

Title: The Physics of Black Hole Interiors: The Most Extreme Physics in the Universe

Date: Nov 10, 2010 02:00 PM

URL: <http://pirsa.org/10110059>

Abstract: This talk will describe the best current understanding of the interior structure of astronomically realistic black holes.

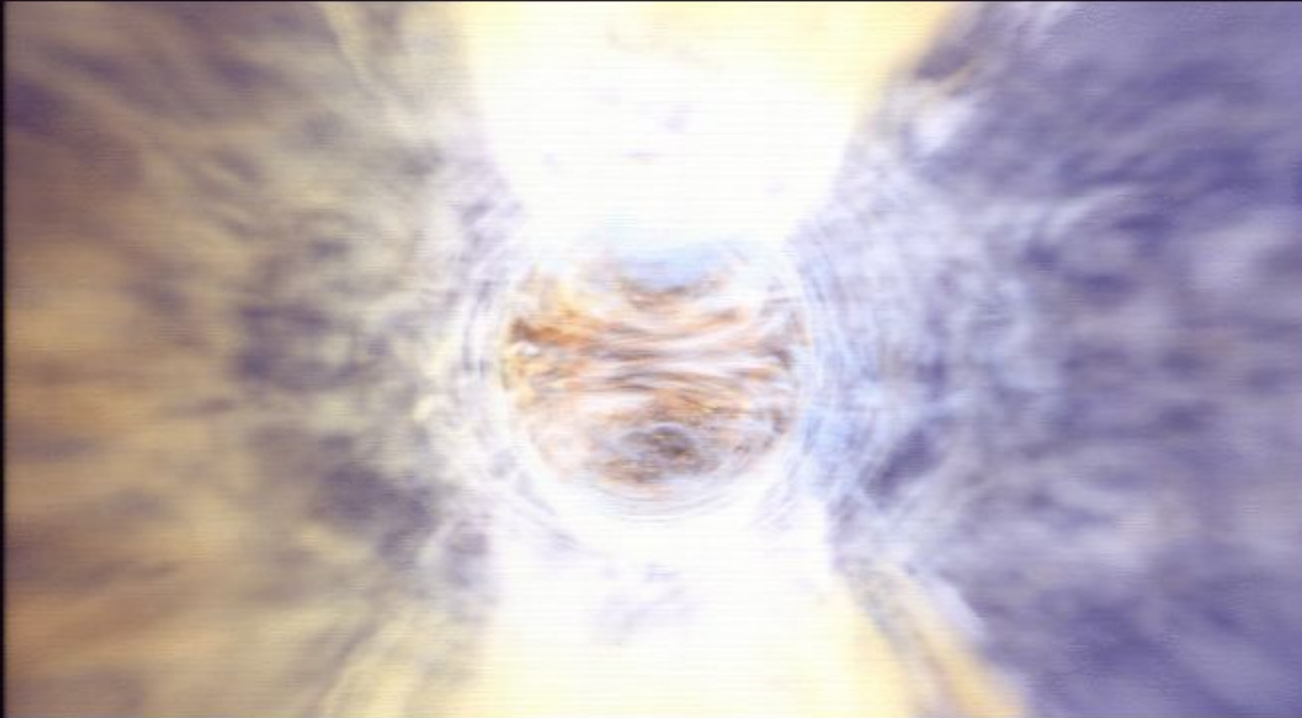
A common misconception is that matter falling into a black hole simply falls to a central singularity, and that's that.

Reality is much more interesting. Rotating black holes have not only outer horizons, but also inner horizons. Penrose (1968) first pointed out that an infaller falling through the inner horizon would see the outside Universe infinitely blueshifted, and he speculated that this would destabilize the inner horizon.

The expectation was supported by linear perturbation theory, but it was not until 1990 that Poisson & Israel were able to clarify the nonlinear evolution of the instability at the inner horizon, which they called mass inflation. Inflation accelerates ingoing (positive energy) and outgoing (negative energy) streams to exponentially huge energies. The black hole thus behaves like a particle accelerator of extraordinary power, accelerating ingoing and outgoing particles to collide with each other at super-Planckian energies. The talk raises the fundamental question:

What does Nature do with this remarkable accelerator?

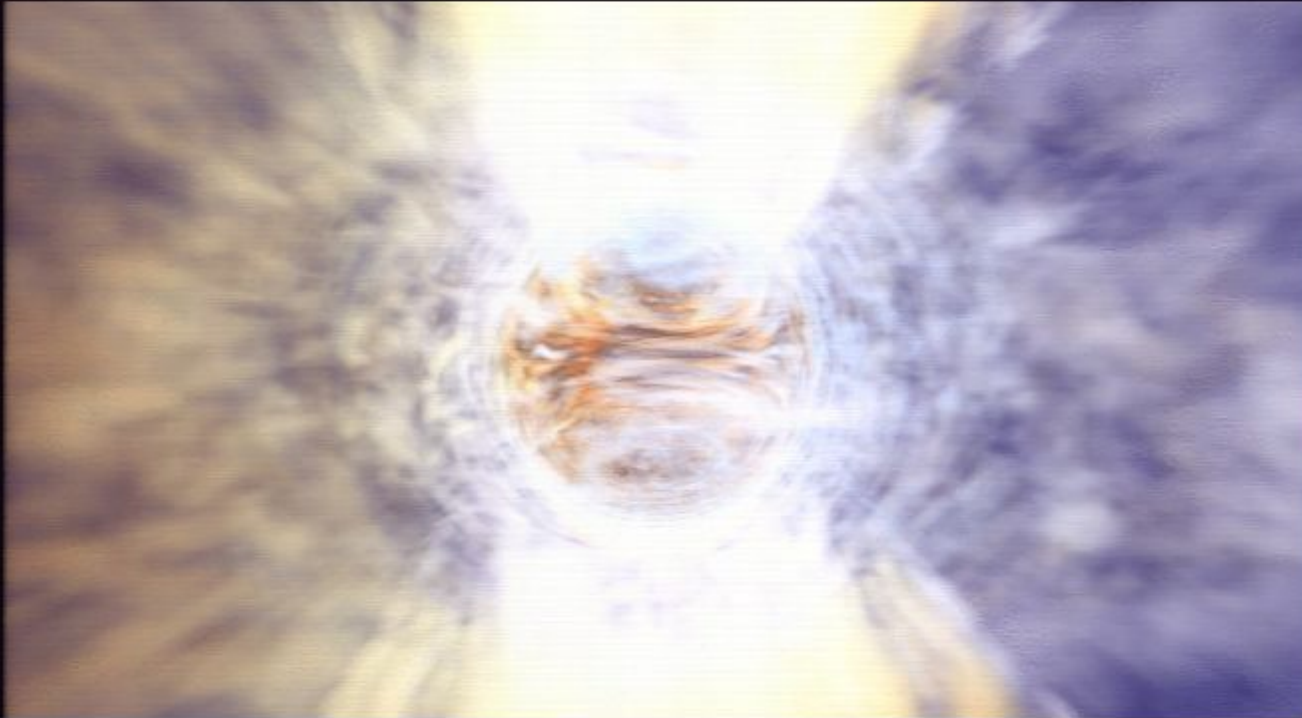
The Physics of Black Hole Interiors: The Most Extreme Physics in the Universe



More extreme than the Big Bang? Yes.

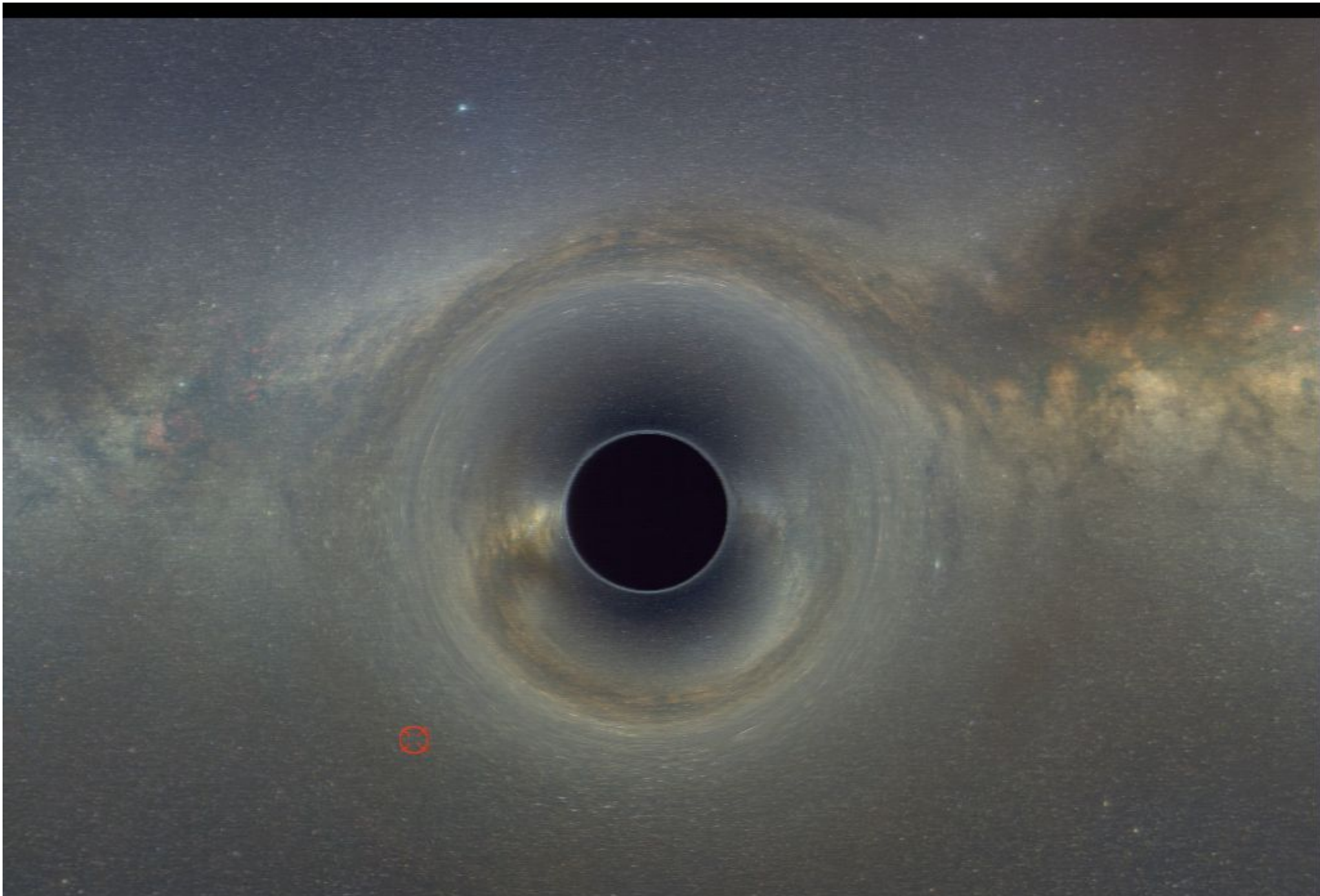
[Schwarzschild black hole](#)

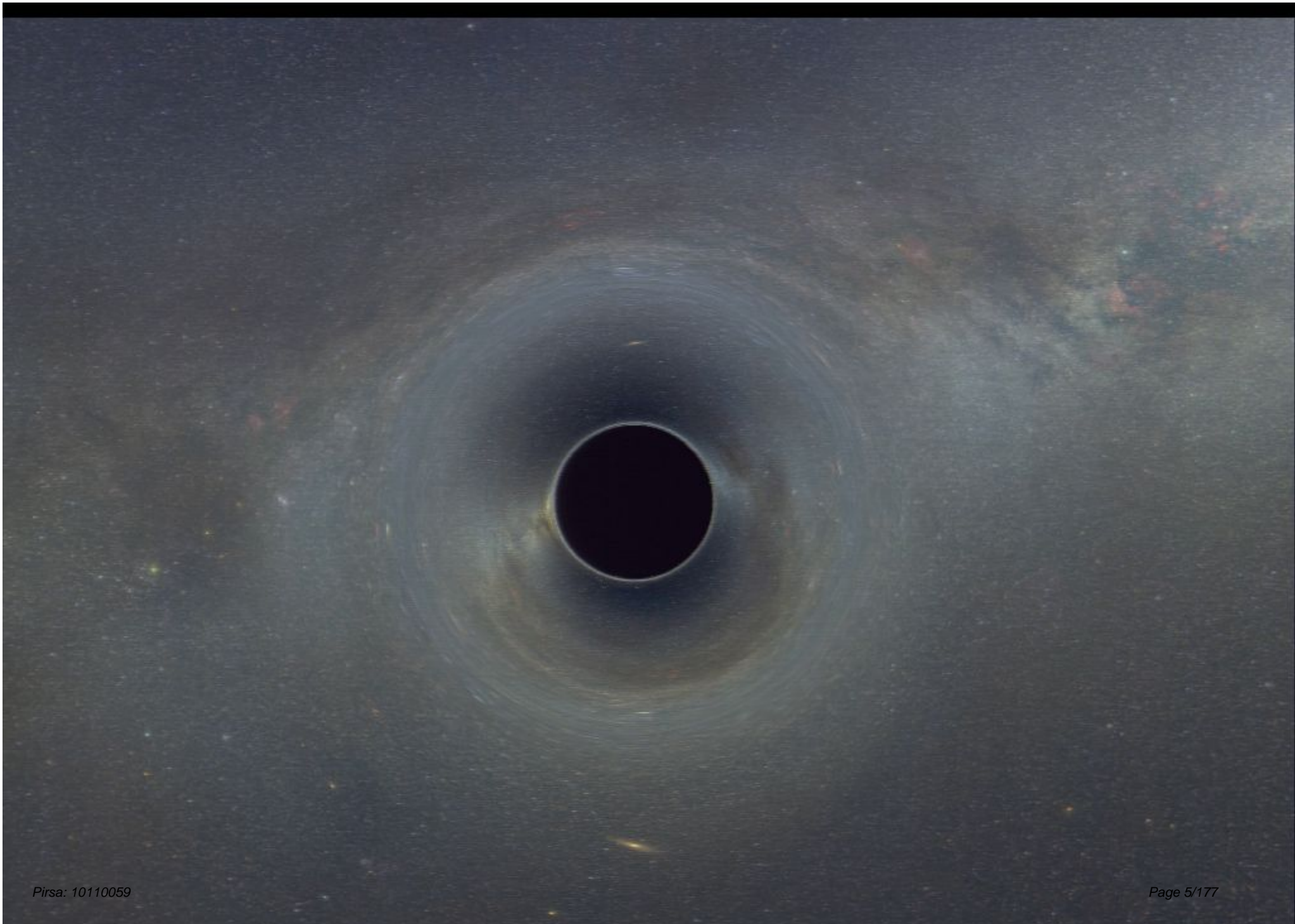
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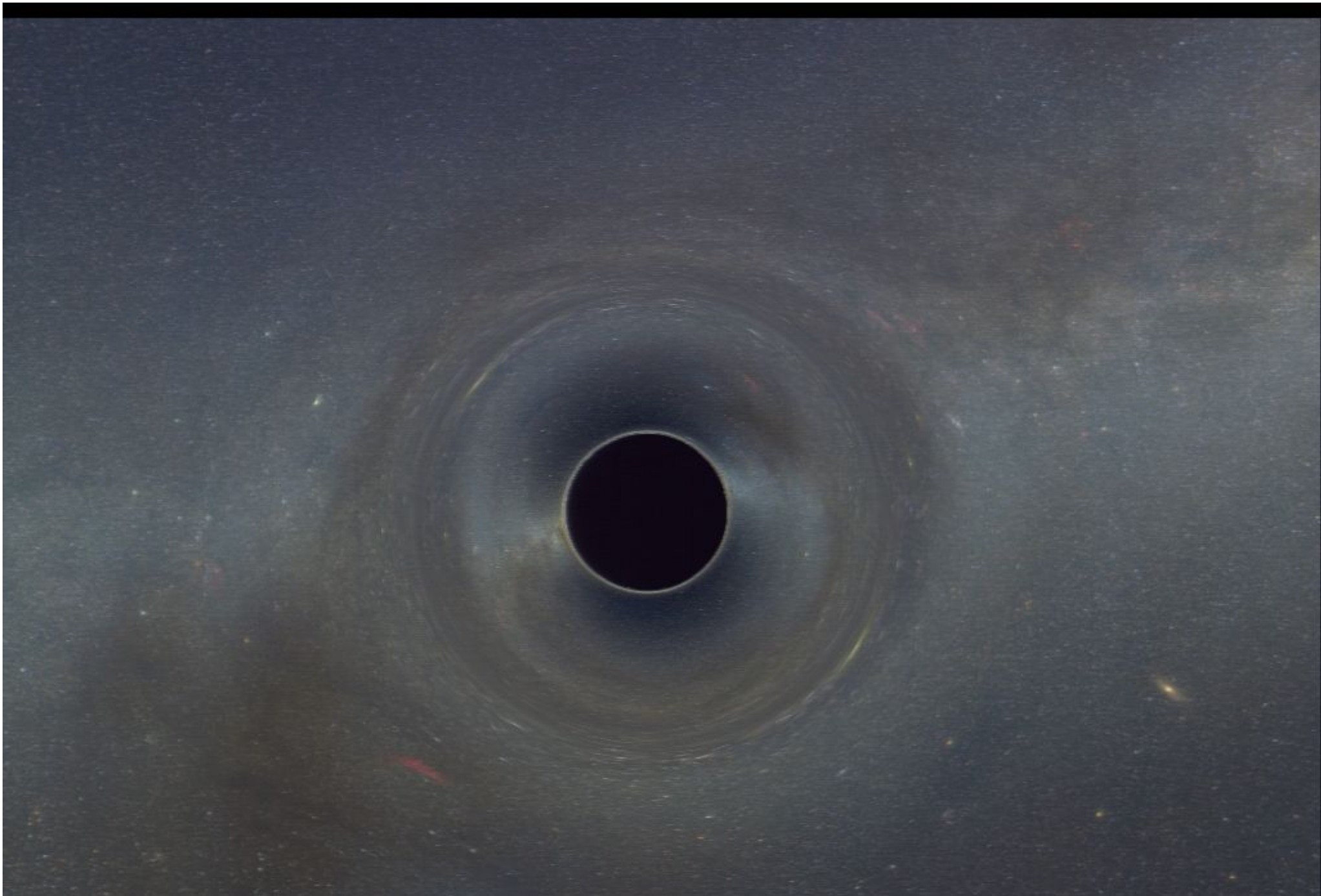
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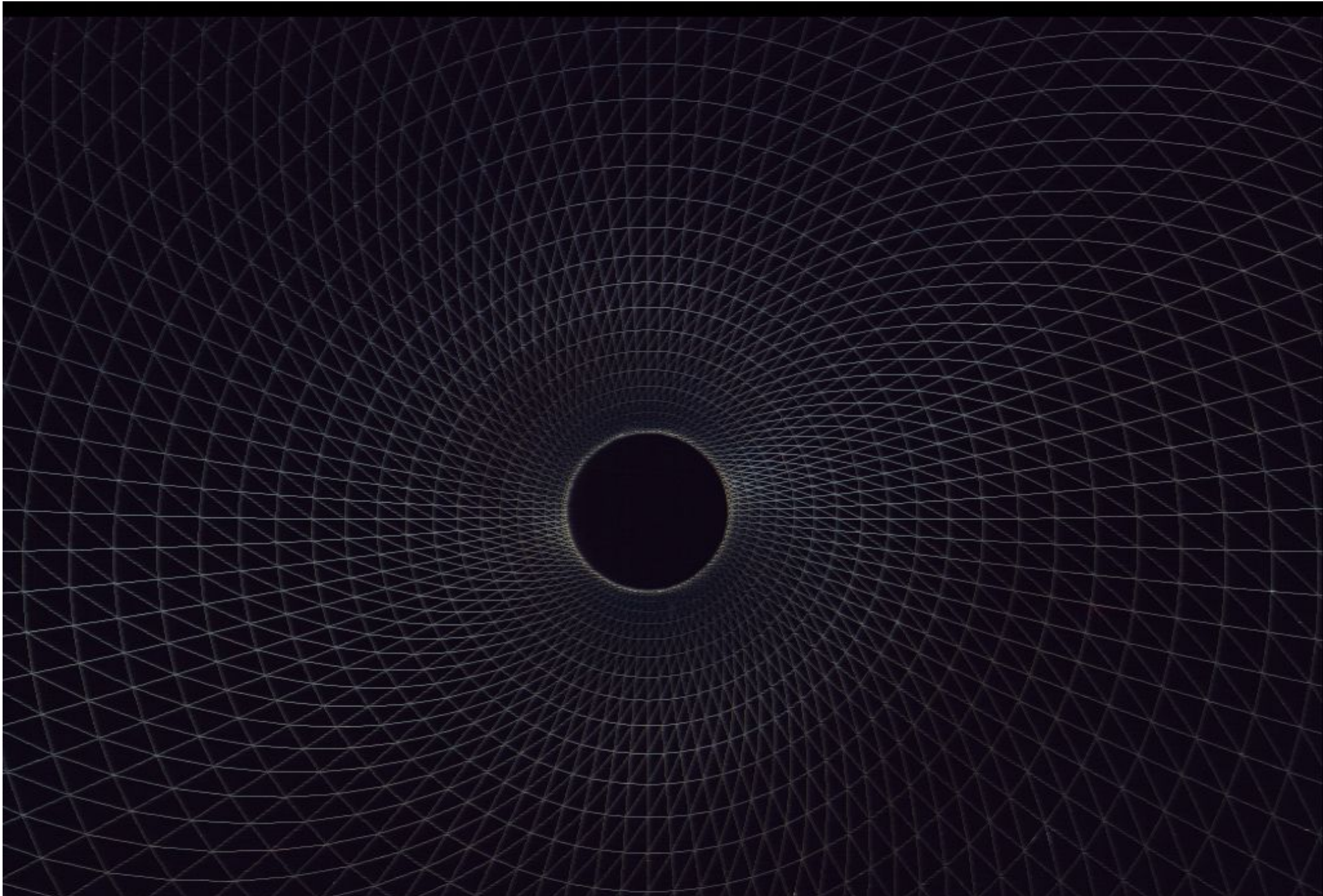
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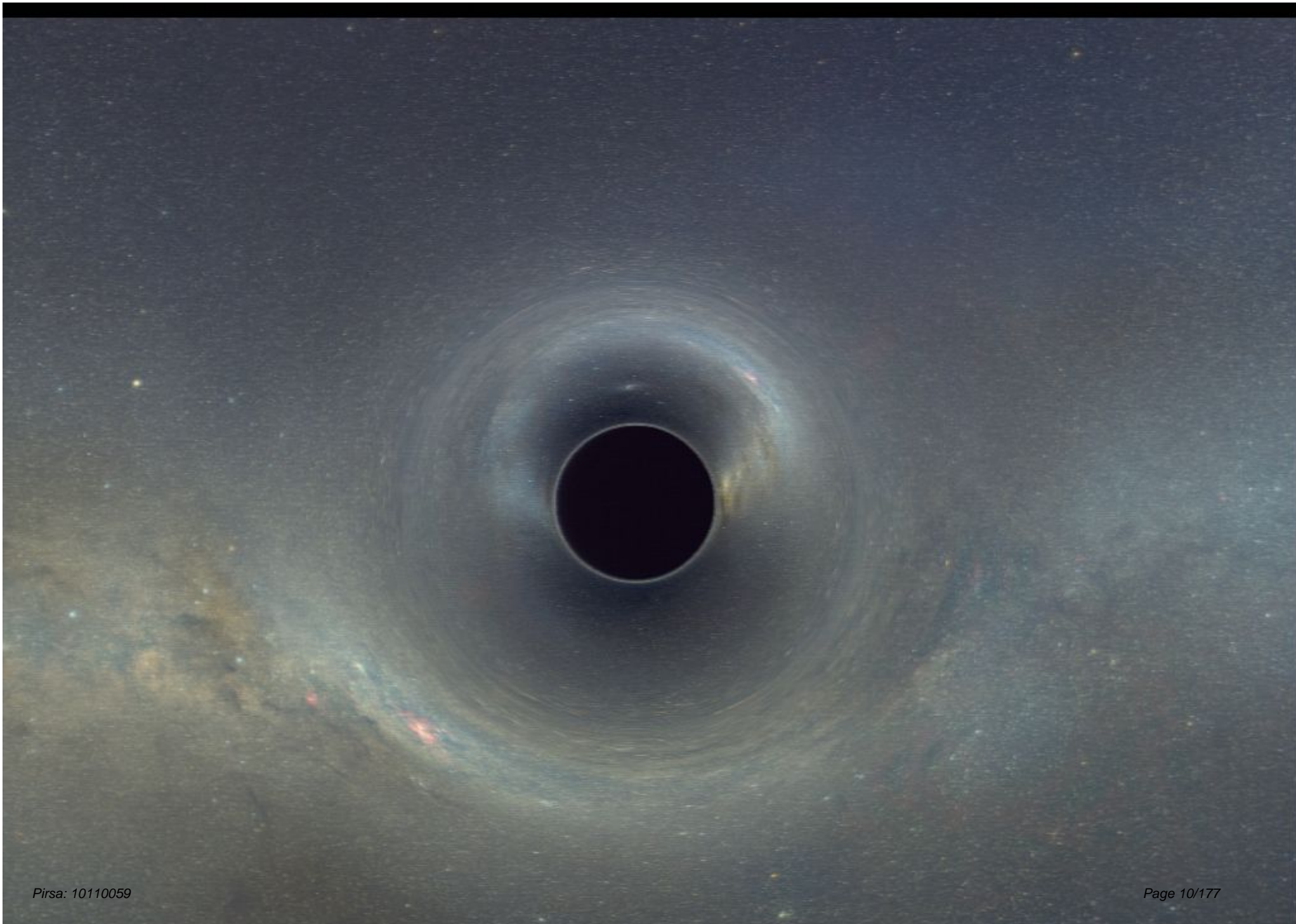


