Title: General Relativistic Simulations of Binary Neutron Star Mergers

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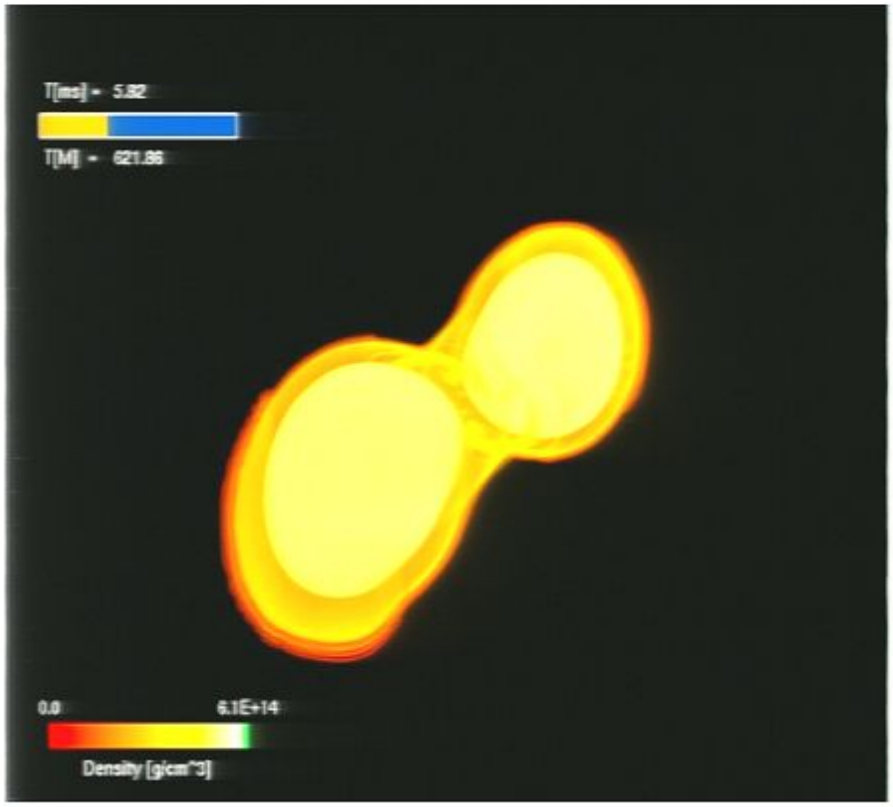
Abstract: Binary neutron stars are among the most important sources of gravitational waves which are expected to be detected by the current or next generation of gravitational wave detectors, such as LIGO and Virgo, and they are also thought to be at the origin of very important astrophysical phenomena, such as short gamma-ray bursts. In order to describe the dynamics of these events one needs to solve the full set of general relativistic magnetohydrodynamics equations through the use of parallel numerical codes. I will report on some recent results obtained with the use of the fully general relativistic magnetohydrodynamic code Whisky in simulating binary neutron stars which inspiral and merge forming an hypermassive neutron star which eventually collapses to form a black hole surrounded by a torus. I will in particular describe how mass, equation of state and magnetic fields can affect the dynamics and consequently the gravitational waves emitted by these systems and discuss about their possible connection with the formation of short gamma ray bursts.

GR SIMULATIONS OF SINGLE AND BINARY NEUTRON STARS



Bruno Giacomazzo

Department of Astronomy, University of Maryland, USA

NASA Goddard Space Flight Center USA

PLAN OF THE TALK

- Introduction

- GWs from neutron star collapse
  - Uniformly rotating NSs
  - Differentially rotating NS

- GWs from equal-mass binary neutron stars
  - The role of the mass and of the EOS
  - The role of magnetic fields

- Unequal-mass binary neutron star mergers
  - Torus formation and GW emission

- Summary and conclusions

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- Like X-ray and γ-ray astronomy they will open a new window on the universe

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- Numerical relativity can provide templates useful for GW searches (matched filtering techniques)

THE CACTUS AND WHISKY CODES

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Cactus (www.cactuscode.org) is a computational "toolkit" developed at the AEI/CCT/LSU over the last 10 years and provides a general infrastructure for the solution in 3D and on parallel computers of PDEs in general and of the Einstein equations in particular.

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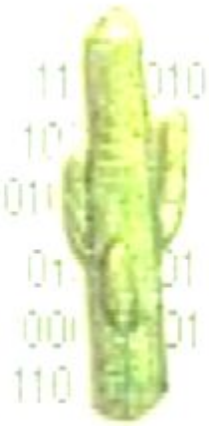

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Whisky (www.whiskycode.org) is a more recent code, initially developed at the AEI and SISSA, for the solution of the general relativistic hydrodynamics and magnetohydrodynamics equations in arbitrary curved spacetimes.

Simulations done with Whisky

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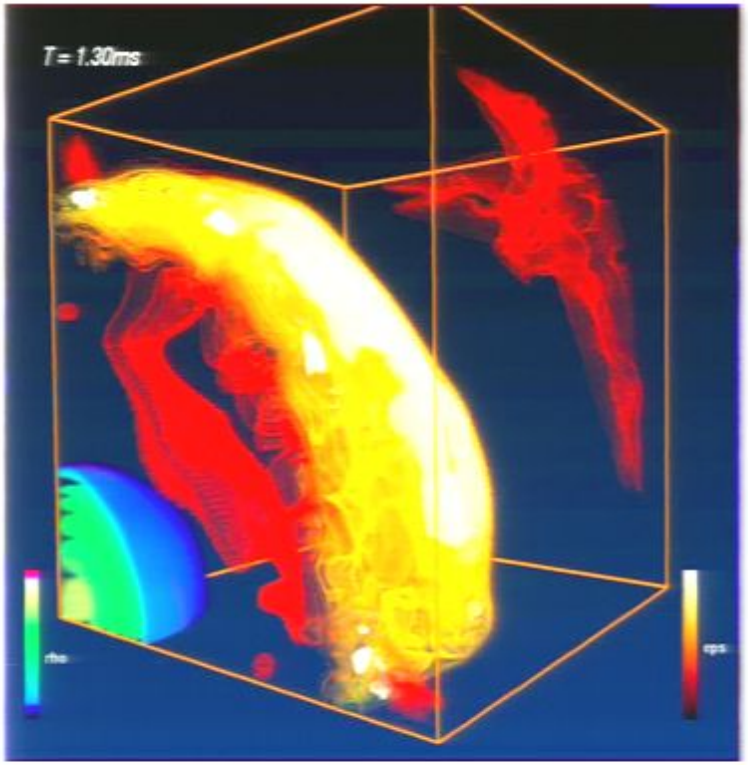
  - Baiotti, Giacomazzo, Pietroniro



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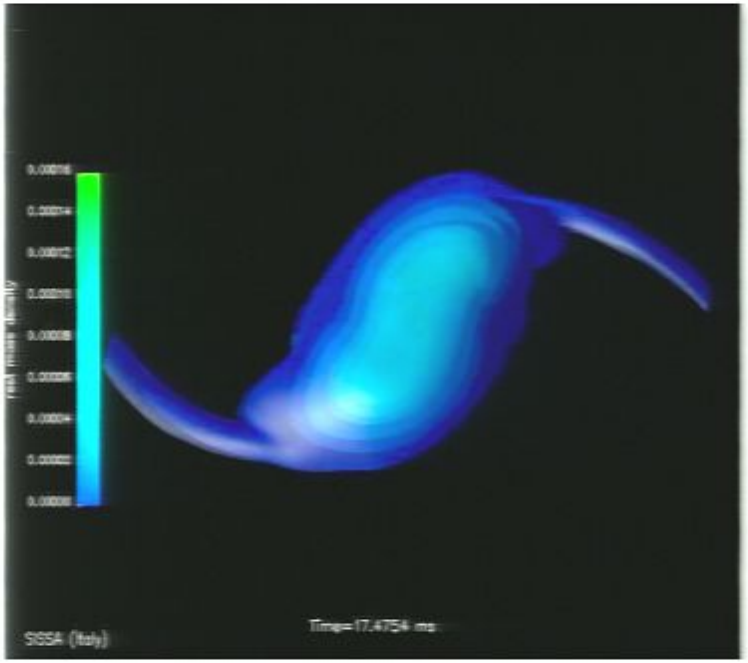

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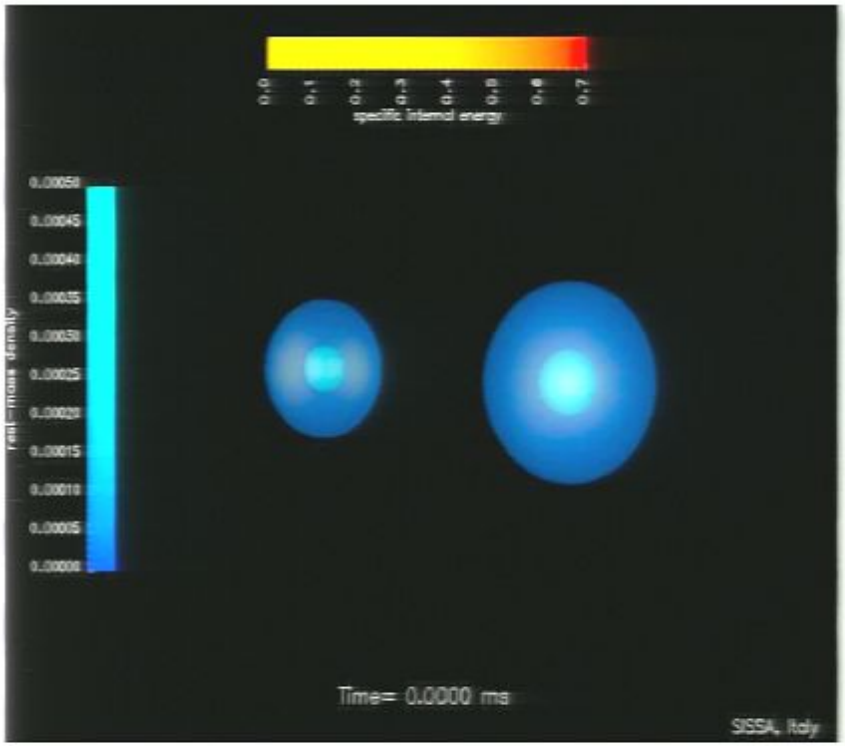

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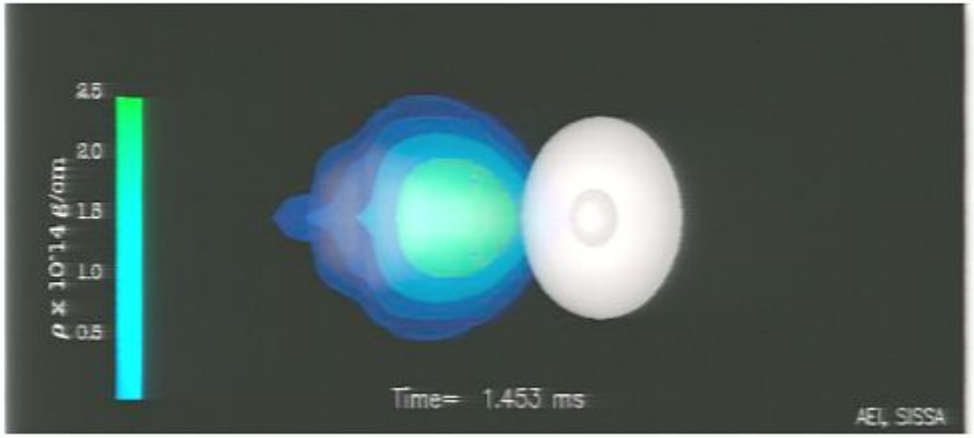

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- Porting to Cactus to [illegible]

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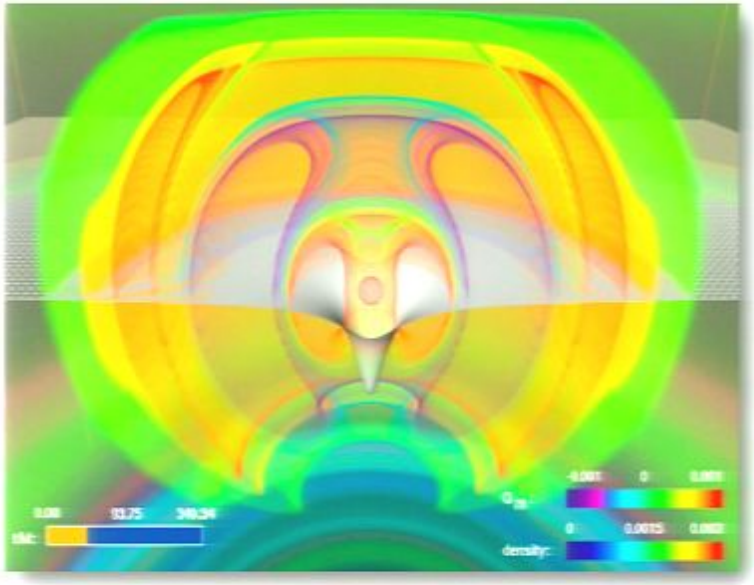

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- o Core-Collapse Supernovae
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- o Matter and EM fields evolution around BBH
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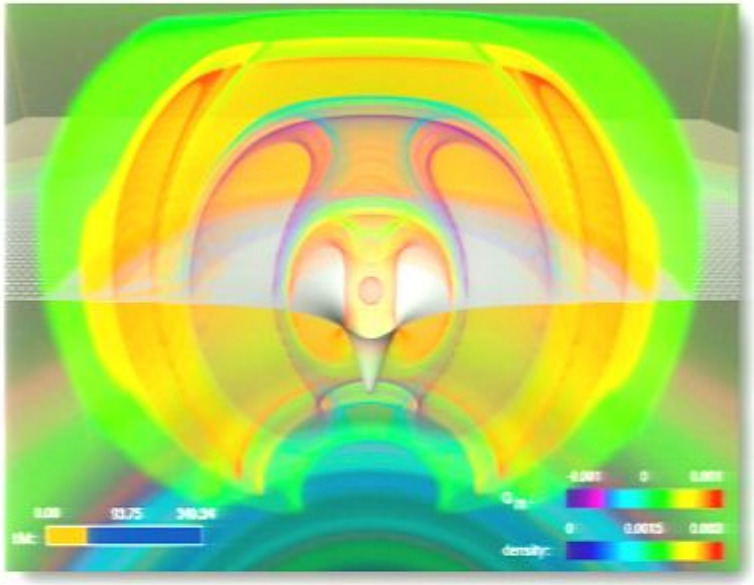
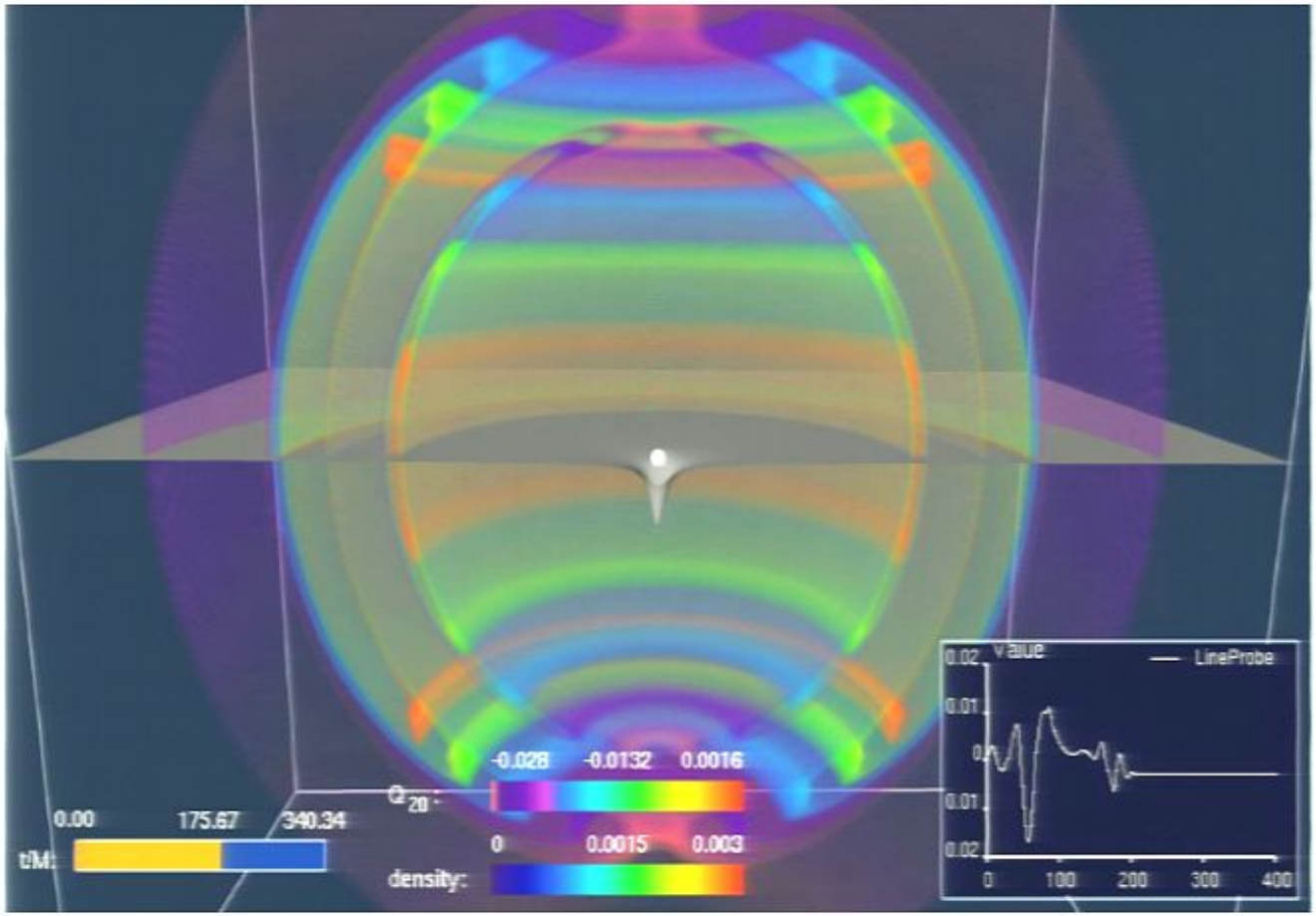


NEUTRON STAR COLLAPSE



- Baiotti, et al., PRD (2005)
- Baiotti, Hawke, Rezzolla, Schnetter, PRL (2005)
- Baiotti, Rezzolla, PRL (2006)
- Baiotti, Hawke, Rezzolla CQG (2007)
- Gizzon, Rezzolla, Stergioulas, in preparation

INITIAL DATA: UNIFORMLY ROTATING NS

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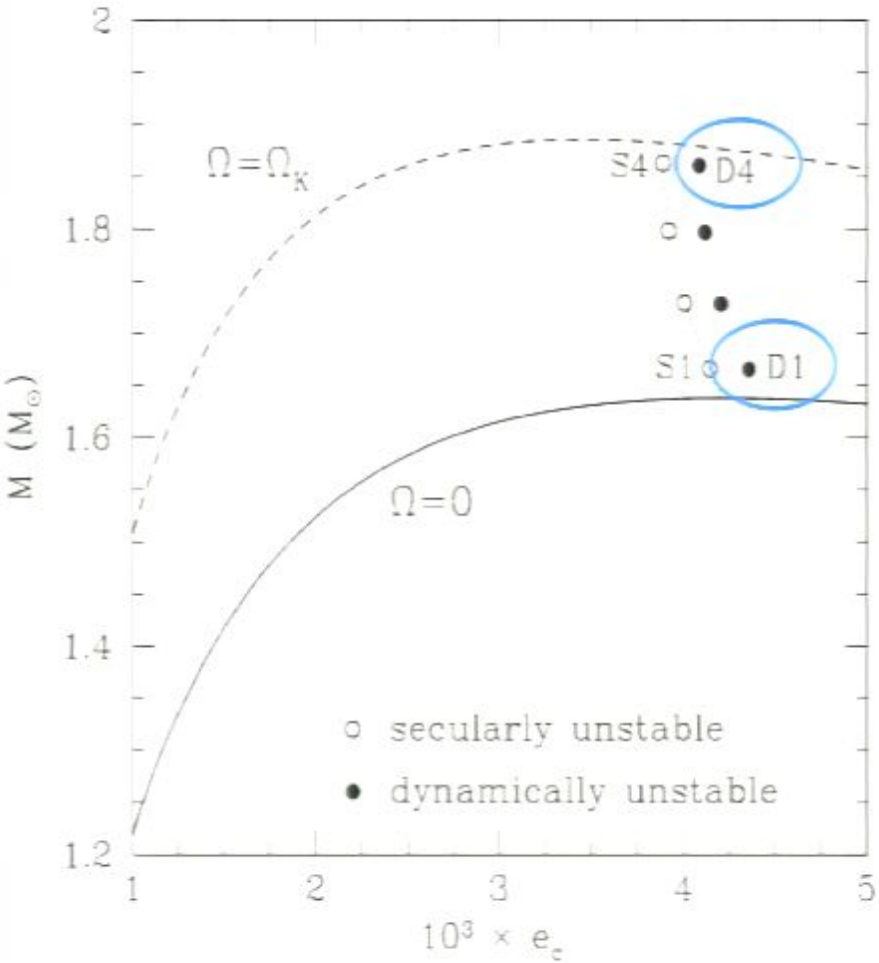


Sequences of uniformly rotating polytropes with constant value of angular momentum, up to the mass-shedding limit, were studied.

For simplicity an ideal fluid EOS was used:

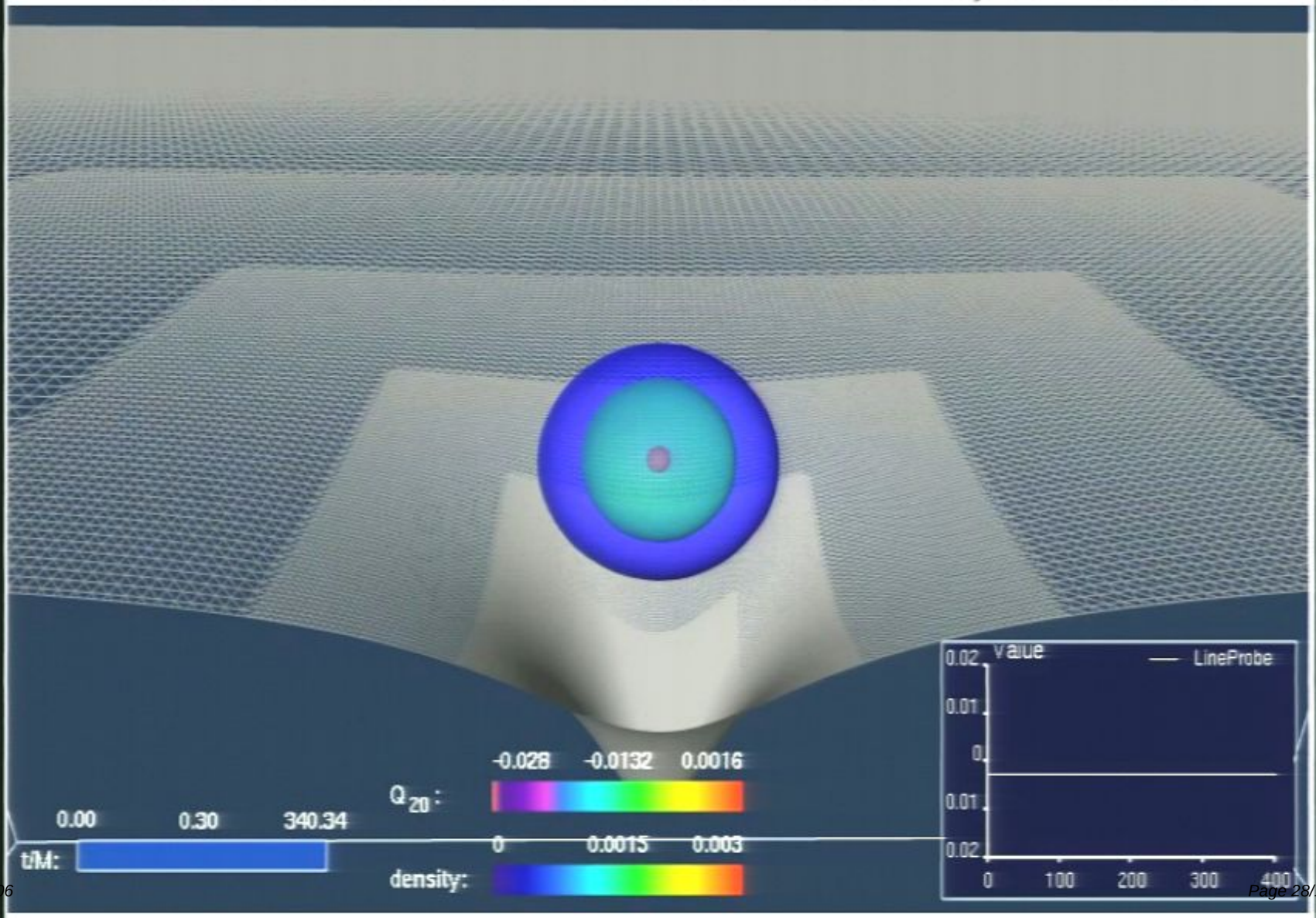
$$p = \rho\varepsilon(\Gamma - 1)$$

with

$$\Gamma = 1 + 1/N = 2$$

UNIFORMLY ROTATING STAR

Baiotti and Rezzolla, PRL 2006: Model D4, $J/M^2=0.543$



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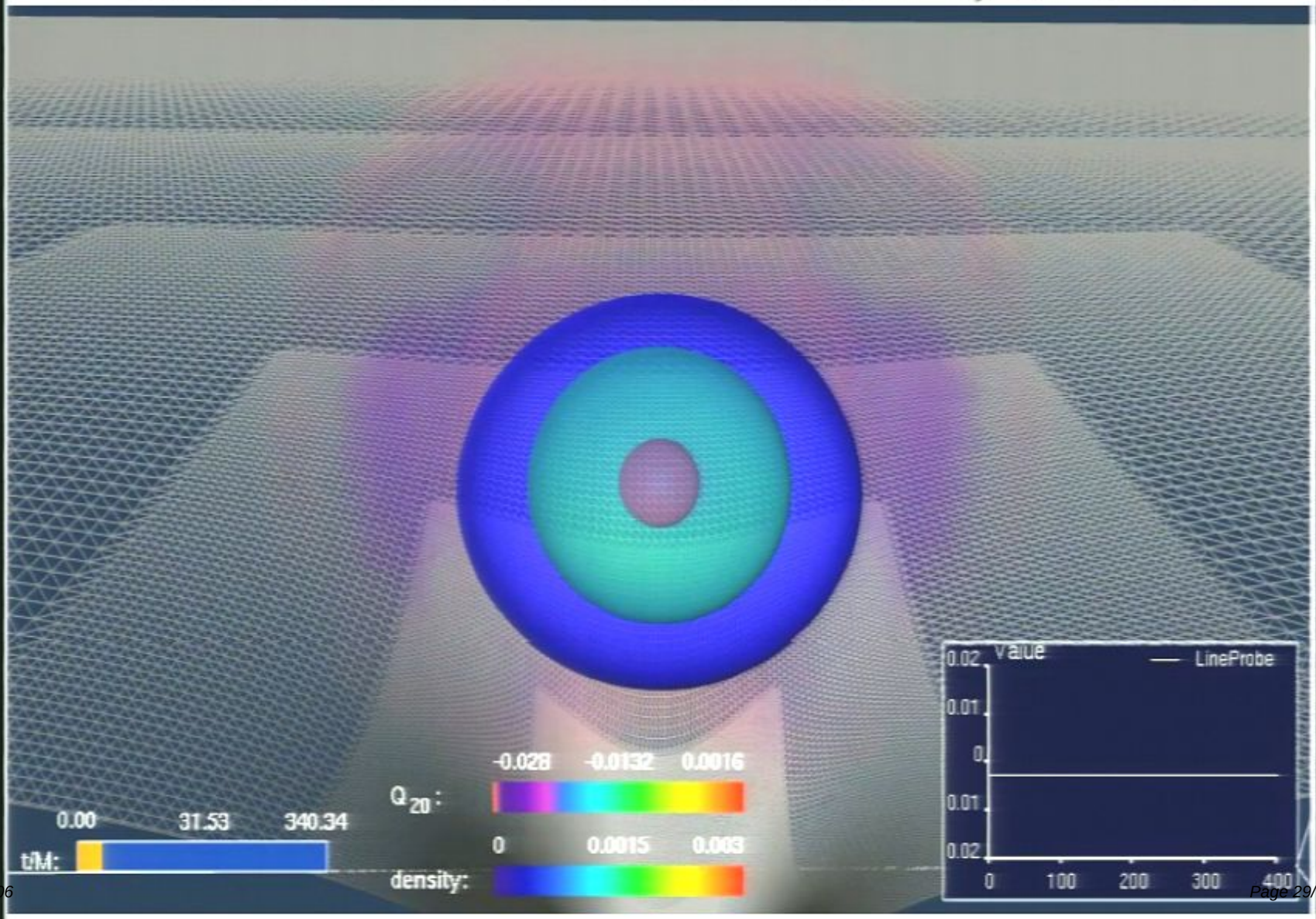

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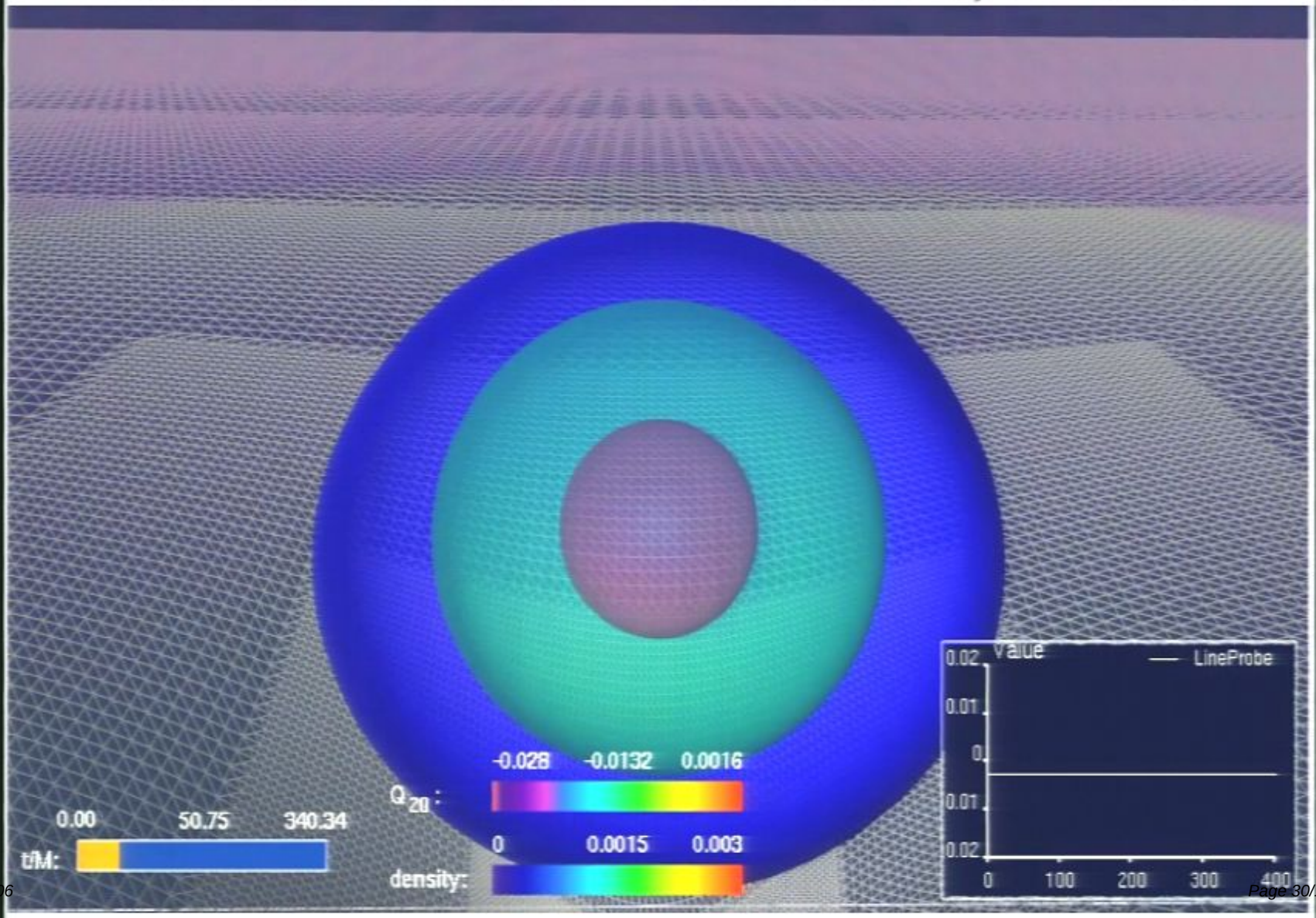

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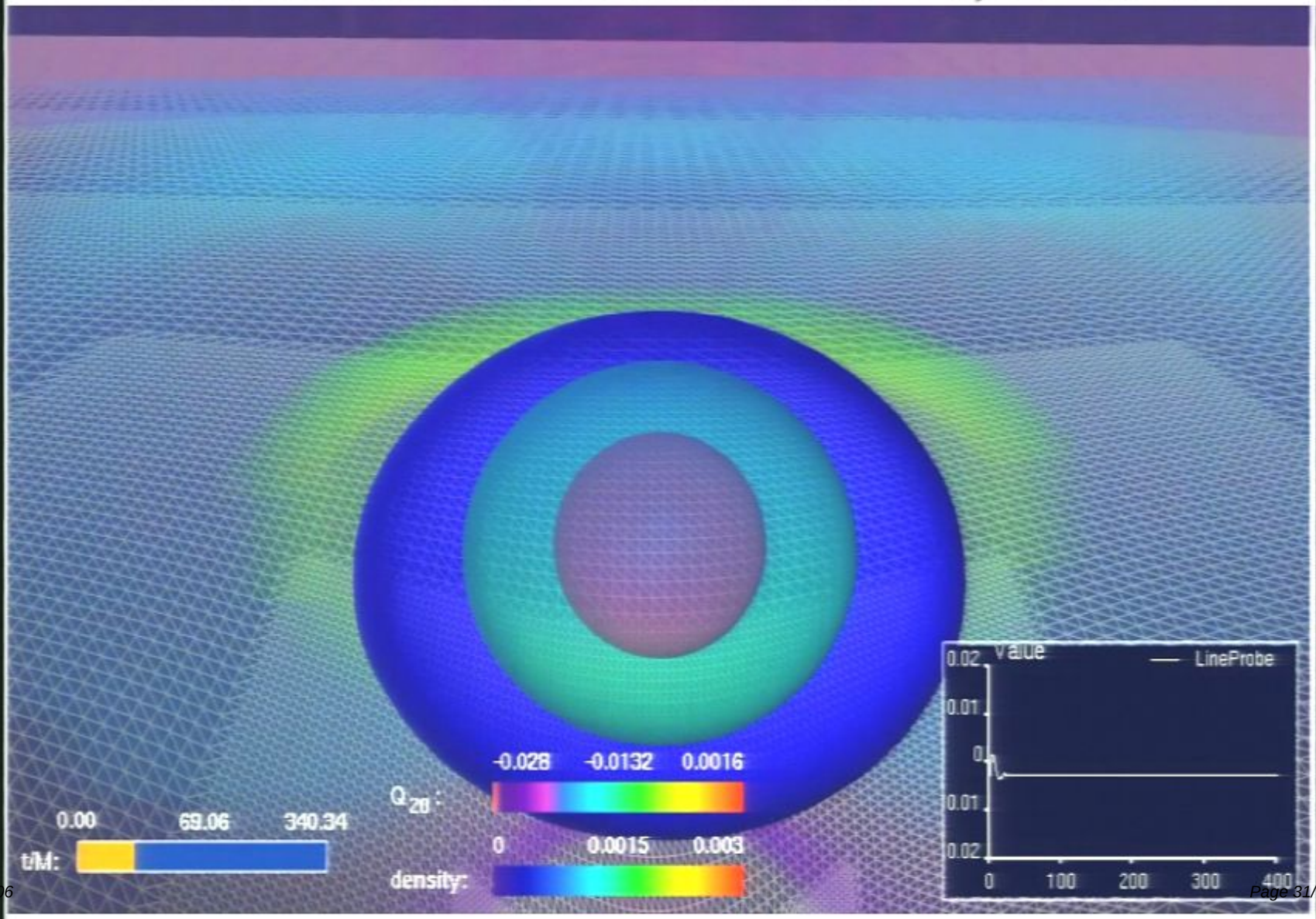

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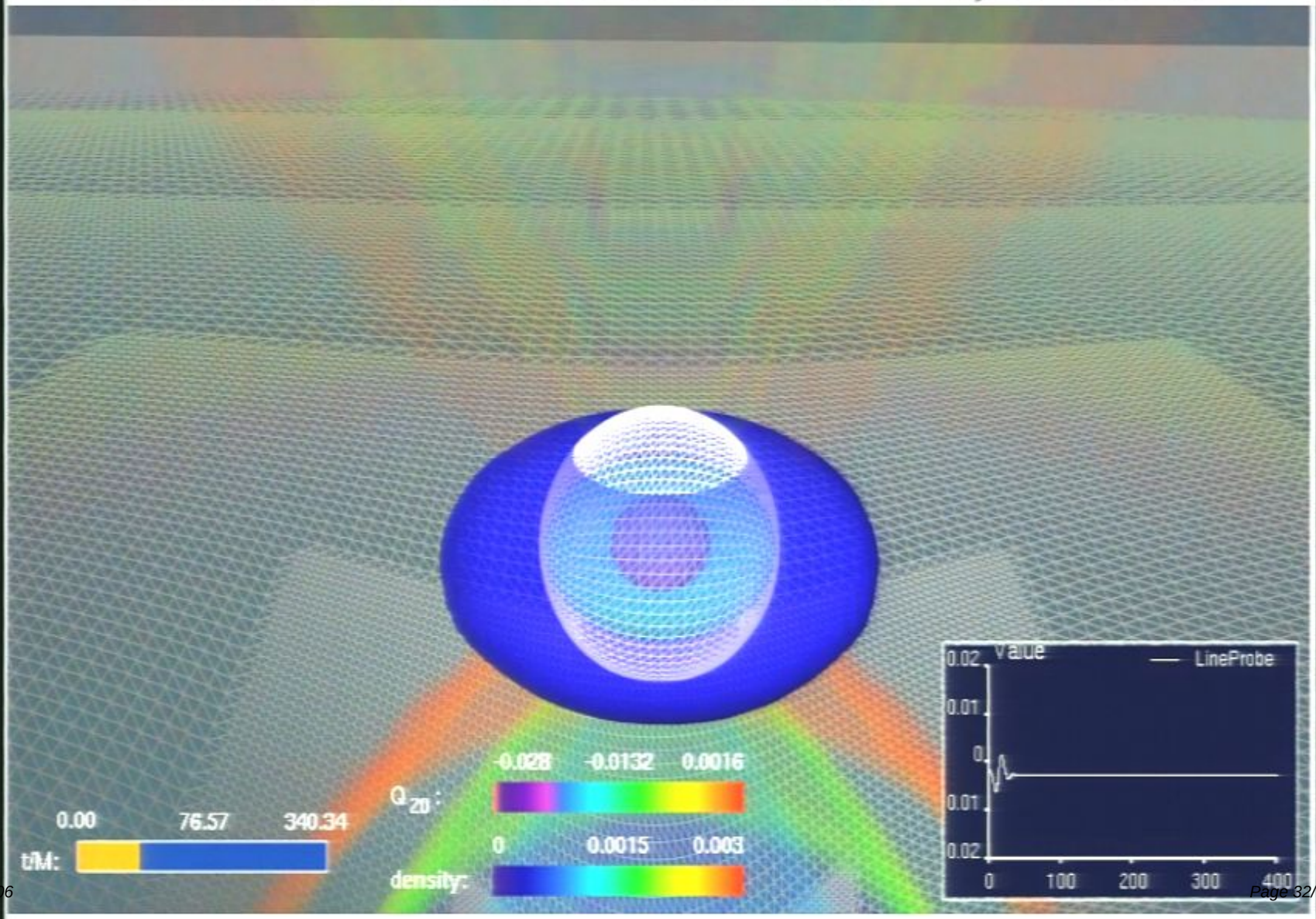

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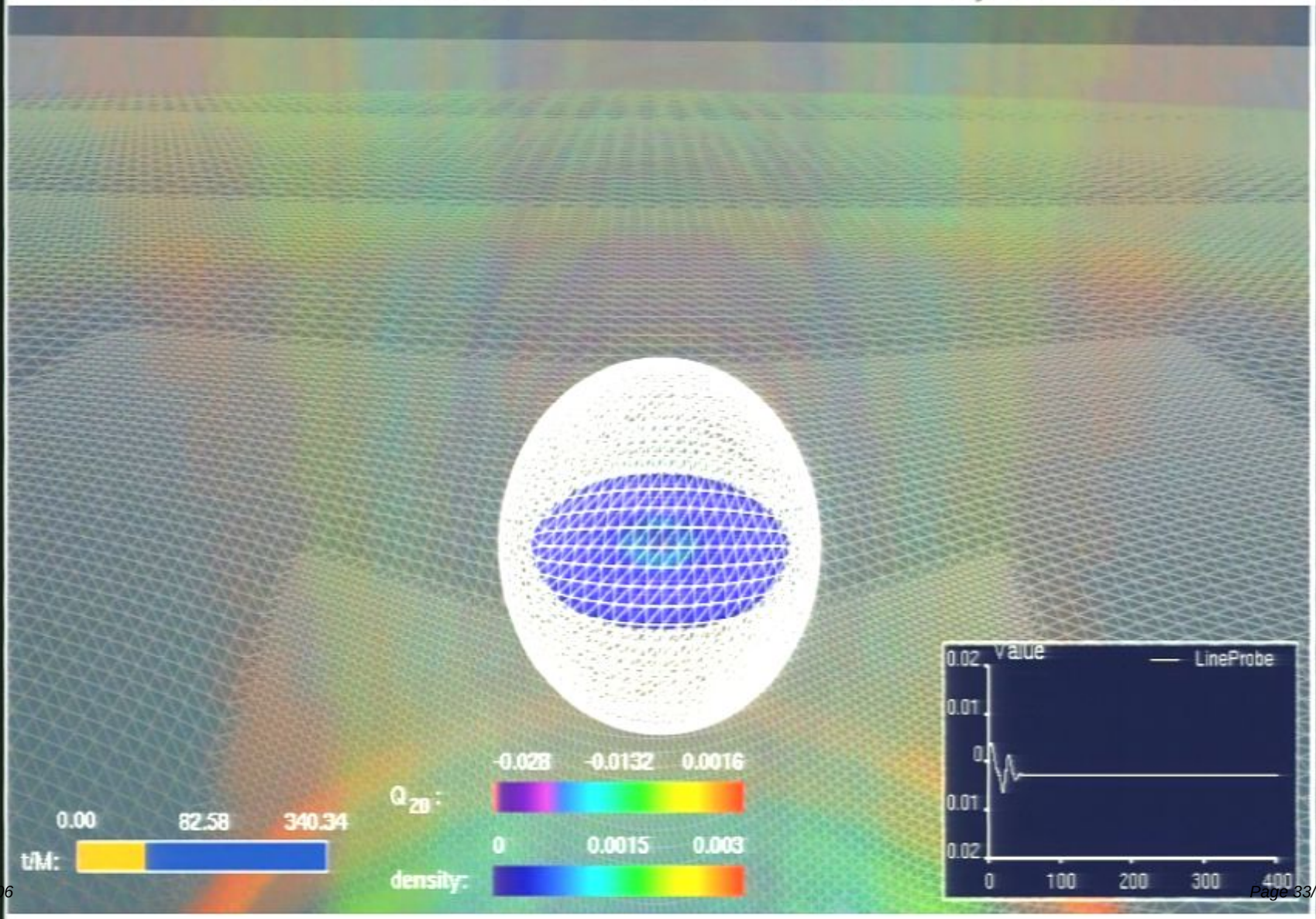

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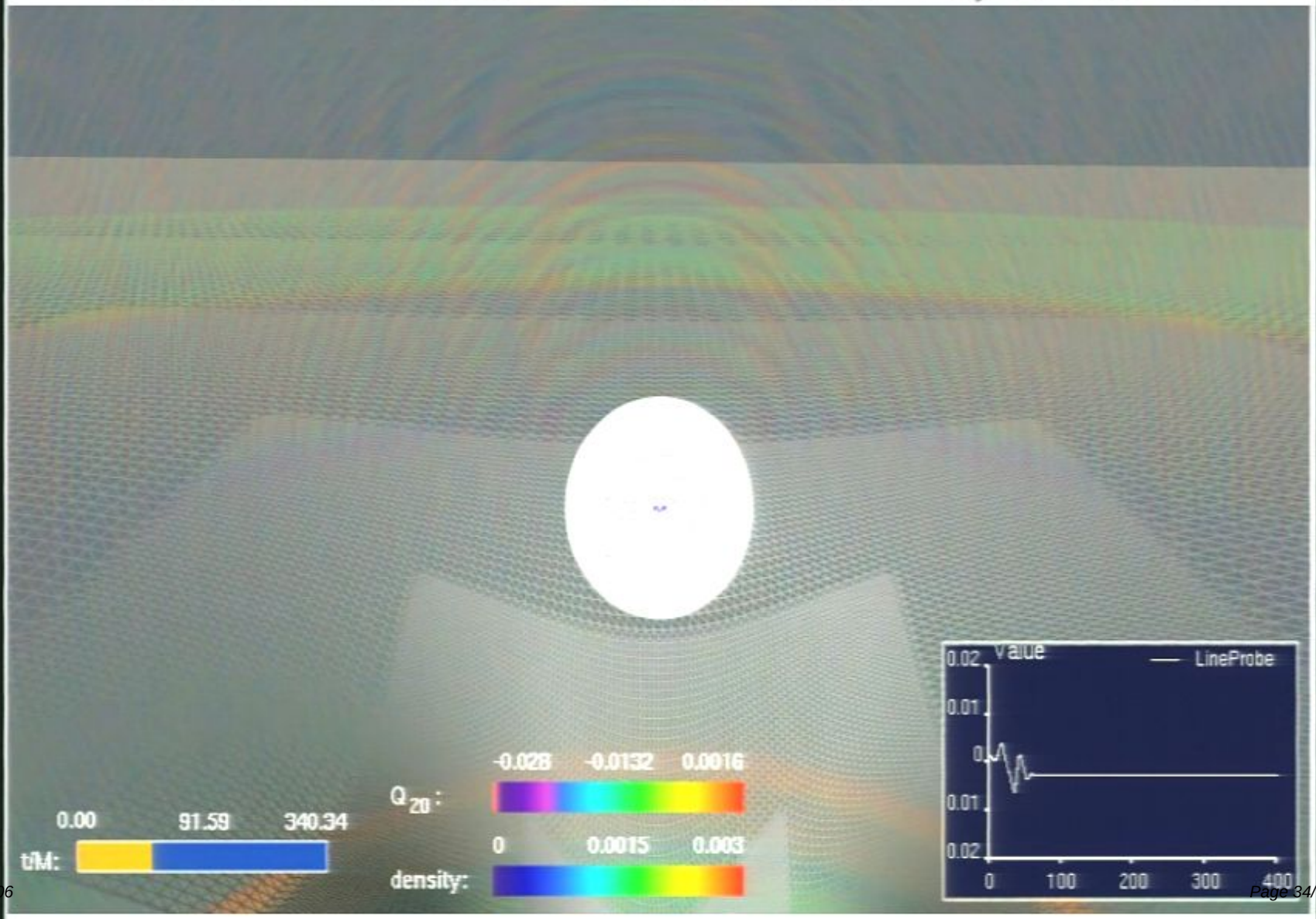

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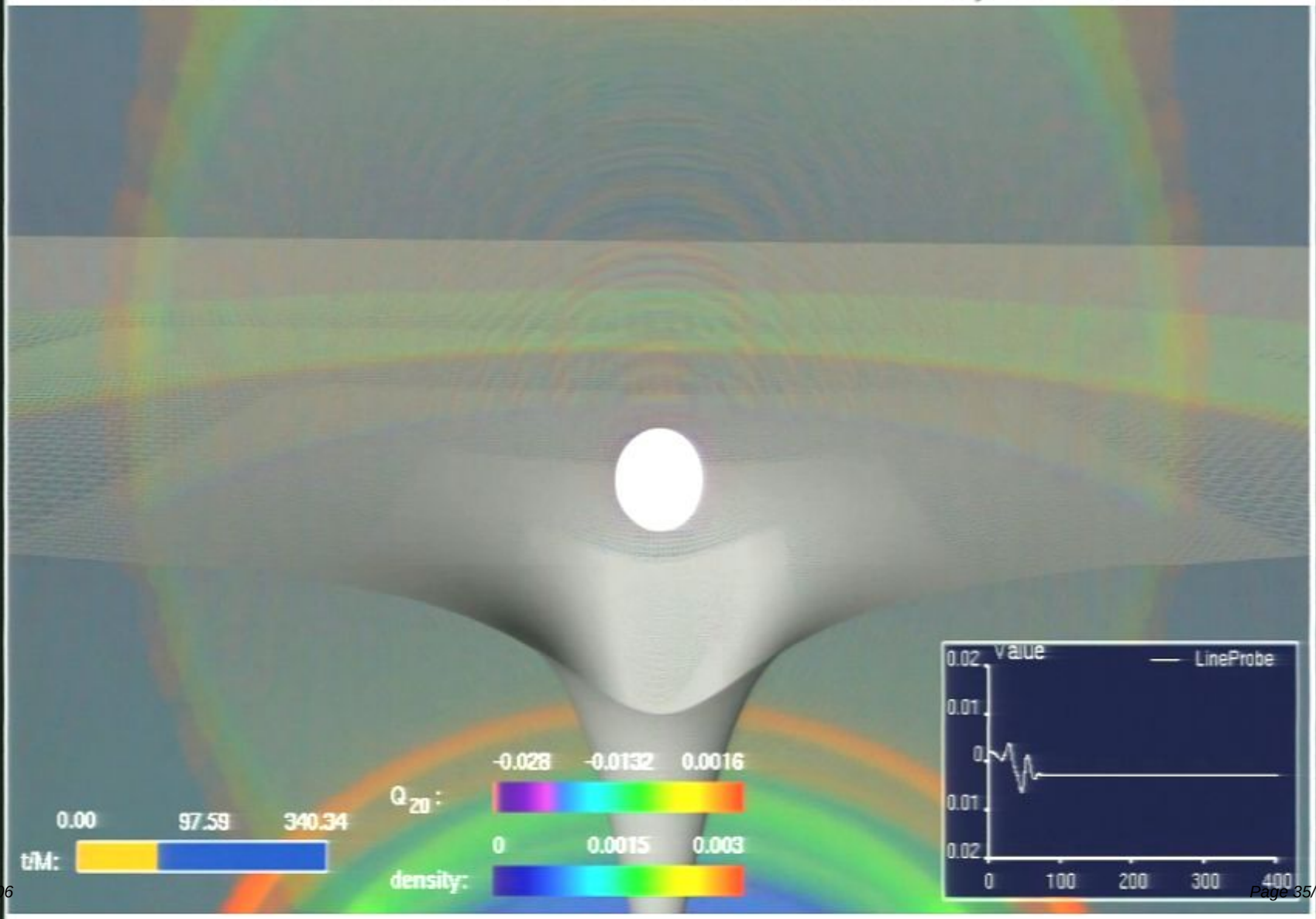

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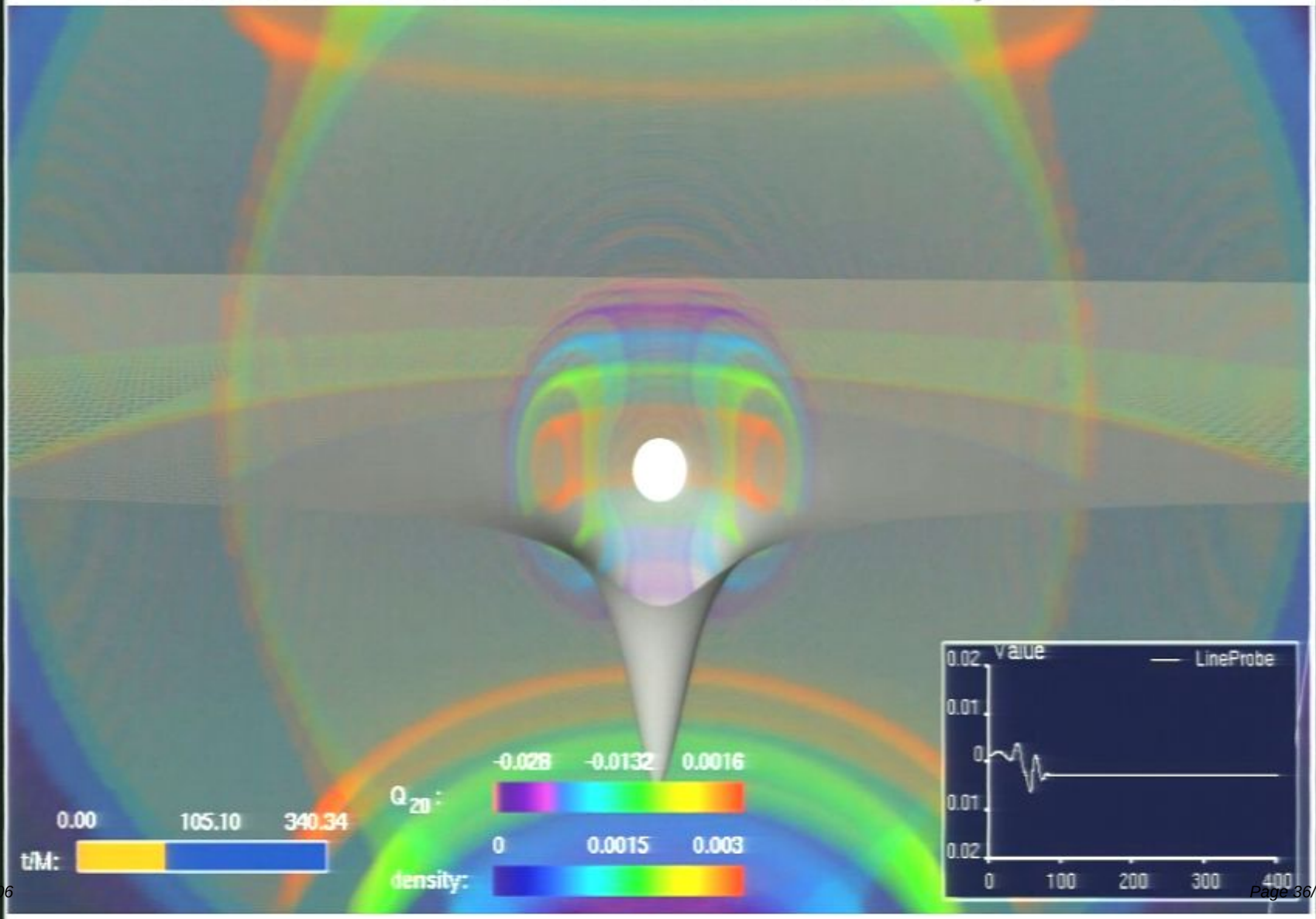

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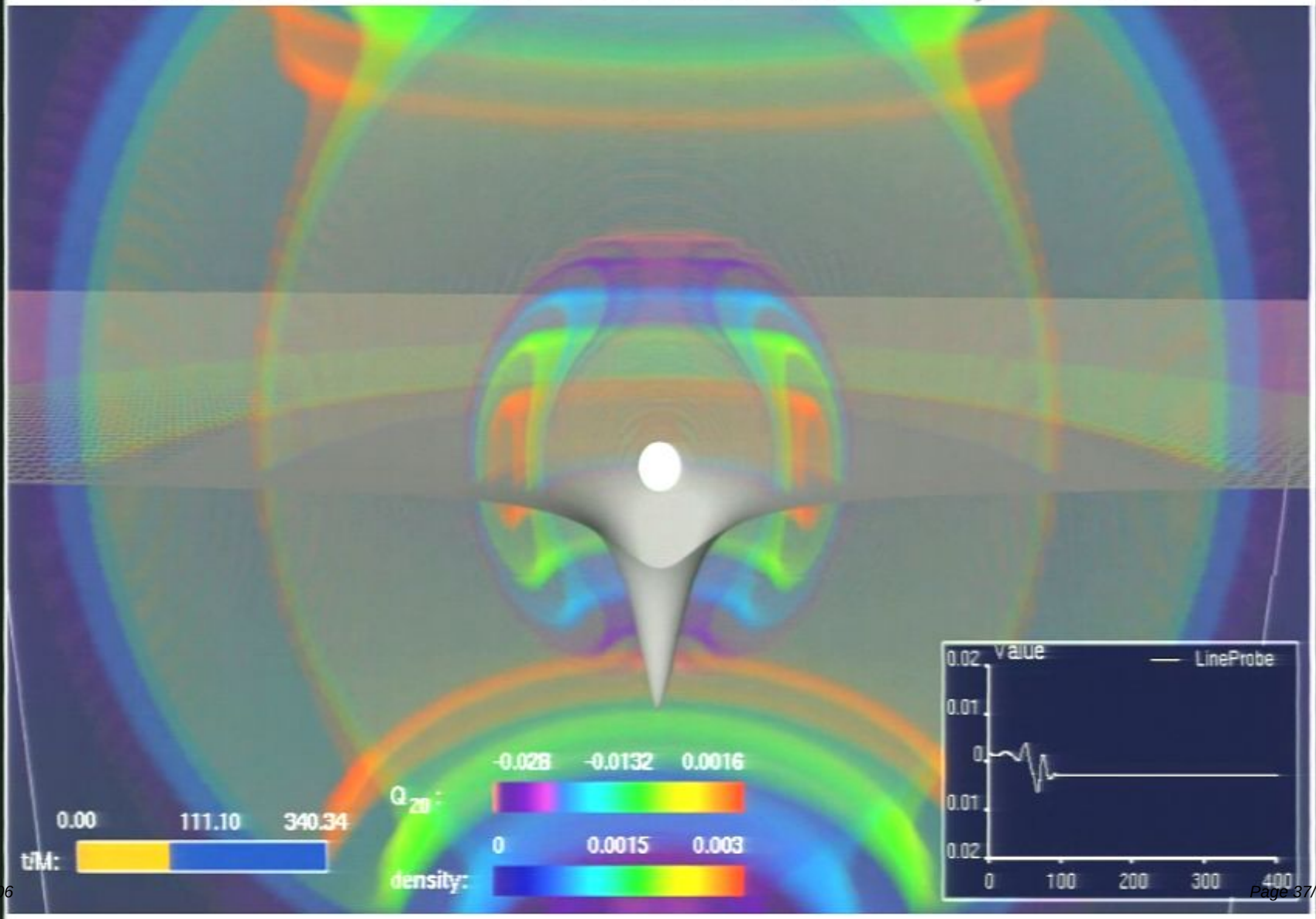

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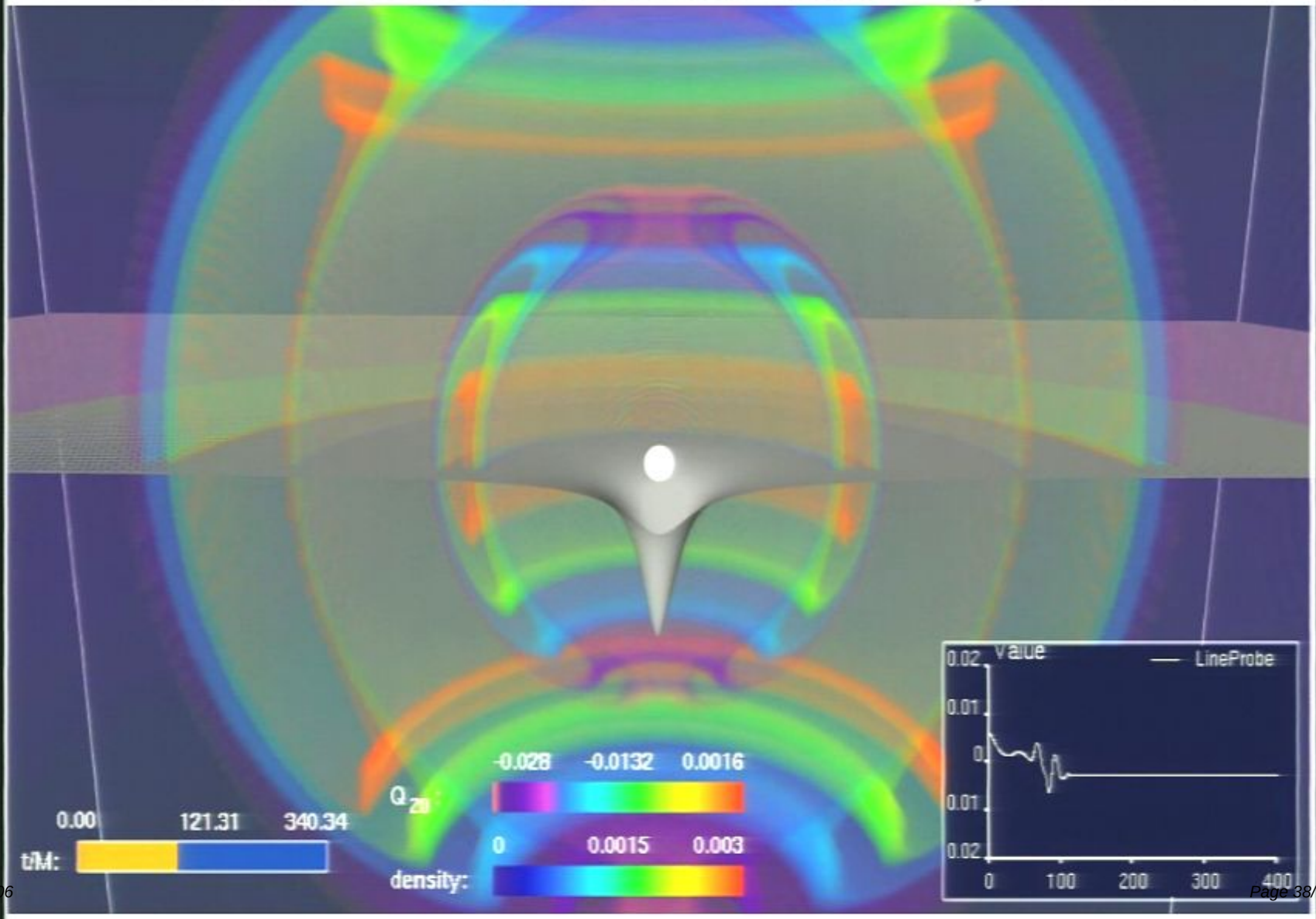

