Merging of neutron star binaries in full general relativity

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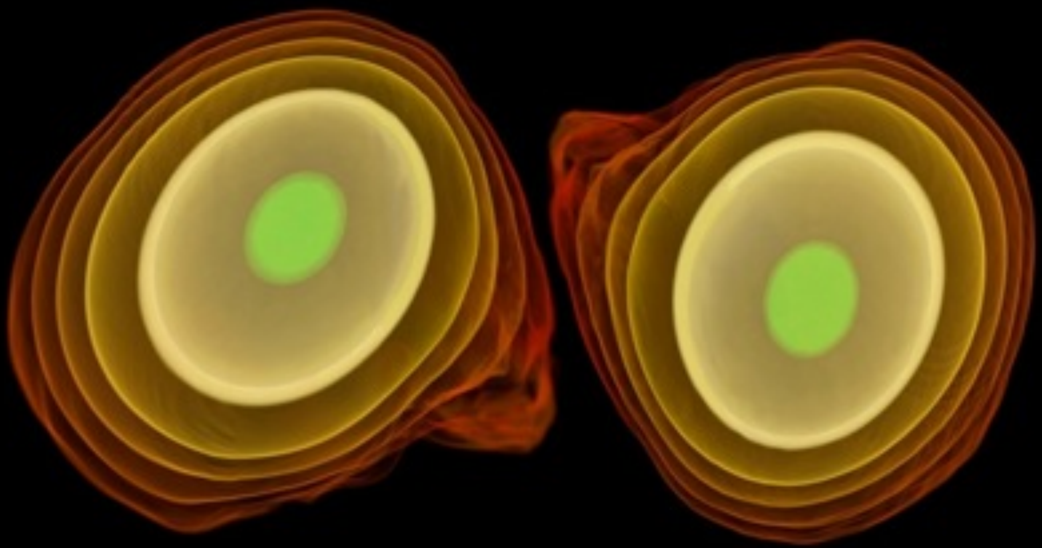


Institute of Nuclear Theory
INT Program INT-14-2a
Seattle, 29.07.14

Plan of the talk

- ✴ broad-brush picture
  - inspiral
  - merger and post-merger
- ✴ what we think we understand about BNSs
- ✴ what we* don't quite understand about BNSs
  - magnetic fields
  - neutrinos
  - ejecta and their evolution

*: LR

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:

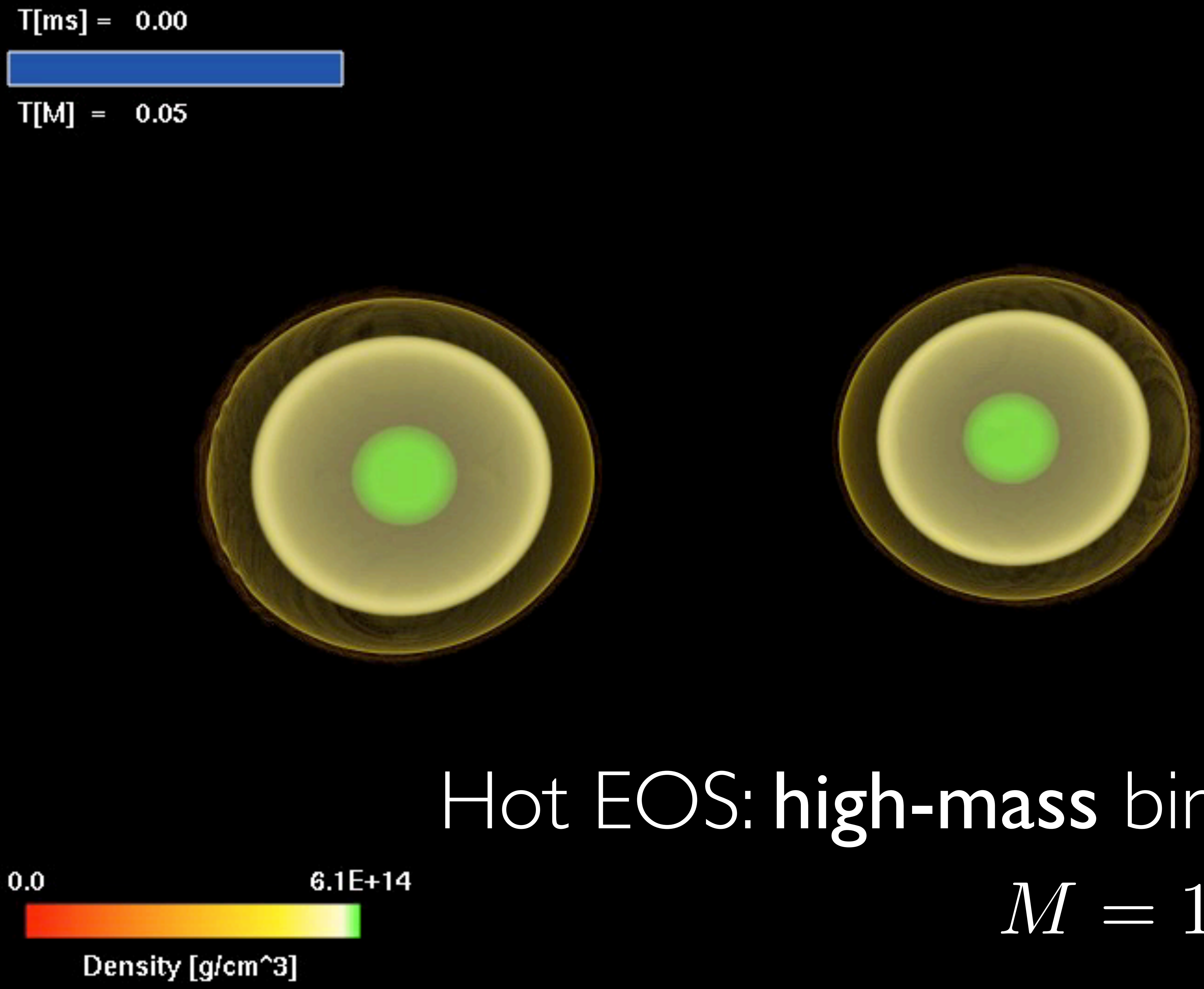
NS + NS → HMNS + **... ?** → BH + torus + **... ?** → BH

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)

Animations: Kaehler, Giacomazzo, Rezzolla



Hot EOS: **high-mass** binary

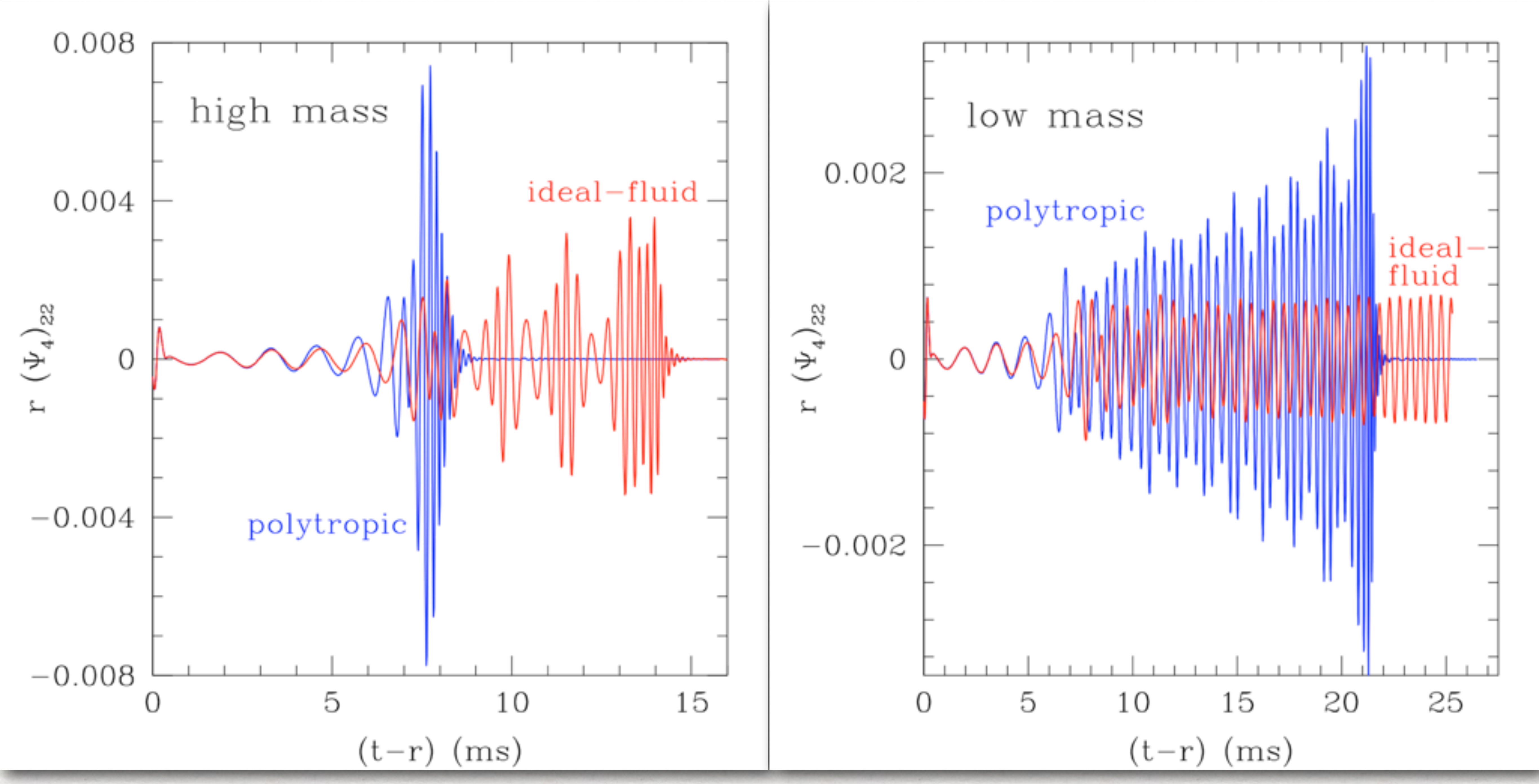
$$M = 1.6\,M_\odot$$

“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

Imprint of the EOS: **hot** vs **cold**



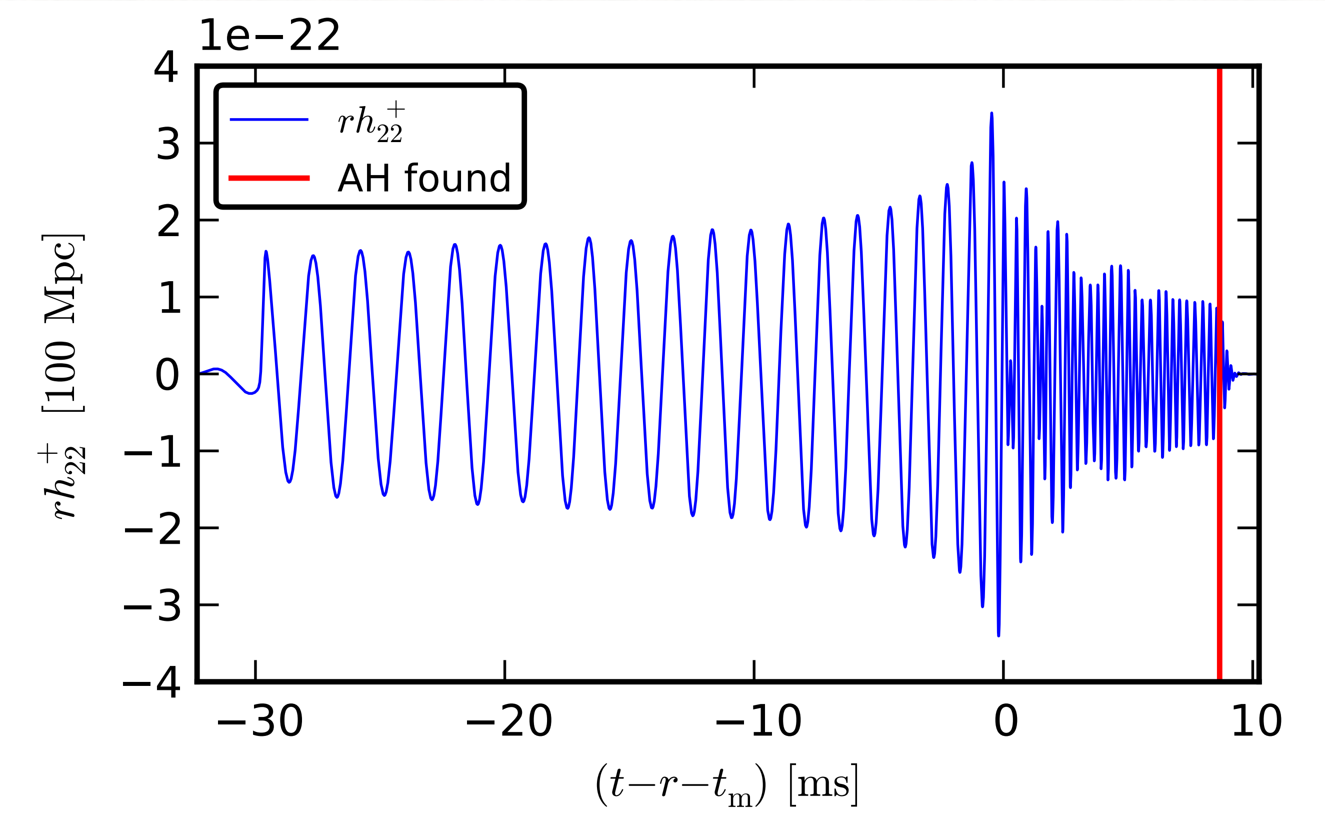
Once detected, GWs will be the Rosetta stone to decipher the NS interior (more later)

Same (qualitative) picture with nuclear hot EOS

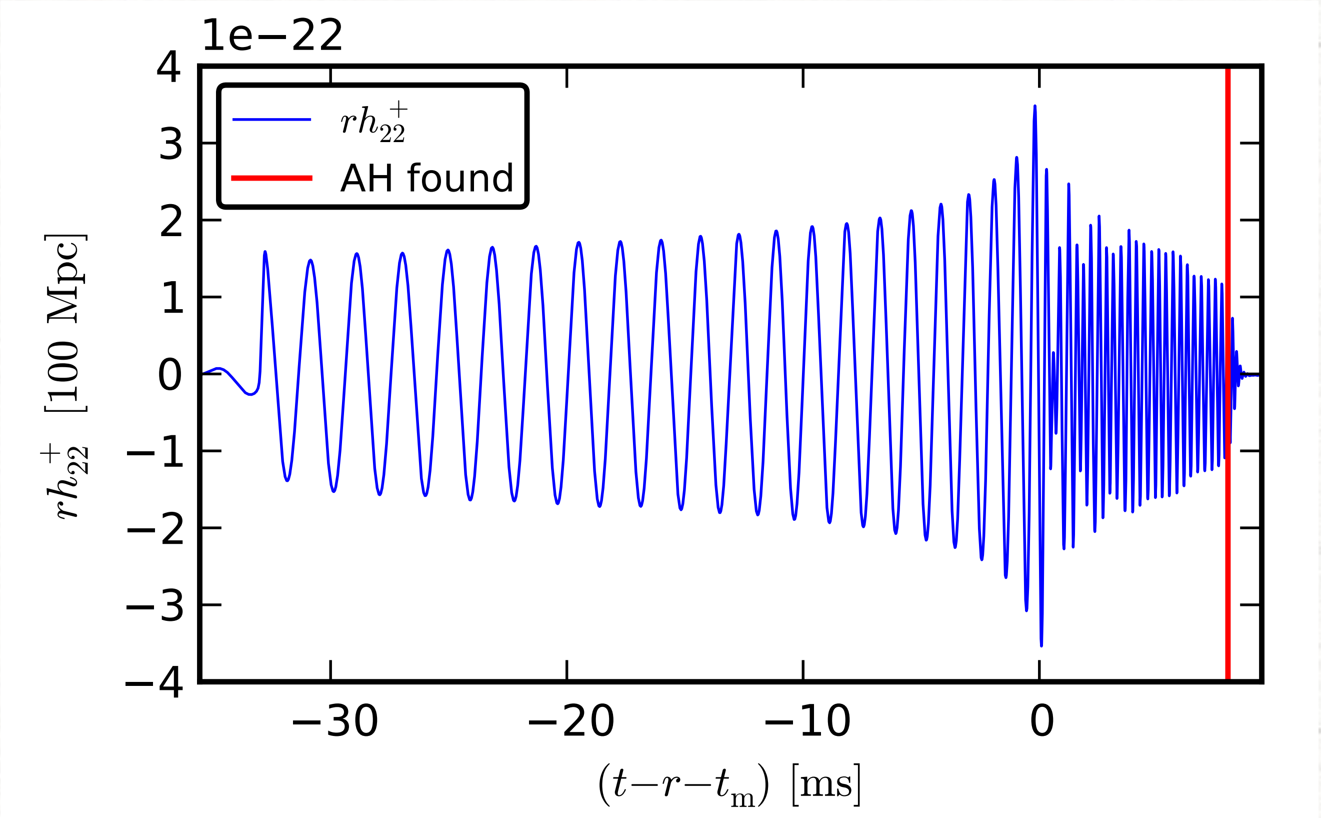
Galeazzi+ (2014, in prep.)

We have extended analysis to account for nuclear hot EOS (LS220, SHT) and qualitative picture remains very robust.

Addition of (aligned) spins also does not introduce dramatic changes and physics which has not been already studied with BBHs.



LS220, s=0



LS220, s=0.5

“merger → HMNS → BH + torus”

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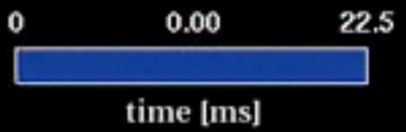
  a binary with an EOS with large thermal capacity (ie hotter after merger) will have more pressure support and collapse later
- **differences induced by MASS ASYMMETRIES:**
  tidal disruption before merger; may lead to prompt BH

Animations: Giacomazzo, Koppitz, LR

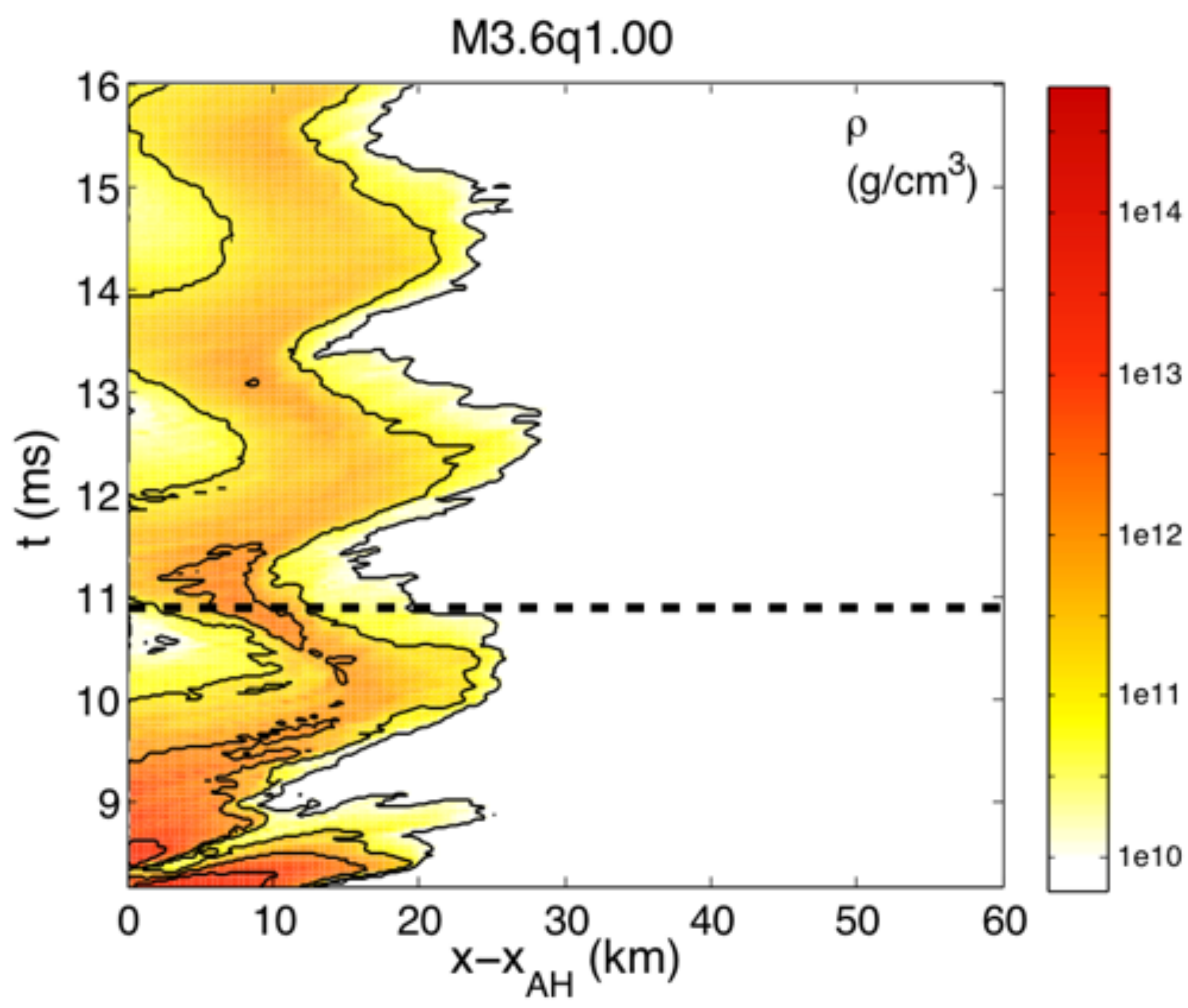
Total mass : $3.37\,M_{\odot}$; mass ratio :0.80;

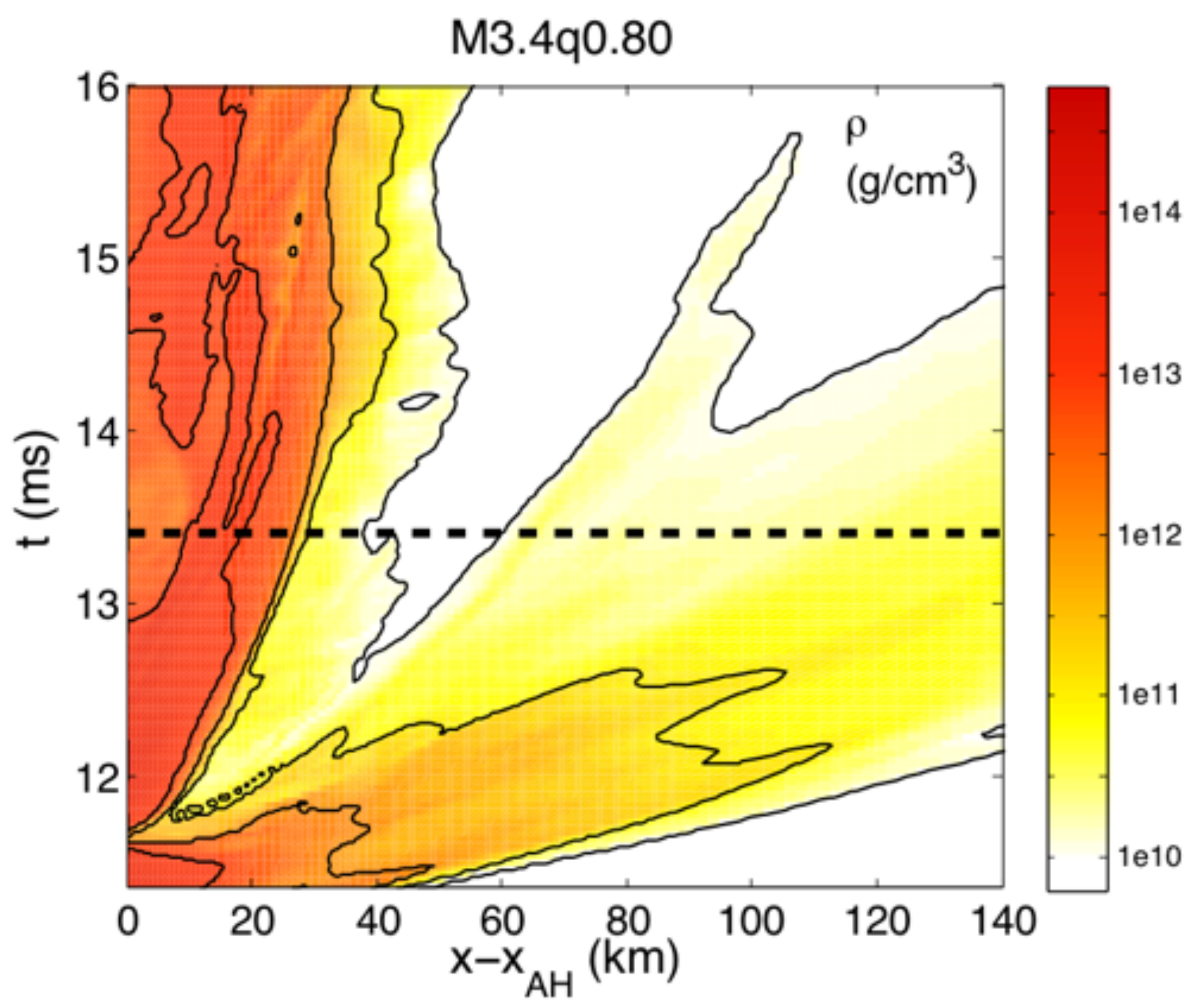


Torus properties: density

Rezzolla+ (2010)

spacetime diagram of rest-mass density along x-direction



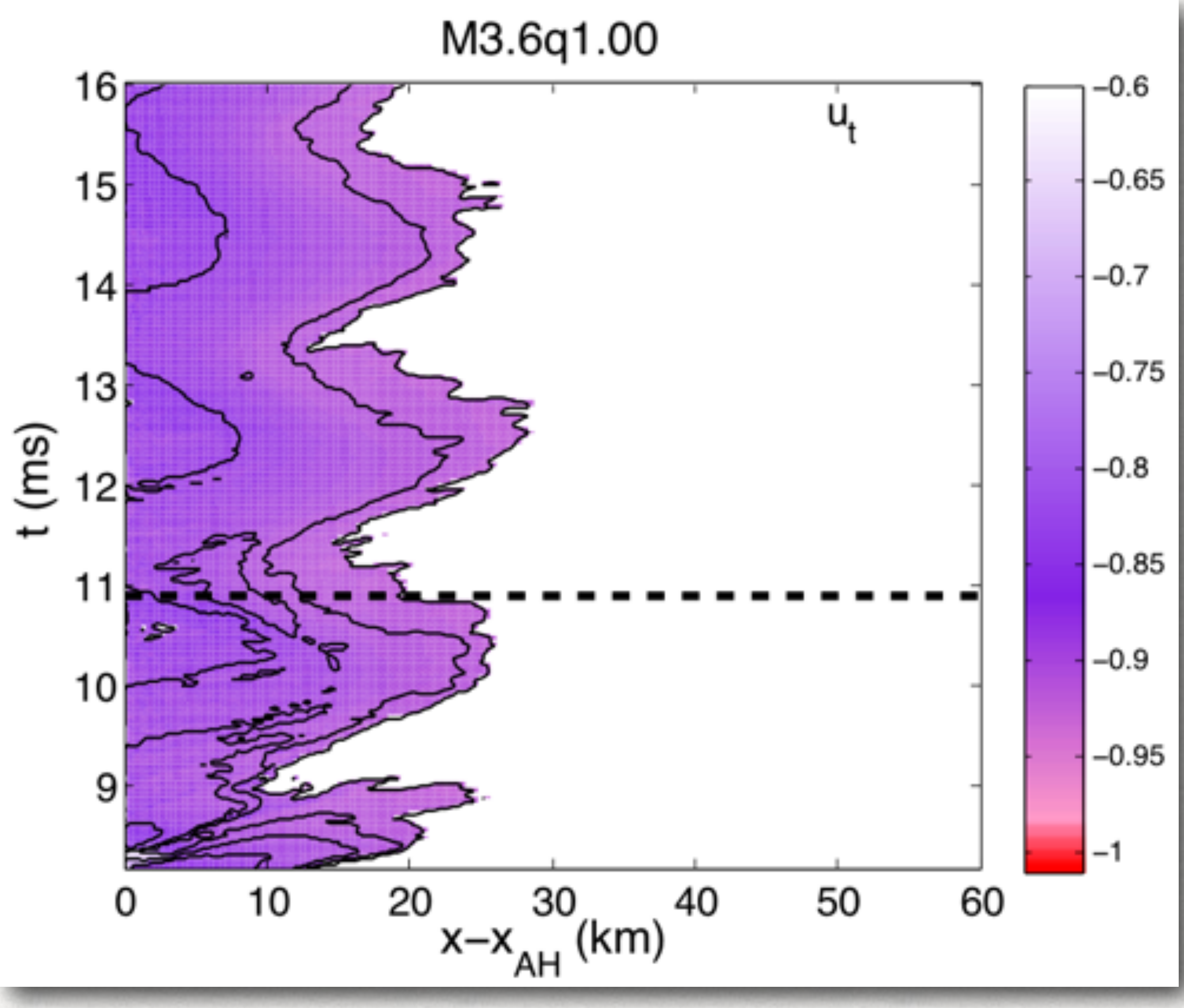


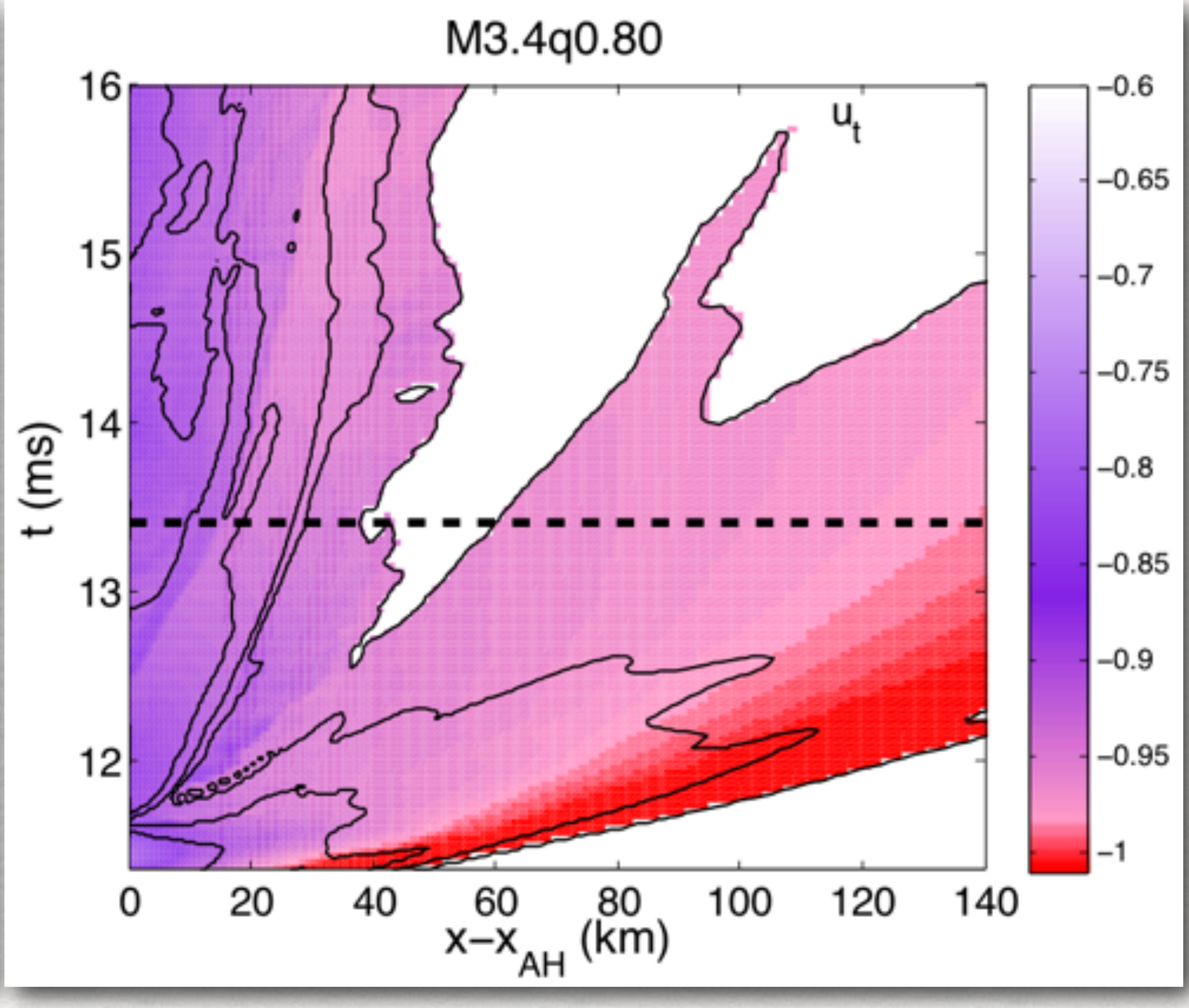
equal mass binary: note the periodic accretion and the compact size; densities are not very high

unequal mass binary: note the continuous accretion and the very large size and densities (temperatures)

