Title: Gravitational Waves from Core-Collapse Supernovae

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Abstract: We present a short overview on the current state of core-collapse supernova modeling and the set of processes expected to emit gravitational waves in a core collapse event. We go on to show new results from 3D GR simulations focusing on failing black-hole forming supernovae and present the gravitational wave signature of such events.

Gravitational Waves from Core-Collapse Supernovae and Black Hole Formation

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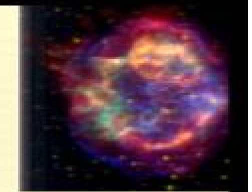

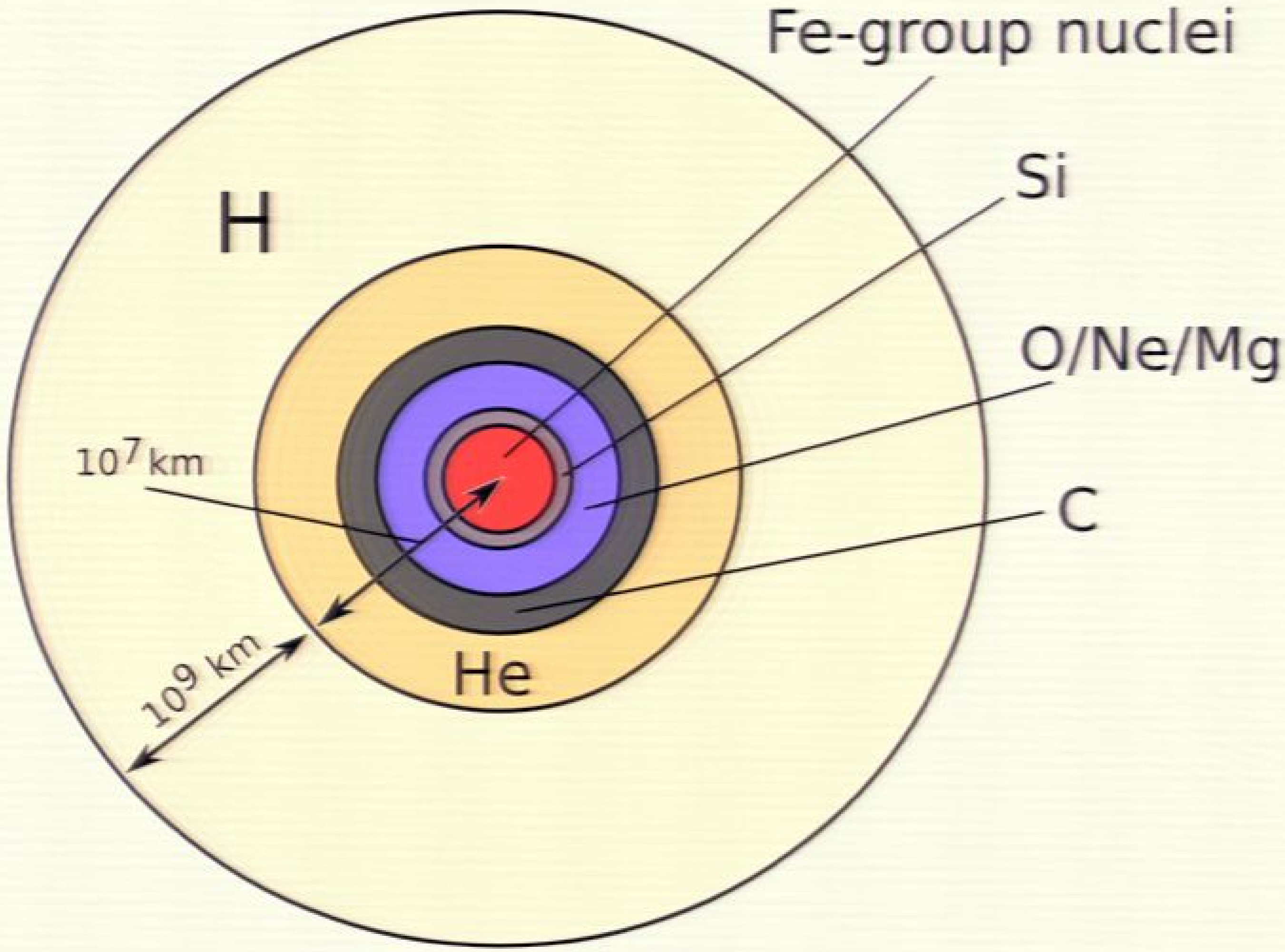

Evolved Massive Star

$M > 8\text{-}10\ M_{SUN}$

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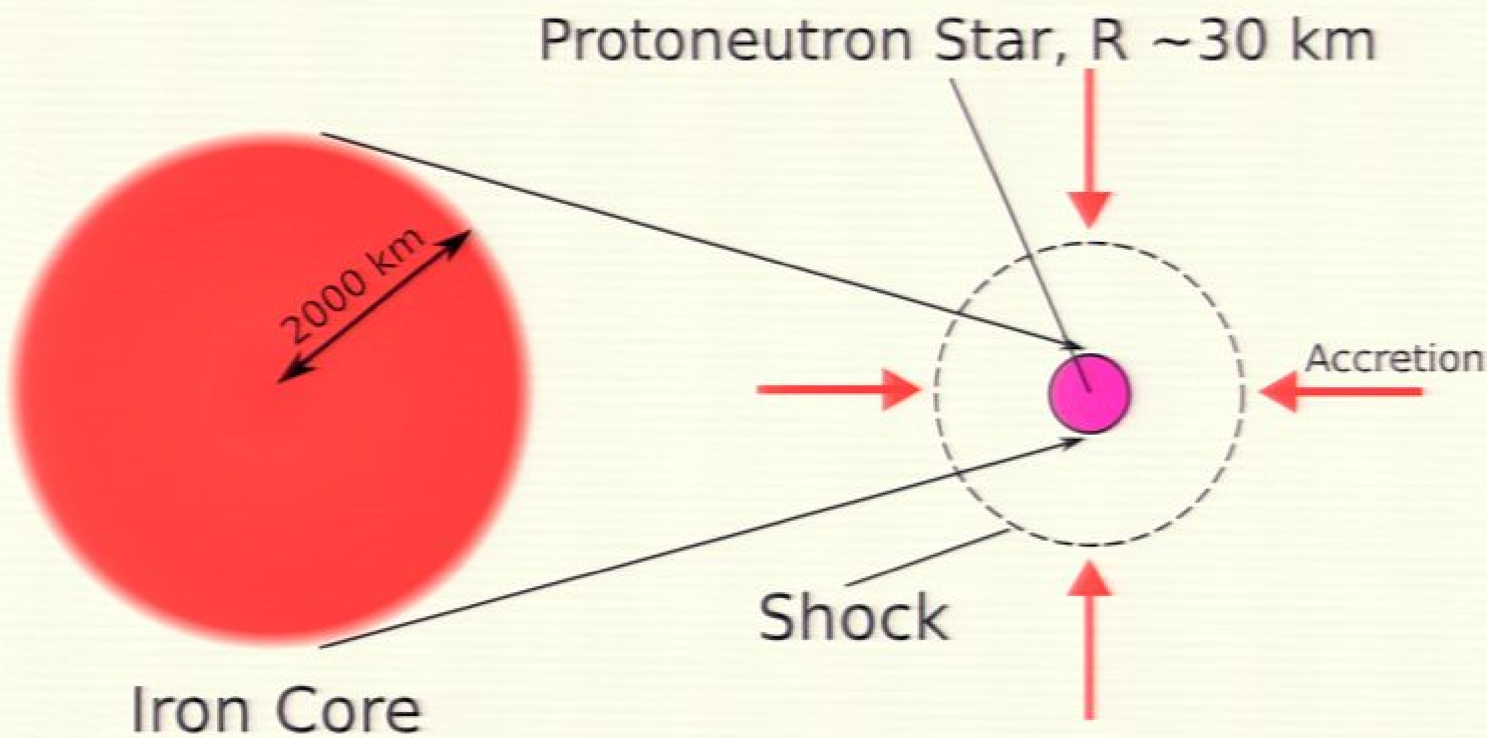

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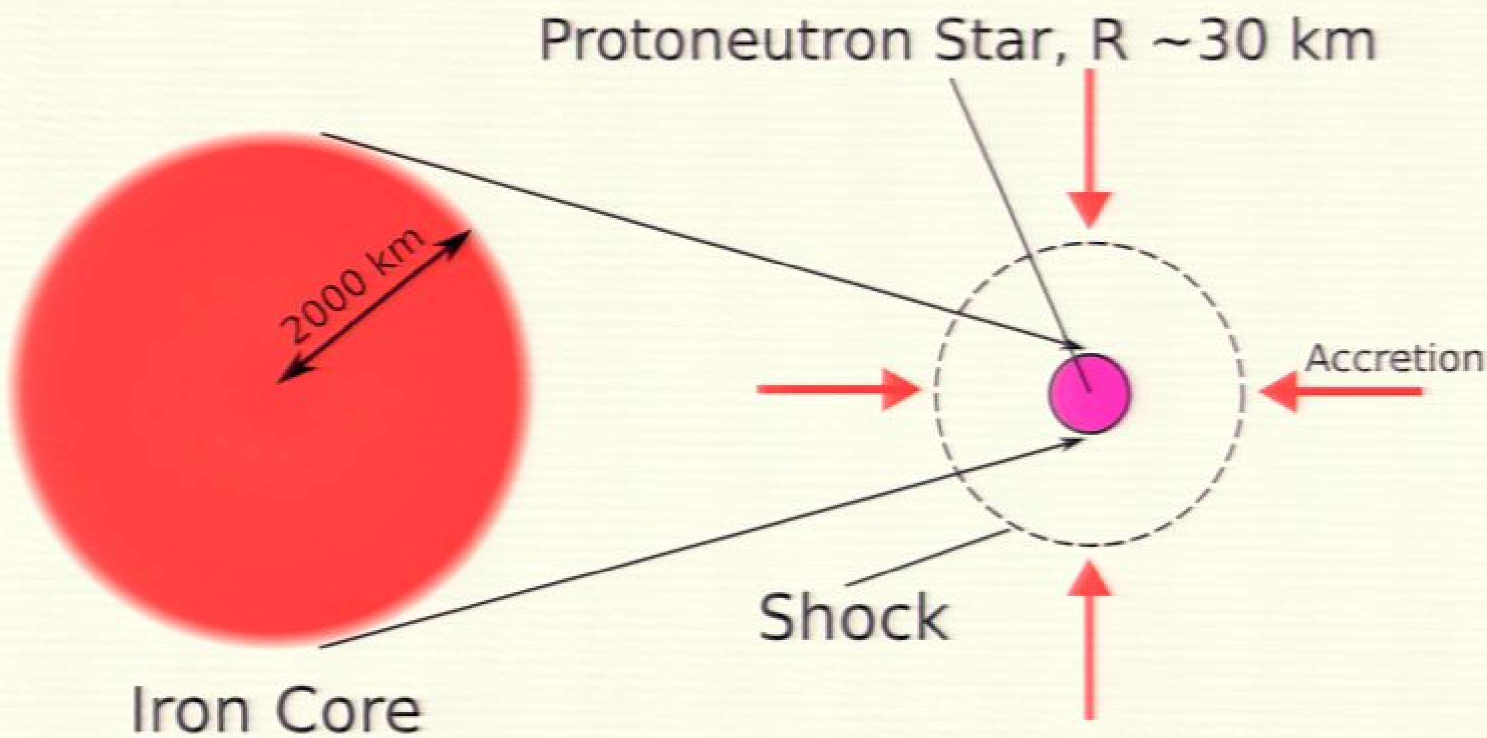

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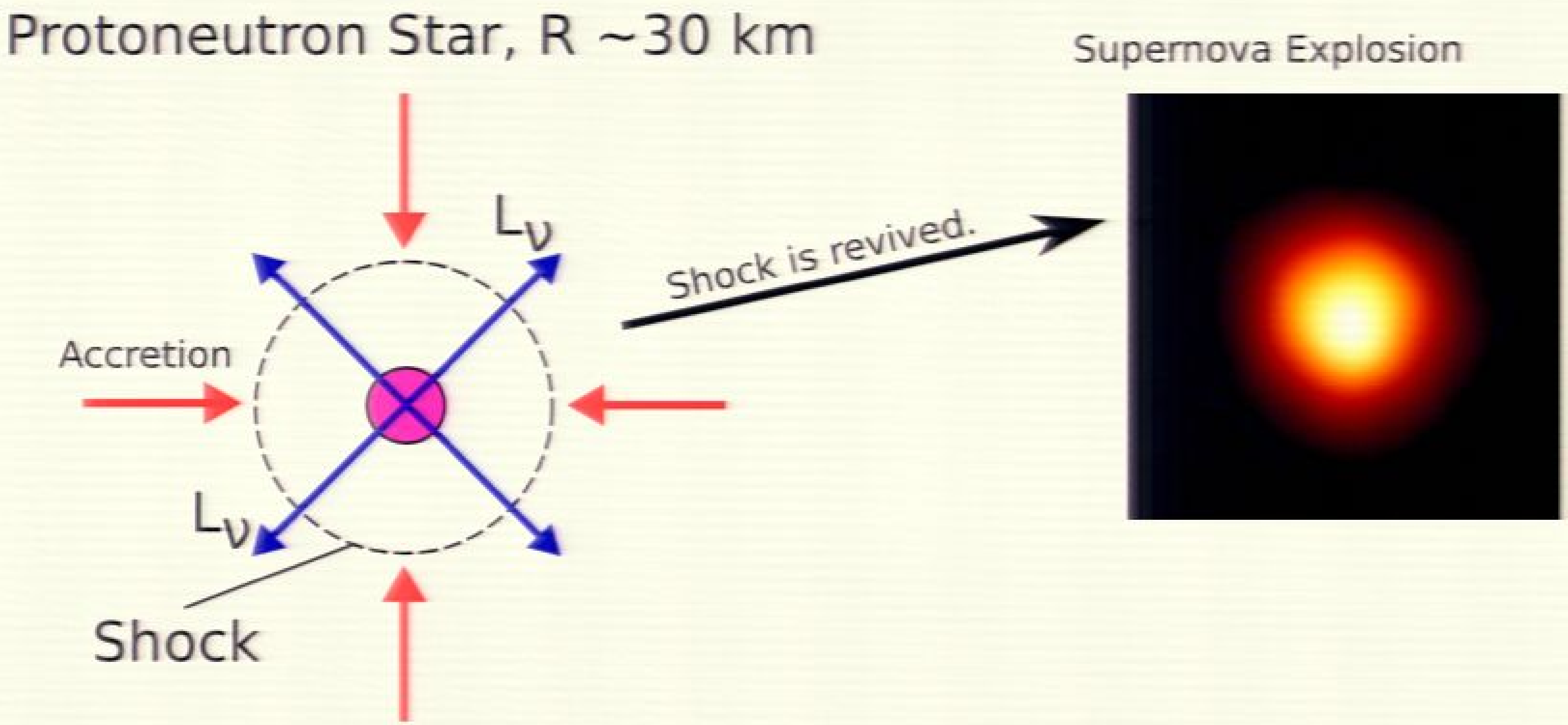

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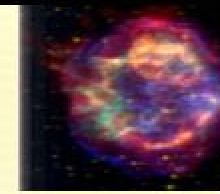

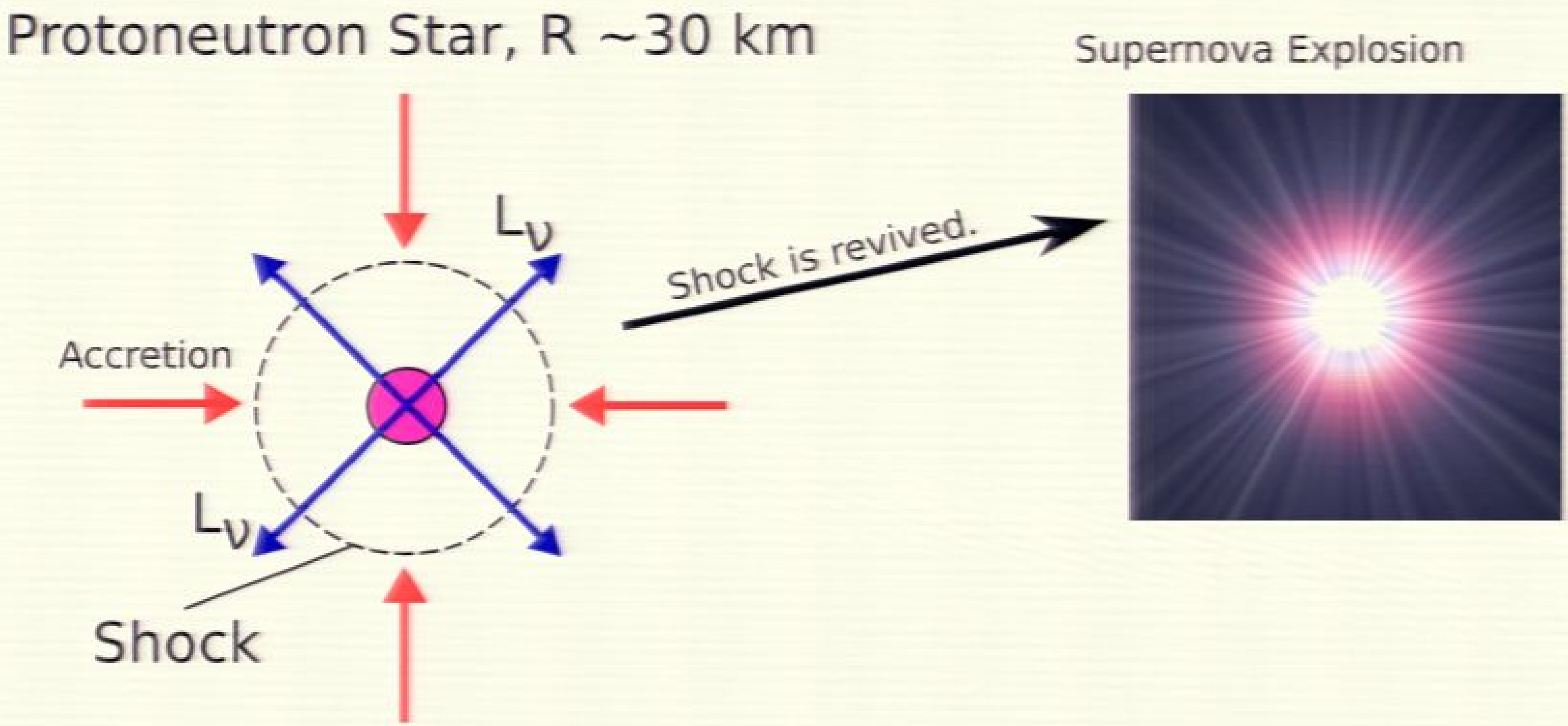

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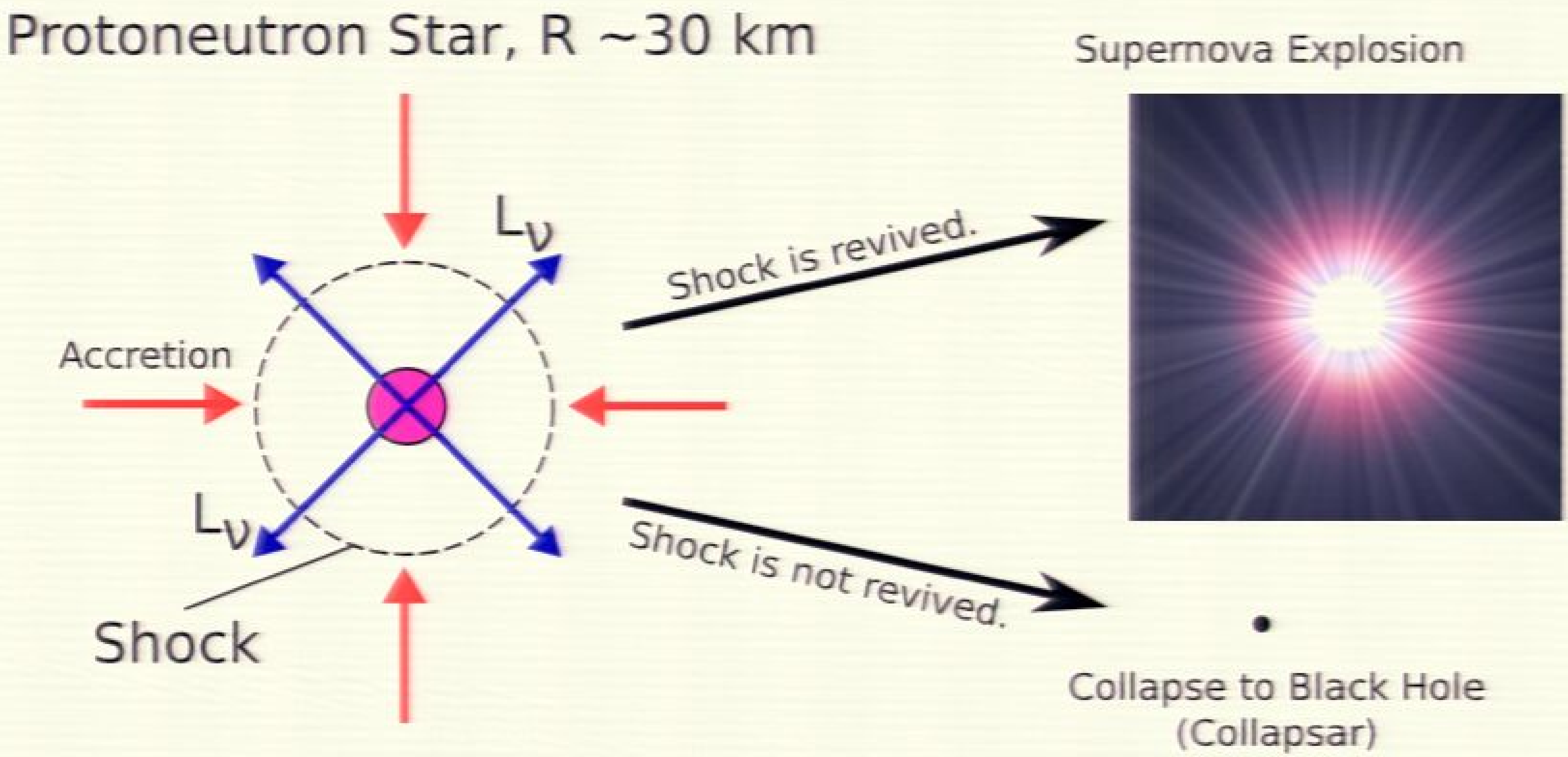

Needed: **Mechanism for Shock Revival** (The "Supernova Mechanism")

Blowing up Massive Stars:
Core-Collapse SN Mechanisms

Neutrino Mechanism

[Colgate & White 1966, Arnett 1966, Wilson 1985, Bethe & Wilson 1985, **recent: Marek & Janka 2009**, Ott et al. 2008, Nordhaus et al. 2010: 3D]

Magnetorotational Mechanism

[LeBlanc & Wilson '70, Bisnovatyi-Kogan et al. '76, Meier et al. '76, Symbalisty 1984, **recent**: Burrows et al. 2007]

Acoustic Mechanism

[proposed by Burrows et al. 2006, 2007; not confirmed by other groups/codes]

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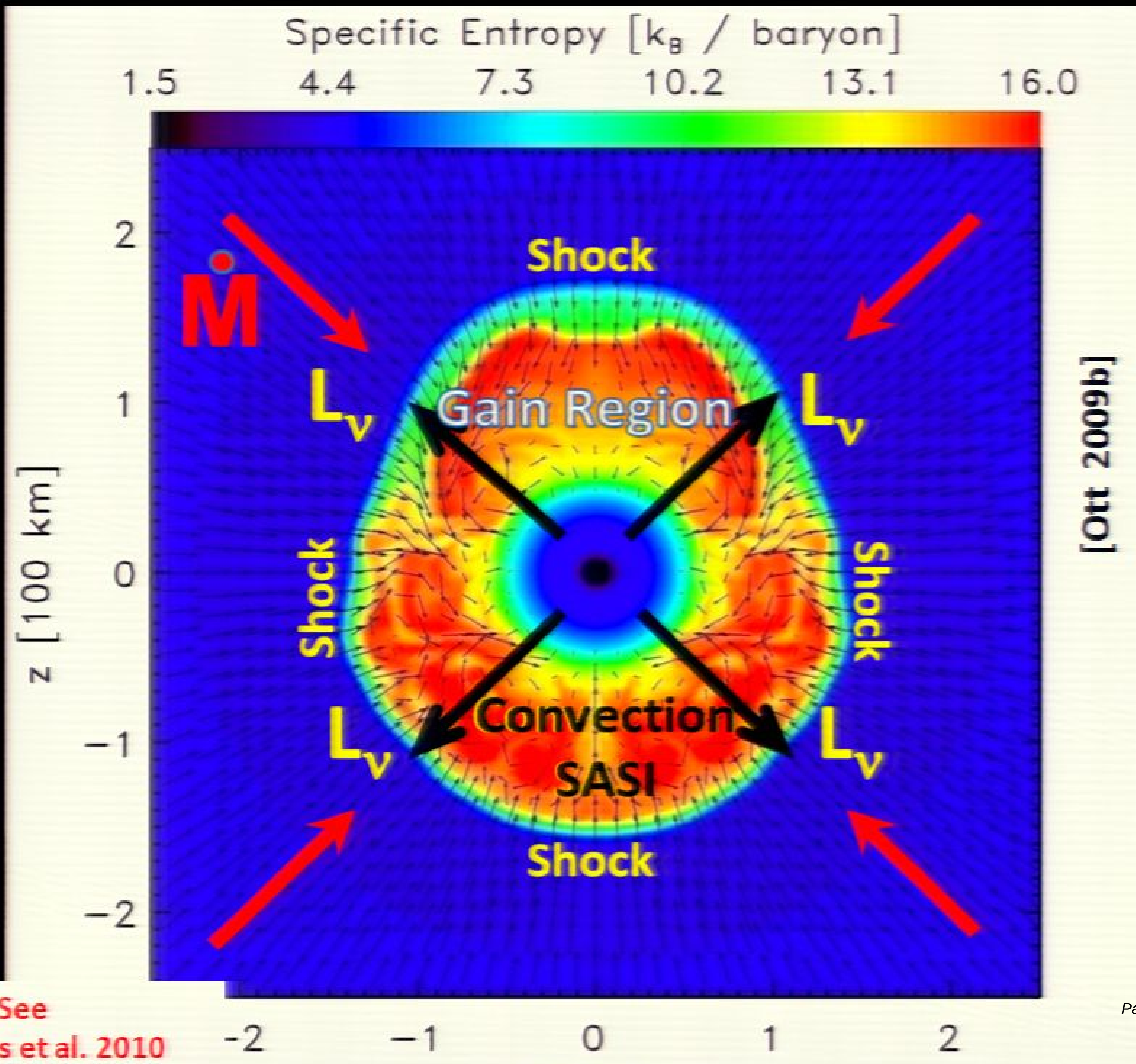

See
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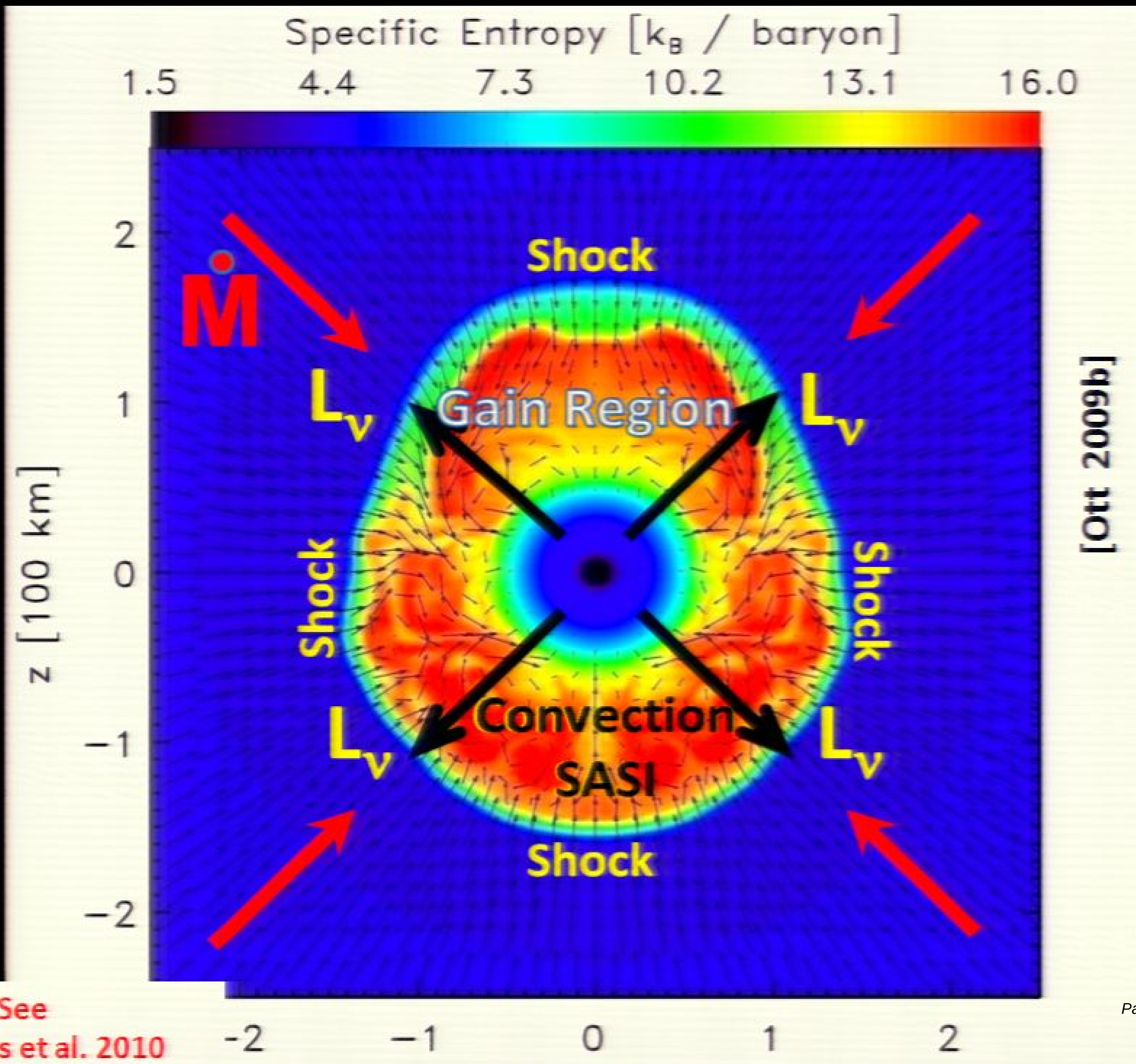

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GW Signature of the Neutrino Mechanism

