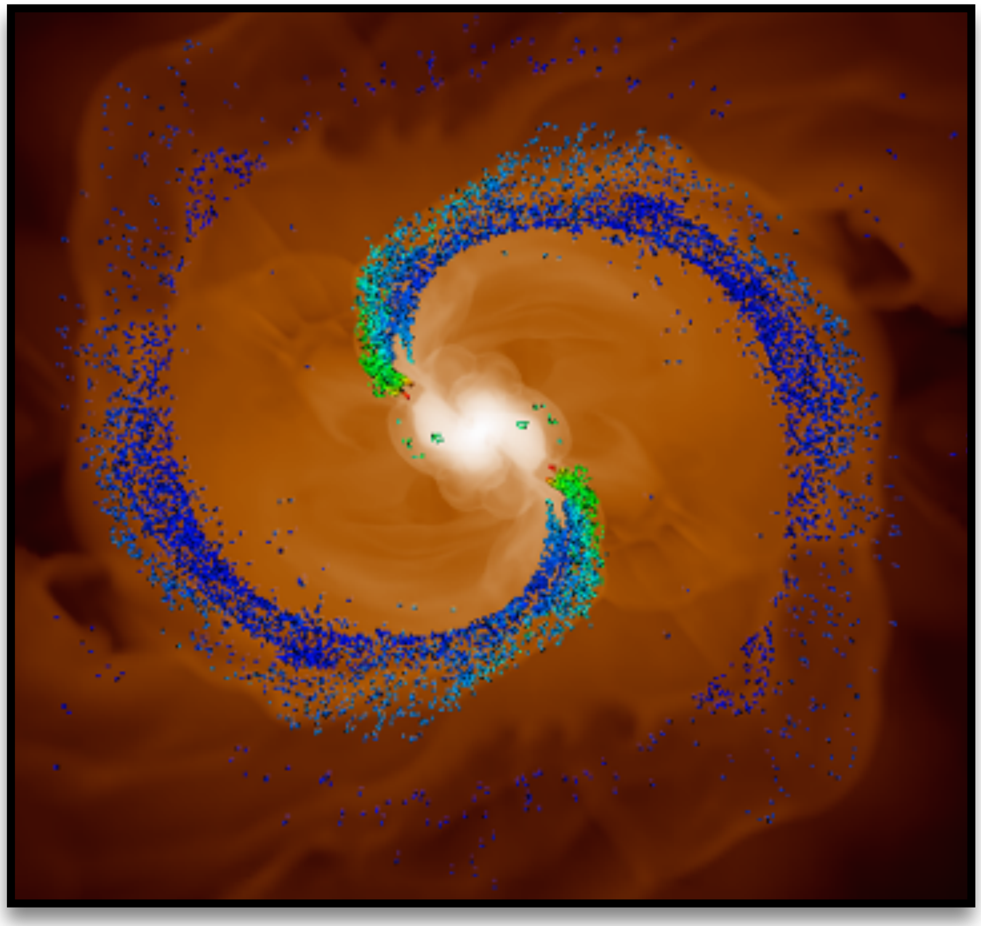


On the properties of the hypermassive neutron star formed in the merger of spinning binaries

Filippo Galeazzi

Institute for Theoretical Physics, Frankfurt am Main, Germany

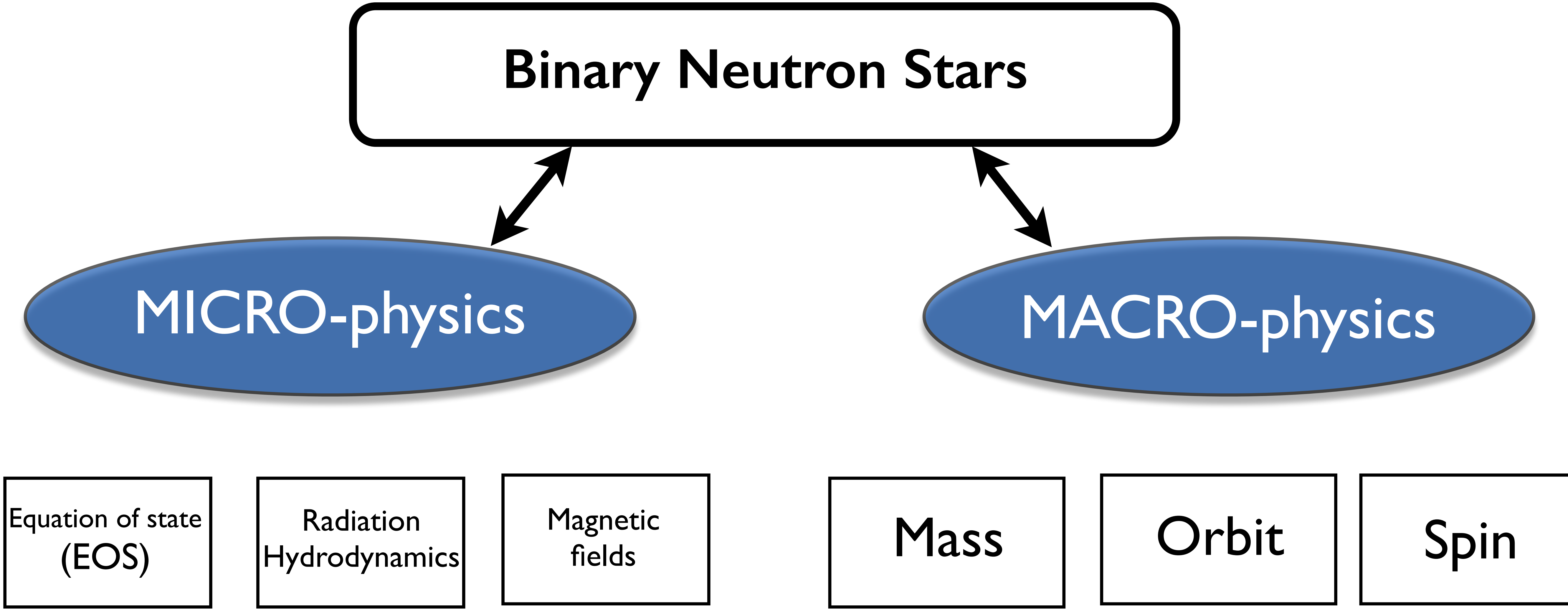
Collaborators: *Wolfgang Kastaun (AEI/UT), Toni Font (UV), Luciano Rezzolla (ITP),*

HIC for FAIR Helmholtz International Center

Outline of the talk

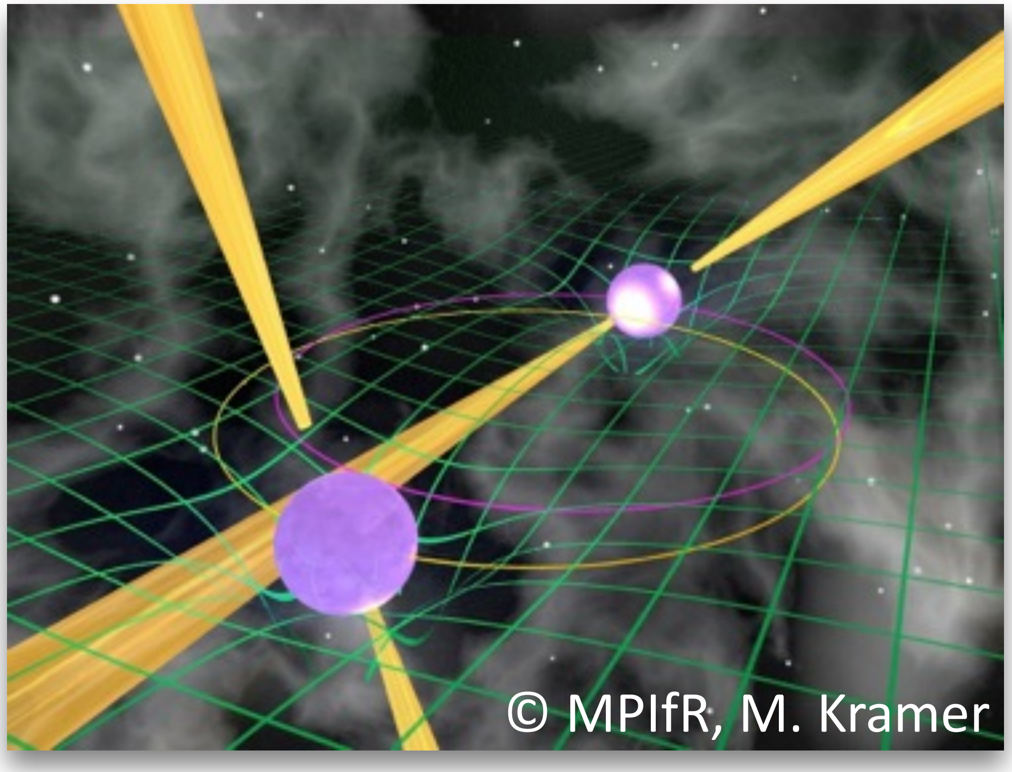
- Spinning binary neutron stars
- Origin of the post-merger oscillations
- Properties of the hypermassive neutron star
- Conclusions

BNS: Physics of many scales



Spinning binary neutron stars

- Initial data for BNS with arbitrary spin
  Tichy PRD `12, Tsokaros `14 (in prep.)
- Constant spin (orbital time scale is shorter than the spin precession time scale for quasi circular ID)
- Numerical simulations of BNS with spin
  Tsatsin et al `13 PRD Kastaun et al `13 Bernuzzi et al PRD `14
- Stellar population synthesis, NS with spin period ~15 ms Oslowski et al MNRAS `11



PSR J0737-3039

Property	Pulsar A	Pulsar B
Spin period	23 ms	2.8 s
Mass	1.337 $M_\odot$	1.250 $M_\odot$
Dimensionless spin	0.02	~0.0

WhiskyThermal

- General Relativistic Hydrodynamics Equations: HRSC methods (PPM, HLLE)
- Runge-Kutta fourth-order for the time stepping (method of lines)
- Einstein Equations (BSSN/CCZ4 formalism): 4th order, finite-differencing
- Equation of state (EOS): tabulated nuclear (hot/cold), piecewise poly
- Neutrino treatment: leakage scheme (Rosswog and Liebendörfer 2003)

We solve numerically the full set of nonlinear equations

Spinning BNS mergers: initial data

How does a change in the total angular momentum of the BNS affect the merger dynamics?

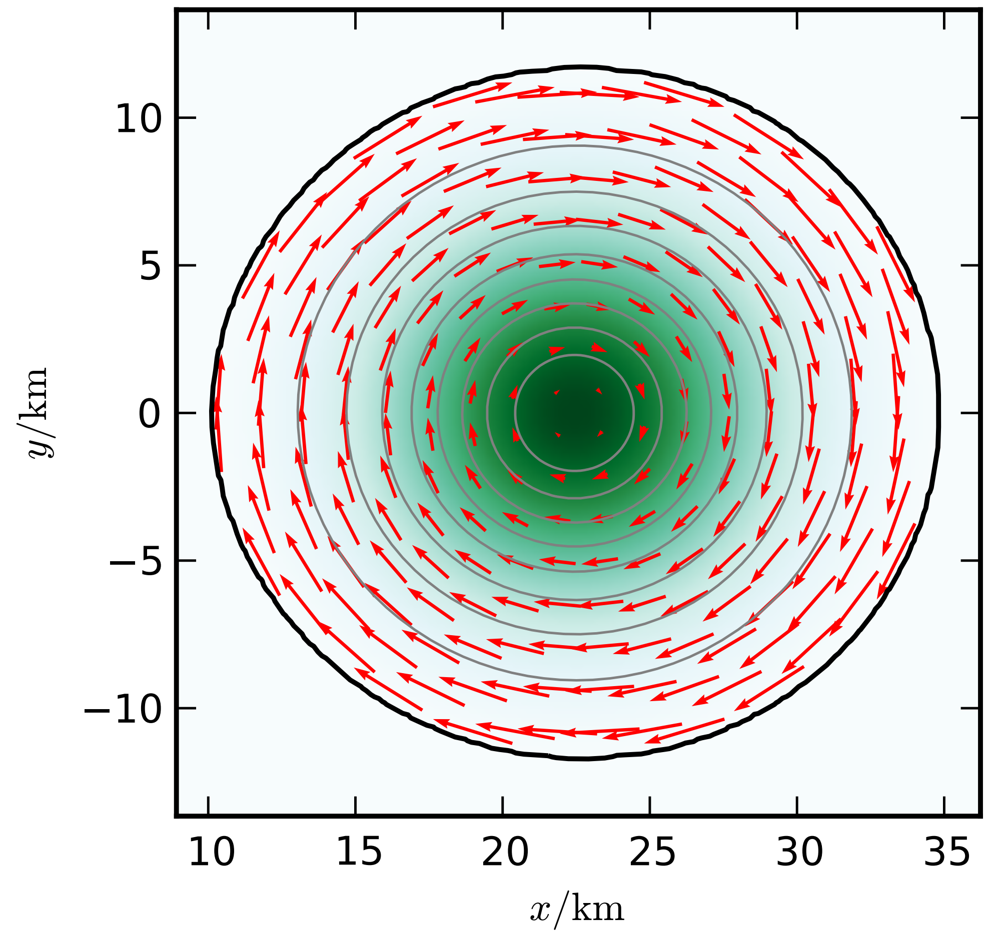
coordinate velocity of the fluid in the star

$$\vec{w} = (1-s)\,\vec{w}_L + s\vec{\Omega} \times \vec{x}$$

$w^i = u^i/u^0$ fluid coord. velocity,

$\vec{\Omega}$ the orbital angular velocity vector,

$\vec{w}_L$ original irrotational velocity field,



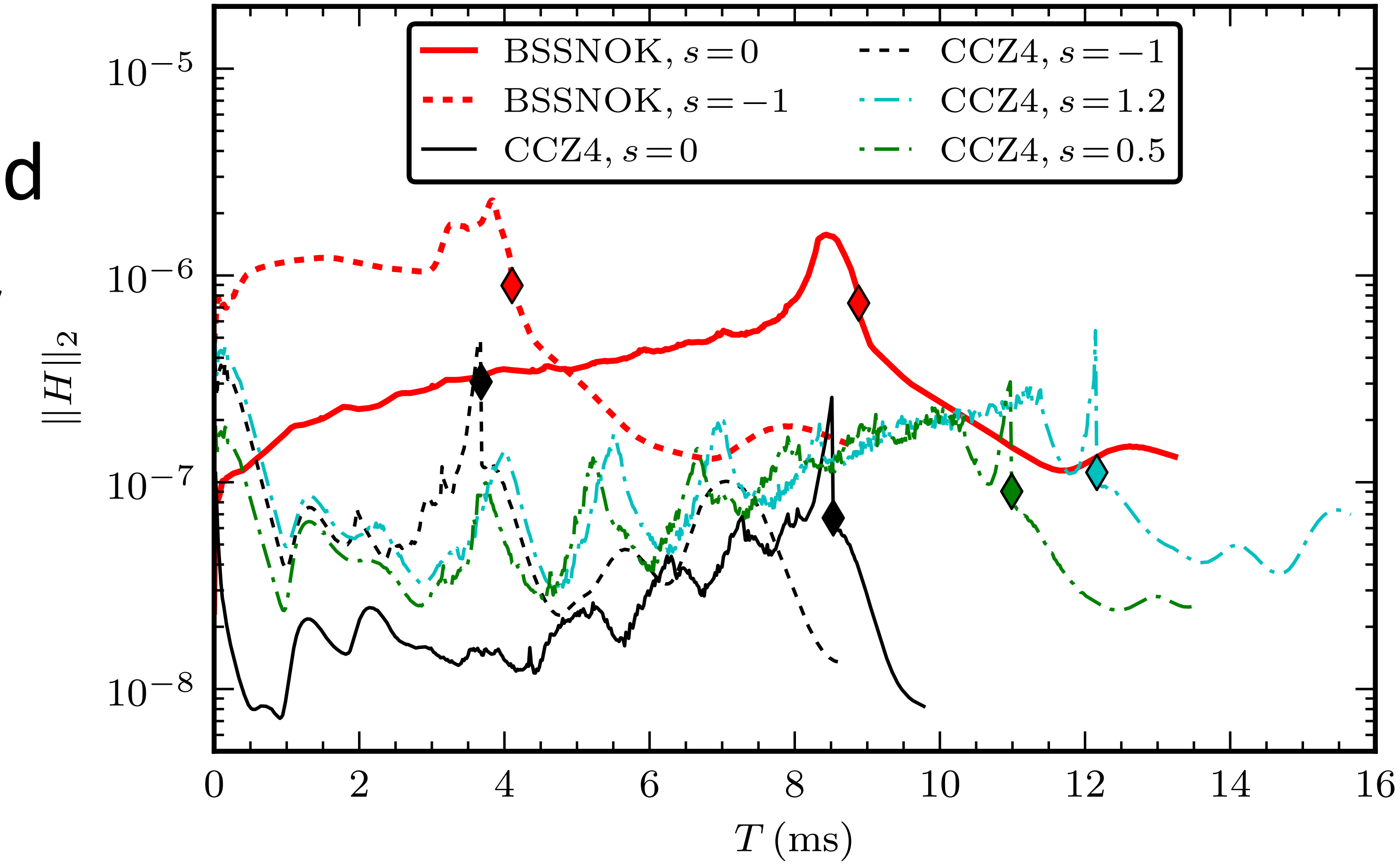
Initial density and velocity distribution of one NS in the binary system

Kastaun, **Galeazzi**, Alic, Rezzolla, Font `13

Spinning BNS mergers: initial data

How does a change in the total angular momentum of the BNS affect the merger dynamics?