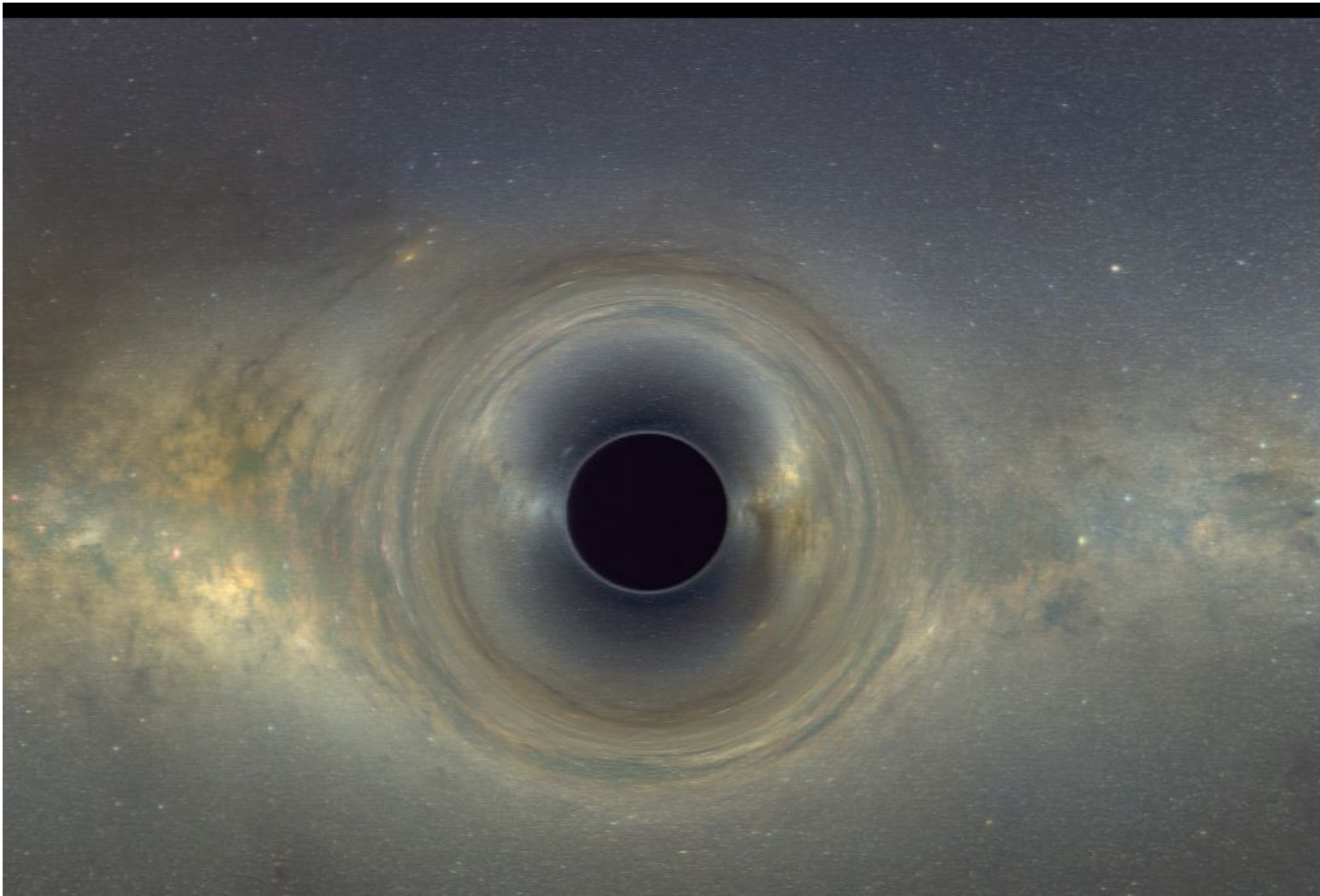




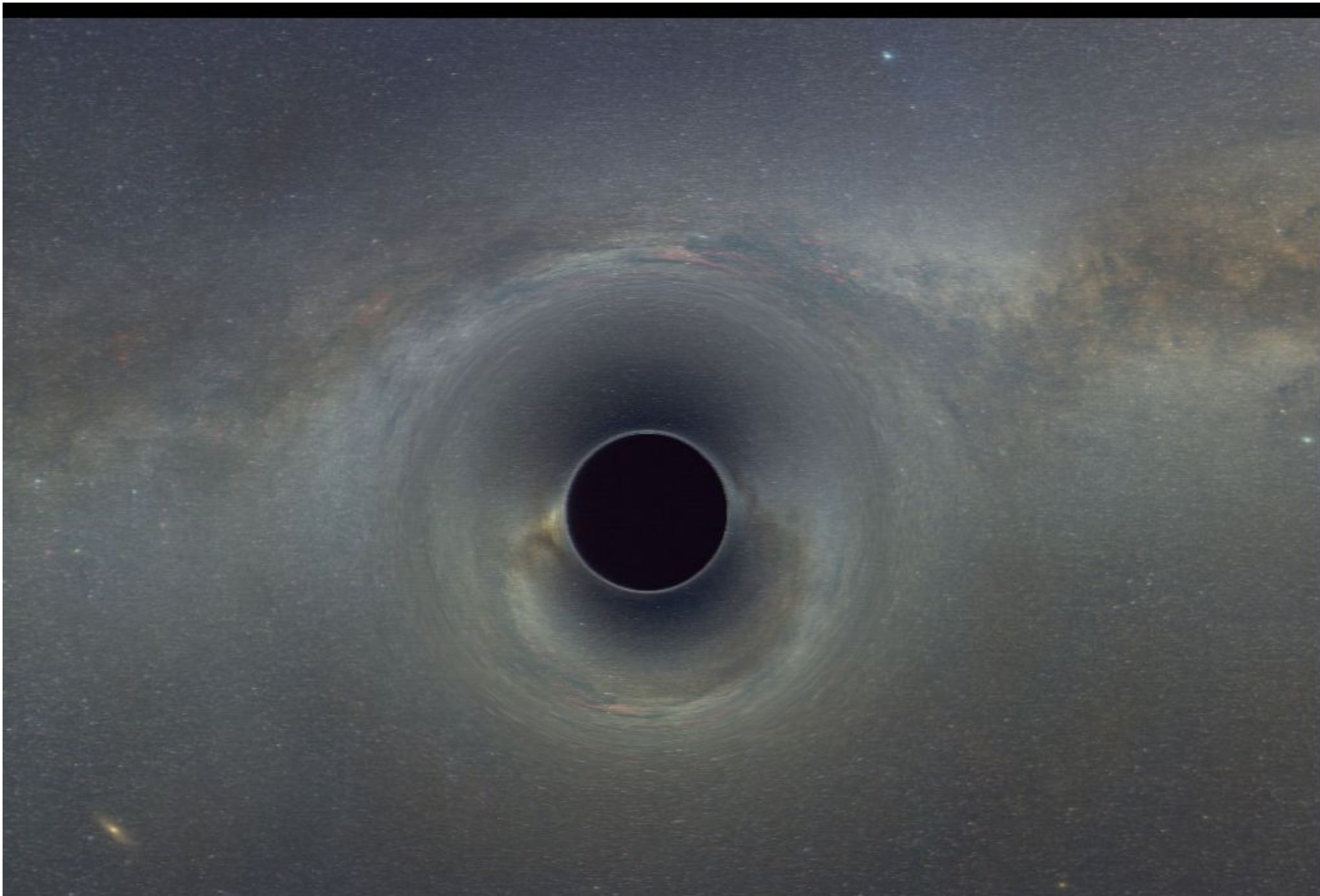


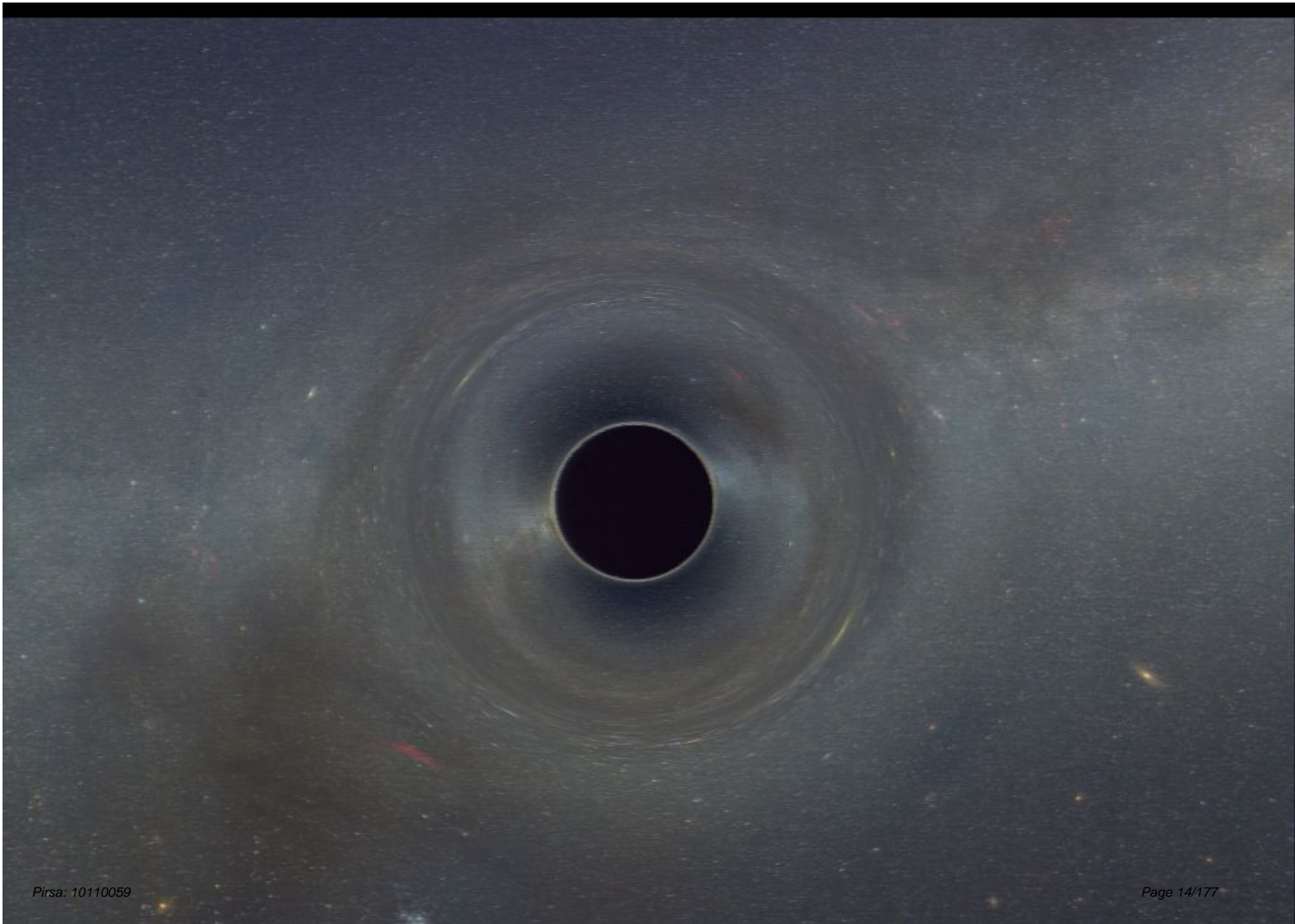


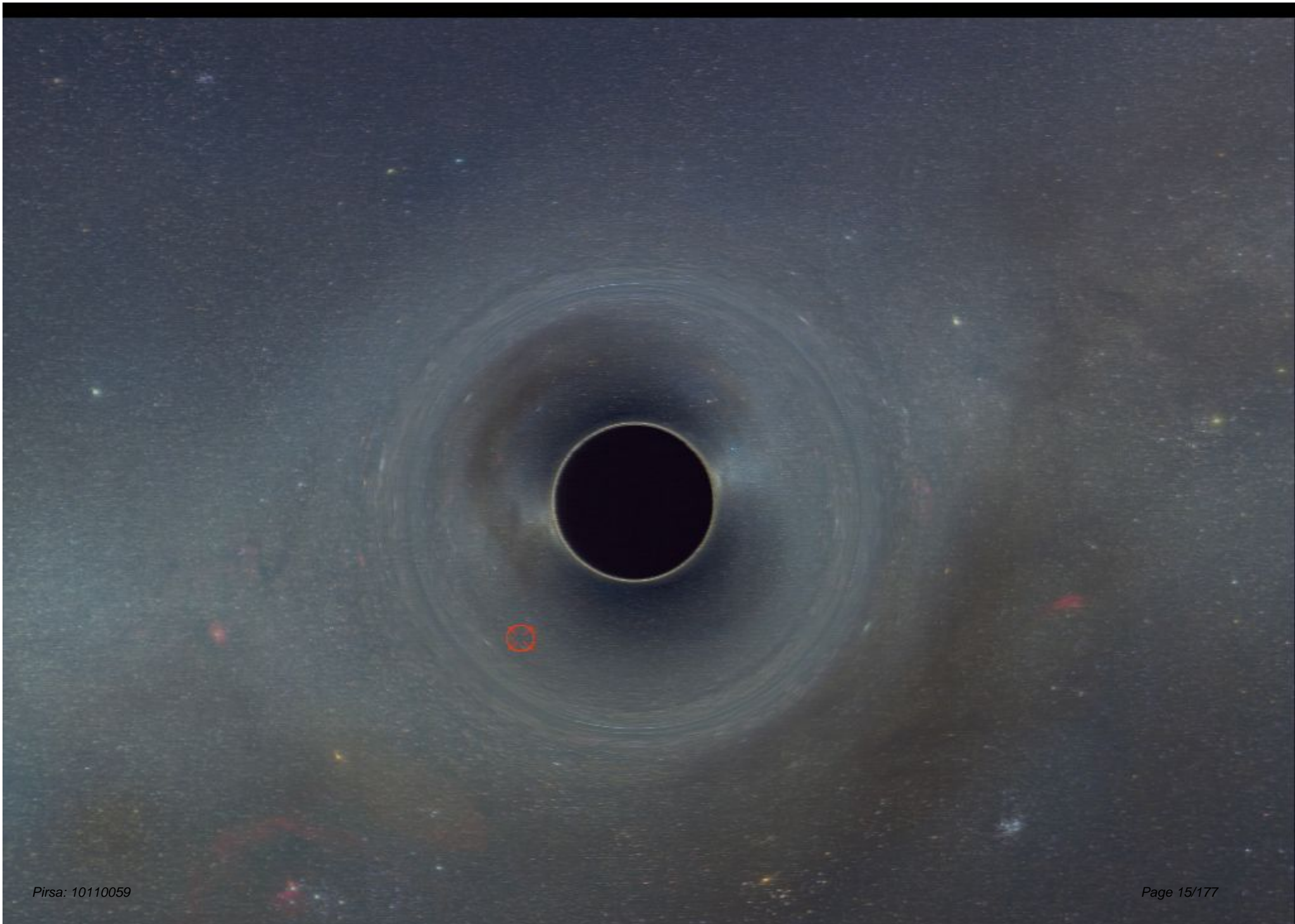


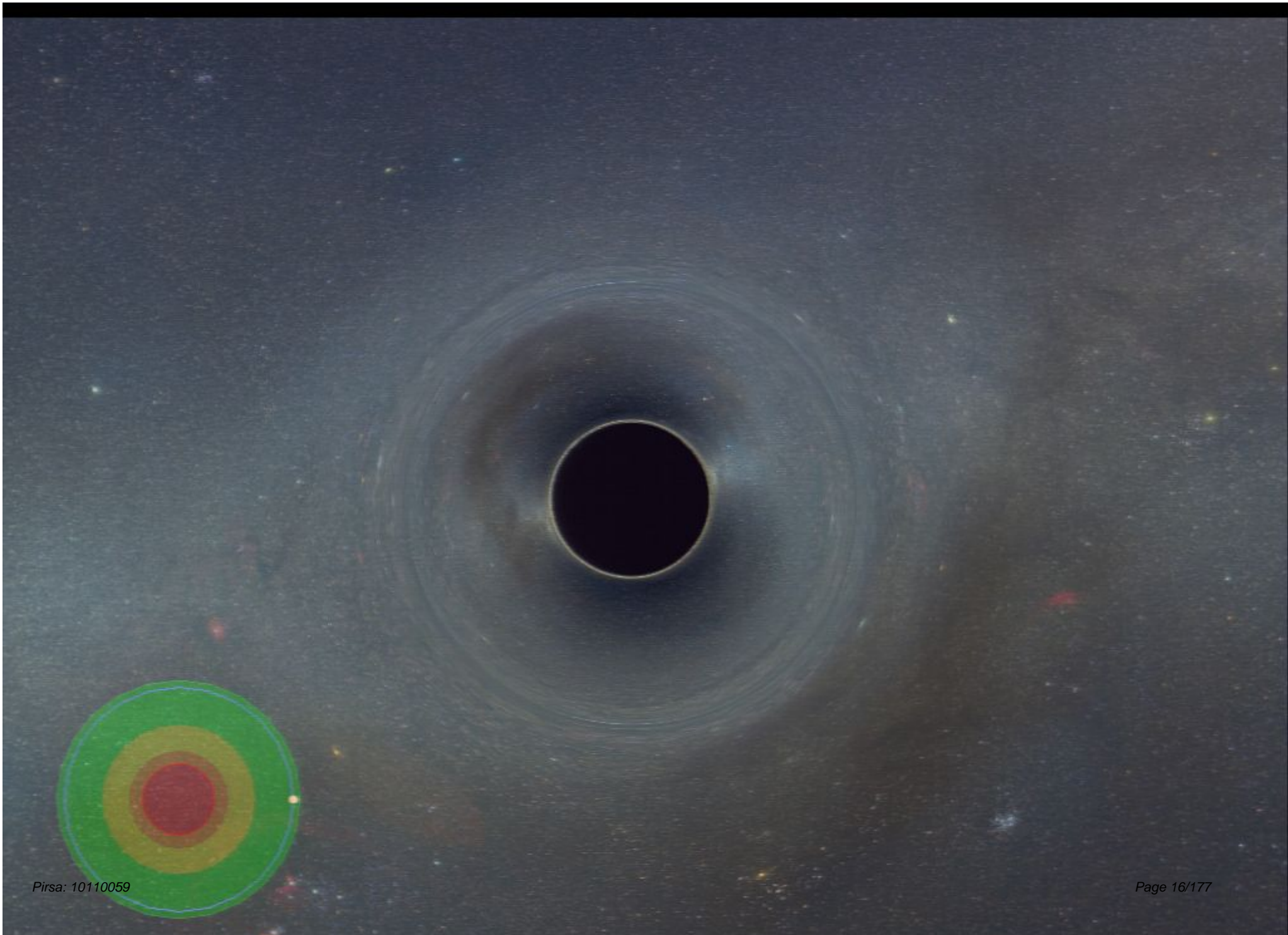


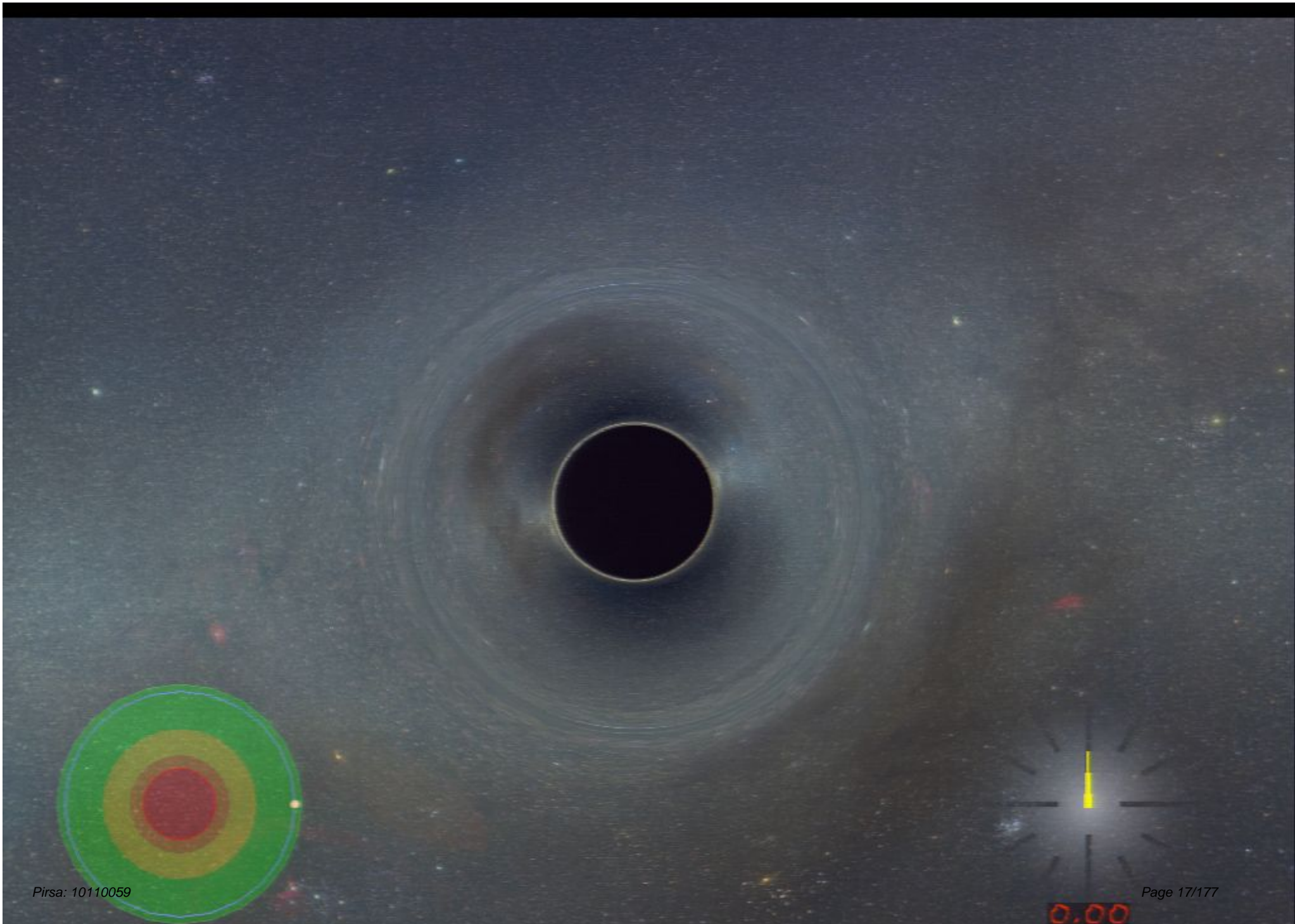


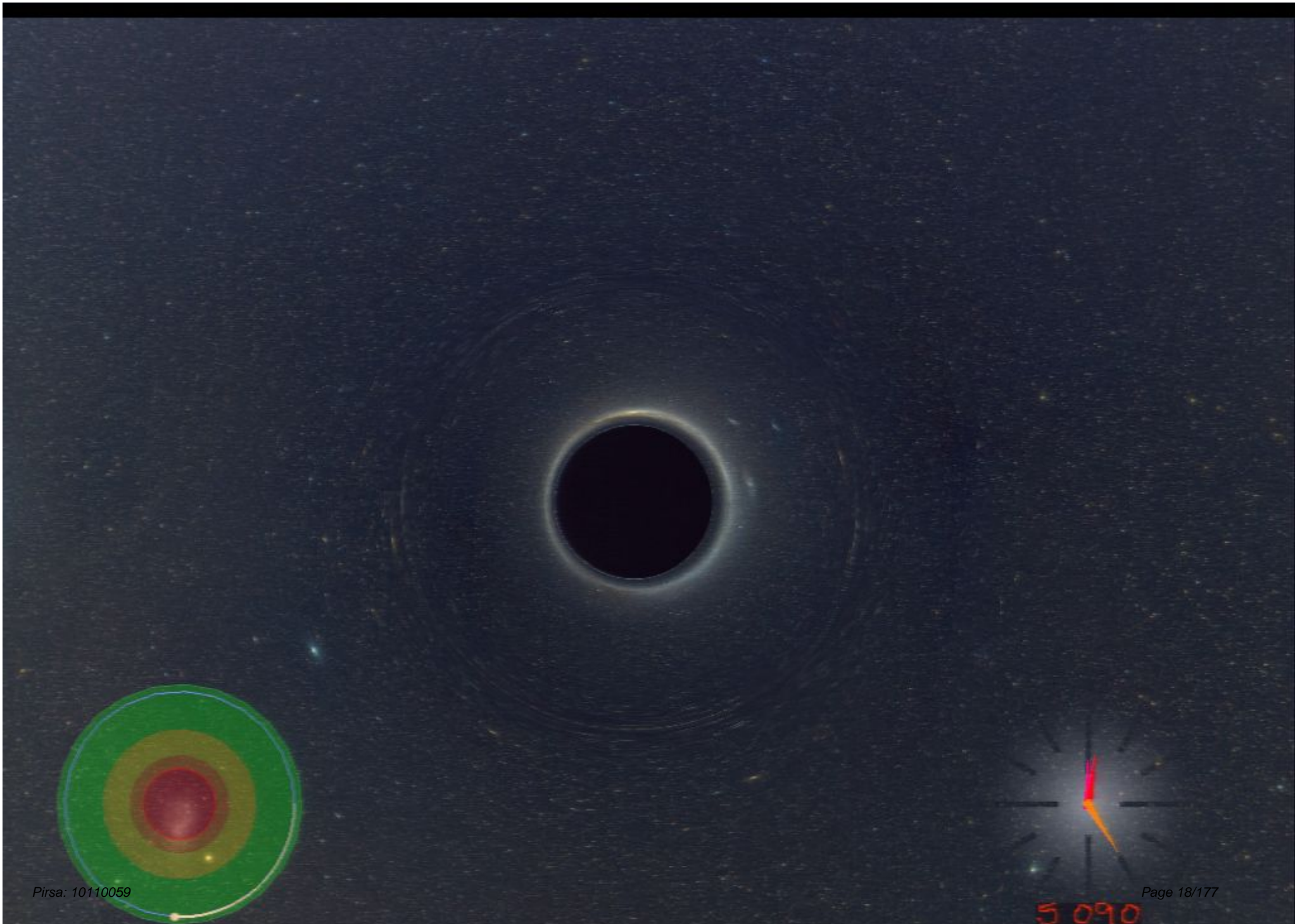


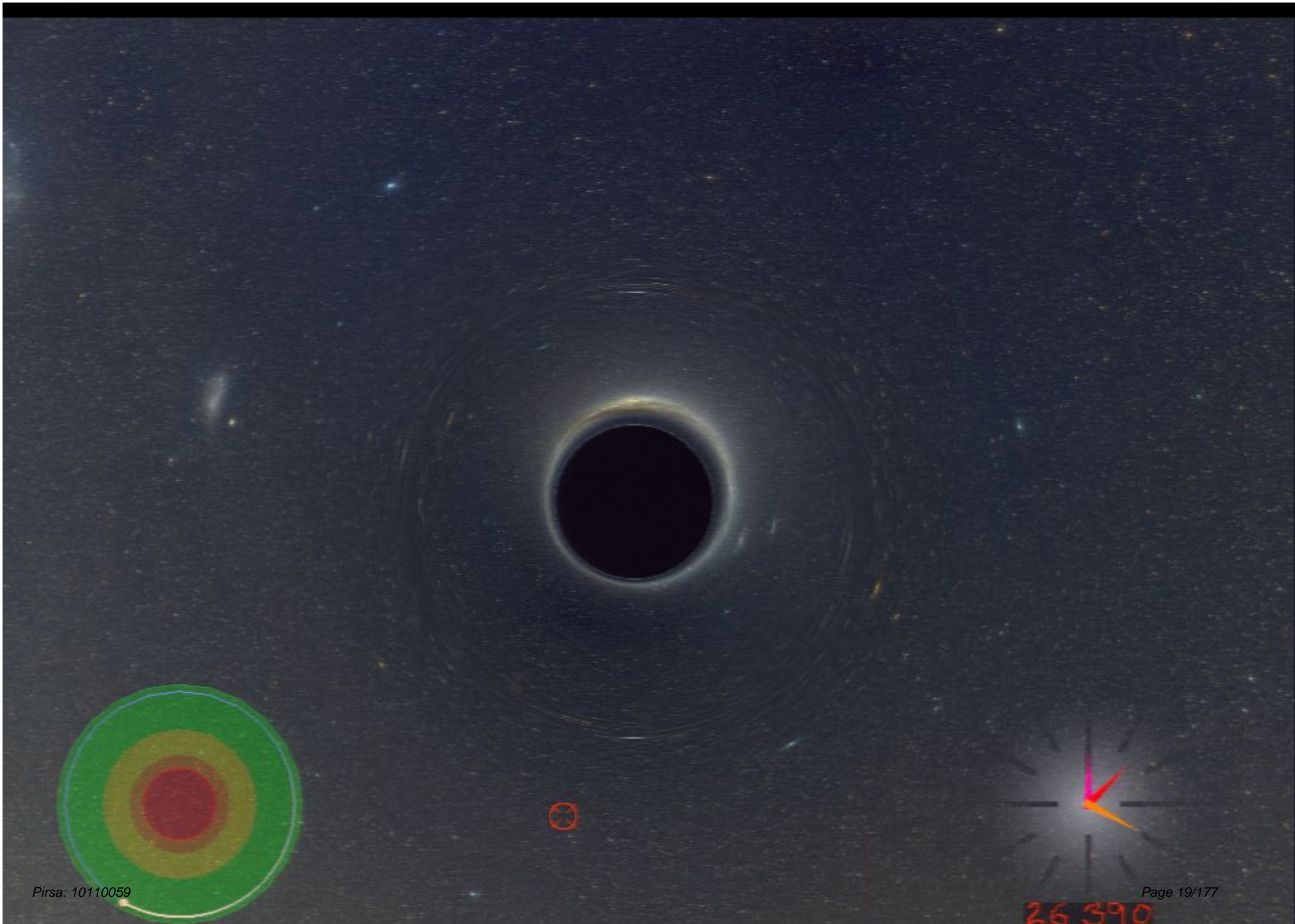








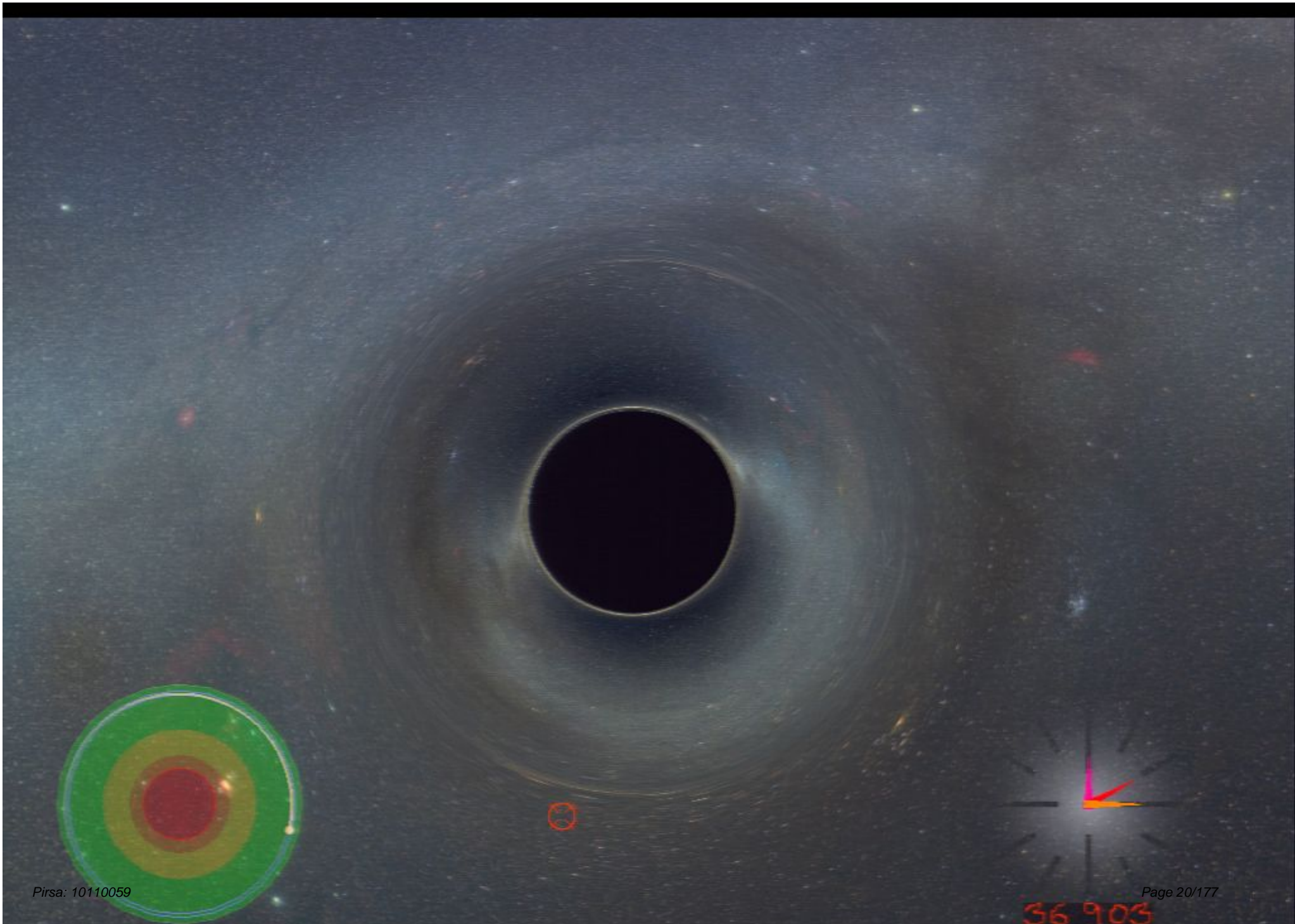


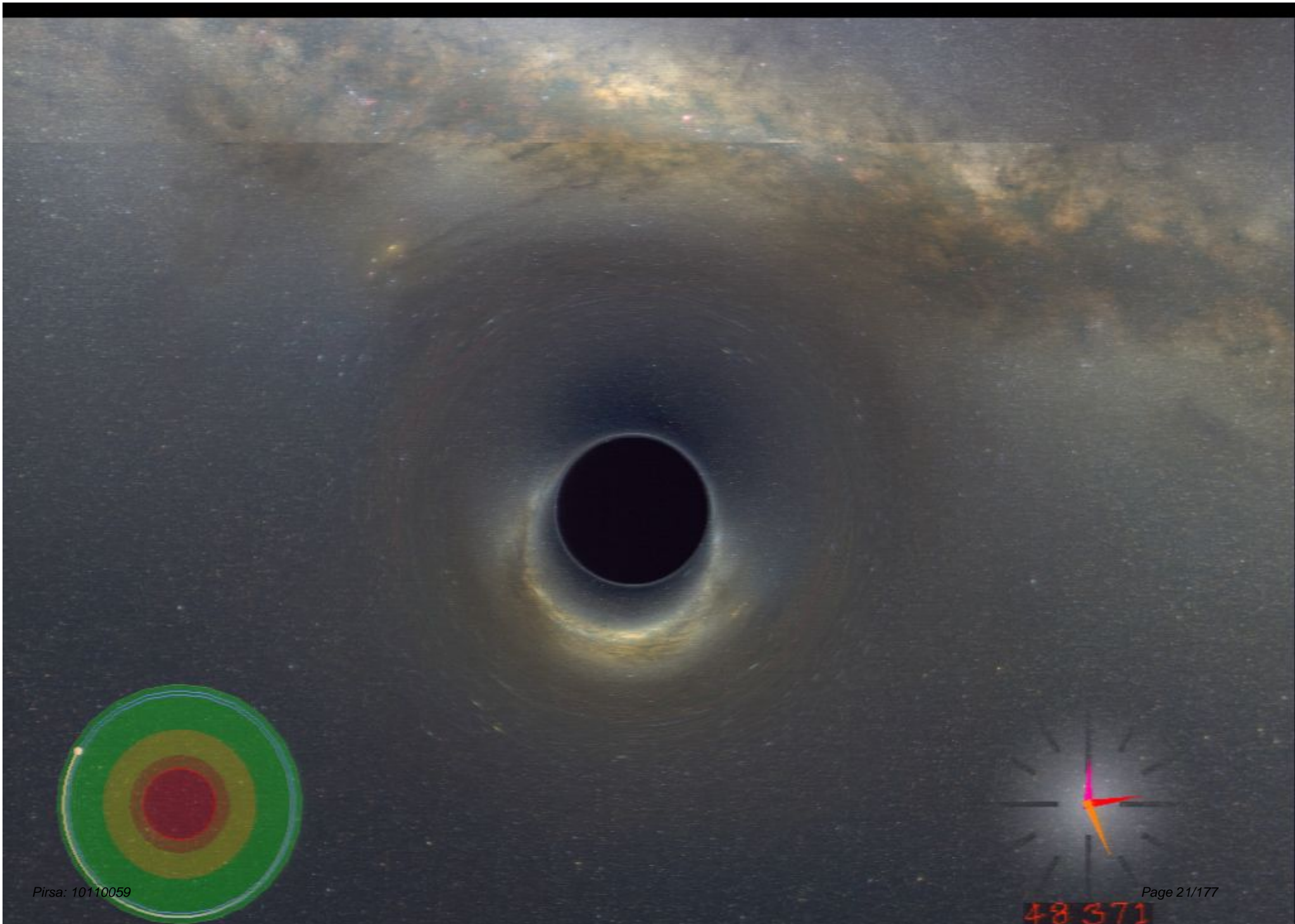


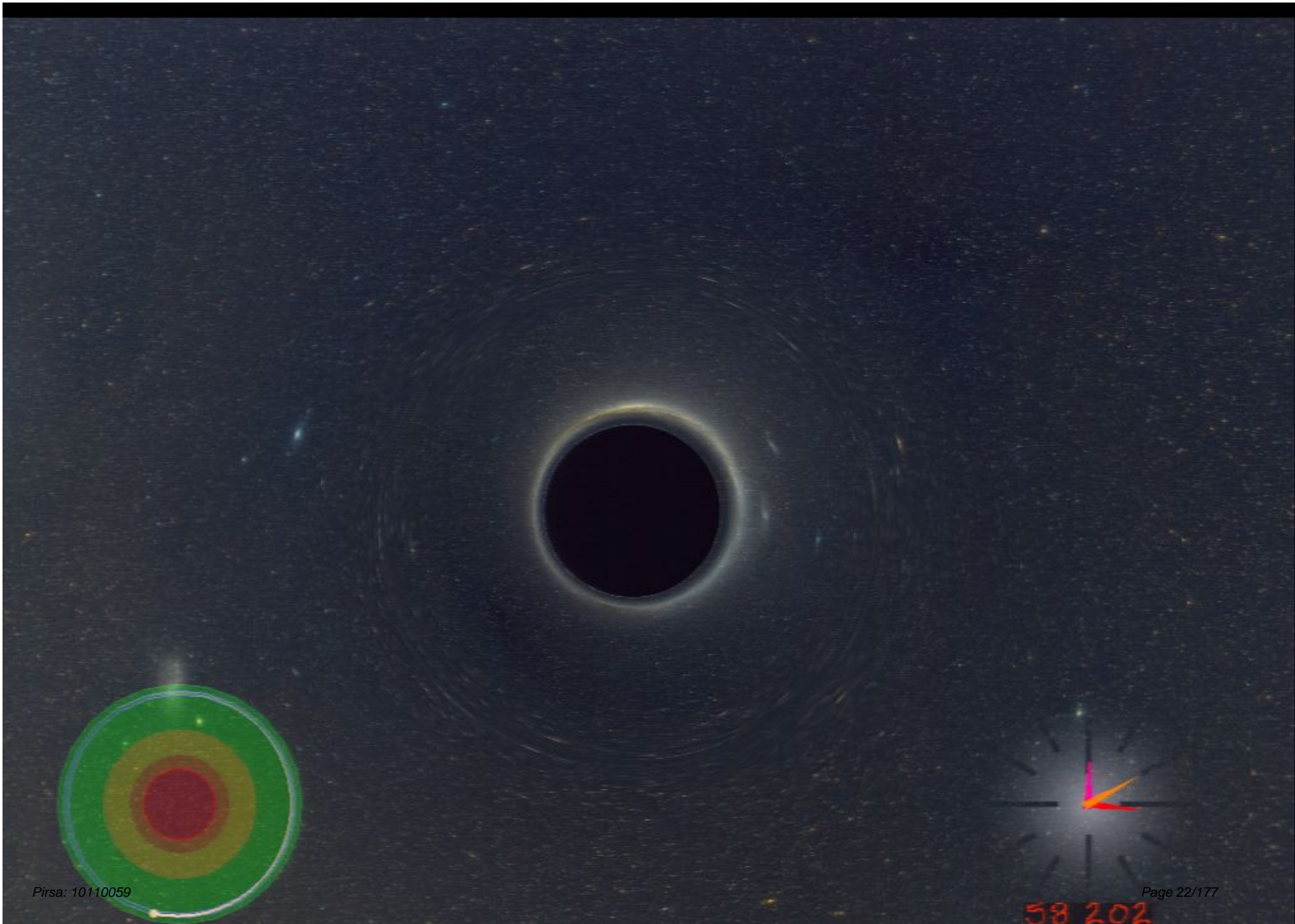
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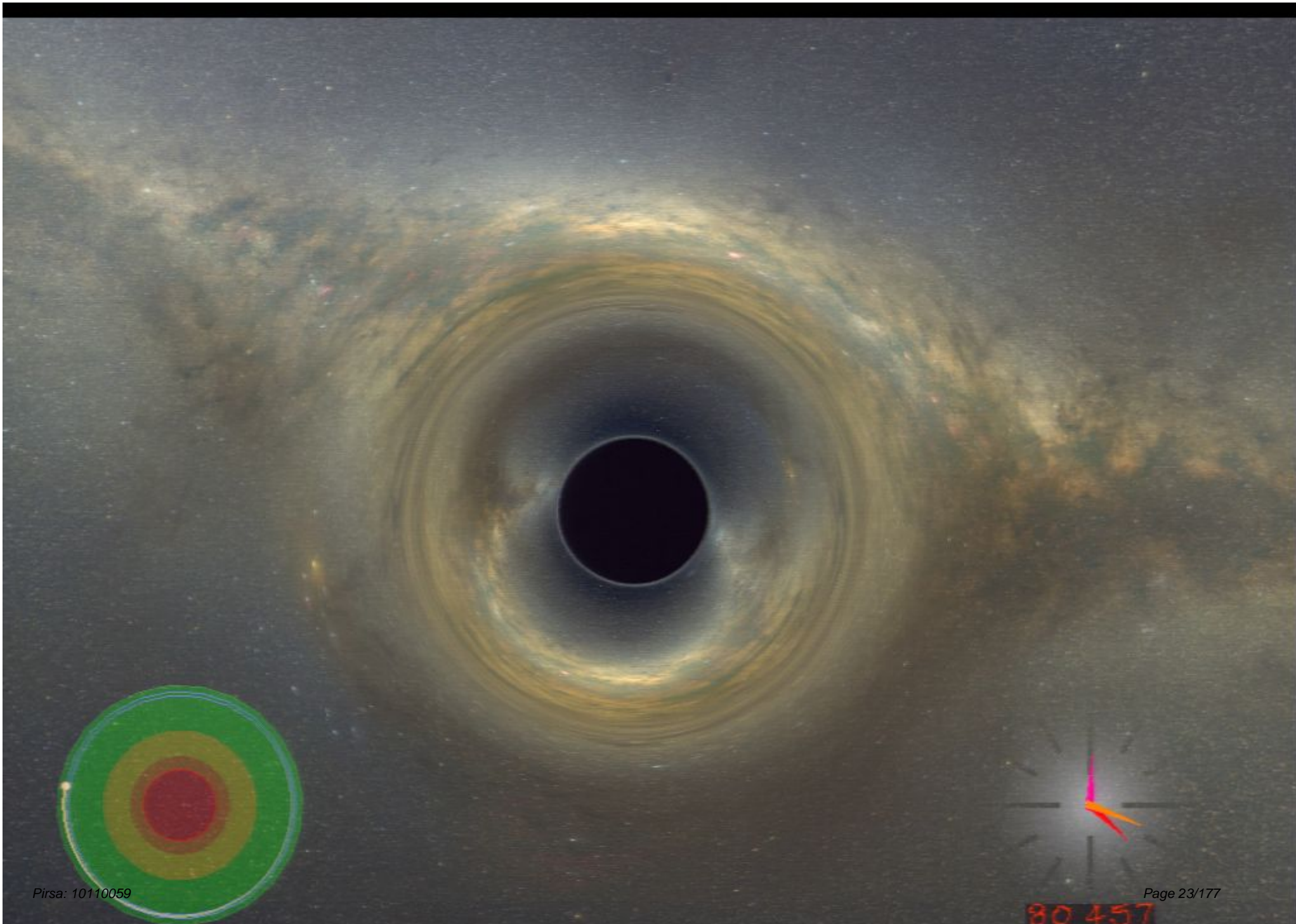
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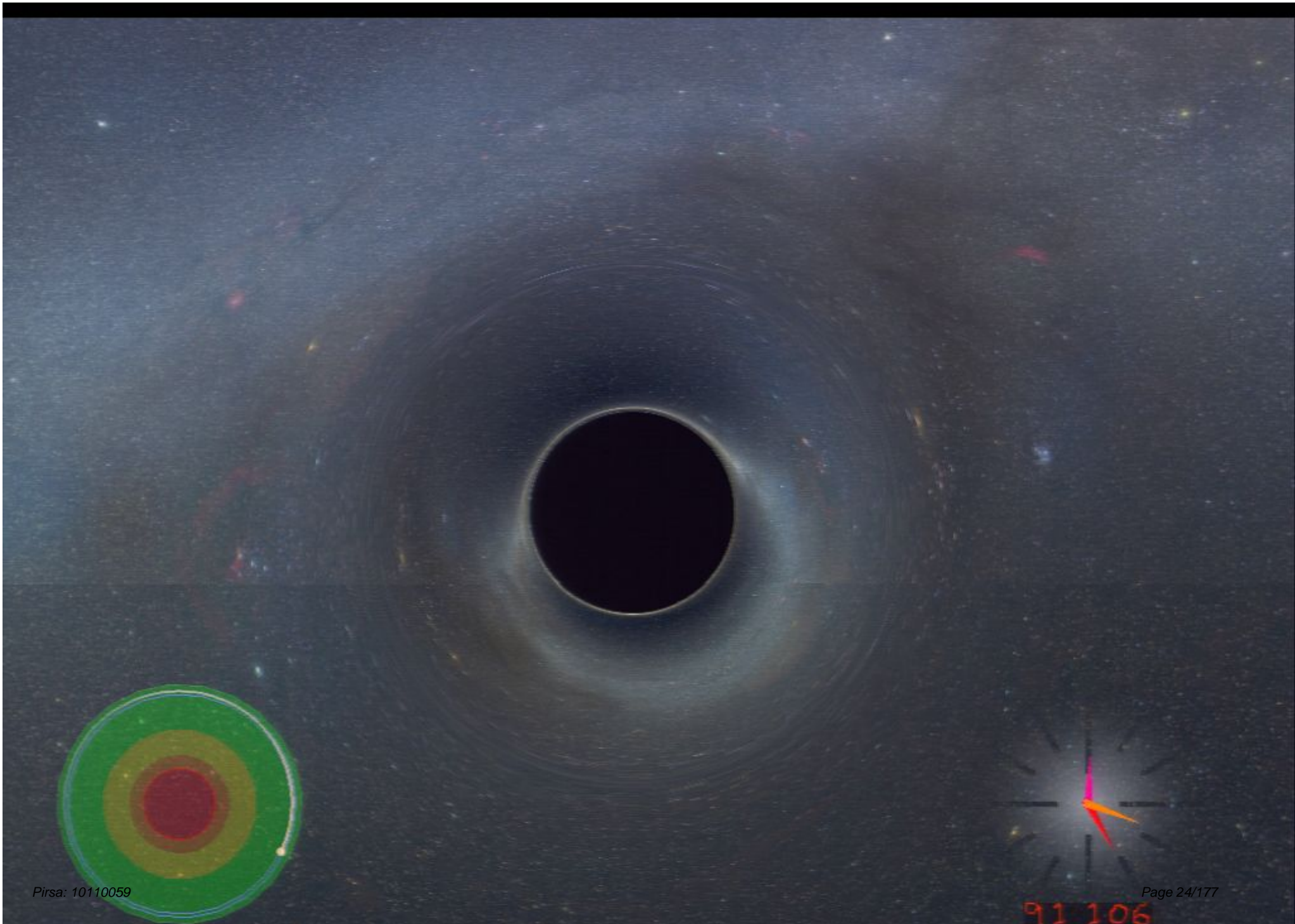
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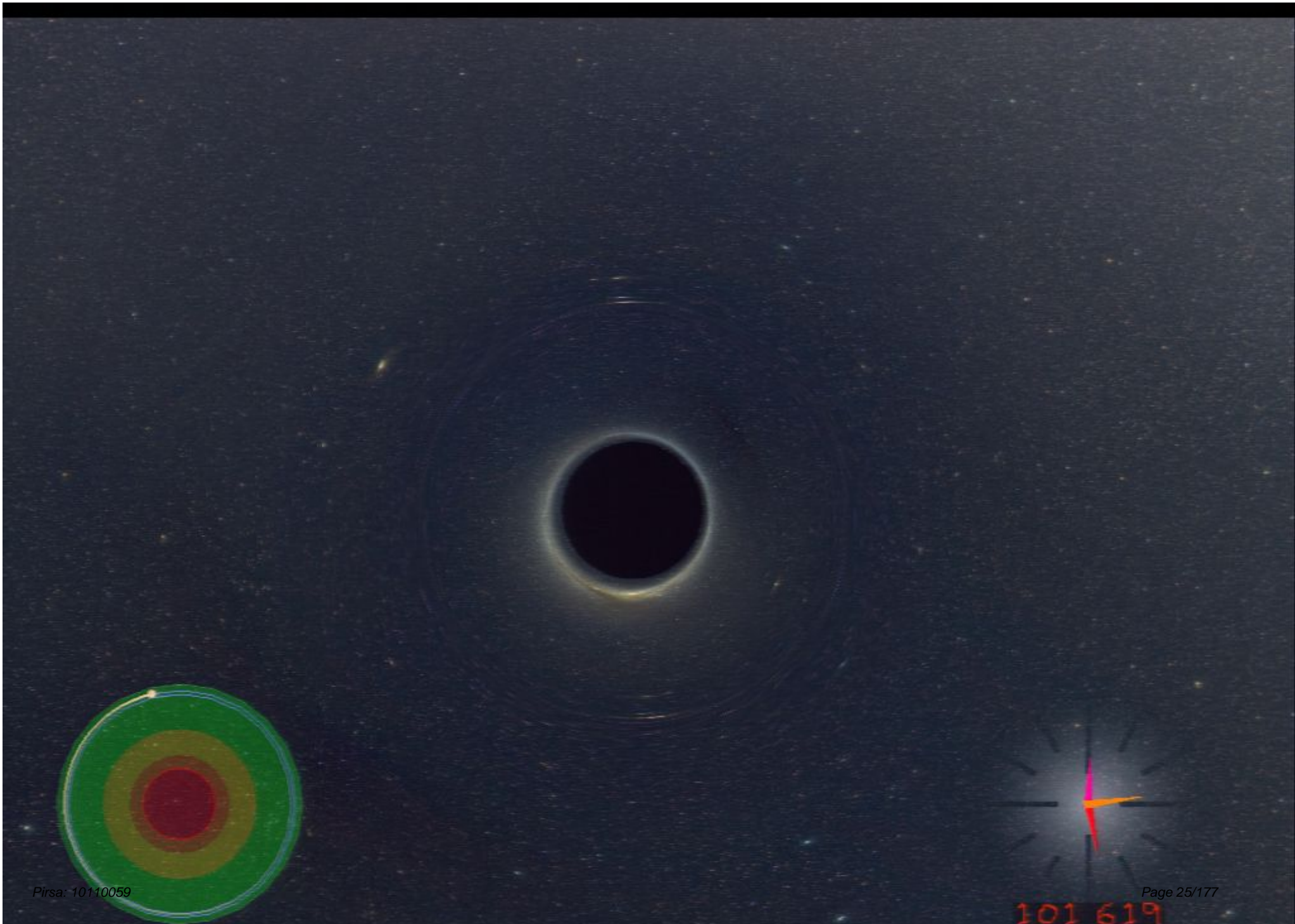


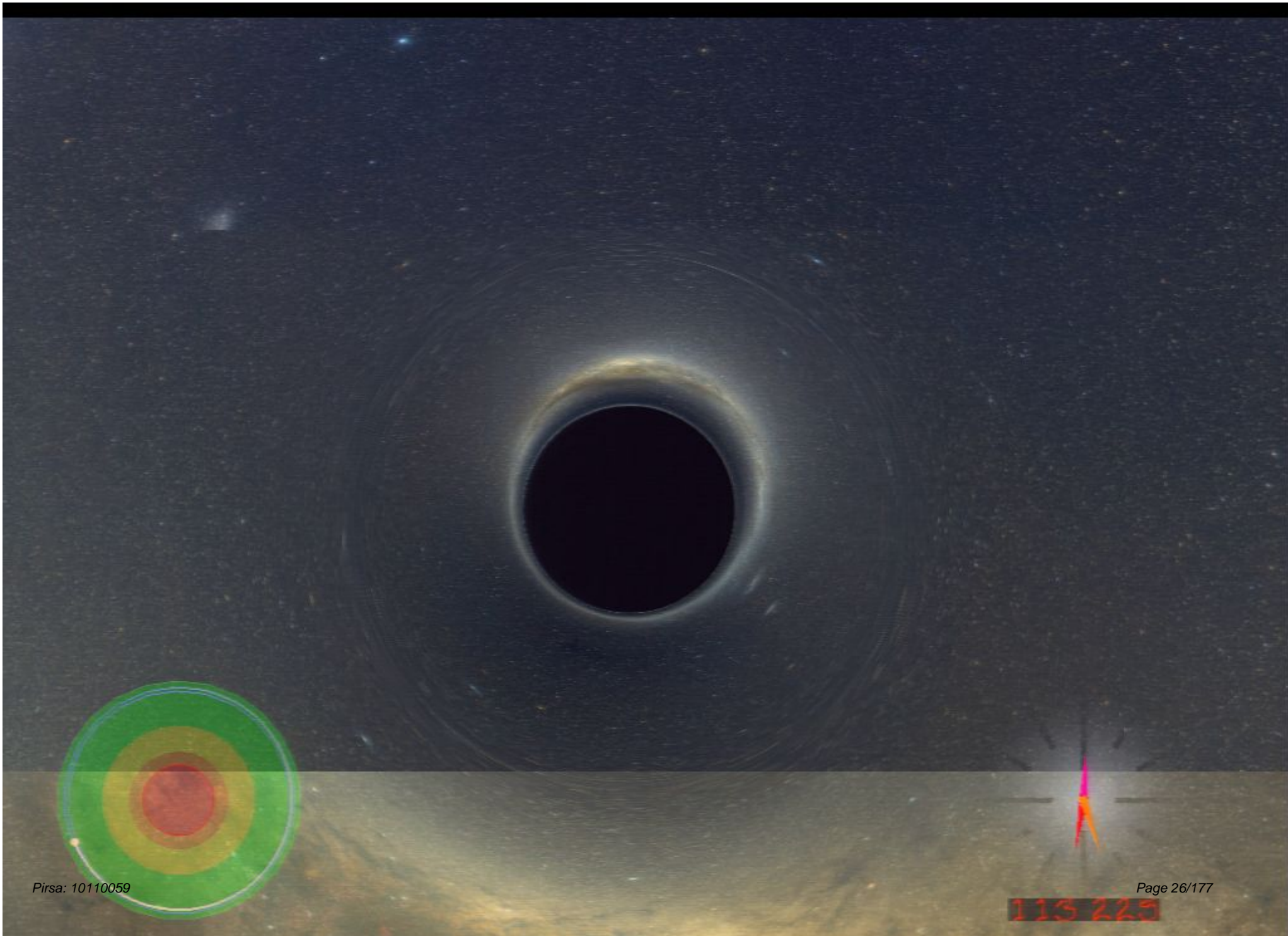


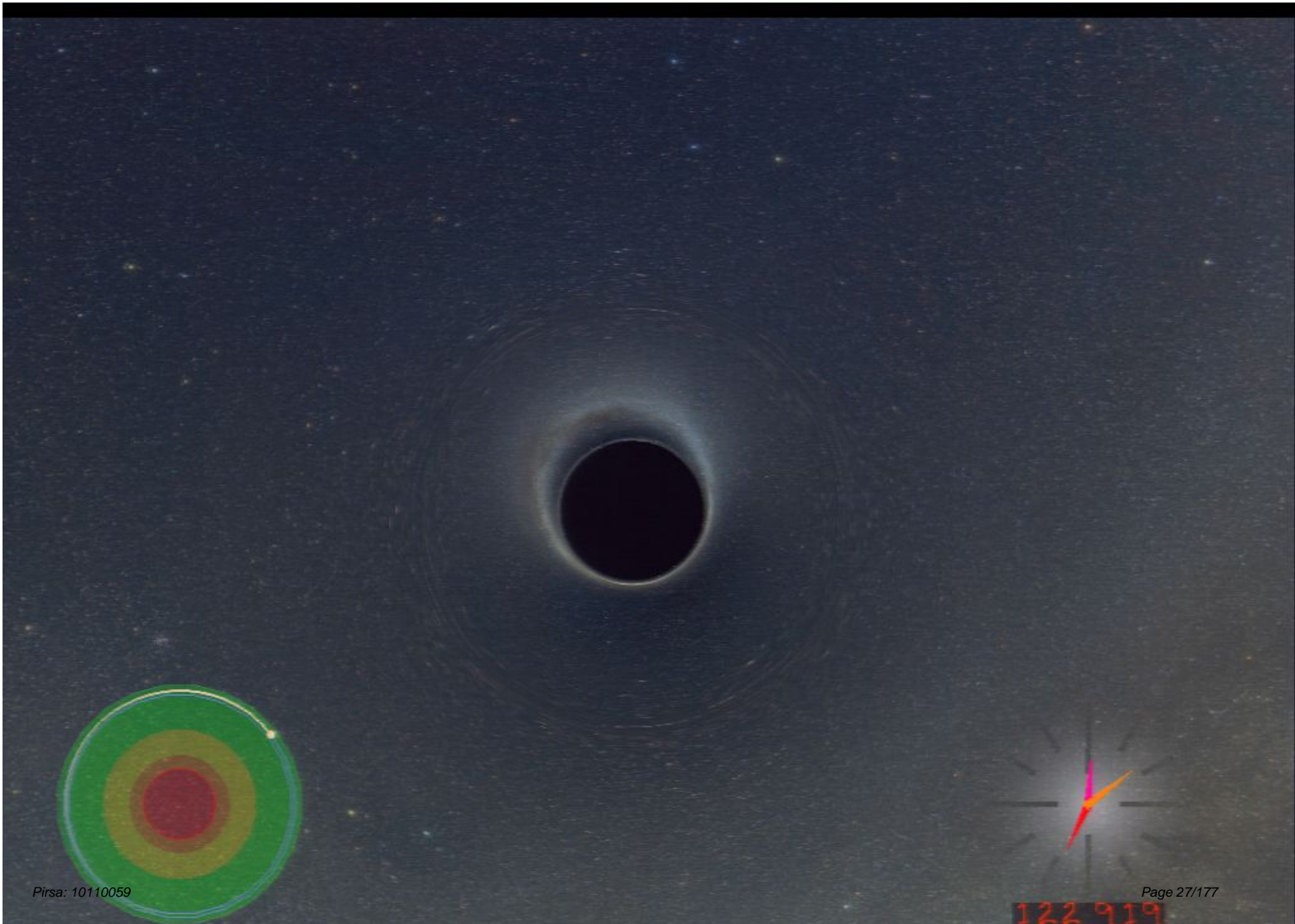
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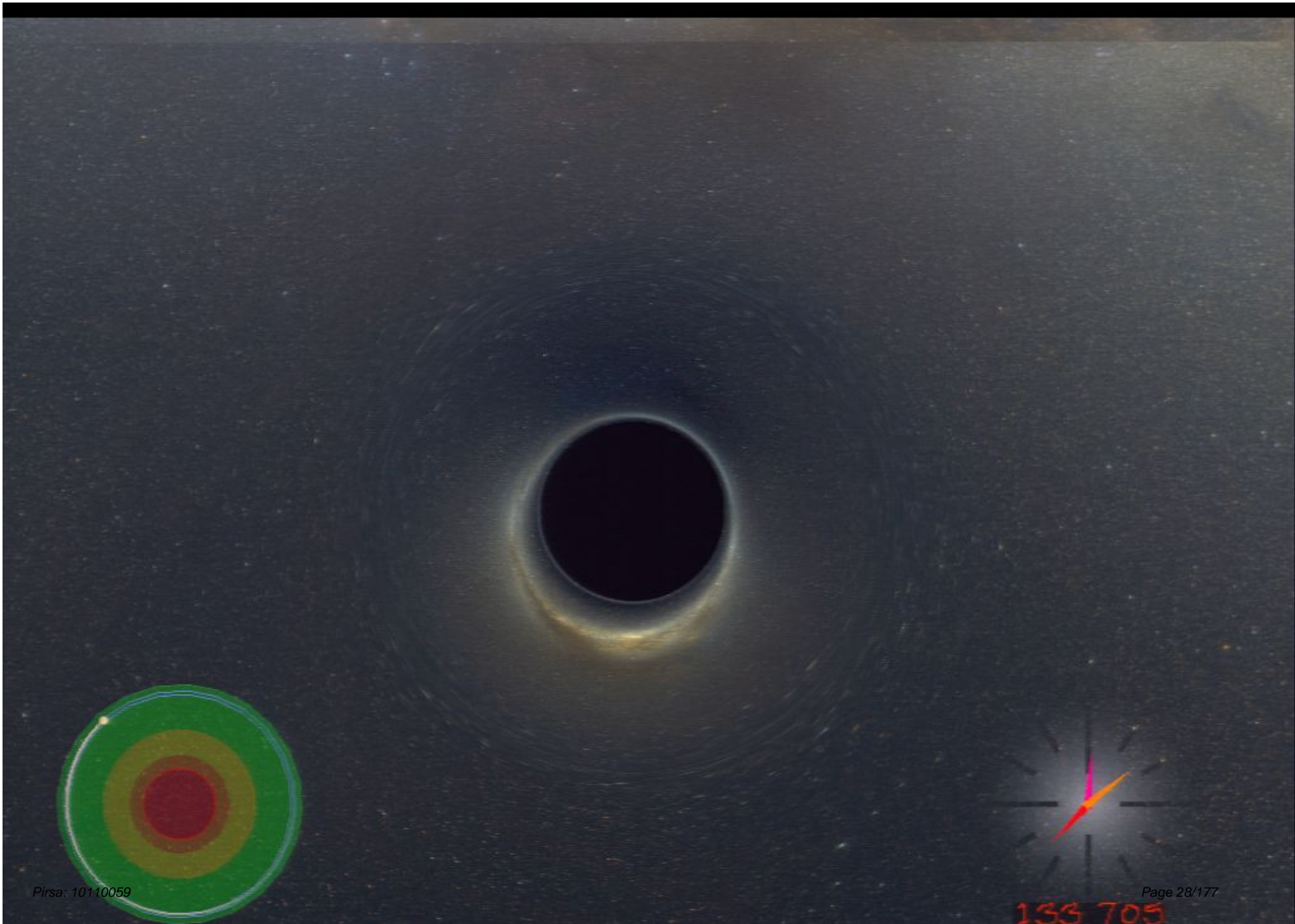
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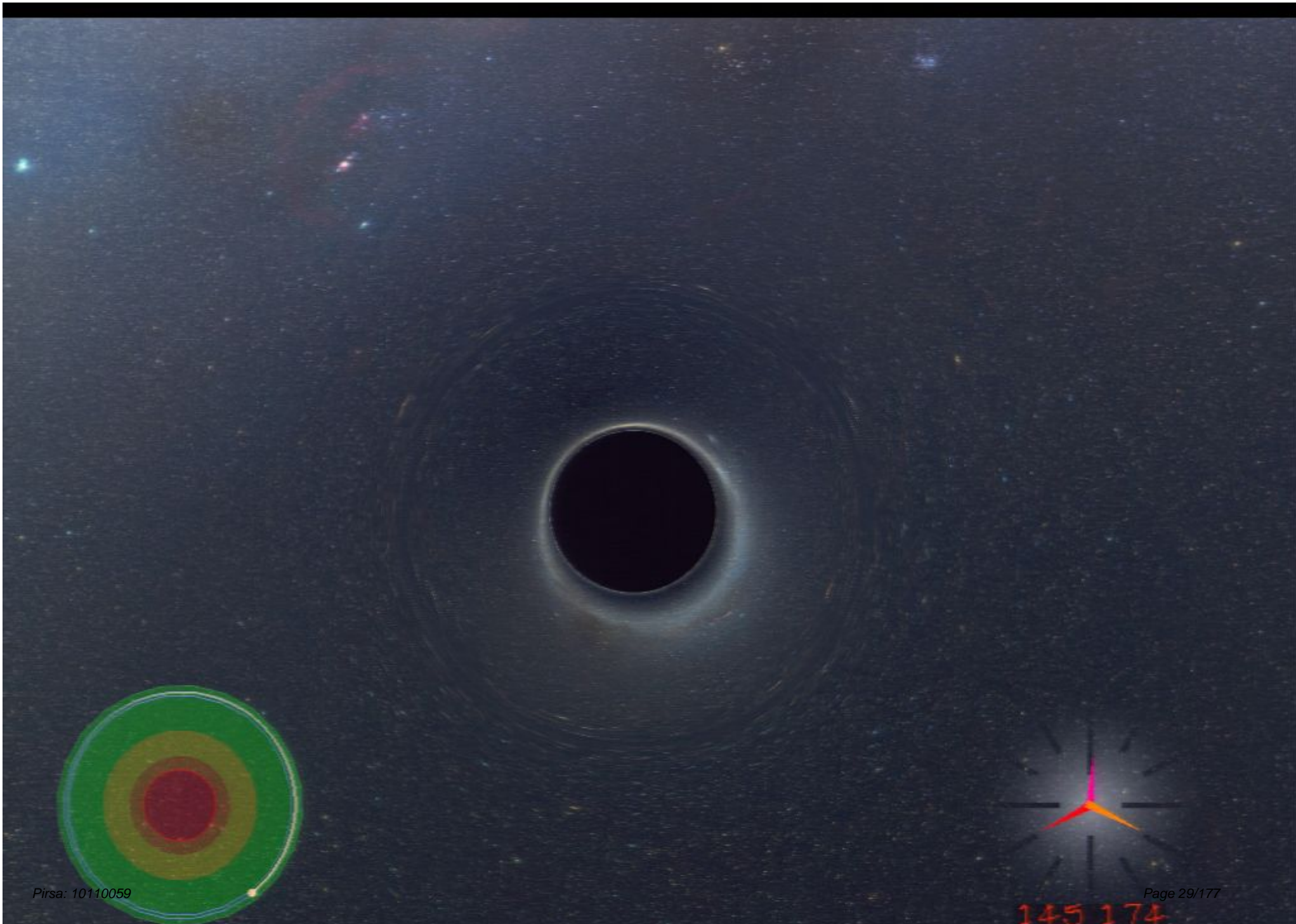
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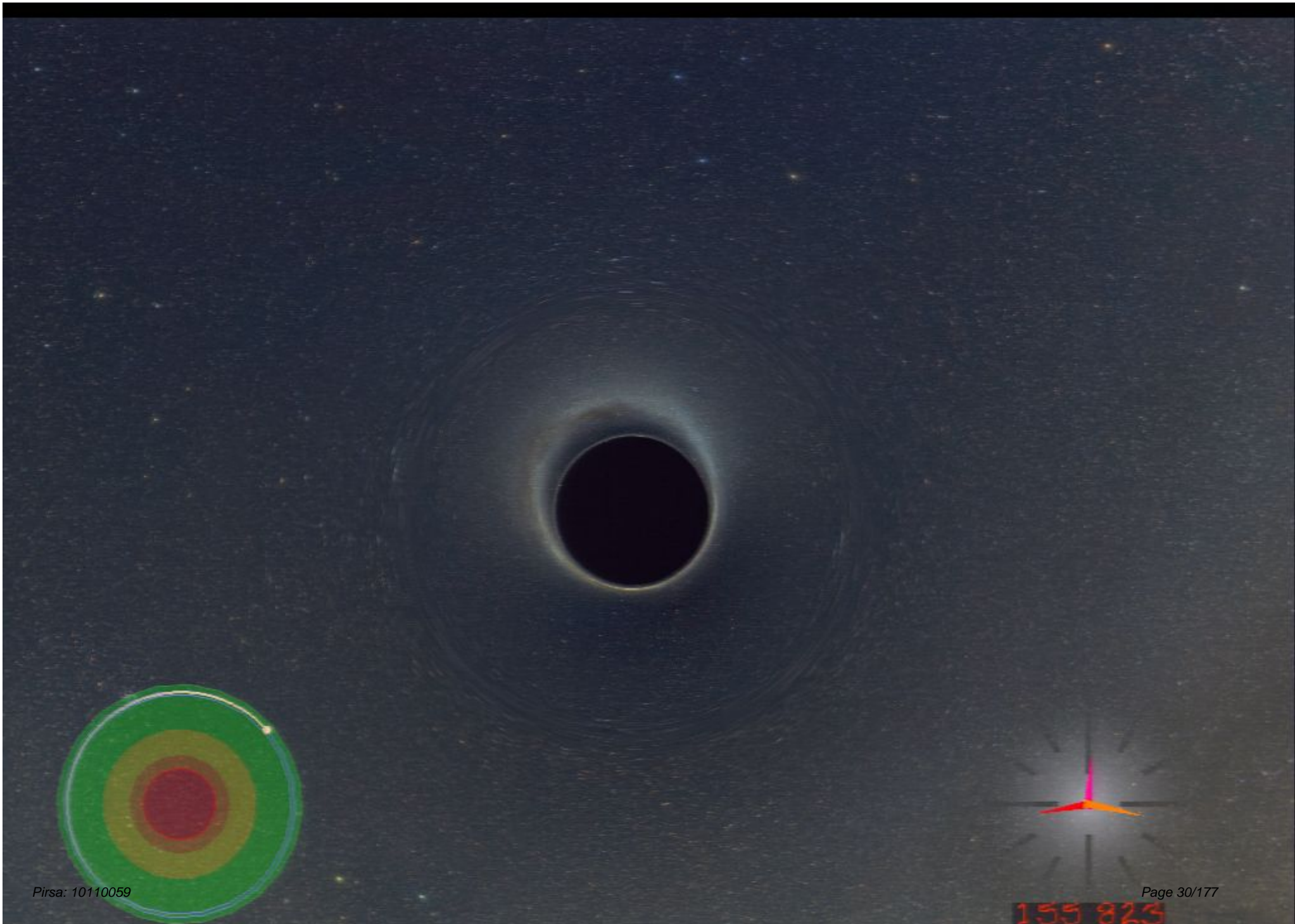


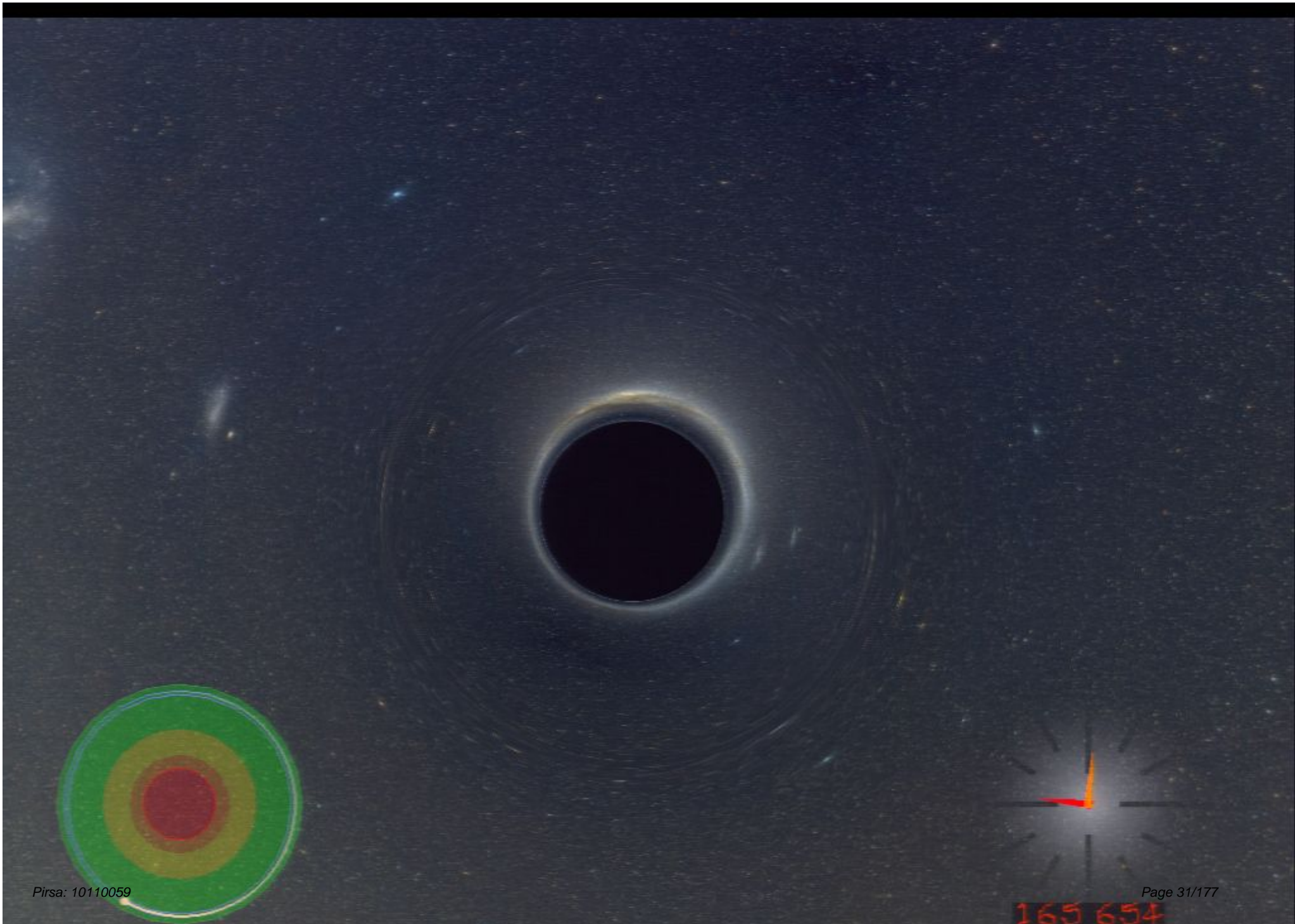


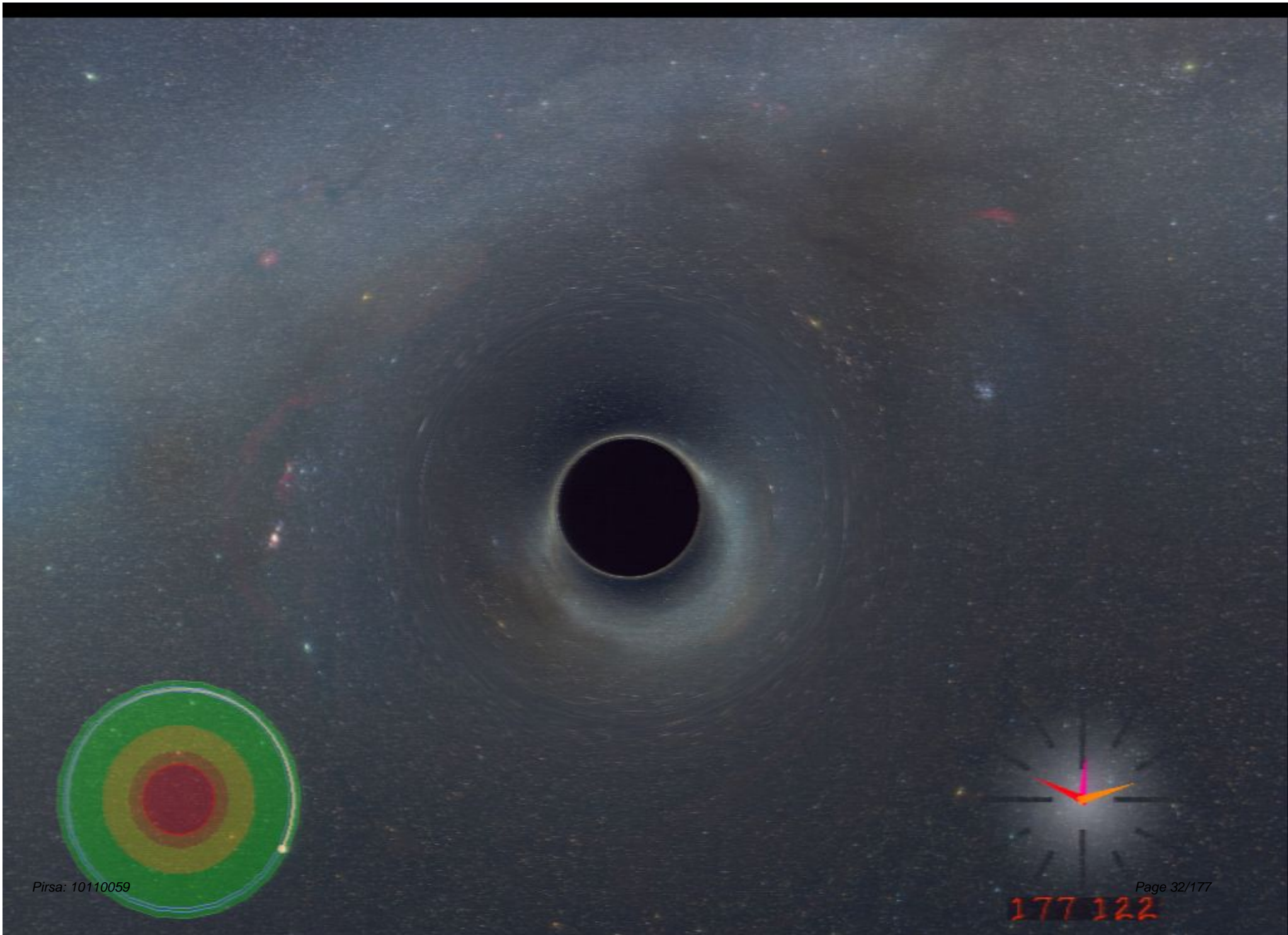








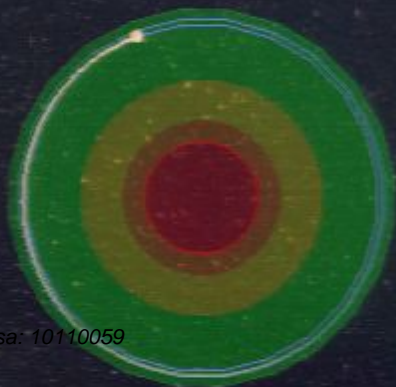




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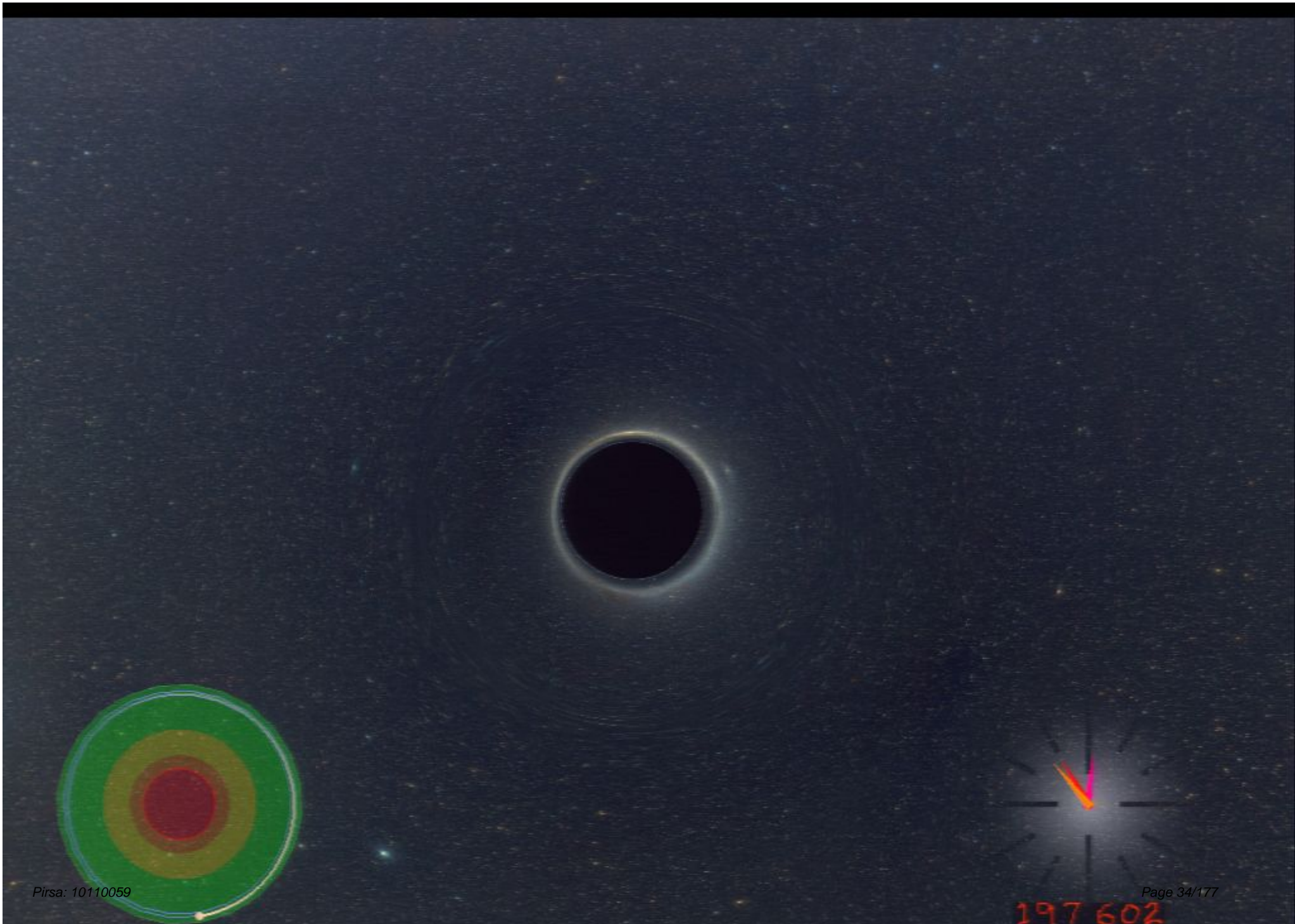


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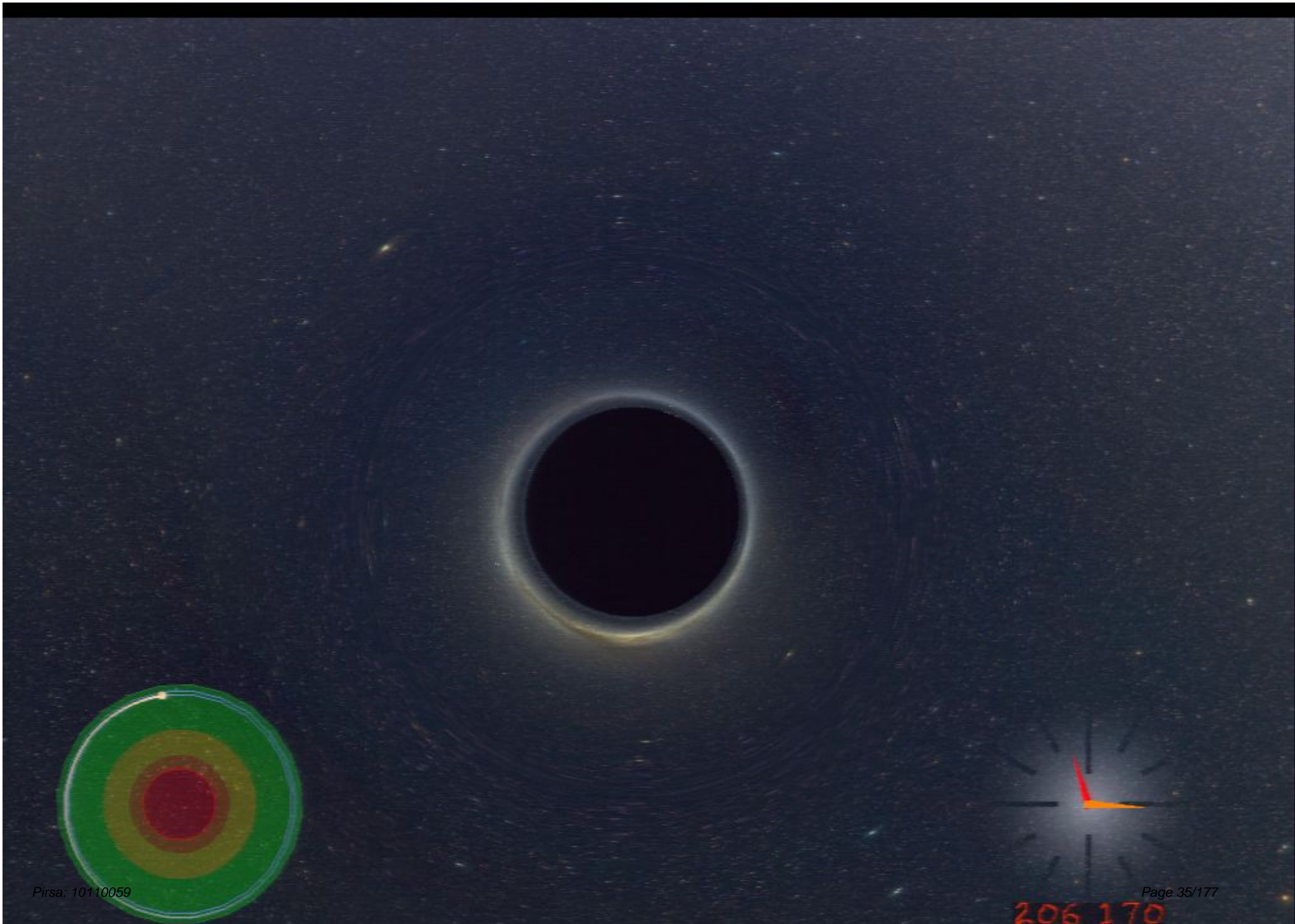
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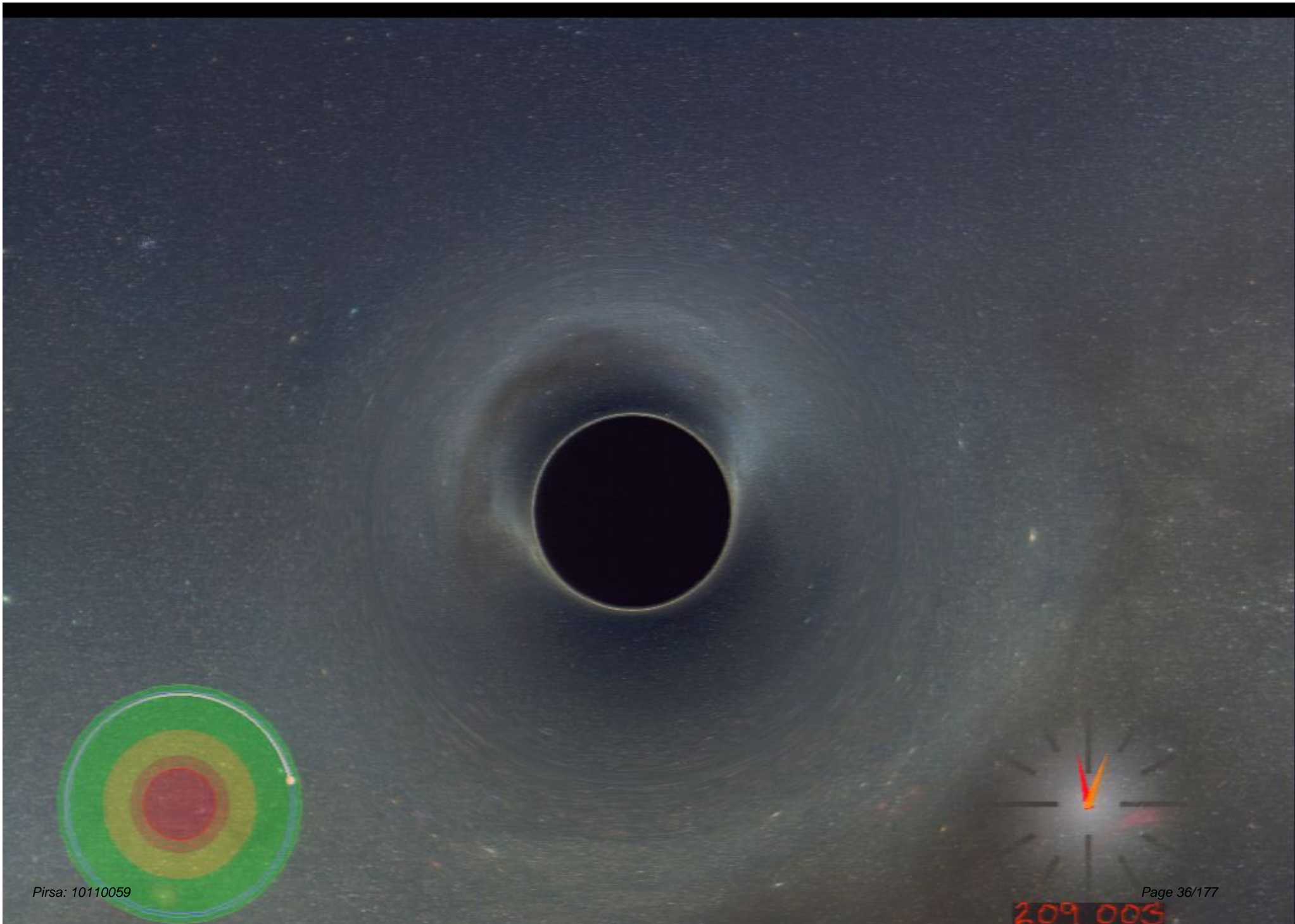


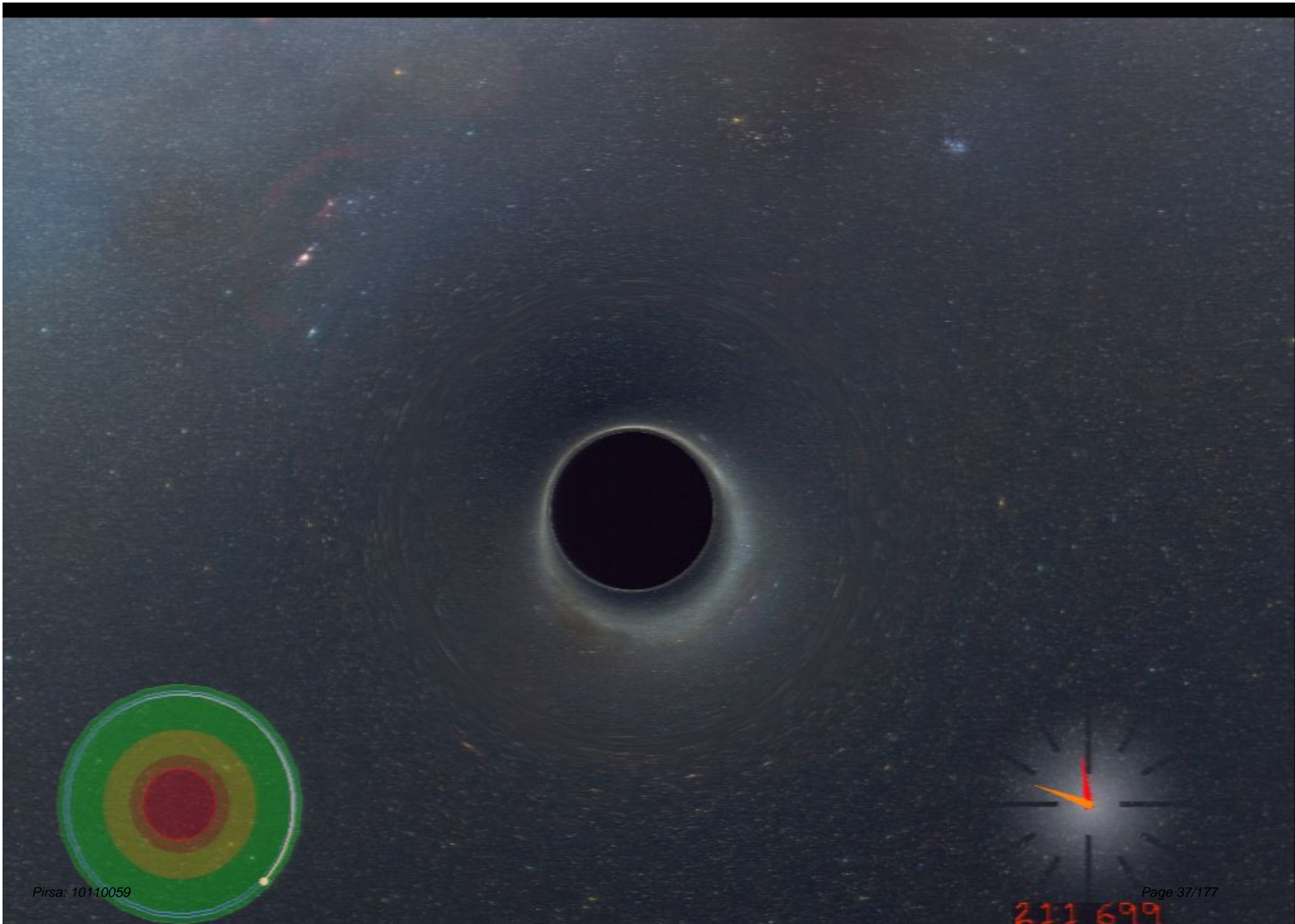
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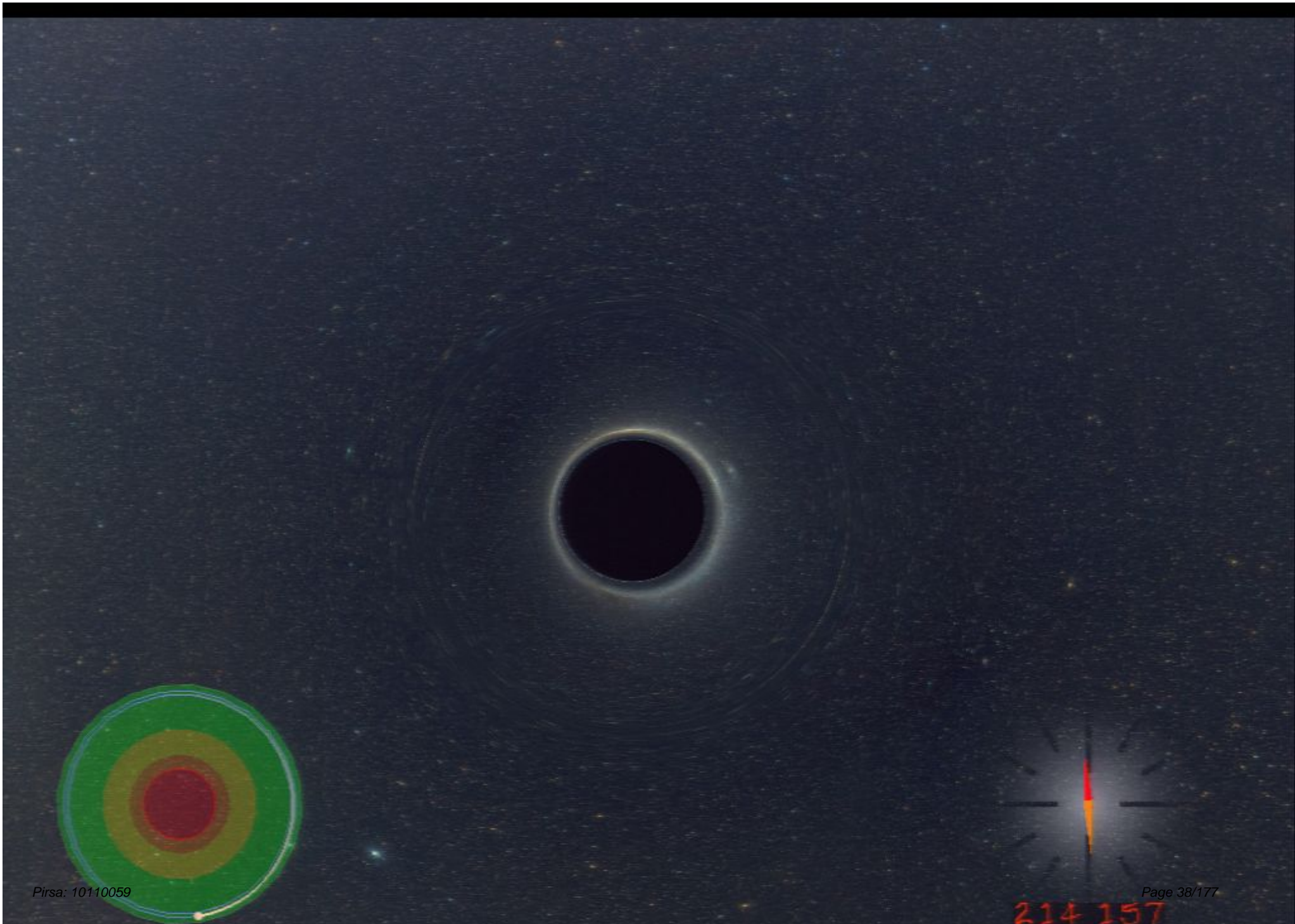
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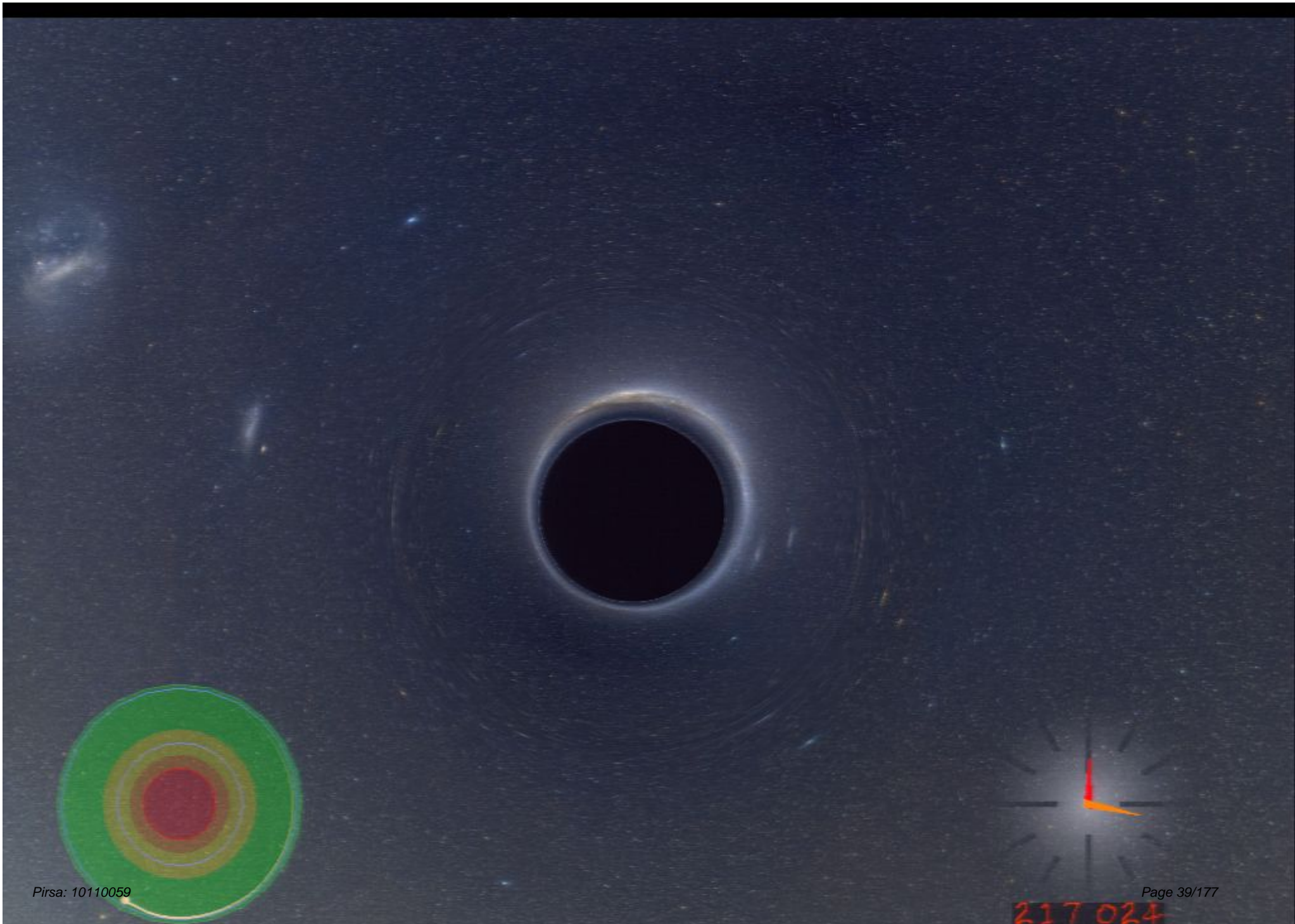


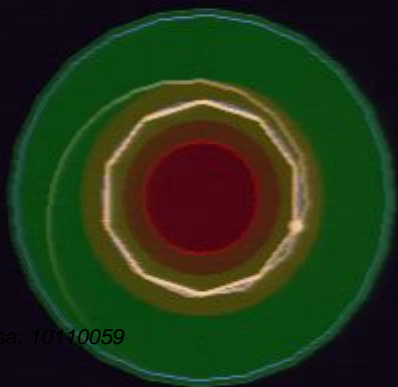
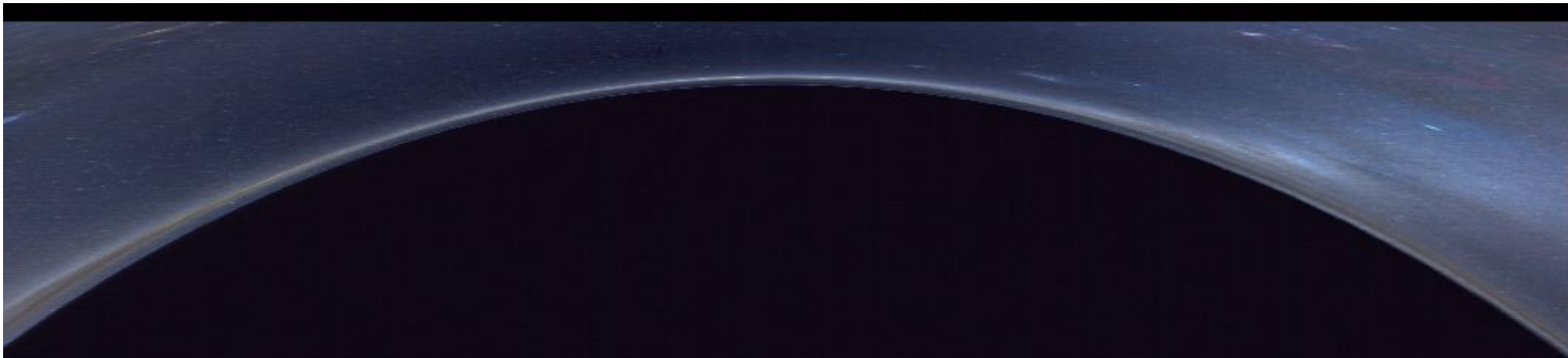


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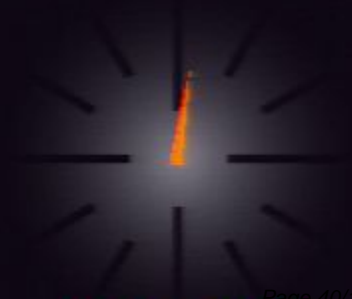
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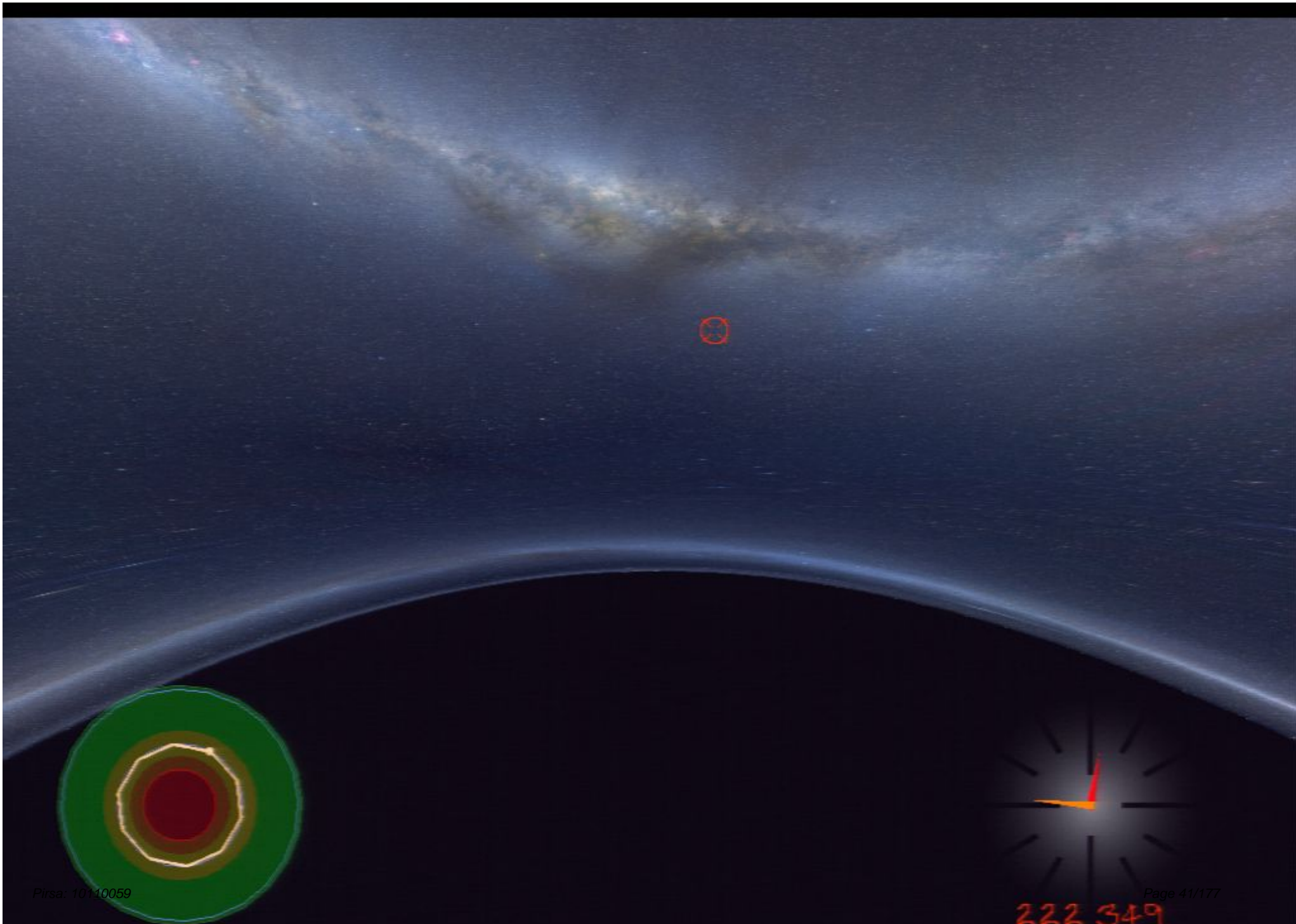


