Galactic Center, Colliding Wind Binaries, & Gamma-ray Binaries:

Hydro simulations to do with Phantom

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Phantom Workshop Feb 21, 2018

Common theme: Colliding Massive-star Winds

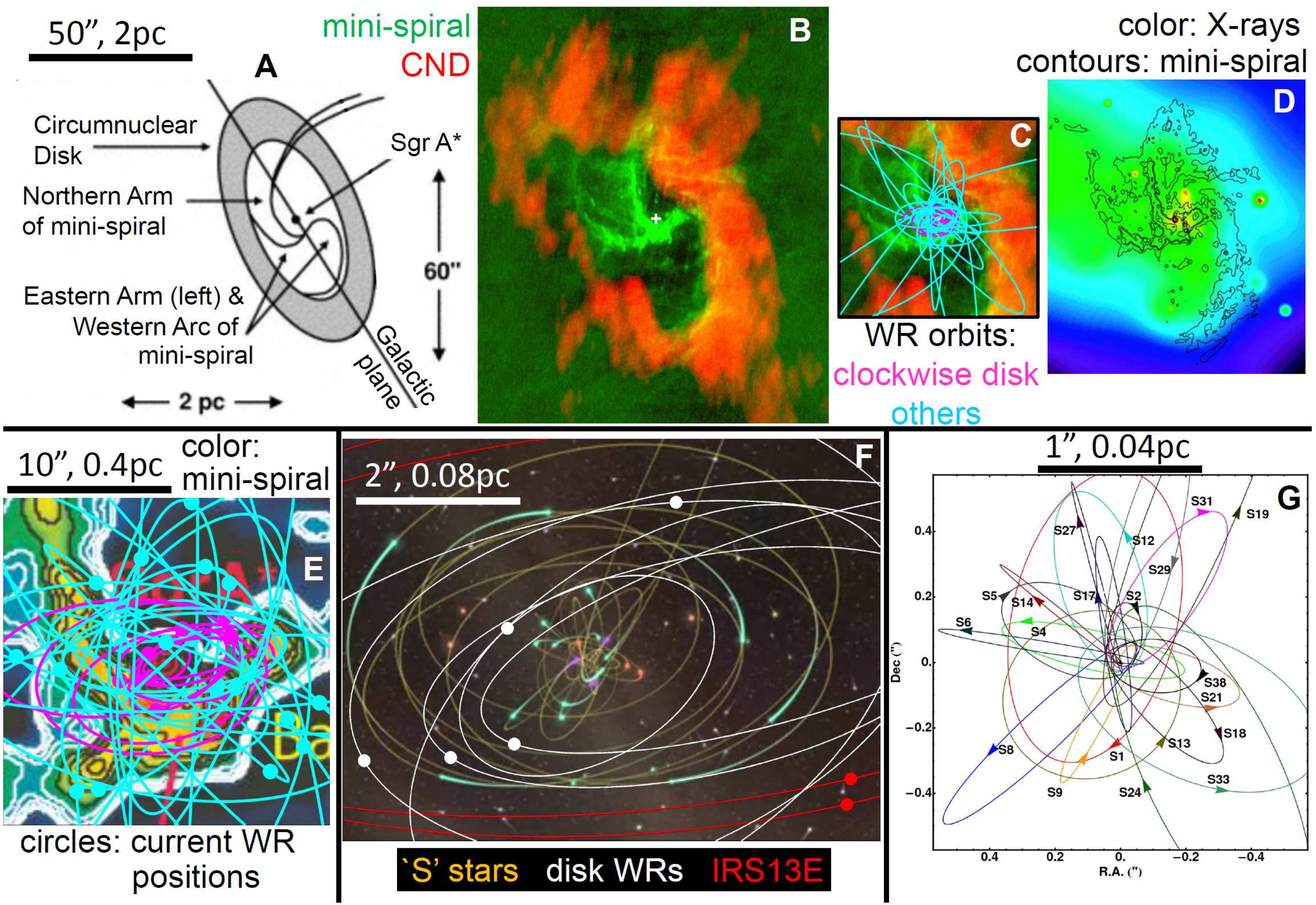
- 3 types of astrophysical sources

- Highlight some pre-Phantom work

- Discuss planned improvements and/or shortcomings of old code, which hopefully can be overcome with Phantom

1. Galactic Center

- Only Galactic nucleus/super massive black hole (SMBH) where spatially resolving elements within ~central parsec is possible
  - Stars: ~30 Wolf Rayets (evolved massive stars), ~100 O, ~dozens 'S' stars
    - All of these have stellar winds
  - Gas structures: mini-spiral (~few x 10^2 Msun), circumnuclear disk (~10^5 Msun)



Baganoff+03
Cuadra+08
Ferrière12
Gillessen+09
Paumard+06
Tsuboi+16
Yelda+14

1. Galactic Center

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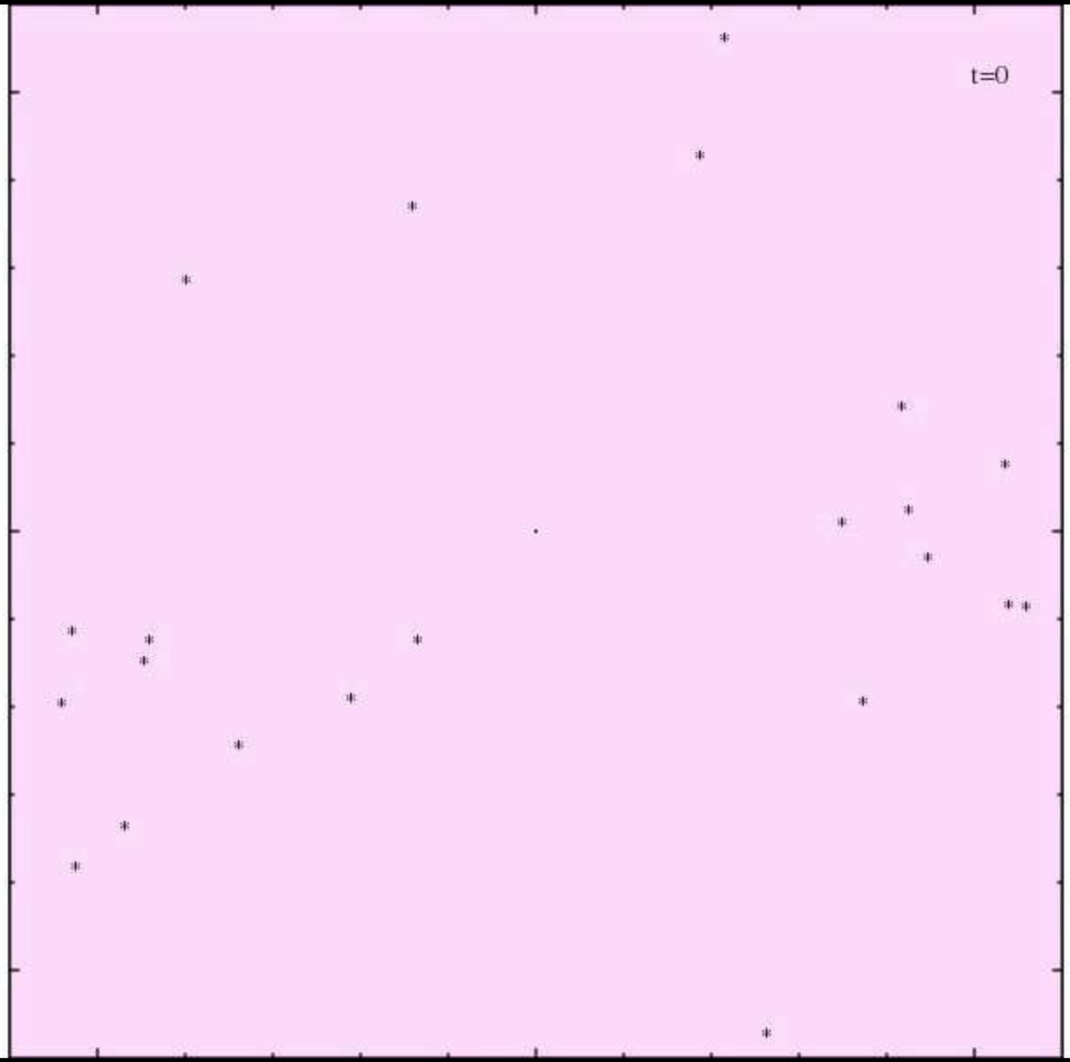
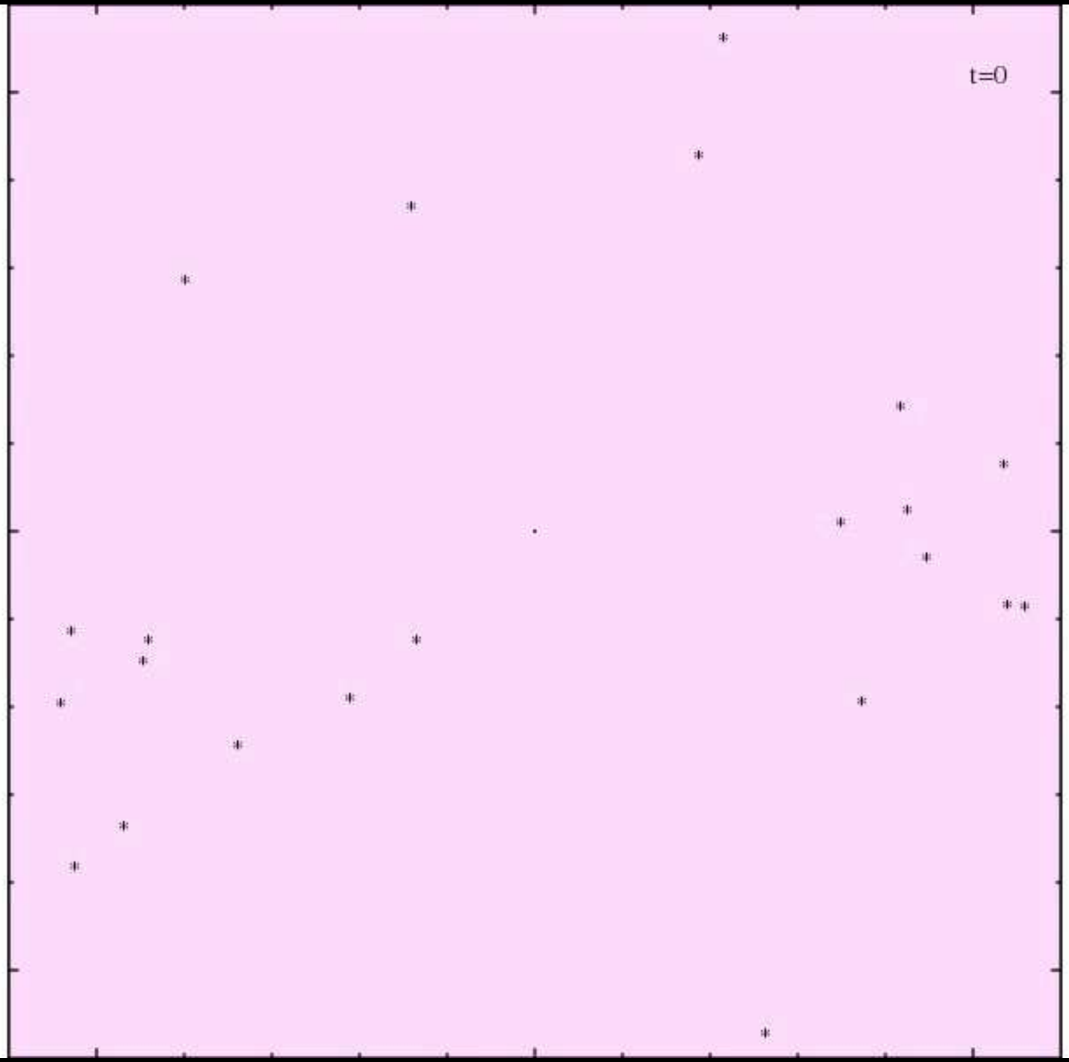
- Present models:
  WRs & SMBH (Cuadra+08)
  WRs & SMBH with various SMBH feedback/outflows (Cuadra+15)
- Observational success: thermal X-ray emission (Russell+17)
  - Requires SMBH to undergo outburst to clear out hot gas around Sgr A*

Sgr A* Outflow (Cuadra+15)

radiatively inefficient accretion flow (RIAF) (Wang+13)
increased X-ray activity in past (Ponti+10)





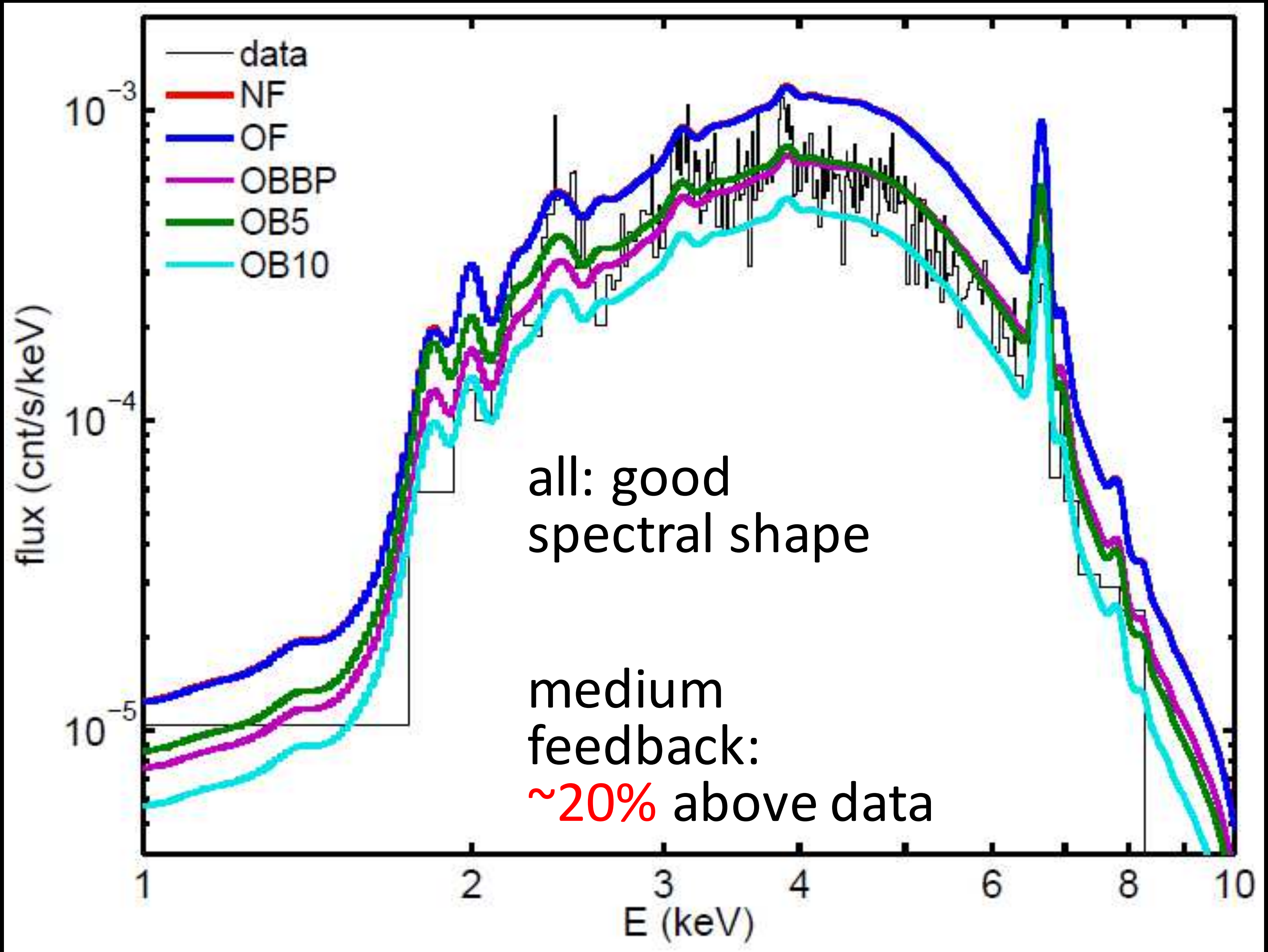
v_out = 5,000 km/s
medium

Mdot_out = 1e-4 M_{sun}/yr
t_out = 400 to 100 yr ago

v_out = 10,000 km/s
strong

X-ray Spectra: Models vs. Data (Russell+17)

