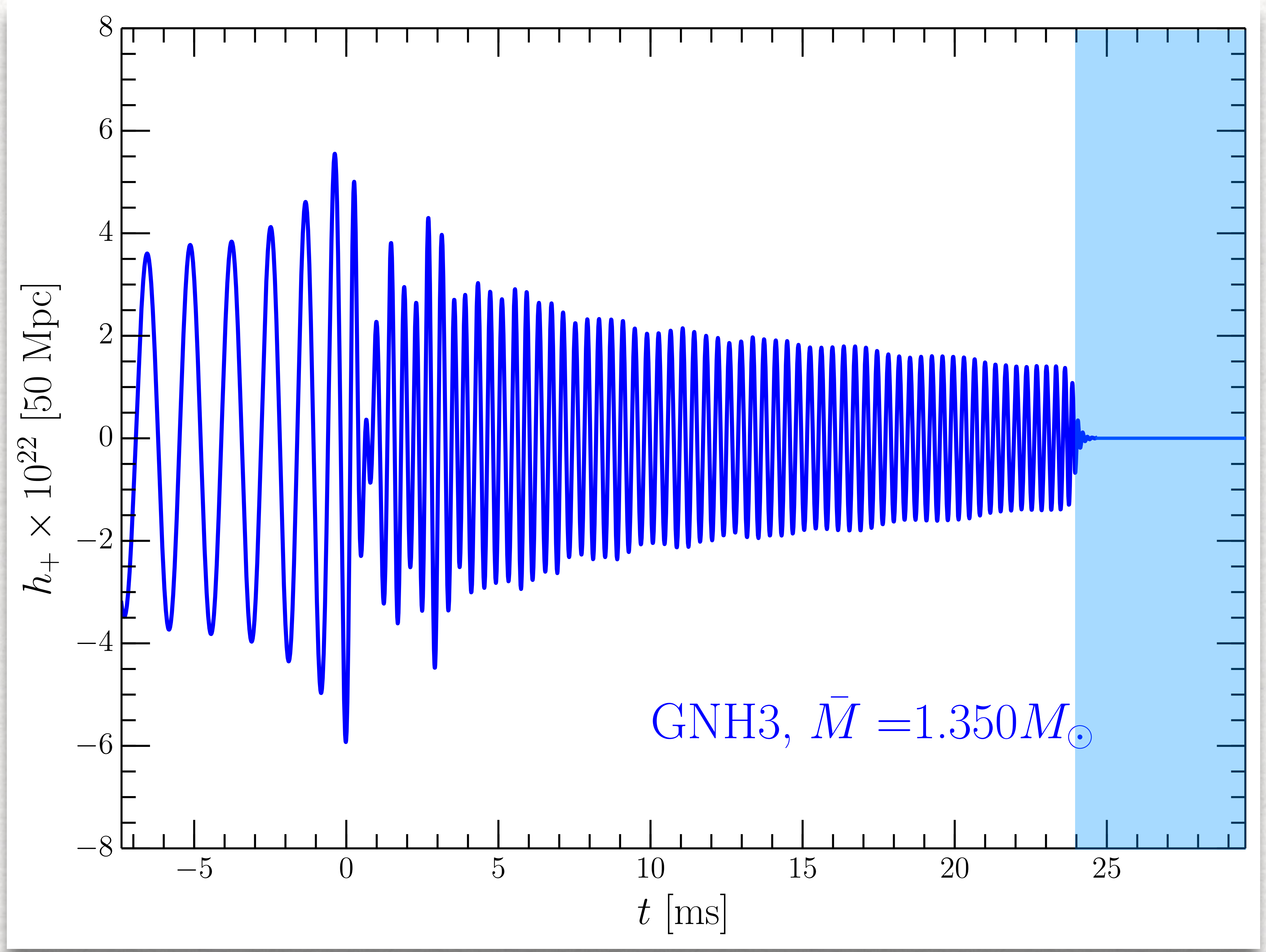
Merger: highly nonlinear but analytic description possible

Anatomy of the GW signal



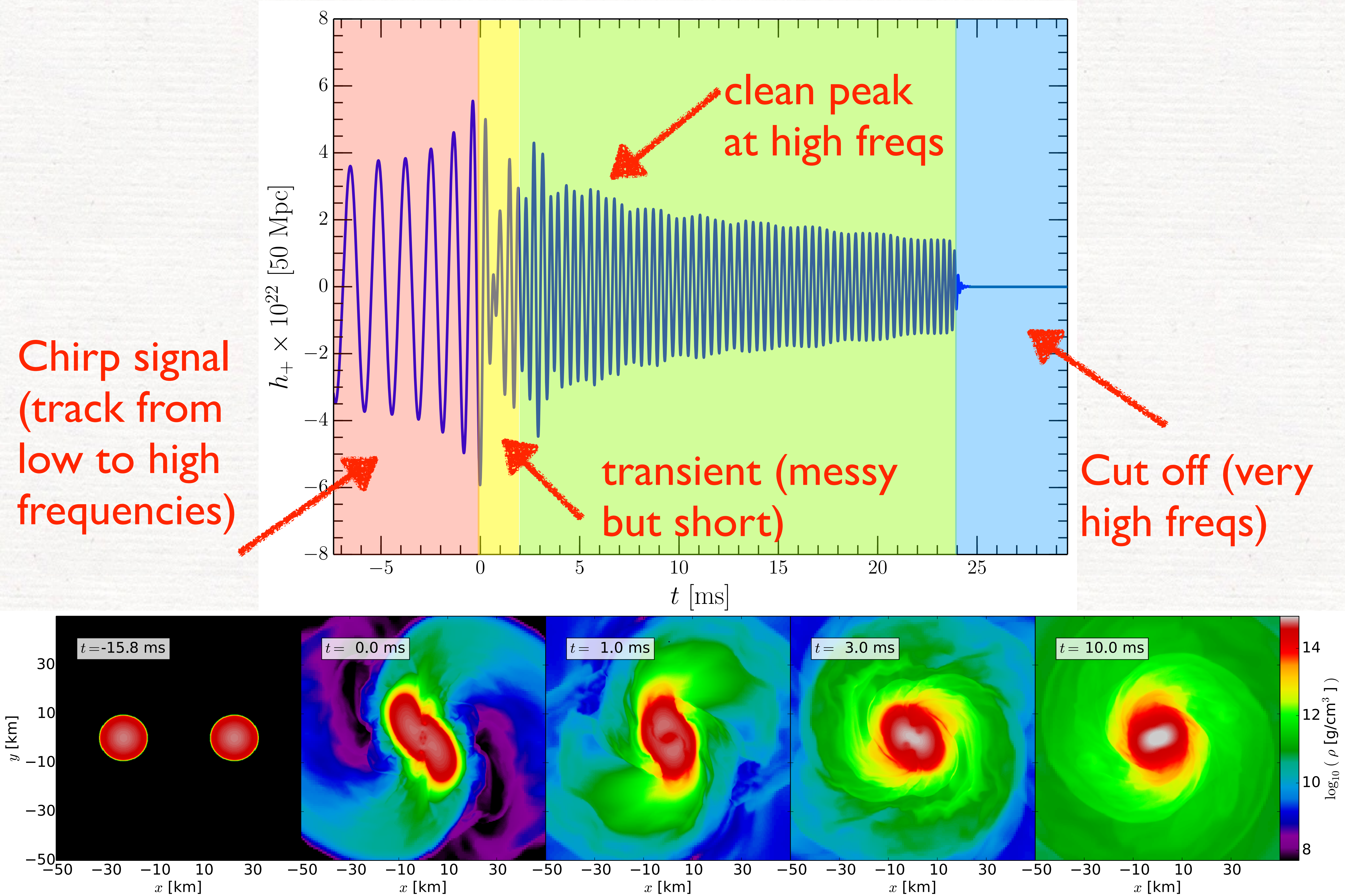
post-merger: quasi-periodic emission of bar-deformed HMNS

Anatomy of the GW signal

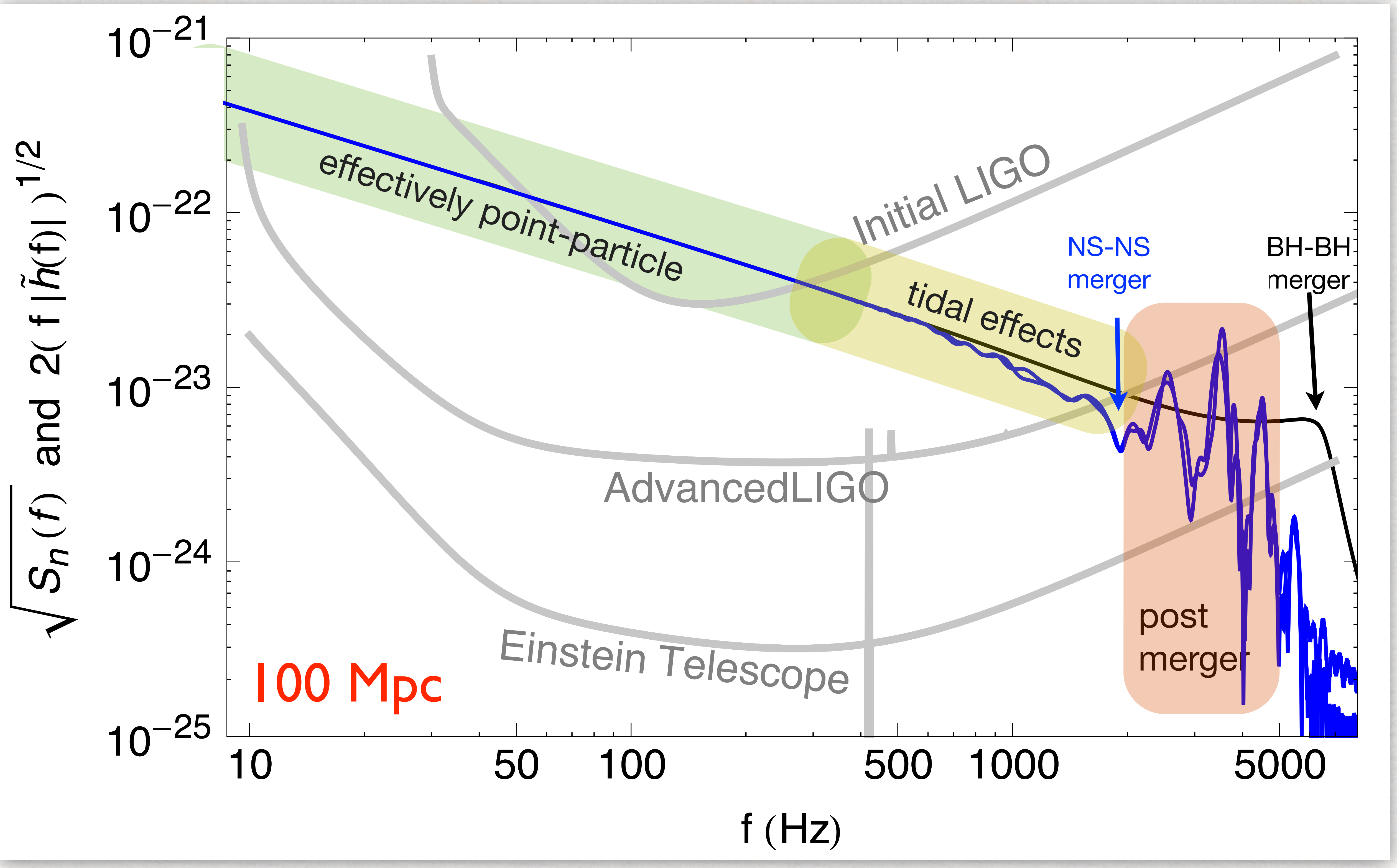


Collapse-ringdown: signal essentially shuts off.

Anatomy of the GW signal



In frequency space

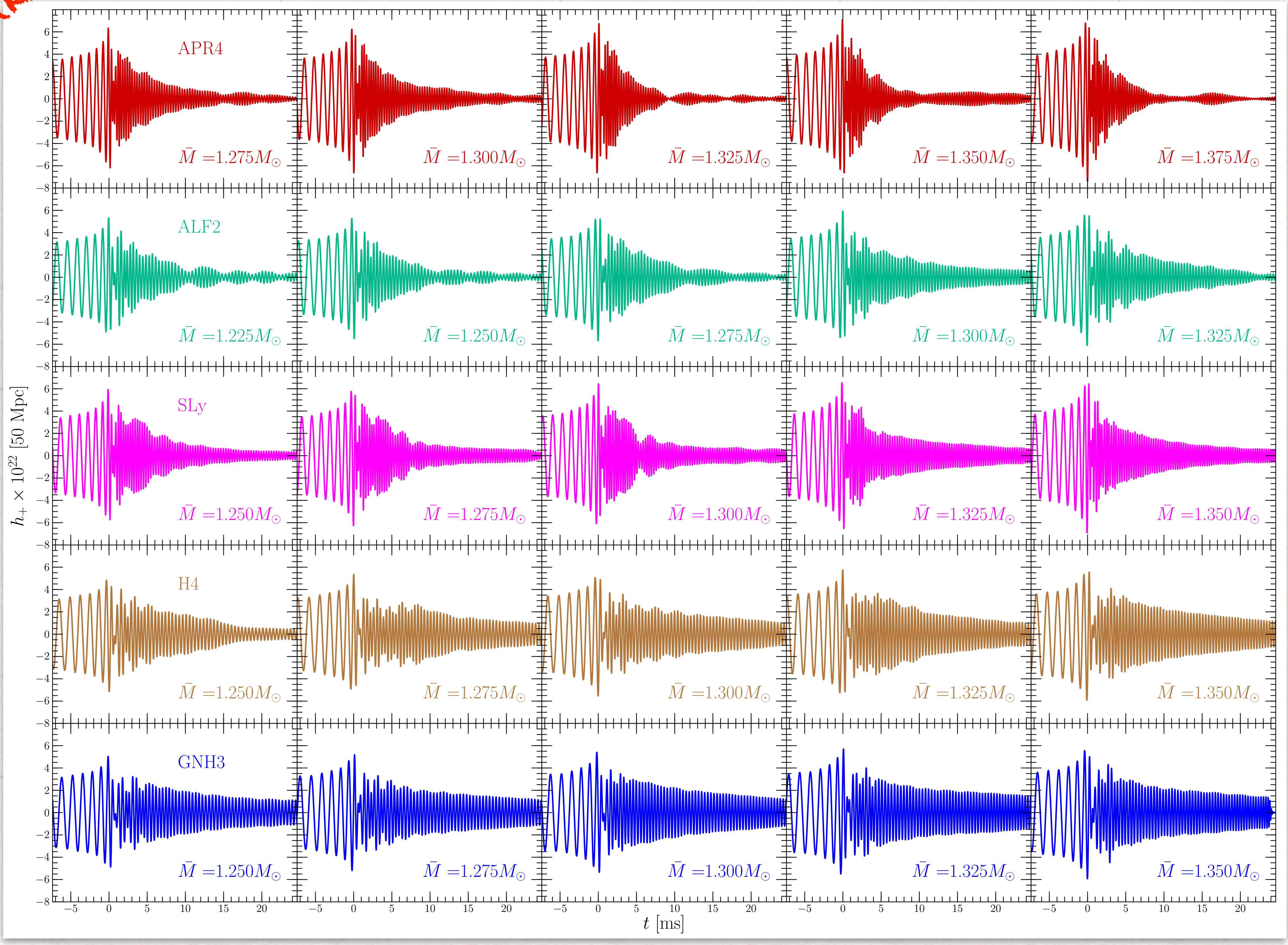


courtesy of Jocelyn Read

Extracting information from EOS

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

see Takami's poster



Extracting information from EOS

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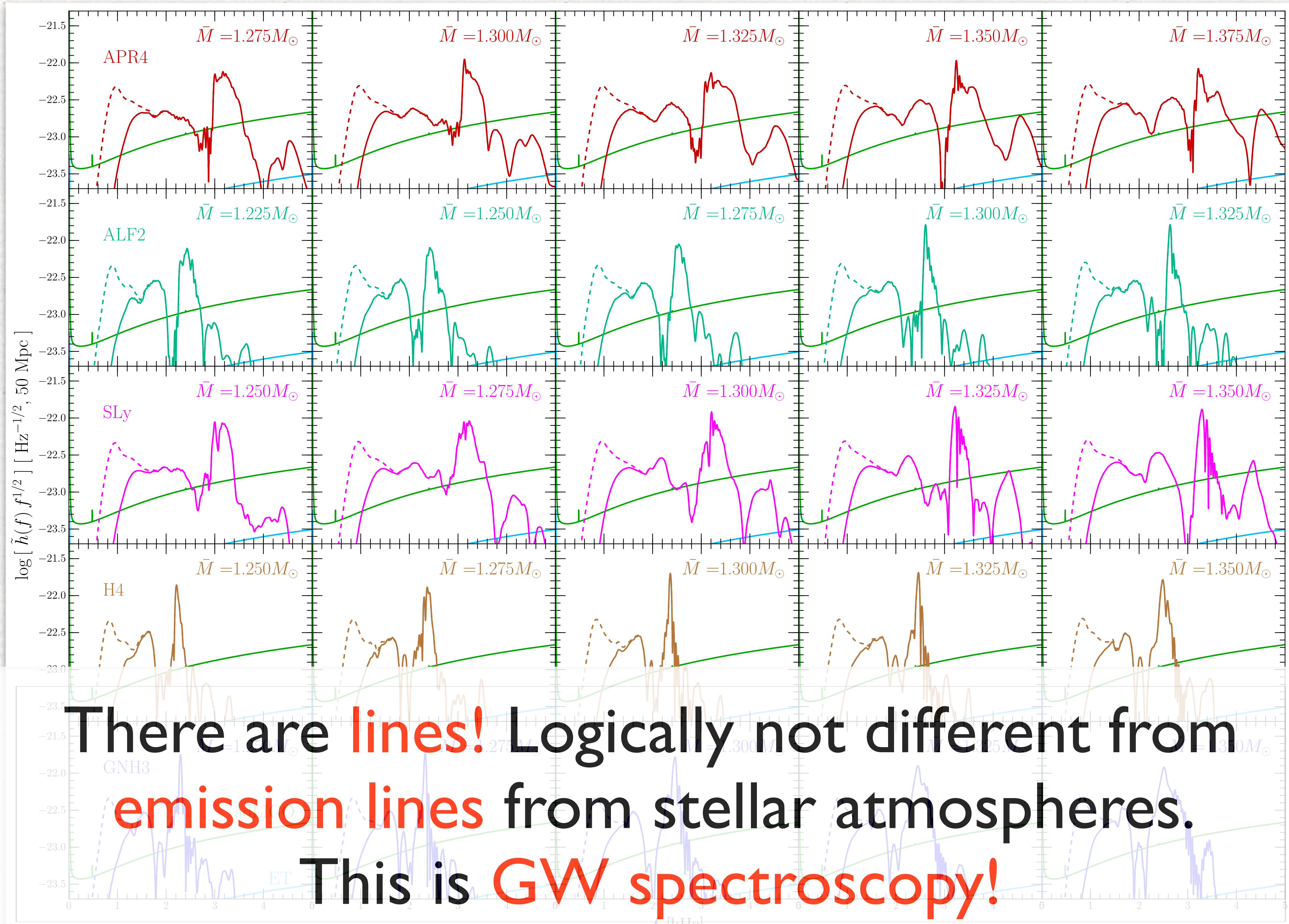


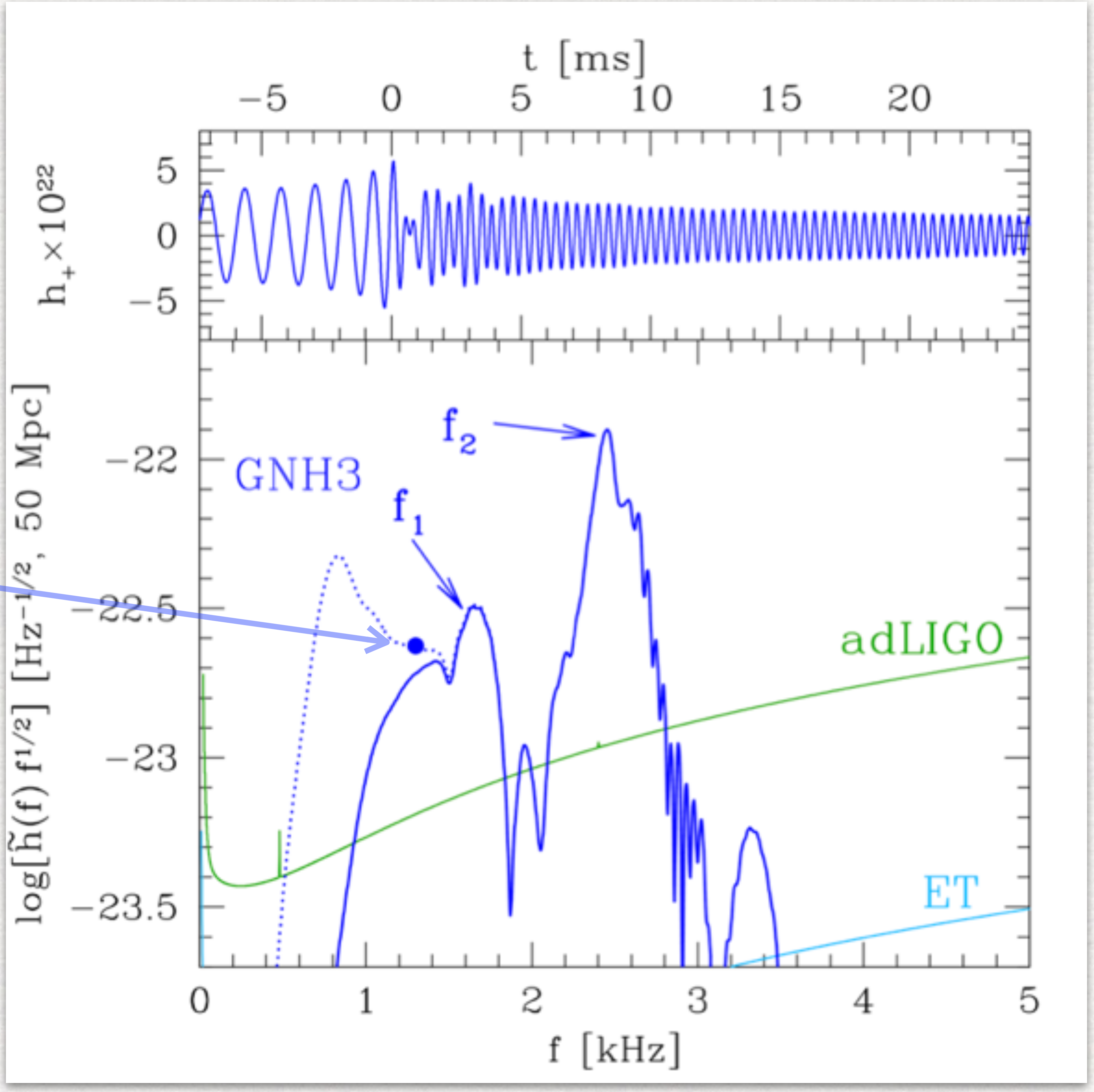
There are lines! Logically not different from emission lines from stellar atmospheres.

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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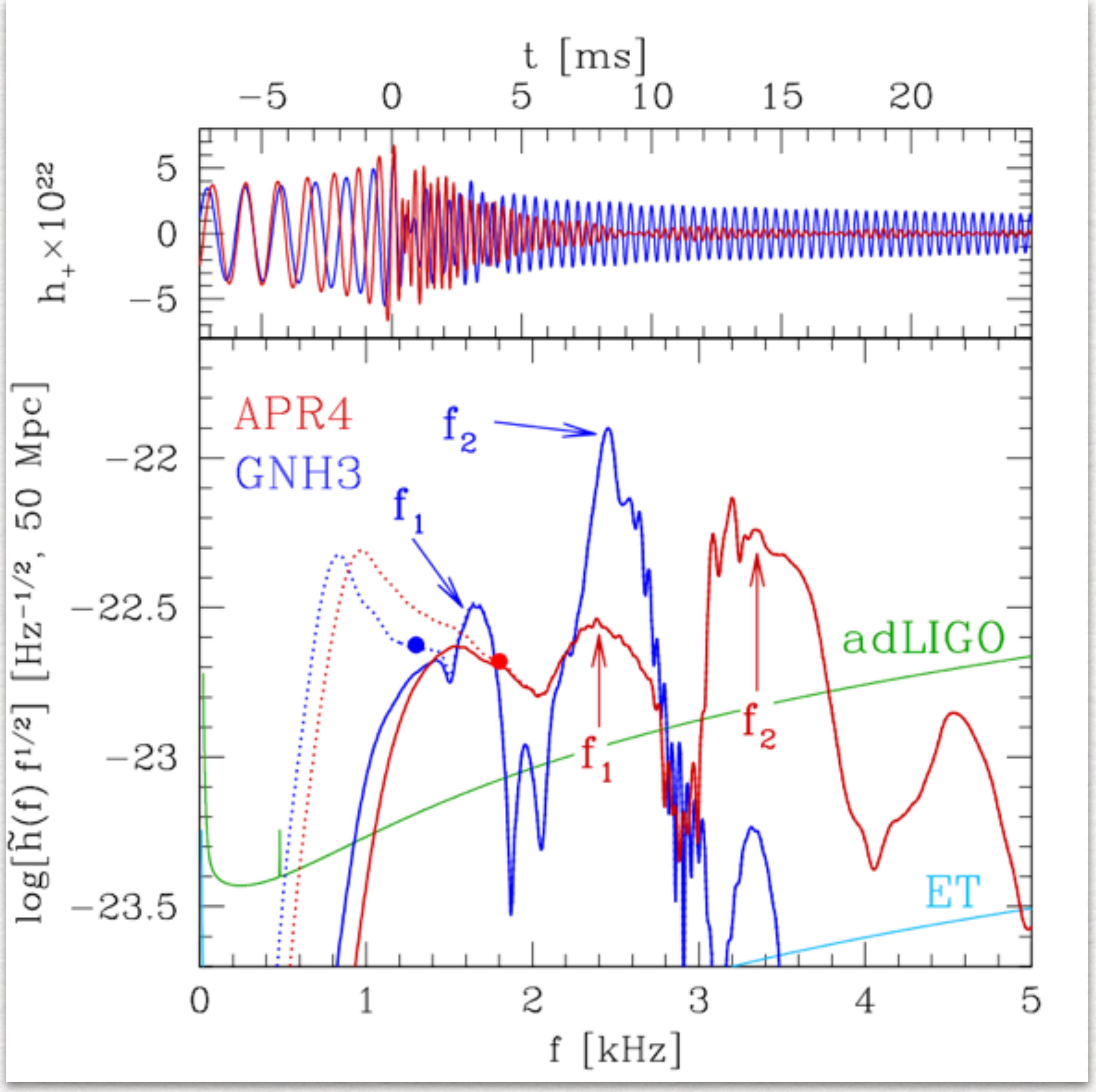
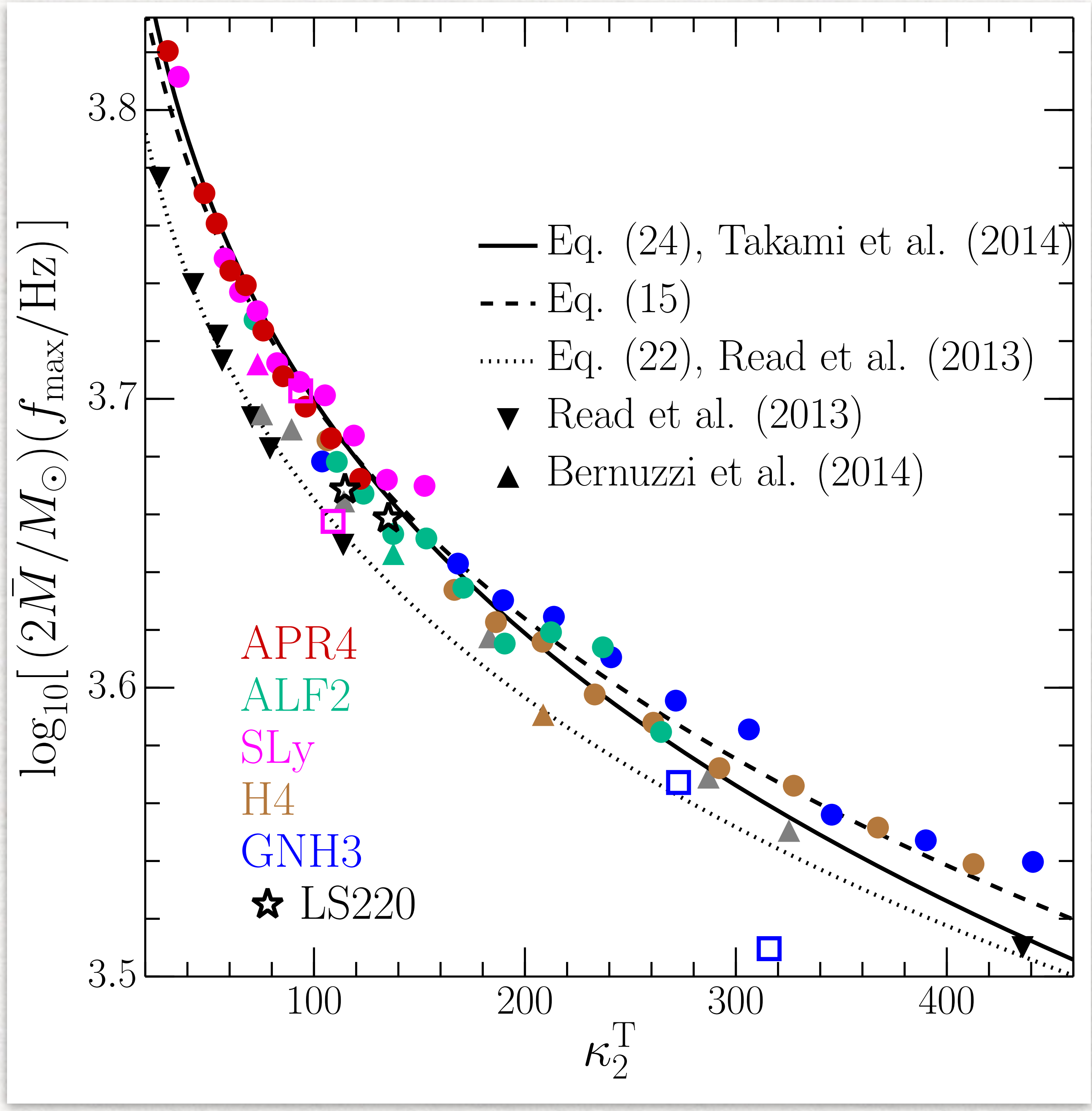


