The physics and astrophysics of merging neutron-star binaries

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15.12.17

Outline

- the irresistible "attraction" of gravity
- beauty and challenges of general relativity
- neutron stars: Einstein's richest laboratory
- binary mergers:

  gravitational waves, gamma-ray bursts, nucleosynthesis,…

Our experience of gravity

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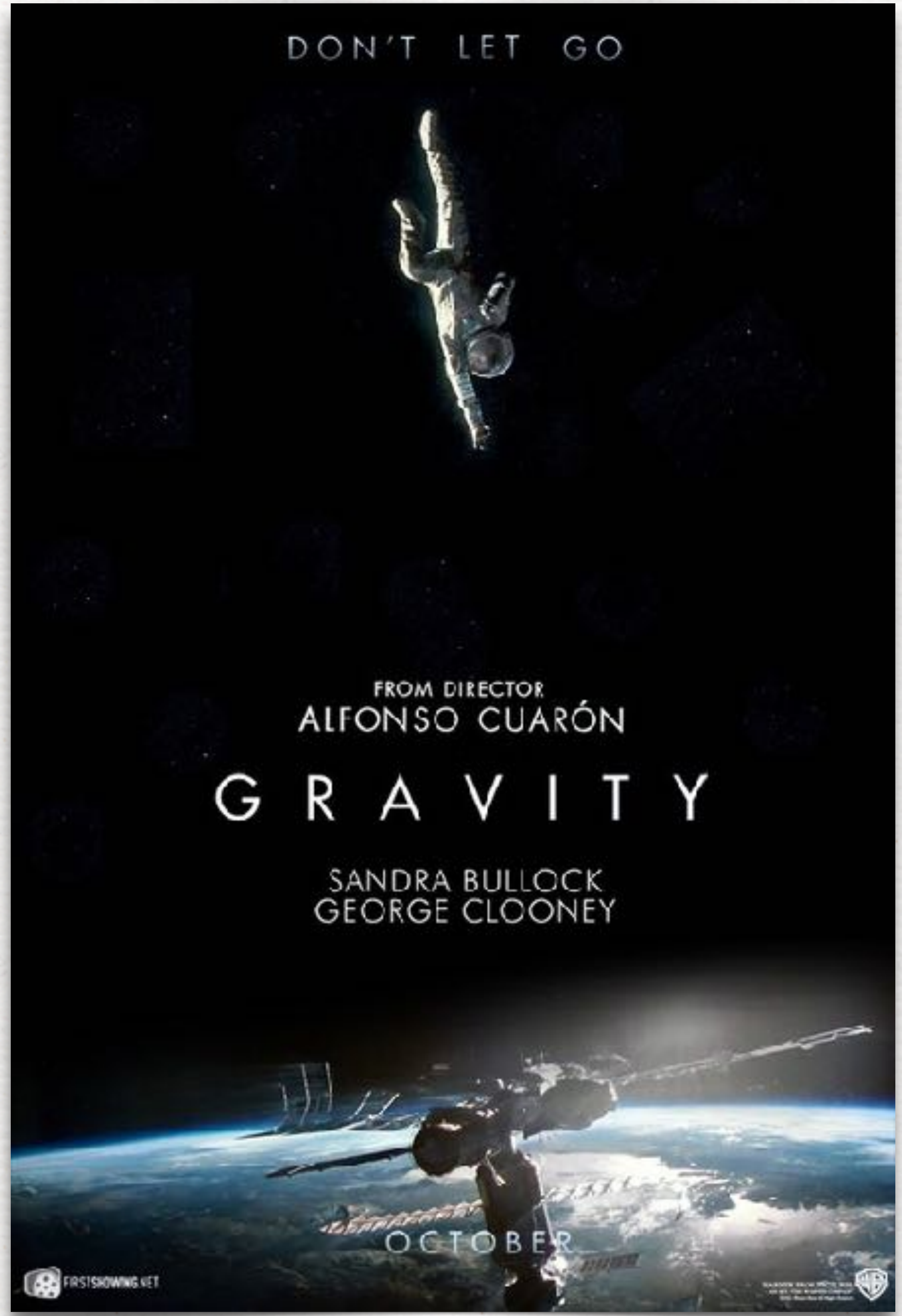
* Instinctive notion

Our experience of gravity

- Instinctive notion
- Intuitive notion

Our experience of gravity

- Instinctive notion
- Intuitive notion
- Imaginative notion

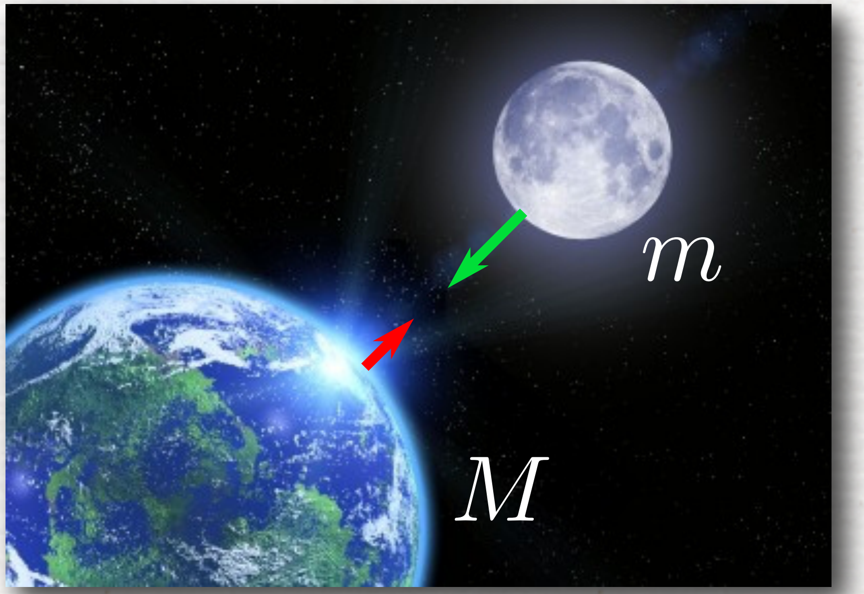


The fathers of gravity

In **1679** Newton publishes his theory of gravity.

Gravity is an instantaneous **force** between two masses proportional to the masses and inversely proportional to the square of the distance.

$$\vec{F} = -\frac{G}{c^2}\frac{Mm}{r^2}\vec{e_r}$$

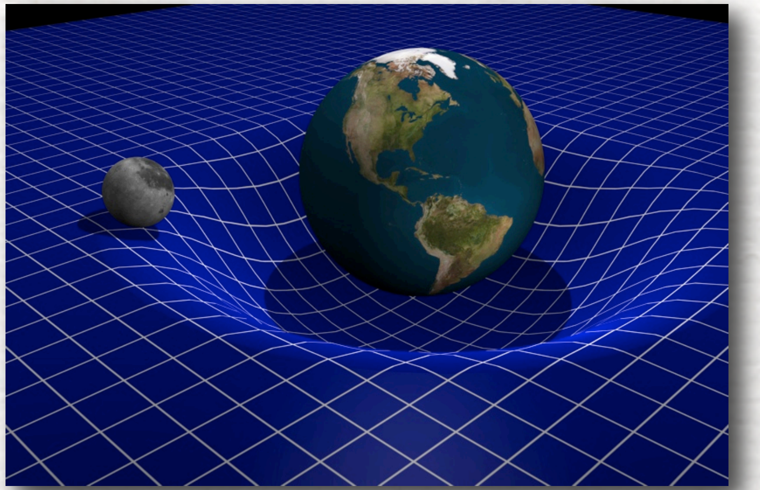


With this theory he could explain essentially **all astronomical** observations of his time.

The fathers of gravity

In **1915** Einstein publishes his theory of gravity (**Allgemeine Relativitätstheorie**) changing our understanding of gravity.

According to Einstein, gravity is the manifestation of spacetime **curvature**.



Any form of mass/energy curves the spacetime.

Implications of this view are: **black holes, neutron stars, gravitational waves.**

Einstein equations

$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

Einstein equations

Einstein tensor

stress-energy tensor

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spacetime
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mass and energy
in the spacetime

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spacetime curvature

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There is a relation between the **curvature** and **mass/energy.**

gravity is the manifestation of spacetime curvature

What is spacetime curvature?

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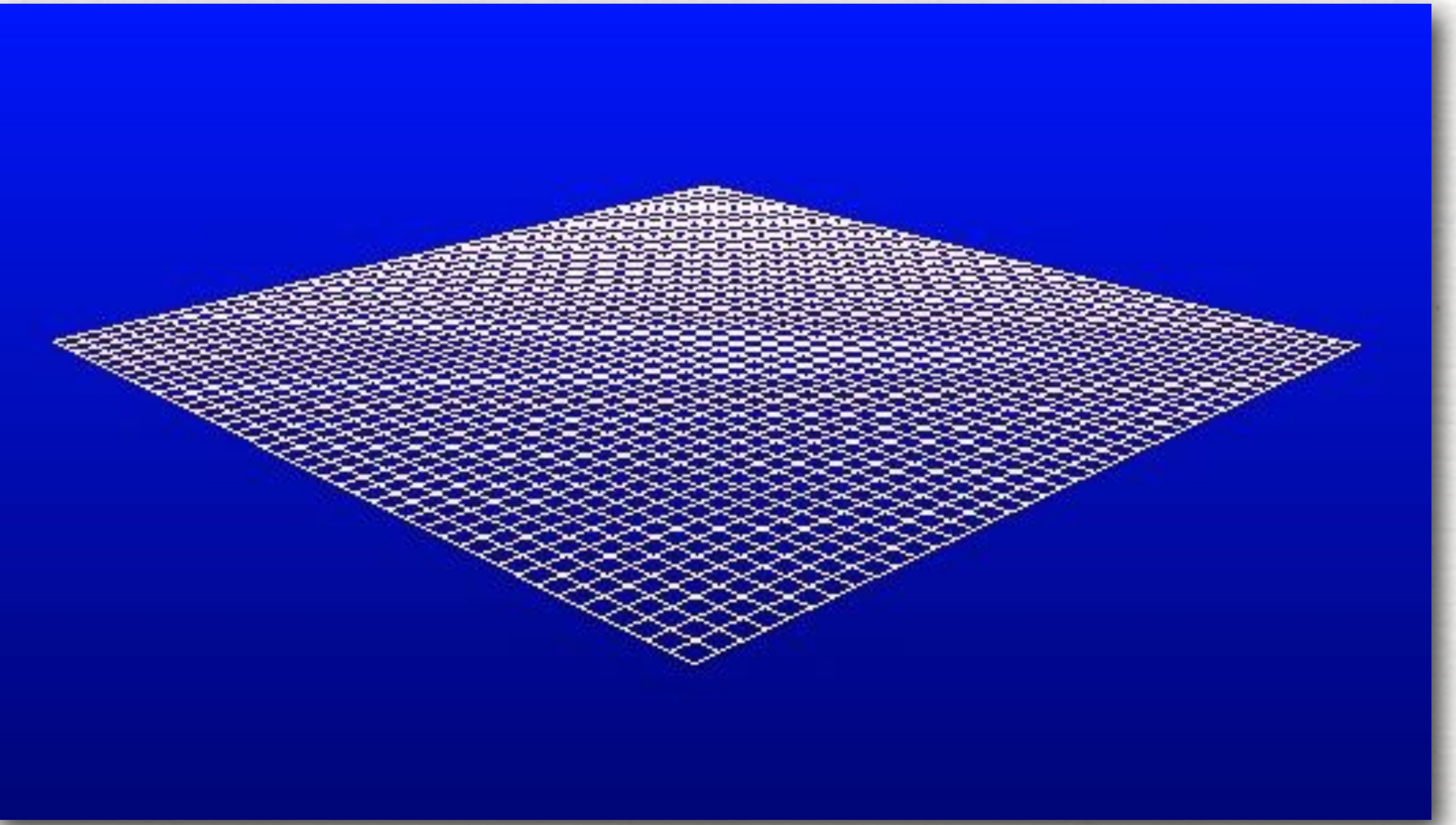
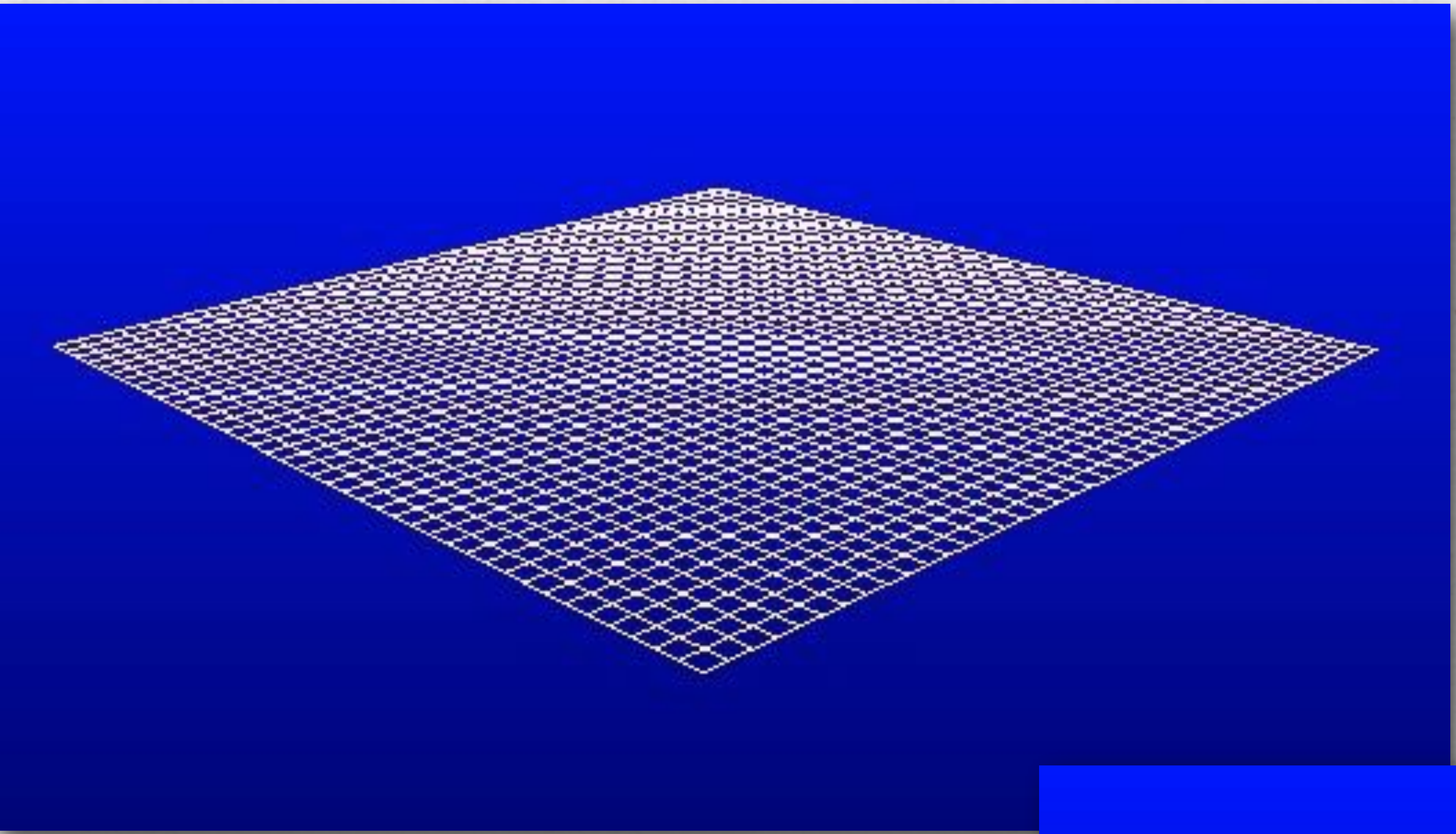


Let's consider a region of space and time (spacetime) void of matter and energy. It will have **zero** curvature and will therefore be **flat**

What is spacetime curvature?



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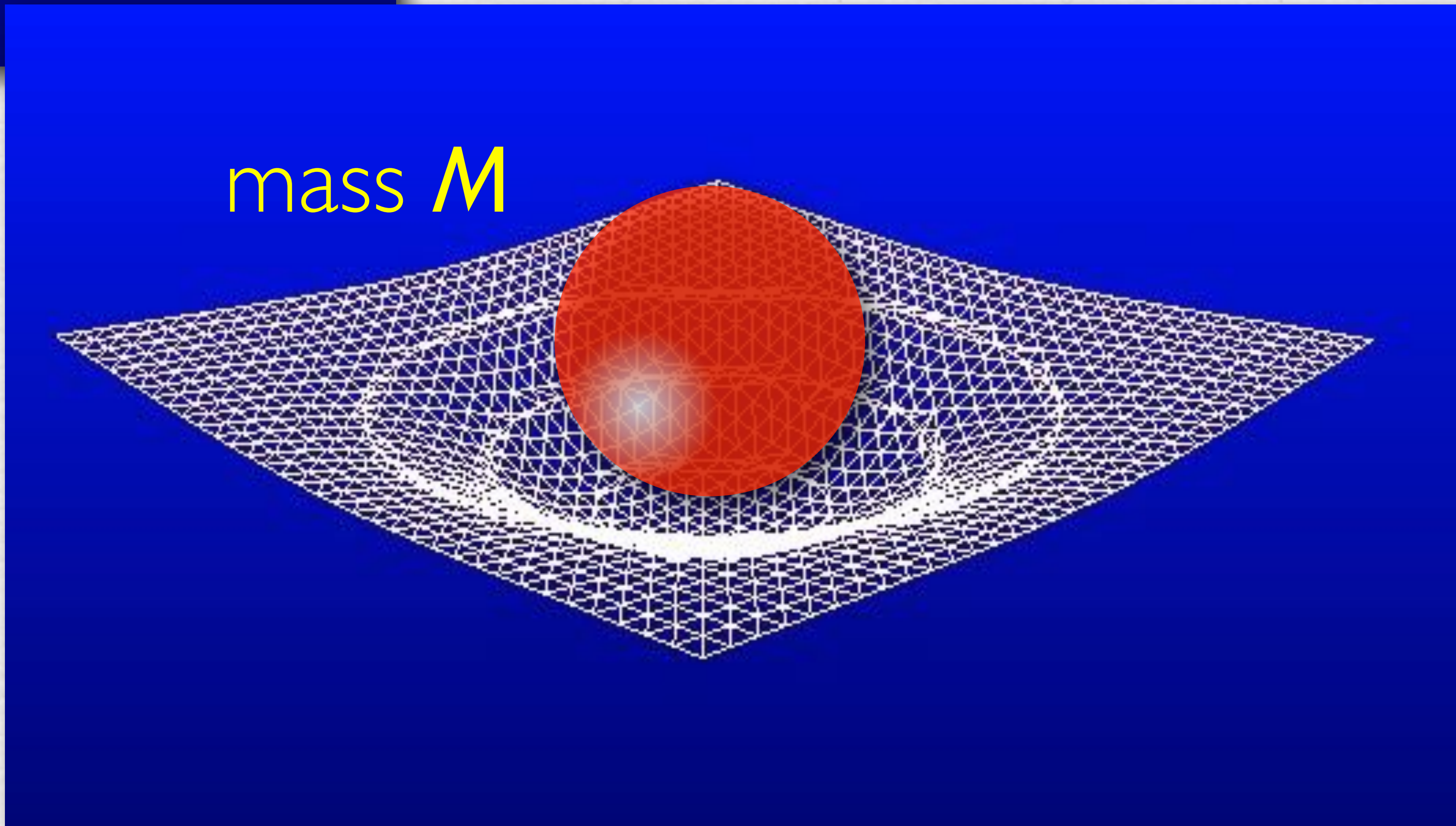
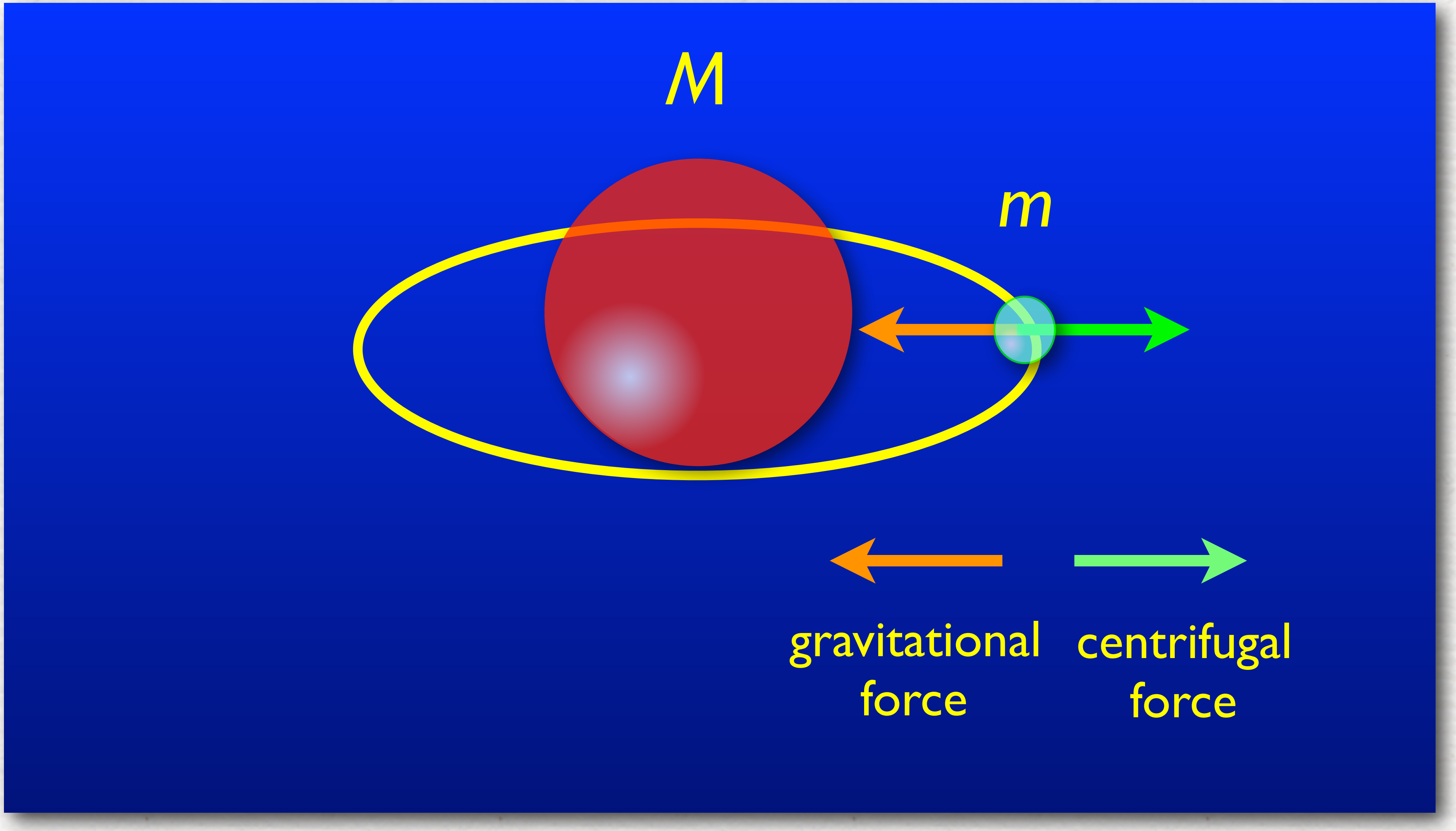
If instead it contains a mass *M*, it will have a nonzero curvature and will therefore be a **curved spacetime**



Gravity à la Newton

Consider orbital motion of an object of small mass ***m*** around an object of large mass ***M*:** (e. g., Earth around the Sun)

Newton: *orbit is the balance between the* ***gravitational force*** *and the* ***centrifugal one***



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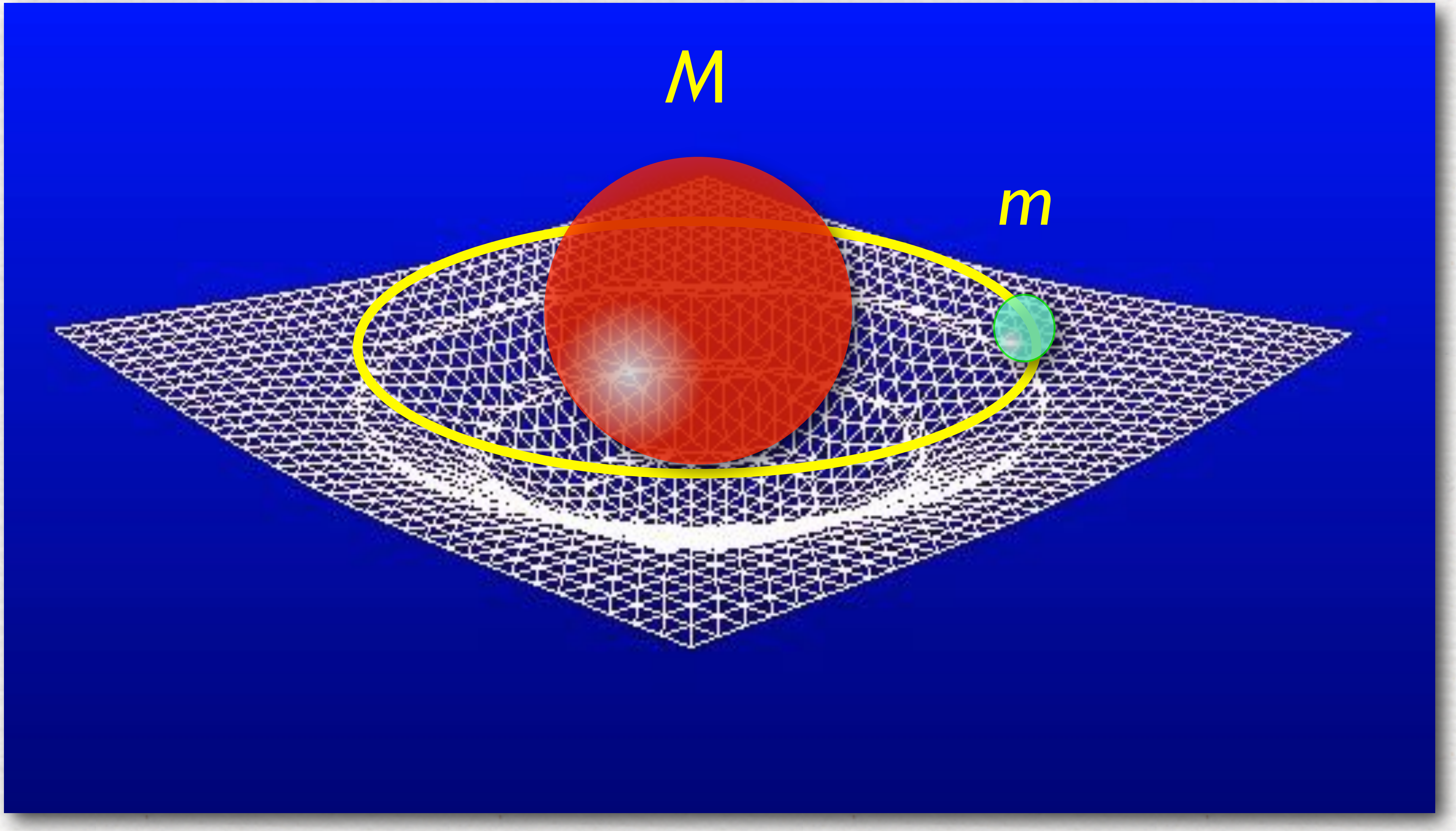
Einstein: *orbit is the motion on a* ***curved surface*** *which avoids the falling in.*



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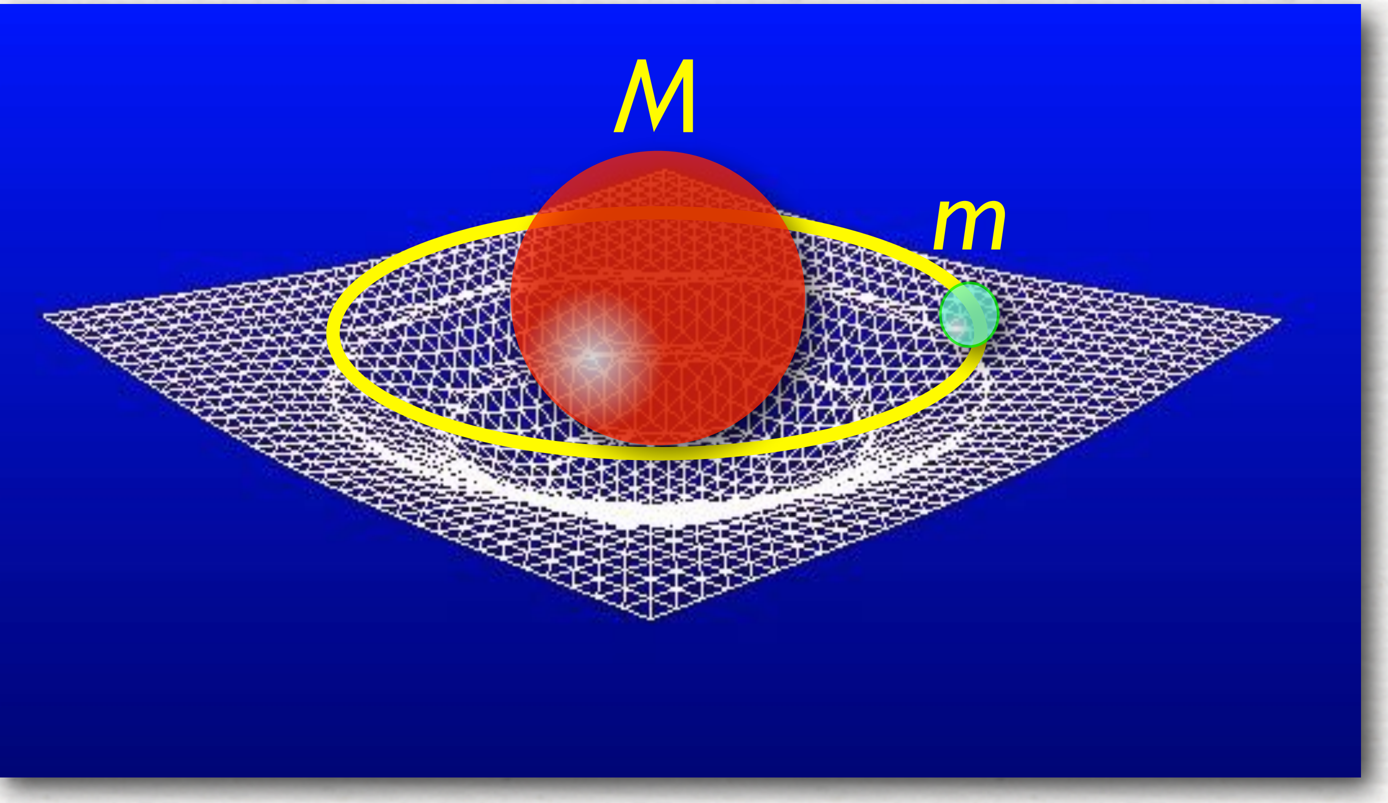

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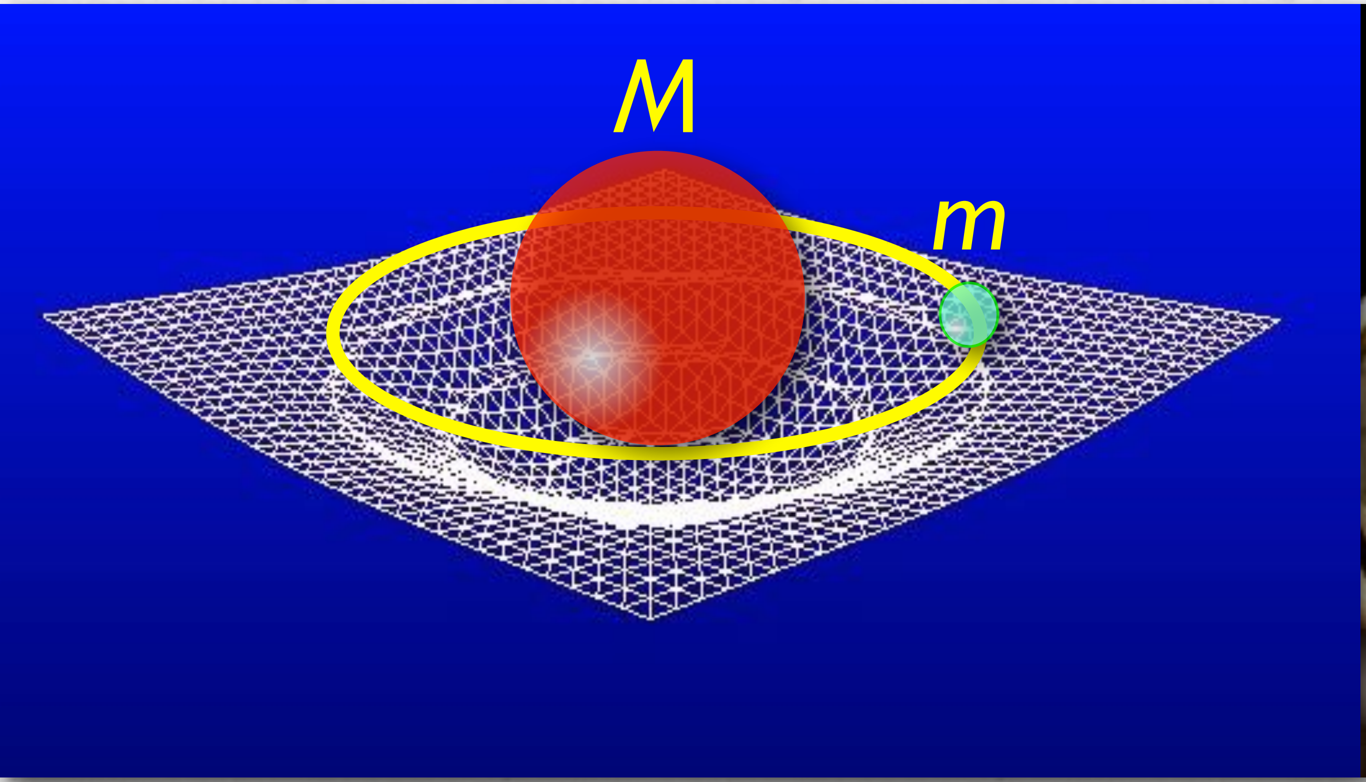

Black holes, neutron stars and gravitational waves two important common features:

- high curvature (compactness, M/R)
- move near speed of light

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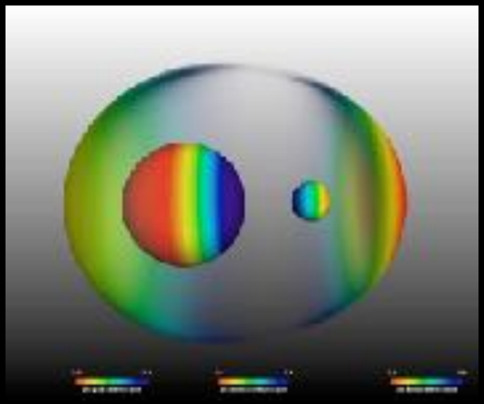
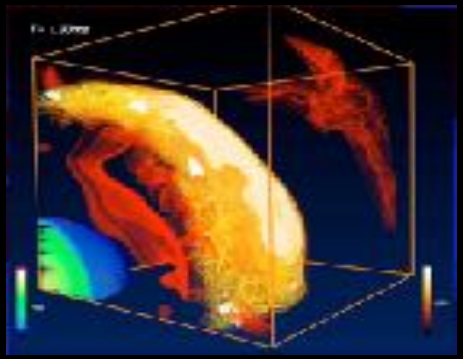
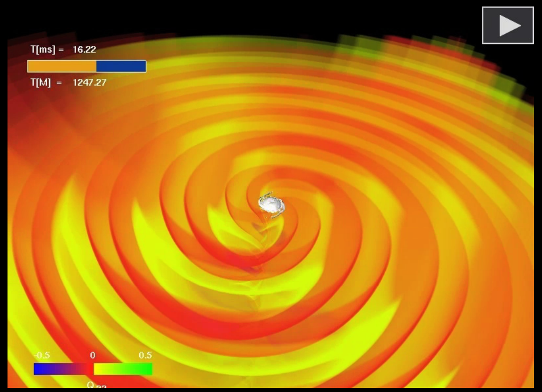
Studying black holes, neutron stars and gravitational waves is not easy!