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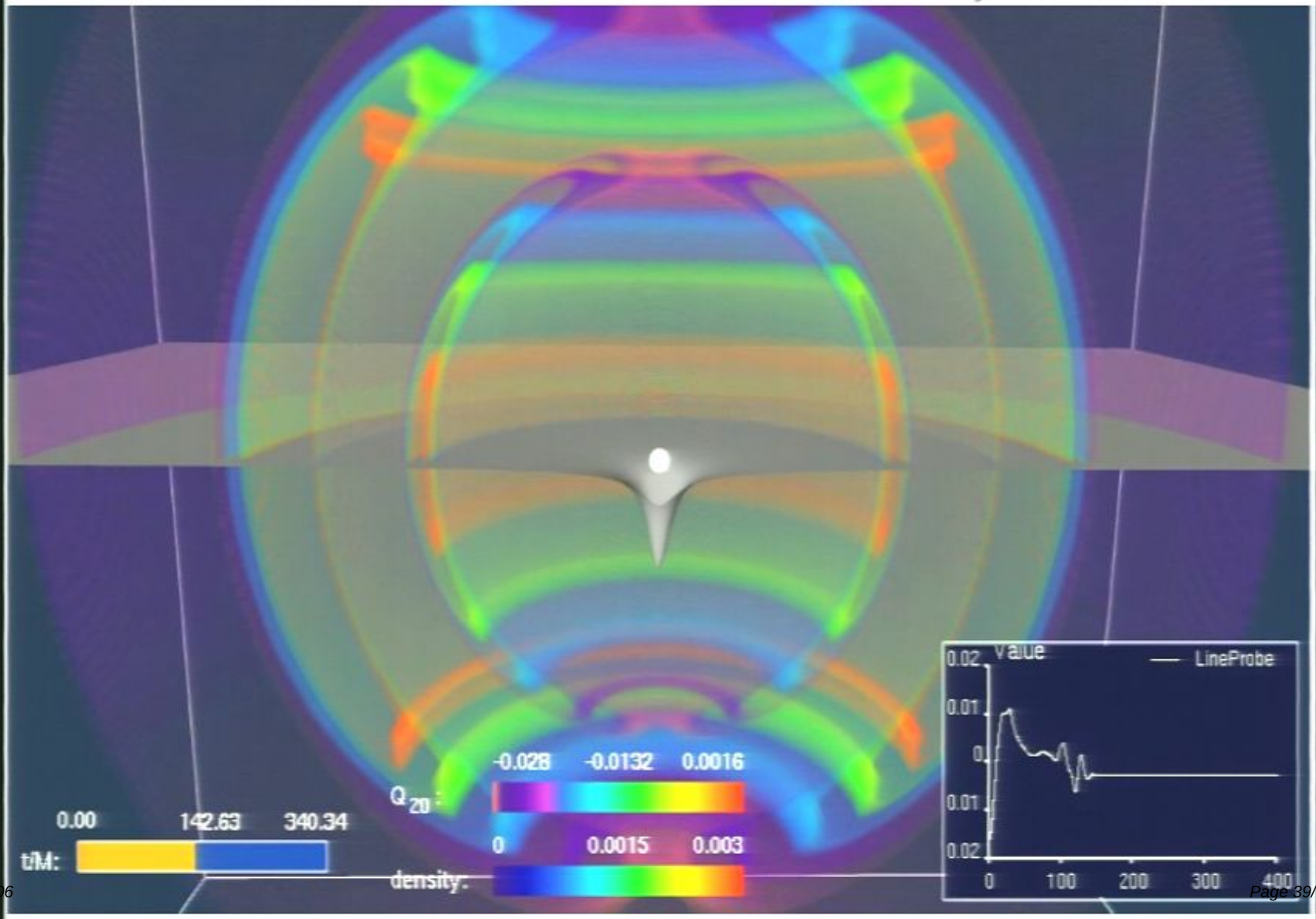

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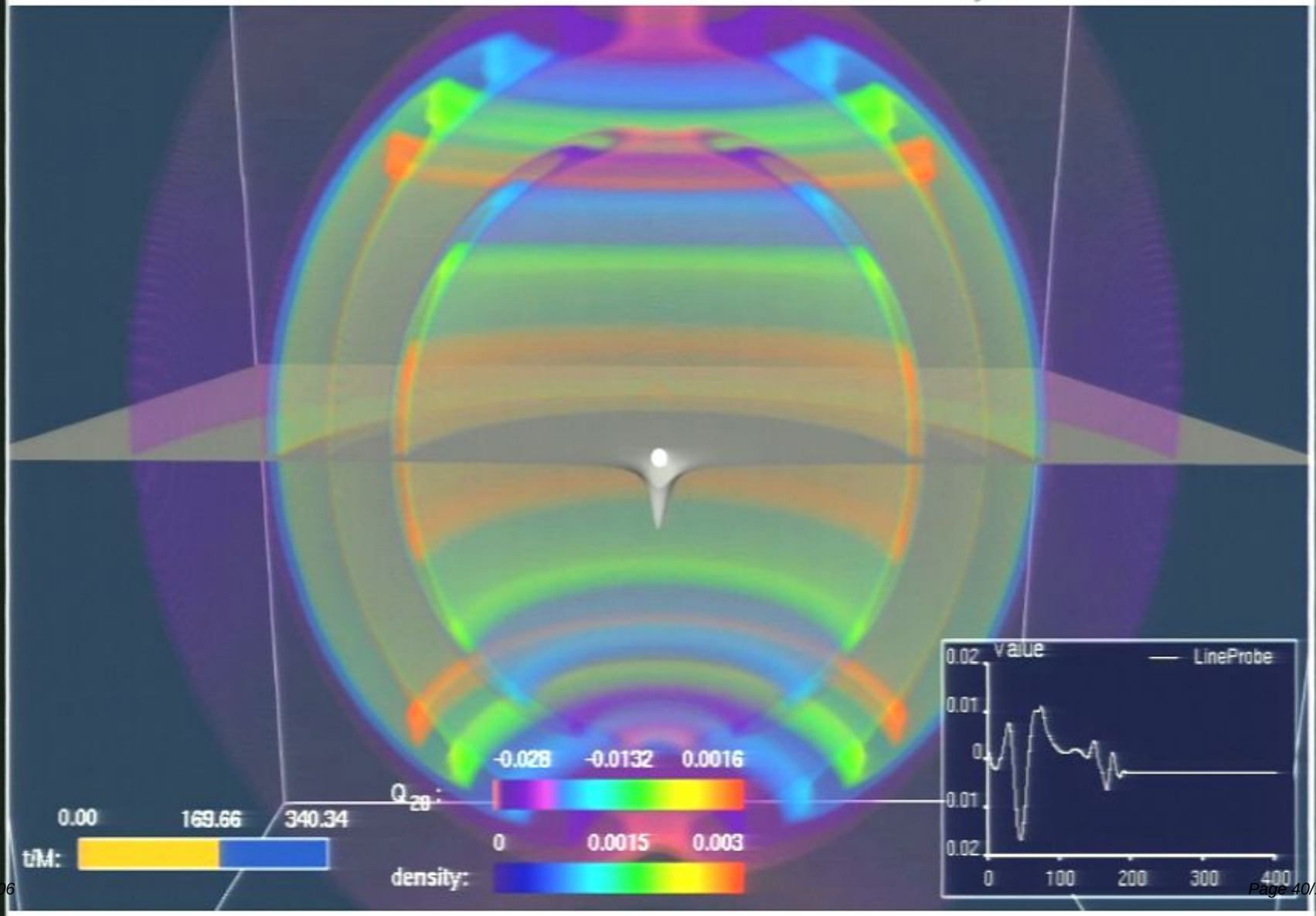

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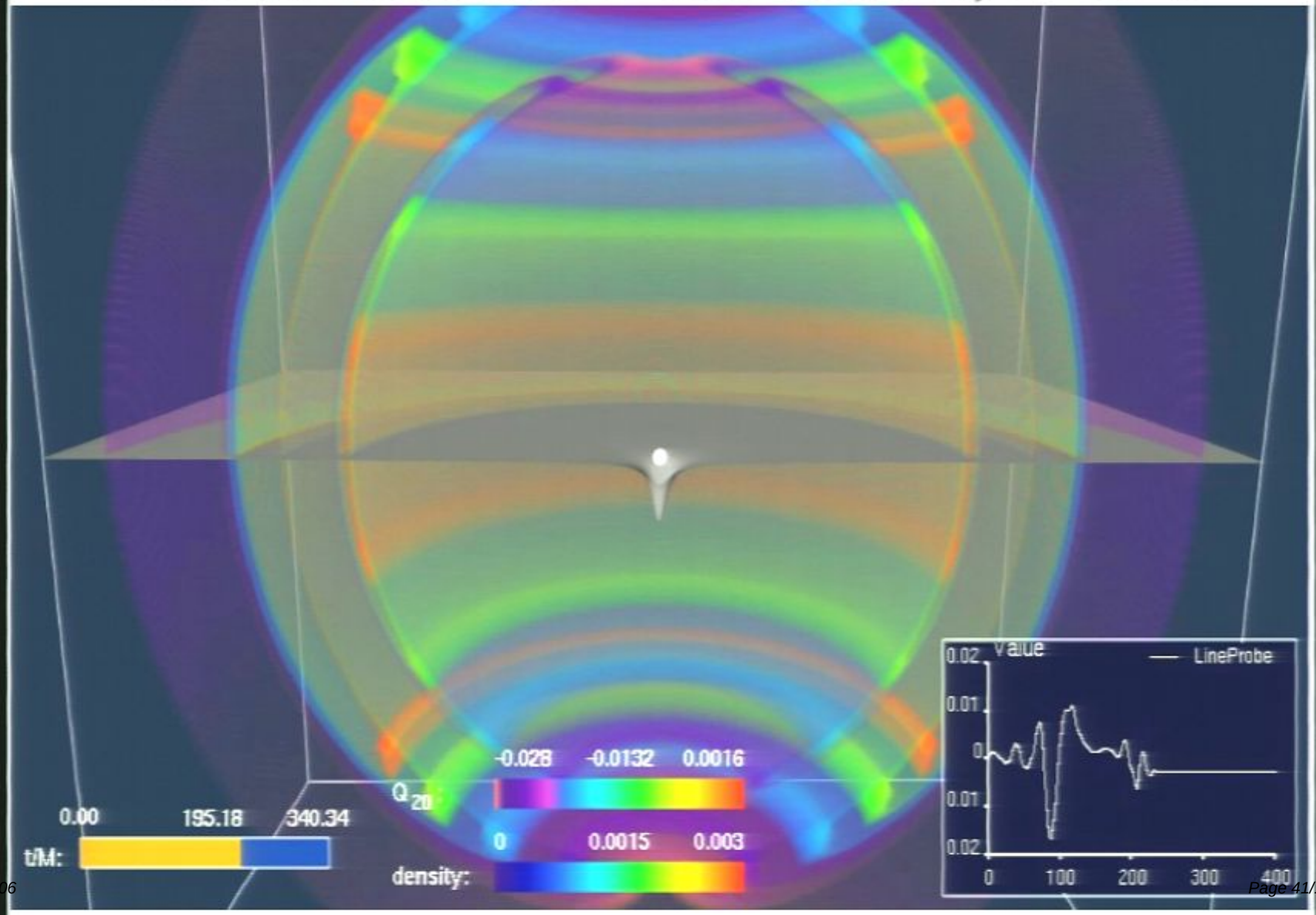

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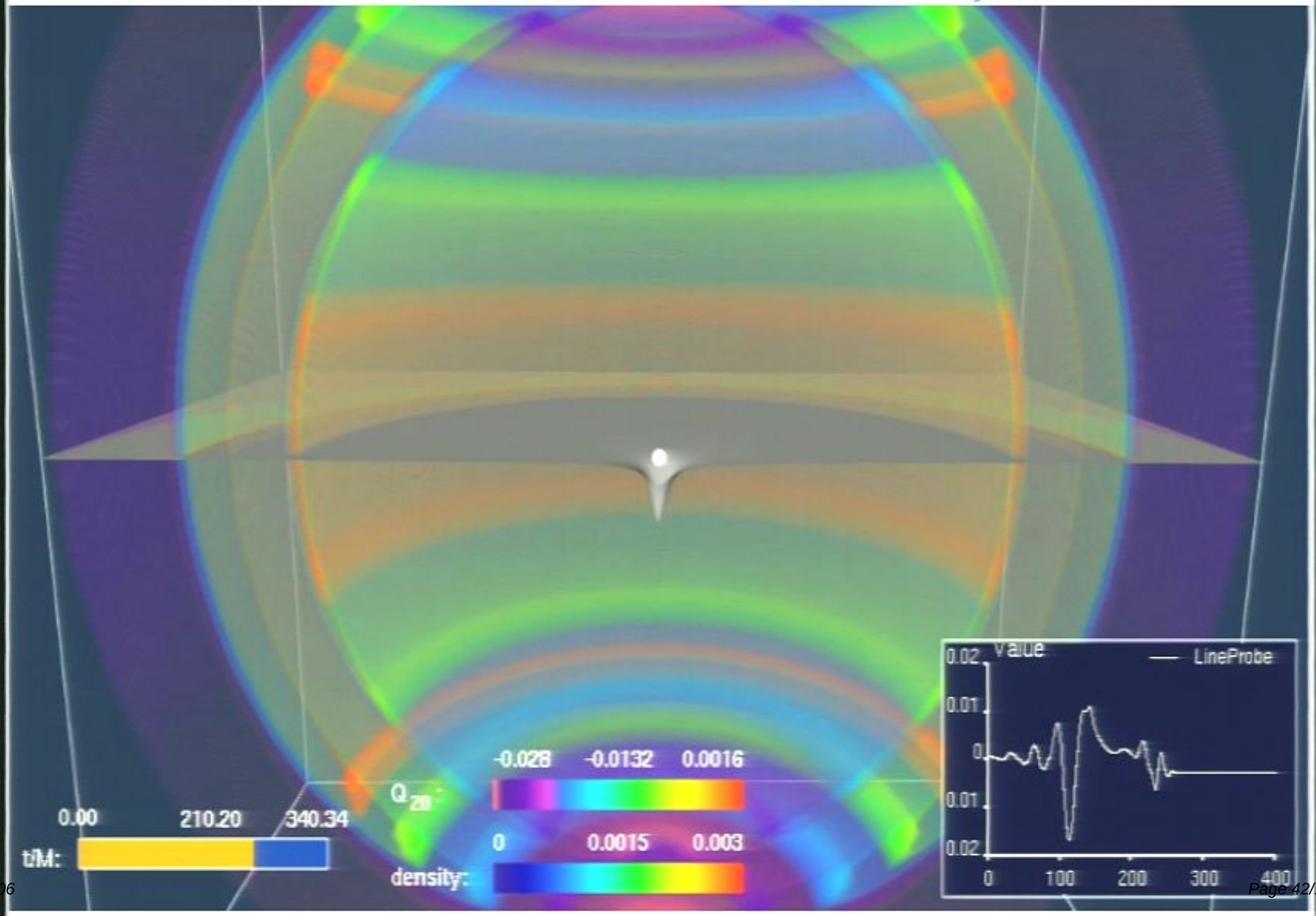

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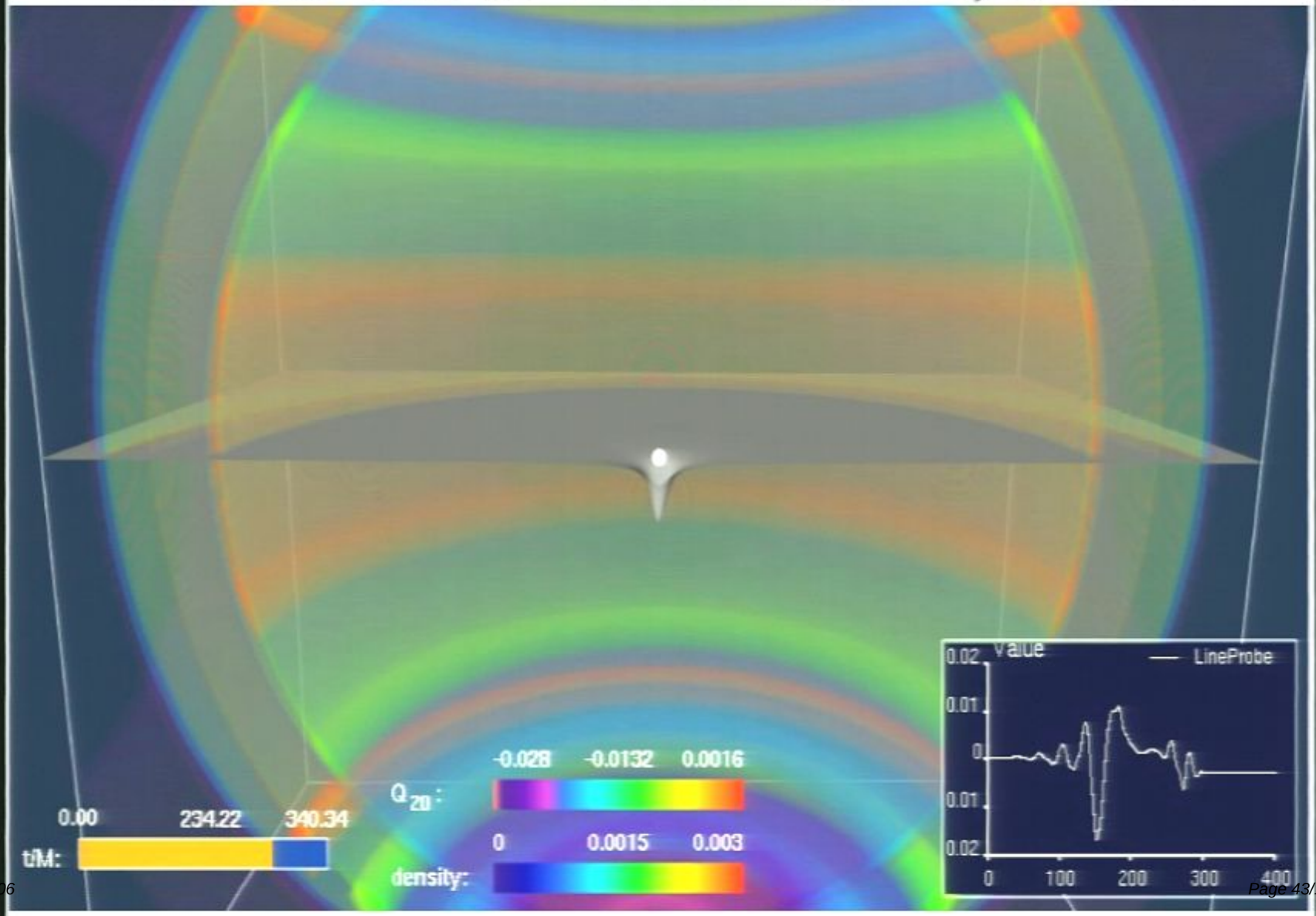

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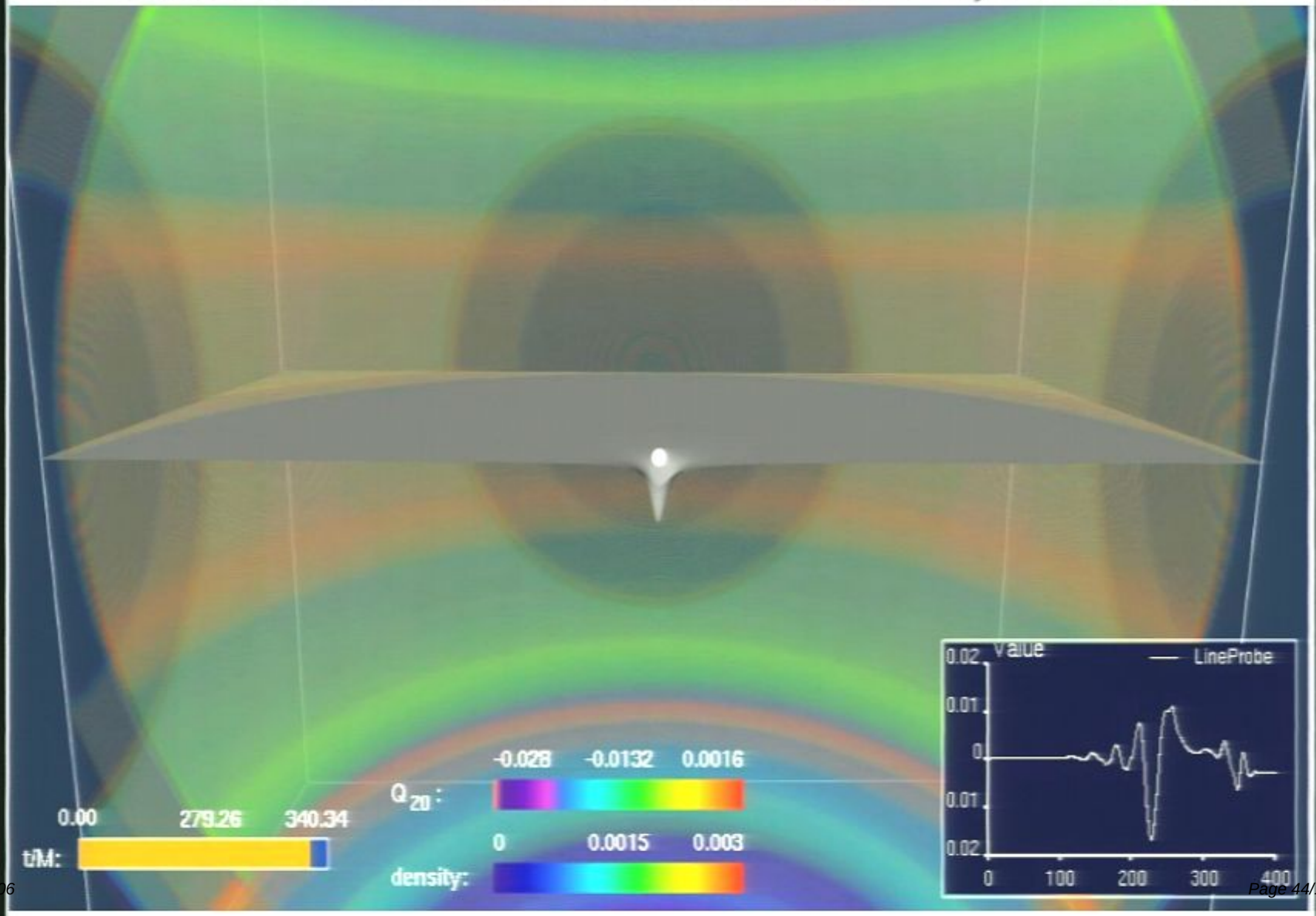

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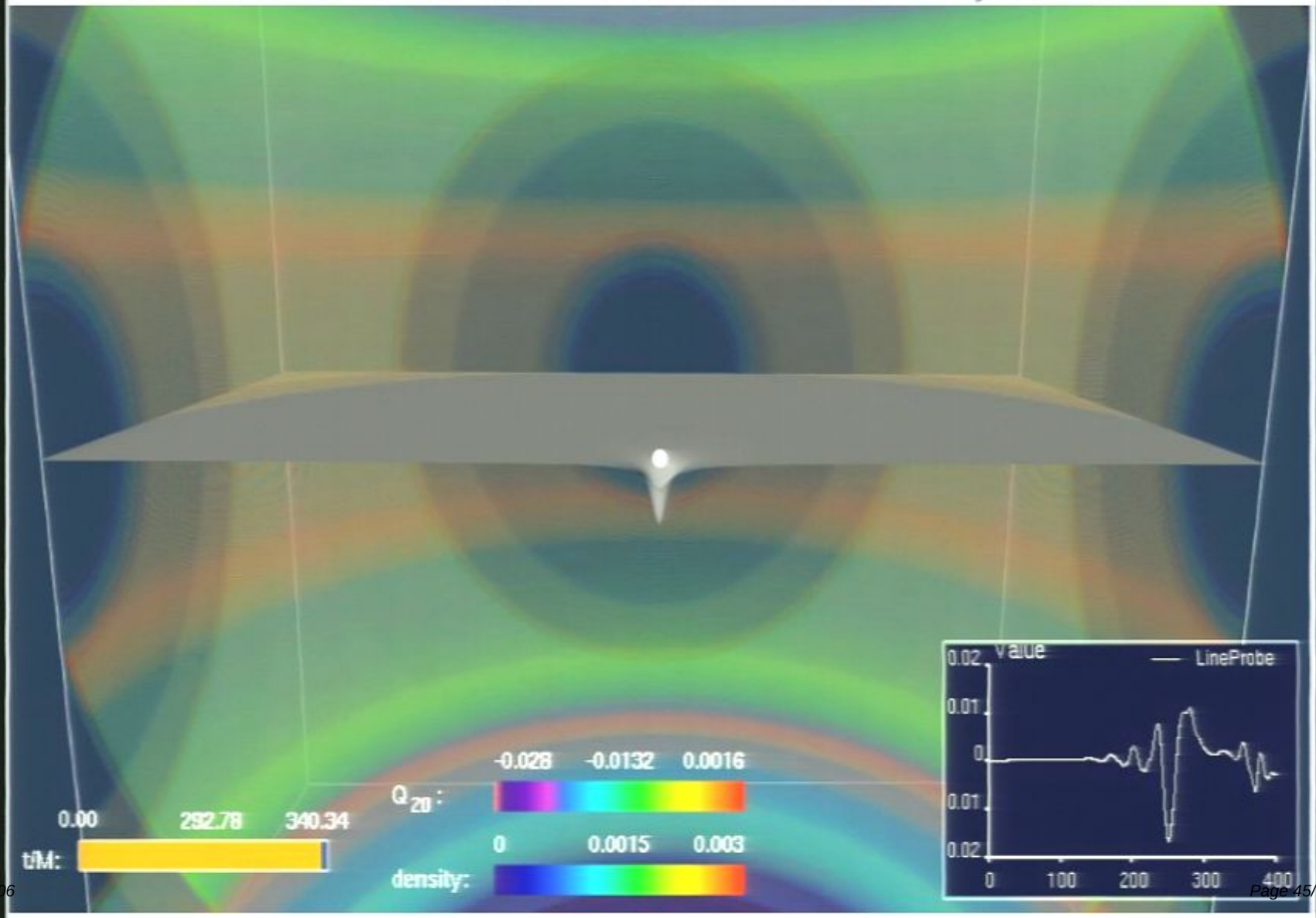
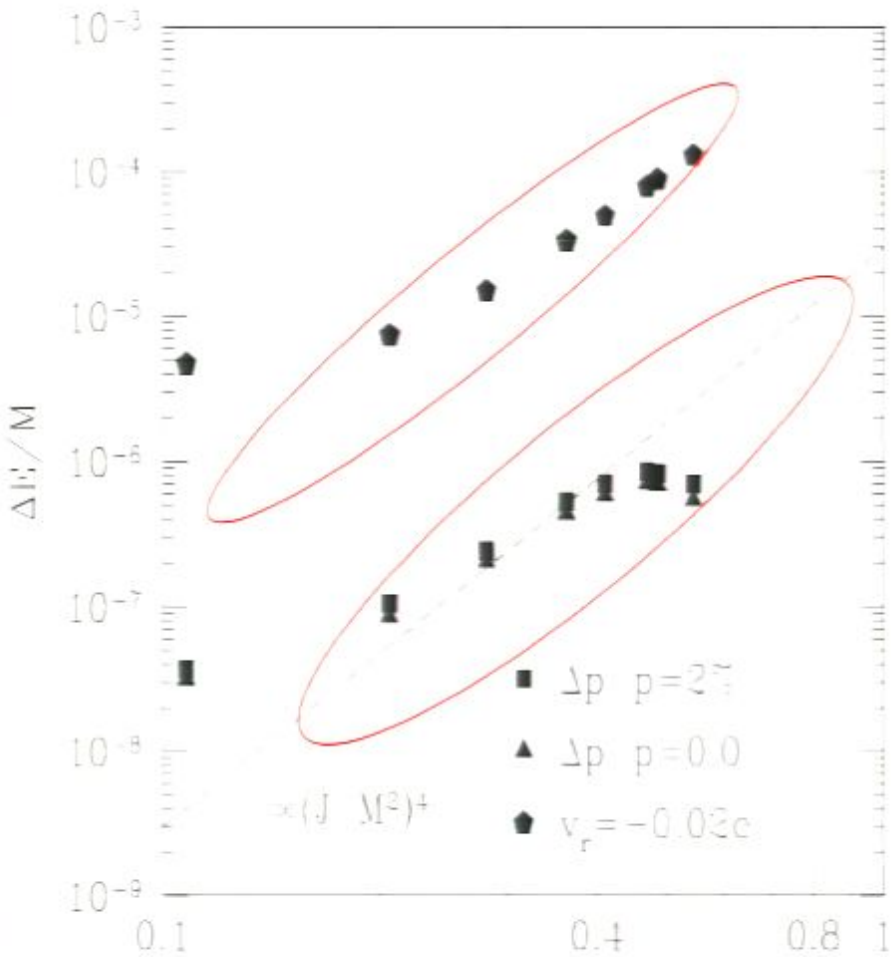


Energy emission from uniformly rotating stars

Energy emission



- The energy emitted is ~ $(J/M^2)^4$ for sufficiently large rotations
- Small (eg. ~2%) pressure perturbations don't modify the collapse and the energy emission
- Additional radial velocities (2%) can boost the collapse and enhance the emission

Overall, the gw emission from uniformly rotating stars is efficient only at very large rotation rates with $S/N>1$ at 10 kpc.

Differentially rotating polytropes

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- A supra-Kerr star cannot collapse promptly to a Kerr bh; something must intervene to remove angular momentum, eg. non-axisymmetric instabilities

DIFFERENTIALLY ROTATING MODELS

Different initial models built with a rotation law given by:

$$(\Omega_c - \Omega) = \left(\frac{r_e}{\hat{A}}\right)^2 \frac{(\Omega - \omega)e^{2\psi}}{1 - (\Omega - \omega)e^{2\psi}}$$

where $\hat{A}$ is a dimensionless parameter such that in the limit $\hat{A} \to \infty$ uniform rotation is recovered

	r_p/r_e	M	R_e	T/W	$J/M^{3/2}$	$\hat{A}$
A1	0.23	1.8	6.2	0.19	0.75	0.6
A2	0.33	2.2	7.9	0.22	0.82	1.0
A3	0.33	2.6	10.7	0.23	0.88	1.4
B1	0.39	1.9	16.8	0.22	1.09	1.0

Differentially rotating polytropes

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Differentially rotating polytropes

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- Differential rotation is expected in a star produced as a result of core-collapse or in the merger of a binary system of NSs

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- A supra-Kerr star cannot collapse promptly to a Kerr bh; something must intervene to remove angular momentum, eg. non-axisymmetric instabilities

DIFFERENTIALLY ROTATING MODELS

Different initial models built with a rotation law given by:

$$(\Omega_c - \Omega) = \left(\frac{r_e}{\hat{A}}\right)^2 \frac{(\Omega - \omega)e^{2\psi}}{1 - (\Omega - \omega)e^{2\psi}}$$

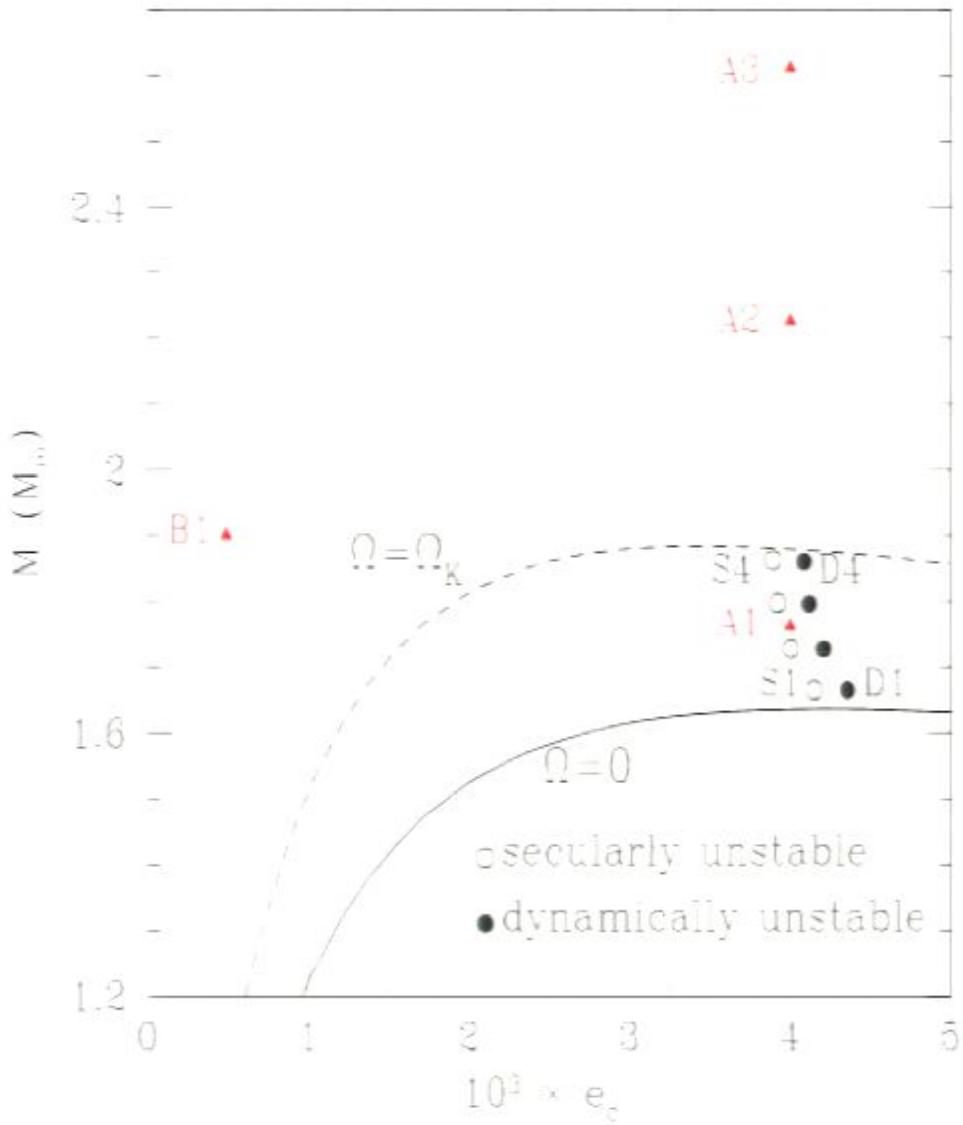
where $\hat{A}$ is a dimensionless parameter such that in the limit $\hat{A} \to \infty$ uniform rotation is recovered

	r_p/r_e	M	R_e	T/W	$J/M^{3/2}$	$\hat{A}$
A1	0.23	1.8	6.2	0.19	0.75	0.6
A2	0.33	2.2	7.9	0.22	0.82	1.0
A3	0.33	2.6	10.7	0.23	0.88	1.4
B1	0.39	1.9	16.8	0.22	1.09	1.0

DIFFERENTIALLY ROTATING MODELS

Different given by:

where $\hat{A}$ that in the limit $\hat{A} \to$



		$\hat{A}$
A1	5	0.6
A2	2	1.0
A3	8	1.4
B1	9	1.0

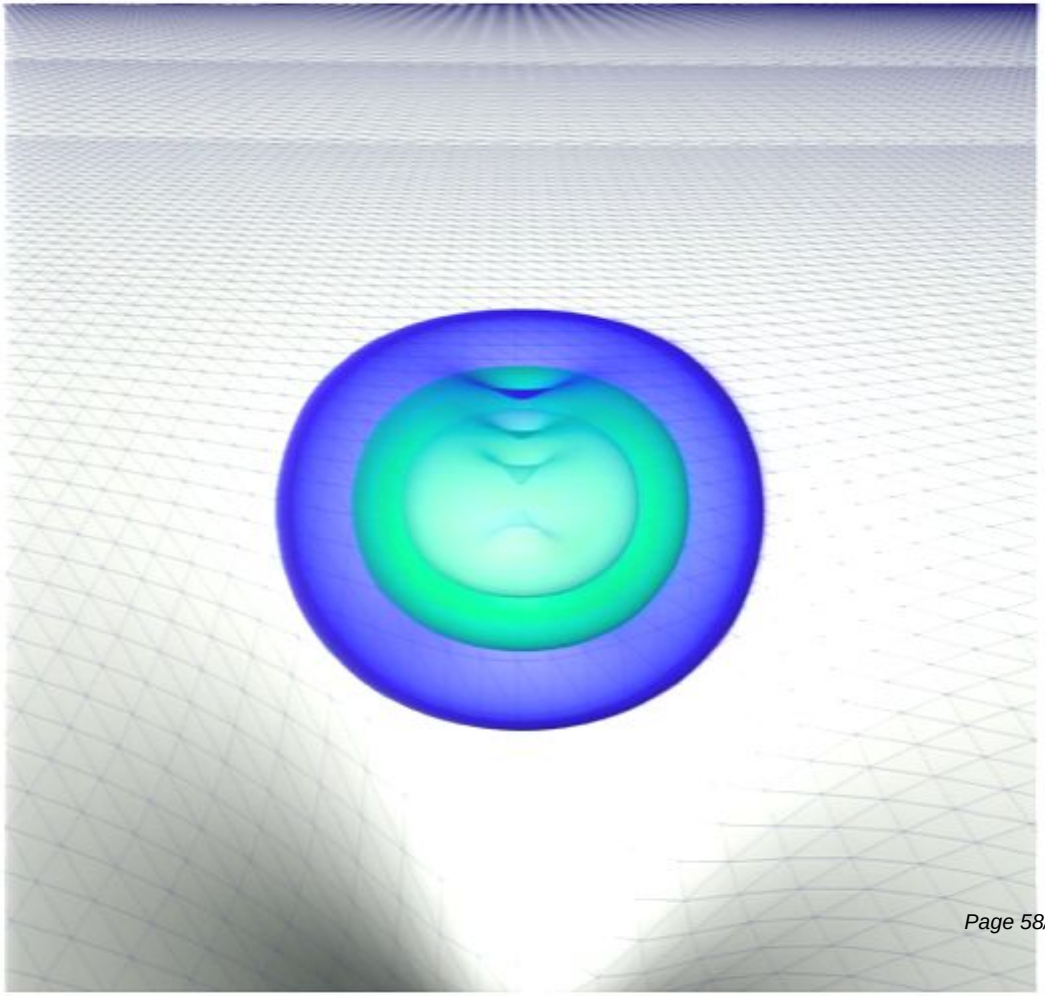
Collapse of sub-Kerr models

The differential rotation changes the structure of the star from quasi-spherical to quasi-toroidal (max(ρ) not located in the centre)

As an example: **A2**

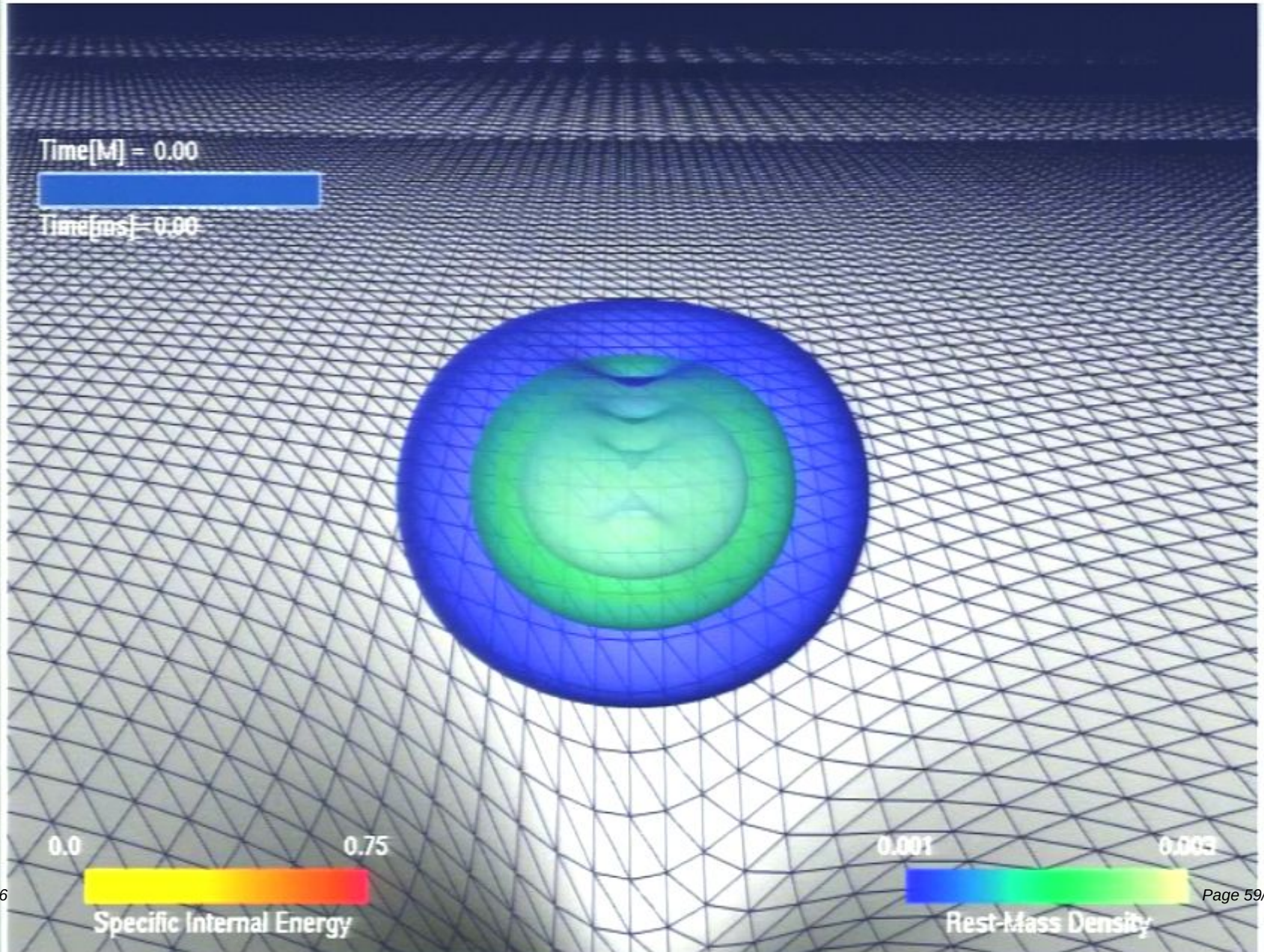
$M = 2.2\ M_{\odot}$; $J/M^2 = 0.82$

$T/|W| = 0.22$; $\Gamma = 2$; $\hat{A} = 1$



COLLAPSE OF MODEL A2

$J/M^2=0.82$



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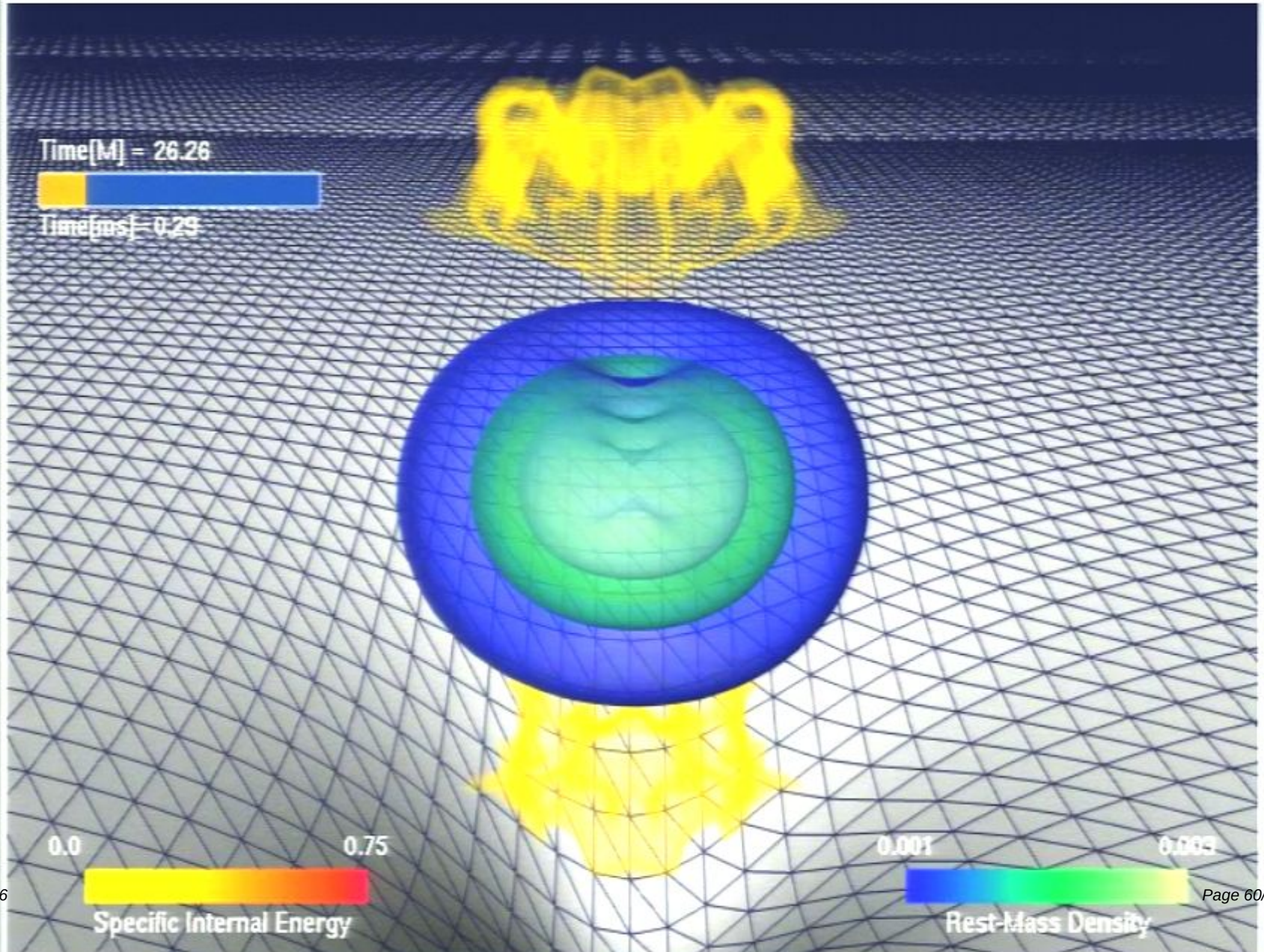

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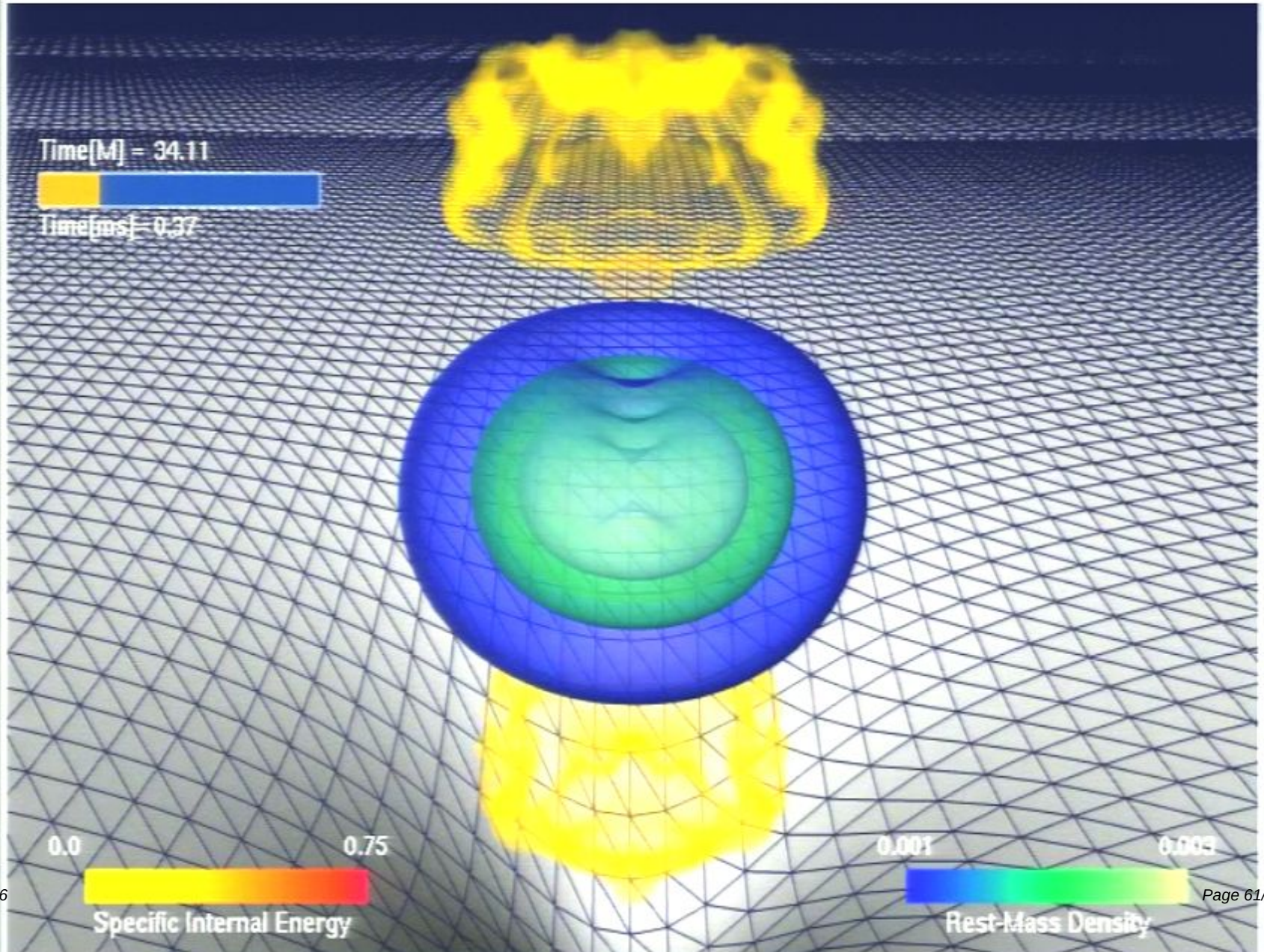

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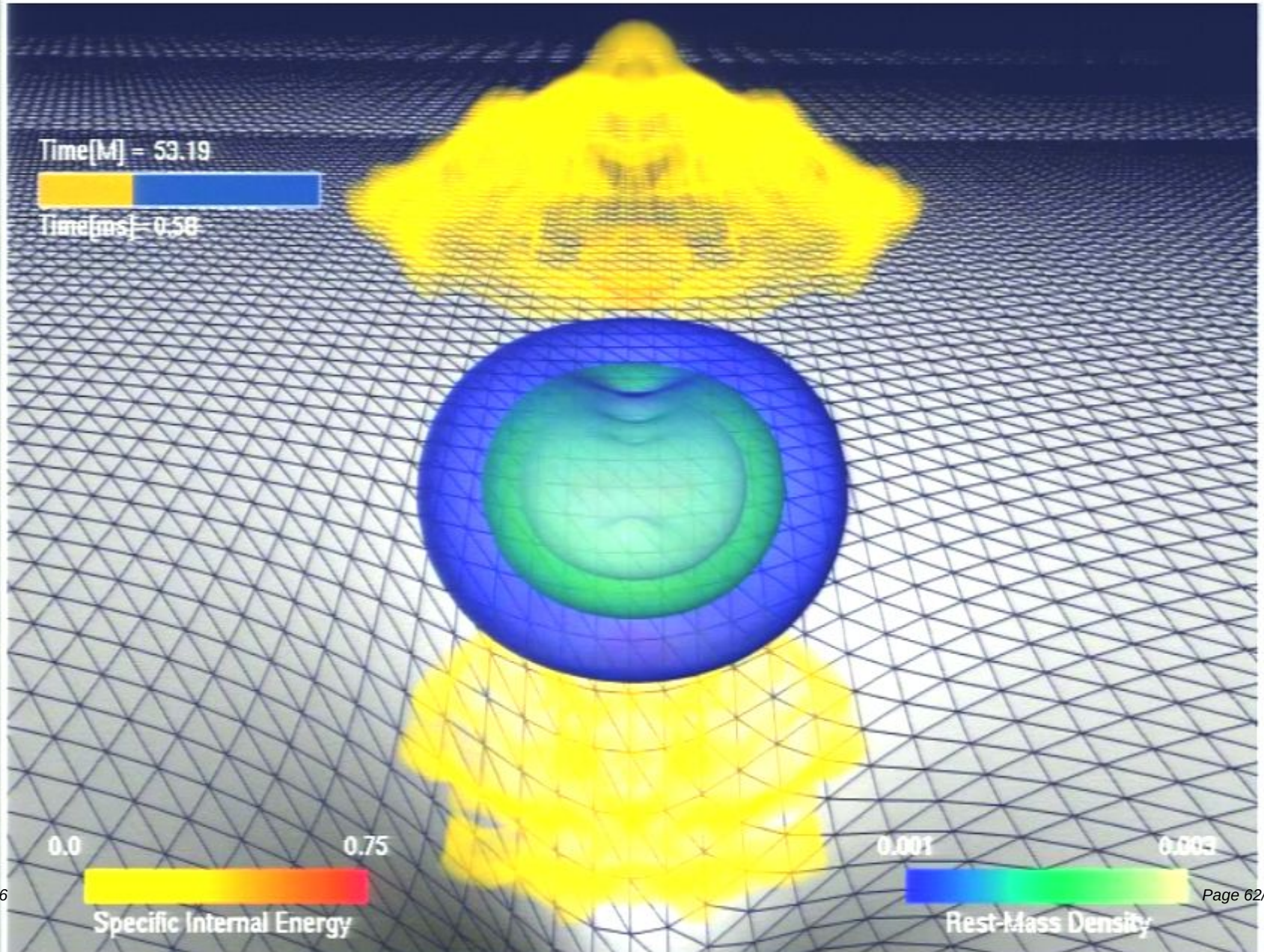

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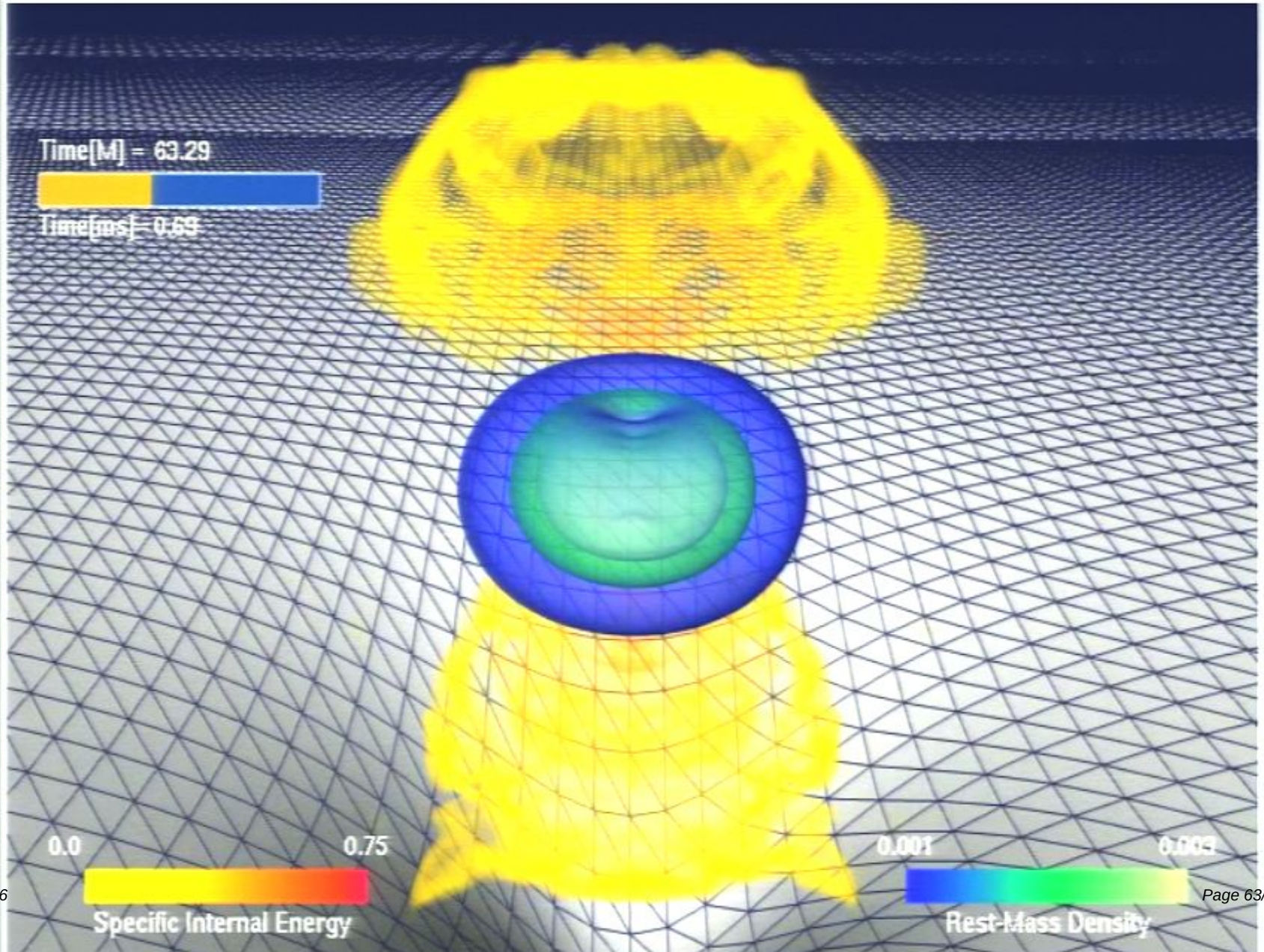

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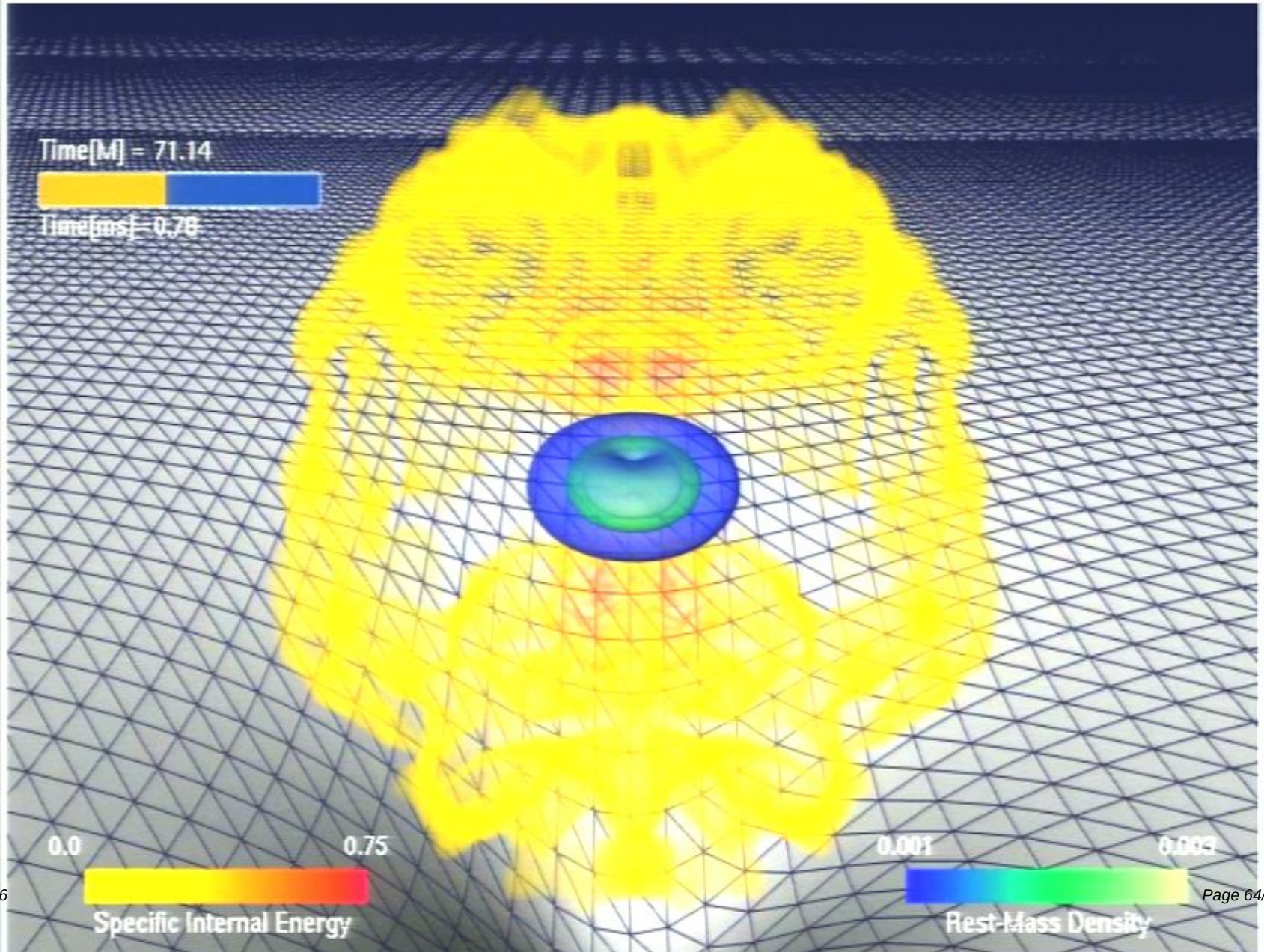

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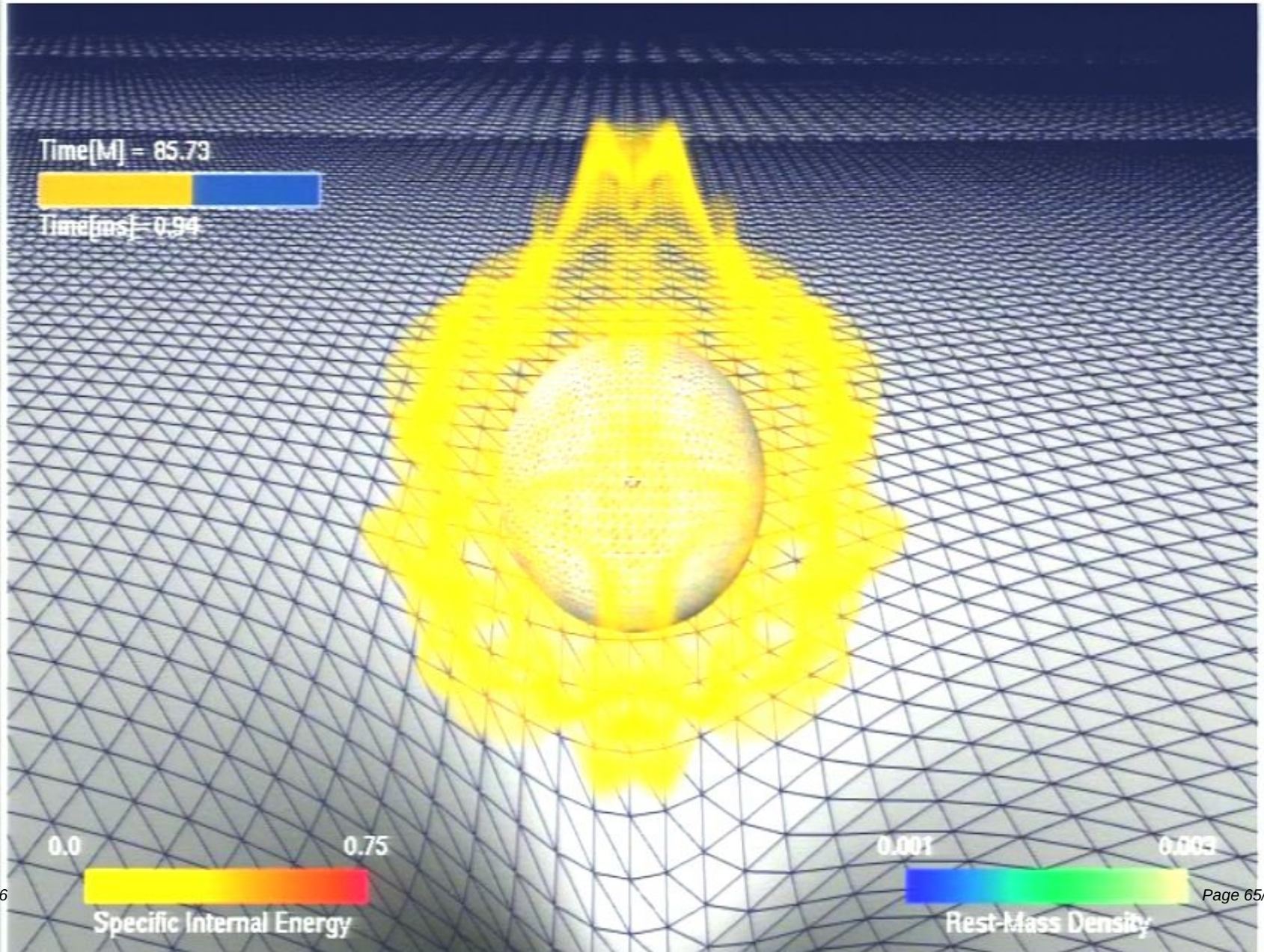

