Probing explosion geometry of CCSNe with light curves of shock breakout

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Outline

1. Supernova shock breakout

    ➡ SN shock breakout in aspherical explosion

2. Simulation

    ➡ aspherical explosion in a compact progenitor

3. Result

4. Summary

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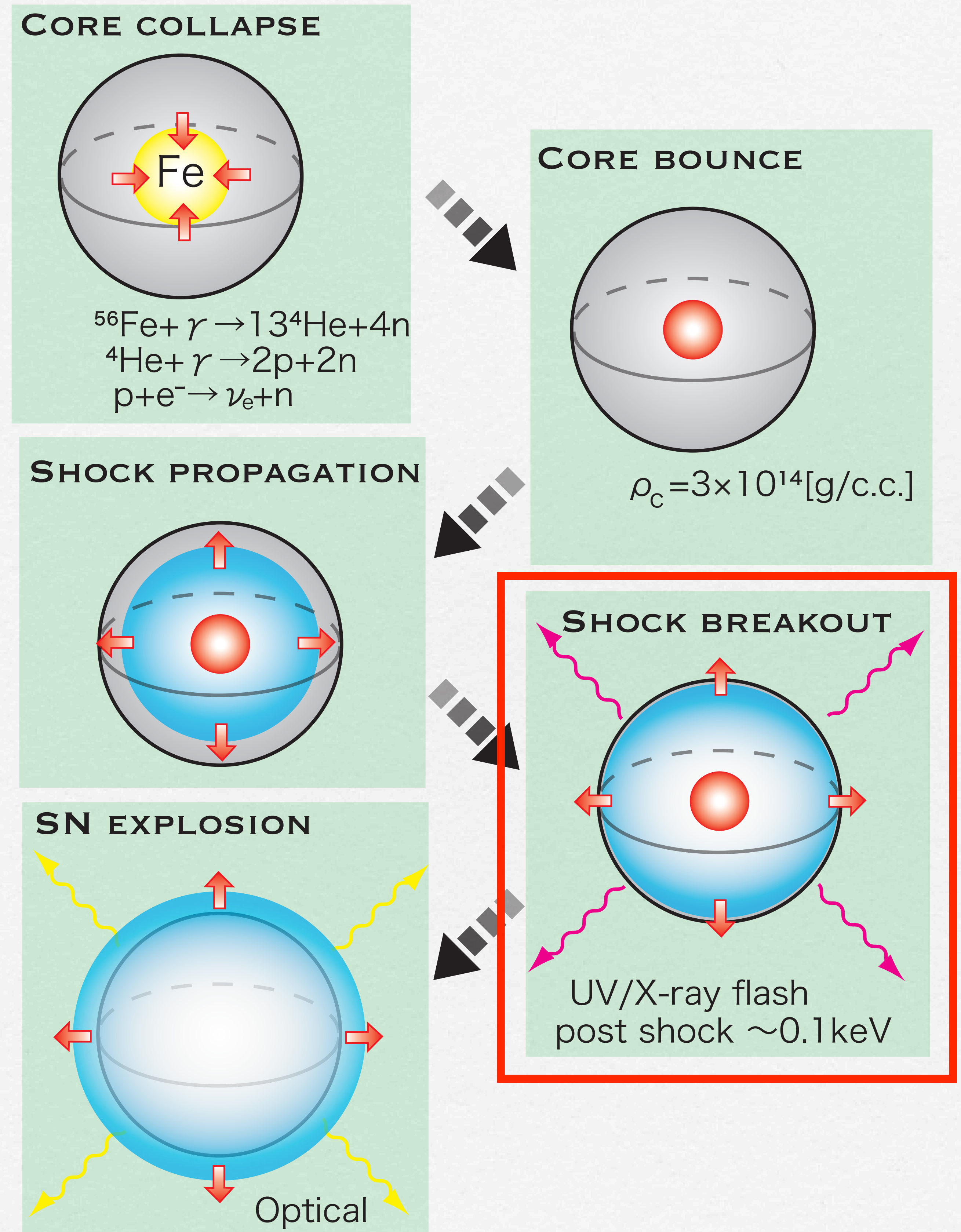
SN shock breakout

- CCSNe: the final evolutionary state of massive stars(M>8-10M$_\odot$)
- Core bounce -> shock generation
- The shock wave emerges from the stellar surface (shock breakout)
- After the emergence, the ejecta outshine in optical bands

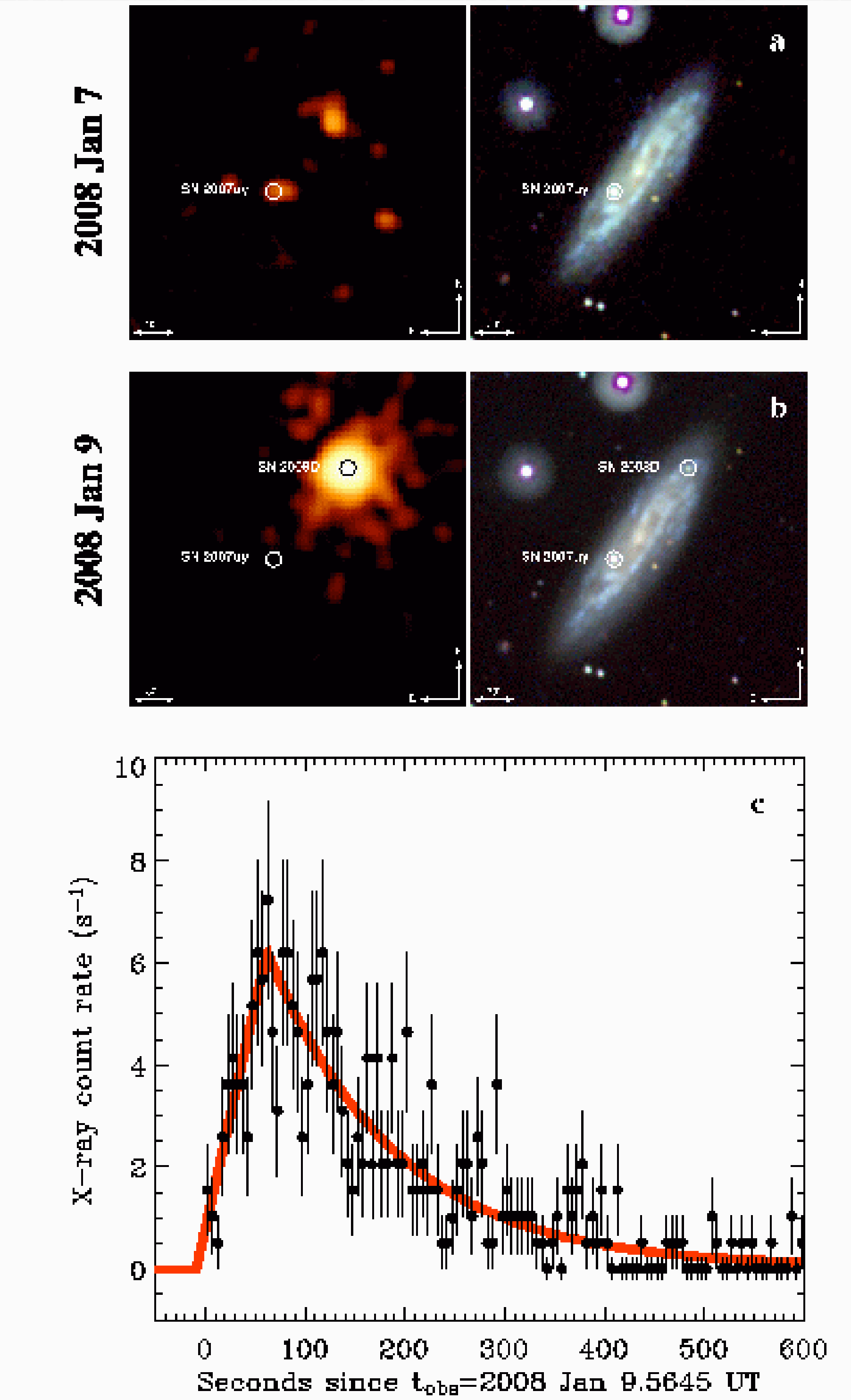


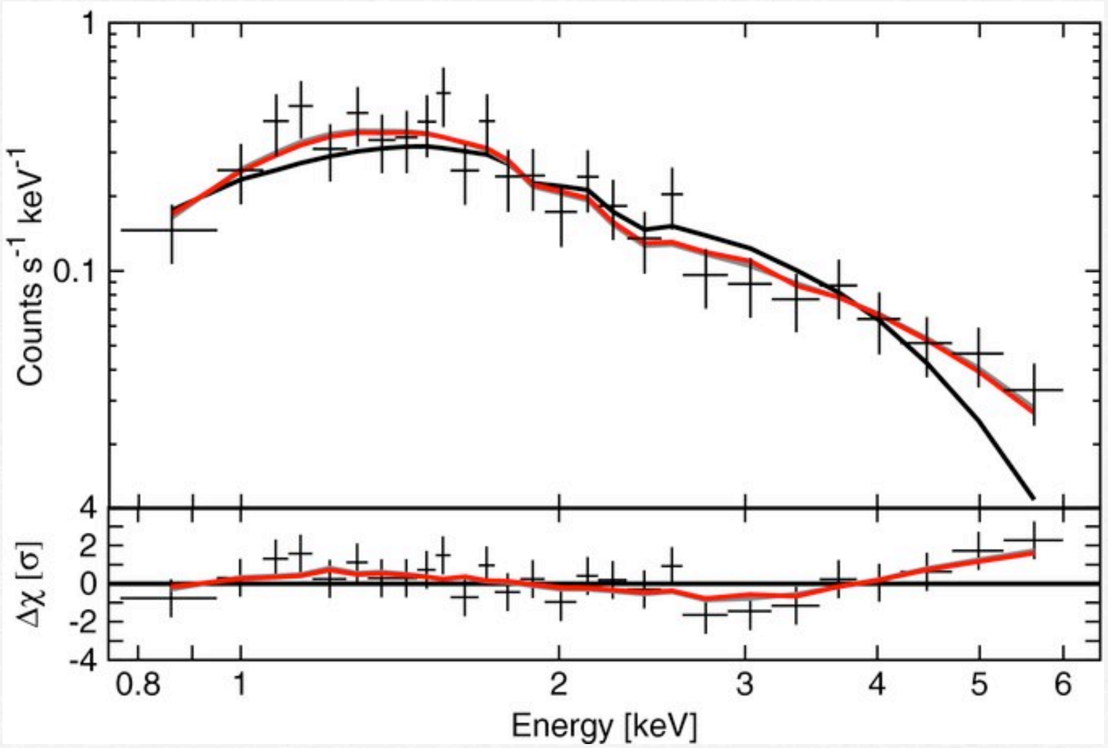
Examples: XRF 080109

- ☑ Swift satellite detected an X-ray flash that is associated with the birth of SN 2008D

- ☑ Duration ~a few 100 sec

Soderberg+(2008)





Modjaz+(2008)

Earlier and Recent studies on shock breakout

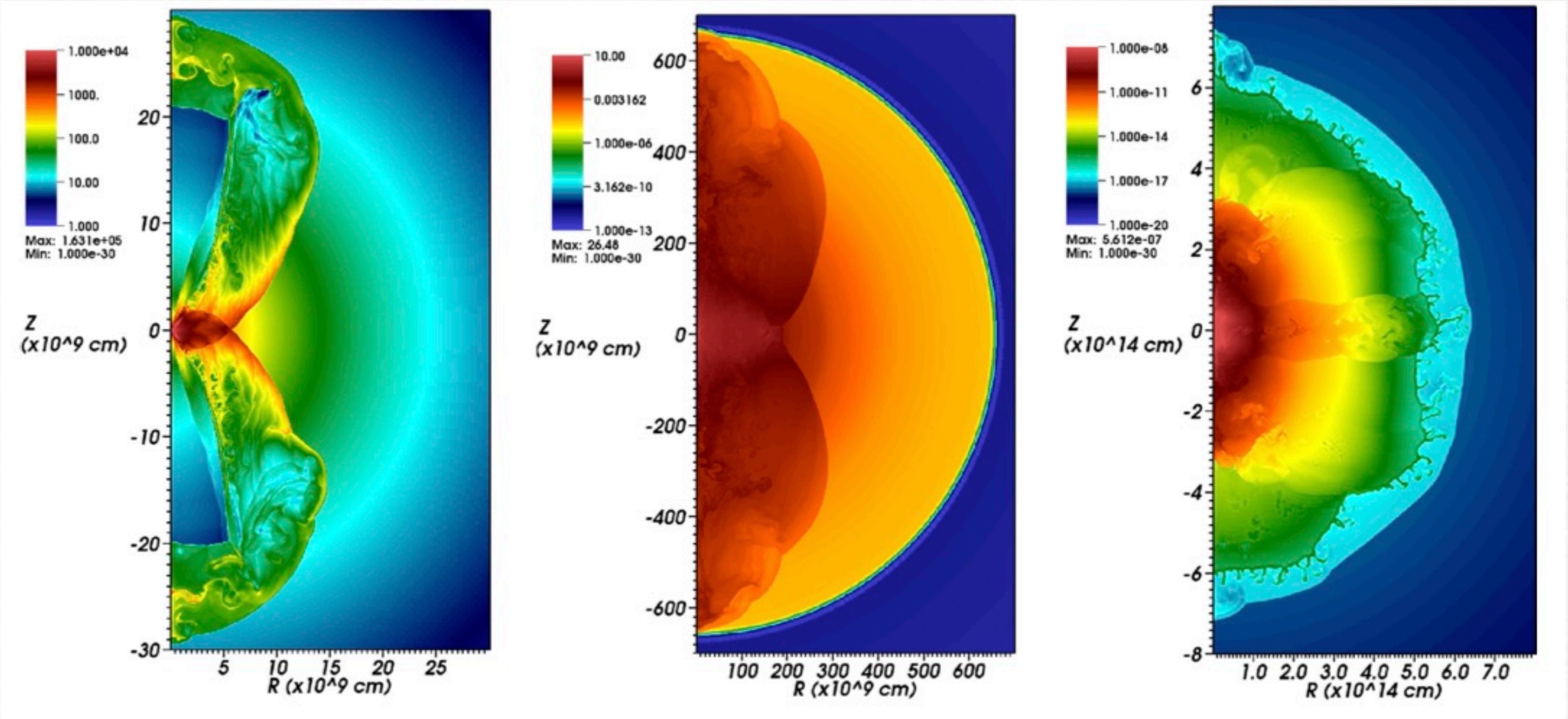
- Many pioneering works (Grassberg+1971, Arnett&Falk 1976, Chevalier 1976, Falk 1978, Klein&Chevalier 1978, etc)
- Semi-analytical models (e.g., Matzner&McKee 1999)
- 1D radiation-hydrodynamical calculations (e.g., Ensman&Burrows 1992)
- Deviation from thermal equilibrium (Katz+2010,Nakar&Sari 2010,Sapir+2011,Rabinak&Waxman+2011)
- Comparison with observations (e.g., Tominaga+2009)
- Breakout in a dense wind (Moriya+2010,Chevalier&Irwin2011)

▶ Most of studies considered spherical explosions

Aspherical explosion

- Effects of aspherical energy deposition in the core on shock breakout light curves are also important.
(Couch et al. 2009,2011, Suzuki&Shigeyama 2010)