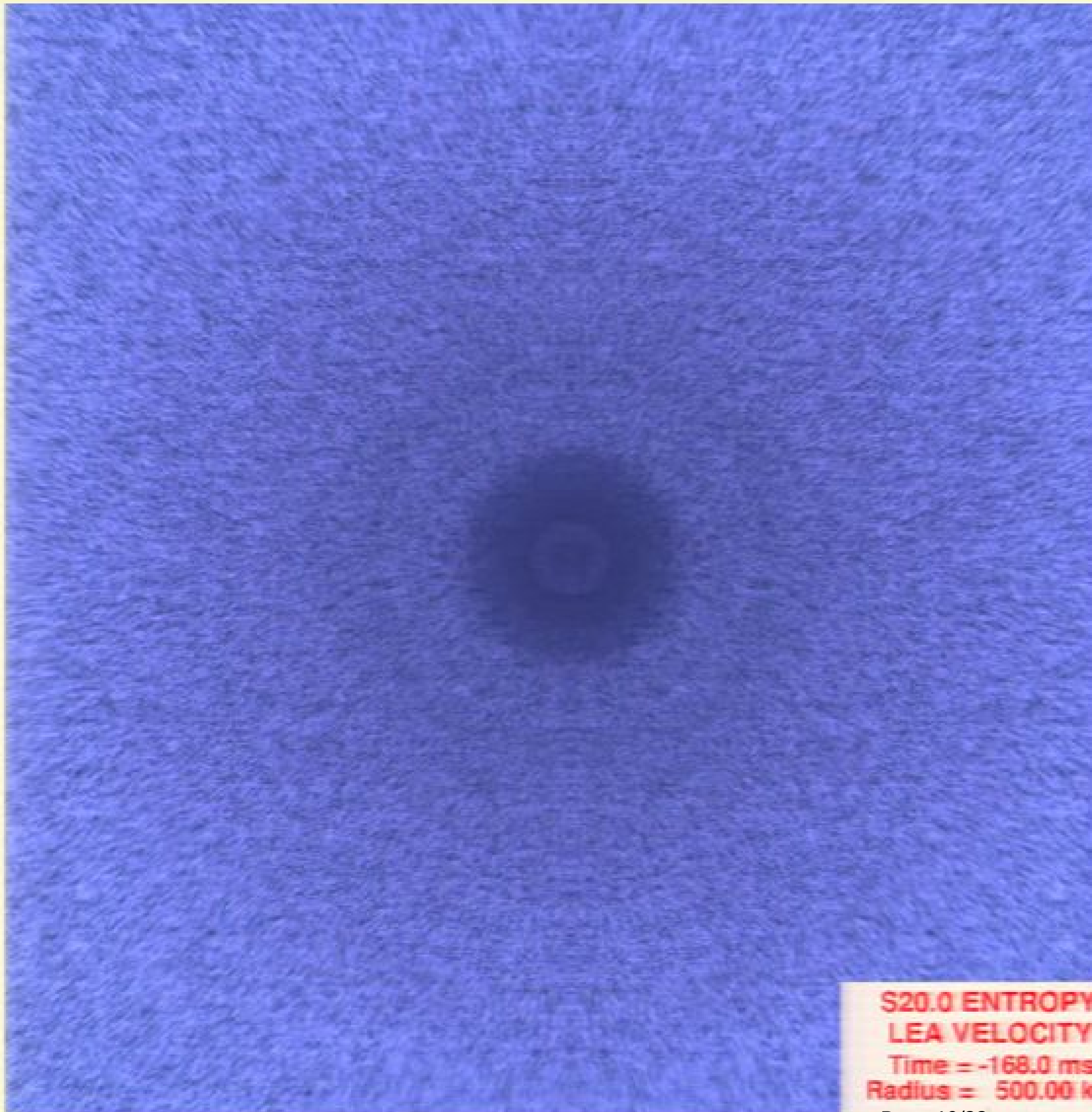
[Marek et al. '09, Murphy, Ott, & Burrows '09, Yakunin et al. '10]

Dominant Multi-D Dynamics:

- Convection/Turbulence in the **protoneutron star** (PNS; $\tau > \sim 10s$)
- Convection/Turbulence in the **postshock region** ($\tau < 1s$)
- Standing accretion shock instability (**SASI**; $\tau < 1s$**)**

Expected GW Signal:

- Broadband
- Random polarization
- Low amplitude: $O(10^{-23} - 10^{-22})$ at 10 kpc



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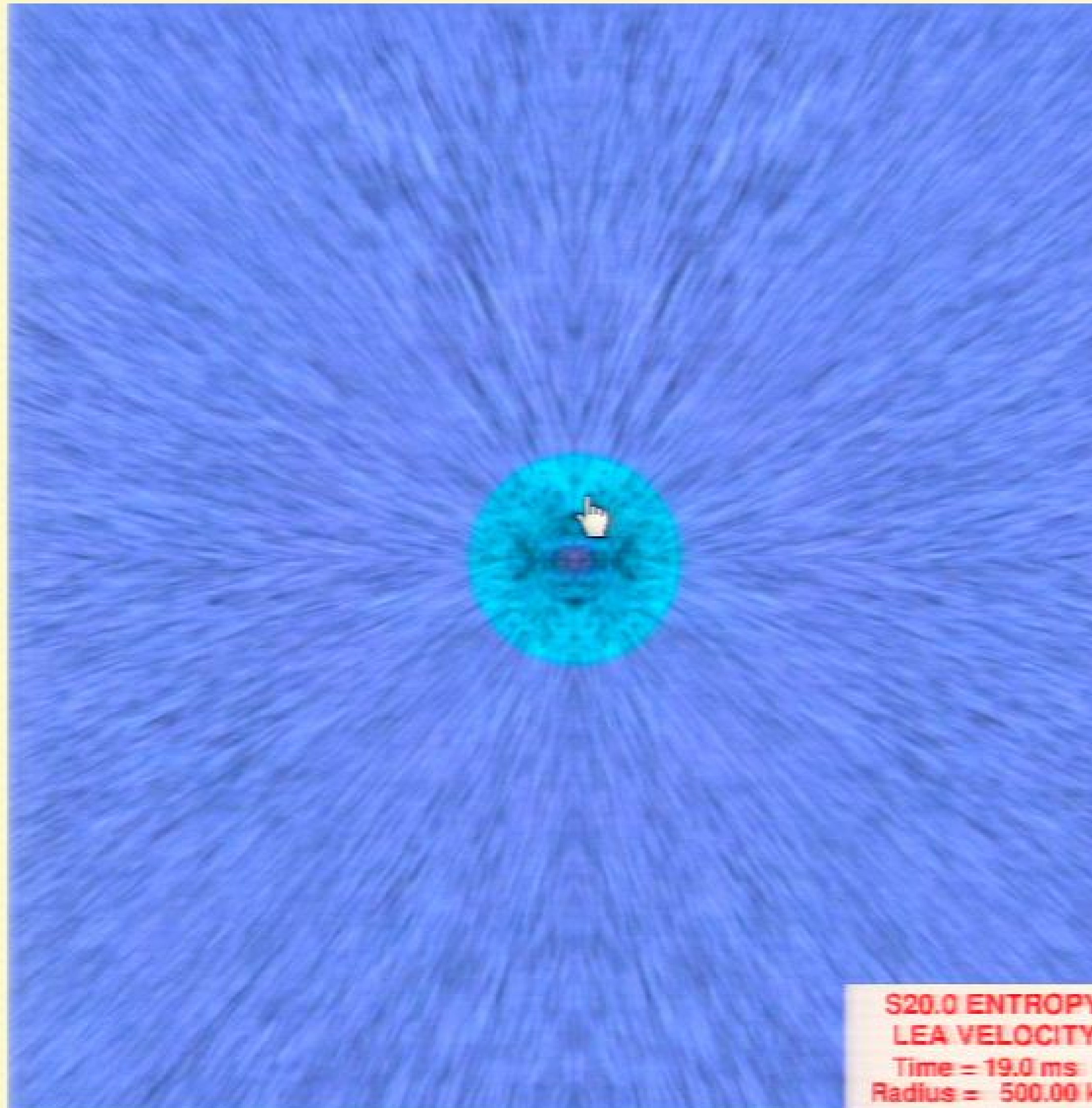

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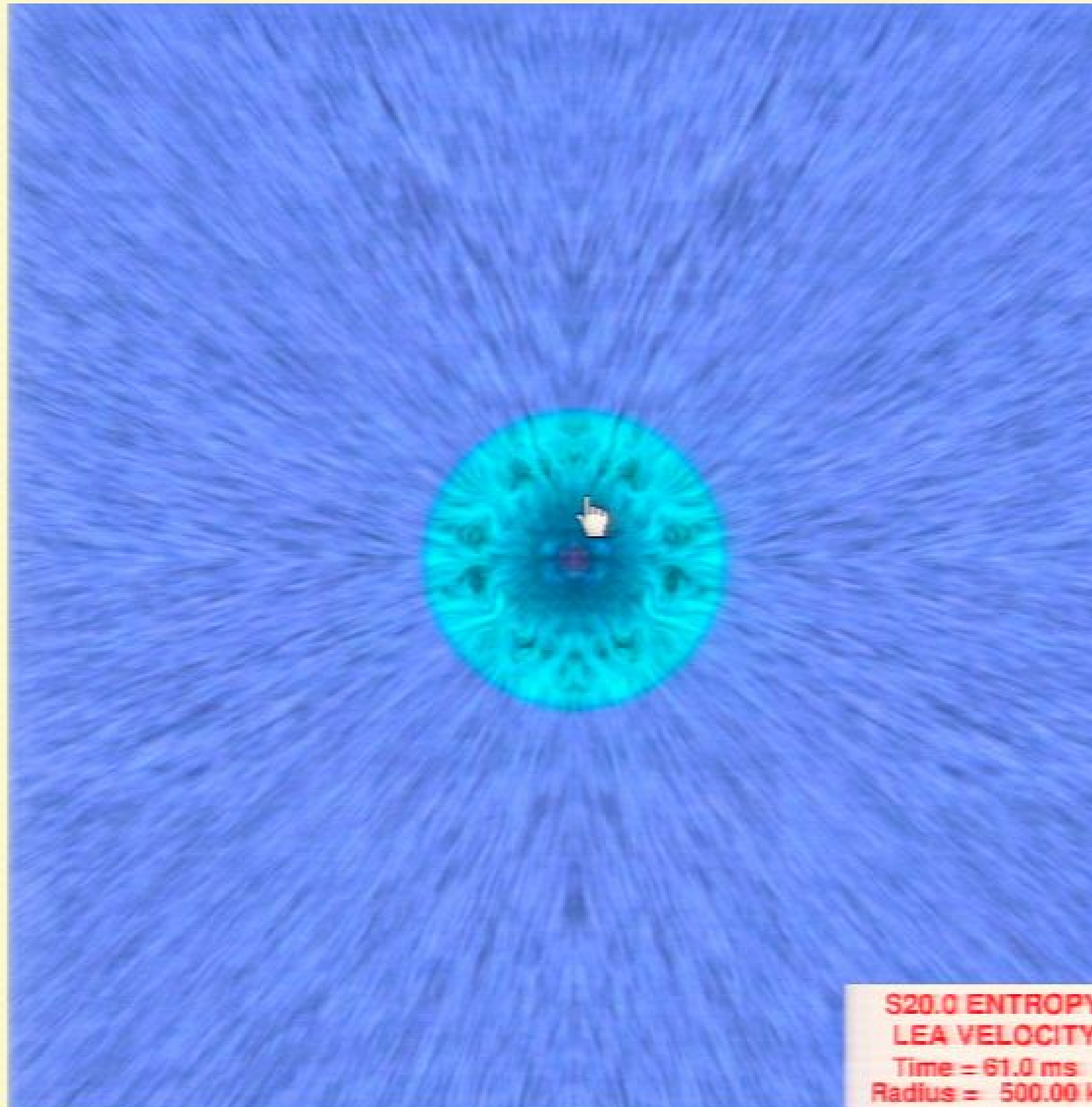

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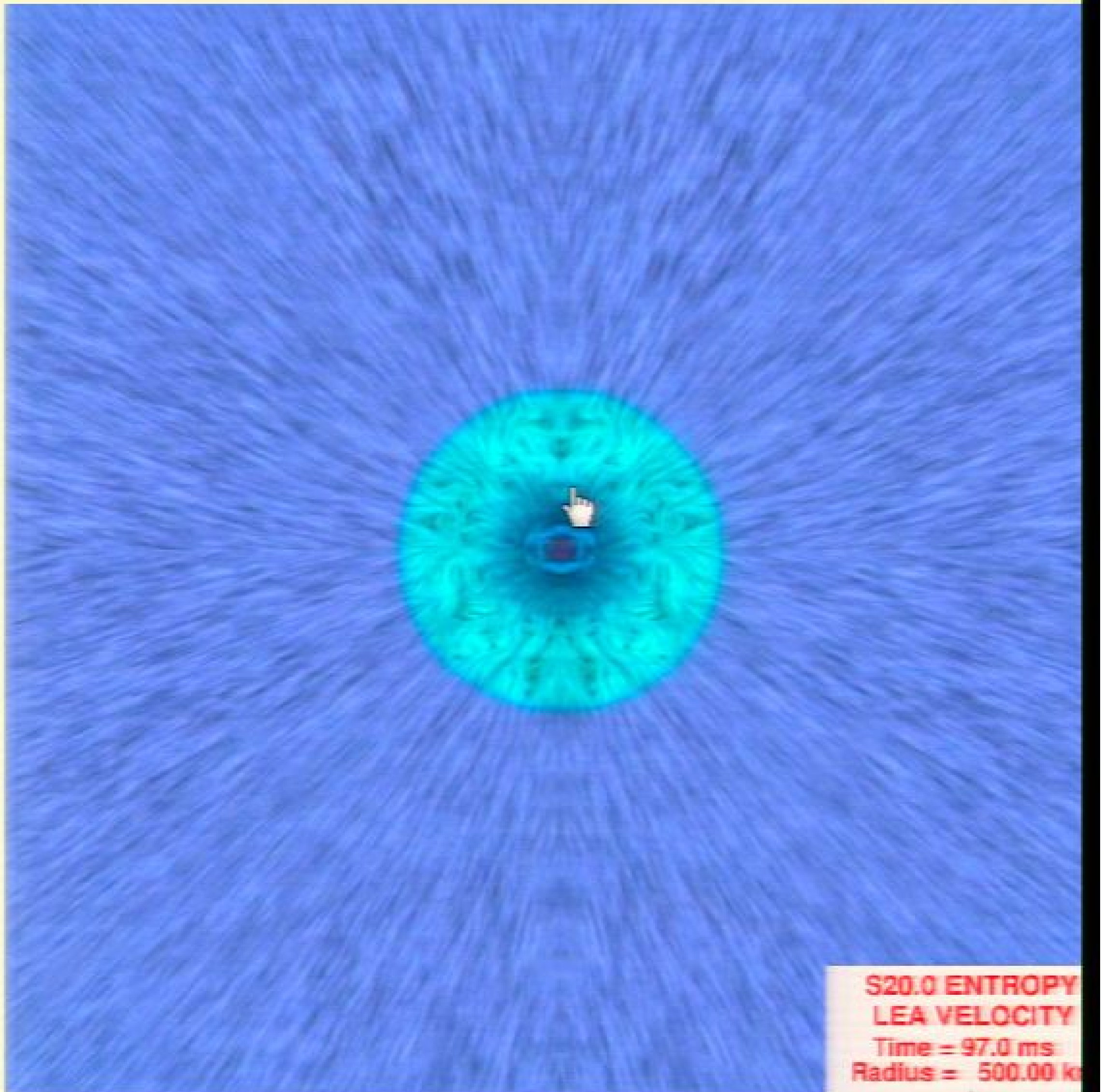

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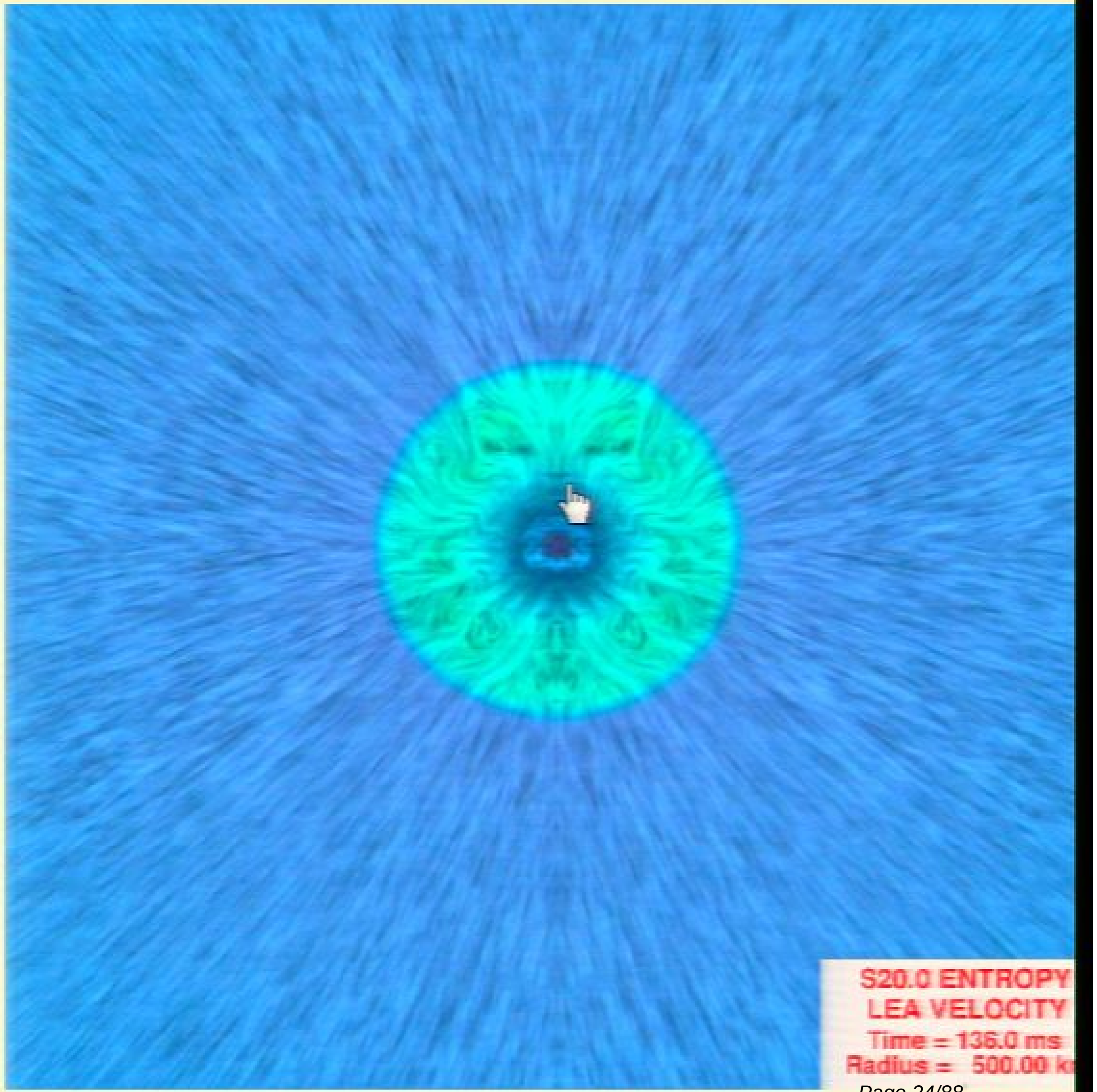

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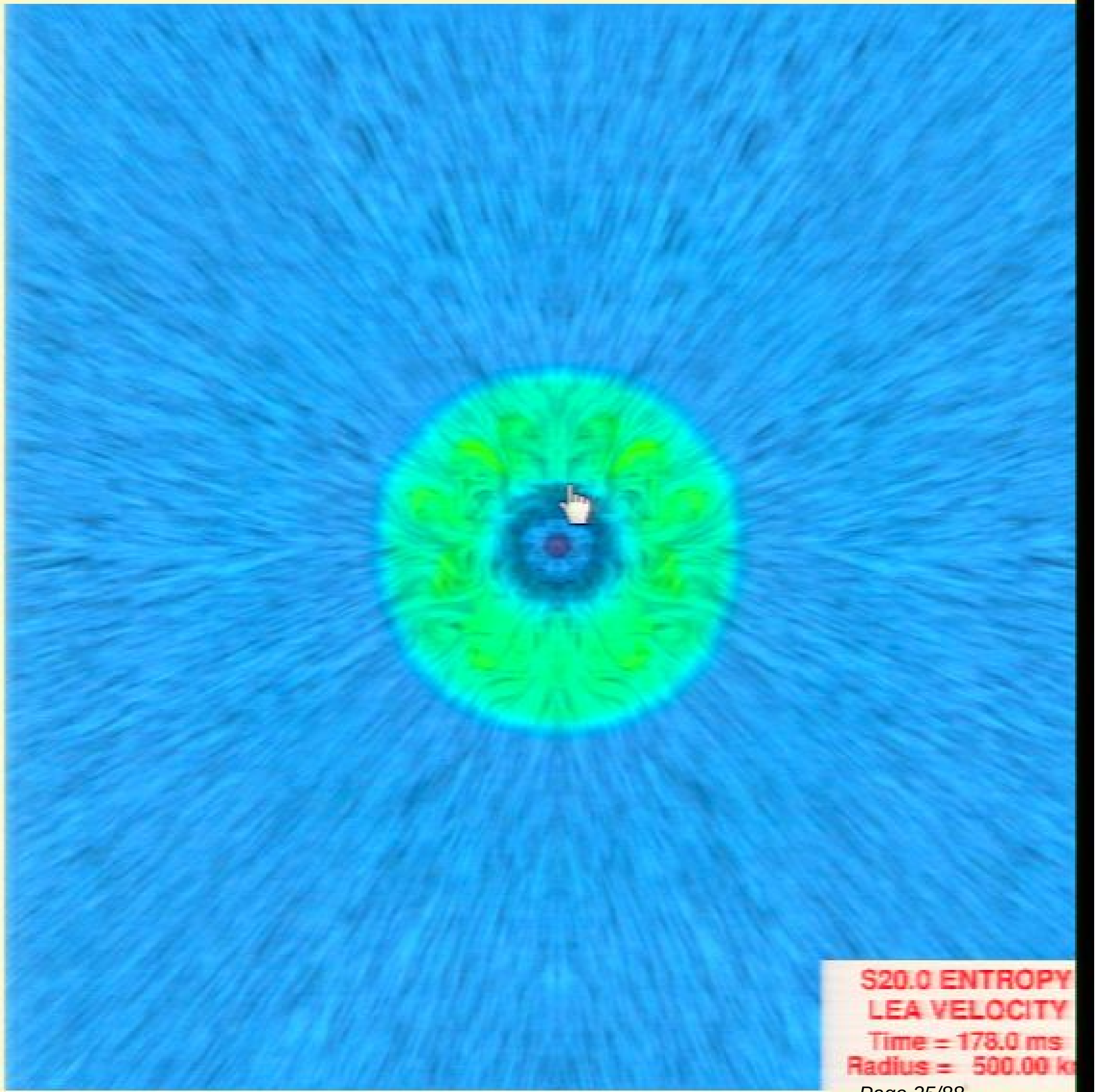

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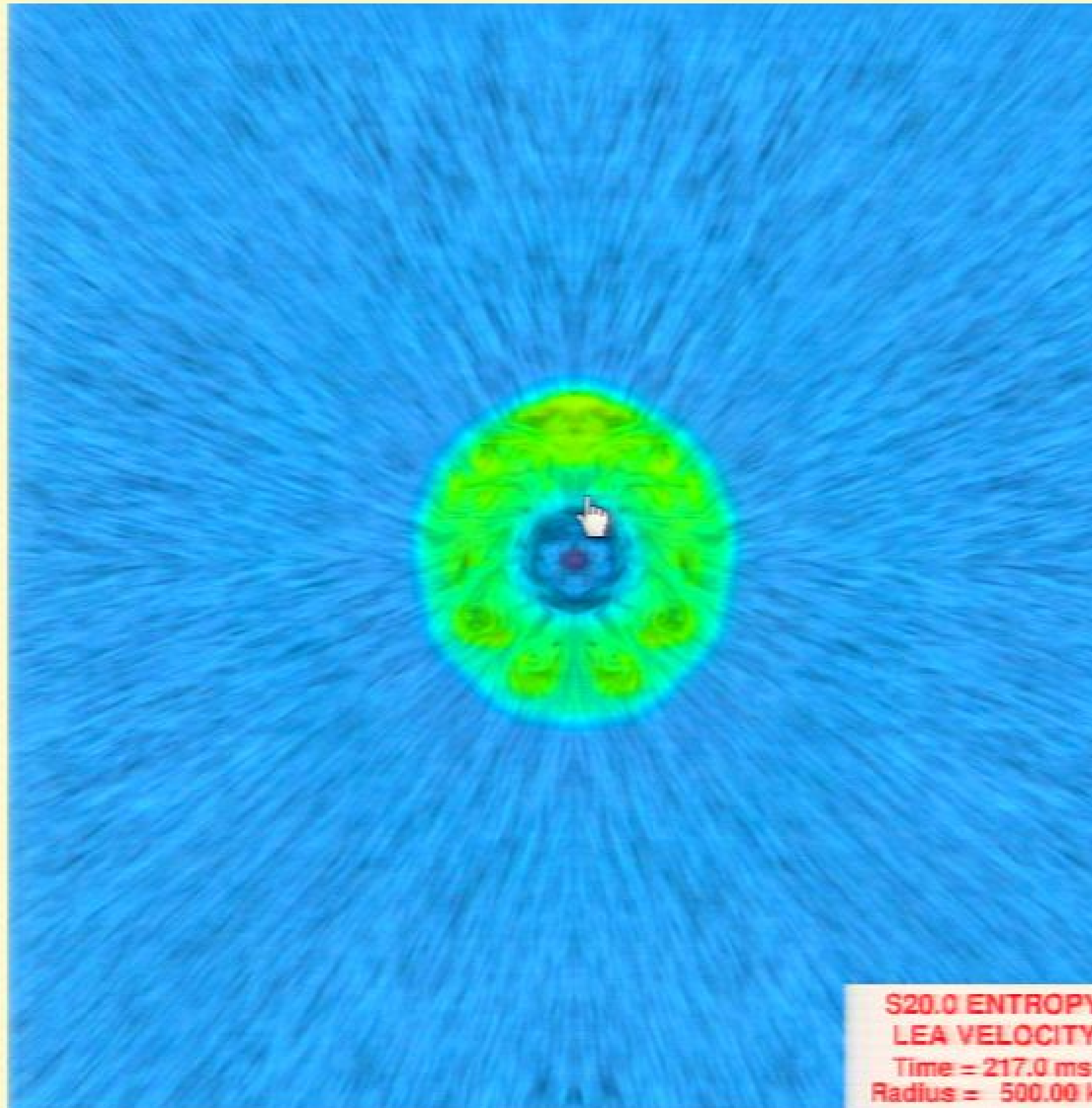

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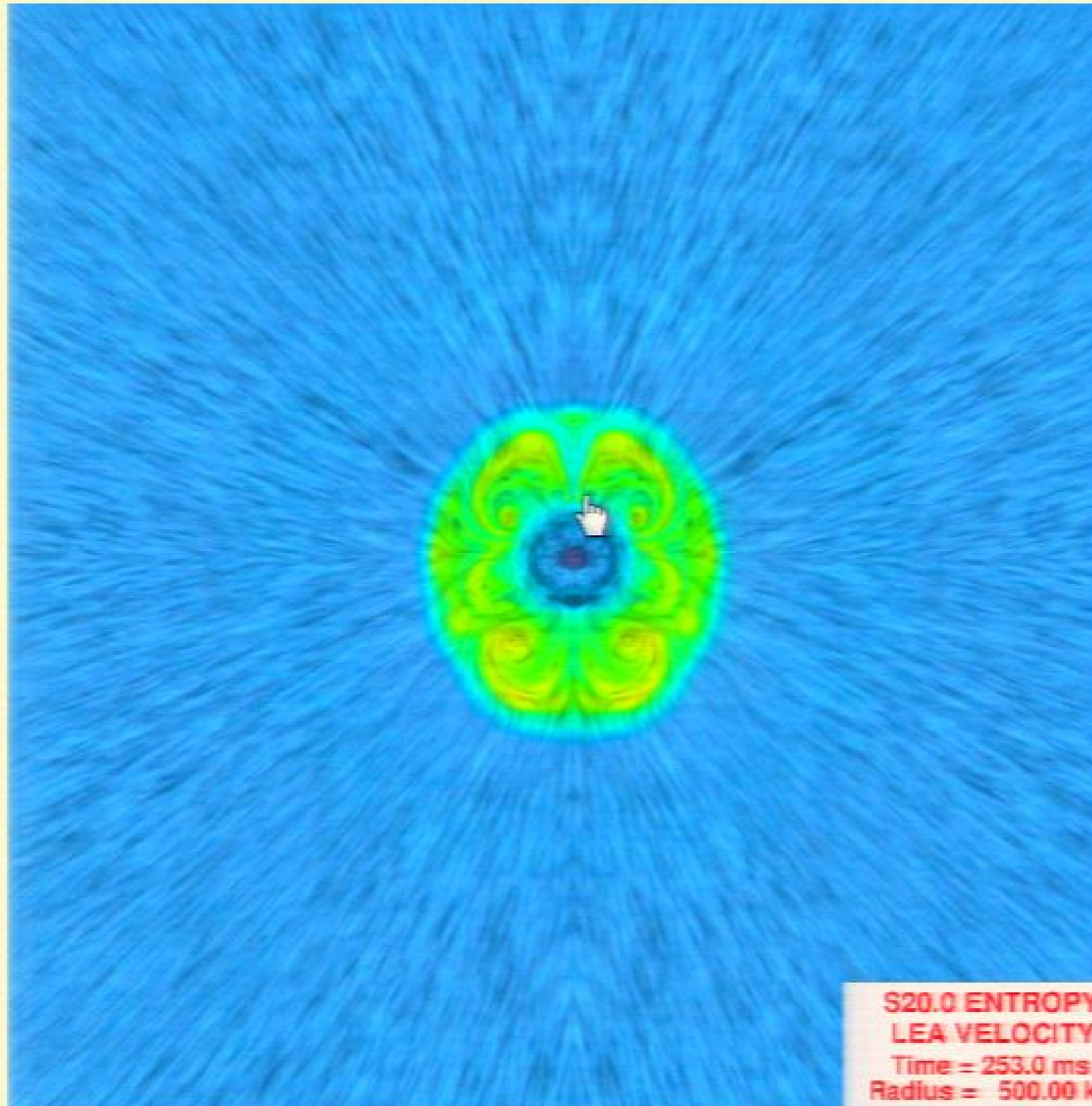