Observation:
Chandra X-ray Visionary Program (Wang+13)



X-ray radiative transfer done in Splash (Price07)

Galactic Center

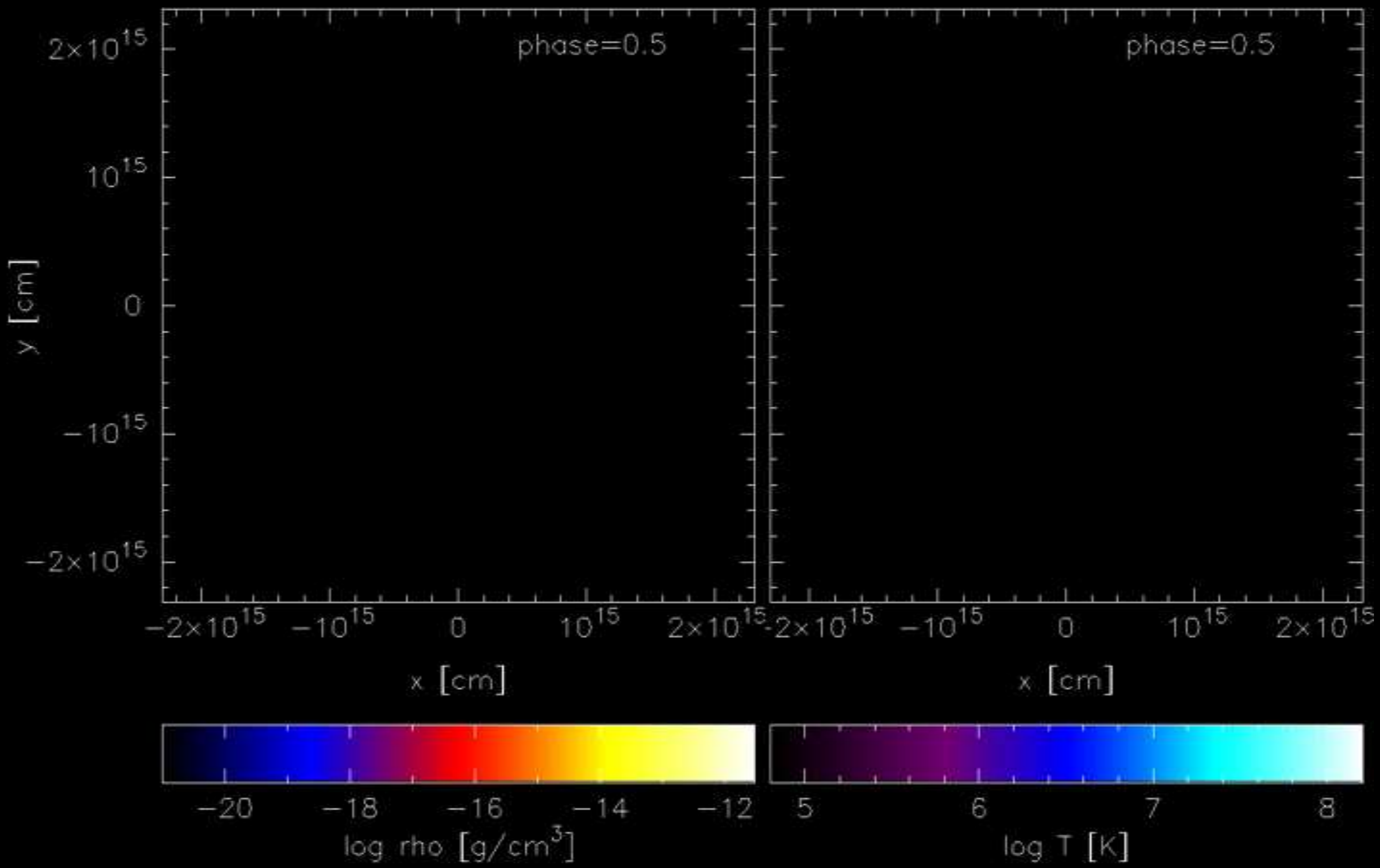
- Outstanding questions
  - Cause of SMBH outbursts
  - Accretion flow properties: components & time variation
- New simulations: incorporate missing components

Galactic Center

- Outstanding questions
    - Cause of SMBH outbursts
    - Accretion flow properties: components & time variation
- New simulations: incorporate missing components
- Adding O and ‘S’ stars: straightforward since same as WR process
- Adding mini-spiral & circumnuclear disk (CND):
  NOT straightforward due to large mass
    - Equal mass particles would severely underresolve stellar winds
    - Option 1: 3 particle types with different masses – wind, mini-spiral, & CND
    - Option 2: gradient in particle masses of mini-spiral & CND
        - Boundaries of these structures have low m_part to interact well with wind particles
        - m_part increases towards center of these structures to make computation feasible
        - good idea?

2. Colliding wind binaries

- Massive star + massive star (O, B, WR, Luminous Blue Variable [LBV])
- Mass-loss key feature of stellar evolution
- Collision of winds → thermal X-rays → independent diagnosis of mass-loss
- Test of shock physics, too
- Hydrodynamic models that incorporate:
  - Injection of particles just outside stellar radii
  - Acceleration of winds particles
  - Radiative cooling
  - Different abundances of winds (if needed; e.g. WR+0)



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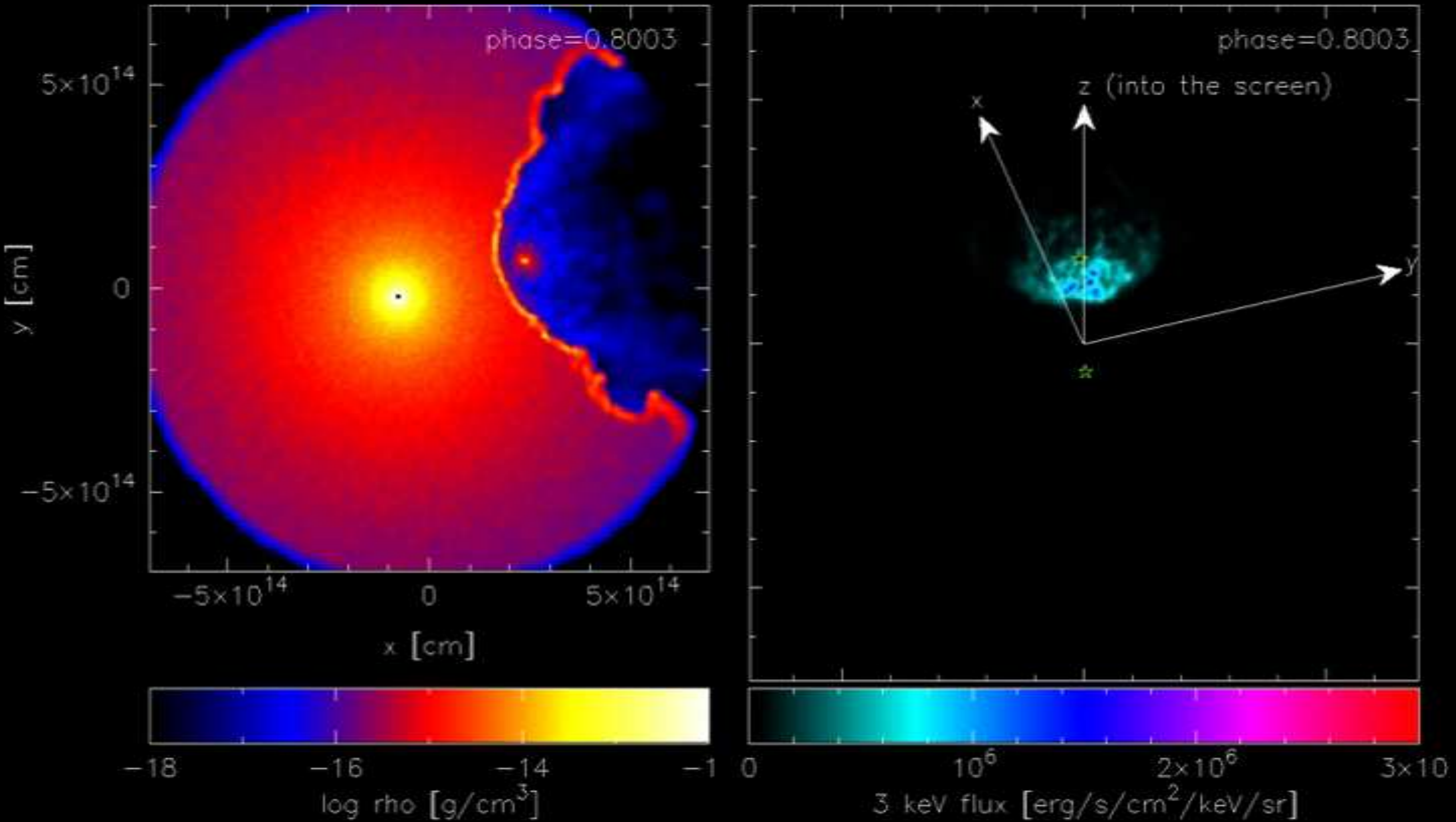
log T [K]

X-ray Radiative Transfer

- Hydro yields ρ & T
- Solve formal solution of radiative transfer
  - emissivity $j_E = n_e n_i \Lambda_E(T)$ where $\Lambda_E(T)$ is from `APEC` models (Smith+01) using `XSpec` (Arnaud96)
  - wind opacity κ_E from `windtabs` (Leutenegger+10)
  - ISM opacity $\kappa_{E,\mathrm{ISM}}$ from `TBabs` (Wilms+00)
  - visualization program `Splash` (Price07) is the basis
- Fold X-ray flux through telescope response function → compare directly with observations

Others interested? Could add to public version of Splash



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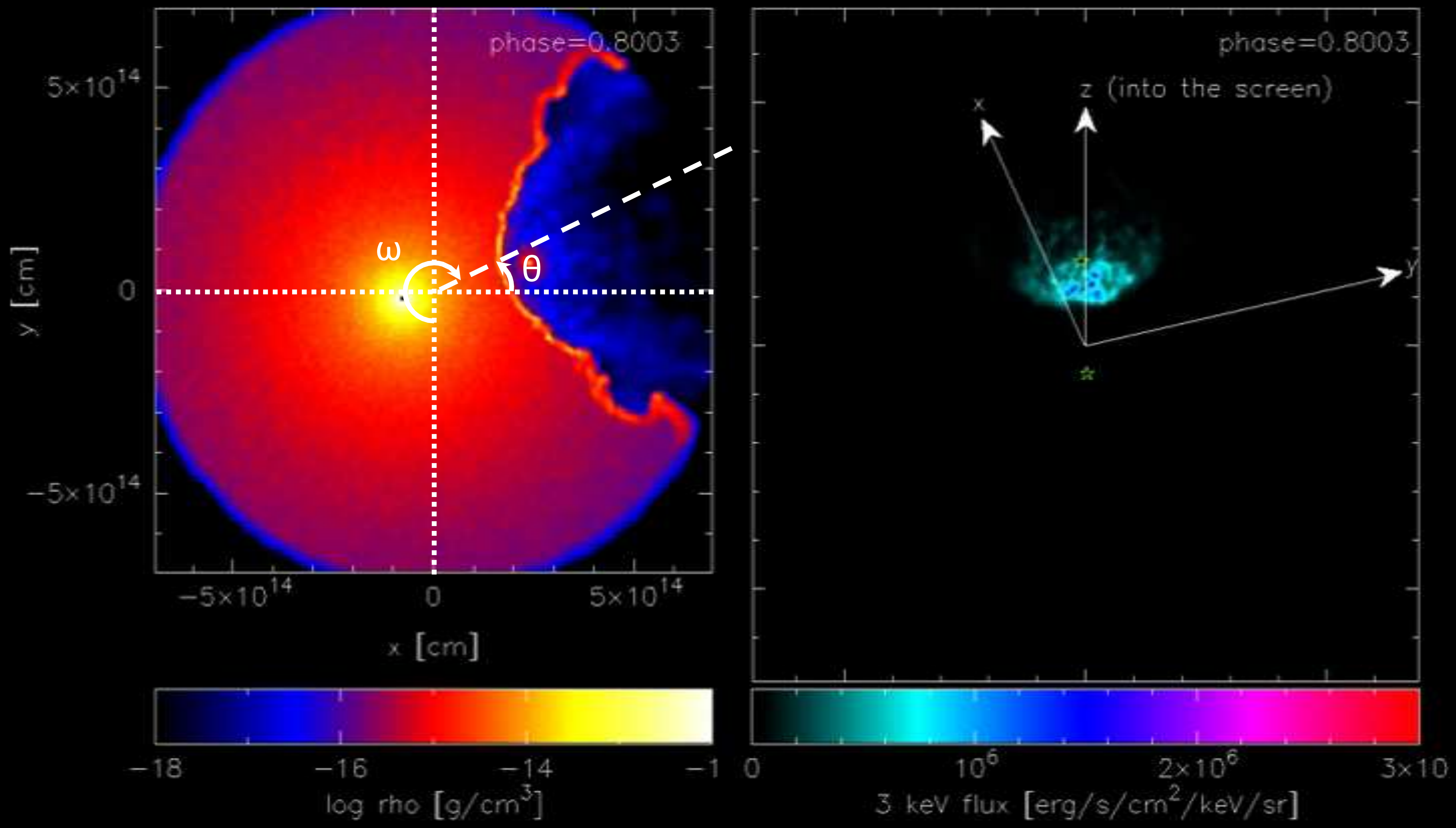

