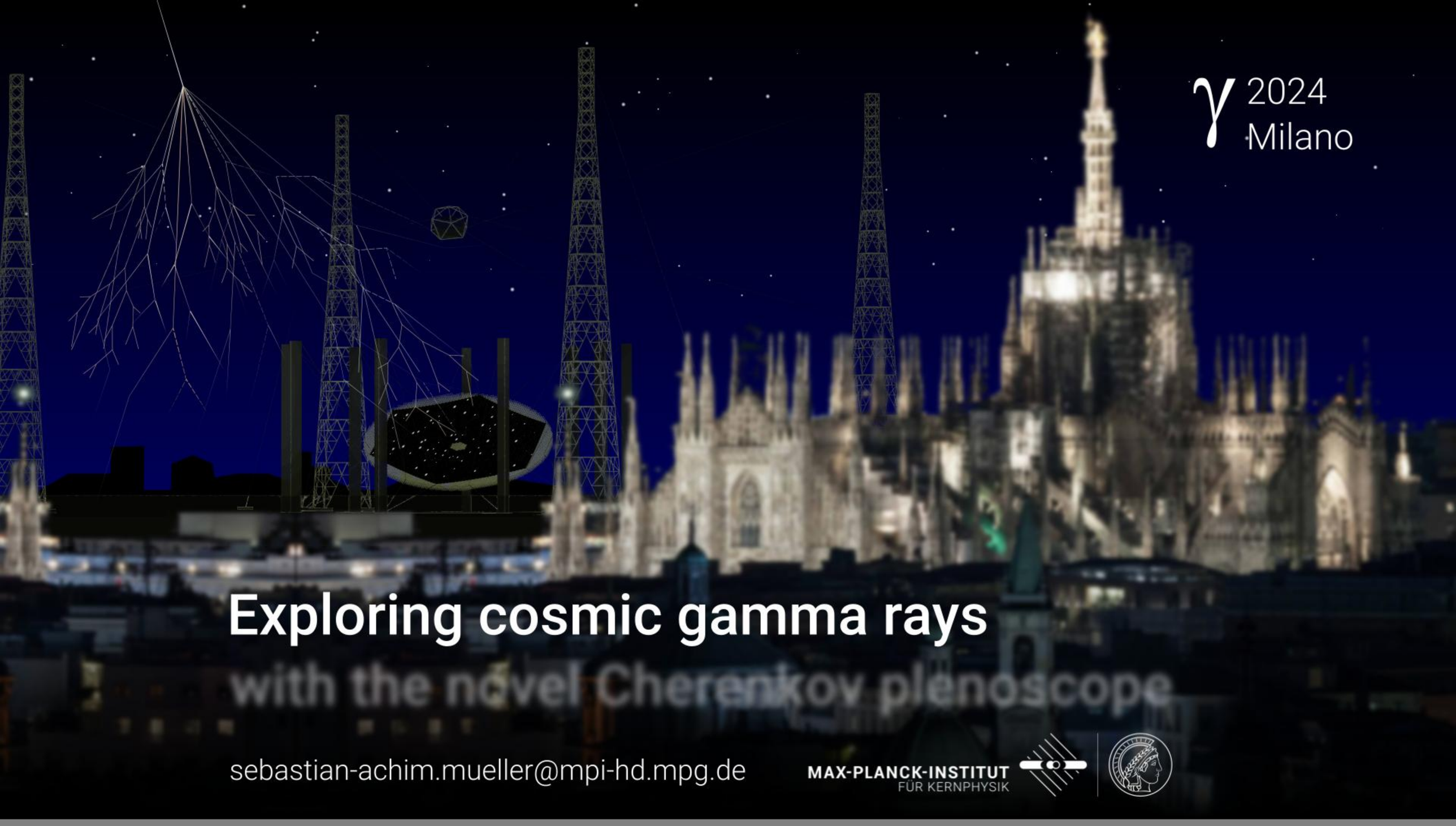
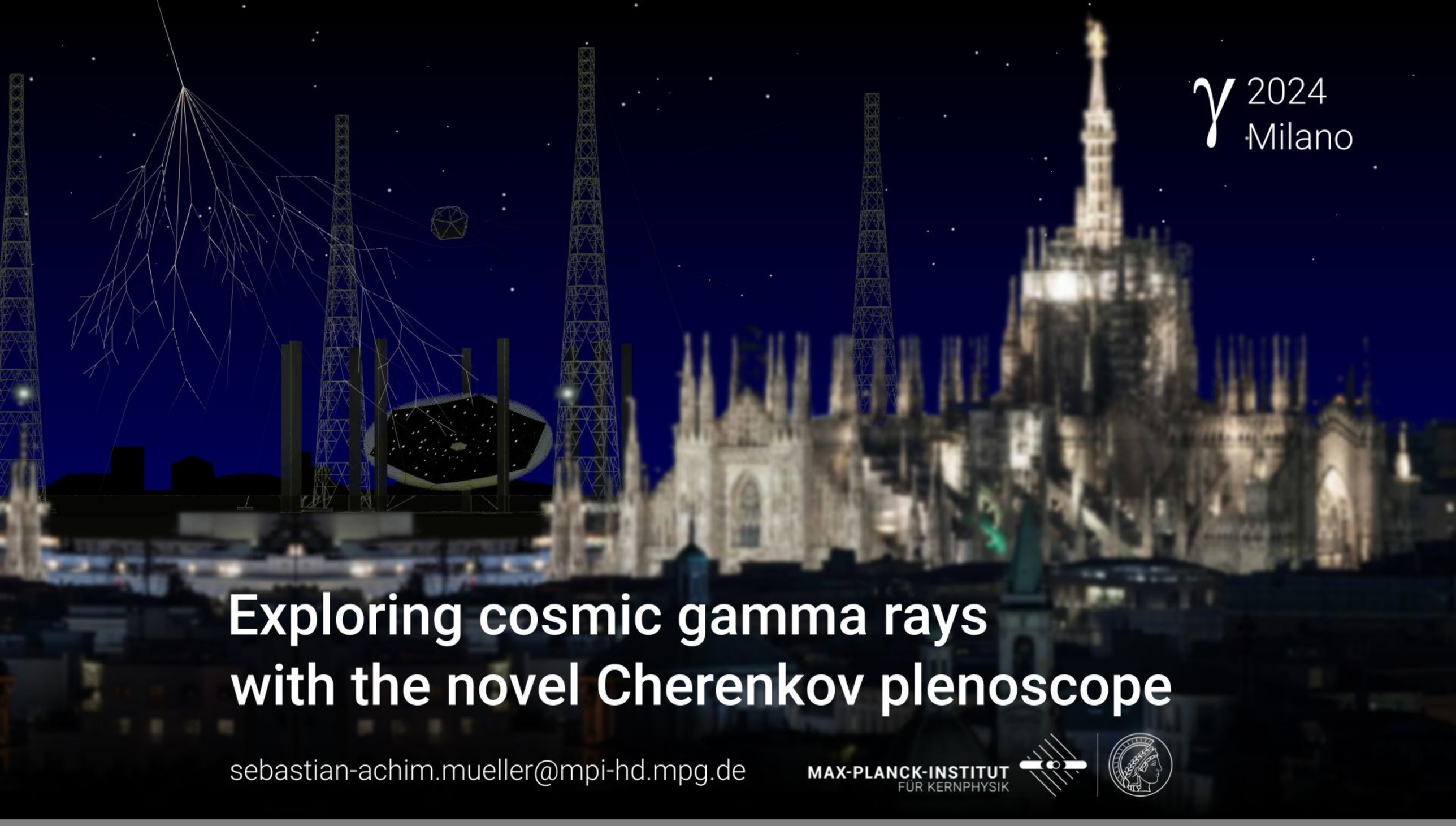
Thank you for having me at the gamma twenty twenty four in milano.

The atmospheric Cherenkov method might have a new tool at its disposal. This is:



Exploring cosmic gamma rays



with the novel Cherenkov plenoscope

γ 2024 Milano

Exploring cosmic gamma rays with the novel Cherenkov plenoscope

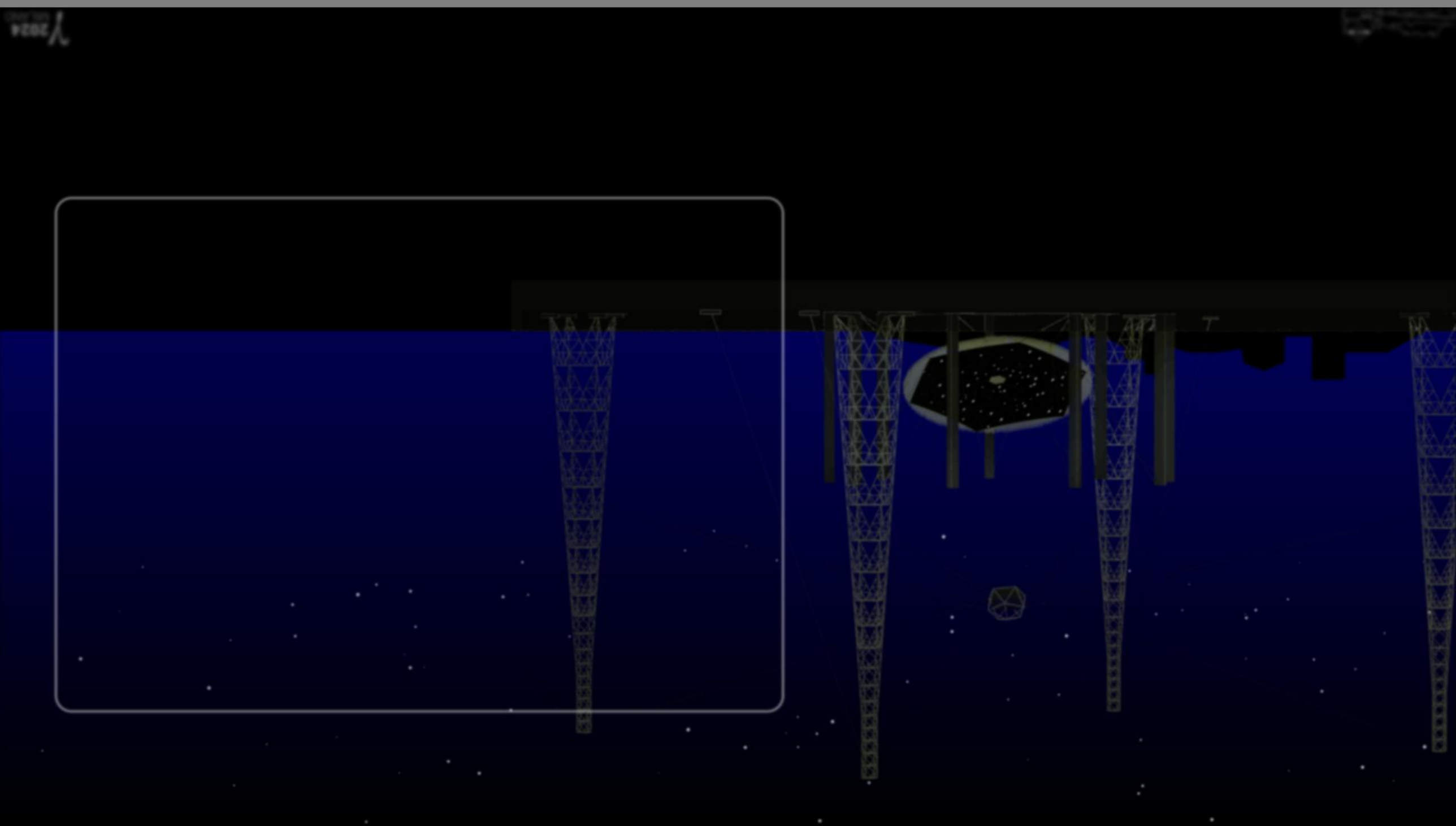
sebastian-achim.mueller@mpi-hd.mpg.de

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

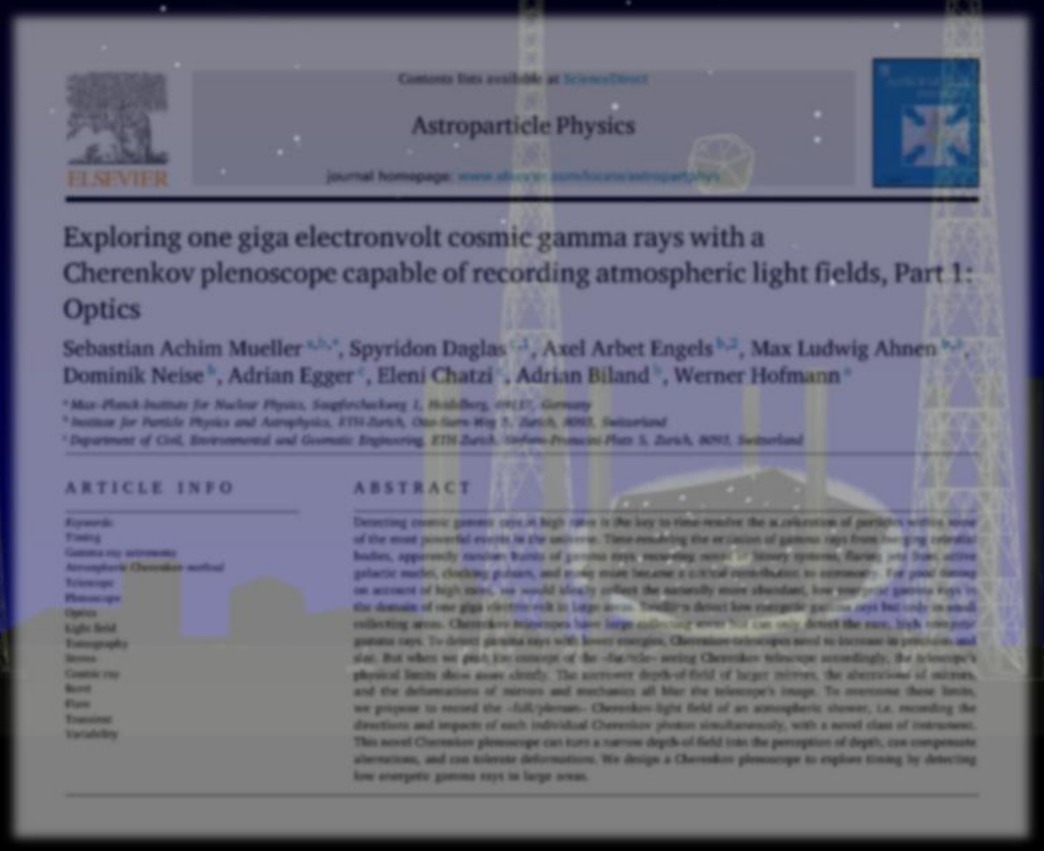
Exploring cosmic gamma rays with the novel Cherenkov plenoscope

sebastian-achim.mueller@mpi-hd.mpg.de

MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK



I will briefly show how gamma ray astronomy improved and pushed the Cherenkov telescope to its physical limits.



Contents lists available at ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropartphys

Exploring one giga electronvolt cosmic gamma rays with a Cherenkov plenoscope capable of recording atmospheric light fields, Part 1: Optics

Sebastian Achim Mueller [a,b,*], Spyridon Daglas [c,d], Axel Arbet Engels [b,2], Max Ludwig Ahnen [b,3], Dominik Neise [b], Adrian Egger [c], Eleni Chatzi [c], Adrian Biland [b], Werner Hofmann [a]

[a] Max-Planck-Institute for Nuclear Physics, Saupfercheckweg 1, Heidelberg, 69117, Germany
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[c] Department of Civil, Environmental and Geomatic Engineering, ETH Zurich, Stefano-Franscini-Platz 5, Zurich, 8093, Switzerland

ARTICLE INFO

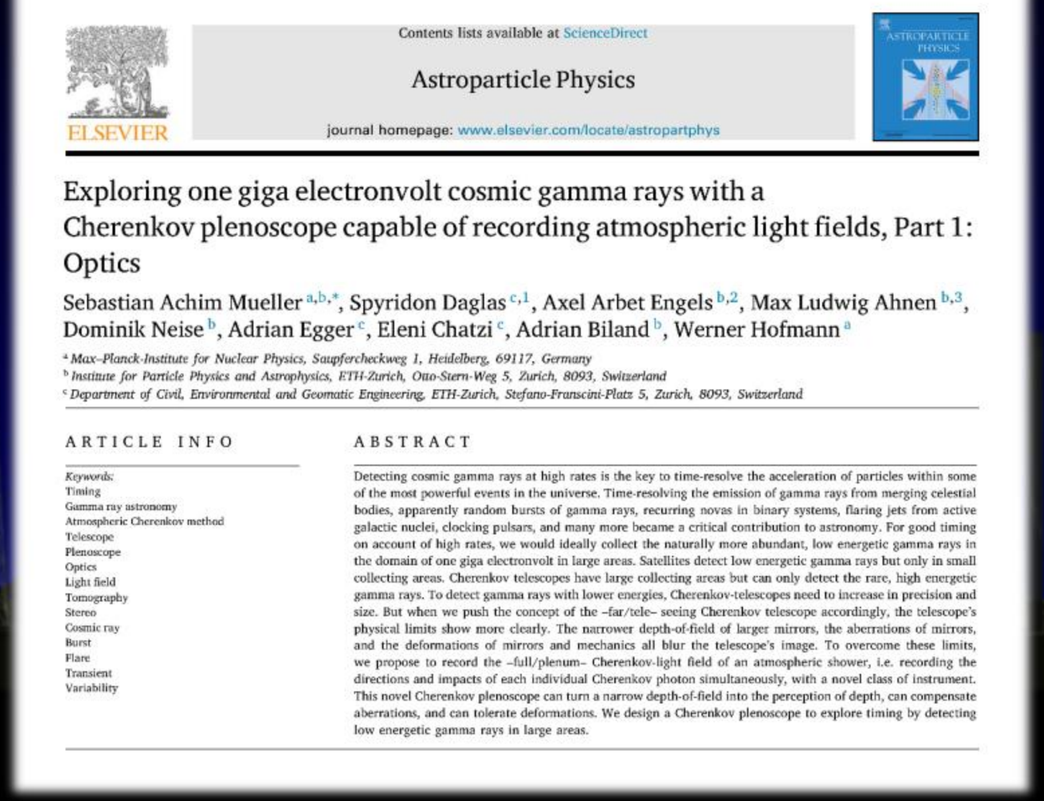
Keywords:
Timing
Gamma-ray astronomy
Atmospheric Cherenkov method
Telescope
Plenoscope
Optics
Light field
Tomography
Stereo
Cosmic ray
Burst
Flare
Transient
Variability

ABSTRACT

Detecting cosmic gamma rays at high rates is the key to time-resolve the acceleration of particles within some of the most powerful events in the universe. Time-resolving the emission of gamma rays from [illegible] celestial bodies, apparently random bursts of gamma rays occurring within [illegible] binary systems, flares [illegible] from active galactic nuclei, crashing galaxies, and many more became a critical contributor to astronomy. For good timing on account of high rates, we would ideally collect the naturally more abundant, low energetic gamma rays in the domain of one giga electronvolt in large areas. Today's direct low energetic gamma rays but only in small collecting areas. Cherenkov telescopes have large collecting areas but can only detect the rare, high energetic gamma rays. To detect gamma rays with lower energies, Cherenkov telescopes need to increase in precision and size. But when we pinch the concept of the -facet- seeing Cherenkov telescope accordingly, the telescope's physical limits show more clearly. The narrower depth-of-field of larger mirrors, the aberrations of mirrors, and the deformations of mirrors and mechanics all blur the telescope's image. To overcome these limits, we propose to record the -full-picture- Cherenkov-light field of an atmospheric shower, i.e. recording the directions and impacts of each individual Cherenkov photon simultaneously, with a novel class of instrument. This novel Cherenkov plenoscope can turn a narrow depth-of-field into the perception of depth, can compensate aberrations, and can tolerate deformations. We design a Cherenkov plenoscope to explore timing by detecting low energetic gamma rays in large areas.

History and limits of telescopes

S. A. Mueller, S. Daglas, A. Arbet Engels, et al. 2024
Exploring one giga electronvolt cosmic gamma rays with a Cherenkov plenoscope capable of recording atmospheric light fields, Part 1: Optics
Astroparticle Physics vol.158 issn.0927-6505 p.102933



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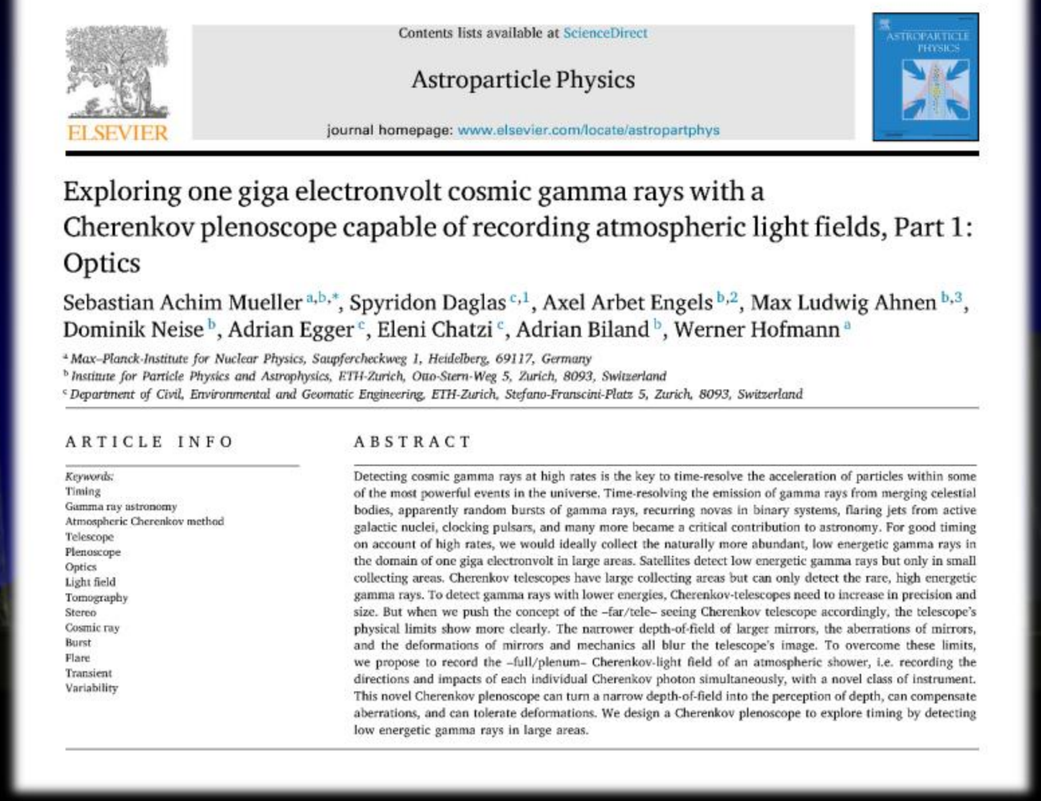
History and limits of telescopes

Combining the atmospheric Cherenkov method with plenoptic perception

S. A. Mueller, S. Daglas, A. Arbet Engels, et al. 2024
Exploring one giga electronvolt cosmic gamma rays with a Cherenkov plenoscope capable of recording atmospheric light fields, Part 1: Optics
Astroparticle Physics vol.158 issn.0927-6505 p.102933

γ2024 MILANO

Then I will propose to combine the atmospheric Cherenkov method with plenoptic perception in order to overcome these limits,



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History and limits of telescopes

Combining the atmospheric Cherenkov method with plenoptic perception

Portal, a possible future 1GeV 'gamma ray timing explorer'

S. A. Mueller, S. Daglas, A. Arbet Engels, et al. 2024
Exploring one giga electronvolt cosmic gamma rays with a Cherenkov plenoscope capable of recording atmospheric light fields, Part 1: Optics
Astroparticle Physics vol.158 issn.0927-6505 p.102933

and by doing so, we will learn about Portal, what might become the next generation's one giga electron volt gamma ray timing explorer.

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journal homepage: www.elsevier.com/locate/astropartphys

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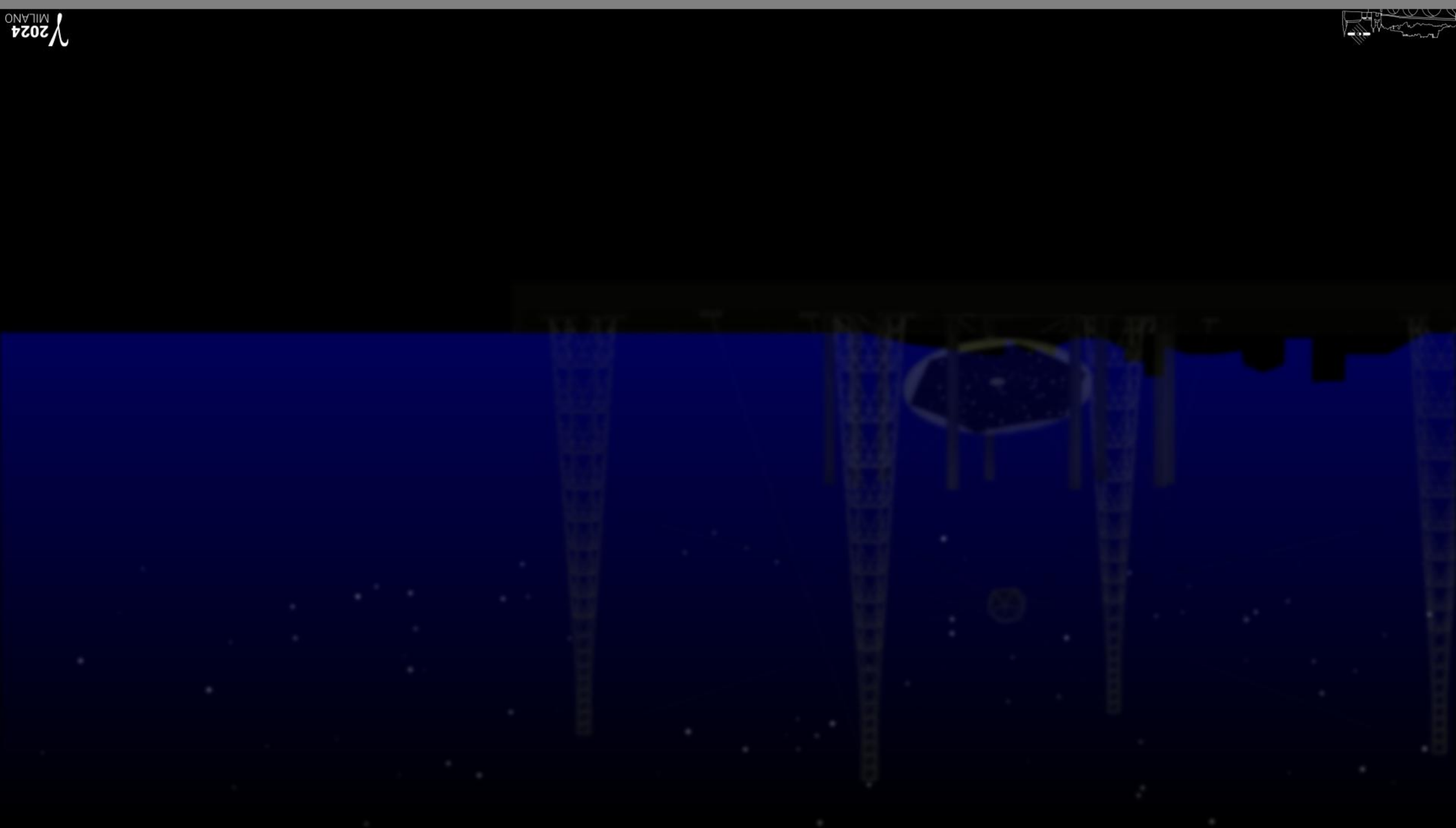
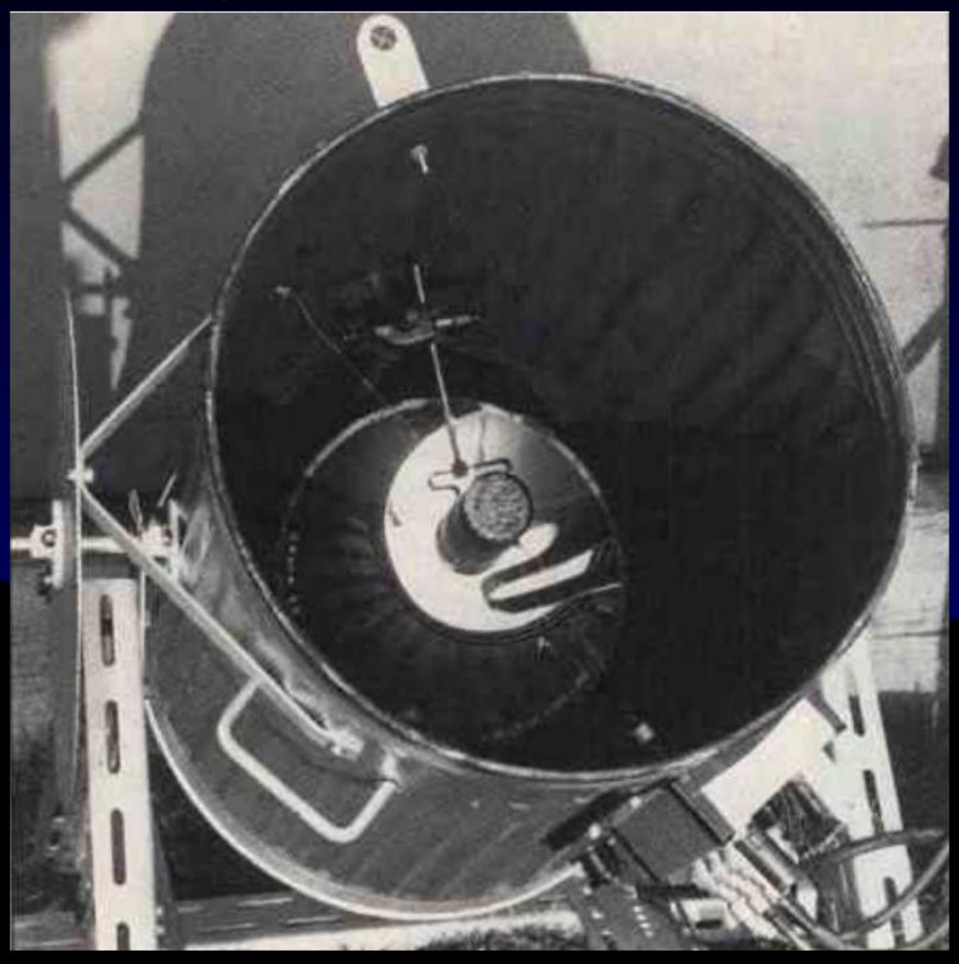

2024
MILANO

Imaging with Telescopes

Imaging with Telescopes

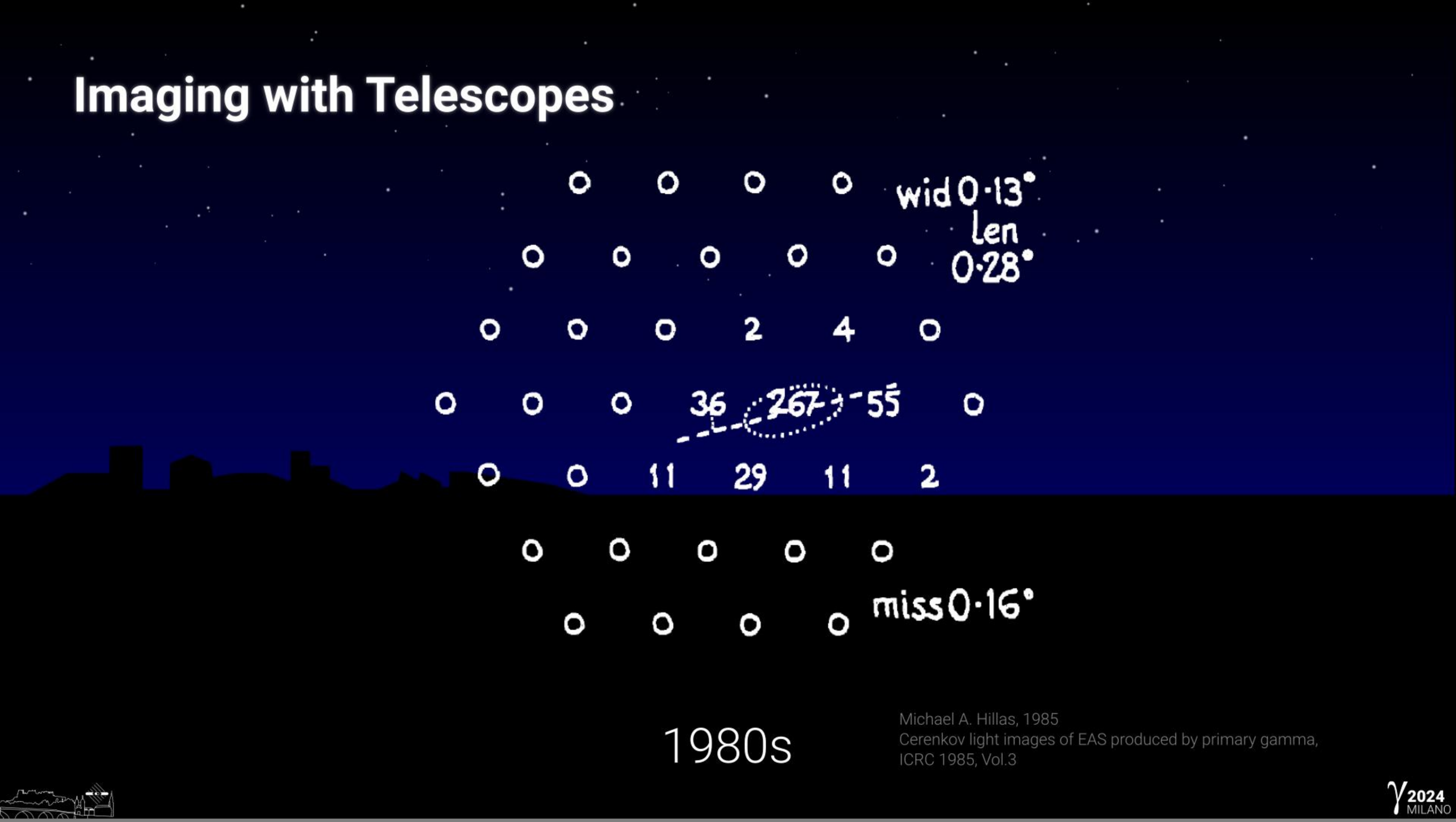


1950s

Galbraith, W., Jelley, J.V. 1953
Light Pulses from the Night Sky associated with Cosmic Rays.
Nature 171: 349-350.

Since we discovered Cherenkov radiation from airshowers, we tried to use it for astronomy.

Imaging with Telescopes



Notably Hillas, Weeks and friends started to think about imaging.

Imaging with Telescopes

1980s

Catanese, Michael and Weekes, Trevor C, 1999
Very High Energy Gamma-Ray Astronomy
Publications of the Astronomical Society of the Pacific
Vol.111, p.1193

So they adopted a left over mirror

Imaging with Telescopes

1980s

Weekes, Trevor C., et al. (Whipple collaboration). 1989. Observation of TeV gamma rays from the Crab nebula using the atmospheric Cerenkov imaging technique. Astrophysical Journal 342: 379-395.

and after some forth and back equiped it with a camere for imaging.

Imaging with Telescopes

1980s

Weekes, Trevor C., et al. (Whipple collaboration). 1989. Observation of TeV gamma rays from the Crab nebula using the atmospheric Cerenkov imaging technique. Astrophysical Journal 342: 379-395.

And imaging turned out to be a good idea.

Imaging with Telescopes

1980s

Weekes, Trevor C., et al. (Whipple collaboration). 1989. Observation of TeV gamma rays from the Crab nebula using the atmospheric Cerenkov imaging technique. Astrophysical Journal 342: 379-395.

In fact, imaging worked so well

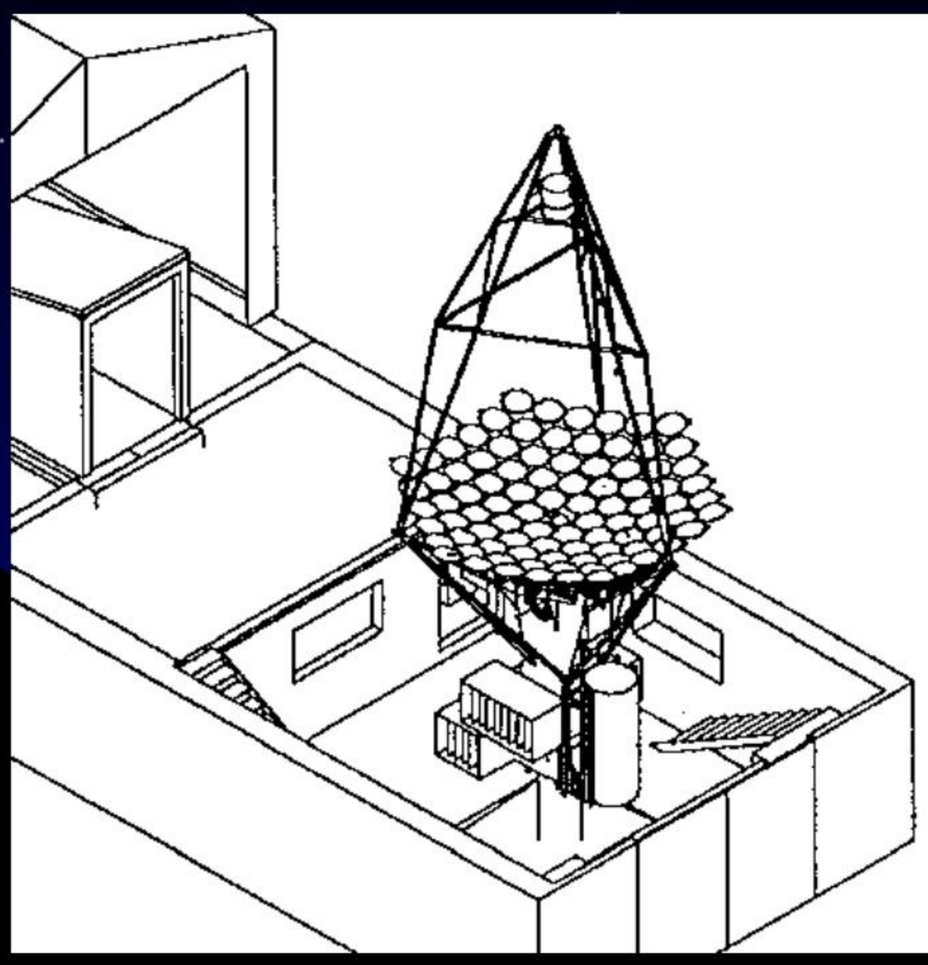
Imaging with Telescopes

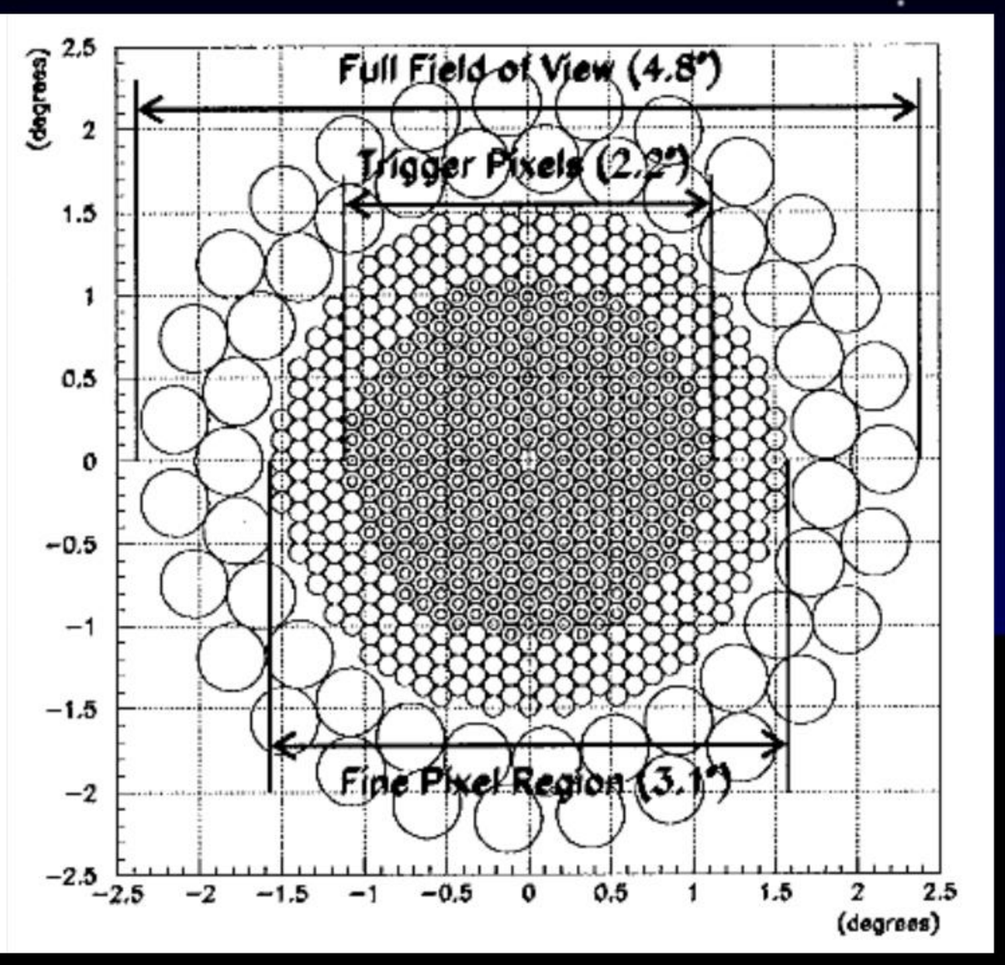
Towards a major atmospheric Cherenkov detector for TeV astroparticle physics.

1992

that we all came together to rush 'Towards a mayor atmospheric Cherenkov detector for astroparticle physics'. From here on, we pushed on three key aspects in particular to lower the energy threshold and imporve the reconstruction power.

Imaging with Telescopes



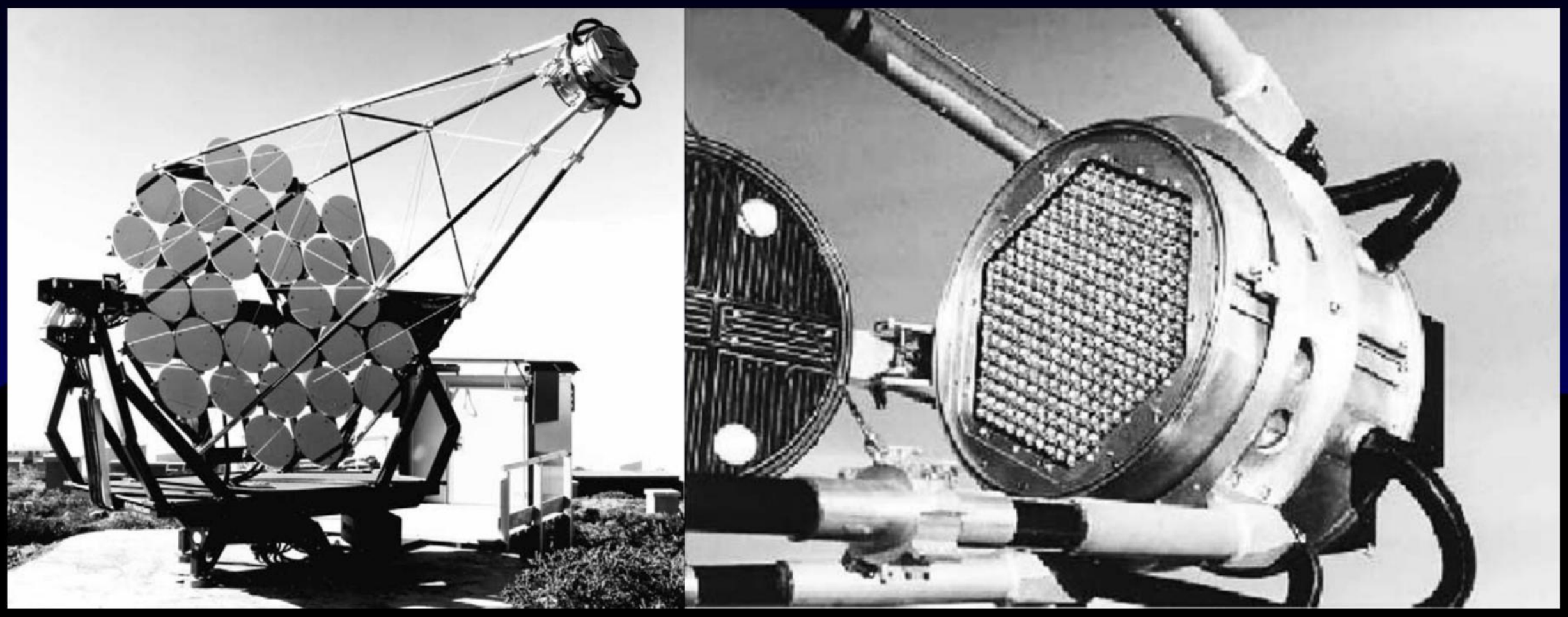


1996

Barrau A., Bazer-Bachi R., Beyer E. et al., 1998
The CAT imaging telescope for very-high-energy gamma-ray astronomy
Nuclear Instruments and Methods Vol.416 II p.278-292

Much finer pixelation.

Imaging with Telescopes



1997

Puehlhofer, G. and Bolz, O. and Goetting, N., 2003
The technical performance of the HEGRA system of imaging air Cherenkov telescopes
Astroparticle Physics, Vol.20 III, p267-291

Finer pixelation and moving up onto mountains.

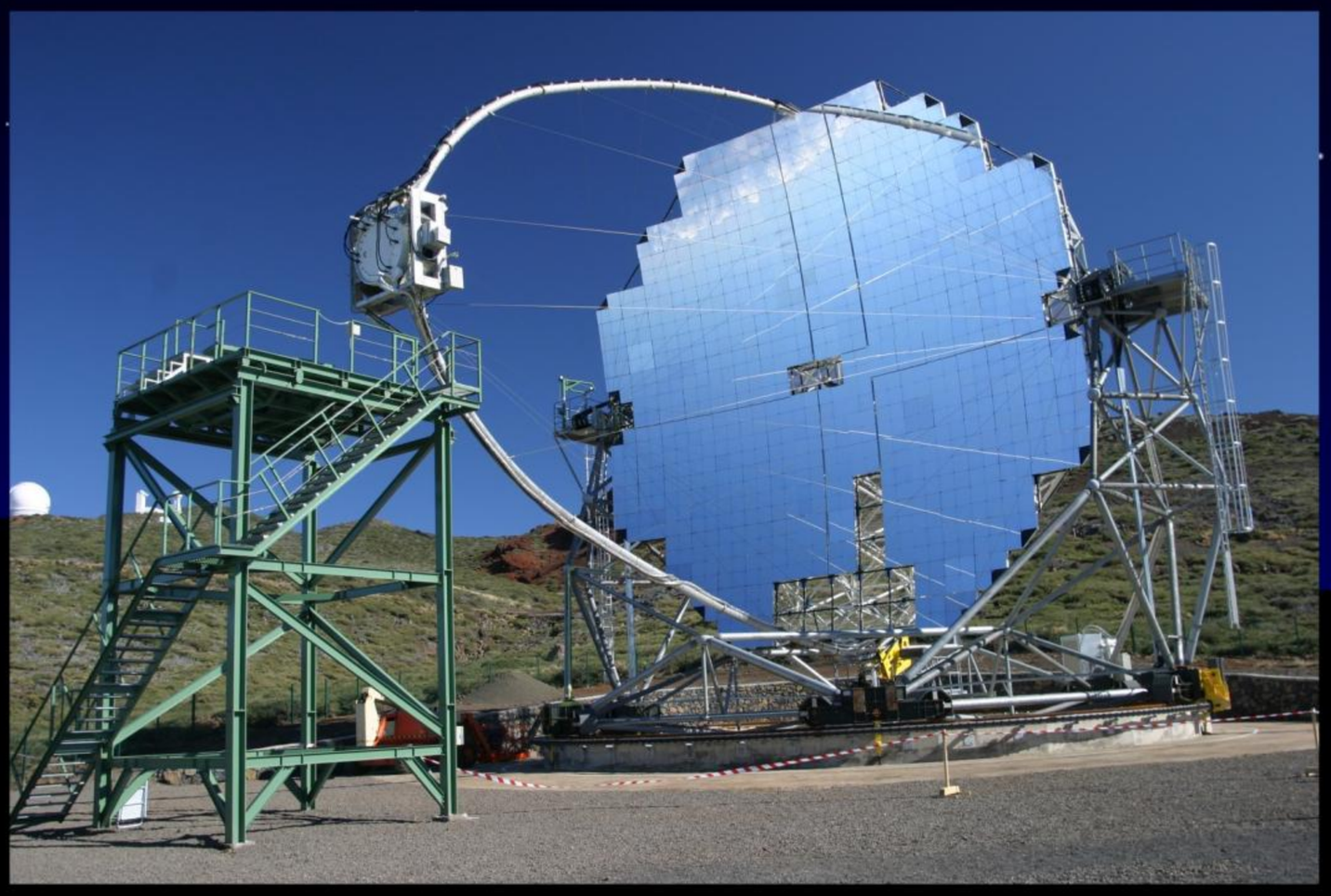
Imaging with Telescopes

2002 - 2004

Credit: Christian Foehr
https://www.mpi-hd.mpg.de/HESS/pages/about/

Larger mirrors and moving up into the highlands.

Imaging with Telescopes



2003

Credit: Robert Wagner
https://magic.mpp.mpg.de/gallery/pictures/Inauguration/index.html

Larger mirrors.

Imaging with Telescopes

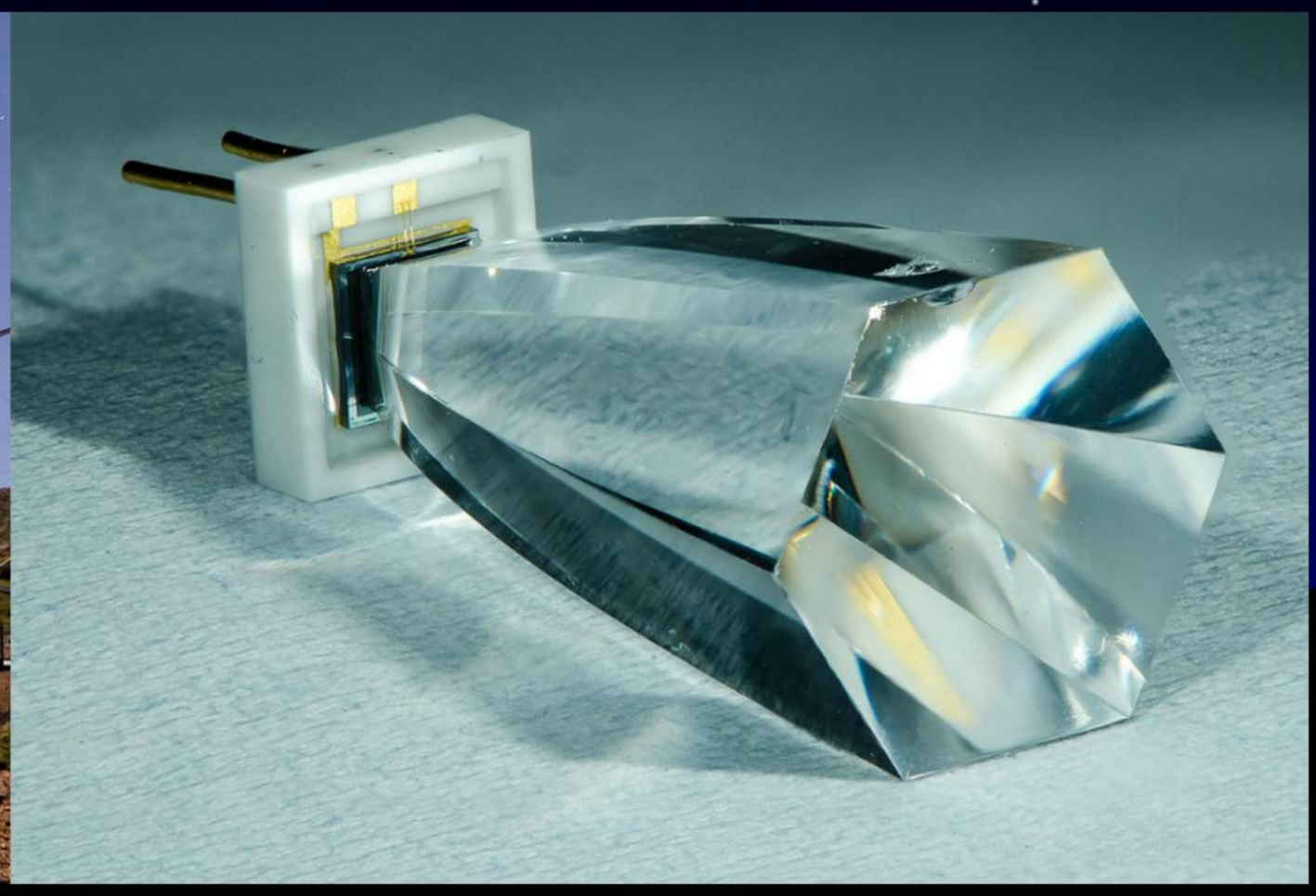
2009

Credit: Robert Wagner
https://magic.mpp.mpg.de/gallery/pictures/Inauguration/index.html

Another large mirror but with finer pixelation.

Imaging with Telescopes

Credit: Jens B. Buss

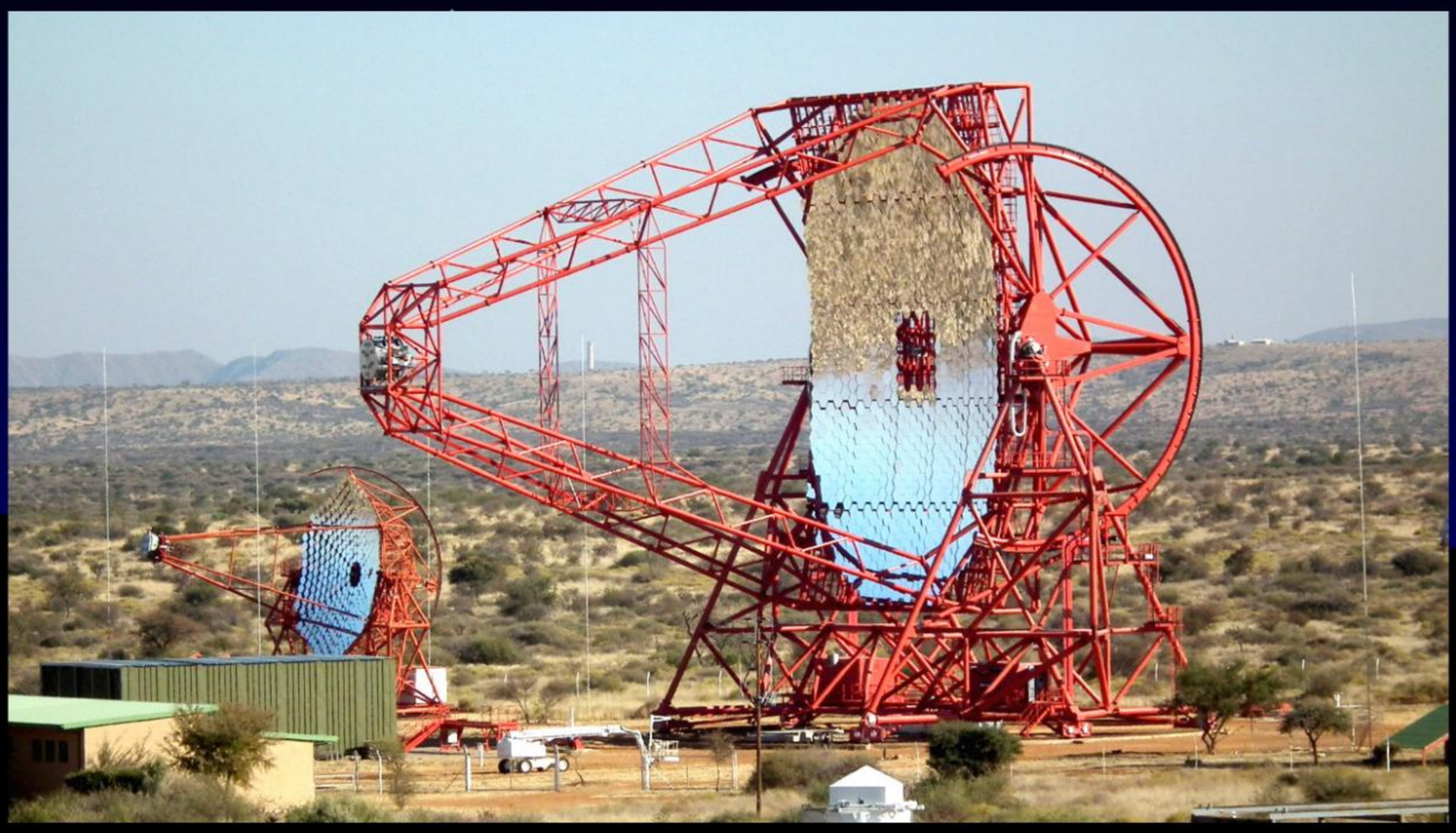


Credit: Thomas Kraehenbuehl

2011

Finer pixelation.

Imaging with Telescopes

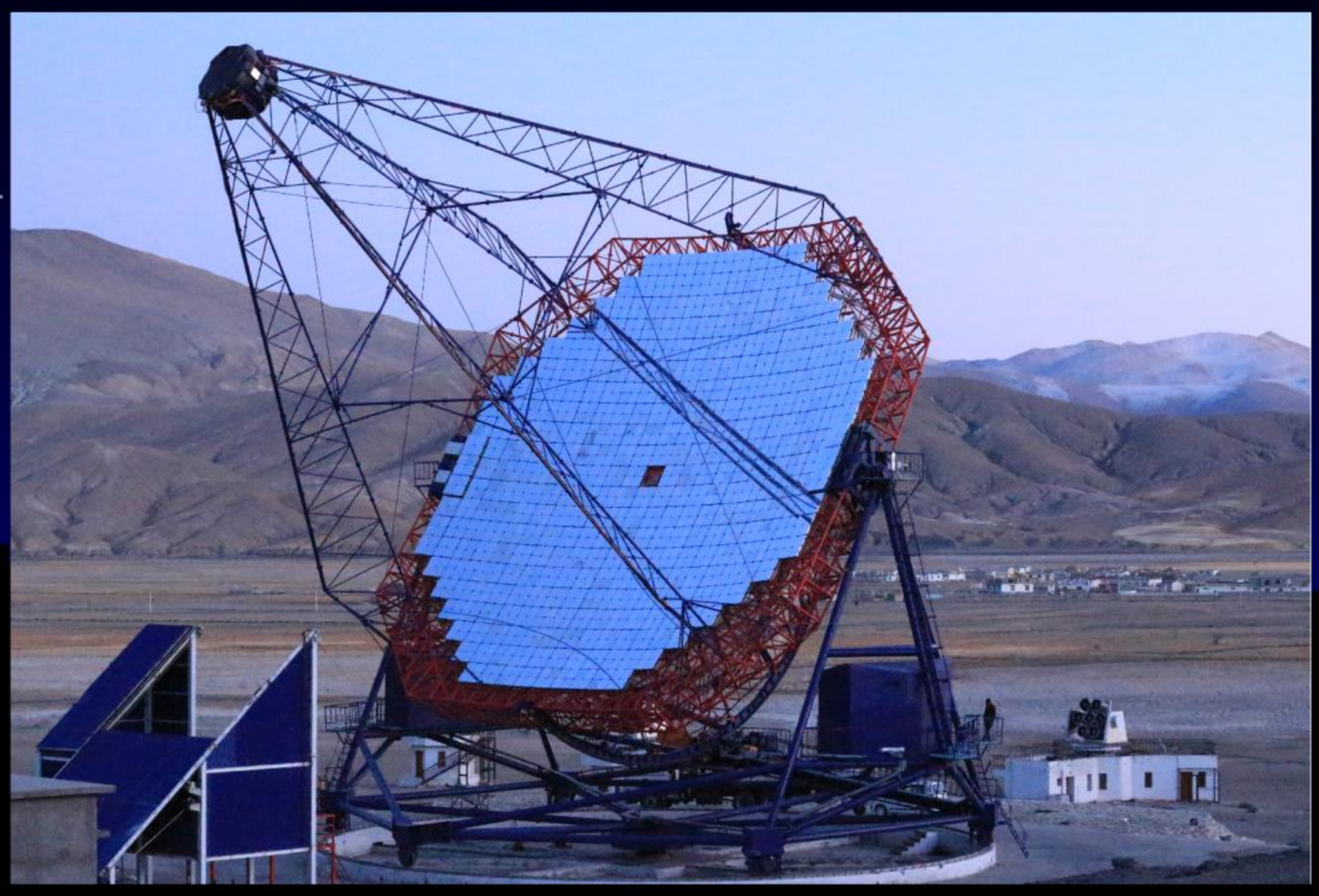


2012

Credit: Christian Foehr
https://www.mpi-hd.mpg.de/HESS/pages/about/

Larger mirrors and finer pixelation.

Imaging with Telescopes



2017

Krishna Kumar Singh, and Kuldeep Kumar Yadav 2021
20 years of Indian gamma ray astronomy using imaging Cherenkov telescopes and road ahead
Universe vol.7 no.IV p.96

Larger mirrors and higher mountains.

Imaging with Telescopes

Credit: Tomohiro Inada

2018

Large mirrors.

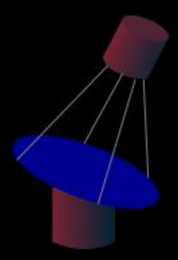
Imaging with Telescopes

Also: A seroius attempt to reduce aberrations and widen the field-of-view.

Imaging with Telescopes

Imaging with Cherenkov telescopes has come a long way.

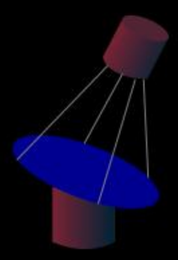
Limits of Telescopes



But now the physical limits of imaging with telescopes start to show.

Limits of Telescopes

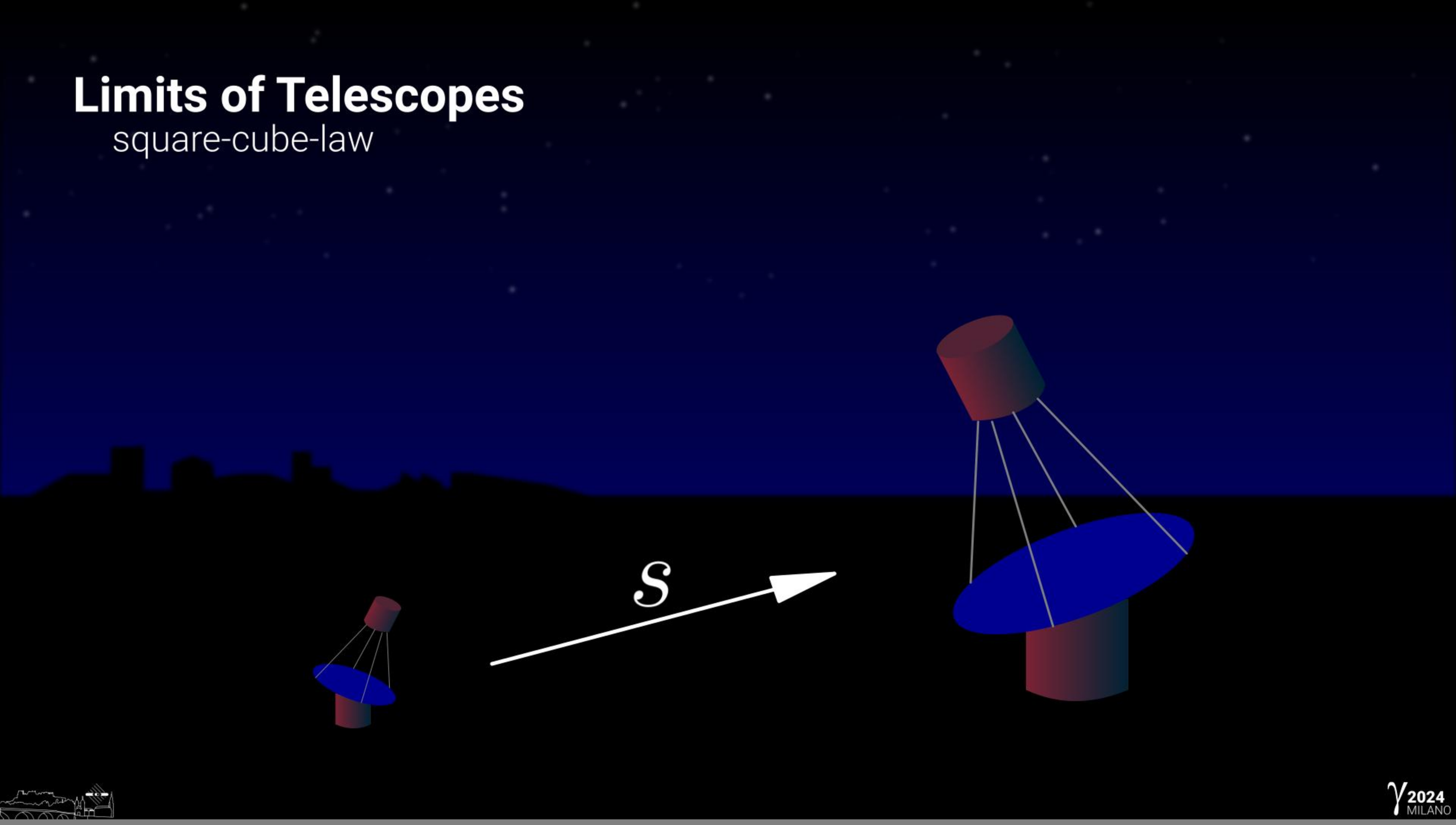
square-cube-law



The square-cube-law makes it increasingly difficult to build...

Limits of Telescopes

square-cube-law

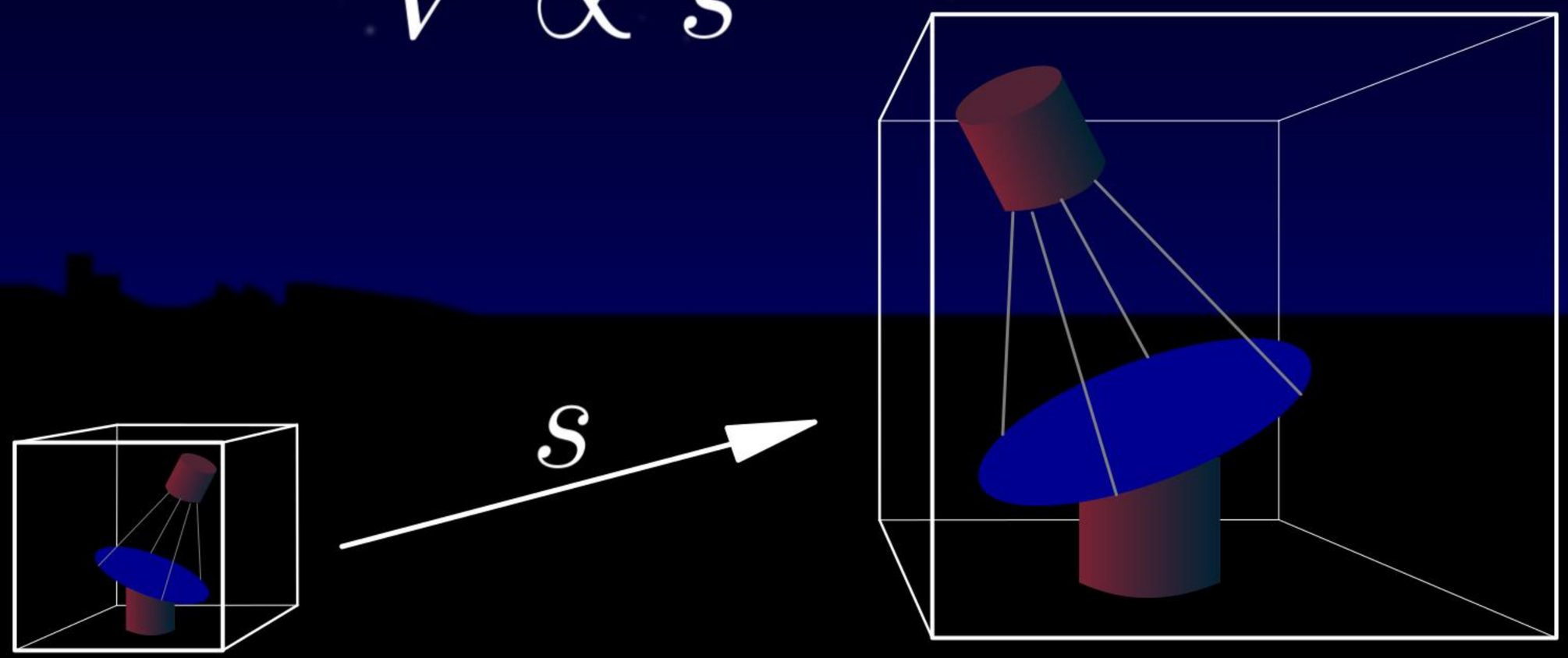


ever larger telescopes because

Limits of Telescopes

square-cube-law

$$V \propto s^3$$

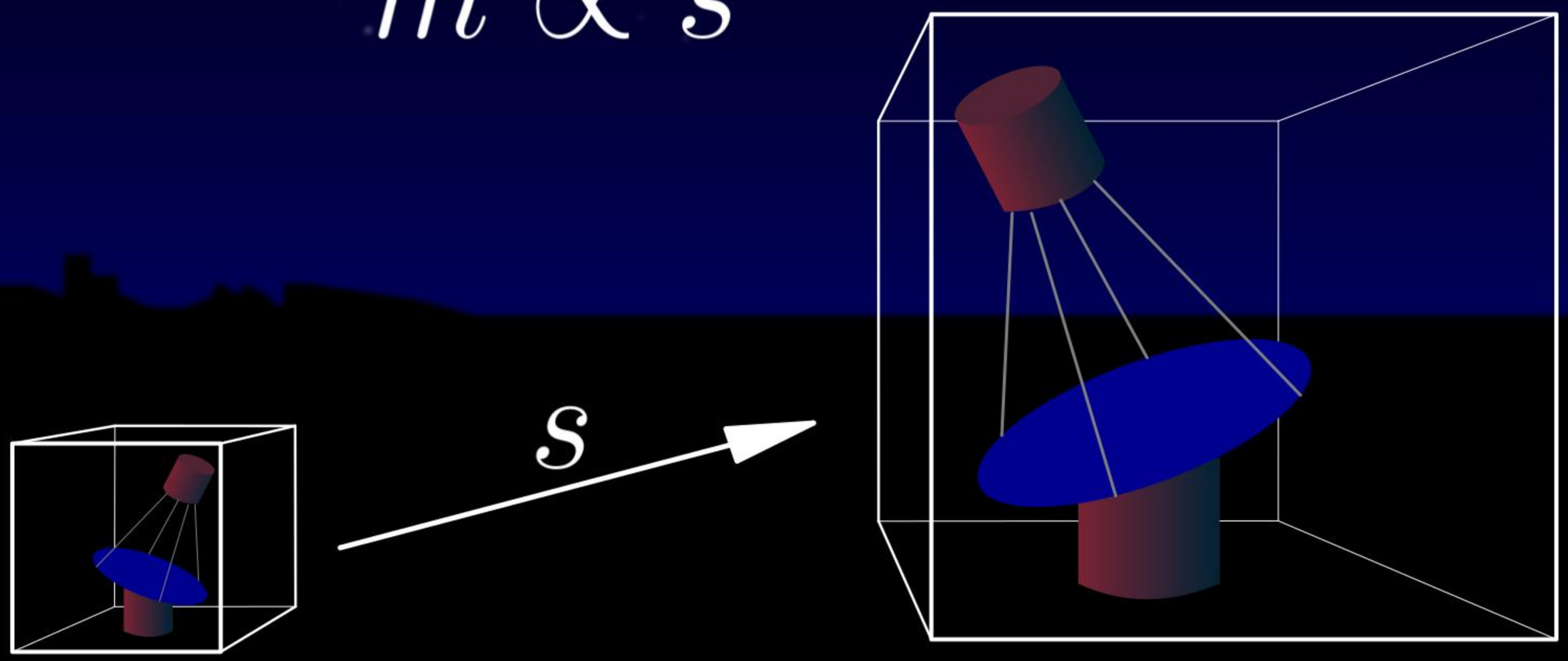


the volume

Limits of Telescopes

square-cube-law

$$m \propto s^3$$

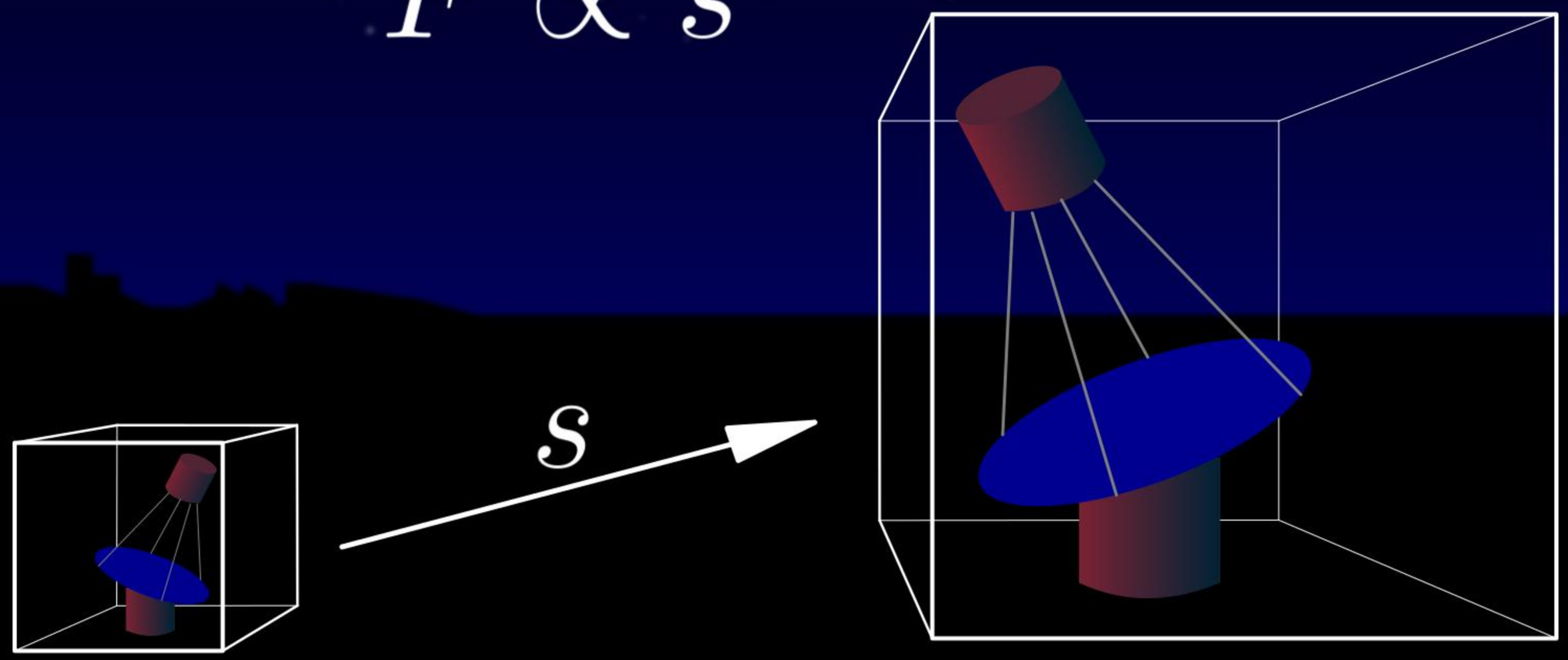


and thus the mass

Limits of Telescopes

square-cube-law

$$F \propto s^3$$



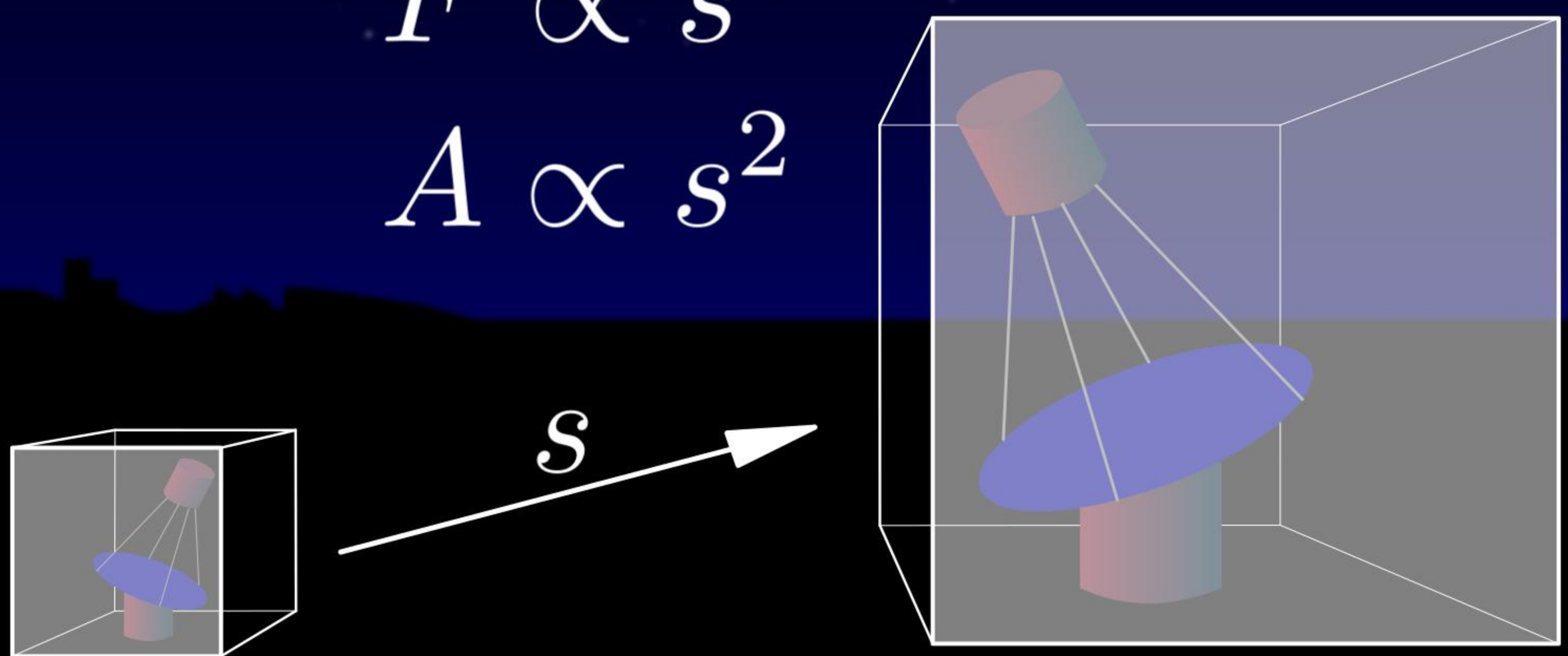
and thus the gravitational forces scale cubic.

Limits of Telescopes

square-cube-law

$$F \propto s^3$$

$$A \propto s^2$$



whereas the areas which have to tolerate these forces only scale quadratic.
While the square-cube-law can at least be postponed by spending more resources and engineering

Limits of Telescopes

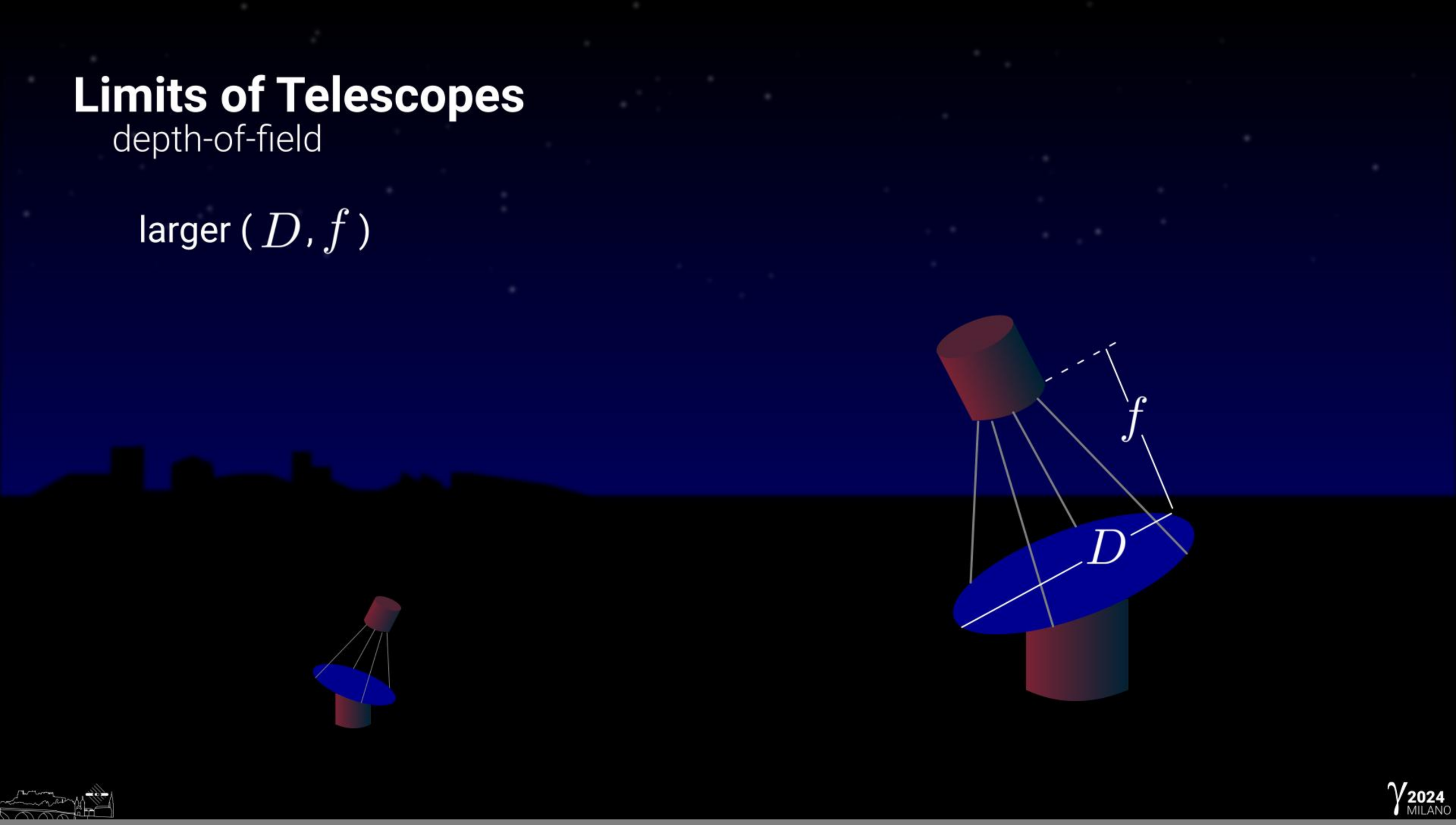
depth-of-field

the limit of a narrowing depth-of-field can not. It turns out that the three key measures we pushed on to lower the energy threshold and improve the reconstruction power, this is ...

Limits of Telescopes

depth-of-field

larger (D, f)



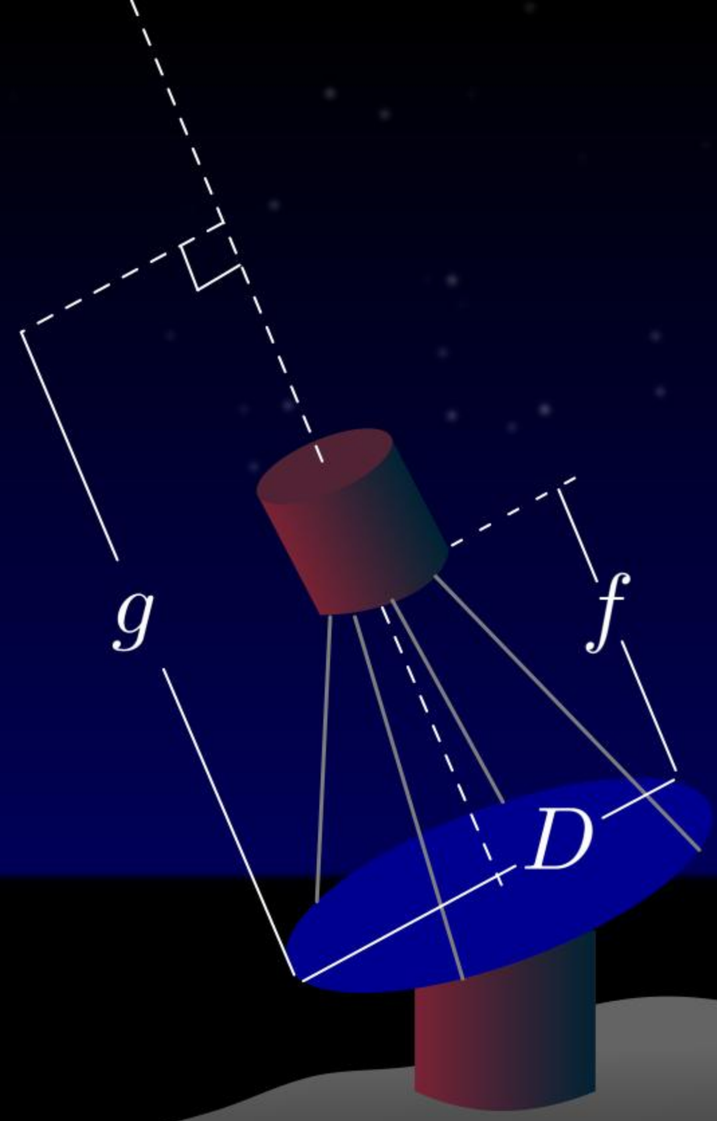
larger mirrors

Limits of Telescopes

depth-of-field

larger (D, f)

on mountains, closer to shower (g)



moving up onto mountains

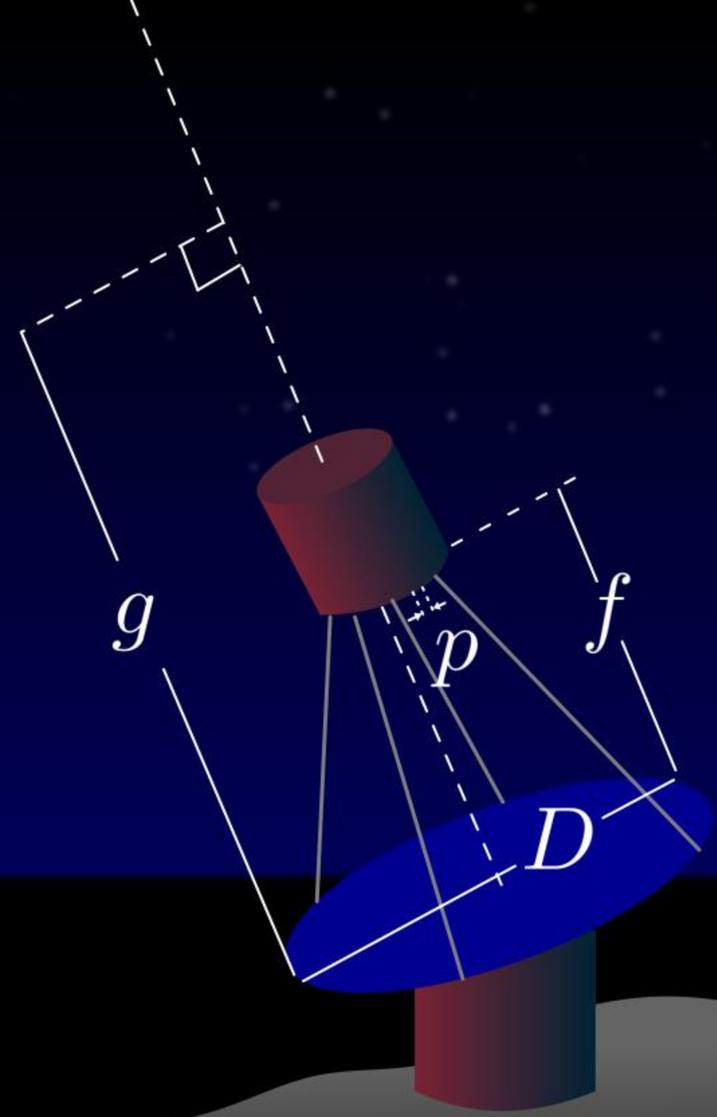
Limits of Telescopes

depth-of-field

larger (D, f)

on mountains, closer to shower (g)

smaller pixels (p)



and finer pixelation

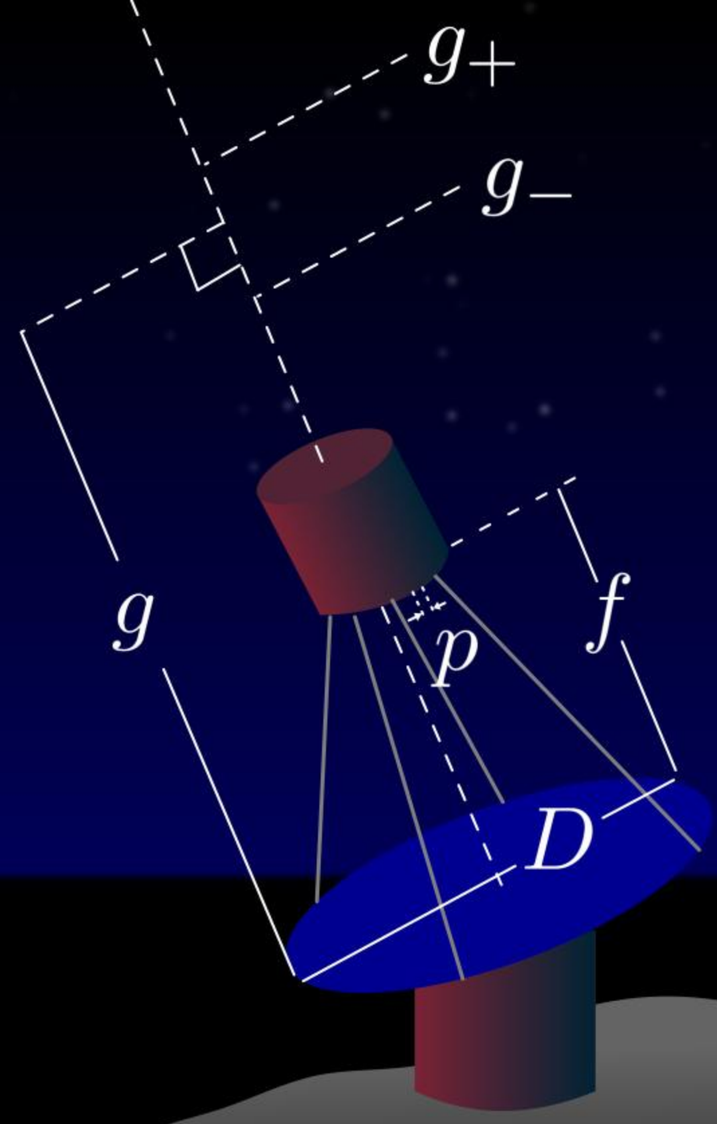
Limits of Telescopes

depth-of-field

larger (D, f)

on mountains, closer to shower (g)

smaller pixels (p)



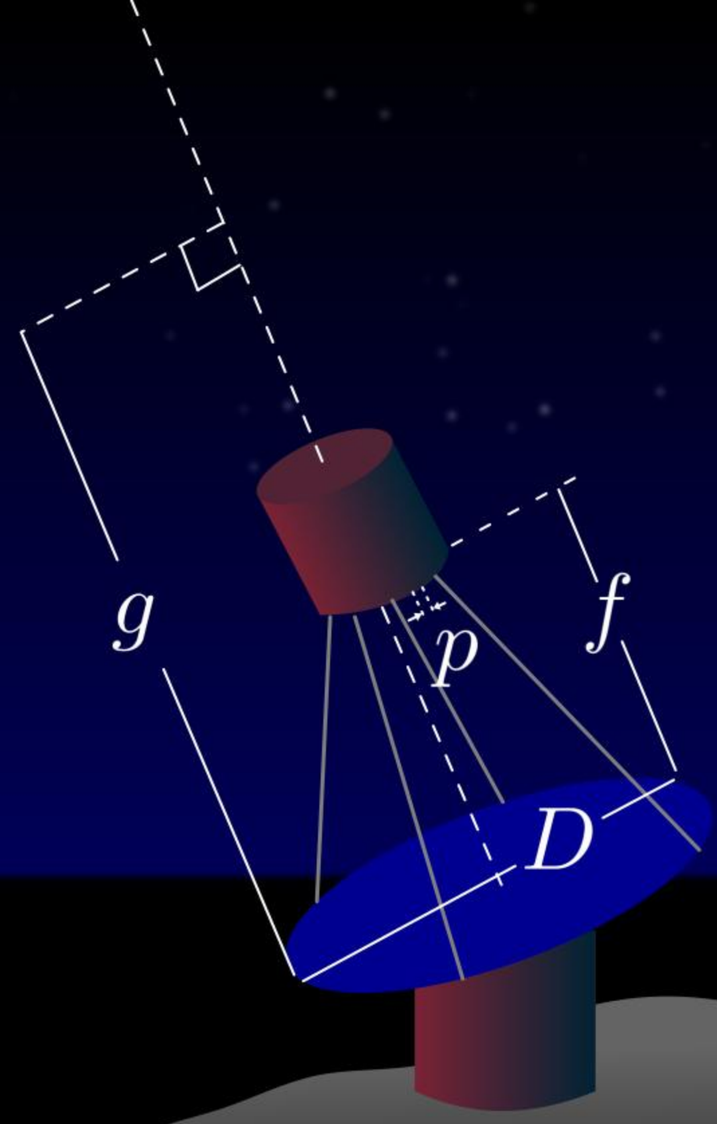
$$g_\pm = g(1 \pm pg/(2fD))$$

K. Bernloehr et al. 2013
Monte Carlo design studies for the Cherenkov Telescope Array
Astroparticle Physics, vol.43 p.171-188

all narrow the telescope's depth-of-field and thus blurr its images.

Limits of Telescopes

depth-of-field



$$g_{\pm} = g(1 \pm pg/(2fD))$$

K. Bernloehr et al. 2013
Monte Carlo design studies for the Cherenkov Telescope Array
Astroparticle Physics, vol.43 p.171-188

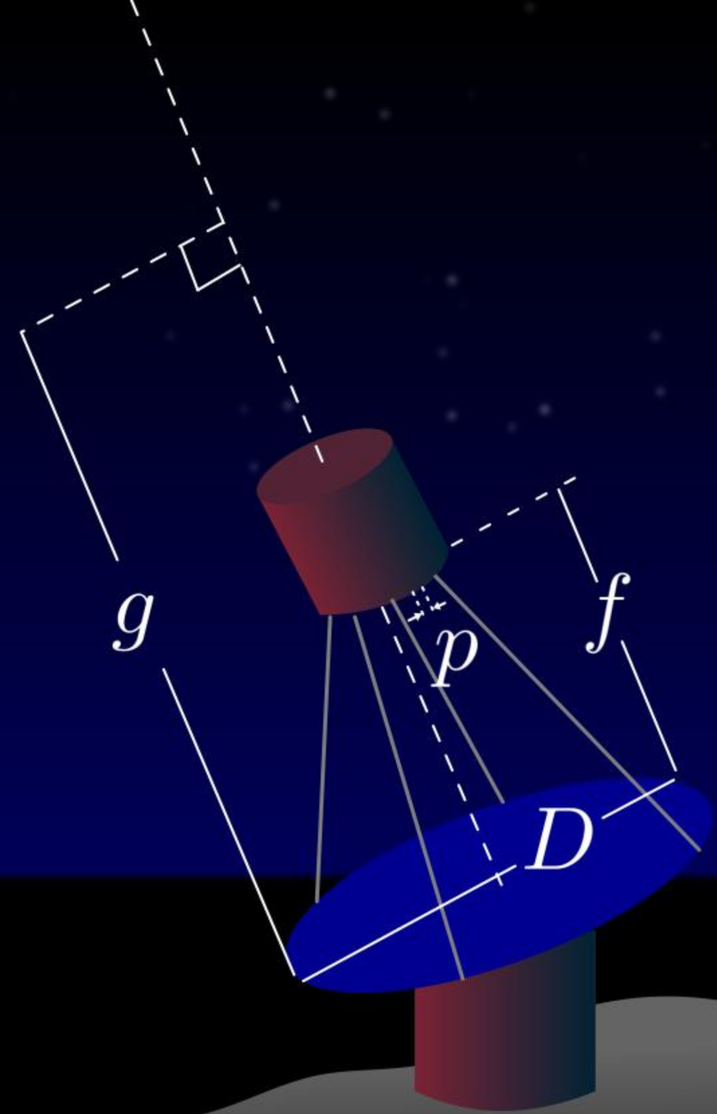
For example, and for reasons which will become obvious in a few moments, an instrument ...

Limits of Telescopes

depth-of-field

$$D = 71\,\mathrm{m}$$

$$g_\pm = g(1 \pm pg/(2fD))$$



with a seventy one meter mirror, ...

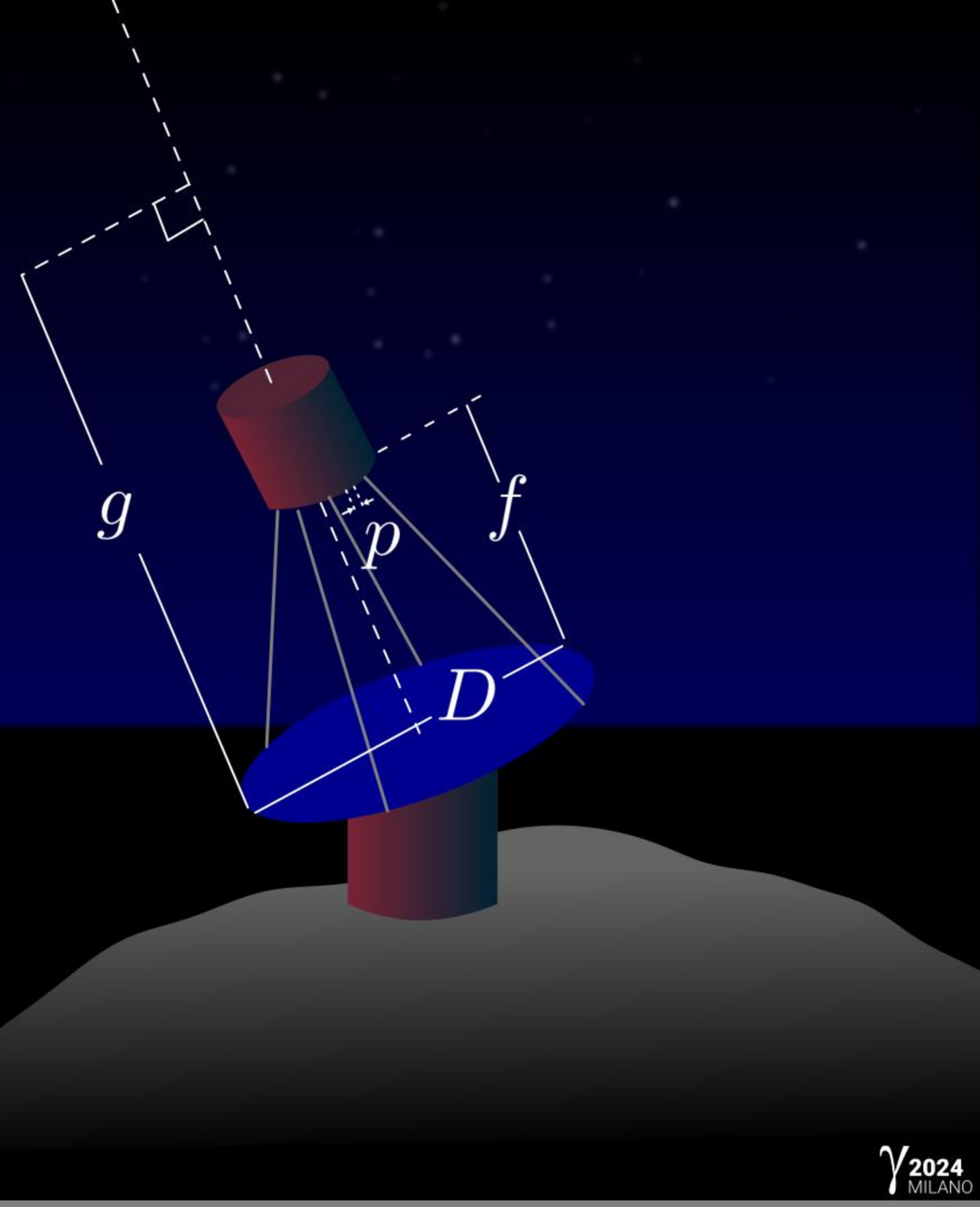
Limits of Telescopes

depth-of-field

$$D = 71\,\mathrm{m}$$

$$f/D = 1.5$$

$$g_\pm = g(1 \pm pg/(2fD))$$



a focal-ratio of one point five, ...