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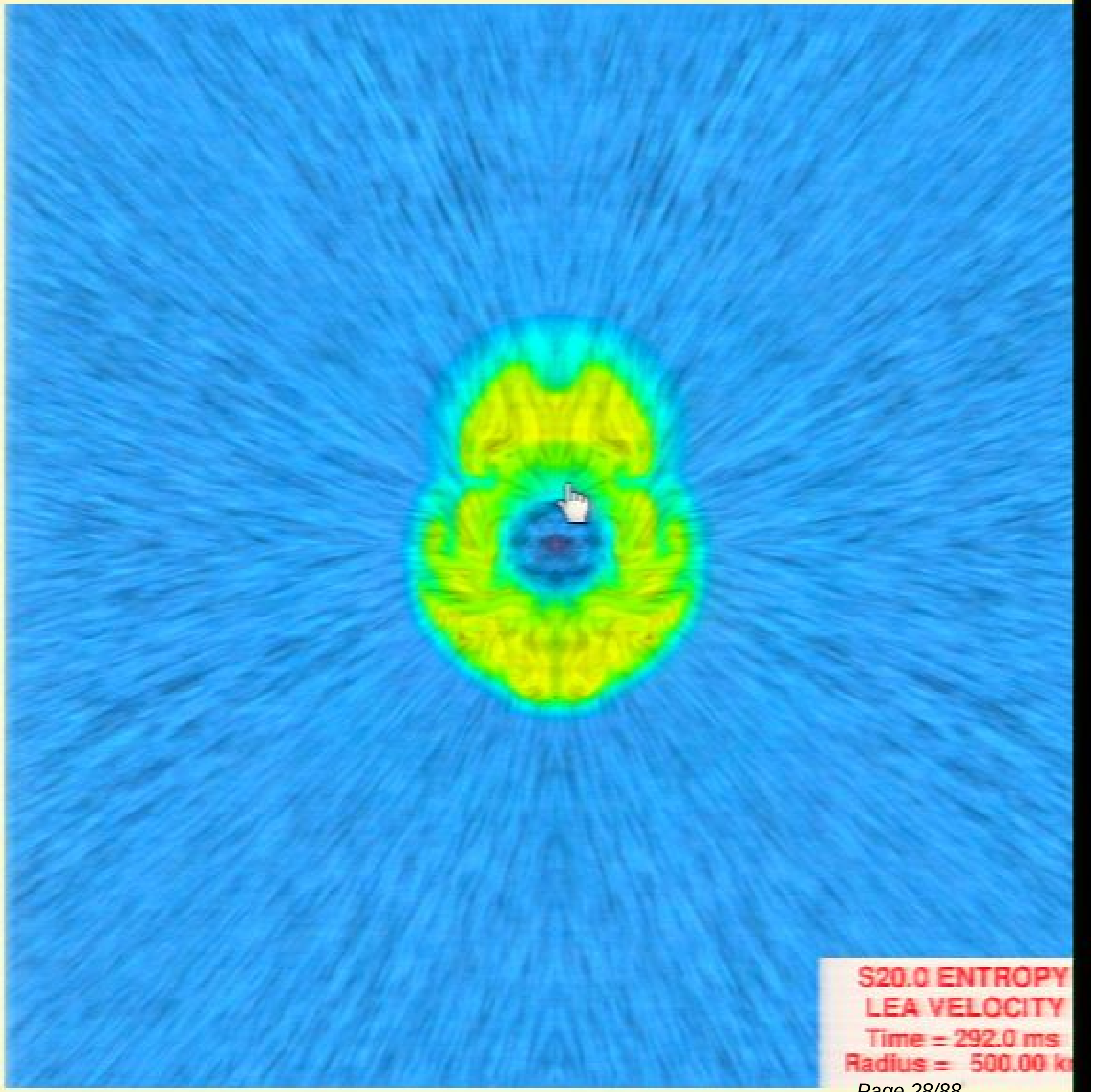

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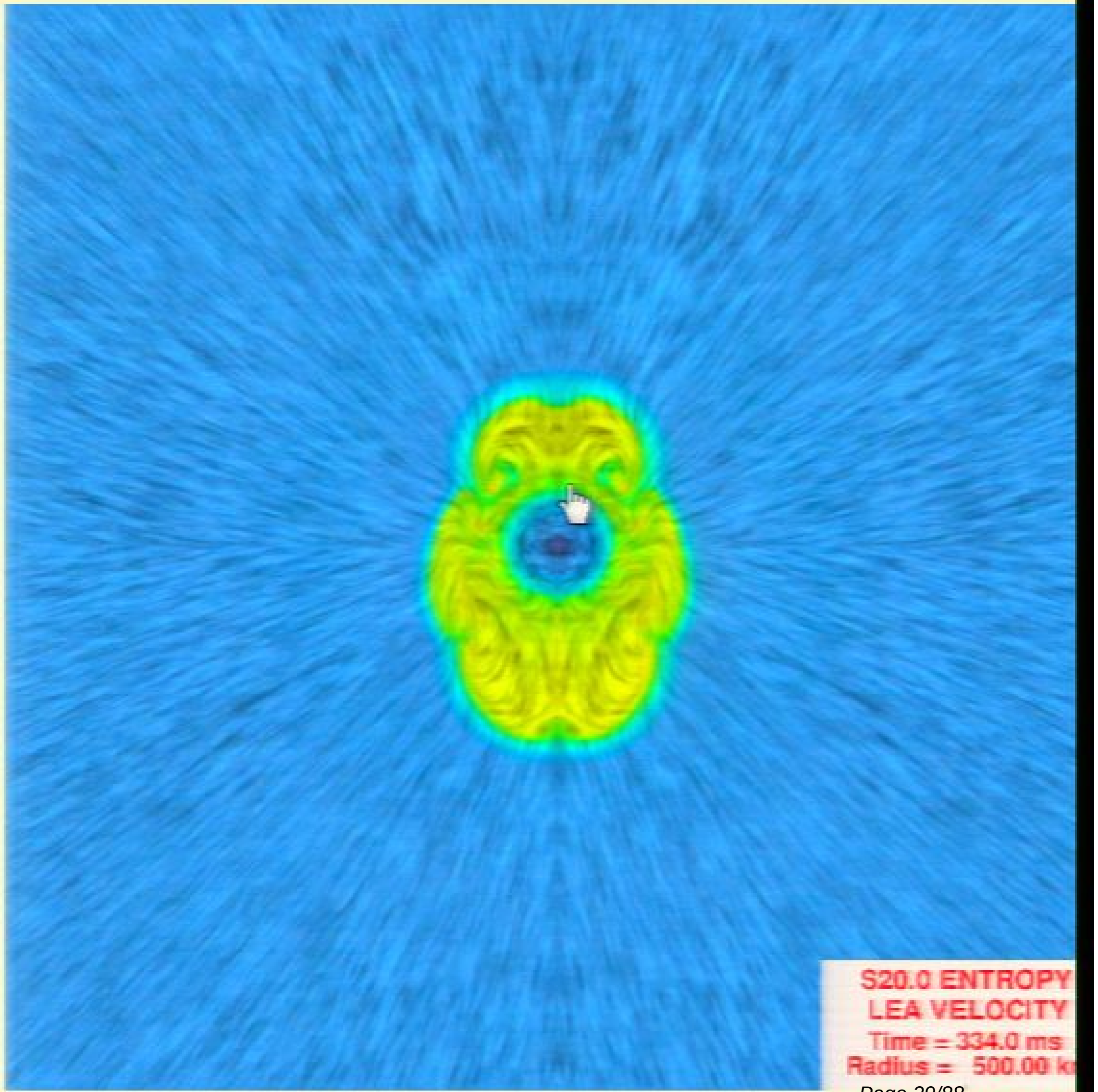

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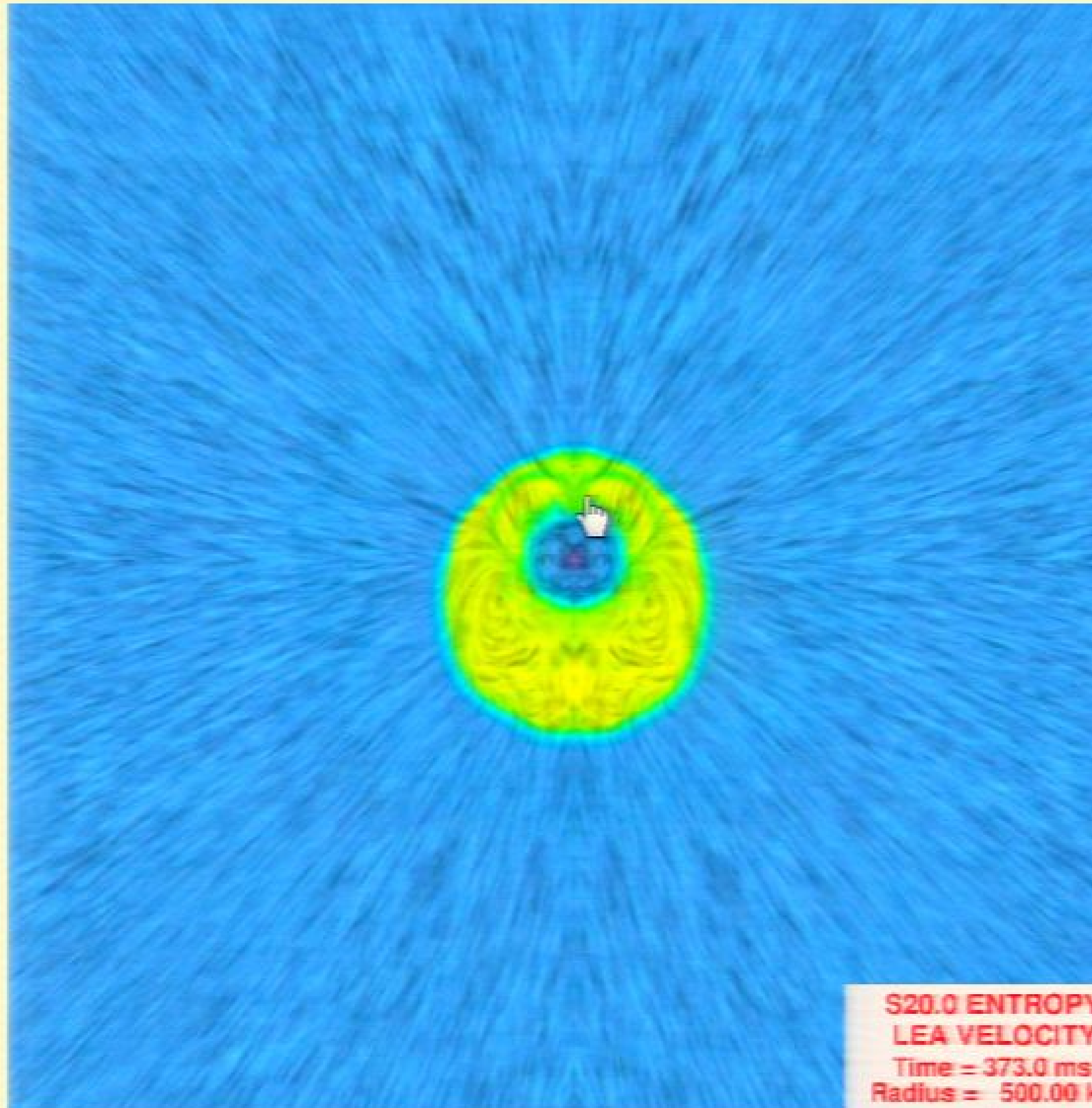

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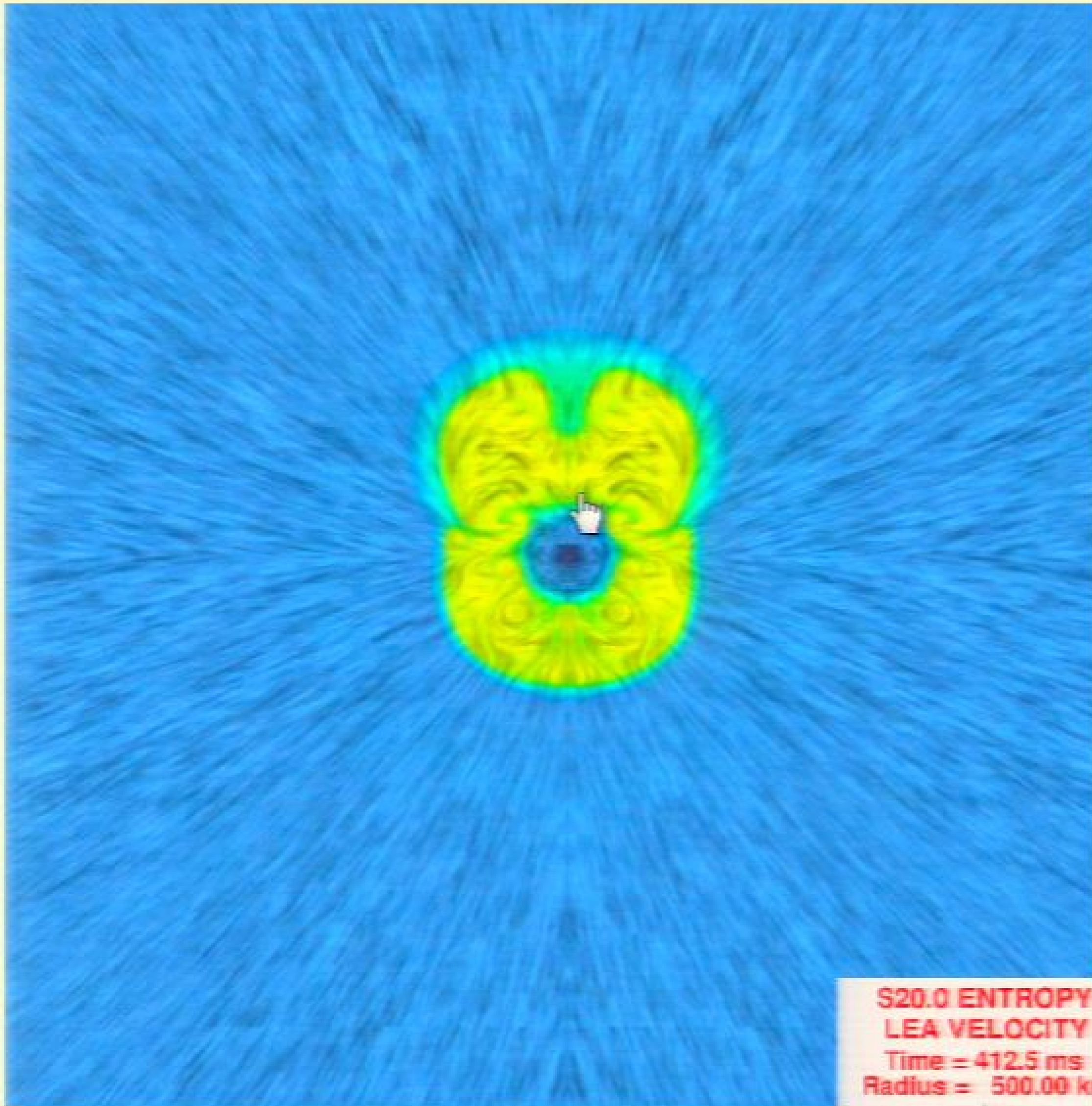

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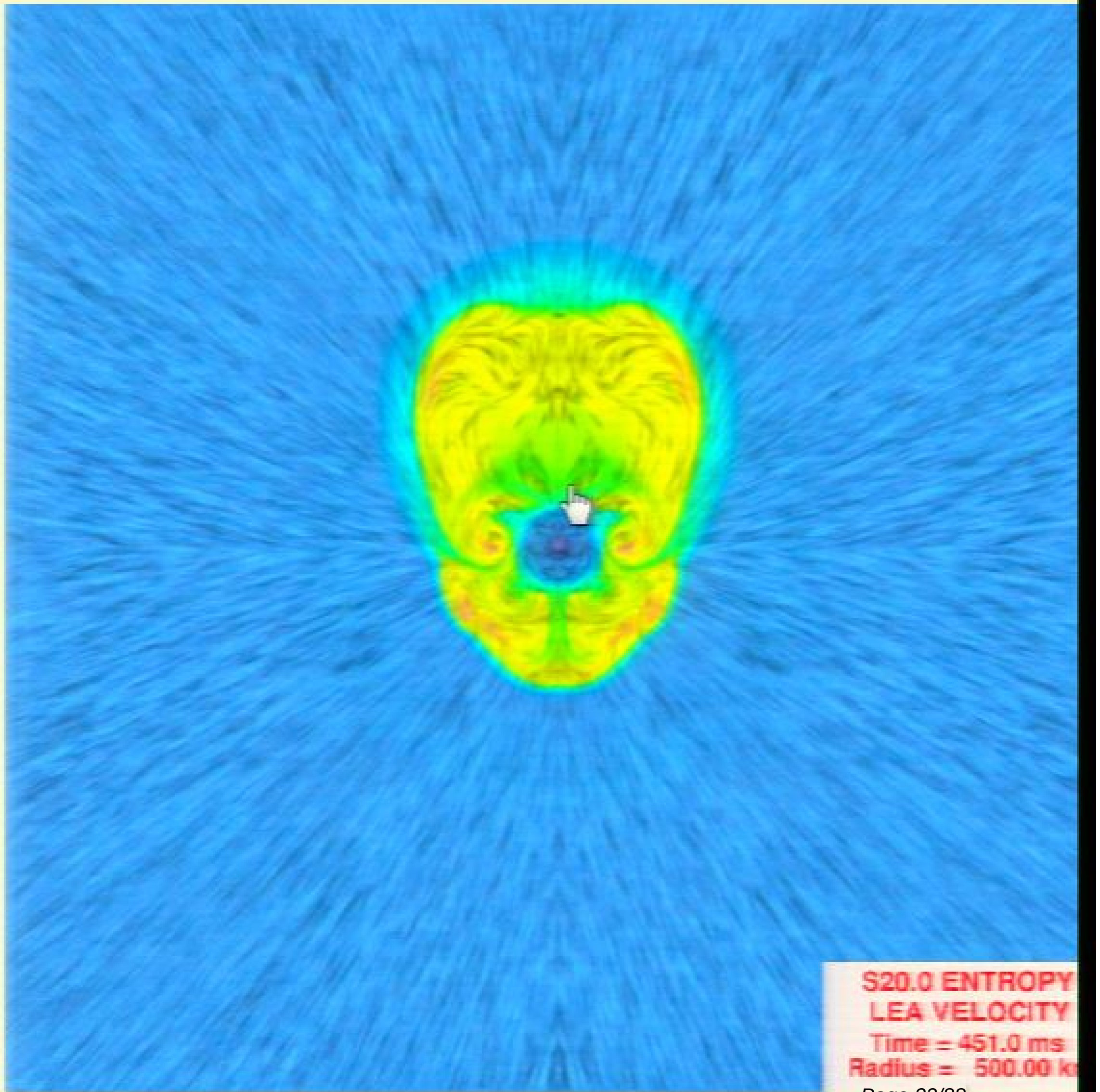

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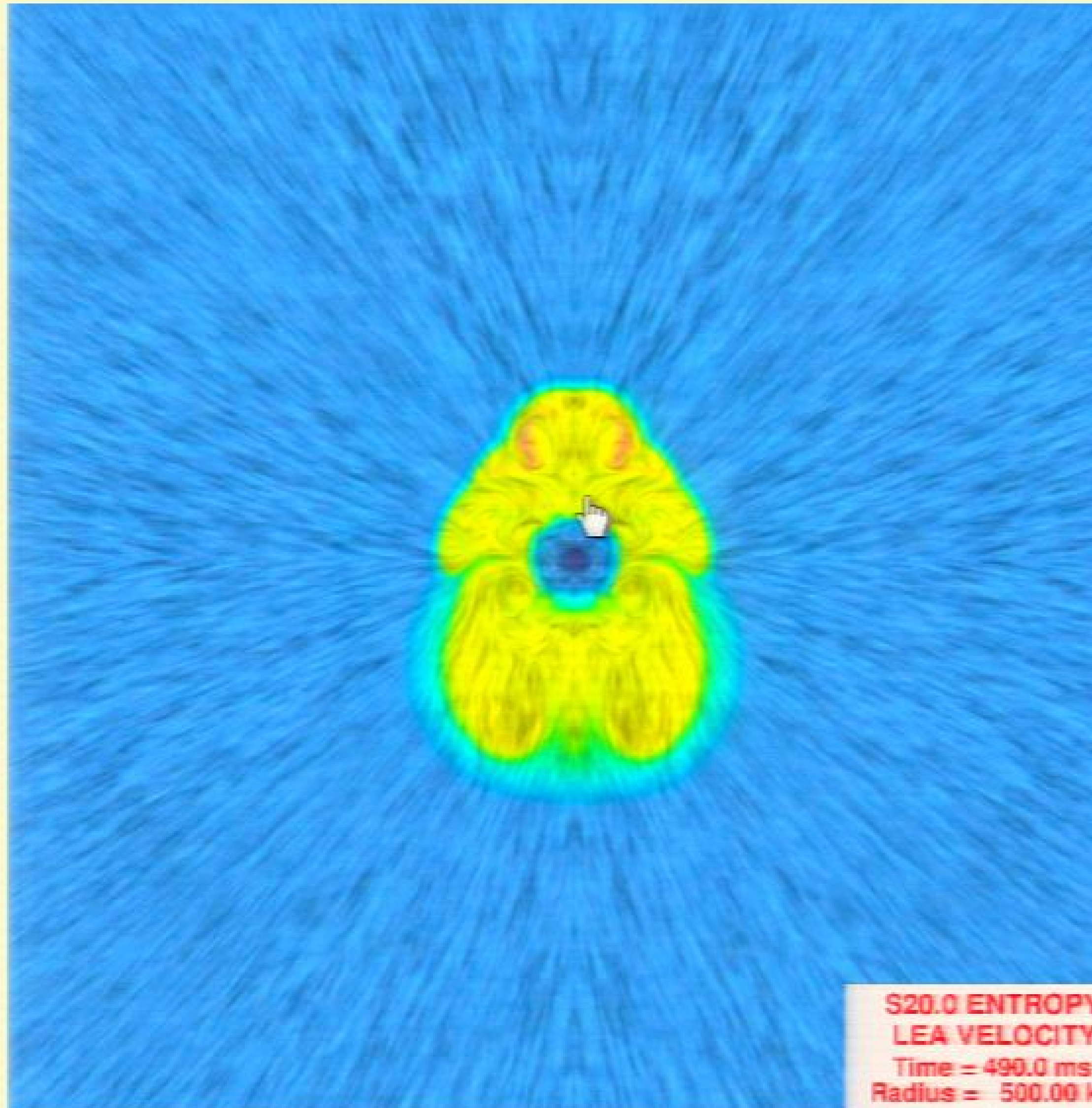

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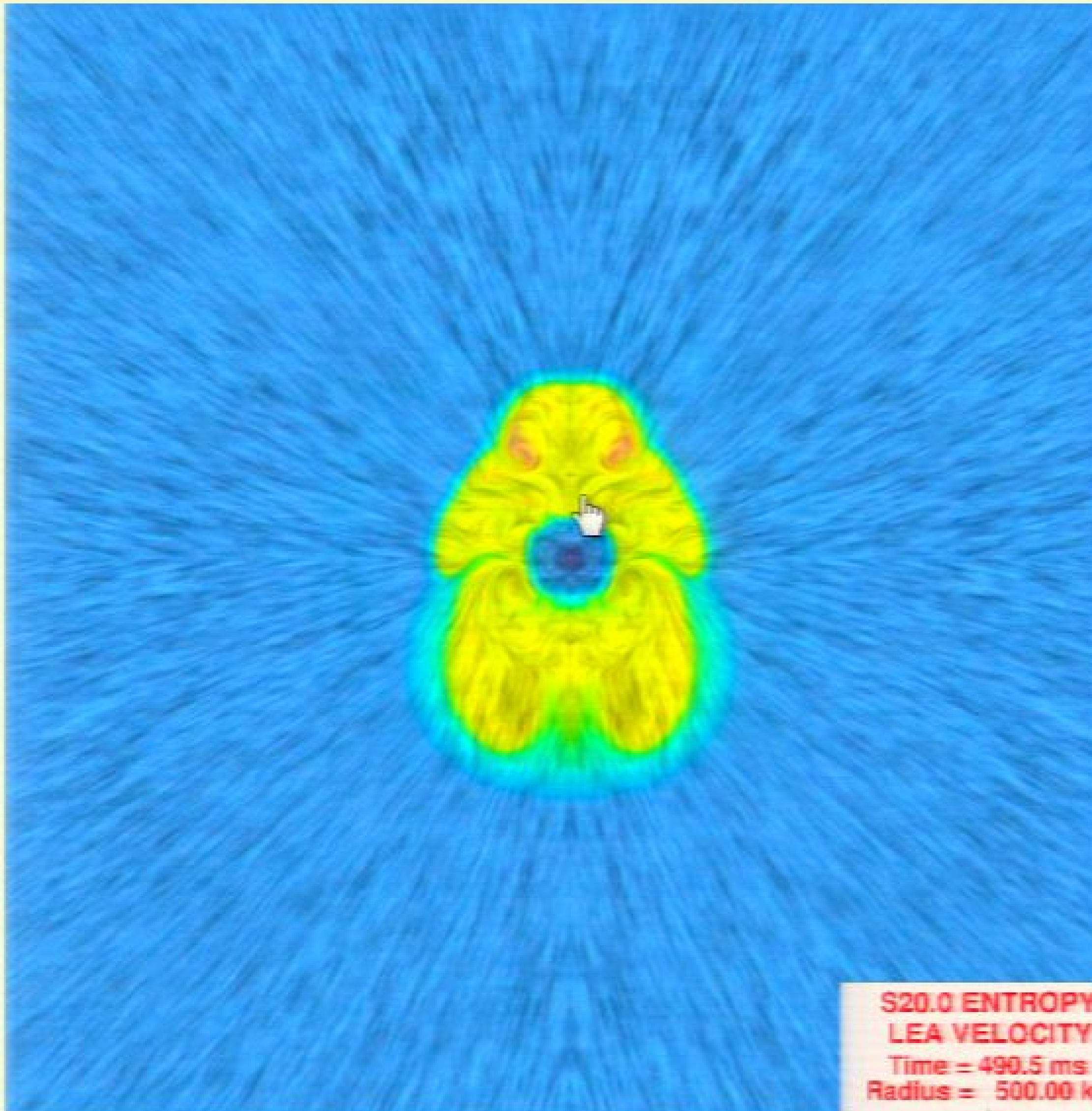

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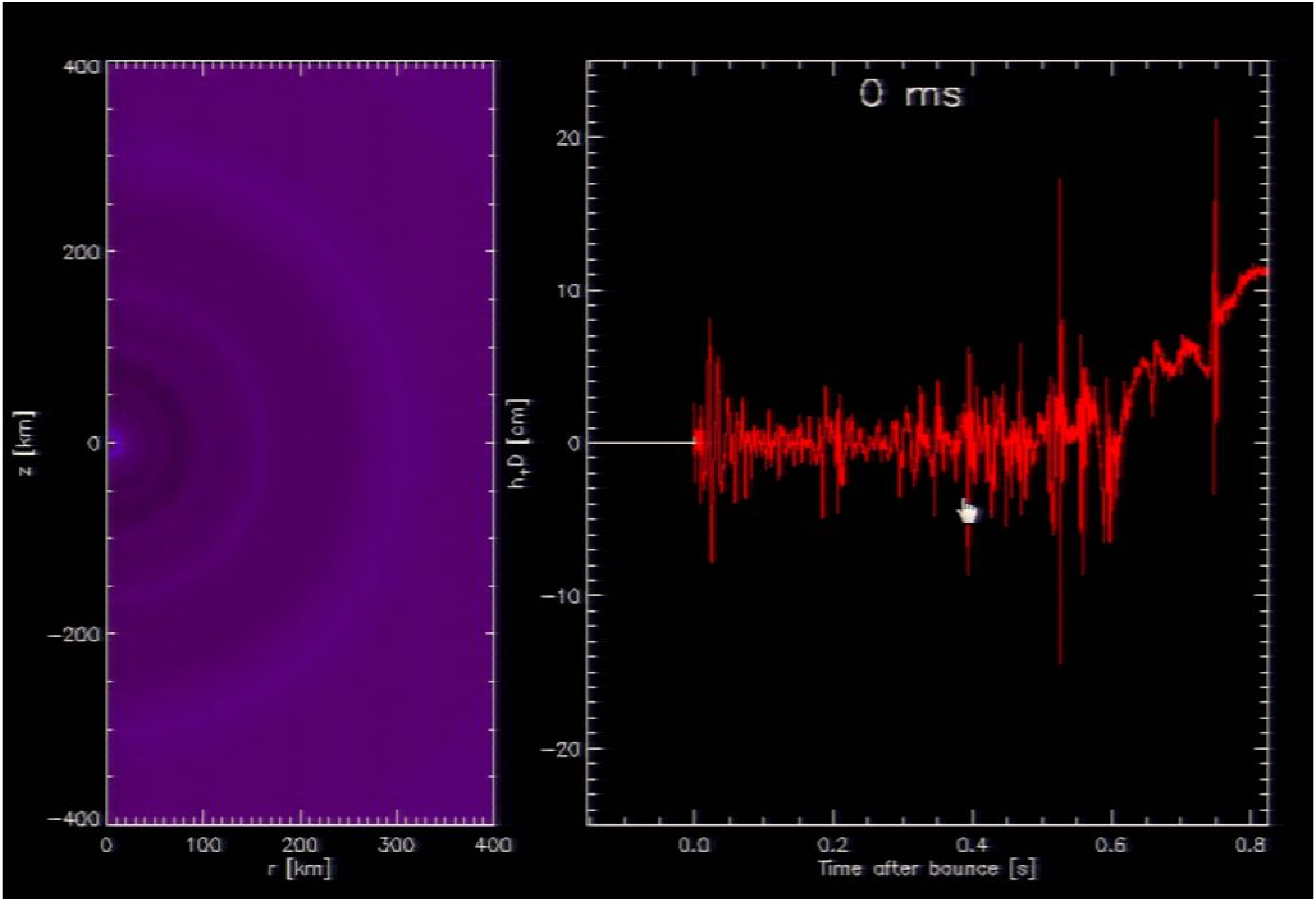

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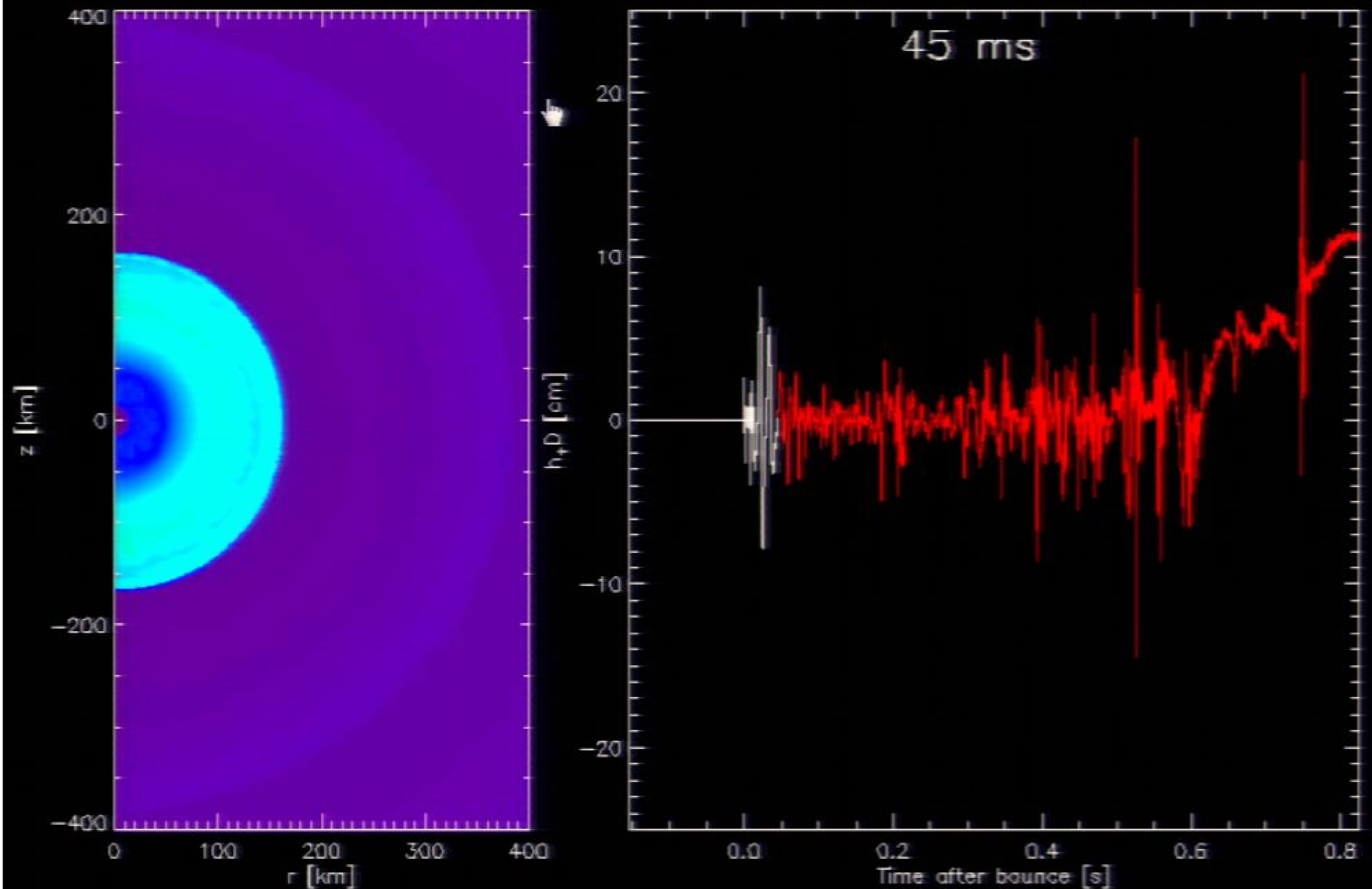