- ✦ constraint equations violated
- ✦ CCZ4 formulation efficiently damps the violations
- ✦ half the Keplerian velocity
- ✦ induces oscillations

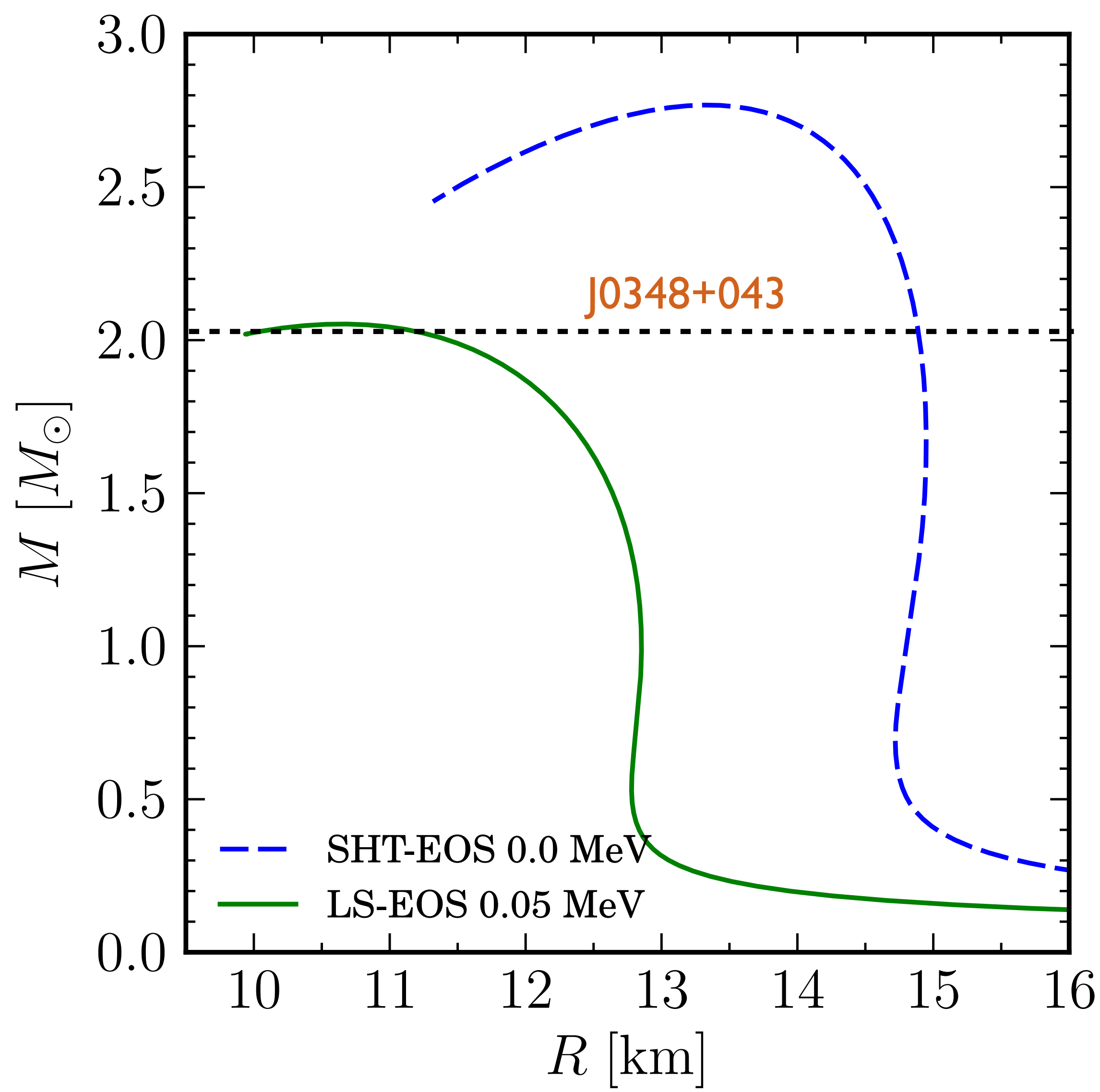


L_2-norm of the Hamiltonian constraint for a number of binaries with different degrees of spin-up/down

Kastaun, **Galeazzi**, Alic, Rezzolla, Font `13

Nuclear equations of state

- measurements of both mass and radius of individual NSs do not exist
- many EOS models available
  - Shen-Horowitz-Teige EOS (SHT) (2010)
    - Relativistic mean-field theory (NL3)
    - incompressibility K = 271
  - Lattimer-Swesty EOS (LS) (1991)
    - Liquid drop model
    - incompressibility K = 220



Mass vs circumferential radius for TOV star sequences. In green LS-EOS (220) and in blue SHT-EOS (NL3)

Nuclear equations of state

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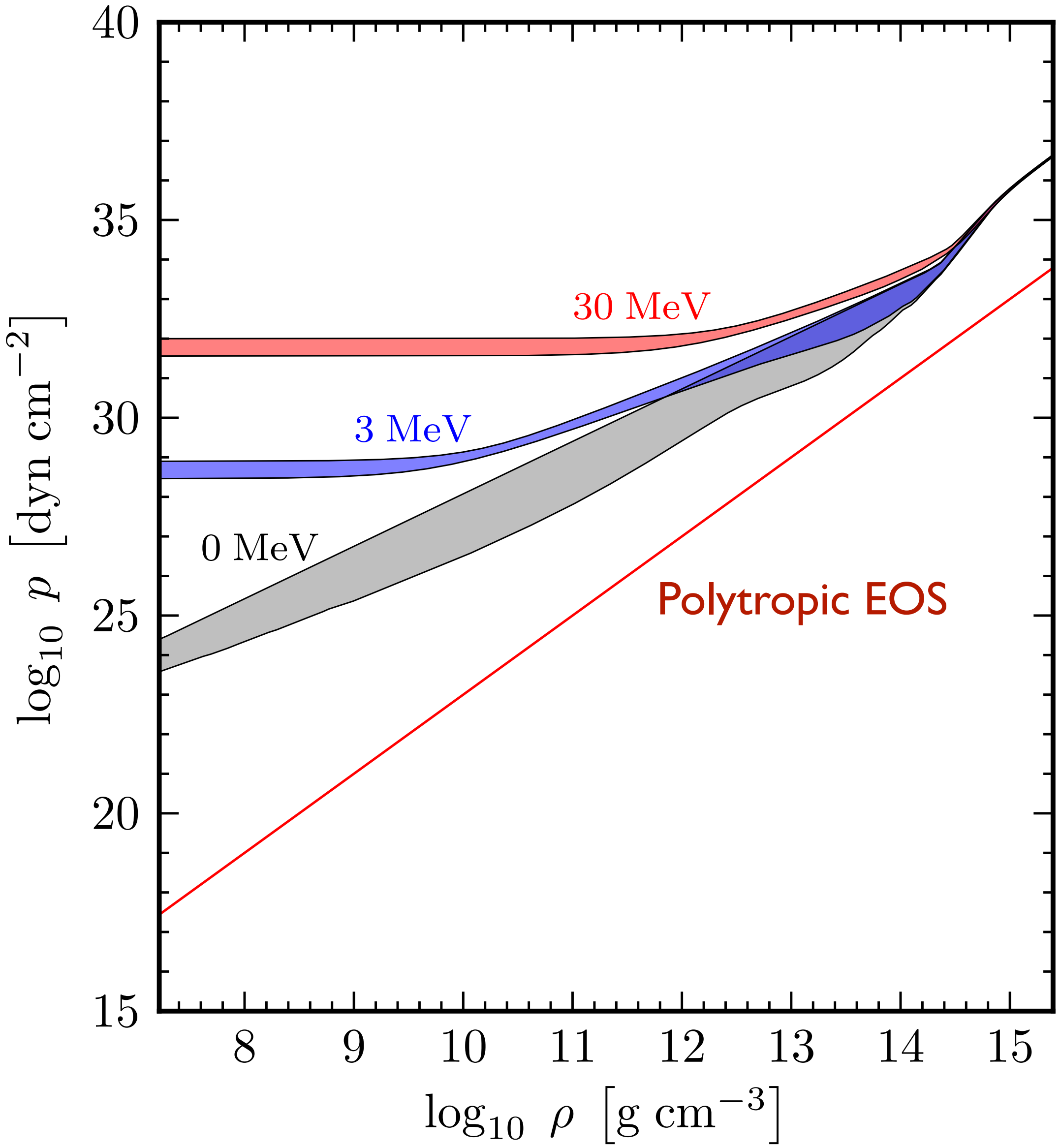
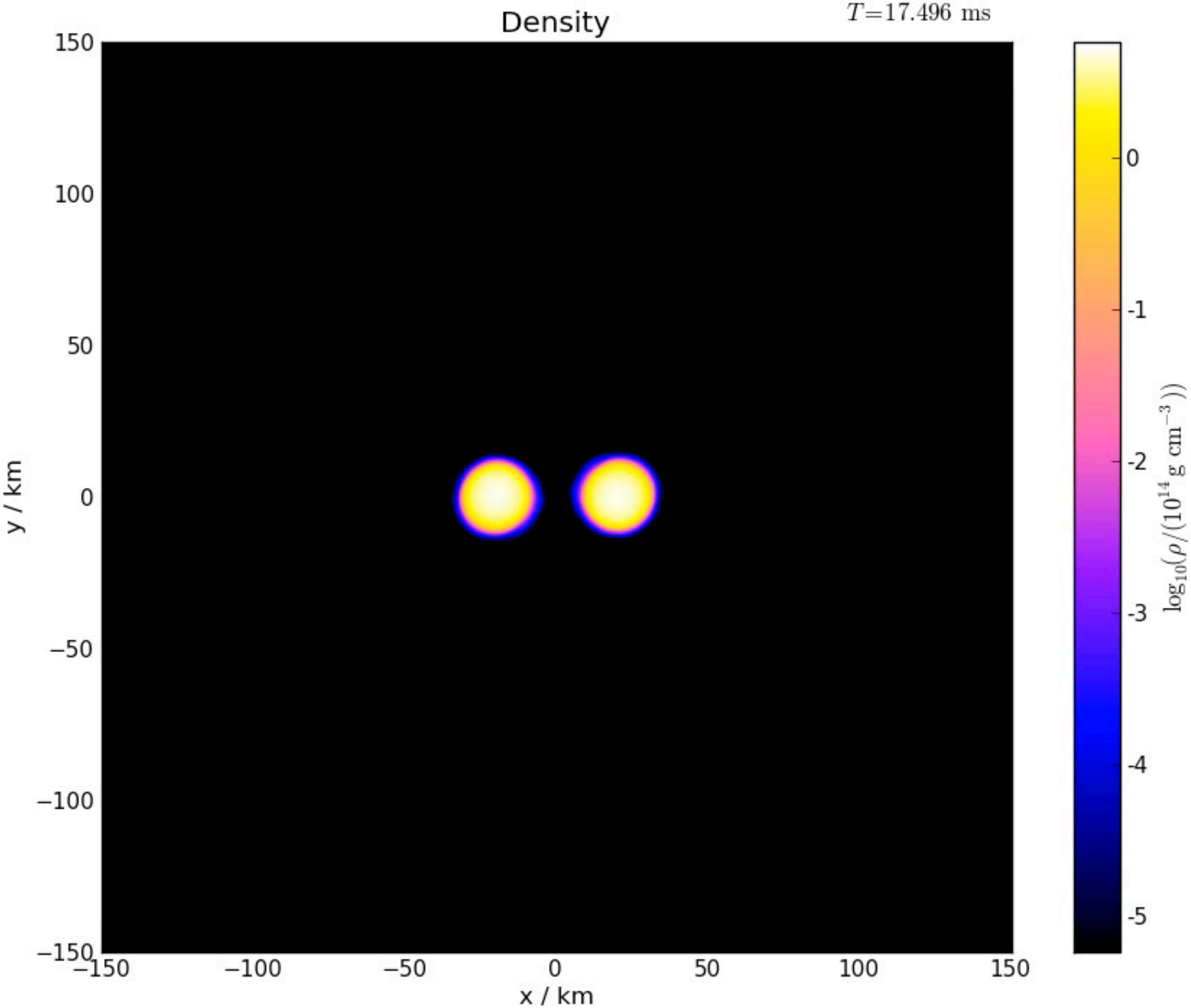


SHT-EOS pressure vs density for different Y_e and temperatures



Density
$T=17.496$ ms
150
100
50
0
−50
−100
−150
y / km
−150
−100
−50
0
50
100
150
x / km
0
-1
-2
-3
-4
-5
$\log_{10}(\rho/(10^{14}\ \mathrm{g\ cm^{-3}}))$