Limits of Telescopes

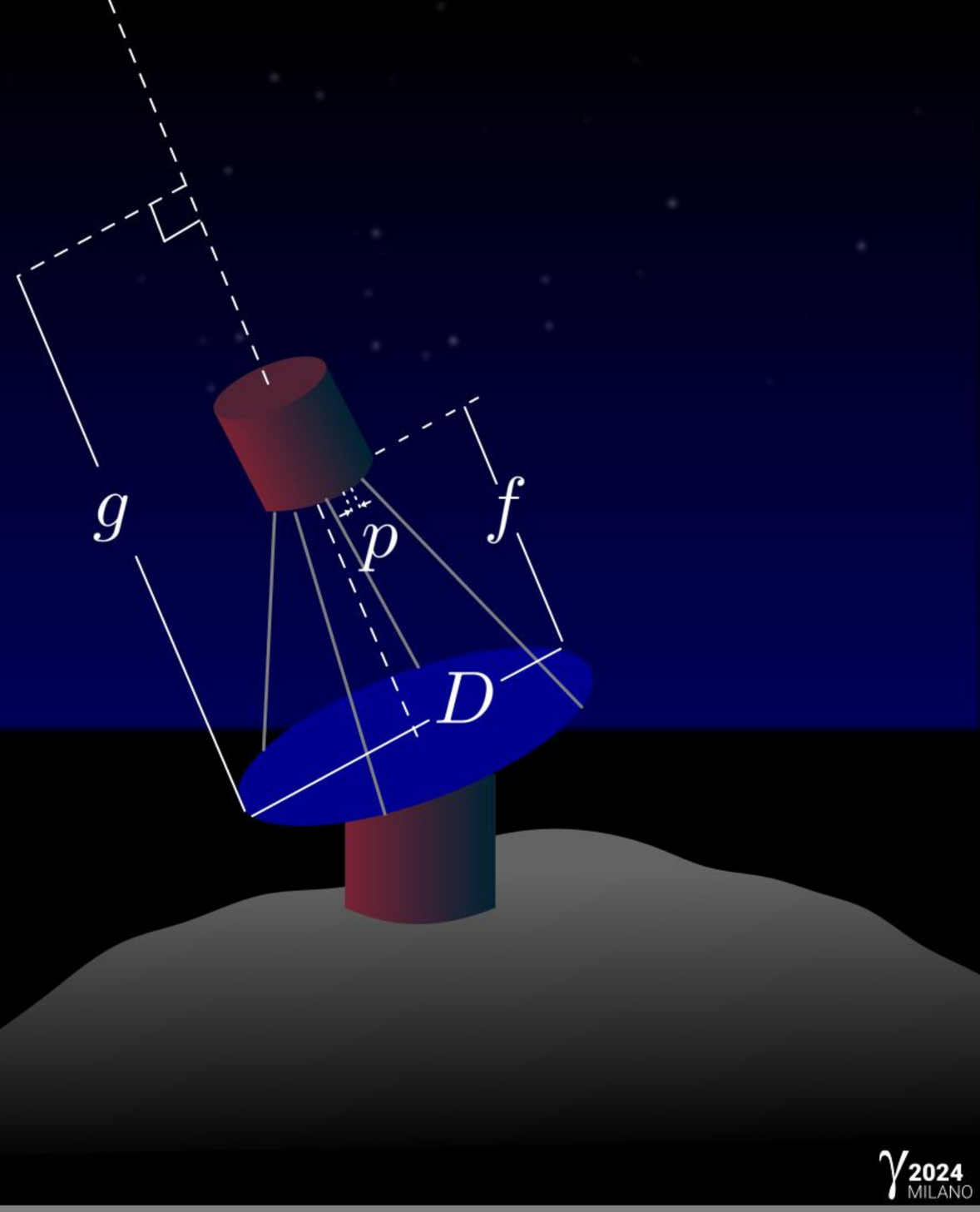
depth-of-field

$$D = 71\,\mathrm{m}$$

$$f/D = 1.5$$

$$p = 124\,\mathrm{mm}\ (0.067°)$$

$$g_\pm = g(1 \pm pg/(2fD))$$



a fine pixelation, ...

Limits of Telescopes

depth-of-field

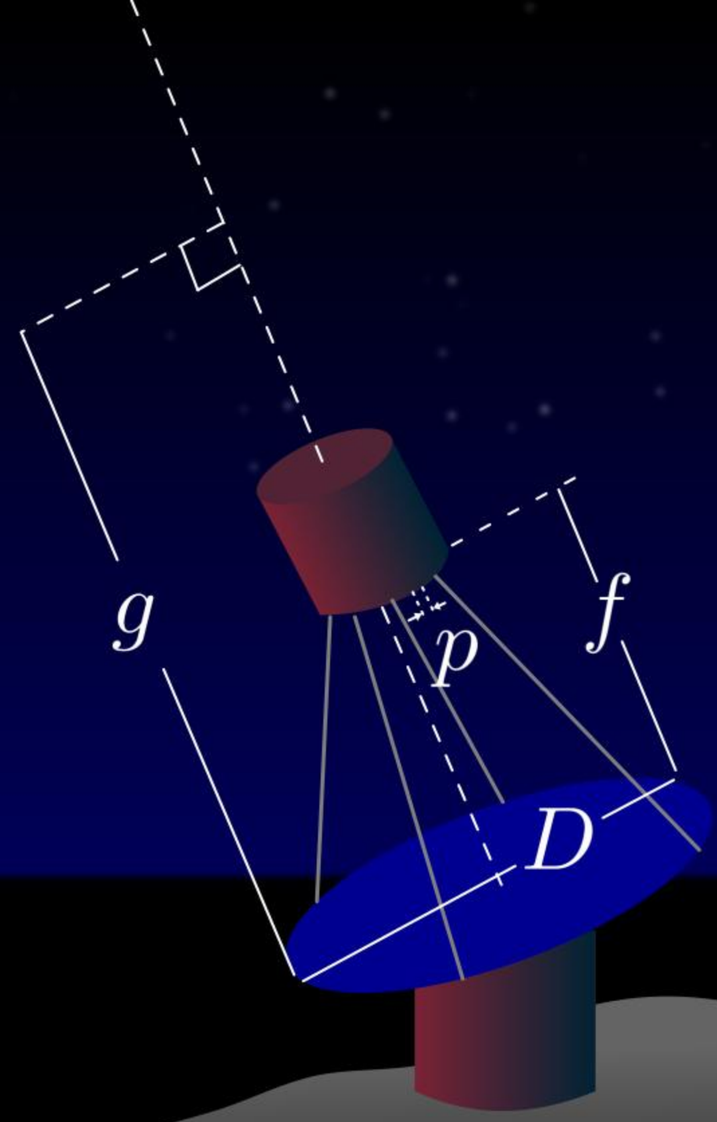
$$D = 71\,\mathrm{m}$$

$$f/D = 1.5$$

$$p = 124\,\mathrm{mm}\ (0.067°)$$

$$g = 10\,\mathrm{km}$$

$$g_\pm = g(1 \pm pg/(2fD))$$



and its focus set to ten kilometers ...

Limits of Telescopes

depth-of-field

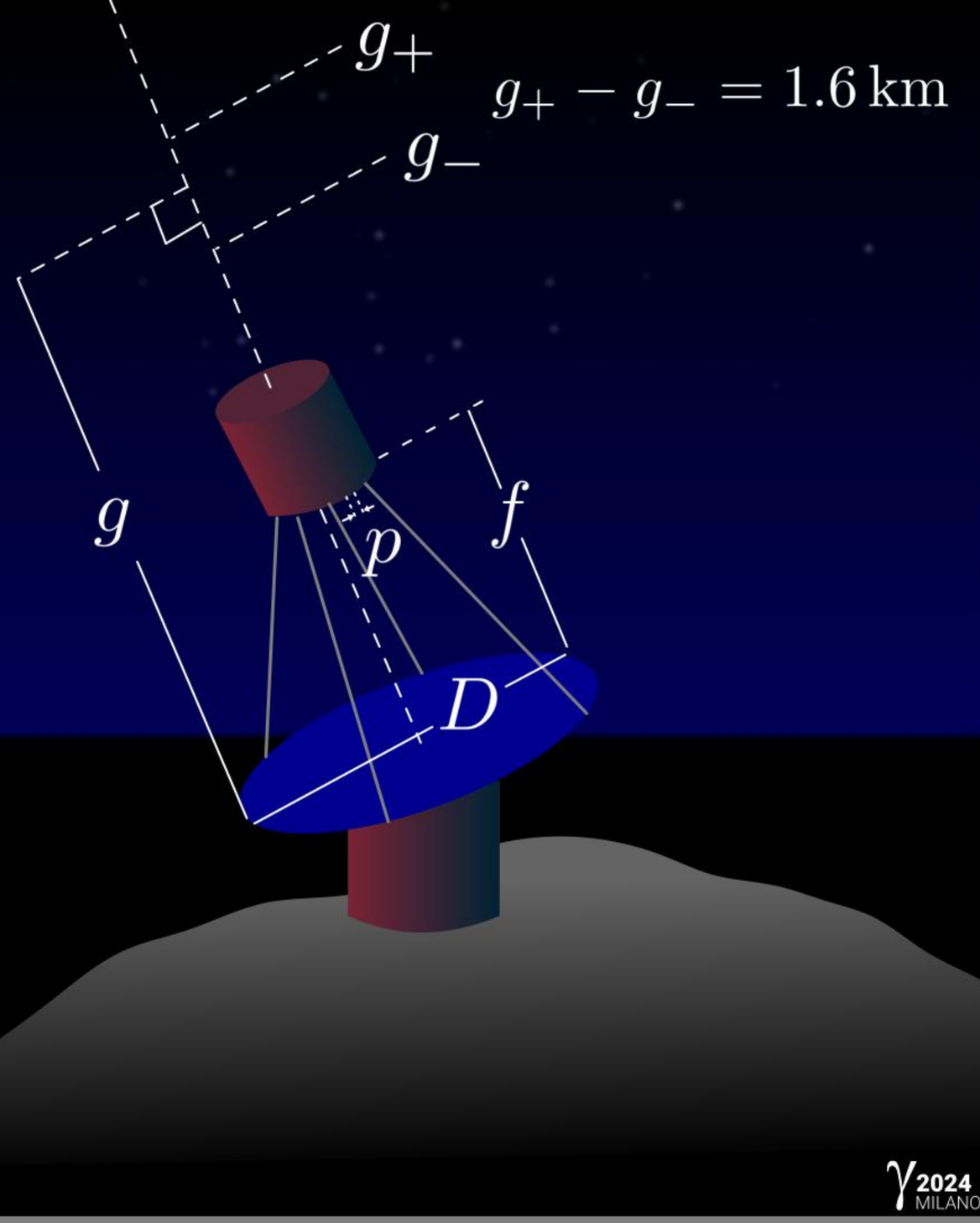
$$D = 71\,\mathrm{m}$$

$$f/D = 1.5$$

$$p = 124\,\mathrm{mm}\ (0.067°)$$

$$g = 10\,\mathrm{km}$$

$$g_\pm = g(1 \pm pg/(2fD))$$



will only be able to make a sharp image within a one point six kilometer wide range.

Limits of Telescopes

depth-of-field

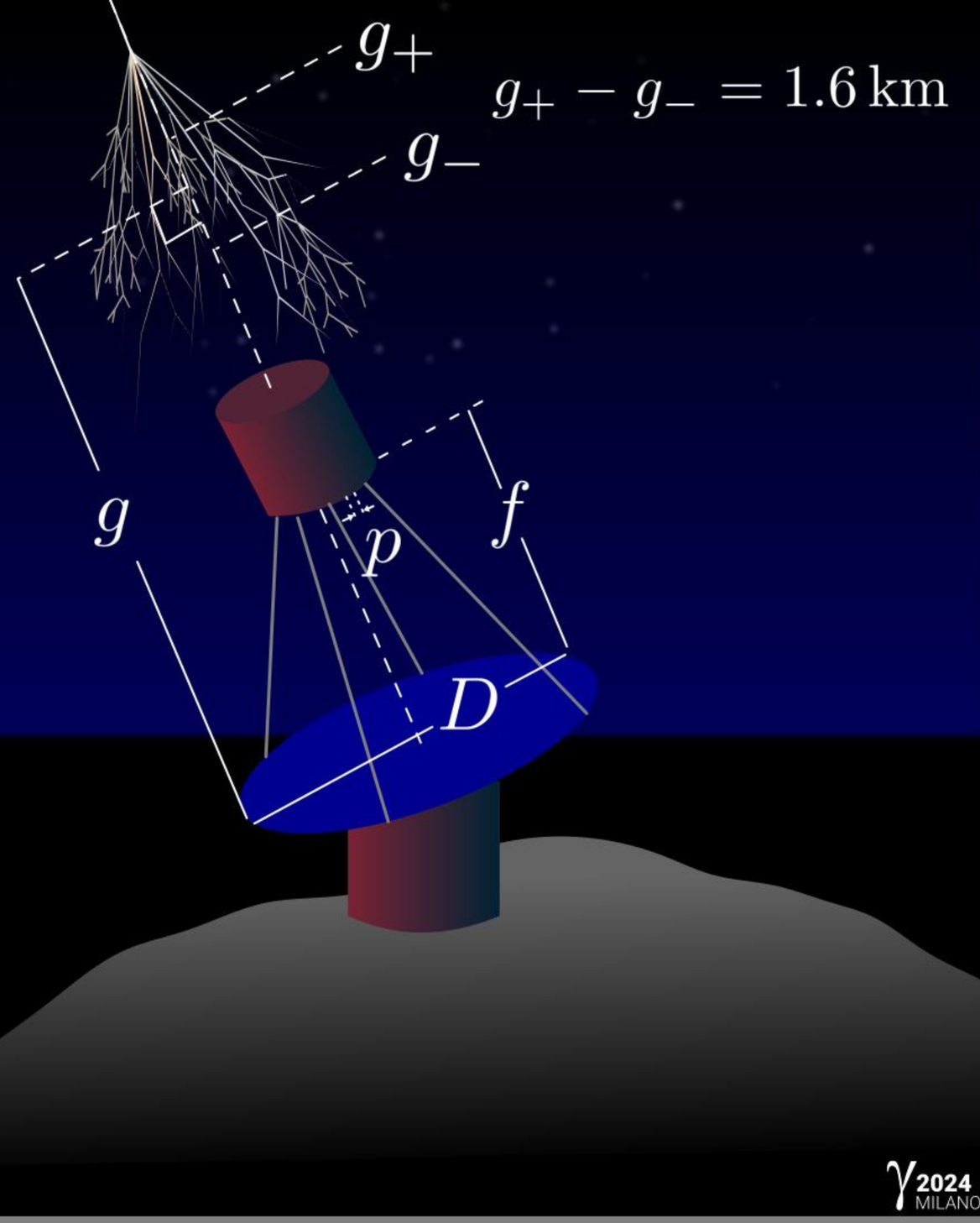
$$D = 71\,\mathrm{m}$$

$$f/D = 1.5$$

$$p = 124\,\mathrm{mm}\ (0.067°)$$

$$g = 10\,\mathrm{km}$$

$$g_\pm = g(1 \pm pg/(2fD))$$



This is a problem because the showers which we want to observe exceed this sharp range by about an order of magnitude.

Motivation

It turns out that the telescope's

Motivation

depth-of-field

aberrations

suffering from aberrations,

Motivation

deformations and misalignments

depth-of-field

aberrations

the cause of its narrow depth-of-field,

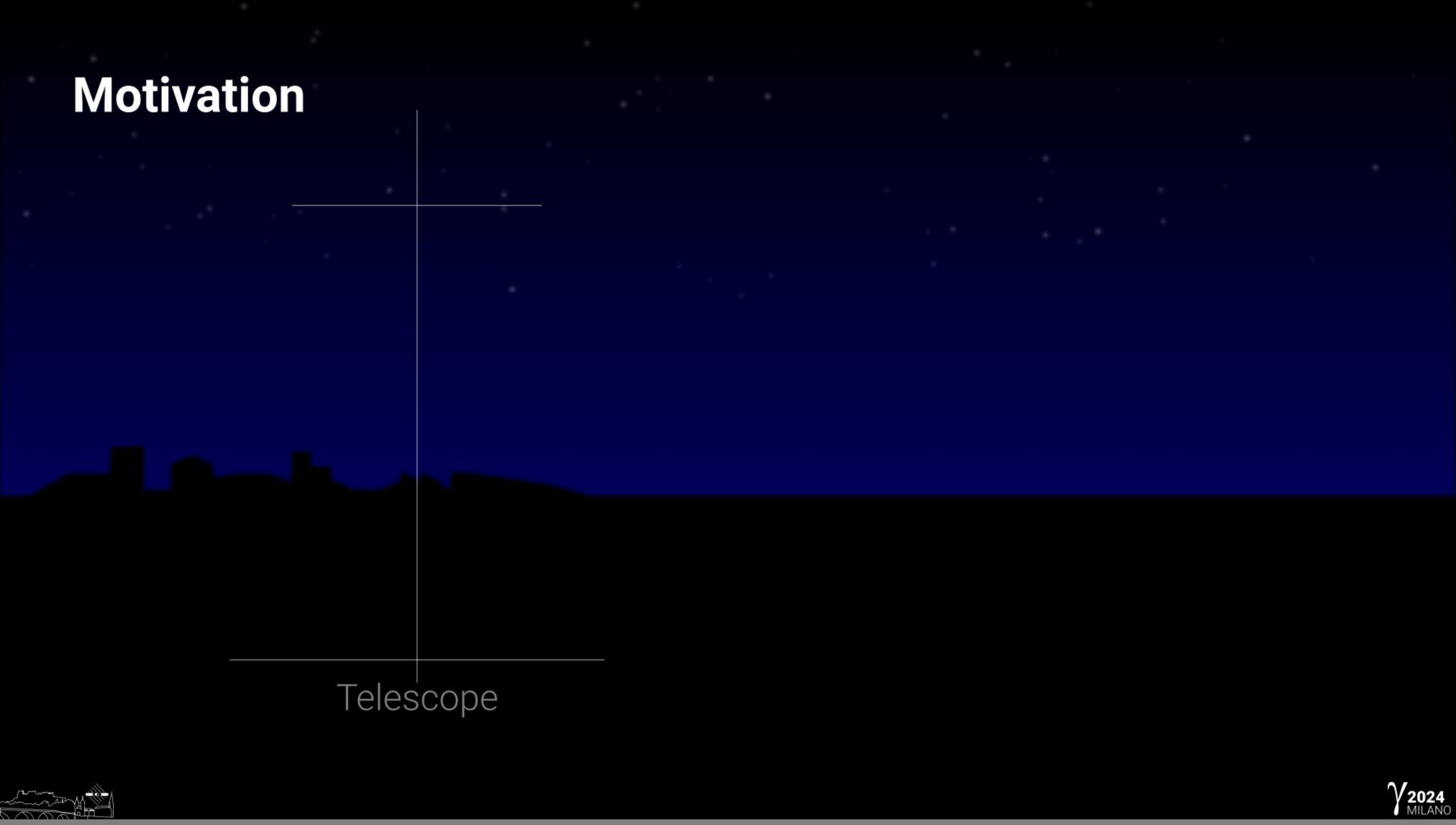
Motivation

deformations and misalignments

depth-of-field

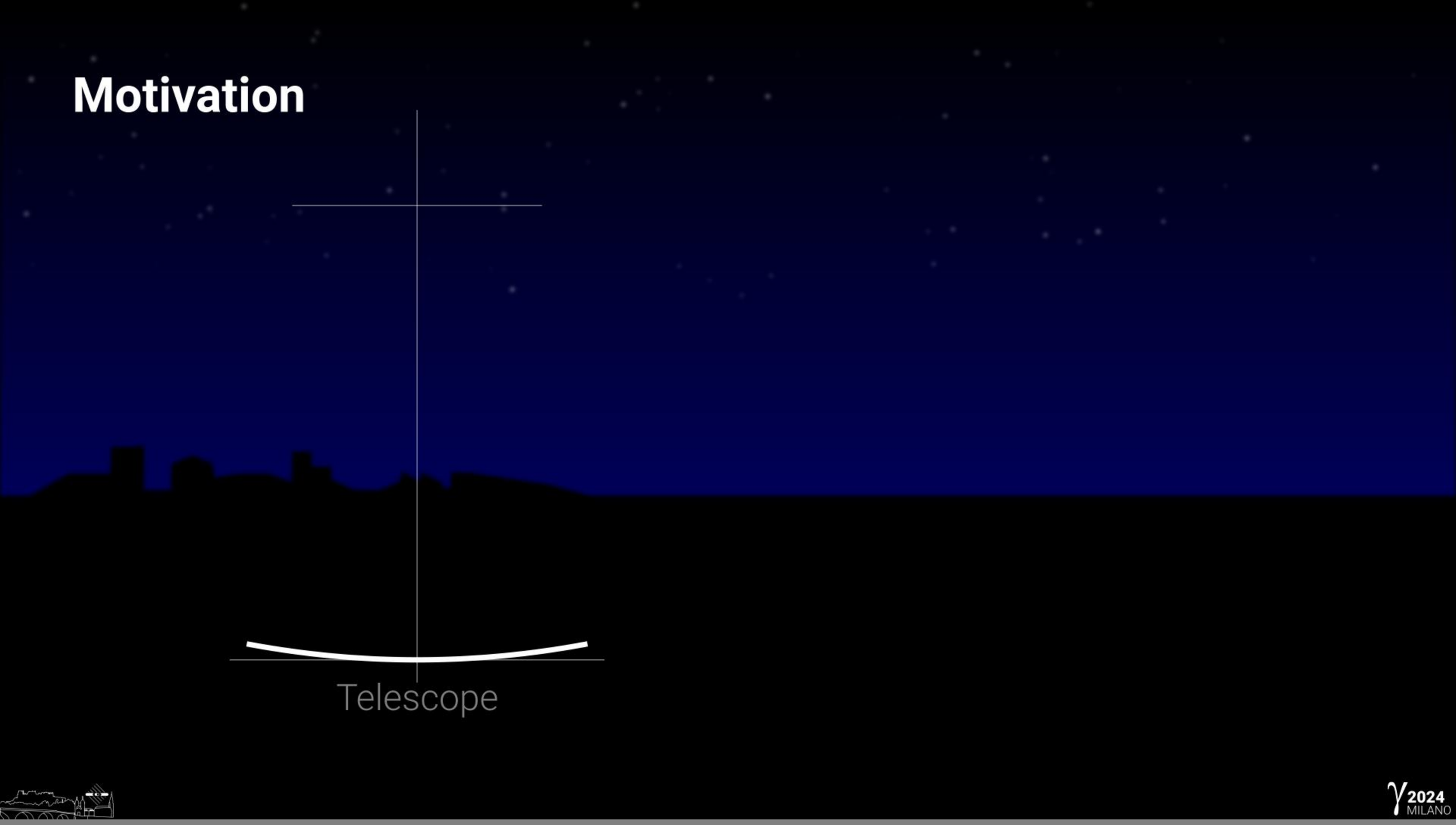
and the telescope's suffering from deformations and misalignments are all related to

Motivation



the telescope

Motivation

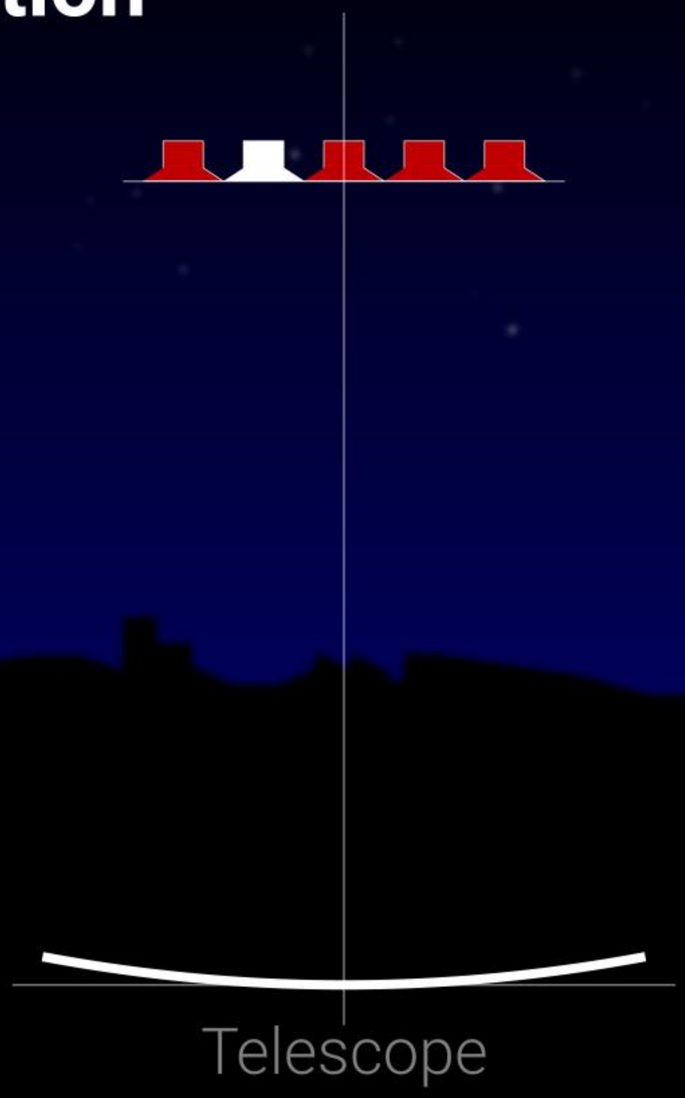


with its mirror

Motivation

and its camera

Motivation

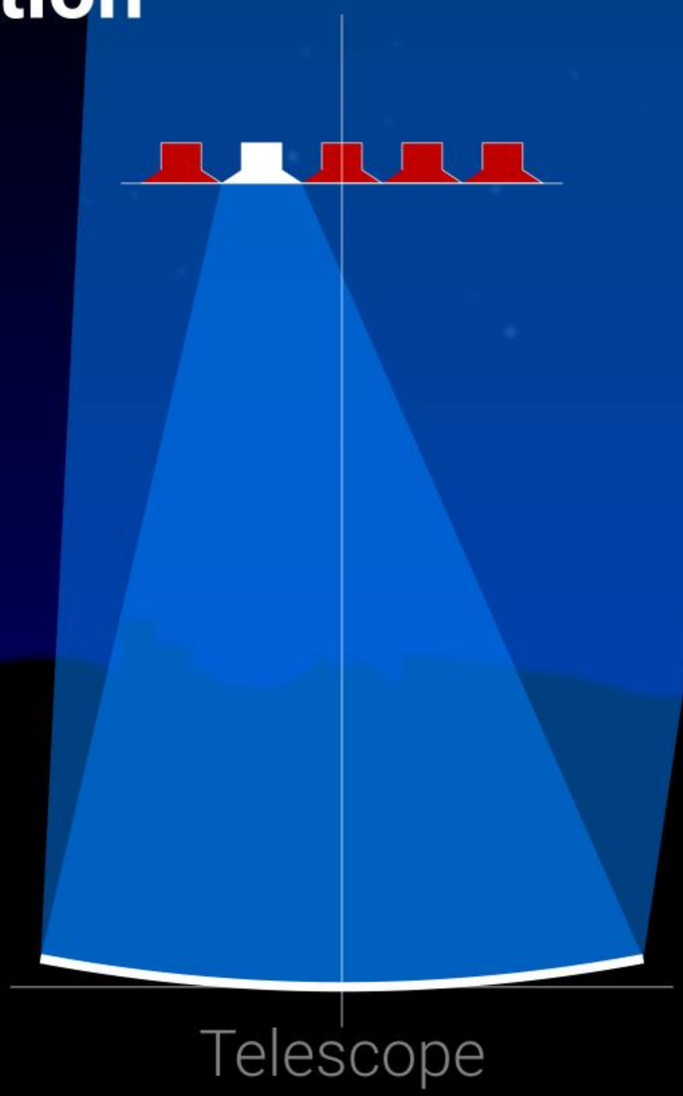


full of photosensors

Motivation

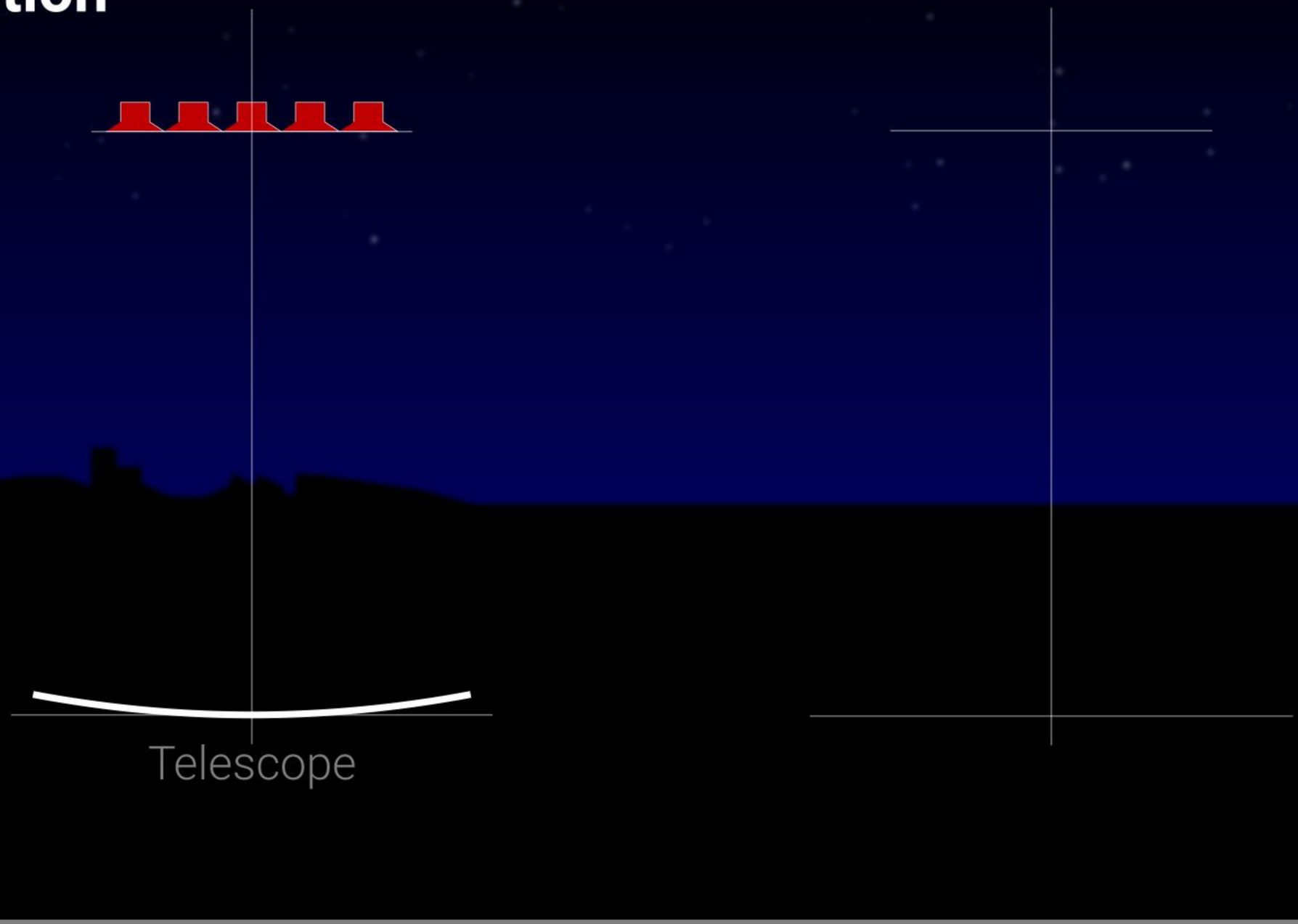
not knowing where a photon was reflected on its mirror.

Motivation



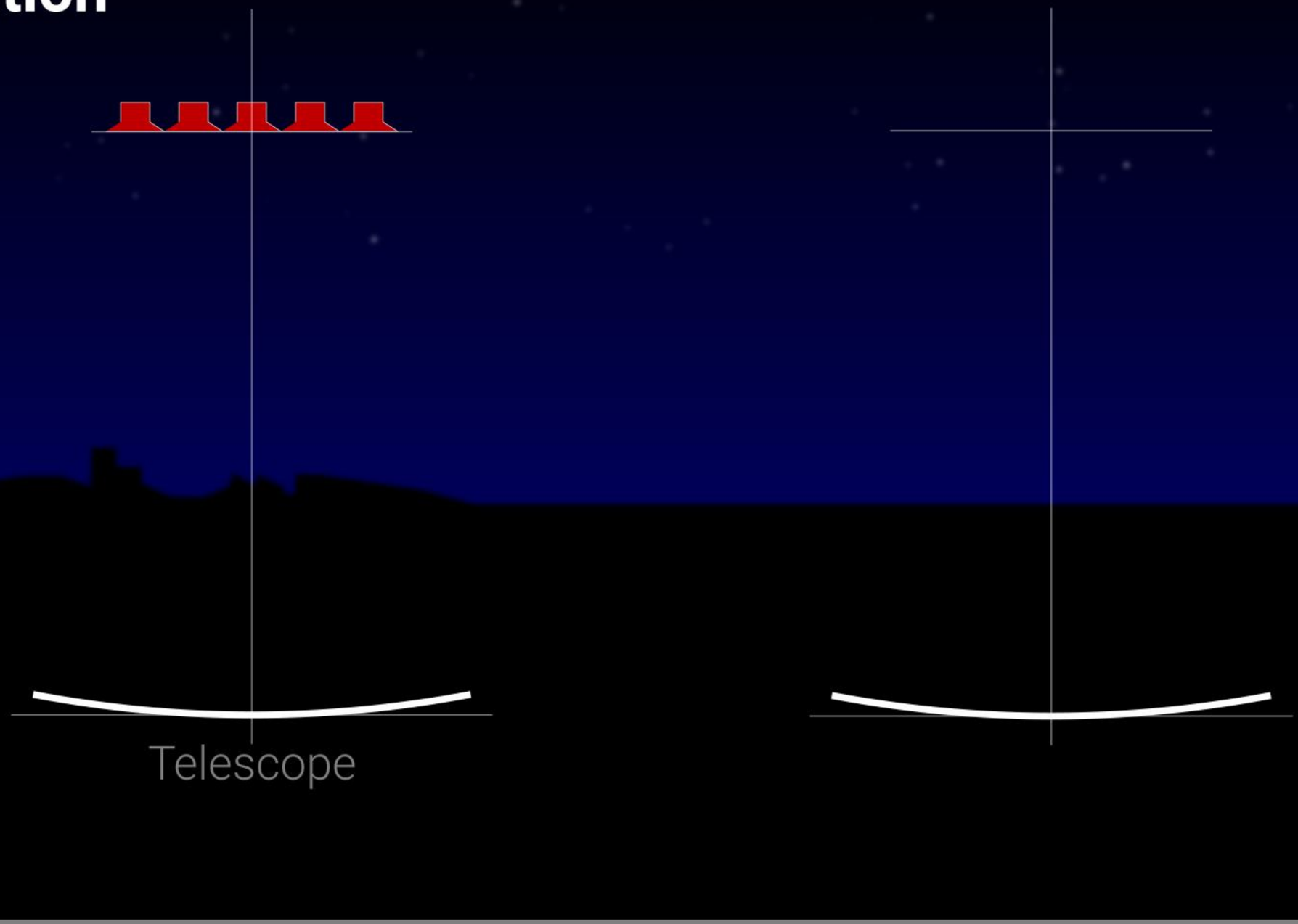
All the photons with trajectories in this beam of light will be absorbed by the same photosensor.

Motivation



Now imagine there was a new class of instrument

Motivation

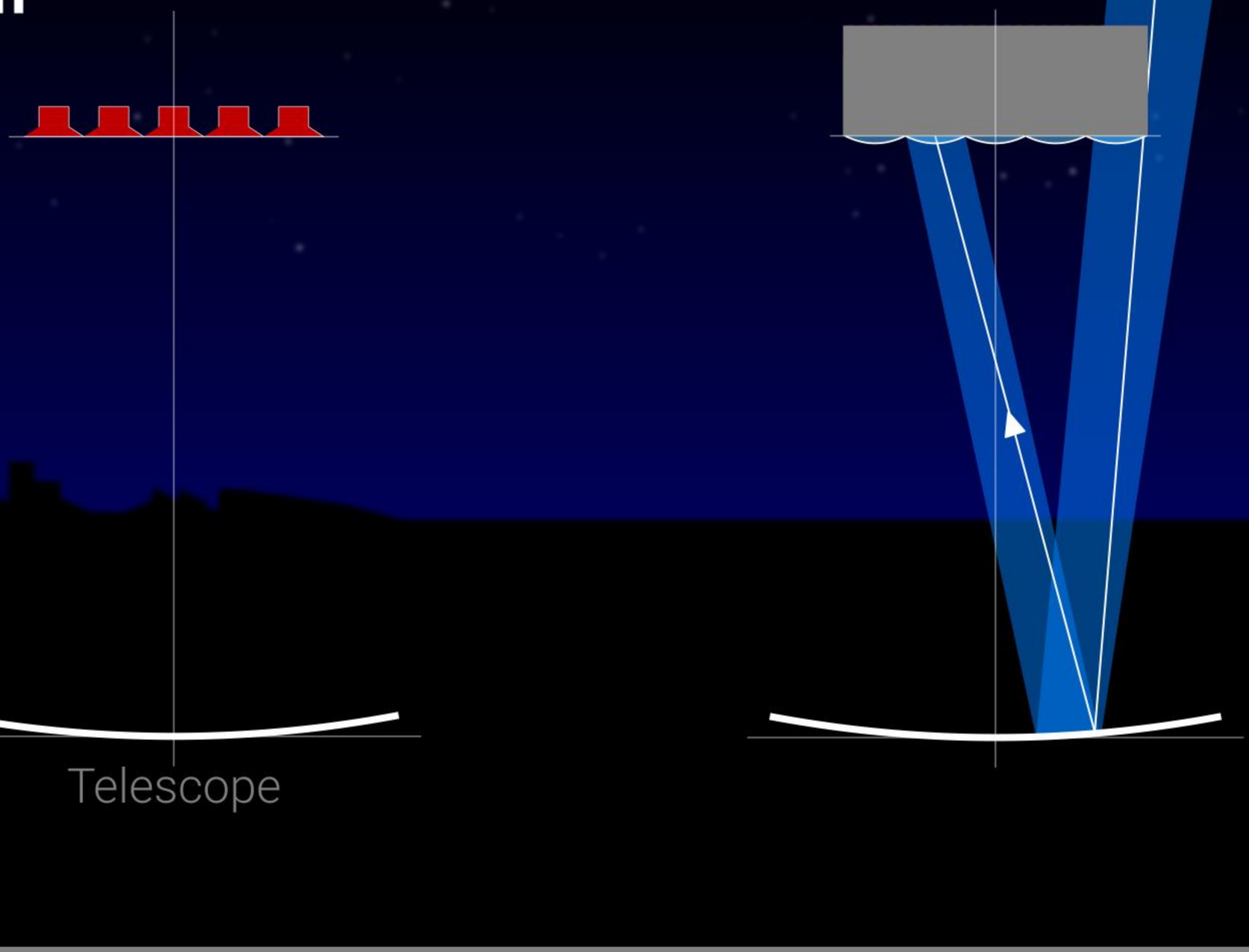


which had a mirror just like the telescope

Motivation

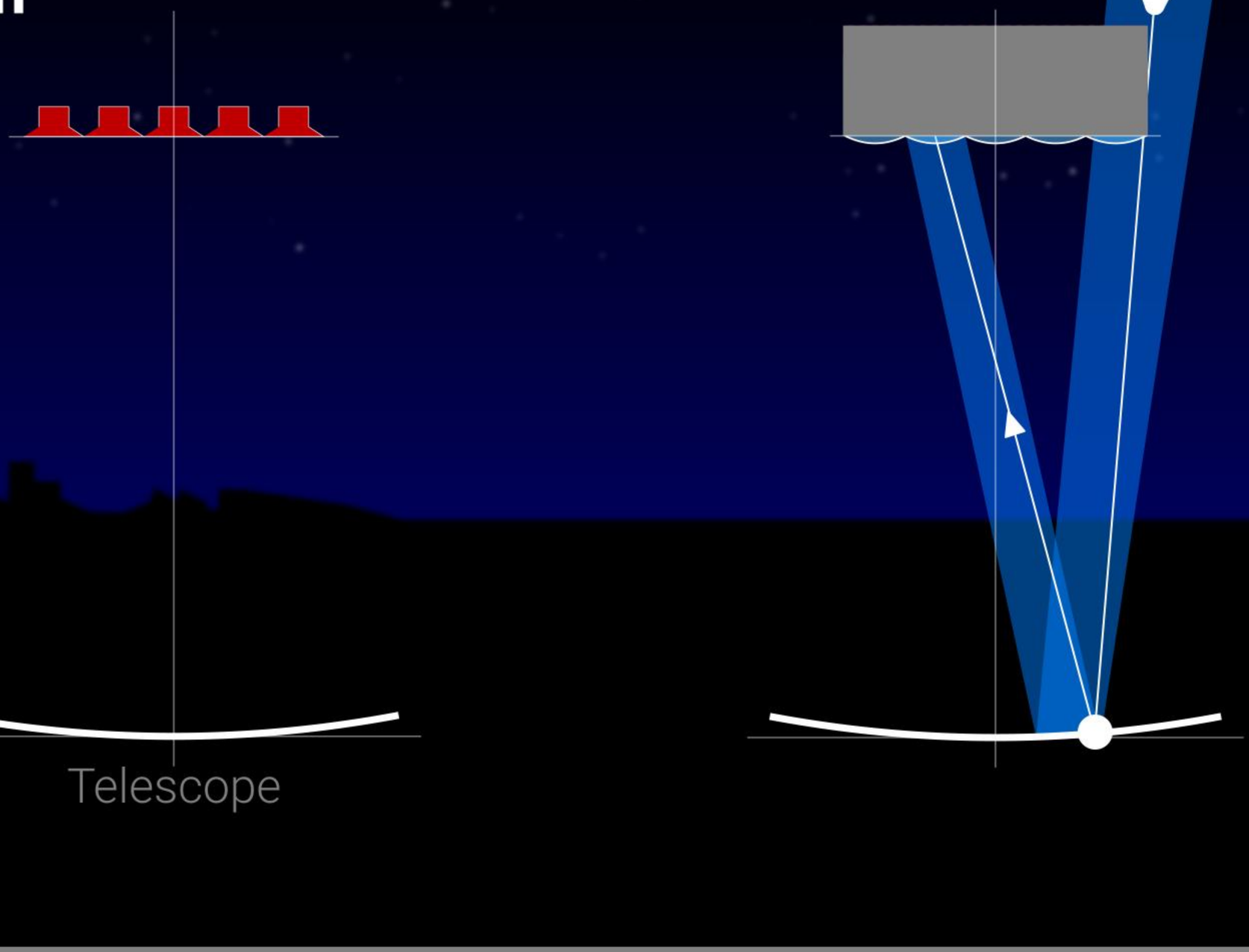
but a camera capable of measuring

Motivation



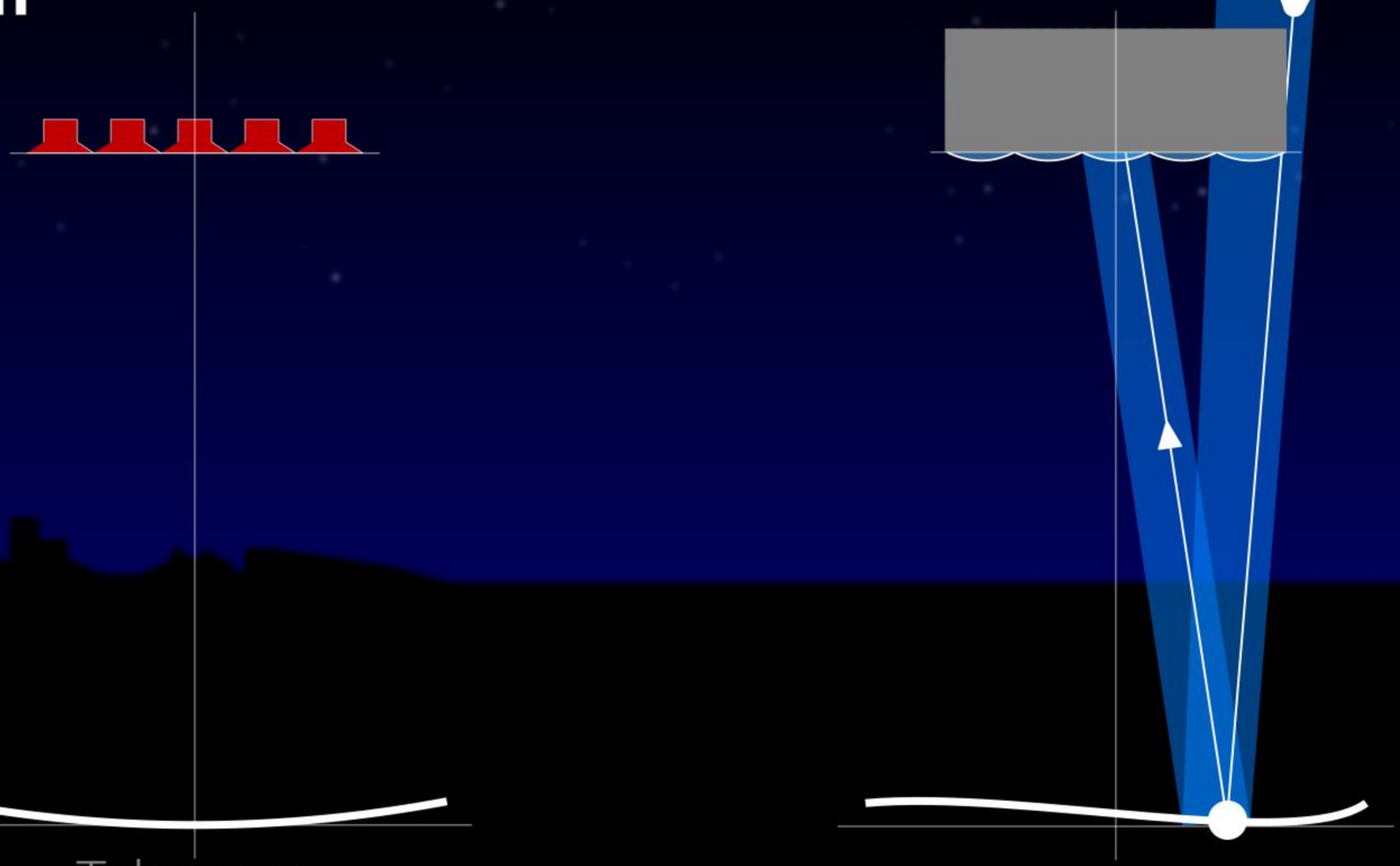
finer beams of light.

Motivation



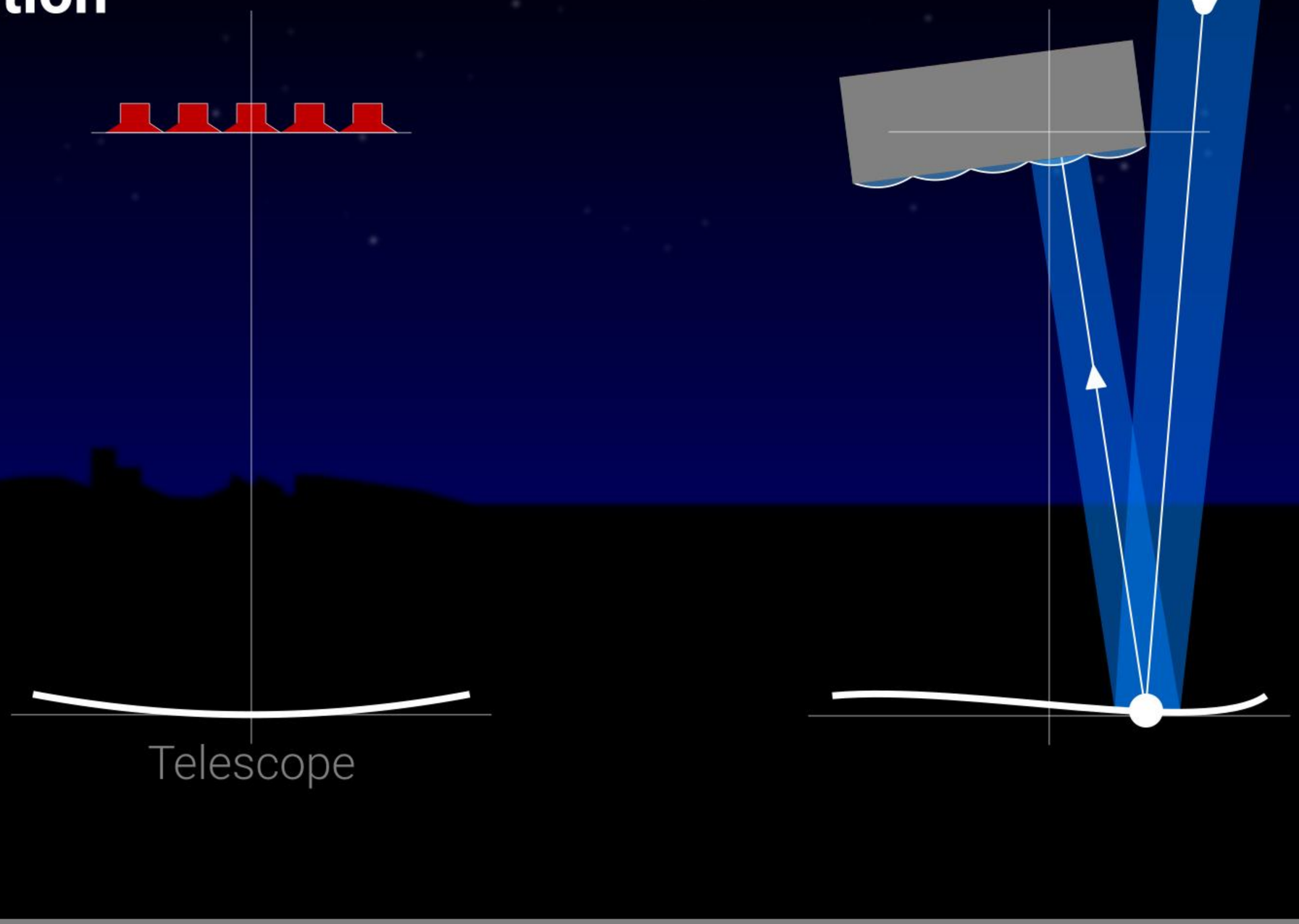
Remeber: The observables we are after to reconstruct the shower are the photons direction and impact position.

Motivation



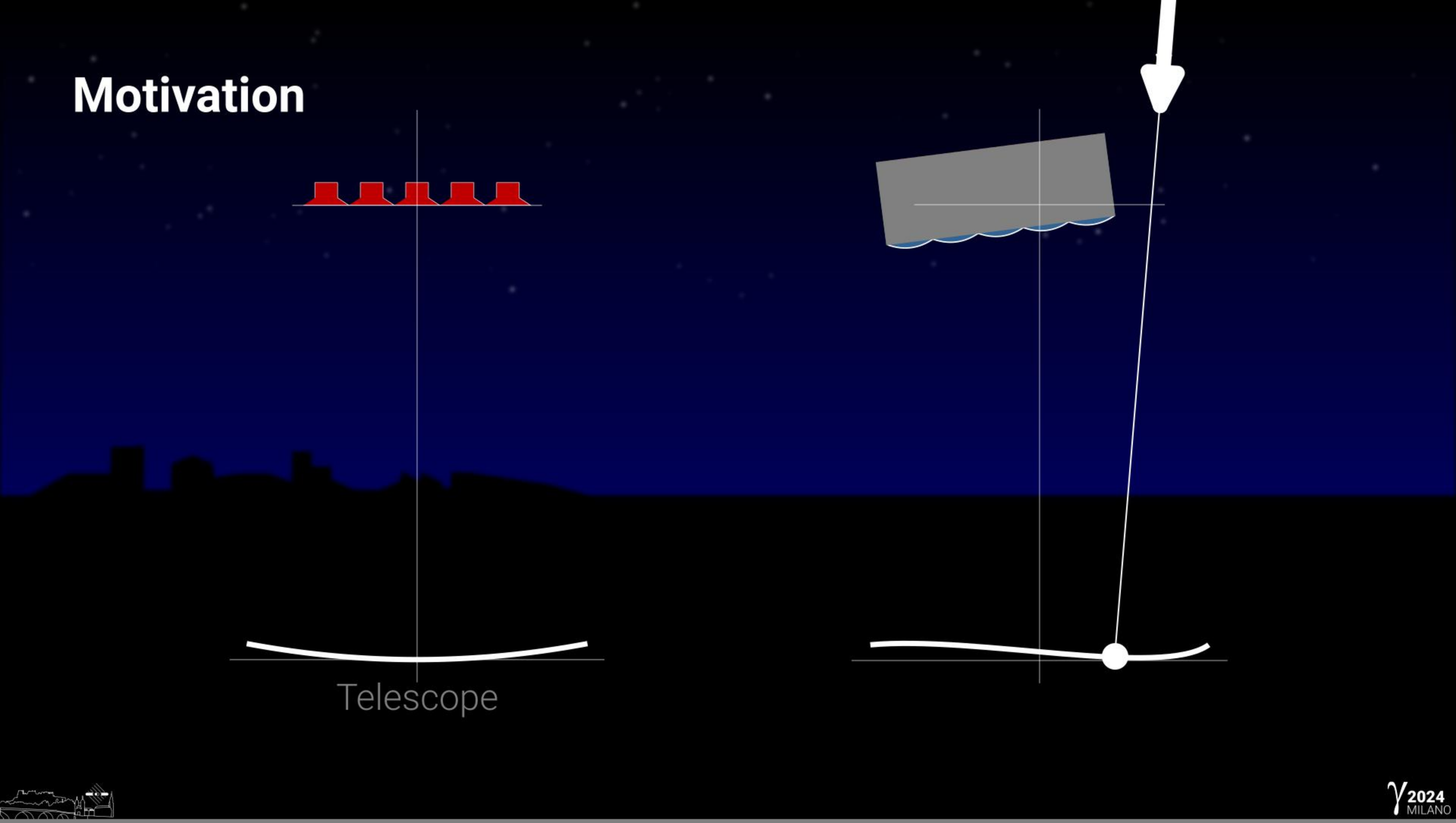
Now even when the mirror of the novel instrument was deformed

Motivation



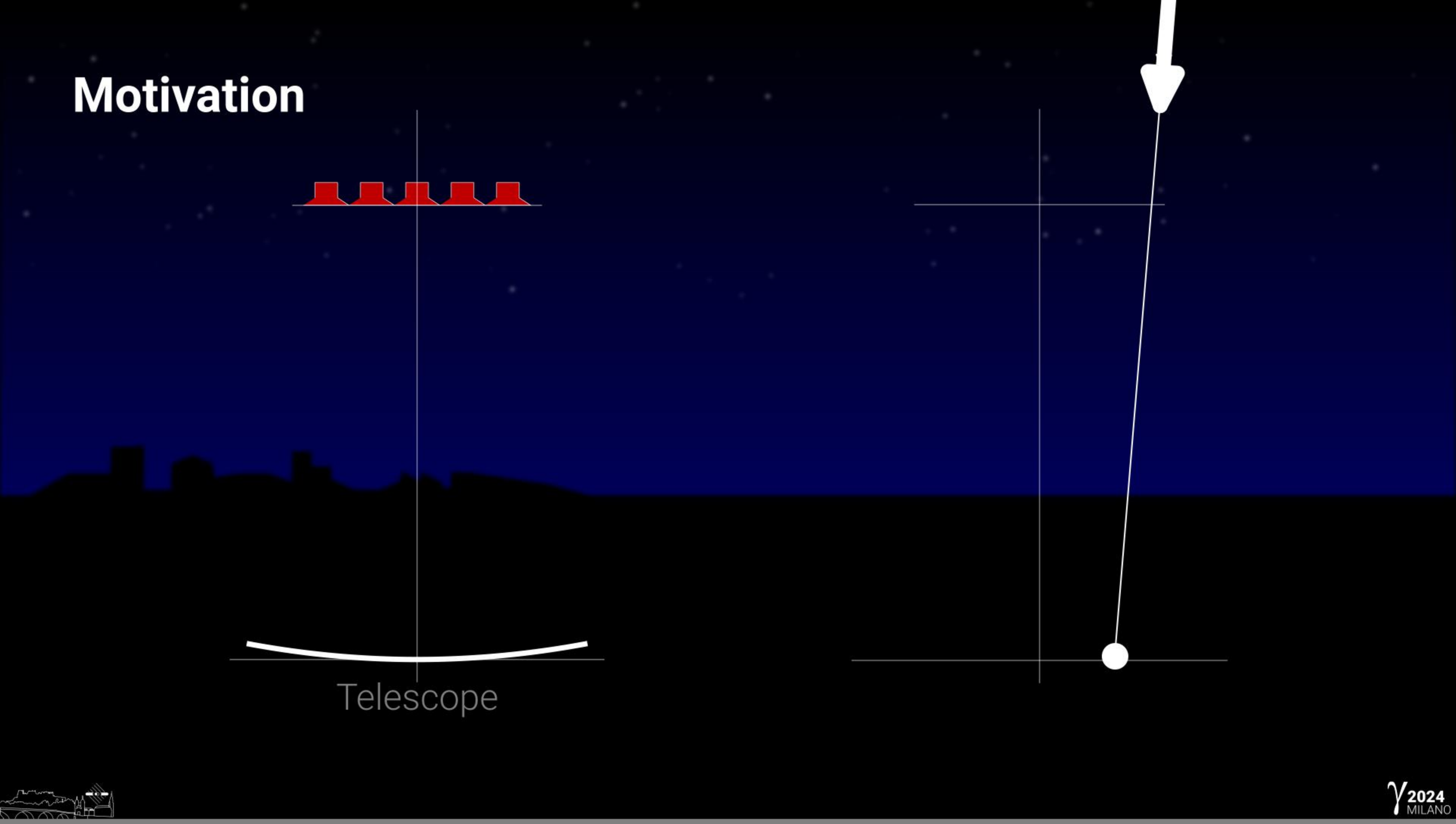
or its camera was misaligned, the fine beams would still allow to constrain the trajectory of the photon with respect to the atmosphere.

Motivation



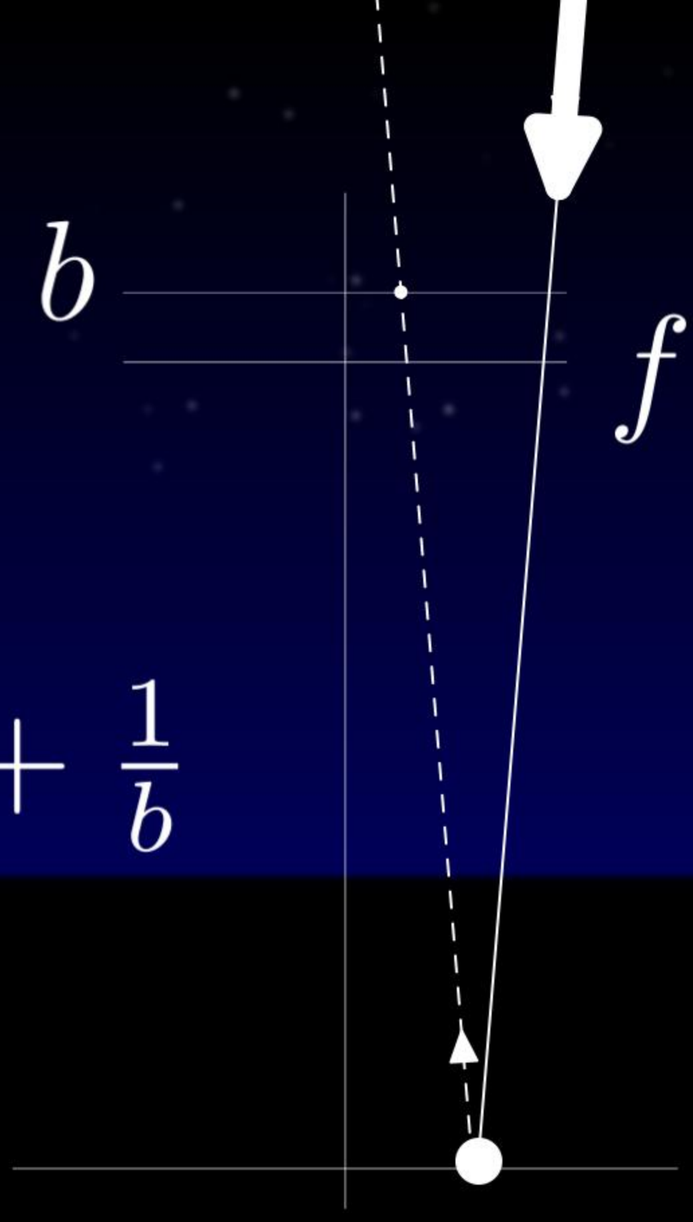
At this point, we can mentally leave all the optics behind ...

Motivation



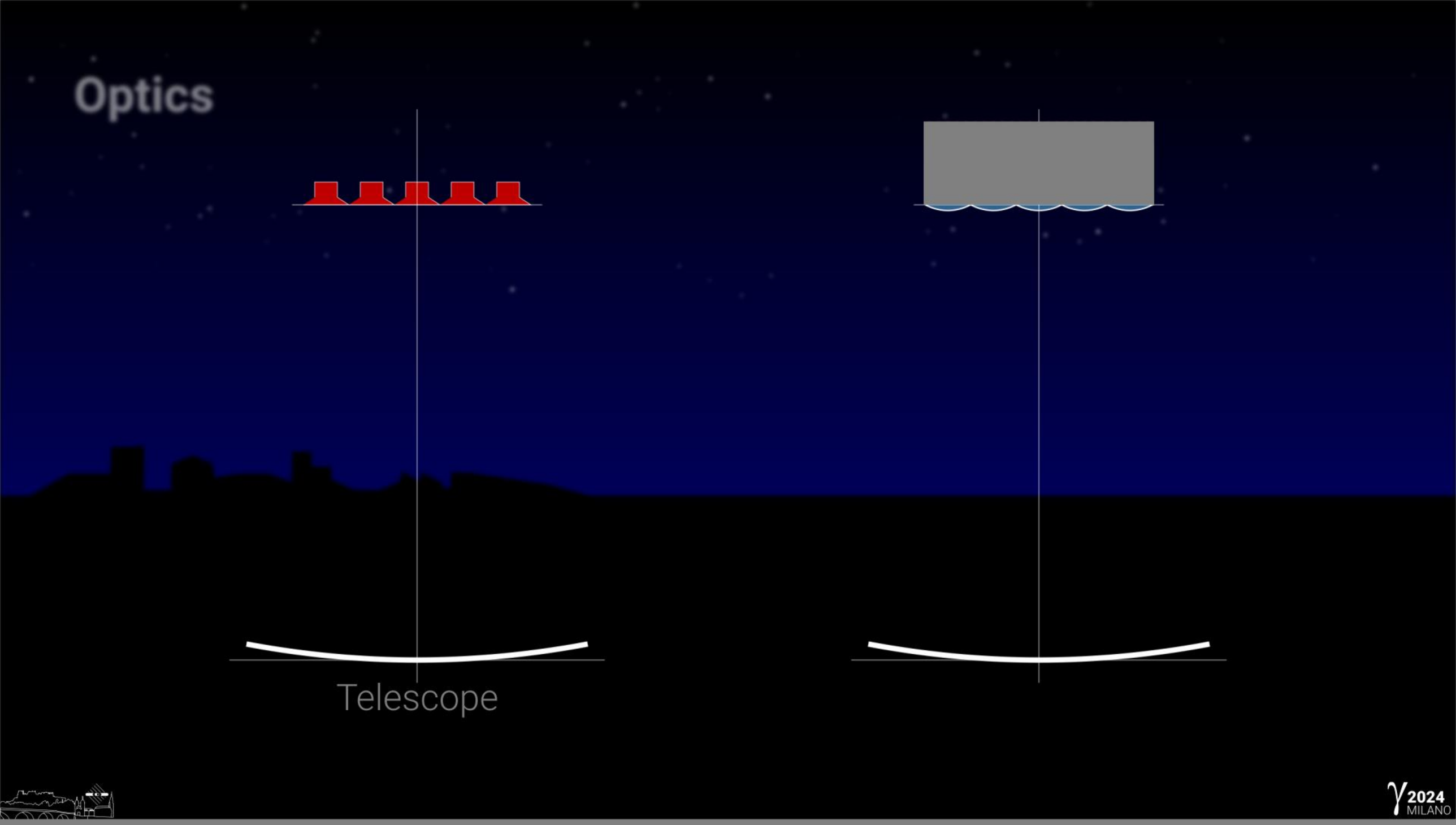
and concentrate on the bundle of measured trajectories instead.

Motivation



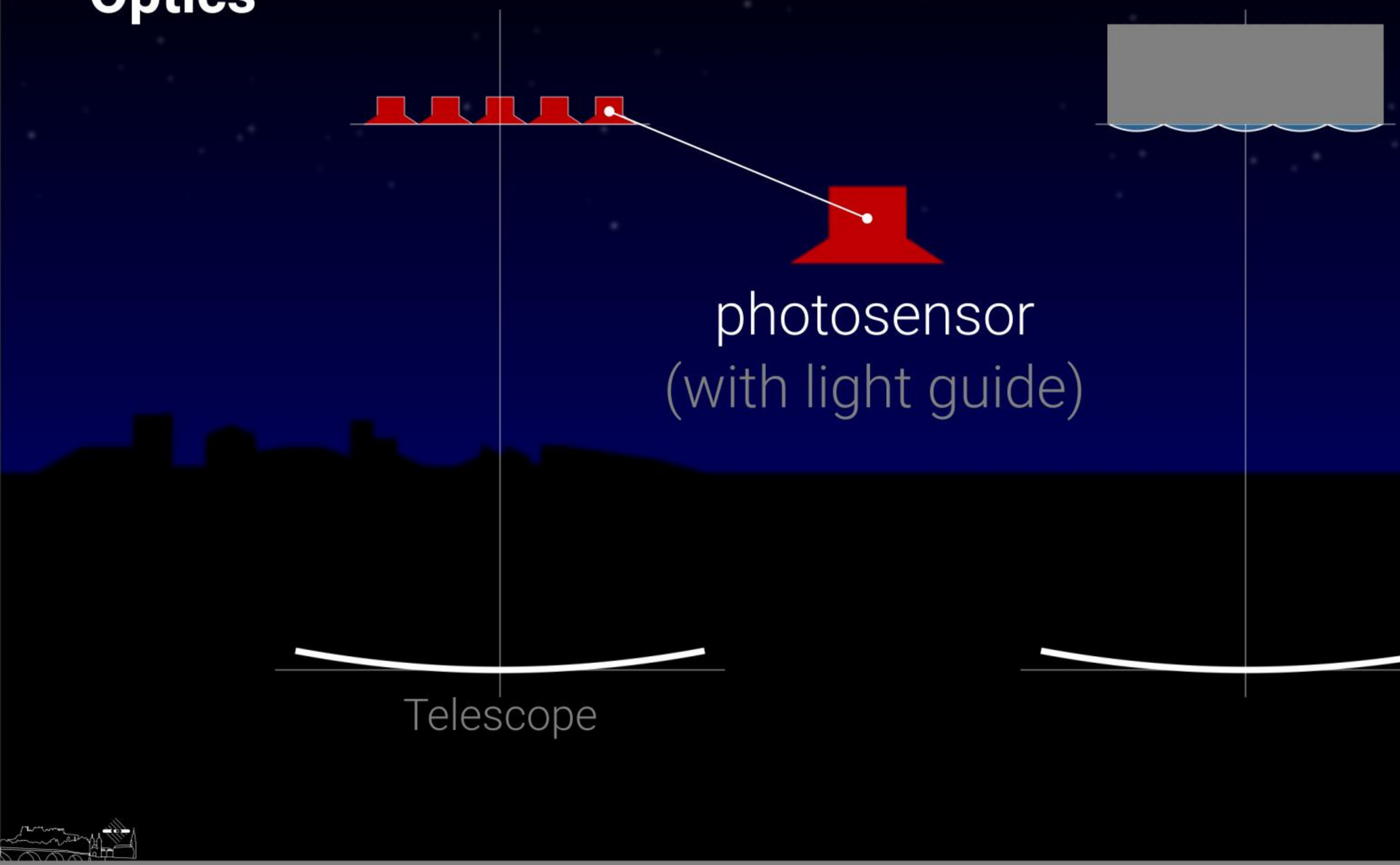
$$\frac{1}{f} = \frac{1}{g} + \frac{1}{b}$$

Now we can trace these photon through a model of a perfect imaging optics, such as the thin lens. Here we can compute images without aberrations and with the focus set to any depth we want.



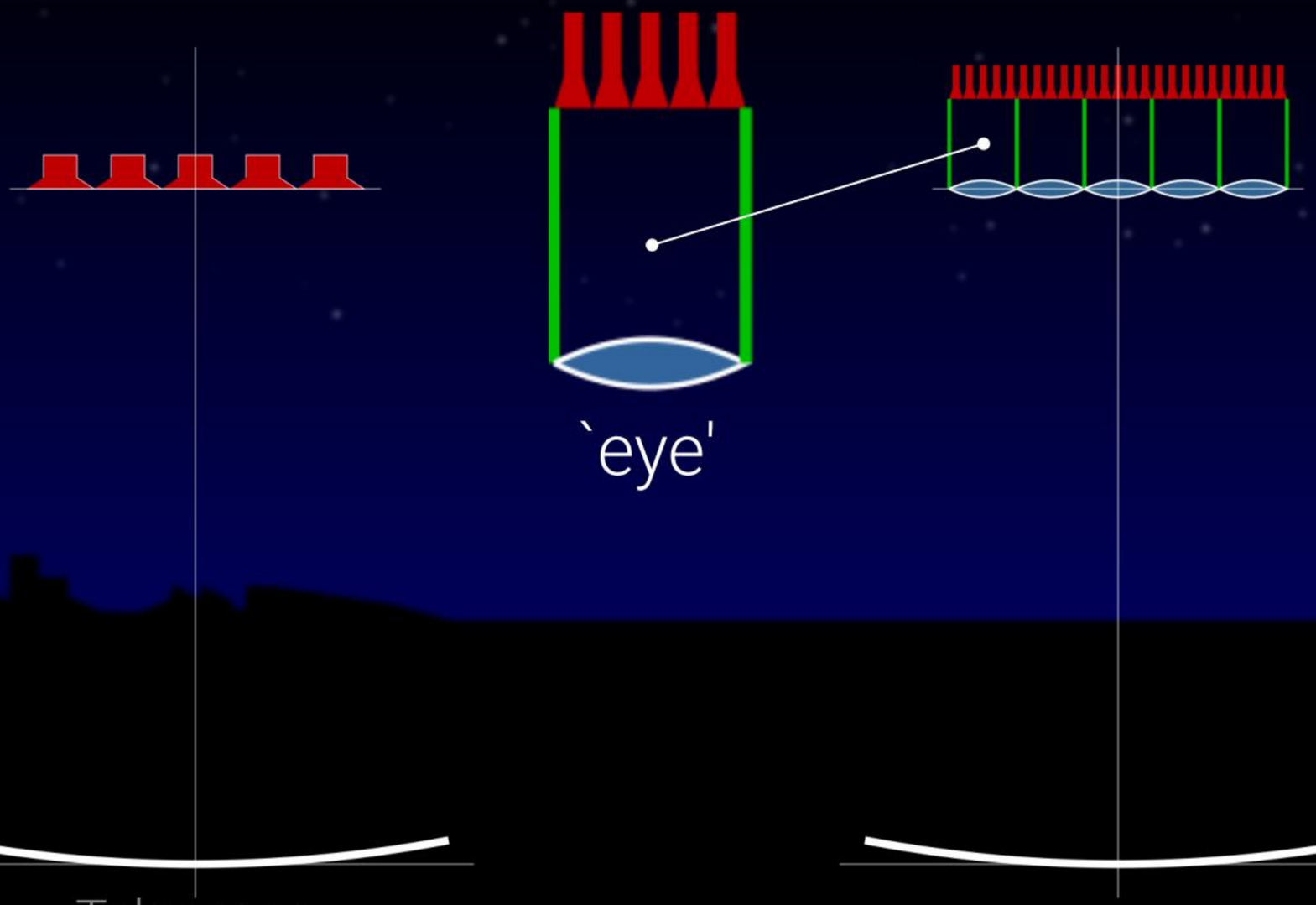
To build such an instrument

Optics



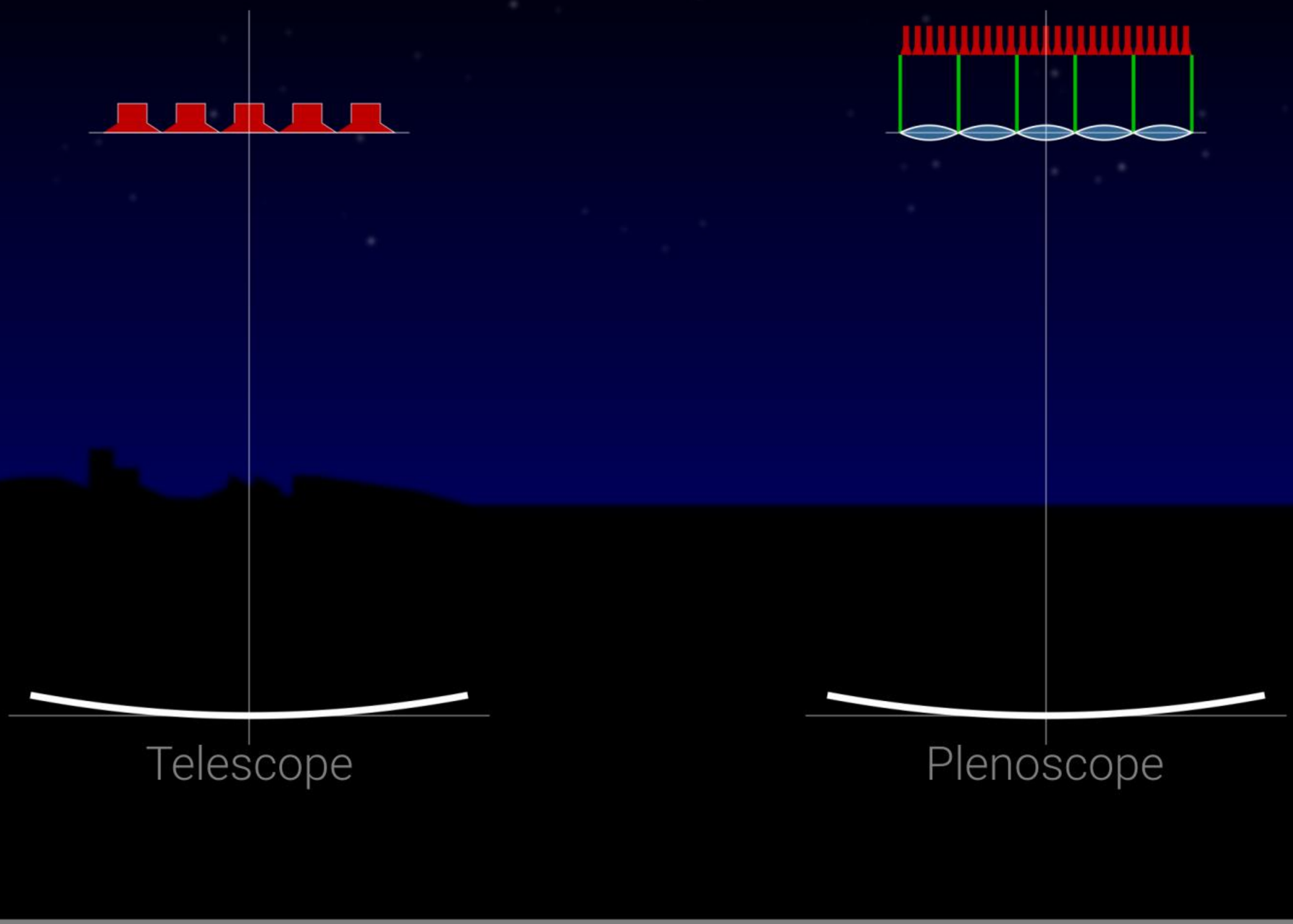
we replace each photosensor of the telescope

Optics



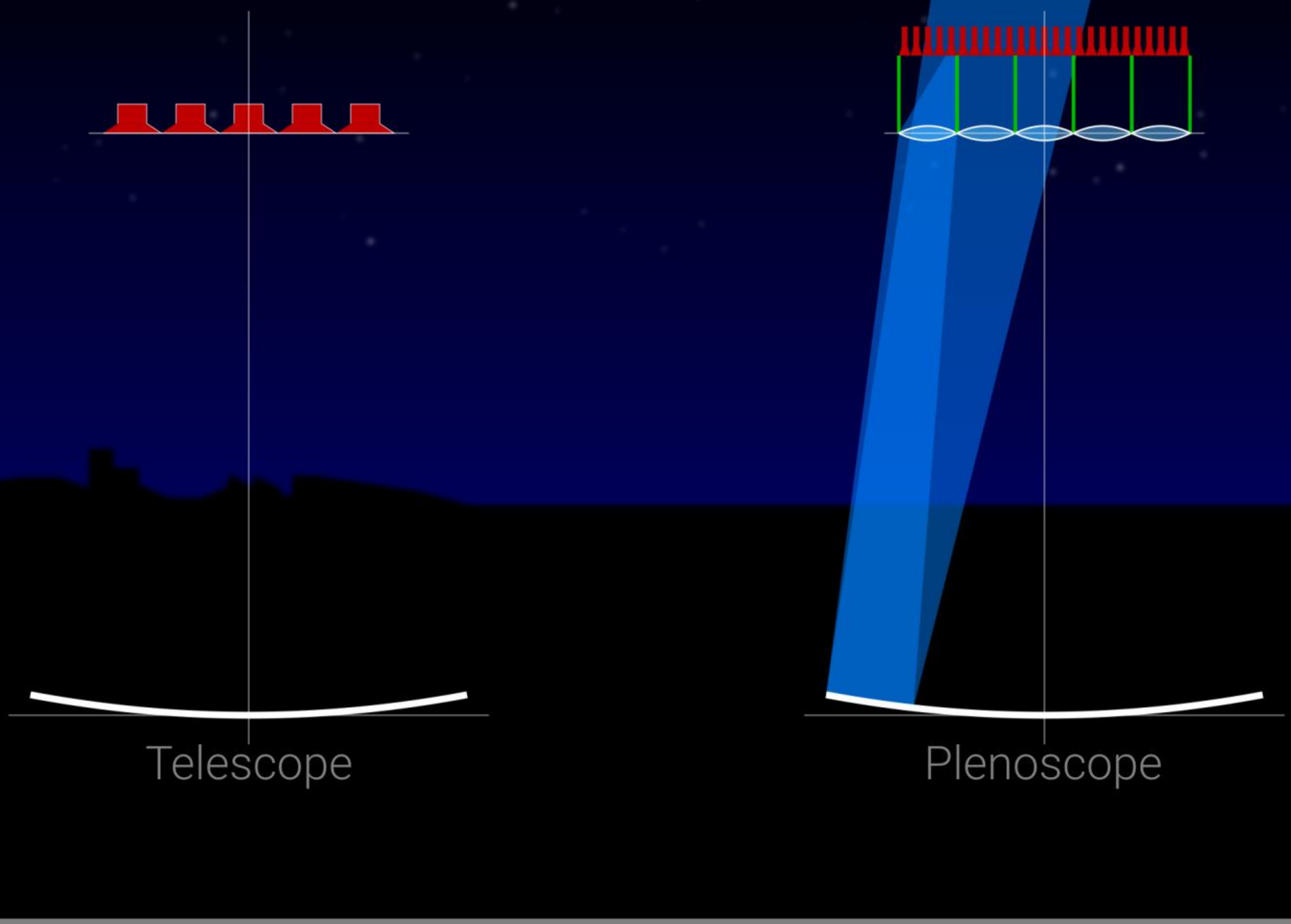
with an 'eye' made out of a lens and an opposing array of photosensors.