Quasi-universal behaviour: inspiral



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

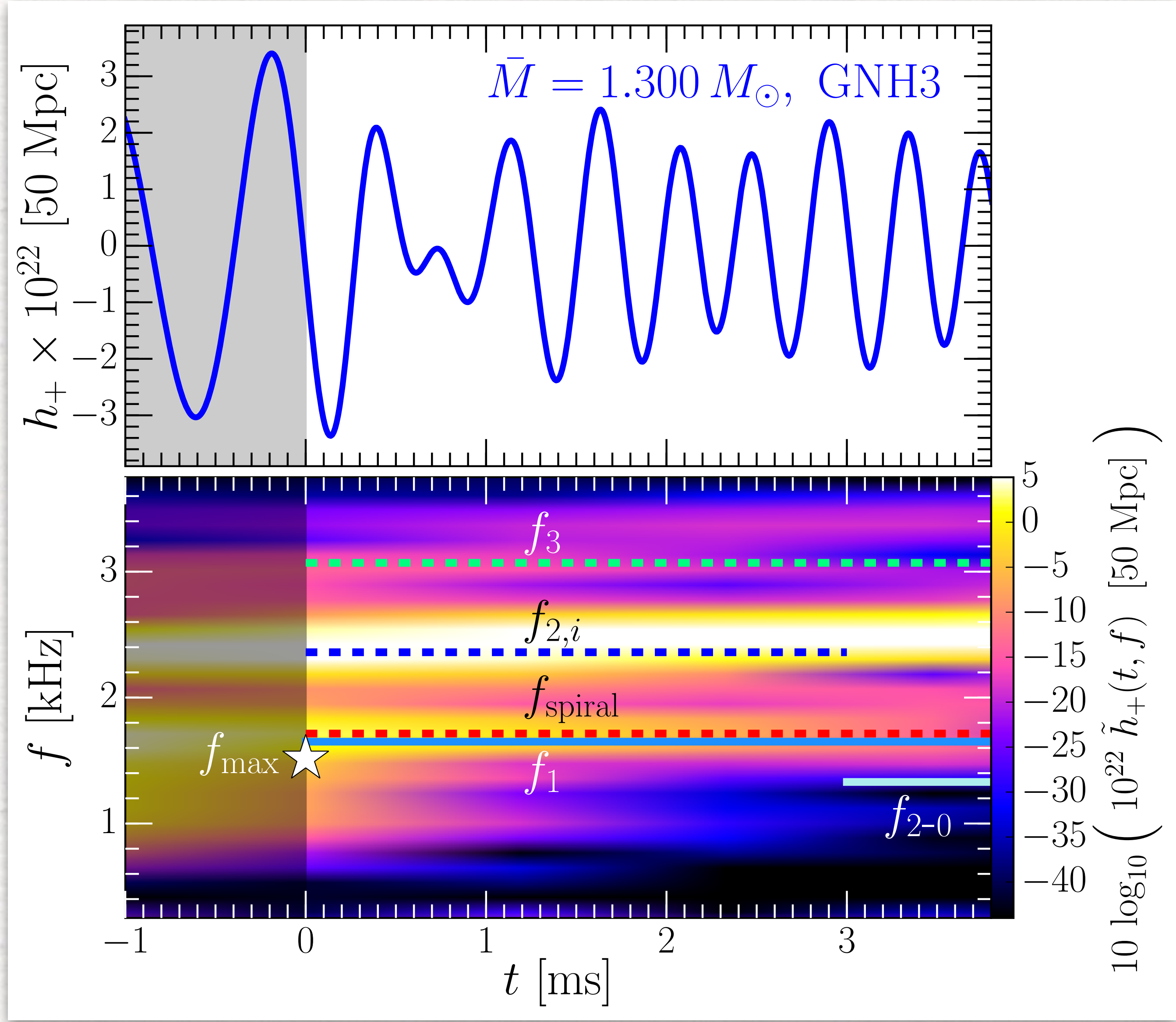
Many other simulations have confirmed this (Bernuzzi+, 2014, Takami+, 2015, LR+2016) .

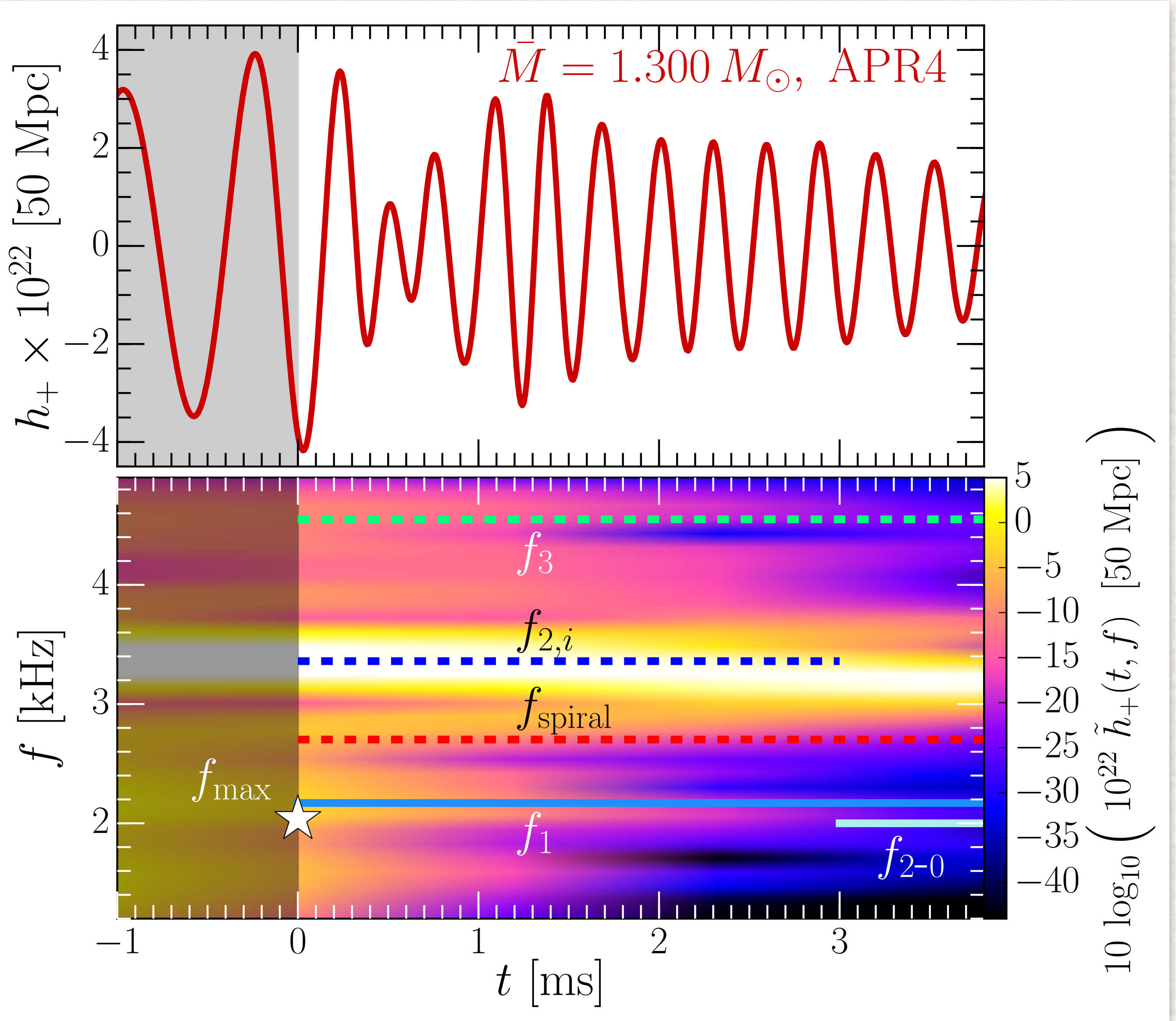
Quasi-universal behaviour in the **inspiral** implies that once **f_{max}** is measured, so is tidal deformability, hence $I, \ Q, \ M/R$

$$\Lambda = \frac{\lambda}{\bar{M}^5} = \frac{16}{3}\kappa_2^T$$ 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**.

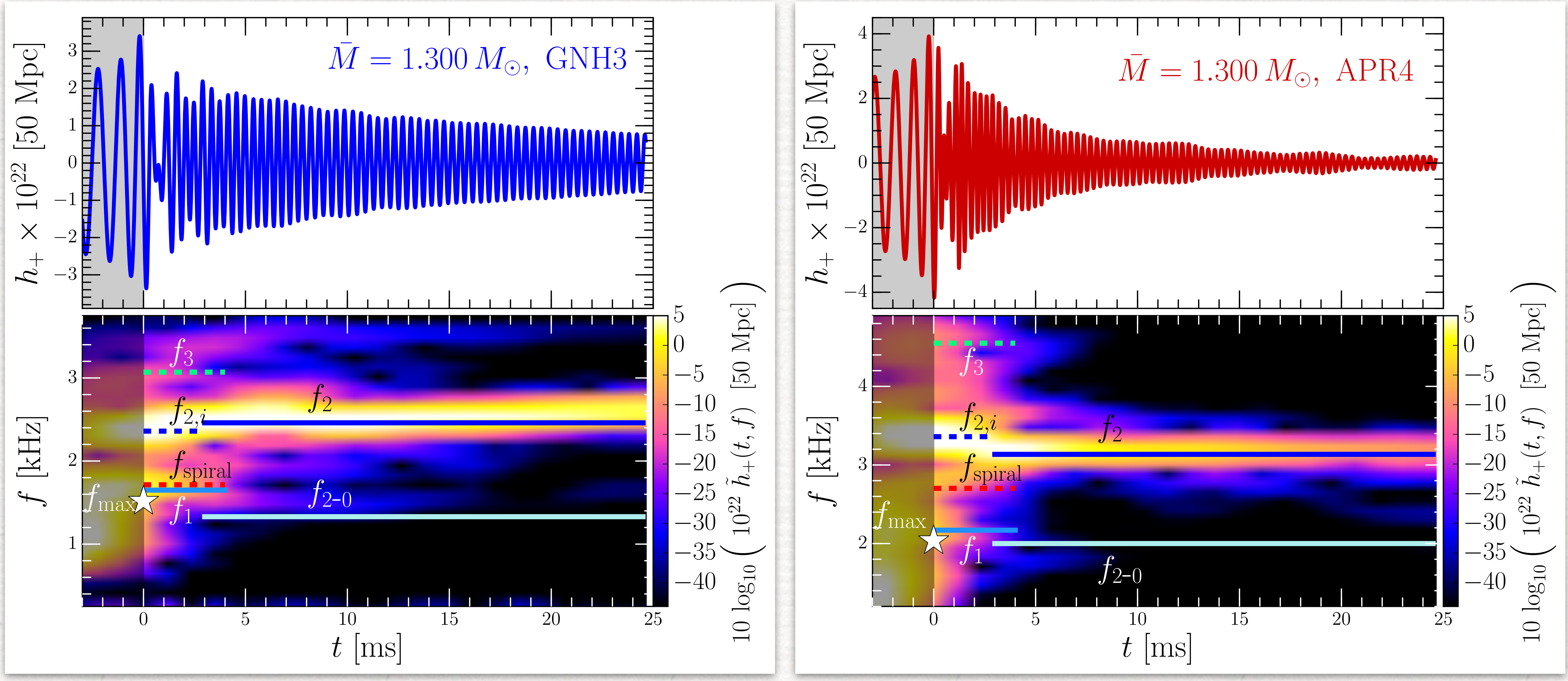




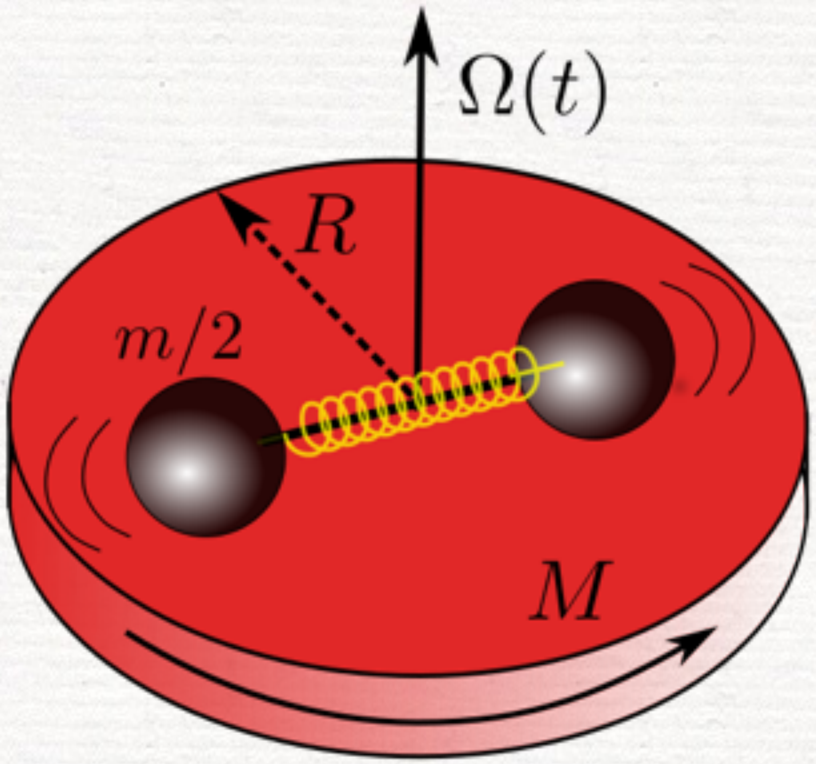
Understanding mode evolution

On a **long** timescale after the merger, only $\mathbf{f_2}$ survives.

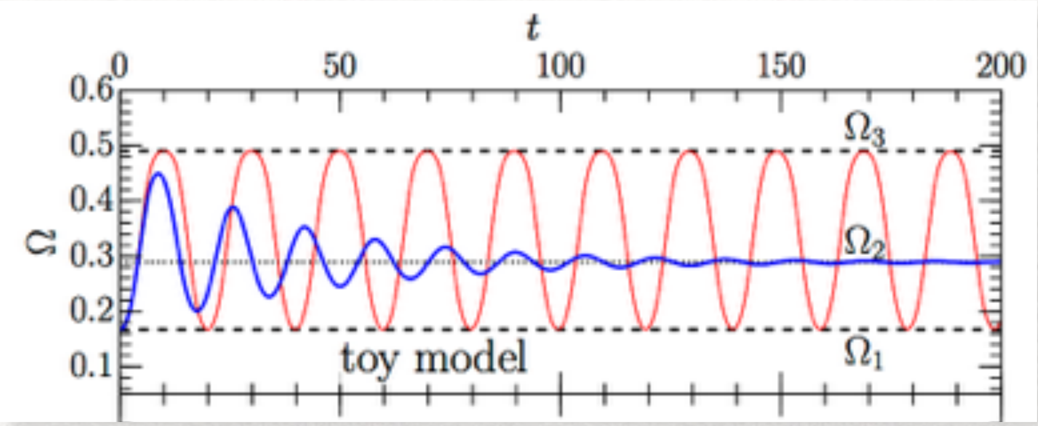
What produces the short-lived $\mathbf{f_1}$ and $\mathbf{f_3}$ modes?



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

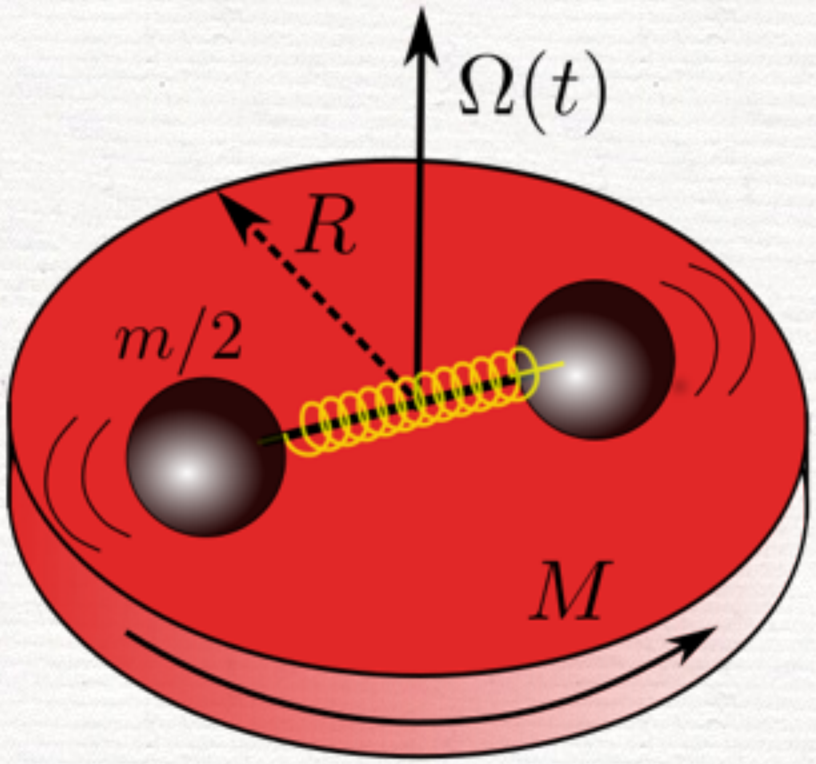


- Consider disk with 2 masses moving along a shaft and connected via a spring ~ HMNS with 2 stellar cores
- Let disk rotate and mass oscillate while conserving angular momentum



- 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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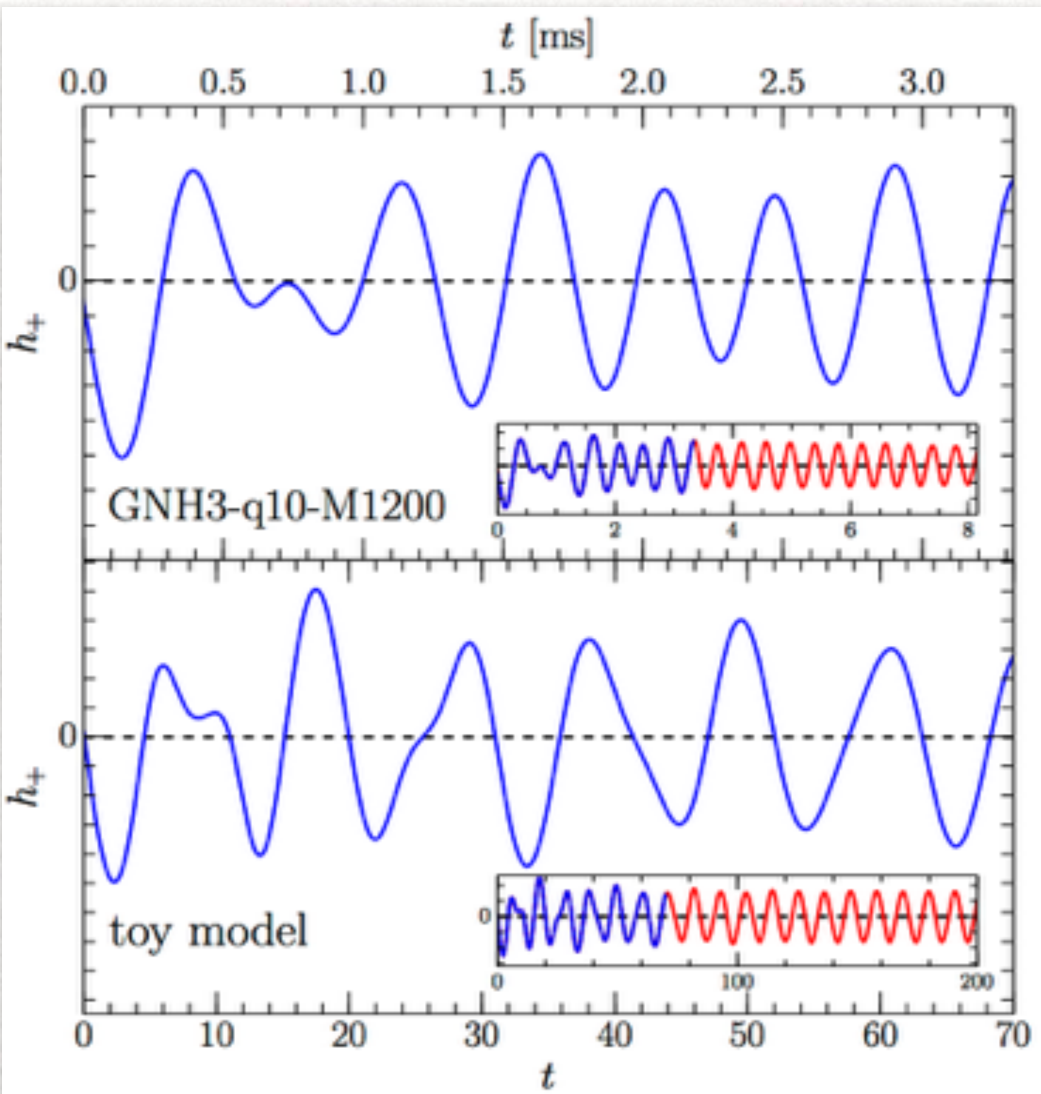

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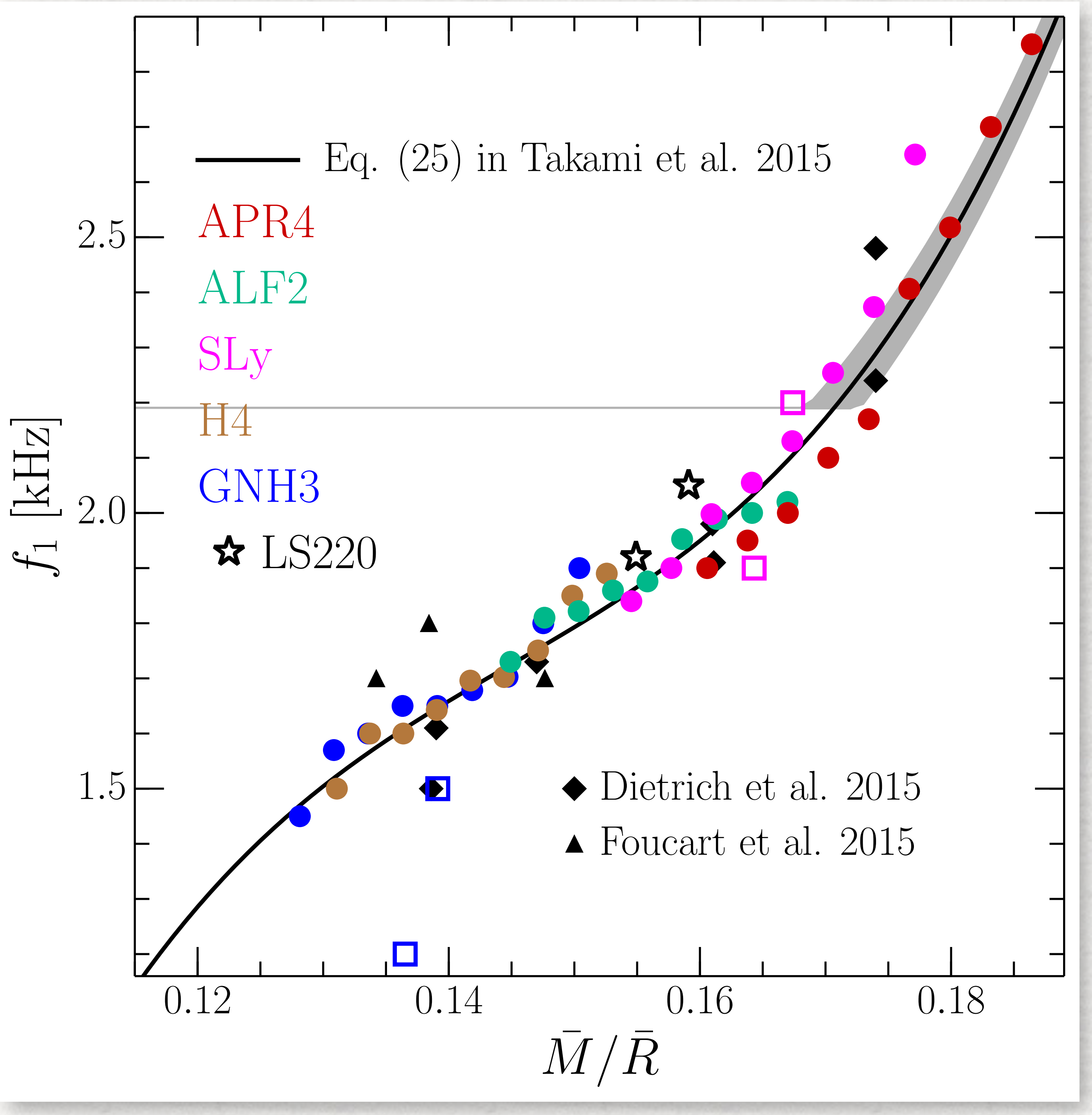
- analytic model possible of post merger (see later).

