Gravitational Wave Astronomy and the Internal Properties of Hypermassive Neutron Stars

NEUTRON STARS IN FUTURE RESEARCH, 11. DECEMBER 2017
MAX-PLANCK-INSTITUT FÜR RADIOASTRONOMIE
BONN, GERMANY

MATTHIAS HANAUSKE, KENTARO TAKAMI, LUKE BOVARD, JOSE FONT, FILIPPO GALEAZZI, JENS PAPENFORT, LUKAS WEIH, ELIAS MOST, ZEKIYE SIMAY YILMAZ, CHRISTINA MITROPOULOS, JAN STEINHEIMER, STEFAN SCHRAMM, DAVID BLASCHKE, MARK ALFORD, KAI SCHWENZER, LAURA TOLOS, GLORIA MONTAÑA, MICHAEL RATTAY, HORST STÖCKER AND LUCIANO REZZOLLA

FRANKFURT INSTITUTE FOR ADVANCED STUDIES
JOHANN WOLFGANG GOETHE UNIVERSITÄT
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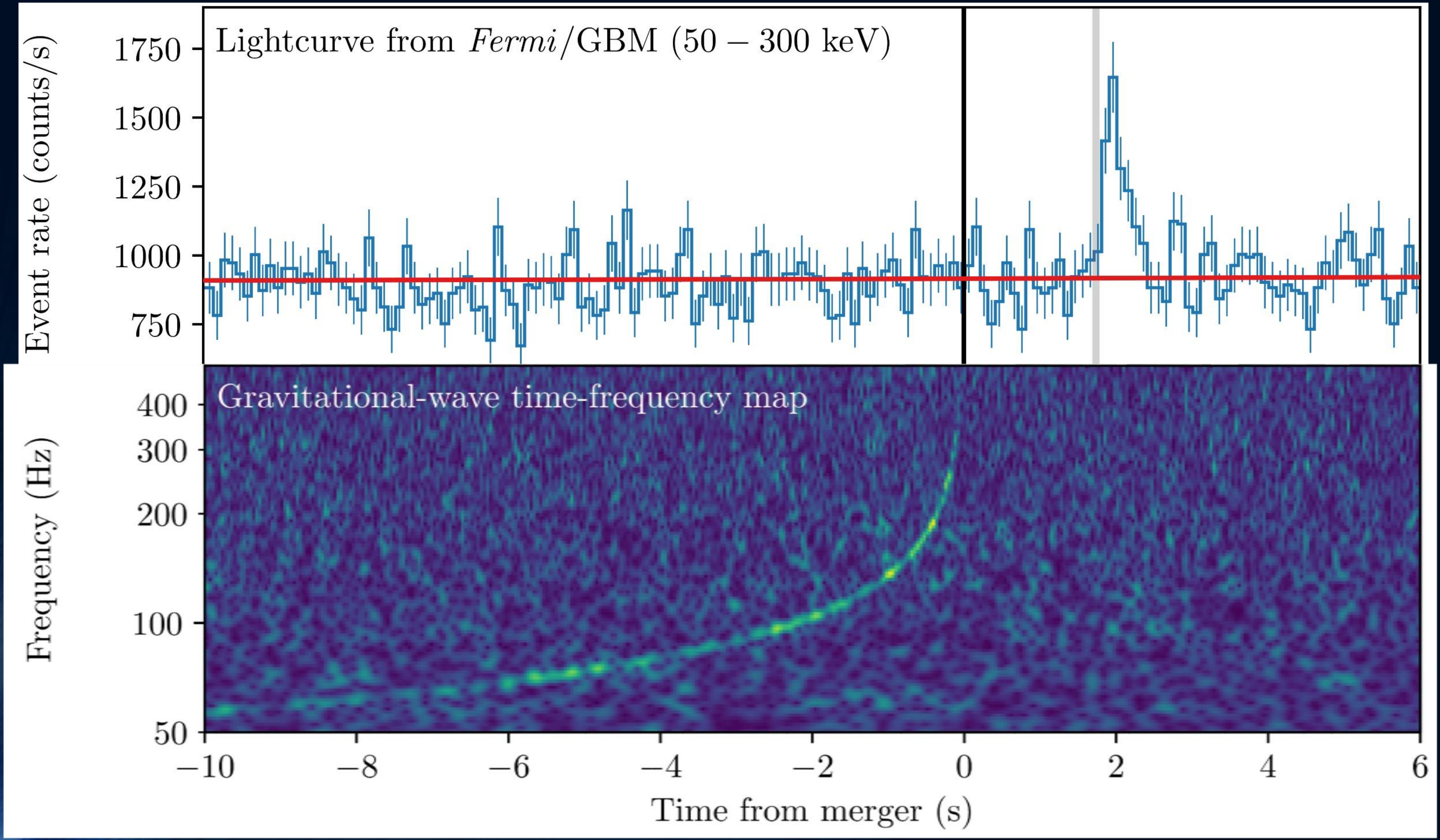
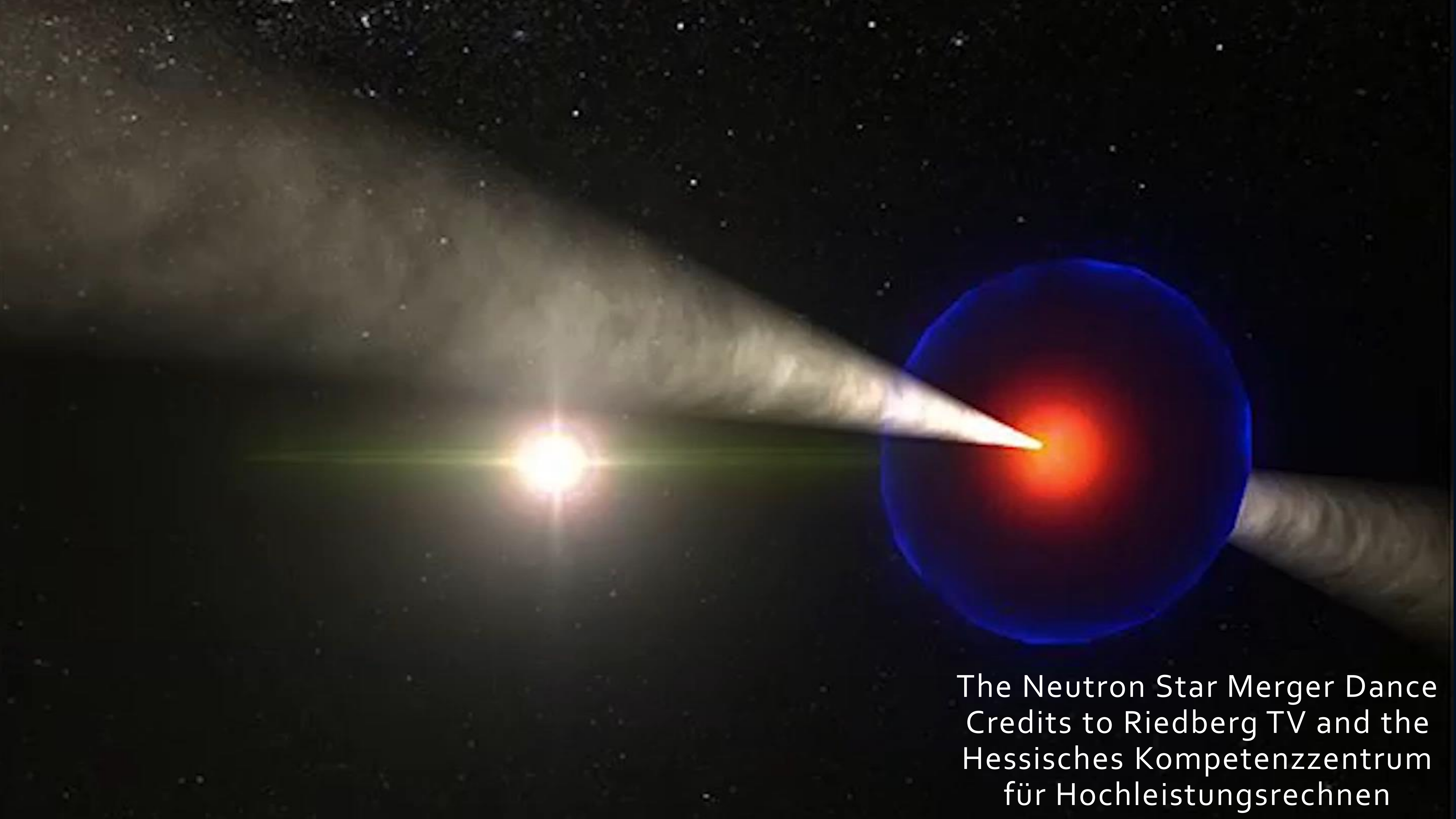
The long-awaited event GW170817

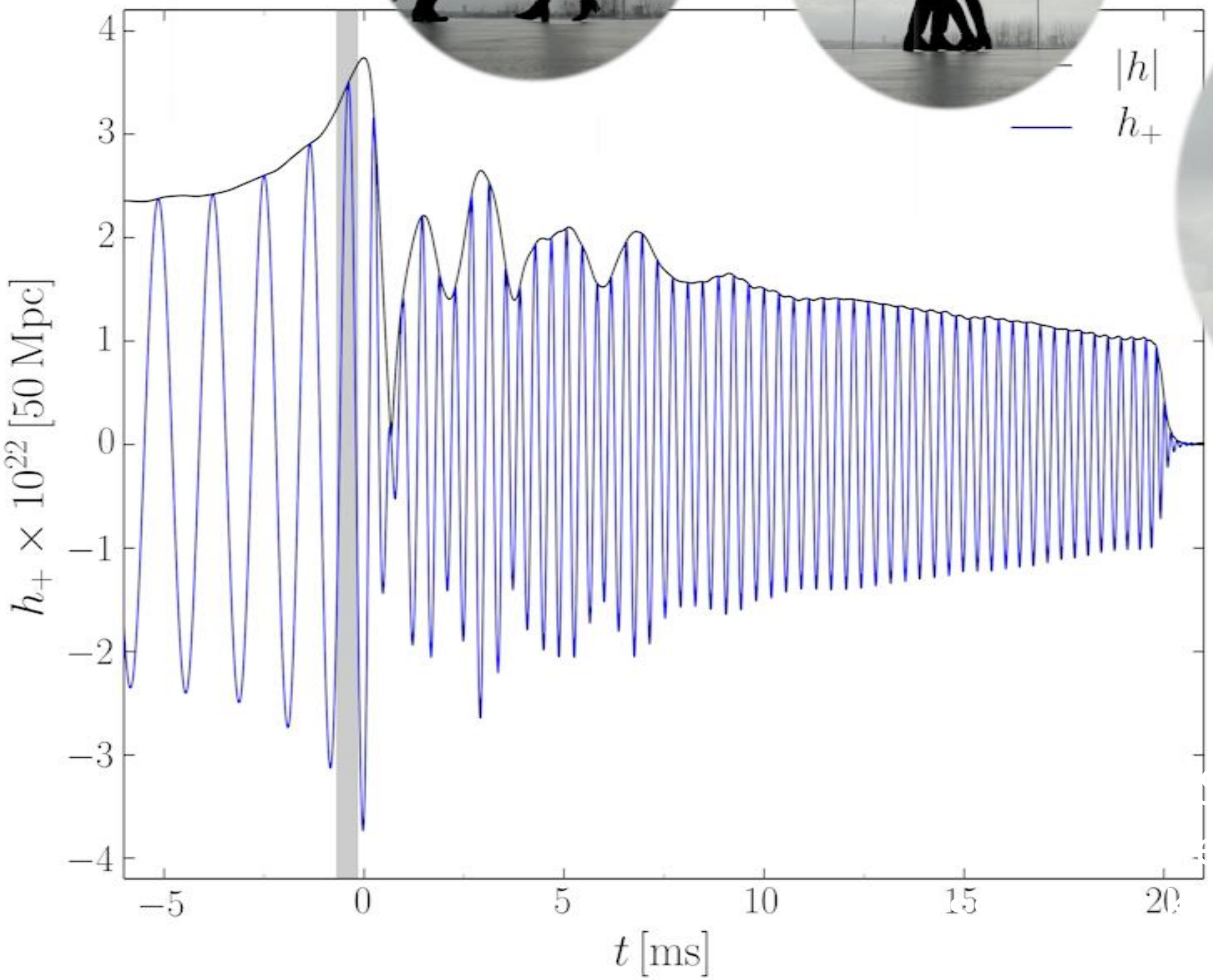
	Low-spin priors ($\lvert\chi\rvert \leq 0.05$)	High-spin priors ($\lvert\chi\rvert \leq 0.89$)
Primary mass m_1	1.36–1.60 $M_\odot$	1.36–2.26 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$	0.86–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance $D_{\rm L}$	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$	$\leq 56°$
Using NGC 4993 location	$\leq 28°$	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400

Gravitational Wave GW170817 and Gamma-Ray Emission GRB170817A

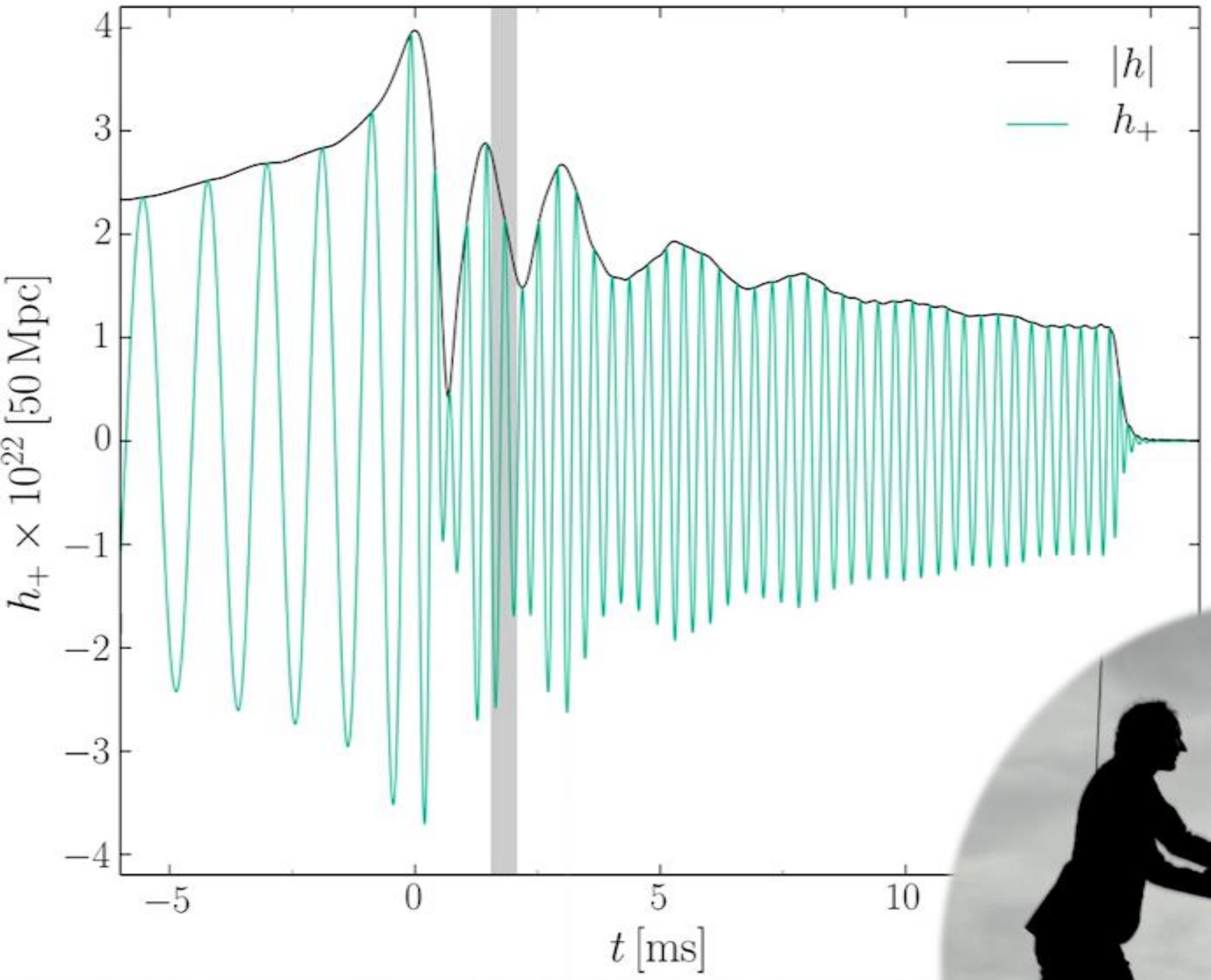


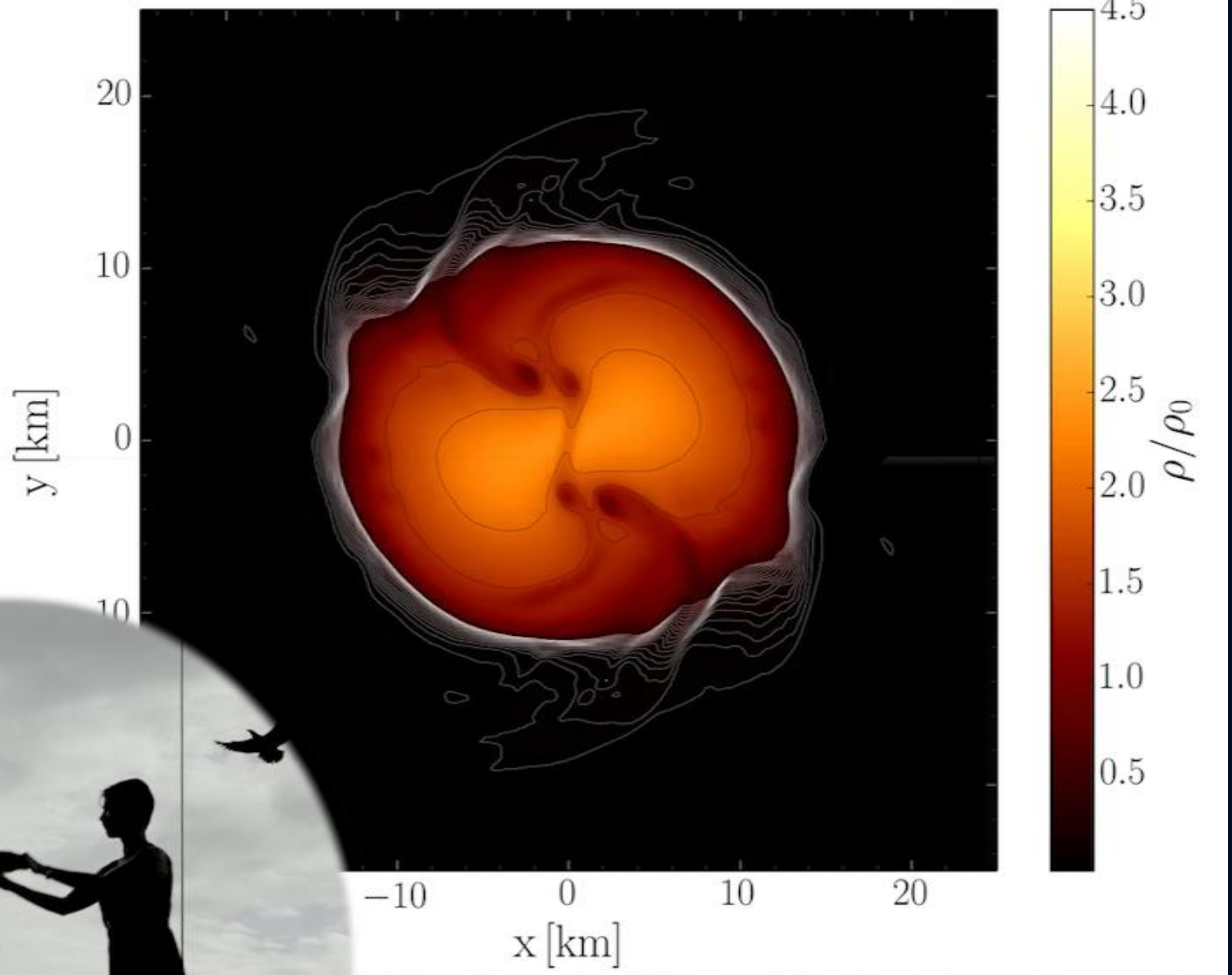


The Neutron Star Merger Dance
Credits to Riedberg TV and the
Hessisches Kompetenzzentrum
für Hochleistungsrechnen