Optics



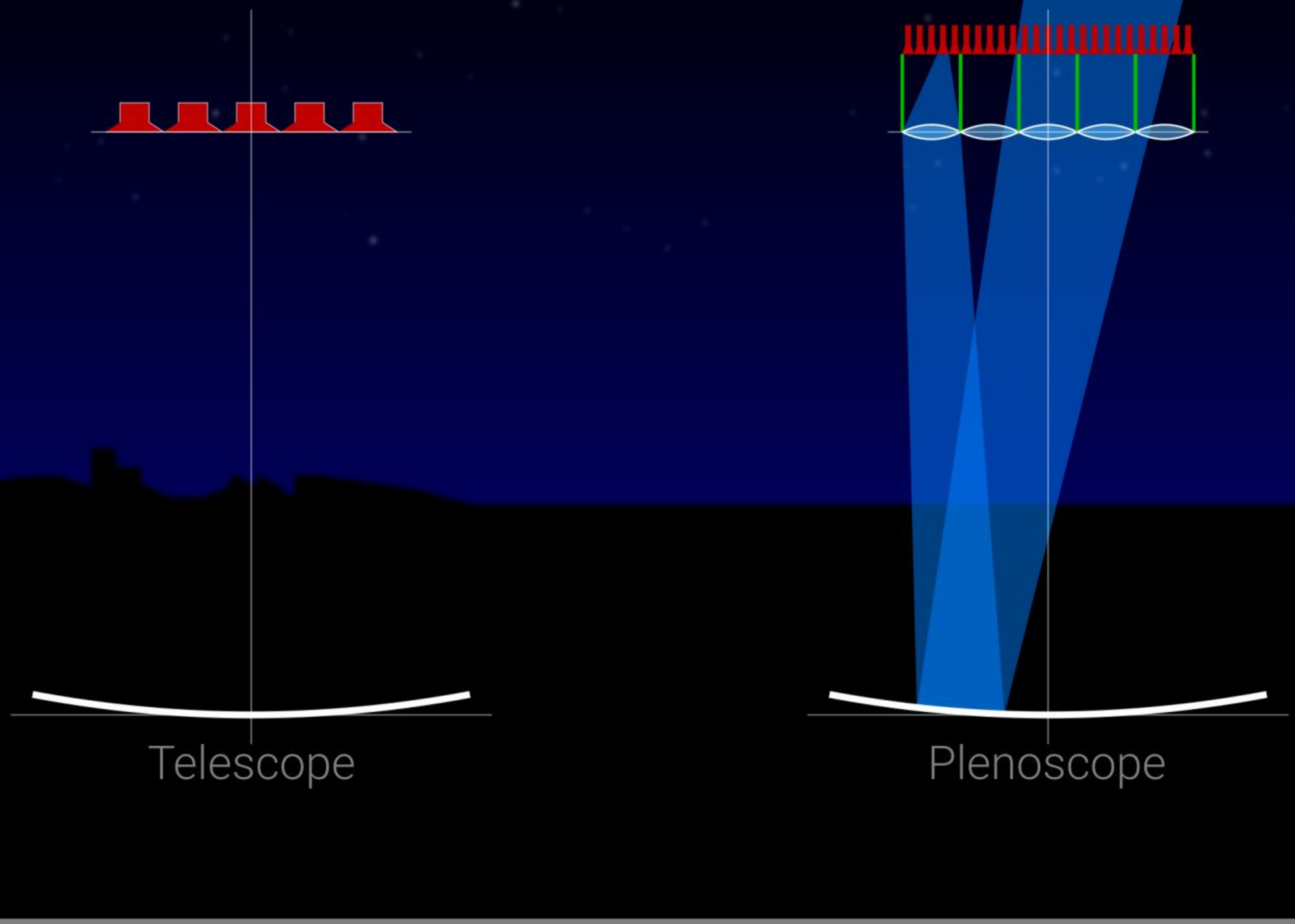
The resulting Cherenkov plenoscope

Optics



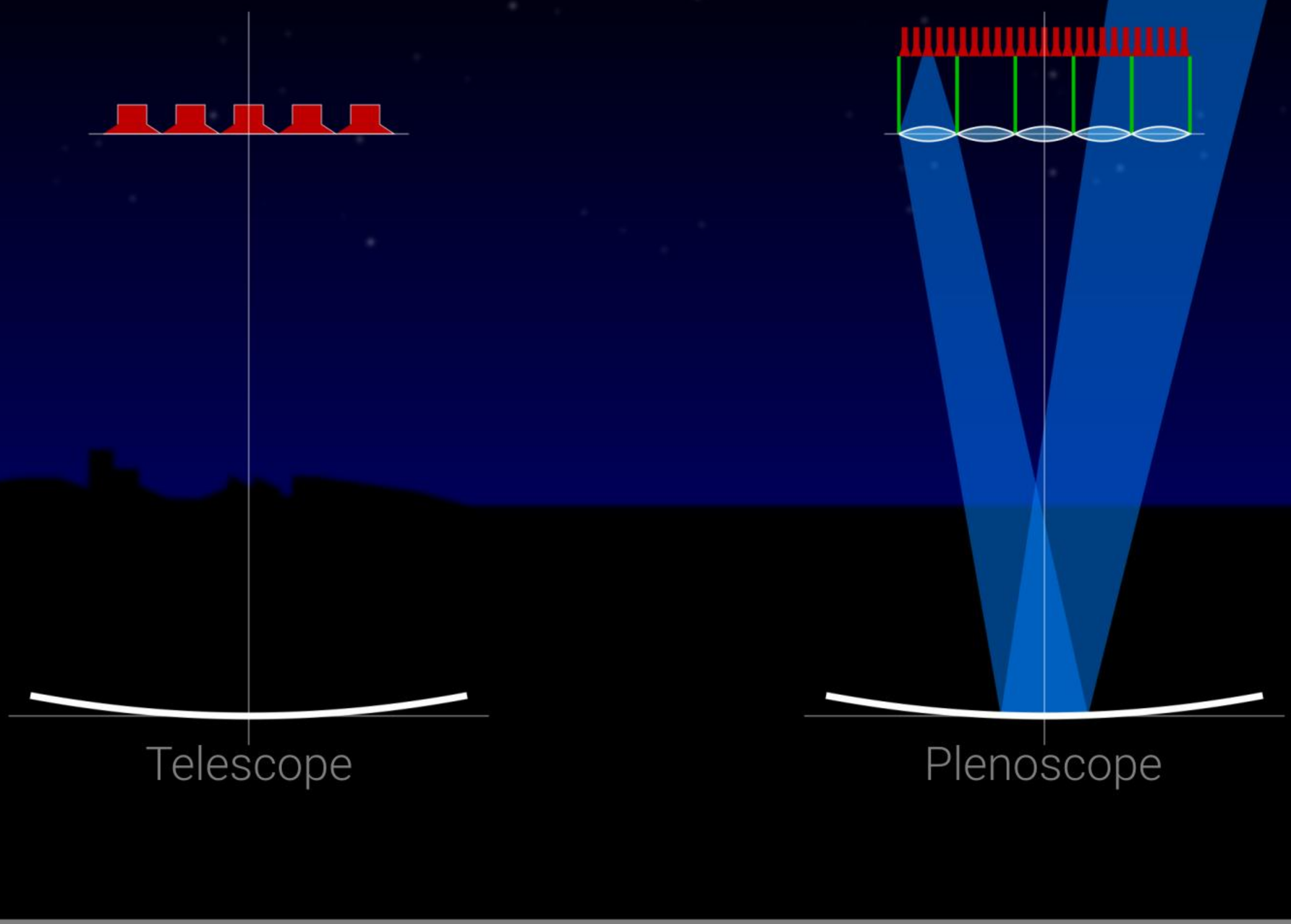
has much

Optics



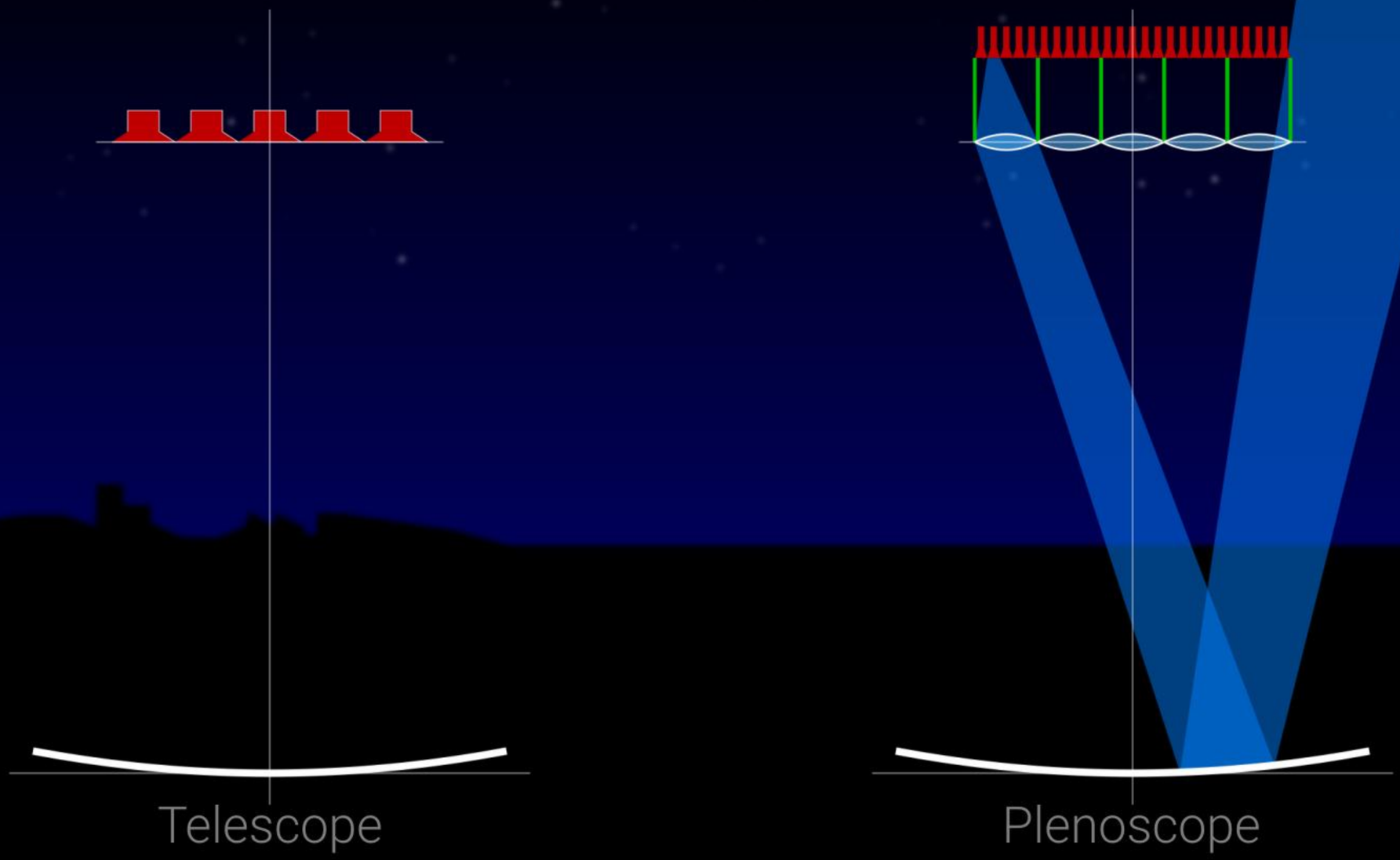
finer beams

Optics



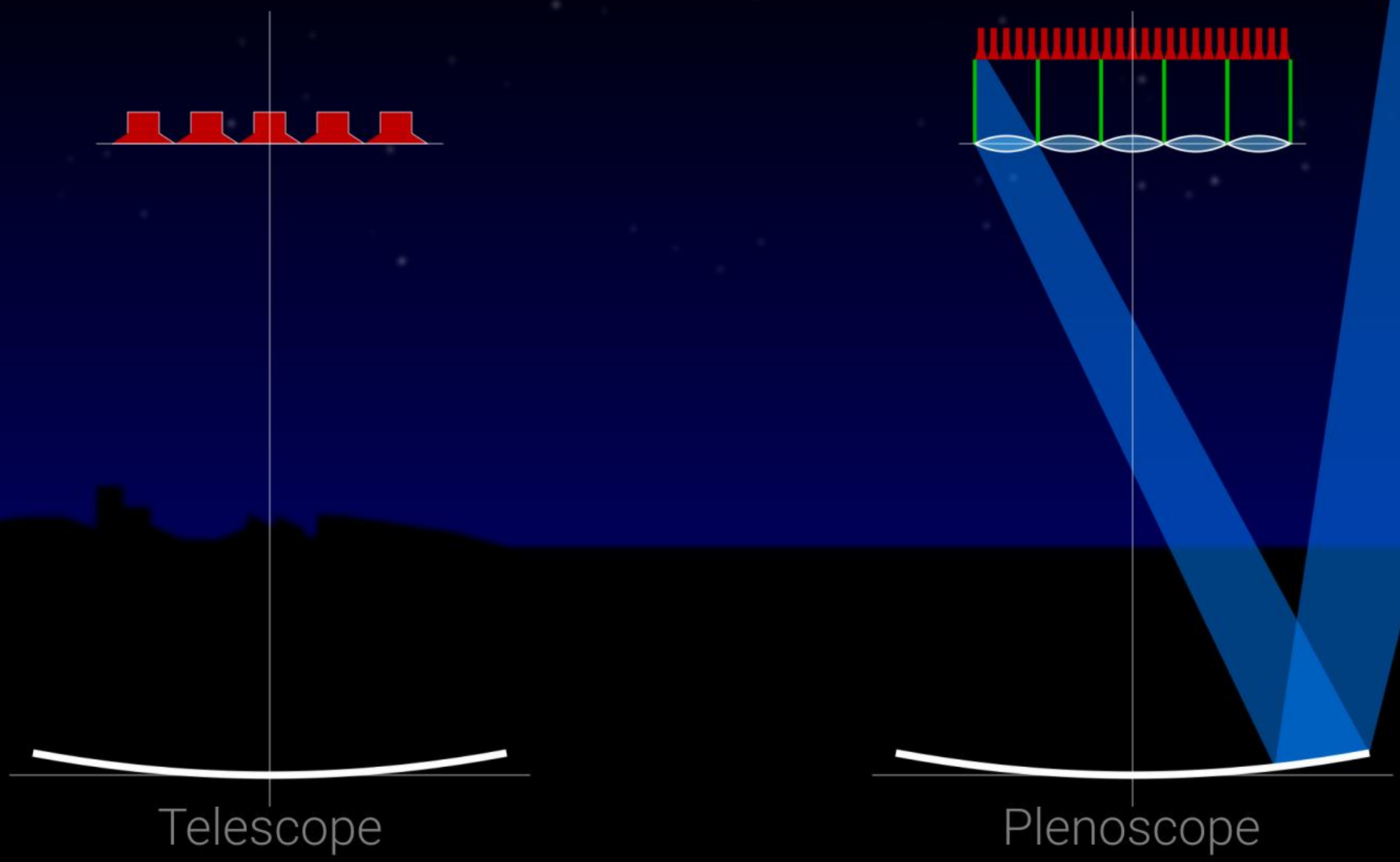
and

Optics



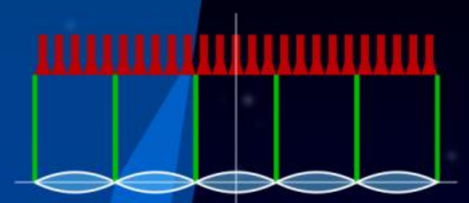
thus

Optics



can

Optics

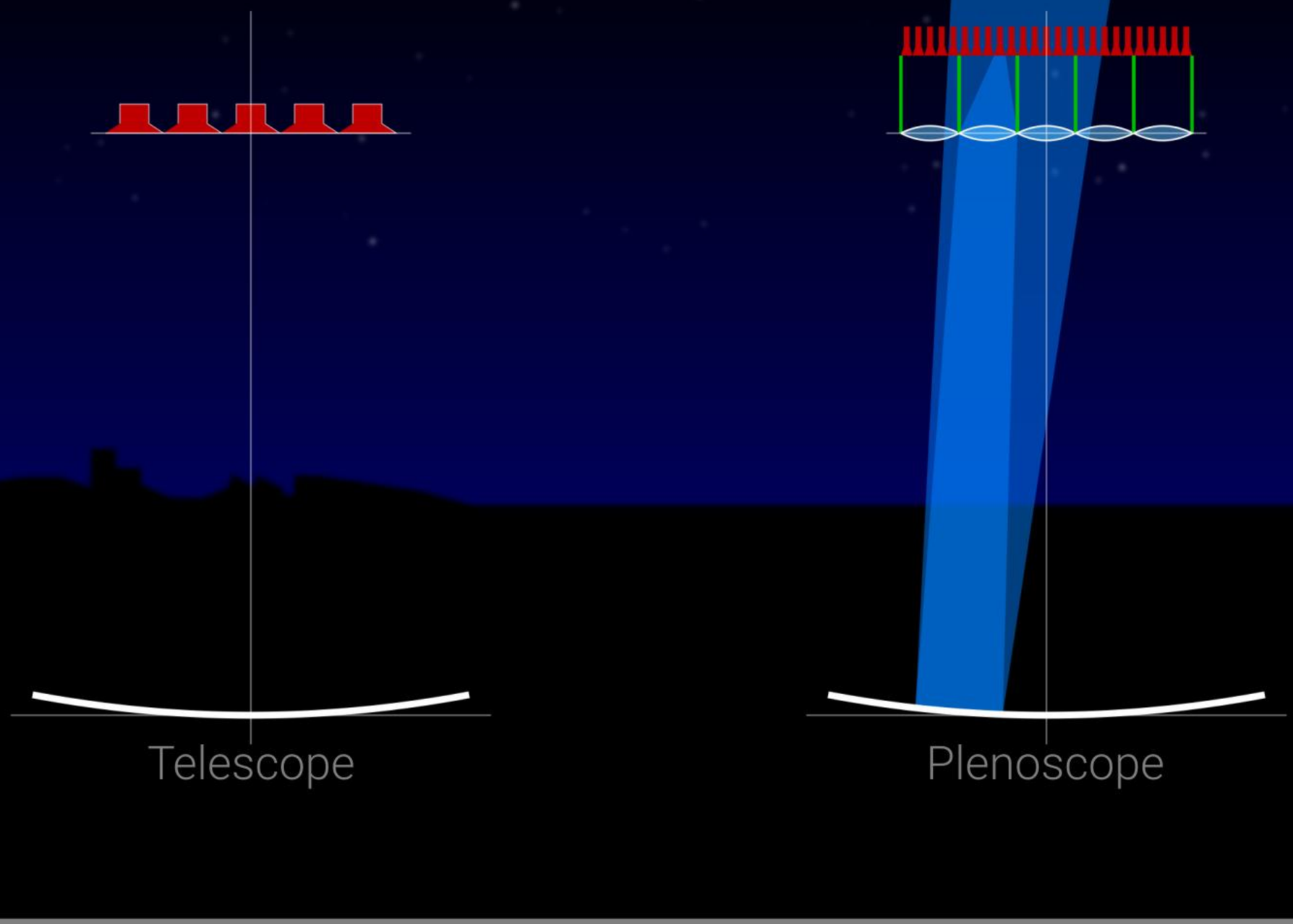


Telescope

Plenoscope

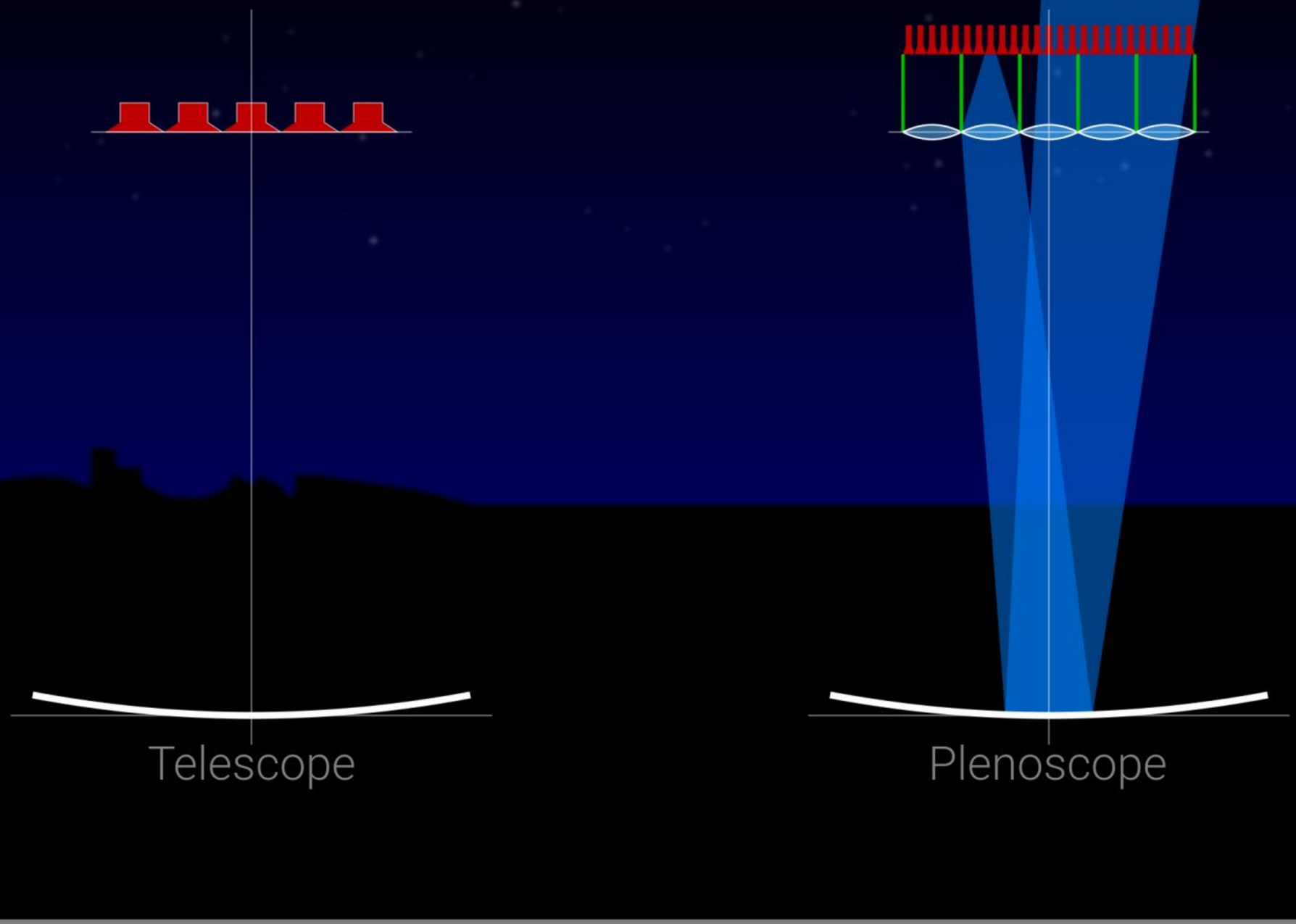
constrain

Optics



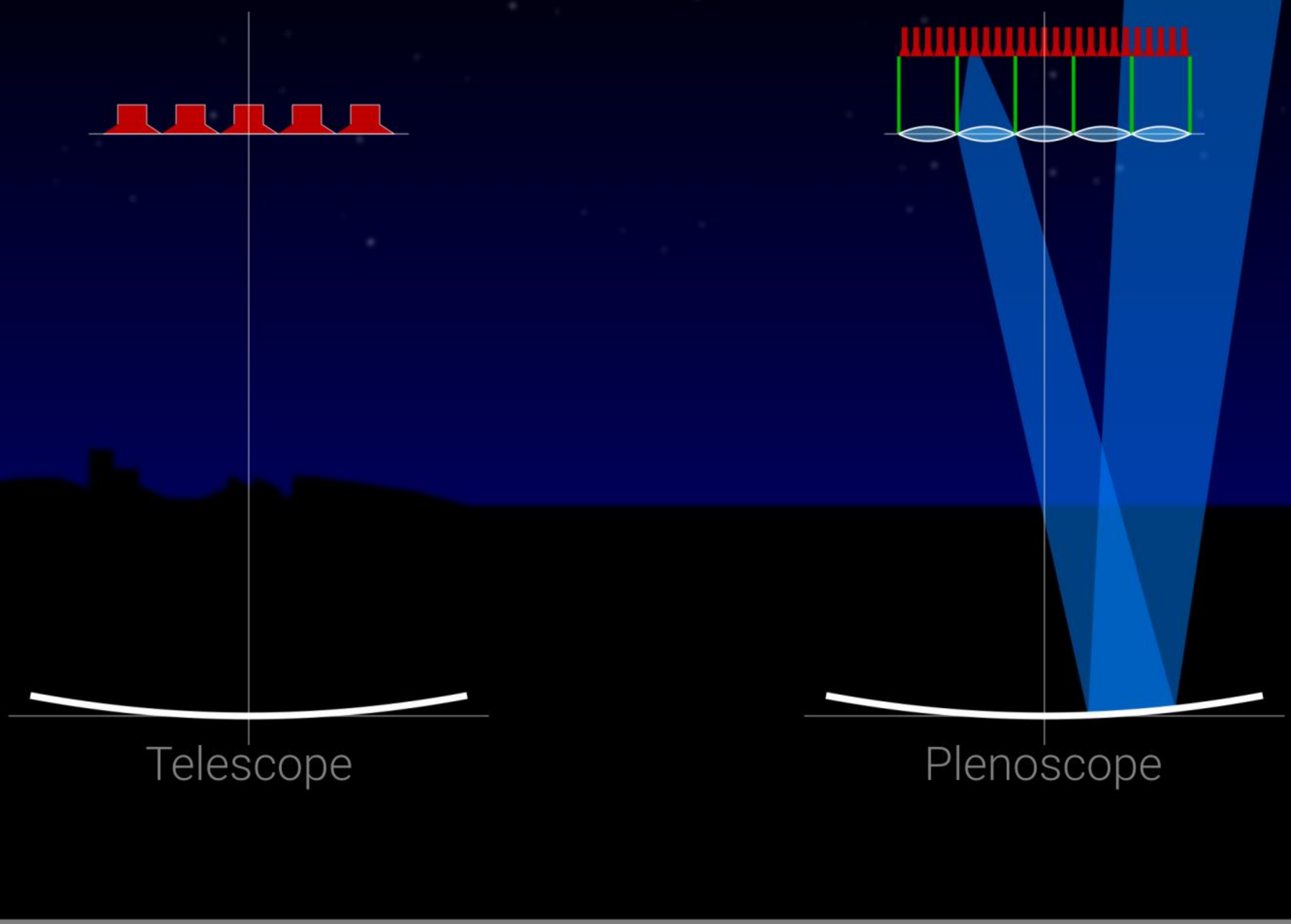
the

Optics



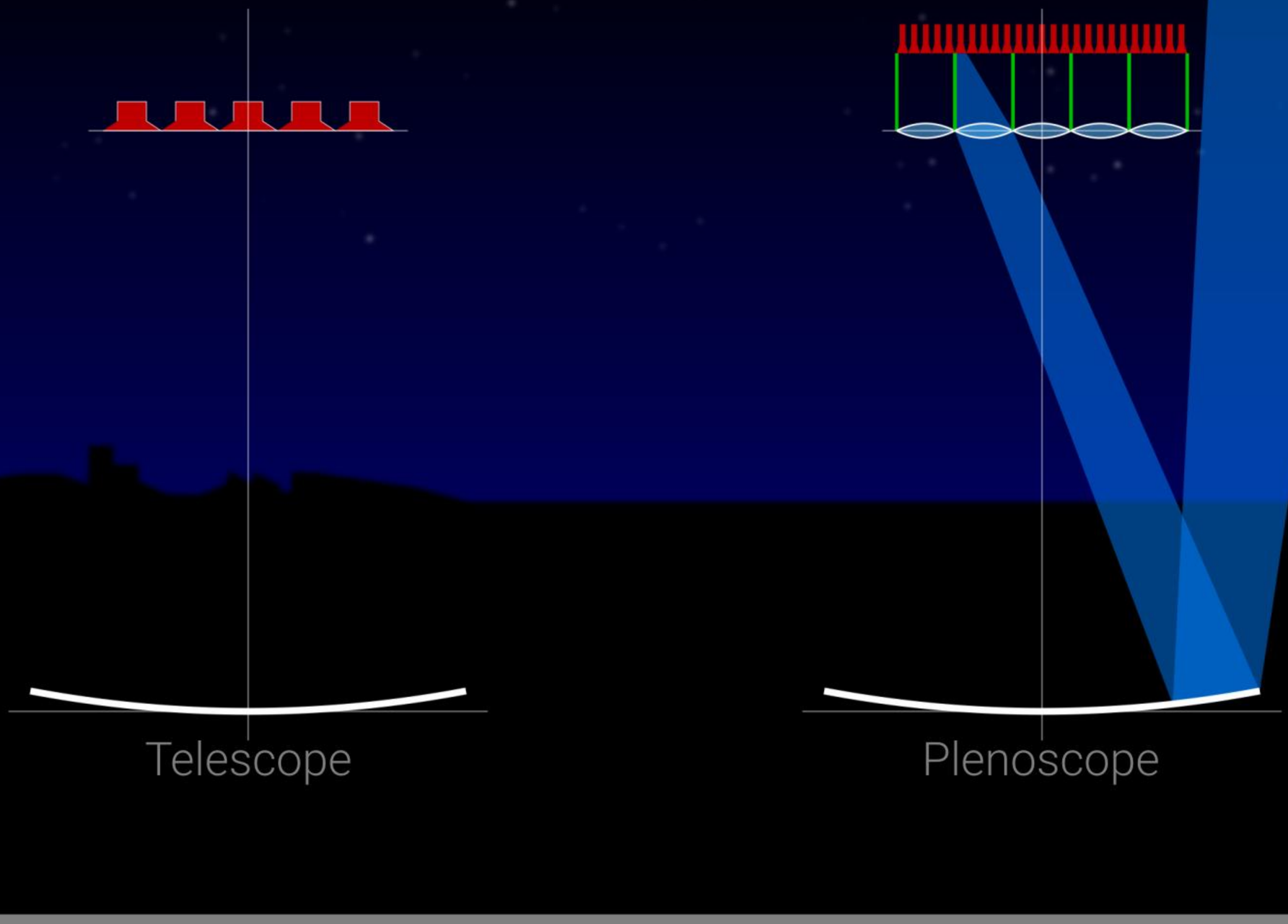
trajectories

Optics



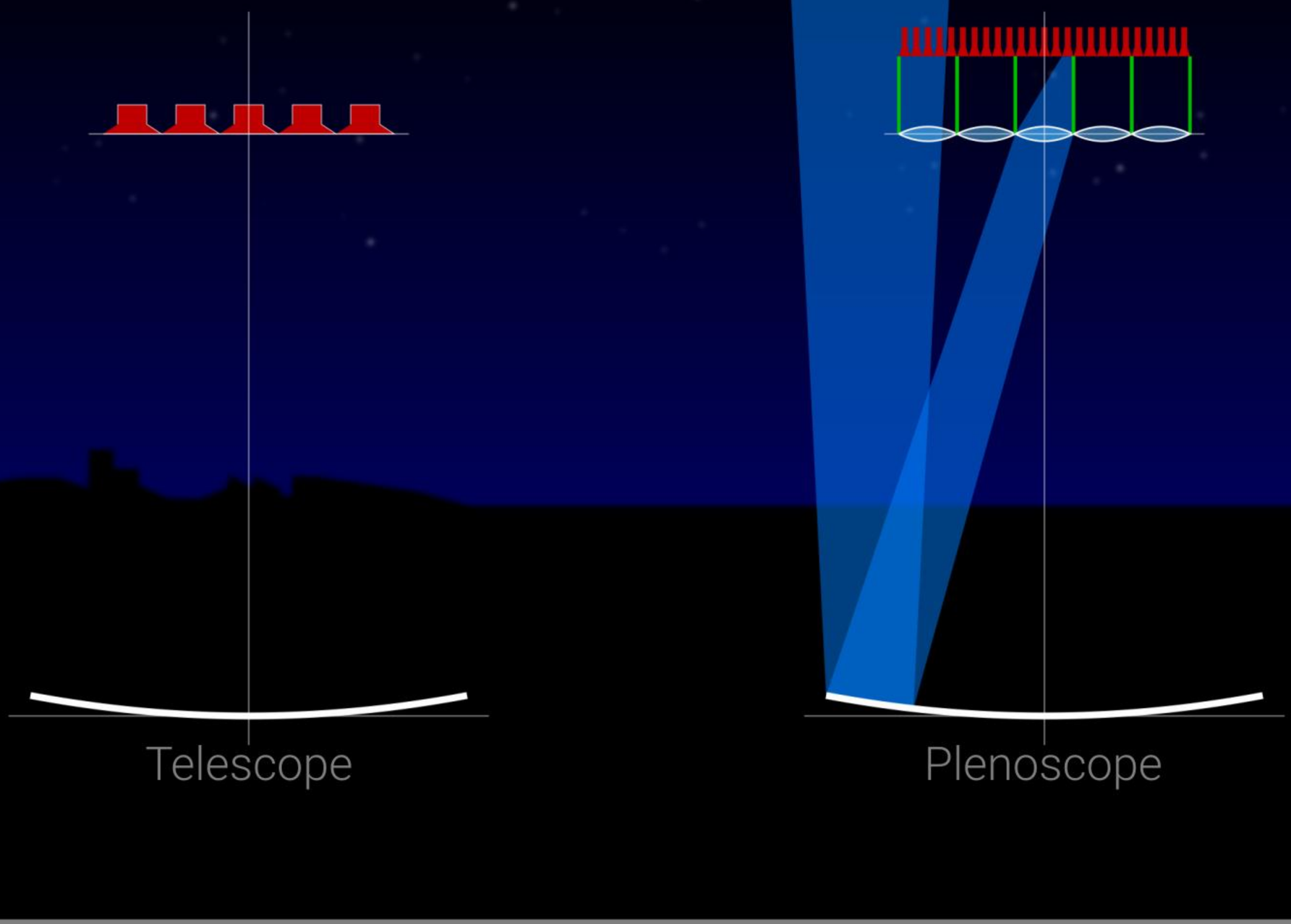
of

Optics



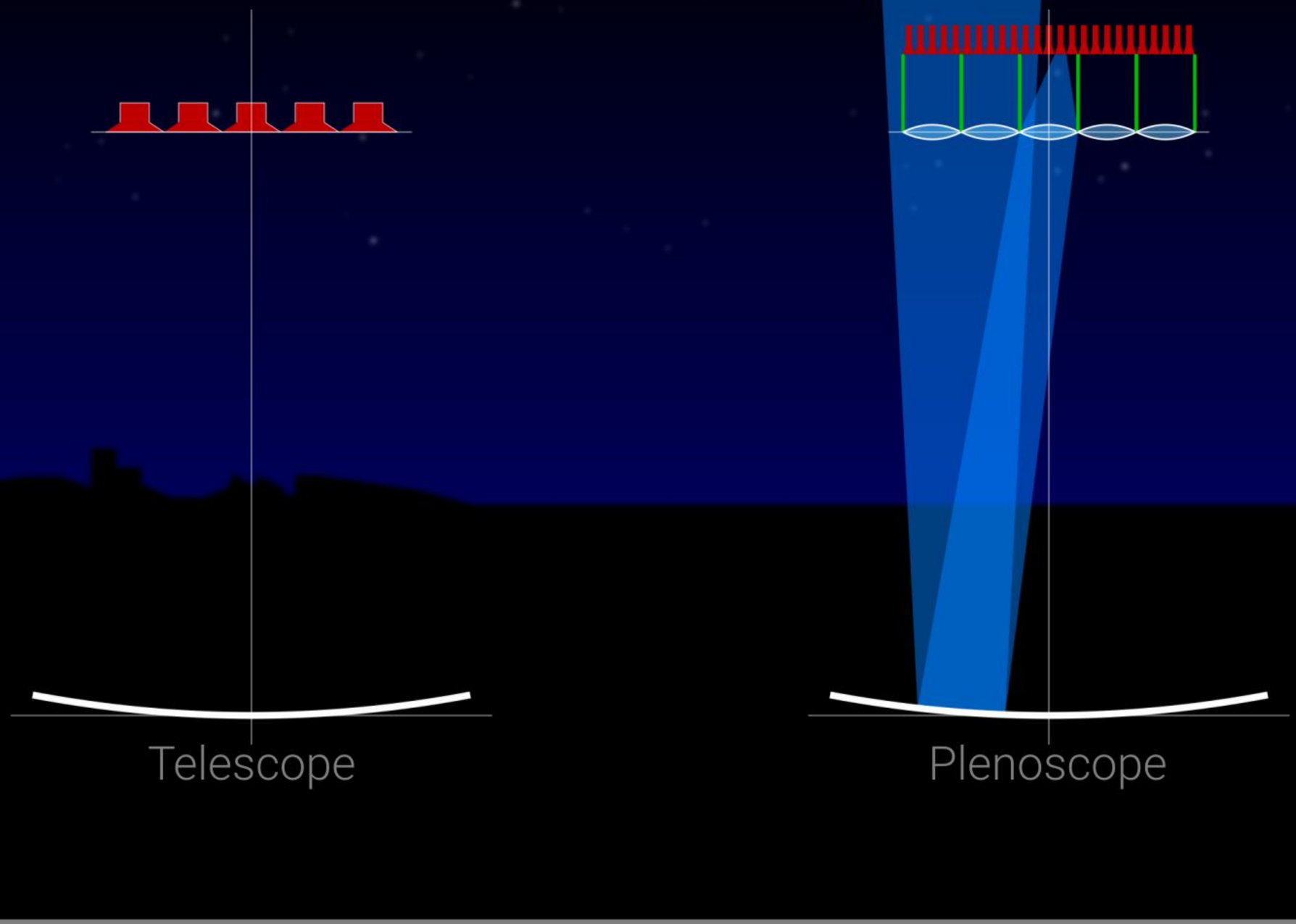
photons

Optics



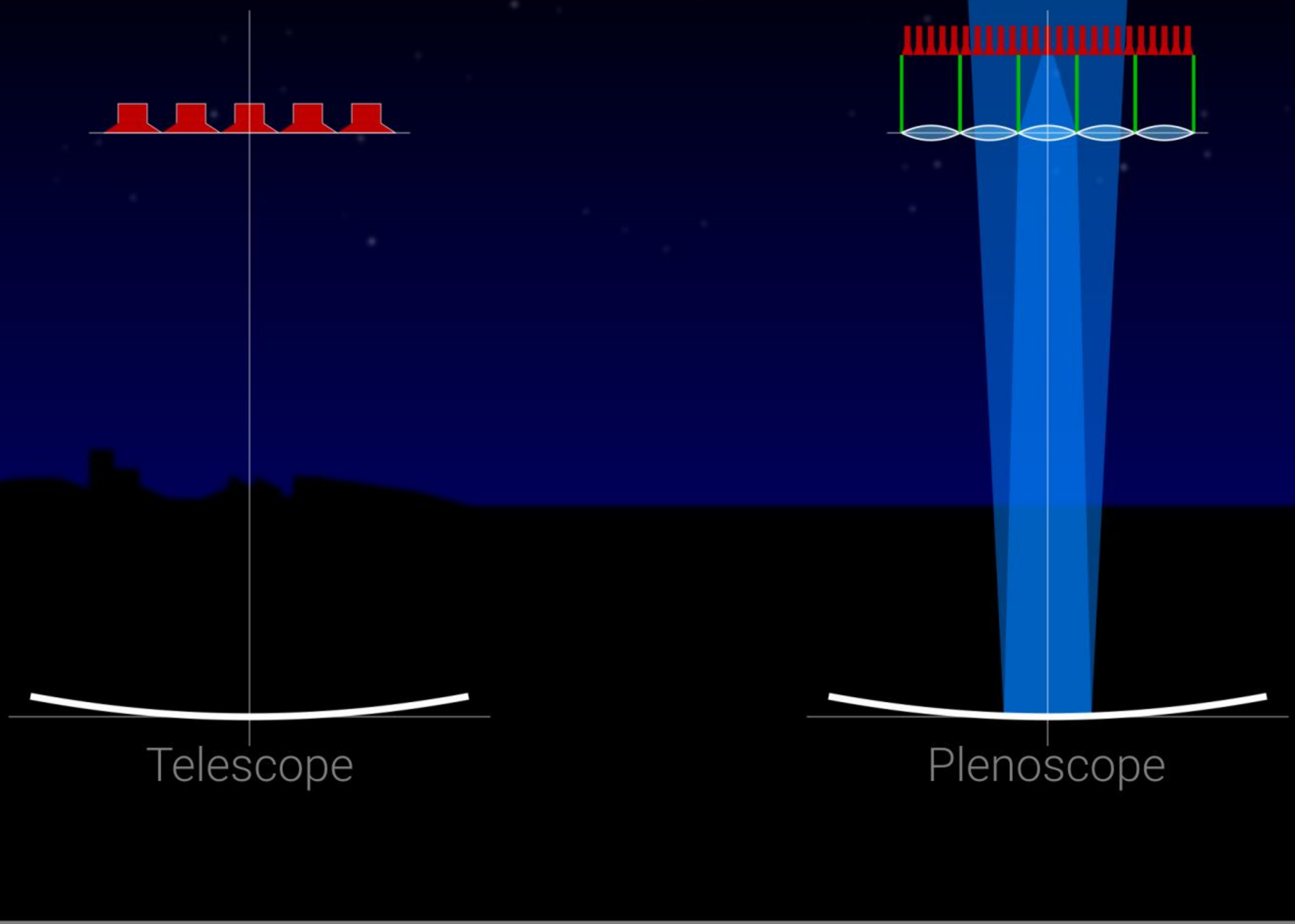
much

Optics



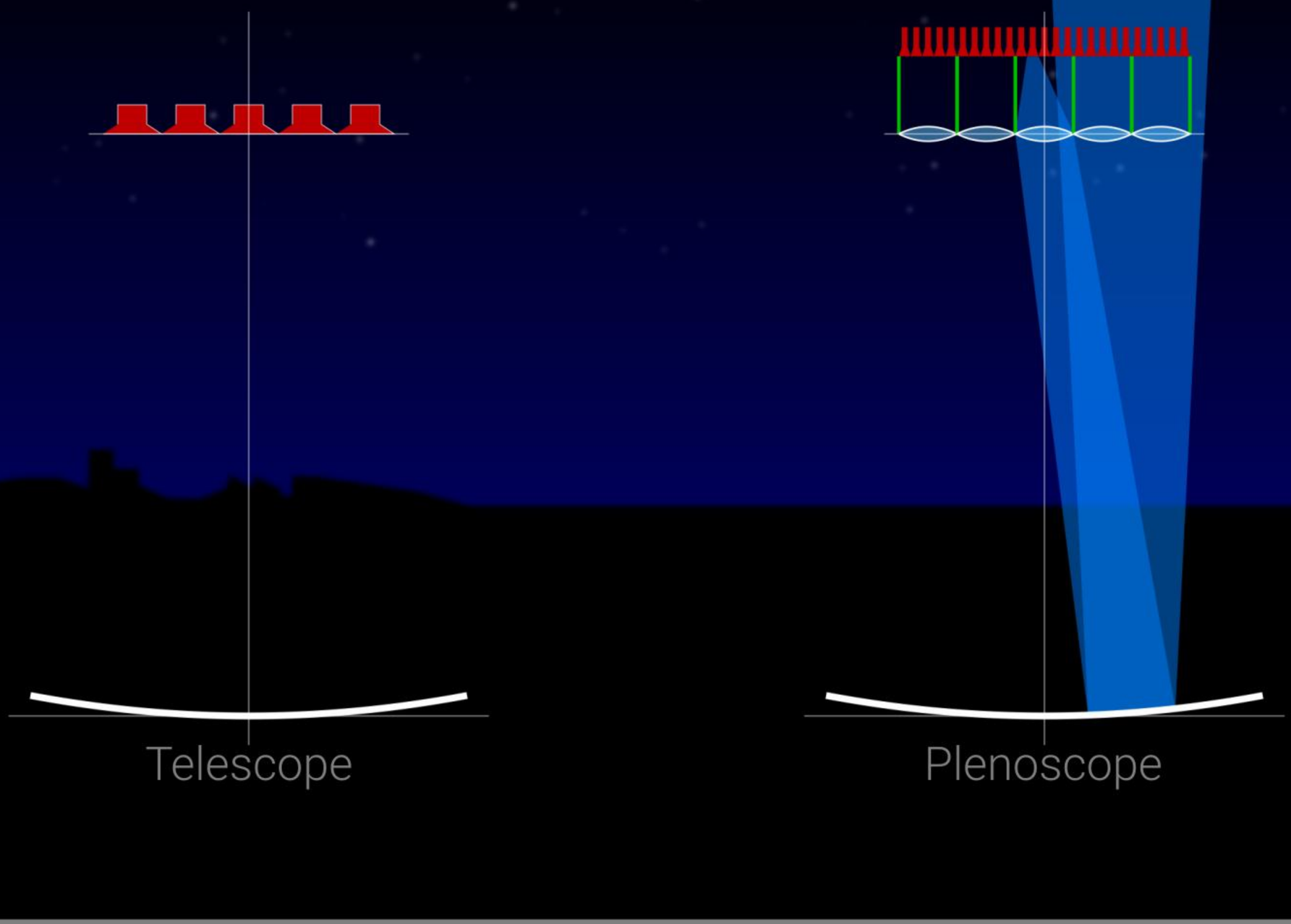
better

Optics



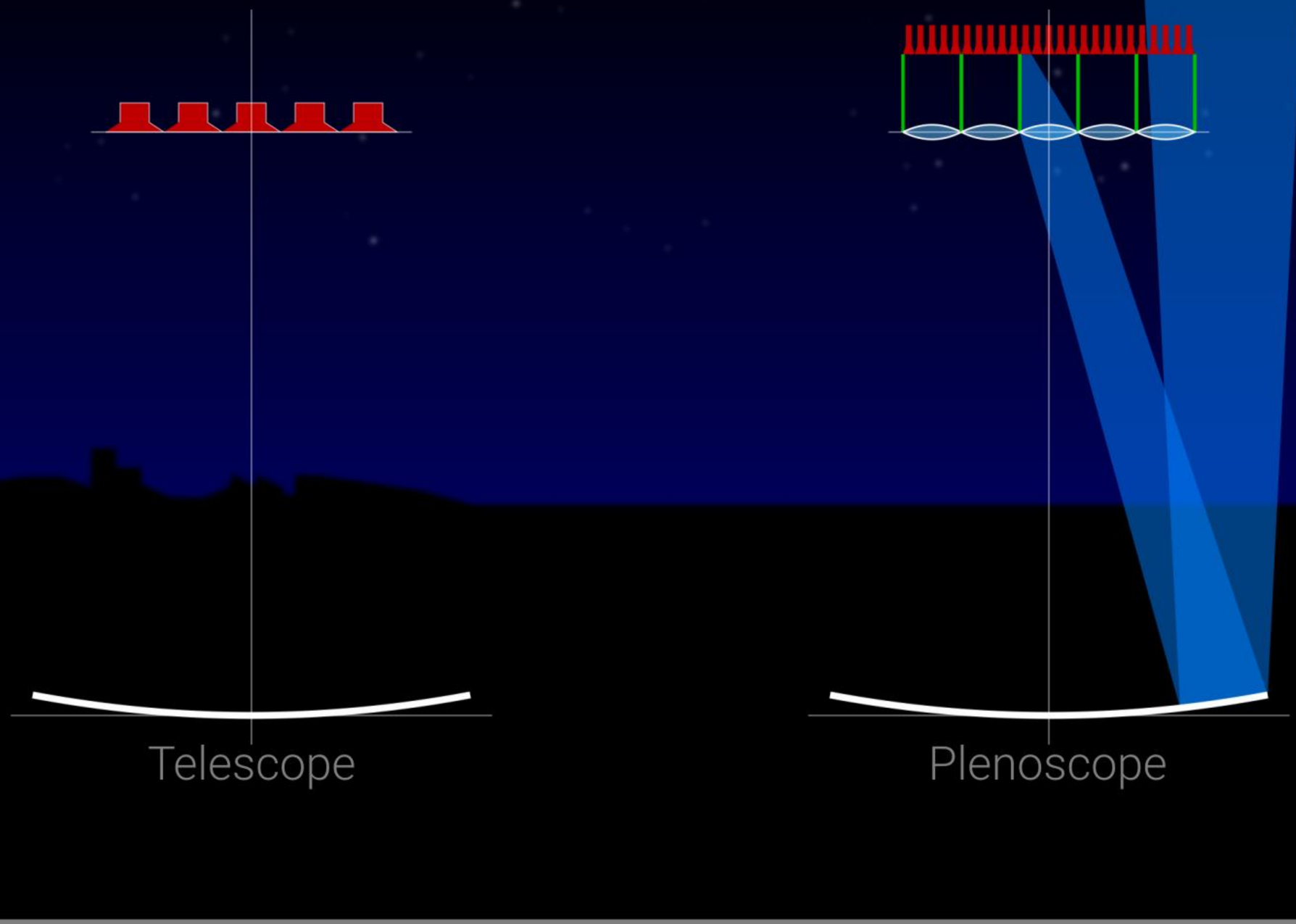
than

Optics



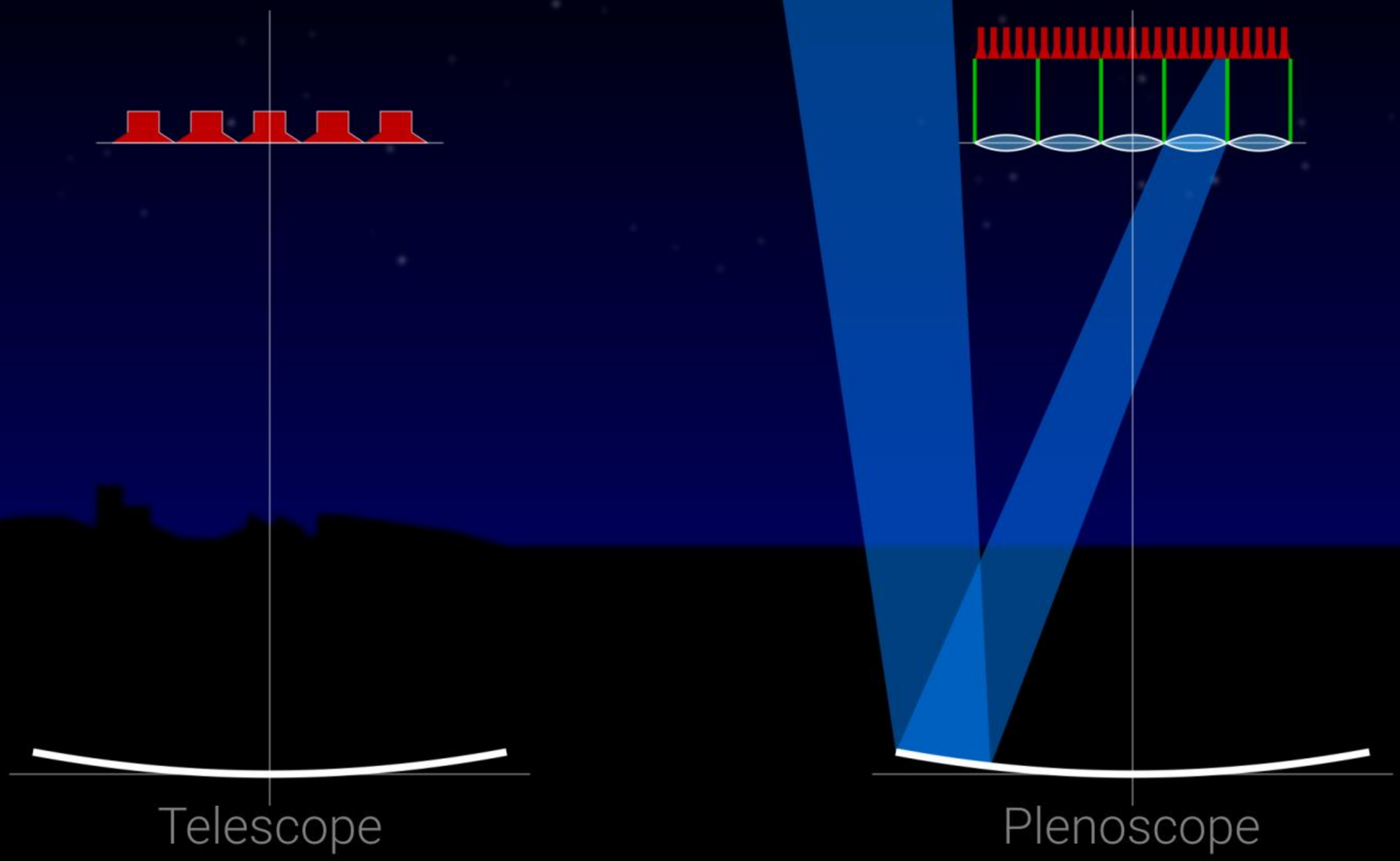
a

Optics

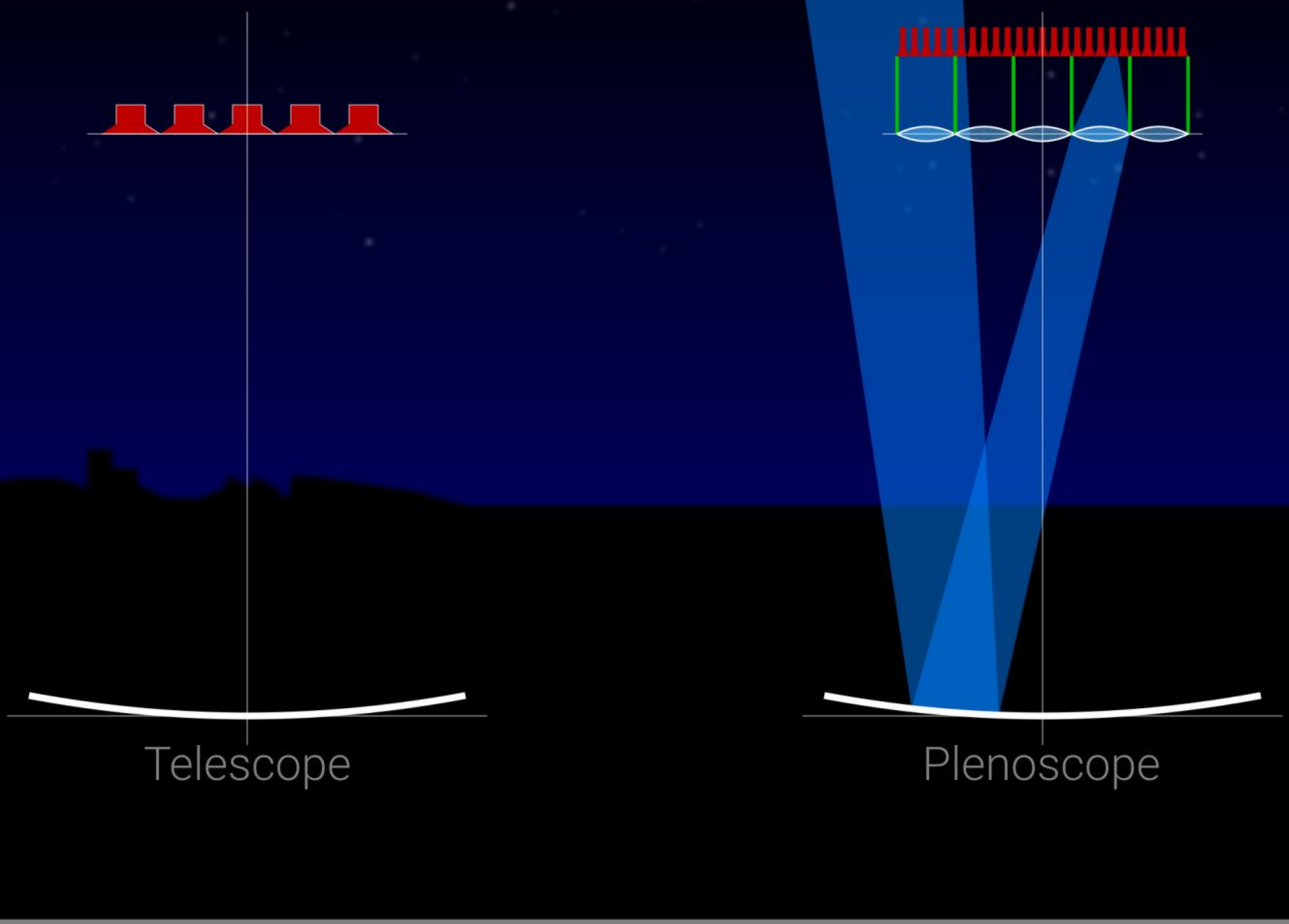


telescope.

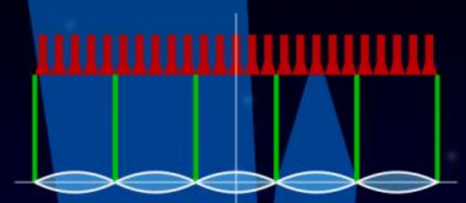
Optics



Optics



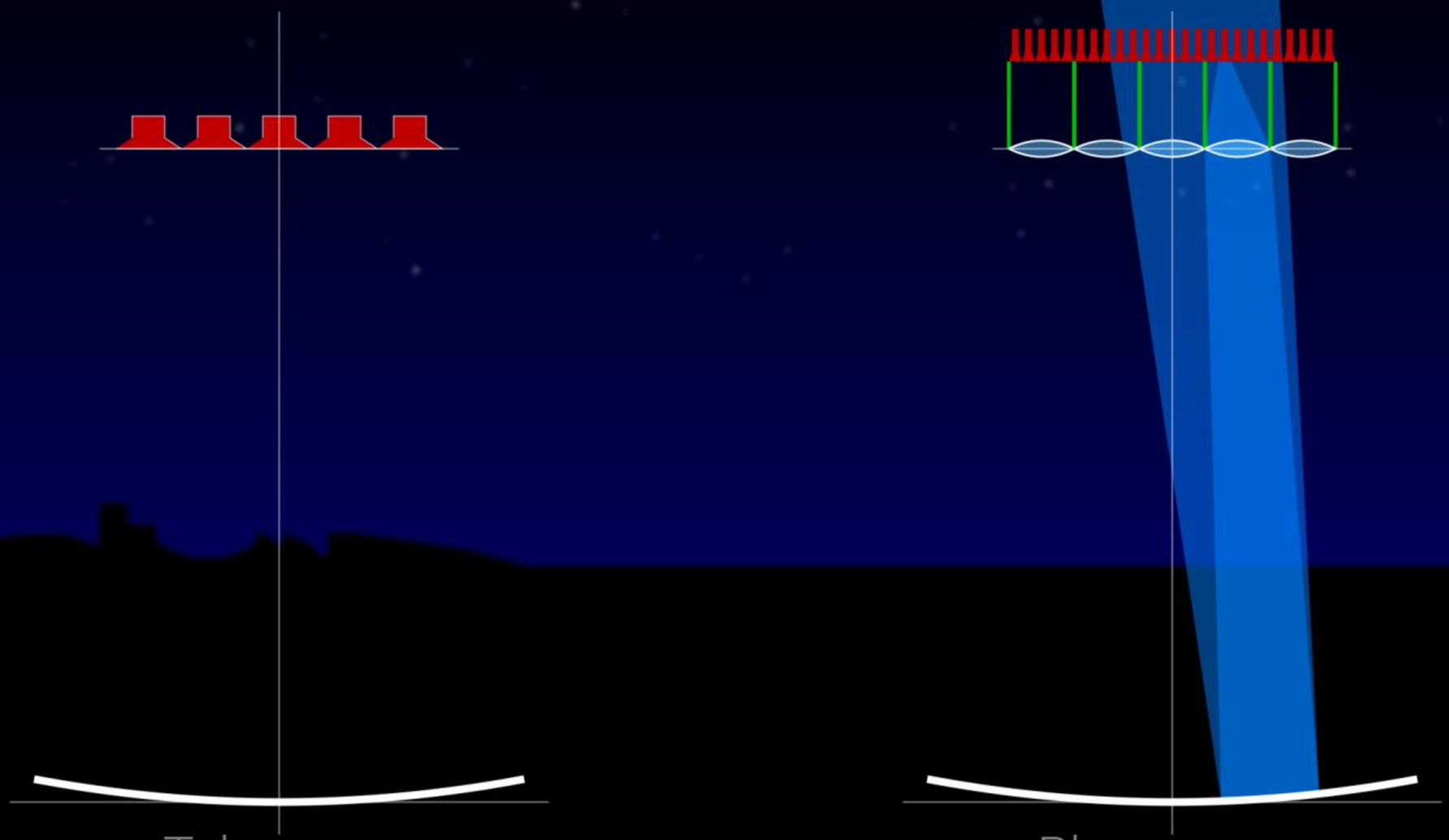
Optics



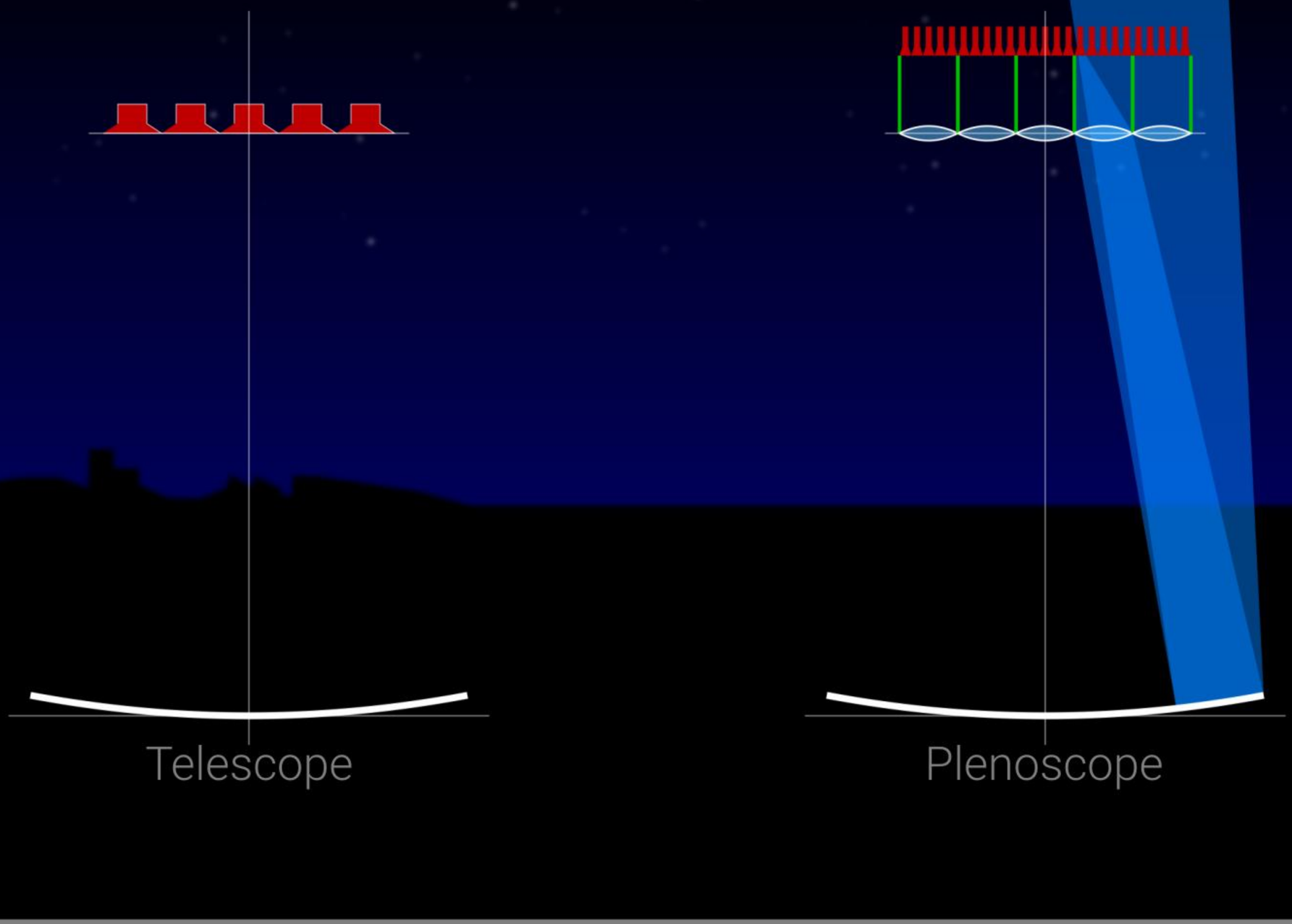
Telescope

Plenoscope

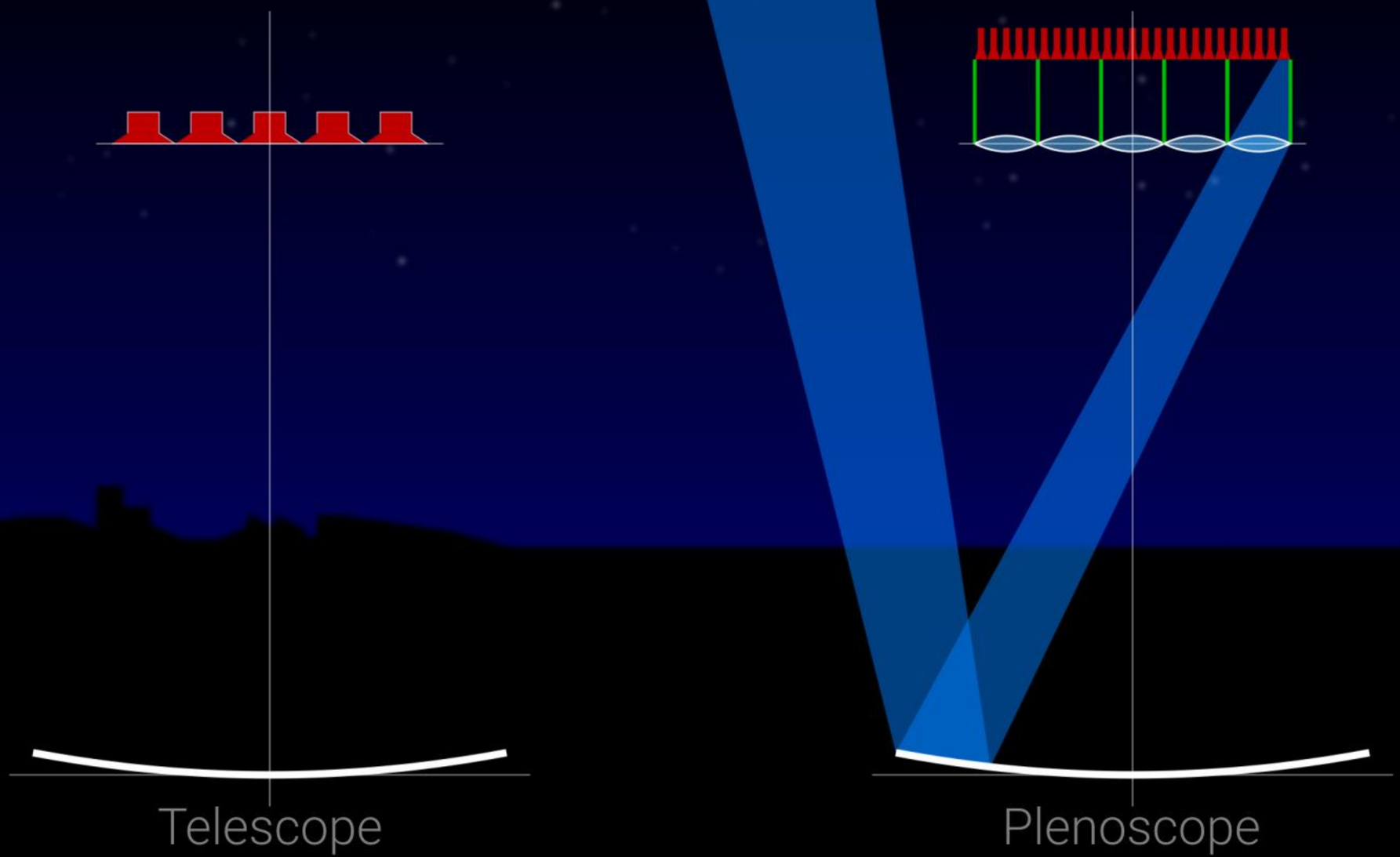
Optics



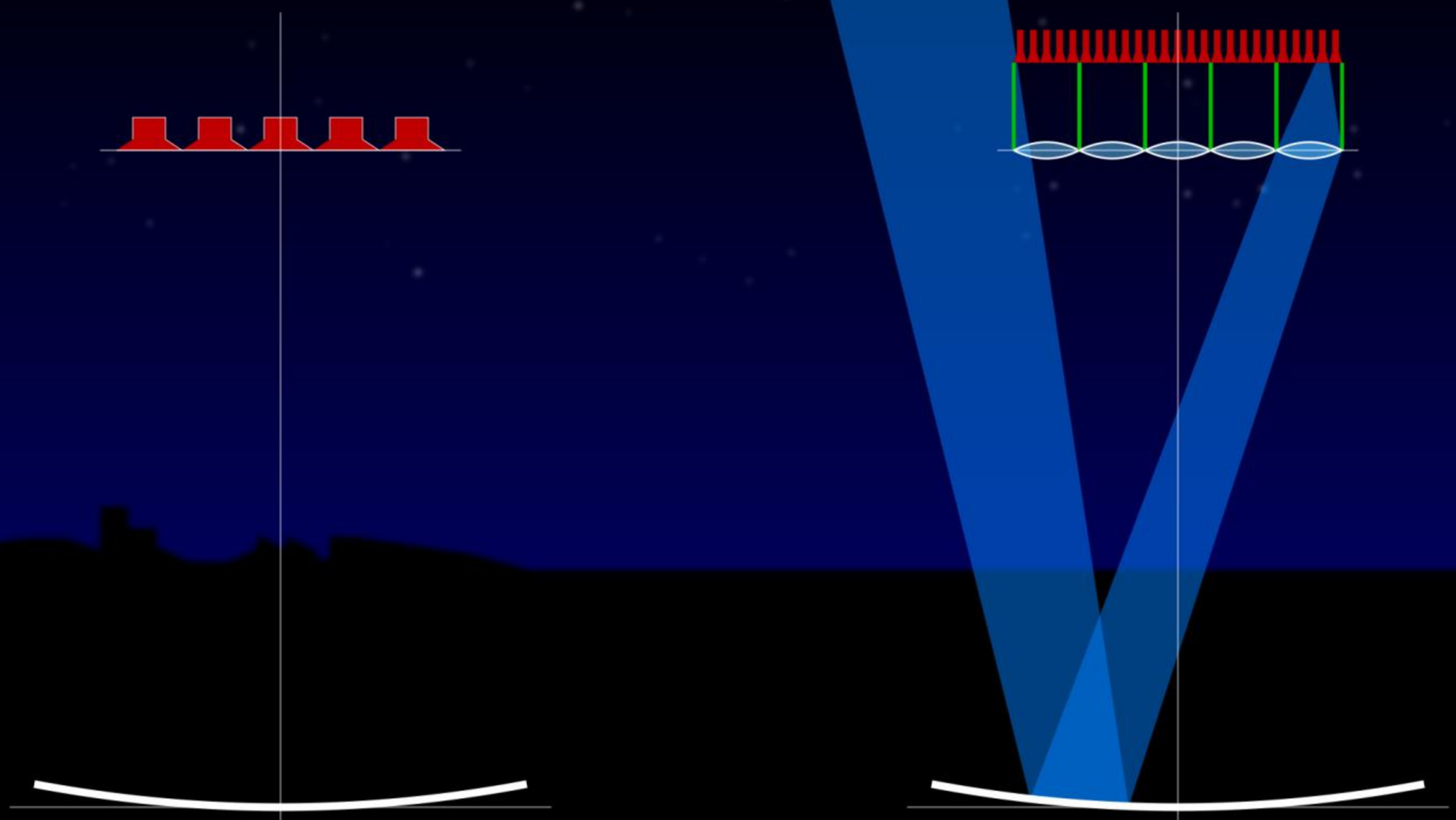
Optics



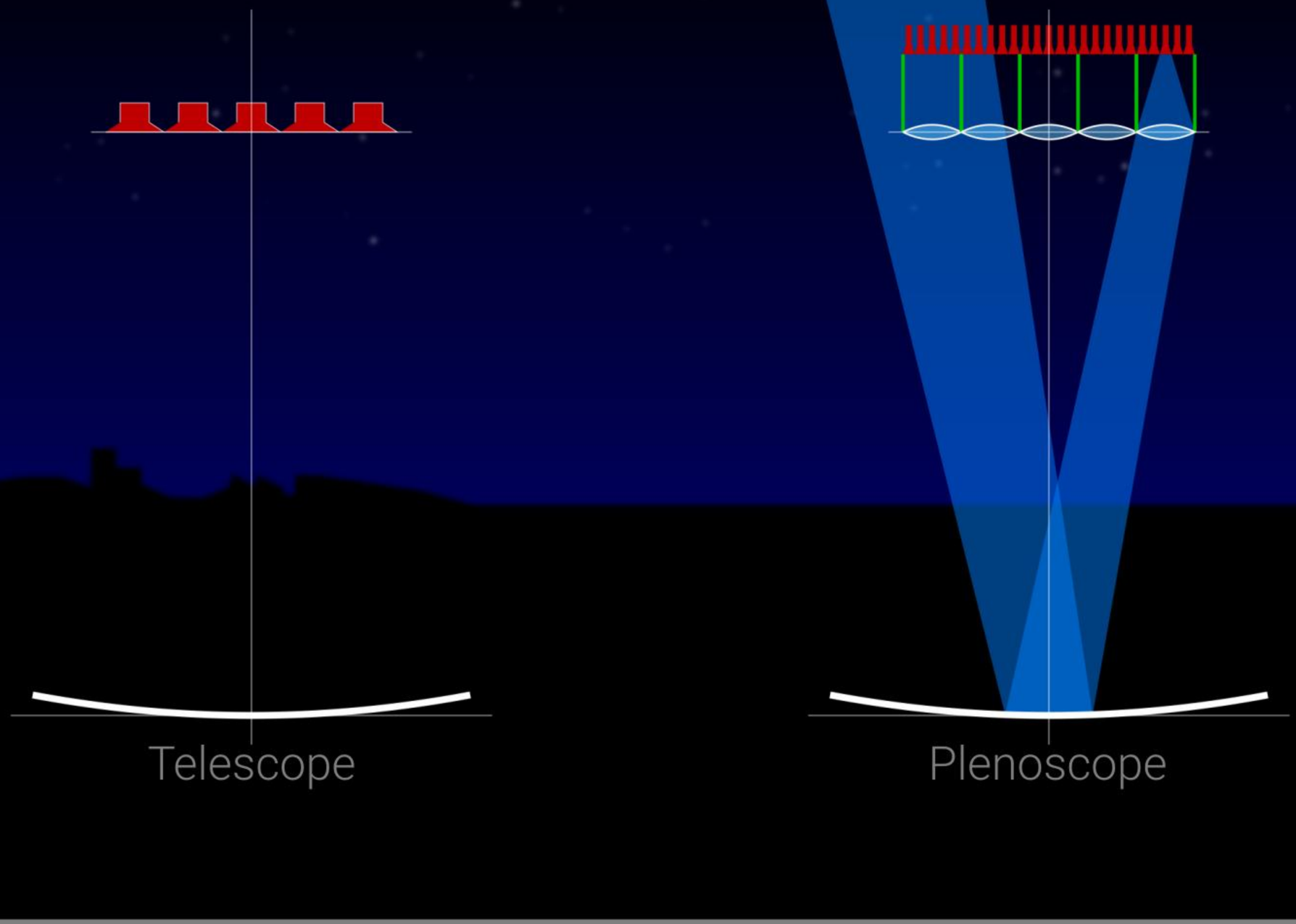
Optics



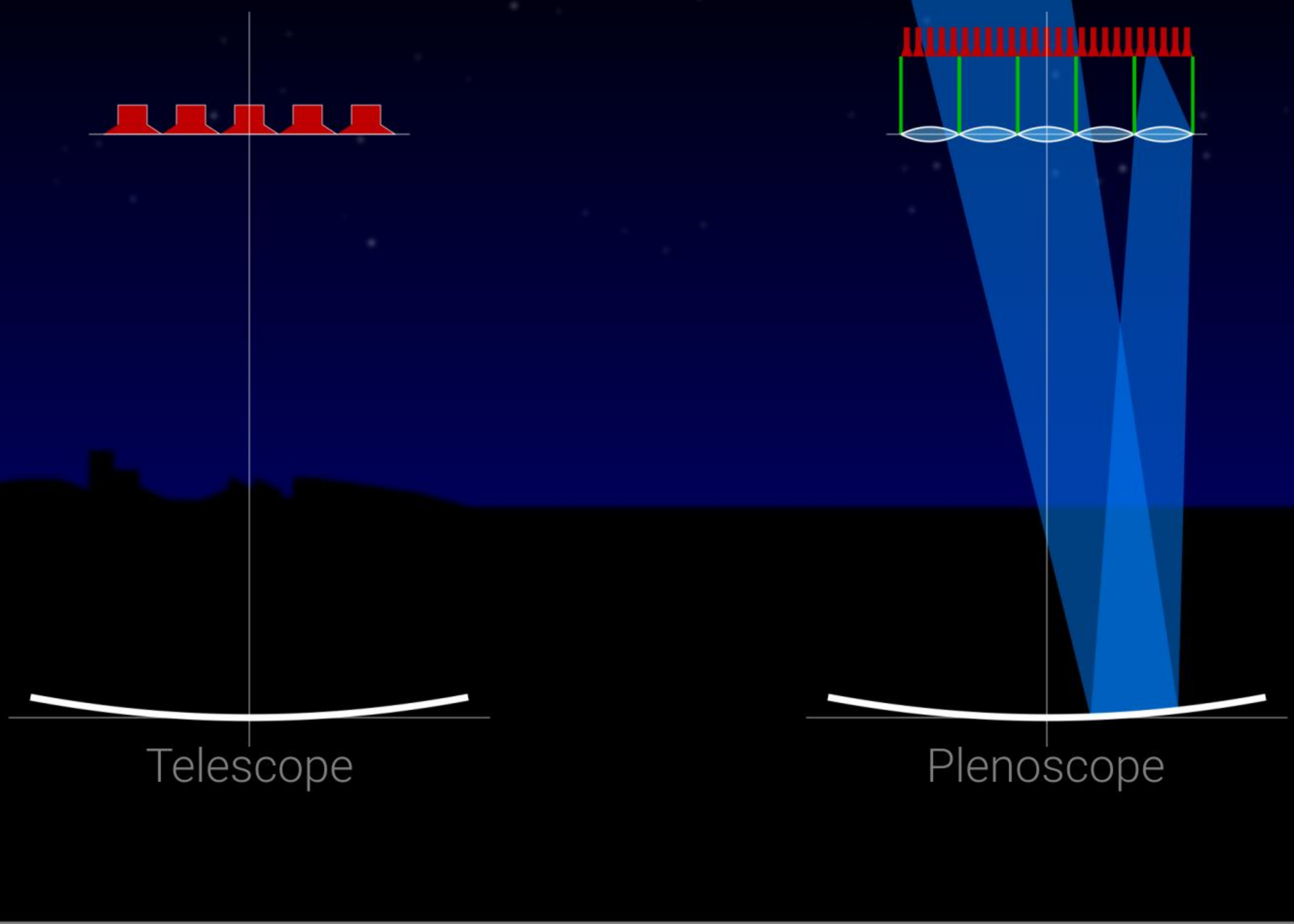
Optics



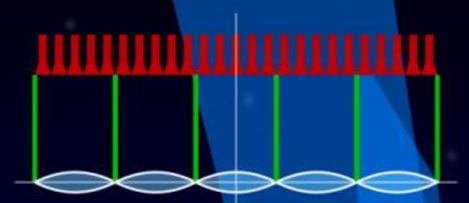
Optics



Optics



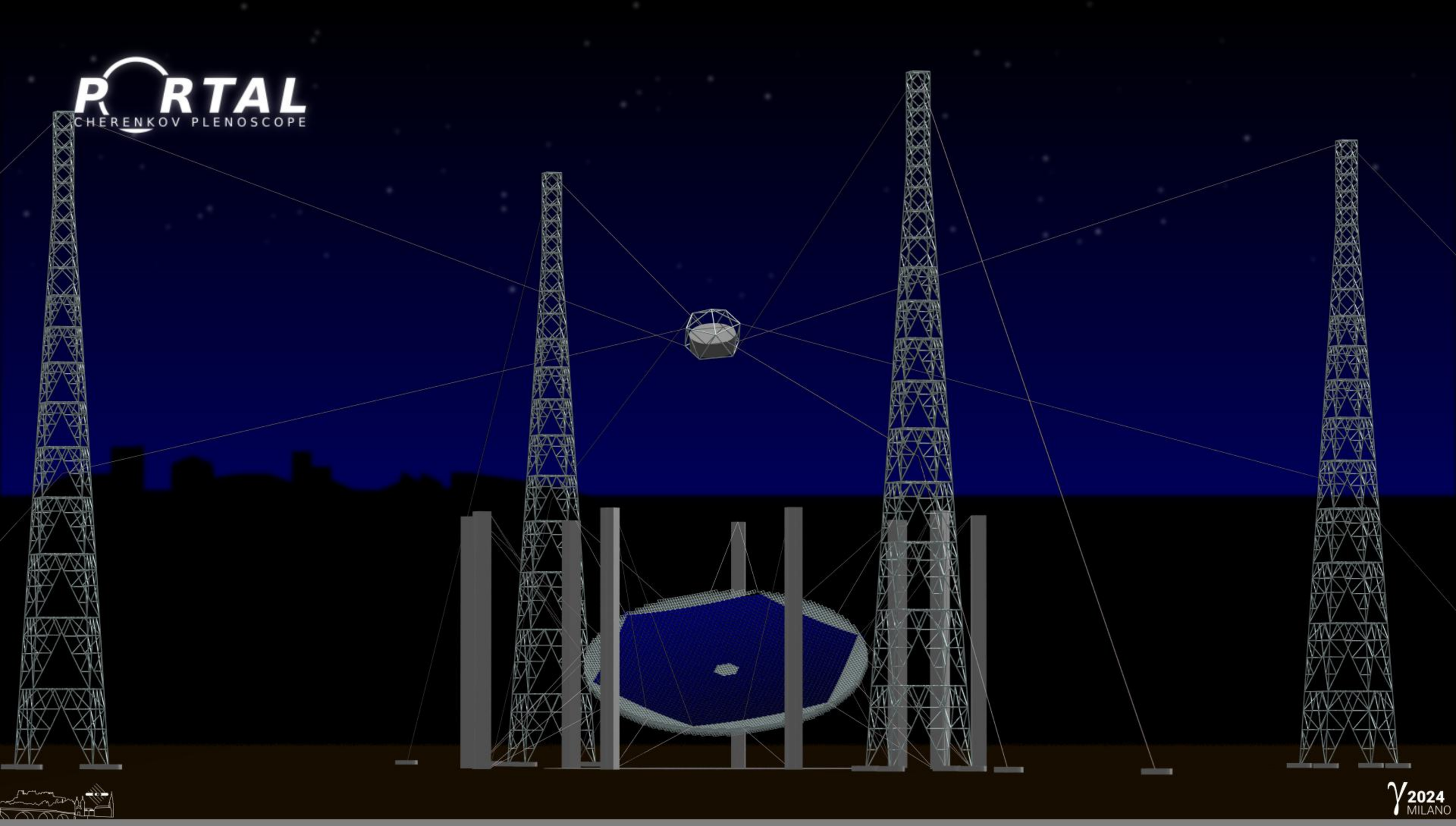
Optics



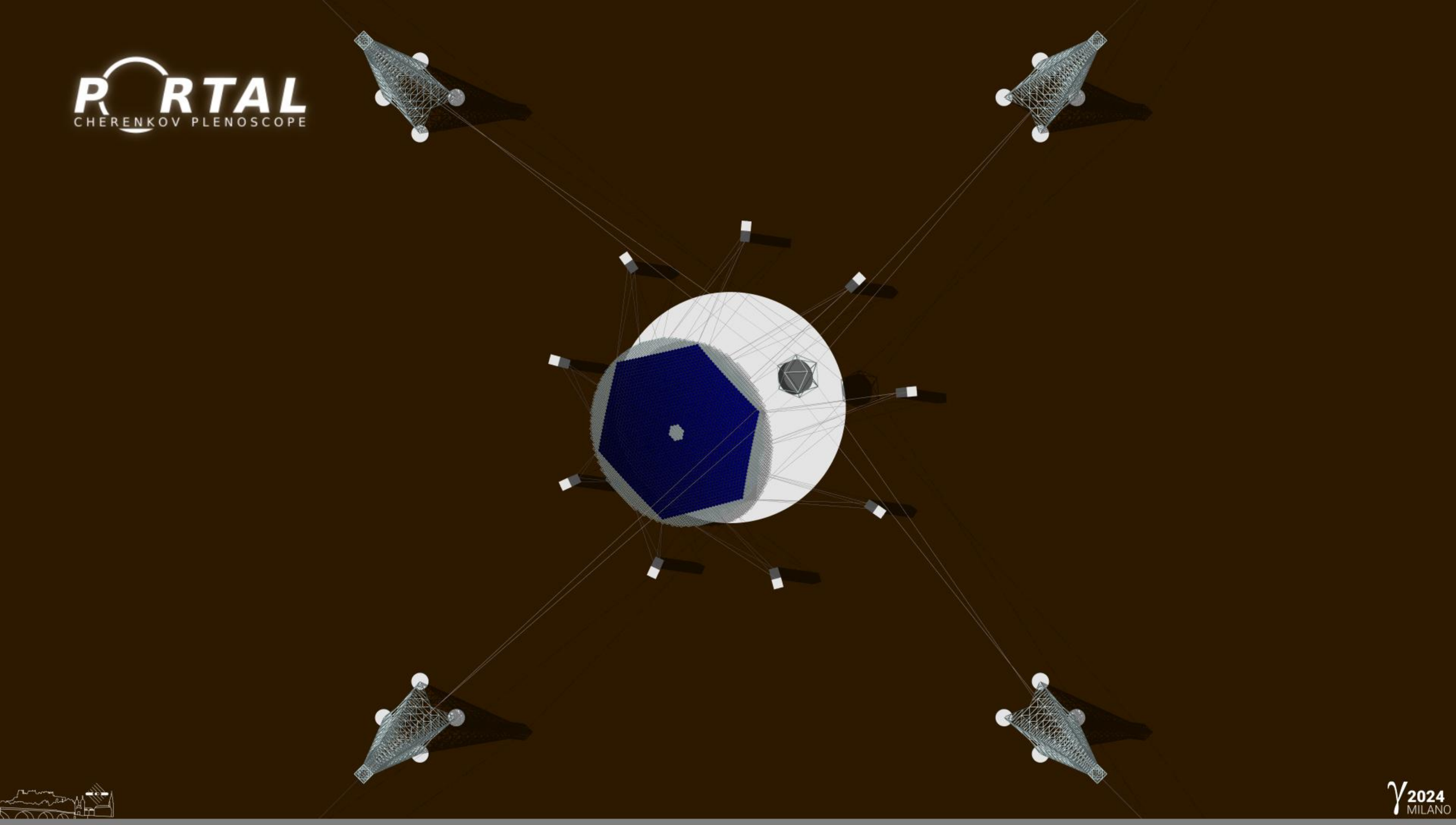
Telescope

Plenoscope

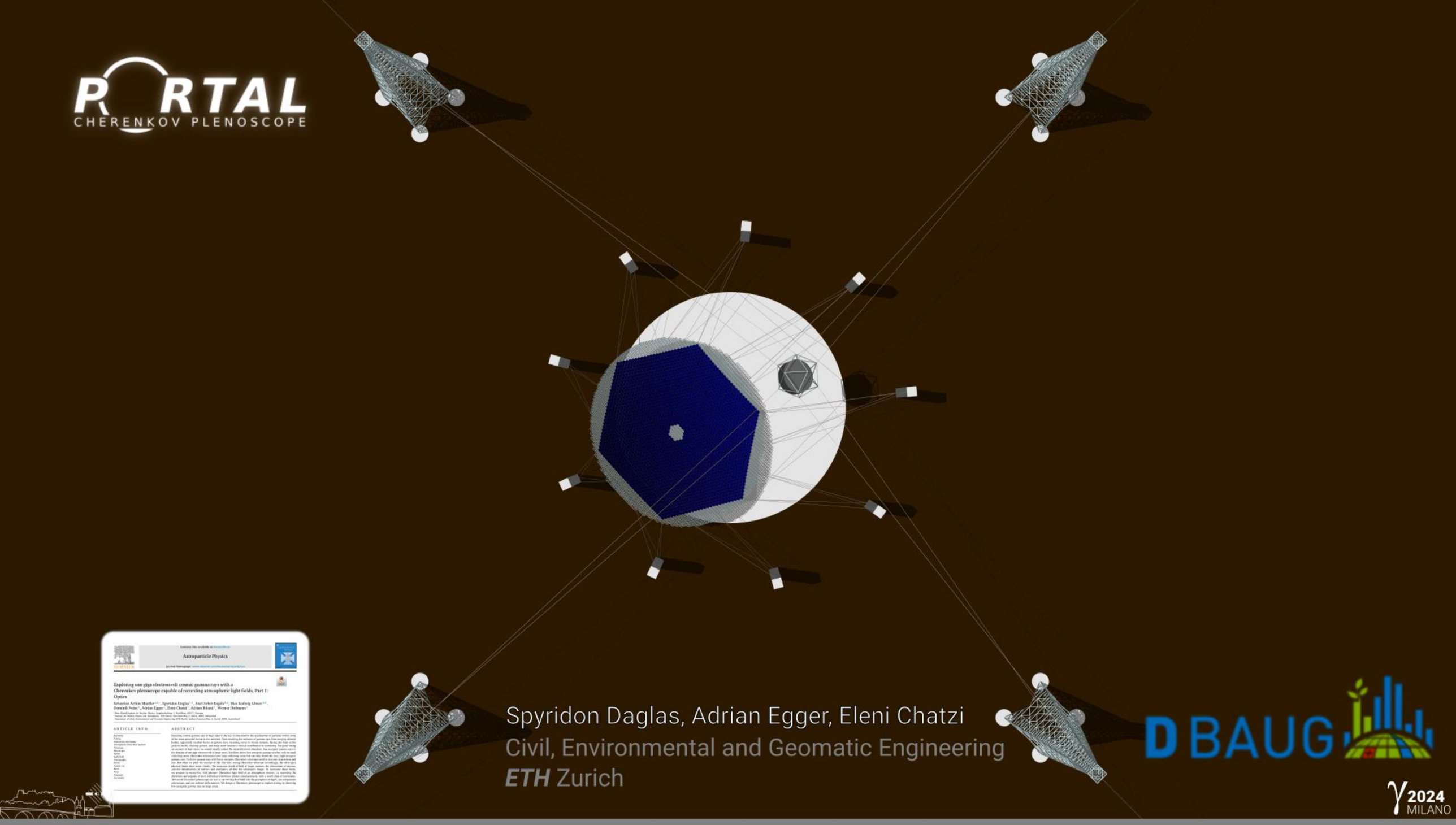
MILANO
2024
MILANO



To discuss the optical performance of plenoptic perception, we now take a look at a specific design for a Cherenkov plenoscope named Portal.



Portal's goal is to lower the energy threshold of the atmospheric Cherenkov method by exploiting the relaxed constrains for deformations and misalignments granted by plenoptic perception.

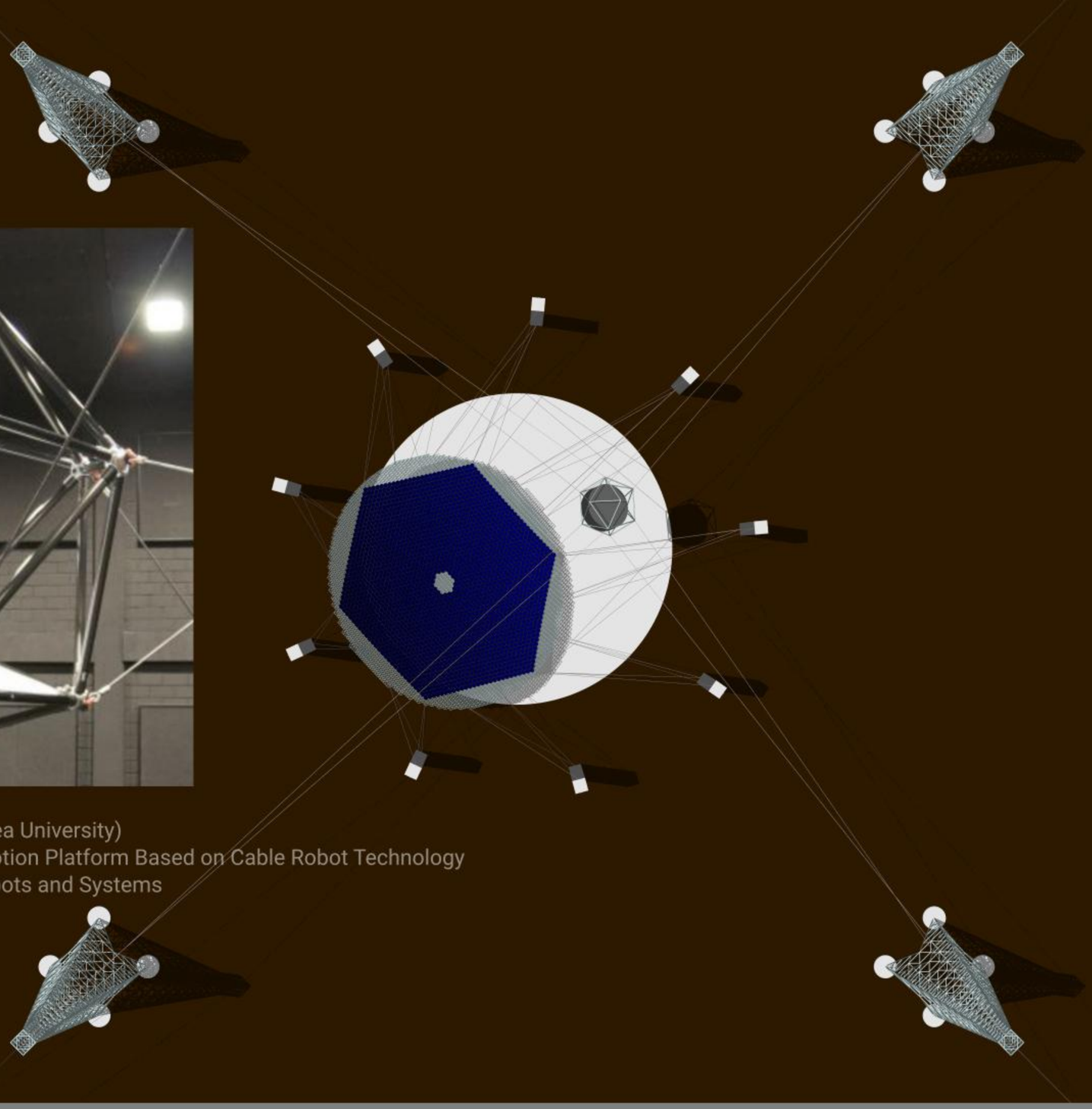


Spyridon Daglas, Adrian Egger, Eleni Chatzi
Civil, Environmental and Geomatic Engineering
ETH Zurich

So together with our colleagues from civil engineers, ...

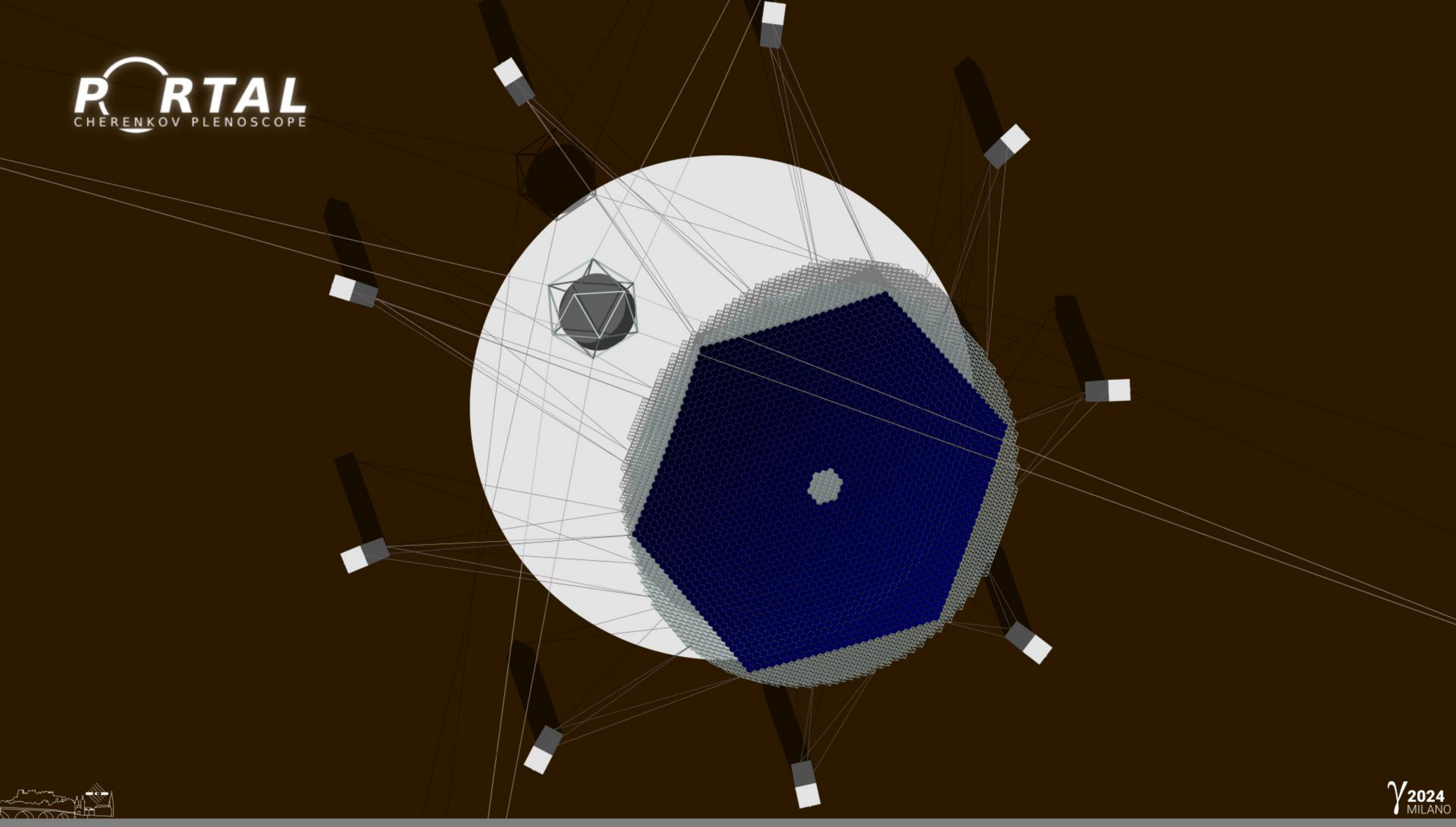
PORTAL
CHERENKOV PLENOSCOPE

Philipp Miermeister et al. 2016
(Fraunhofer IPA, MPI bio. Cybernetics, Korea University)
The CableRobot Simulator: Large Scale Motion Platform Based on Cable Robot Technology
International Conference on Intelligent Robots and Systems
Daejeon, Korea

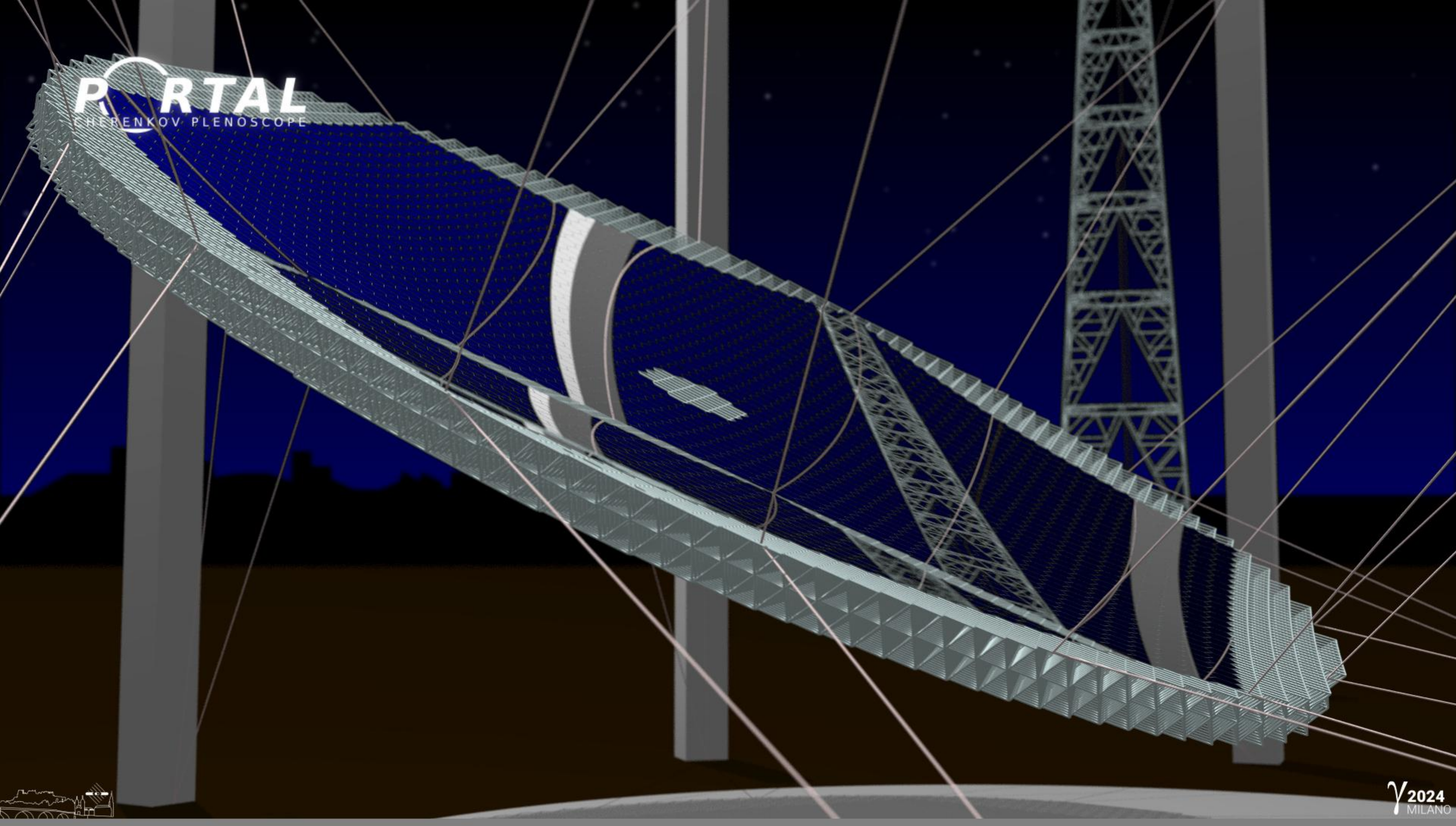


γ2024 MILANO

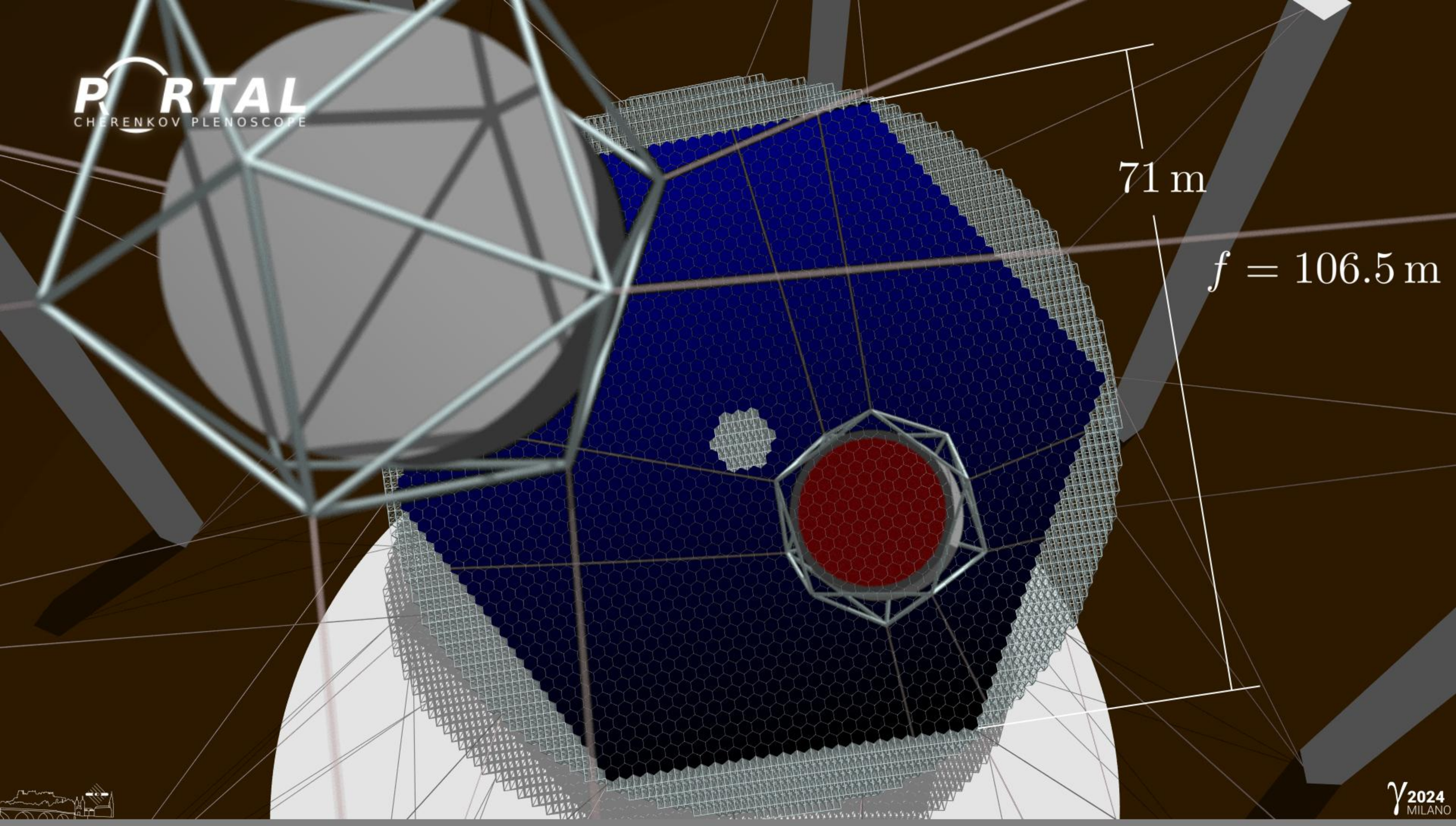
we gave Portal two independent cable-robots to mount and point its camera



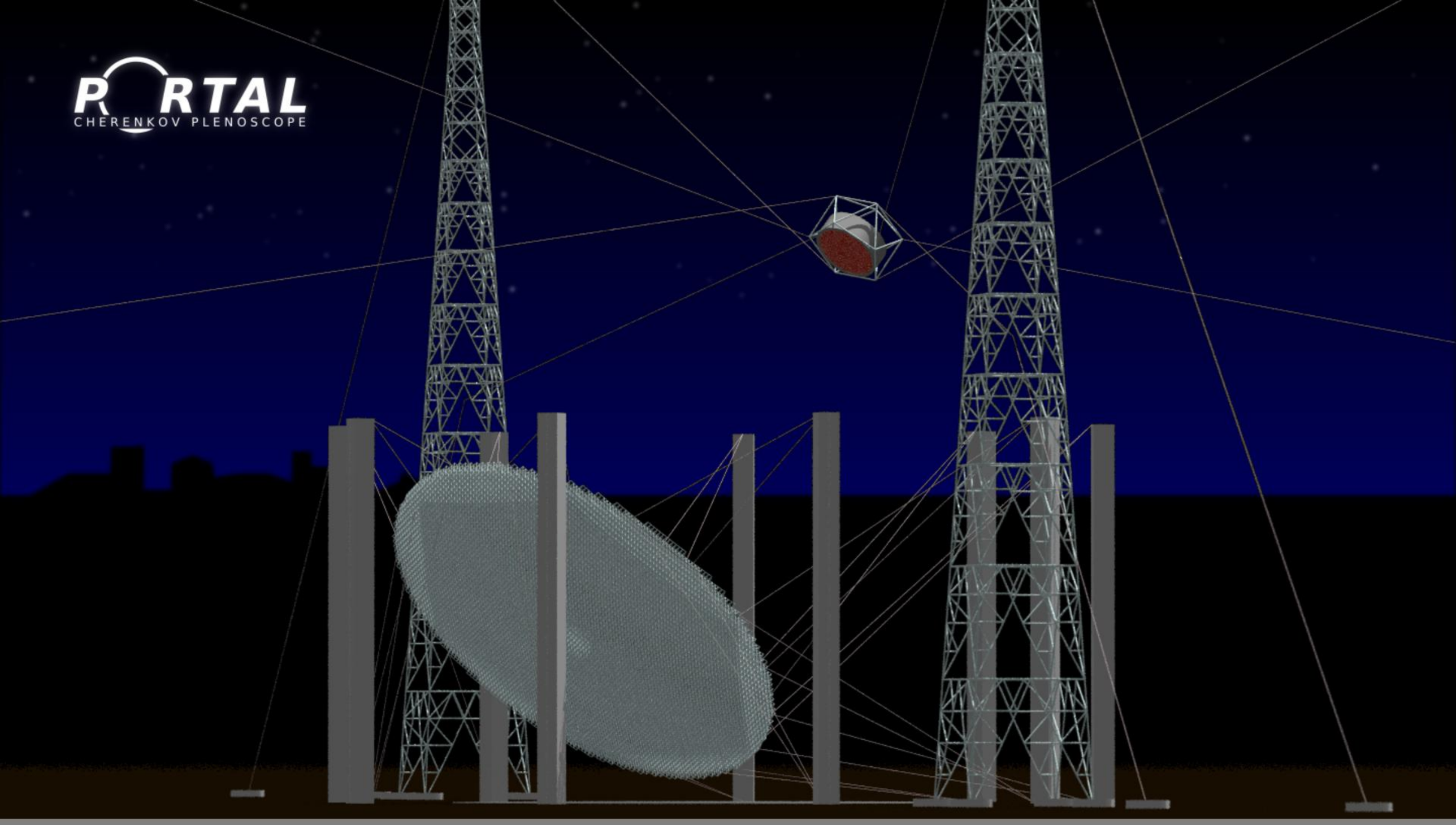
and mirror separately.



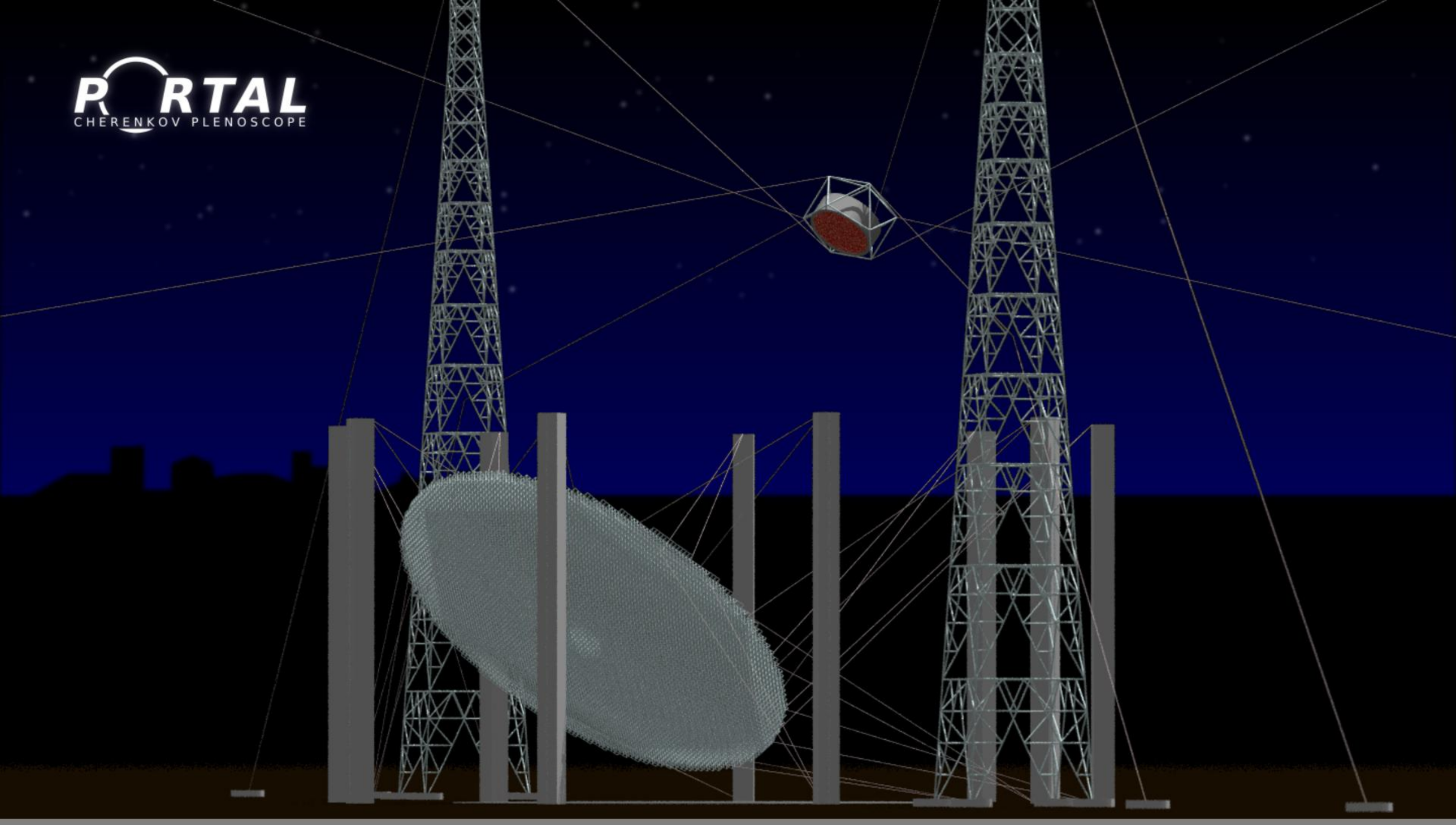
Portals mirror is seventy one meters in diameter,



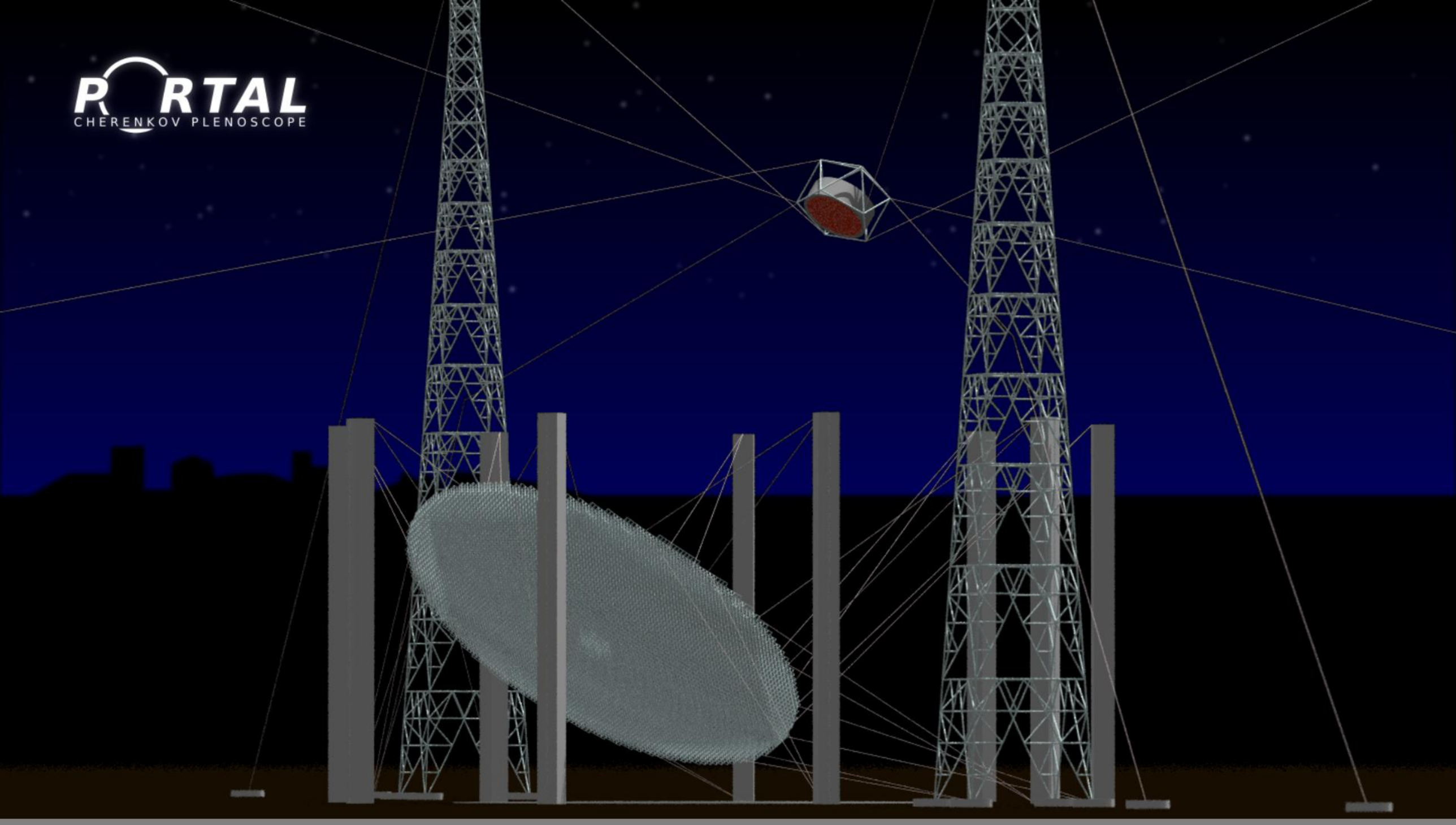
has a focal-ratio of one point five.



When pointing, the cablerobots move in opposite directions to effectively rotate both mirror and camera around their common center.