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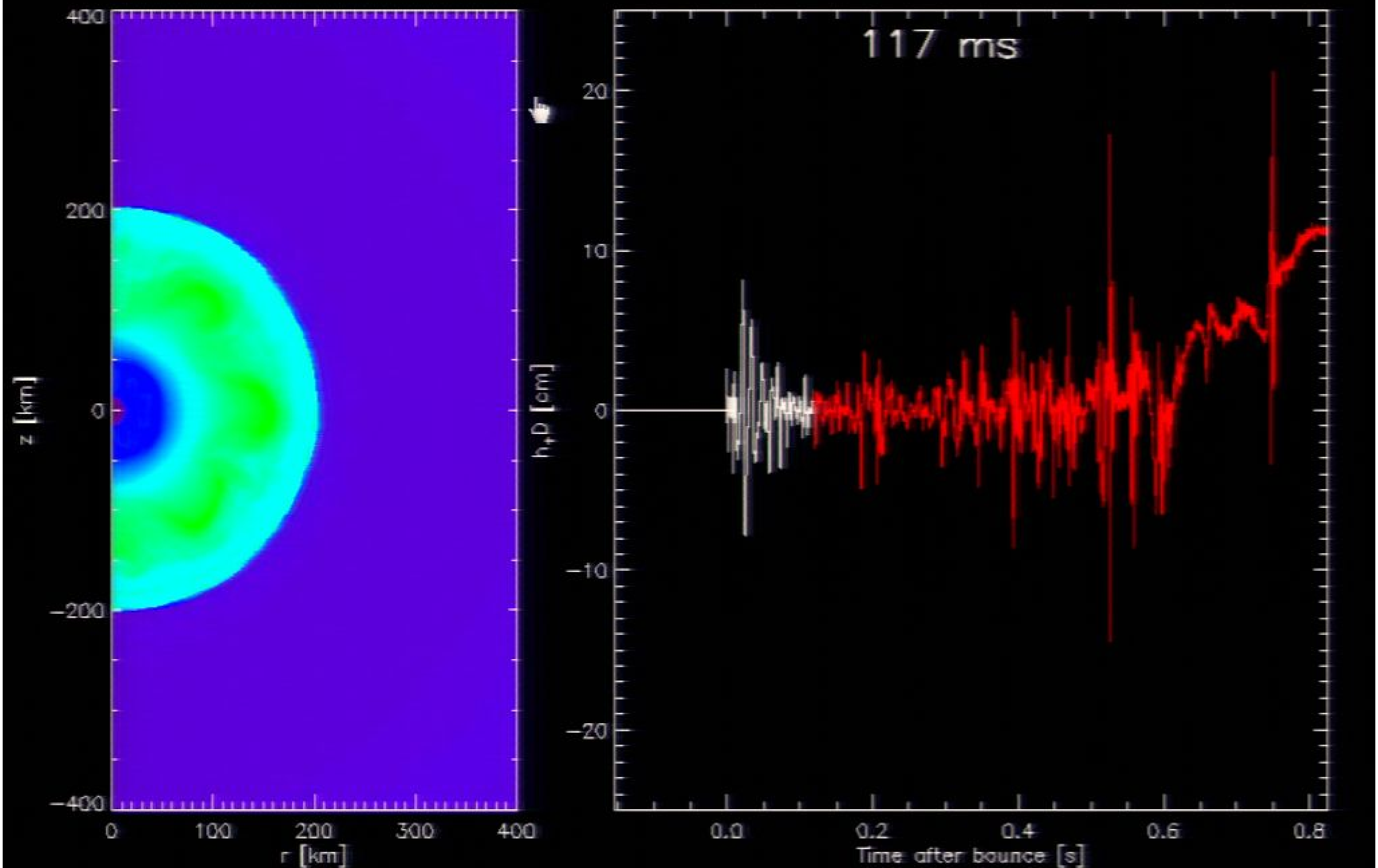

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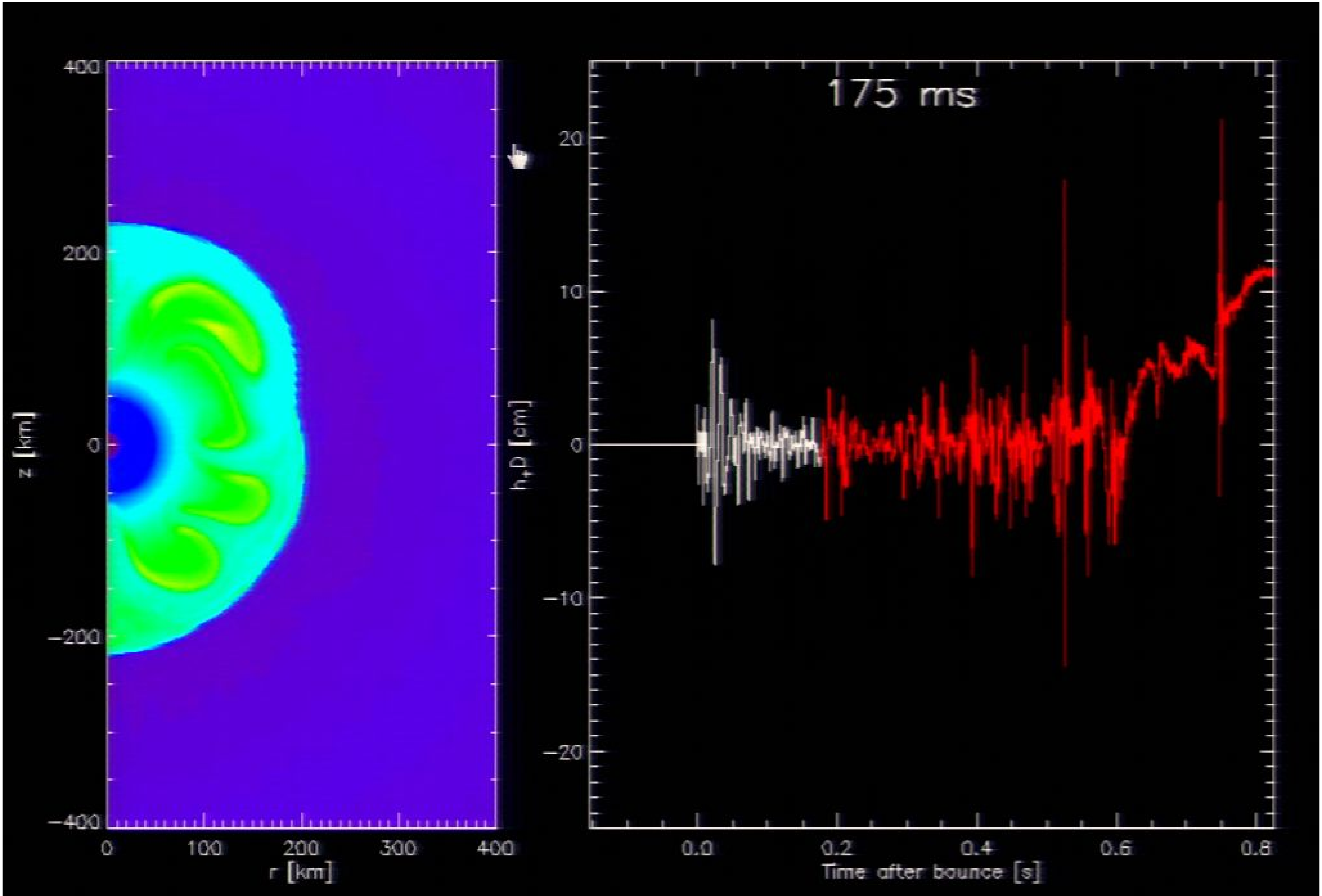

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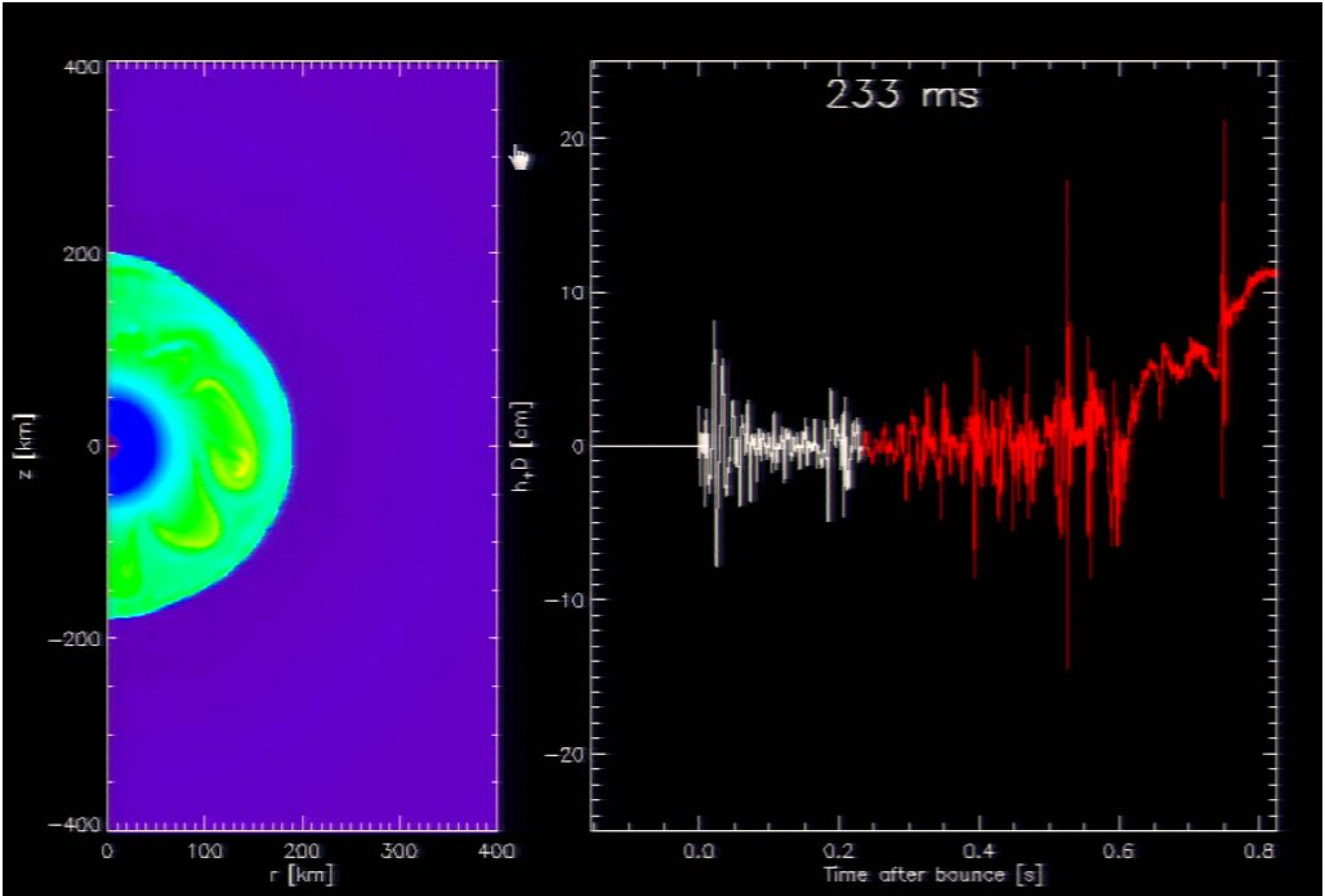

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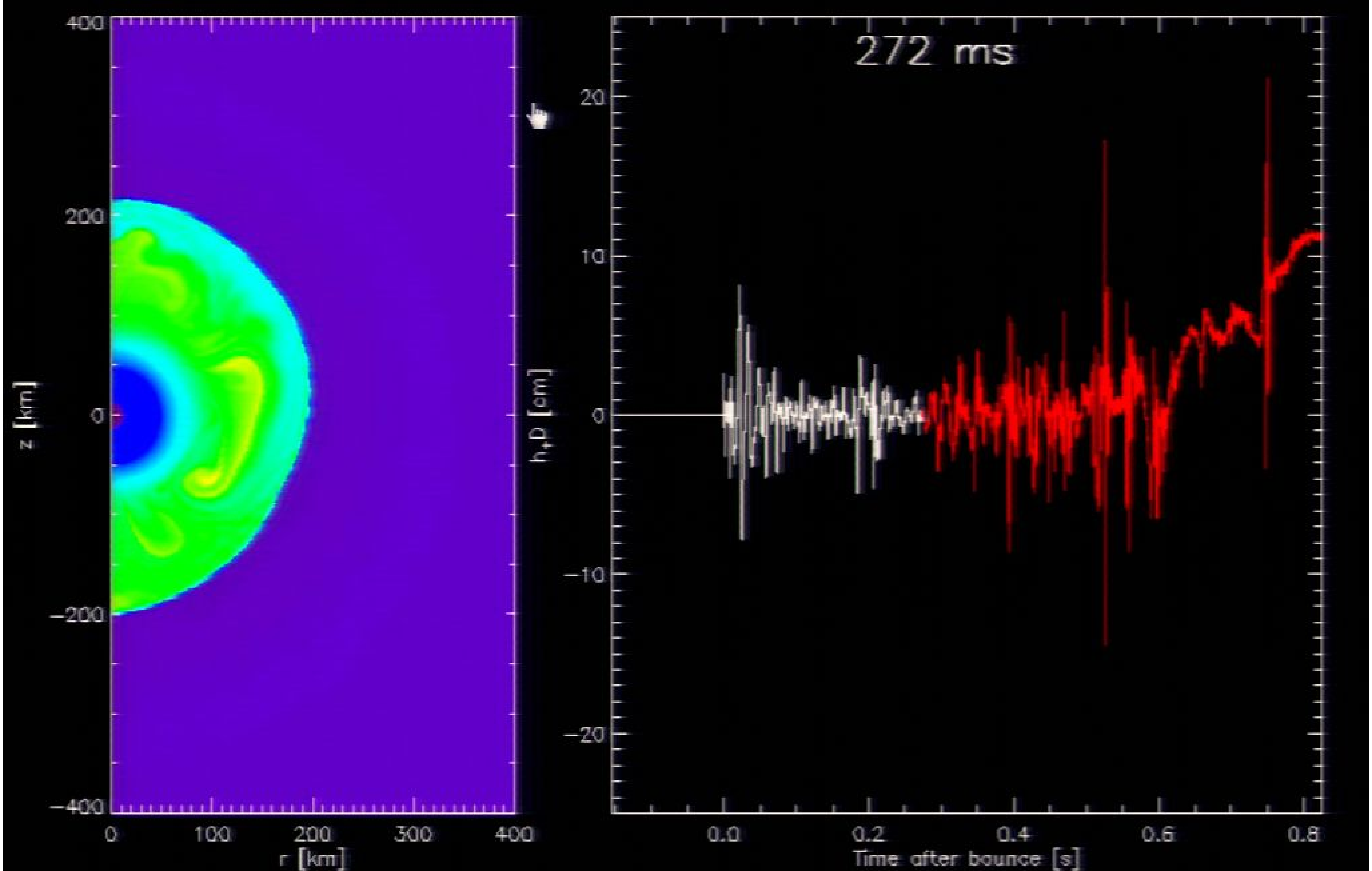

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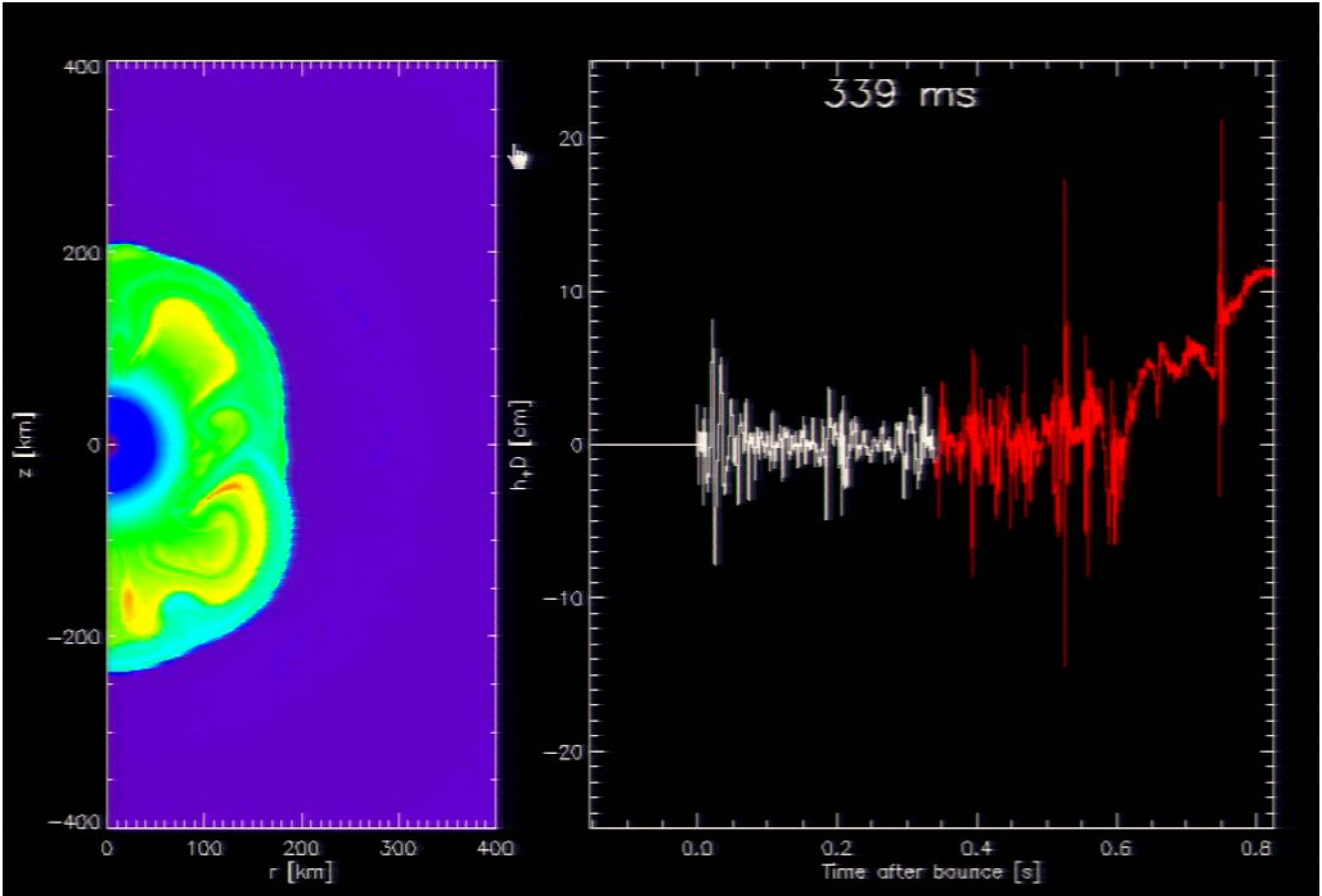

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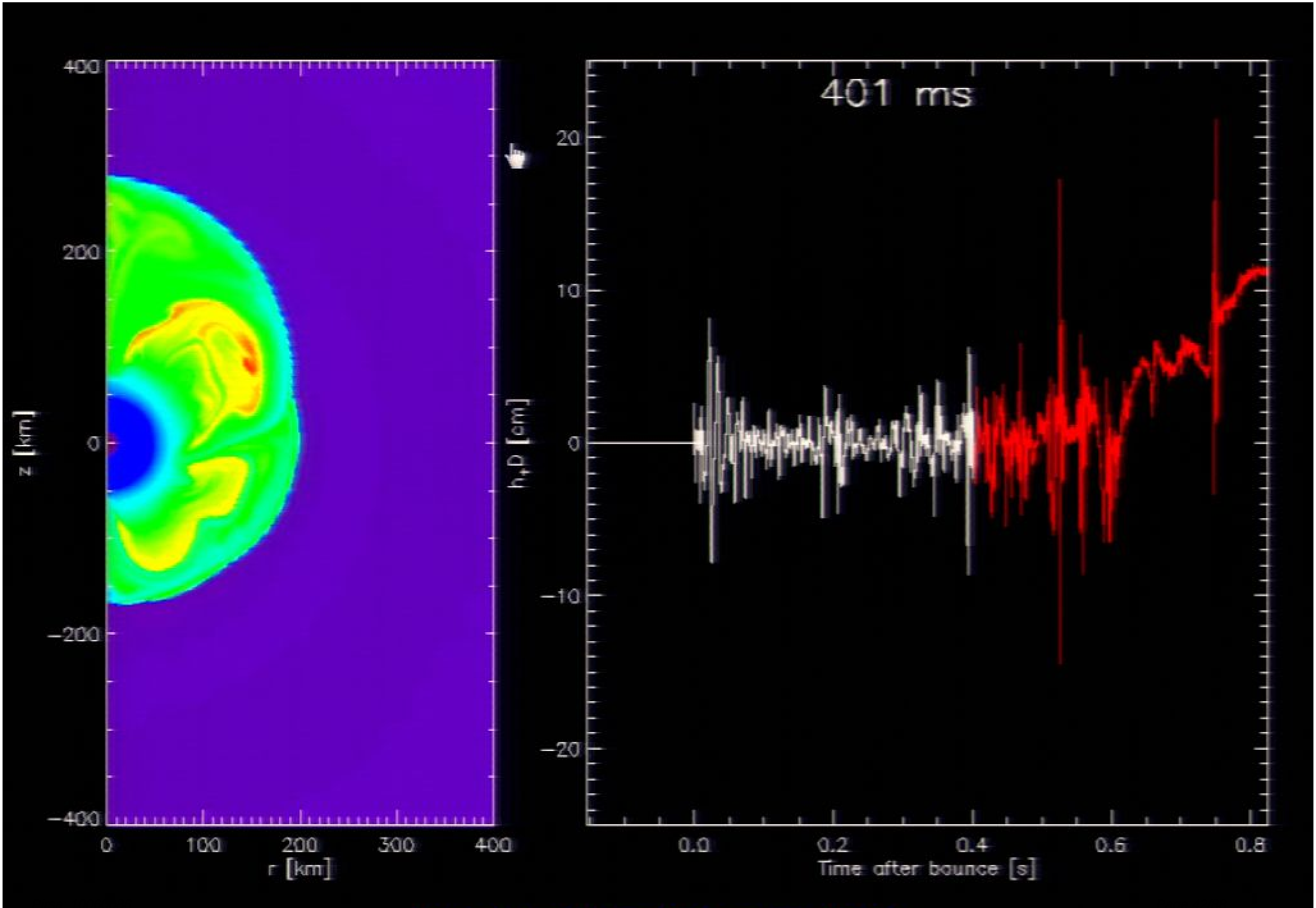

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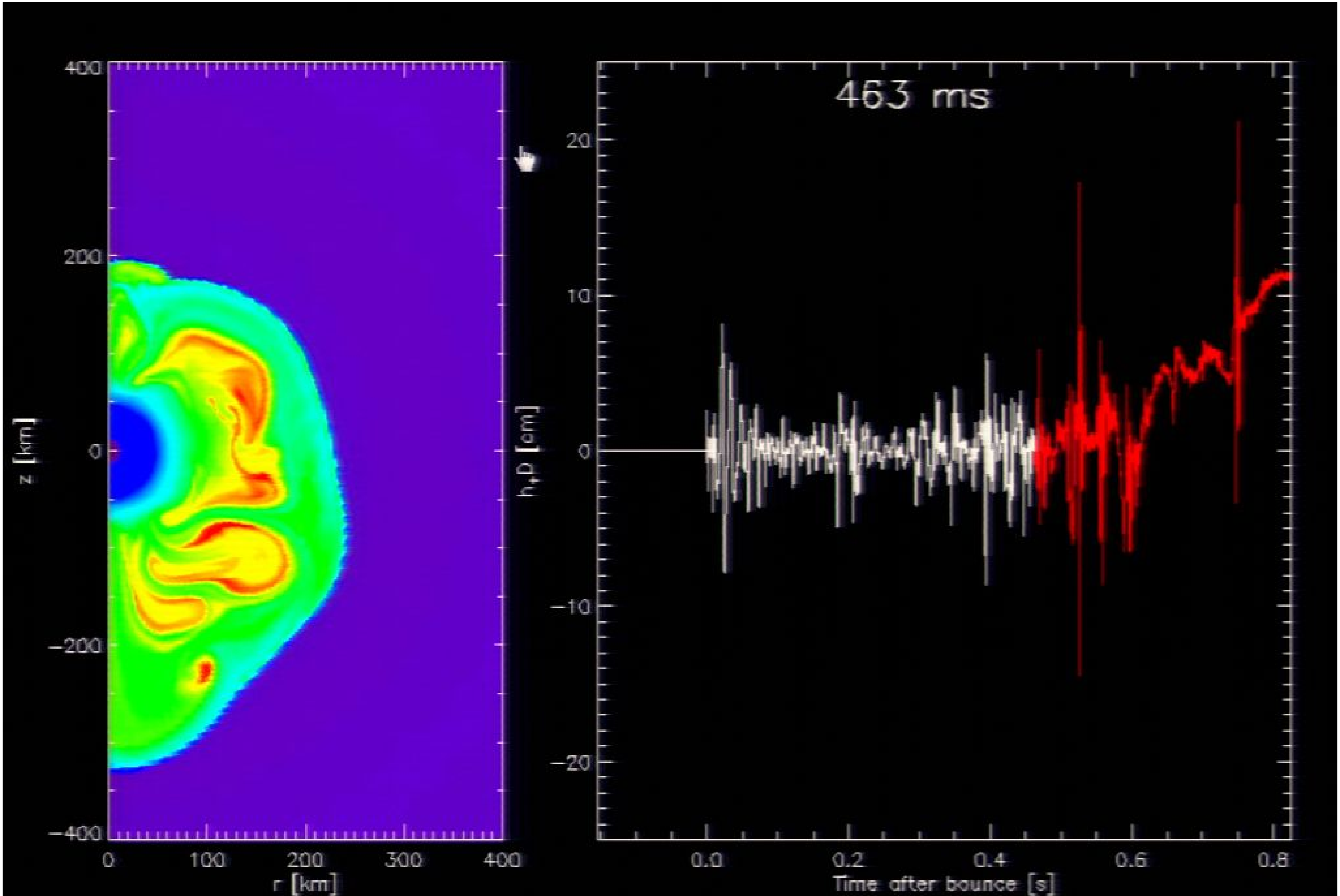

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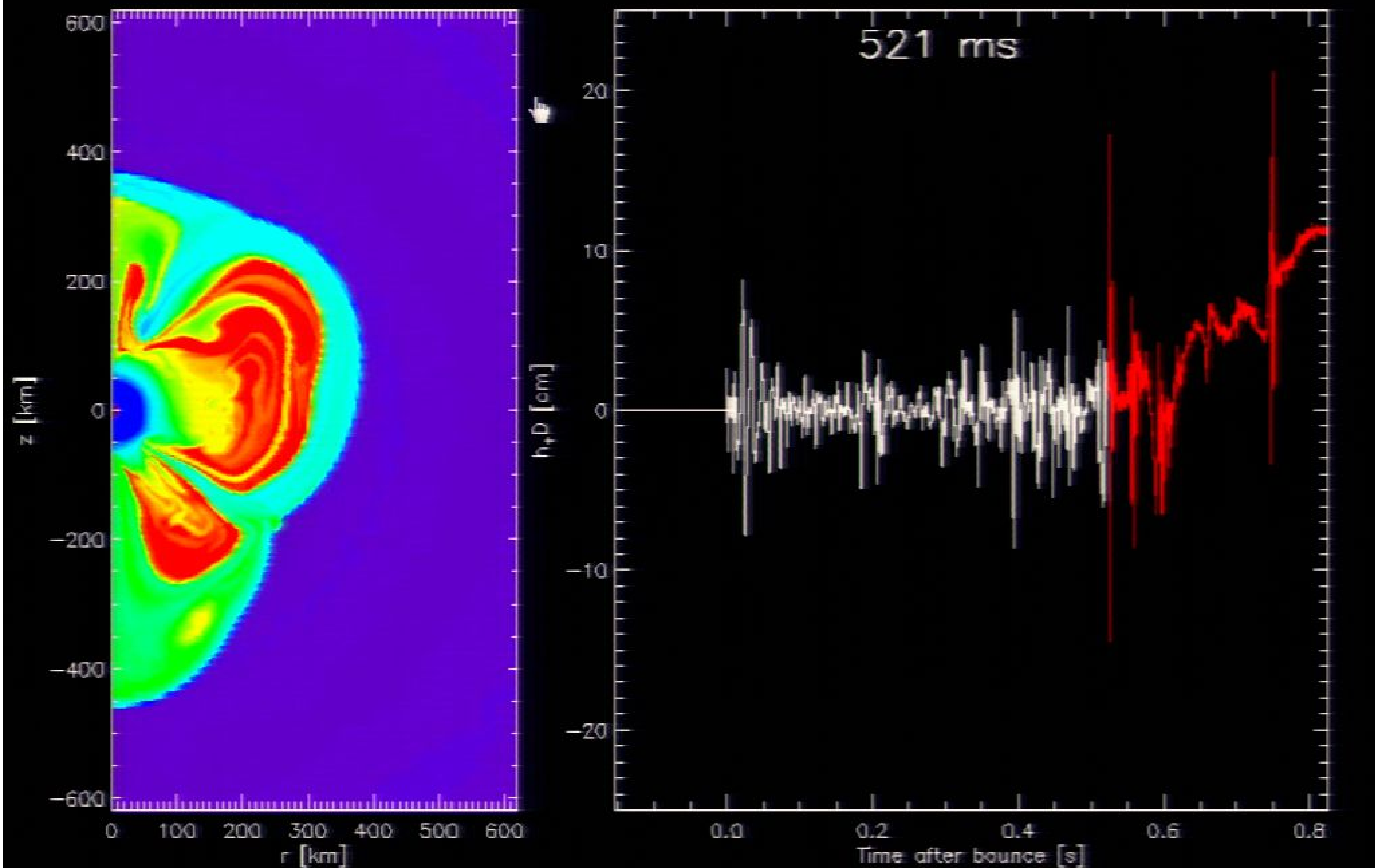