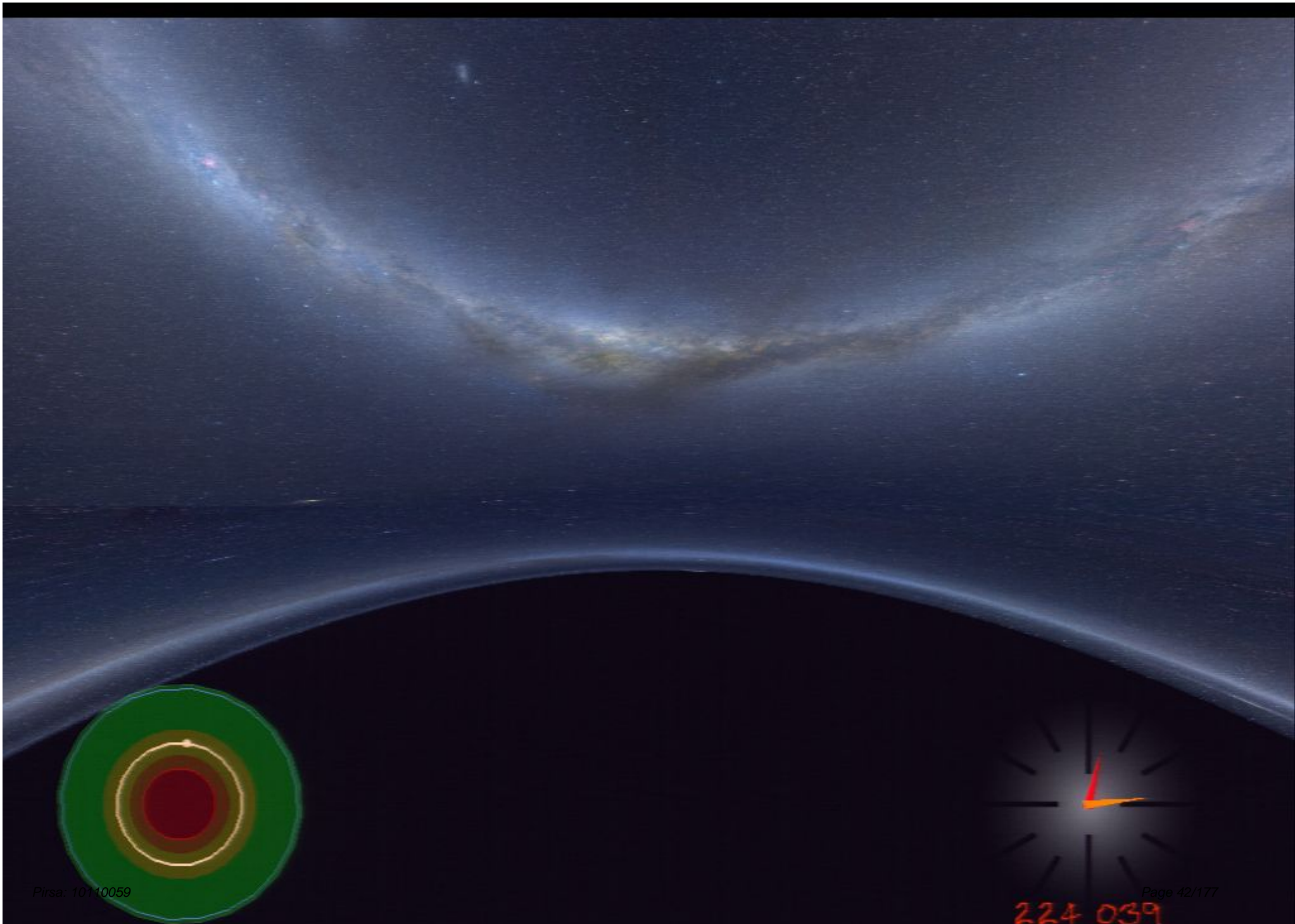
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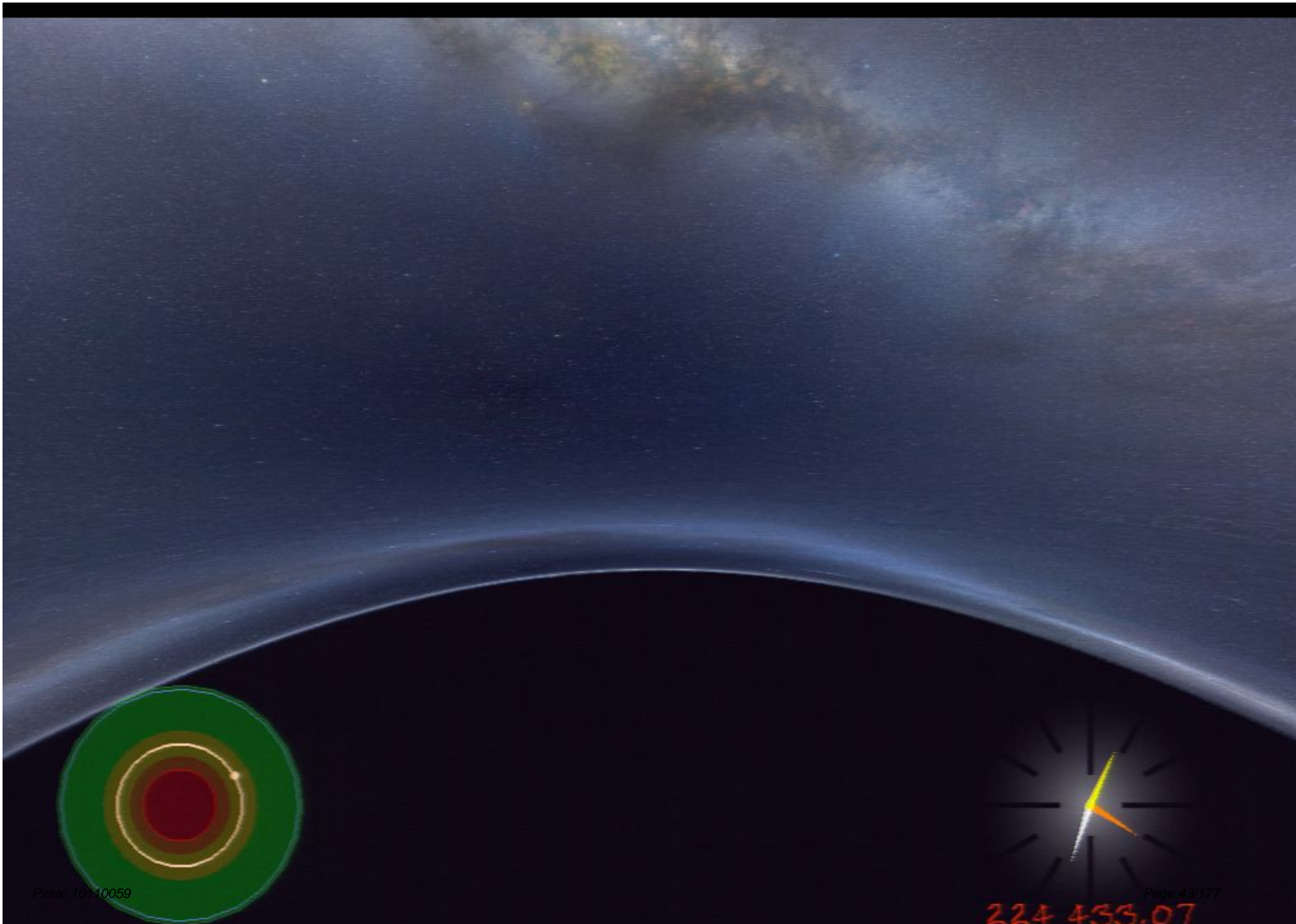


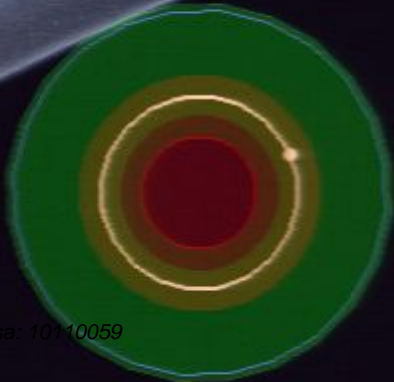
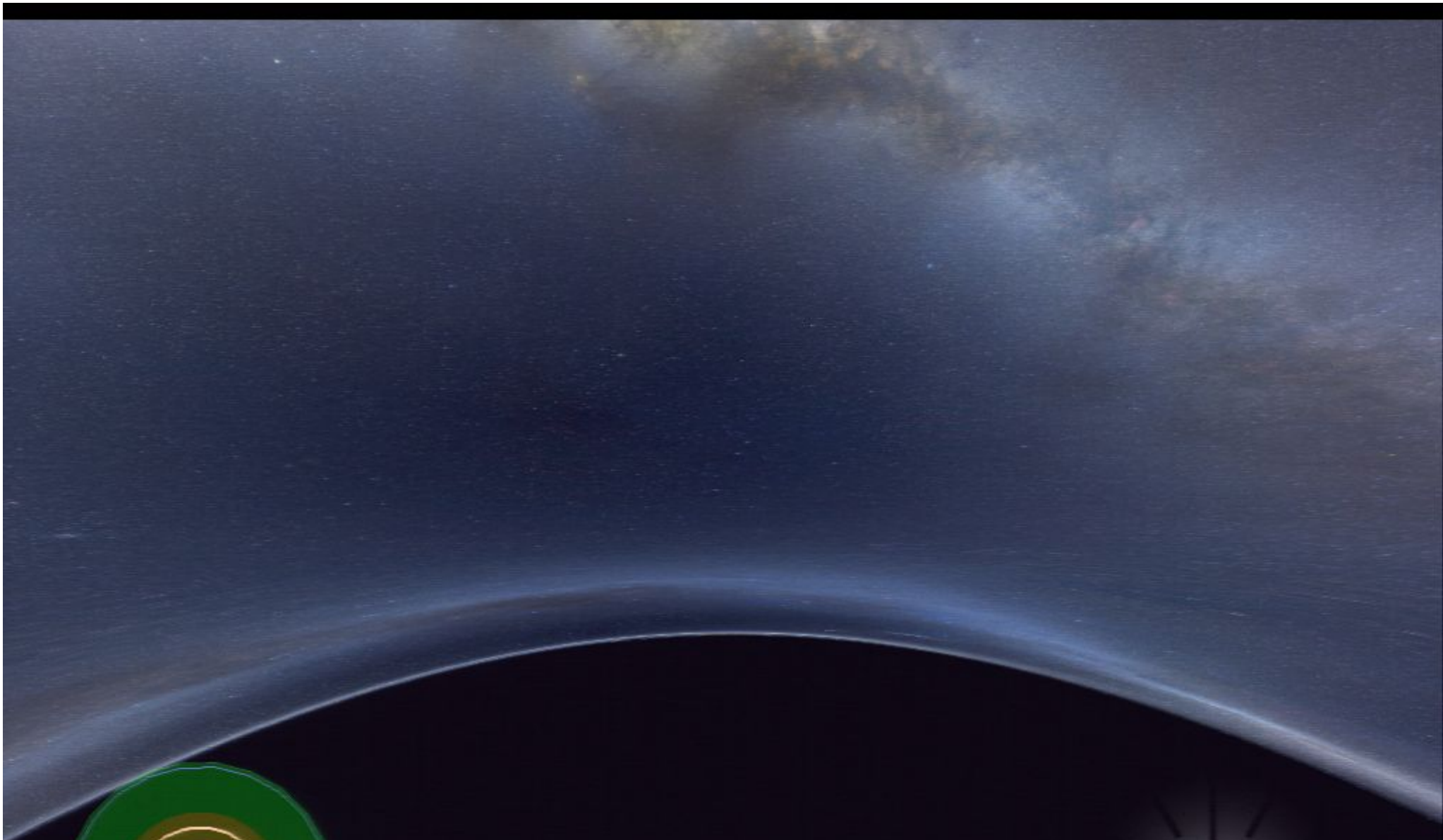
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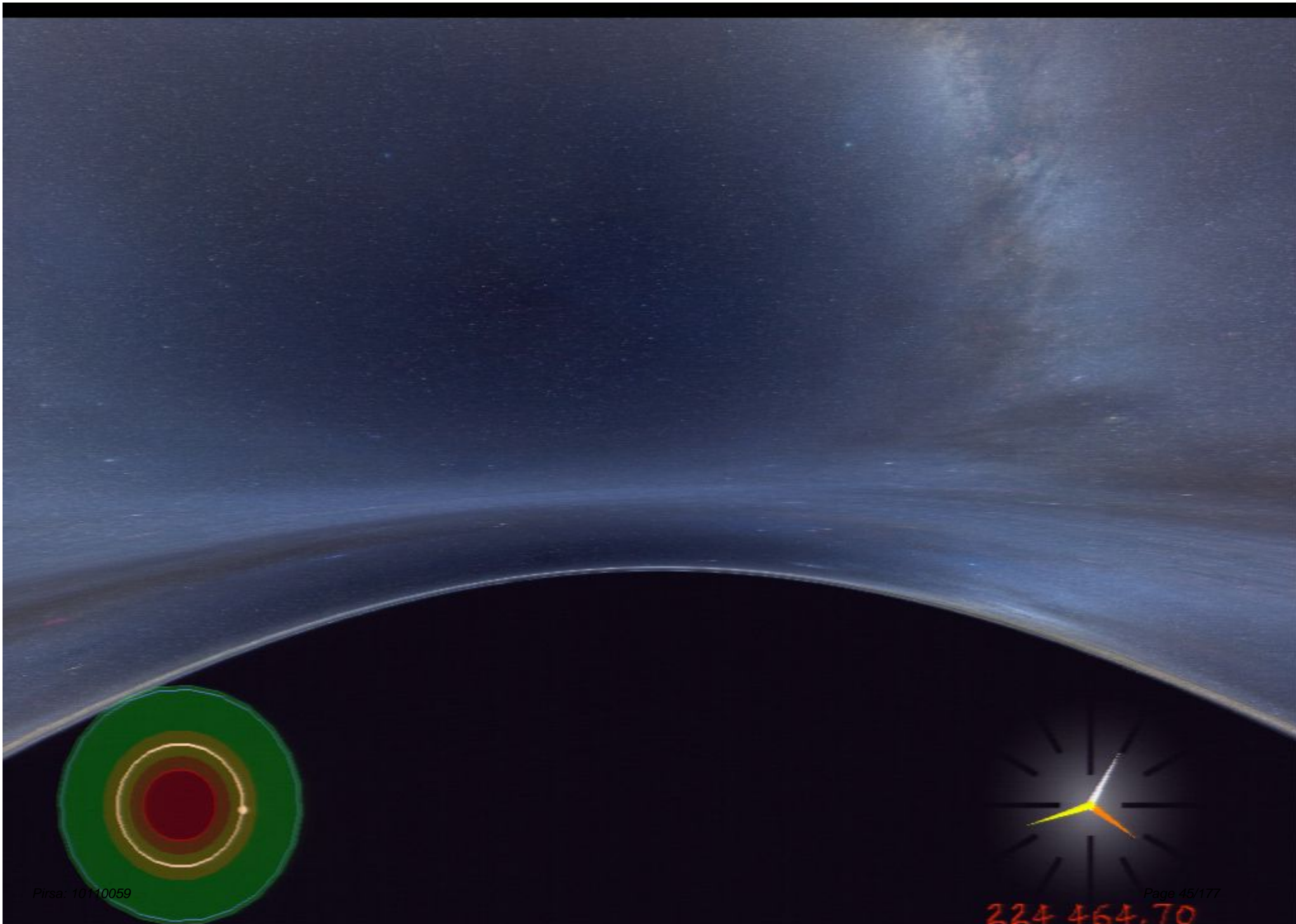


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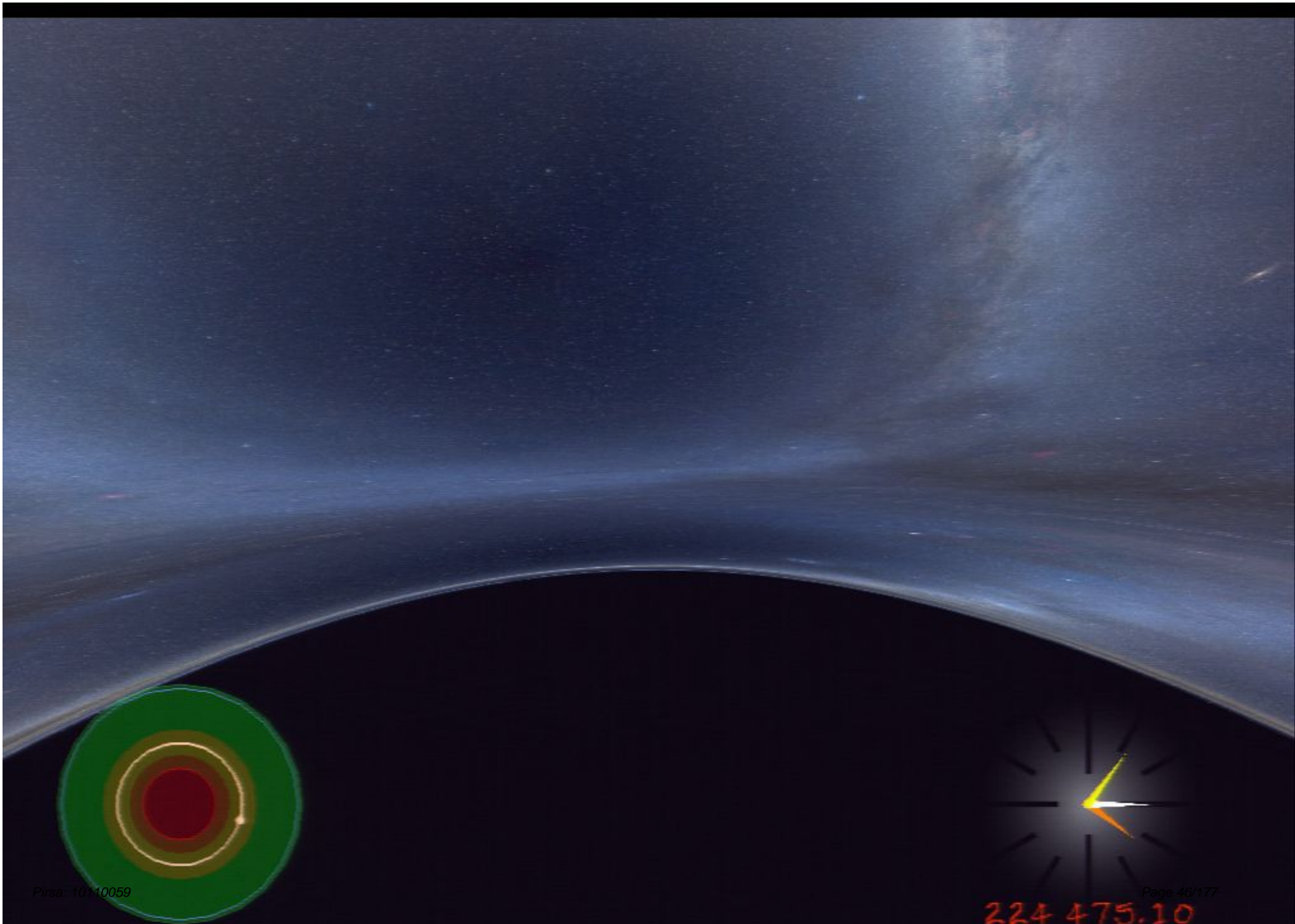
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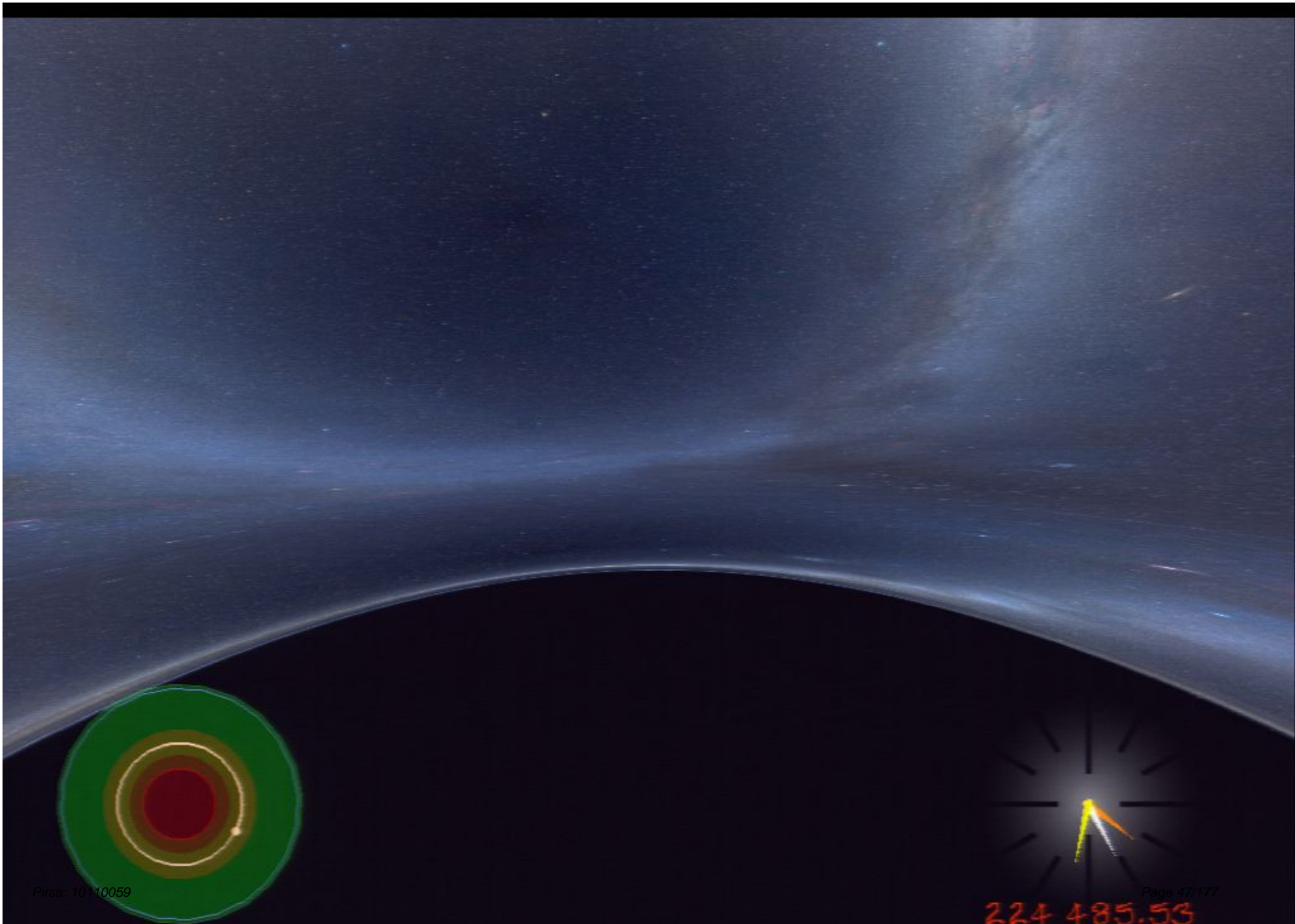


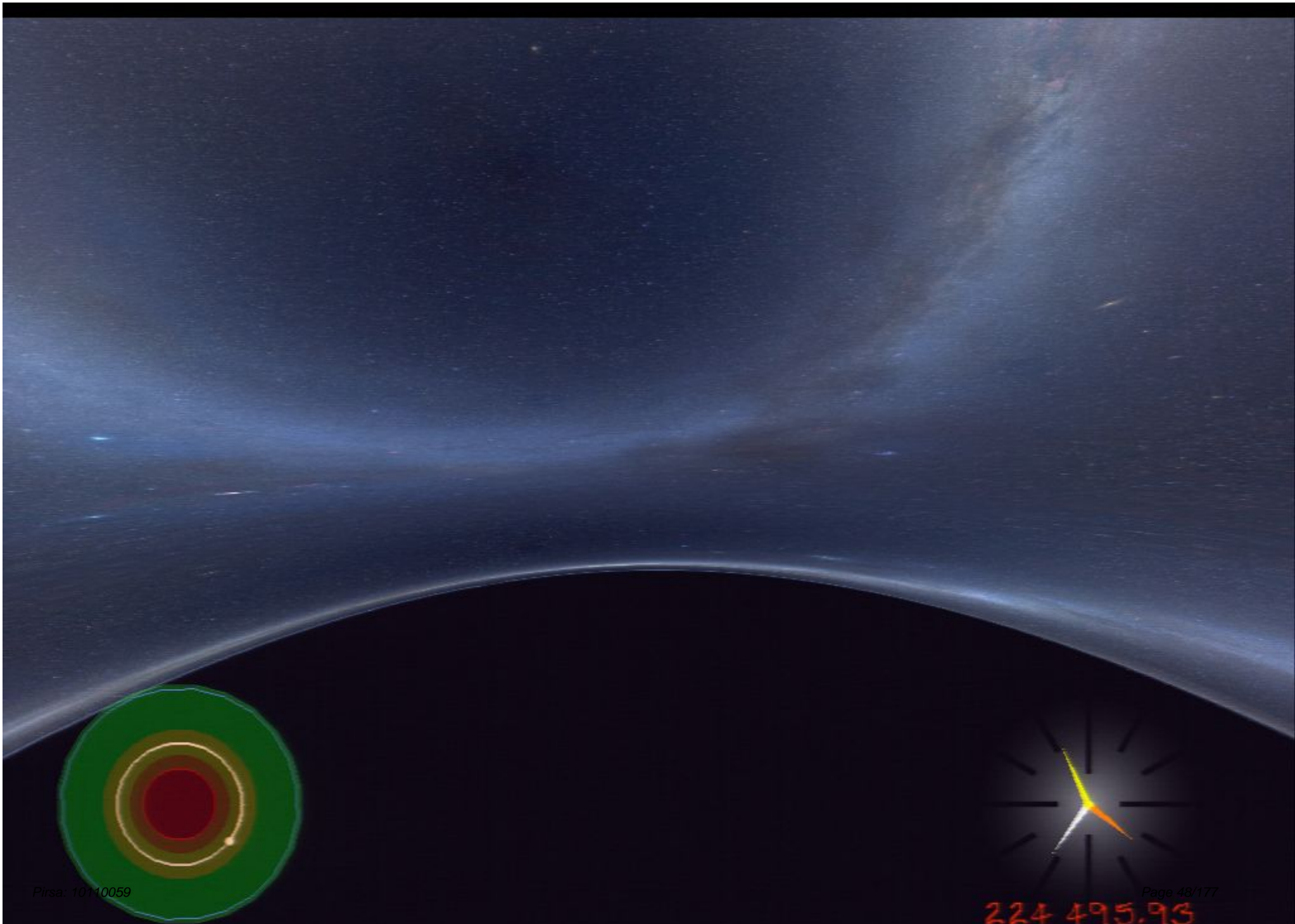
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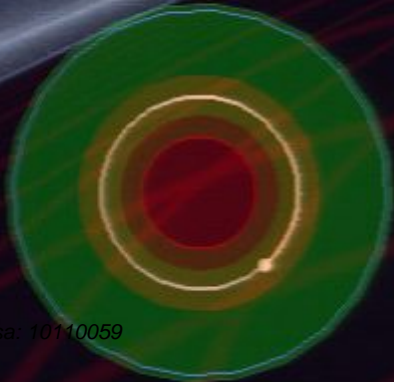
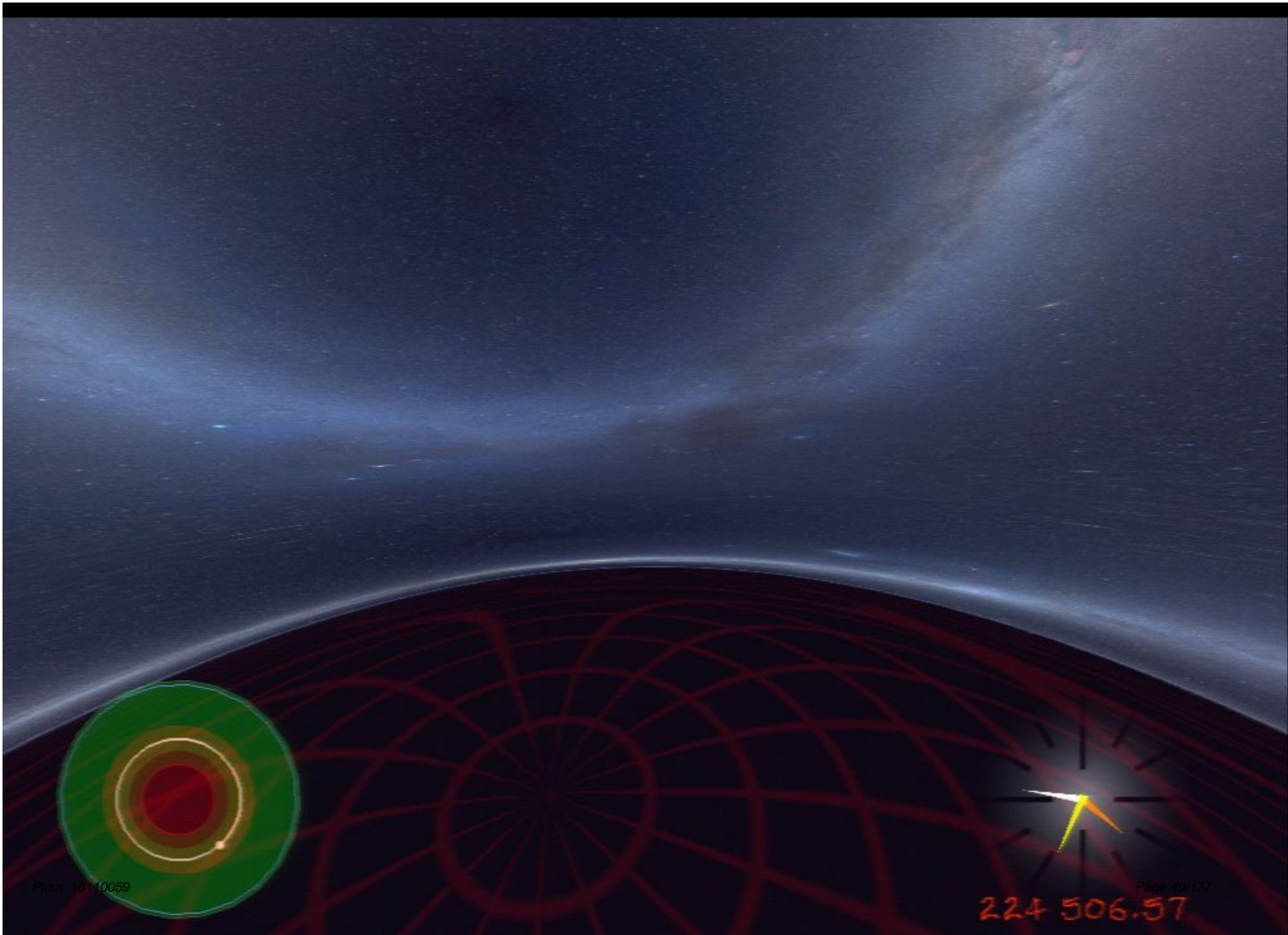
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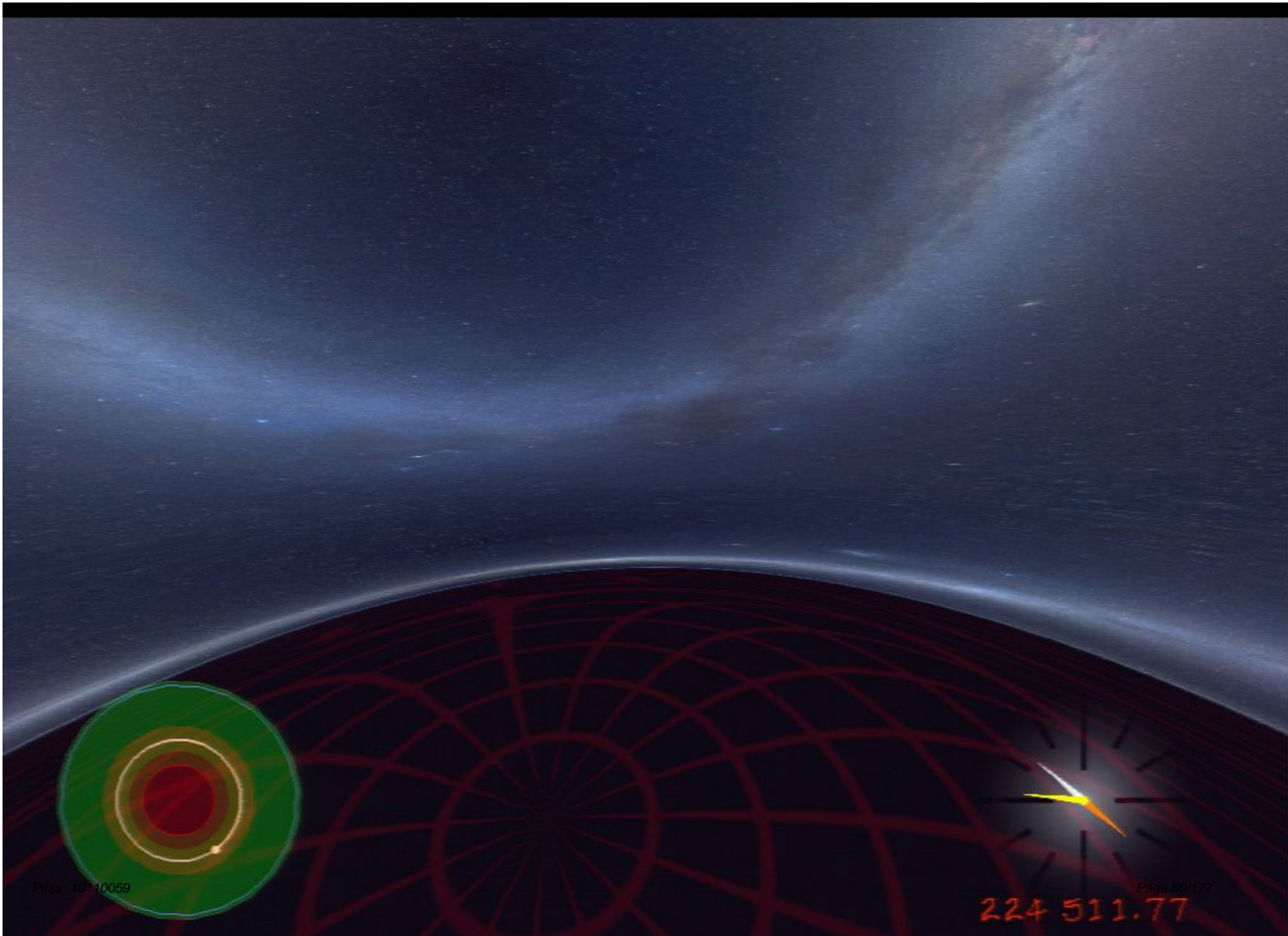


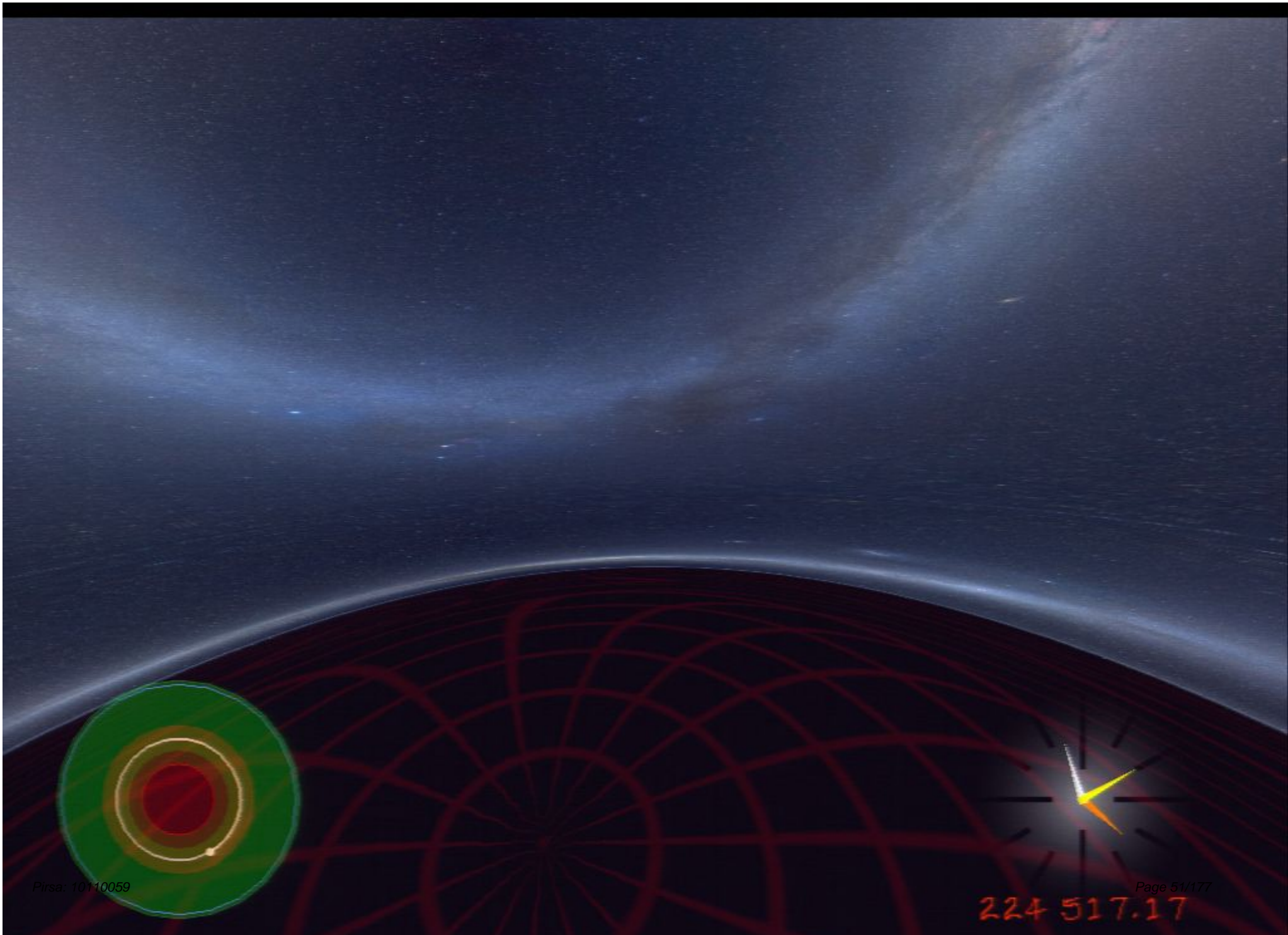
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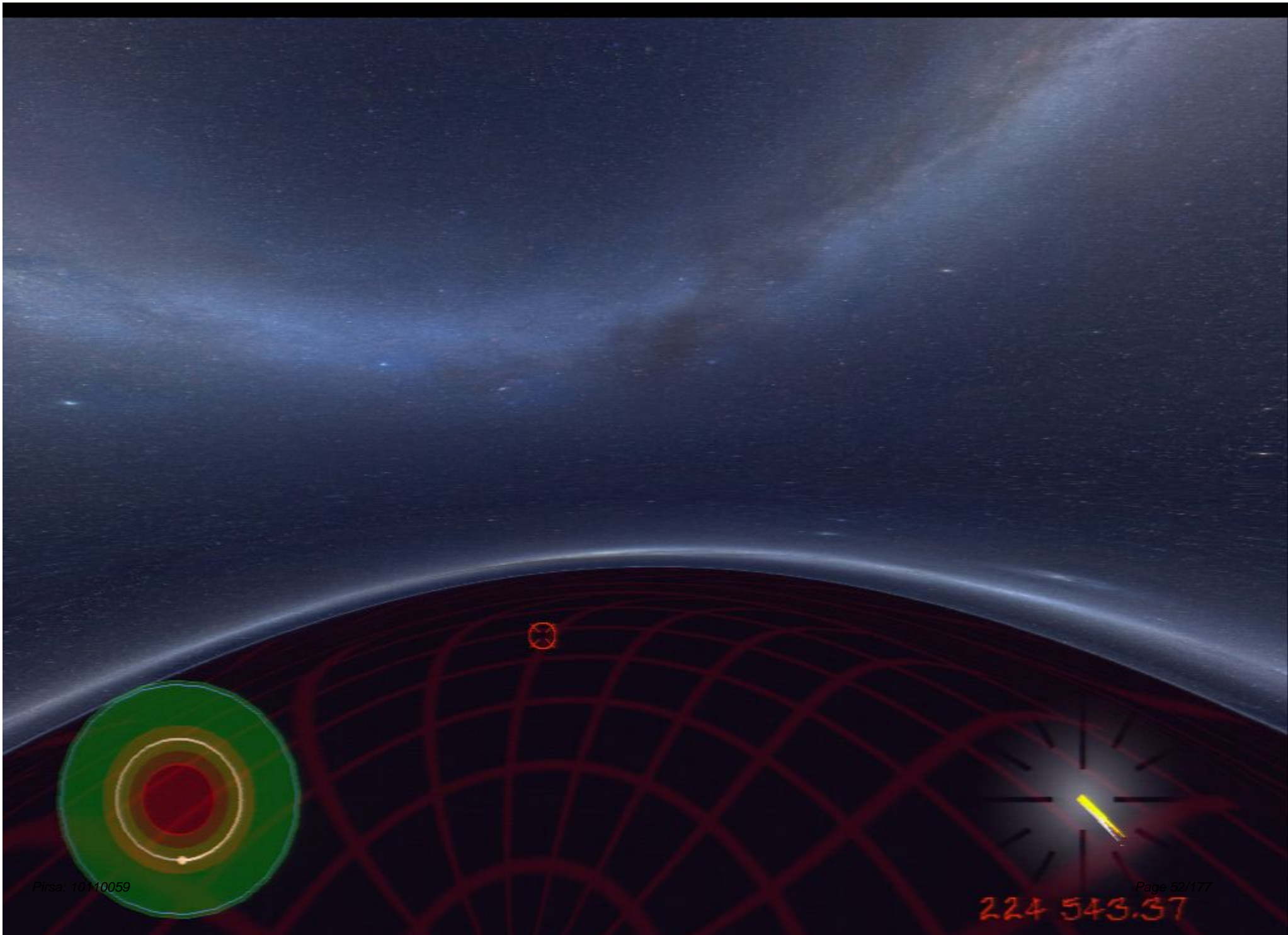


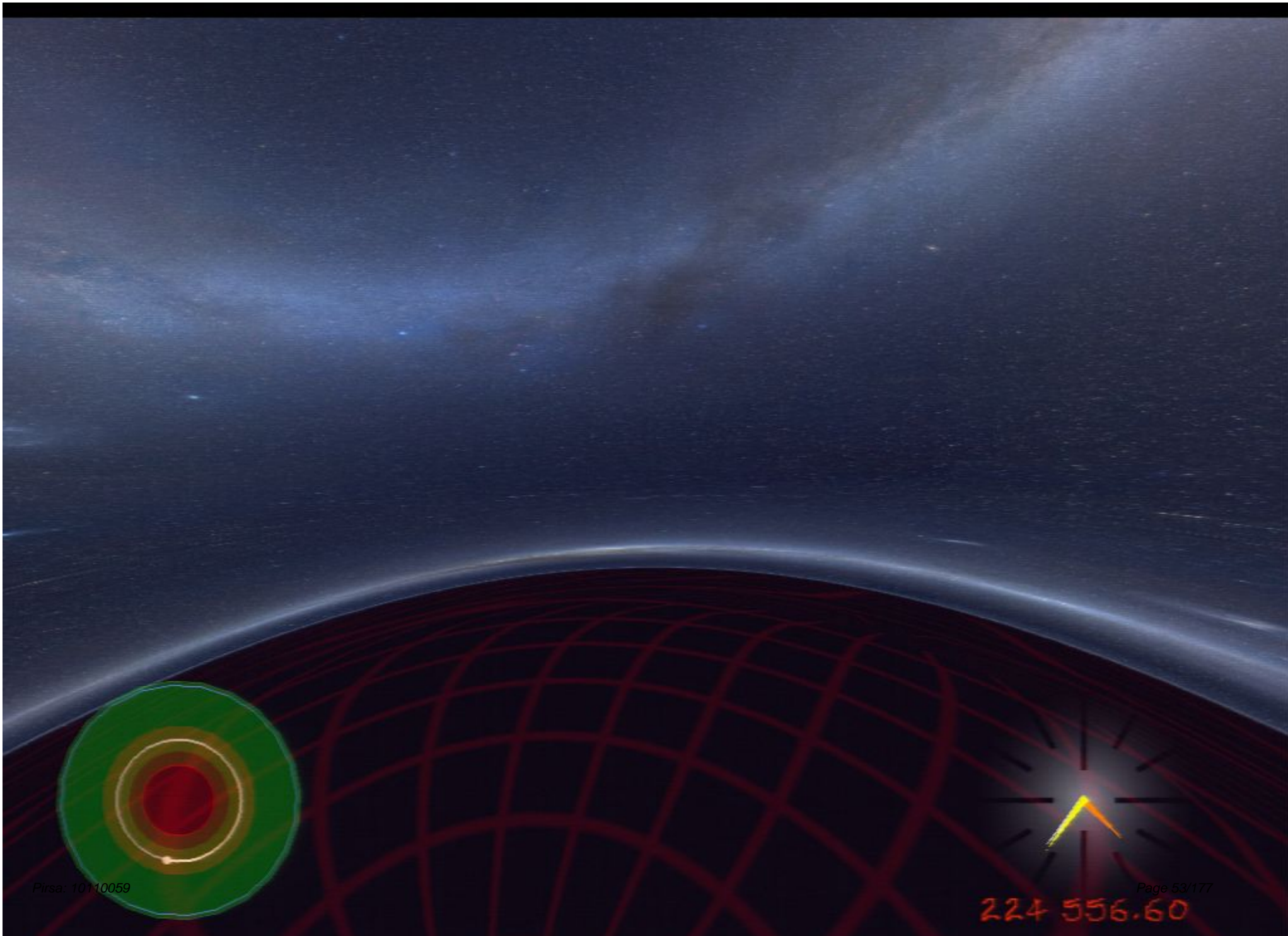
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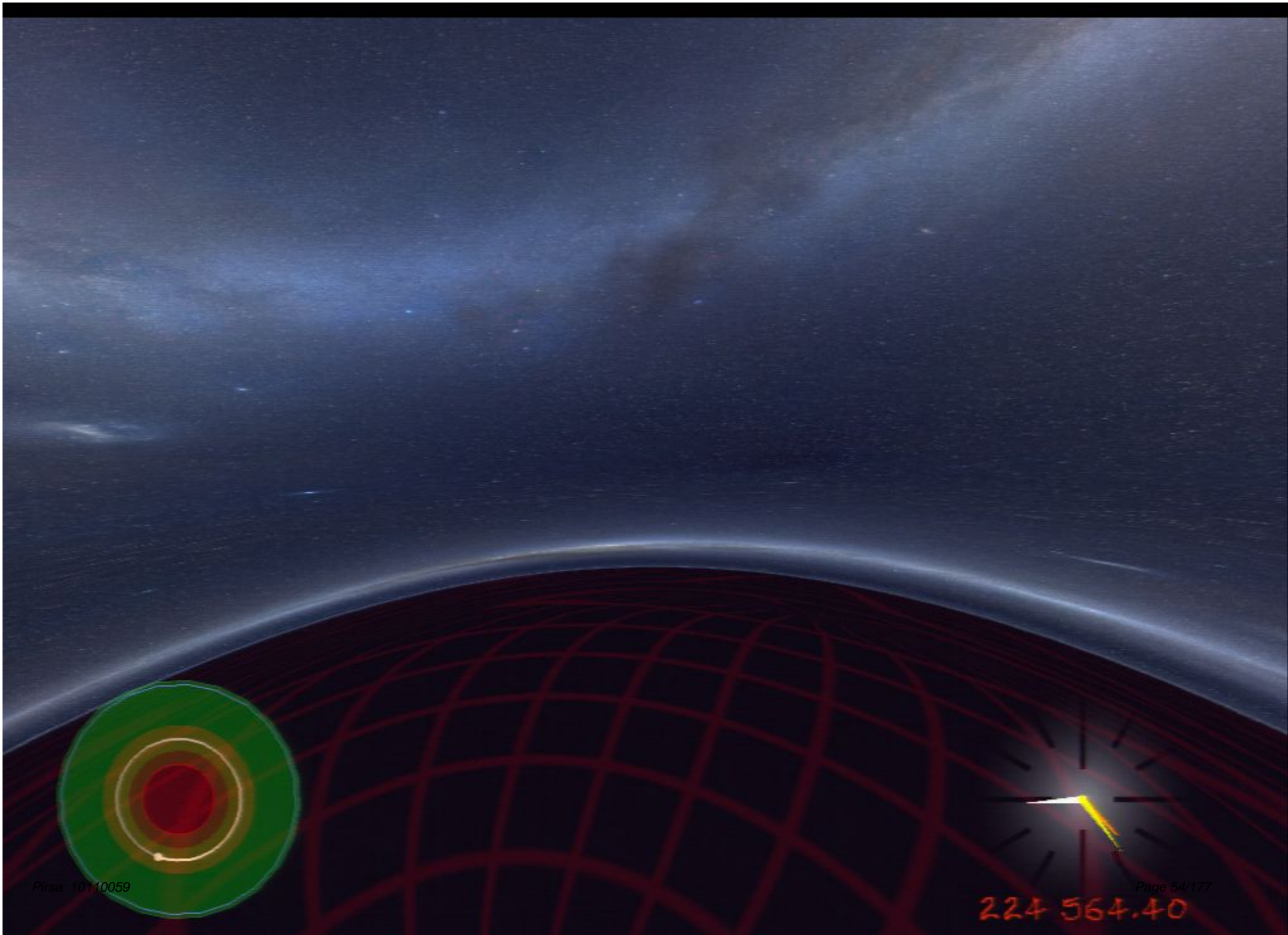
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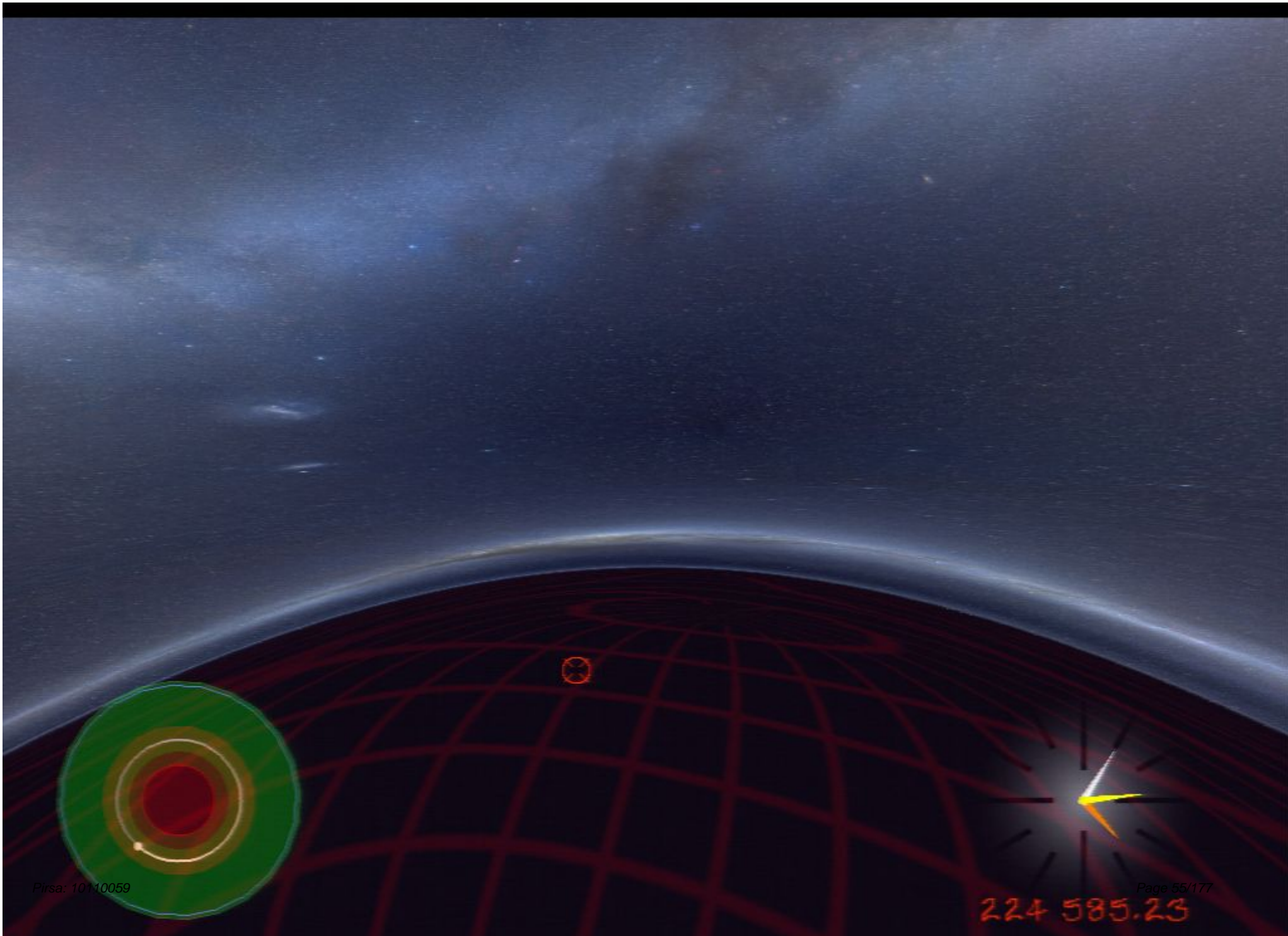