Unlike the altitude-azimuth mount, the cablerobot has no singularity near the zenith what allows it to always move along the great circle and thus makes it intrinsically faster.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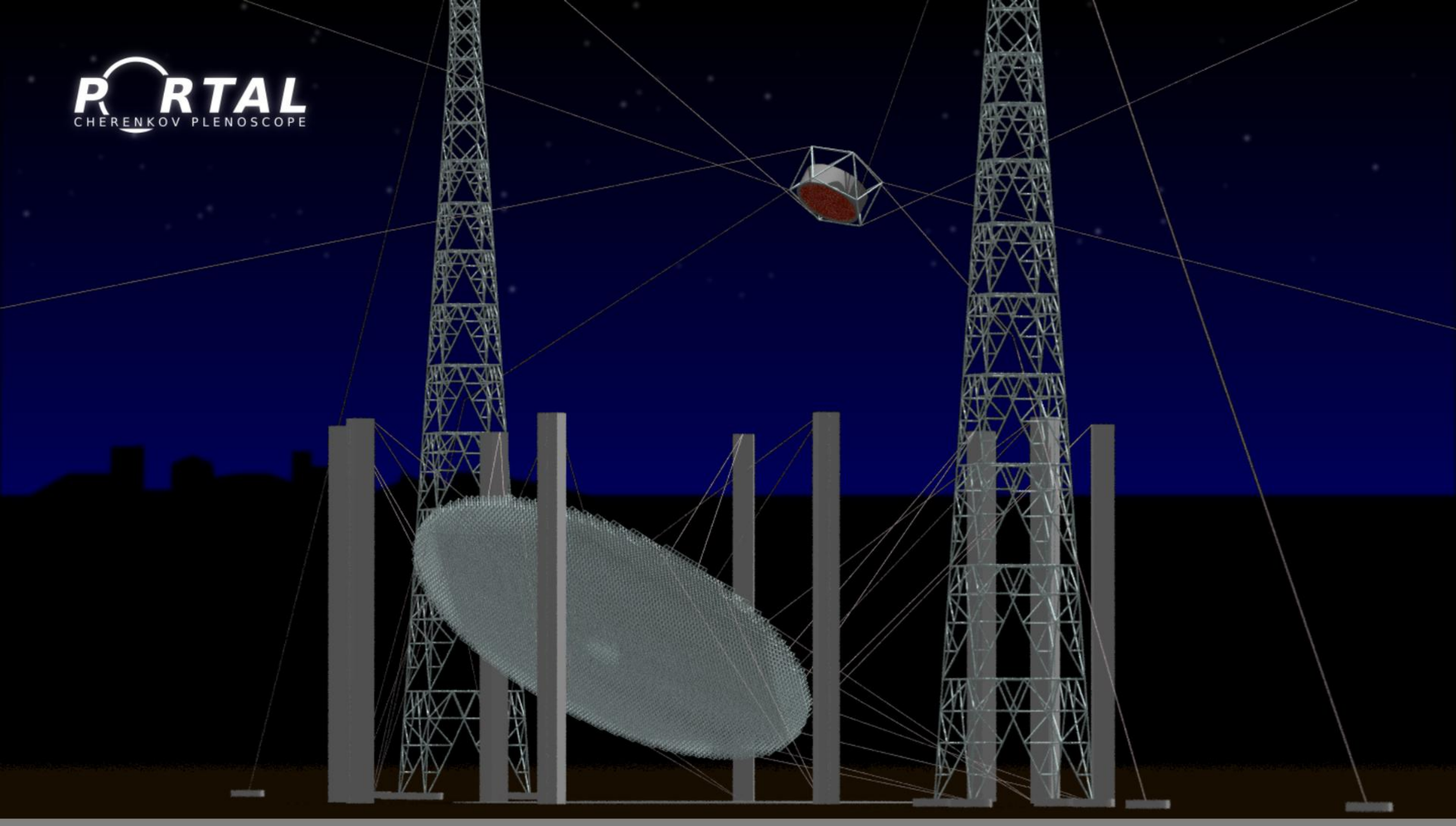
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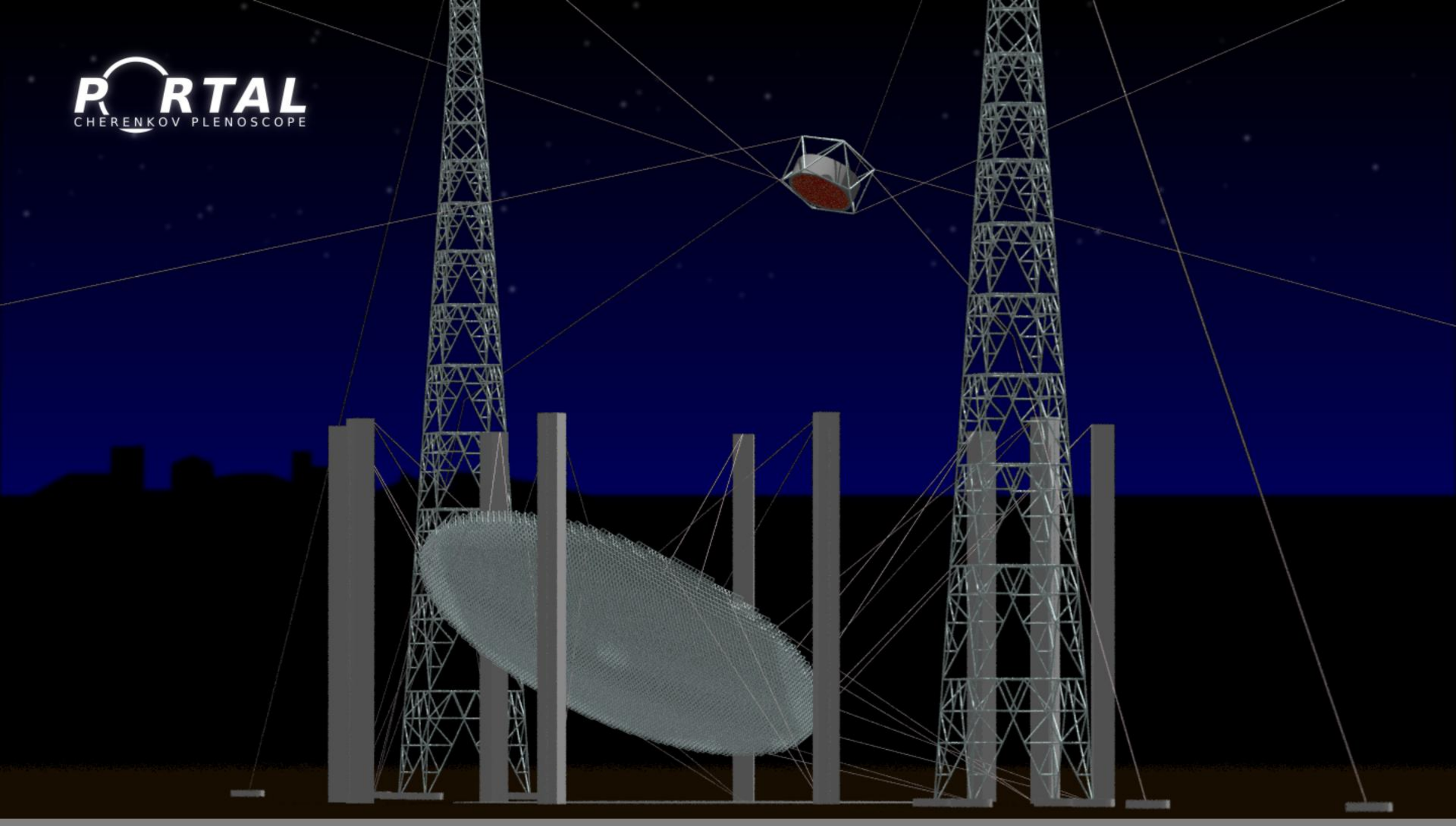
CHERENKOV PLENOSCOPE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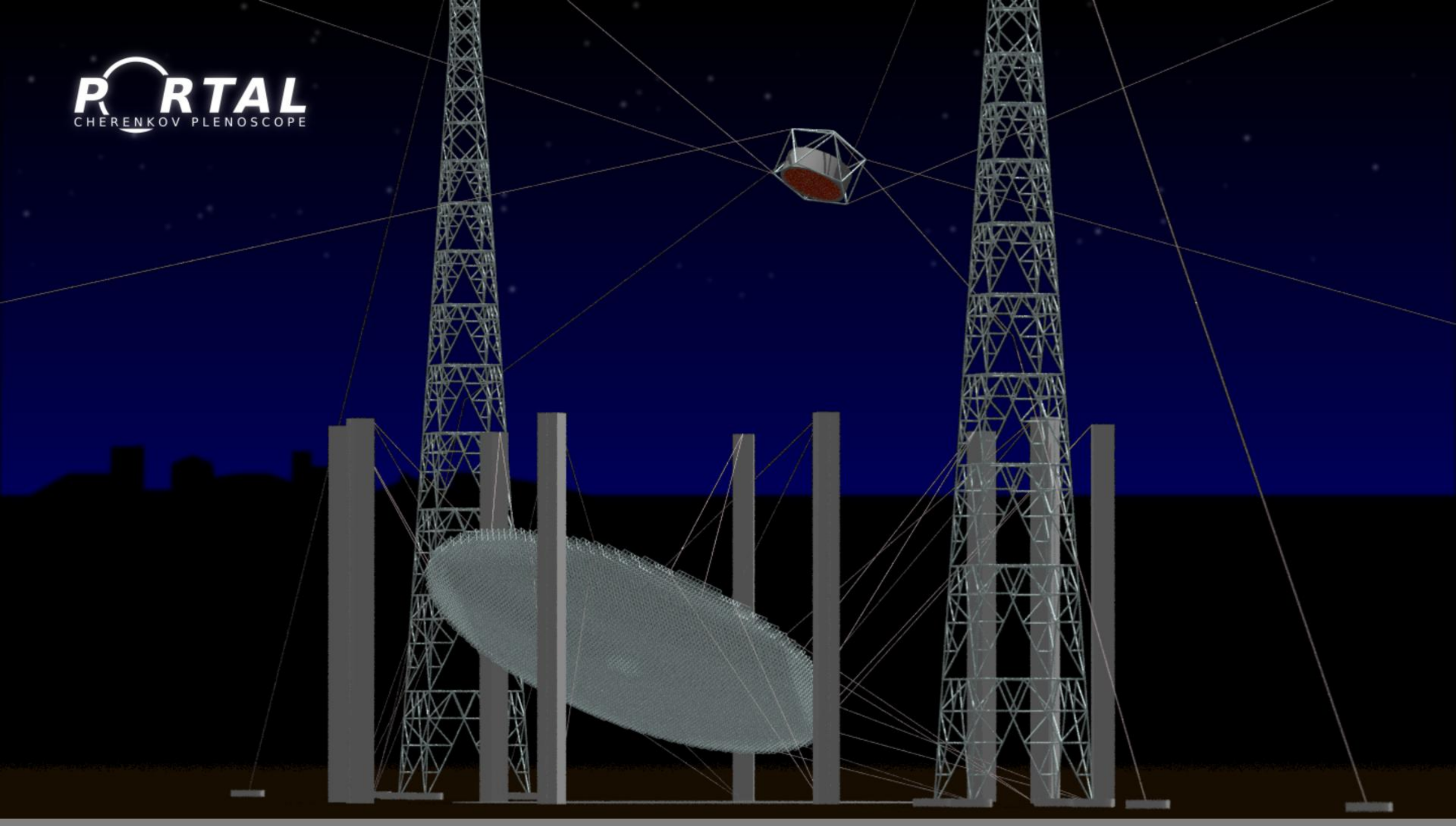
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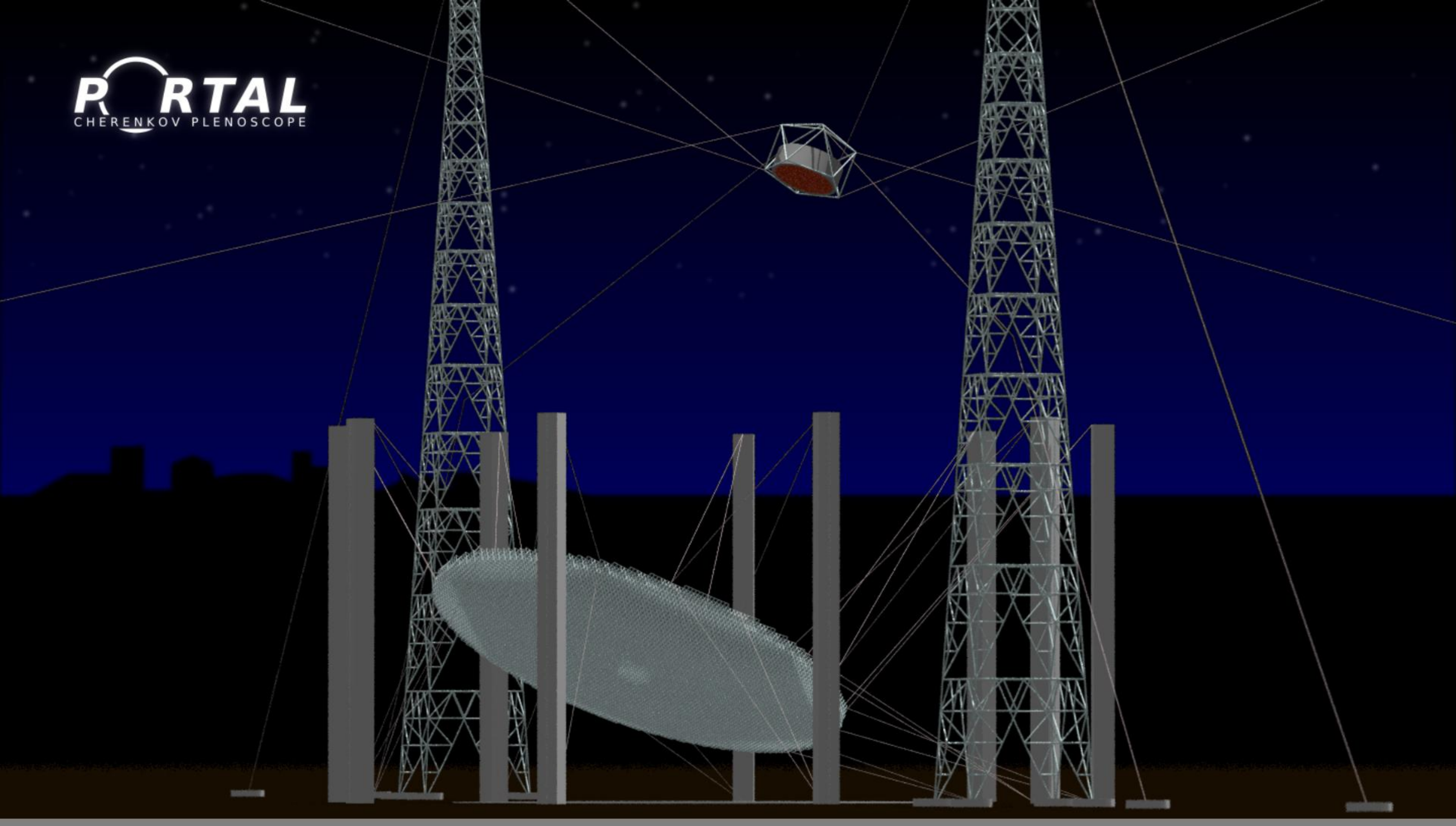
CHERENKOV PLENOSCOPE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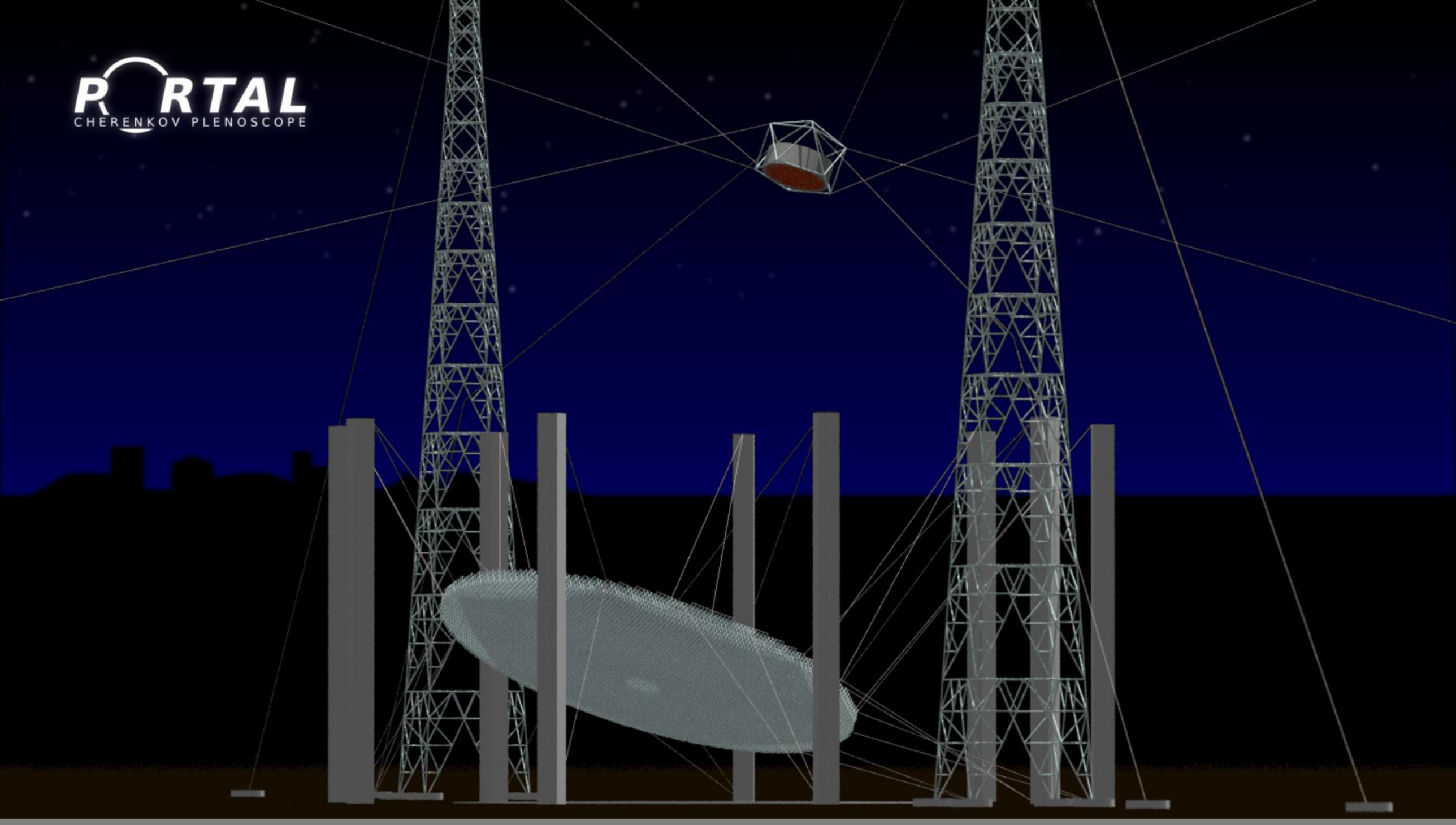
CHERENKOV PLENOSCOPE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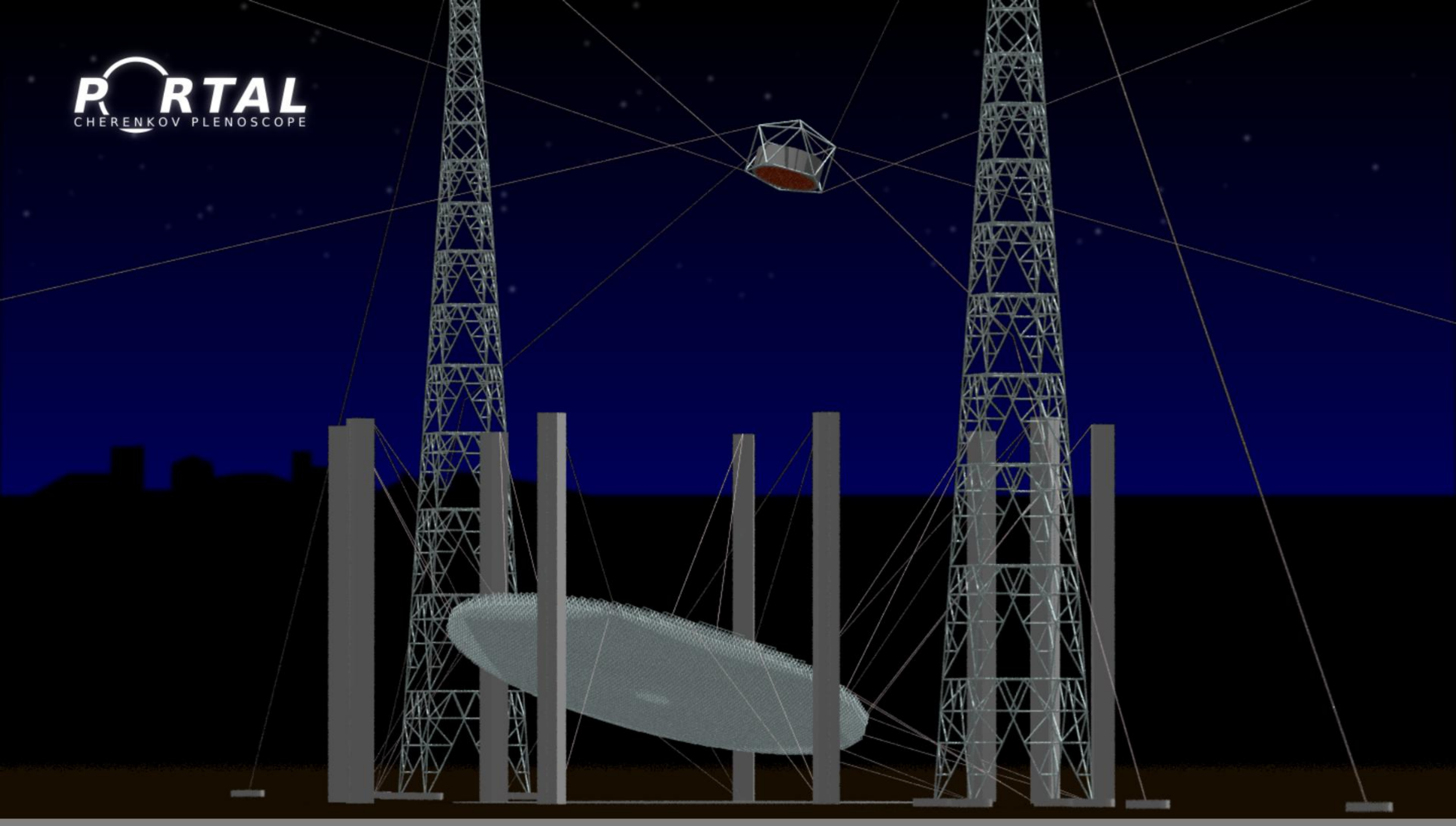
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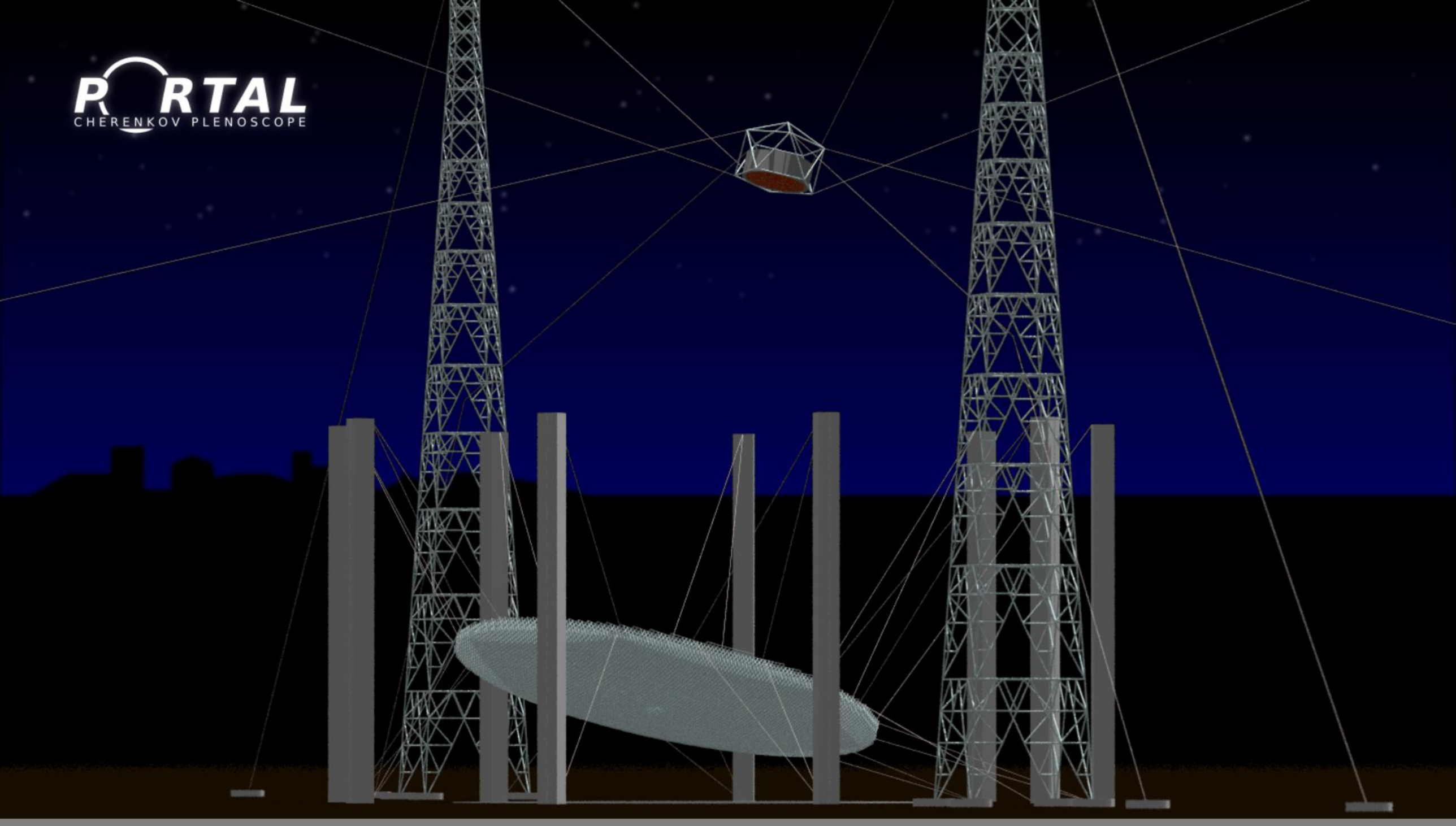
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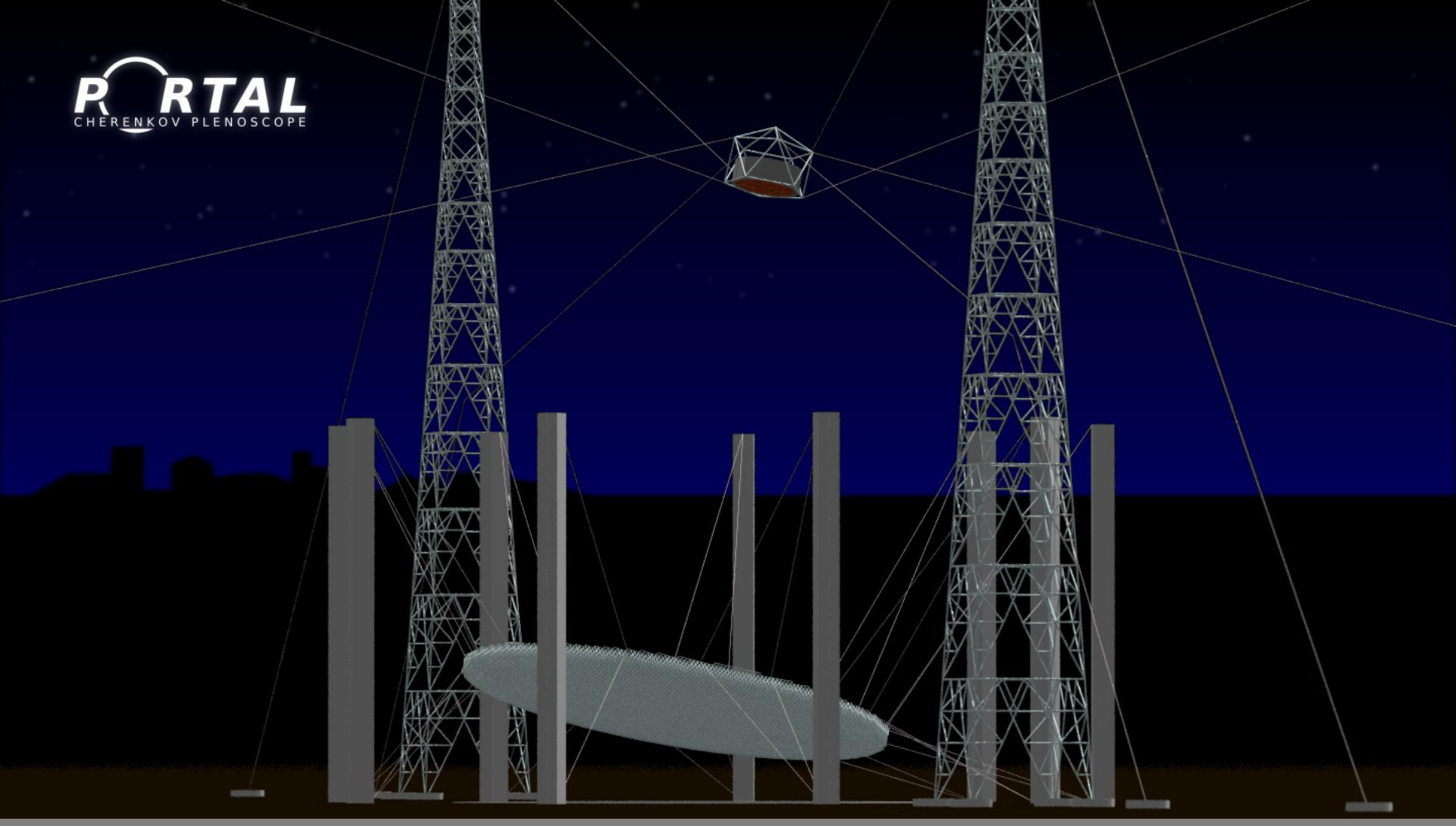
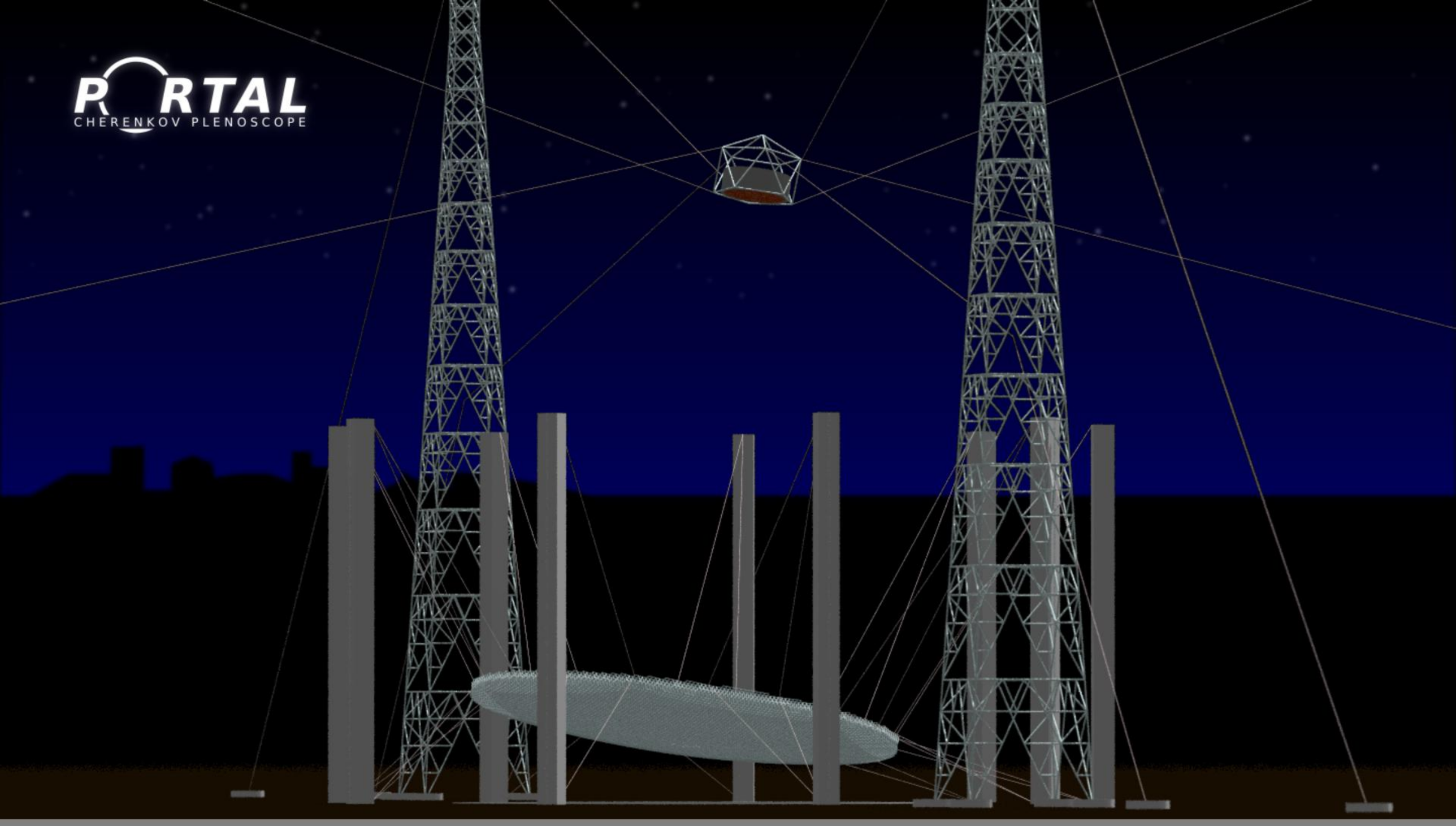
CHERENKOV PLENOSCOPE


PORTAL
CHERENKOV PLENOSCOPE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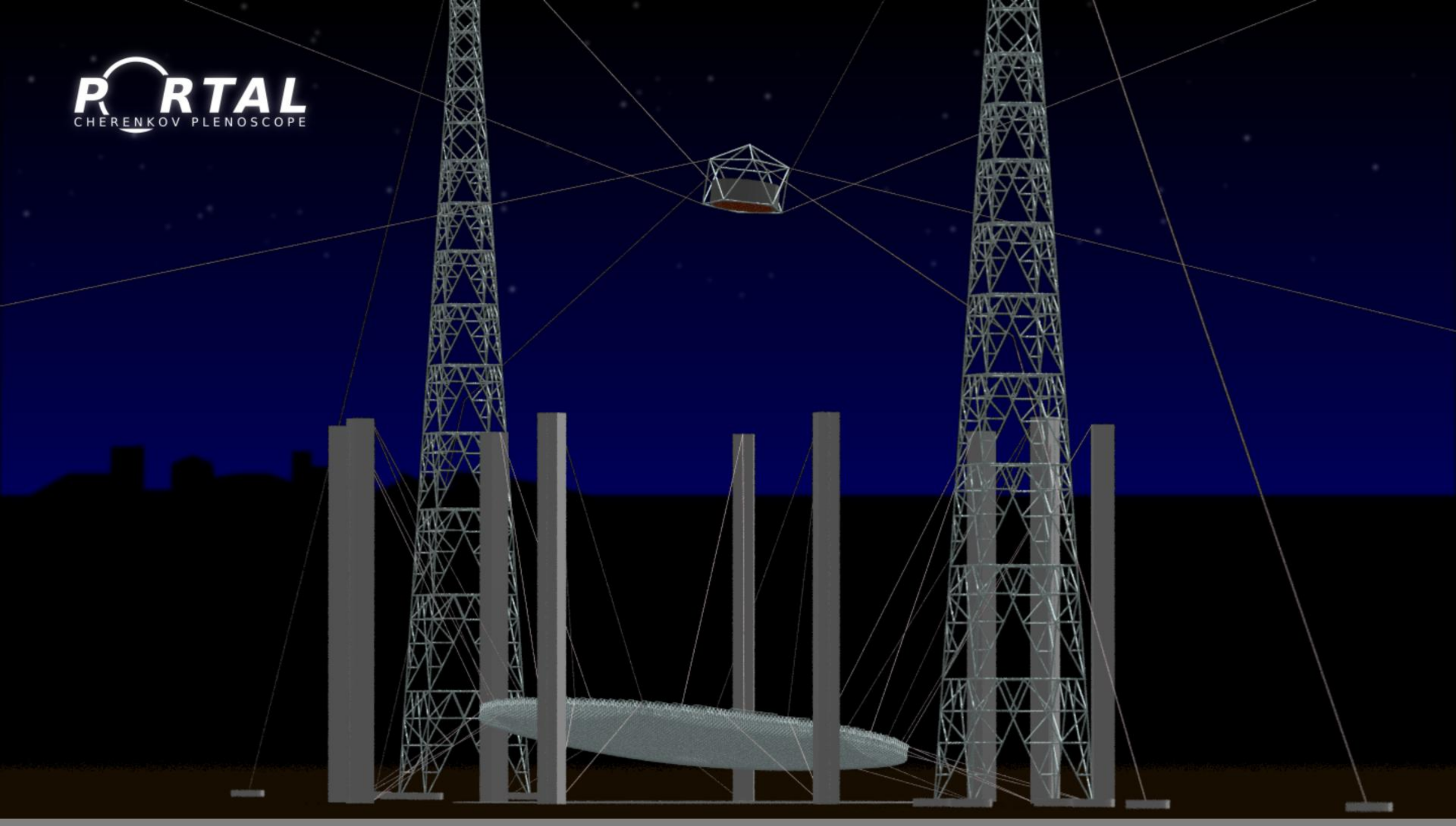
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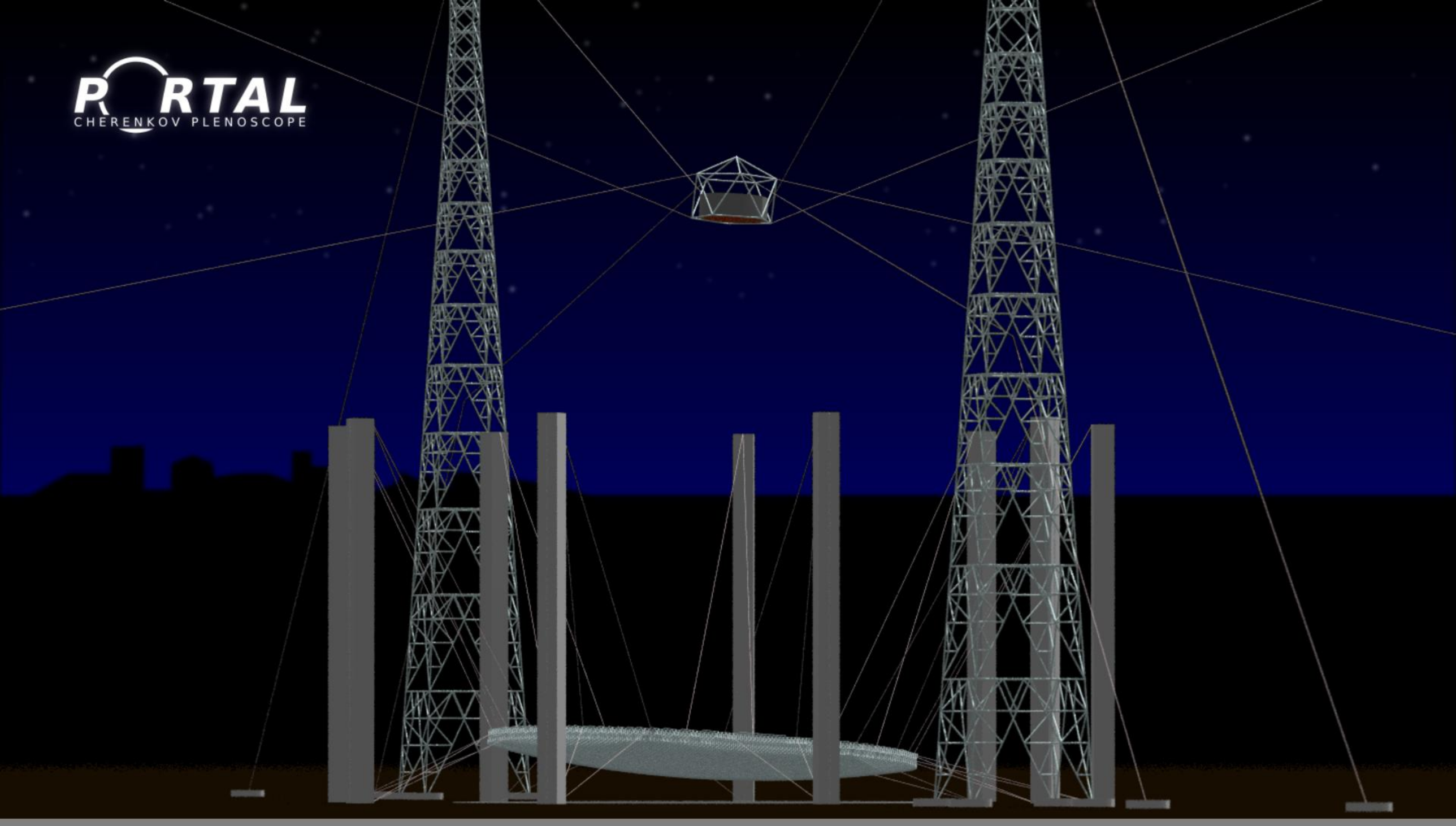
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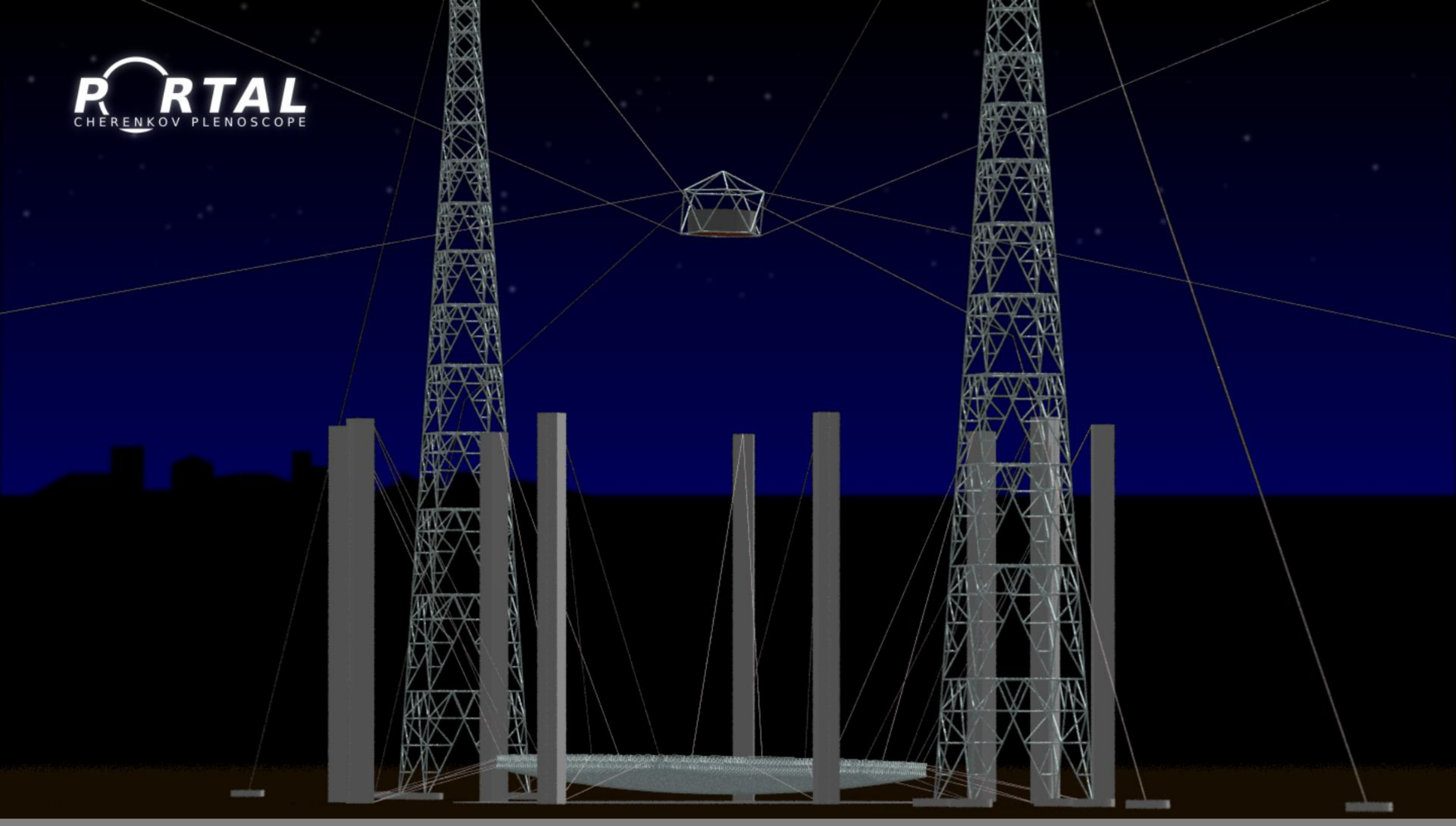
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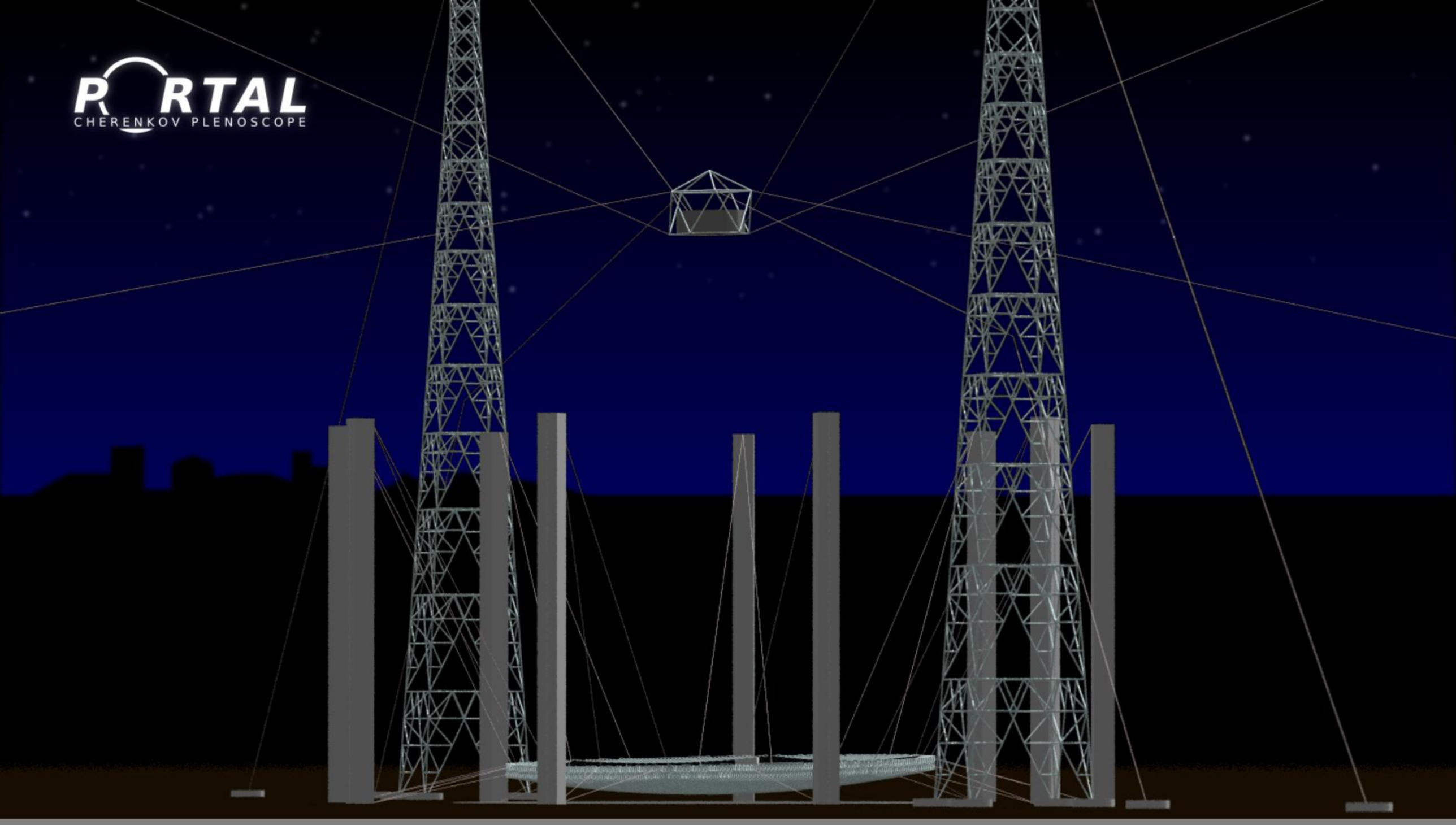
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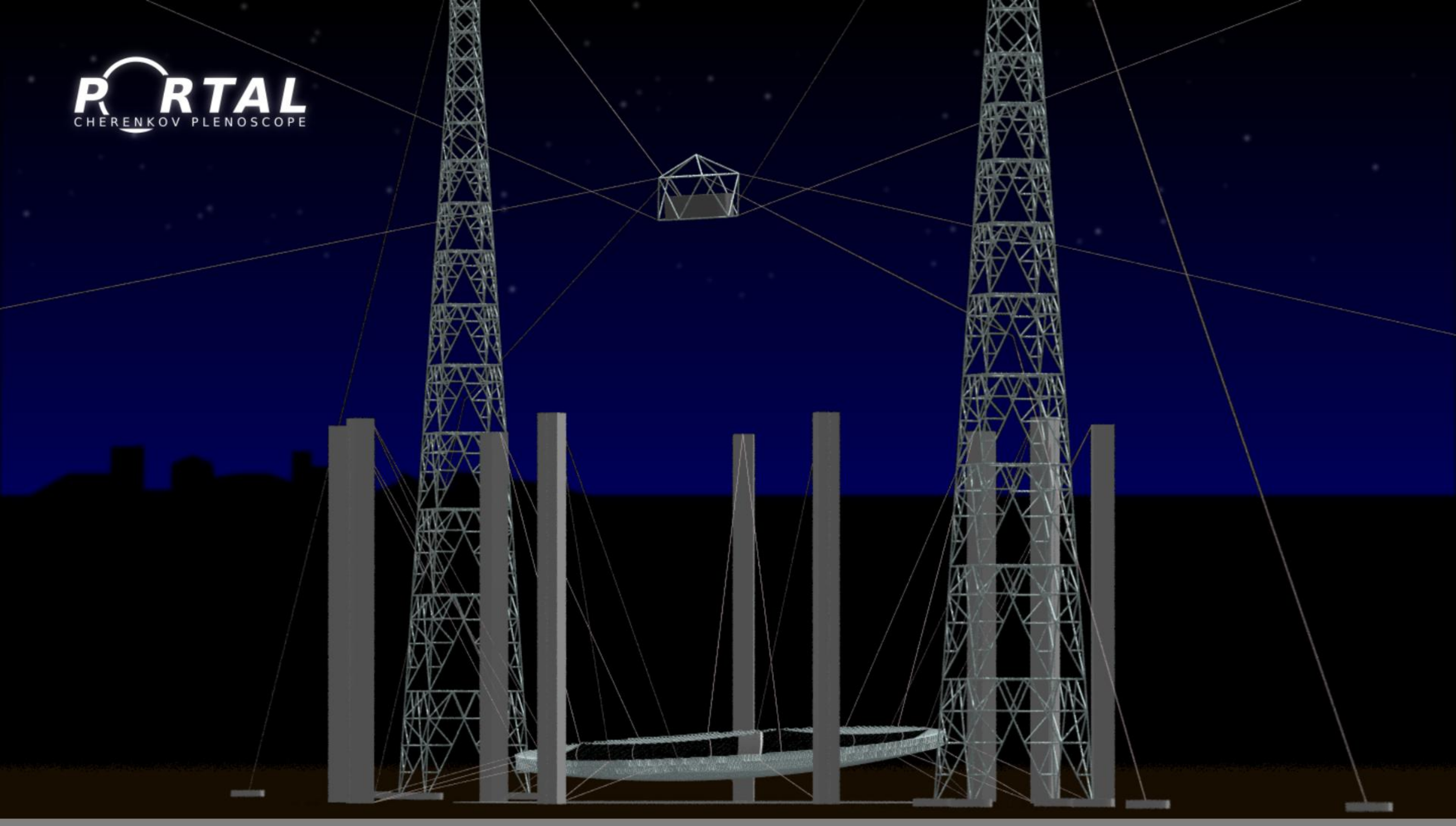
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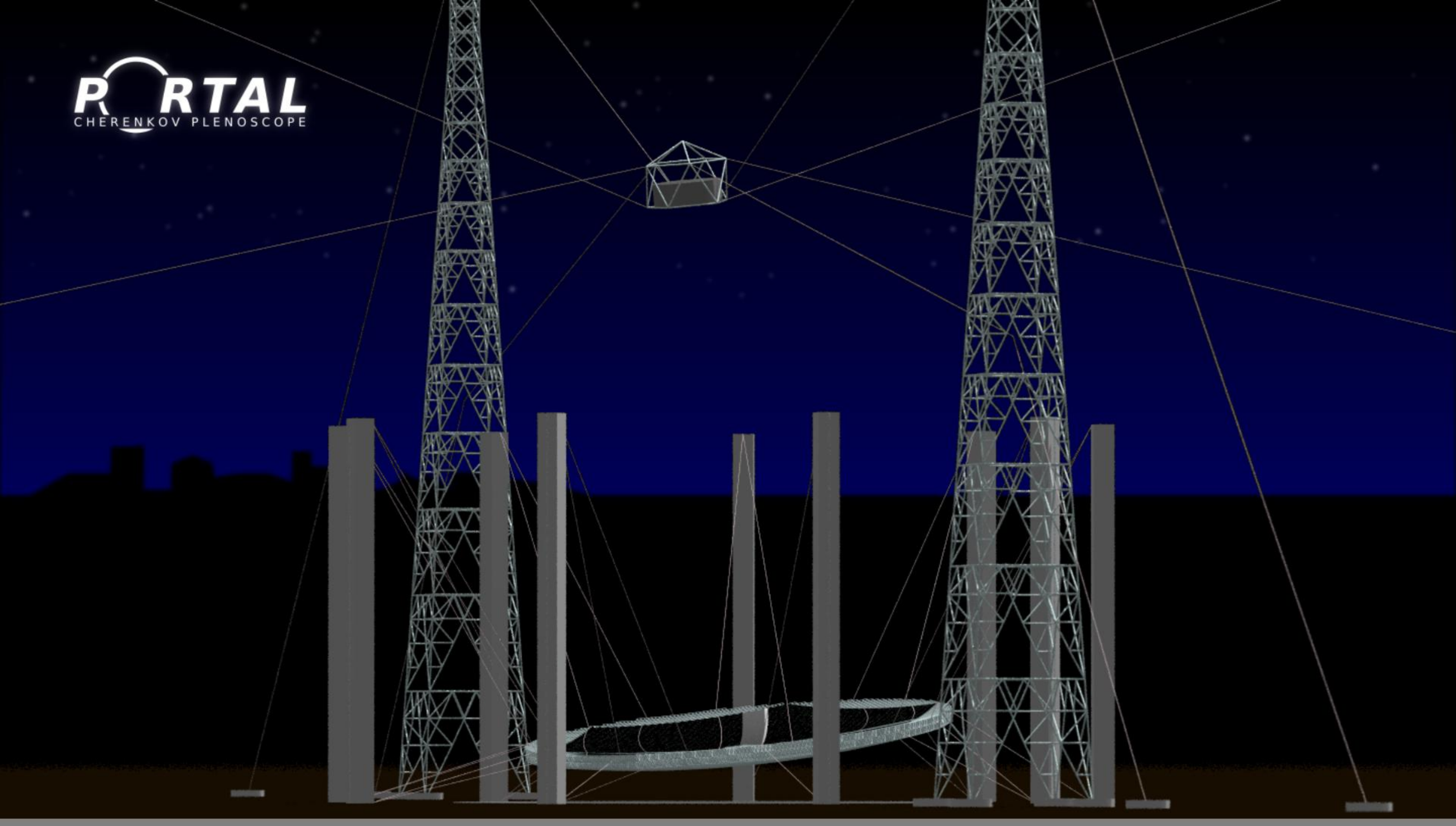
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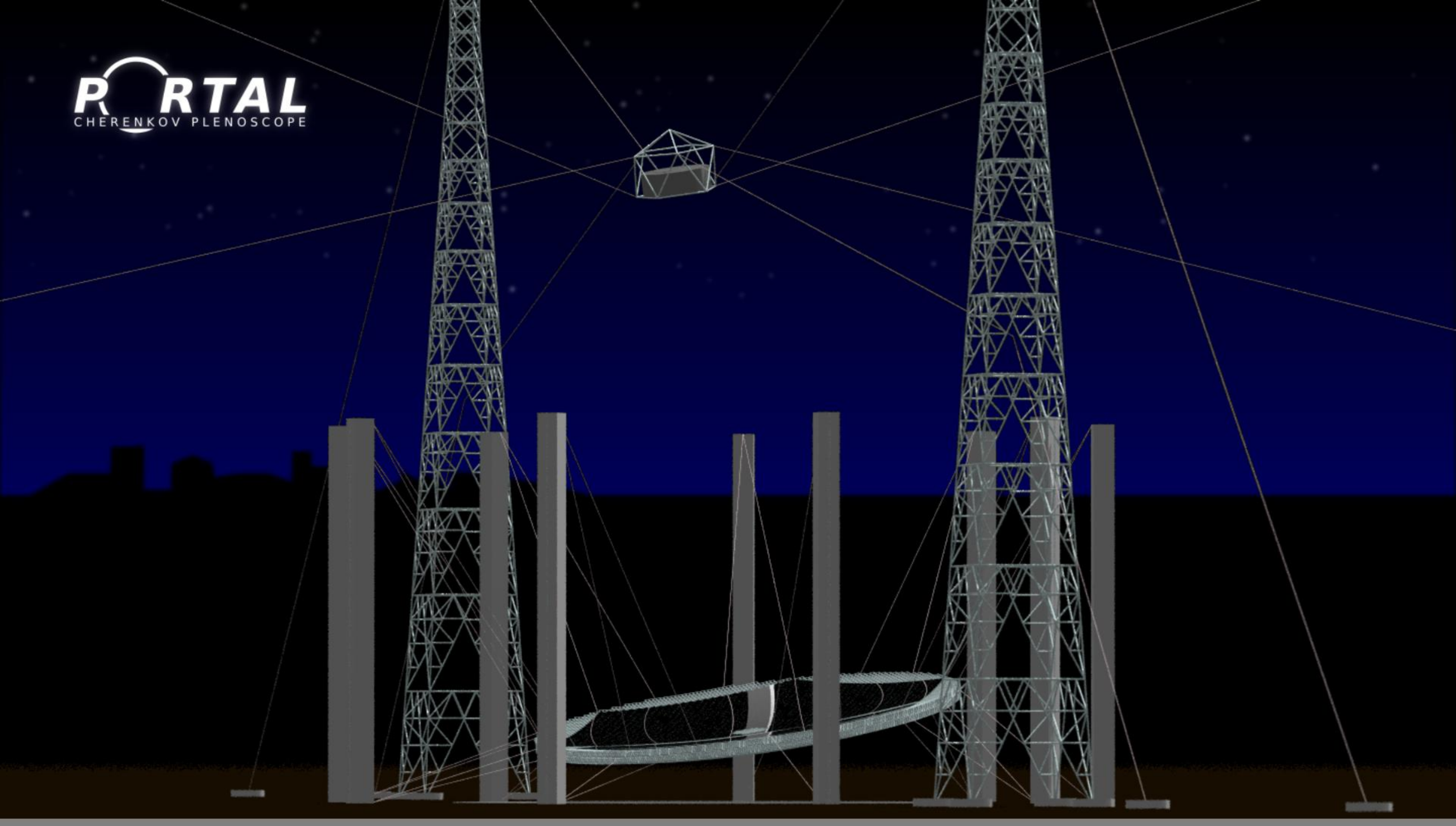
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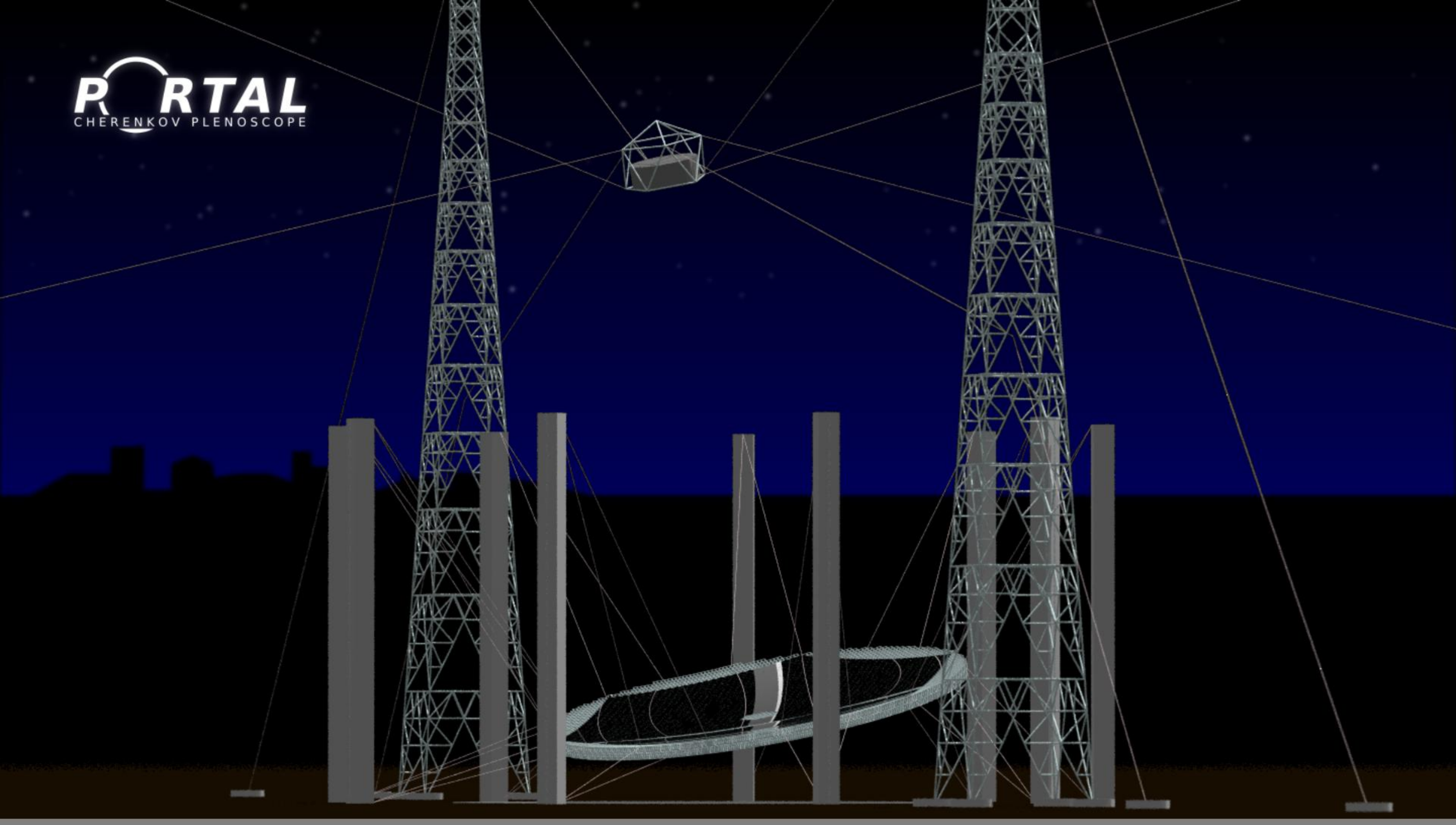
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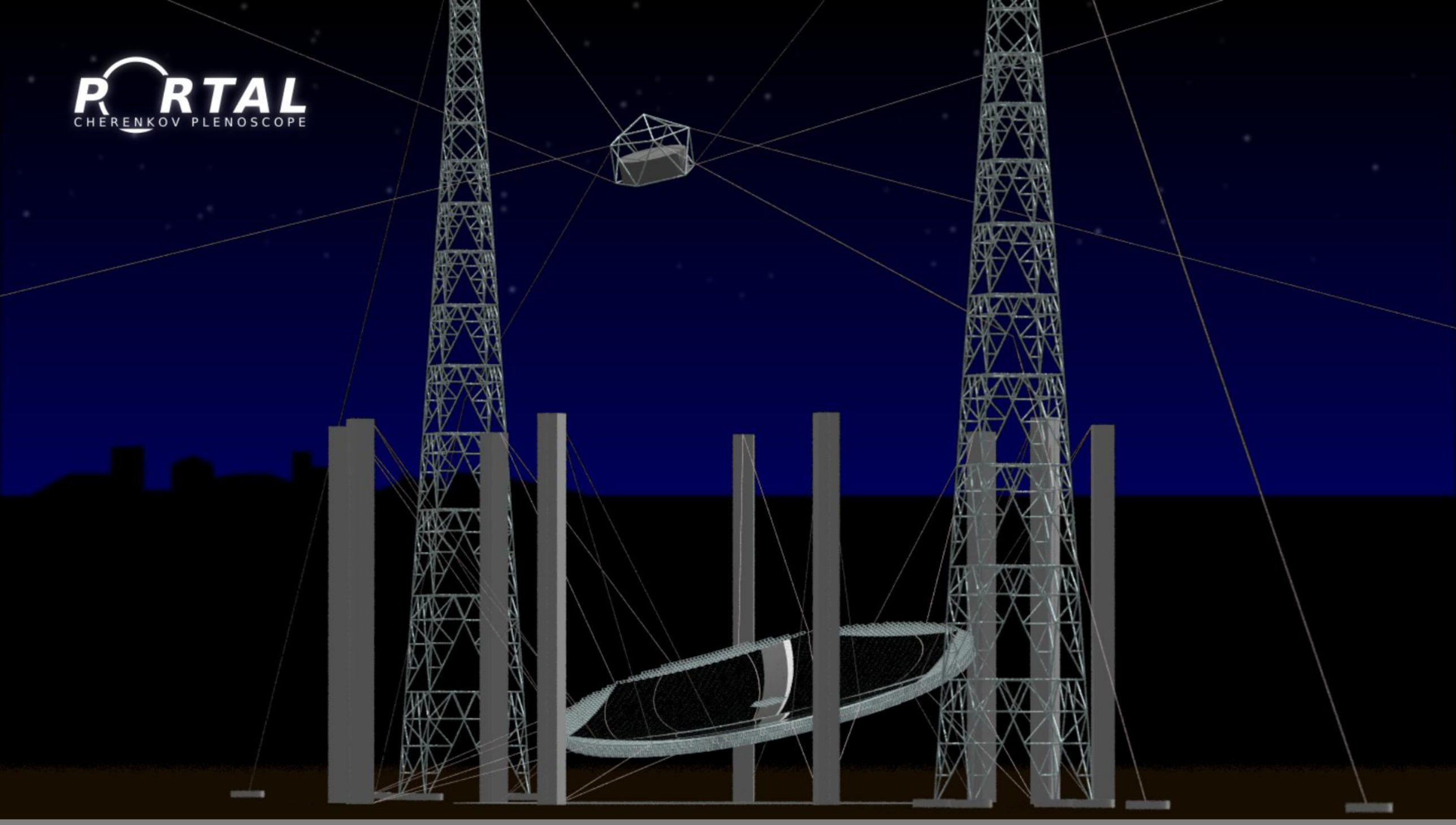
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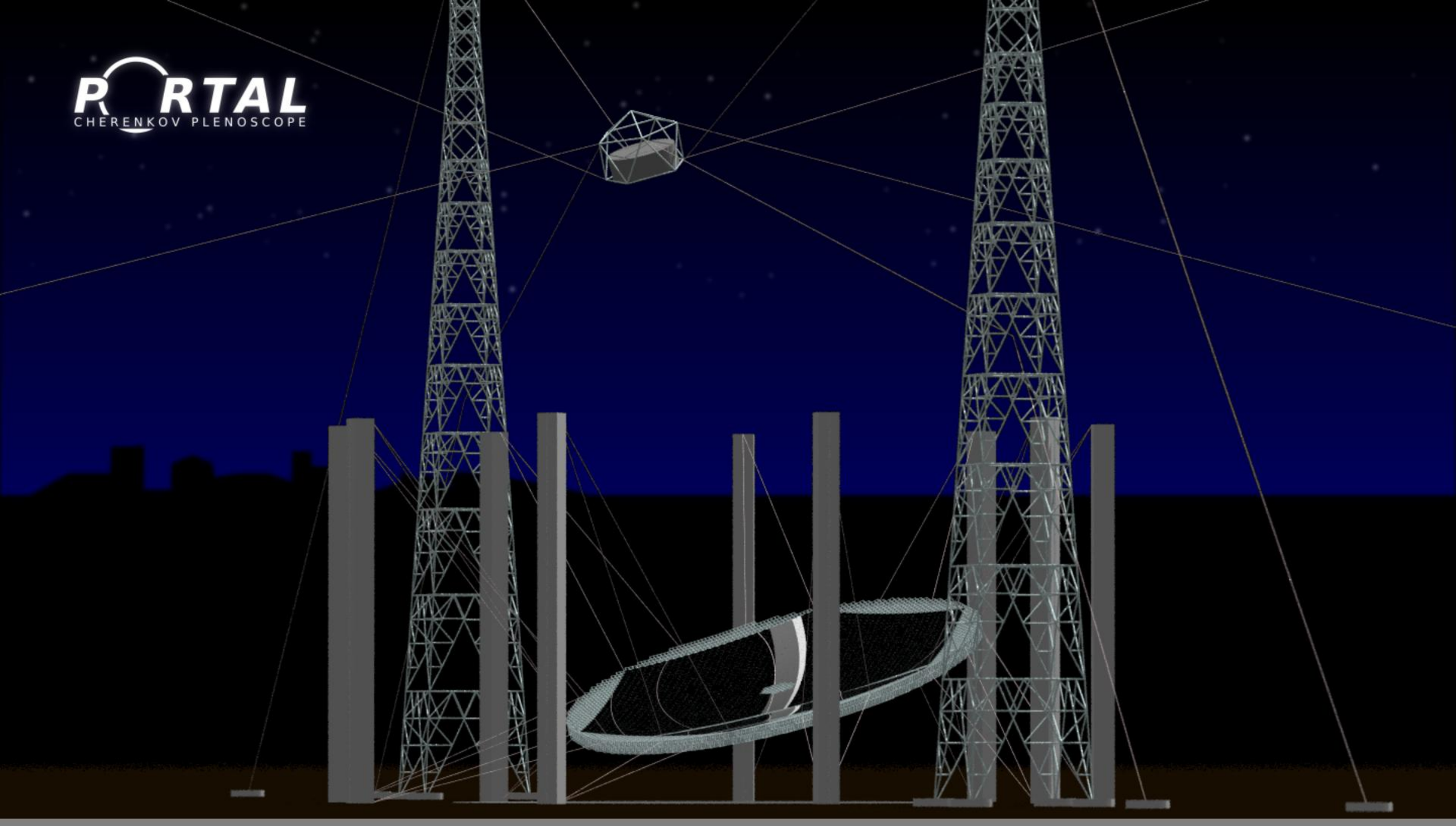
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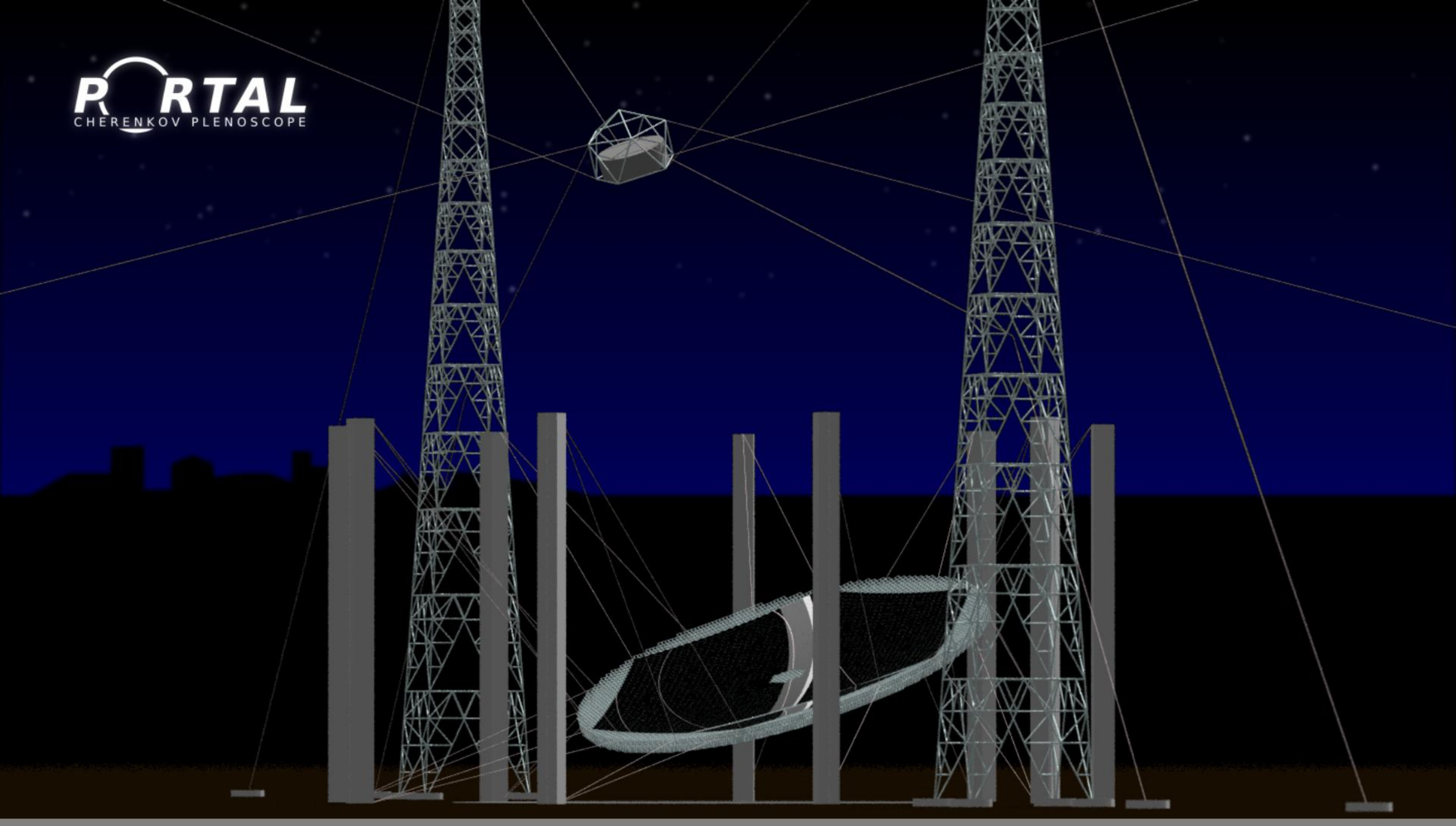
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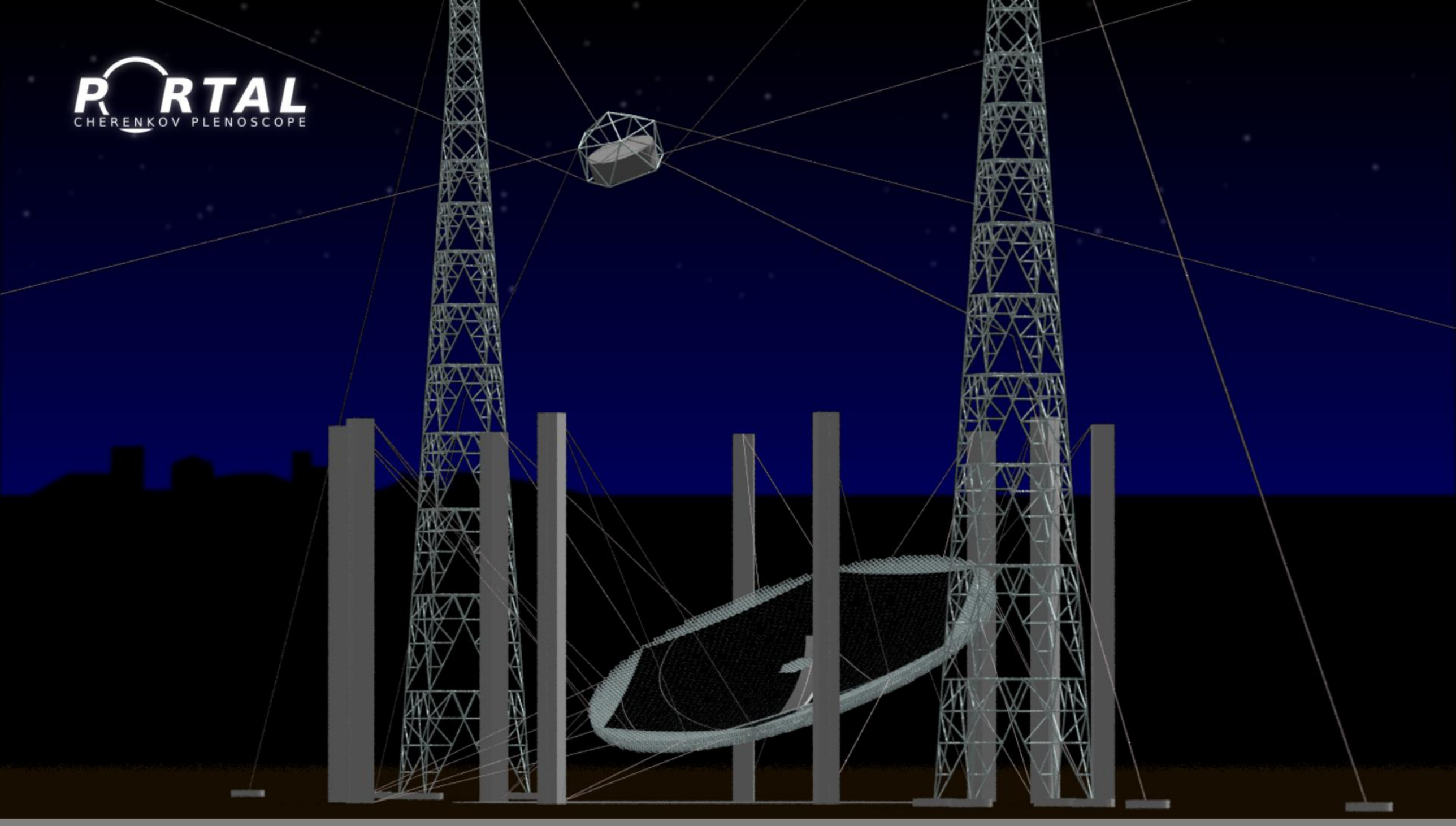
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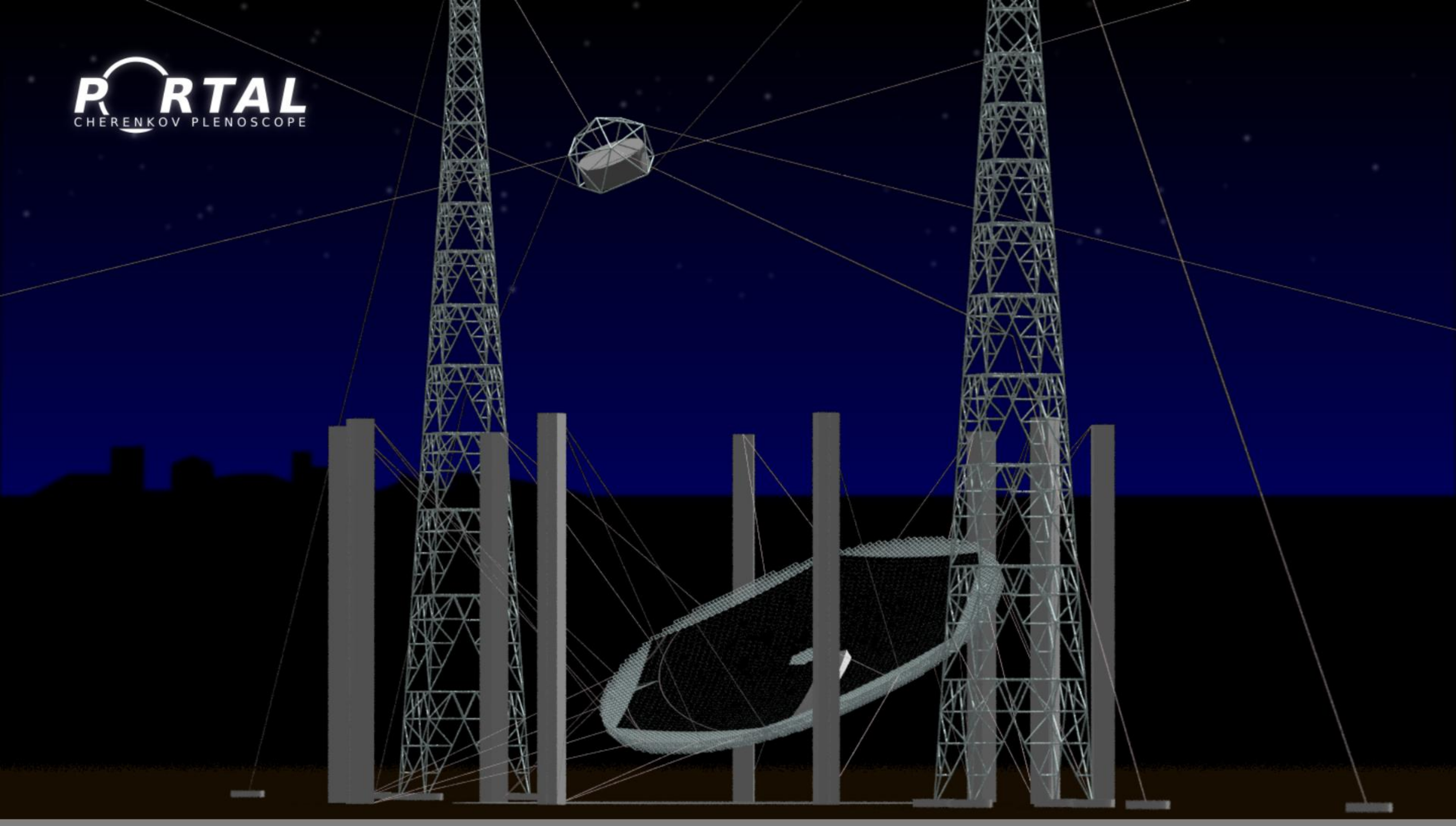
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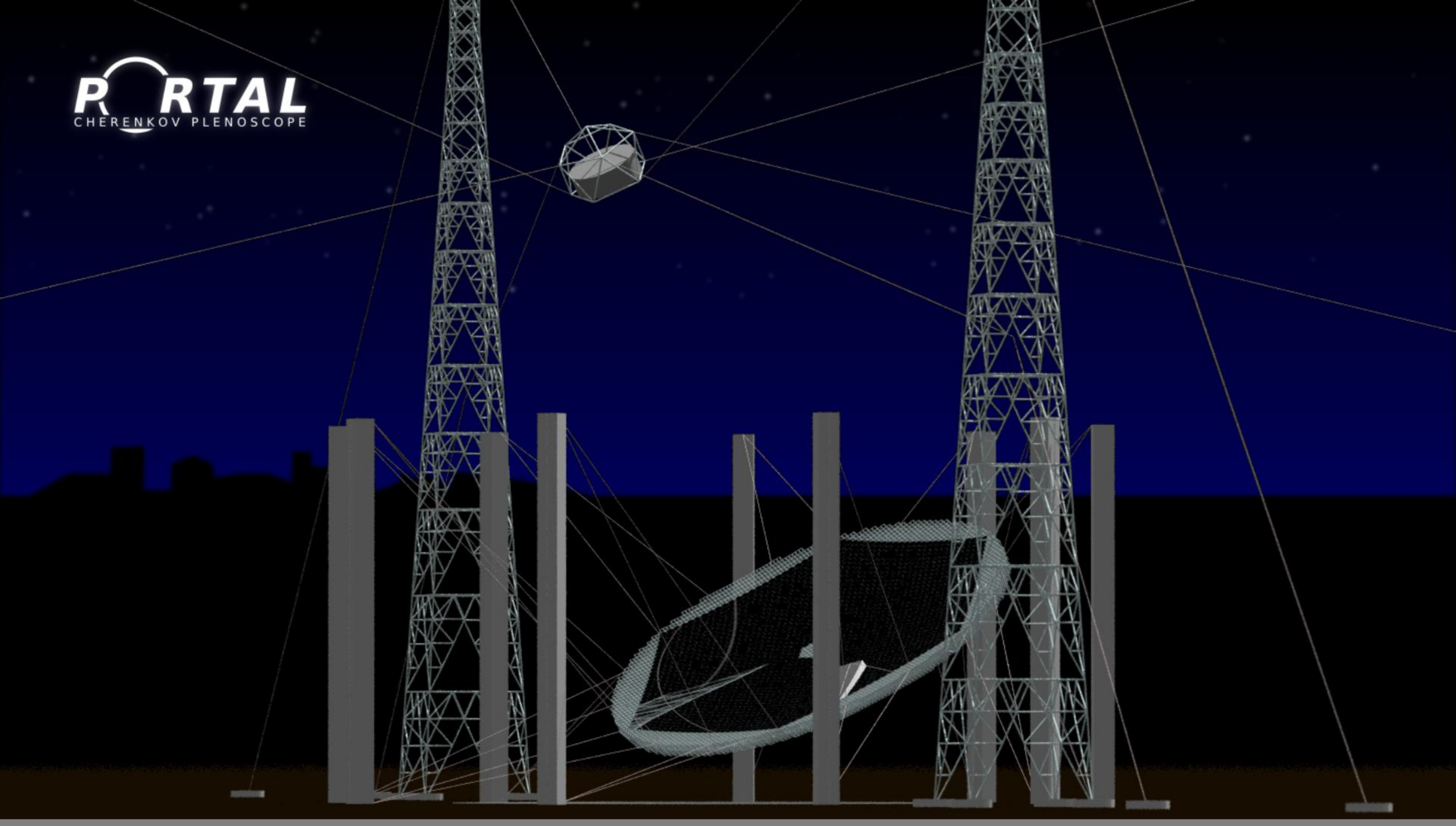
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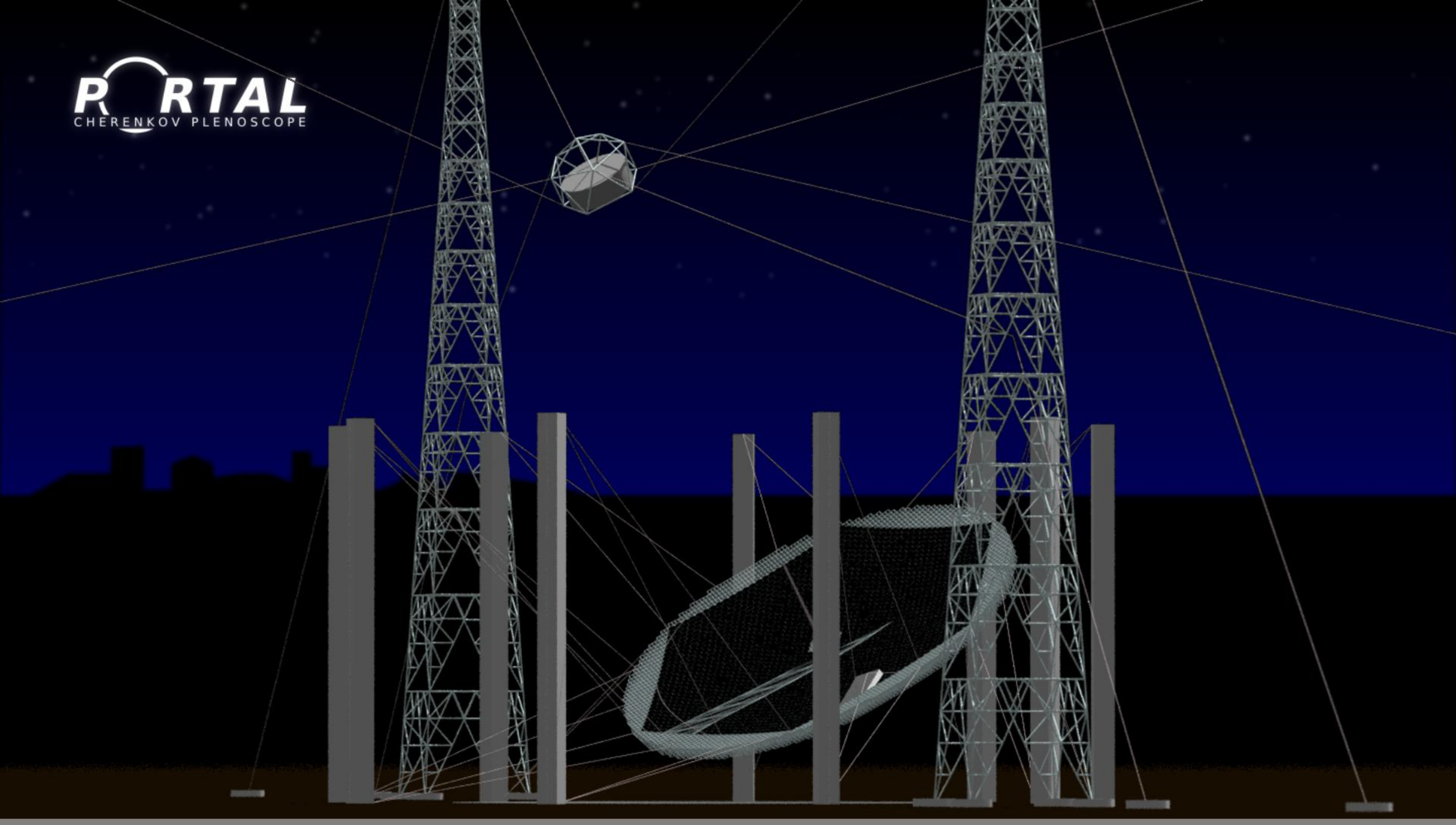
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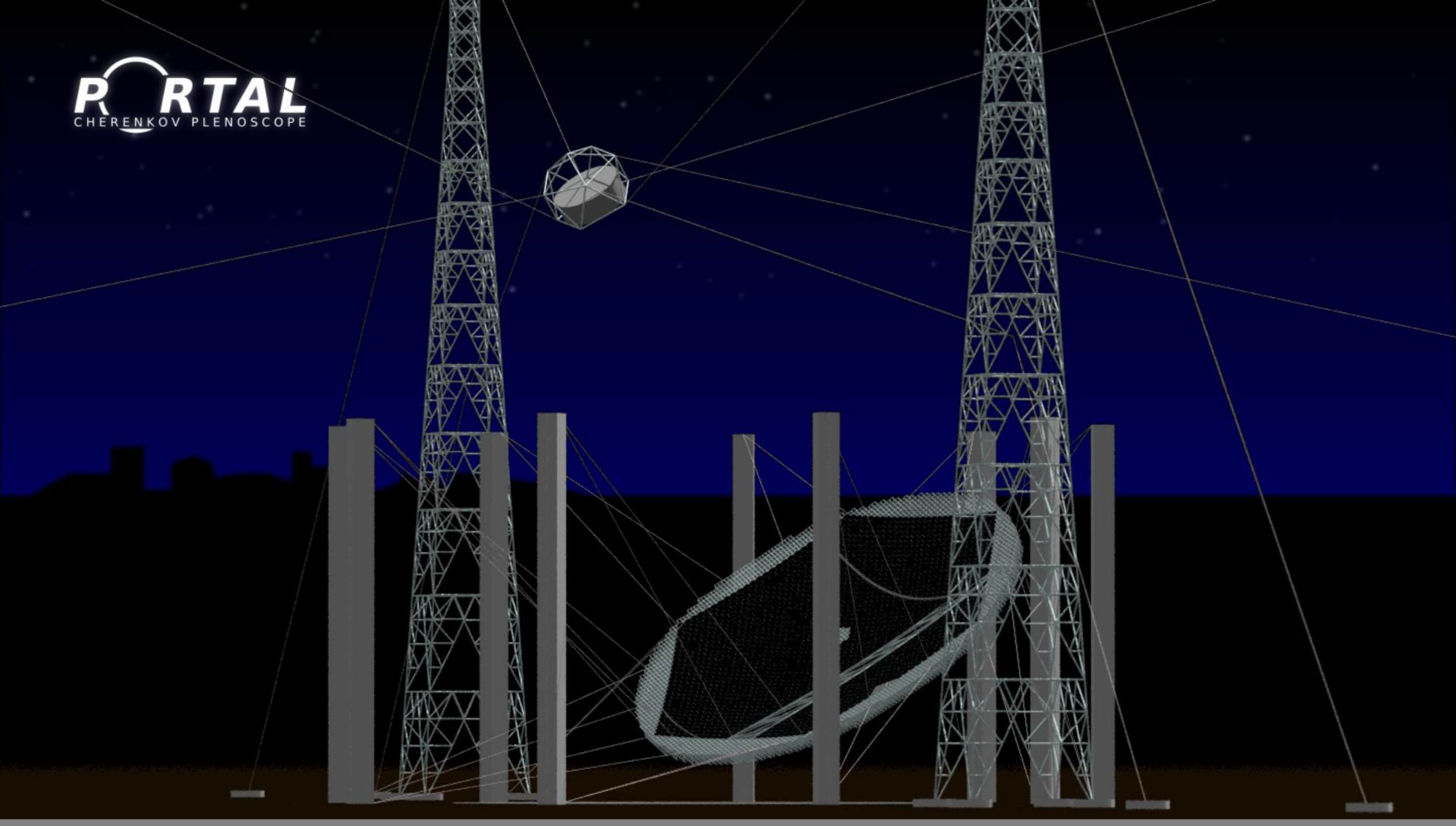
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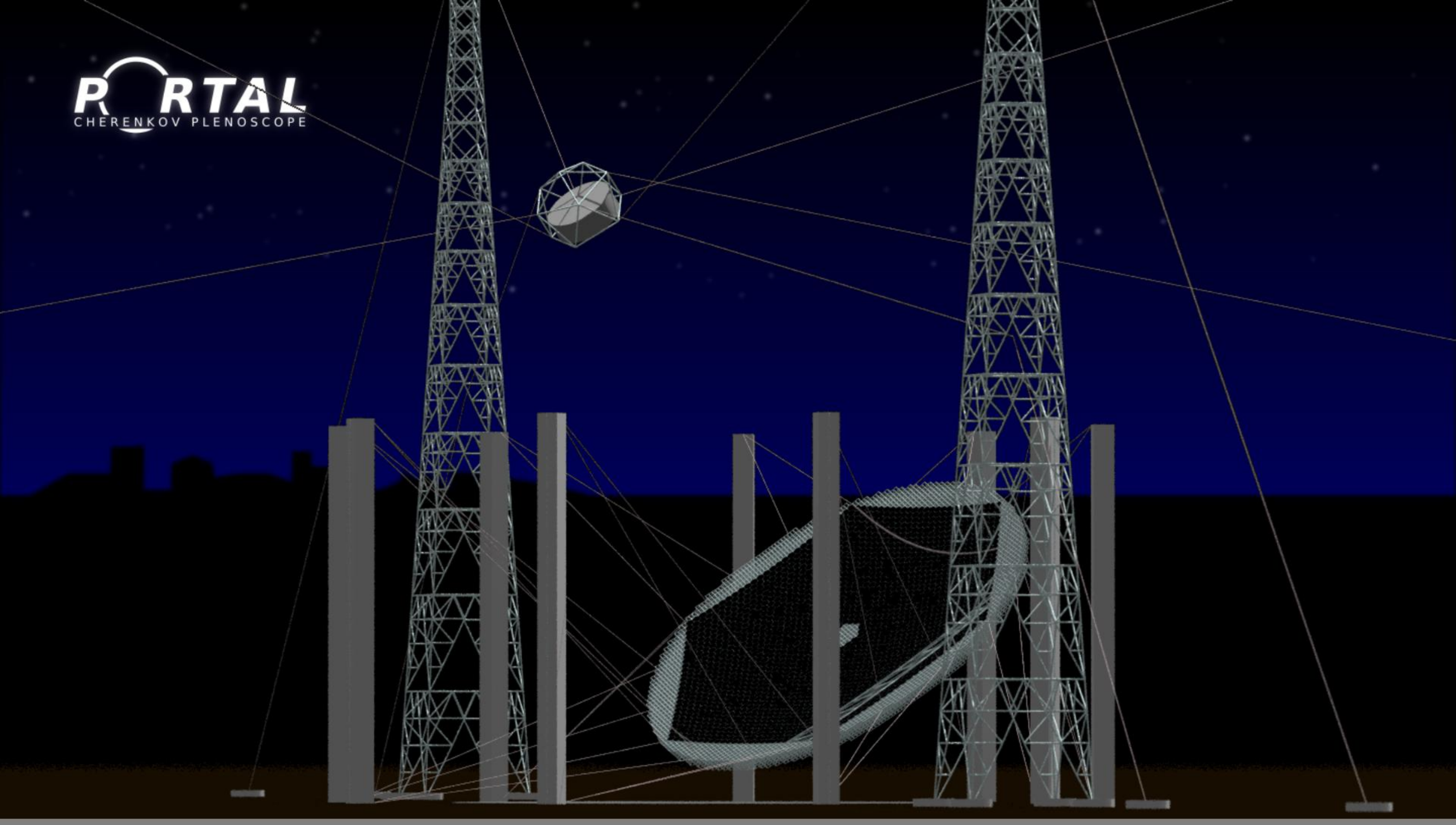
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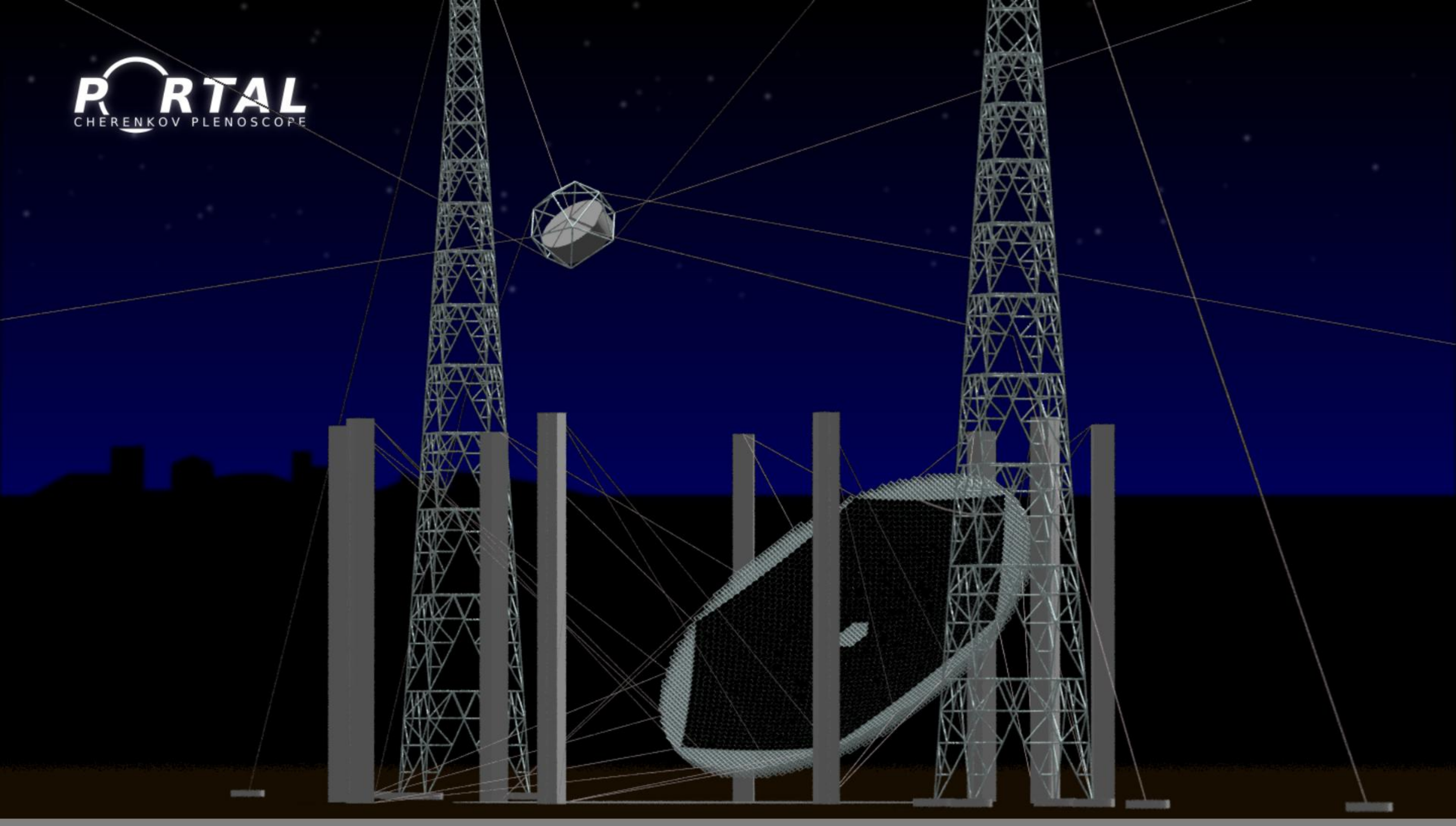
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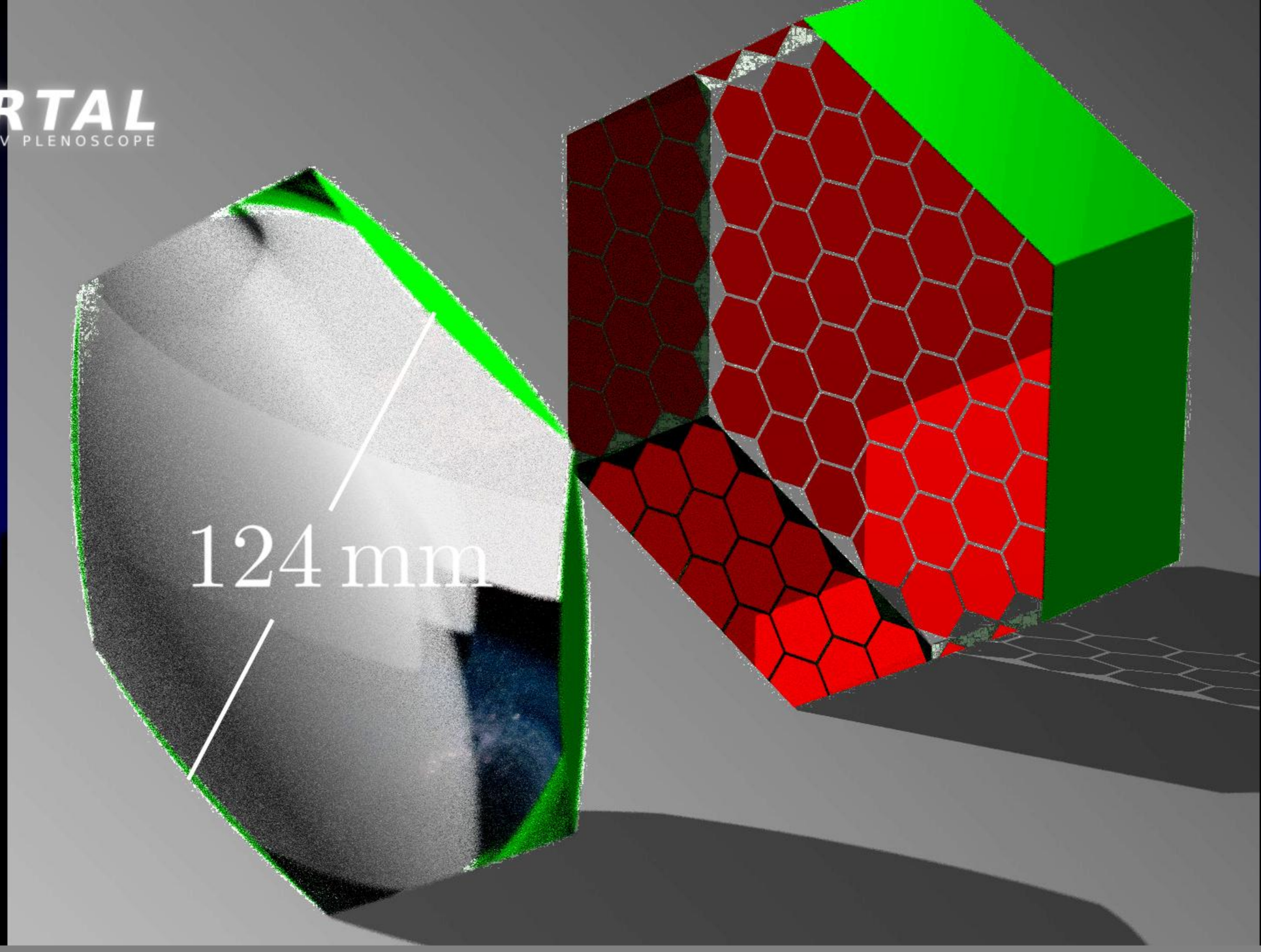
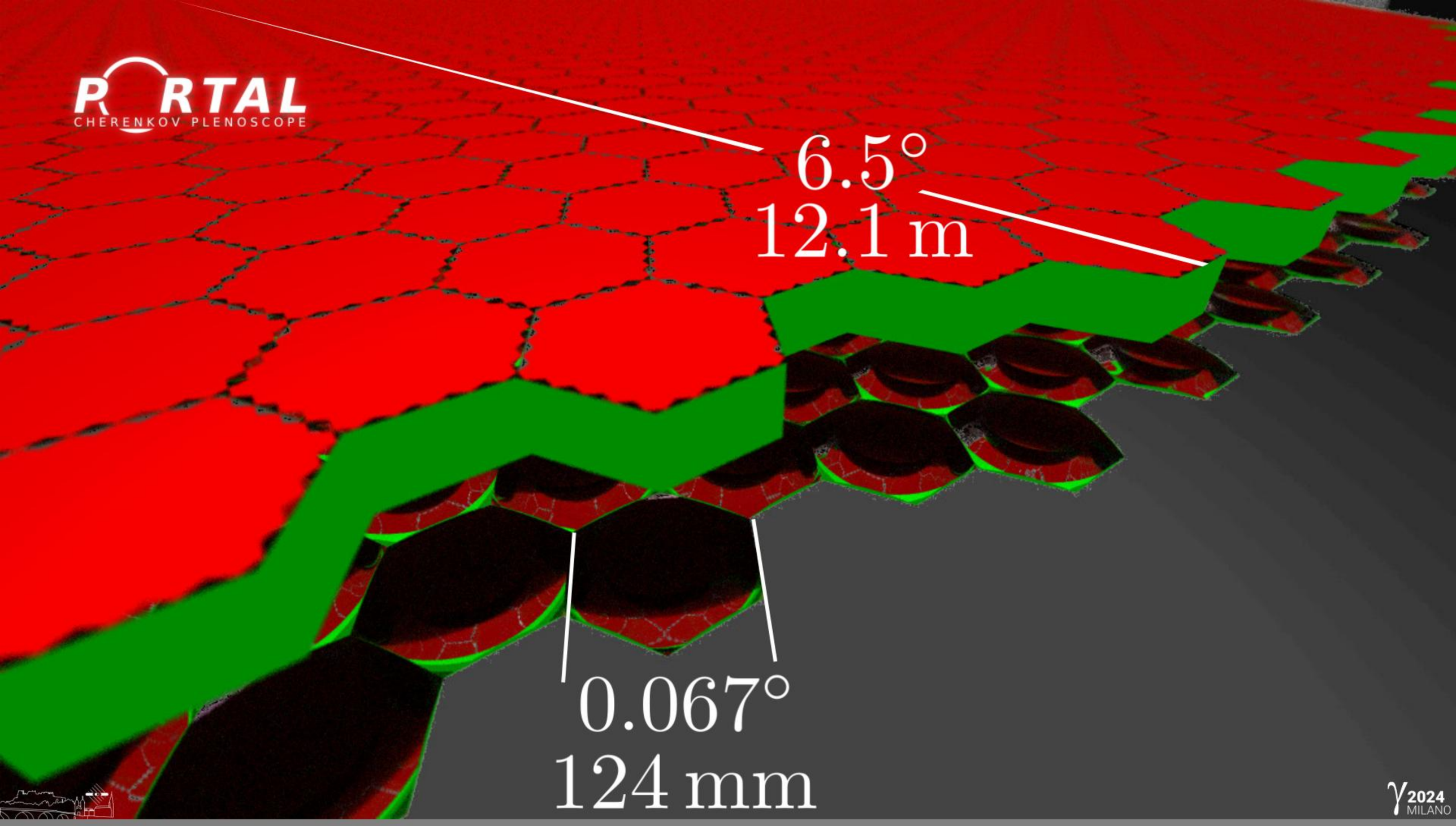


Portal's eyes are made out of a spherical lens and an array of sixty one red photosensors.



