

γ 2024
Milano

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MAX-PLANCK-INSTITUT
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Exploring cosmic gamma rays

with the novel Cherenkov plenoscope

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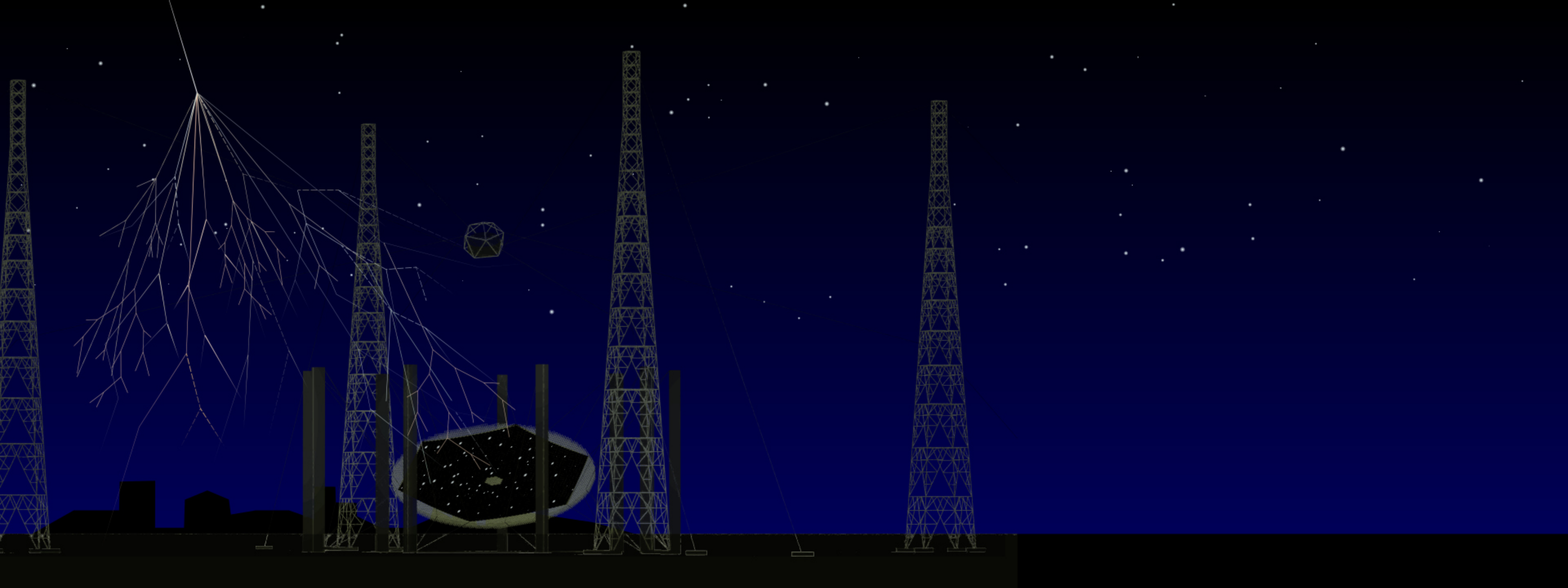
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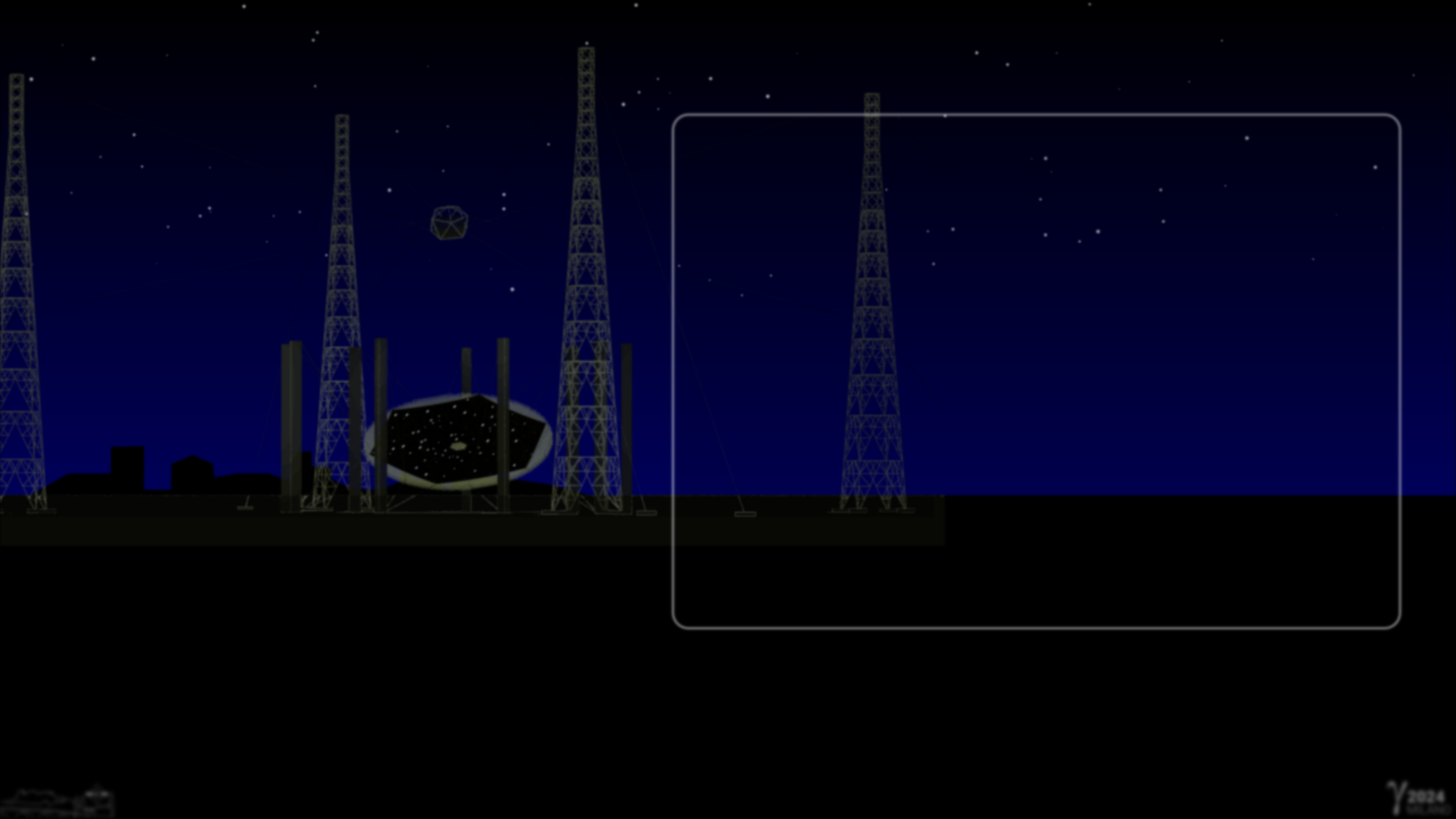


Exploring cosmic gamma rays with the novel Cherenkov plenoscope

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History and limits of telescopes

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,c,*}, Spyridon Daglas^{c,1}, 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-Institut für Nuclear Physics, Saupfercheckweg 1, Heidelberg, 69117, Germany
^b Institute for Particle Physics and Astrophysics, ETH Zurich, Otto-Stern-Weg 5, Zurich, 8093, Switzerland
^c Department of Civil, Environmental and Geomatic Engineering, ETH Zurich, Stefano-Fransoni-Platz 5, Zurich, 8093, Switzerland

ARTICLE INFO

Keywords:
 Timing
 Gamma ray astronomy
 Atmospheric Cherenkov method
 Telescope
 Plenoscope
 Optics
 Light field
 Tomography
 Mirror
 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 merging celestial bodies, apparently random bursts of gamma rays, recording neutrino-lensing systems, flaring jets from active galactic nuclei, clashing galaxies, and more must become a critical contribution 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 detect 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 push the concept of the *big/old*-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/plenous*-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



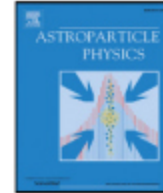


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History and limits of telescopes

Combining the atmospheric Cherenkov method with plenoptic perception

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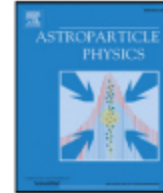


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Portal, a possible future 1GeV 'gamma ray timing explorer'