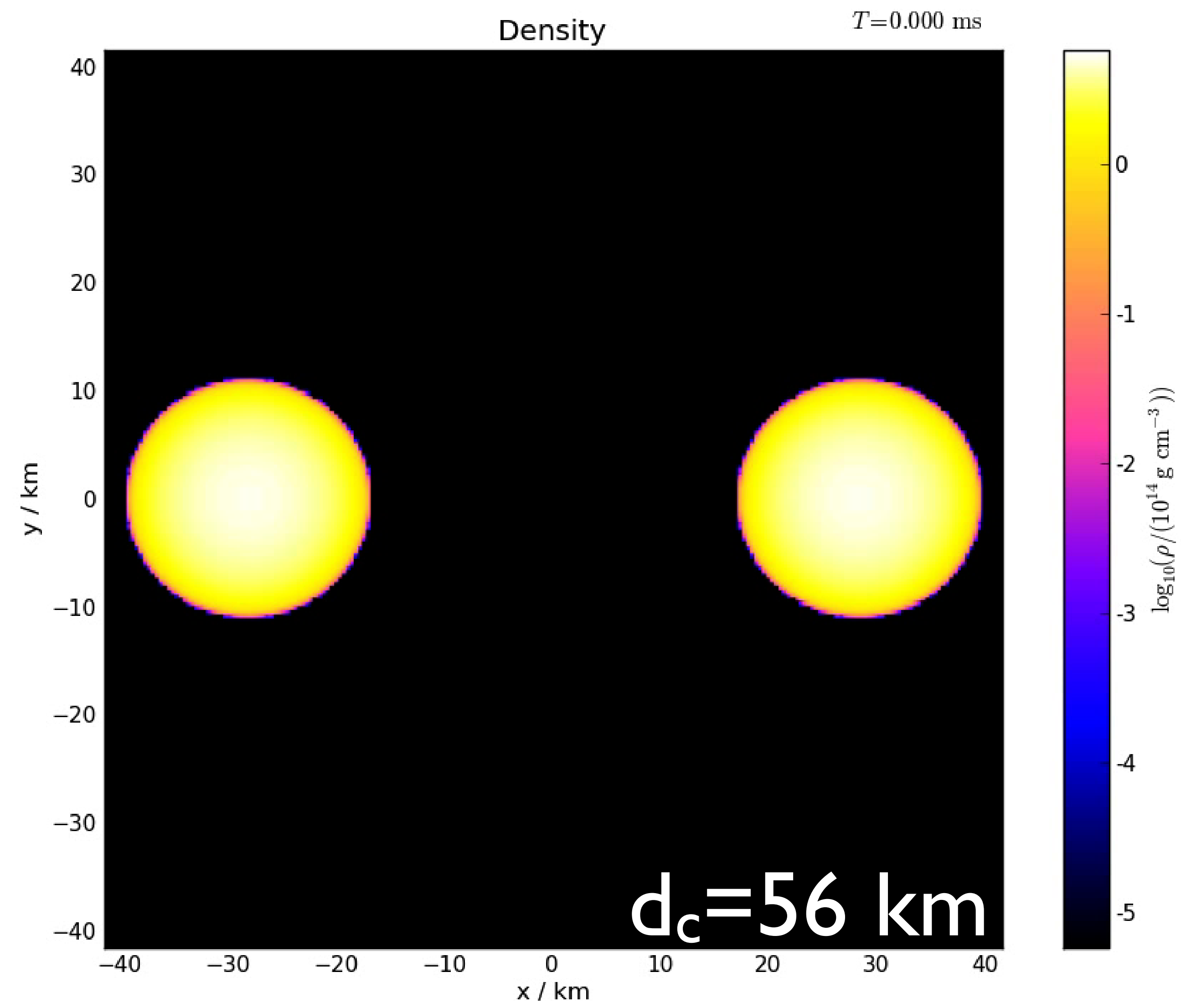
BNS: Phenomenology

merger →

MASS: a binary with smaller mass will produce a HMNS further away from the stability threshold and will collapse at a later time

EOS: imprint of nuclear EO in the lifetime of the HMNS and its oscillations

RADIATIVE PROCESSES: radiative losses may alter the equilibrium of the HMNS



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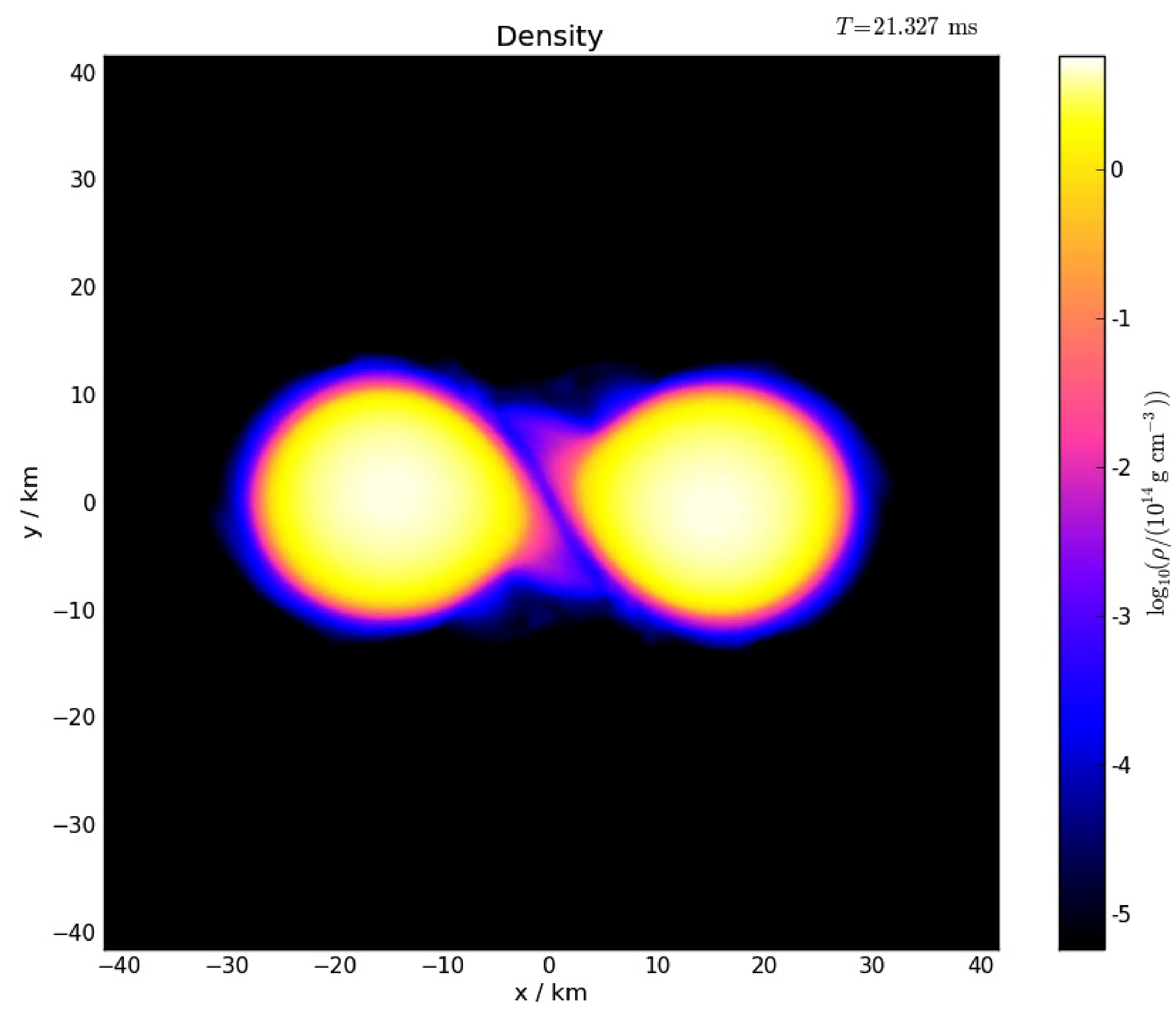

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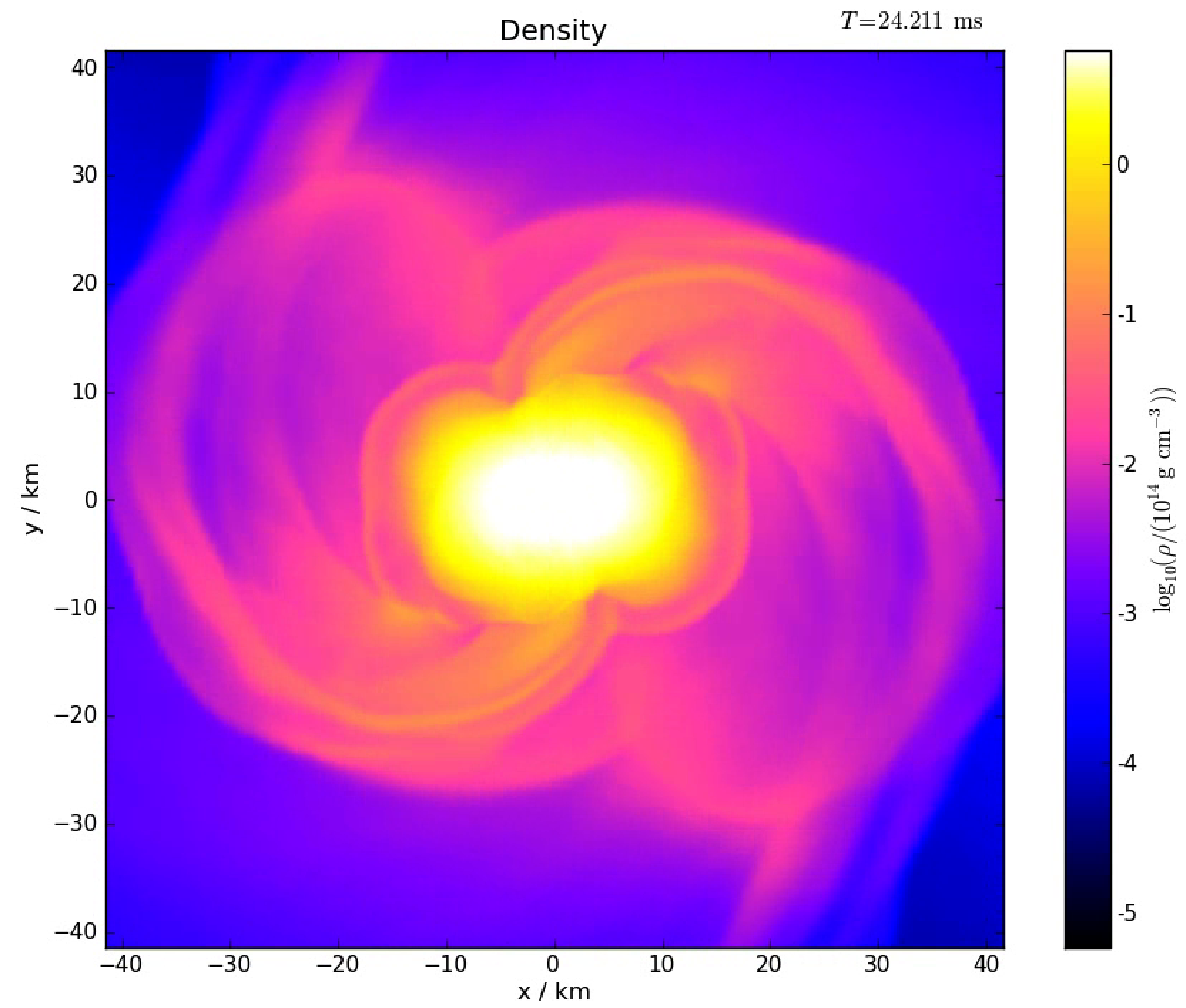
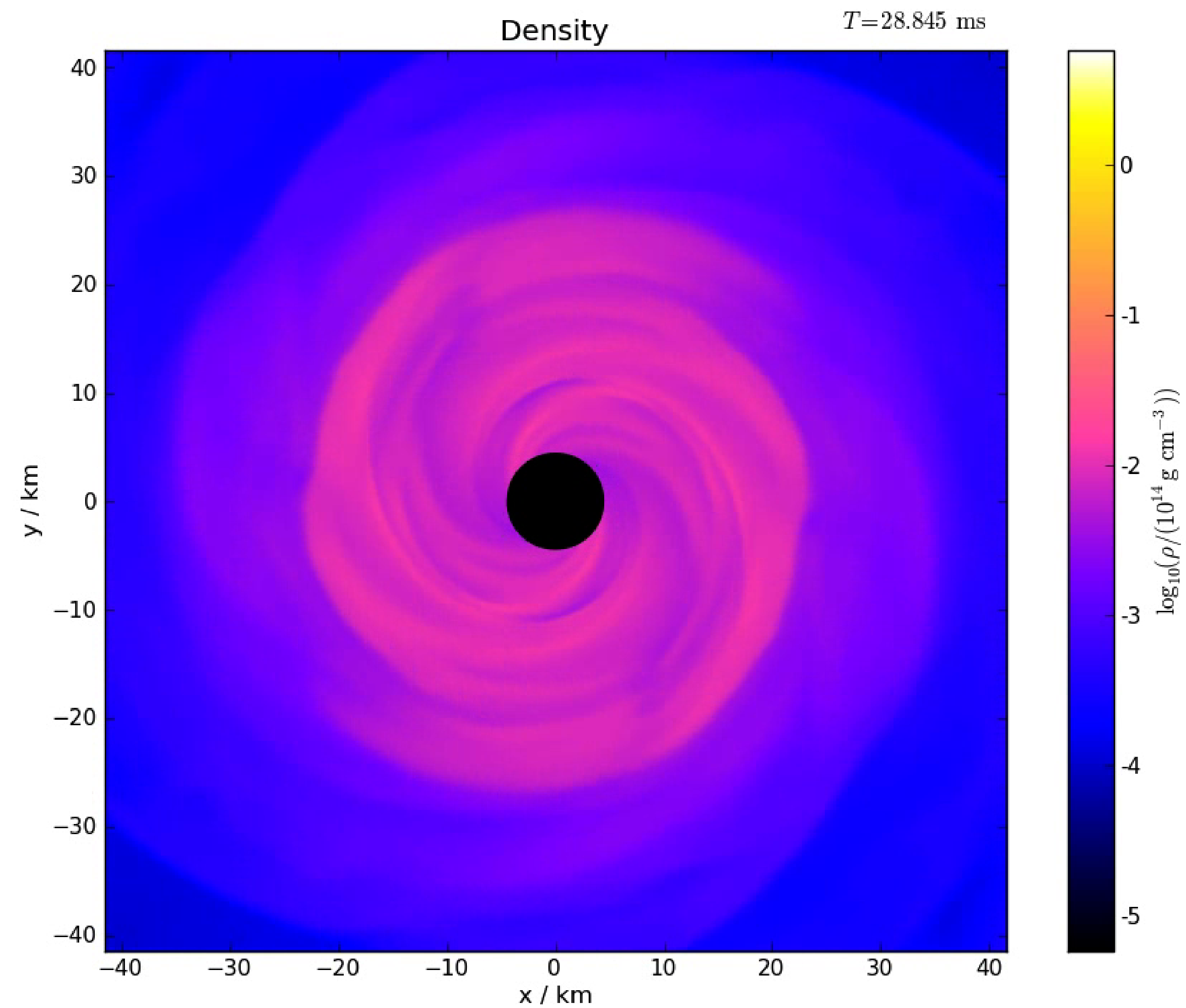


BNS: Phenomenology

merger → *HMNS* → *BH + torus*

MASS: a binary with smaller mass will produce a HMNS further away from the stability threshold and will collapse at a later time