Torus properties: bound matter

spacetime diagram of local fluid energy: u_t

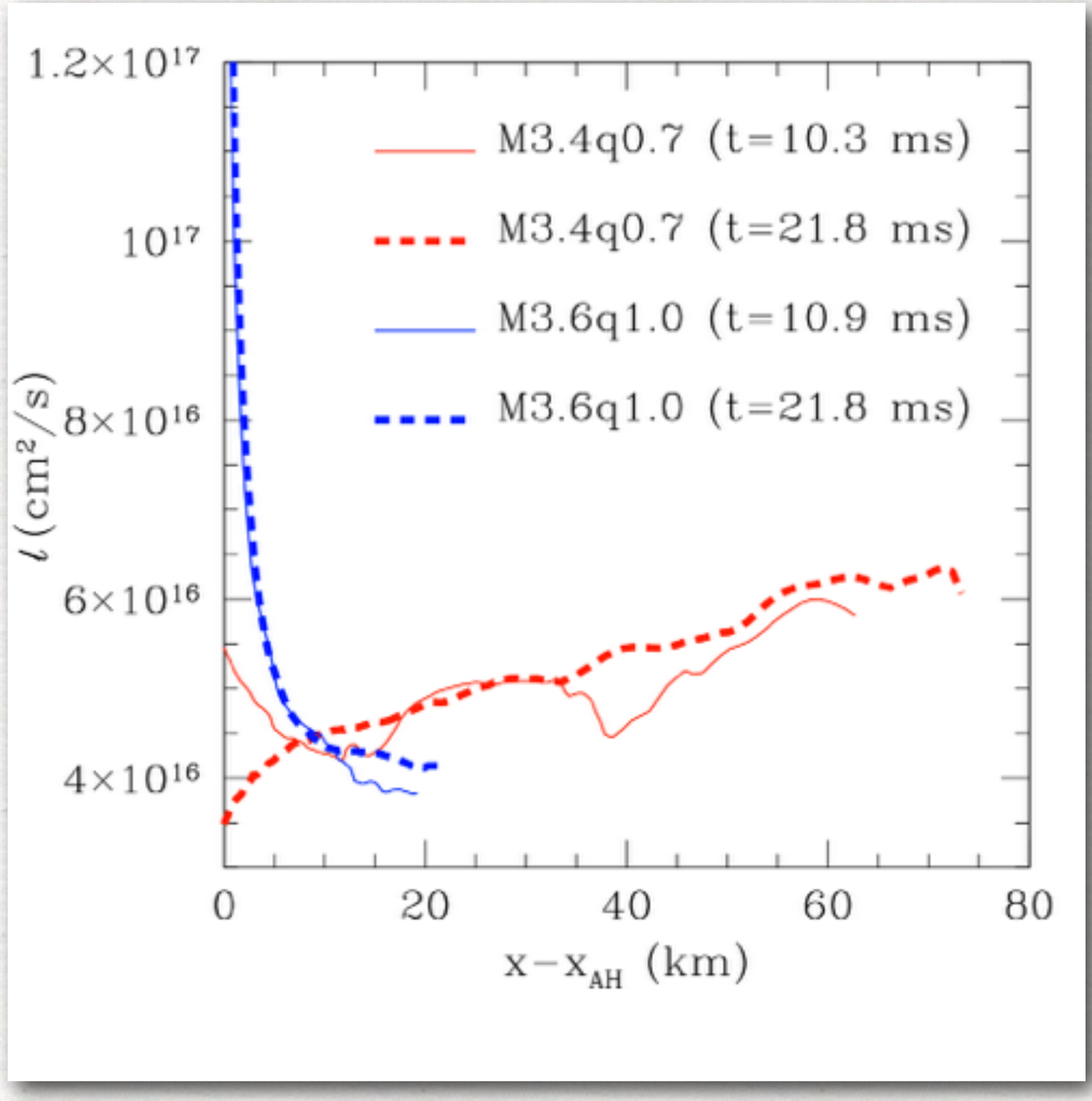


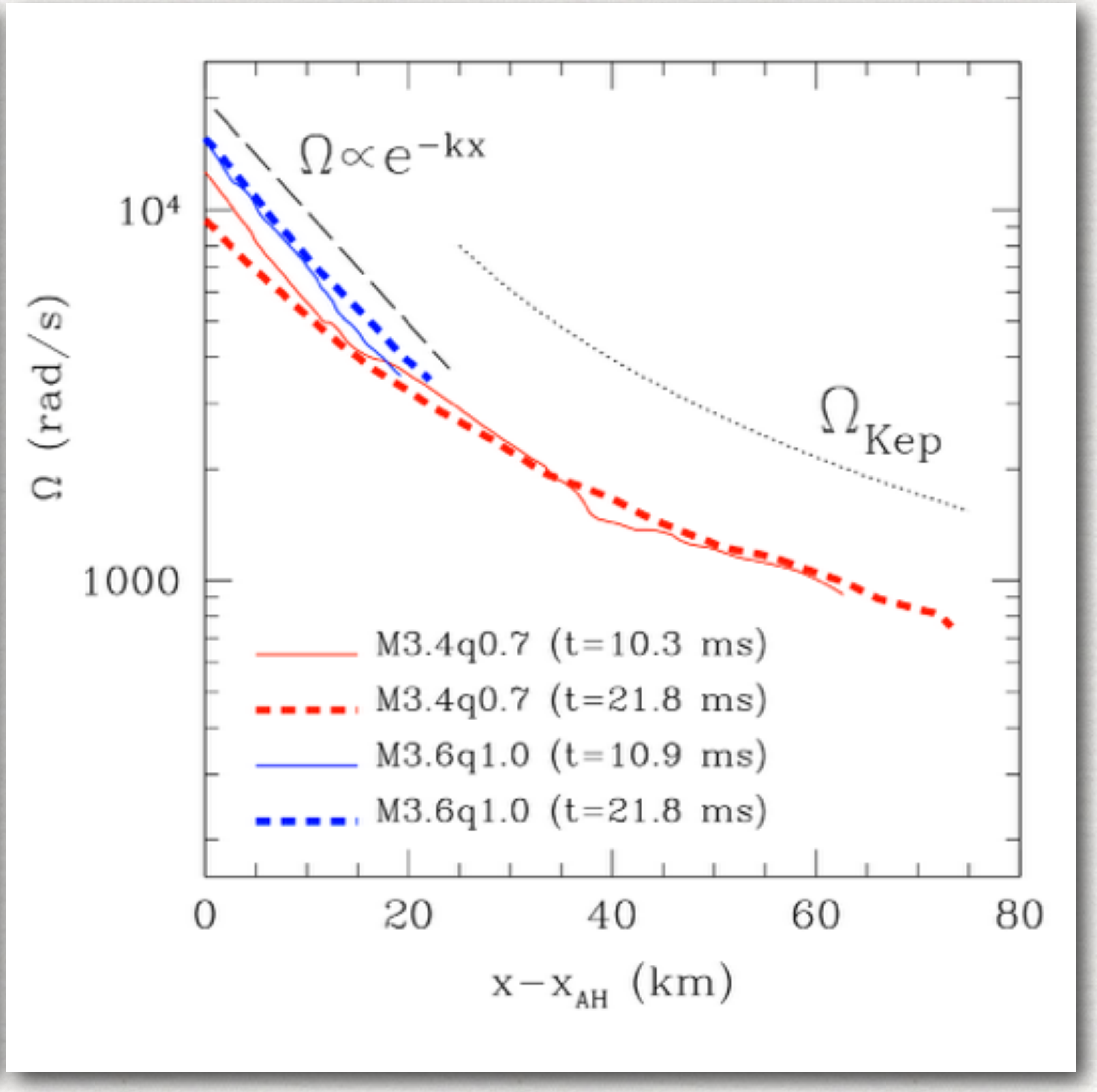


equal mass : all matter is clearly bound, i.e. $u_t < -1$

Note the accretion is quasi-periodic

unequal mass: some matter is unbound while other is ejected at large distances (cf. scale). In these regions r-processes can take place



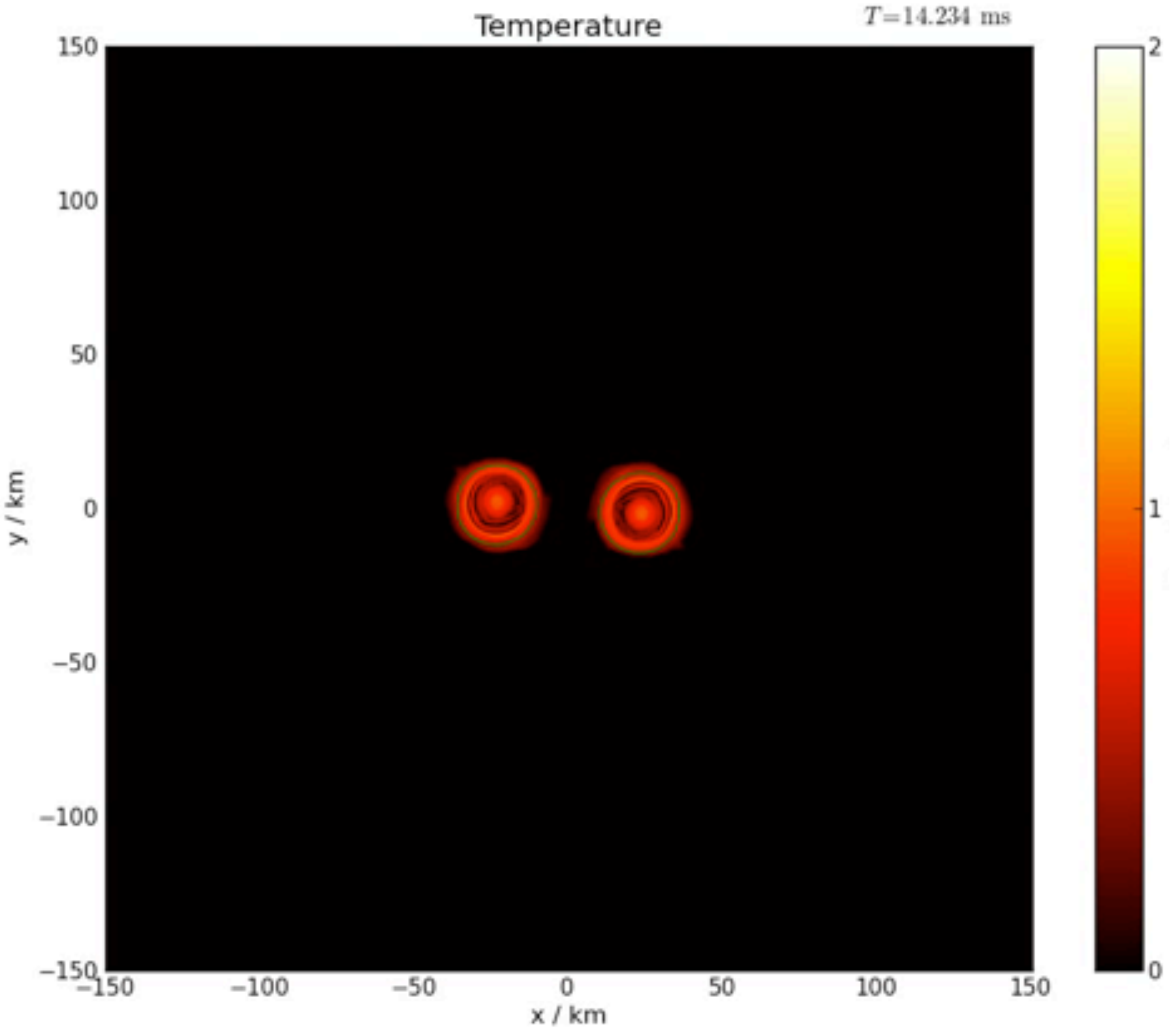


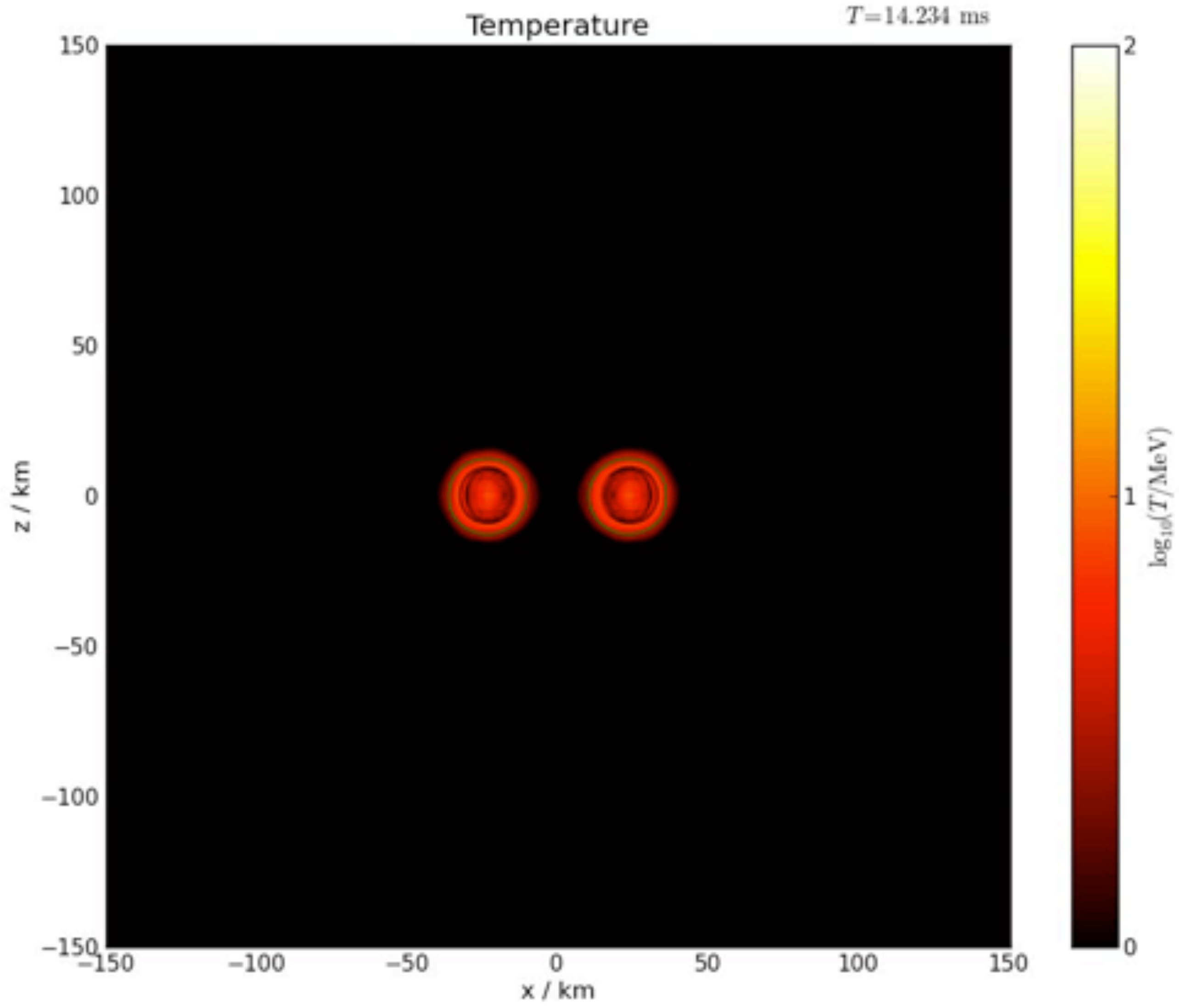
- specific angular momentum has very different behaviour in the two cases: $d\ell/dx \geq 0$ for stability
- equal-mass binary has exponential differential rotation while the unequal-mass is essentially Keplerian

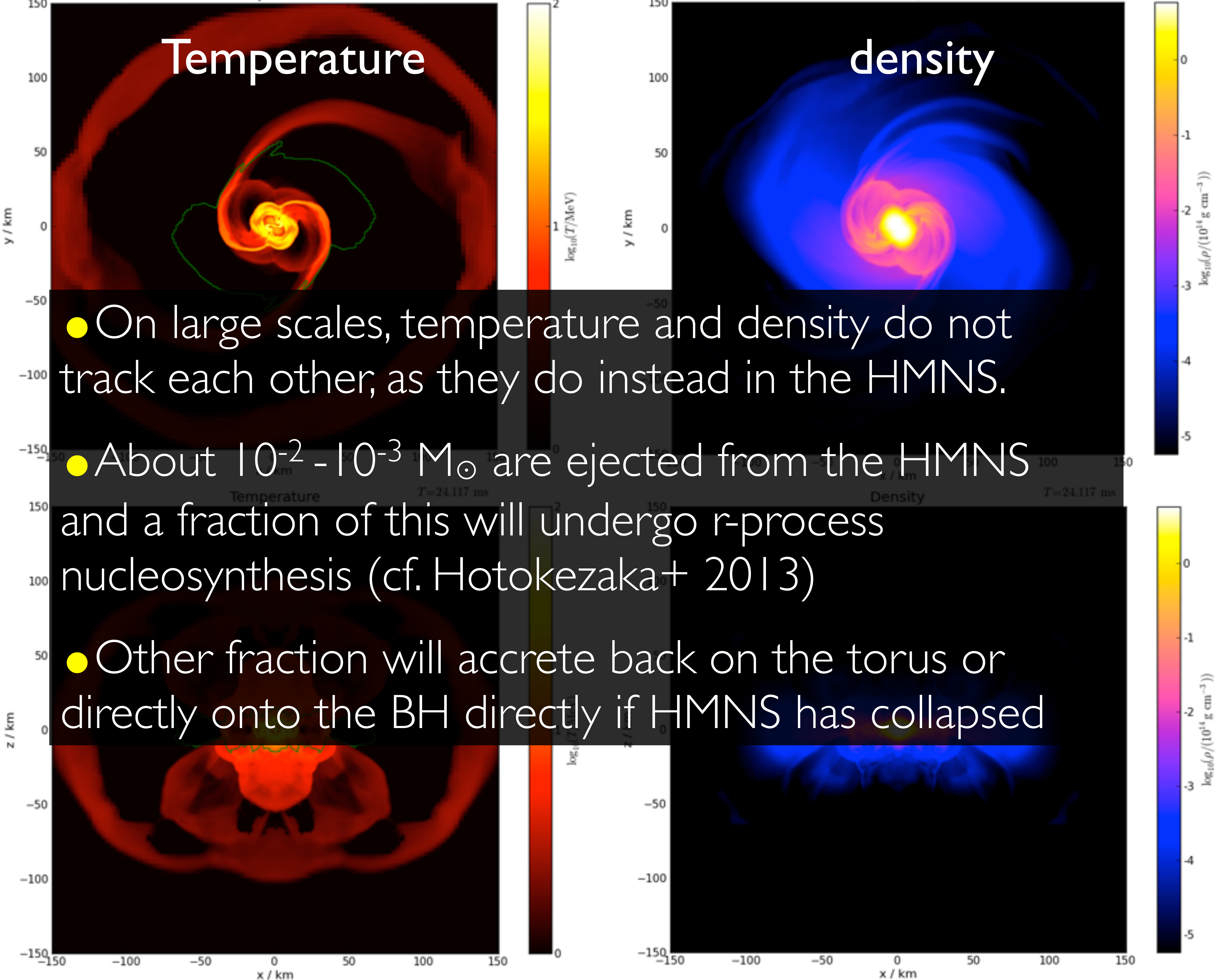
Extending the work to hot realistic EOSs

Galeazzi+ (2014, in prep.)

Particularly interesting are the evolutions of the **temperature** and of the **electron fraction**







- On large scales, temperature and density do not track each other, as they do instead in the HMNS.
- About 10^{-2} - 10^{-3} $M_\odot$ are ejected from the HMNS and a fraction of this will undergo r-process nucleosynthesis (cf. Hotokezaka+ 2013)
- Other fraction will accrete back on the torus or directly onto the BH directly if HMNS has collapsed

“merger → HMNS → BH + torus”

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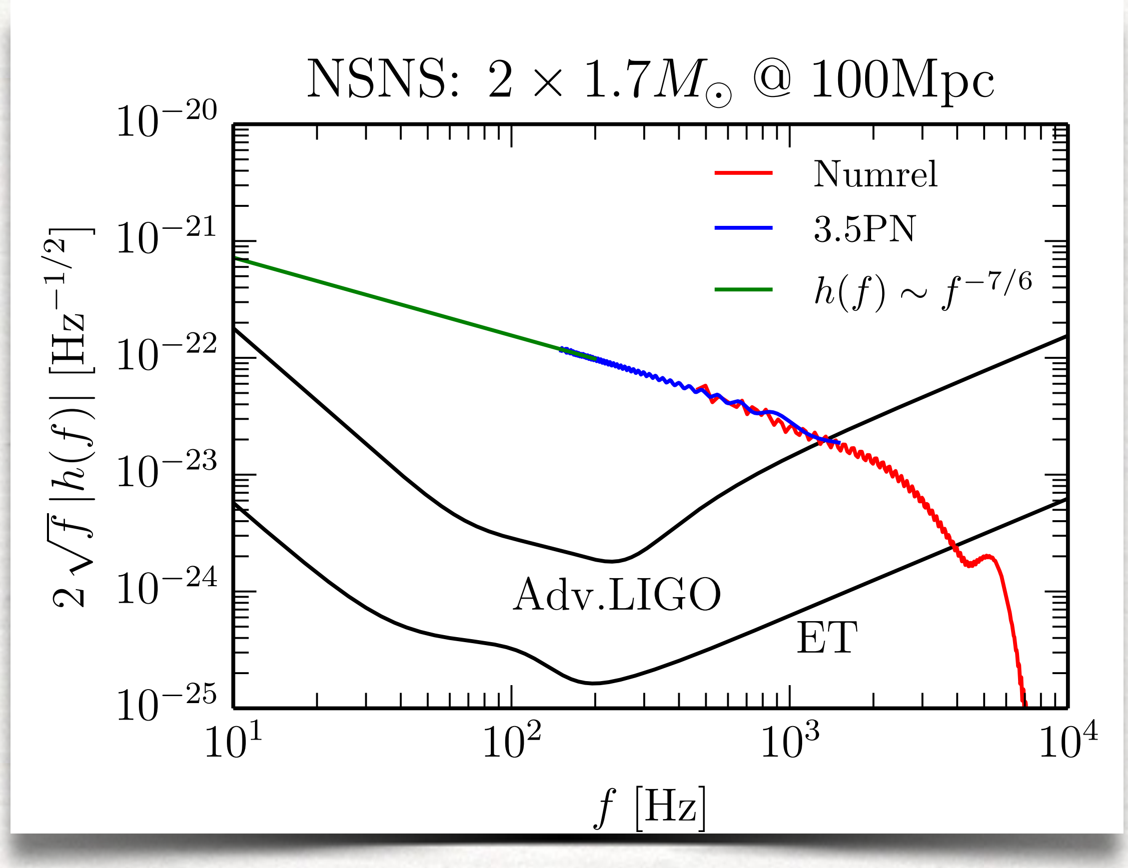
- **differences induced by MASS ASYMMETRIES:**
  tidal disruption before merger; may lead to prompt BH
- **differences induced by MAGNETIC FIELDS:**
  the angular momentum redistribution via magnetic braking or MRI can increase/decrease time to collapse
- **differences induced by RADIATIVE PROCESSES:**
  radiative losses will alter the equilibrium of the HMNS

Do we understand the inspiral?

It's the "cleanest" part of the problem: PN predicts **point-particle dynamics + tidal corrections.** Can we measure them?



Not trivial! Numerical errors and tidal corrections yield the same dynamics: **merger occurs earlier.**

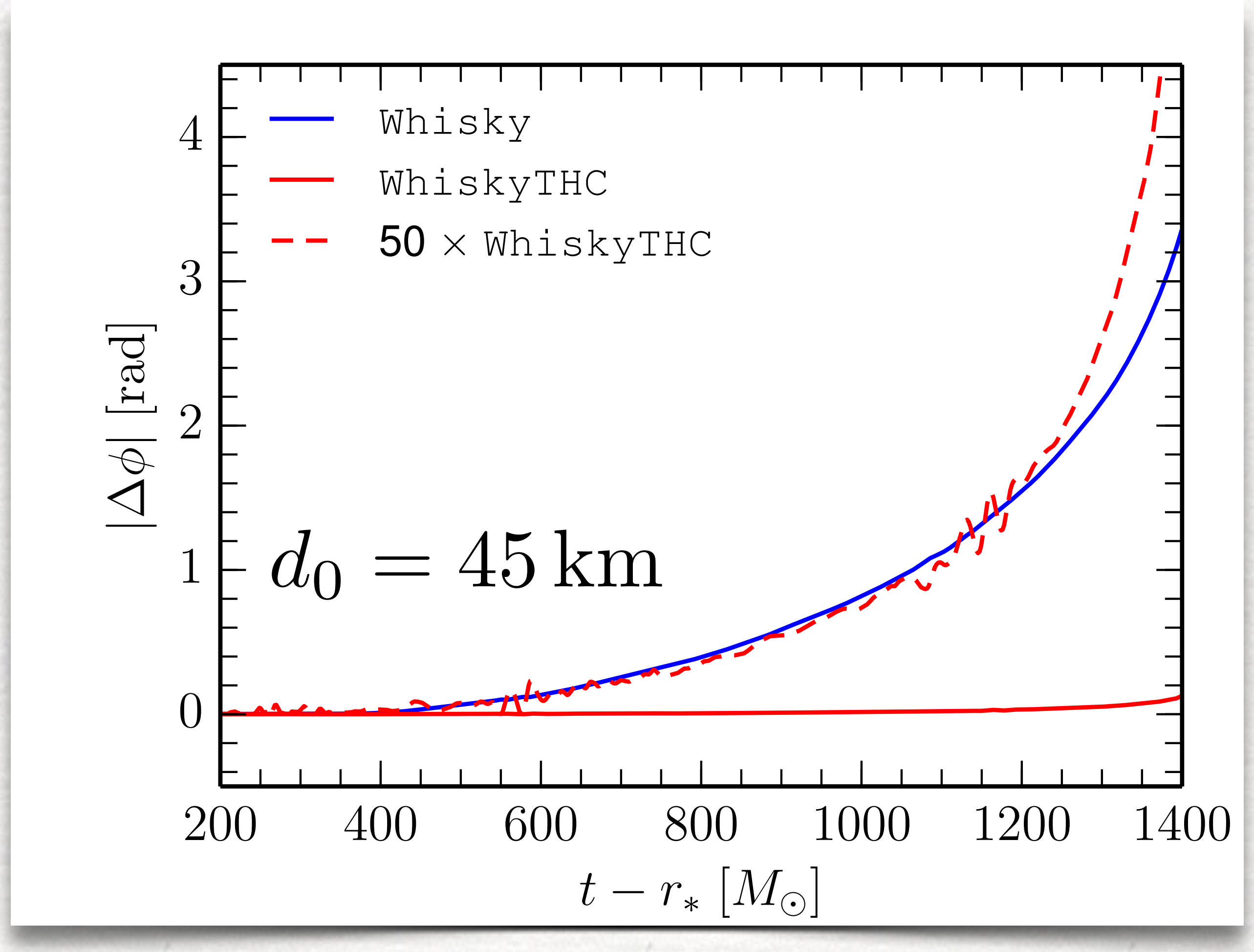
High accuracy is notoriously difficult: stellar surface reduces order to < 2.