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$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$
$$\nabla_\mu T^{\mu\nu} = 0$$
$$\nabla_\mu \left(\rho u^\mu\right) = 0$$

Hard not to be fascinated by the compact beauty of these equations and by their profound implications.

but then reality kicks in…

$$
\begin{aligned}
\partial_t\tilde{\gamma}_{ij} &= -2\alpha\tilde{A}_{ij}^{\mathrm{TF}} + 2\tilde{\gamma}_{k(i}\partial_{j)}\,\beta^k - \frac{2}{3}\tilde{\gamma}_{ij}\partial_k\,\beta^k + \beta^k\partial_k\tilde{\gamma}_{ij}\,, \\
\partial_t\tilde{A}_{ij} &= \phi^2\left[-\nabla_i\nabla_j\alpha + \alpha\left(R_{ij} + \nabla_i Z_j + \nabla_j Z_i - 8\pi S_{ij}\right)\right]^{\mathrm{TF}} + \alpha\tilde{A}_{ij}\left(K - 2\Theta\right) \\
&\quad -2\alpha\tilde{A}_{il}\tilde{A}^l_j + 2\tilde{A}_{k(i}\partial_{j)}\,\beta^k - \frac{2}{3}\tilde{A}_{ij}\partial_k\,\beta^k + \beta^k\partial_k\tilde{A}_{ij}\,, \\
\partial_t\phi &= \frac{1}{3}\alpha\phi K - \frac{1}{3}\phi\partial_k\beta^k + \beta^k\partial_k\phi\,, \\
\partial_t K &= -\nabla^i\nabla_i\alpha + \alpha\left(R + 2\nabla_i Z^i + K^2 - 2\Theta K\right) + \beta^j\partial_j K - 3\alpha\kappa_1\left(1+\kappa_2\right)\Theta + 4\pi\alpha\left(S - 3\tau\right)\,, \\
\partial_t\hat{\Gamma}^i &= 2\alpha\left(\tilde{\Gamma}^i_{jk}\tilde{A}^{jk} - 3\tilde{A}^{ij}\frac{\partial_j\phi}{\phi} - \frac{2}{3}\tilde{\gamma}^{ij}\partial_j K\right) + 2\tilde{\gamma}^{ki}\left(\alpha\partial_k\Theta - \Theta\partial_k\alpha - \frac{2}{3}\alpha K Z_k\right) - 2\tilde{A}^{ij}\partial_j\alpha \\
&\quad +\tilde{\gamma}^{kl}\partial_k\partial_l\beta^i + \frac{1}{3}\tilde{\gamma}^{ik}\partial_k\partial_l\beta^l + \frac{2}{3}\tilde{\Gamma}^i\partial_k\beta^k - \tilde{\Gamma}^k\partial_k\beta^i + 2\kappa_3\left(\frac{2}{3}\tilde{\gamma}^{ij}Z_j\partial_k\beta^k - \tilde{\gamma}^{jk}Z_j\partial_k\beta^i\right) \\
&\quad +\beta^k\partial_k\hat{\Gamma}^i - 2\alpha\kappa_1\tilde{\gamma}^{ij}Z_j - 16\pi\alpha\tilde{\gamma}^{ij}S_j\,, \\
\partial_t\Theta &= \frac{1}{2}\alpha\left(R + 2\nabla_i Z^i - \tilde{A}_{ij}\tilde{A}^{ij} + \frac{2}{3}K^2 - 2\Theta K\right) - Z^i\partial_i\alpha + \beta^k\partial_k\Theta - \alpha\kappa_1\left(2+\kappa_2\right)\Theta - 8\pi\alpha \\
\partial_t\alpha &= -2\alpha\left(K - 2\Theta\right) + \beta^k\partial_k\alpha\,, \\
\partial_t\beta^i &= f B^i + \beta^k\partial_k\beta^i\,, \\
\partial_t B^i &= \partial_t\hat{\Gamma}^i - \beta^k\partial_k\hat{\Gamma}^i + \beta^k\partial_k B^i - \eta B^i\,,
\end{aligned}
$$

In other words: Einstein's theory is as **beautiful** as it is **intractable** analytically

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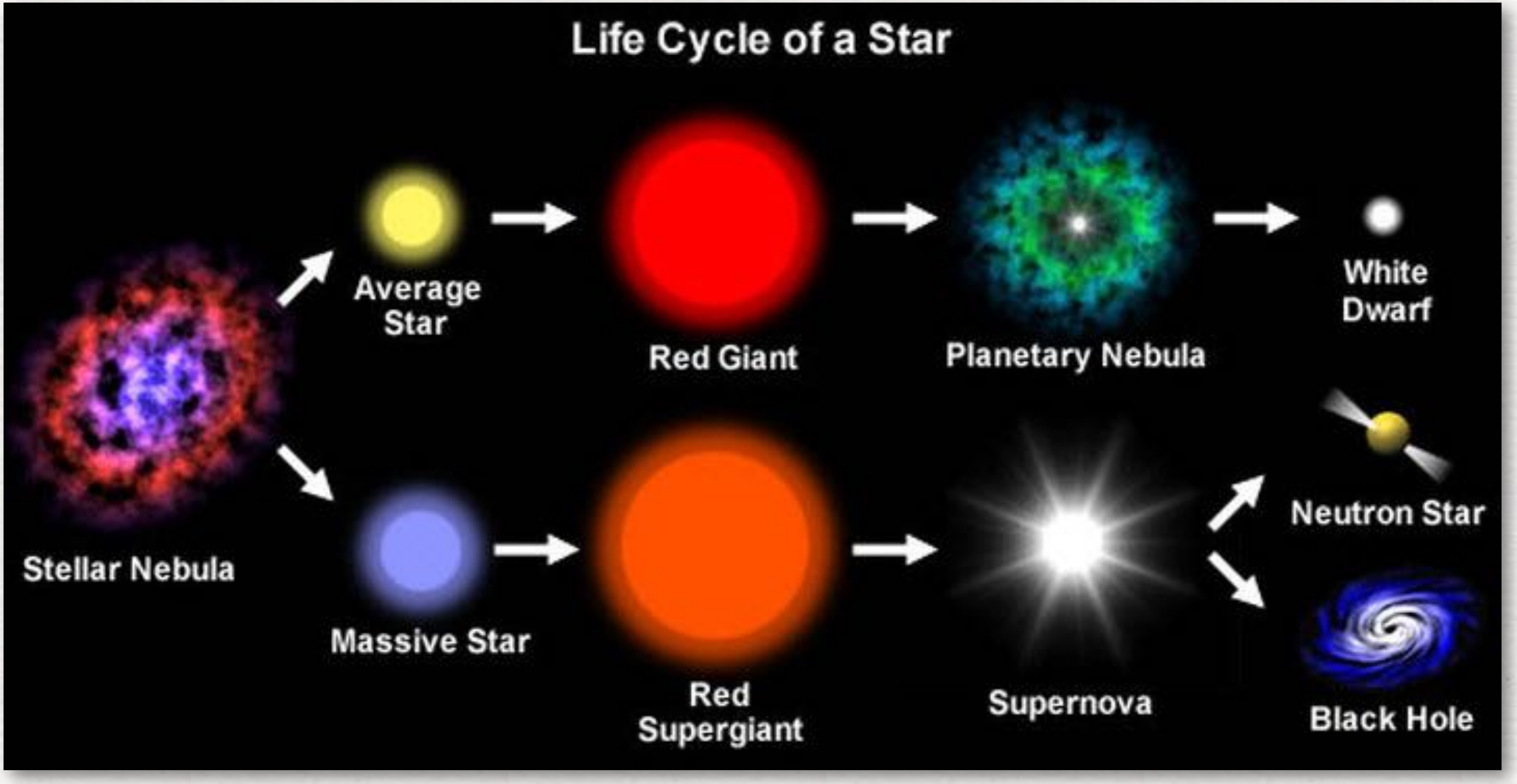
Neutron stars

What is a neutron star?



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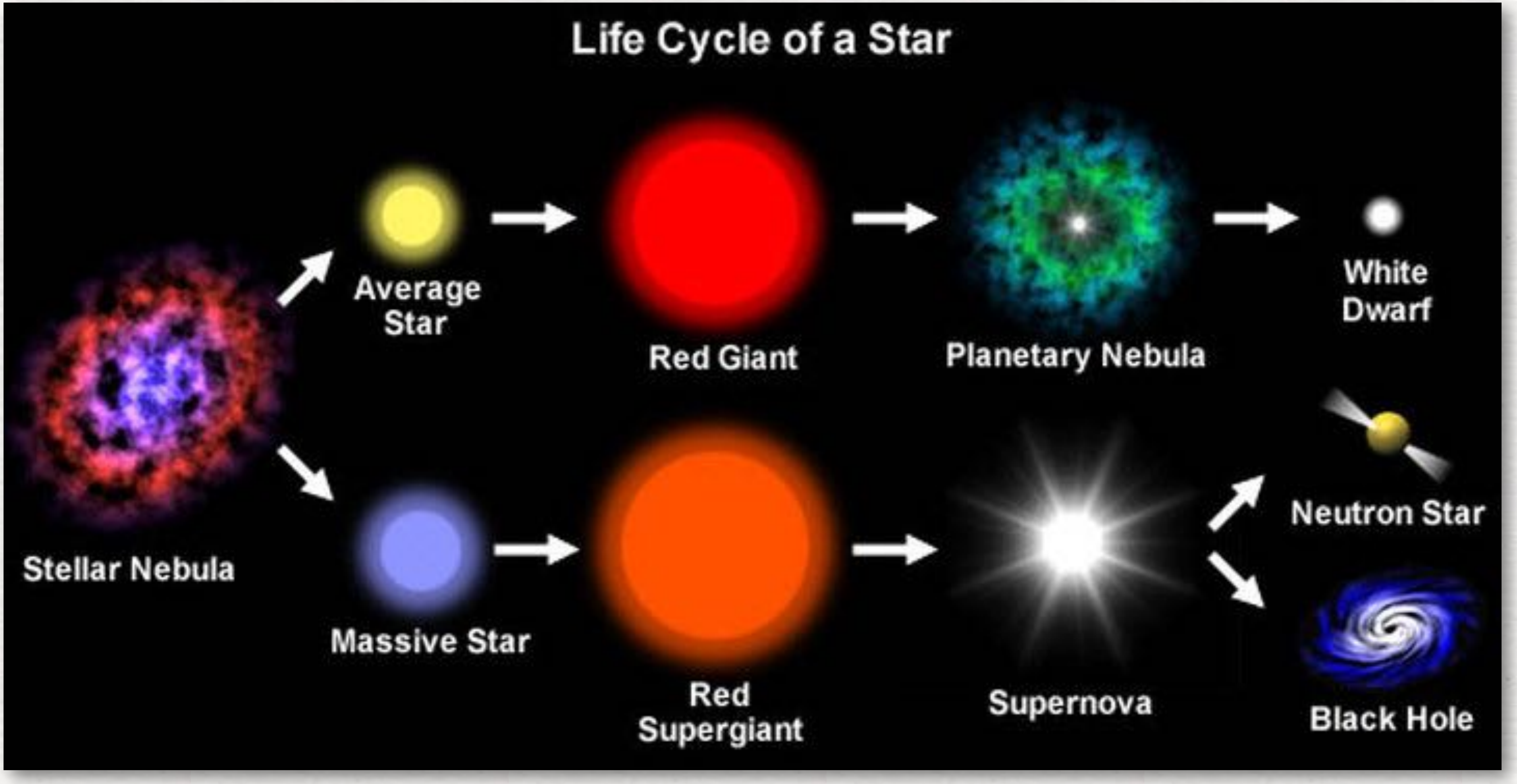


Neutron stars are the most common end of the evolution of massive stars, ie stars with mass

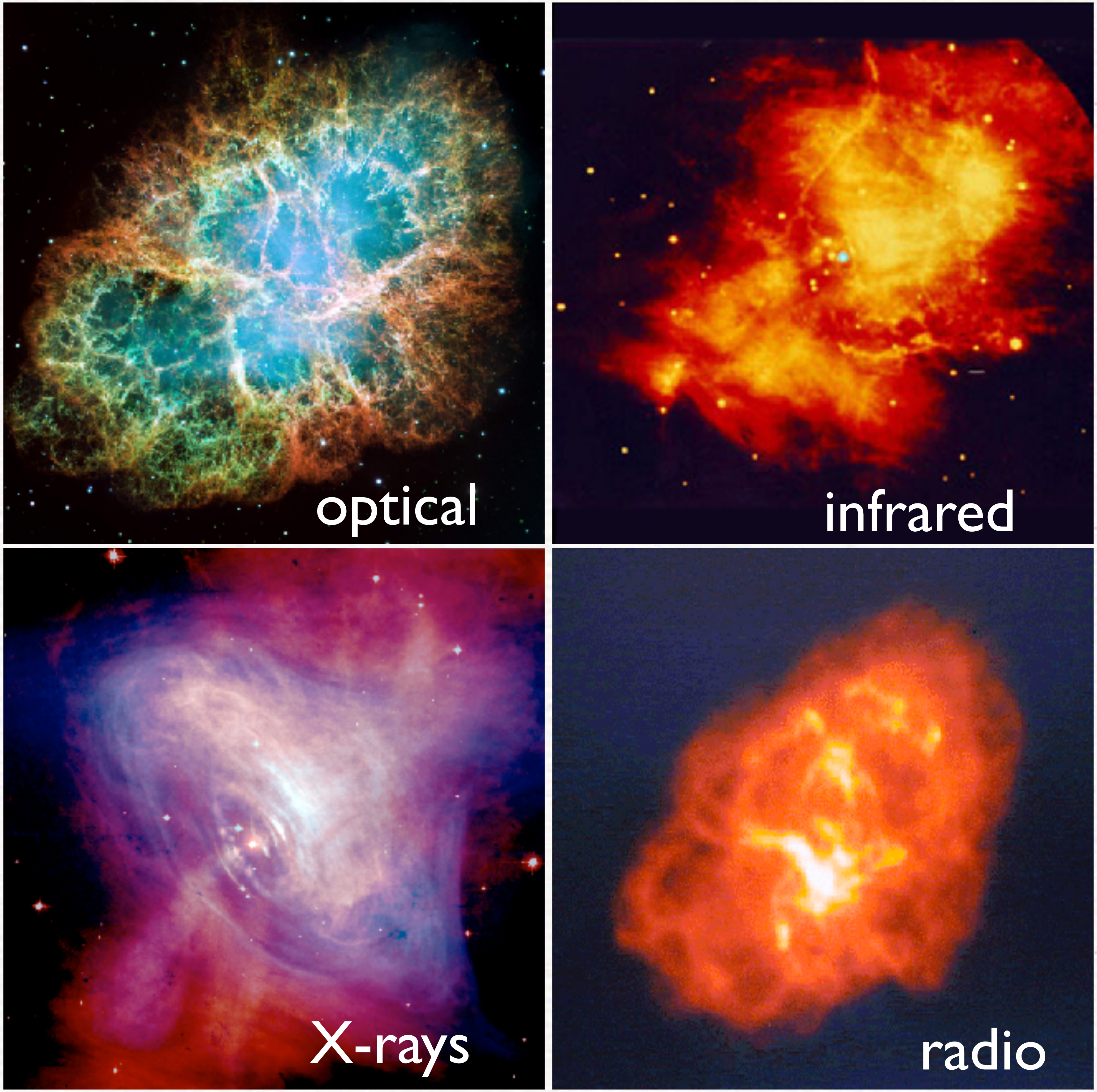
$$10M_{\odot} \lesssim M \lesssim 100M_{\odot}$$

Such stars end their evolution as **supernovae**

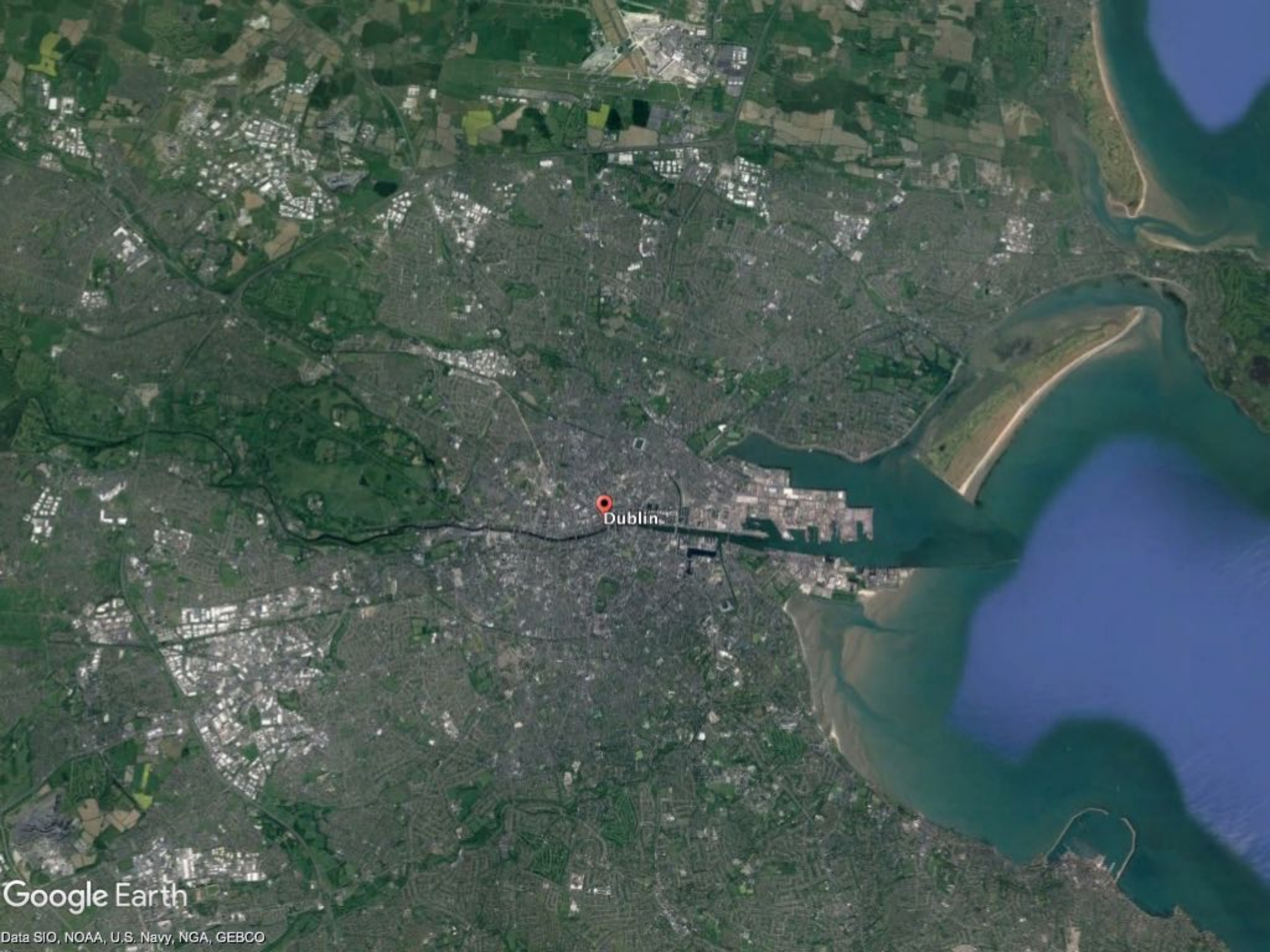
A beautiful example

China, **1054 AC:** a new star appears in the sky and is visible even in daylight in the Crab constellation.

In reality it was a **supernova** that had produced a **neutron star:** *Crab pulsar.*



Neutron stars are real marvels of nature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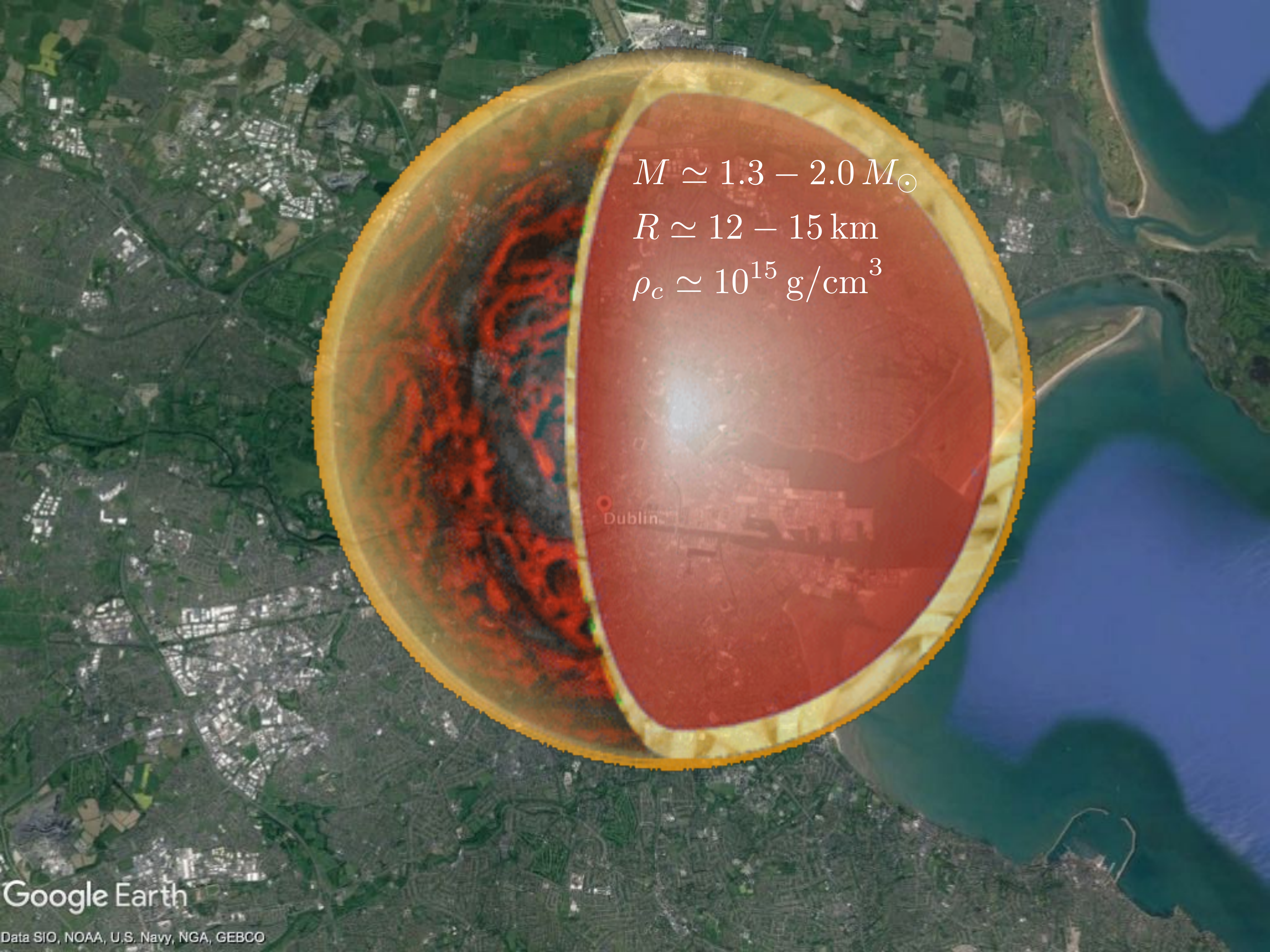
$M \simeq 1.3 - 2.0\, M_\odot$
$R \simeq 12 - 15\,\mathrm{km}$
$\rho_c \simeq 10^{15}\,\mathrm{g/cm^3}$
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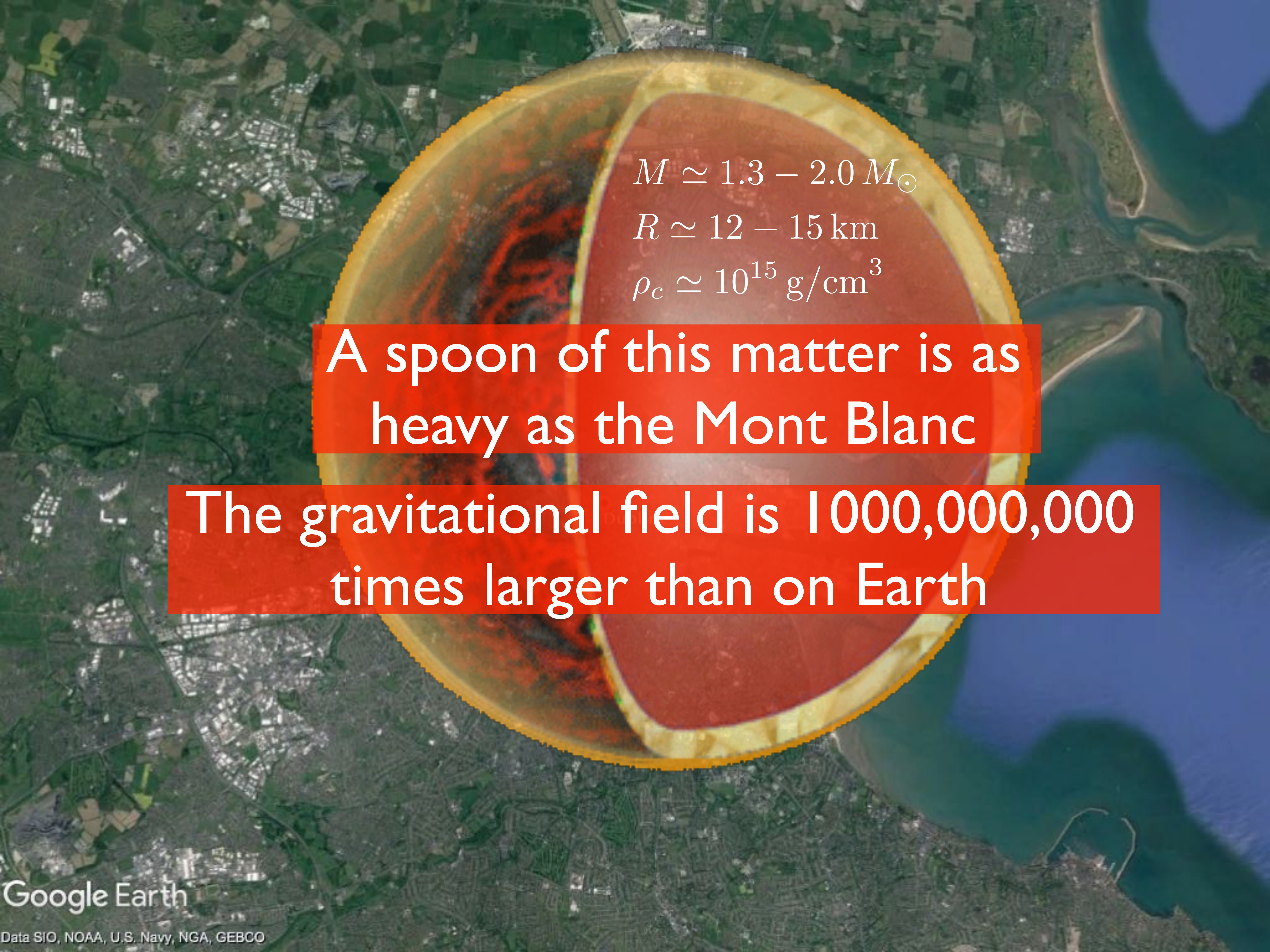
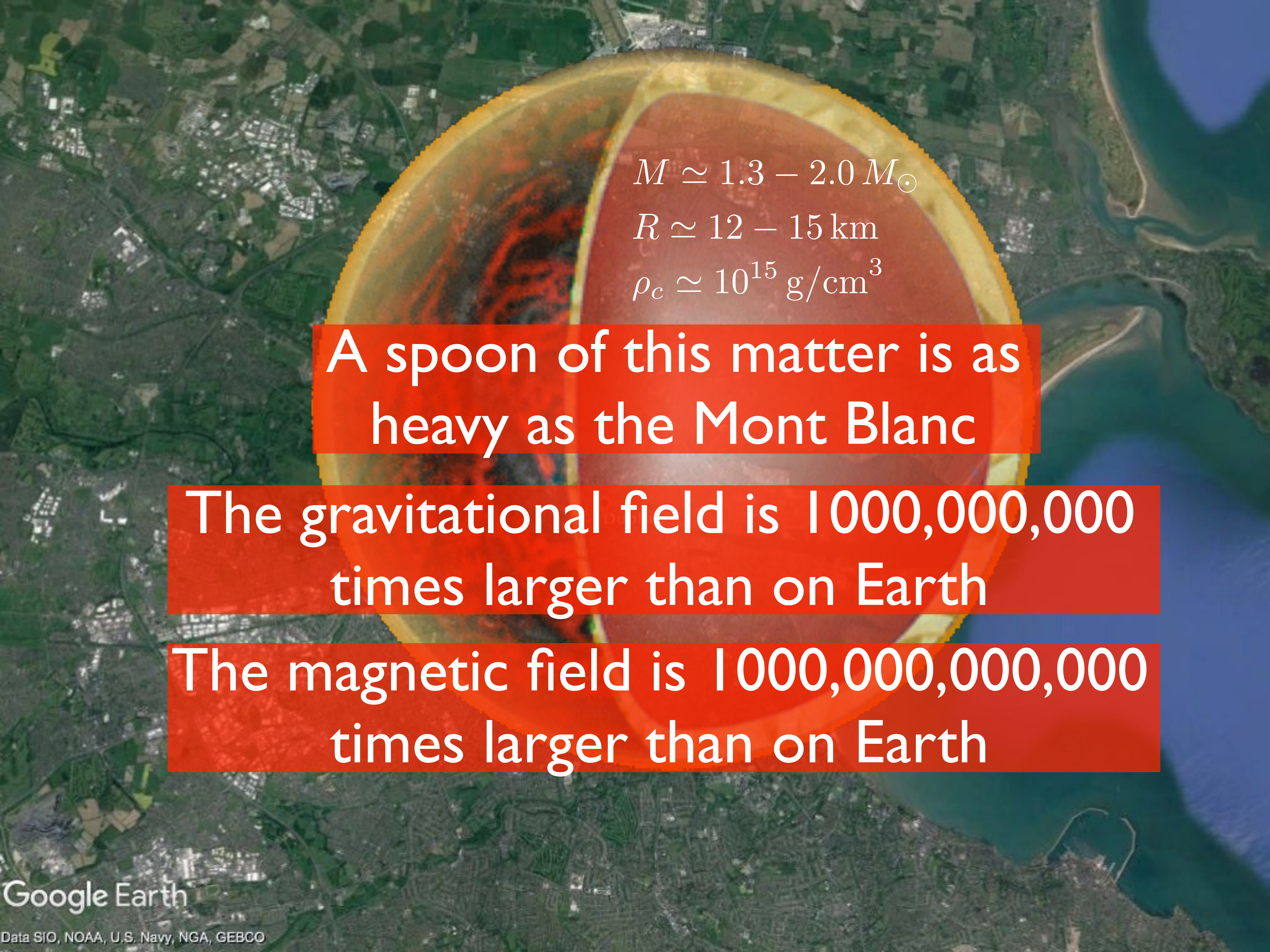
The gravitational field is 1000,000,000 times larger than on Earth