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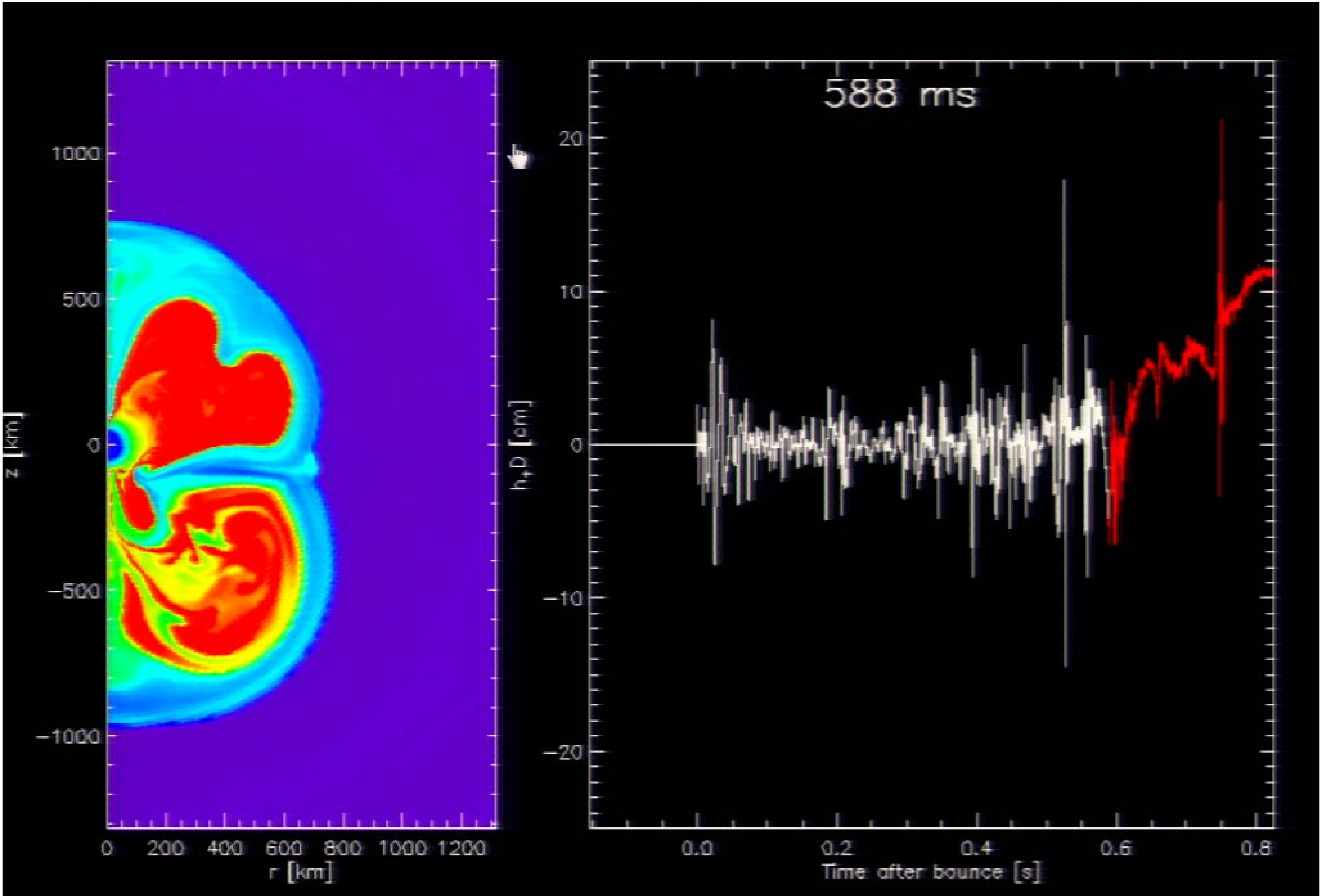

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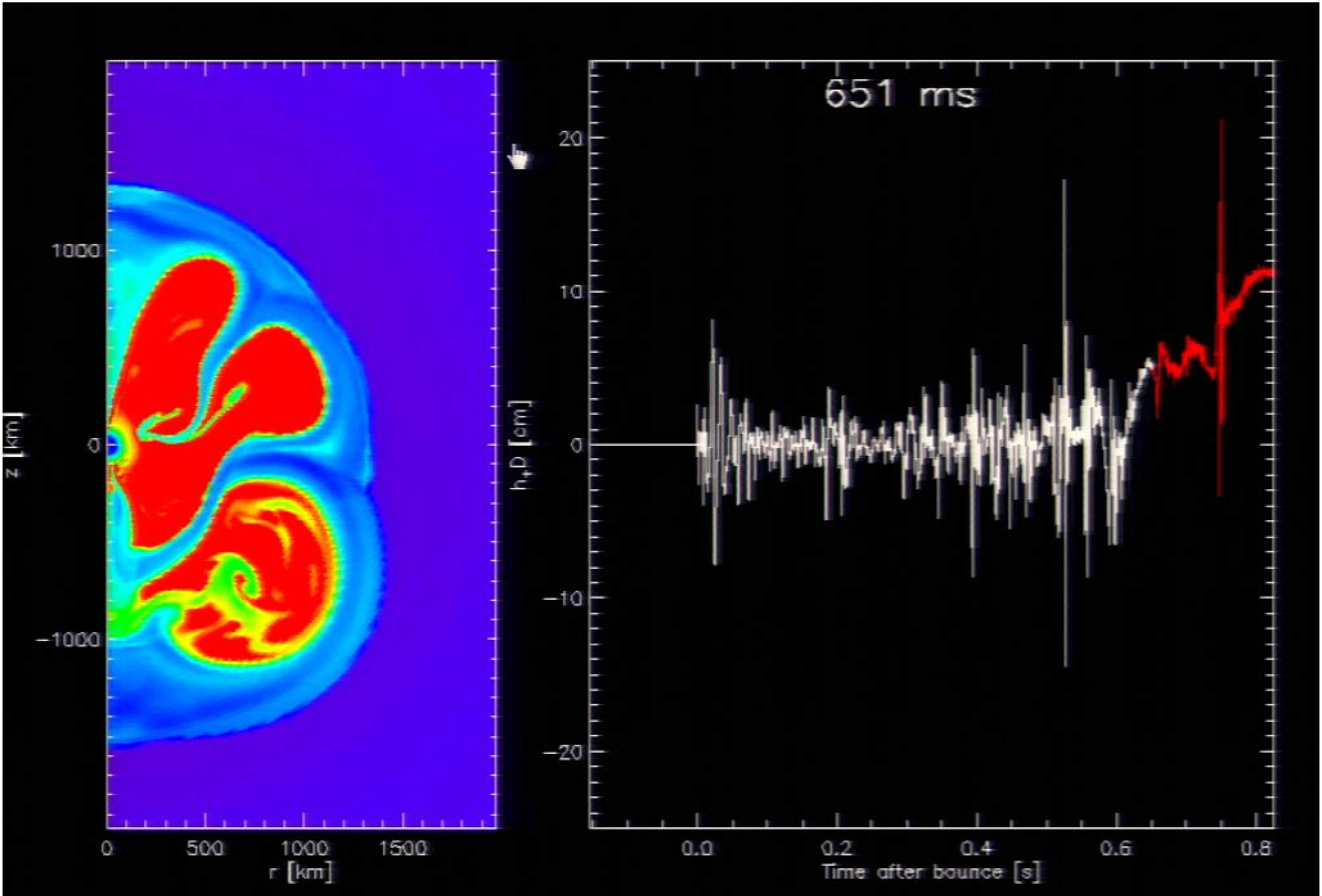

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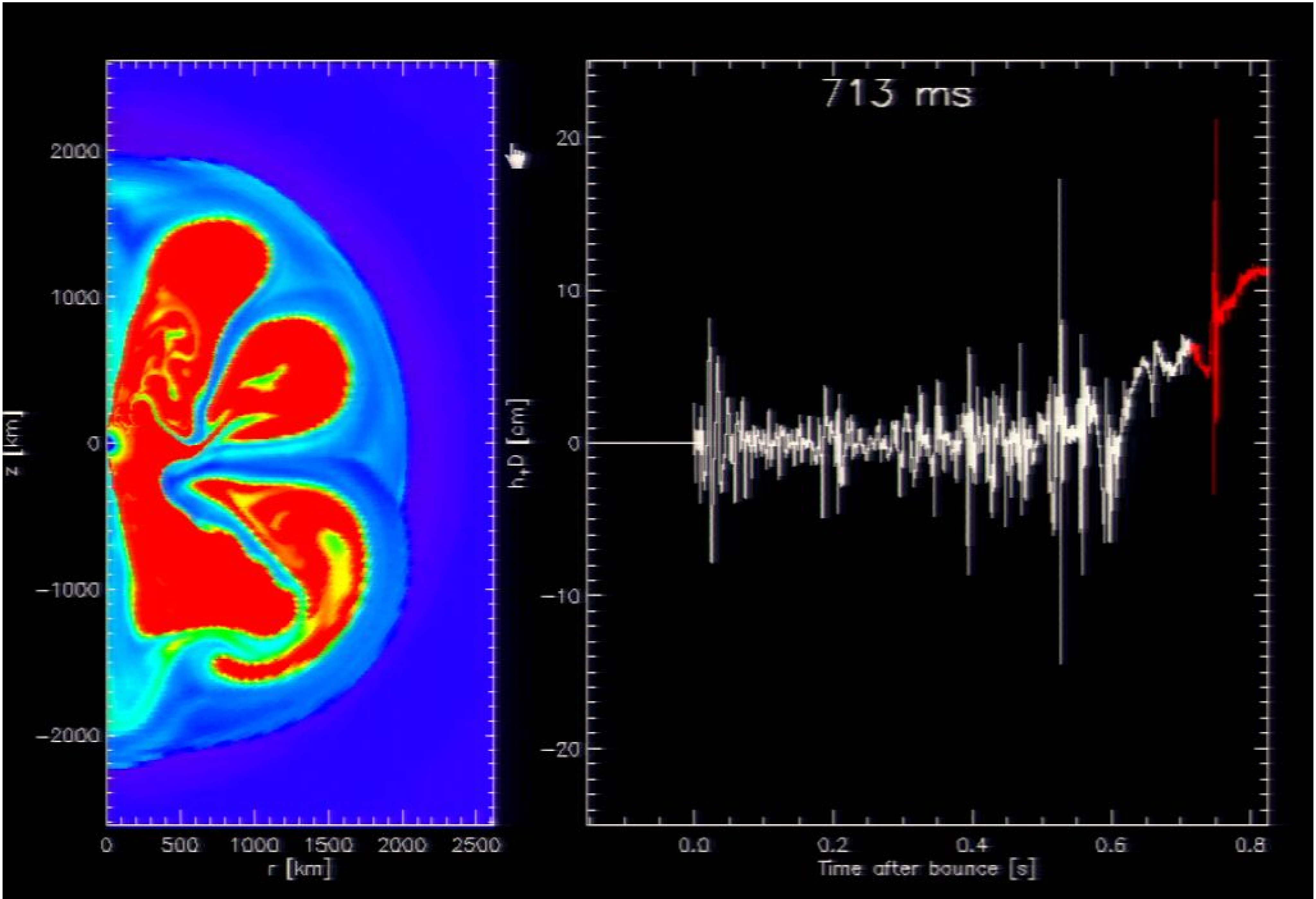

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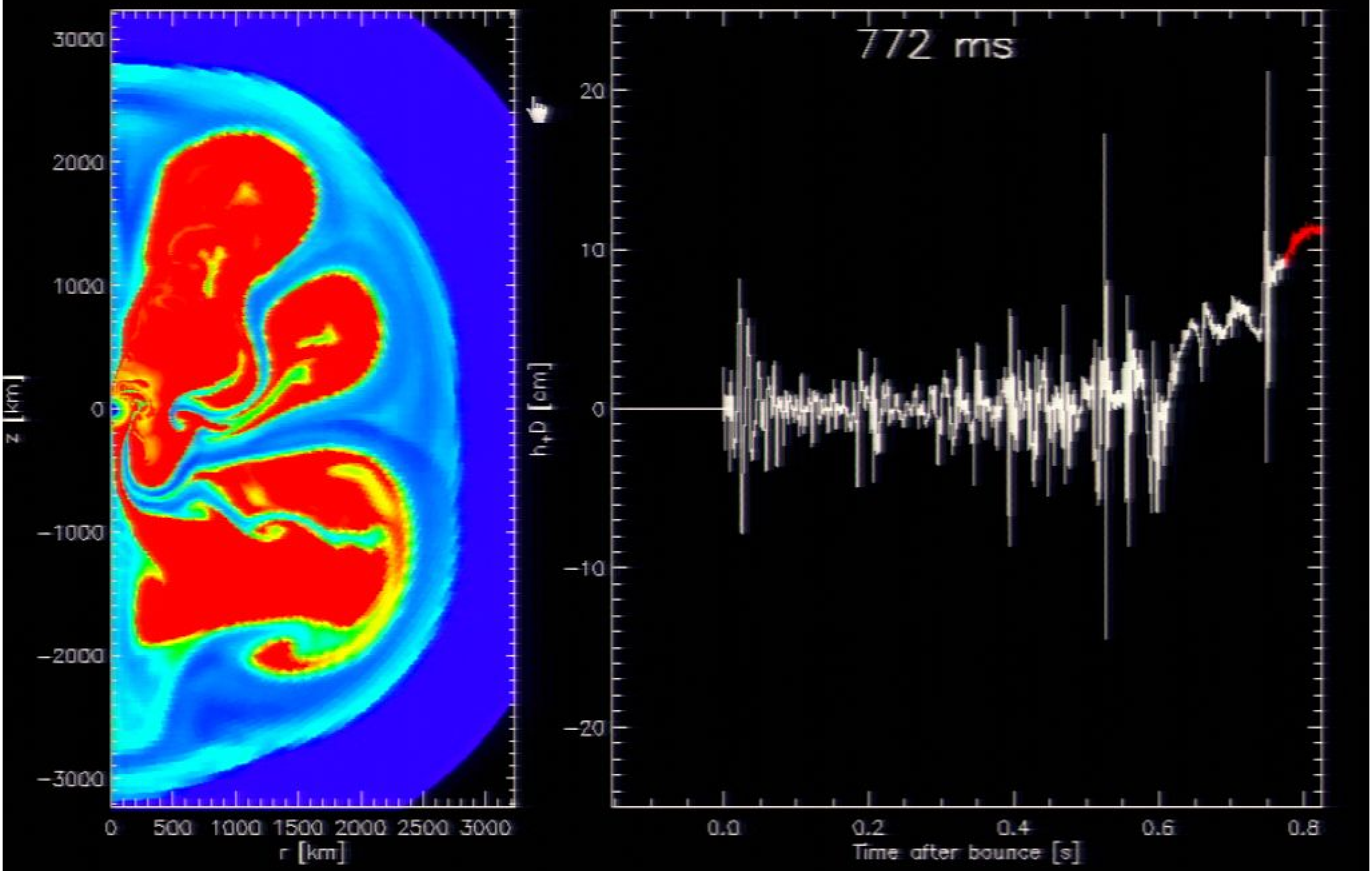

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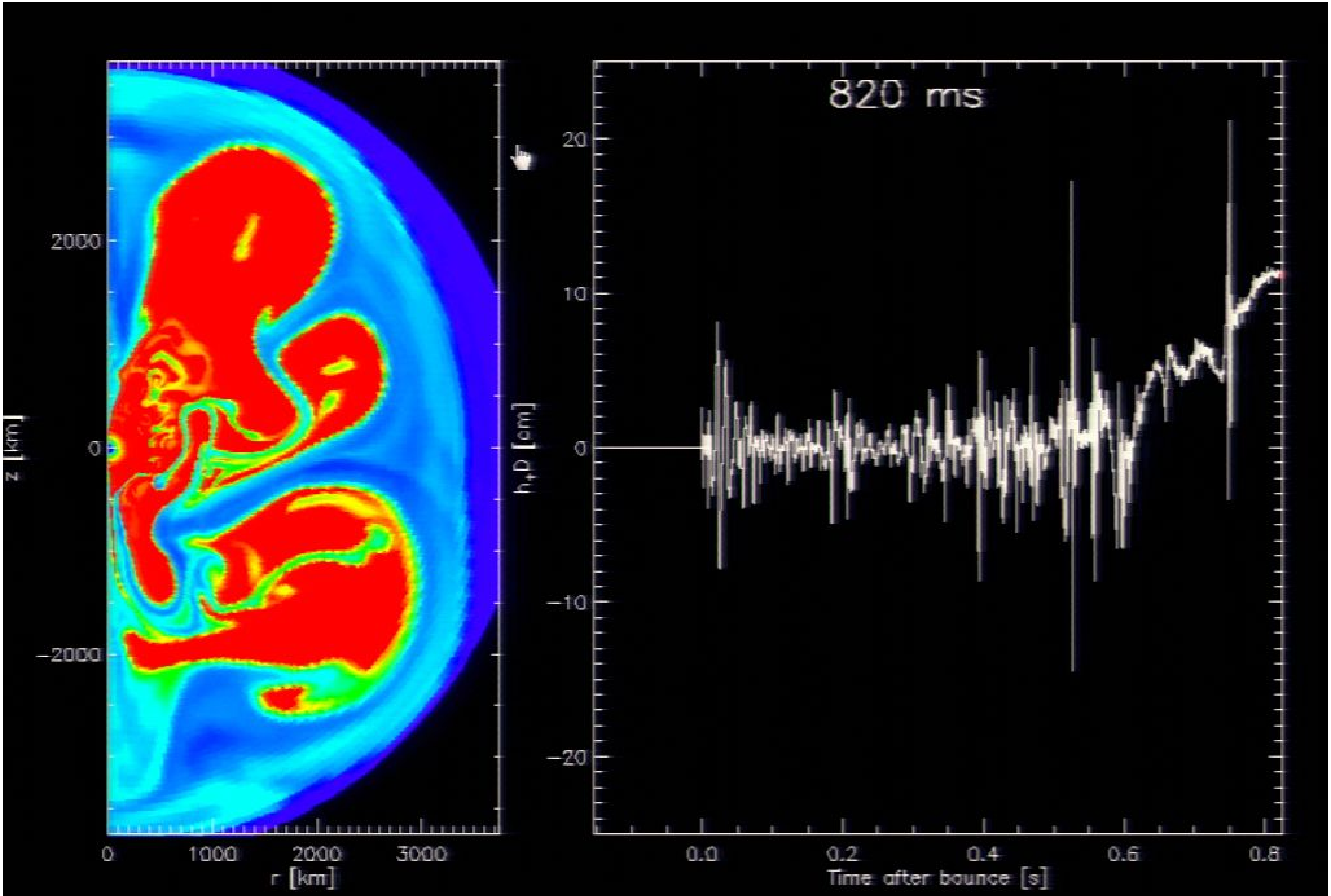

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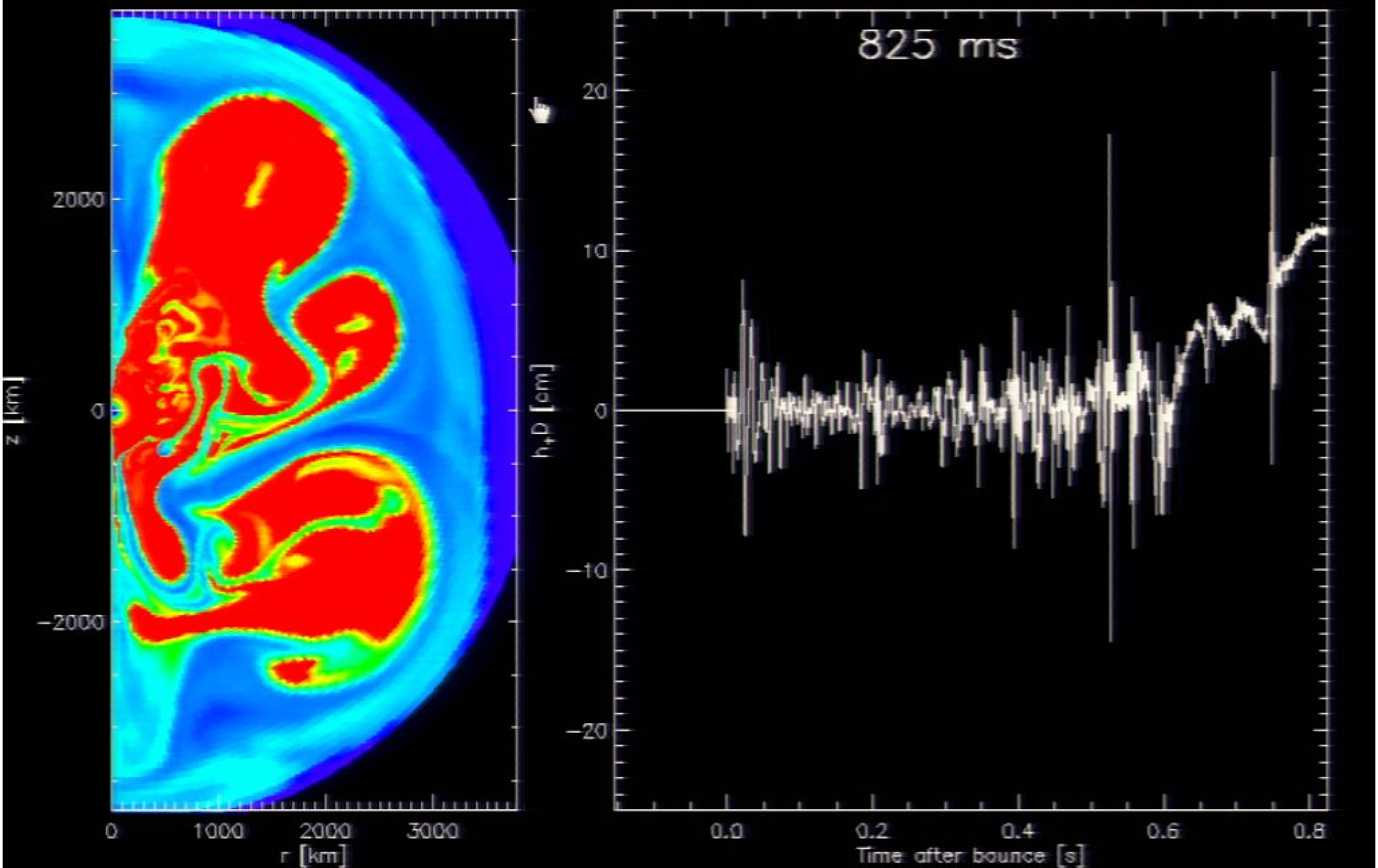

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Detectability; Dependence on Progenitor & ν-Luminosity

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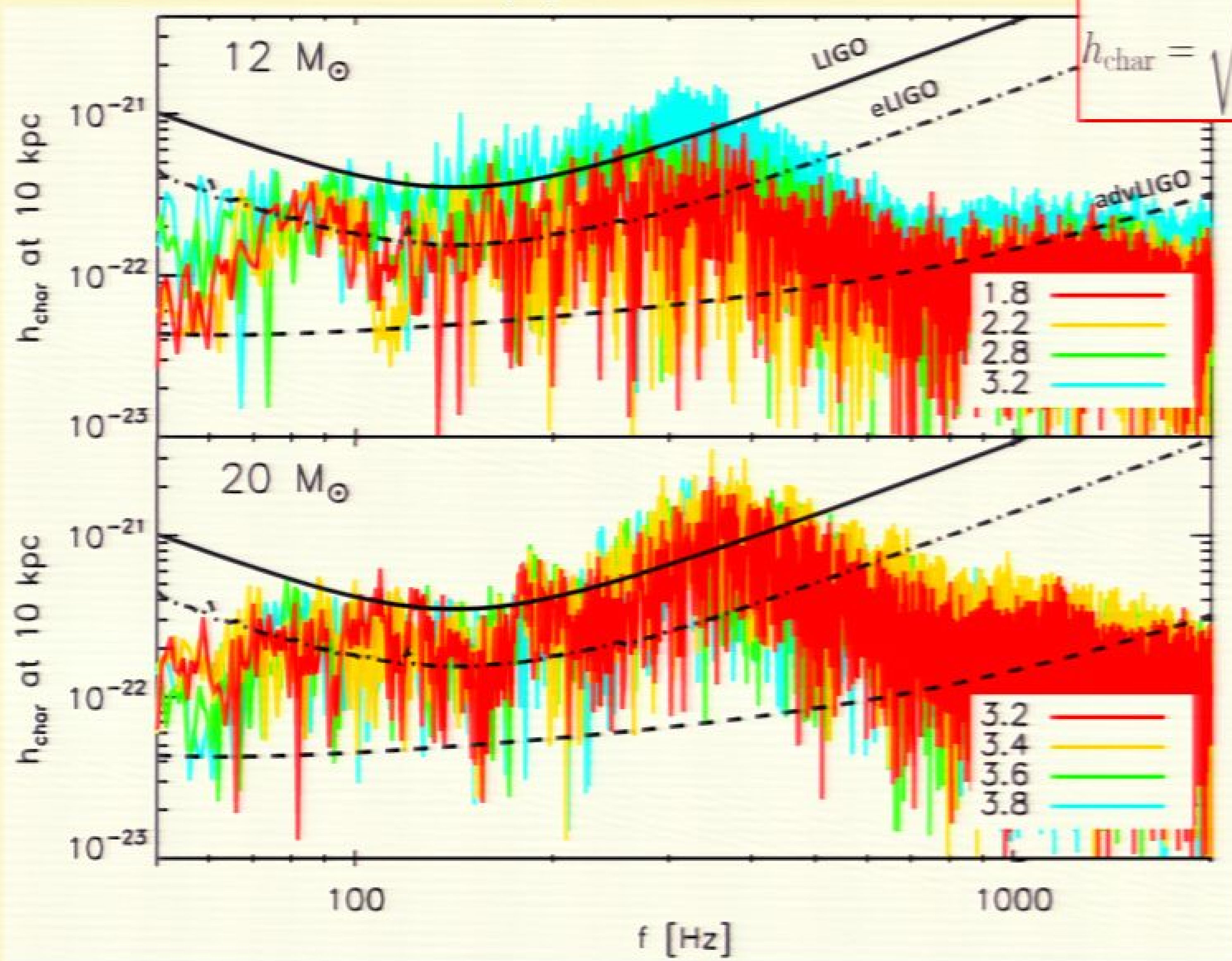
$$h_{\mathrm{char}} = \sqrt{\frac{2}{\pi^2}\frac{1}{D^2}\frac{G}{c^3}\frac{dE_{\mathrm{GW}}}{df}}$$

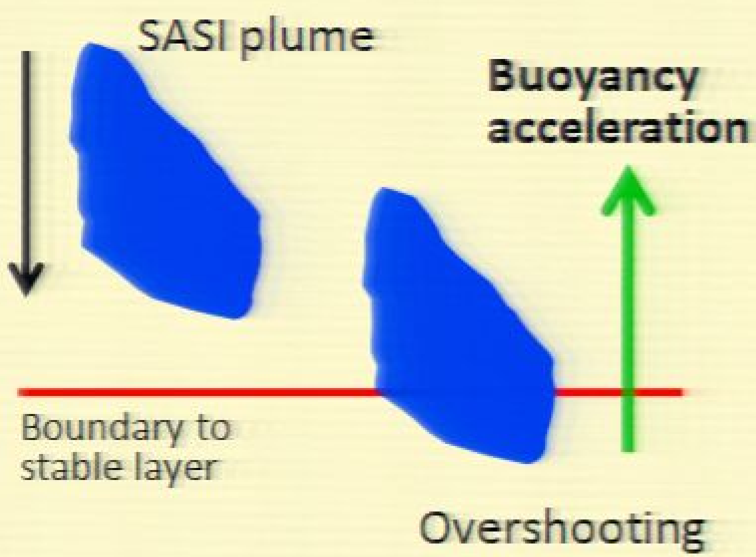


- **More massive progenitor** -> higher accretion rate -> greater L_ν / heating

Understanding the Characteristic GW Frequencies

[Murphy, Ott & Burrows 2009]

- **Assumption**: Strongest GW emission comes from SASI a downflow plume that is decelerated at the PNS surface.
- Use convection theory to study behavior in linear limit.



Brunt-Väisälä:

$$N^2 = \left(\frac{GM_r}{r^3}\right)\left(\frac{1}{\Gamma_1}\frac{d\ln P}{d\ln r} - \frac{d\ln \rho}{d\ln r}\right)$$

$N^2 > 0$: stable, $N^2 < 0$: unstable

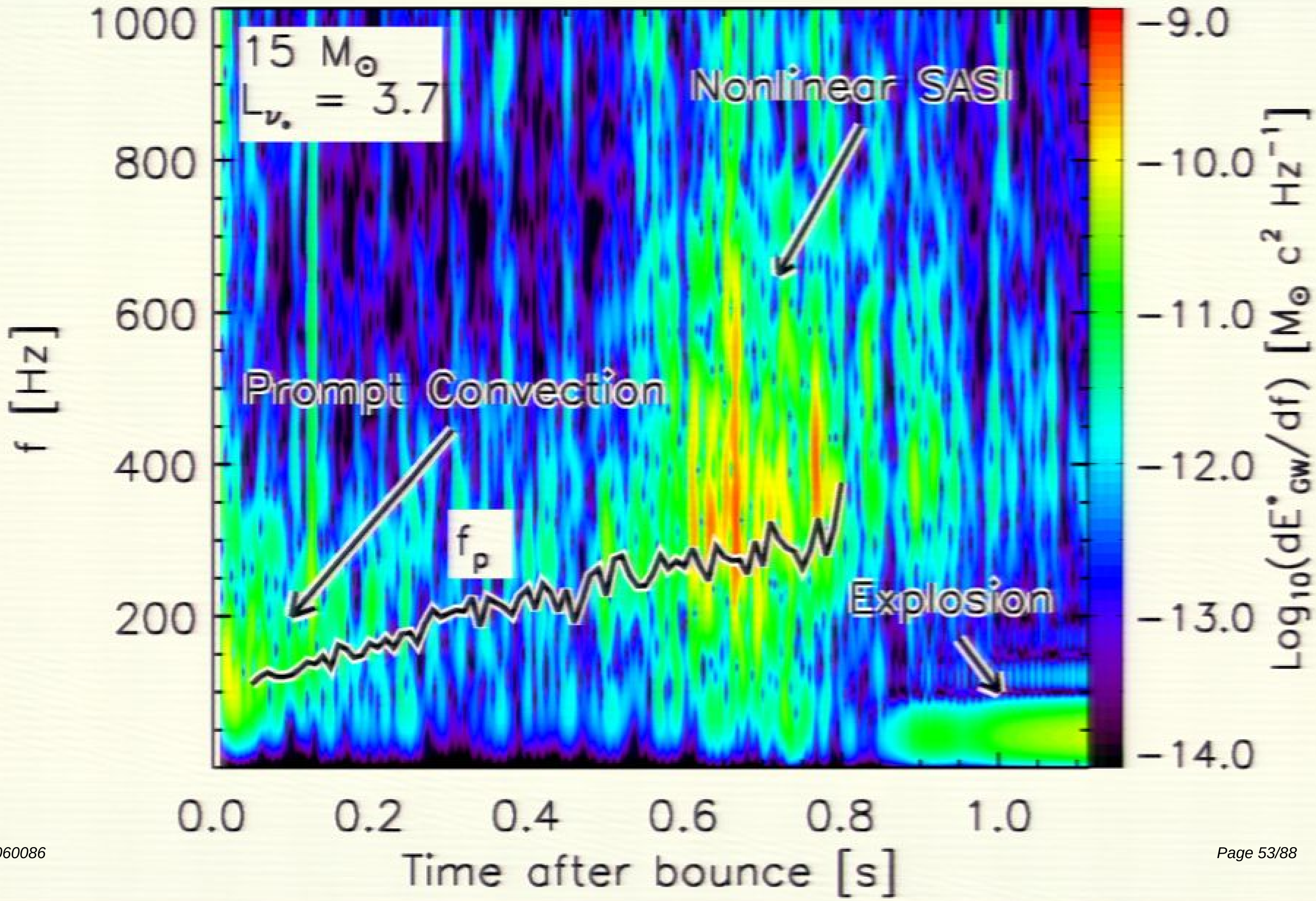
- Characteristic frequencies: Obtained through integration of buoyancy acceleration and analytic model for turning point:

$f_p = 1/(2\pi t_p)$

$$f_p \sim \frac{N}{2\pi}$$

GW Time-Frequency Evolution

[Murphy, Ott & Burrows 2009]



GW Extraction from CCSN Spacetimes

[Reisswig, Ott, Sperhake, Schnetter, Pollney, Bishop]

GW Extraction in CCSN Spacetimes

[Reisswig, Ott et al. 2010]

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$$h_{jk}^{TT}(t,\vec{x}) = \left[\frac{2}{c^4}\frac{G}{|\vec{x}|}\ddot{I}_{jk}(t - \frac{|\vec{x}|}{c})\right]^{TT}$$

- Problems: not gauge invariant, definition of I_{jk} ambiguous in GR.
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- *How does this translate to core collapse?*
  Cerda-Duran et al. '05: CFC+ (2PN "waves") -> little change to QF results.
  Shibata & Sekiguchi '05: QF+ZM in extreme nonaxisymmetric case.
  -> extraction near core: QF < ZM amplitudes, but ZM not converged.