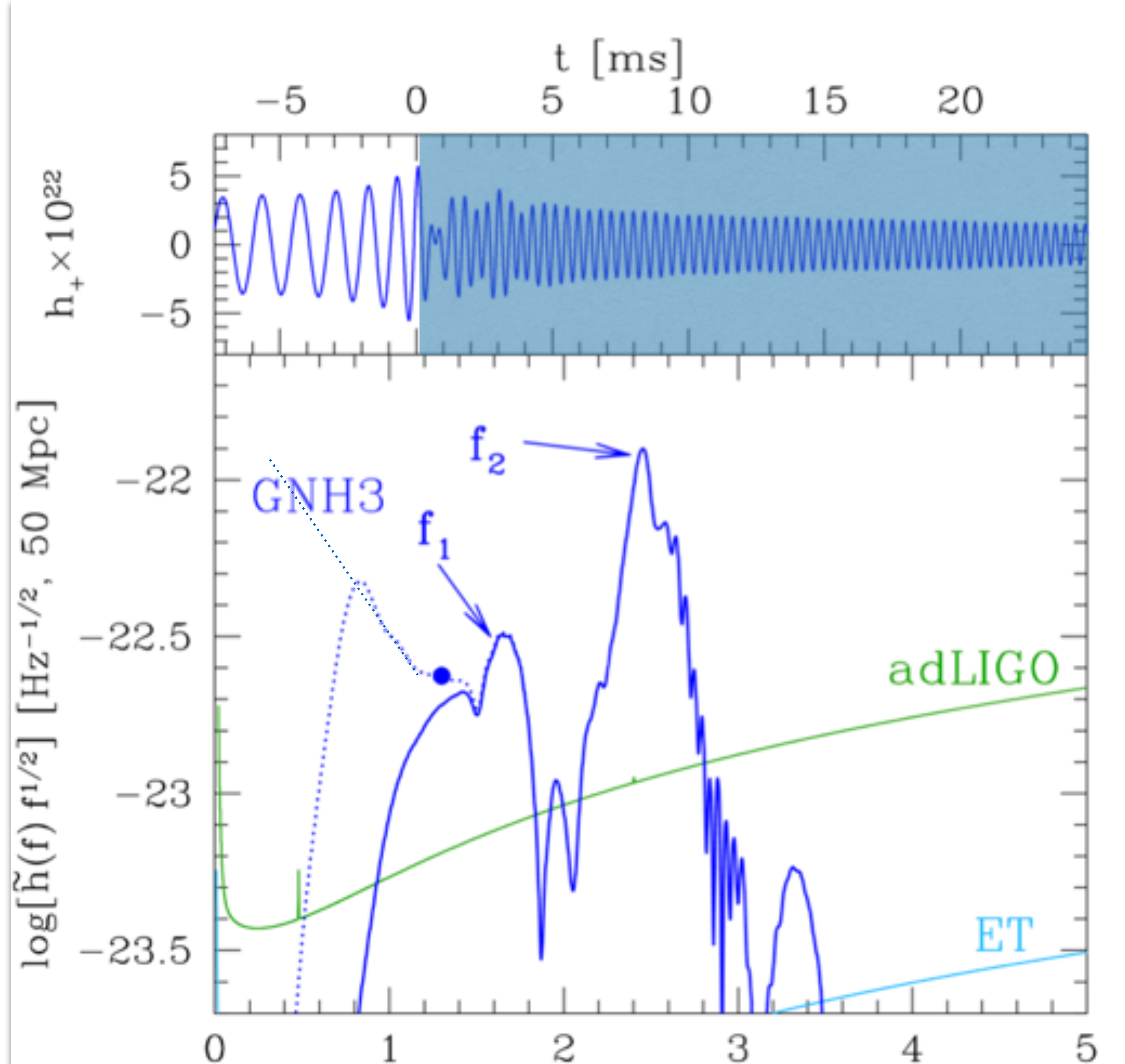
EOS: imprint of nuclear EO in the lifetime of the HMNS and its oscillations

RADIATIVE PROCESSES: radiative losses may alter the equilibrium of the HMNS

Gravitational Waves

The gravitation wave signal from BNS mergers can be divided in three phases:

- Inspiral
- Merger
- post-merger (and ring-down in case a black hole is formed)



Takami et al. `13

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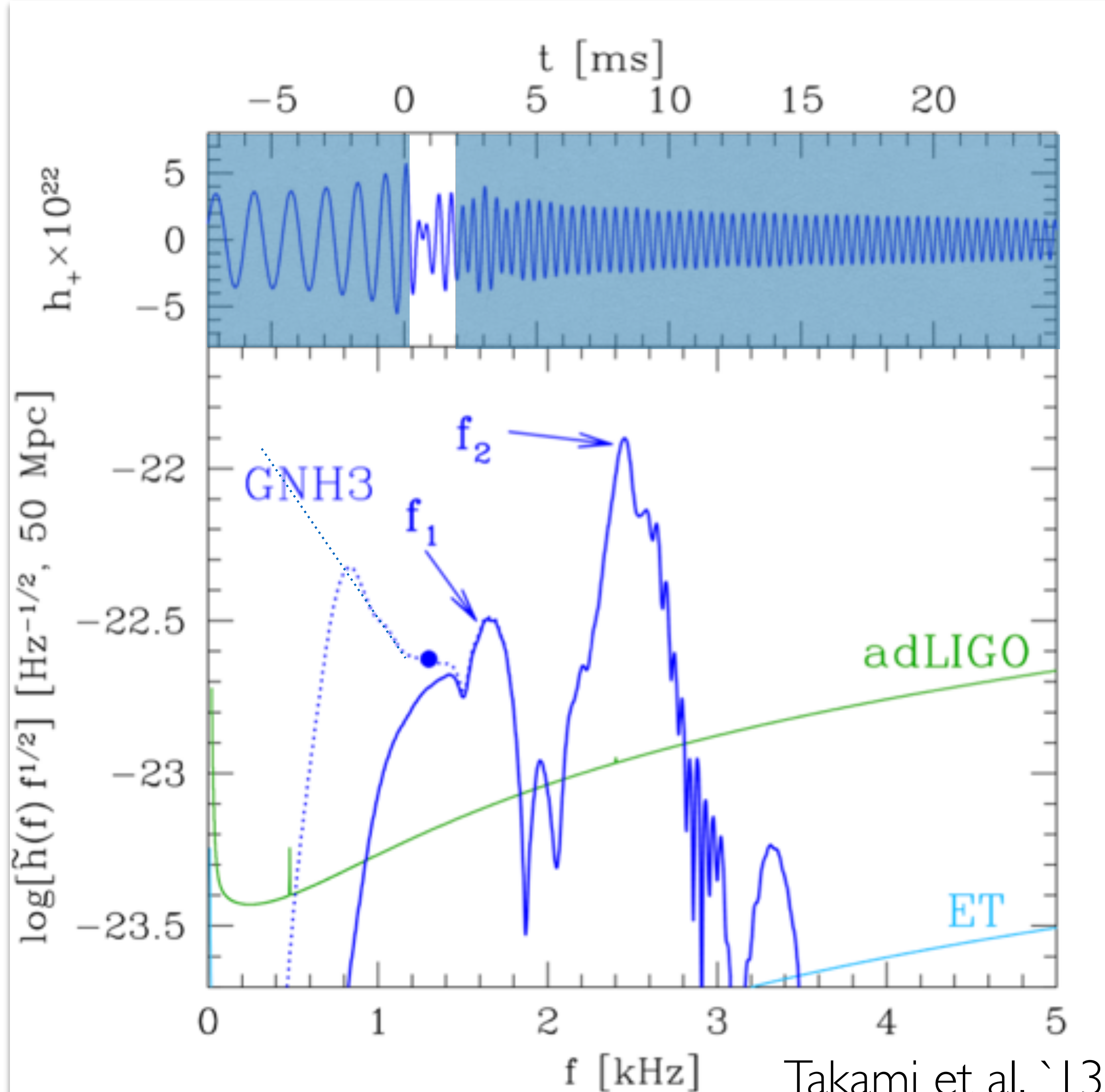

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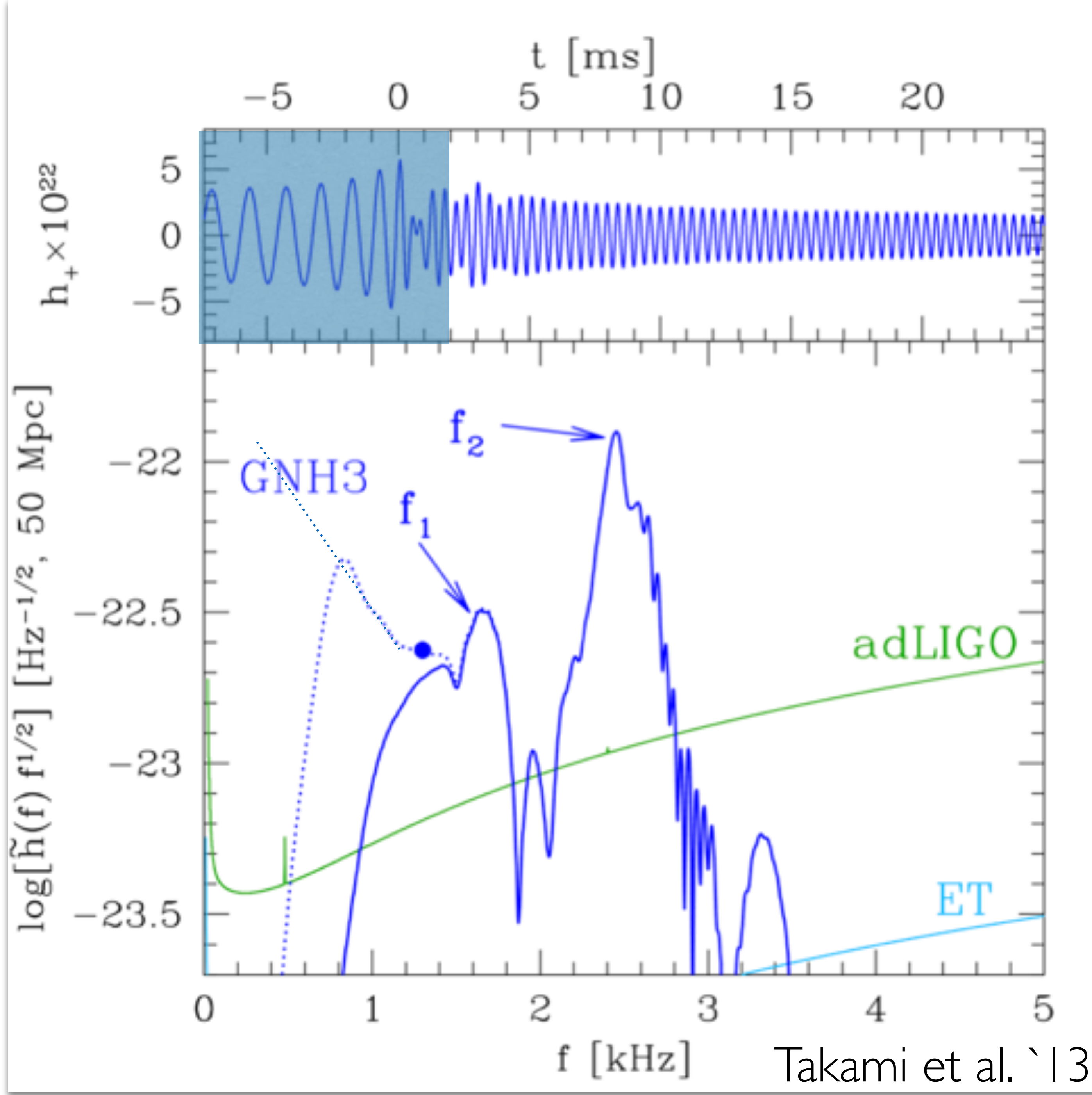

Takami et al. `13

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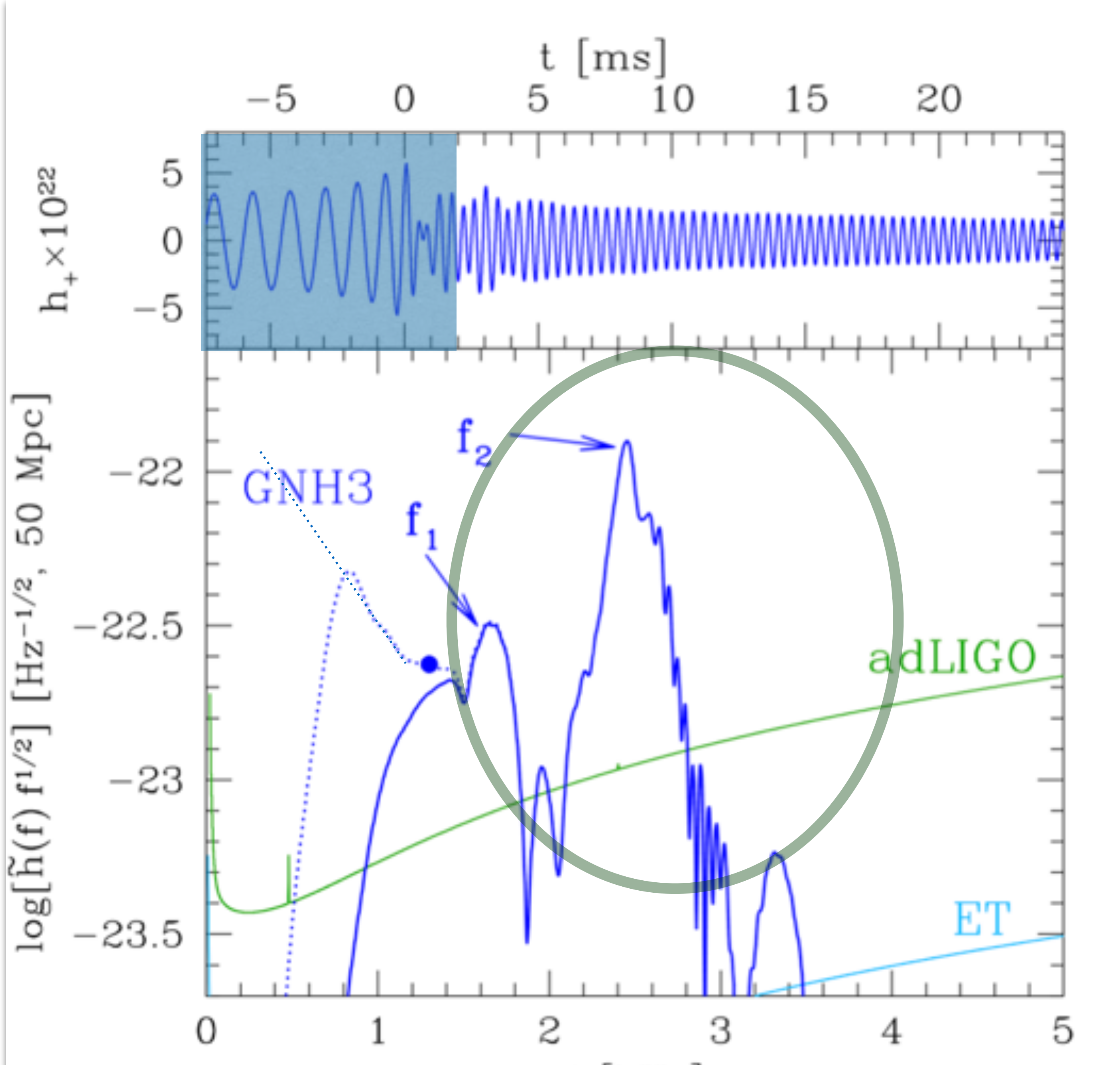
Peaks stand above the sensitivity curve of the advance/future generation of GW detectors