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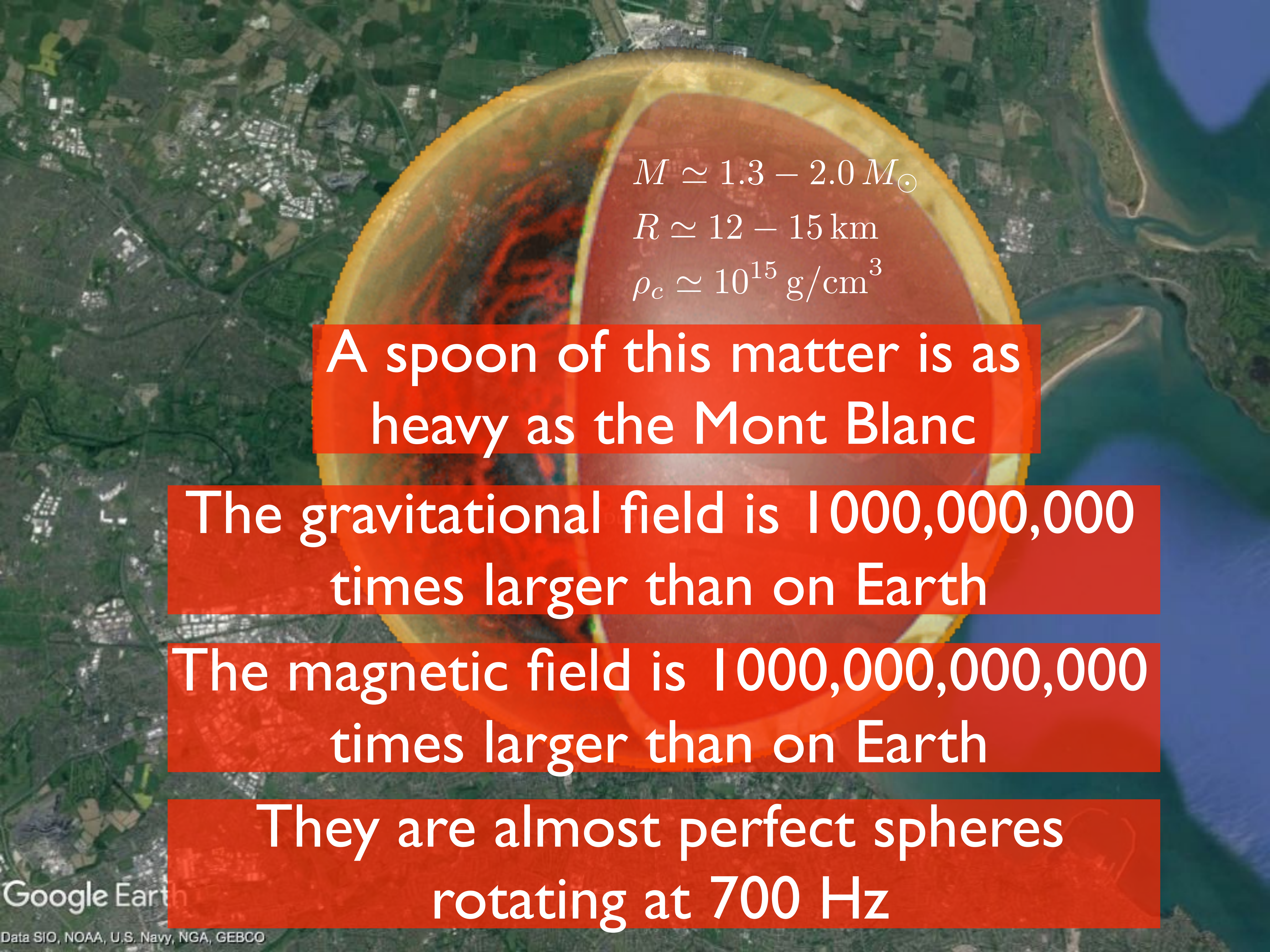

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They are almost perfect spheres rotating at 700 Hz

Let's compare sizes and compactness

$$R_\odot \simeq 70,000\,\mathrm{km};\ M/R \simeq 10^{-6}$$

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Sun

white dwarf

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white dwarf

neutron star

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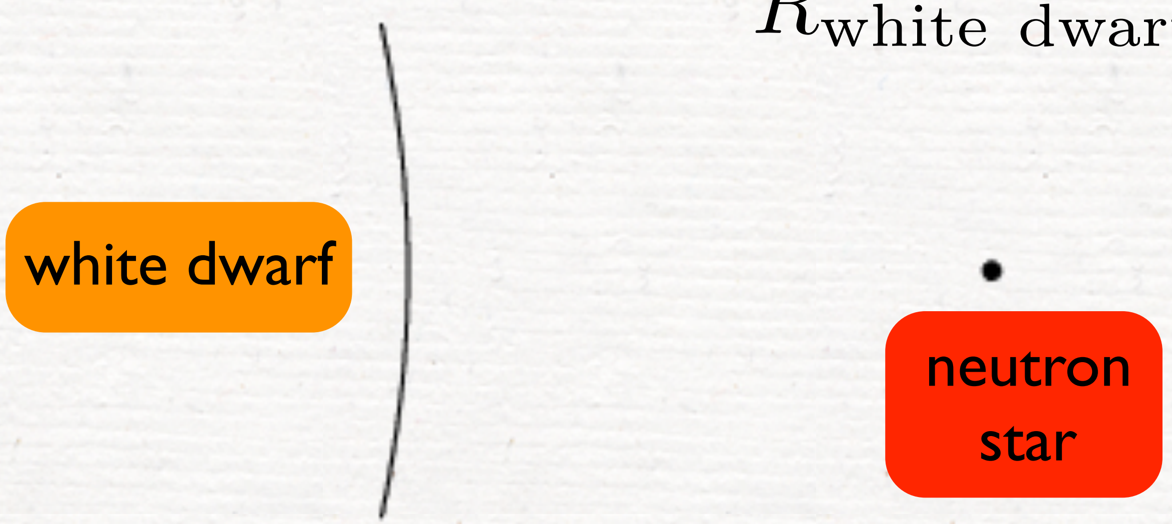

$R_{\mathrm{white\ dwarf}} \simeq 10000\,\mathrm{km};\ M/R \simeq 10^{-4} - 10^{-5}$

$R_{\mathrm{neutron\ star}} \simeq 12\,\mathrm{km};\ M/R \simeq 0.15 - 0.25$

$R_{\mathrm{black\ hole}} \simeq 1.5\,\mathrm{km};\ M/R = 0.5$

Neutron Star vs Black Hole

In terms of compactness *(M/R)* neutron stars and black holes are very similar: **extreme!**

$M/R = 0.44444$ $\sqrt{-g_{tt}}$ $M/R = 0.5000$ $\sqrt{-g_{tt}}$

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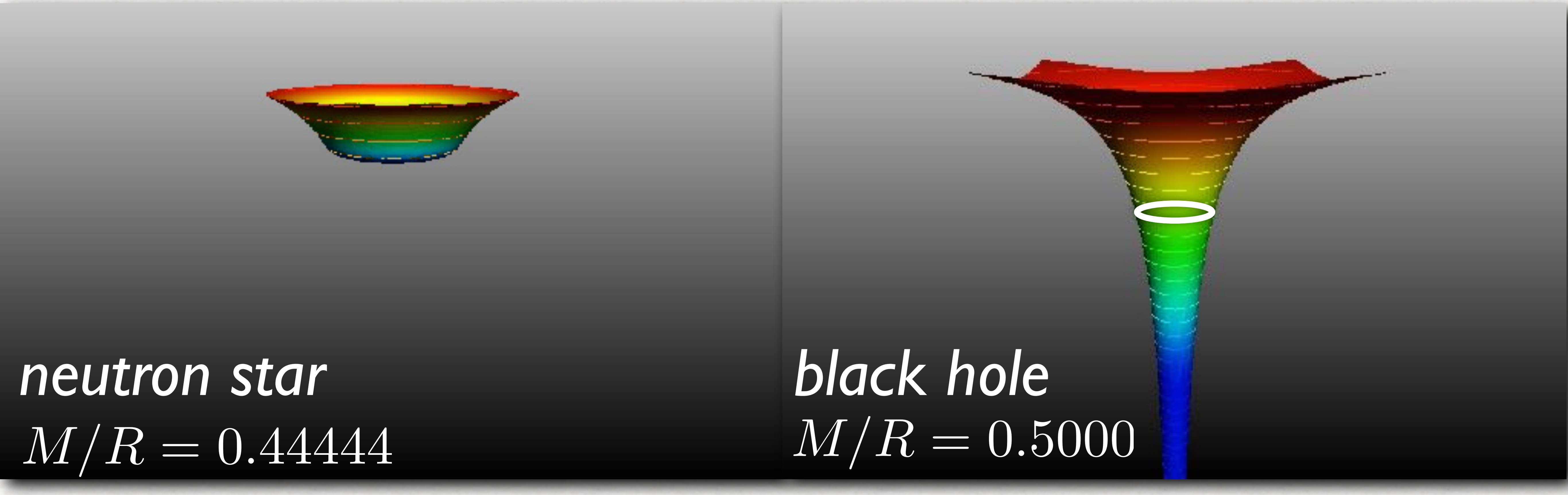


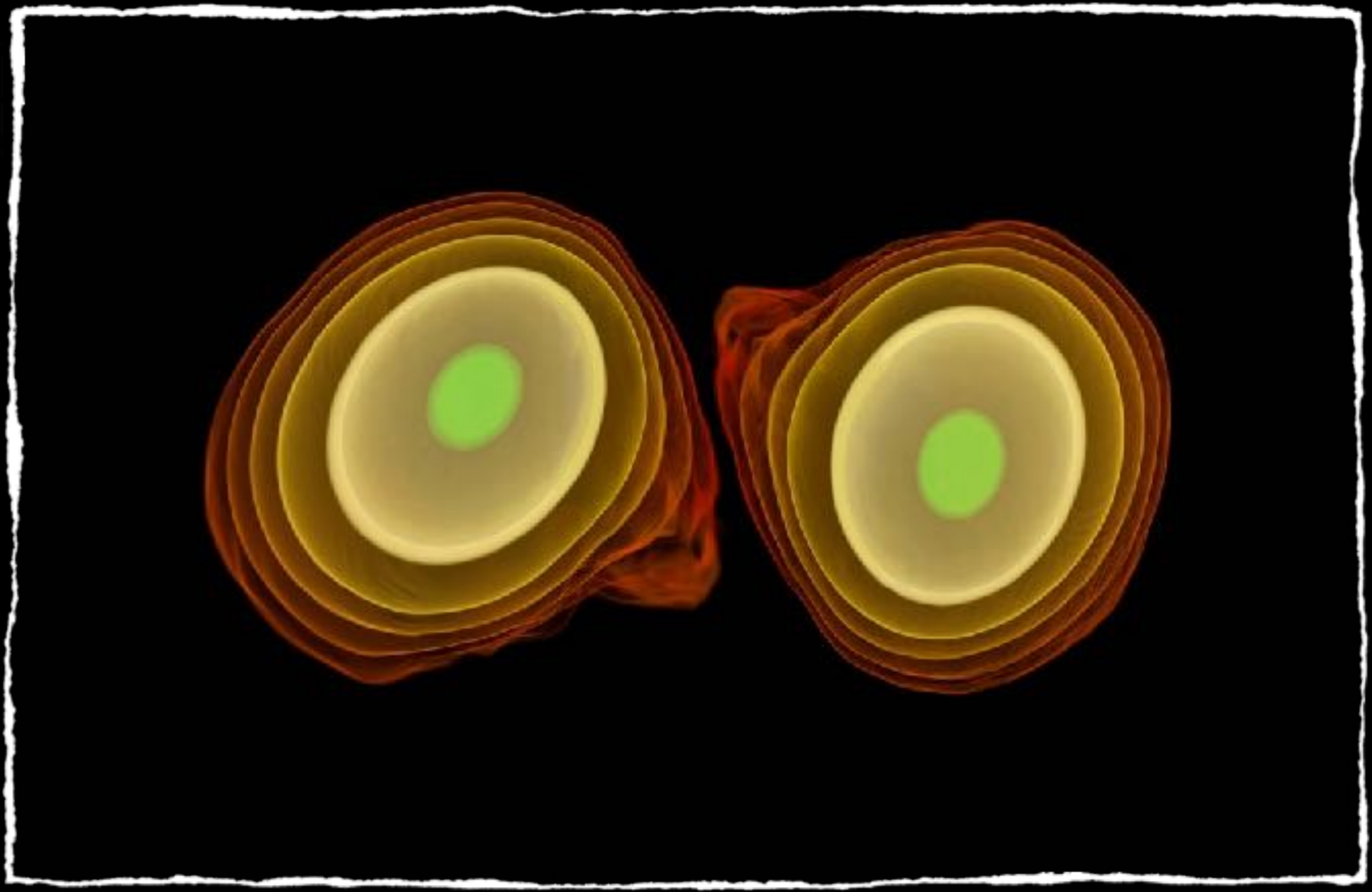
Neutron Star vs Black Hole

In terms of compactness (*M/R*) neutron stars and black holes are very similar: **extreme!**

In two things they differ:

neutron stars have a ***hard surface*** and finite curvature;
black holes ***have no surface***, central curvature is ***infinite!***

Binary neutron stars



The two-body problem: Newton vs Einstein

Neutron stars are found in binary systems

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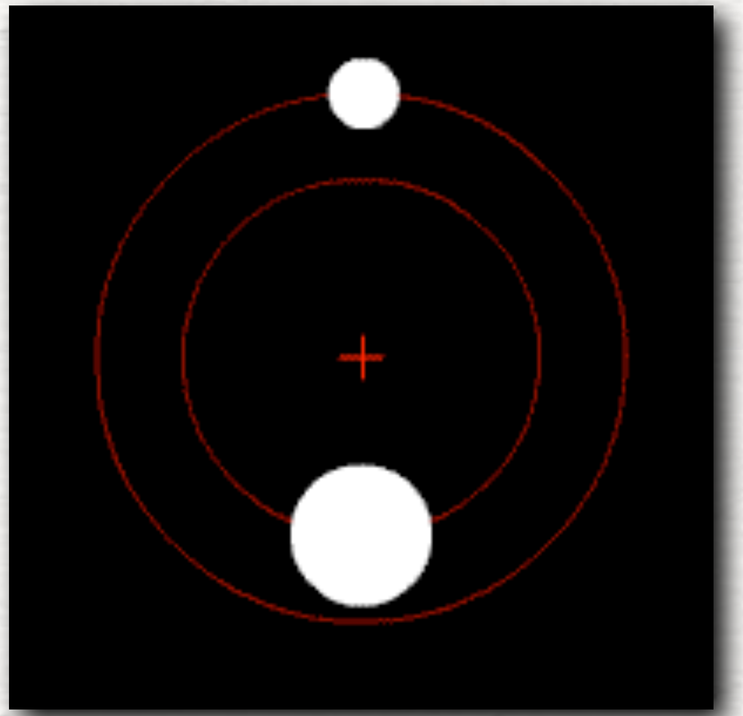

Take two objects of mass m_1 and m_2 interacting only gravitationally

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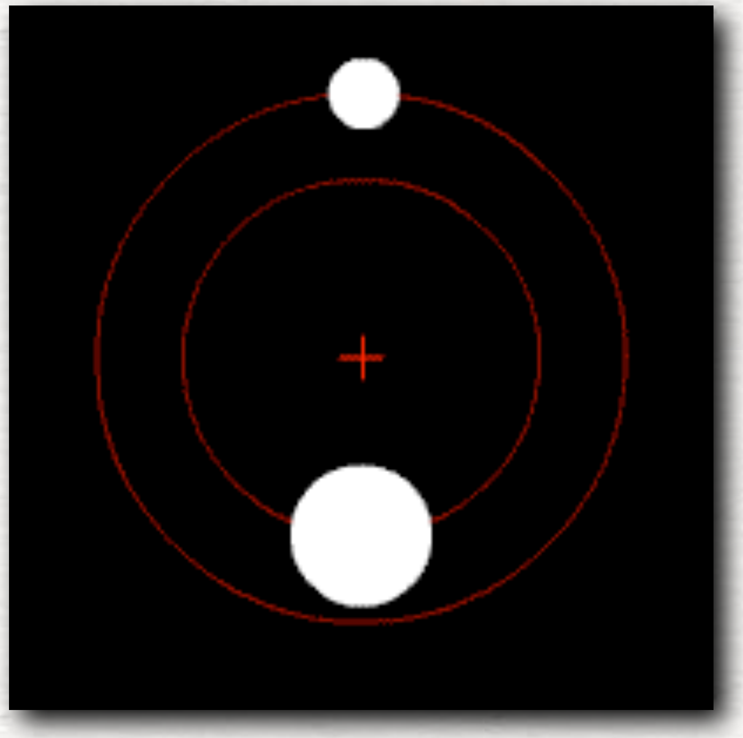

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where $M \equiv m_1 + m_2\,, \boldsymbol{r} \equiv \boldsymbol{r}_1 - \boldsymbol{r}_2\,, d_{12} \equiv |\boldsymbol{r}_1 - \boldsymbol{r}_2|\,.$

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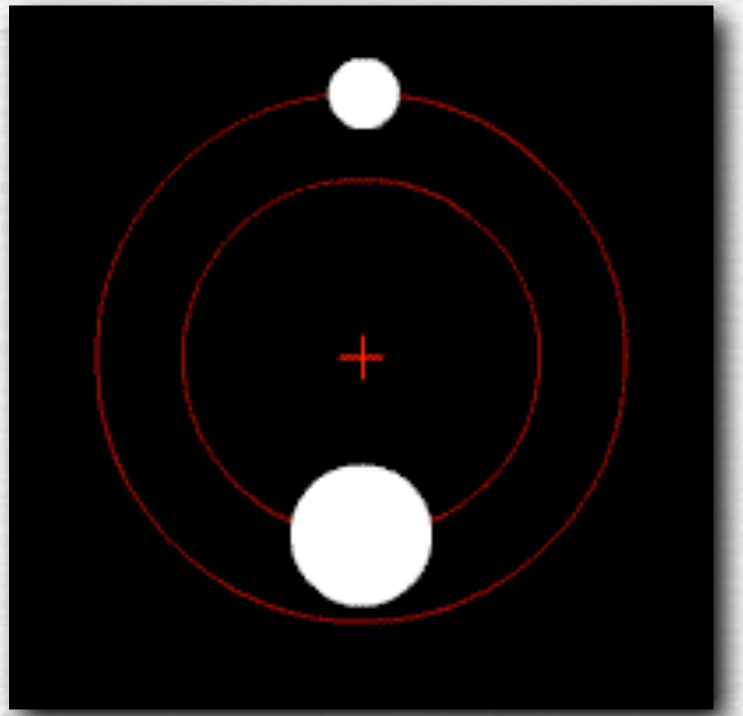

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In **Einstein's gravity** no analytic solution!

No closed orbits: the system loses energy/angular momentum via **gravitational waves.**

The two-body problem in GR

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

BH + BH $\longrightarrow$ BH + GWs

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- 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

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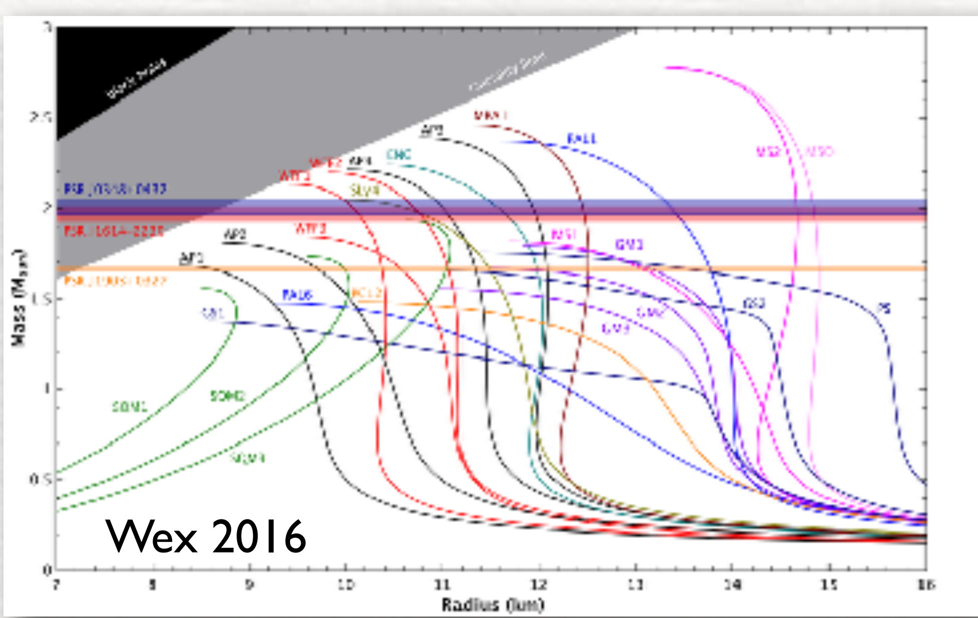

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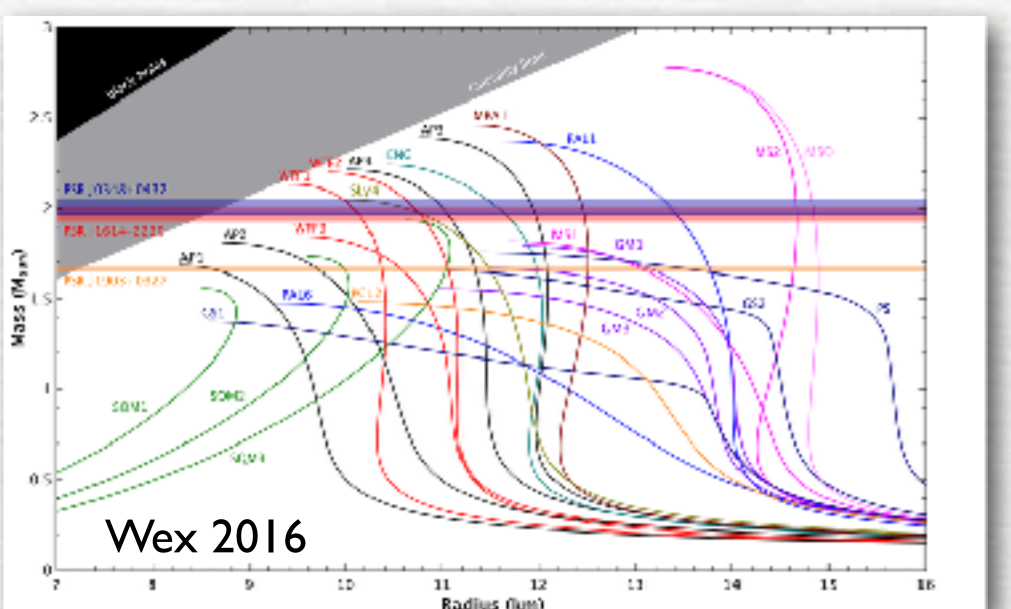

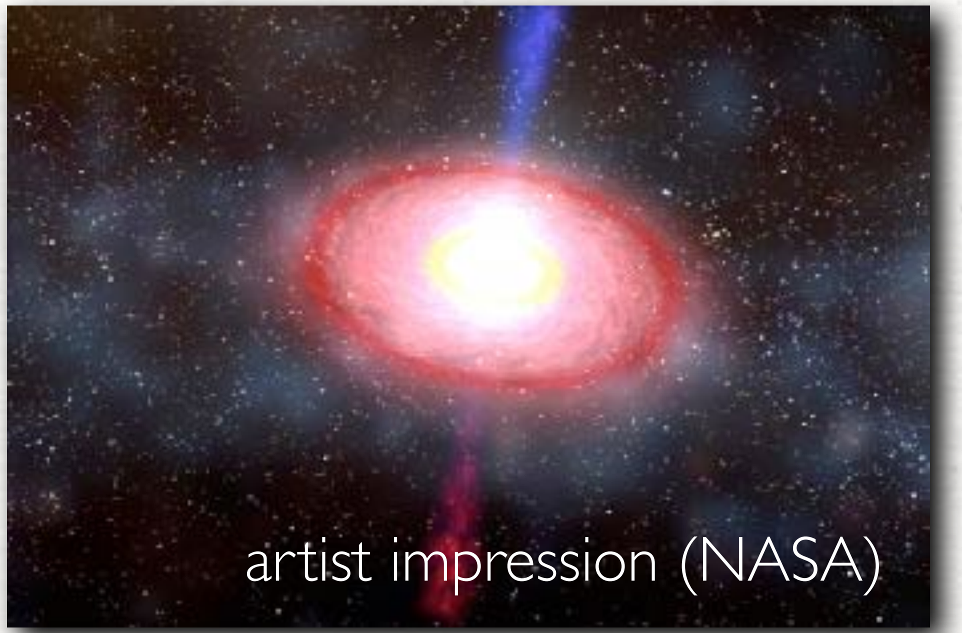

- **BH+torus** system may tell us on the central engine of **GRBs**

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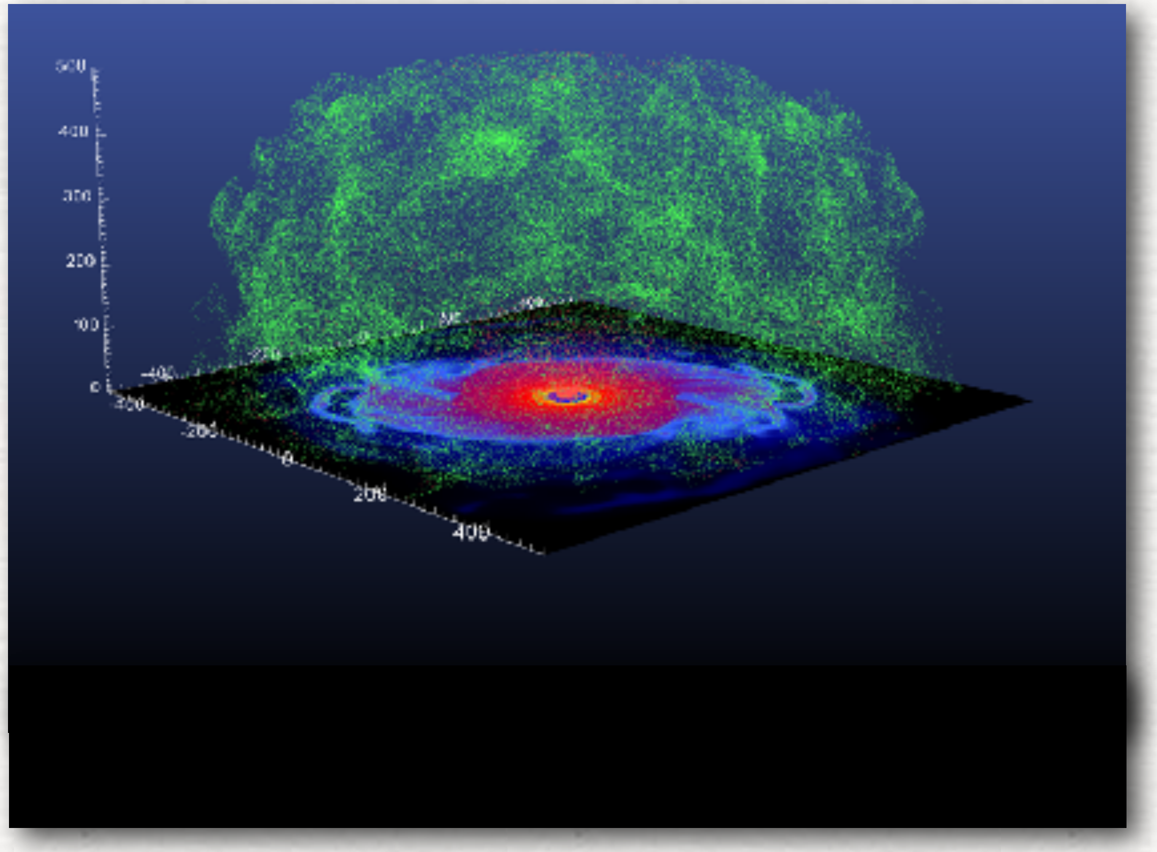

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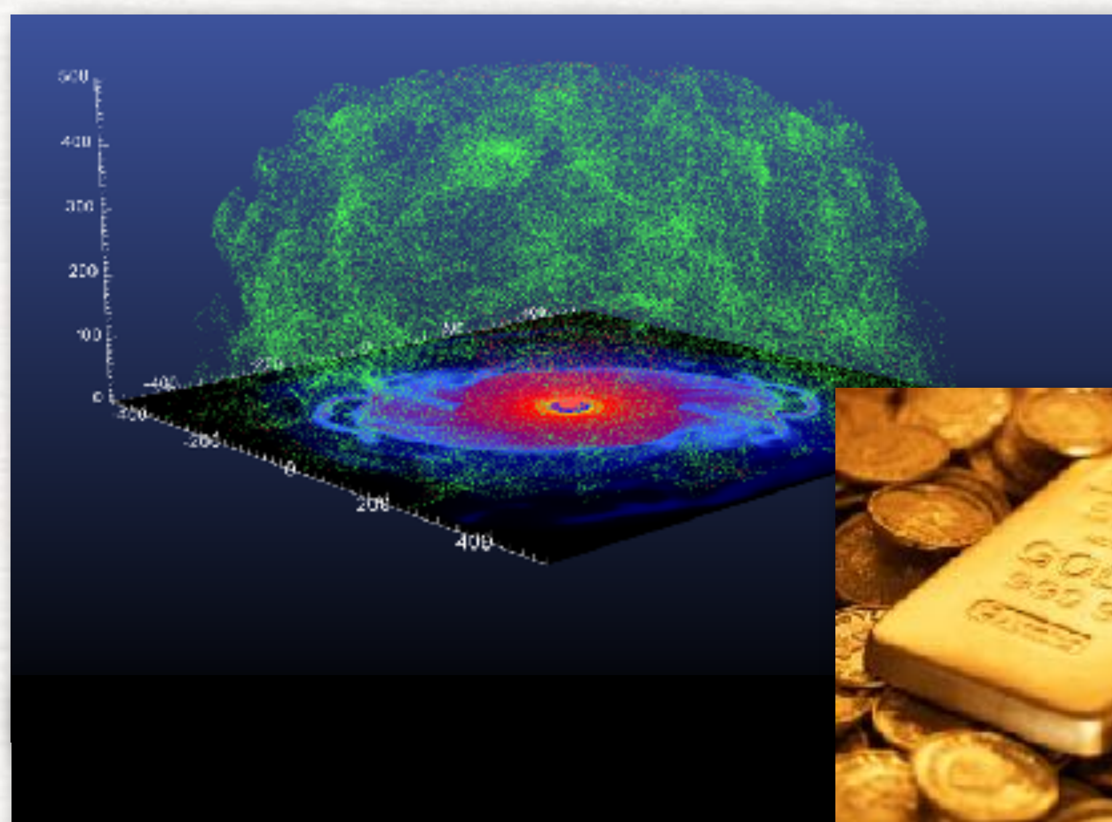


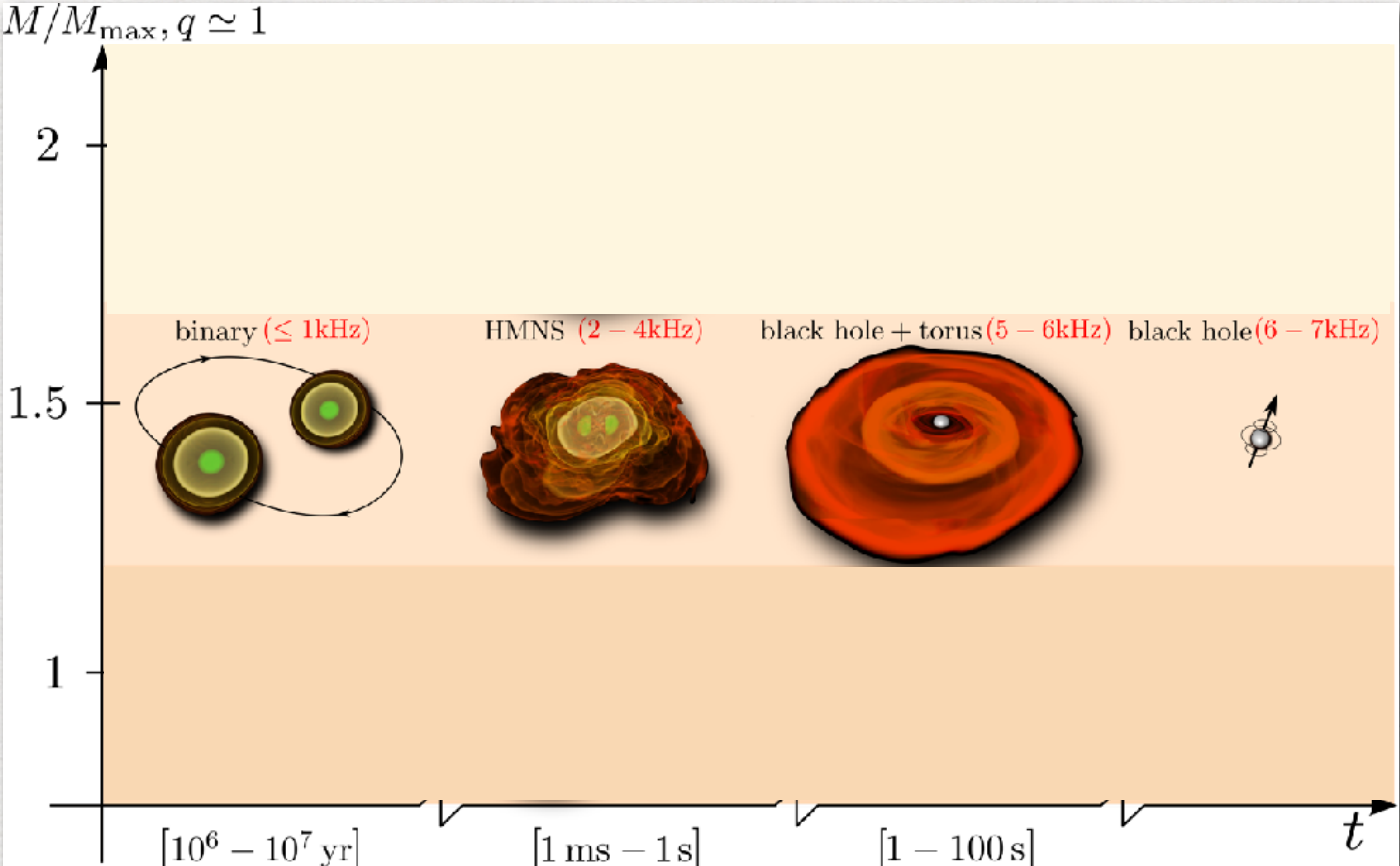
Animations: Breu, Radice, LR

$$M = 2 \times 1.35\, M_\odot$$

LS220 EOS

merger → HMNS → BH + torus

Broadbrush picture



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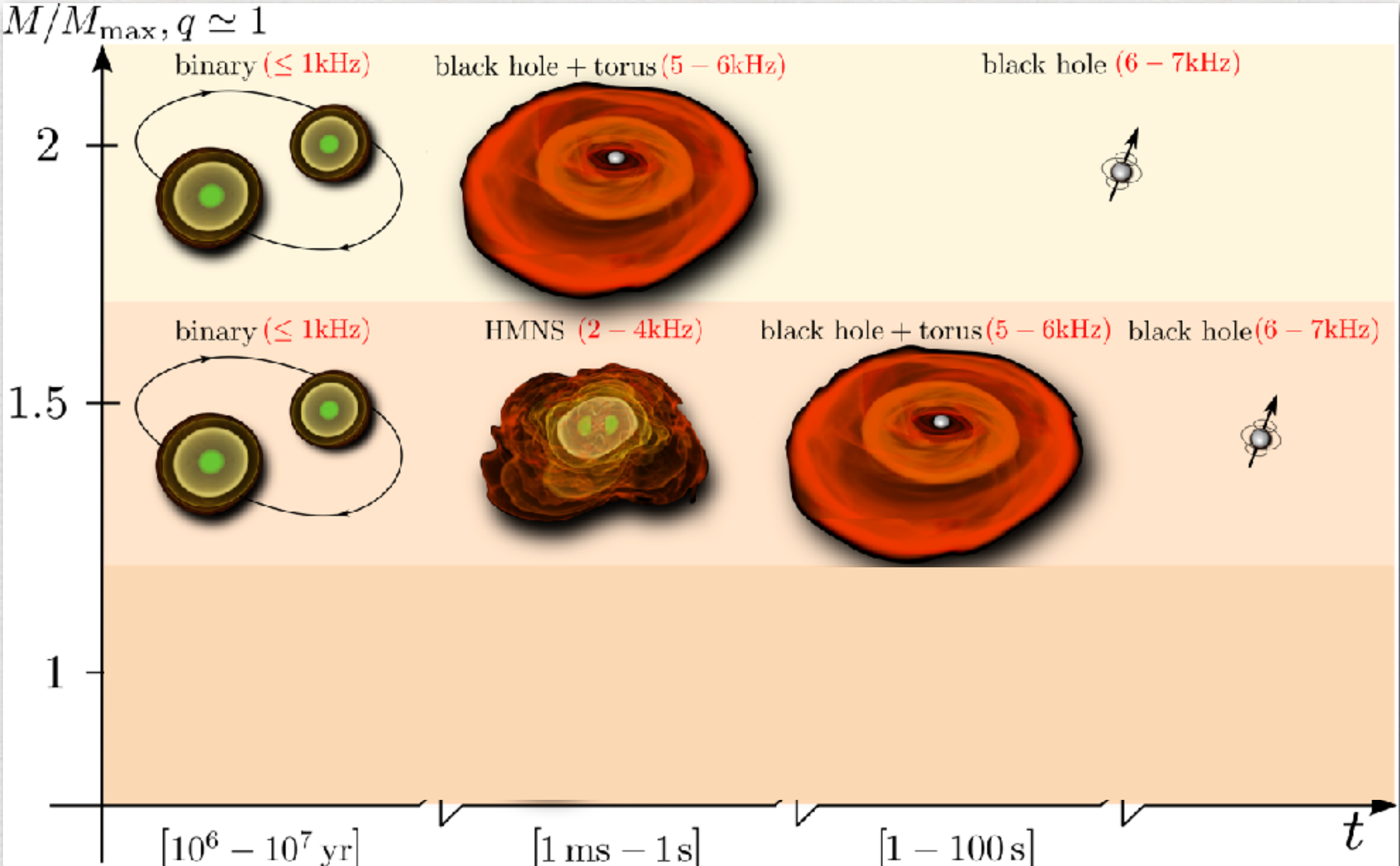