GW Extraction in CCSN Spacetimes

[Reisswig, Ott et al. 2010]

- Collapse simulations with the open-source Zelmani core collapse simulation package.
  -> Based on Cactus, Carpet AMR driver, and
  EinsteinToolkit GRHydro code.
- Focusing on the axisymmetric GW signal of rotating core collapse:
  -> Physics is well understood and robust predictions can be made.
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- Focusing on the axisymmetric GW signal of rotating core collapse:
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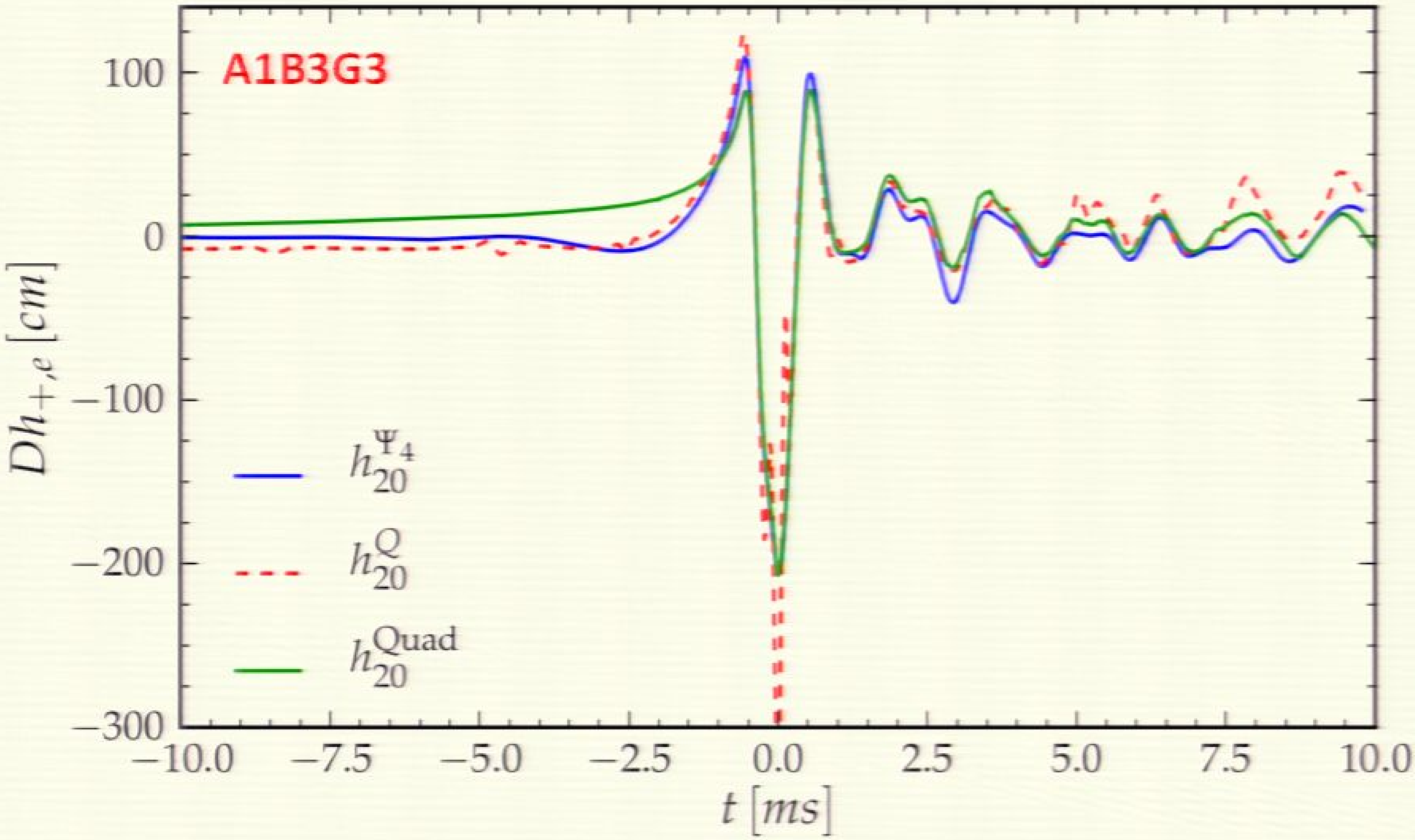
- Use Ψ_4, ZM, (& Cauchy-Characteristic Extraction [to come soon])
- Pick 3 models of Dimmelmeier et al. 2002 with simplified microphysics (hybrid cold + thermal EOS):
  A1B3G3 – standard model, typical h_+
  A1B3G5 – rapid collapse model (soft subnuclear EOS; small h_+)
  A3B3G3 – rapid rotation, high h_+
- Extraction at large radii (> 1500 km).

GW Extraction: Preliminary Results

[Reisswig, Ott et al. 2010]



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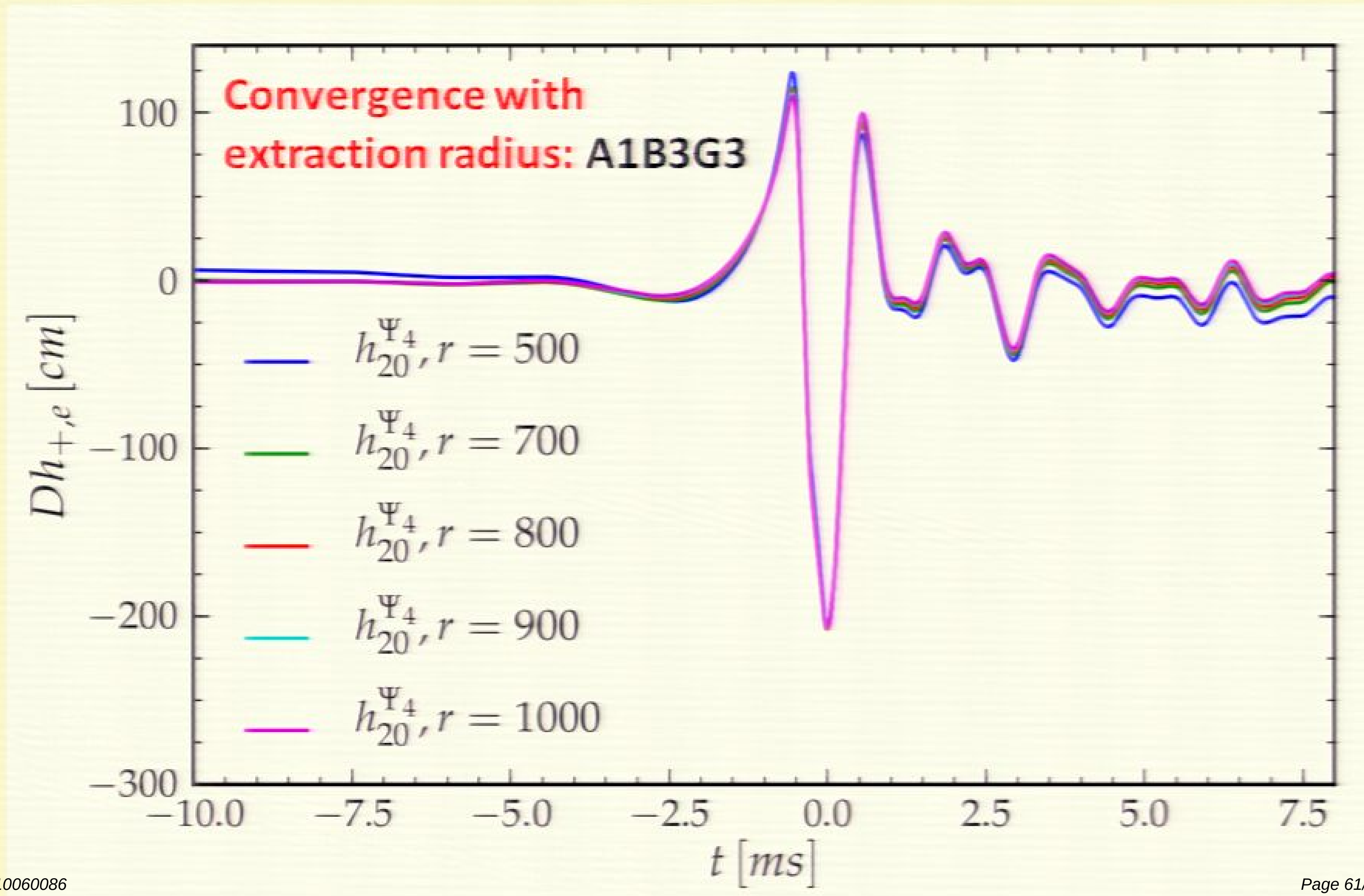
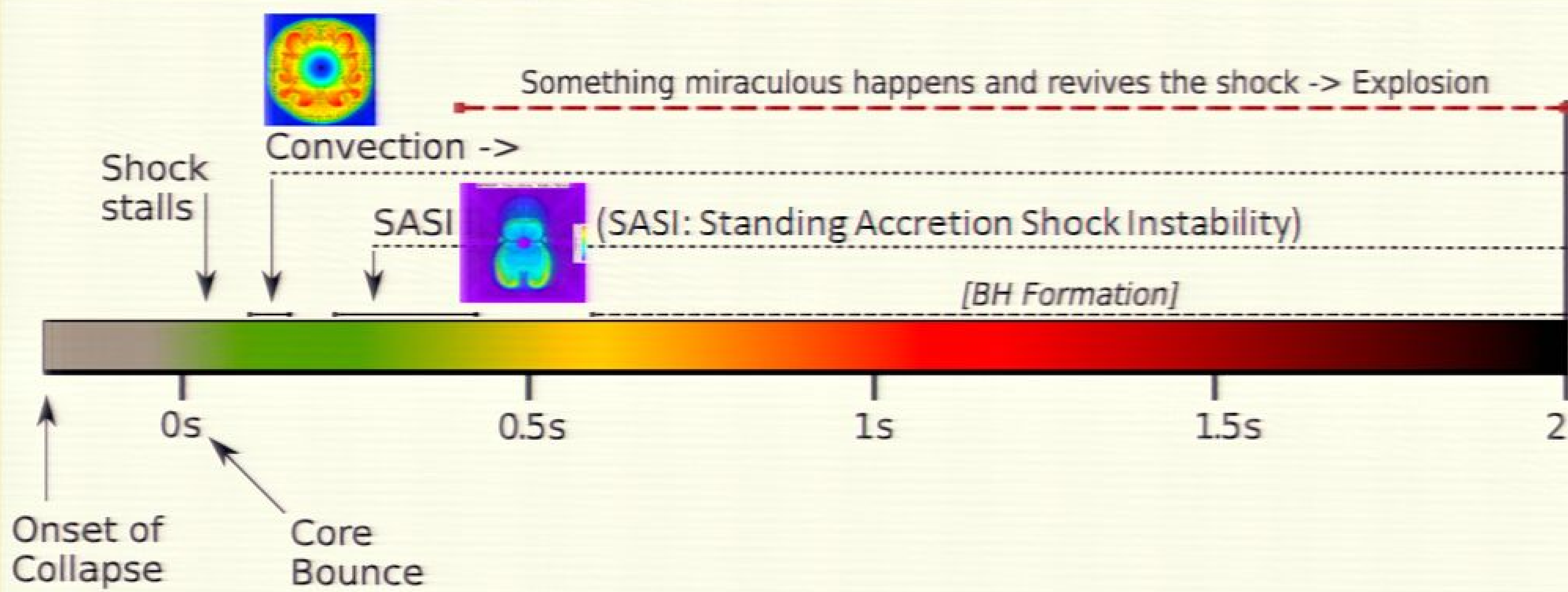


When Supernovae Fail:

Black Hole Formation

Core Collapse Timeline



- Energy reservoir: few x 10^{53} erg (100 B)
- Explosion energy: ~1 B
- Time frame for explosion: ~0.3 – 2.0 s after bounce.
- BH formation at baryonic PNS mass $\geq 1.8 - 2.5\ M_{Sun}$ (?).

GR1D [O'Connor & Ott 2010 CQG]

- **GR1D**: ***Open-Source 1.5D GR hydrodynamics code.***
- Available from http://www.stellarcollapse.org .
- **Eulerian Radial-gauge, polar-slicing** (-> Schwarzschild-like coordinates).

$$ds^2 = -\alpha(r,t)^2 dt^2 + X(r,t)^2 dr^2 + r^2 d\Omega^2$$

$$\alpha(r,t) = \exp[\phi(r,t)], \quad X(r,t) = \left(1 - \frac{2m(r,t)}{r}\right)^{-1/2}$$

- **Choice of coordinates greatly simplifies GR hydro equations (zero shift).**
- **Disadvantage: Cannot evolve past horizon formation**
  (like May & White, Misner & Sharp, van Riper formulations).

- **GR Hydro equations in GR1D**
  Implemented as finite-volume scheme with PPM & HLLE.

$$\partial_t \vec{U} + \frac{1}{r^2}\partial_r \left[\frac{\alpha r^2}{X}\vec{F}\right] = \vec{S}$$

GR1D: Approximate Rotation

- **Rotation in 1D: "Shellular"** – constant Ω on spherical shells.
  Effective centrifugal force: $f_{\rm cent} = 2/3\,\omega^2 r$

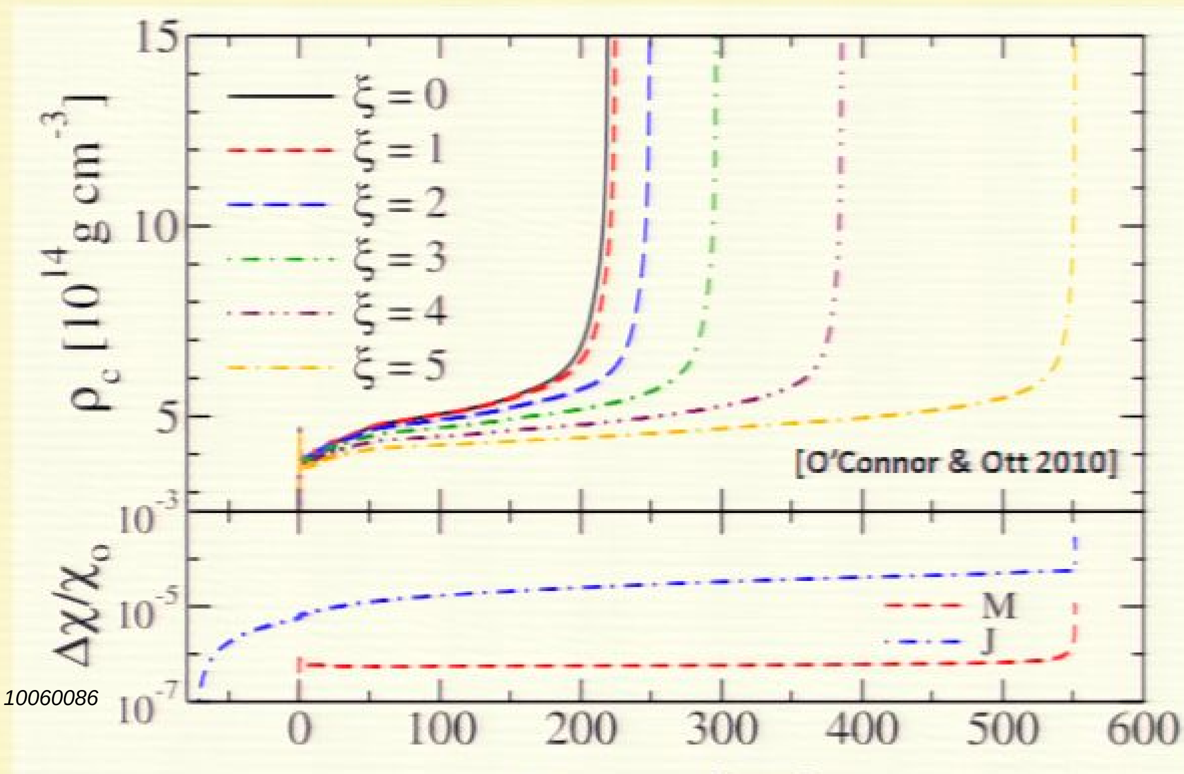
$$\partial_t(S_\phi) + \frac{1}{r^2}\partial_r\left(\frac{\alpha r^2}{X}F_\phi\right) = \mathcal{S}_\phi$$

$$S_\phi = \rho h W^2 v_\varphi r\ ,$$
$$F_\phi = \rho h W^2 v_\varphi r v = S_\phi v\ ,$$
$$\mathcal{S}_\phi = \rho h W^2 \alpha v v_\varphi X\left[4\pi r^2 P + \frac{m}{r}\right]$$

Extra term in equation for r momentum:

$$+\alpha\frac{2}{3}\left(\frac{\rho h W^2 {v_\varphi}^2}{X r}\right)$$

+ additional terms in metric quantities due to φ momentum.



Central density, 40-M_{Sun} model put into rotation with increasing initial central angular velocities.

Conservation of baryonic mass and angular momentum.

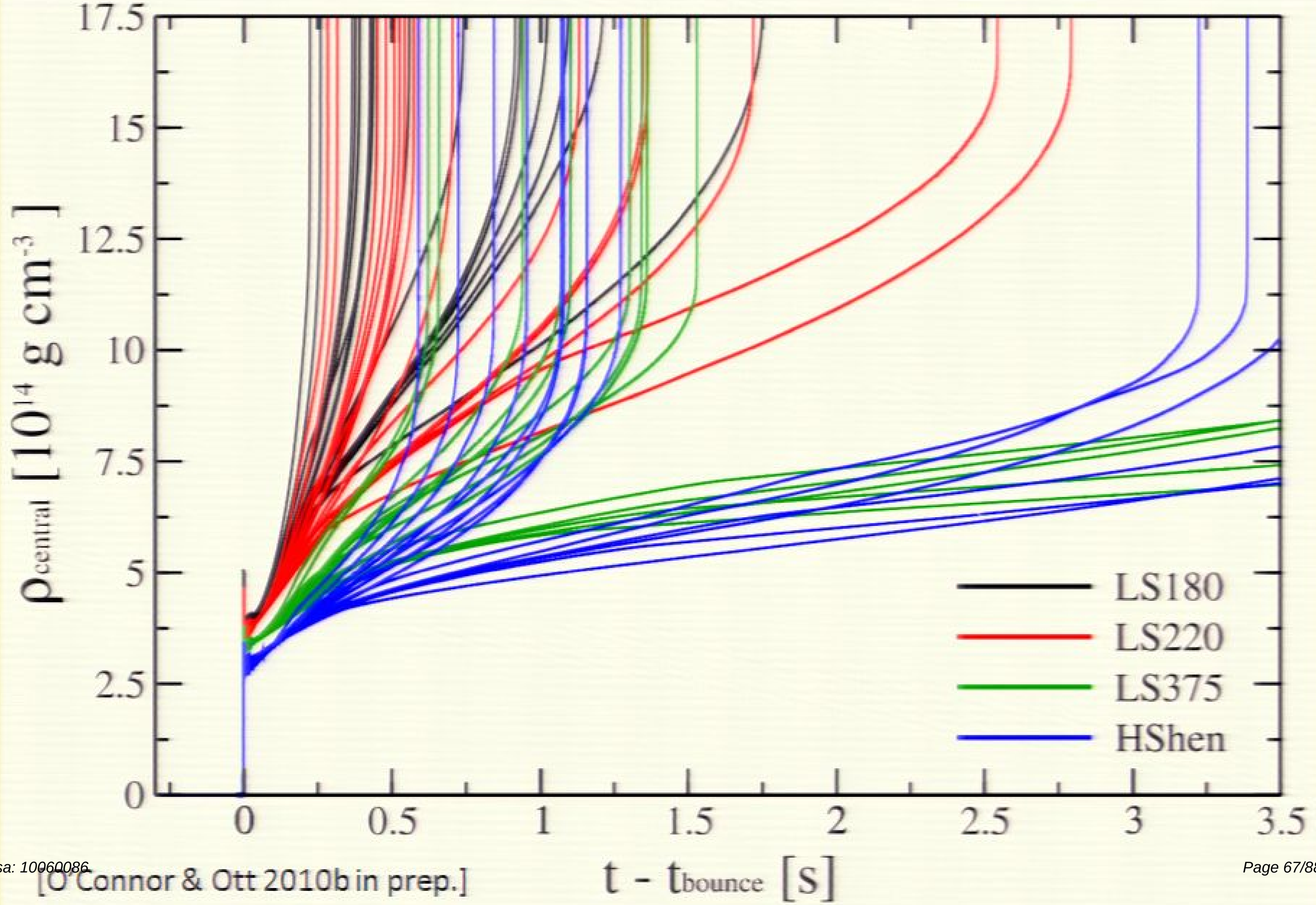
GR1D: EOS & Microphysics

- Multiple finite-temperature microphysical nuclear EOS:
  H. Shen et al. 1998, Lattimer & Swesty 1991 with K={180,220,375} MeV.
  EOS tables available in HDF5 format on http://www.stellarcollapse.org .
- Low-density EOS: Timmes EOS (tabulated & matched).
- Neutrinos during collapse: effective $Y_e(\rho)$ approx. [Liebendörfer '05].
- Postbounce: 3-flavor, energy-averaged (gray) neutrino leakage scheme
- Approximate neutrino heating:

$$Q_{\nu_i}^{\mathrm{heat}}(r) = f_{\mathrm{heat}} \frac{L_{\nu_i}^{\mathrm{FRF}}(r)}{4\pi r^2} \sigma_{\mathrm{heat},\nu_i} \frac{\rho}{m_u} X_i \left\langle \frac{1}{F_{\nu_i}} \right\rangle e^{-2\tau_{\nu_i}}$$

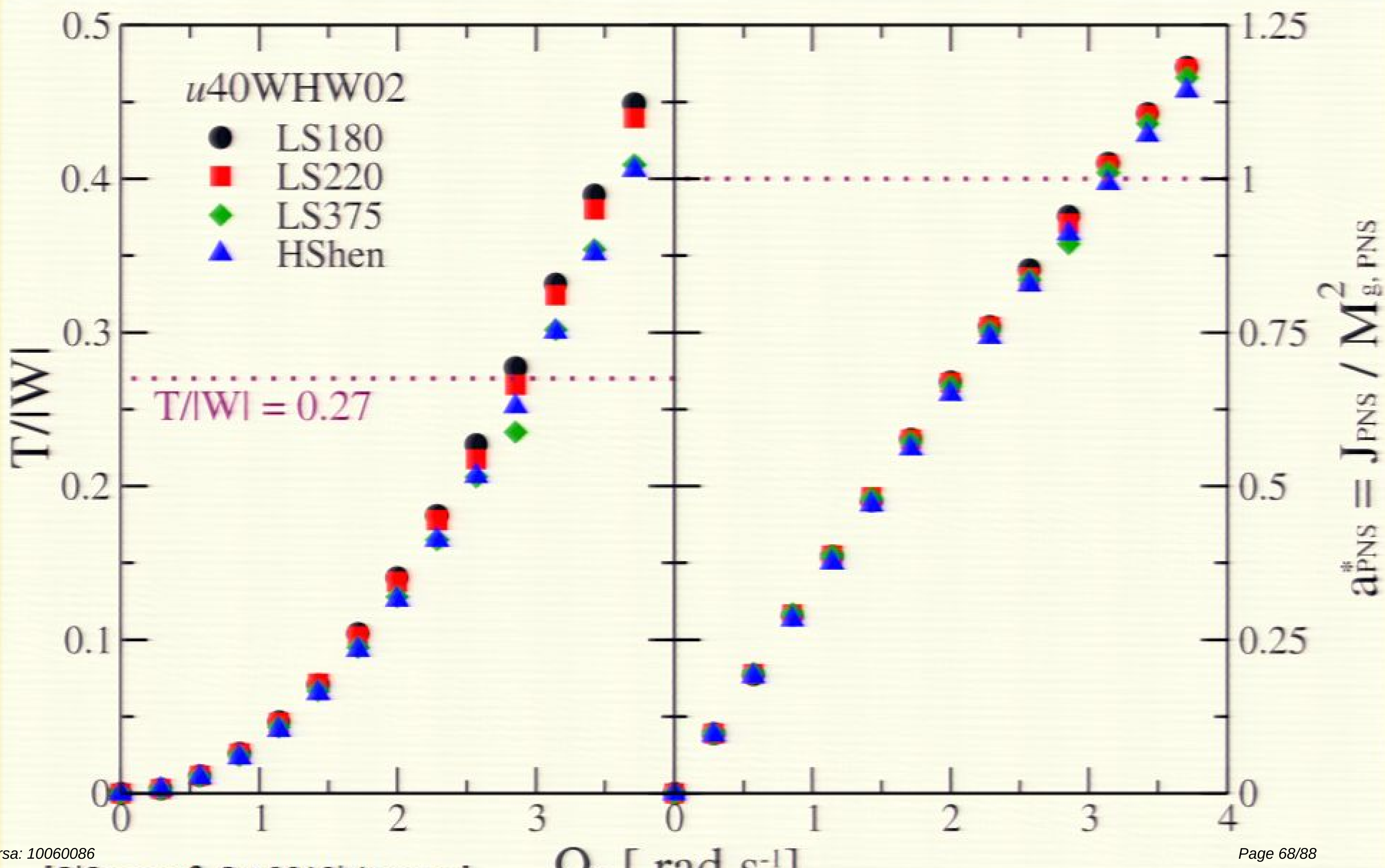
- Nuclear Reaction Network & consistent multi-species advection.
  (work in progress)

Parameter Study...

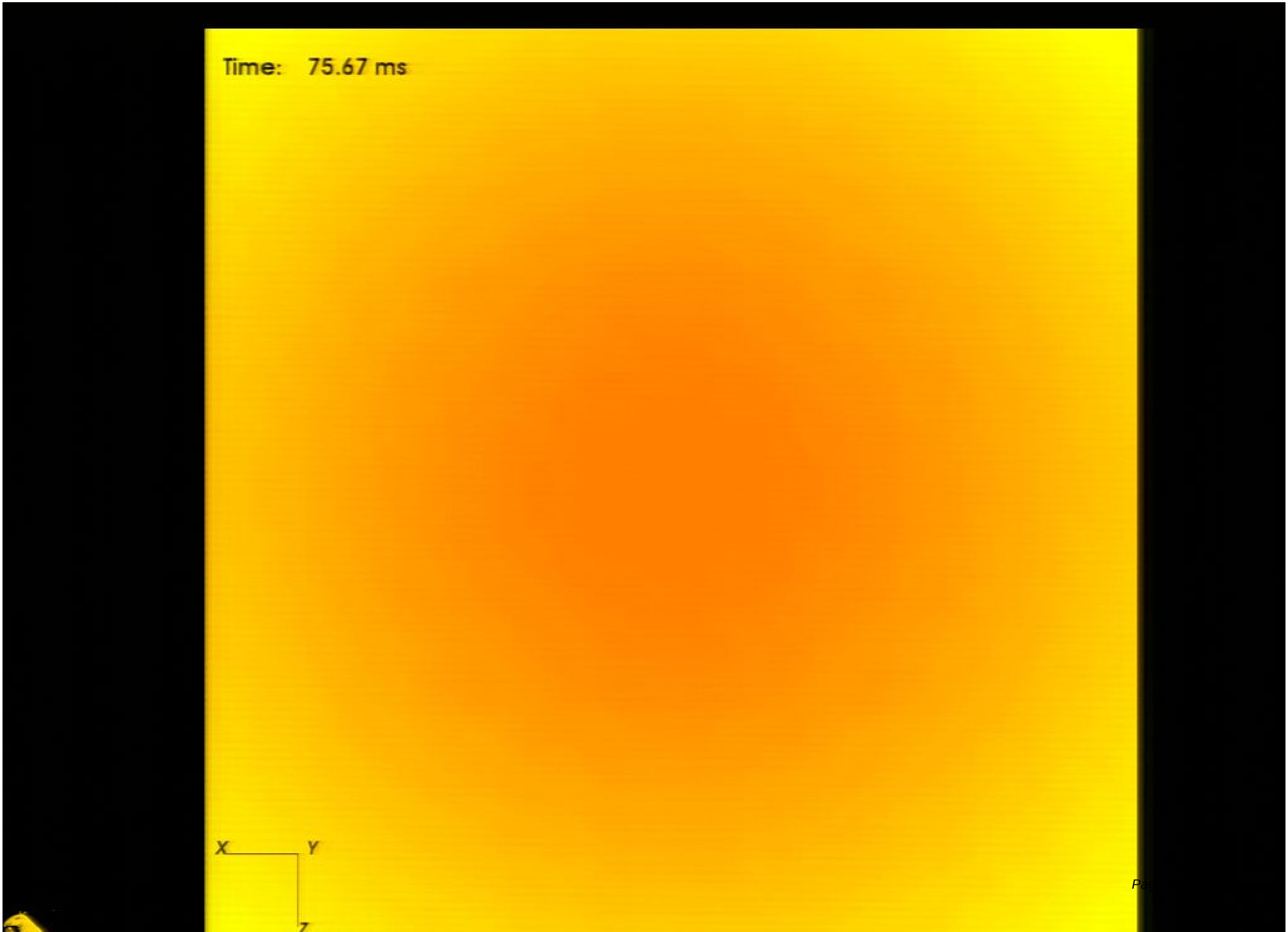


[O'Connor & Ott 2010b in prep.]