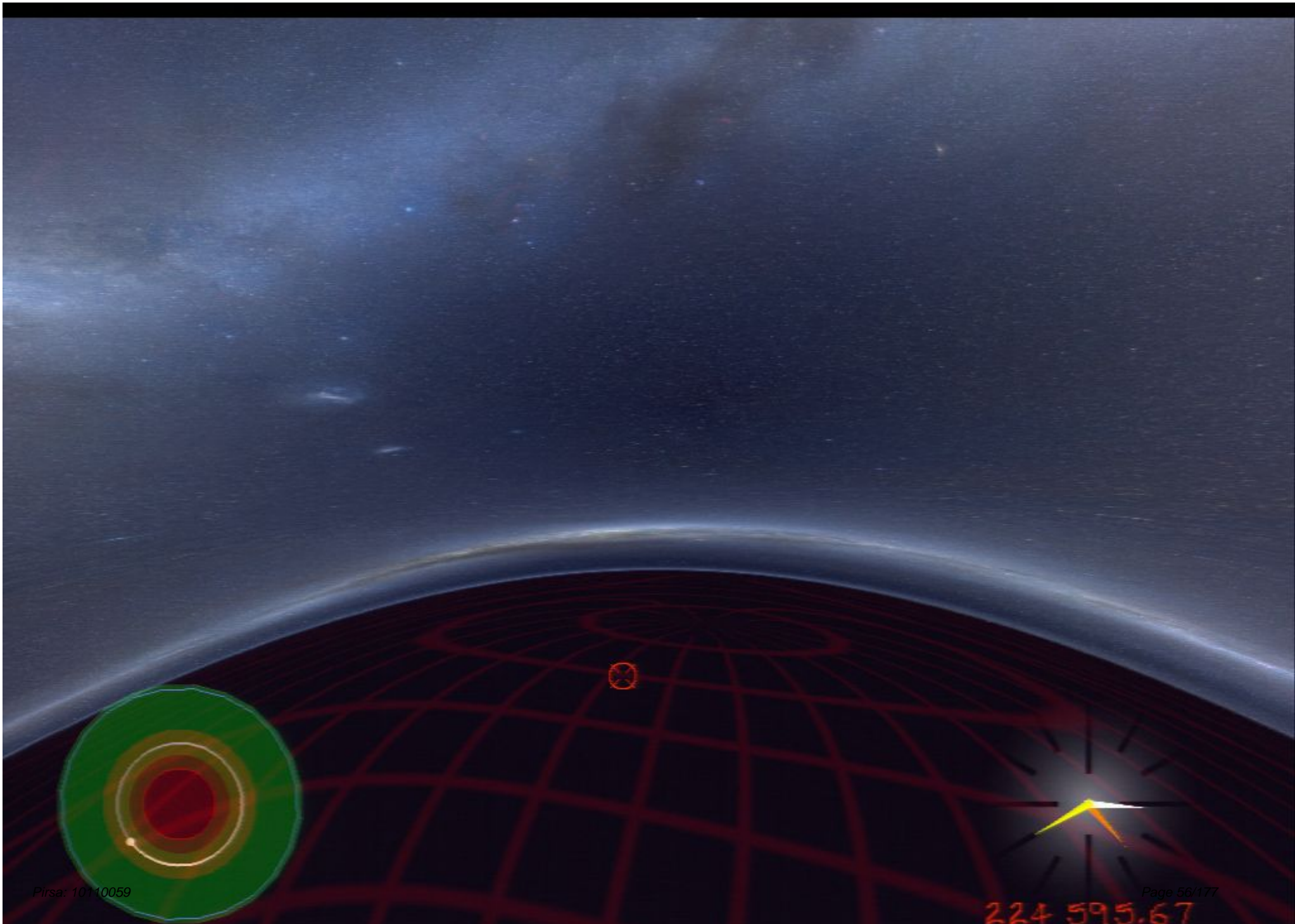


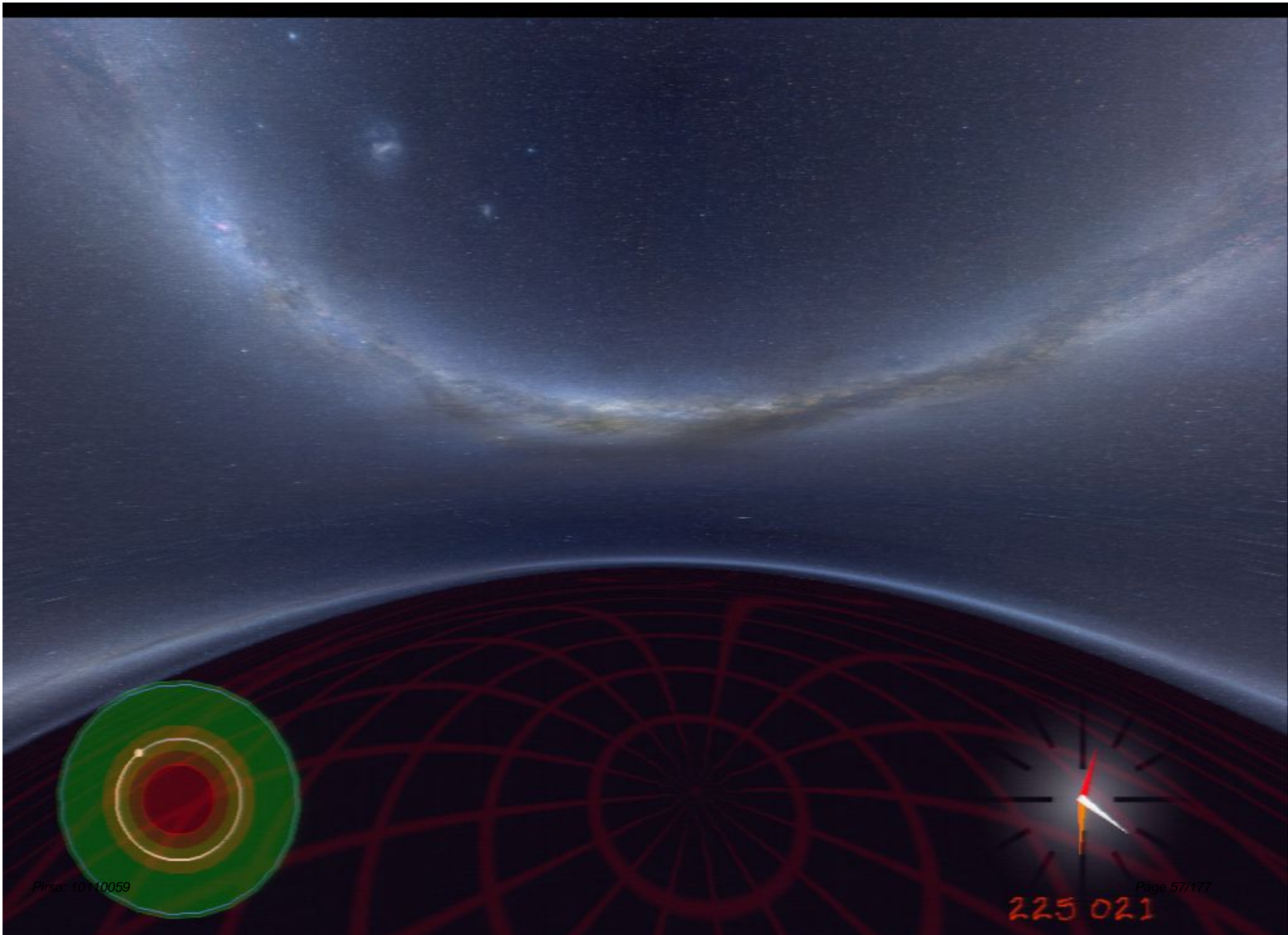


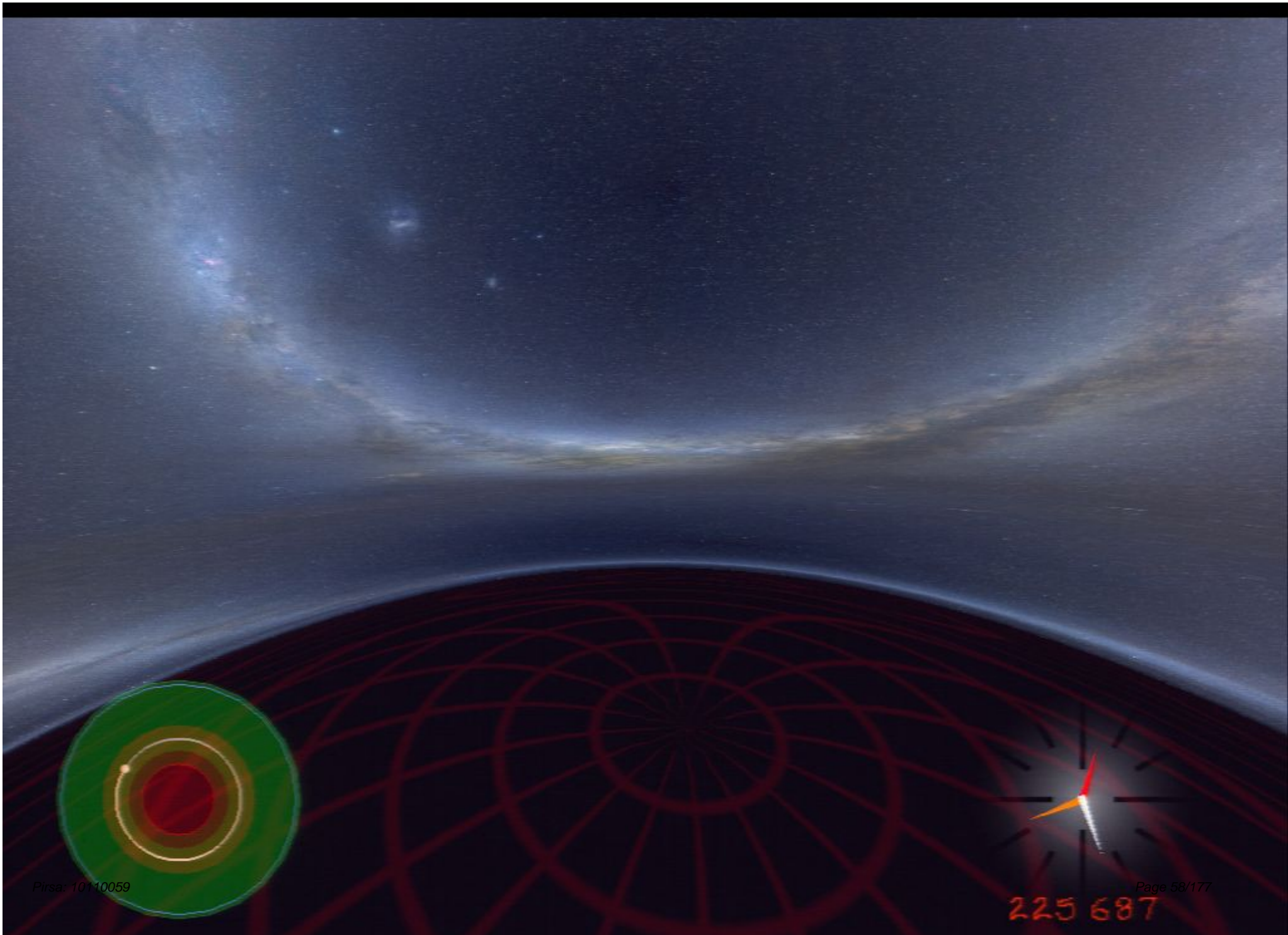


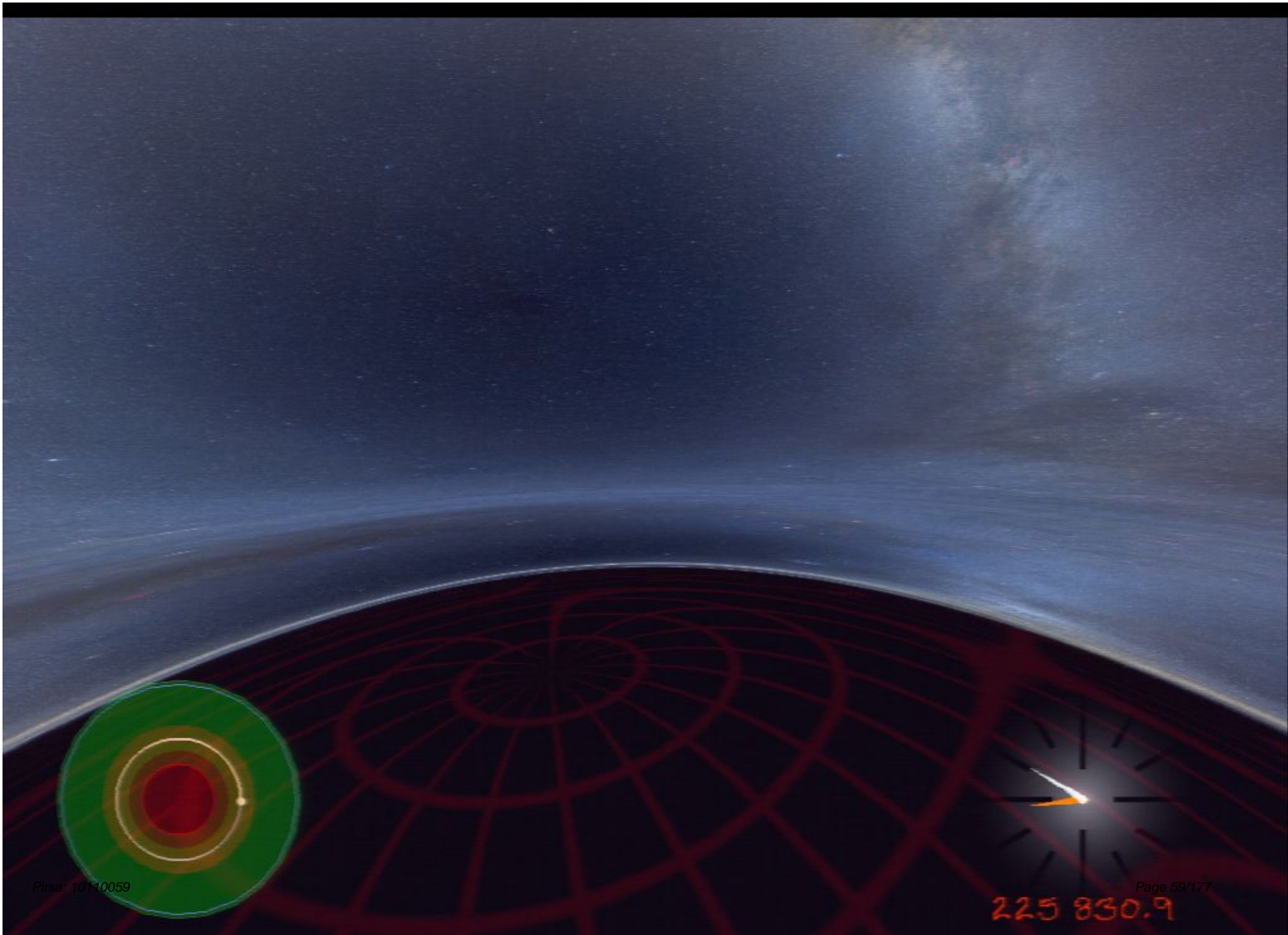


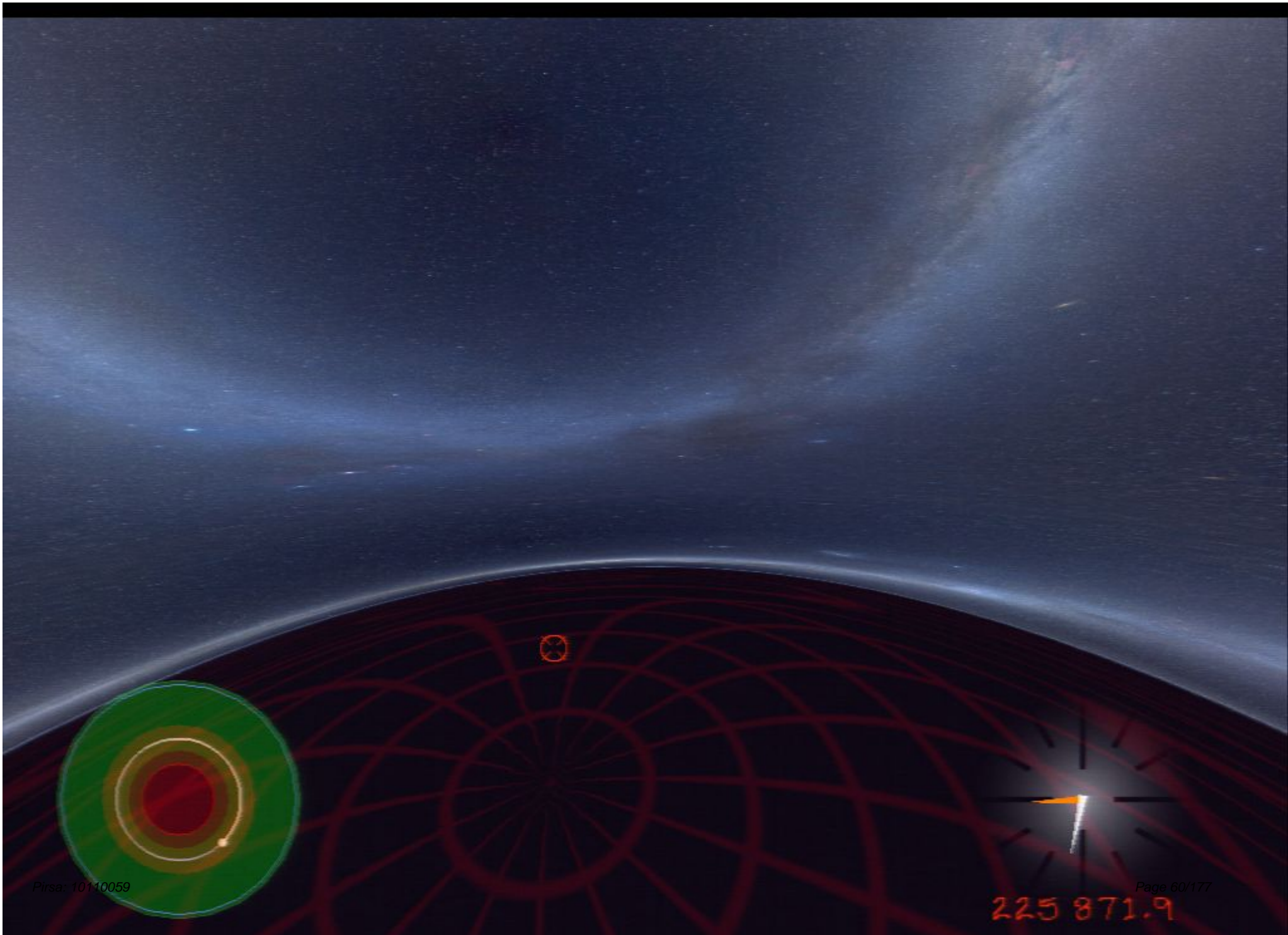


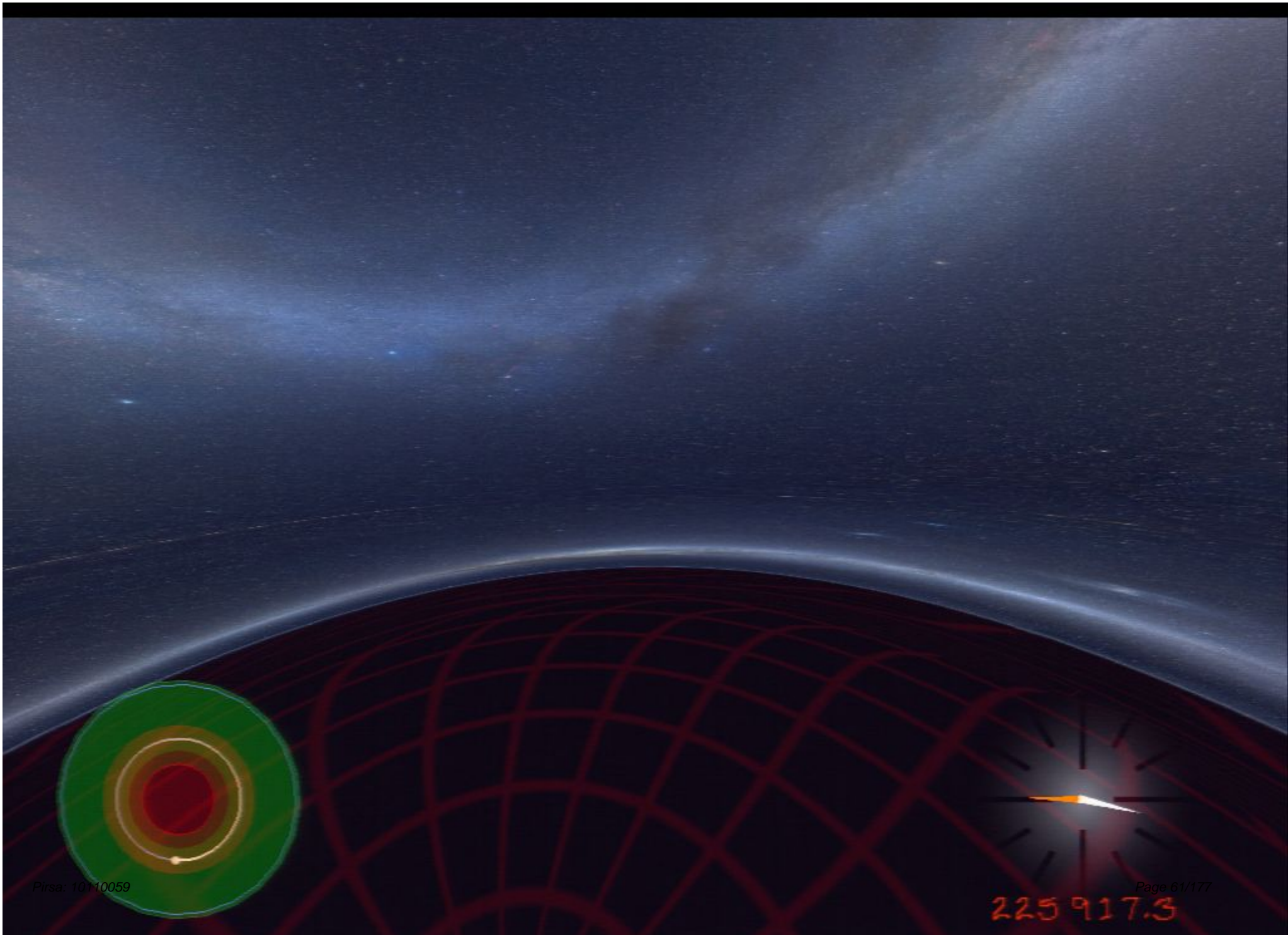


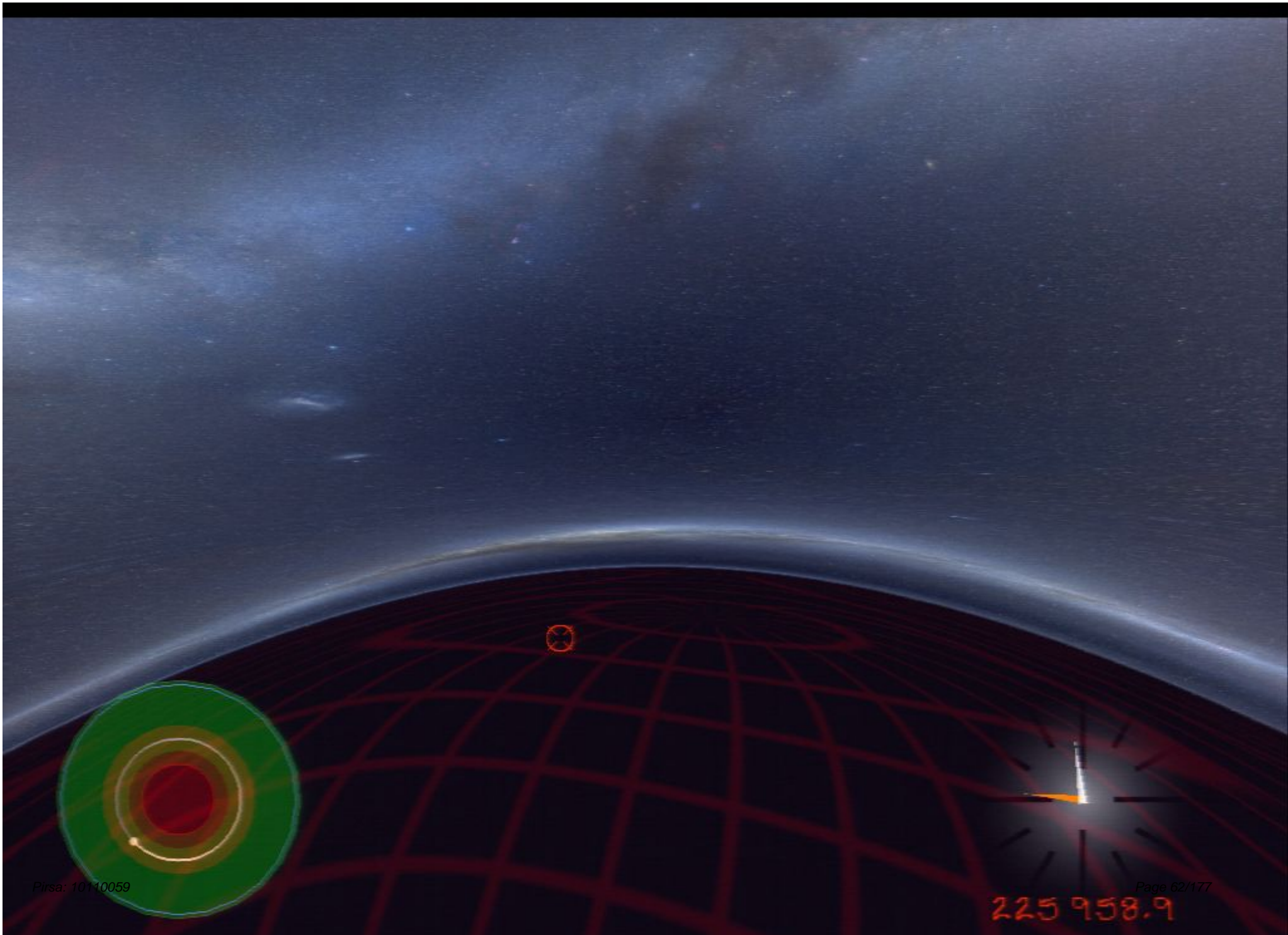


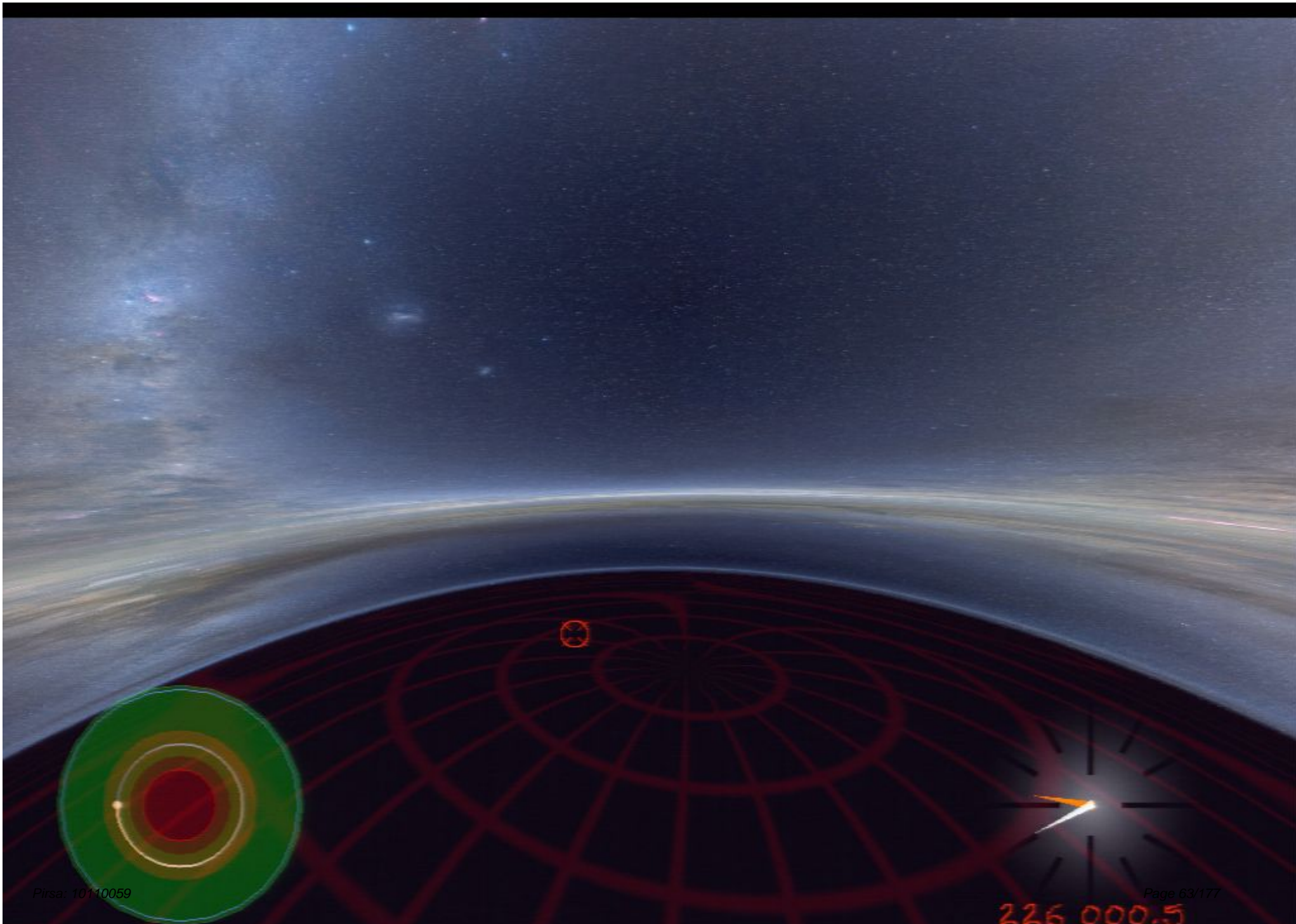


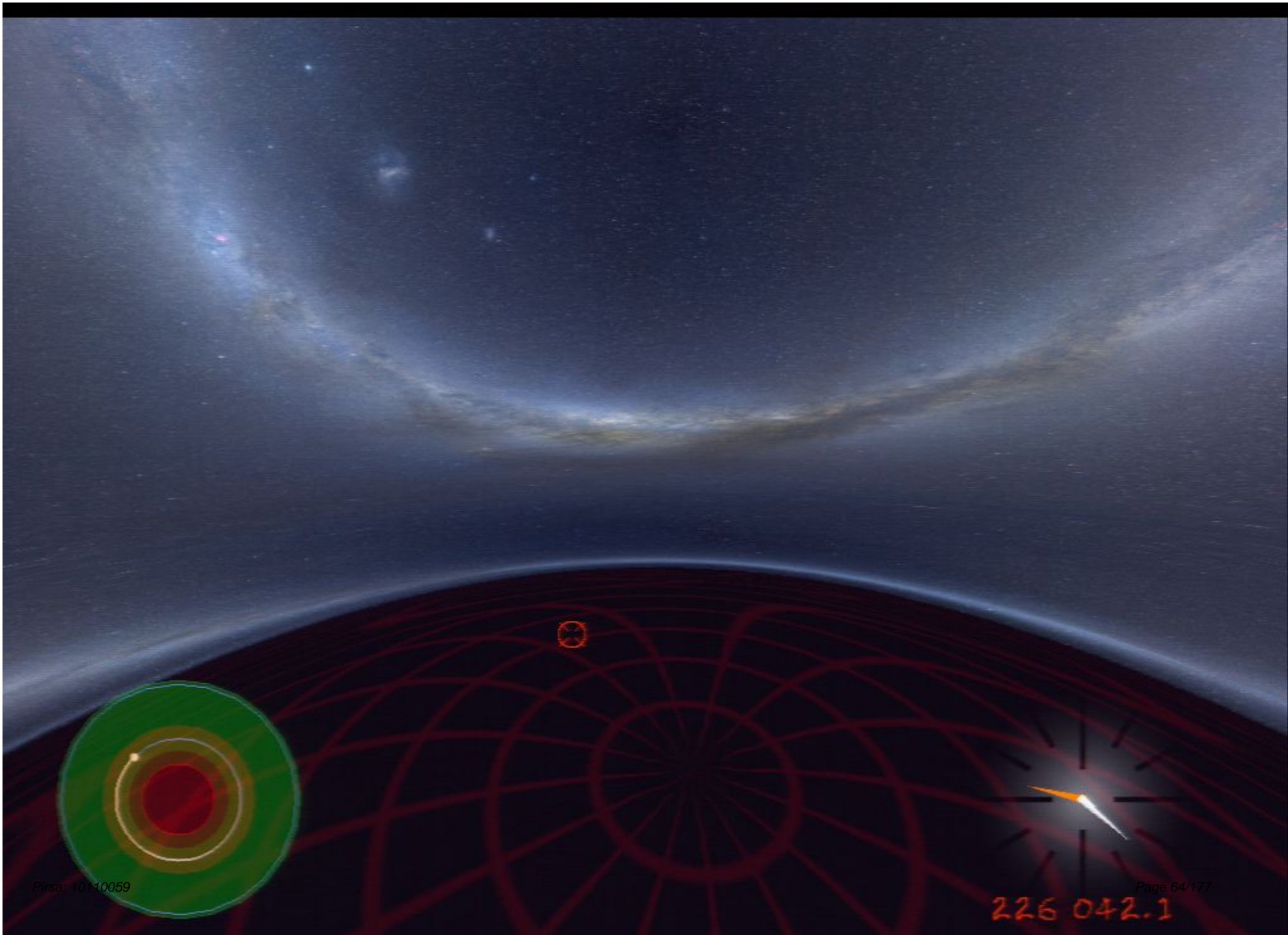


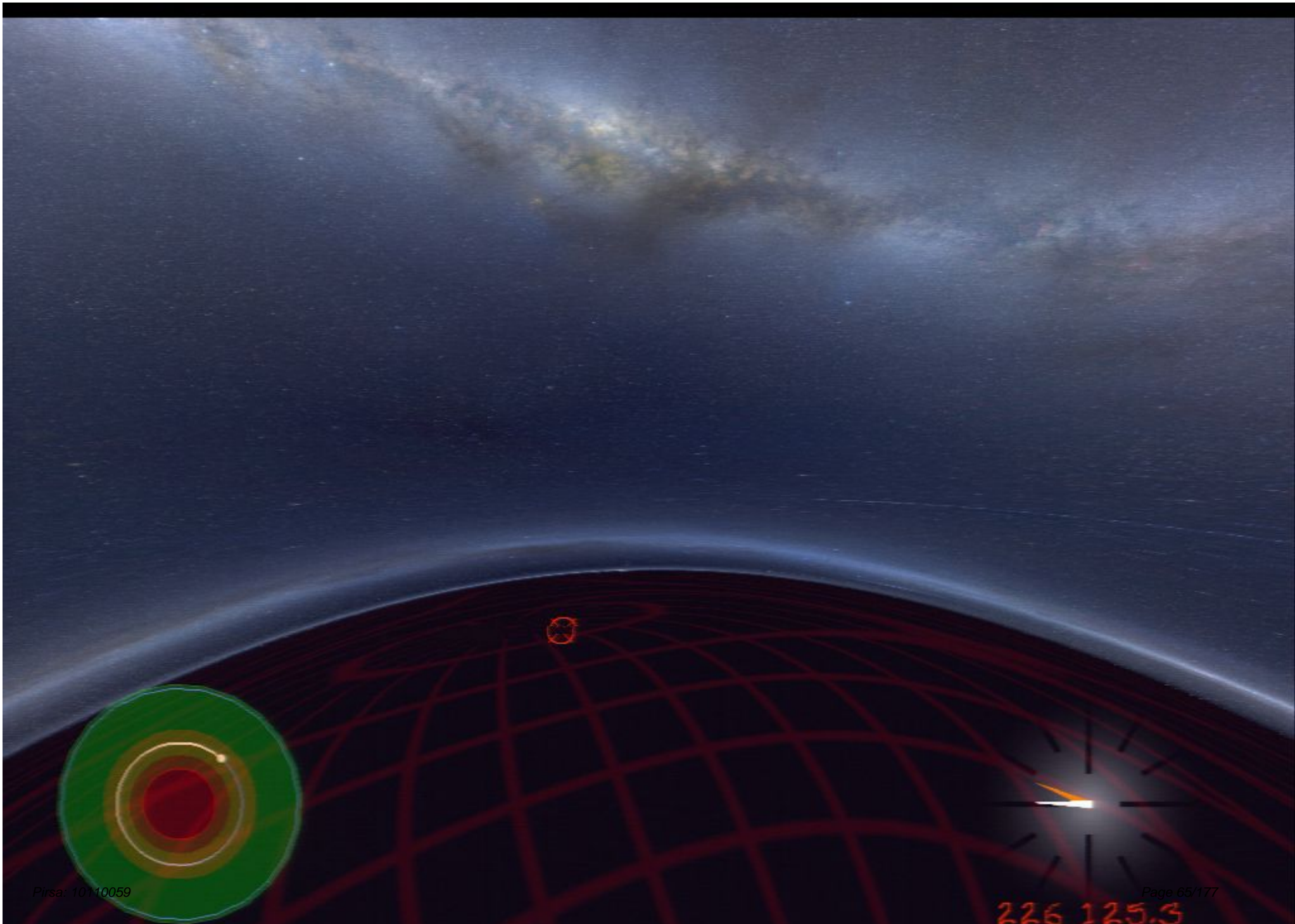


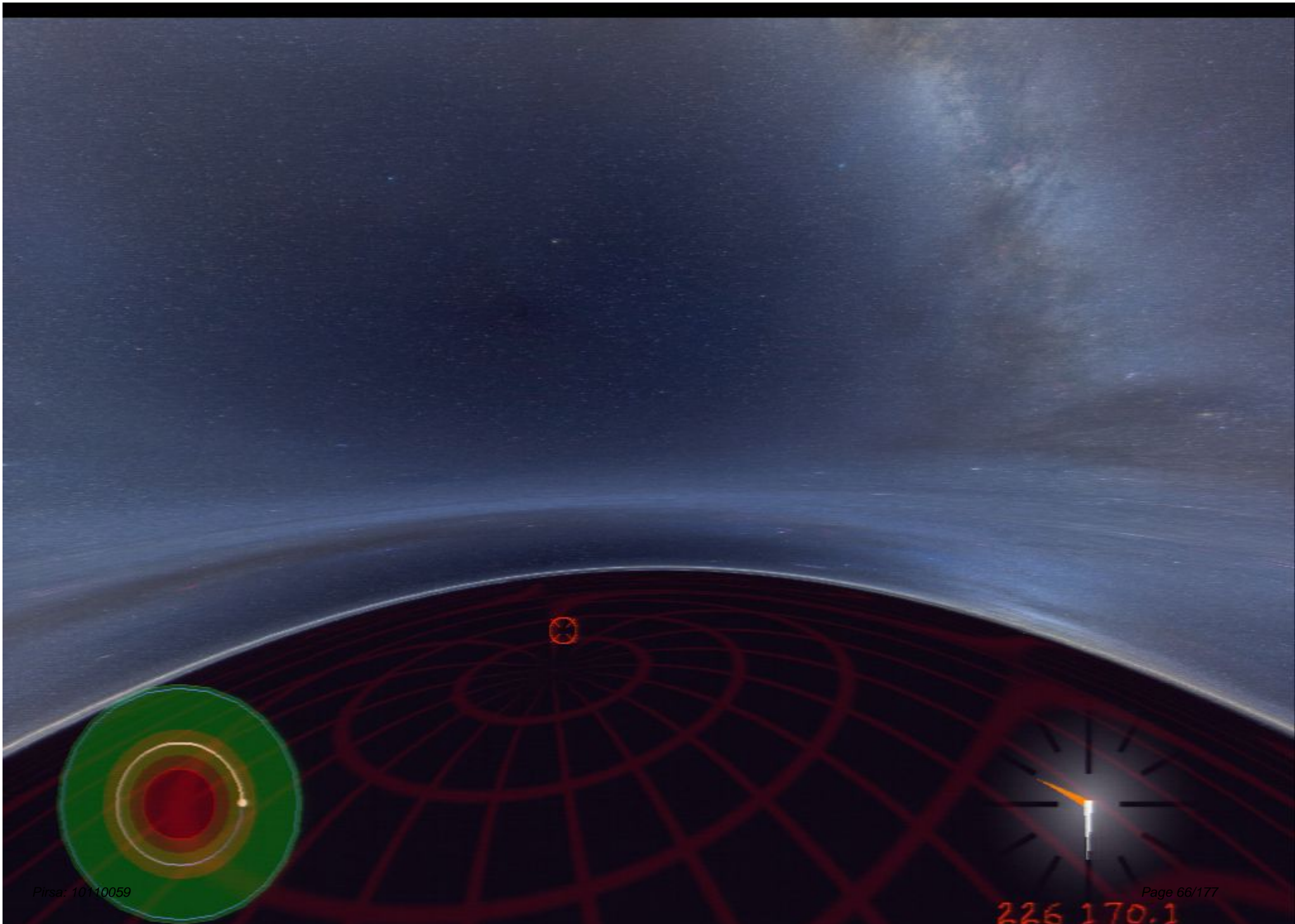


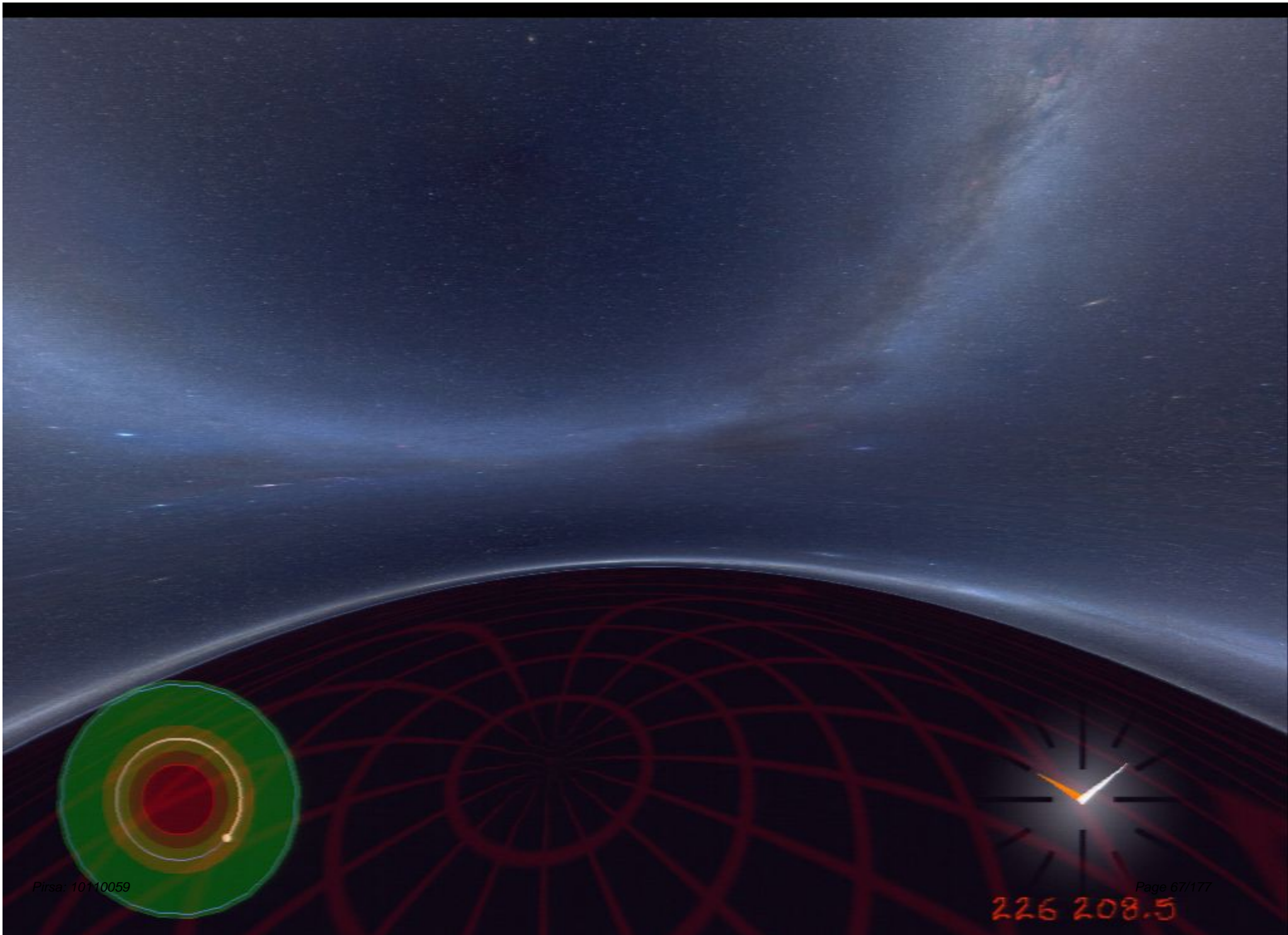


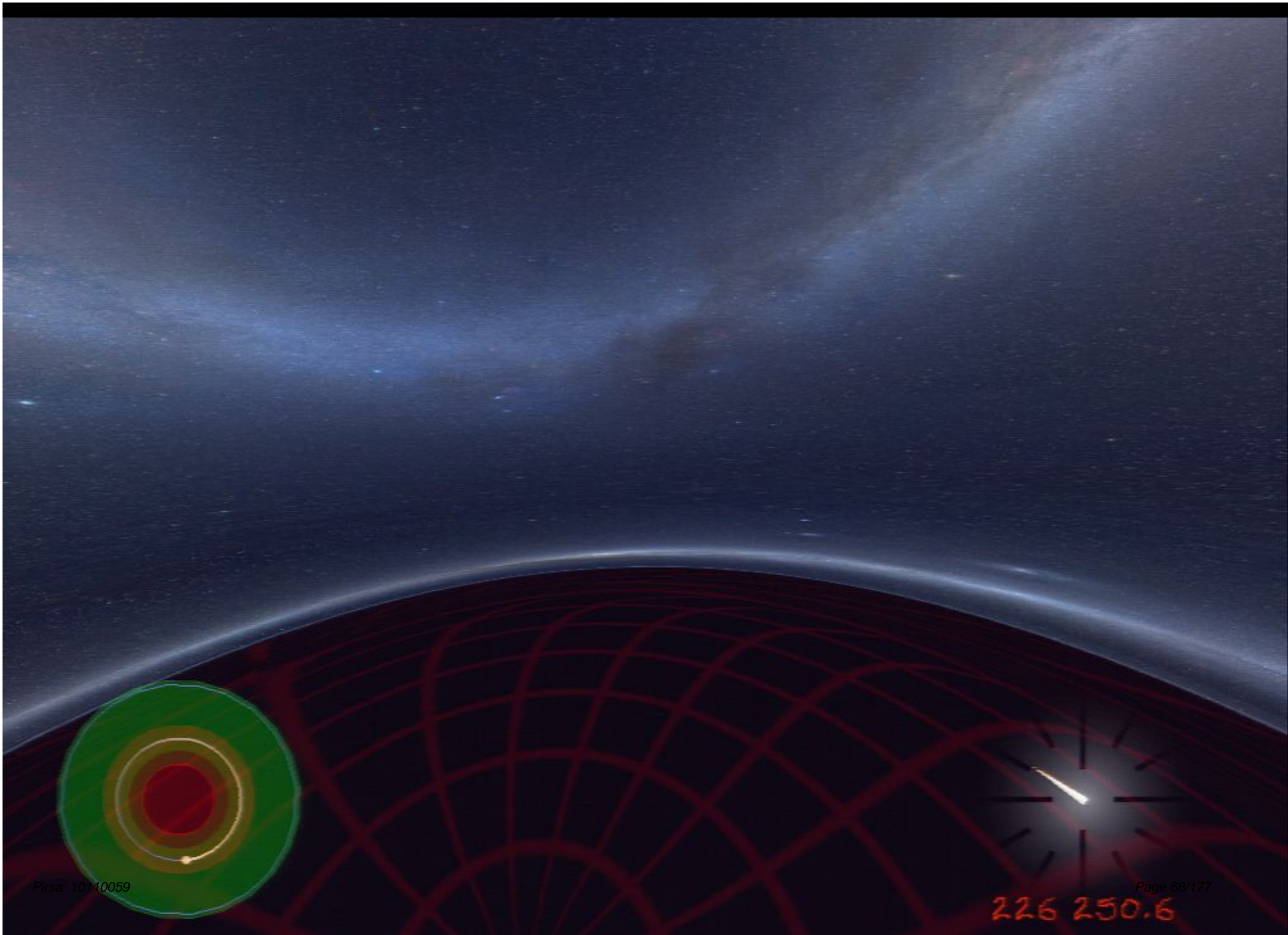


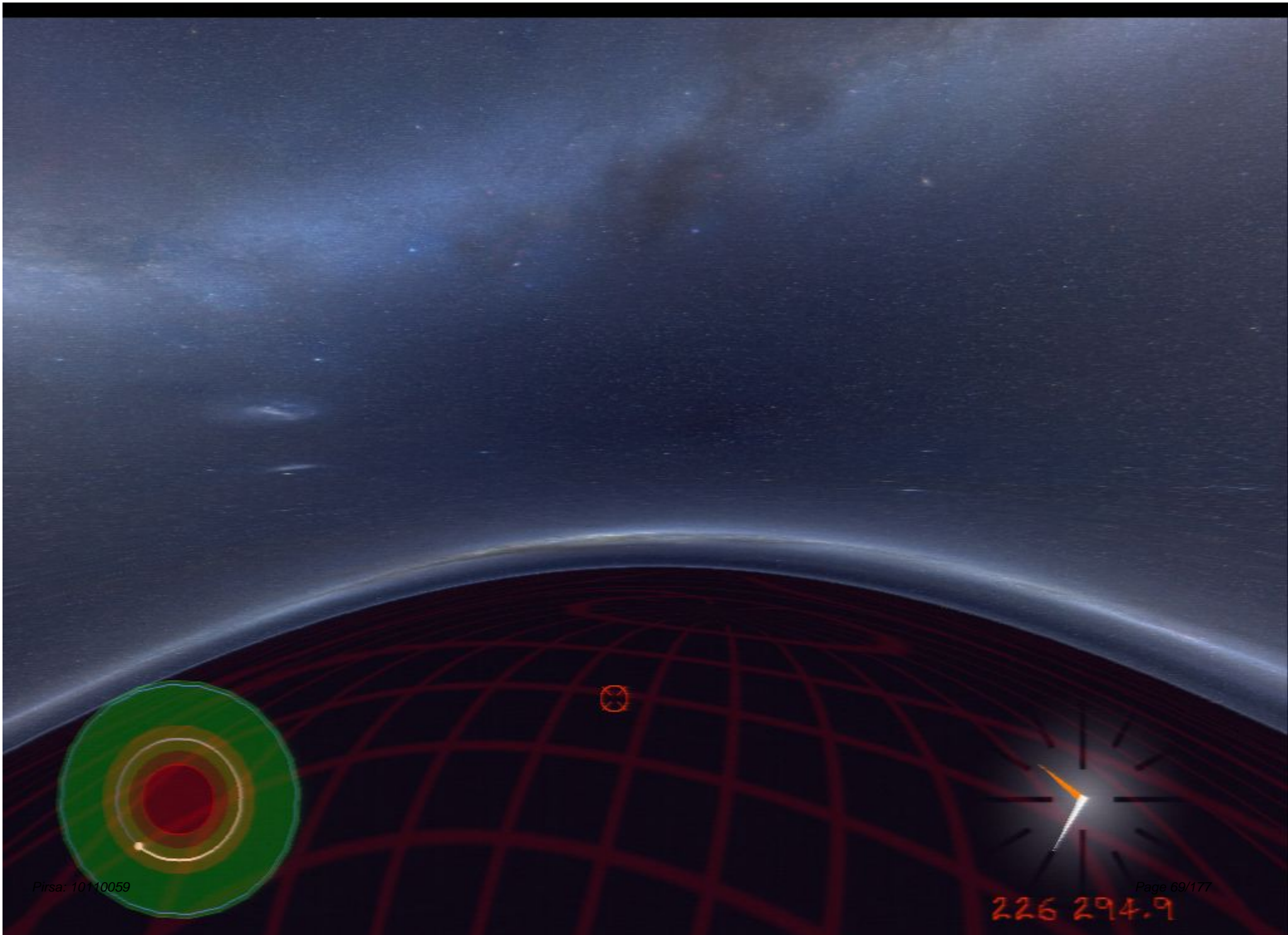


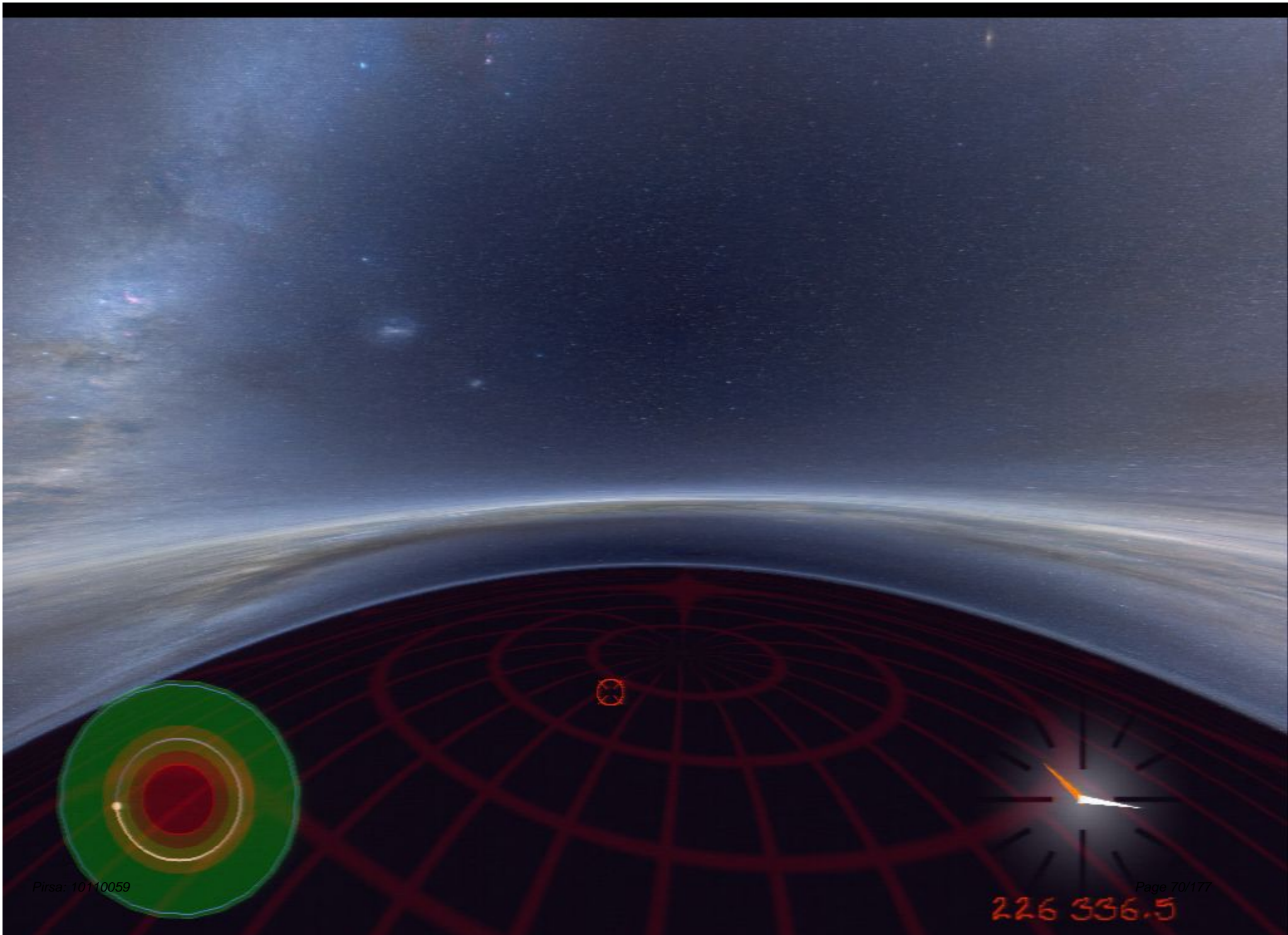


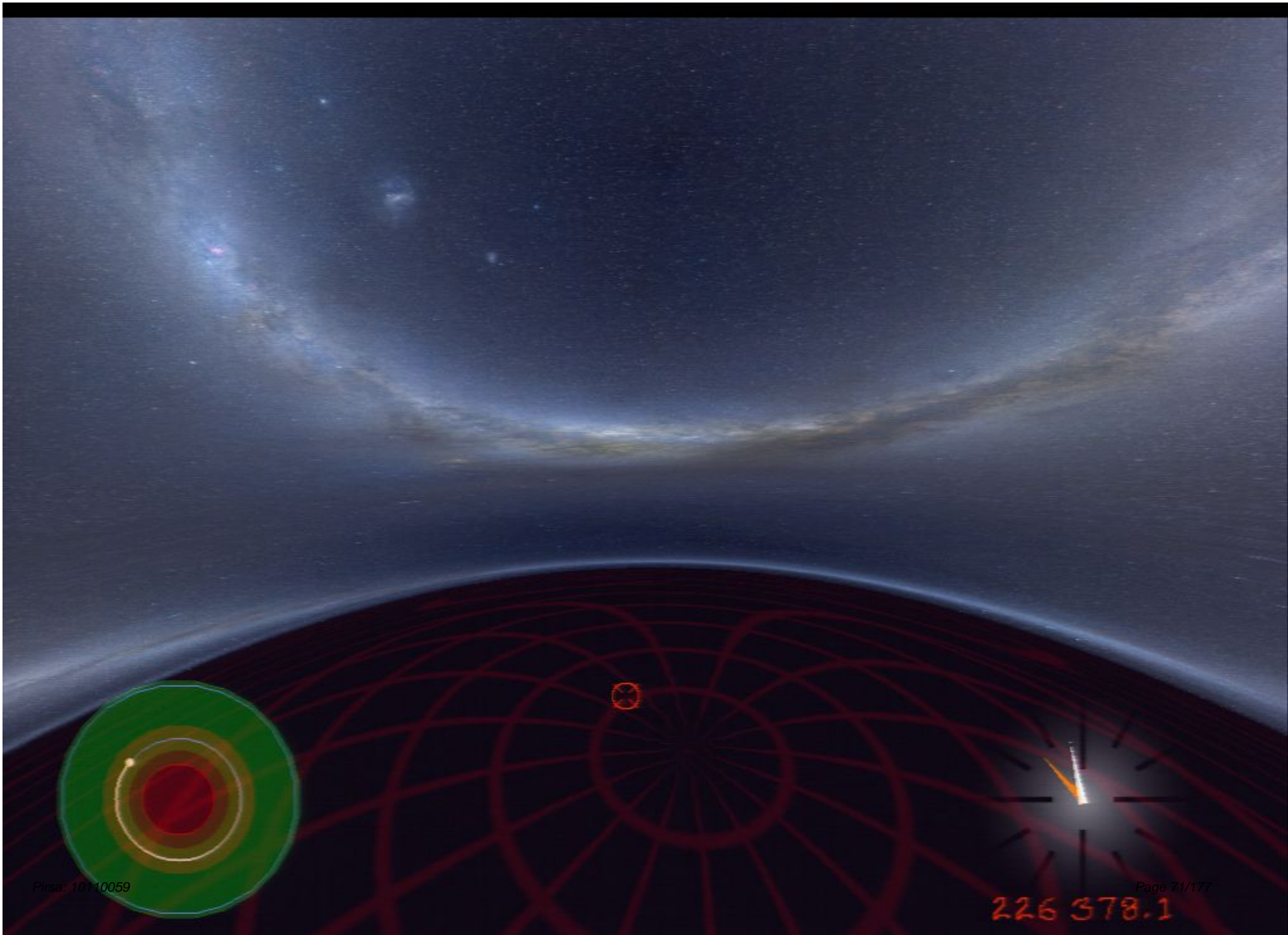


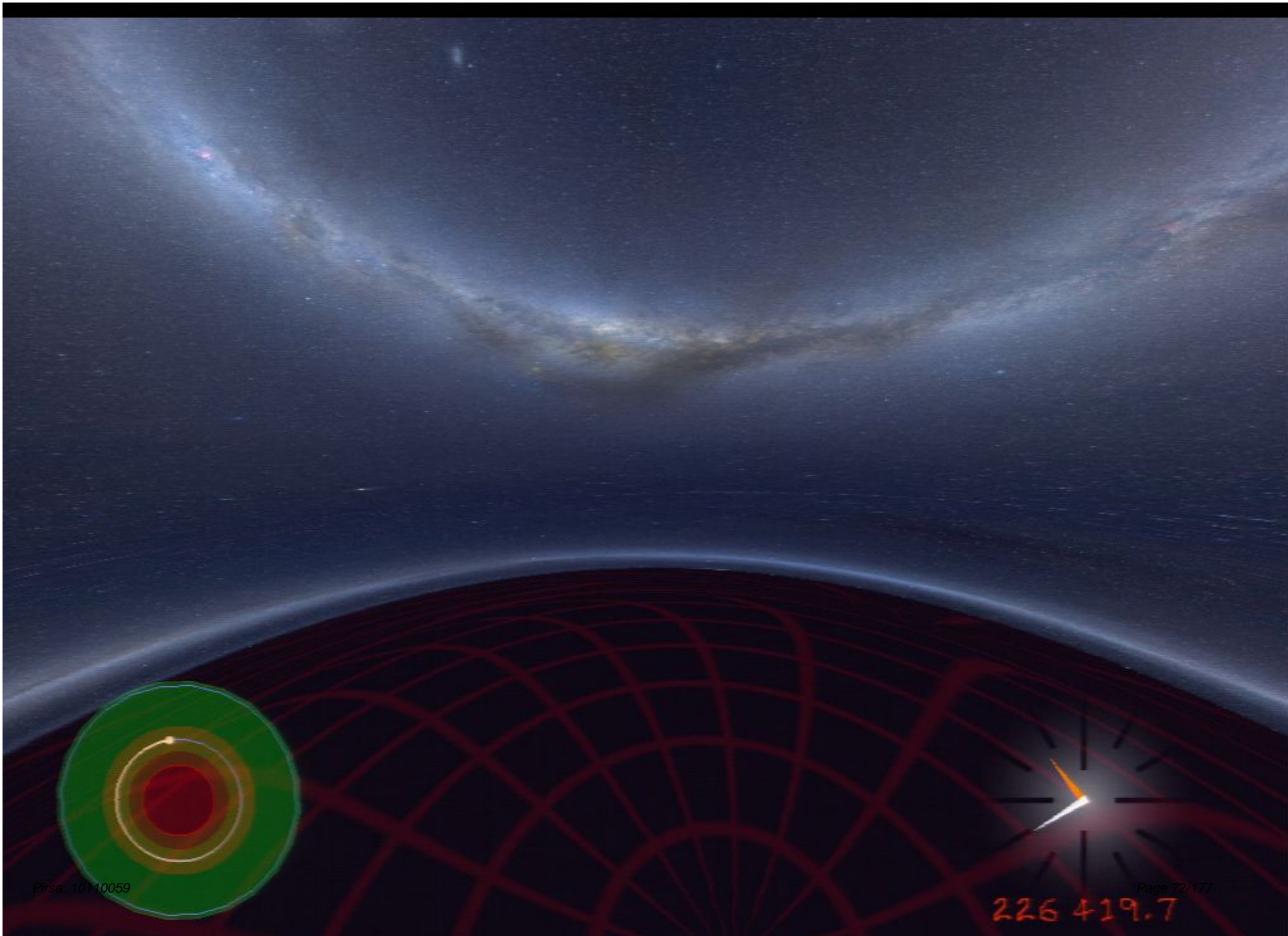


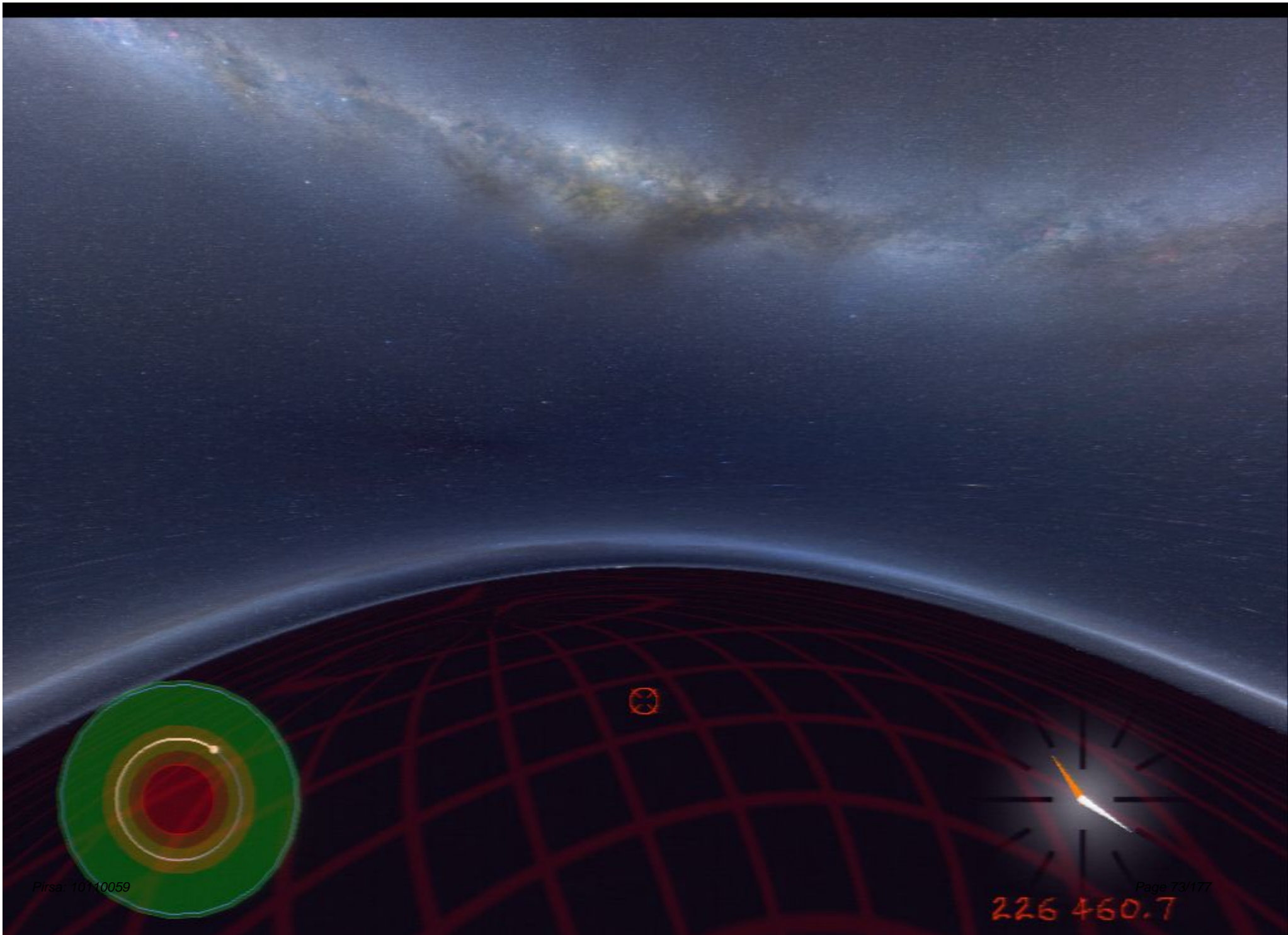


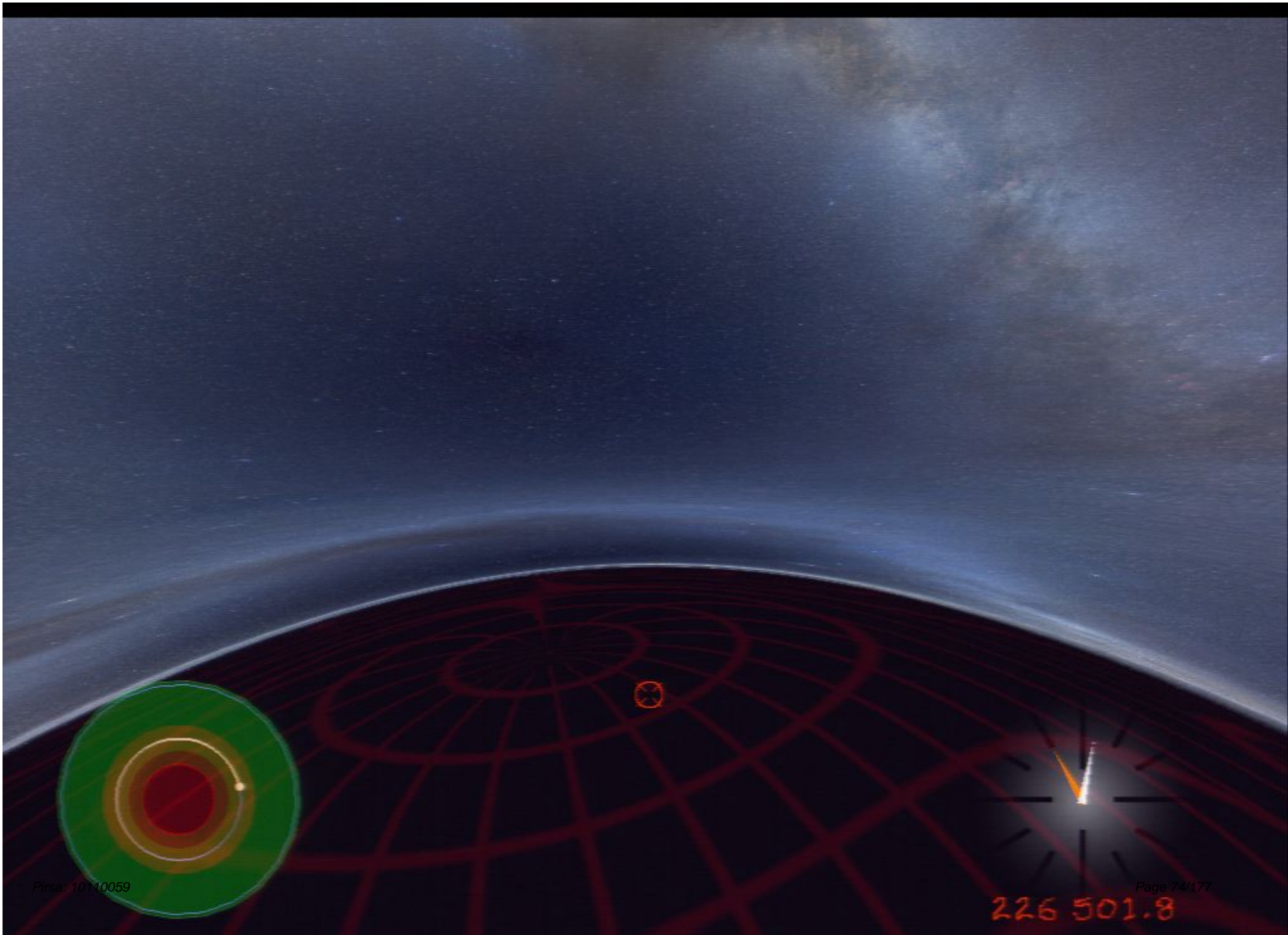


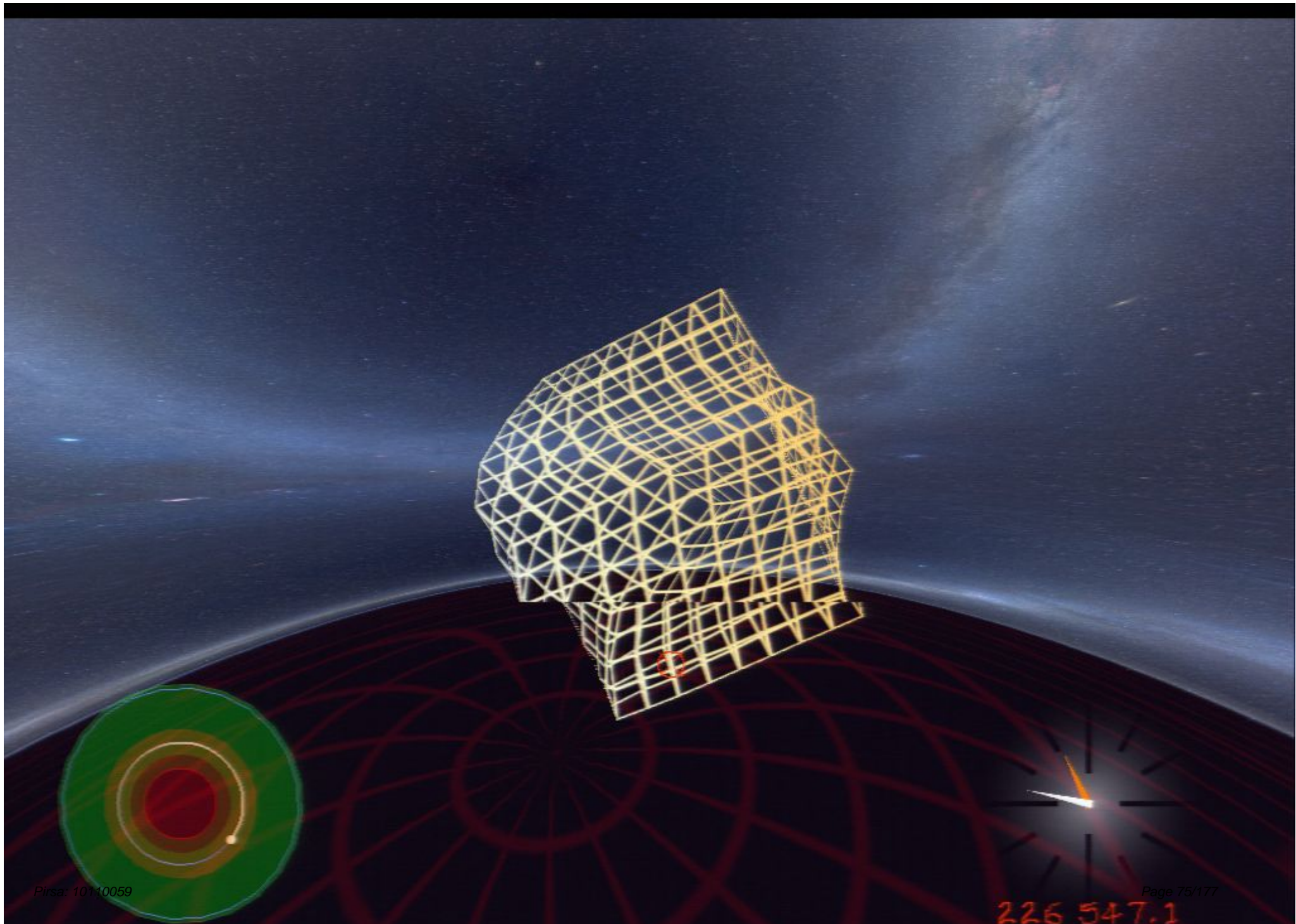


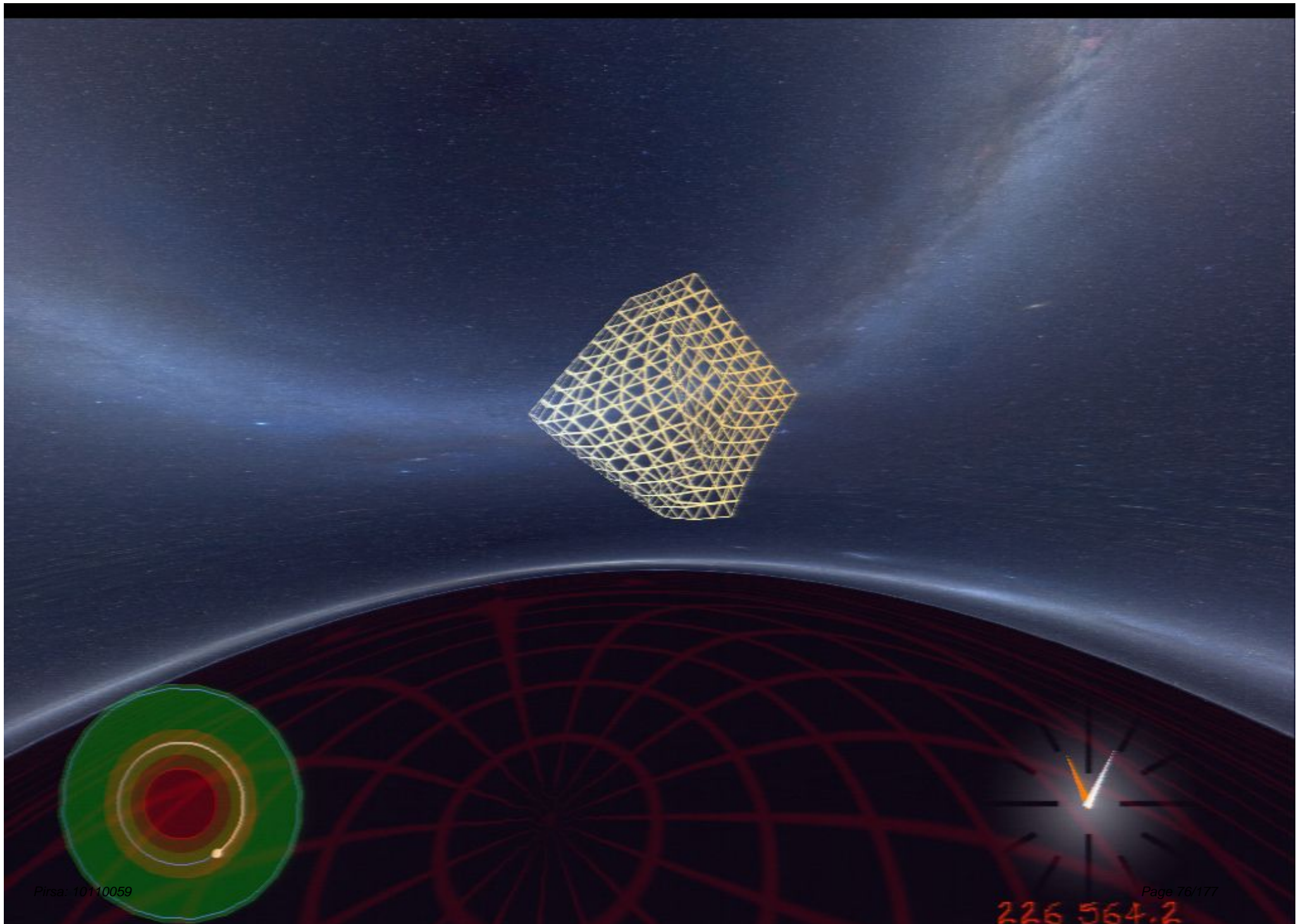


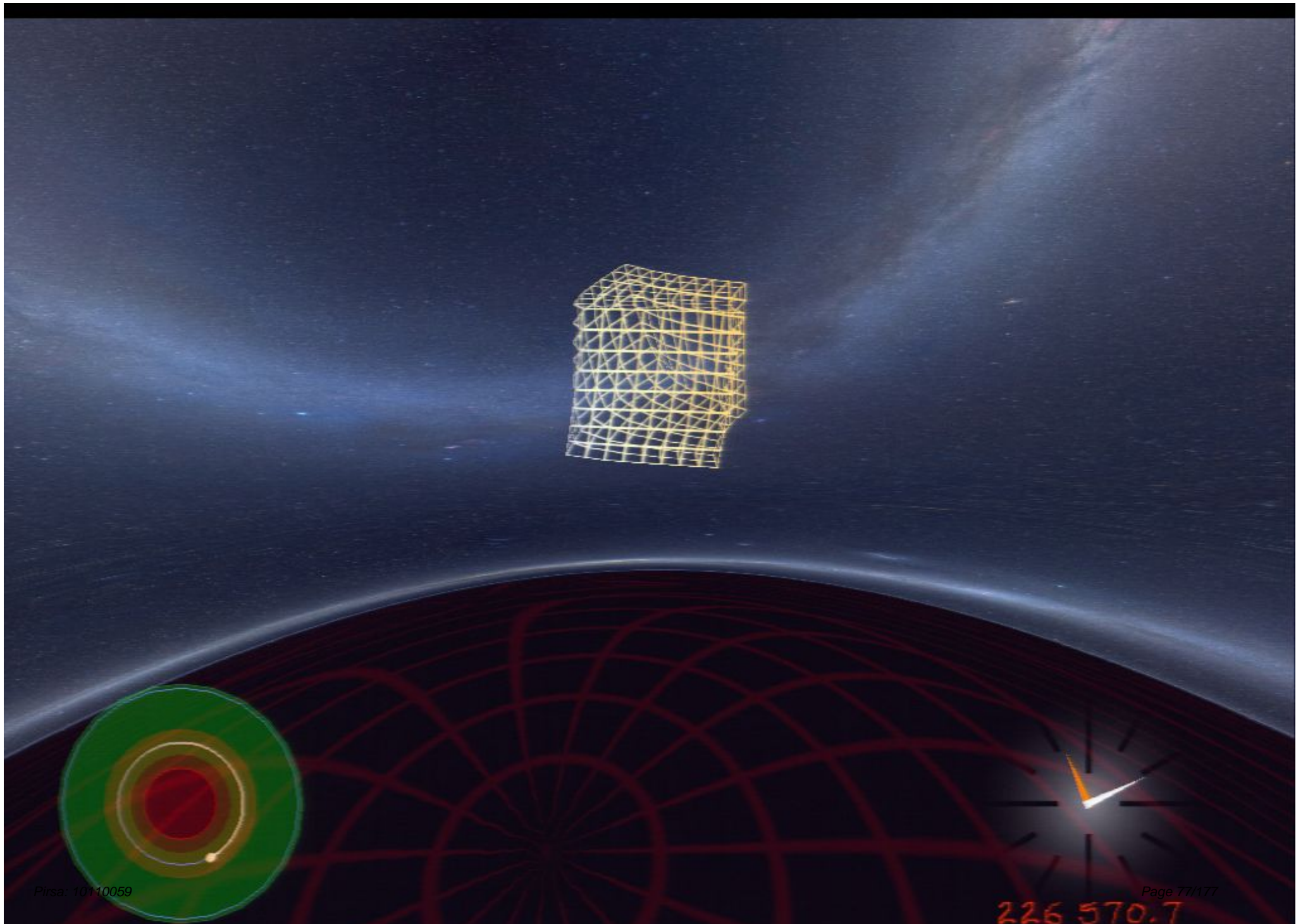


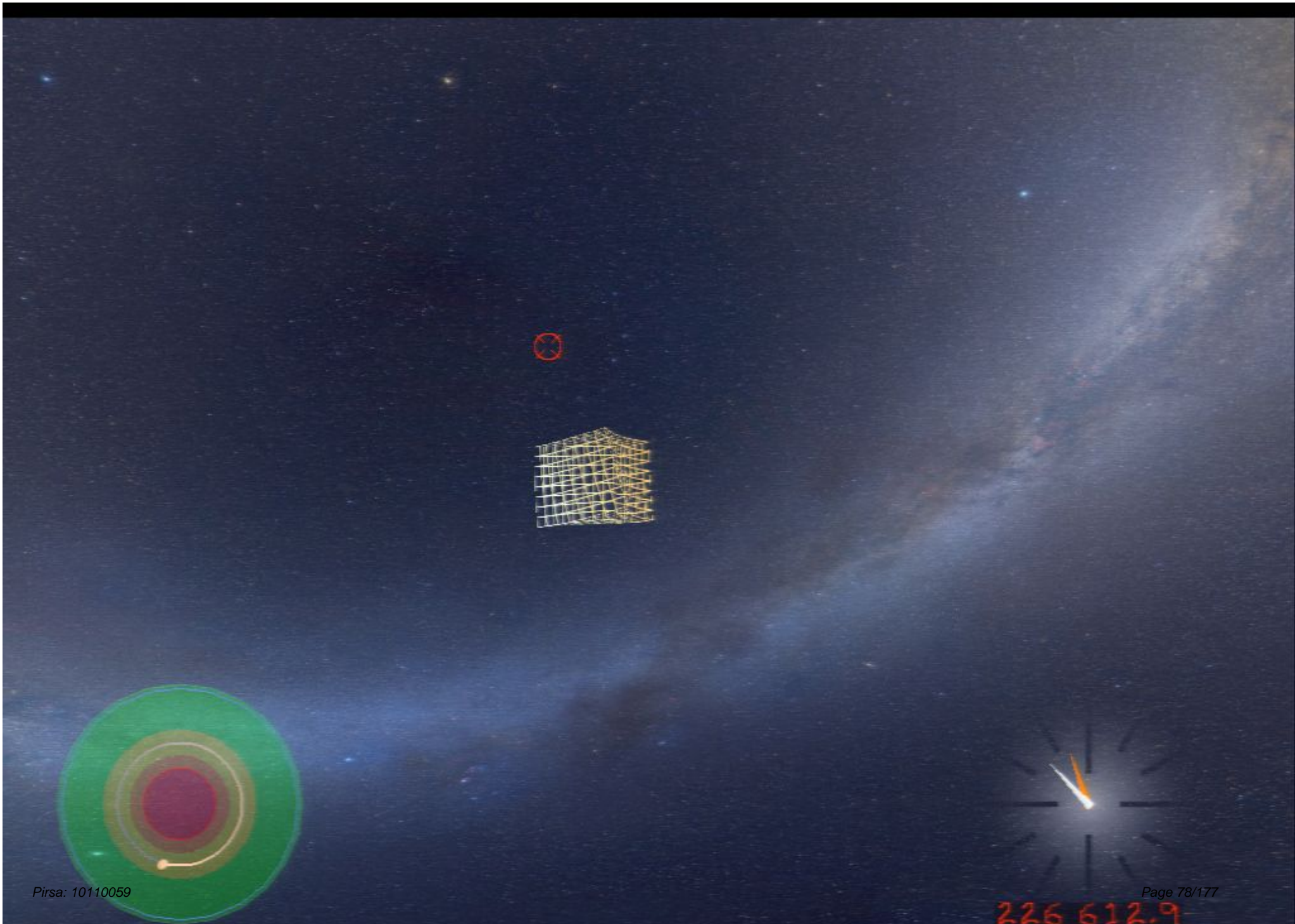


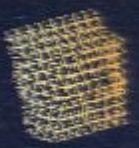
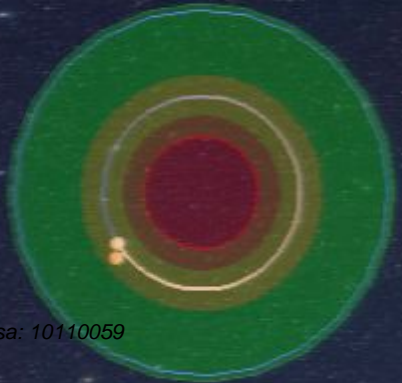