(Oechslin et al 2007, Baiotti et al2008)



Takami et al. `13

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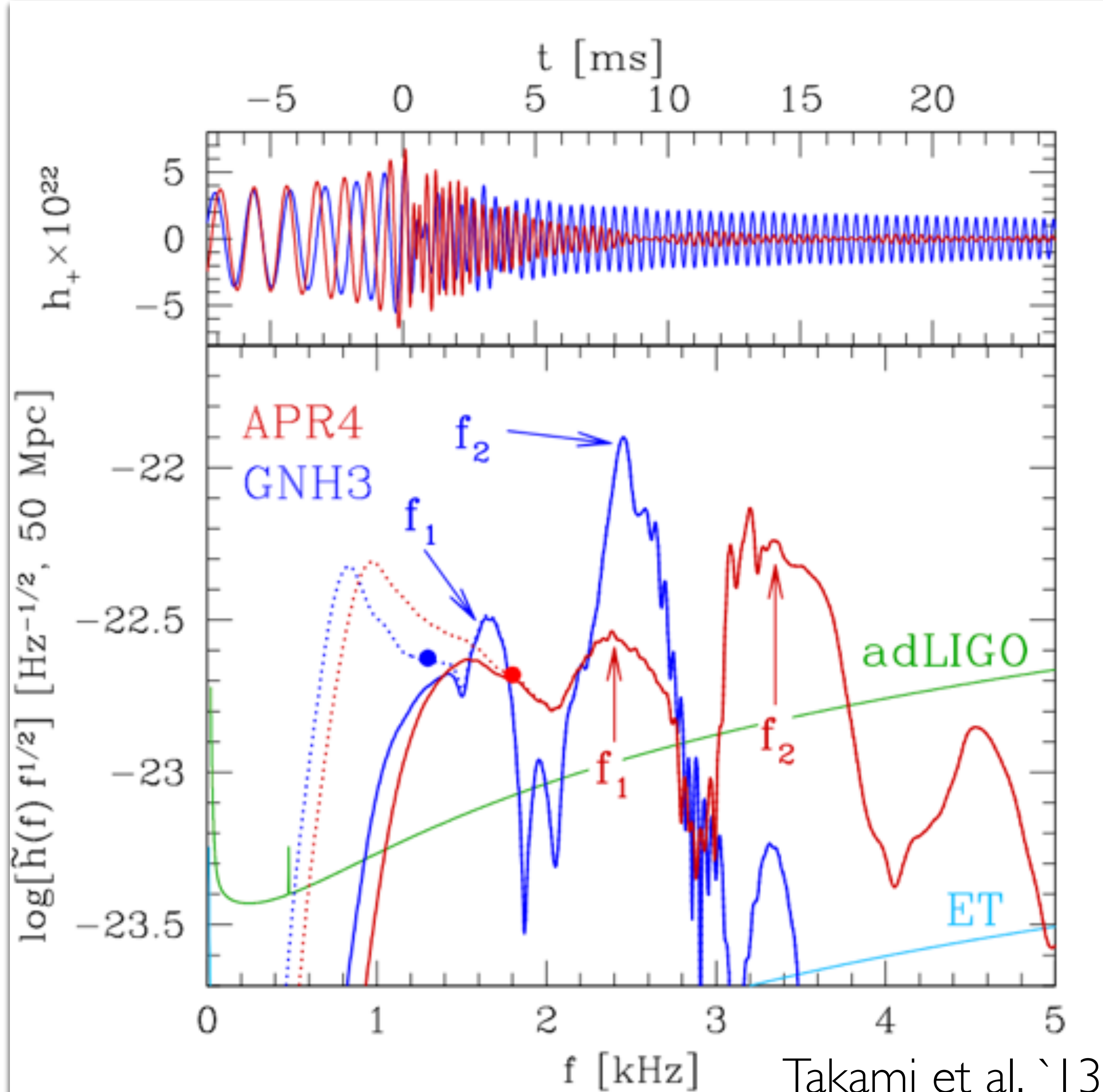


Takami et al. `13

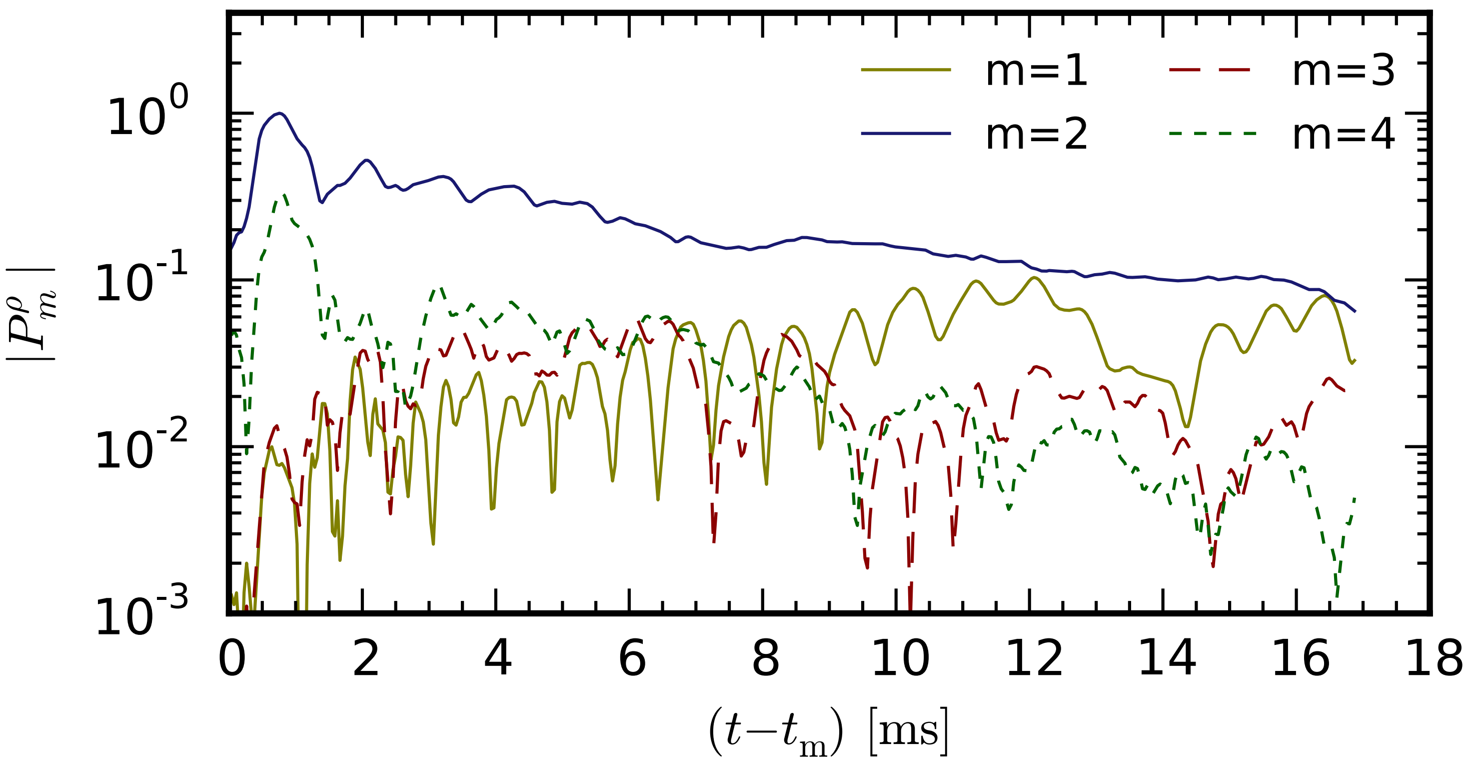
Origin of the post-merger oscillations

What is the origin of the different peaks in the GW spectrum?

- dominant peak f_2 clearly originates from the HMNS

What about the other peaks?

- caused by the non-linear coupling to the fundamental quasi-radial mode (Stergioulas et al. `11)



Equal-mass BNS, SHT-EOS $M_b = 4.01\ M_\odot$

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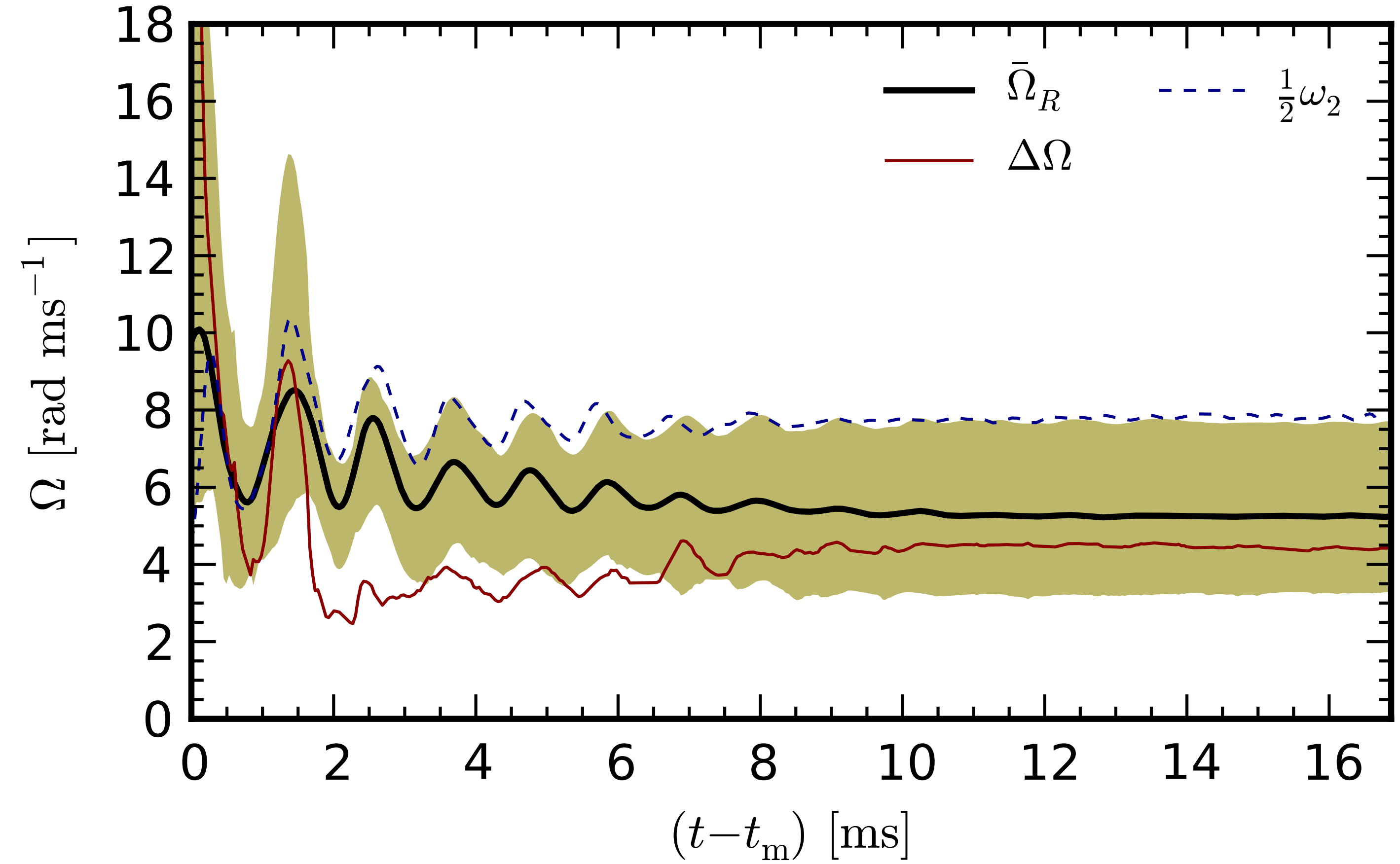

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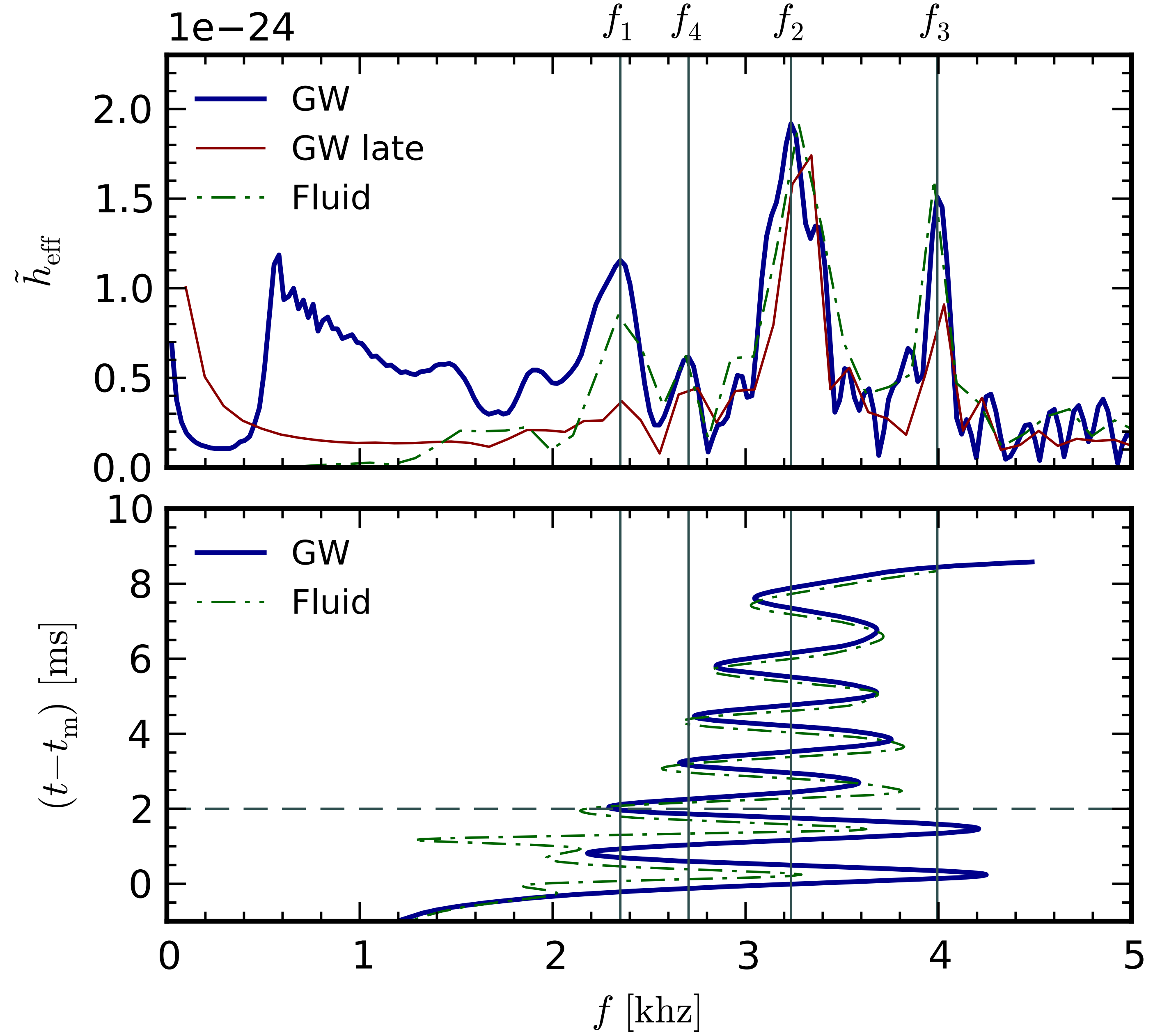
Origin of the post-merger oscillations

What is the origin of the different peaks in the GW spectrum?