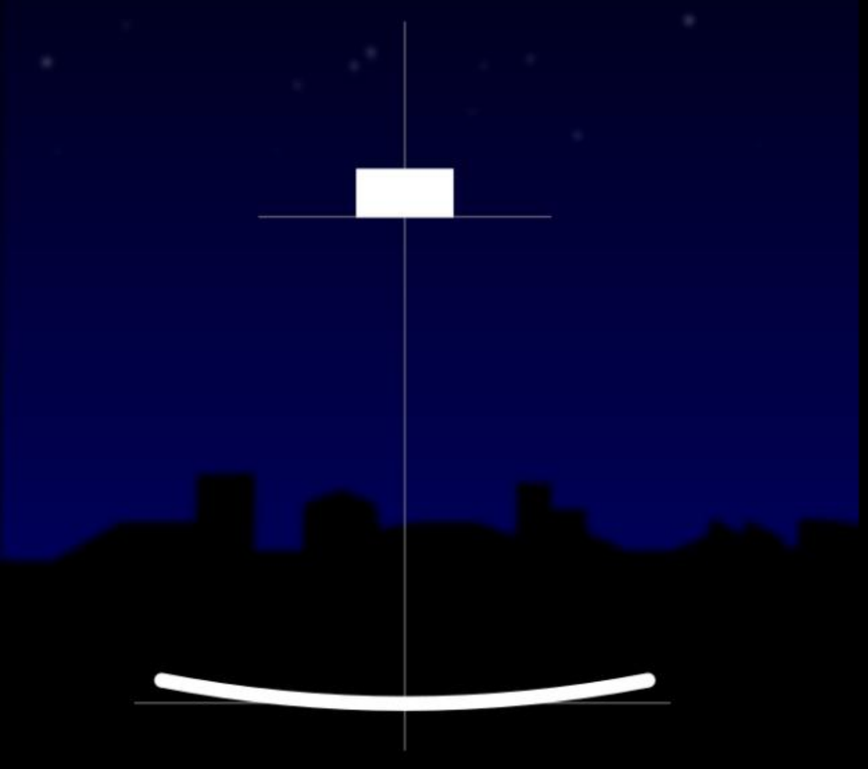
Looking inside Portal's camera, we find the eyes being densly packed.

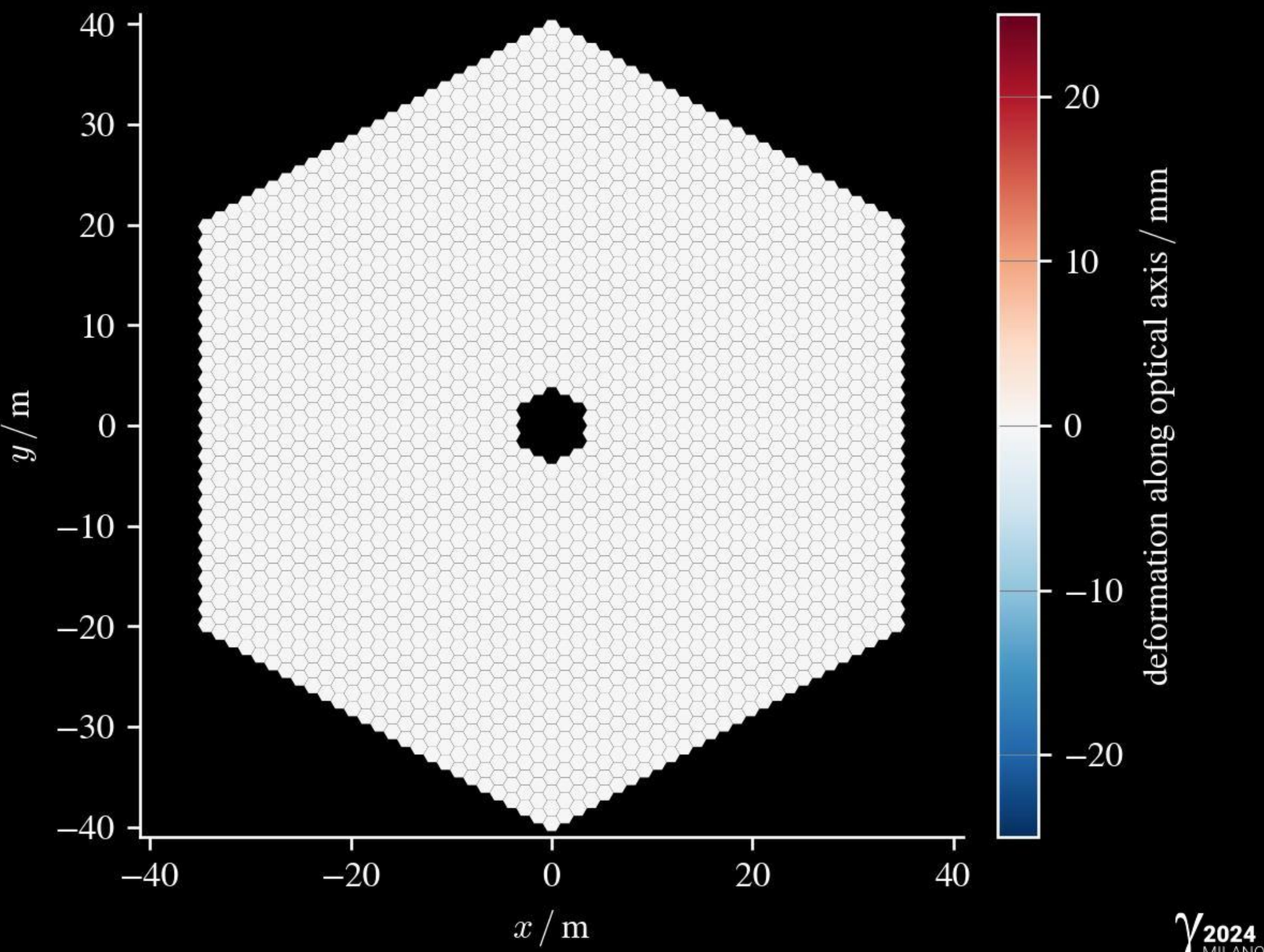
Optics

mirror deformations

But designing a plenoscope is not enough.

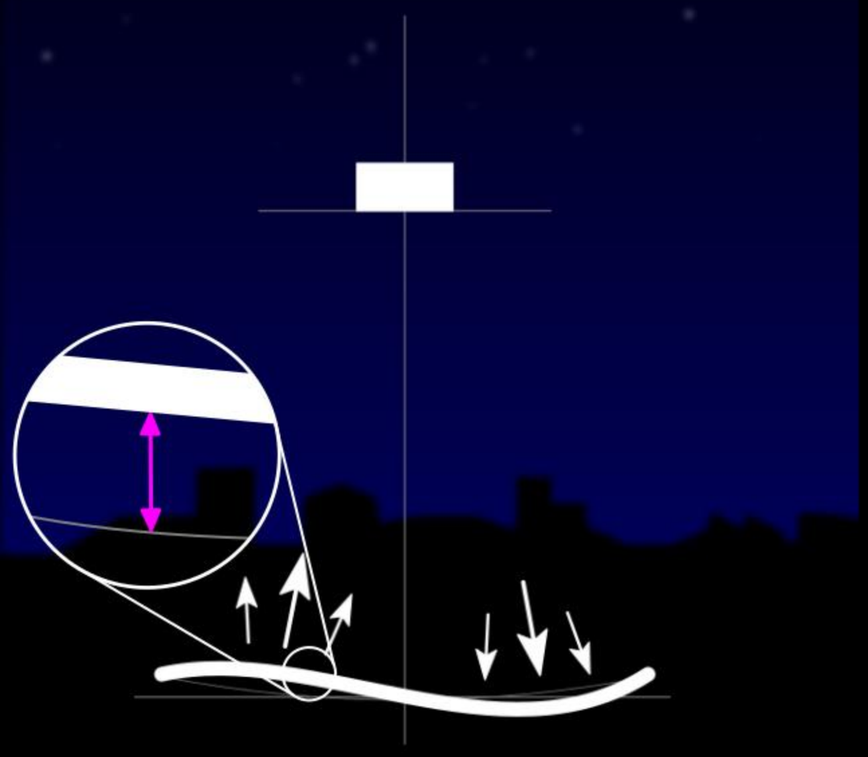
Optics
mirror deformations

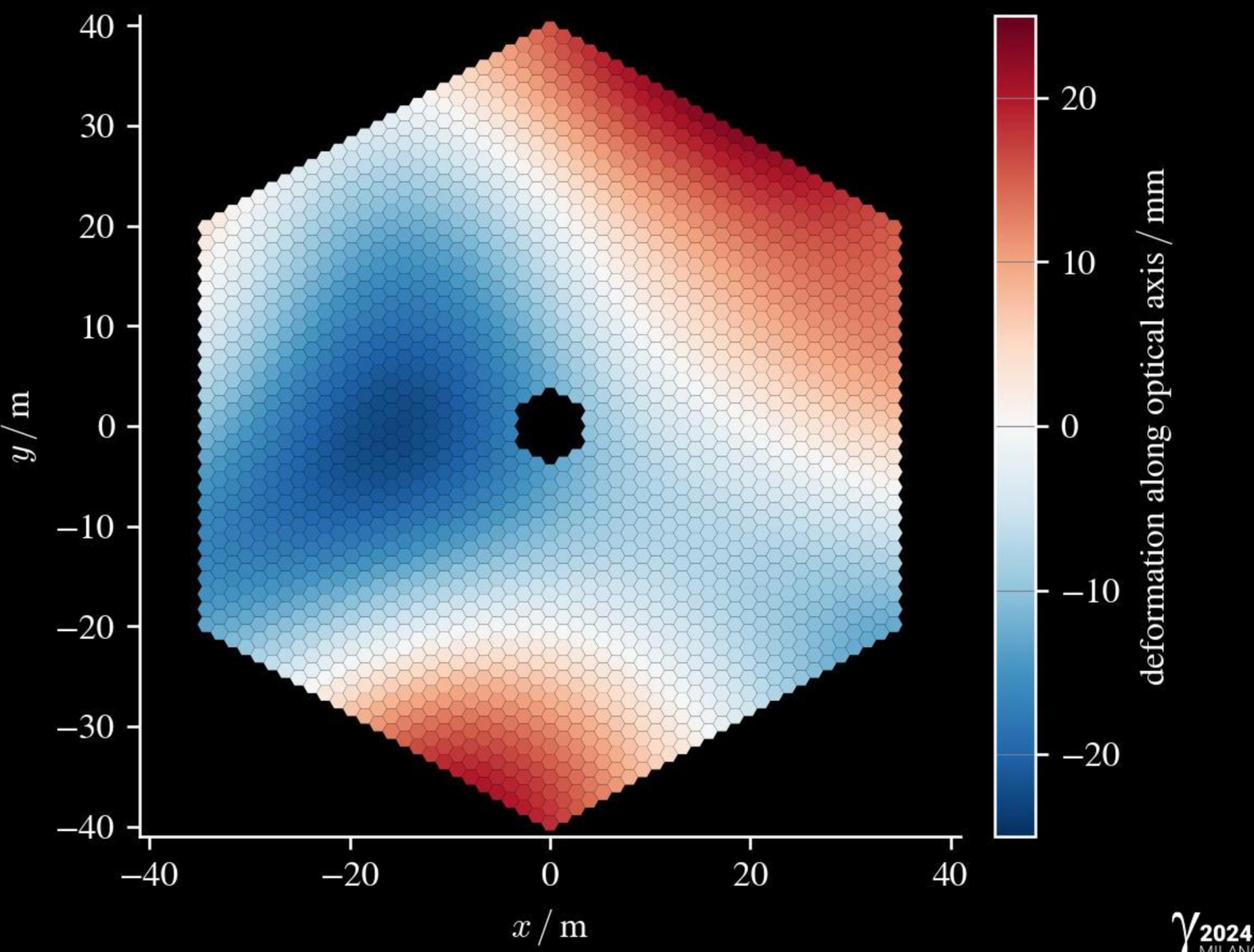




To see plenoptics in action we deform ...

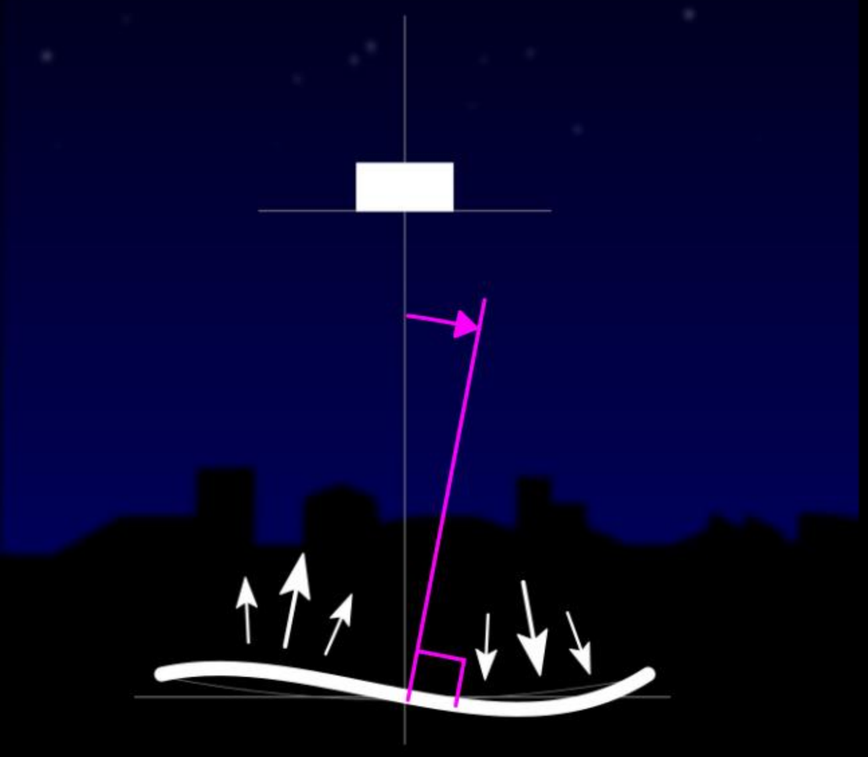
Optics
mirror deformations

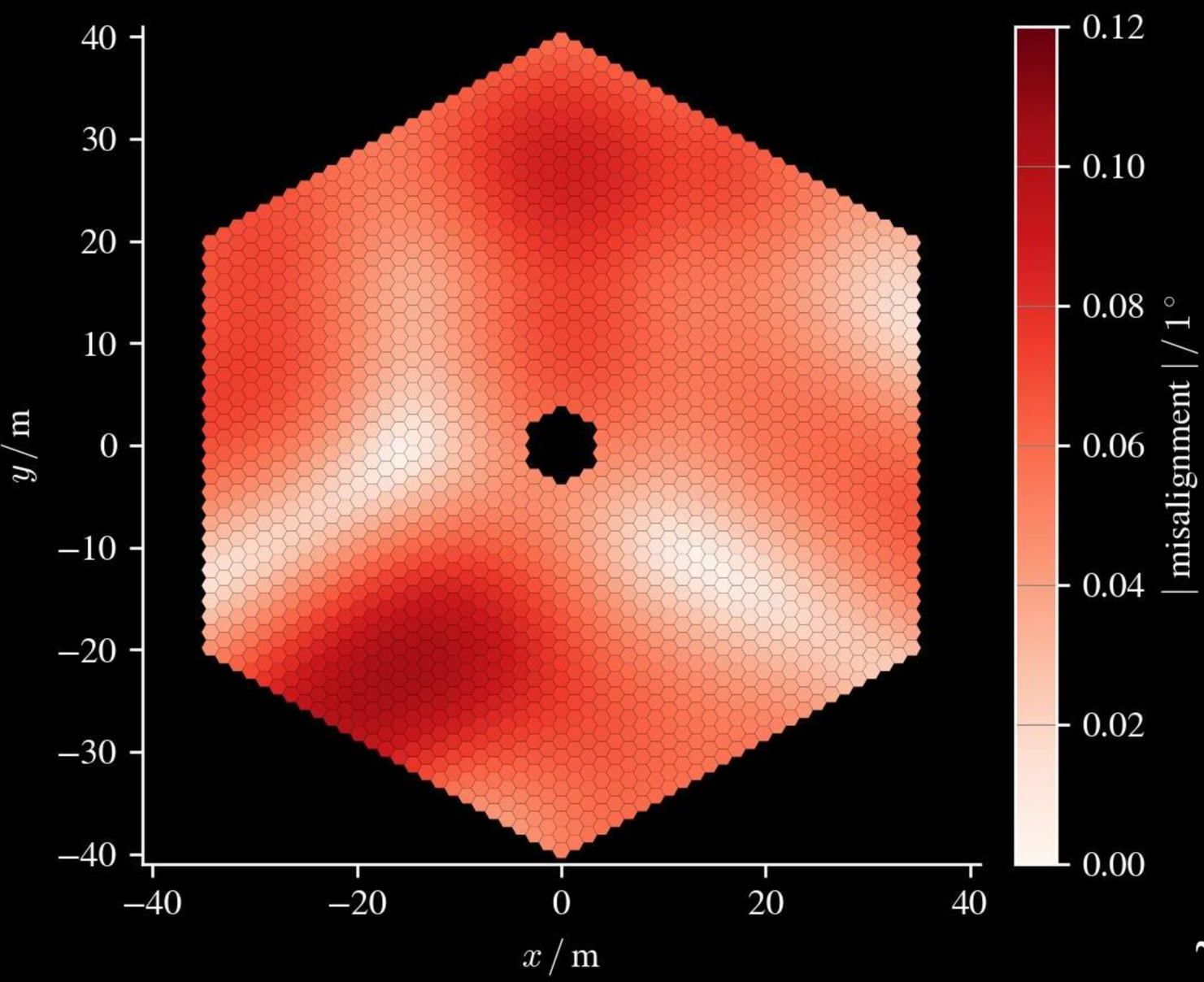




Portal's mirror on purpose,

Optics
mirror deformations

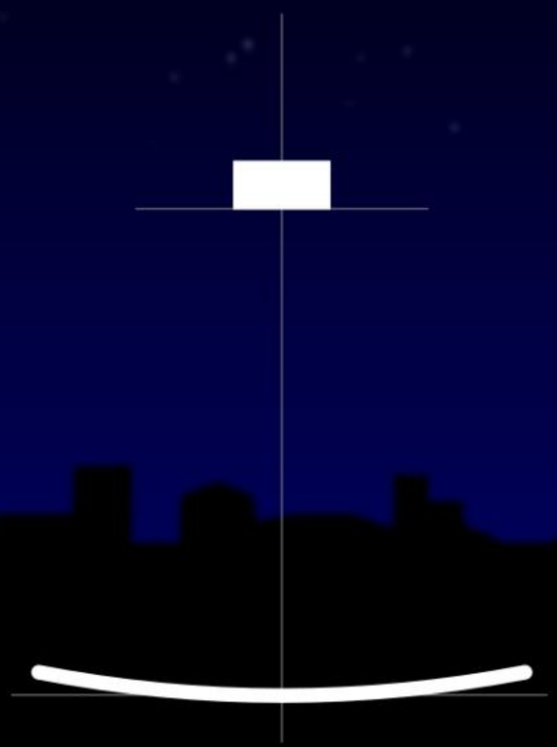




to cause a significant distortion of the mirror's surface.

Optics

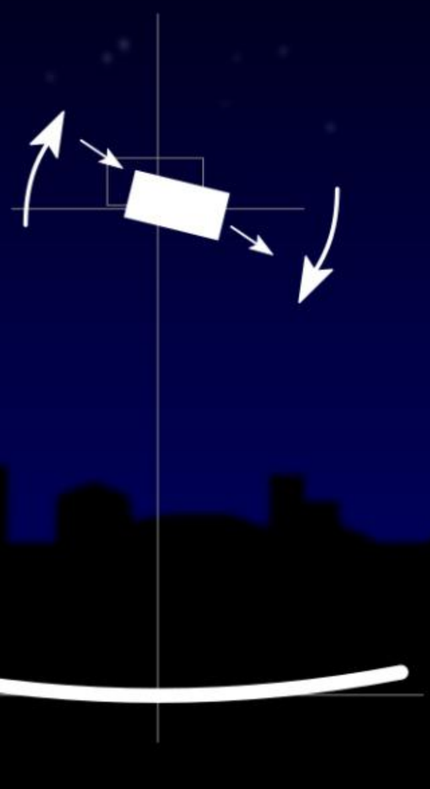
camera misalignment



Further we define

Optics

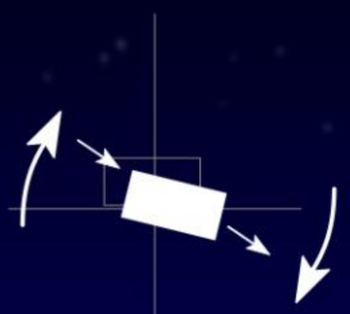
camera misalignment



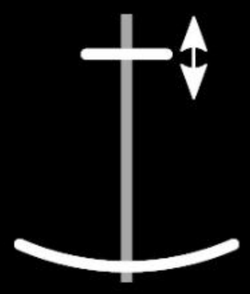
$$
\begin{aligned}
\text{Tait-Bryan-}xyz &= (1.0,\, 3.0,\, 5.0)^\circ \\
\text{translation-}xyz &= (-100,\, 200,\, -532.5)\,\text{mm} \\
&= (-0.1,\, 0.2,\, -0.5)\%f
\end{aligned}
$$

a misalignment for the camera ...

Optics
camera misalignment



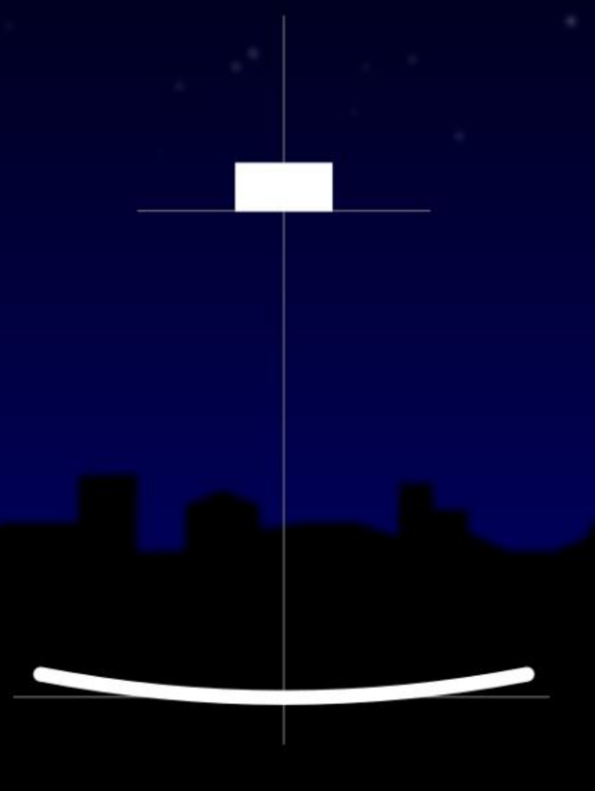
$$\begin{aligned}\text{Tait-Bryan-}xyz &= (1.0,\, 3.0,\, 5.0)^\circ \\ \text{translation-}xyz &= (-100,\, 200,\, -532.5)\,\text{mm} \\ &= (-0.1,\, 0.2,\, -0.5)\%f\end{aligned}$$



$$g = 10.0\,\text{km} \rightarrow g \approx 18.6\,\text{km}$$

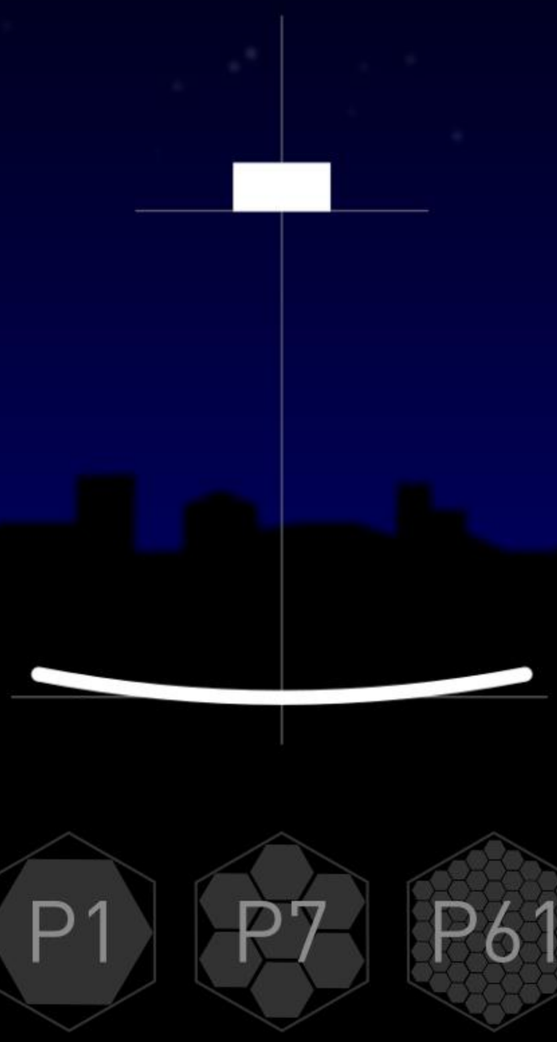
which also will turn out to be significant.

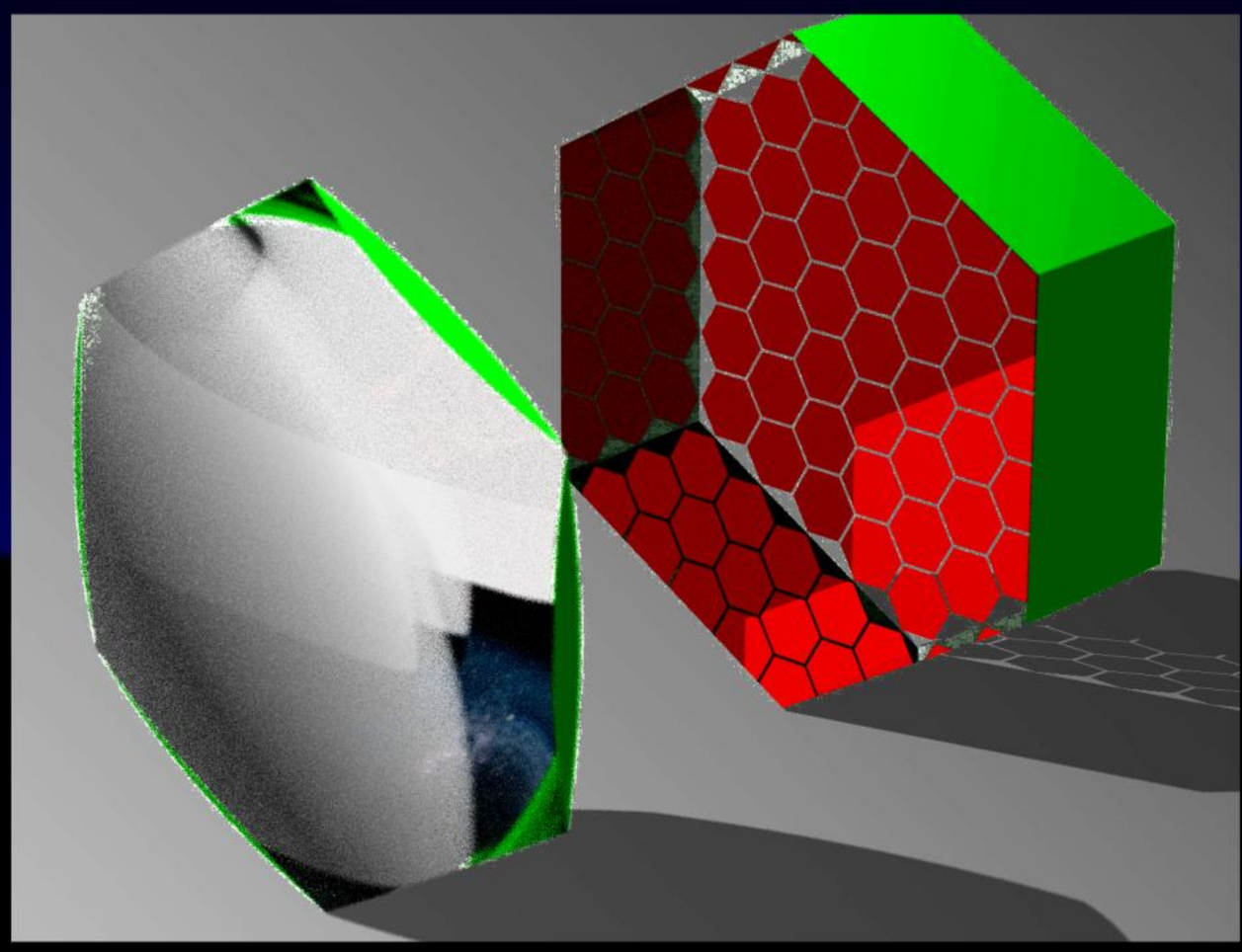
Optics
cameras



To compare the plenoscope to a telescope, and to get a feeling for the scaling of plenoptic perception we introduce two more instruments which are identical to Portal. Except for

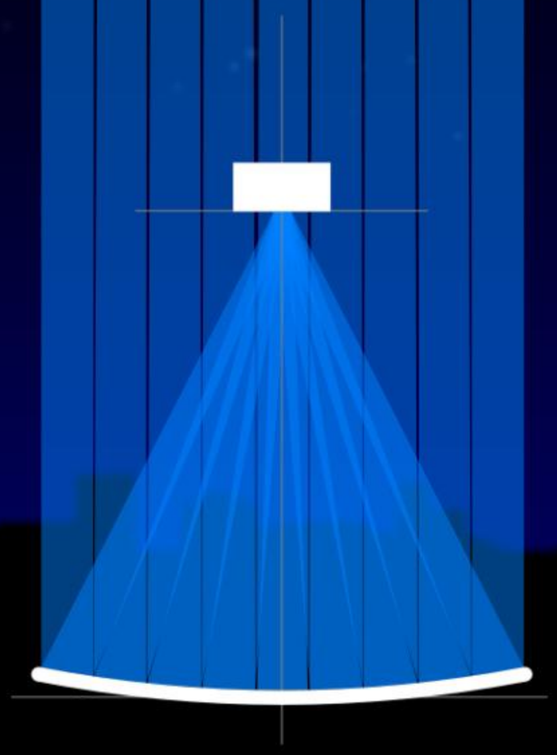
Optics
cameras

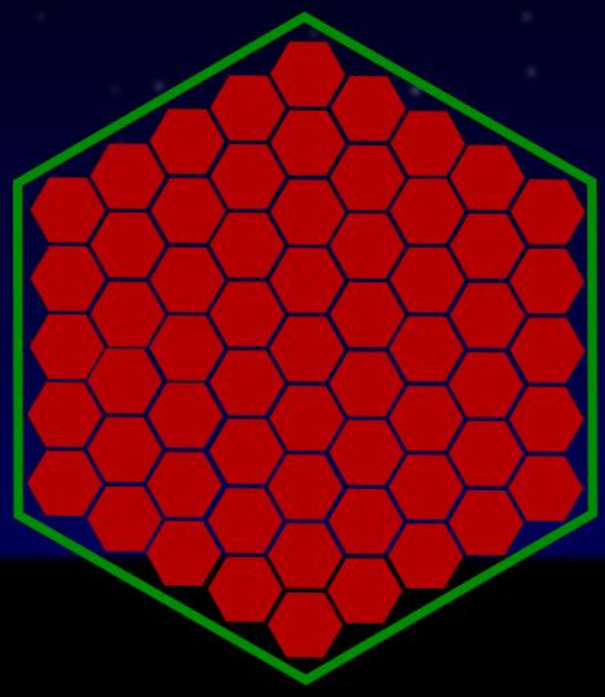




Where Portal has sixty-one photosensors

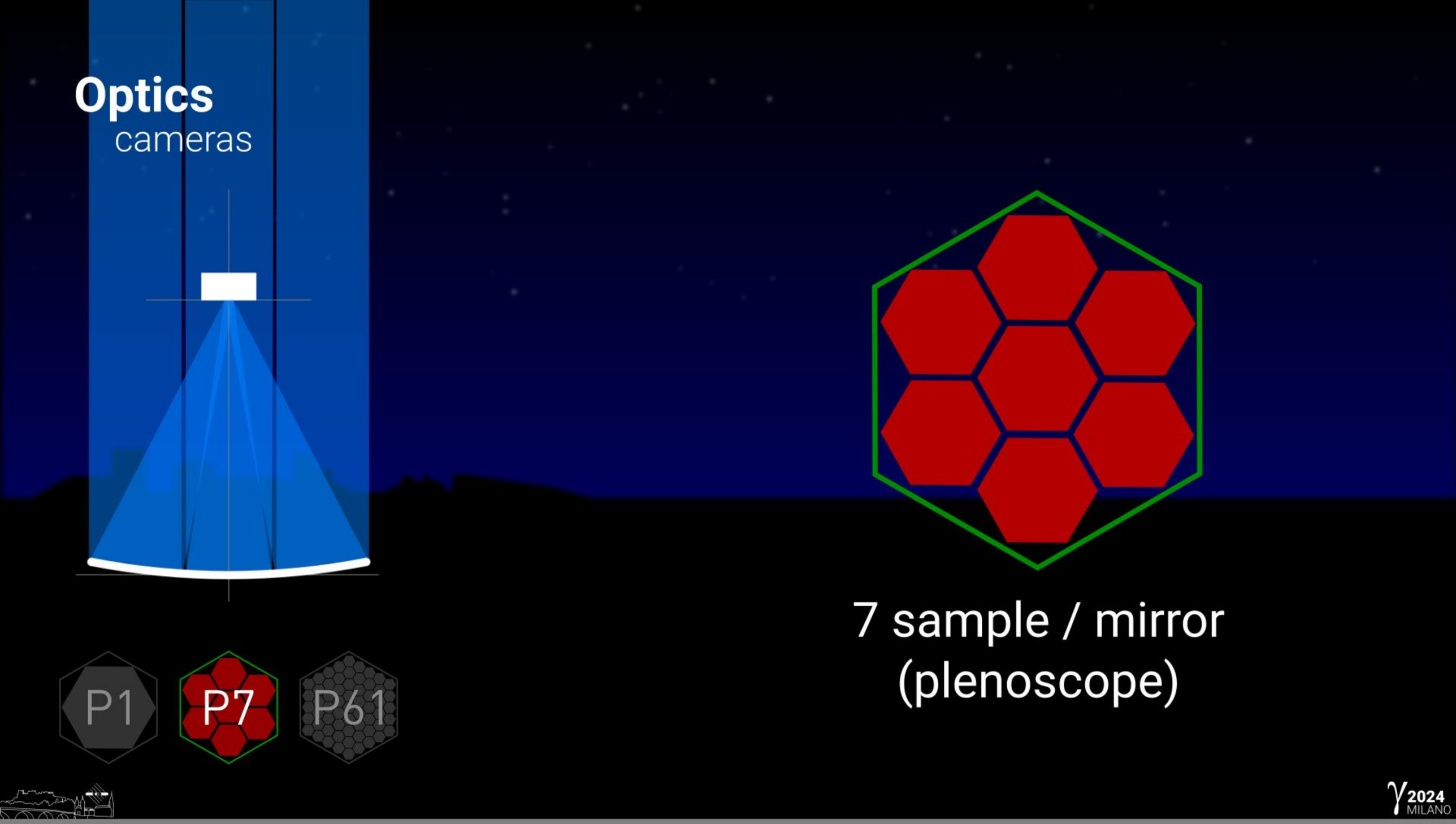
Optics
cameras





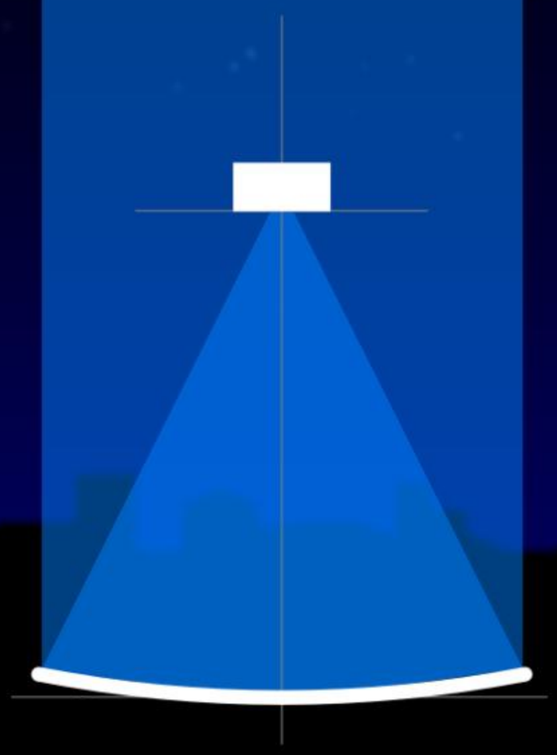
61 sample / mirror
(plenoscope)

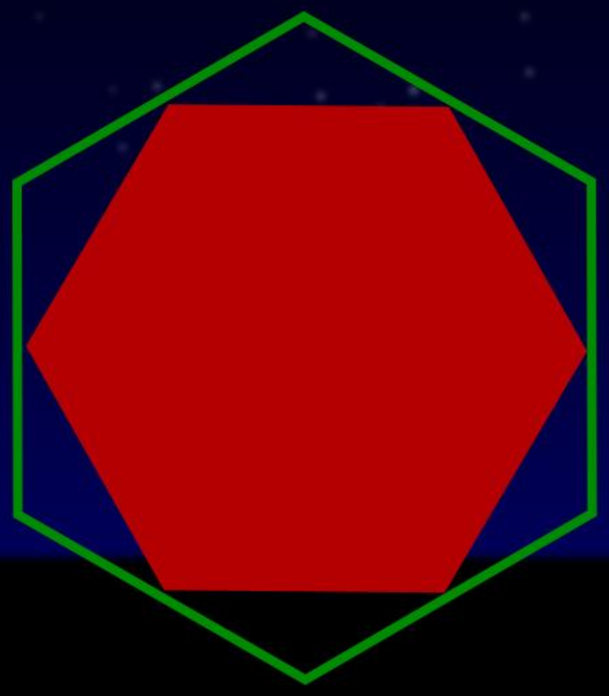
in each eye



the plenoscope named p-seven has only seven photosensors in its eye.

Optics
cameras





1 sample / mirror
(telescope)

And the telescope named p-one, only has one photosensor in its eye.

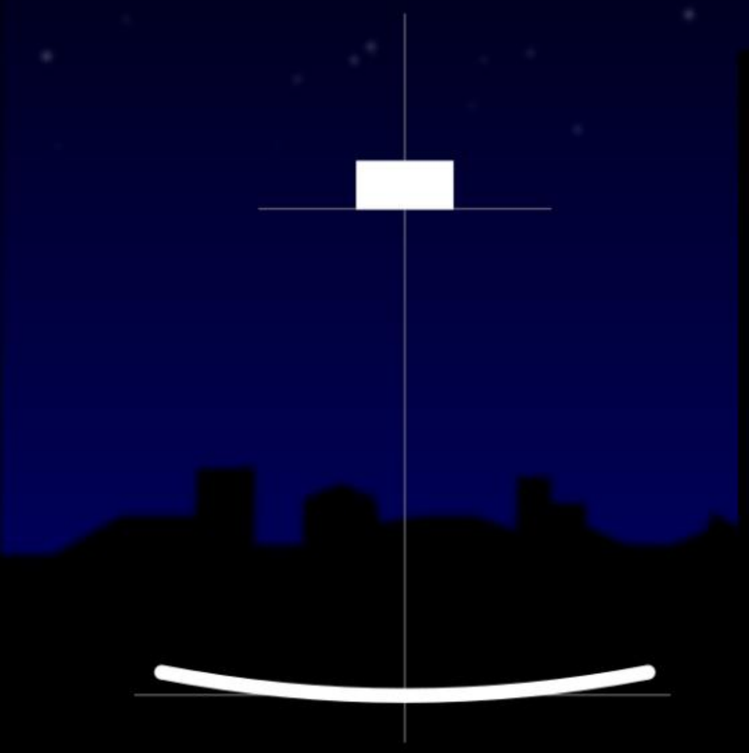
Optics

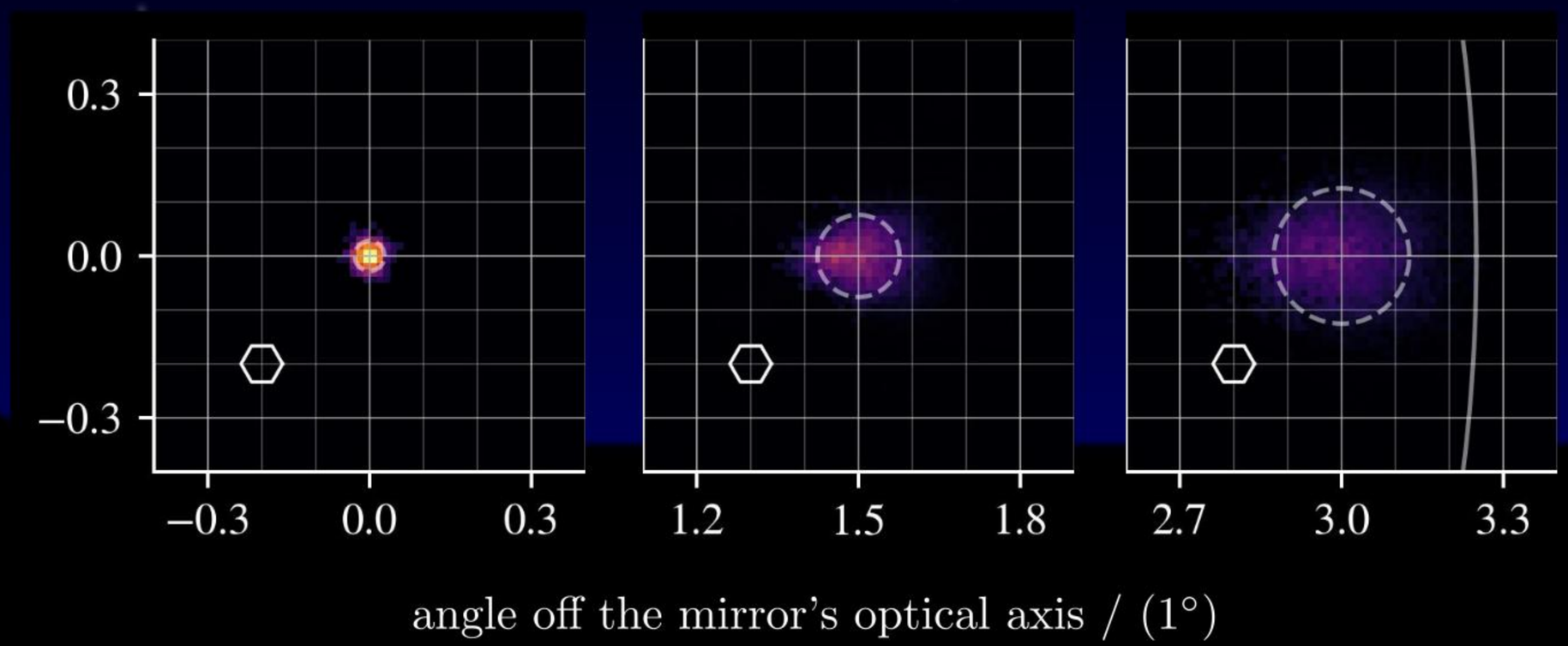
starlight performance

Now lets have a look at the point-spread-functions.

Optics

starlight performance

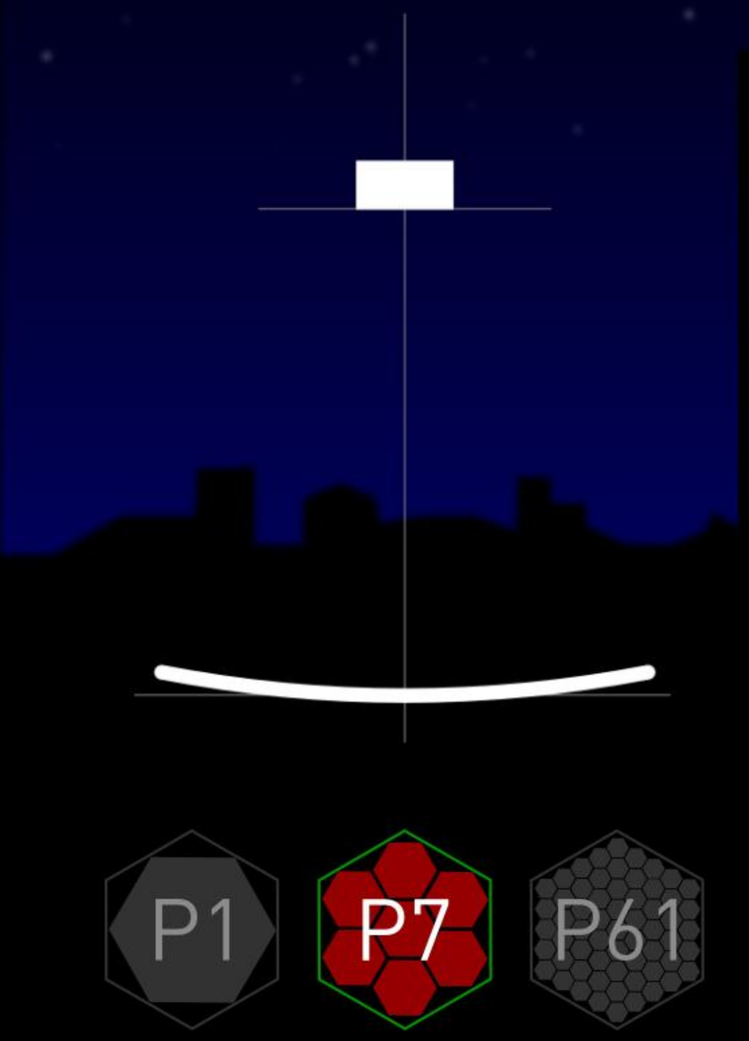


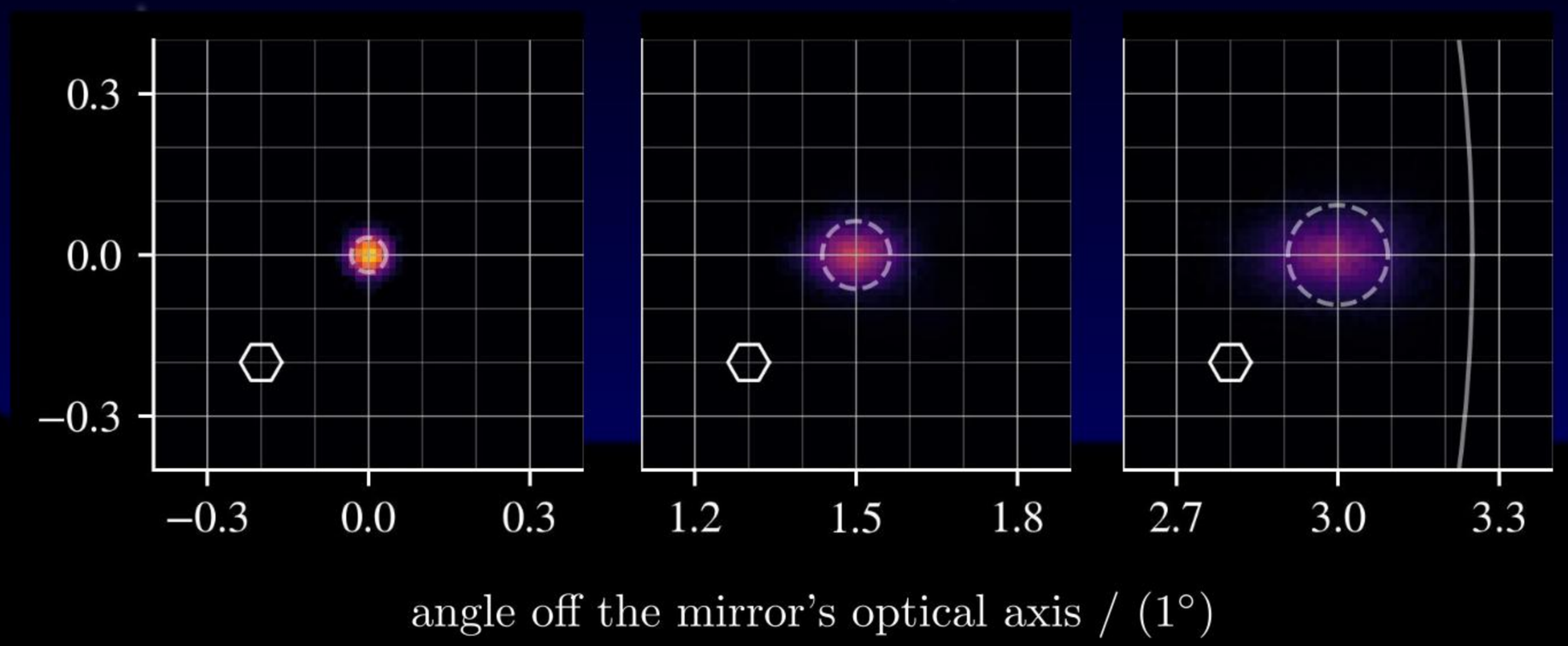


We start with the telescope p-one when the mirror is in good shape and the camera is well aligned. As we expect, the center of the image is sharp but aberrations quickly blur the image when we go off the optical axis.

Optics

starlight performance





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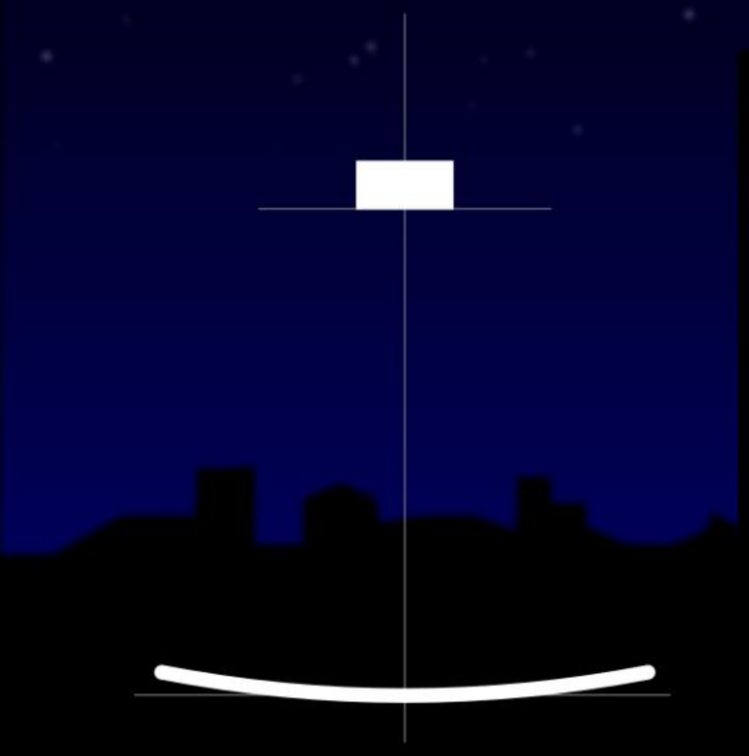
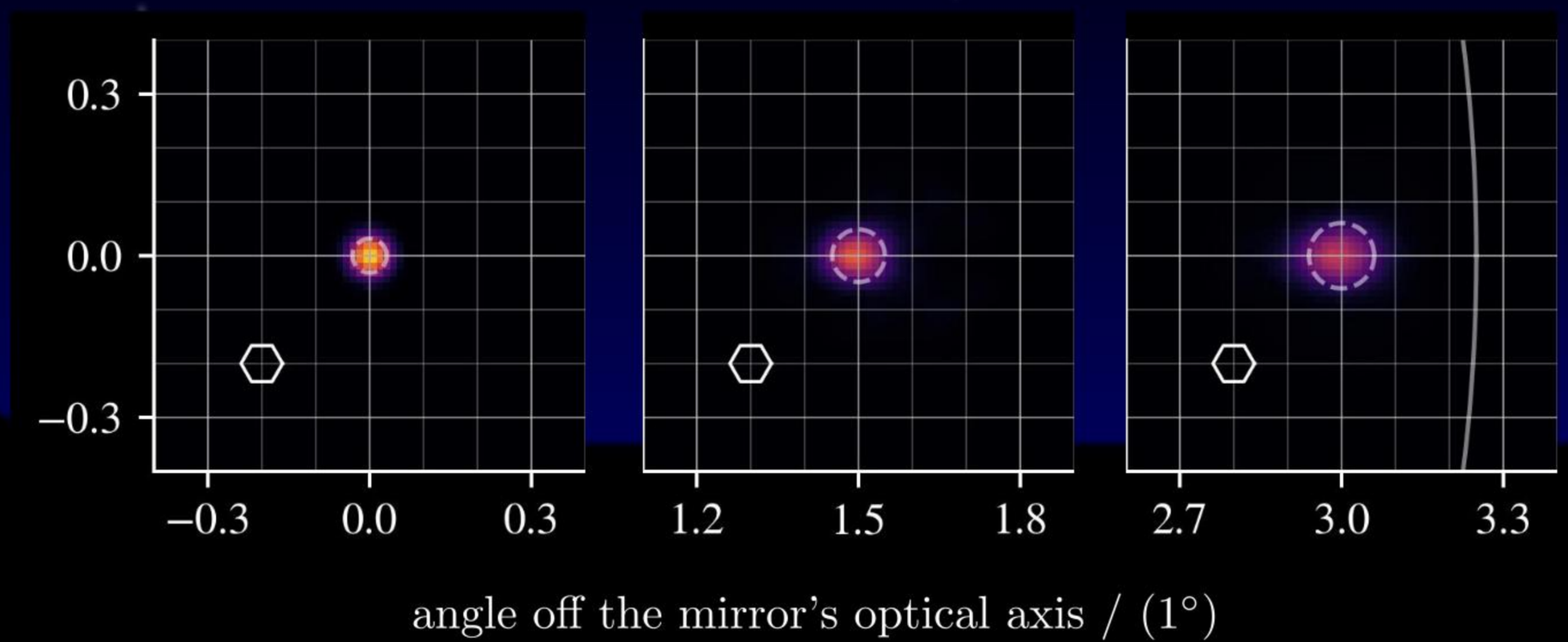
Alredy the plenoscope p-seven is able to reduce the aberrations significantly.

Optics

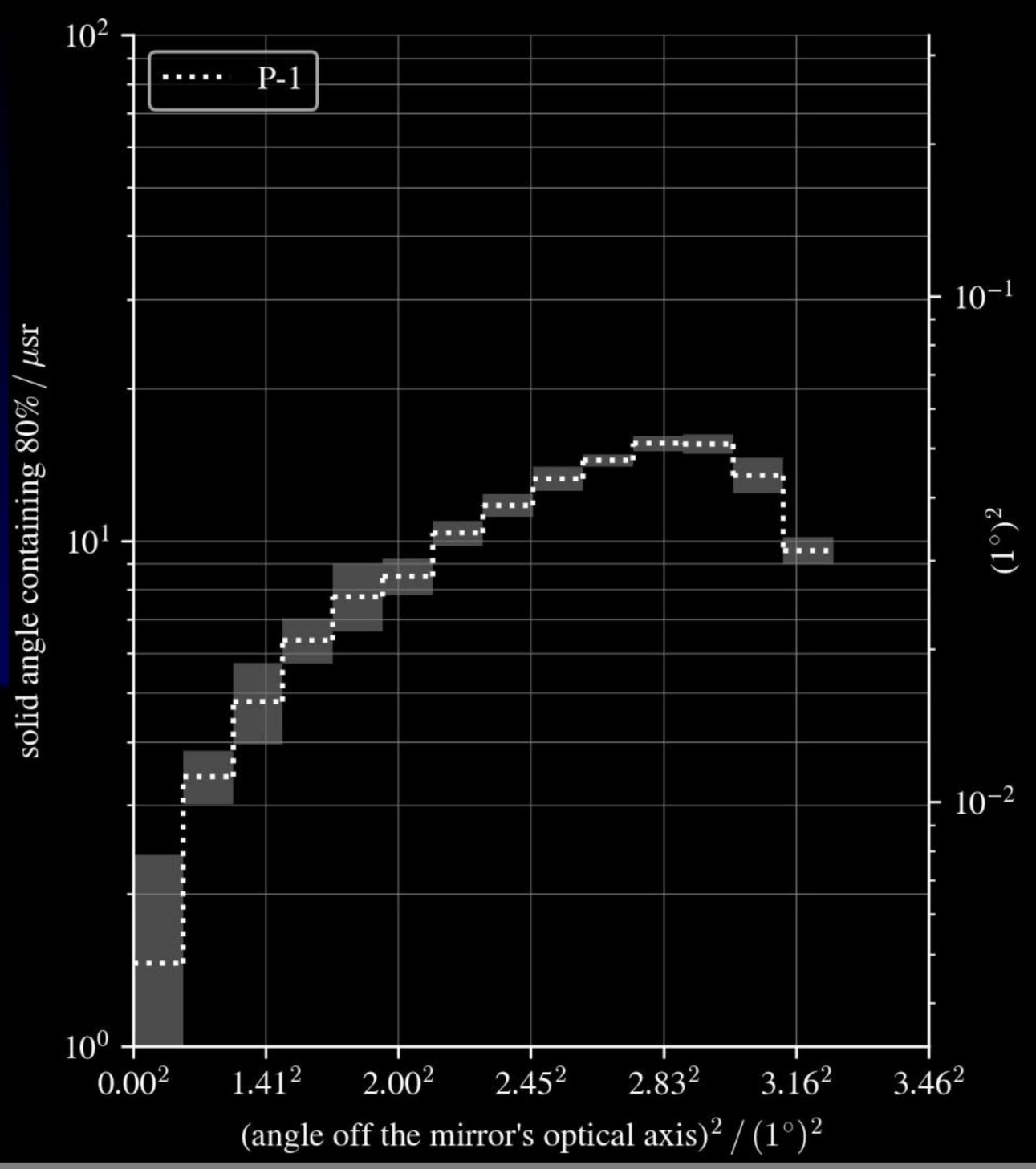
starlight performance



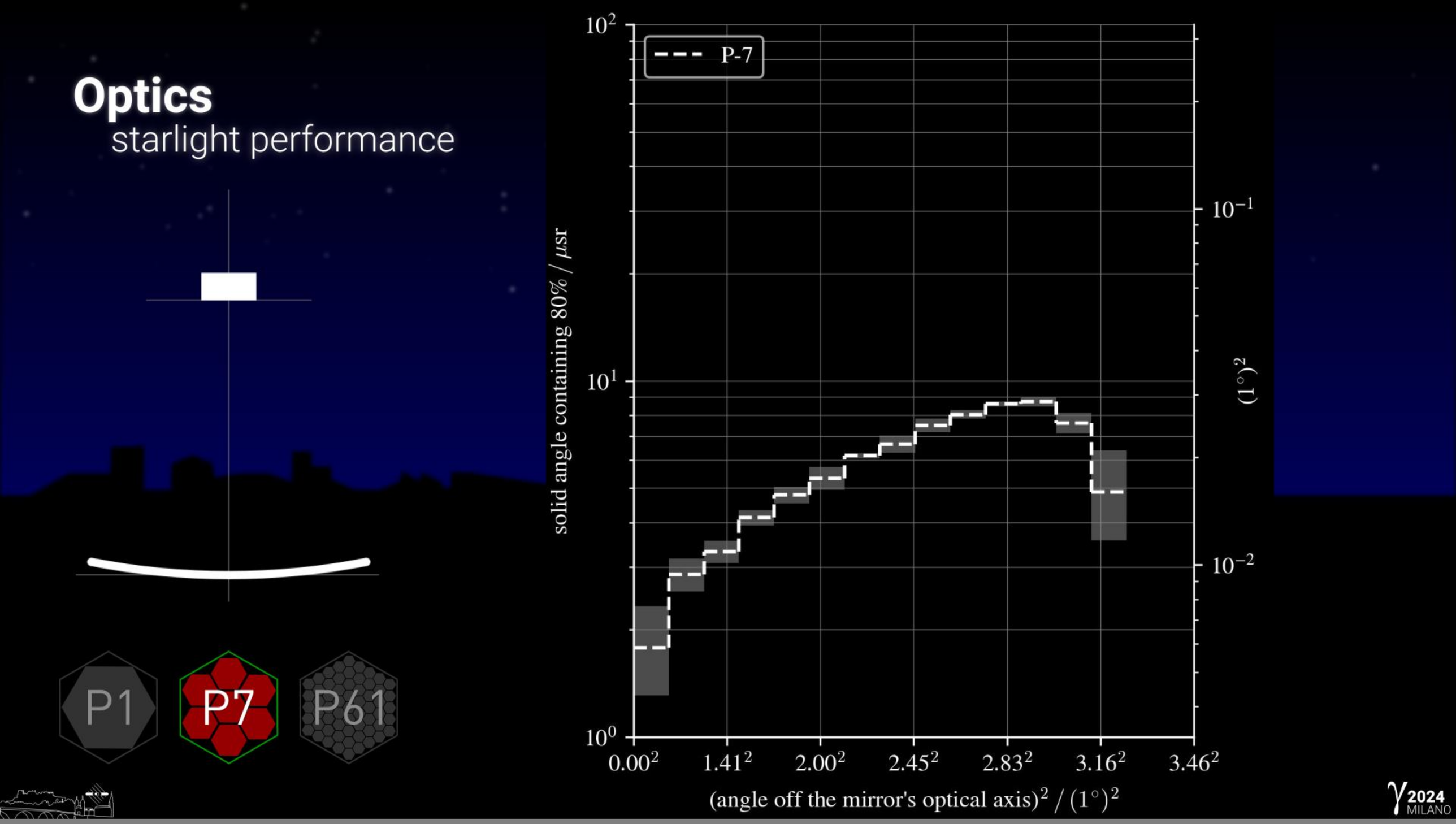


With the Portal plenoscope p-sixty-one, aberrations are practically gone.

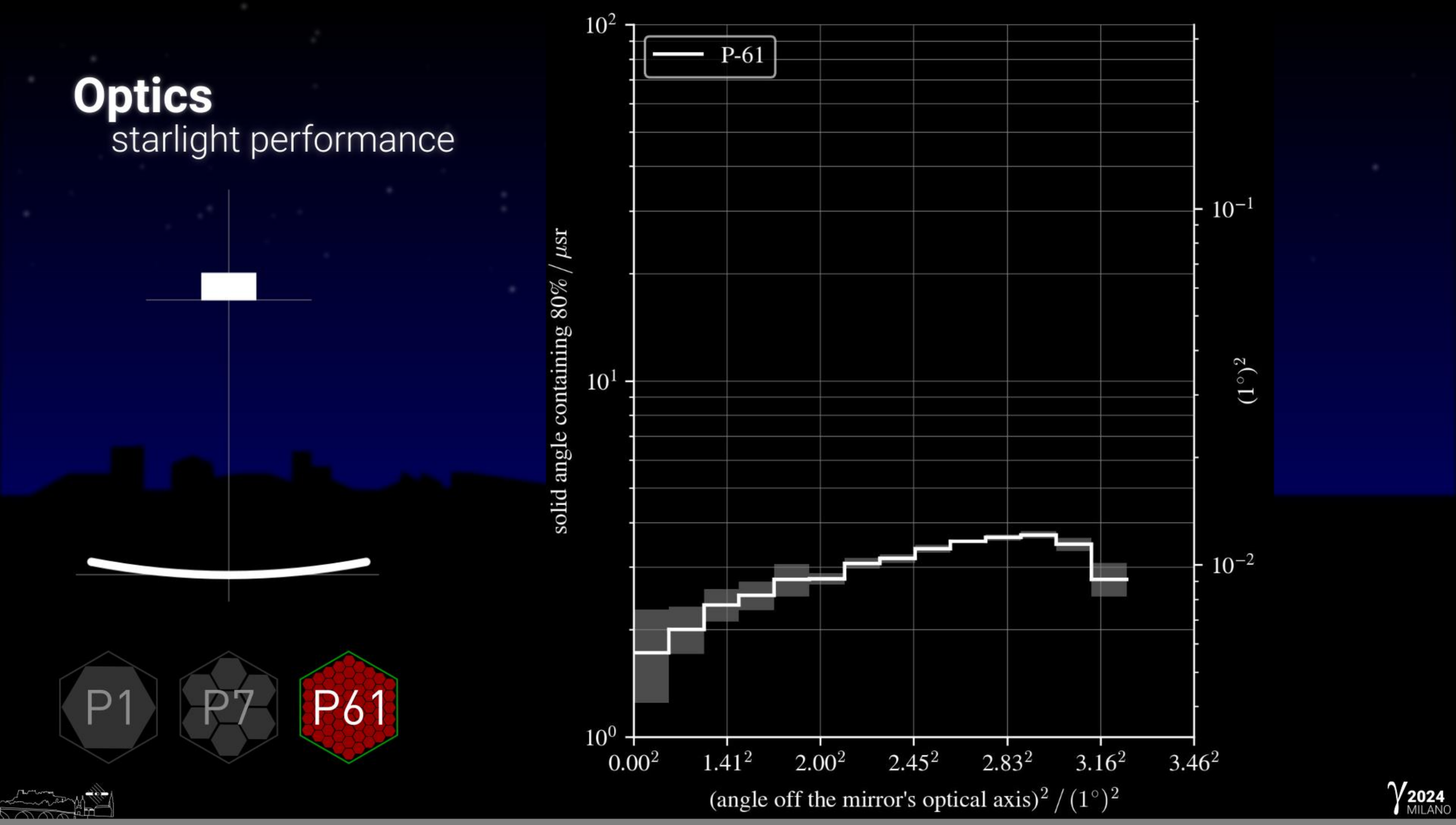
Optics
starlight performance



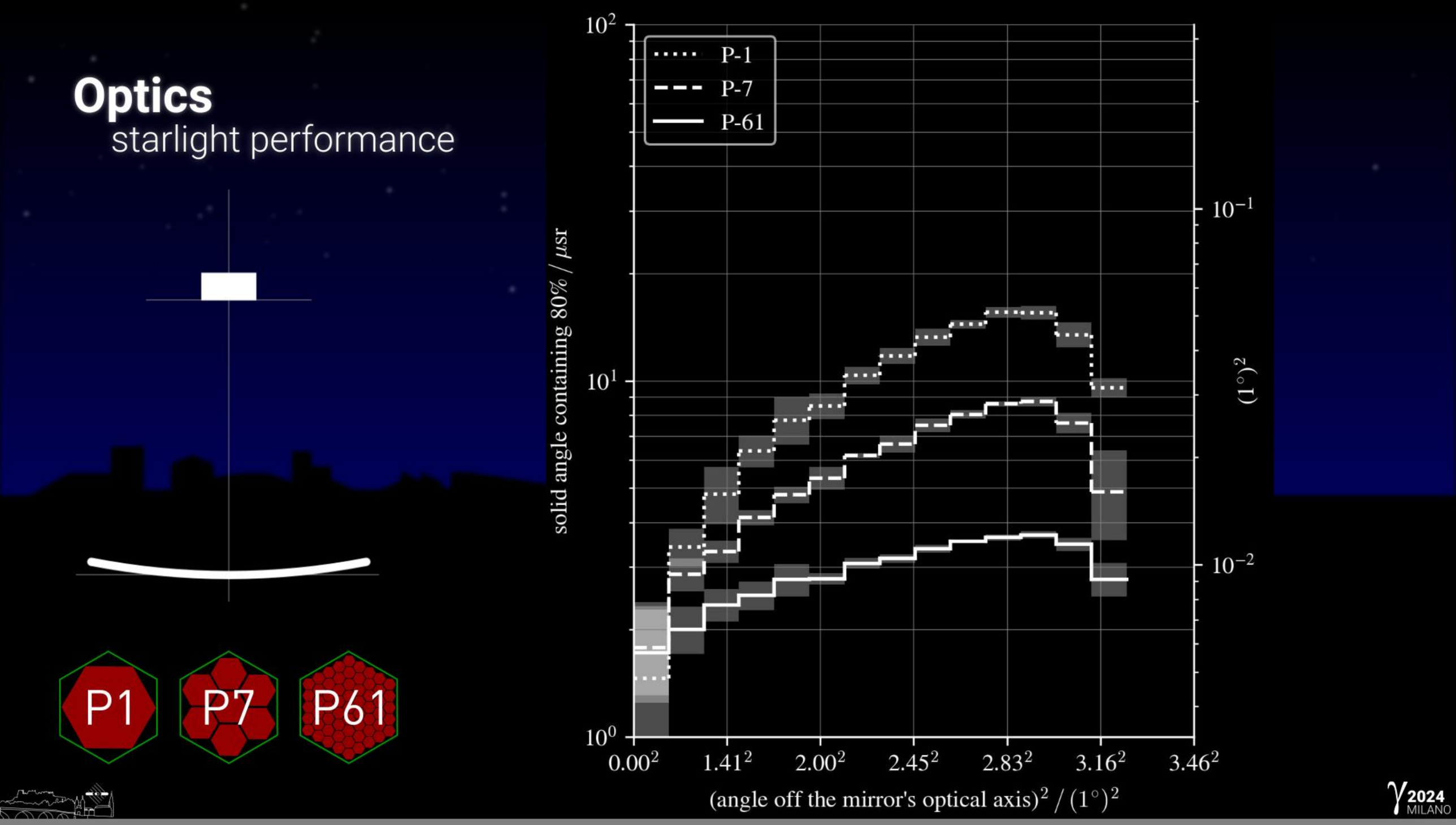
This is again the telescope p-one. We see the solid angle of its point-spread-function versus the angle off the optical axis.



By contrast, here is the plenoscope p-seven ...



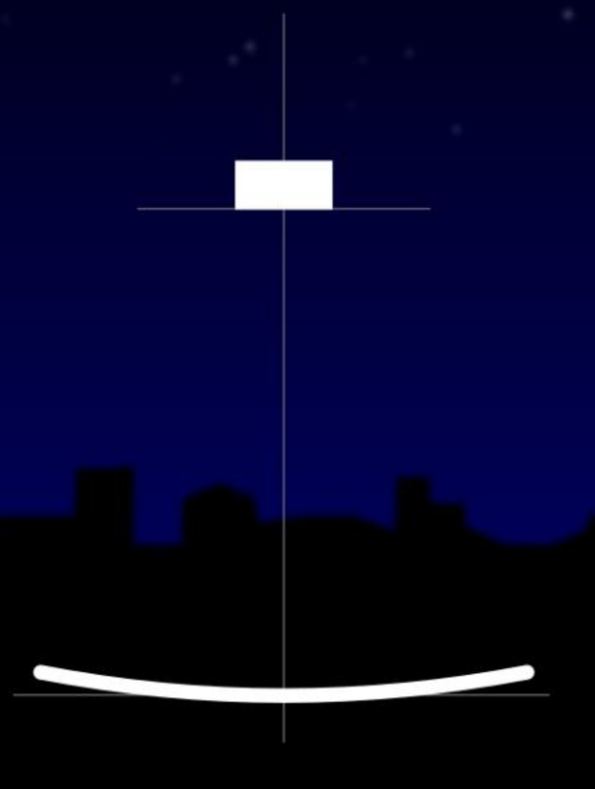
and the Portal plenoscope p-sixty-one.



Here they are all together. Note, that this is a logarithmic scale.

Optics

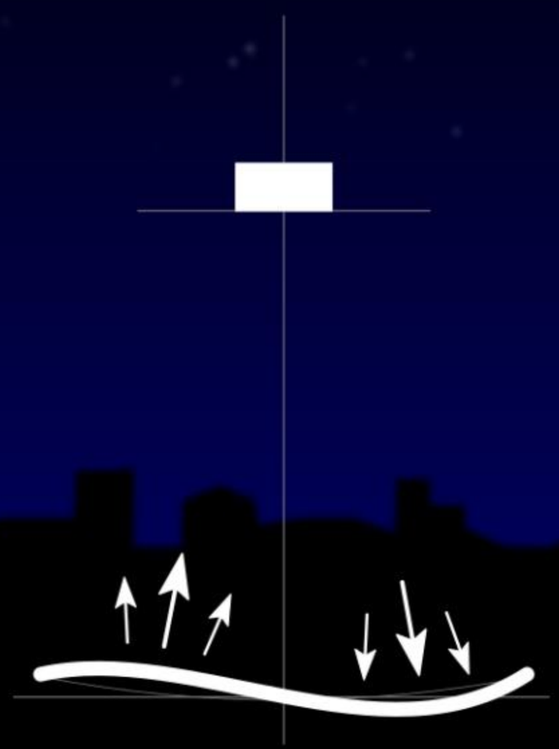
starlight performance



Ok, but what if ...

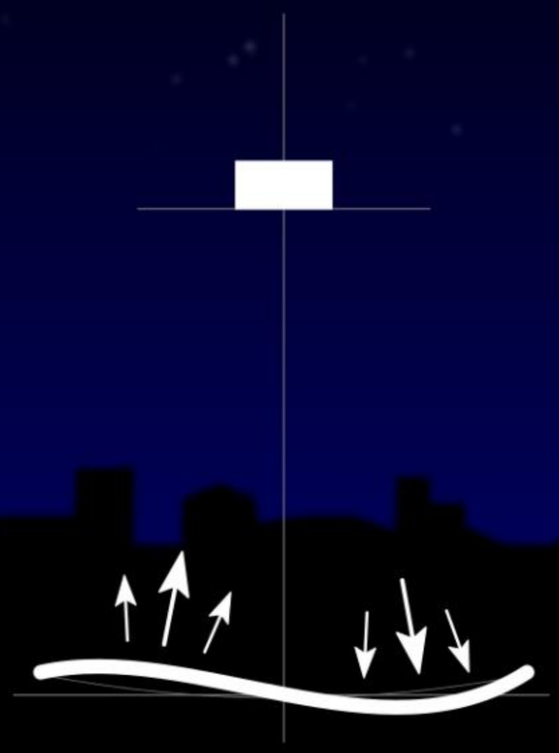
Optics

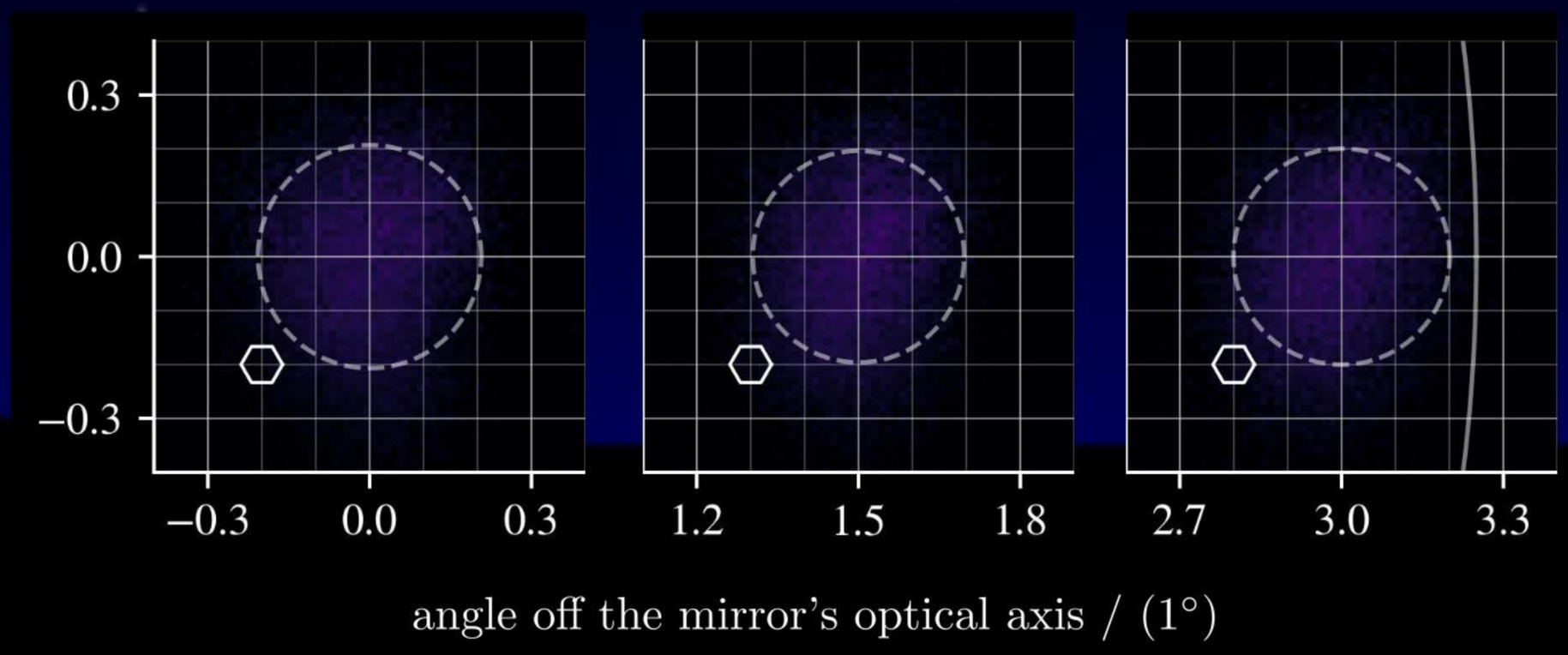
starlight performance



the mirror is beeing deformed?

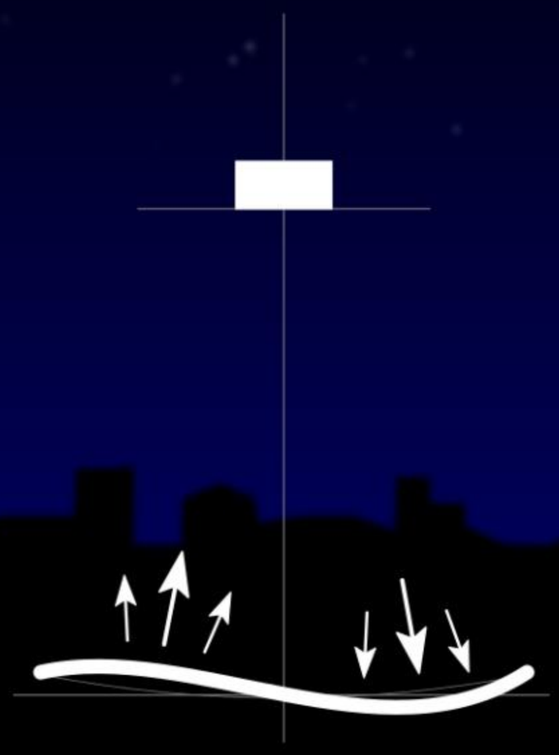
Optics
starlight performance

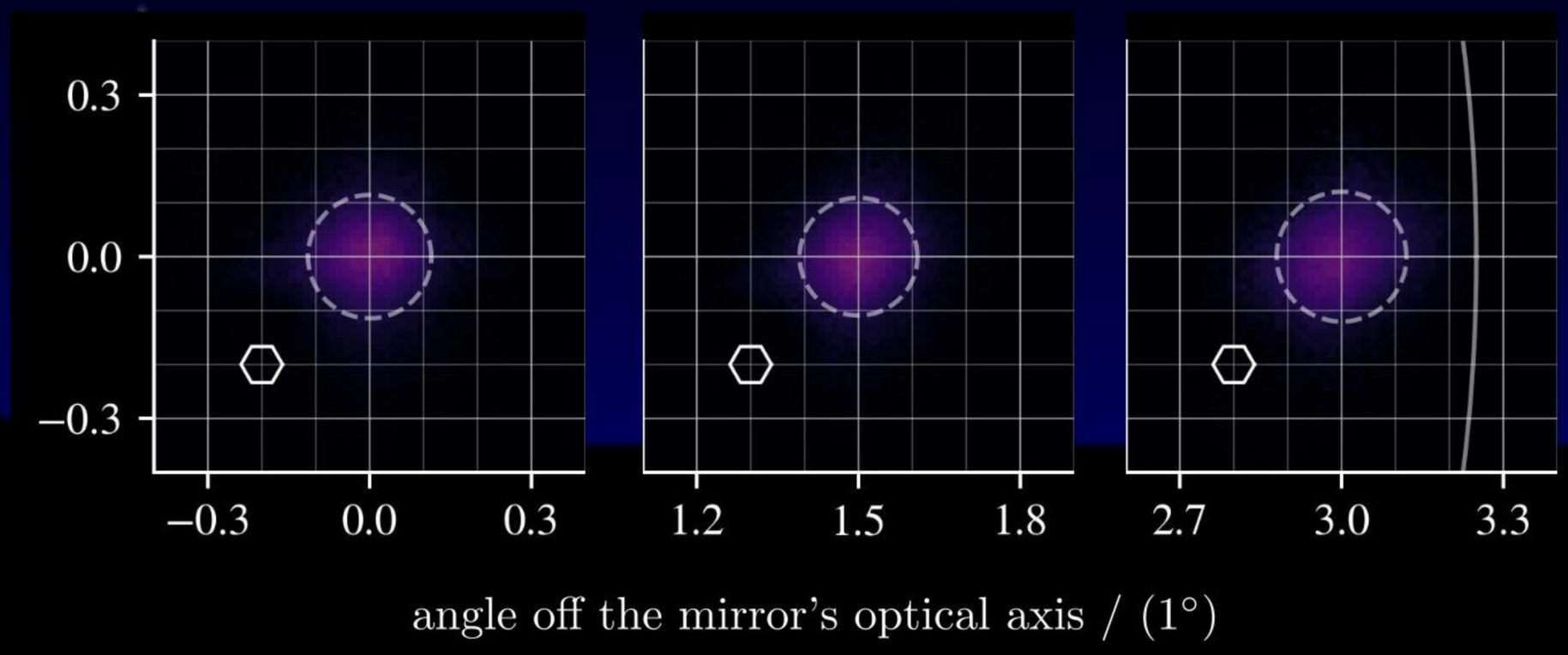




Oooofff. As expected the telescope p-one does not like this.

Optics
starlight performance

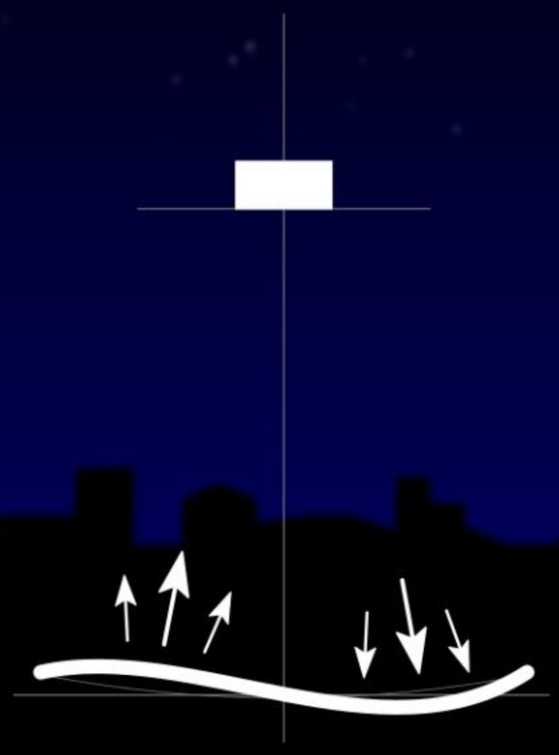


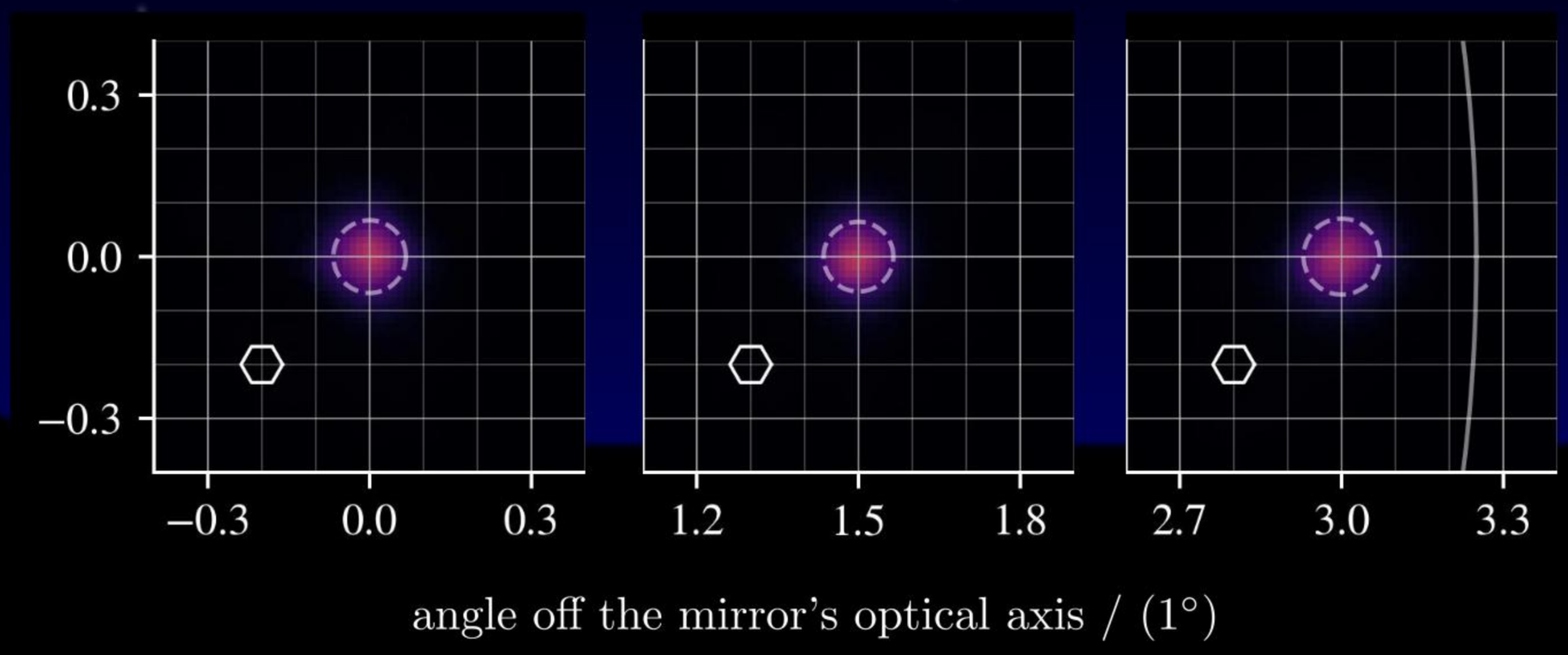


By contrast, this is the plenoscope p-seven, ...

Optics

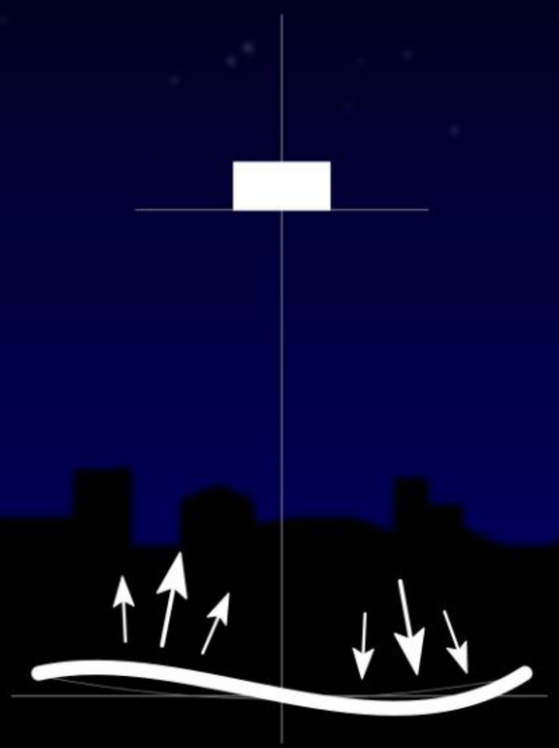
starlight performance

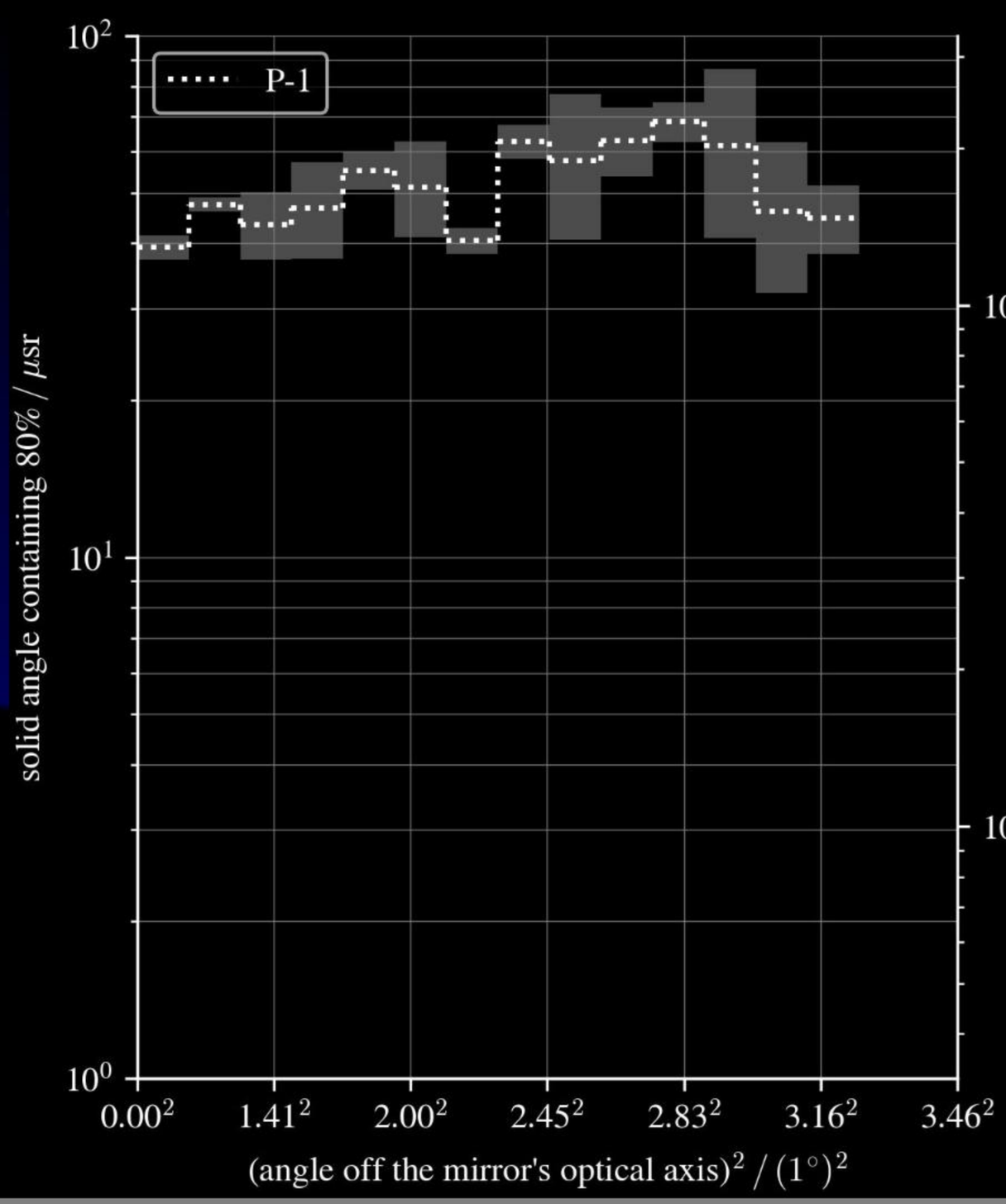




and this is the Portal plenoscope p-sixty-one. Looks like we are back in business!