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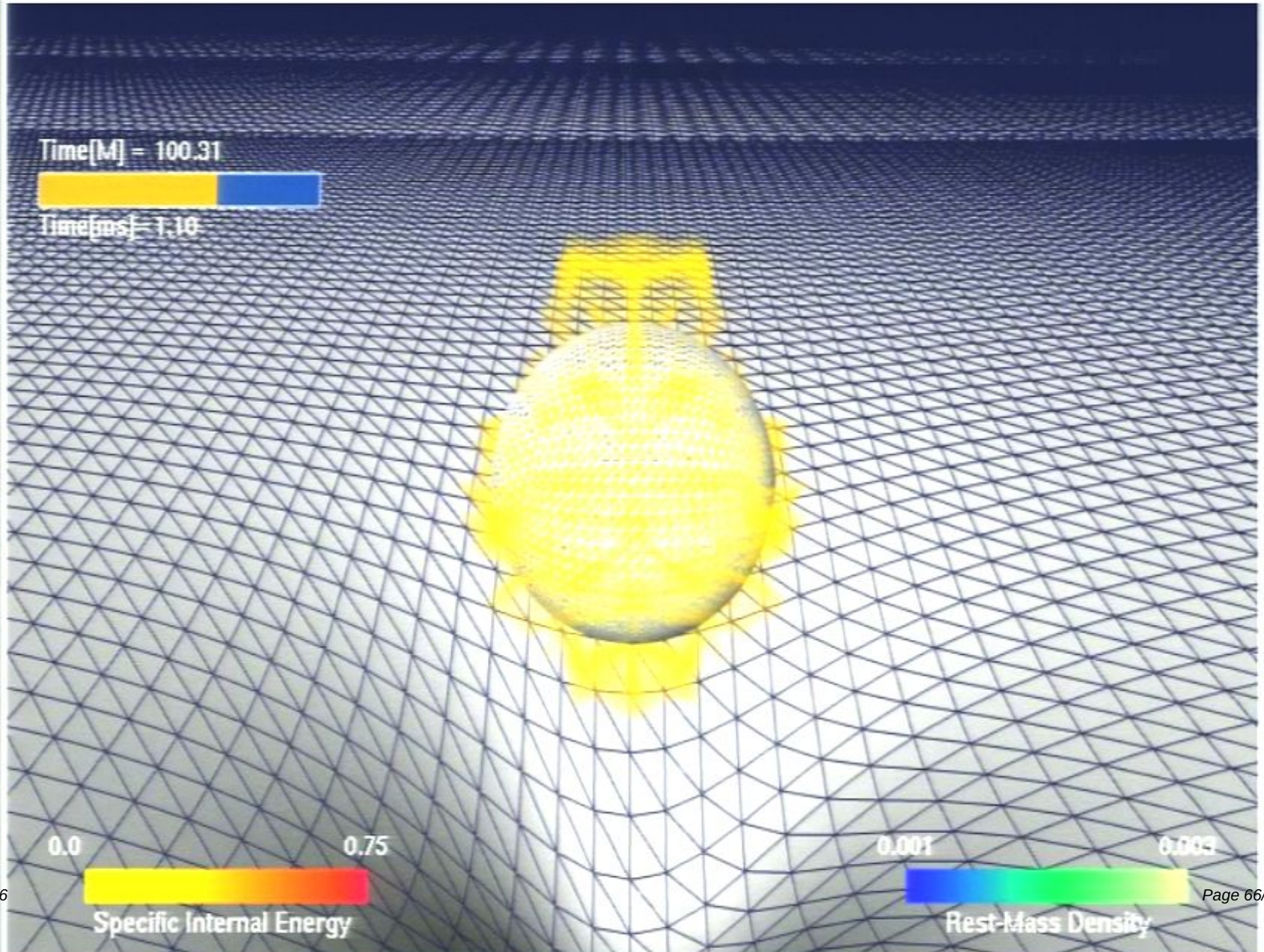

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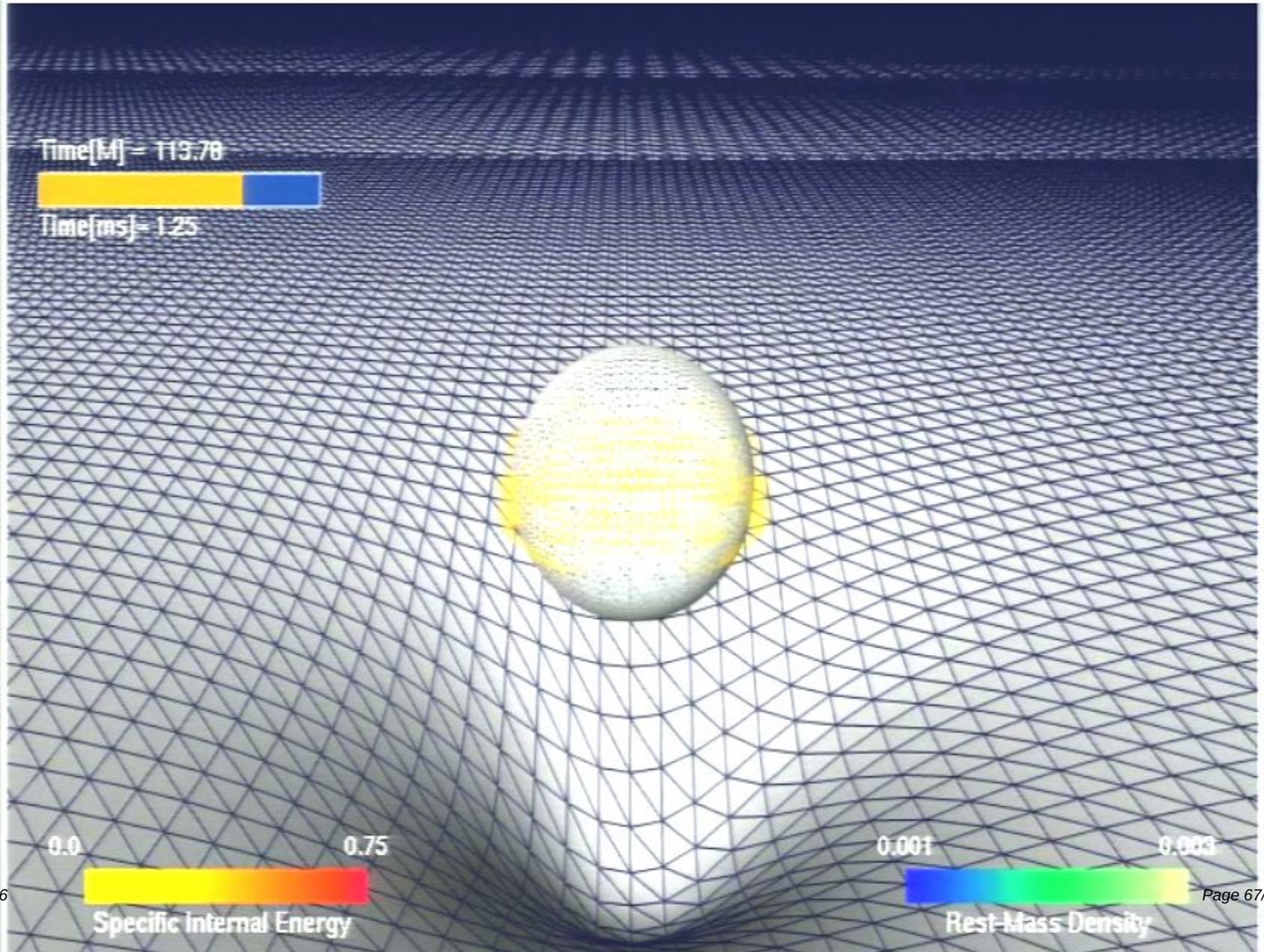

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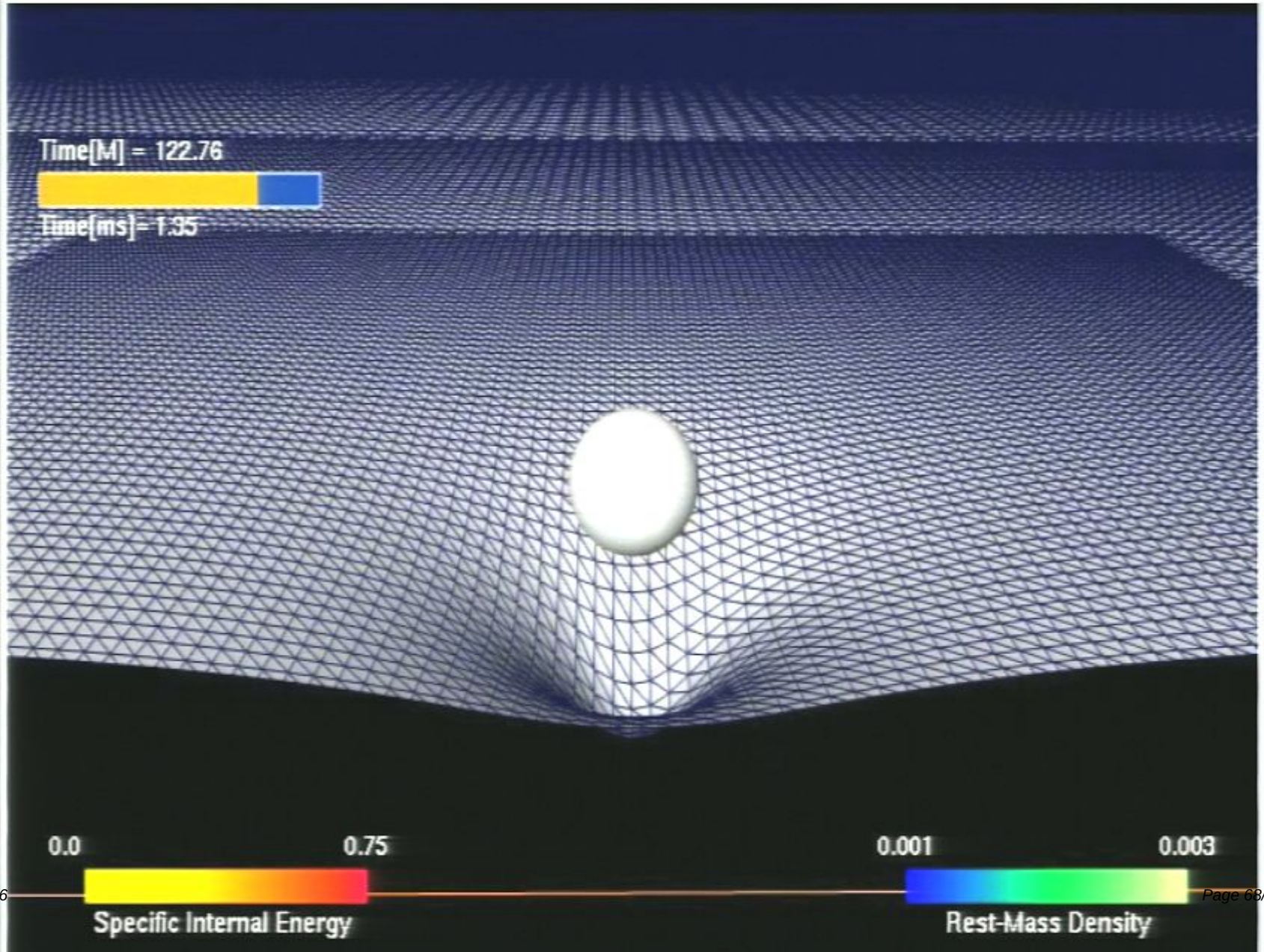

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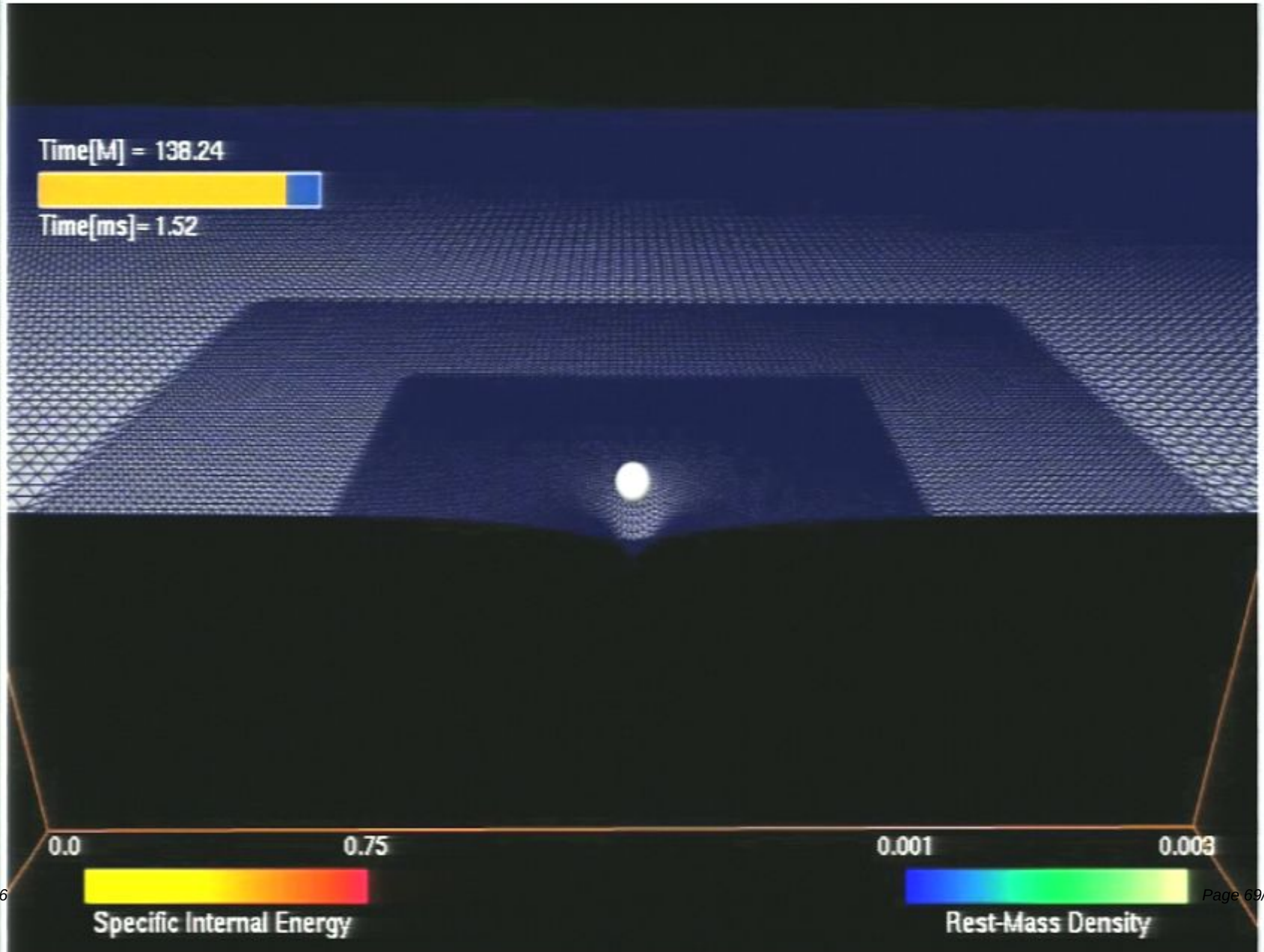

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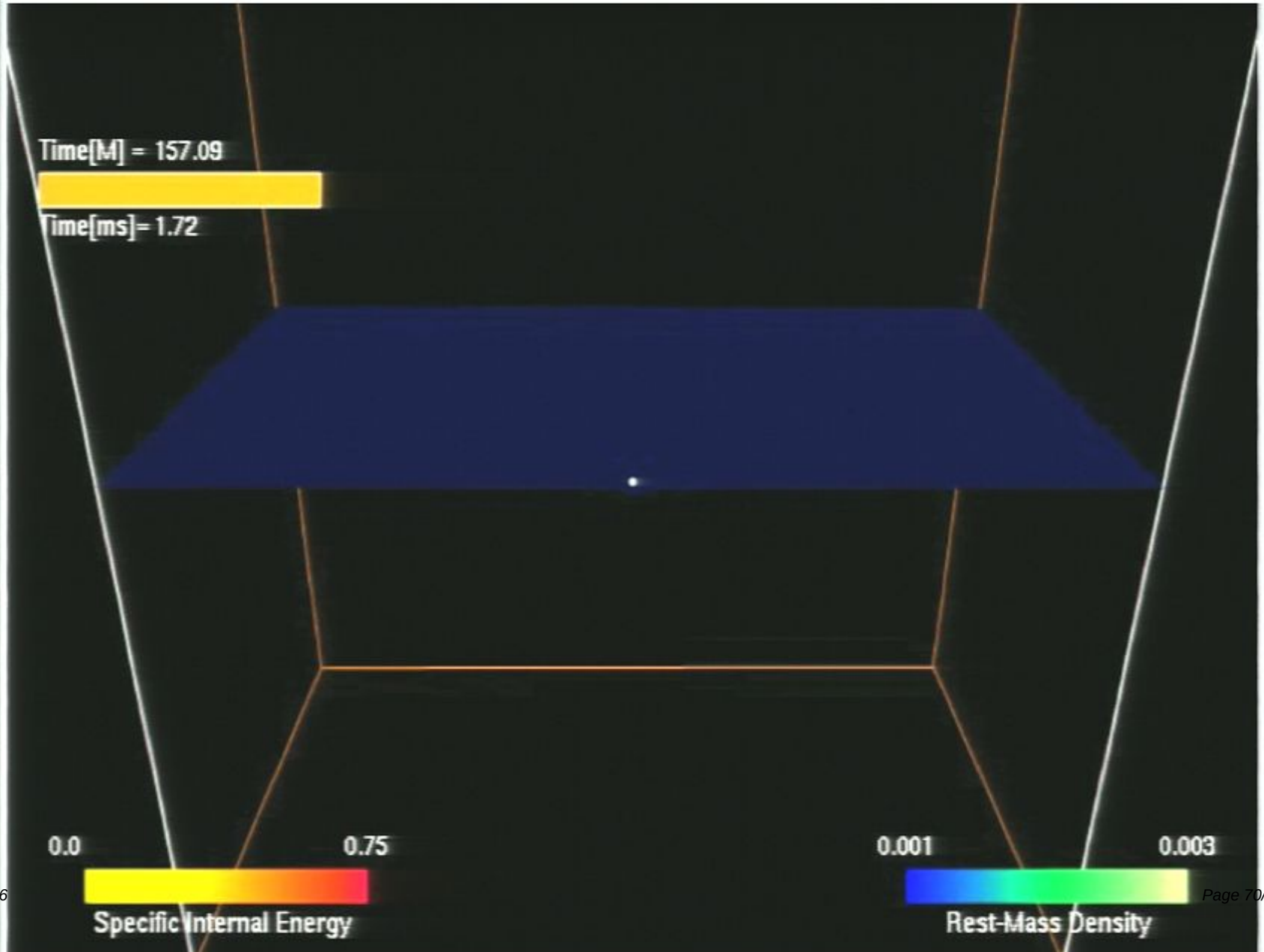
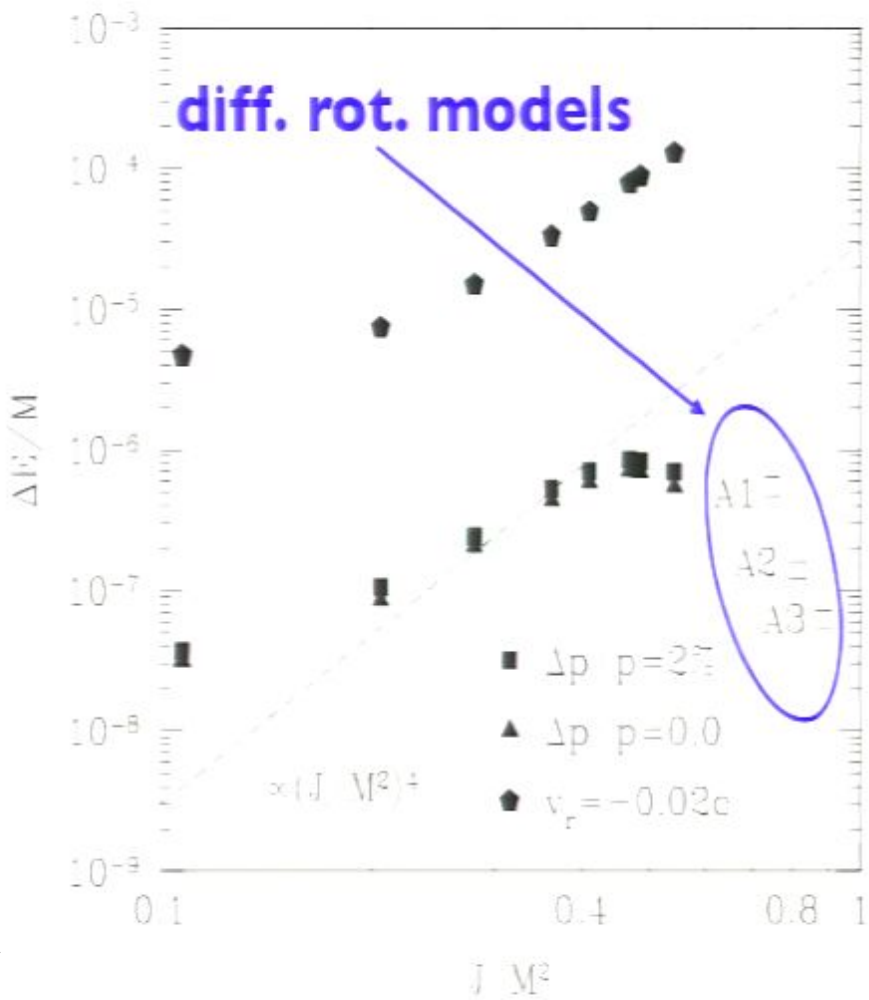


Characterizing the energy emission

Energy emission



Note the very steep decrease in the energy efficiency as the spin (J/M^2) is increased.

SNR for a source at 10 kpc

Slow	Rapid	Diffrntl rotation	detector
0.2	2.1	3.8	Virgo/LIGO
1.2	11	37.5	Advanced
3.3	28	21.6	Dual

Collapse of a supra-Kerr model

Equally simple is to construct supra-Kerr models.

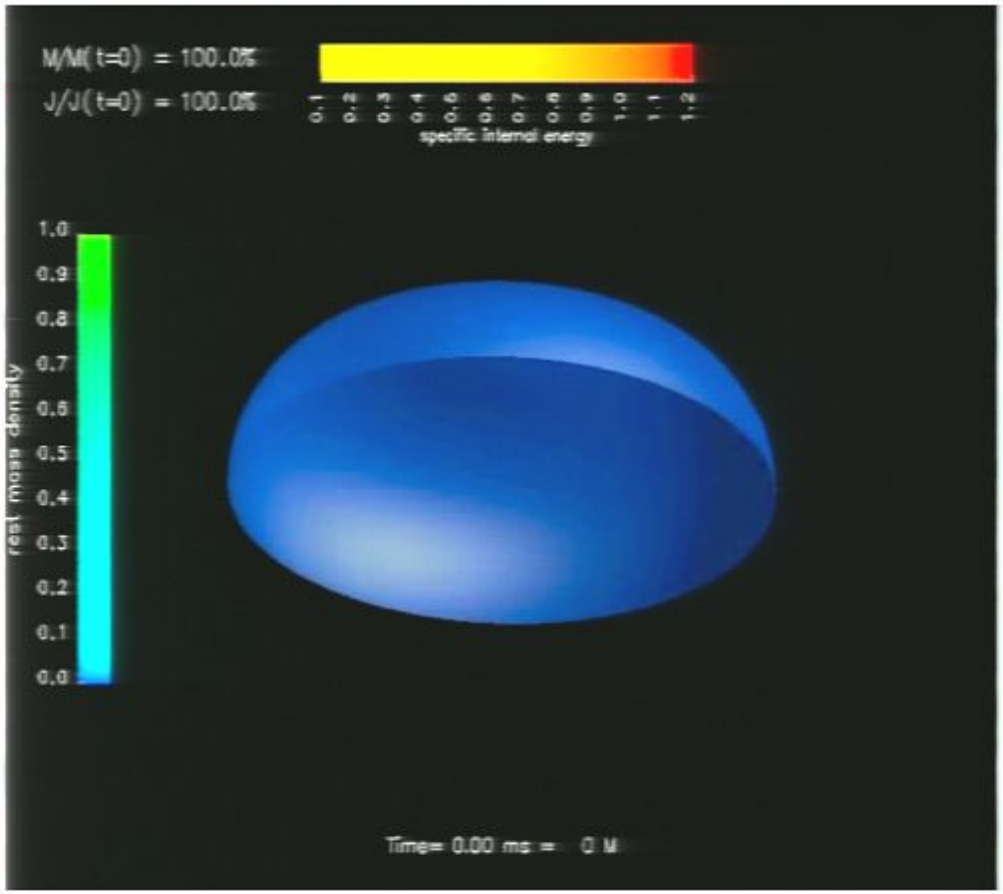
As an example **B1**:

$M = 1.91\ M_\odot$; $r_p/r_e = 0.39$

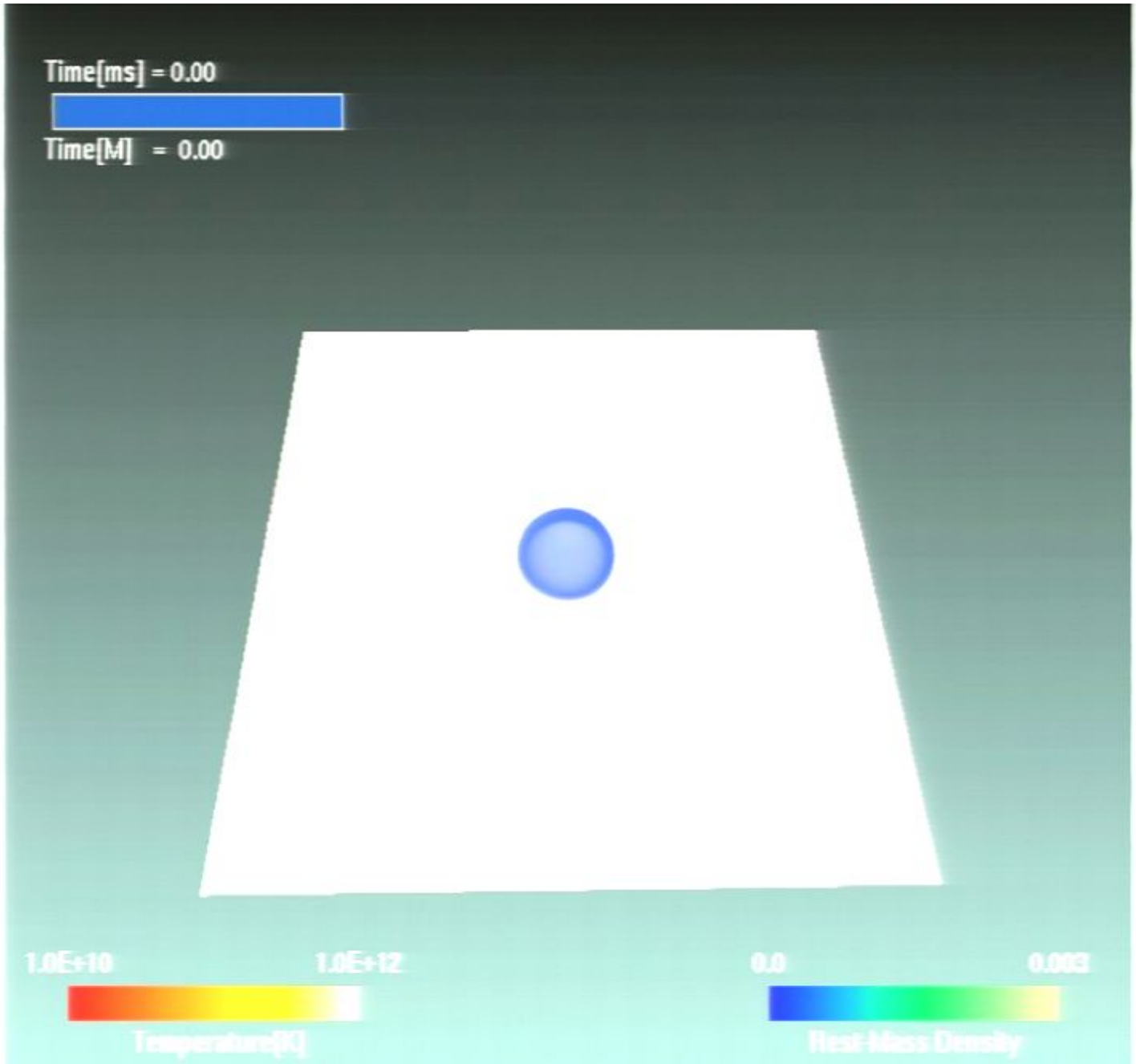
$J/M^2 = 1.09$; $T/|W| = 0.22$

$\Gamma = 2$

Note the collapse was triggered with a pressure depletion of **99%**



COLLAPSE OF MODEL B1 (J/M^2=1.09)



Visualization by Kaehler, Giacomazzo, Rezzolla

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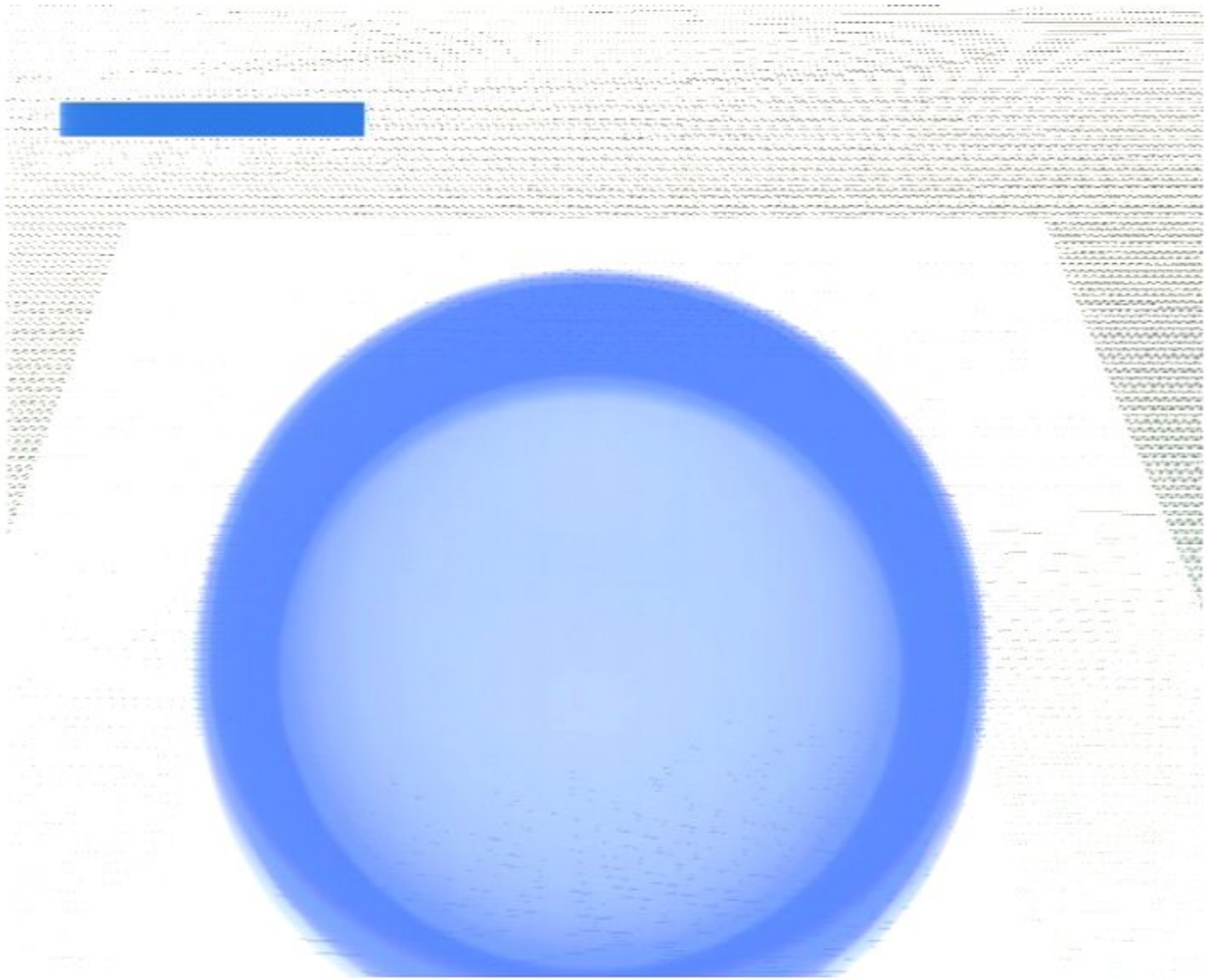

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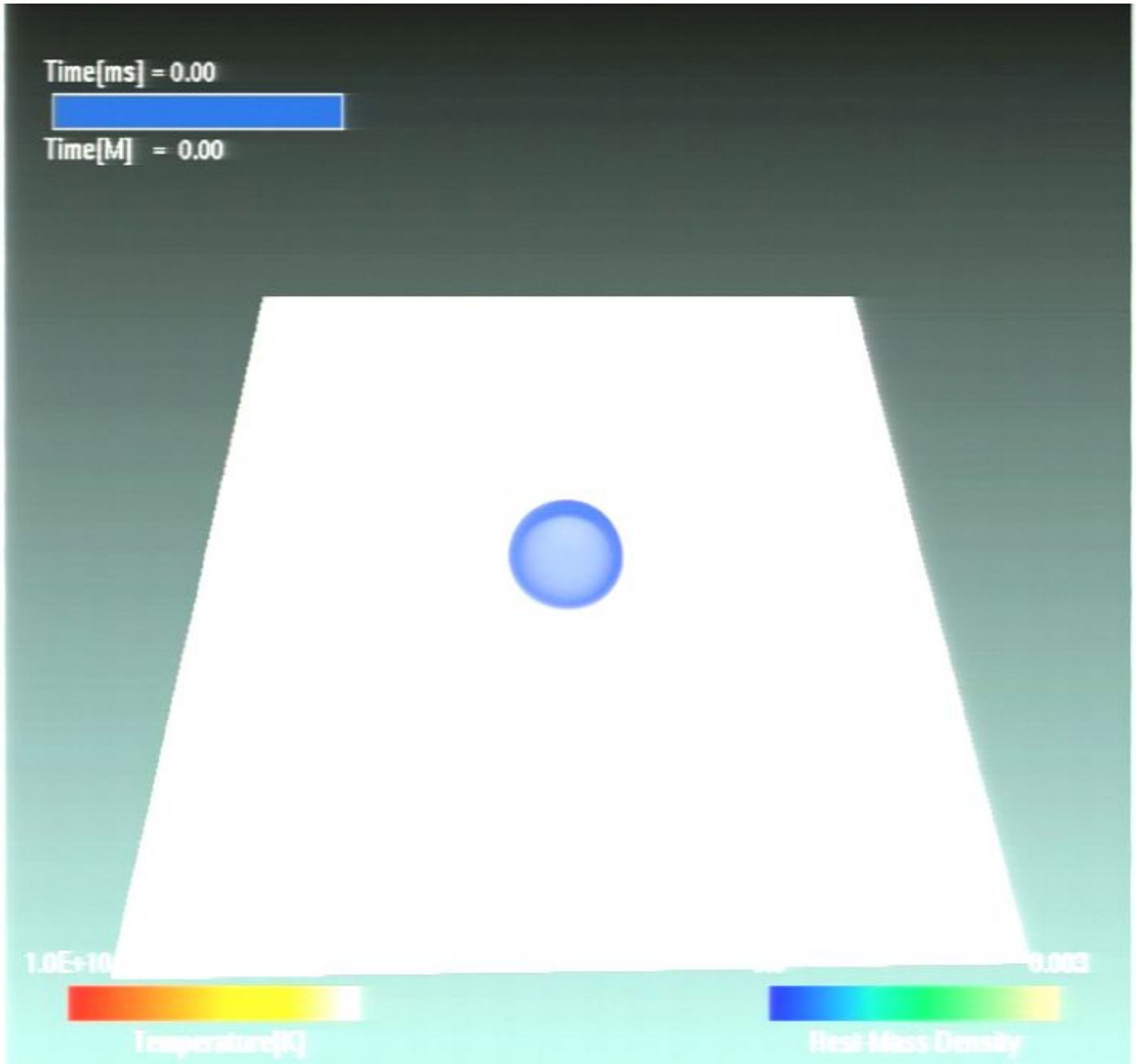

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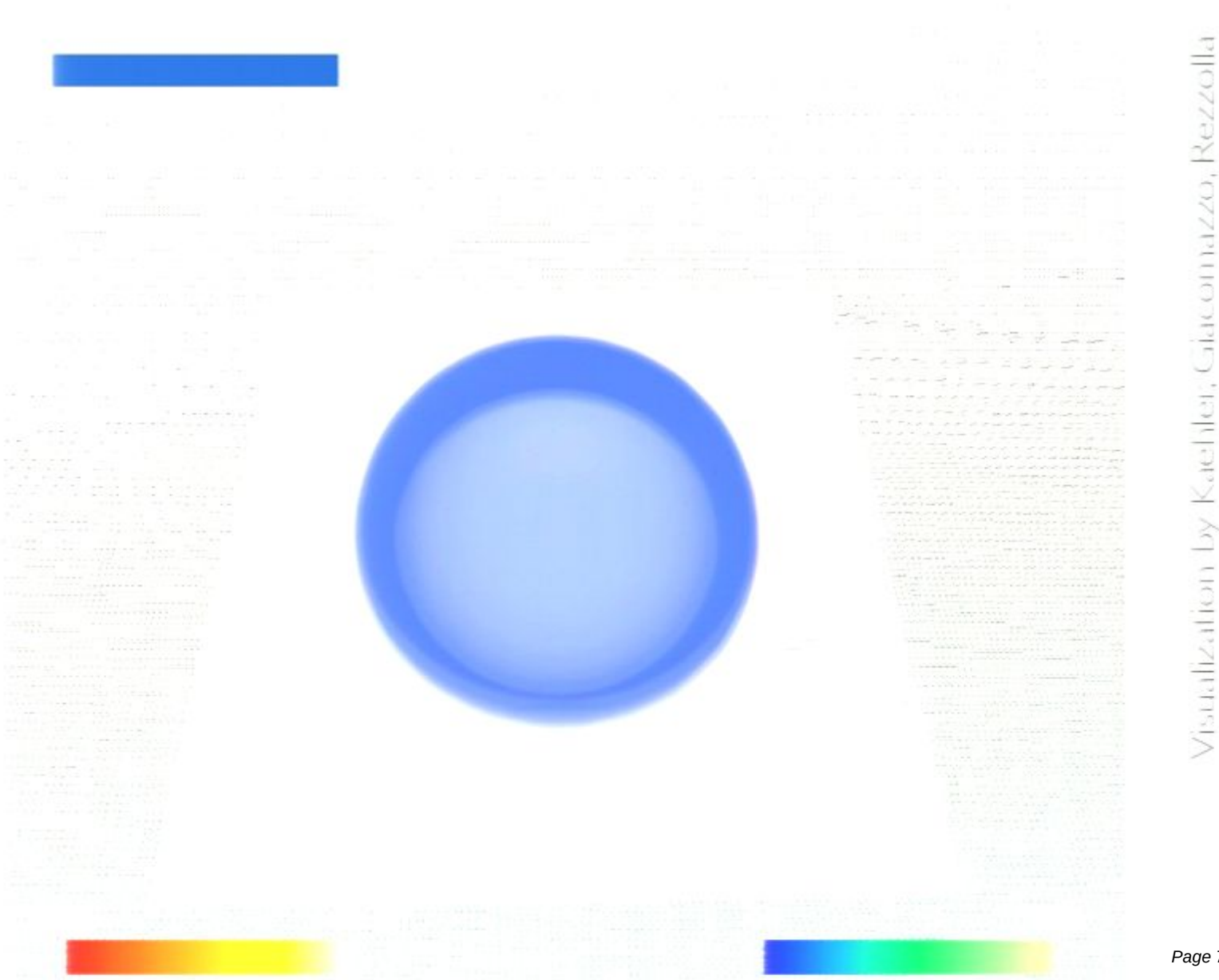

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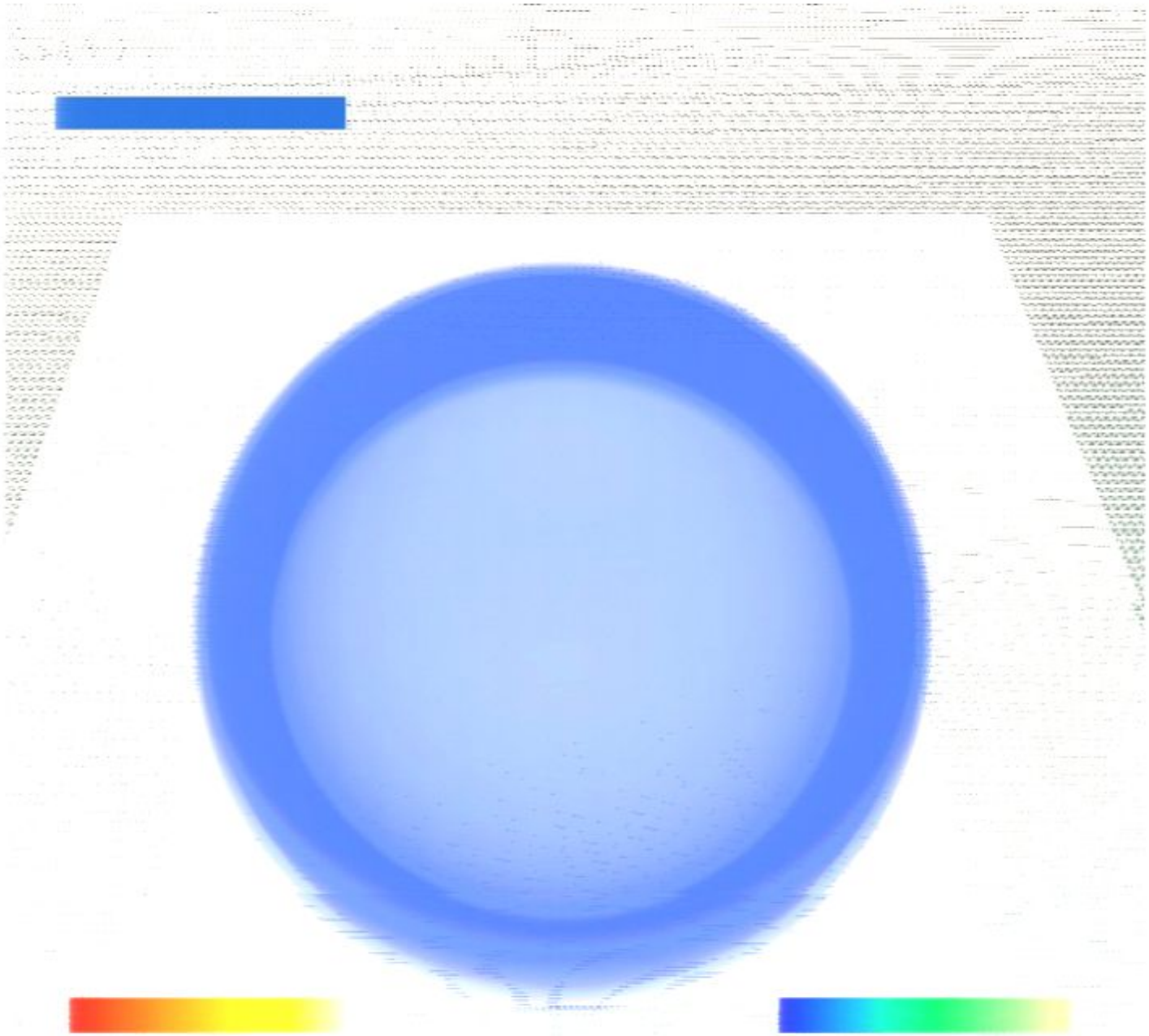

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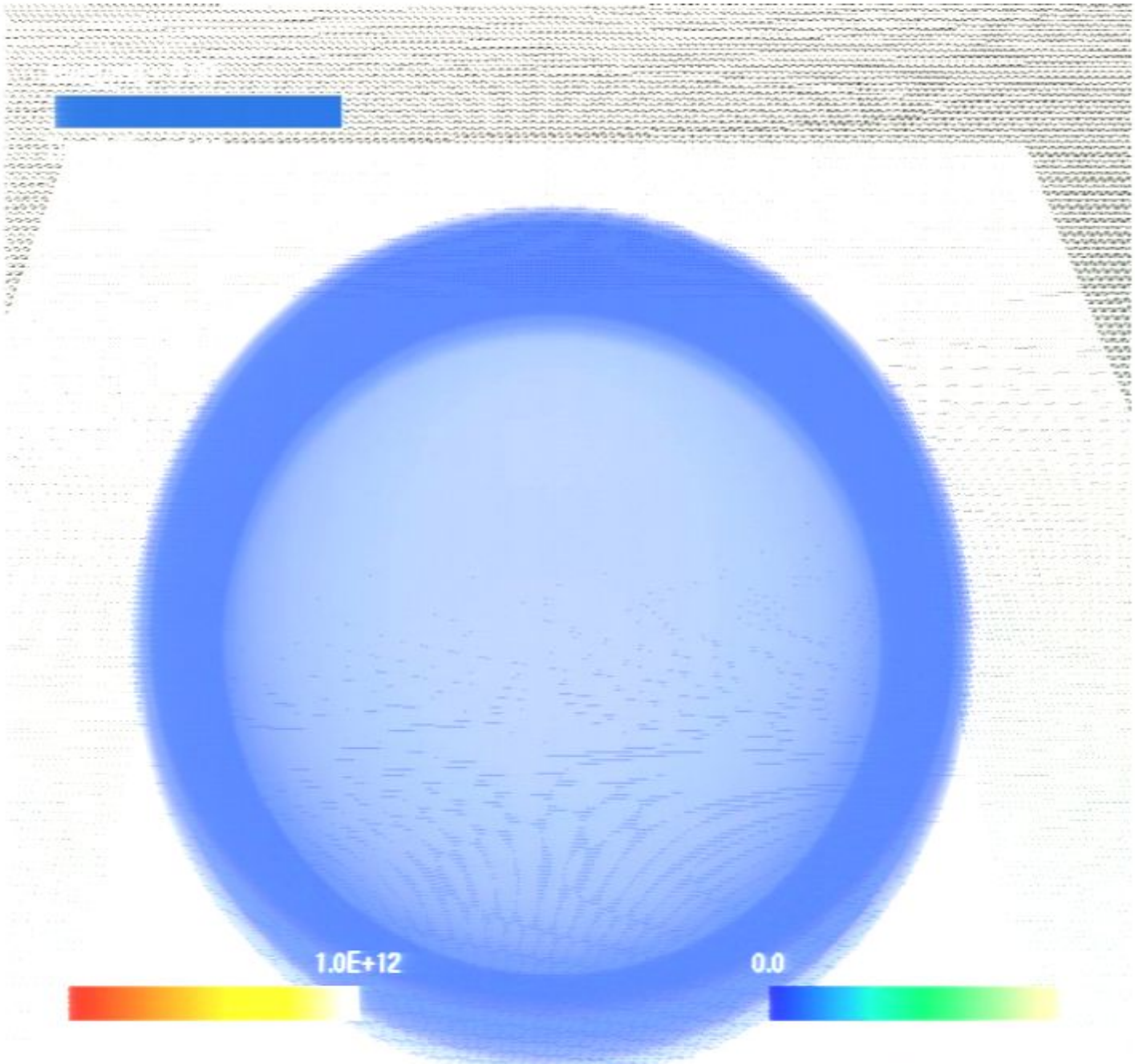

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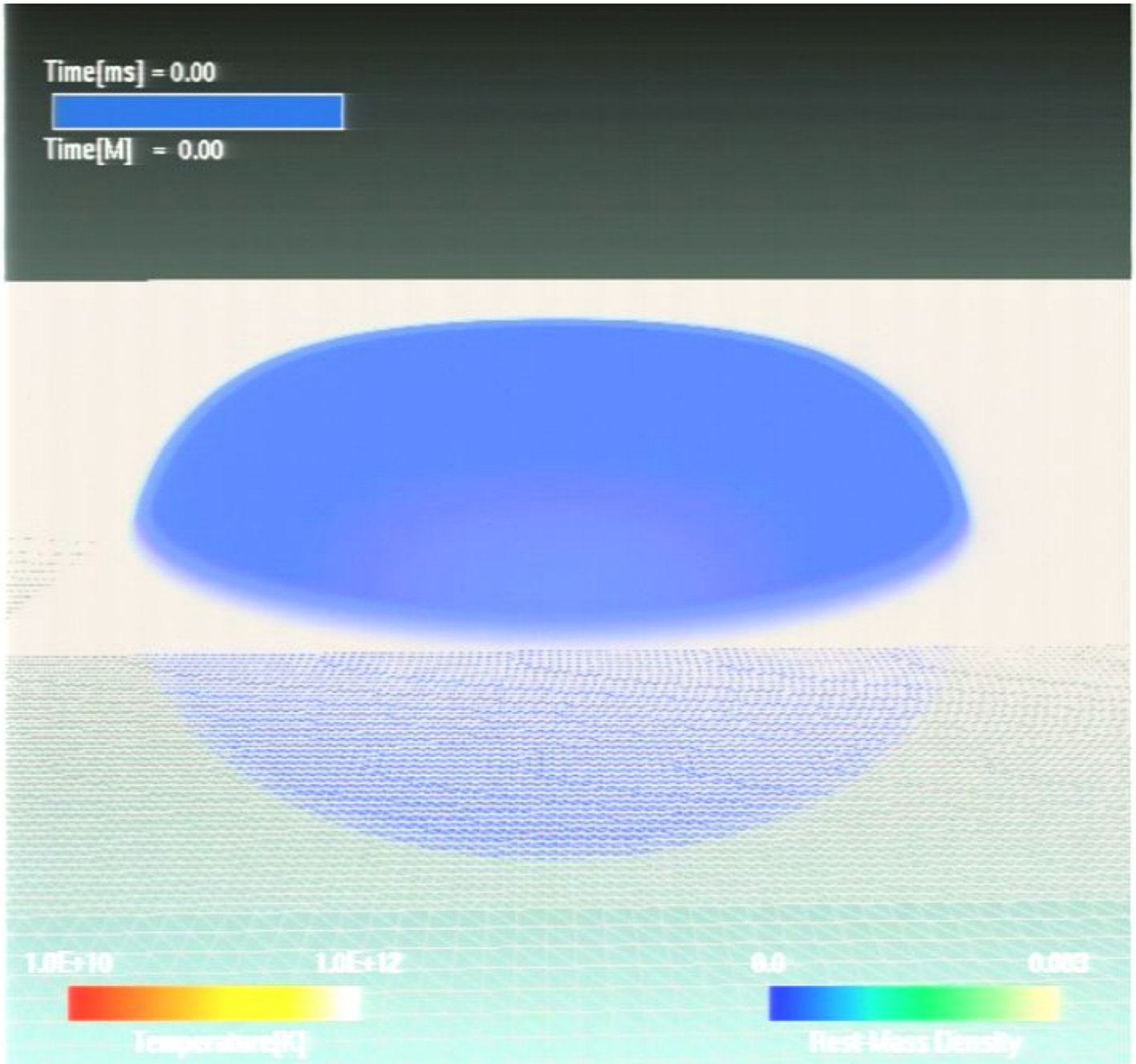

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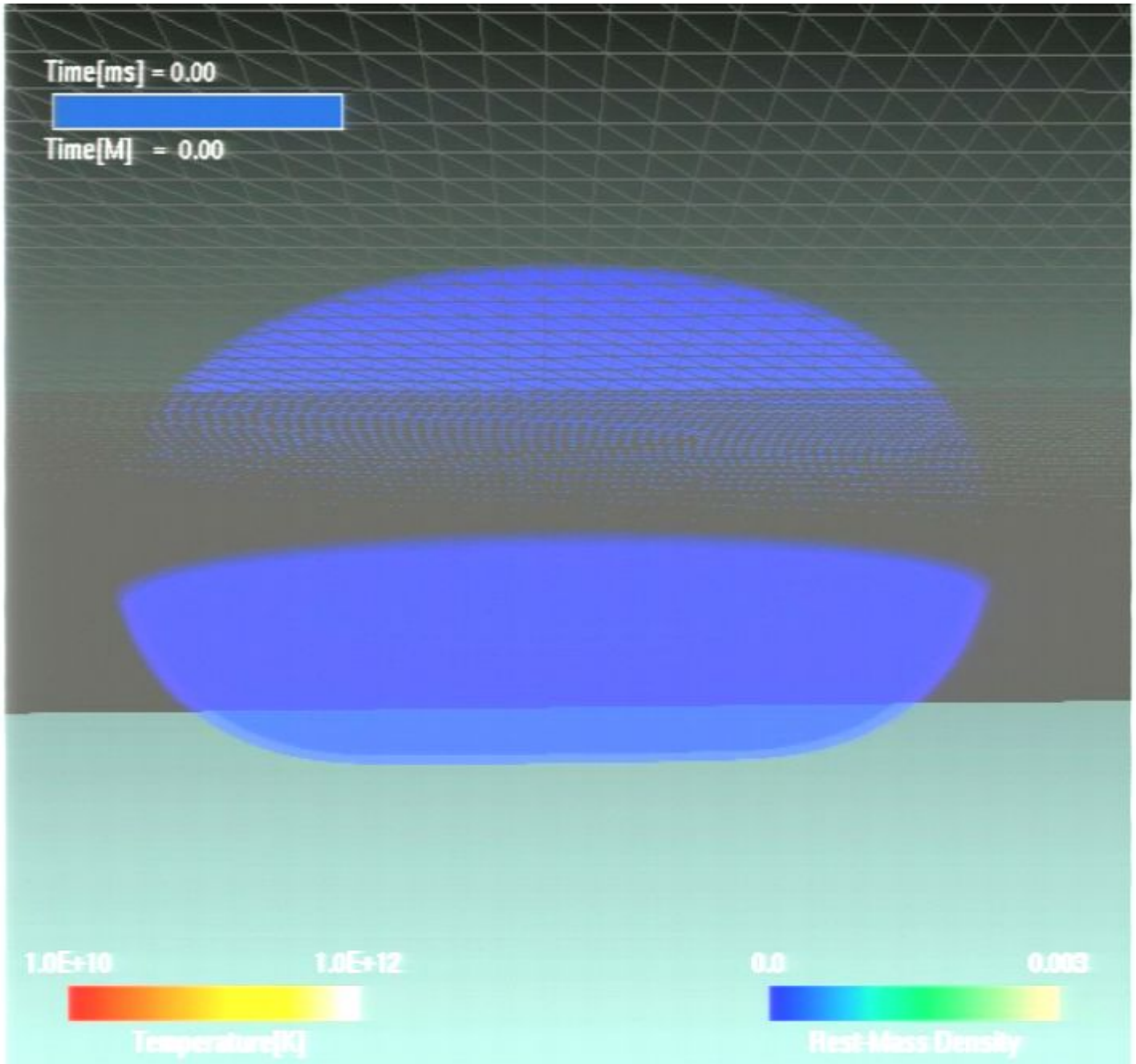

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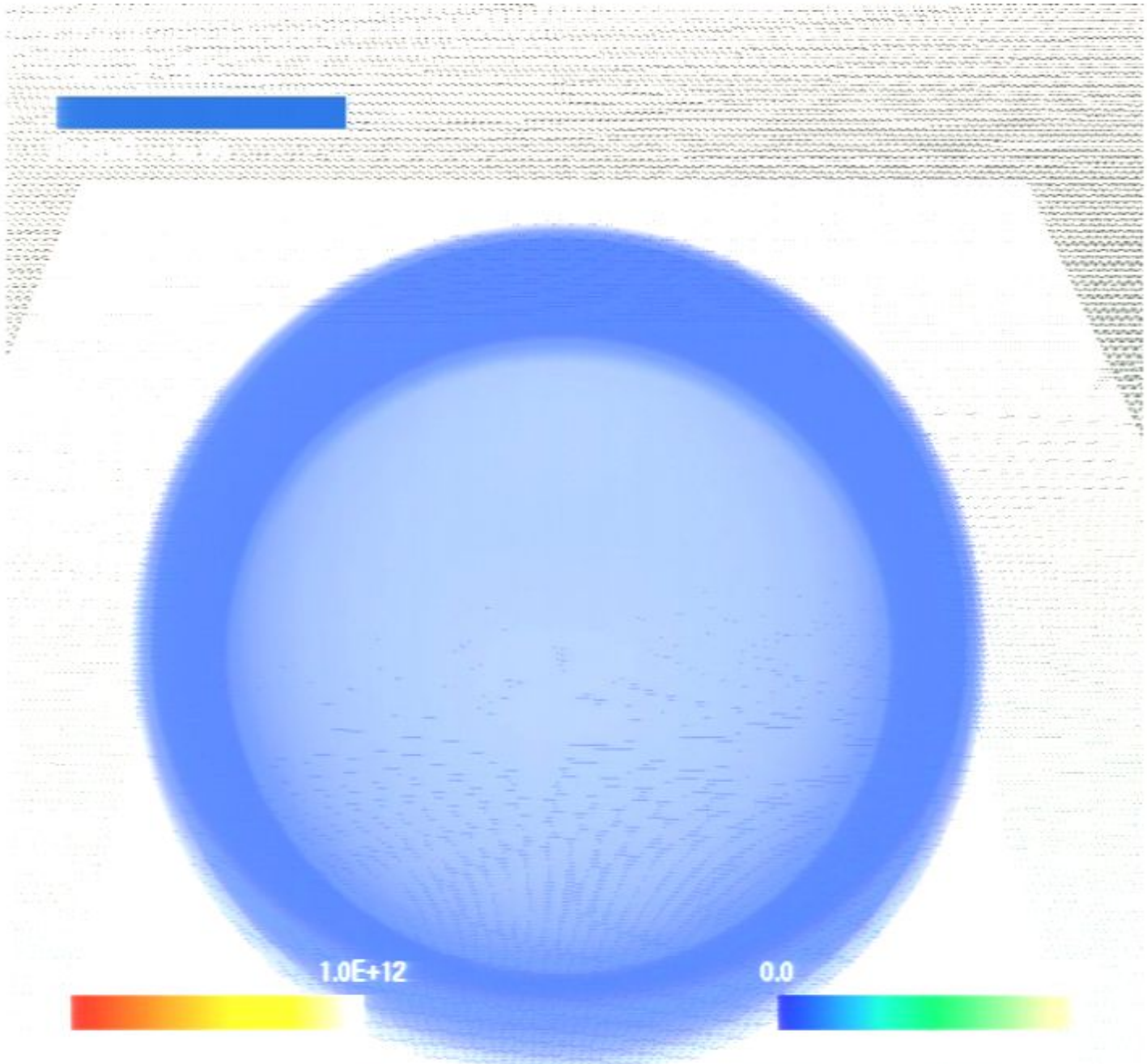

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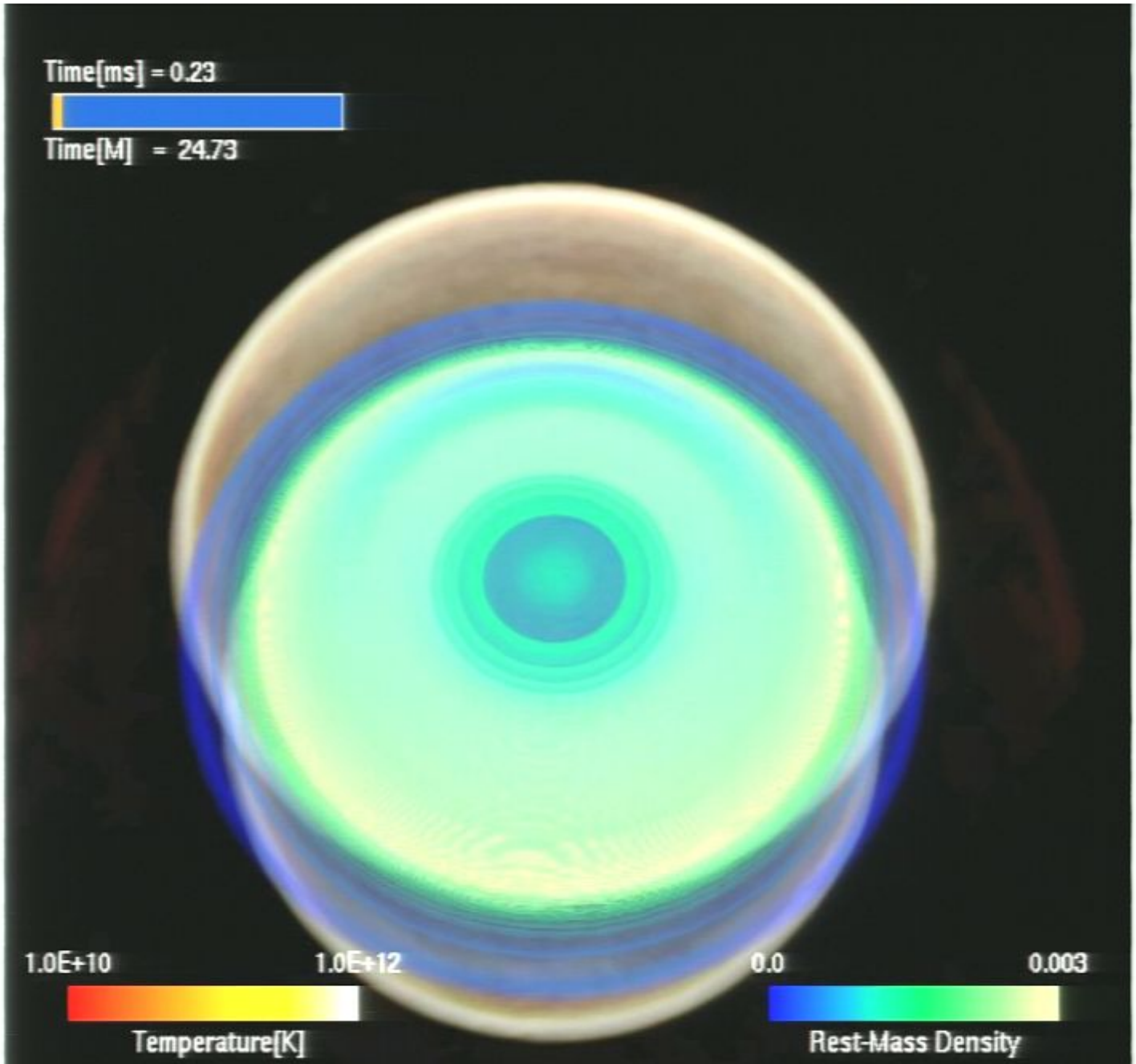