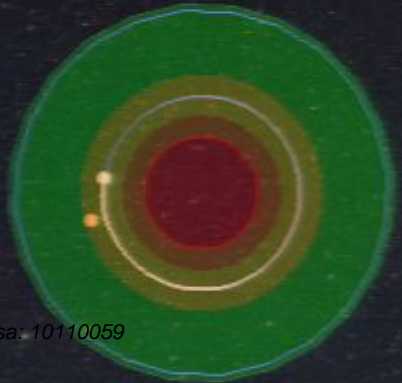


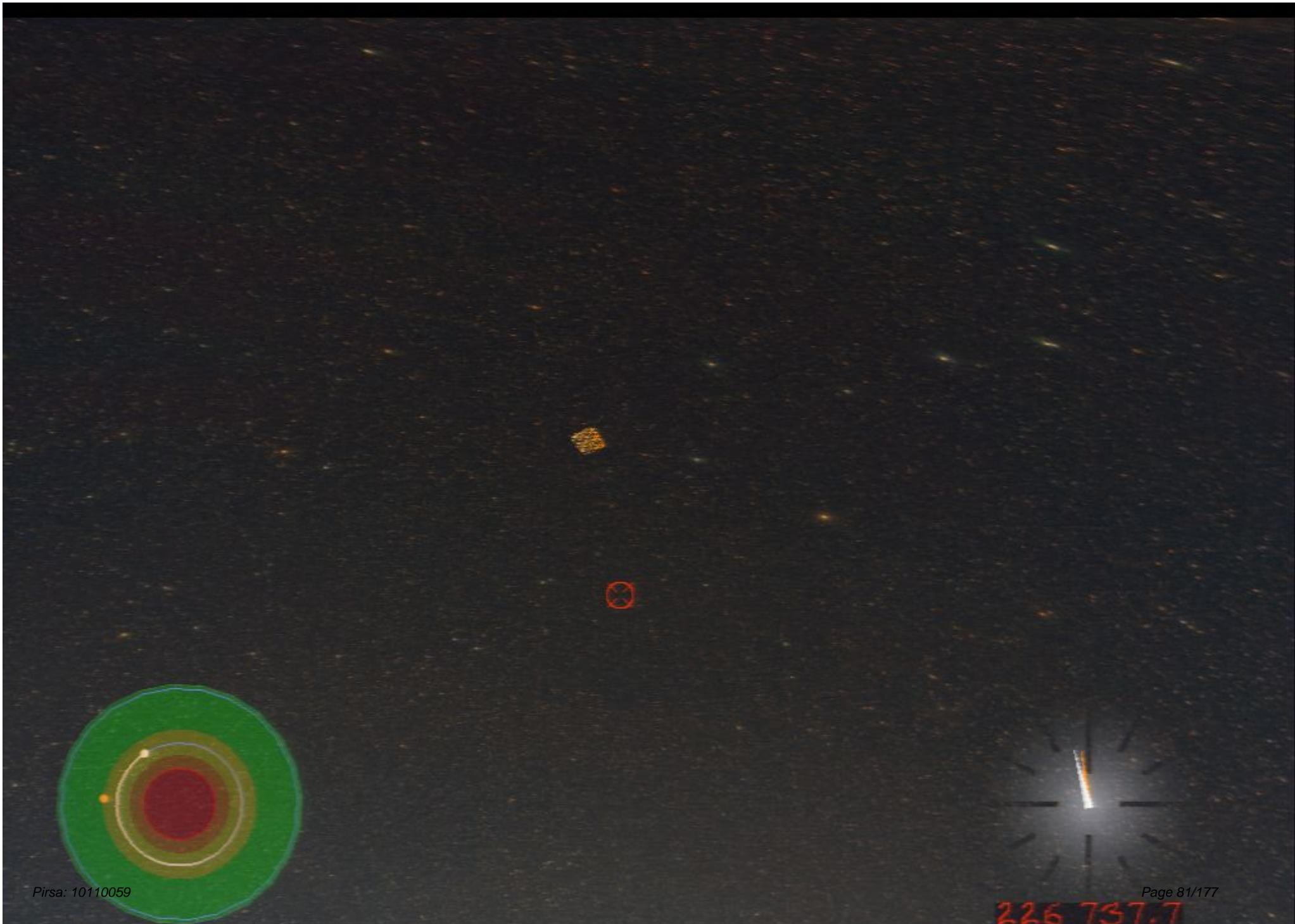


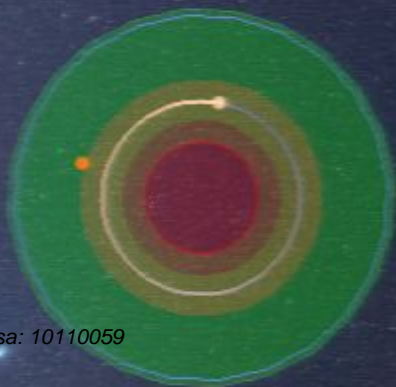
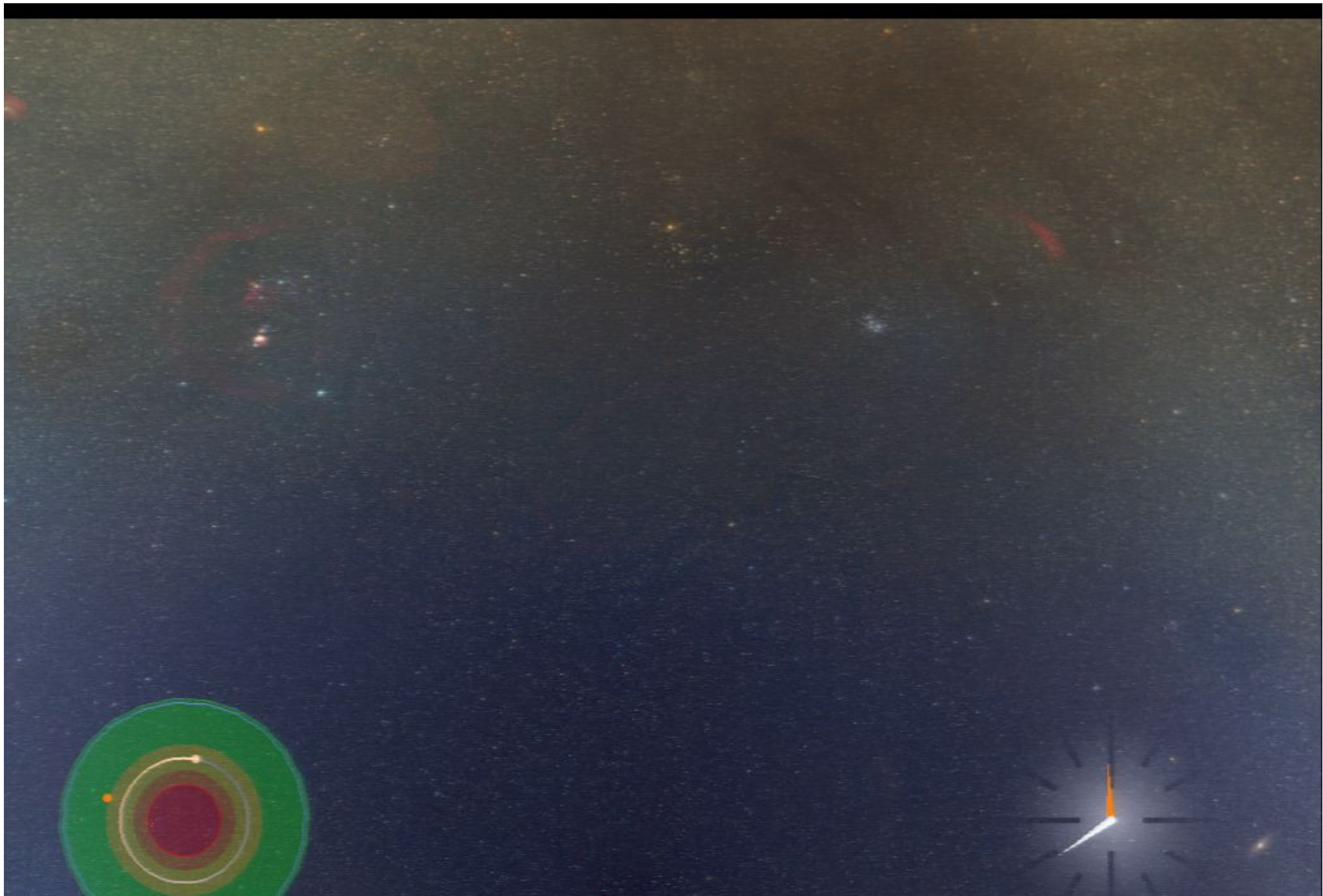








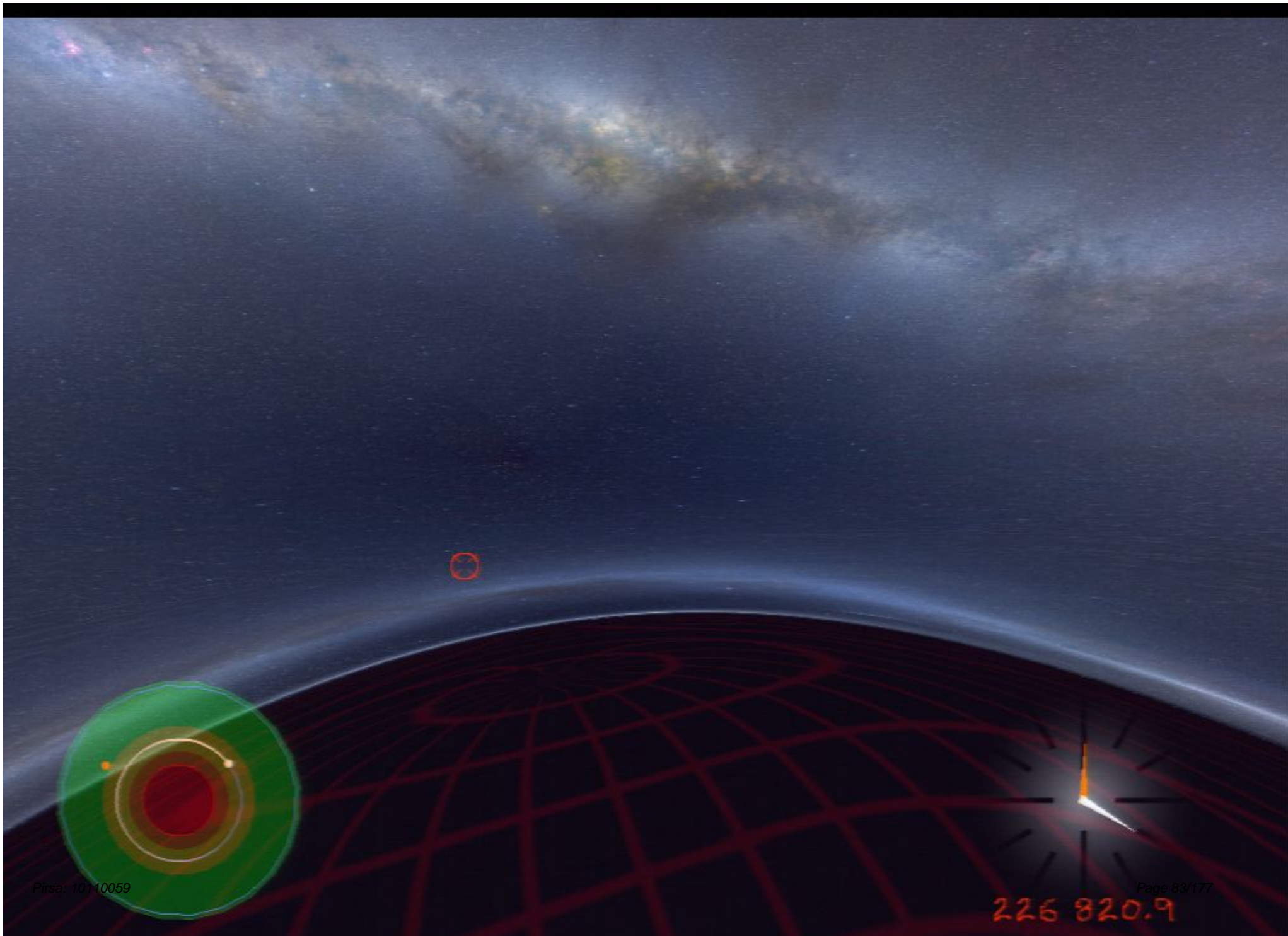


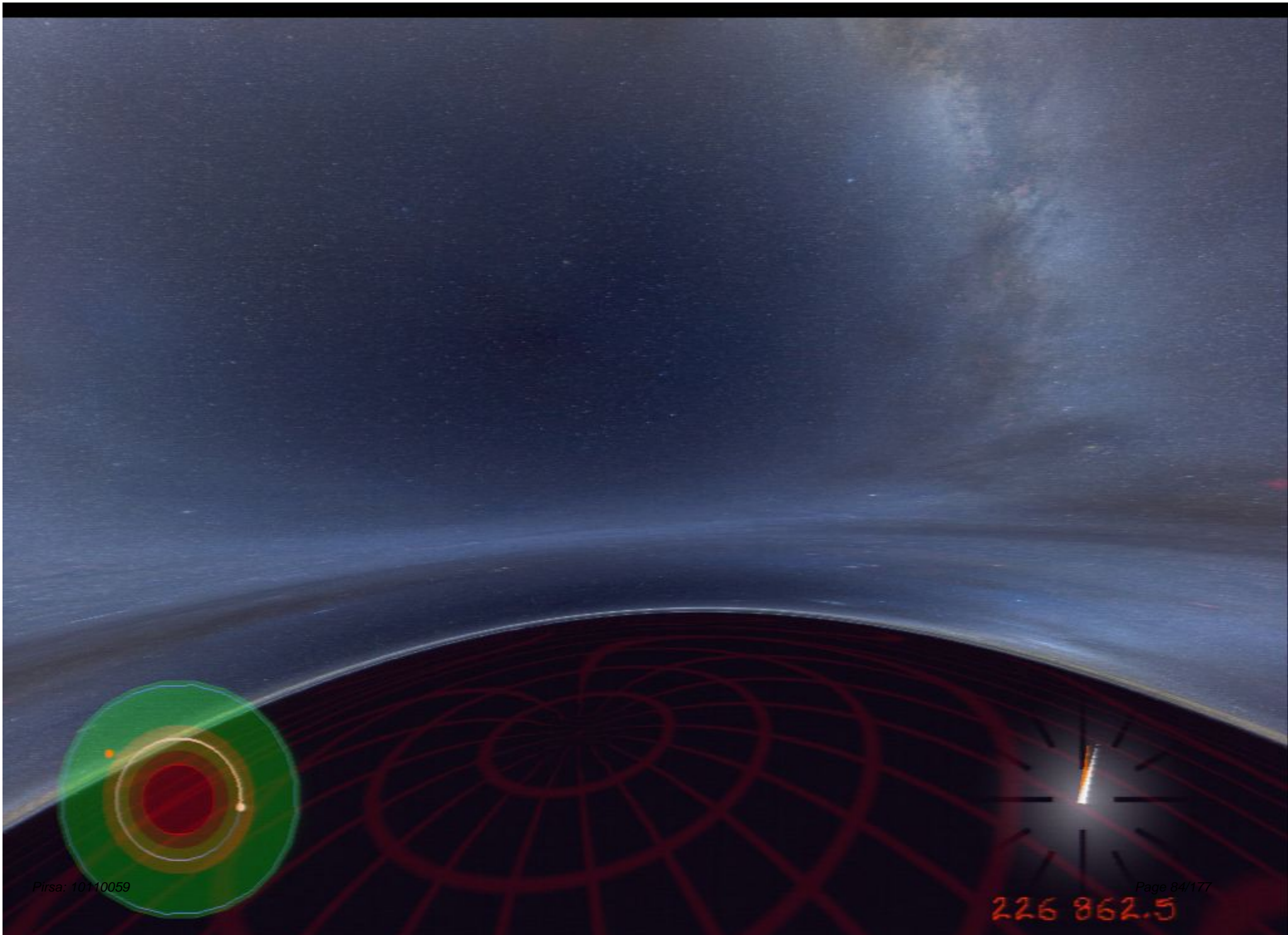


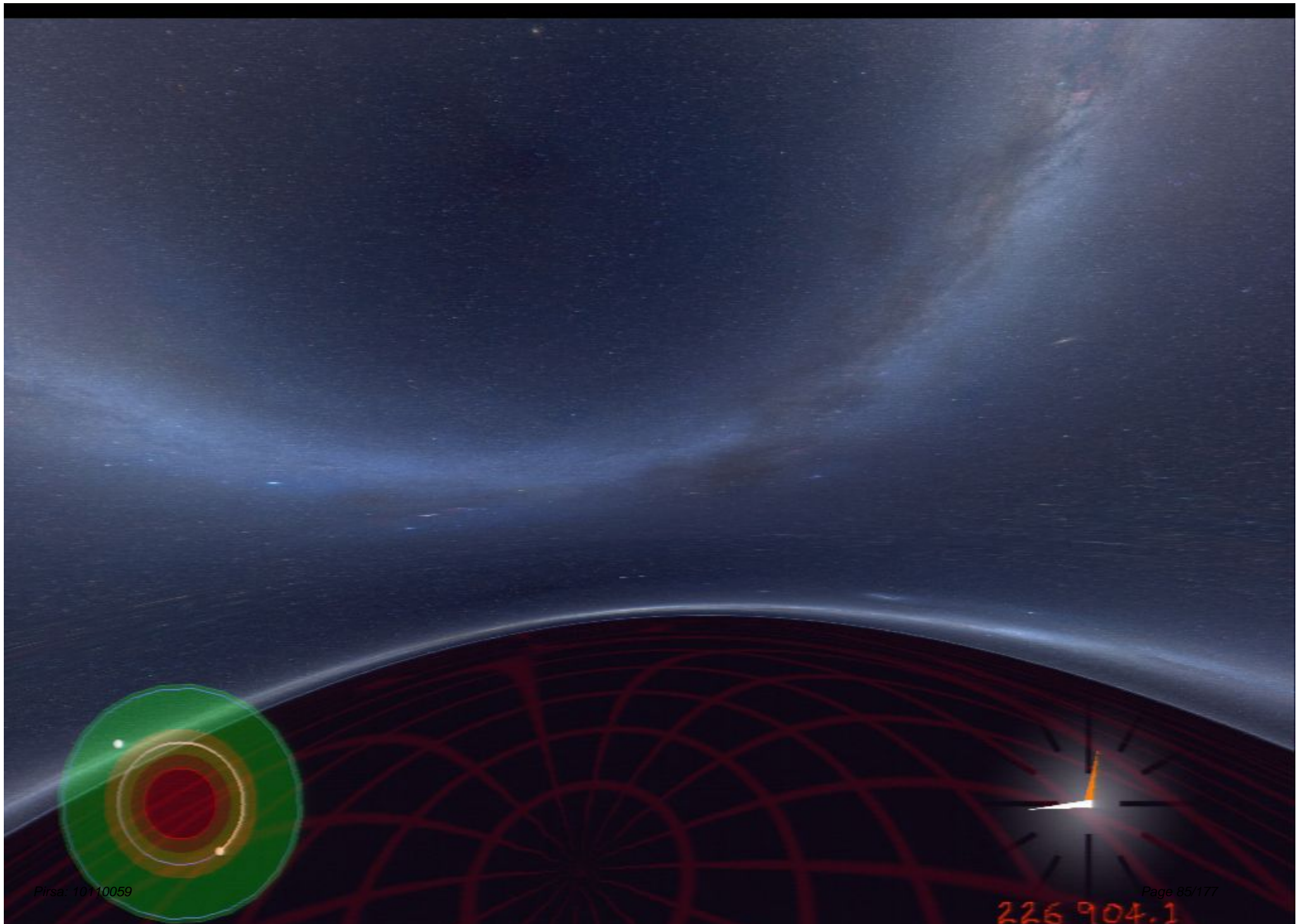
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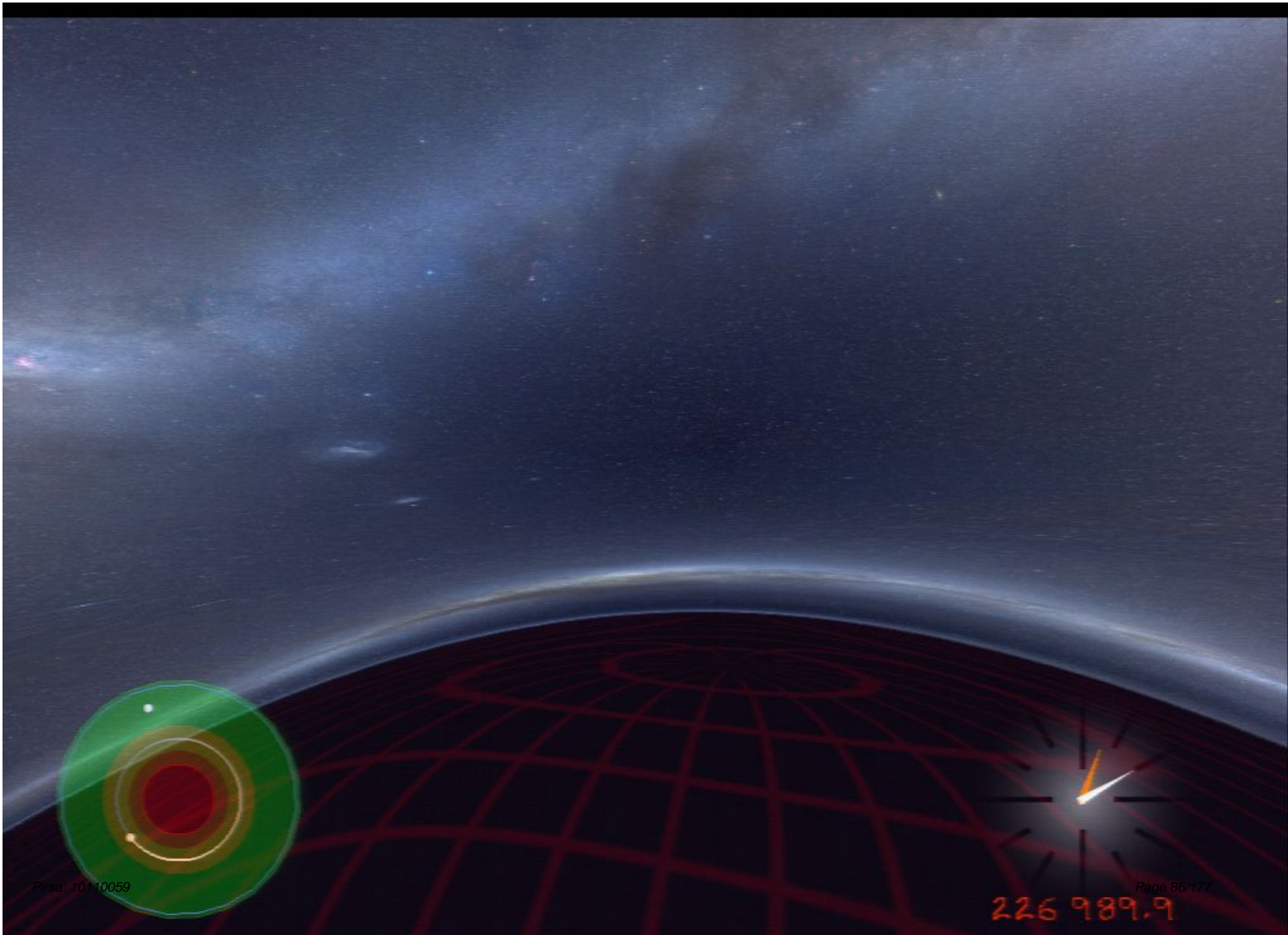


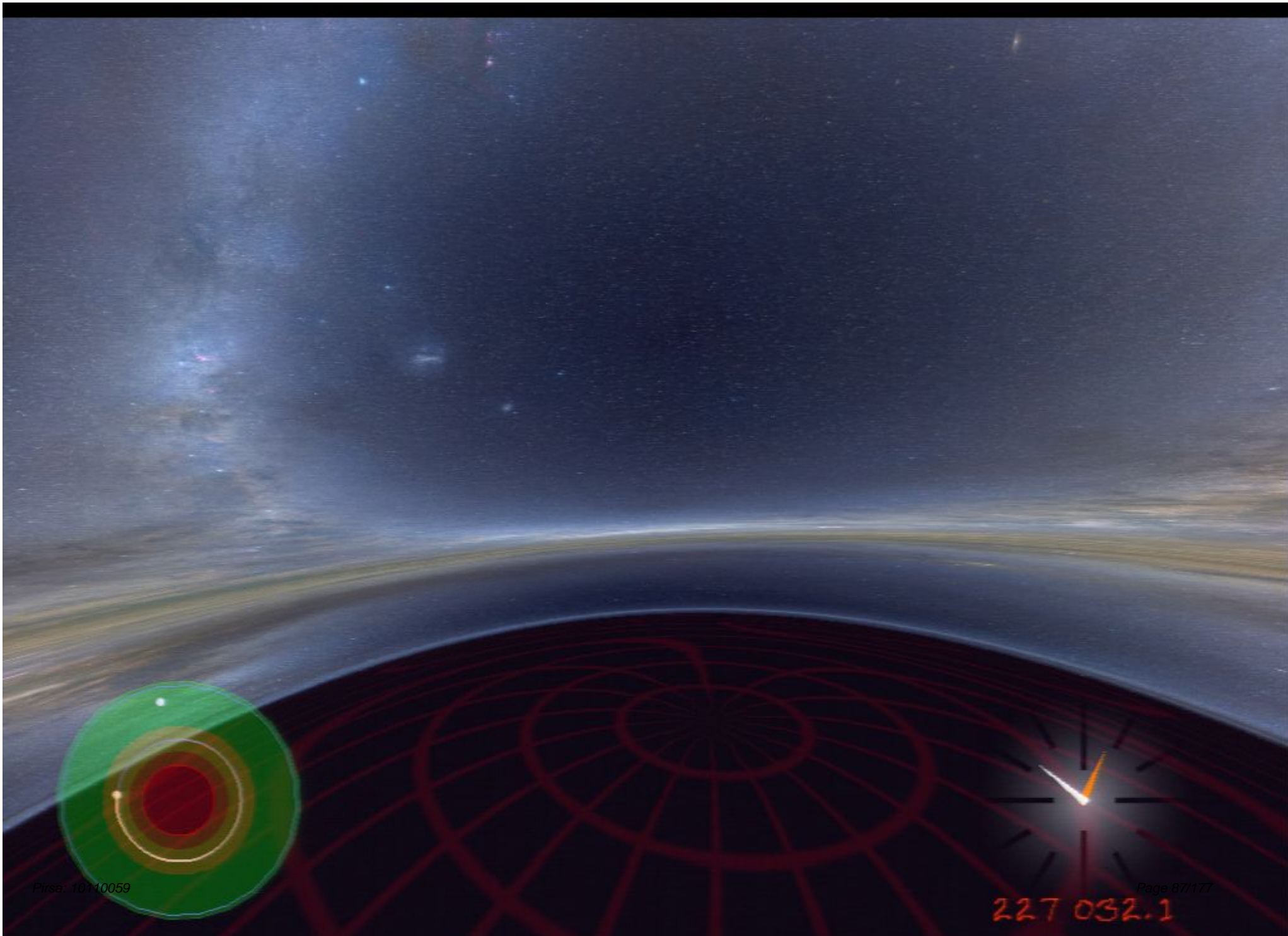


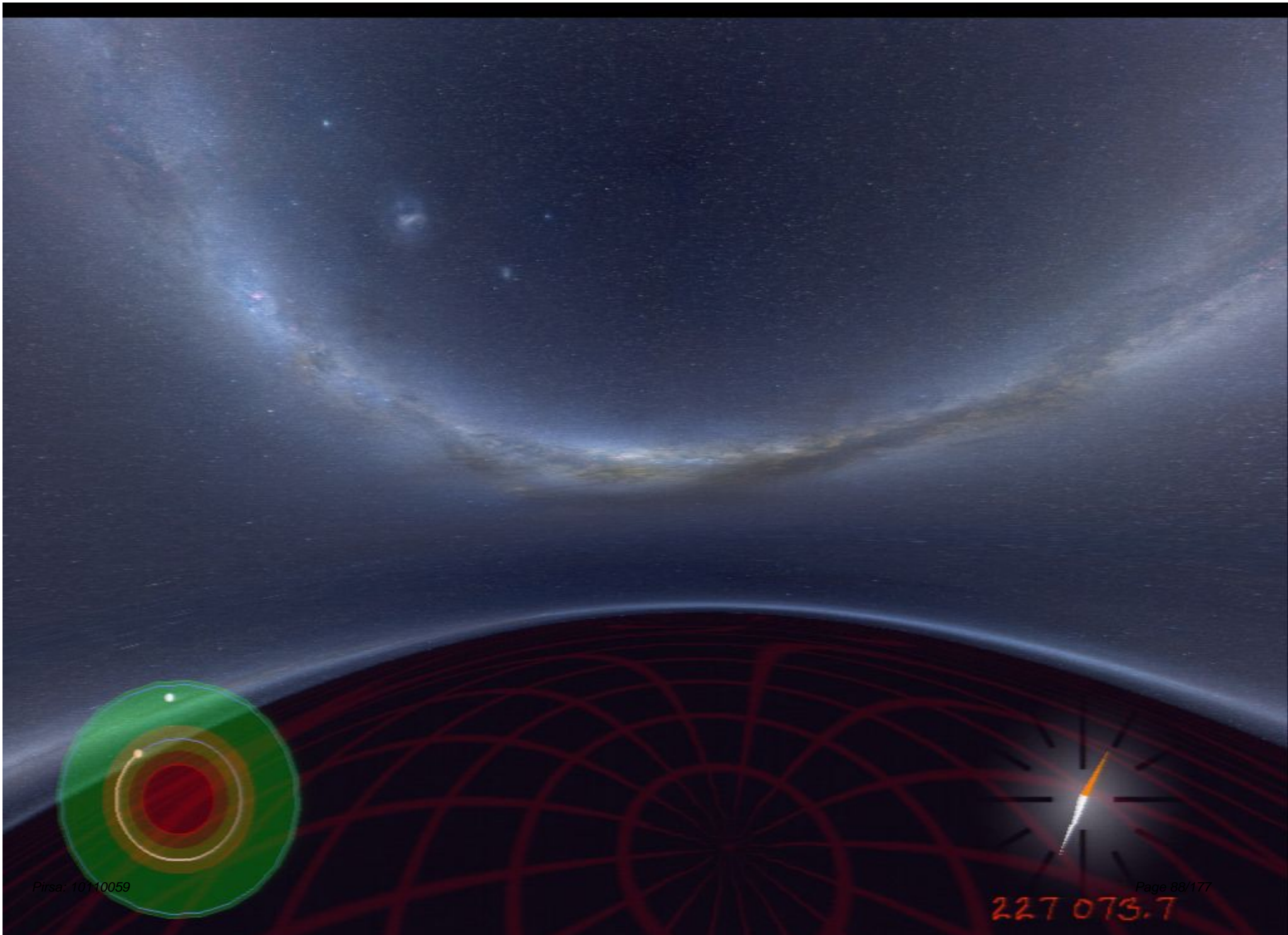
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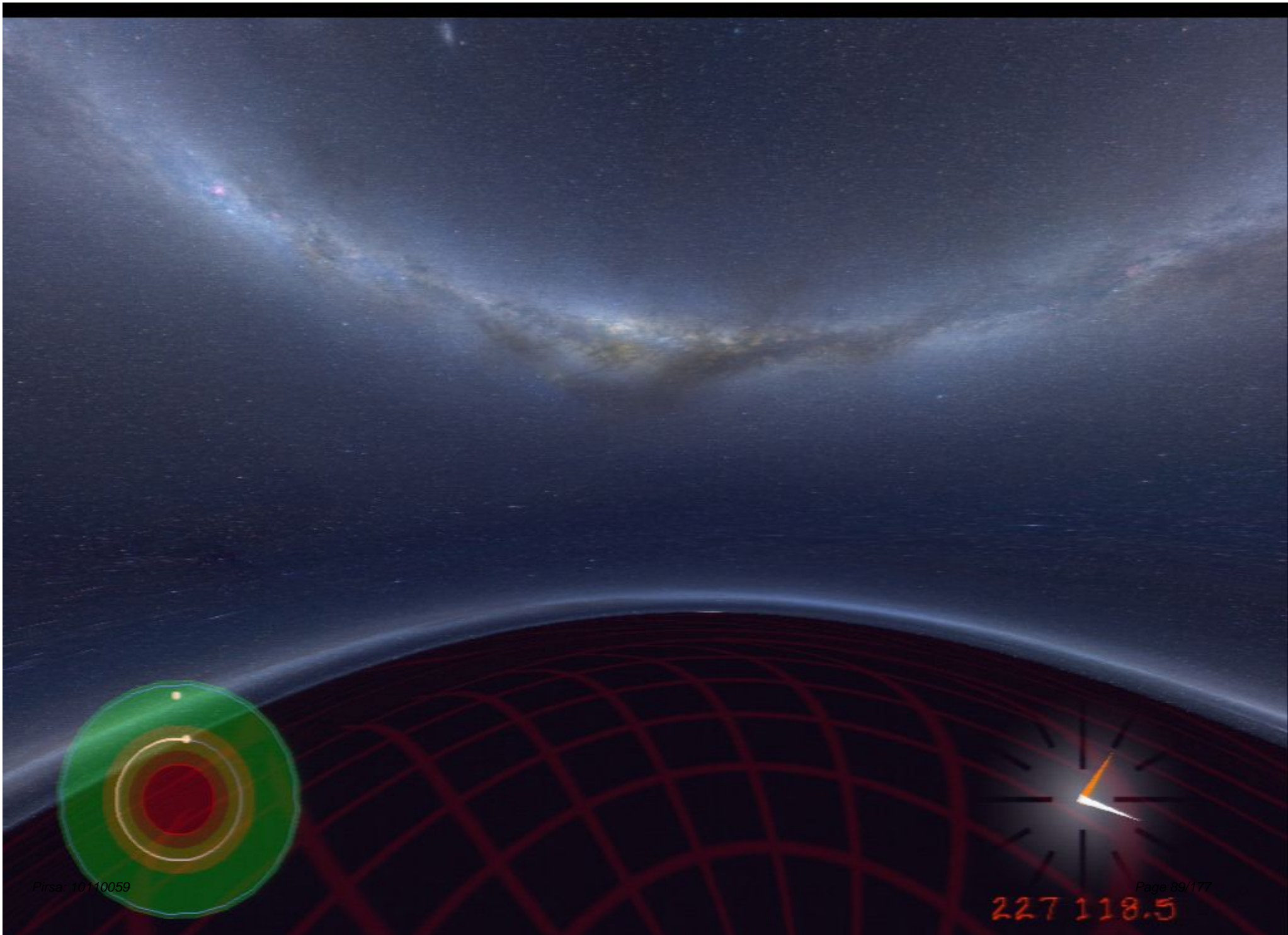
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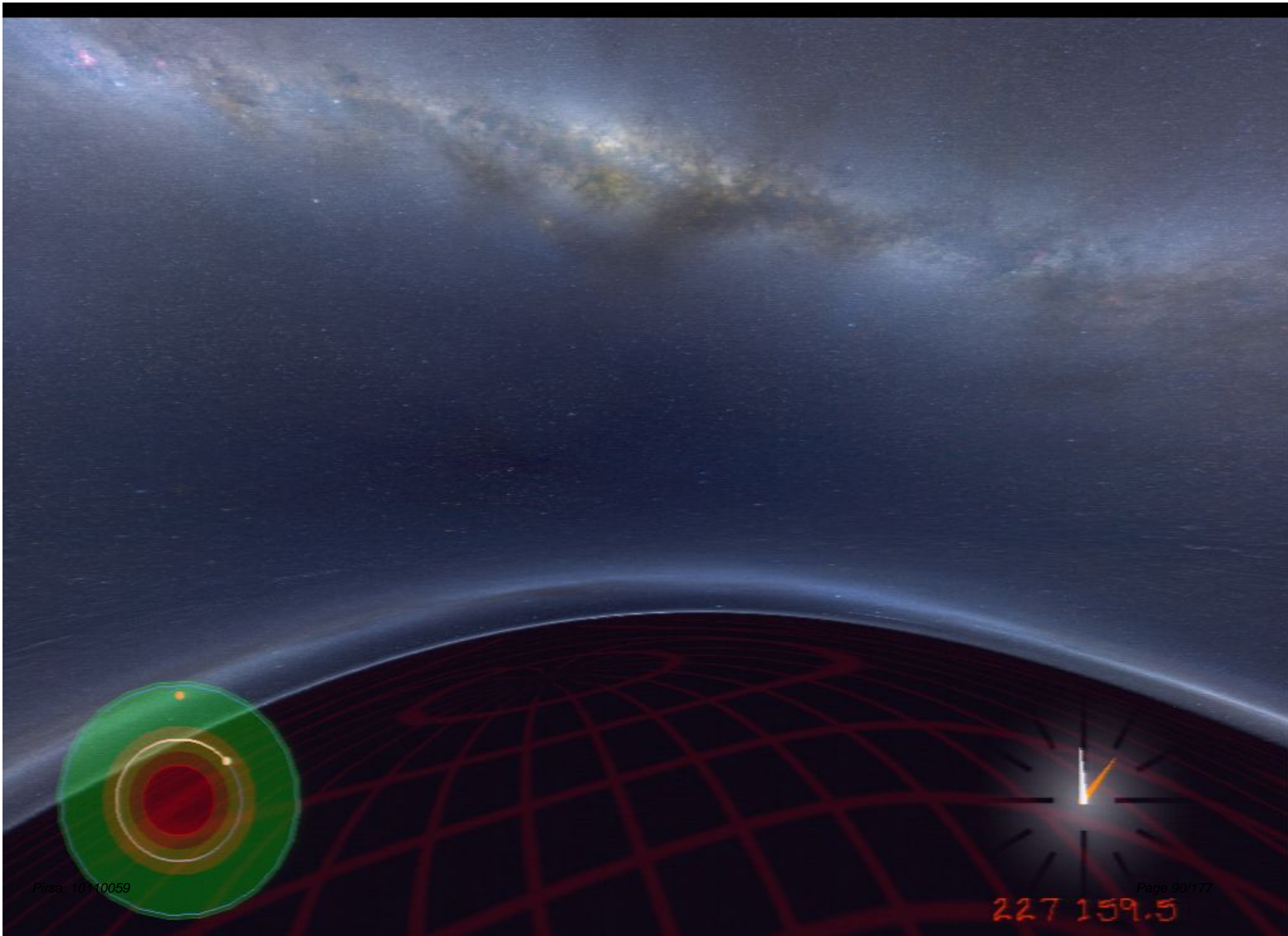
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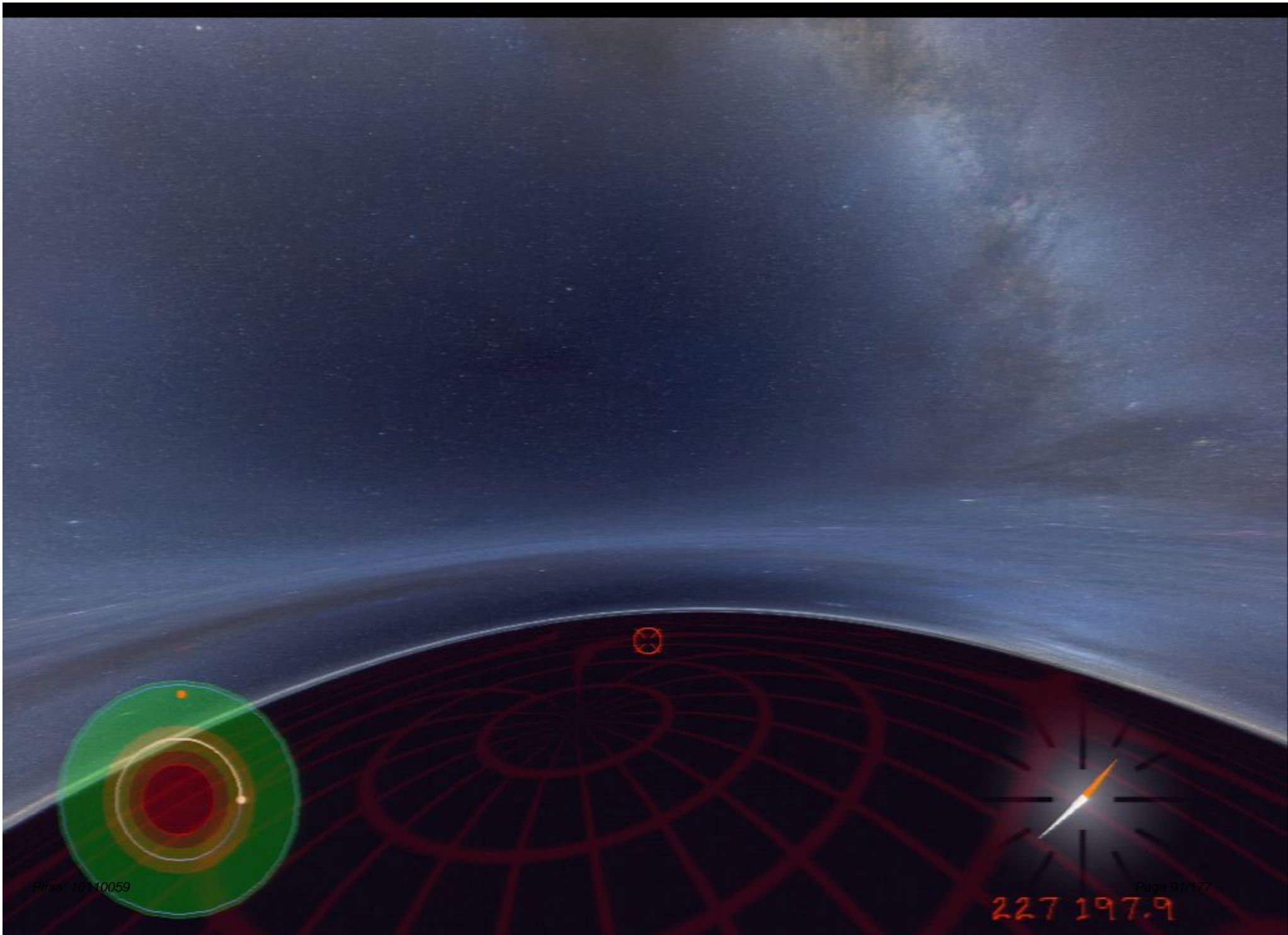


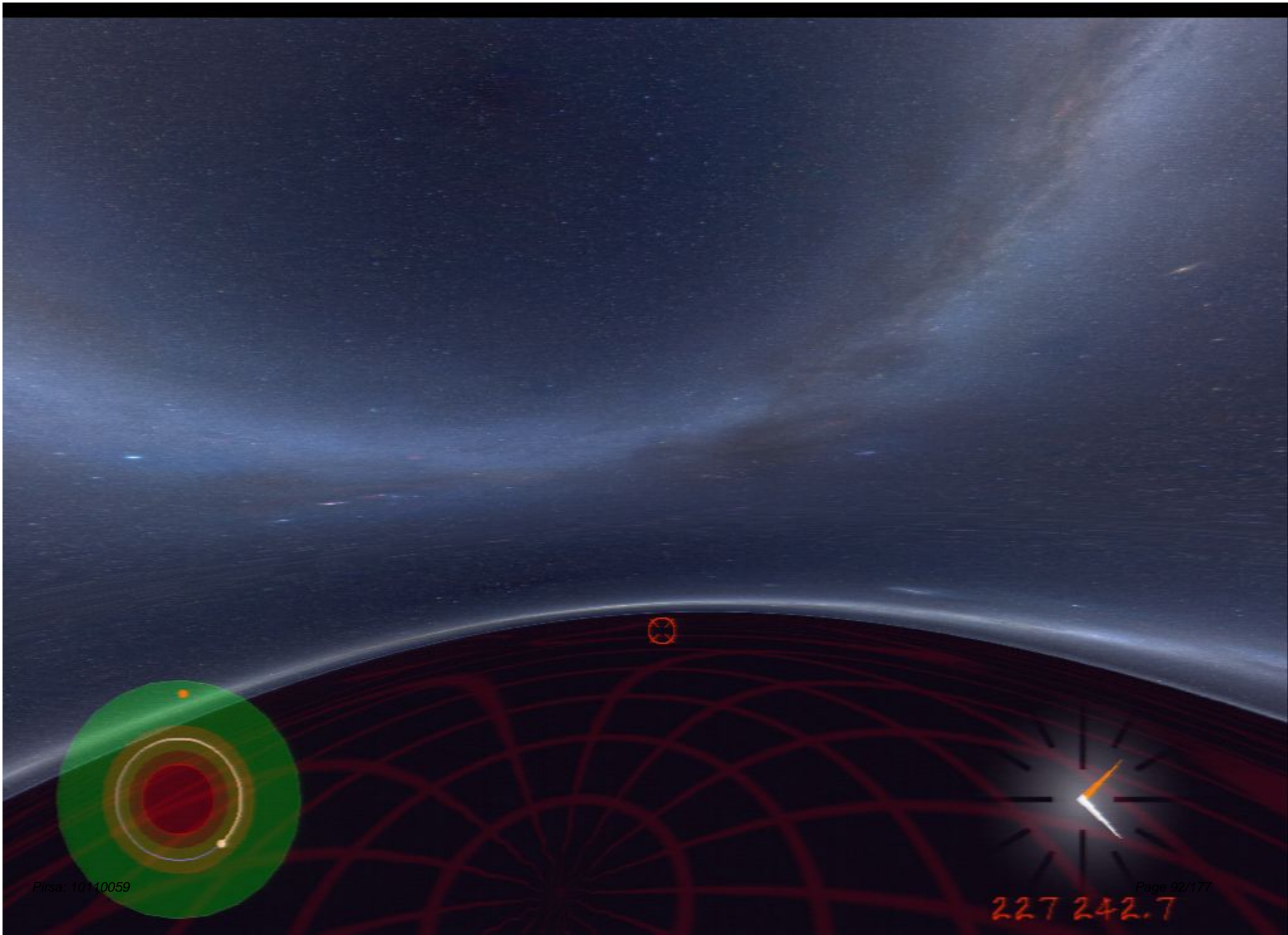


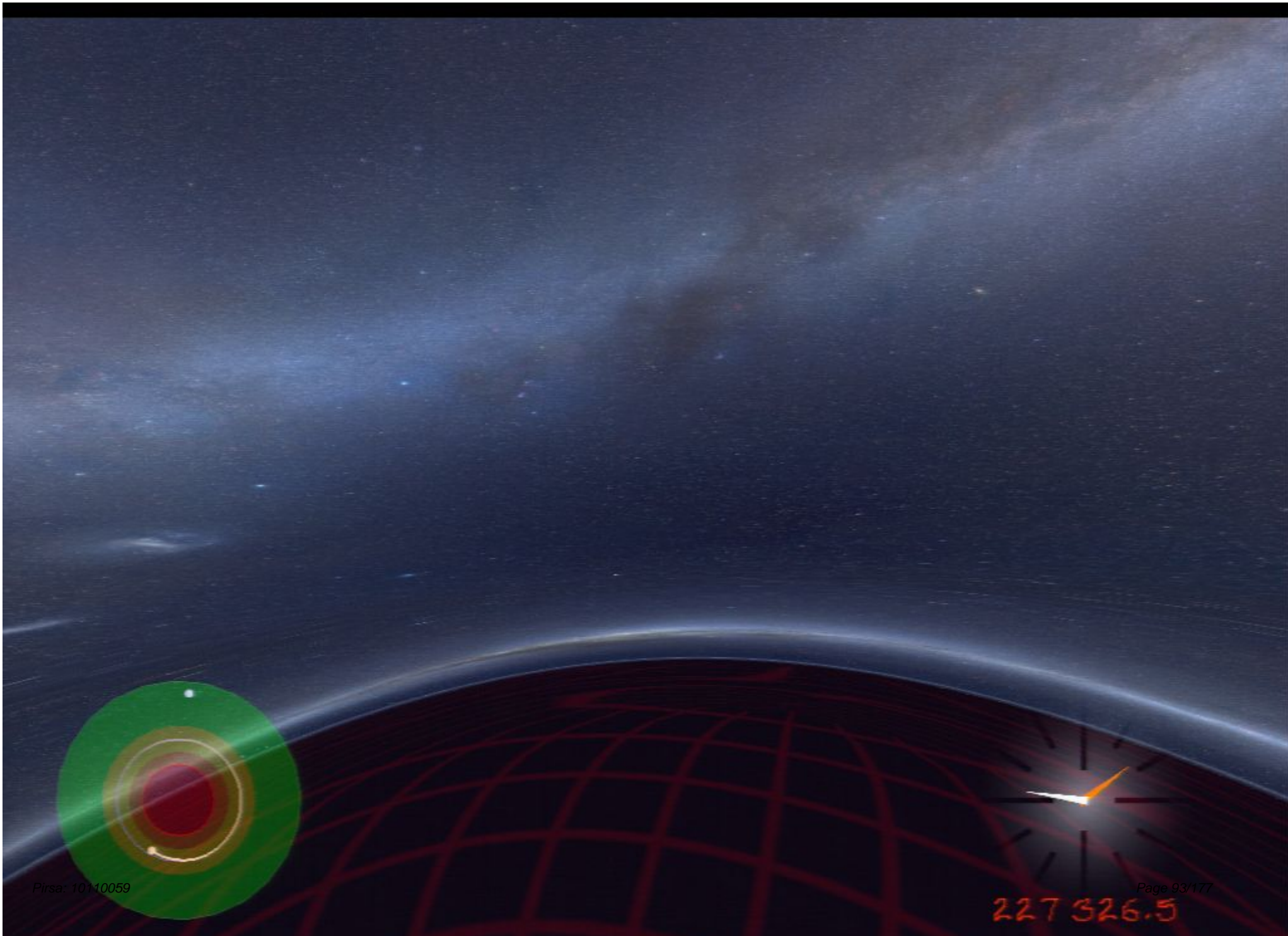


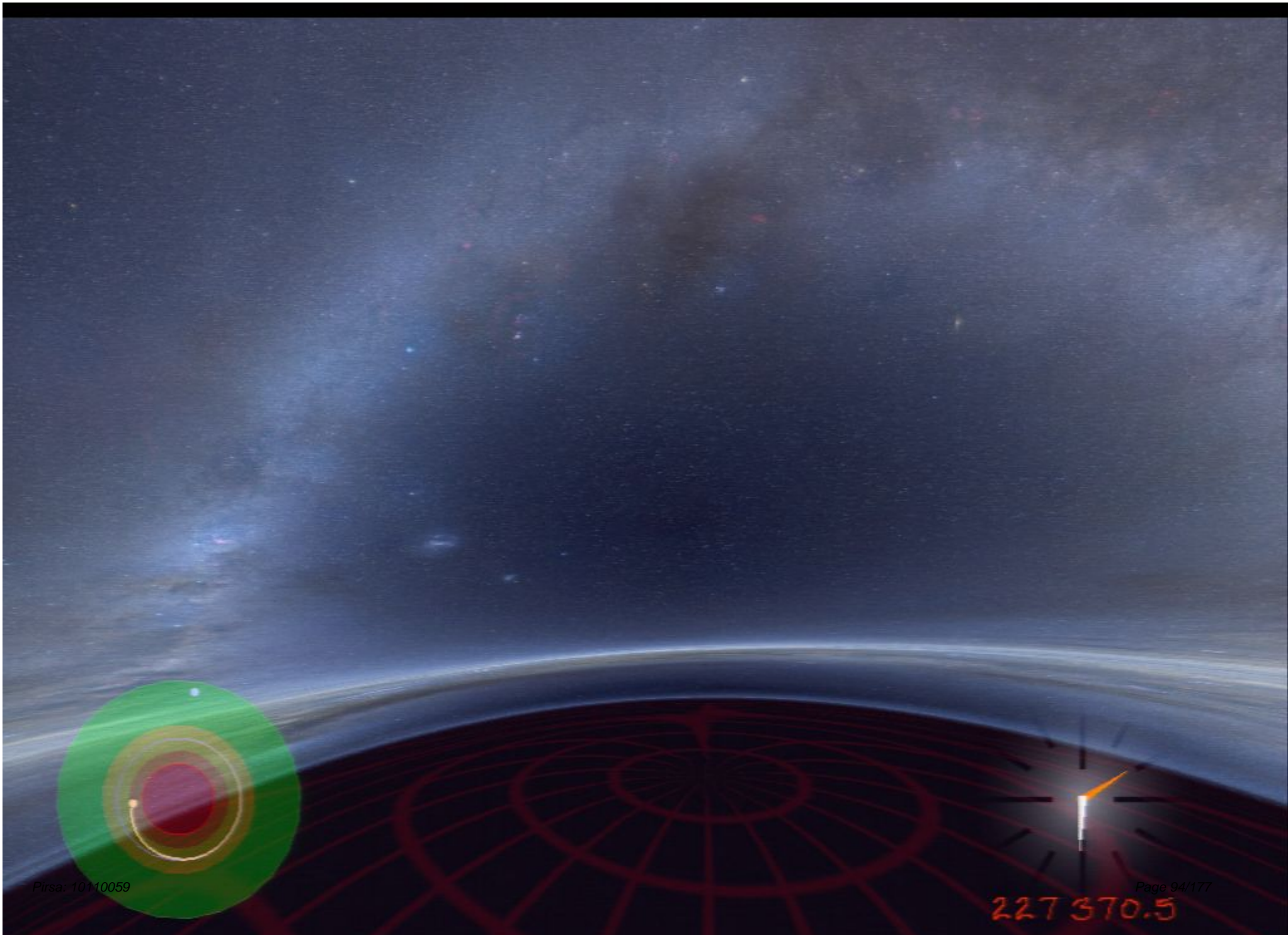


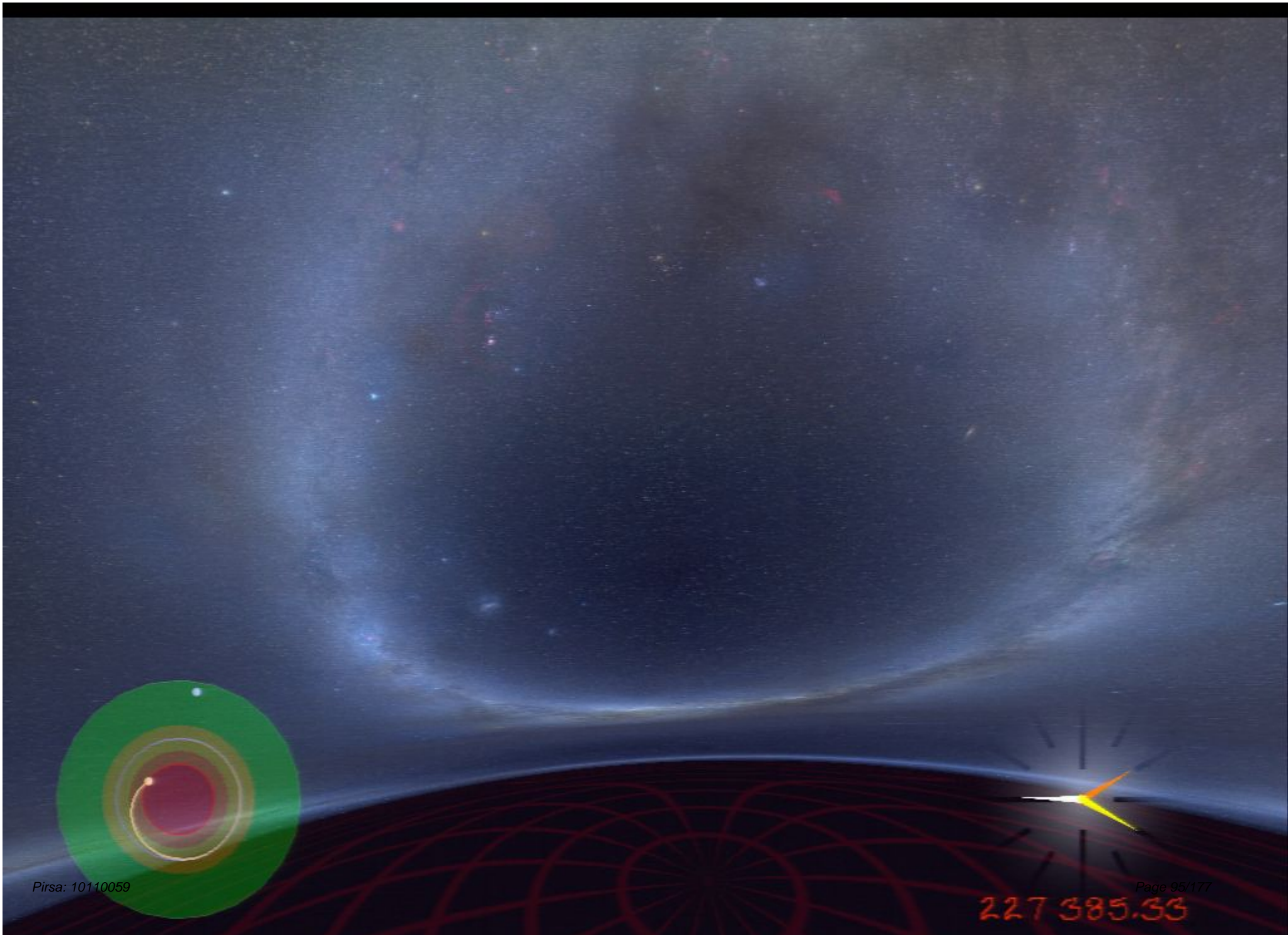


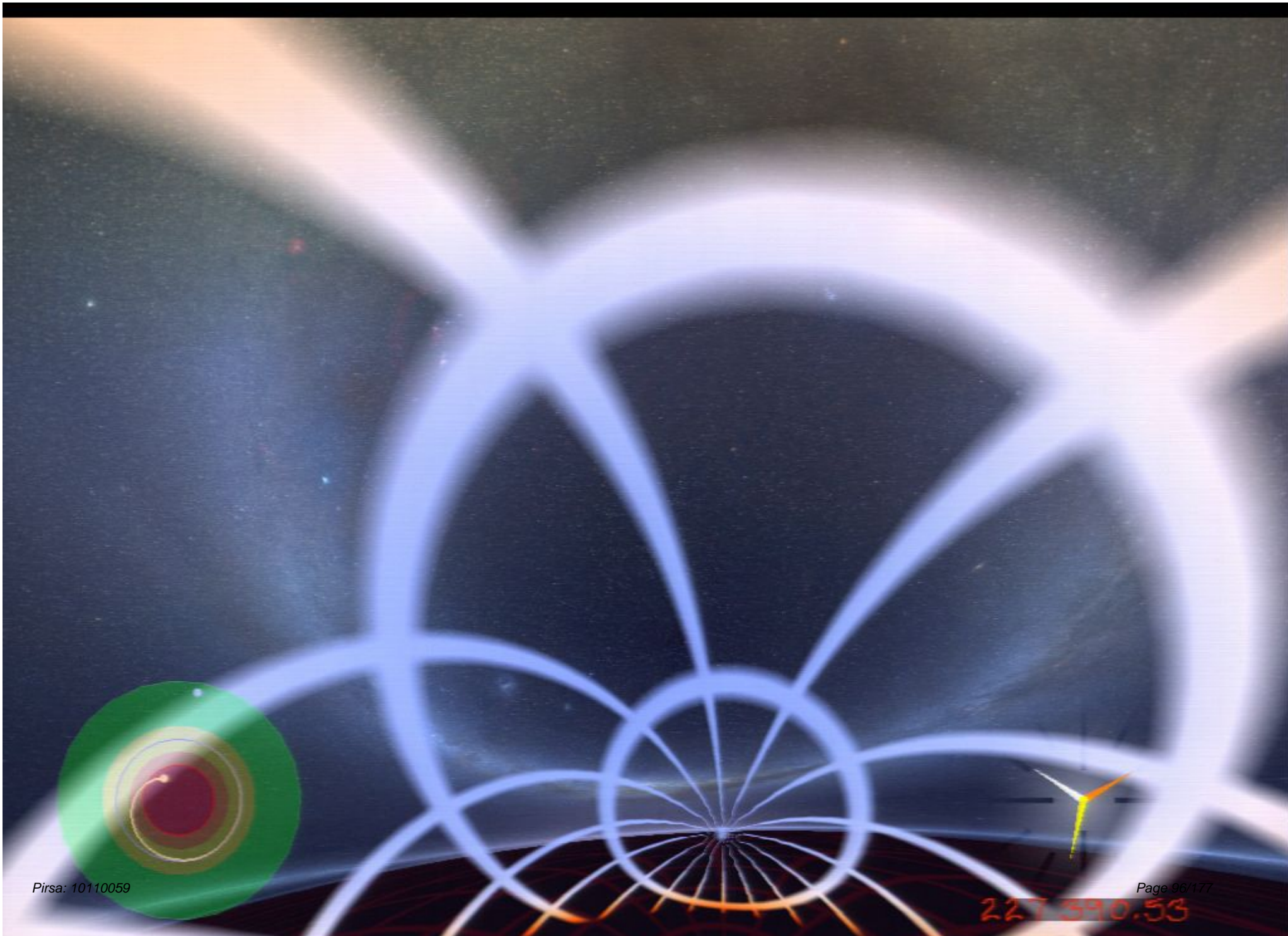


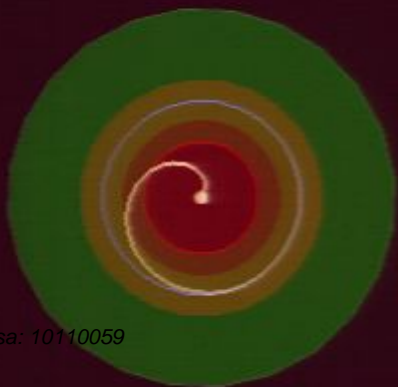










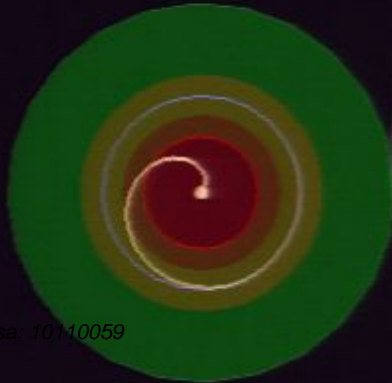


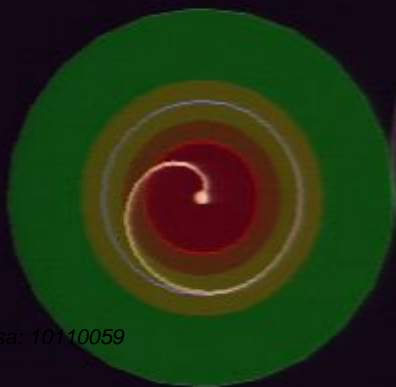
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227 394.33