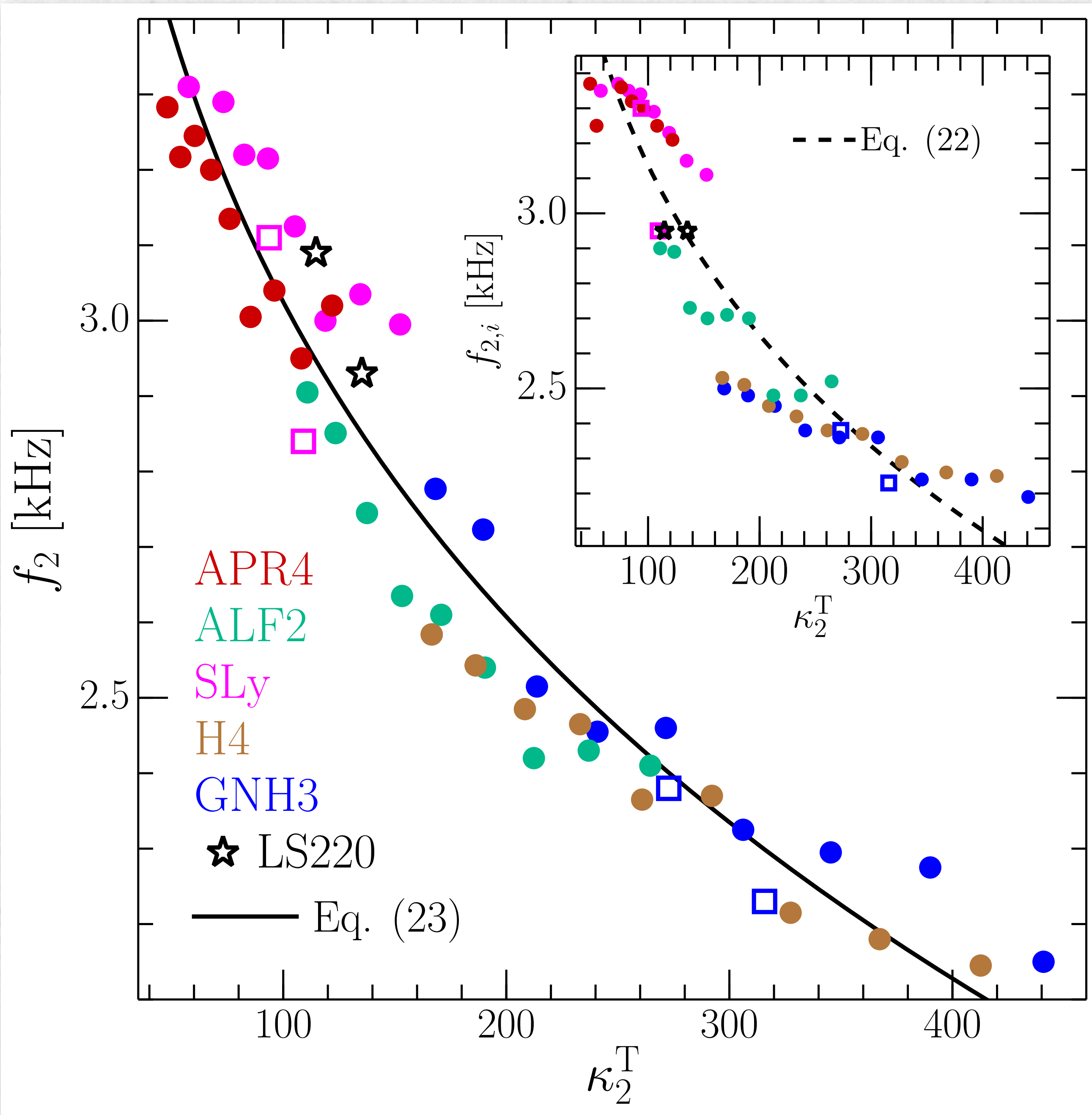
Quasi-universal behaviour: post-merger



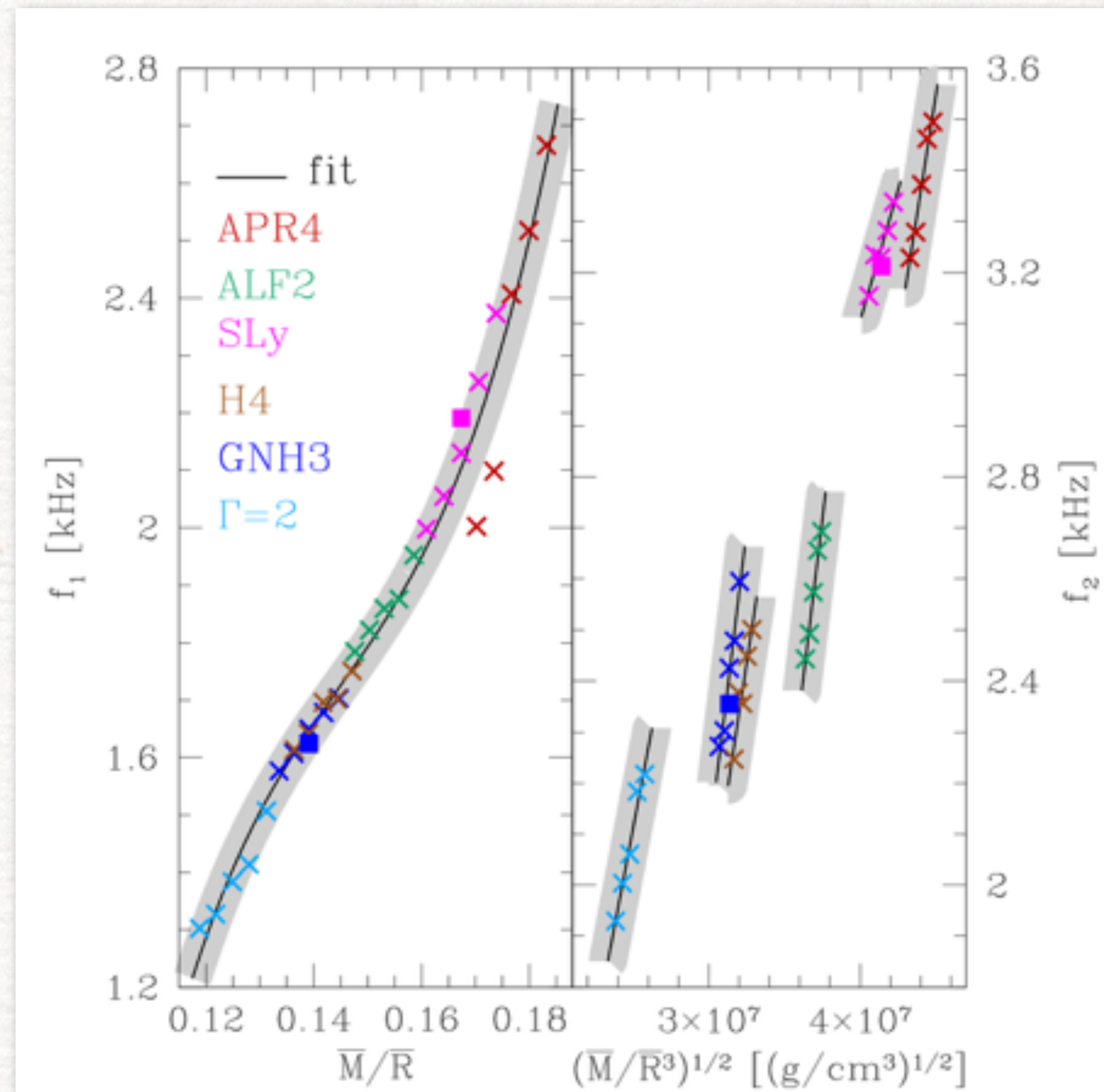
We have found **quasi-universal behaviour:** i.e., the properties of the spectra are only weakly dependent on the EOS.

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



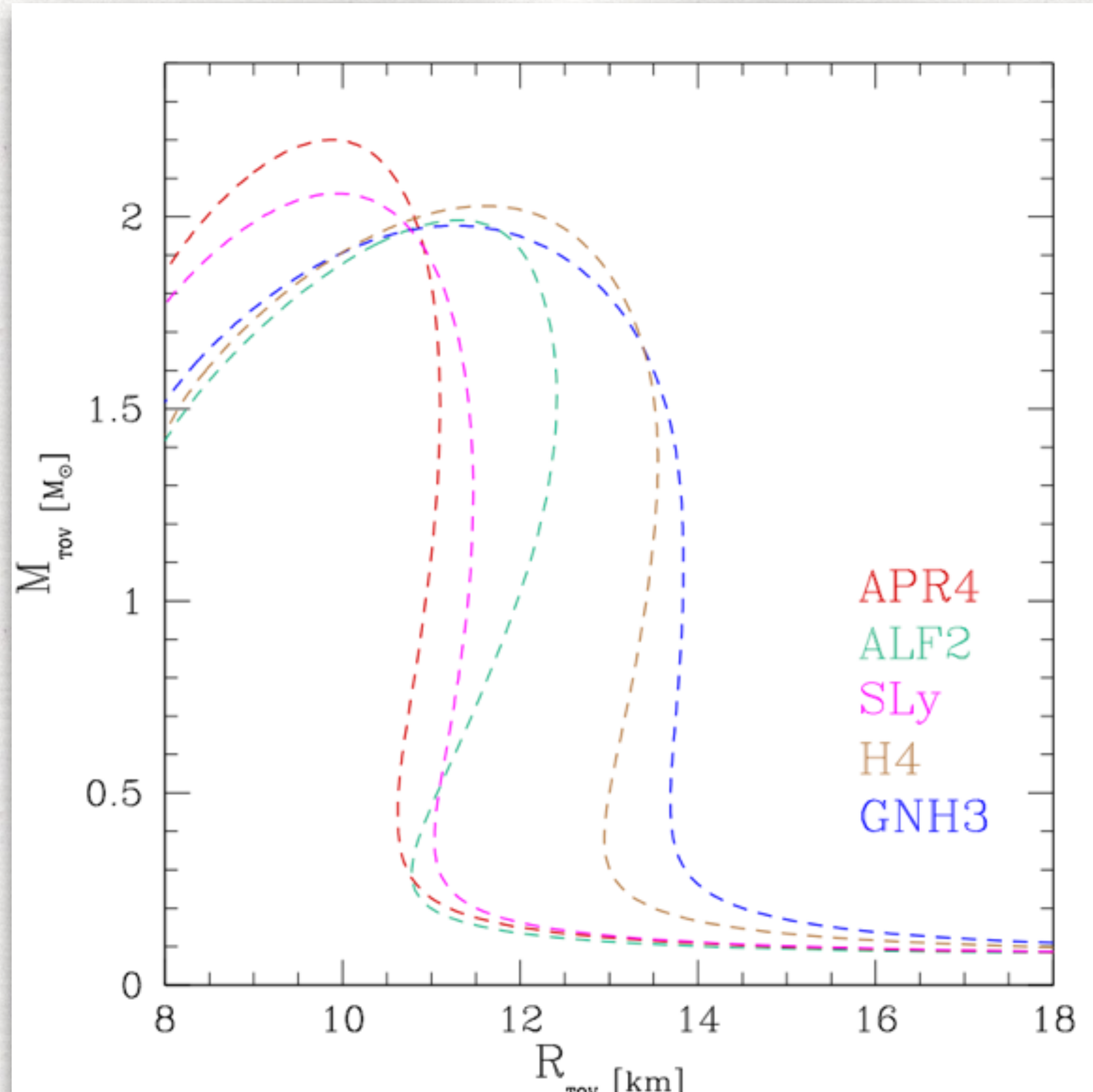
Correlations also with compactness

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.

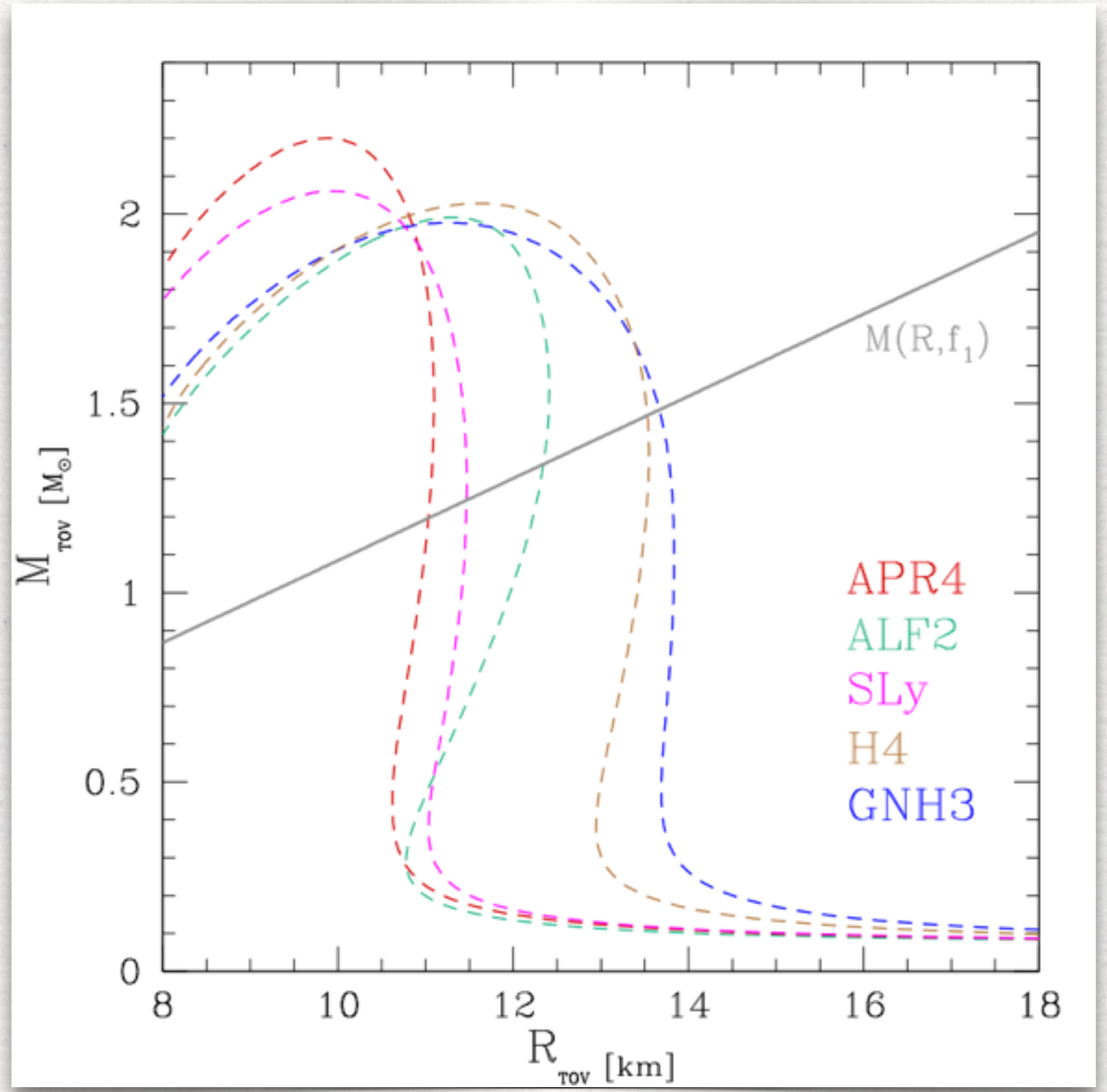
Consider your best choices as candidate EOSs



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

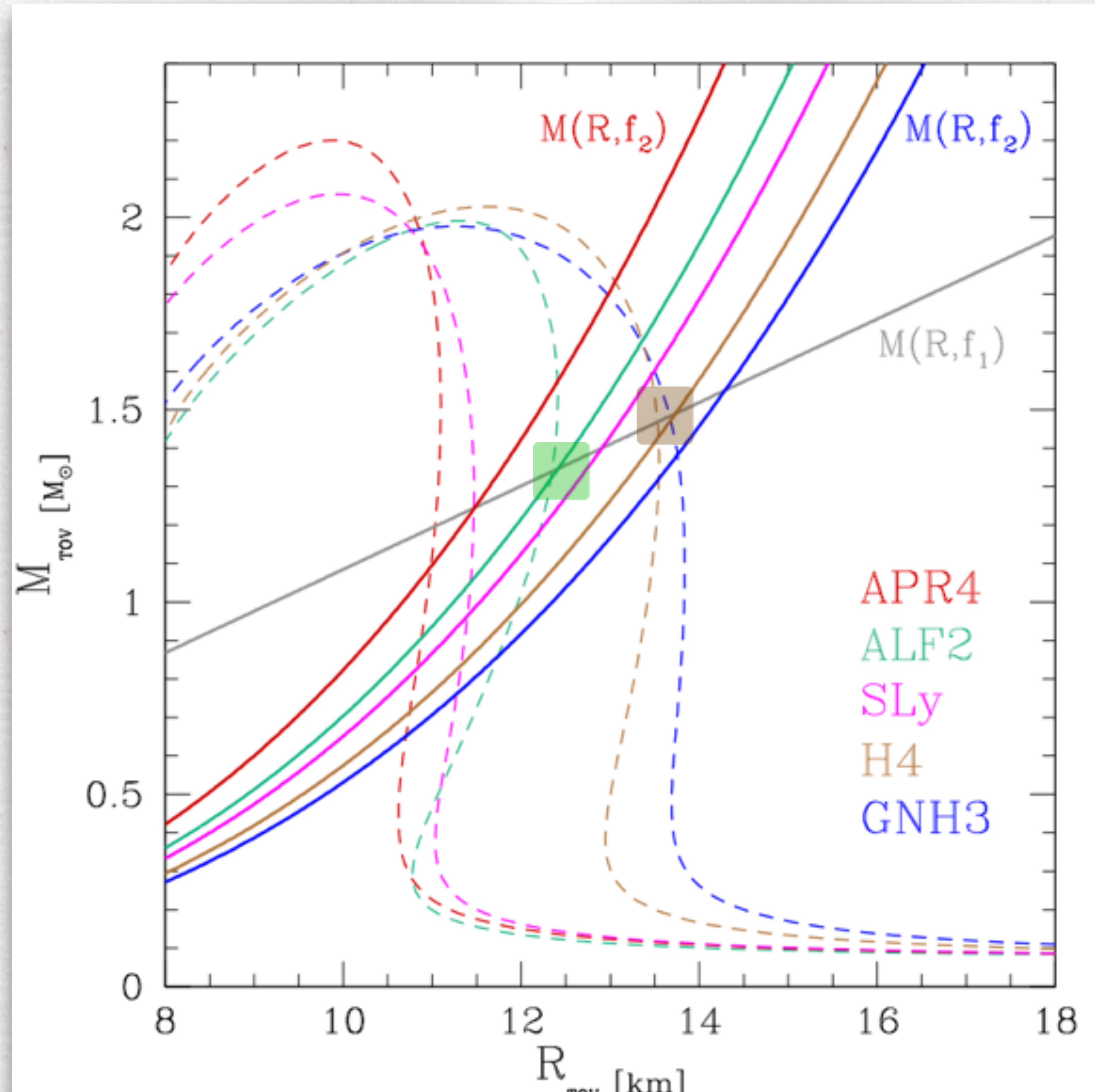
All EOSs will have **one** constraint (crossing).



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.

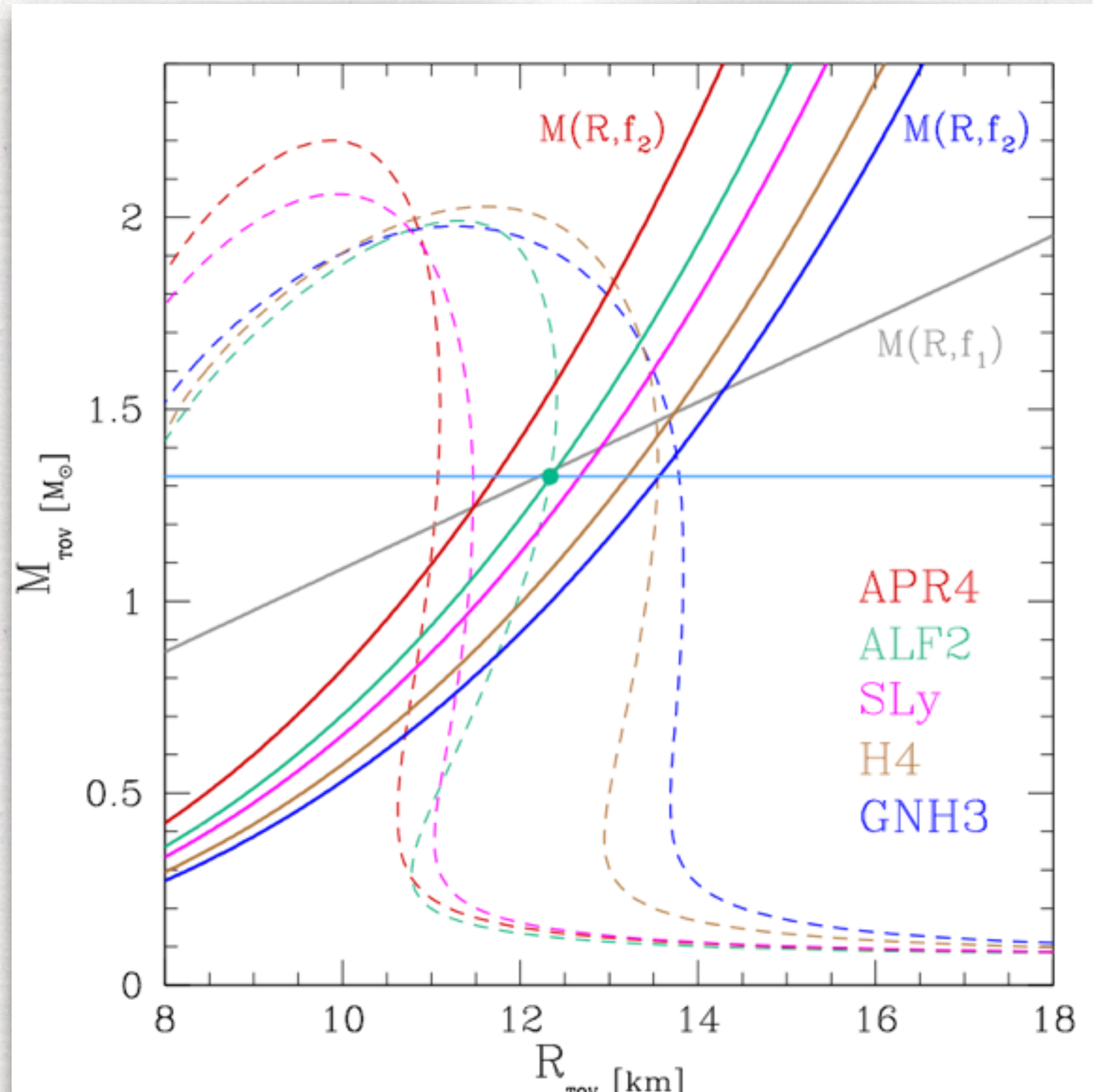
The right EOS will have **three** different constraints (APR, GNH3, SLy excluded)



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.

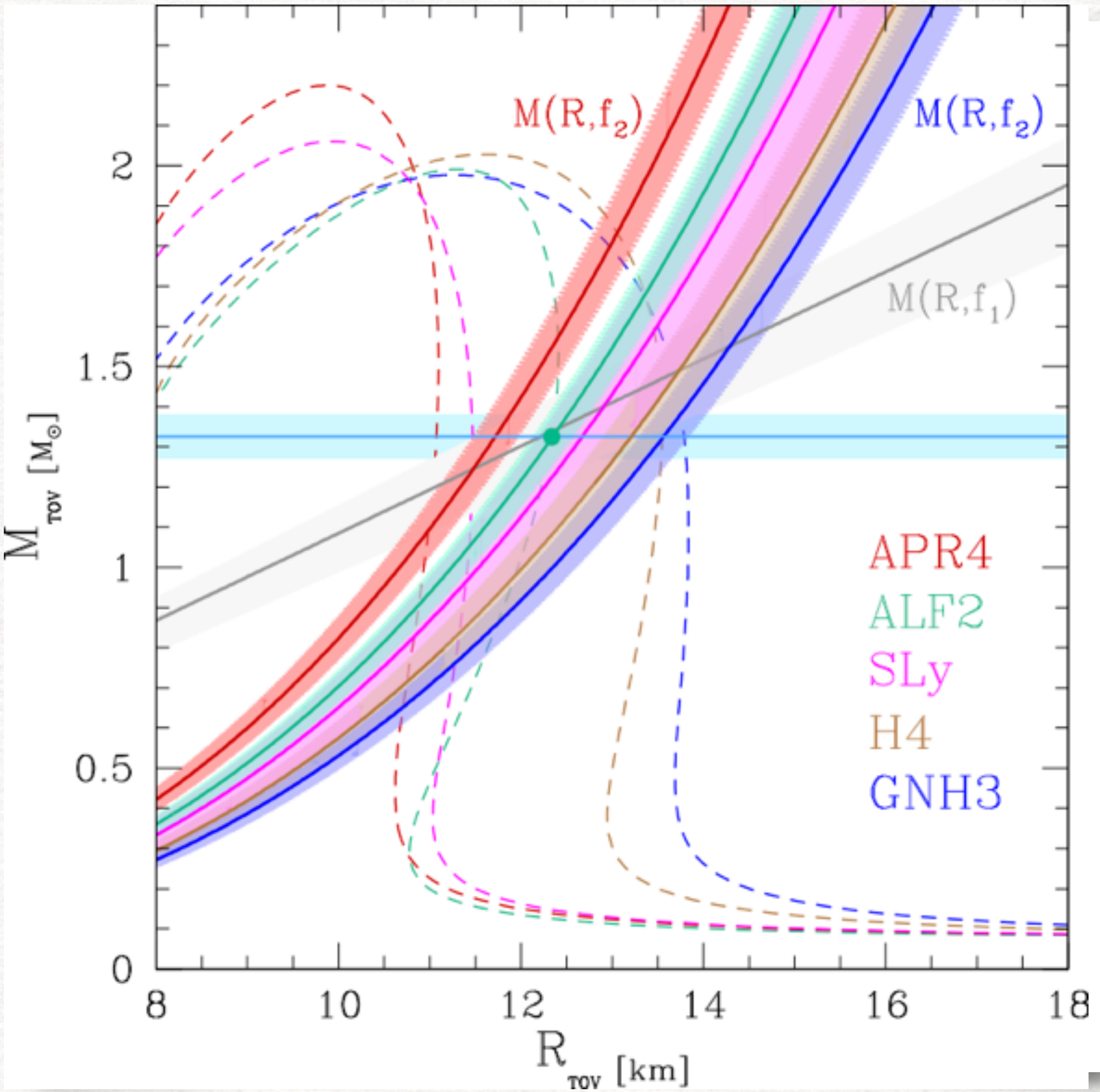


This works for all EOSs considered

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

Some numbers:

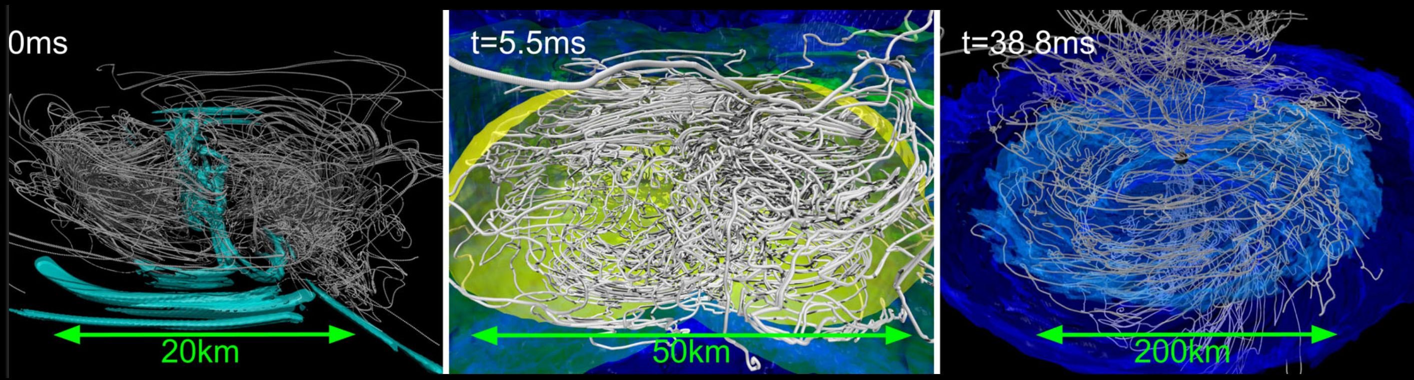
- at 50 Mpc, freq. uncertainty from Fisher matrix is 100 Hz
- at SNR=2, the event rate is 0.2-2 yr^{-1} for different EOSs.