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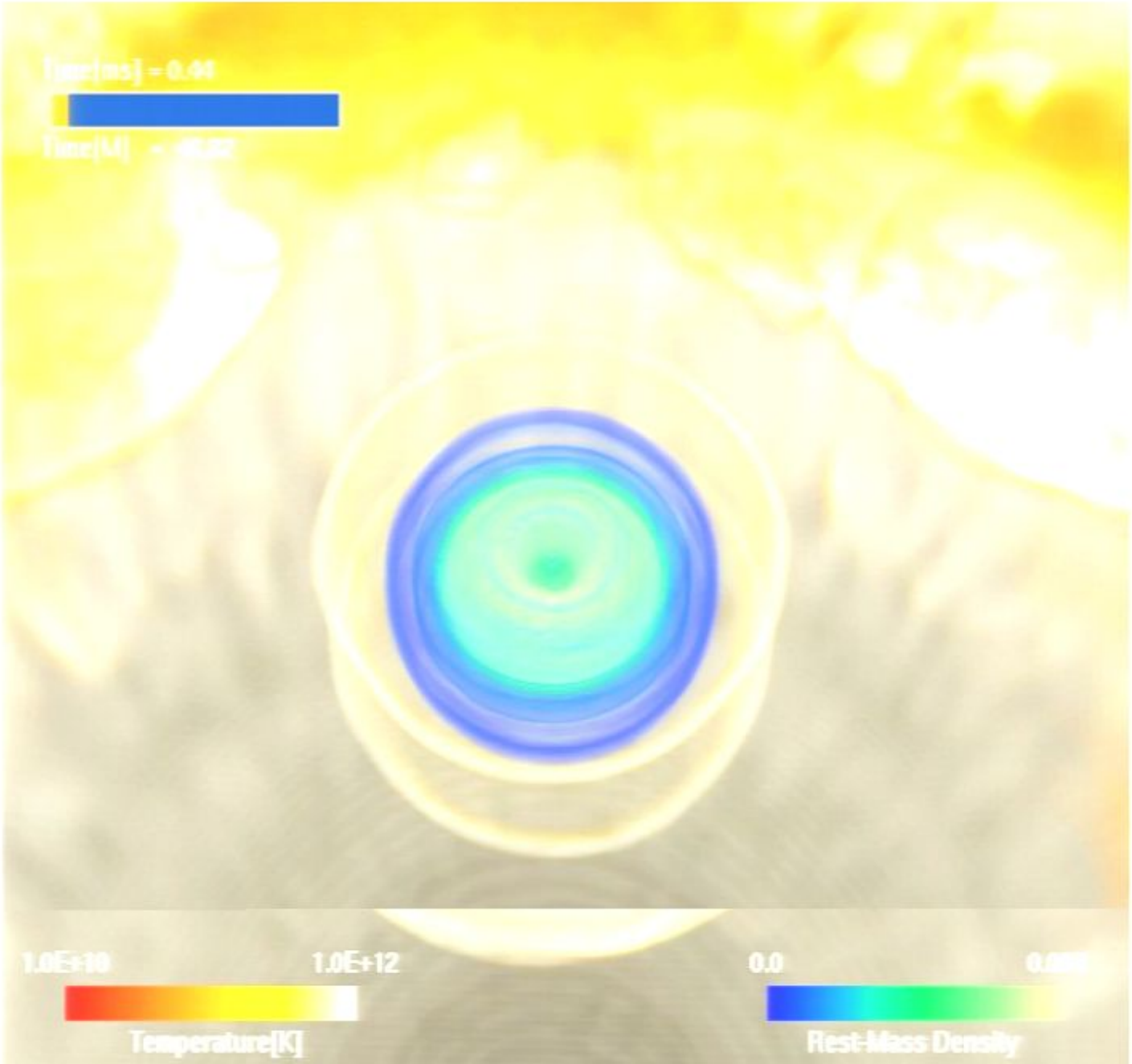

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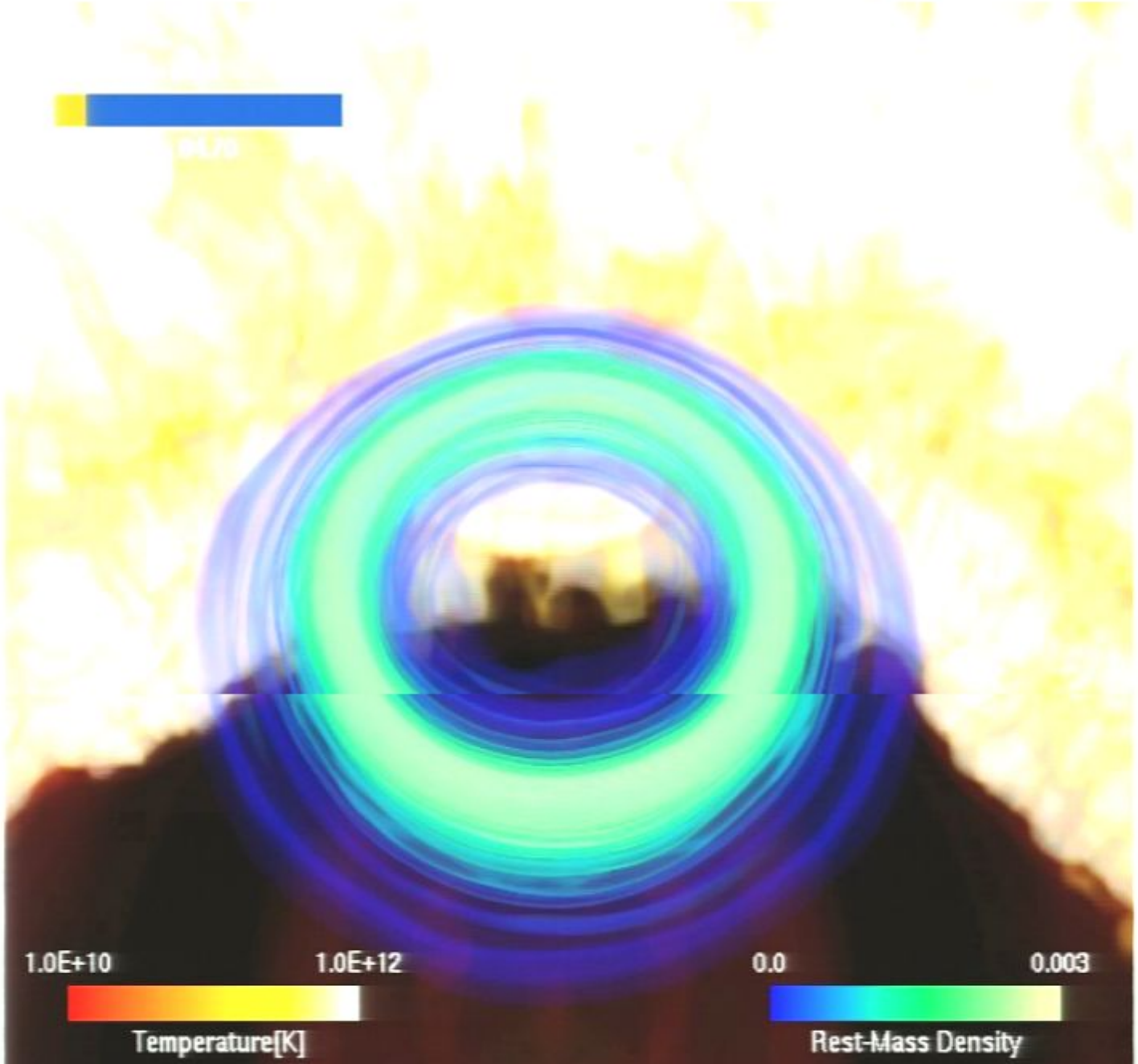

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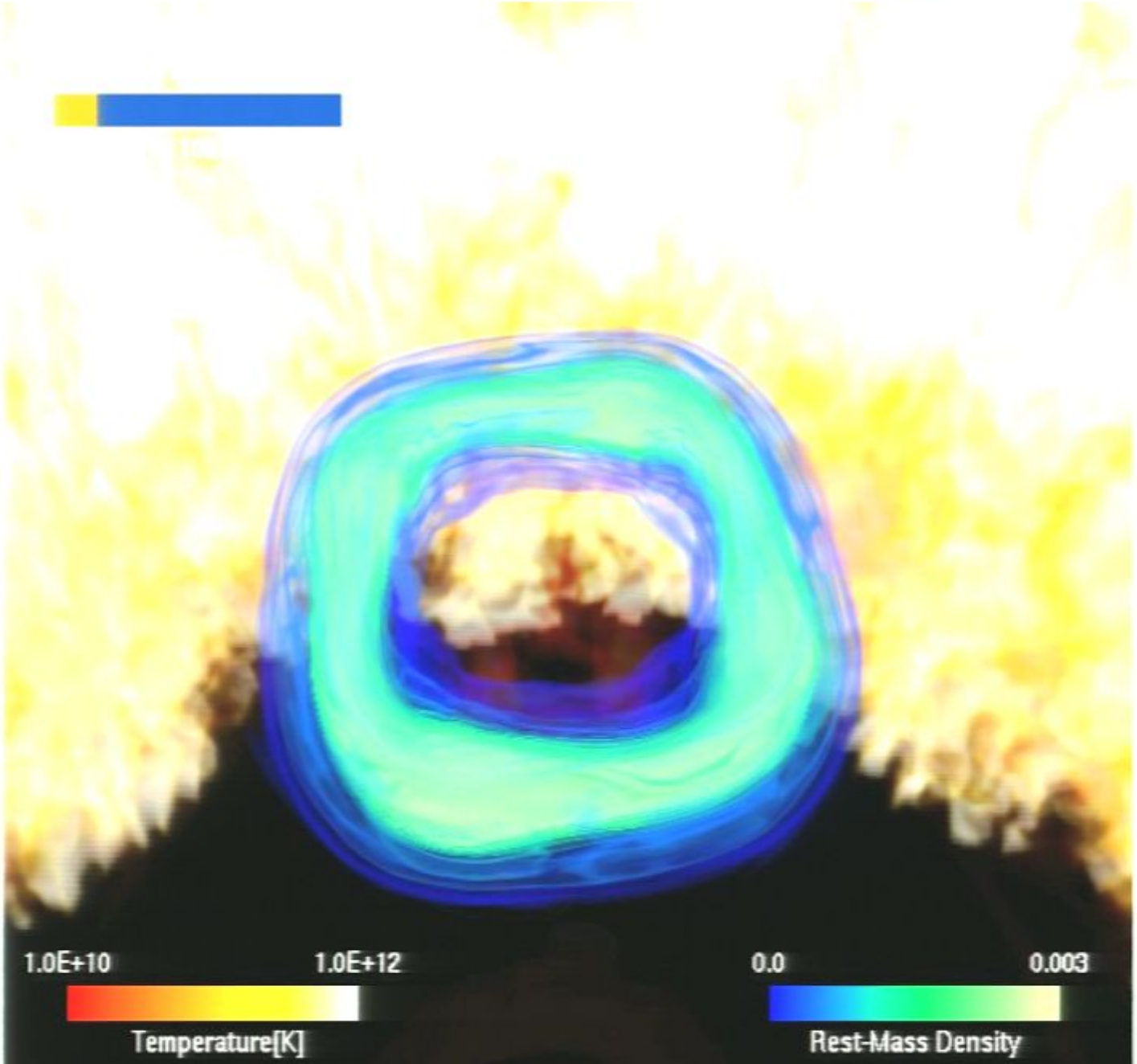

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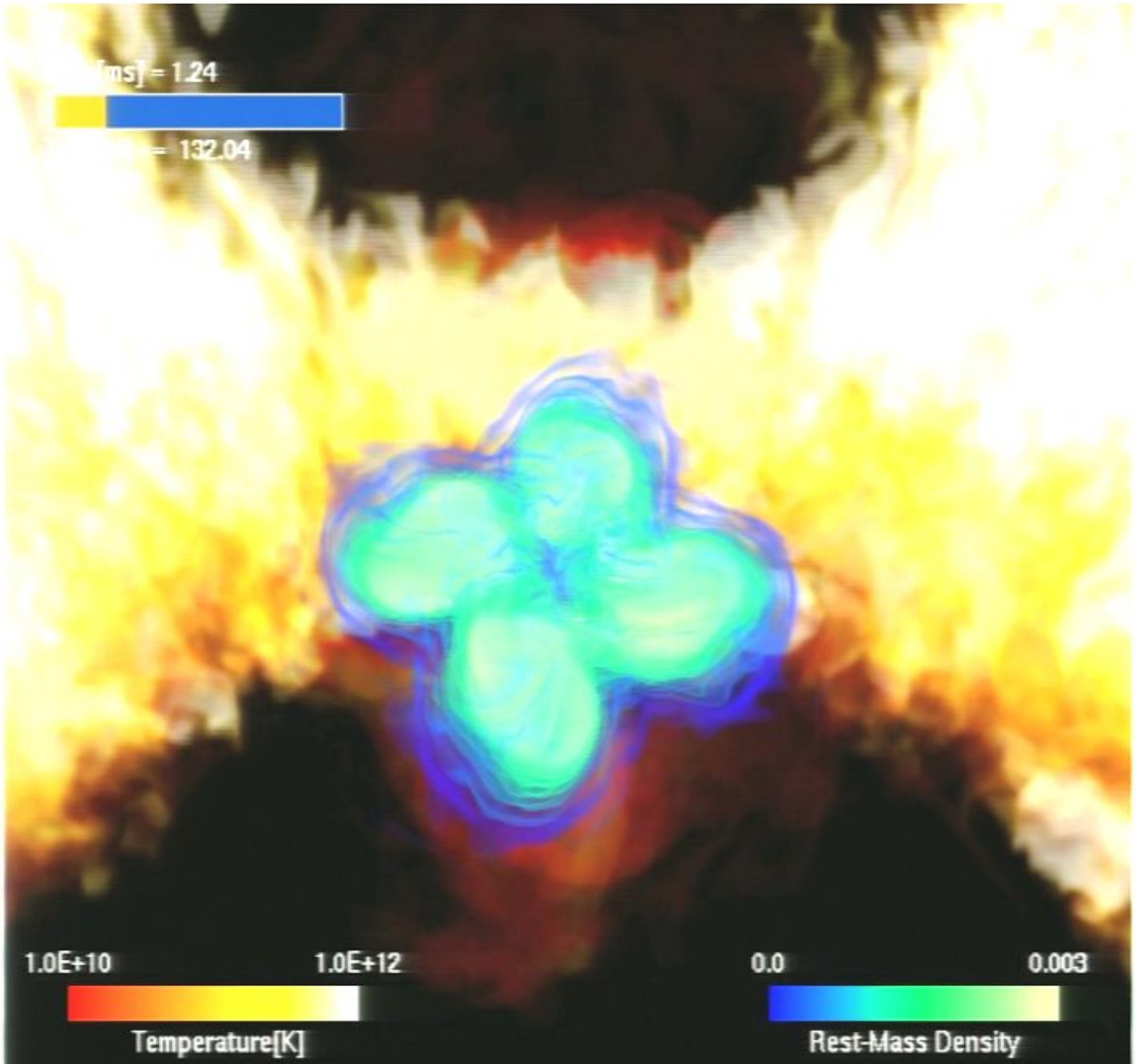

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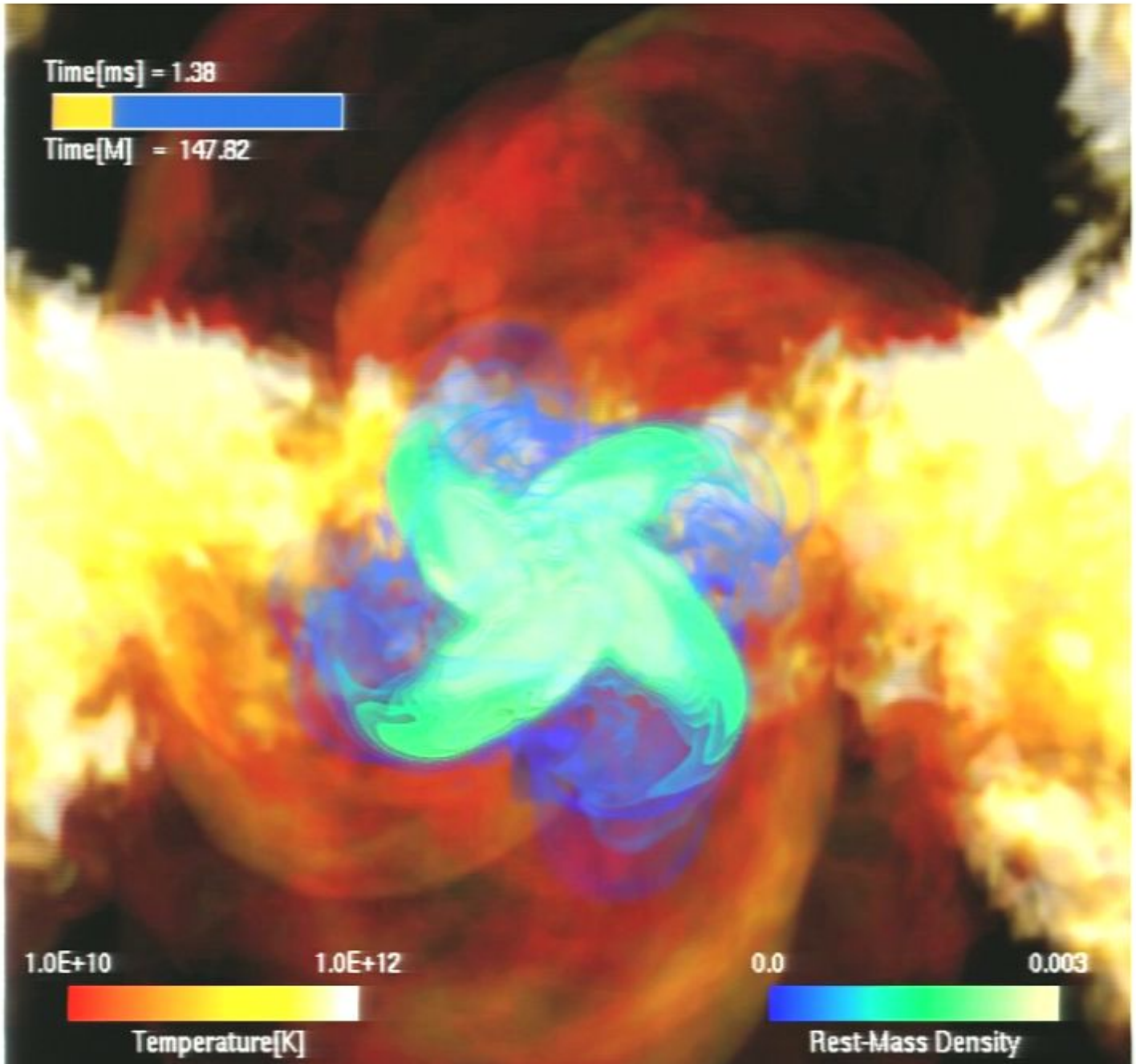

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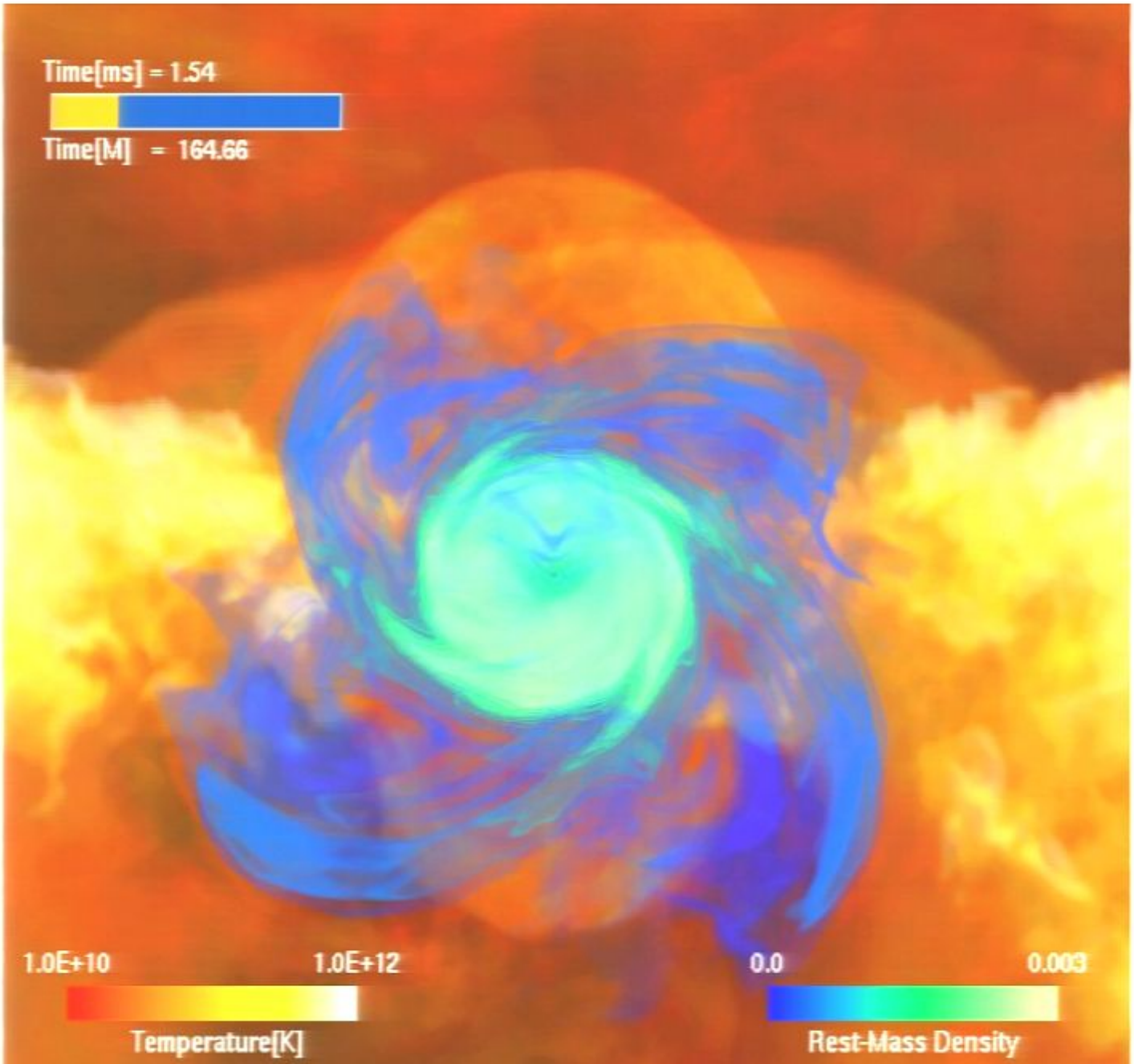

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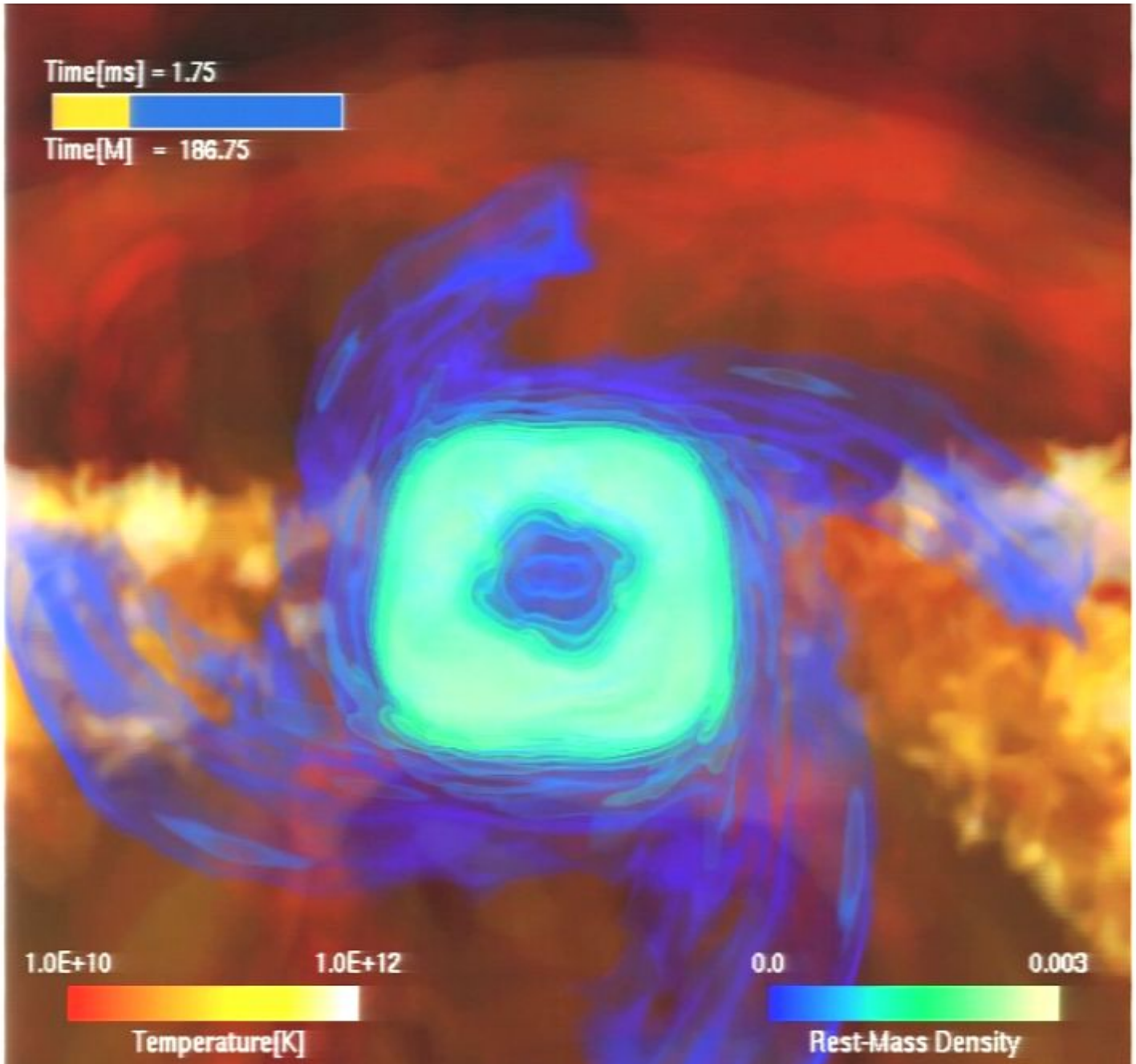

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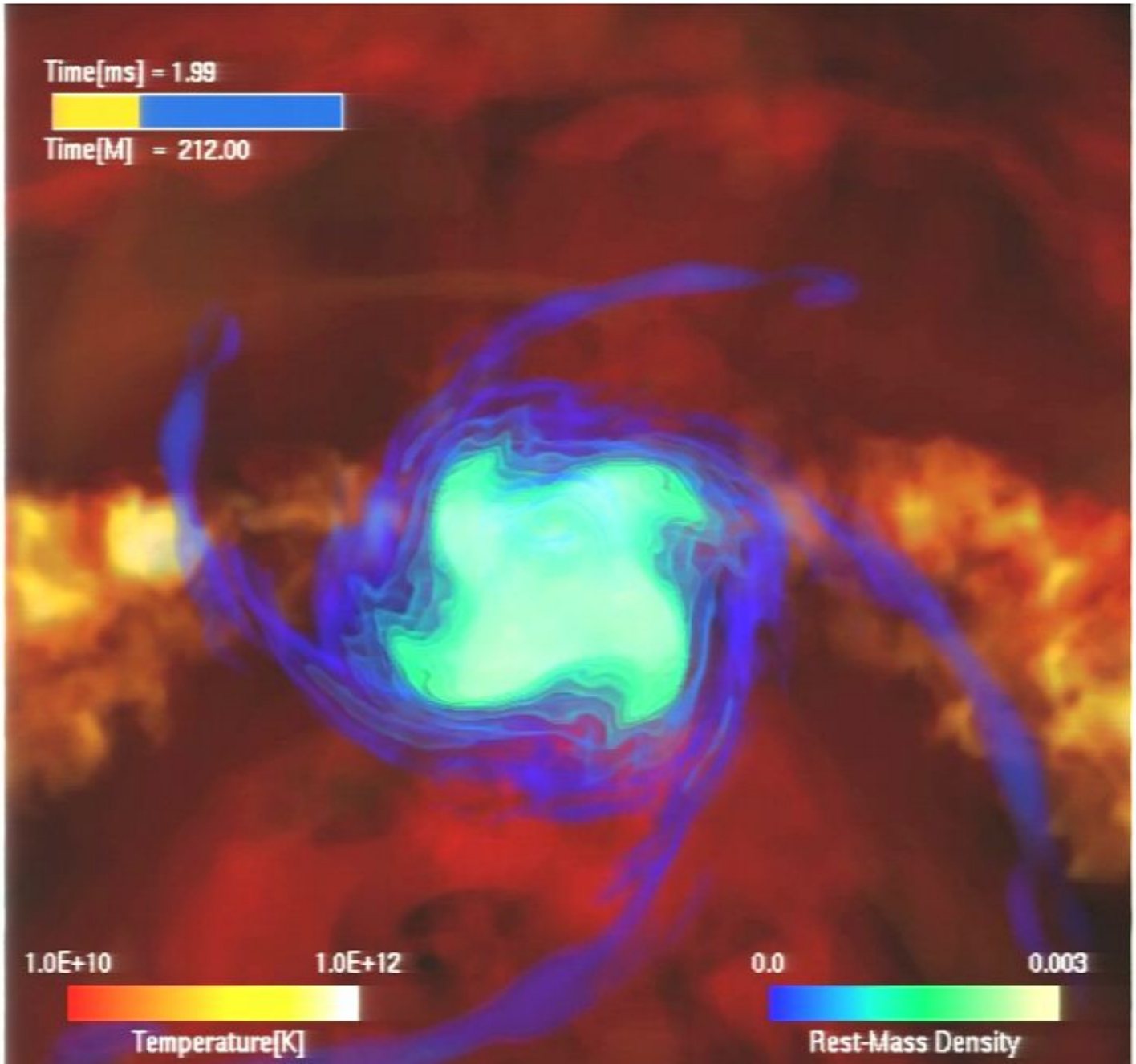

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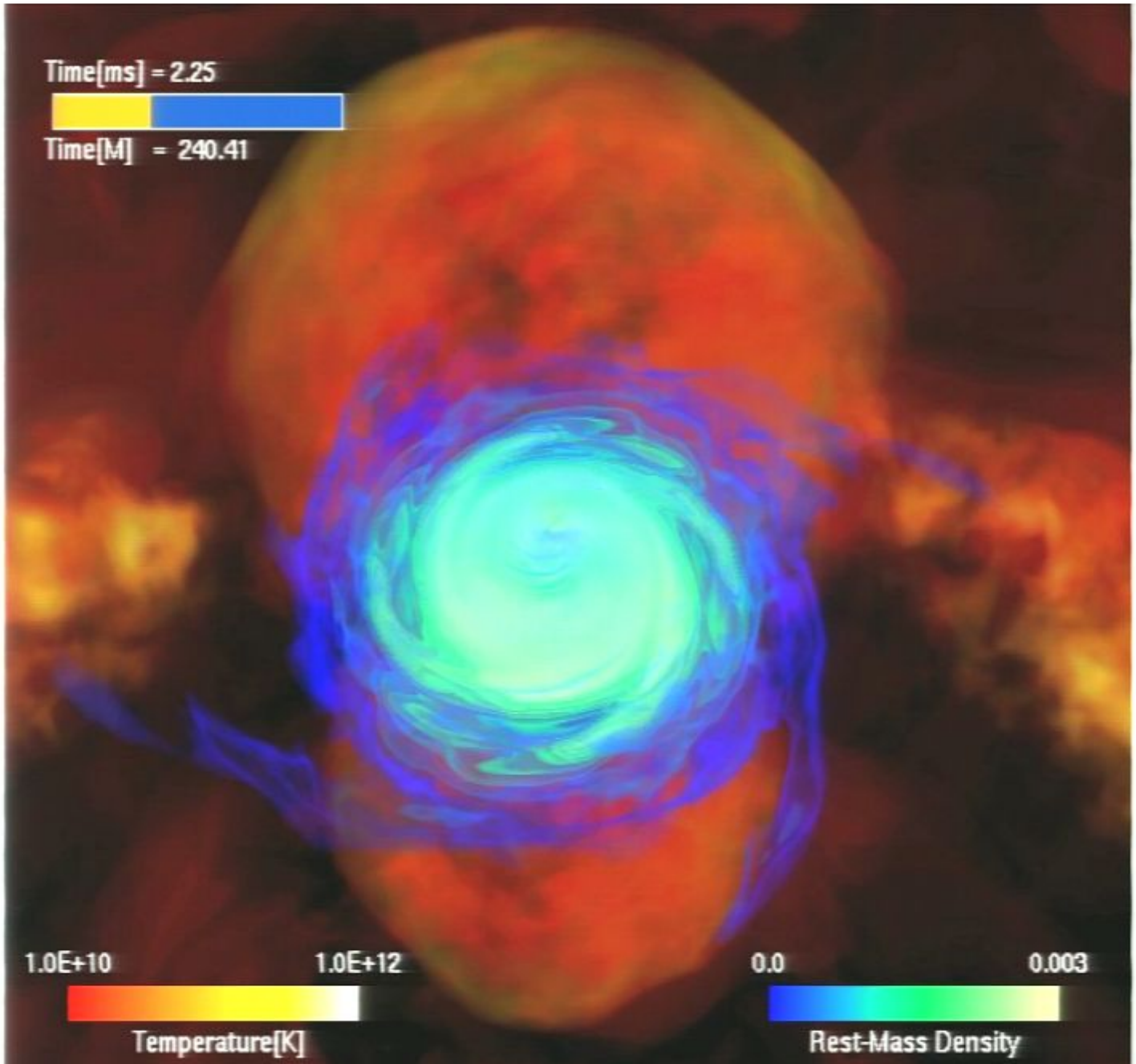

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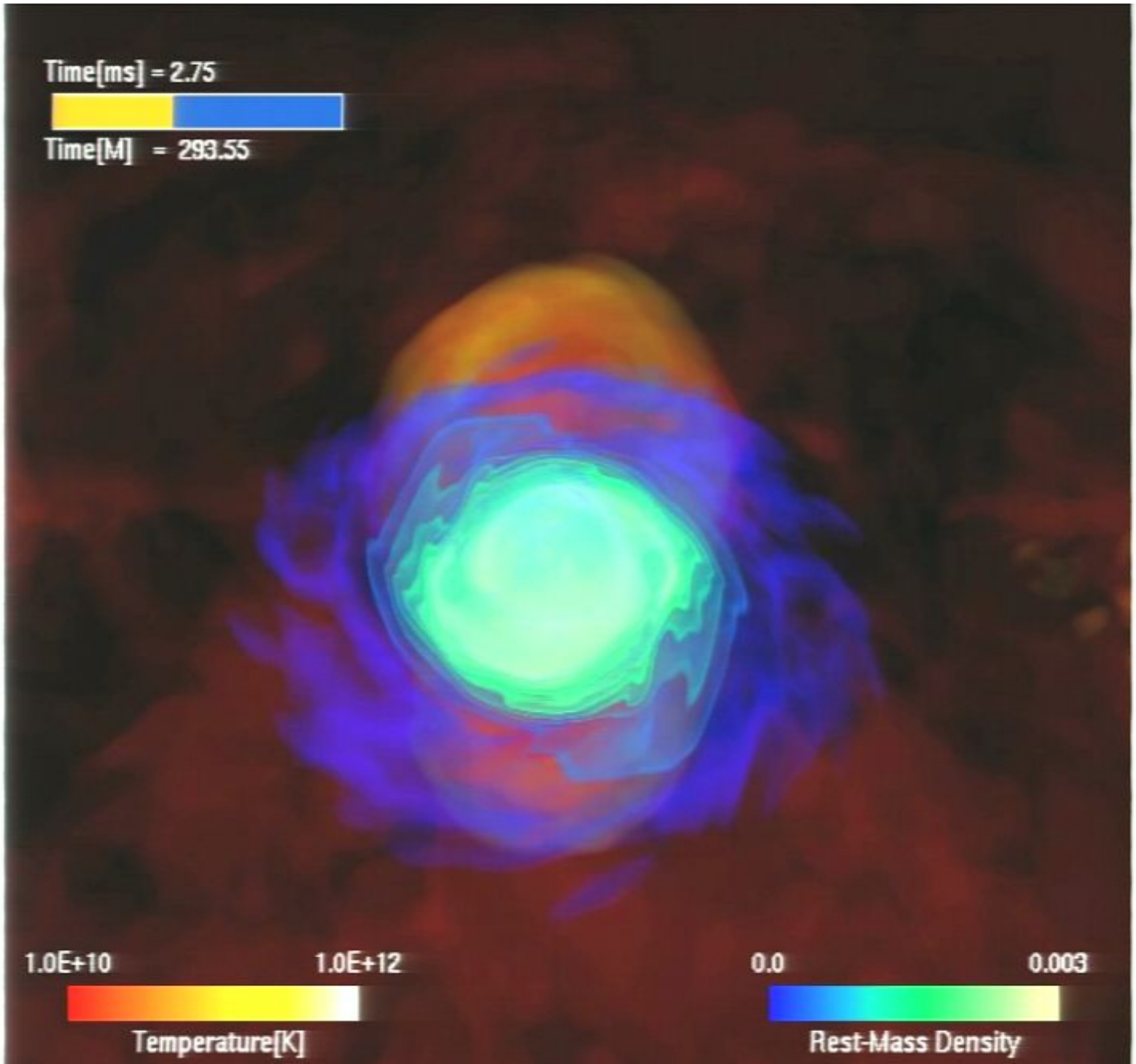

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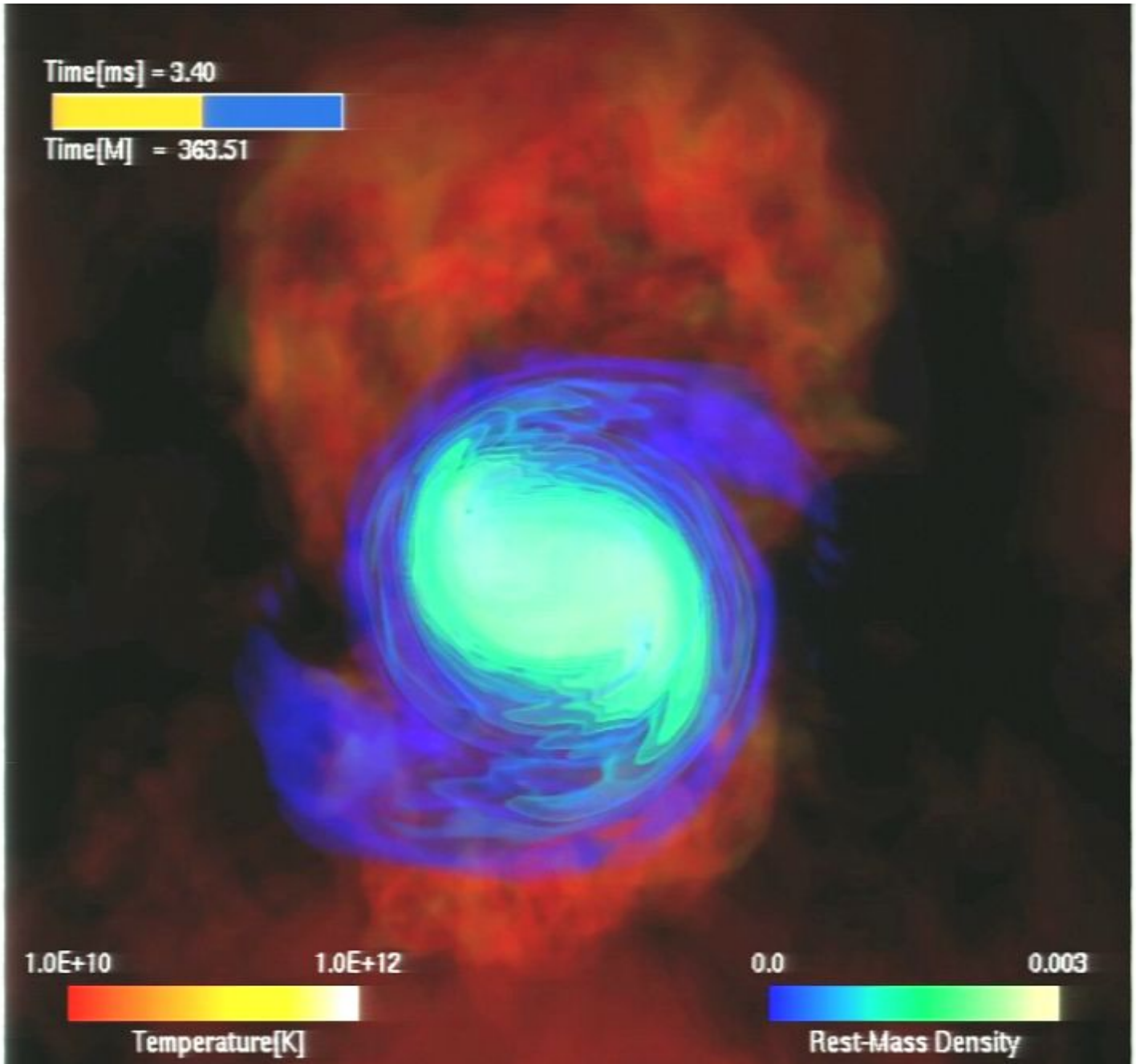

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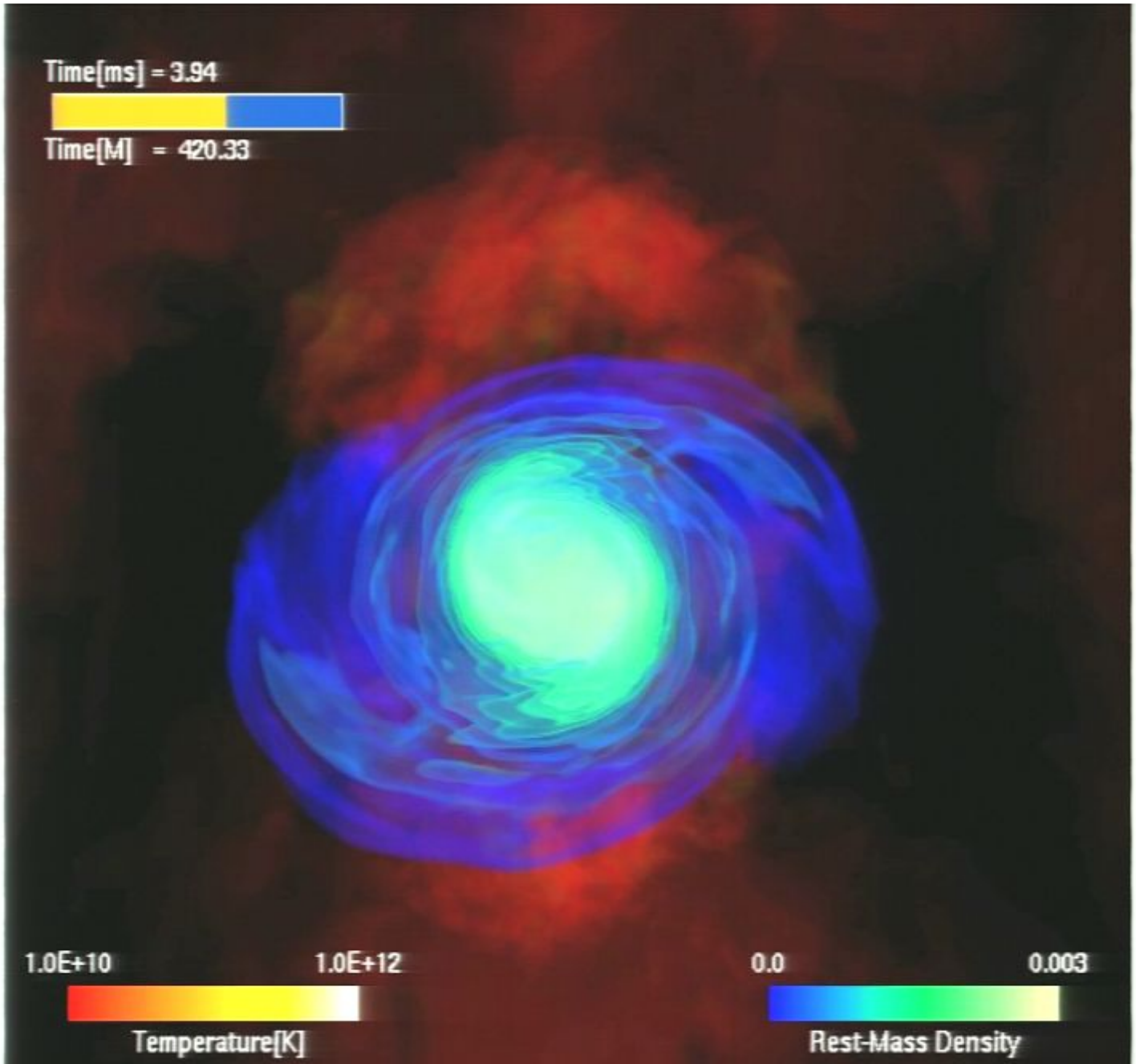

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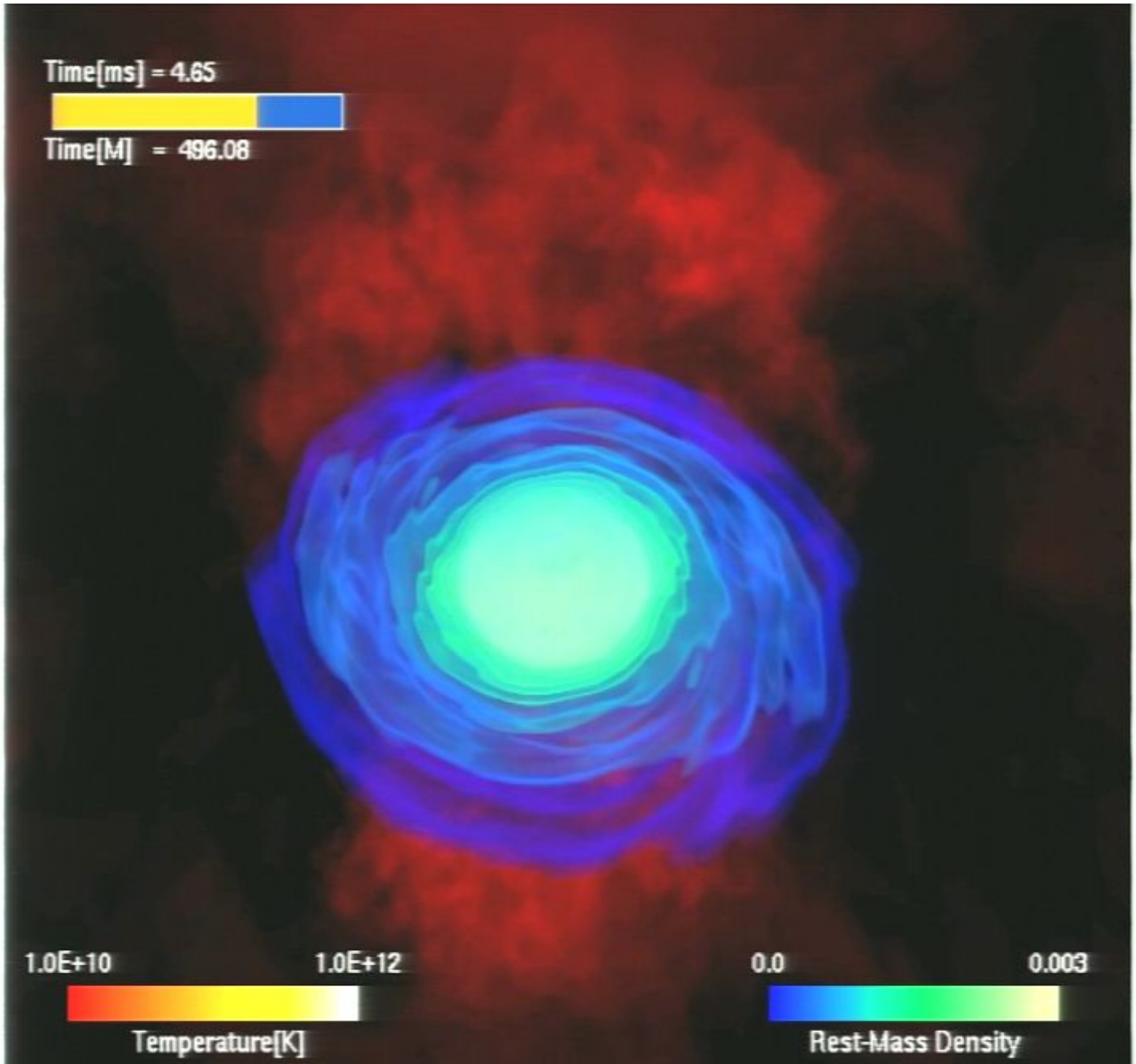

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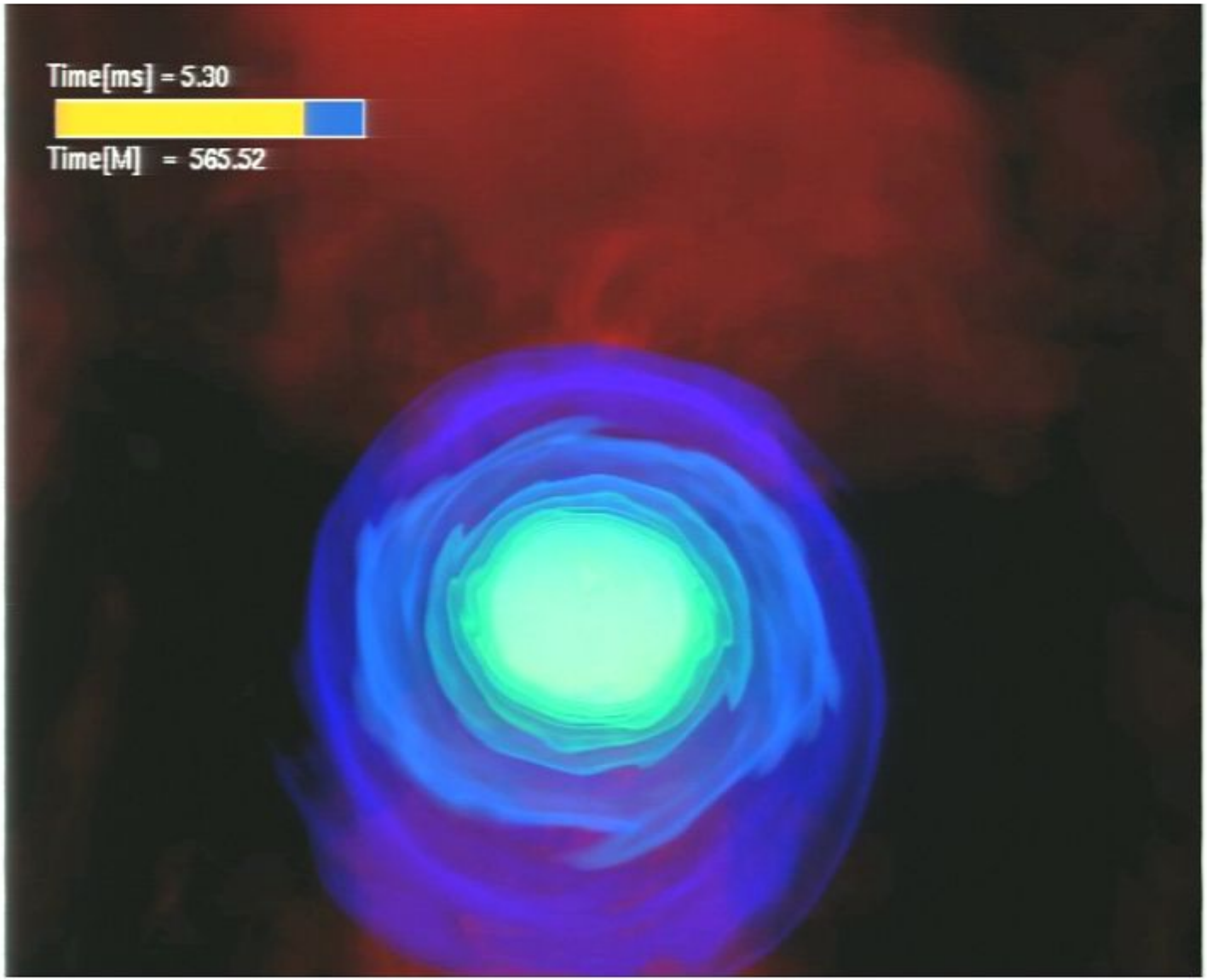

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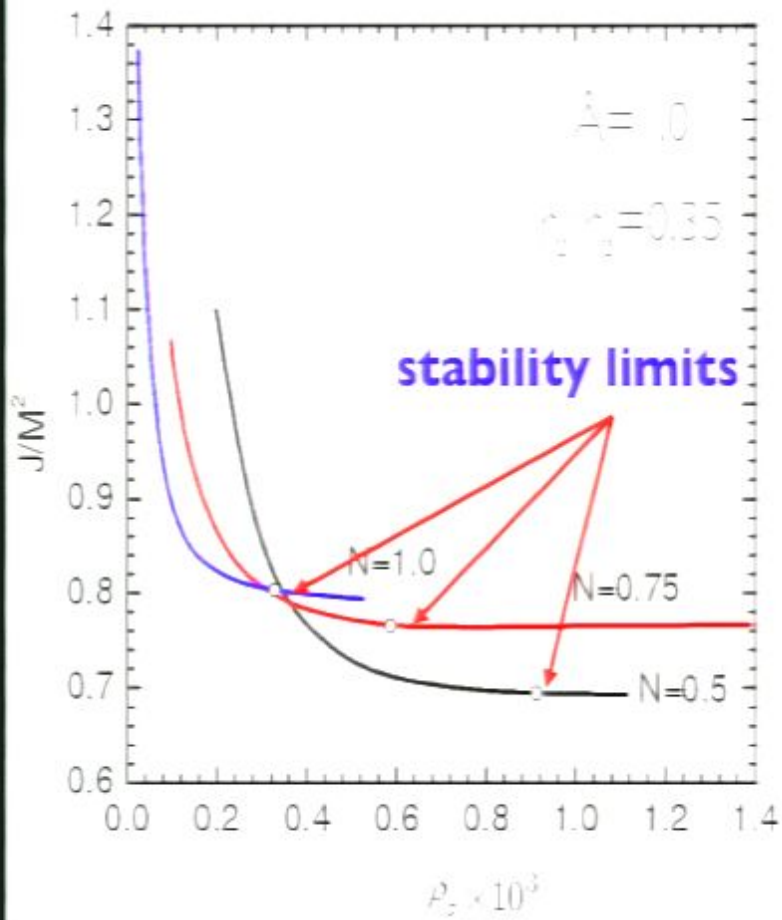
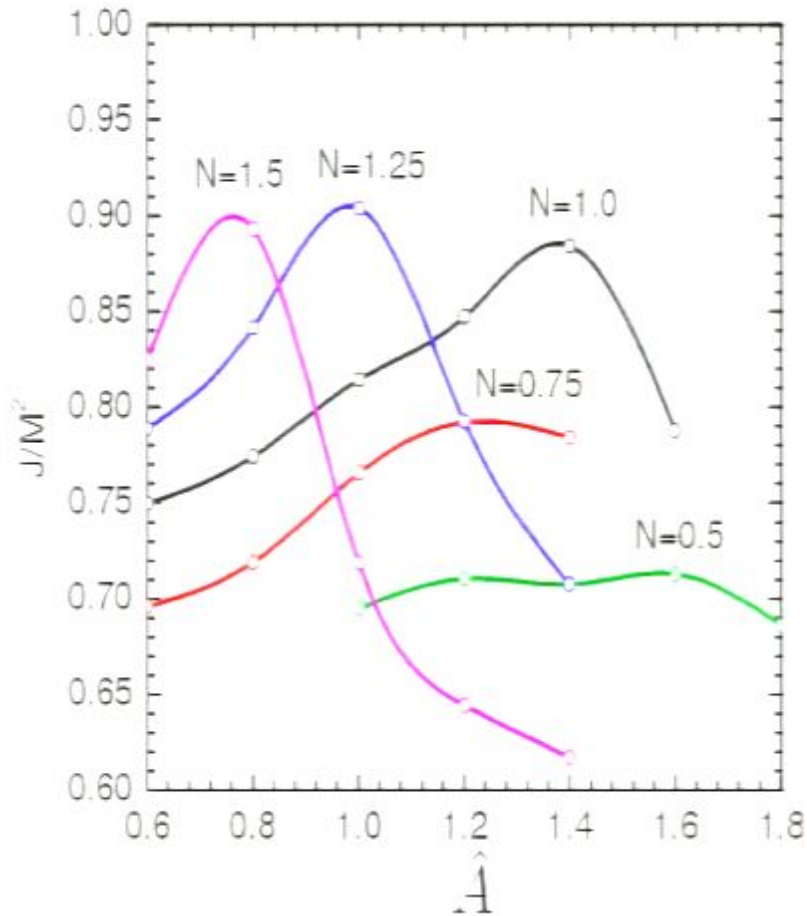
More on differentially rotating polytropes

J/M^2 vs central rest-mass density



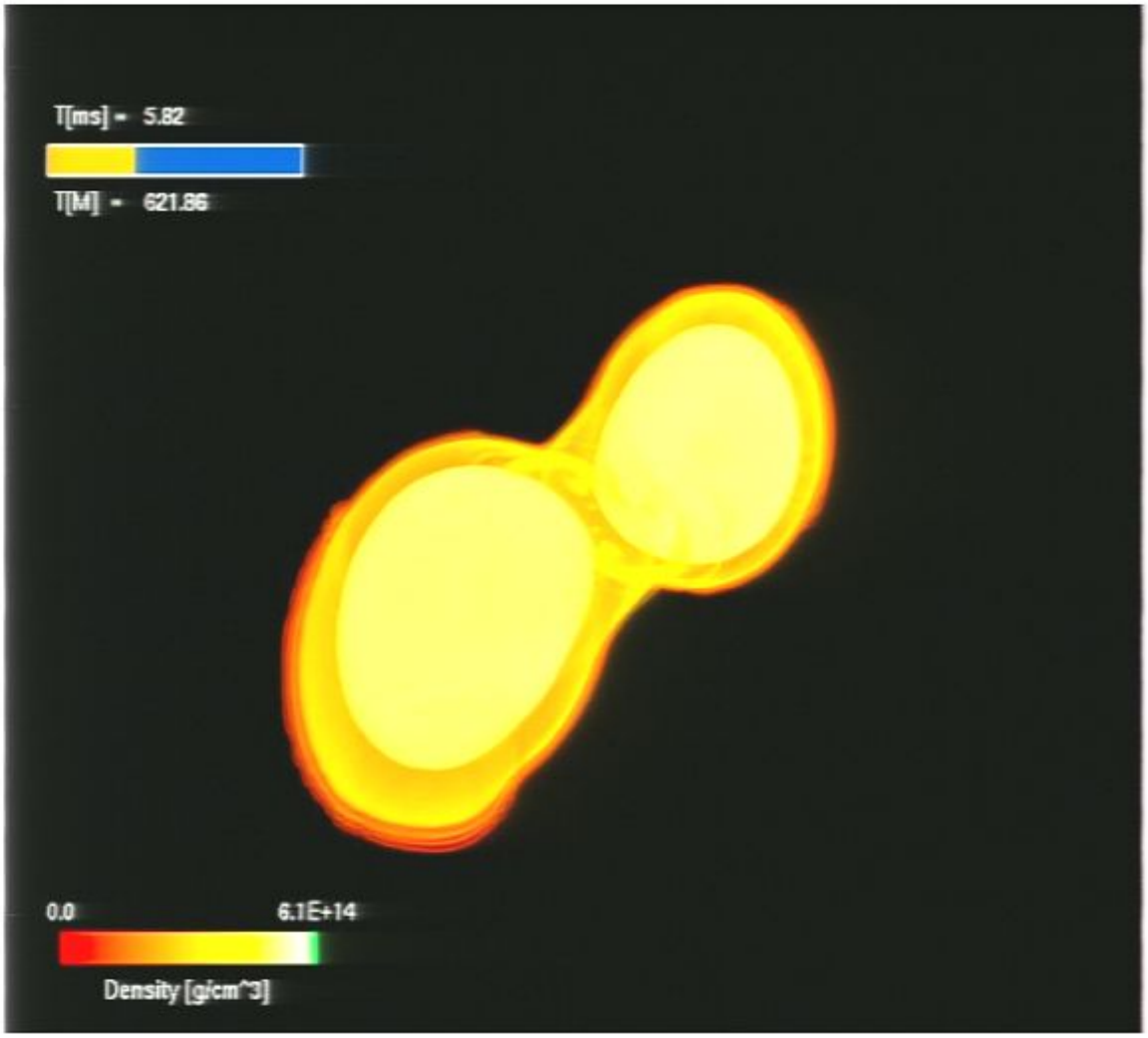
Maximum J/M^2 for unstable models



Circle denotes the separation between stable (at the left) and unstable (at the right) models

All the unstable models have a ratio of J/M^2 less than 1!