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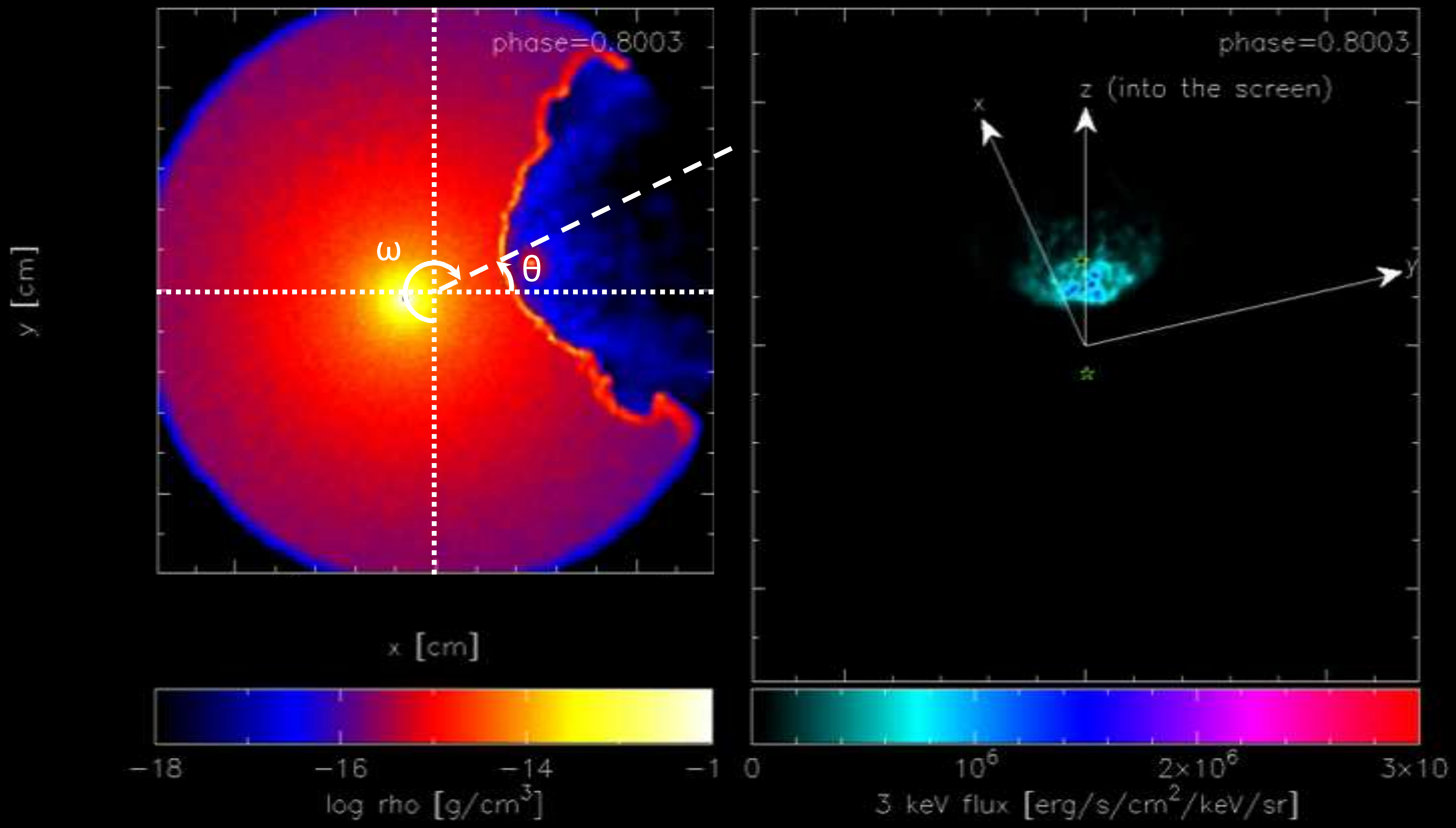
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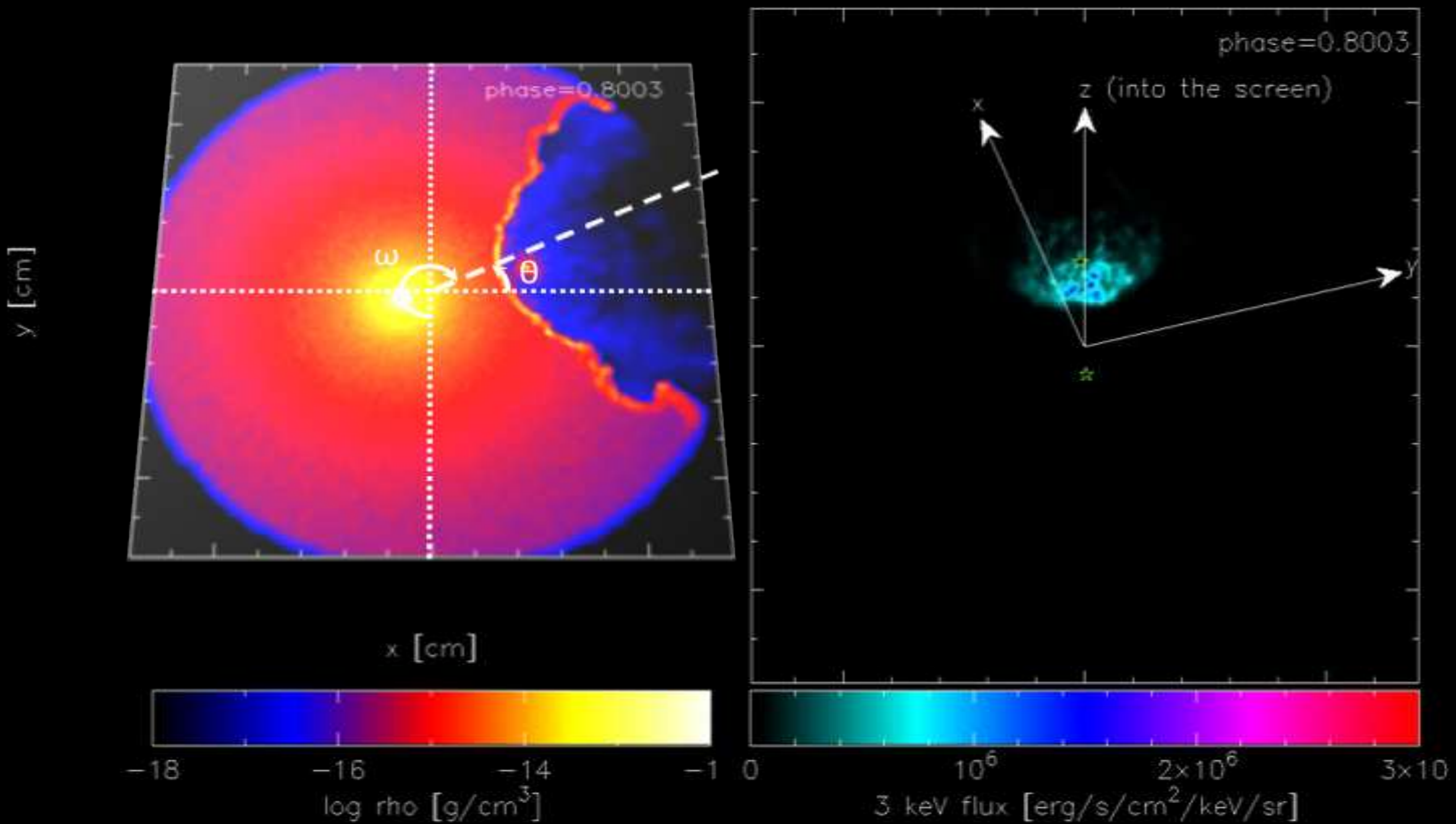

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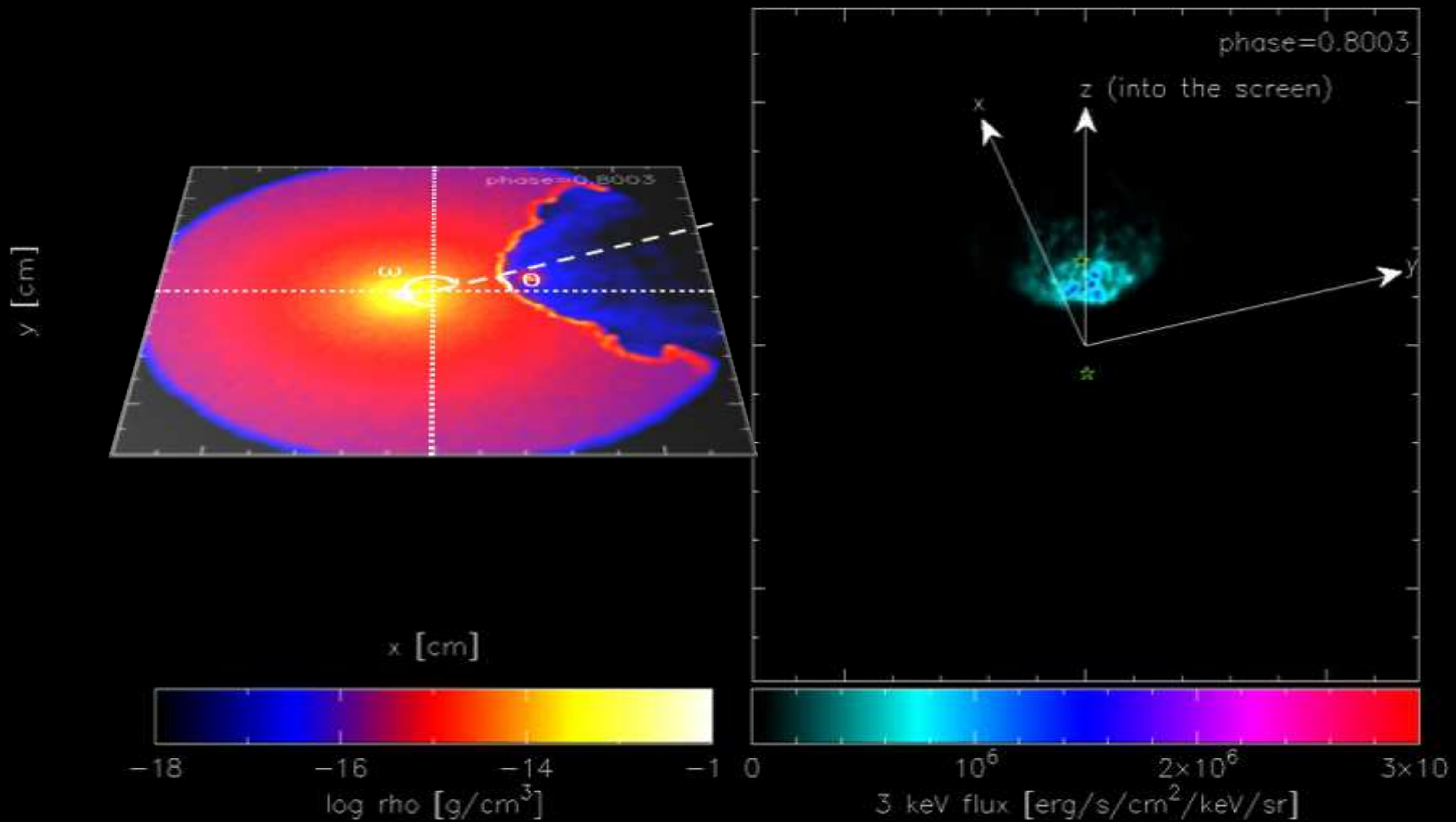
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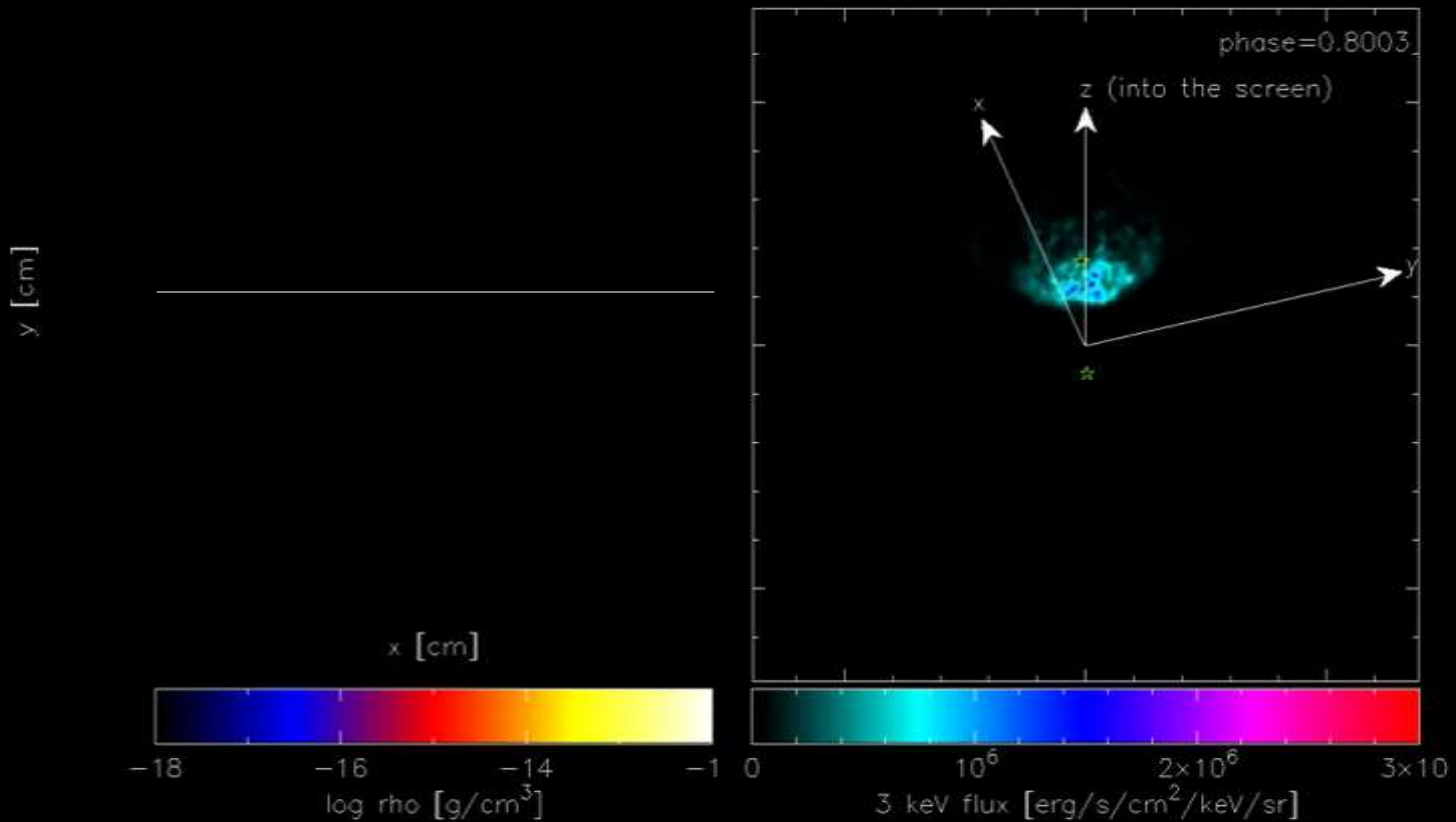
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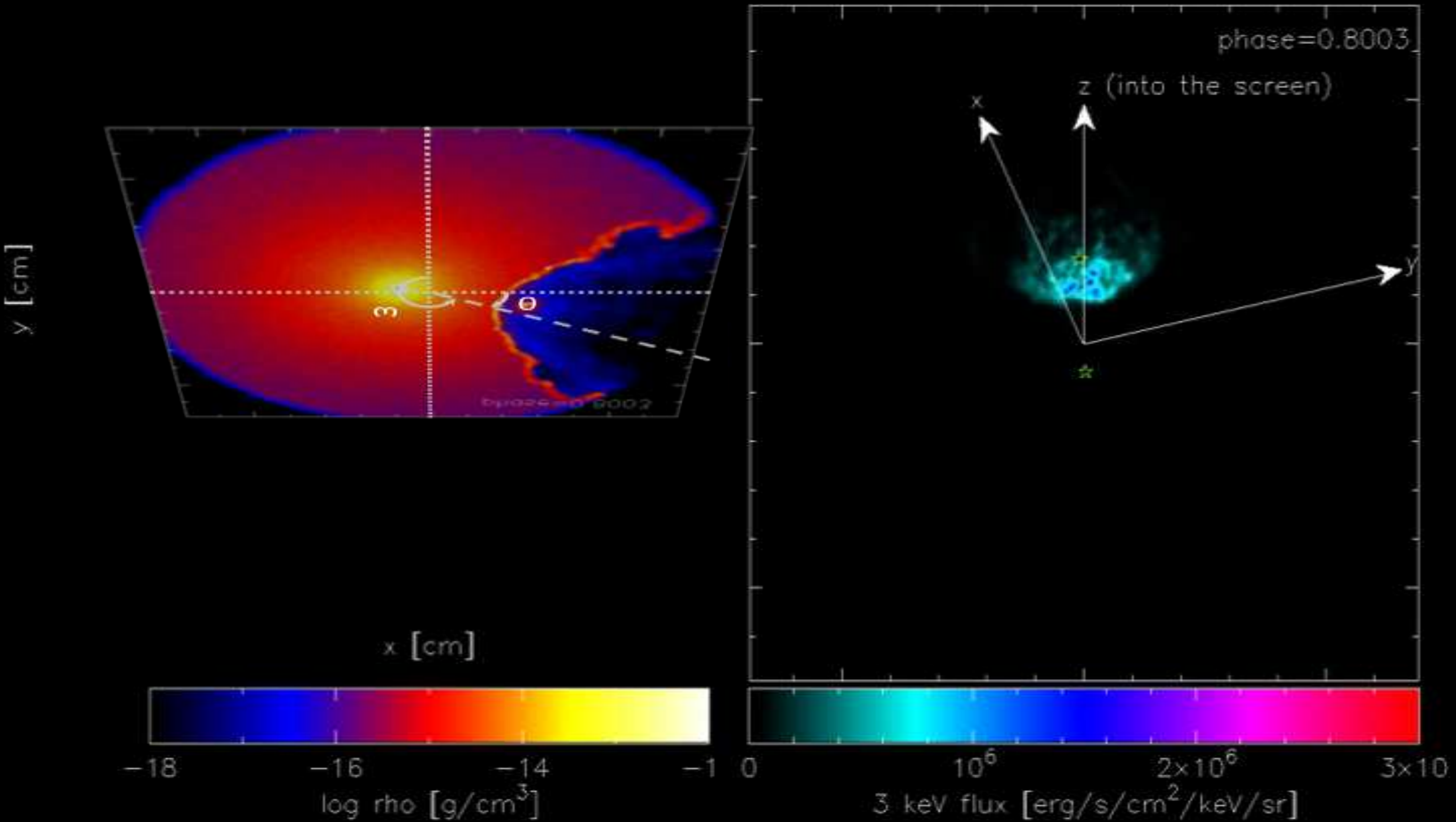