Accuracy is expensive and **clean convergence** hard to reach.

Important recent progress: high-order accuracy with clean convergence (**i.e. 3+**) is possible for BNSs (Radice+ 2013a,b).

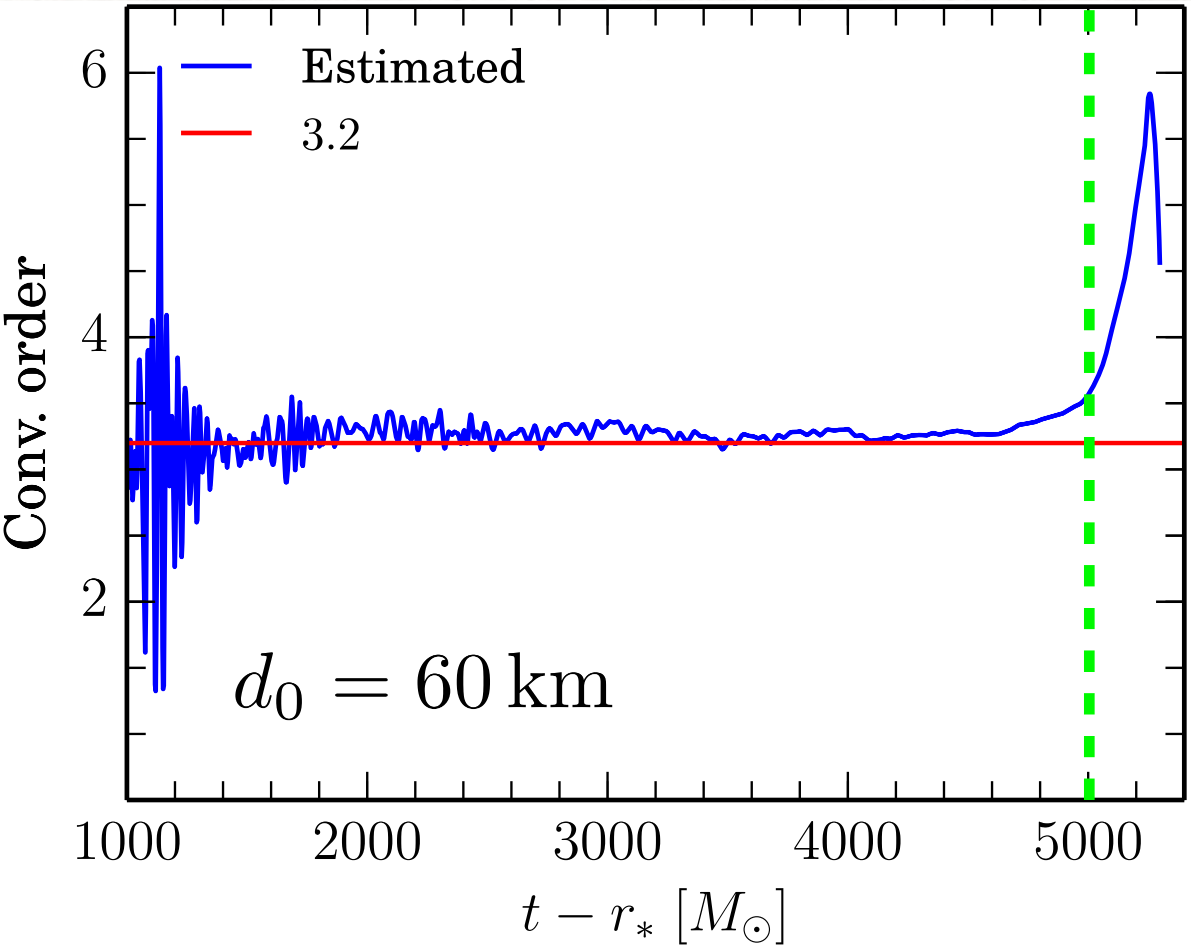
Do we understand the inspiral?

Radice+ (2013a,b)

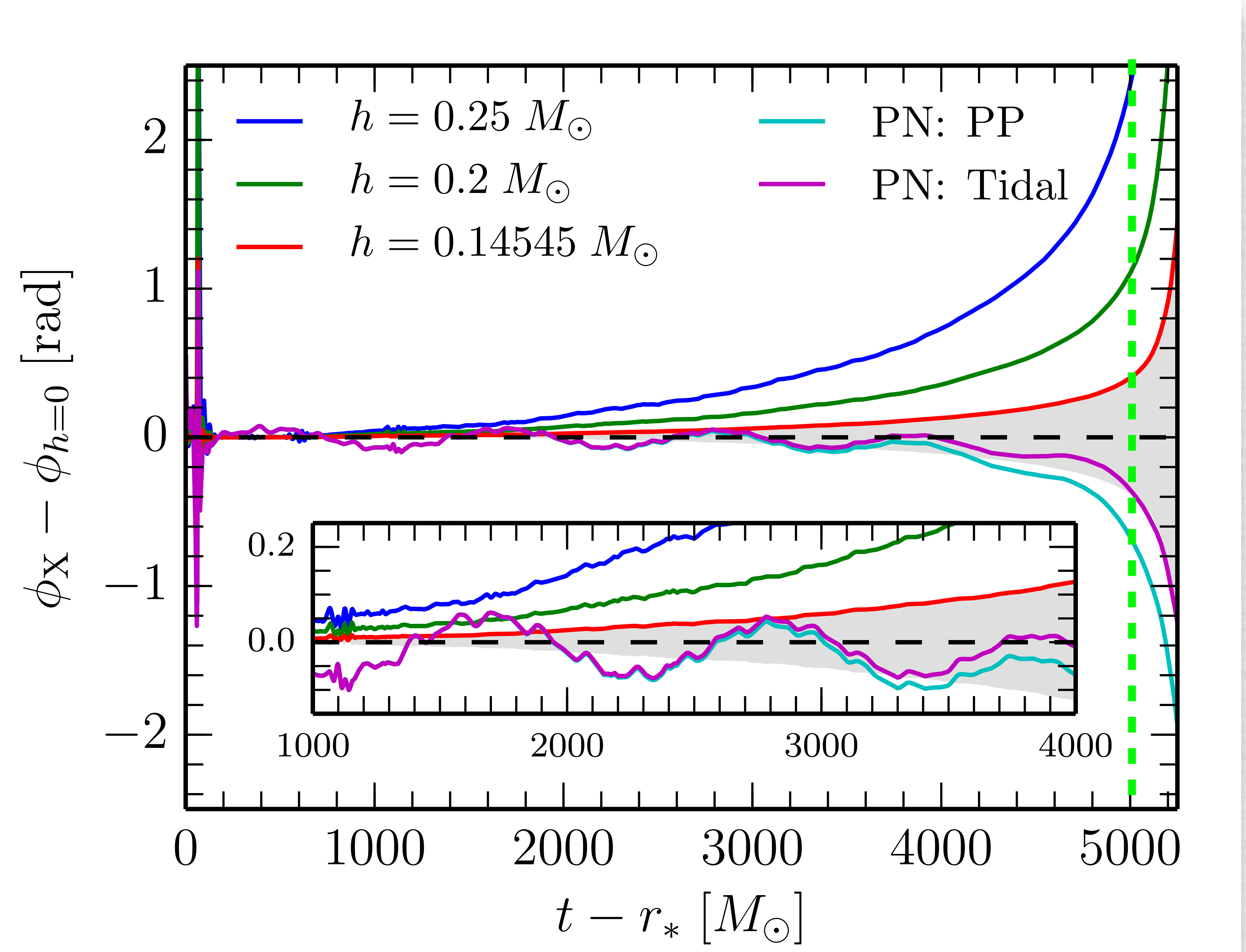


Computational saving best appreciated comparing phase error at the same resolution:
Whisky (order ~1.8)
WhiskyTHC (order ~3.2)

Cleaning convergence is essential for reliable results. Rarely figures of this type are shown for BNSs.



Do we understand the inspiral?



We can distinguish what is **numerics** from what is **physics.**

Yet, a systematic investigation is a computational challenge.

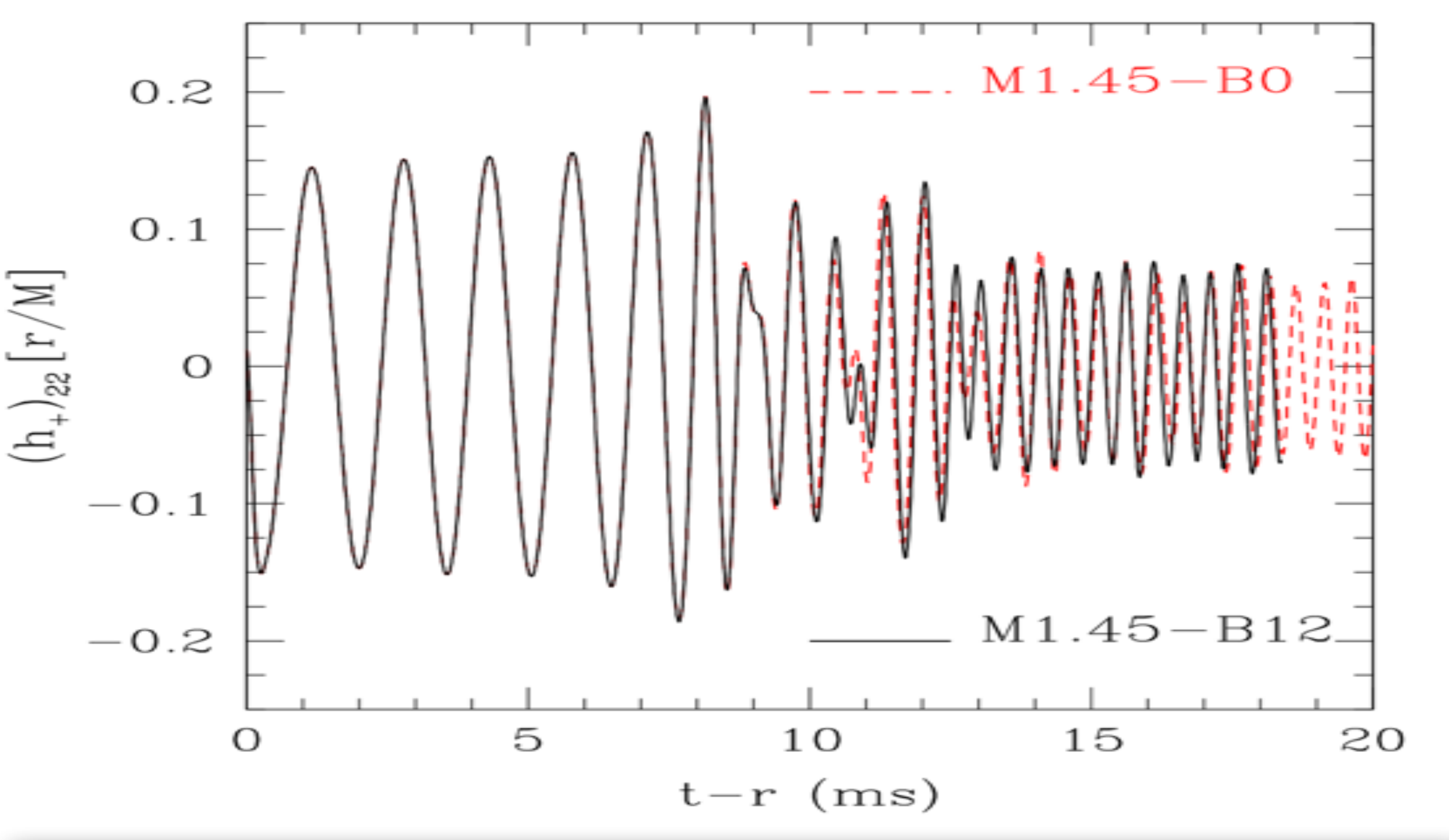
Do we understand the role of B-fields?

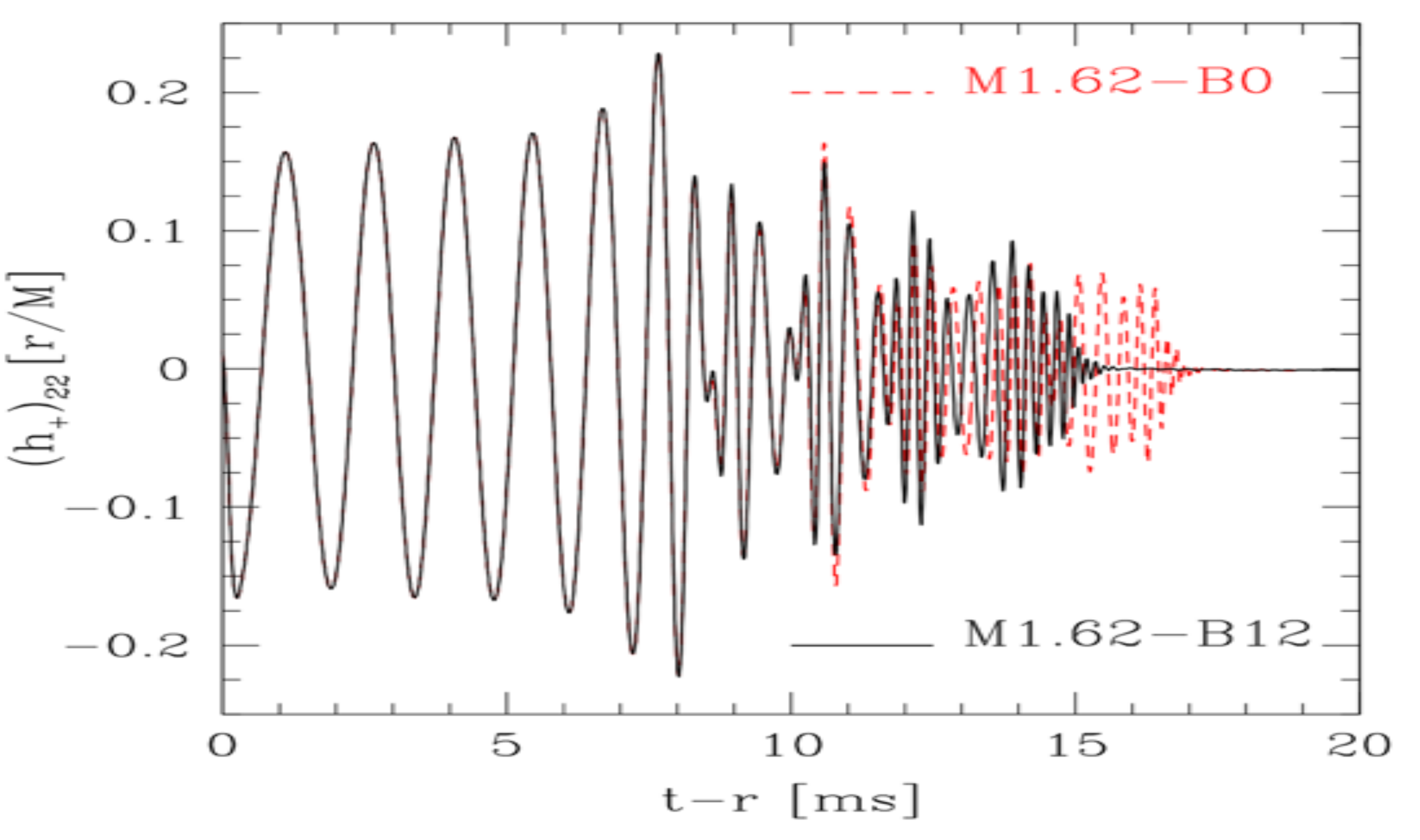
- Not easy but can be done: *ideal-MHD* (infinite conductivity).
- The B-fields are initially contained inside the stars
- First interesting results in *resistive-MHD;* (Palenzuela+13; not here)

In what follows I will review present understanding of:

- ✶magnetic fields before merger
- ✶ magnetic fields during the HMNS phase
- ✶ magnetic fields after BH formation

Can we detect B-fields in the inspiral?





Giacomazzo+ (2010, 2011)

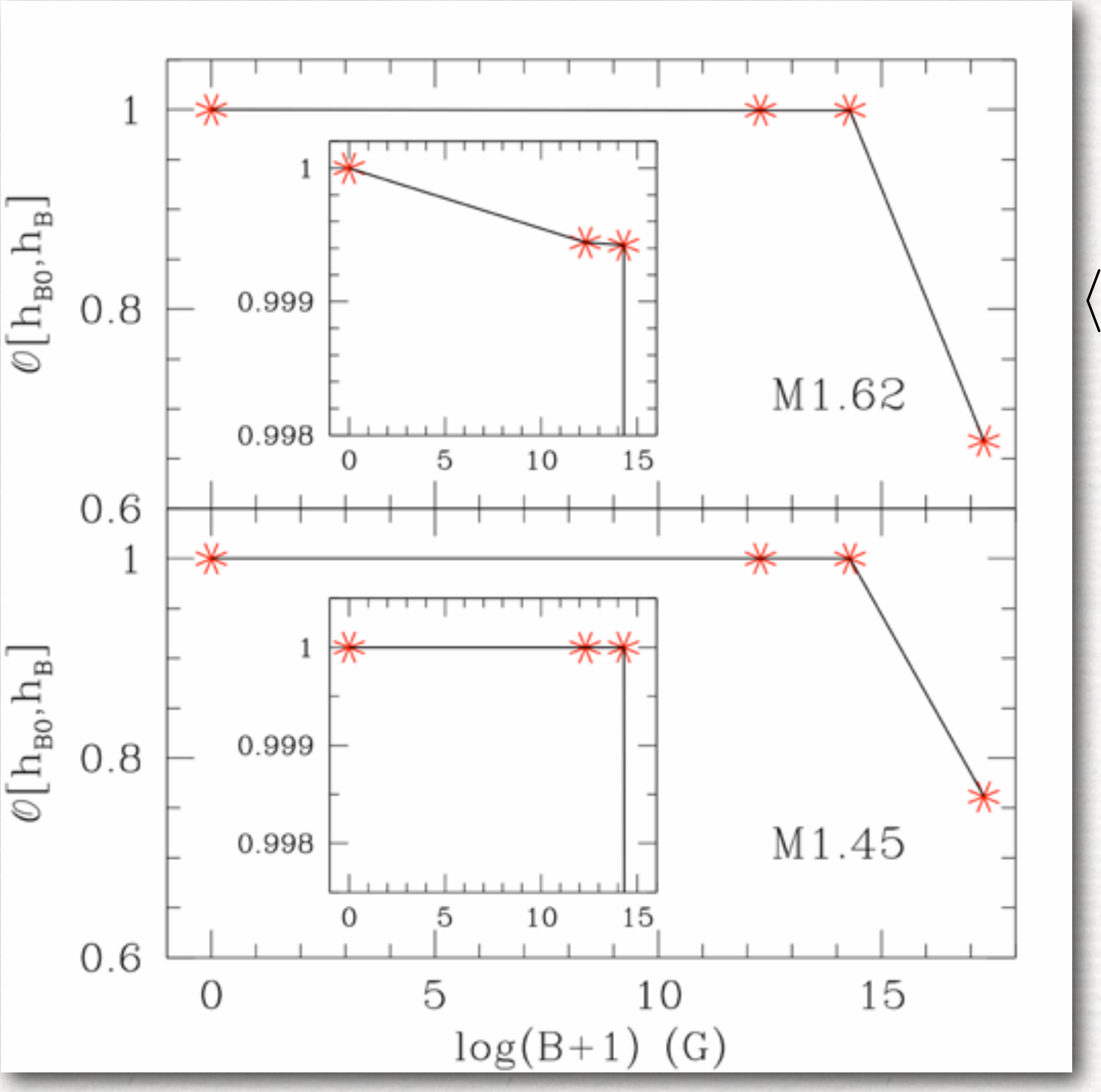
Perform ideal-MHD simulations with and without B-fields and compare…

- the evolution in the **inspiral** is different but only for ultra large B-fields (i.e. B~10^{17} G).

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

Can we detect B-fields in the inspiral?

To quantify the differences and determine whether detectors will see a difference in the inspiral, we calculate the overlap



$$\mathcal{O}[h_{B1},h_{B2}] \equiv \frac{\langle h_{B1}|h_{B2}\rangle}{\sqrt{\langle h_{B1}|h_{B1}\rangle\langle h_{B2}|h_{B2}\rangle}}$$

where the scalar product is

$$\langle h_{B1}|h_{B2}\rangle \equiv 4\Re\int_0^\infty df\,\frac{\tilde{h}_{B1}(f)\tilde{h}^*_{B2}(f)}{S_h(f)}$$

In essence, at these res:

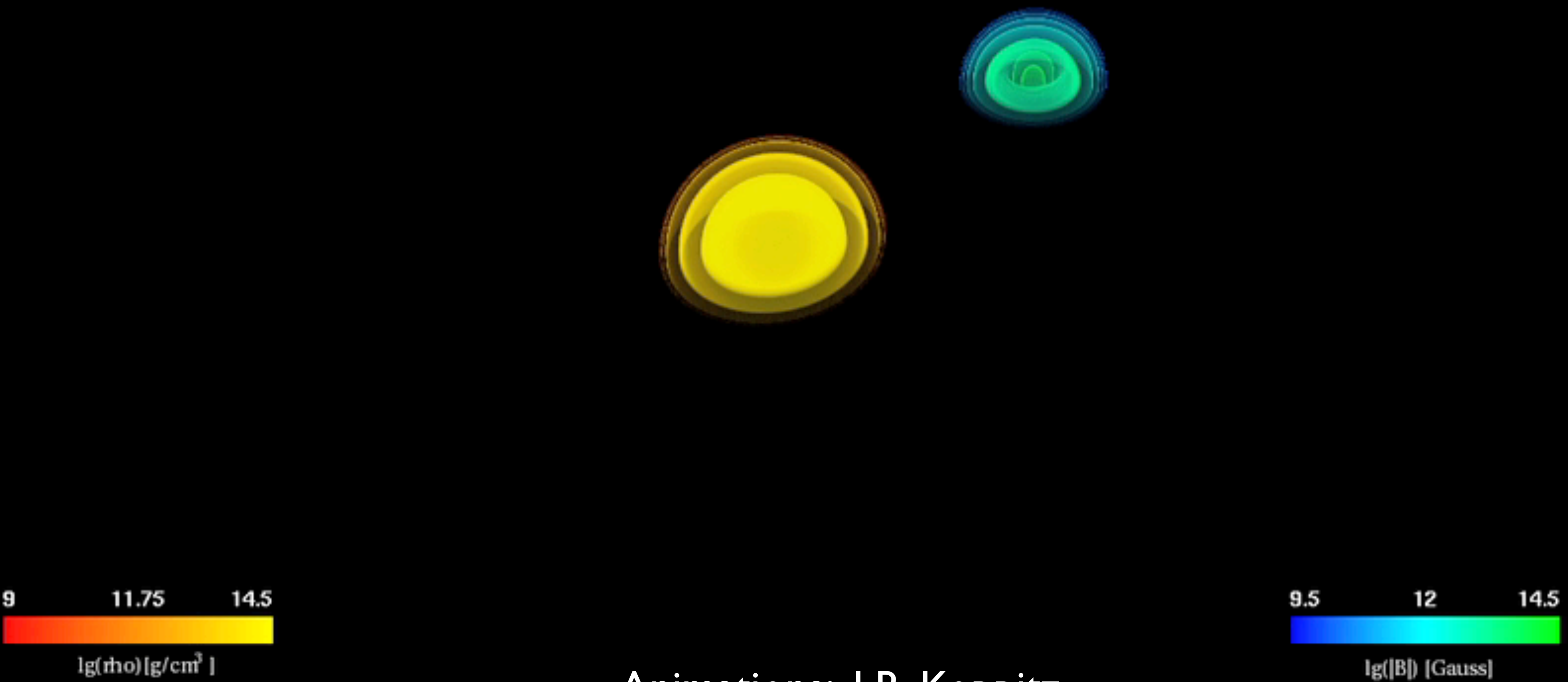
$$\mathcal{O}[h_{B0},h_B] \gtrsim 0.999$$

for $\mathrm{B} \lesssim 10^{17}$ G

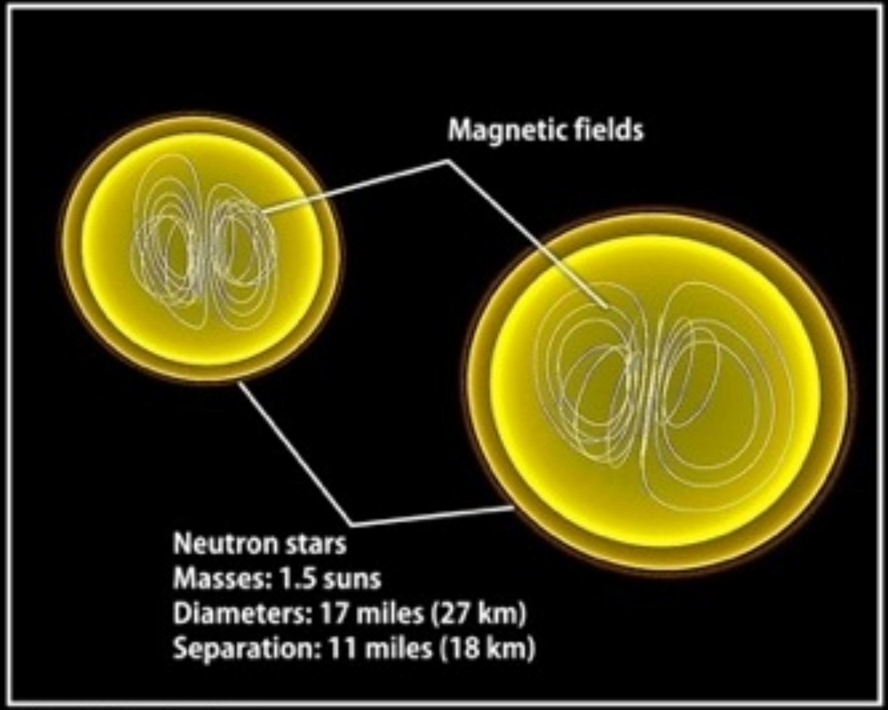
Because detectable mismatch is $\lesssim 0.995$, the influence of B-fields on the inspiral is **unlikely to be detected**

B-fields during inspiral phase

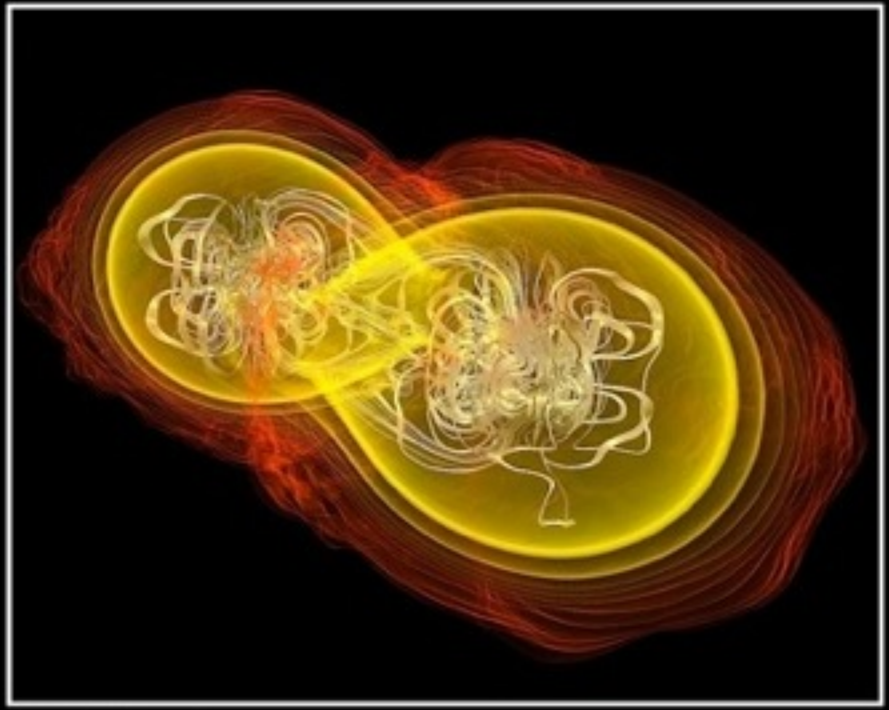
Typical evolution for a magnetized binary (hot EOS) $M = 1.5\,M_{\odot}, B_0 = 10^{12}\,\mathrm{G}$