BINARY NEUTRON STARS



- Baiotti, Giacomazzo, Rezzolla 2008, PRD 78, 084033
- Baiotti, Giacomazzo, Rezzolla 2009, CQG 26, 114005
- Giacomazzo, Rezzolla, Baiotti, 2009, MNRAS 399, L164-L168
- Rezzolla, Baiotti, Giacomazzo, Link, Font, Arxiv1001.3074

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Due to their duration and dynamics, Binary Neutron Stars are very good sources for gravitational wave detectors such as Virgo (Italy) and Ligo (USA)

Virgo (Pisa, Italy)

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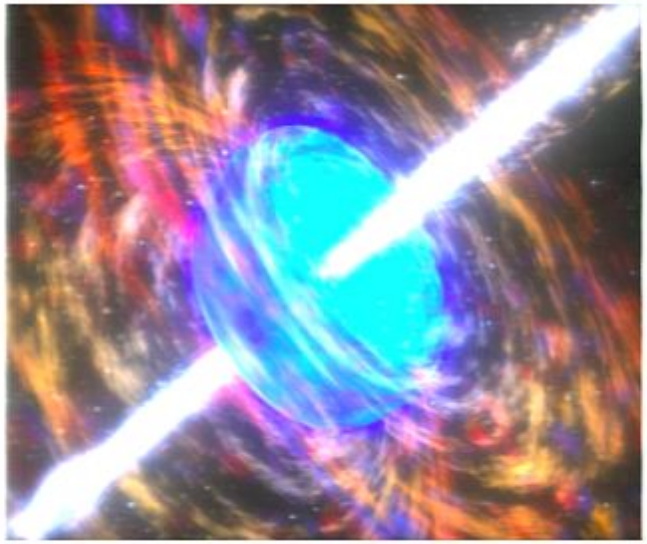
Virgo (Pisa, Italy)



Binary neutron stars mergers are also possible sources for short gamma-ray bursts

INITIAL MODELS

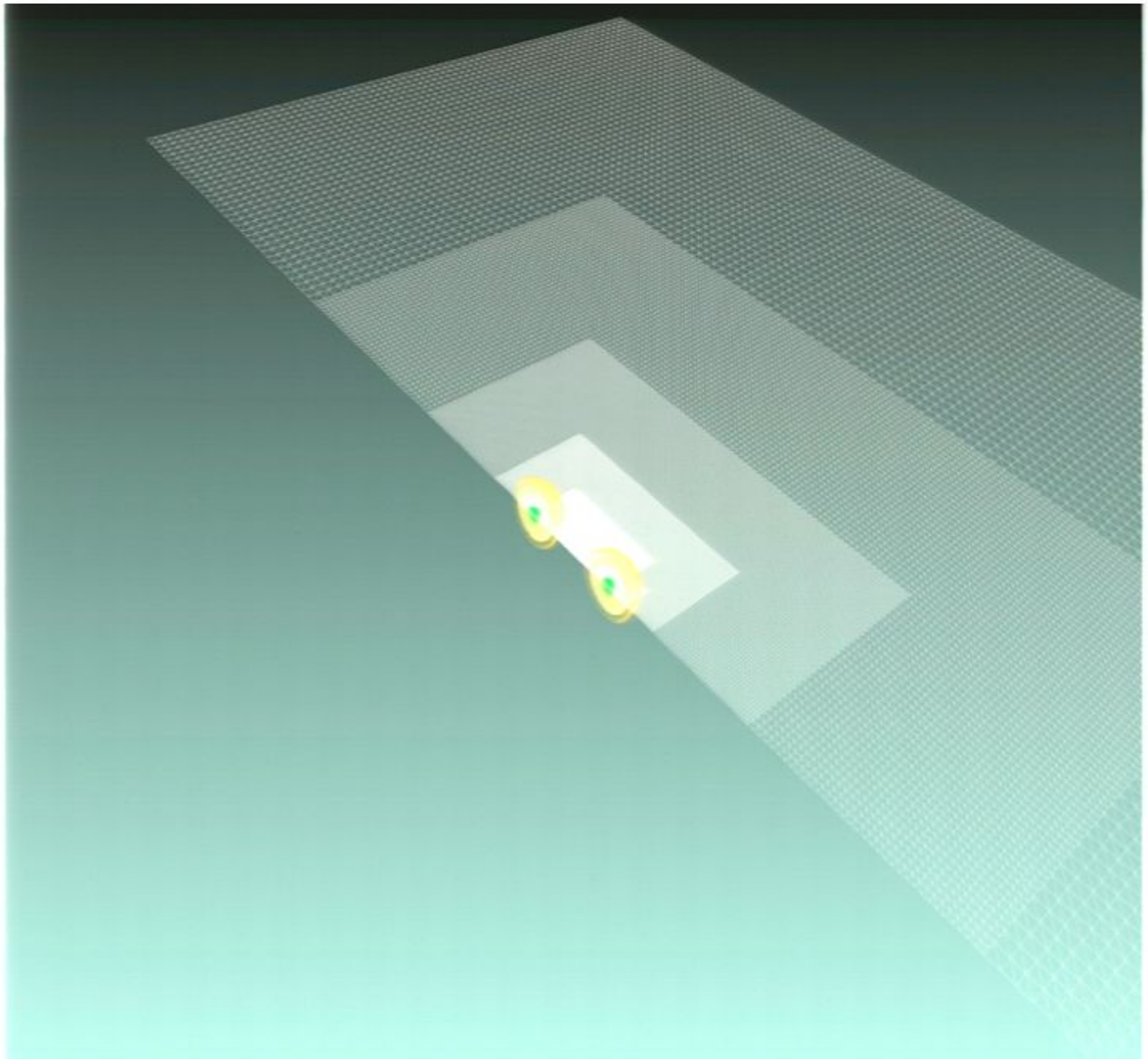
All the initial models are computed using the Lorene code for unmagnetized binary NSs (Bonazzola et al. 1999):

Model	M1,M2	d (km)
low-mass	1.45	45
high-mass	1.62	45

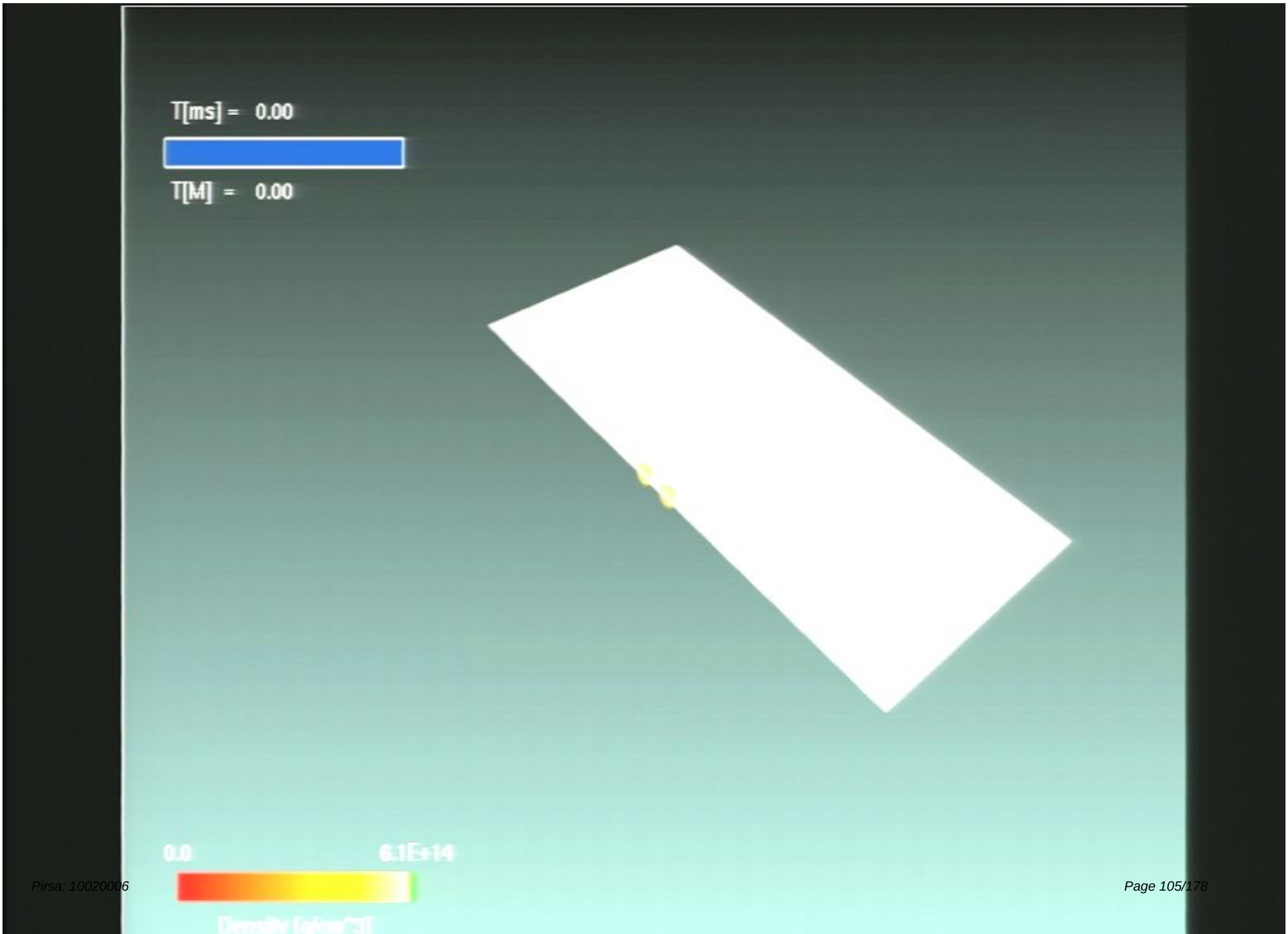
Technical data for the simulations:

- polytropic or ideal-fluid EOS
- outer boundary: ~370 km
- 8 refinement levels; res. of finest level: ~0.2km
- PPM for the reconstruction
- Marquina flux formula
- Runge Kutta (3rd-order)

POLYTROPIC EOS: HIGH-MASS BINARY



Visualization by Giacomazzo, Kaehler, Rezzolla


T[ms] = 0.00
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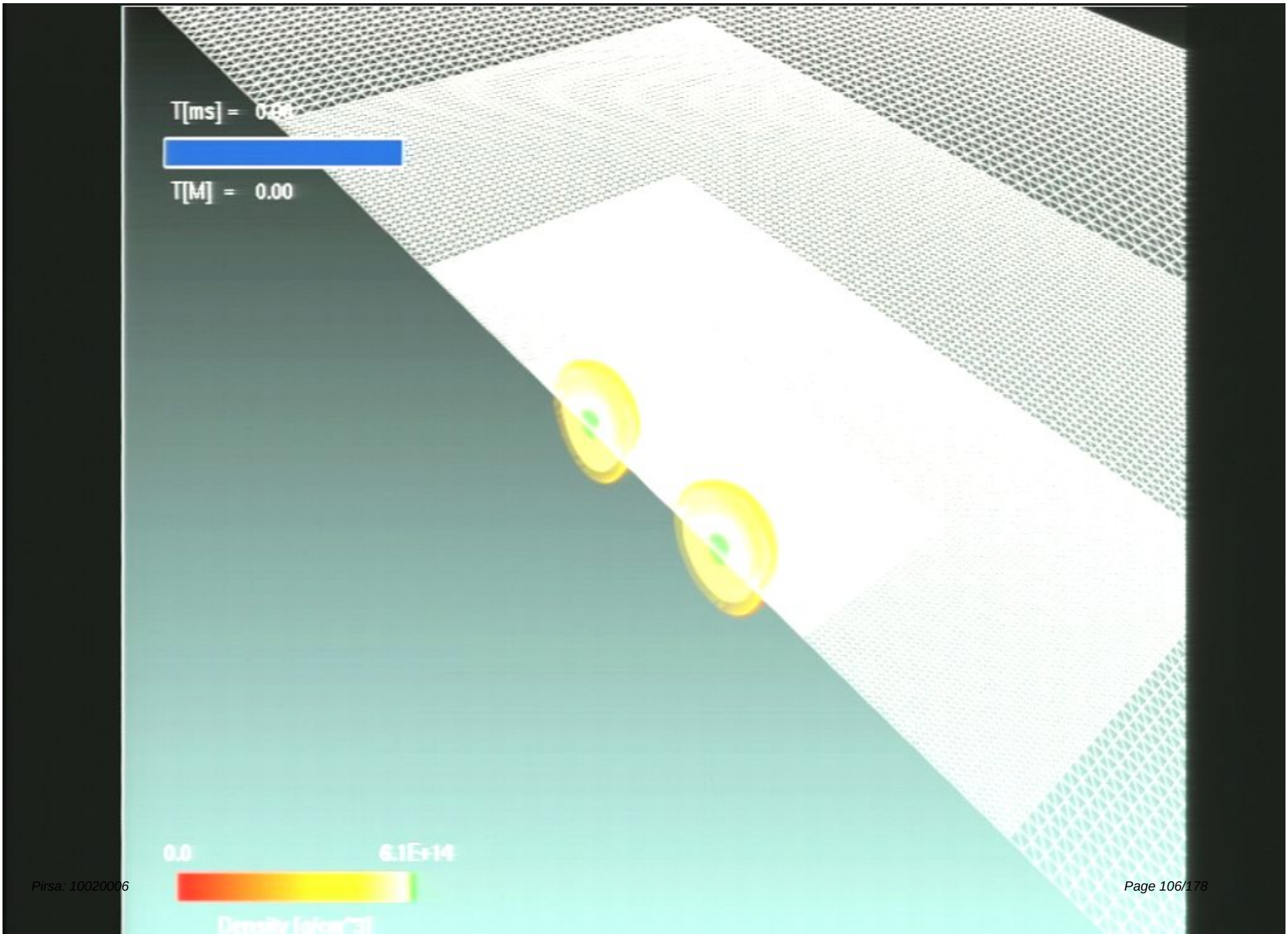
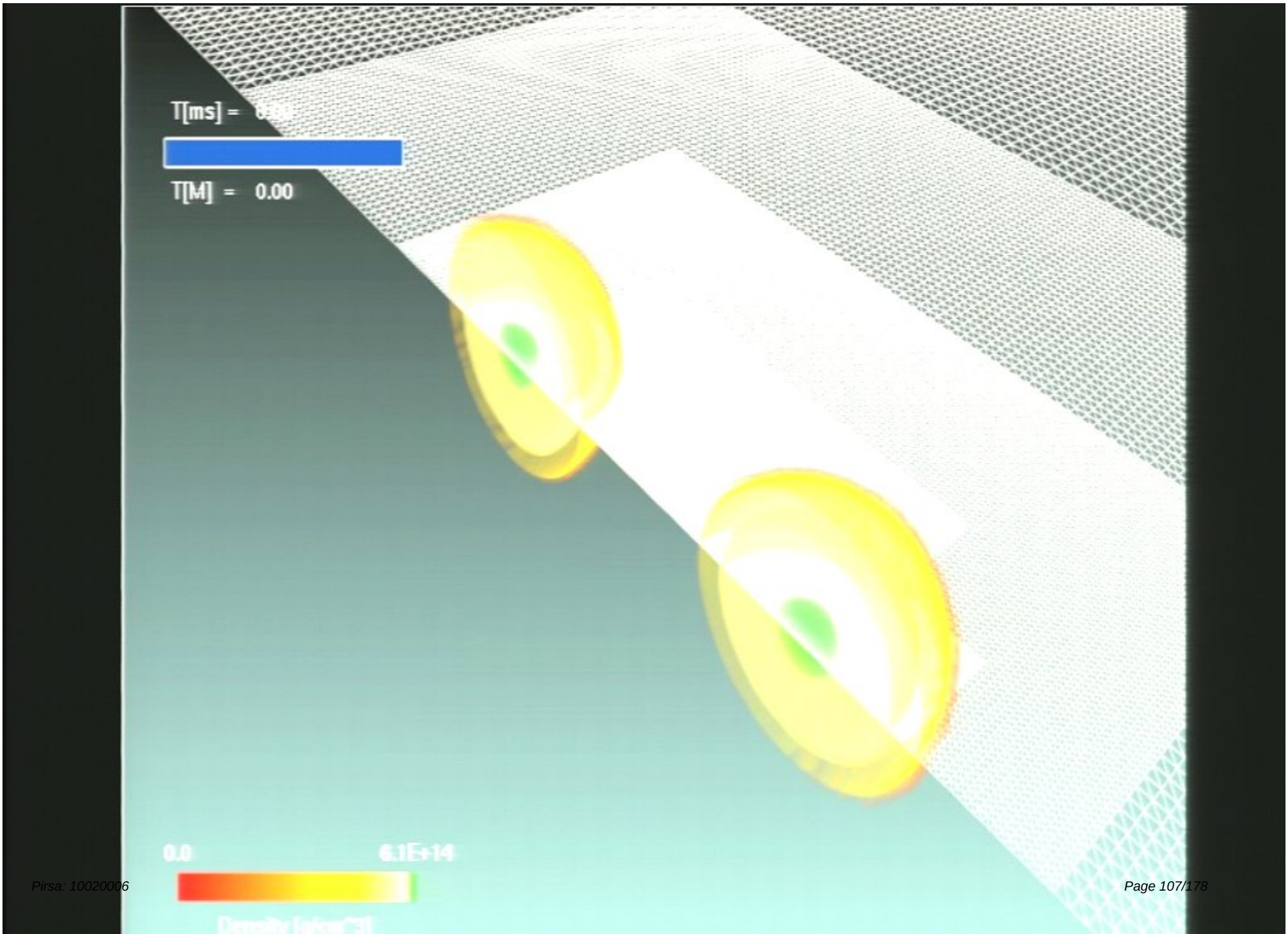
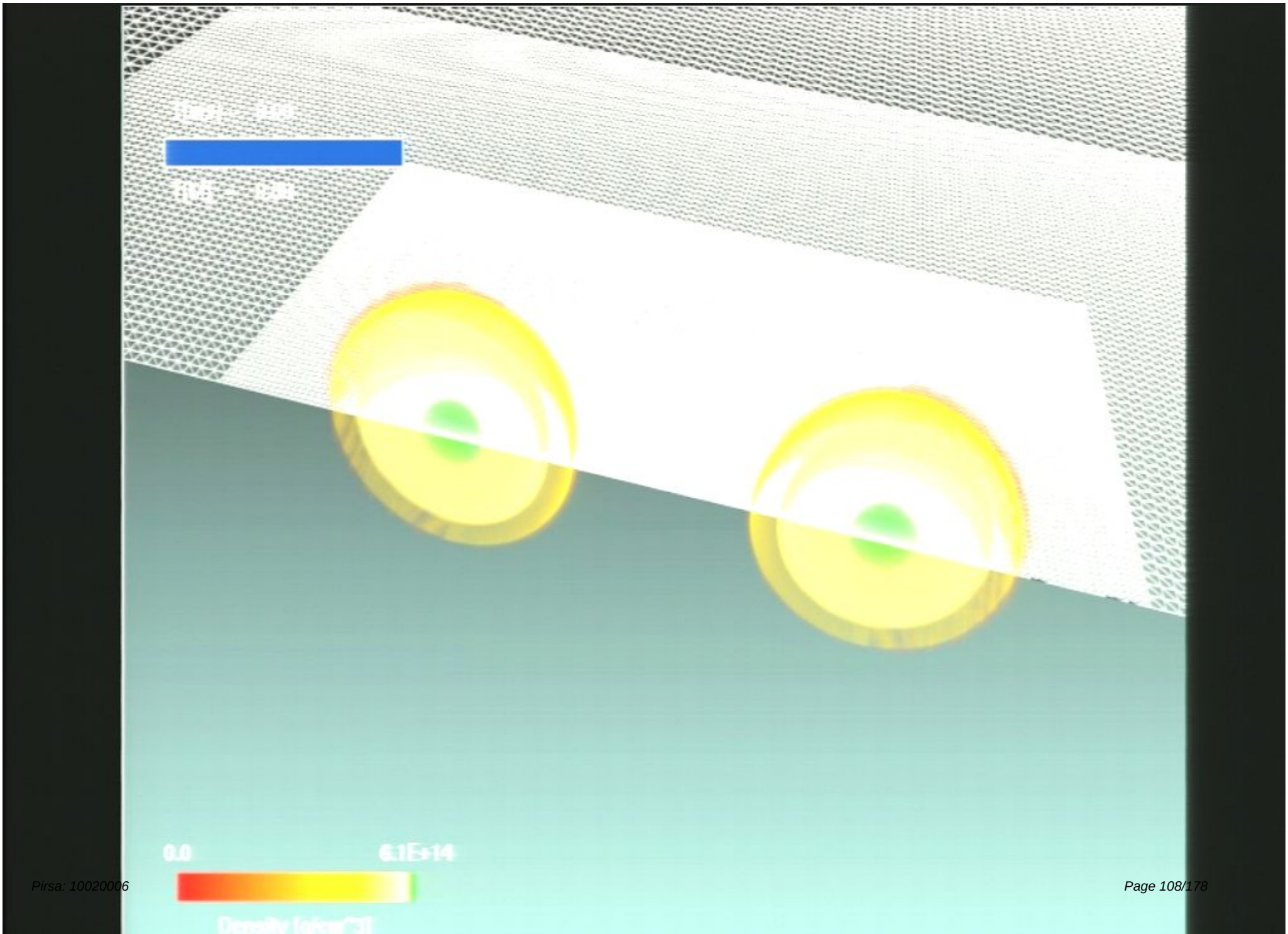
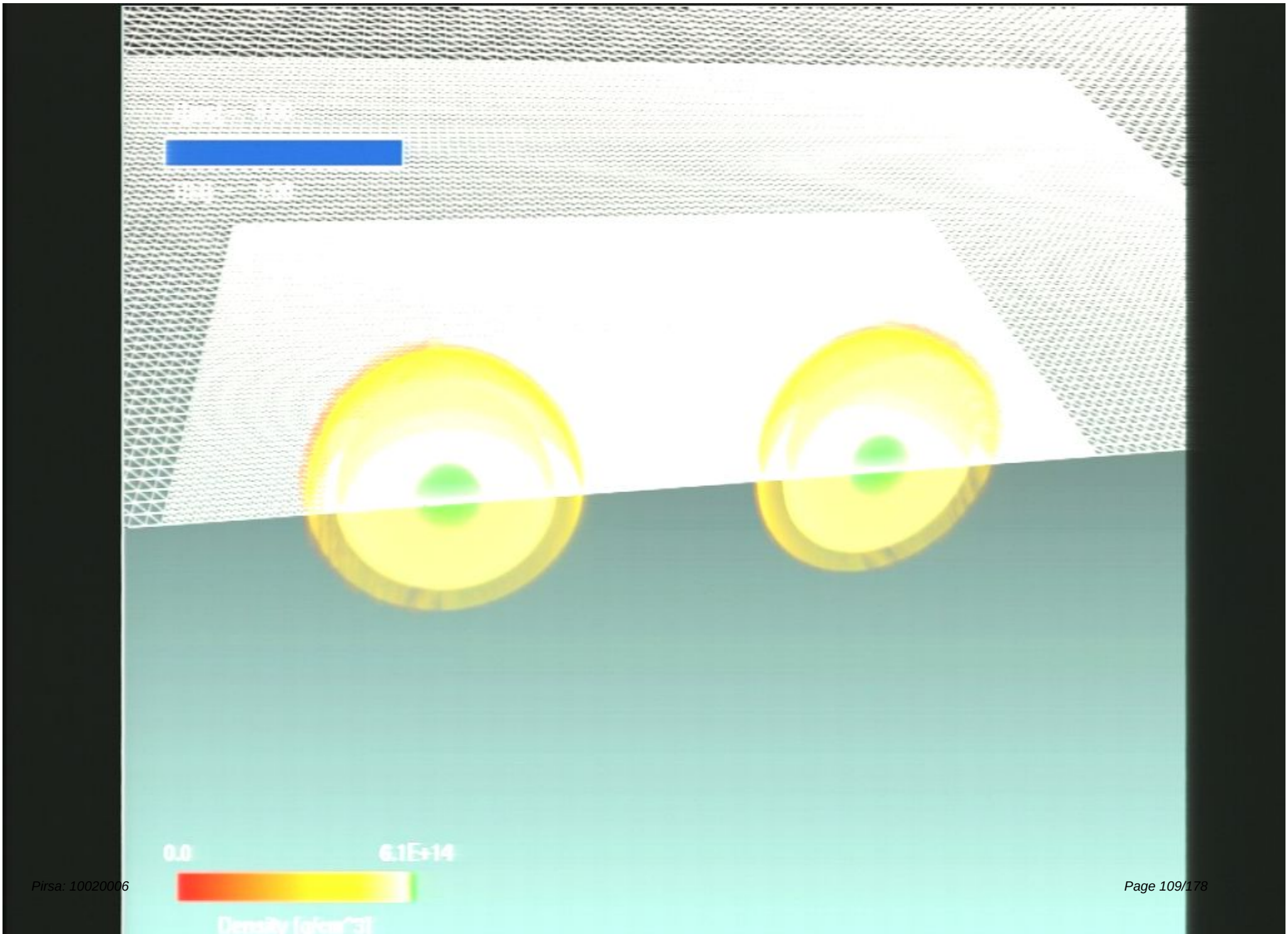
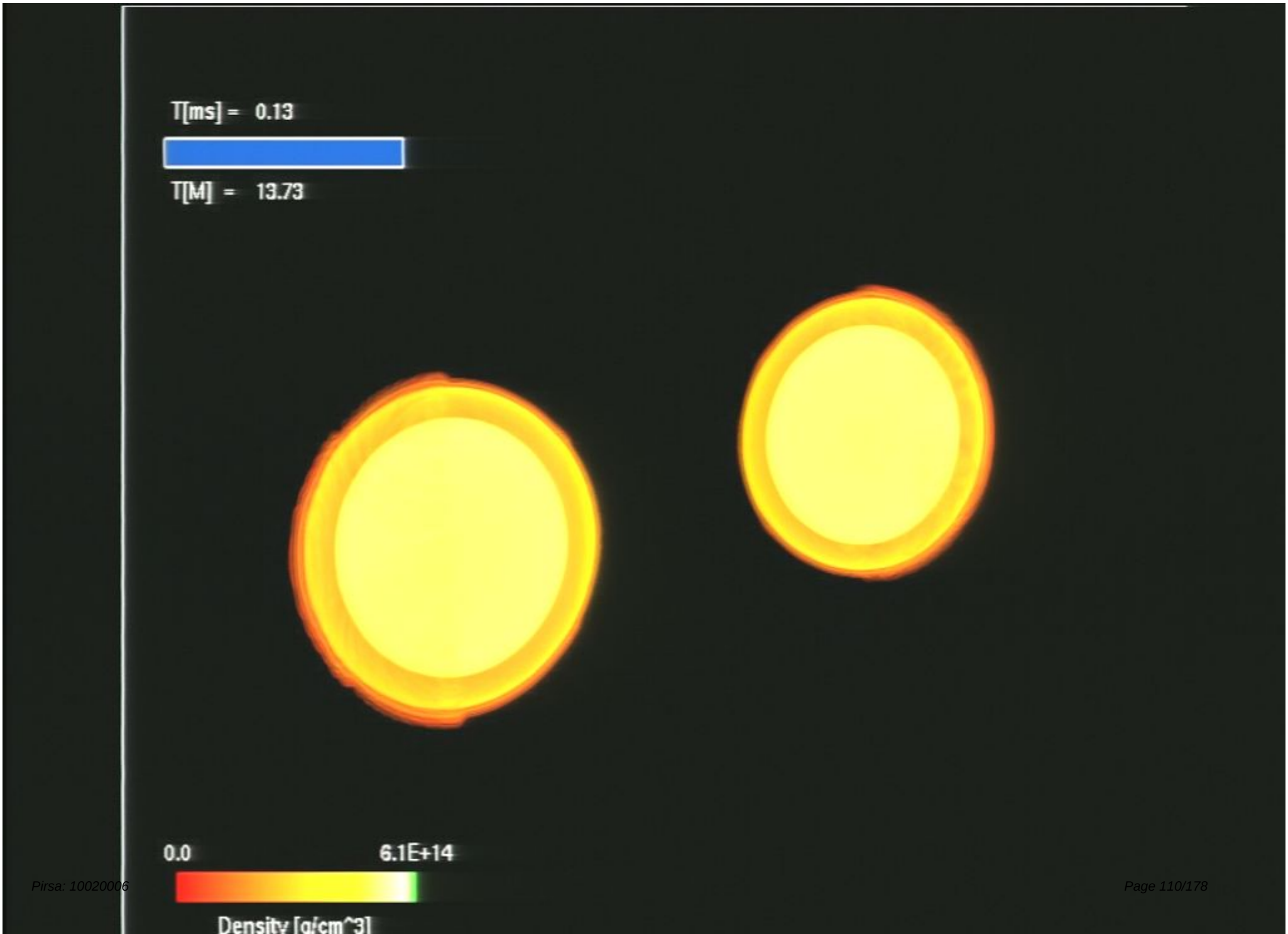
0.0
6.1E+14

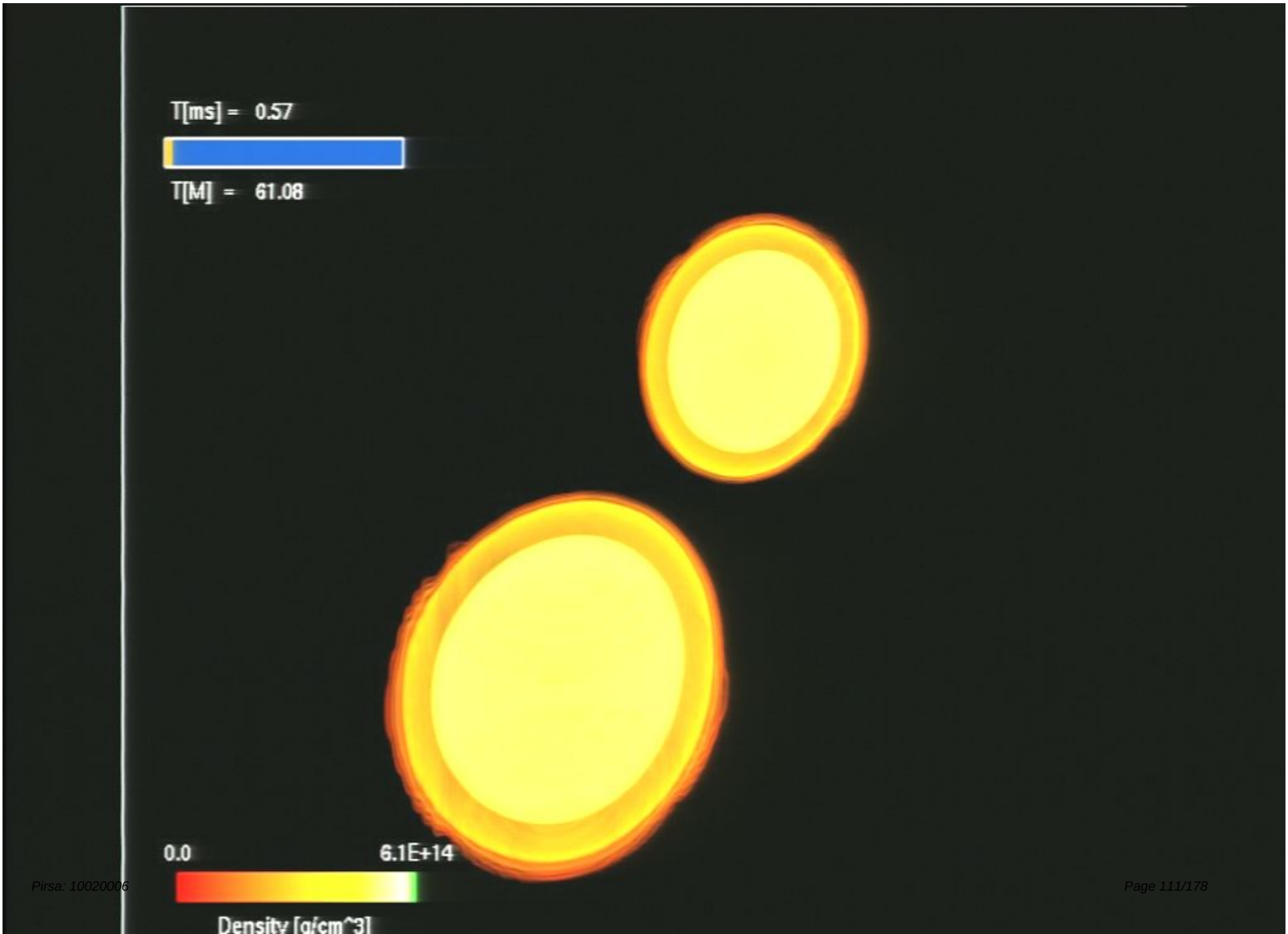

T[ms] =
T[M] = 0.00
0.0
6.1E+14

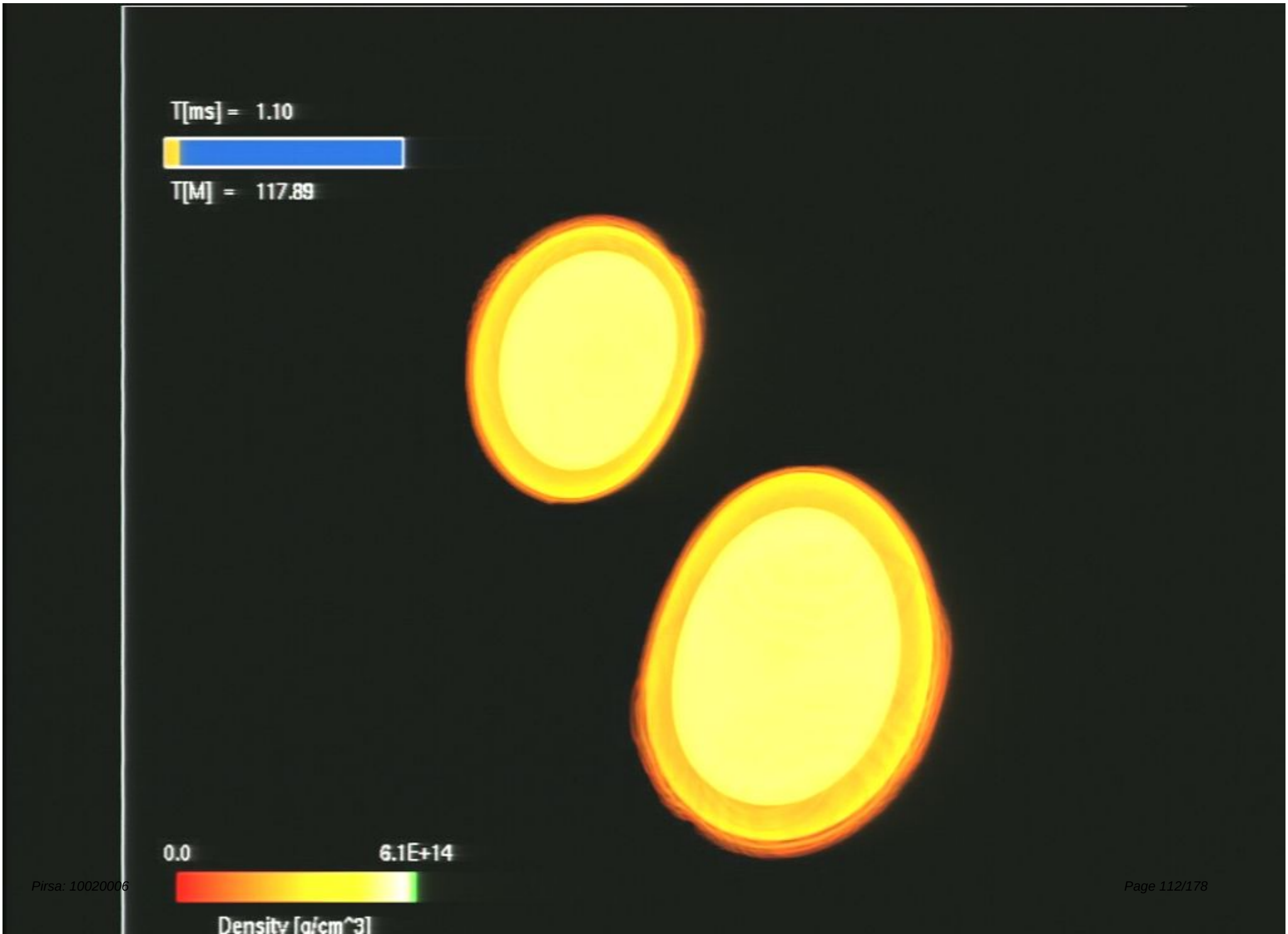

T[ms] =
T[M] = 0.00
0.0
6.1E+14

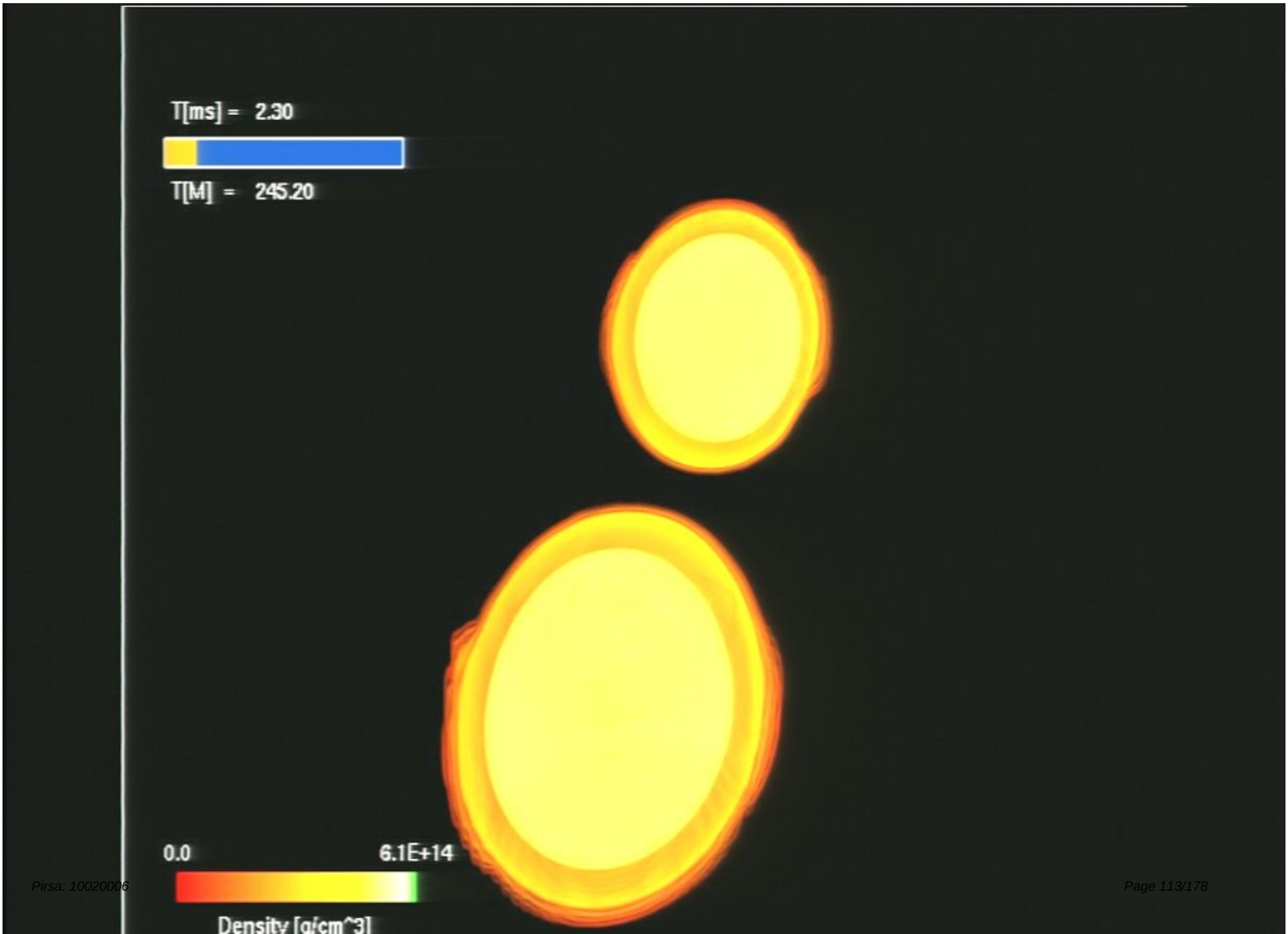

0.0
6.1E+14


0.0
6.1E+14

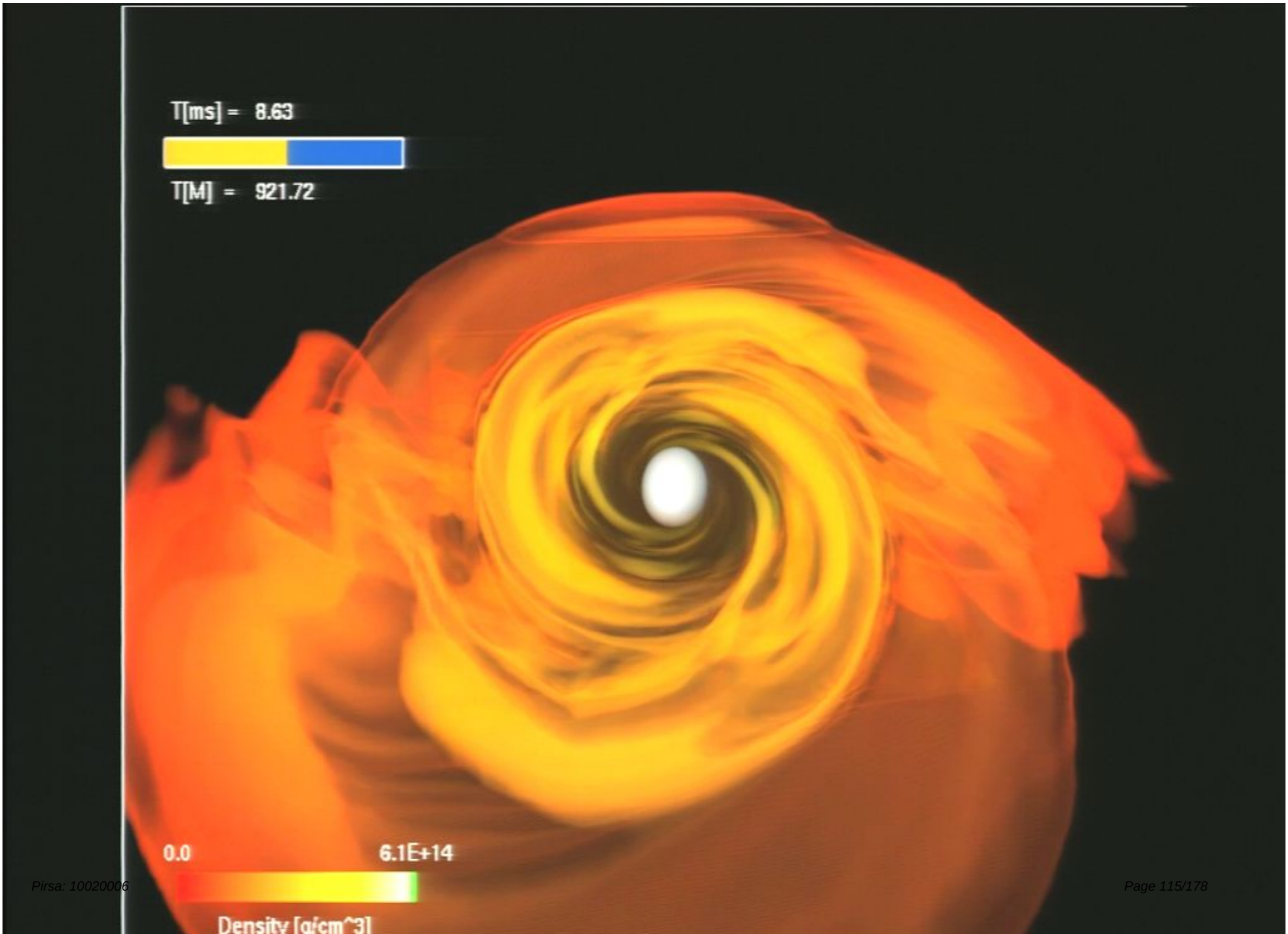

T[ms] = 0.13
T[M] = 13.73
0.0
6.1E+14
Density [g/cm^3]

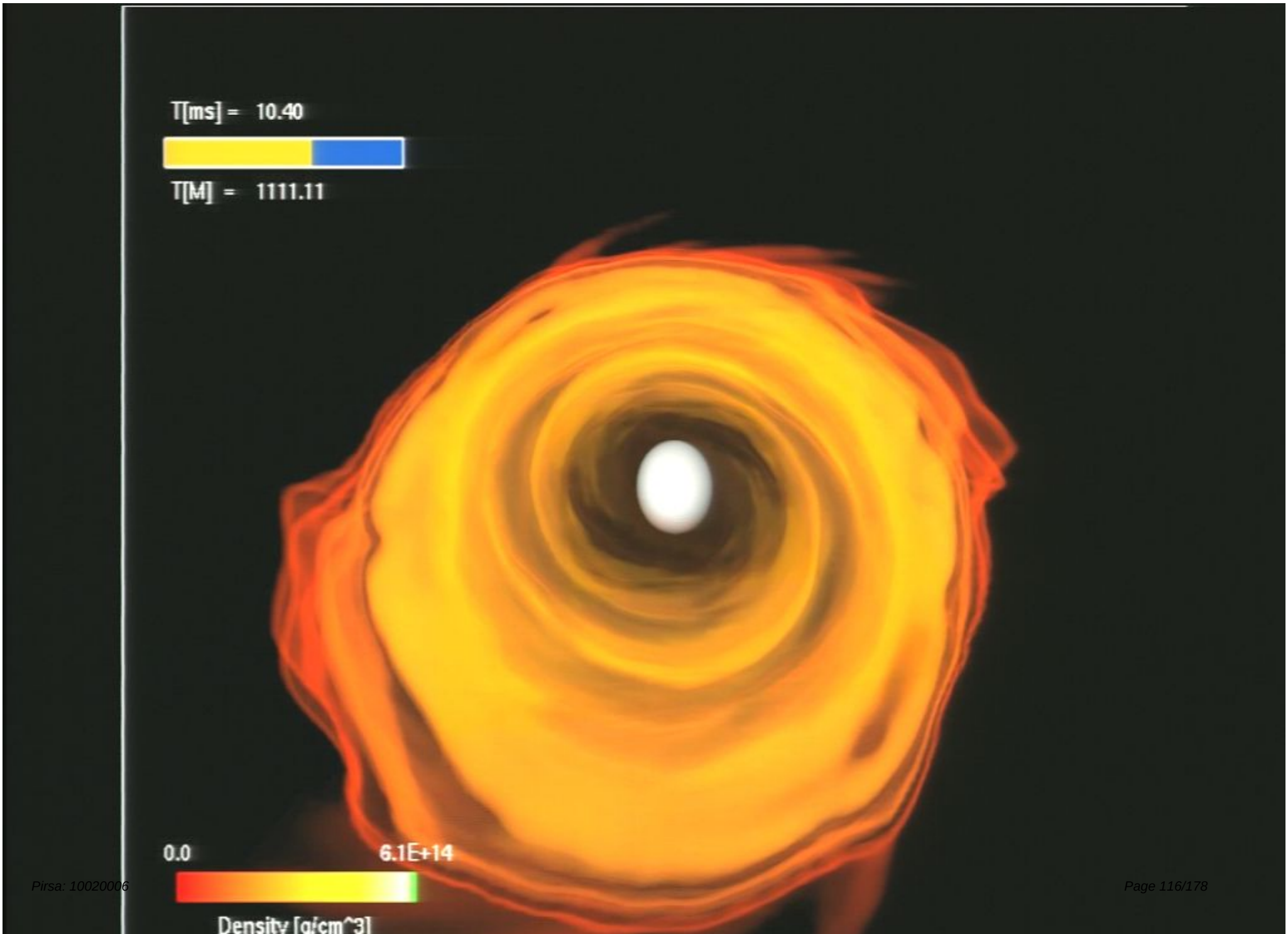

T[ms] = 0.57
T[M] = 61.08
0.0
6.1E+14
Density [g/cm^3]


T[ms] = 1.10
T[M] = 117.89
0.0
6.1E+14
Density [g/cm^3]


T[ms] = 2.30
T[M] = 245.20
0.0
6.1E+14
Density [g/cm^3]

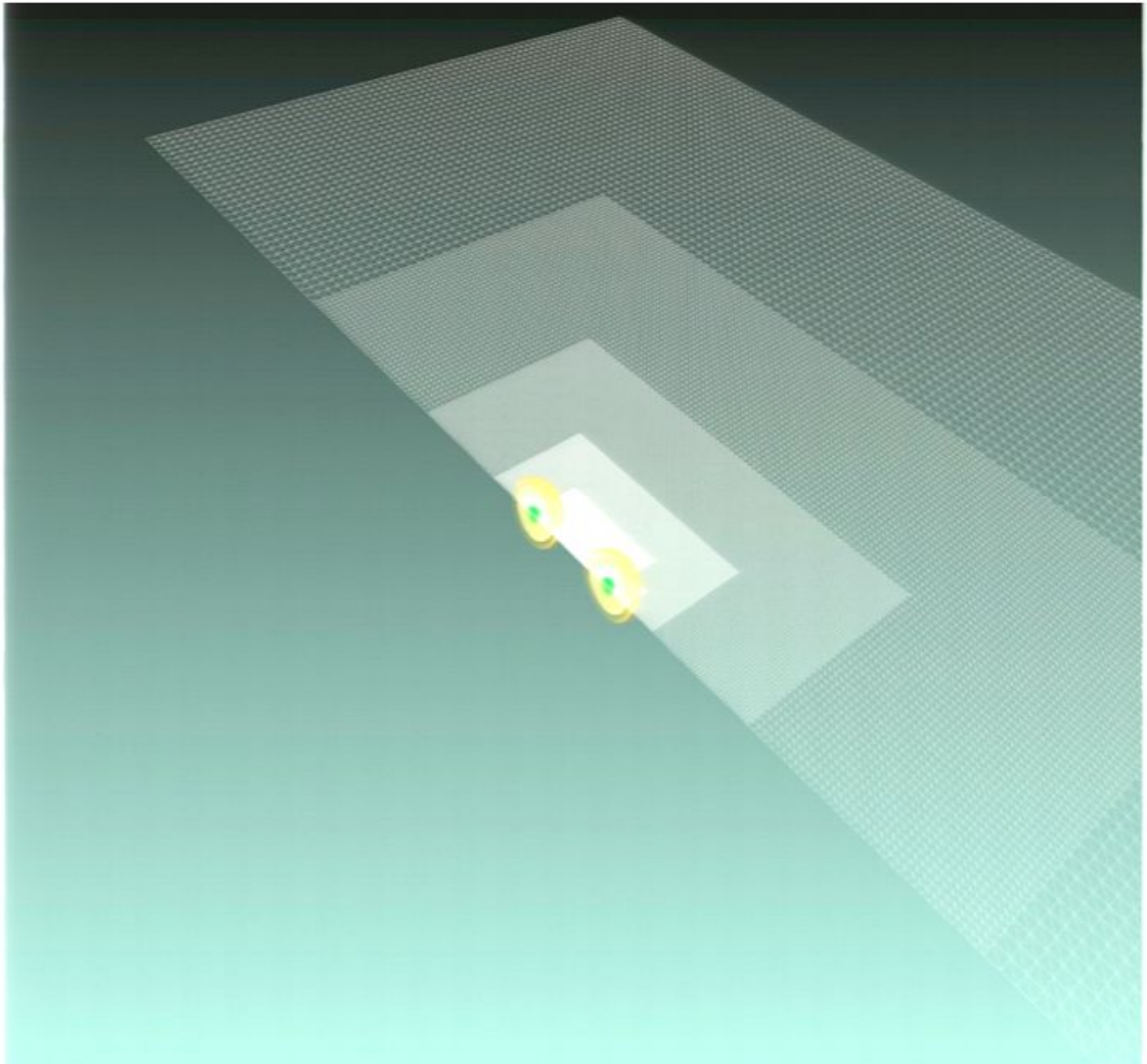
T[ms] = 5.98
T[M] = 638.70
0.0
6.1E+14
Density [g/cm^3]


T[ms] = 8.63
T[M] = 921.72
0.0
6.1E+14
Density [g/cm^3]

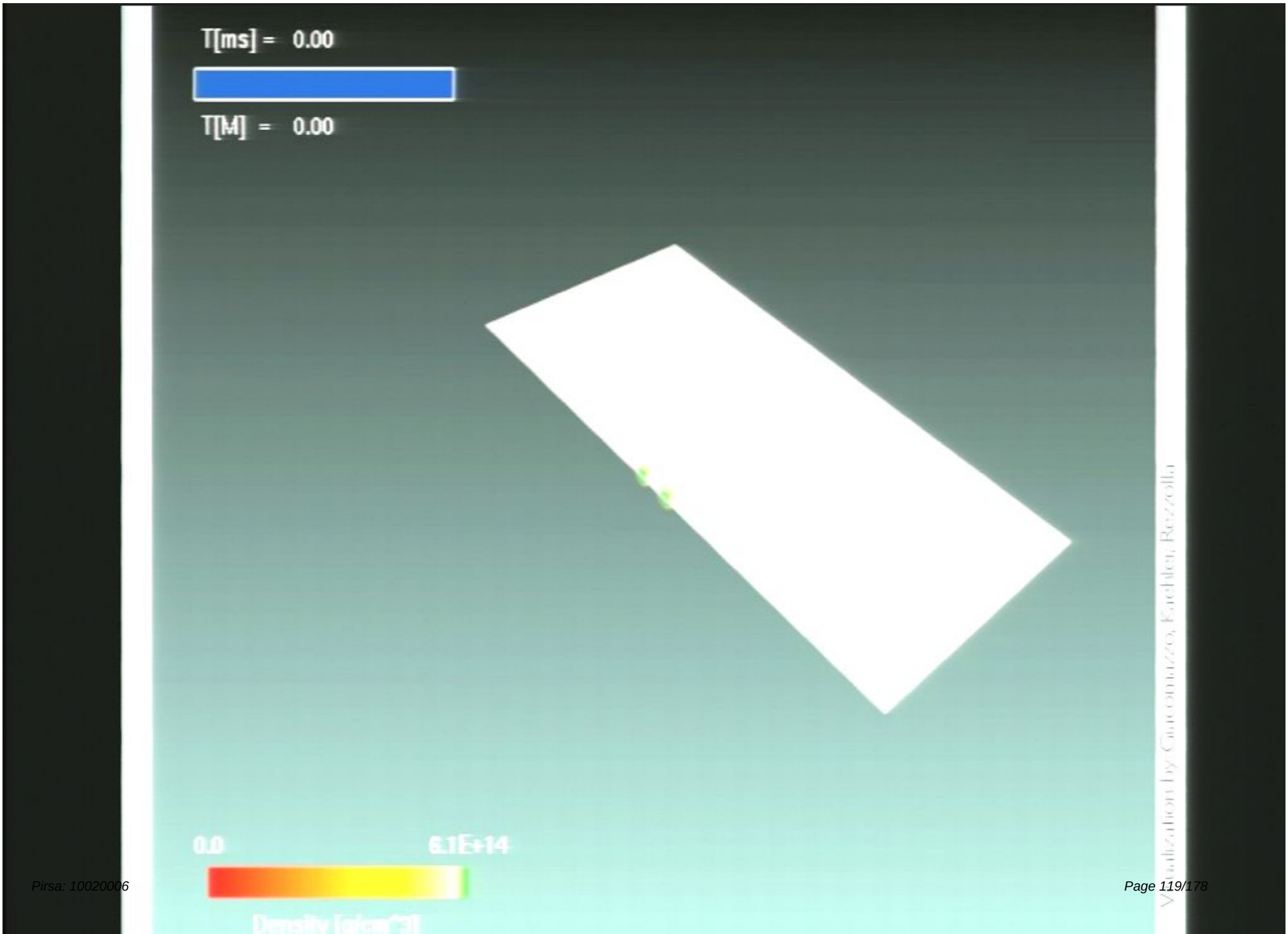

T[ms] = 10.40
T[M] = 1111.11
0.0
6.1E+14
Density [g/cm^3]

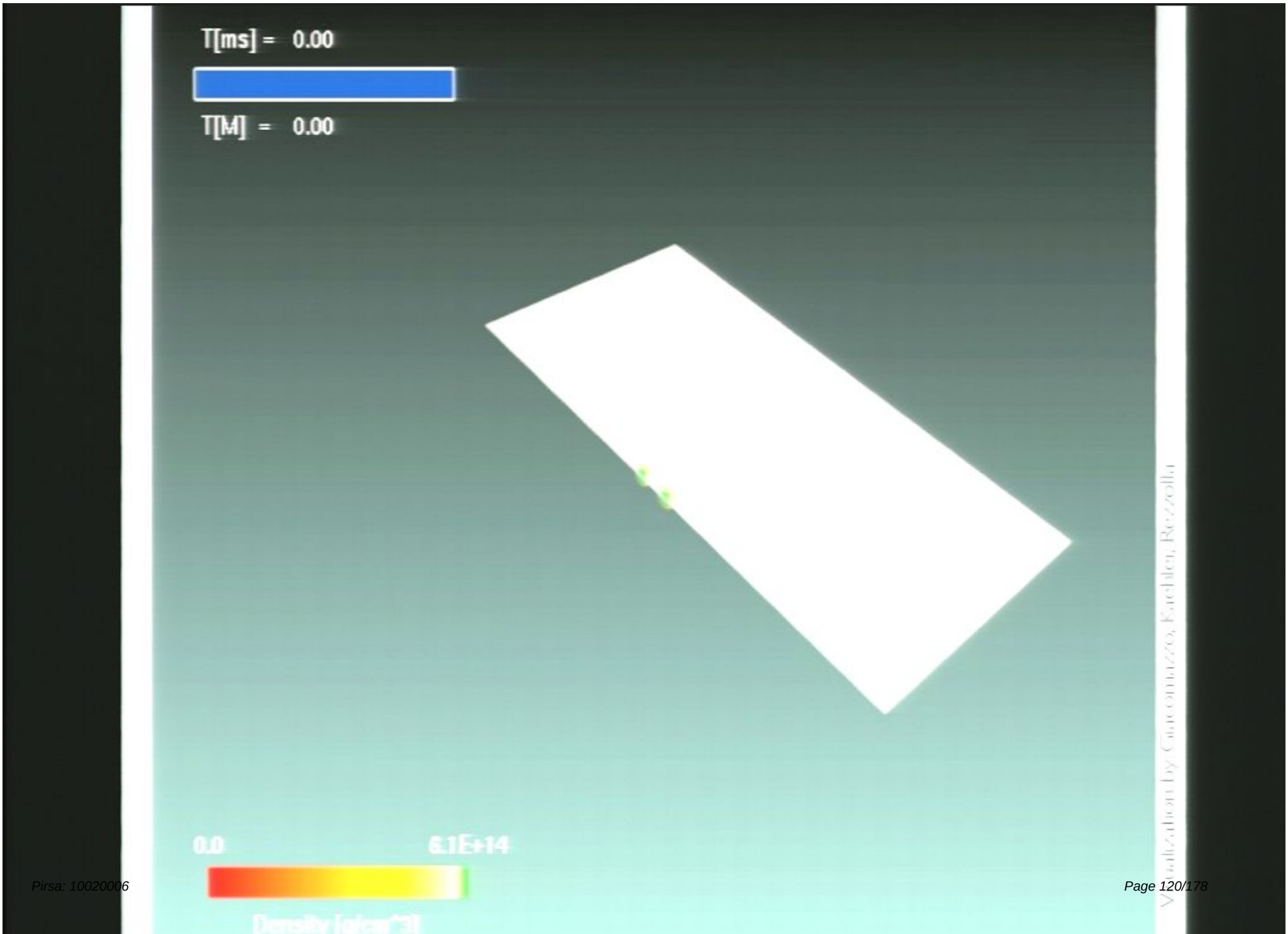
GWS FROM BNS: THE ROLE OF THE MASS

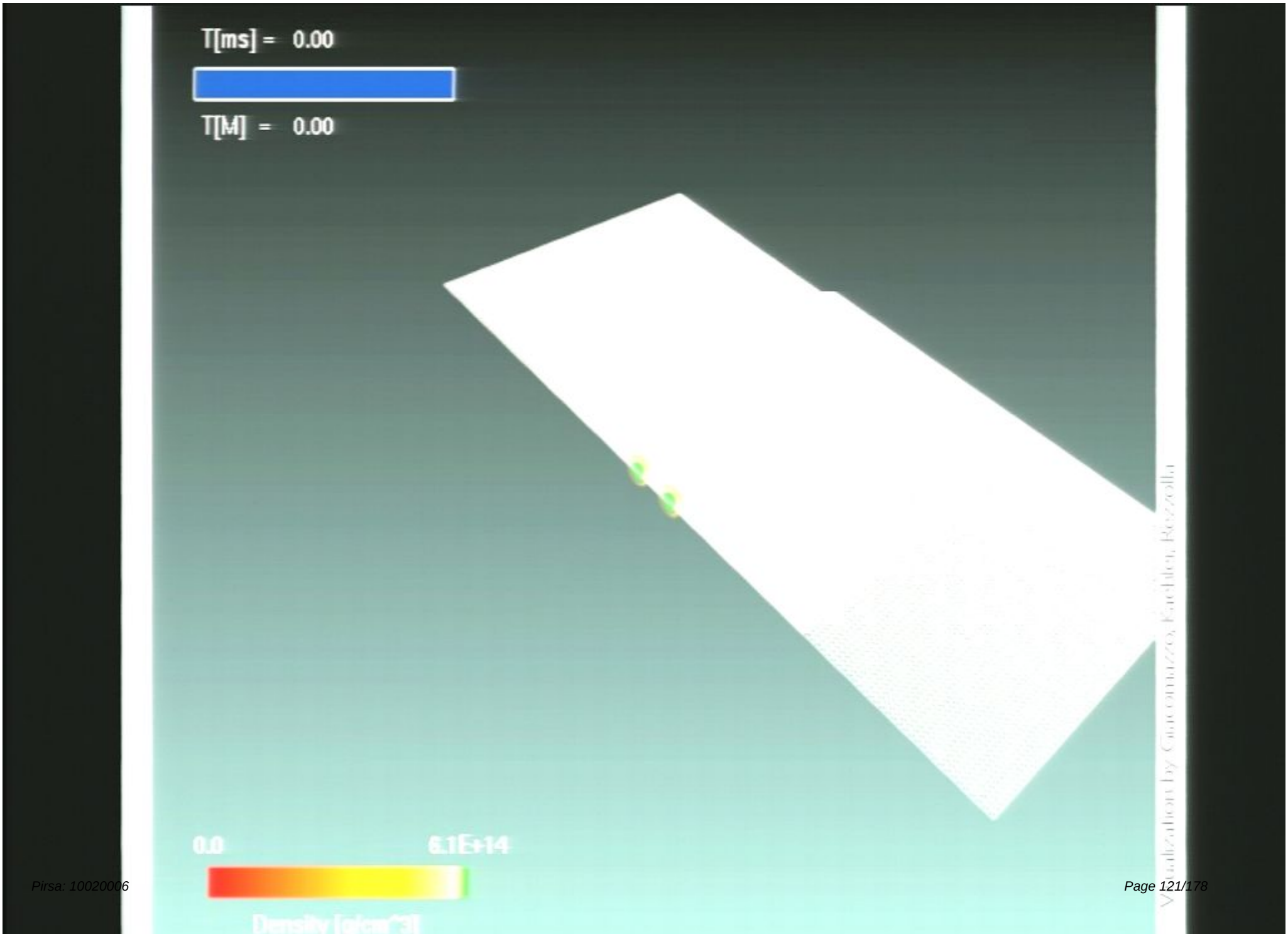
POLYTROPIC EOS: LOW-MASS BINARY

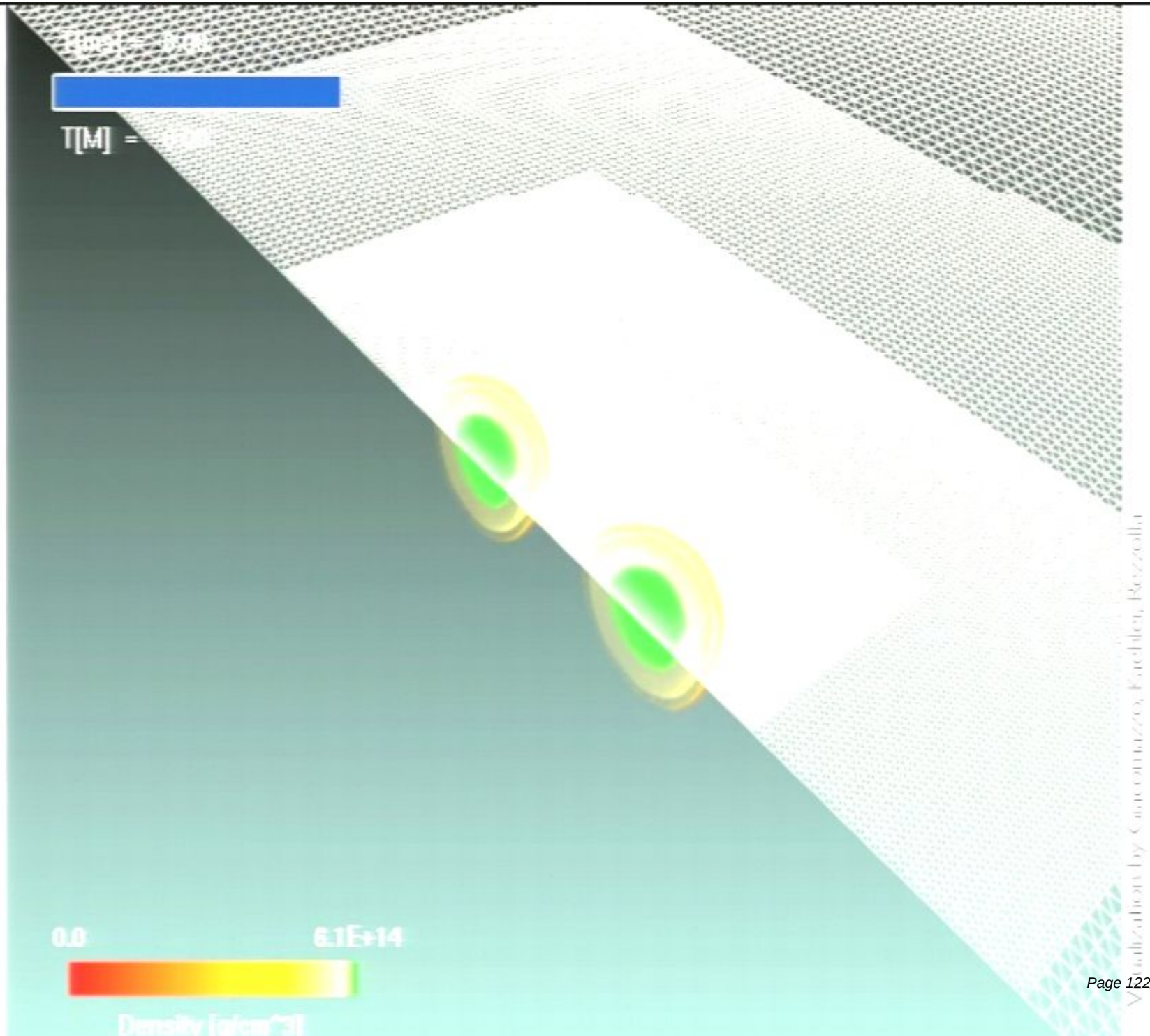


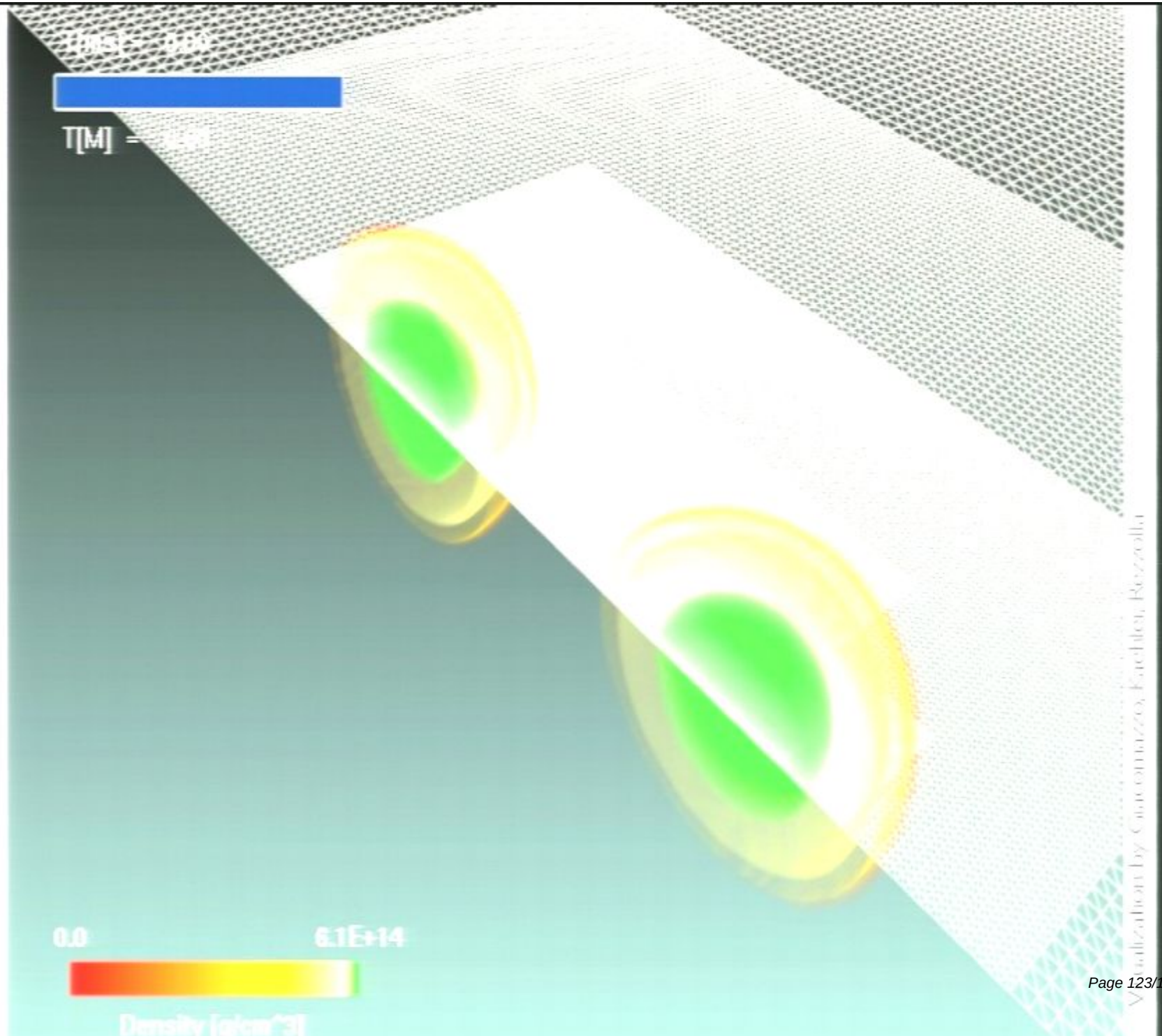
Visualization by Giacomazzo, Kaehler, Rezzolla