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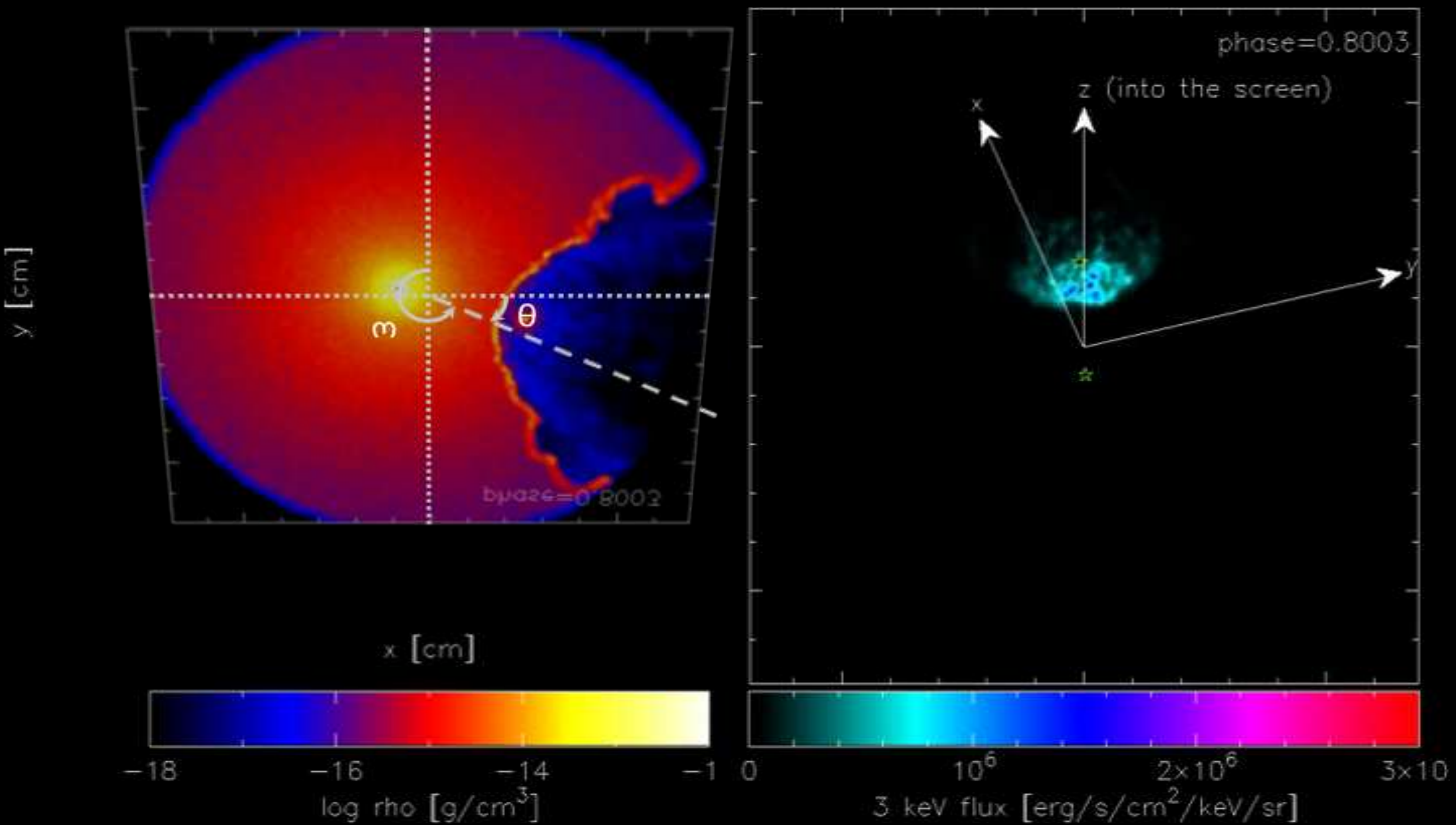

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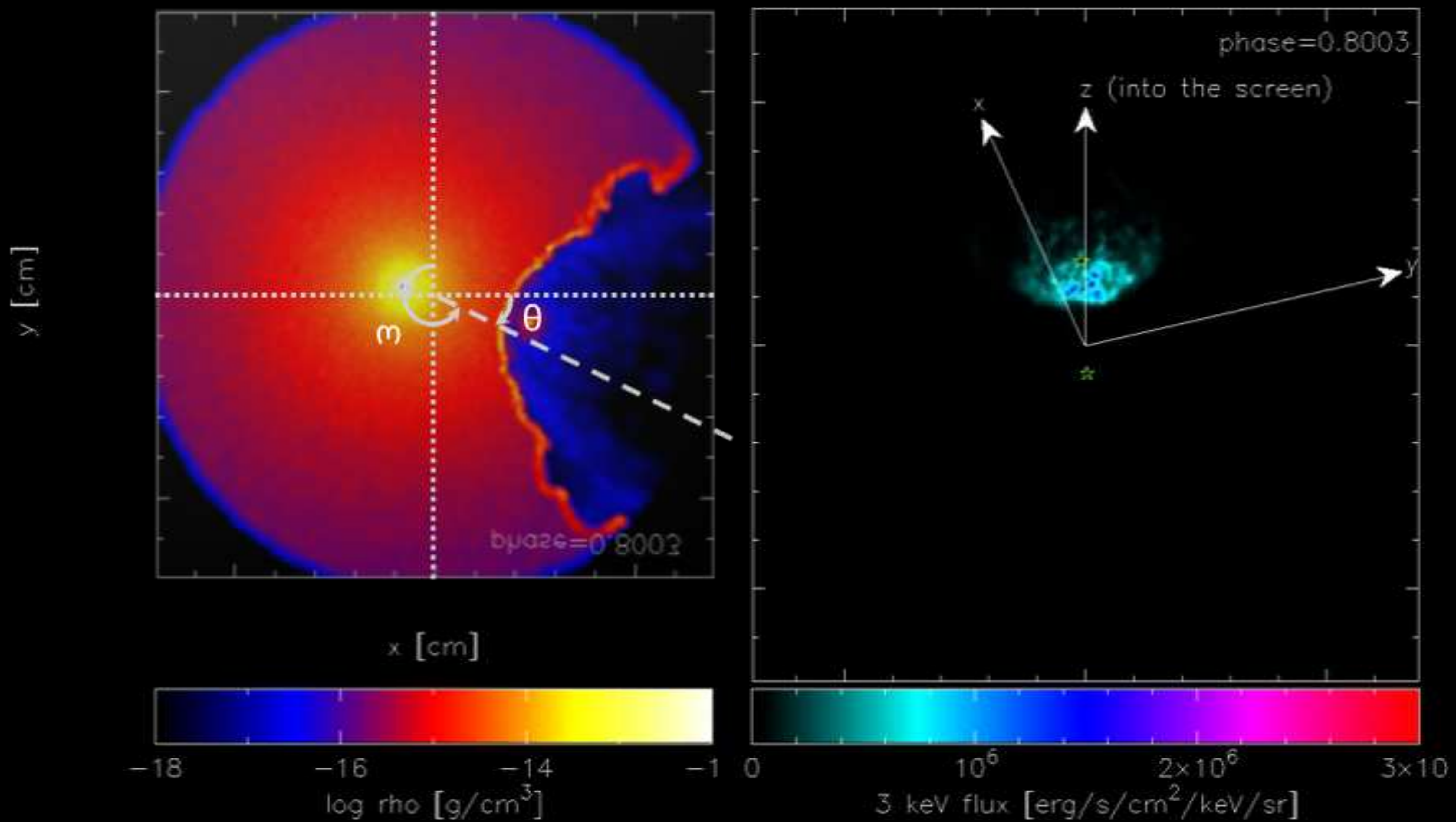

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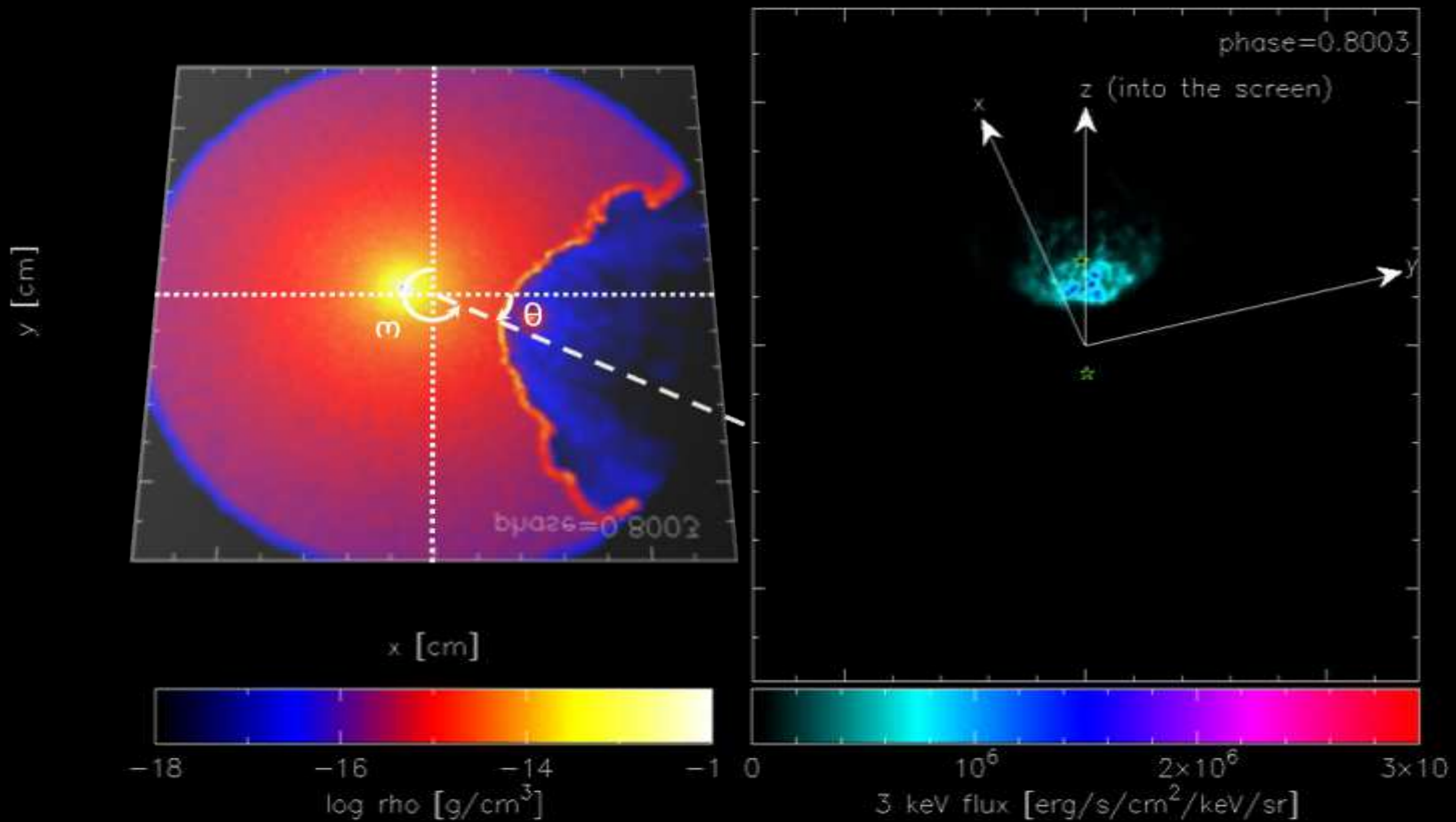

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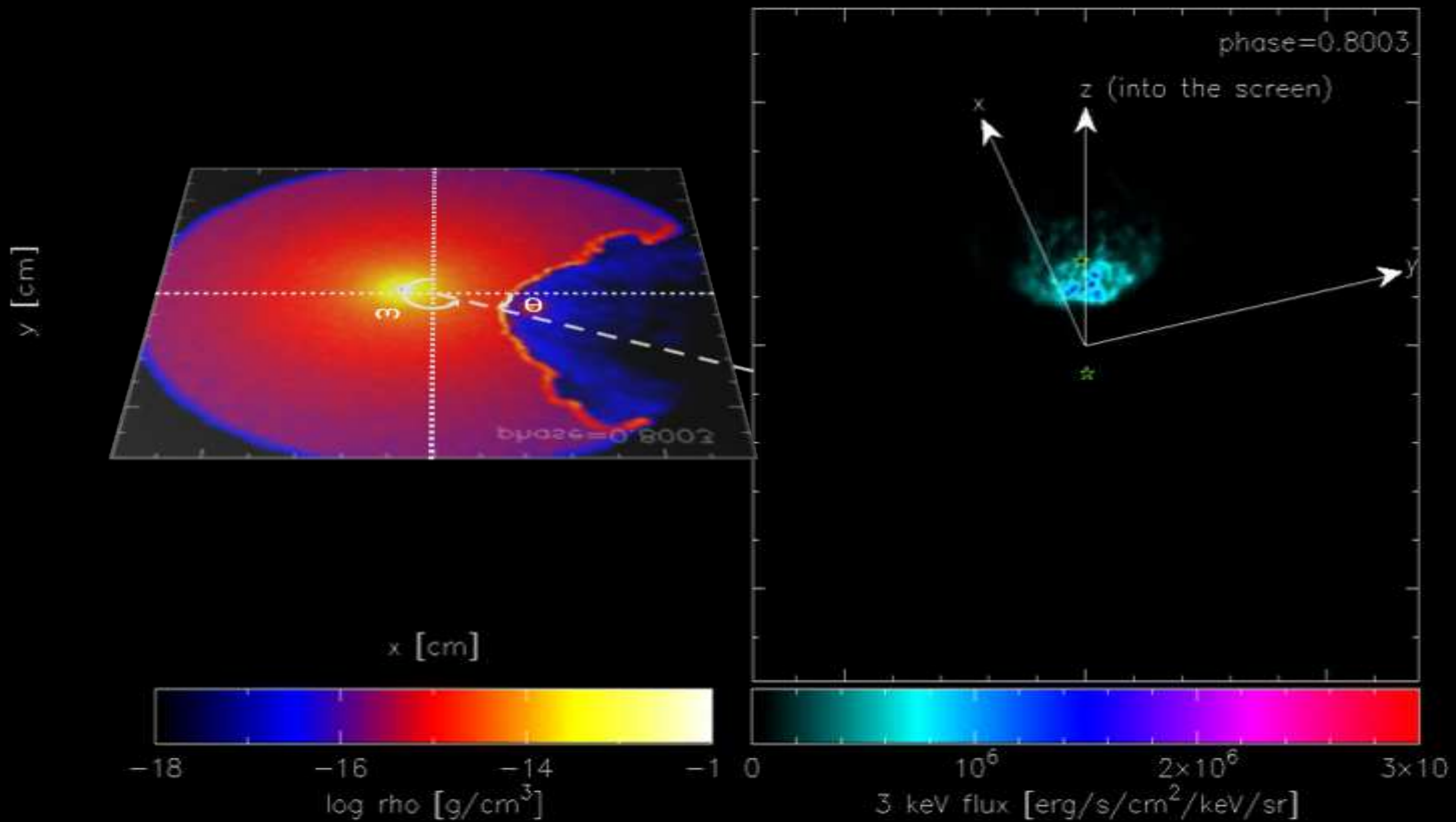