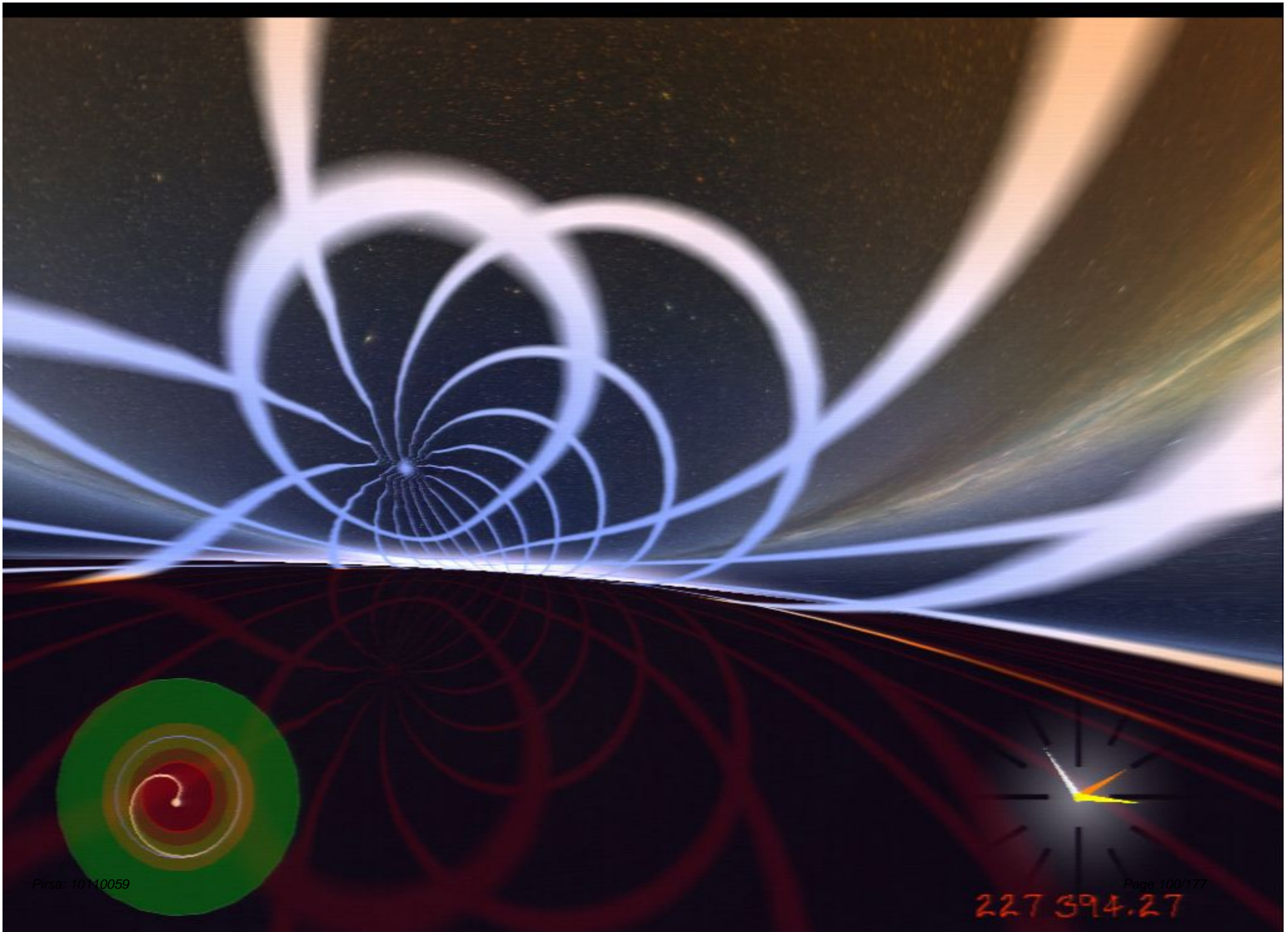


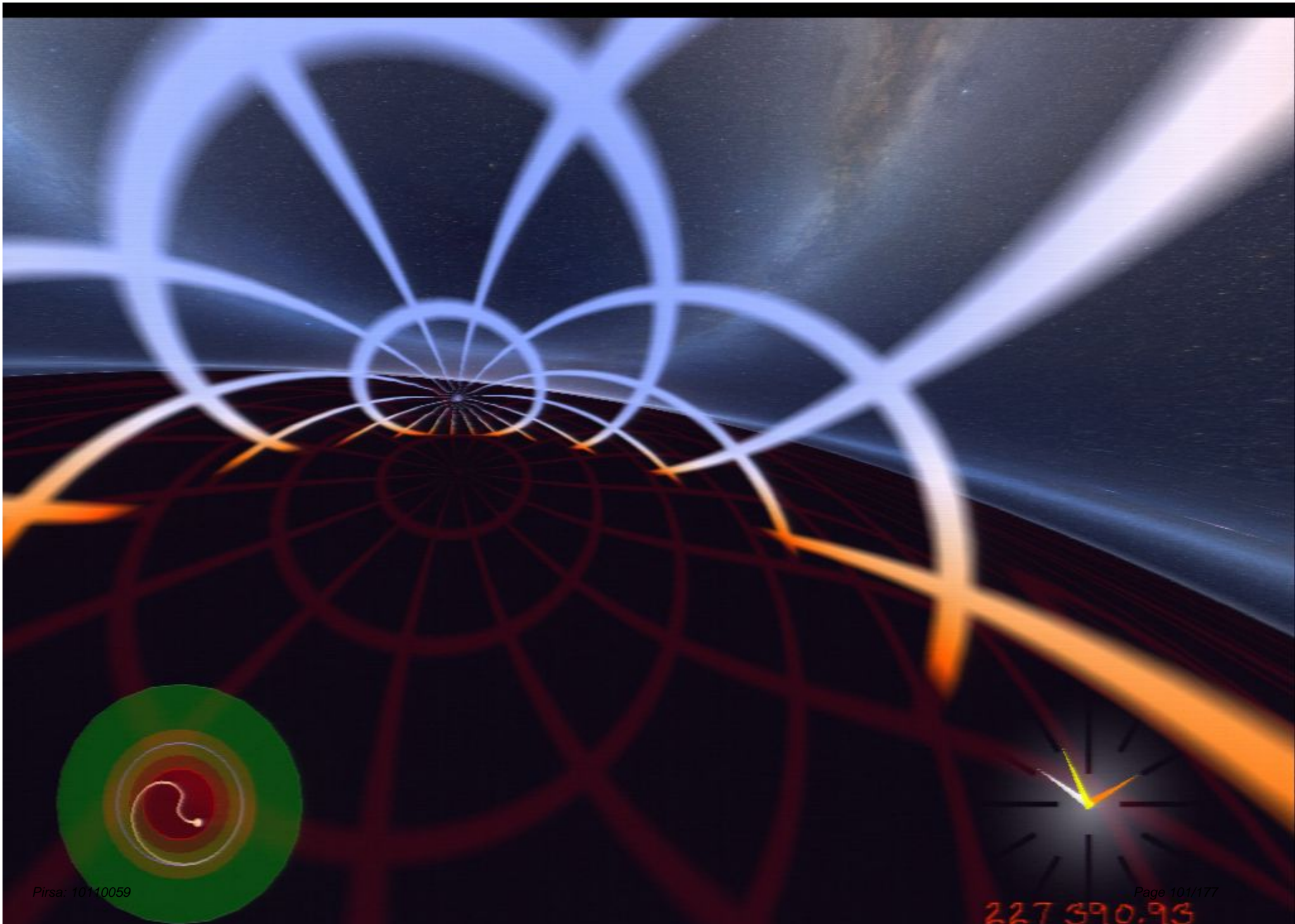
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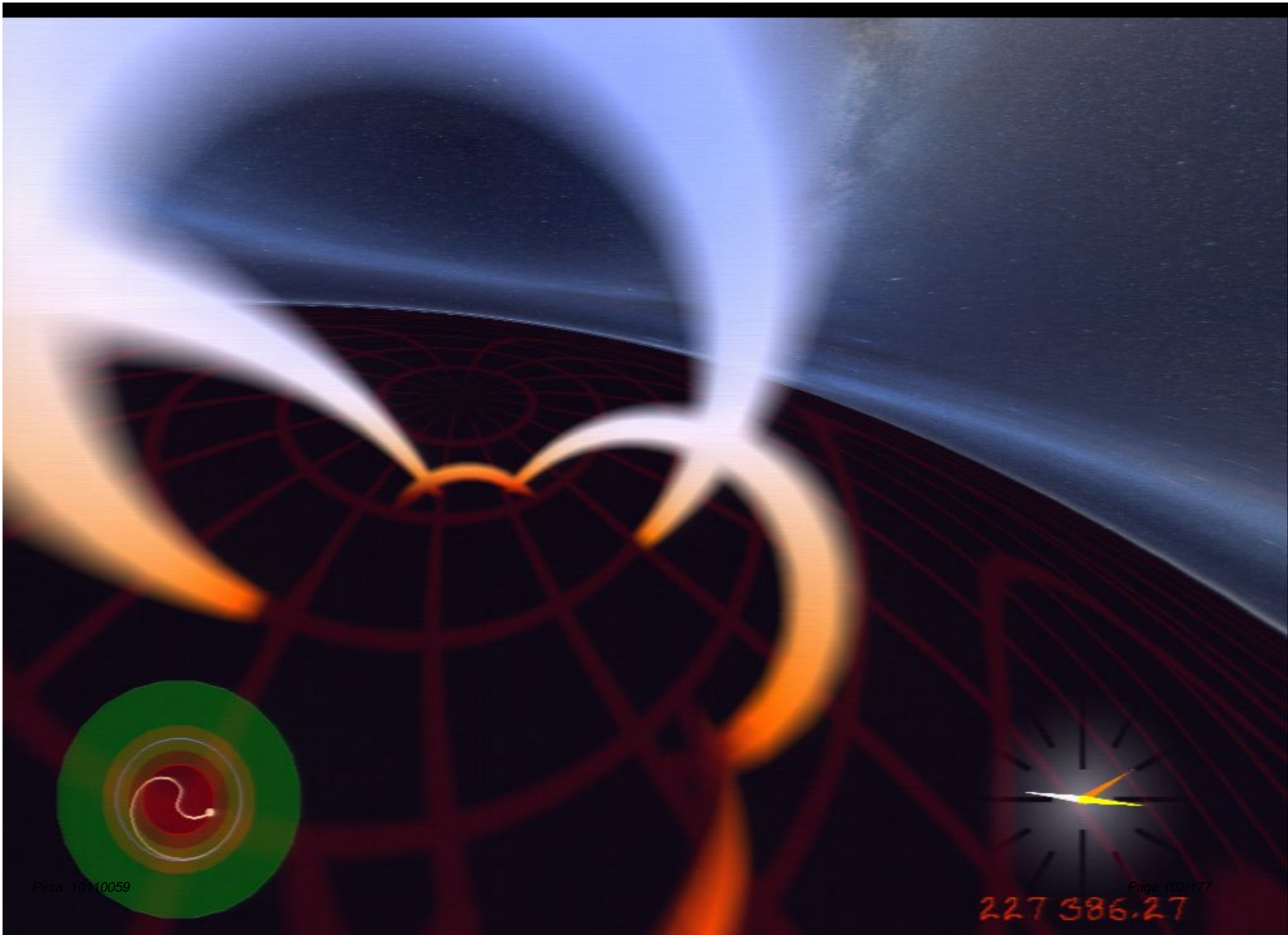


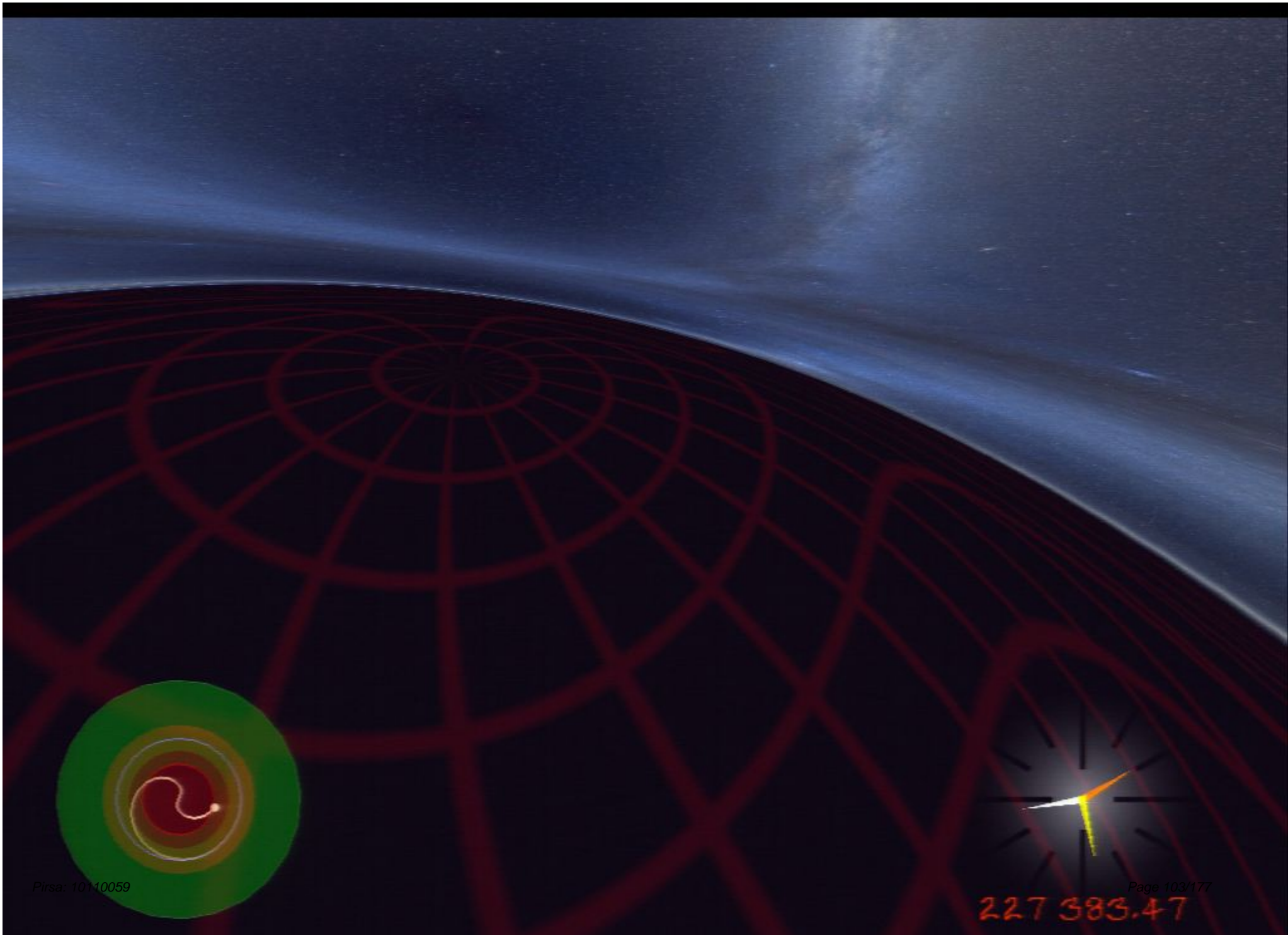
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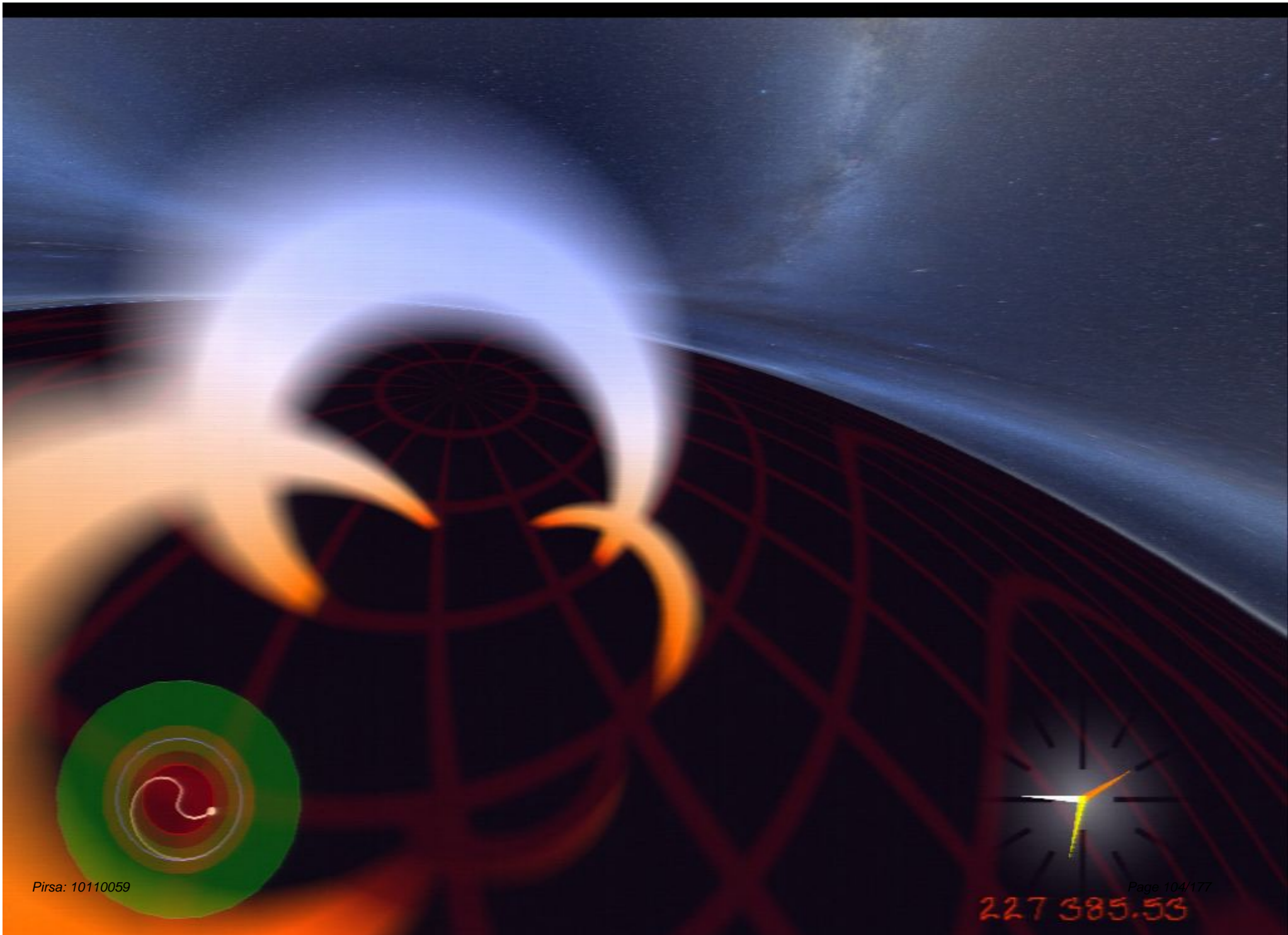
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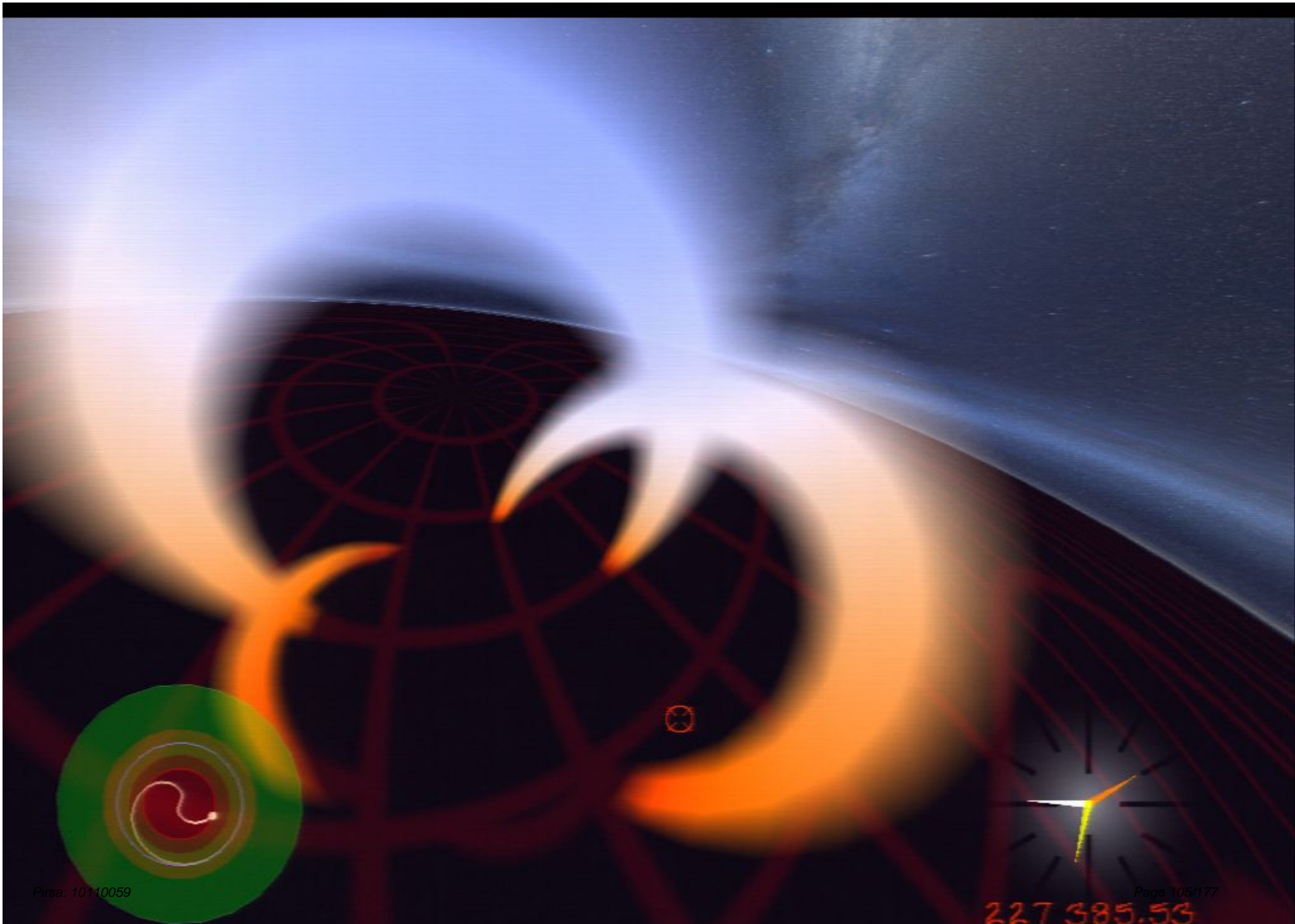


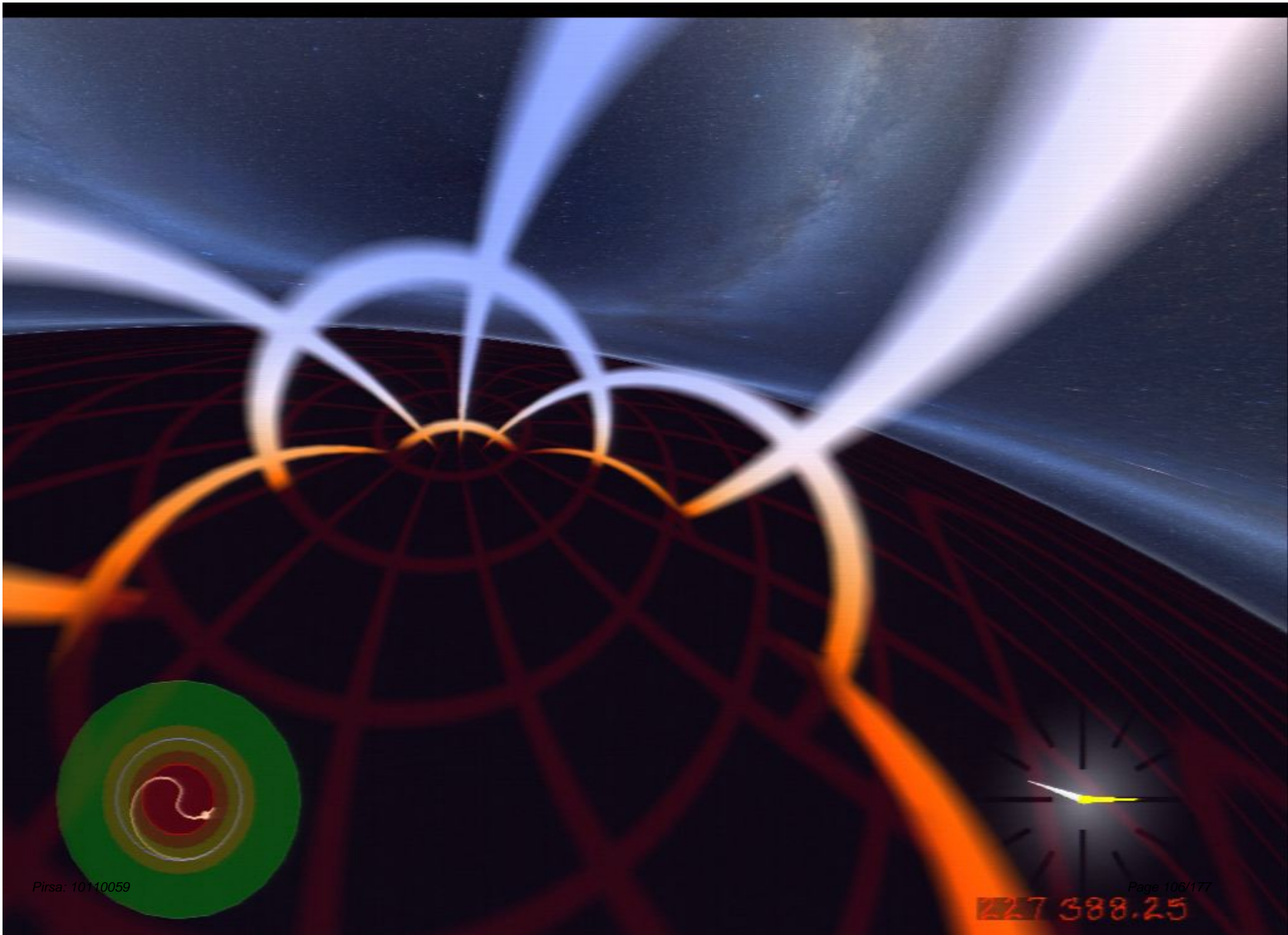


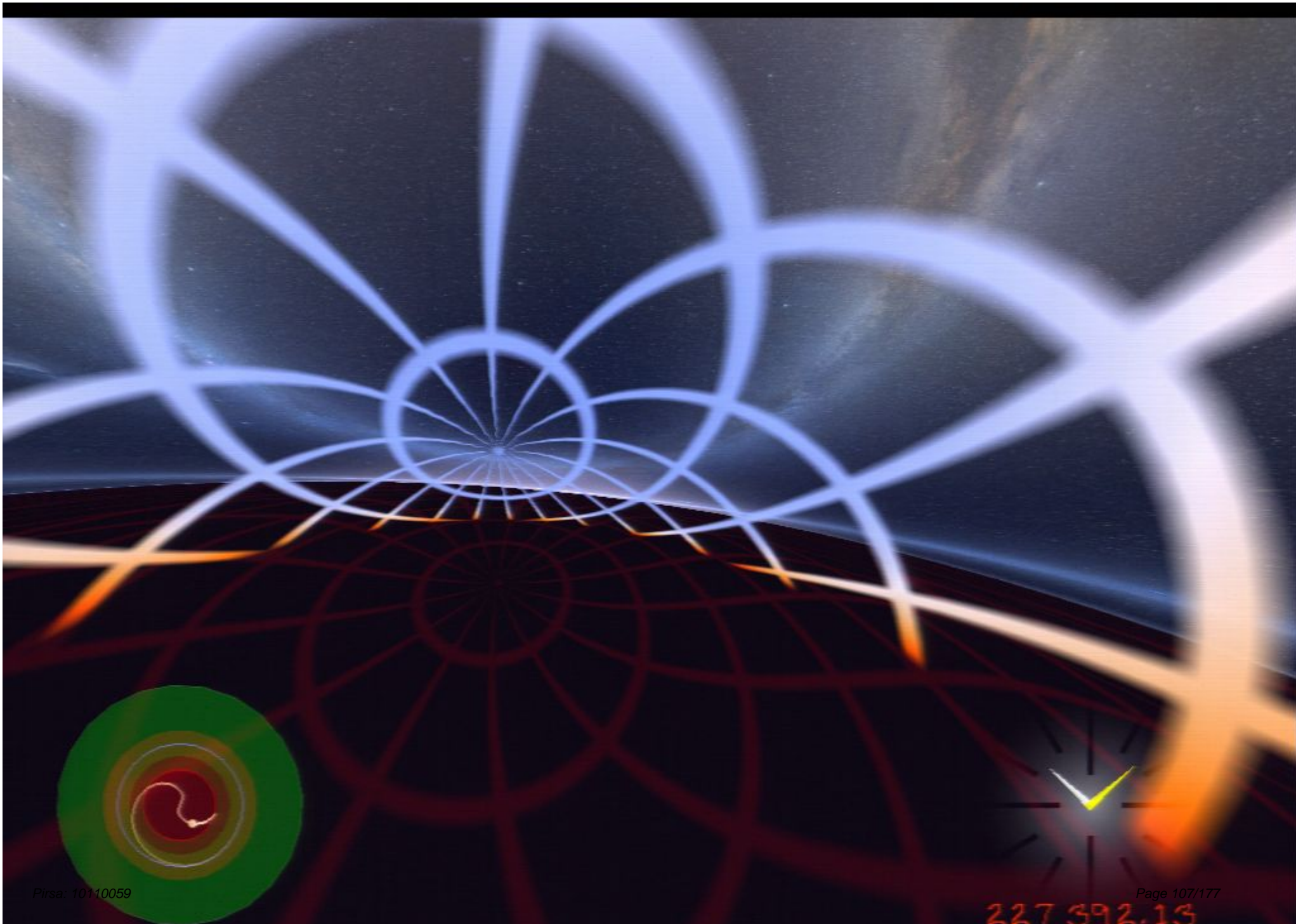


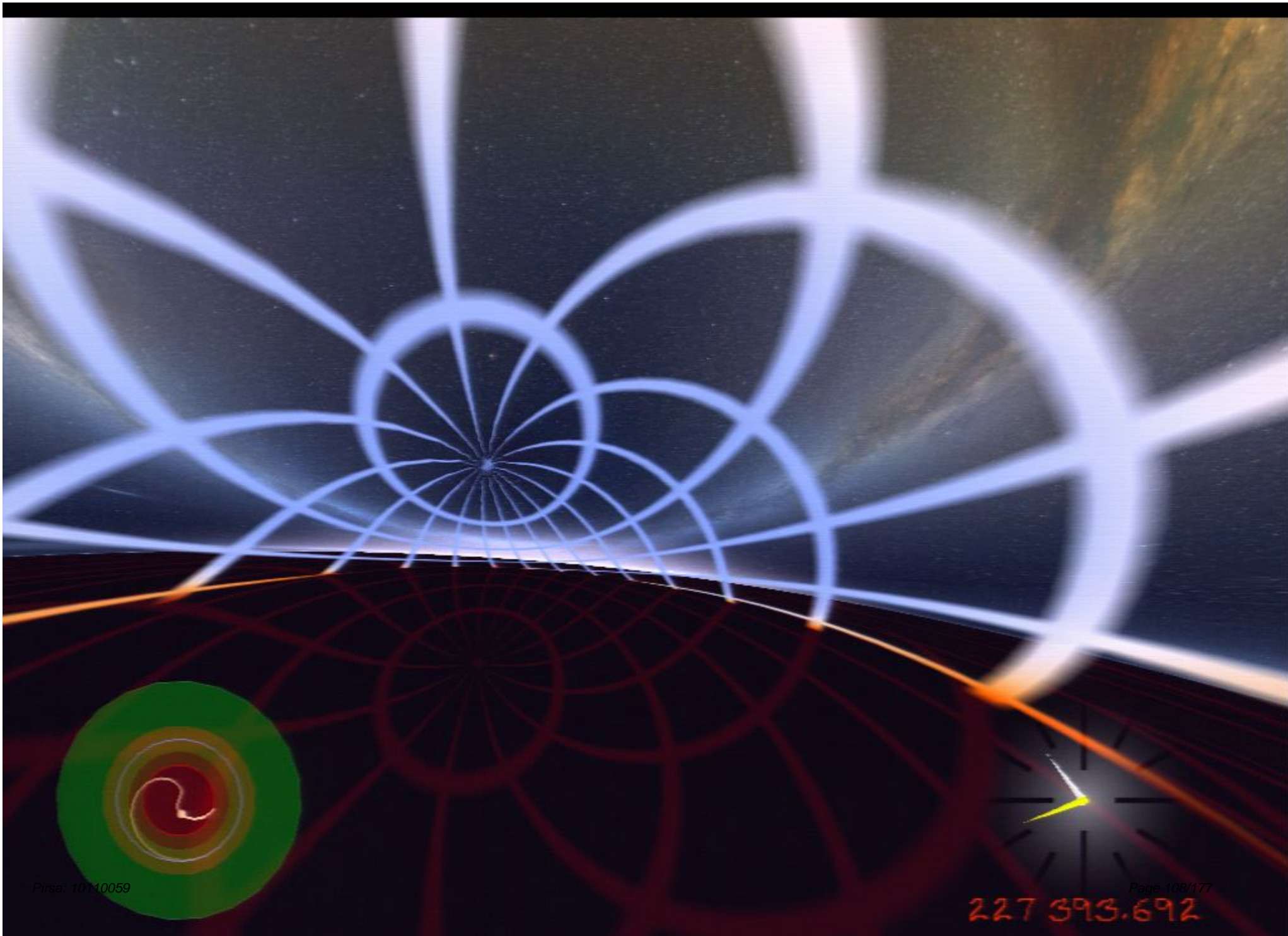


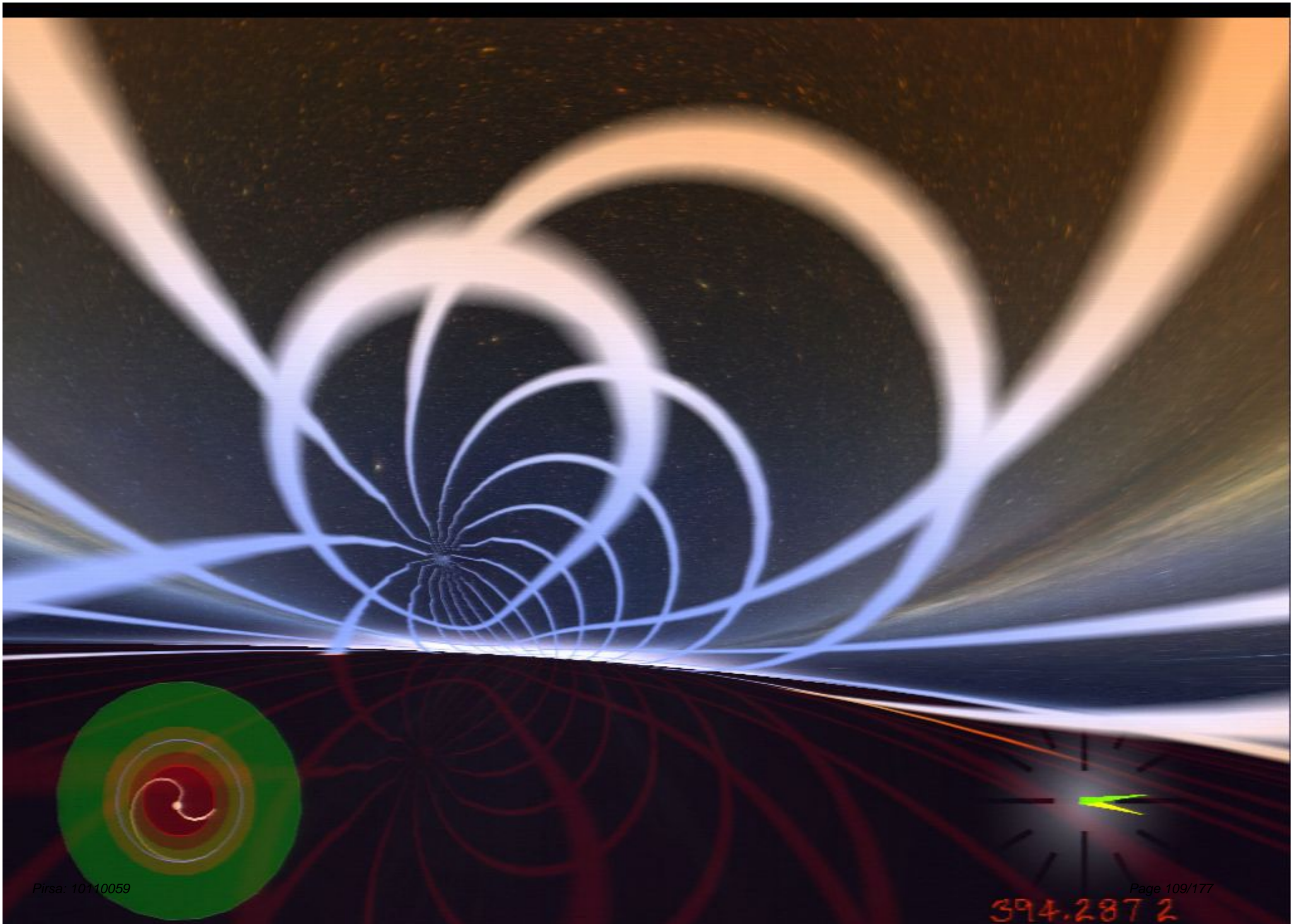


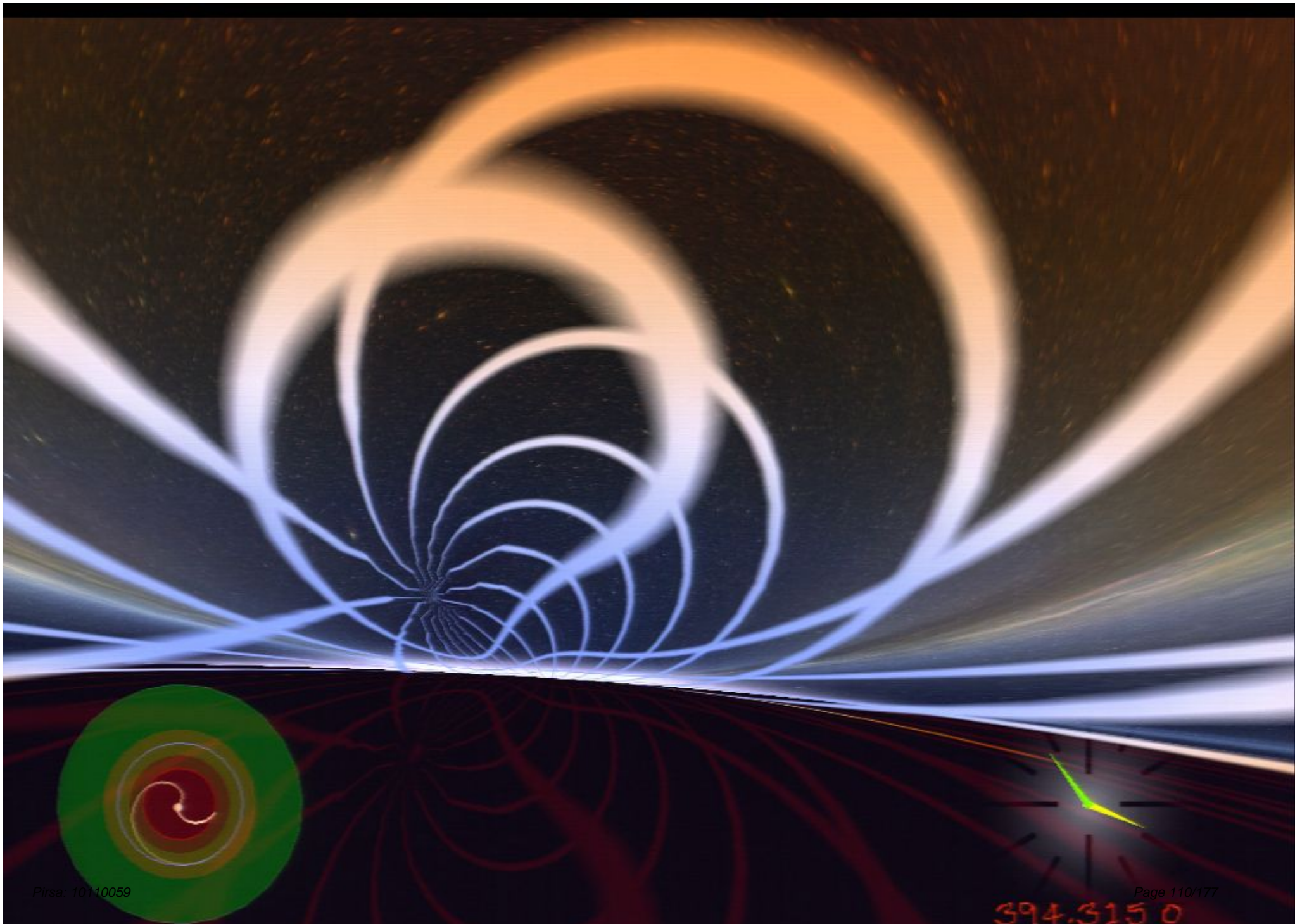


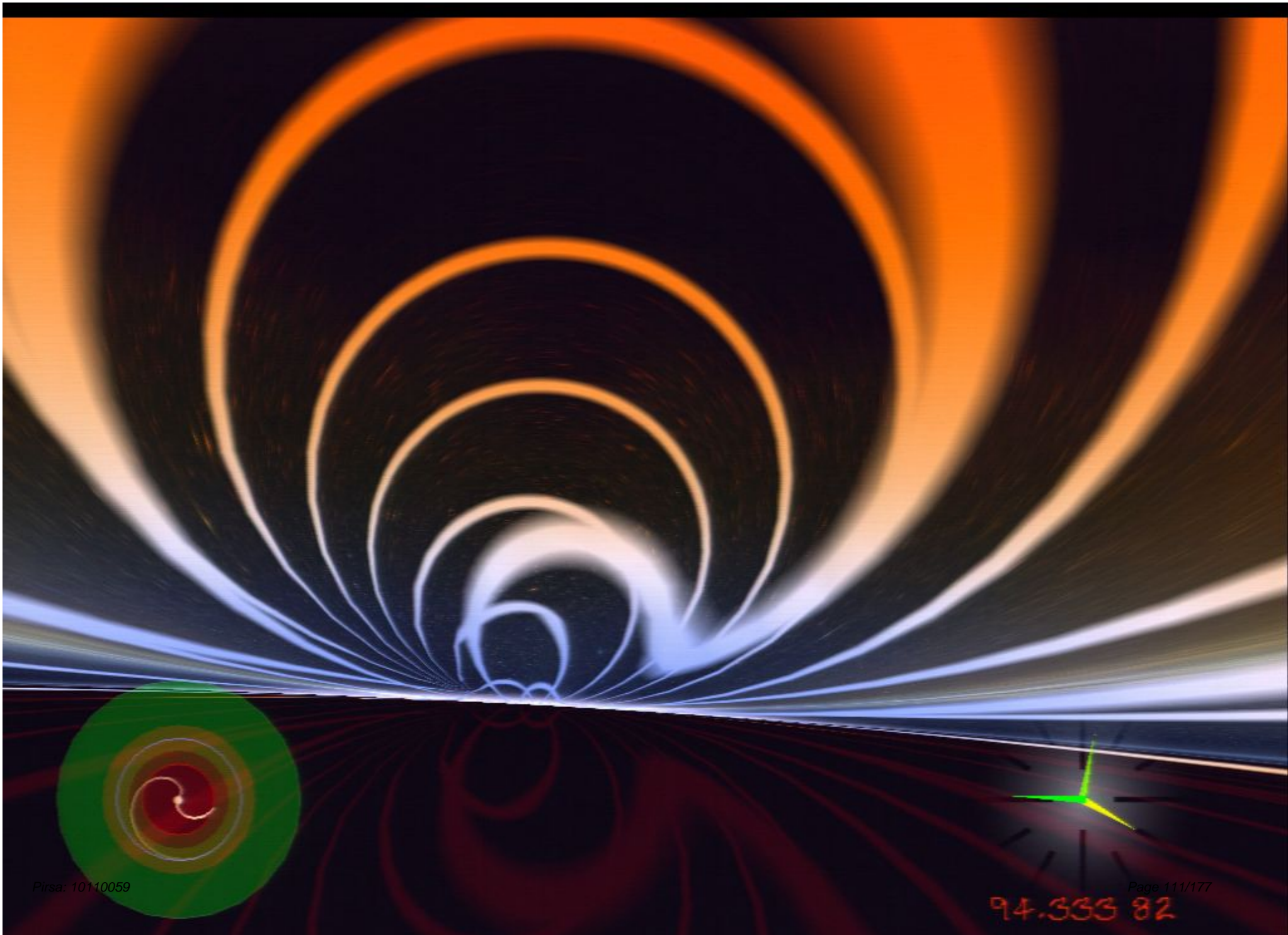


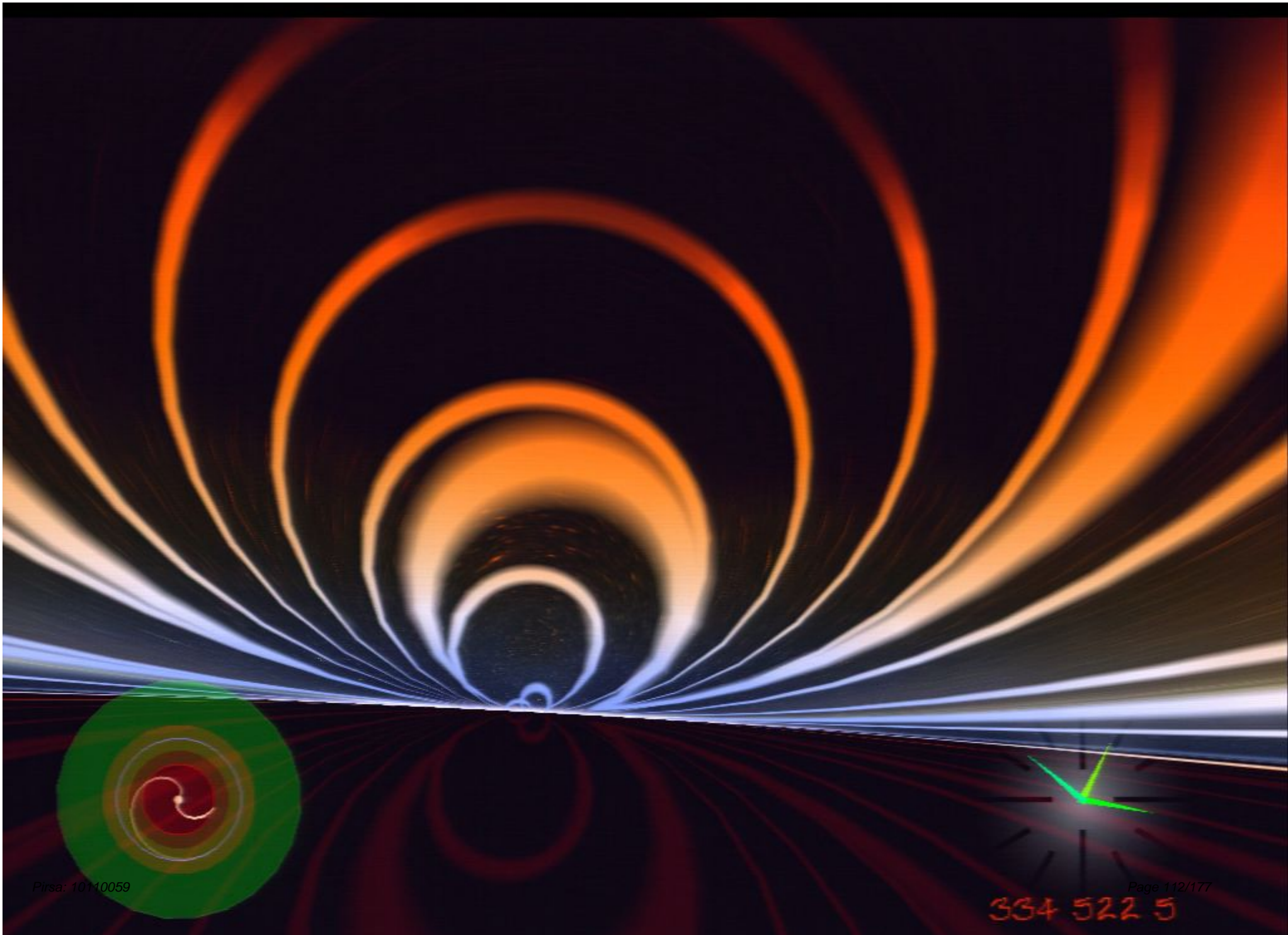


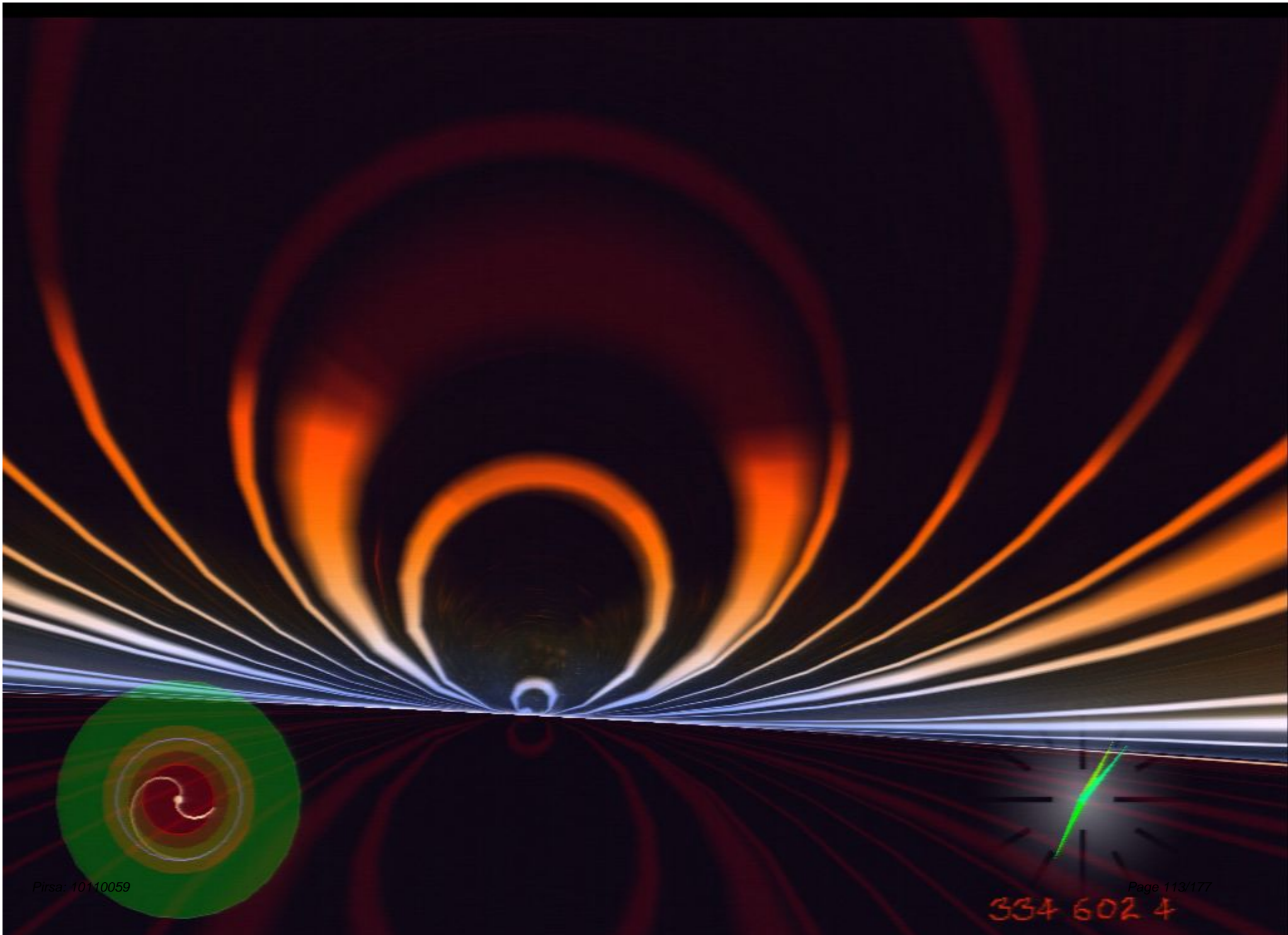


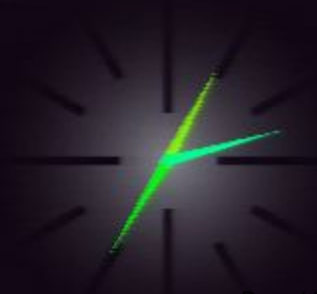
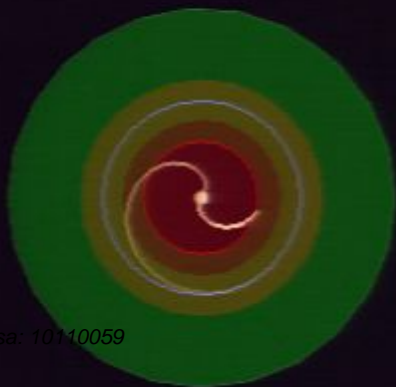


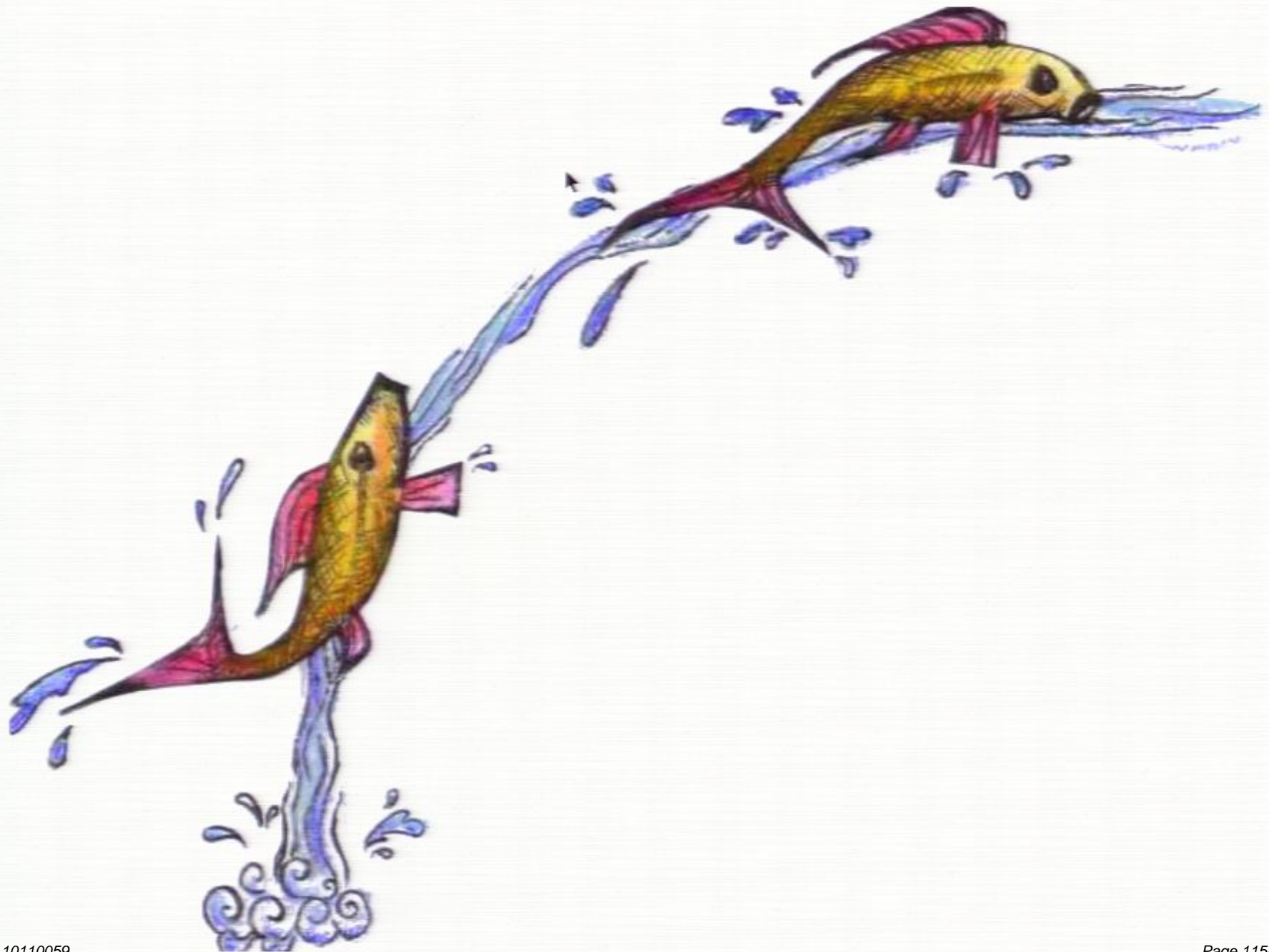




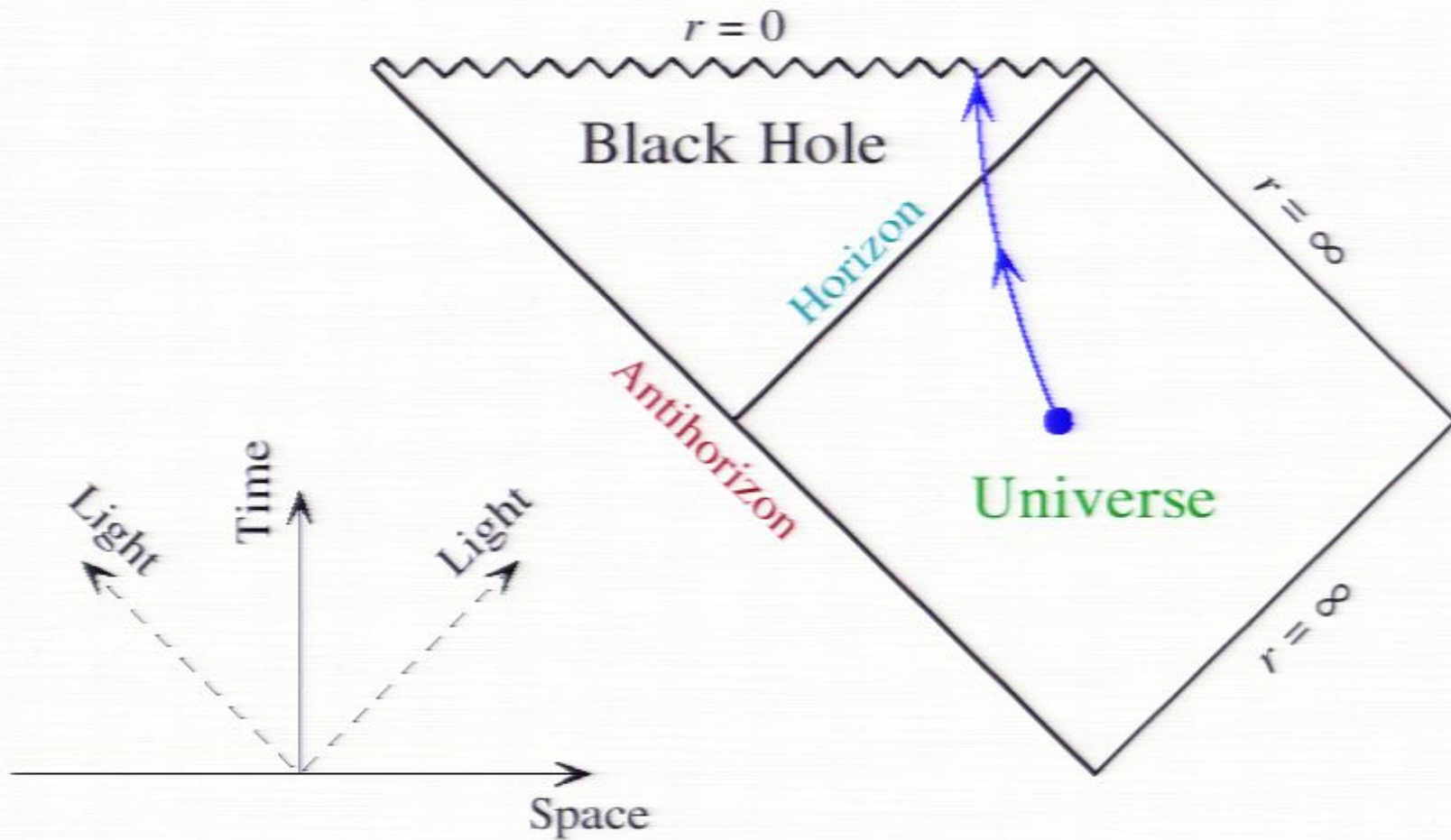




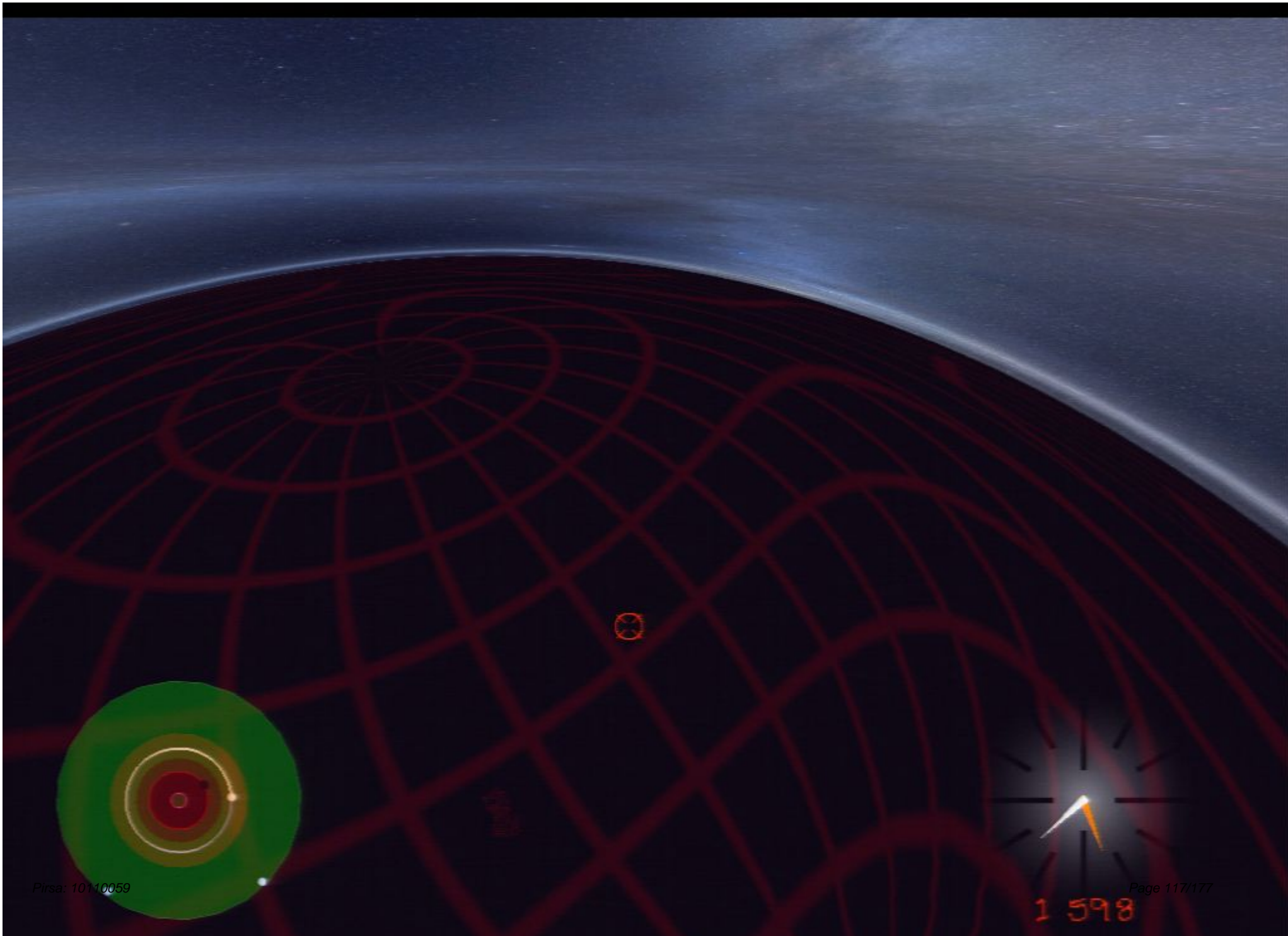


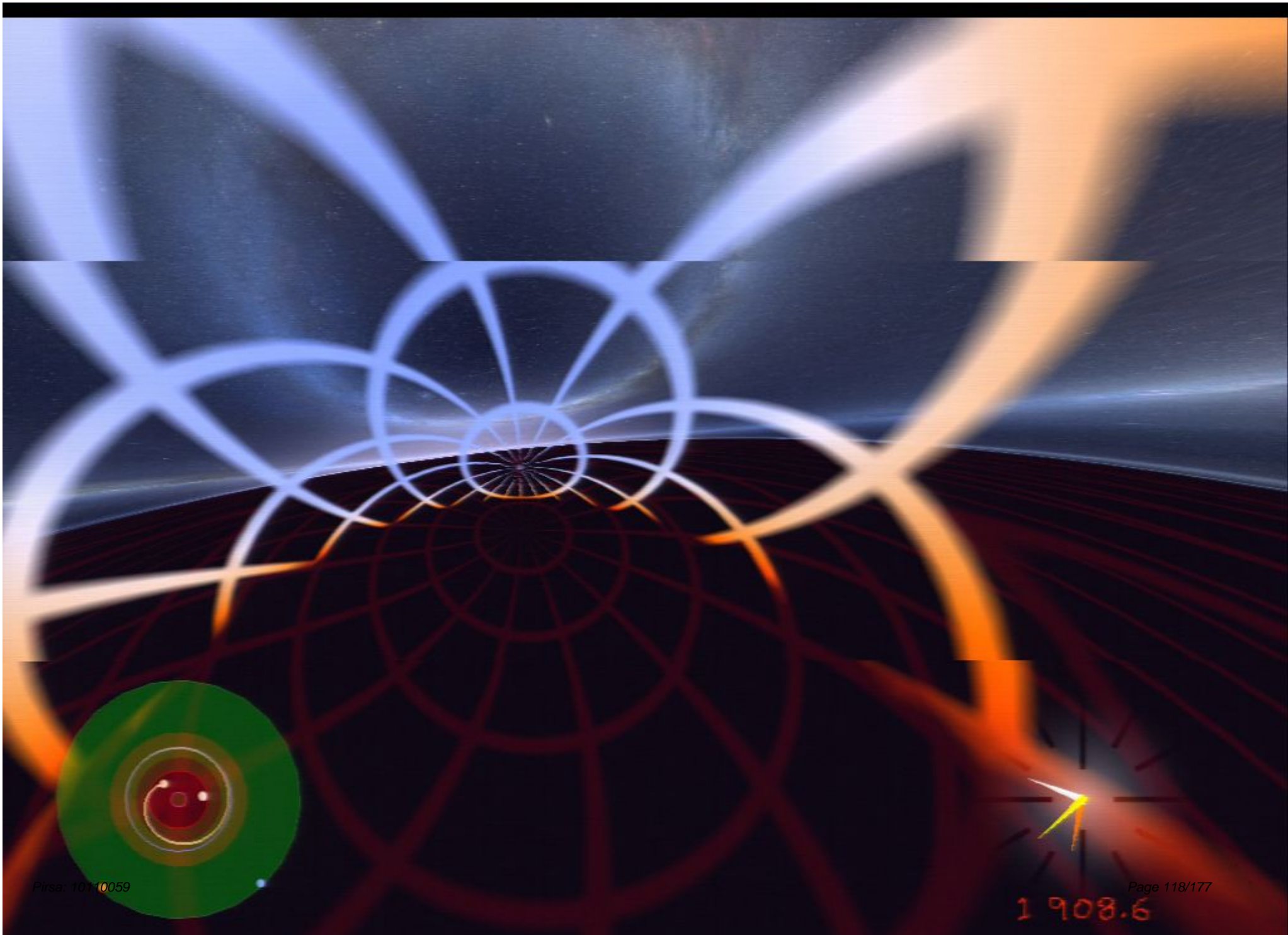


Penrose diagram of a Schwarzschild Black Hole

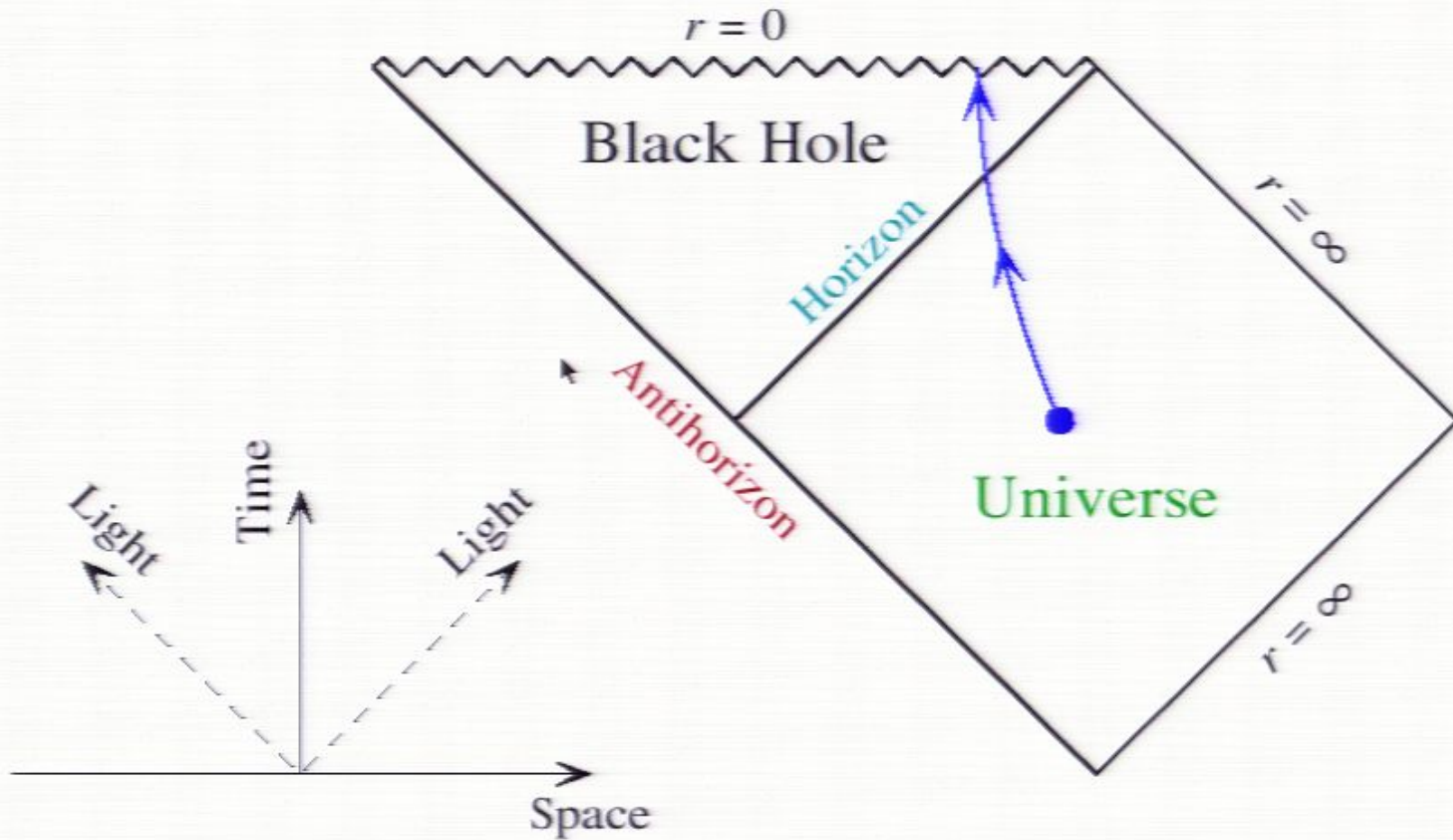


[No hair theorem](#)