BH Birth Spin



[O'Connor & Ott 2010b in prep.]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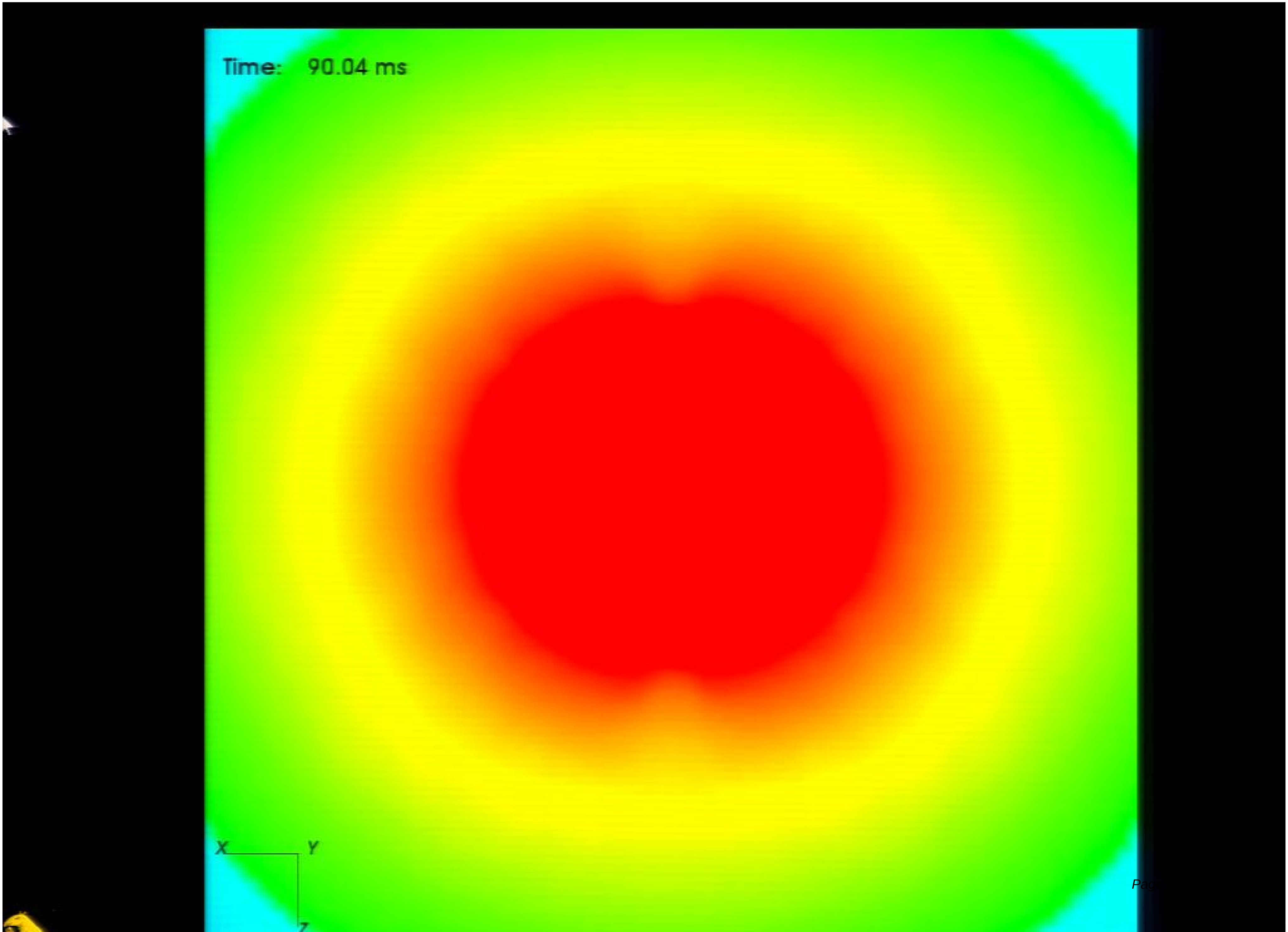
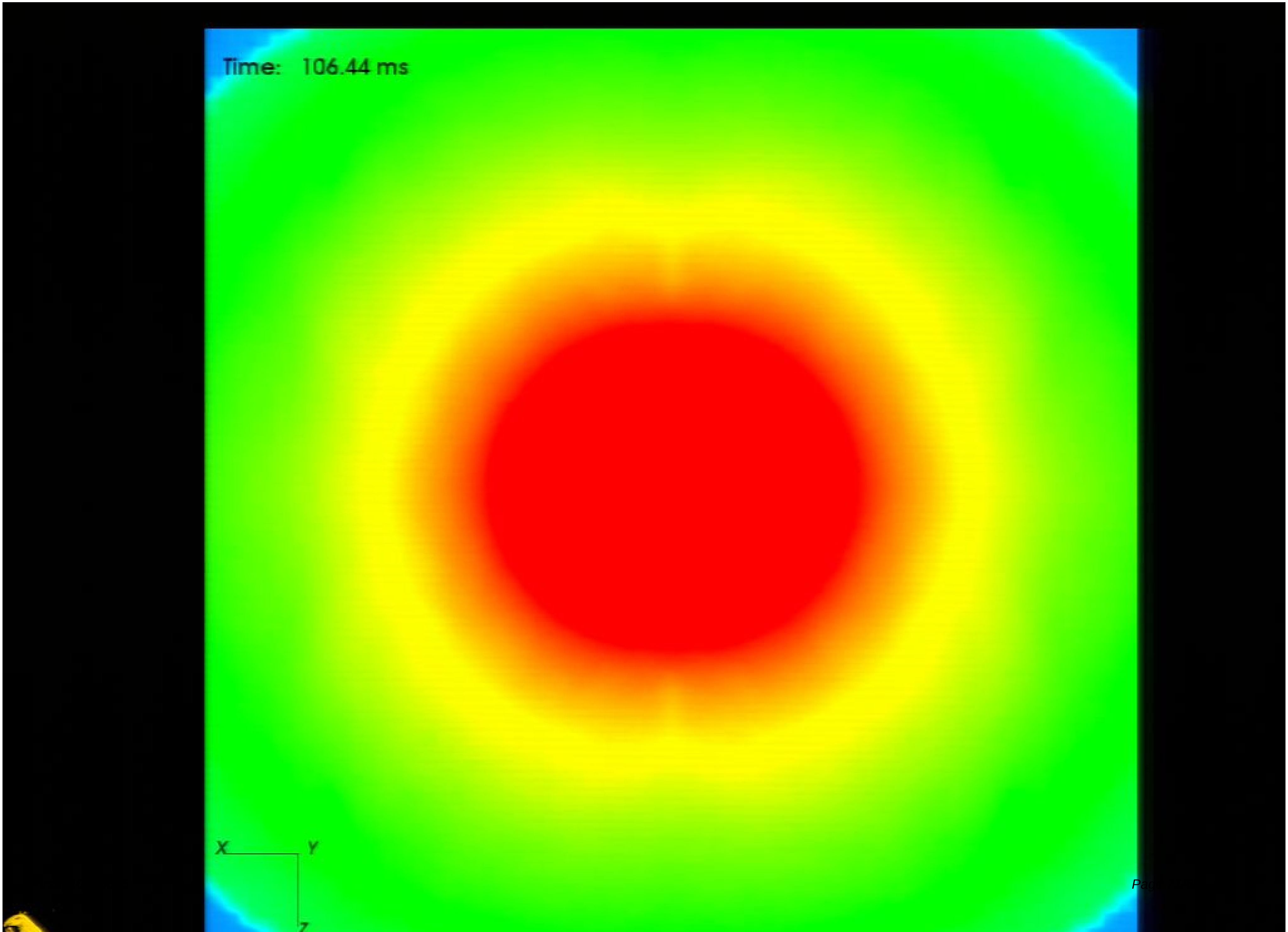
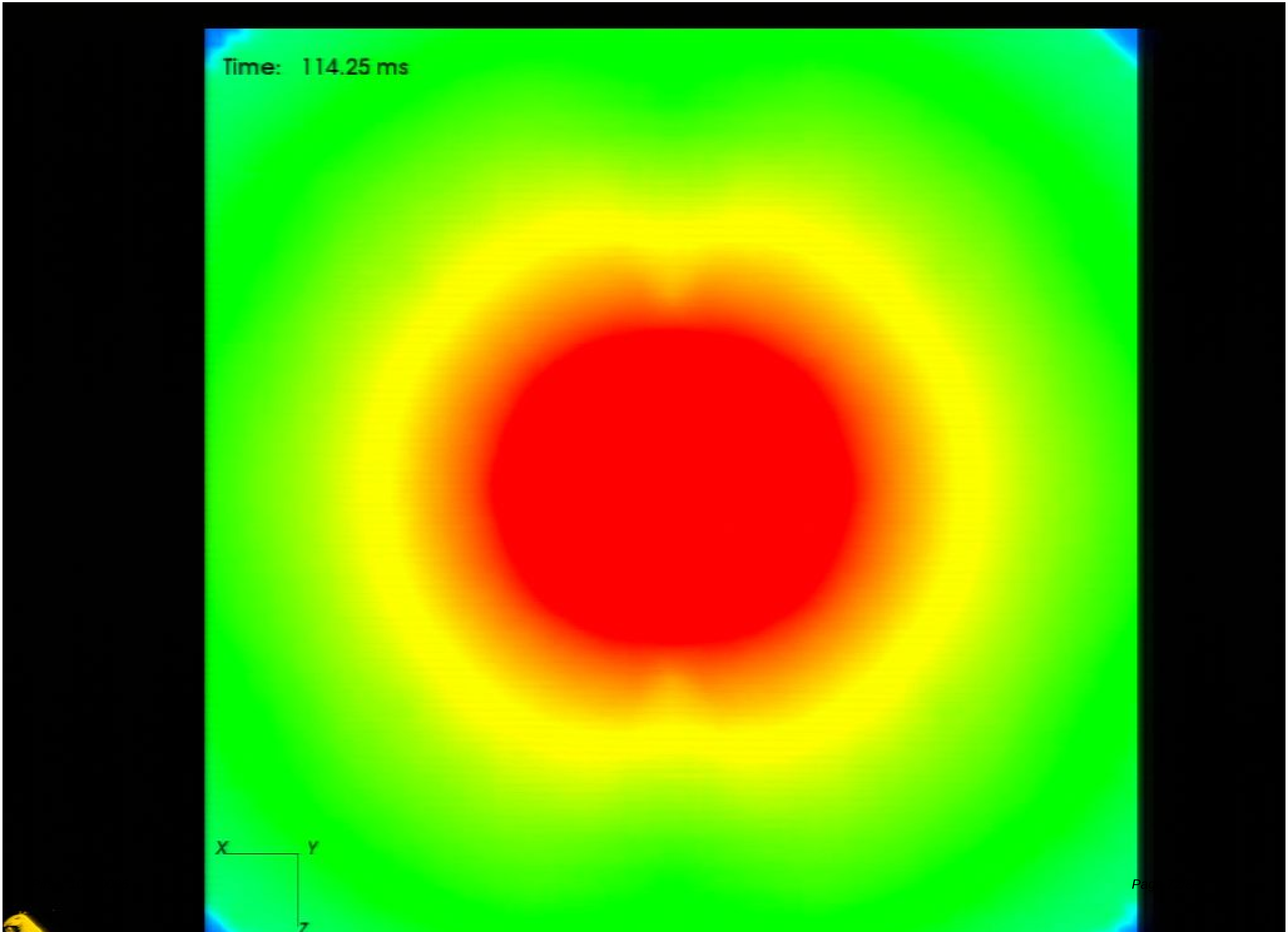
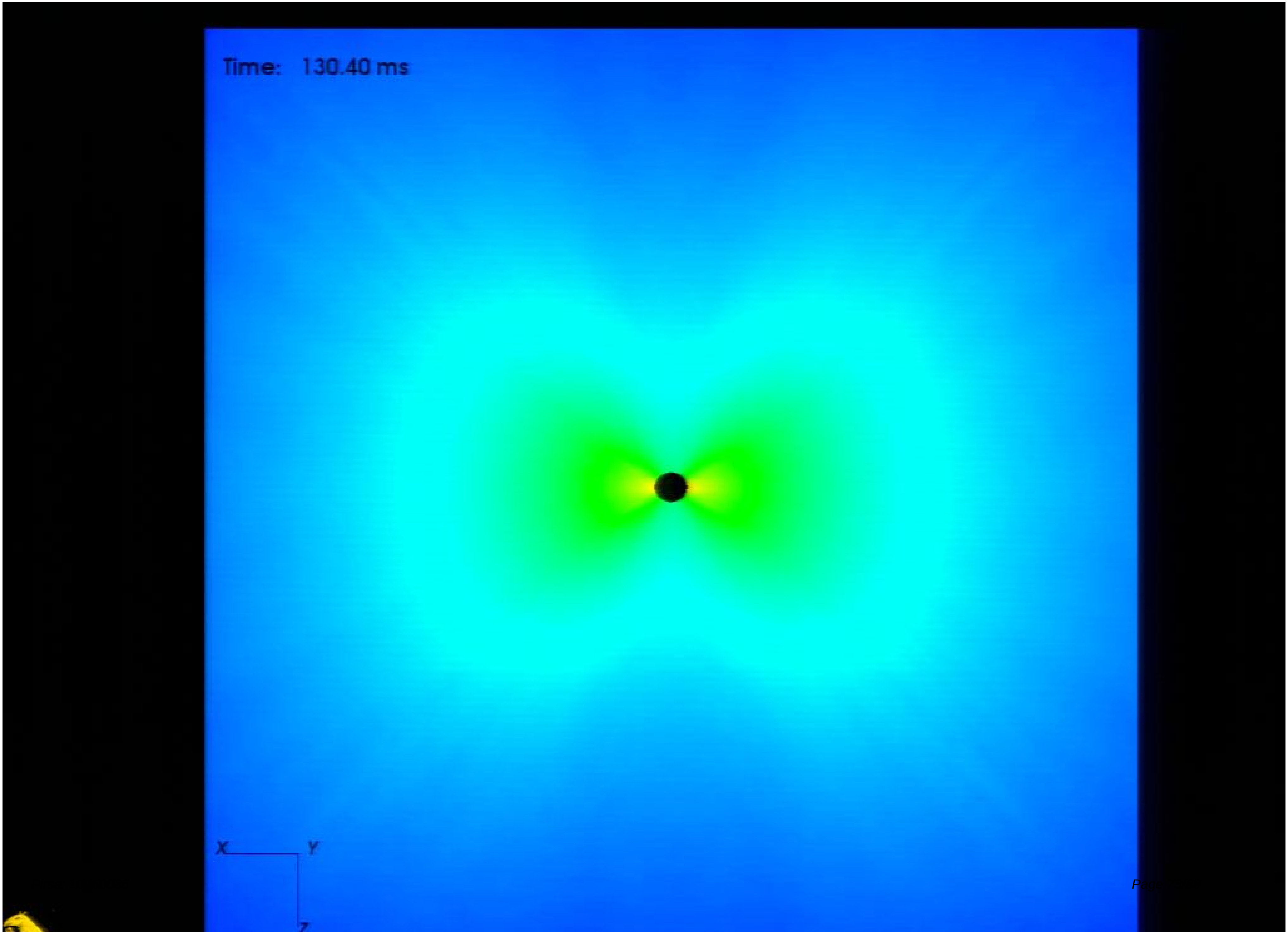
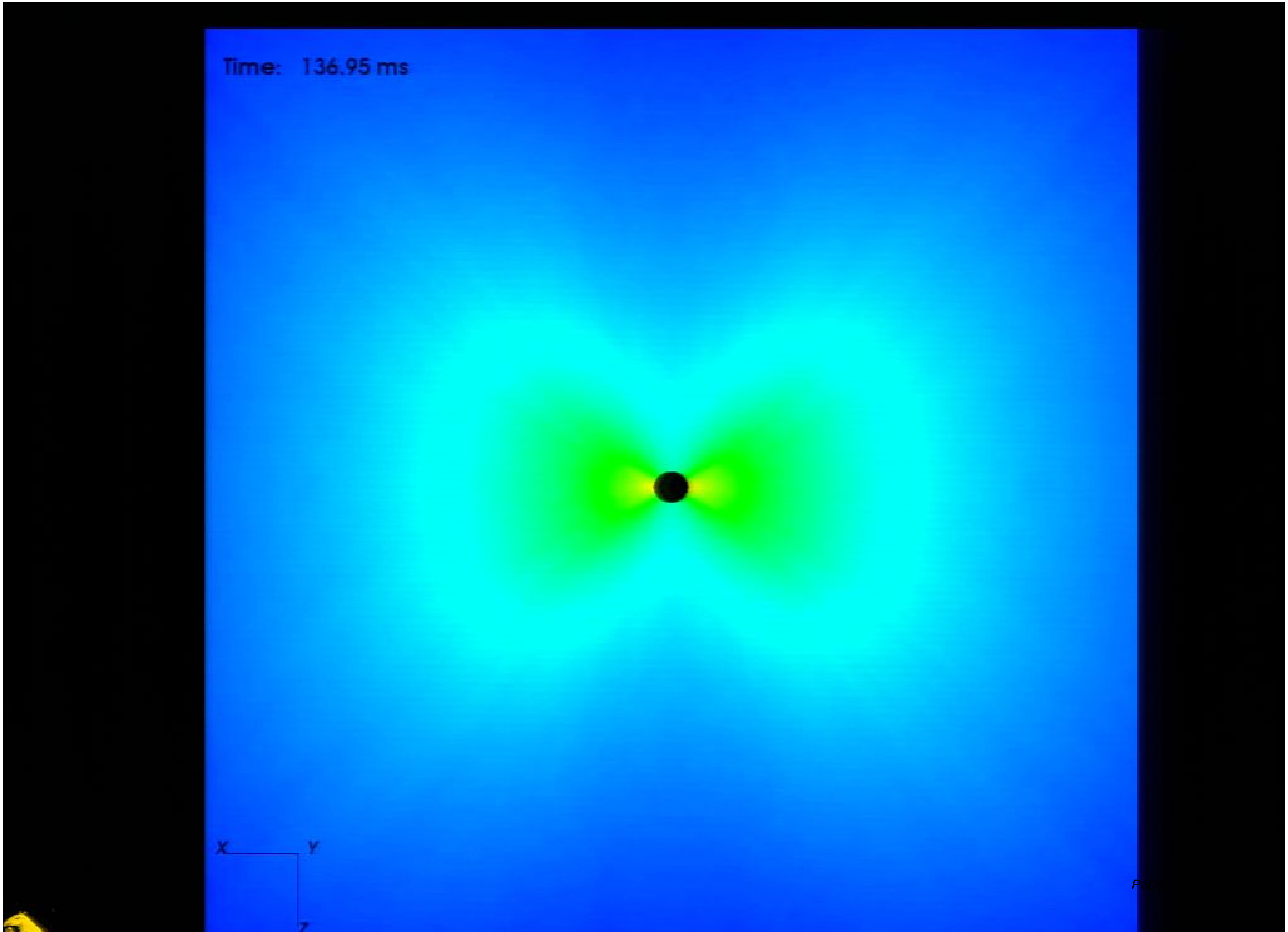
X
Y
Z