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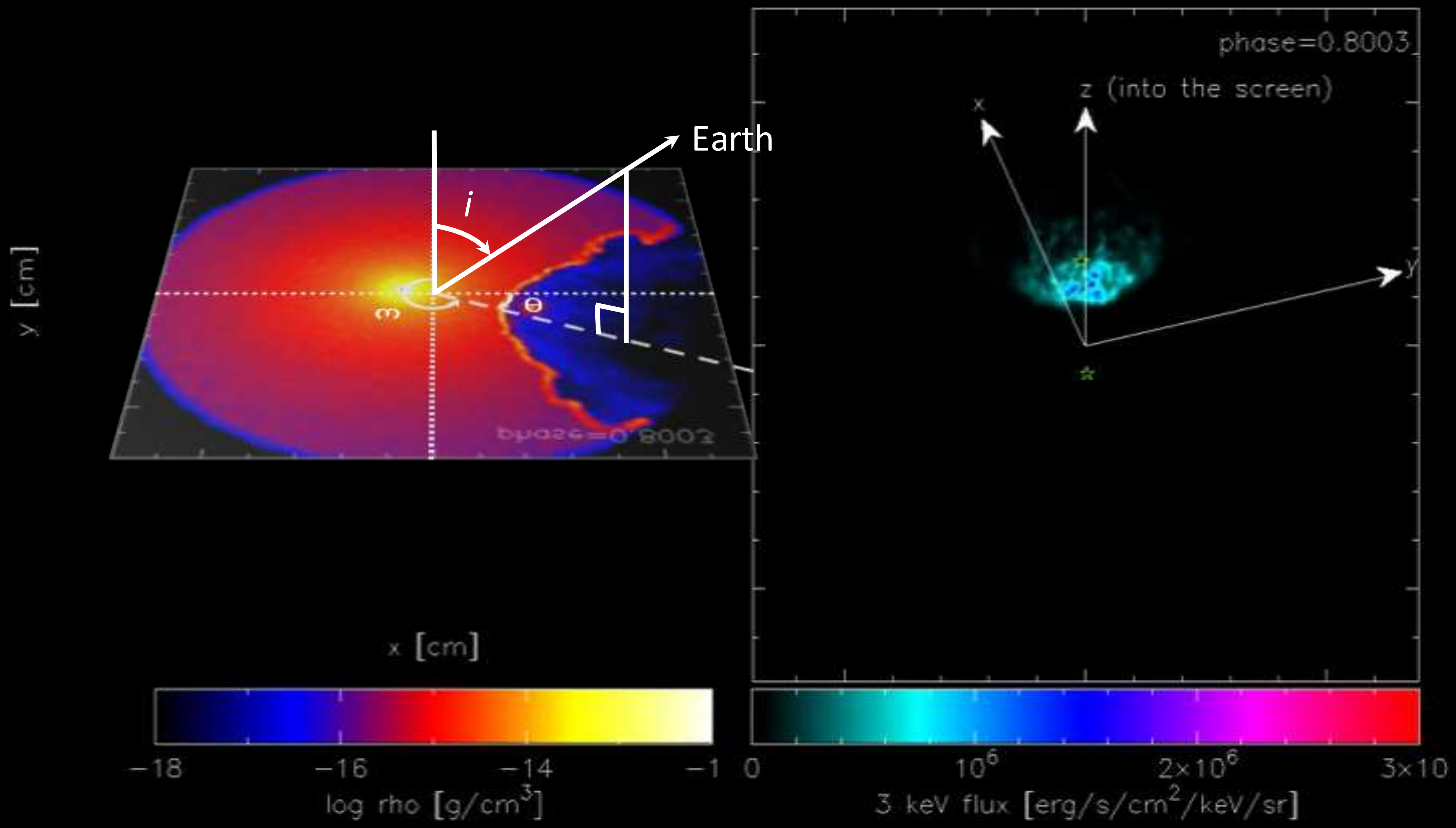

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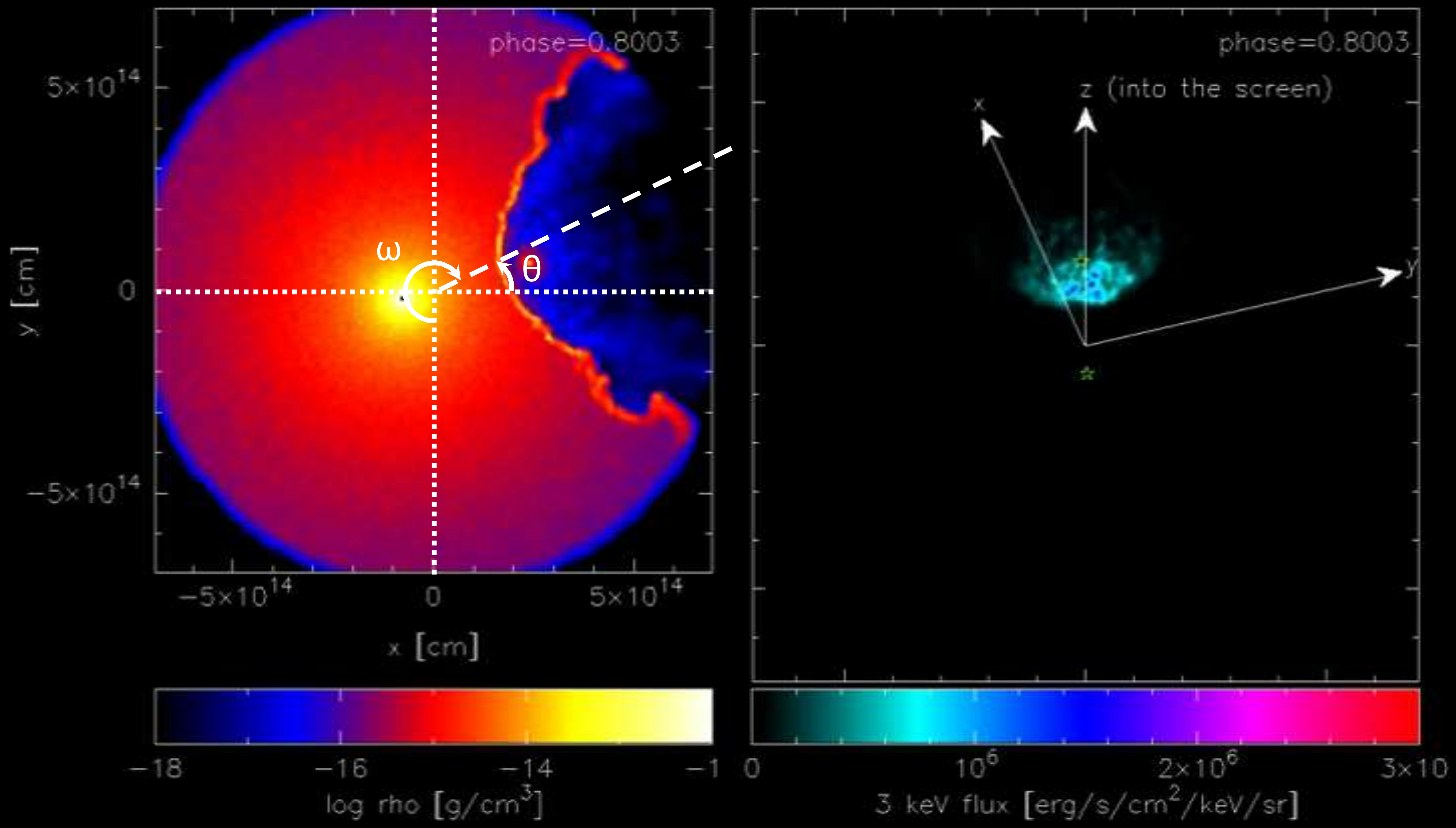

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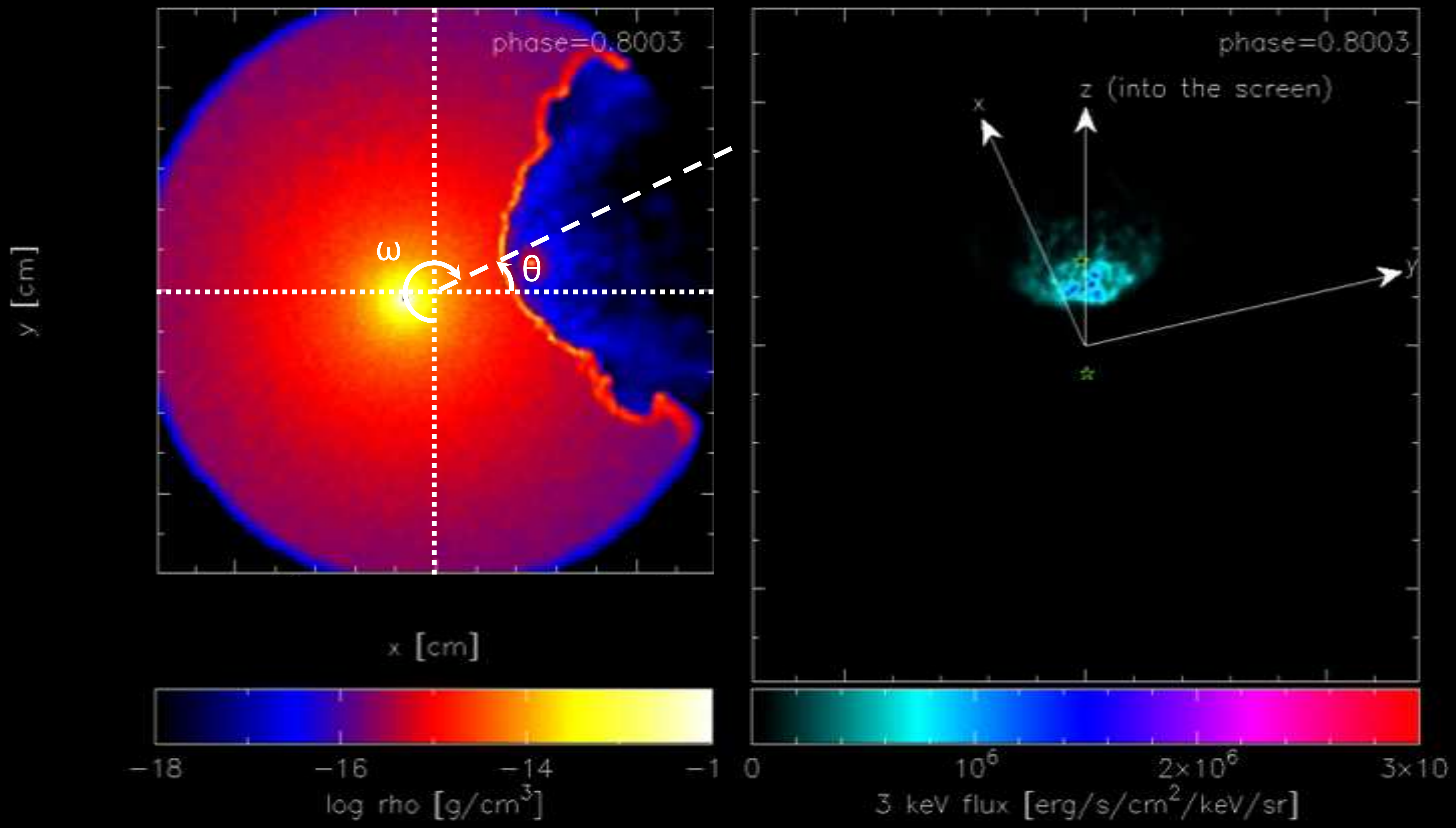