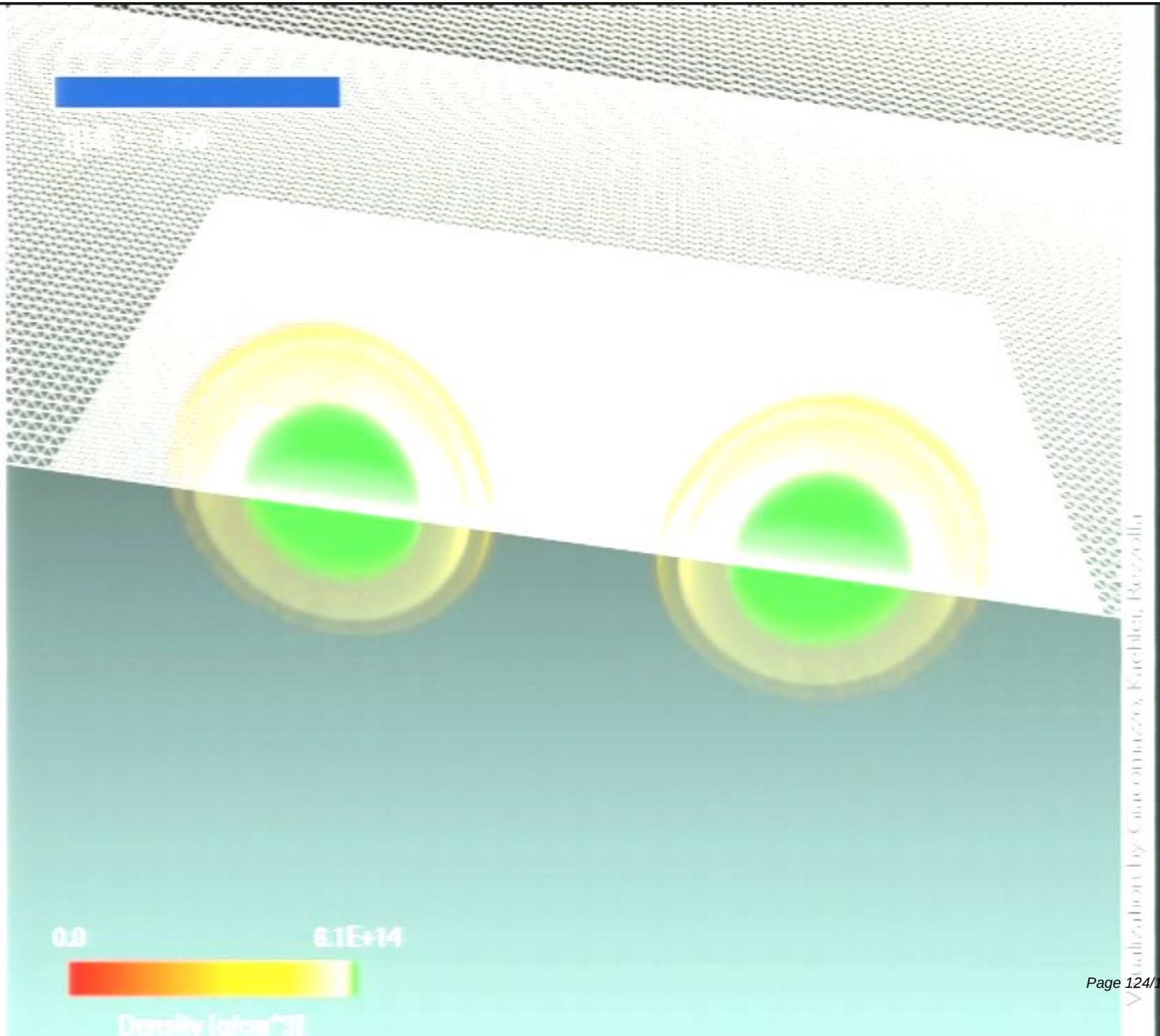

T[ms] = 0.00
T[M] = 0.00
0.0
6.1E+14
Density [g/cm^3]
Visualization by Gary Guzzo, Kaelber, Reczelh

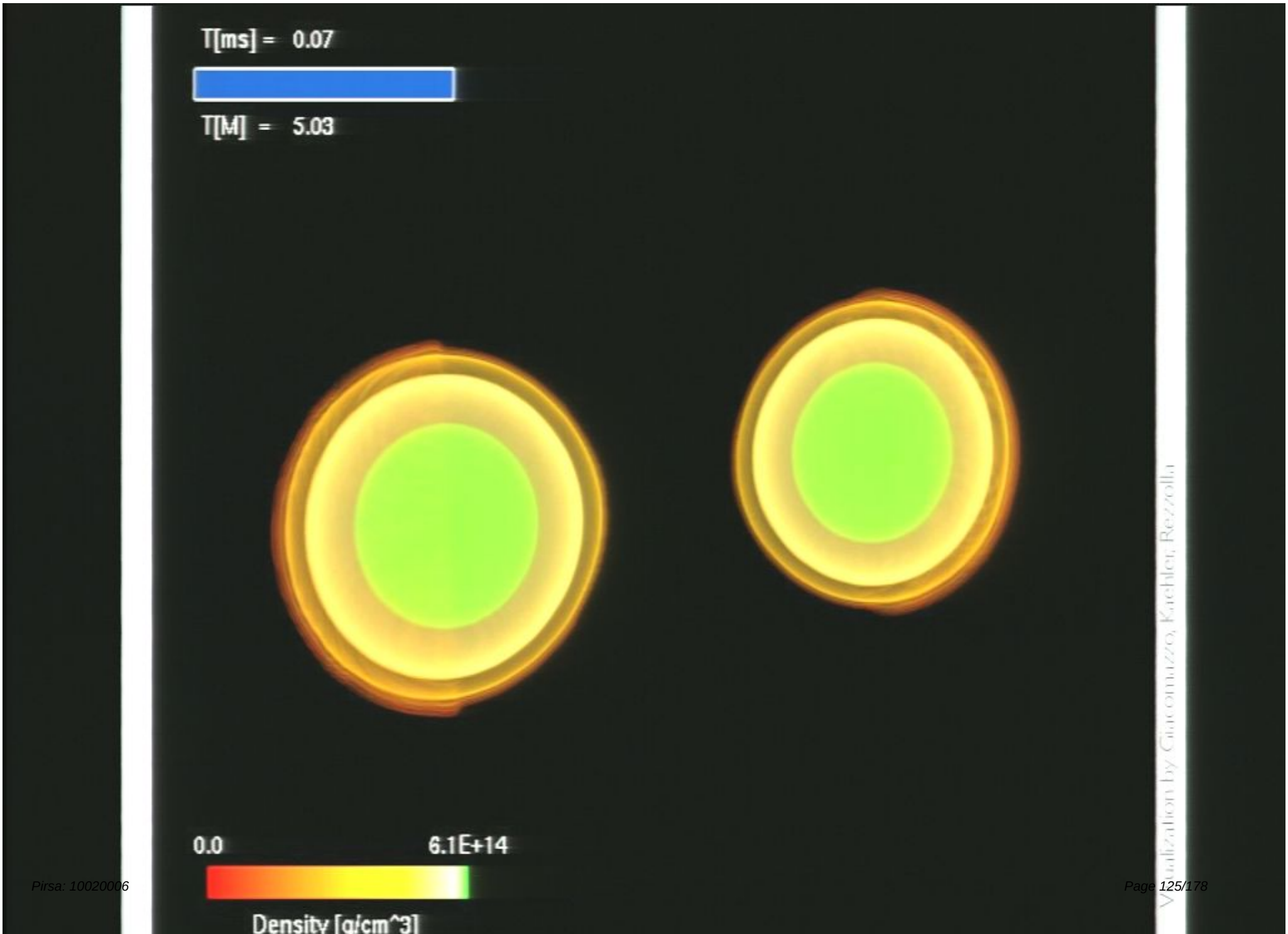

T[ms] = 0.00
T[M] = 0.00
0.0
6.1E+14
Density [g/cm^3]
Visualization by Giovanni Kopelan Rezzolla

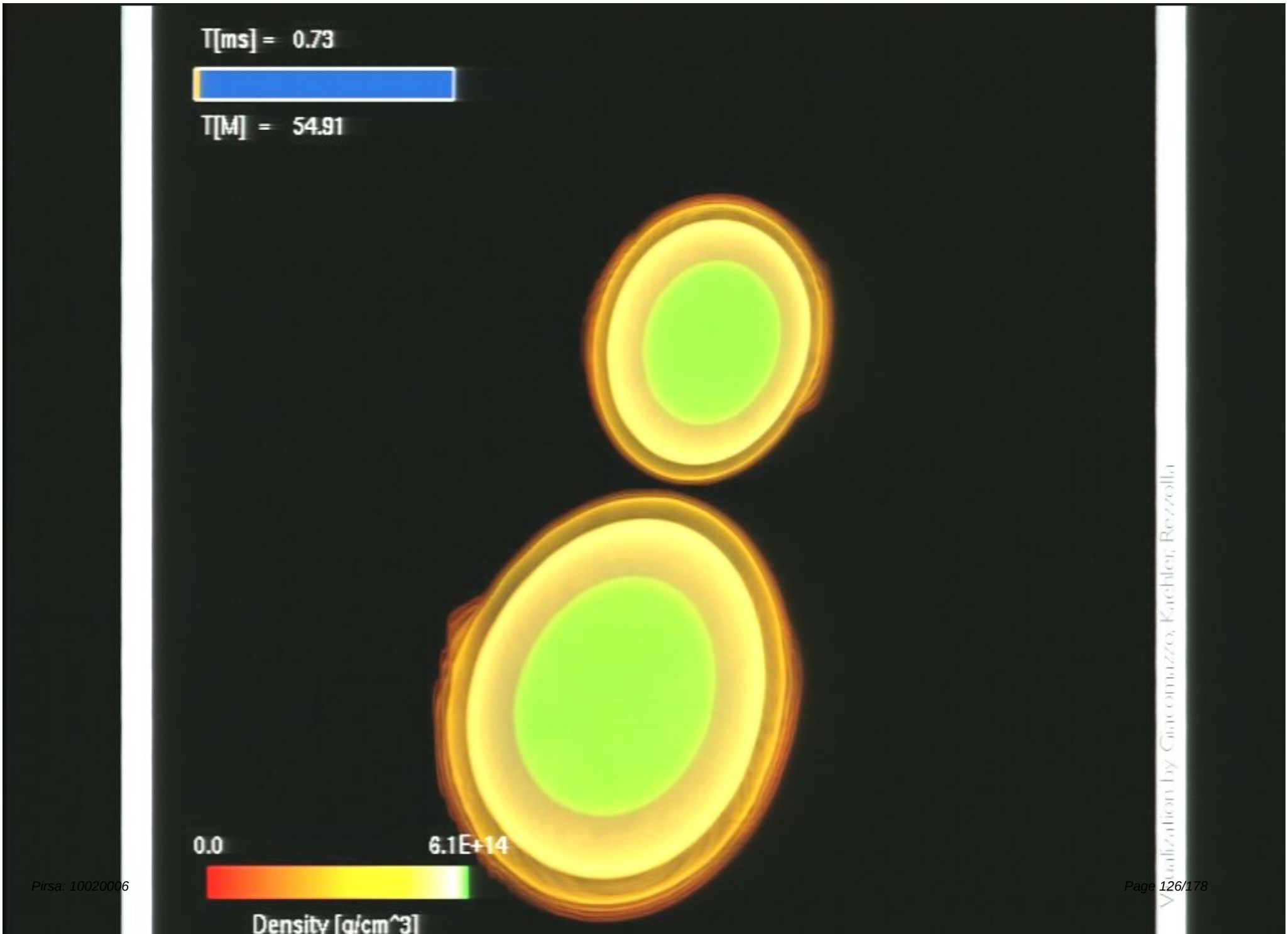

T[ms] = 0.00
T[M] = 0.00
0.0
6.1E+14
Density [g/cm^3]
Visualization by Giovanni Poggi, Kaethe Rozelle

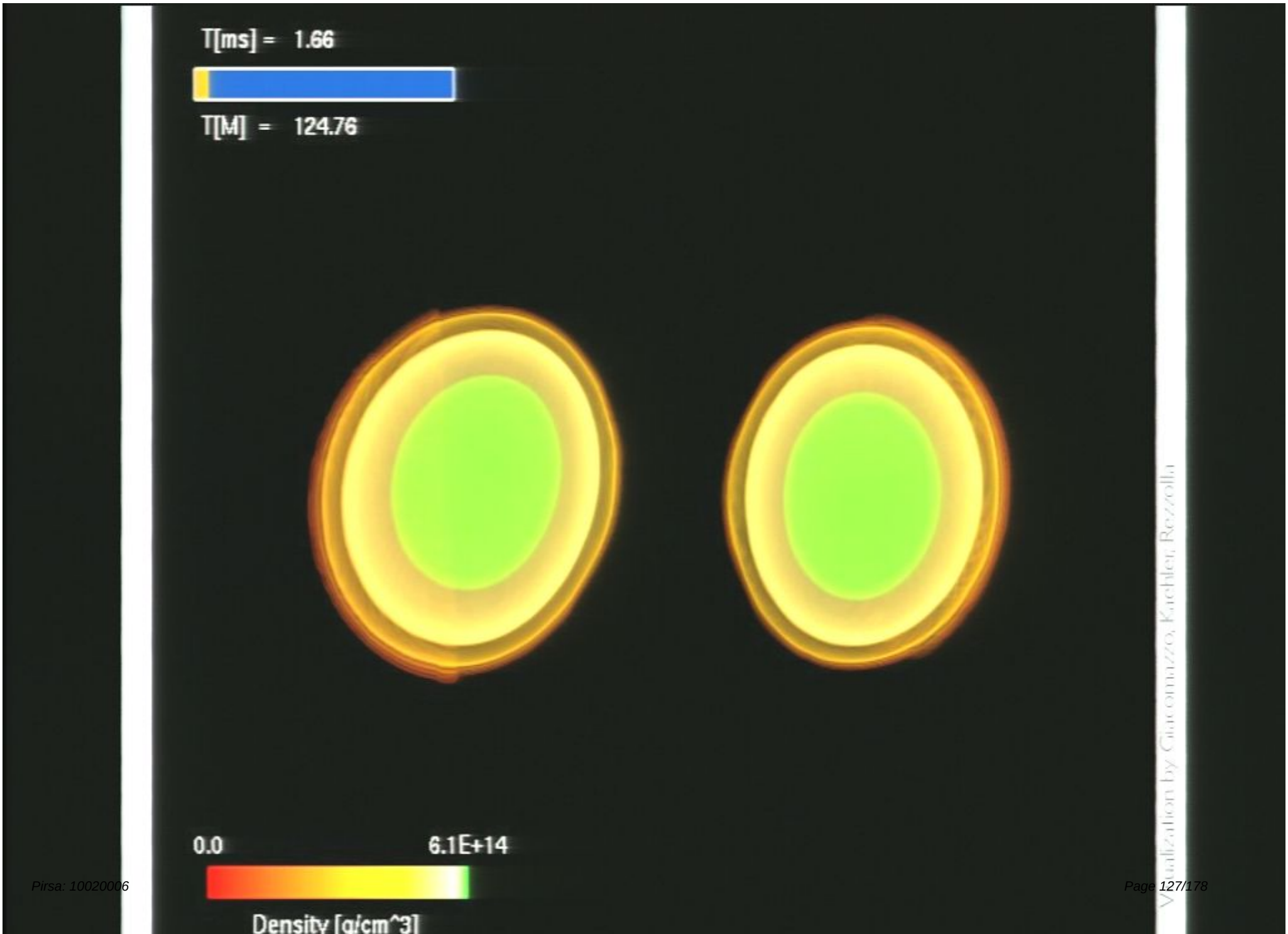

T[M] =
0.0
6.1E+14
Density [g/cm^3]
Visualization by Gaurav Muzzo, Kaelden, Rezzolla

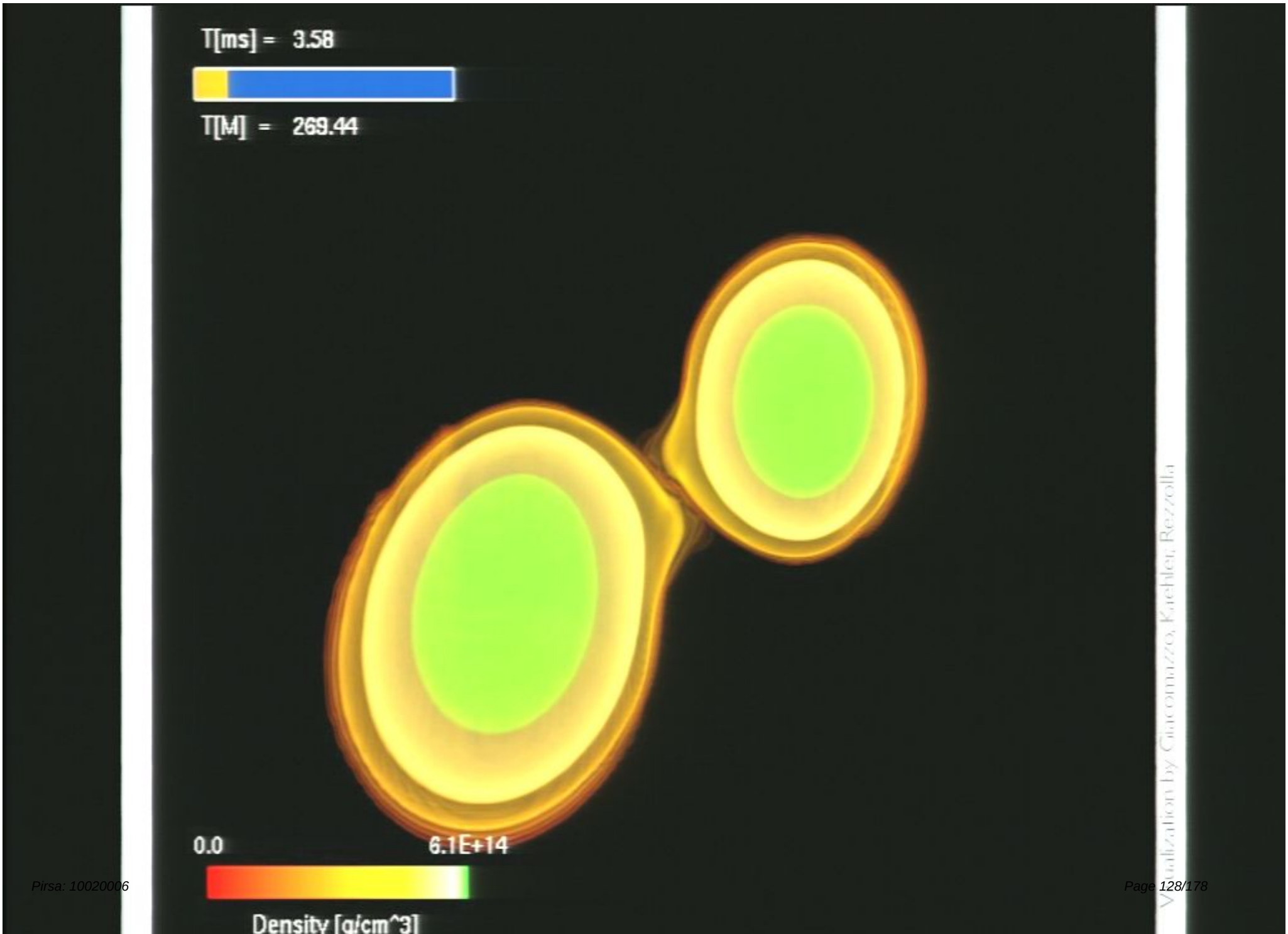

T[M] =
0.0
6.1E+14
Density [g/cm^3]
Visualized by Concannon, Kaehler, Rezzolla

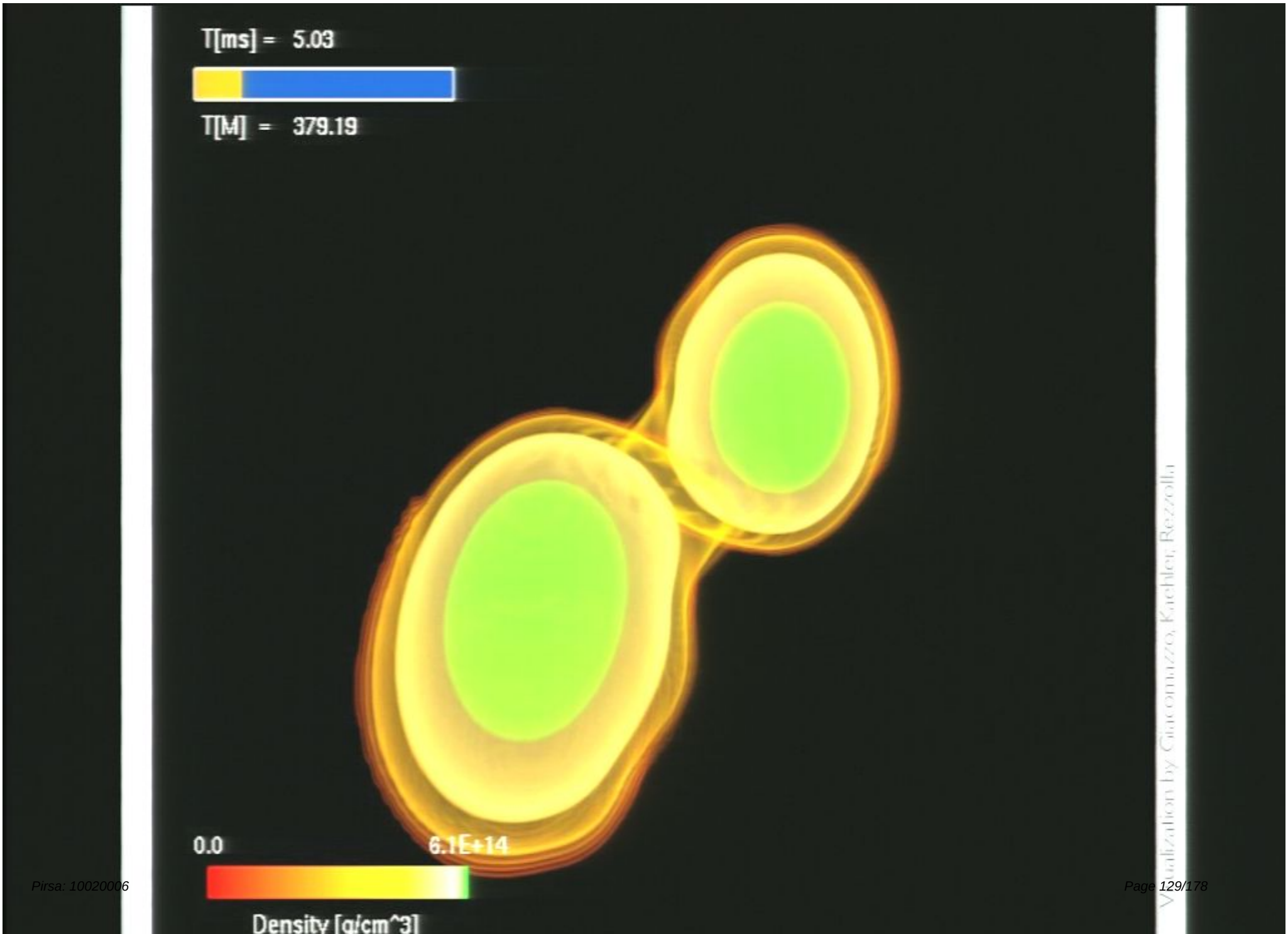

0.0
6.1E+14
Density [g/cm^3]
Visualized by Giovanni Kaehler, Kazeolla

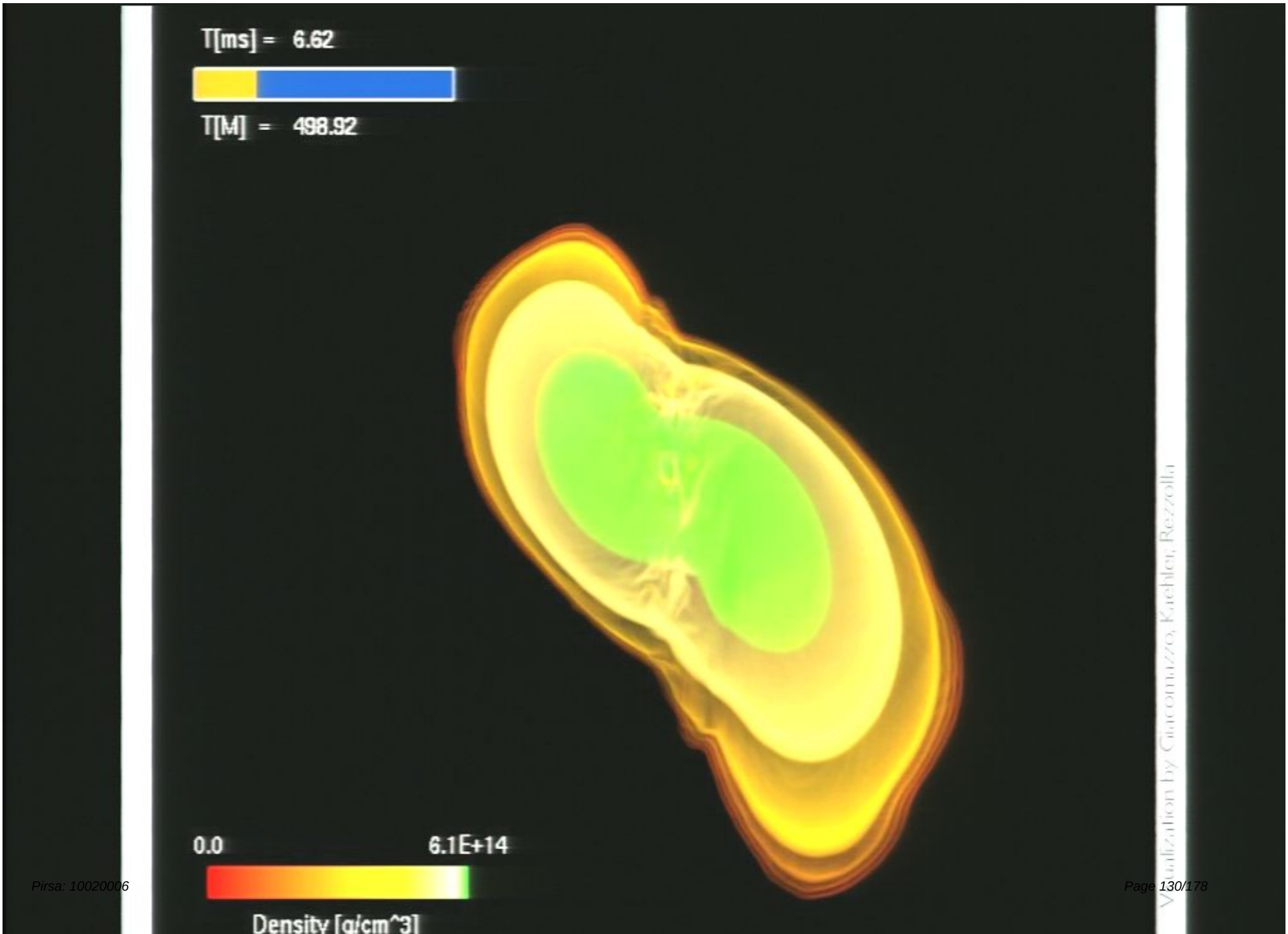

T[ms] = 0.07
T[M] = 5.03
0.0
6.1E+14
Density [g/cm^3]
Visualization by Giacomuzzo, Kaehler, Rezzolla

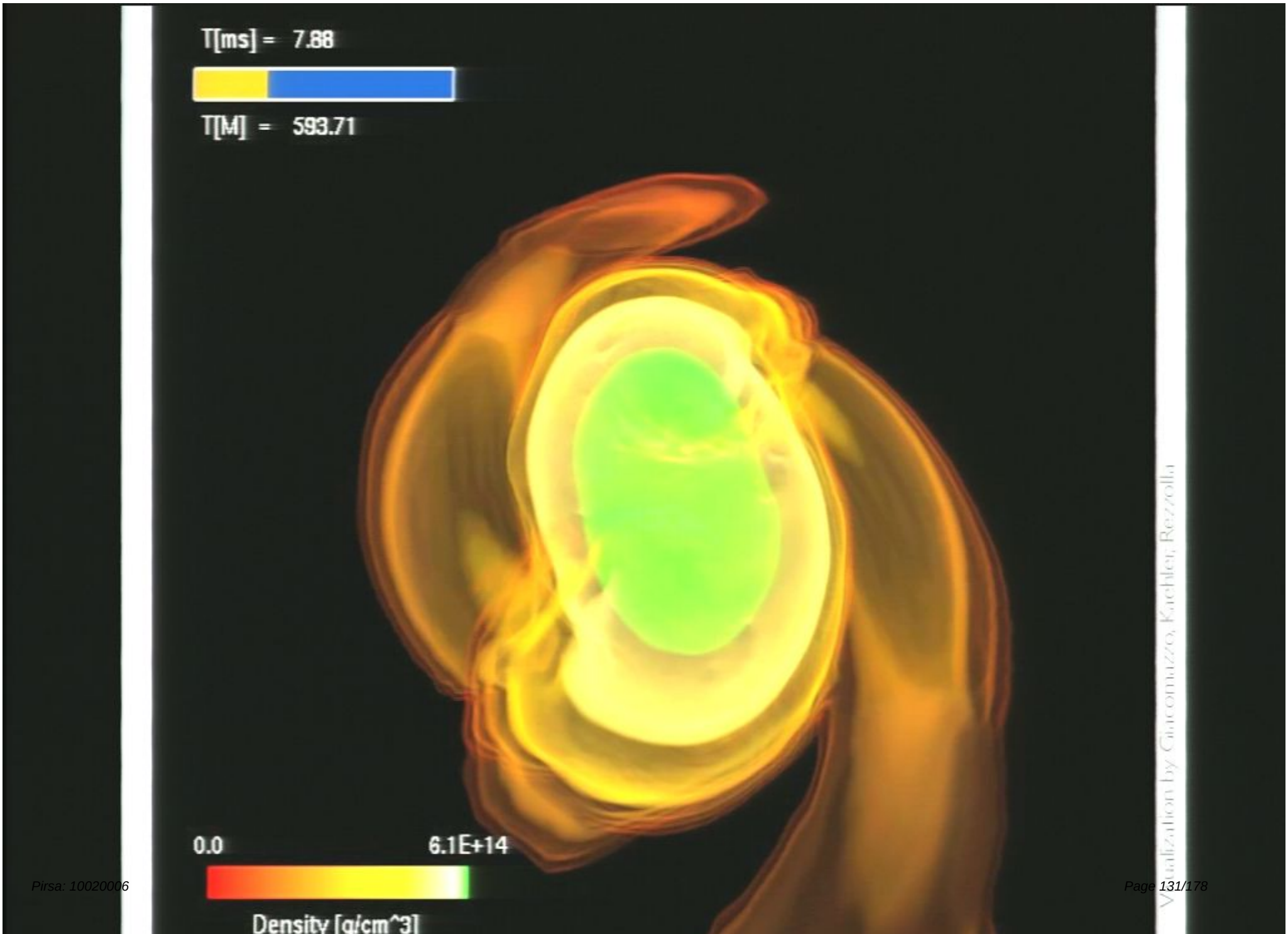

T[ms] = 0.73
T[M] = 54.91
0.0
6.1E+14
Density [g/cm^3]
Visualization by Giovanni Zacchi, Kaehler, Rezzolla

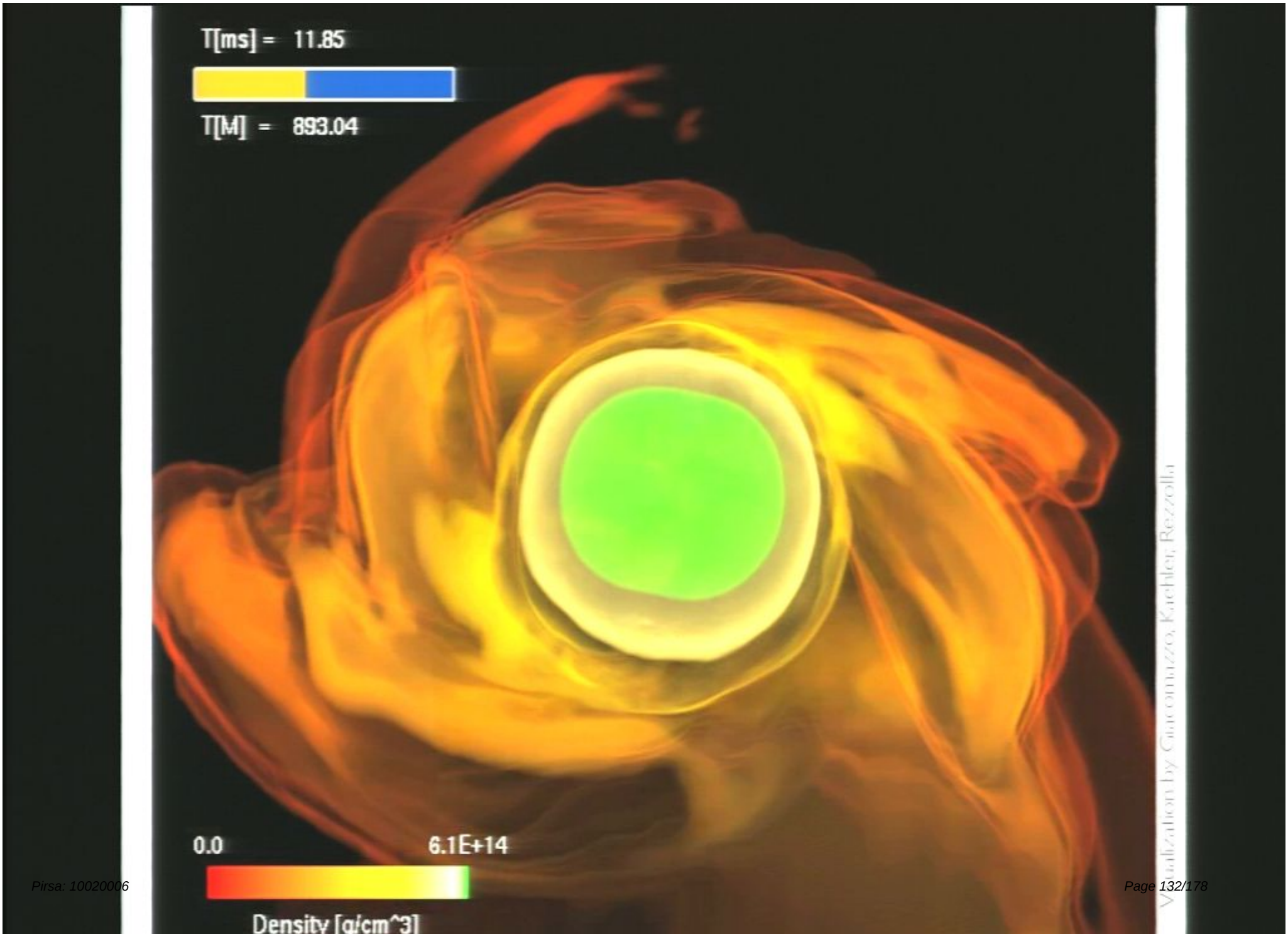

T[ms] = 1.66
T[M] = 124.76
0.0
6.1E+14
Density [g/cm^3]
Visualization by Giovanni Zanzo, Kaehler, Rezzolla

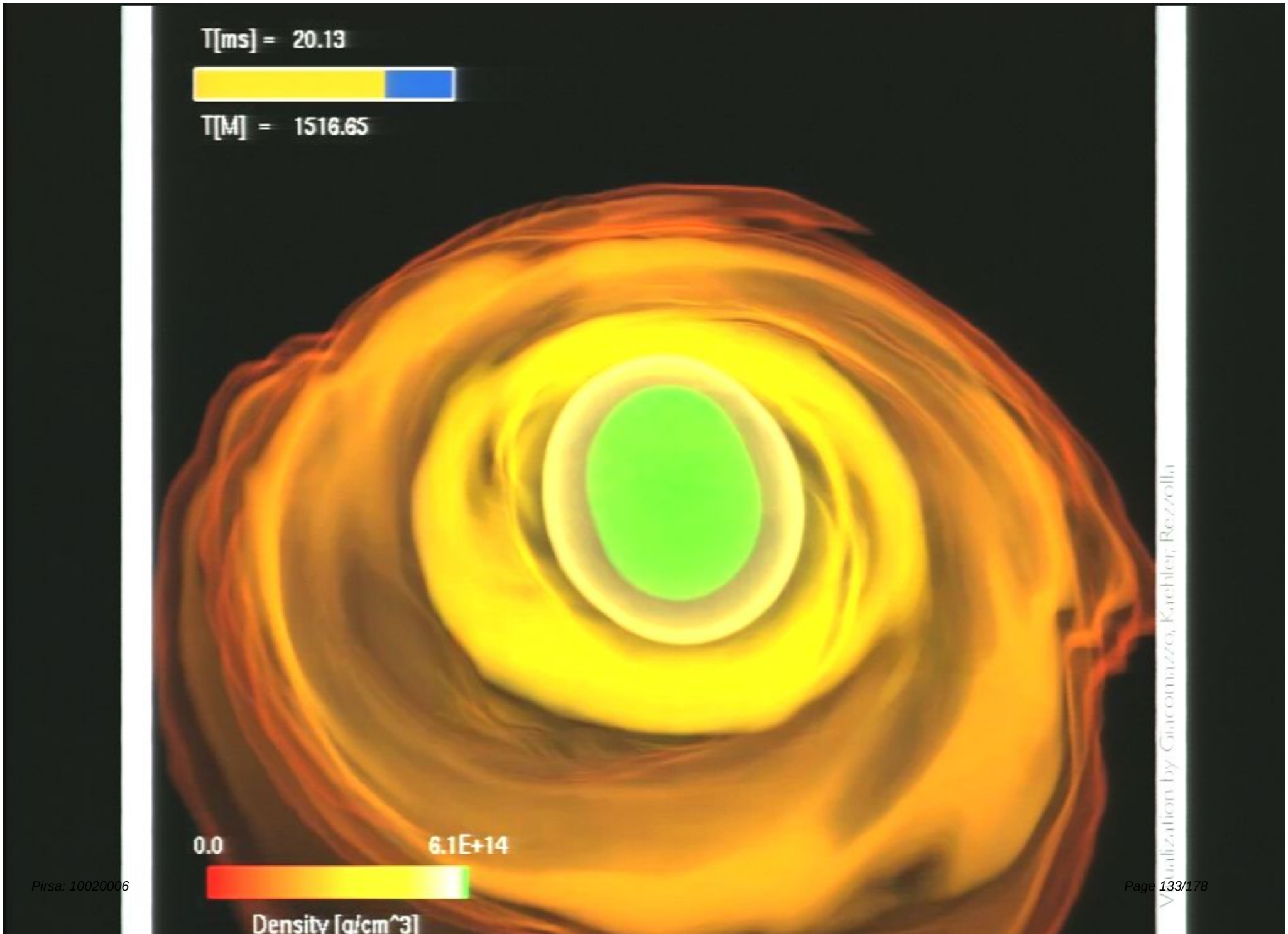

T[ms] = 3.58
T[M] = 269.44
0.0
6.1E+14
Density [g/cm^3]
Visualization by Giacomazzo, Kaehler, Rezzolla

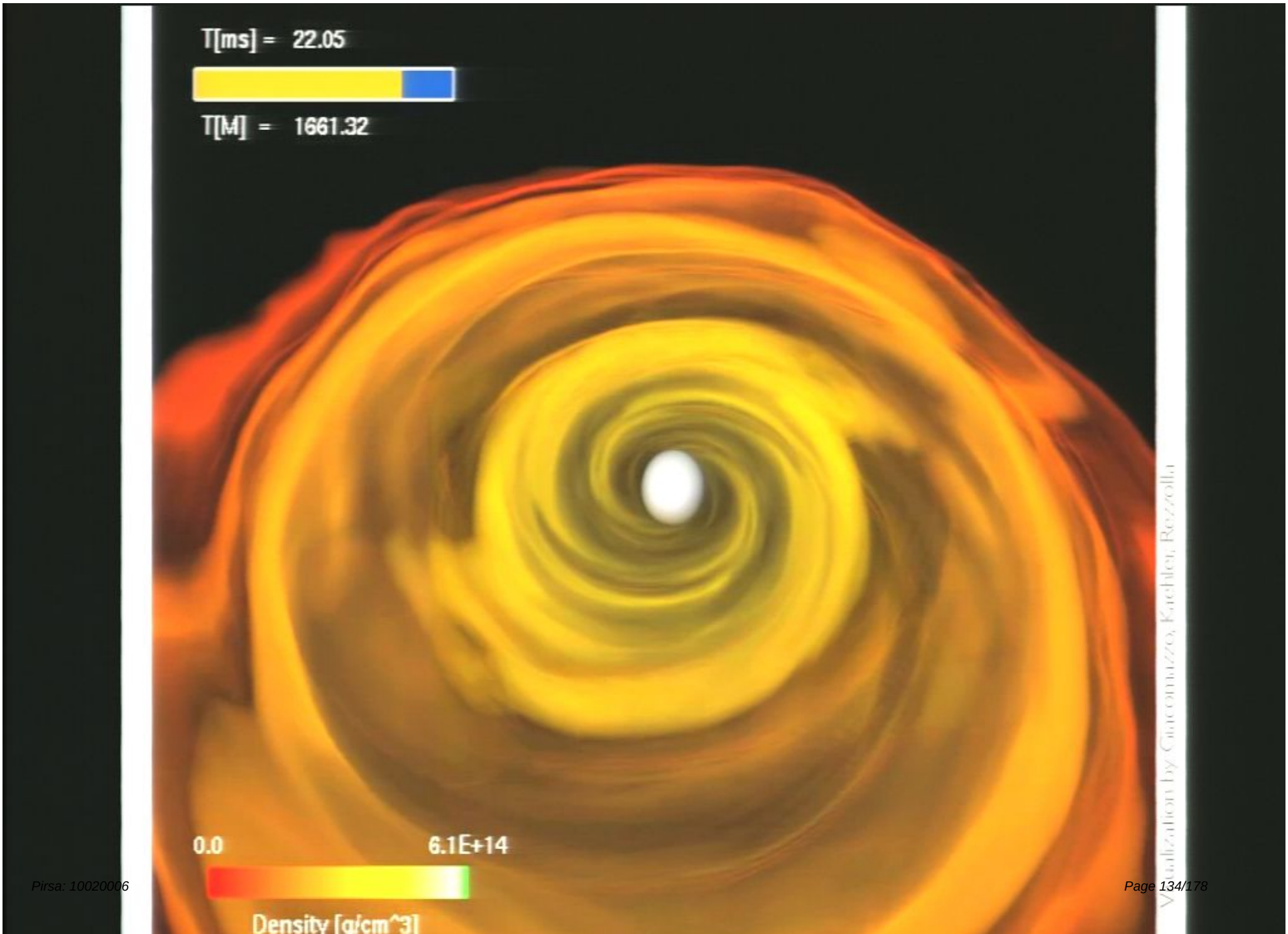

T[ms] = 5.03
T[M] = 379.19
0.0
6.1E+14
Density [g/cm^3]
Visualization by Giovanni Zacchi, Kaehler, Rezzolla

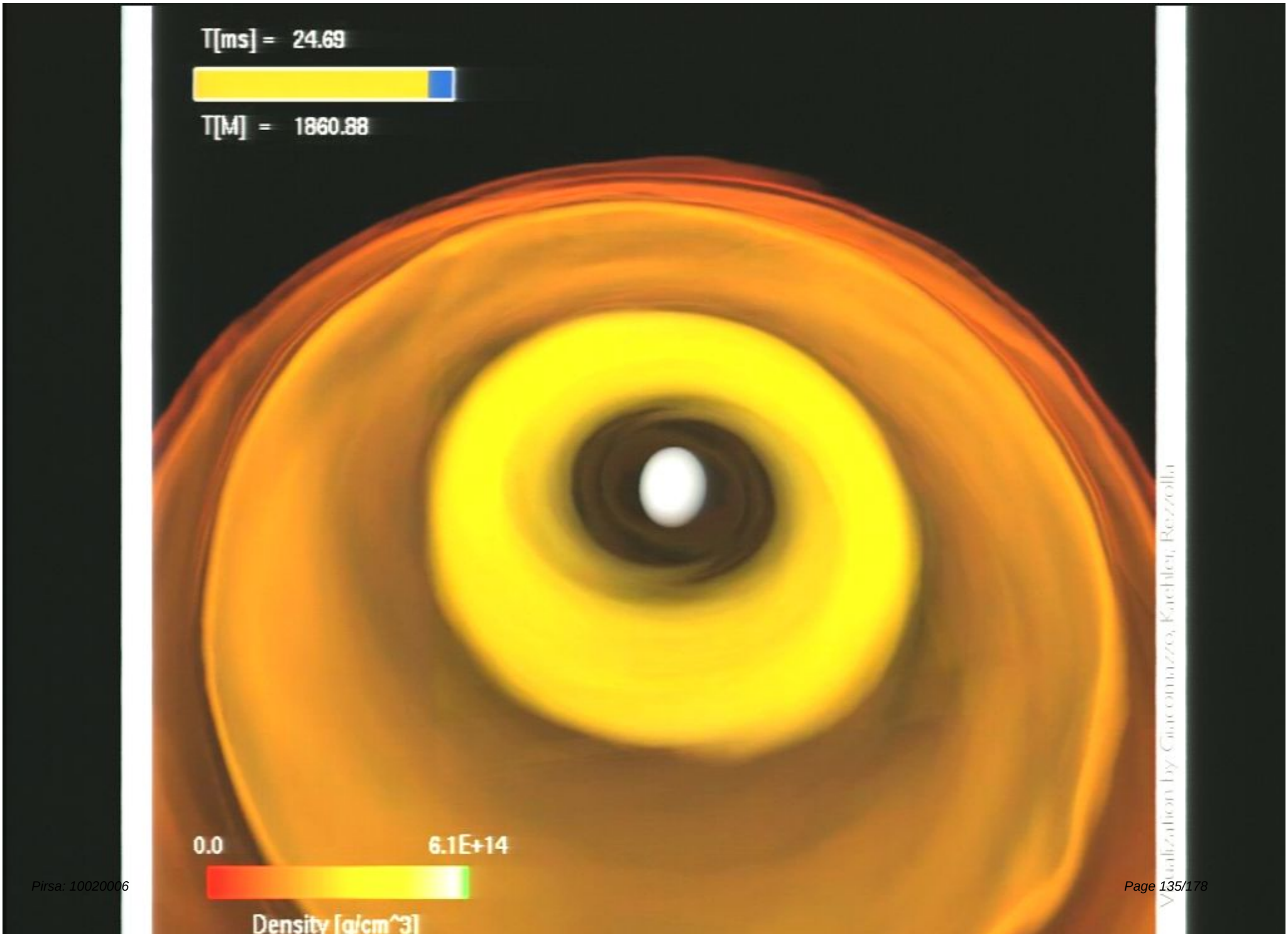

T[ms] = 6.62
T[M] = 498.92
0.0
6.1E+14
Density [g/cm^3]
Visualization by Giacomazzo, Kaehler, Rezzolla

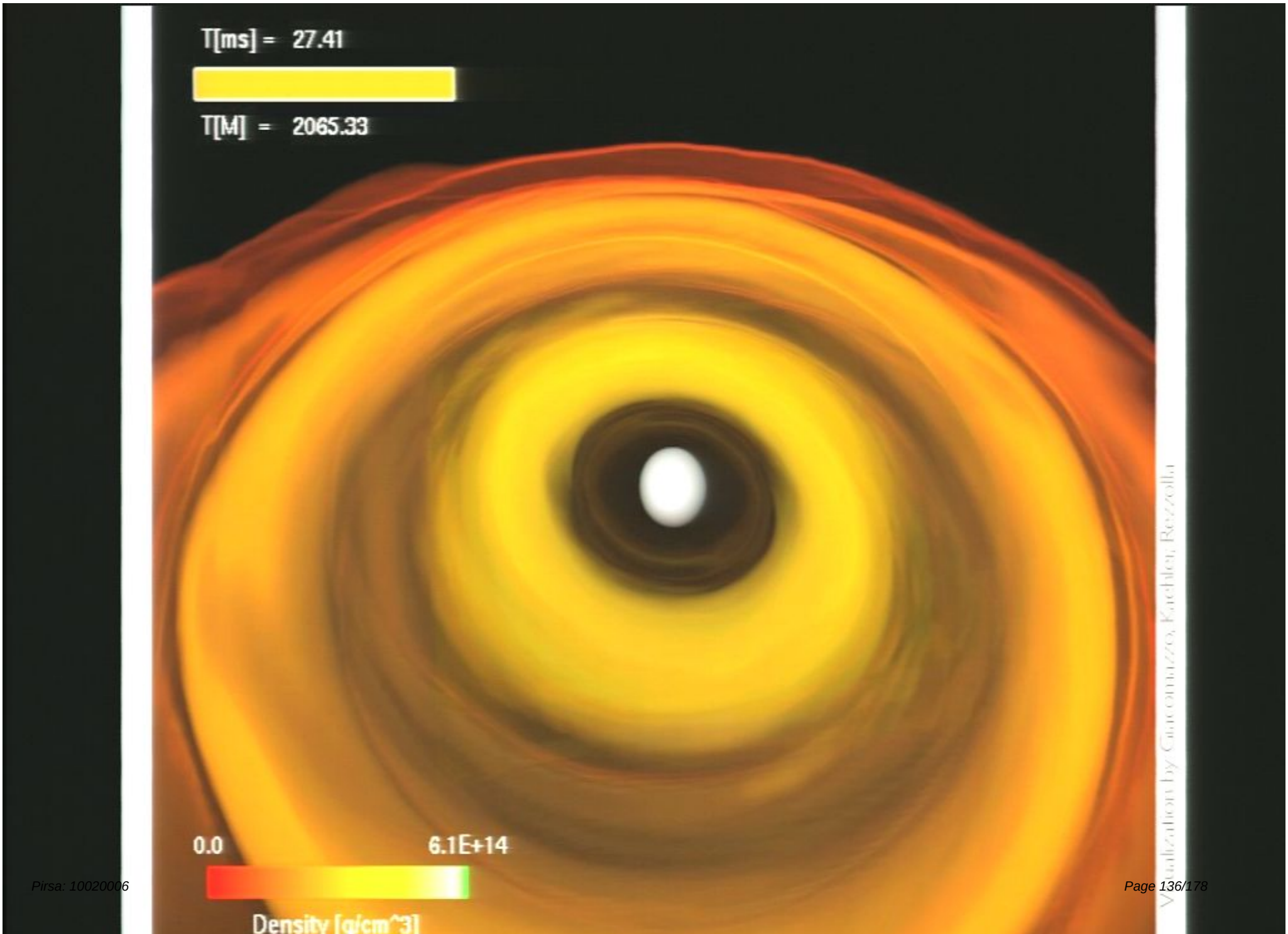

T[ms] = 7.88
T[M] = 593.71
0.0
6.1E+14
Density [g/cm^3]
Visualization by Giacomuzzo, Kuebler, Rezzolla


T[ms] = 11.85
T[M] = 893.04
0.0
6.1E+14
Density [g/cm^3]
Visualization by Giacomazzo, Kaehler, Rezzolla


T[ms] = 20.13
T[M] = 1516.65
0.0
6.1E+14
Density [g/cm^3]
Visualization by Giacomazzo, Kaehler, Rezzolla

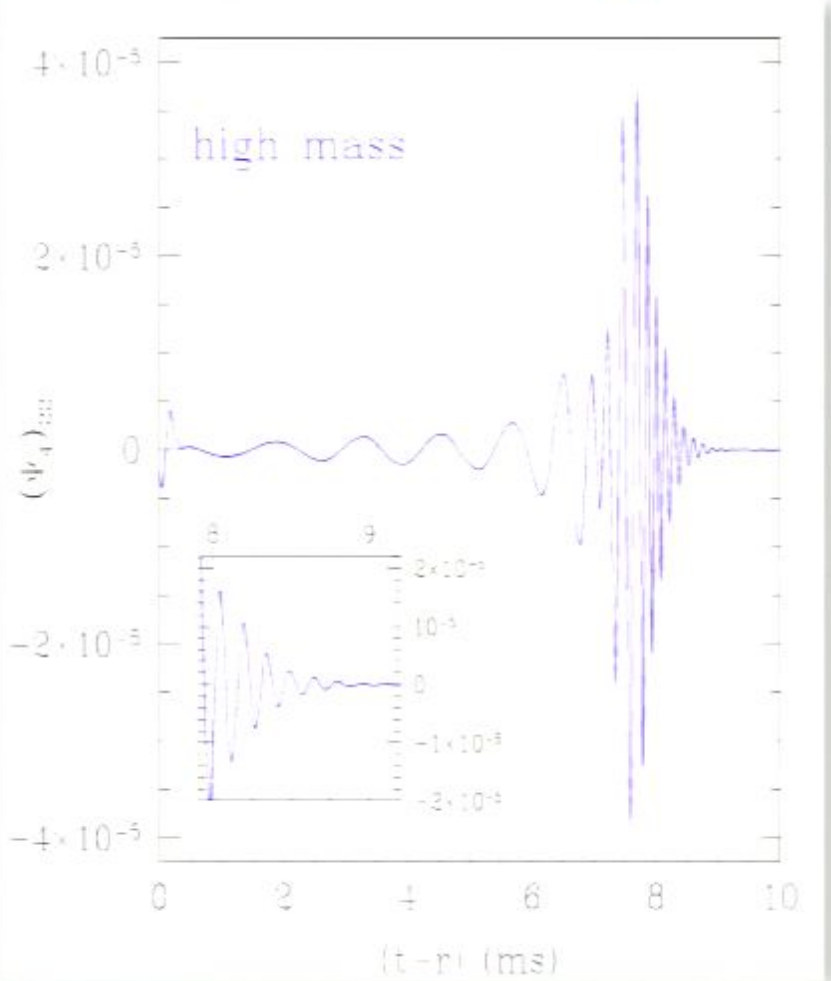

T[ms] = 22.05
T[M] = 1661.32
0.0
6.1E+14
Density [g/cm^3]
Visualization by Giovanni Lacchen, Roezolh


T[ms] = 24.69
T[M] = 1860.88
0.0
6.1E+14
Density [g/cm^3]
Visualization by Giovanni Zacchi, Kaehler, Rezzolla

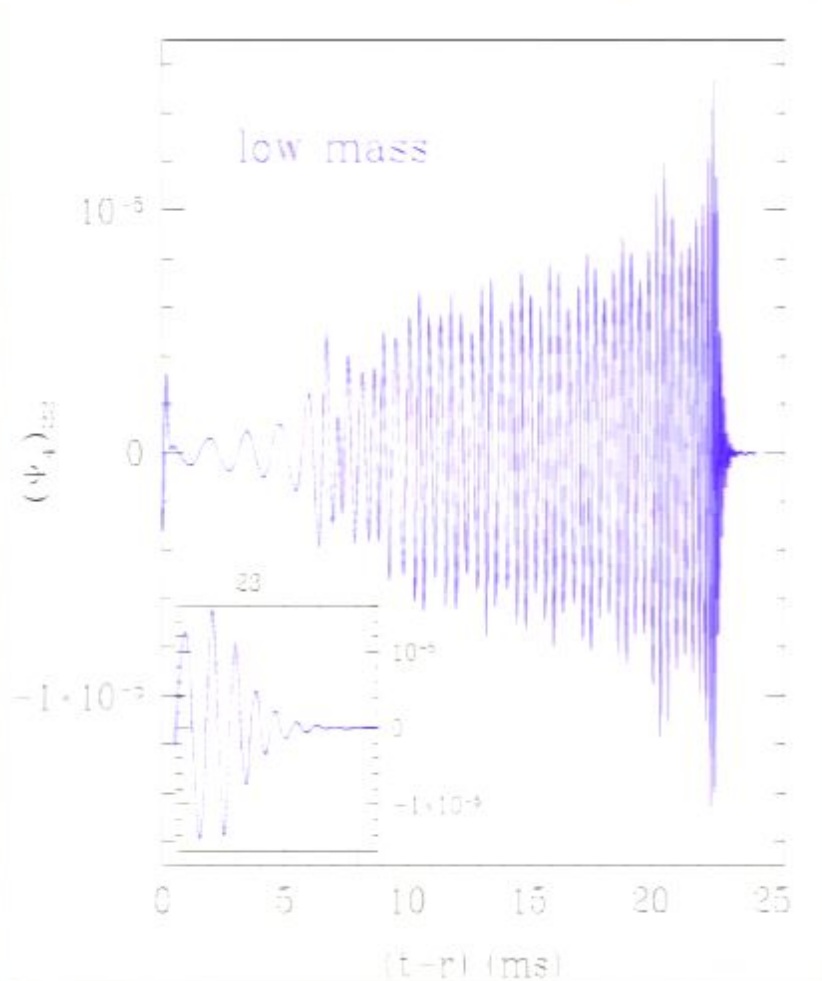

T[ms] = 27.41
T[M] = 2065.33
0.0
6.1E+14
Density [g/cm^3]
Visualization by Giovanni Lacanna, Kaehler, Rezzolla

WAVEFORMS: THE ROLE OF THE MASS

high-mass binary



low-mass binary



Prompt collapse to BH: only inspiral, merger, ringdown

Delayed collapse to BH: inspiral, merger, HMNS evolution, ringdown

GWS FROM BNS: THE ROLE OF THE EOS

Binary Neutron Stars: The Role of the Equation of State

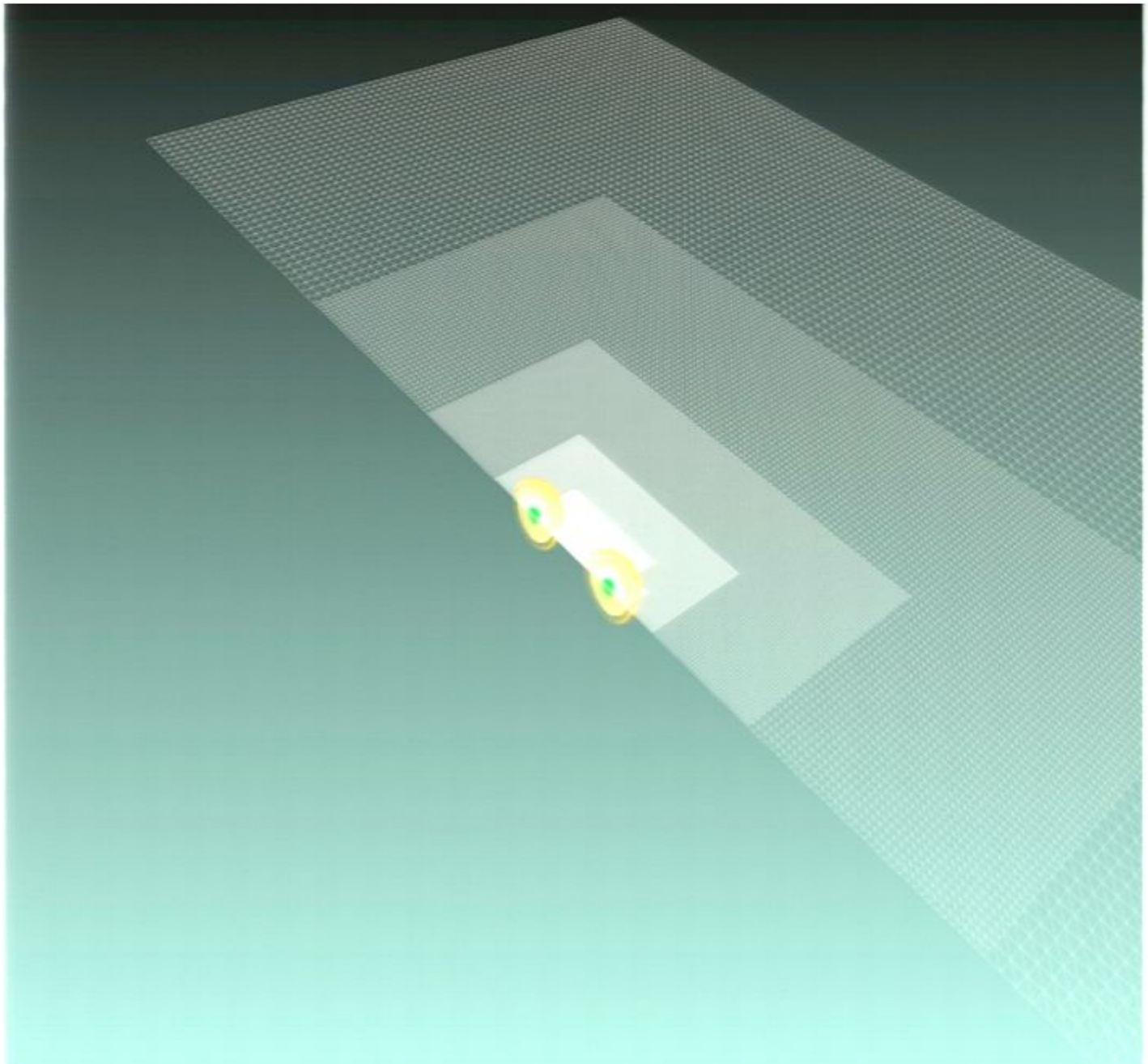
So far considered **polytropic EOS** which is isentropic. Entropy cannot change and the thermal energy cannot increase

$$P = \kappa \rho^{\Gamma}$$

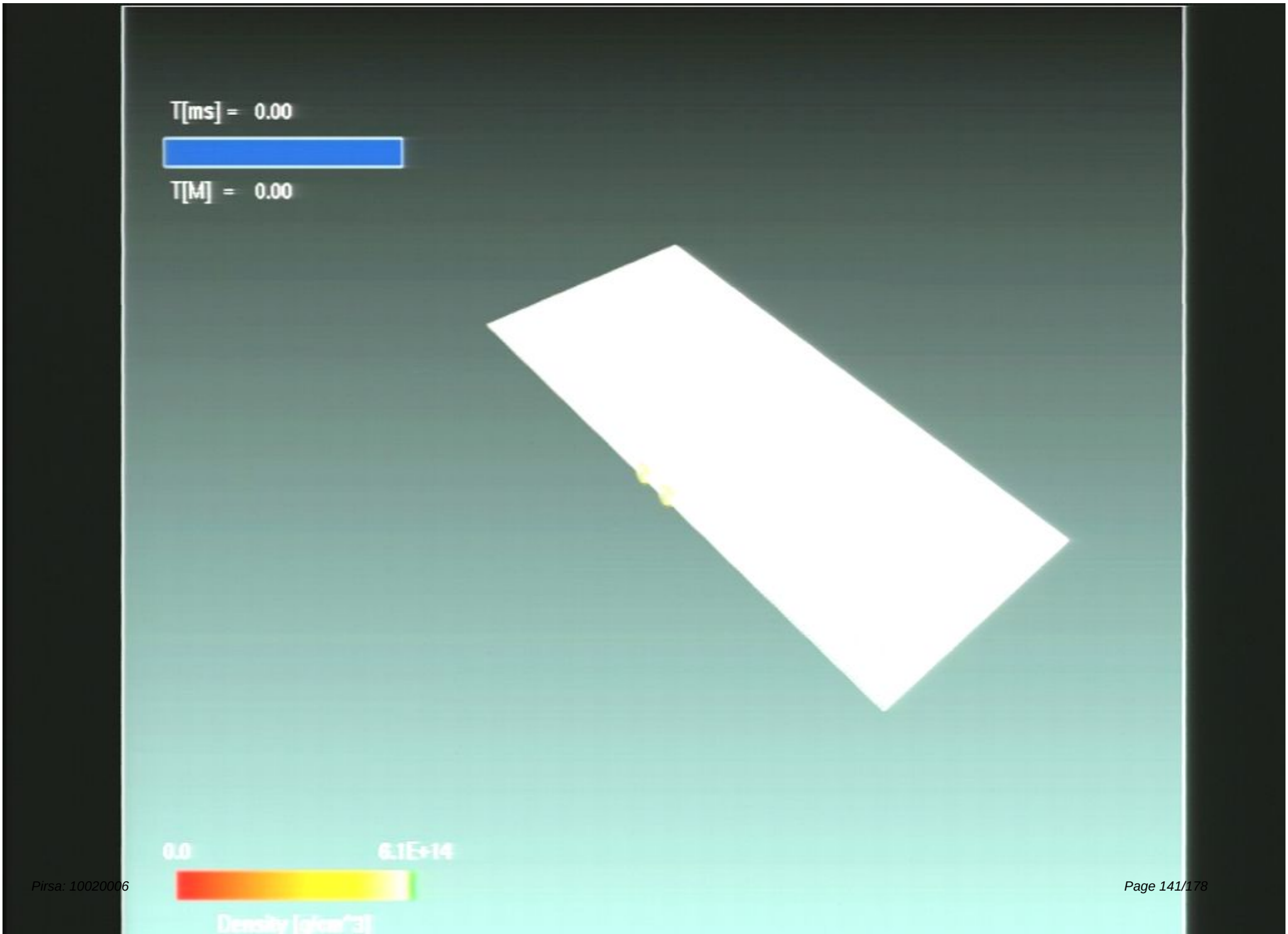
A step forward before implementing realistic EOSs can be made with an **ideal-fluid EOS**, non-isentropic if shocks are present. The thermal energy is expected to increase.