Couch+(2011)
He star
+ jet-like explosion



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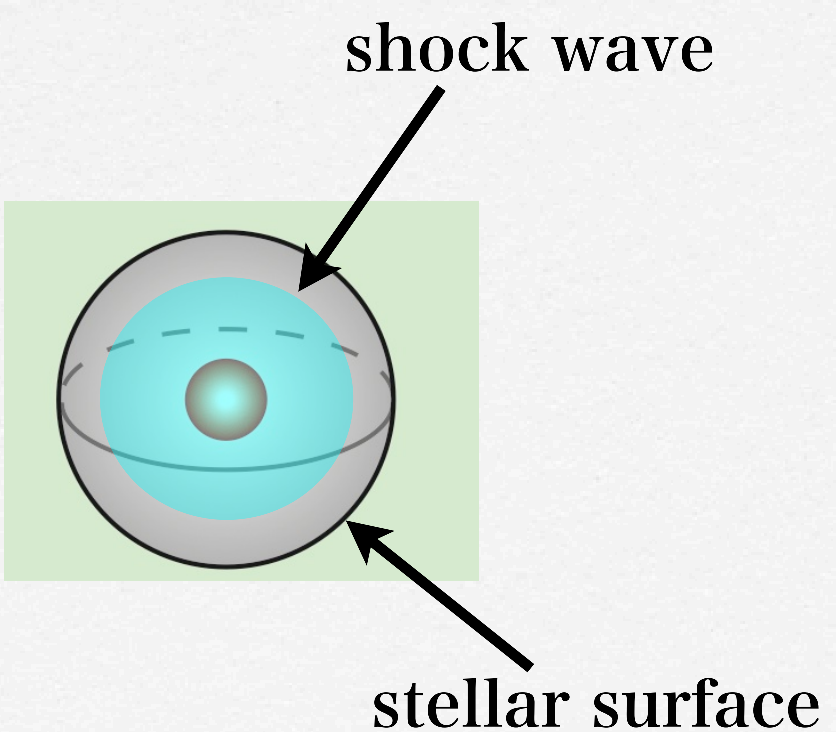

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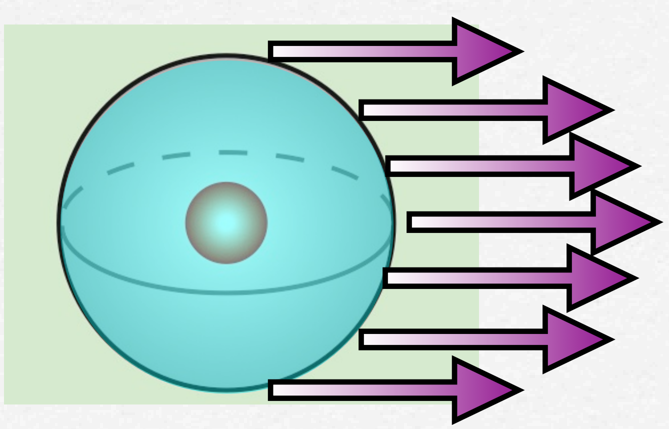

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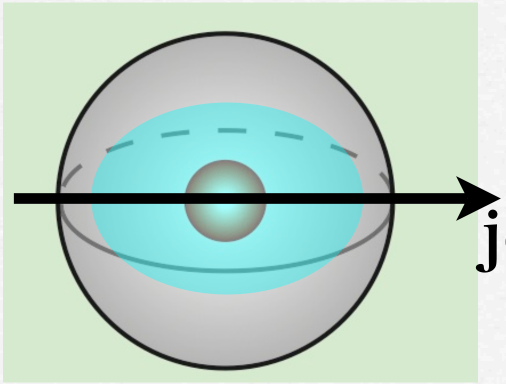

jet axis

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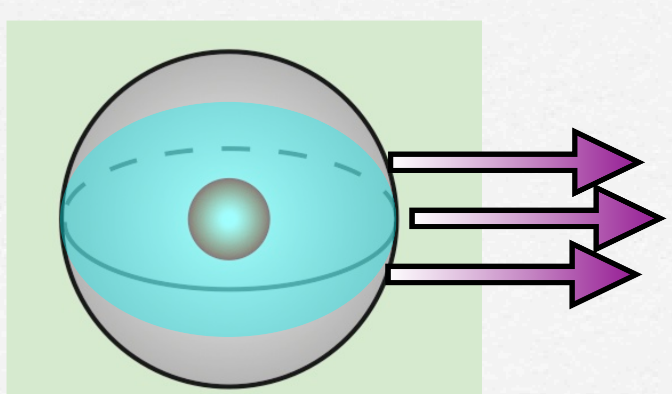

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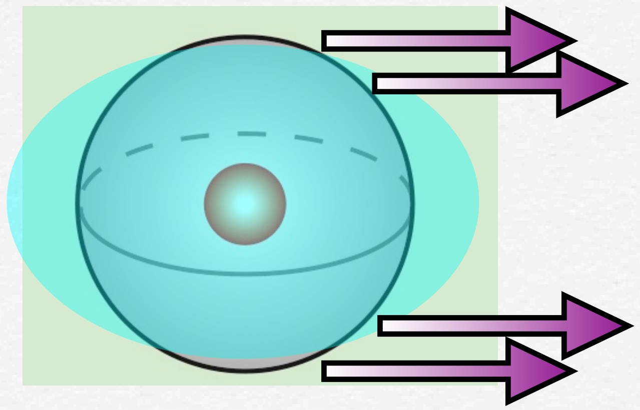

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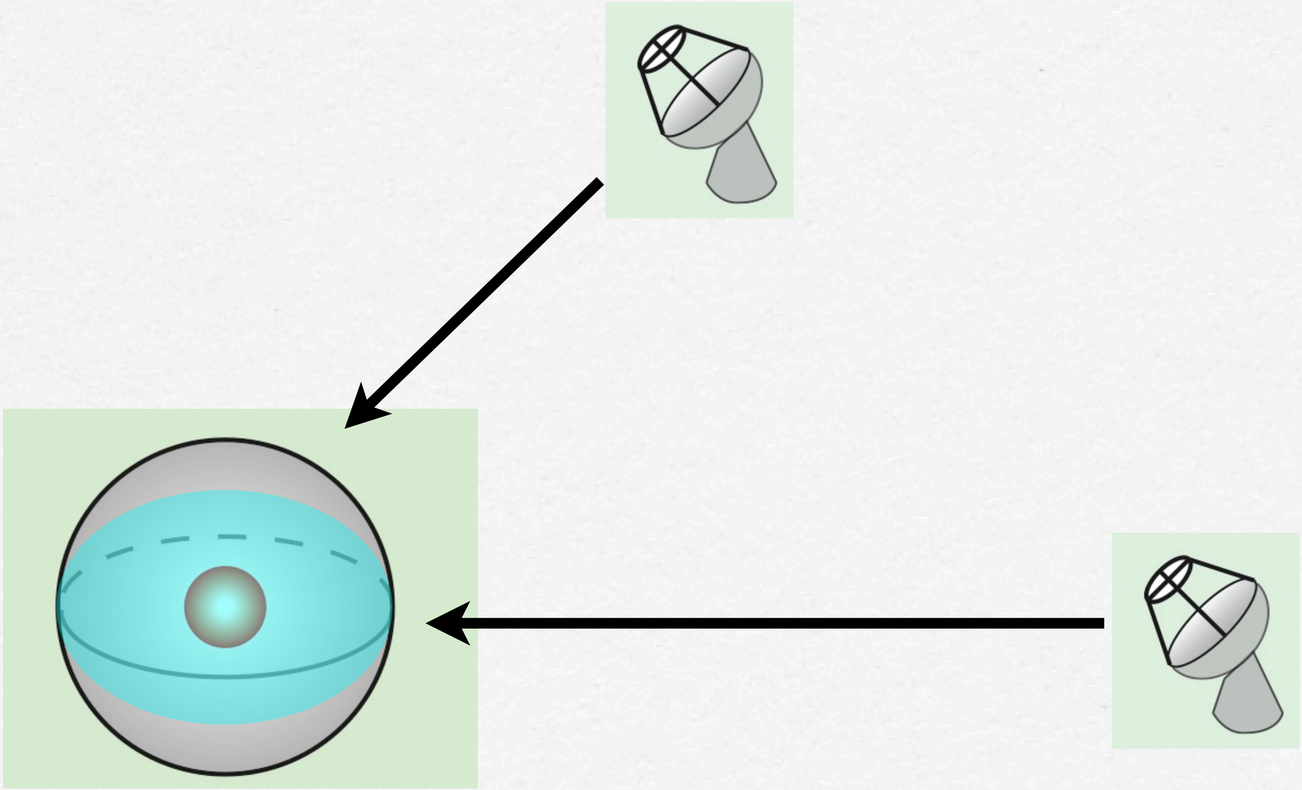

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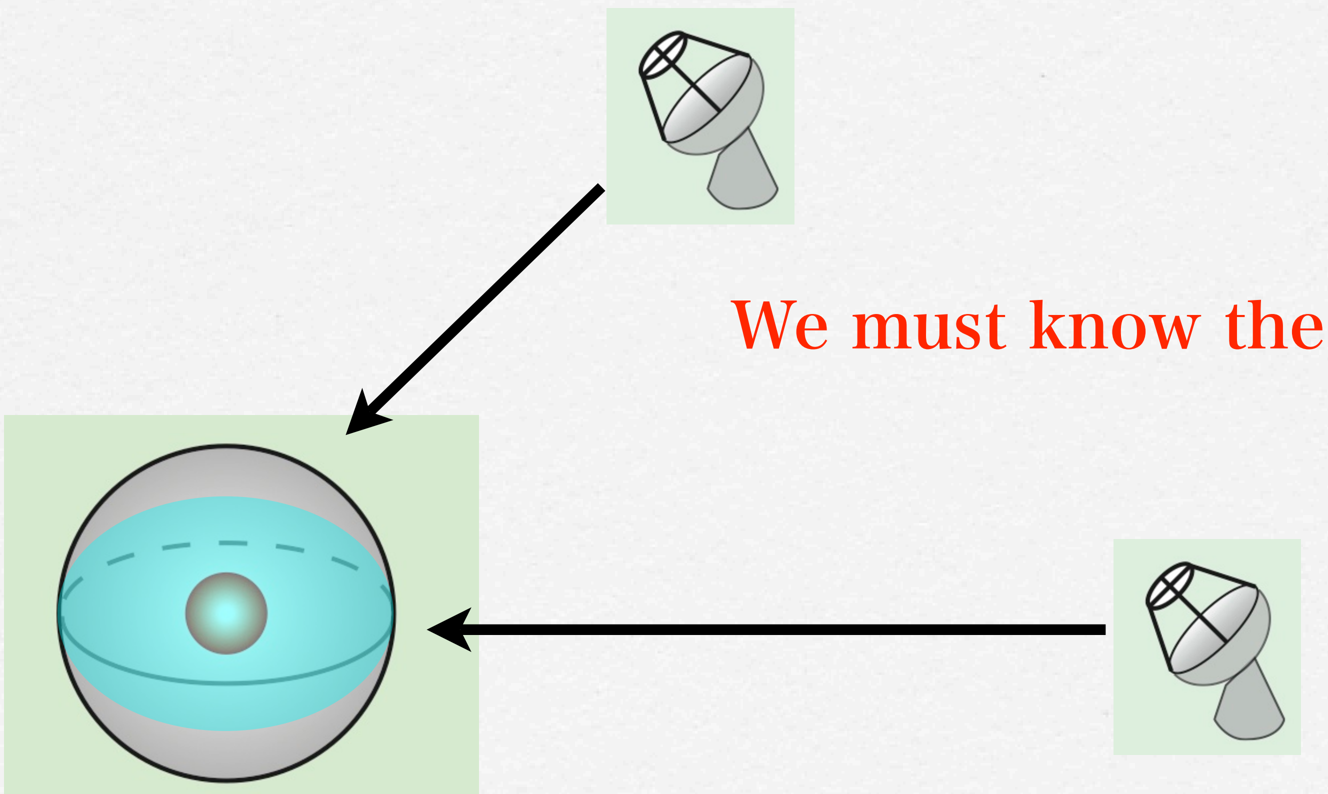

We must know the time of the shock emergence
for each point on the surface!

Hydrodynamical calculations

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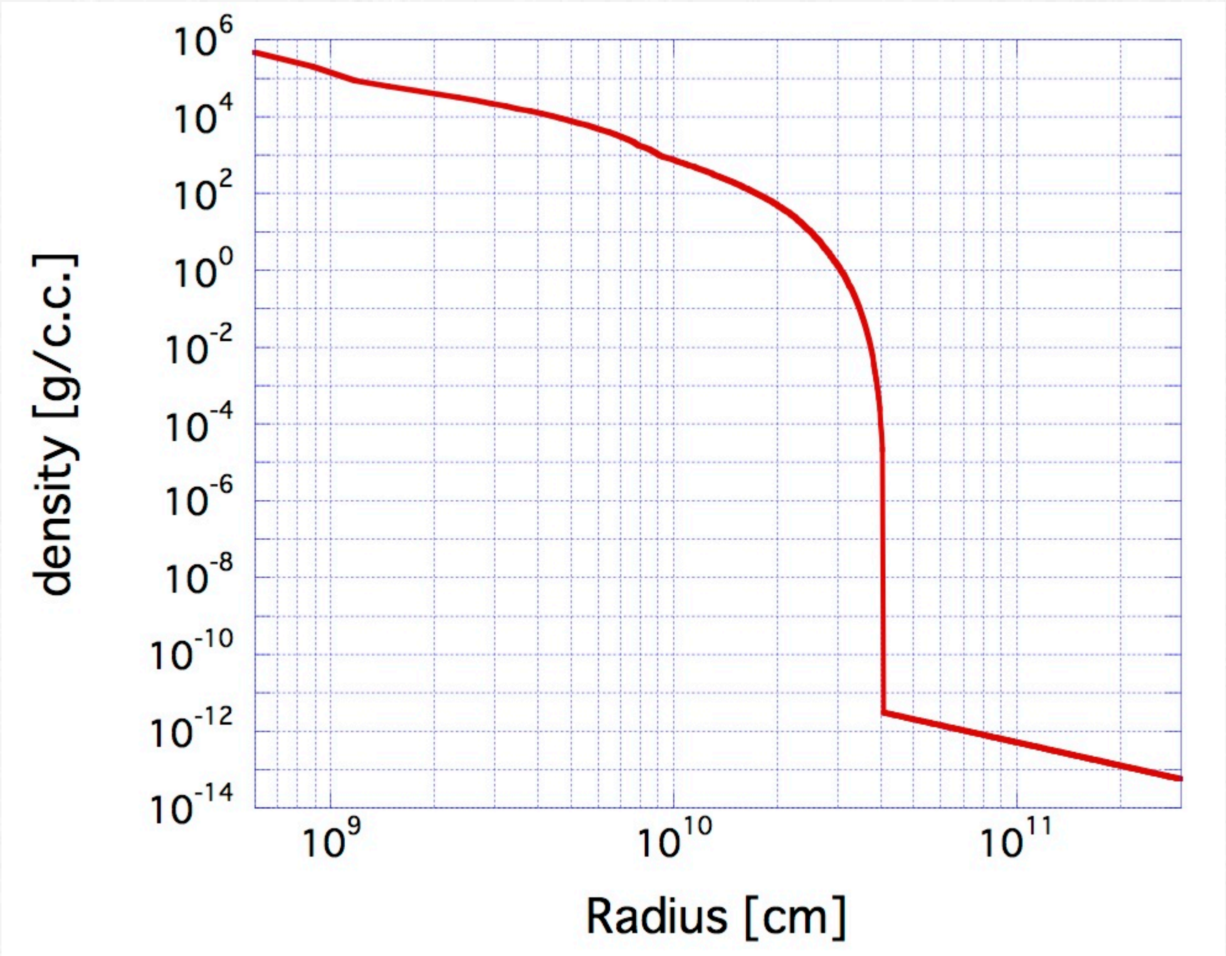
2D hydrodynamical calculation

- ☑ 2D SRHD code
- ☑ EOS: ideal gas with $\gamma = 4/3$
- ☑ progenitor: $14M_\odot$ CO star ($R = 4\times10^{10}$cm) + wind (Woosley&Heger 2006)