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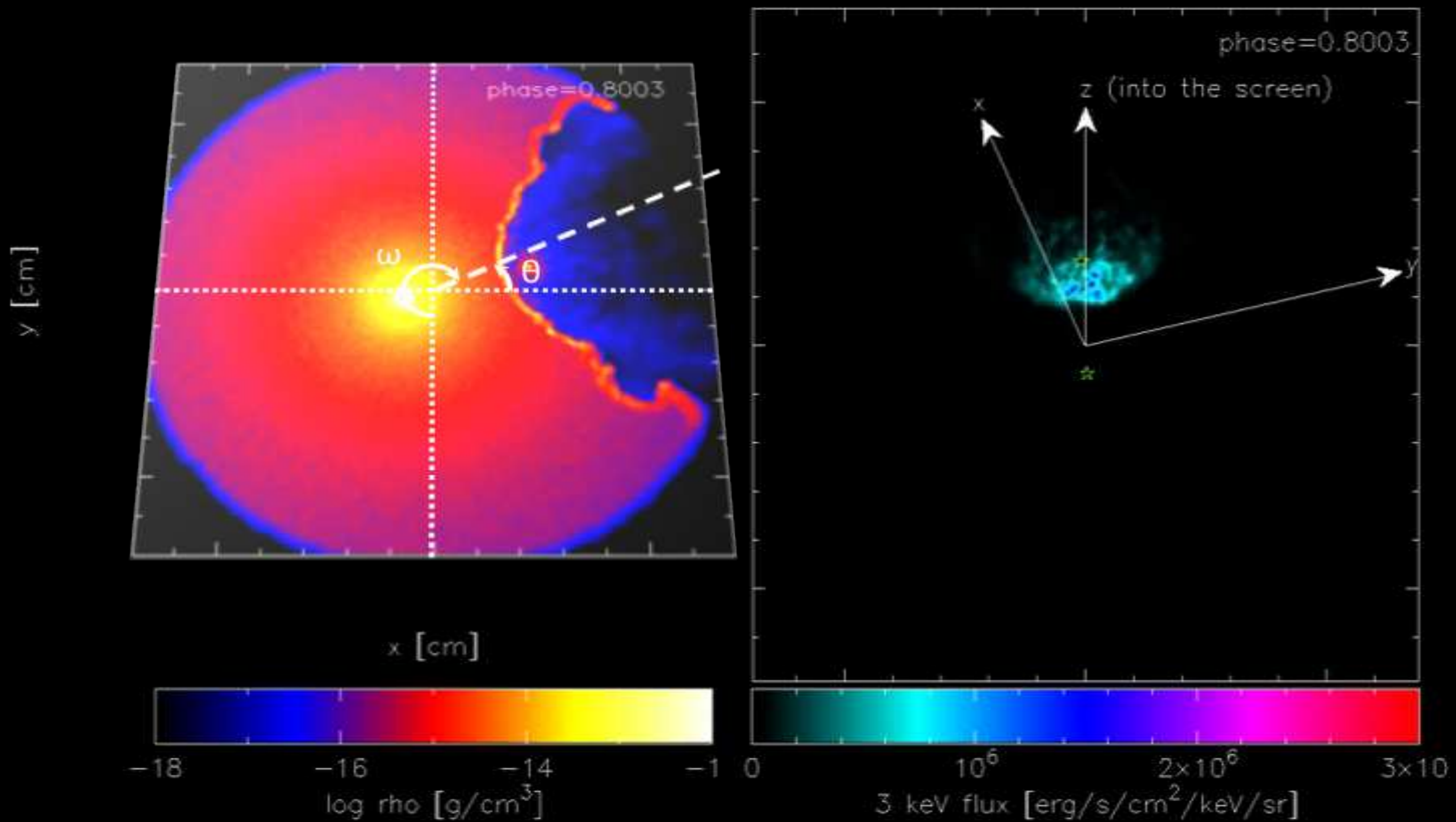
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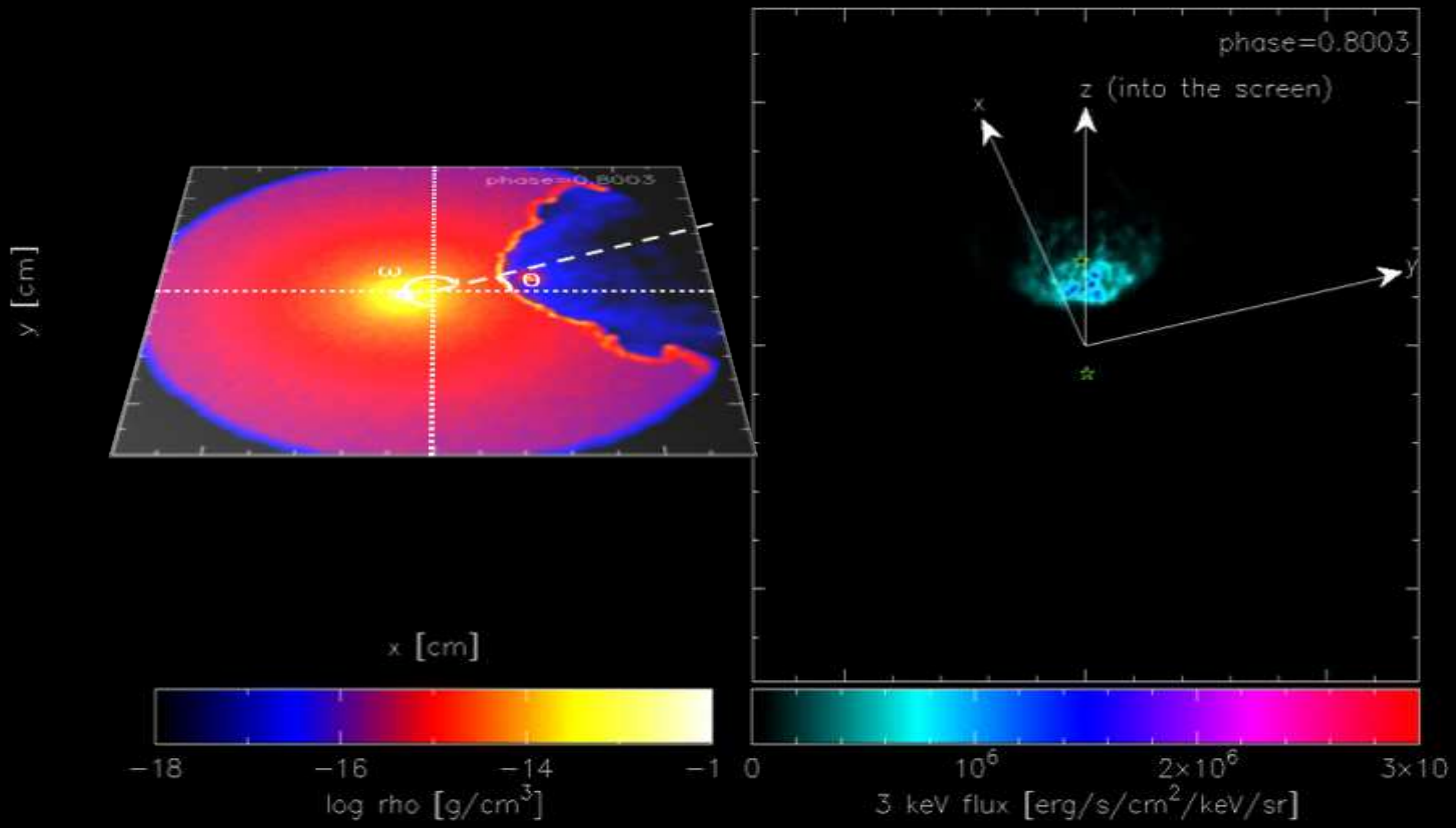
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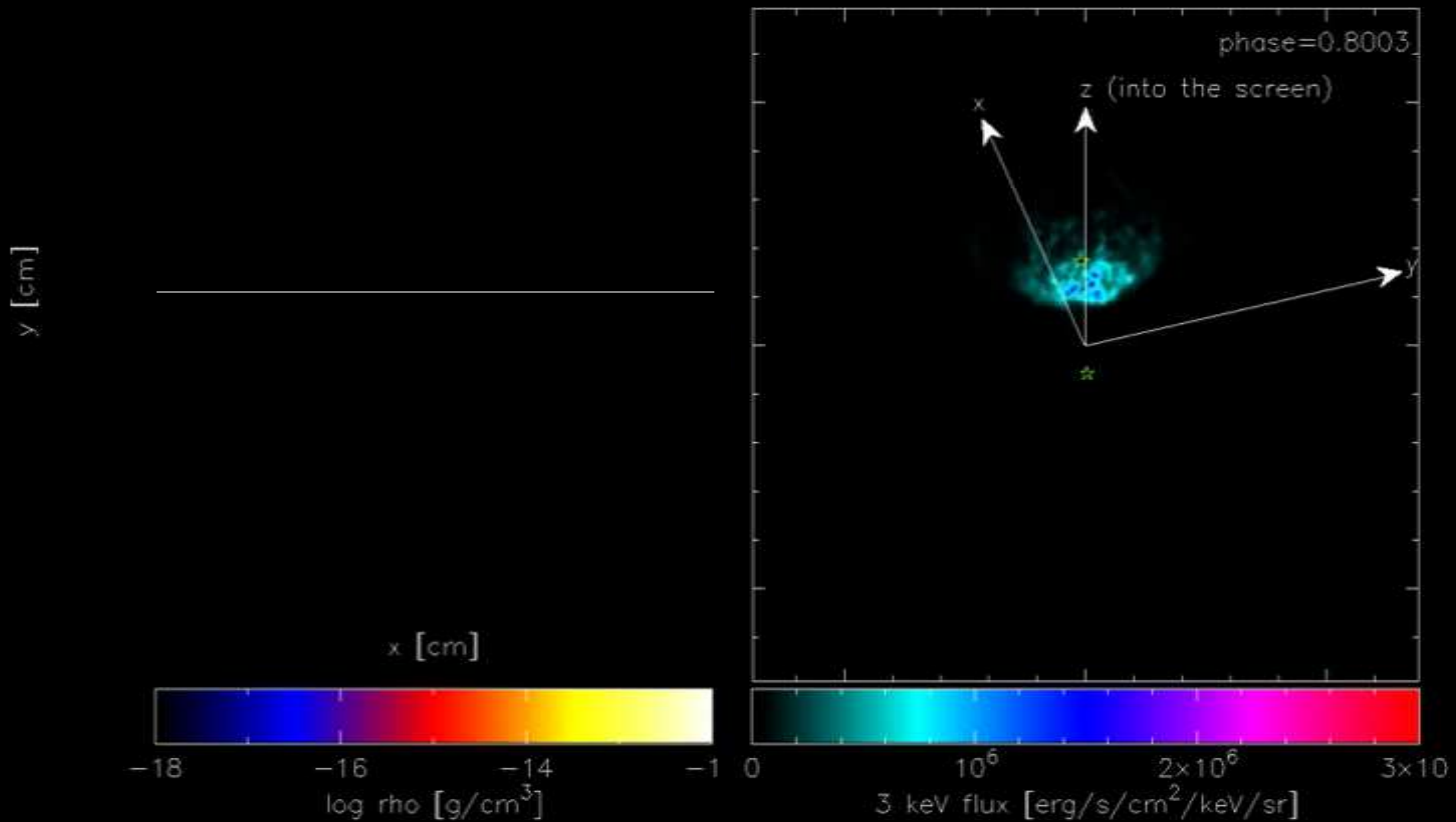

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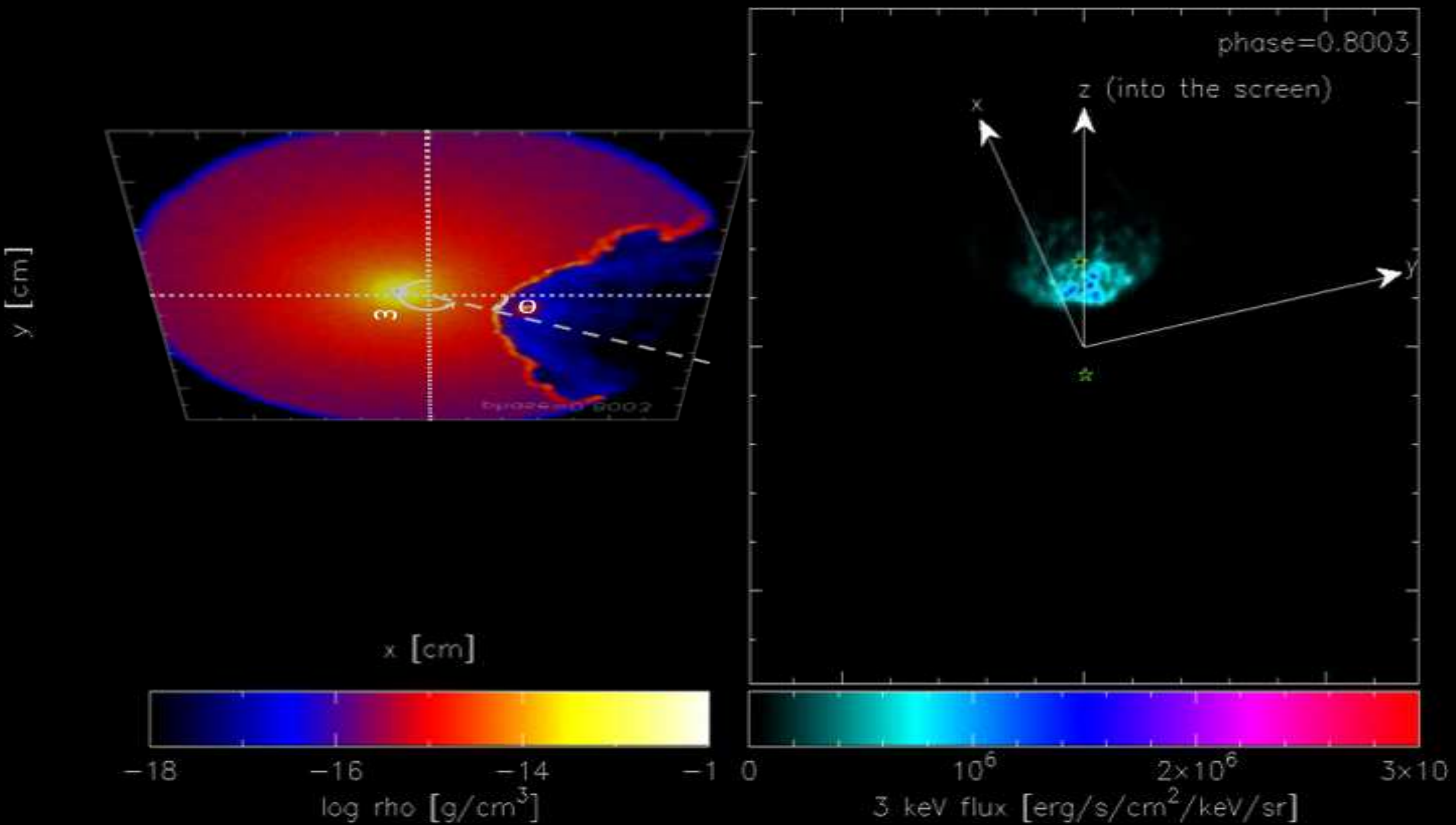
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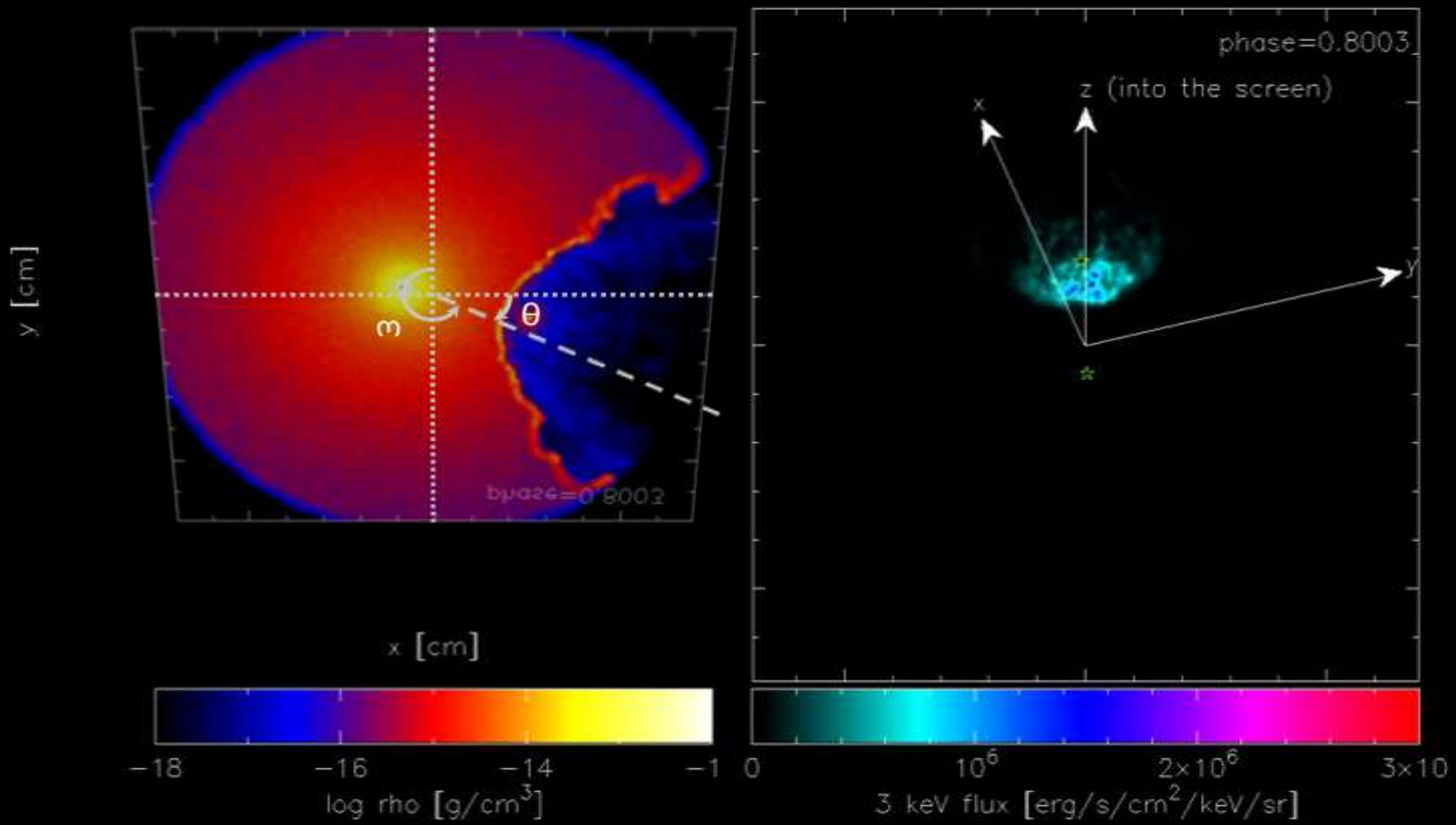

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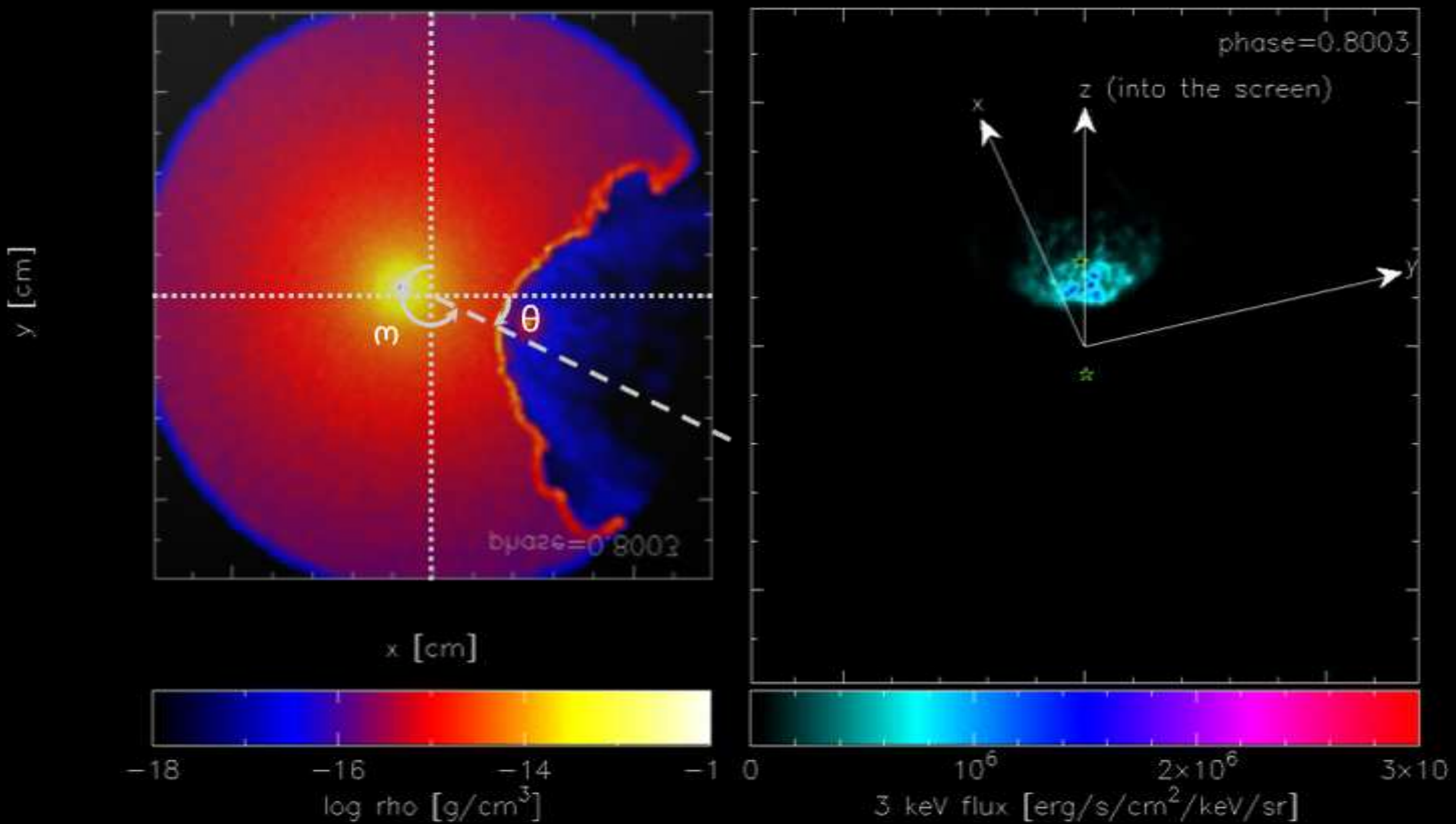