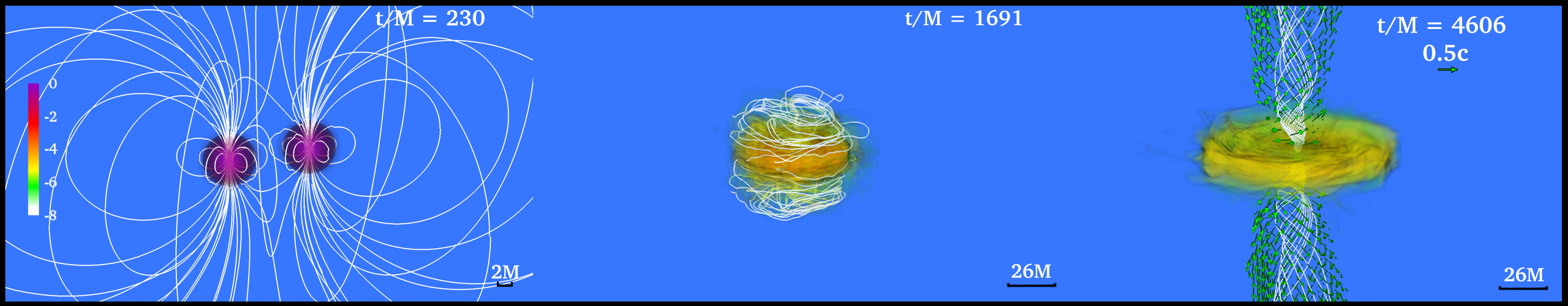
The importance of B-fields

LR+ 2011

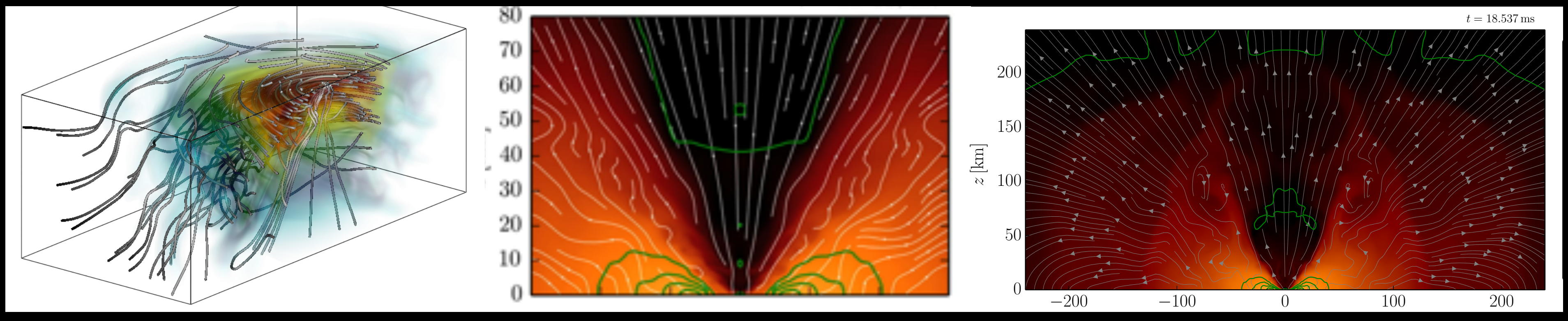
Kiuchi+ 2014



Ruiz+ 2016



Kawamura+2016



Dionysopoulou+ 2015

Importance of B-fields

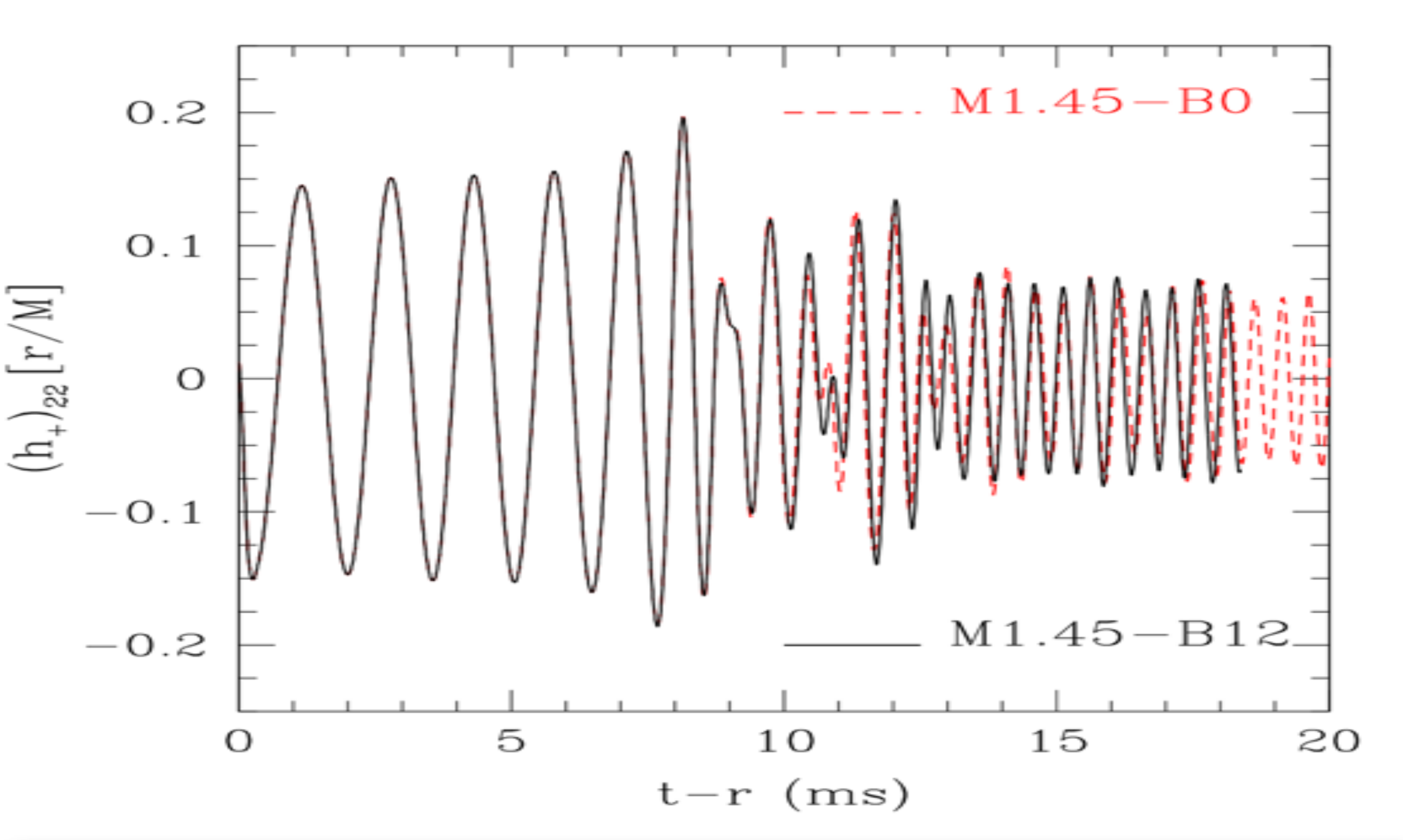
B-fields essential for EMCs. Most simulations use **ideal MHD**: infinite conductivity, magnetic field advected.

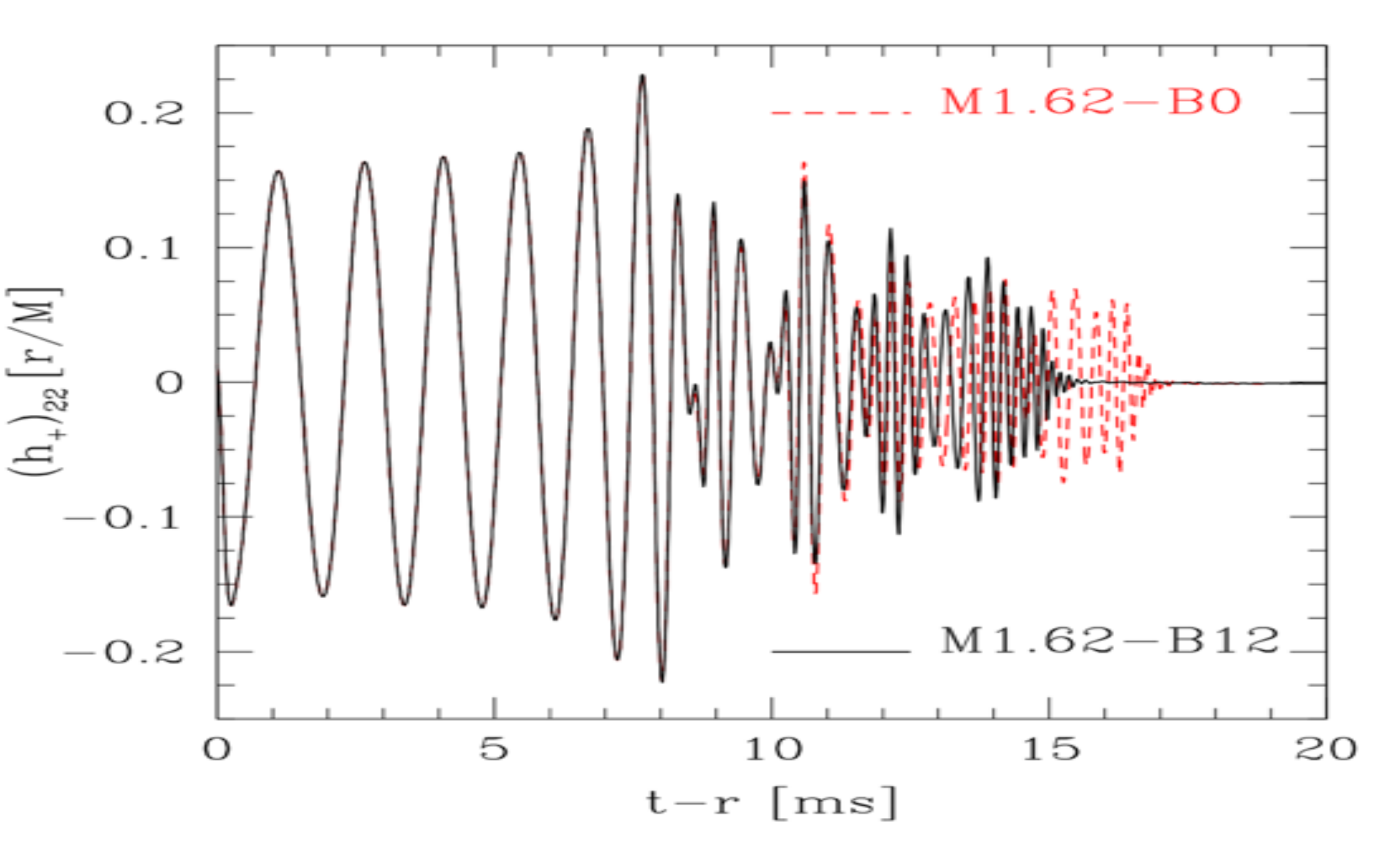
You can ask some simple questions.

- can B-fields be measured during the inspiral? ✅
- is EMC produced before merger? ❓
- do B-fields grow after merger and yield EMC? ⁉️
- does jet appear 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

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:

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

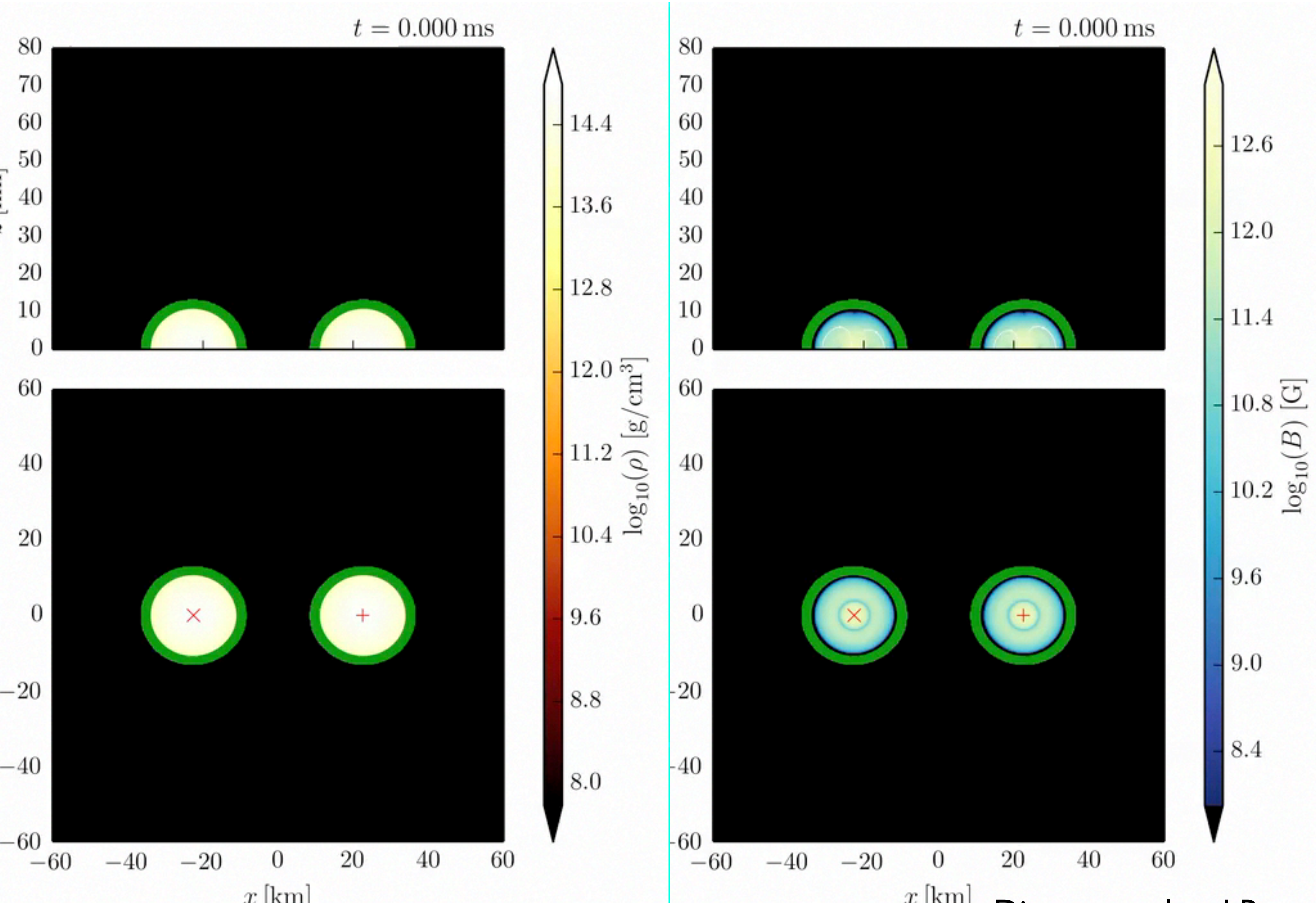
$\sigma \to \infty$ ideal-MHD (IMHD)

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

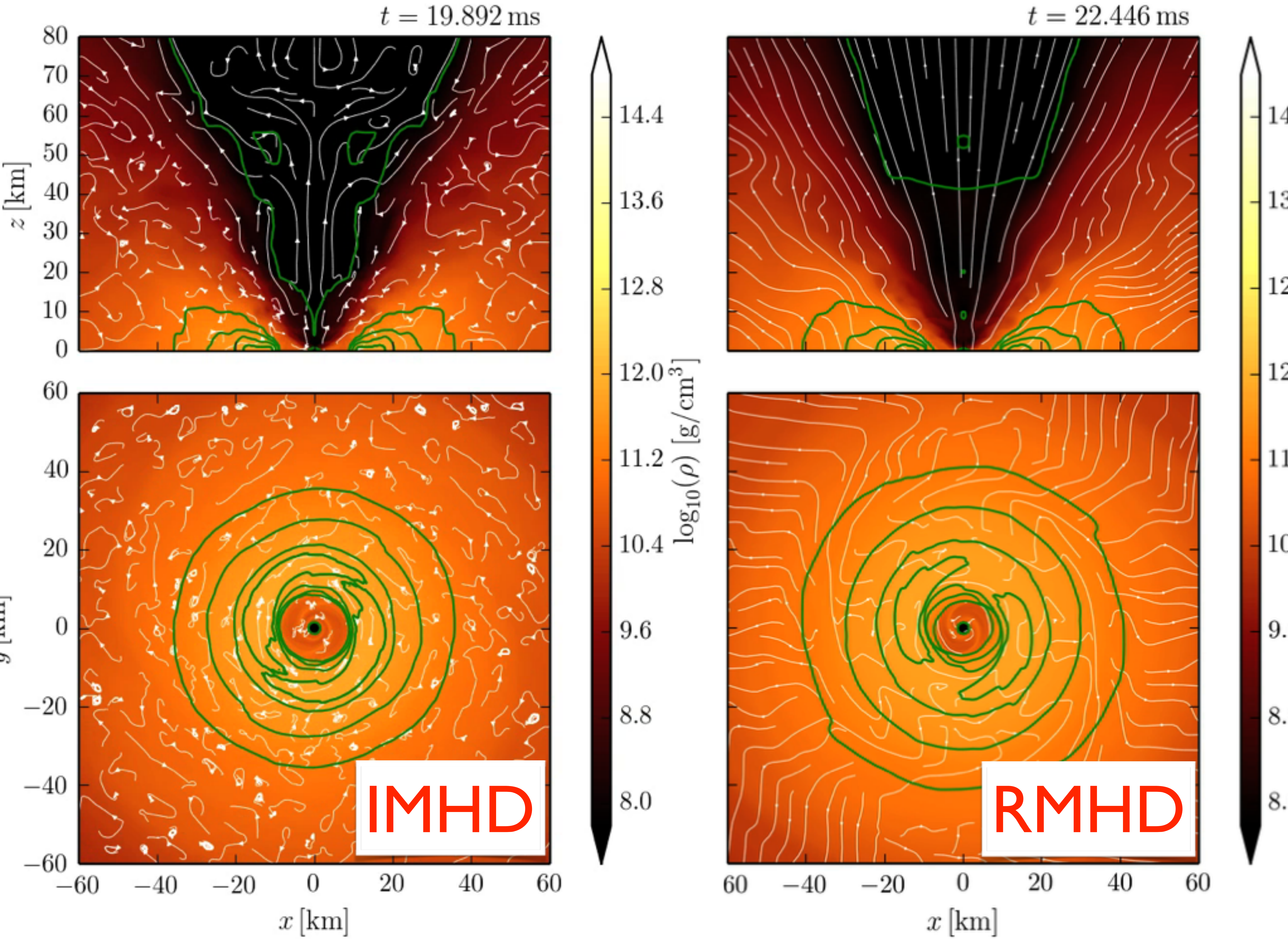
$\sigma \to 0$ electrovacuum

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

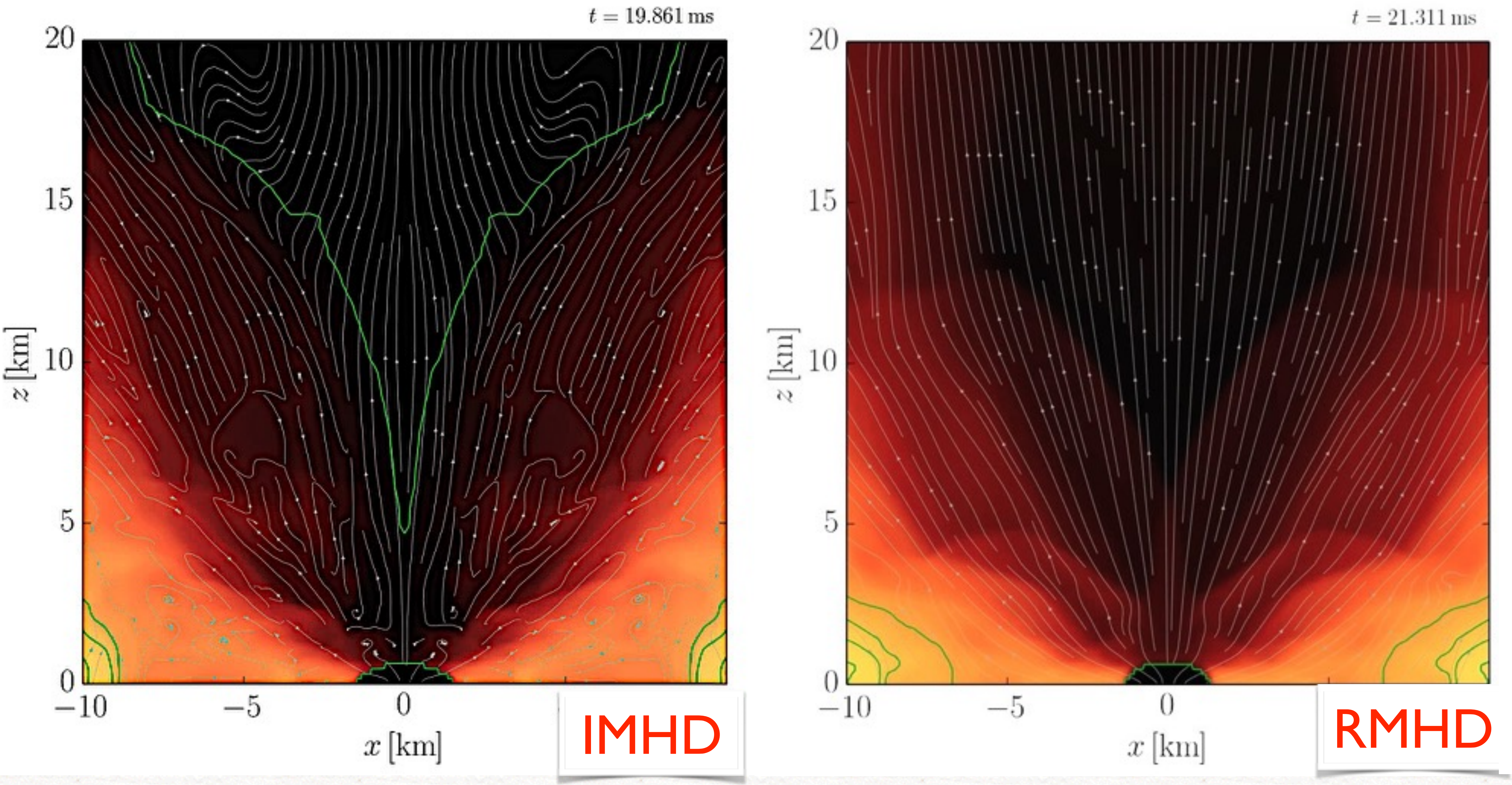
phenomenological prescription



Dionysopoulou, LR



t = 19.892 ms
t = 22.446 ms
z [km]
x [km]
x [km]
log10(ρ) [g/cm^3]
14.4
13.6
12.8
12.0
11.2
10.4
9.6
8.8
8.0
IMHD
RMHD



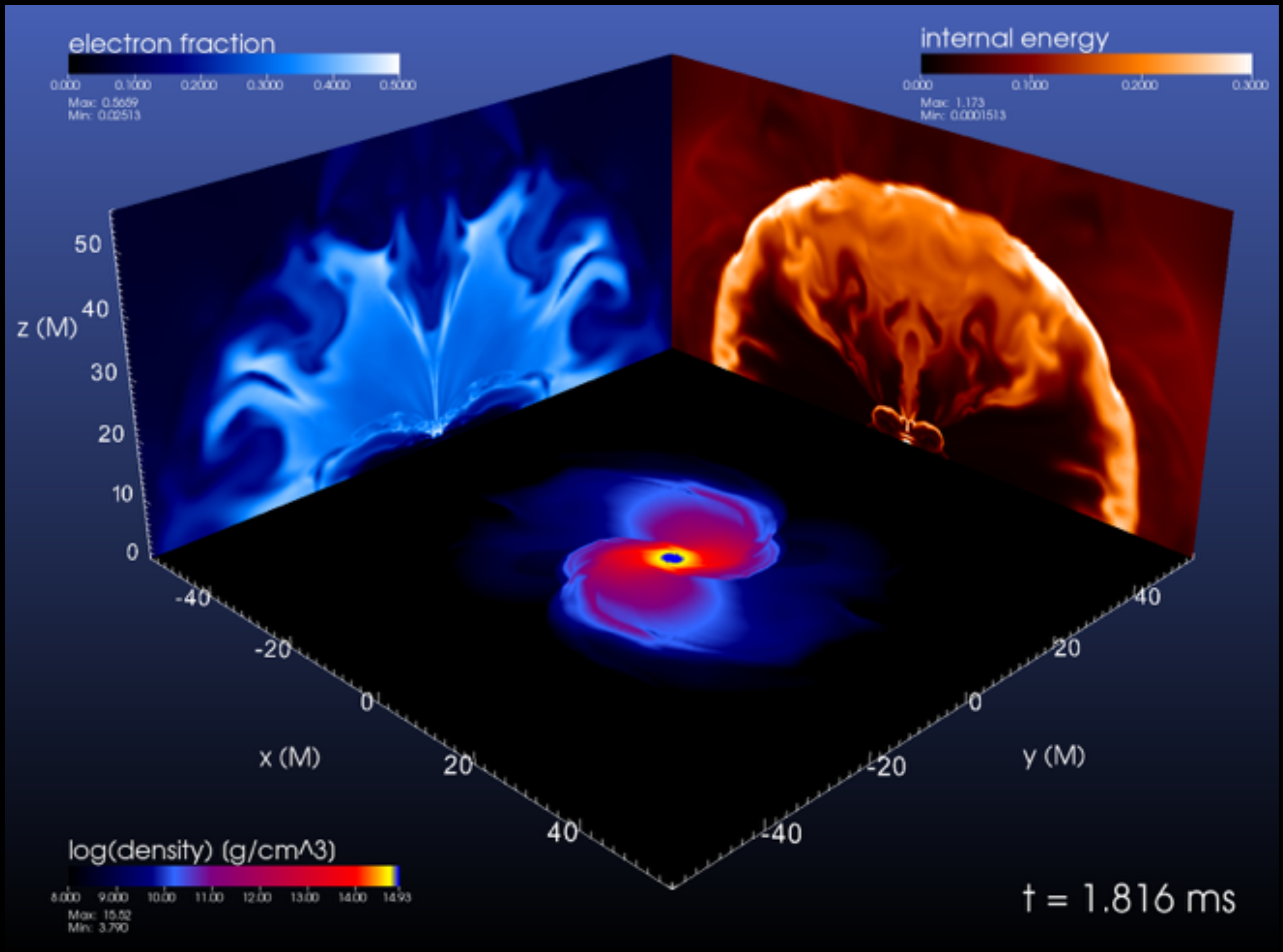
NOTE: the magnetic jet structure is **not** an **outflow**. It's a plasma-confining structure.