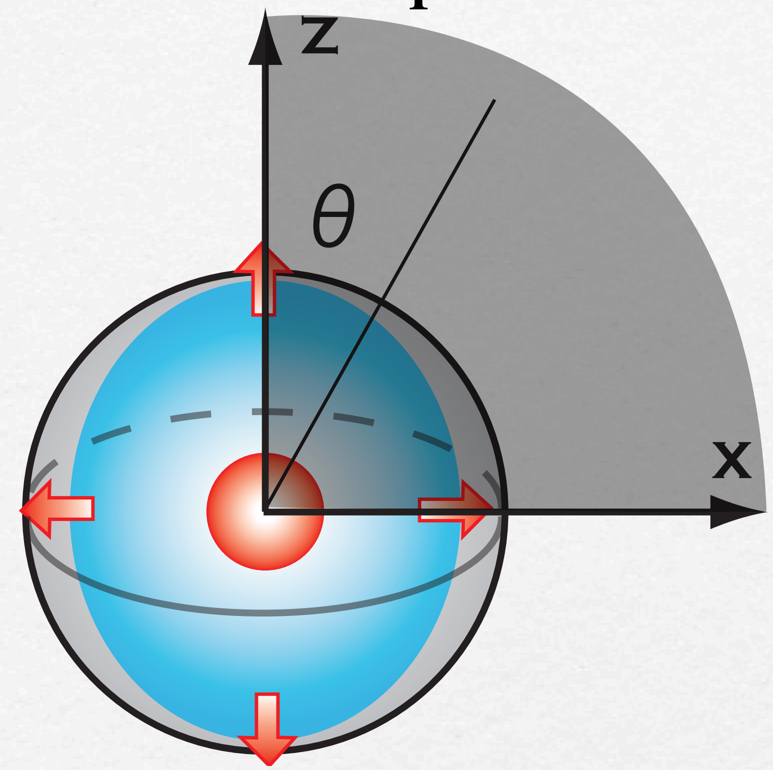


Simulation setups

- ☑ computational domain = 1/4 of the meridional plane: 1024×128 mesh
- ☑ axial symmetry, equatorial symmetry
- ☑ total energy of $E_{tot}=10^{51}$erg is deposited from the inner boundary $r_{in}=3\times10^8$cm as a kinetic energy within τ =0.1 sec

$$\frac{\rho v_{\mathrm{r}}^2}{2} v_{\mathrm{r}} = \frac{E_{\mathrm{tot}}}{4\pi r_{\mathrm{in}}^2 \tau}(1+\alpha\cos 2\theta)$$

- ☑ α: degree of deviation from spherical explosion ($0\leqq\alpha\leqq1$)



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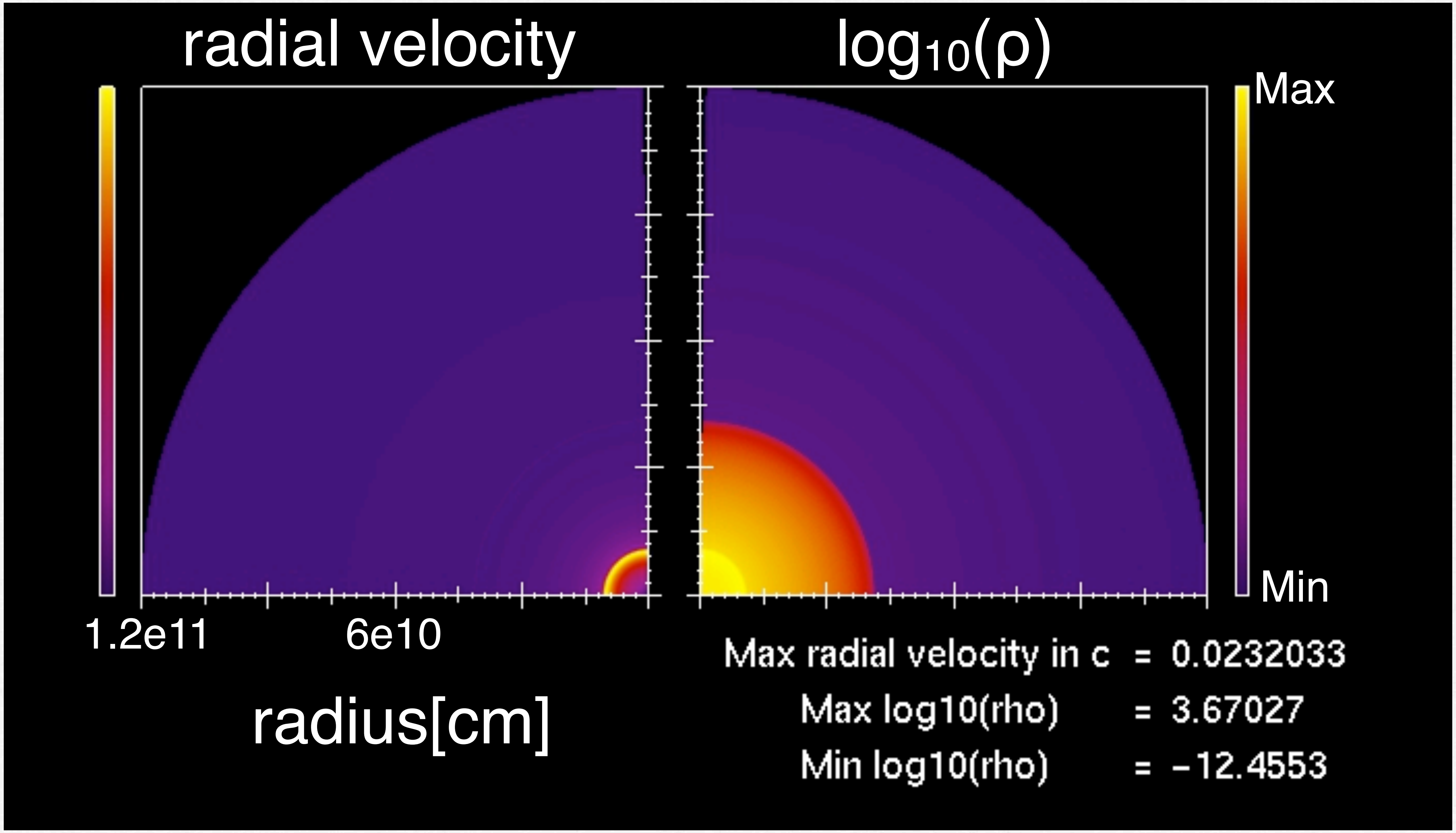
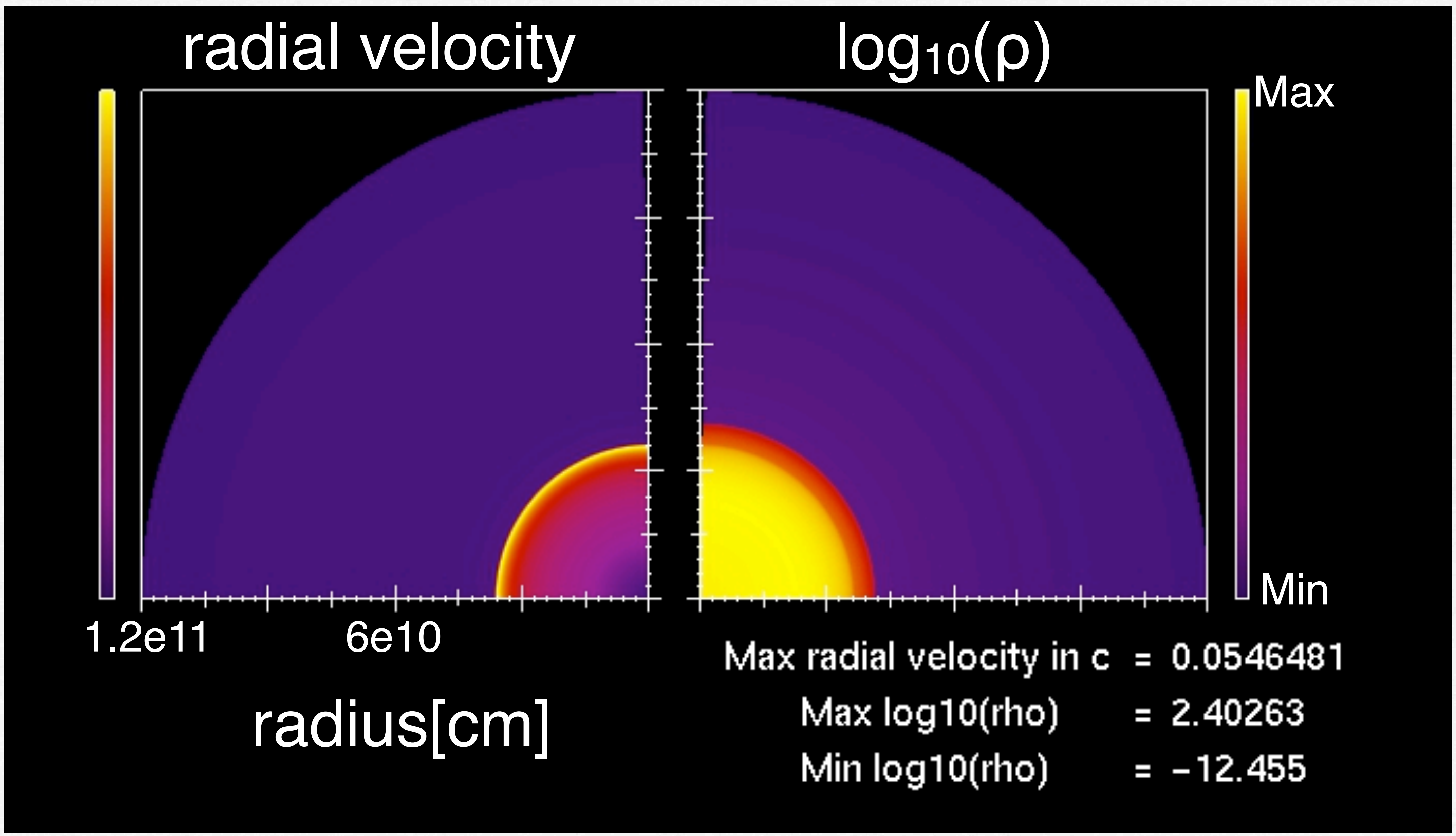
Results: spherical case (α=0)

t=1 [sec]



Results: spherical case (α=0)

t=34 [sec]



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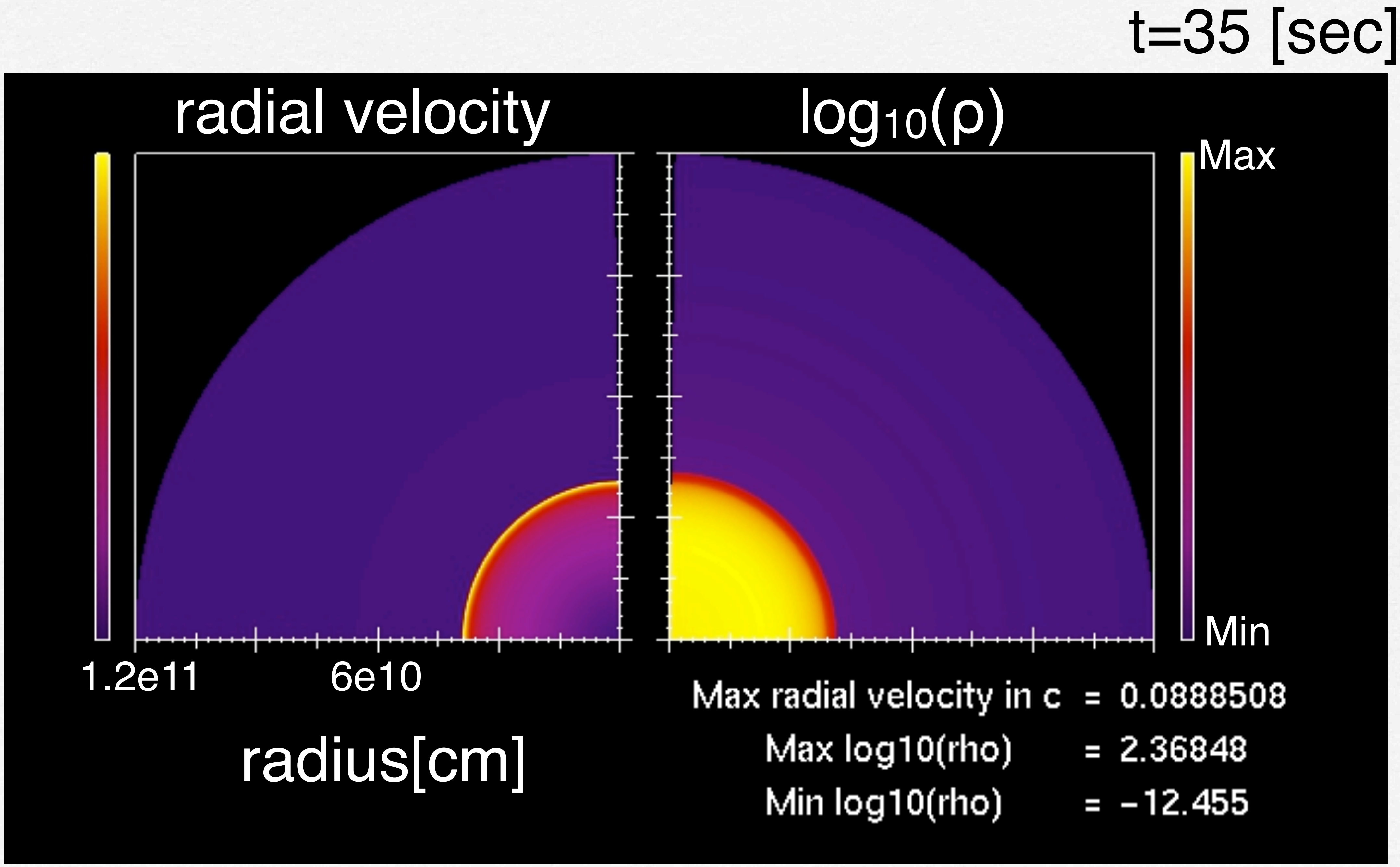
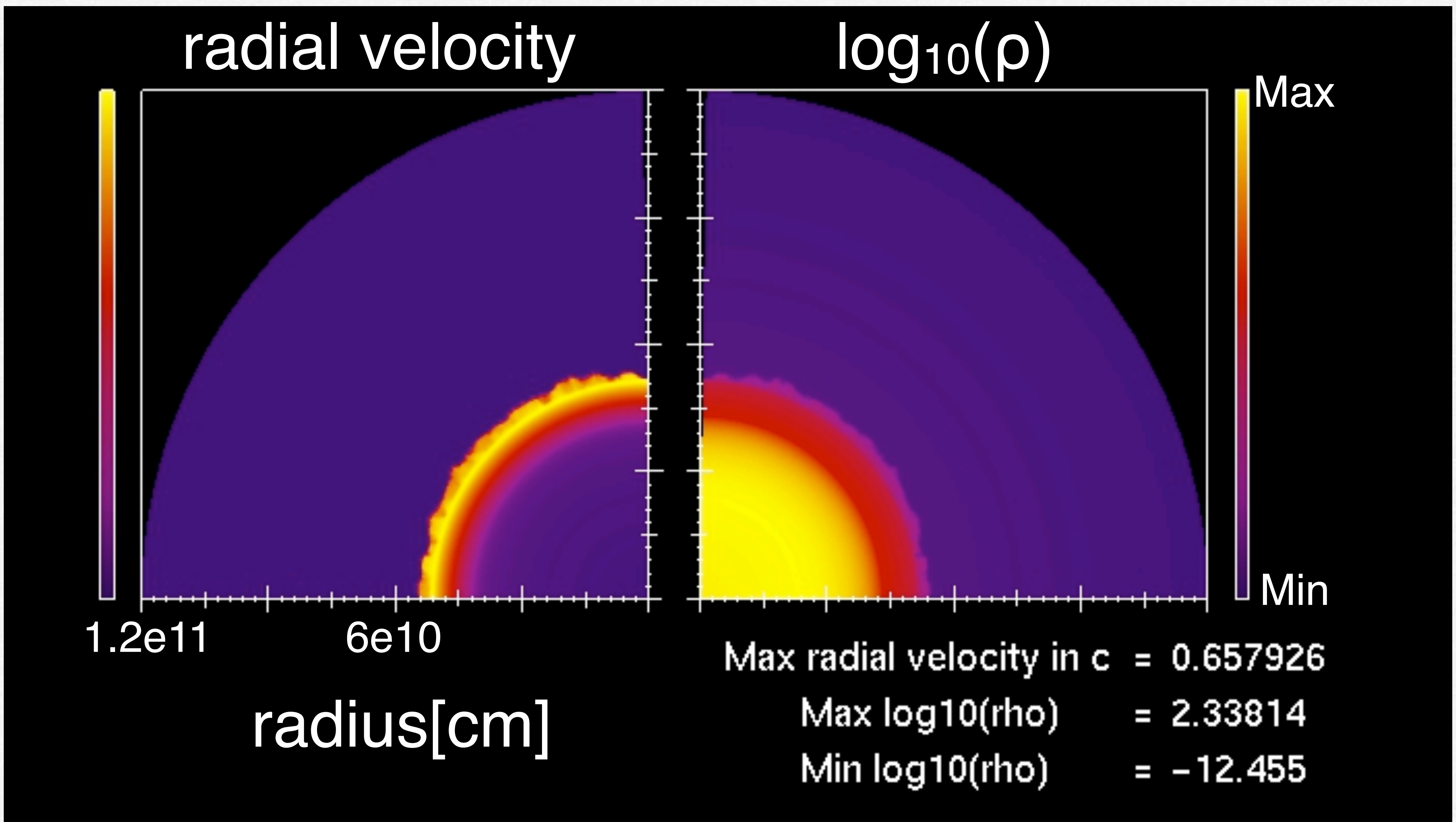