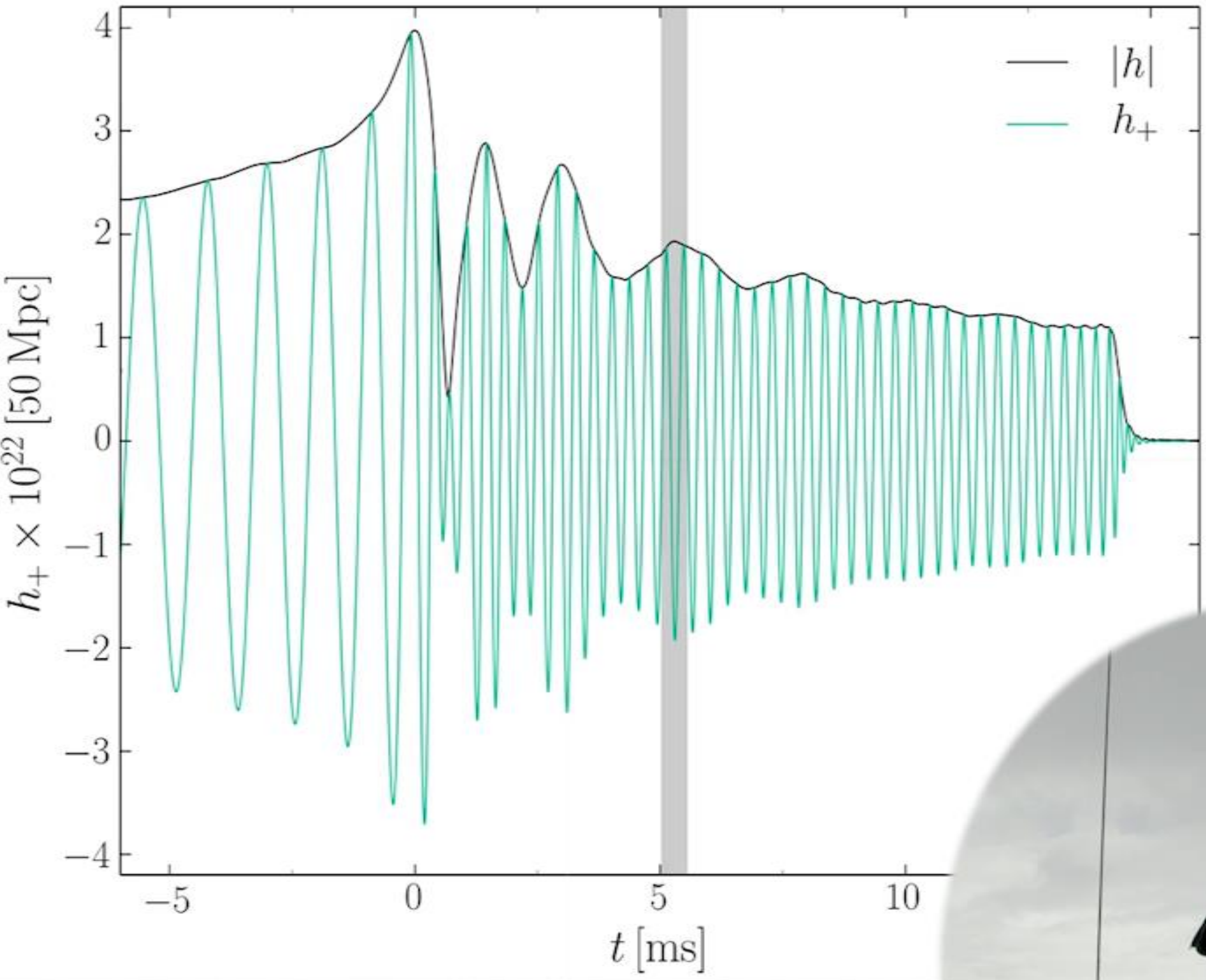

$|h|$
h_+
$h_+ \times 10^{22}\,[50\,\mathrm{Mpc}]$
4
3
2
1
0
−1
−2
−3
−4
−5
0
5
10
15
20
$t\,[\mathrm{ms}]$

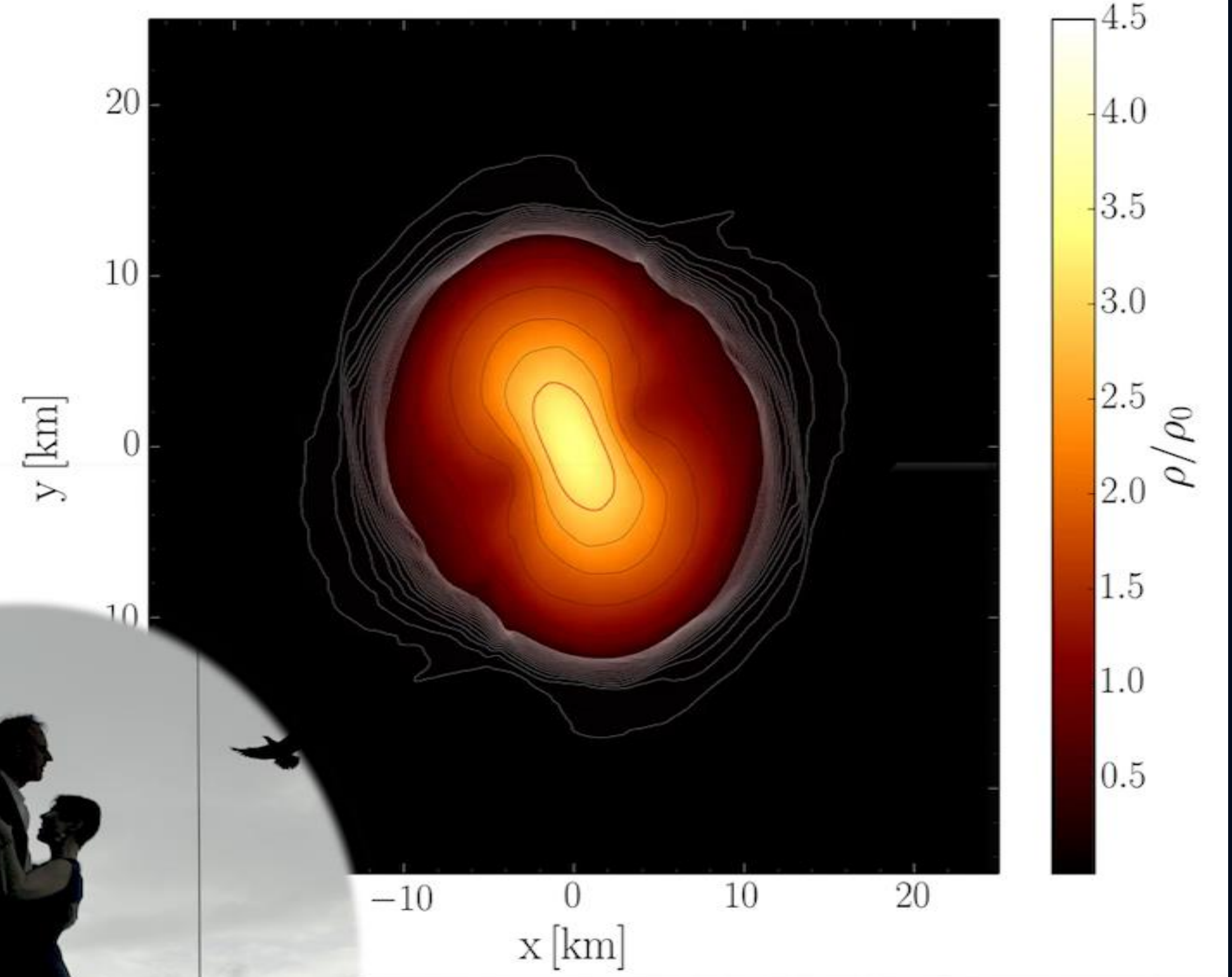

Wiener Walzer


|h|
h_+
$h_+ \times 10^{22}$ [50 Mpc]
t [ms]
4
3
2
1
0
−1
−2
−3
−4
−5
0
5
10

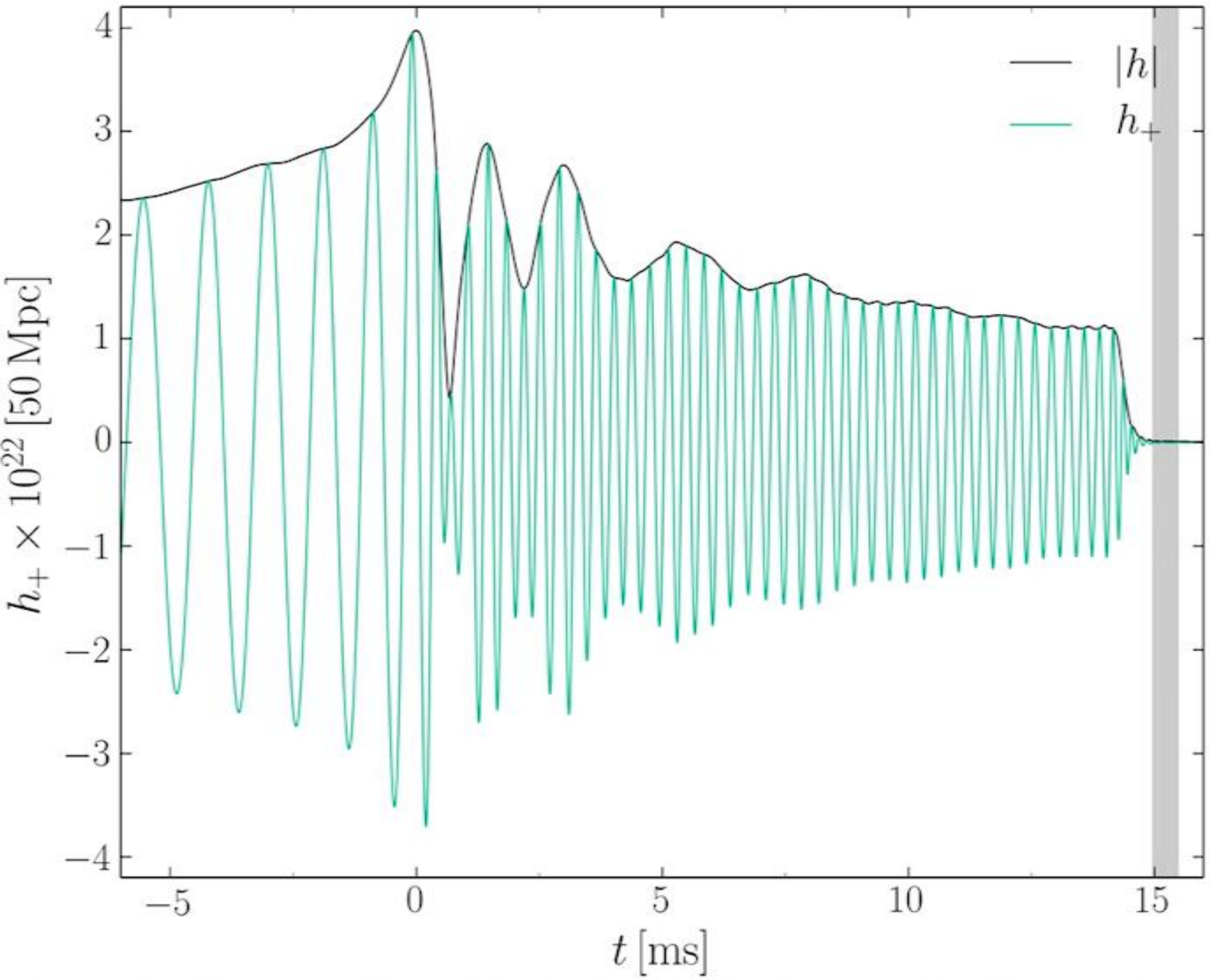

y [km]
x [km]
ρ/ρ_0
20
10
0
−10
0
10
20
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5

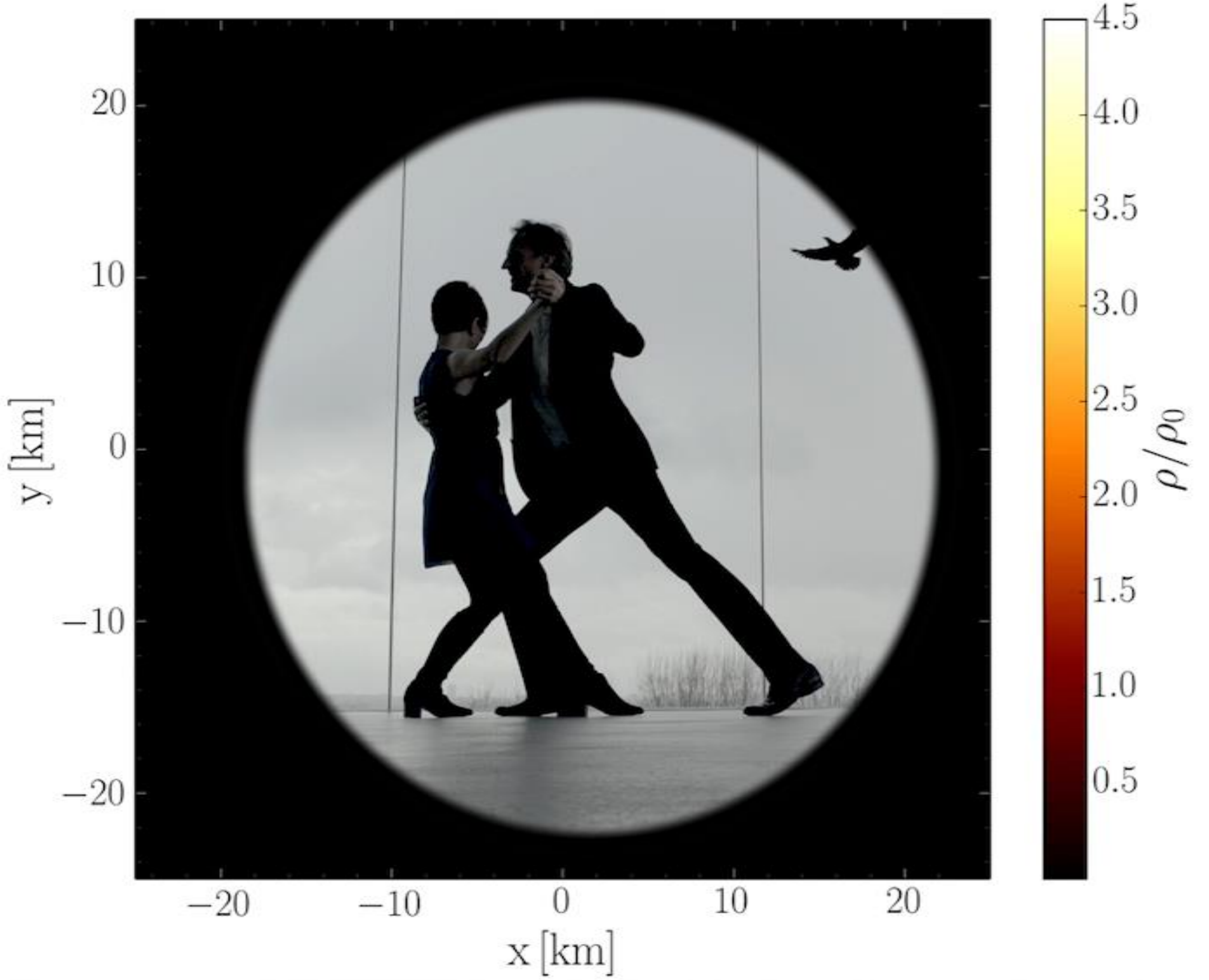
Disco Fox


|h|
h+
h+ × 10^22 [50 Mpc]
t [ms]
4
3
2
1
0
−1
−2
−3
−4
−5
0
5
10


y [km]
x [km]
ρ/ρ0
20
10
0
−10
−10
0
10
20
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5

Merengue


$|h|$
h_+
$h_+ \times 10^{22}\,[50\,\mathrm{Mpc}]$
t [ms]
4
3
2
1
0
−1
−2
−3
−4
−5
0
5
10
15


y [km]
x [km]
20
10
0
−10
−20
ρ/ρ_0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5

Tango

Ludmila und [redacted]

Matthias Hanauske

Kamera Pablo Rengel
Lorena

Schnitt Luise Schulte

The Neutron Star Merger Dance
Credits to Riedberg TV and the
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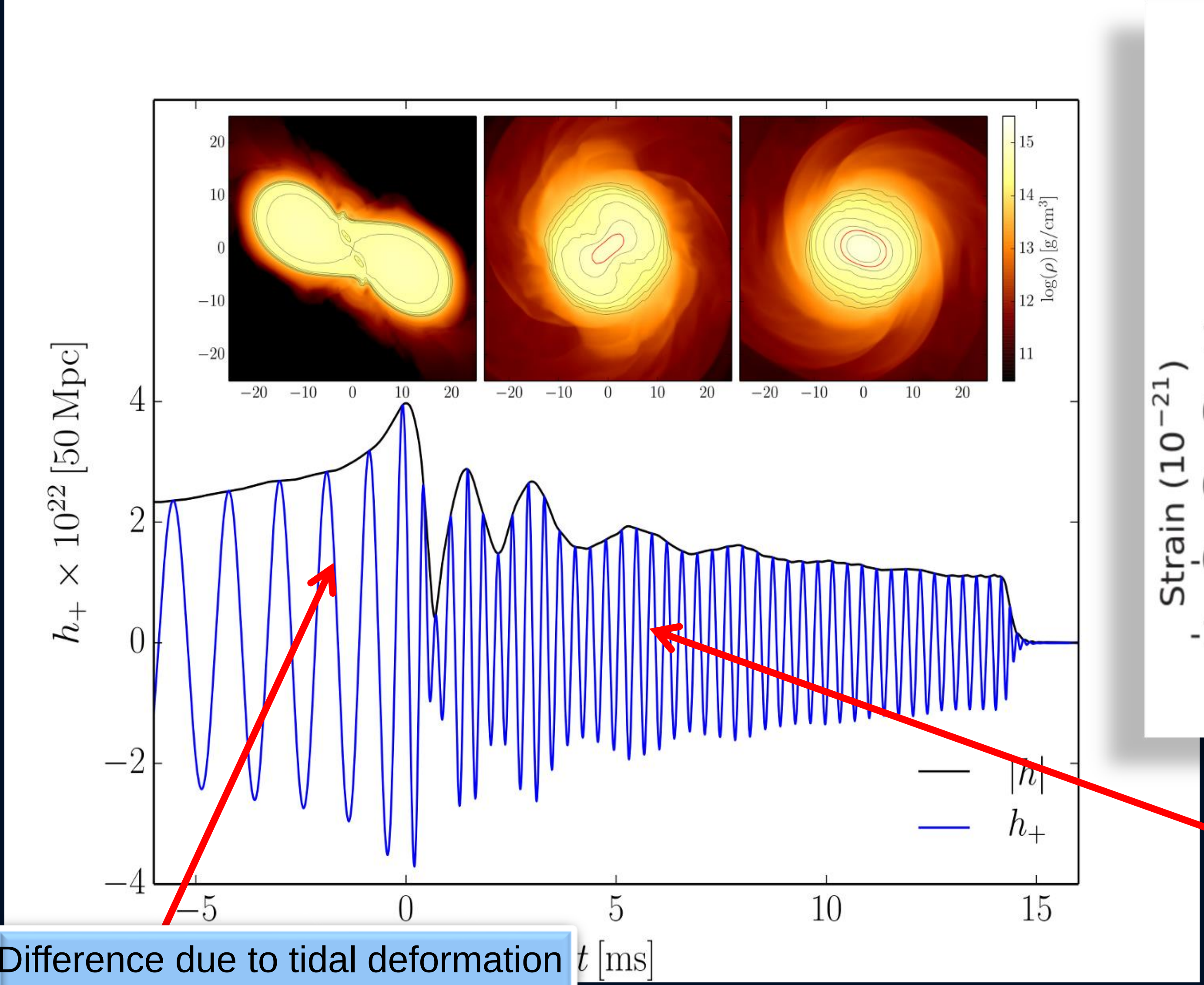
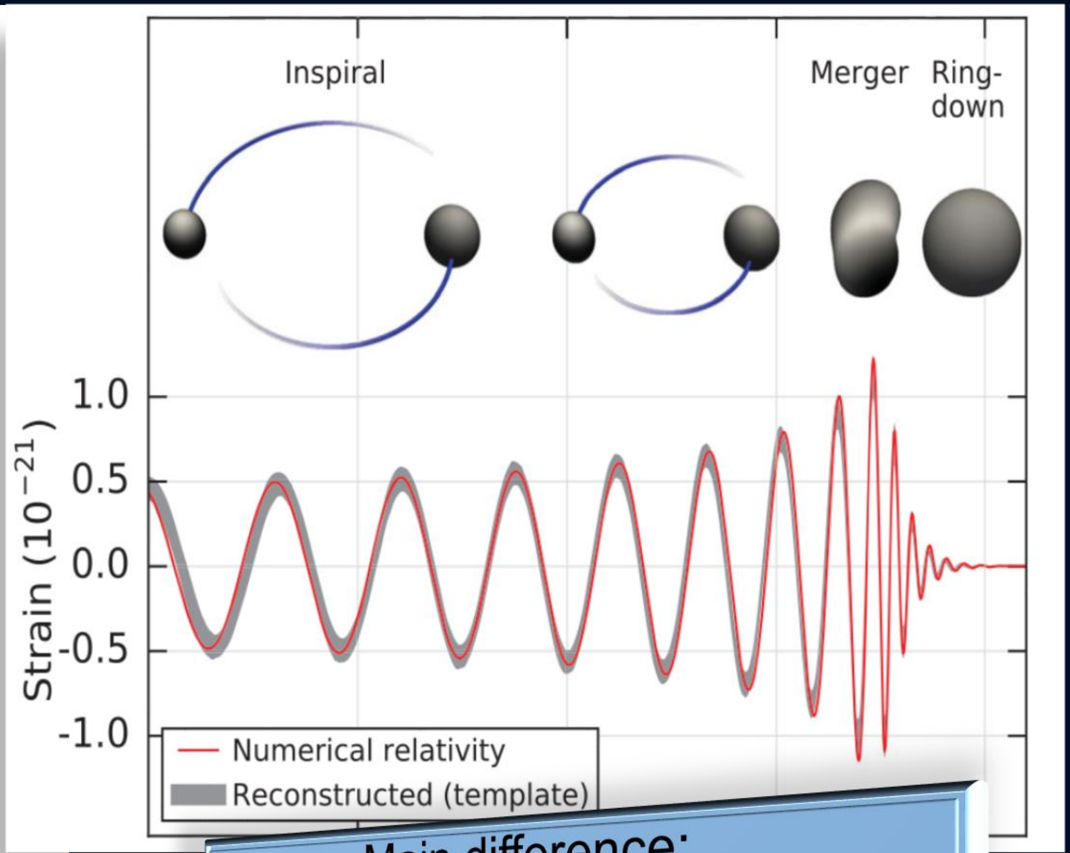
Gravitational Waves from Neutron Star Mergers