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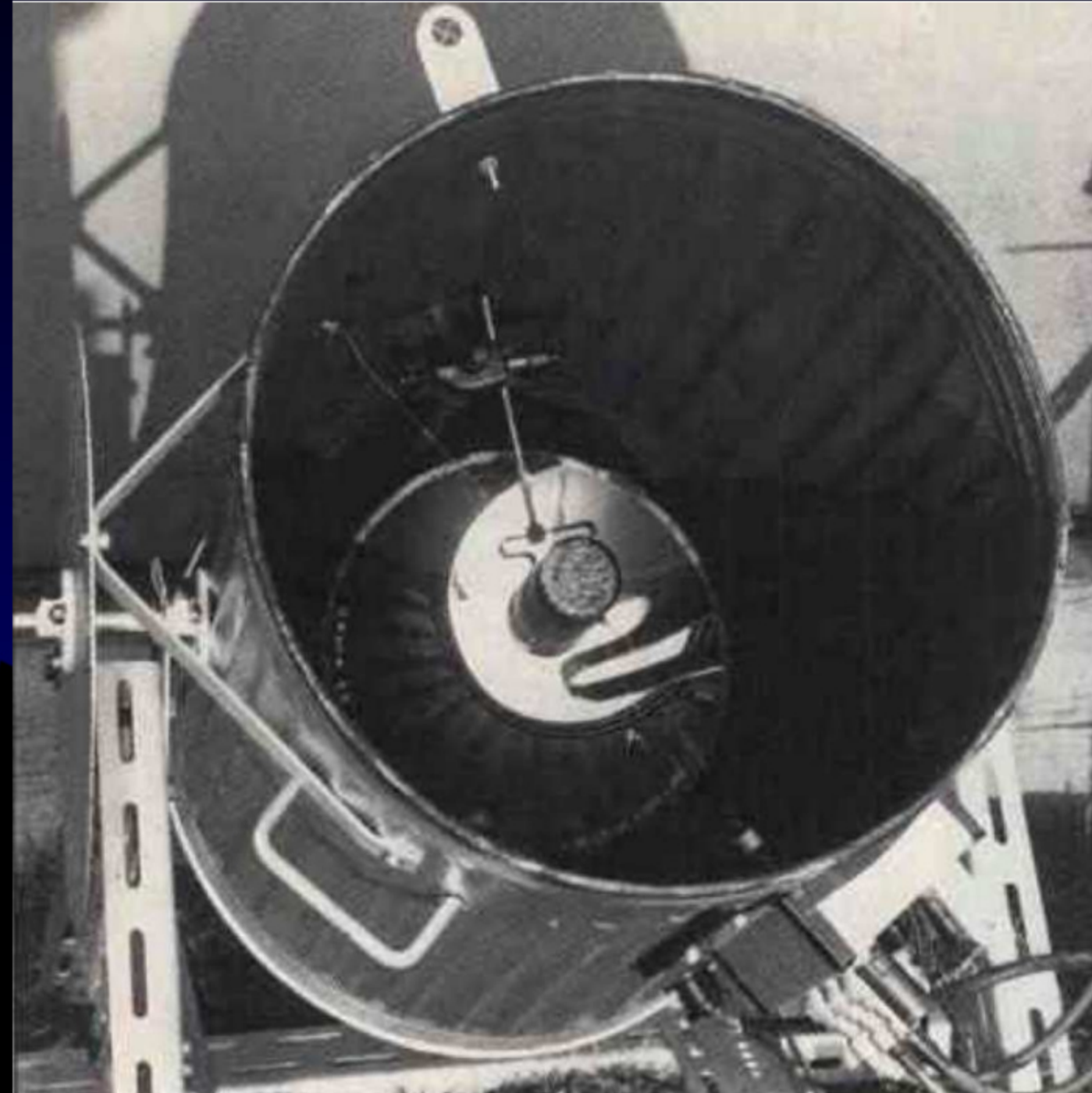




Imaging with Telescopes



Imaging with Telescopes



1950s

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



Imaging with Telescopes



1980s

Michael A. Hillas, 1985
Cerenkov light images of EAS produced by primary gamma,
ICRC 1985, Vol.3



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



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.



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.



Imaging with Telescopes



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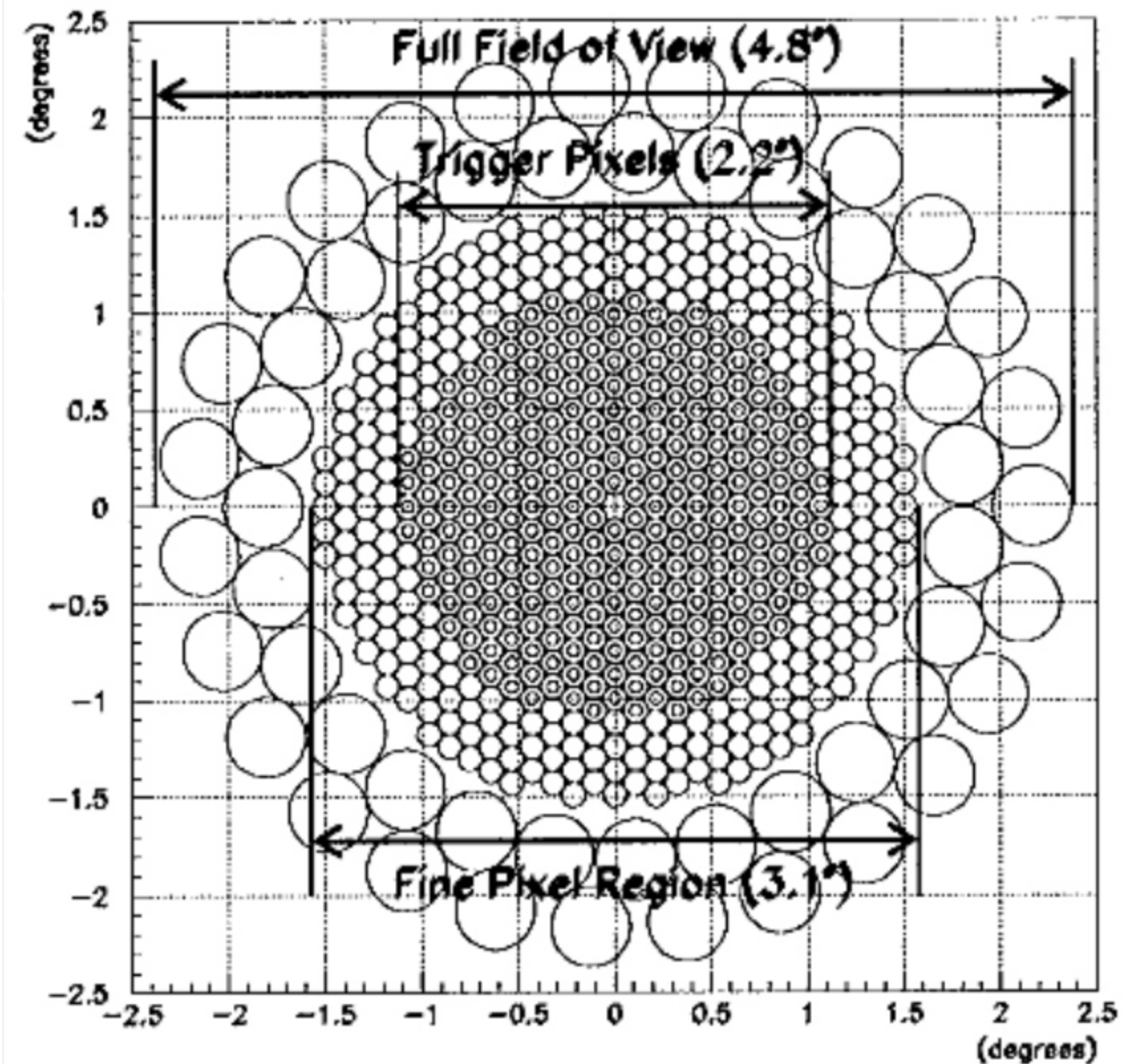
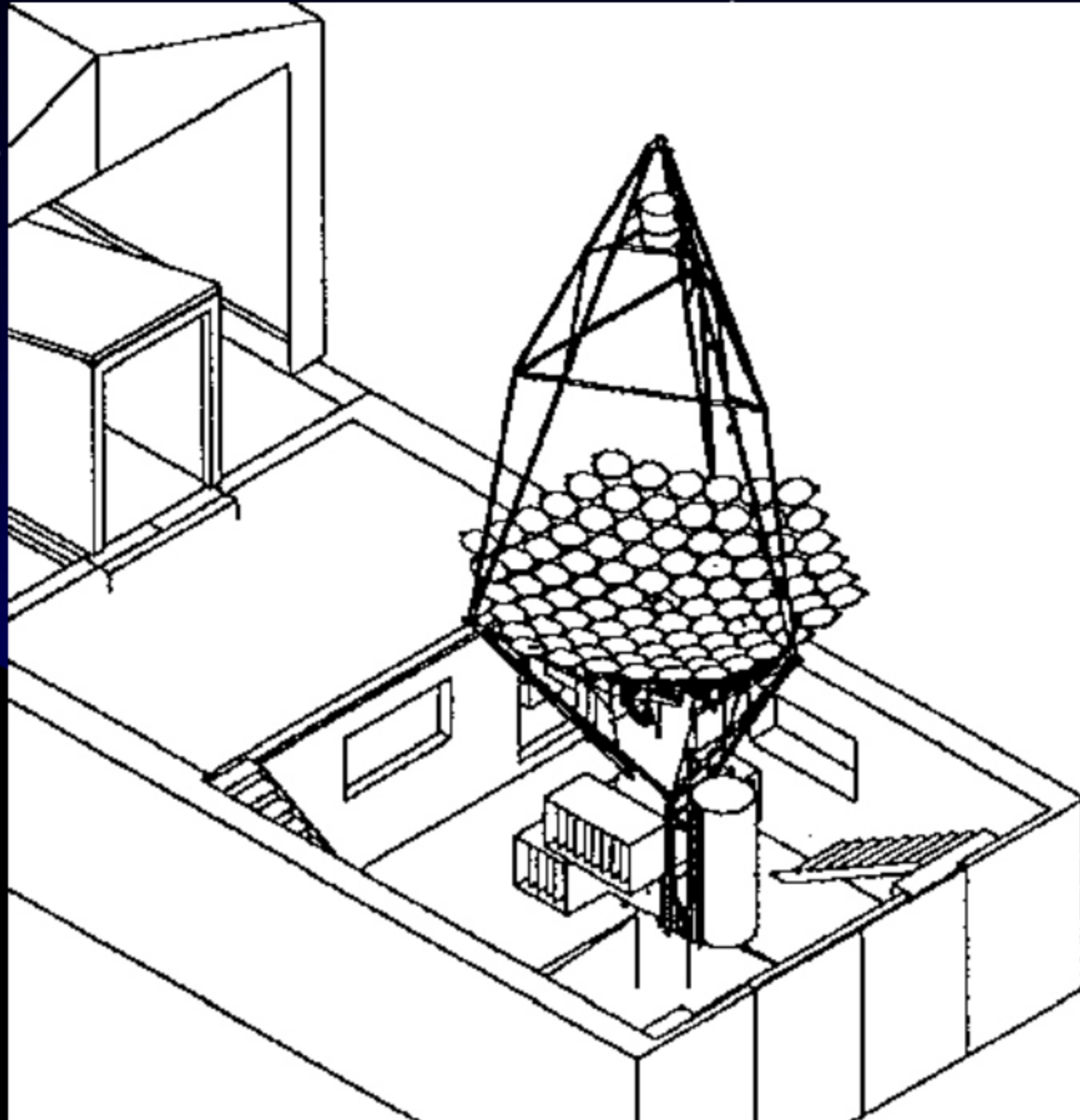
Imaging with Telescopes



Towards a major atmospheric Cherenkov detector for TeV astroparticle physics.