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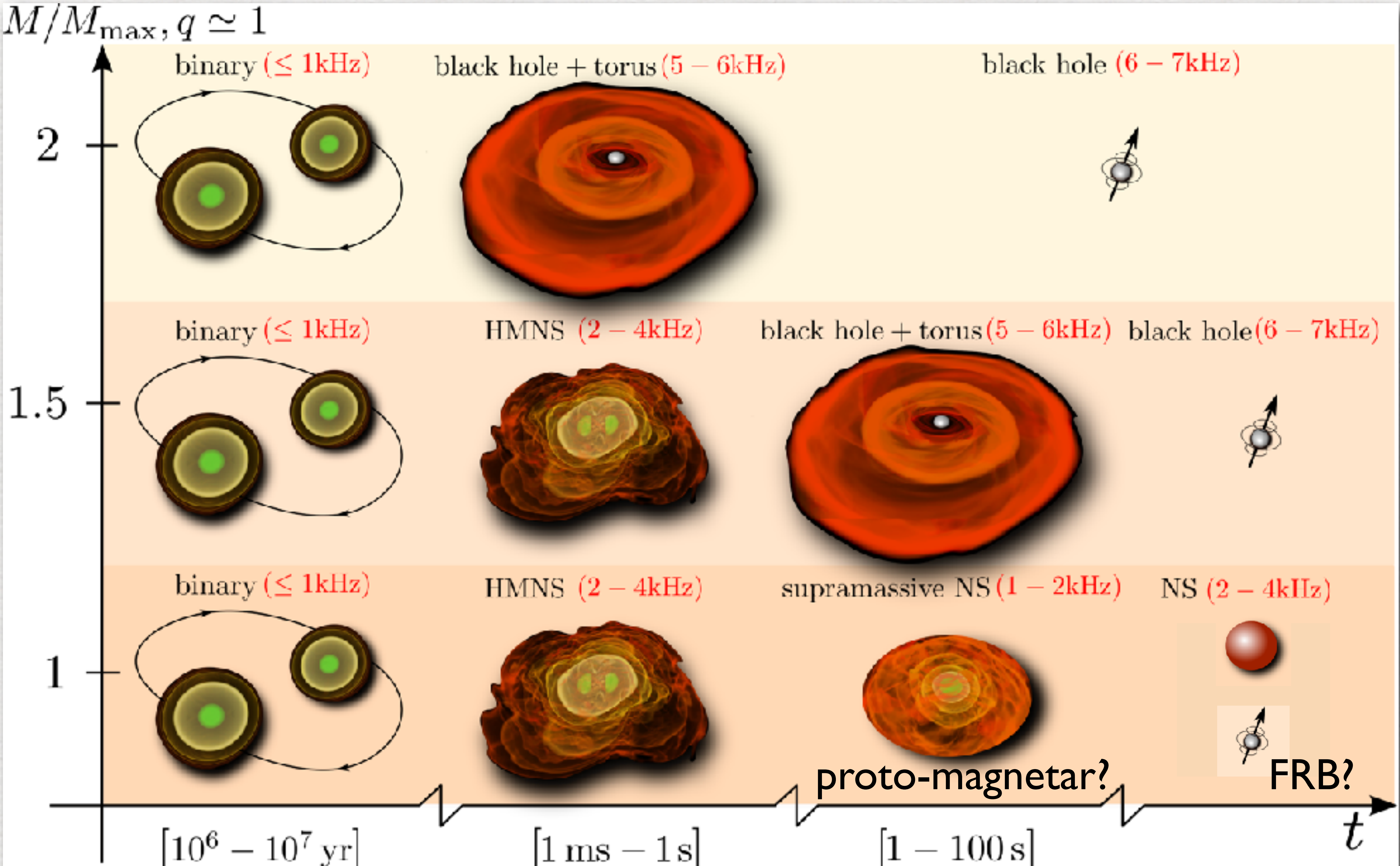


merger $\longrightarrow$ HMNS $\longrightarrow$ BH + torus

Quantitative differences are produced by:

- **total mass (prompt vs delayed collapse)** merger ⟶ HMNS ⟶ BH + torus

Quantitative differences are produced by:

- total mass (prompt vs delayed collapse)
- mass asymmetries (HMNS and torus)

0 0.00 22.5

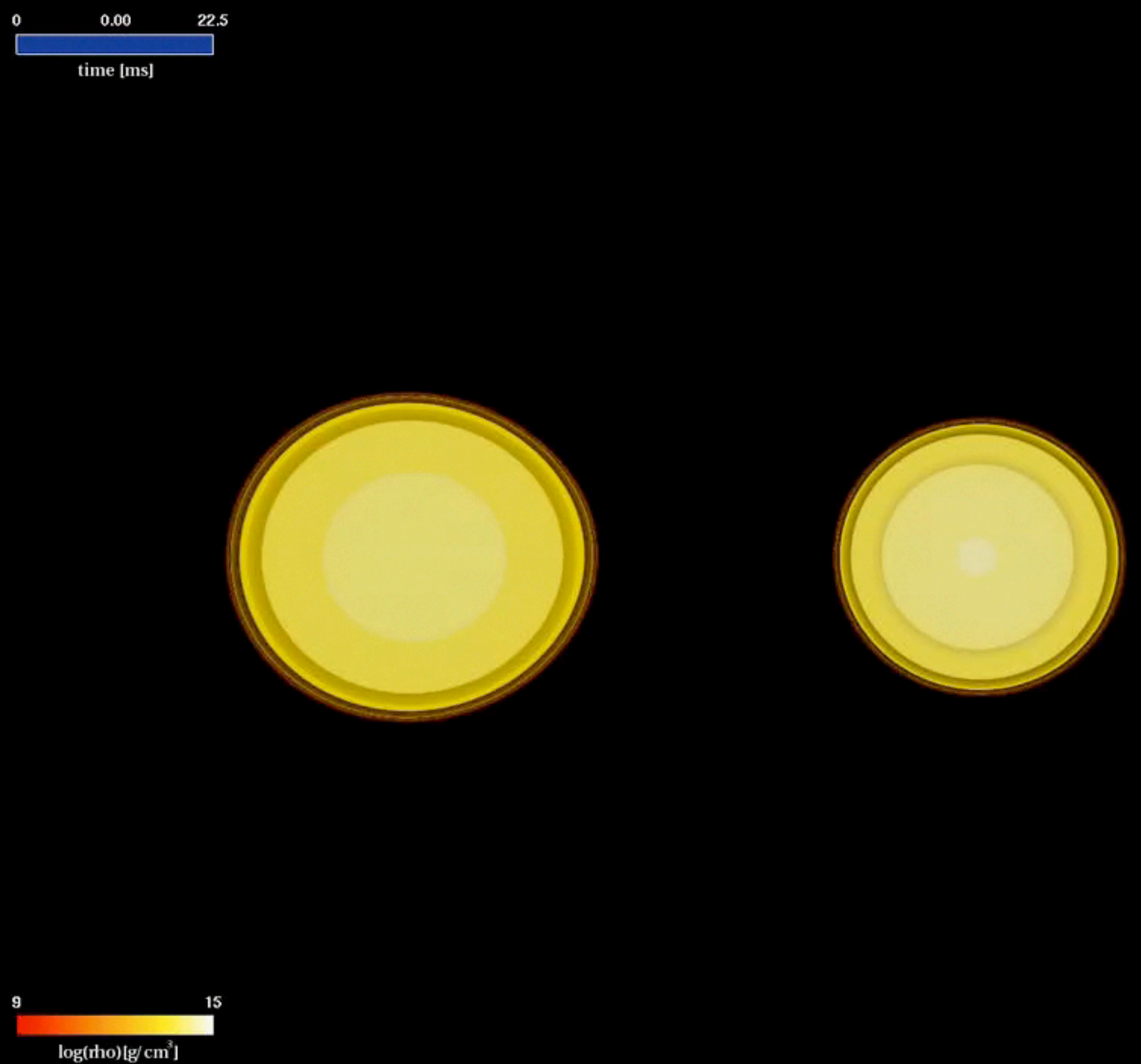
time [ms]

Animations: Giacomazzo, Koppitz, LR

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

9 15

log(rho)[g/cm^3]


0
0.00
22.5
time [ms]
9
15
log(rho)[g/cm3]

- the torii are generically more massive
- the torii are generically more extended
- the torii tend to stable quasi-Keplerian configurations
- overall unequal-mass systems have all the ingredients needed to create a GRB

merger $\longrightarrow$ HMNS $\longrightarrow$ BH + torus

Quantitative differences are produced by:

- total mass (prompt vs delayed collapse)
- mass asymmetries (HMNS and torus)

merger $\longrightarrow$ HMNS $\longrightarrow$ BH + torus

Quantitative differences are produced by:

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merger ⟶ HMNS ⟶ BH + torus

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- mass asymmetries (HMNS and torus)
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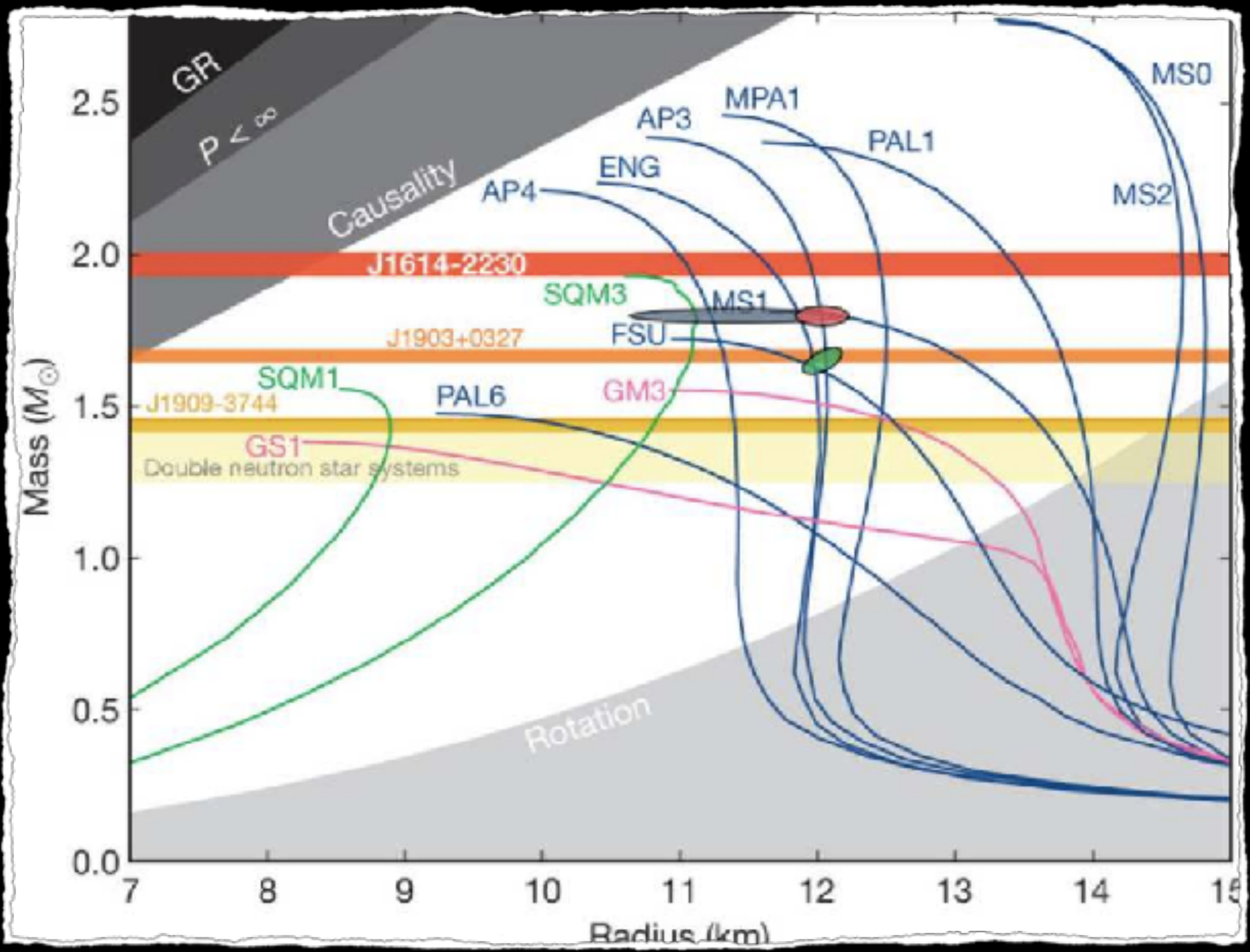
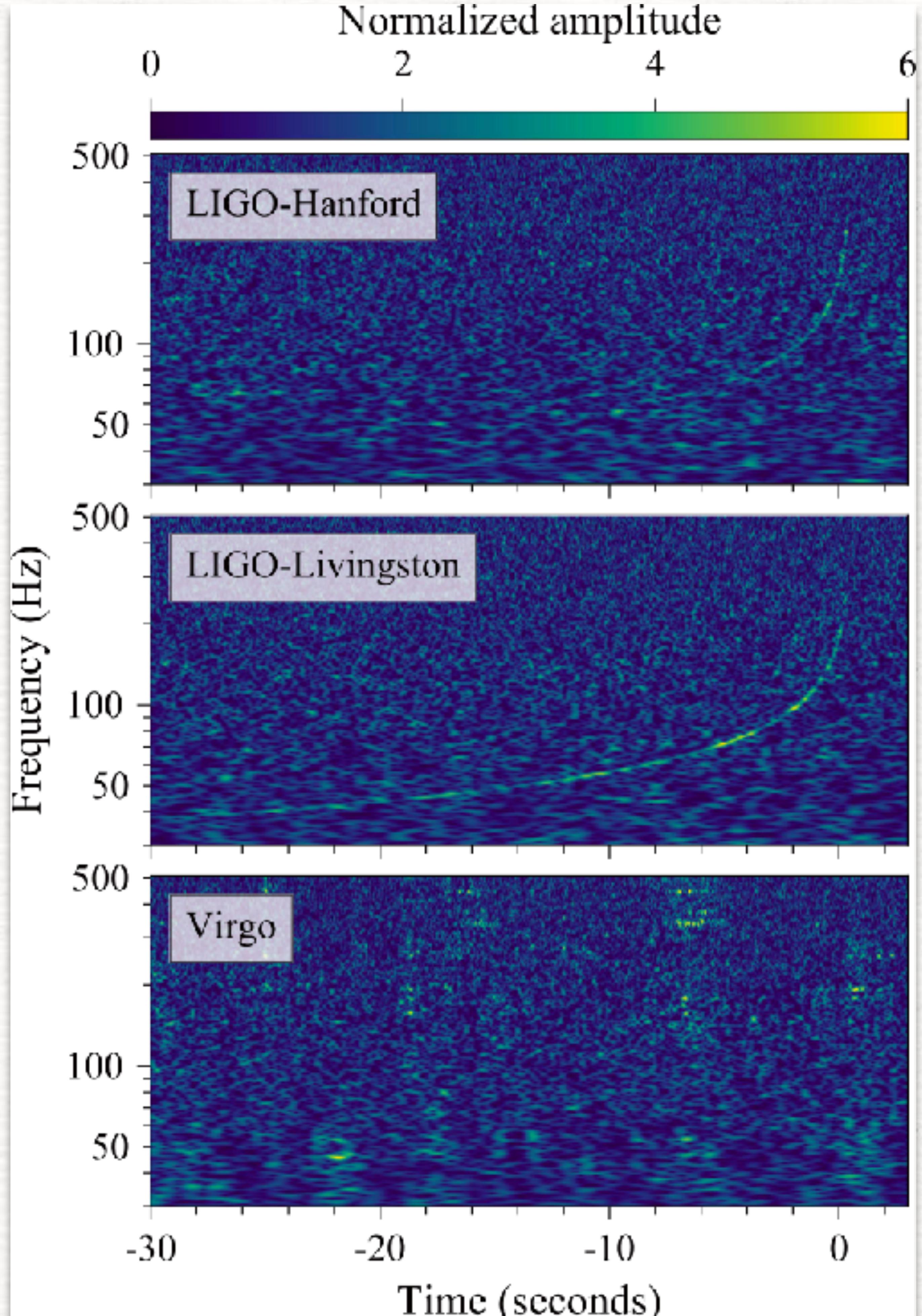
- magnetic fields (equil. and EM emission)
- radiative losses (equil. and nucleosynthesis)

How to constrain the EOS



GW170817

- On 16 October 2017 the LSC/Virgo collaboration announced detection of the gravitational signal from merging binary neutron-star system.



GW170817

- On 16 October 2017 the LSC/Virgo collaboration announced detection of the gravitational signal from merging binary neutron-star system.

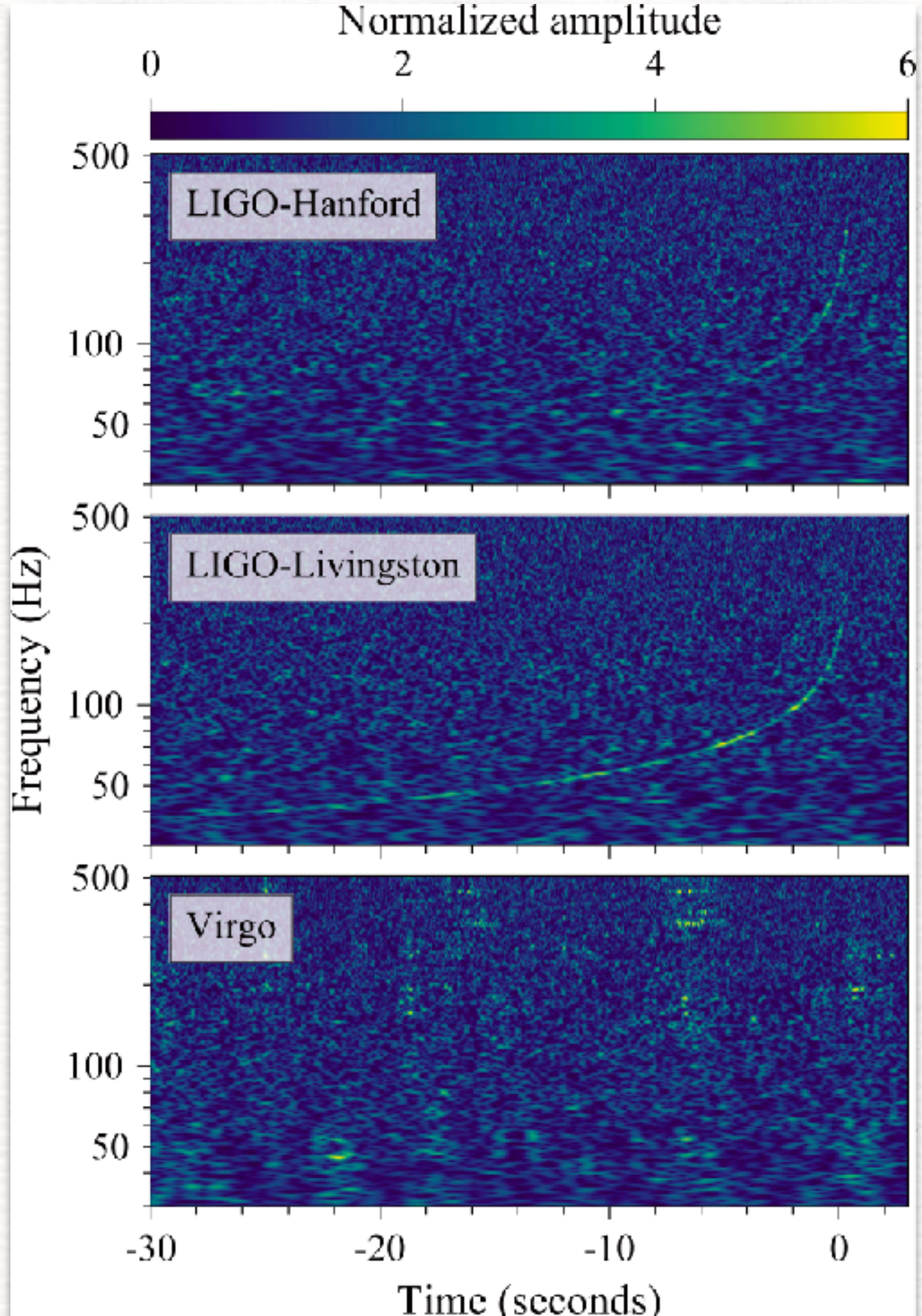
- Total mass:

$$M_1 + M_2 = 2.74^{+0.04}_{-0.01} M_\odot$$

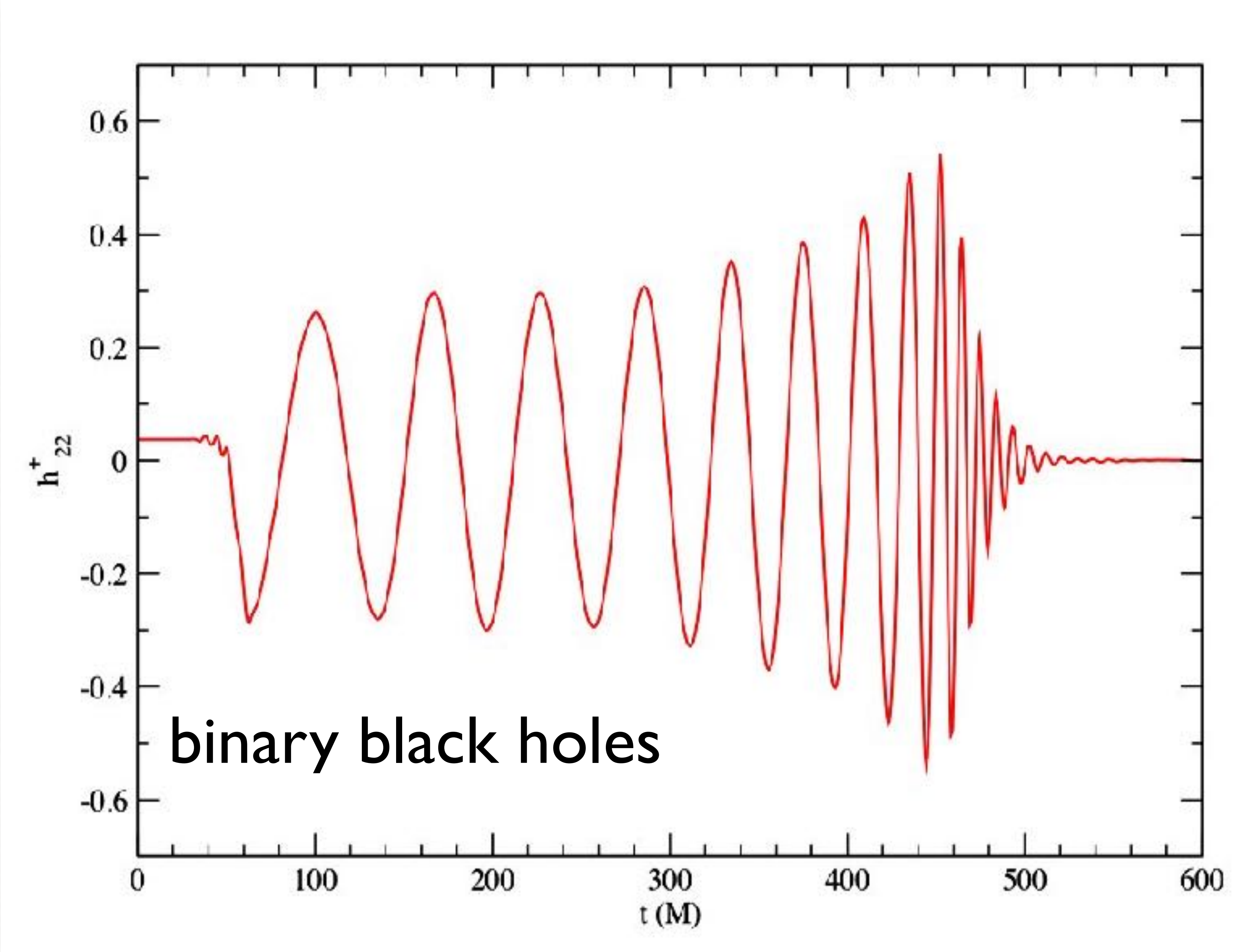
- Individual masses:

$$M_1 = 1.36 - 1.60 M_\odot$$

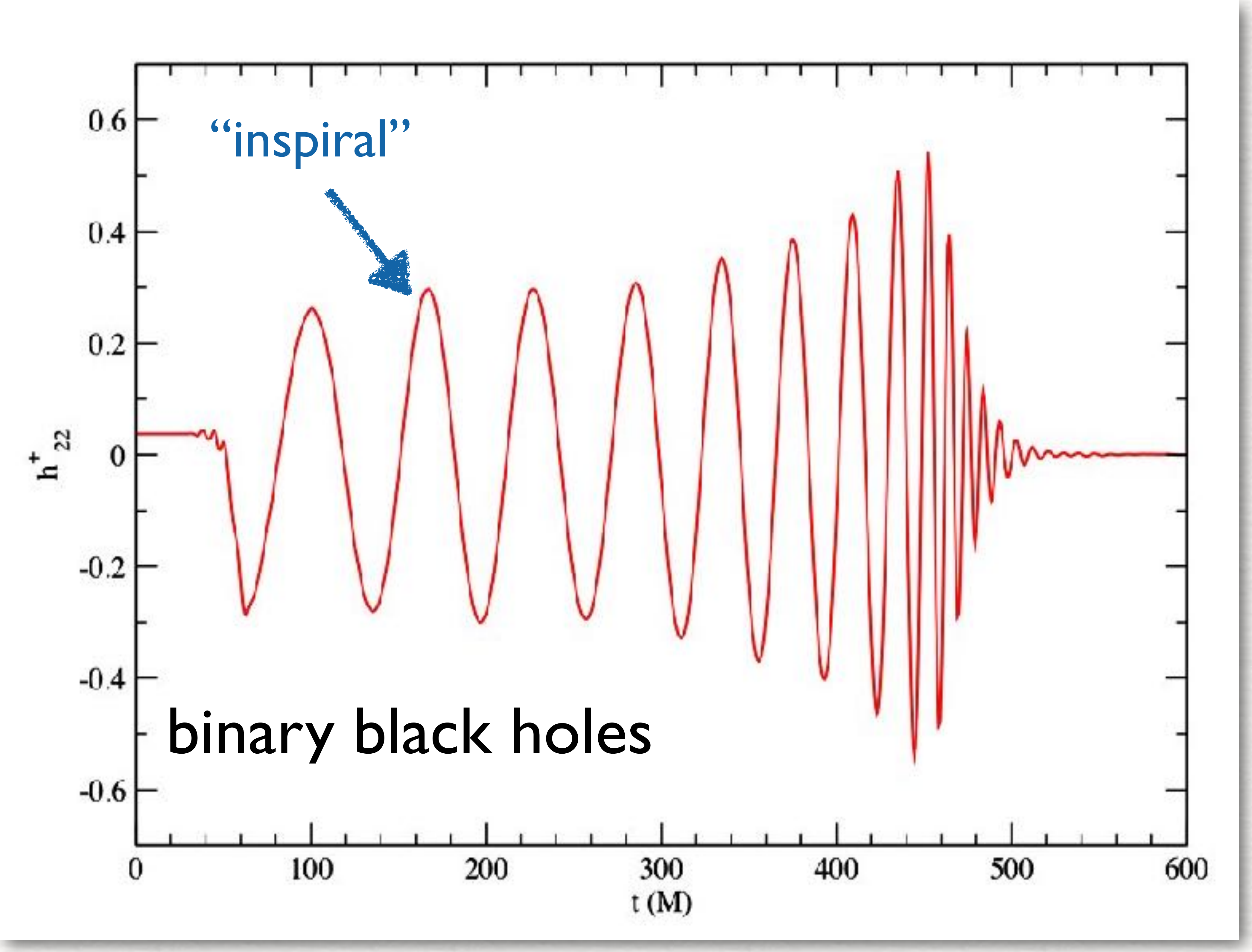
$$M_2 = 1.17 - 1.36 M_\odot$$



Anatomy of the GW signal



Anatomy of the GW signal



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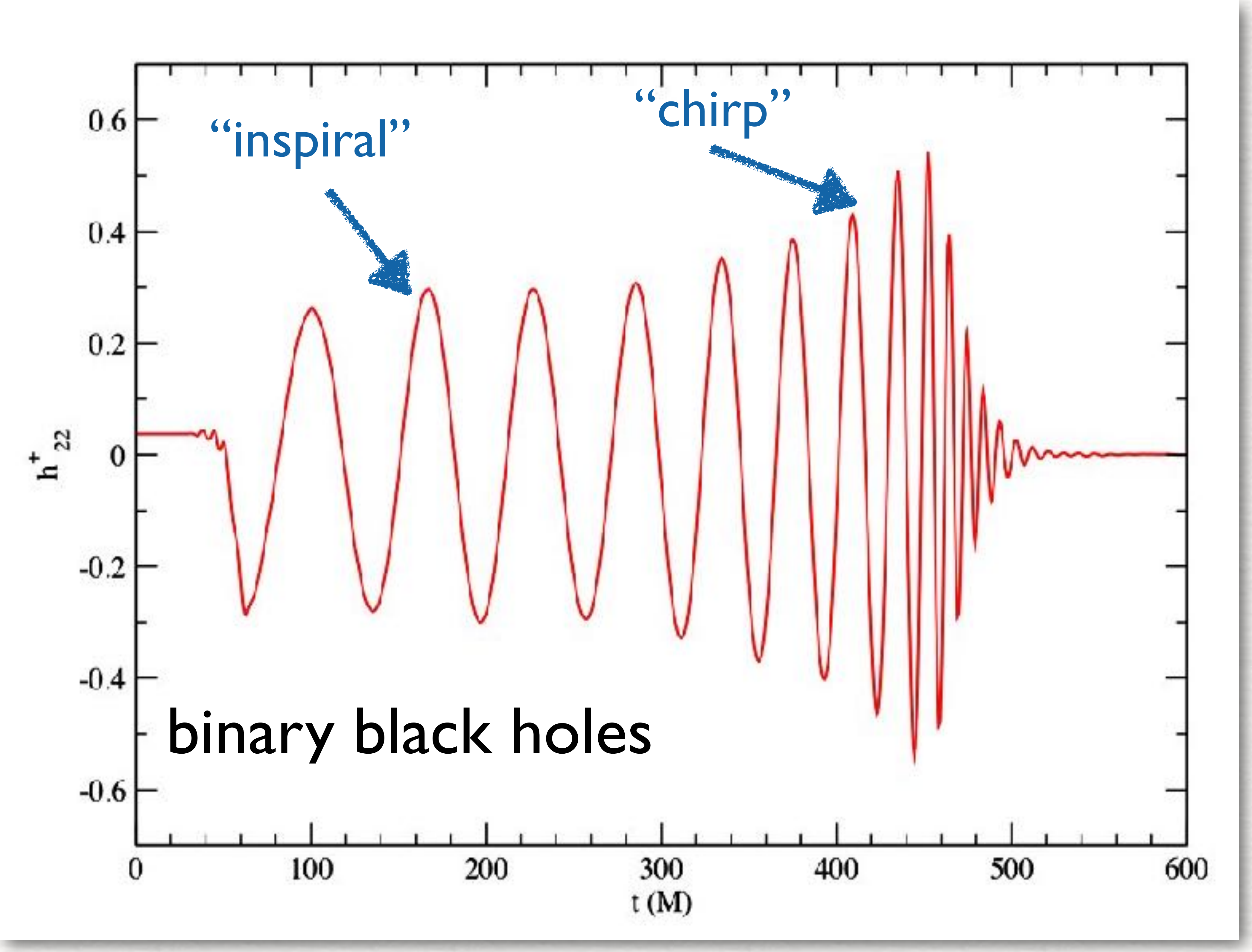