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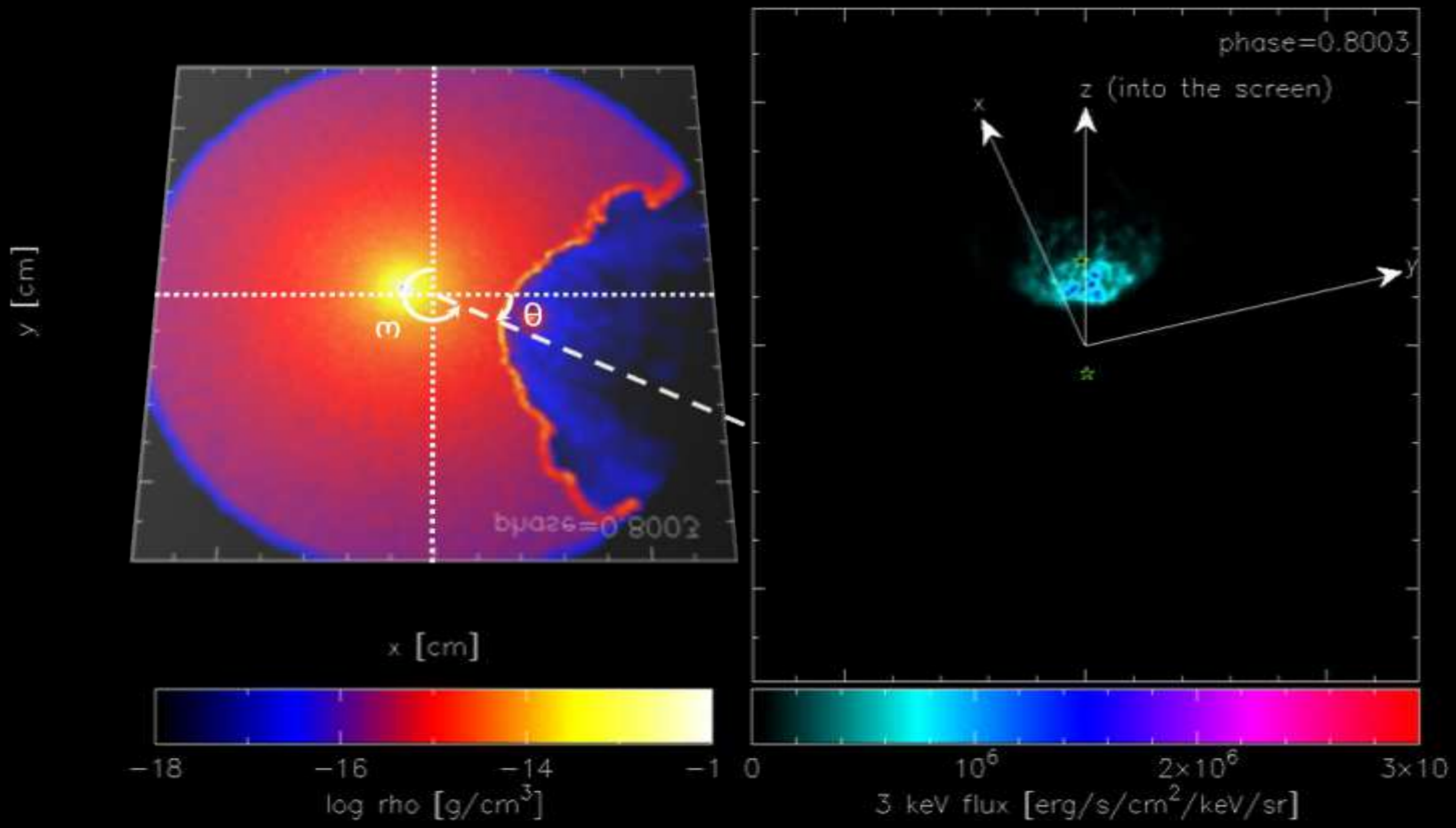

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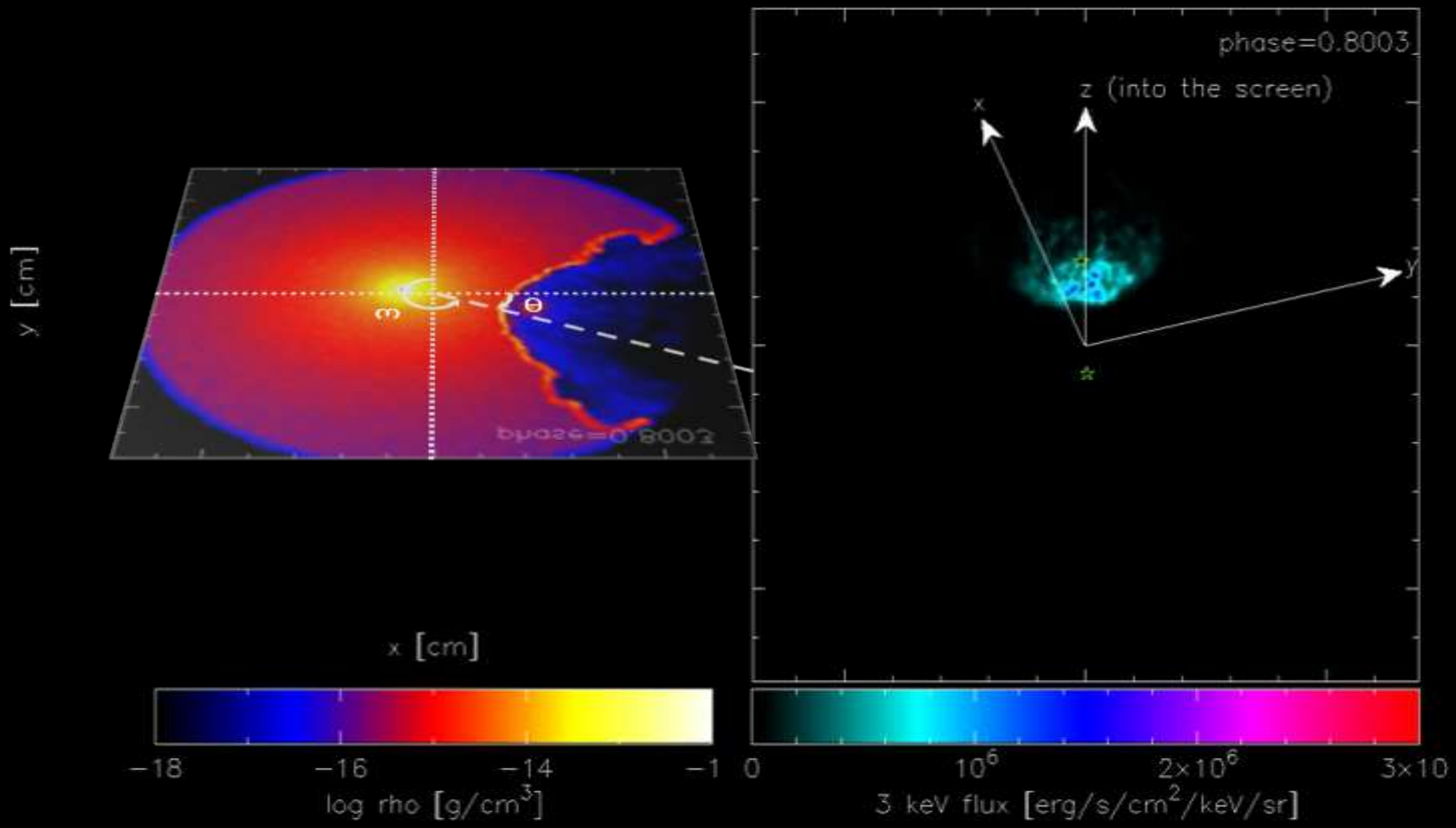

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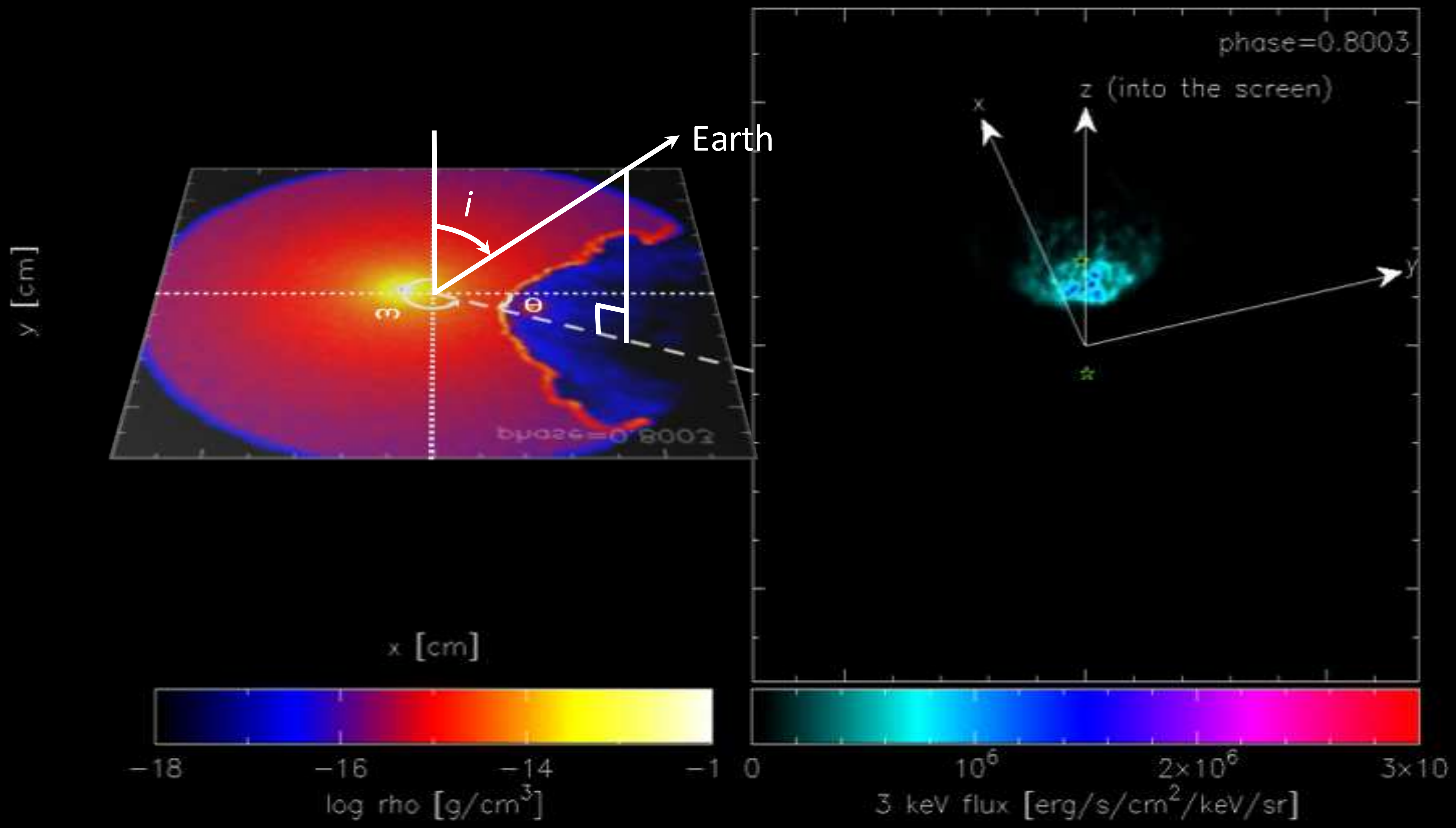

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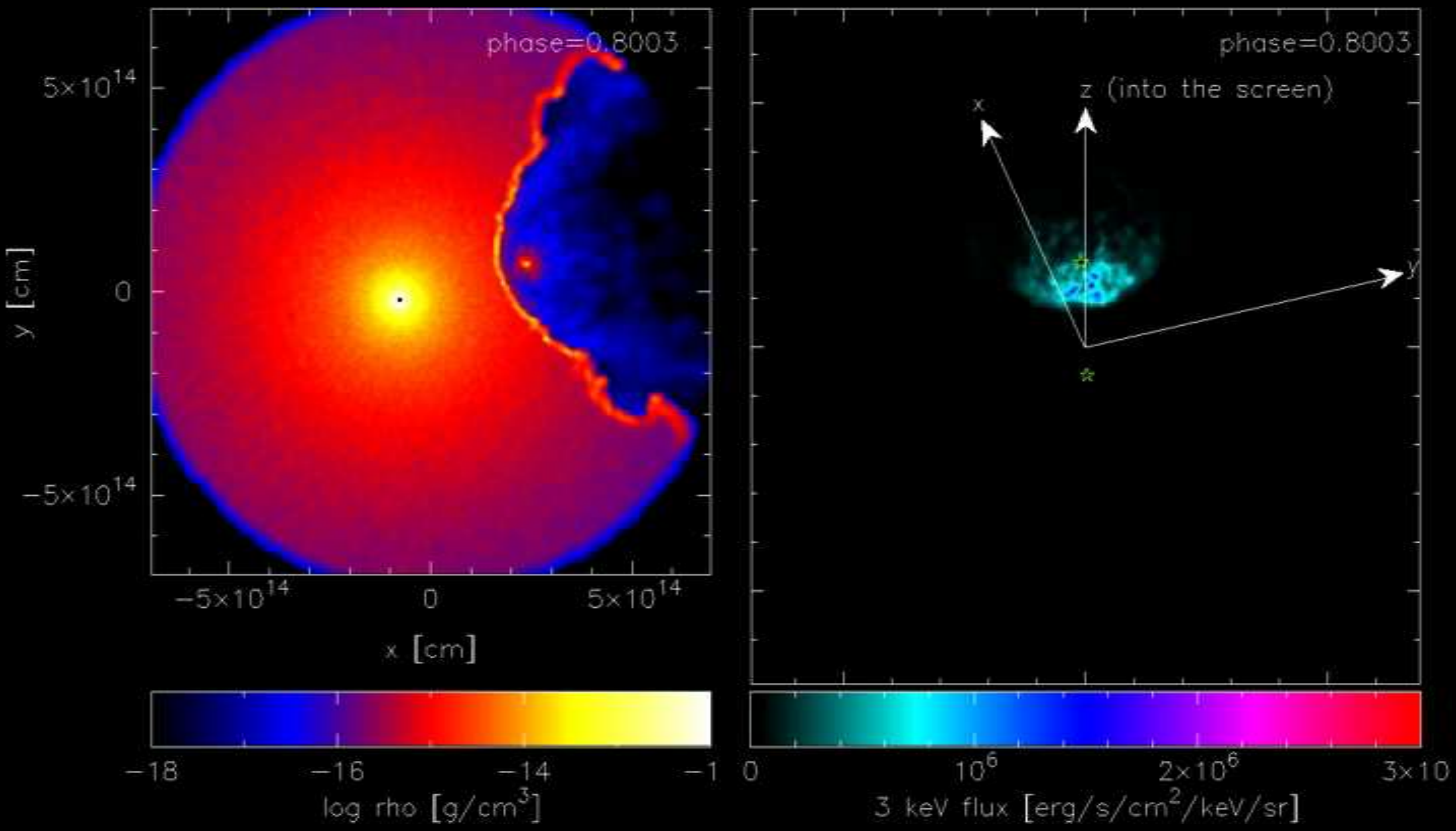