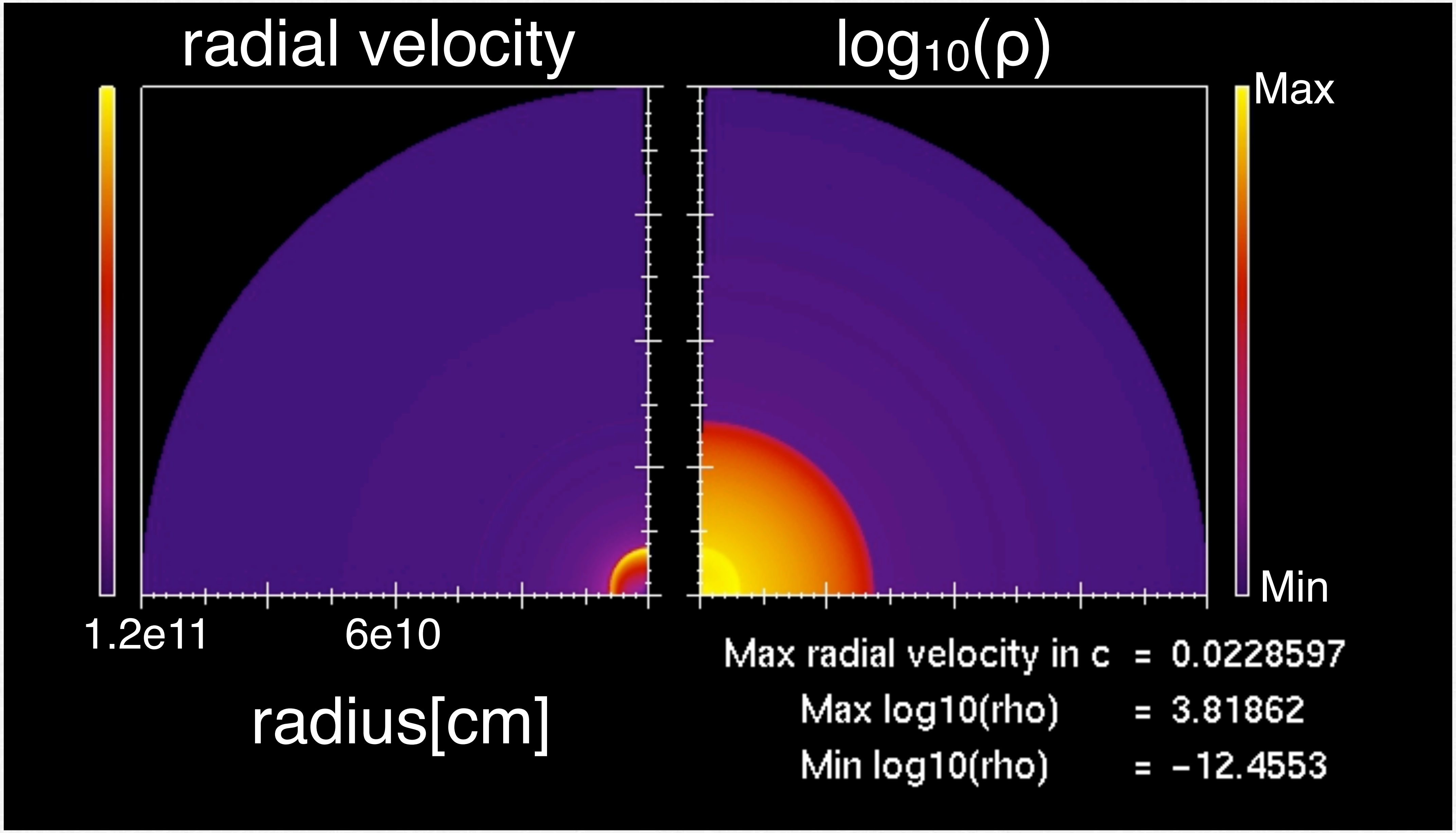
Results: spherical case (α=0)

t=36 [sec]



Results: aspherical (α=0.8)

t=1 [sec]



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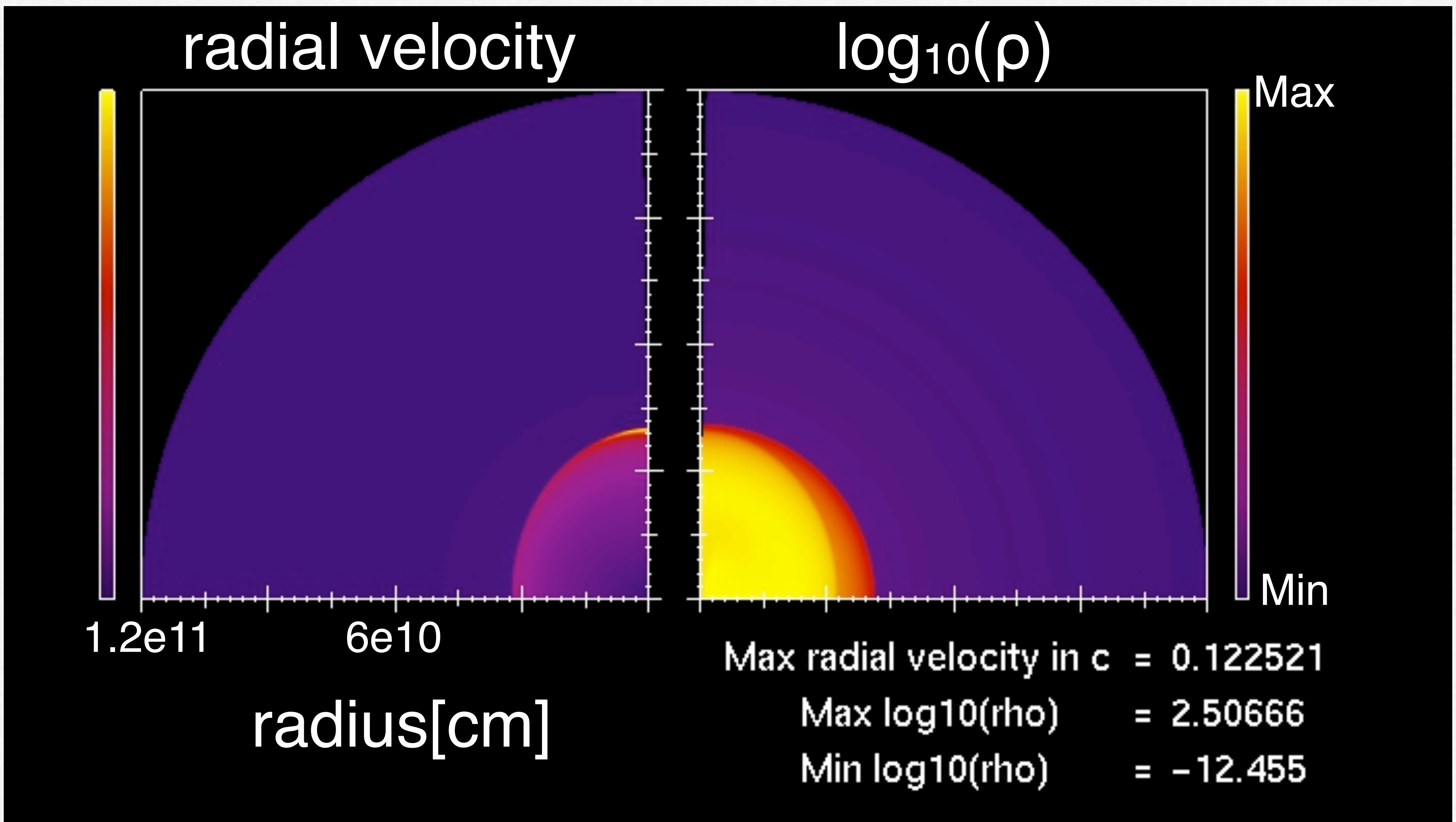

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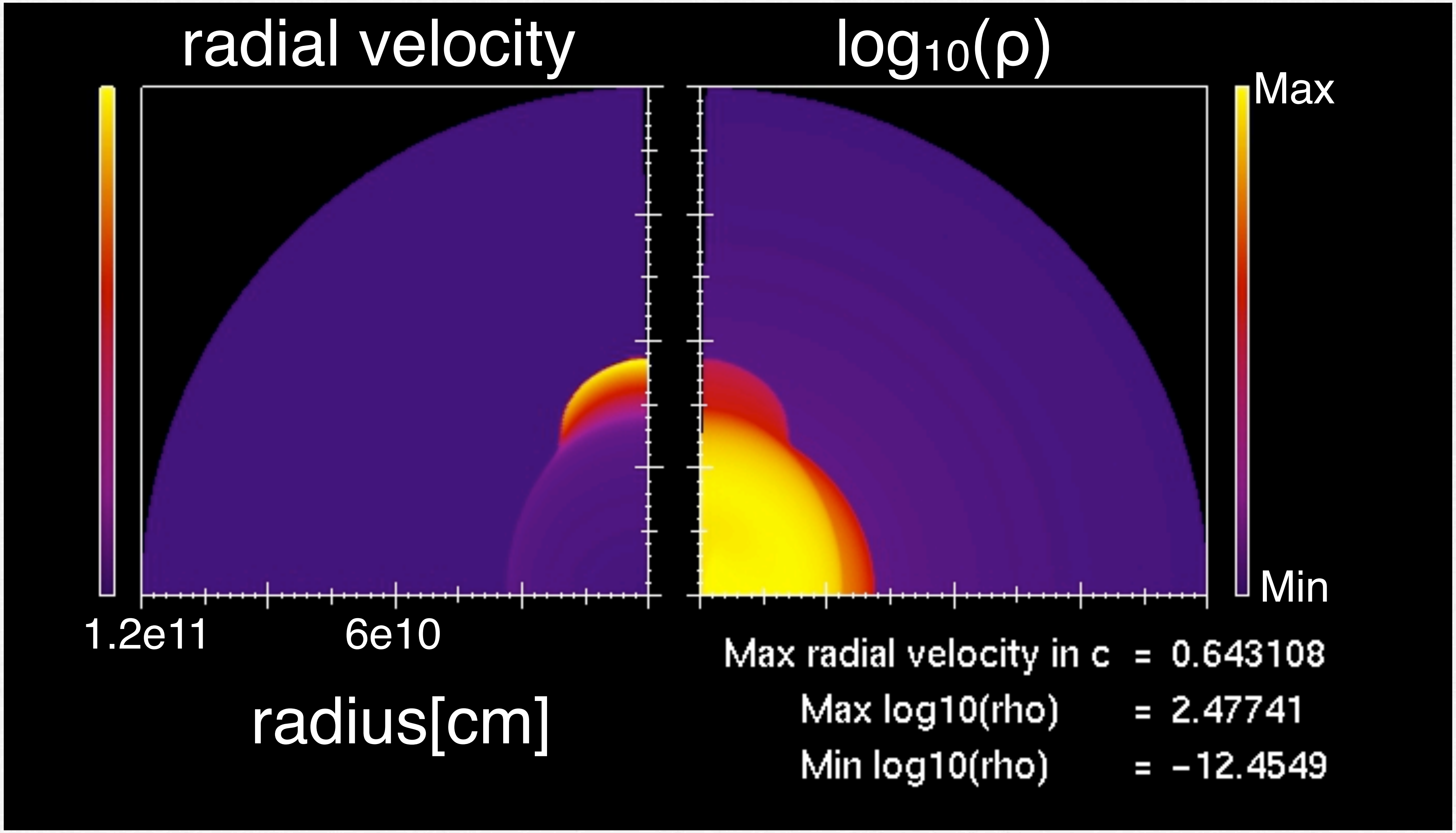

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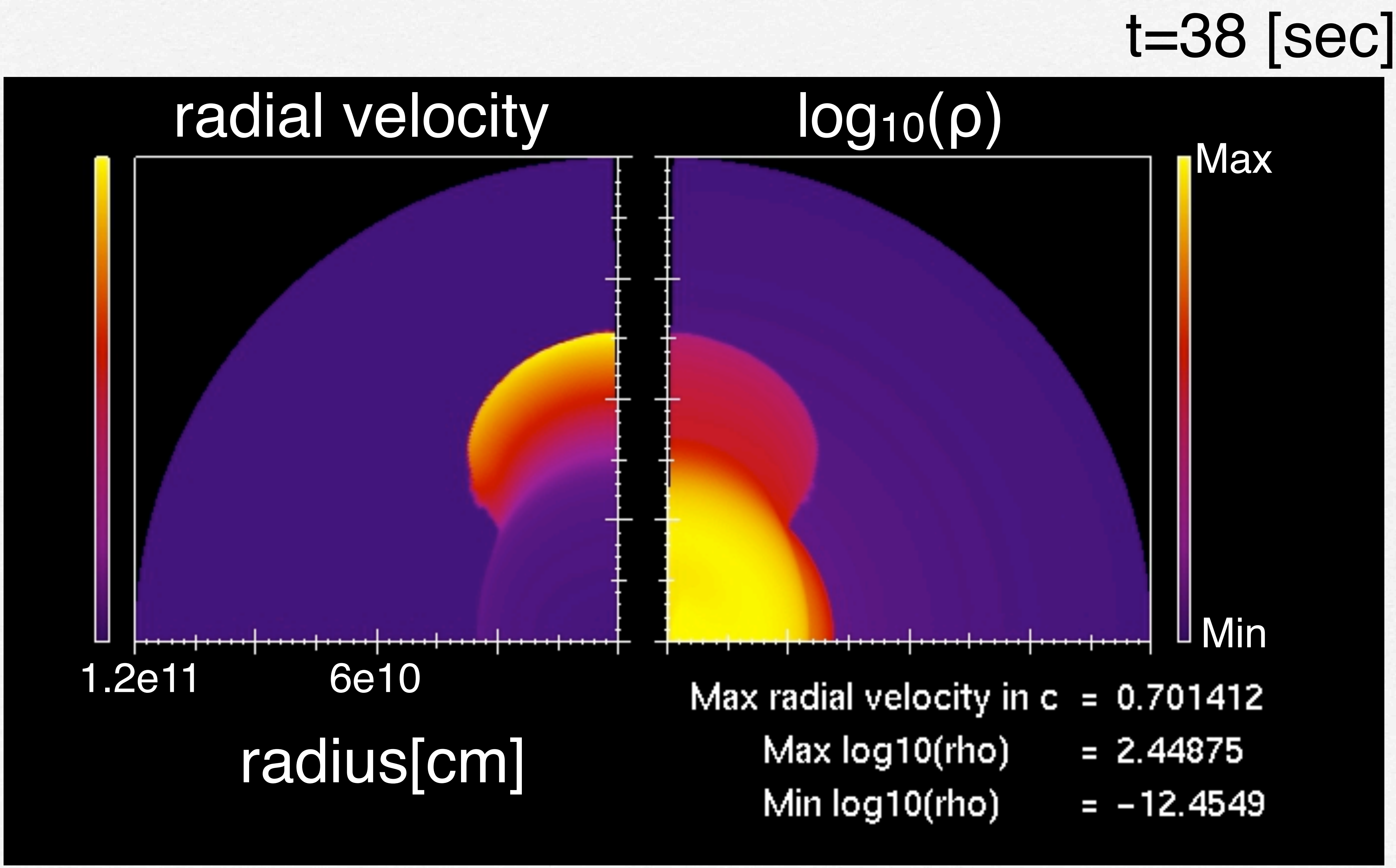