Neutron Star Collision (Simulation)

Collision of two Black Holes



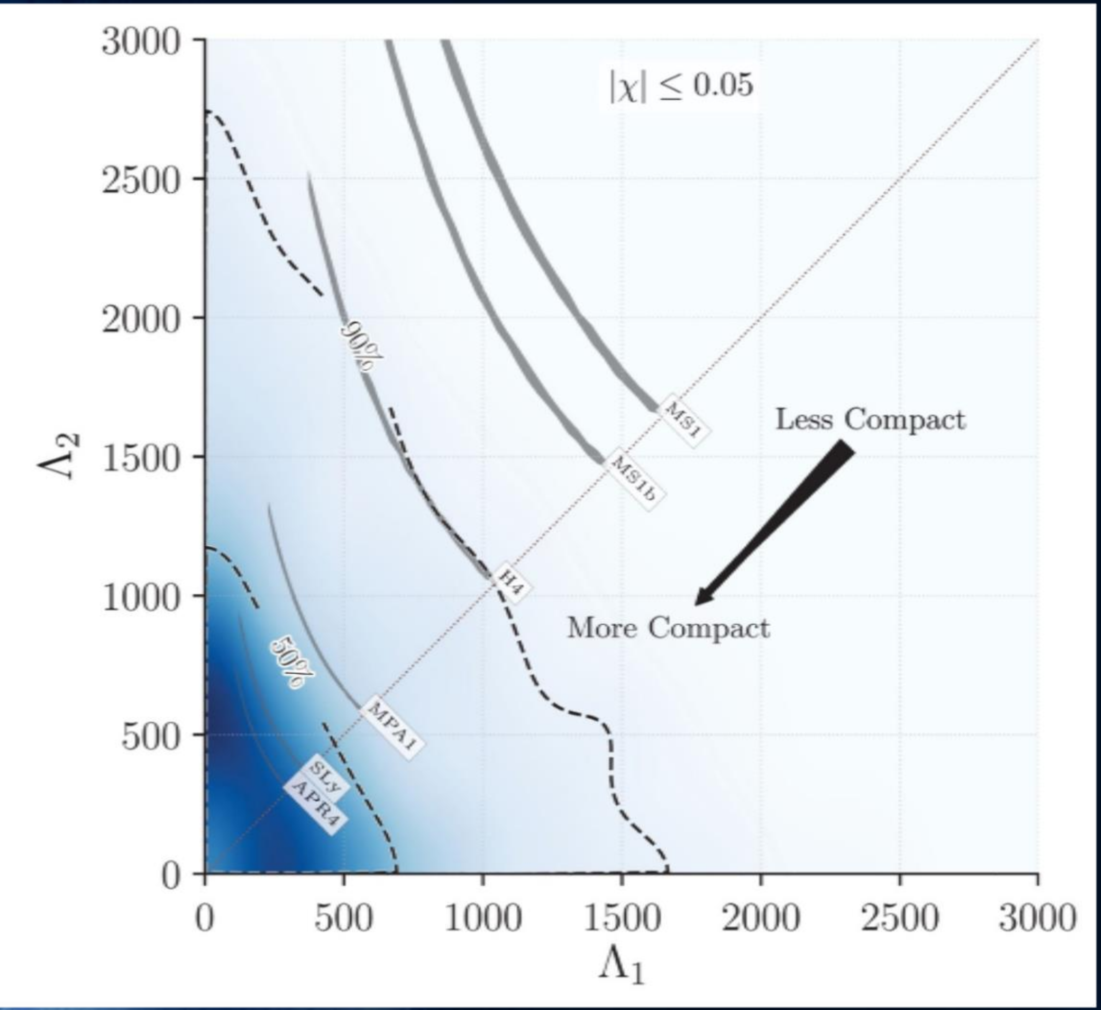


Difference due to tidal deformation in the late Inspiral phase

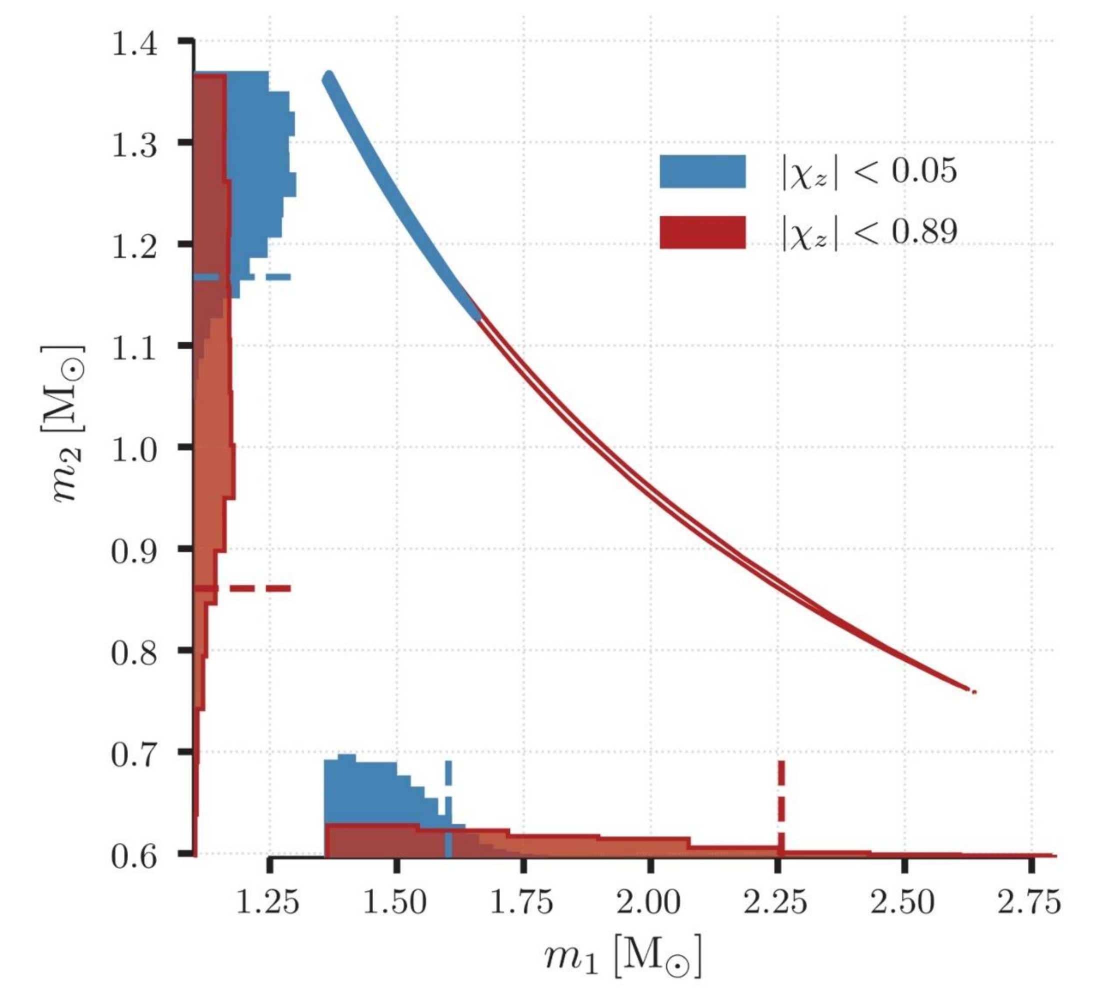
<u>Main difference:</u>

In binary neutron star mergers a **Post-Merger Phase** often exists

GW170817:
Restrictions on Equation of State (EOS) and Mass Ratio



Tidal Deformability (high low spin assumption)



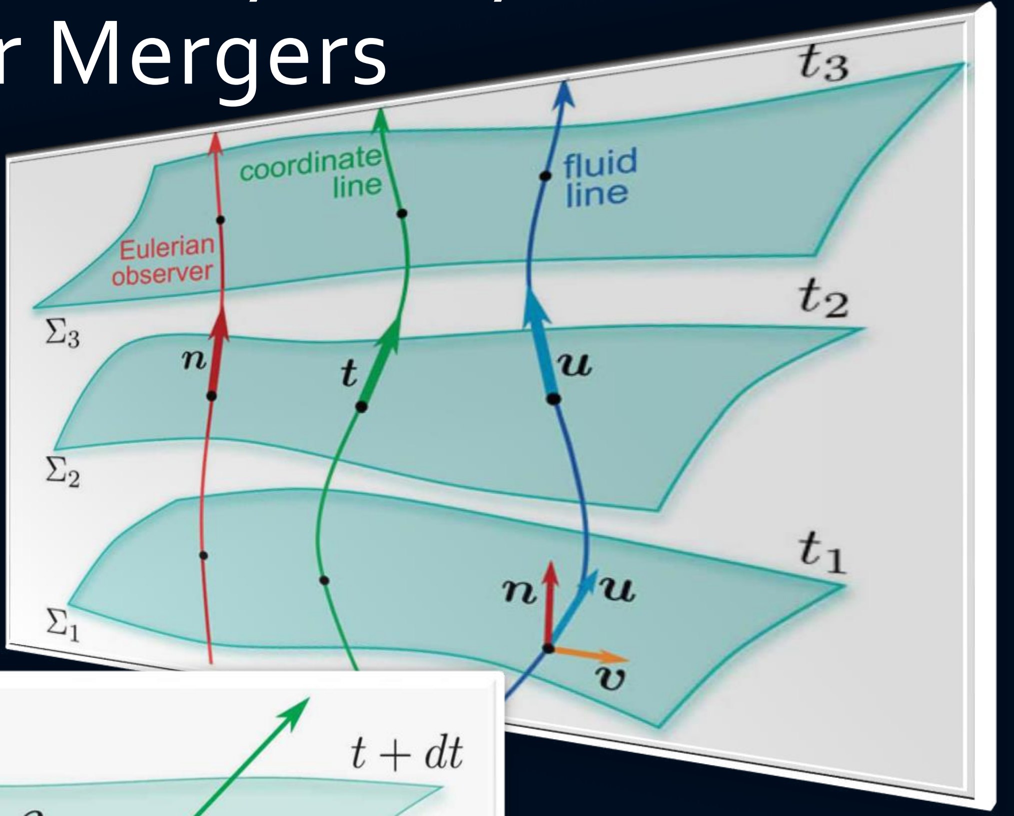
Measured Mass Ratio of GW170817
(for high and low spin assumption)

Numerical Relativity and Relativistic Hydrodynamics of Binary Neutron Star Mergers

Numerical simulations of a merger of two compact stars are based on a (3+1) decomposition of spacetime of the Einstein and hydrodynamic equations.

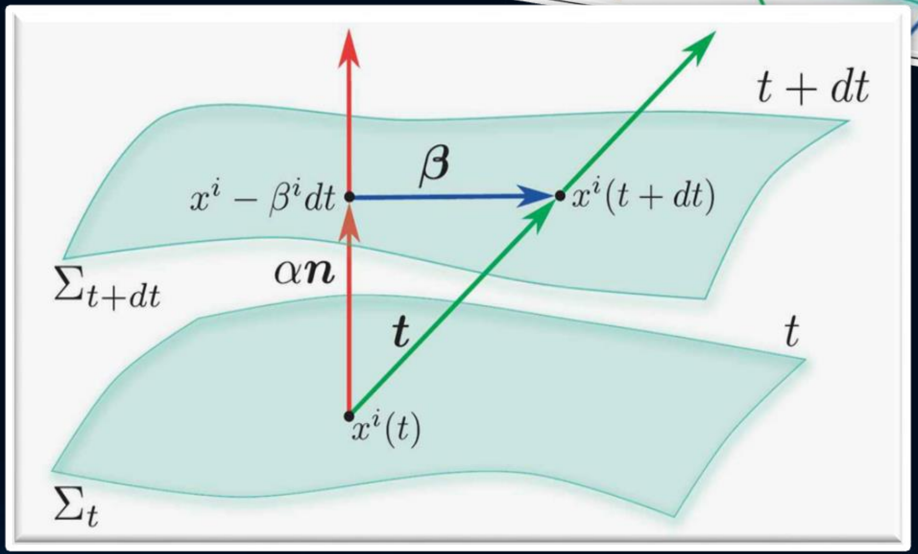
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi T_{\mu\nu}$$

$$\nabla_\mu (\rho u^\mu) = 0\,, \qquad \nabla_\nu T^{\mu\nu} = 0\,.$$



(3+1) decomposition of spacetime

$$g_{\mu\nu} = \begin{pmatrix} -\alpha^2 + \beta_i \beta^i & \beta_i \\ \beta_i & \gamma_{ij} \end{pmatrix}$$



$$d\tau^2 = \alpha^2(t, x^j) dt^2$$

$$x^i_{t+dt} = x^i_t - \beta^i(t, x^j) dt$$

All figures and equations from: Luciano Rezzolla, Olindo Zanotti: Relativistic Hydrodynamics, Oxford Univ. Press, Oxford (2013)

HMNS Evolution for different EoSs

High mass simulations (M=1.35 Msolar)

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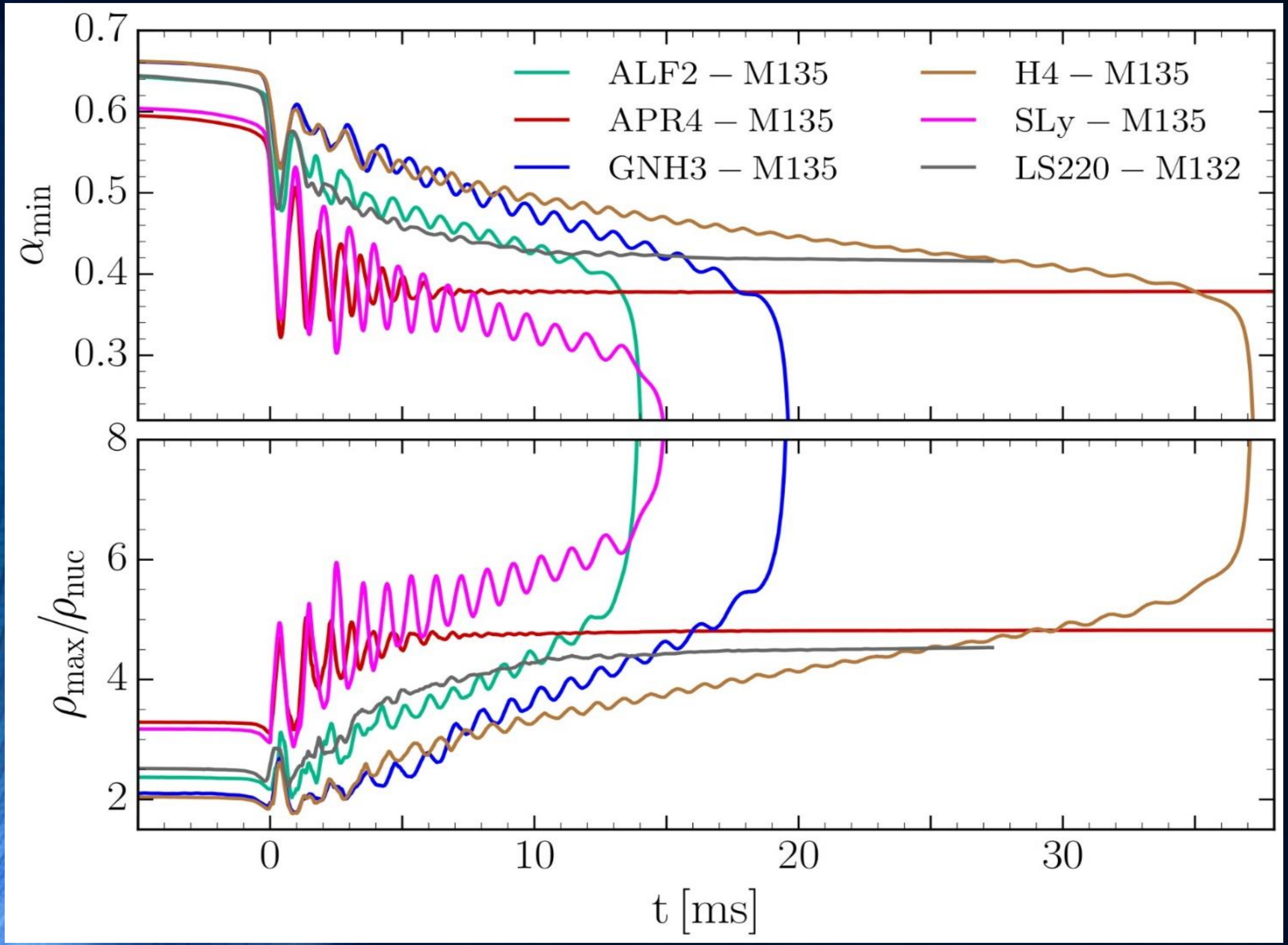
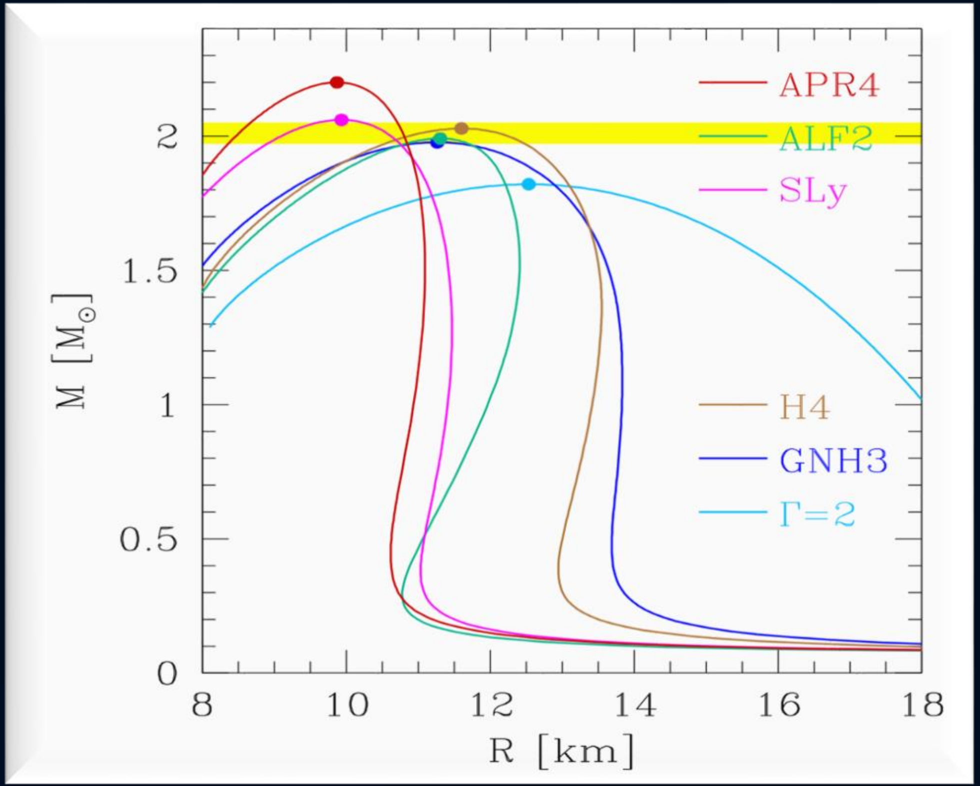
Rotational properties of hypermassive neutron stars from binary mergers