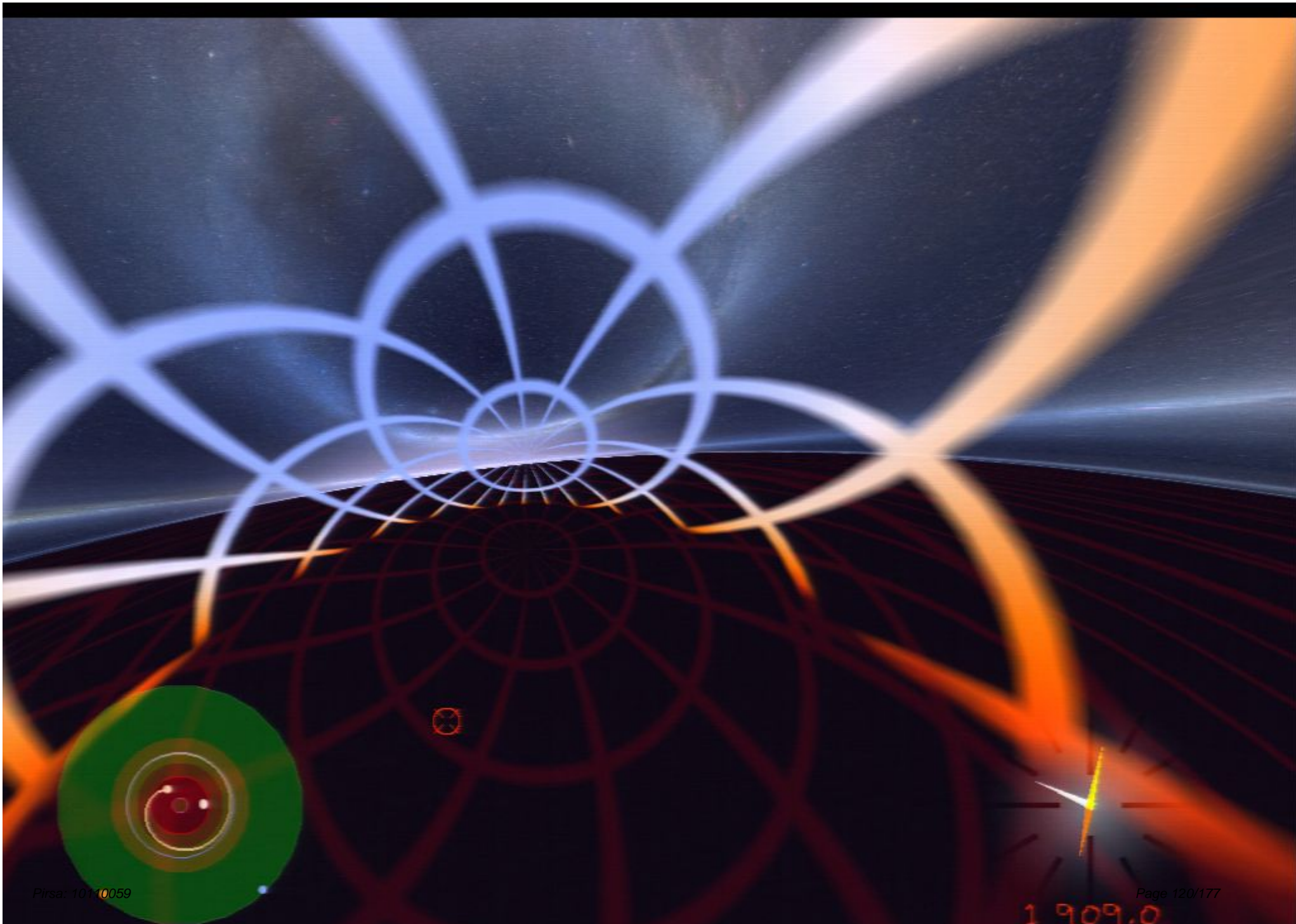




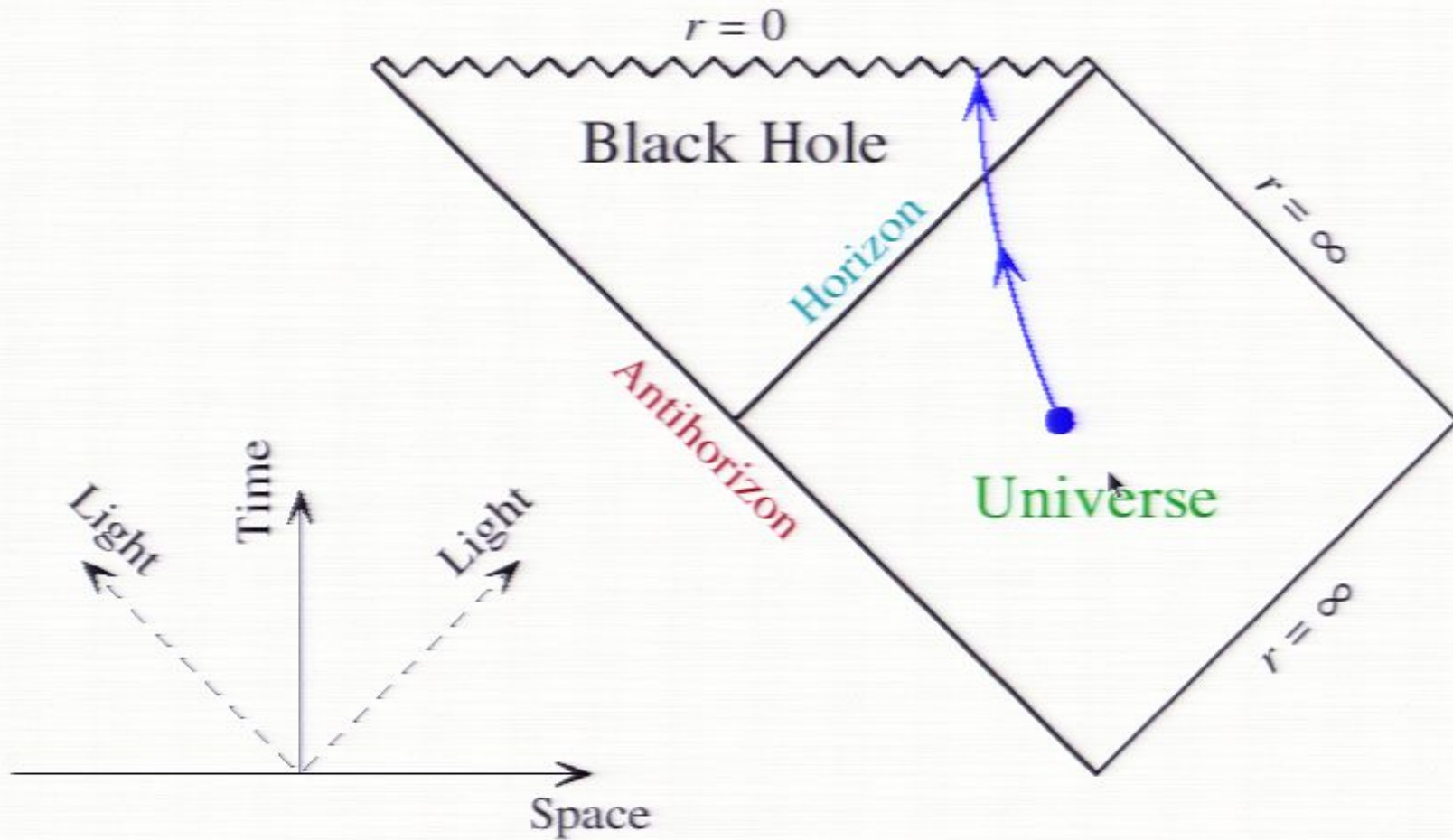
Penrose diagram of a Schwarzschild Black Hole



[No hair theorem](#)



Penrose diagram of a Schwarzschild Black Hole



[No hair theorem](#)

No hair theorem

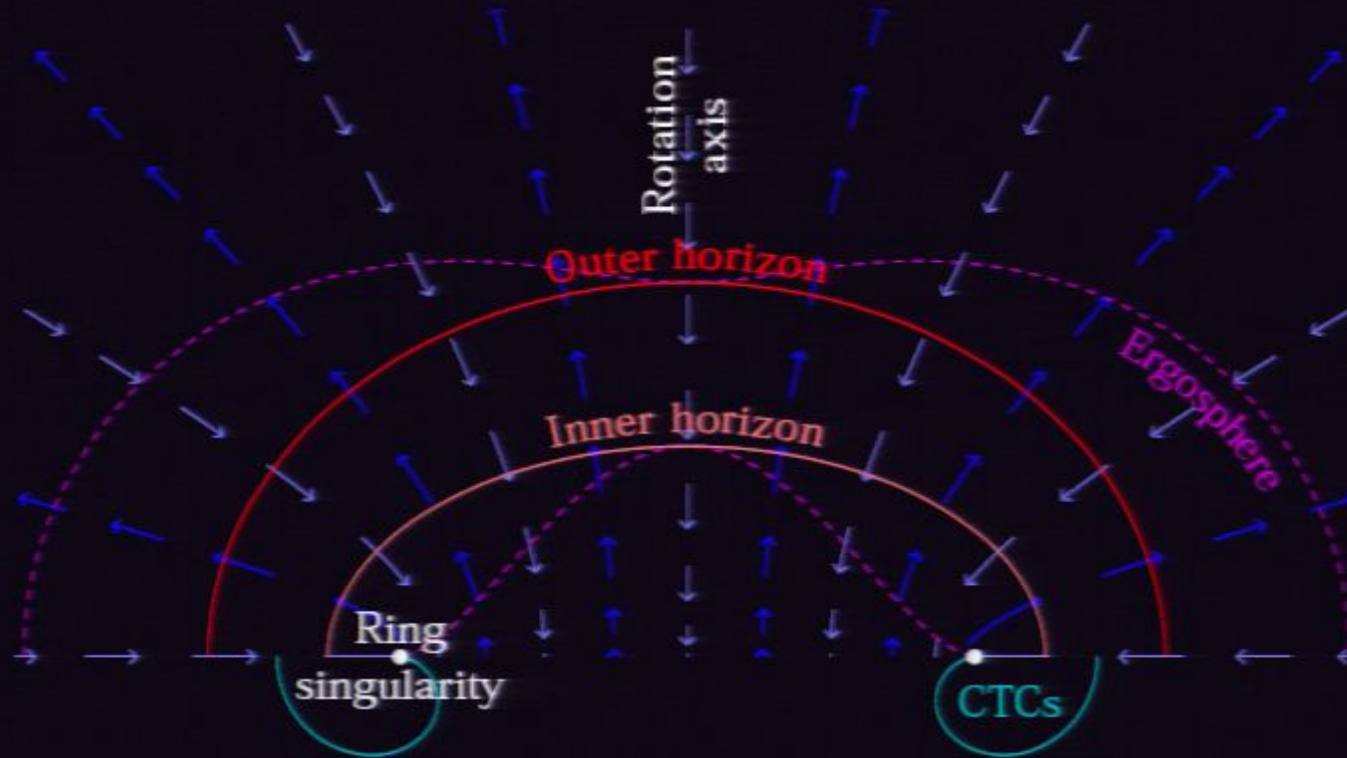
Outside its horizon, an isolated black hole rapidly (on few light crossing times) evolves to a state characterized by just 3 properties:

- Mass
- Electric charge
- Spin

It loses its “hair” by gravitational radiation.

➔ [Kerr \(rotating\) black hole](#)

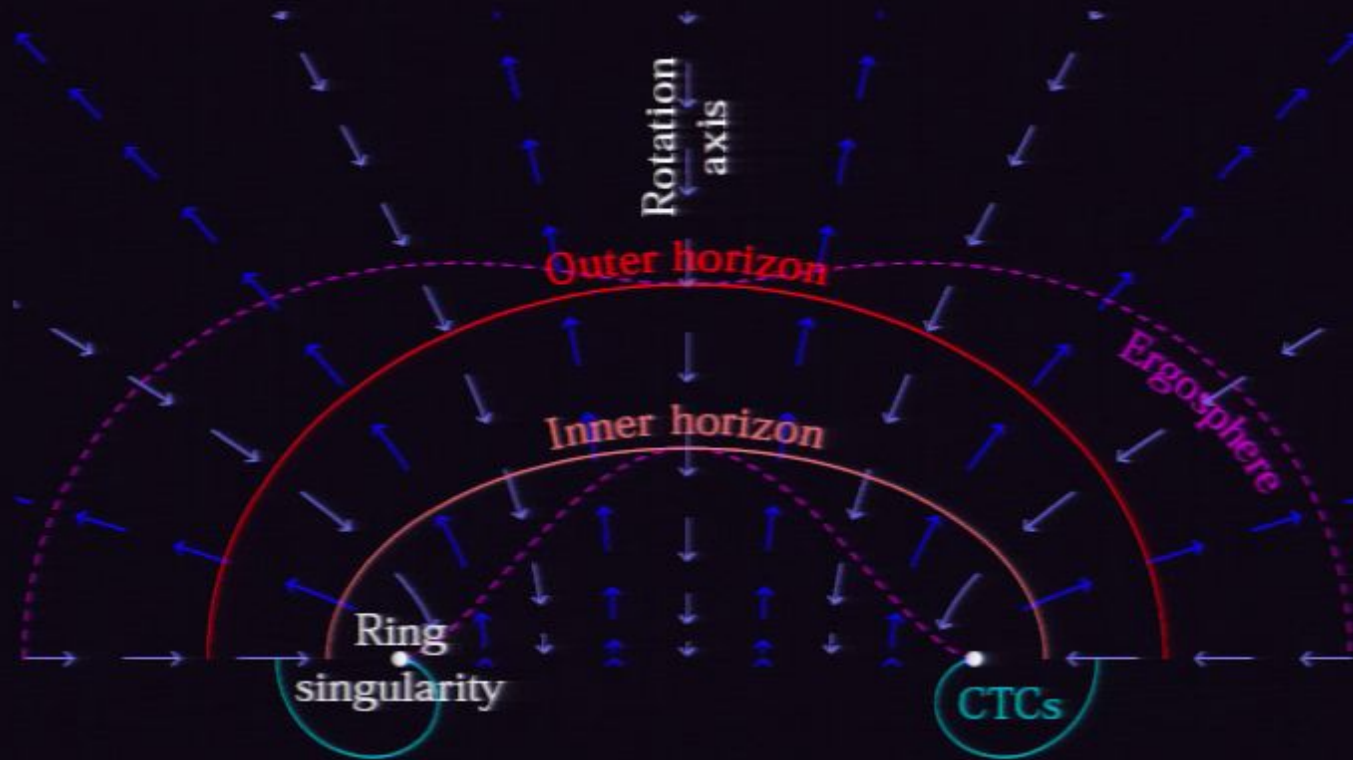
Kerr (rotating) black hole



Reissner-Nordström (charged) black hole

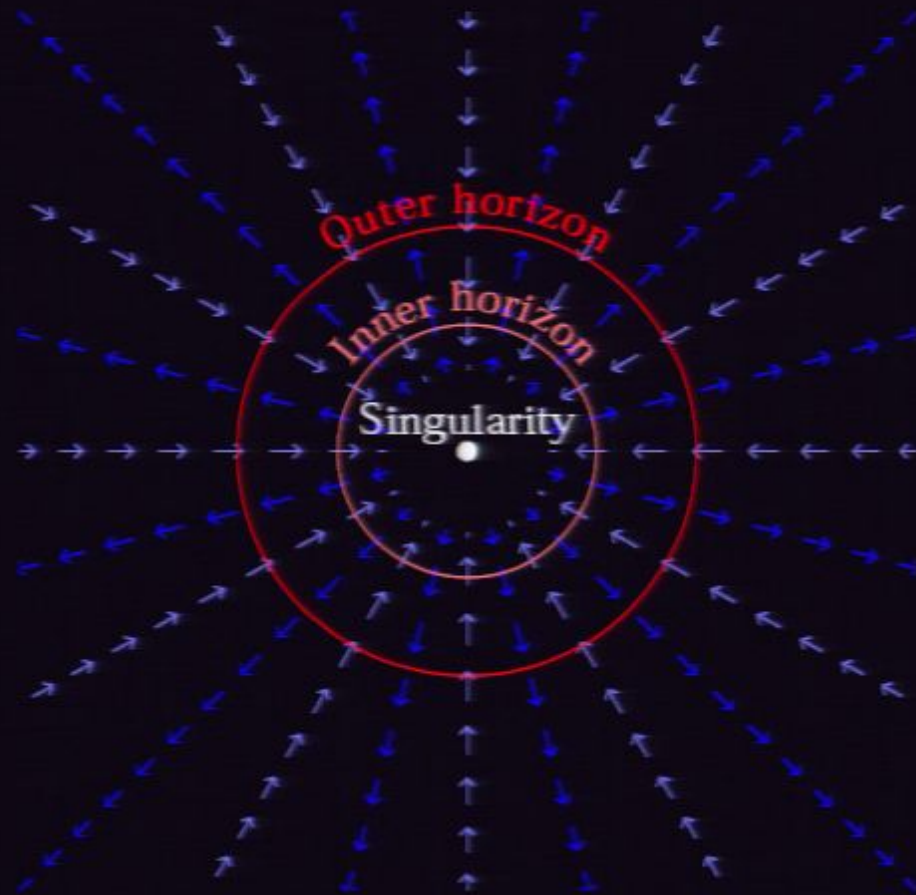
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Kerr (rotating) black hole



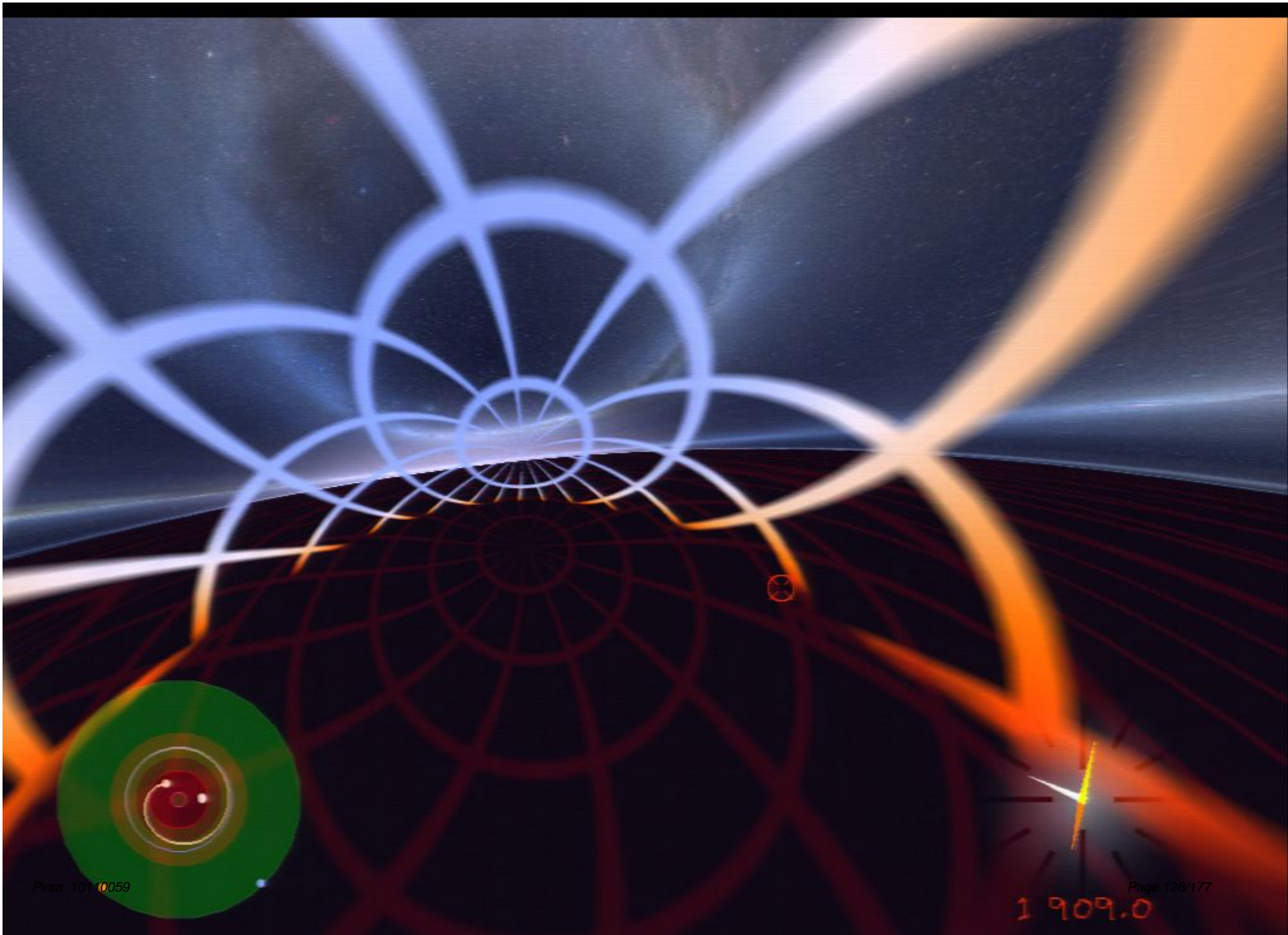
Reissner-Nordström (charged) black hole

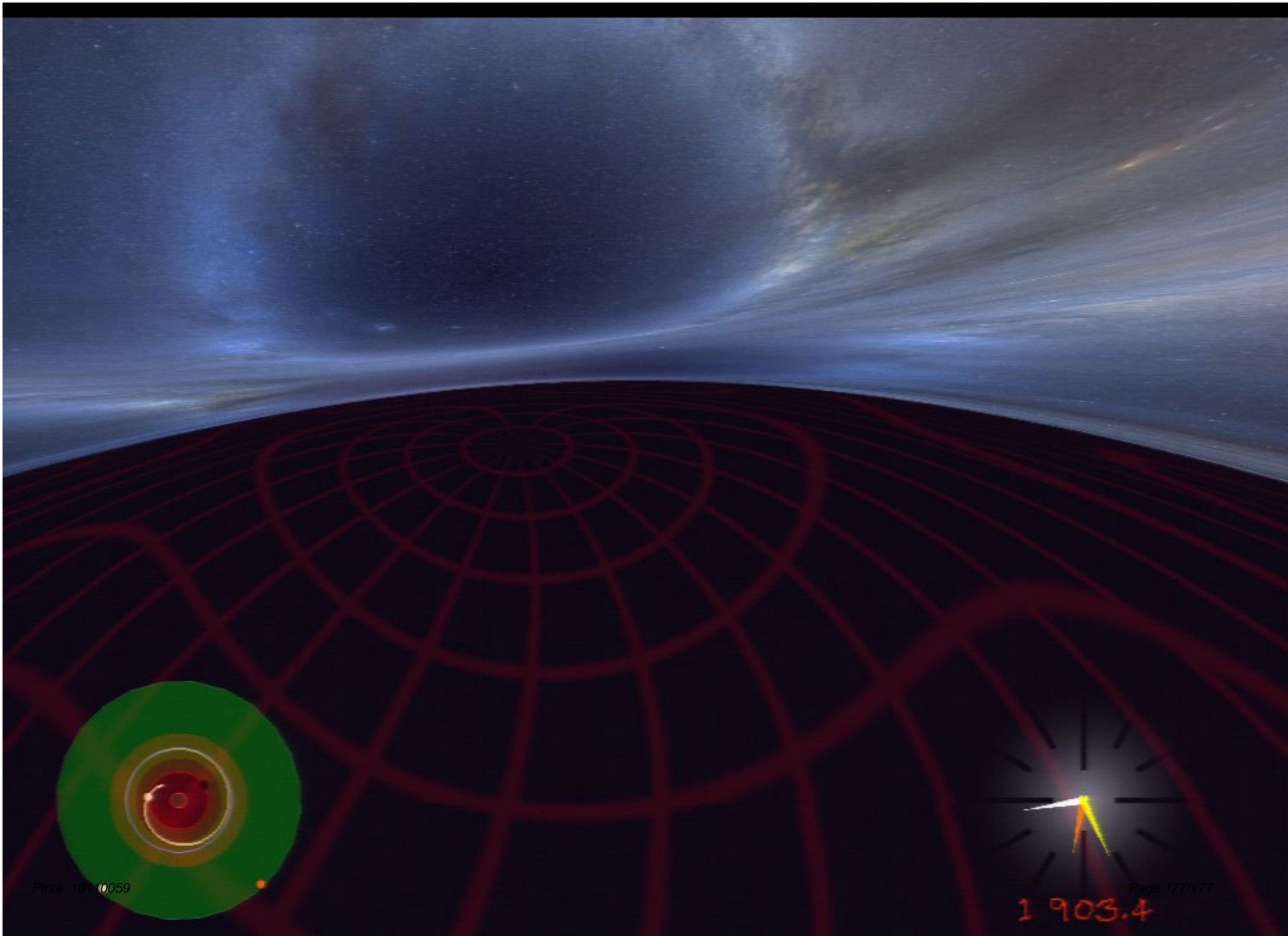
Reissner-Nordström (charged) black hole

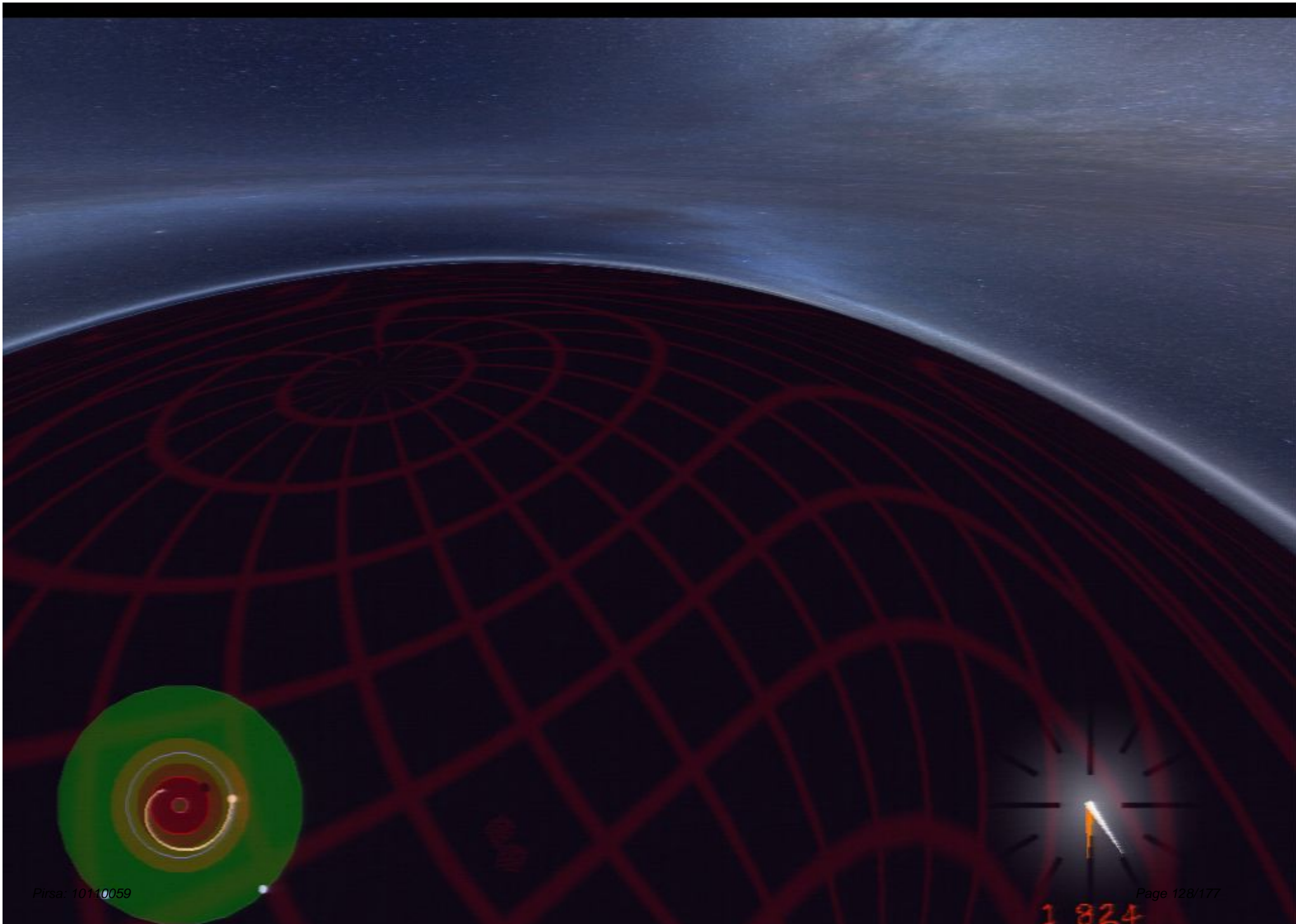


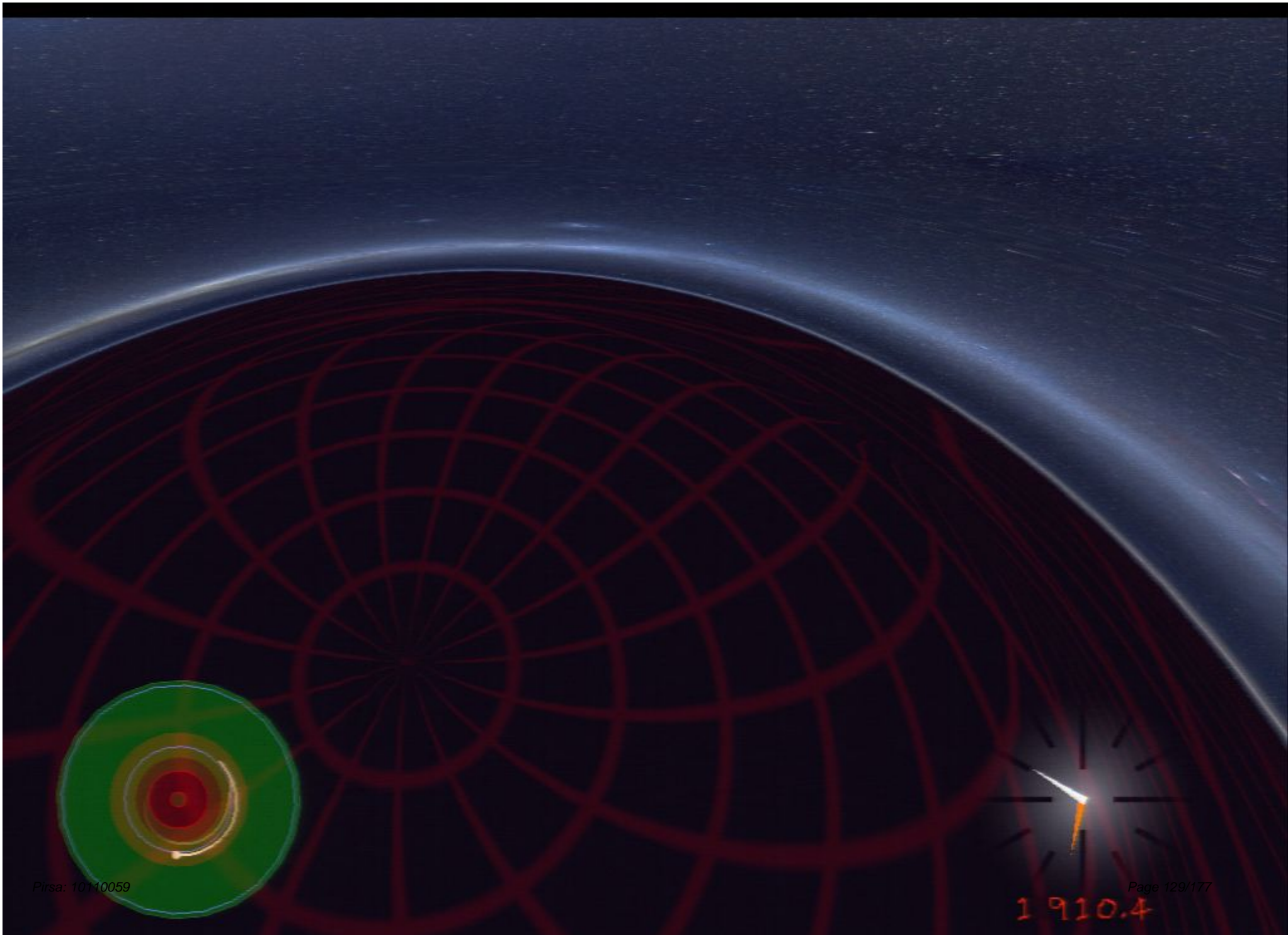
Penrose diagram of a Kerr-Newman (rotating) black hole

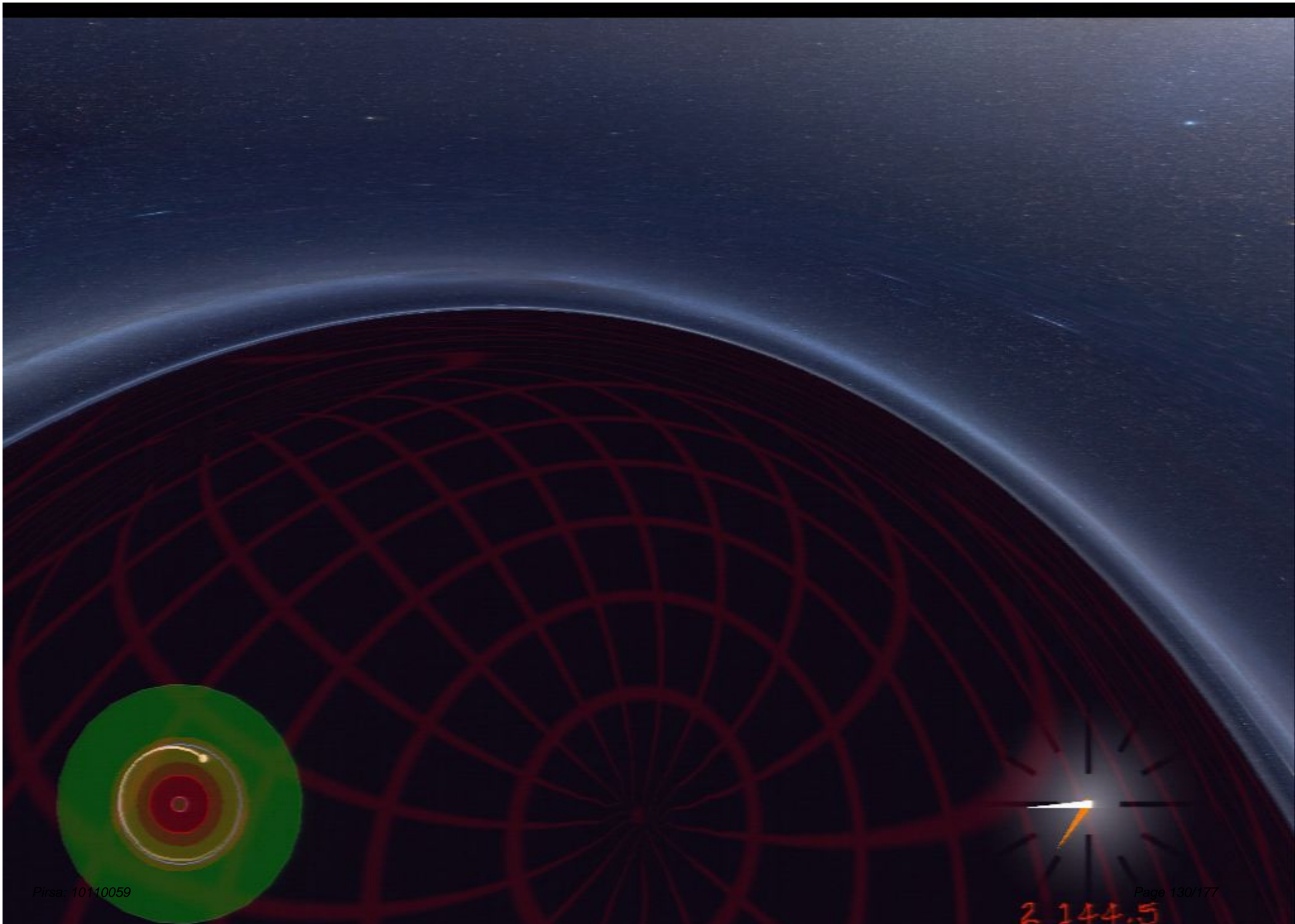


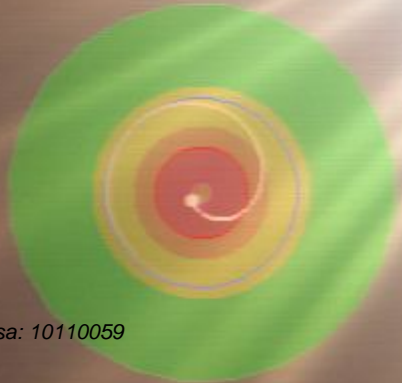












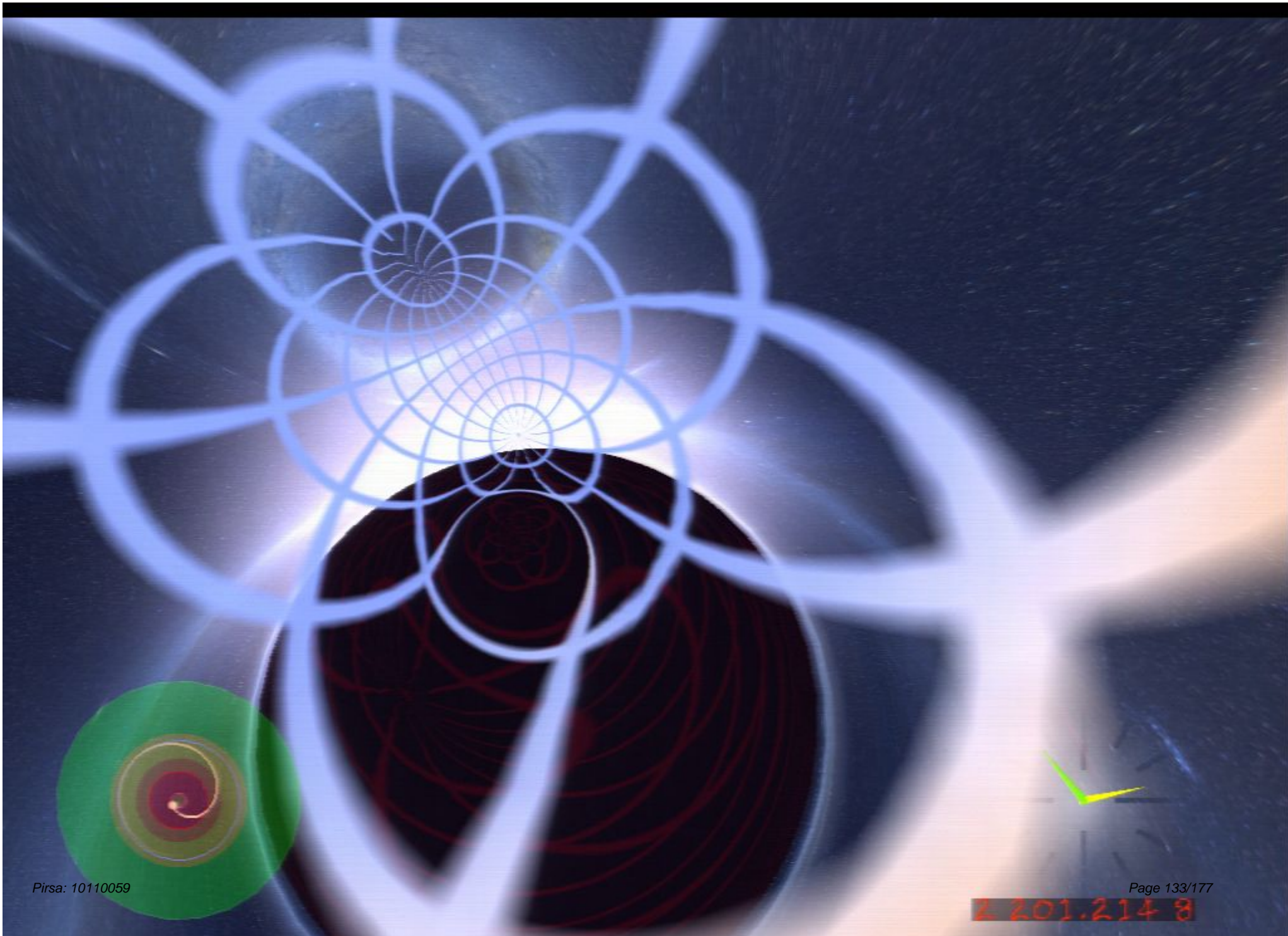
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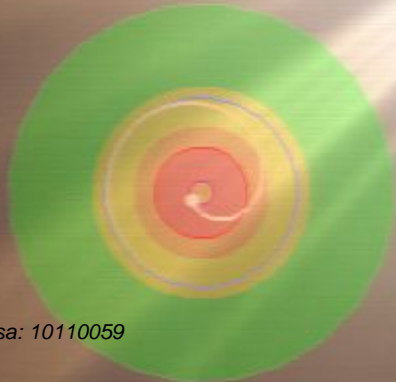


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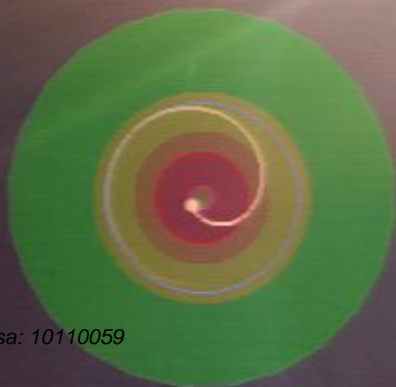


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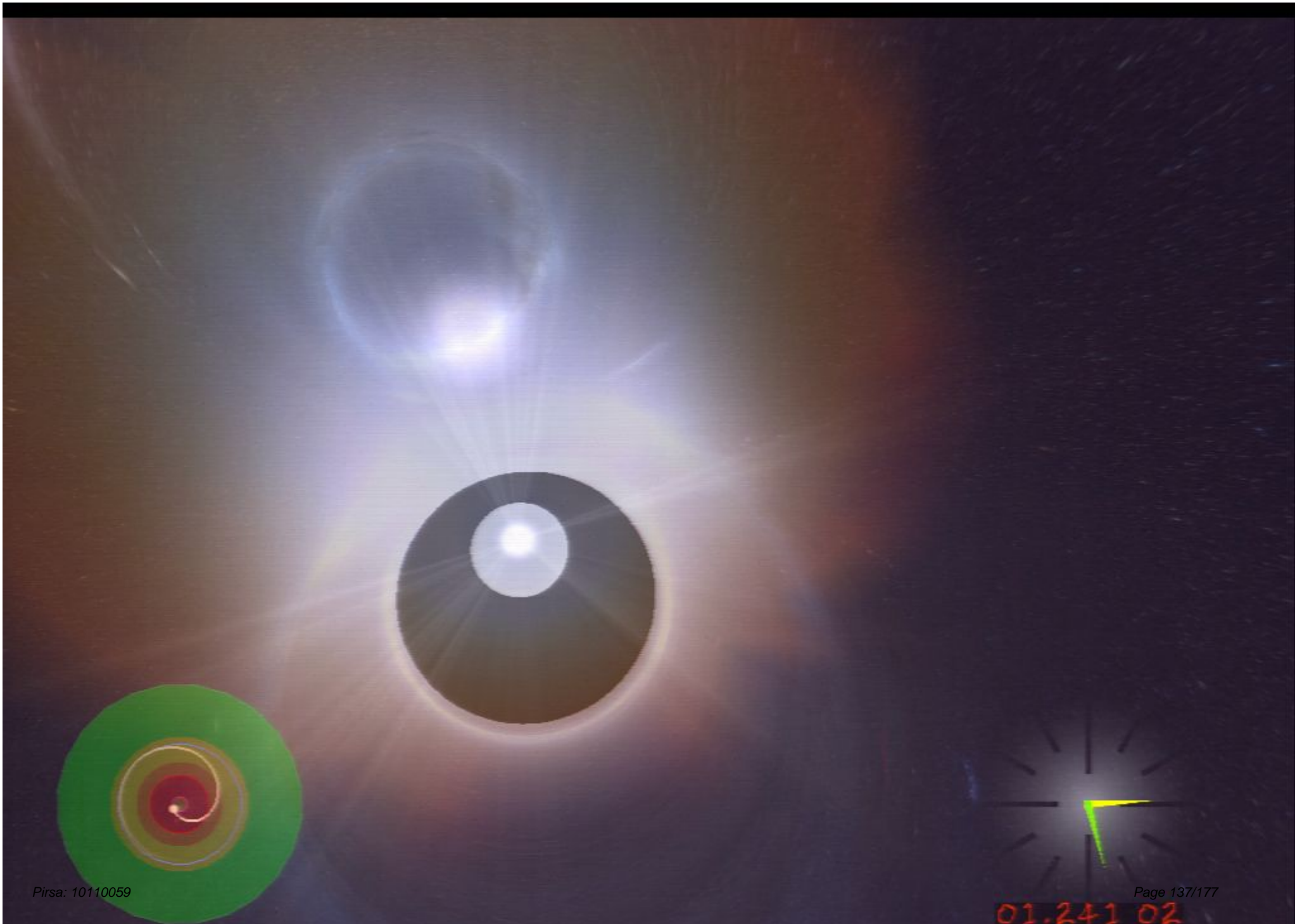
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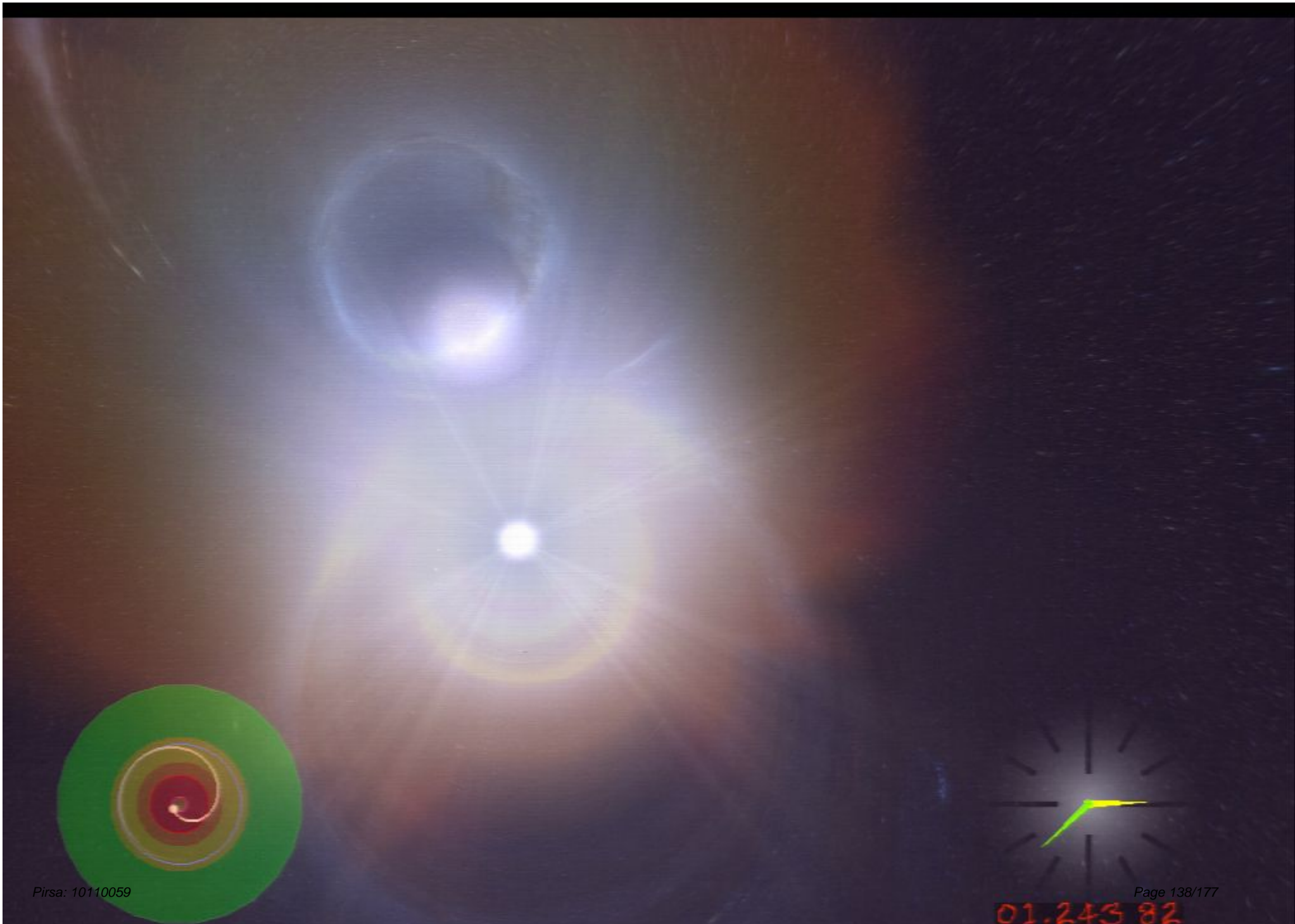


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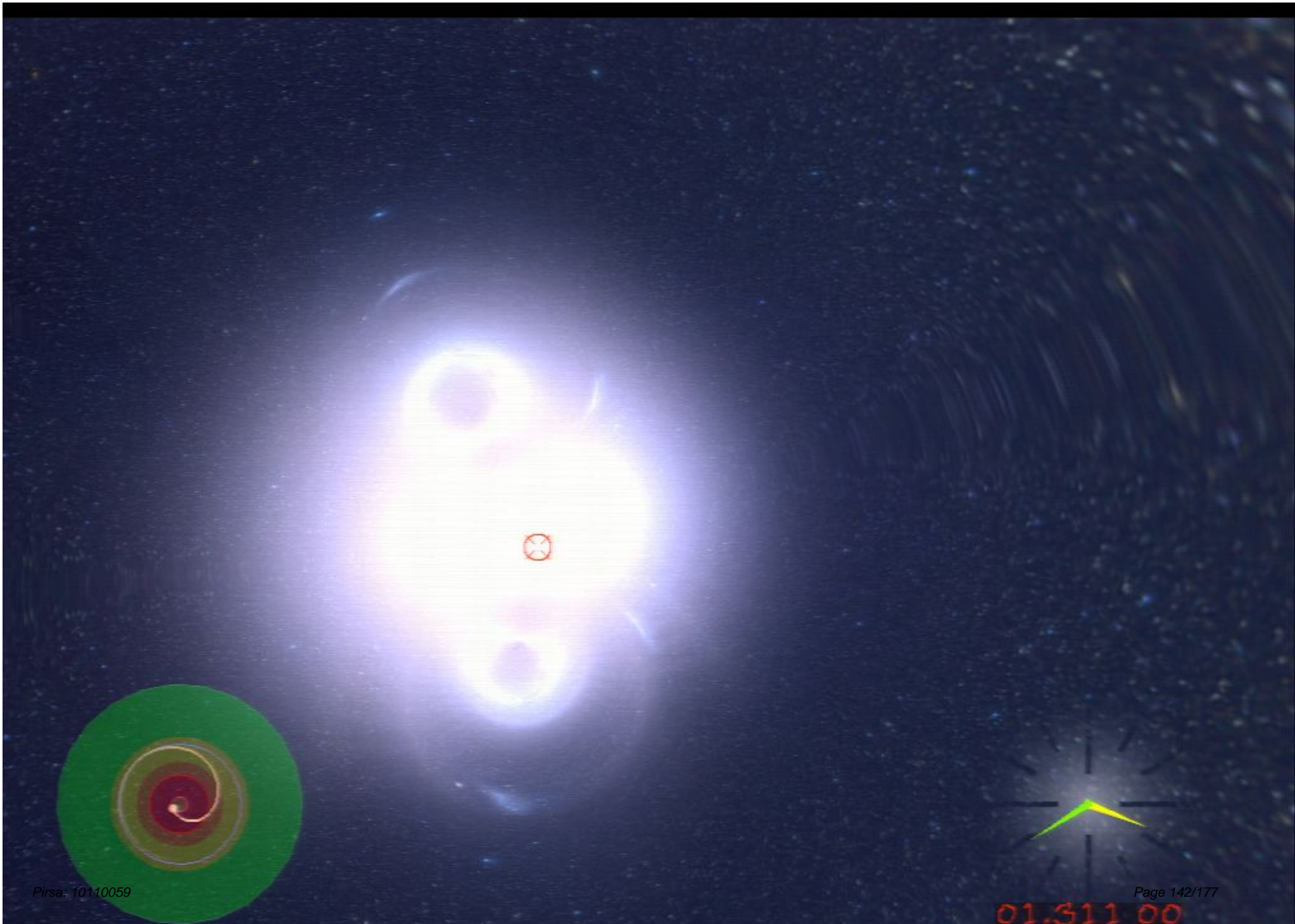






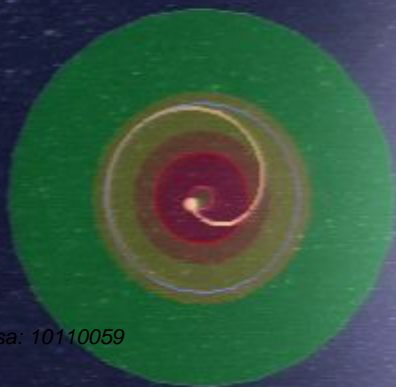




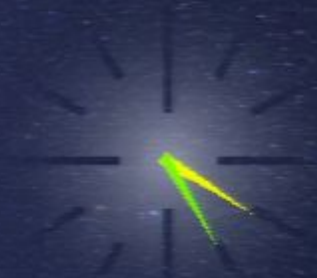




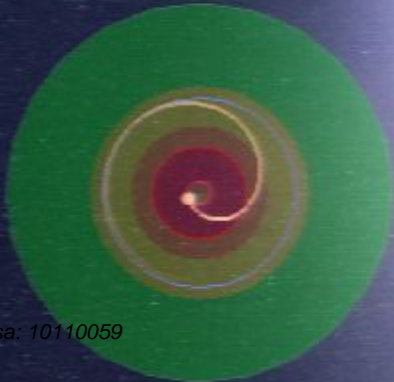




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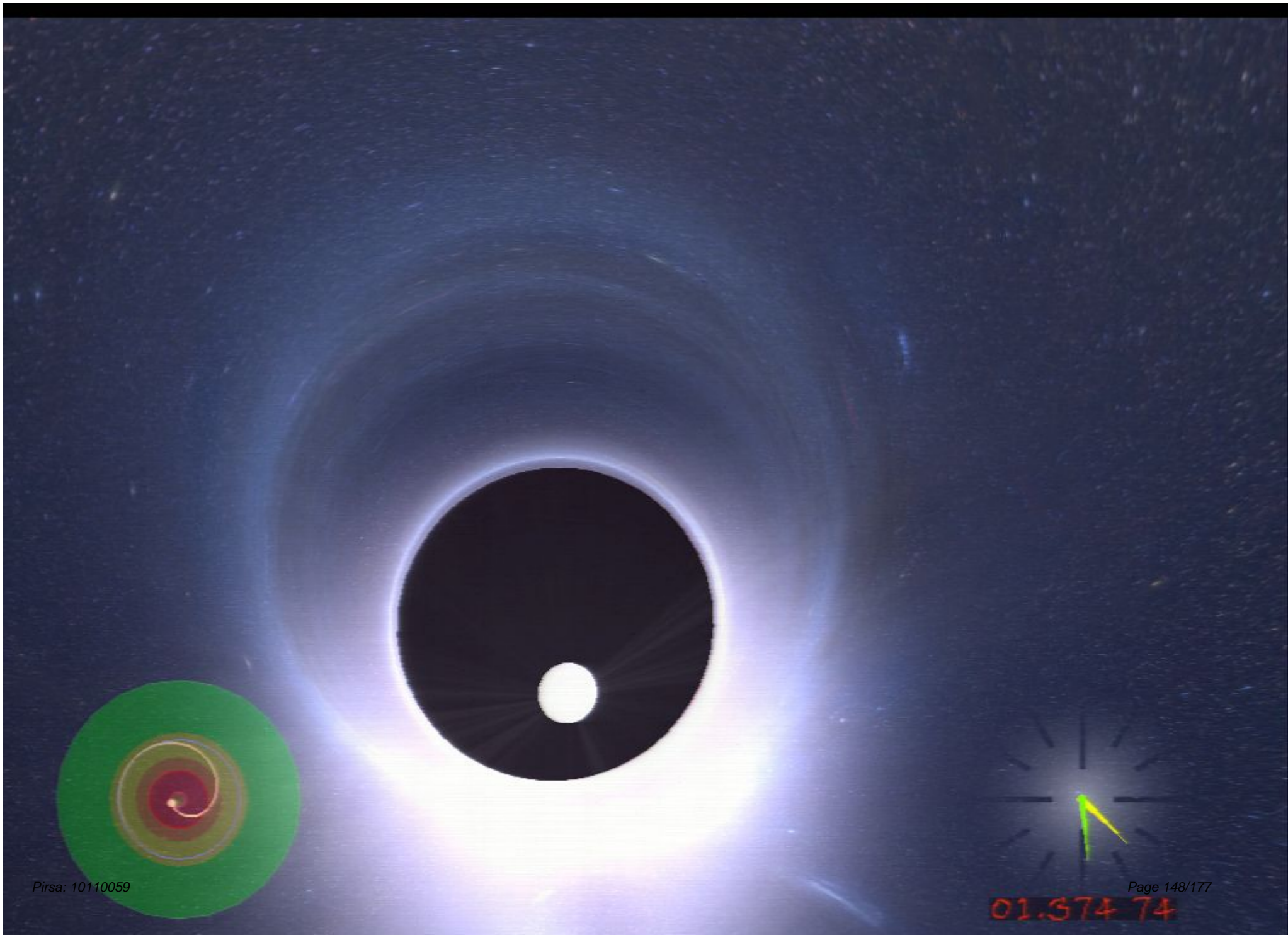
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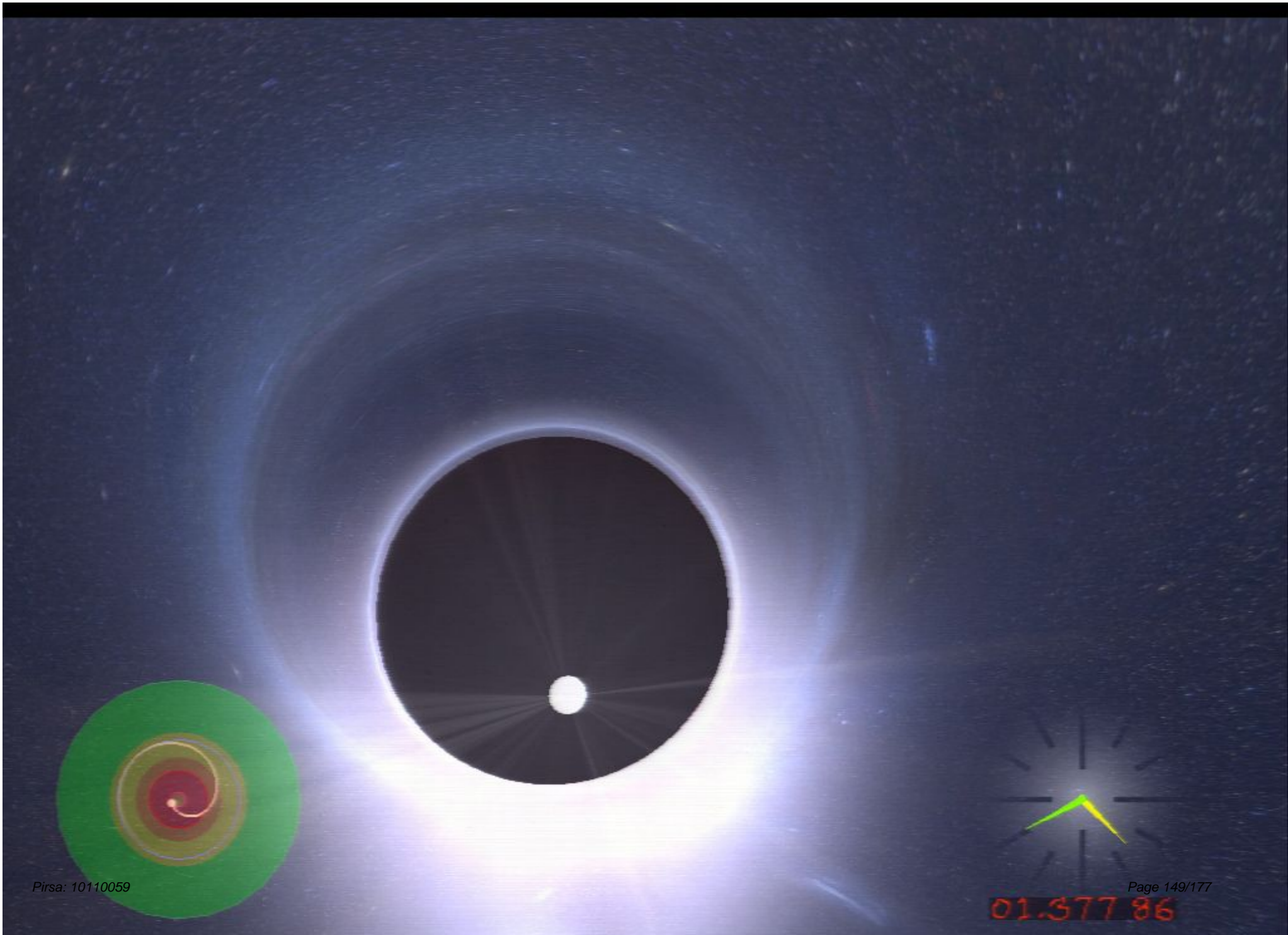
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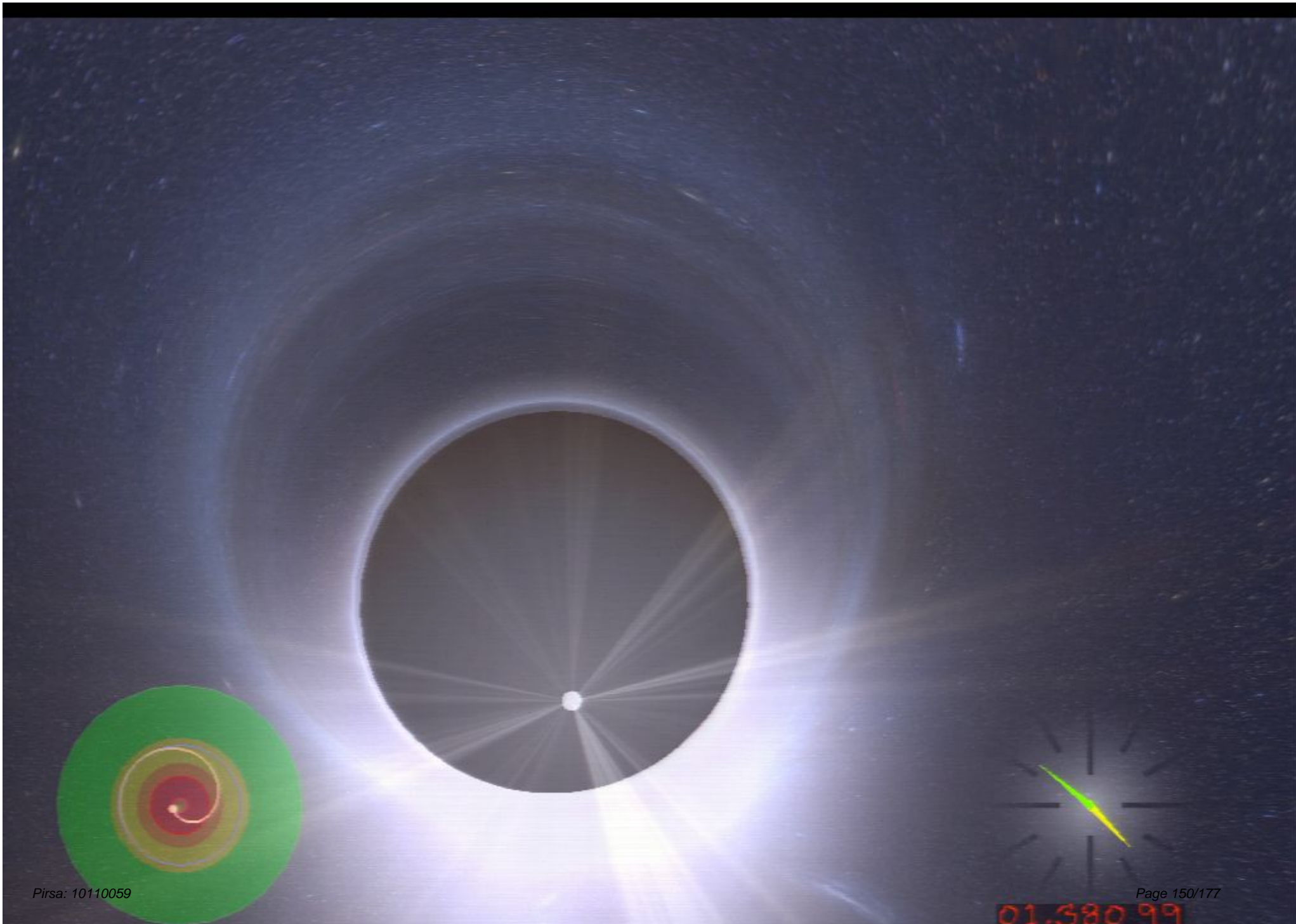