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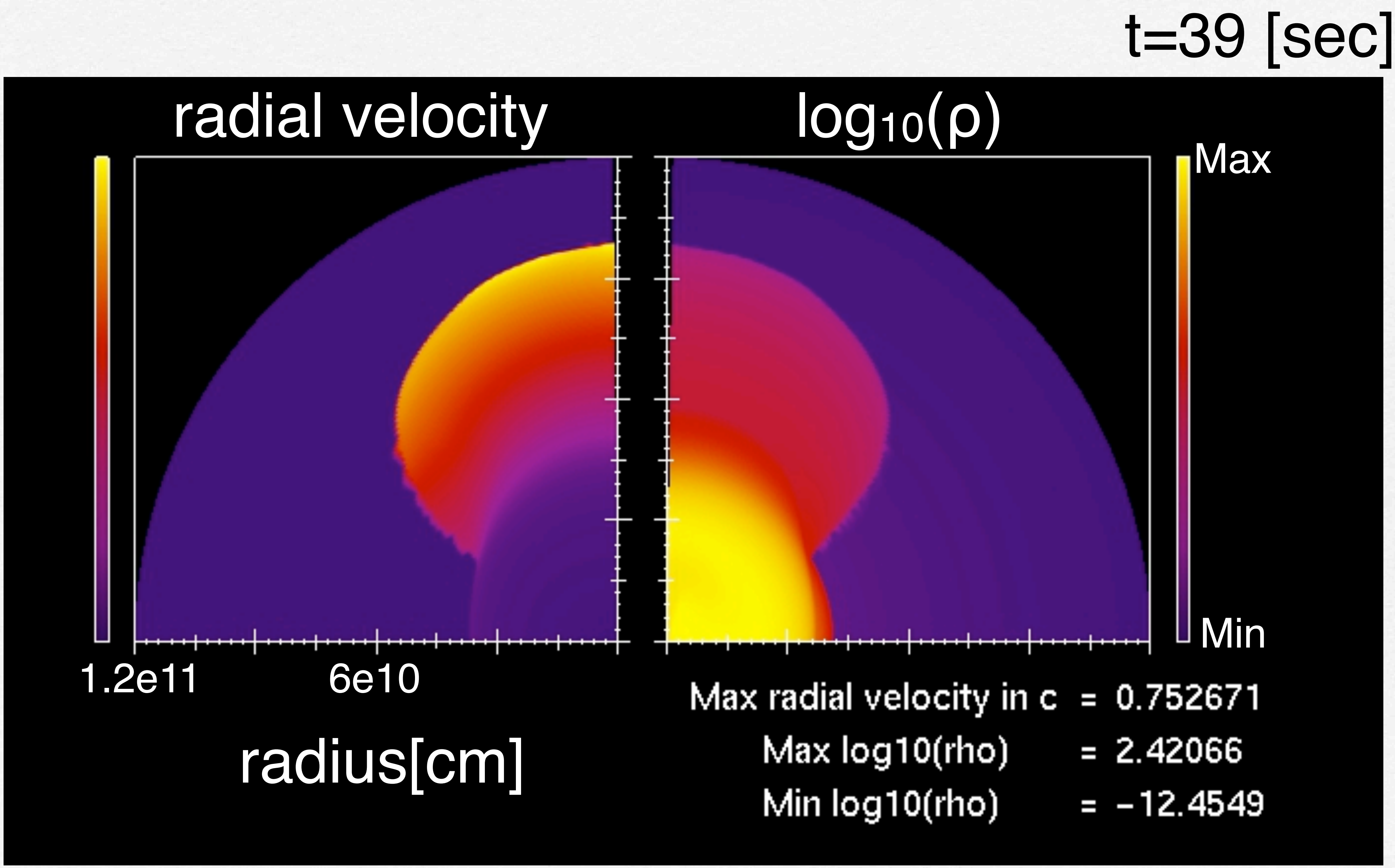


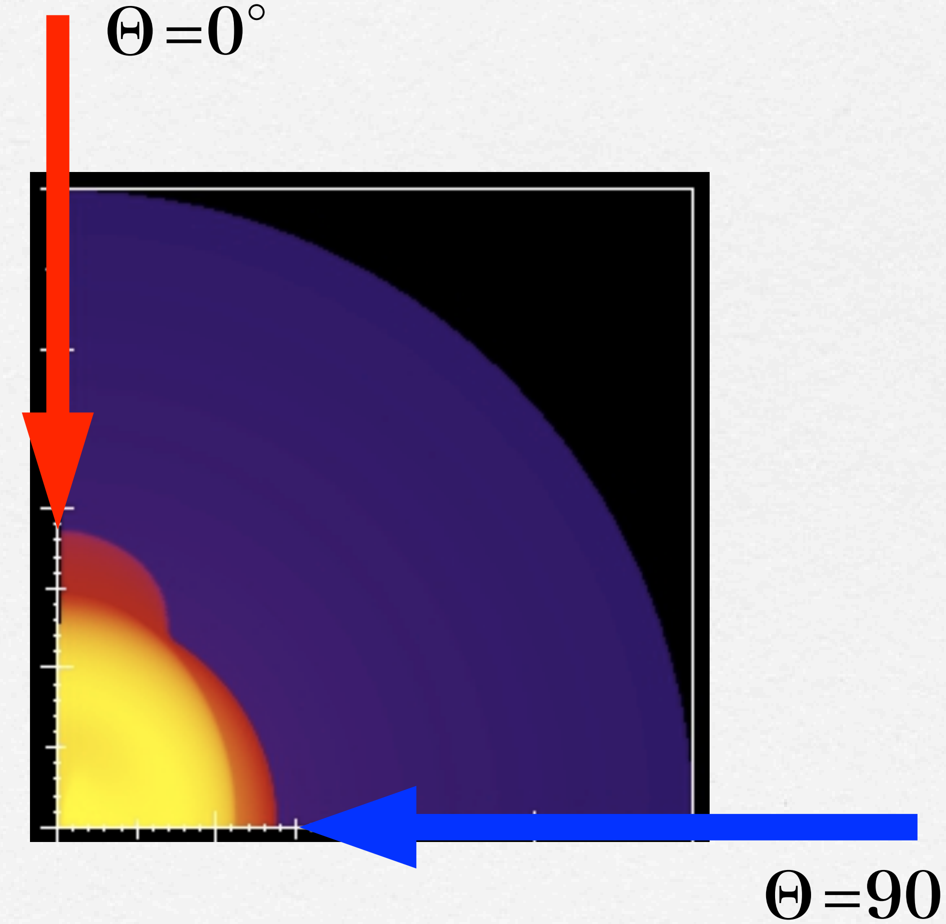
Light curve calculation

- ☑ 2D snapshots are mapped into 3D space.

- ☑ Photospheres from observers with $\Theta=0^\circ$, 90°, are determined by calculation the optical depth (Thomson opacity σ_T is used).

- ☑ The radiation temperature at each point on the photosphere is derived by Pressure = $a_r T^4/3$ (typically, kT~0.1 [keV])

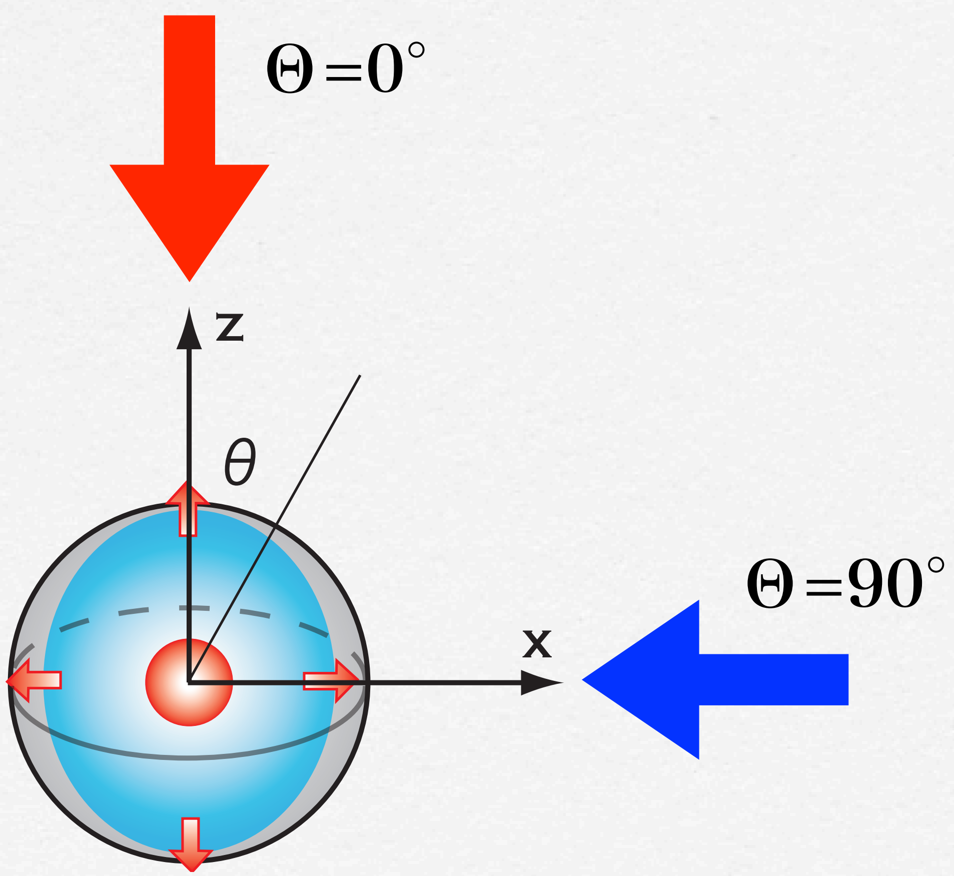
- ☑ Assuming the blackbody radiation from each point, the bolometric light curve is calculated.

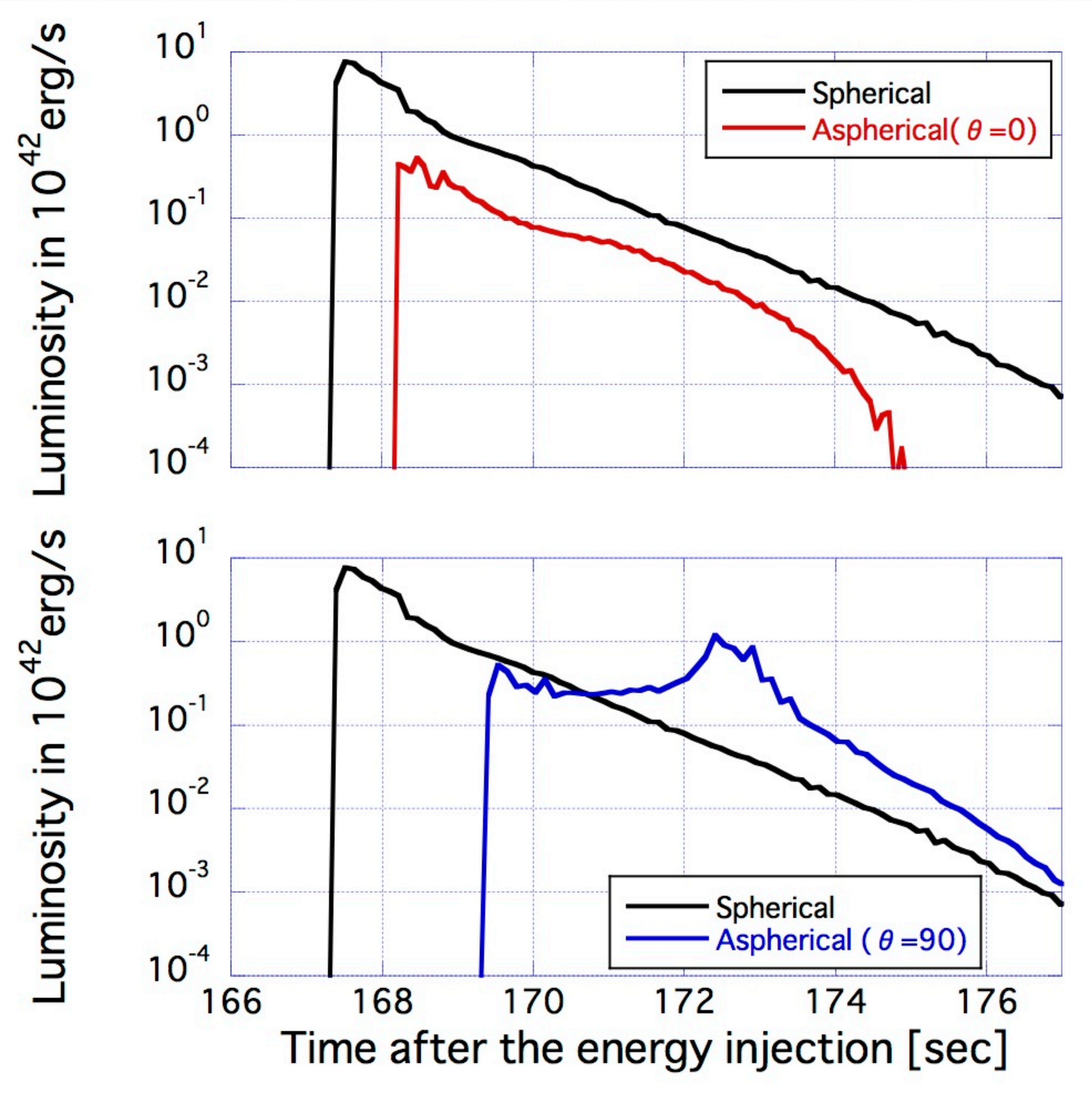


(both observers are at $r=100R_\star$)

Bolometric light curves

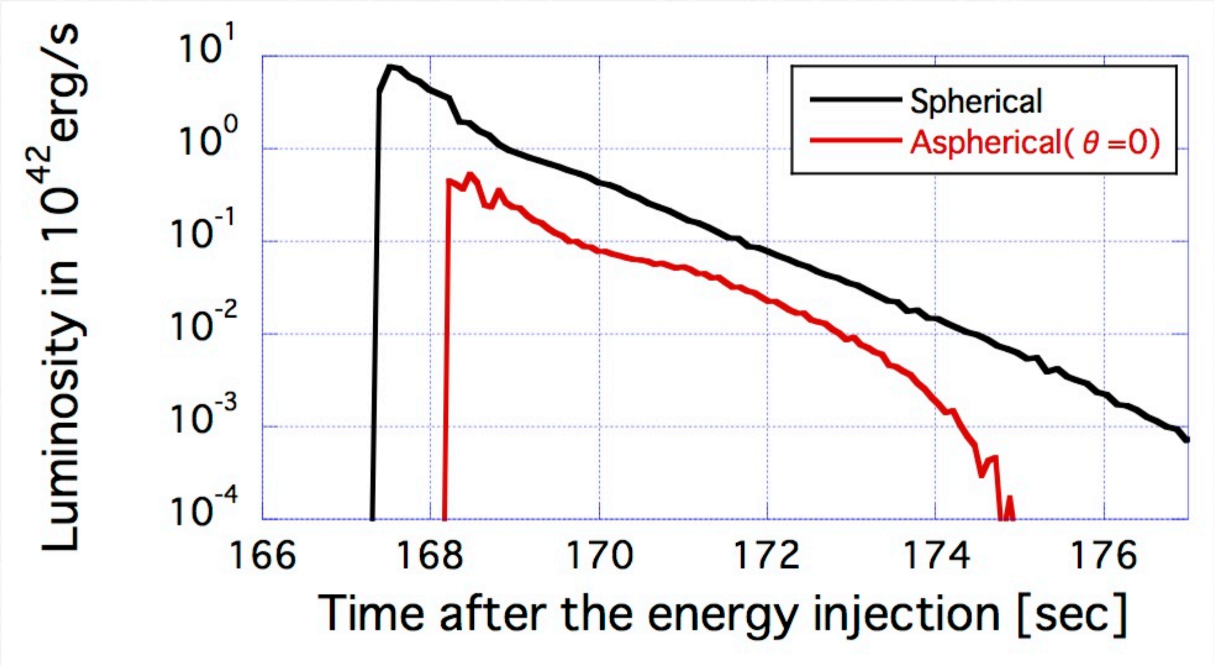
- Black: Spherical
- Red: Aspherical ($\Theta=0^\circ$)
- Blue: Aspherical ($\Theta=90^\circ$)





What makes the difference?