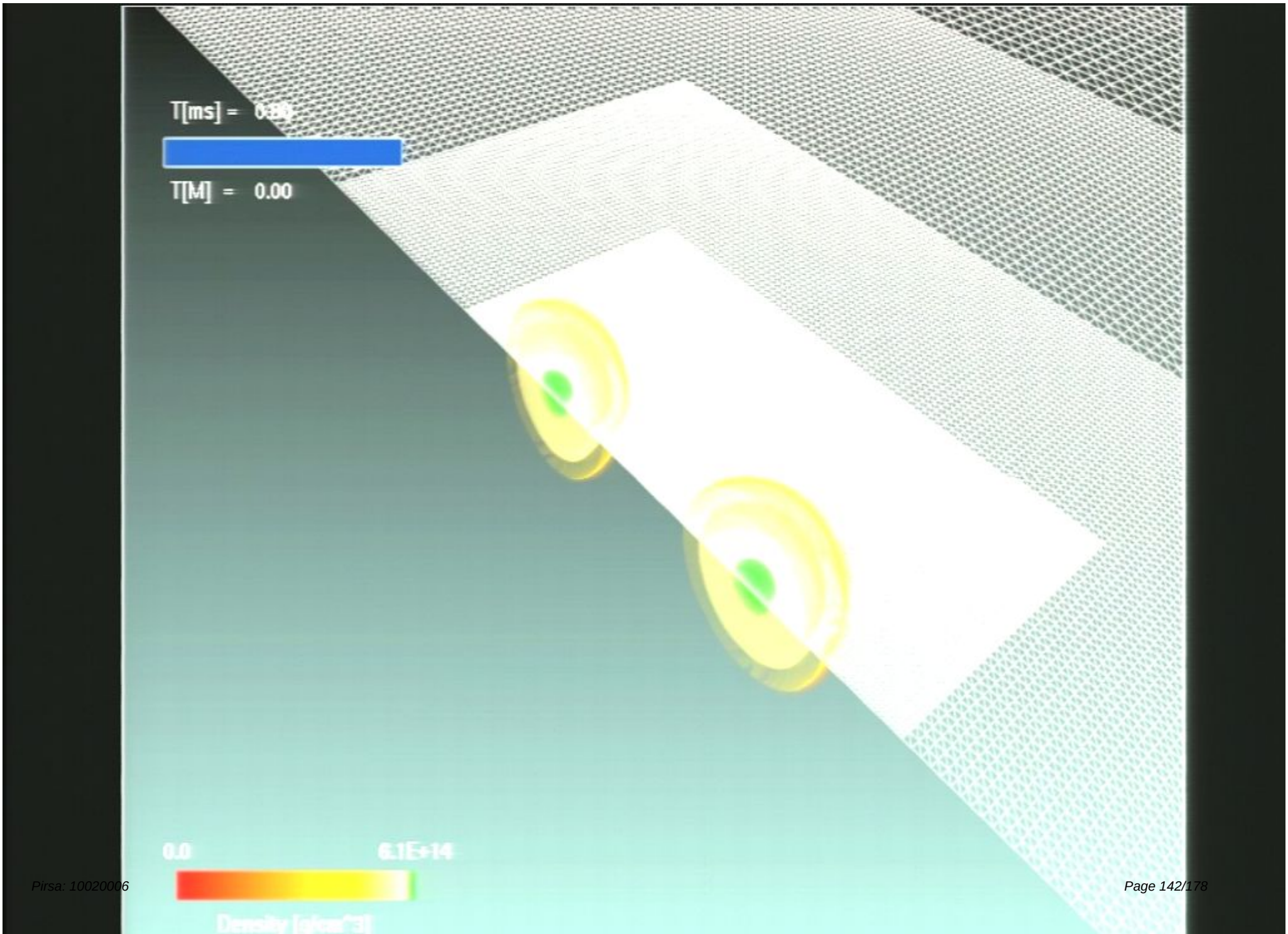
$$P = \rho \epsilon (\Gamma - 1)$$

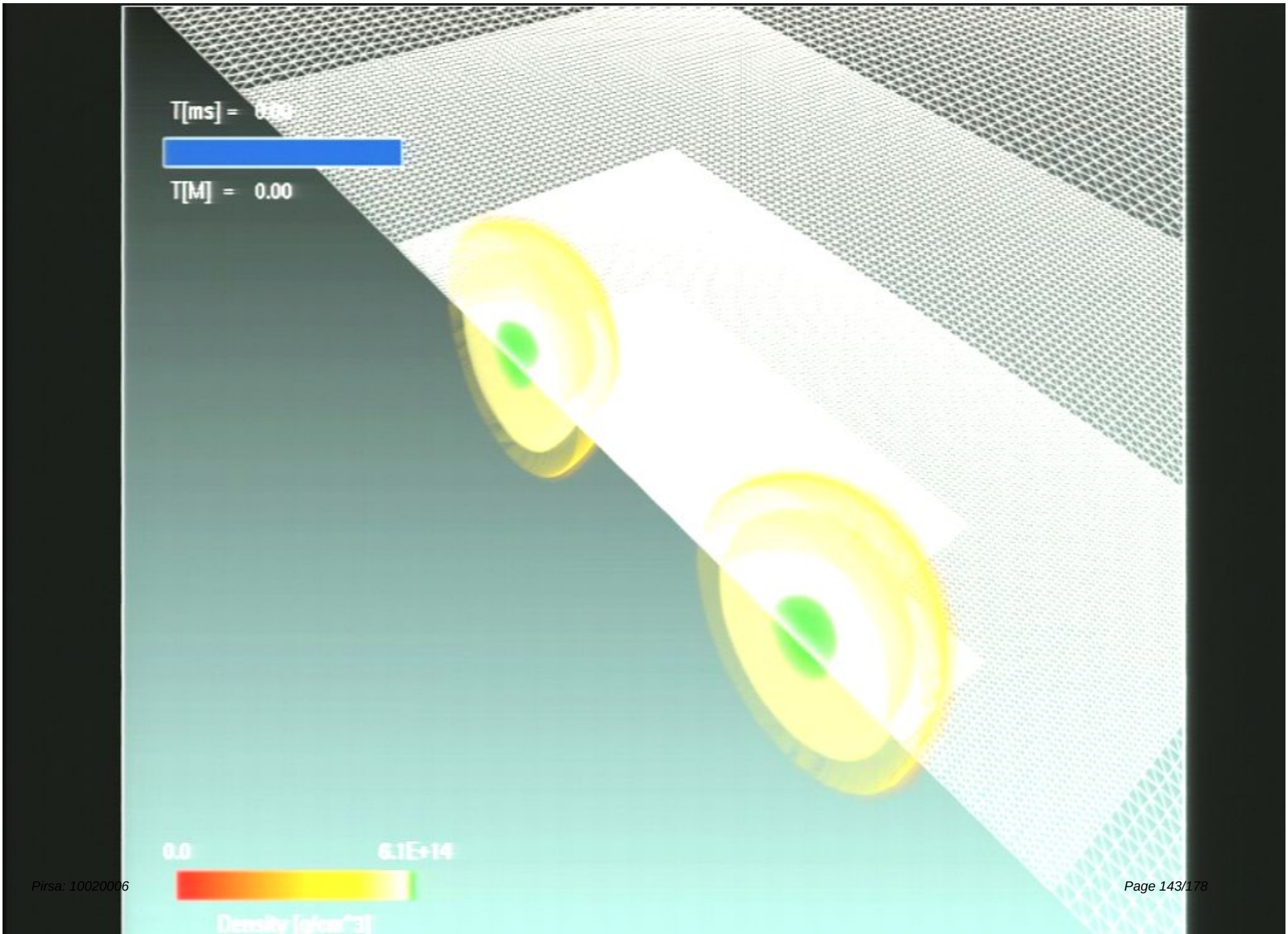
IDEAL FLUID EOS: HIGH-MASS BNS

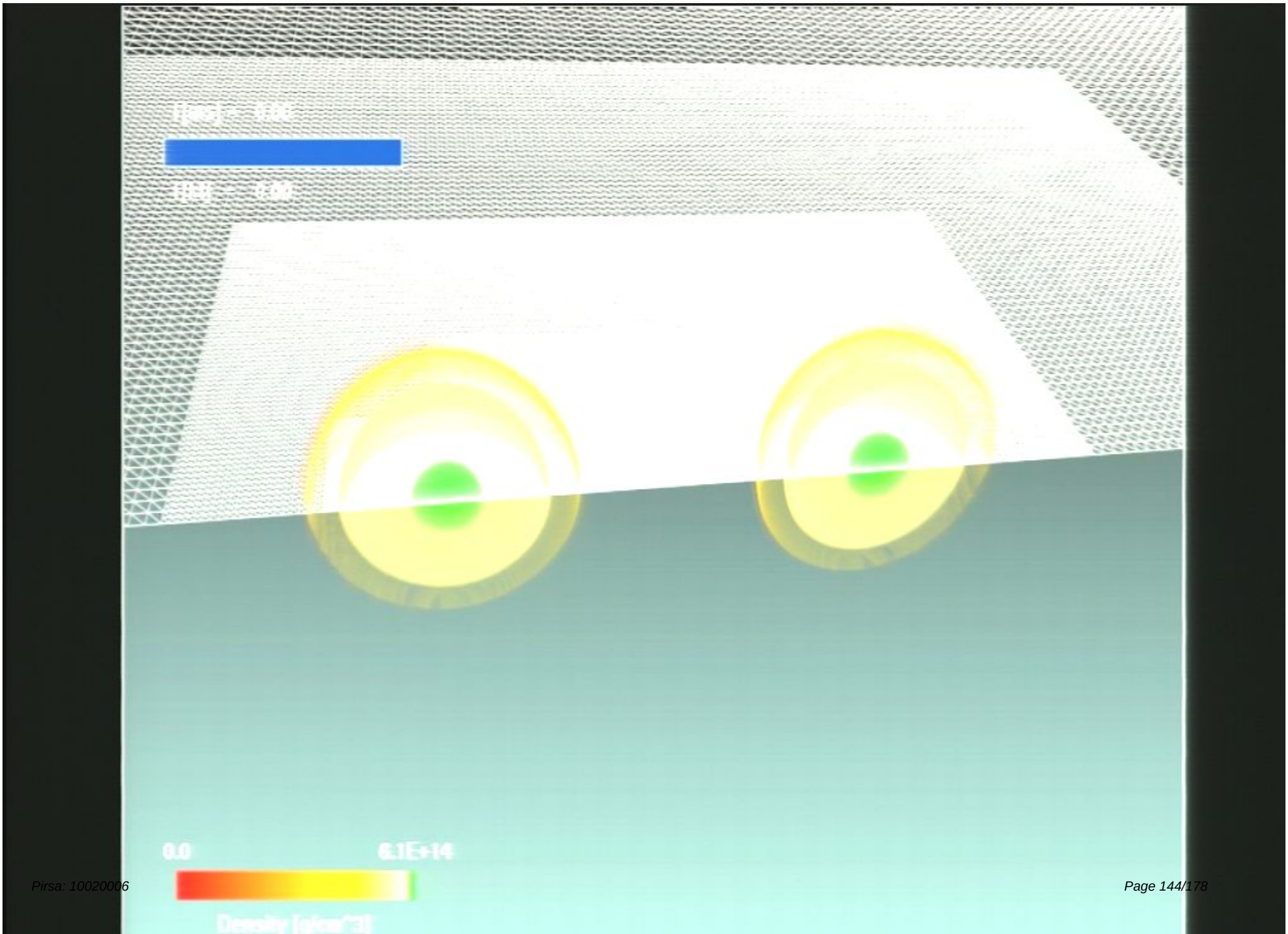


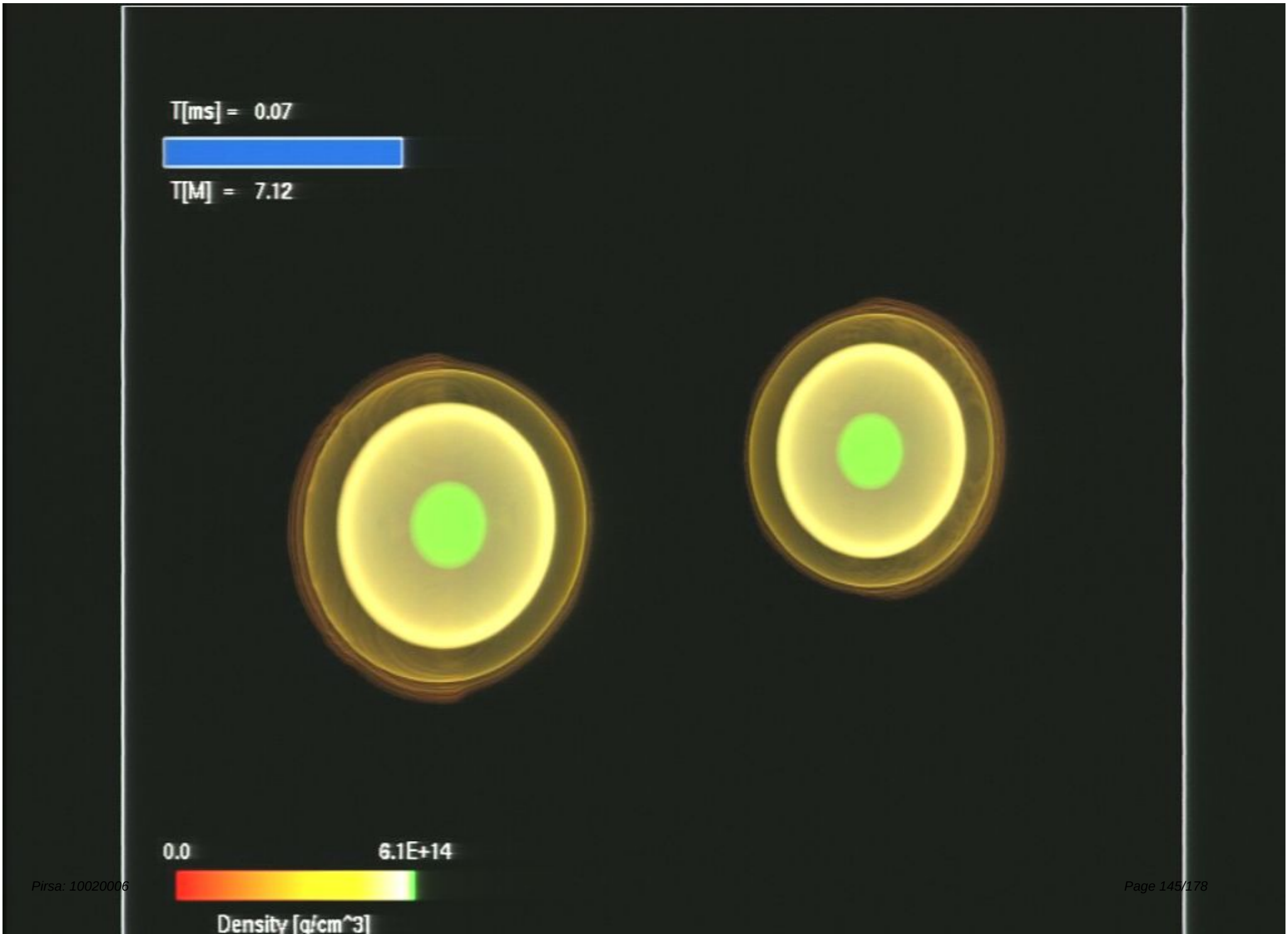
Visualization by Giacomazzo, Kaehler, Rezzolla

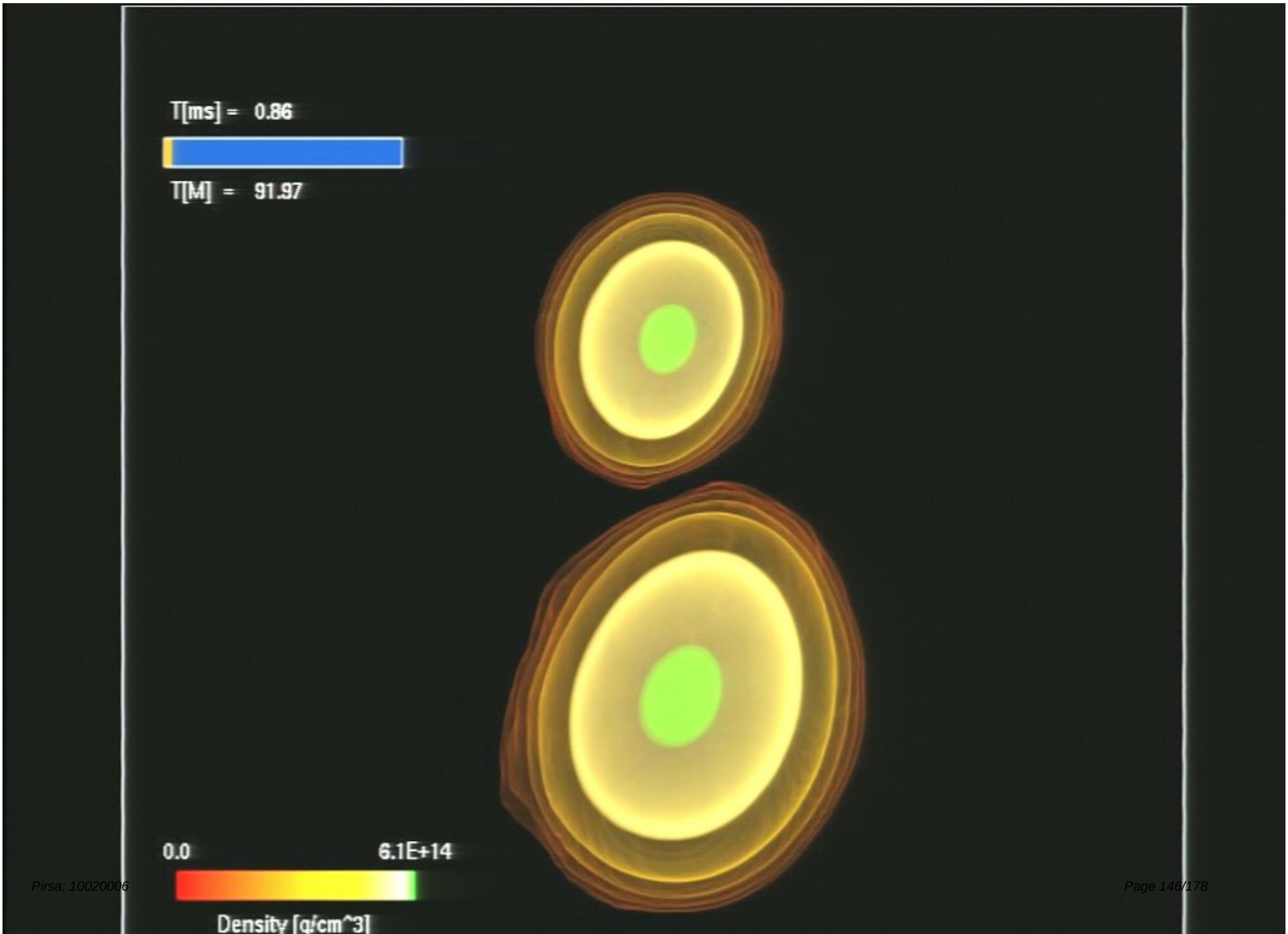

T[ms] = 0.00
T[M] = 0.00
0.0
6.1E+14
Density [g/cm^3]

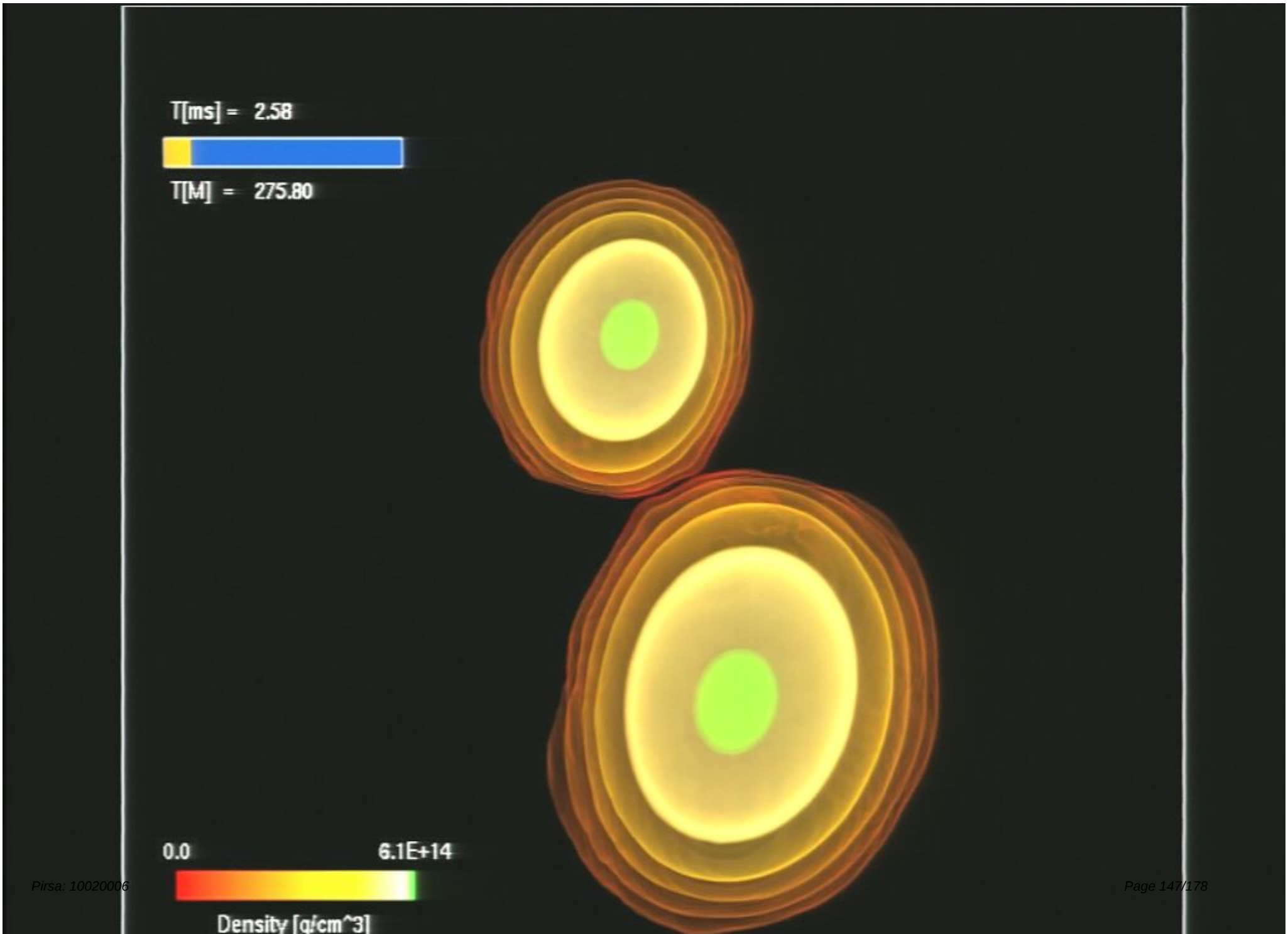

T[ms] =
T[M] = 0.00
0.0
6.1E+14

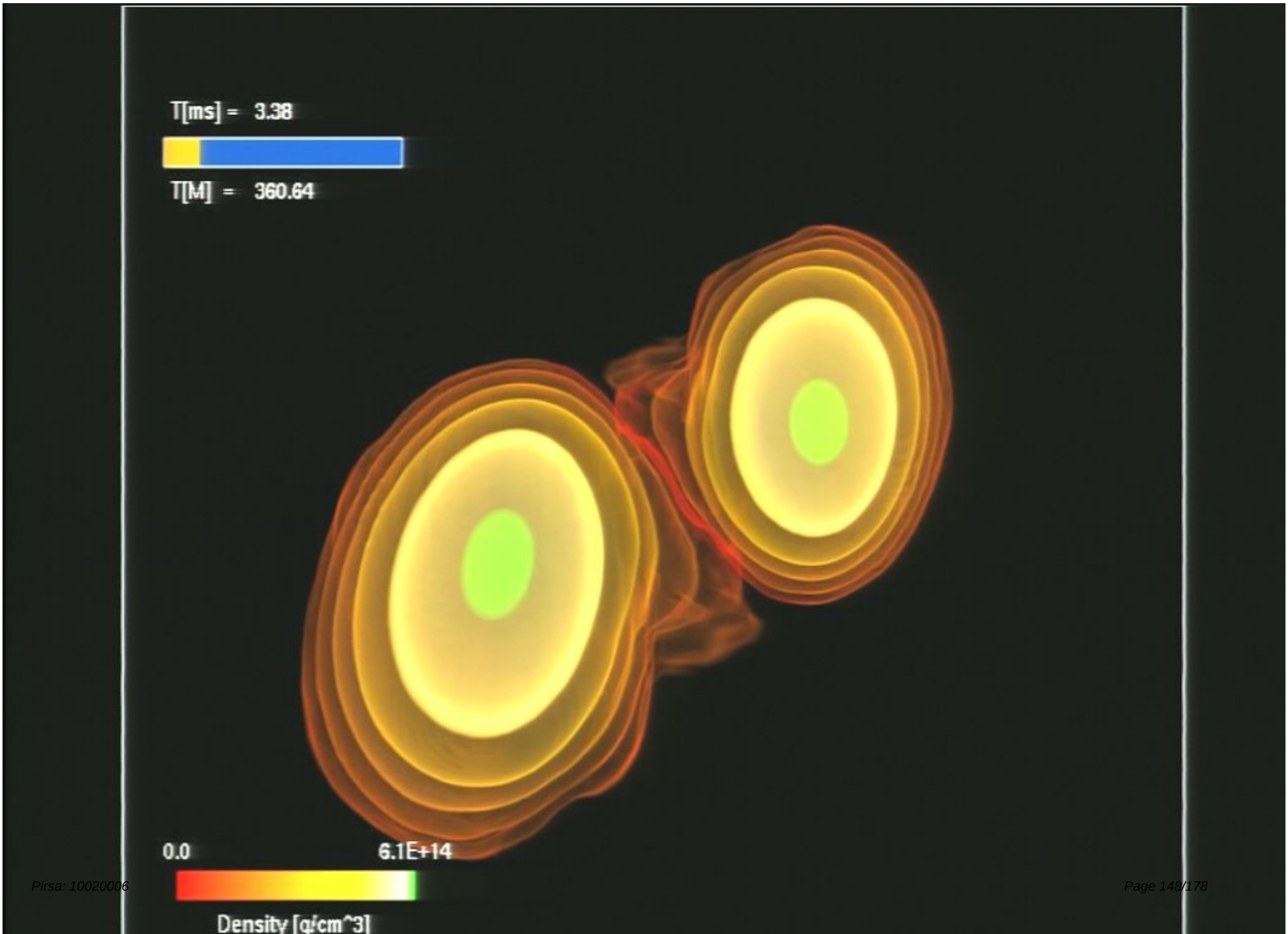

T[ms] =
T[M] = 0.00
0.0
6.1E+14

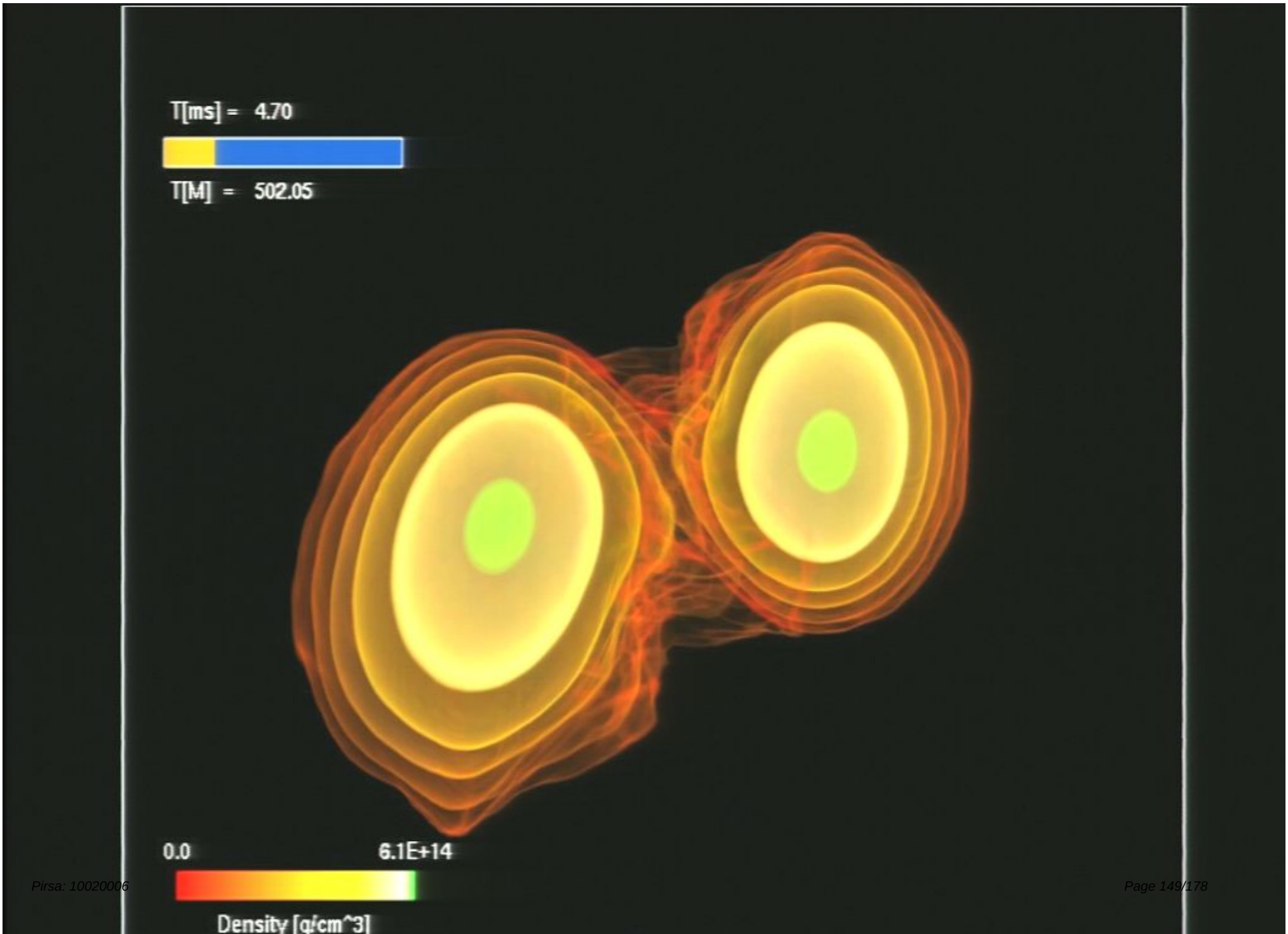

0.0
6.1E+14
Density [g/cm^3]

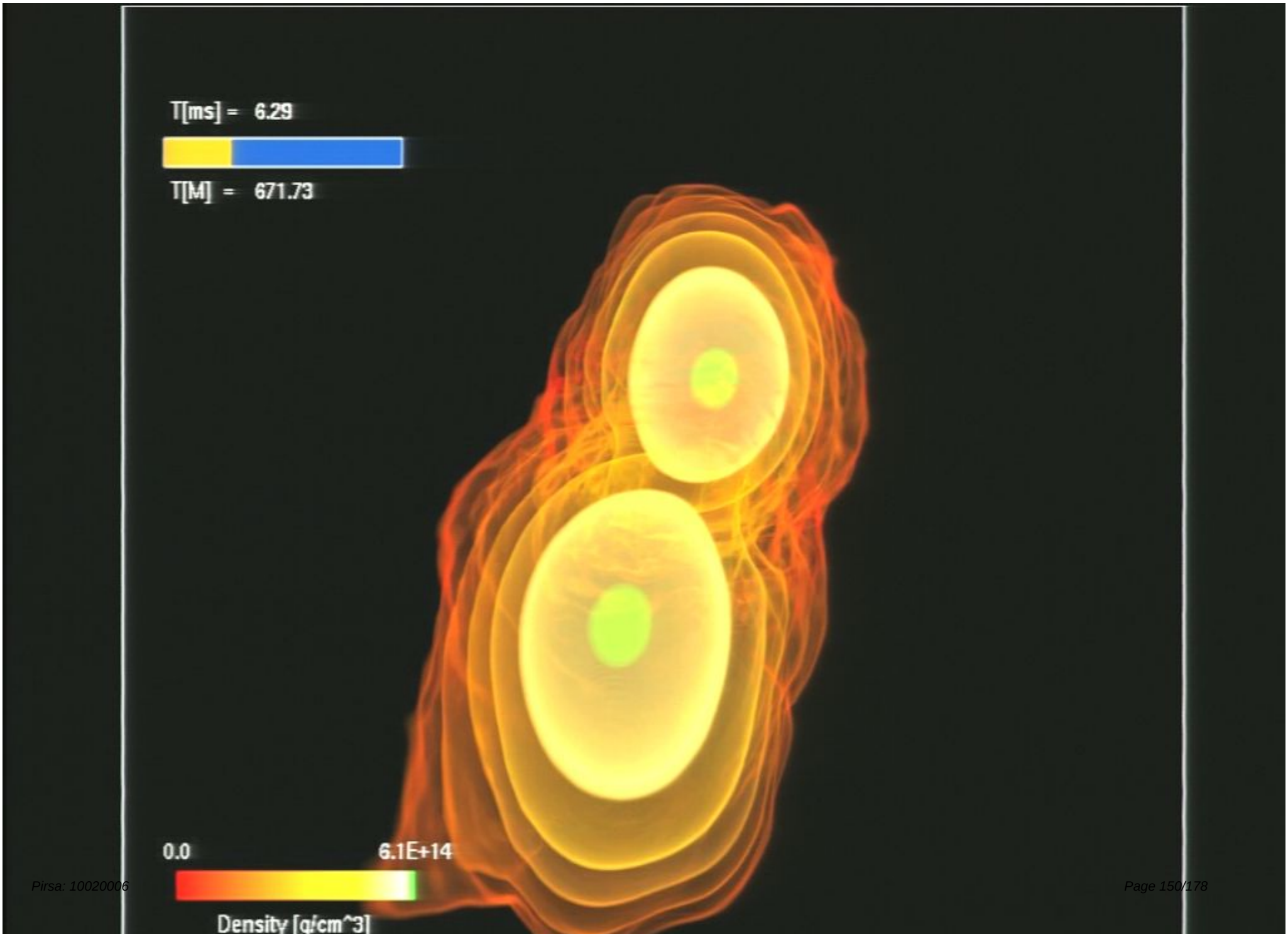

T[ms] = 0.07
T[M] = 7.12
0.0
6.1E+14
Density [g/cm^3]

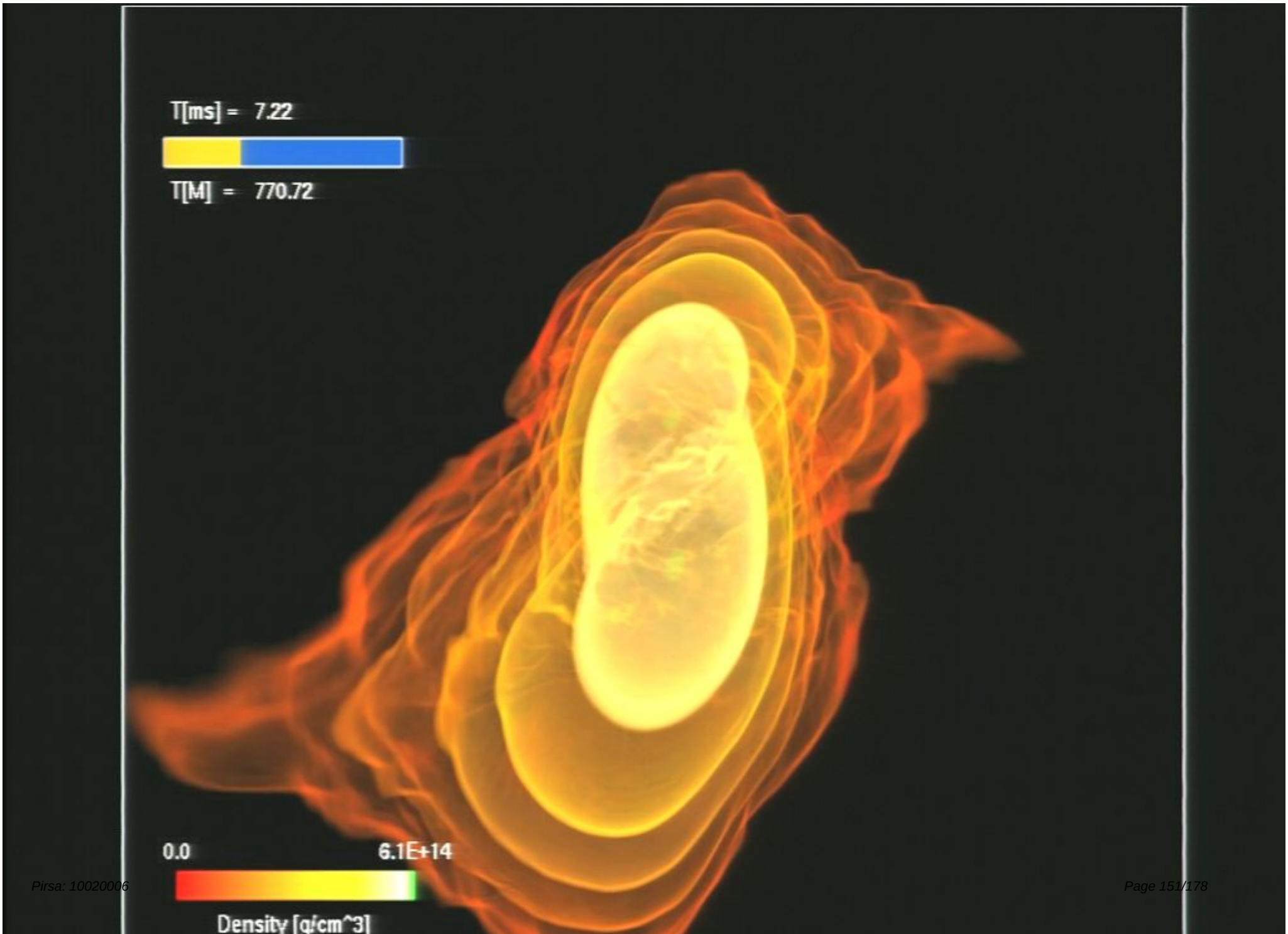

T[ms] = 0.86
T[M] = 91.97
0.0
6.1E+14
Density [g/cm^3]

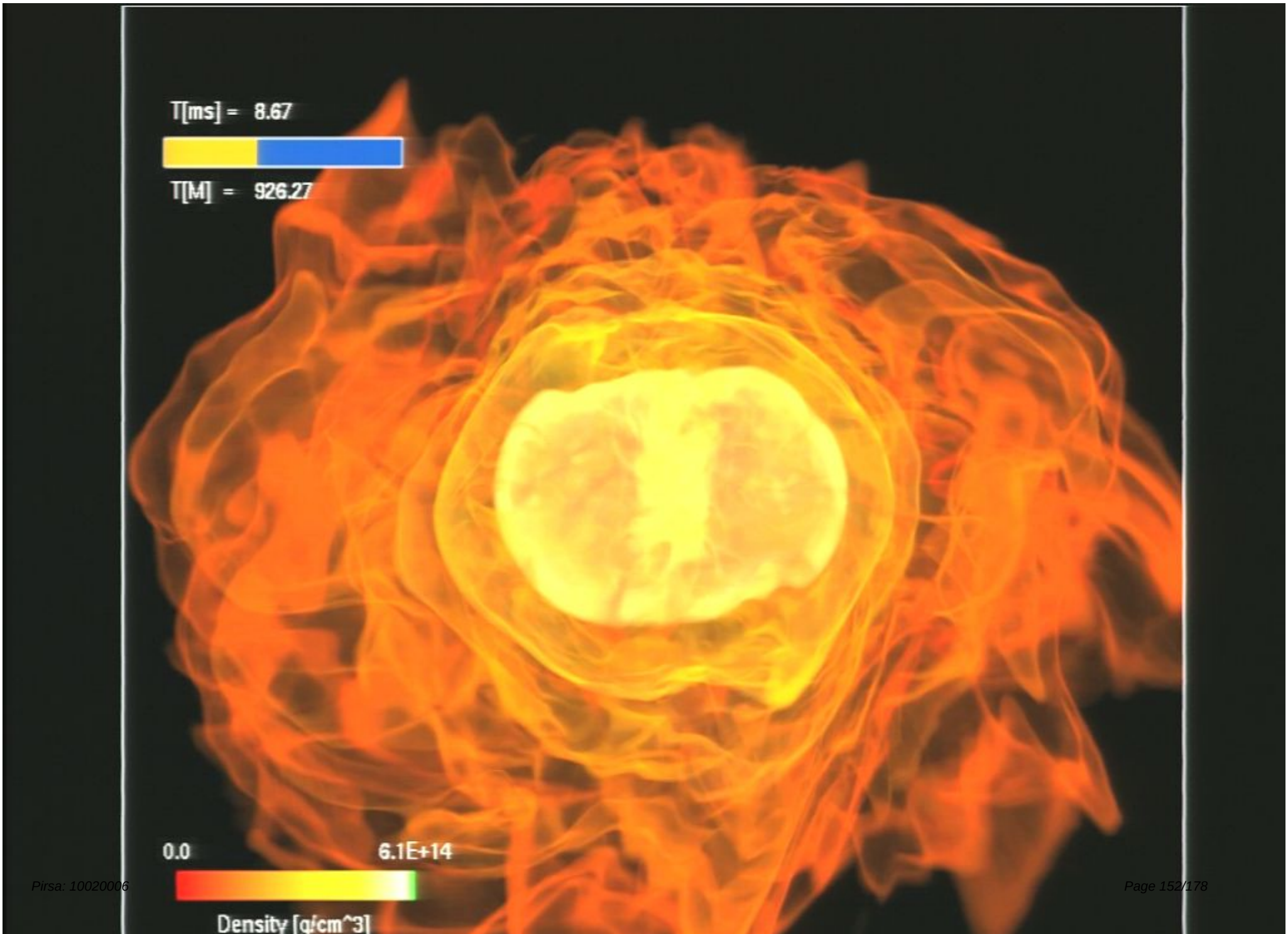

T[ms] = 2.58
T[M] = 275.80
0.0
6.1E+14
Density [g/cm^3]

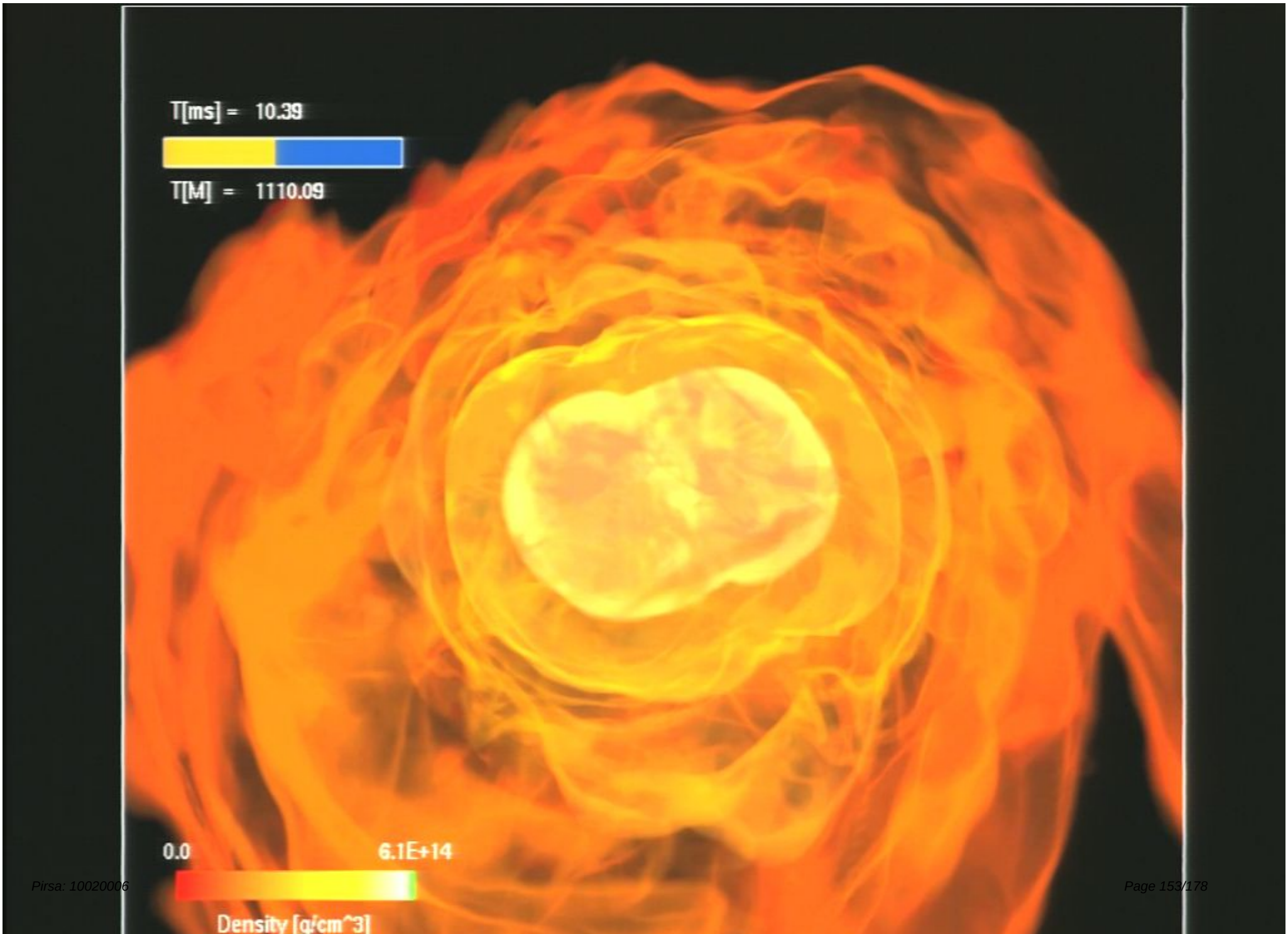

T[ms] = 3.38
T[M] = 360.64
0.0
6.1E+14
Density [g/cm^3]

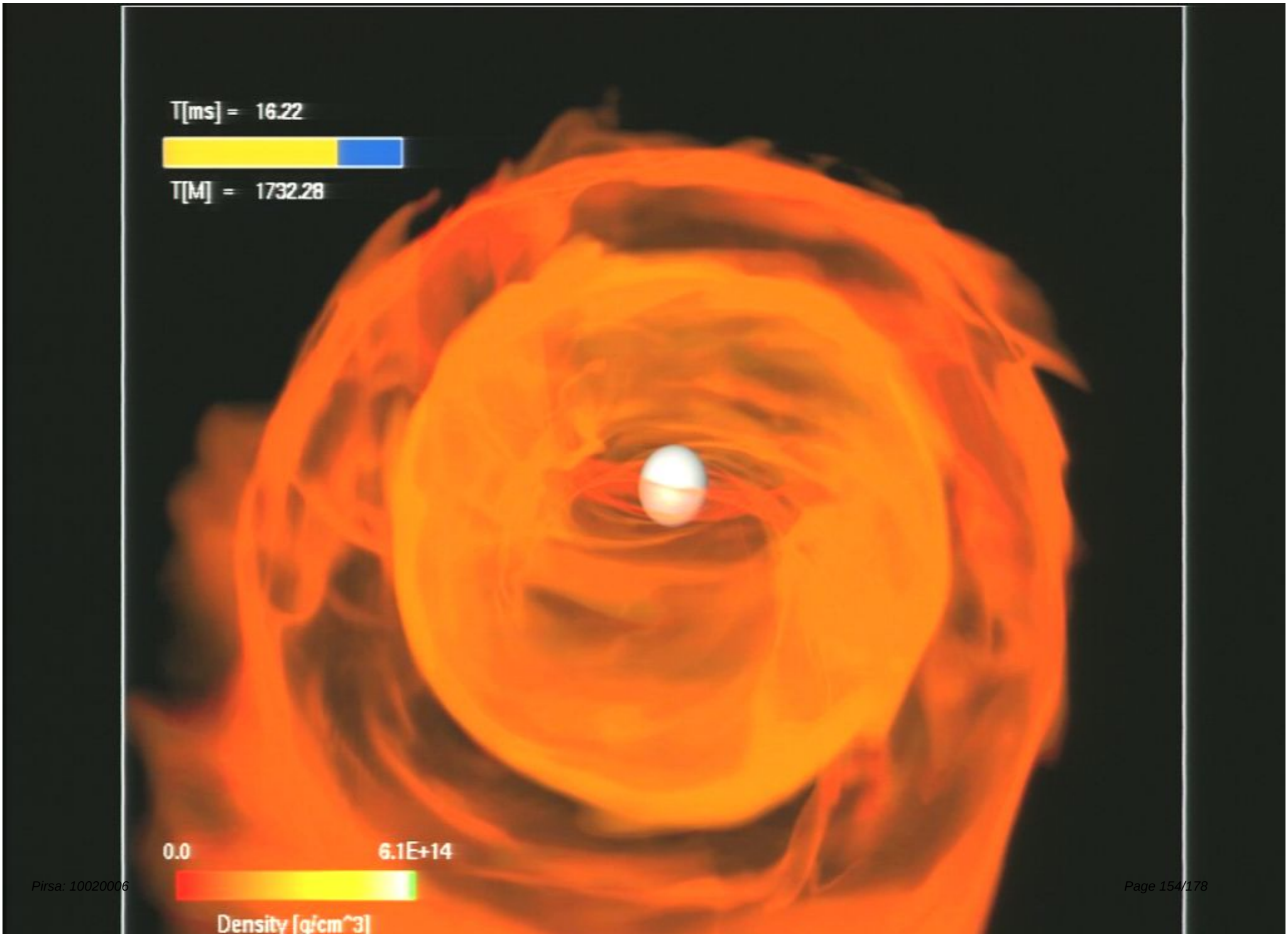

T[ms] = 4.70
T[M] = 502.05
0.0
6.1E+14
Density [g/cm^3]

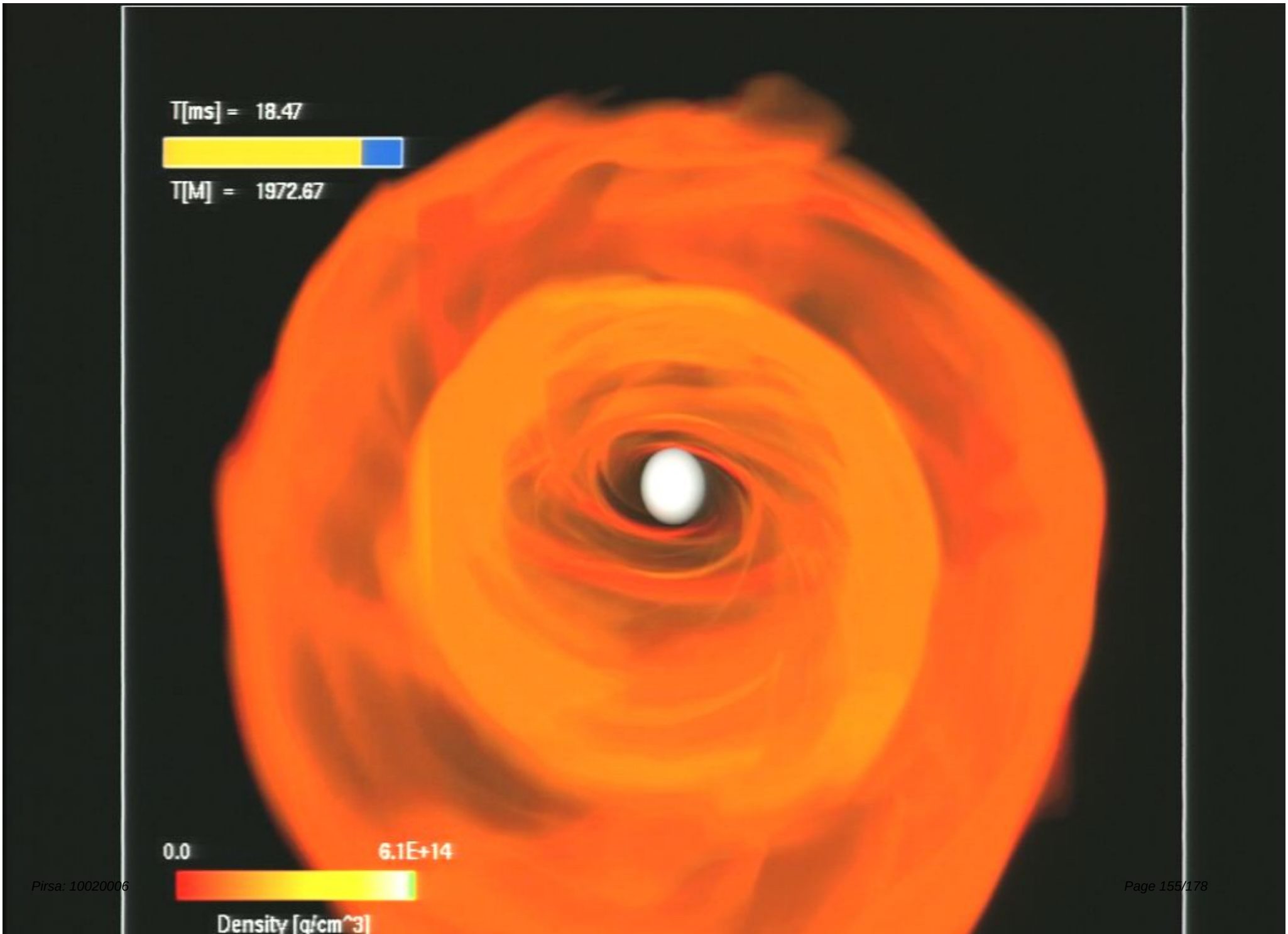

T[ms] = 6.29
T[M] = 671.73
0.0
6.1E+14
Density [g/cm^3]

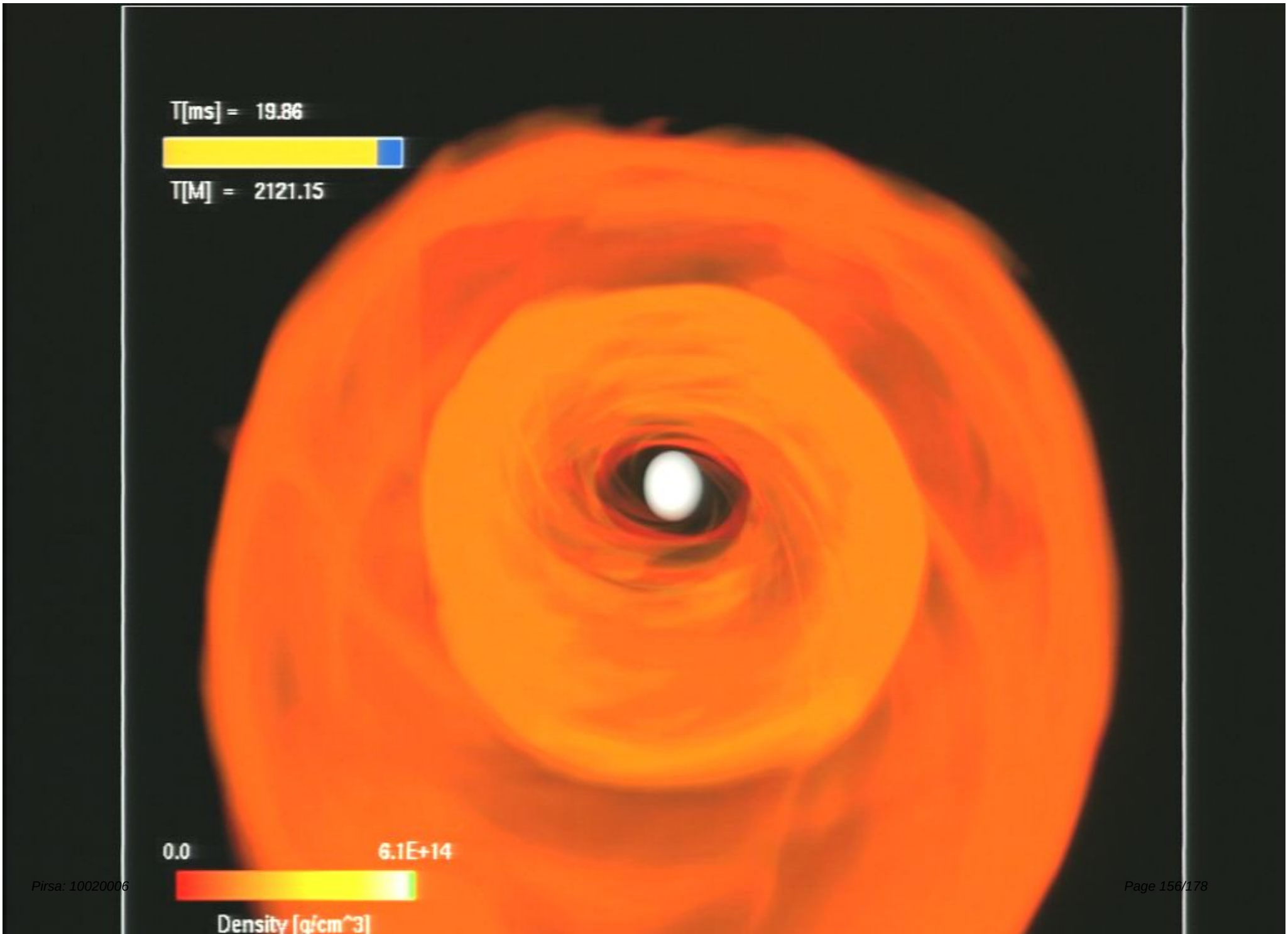

T[ms] = 7.22
T[M] = 770.72
0.0
6.1E+14
Density [g/cm^3]


T[ms] = 8.67
T[M] = 926.27
0.0
6.1E+14
Density [g/cm^3]

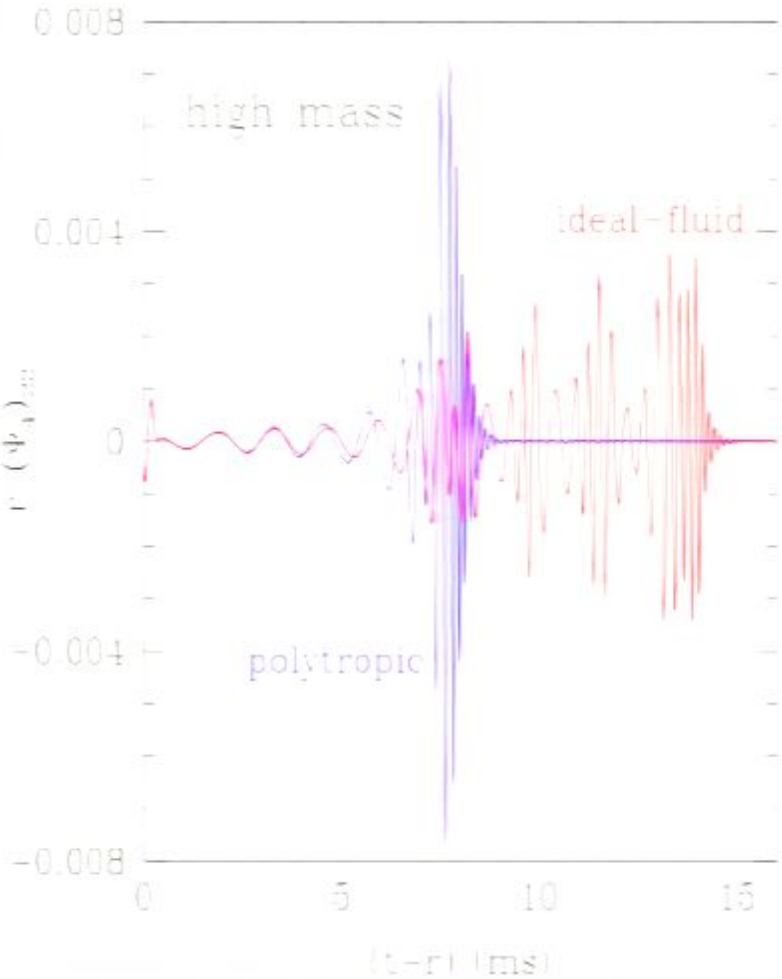

T[ms] = 10.39
T[M] = 1110.09
0.0
6.1E+14
Density [g/cm^3]