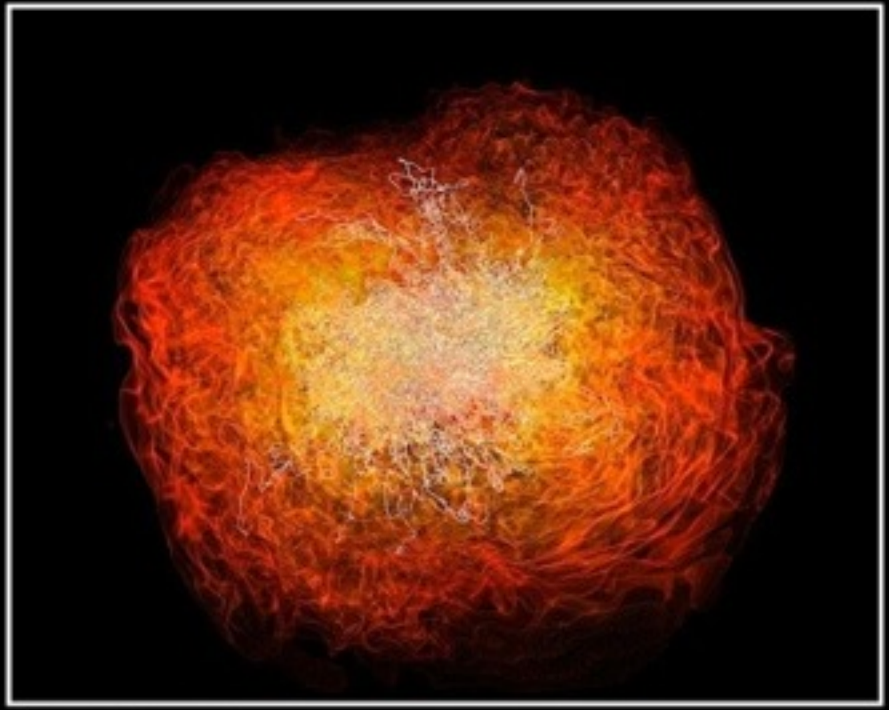
Animations:, LR, Koppitz



Simulation begins



7.4 milliseconds



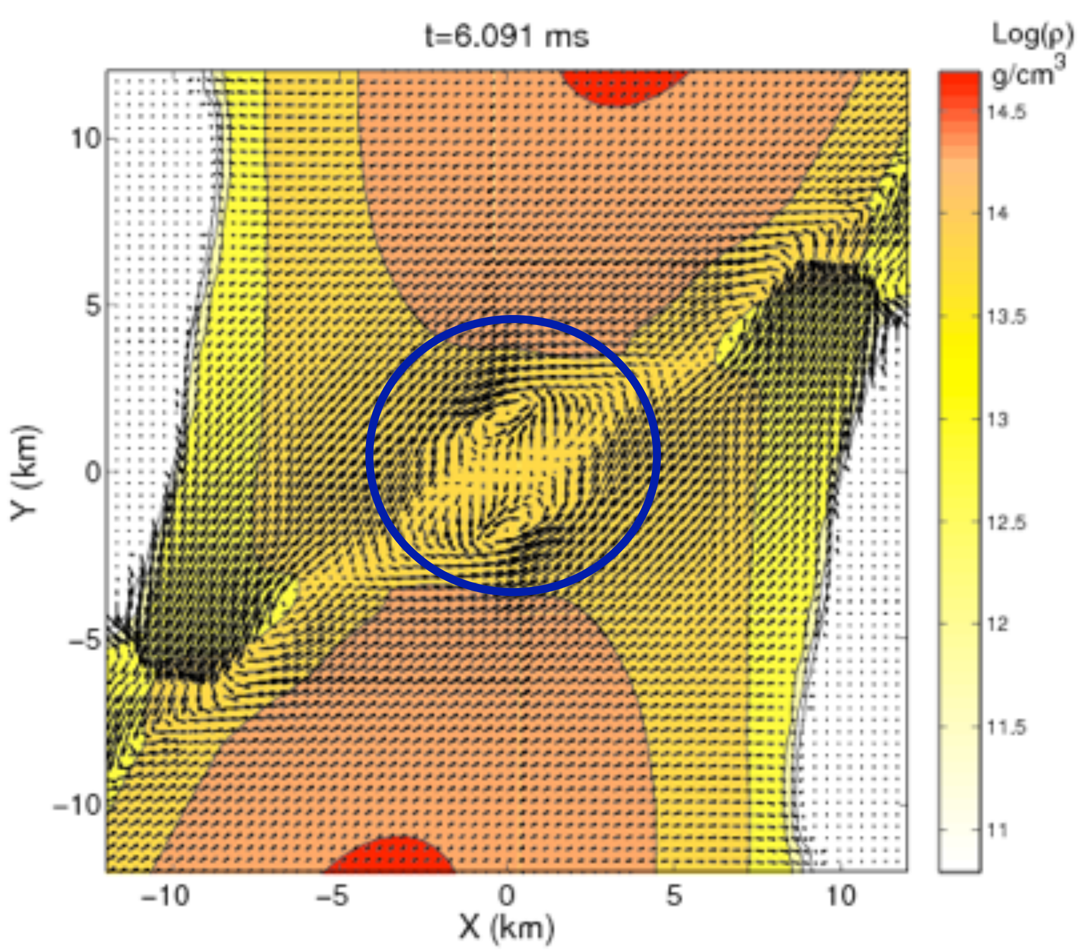
13.8 milliseconds

Open questions:

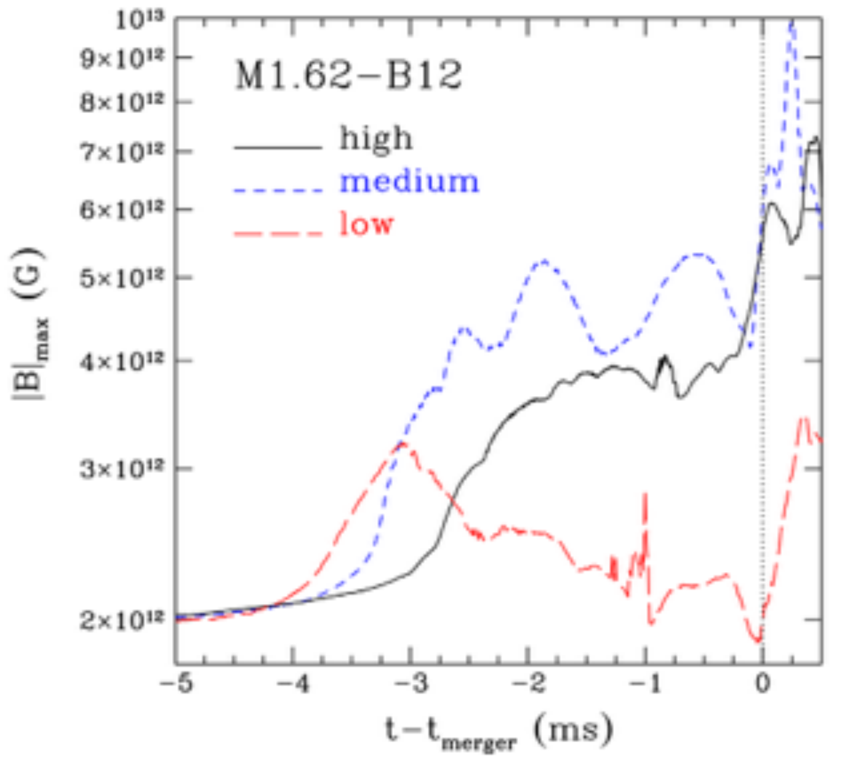
- does a KH instability develop at merger?
- what happens during the HMNS phase? MRI?
- can a magnetic wind be driven?
- for how long? can this explain X-ray plateaus?

KH instability: myths and realities

Vortices are produced in the shear boundary layer (Baiotti+ 2008; h~177m)

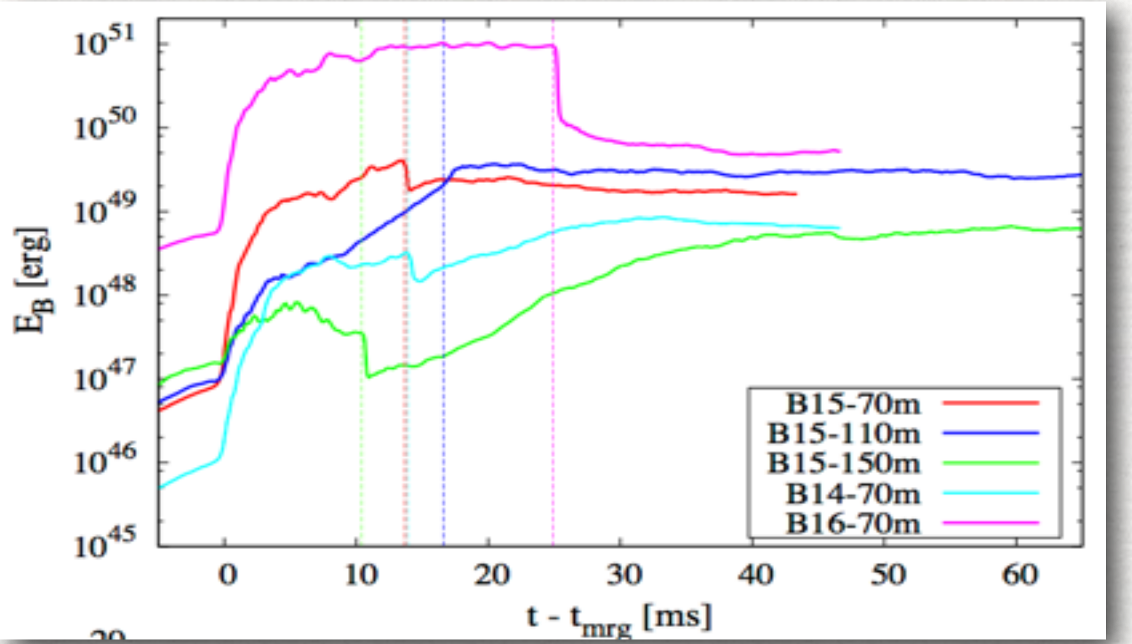


Local simulations predict amplification factor ~ 20 (Obergaulinger+ 2010)
Exponential growth (<~ 10) seen in MHD (Giacomazzo+ 2011; h~354, 221, 177m).



Very high-res simulations (Kiuchi+ 2014; h~70m) confirm general trend. Unstable shear layer disappears in a dynamical time scale of ~ 0.1ms, because the compression.

Global amplification factor likely less 100



MRI under controlled conditions

MRI in a nutshell (and a number of assumptions)

$$\tau_{\rm MRI} = {\rm Im}(\omega_{\rm MRI})^{-1} \sim \frac{1}{\Omega} \qquad \lambda_{\rm MRI} \sim \frac{2\pi}{\Omega}\,\frac{\mathbf{B}\cdot\mathbf{e}_k}{\sqrt{4\pi\rho}}$$

- tipically $\lambda_{\rm MRI}$ is much smaller than typical size of astrophysical system, eg accretion discs, core-collapse supernovae, HMNS

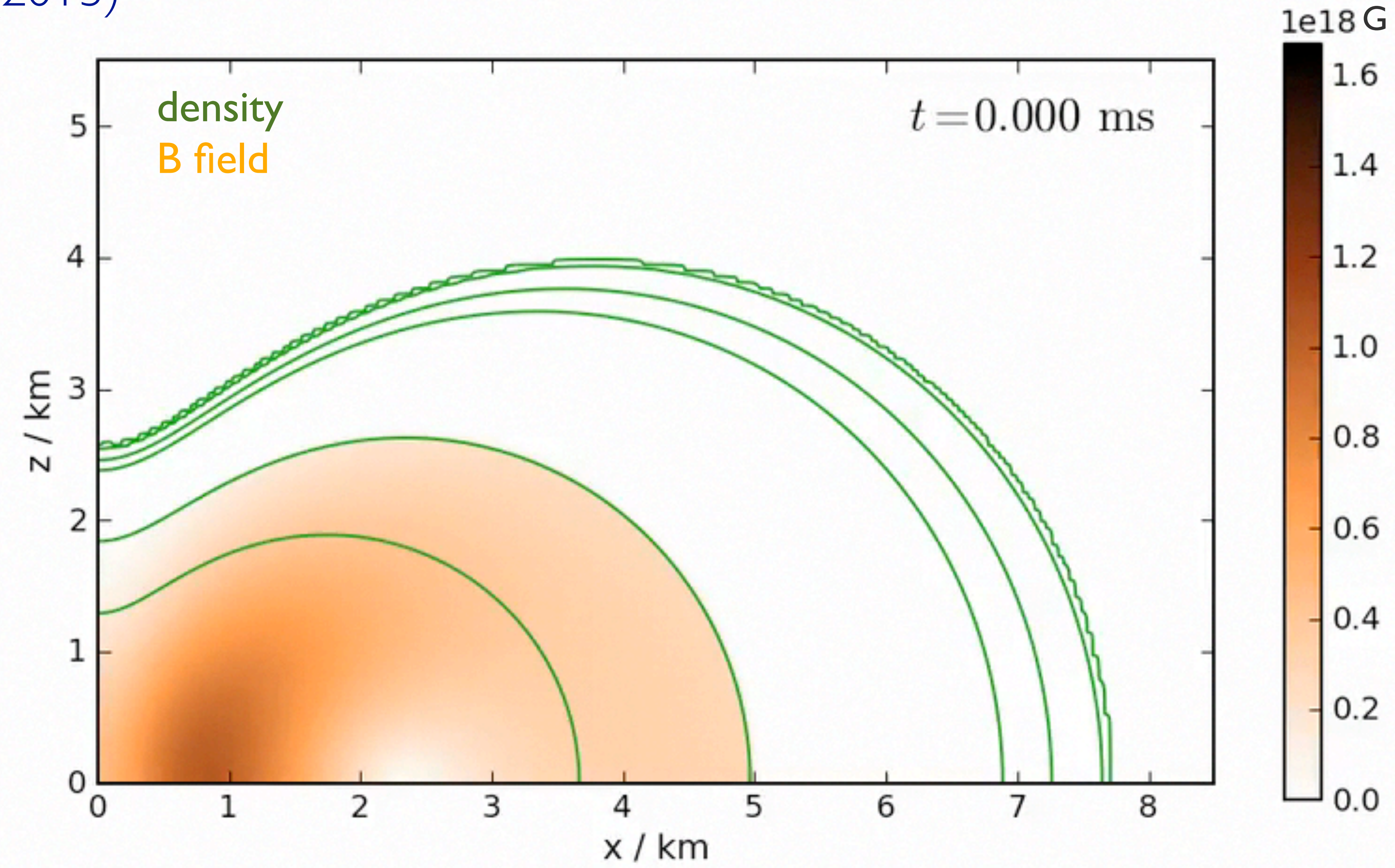
- if unresolved, simulations cannot reproduce development of MRI

- so far the problem has been investigated either via

  - ✴ local simulations
  - ✴ axisymmetry (Hawley & Balbus 92; Obergaulinger+ 06a,b, 09; Duez+ 06)
  - ✴ very high (unrealistic) magnetic fields that accelerate dynamics
  - ✴ huge resolutions and computational costs (Siegel+ 2014, Kiuchi+ 2014)

First global simulations in full GR

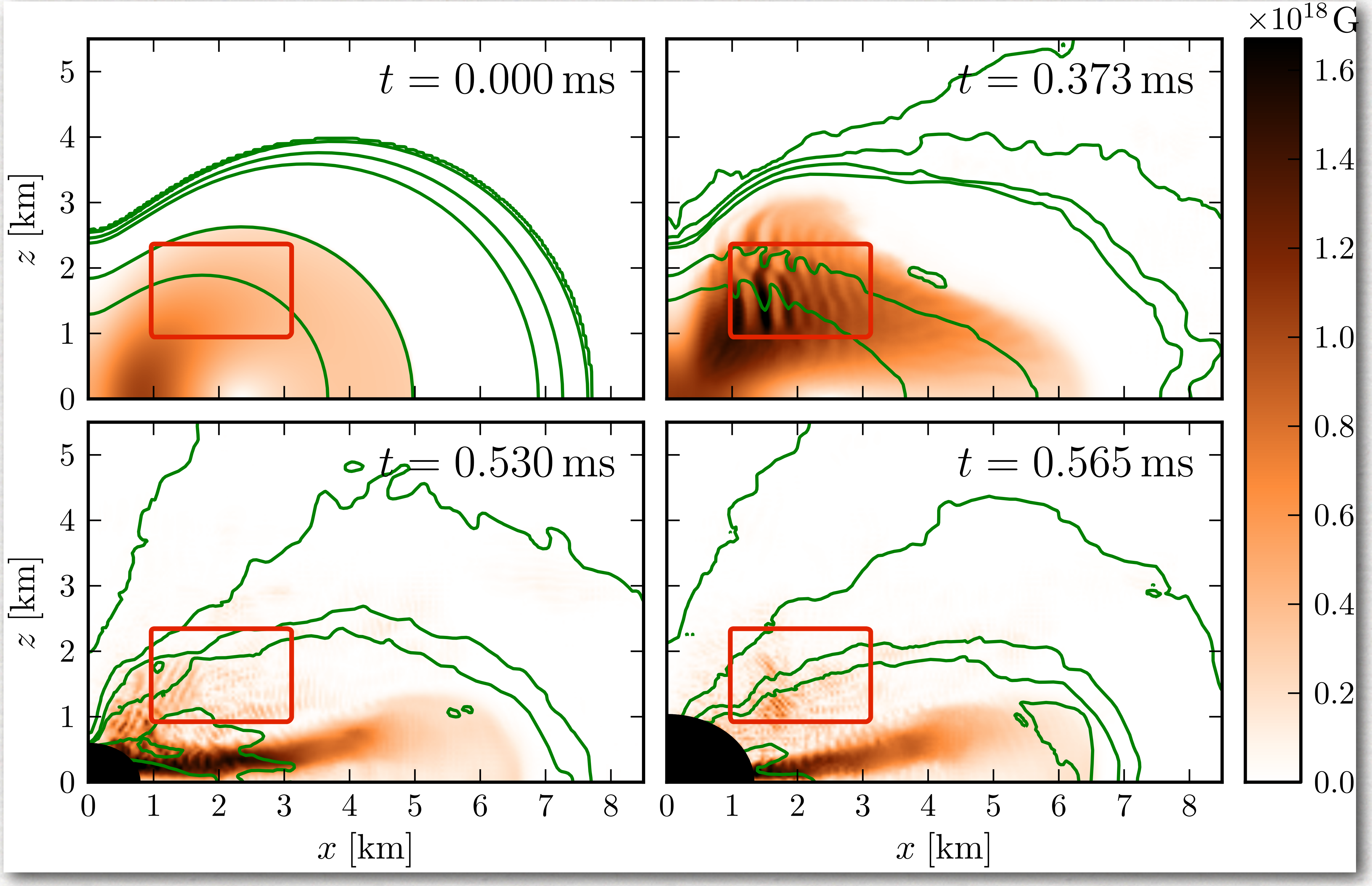
Siegel + (2013)



- ideal MHD (WhiskyMHD code)
- ideal-fluid EOS, $p = (\Gamma - 1)\rho\epsilon$
- spacetime evolution (1+log slicing, Gamma-driver)
- axisymmetric initial model $(M = 2.23 M_\odot)$
  - purely poloidal B field $(B_c^{\mathrm{in}} = 5\mathrm{e}17\,\mathrm{G})$
  - differential rotation: *j*-constant law

- cartesian grid $[0, 94.6] \times [0, 94.6] \times [0, 53.9]\,\mathrm{km}$
- 4 refinement levels, finest gridspacing $h = 44\,\mathrm{m}$
- $\pi/2$ and z-reflection symmetry

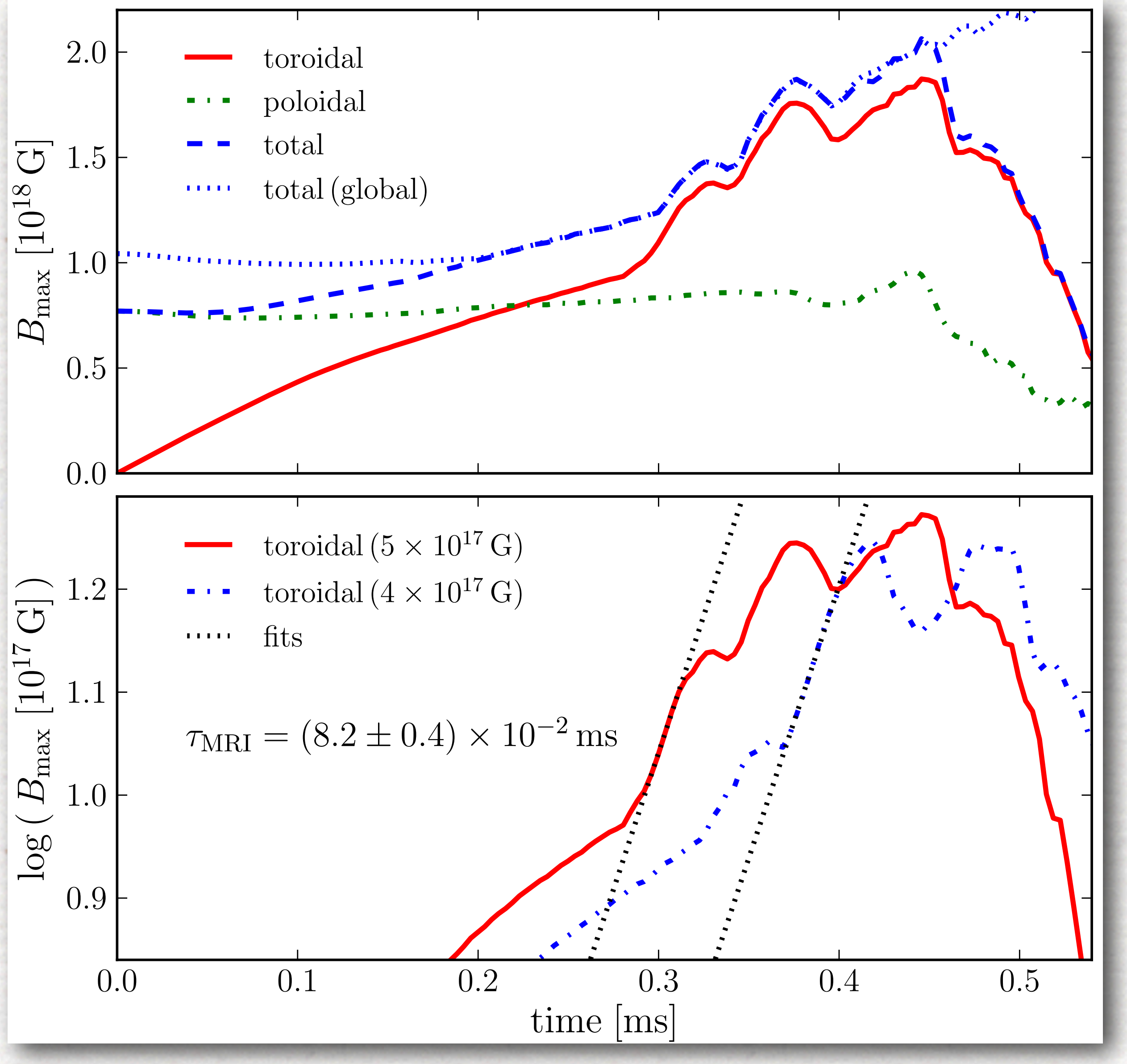
A local view in a global simulation



red box used for analysis has dimensions

$$(x, z) \in [1.0,\ 3.0] \times [1.0,\ 2.3]\ \mathrm{km}$$

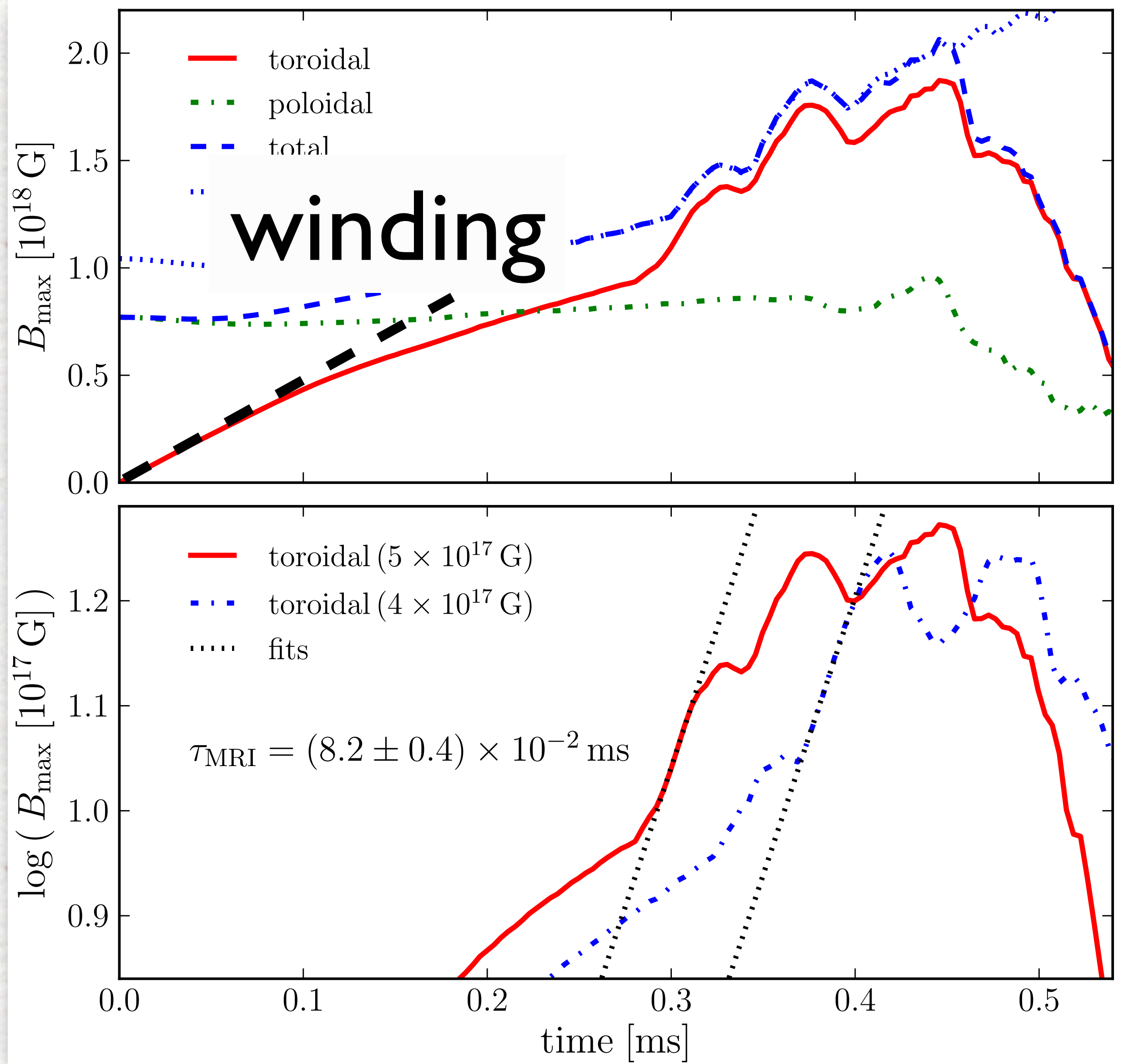
Magnetic field growth: linear and exponential