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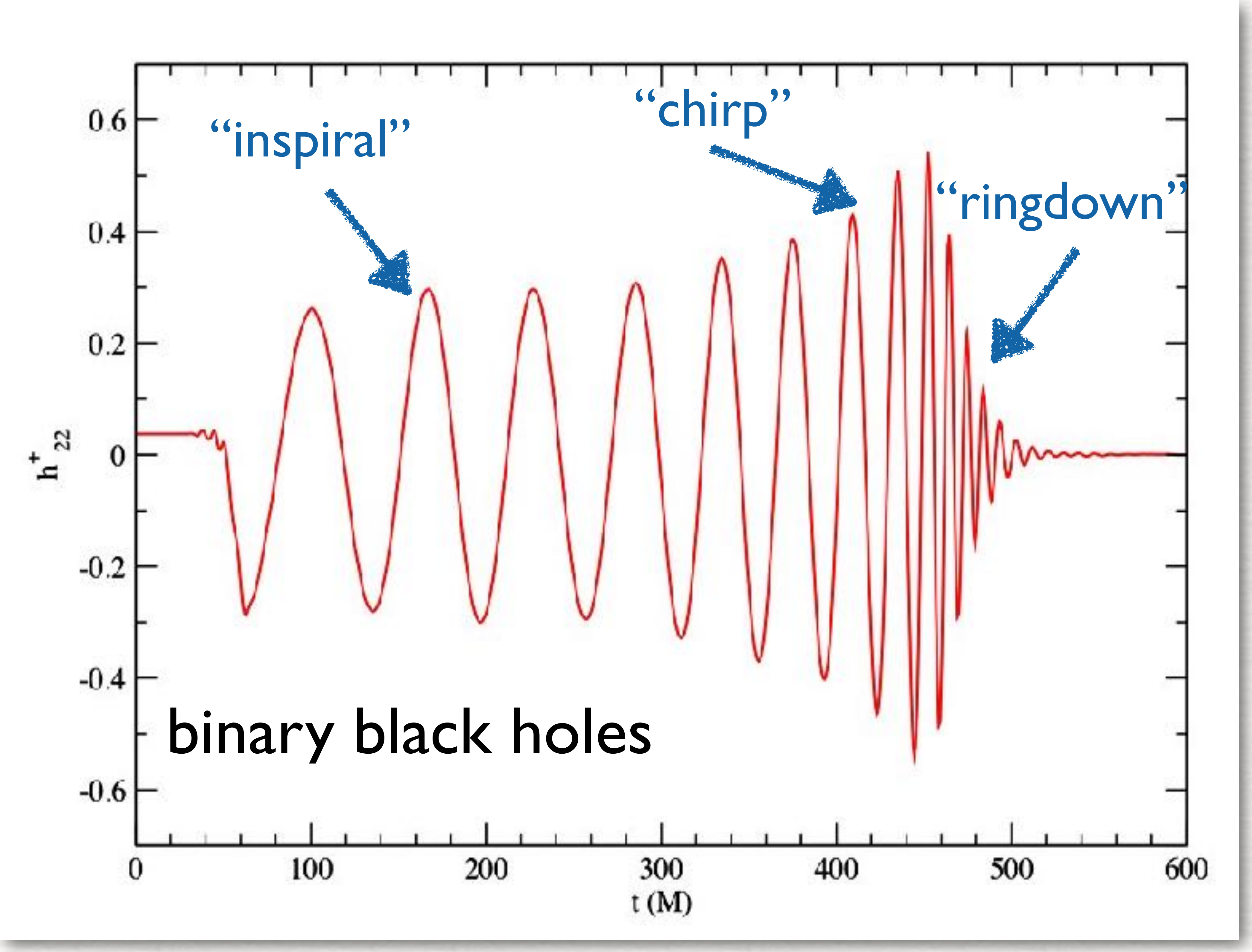
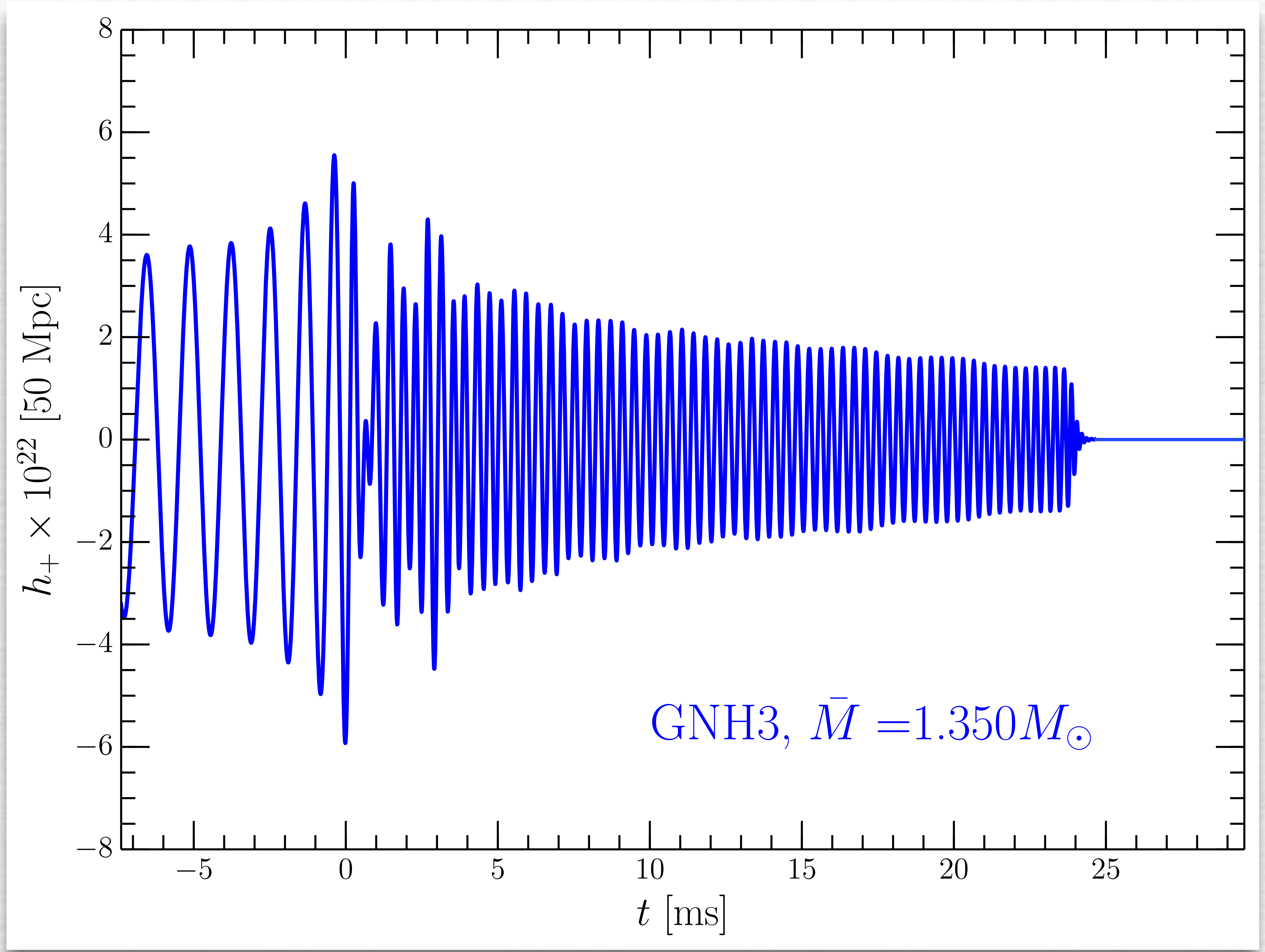
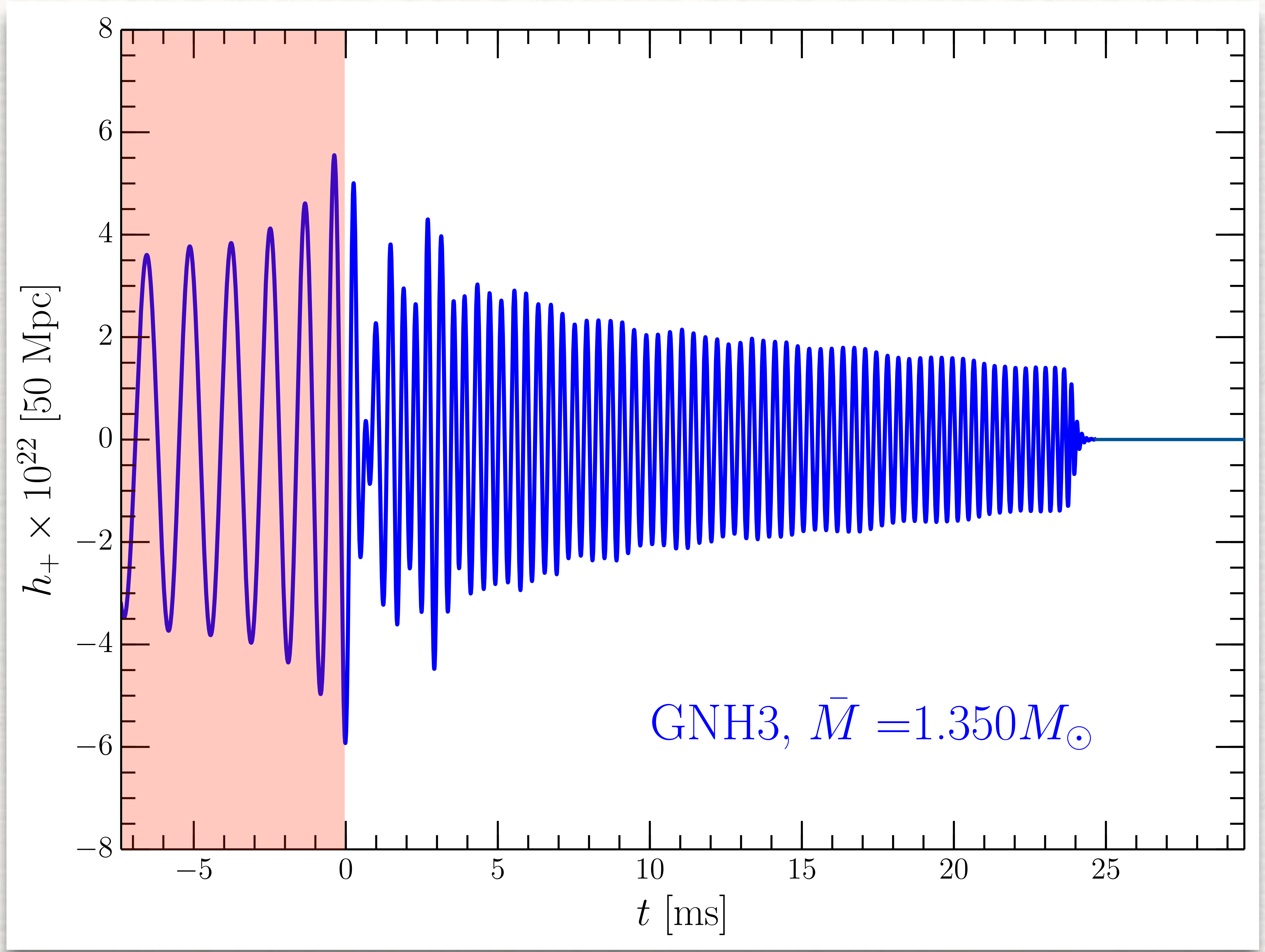


Anatomy of the GW signal

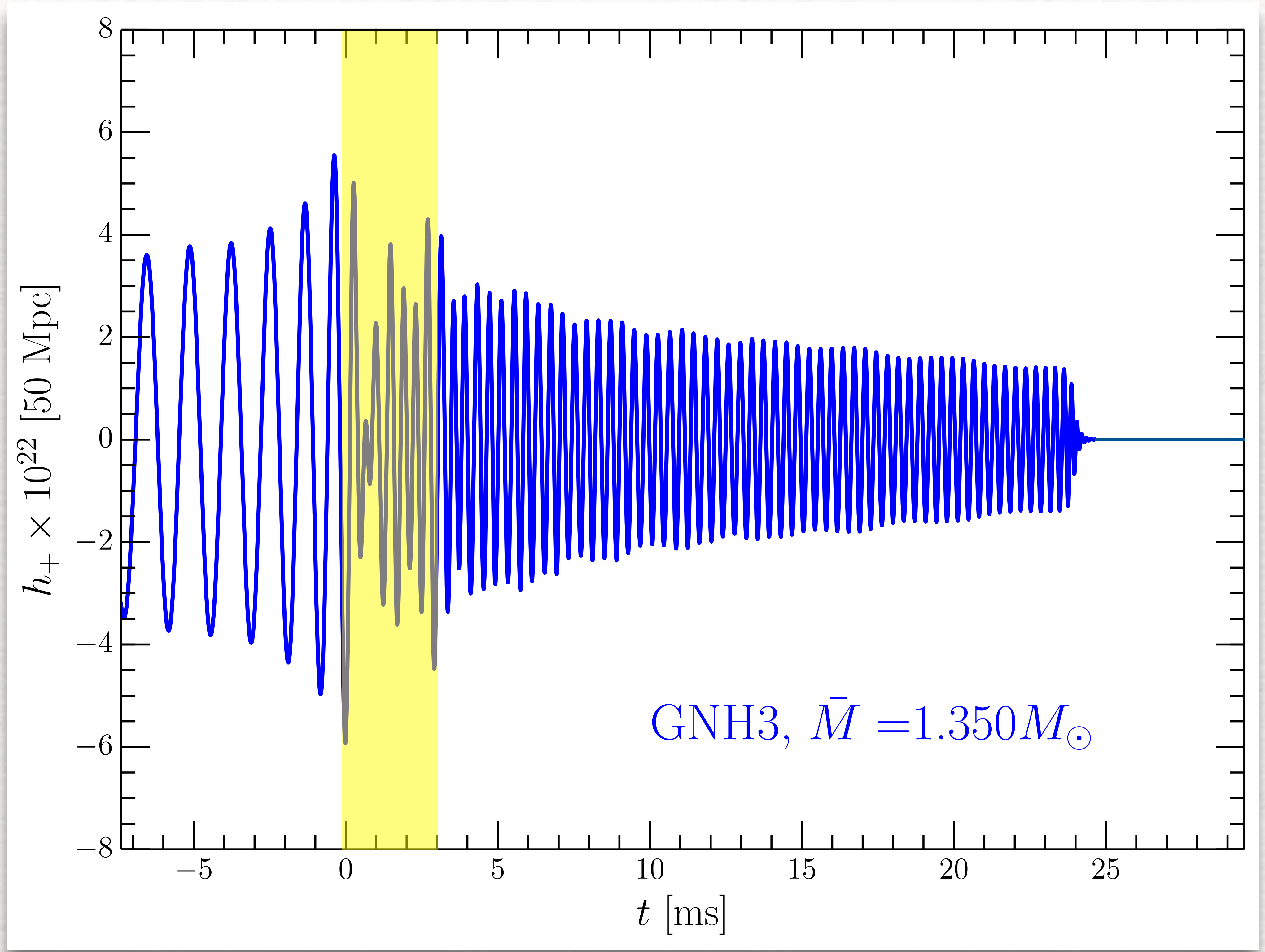


Anatomy of the GW signal



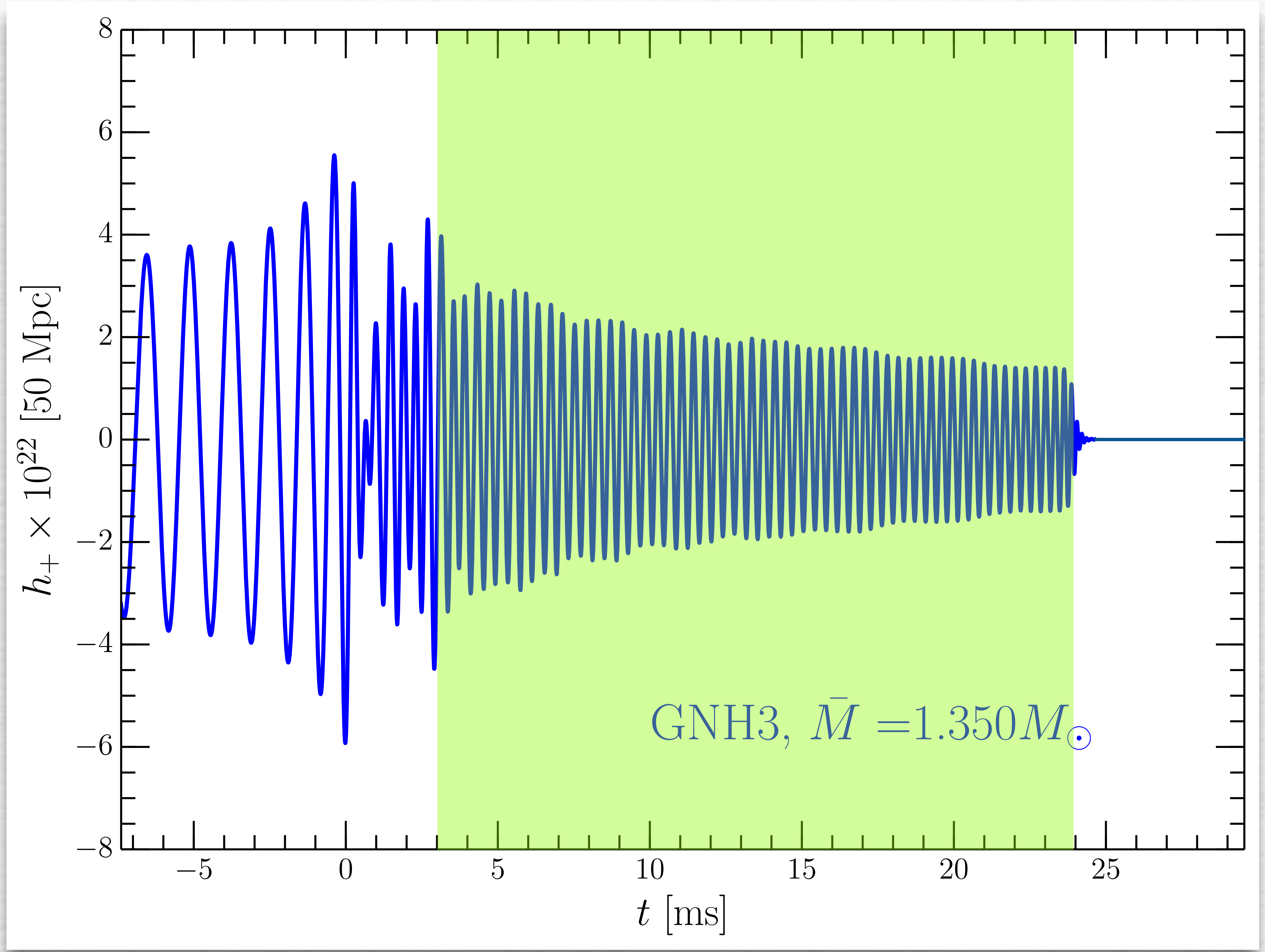
Inspiral/chirp: well approximated by semianalytic approaches

Anatomy of the GW signal



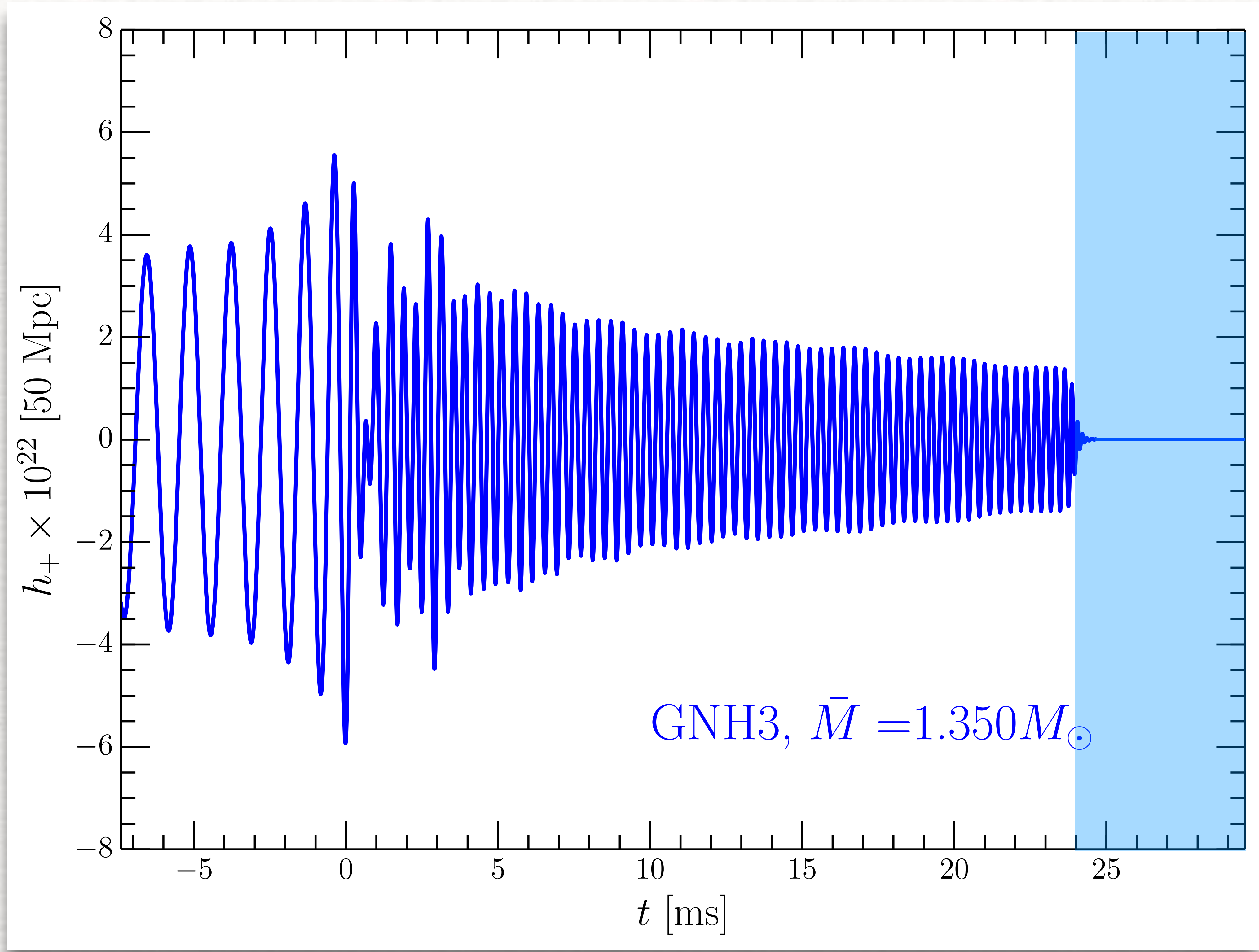
Merger: highly nonlinear but analytic description possible

Anatomy of the GW signal



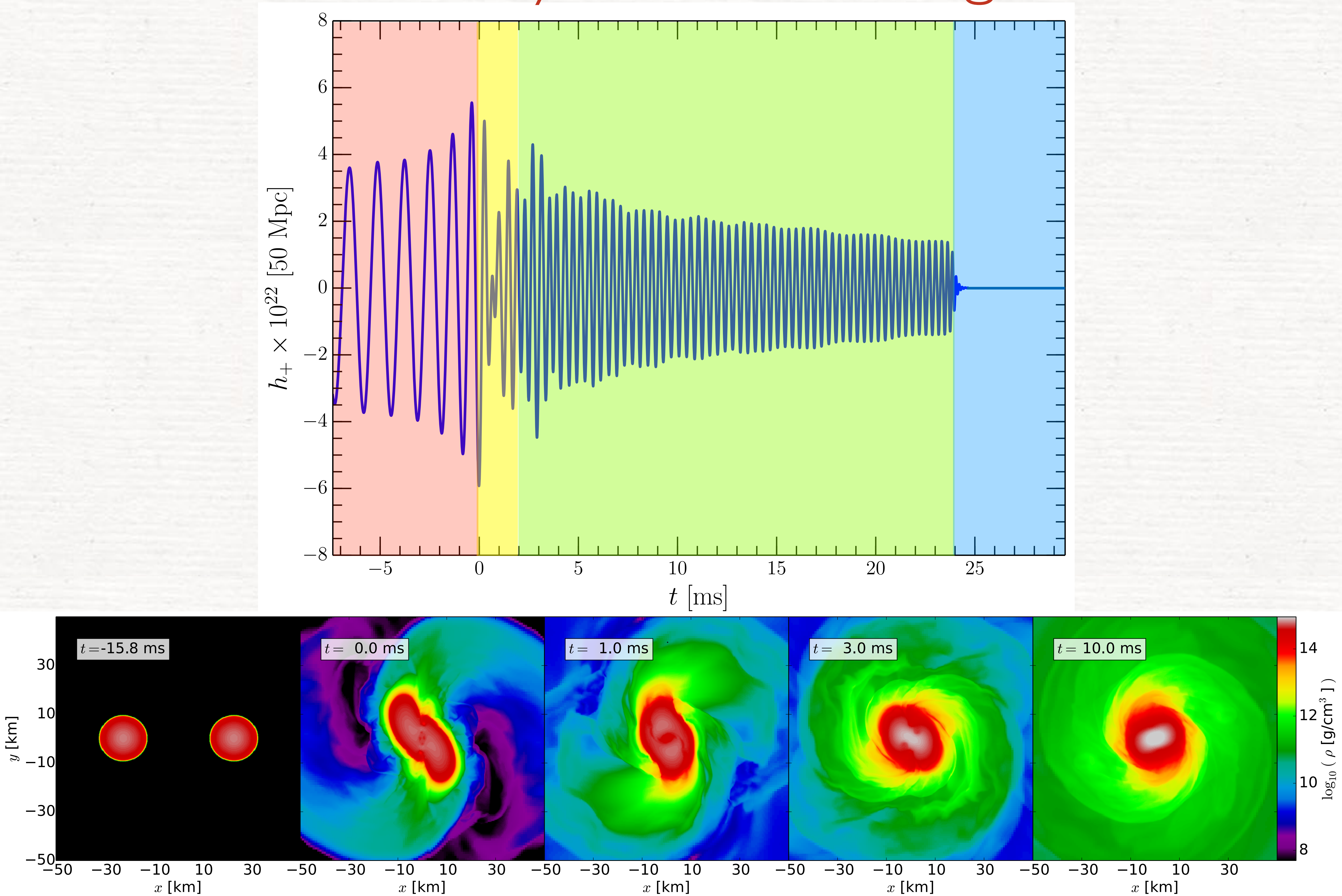
post-merger: quasi-periodic emission of bar-deformed HMNS

Anatomy of the GW signal

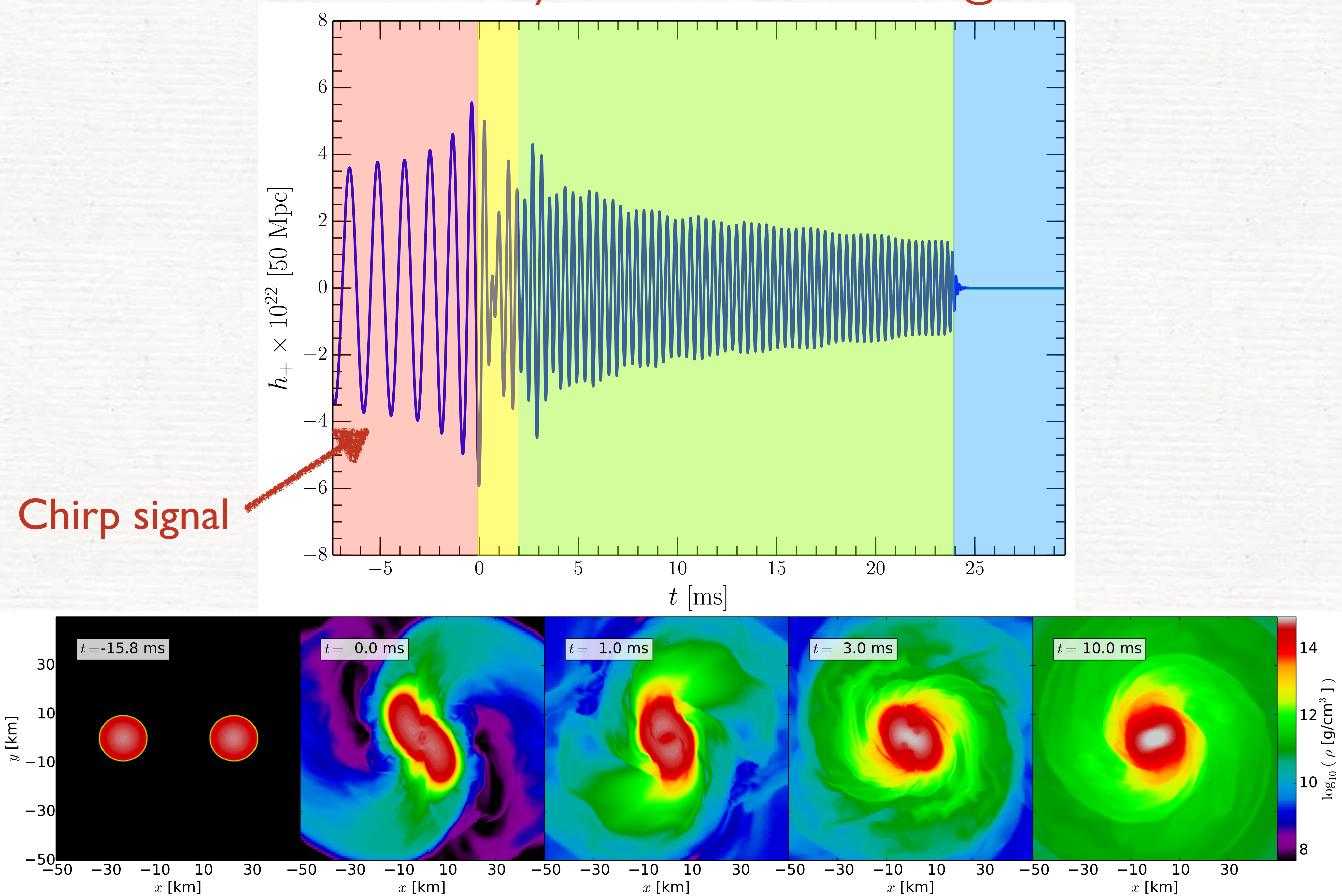


Collapse-ringdown: signal essentially shuts off.