Optics
starlight performance





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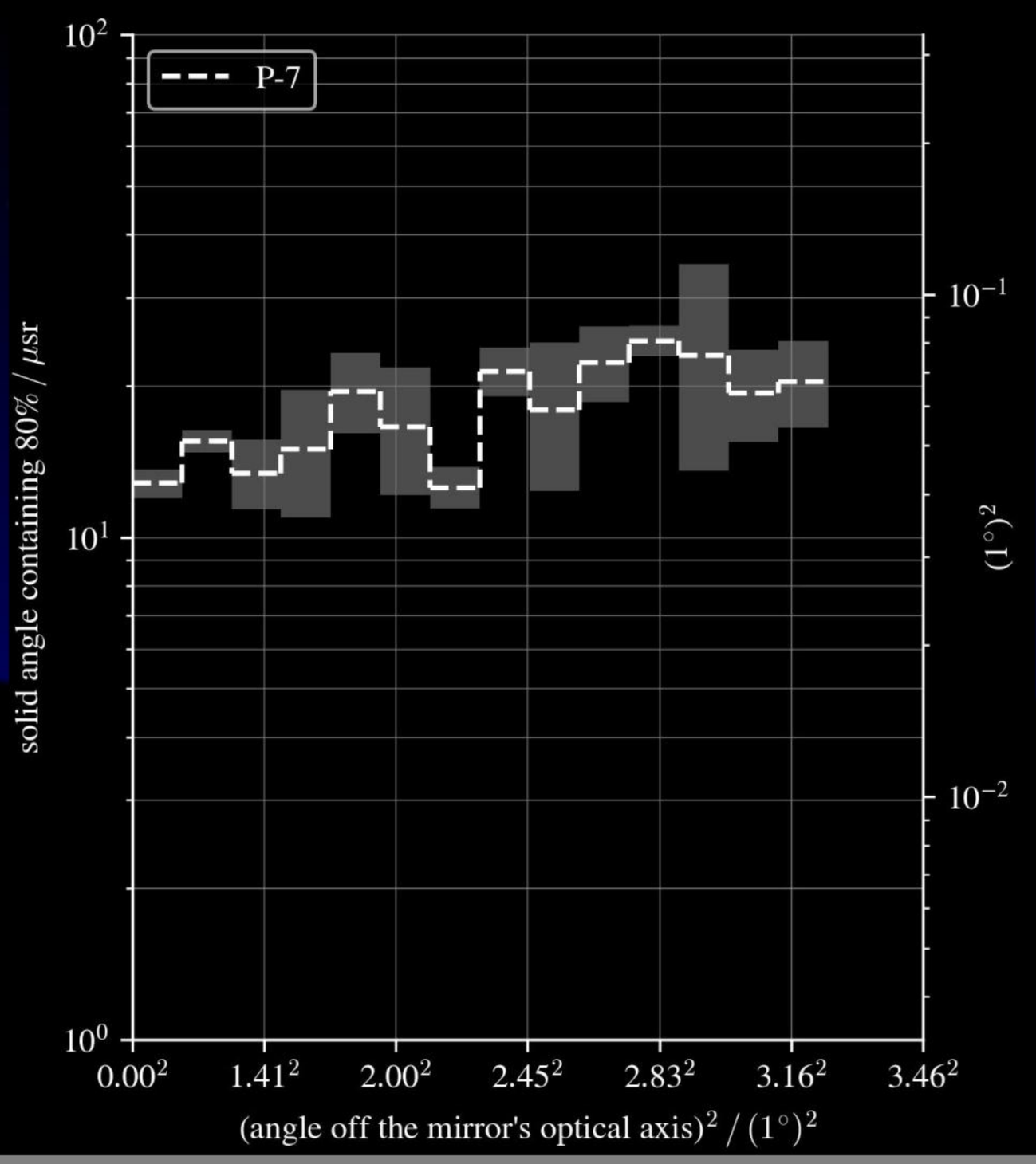
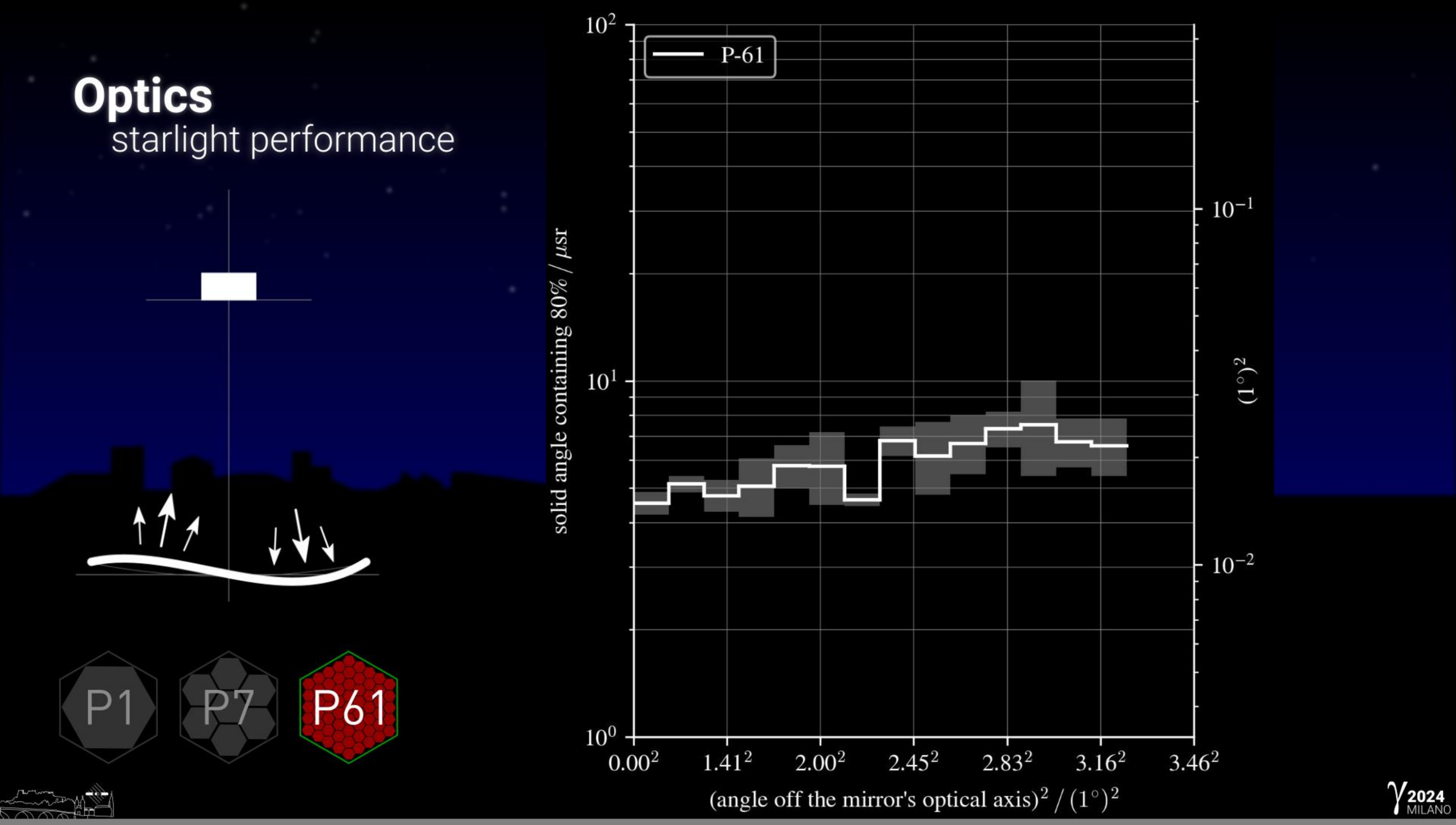
Telescope p-one, ...

Optics
starlight performance

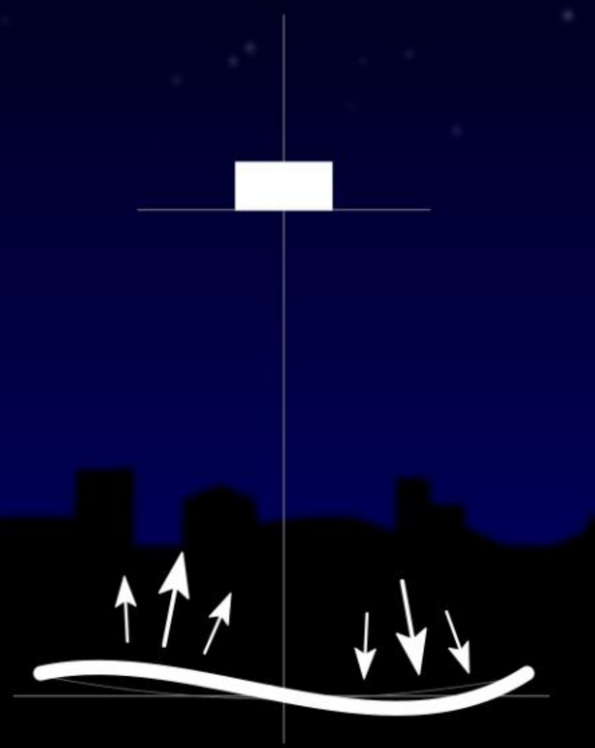


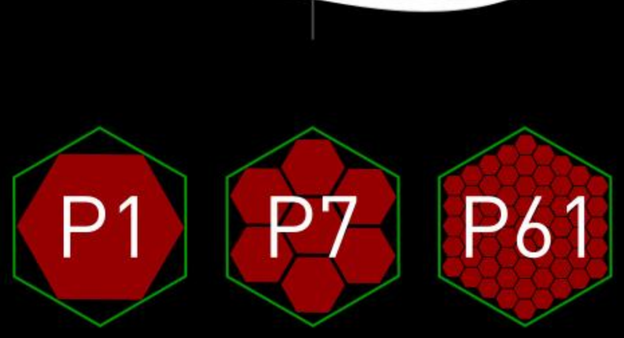
plenoscope p-seven

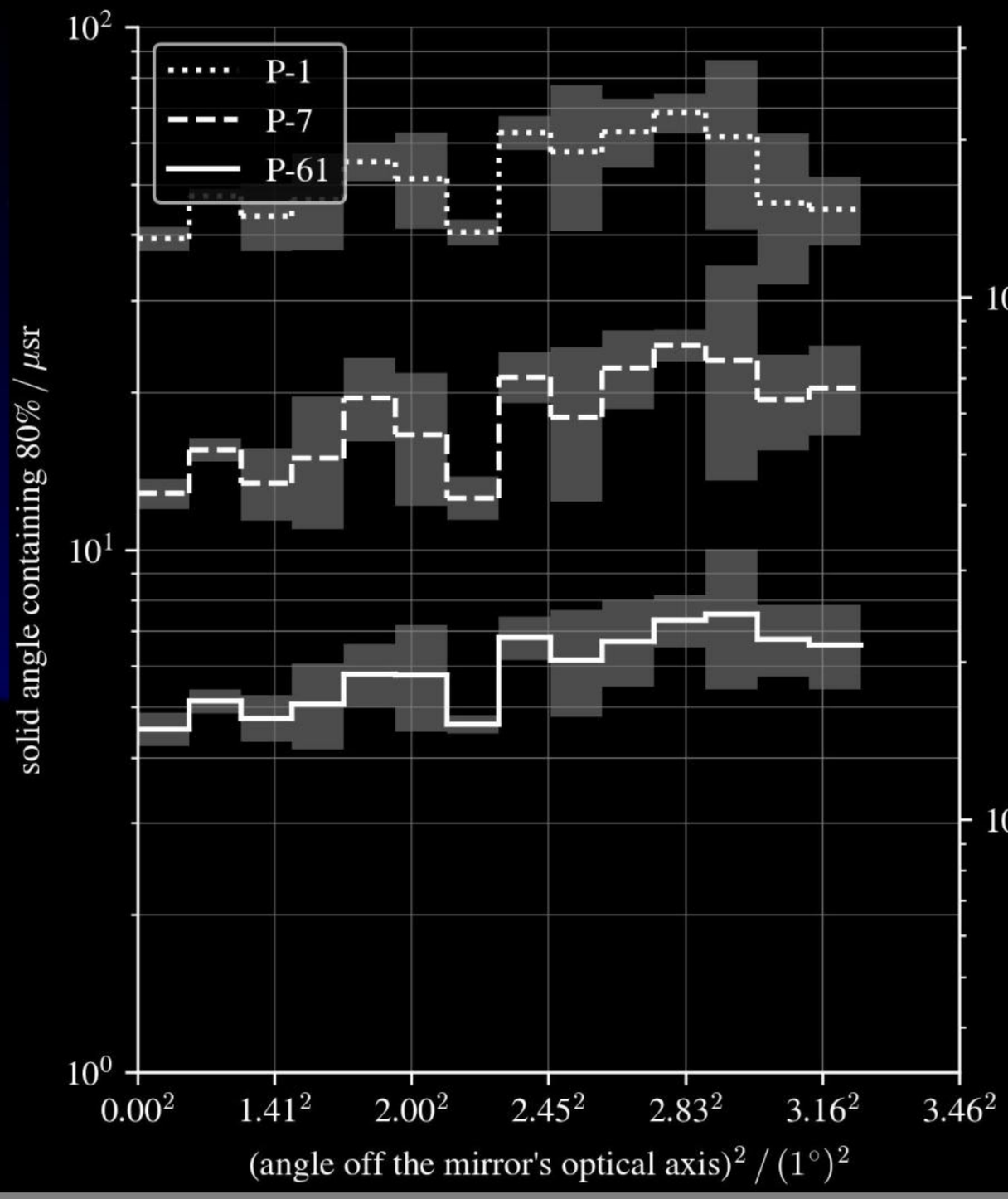


and Portal plenoscope p-sixty-one.

Optics
starlight performance







There are worlds between these instruments.

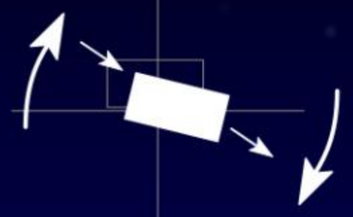
Optics

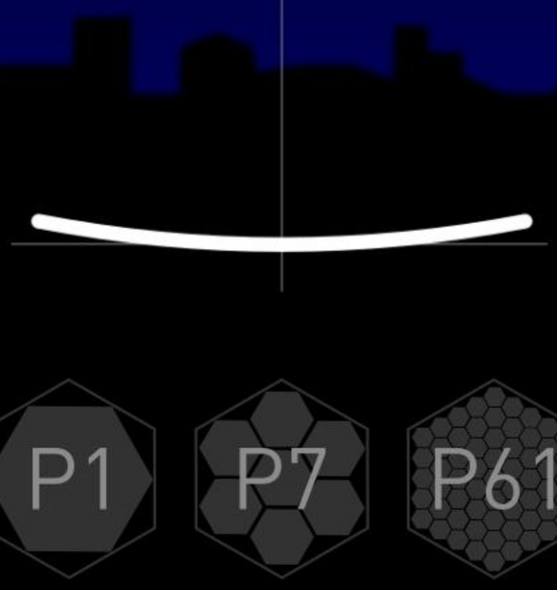
starlight performance

P1 P7 P61

Optics

starlight performance

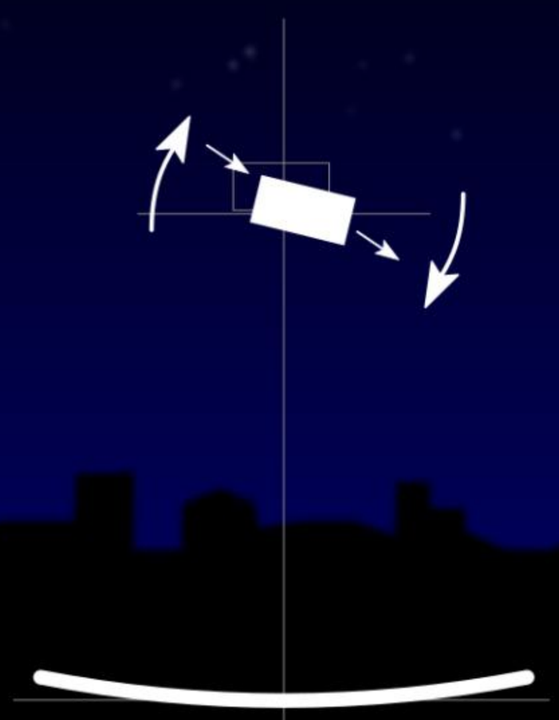


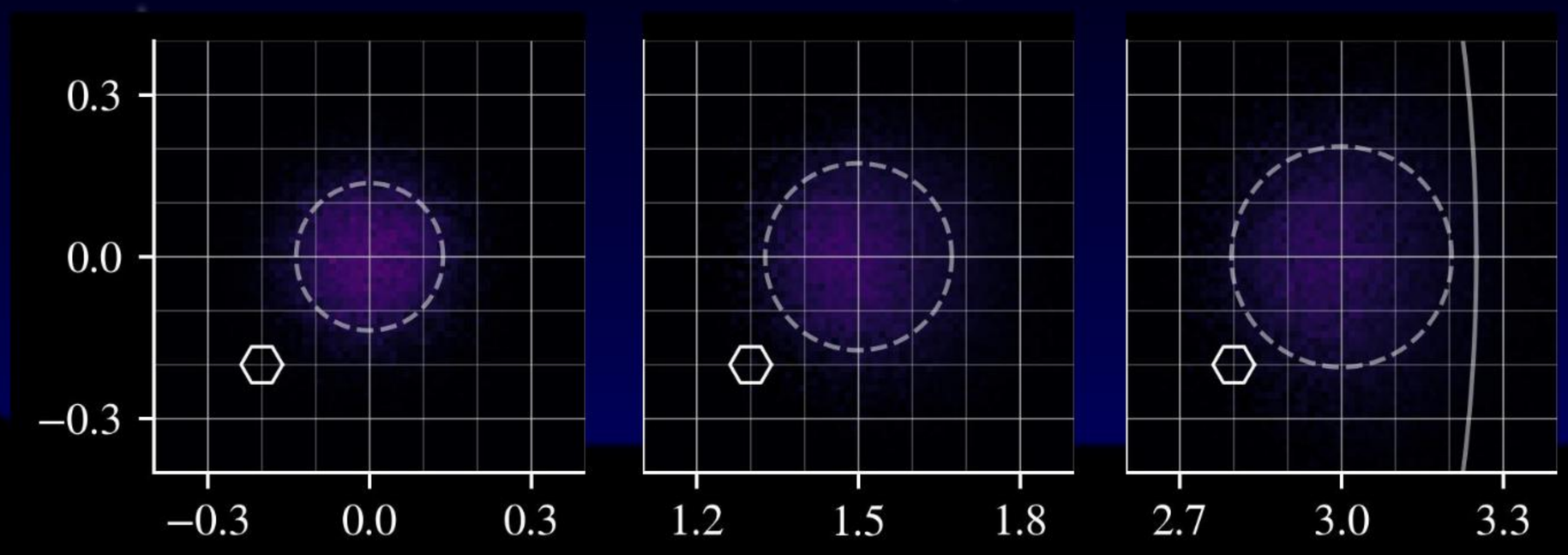


Now what if the camera is beeing misaligned?

Optics

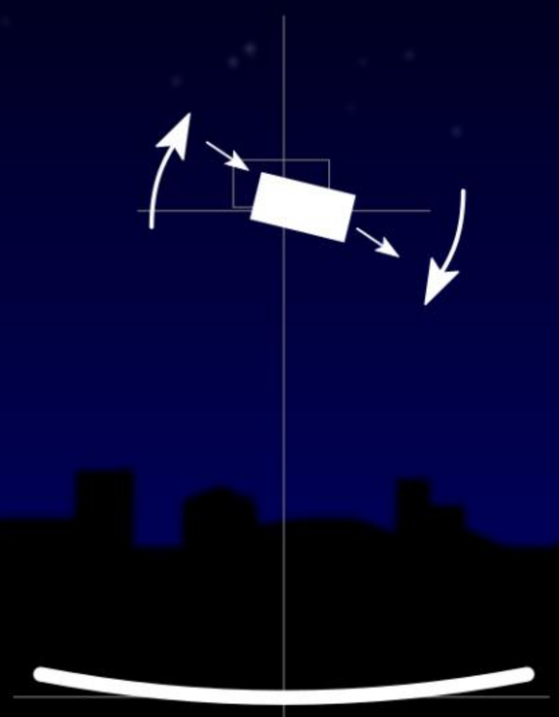
starlight performance

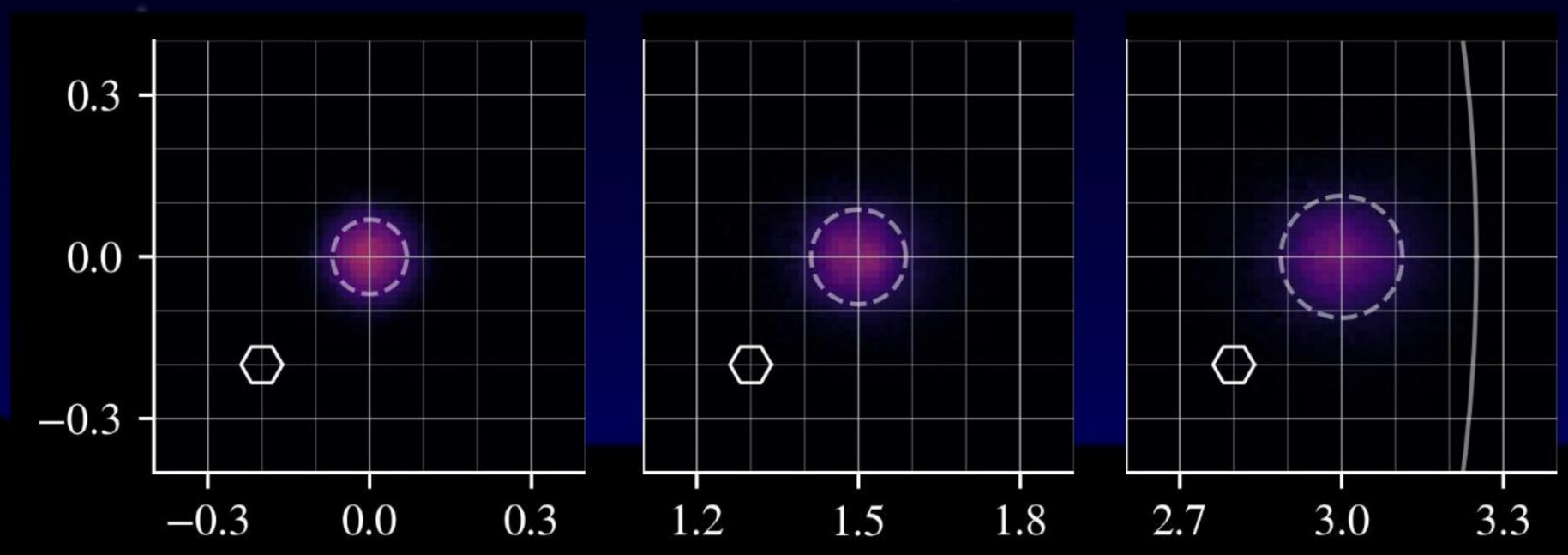




Again, the telescope p-one does not like this at all.

Optics
starlight performance

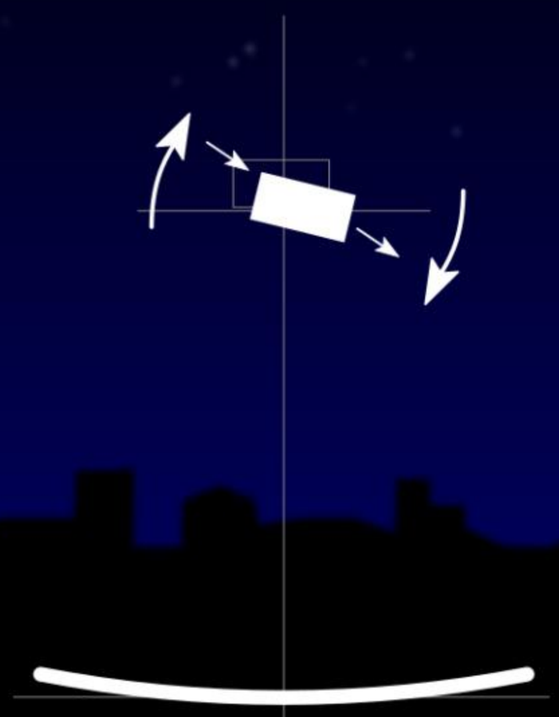


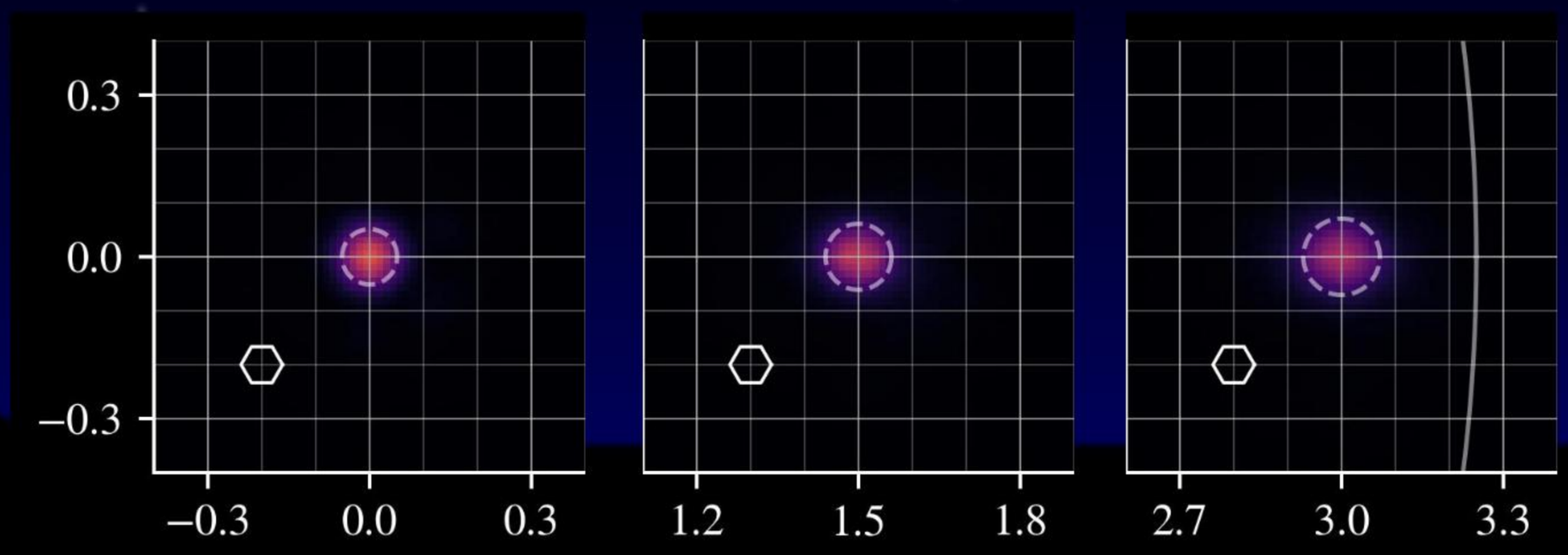


By contrast, the plenoscope p-seven,

Optics

starlight performance

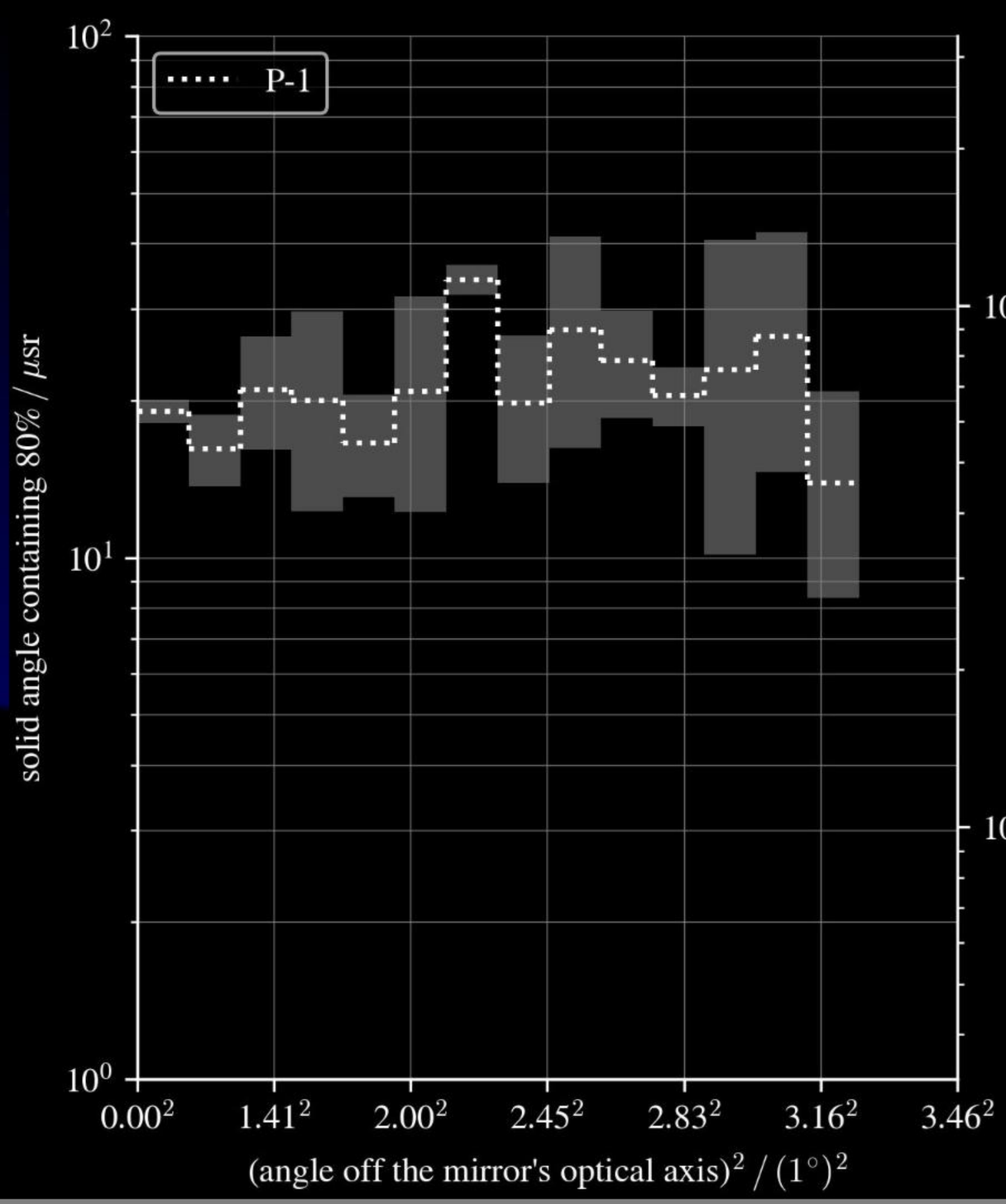




and especially the Portal plenoscope p-sixty-one bring us back into buisness.

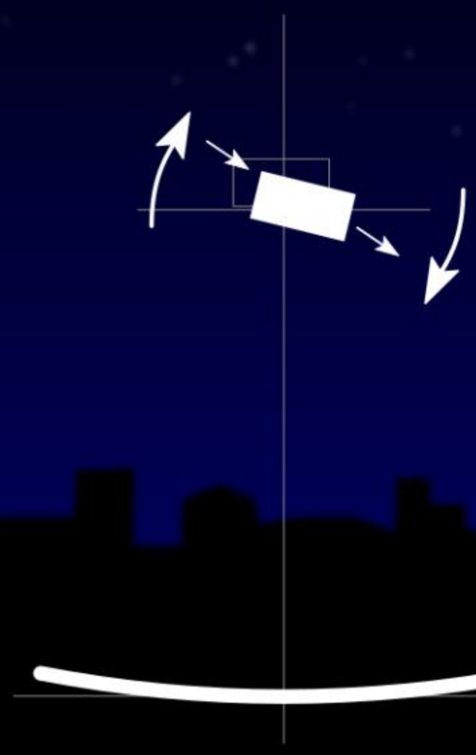
Optics
starlight performance

P1 P7 P61

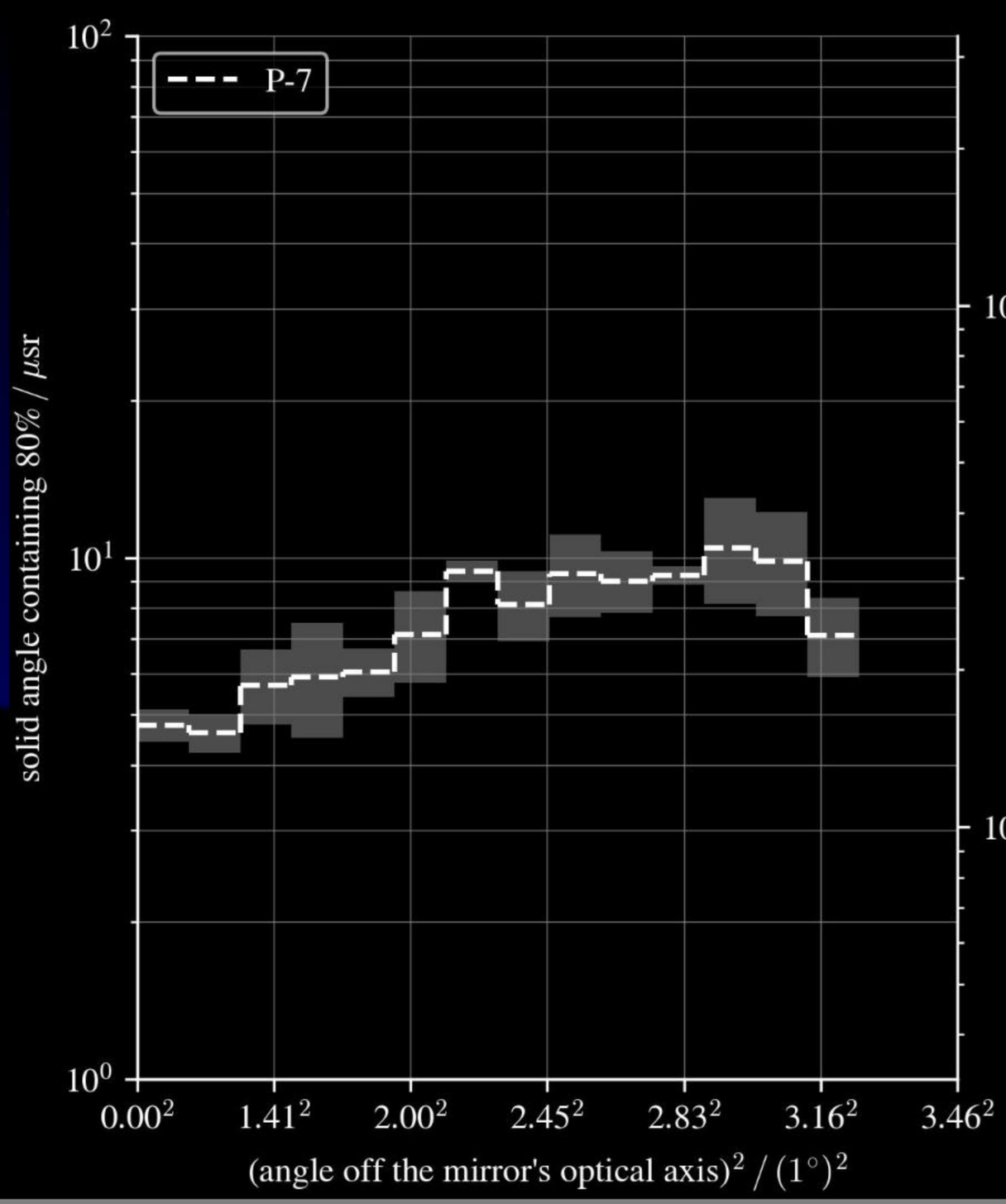


Telescope p-one,

Optics
starlight performance

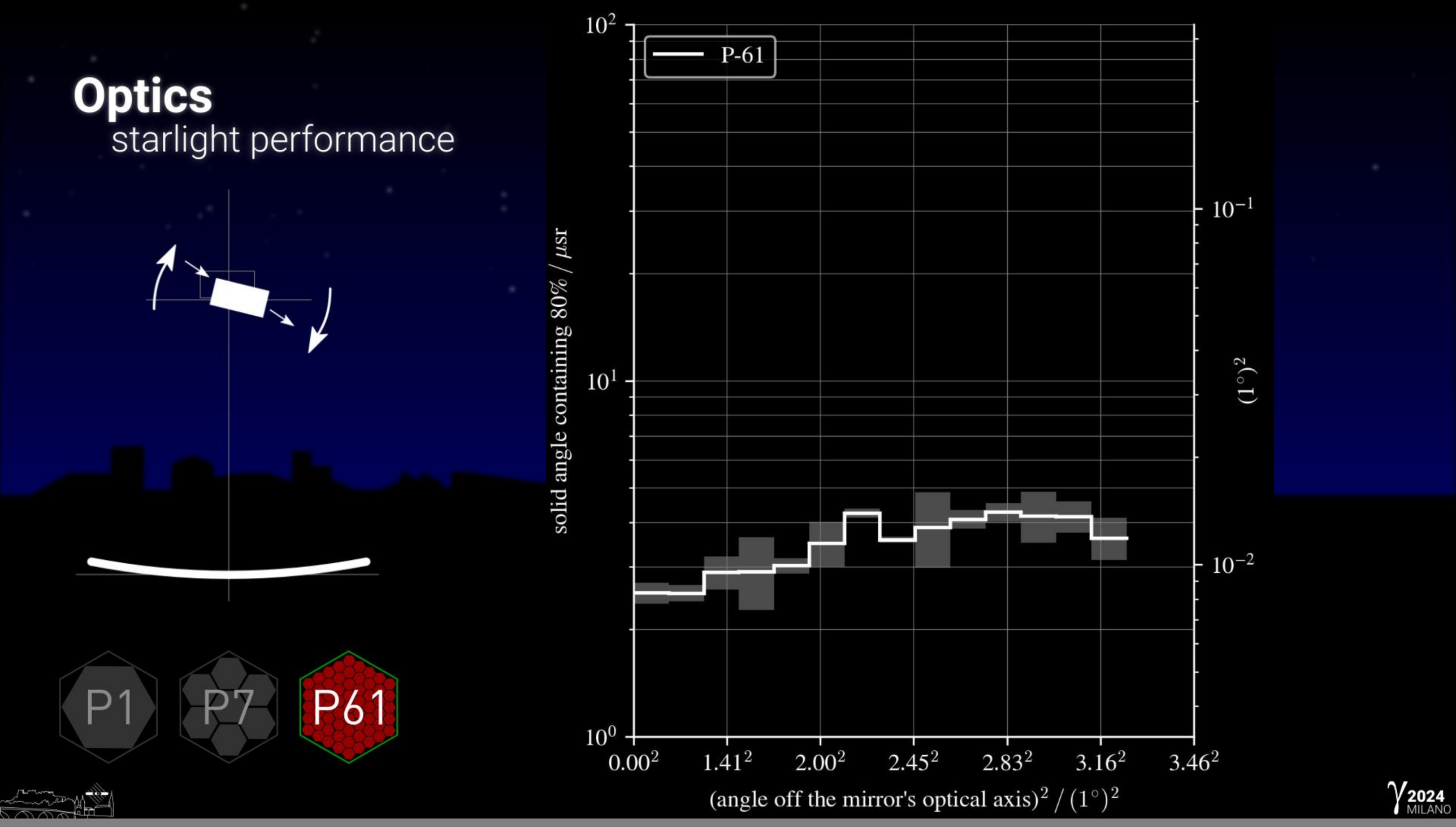


P1 P7 P61

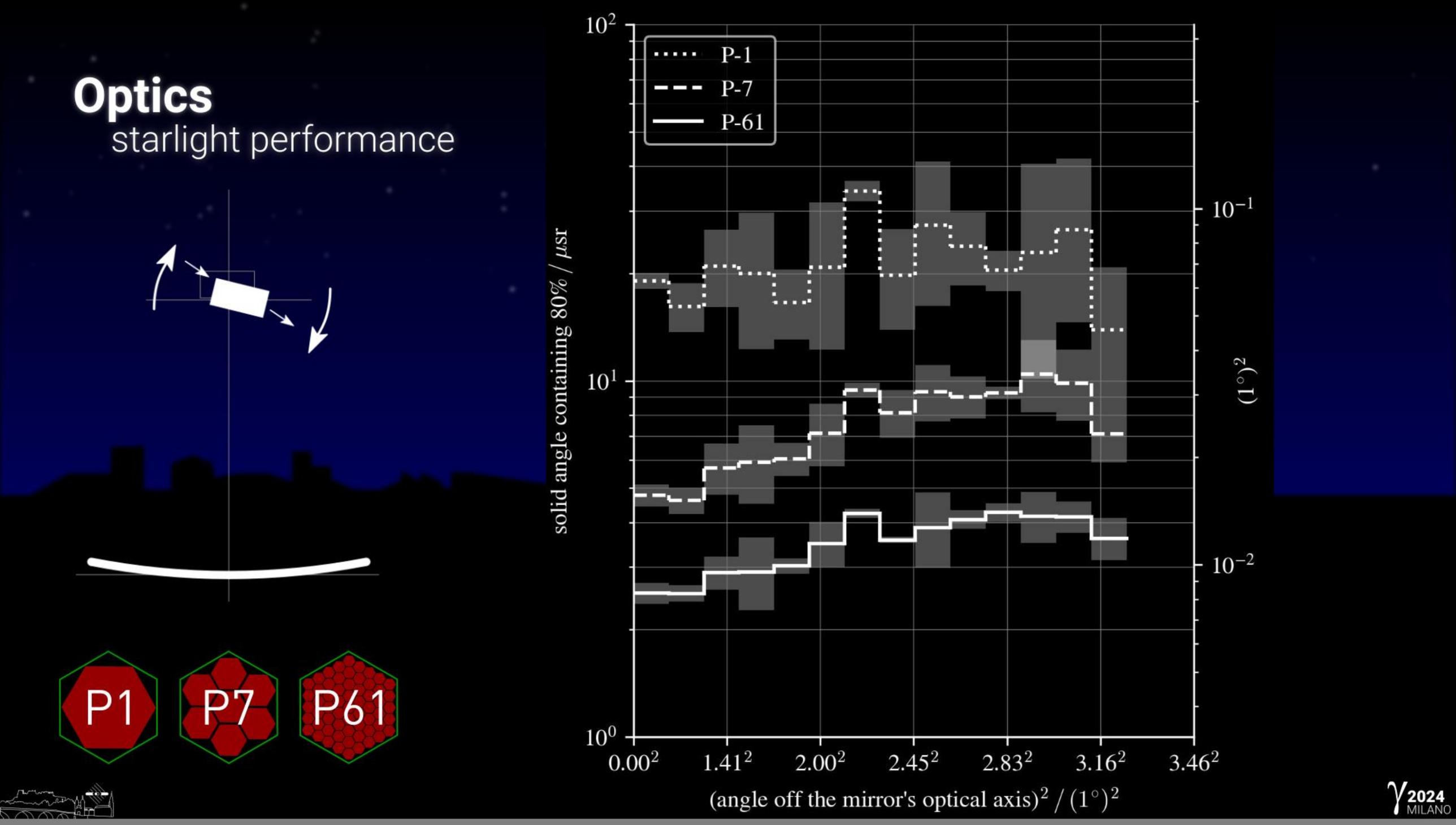


γ 2024 MILANO

plenoscope p-seven,



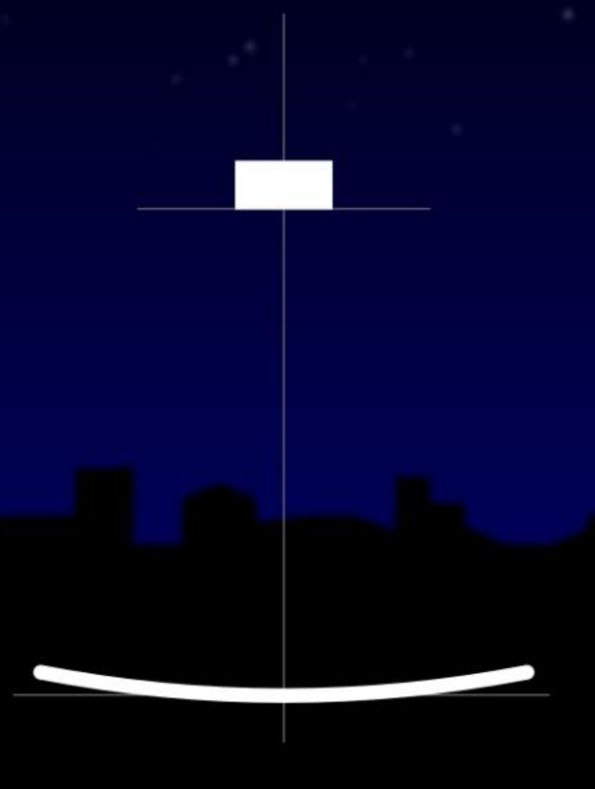
and the Portal plenoscope p-sixty-one.



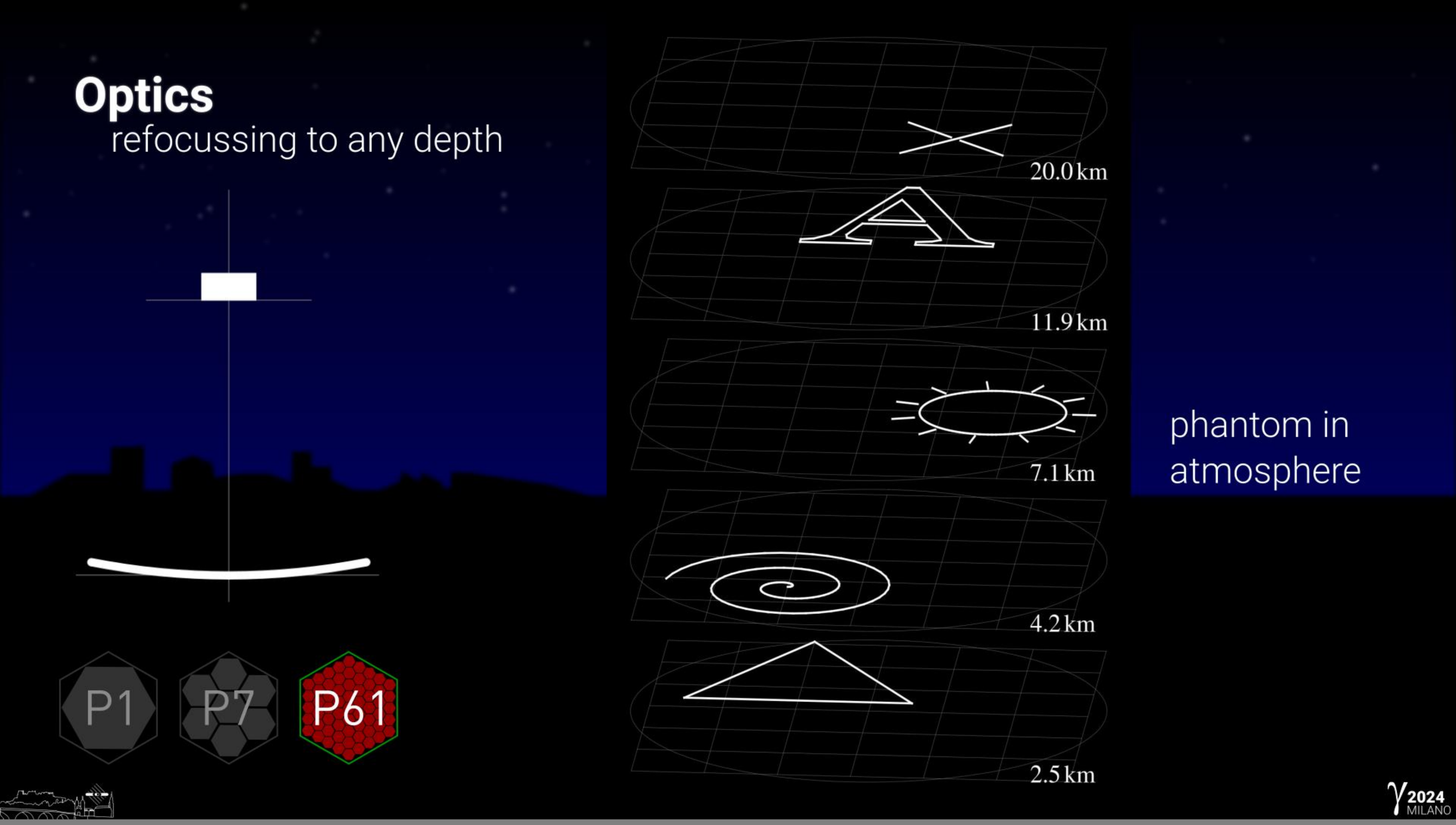
I think it is safe to say: The plenoscope is in a class of its own.

Optics

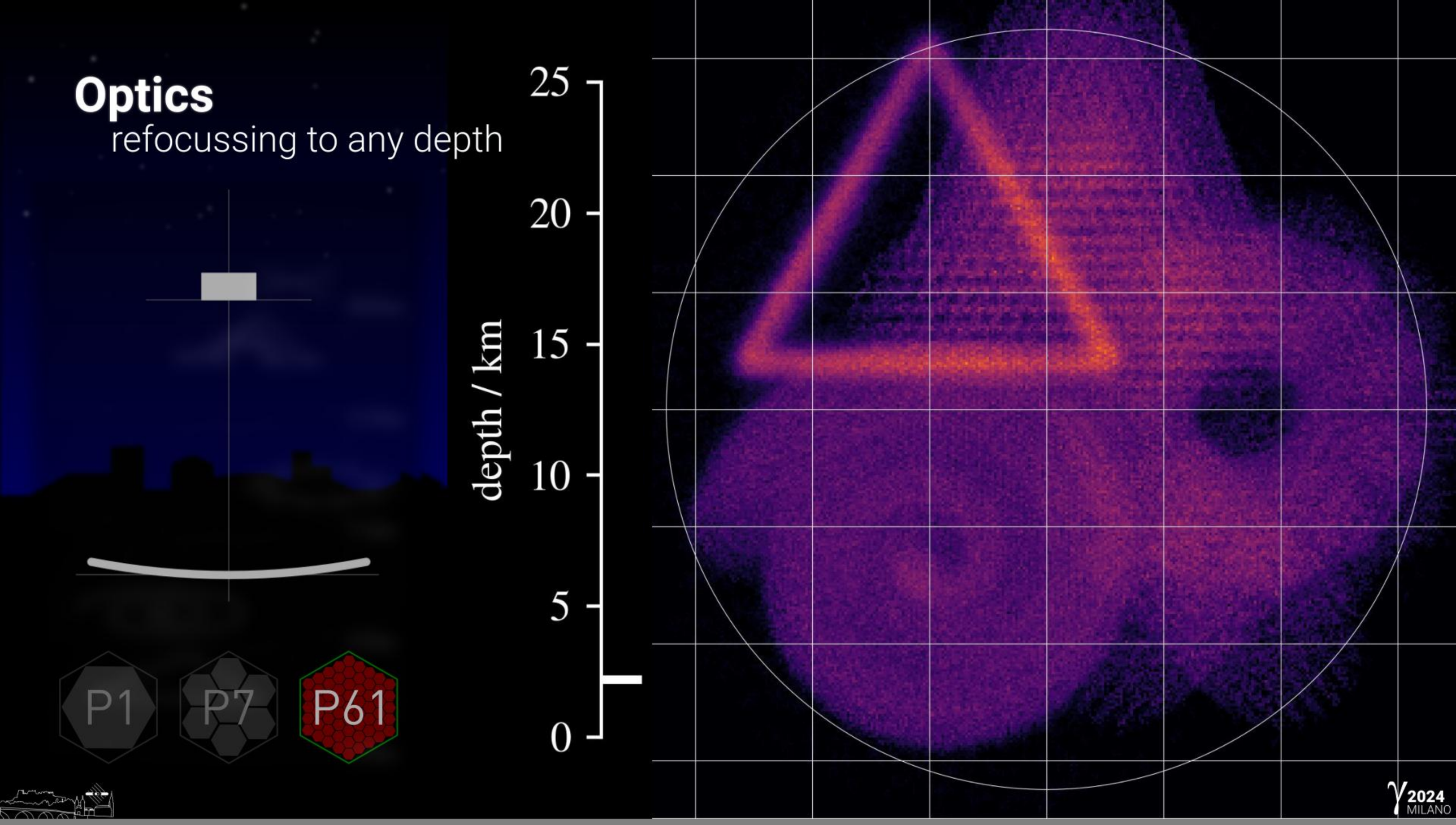
refocussing to any depth



Another unique feature of the plenoscope is its ability to refocus images in post after the recording. To demonstrate this, we set up ...



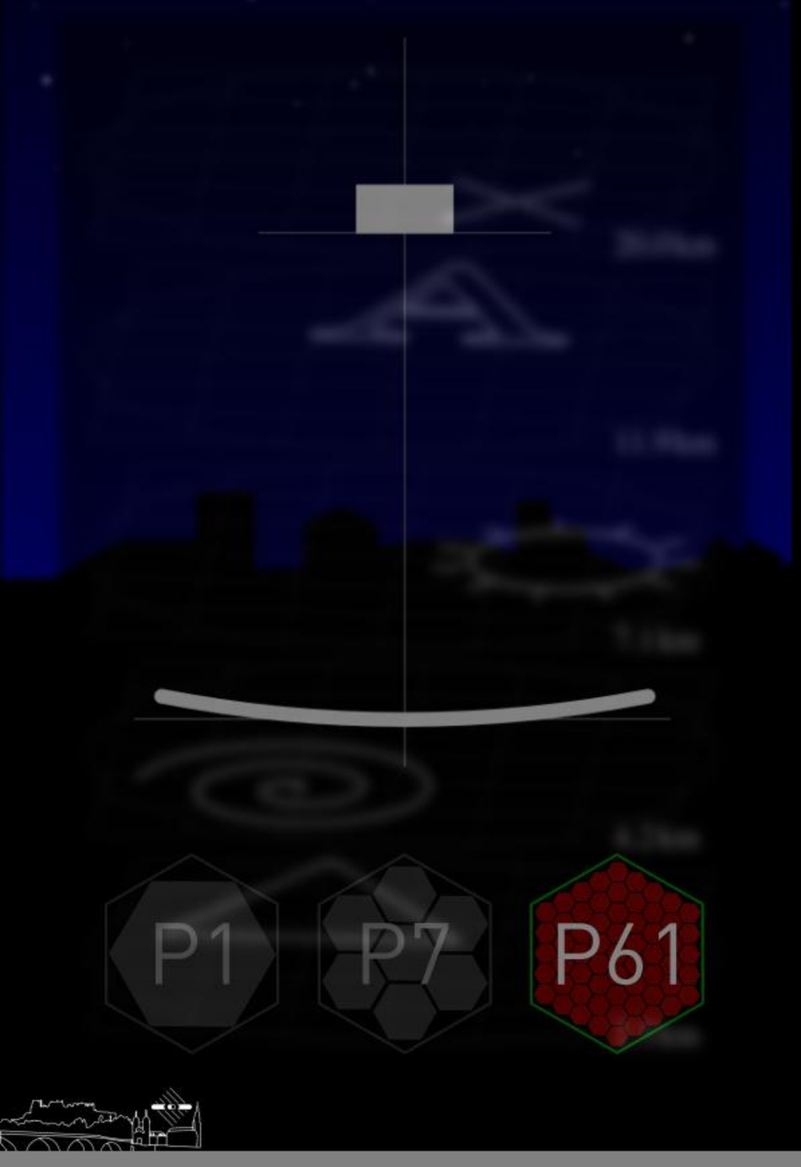
a phantom source. The pahntom source was chosen so that everyone can formulate a clear expectation of what a refocussed image should look like.

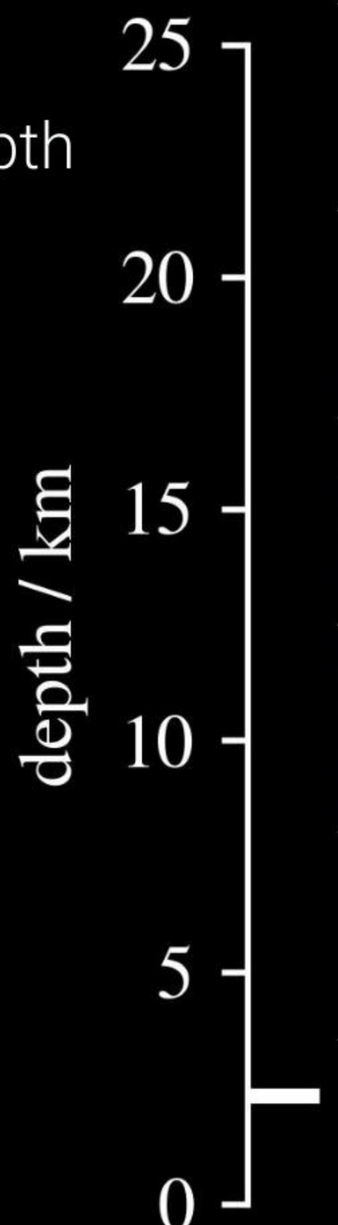


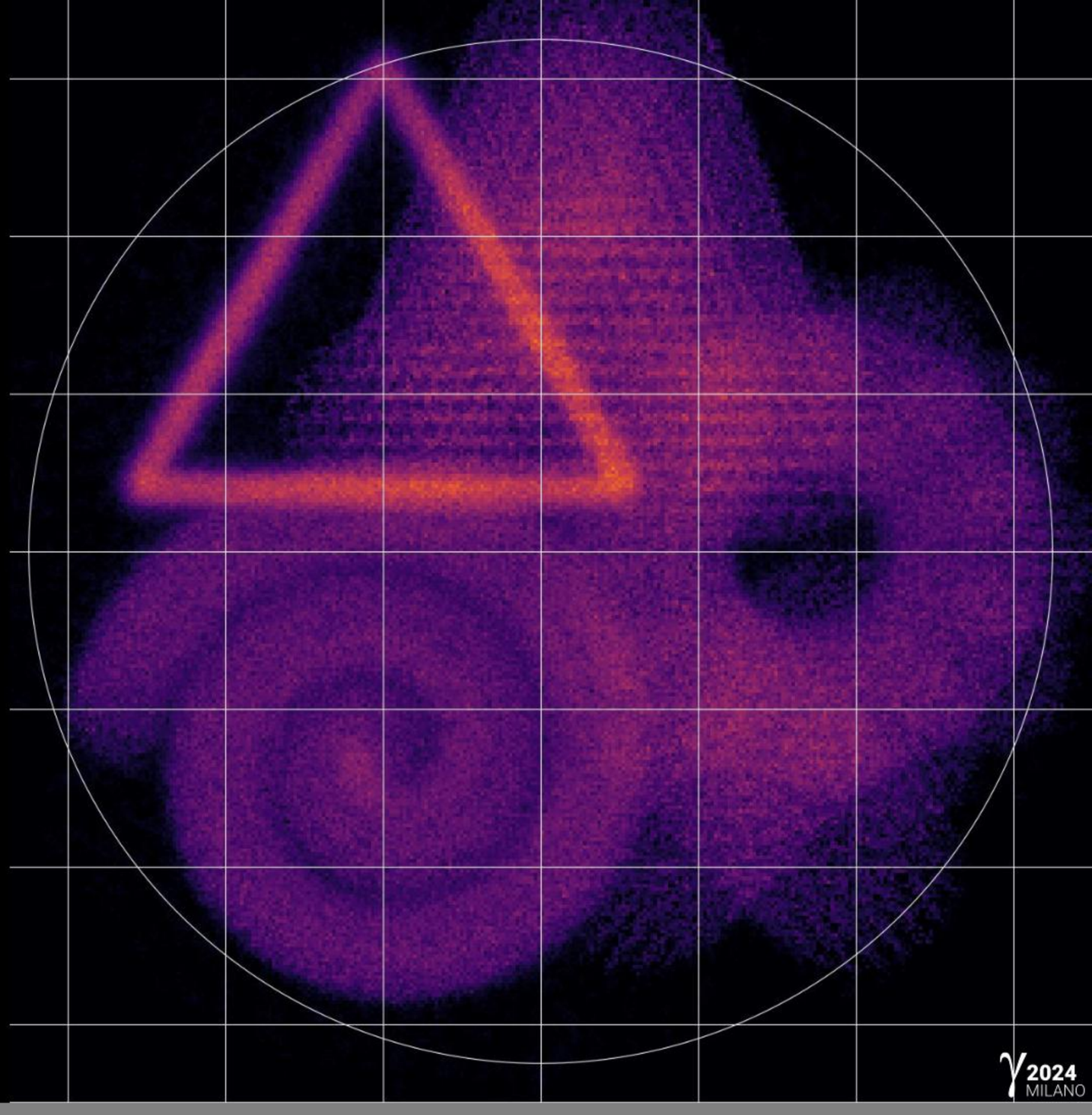
So we project the recordings onto an image with its focus set to two kilometers.

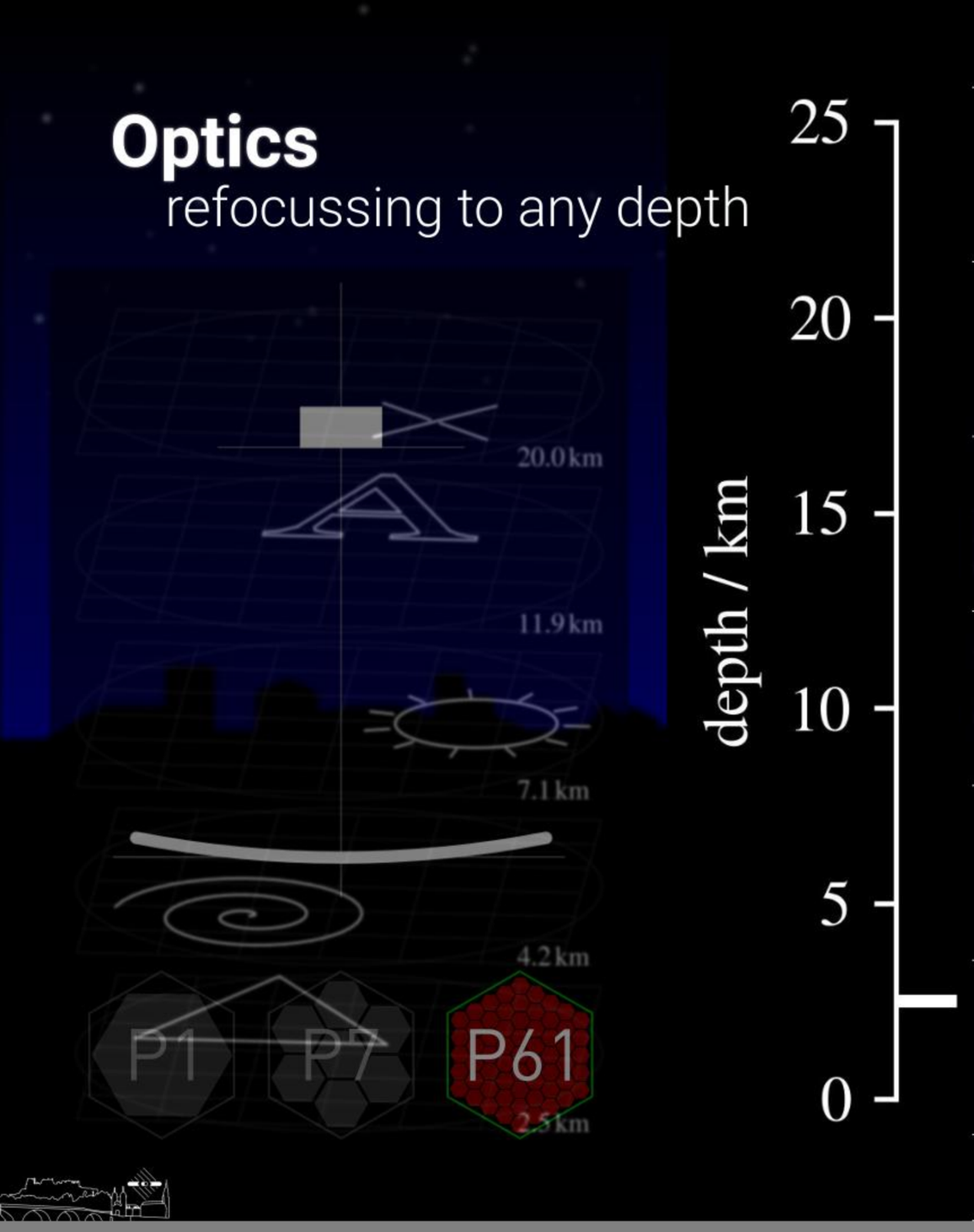
Optics

refocussing to any depth





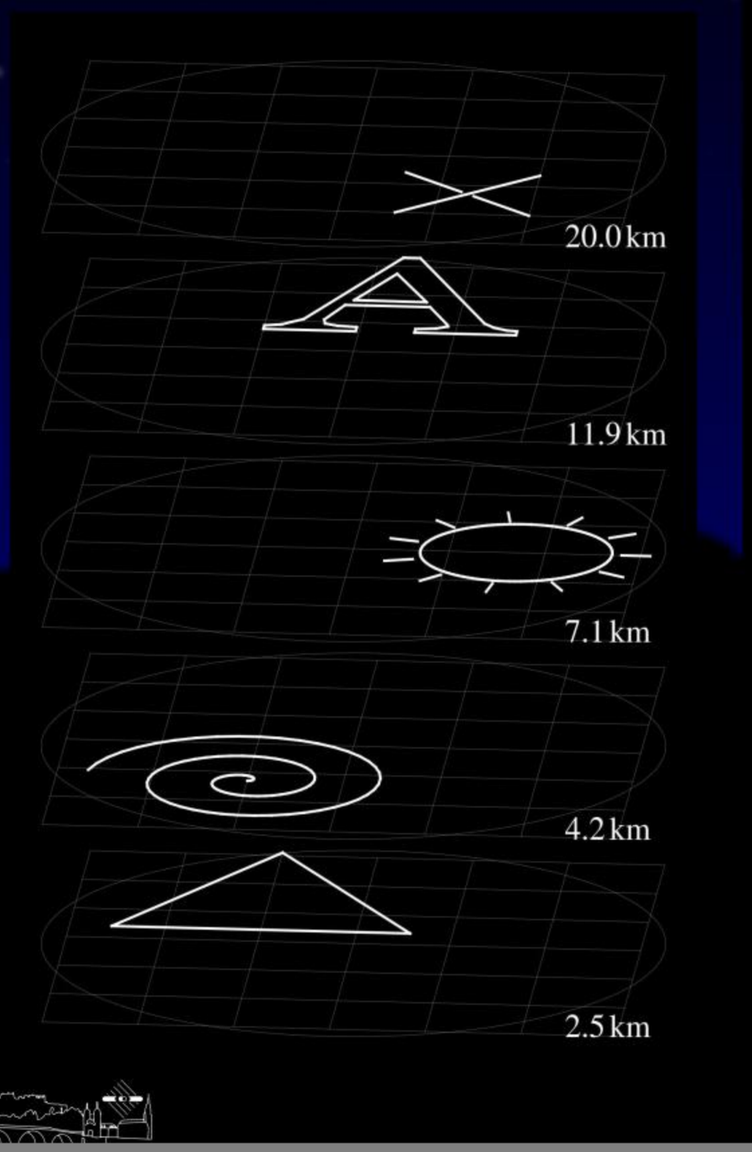


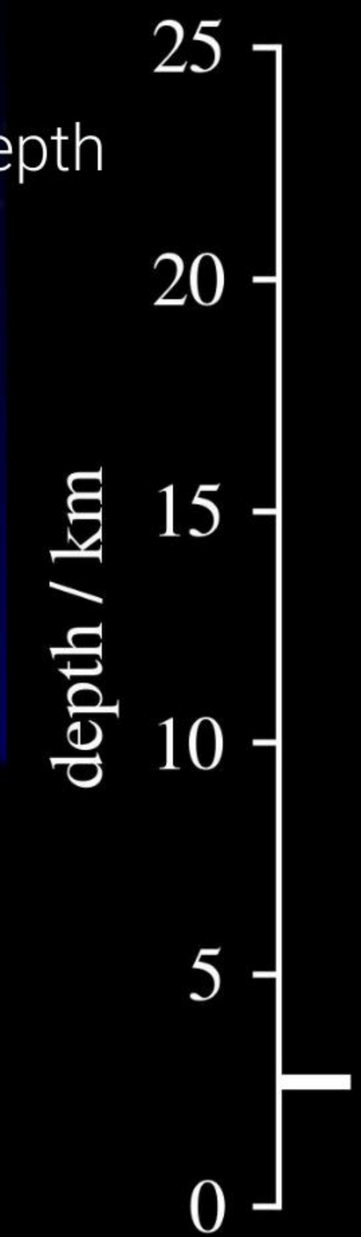


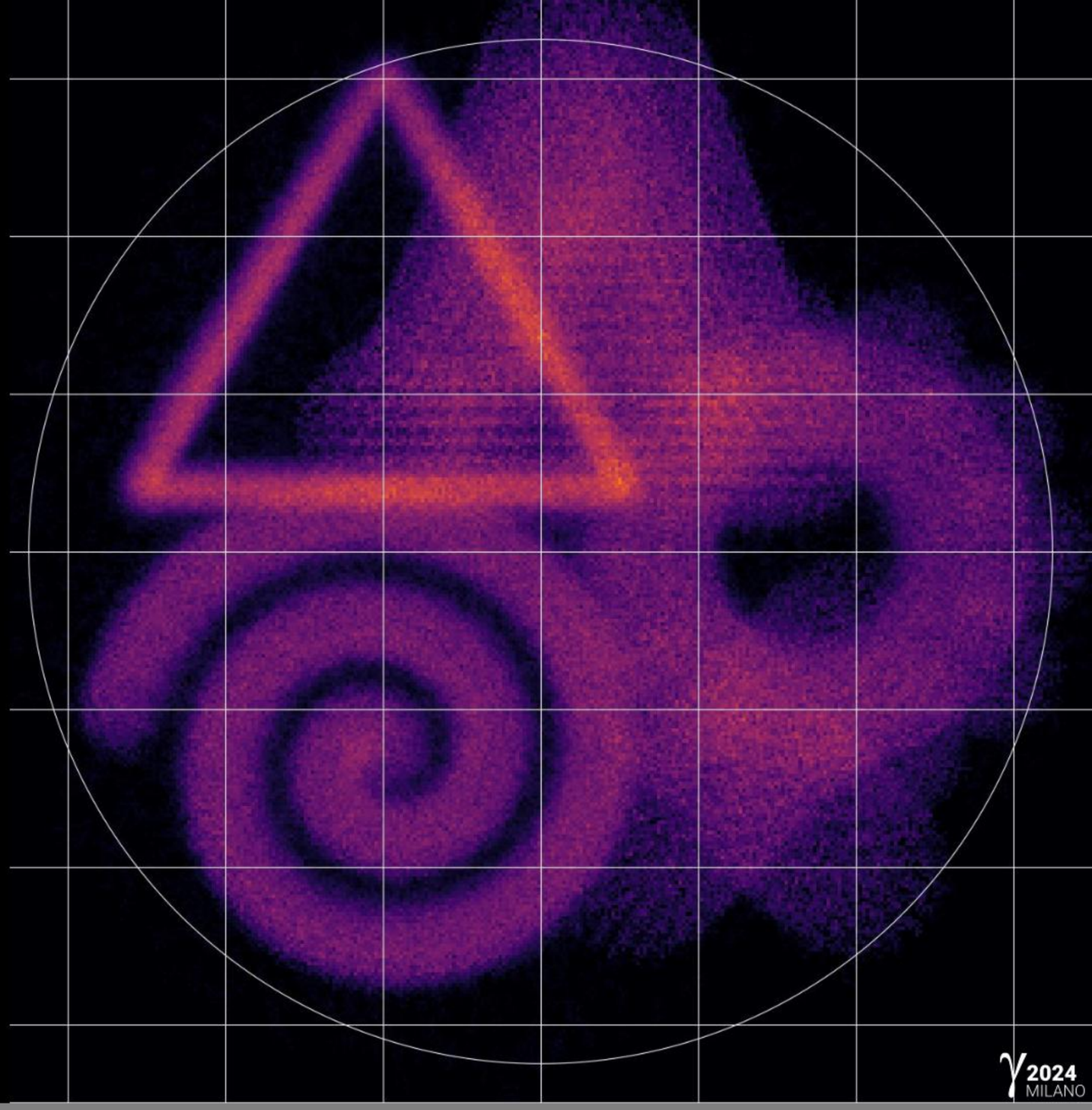
First, we find the triangle at about two to three kilometers. Remeber the triangle, it is going to be important later.