- poloidal field is not amplified during the evolution
- toroidal field initially generated by magnetic winding:

$$B_{\rm tor} \approx (rB^i \partial_i \Omega)t = a_{\rm w} t$$

Magnetic field growth: linear and exponential



winding

- poloidal field is not amplified during the evolution
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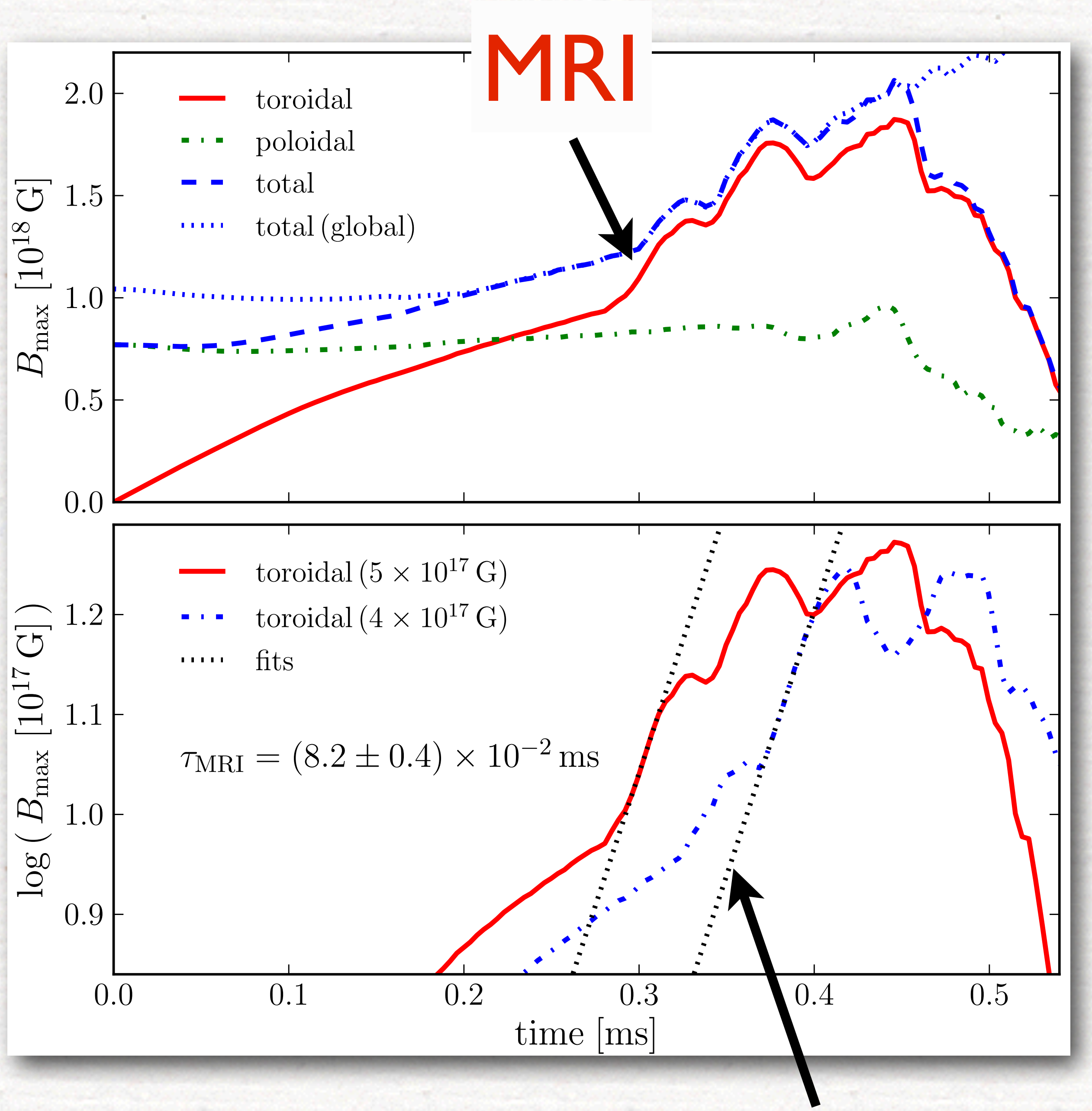
Magnetic field growth: linear and exponential



MRI

- poloidal field is not amplified during the evolution
- toroidal field initially generated by magnetic winding:

$$B_{\rm tor} \approx (rB^i\partial_i\Omega)t = a_{\rm w}t$$

- at $0.28\,{\rm ms}$ MRI sets in with growth time:

measured

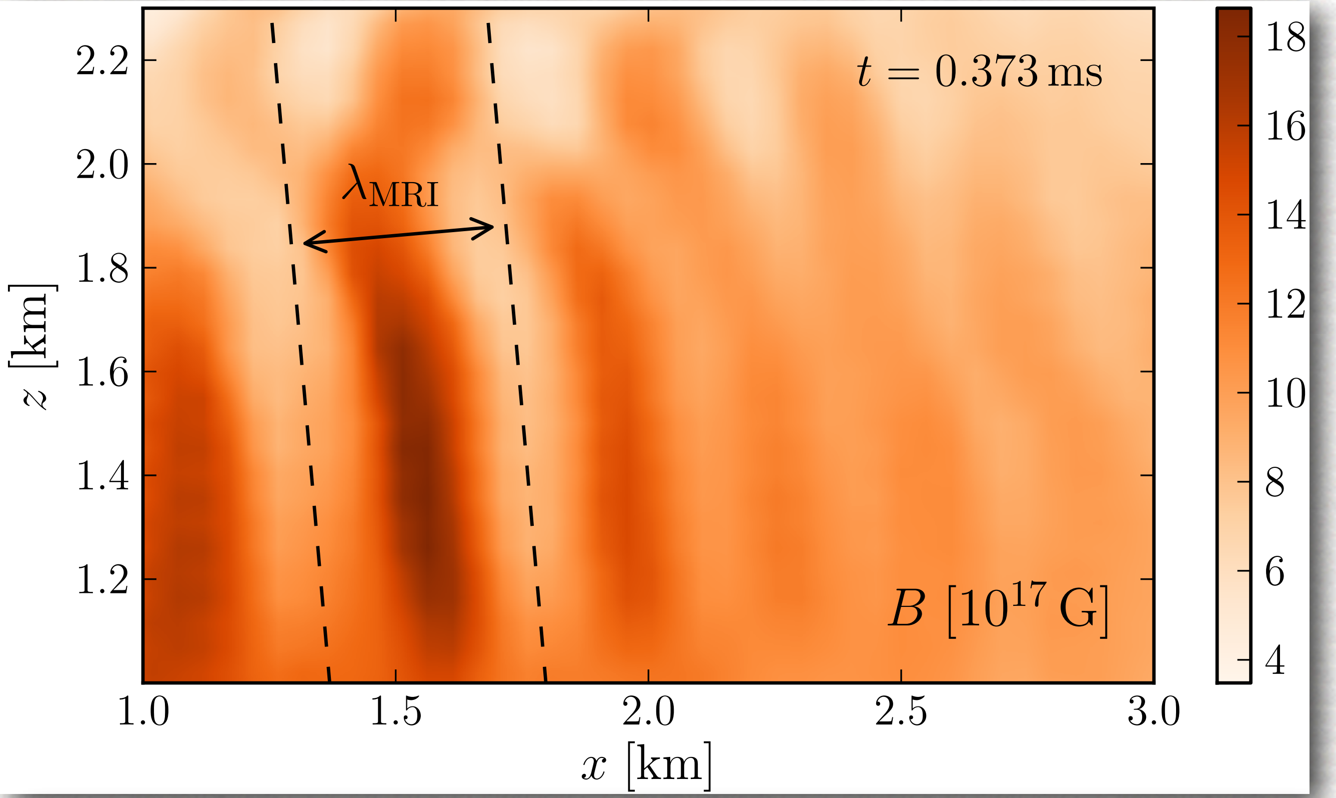
$$\tau_{\rm MRI,fit} = (8.2\pm0.4)\times10^{-2}\,{\rm ms}$$

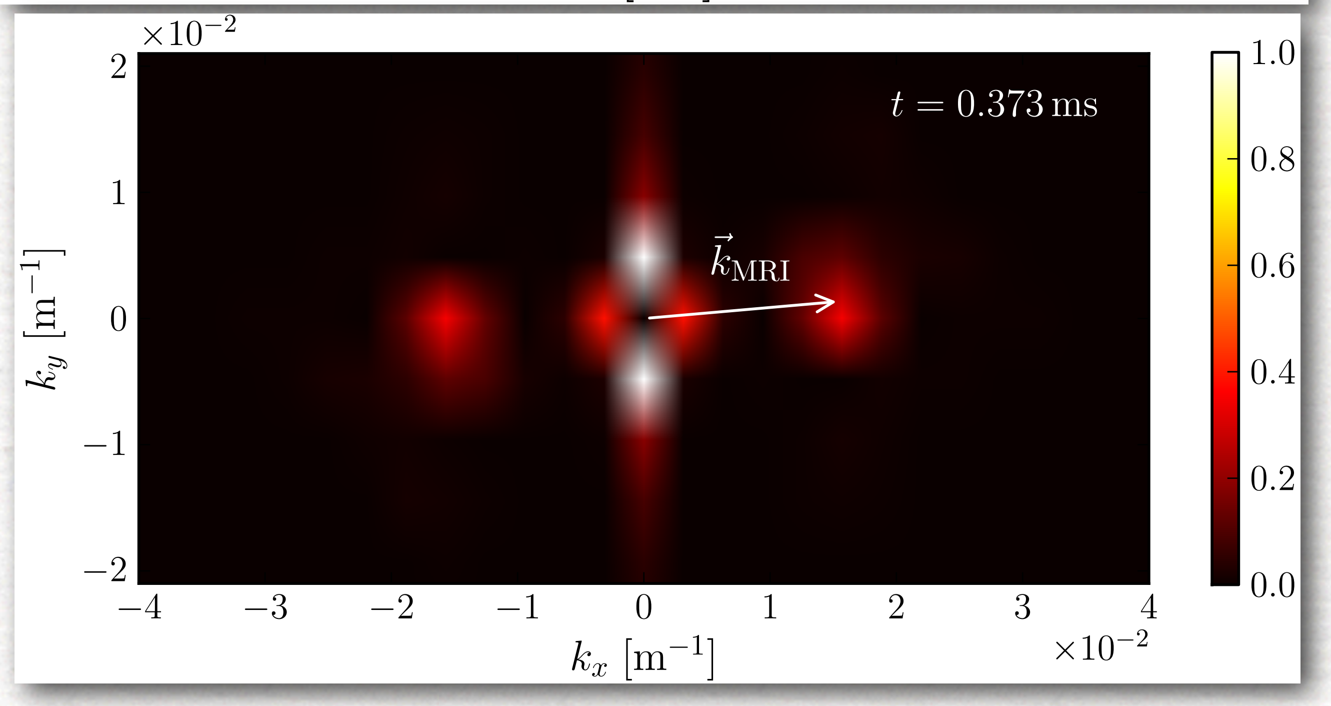
order-of-mag. prediction

$$\tau_{\rm MRI} \sim \Omega^{-1} \approx (4-5)\times10^{-2}\,{\rm ms}$$

$\tau_{\rm MRI}$ does not depend on magnetic field strength

An important signature: channel flows





- onset of channel-flow merging visible in upper part
- power spectrum reveals a single dominant mode $\boldsymbol{k}_{\mathrm{MRI}}$

  (apart from contributions from large-scale gradients)
- wavelength consistent with channel flows

measured

$$\lambda_{\mathrm{MRI}} \approx 0.4\,\mathrm{km}$$

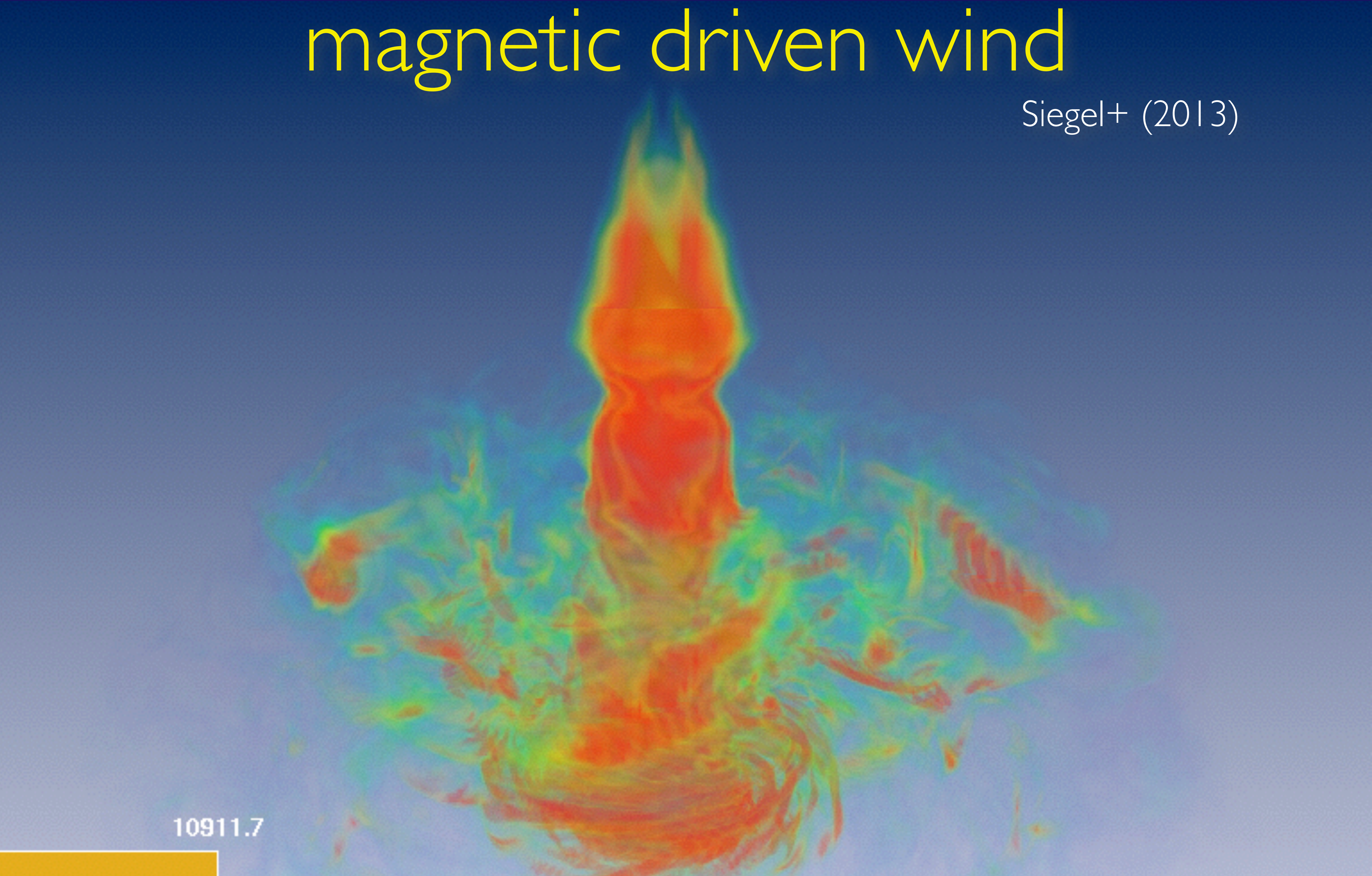
order-of-mag. prediction

$$\lambda_{\mathrm{MRI}} \sim (0.5 - 1.0)\,\mathrm{km}$$

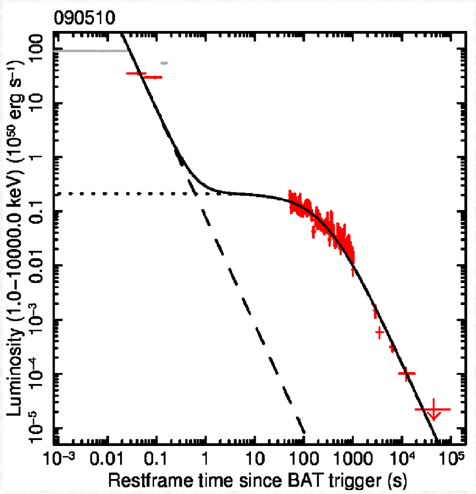
Altogether: first evidence for development of MRI in HMNSs

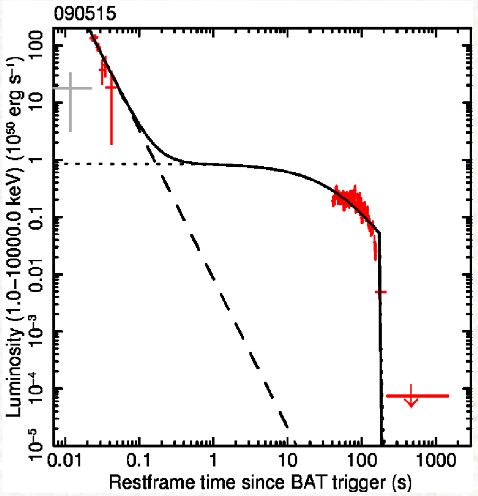
B-fields during HMNS phase: magnetic driven wind

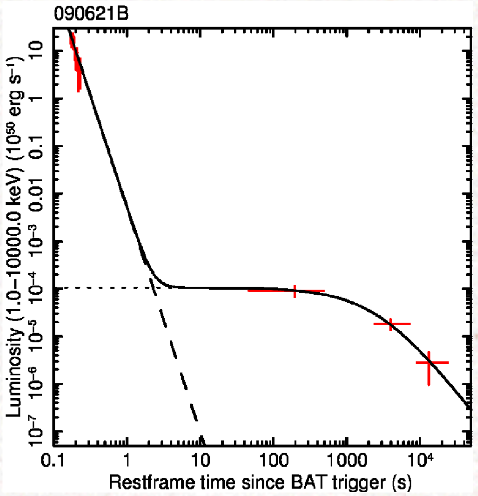
Siegel+ (2013)



If B-fields can grow, what is their impact?





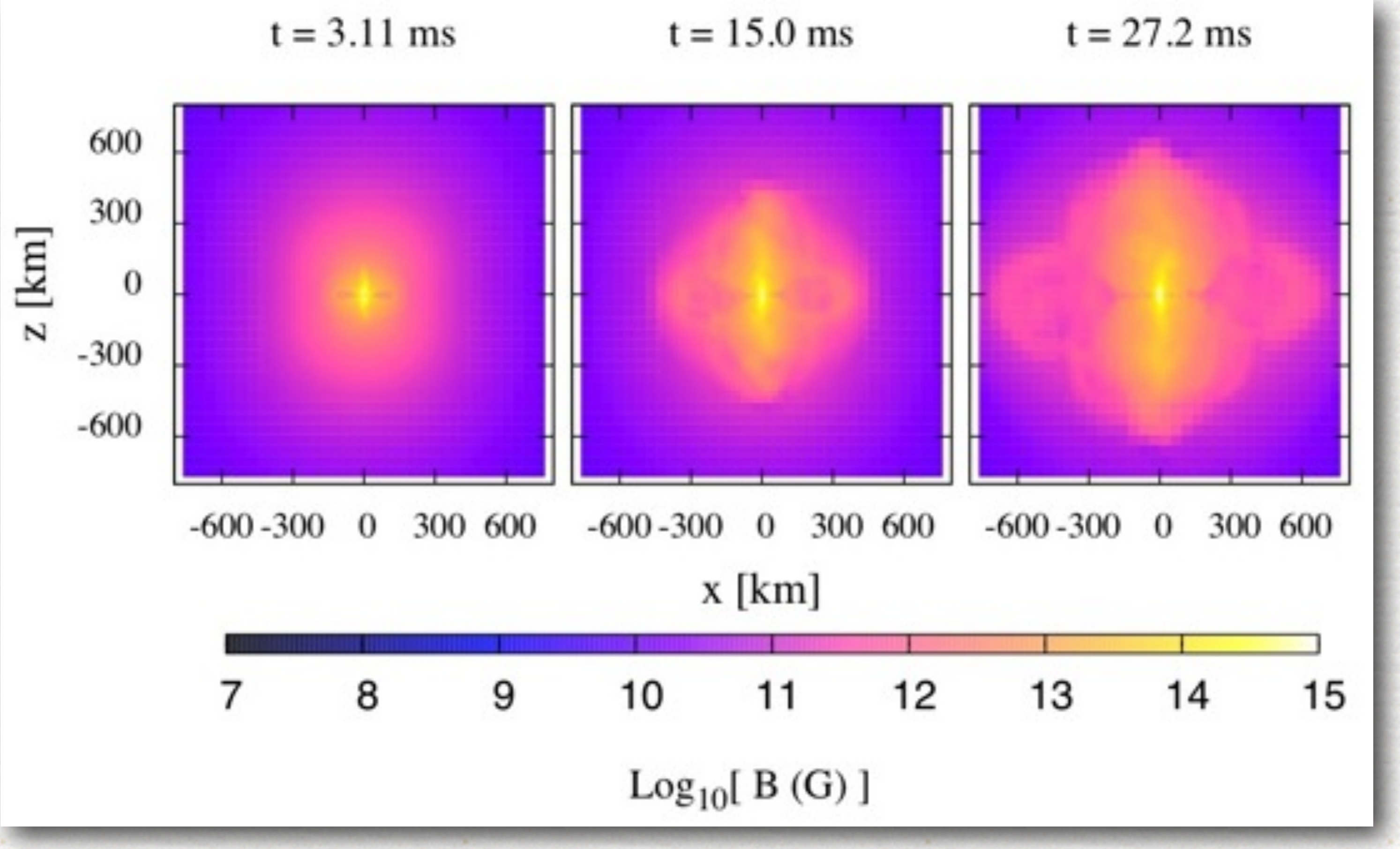


- X-ray afterglows have been observed by Swift lasting as long as 10^2-10^4 s (Rowlinson+ 13; Gompertz+13)

- The x-ray afterglow is produced by "dissipation of a proto-magnetar wind" with $L_x \sim 10^{49}\ \mathrm{erg\ s}^{-1}$ (Zhang & Mezsaros 01, Metzger+ 11, Zhang 13).
  - ★ is dipolar emission really taking place?
  - ★ what is the geometry of the wind? Collimated or spherical?
  - ★ how large is the luminosity?
  - ★ how sensitive are the results to the field topology

"proto-magnetar" winds

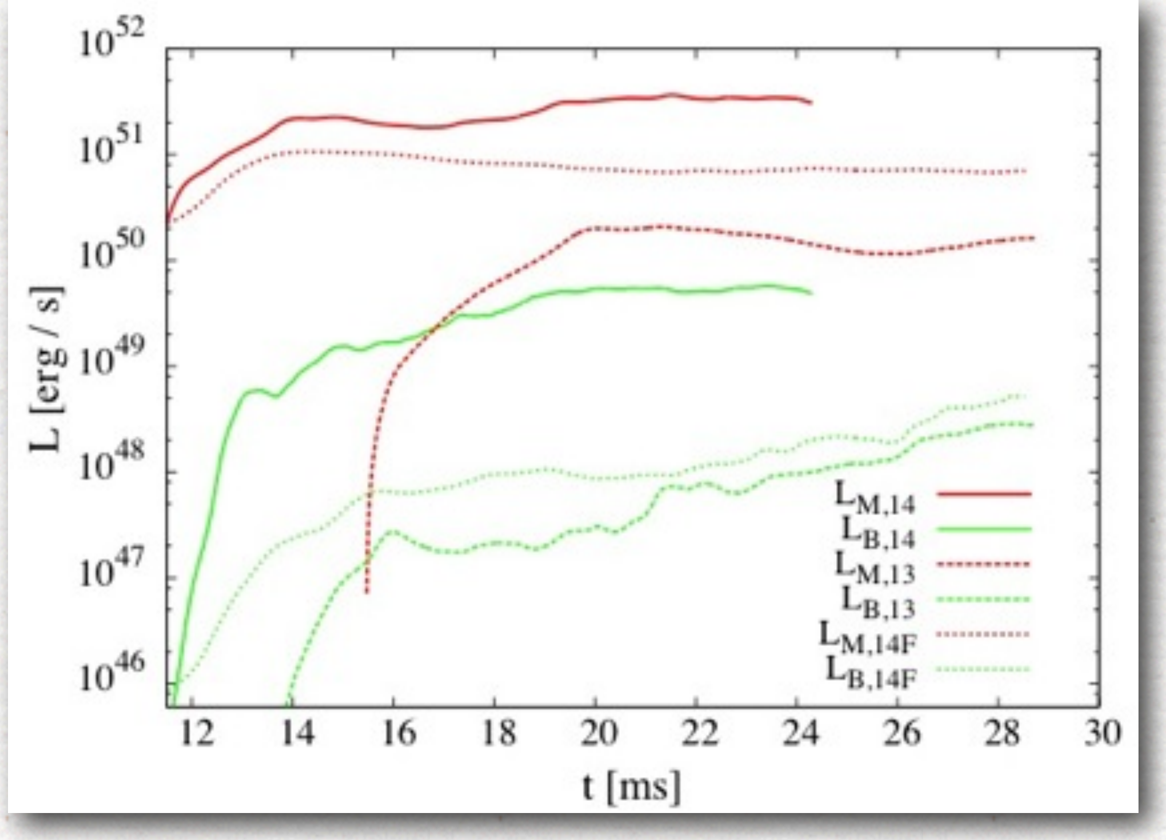
First simulations have been made (Shibata+11; Bucciantini+ 12; Kiuchi+12).



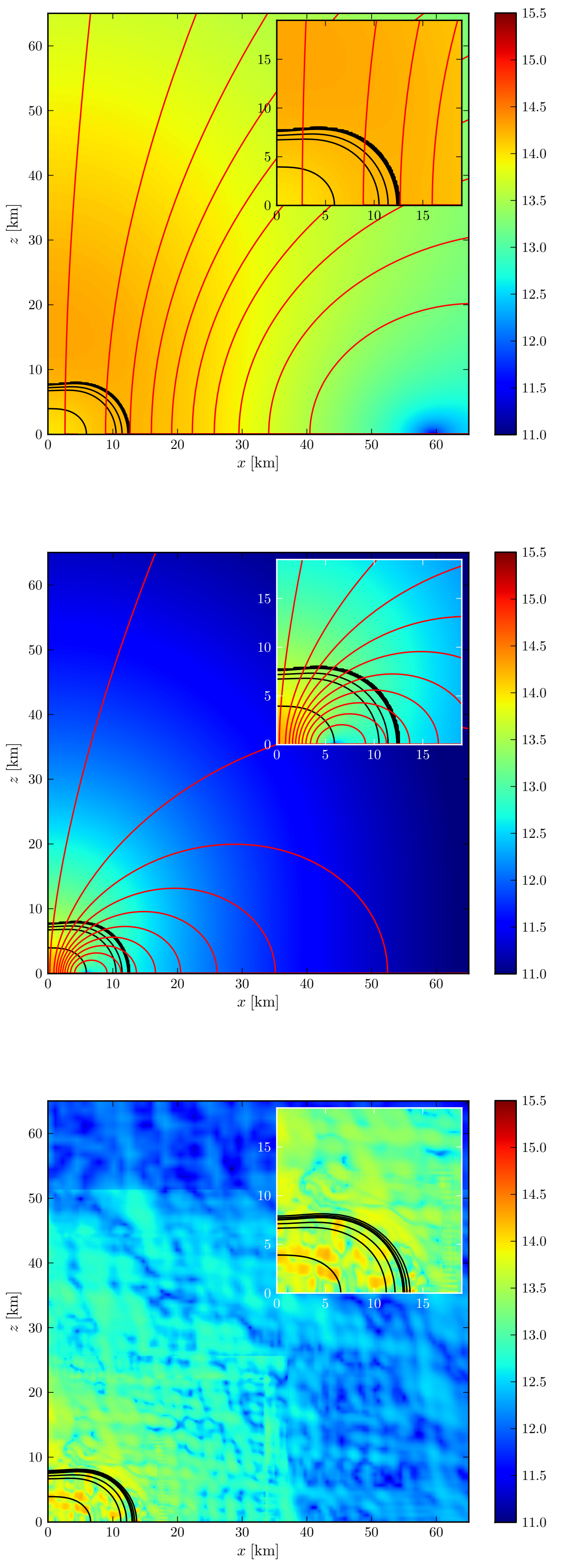
Example of 3D ideal-MHD simulations: magnetic fields grow moderately but a large-scale collimated outflow appears (Kiuchi+ 2012).

Luminosities as large as 10^{50} erg/s are produced from initial magnetic fields of ~ 10^{14} G.

How sensitive are the results on the initial conditions?



What is to be expected?