1992

Imaging with Telescopes

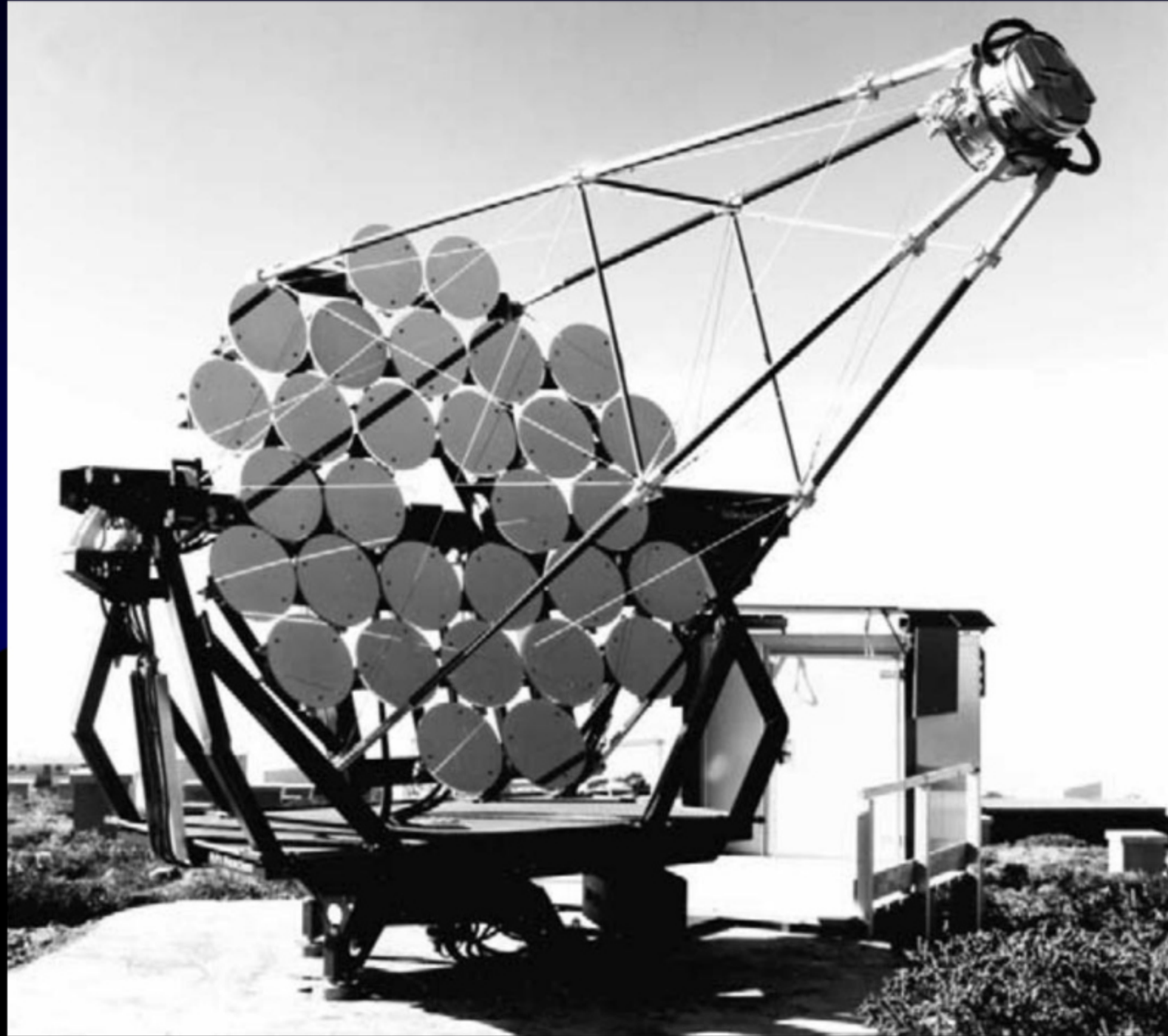


1996

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



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



Imaging with Telescopes

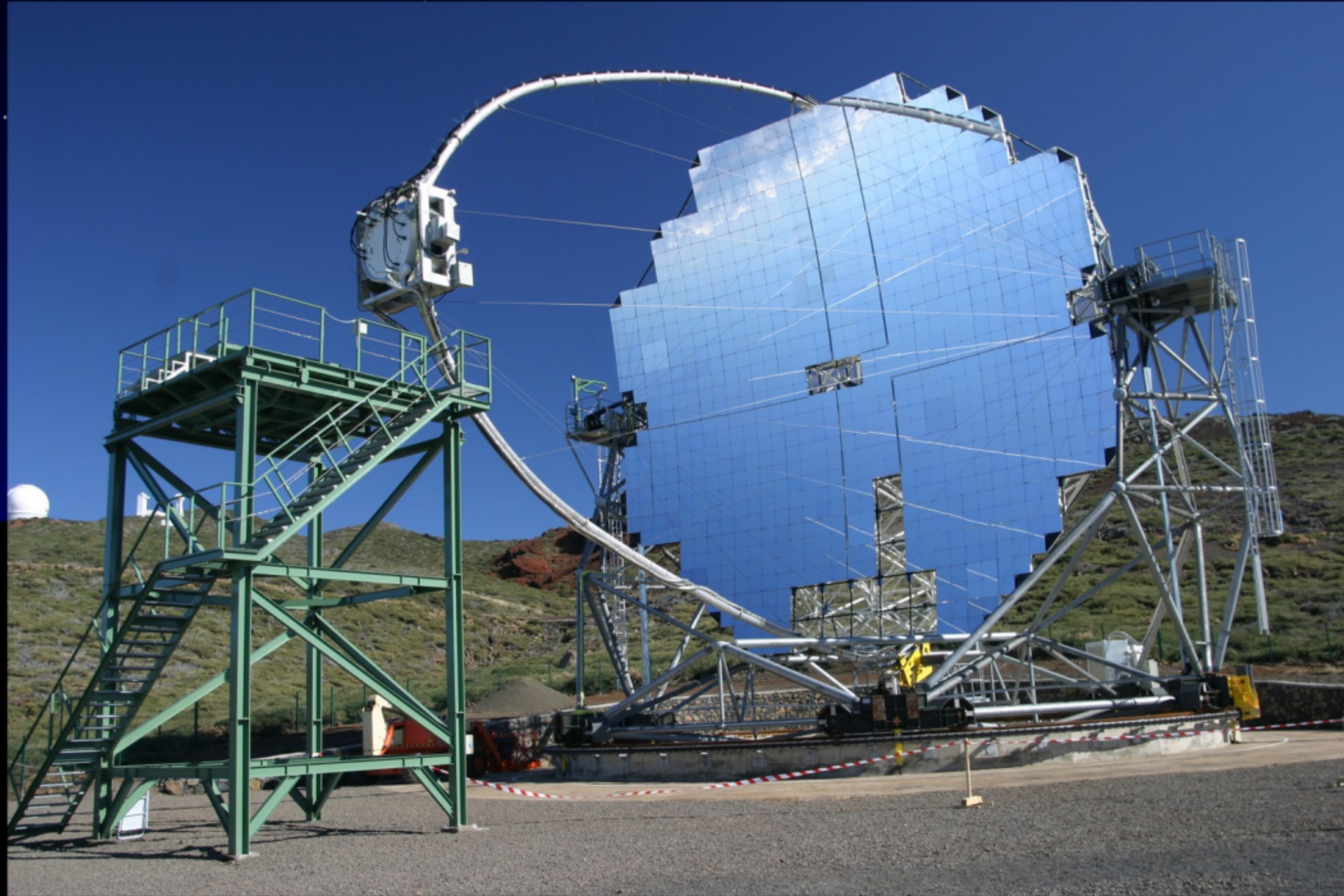


2002 - 2004

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



Imaging with Telescopes



2003

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



Imaging with Telescopes



2009

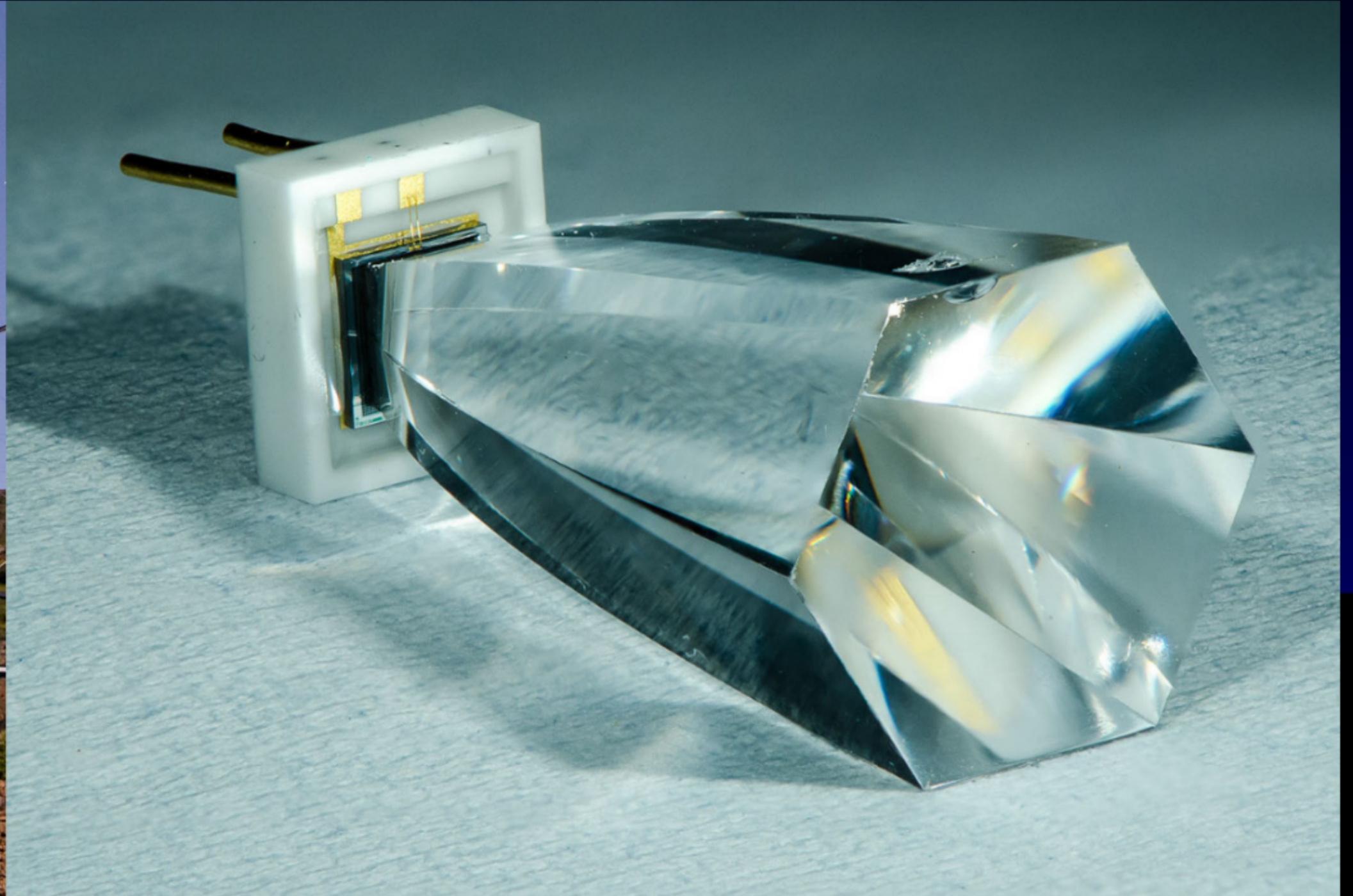
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<https://magic.mpp.mpg.de/gallery/pictures/Inauguration/index.html>