T[ms] = 16.22
T[M] = 1732.28
0.0
6.1E+14
Density [g/cm^3]


T[ms] = 18.47
T[M] = 1972.67
0.0
6.1E+14
Density [g/cm^3]

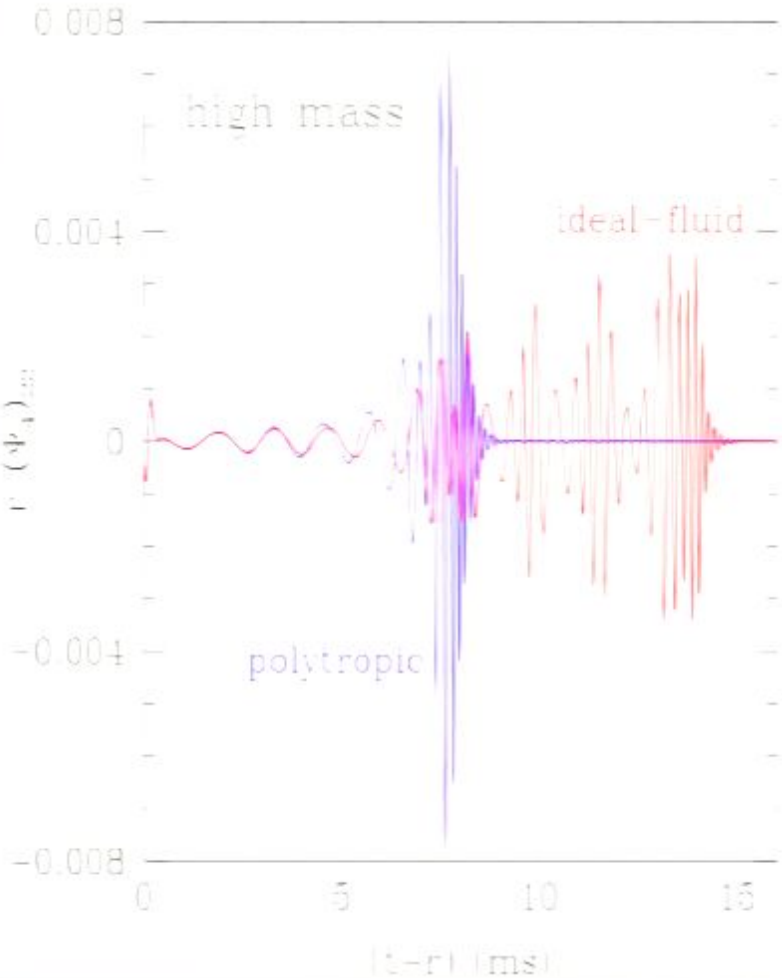

T[ms] = 19.86
T[M] = 2121.15
0.0
6.1E+14
Density [g/cm^3]

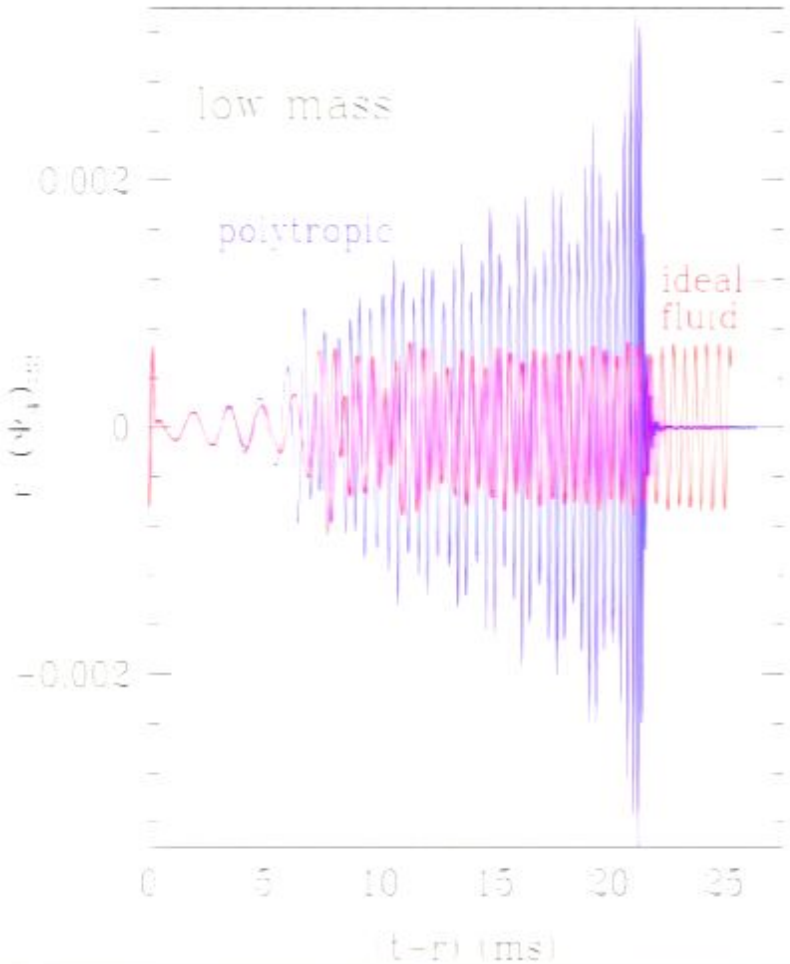
GWS: ROLE OF EOS AND MASS



In the high-mass case shock heating delays the collapse to BH of ~10ms

GWS: ROLE OF EOS AND MASS

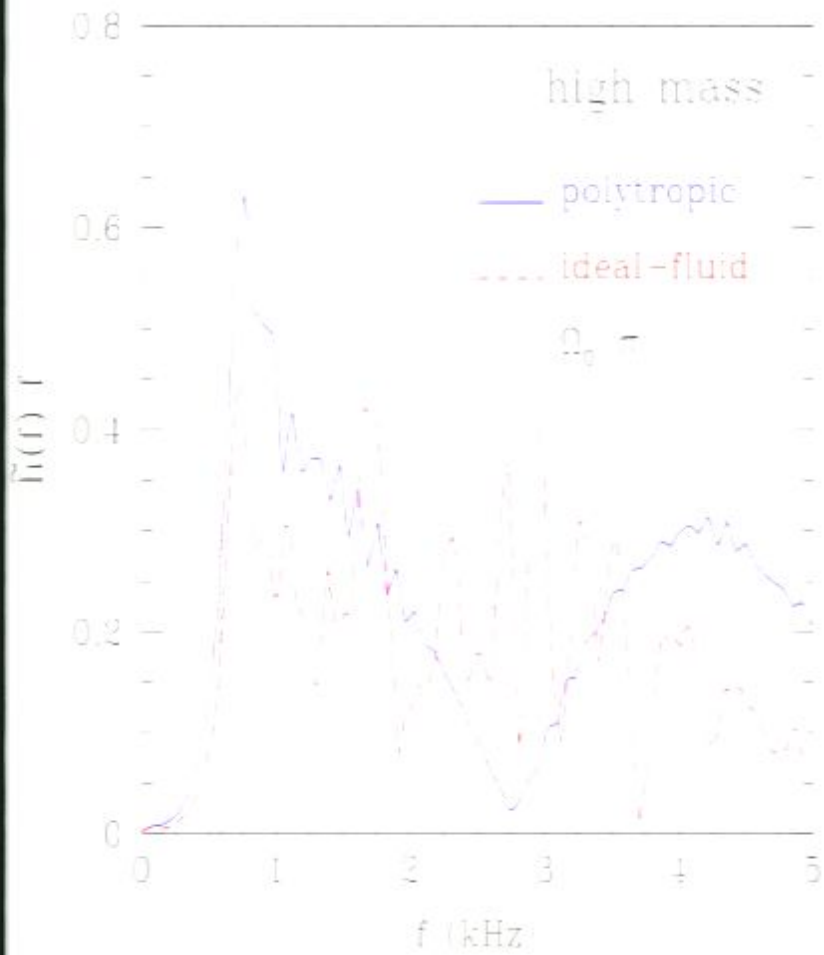


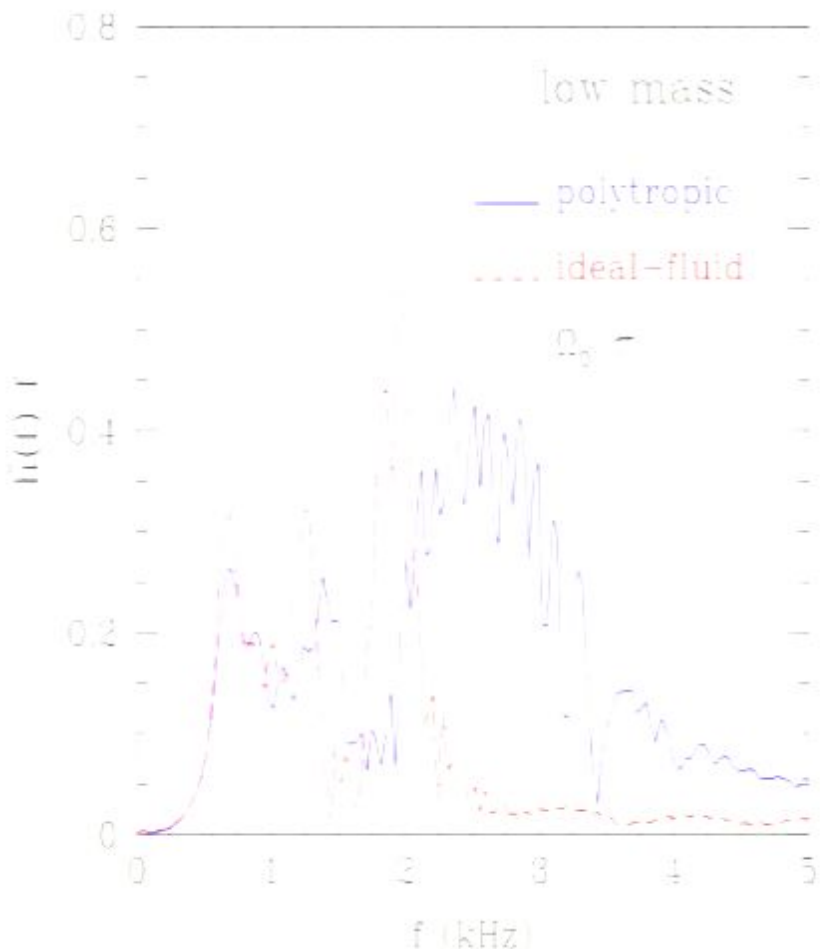


In the high-mass case shock heating delays the collapse to BH of ~10ms

In the low-mass case a BH is always produced over a timescale larger or much larger than the dynamical one

GWS SPECTRUM





The pre-merger dynamics is very similar; the post-merger phase is very different

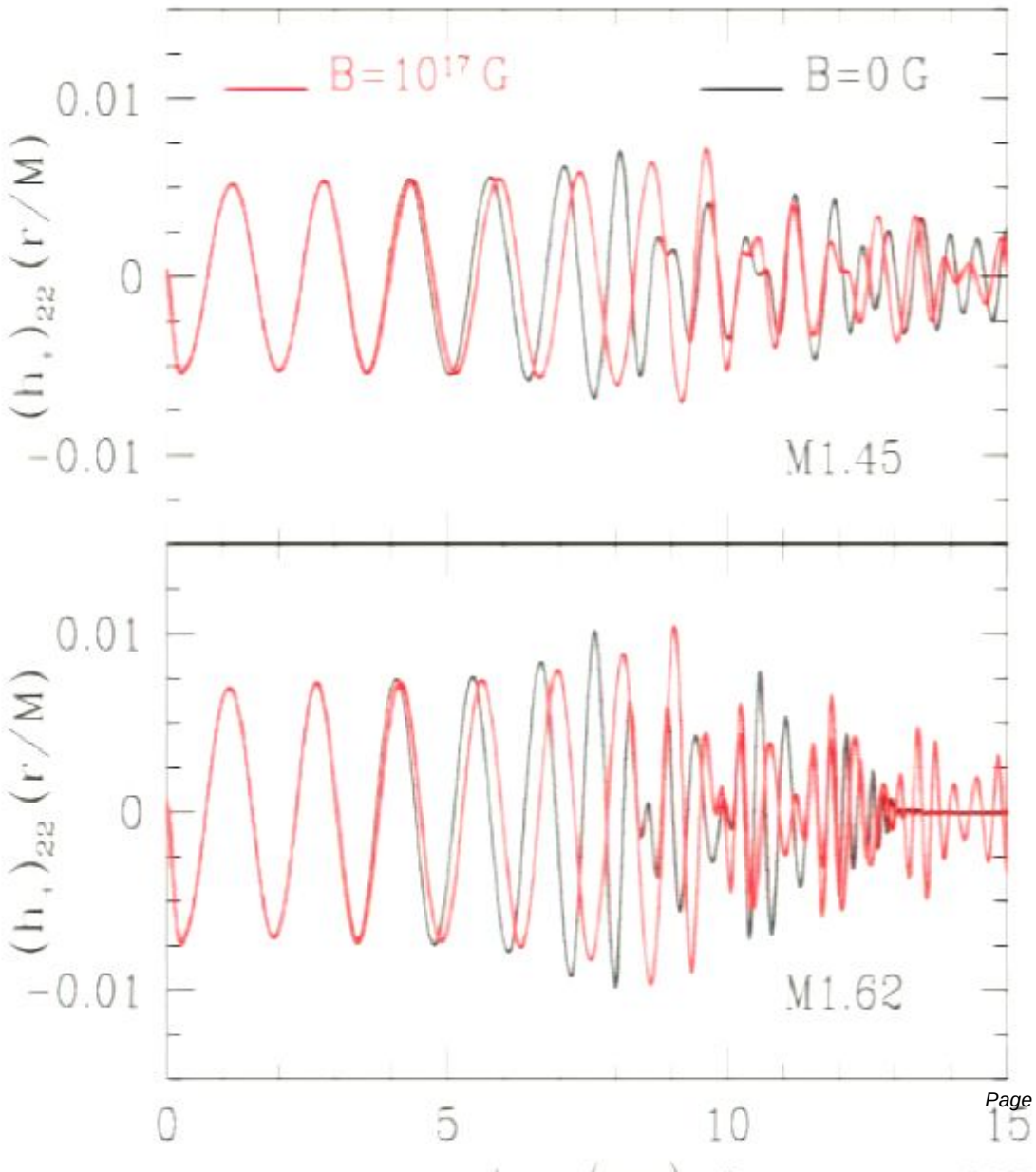
GWS FROM BNS: THE ROLE OF MAGNETIC FIELDS

Giacomazzo, Rezzolla, Baiotti 2009, MNRAS, 399, L164-168
Giacomazzo, Rezzolla, Baiotti 2010, in preparation

GRAVITATIONAL WAVES

An initial magnetic field of 10^{17} Gauss leads to very different waveforms both in the low-mass and in the high-mass case.

In the high-mass case the magnetic pressure delays the collapse to BH.

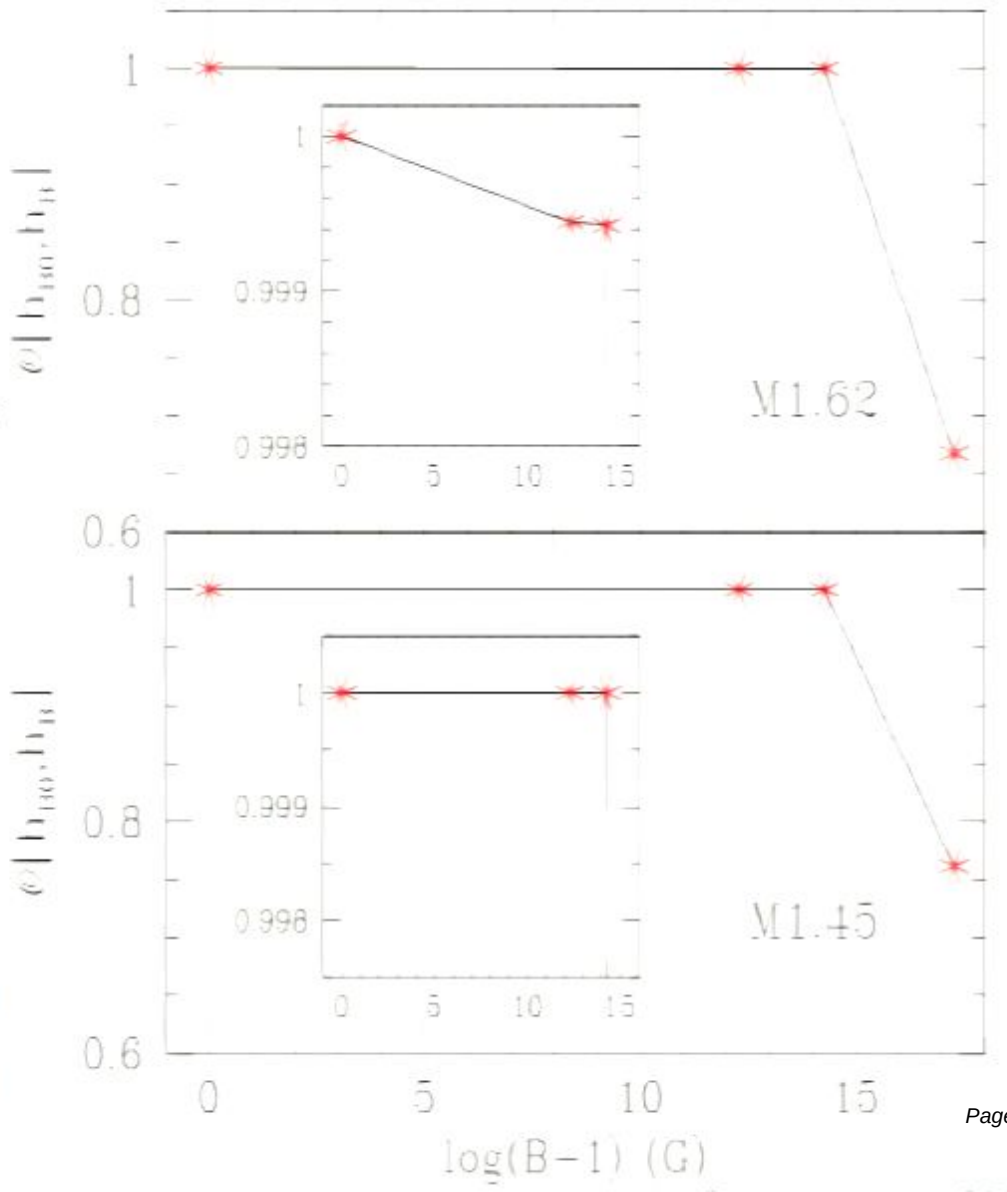


DETECTABILITY IN THE INSPIRAL GWS

We have computed the overlap between the different waveforms:

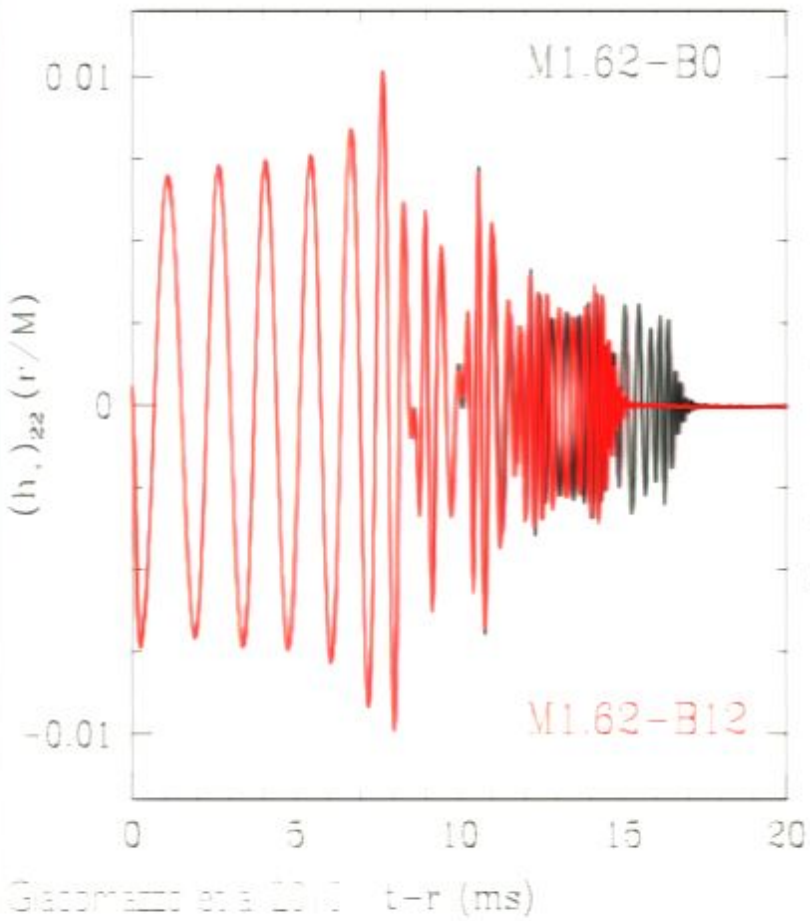
$$\mathcal{O}[h_{B1}, h_{B2}] \equiv \frac{\langle h_{B1} | h_{B2} \rangle}{\sqrt{\langle h_{B1} | h_{B1} \rangle \langle h_{B2} | h_{B2} \rangle}}$$

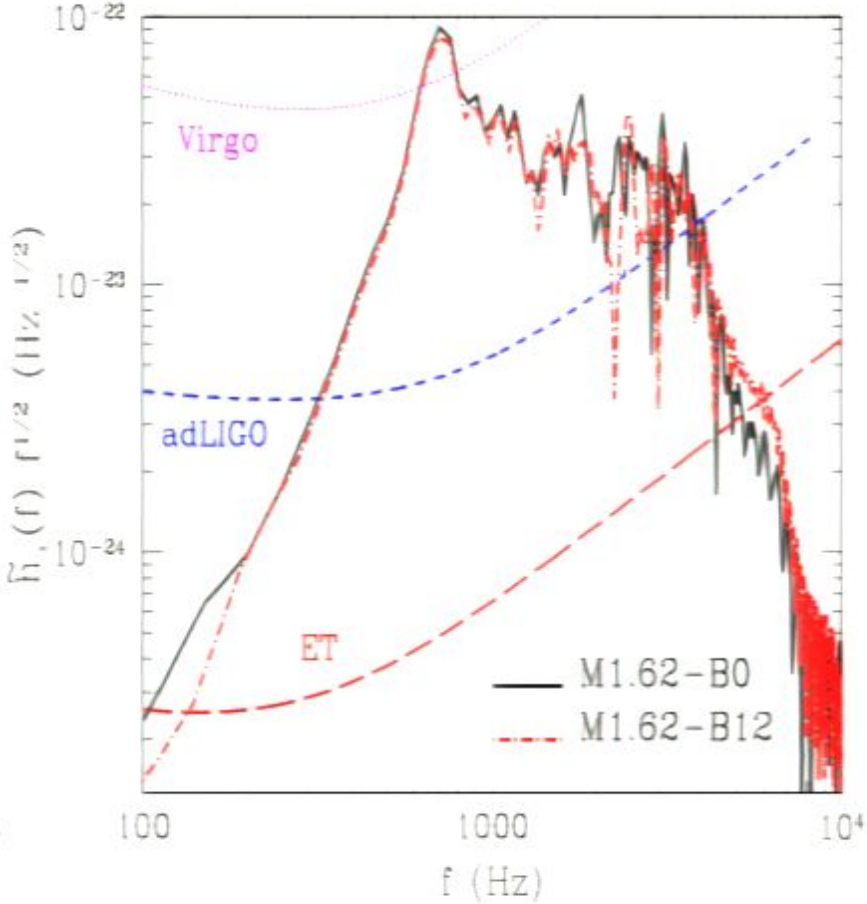
$$\langle h_{B1} | h_{B2} \rangle \equiv 4\Re \int_0^{\infty} df \frac{\tilde{h}_{B1}(f) \tilde{h}^{*}_{B2}(f)}{S_h(f)}$$



Effects in the inspiral can be detected only for very large unrealistic magnetic fields

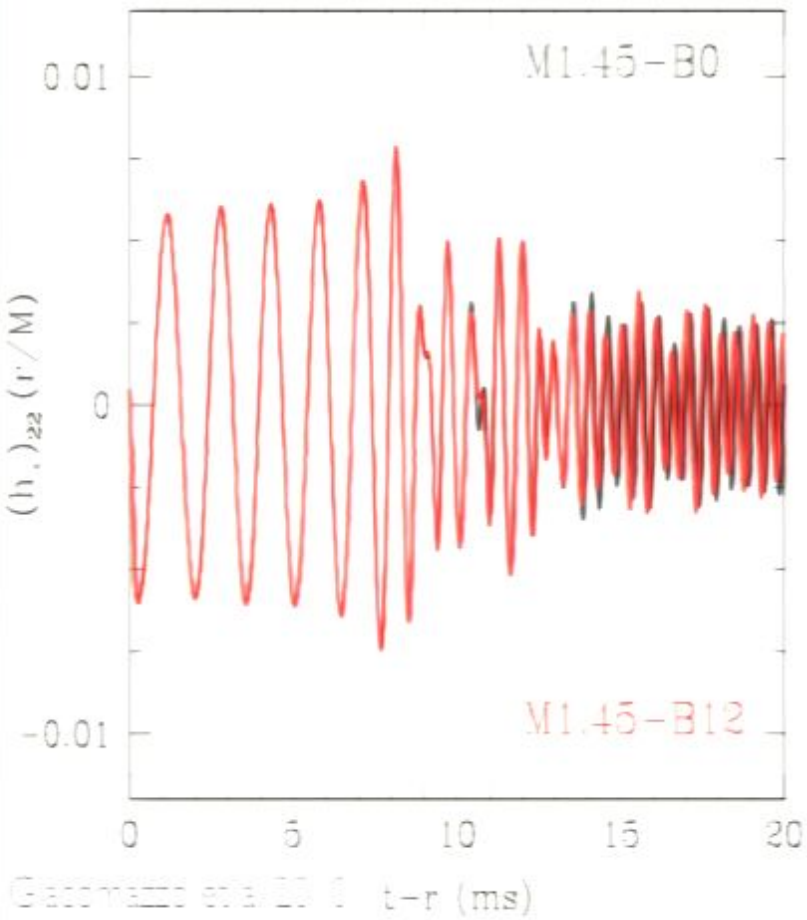
MAGNETIC FIELD EFFECTS AFTER THE MERGER

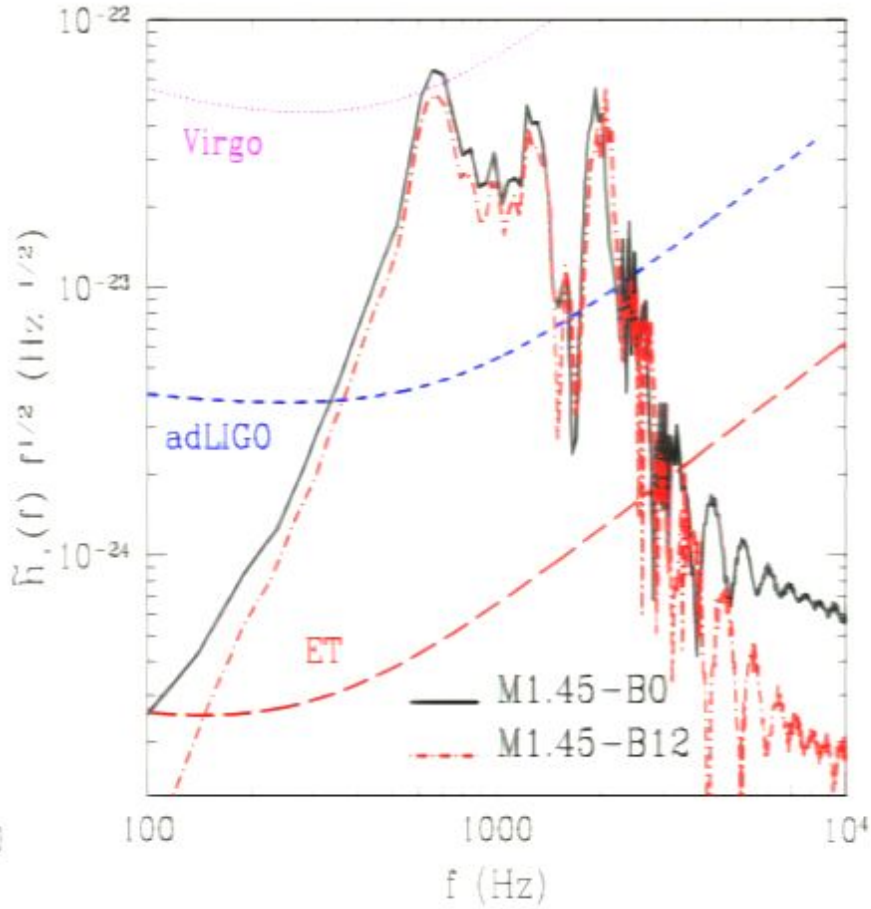




high-mass case: the magnetic field accelerates the collapse of the HMNS. Hard though to detect differences in the GWs.

DETECTABILITY OF MAGNETIC FIELD EFFECTS





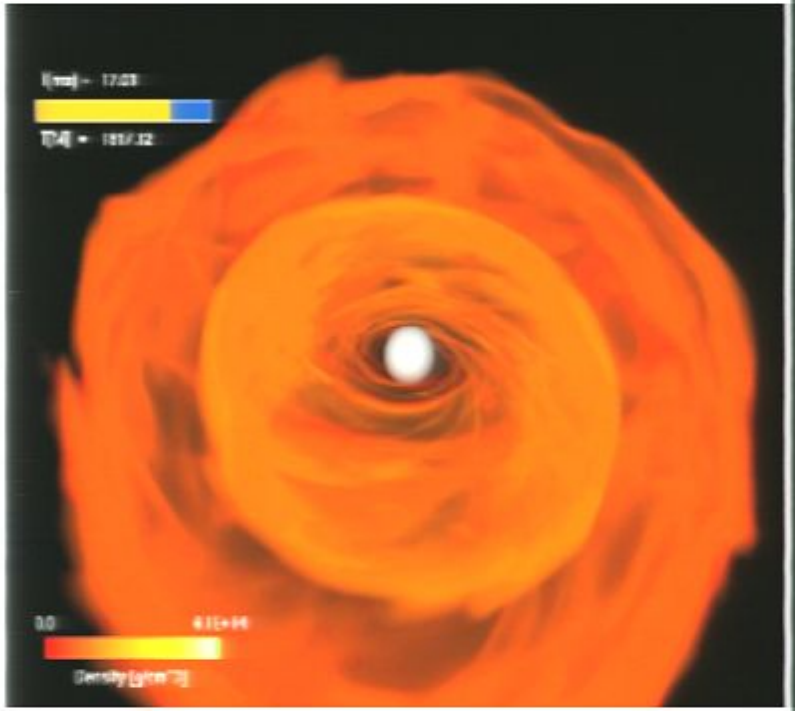
low-mass case: because of the longer evolution, the HMNS is strongly affected by the magnetic field and this starts to be visible in the GW spectra.

UNEQUAL-MASS BNS: TORUS FORMATION AND GWS

Rezzolla, Baiotti, Giacomazzo, Link, Font 2010, ArXiv:1001.3074

Mass of the Torus and of the BH (equal-mass case)

The torus undergoes initial rapid accretion but then settles to be:



Average mass: $<0.1\ M_\odot$
Average size (z-x): 20-40 km
Average density: $\sim 10^{11}$-10^{12} g/cm^3
Average temperature: $\sim 10^{11}$K

BH parameters:
Mass: 2.9 (high-mass case)
J/M^2: 0.8

Torus properties: unequal-mass case

We have considered the inspiral and merger of 7 irrotational binaries with variable total mass and mass ratio

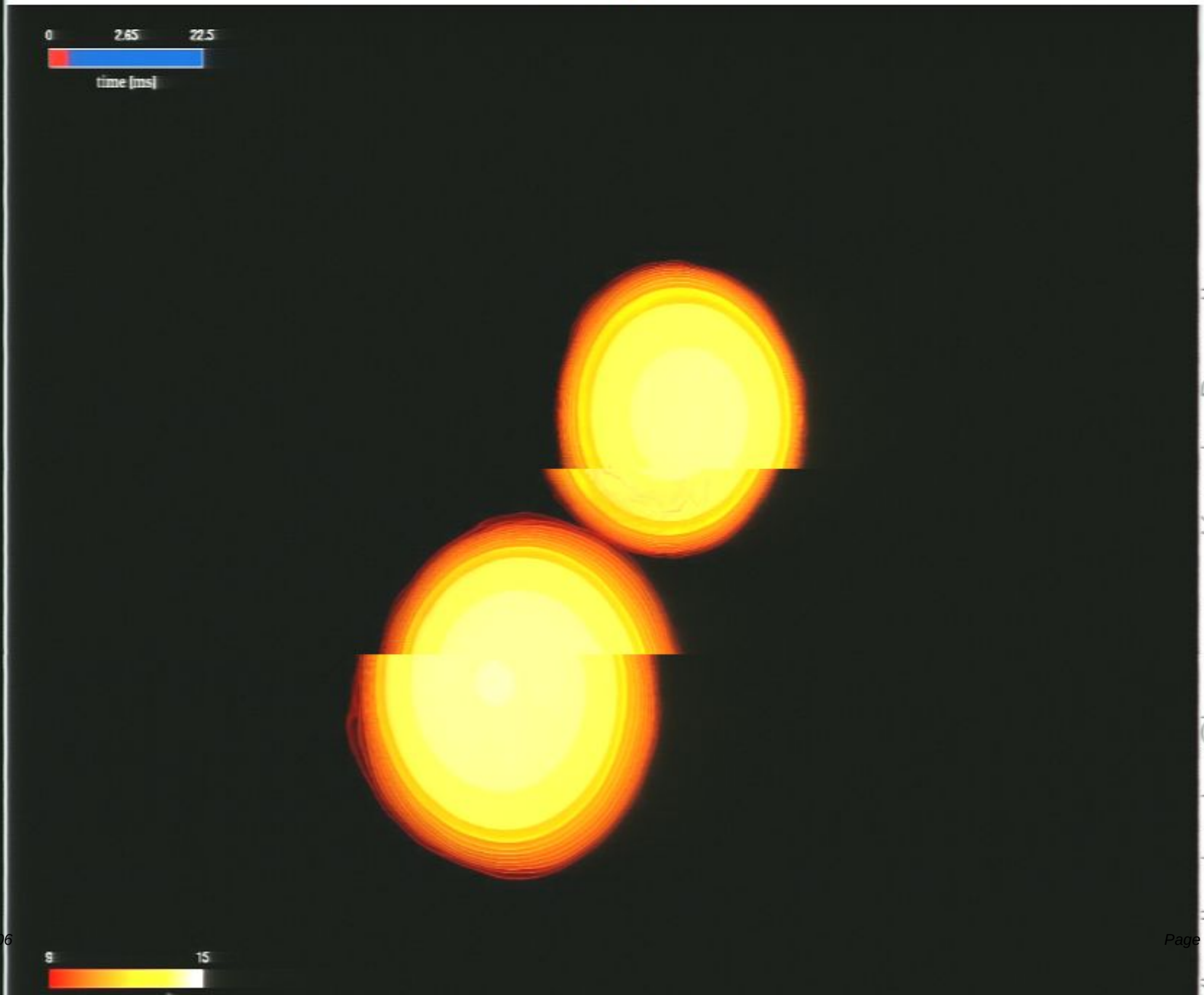
Model	Total ADM Mass	M1, M2
M3.6q1.00	3.23	1.64, 1.64
M3.7q0.94	3.33	1.64, 1.74
M3.4q0.91	3.11	1.51, 1.64
M3.4q0.80	3.08	1.40, 1.72
M3.5q0.75	3.14	1.39, 1.80
M3.4q0.70	3.07	1.30, 1.81

Total initial mass chosen to have prompt collapse to BH

M3.4q0.80

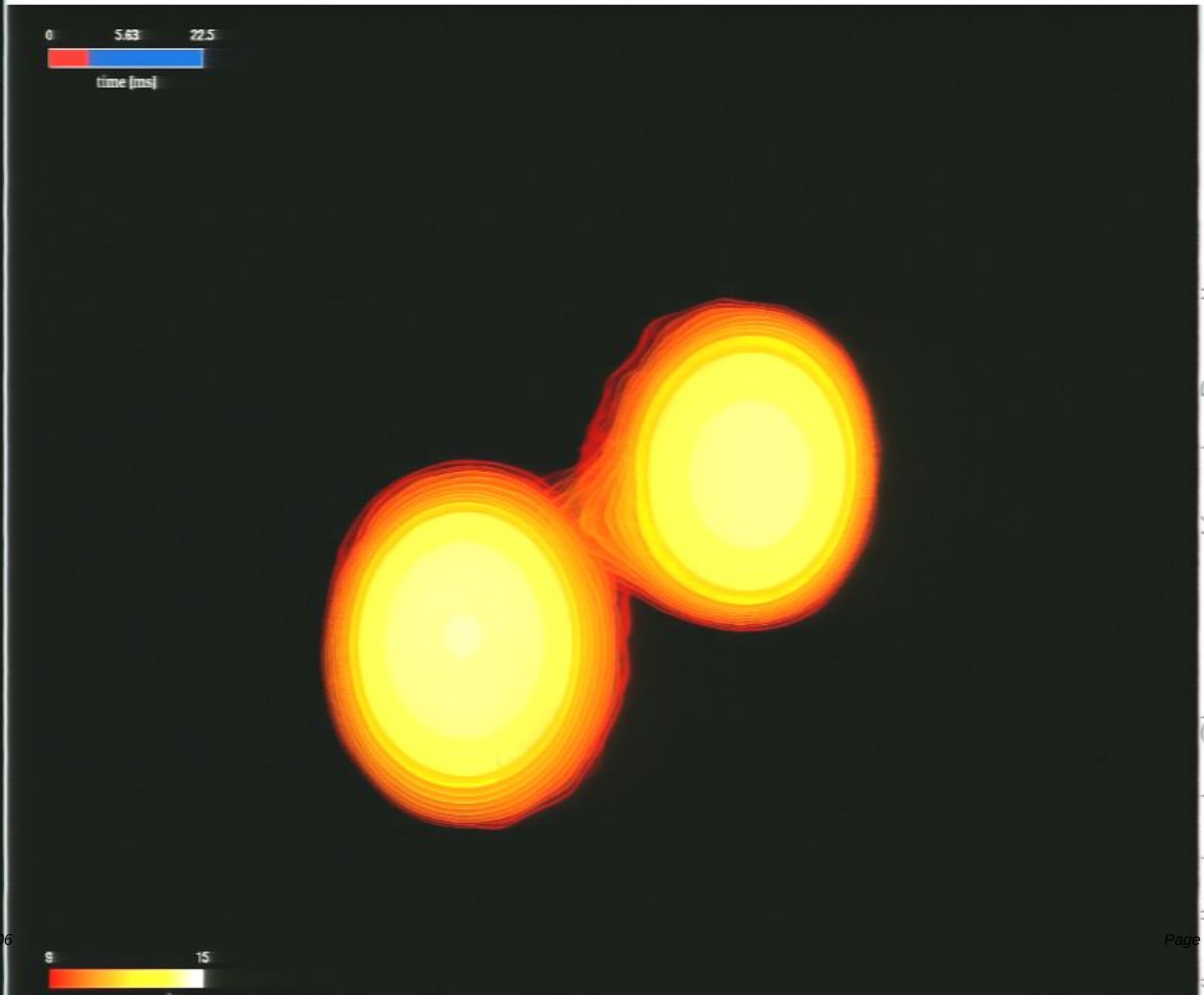
Visualization by Giacomazzo, Koppitz, Rezzolla

M3.4q0.80



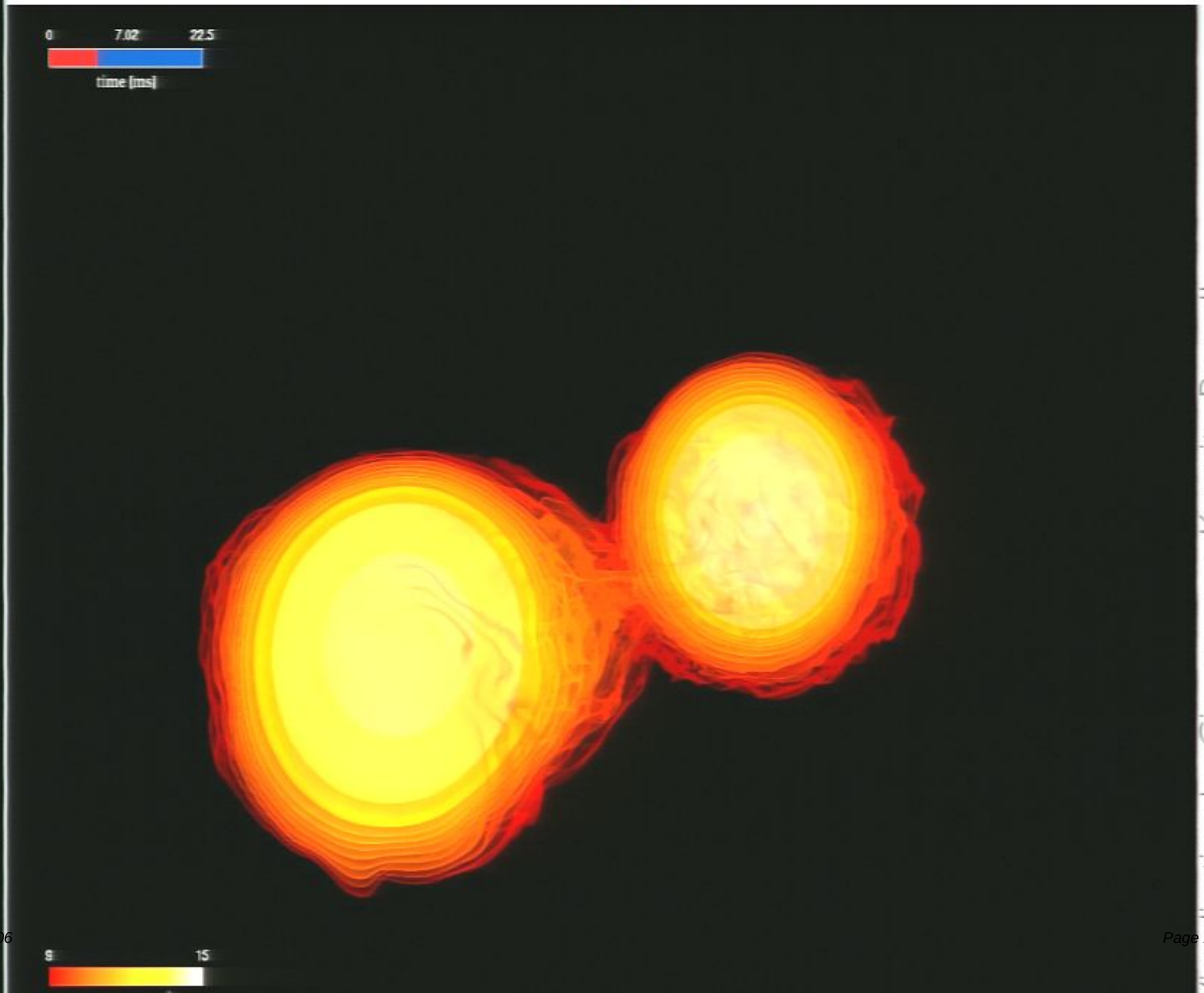
Visualization by Giacomazzo, Koppitz, Rezzolla

M3.4q0.80



Visualization by Giacomazzo, Koppitz, Rezzolla

M3.4q0.80



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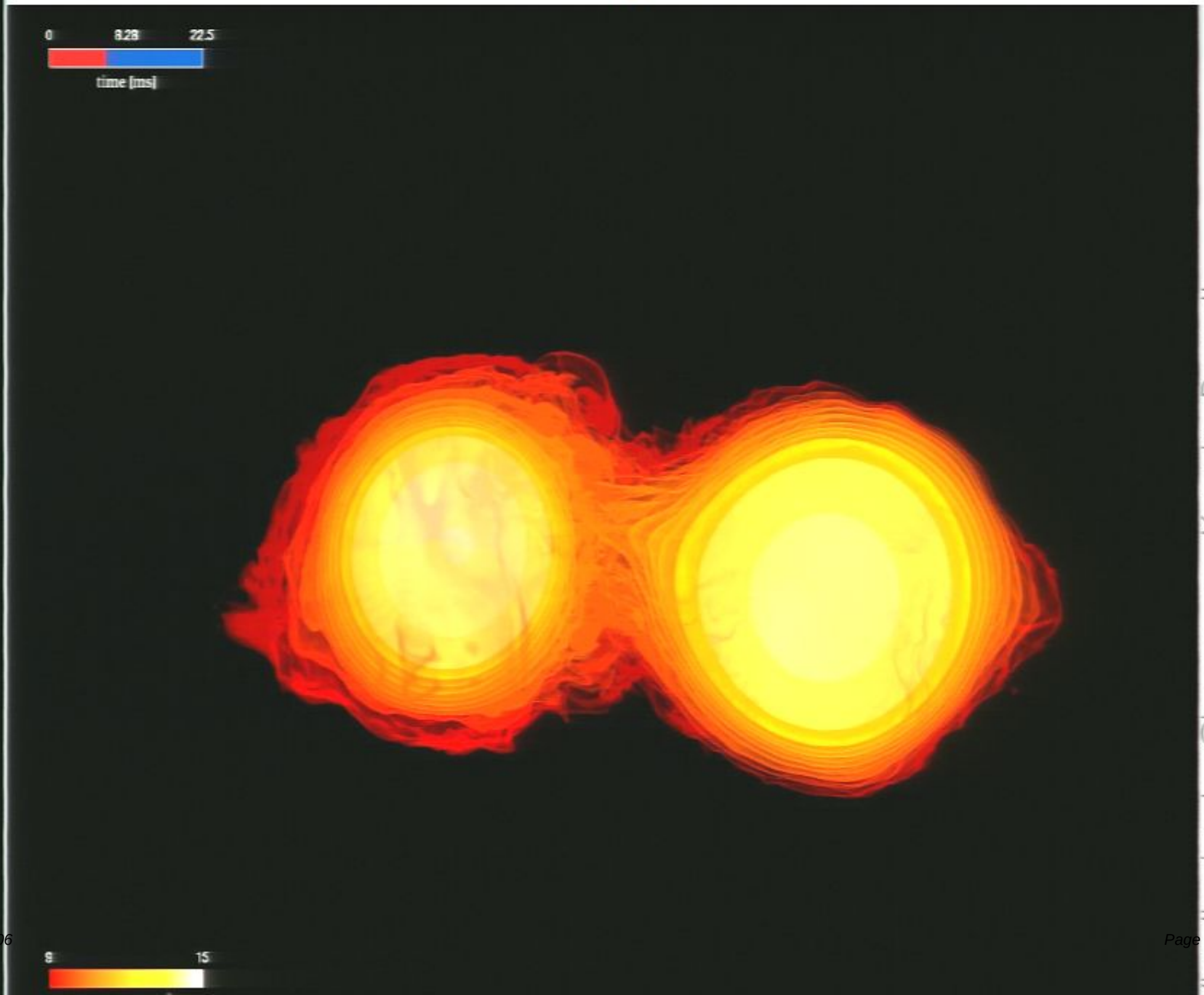
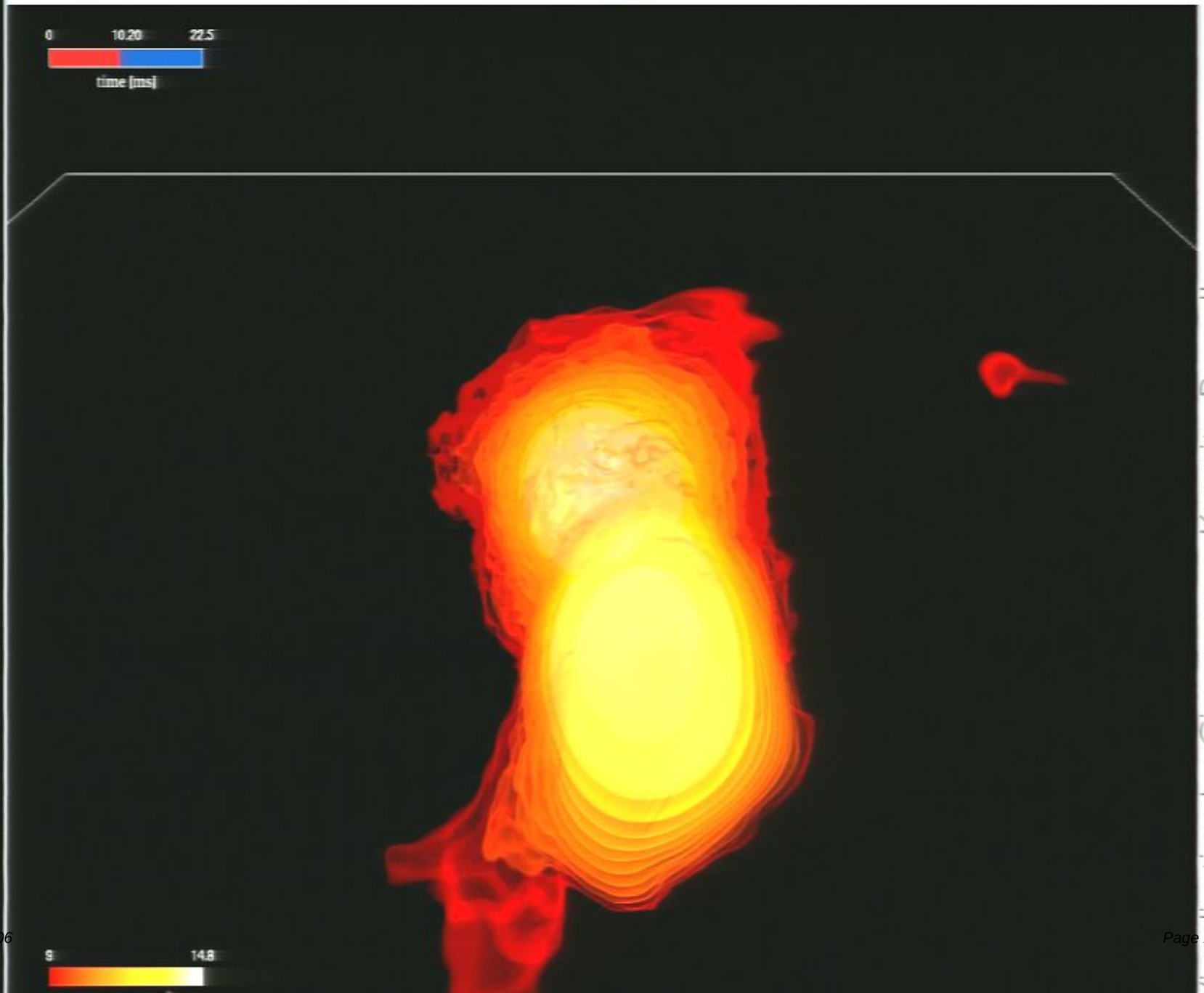


Visualization by Giacomazzo, Koppitz, Rezzolla

M3.4q0.80



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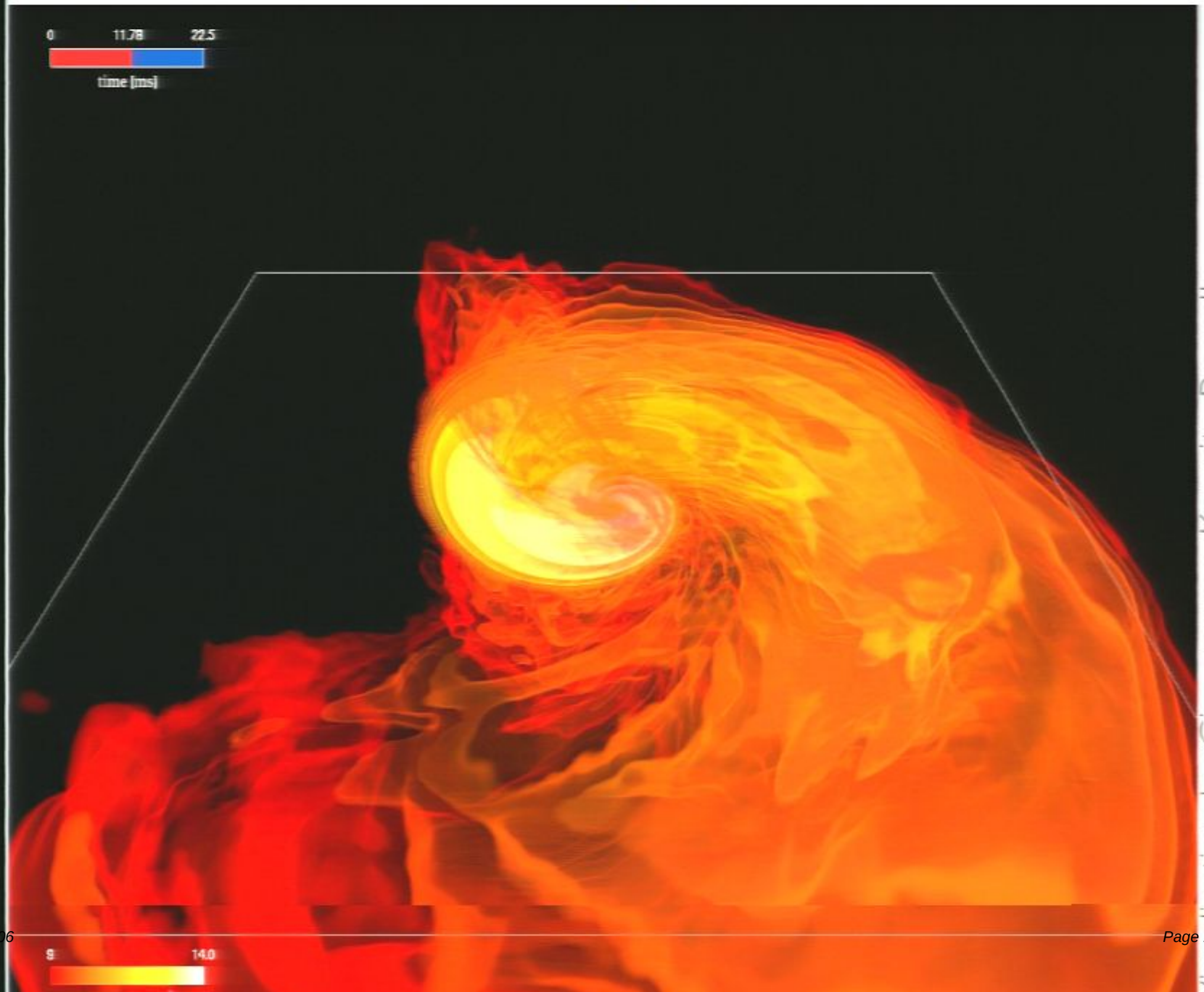

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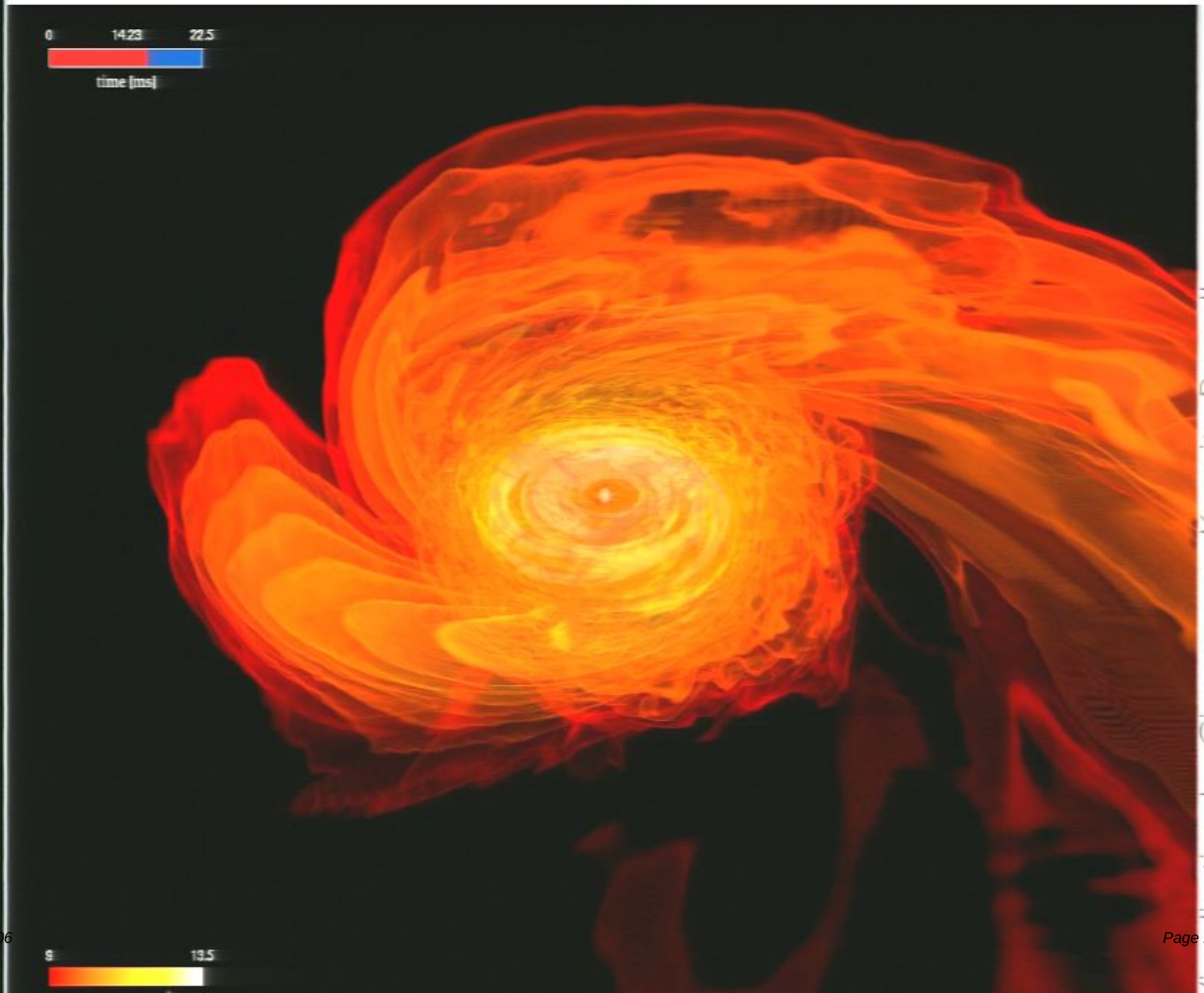
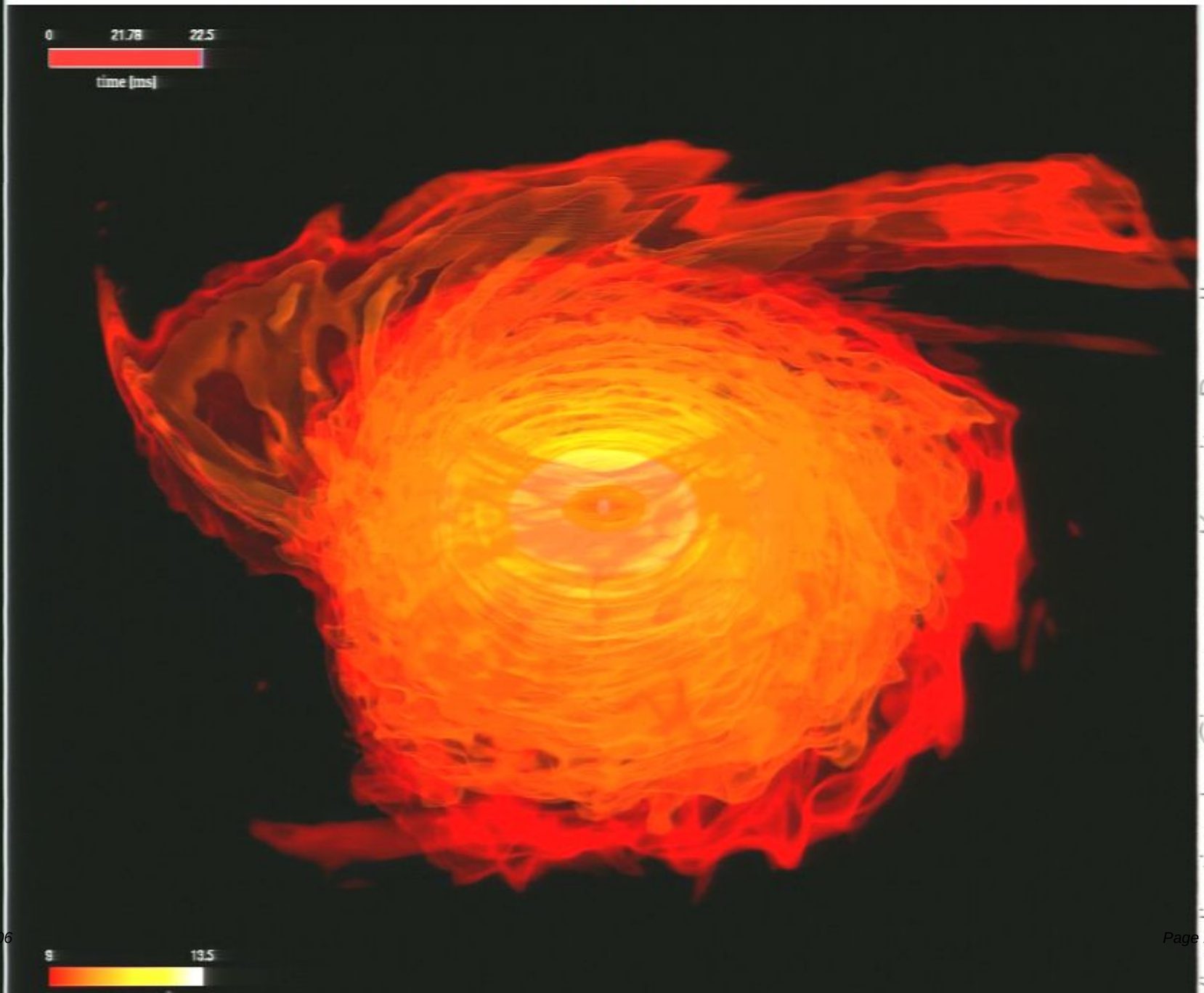


Visualization by Giacomazzo, Koppitz, Rezzolla

M3.4q0.80



Visualization by Giacomazzo, Koppitz, Rezzolla

FUTURE DIRECTION

We are currently working to add to Whisky

- **neutrino emission**, in collaboration with:
  - E. Abdikamalov (LSU)
  - J. Barranco (AEI)
  - F. Galeazzi (AEI)
- **more realistic EOSs**, in collaboration with:
  - G. Corvino (Univ. of Rome "La Sapienza")
  - A. Tonita (AEI)
- **resistive MHD**, in collaboration with:
  - D. Alic (AEI)
  - C. Palenzuela (CITA)

For movies and pictures about BNS merger simulations:
http://numrel.aei.mpg.de/Visualisations/index.html

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