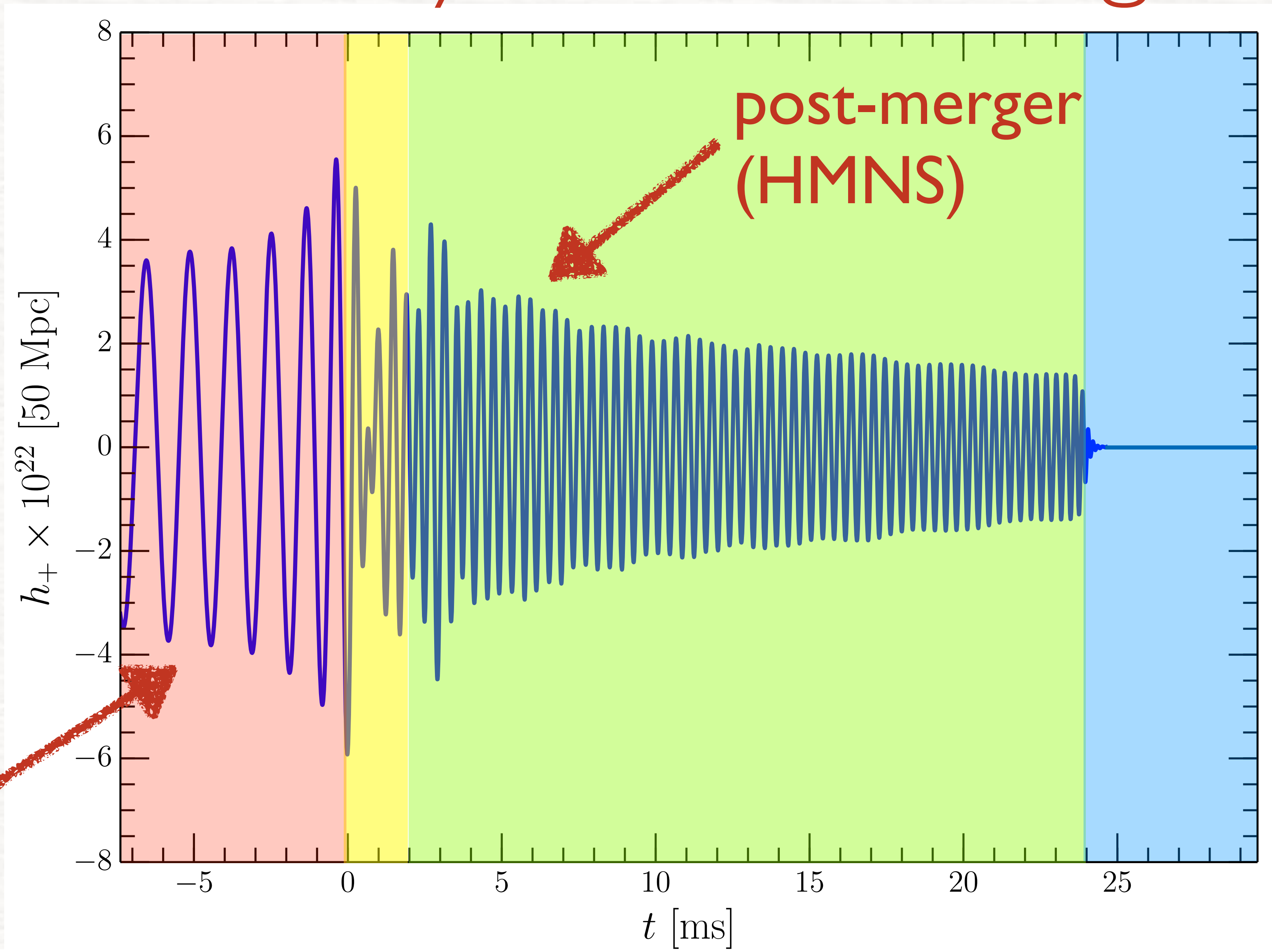
Anatomy of the GW signal

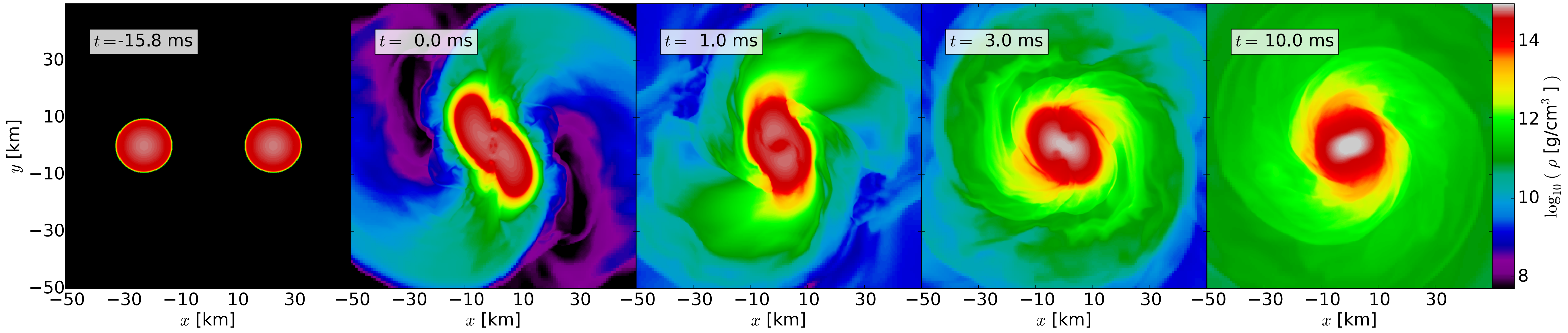


Anatomy of the GW signal

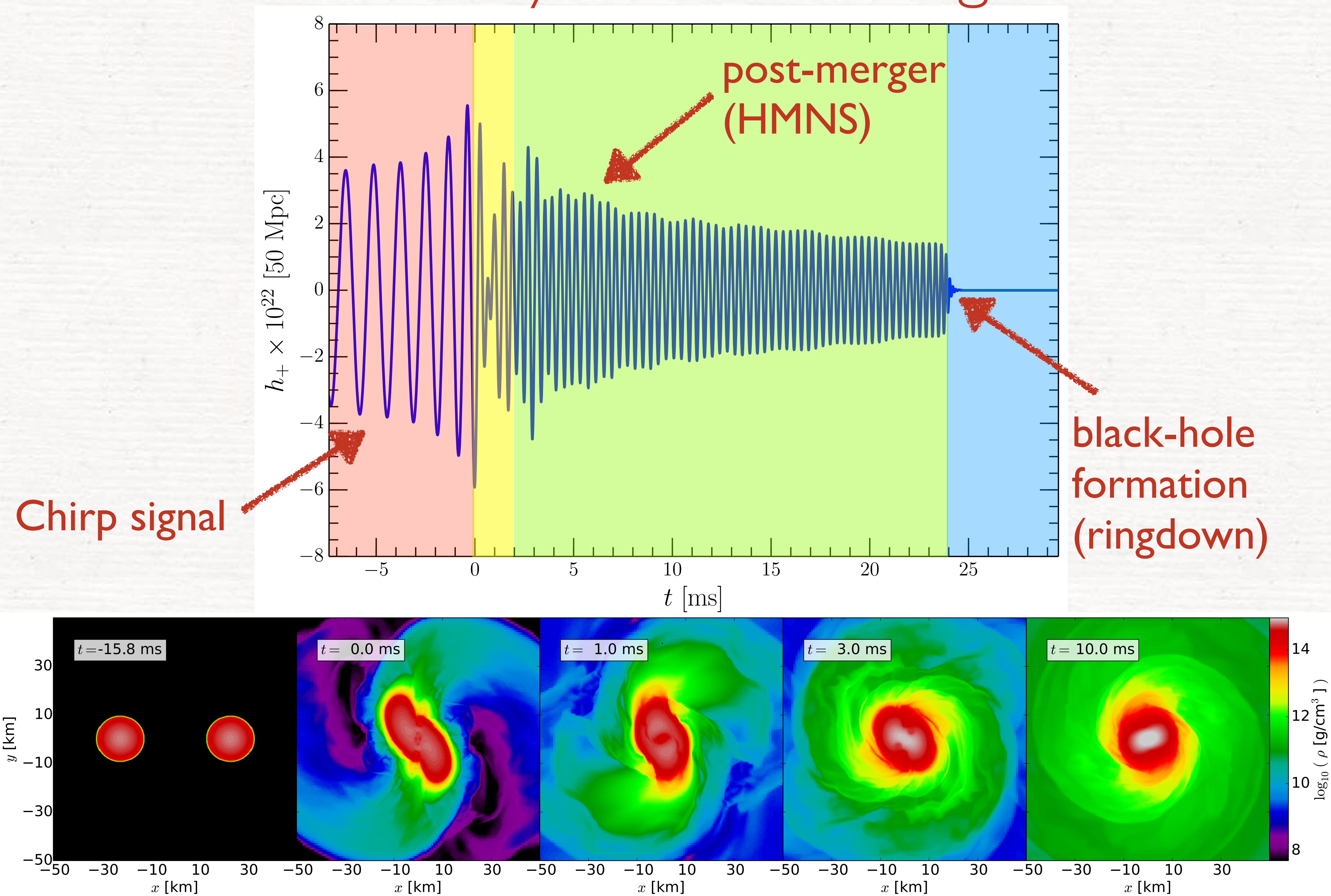


Anatomy of the GW signal

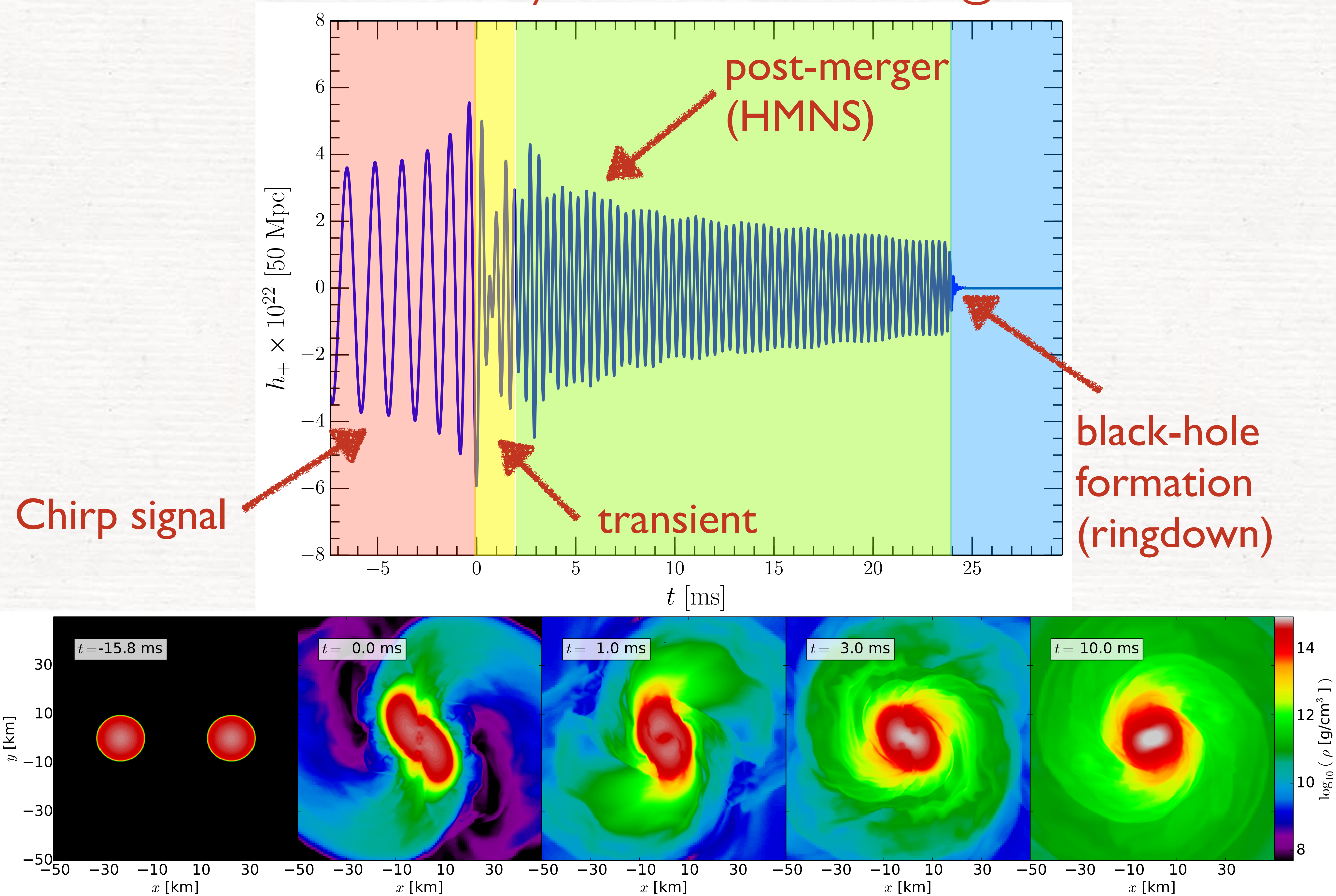




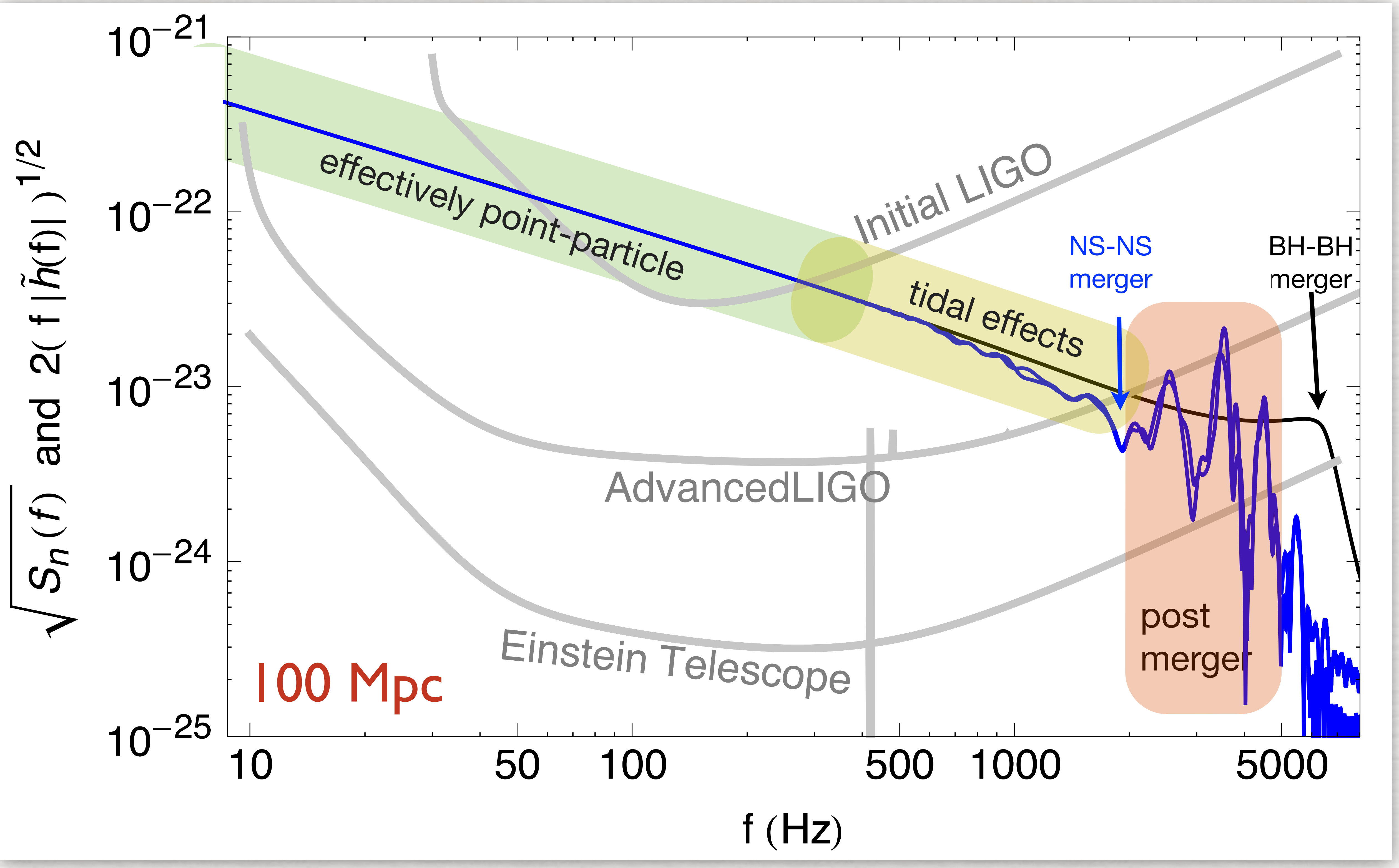
Anatomy of the GW signal



Anatomy of the GW signal

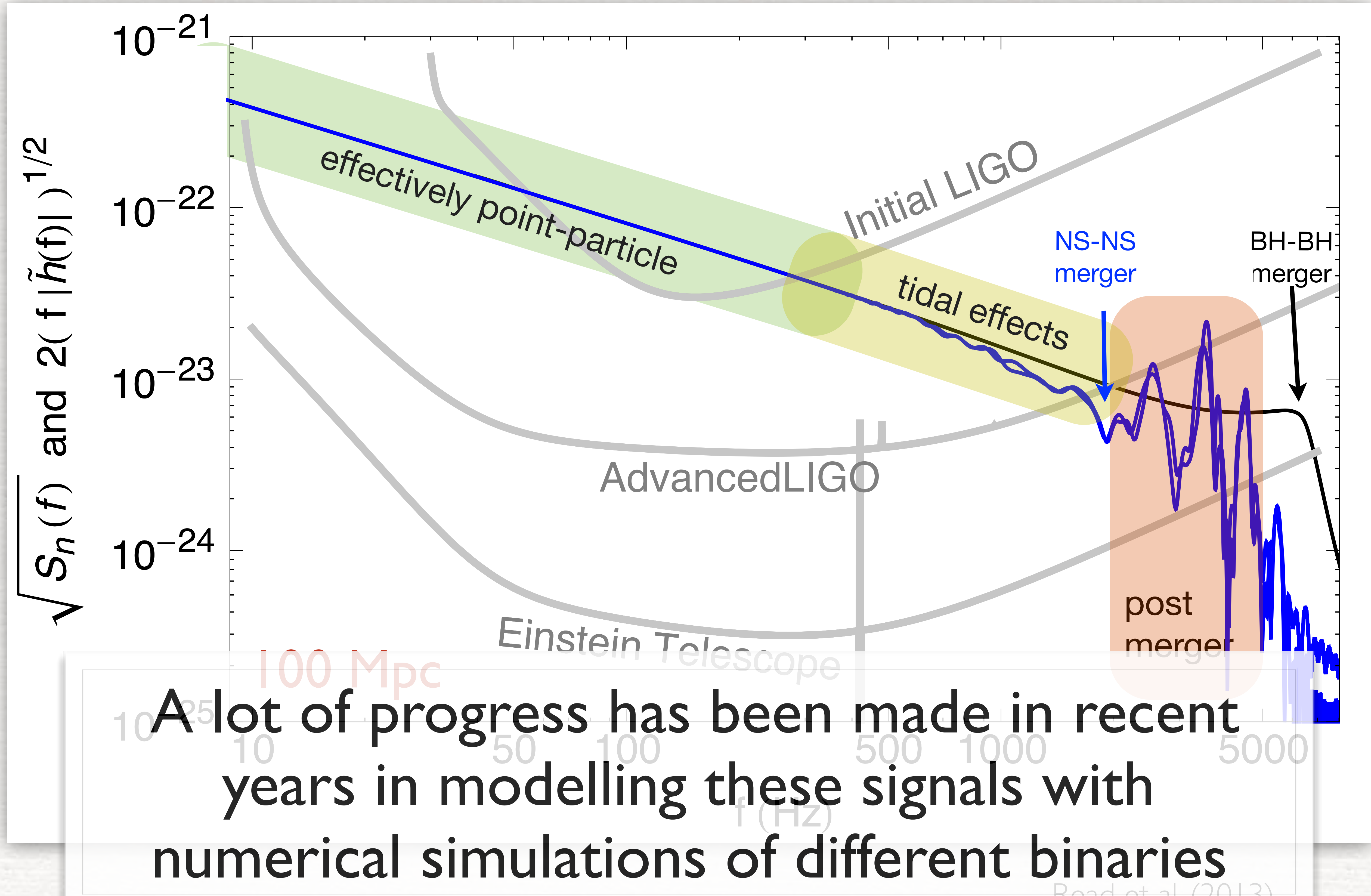


In frequency space



Read et al. (2013)

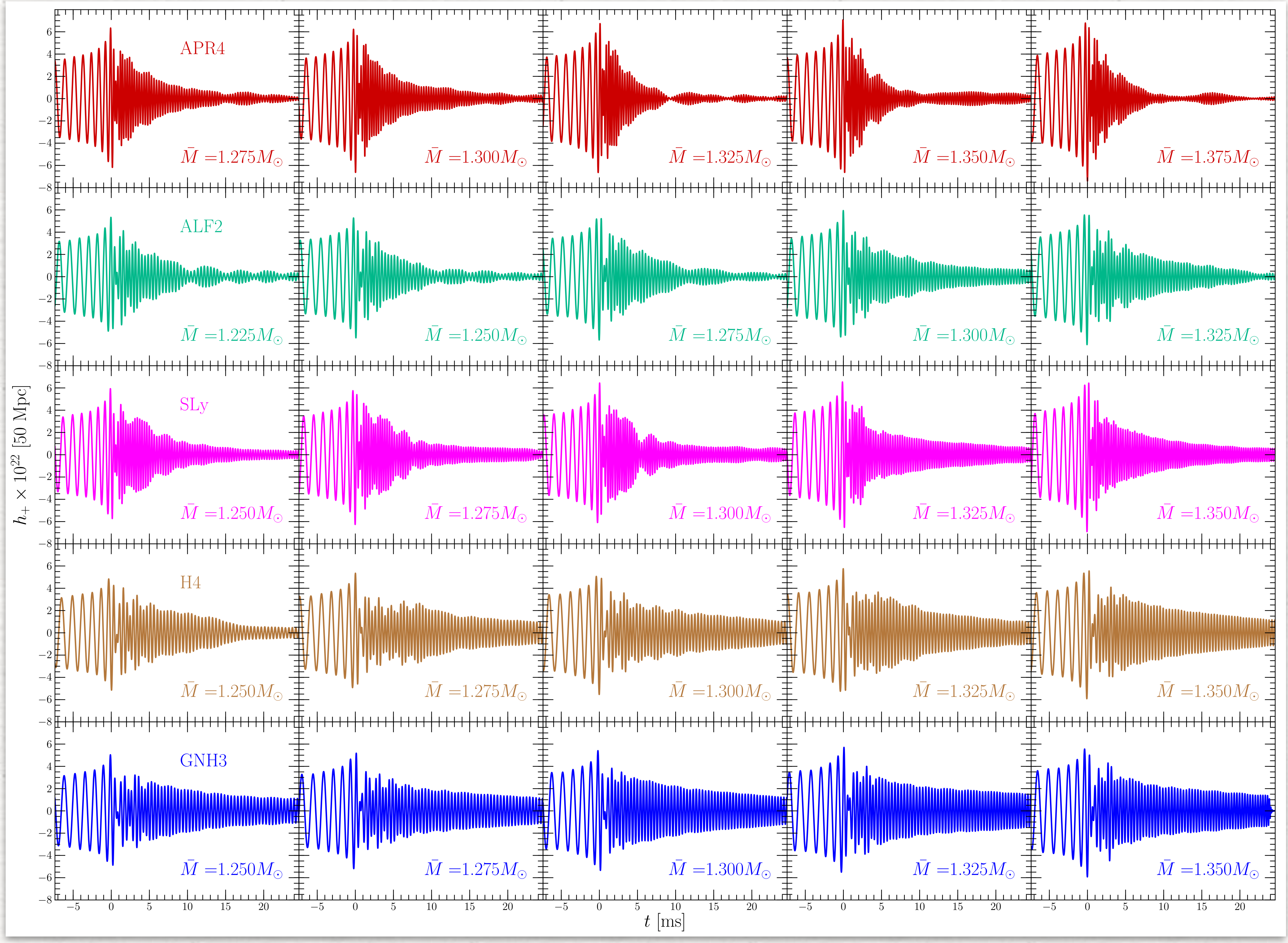
In frequency space



A lot of progress has been made in recent years in modelling these signals with numerical simulations of different binaries

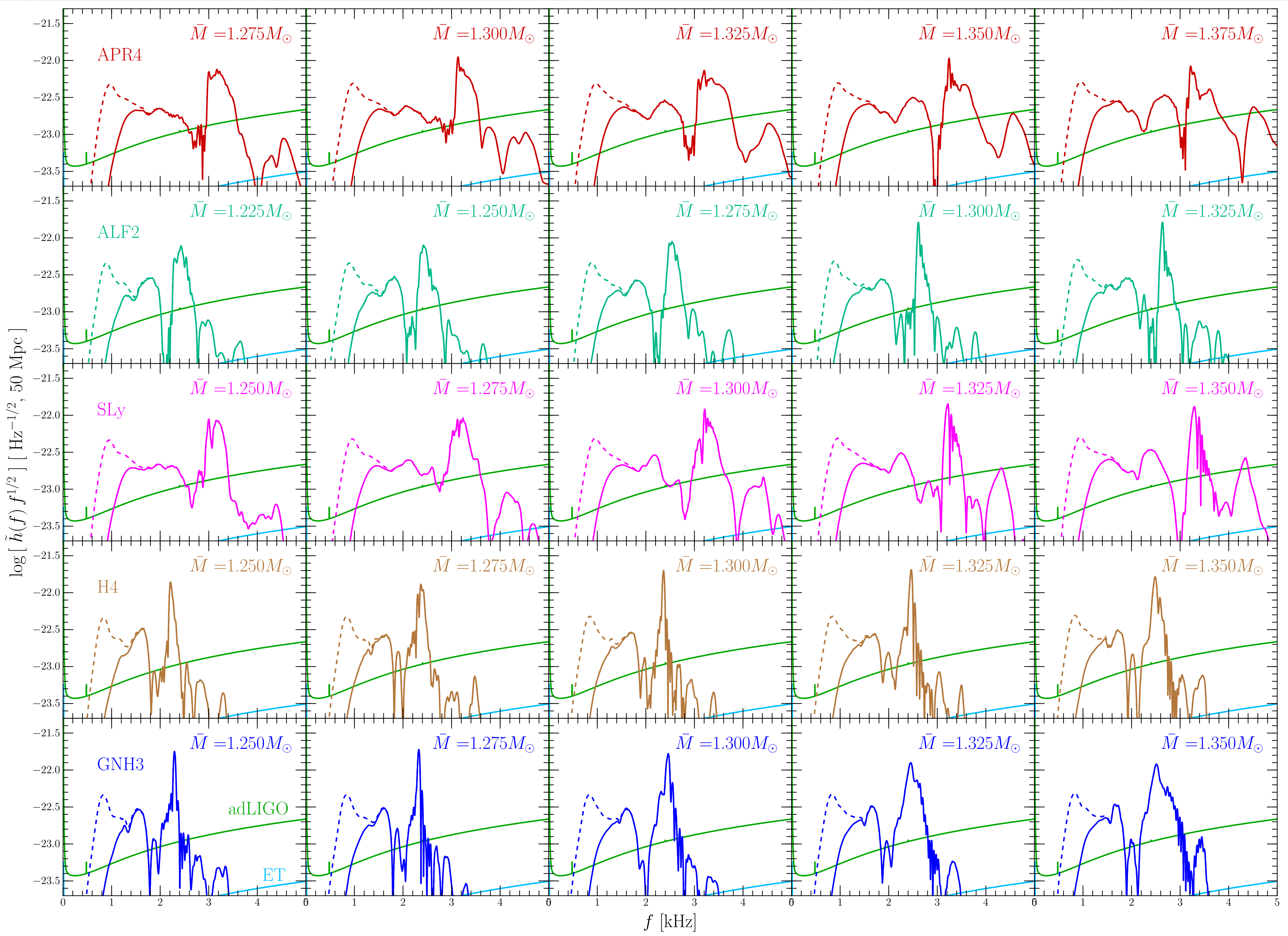
What we can do nowadays

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



Extracting information from the EOS

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



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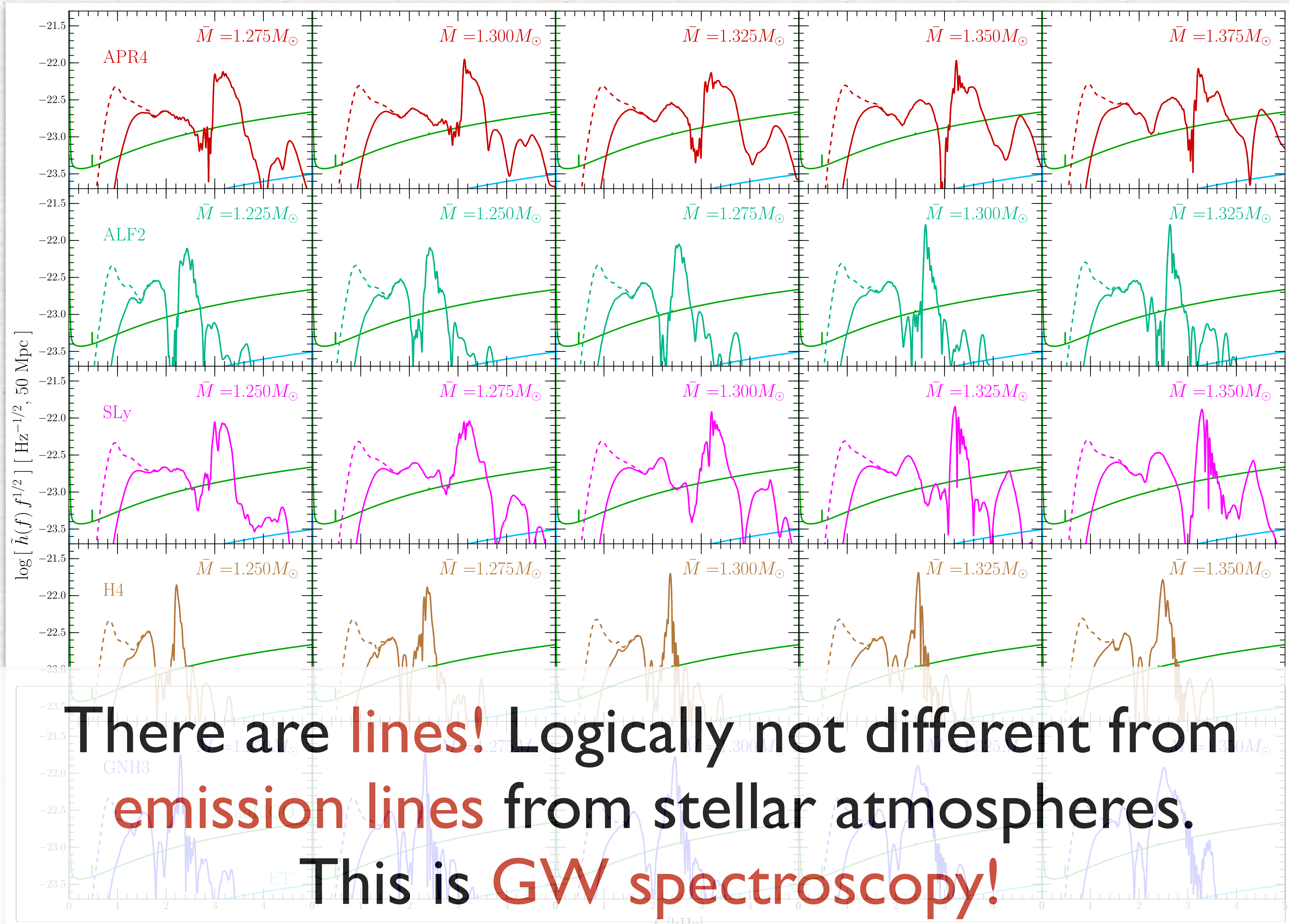


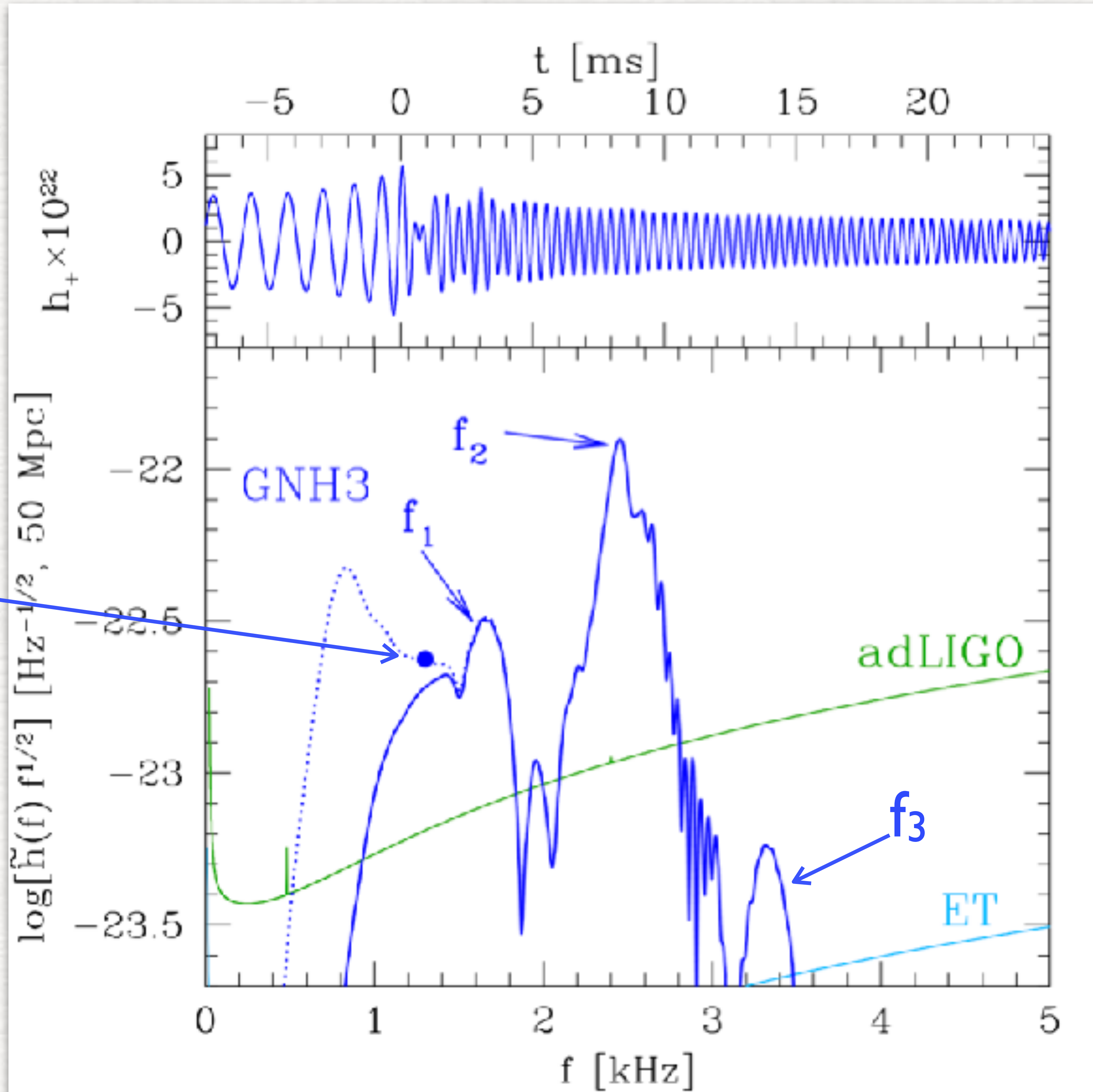
There are **lines!** Logically not different from **emission lines** from stellar atmospheres.