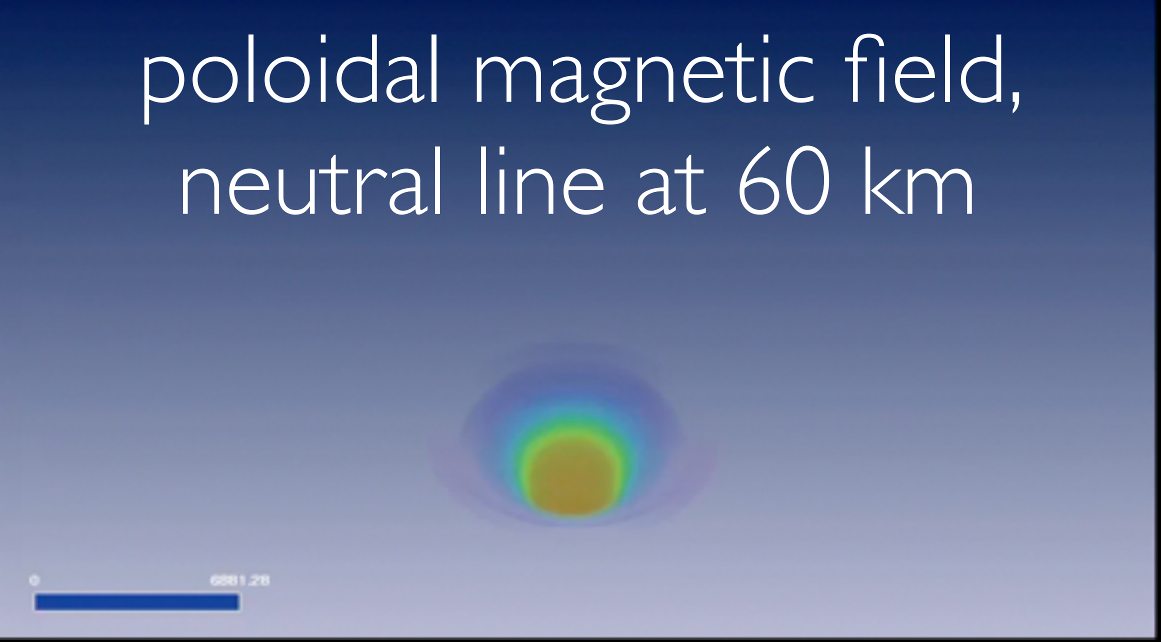


Interested in correlations between field topology and:

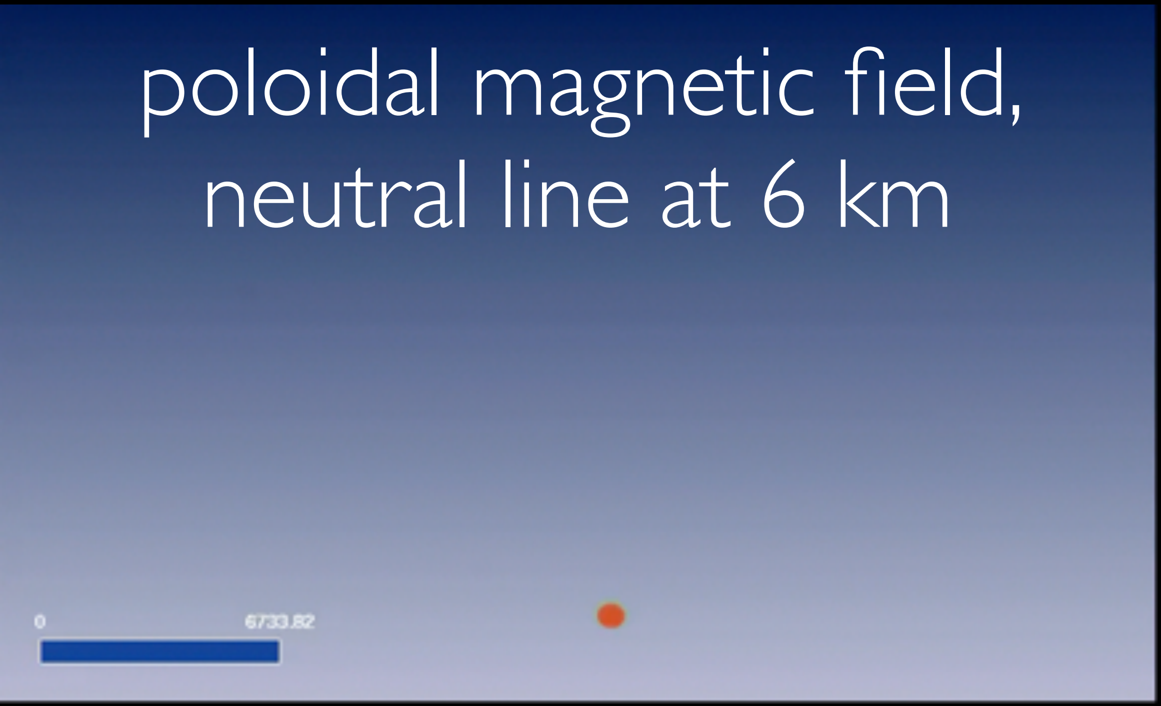
- efficiency of the emission
- geometry of the outflow
- physical properties of the outflow

Considered 3 field topologies that covering the ranges of possible behaviours.

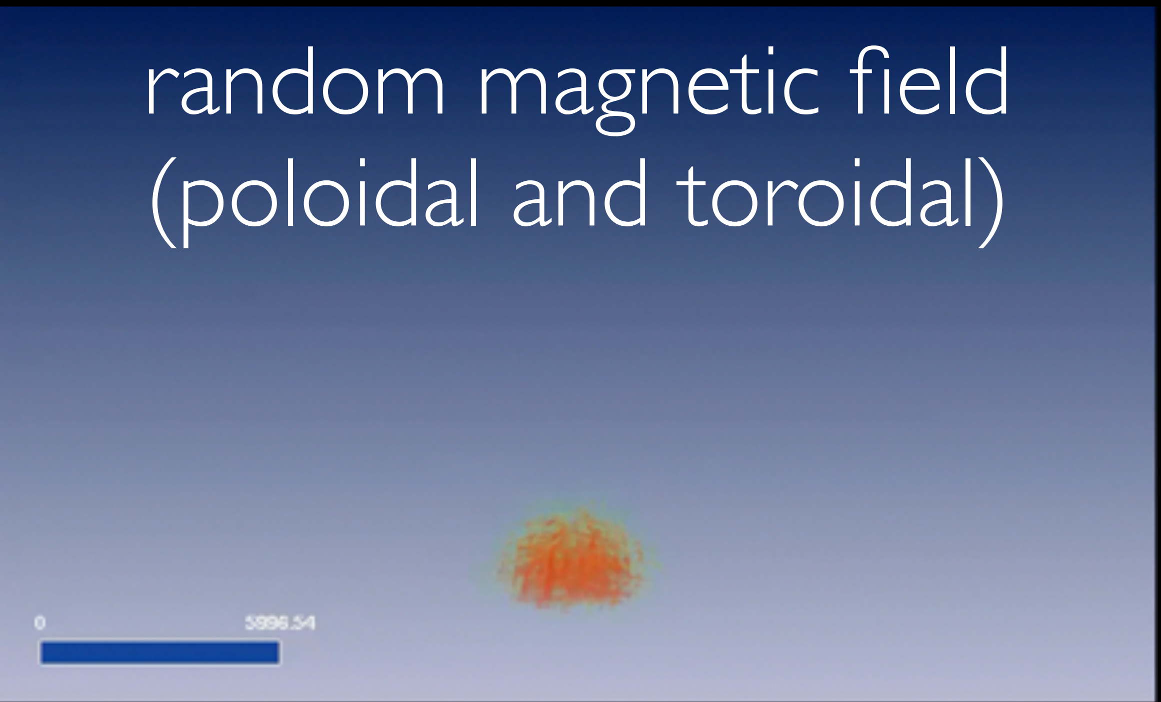
Used simplified initial data (axisymmetric) but evolutions in 3D with very high resolutions.



poloidal magnetic field,
neutral line at 60 km



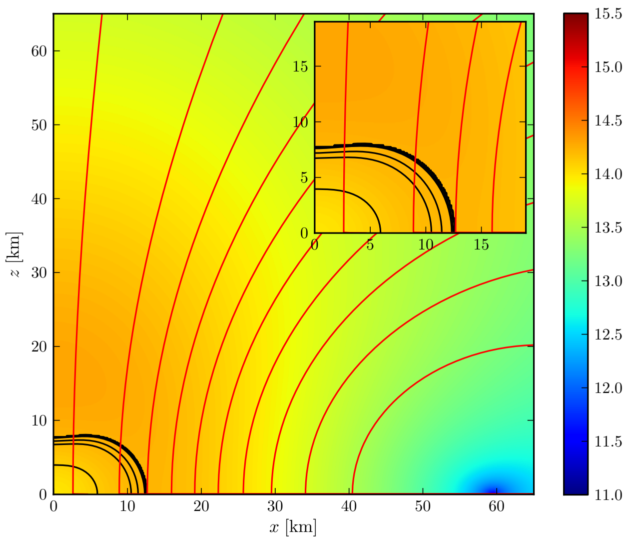
poloidal magnetic field,
neutral line at 6 km

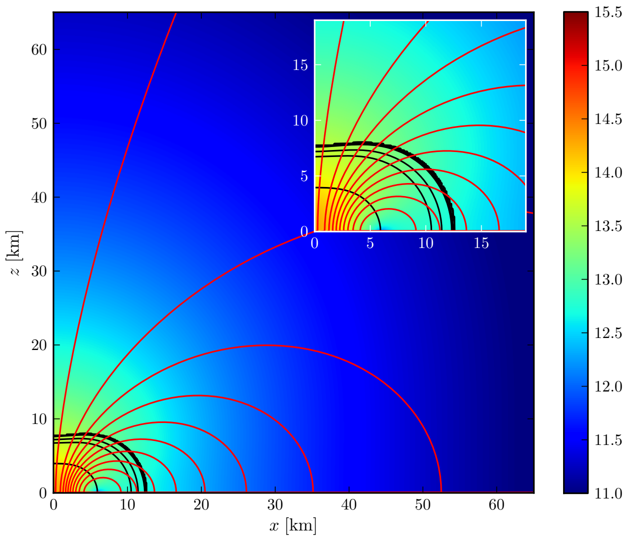


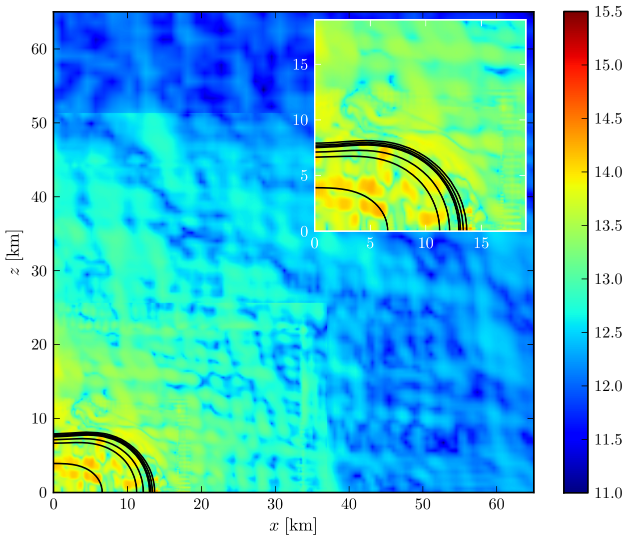
random magnetic field
(poloidal and toroidal)

- **ideal MHD:** $B_{\max} \simeq 2 \times 10^{14}\,\mathrm{G}$
- **ideal-fluid EOS,**
- **standard gauges**
- **max extents:** $[800 \times 800 \times 553]\,M_\odot$ $[1160 \times 1160 \times 800]\,\mathrm{km}$
- **fine resolution:** $0.096\,M_\odot, \sim 140\,\mathrm{m}$
- **7 refinement levs.**
- **z-reflection and rotation symmetry**
- **initial model**
  - **axisymmetric**
  - **differential rotation: *j*-constant law**

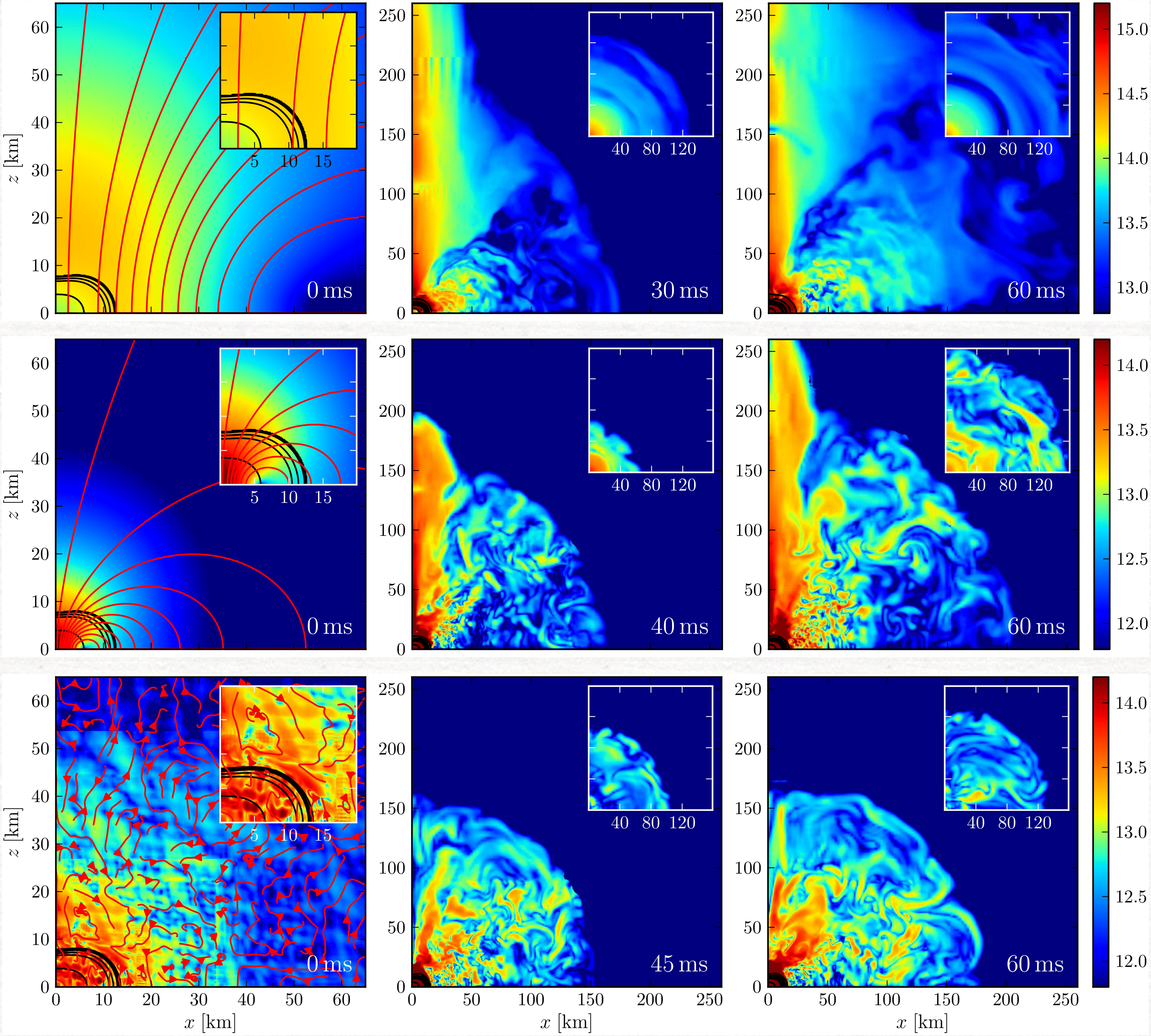
poloidal magnetic field,
neutral line at 60 km
poloidal magnetic field,
neutral line at 6 km
random magnetic field
(poloidal and toroidal)







Comparative table

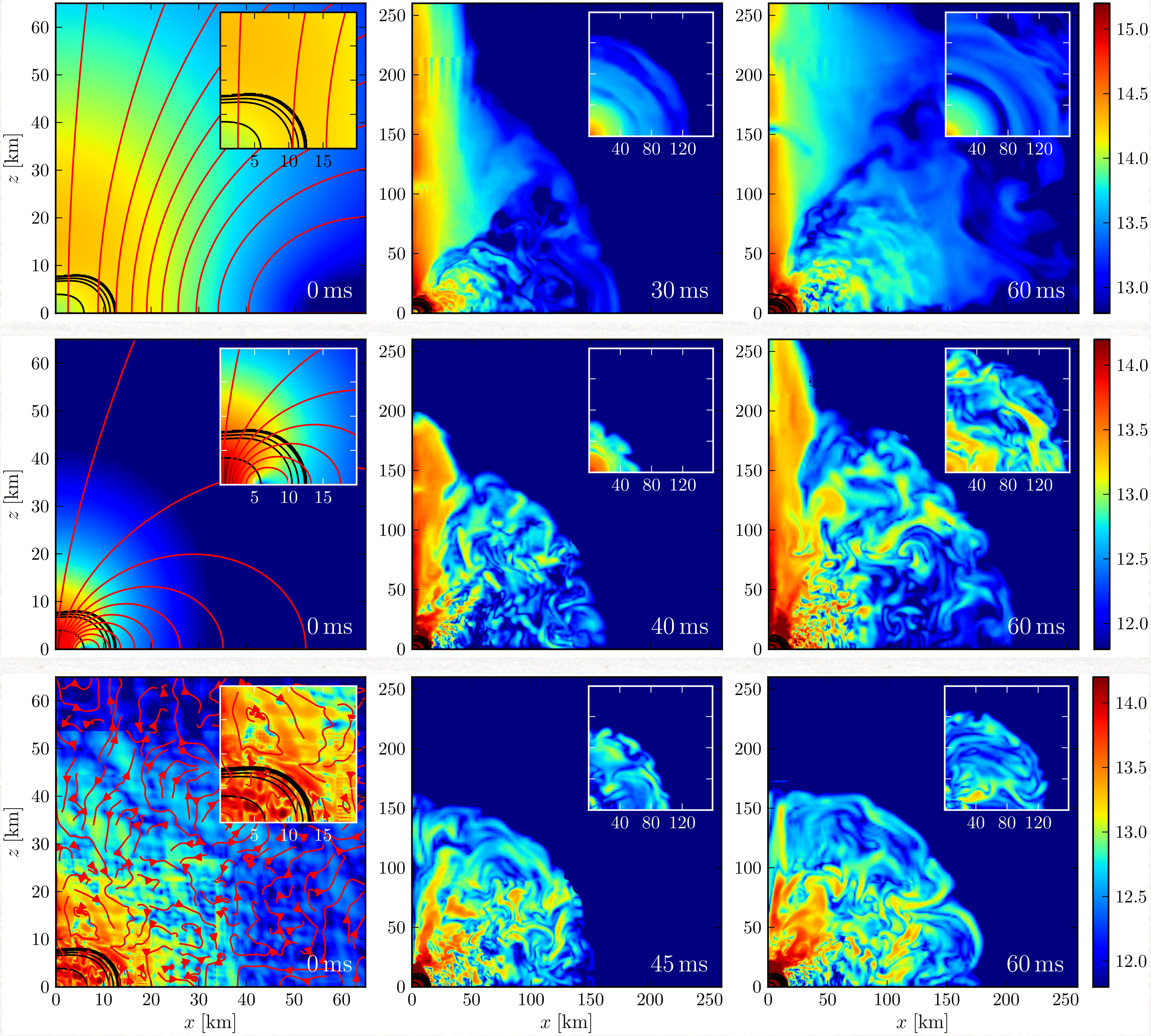


neutral line at 60 km

neutral line at 6 km

random field

Comparative table

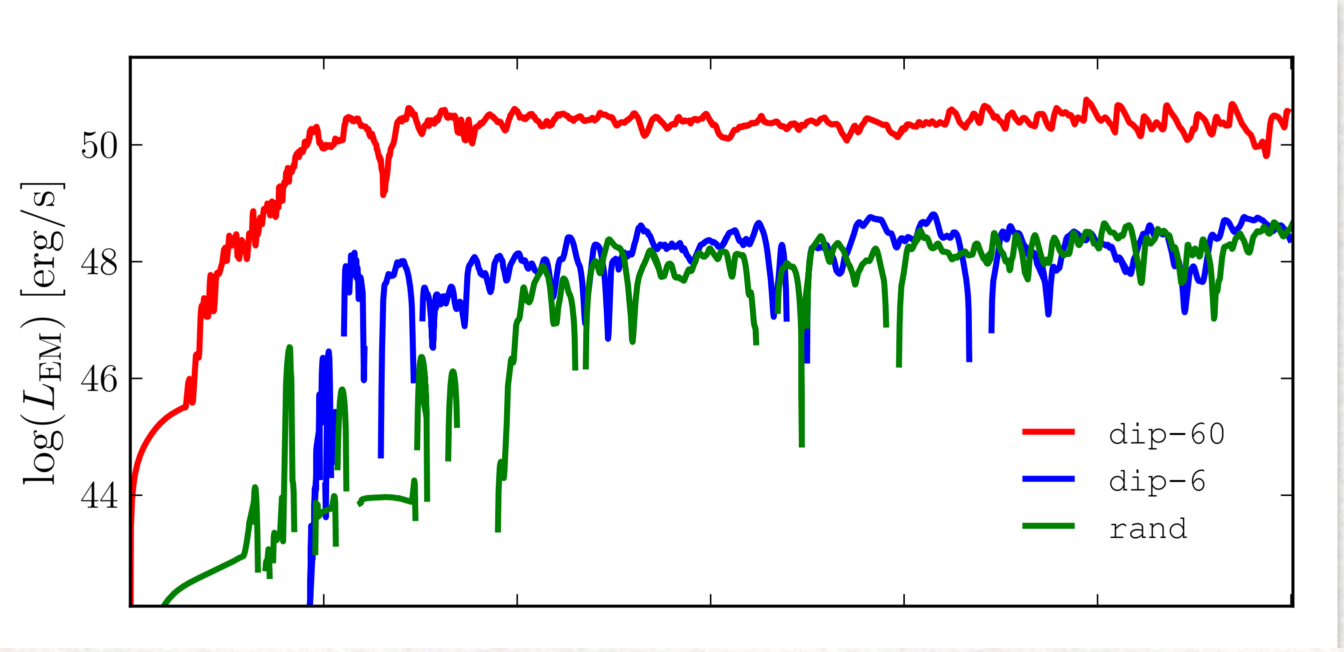


Uniform B-field inside the HMNS leads to highly collimated flow and modest isotropic wind.

Dipolar B-field inside the HMNS leads to collimated collimated flow and isotropic wind.

Random B-field inside the HMNS leads to absence of collimated flow and highly isotropic wind.

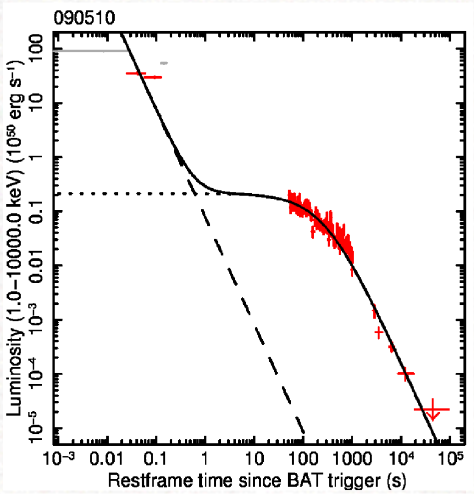
Electromagnetic luminosities

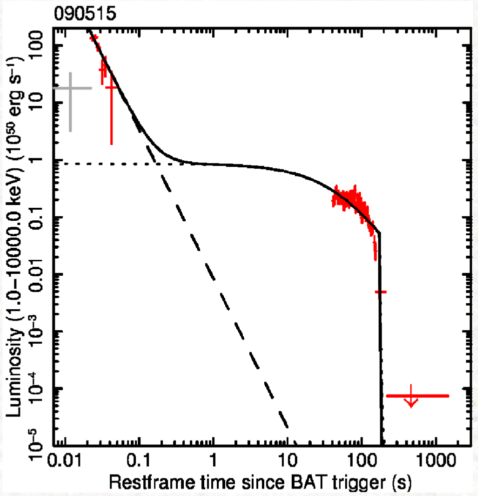


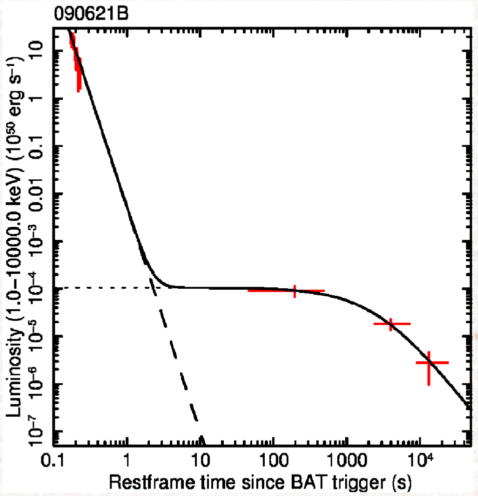
- luminosities compatible with observations for random B-field.
- the geometry does make a difference in terms of luminosity
- poloidal B-field at 60 km yields luminosity ~ 100 times larger.
- other topologies yield comparable luminosities.
- what matters is the energy in the system; when rescaled, B-field at 60 km yields same luminosity.

$$L_{\rm EM} \simeq 10^{48} \chi \left(\frac{B_0}{10^{14}\,{\rm G}}\right)^2 \left(\frac{R_e}{10^6\,{\rm cm}}\right)^3 \left(\frac{P}{10^{-4}\,{\rm s}}\right)^{-1} {\rm erg\,s^{-1}},$$

If B-fields can grow, what is their impact?







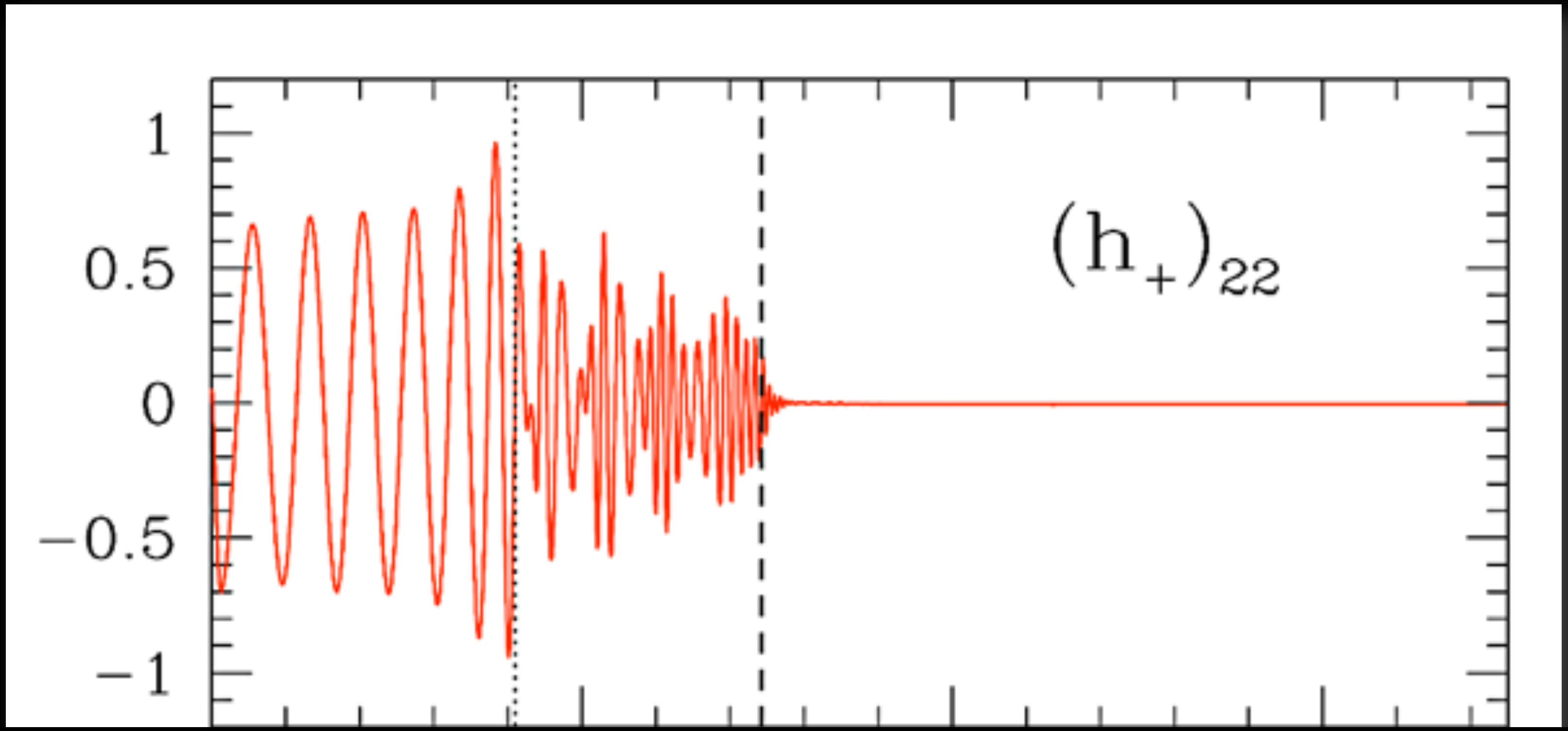
- X-ray afterglows have been observed by Swift lasting as long as 10^2-10^4 s (Rowlinson+ 13; Gompertz+13)

- The x-ray afterglow is produced by "dissipation of a proto-magnetar wind" with $L_x \sim 10^{49}\ \mathrm{erg\ s}^{-1}$ (Zhang & Mezsaros 01, Metzger+ 11, Zhang 13).
  - ★ is dipolar emission really taking place?
  - ★ what is the geometry of the wind? Collimated or spherical?
  - ★ how large is the luminosity?
  - ★ how sensitive are the results to the field topology

✴Many of these questions have been addressed but plateaus remain a **riddle**: diff. rot. will be lost in <~ 10 s (cf. 10^3s).

✴Dipolar emission is way out; how gamma emission and jet?