Imaging with Telescopes



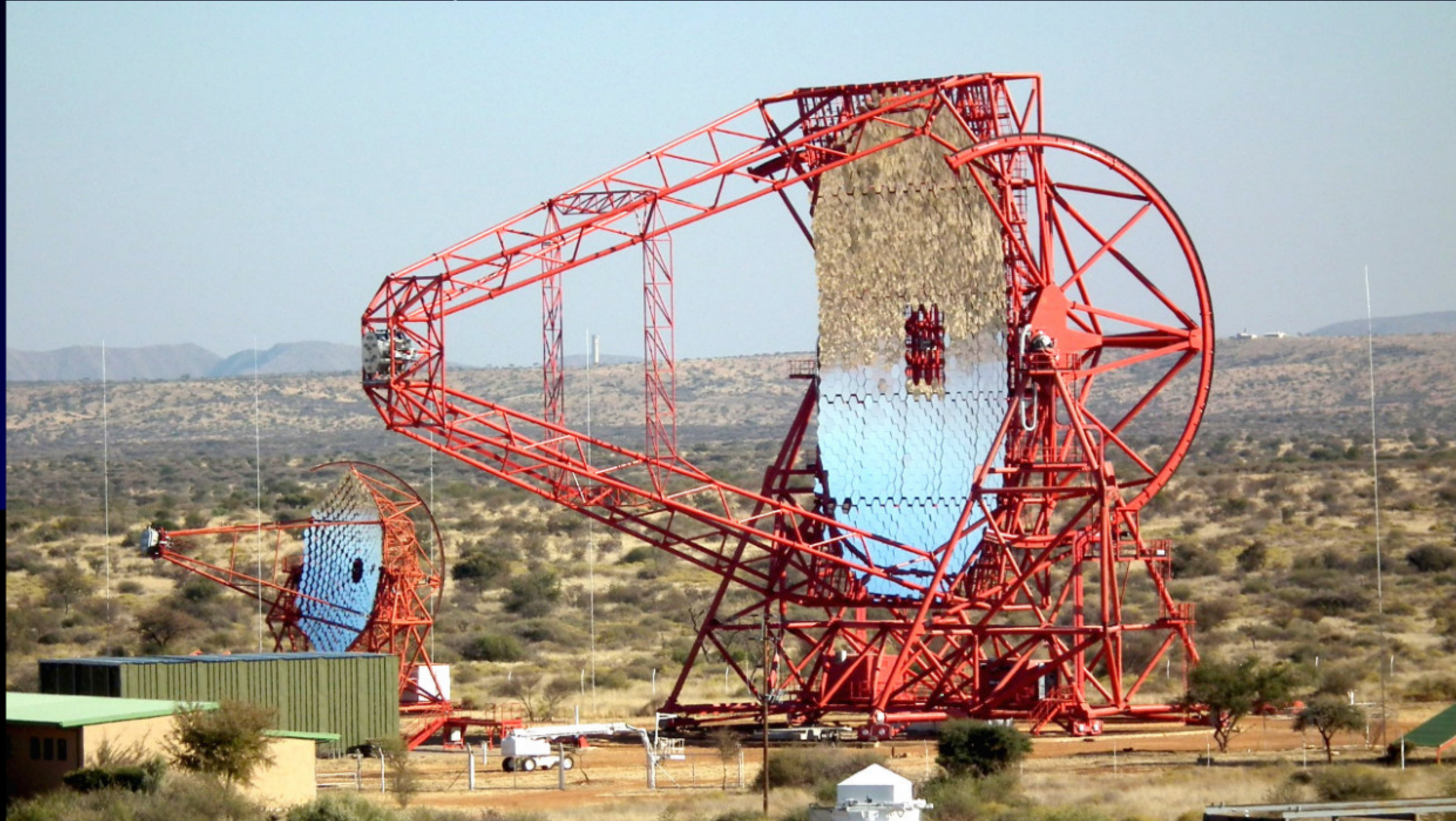
Credit: Jens B. Buss



Credit: Thomas Kraehenbuehl

2011

Imaging with Telescopes

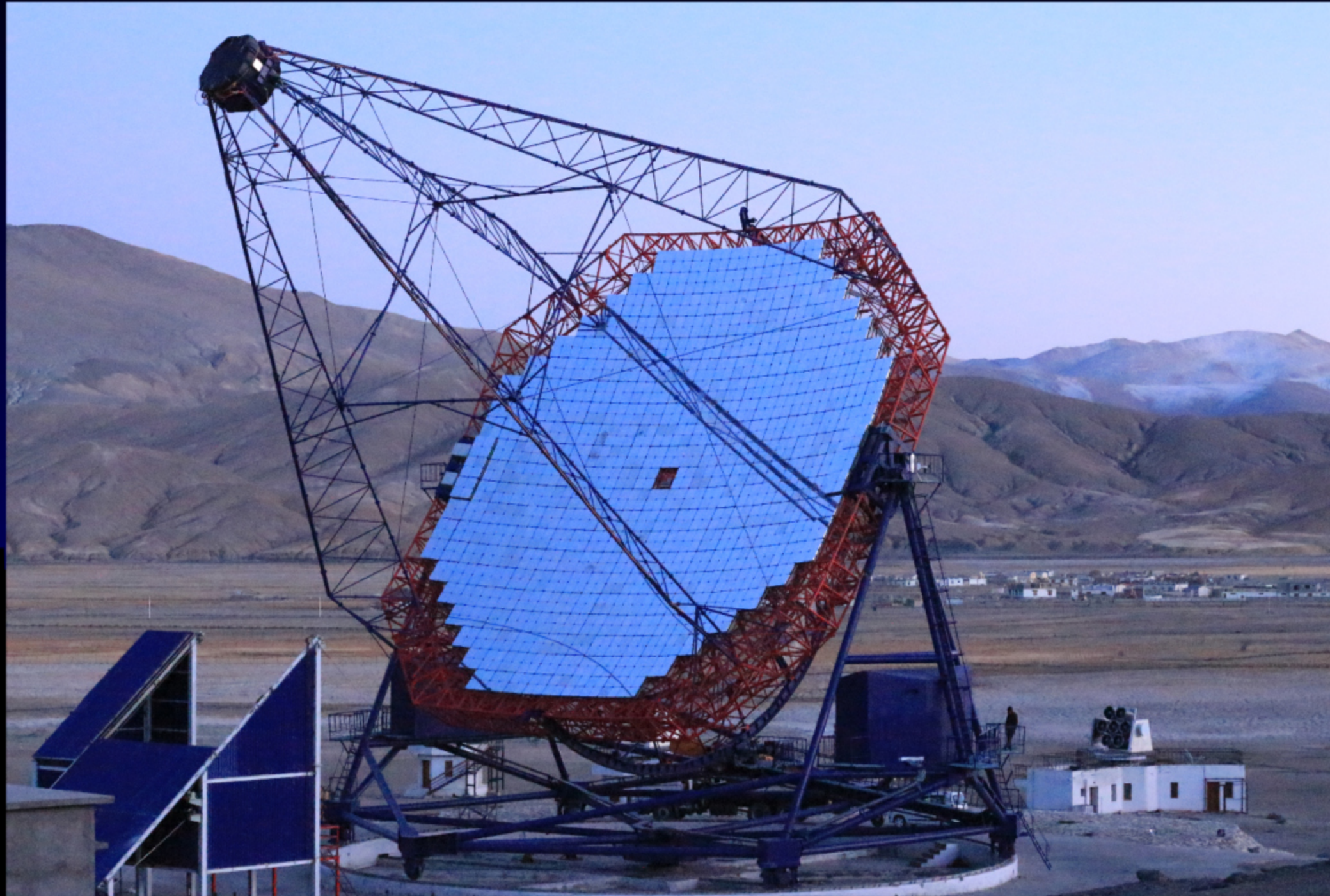


2012

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



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



Imaging with Telescopes



Credit: Tomohiro Inada

2018



Imaging with Telescopes



2019

Fred Lawrence Whipple Observatory Amado AZ 2019-01-17
<https://cta-psct.physics.ucla.edu/news.html>



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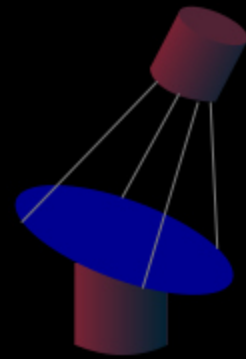


future?