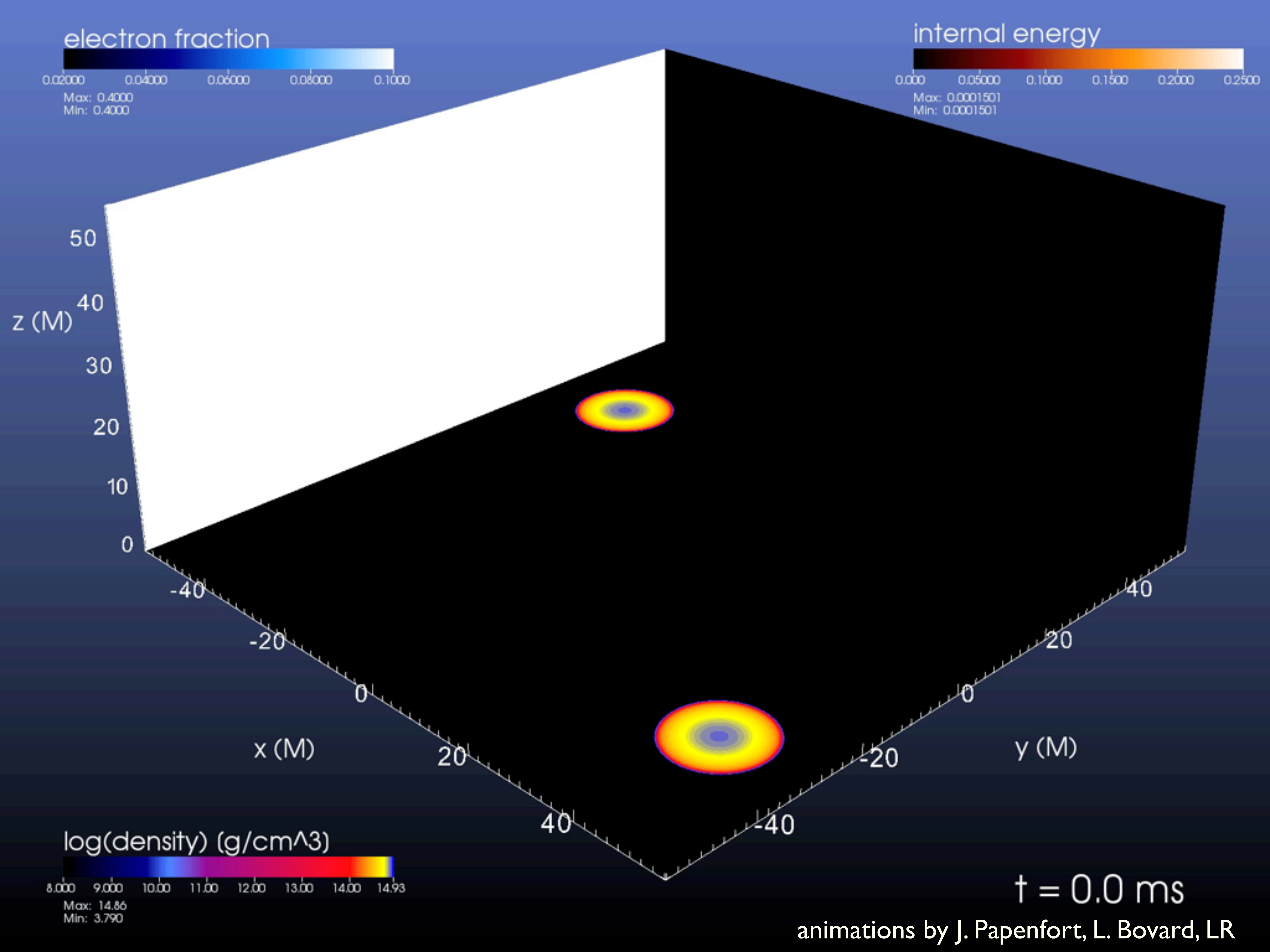
In IMHD the magnetic jet structure is present but less regular.

In RMHD it is more regular at all scales.

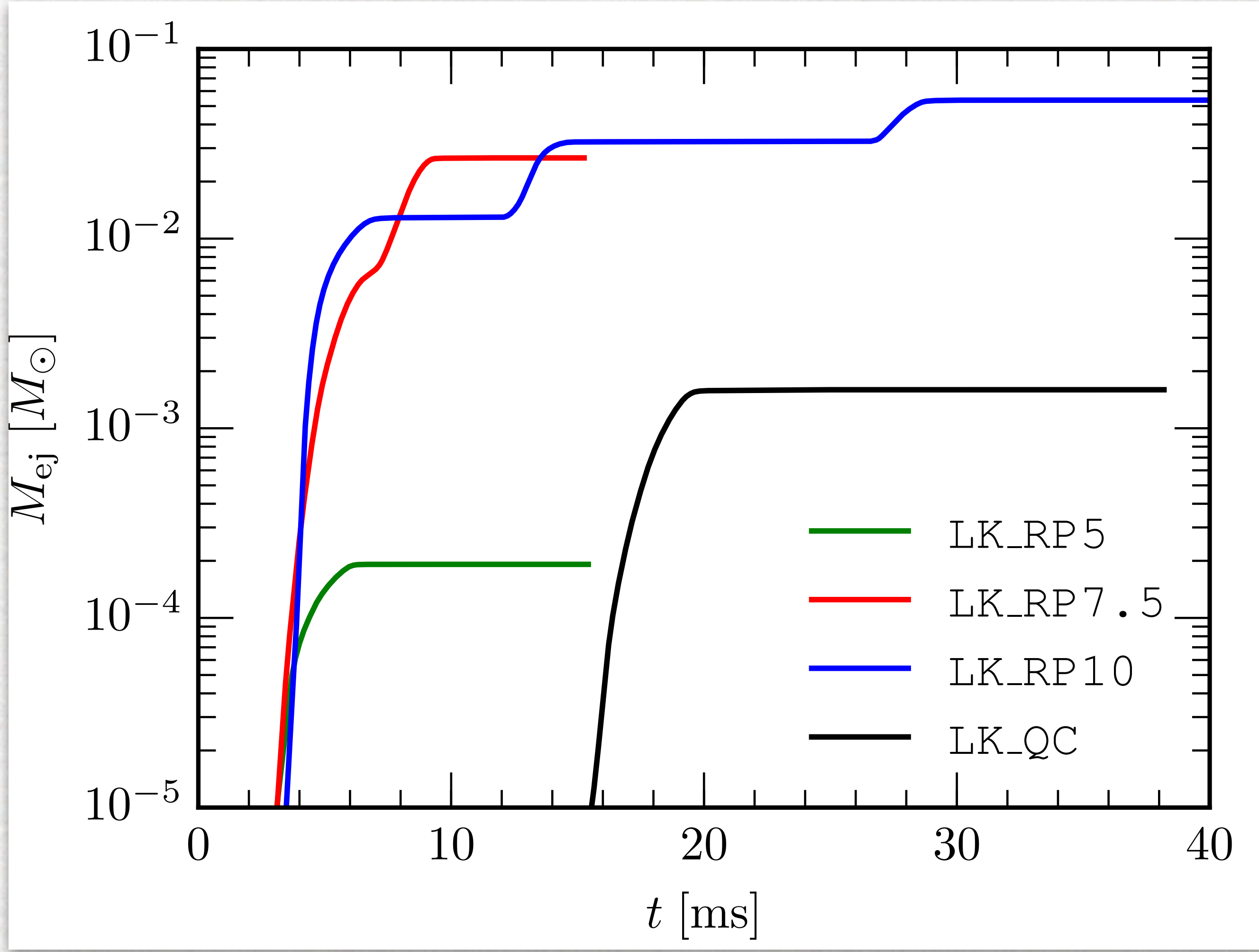
Dynamically captured binaries and nucleosynthesis

see Piran's, Sekiguchi's, and Tanaka's talks



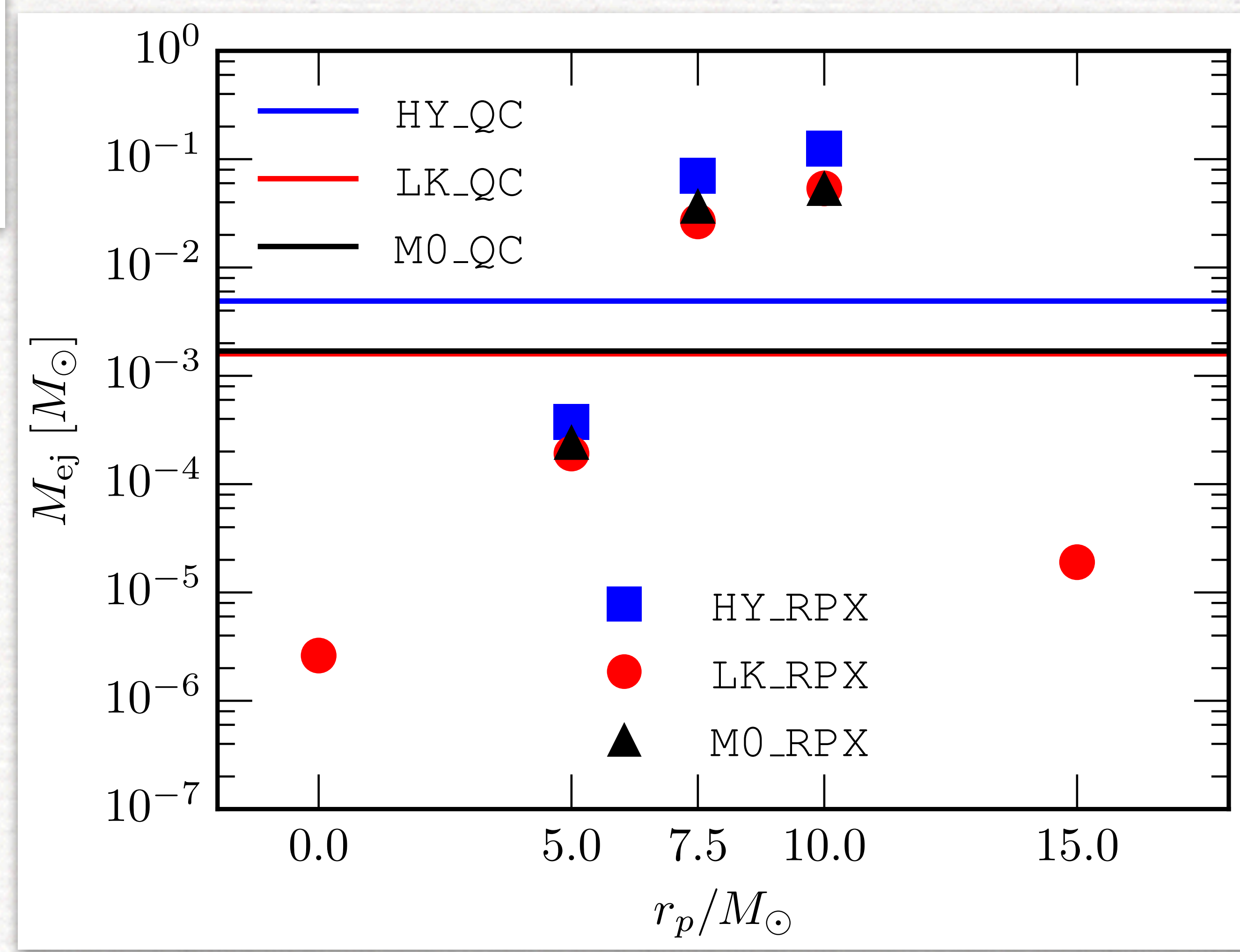

electron fraction
0.02000 0.04000 0.06000 0.08000 0.1000
Max: 0.4000
Min: 0.4000
internal energy
0.000 0.05000 0.1000 0.1500 0.2000 0.2500
Max: 0.0001501
Min: 0.0001501
z (M)
50 40 30 20 10 0
-40 -20 0 20 40
x (M)
40 20 0 -20 -40
y (M)
log(density) (g/cm^3)
8.000 9.000 10.00 11.00 12.00 13.00 14.00 14.93
Max: 14.86
Min: 3.790
t = 0.0 ms
animations by J. Papenfort, L. Bovard, LR

Mass ejection

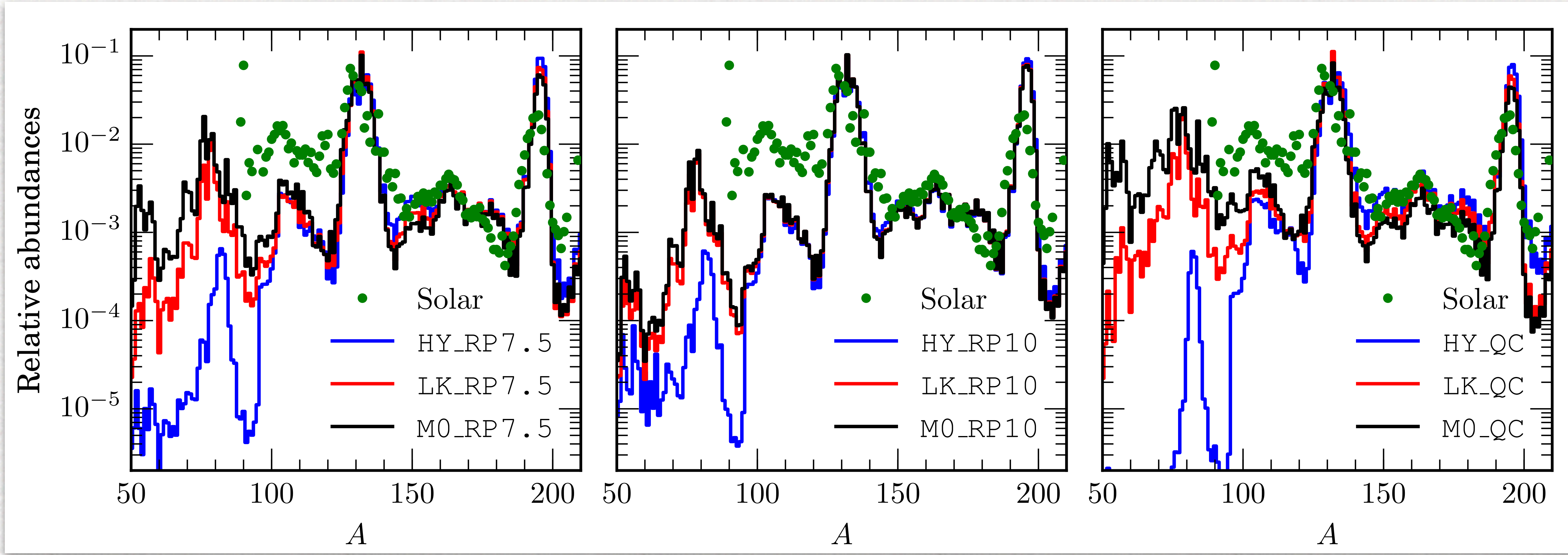


- Mass ejected depends on impact parameter and takes place at each encounter.
- Quasi-circular binaries have smaller ejected masses (1-2 orders of magnitude)

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



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

Macronova emission

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

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

The **peak bolometric luminosity** is estimated to be (“ectonova”)

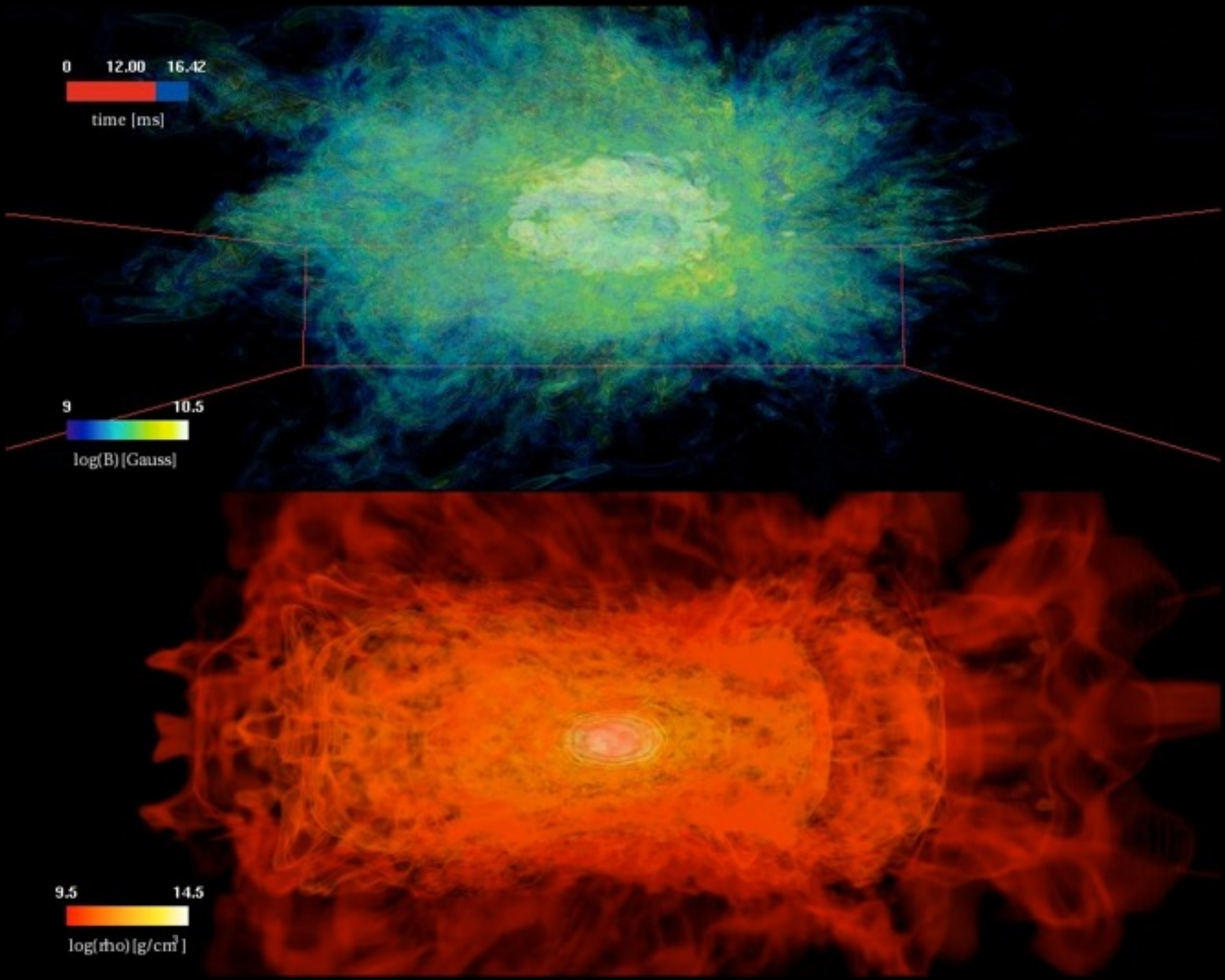
$$L = 2.5\times 10^{40} \left(\frac{M_{\rm ej}}{10^{-2}\ M_\odot}\right)^{1-\alpha/2} \times \left(\frac{\kappa}{10\ {\rm cm}^2\ {\rm g}^{-1}}\right)^{-\alpha/2} \left(\frac{\langle v_\infty \rangle}{0.1\ c}\right)^{\alpha/2} \quad {\rm erg\ s}^{-1}\,.$$

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

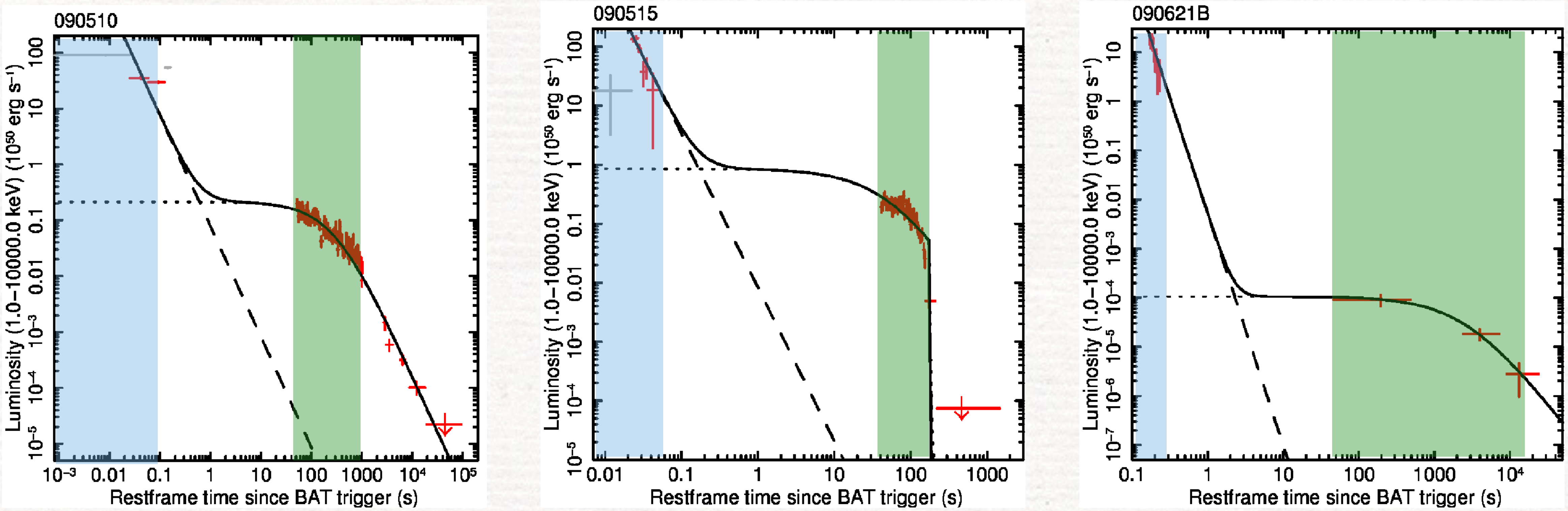
Eccentric binaries: ~ **4 times more luminous** than quasi-circular; **delayed peak emission:** ~ 8 days (cf. 1.5 days)

X-ray emission

see Zhang's talk



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).

The elephant in the room…

Magnetars are appealing for simplicity but not necessarily 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.

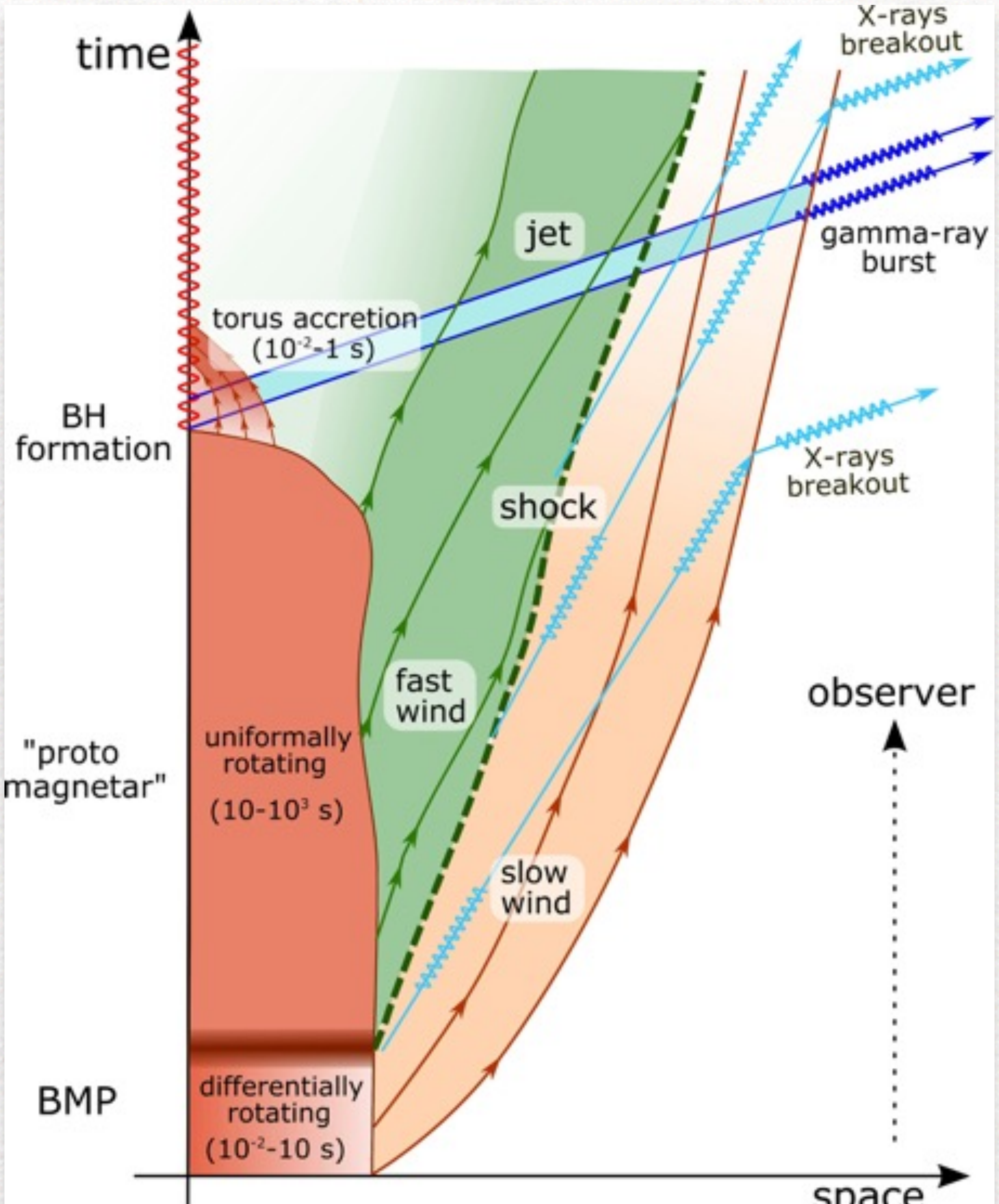
Recap:

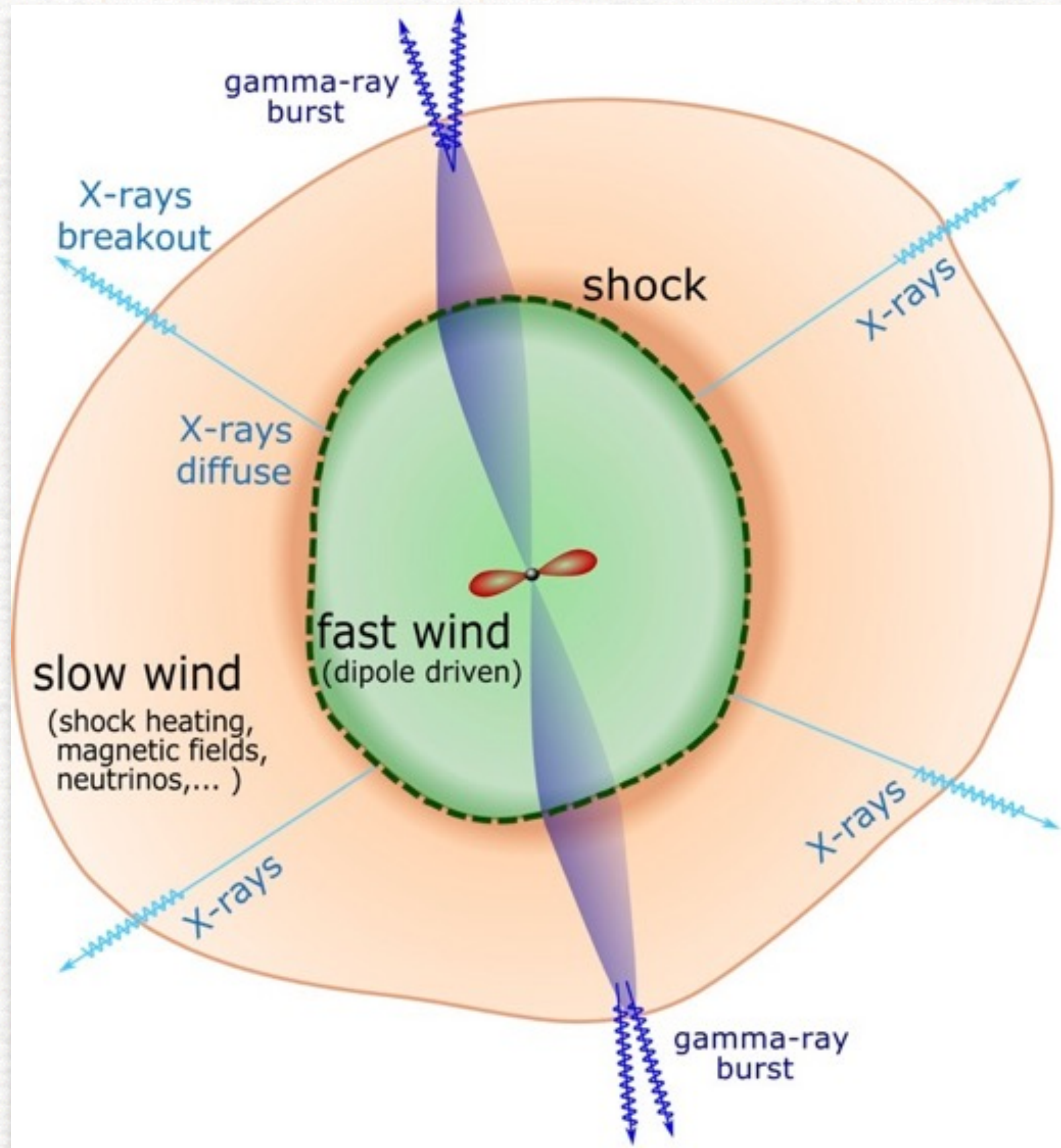
- X-rays produced by metastable magnetar
- gamma-rays produced by jet and BH-torus system

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?