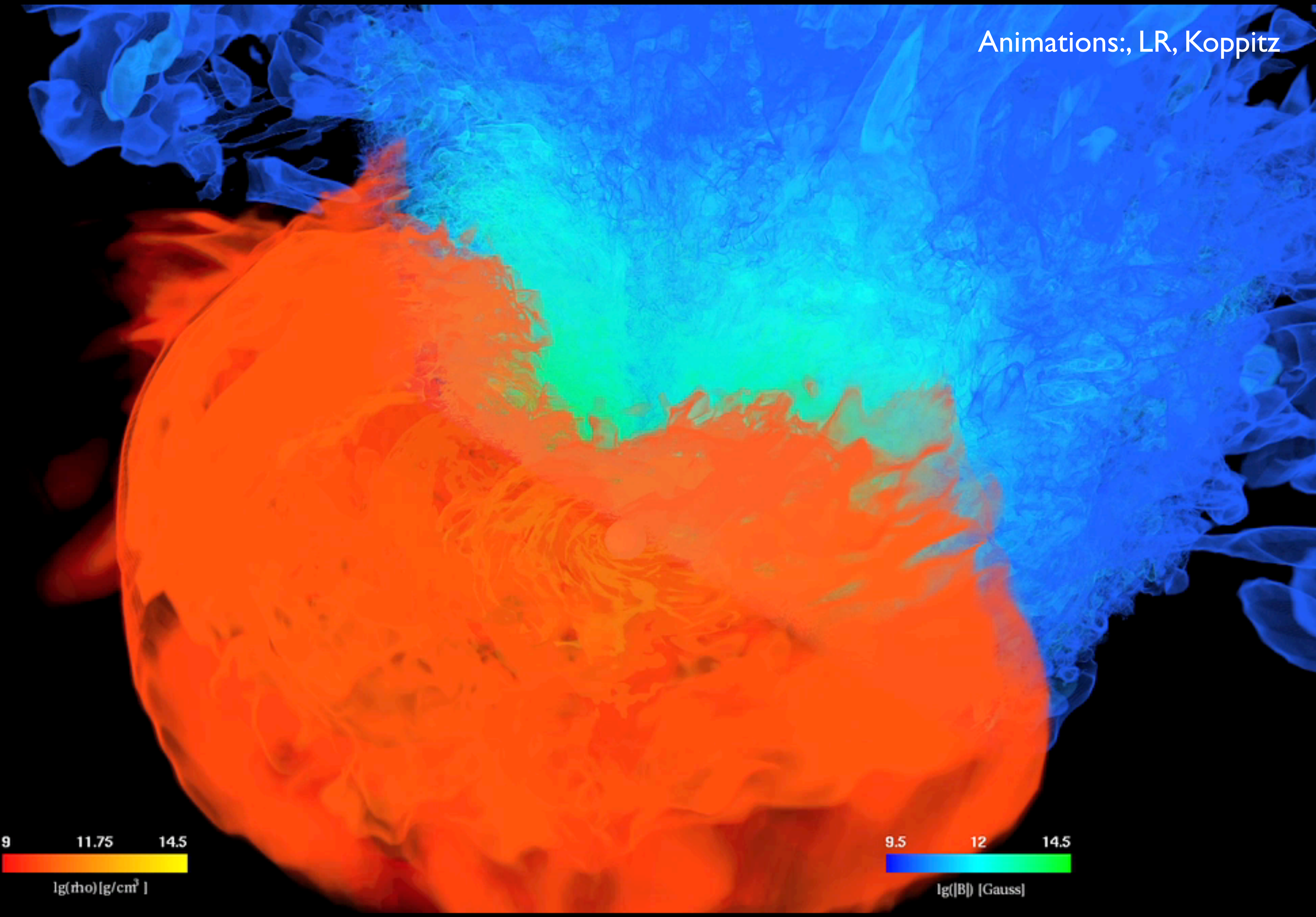
B-fields after BH formation



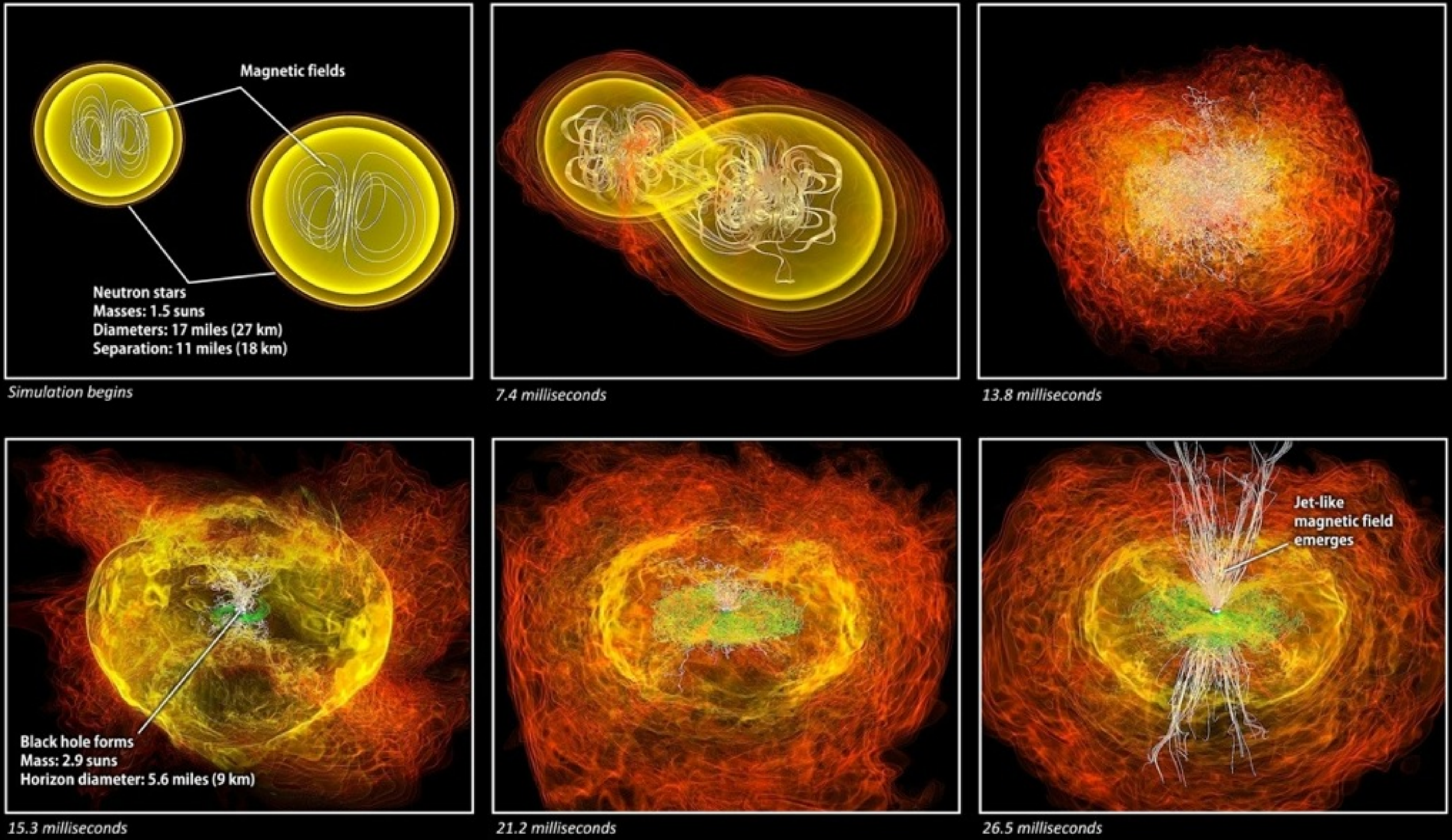
From a GW point of view, the binary becomes silent after BH formation and ringdown.

Is this really the end of the story?

Animations:, LR, Koppitz



Crashing neutron stars can make gamma-ray burst jets

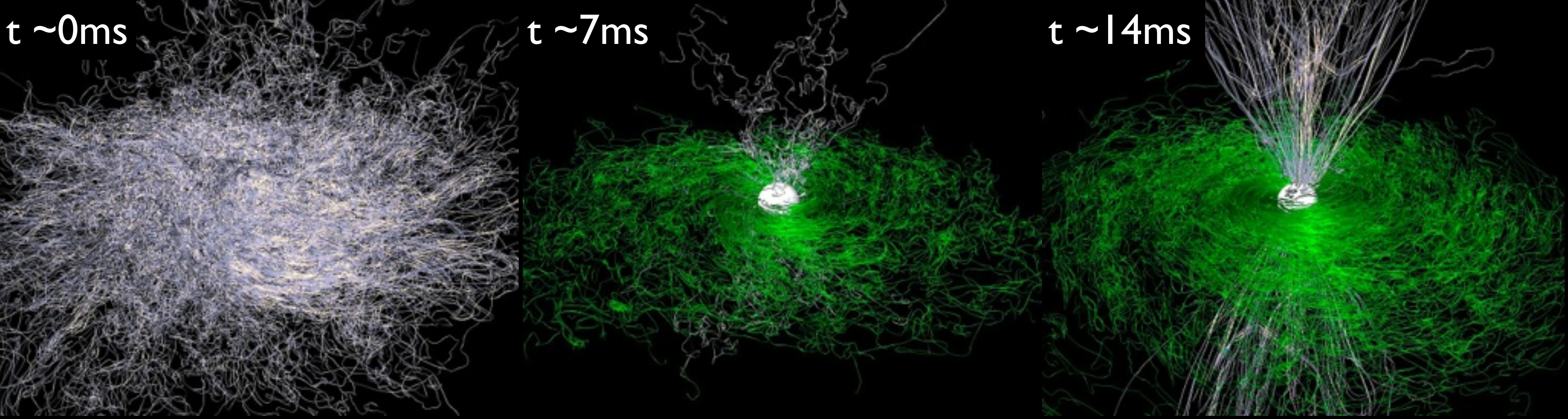


Simulation begins *7.4 milliseconds* *13.8 milliseconds*

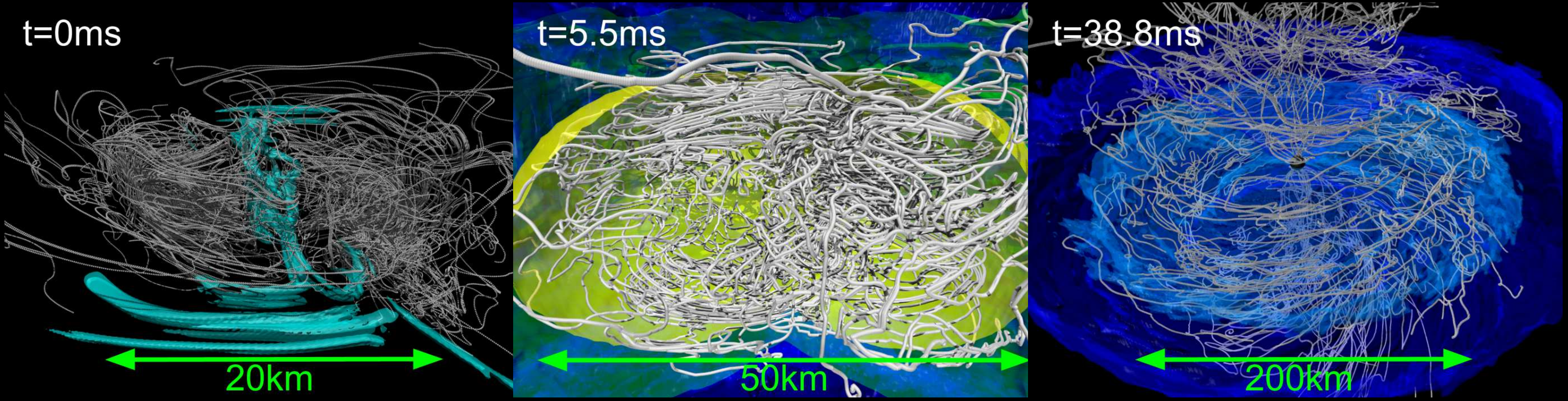
15.3 milliseconds *21.2 milliseconds* *26.5 milliseconds*

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

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



Rezzolla+ (2011); h~220m

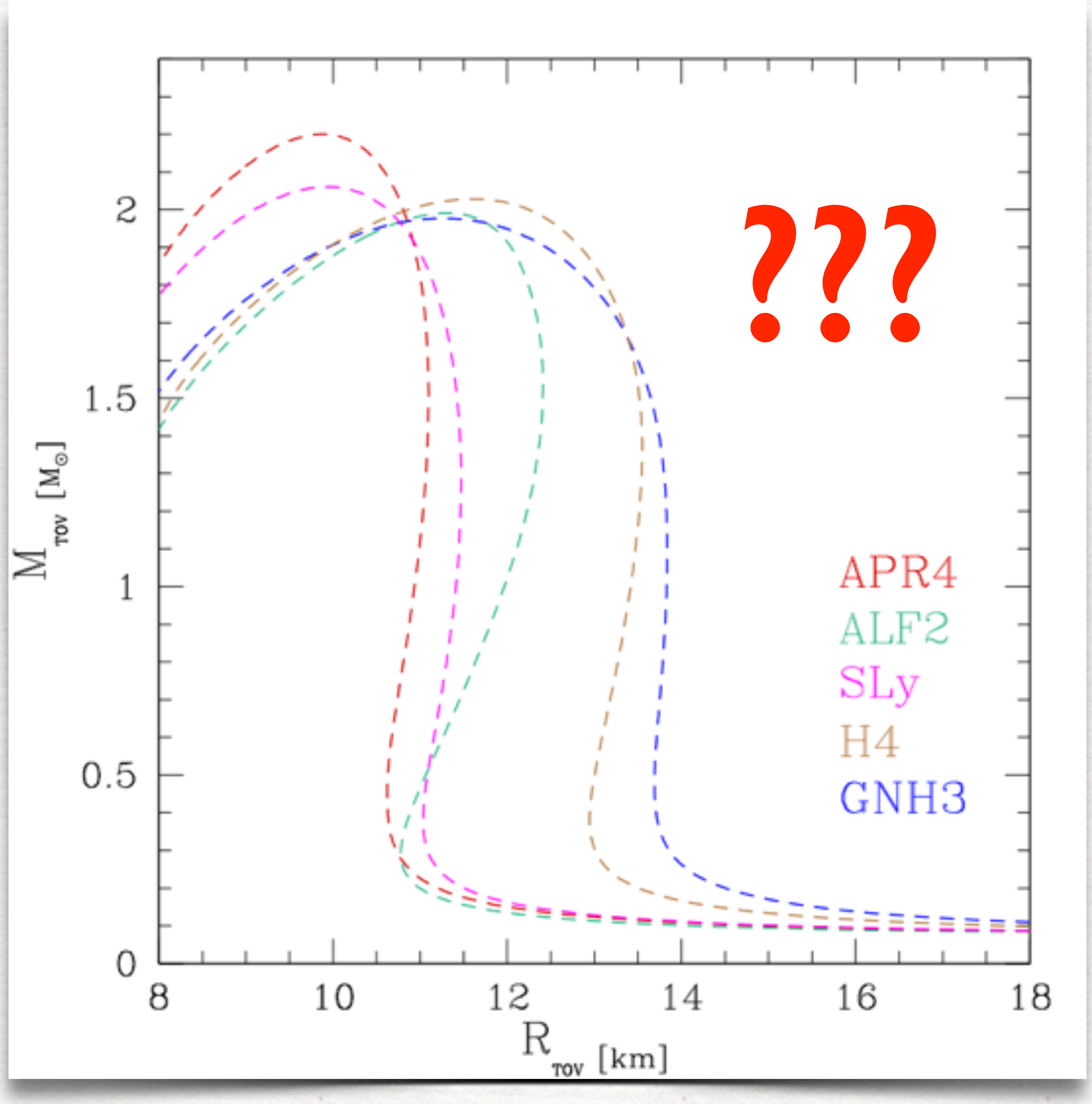


Kiuchi+ (2014); h~70m

Visualizing the field lines takes a lot of effort (no. of seeds, location, etc). Despite different setups, simulations are very similar (cf. south emisphere).

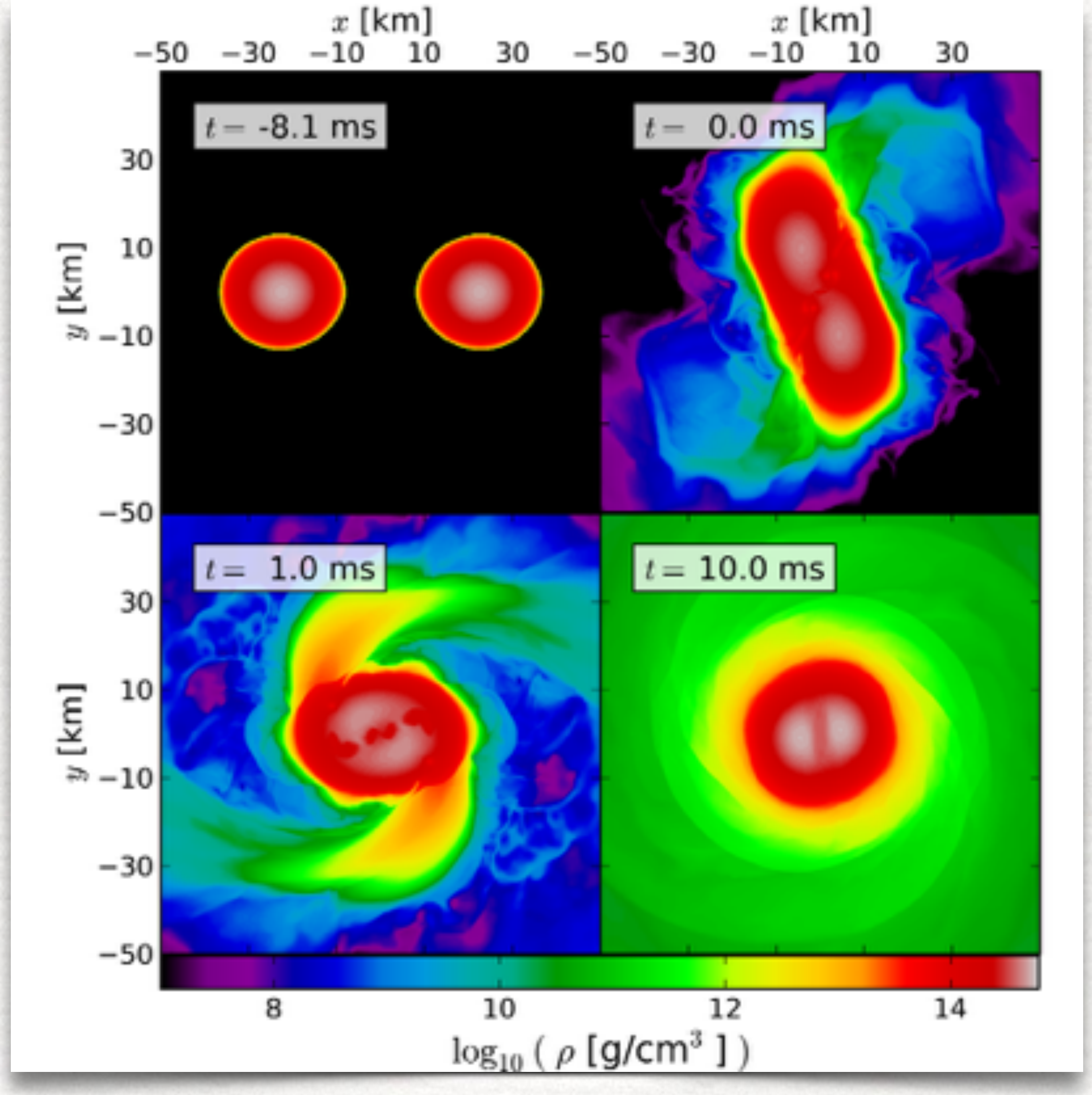
A new approach to constrain the EOS

Takami+ (2014)

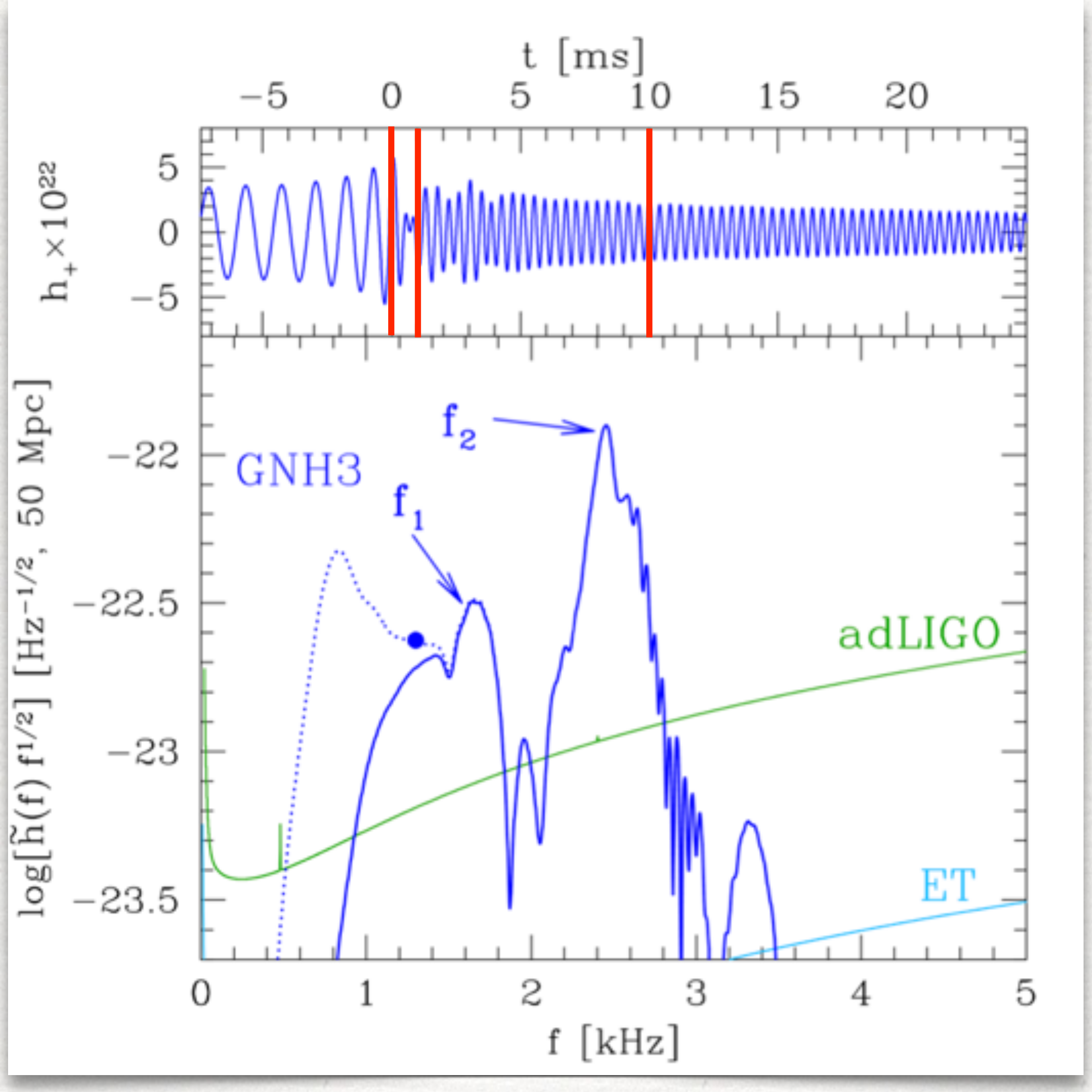


A new approach to constrain the EOS

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



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



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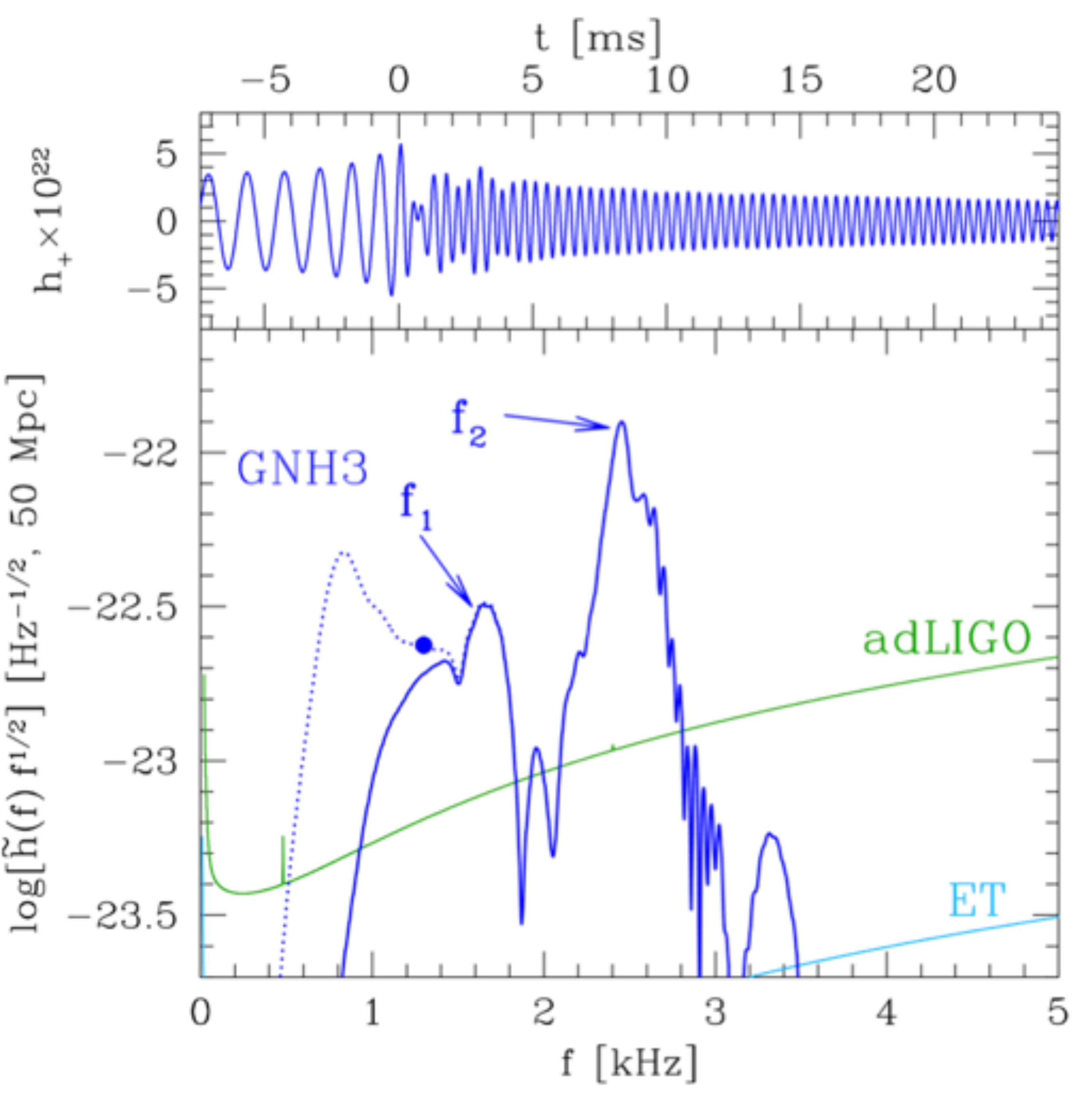

The high-freq. peak (f_2) been studied carefully and produced by HMNS (Bauswein+ 2011, 2012, Stergioulas+ 2011, Hotokezaka+ 2013)