Fred Lawrence Whipple Observatory Amado AZ 2019-01-17
<https://cta-psct.physics.ucla.edu/news.html>

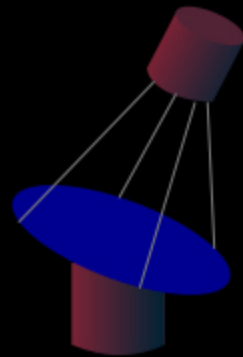


Limits of Telescopes



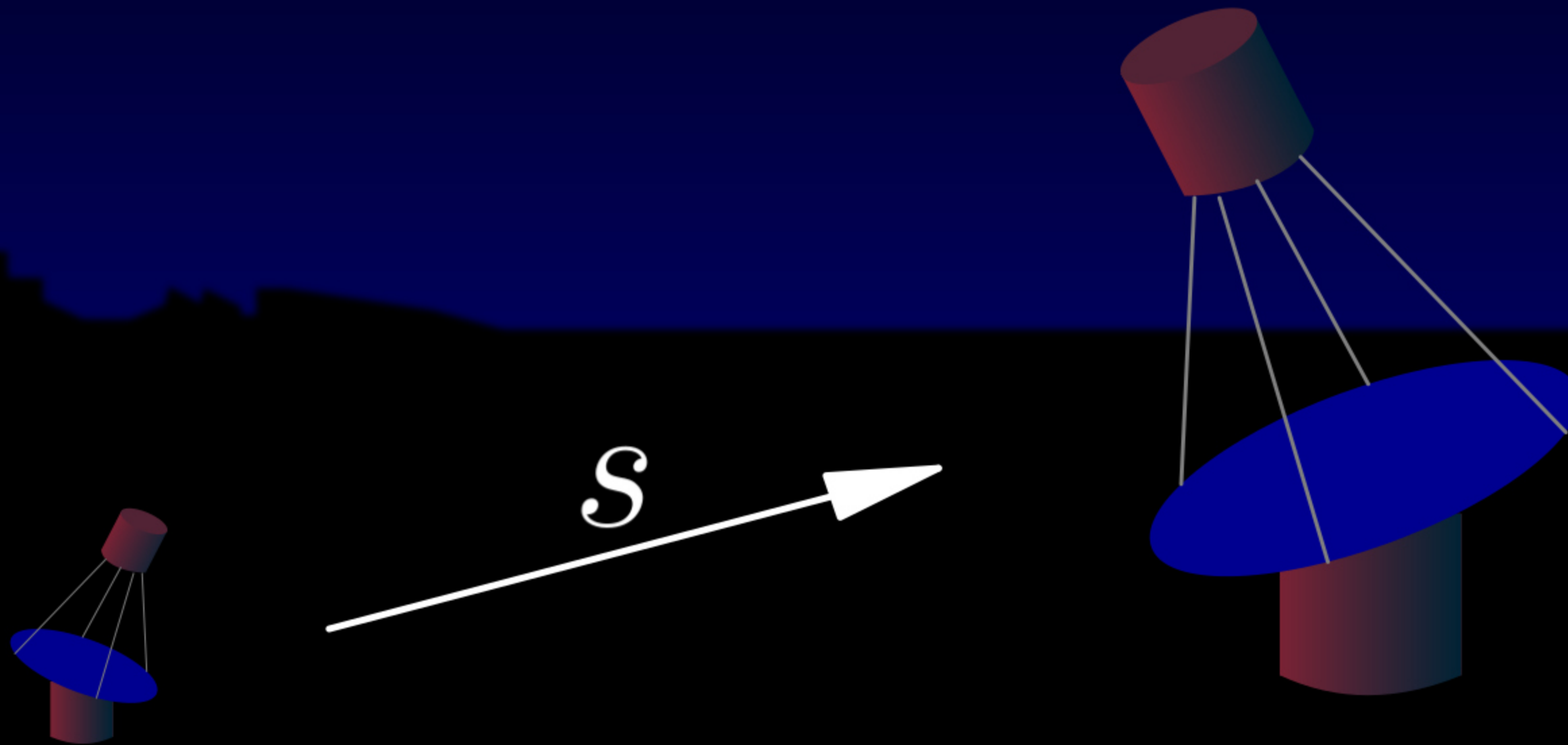
Limits of Telescopes

square-cube-law



Limits of Telescopes

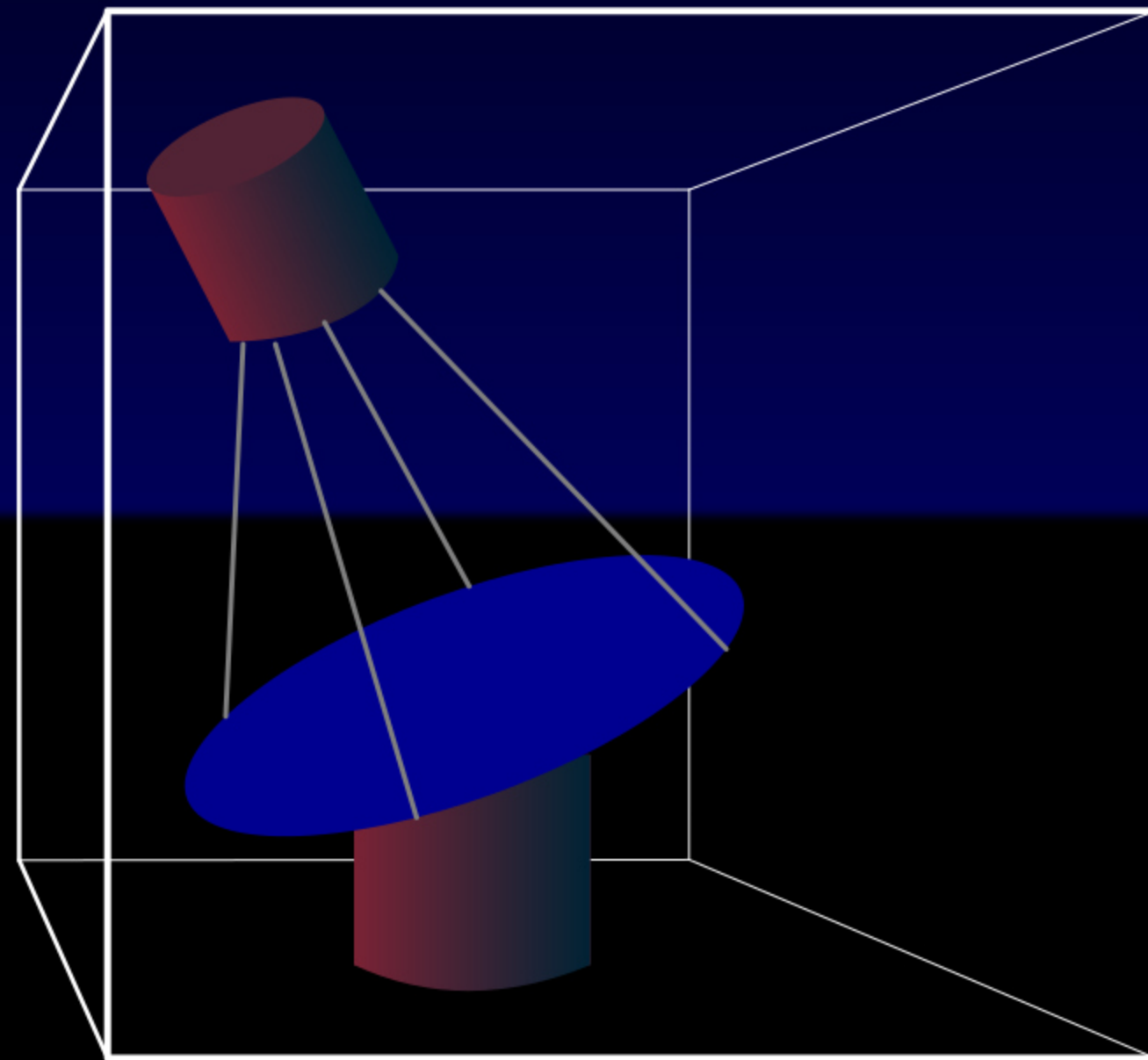
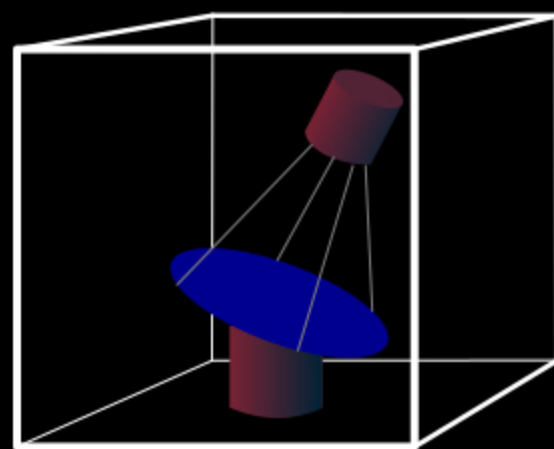
square-cube-law