Matthias Hanauske, Kentaro Takami, Luke Bovard, Luciano Rezzolla, José A. Font, Filippo Galeazzi, and Horst Stöcker

Phys. Rev. D **96**, 043004 – Published 7 August 2017

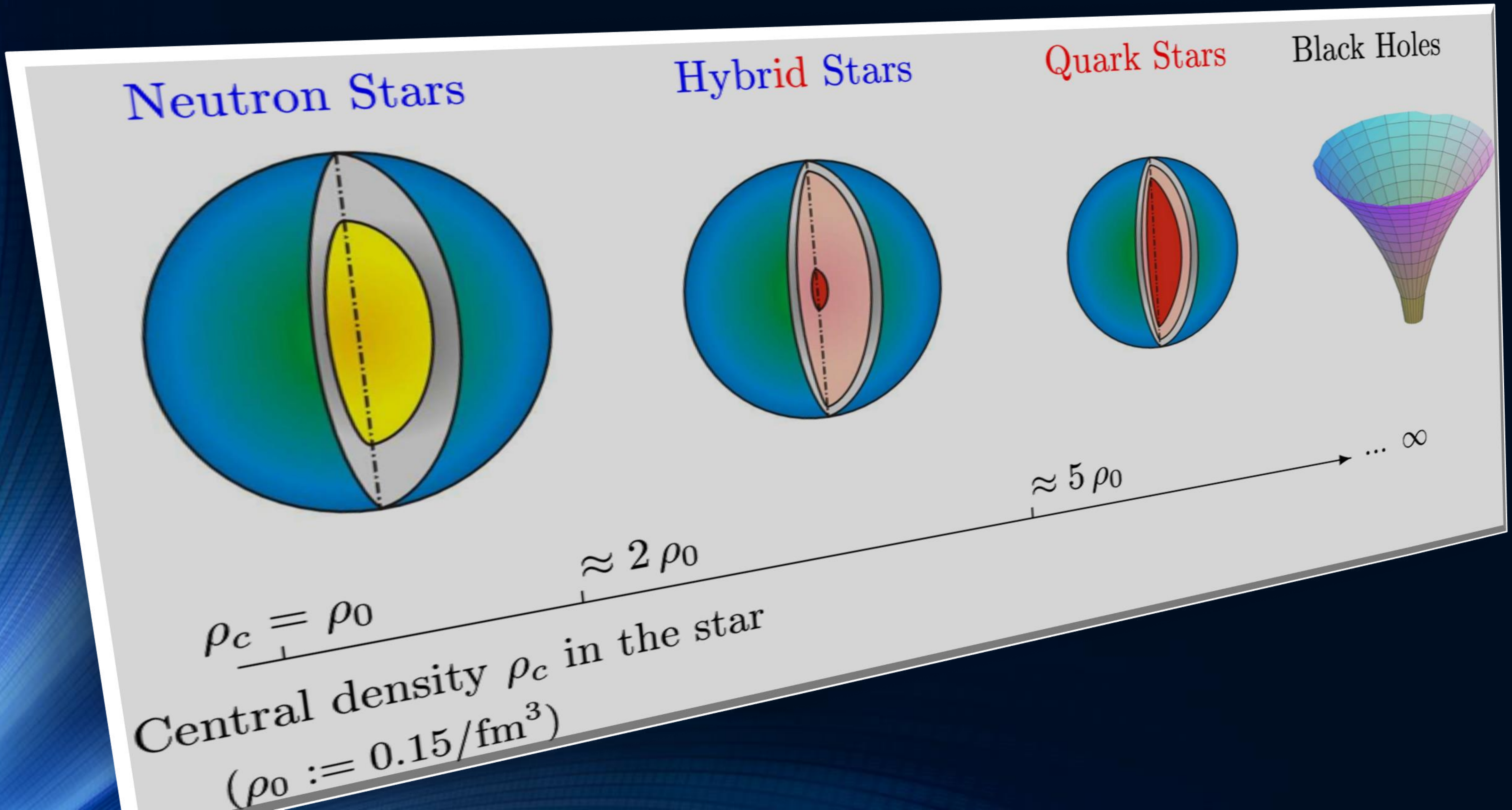


Central value of the lapse function α_c (upper panel) and maximum of the rest mass density ρ_{max} in units of ρ_0 (lower panel) versus time for the high mass simulations.

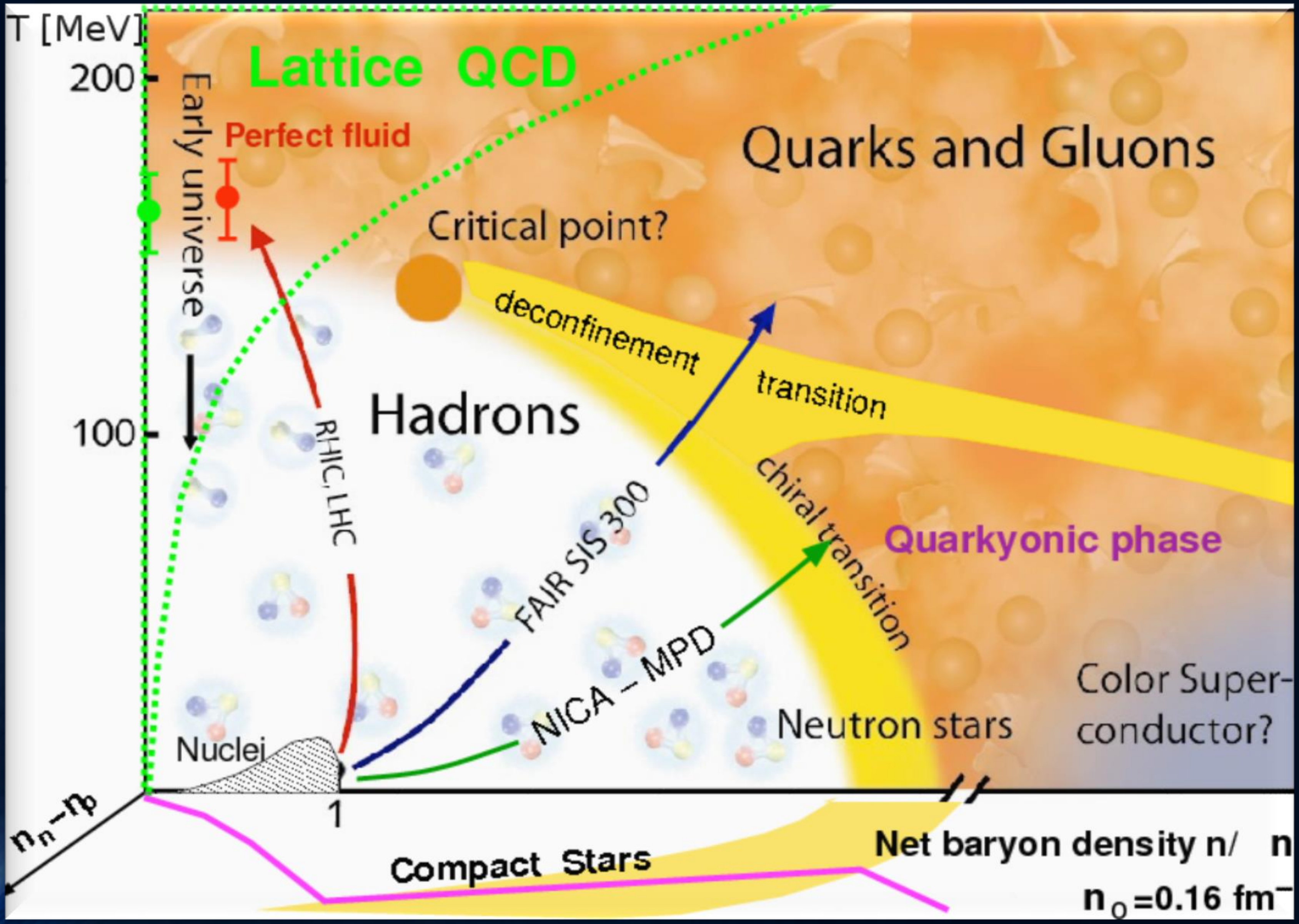


Mass-Radius relation for different EOSs

Neutron Stars, Hybrid Stars, Quark Stars and Black Holes

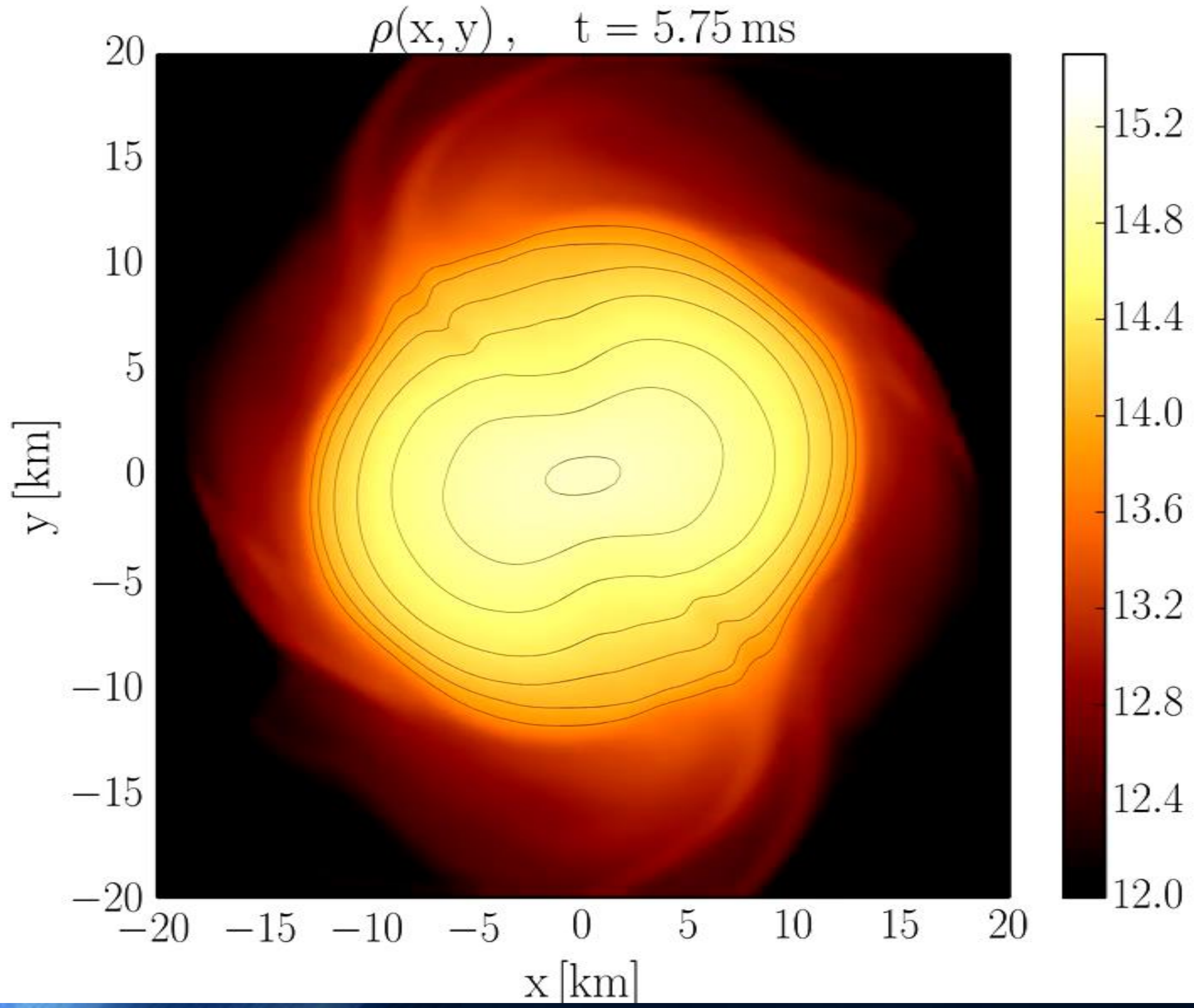


The Hadron-Quark Phasetransition

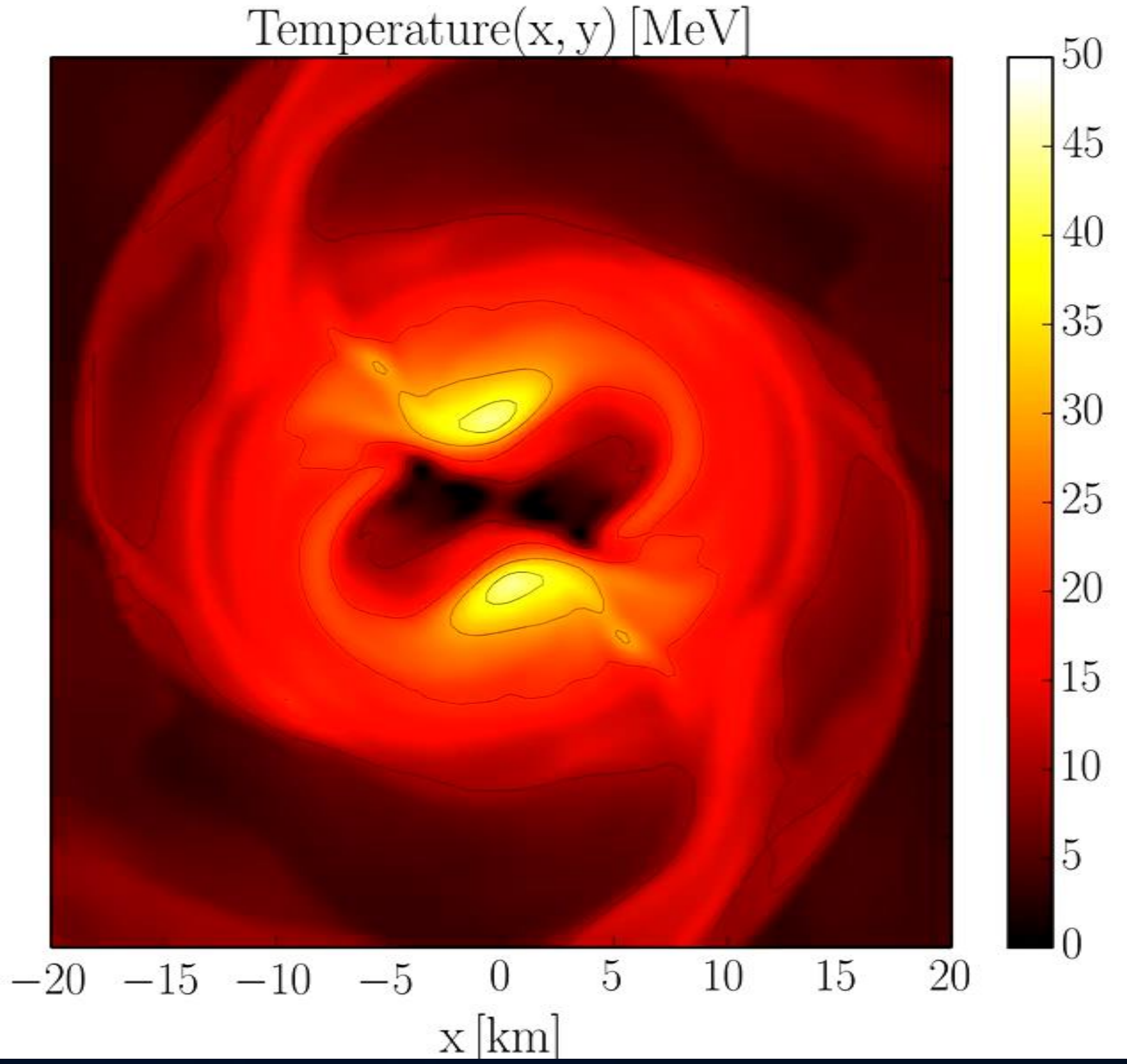


Credits to http://inspirehep.net/record/823172/files/phd_qgp3D_quarkyonic2.png

Logarithm of the density

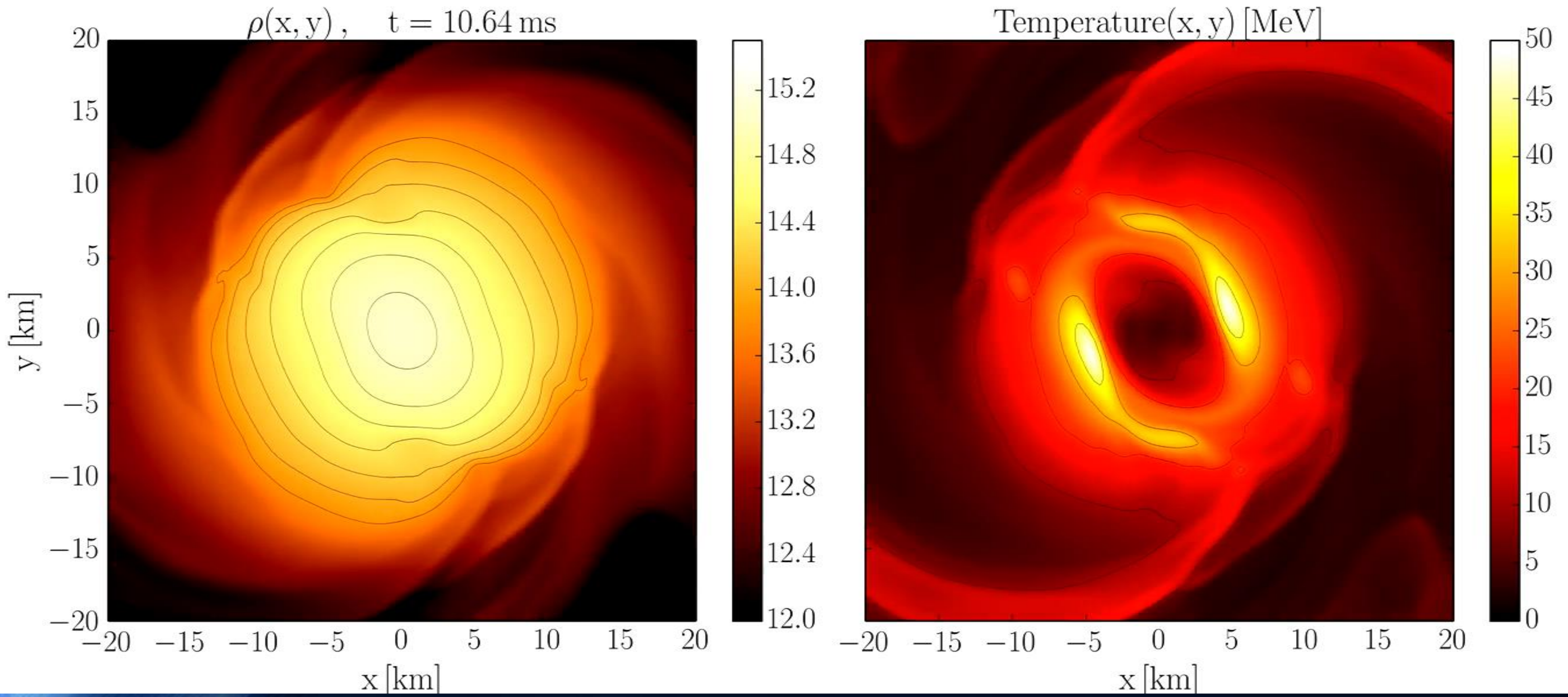


Temperature



M. Hanauske, J. Steinheimer, L. Bovard, A. Mukherjee, S.Schramm, K. Takami, J.Papenfort, N.Wechselberger, L.Rezzolla, Luciano and H.Stöcker; "Concluding Remarks: Connecting Relativistic Heavy Ion Collisions and Neutron Star Mergers by the Equation of State of Dense Hadron-and Quark Matter as signalled by Gravitational Waves"; Journal of Physics: Conference Series, 878(1), p.012031 (2017)