- ☑ Black: Spherical
- ☑ Red: Aspherical ($\Theta = 0^\circ$)
- ➡ under luminous
- ➡ rapid decrease of the luminosity



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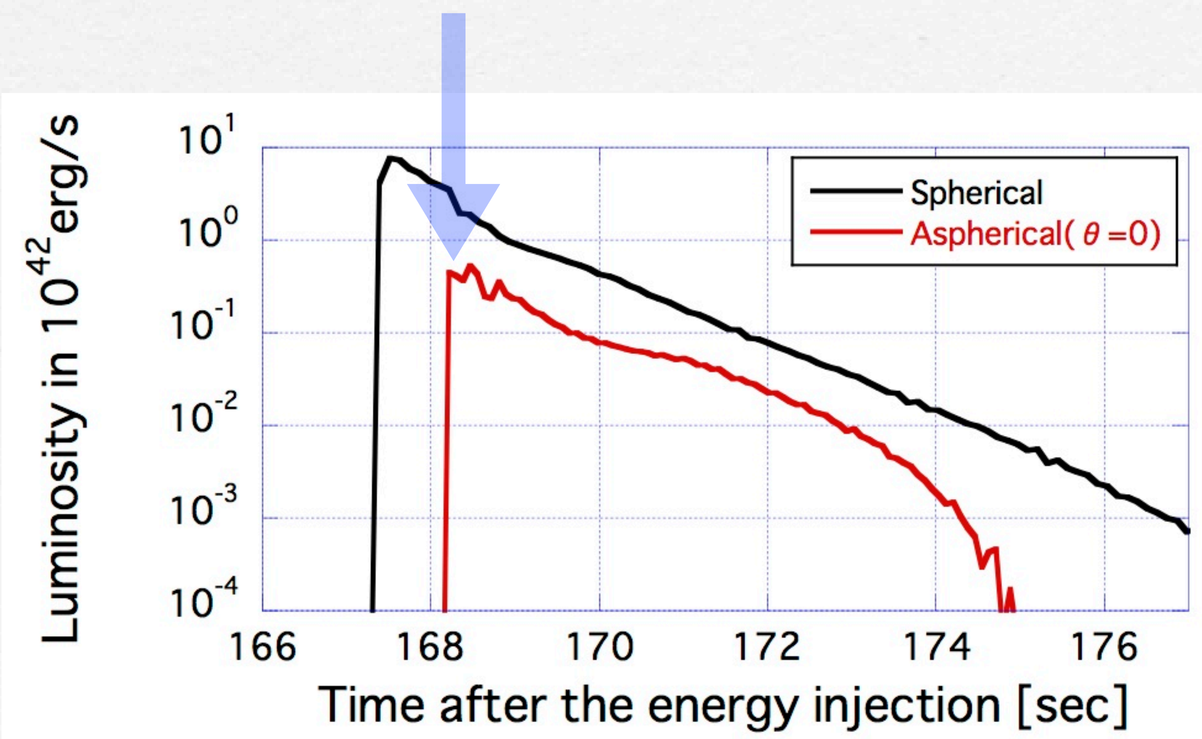
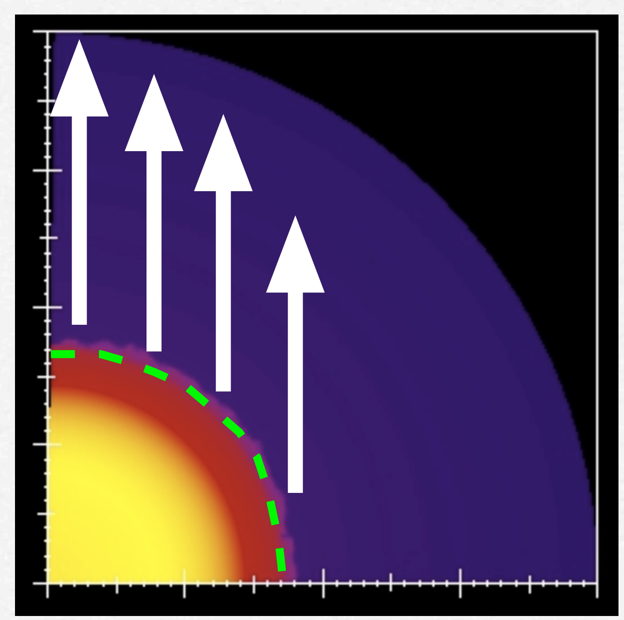
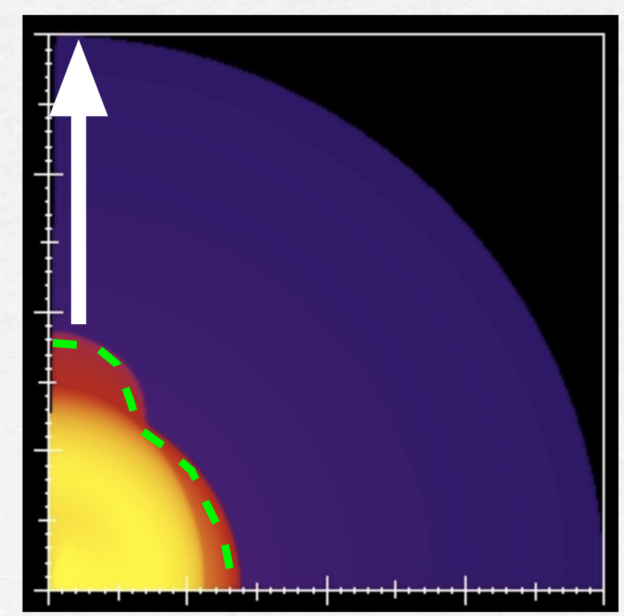




Spherical



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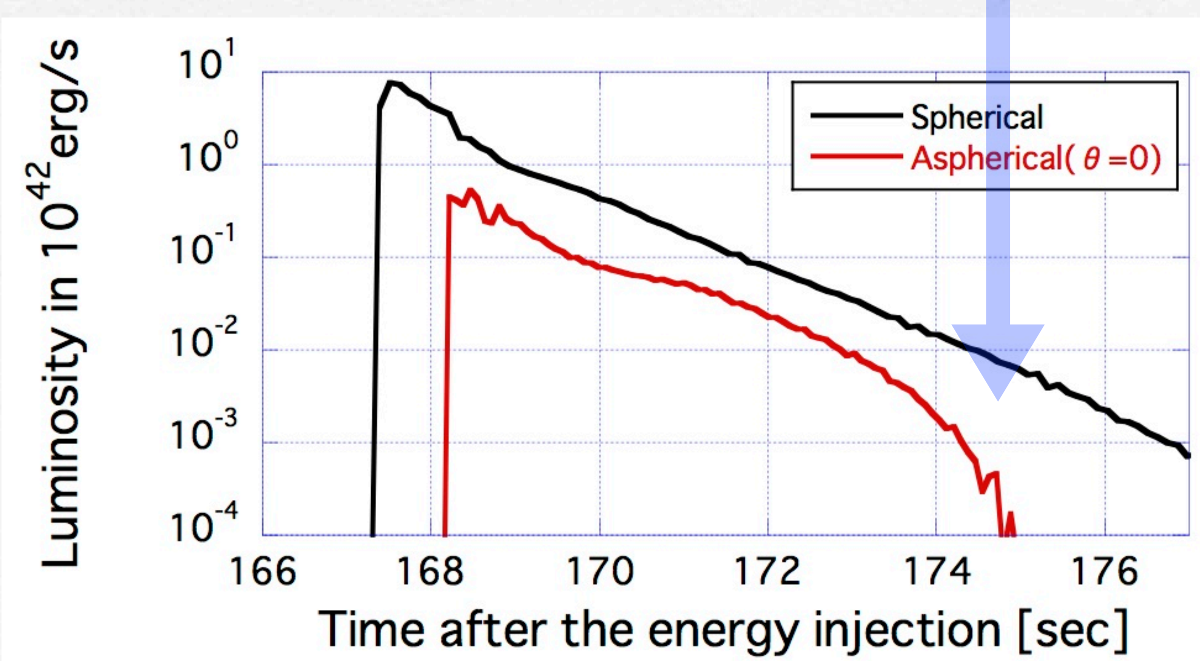

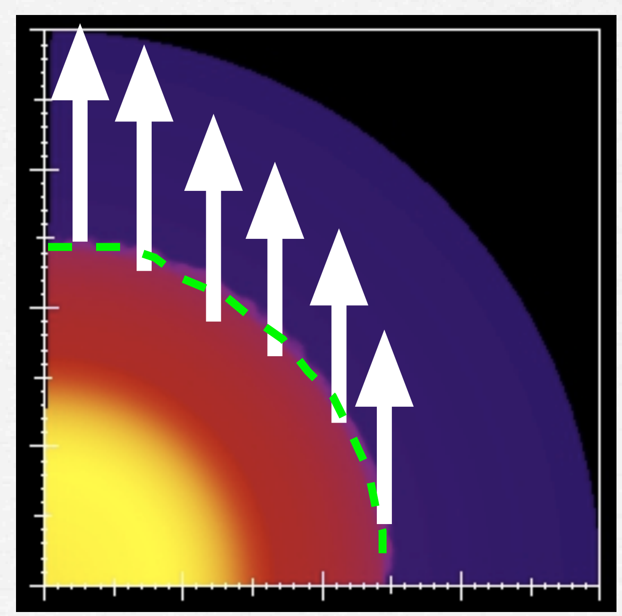

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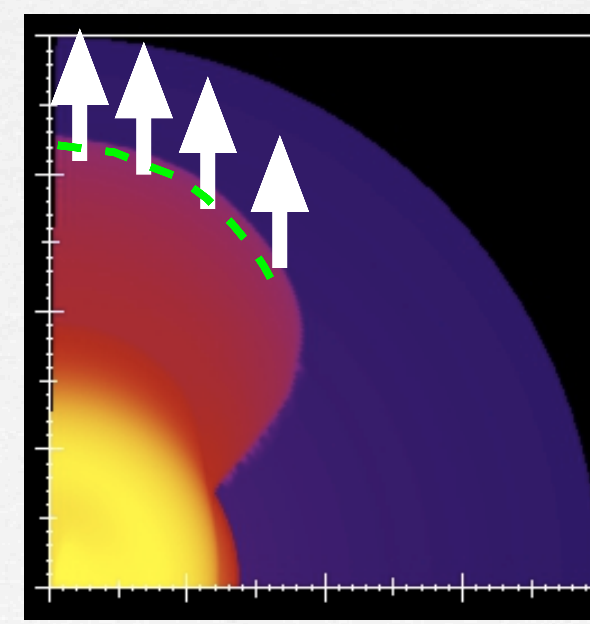

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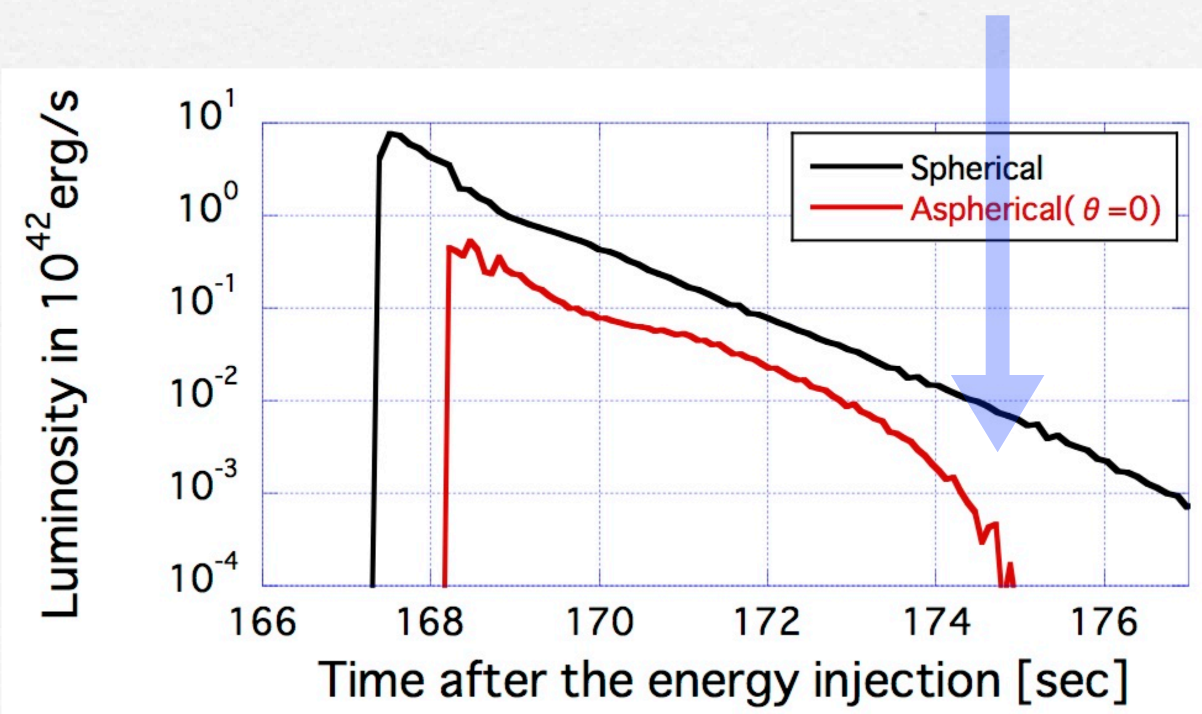