Optics

refocussing to any depth

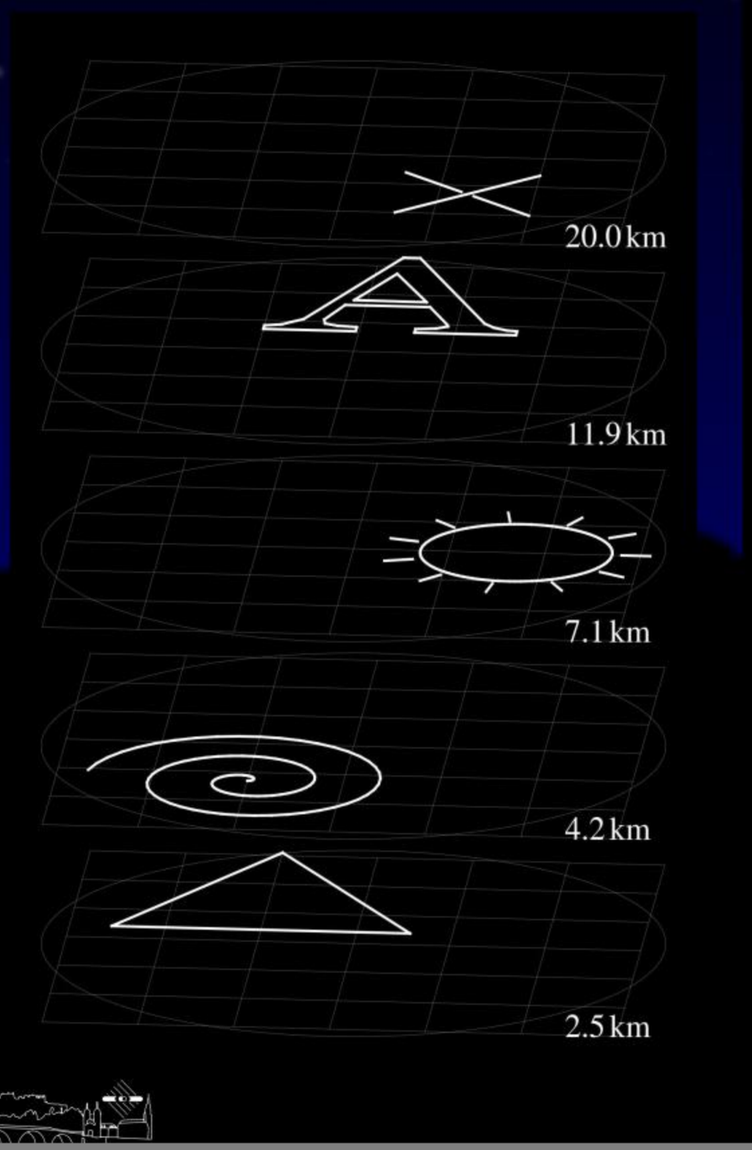


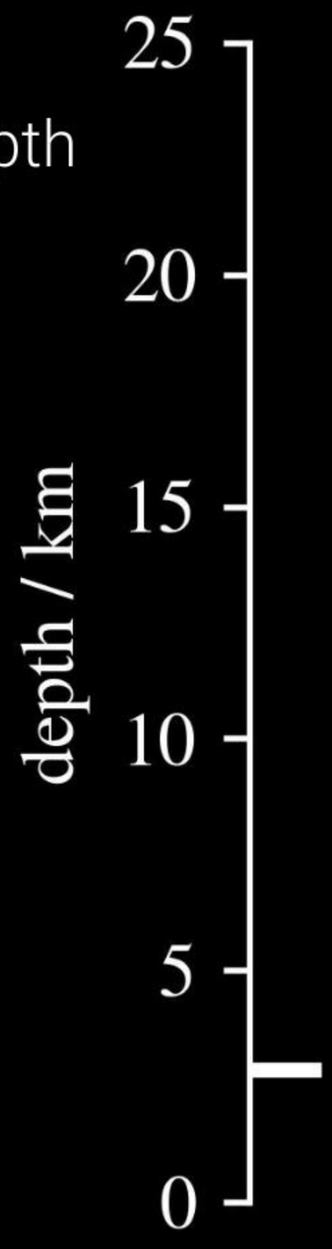


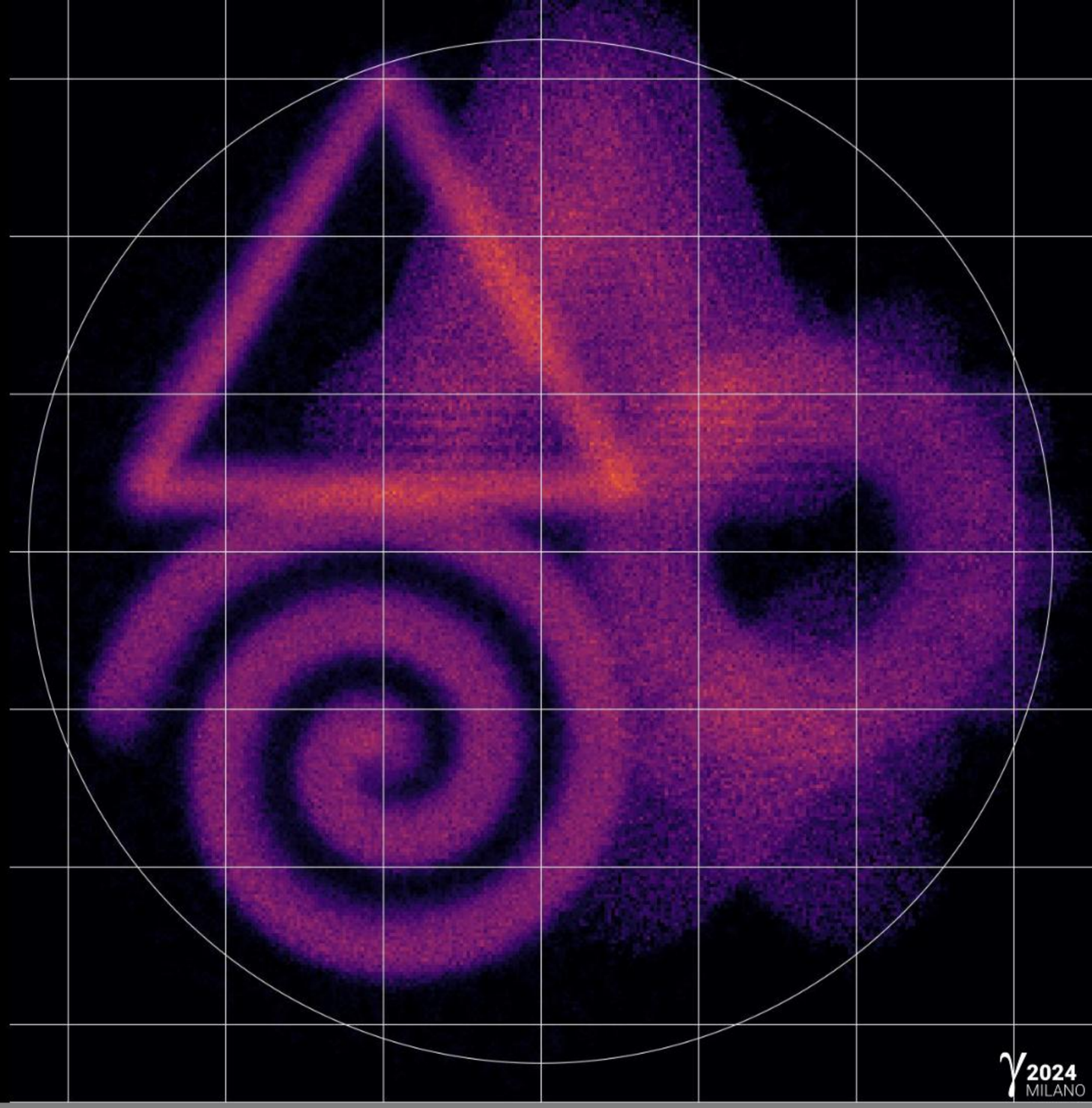


Optics

refocussing to any depth

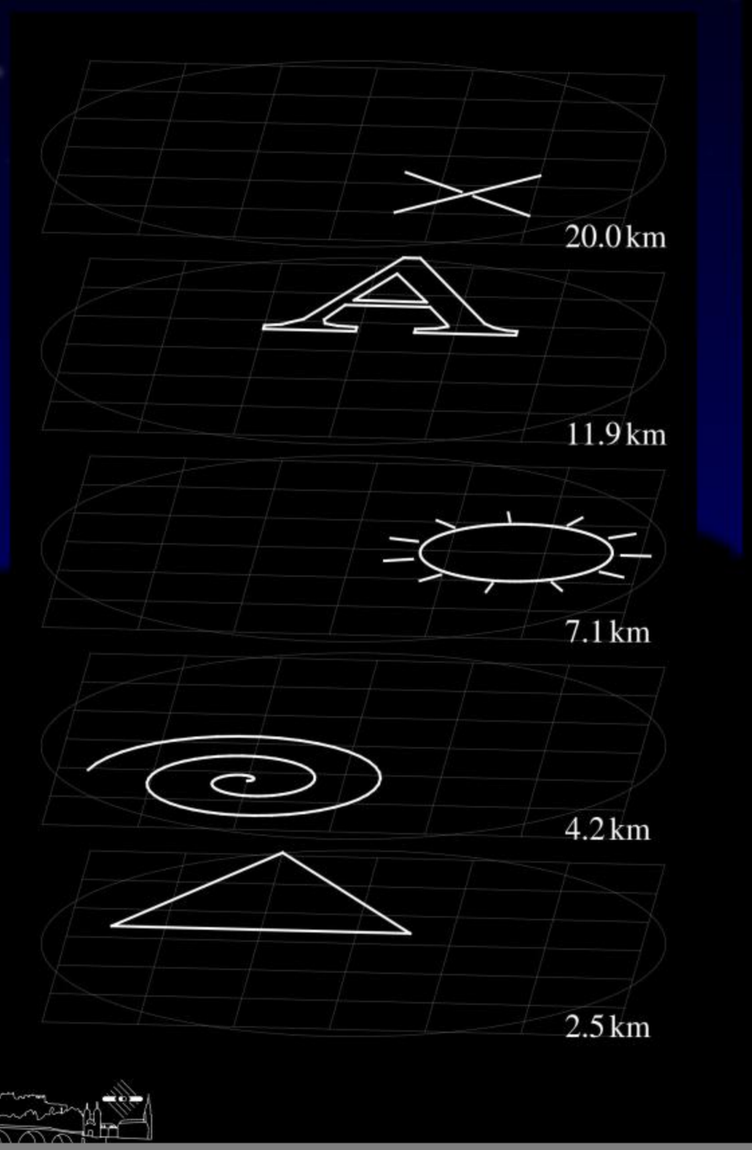


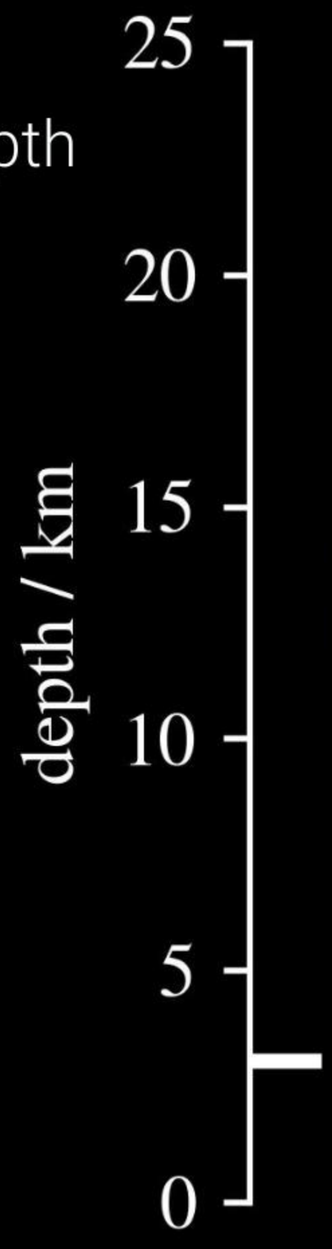


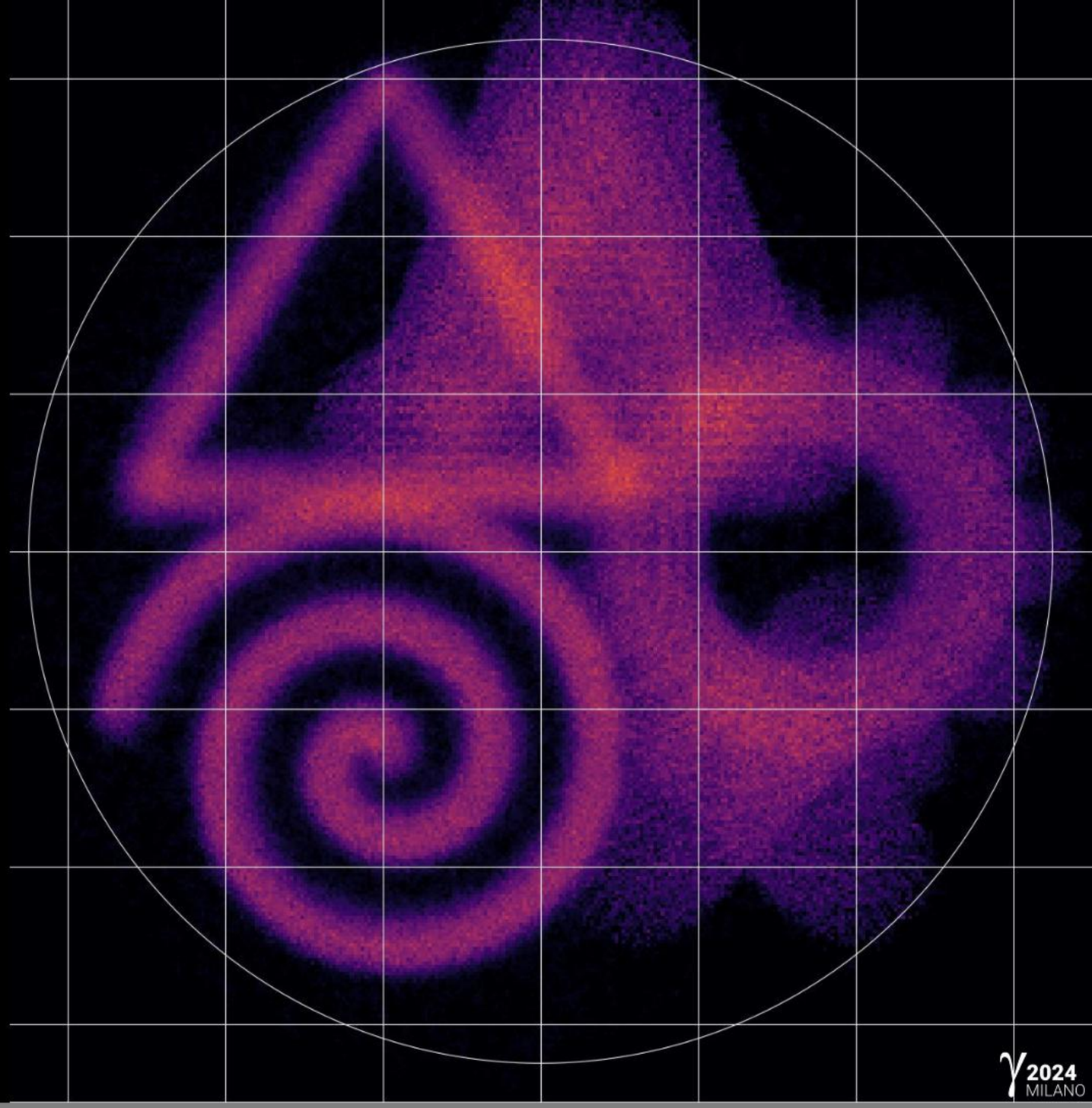


Optics

refocussing to any depth

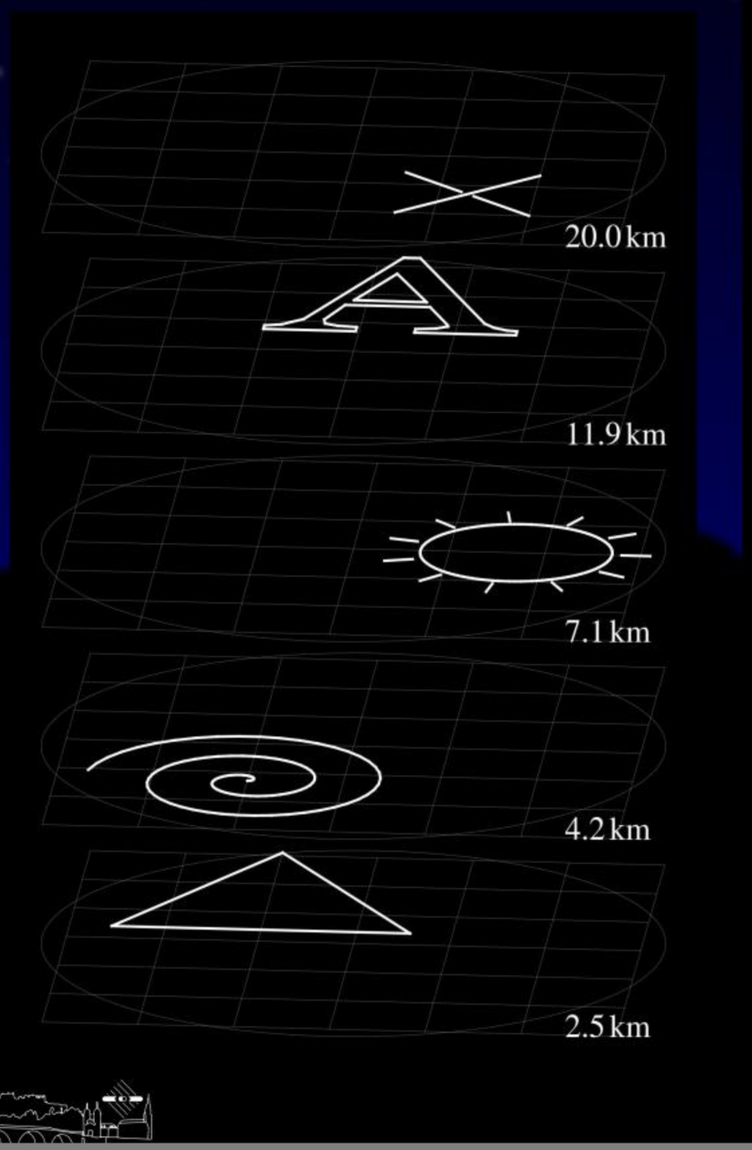


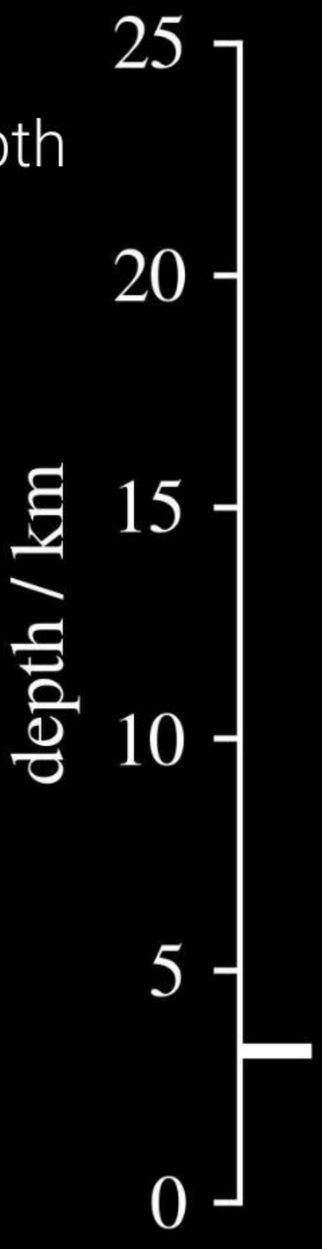


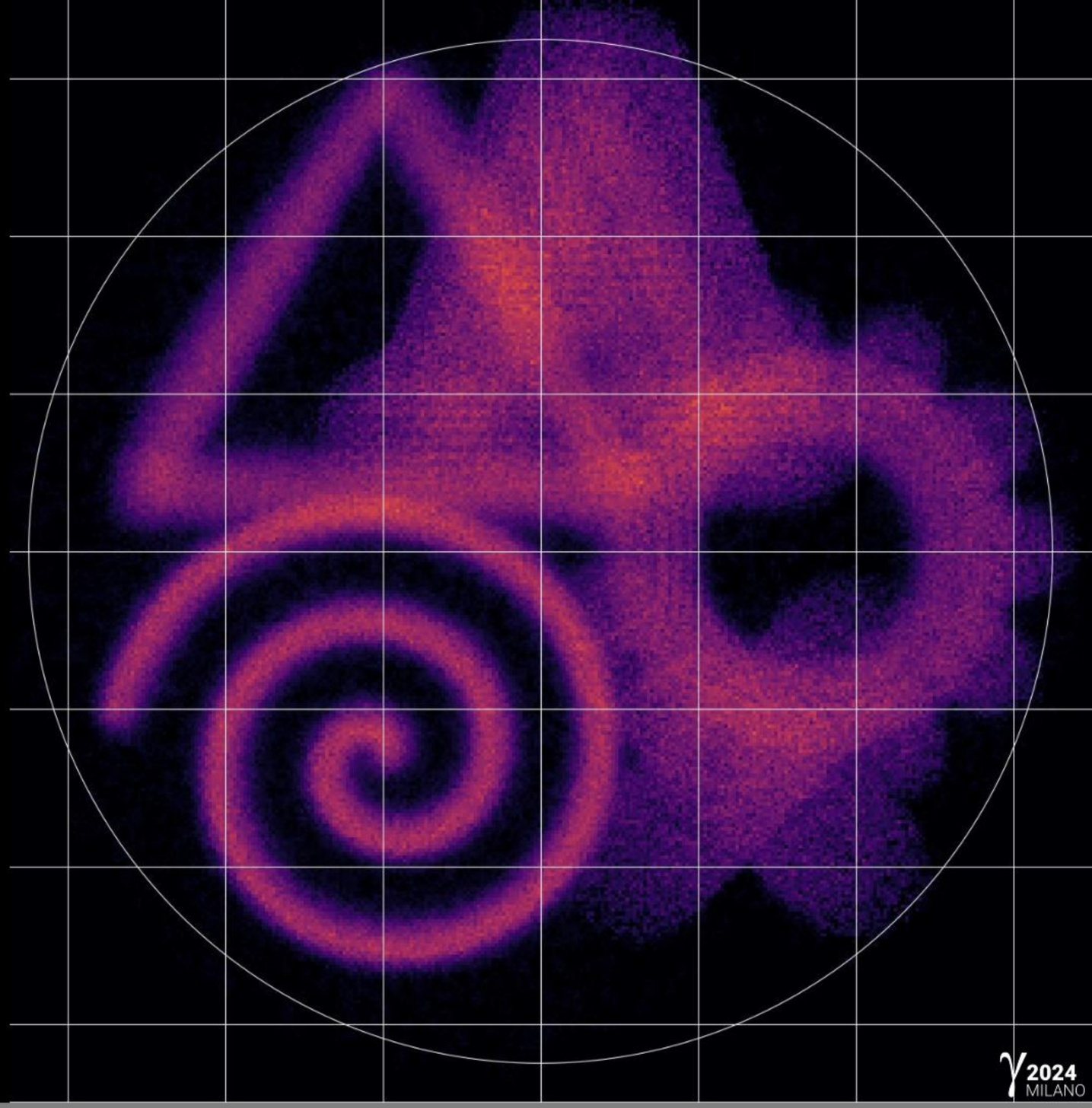


Optics

refocussing to any depth

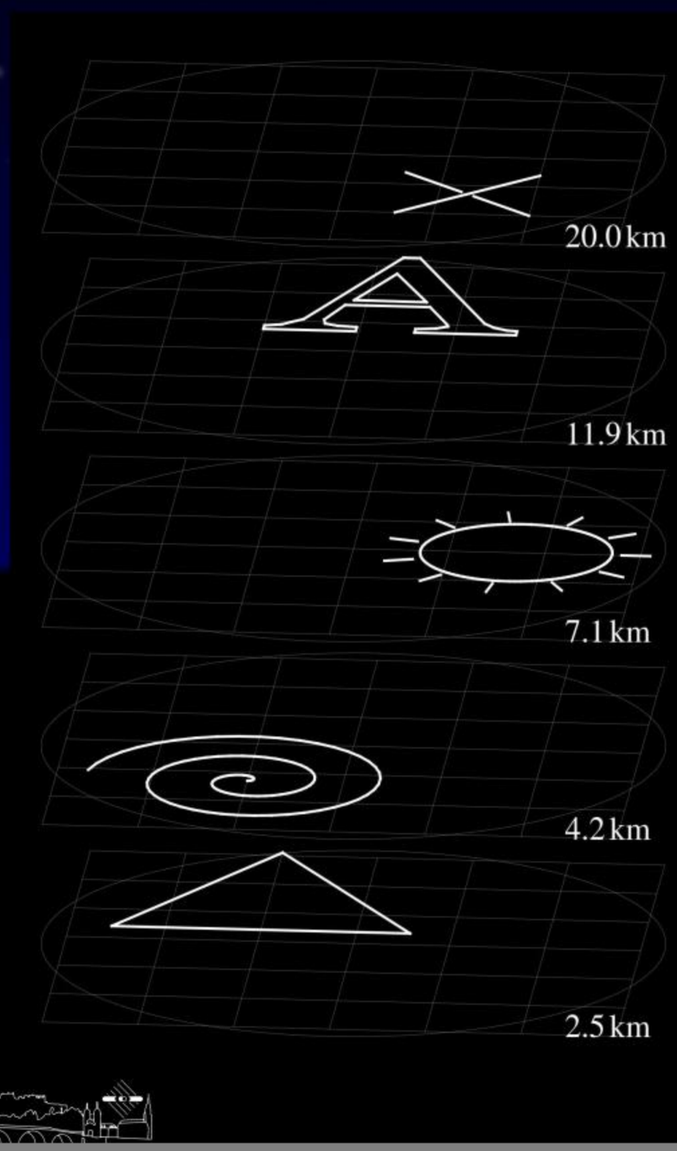


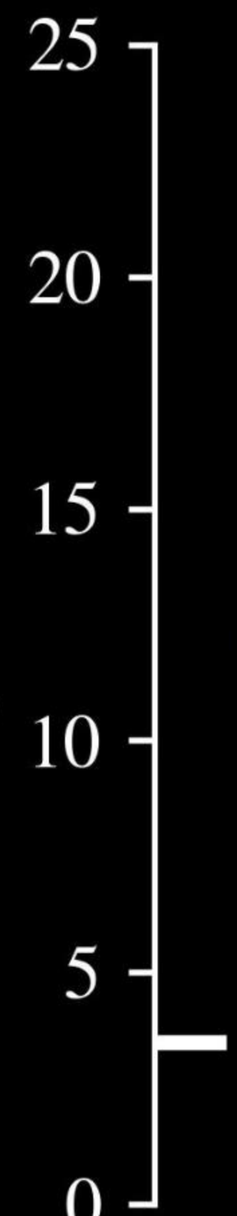


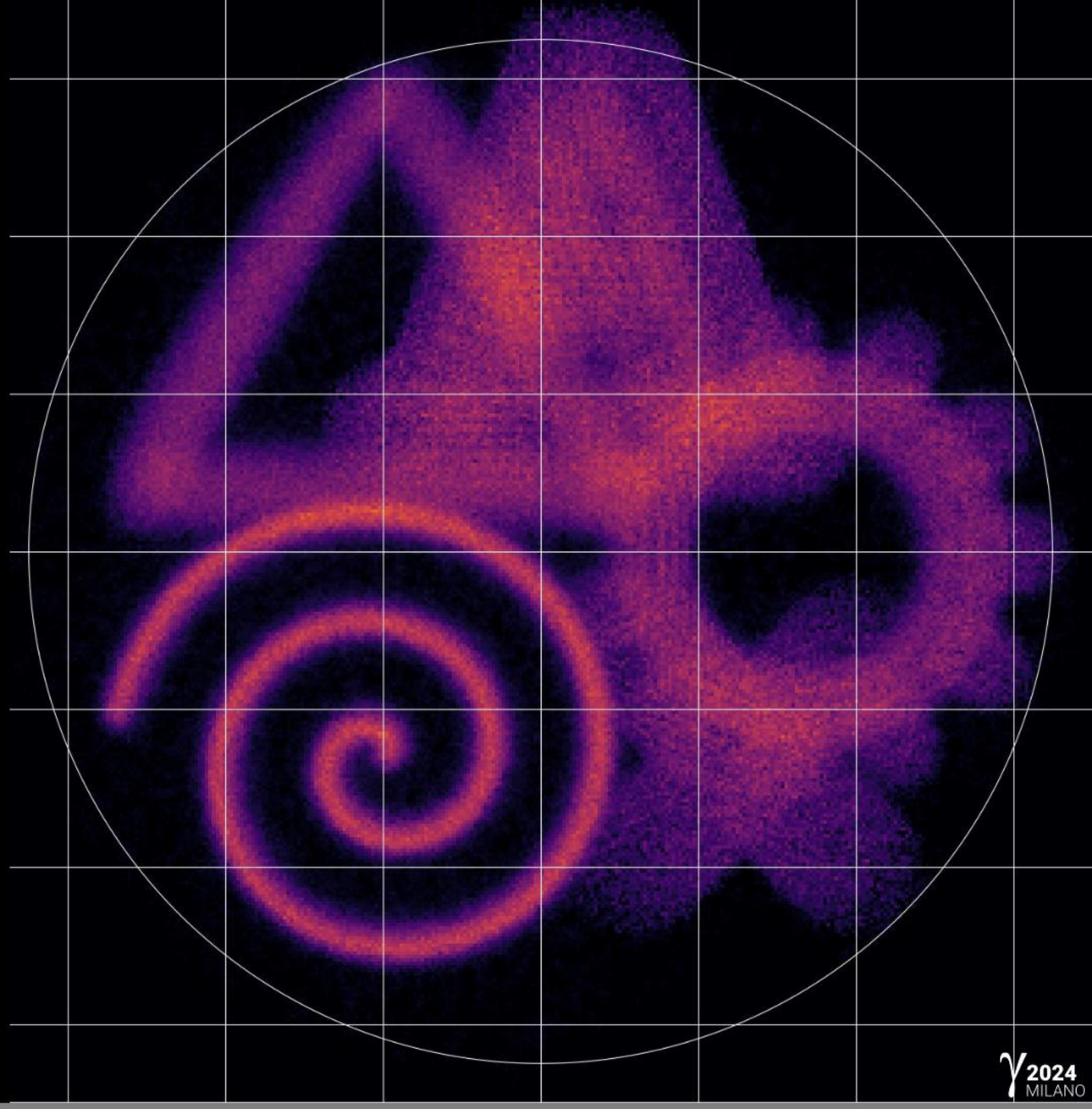


Optics

refocussing to any depth

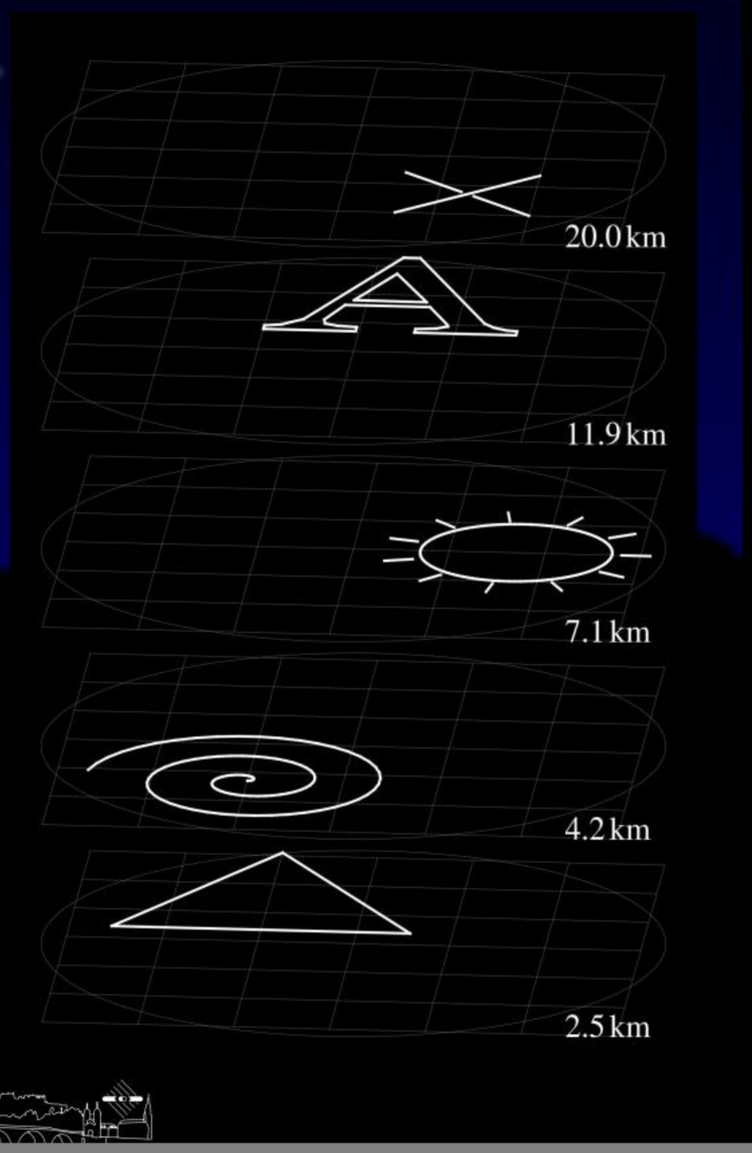


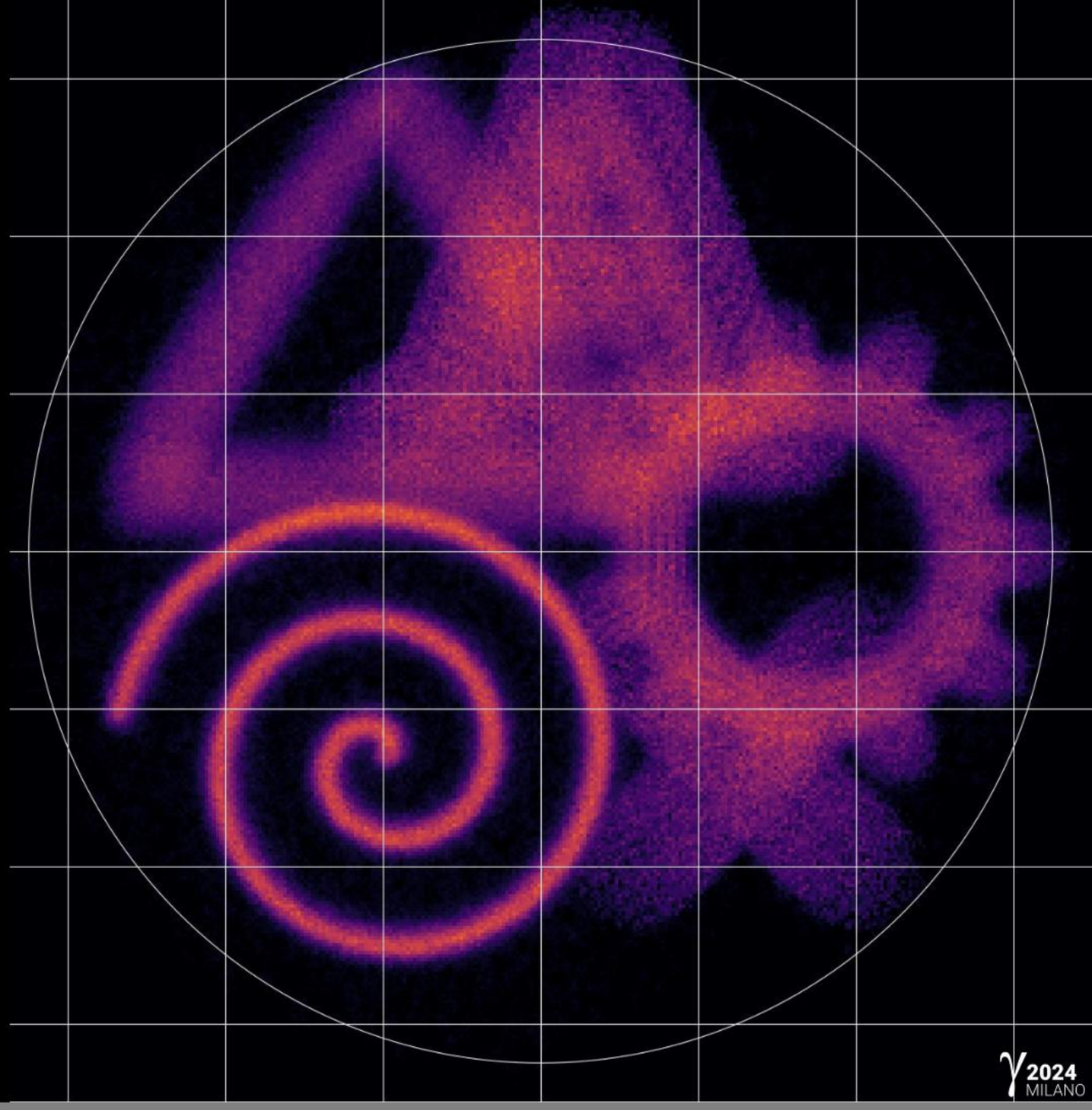




Optics

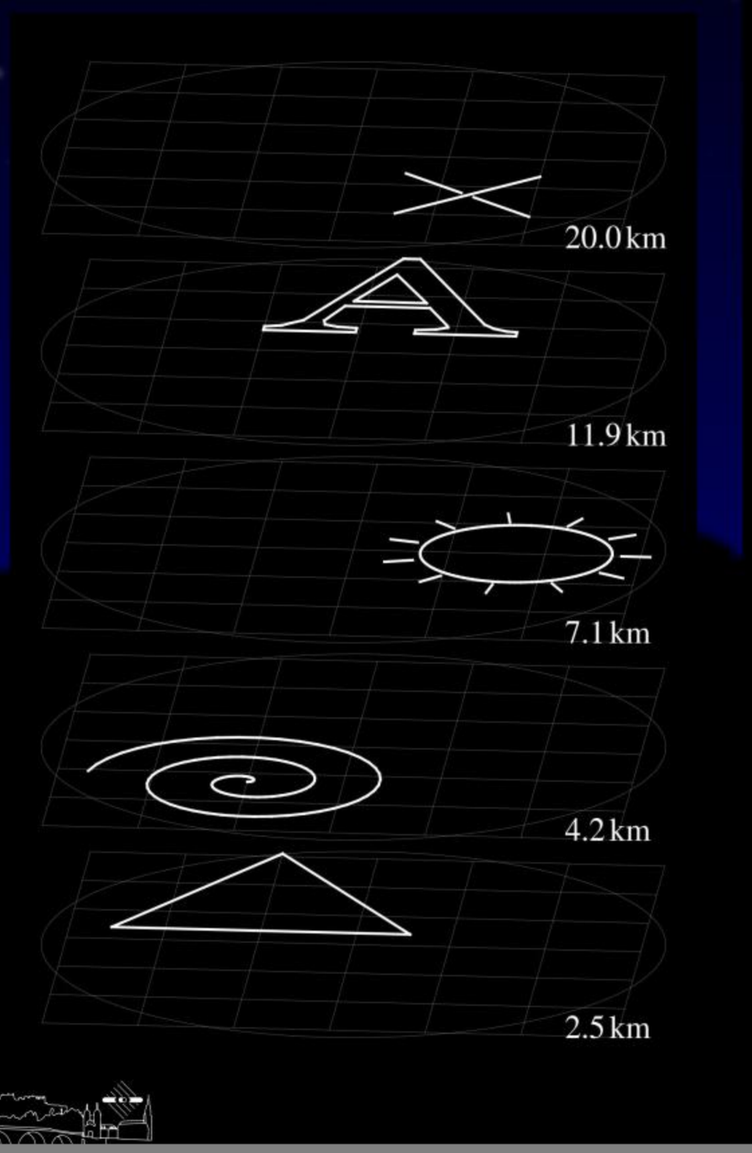
refocussing to any depth

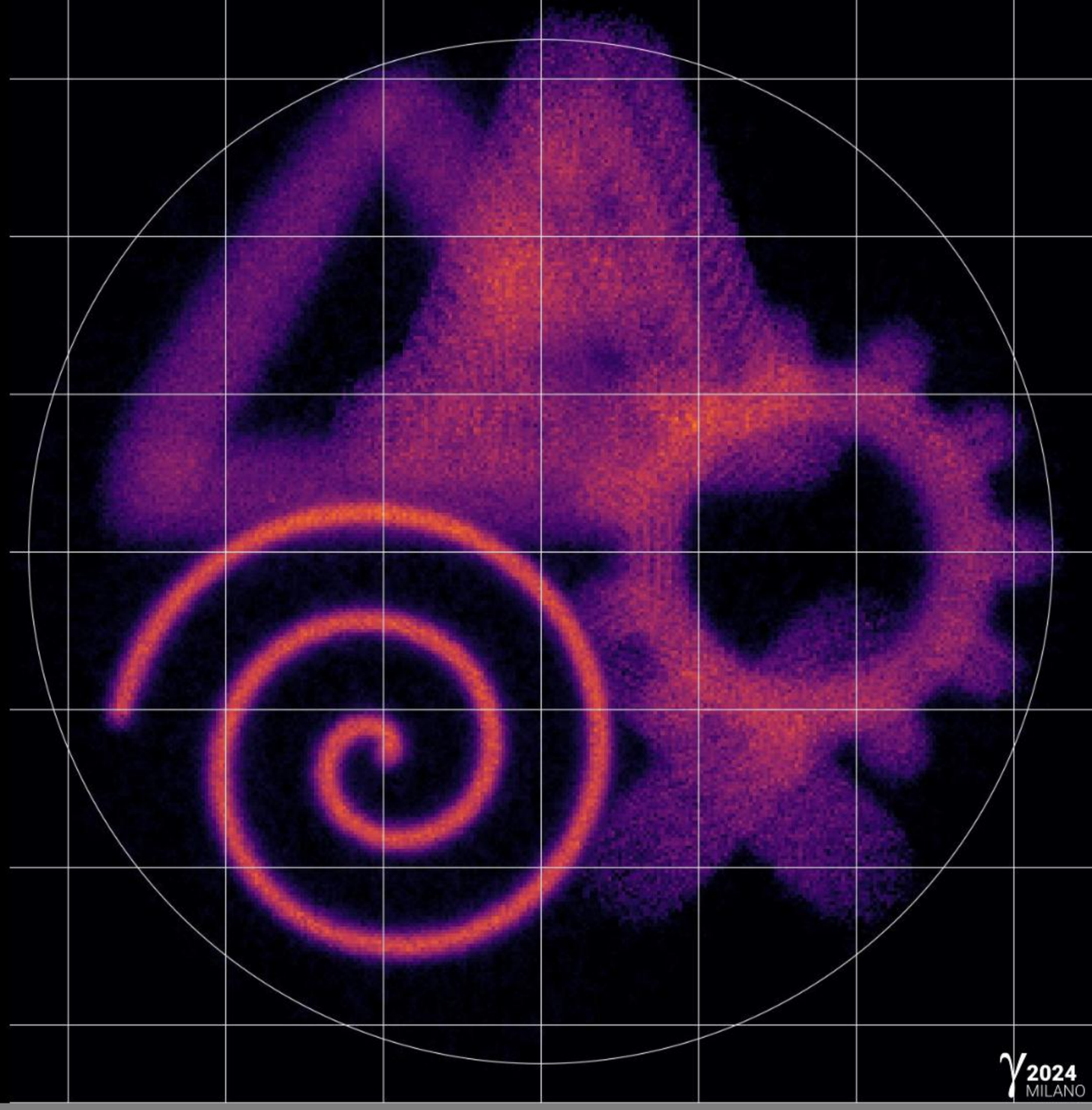


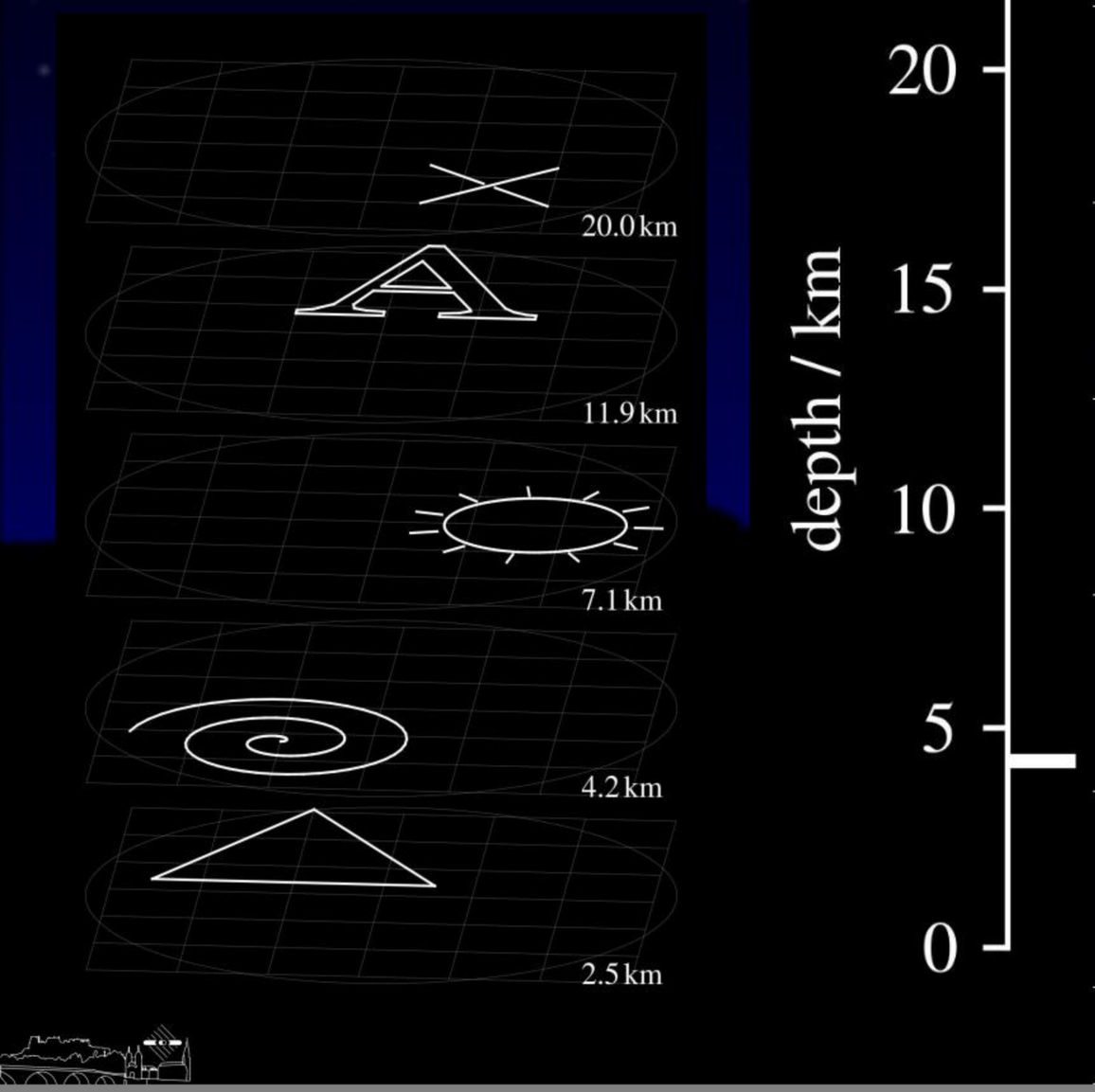


Optics

refocussing to any depth



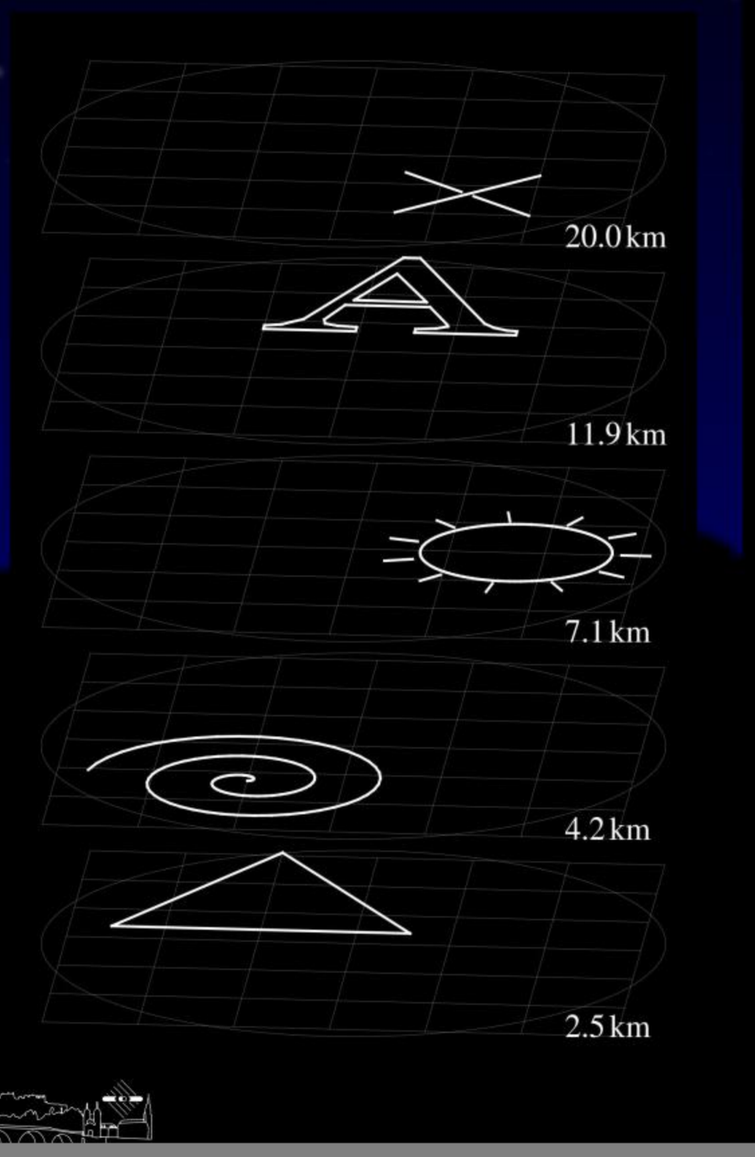


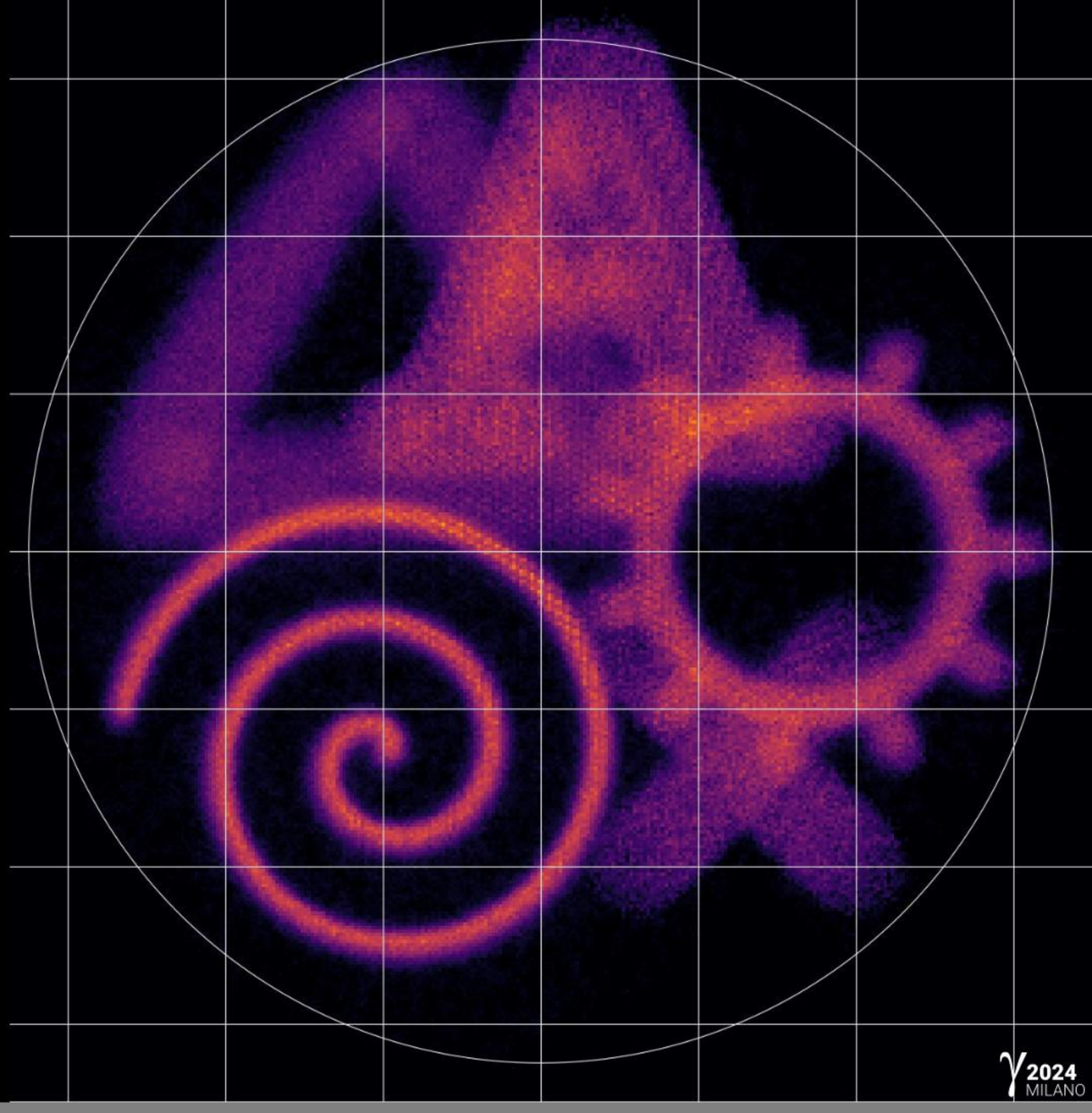


At about four kilometers, we find the spiral to be sharpest. Note how flat the image is. The spiral looks sharp over the entire field-of-view.

Optics

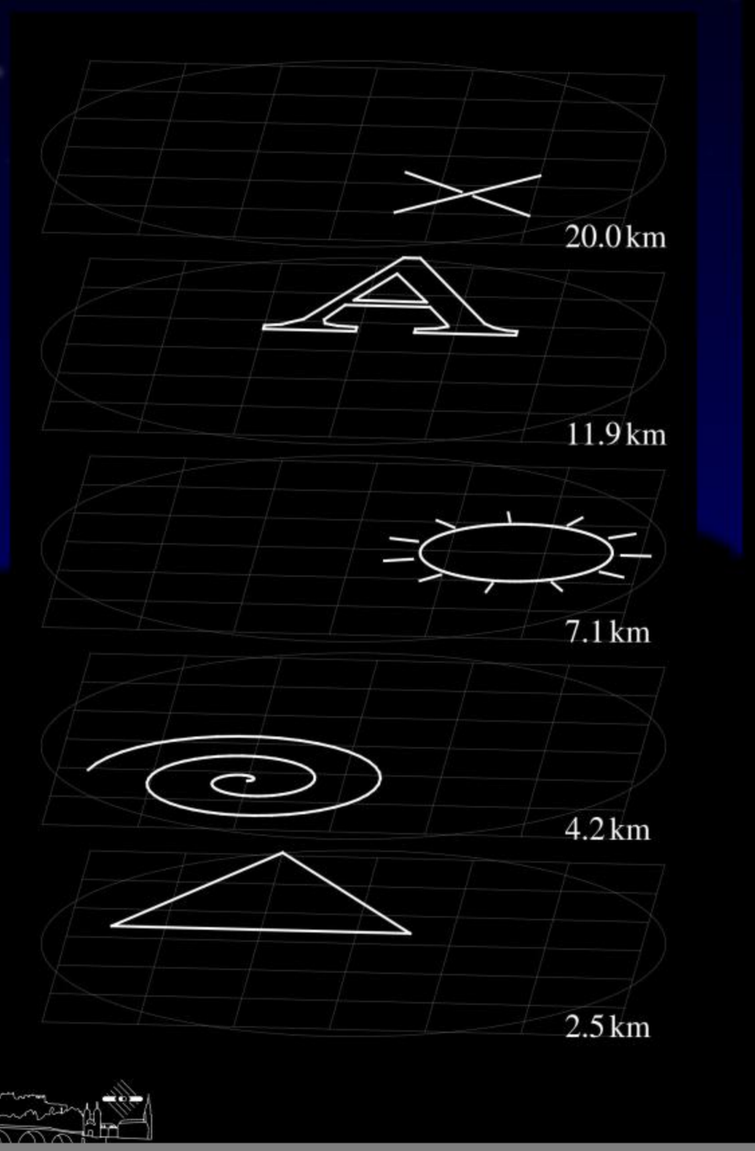
refocussing to any depth

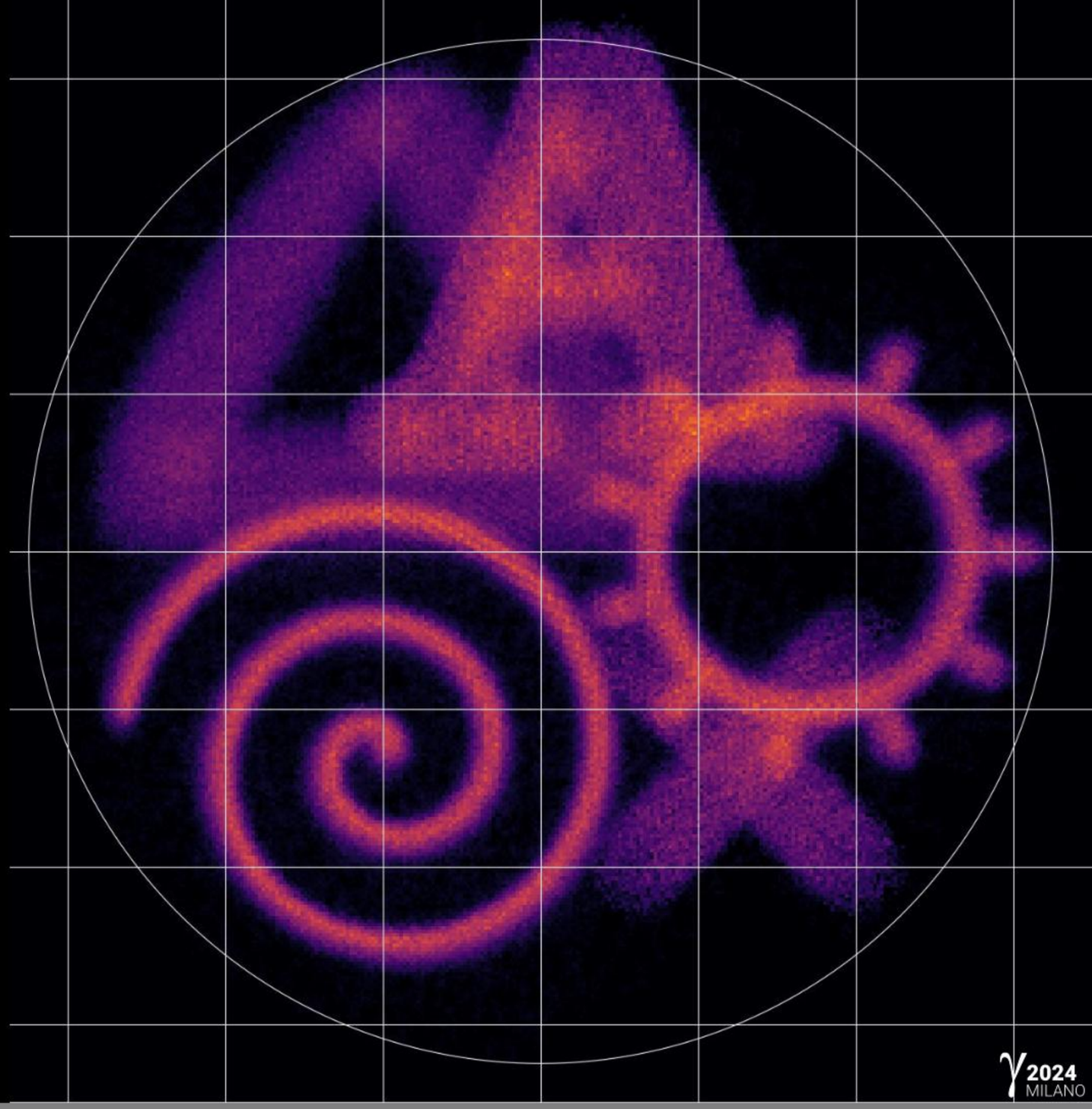




Optics

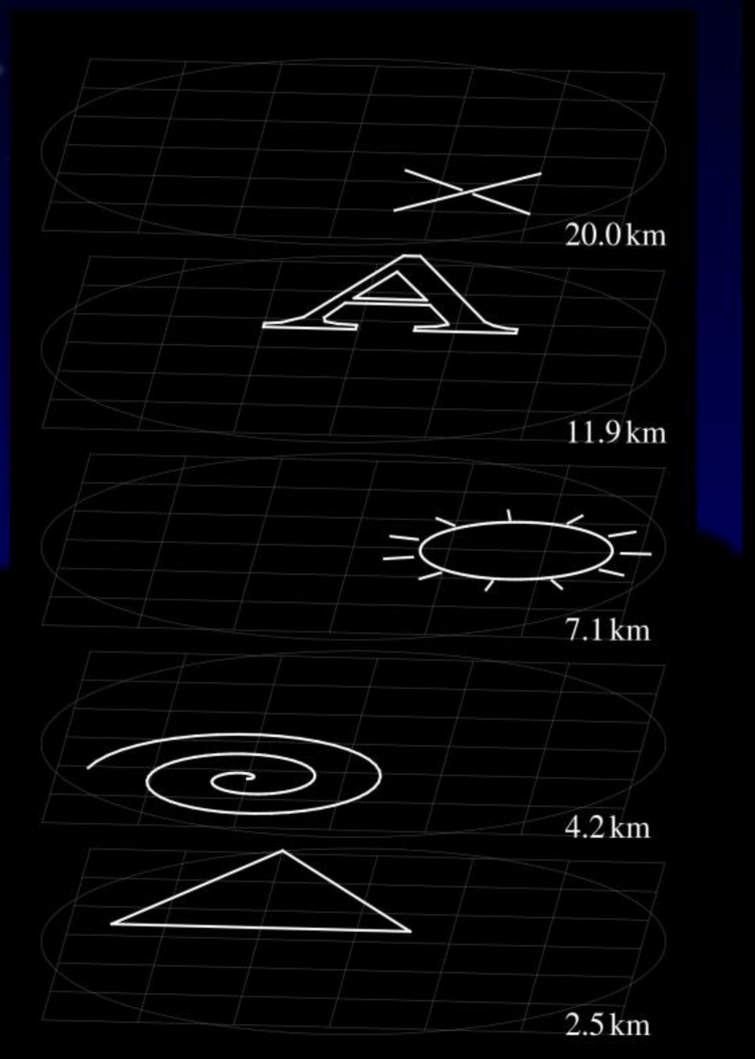
refocussing to any depth

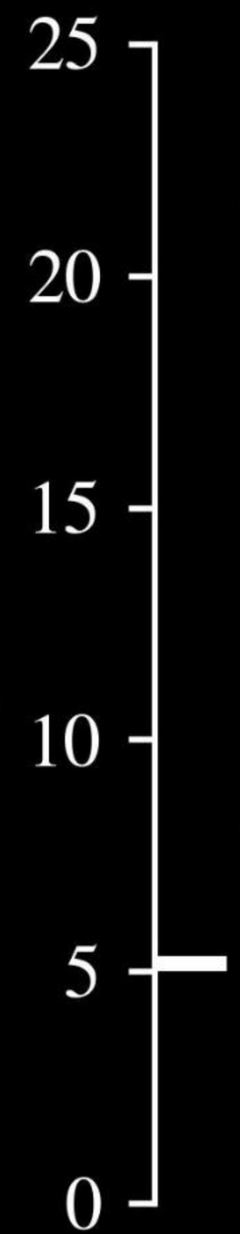


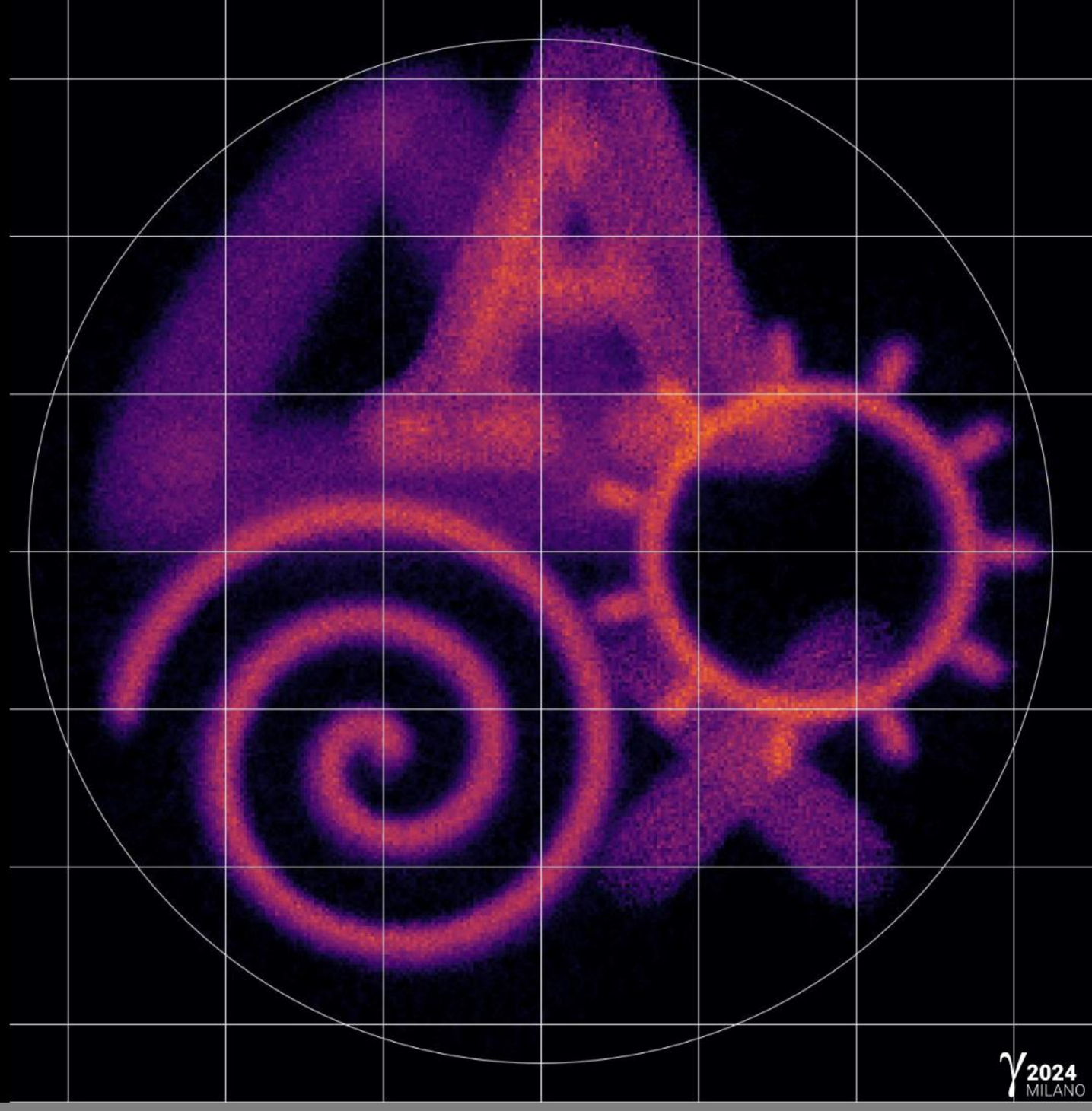


Optics

refocussing to any depth

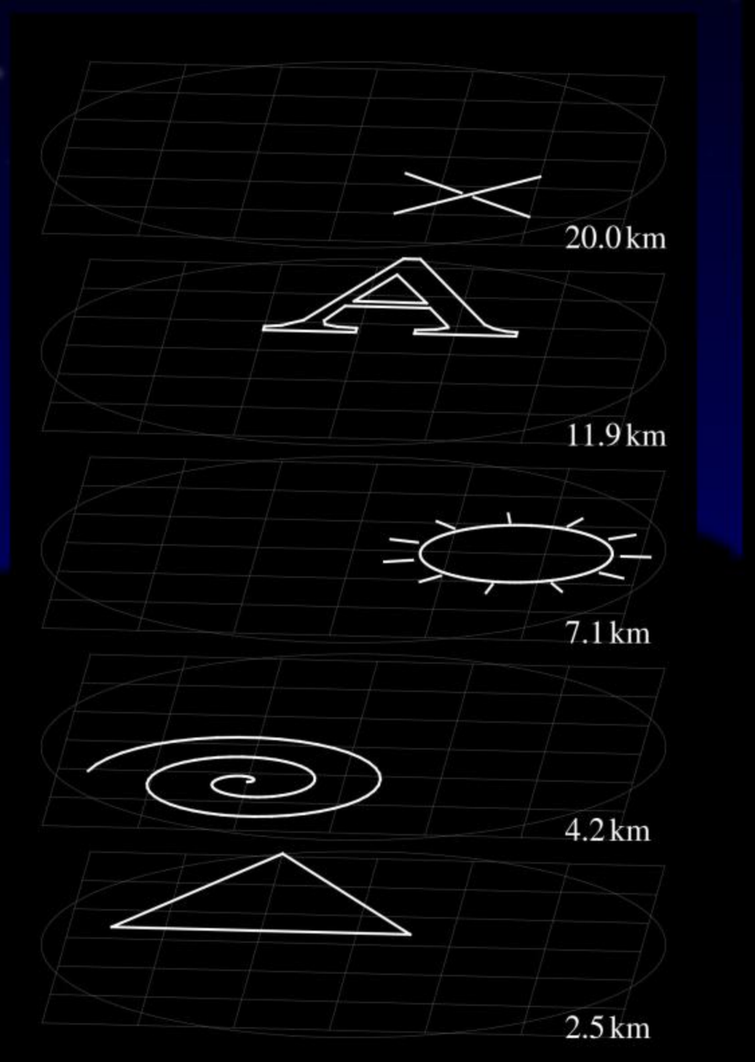


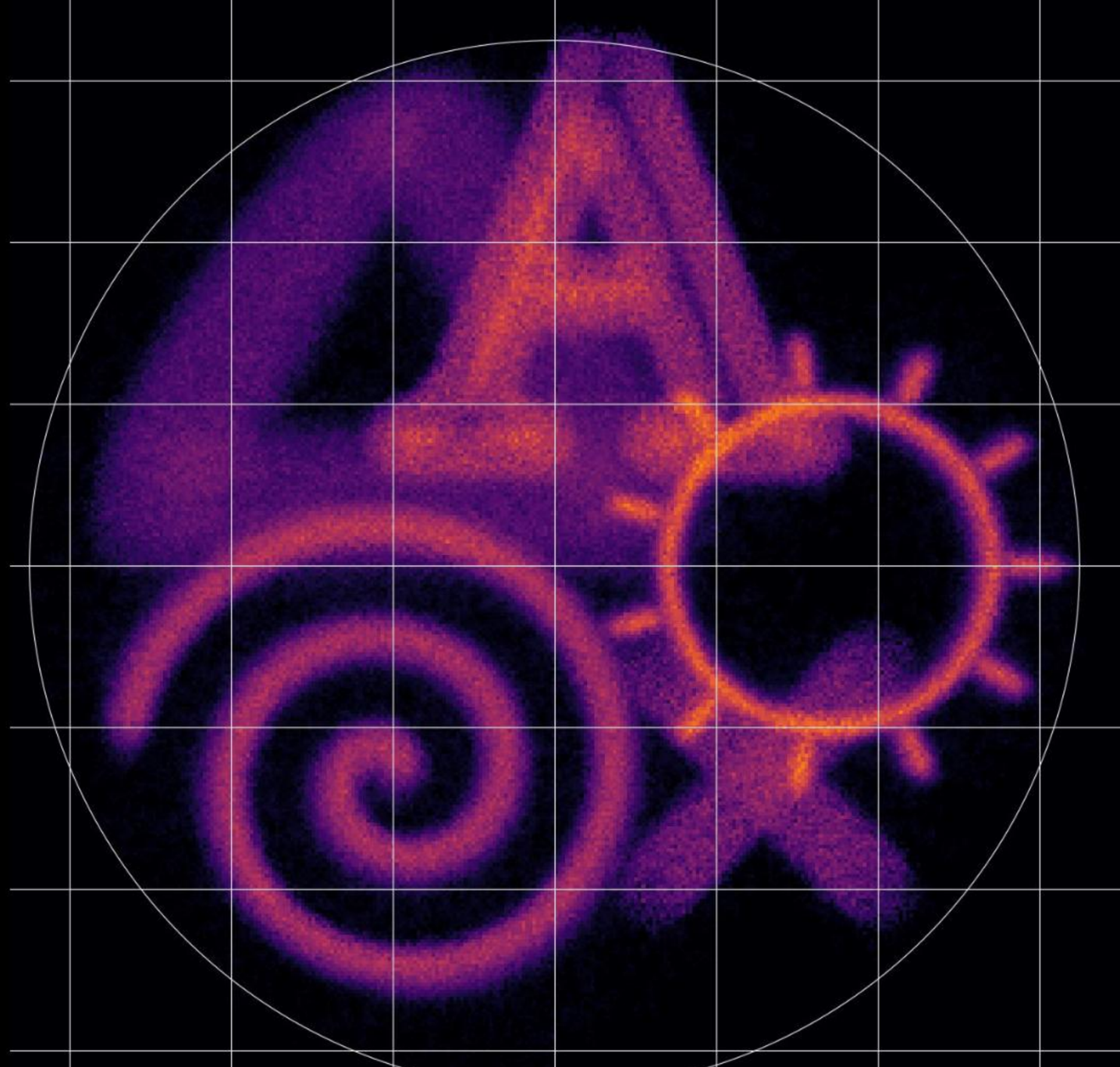




Optics

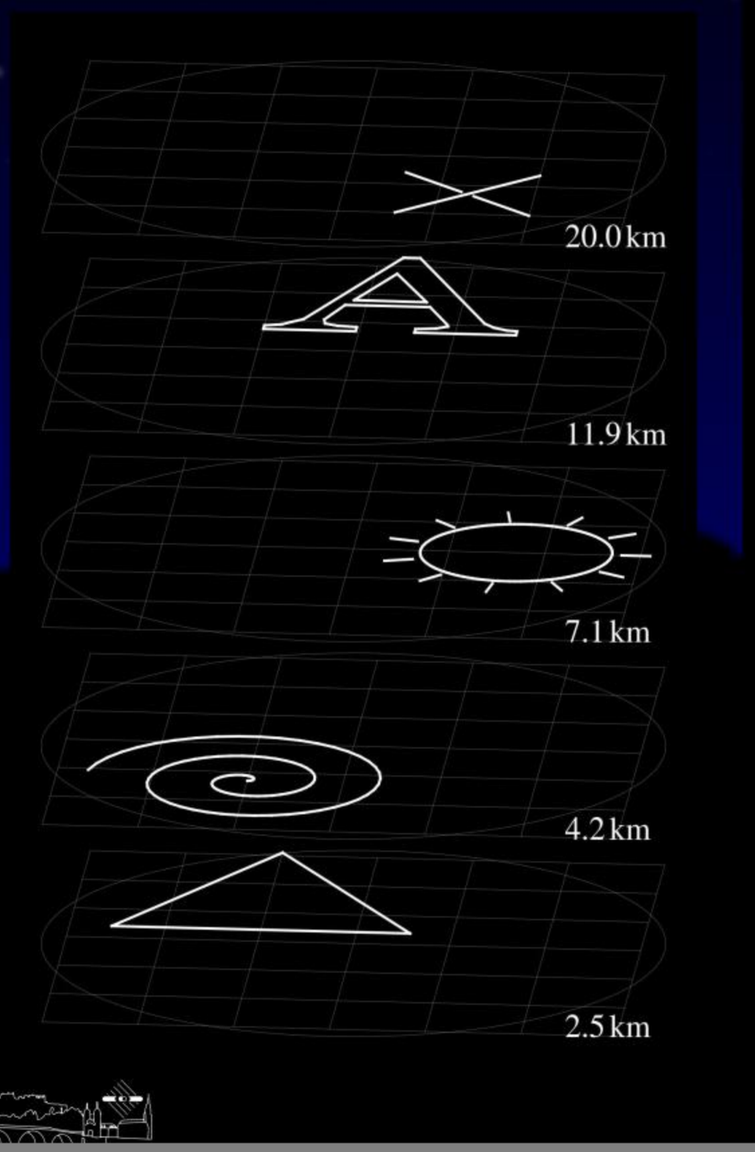
refocussing to any depth

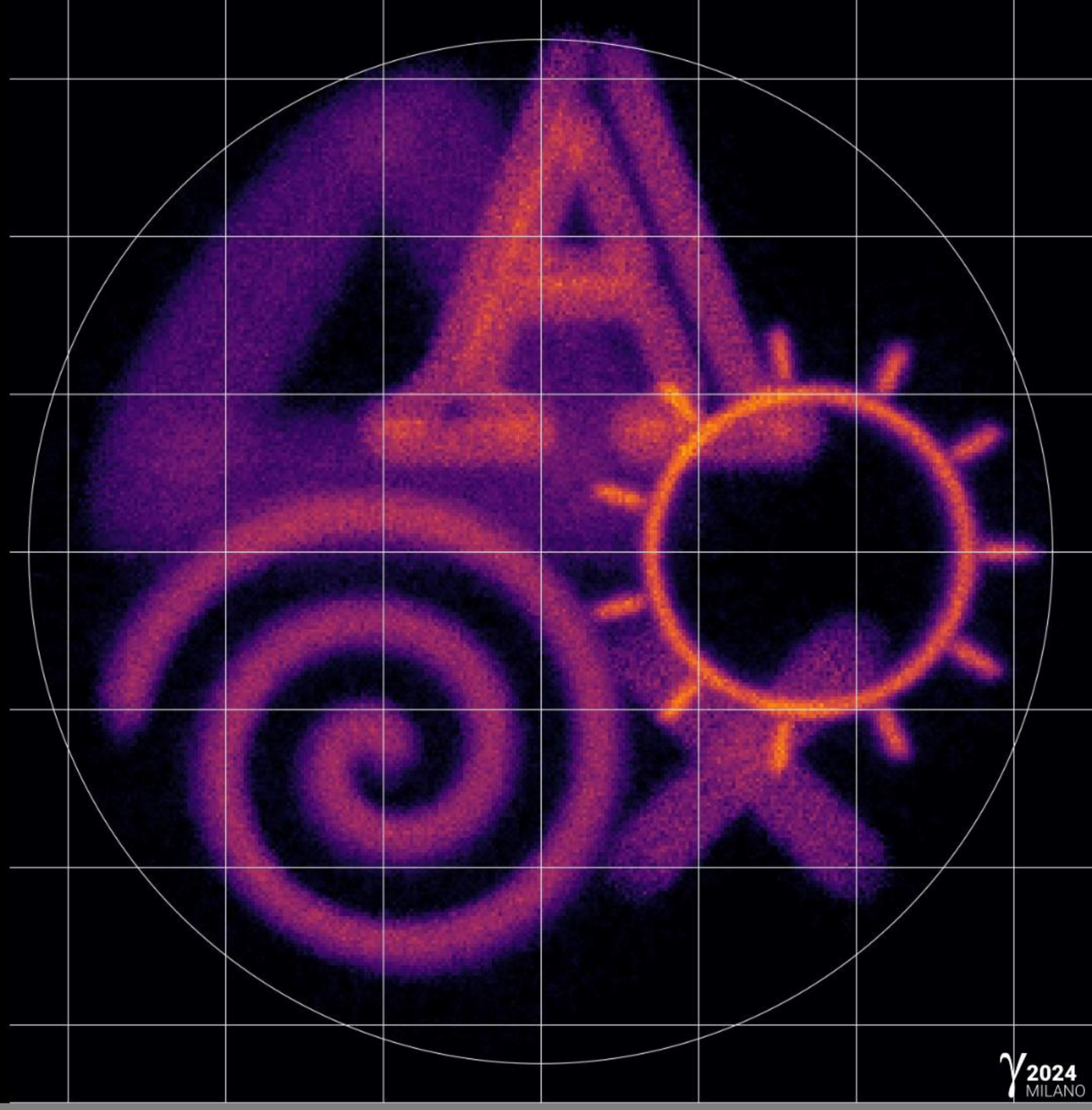




Optics

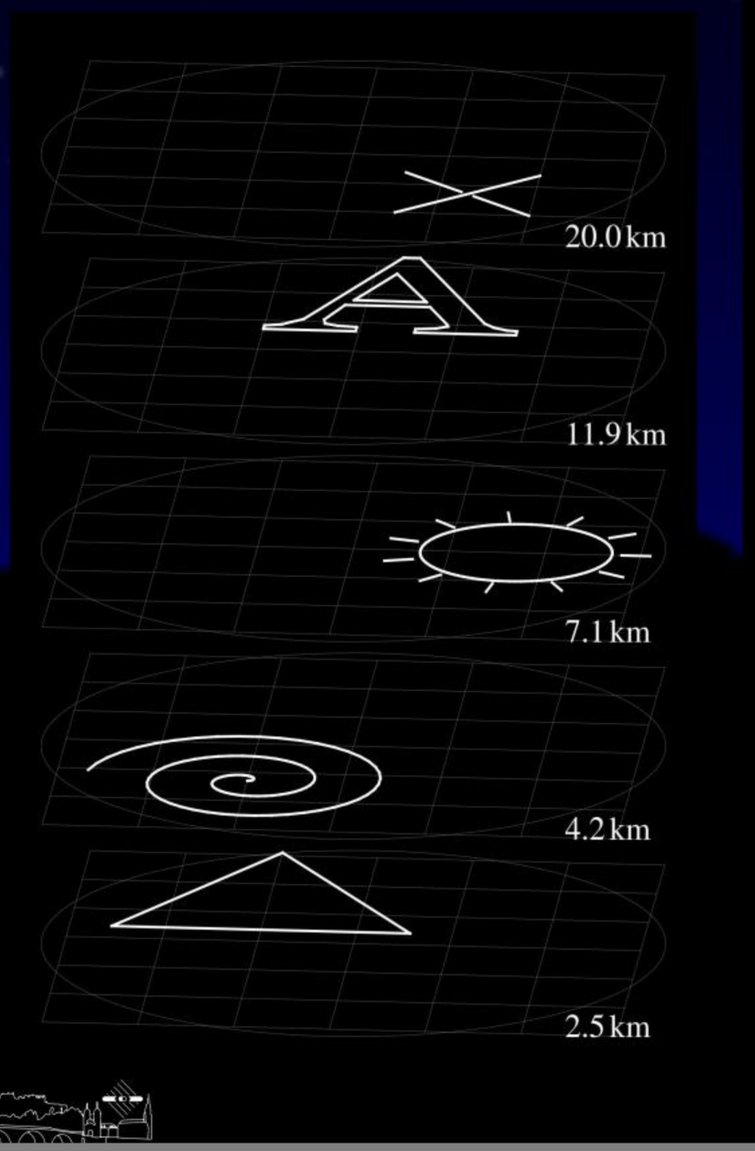
refocussing to any depth

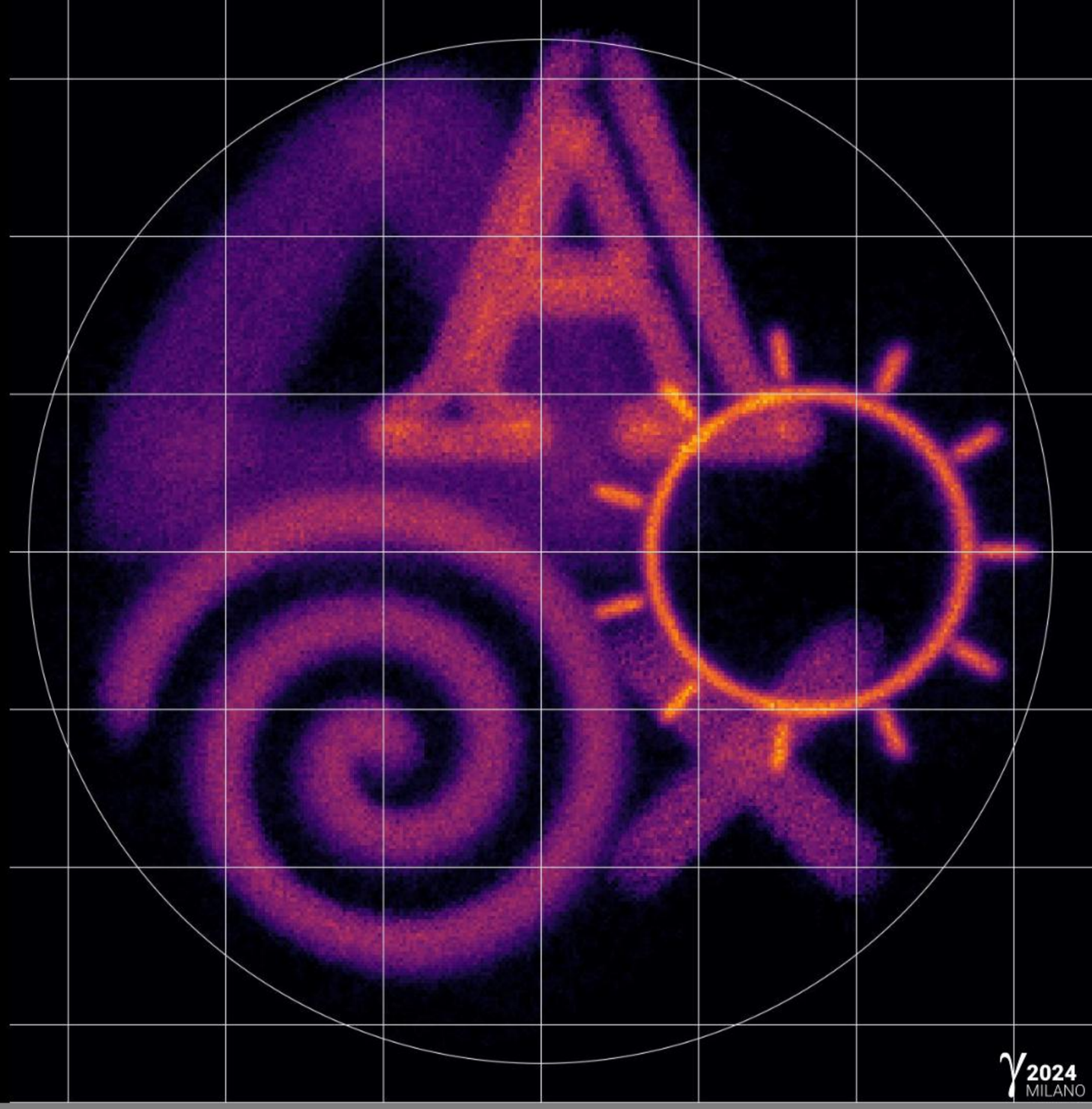




Optics

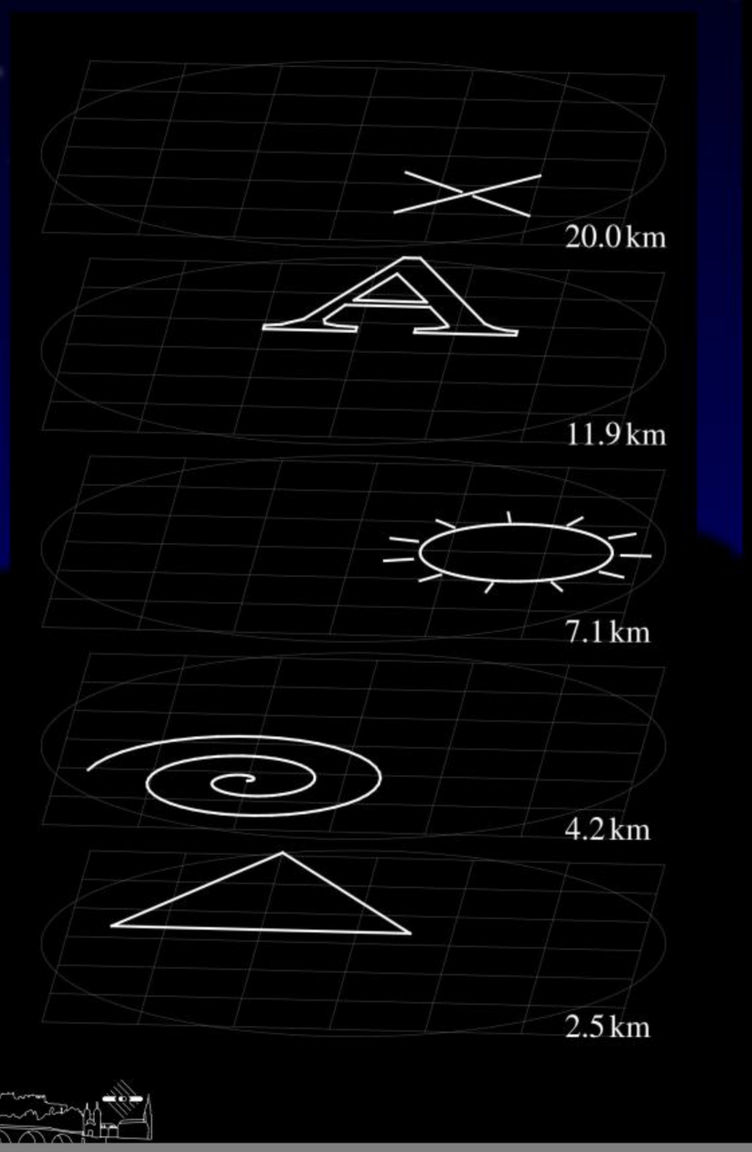
refocussing to any depth

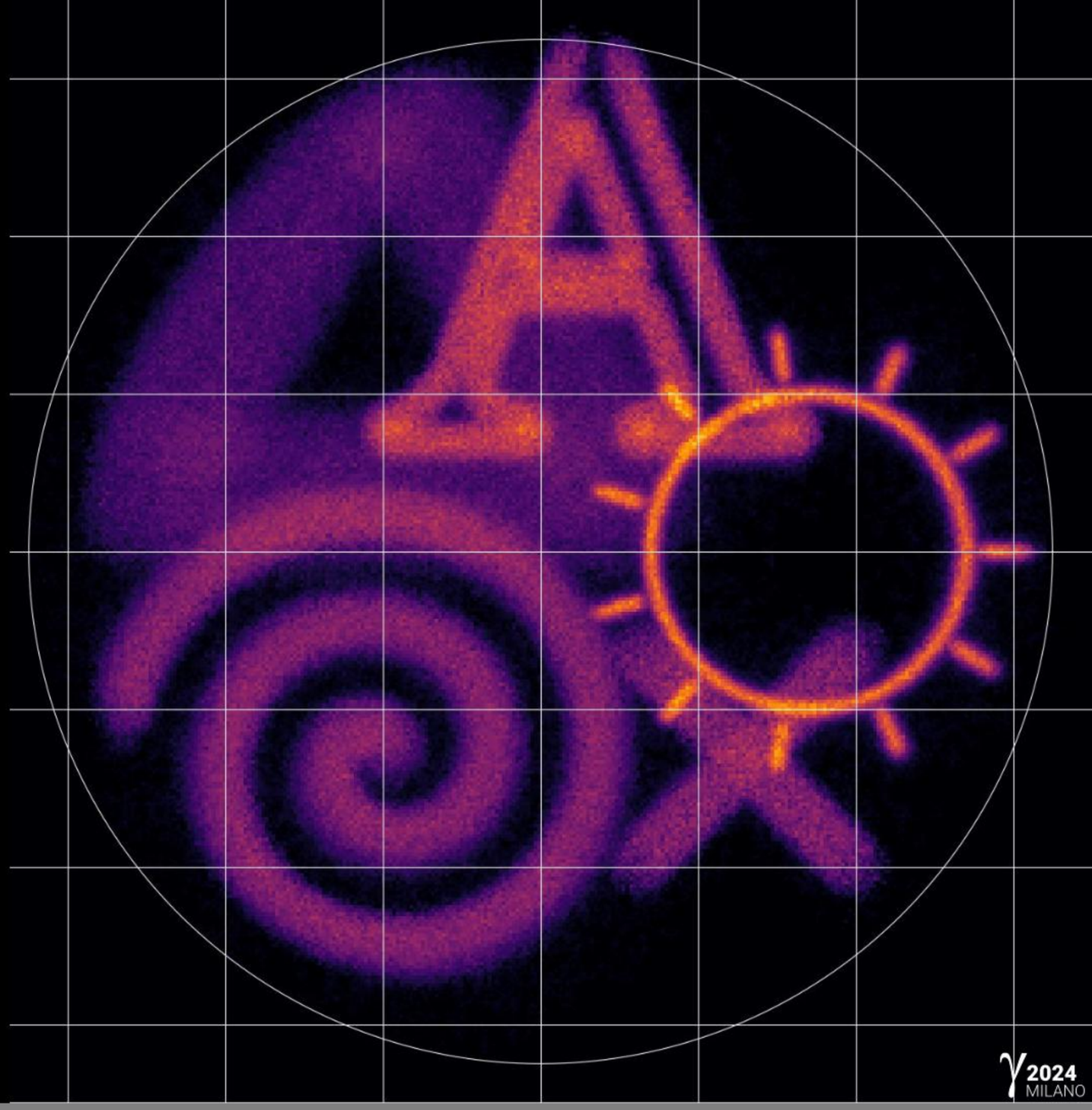




Optics

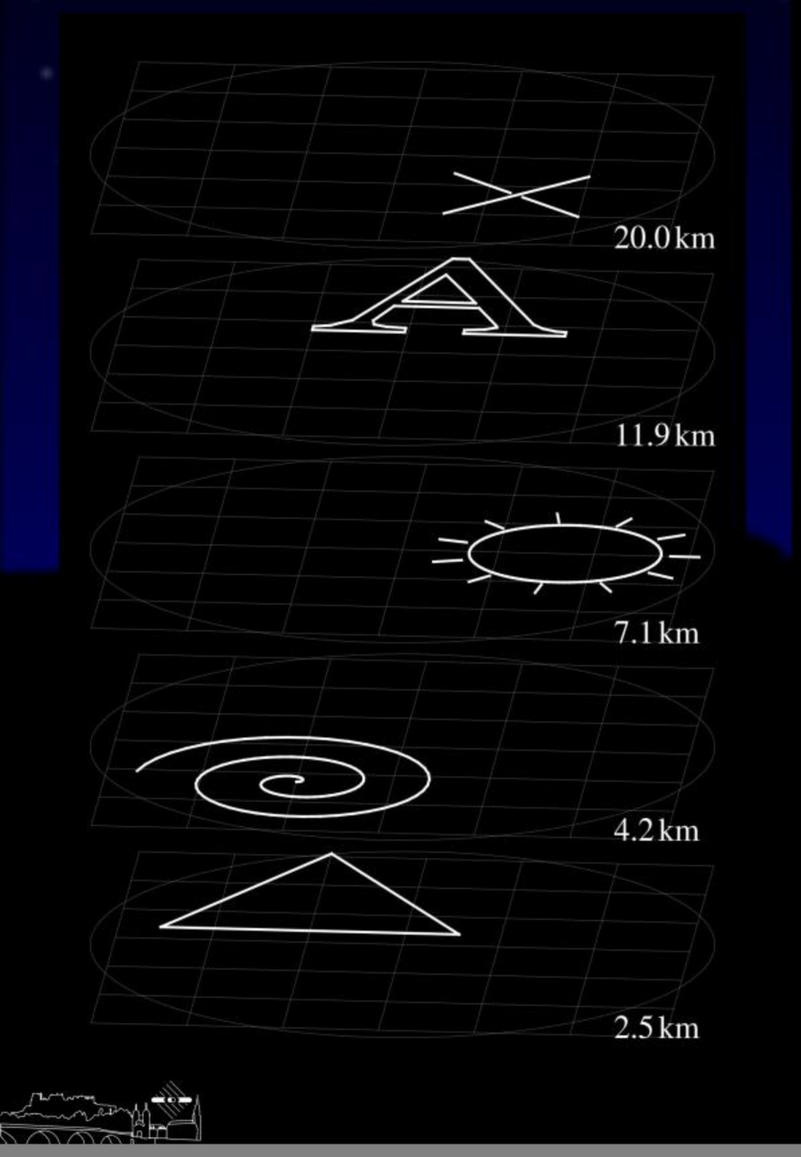
refocussing to any depth

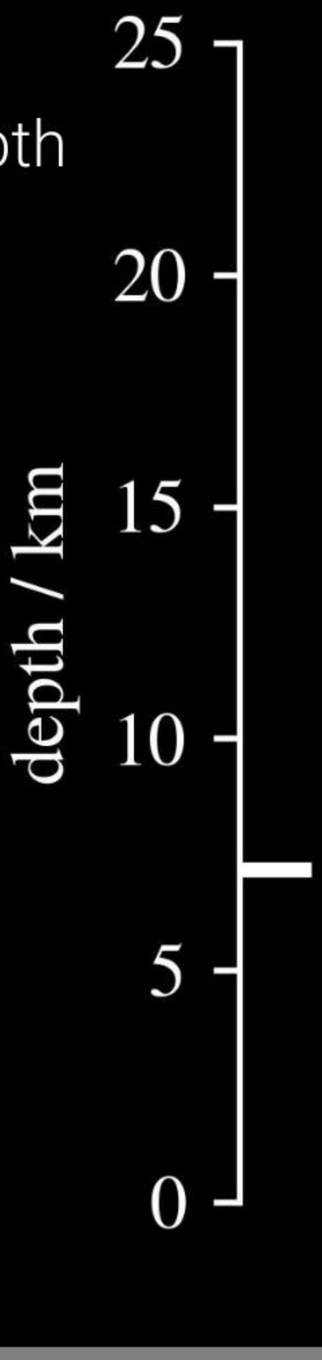


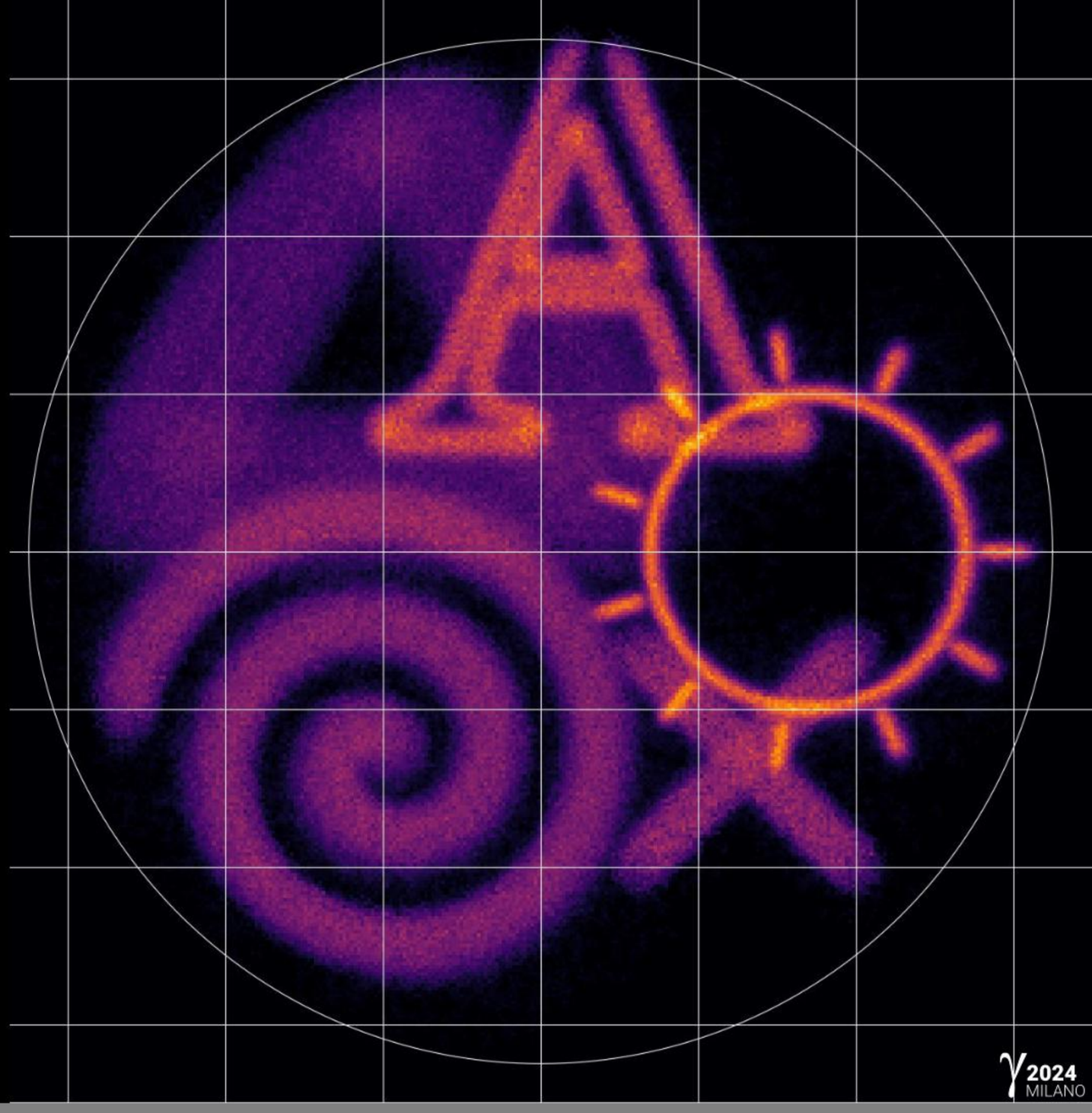


Optics

refocussing to any depth

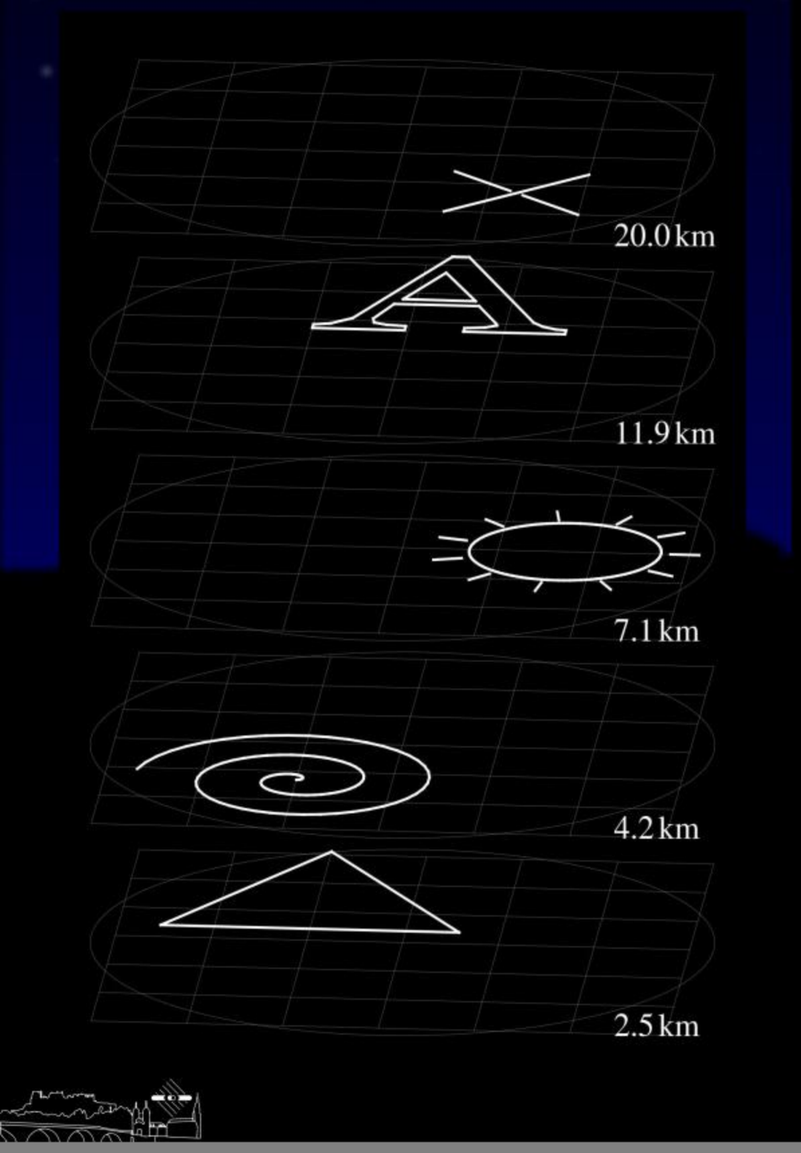


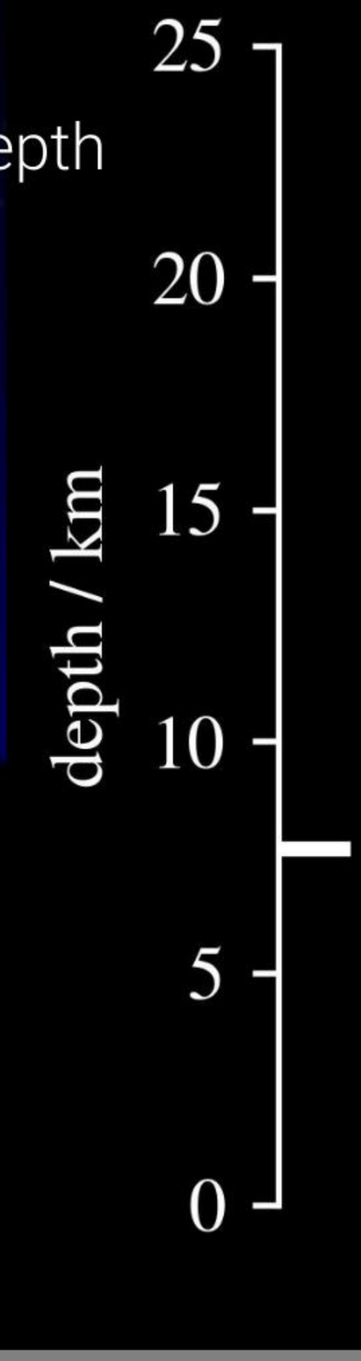


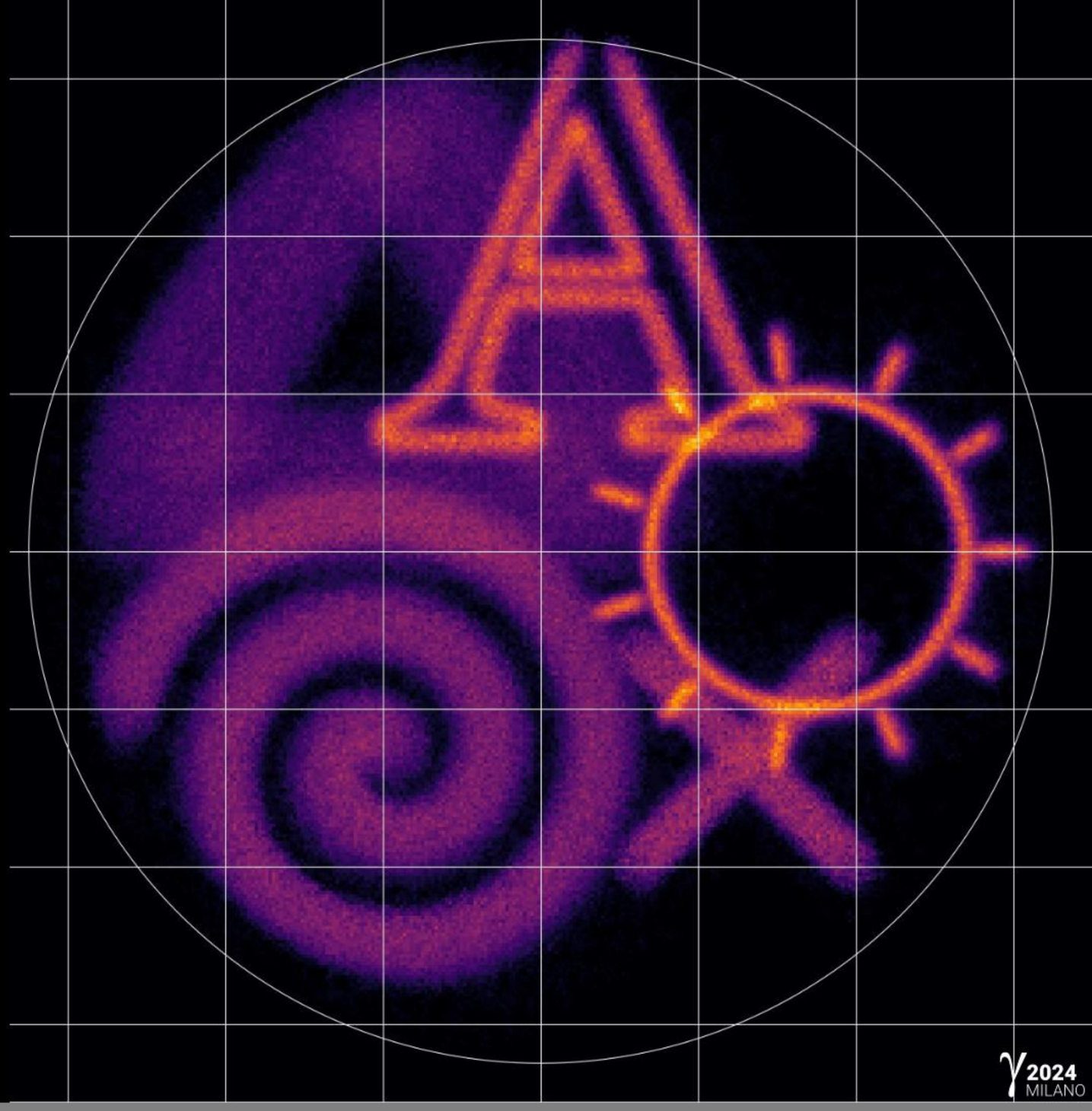


Optics

refocussing to any depth



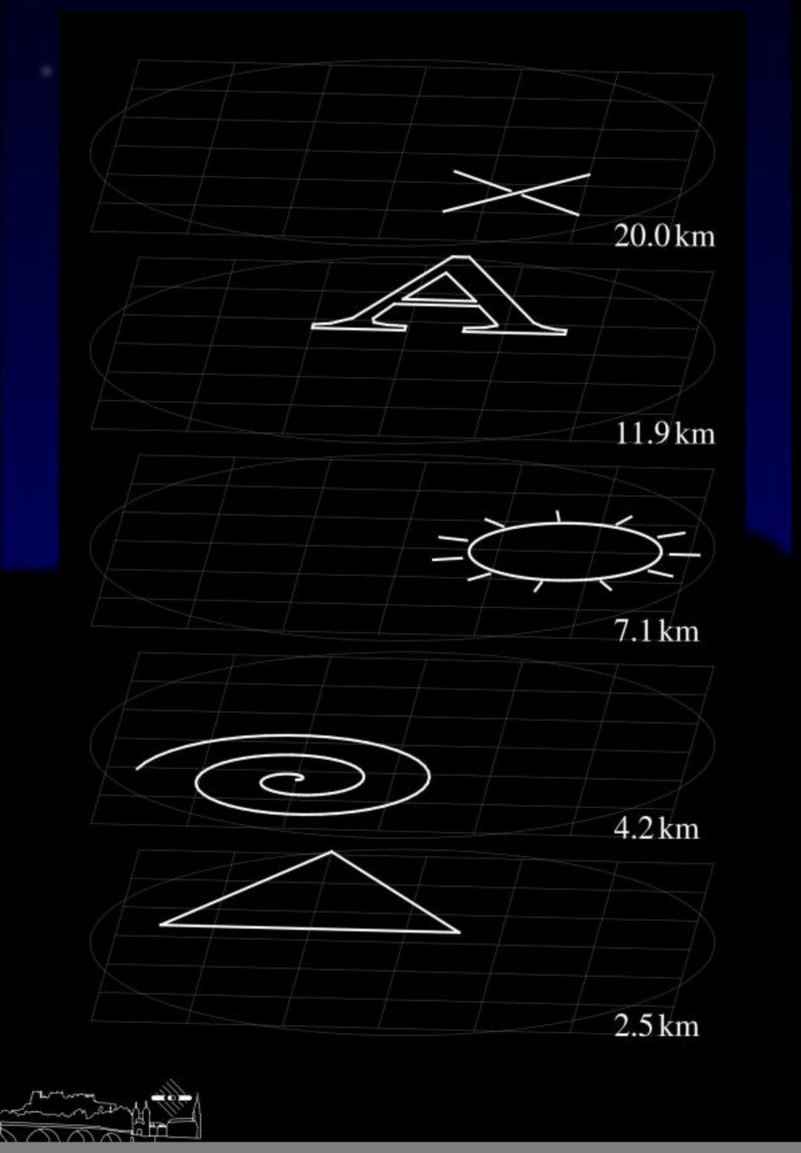


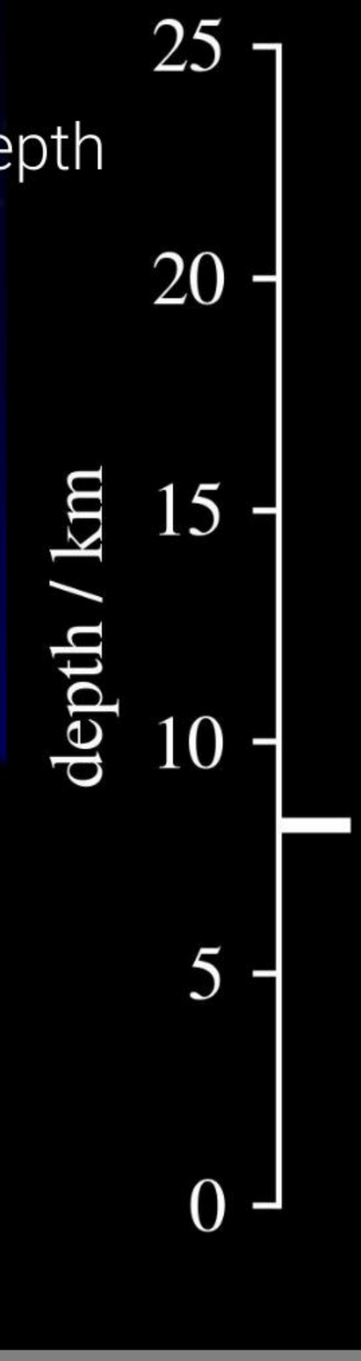


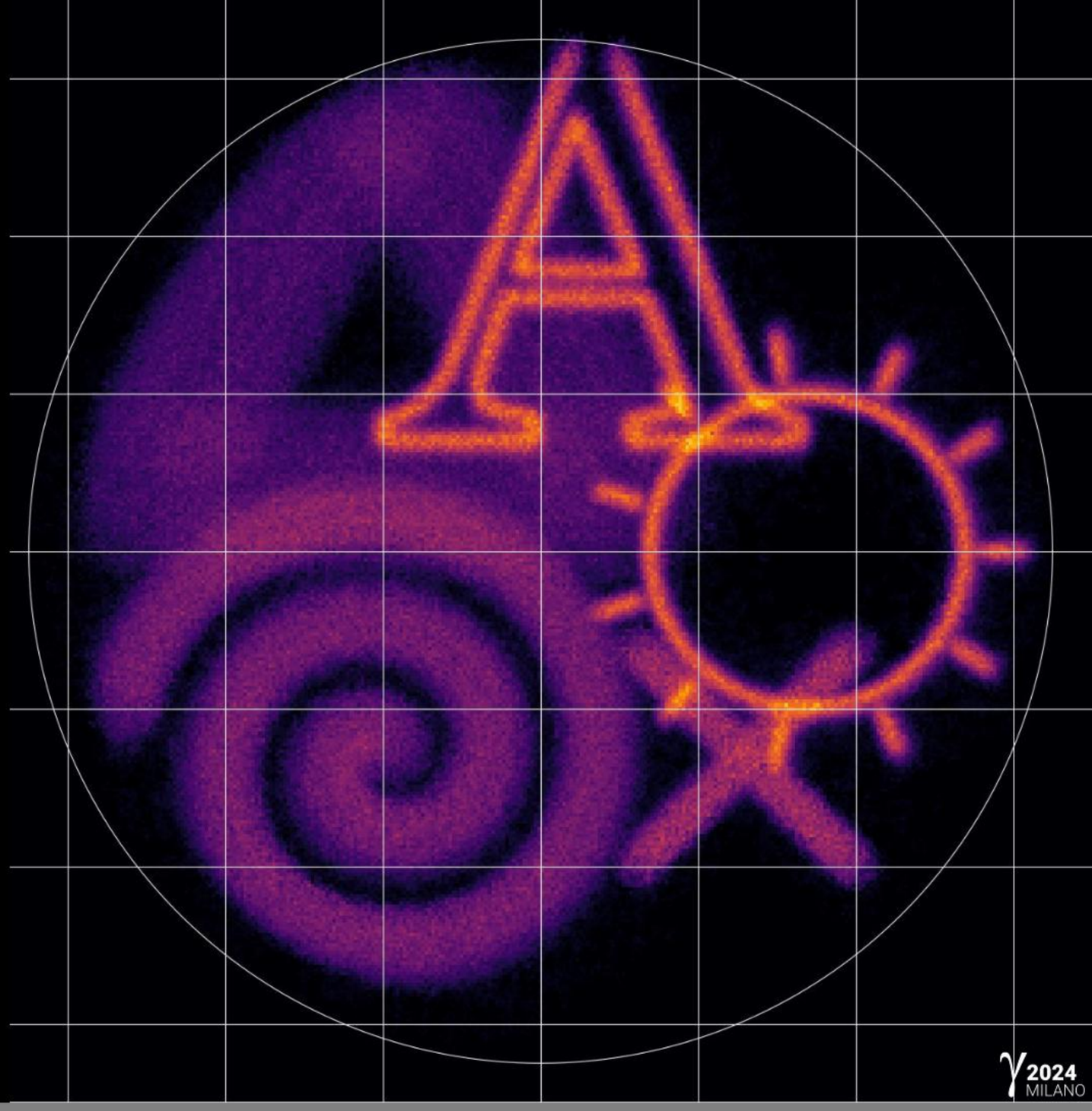
At about seven kilometers we find the sun with its flares. Again, look how flat the image is. One can hardly see any aberrations.