Logarithm of the density   Temperature



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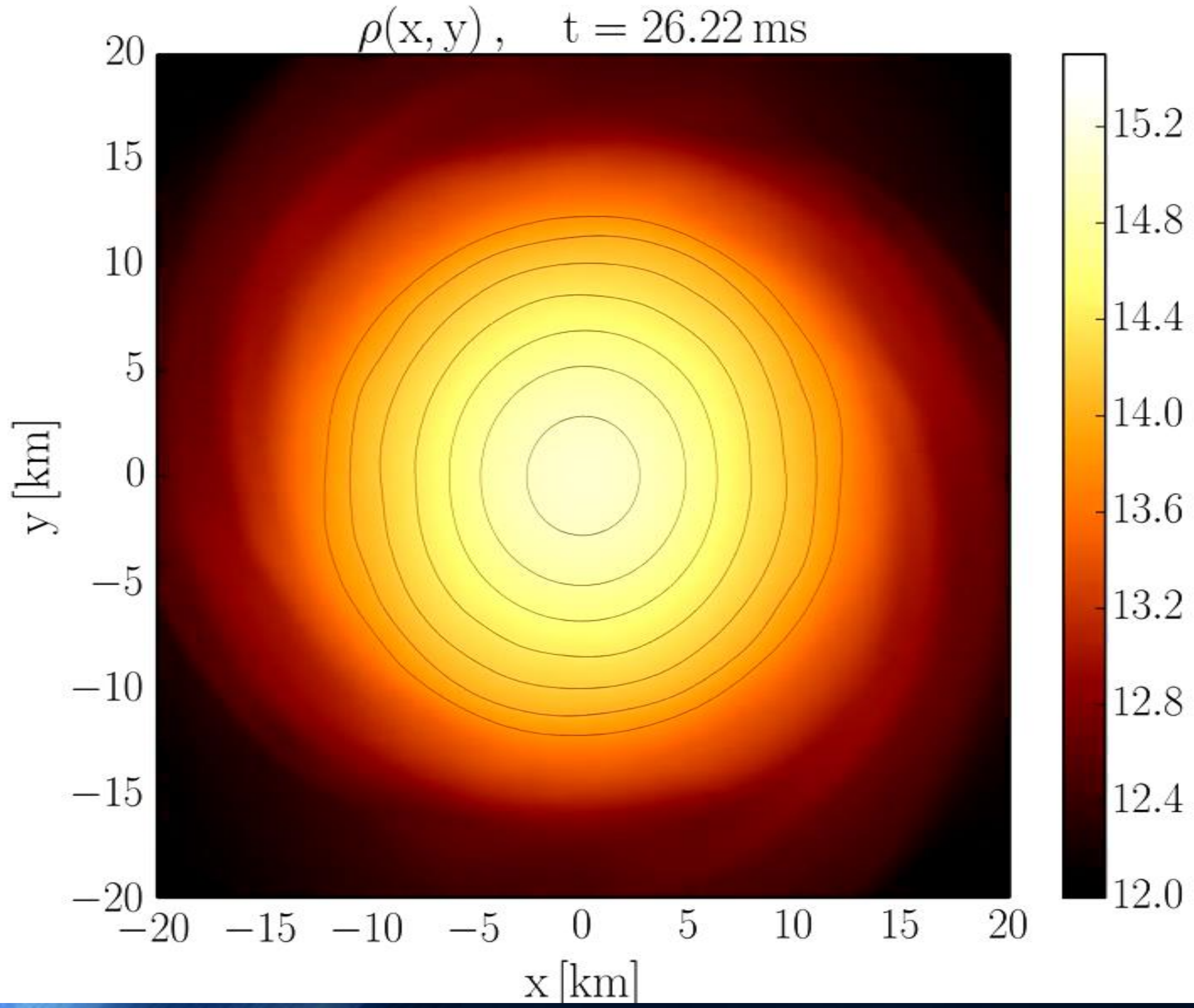
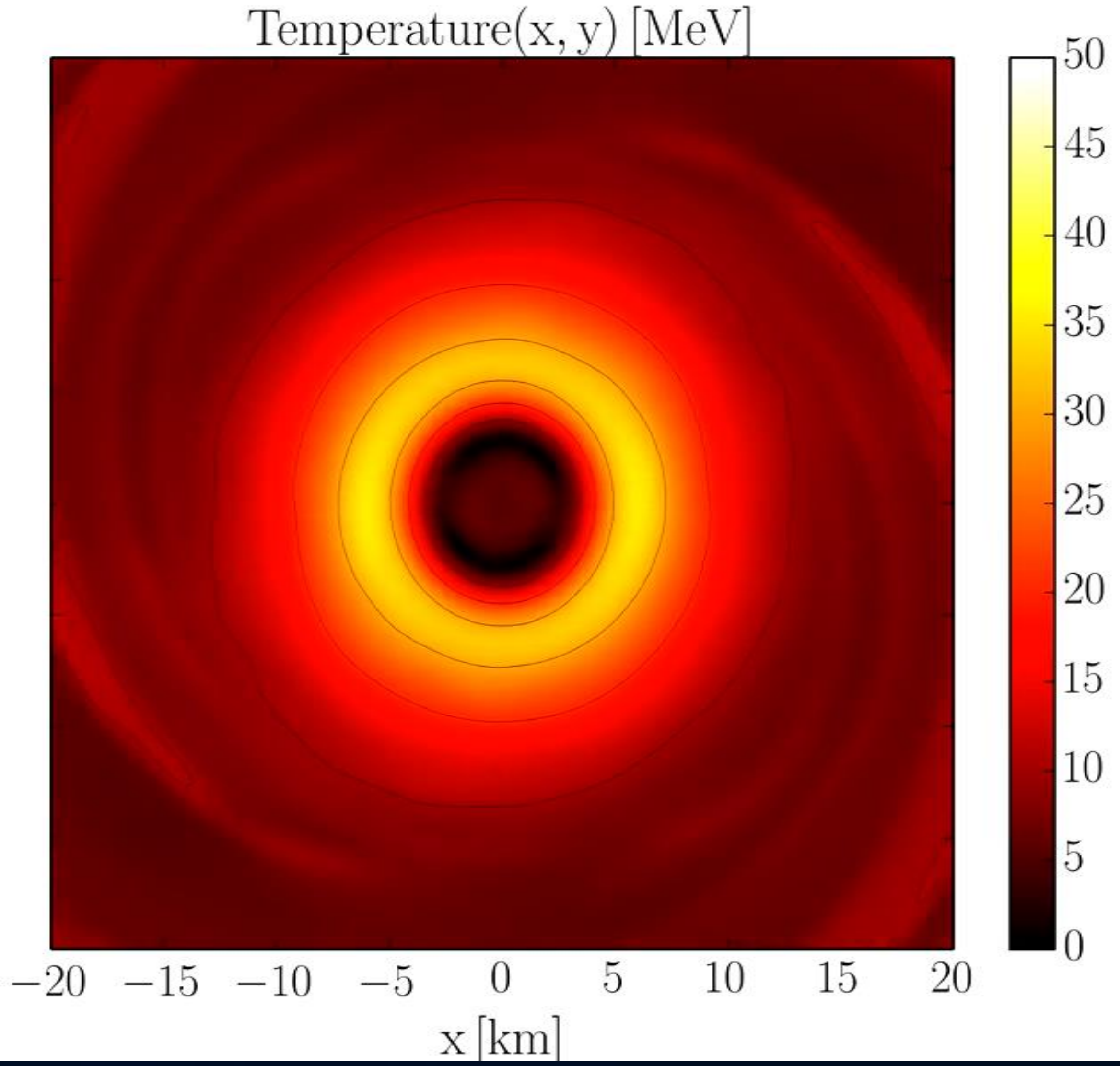
Logarithm of the density Temperature





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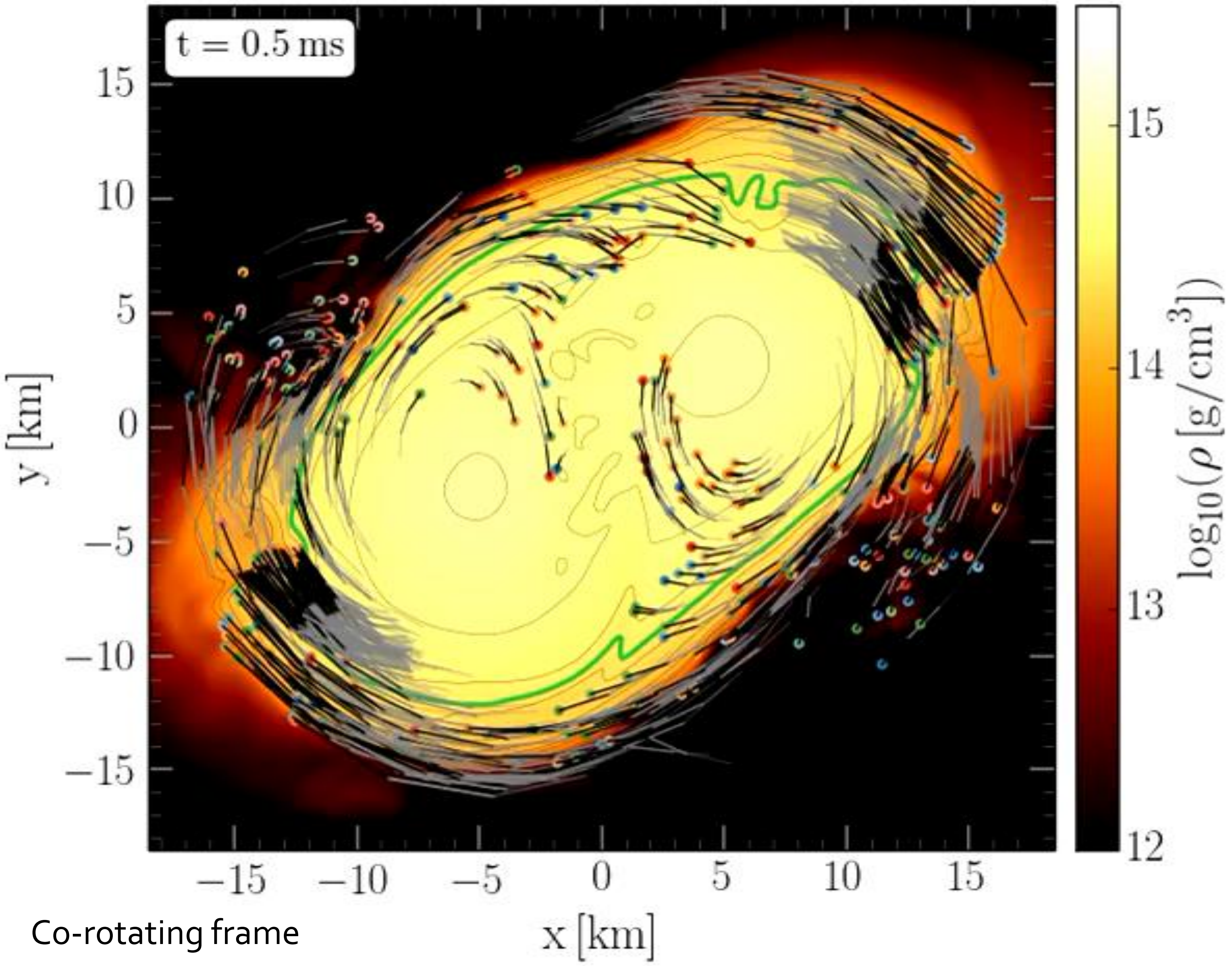
Evolution of Tracer-particles tracking individual fluid elements in the equatorial plane of the HMNS at post-merger times

M.G. Alford, L. Bovard, M. Hanauske, L. Rezzolla and K. Schwenzer
"On the importance of viscous dissipation and heat conduction in binary neutron-star mergers" (submitted to PRL, see arxiv)

Different rotational behaviour of the quark-gluon-plasma produced in non-central ultra-relativistic heavy ion collisions
L. Adamczyk et.al., "Global Lambda-hyperon polarization in nuclear collisions: evidence for the most vortical fluid", Nature 548, 2017



Co-rotating frame

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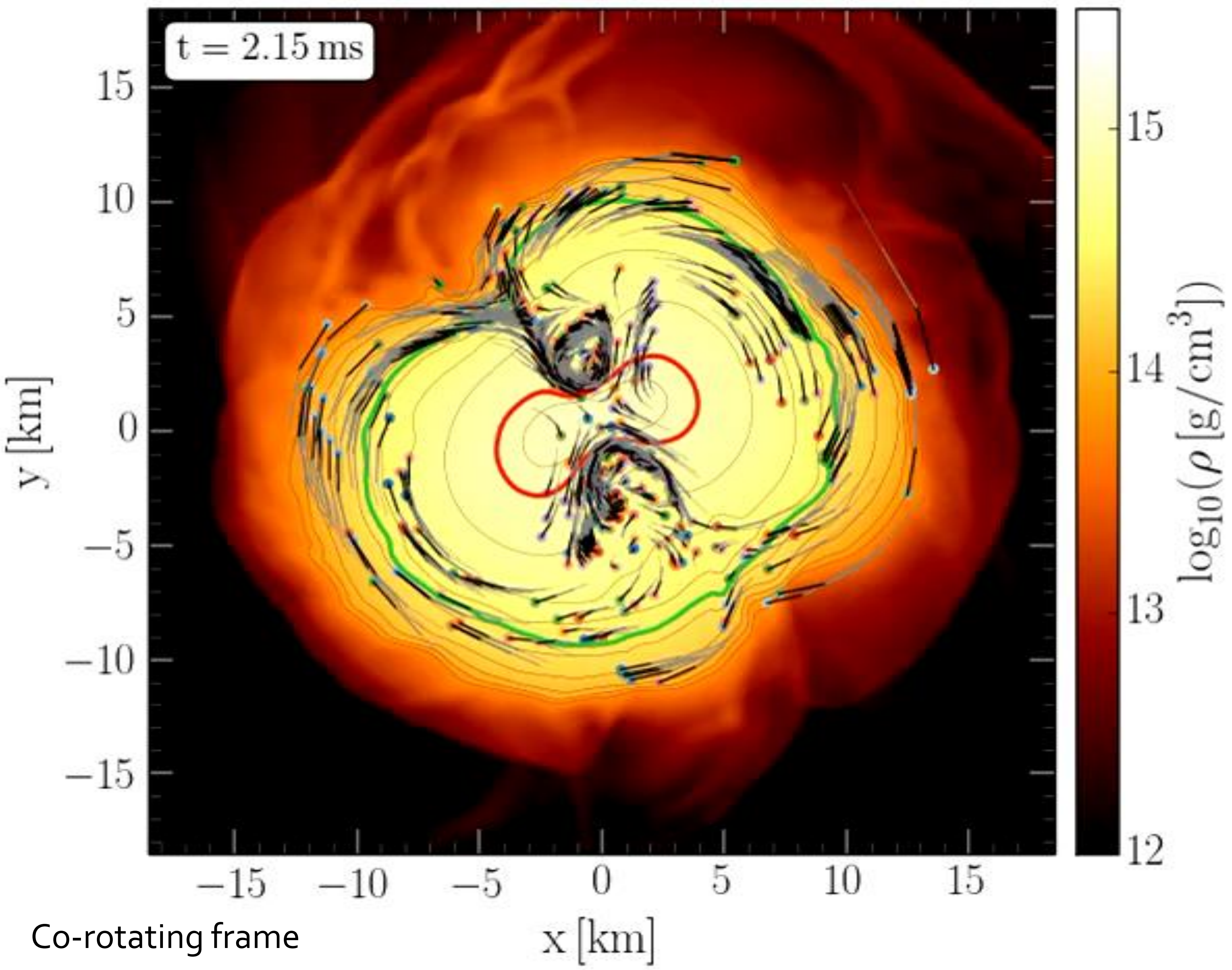

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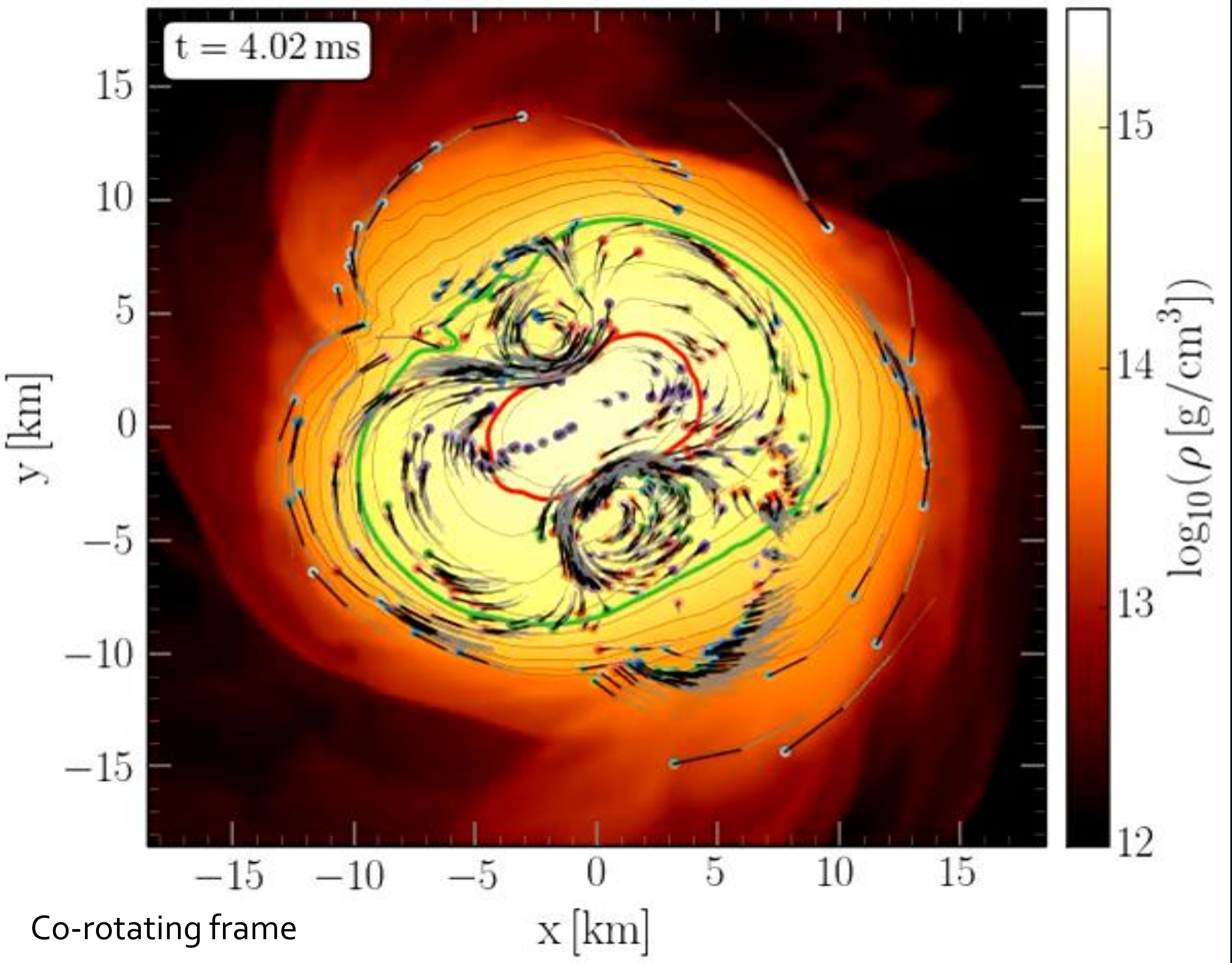

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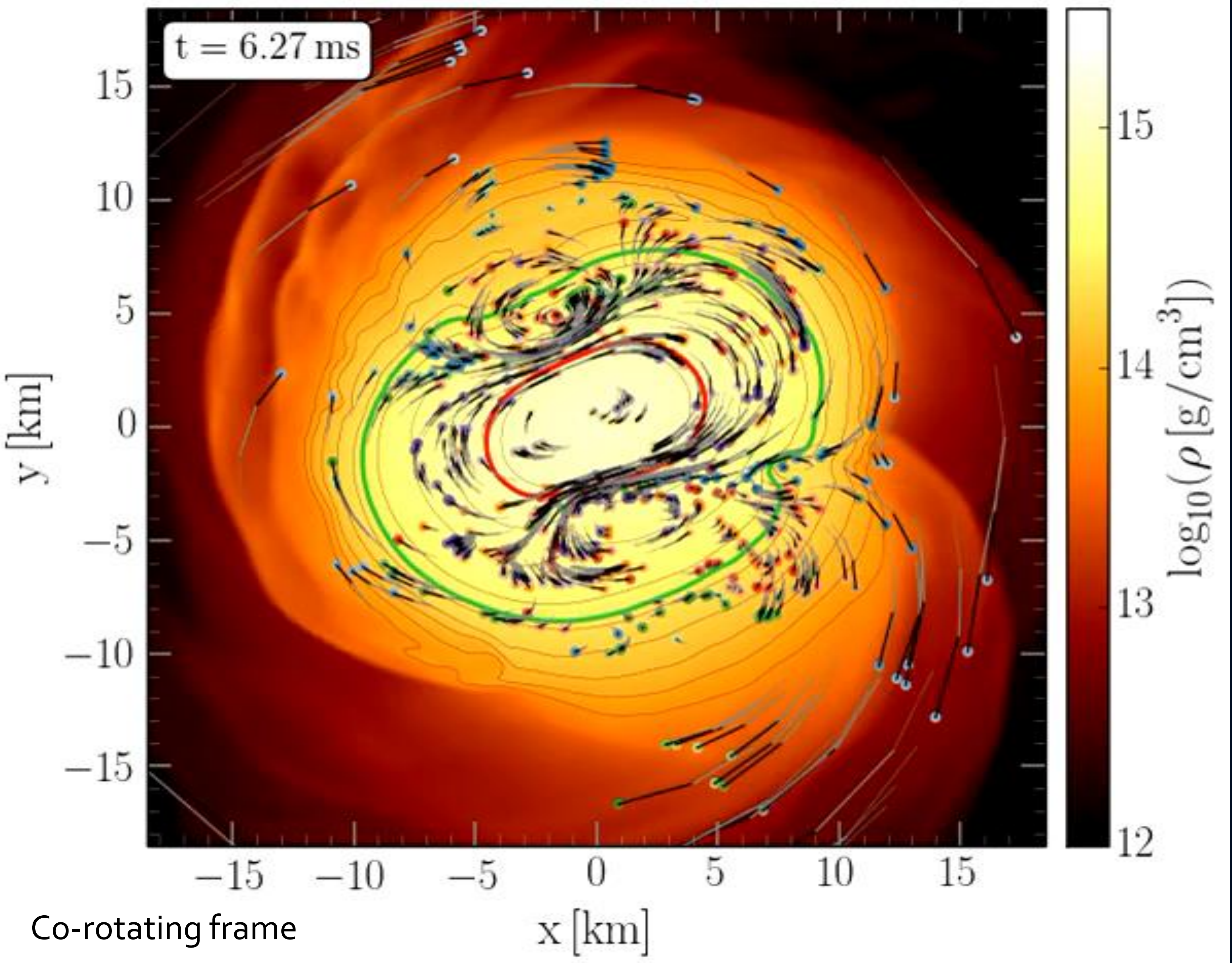