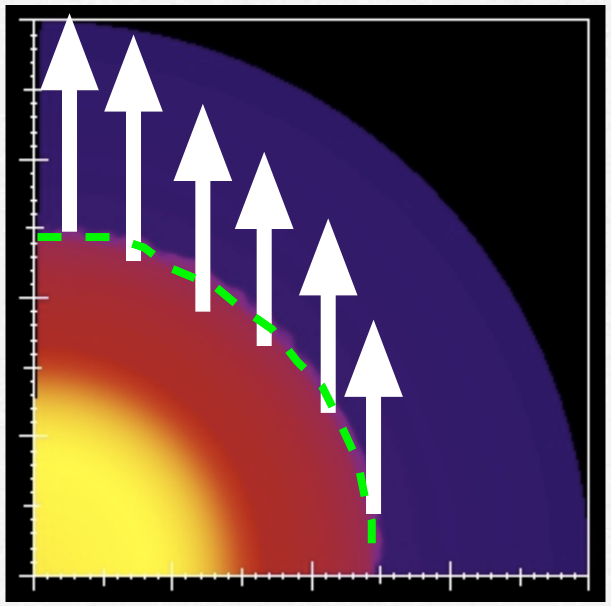

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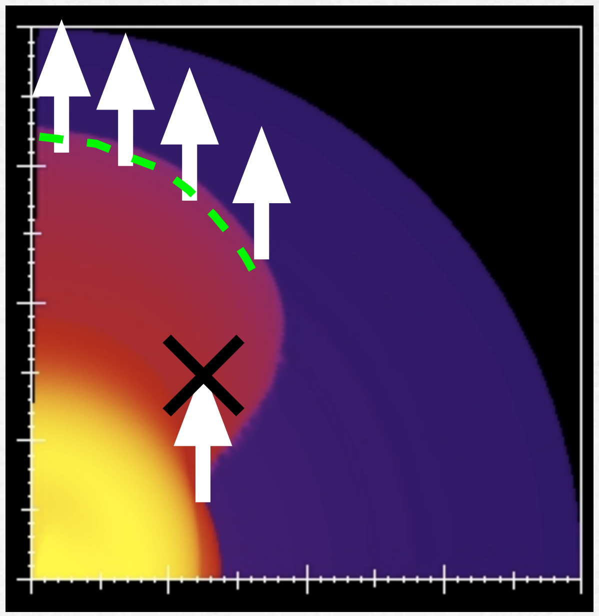
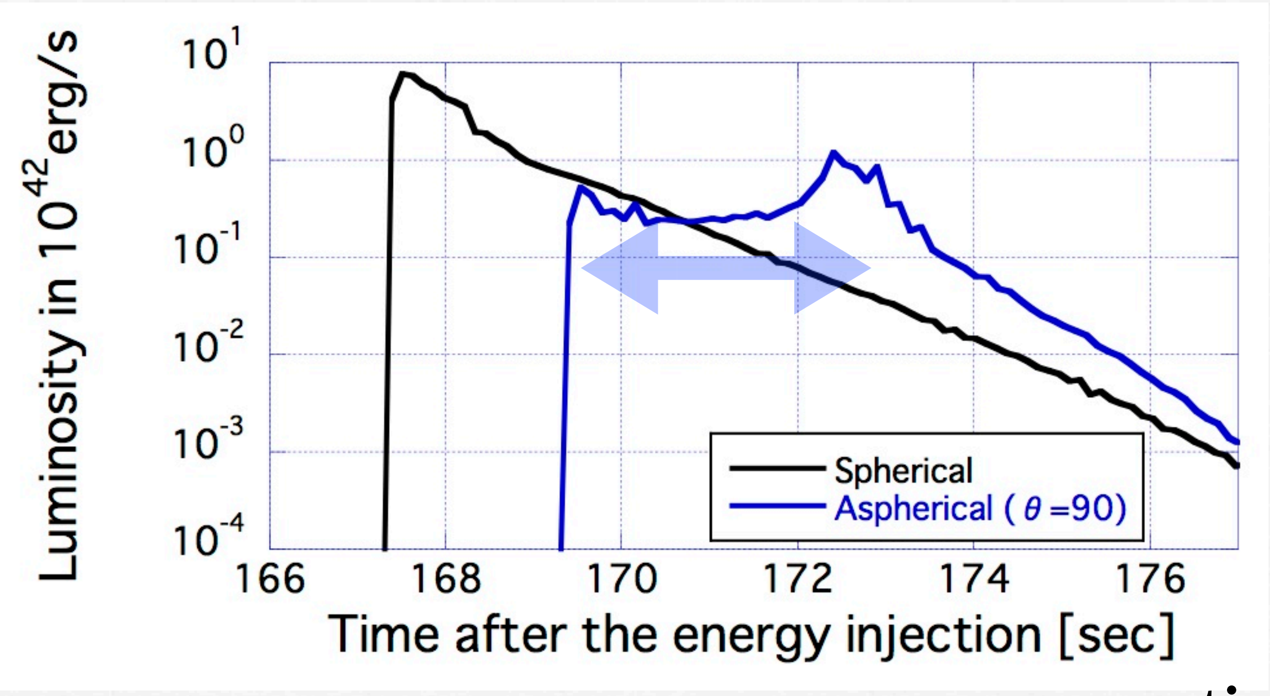
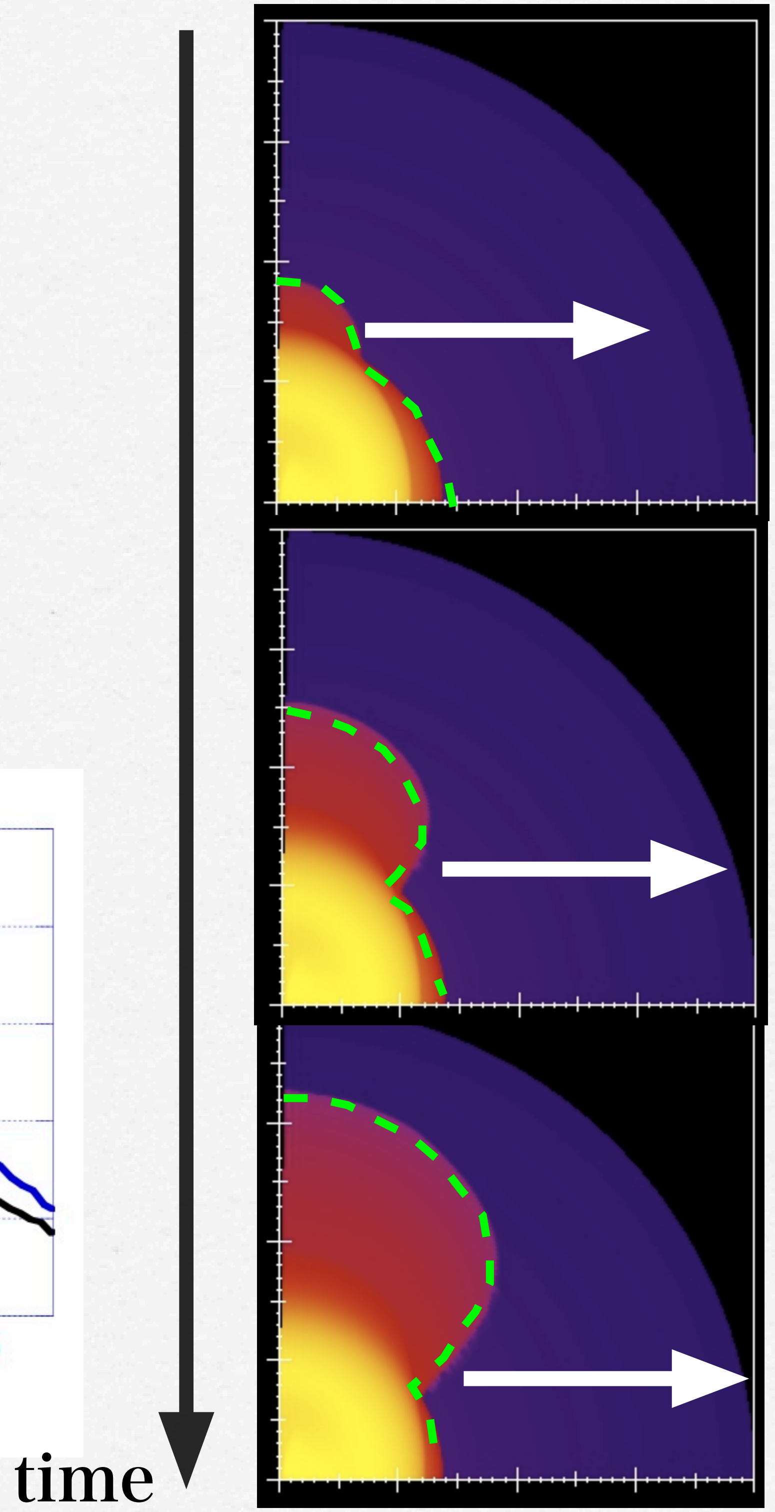


Aspherical

What makes the difference?

- ☑ Black: Spherical
- ☑ Blue: Aspherical (Θ=90°)
- ➡ long duration of the plateau-like part (+ 2nd peak?)





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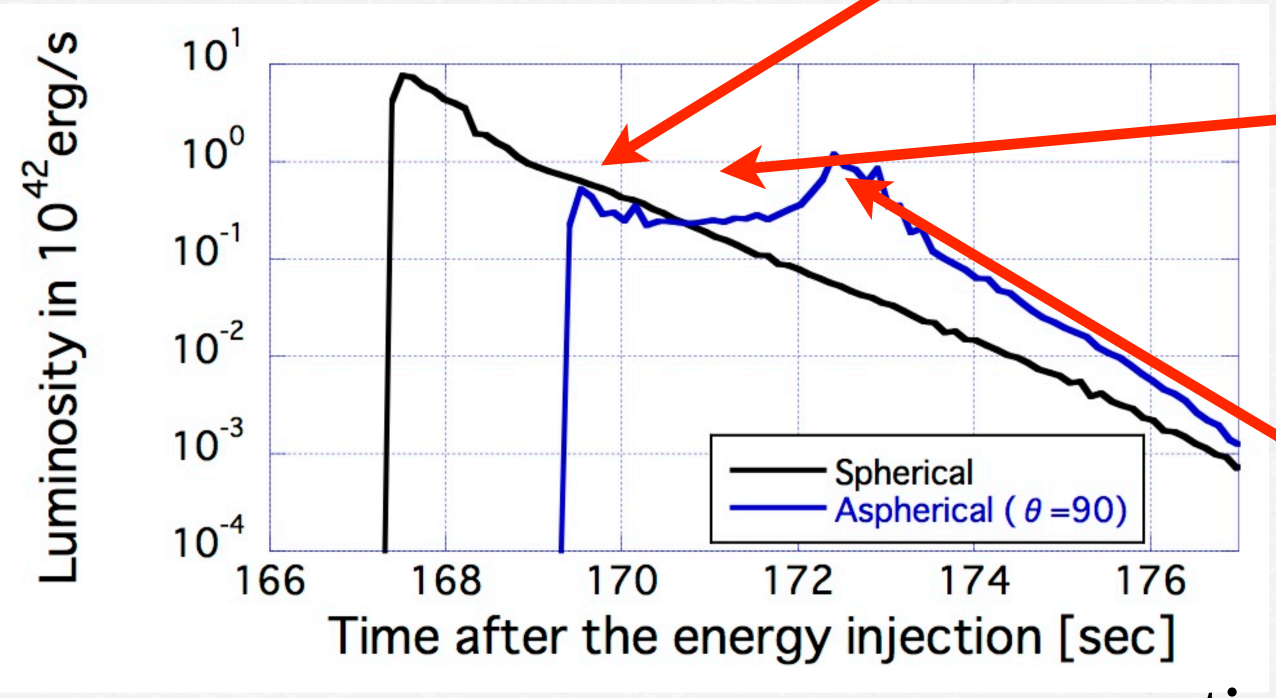

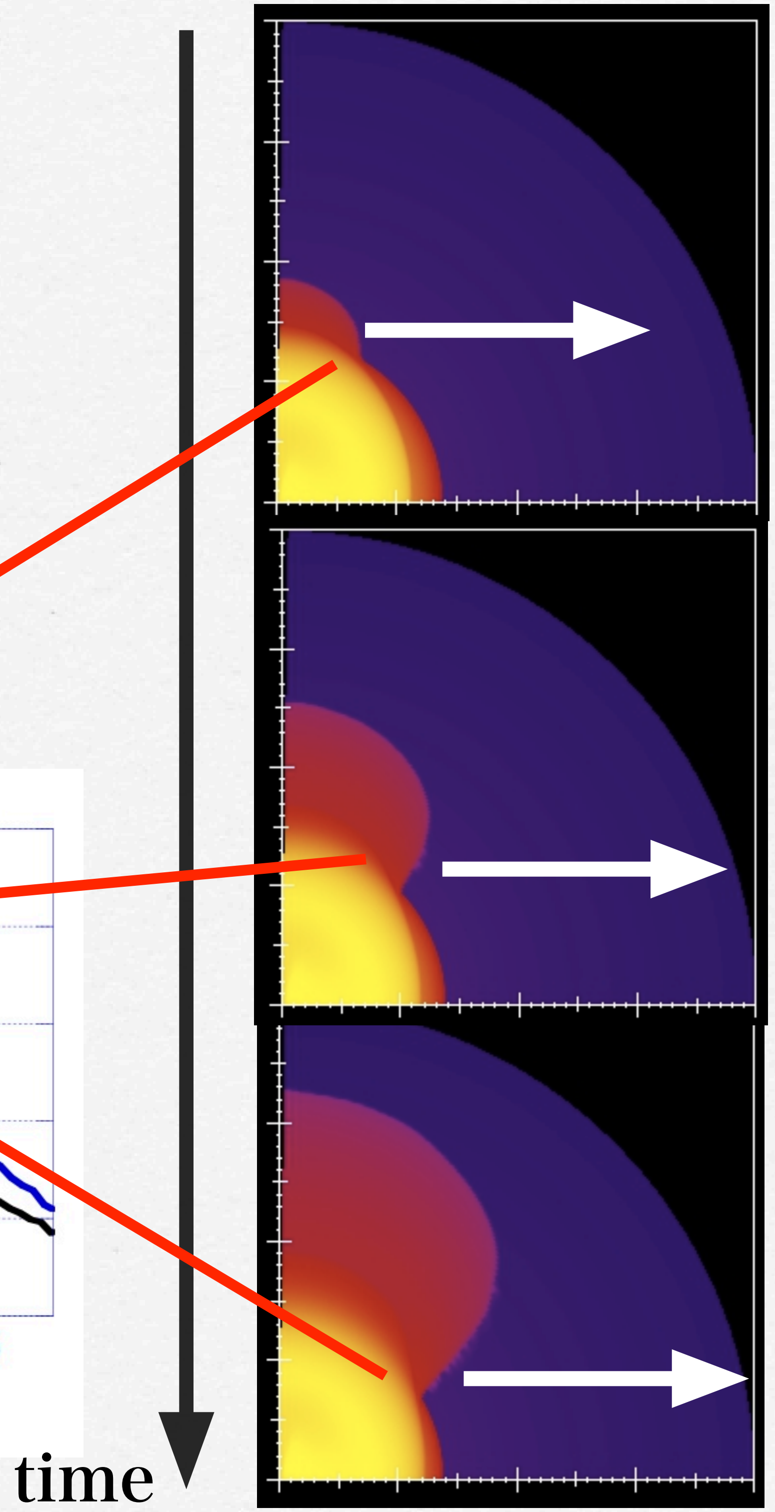

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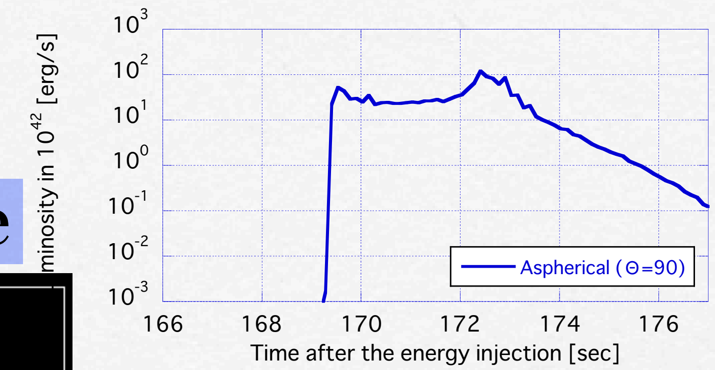
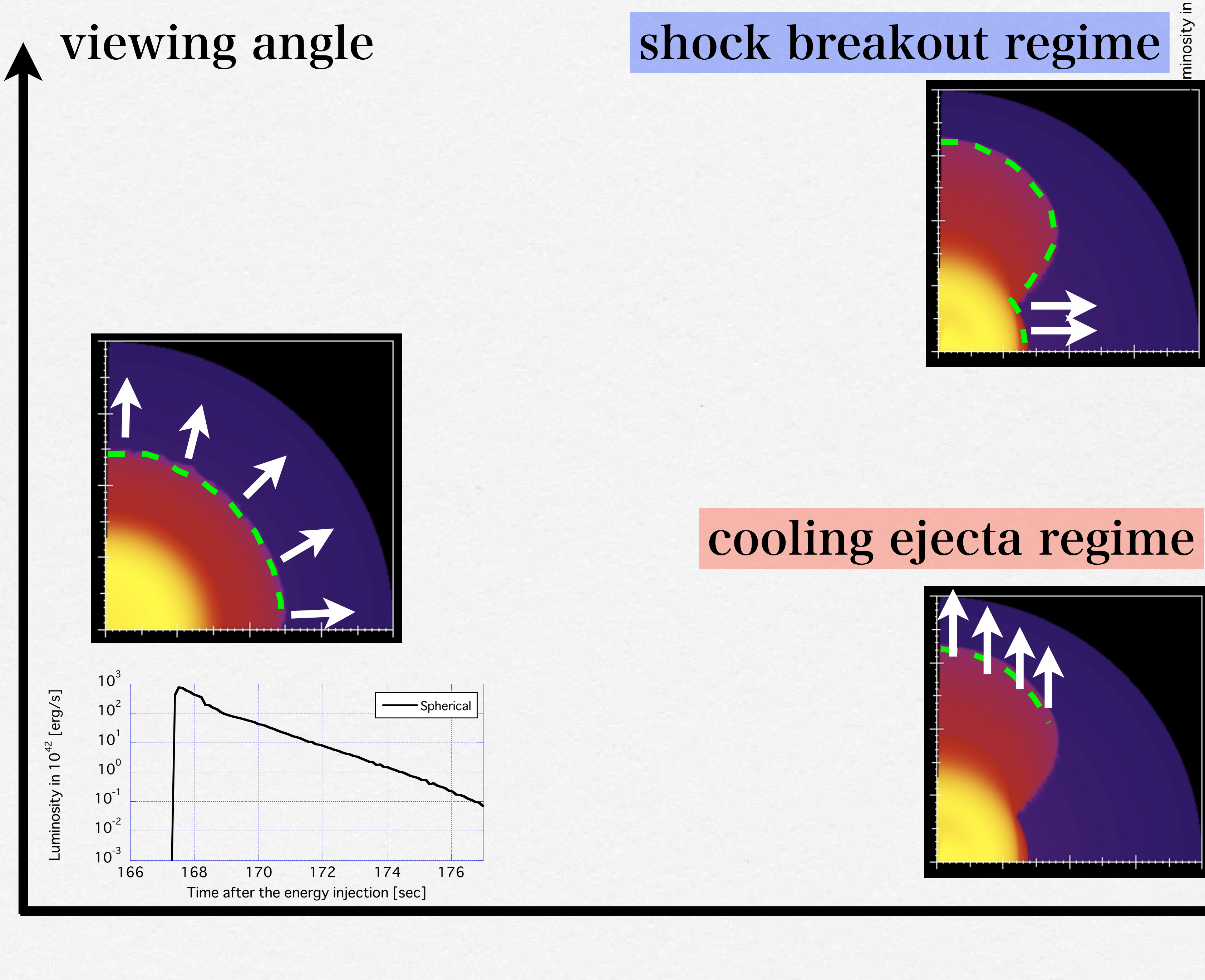
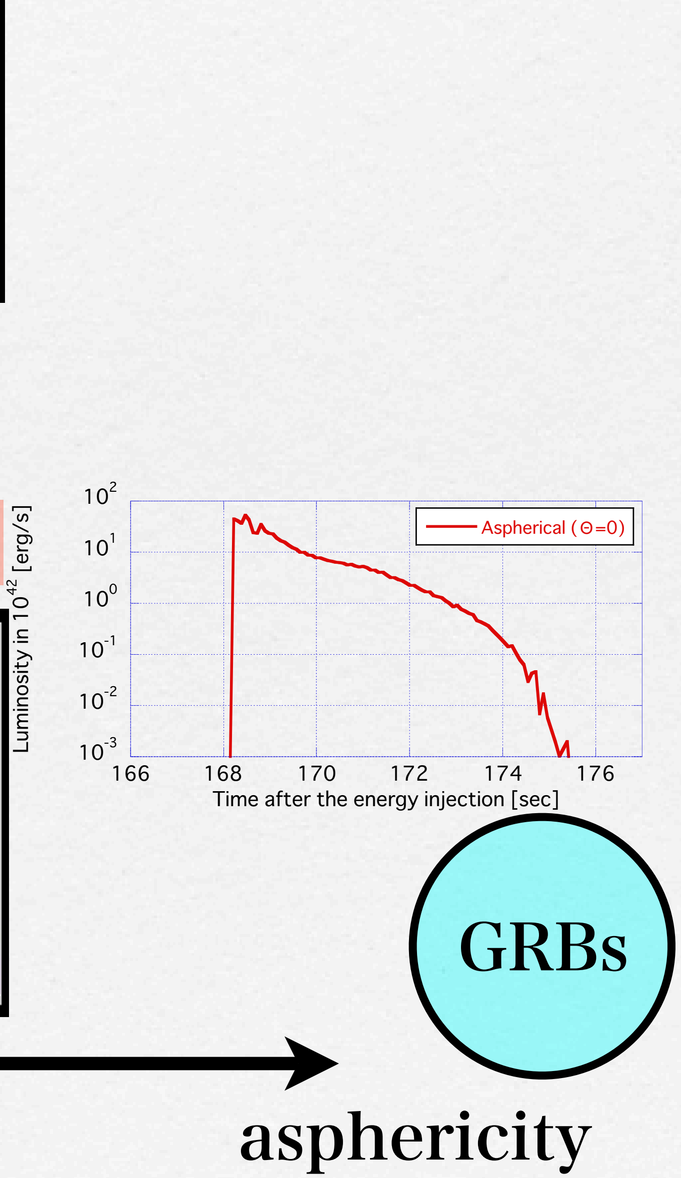