Limits of Telescopes

square-cube-law

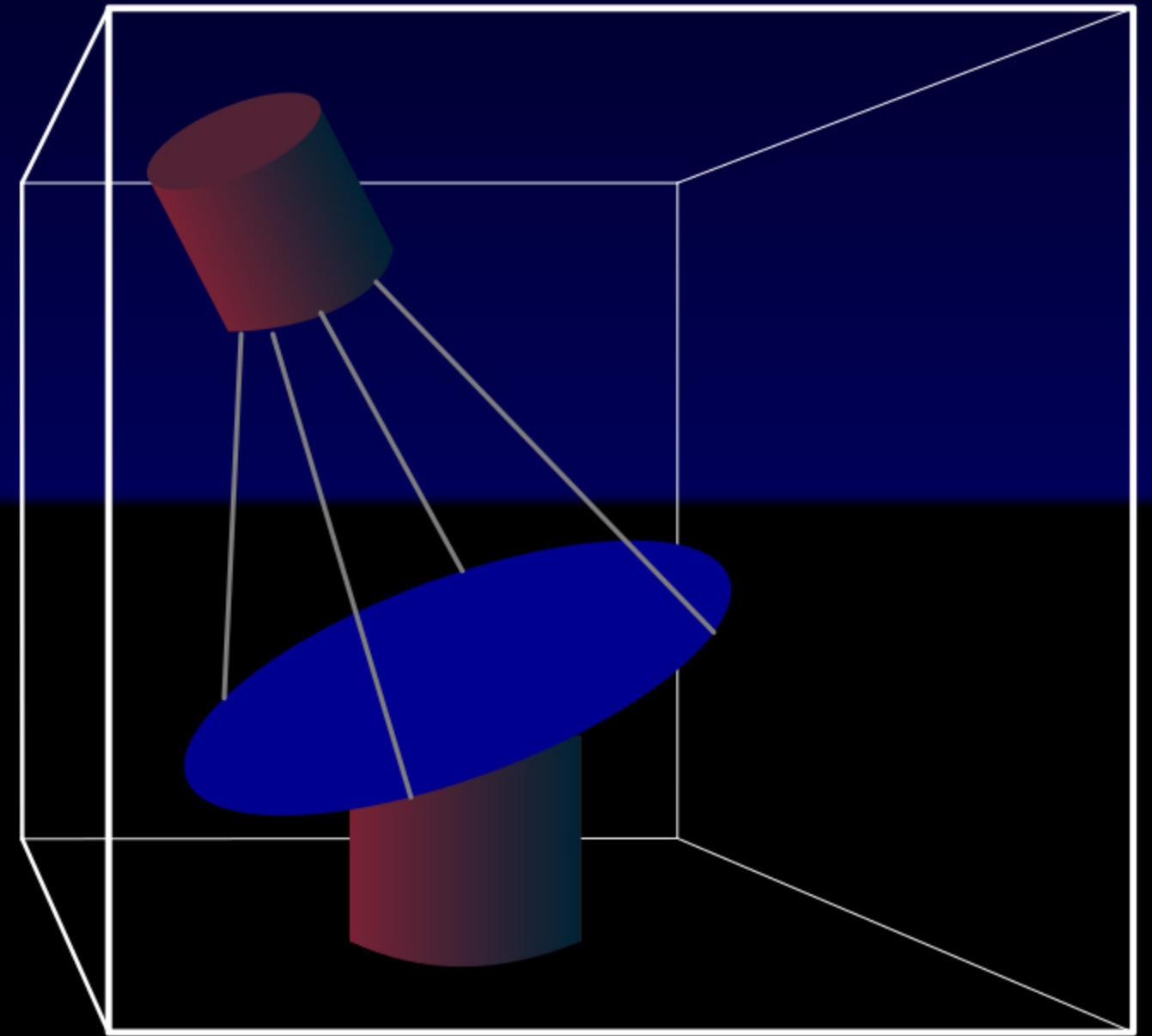
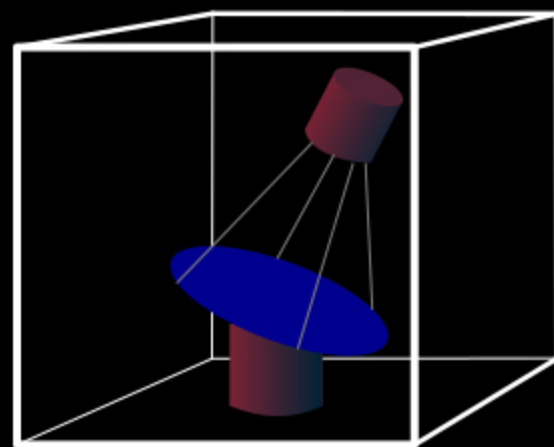
$$V \propto s^3$$



Limits of Telescopes

square-cube-law

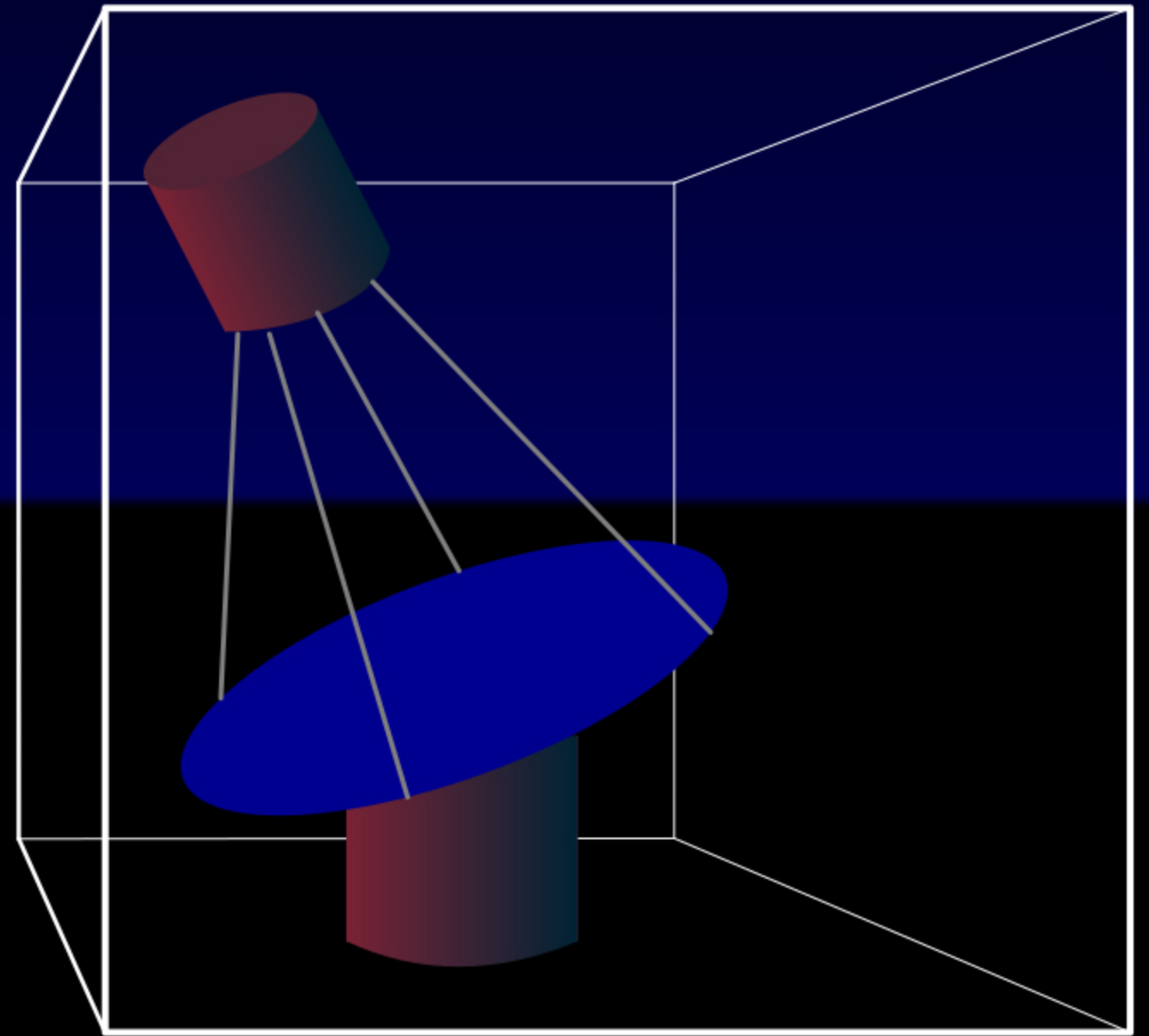
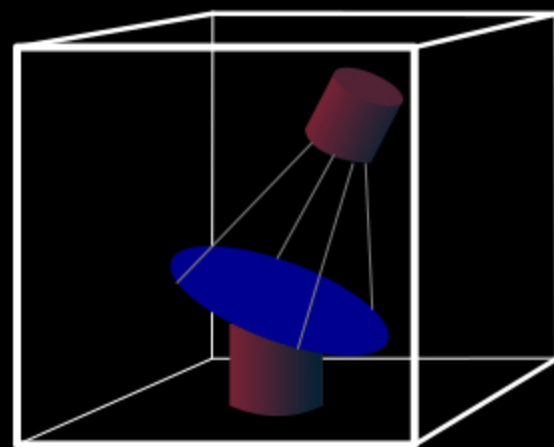
$$m \propto s^3$$