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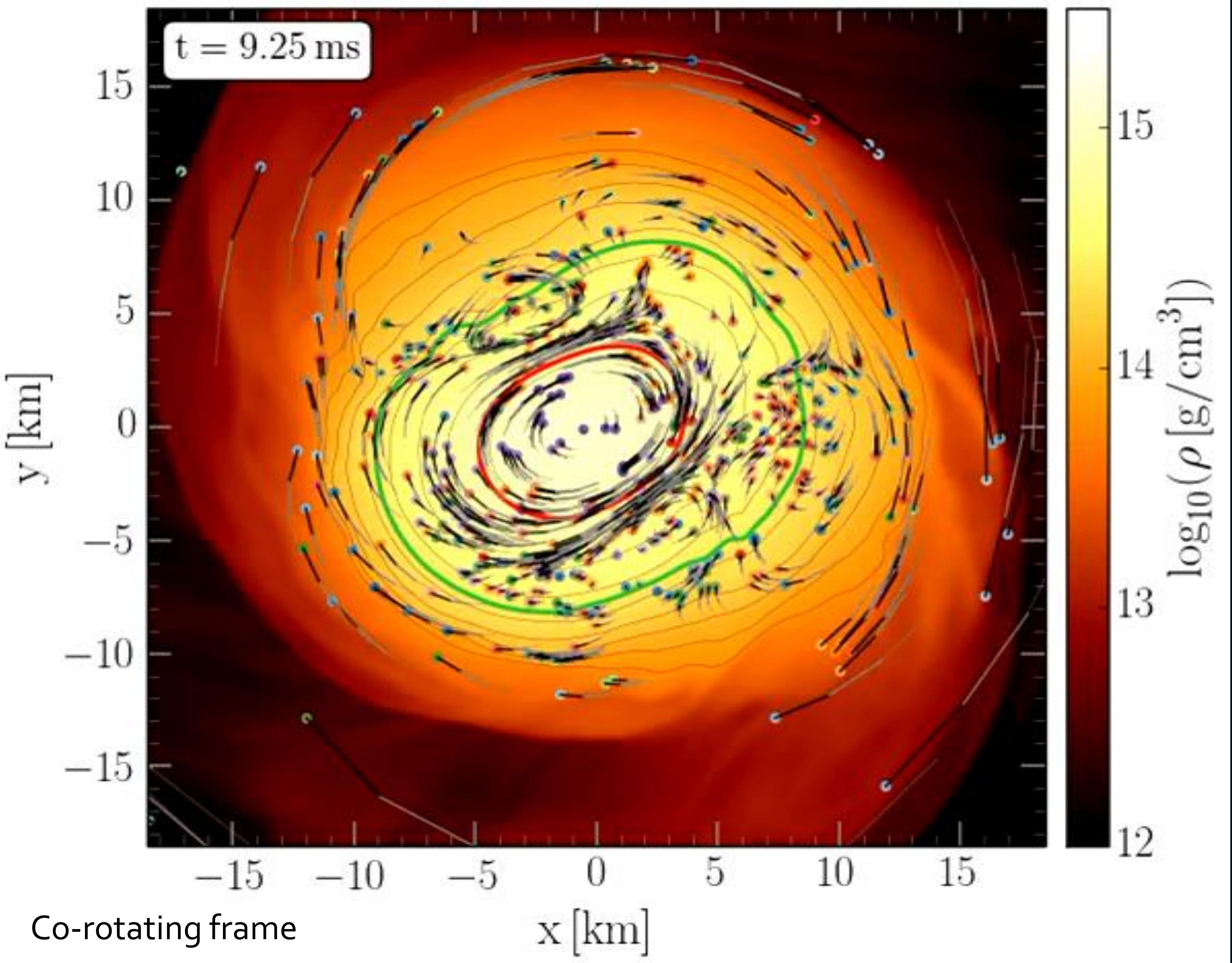

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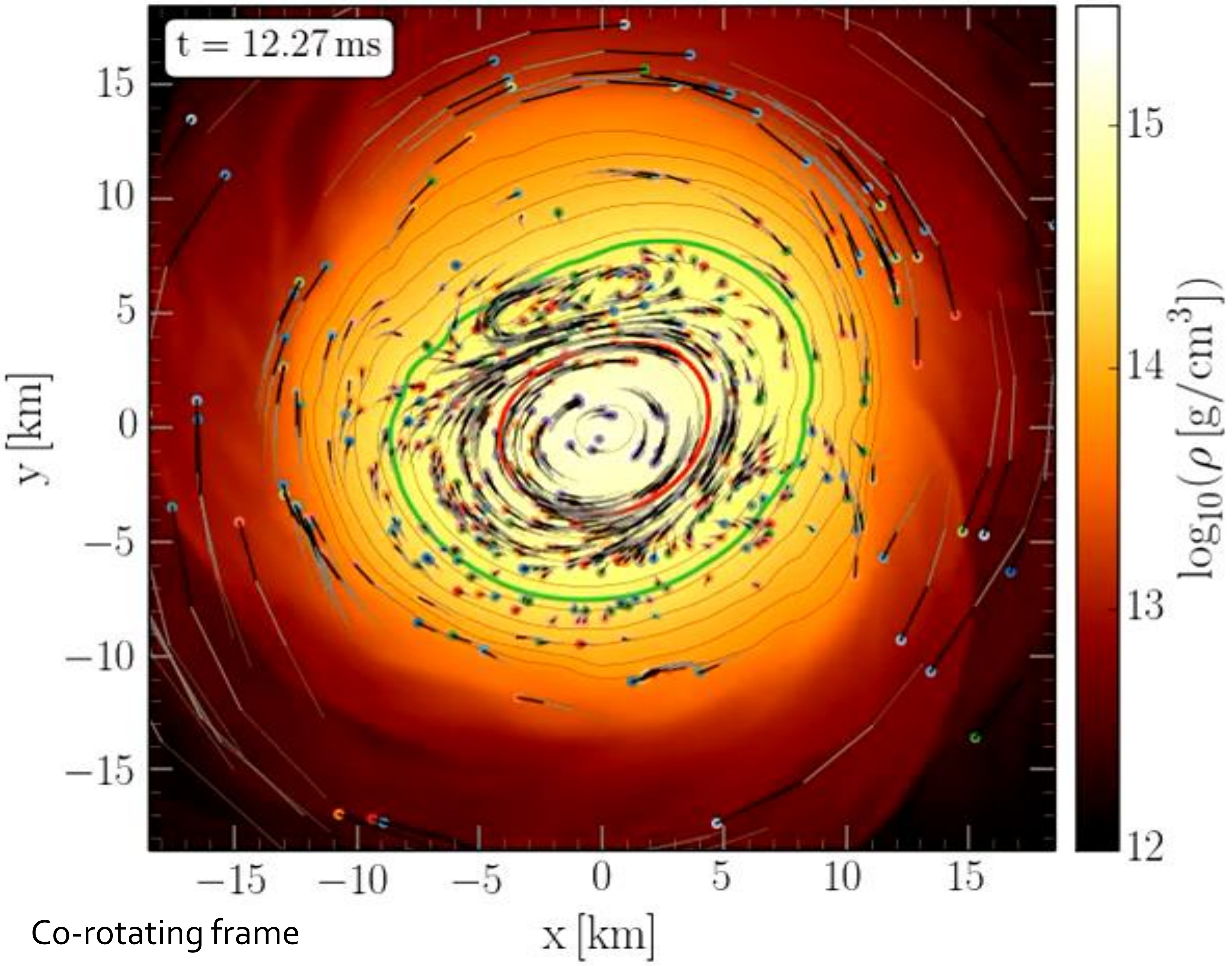
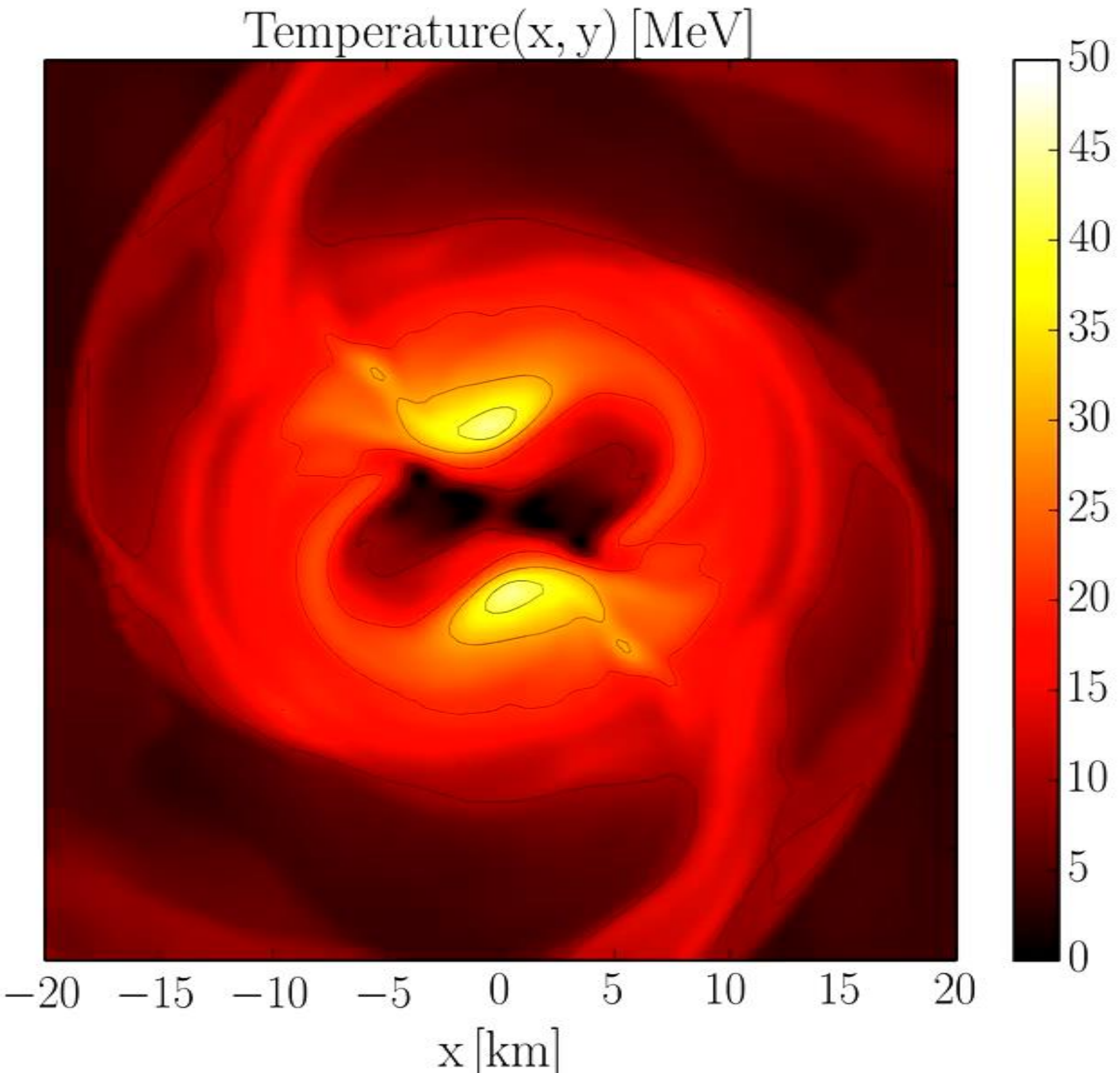
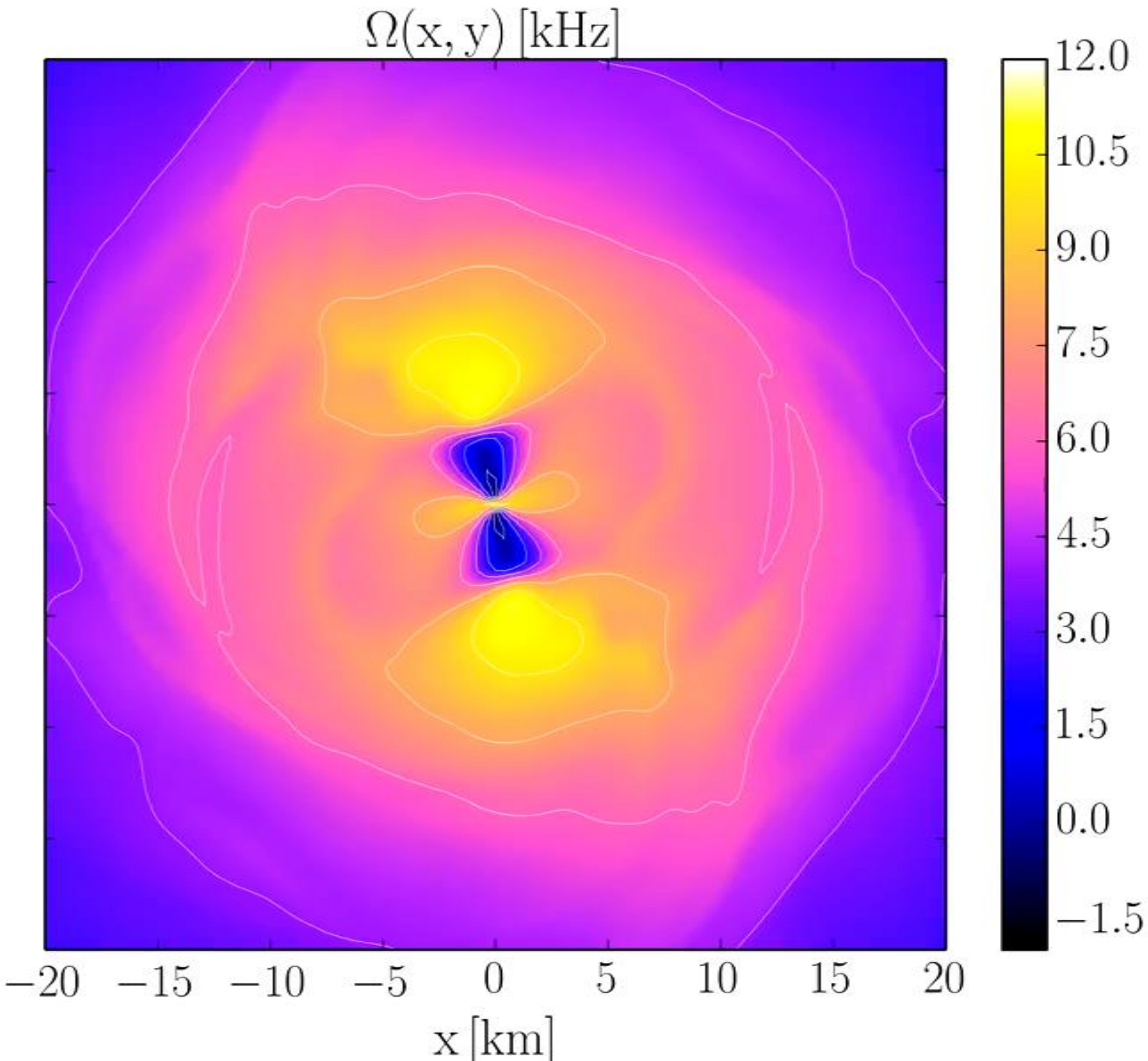