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, Palenzuela+ 15, Lehner+ 2016, LR+2016…

merger frequency f_{max}



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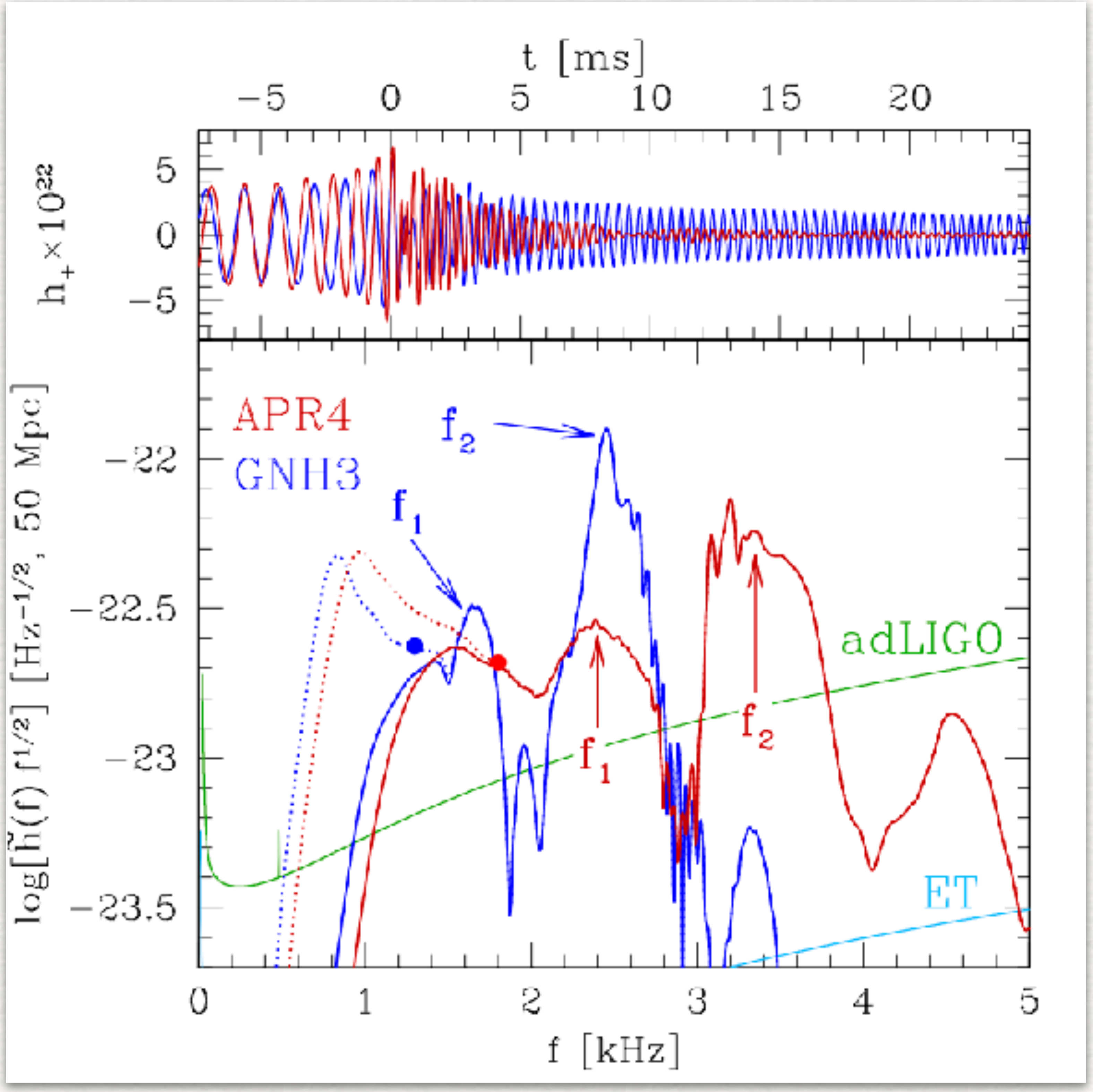

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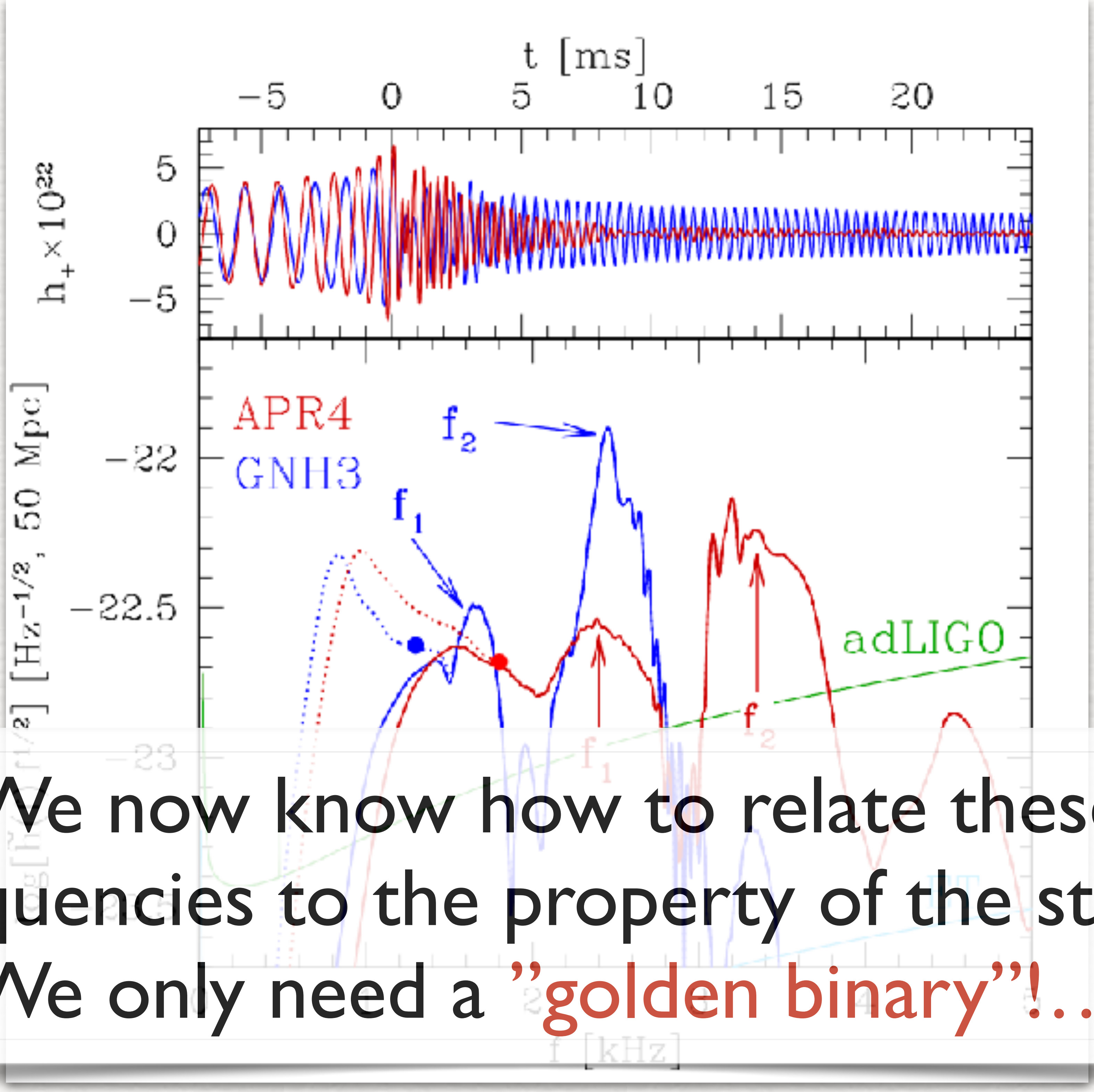
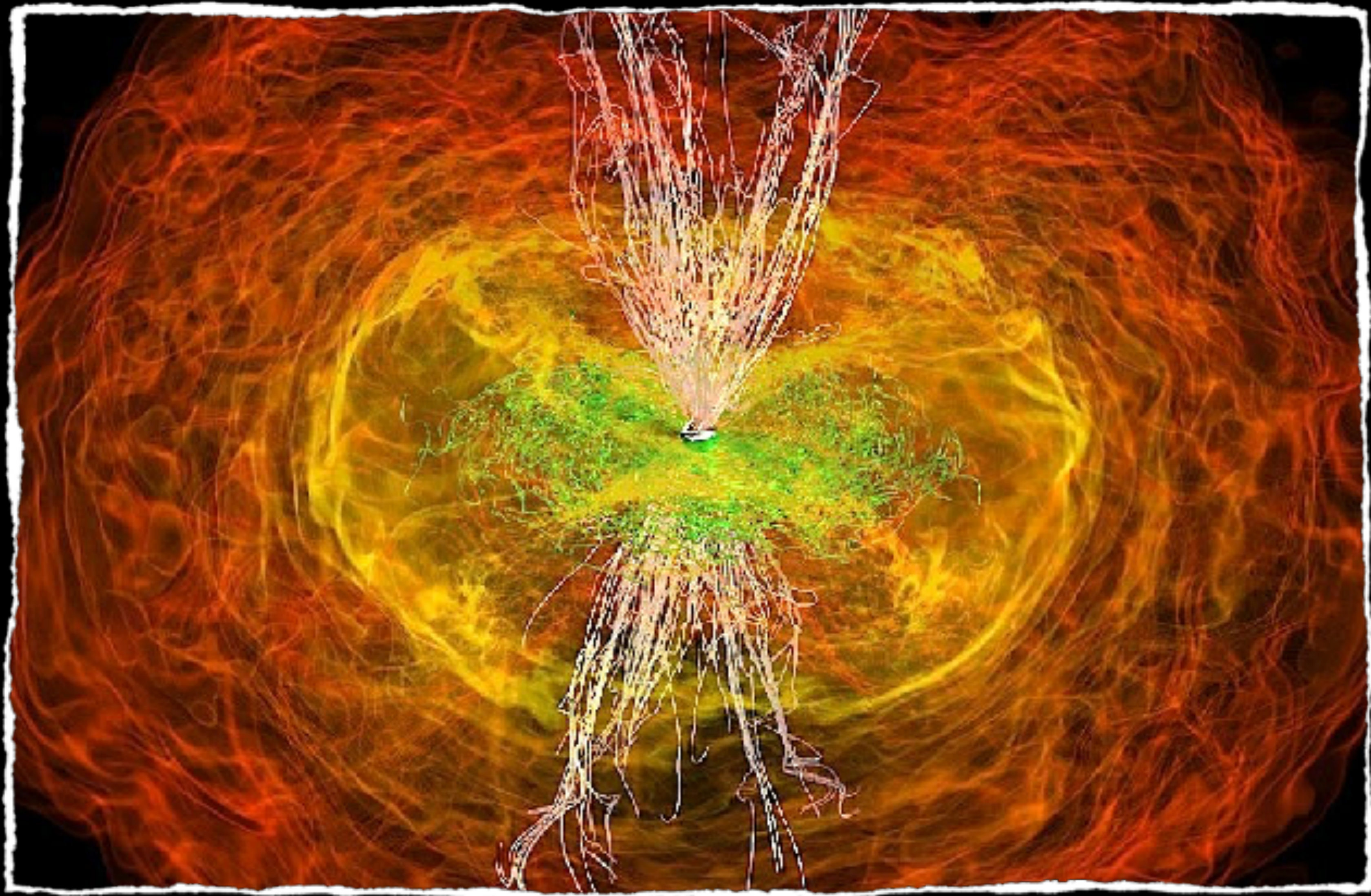


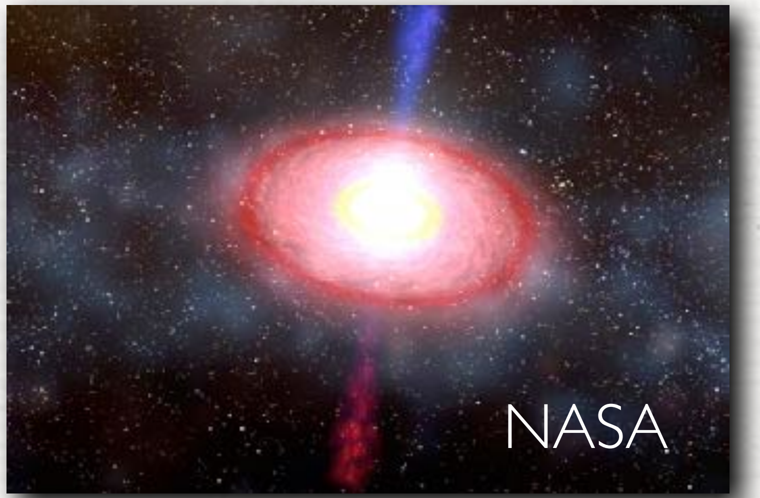
We now know how to relate these frequencies to the property of the stars! We only need a "golden binary"!…

Electromagnetic counterparts



Electromagnetic counterparts

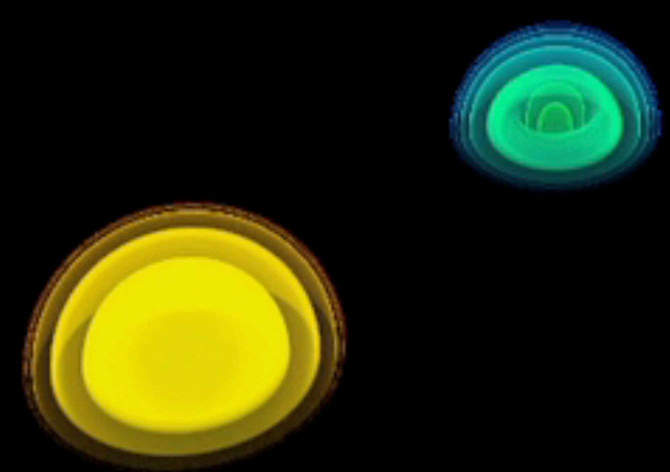
- Already in the 70's, astronomers realised that very rapid flashes of gamma rays are observed regularly by satellites
- These flashes come from most remote corners and have enormous energies of $10^{50\text{-}53}$ erg: **gamma-ray bursts**.
- There are two families of bursts: "**long**" and "**short**"
- The first ones last **tens** or more of **seconds** and seem to be due to the collapse of very massive stars.
- The second ones last **less** than a **second**.
- Merging neutron stars always though to be most reasonable explanation but how do you produce a **jet**?



What happens when magnetised stars collide?

What happens when magnetised stars collide?

Need to solve equations of magnetohydrodynamics in addition to the Einstein equations

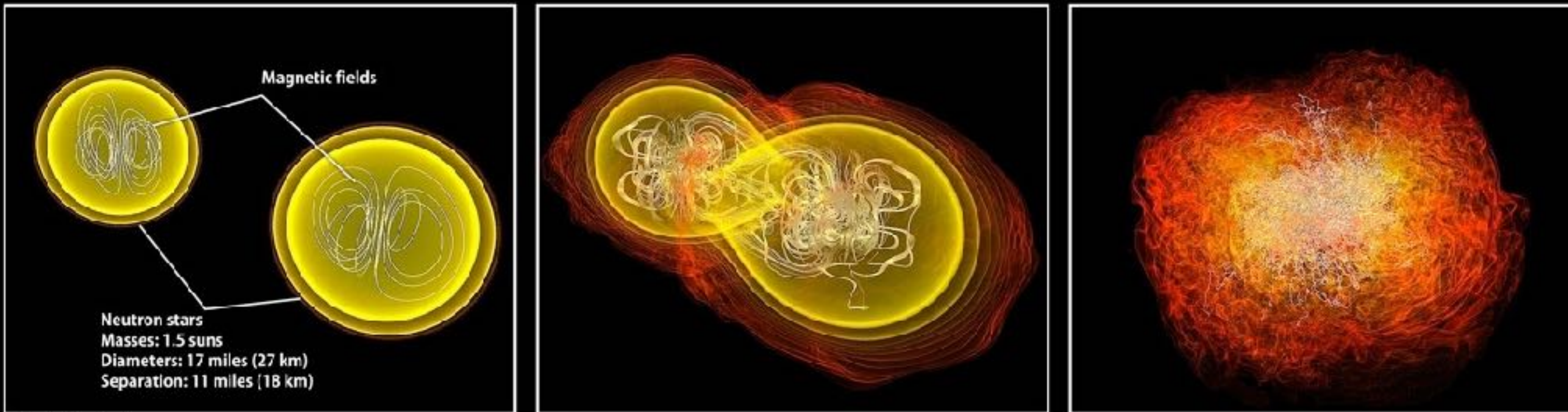


$$M = 1.5\,M_\odot, B_0 = 10^{12}\,\mathrm{G}$$

Animations:, LR, Koppitz


9
11.75
14.5
lg(rho) [g/cm3]
9.5
12
14.5
lg(|B|) [Gauss]

What happens when magnetised stars collide?

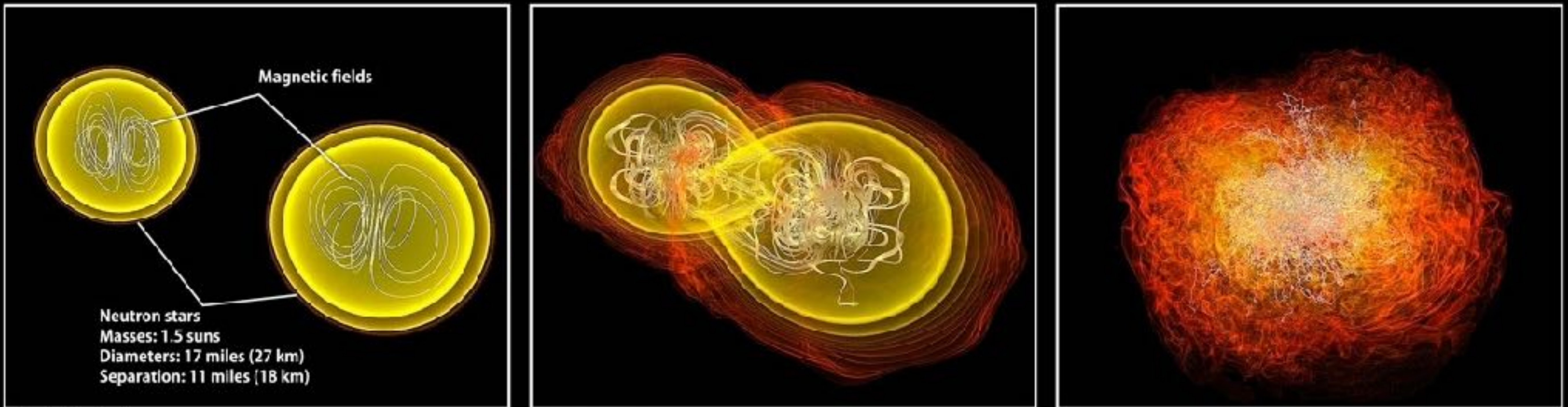


Simulation begins

7.4 milliseconds

13.8 milliseconds

What happens when magnetised stars collide?

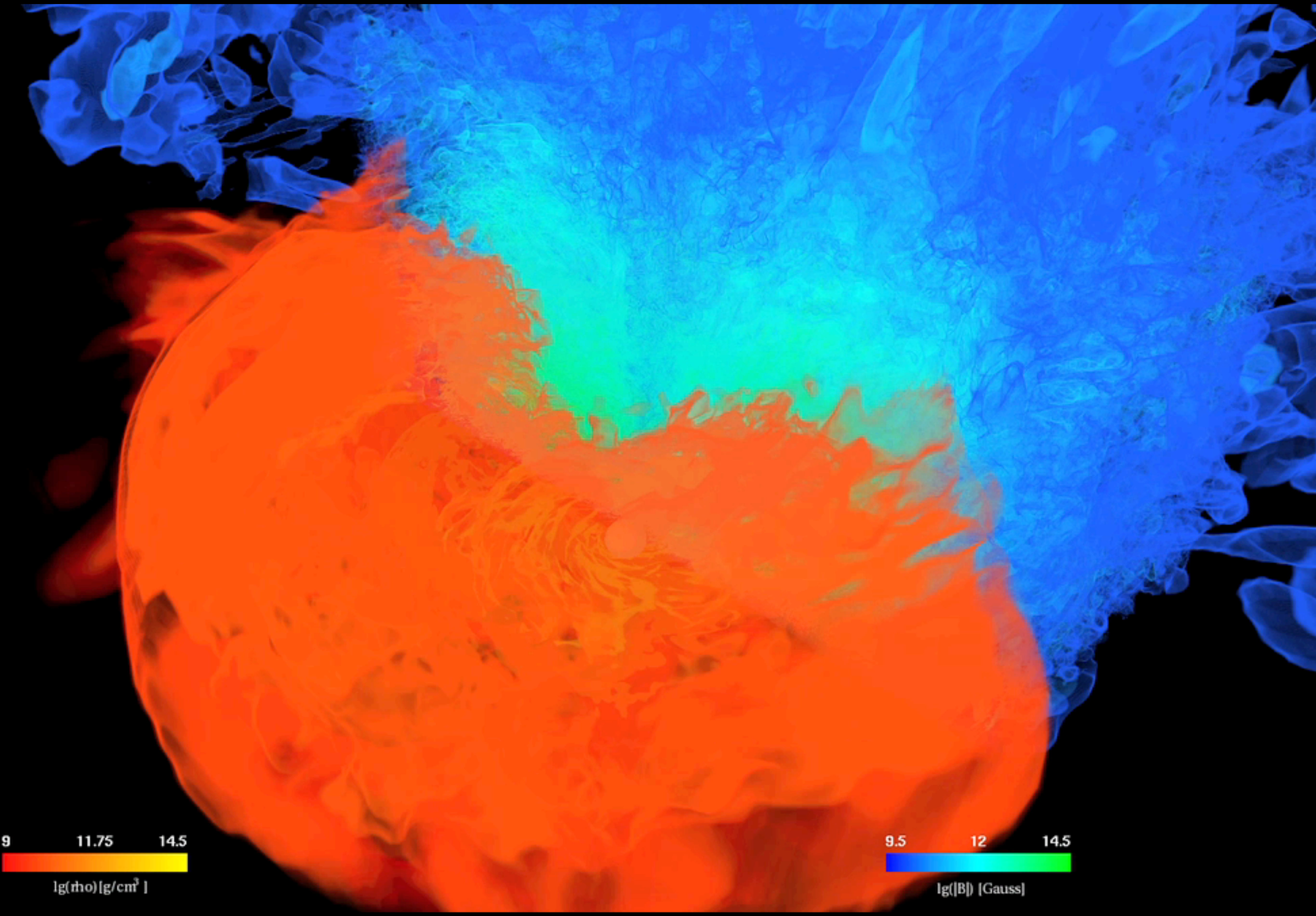


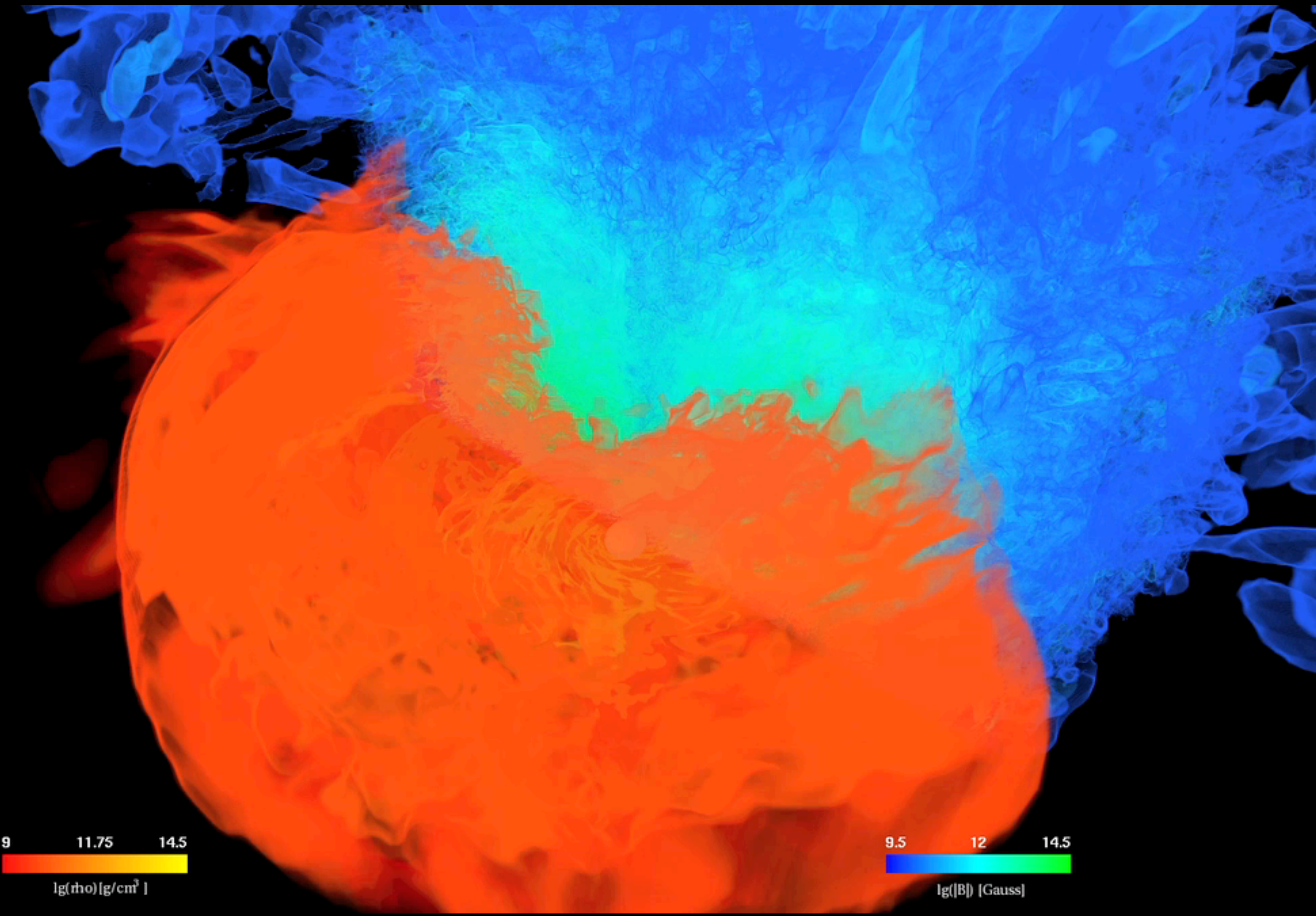
Simulation begins

7.4 milliseconds

13.8 milliseconds

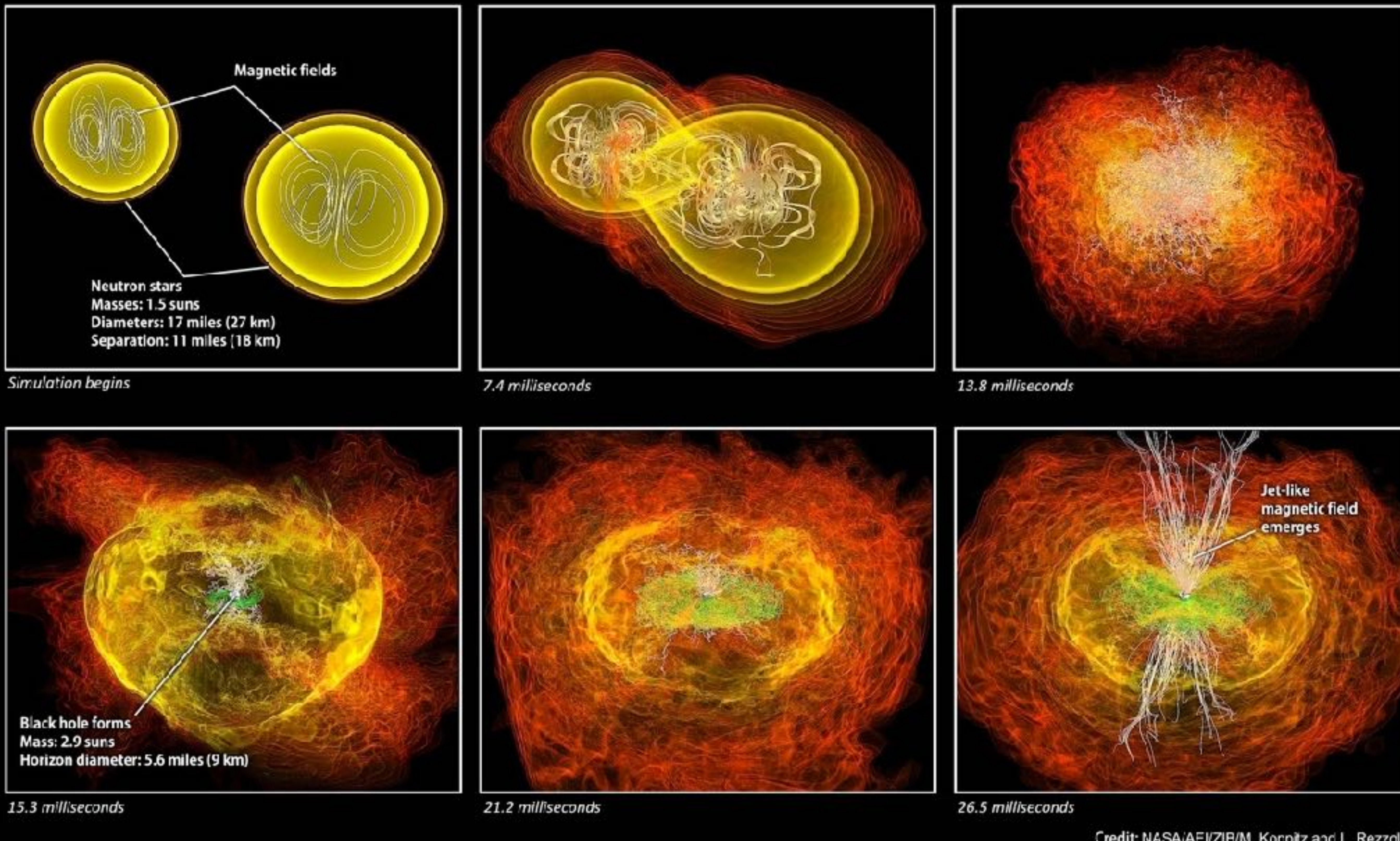
Magnetic fields in the HMNS have complex topology: dipolar fields are destroyed.


9
11.75
14.5
lg(rho) [g/cm³]
9.5
12
14.5
lg(|B|) [Gauss]



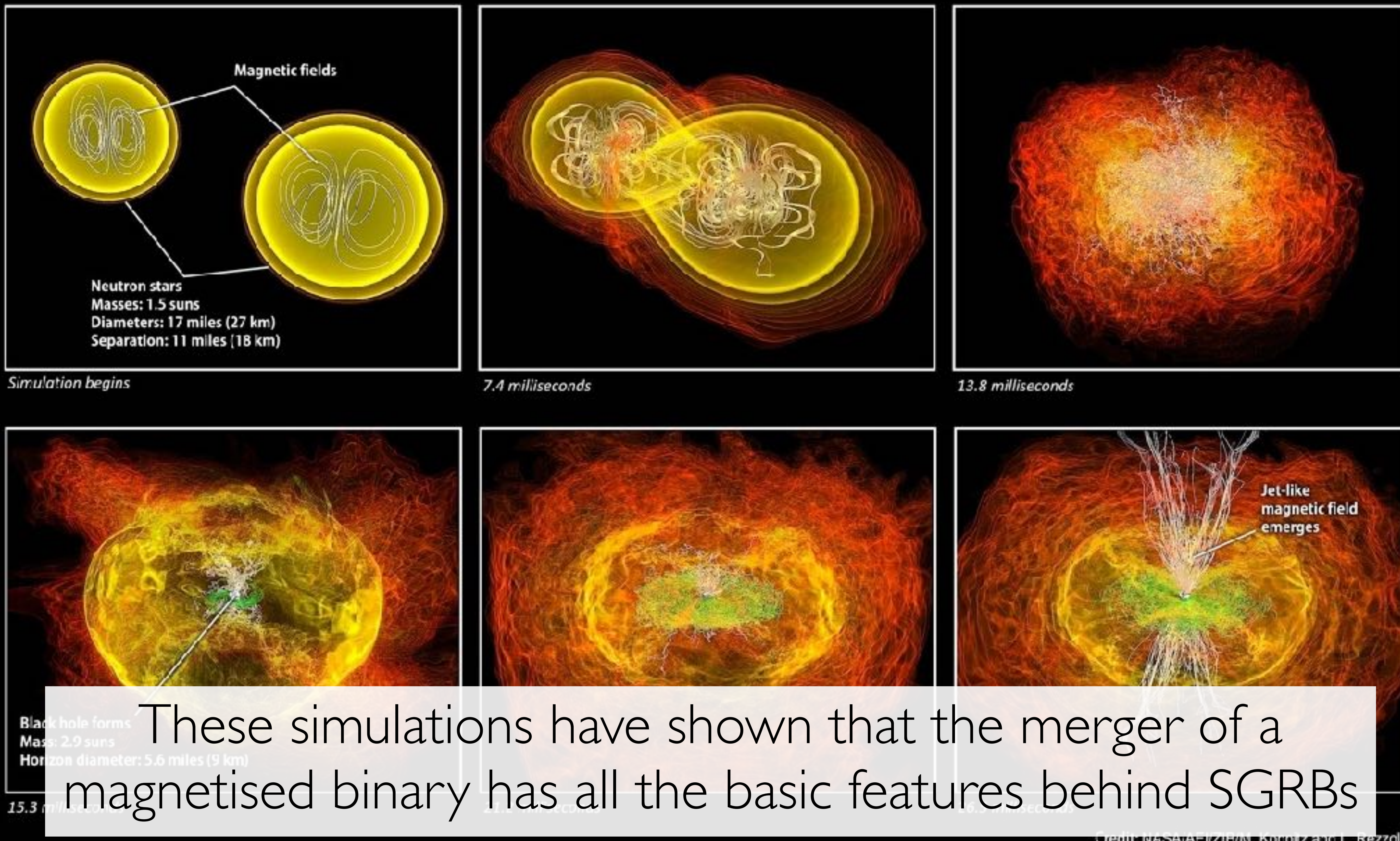
9
11.75
14.5
lg(rho) [g/cm³]
9.5
12
14.5
lg(|B|) [Gauss]