Limits of Telescopes

square-cube-law

$$F \propto s^3$$

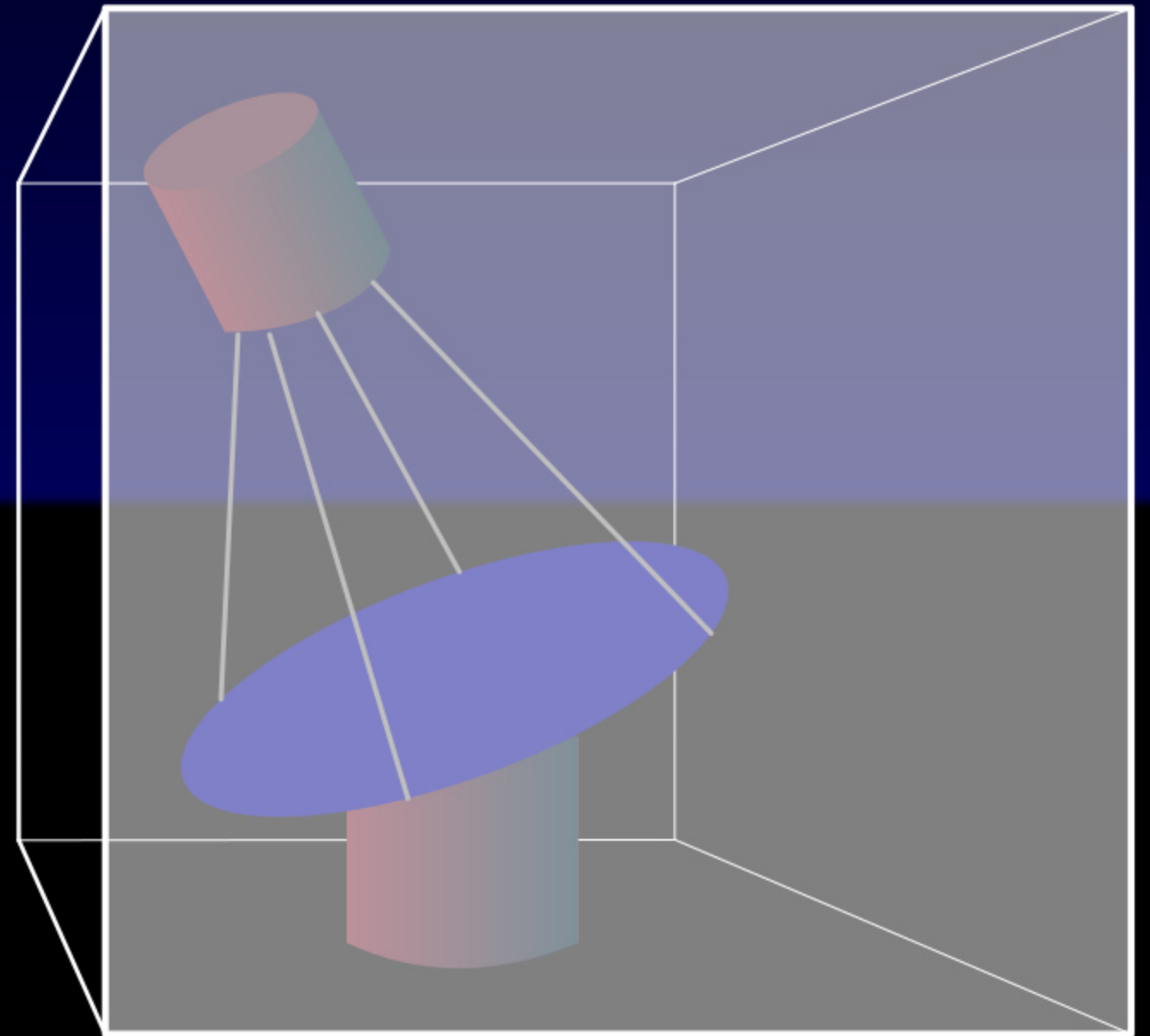
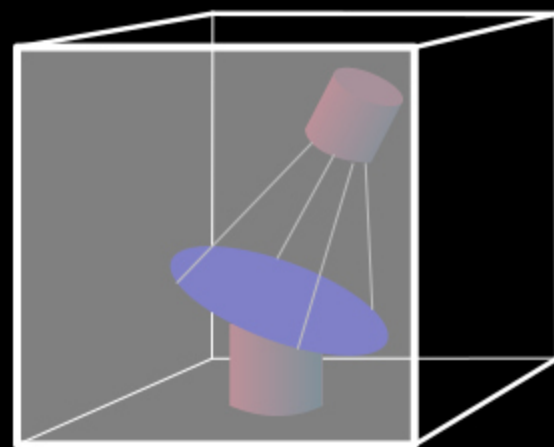


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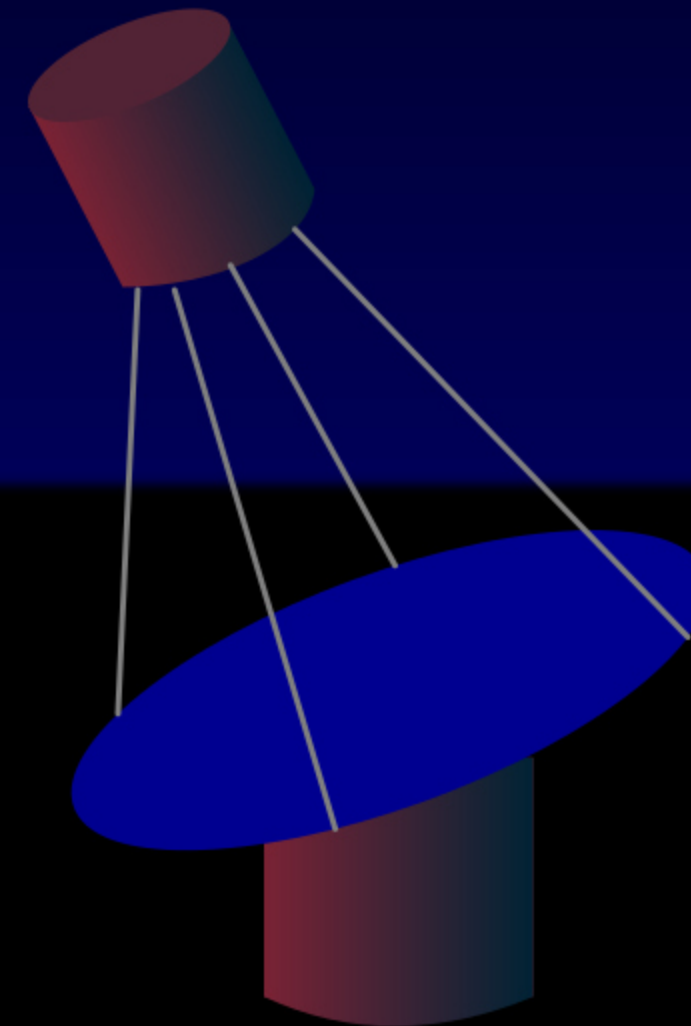
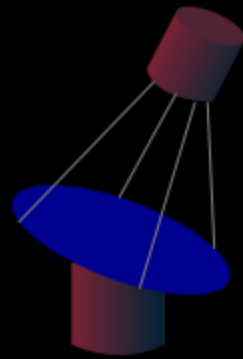
$$F \propto s^3$$

$$A \propto s^2$$



Limits of Telescopes

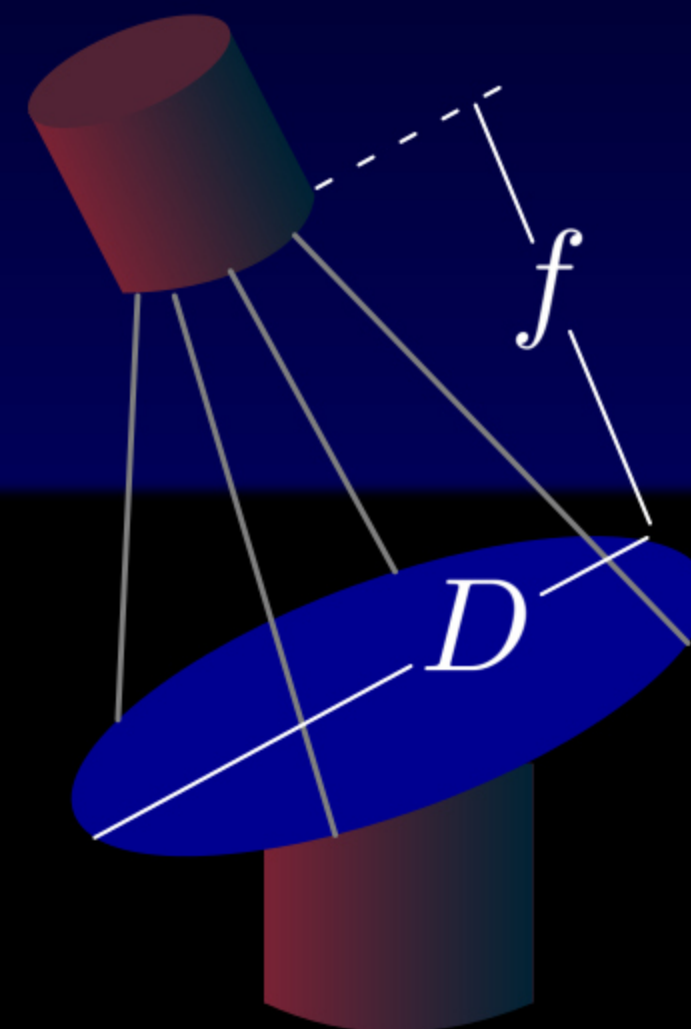
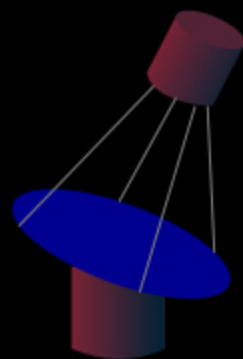
depth-of-field



Limits of Telescopes

depth-of-field

larger (D, f)