- dominant peak f_2 clearly originates from the HMNS

What about the other peaks?

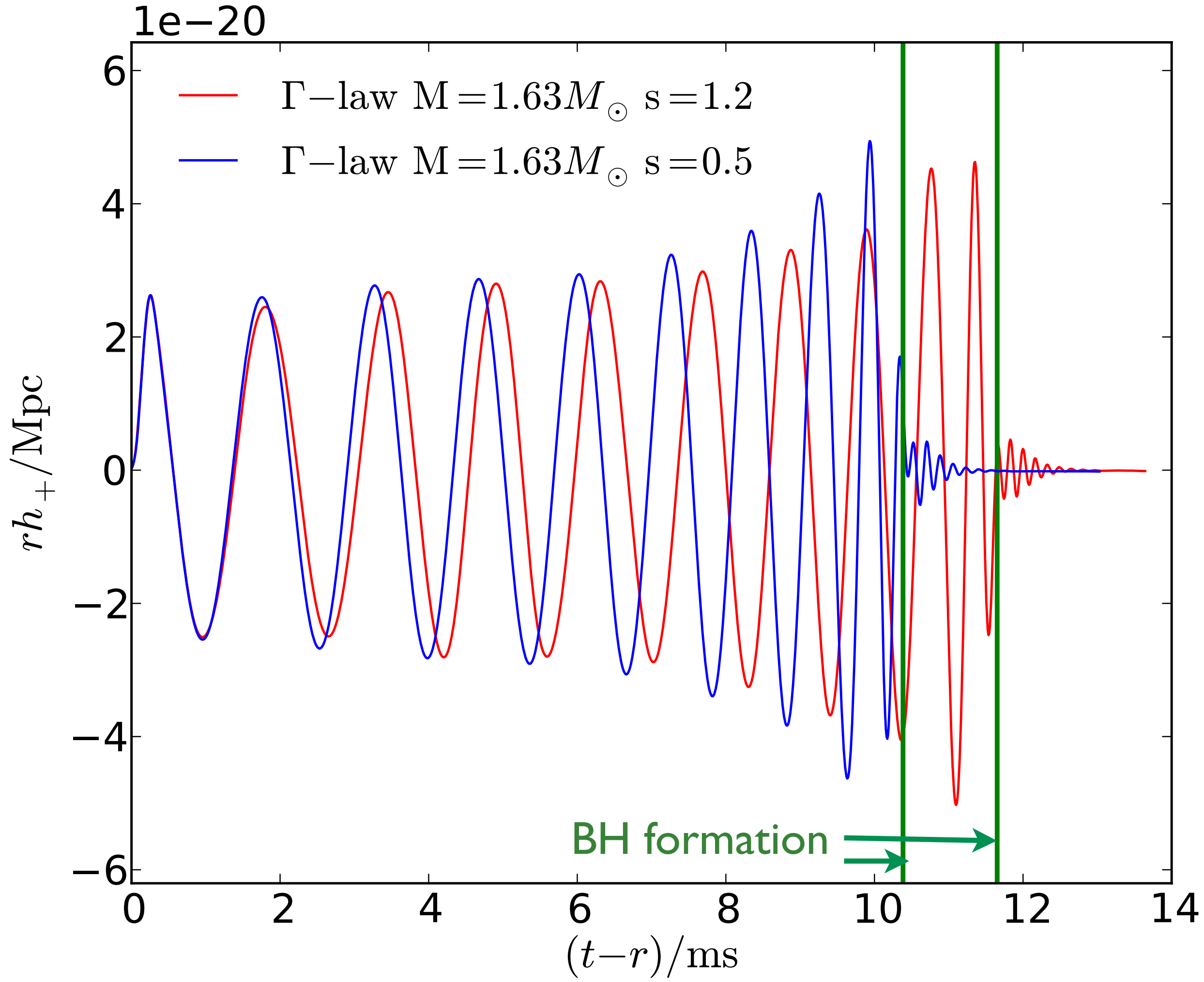
- strong modulation of the frequency of m=2 mode create additional peaks
- maximum frequency reached when the star is most compact leads to separate high-frequency peak



Equal-mass BNS, LS-EOS $M_b = 3.12\ M_\odot$

BNS: the effects of spin

- orbital hang-up (confirmed by Bernuzzi et al. PRD `13)
- In the case of BH formation
  - maximum BH spin reached for prompt collapse models
- threshold mass for BH formation found by Bauswein et al `10 confirmed (irrotational)



GW strain (l=m=2) extracted at 590 km from the BNS

Kastaun, **Galeazzi**, Alic, Rezzolla, Font PRD`13

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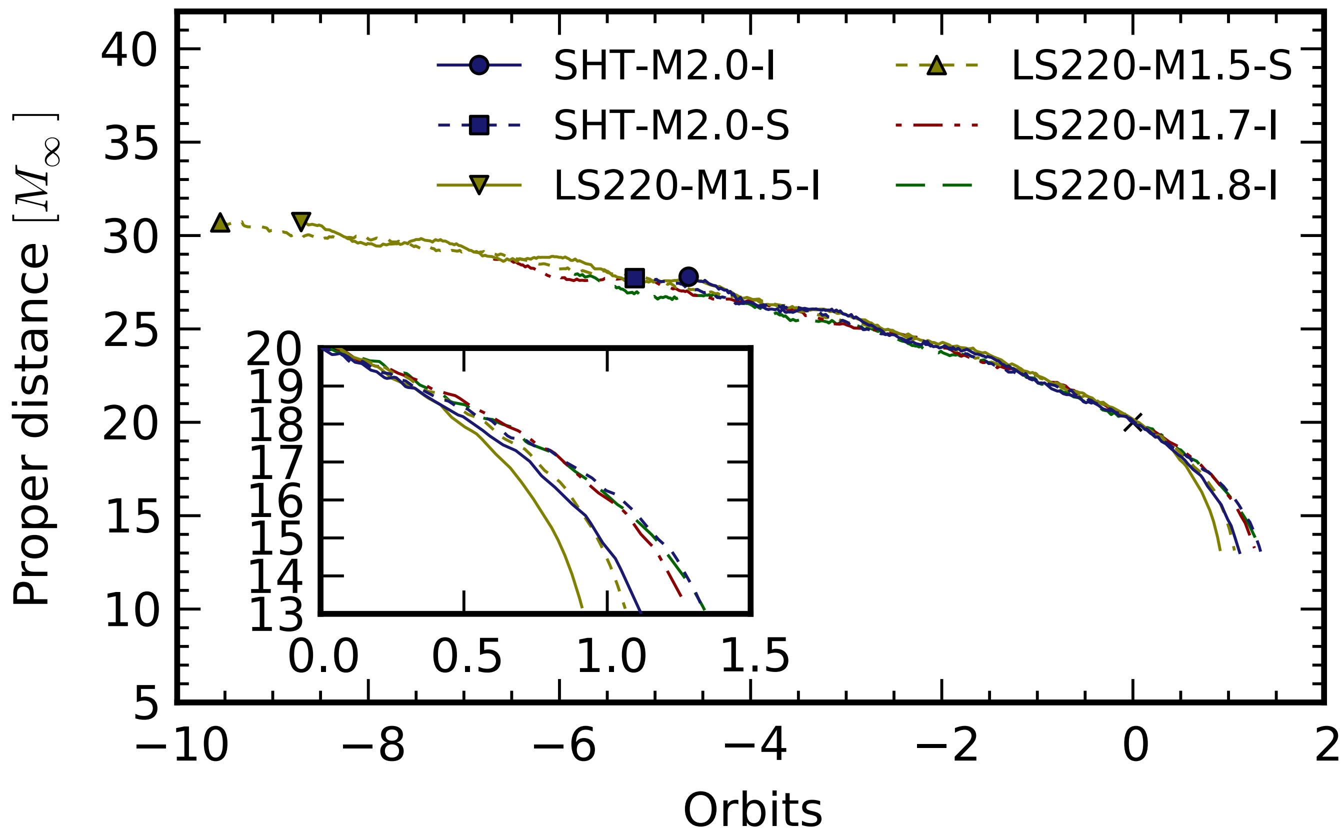
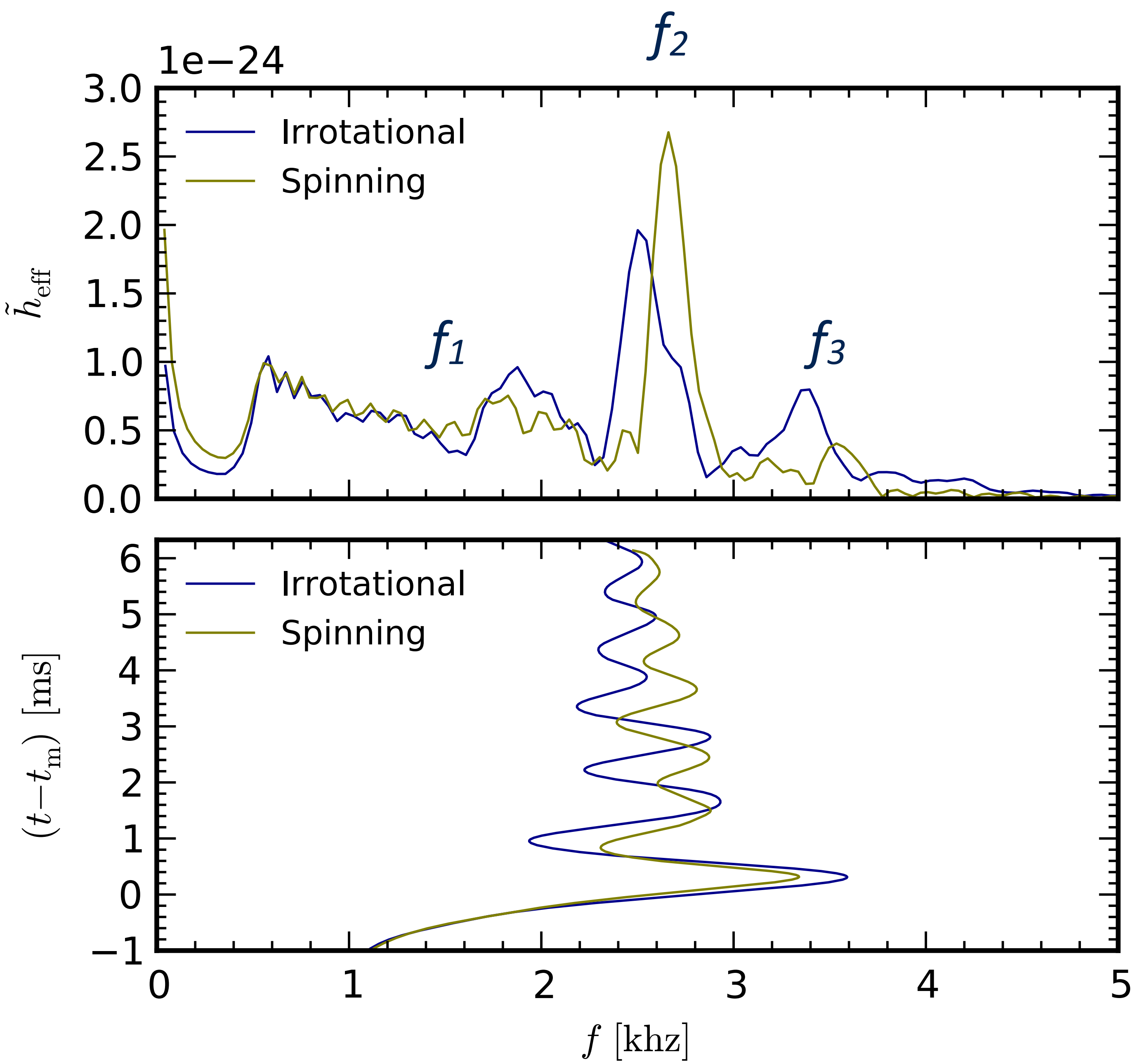


Proper separation of maximum density location versus orbital phase

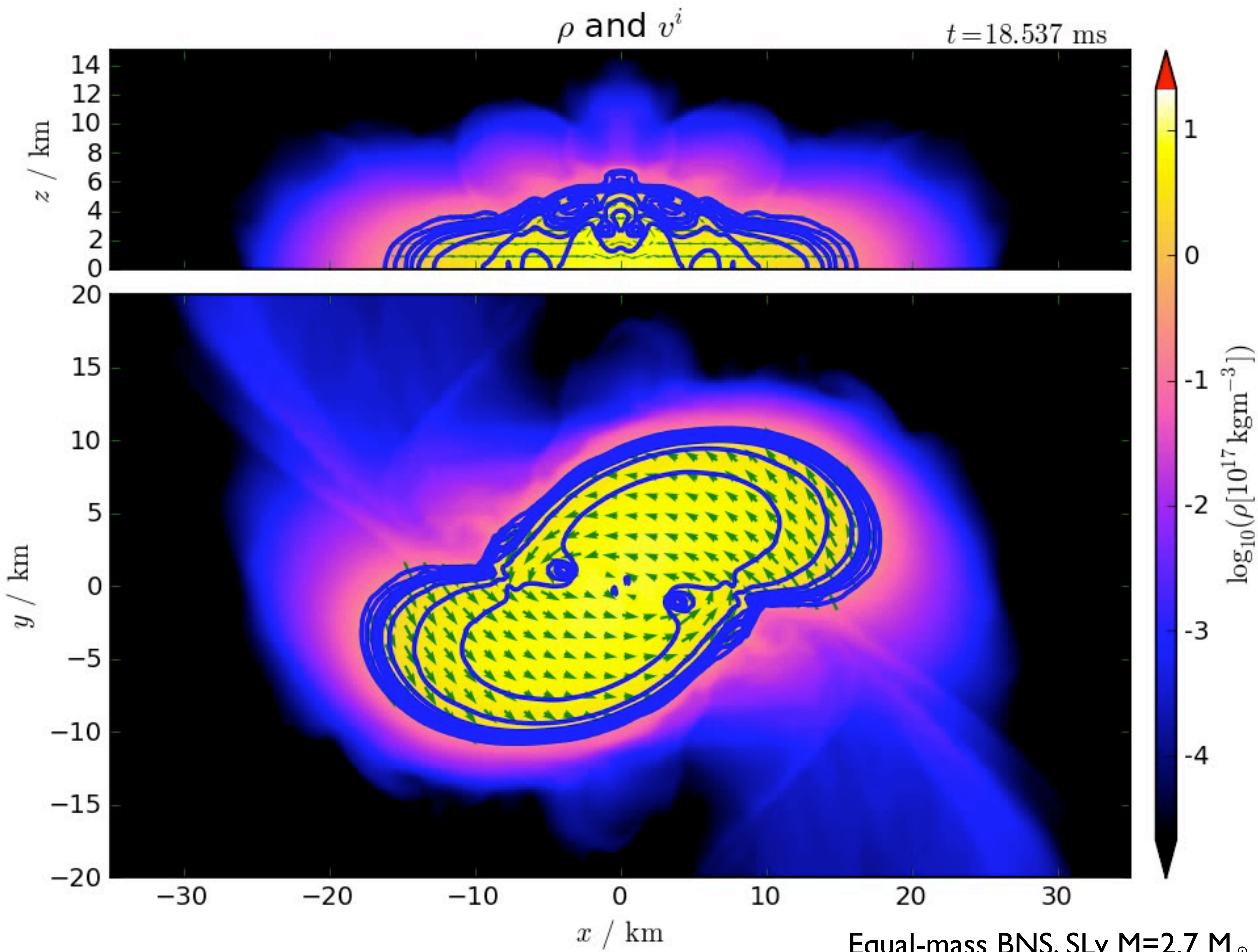
Kastaun, **Galeazzi**, Alic, Rezzolla, Font PRD`13