Optics

refocussing to any depth

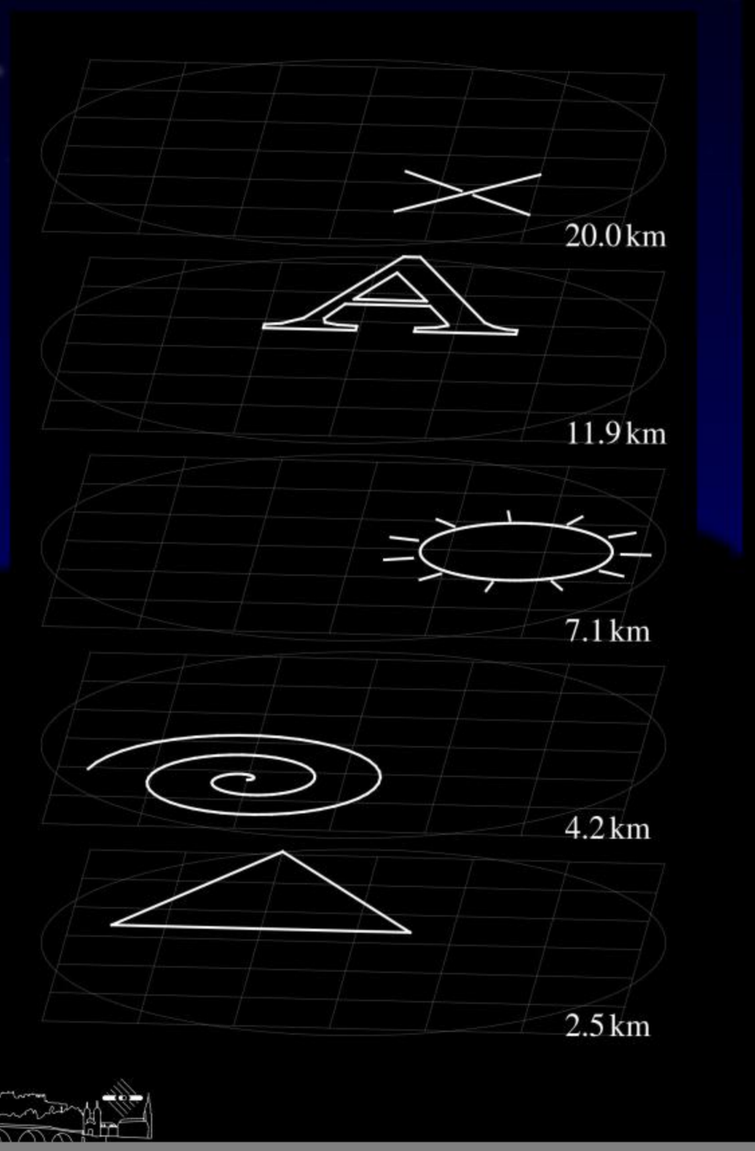


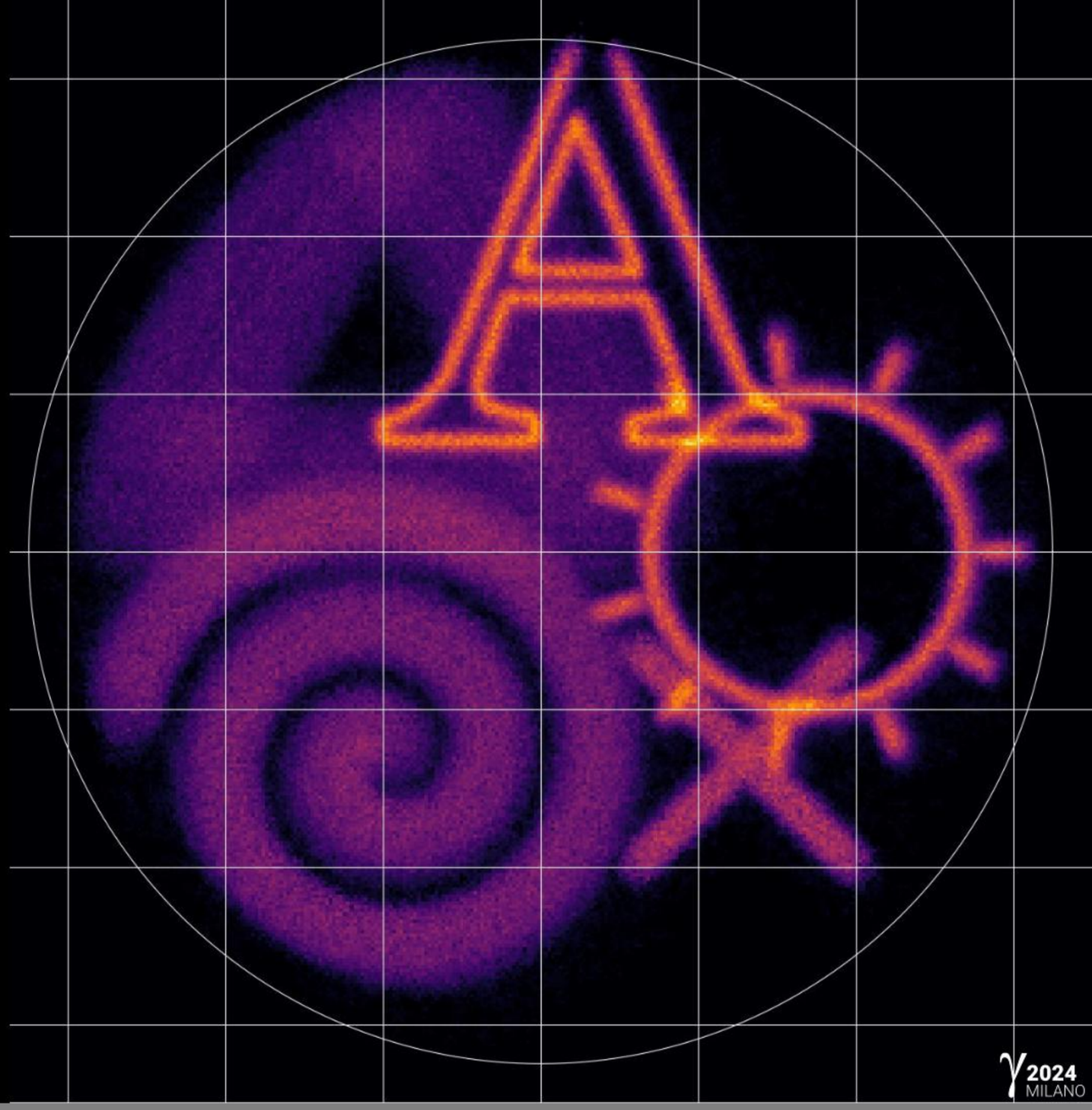




Optics

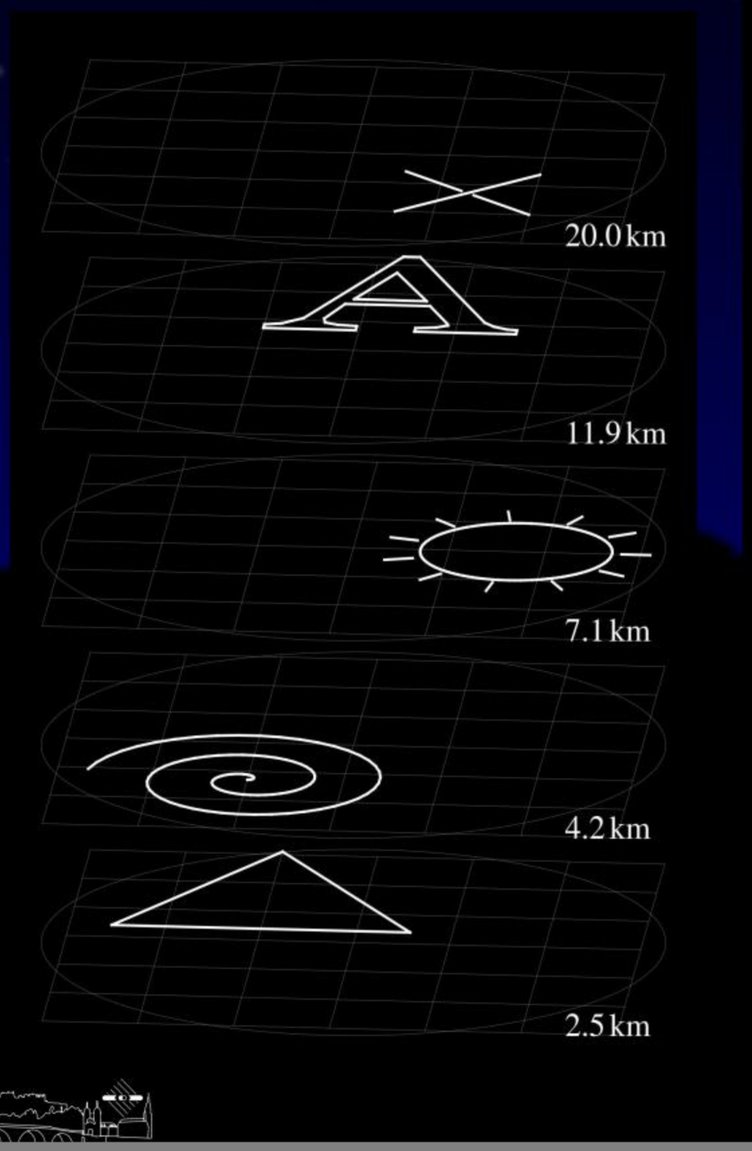
refocussing to any depth

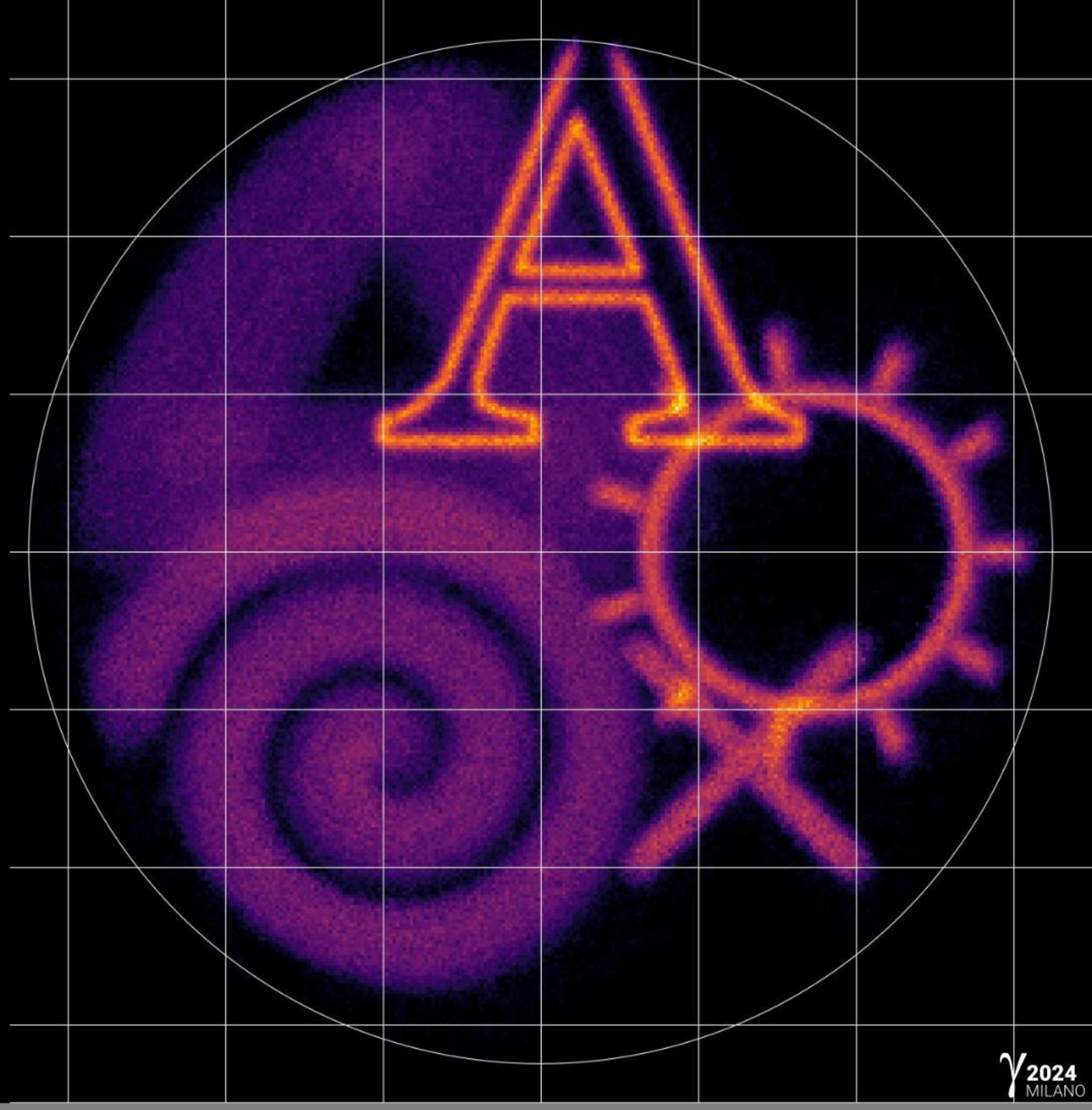




Optics

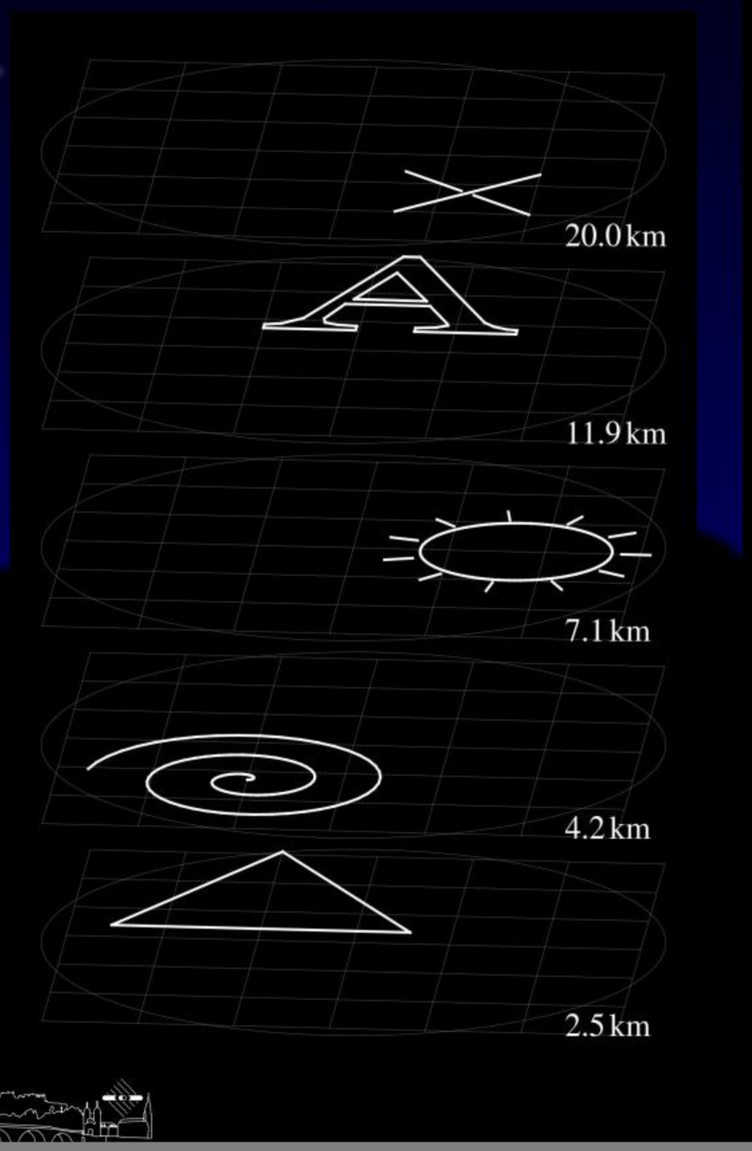
refocussing to any depth

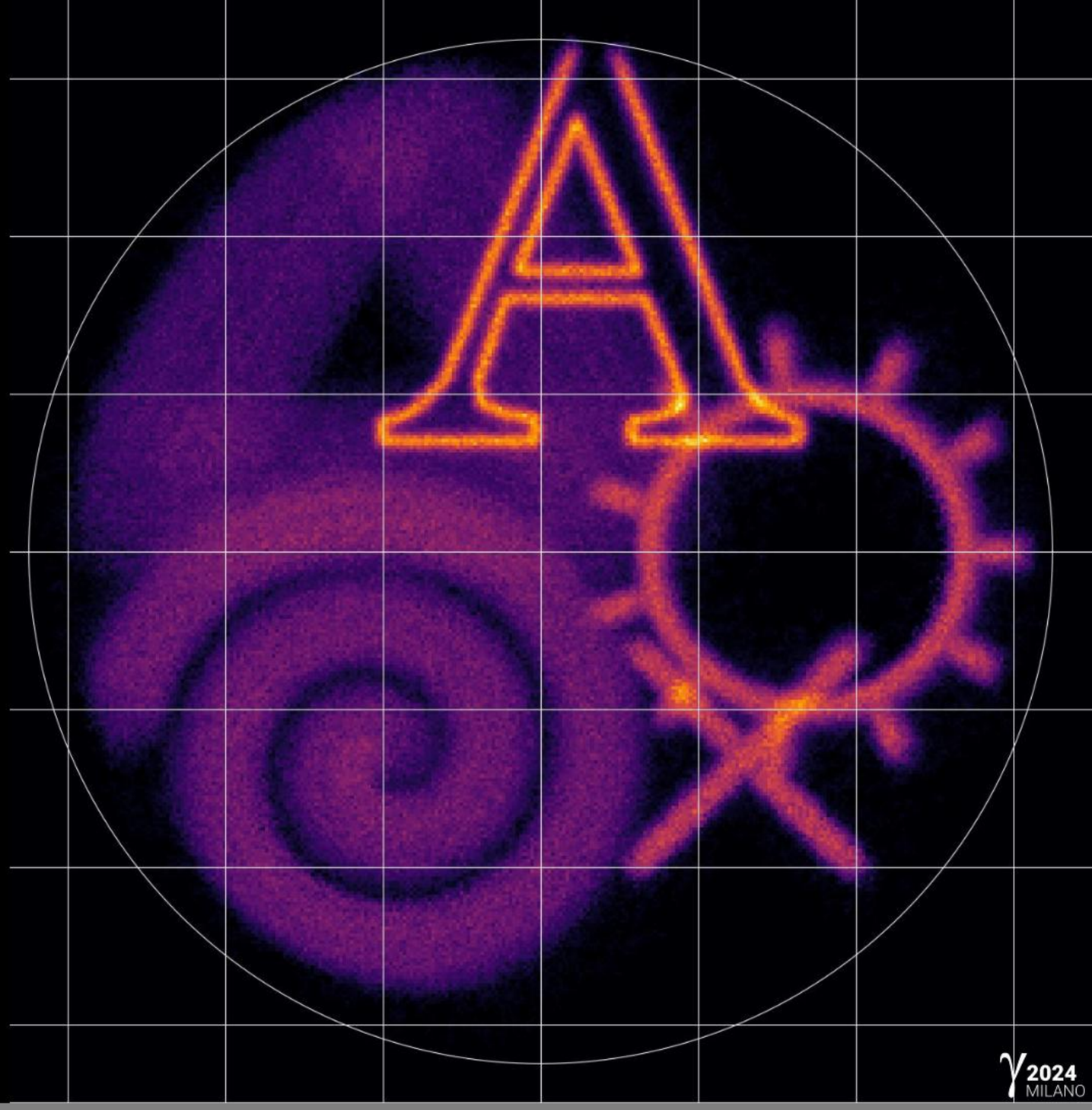




Optics

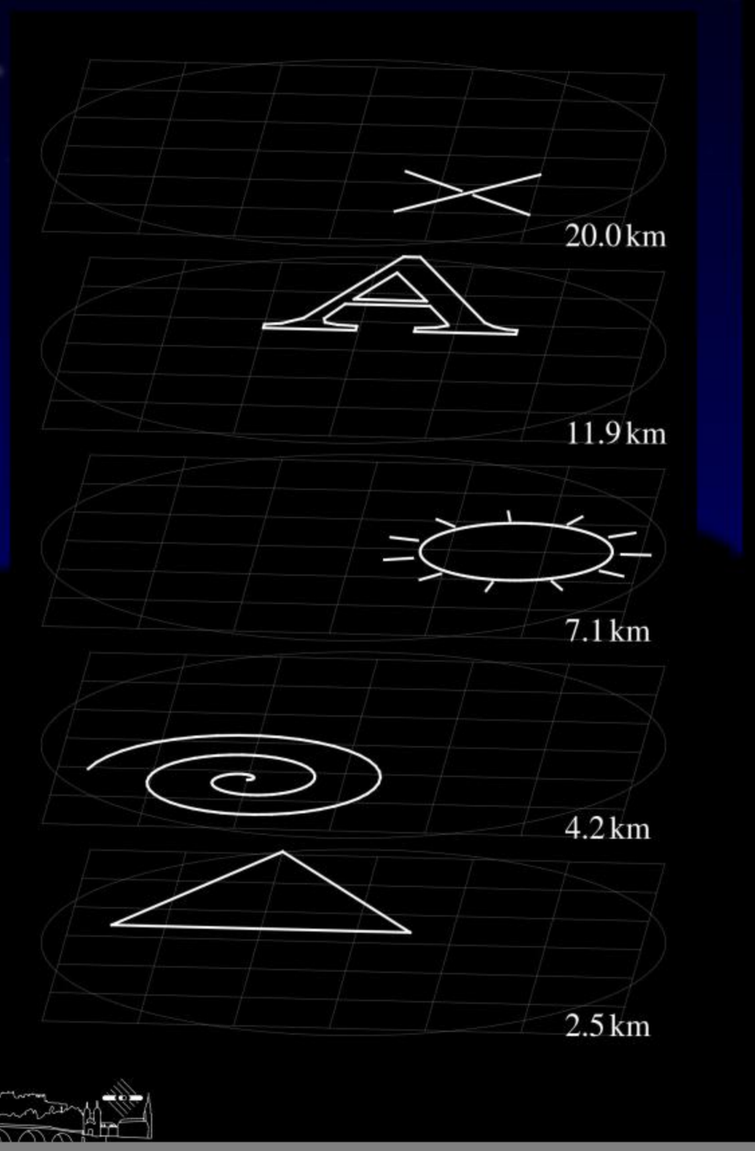
refocussing to any depth

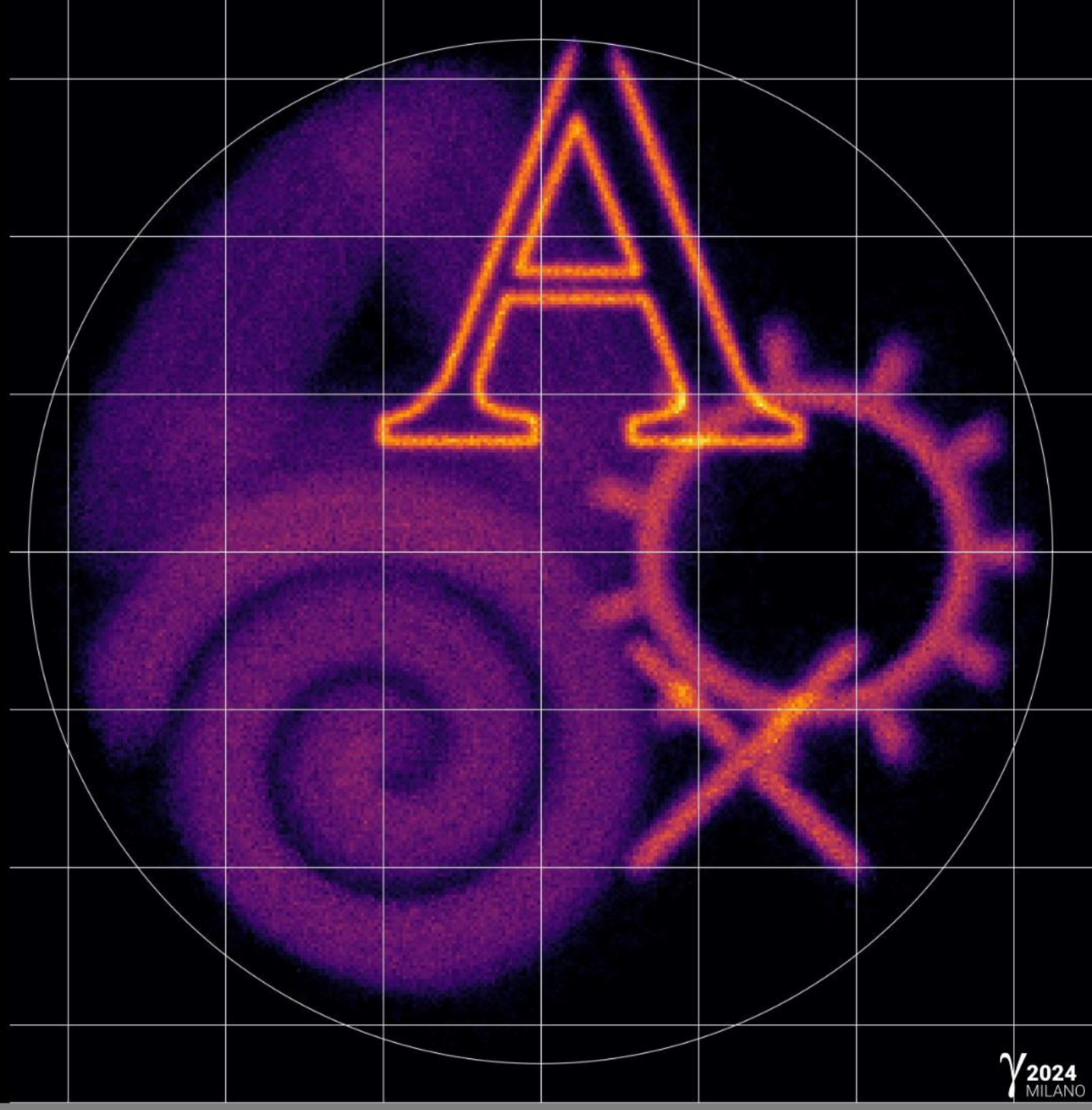


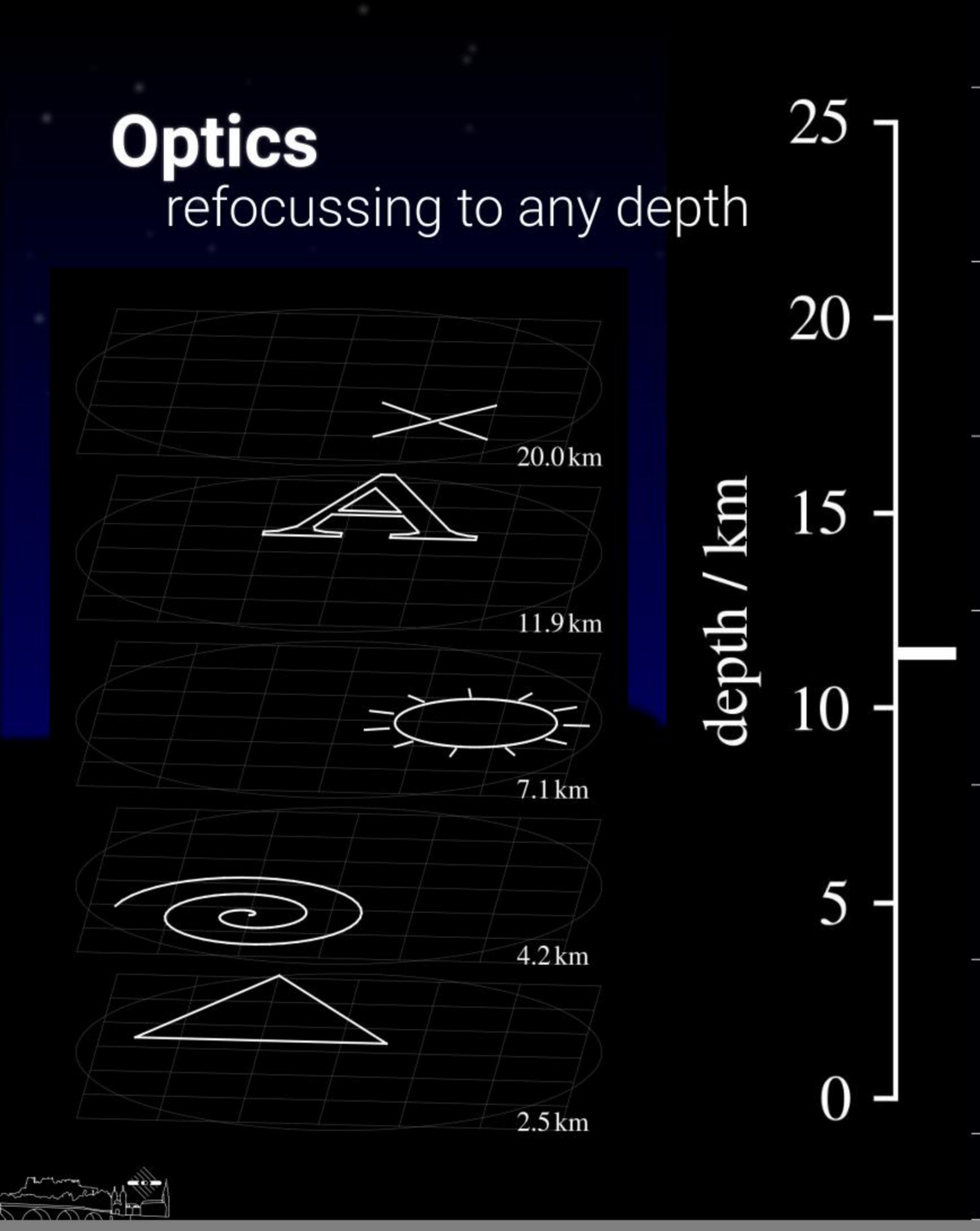


Optics

refocussing to any depth



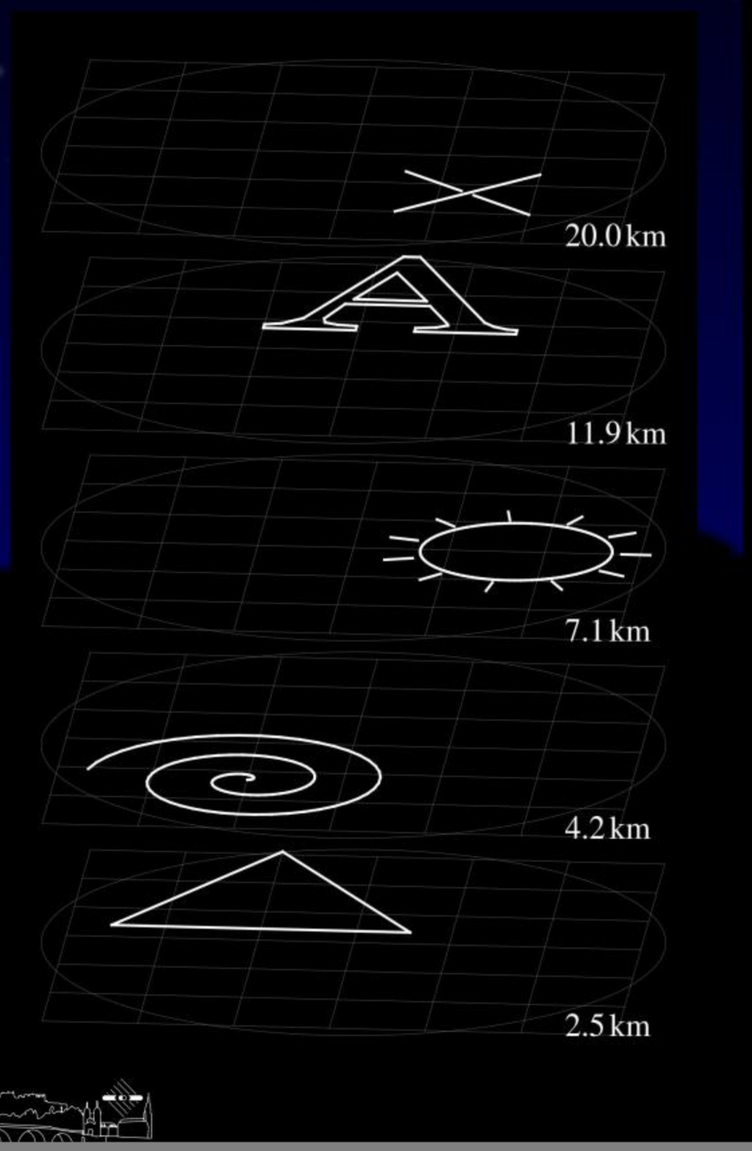


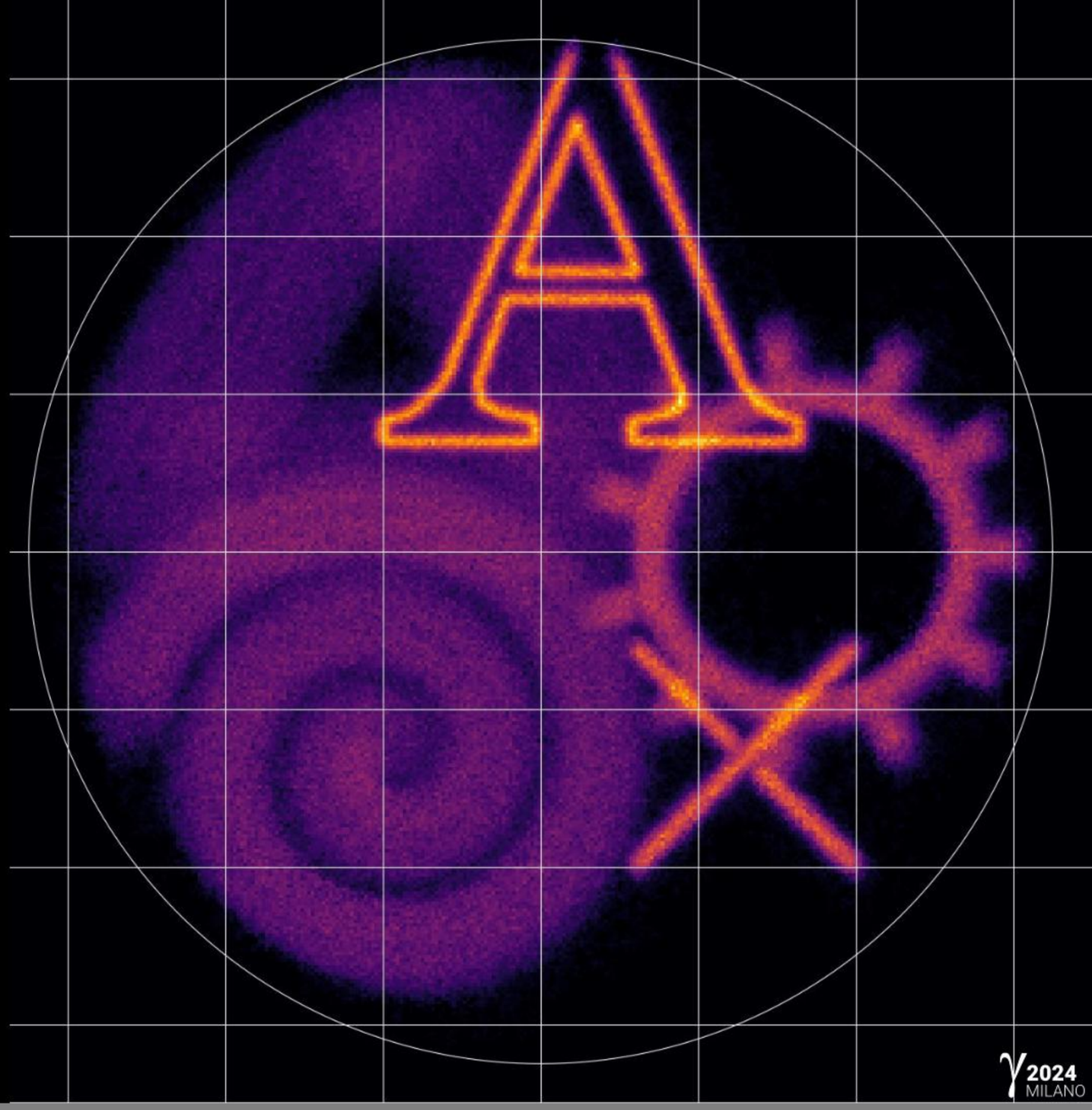


At twelve kilometers we find the capital letter 'A'. Look how straight the line are. There is no sign of distortions.

Optics

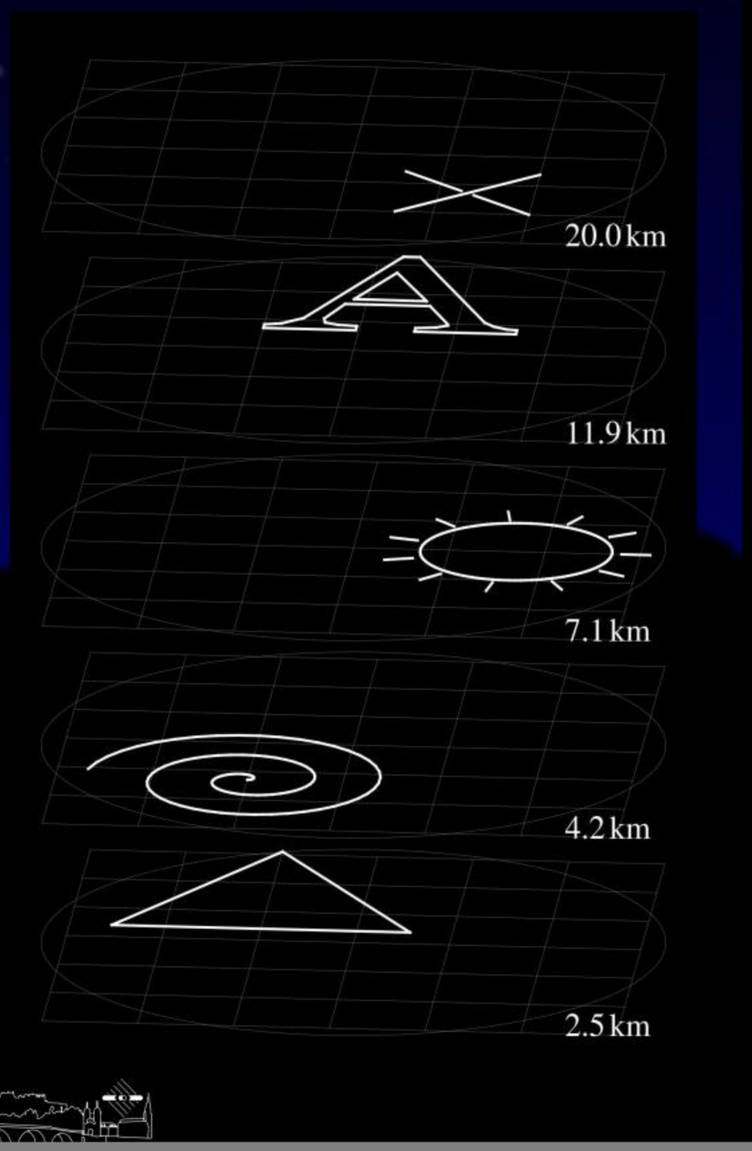
refocussing to any depth

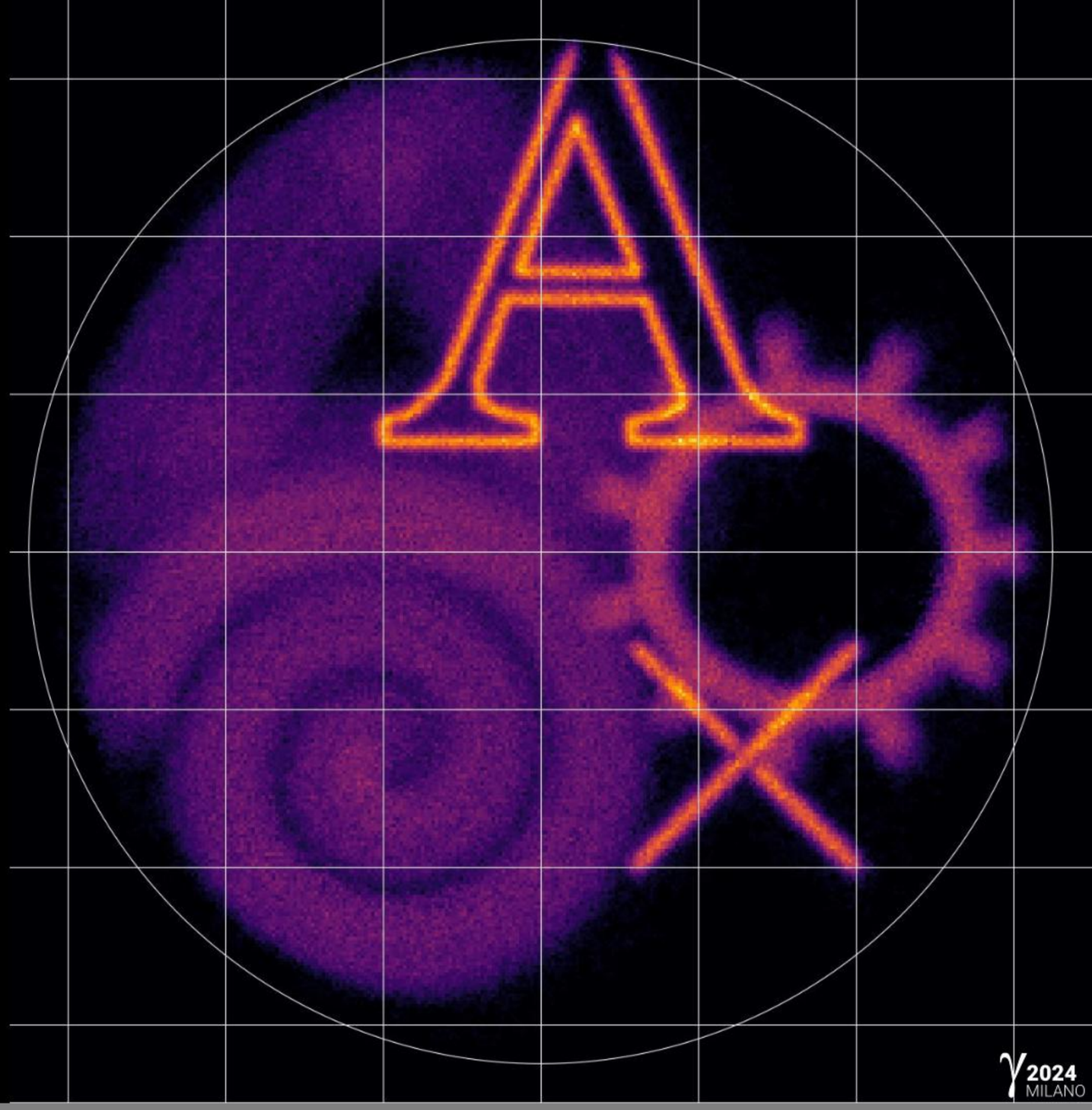




Optics

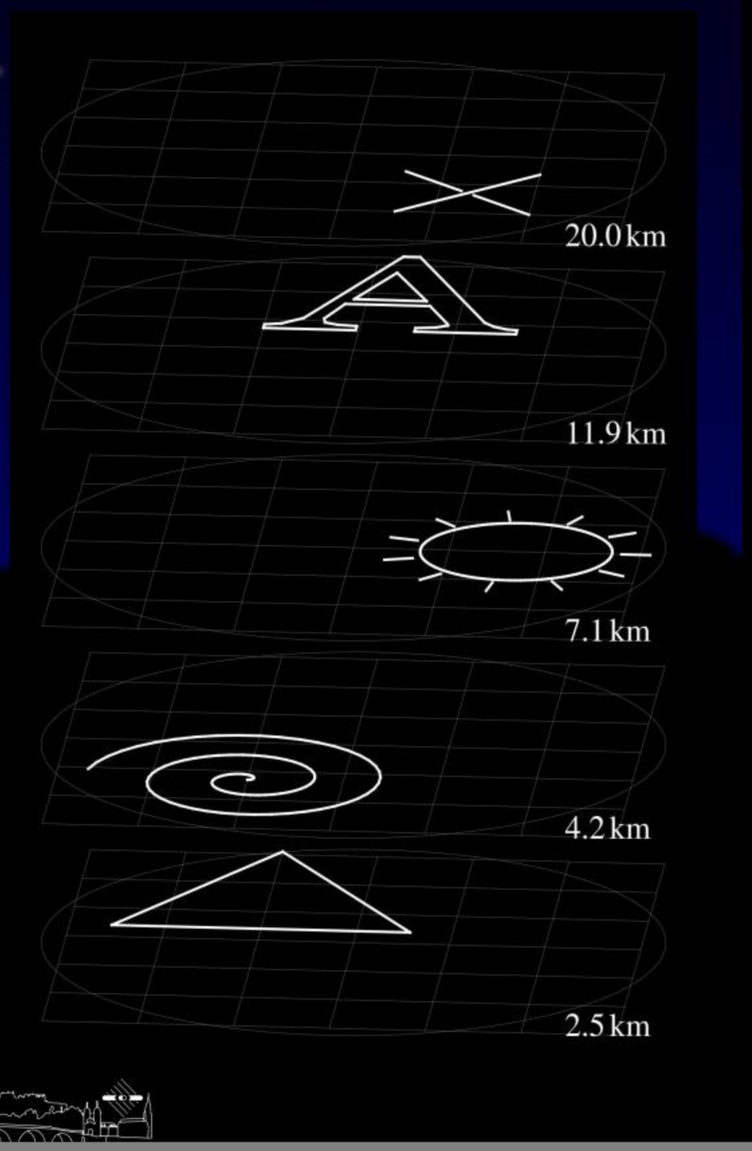
refocussing to any depth

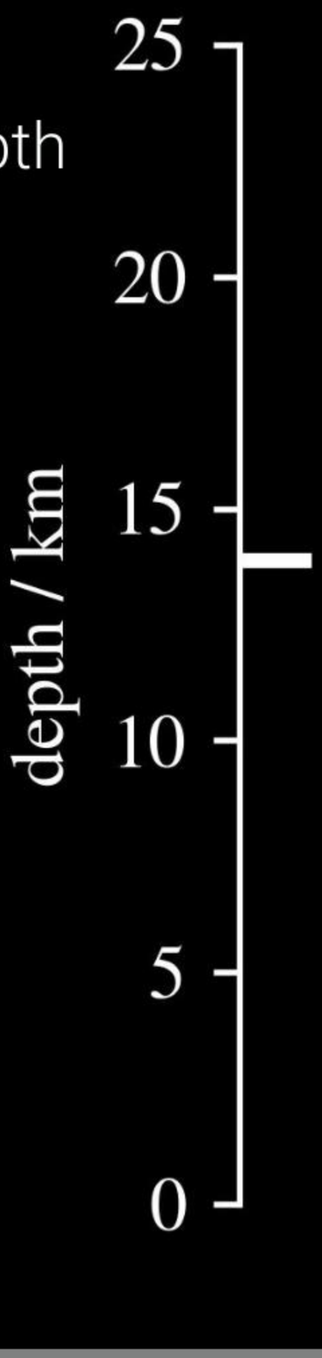


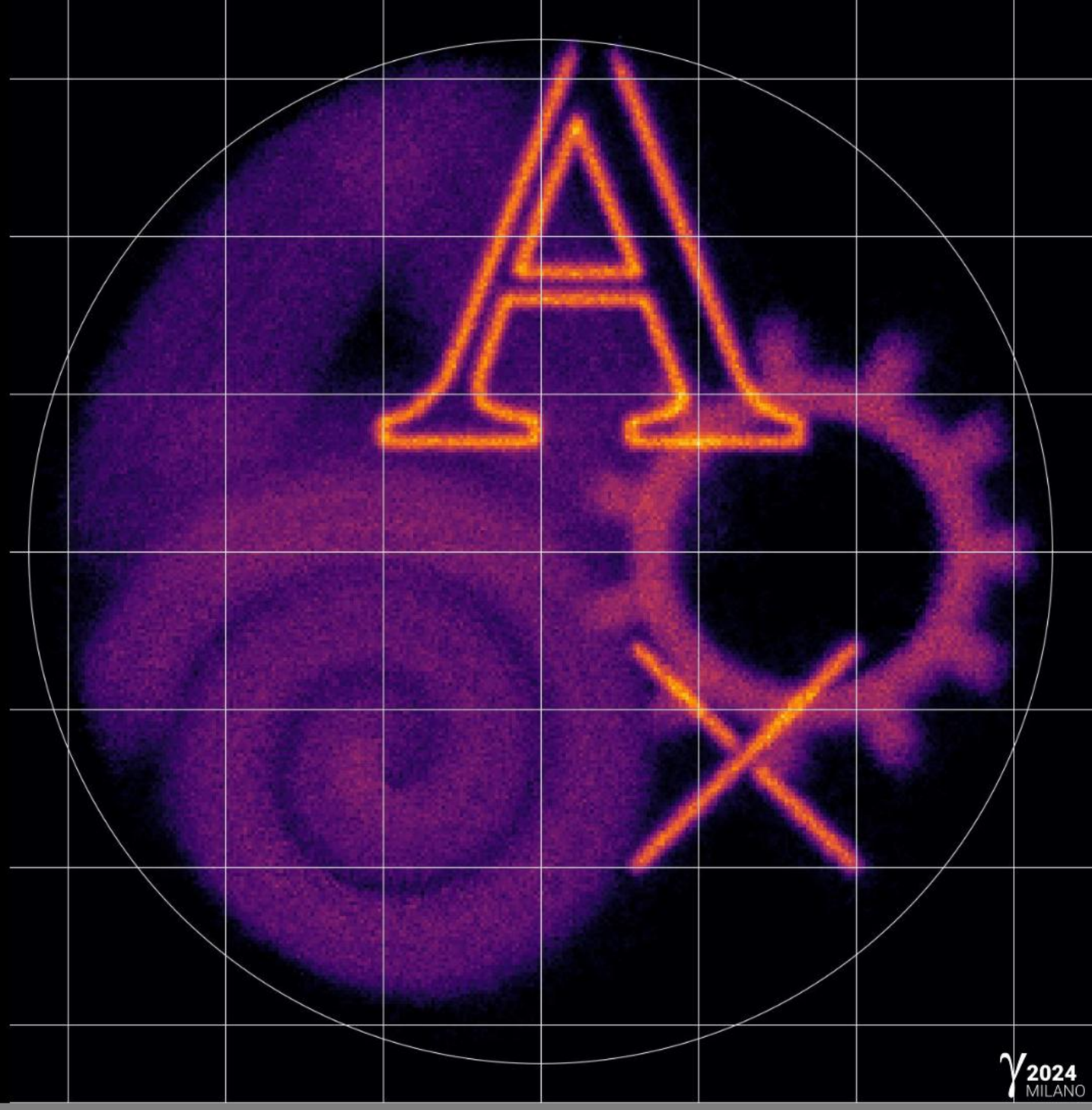


Optics

refocussing to any depth

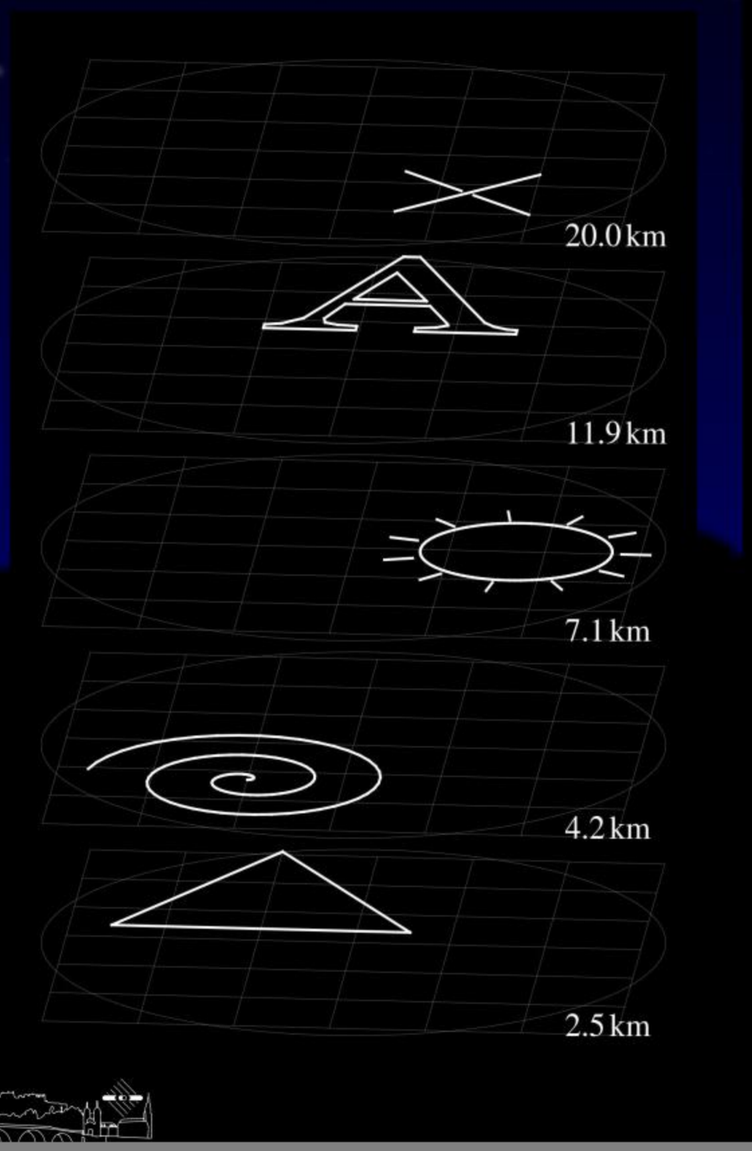


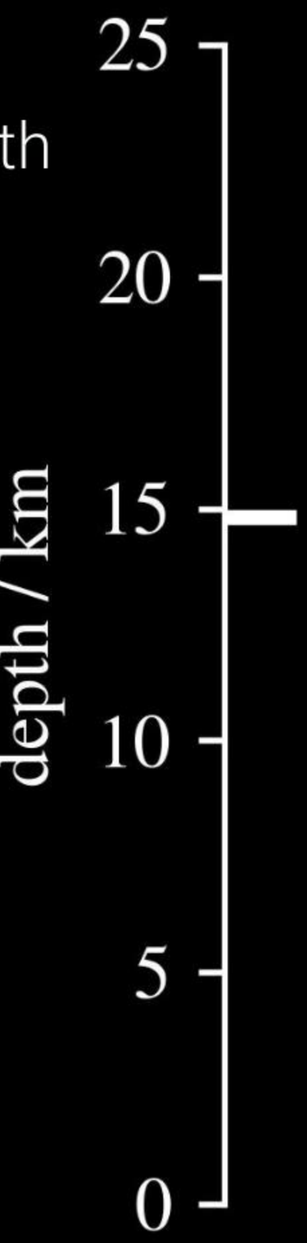


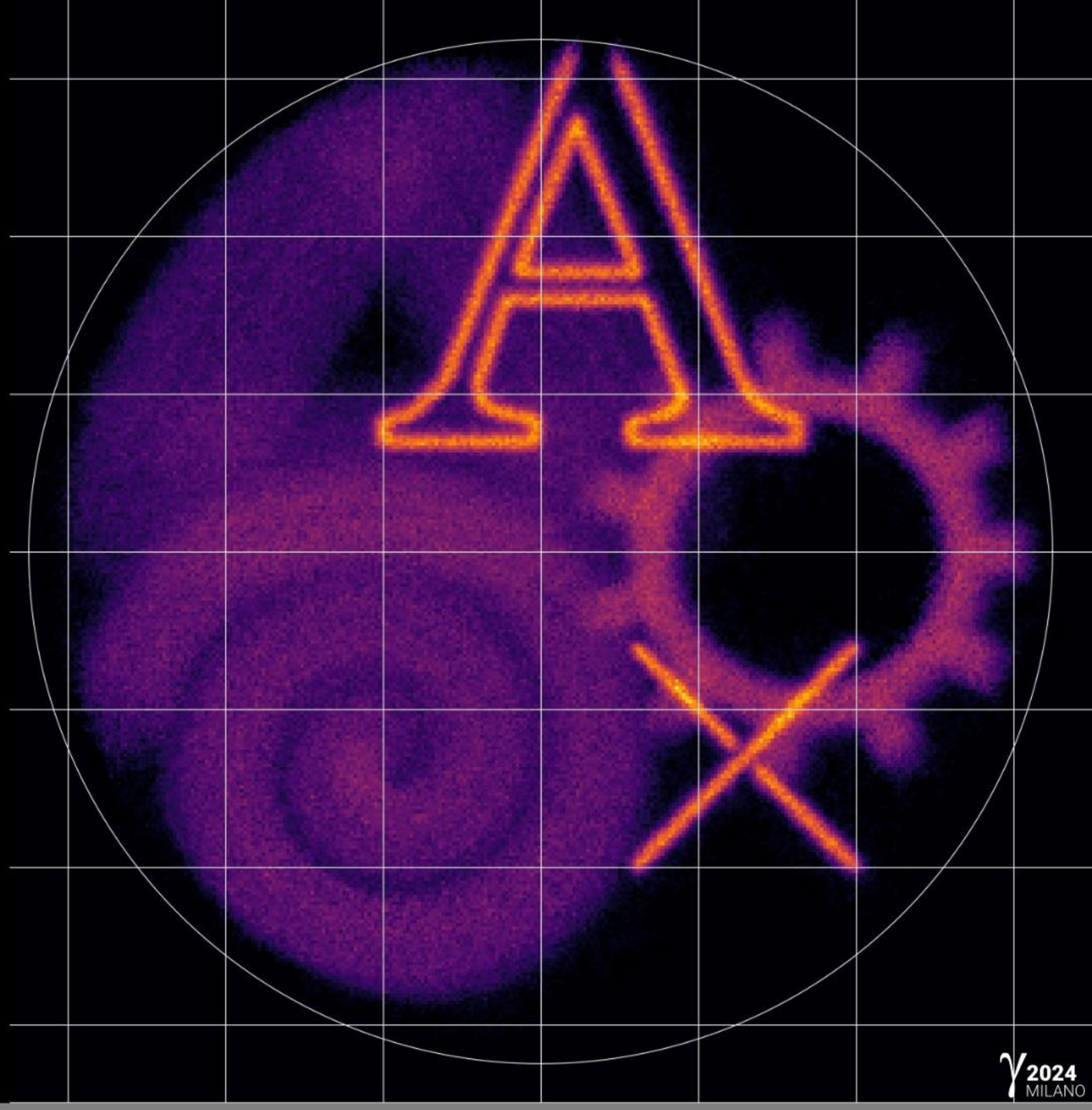


Optics

refocussing to any depth

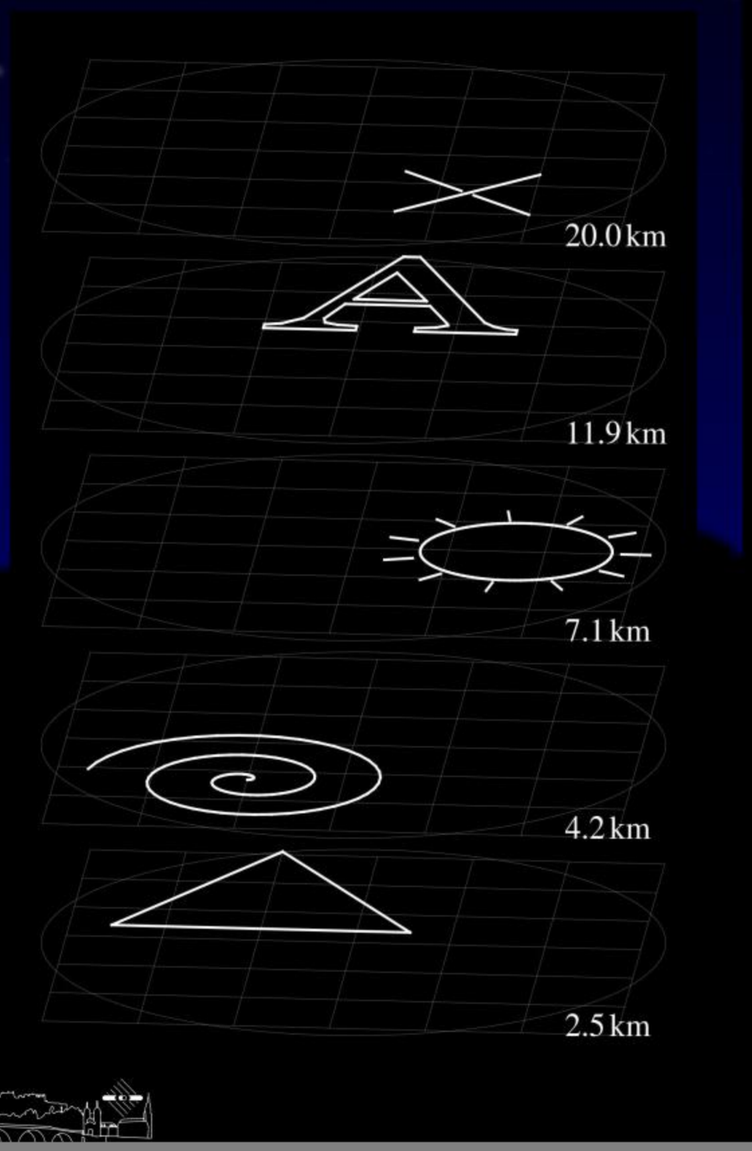


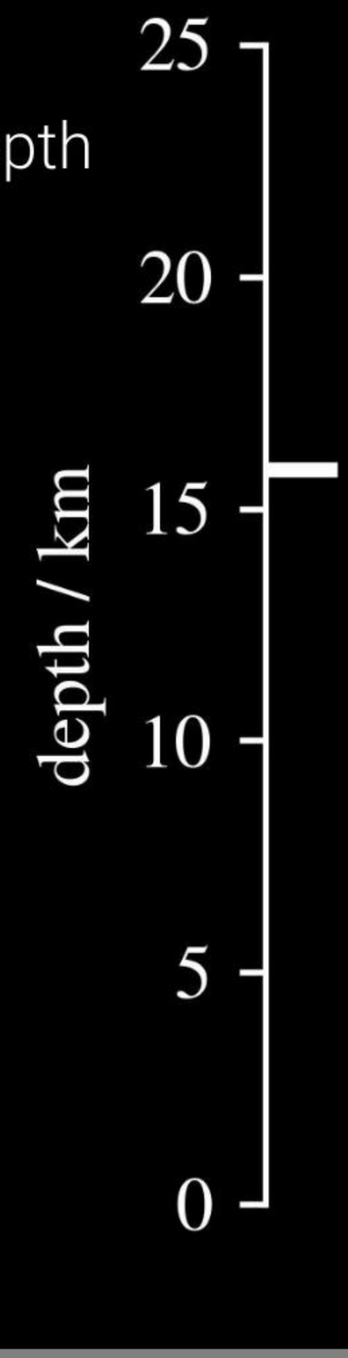


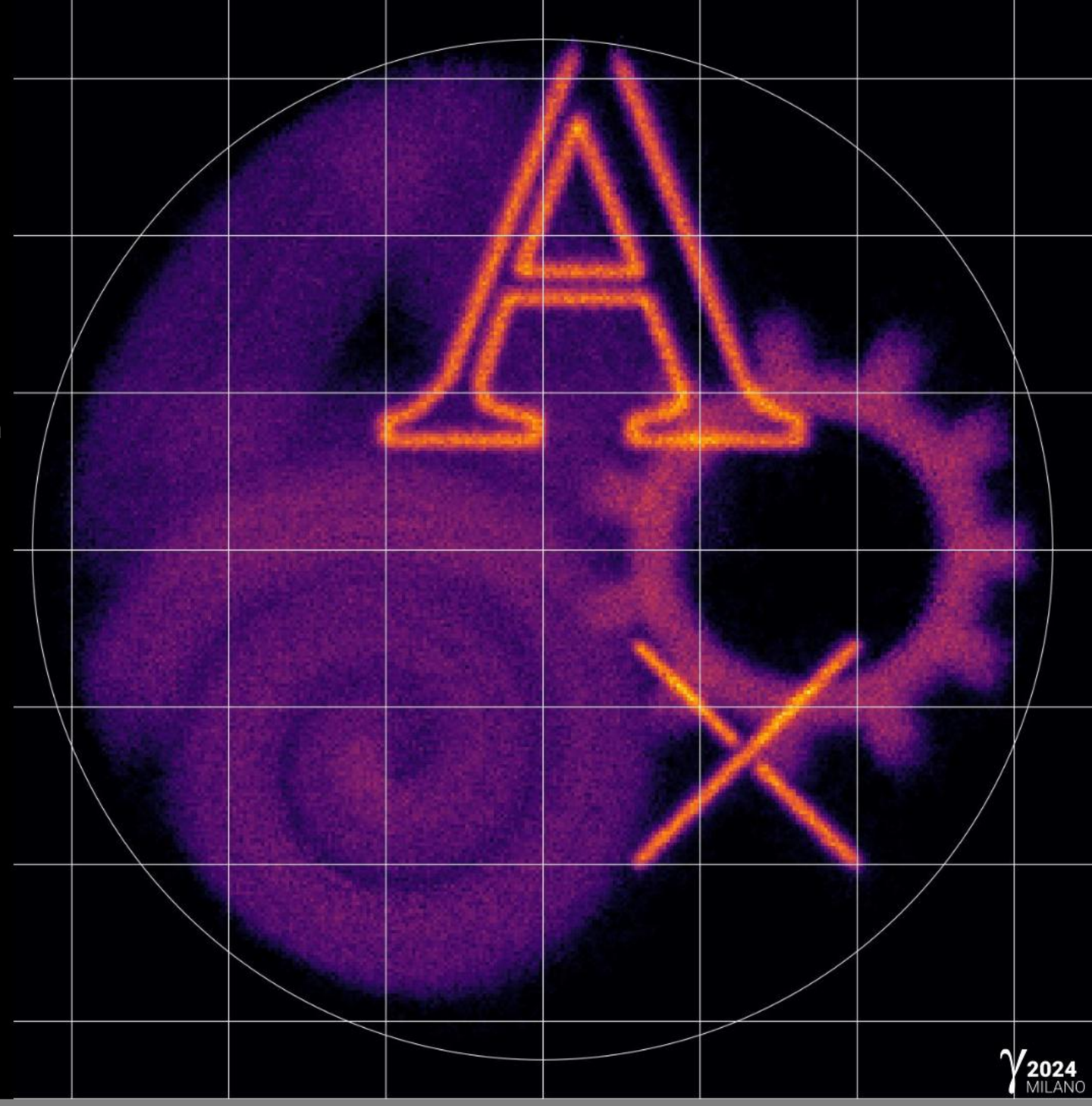


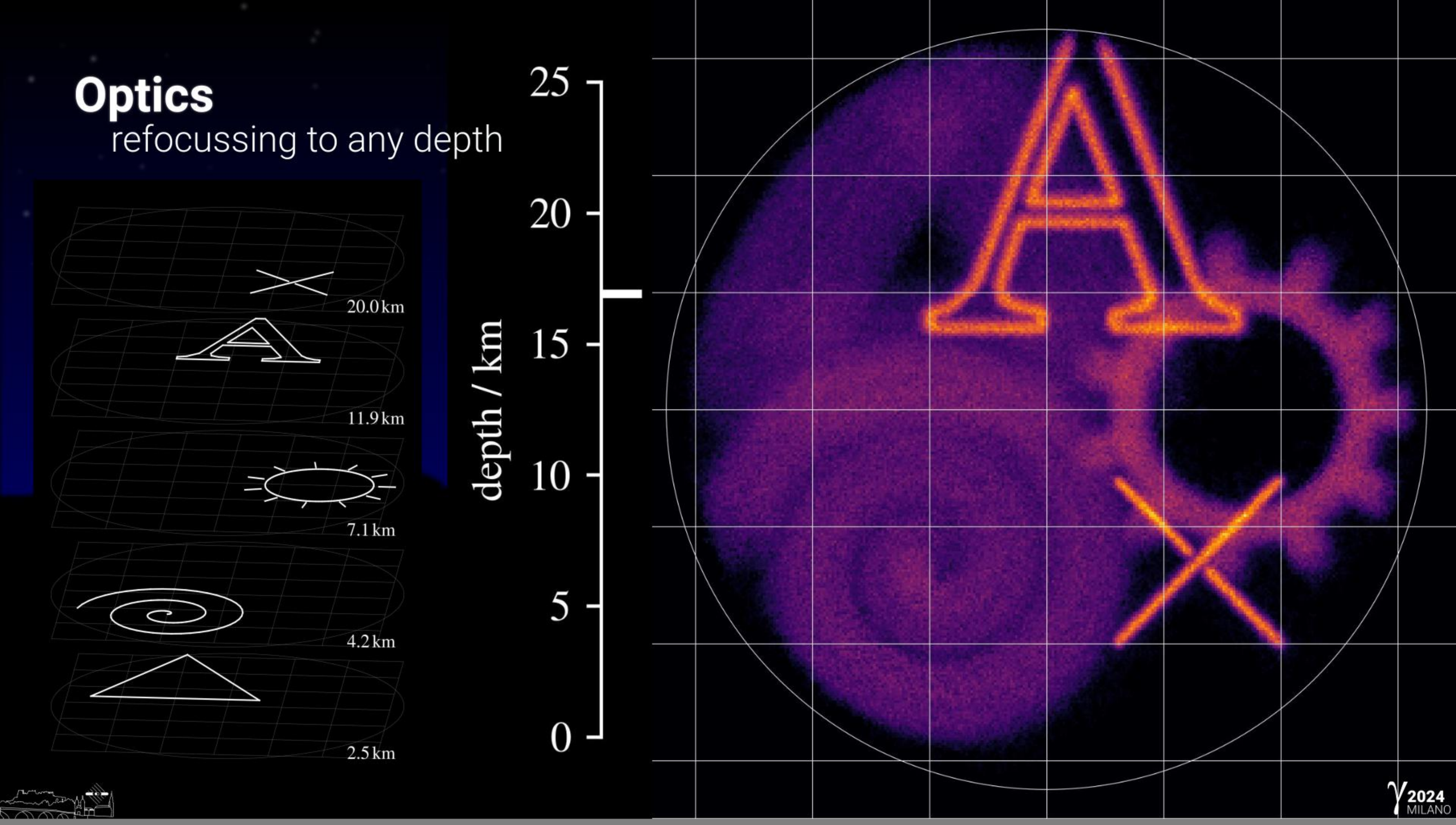
Optics

refocussing to any depth





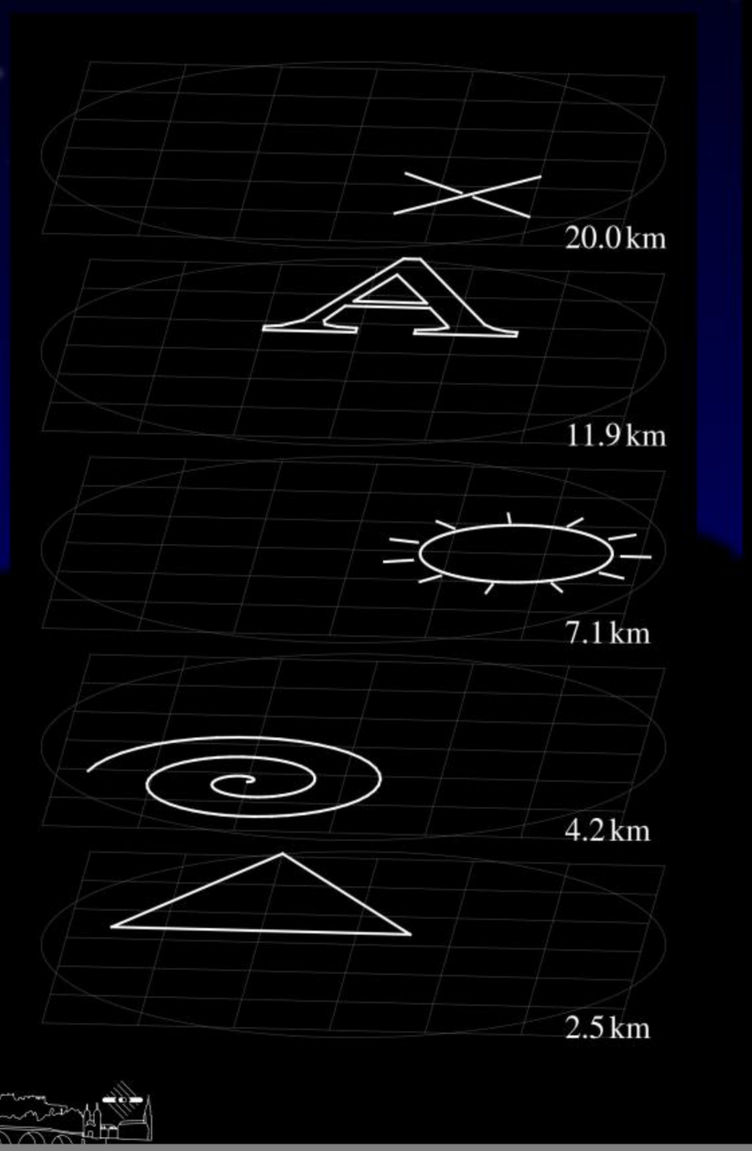


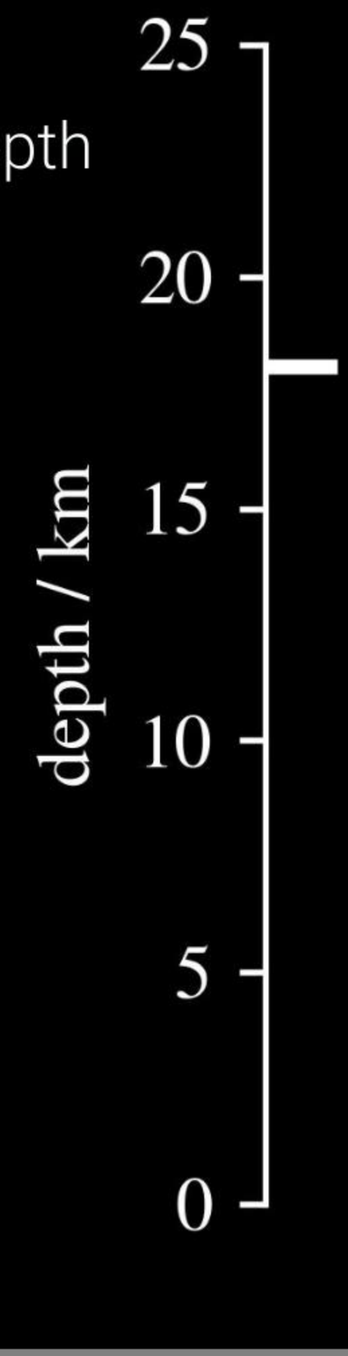


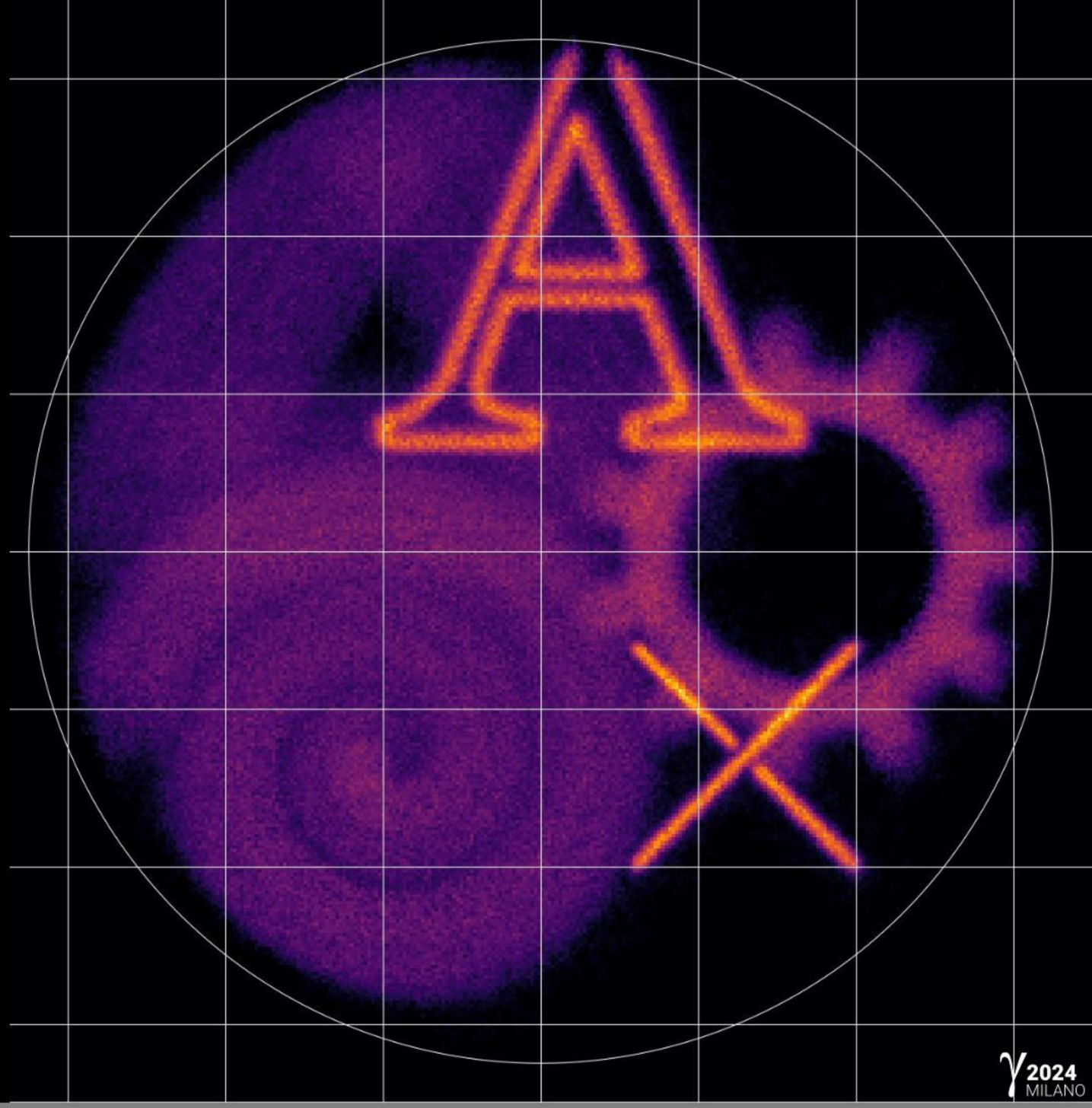
And finally, at about twenty kilometers we find the cross.

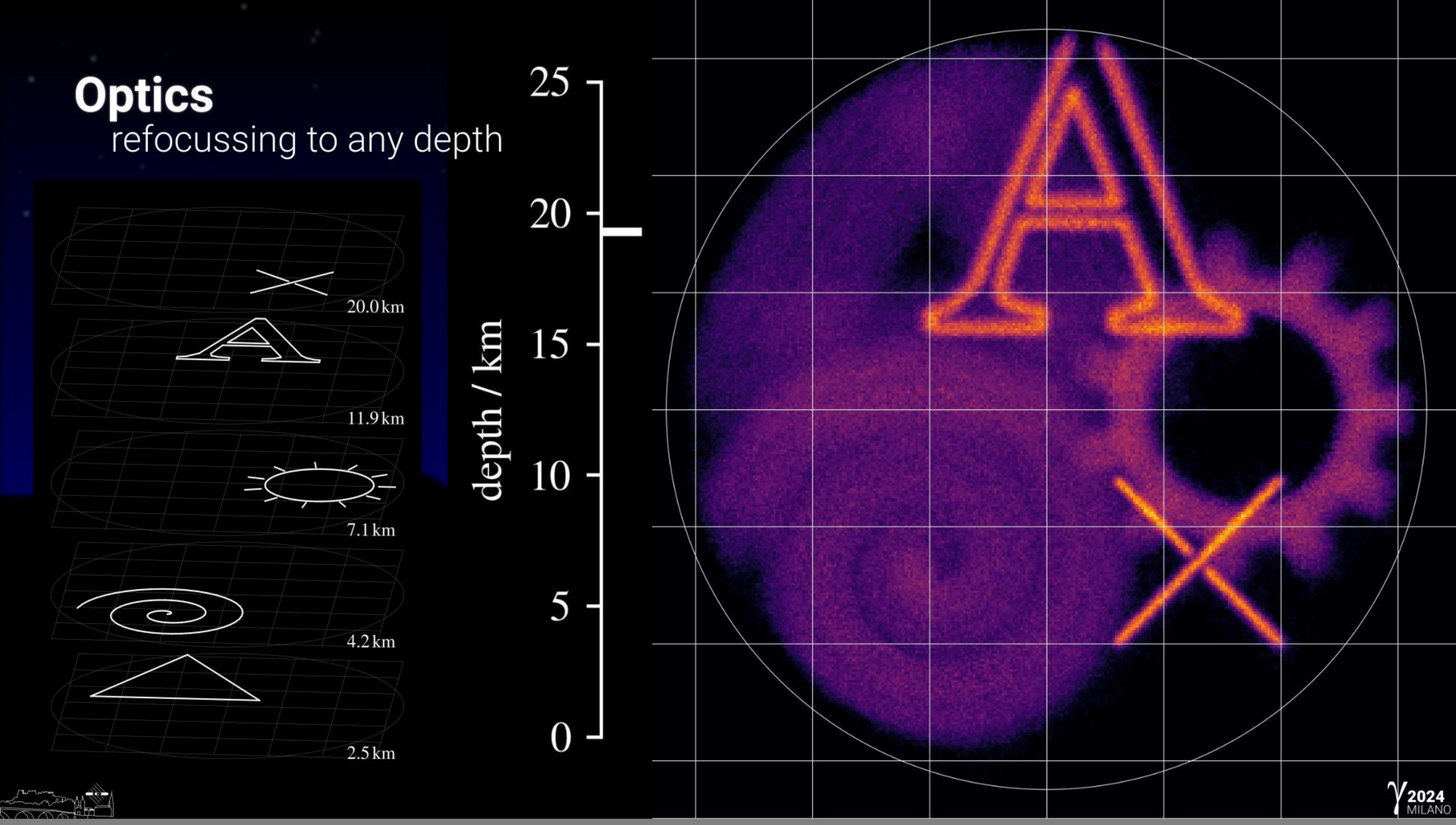
Optics

refocussing to any depth





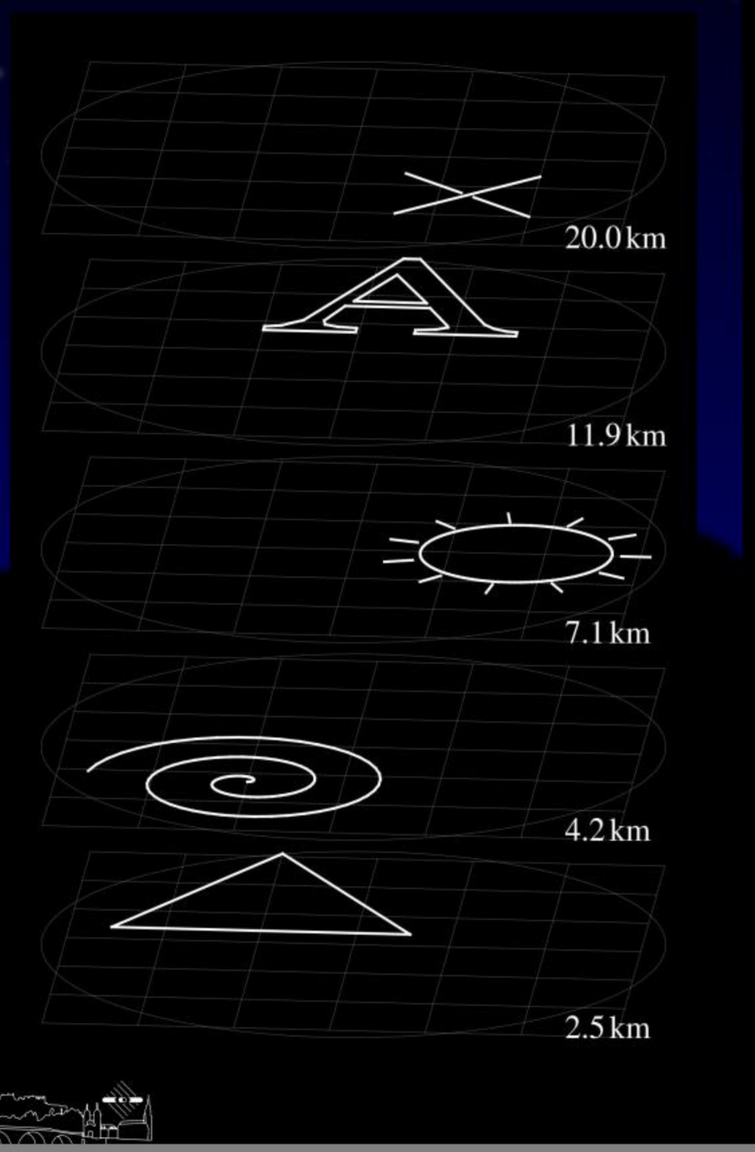


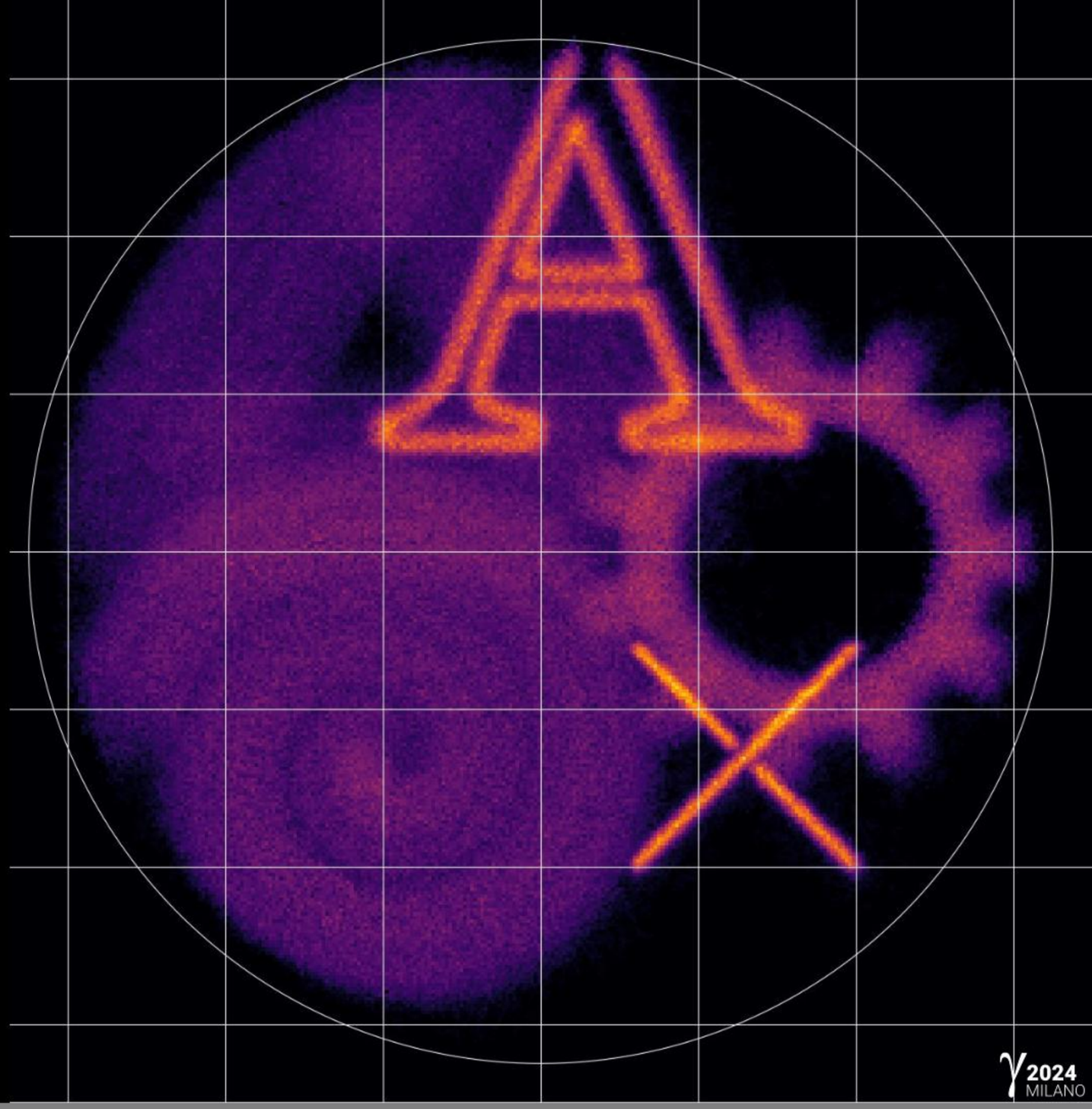


Now wait a moment. I told you the triangle will be important later on. But where is the triangle gone? The triangle is blurred beyond recognition. If this image was recorded by a telescope, you would not have known that there was a triangle. This is what the physical limit of a narrow depth-of-field is all about.

Optics

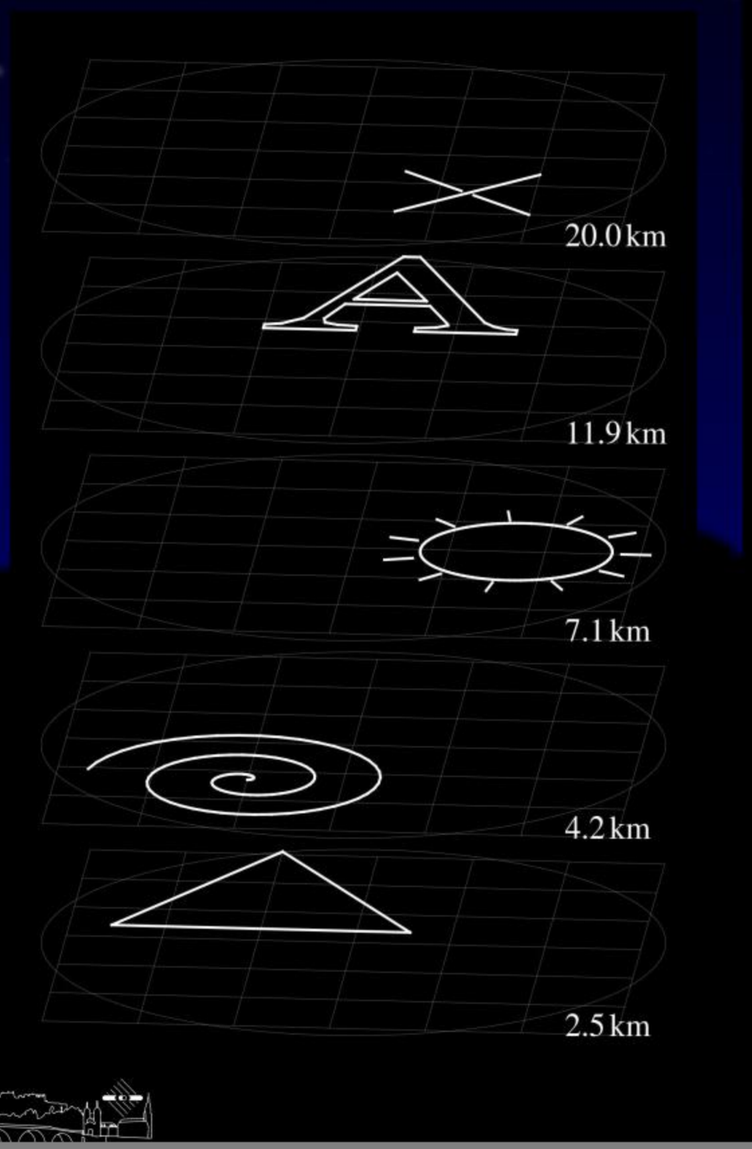
refocussing to any depth

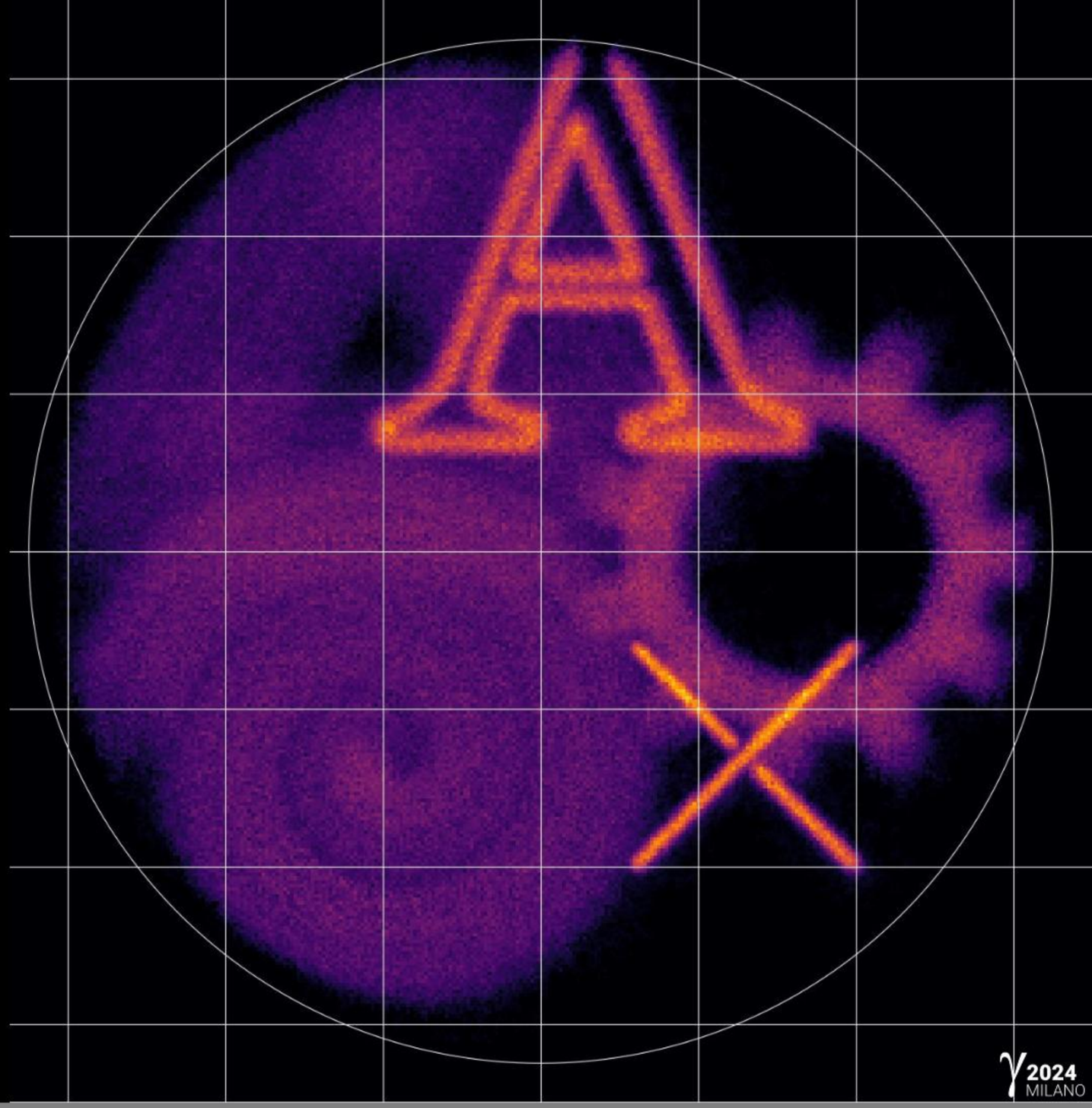




Optics

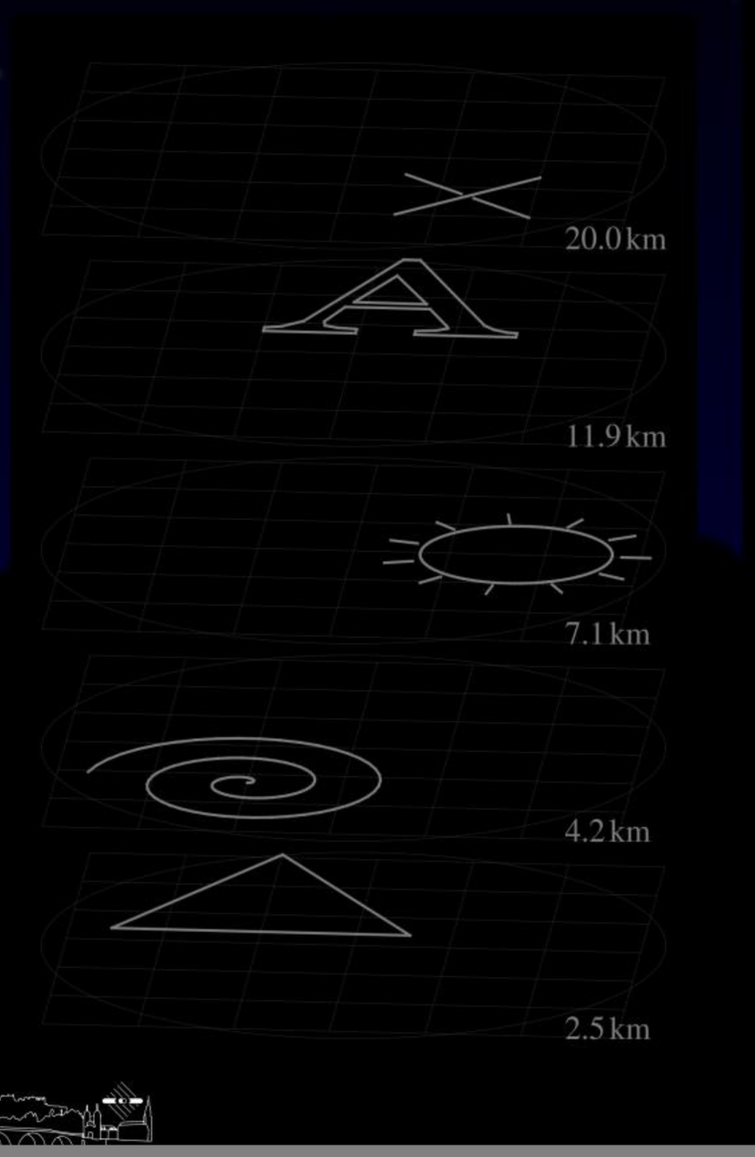
refocussing to any depth

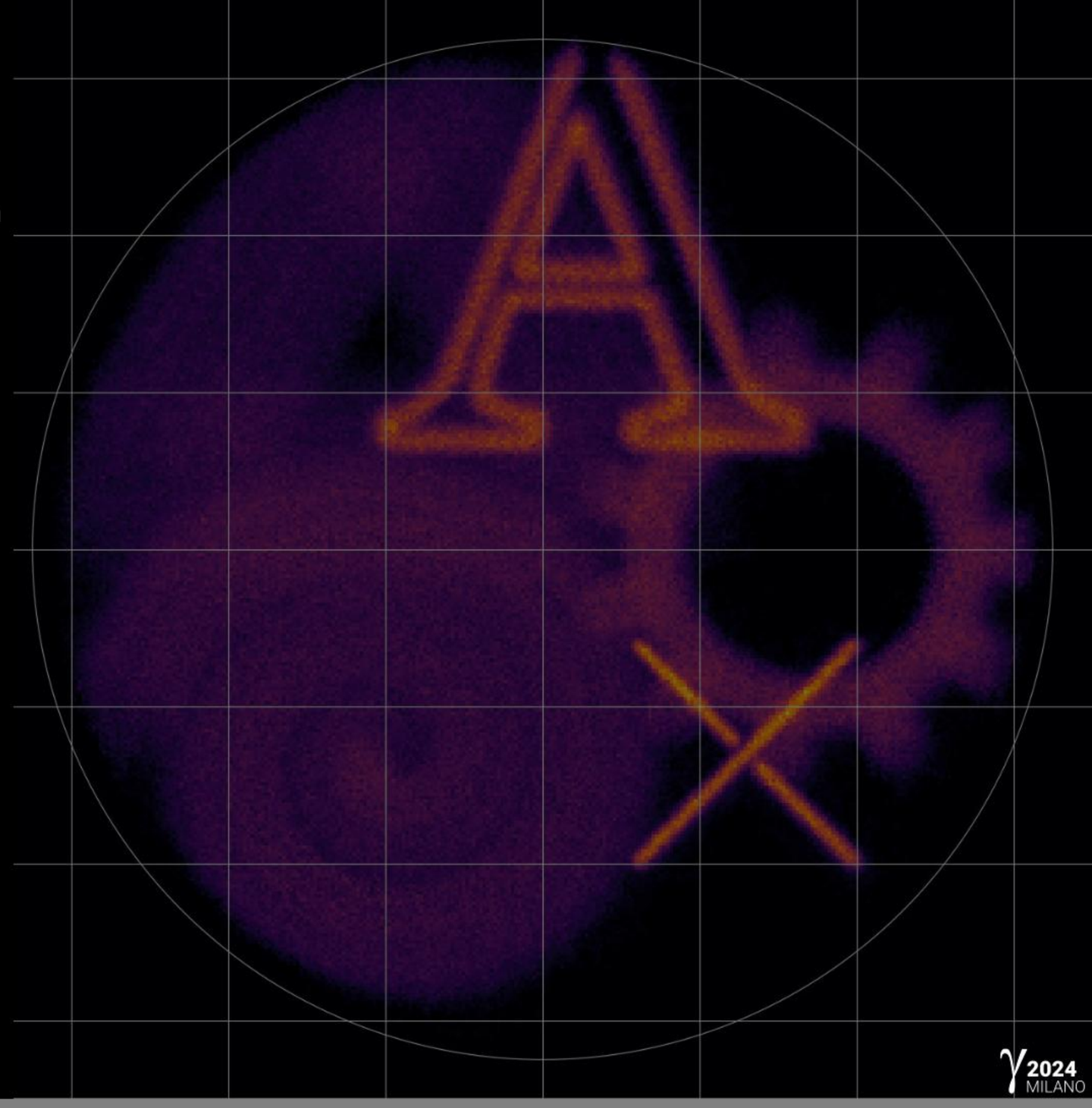




Optics

refocussing to any depth





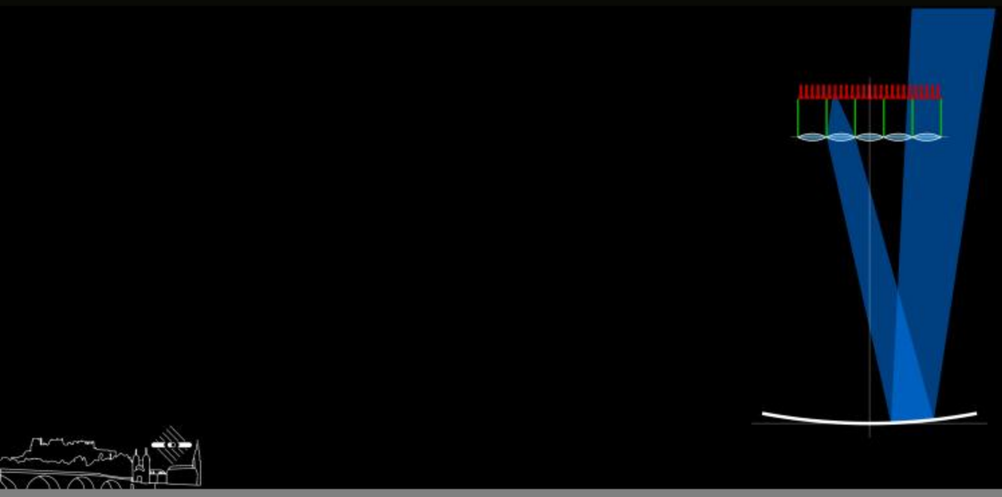
Conclusion

The atmospheric Cherenkov method has a new tool at its disposal.

Conclusion

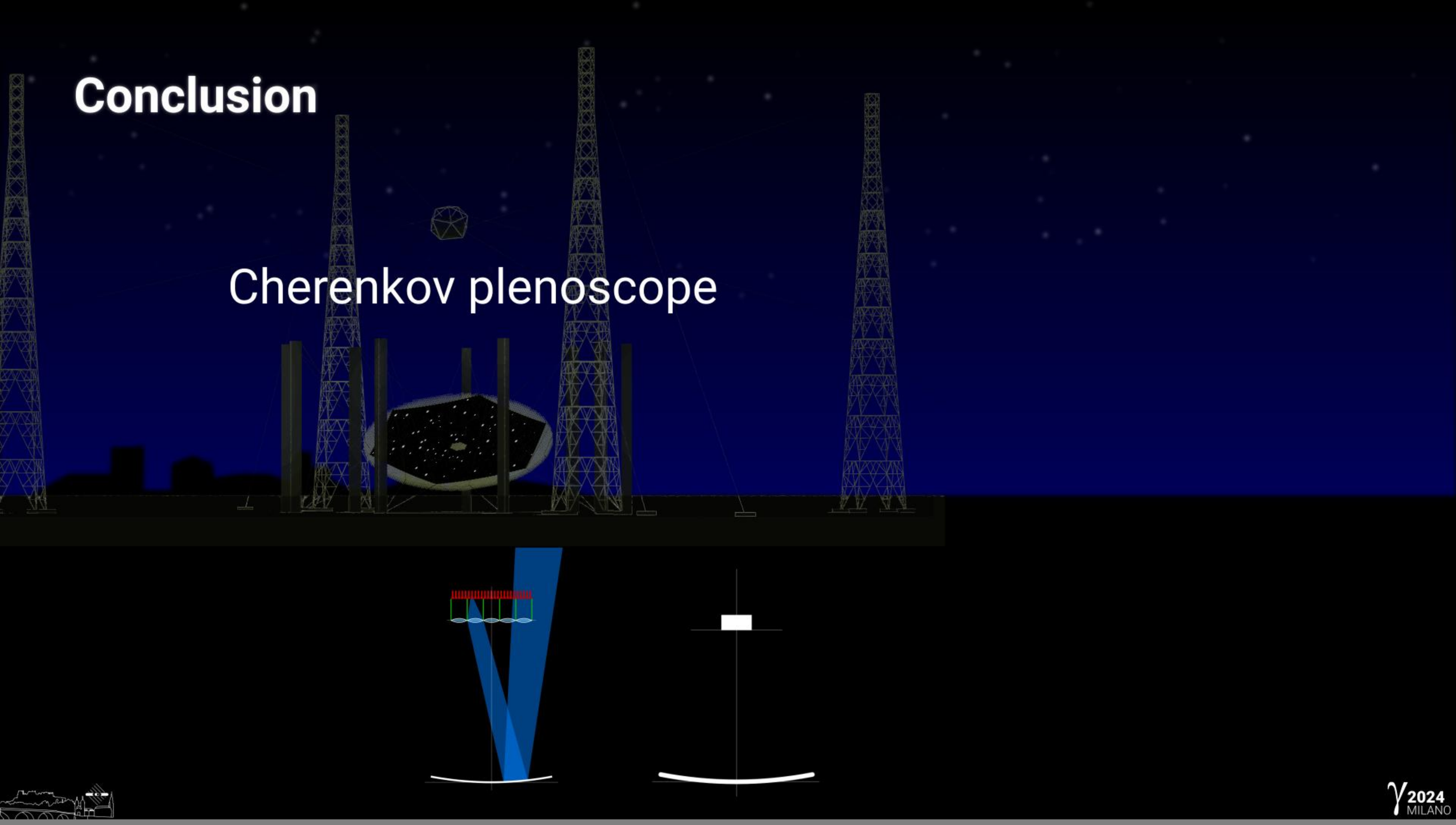
The Cherenkov plenoscope has the potential to push the atmospheric Cherenkov method beyond the physical limts of the telescope.

Conclusion



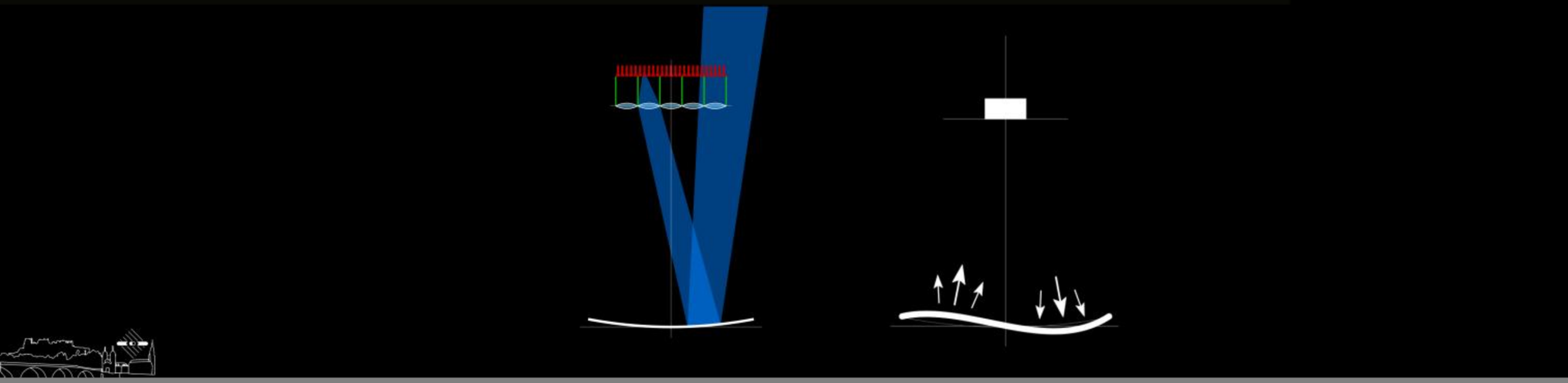
The concept of modelling beams of light and computing images after the fact has great potential to widen the yield-of-view

Conclusion



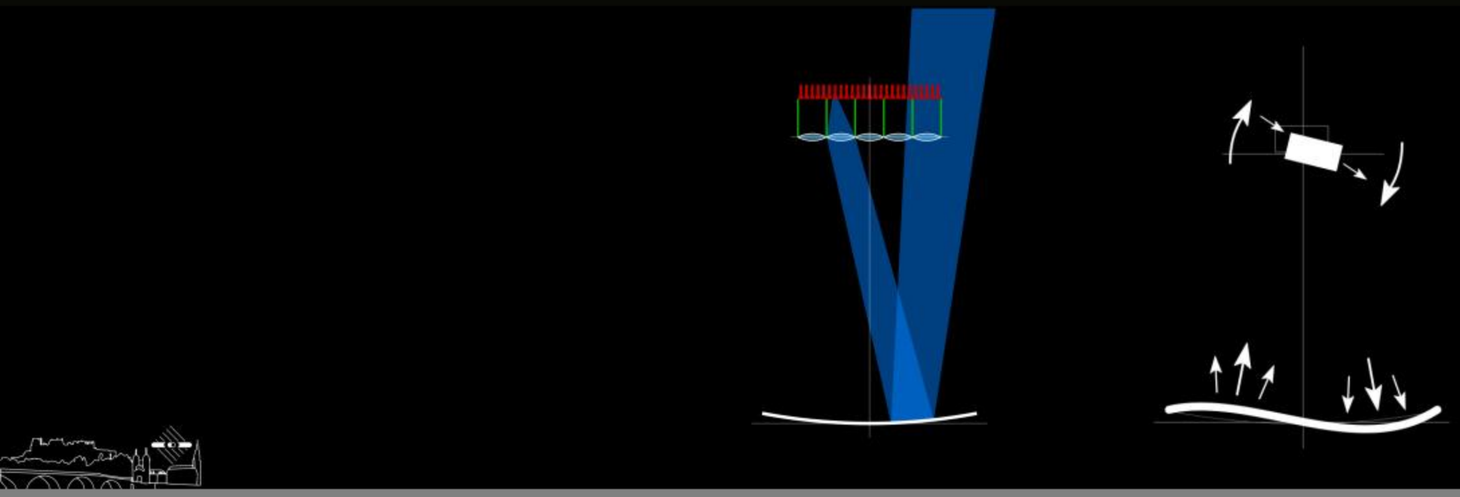
to compensate

Conclusion



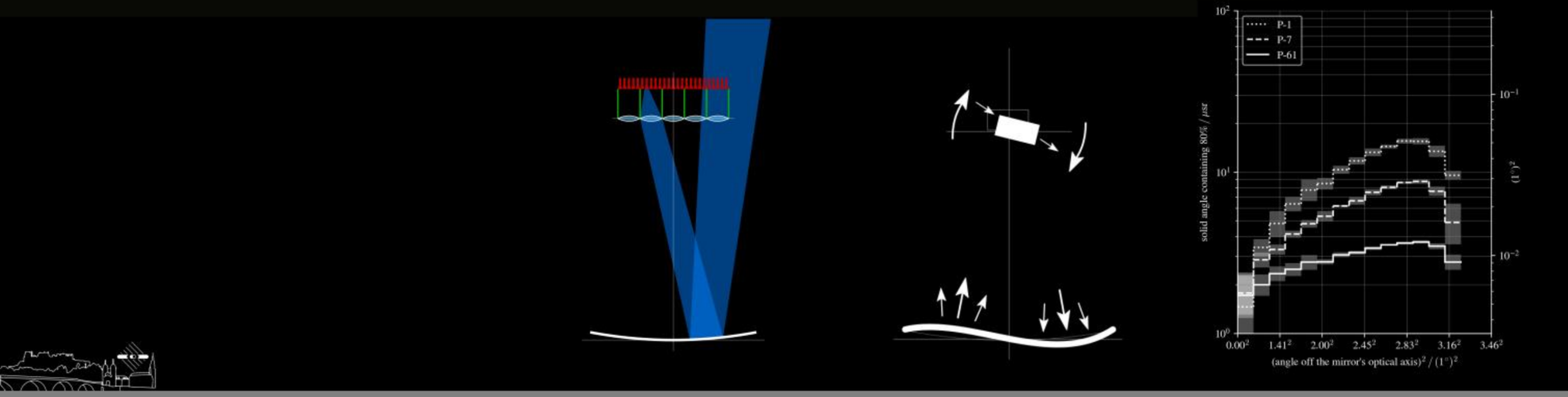
deformations in the mirror,

Conclusion



to compensate misalignments of the camera,

Conclusion



and to effectively overcome astronomy's arch nemesis: aberrations. So the next time when you want to upgrade something, or when you want to build something new, the novel Cherenkov plenoscope will be ready in your toolbox.