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

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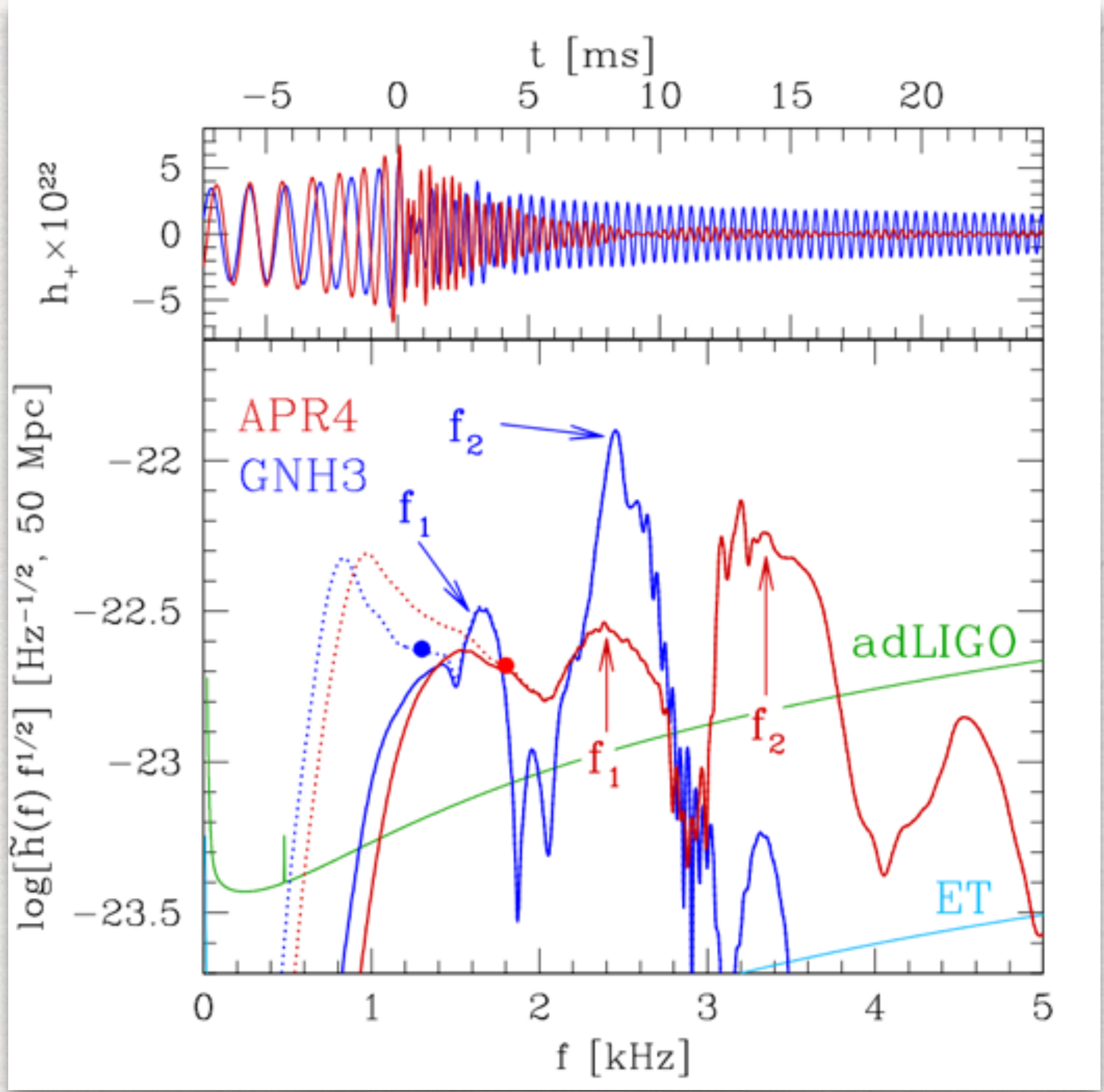
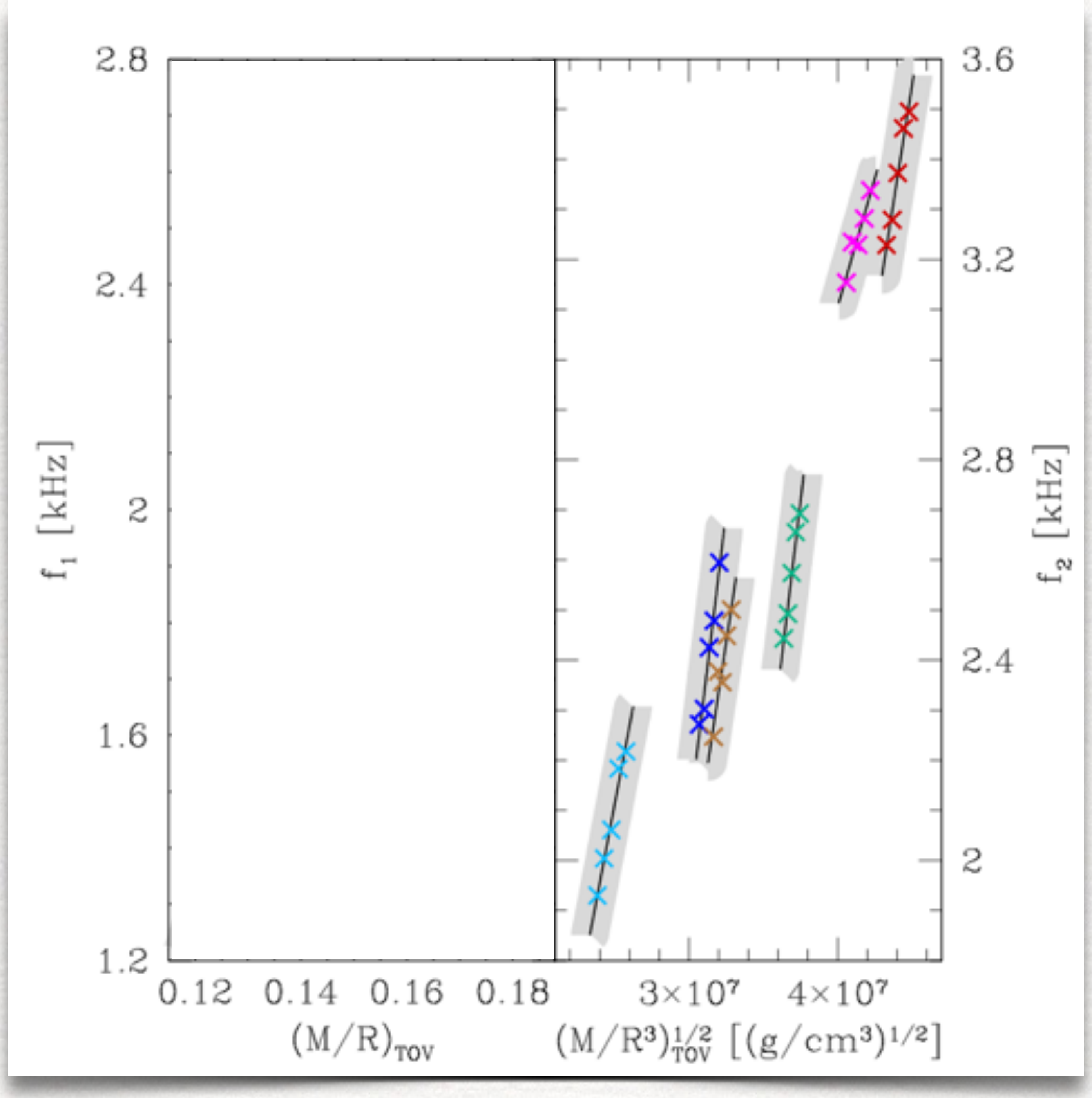


A new approach to constrain the EOS

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

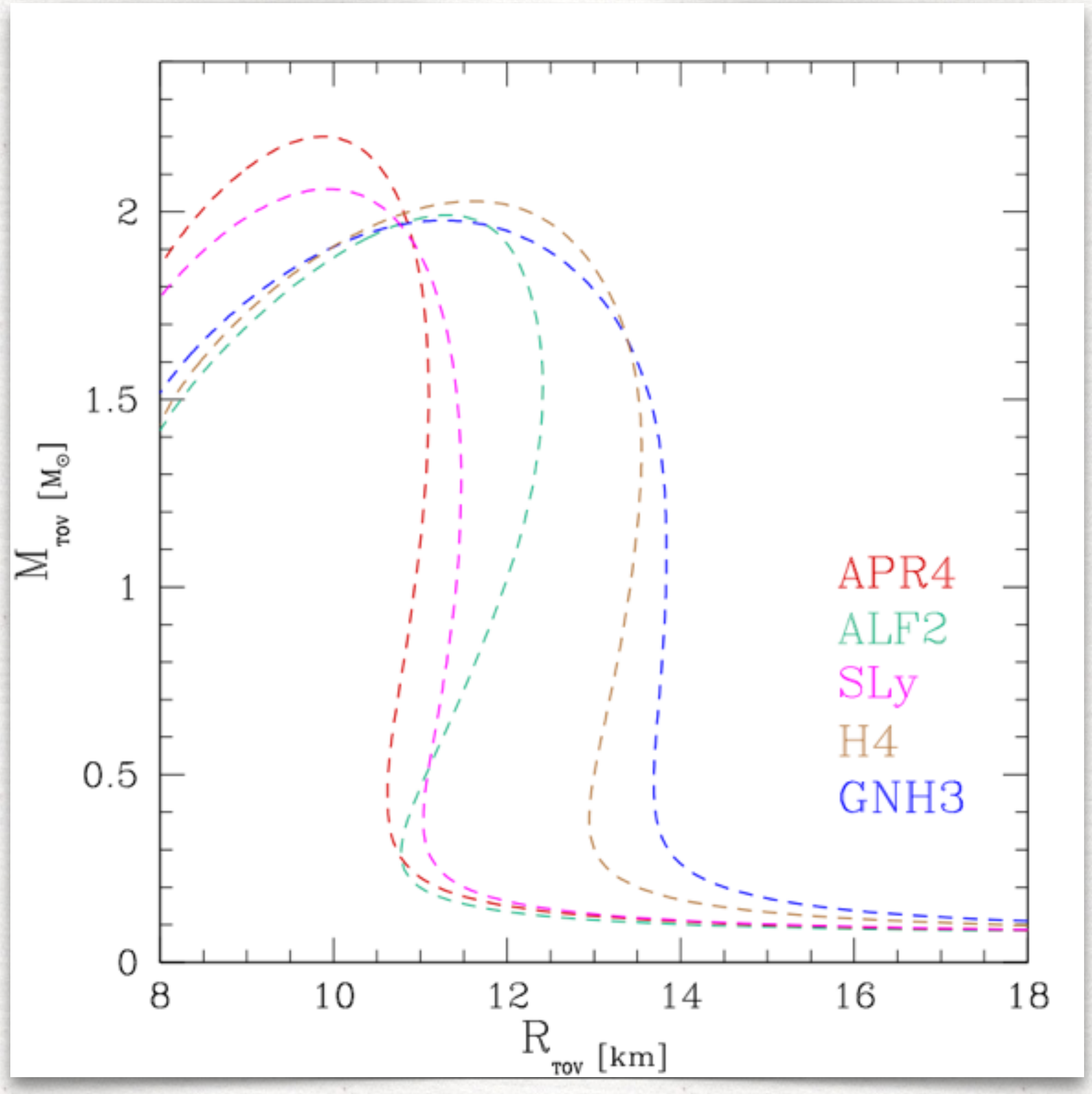
The high-freq. peak f_2 has been shown to correlate with stellar properties, e.g., R_{max}, $R_{1.6}$,. etc (Bauswein+ 2011, 2012, Hotokezaka+ 2013). The correlation **depends** on EOS

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.

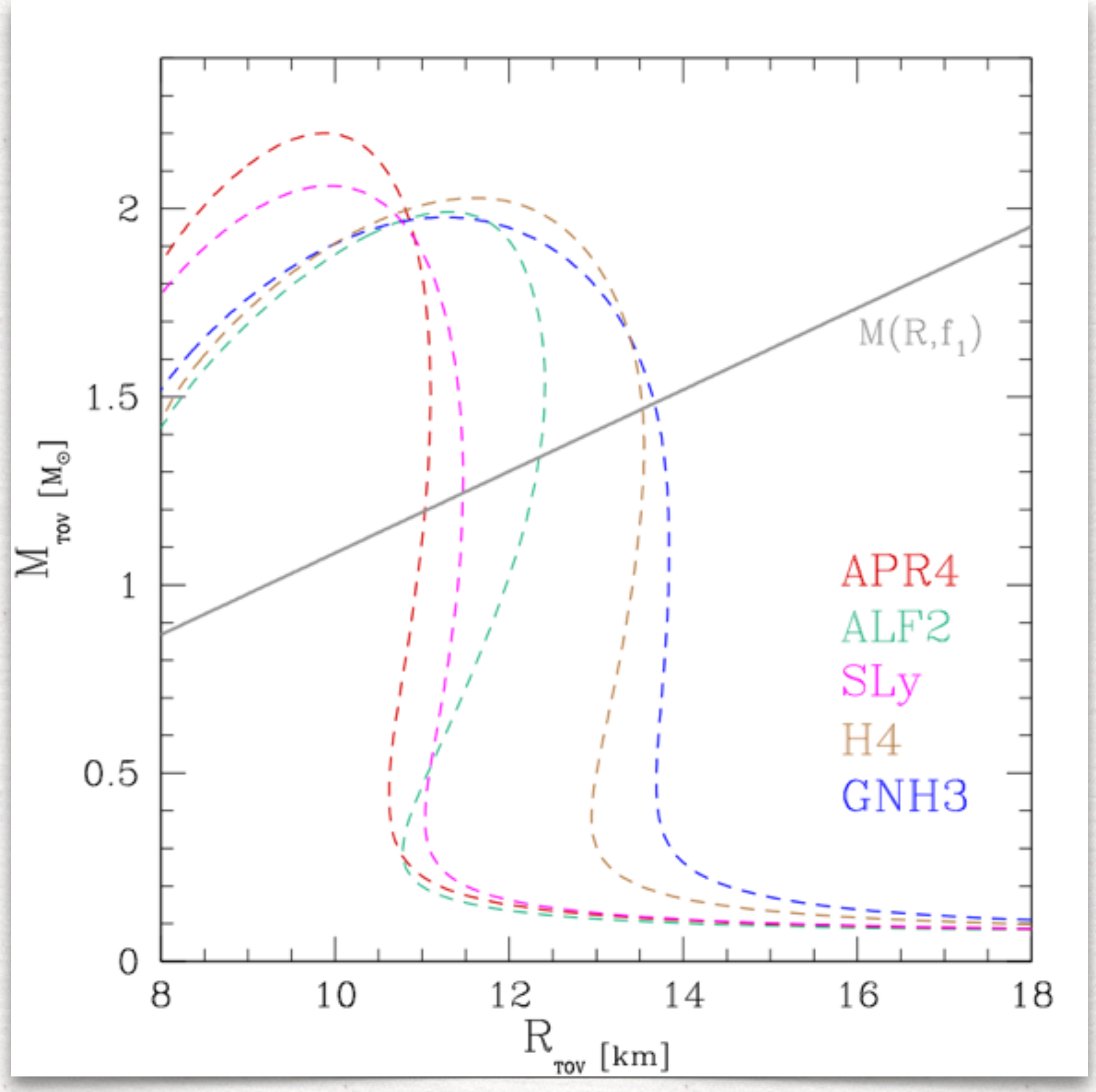
Consider your best choices as candidate EOSs



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

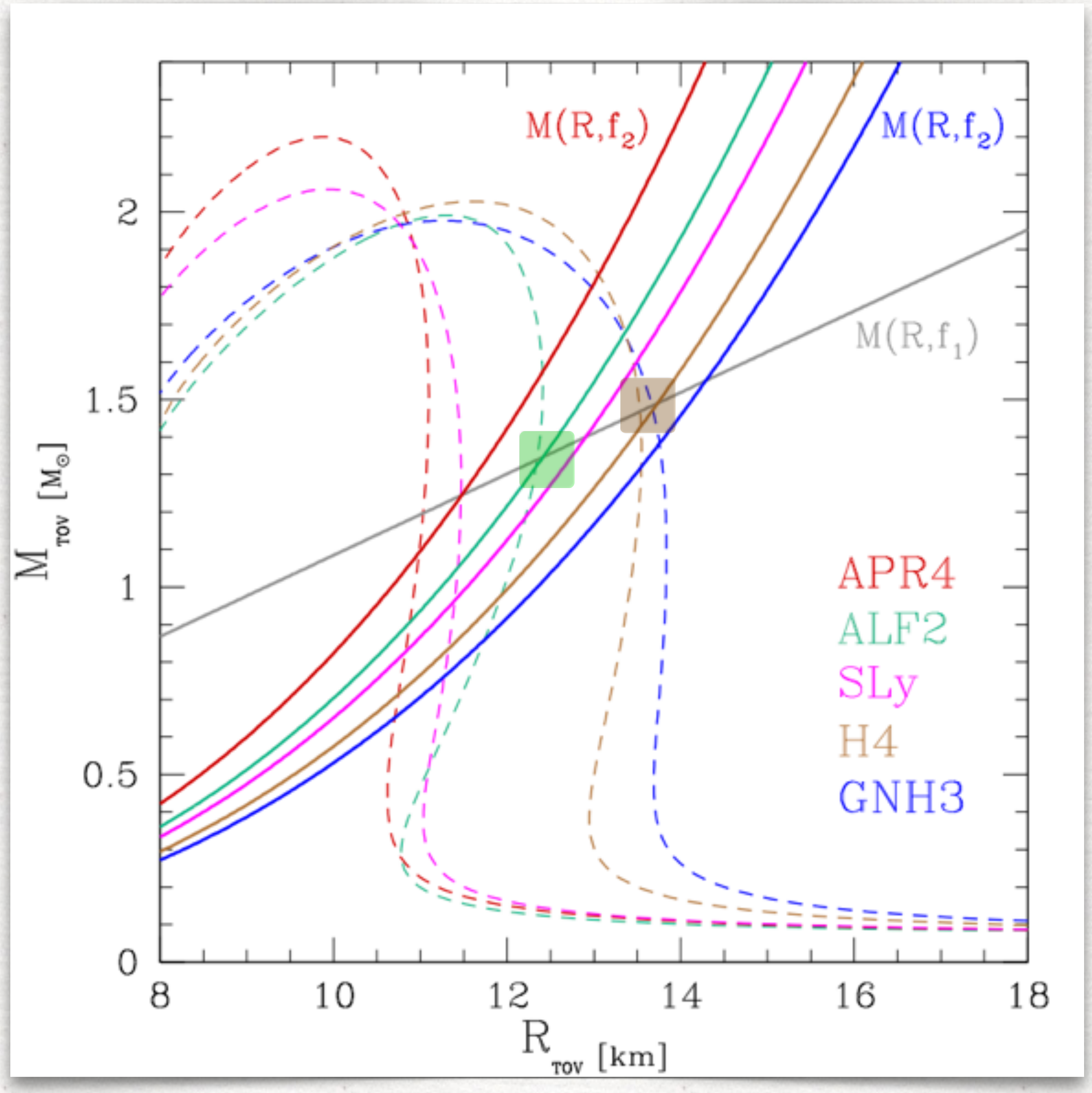
All EOSs will have **one** constraint (crossing)



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.

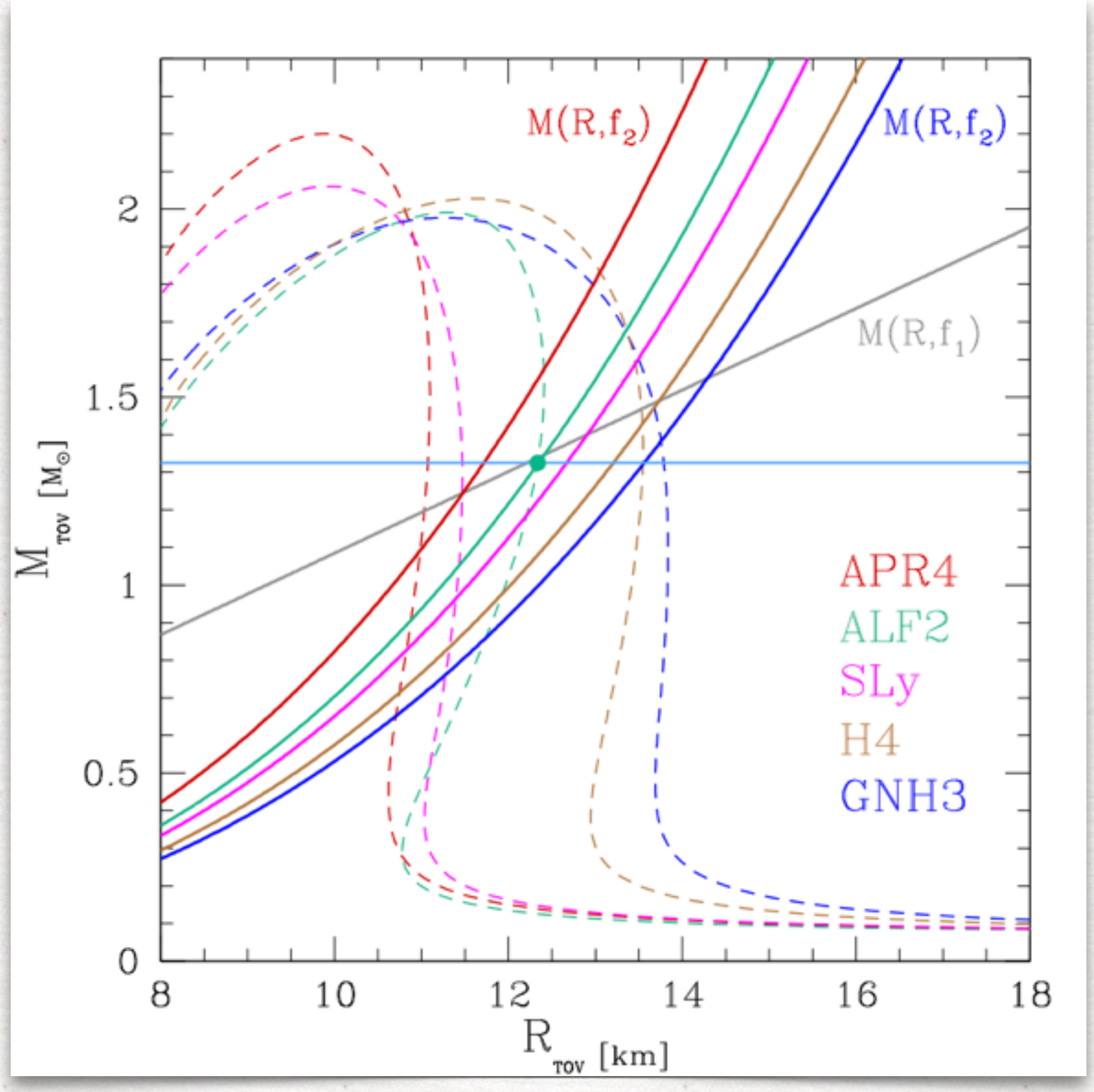
The right EOS will have **three** different constraints (APR, GNH3, SLy excluded)



An example: use measure of the mass

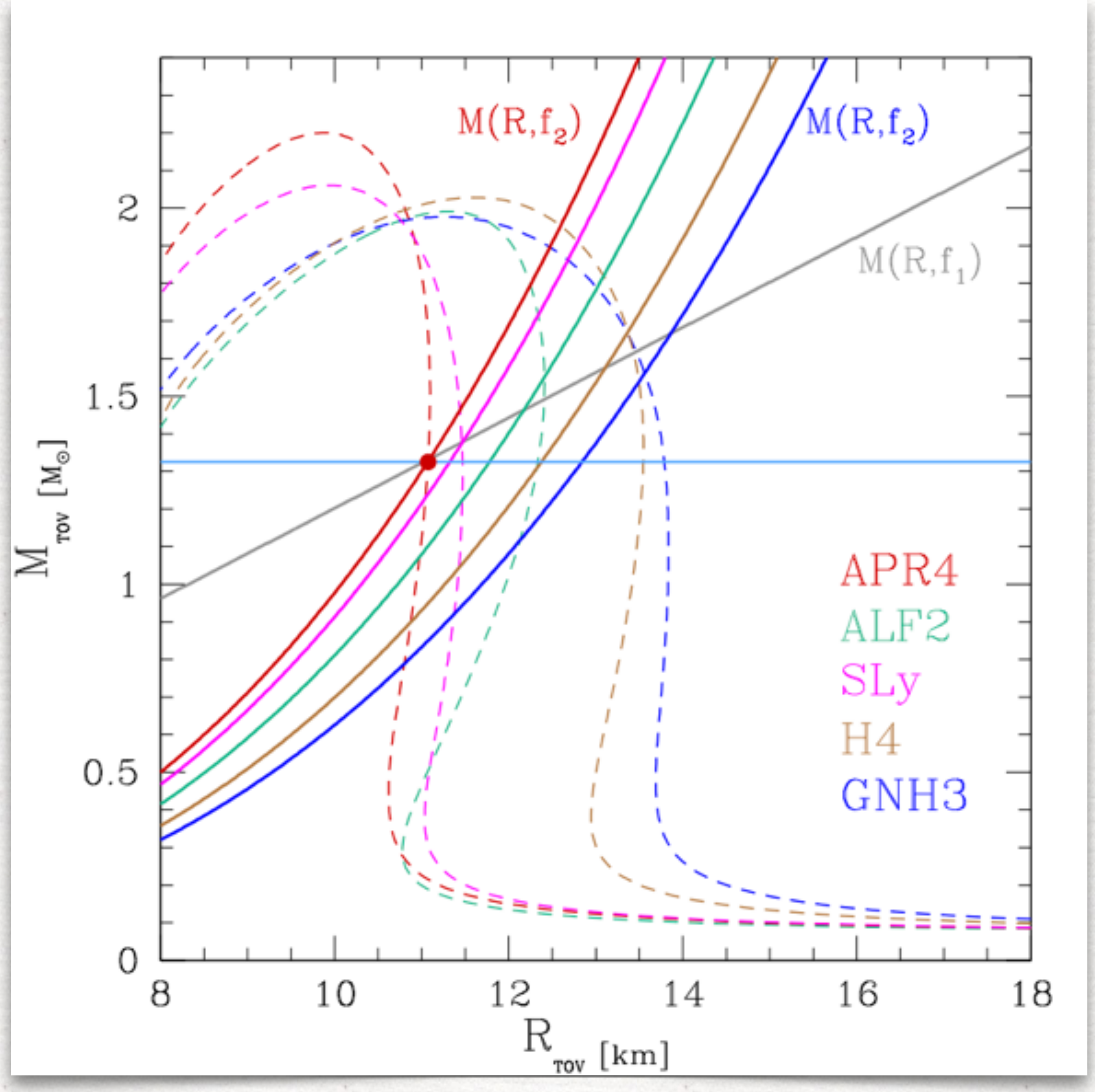
If the mass of the binary is measured from the inspiral, an additional constraint can be imposed.

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



An example: works for all EOSs considered

We have checked that the approach works well for all EOSs considered.

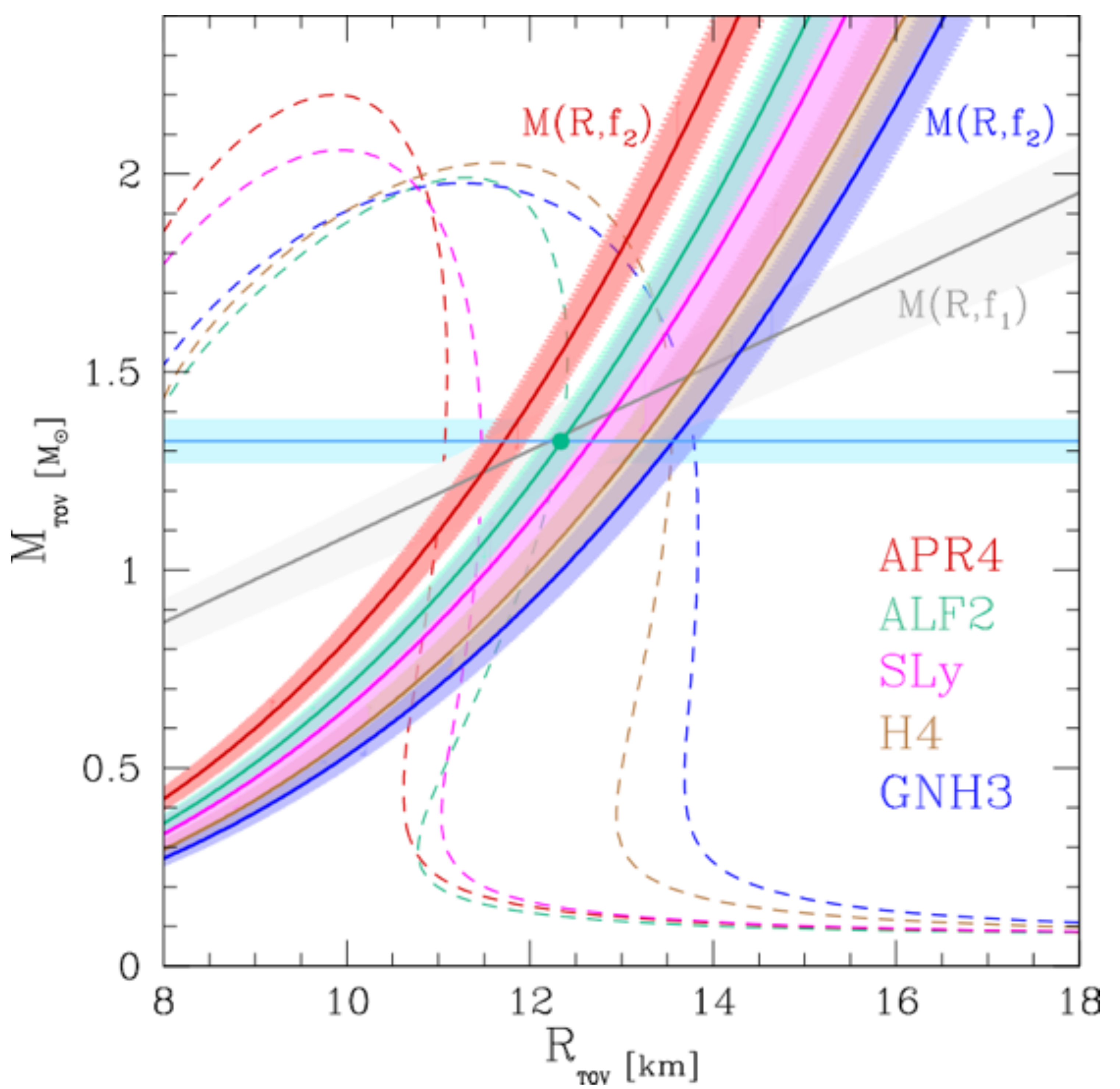


This works for all EOSs considered

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.



Conclusions

What we think we do understand about BNSs:

✳ Modelling of binary NSs in full GR is **mature**: GWs from the inspiral can be computed essentially exactly (given a model; spins?).

✳ Calculation of the tidal deformability is expensive but doable. Could use GWs to measure Love number and hence EOS.

✳Spectra of PM shows correlations (some are ”**universal**”). Terrific tool but need more precision. Hard to detect anyway.

✳Magnetic fields unlikely to be detected during the inspiral but **important** after the merger: **KH (?), MRI** or **magnetic jet**.

✳ EM counterparts from inspiral are possible but hard to detect.

✳HMNS can drive isotropic **winds** with luminosities and durations compatible with observations of X-ray **afterglows.**

Conclusions

What we* think we* do not understand about BNSs:

✳ Post-merger (PM) physics is much **richer** but poorly modelled.

✳X-ray plateaus are a **riddle**: how can emission be sustained for ~**10^3 s?** Magnetic driven wind will stop after diff. rotation is lost (10 s).

✳ Dipolar emission can be solution but how does one produce the **gammas?** How about the **jet?** BH+torus totally **irrelevant?**

✳**Ideal-MHD** inadequate for ejecta. **Resistive MHD** the solution?

✳Are estimates of **mass ejection** robust? Needs better numerics (TESS?). Kilonova emission and r-processes are great motivations to improve.

✳ **Neutrinos** will play a role for low-mass HMNS. Hard problem with many degrees of freedom. Sekiguchi+ (2012,…) setting the frontier.

"We are excited by attacking difficult problems, which show all of their worth by attacking back" C. W. Misner