HMNS: the effects of spin

- increased life of the HMNS
- different freq. modulation during the HMNS phase
- the frequency shift of the main peak is smaller than the width of the peak
- maximum instantaneous frequency is smaller for the spinning models
- weaker radial oscillations



GW strain (l=m=2) for equal-mass BNS, SHT-EOS $M_b = 4.01\ M_\odot$

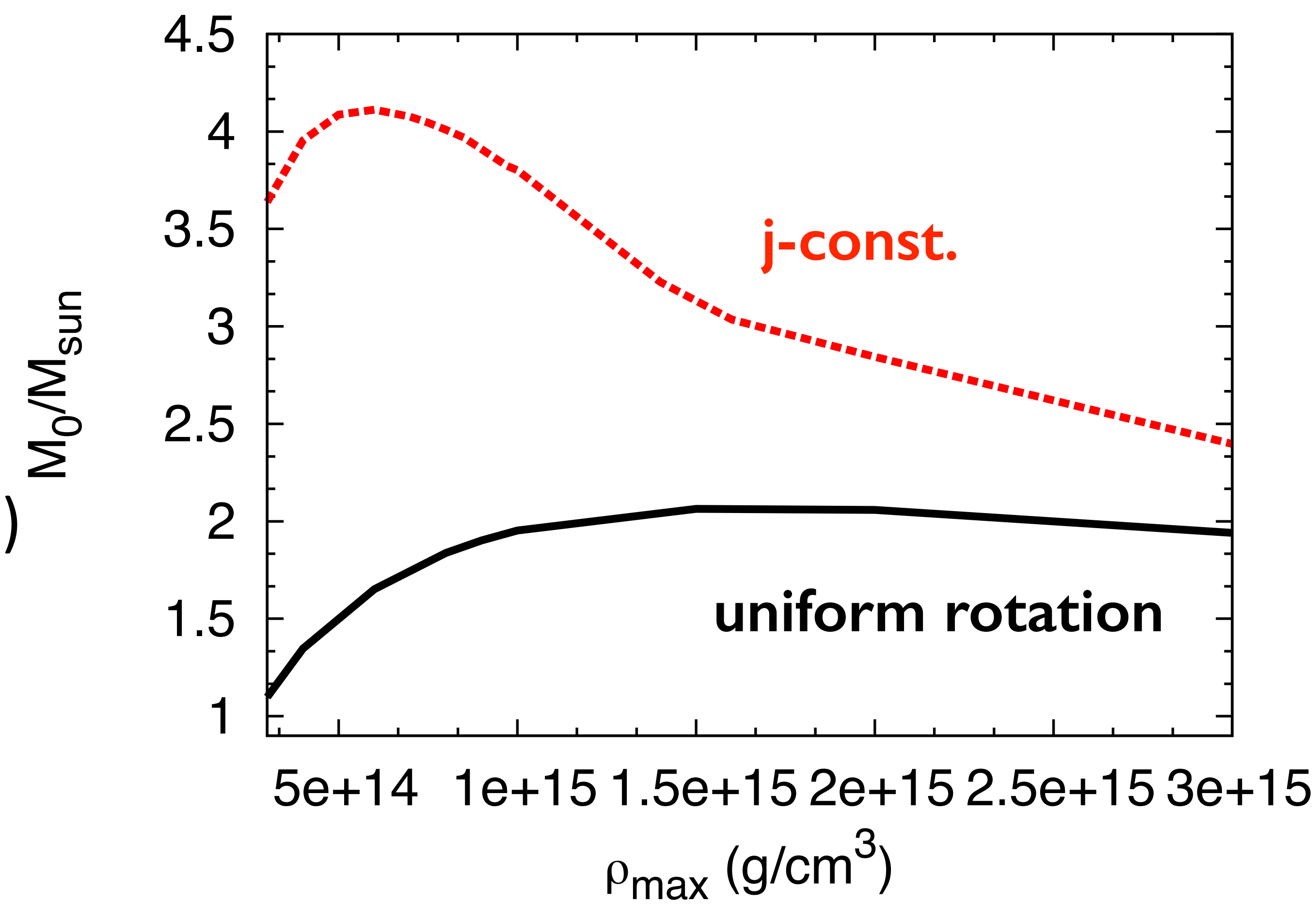


Equal-mass BNS, SLy M=2.7 M$_\odot$

Hypermassive neutron star properties

- Is the HMNS supported against collapse by differential rotation?

isolated differentially rotating NSs can support large masses (Baumgarte et al `00)



Baumgarte et al ApJ `00

Hypermassive neutron star properties

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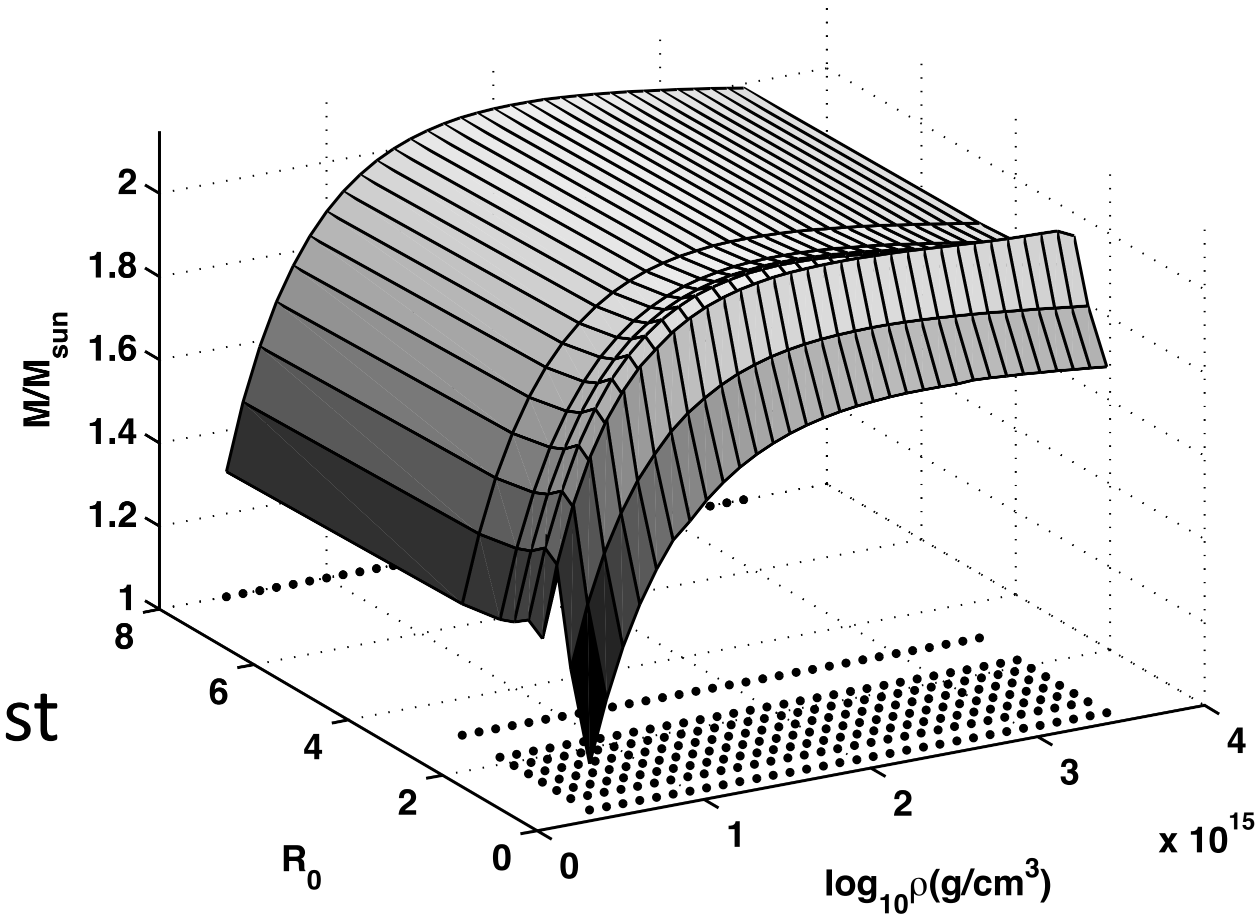
only if the rotation law is j-const



Galeazzi, Yoshida, Eriguchi A&A `12

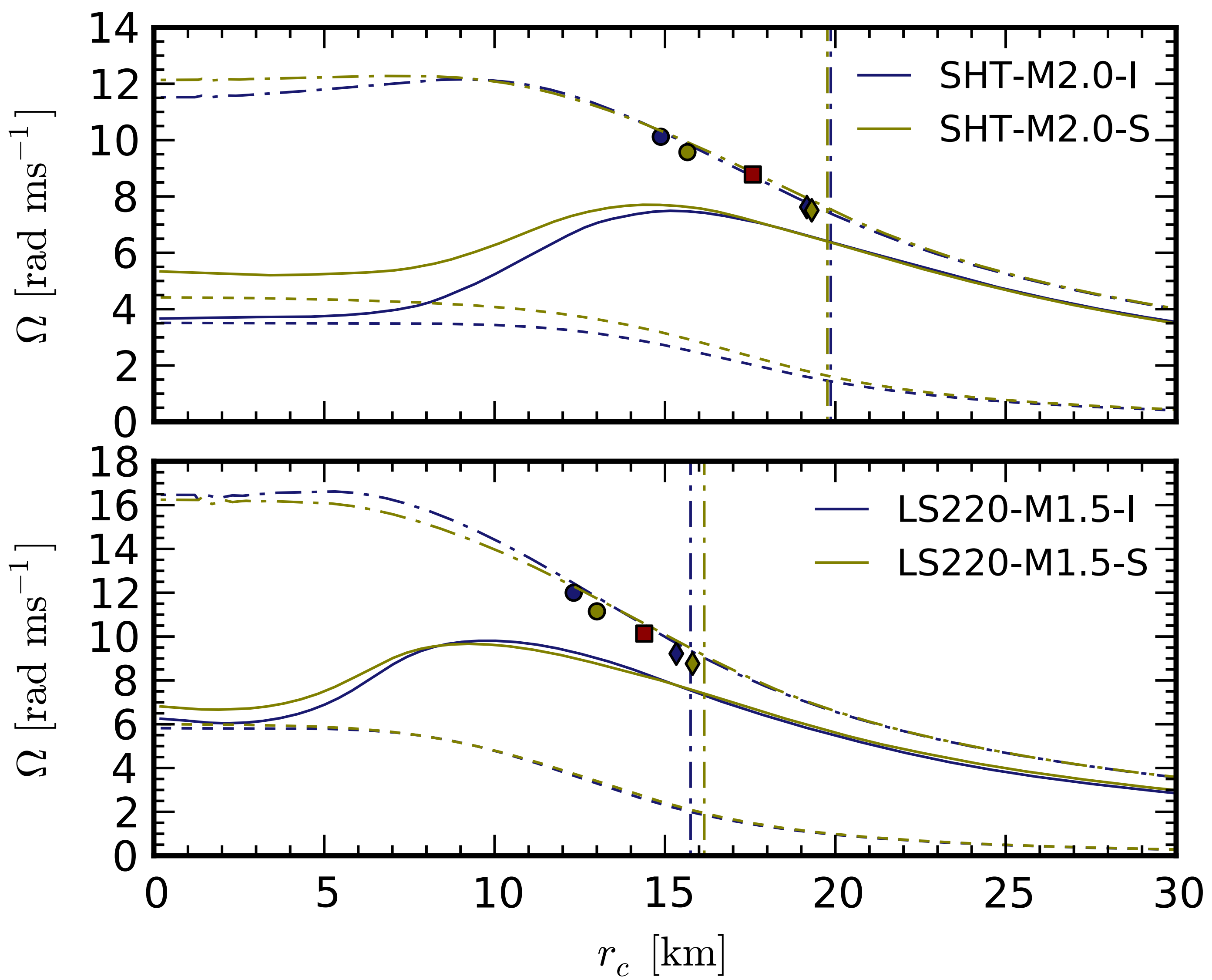
- Is the HMNS supported against collapse by thermal effects?

only if the EOS is a simple ideal gas

(Paschalidis et al `12, Kaplan et al `14)

Hypermassive neutron star properties

- differential rotation supports larger masses than the maximally but uniformly rotating models
- rotation laws where the core rotates faster than the outer layers
- in our simulations the center rotates slower compared to the outer envelope (also in Shibata et al. `03)
- the rotation rate of the core is lower than for a uniformly rotation model close to the Kepler limit



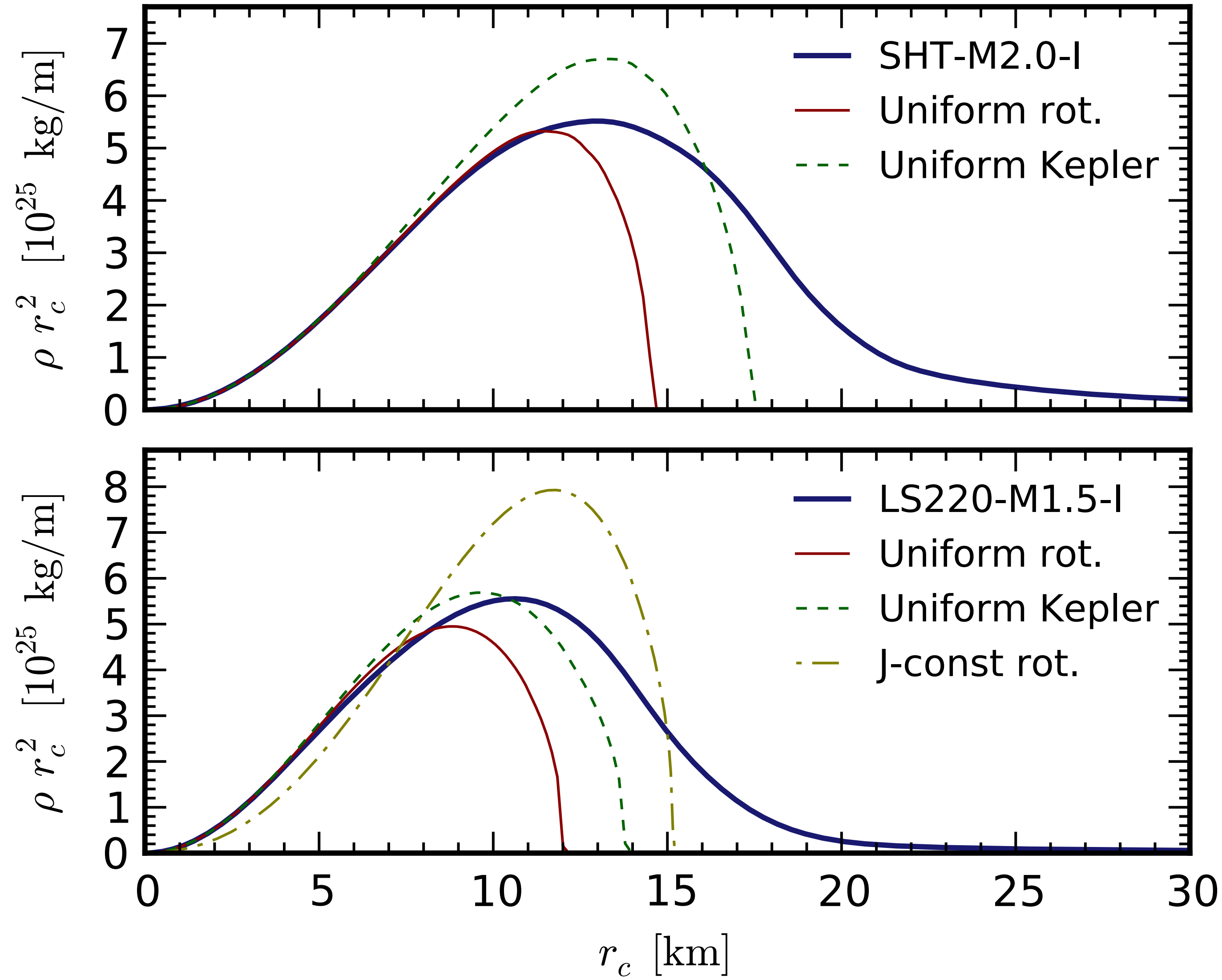
Average rotation profile and Keplerian angular velocity profile