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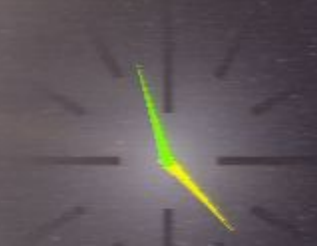
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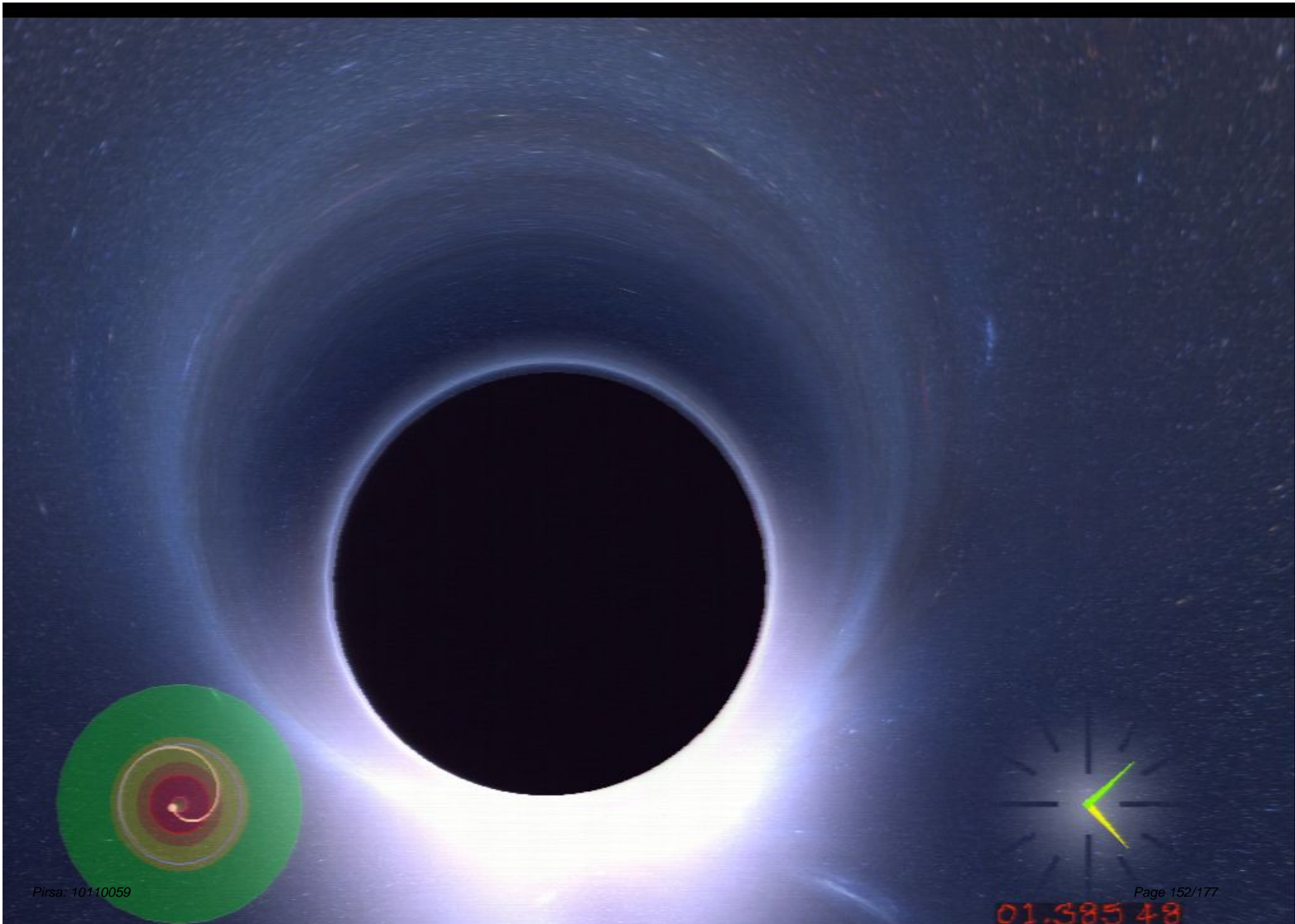


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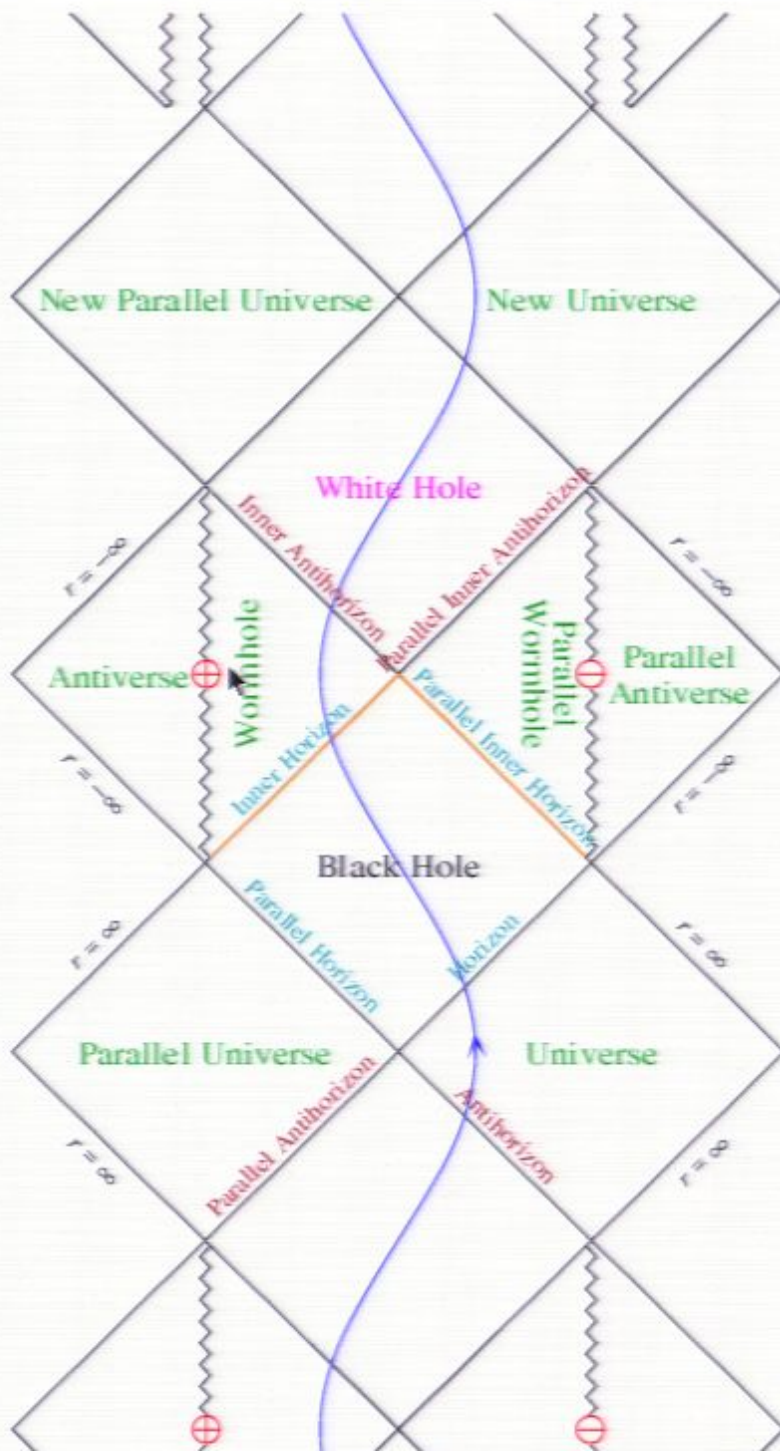


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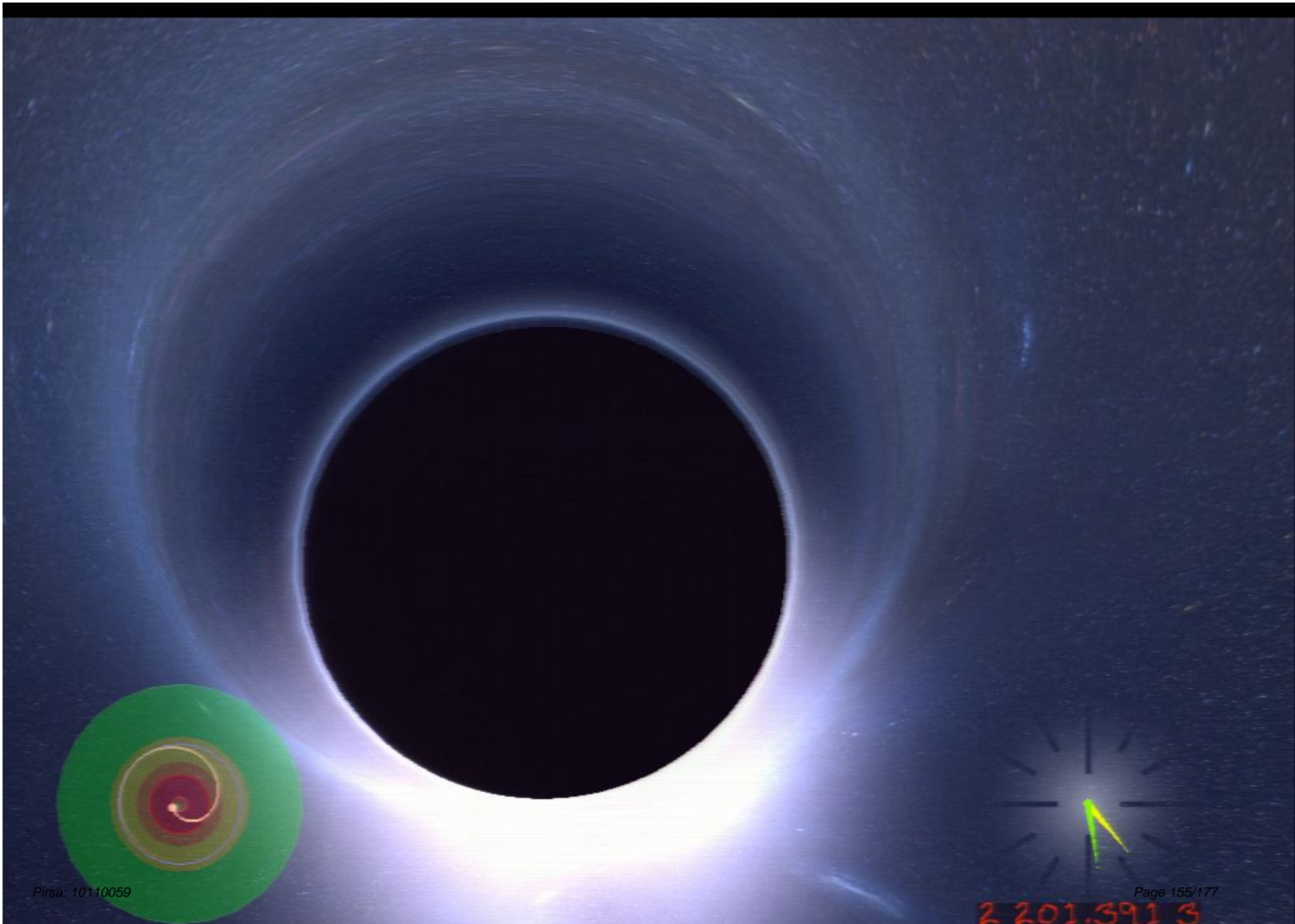
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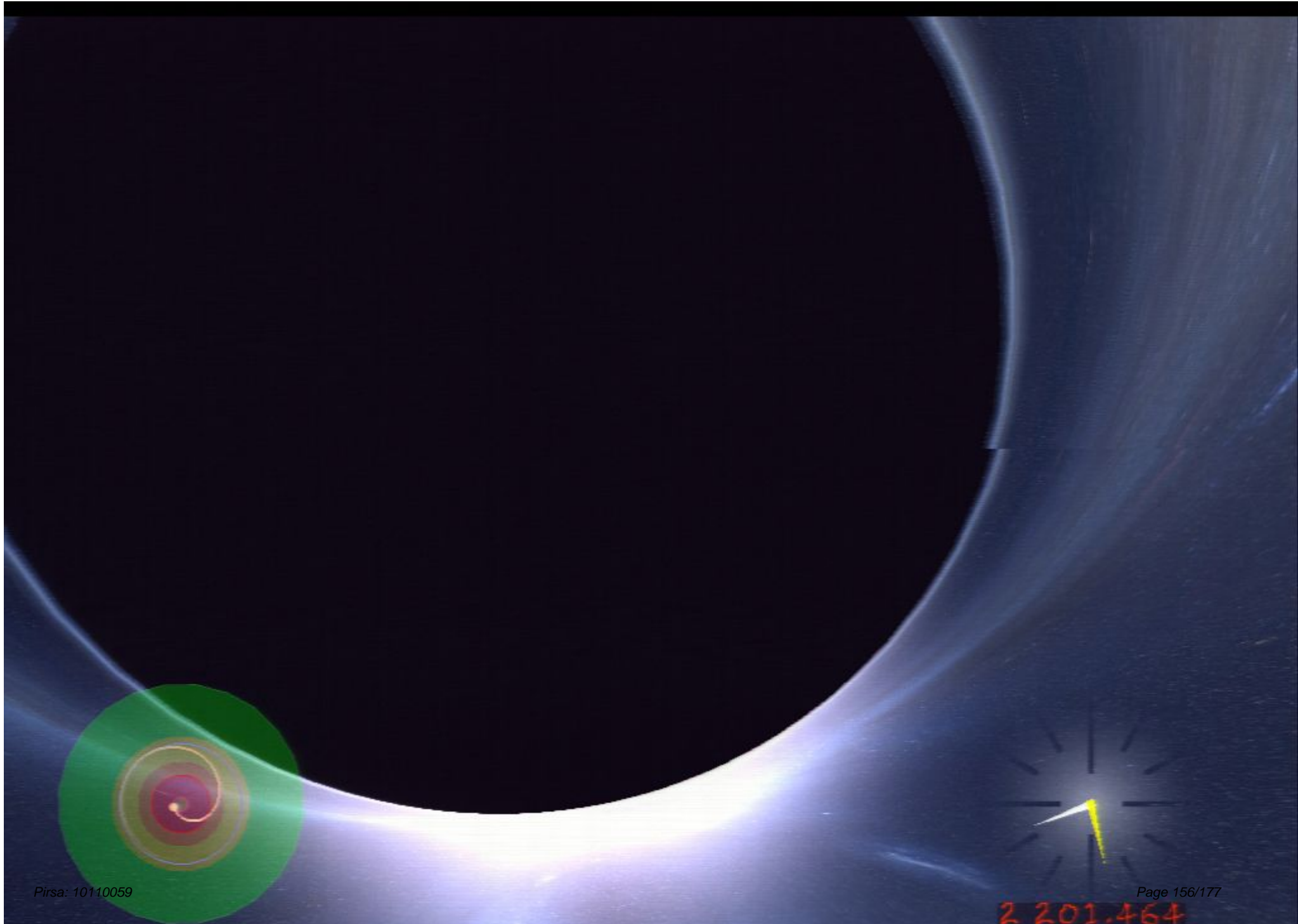
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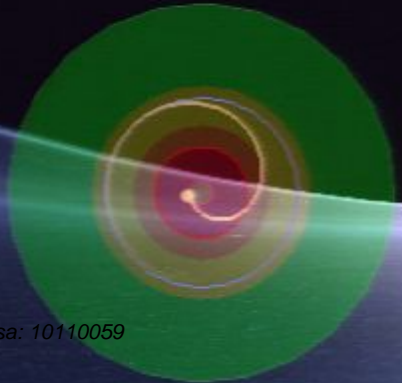


Penrose diagram of a Kerr-Newman (rotating) black hole

The Penrose diagram of a black hole Reissner-Nordström (charged) is similar.

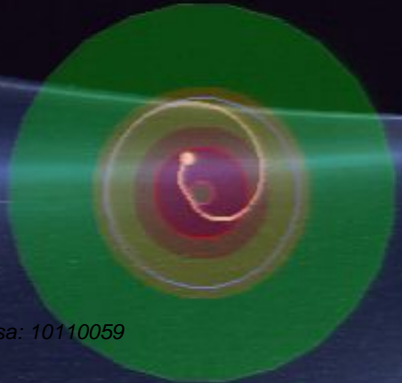


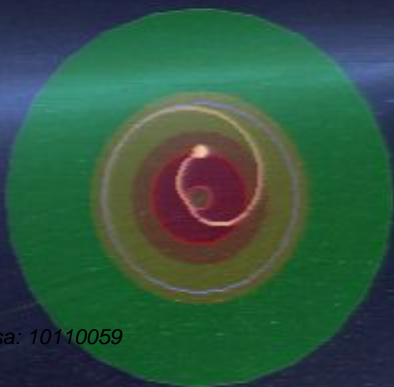


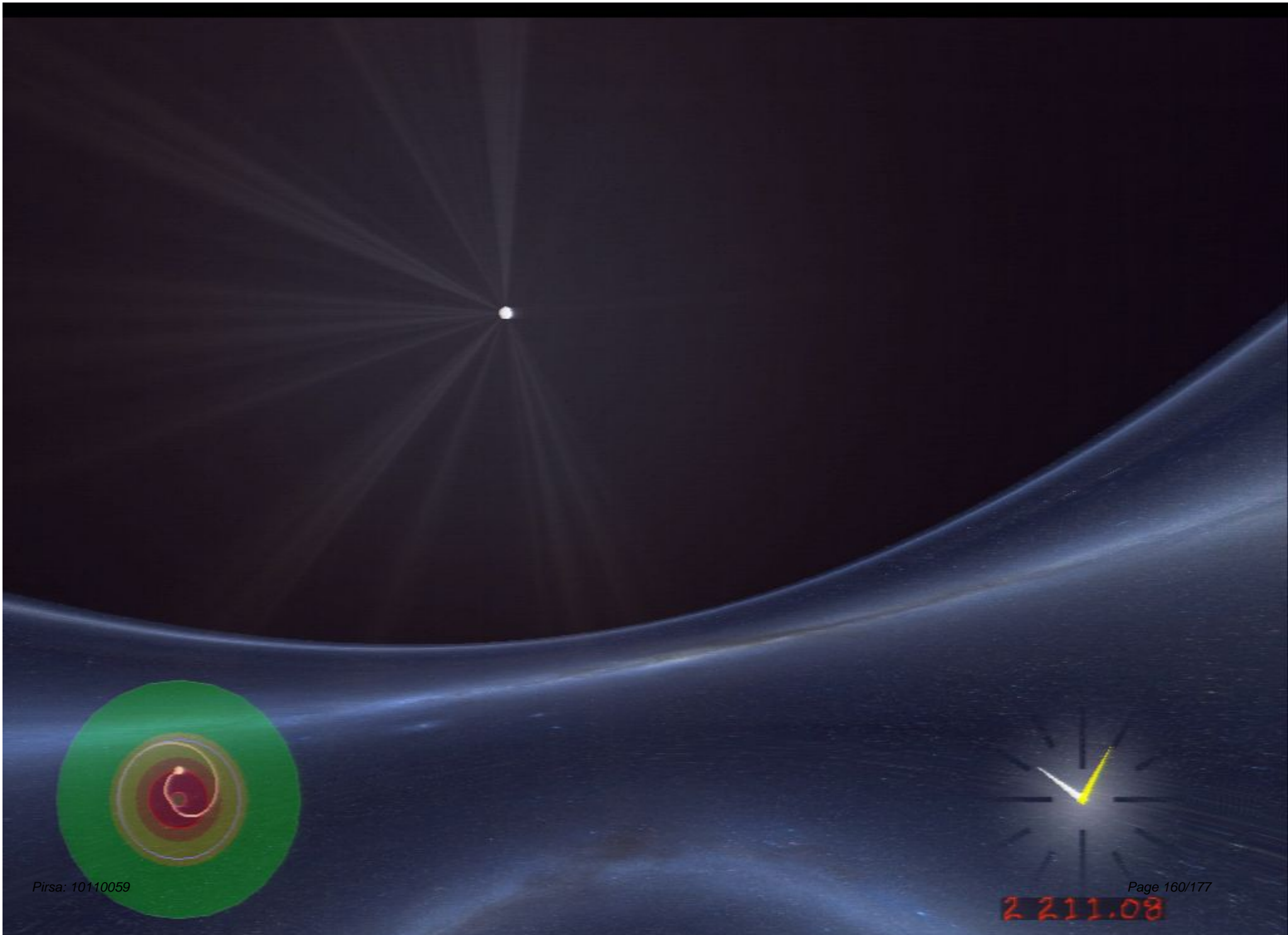


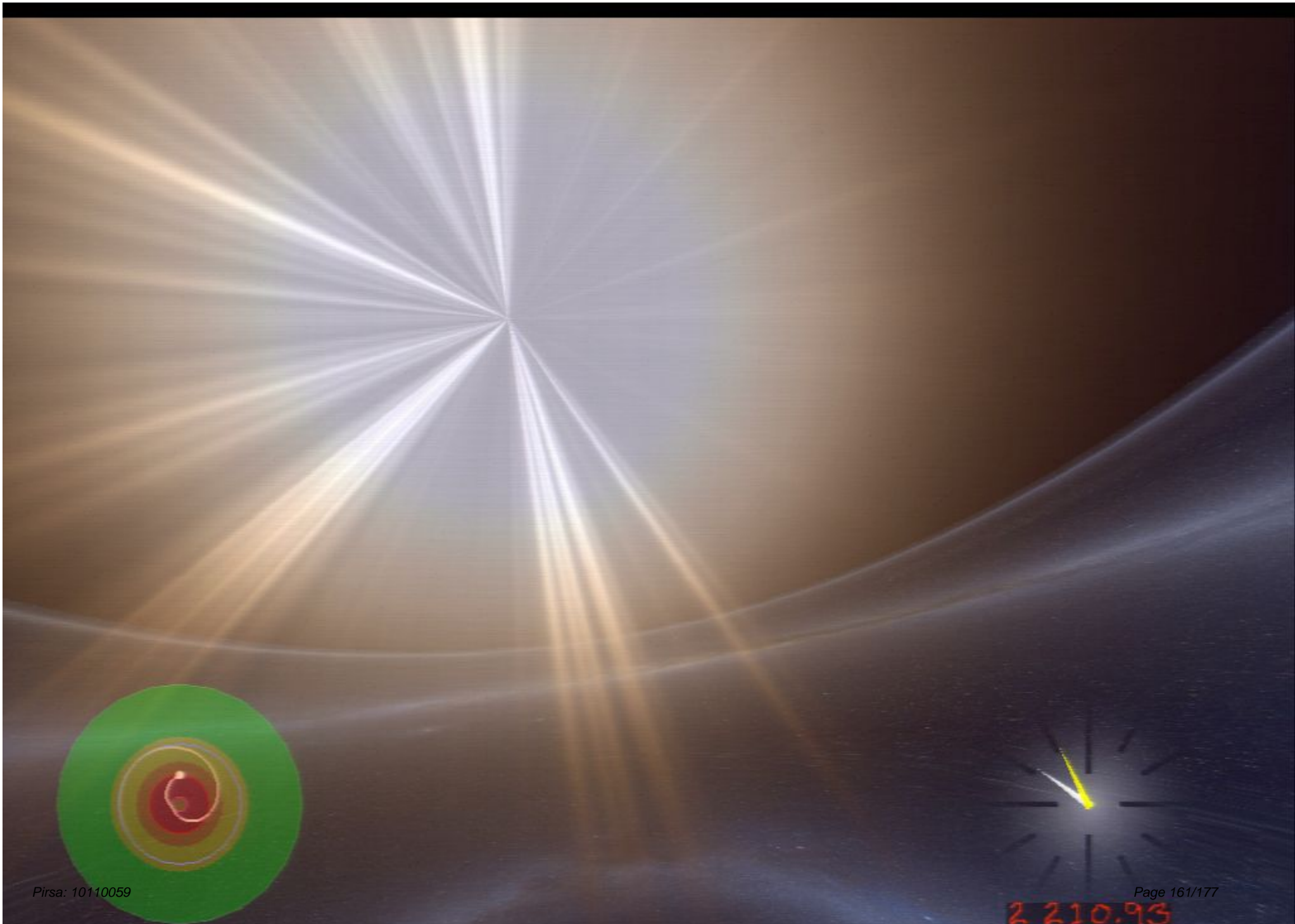
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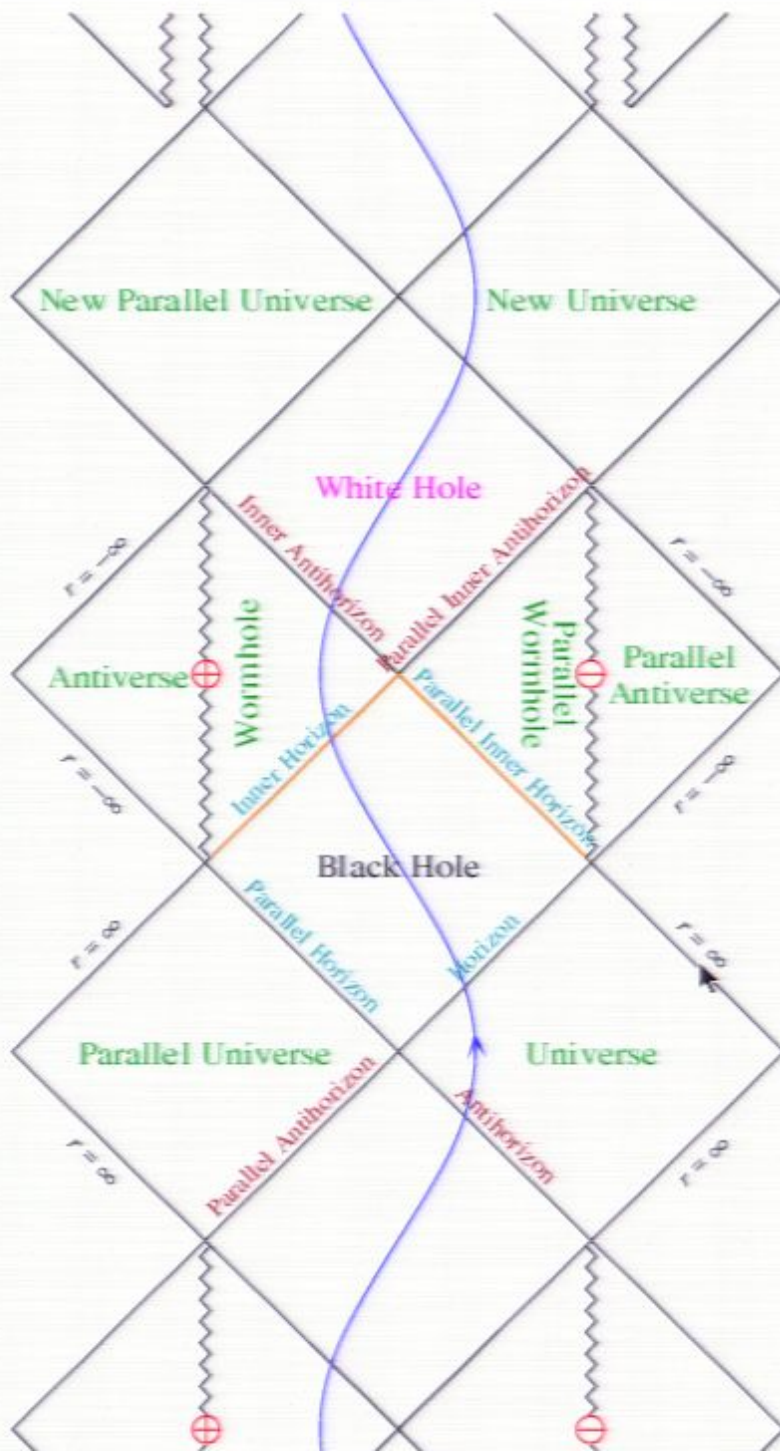
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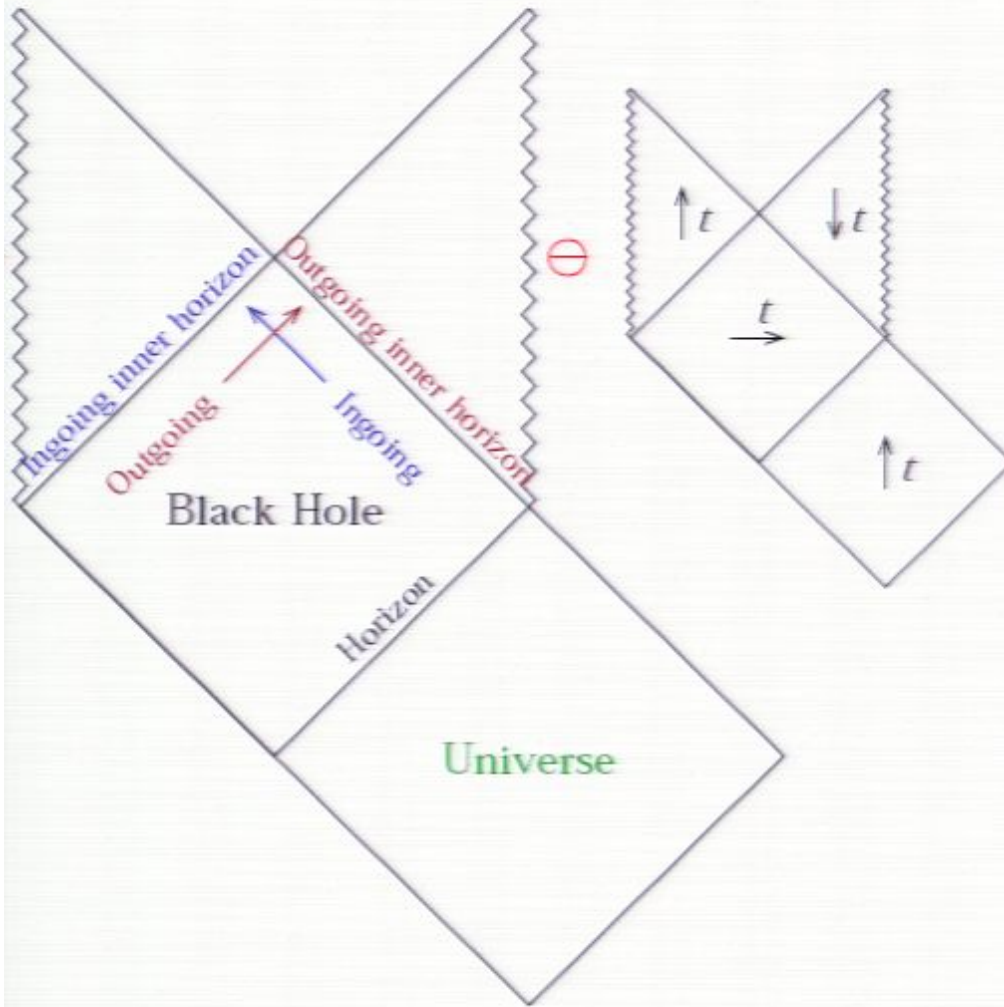
Penrose diagram of a Kerr-Newman (rotating) black hole

The Penrose diagram of a black hole Reissner-Nordström (charged) is similar.

Wormhole waterfall



Mass inflation



Penrose (1968) first pointed out that a person crossing an (outgoing) inner horizon would see the outside universe infinitely blueshifted. Poisson & Israel (1990) clarified the full non-linear nature of the instability, which they called “mass inflation”.

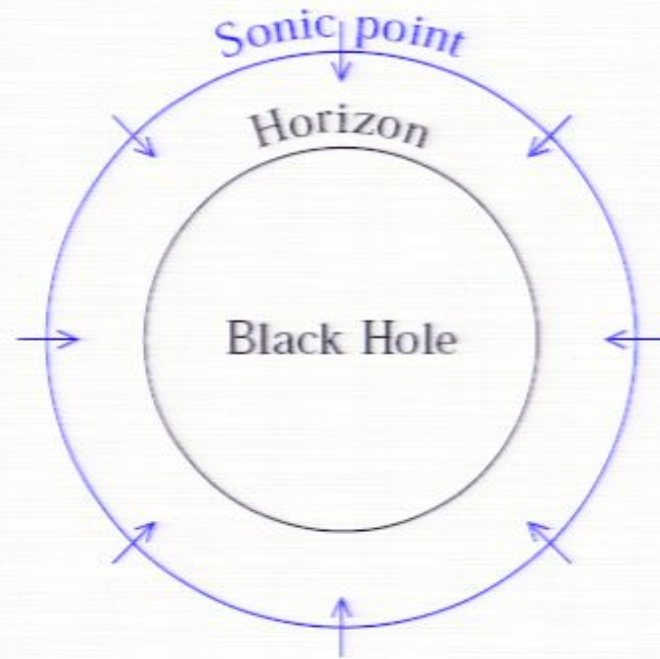
Mass inflation is caused by relativistic counter-streaming between ingoing and outgoing streams near the inner horizon. To drop through the inner horizon, the streams must exceed the speed of light relative to each other, which they cannot do.

The counter-streaming pressure generates a gravitational force, which accelerates the streams faster through each other.

[Self-similar model](#)

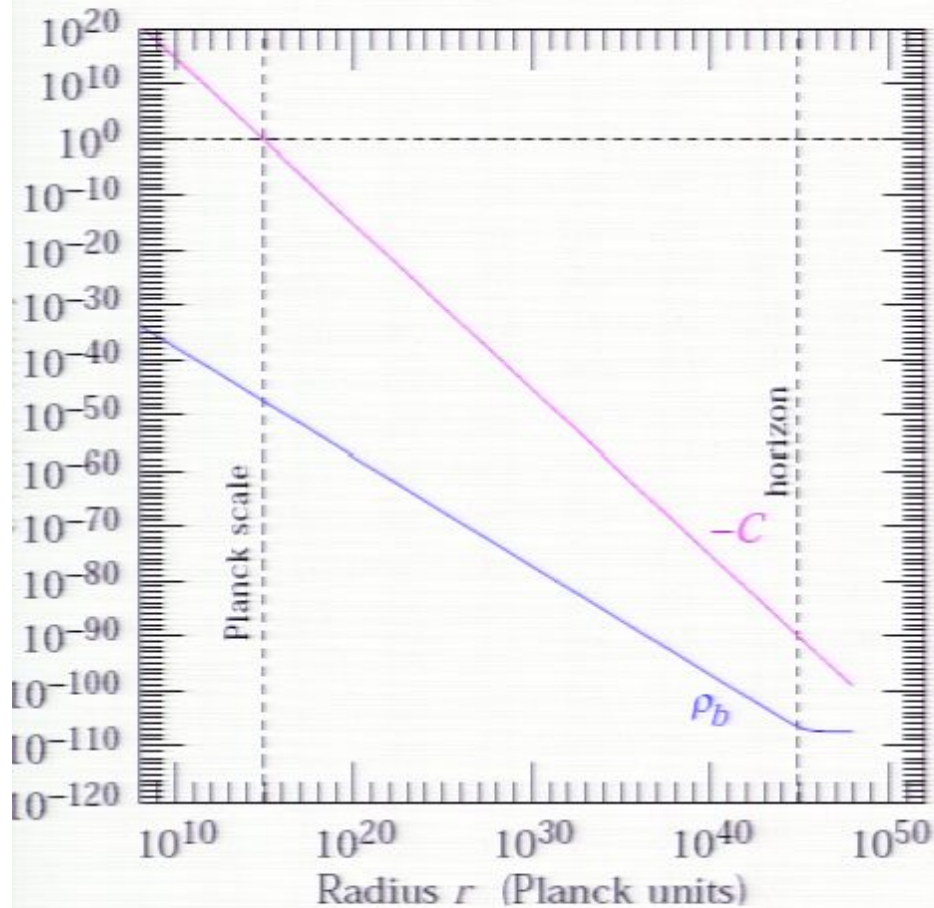
self-similar model

opt fully non-linear general relativistic model in which black hole accretes self-similarly with $M \propto t$.



Uncharged black hole

uncharged black hole

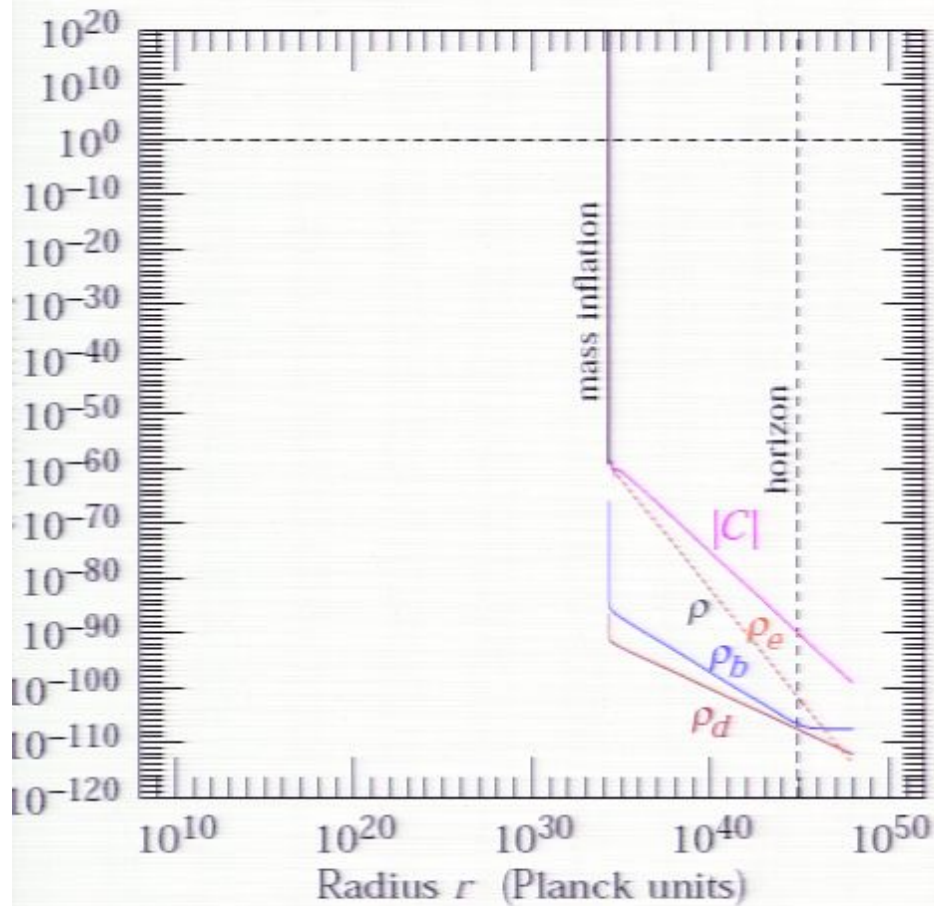


The familiar “Schwarzschild” case: the plasma plunges to a central curvature-dominated singularity.

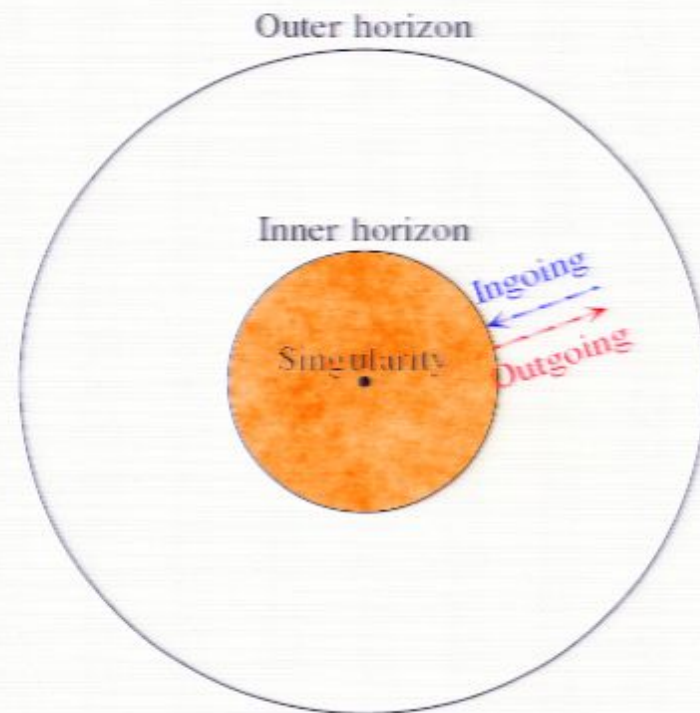
- Black hole mass $M_{\bullet} = 4 \times 10^6 M_{\odot}$
- Accretion rate dM_{\bullet}/dt
 $= 4 \times 10^6 M_{\odot} / \text{Age of Universe}$
 $\approx 20 \text{ sec} / 4 \times 10^{17} \text{ sec} \approx 10^{-16}$

Mass inflation by counter-streaming baryons and dark matter

Mass inflation by counter-streaming baryons and dark matter

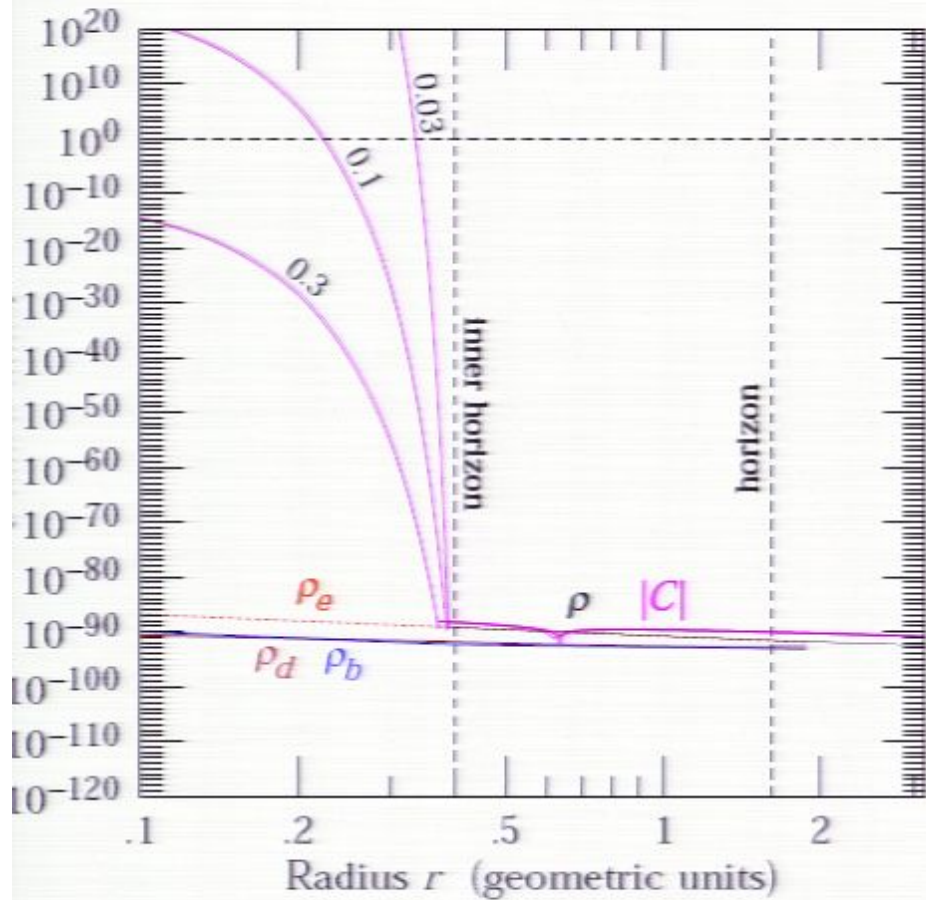


But if the black hole is charged, so it has an inner horizon like a rotating black hole, then relativistic counter-streaming between ingoing matter and outgoing matter, here dark matter and baryons, causes the center-of-mass density and curvature to exponentiate to huge values.



[Lower accretion rates yield faster inflation](#)

Lower accretion rates yield faster inflation



The smaller the accretion rate, the faster inflation exponentiates.

Almost all the energy is in the counter-streaming energy. The baryon and dark matter streams themselves remain relatively cold.

The center-of-mass energy exceeds the Planck energy, but the entropy remains low.

The label on each curve is the accretion rate dM_\bullet/dt .

Sagittarius A* parameters

The Milky Way Black Hole

Mass = 4 million solar masses

Radius = $G M / c^2 = 6$ million km = 10 solar radii

Natural timescale = $G M / c^3 = 20$ seconds

Dimensionless accretion rate = $\frac{20 \text{ seconds}}{\text{Age of Universe}} = 10^{-16}$

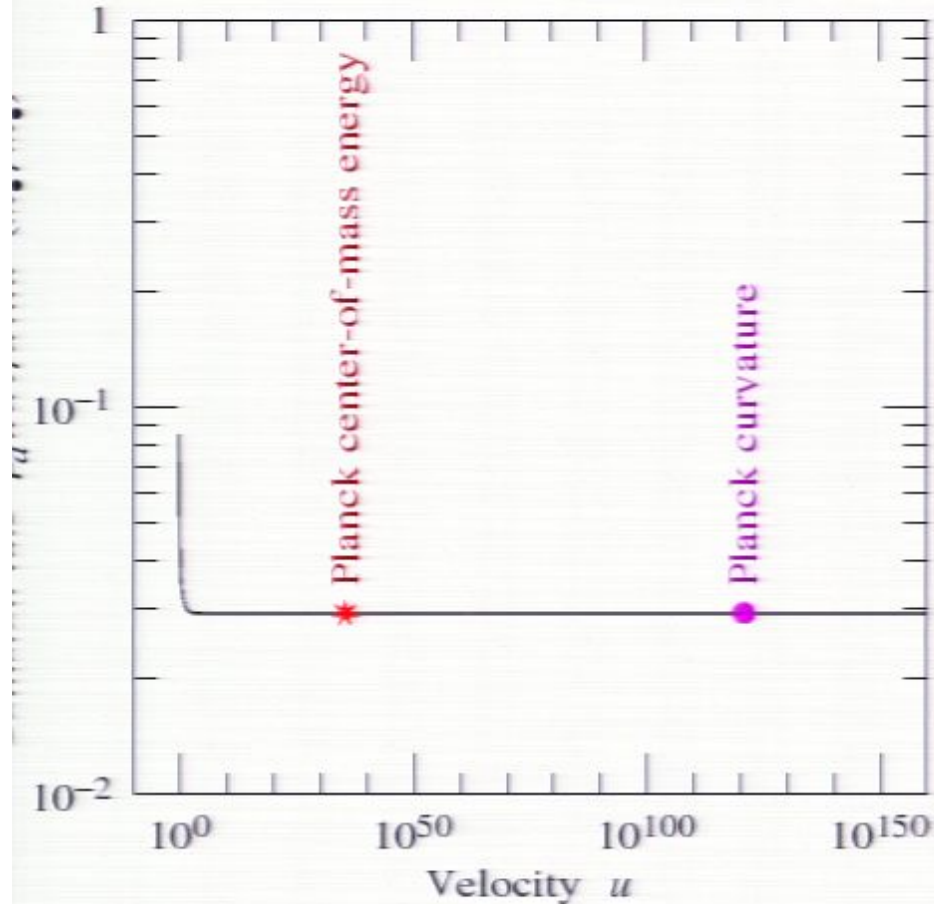
Inflationary scale length = $10^{-16} \times \text{Radius} = 10^{-3}$ millimeters

⇒ In 1 millimeter, the streaming velocity, density, curvature, at the inner horizon exponentiate by e^{1000} , exceeding Planck.

If quantum gravity did not intervene, the streaming velocity would exponentiate to $e^{10^{16}}$ before inflation ends and streams collapse to singularity at zero radius.

The black hole particle accelerator

The black hole particle accelerator



The black hole acts like a particle accelerator. The acceleration is exponential: particles undergo equal numbers of collisions in equal decades of Lorentz factor.

The collider is powered by its own gravity. The pressure of the counter-streaming generates gravity that accelerates the streams faster through each other.

The smaller the accretion rate, the faster the acceleration, and correspondingly the smaller the luminosity. For $dM_{\bullet}/dt = 10^{-16}$, luminosity = 10^{35} fb^{-1} per year.

[Baby universes?](#)

Can the black hole particle accelerator make baby universes?

- + Easily enough energy, and oodles of luminosity.
- **Cooling problem.** Our Universe began with a low entropy, vacuum-dominated equation of state, over at least several Planck lengths. Smashing things together in a particle accelerator tends to produce lots of entropy.
- ? **Future work.** The prevailing idea is that super-Planckian collisions generically produce mini-black holes. This would (we expect) predict a burst of mini-black hole creation, followed by hastened collapse.

History

black hole history

1915 Schwarzschild discovers the solution for a spherical black hole.

1963 47 years later, Kerr discovers the exterior solution for a rotating black hole.

2010 47 years later, “No satisfactory interior solutions are known”
— Stephani et al. *Exact Solutions to Einstein's Field Equations*, 2nd edition.

Rotating inflationary black hole solutions

Black hole history

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Rotating inflationary black hole solutions

Rotating inflationary black hole solutions

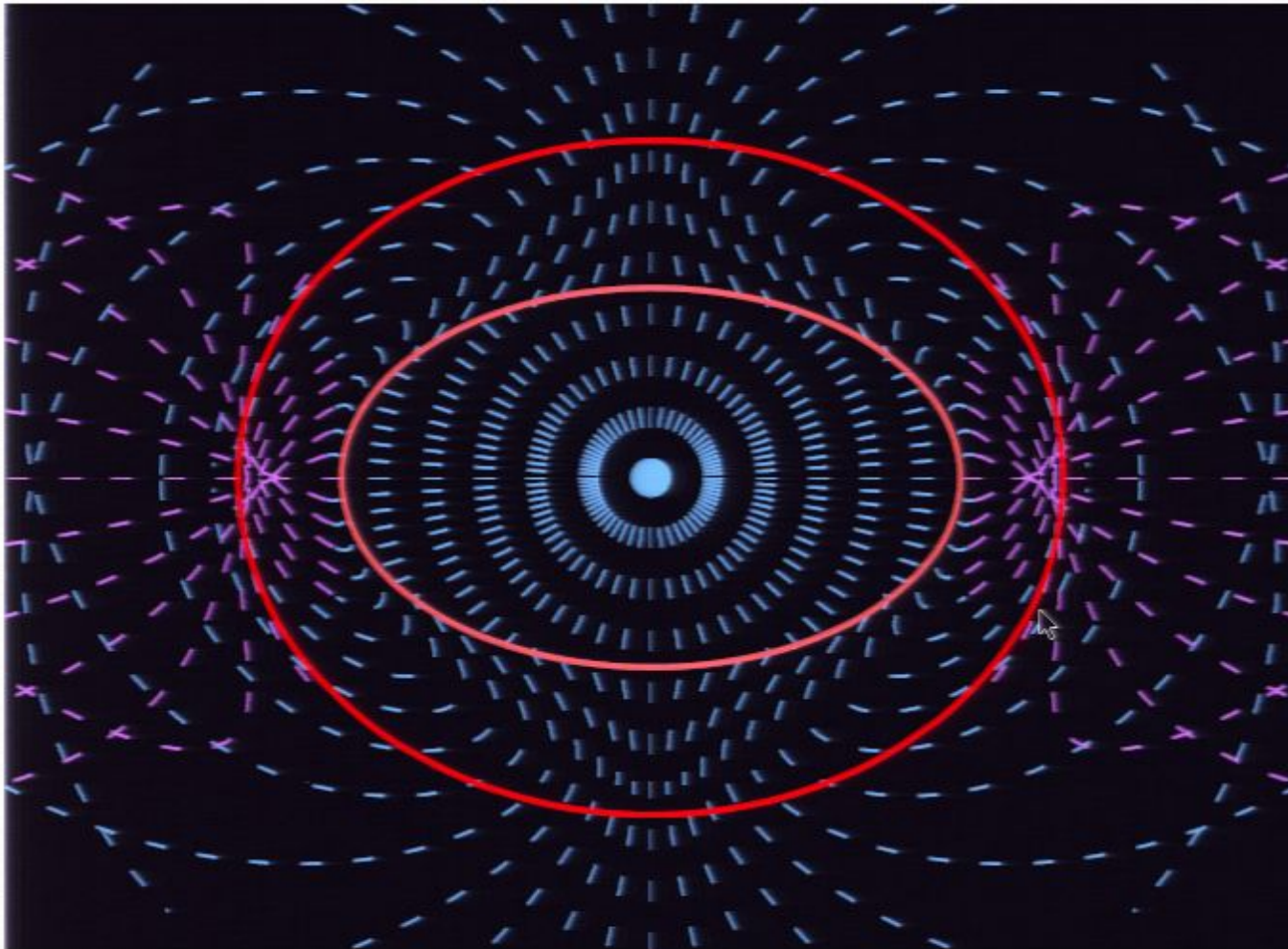
Hamilton & Polhemus (2010) arXiv:1010.1269,71,72

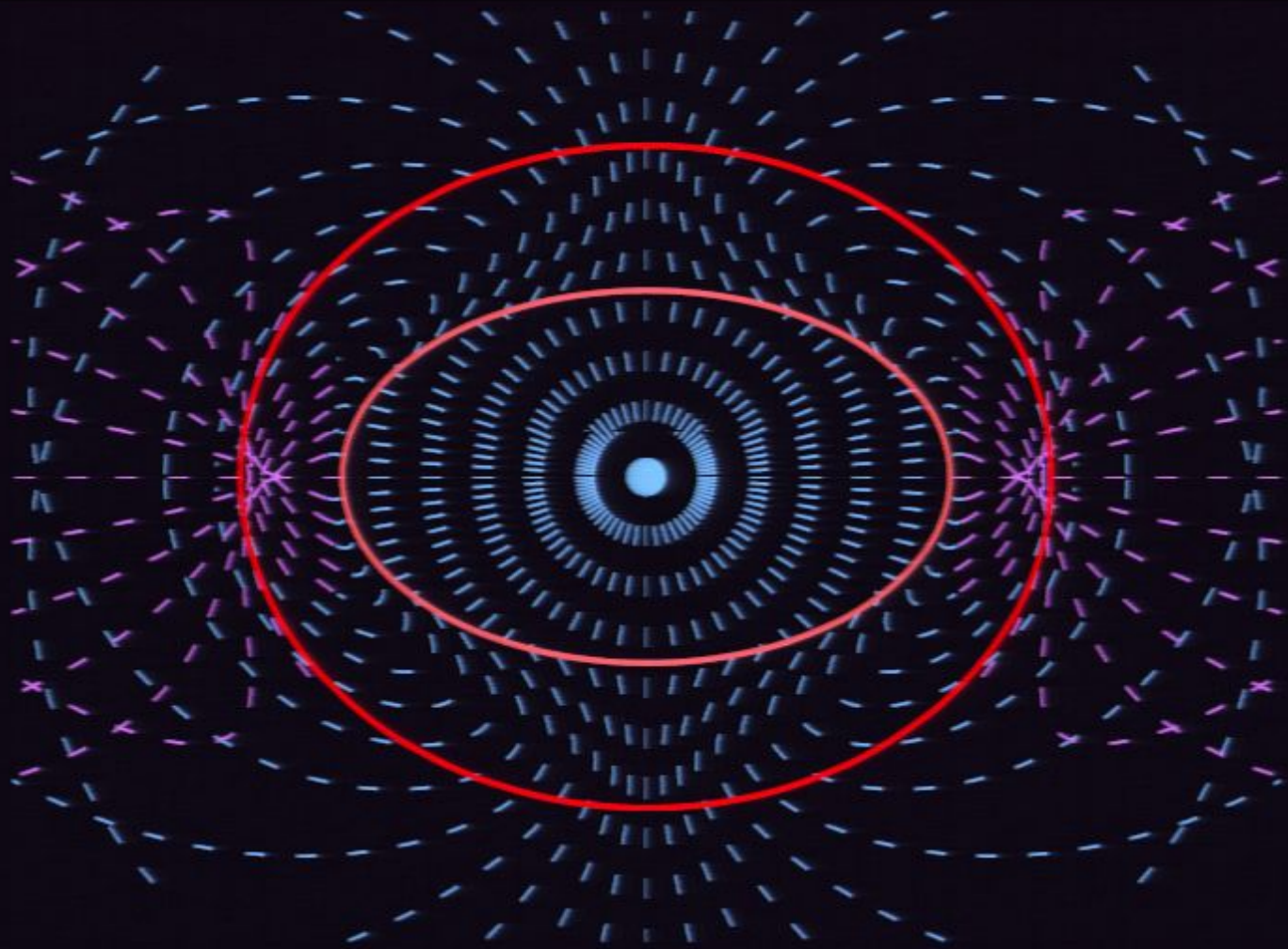
Rotating black hole accretes collisionless fluid.

Hyper-relativistic counter-streaming drives inflation just above inner horizon.

Solutions are exact, conformally stationary, axisymmetric, separable.

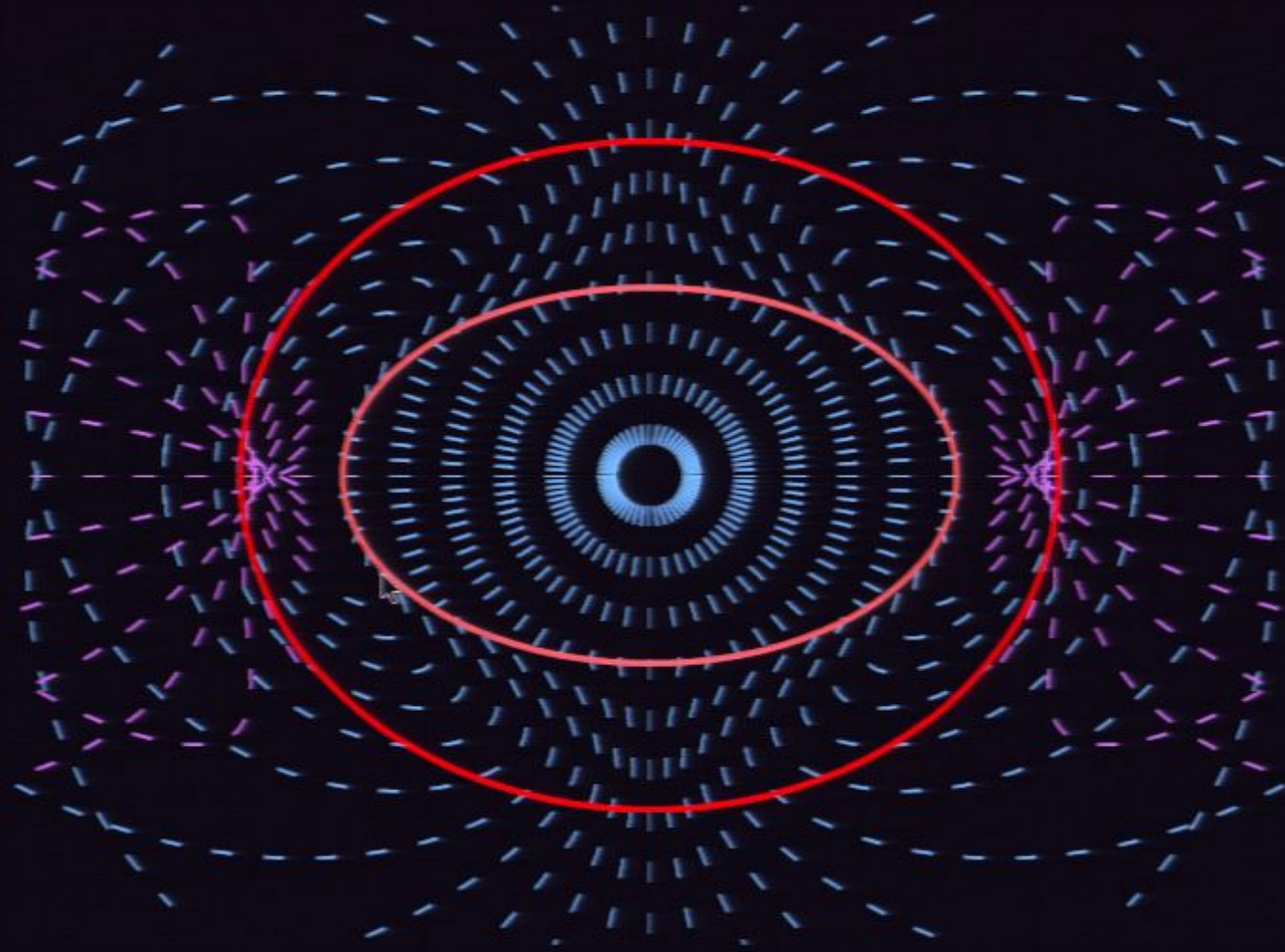
Separability requires special flow pattern incident on inner horizon.





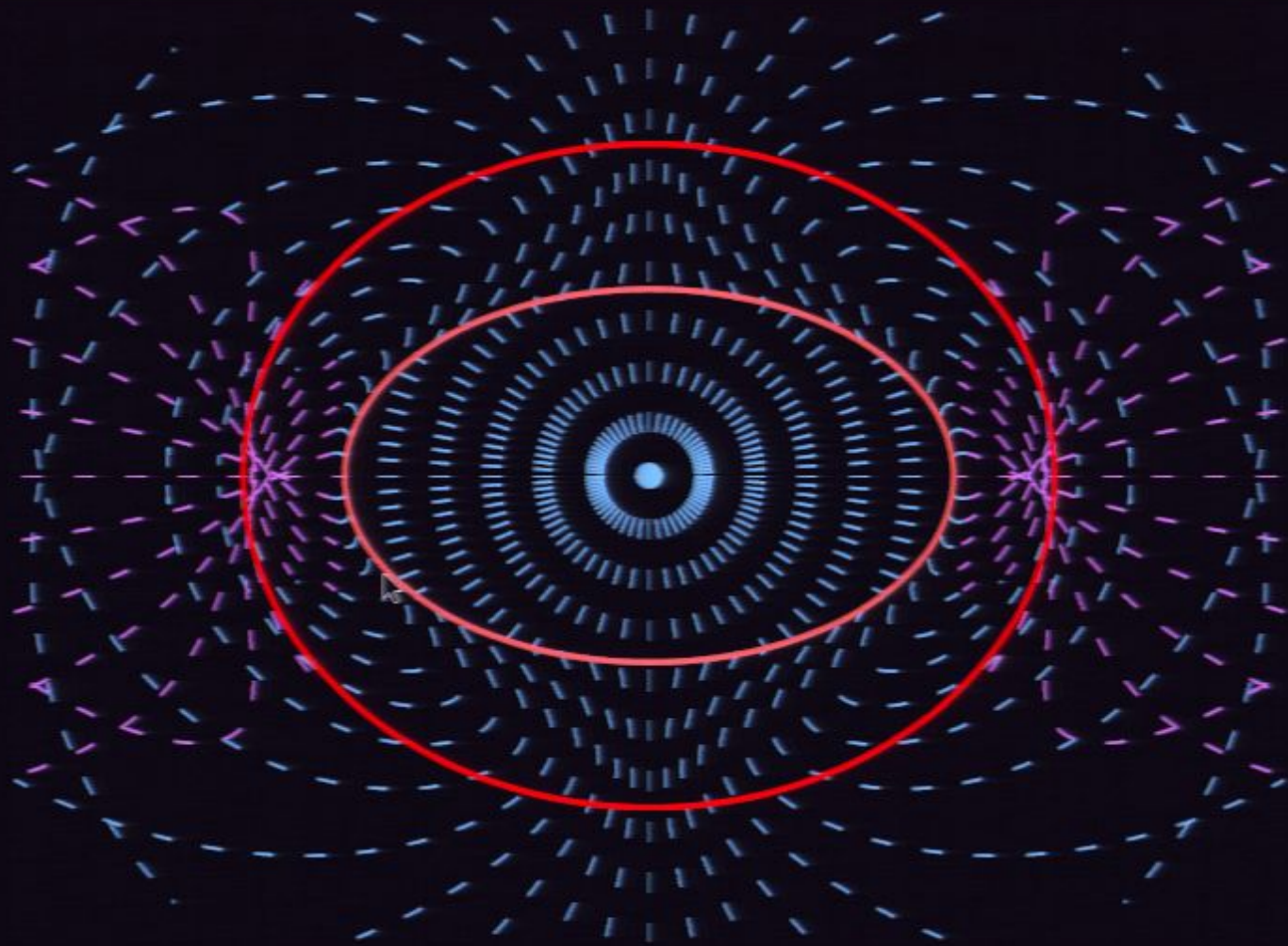
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- A black hole is a place where space falls faster than light.
- The inflationary instability at the inner horizon acts like a particle accelerator of extraordinary power.
- There exist exact solutions for rotating black holes that undergo inflation at the inner horizon.
- Why does Nature do what she does inside black holes?



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