Co-rotating frame

Temperature

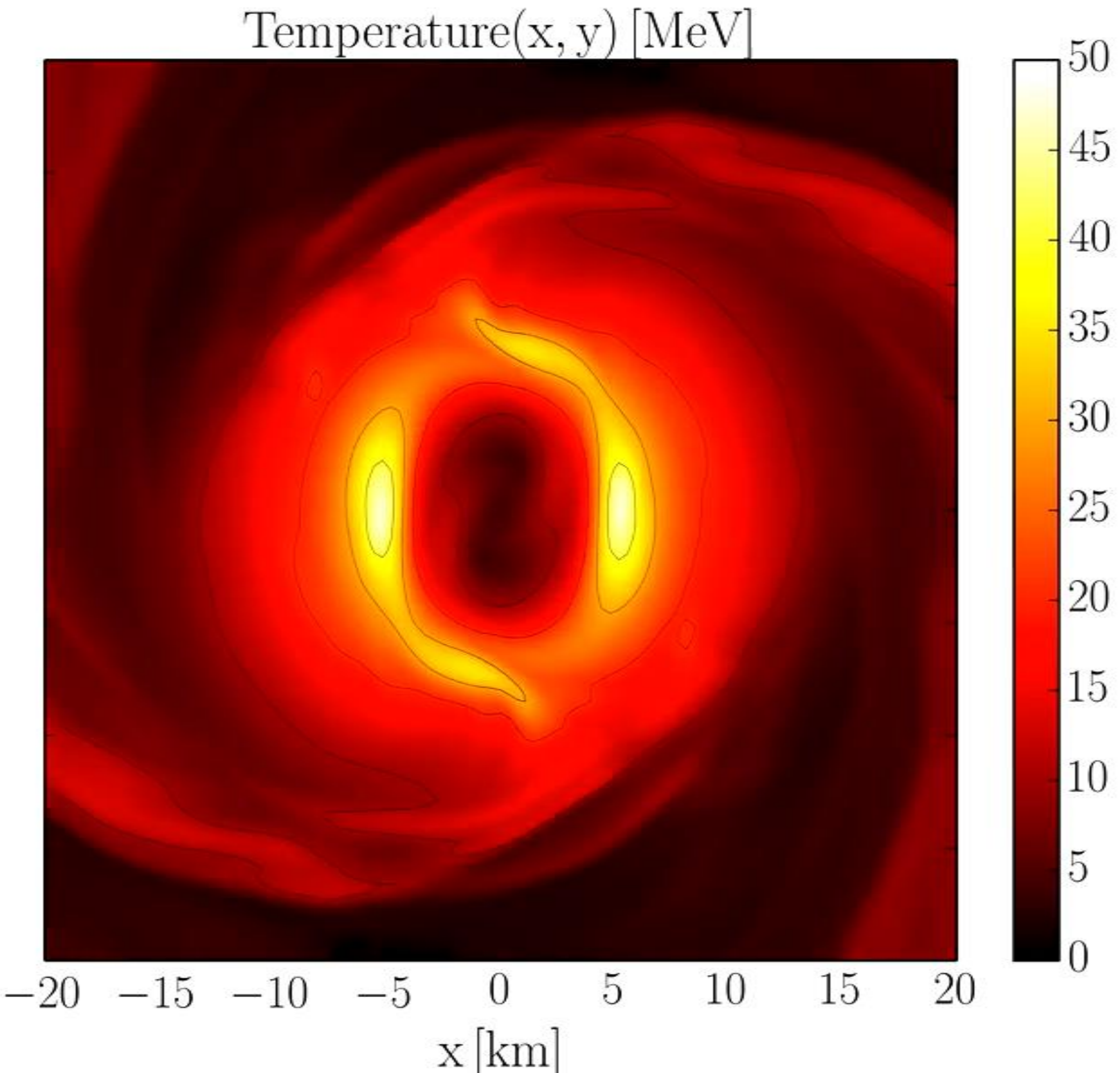


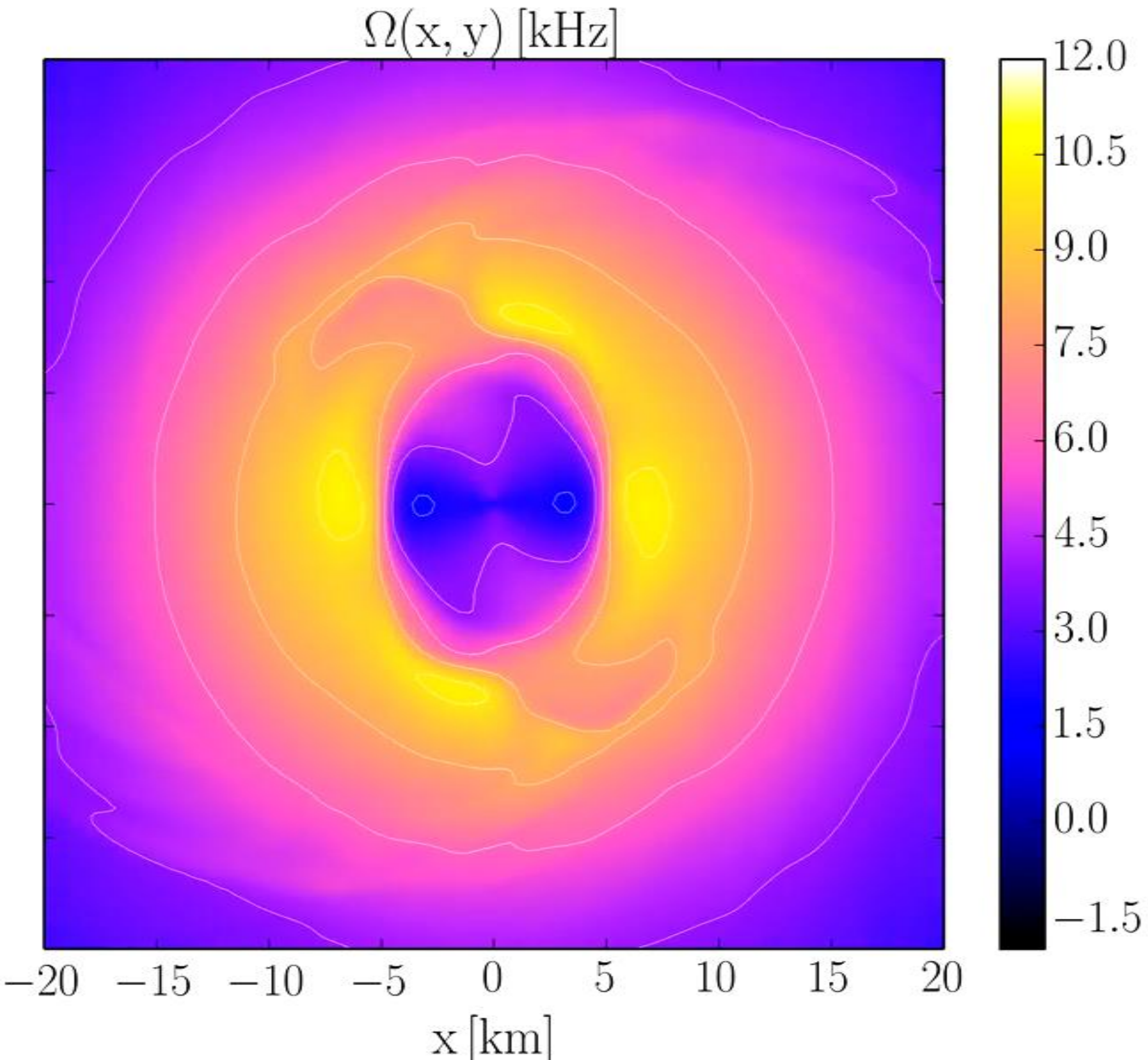
Angular Velocity



Temperature

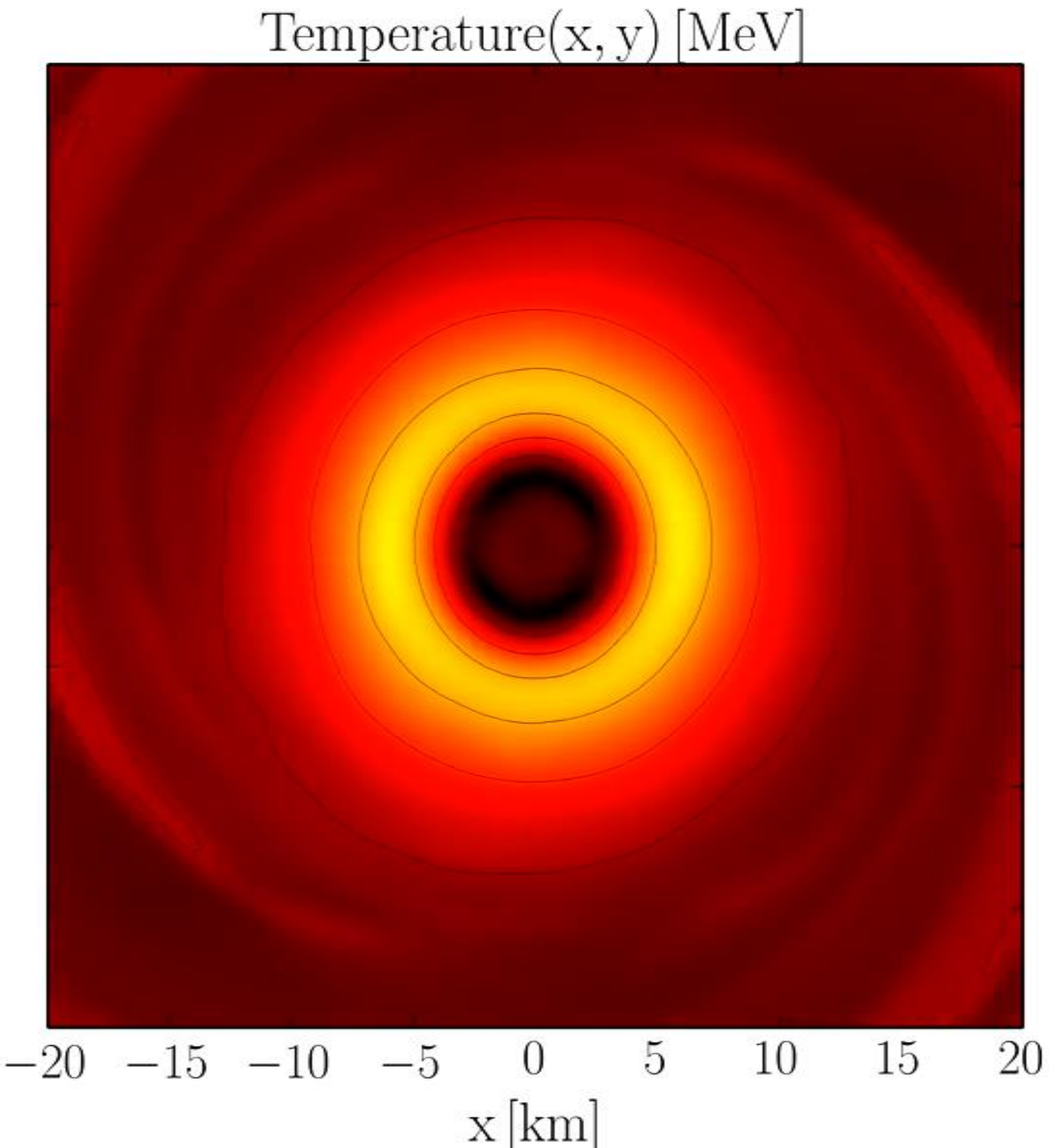
Angular Velocity

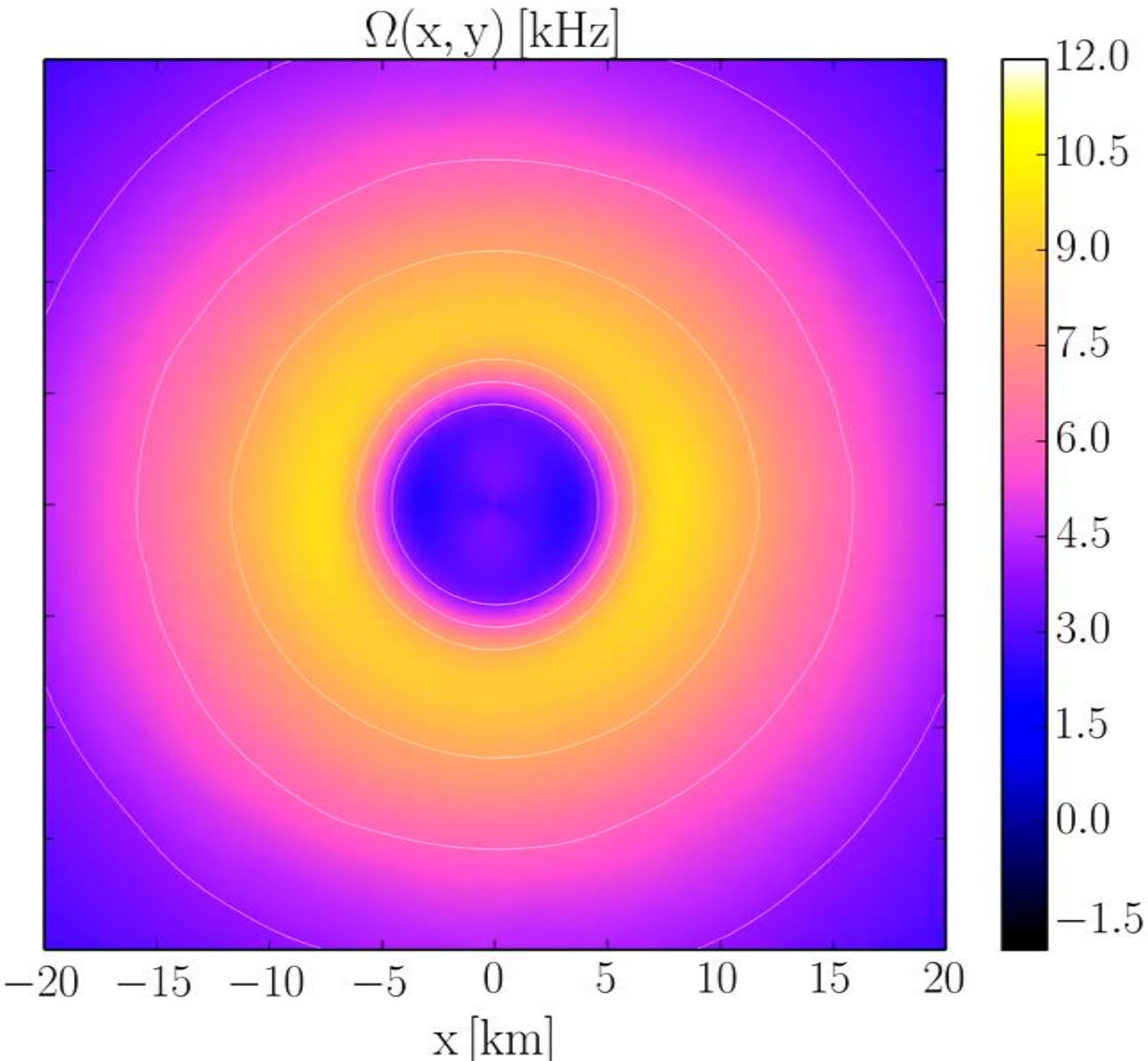




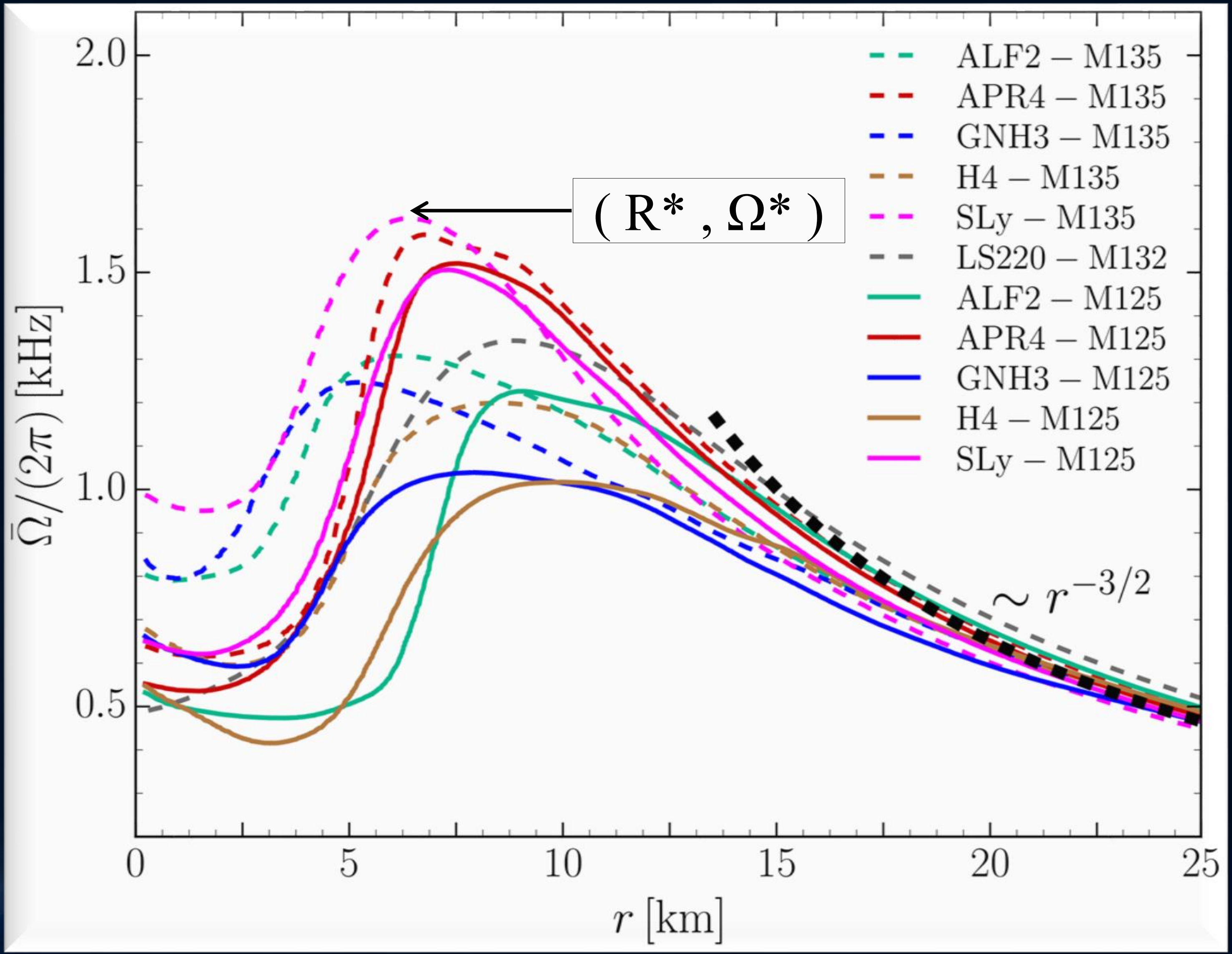
Temperature

Angular Velocity





Time-averaged Rotation Profiles of the HMNSs

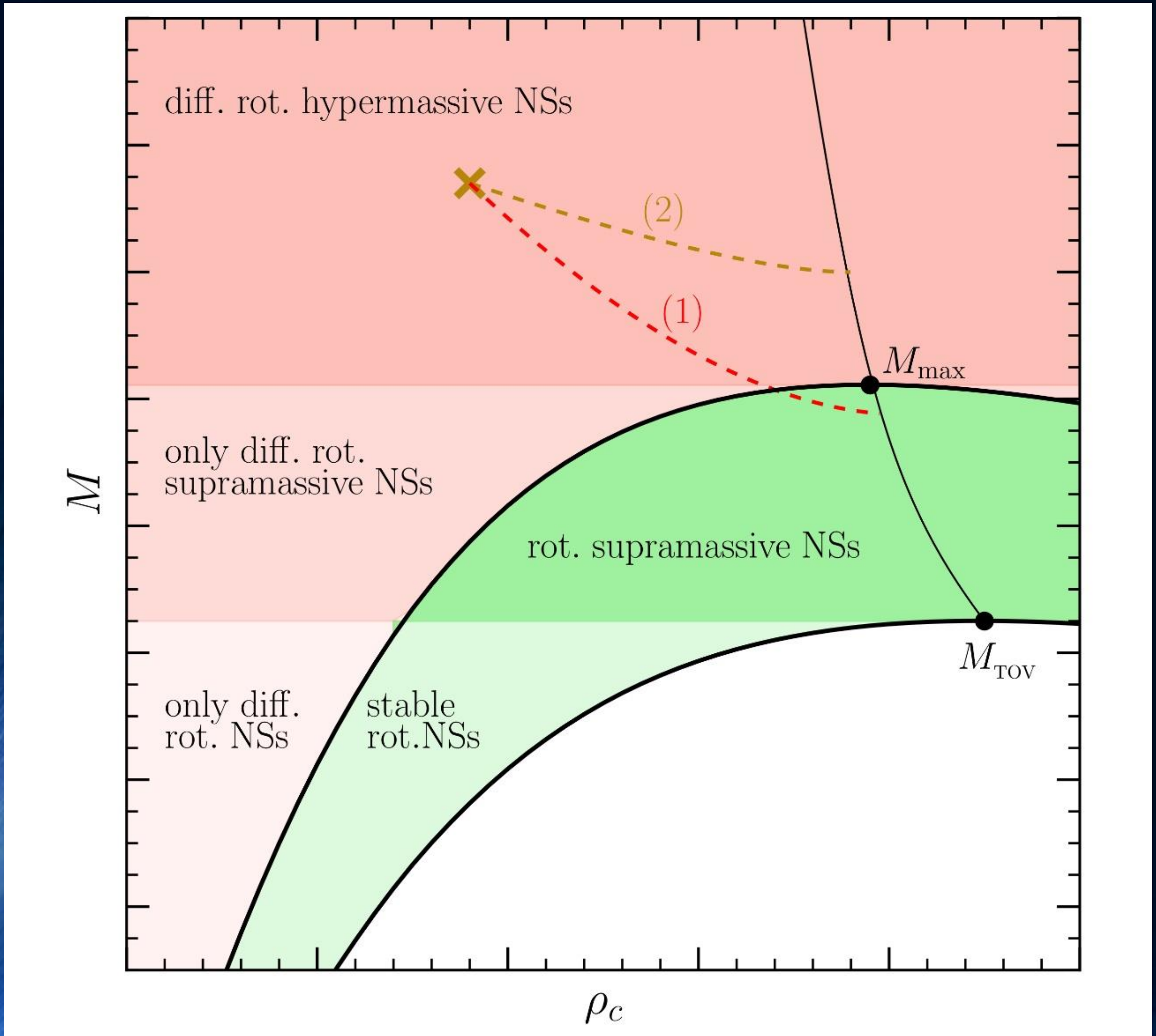


Soft EoSs:
Sly
APR4

Stiff EoSs:
GNH3
H4

Time-averaged rotation profiles for different EoS
Low mass runs (1.25 Msolar, solid curves), high mass runs (1.35 Msolar, dashed curves).

GW170817: Evolution of the HMNS until BH formation

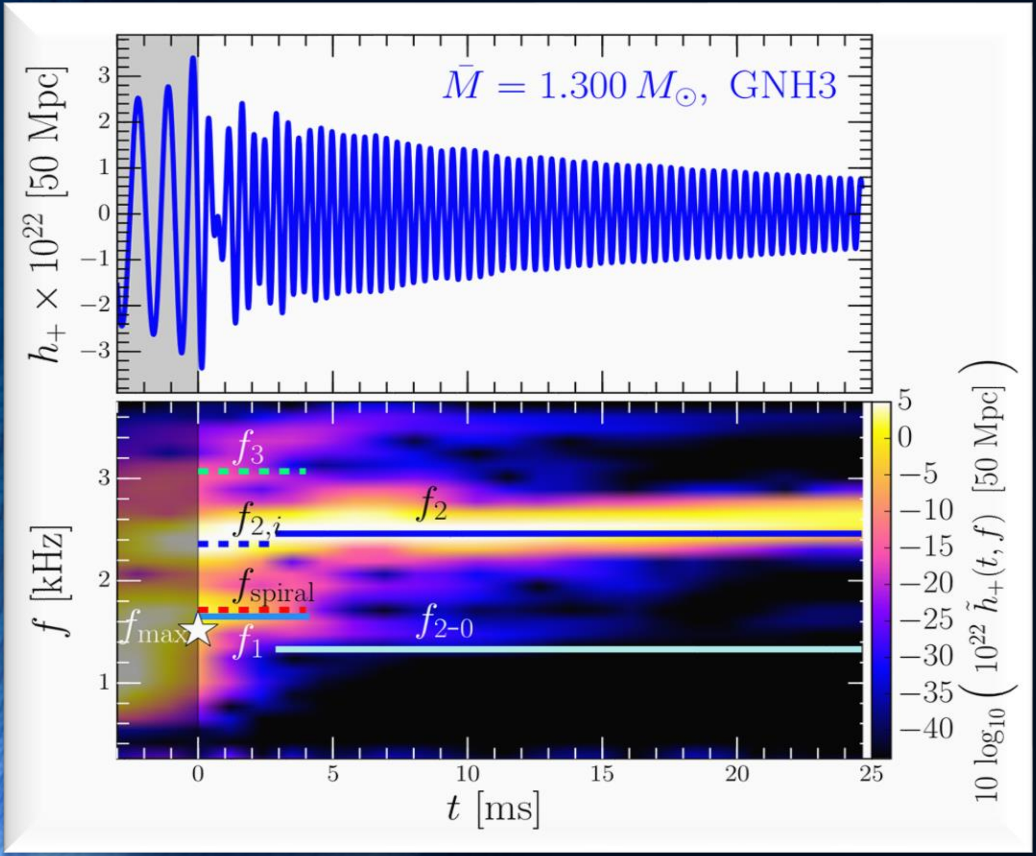


The highly differentially rotating hypermassive/supramassive neutron star will spin down and redistribute its angular momentum (e.g. due to magnetic braking, viscosity effects). After ~1 second it will cross the stability line as a uniformly rotating supramassive neutron star (close to M_{max}) and collapse to a black hole. Parts of the ejected matter will fall back into the black hole producing the gamma-ray burst.