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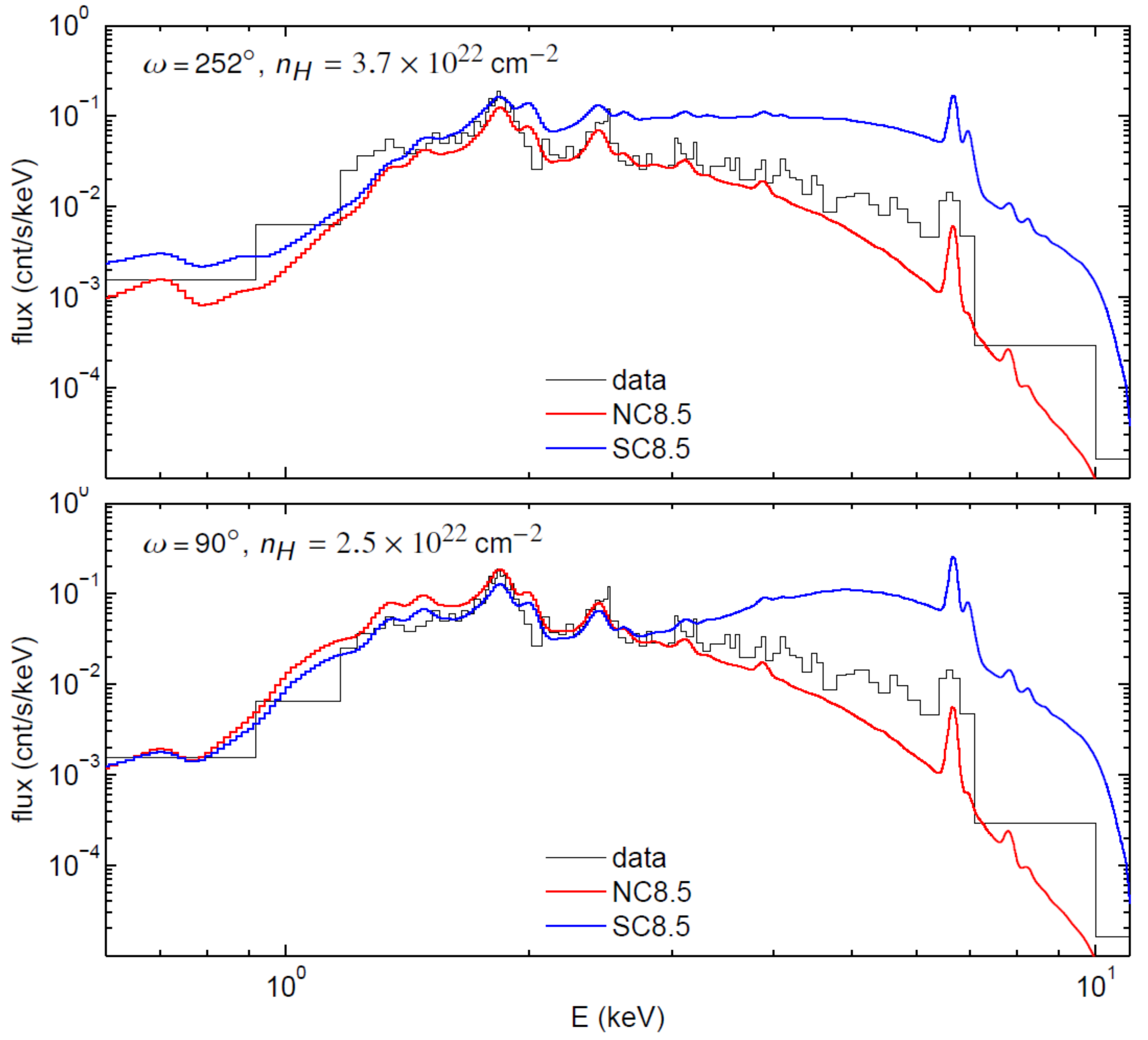
Chandra Spectra

- Taken at periastron when system is changing dramatically
- Models bound X-ray emission

Russell+16



Acceleration Mechanism for Stellar Winds

- Stellar radiation imparts momentum onto outer layers → stellar wind
- Force proportional to velocity gradient (CastroAbbottKlein75)
  - Updates have occurred, but still need to calculate velocity gradients
- Formalism worked out, but veloc grad is too noisy in current code
- Better in Phantom?

Using summation convention, the development of the velocity gradient might be along the lines of

$$\left[\mathbf{n}\cdot\nabla(\mathbf{n}\cdot\mathbf{v})\right]_a = n_i n_j \frac{\partial v_{j,a}}{\partial x_i} = \frac{n_i n_j}{\rho}\left[\frac{\partial(\rho v_{j,a})}{\partial x_i} - v_{j,a}\frac{\partial\rho}{\partial x_i}\right] = \frac{n_i n_j}{\rho}\left[\sum_b v_{j,b} m_b \frac{\partial W}{\partial x_i} - v_{j,a}\sum_b m_b \frac{\partial W}{\partial x_i}\right]$$

$$= \frac{1}{\rho}\left[\sum_b m_b(\mathbf{n}\cdot\mathbf{v}_b)(\mathbf{n}\cdot\nabla)W - (\mathbf{n}\cdot\mathbf{v}_a)\sum_b m_b(\mathbf{n}\cdot\nabla)W\right]$$

$$= \frac{1}{\rho}\sum_b m_b\left[\mathbf{n}\cdot(\mathbf{v}_b - \mathbf{v}_a)\right](\mathbf{n}\cdot\nabla)W,$$

where I have not explicitly given the argument of *W*. Compare with your eq. (3.10).

JWST Early Release Science (ERS)

- “Establishing Extreme Dynamic Range with JWST:
  Decoding Smoke Signals in the Glare of a Wolf-Rayet Binary”
  (PI: R. Lau)

- WR140: WC7+O4-5, dust produced in wind-wind collision region
  - High density at shock location
  - Travels downstream from system and cools, allowing dust to form
- Hydro improvement: Ability to locate particles that could form dust
  - Zeroth order: requirement 1 – did particle go through shock
    requirement 2 – did particle cool
  - Collaborate?

3. Gamma-ray Binaries

- Massive star + compact object
- Peak in emission (νF_ν) is above 1 MeV (Dubus13)

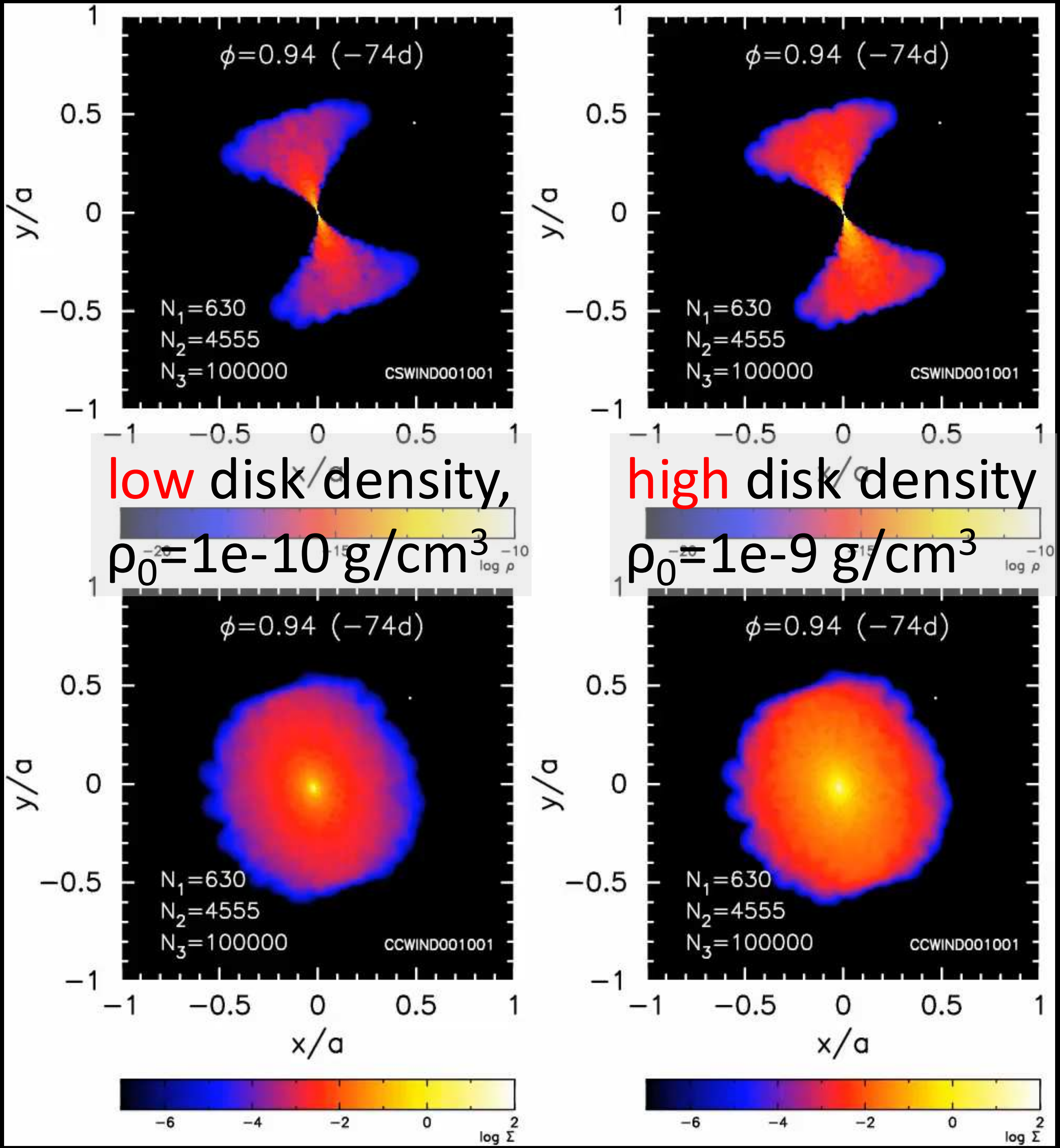
‡special relativistic: γ=10 would be goal

- Option 1: massive star + neutron star (NS)
  - NS has relativistic wind‡ → γ-rays generated at wind-wind collision region via Fermi accel
- Option 2: massive star + black hole (BH)
  - BH has relativistic jet → γ-rays generated at collision between relativistic jet and stellar wind

- 1 system confirmed as massive star + NS: PSR B1259
  - Most of others (7 in total) are most likely also massive star + NS (Dubus13)
- Next generation gamma-ray telescope, Cherenkov Telescope Array (CTA), will increase number of sources by ~an order of magnitude

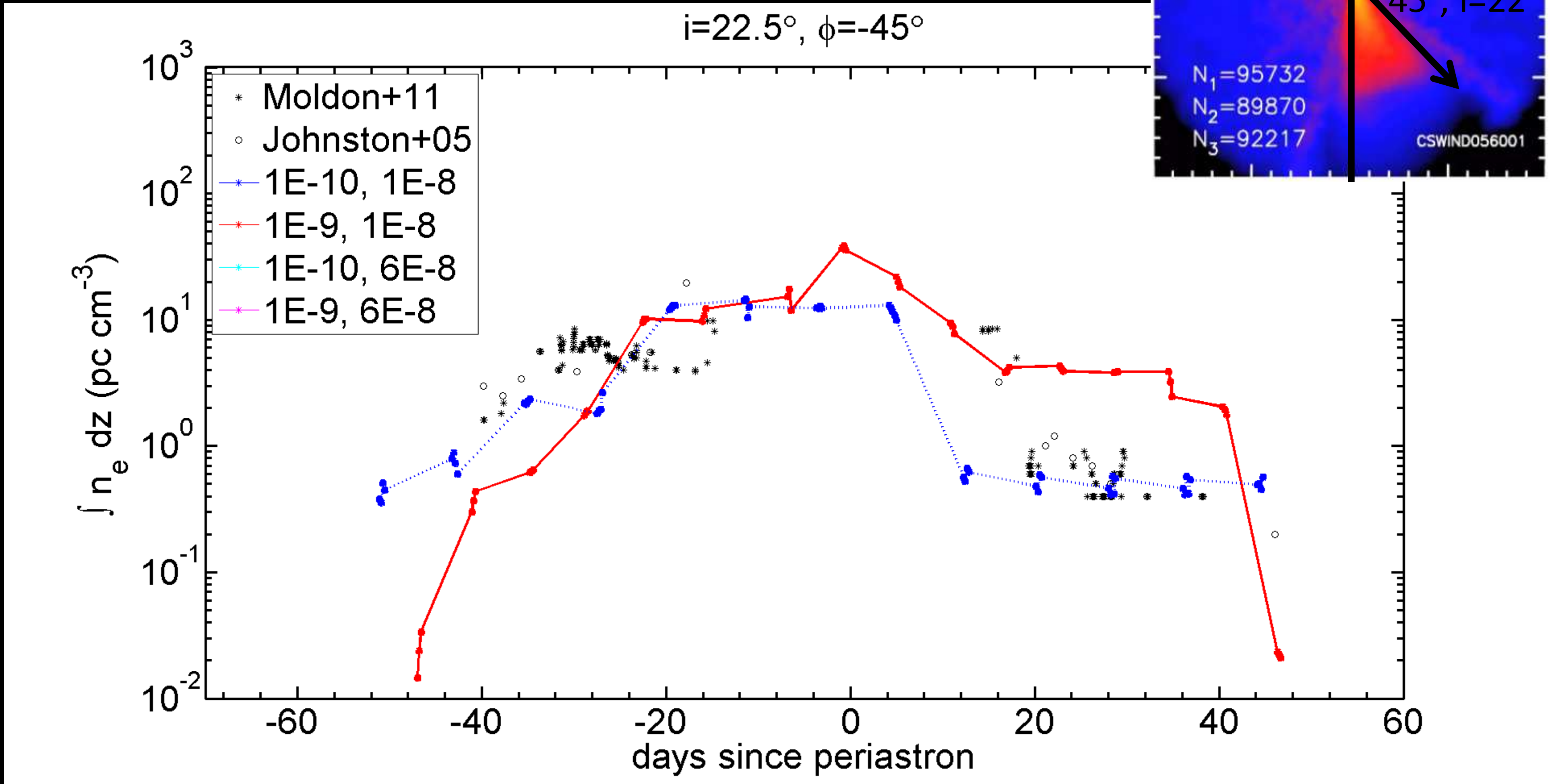
ρ in orbital plane

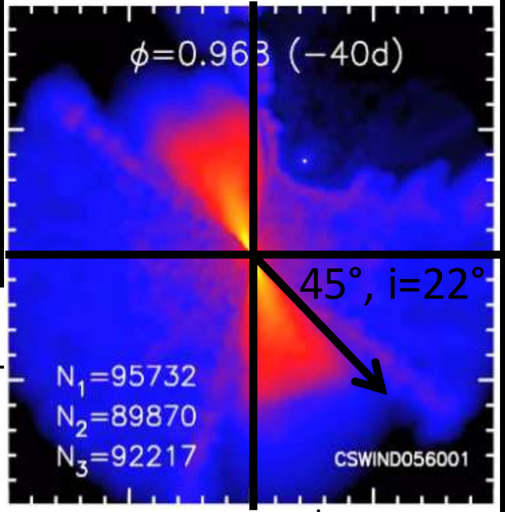
column density



Takata+12,
Okazaki &
Russell,
in prep

PSR B1259-63: PDM





Solid: Be wind ionized

Dashed: Be wind & disk ionized

Okazaki & Russell, in prep

Summary

Topic	Alterations/improvements
• Galactic Center	unequal particle masses
• Colliding Wind Binaries	CAK acceleration of stellar winds dust formation locations
• Gamma-ray binaries	relativistic pulsar winds