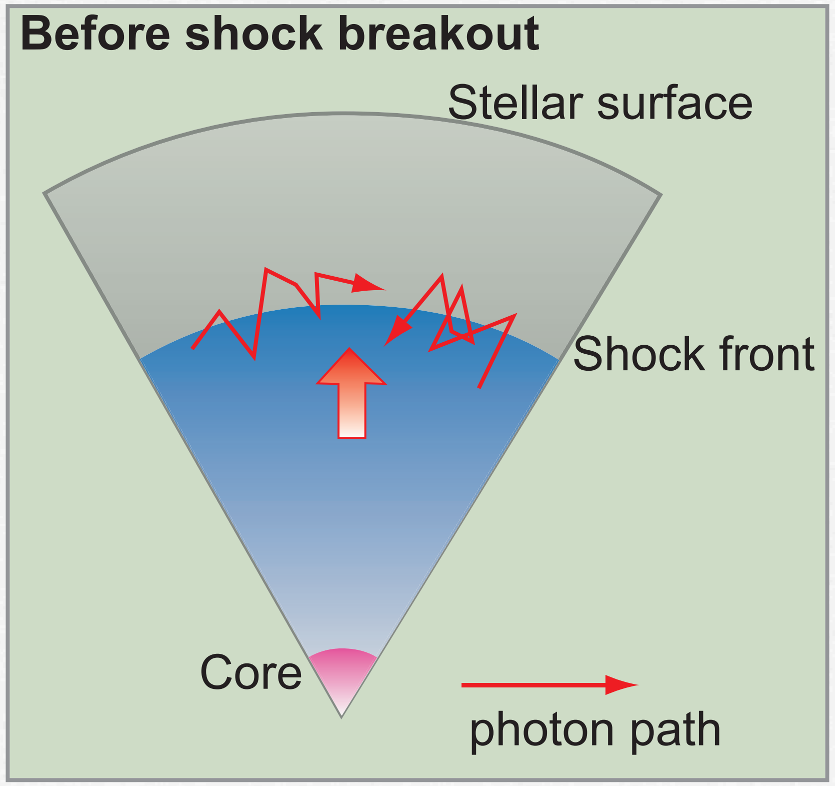


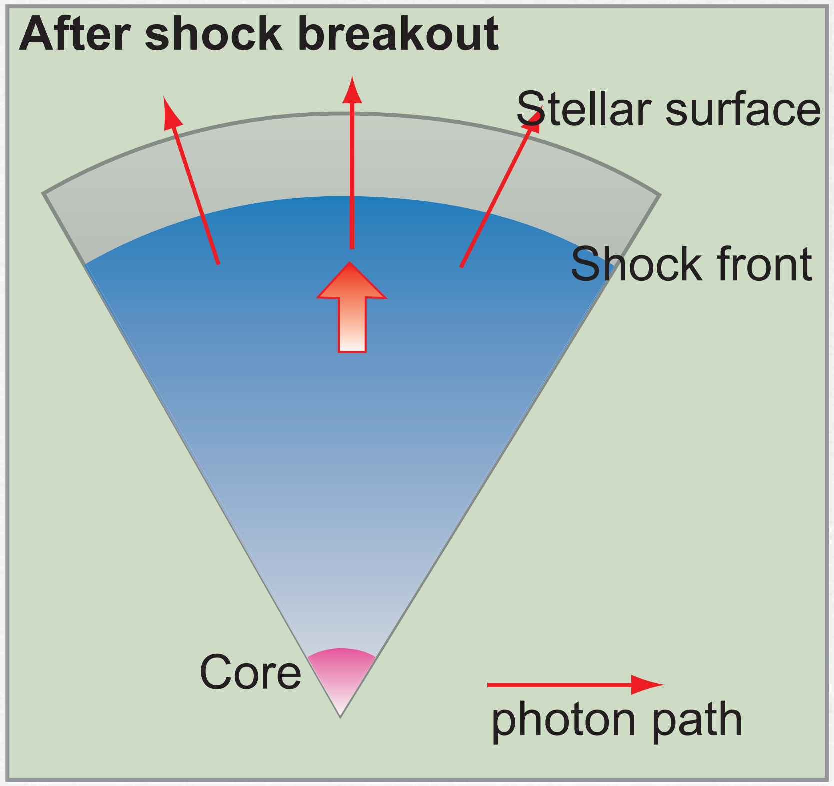
Summary

- We have examined effects of aspherical explosion on shock breakout light curves.
- 2D hydrodynamical calculations + simple blackbody model
- clear differences between the models:
  - ➡ deviation from spherical case
  - ➡ viewing angle effect
- Asphericity is an important factor to determine the shape of shock breakout light curves
- There are some effects which we need to consider:
  - ➡ more sophisticated emission model (e.g., Katz et al. 2010)

SN shock breakout

- UV/X-ray flash that occurs at the moment of the emergence of the shock wave from the stellar surface.
- In the case of CCSNe, a radiation-mediated shock propagates in the stellar envelope.
- After the shock breakout phase, we can observe supernovae by electromagnetic radiation.



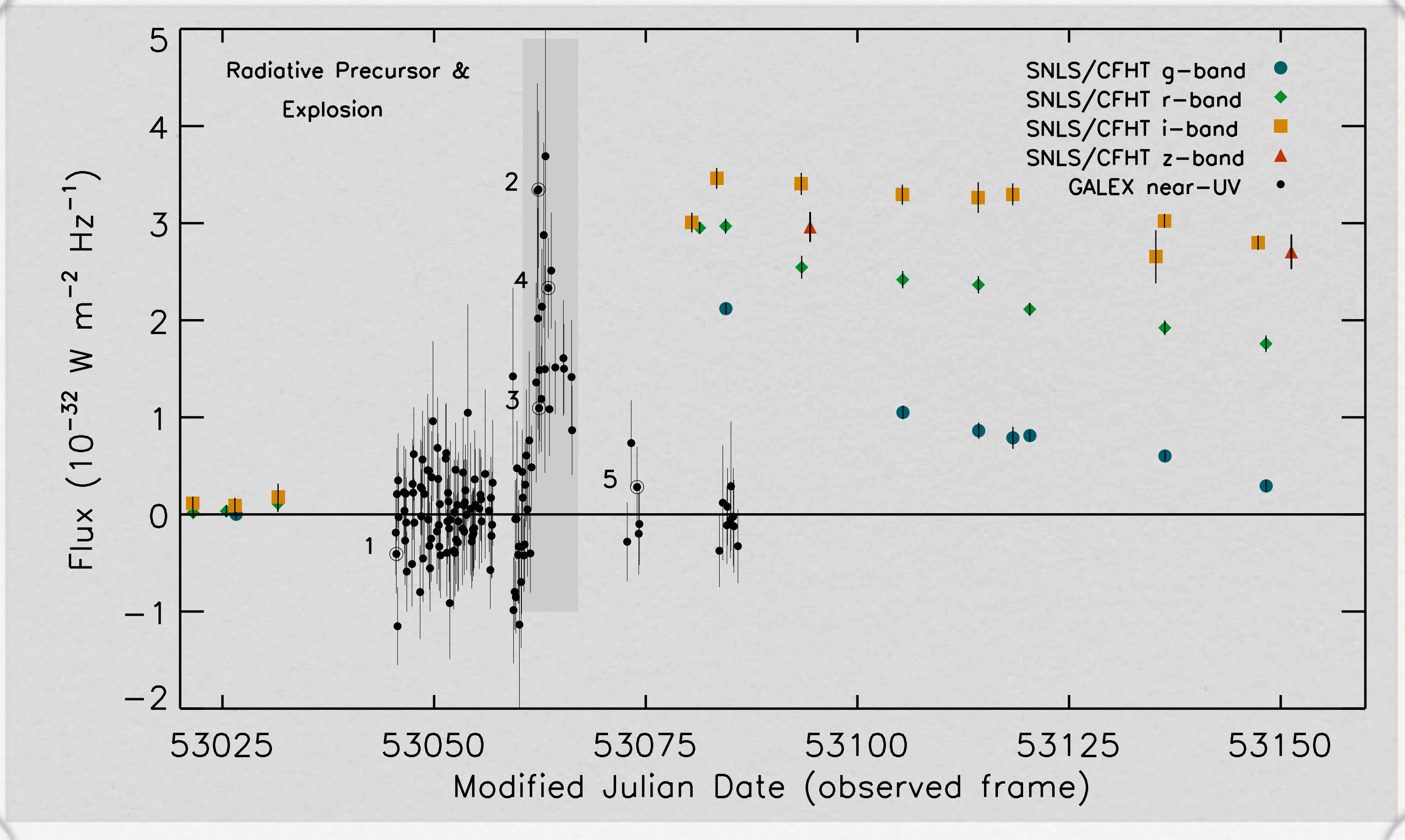


Examples: SNLS-04D2DC

- discovered by Supernova Legacy Survey

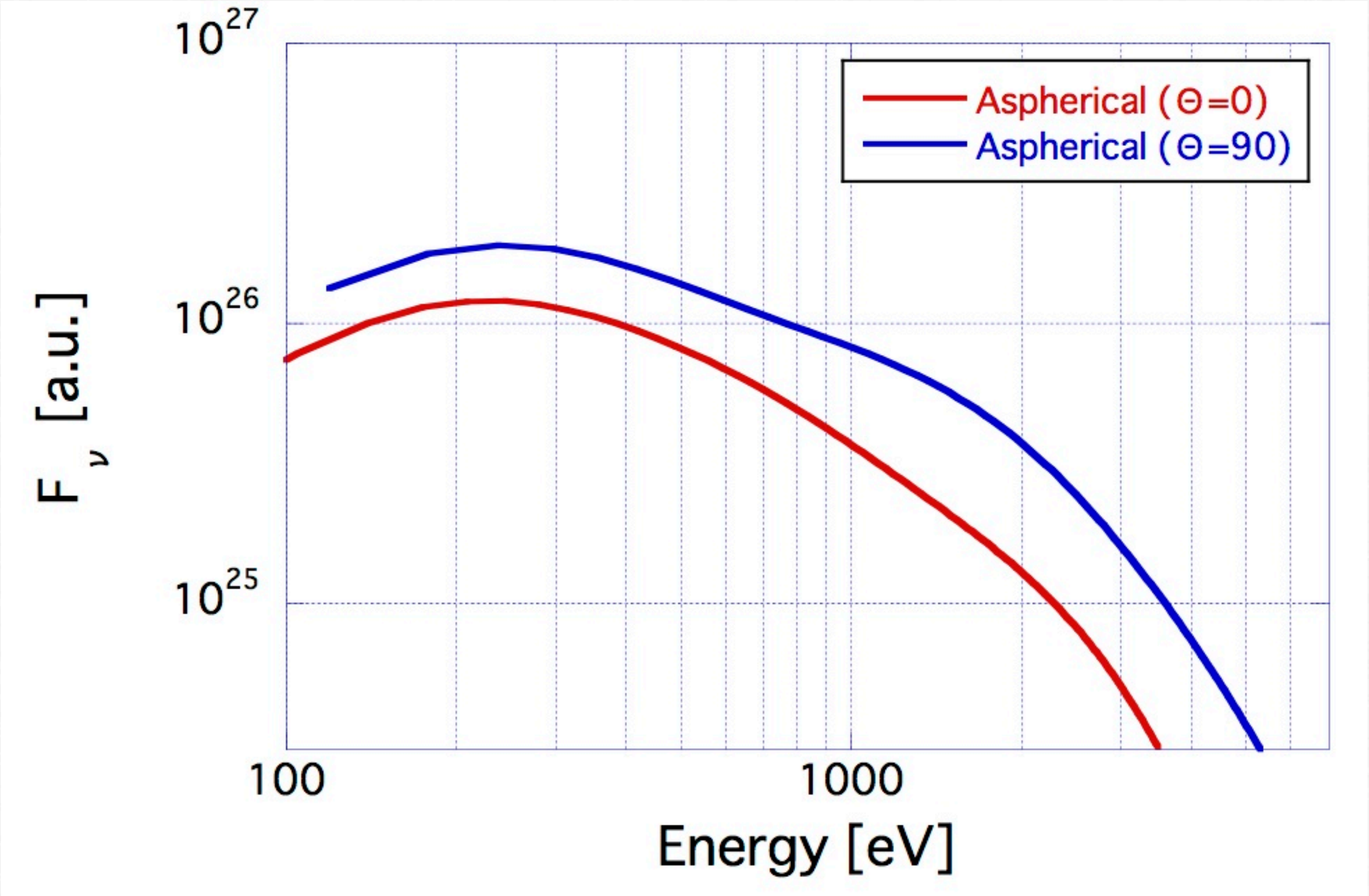
- Association of a UV flash with the birth of the SN.

Schawinski+(2008)



Spectrum

- Multi-color blackbody
- Similar behavior for both models



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