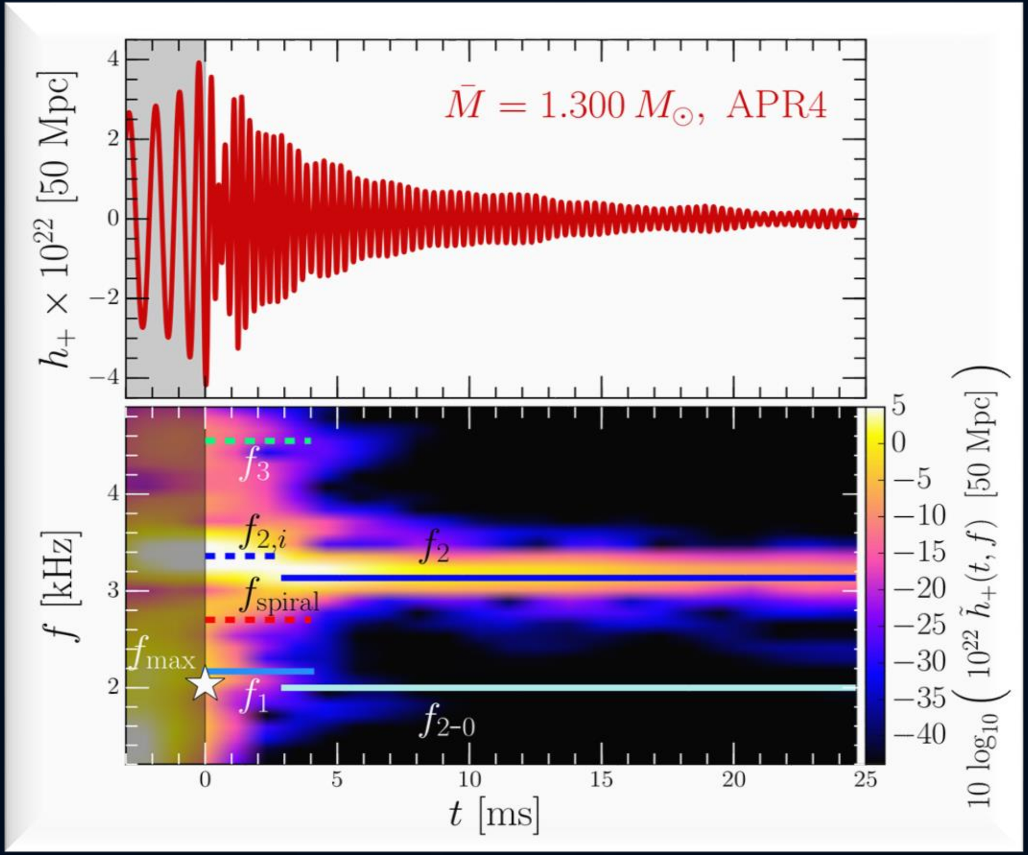
Constraining the Maximum Mass and the EOS
L.Rezzolla, E.Most and L.Weih
(arXiv:1711.00314v1, 1 Nov 2017)

Time Evolution of the GW-Spectrum

The power spectral density profile of the post-merger emission is characterized by several distinct frequencies f_{max}, f_1, f_2, f_3 and f_{2-0}. After approximately 5 ms after merger, the only remaining dominant frequency is the f_2-frequency (See L.Rezzolla and K.Takami, arXiv:1604.00246)



Stiff EOS



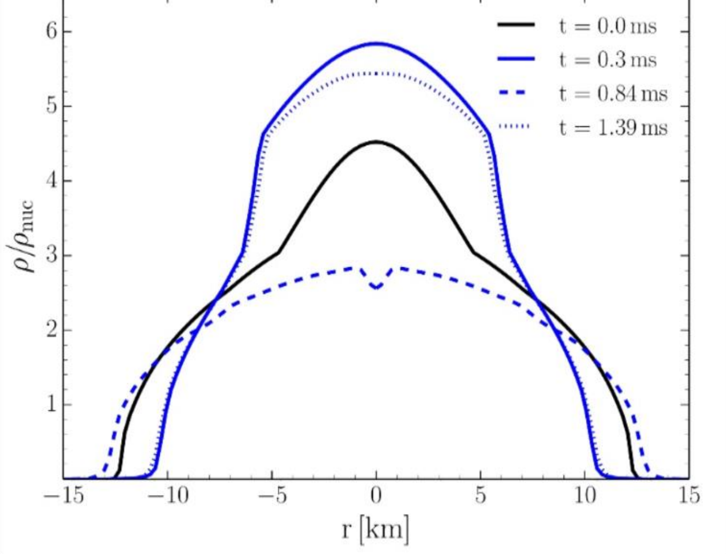
Soft EOS

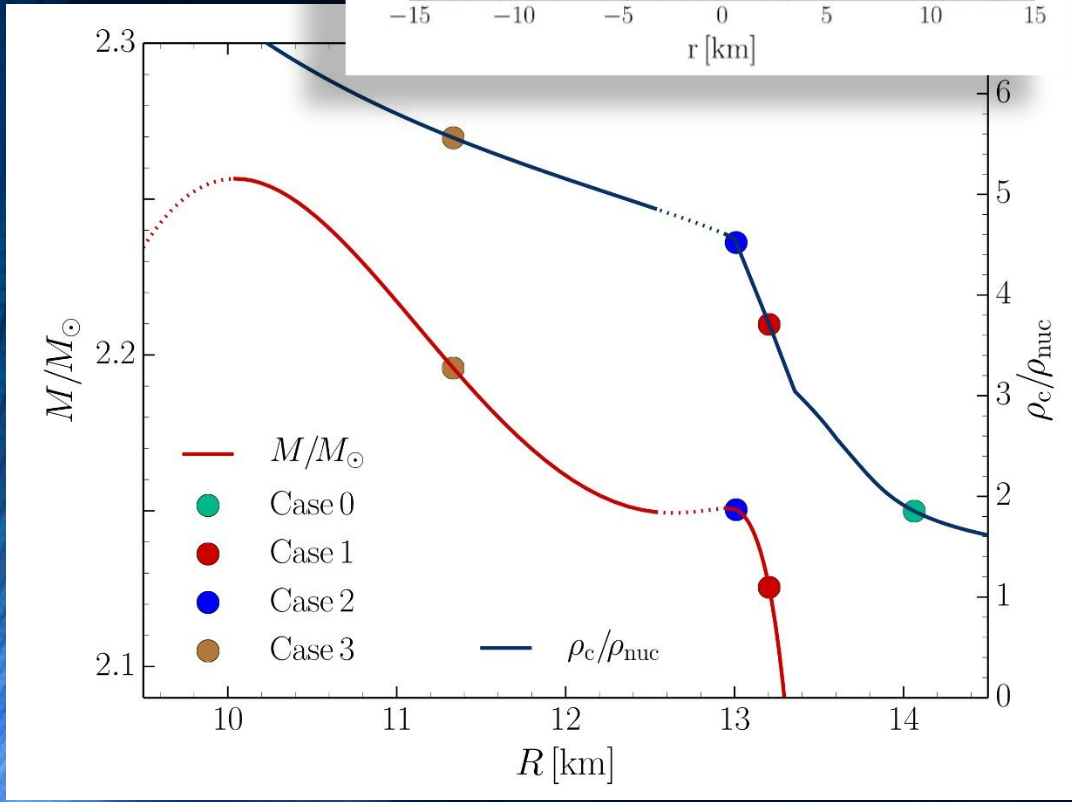
Unfortunately, due to the low sensitivity at high gravitational wave frequencies, no post-merger signal has been found in GW170817.

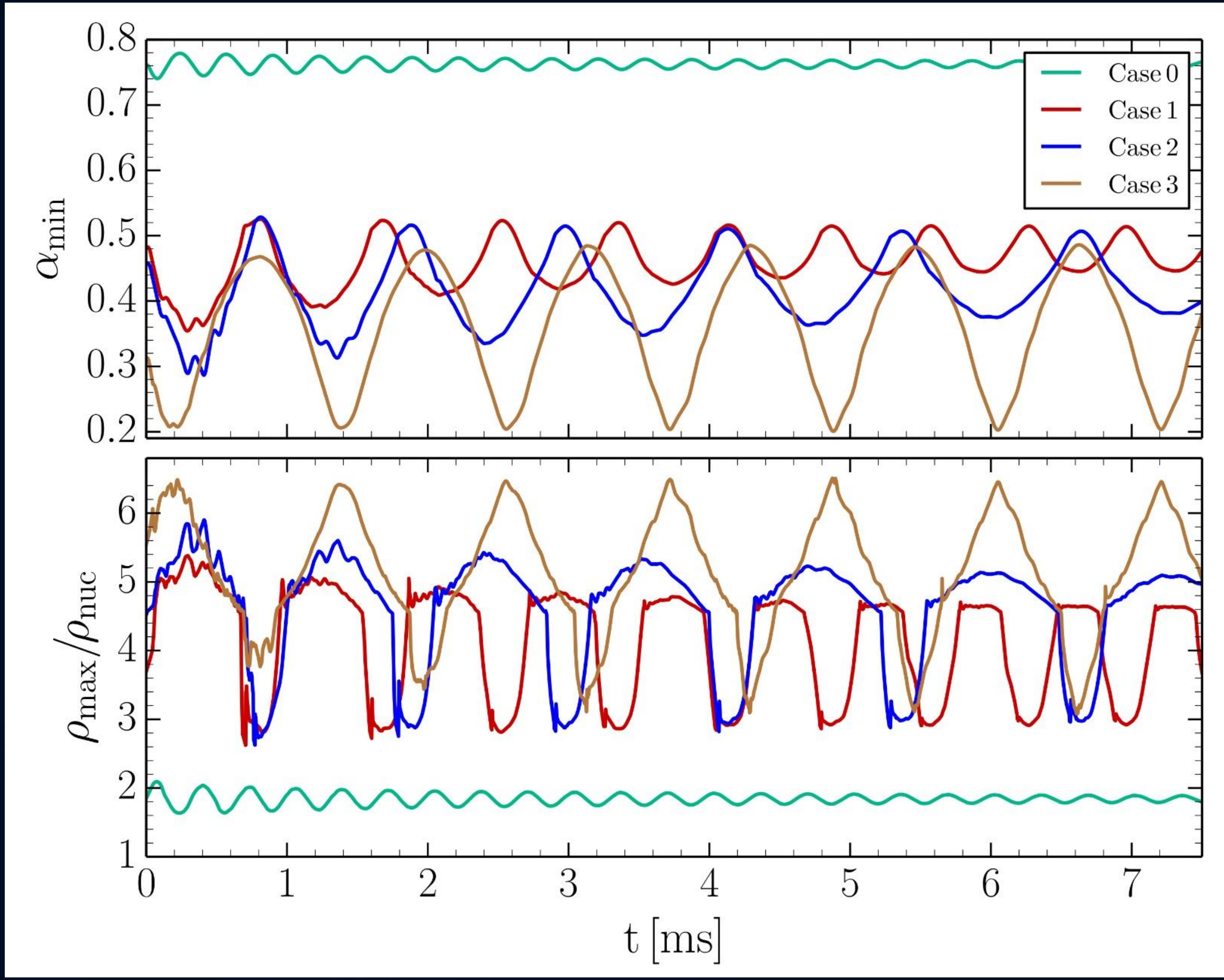
But advanced detectors / next-generation detectors will be able to detect!

Evolution of the frequency spectrum of the emitted gravitational waves for the stiff GNH3 (left) and soft APR4 (right) EOS.

The Twin Star collapse



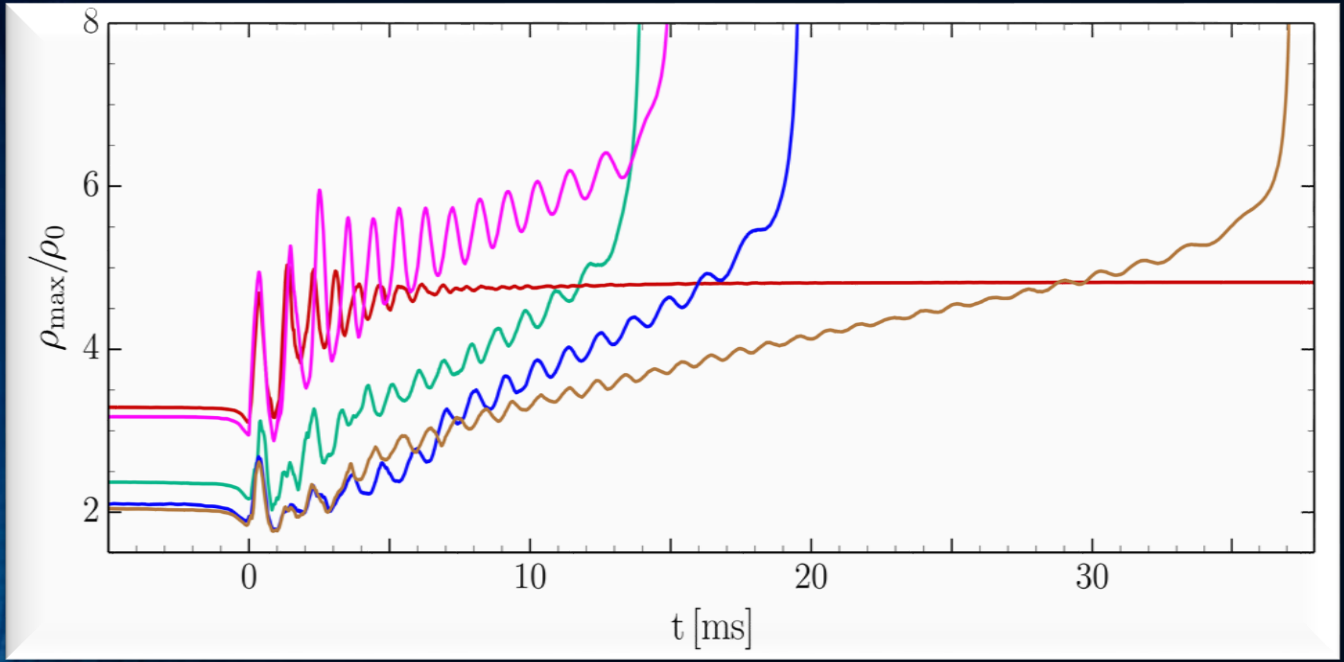


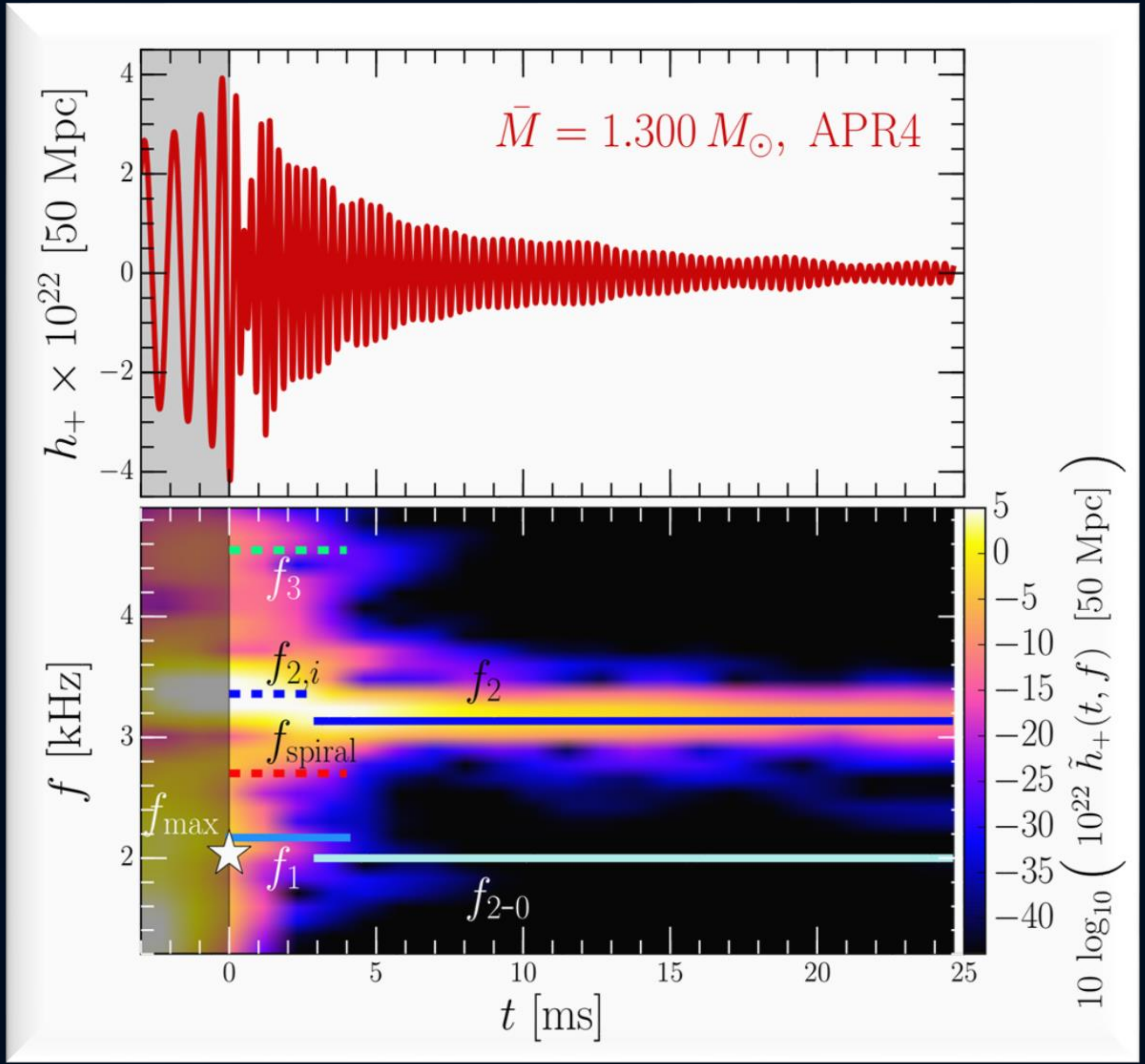


Radial oscillations of twin star configurations

M. Hanauske, Z.S. Yilmaz, C. Mitropoulos, L. Rezzolla and H. Stöcker
"Gravitational waves from binary compact star mergers in the context of strange matter", in Proceedings SQM2017

How to observe the QGP with gravitational waves from NS mergers?





The appearance of the hadron-quark phase transition in the interior region of the HMNS will change the spectral properties of the emitted GW if it is strong enough. If the unstable twin star region will be reached during the "post-transient" phase, the f2-frequency peak of the GW signal will change rapidly due to the sudden speed up of the differentially rotating HMNS.

Hybrid star mergers represent optimal astrophysical laboratories to investigate the QCD phase structure and in addition with the observations from heavy ion collisions it will be possibly reach a conclusive picture on the QCD phase structure at high density and temperature.

Summary

- On August 17, 2017, a long-awaited event has taken place: the Advanced LIGO and Virgo gravitational-wave detectors have recorded the signal from the inspiral and merger of a binary neutron-star system.
- The analysis of the gravitational wave data in combination with the independently detected gamma-ray burst and electromagnetic counterpart results in a neutron star merger scenario which is in good agreement with numerical simulations of binary neutron star mergers performed in full general relativity.
- During the post-merger phase, the value of central rest-mass density will reach extreme values and it is expected that a hadron-quark phase transition will be present in the interior region of the HMNS.
- Astrophysical observables of the hadron-quark phase transition may be detectable when advanced gravitational wave detectors reach design sensitivity or with next-generation detectors.