Hypermassive neutron star properties

- the HMNS extends well beyond the surface of the uniformly rotating star model
- the excess of mass is contained in an extended disk that surrounds the star
- the disk has a almost Keplerian velocity profile

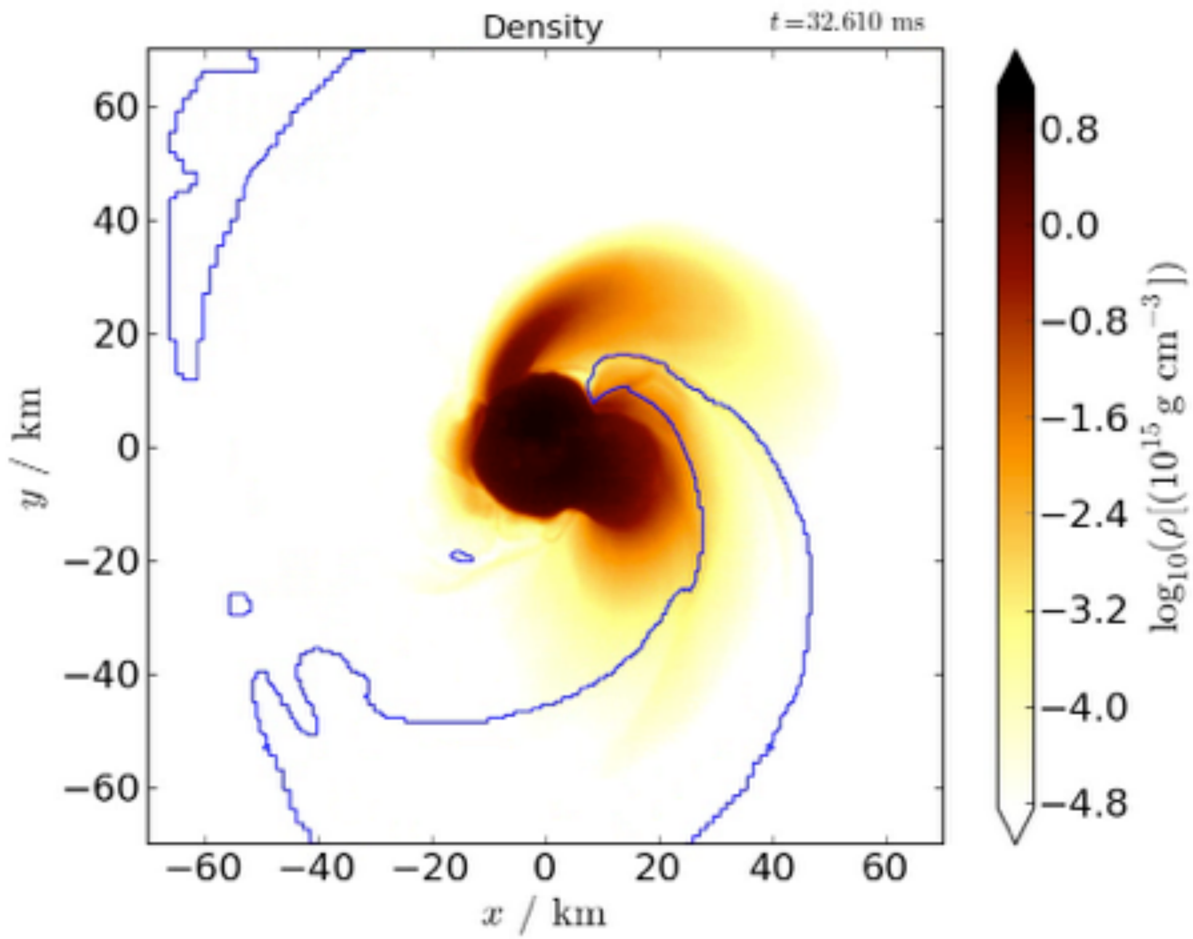
Hunch:

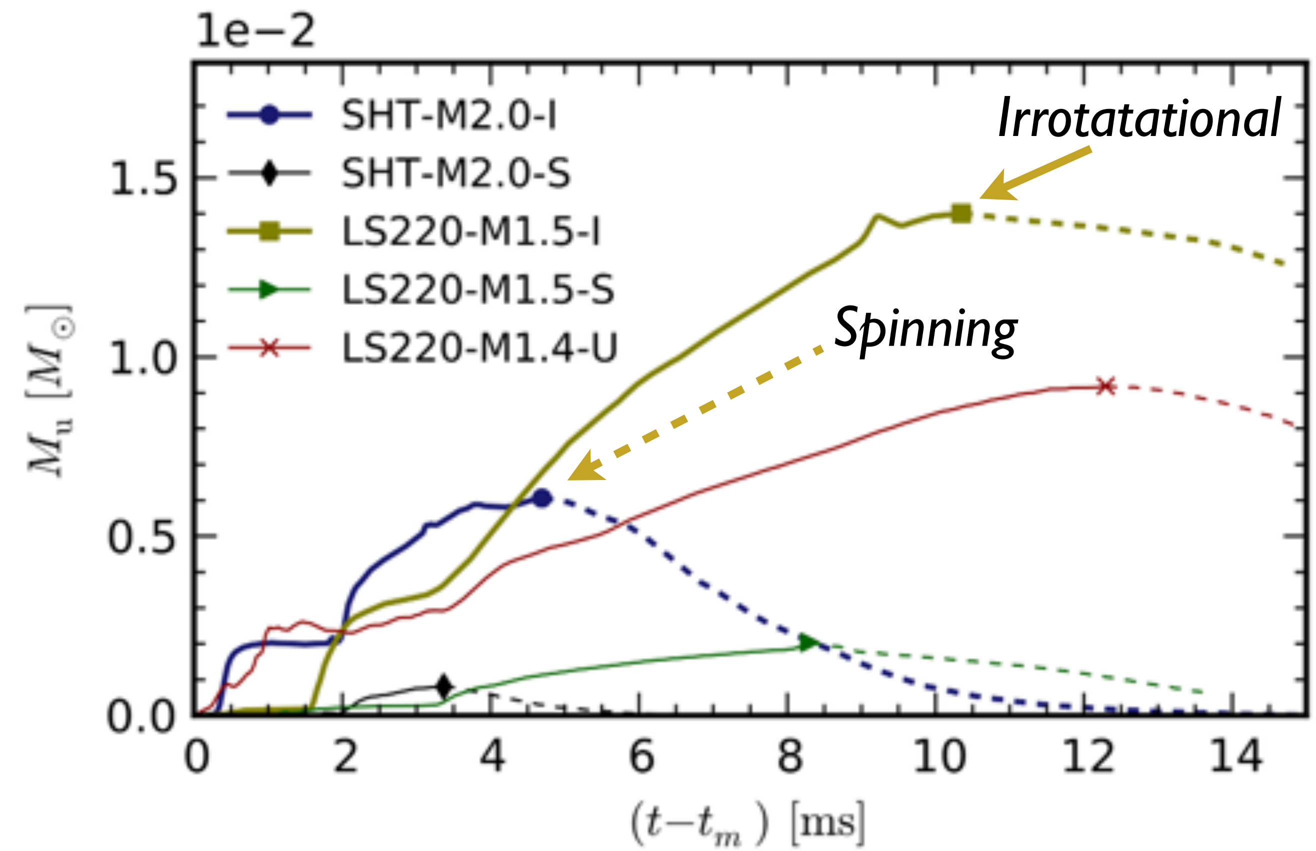
the presence of a massive disk helps to prevent immediate collapse



Density profile in the equatorial plane of the time and ϕ-averaged HMNS

Mass ejection from spinning BNS





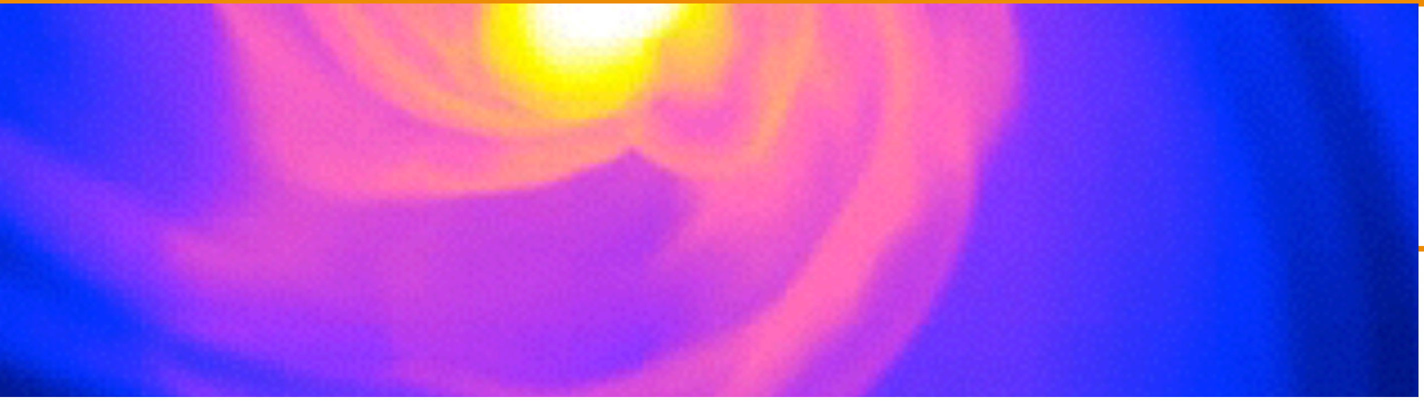
- ejecta are extremely neutron rich
- ejecta undergo rapid neutron-capture process (r-process)
- kilonova from short GRB

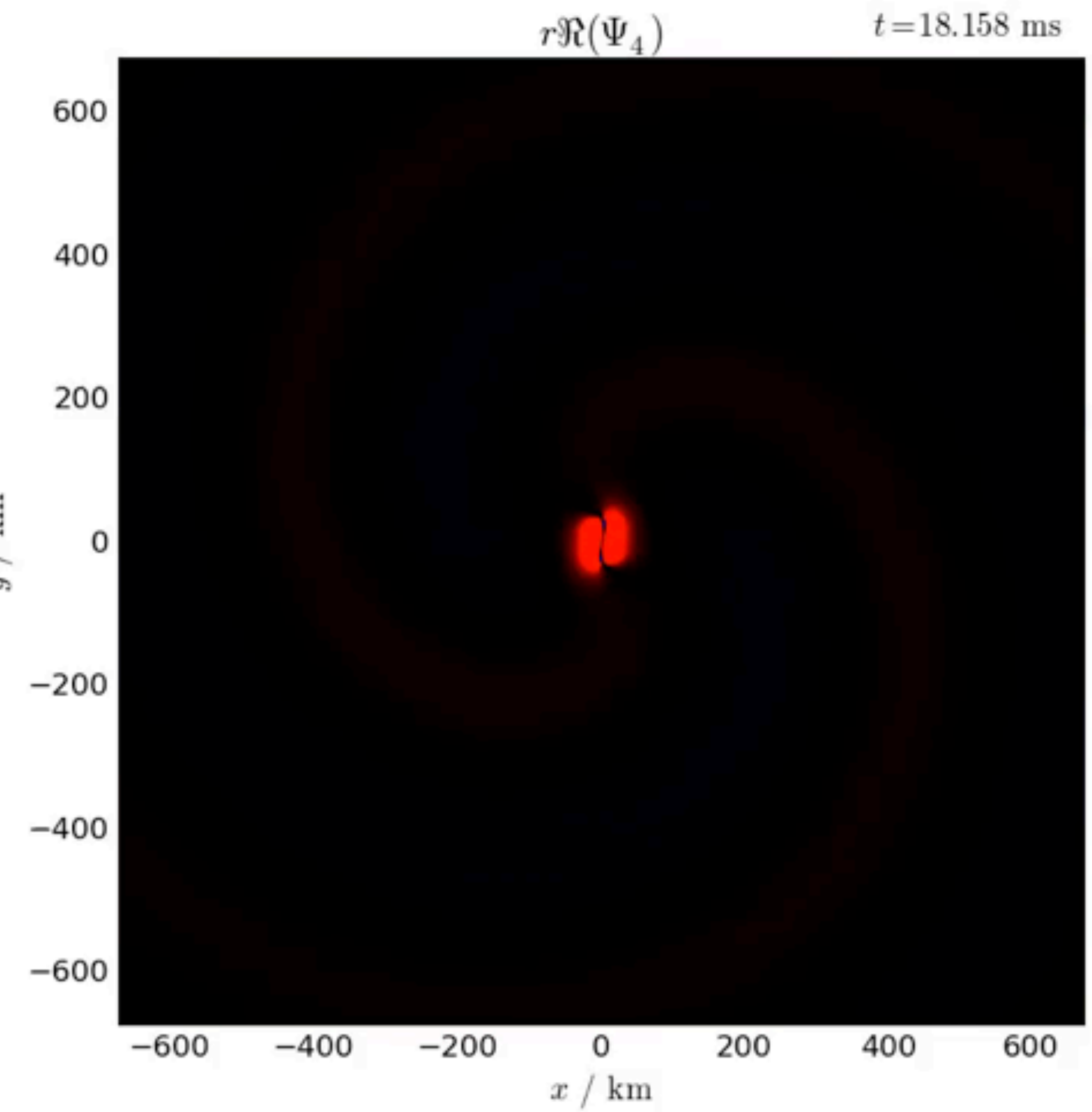
- Thermodynamical properties of the ejecta dependent on EOS and neutrino cooling

input from experiments (FAIR):
fission yields for r-process nuclei

Conclusions

- Gravitational waves from BNSs may be directly detected within the decade. Maximising science will require an accurate modelling of the microphysics involved.
- The study of the gravitational wave signal from the merger will allow us to constraint NS masses and radii and so the EOS. Effects for realistic spin values are small in the HMNS frequencies.
- Steps towards modelling a unique astrophysical laboratory.





Thank you for your attention

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