LR+ 2011



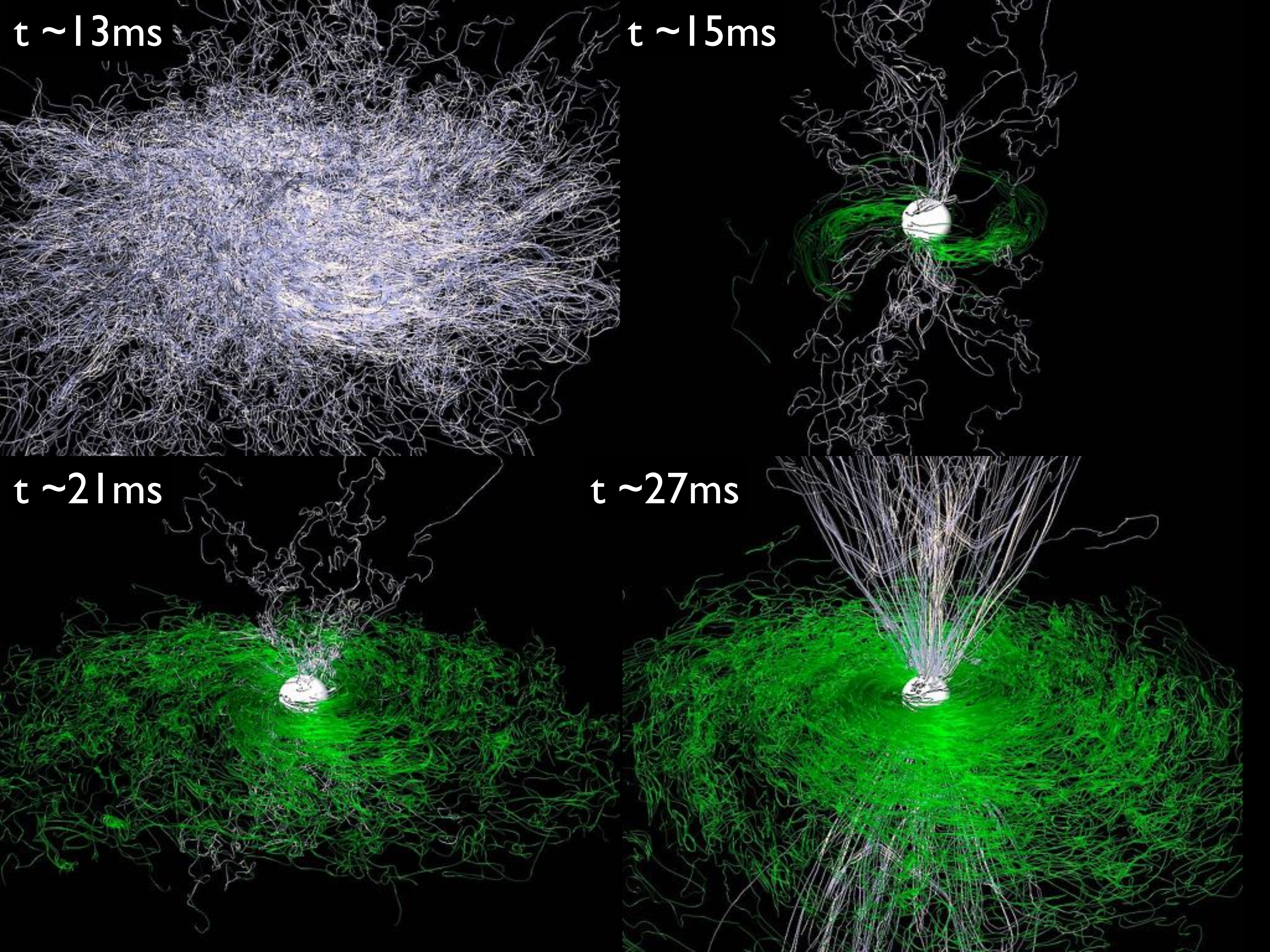
$J/M^2 = 0.83$ $\quad$ $\mathrm{M_{tor}} = 0.063 M_\odot$ $\quad$ $\mathrm{t_{accr}} \simeq M_{\rm tor}/\dot{M} \simeq 0.3\ \mathrm{s}$

LR+ 2011

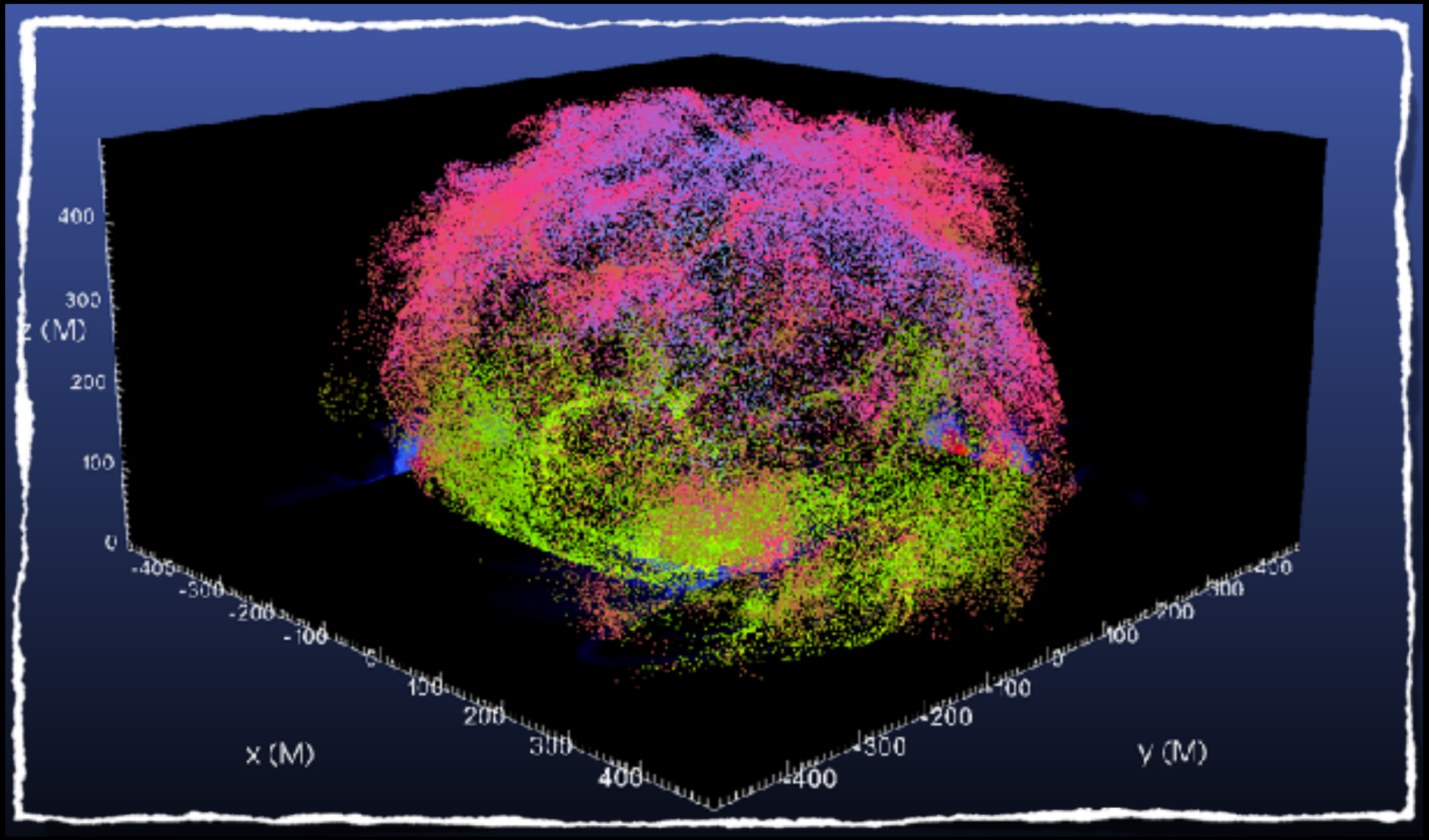


These simulations have shown that the merger of a magnetised binary has all the basic features behind SGRBs

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

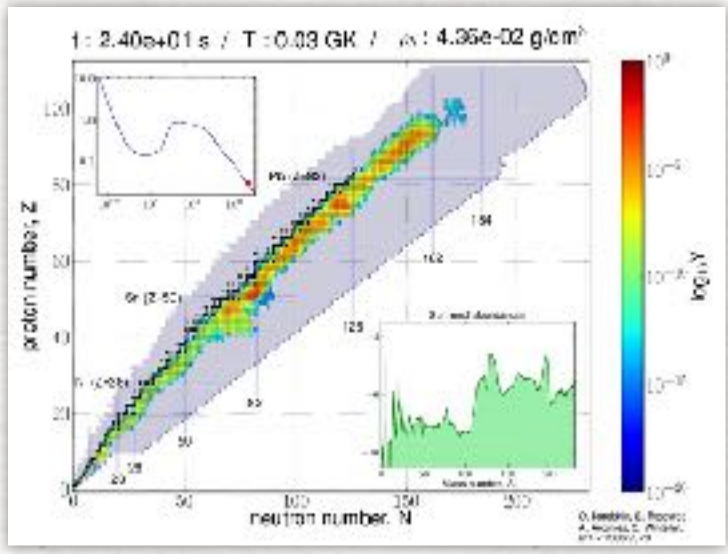

t ~13ms
t ~15ms
t ~21ms
t ~27ms

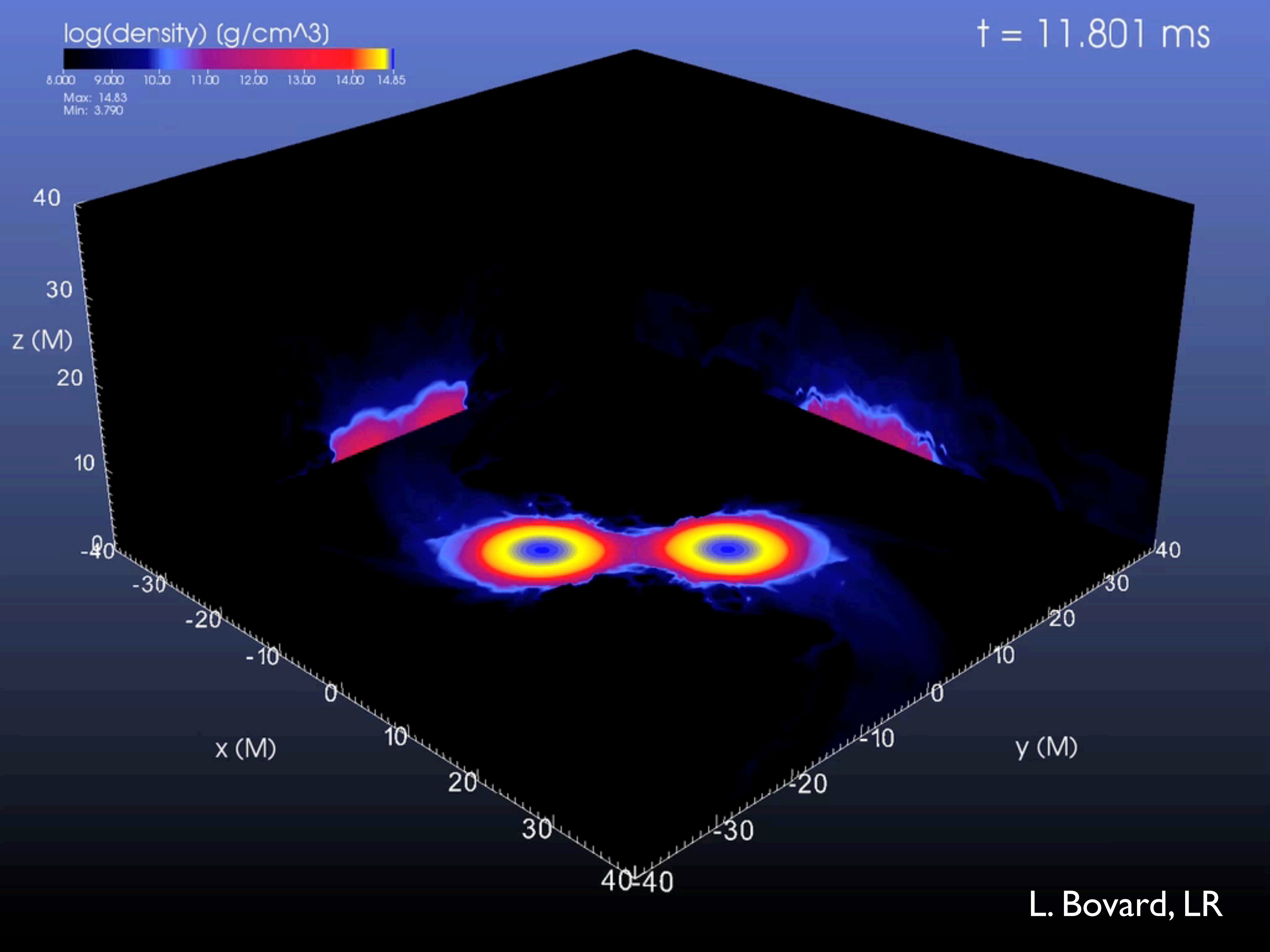
Ejected matter and nucleosynthesis

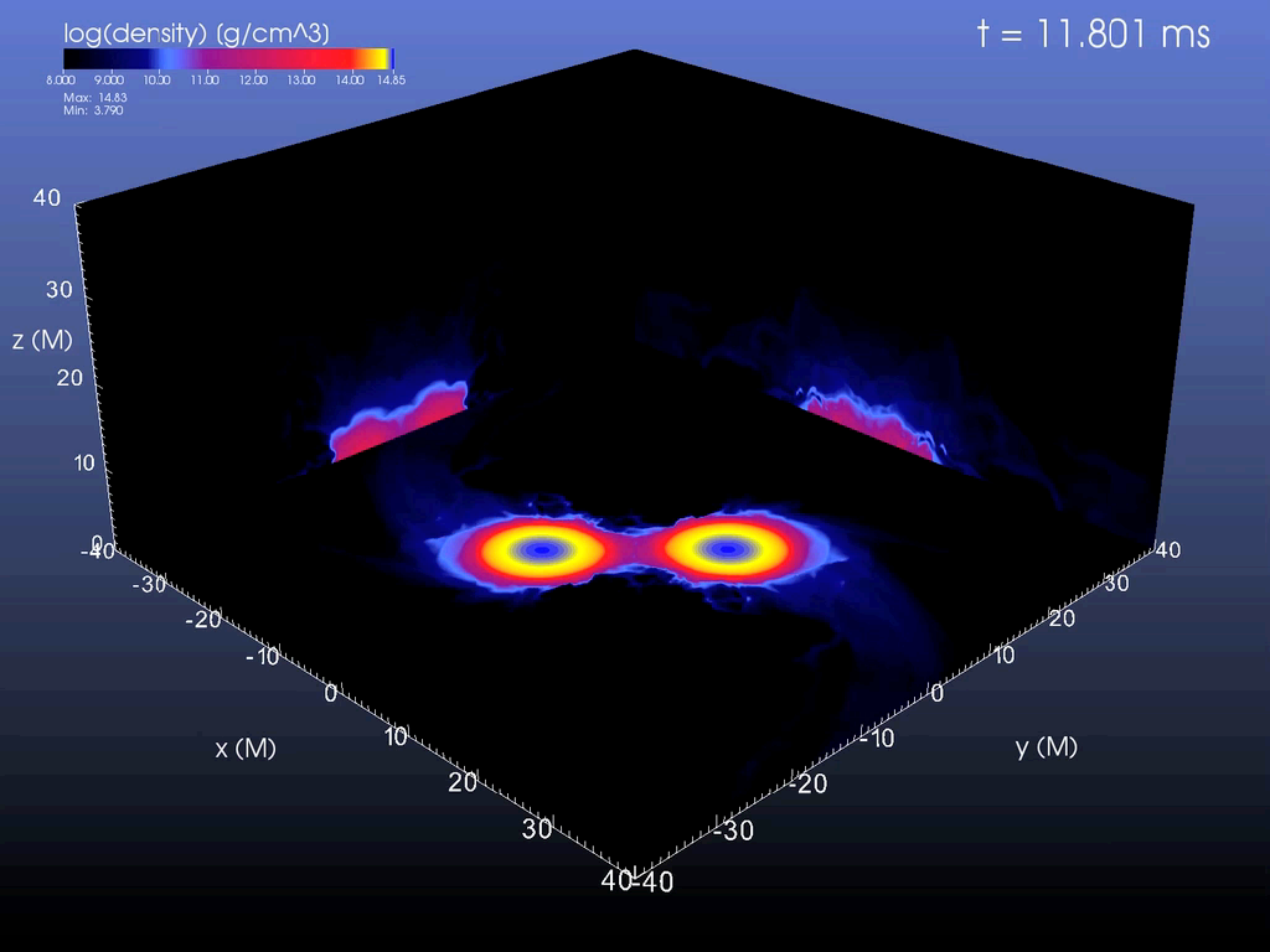


Nucleosynthesis

- Already in the 50's, nuclear physicists had tracked the production of elements in stars via nuclear fusion.
- **Heavy elements** $(A \gtrsim 56)$ cannot be produced in stellar interiors but can be synthesised during a **supernova**.
- Modern numerical simulations of supernovae have shown that the temperature and energies are not large enough to produce the **"very heavy" elements** $(A \gtrsim 120)$.
- To produce such elements one needs very high temperatures and **"neutron-rich"** material.
- **Neutron-star mergers** seem perfect candidates for this process!




log(density) (g/cm^3)
8.000
9.000
10.00
11.00
12.00
13.00
14.00
14.85
Max: 14.83
Min: 3.790
t = 11.801 ms
z (M)
x (M)
y (M)
L. Bovard, LR



log(density) (g/cm^3)
8.000 9.000 10.00 11.00 12.00 13.00 14.00 14.85
Max: 14.83
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z (M)
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y (M)

Relative abundances

Relative abundances

- Abundance pattern for ***A>120*** in good agreement with solar.

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Relative abundances

Bovard+ 17

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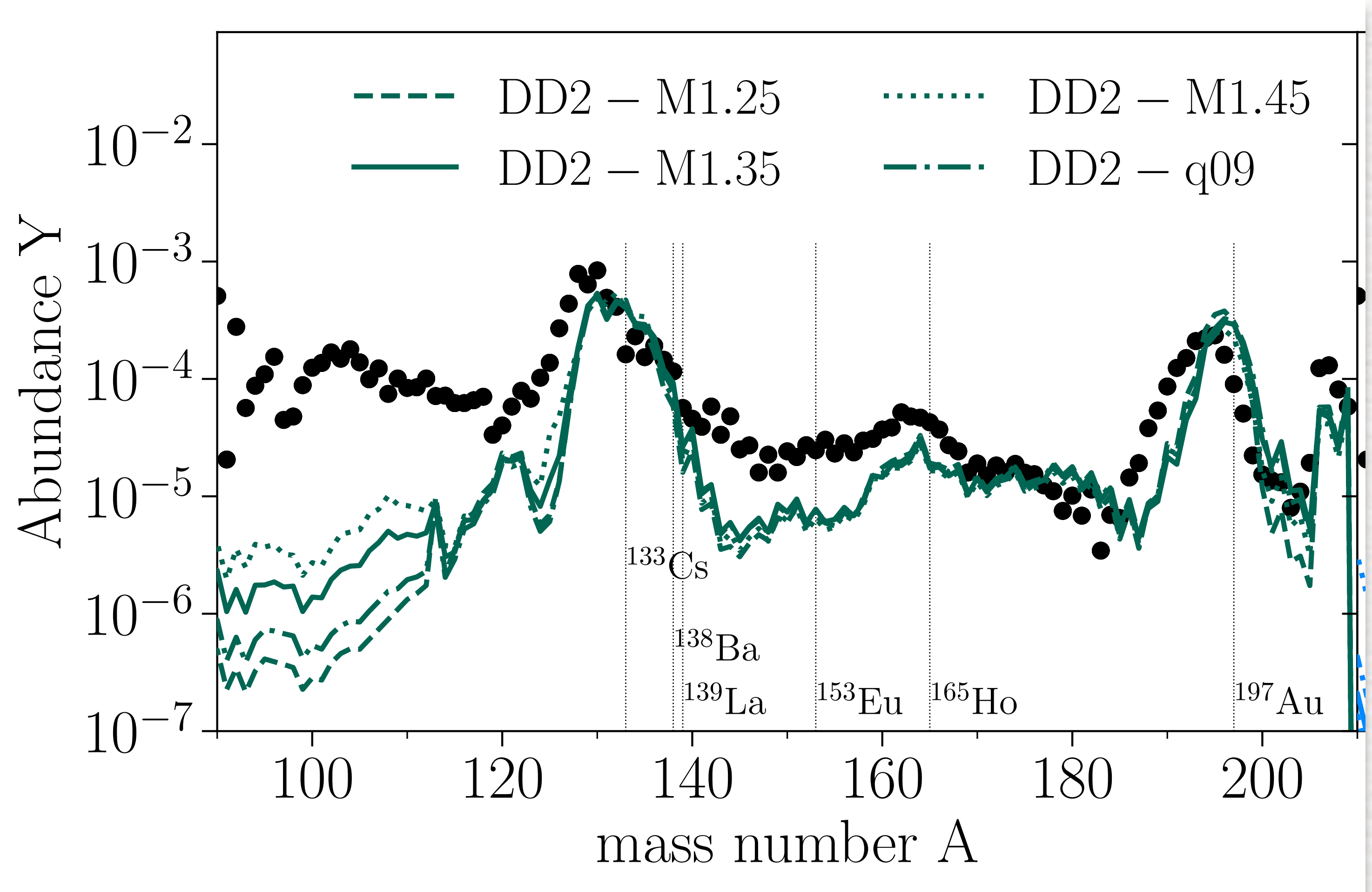
- Even **tiny amounts** of ejected matter ($0.01 M_{\odot}$) sufficient to explain observed abundances.
- Extremely **robust** behaviour across different **EOSs, masses, nuclear reactions and merger type**



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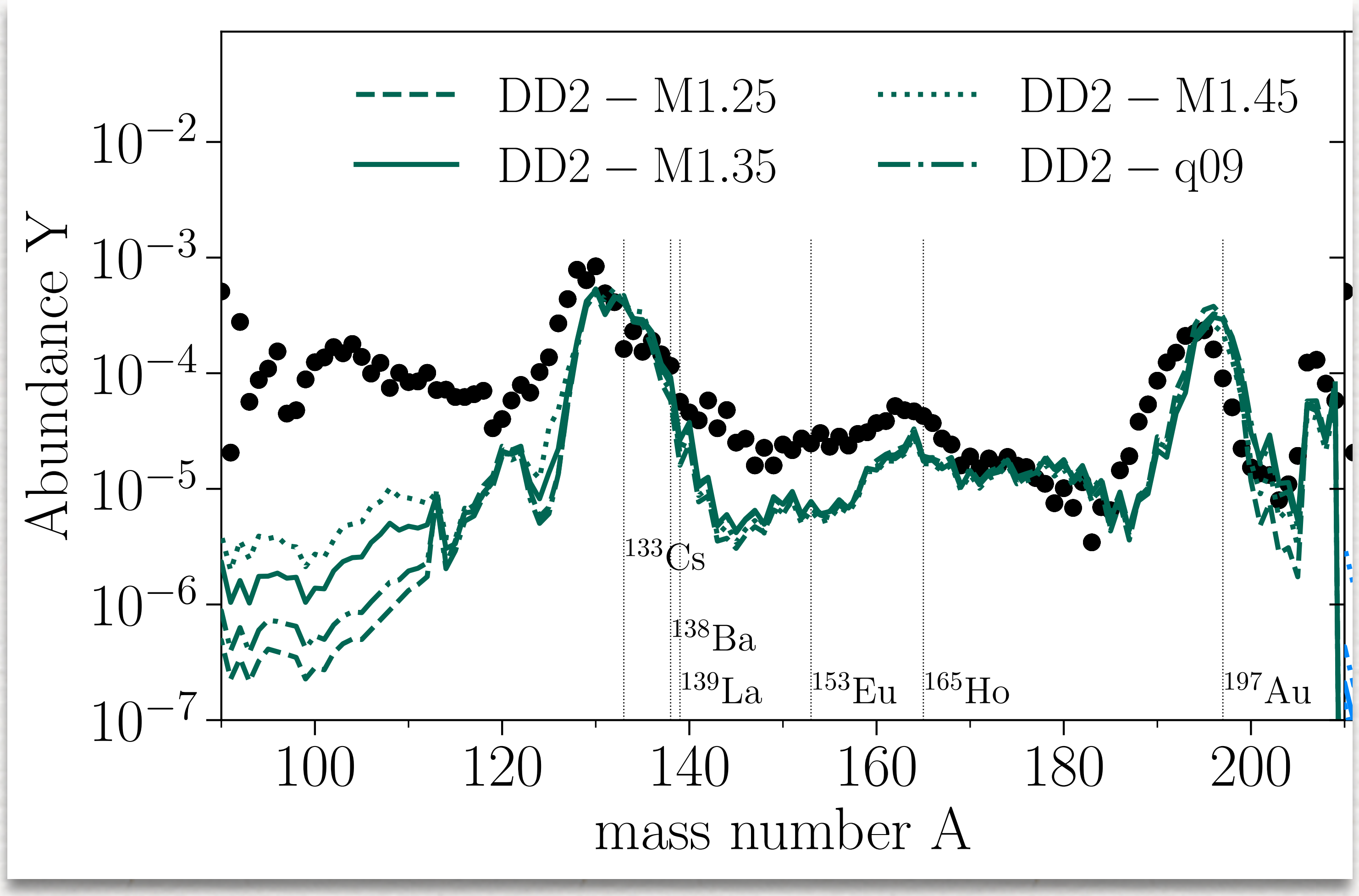

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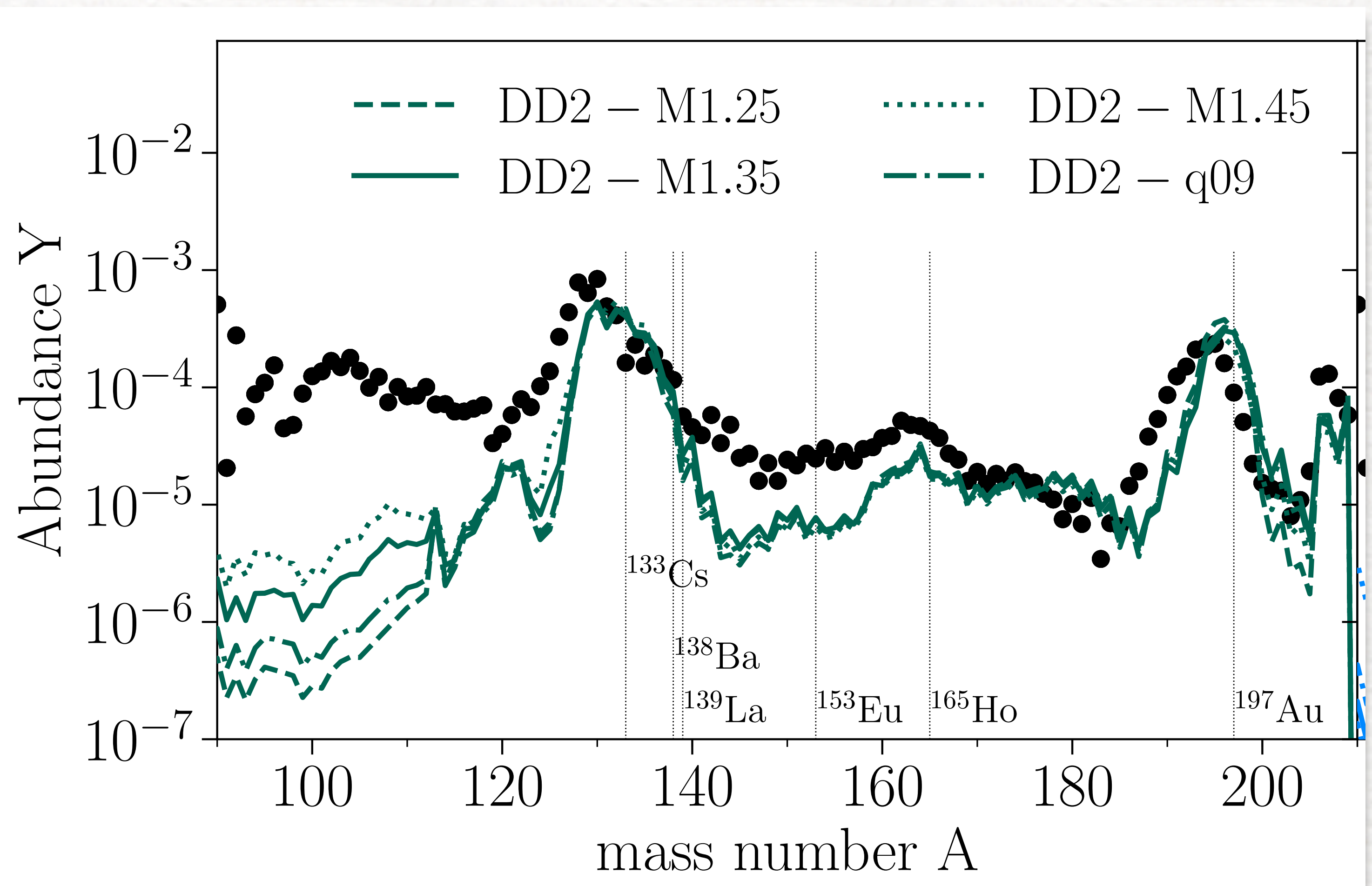
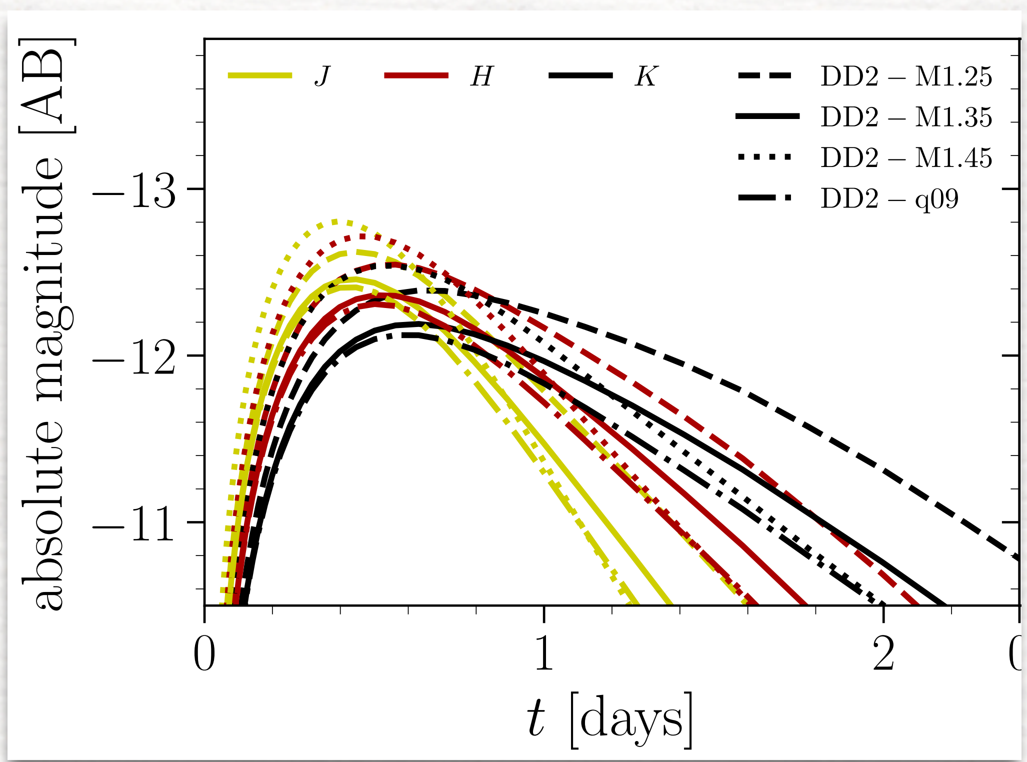


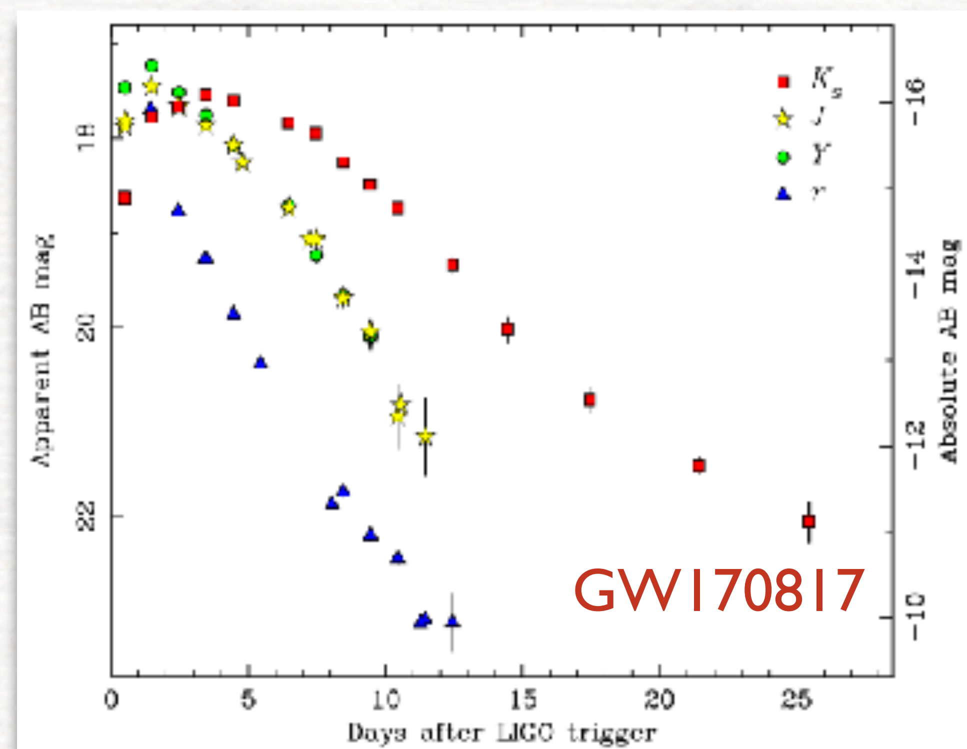
- GW170817 produced total of **16,000** times the mass of the Earth in heavy elements (**10** Earth masses in **gold/platinum**)
- We are not only **stellar dust** but also **neutron-star dust!**

Kilonova emission

- Ejected matter undergoes **nucleosynthesis** as expands and cools.
- When critical densities and temperatures are reached, matter undergoes radioactive decay emitting light (optical/infrared): **kilonova/macronova** (Li & Paczynski '98).



simulations



observations

- Astronomical observations of GW170817 show **kilonova emission**: evidence connection **GRBs** and **binary neutron stars!**

Conclusions

✴ Binary neutron stars are arguably Einstein's richest laboratory.

✴ They combine extreme gravity with some of the most extreme states of matter in the universe.

✴ Exploring these objects requires advanced mathematical and numerical methods and the power of supercomputers.

✴ Gravitational waves from these systems can teach us a lot about gravity, nuclear physics and solve astrophysical puzzles.

✴ A single detection (GW170817) has already provided us with a wealth of information: more are to come in the near future.

Working in this area has never been as exciting!…