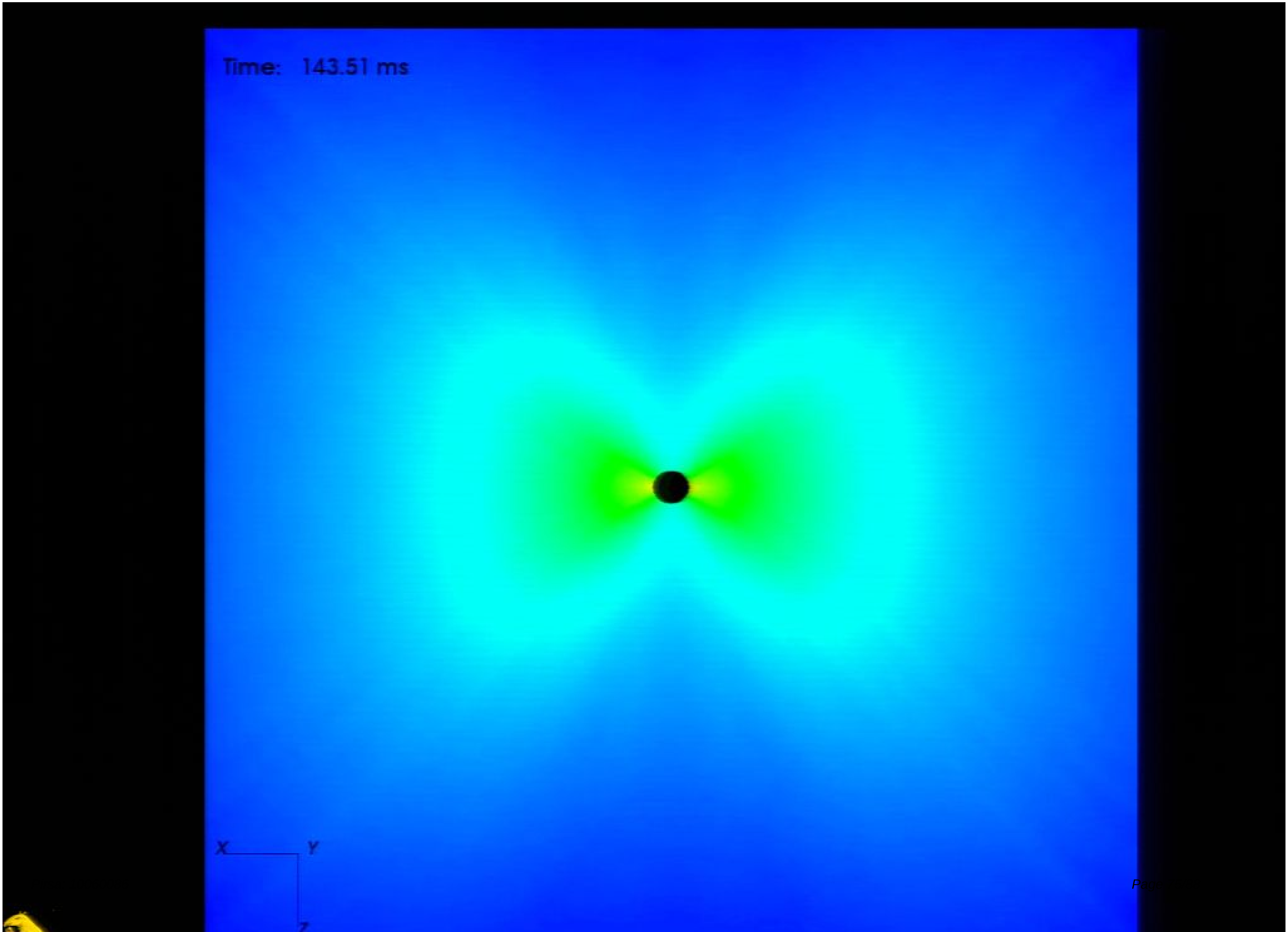

Time: 90.04 ms
X
Y

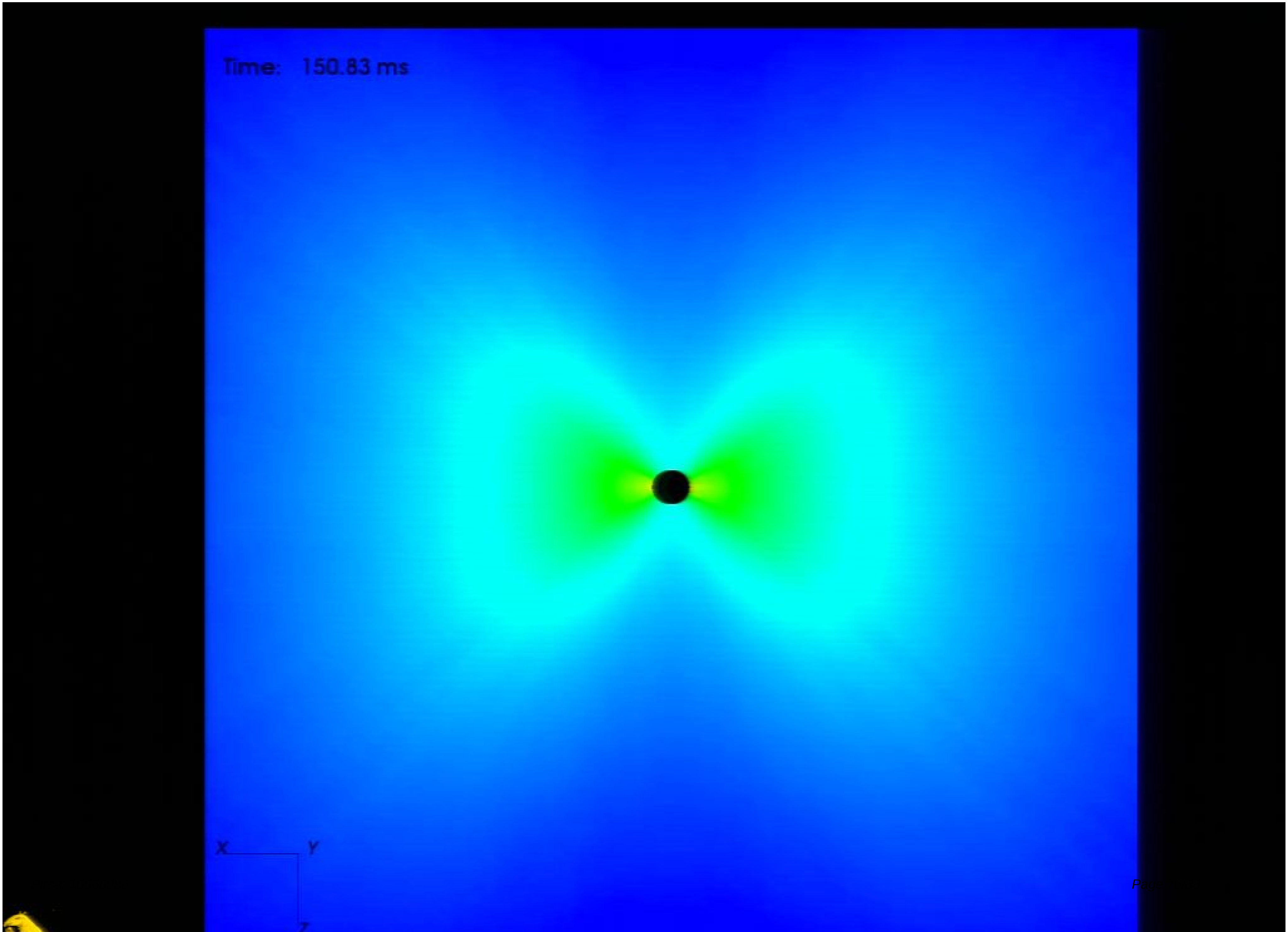

Time: 106.44 ms
X
Y
Z


Time: 114.25 ms
X
Y
Z


Time: 130.40 ms
X
Y
Z


Time: 136.95 ms
X
Y
Z


Time: 143.51 ms
X
Y
Z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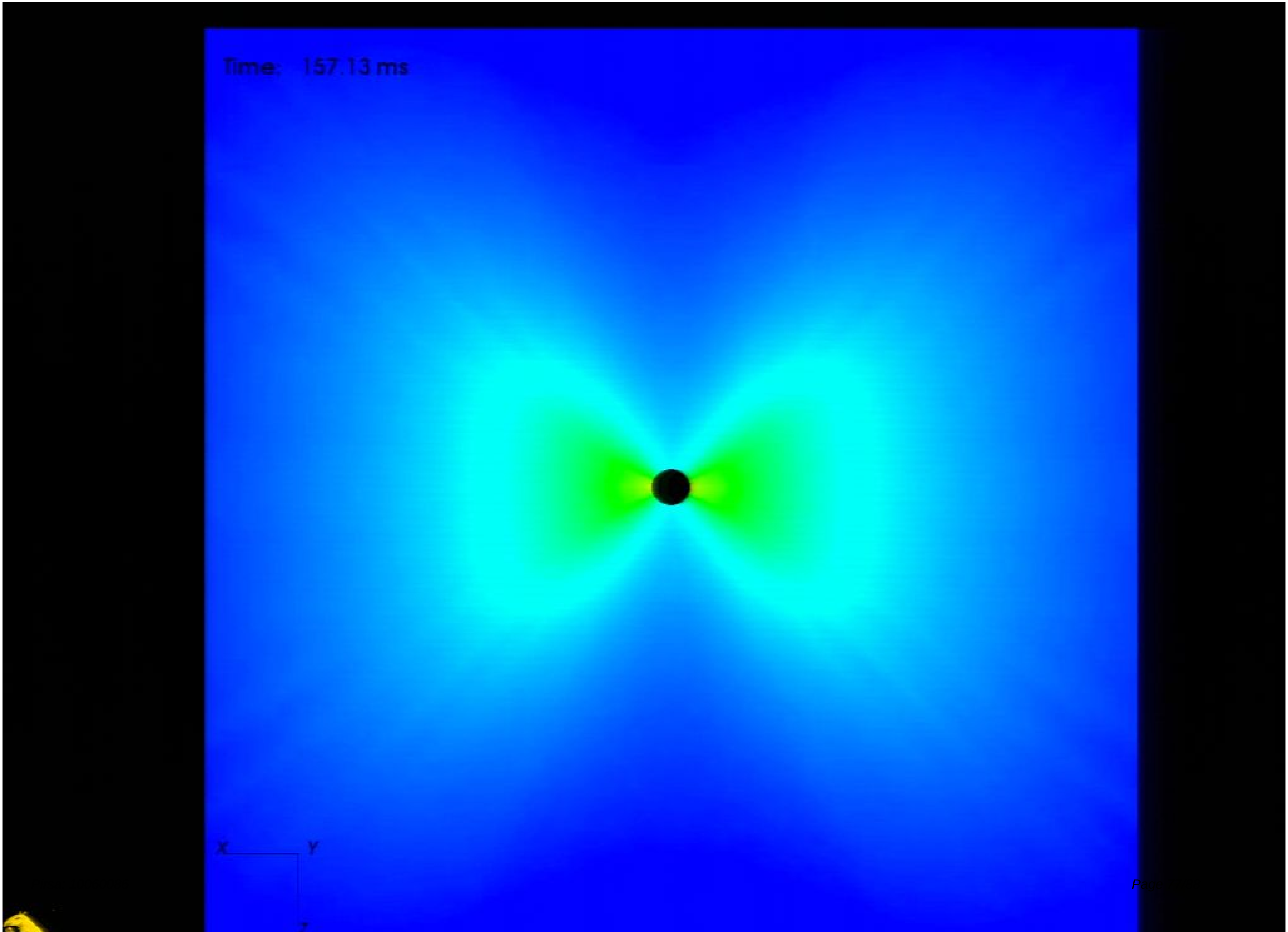
X
Y
Z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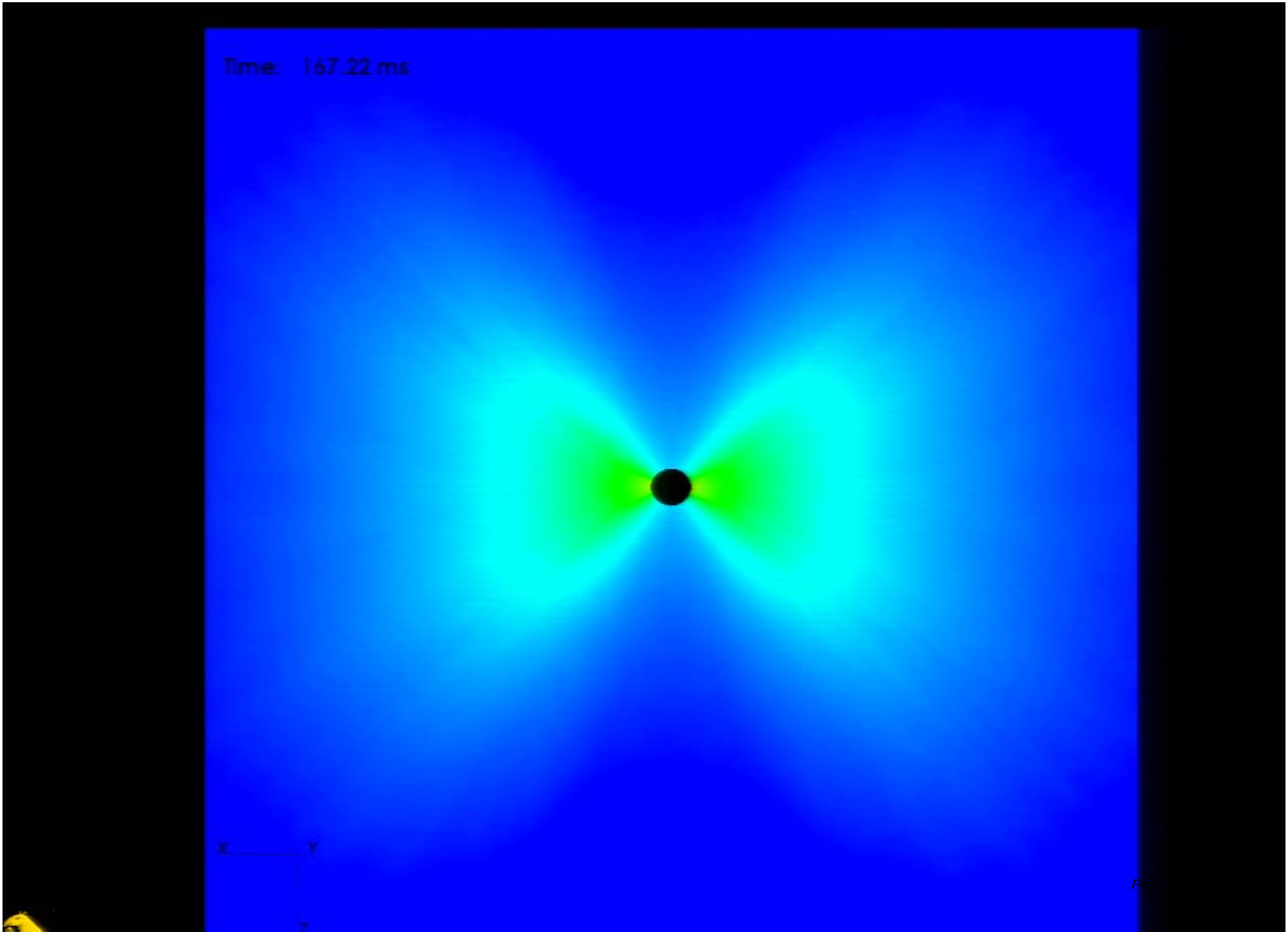
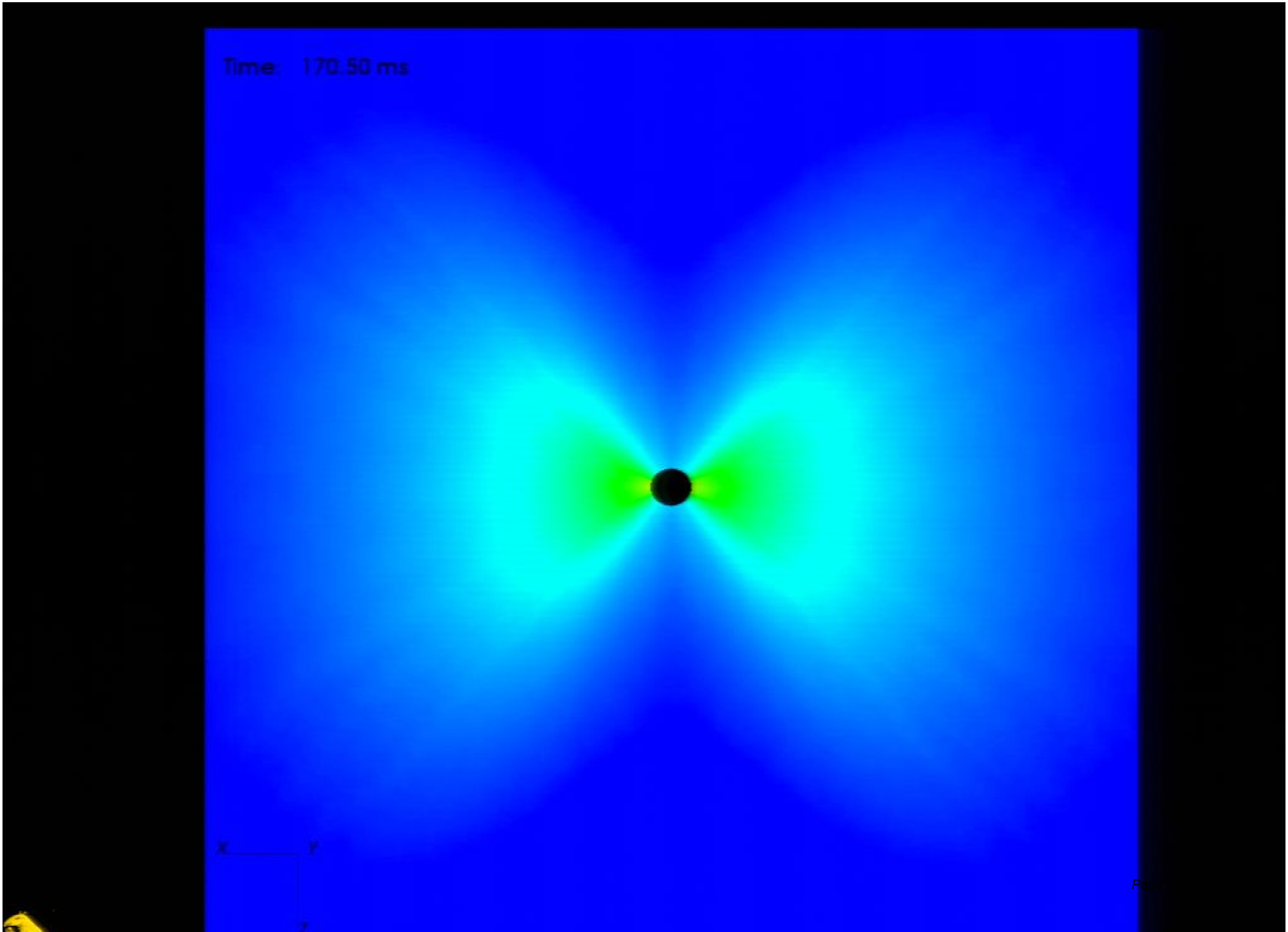
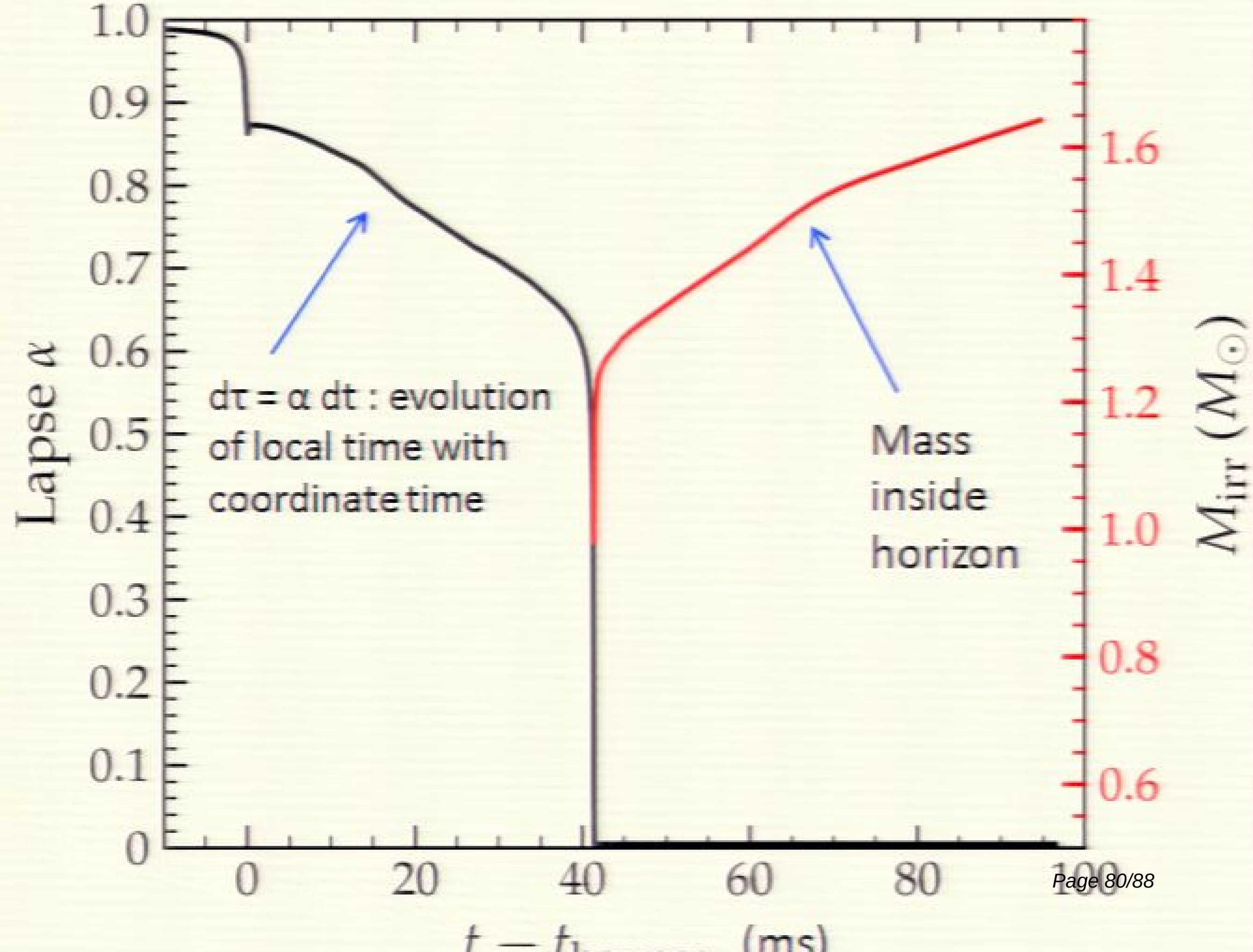
X
Y
Z


Time: 167.22 ms
x
y
z


Time: 170.50 ms

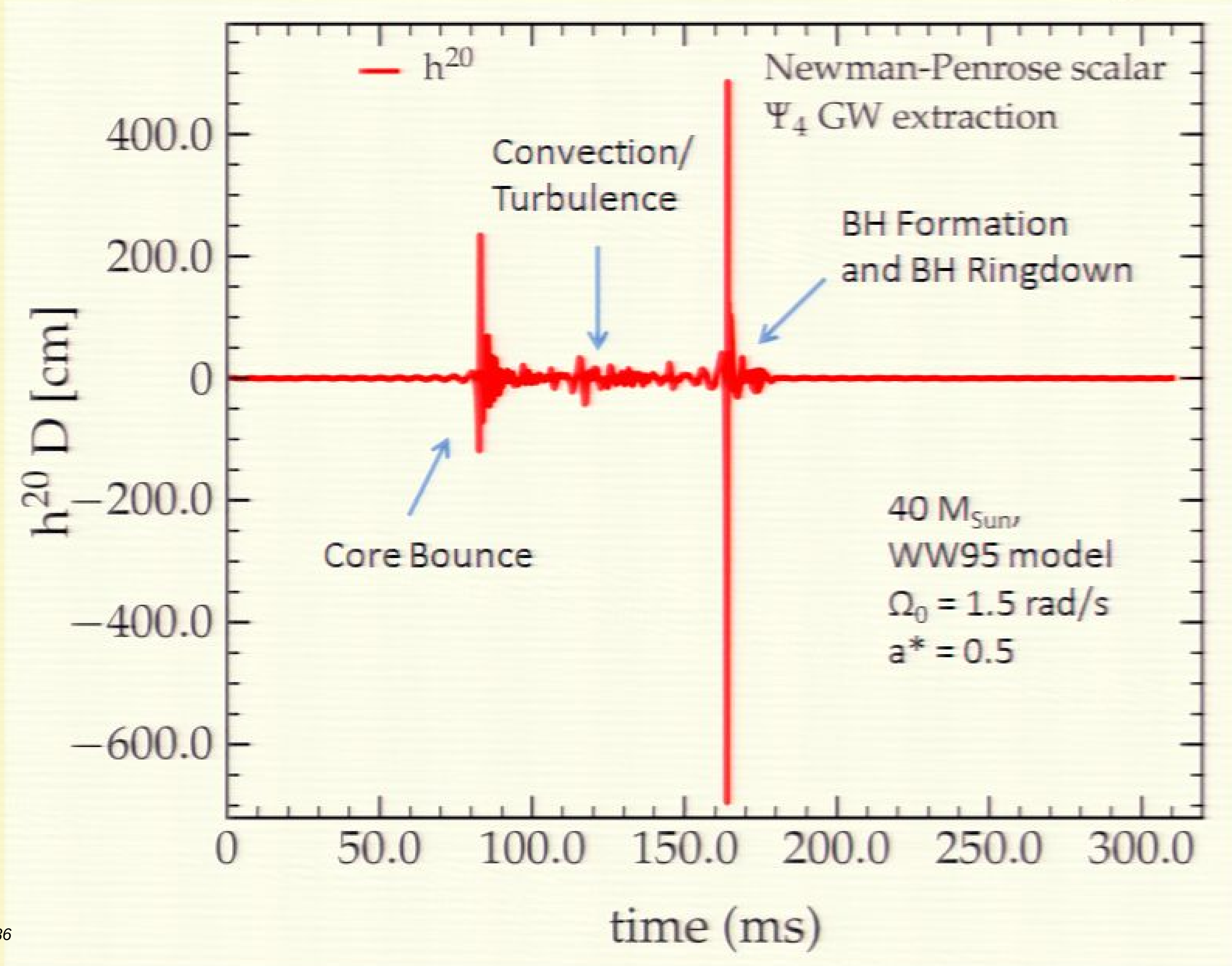
3D BH Formation [Ott et al. 2010 in prep.]

- Exploratory calculation: 3D, but restricted to octant ($m \geq 4$).
  - 40-M_{Sun} Woosley & Weaver 1995 progenitor.
  - Simplified EOS: Piecewise polytrope with thermal component, Γ=2 supernuclear
  - Moderate rotation, Ω_0= 1.5 rad/s.
  - 11 levels of AMR.
  - BH forms with Kerr spin parameter $a^* = J/M^2 \sim 0.5$



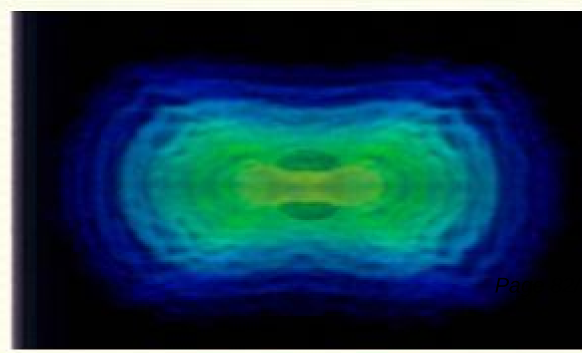
Gravitational Waves from BH Formation

[Ott et al. 2010 in prep.]



Summary

- **Physical model for the spectral characteristics of GW emission from neutrino-driven core-collapse supernovae.**
- **Comparison of quadrupole formula with Zerilli-Moncrief and Newman-Penrose for core collapse spacetimes.**
  QF good enough, considering SN physics/distance uncertainties.
- **Comprehensive study of black hole formation in 1.5D:**
  - No 'prompt' black hole formation in ordinary massive stars.
  - Protoneutron stars that would make super-Kerr BHs go nonaxisymmetrically unstable (-> limit on BH spin!)
- **First preliminary results from 3D GR simulations of failing core-collapse supernovae and black hole formation.**



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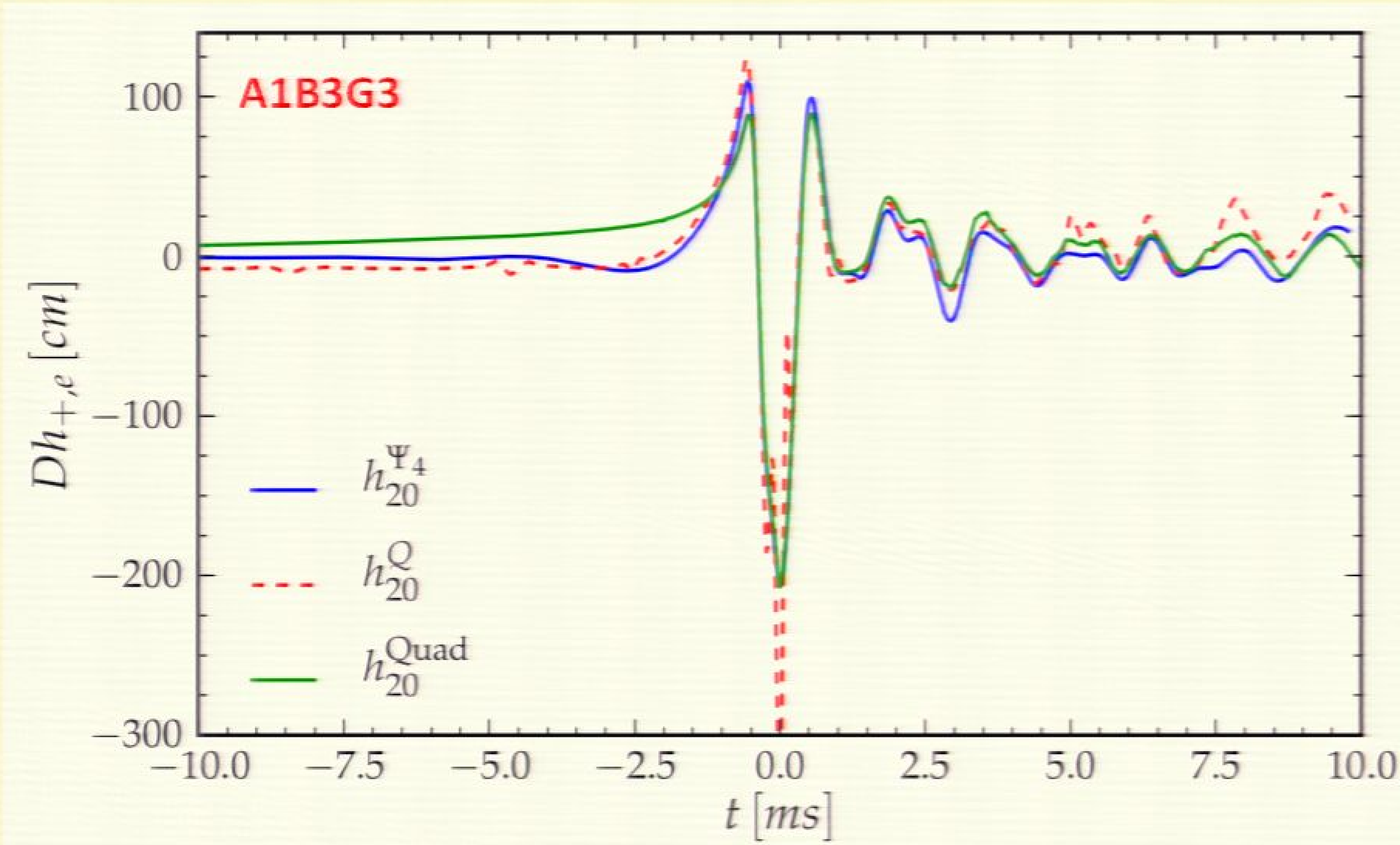
GW Extraction: Preliminary Results

[Reisswig, Ott et al. 2010]



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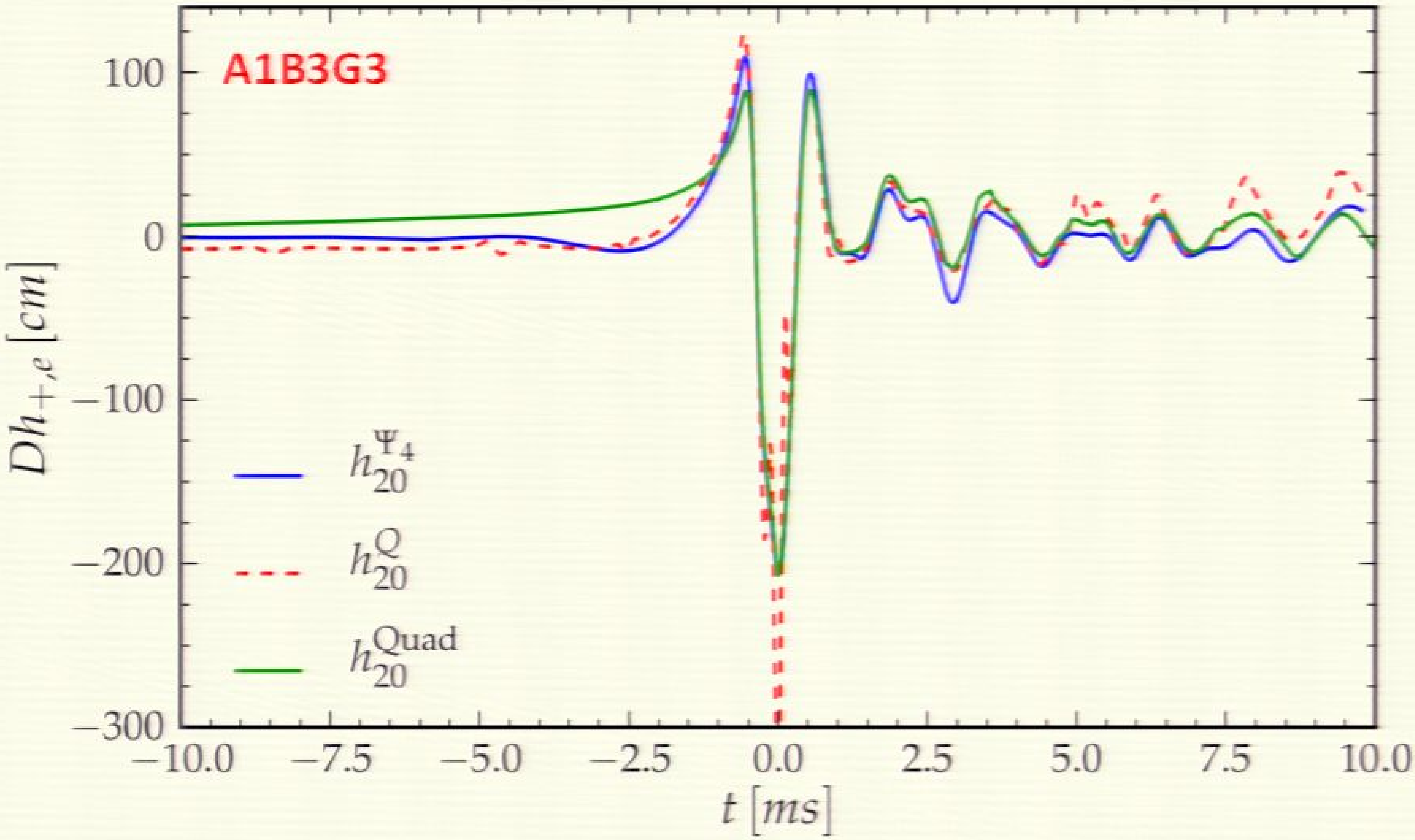

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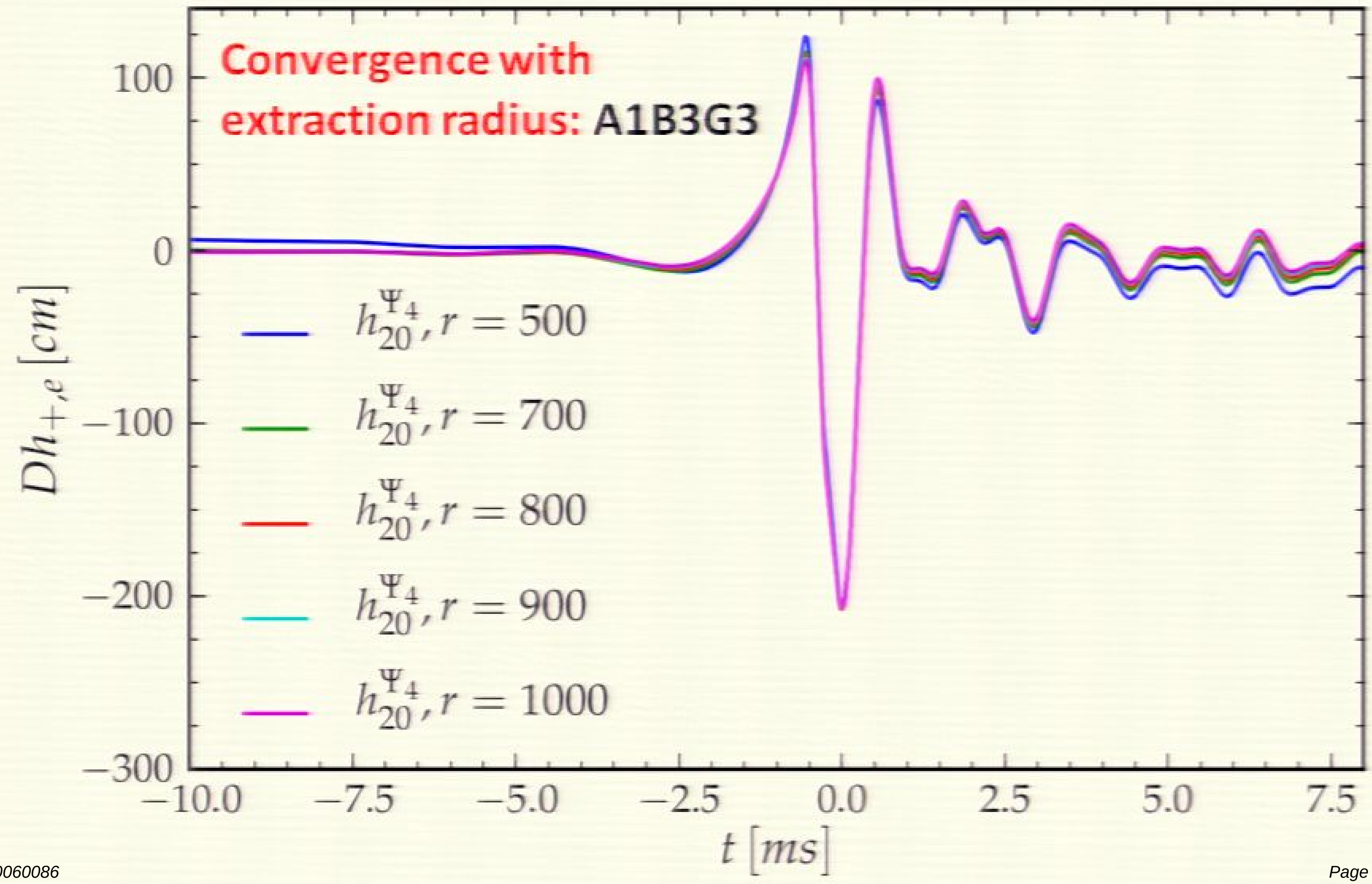

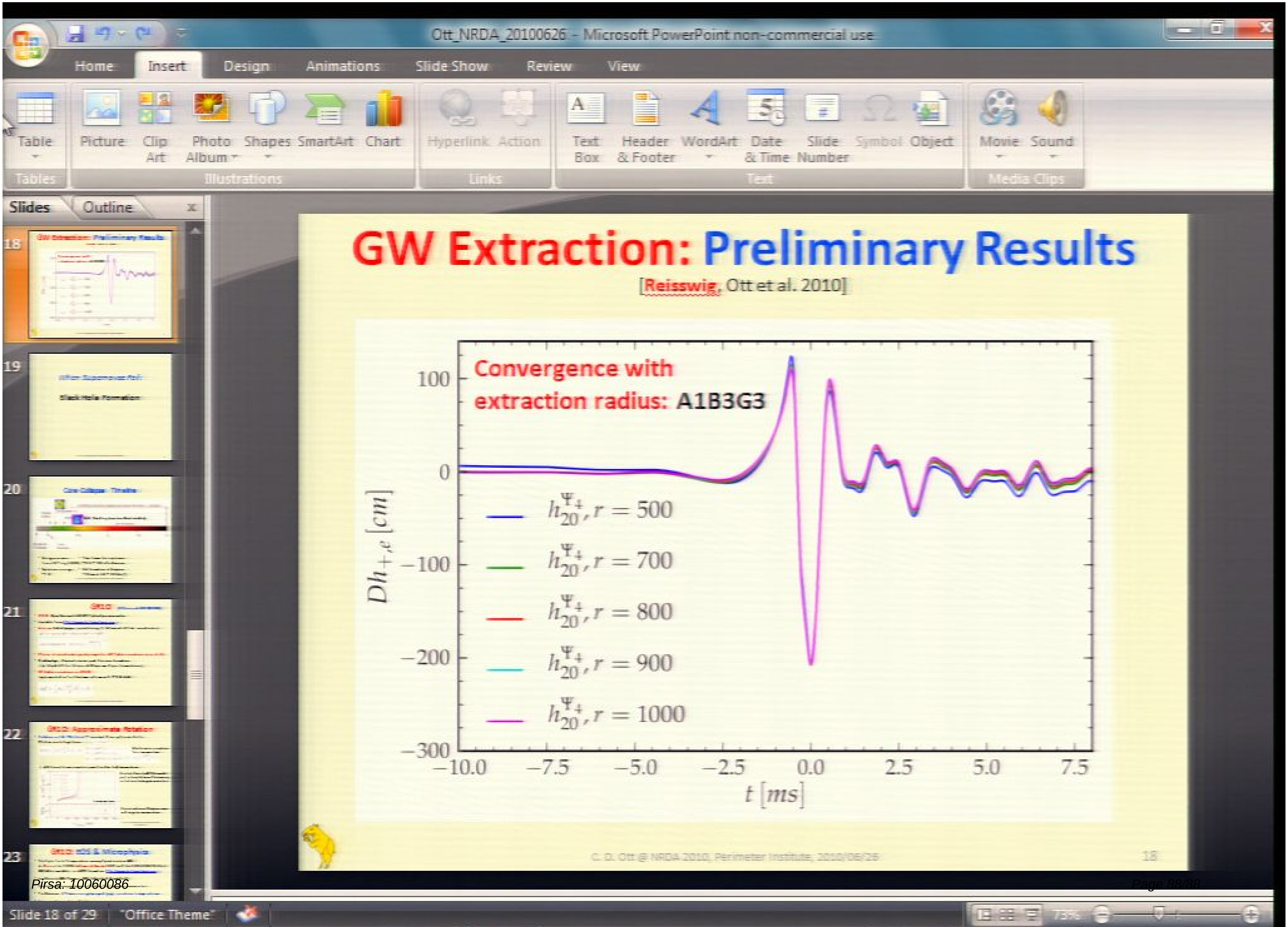
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Home
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Animations
Slide Show
Review
View
GW Extraction: Preliminary Results
[Reisswig, Ott et al. 2010]
Convergence with
extraction radius: A1B3G3
$h_{20}^{\Psi_4}, r = 500$
$h_{20}^{\Psi_4}, r = 700$
$h_{20}^{\Psi_4}, r = 800$
$h_{20}^{\Psi_4}, r = 900$
$h_{20}^{\Psi_4}, r = 1000$
$Dh_{+,e}$ [cm]
t [ms]
C. D. Ott @ NRDA 2010, Perimeter Institute, 2010/06/26
18
Slide 18 of 29
"Office Theme"