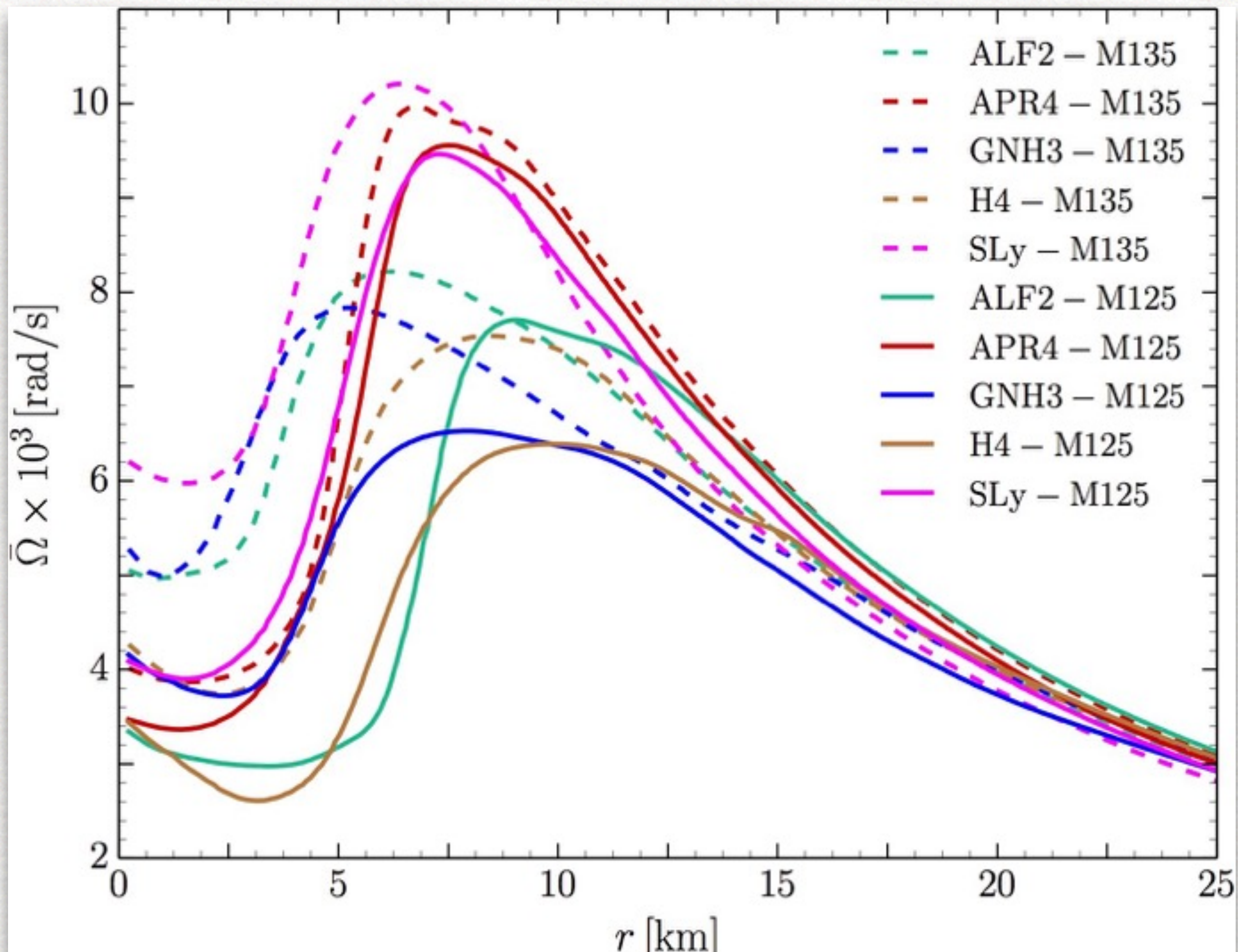
LR, Kumar (2014)

- ***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).

An important requirement

Hanauske+ 2016

Angular velocity profiles of HMNS for different EOSs/masses: inner core uniformly rotating and "disk" on Keplerian orbits



An important requirement

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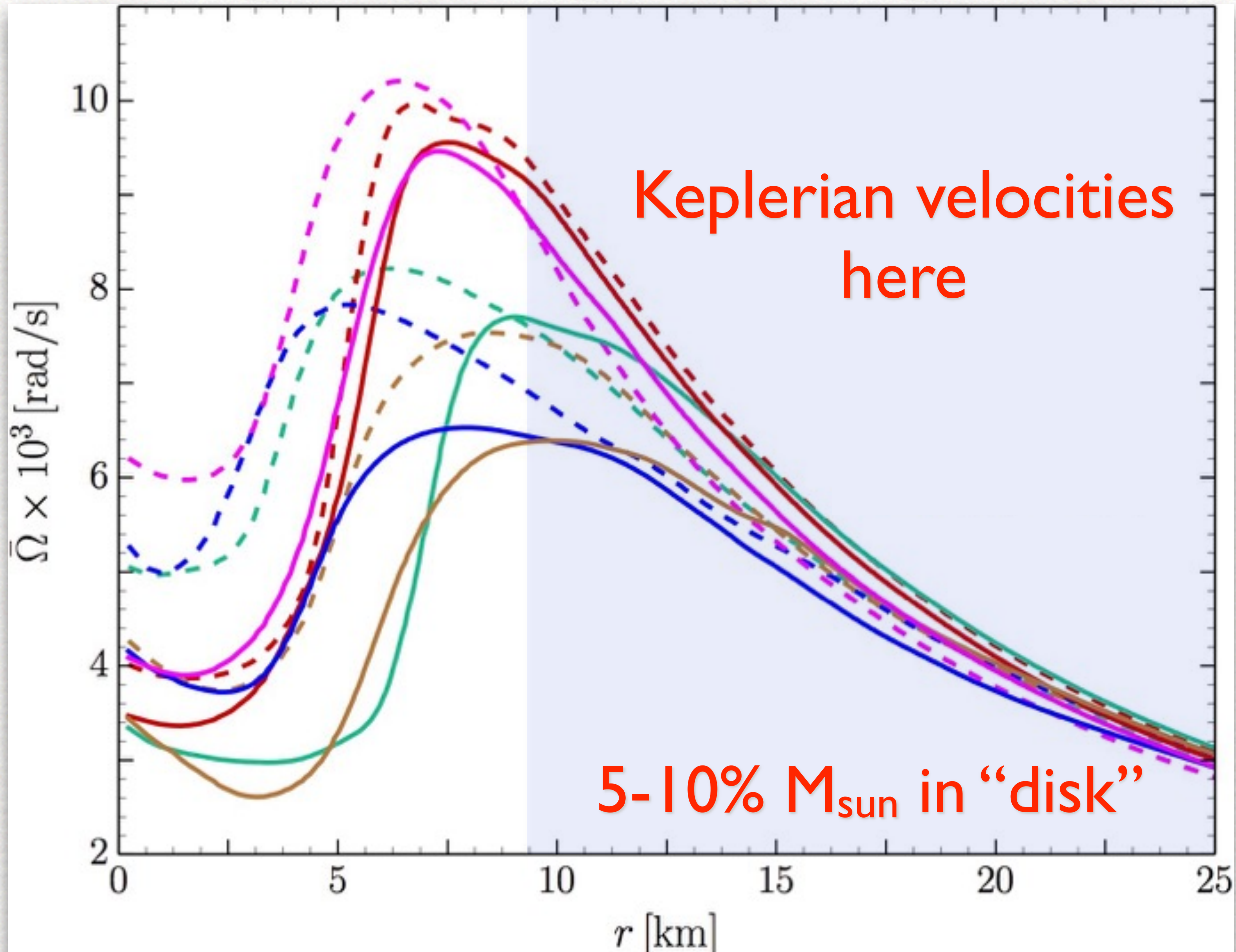
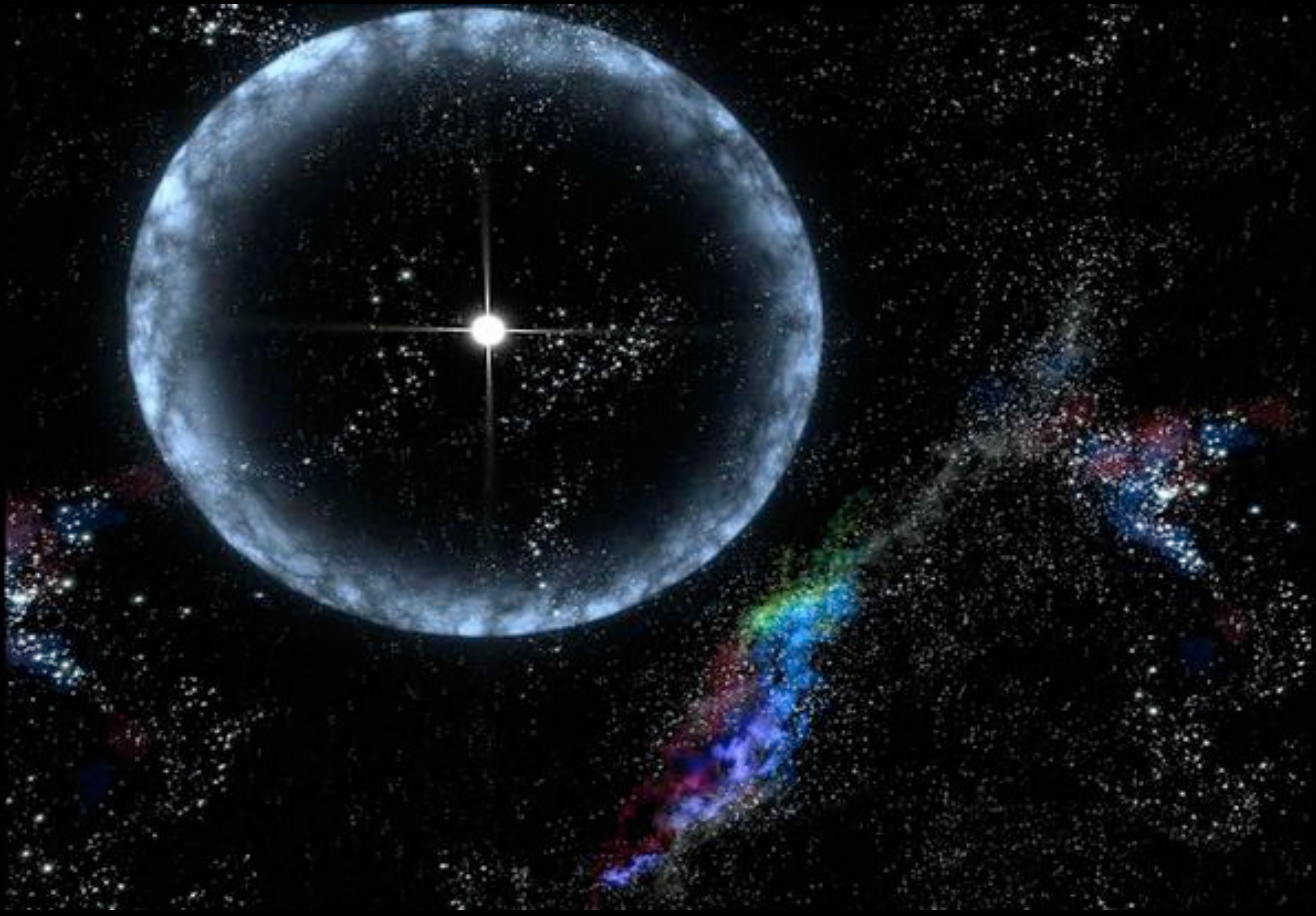


The riddle of FRBs

see Lorimer's and Zhang's talks



Fast Radio Bursts

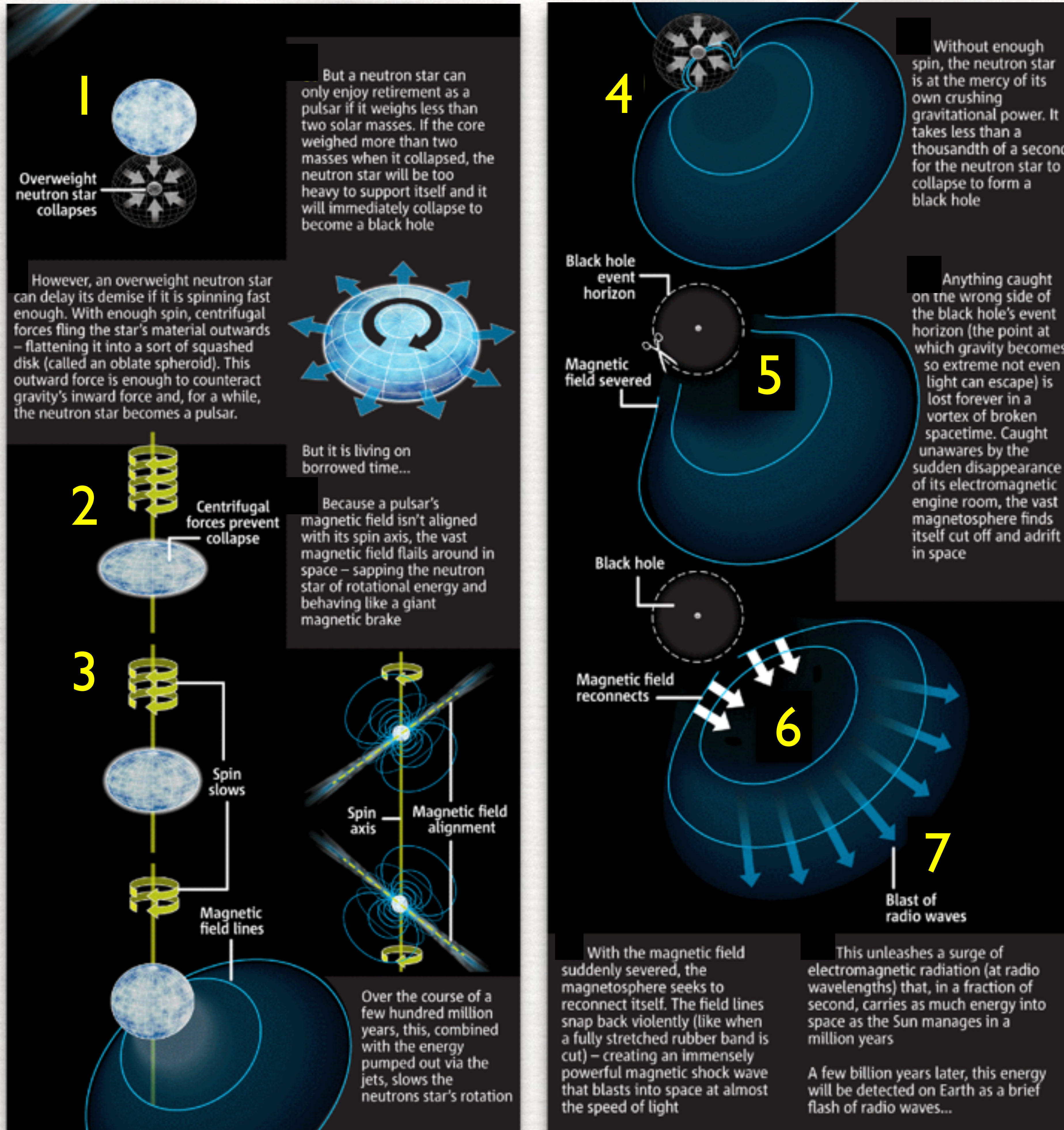
Several **fast radio bursts** (FRBs) have been discovered recently (Keane+ 2012, Thornton+ 2013, Spitler+ 2014):

- single bright, highly dispersed millisecond radio pulses;
- 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.

A cartoon…



@GilliCosm on Twitter Graphic: BEN GILLILAND

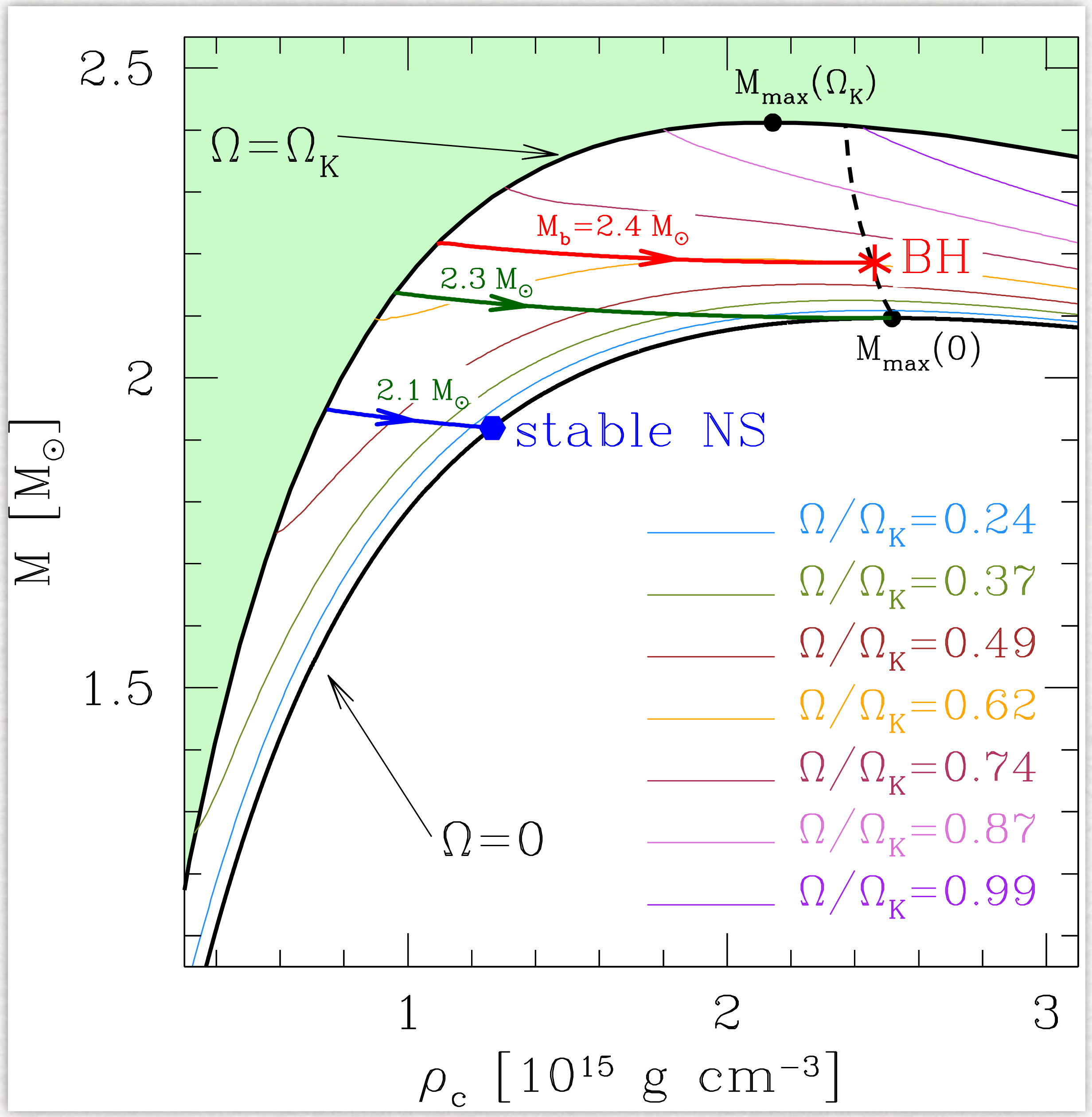
www.cosmonline.co.uk

"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. 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.

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:

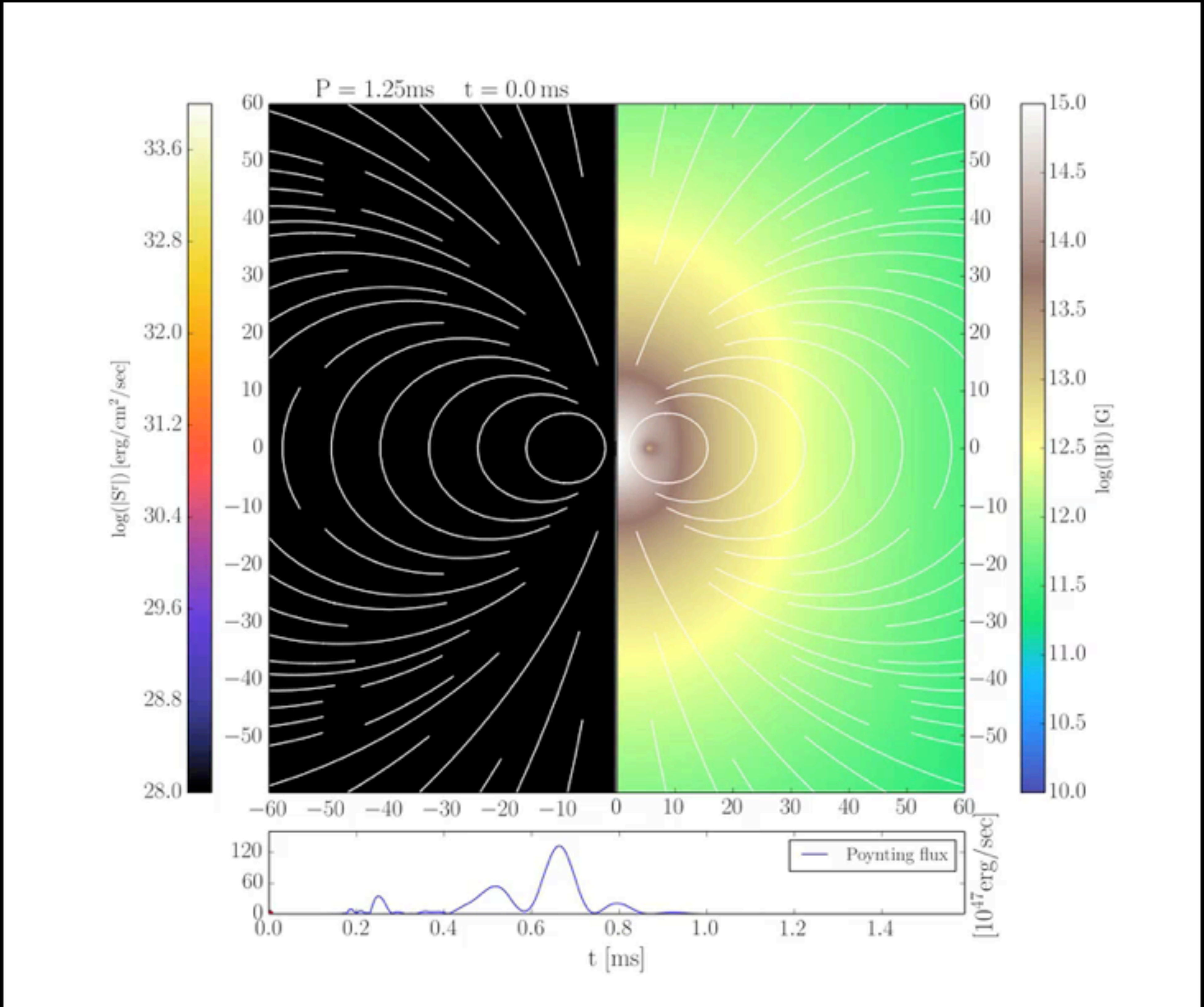
$$\nu_{\rm p} = \frac{\omega_{\rm p}}{2\pi} = \sqrt{\frac{eB\Omega}{2\pi^2 c m_{\rm e}}} \simeq 38.6\ f_{0.1}^{1/2}\ \kappa_{\rm GJ}^{1/2}\, b_{12}^{1/2}\ m_2^{1/4}\ r_{10}^{-3/4}\ \ {\rm GHz}\,.$$

- Need relativistic particles but “reasonably” relativistic:

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

Overall dynamics

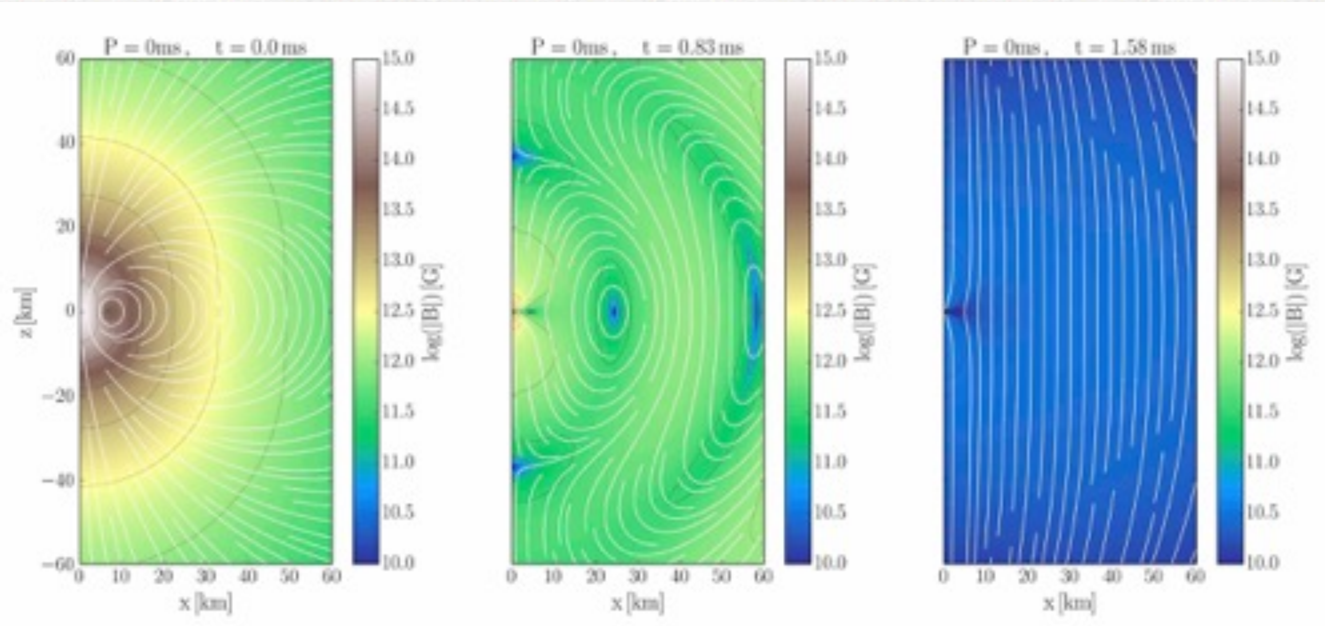
Most, Nathanail, LR 2016

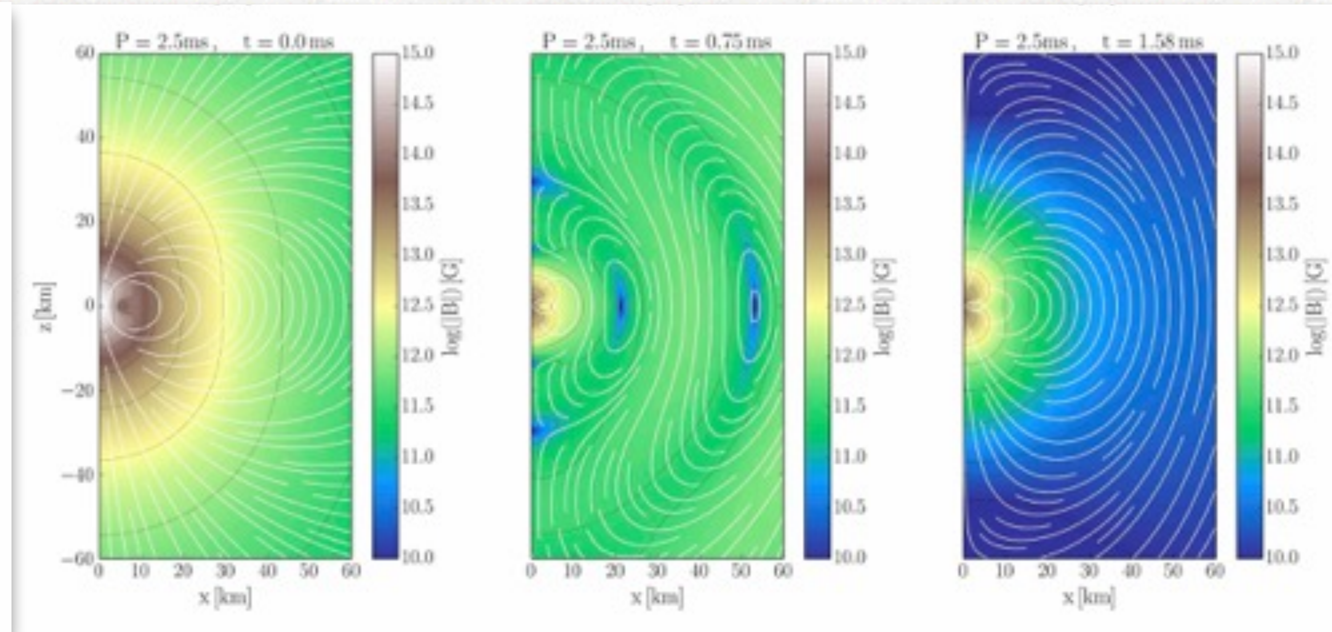


Overall dynamics

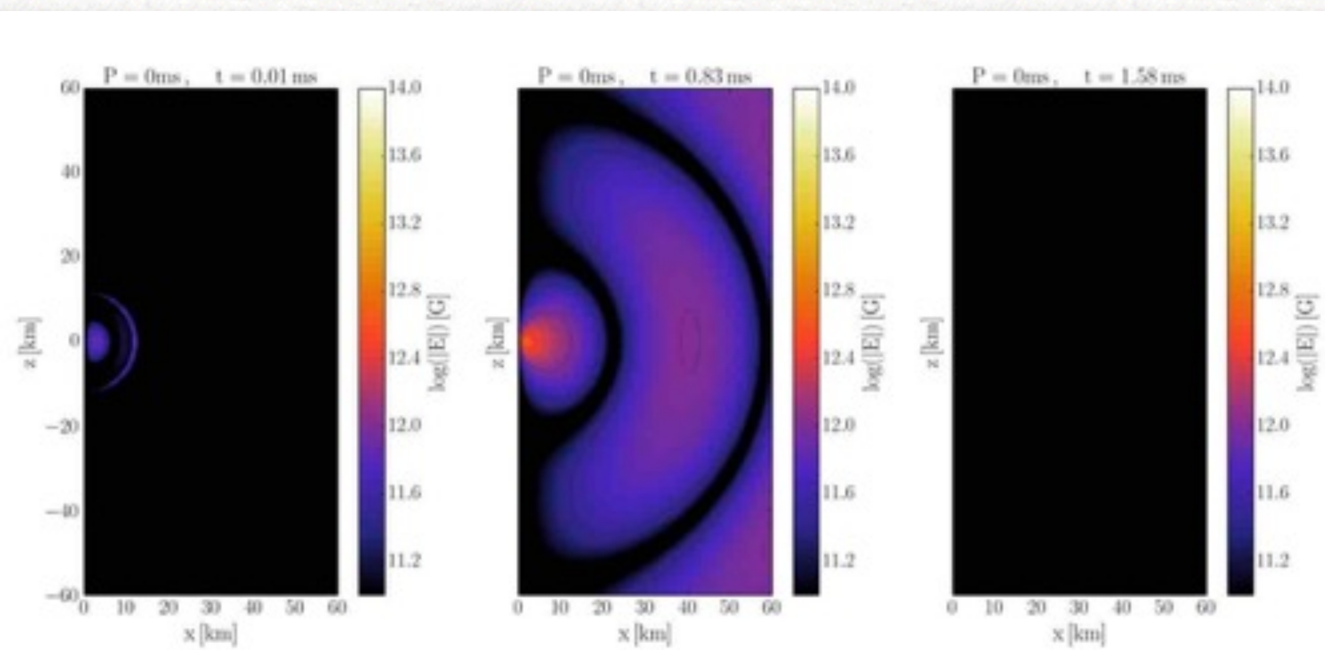
Most, Nathanail, LR 2016

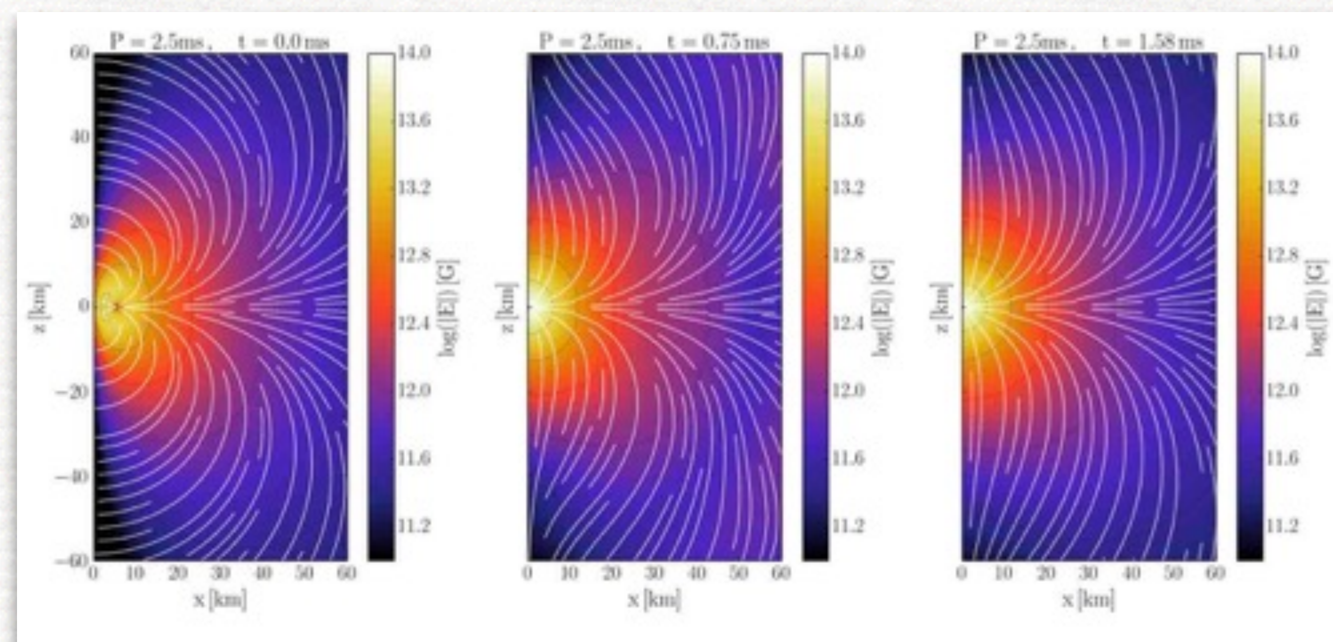
nonrotating magnetised star **rotating magnetised star**





B-field



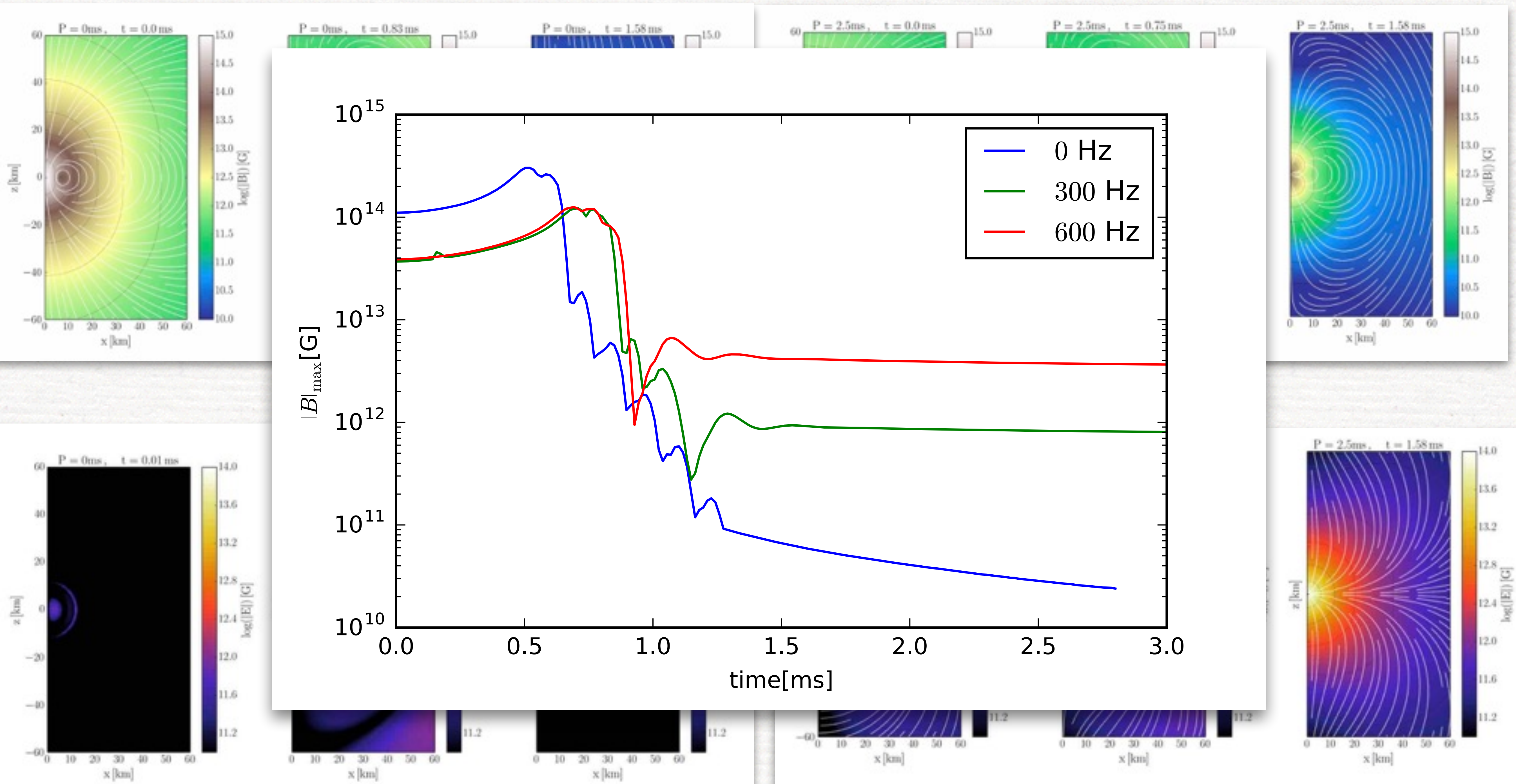


Poynting flux

Overall dynamics

Most, Nathanail, LR 2016

nonrotating magnetised star **rotating magnetised star**

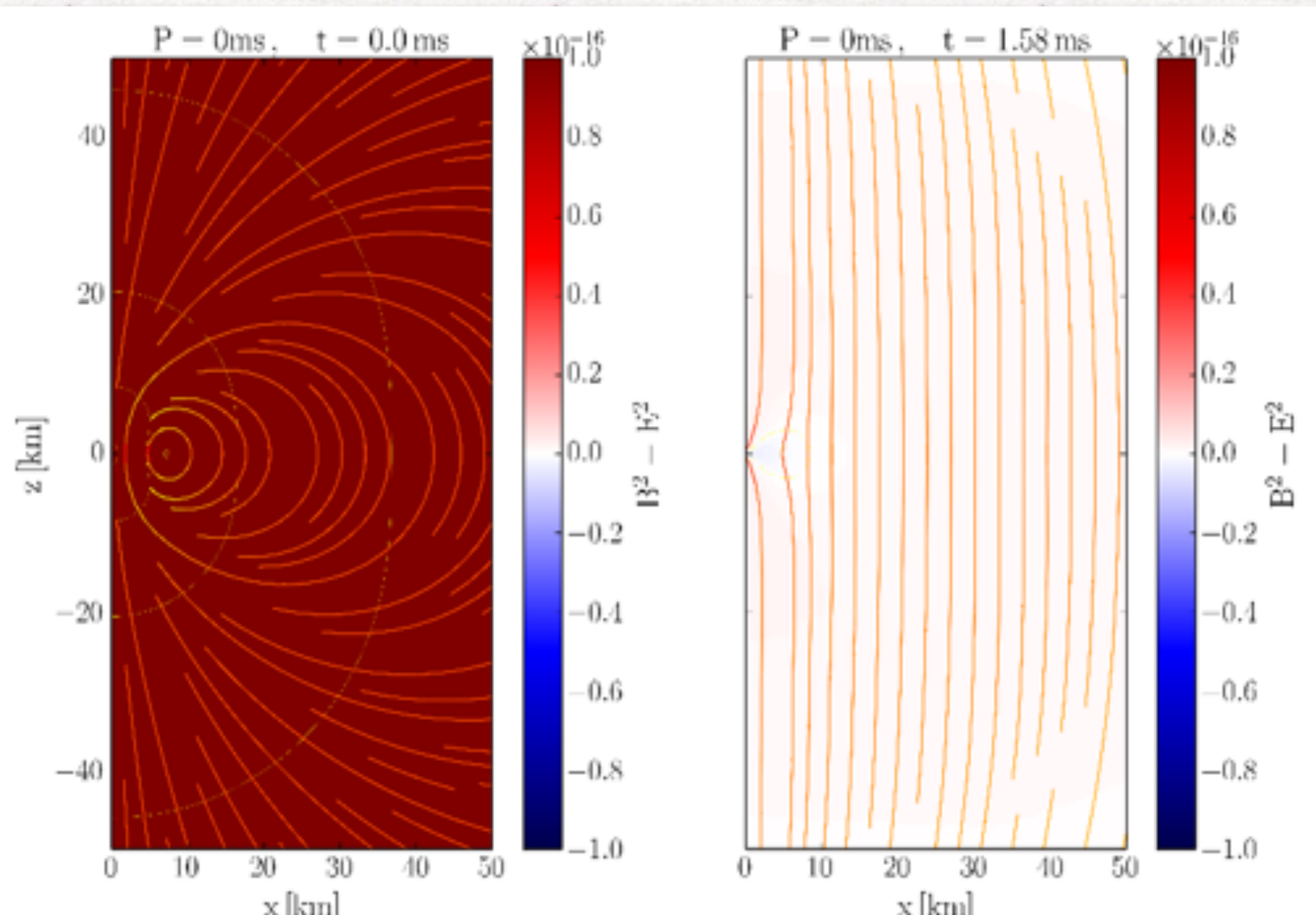


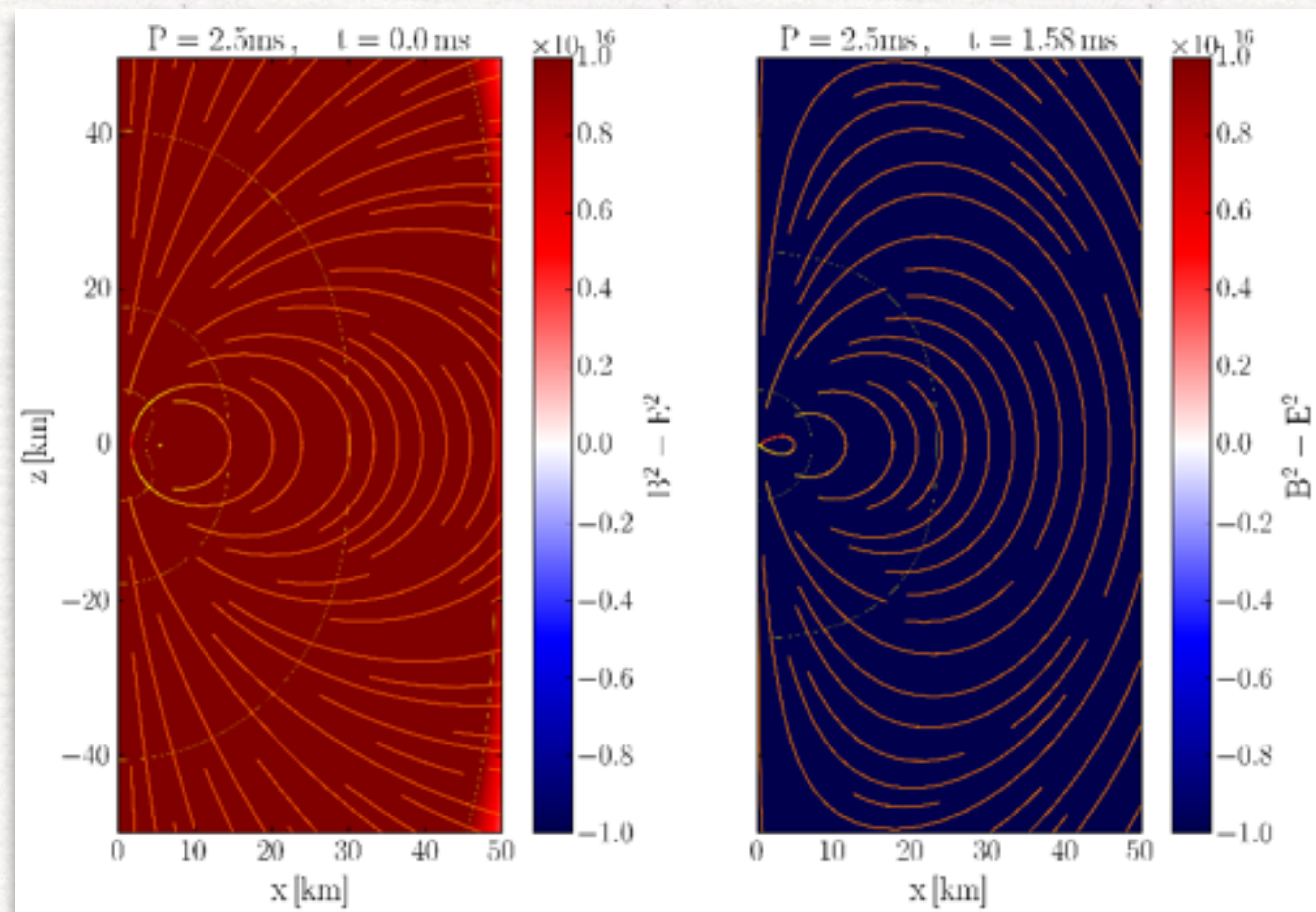
Poynting flux

Collapse to what?

Nathanail, Most, LR 2016

nonrotating magnetised star | **rotating magnetised star**





$$\frac{1}{2}F^{\mu\nu}F_{\mu\nu} = \boldsymbol{B}^2 - \boldsymbol{E}^2 = 0$$

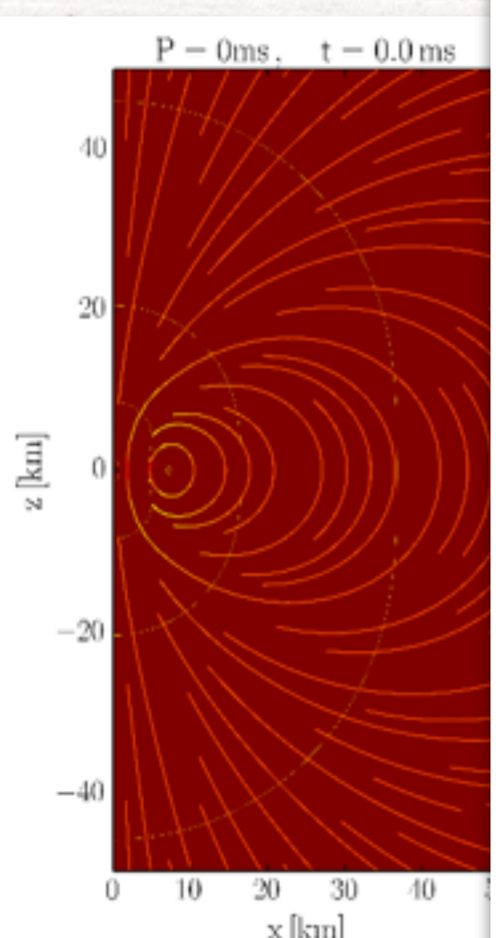
$$\frac{1}{2}F^{\mu\nu}F_{\mu\nu} = \boldsymbol{B}^2 - \boldsymbol{E}^2 < 0$$

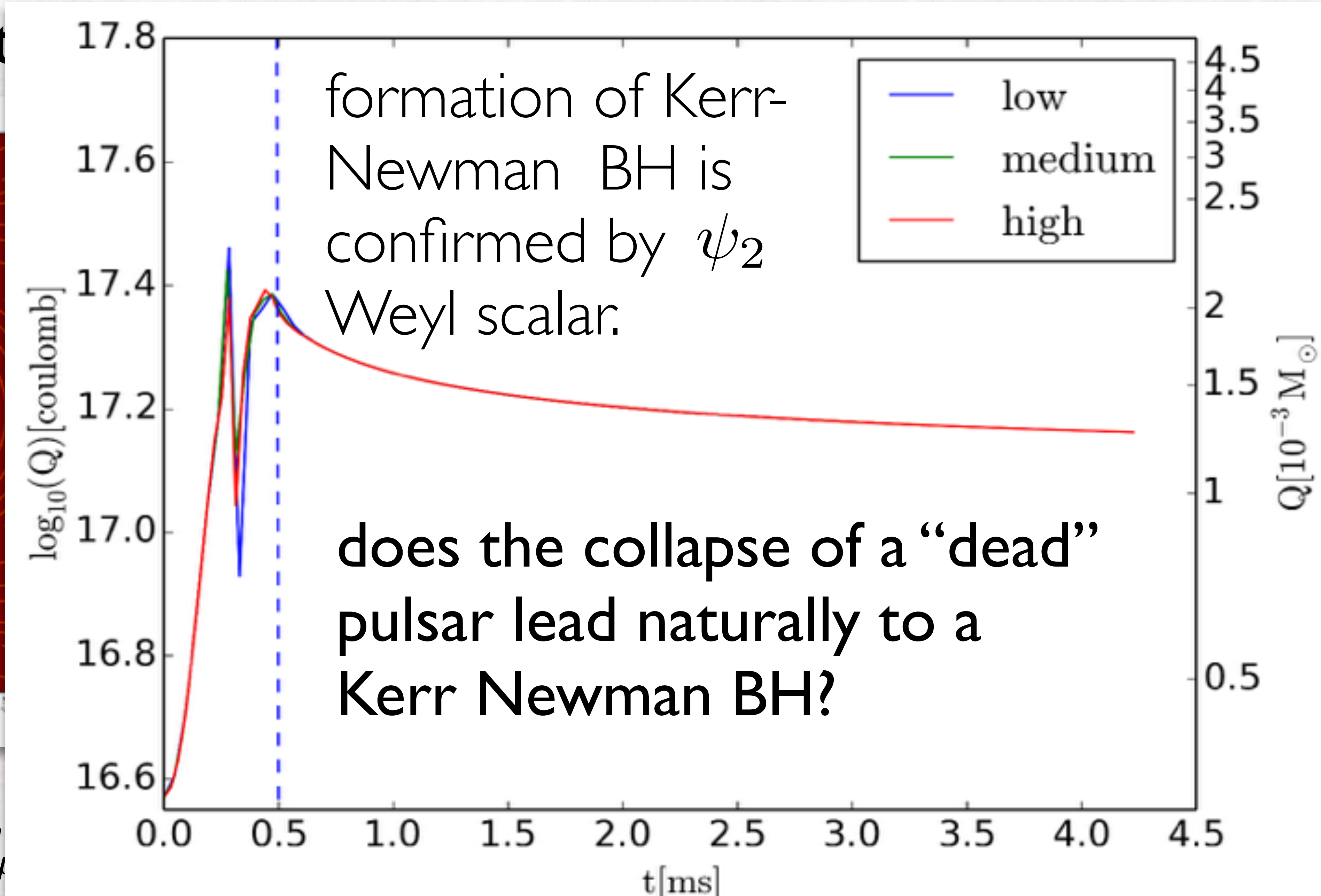
collapse to **Schwarzschild BH** | collapse to **Kerr-Newman BH**

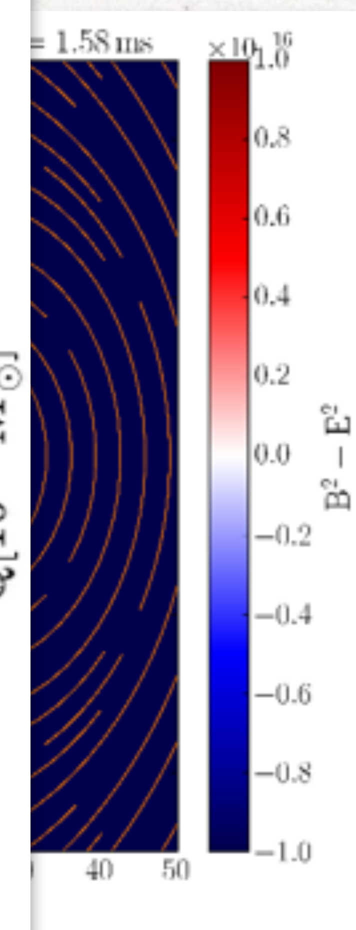
Collapse to what?

Nathanail, Most, LR 2016

nonrotat ... star





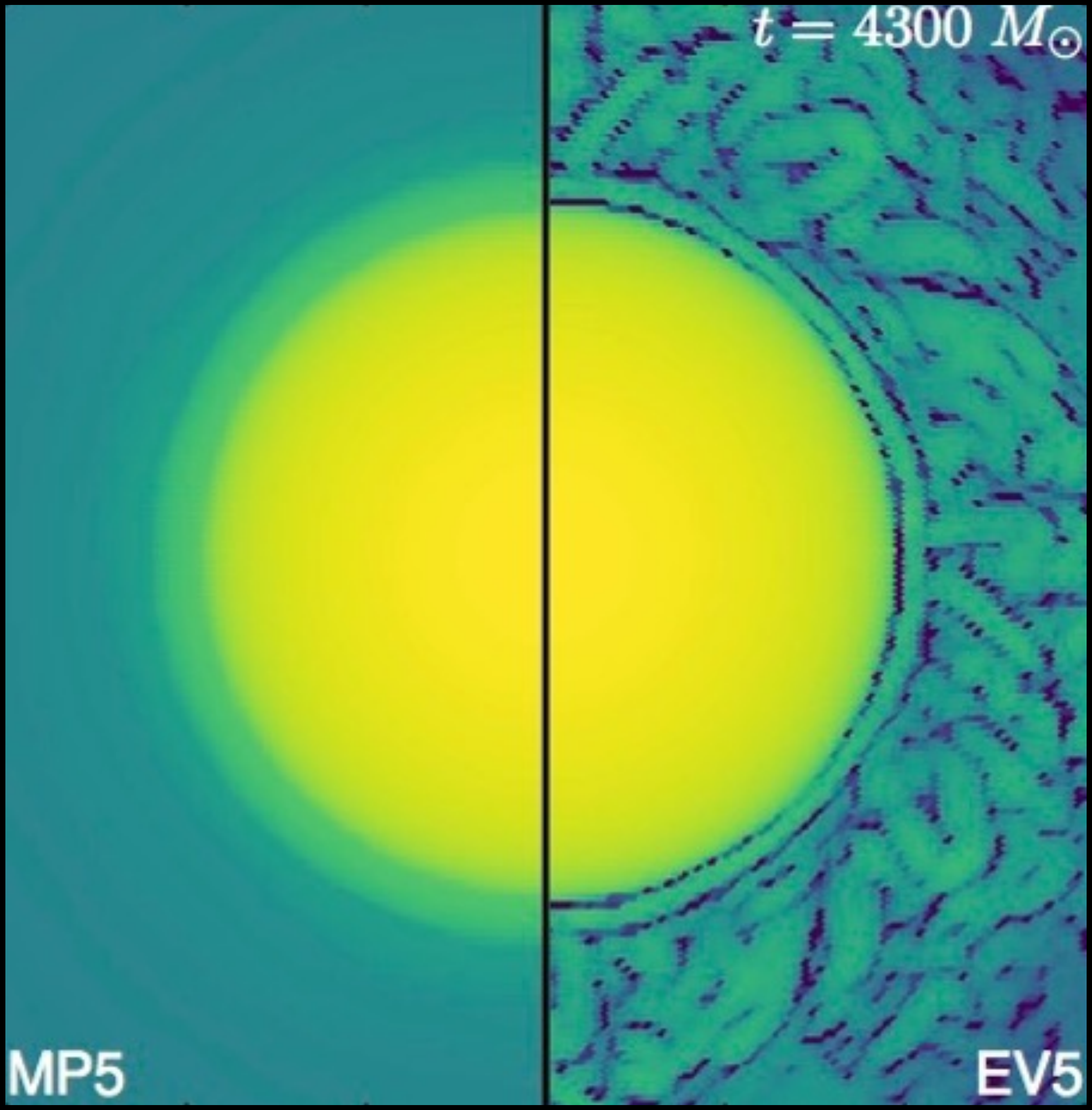


$\frac{1}{2}F^{\mu\nu}F_{\mu\nu}$ ... < 0

collapse to **Schwarzschild BH** collapse to **Kerr-Newman BH**

ELH: Entropy Limited Hydroynamics

Guercilena, Radice, LR 2016

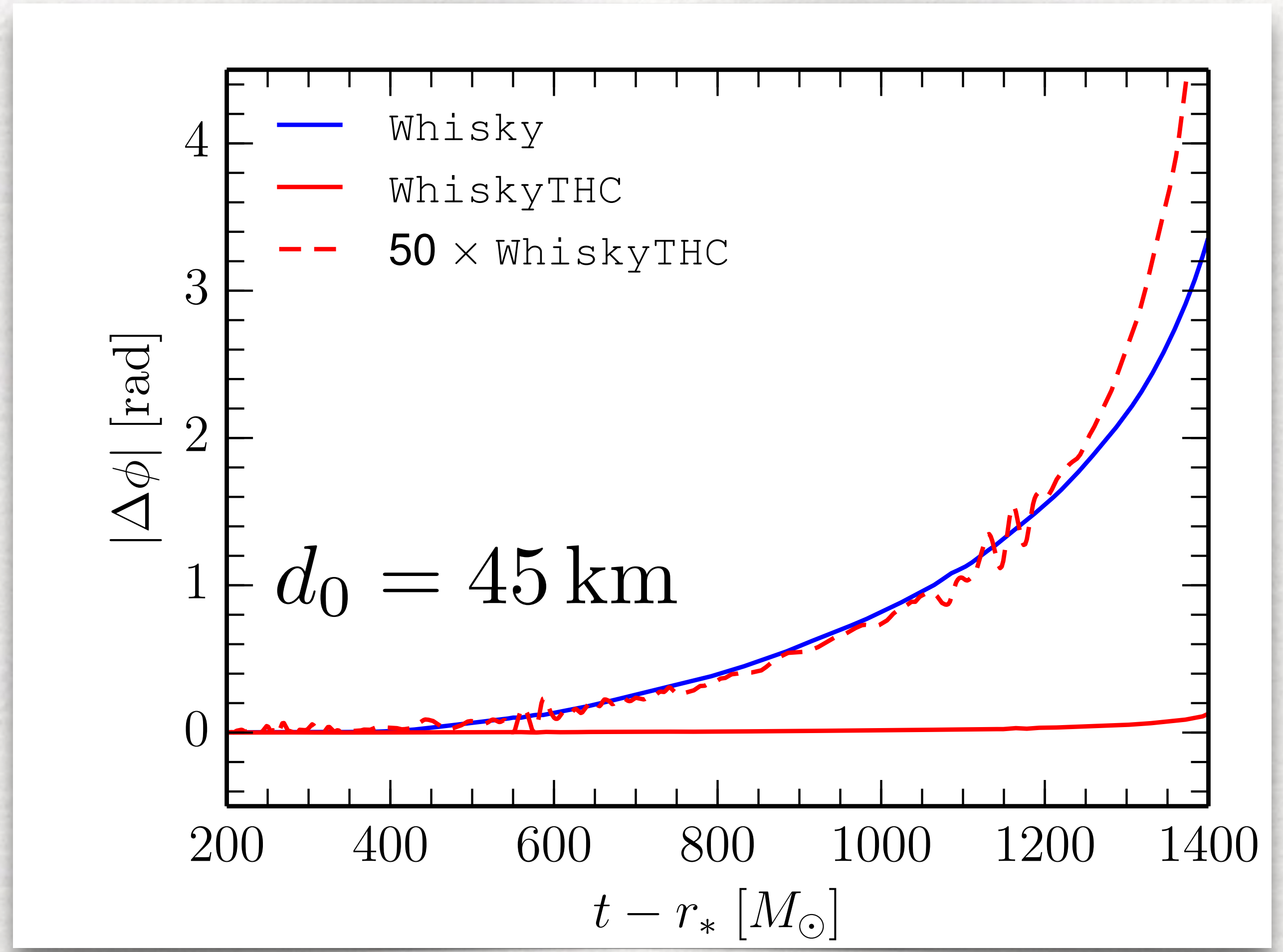


The need for high accuracy

- Inspiral is the "cleanest" part of the problem: PN predicts **point-particle dynamics + tidal corrections.**
- These corrections come at very high (5) PN order an are therefore intrinsically small but near the merger.
- Computing these corrections is not trivial! Numerical errors and tidal corrections yield the same dynamics: **merger occurs earlier.**
- "Clean" high-order convergence is difficult to achieve: stellar surface reduces order to be < 2.
- High-order accuracy is now possible also for binary NSs: WhiskyTHC has convergence of **3.2**. (Radice+2013)

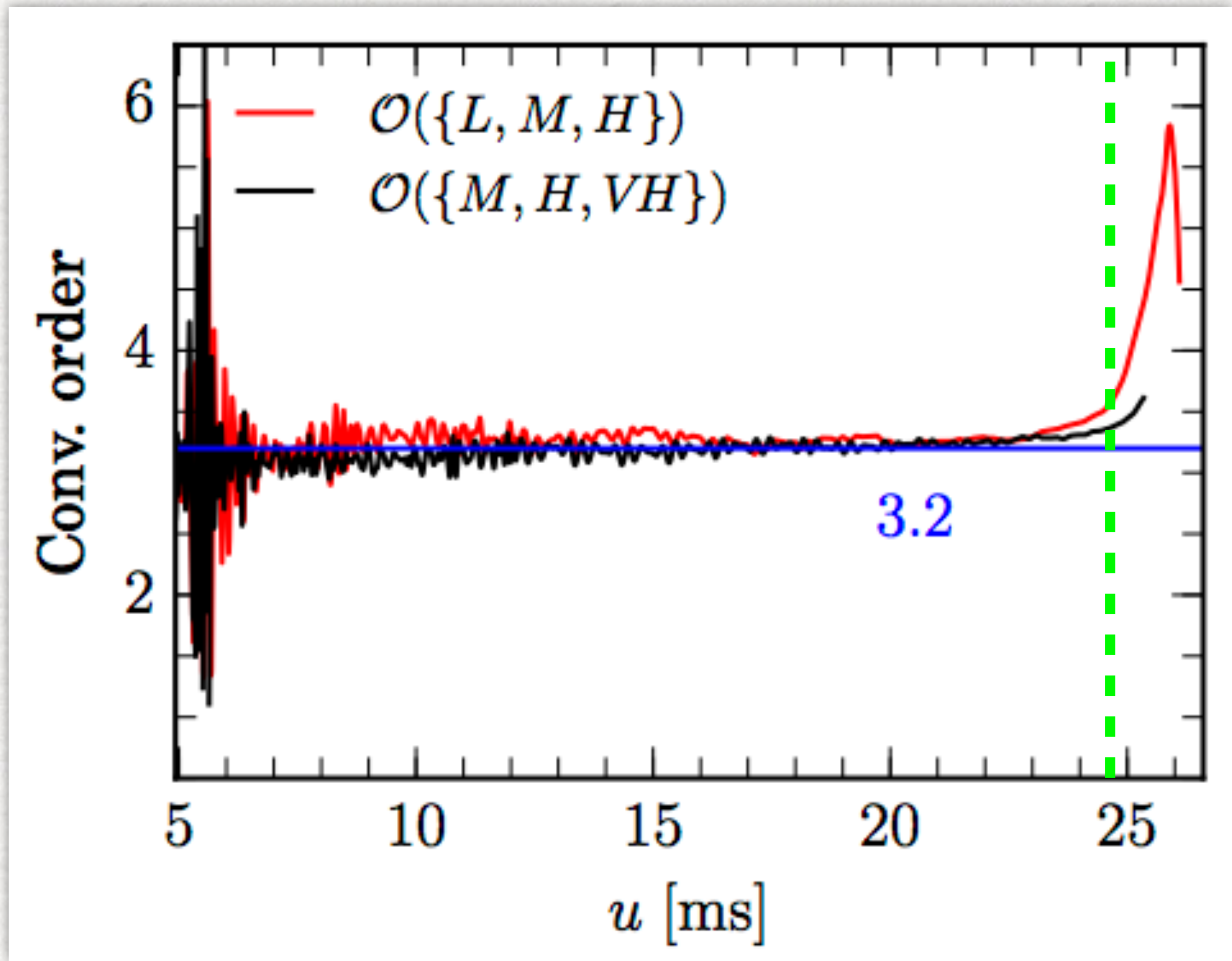
WhiskyTHC: a high-order hydro code

Radice+ (2013a,b)



Computational saving best appreciated comparing phase error at the same resolution:
Whisky (order ~1.8)
WhiskyTHC (order ~3.2)

Clean convergence is essential for reliable results.
Rarely figures of this type are shown for BNSs.
$\{L,M,H,VH\}$=$\{370, 295, 215, 147\}$ m



Entropy Limited Hydrodynamics: ELH

Guercilena, Radice, LR 2016

The equations of relativistic hydrodynamics are normally cast in a flux-conservative formulation of the type

$$\partial_t \boldsymbol{U} + \partial_i \boldsymbol{F}^i = \boldsymbol{S} \, .$$

WhiskyTHC uses finite-differences and a characteristics variables decomposition with Lax-Friedrichs flux-splitting for upwinding. The fluxes are reconstructed at high-order: 5 or 7.

In **ELH** the flux is expressed as a limiter, i.e.,

$$f_{i+1/2} = \theta f^{\mathrm{HO}}_{i+1/2} + (1-\theta) f^{\mathrm{LF}}_{i+1/2} \, ,$$

where $\theta \in [0,1]$, $f^{\mathrm{HO}}_{i+1/2}$ is the standard high-order flux and

$$f^{\mathrm{LF}}_{i+1/2} := \frac{1}{2}\left(f_i + f_{i+1}\right) - \frac{\alpha}{2}\left(u_i - u_{i+1}\right)$$

The limiter should be unity in smooth flows and small in regions of large discontinuities, where entropy is generated

$$\theta = \min[\tilde{\theta}, 1 - \nu]$$

An effective definition is therefore

$$\nu = \max[c_1 |\mathcal{R}|, \ c_2 \lambda]$$

where

$$\mathcal{R} := \nabla_\mu (s \rho u^\mu) \geq 0$$

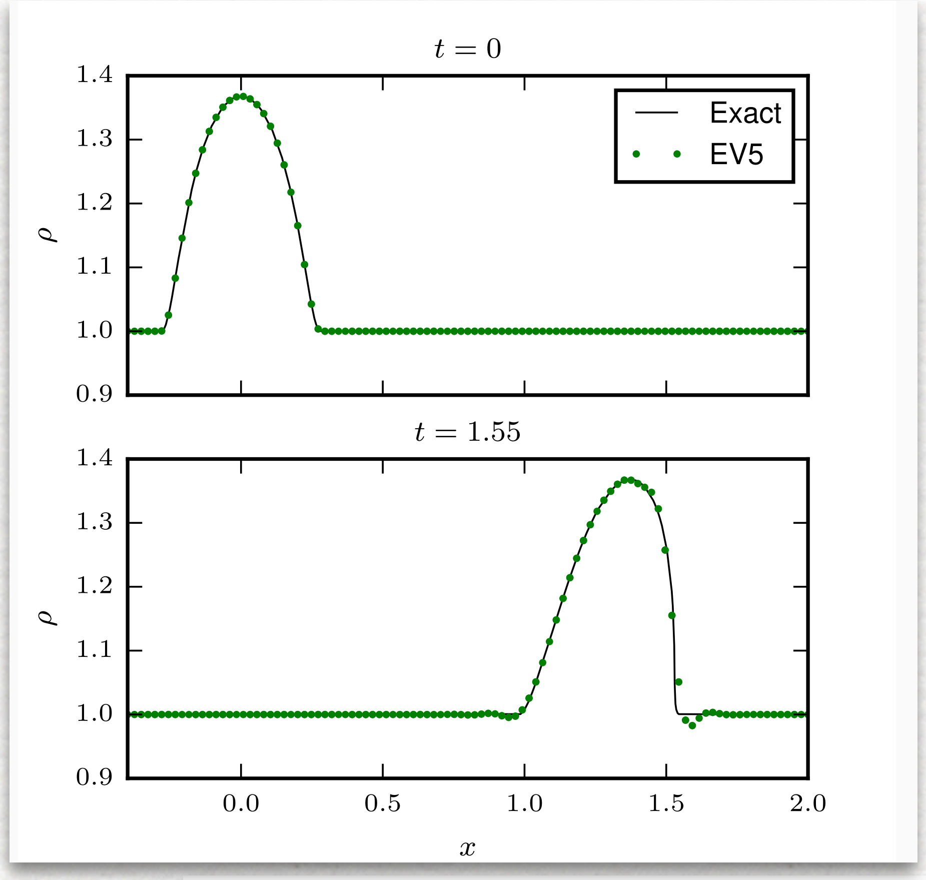
and s the specific entropy.

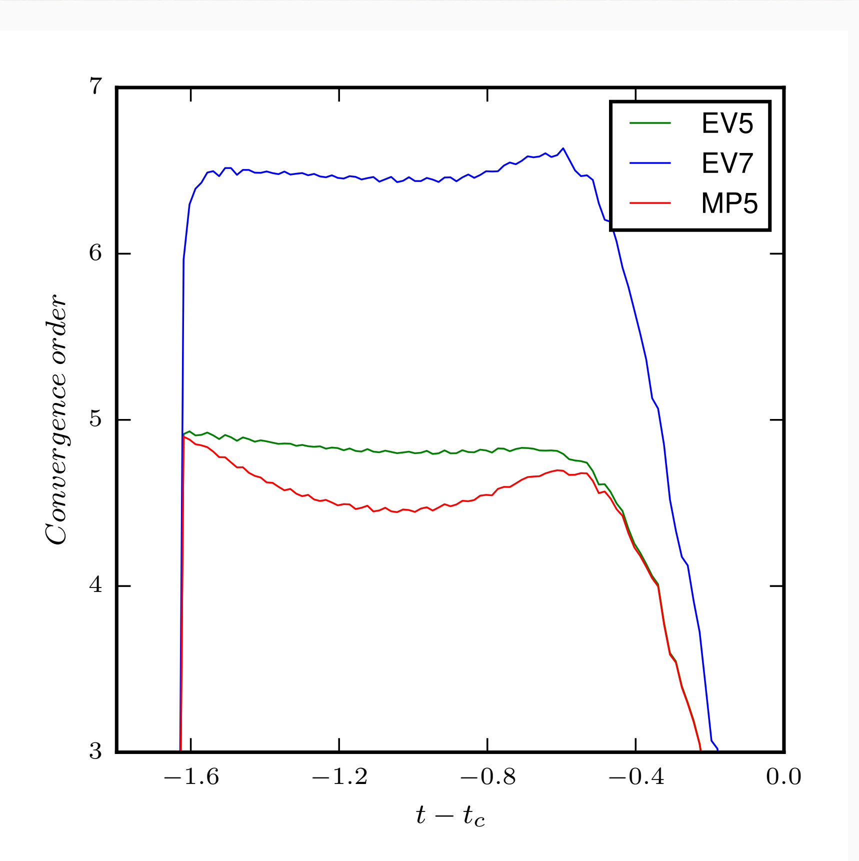
In other words, the flux is limited in those very localised regions where entropy is generated, i.e. **at shocks.**

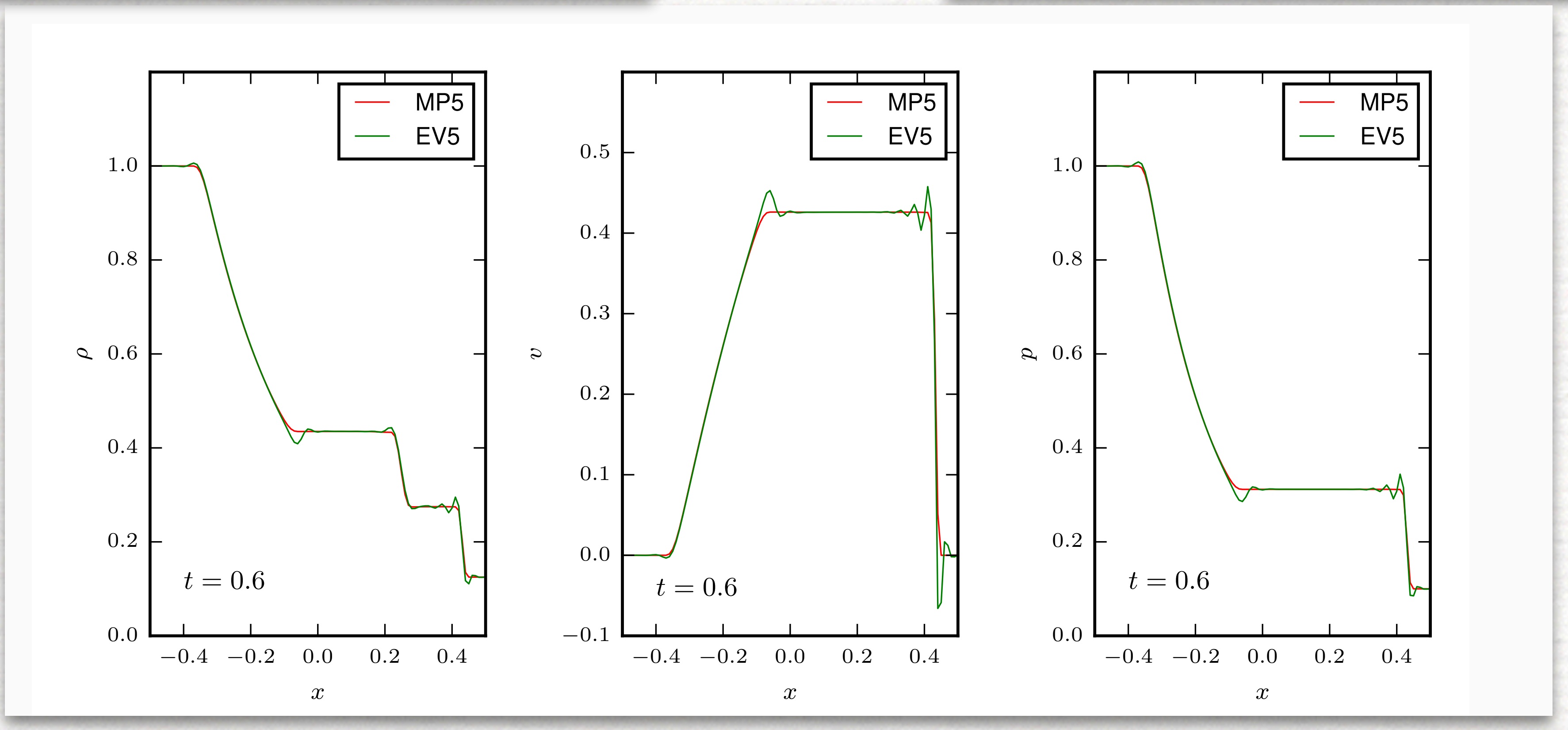
The advantages are: **accuracy** (HO), **speed** (FD), **simplicity and extendability.**

Does it work?

Guercilena, Radice, LR 2016

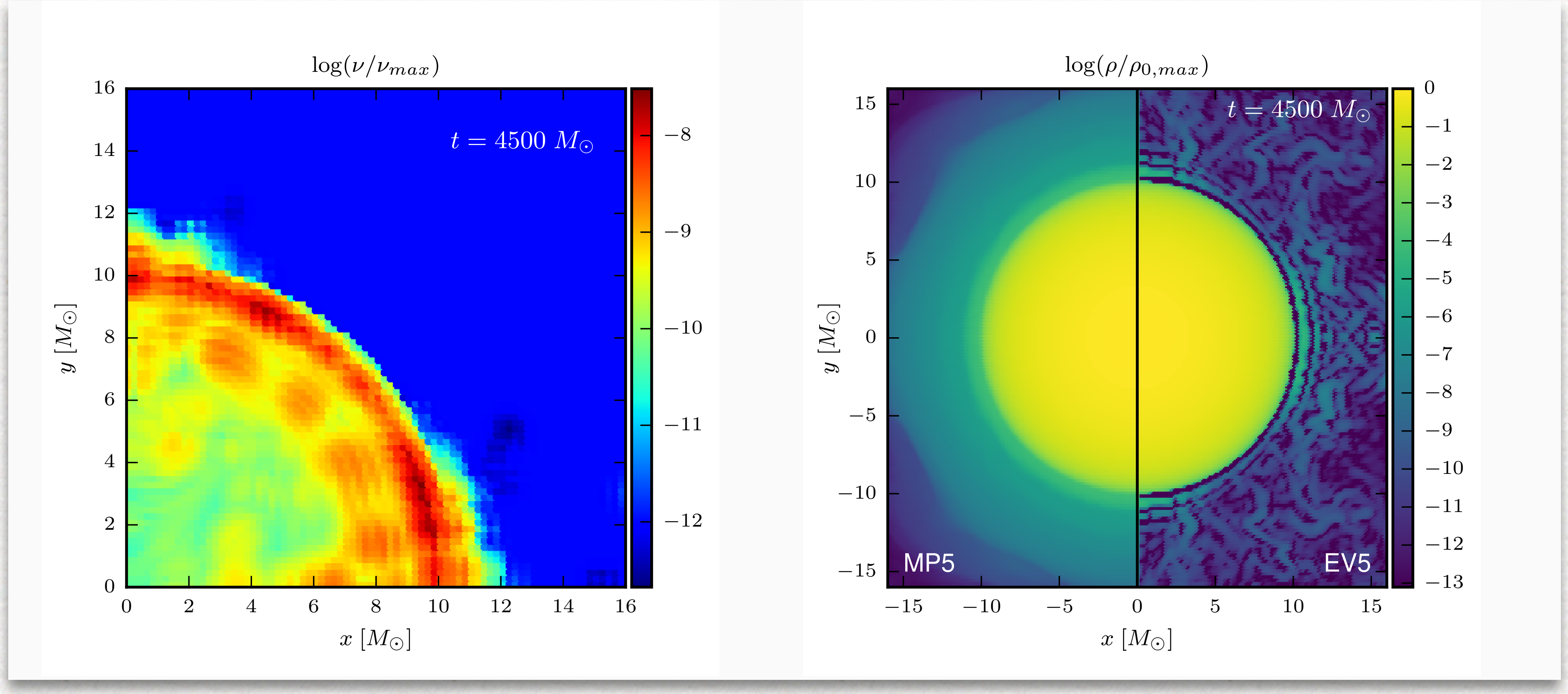


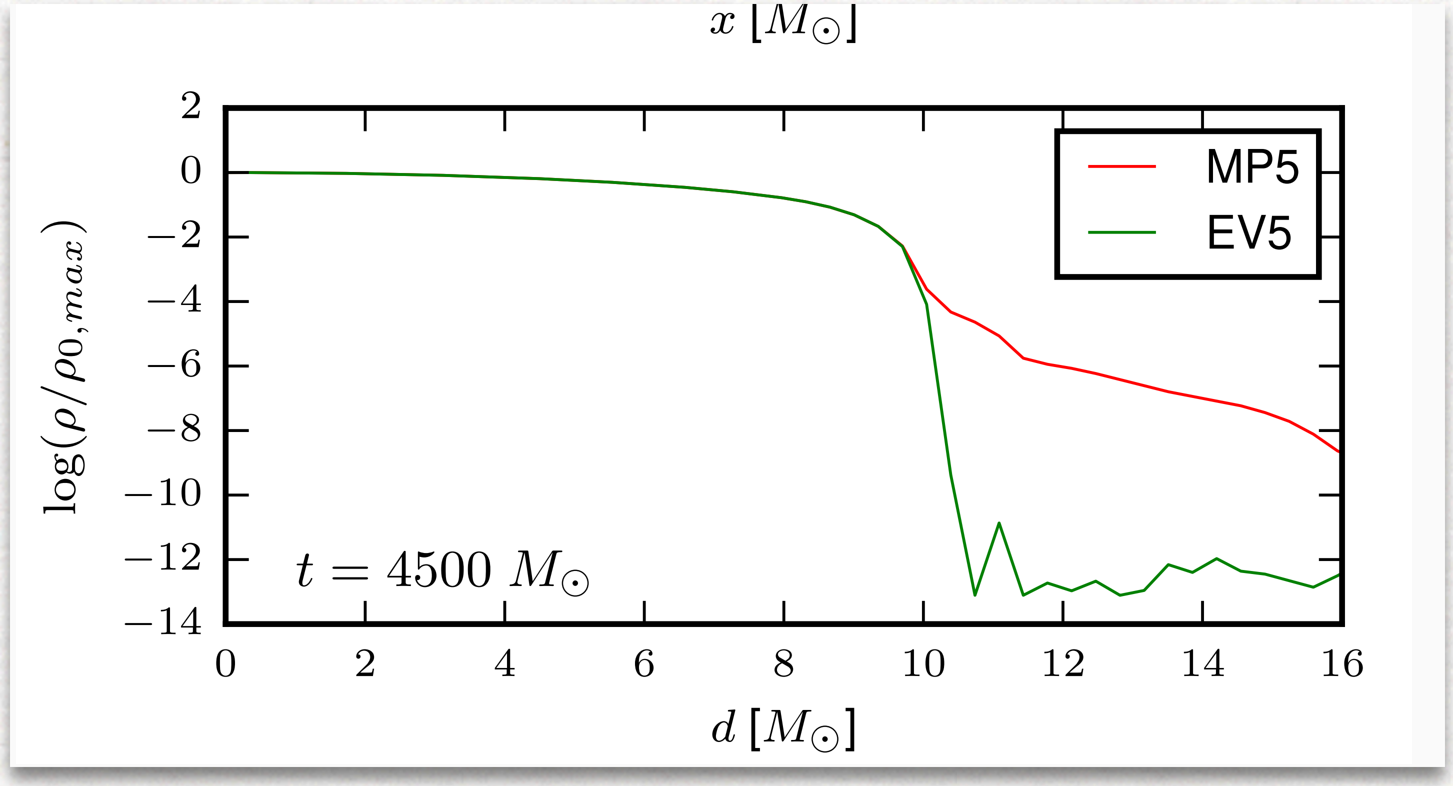




Does it work?

Guercilena, Radice, LR 2016





An exhaustive series of tests in full GR shows that ELH provides all of the advantages expected.

Conclusions

- ✴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
- ✴**Blitzars** are a simple manner to obtain an FRB phenomenology but may not be answer to the riddle.
- ✴ **Eccentric** binaries are rare but with larger ejected matter and macronova emission. “high-*A*” nucleosynthesis very robust.
- ✴ **Entropy Limited Hydrodynamics** is promising new approach to relativistic hydrodynamics and may become a new standard.