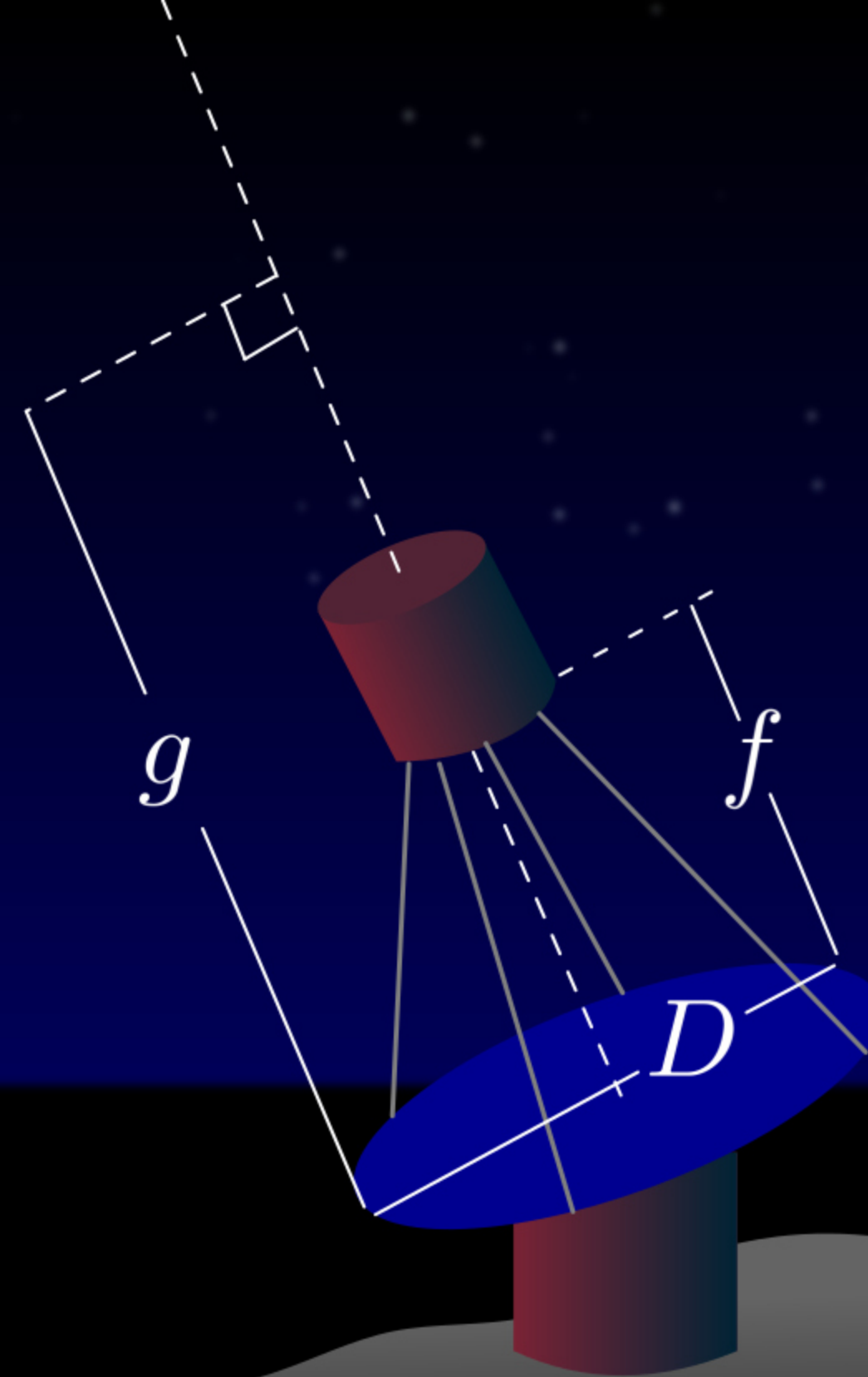


Limits of Telescopes

depth-of-field

larger (D, f)

on mountains, closer to shower (g)



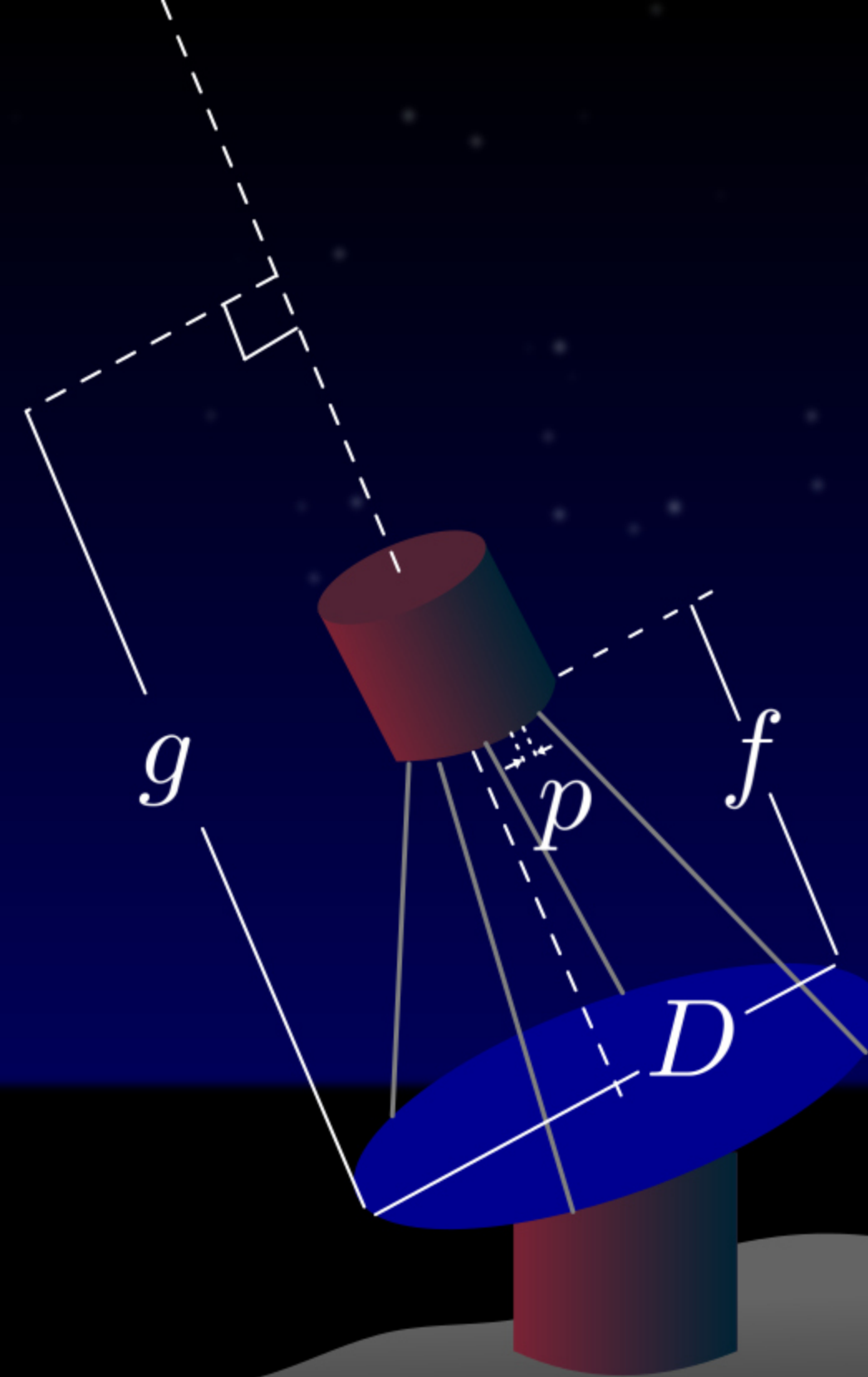
Limits of Telescopes

depth-of-field

larger (D, f)

on mountains, closer to shower (g)

smaller pixels (p)



Limits of Telescopes

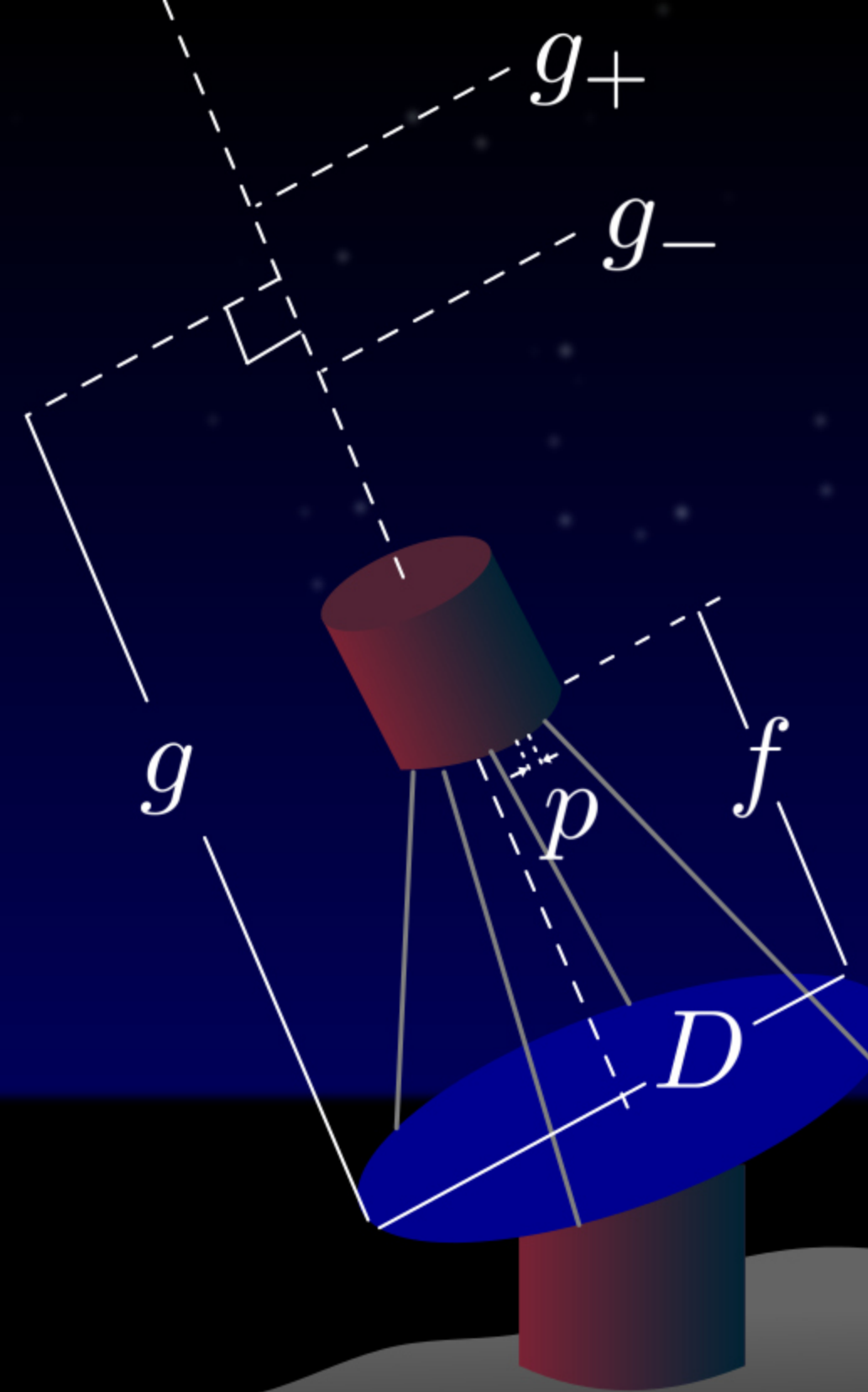
depth-of-field

larger (D, f)

on mountains, closer to shower (g)

smaller pixels (p)

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



K. Bernloehr et al. 2013

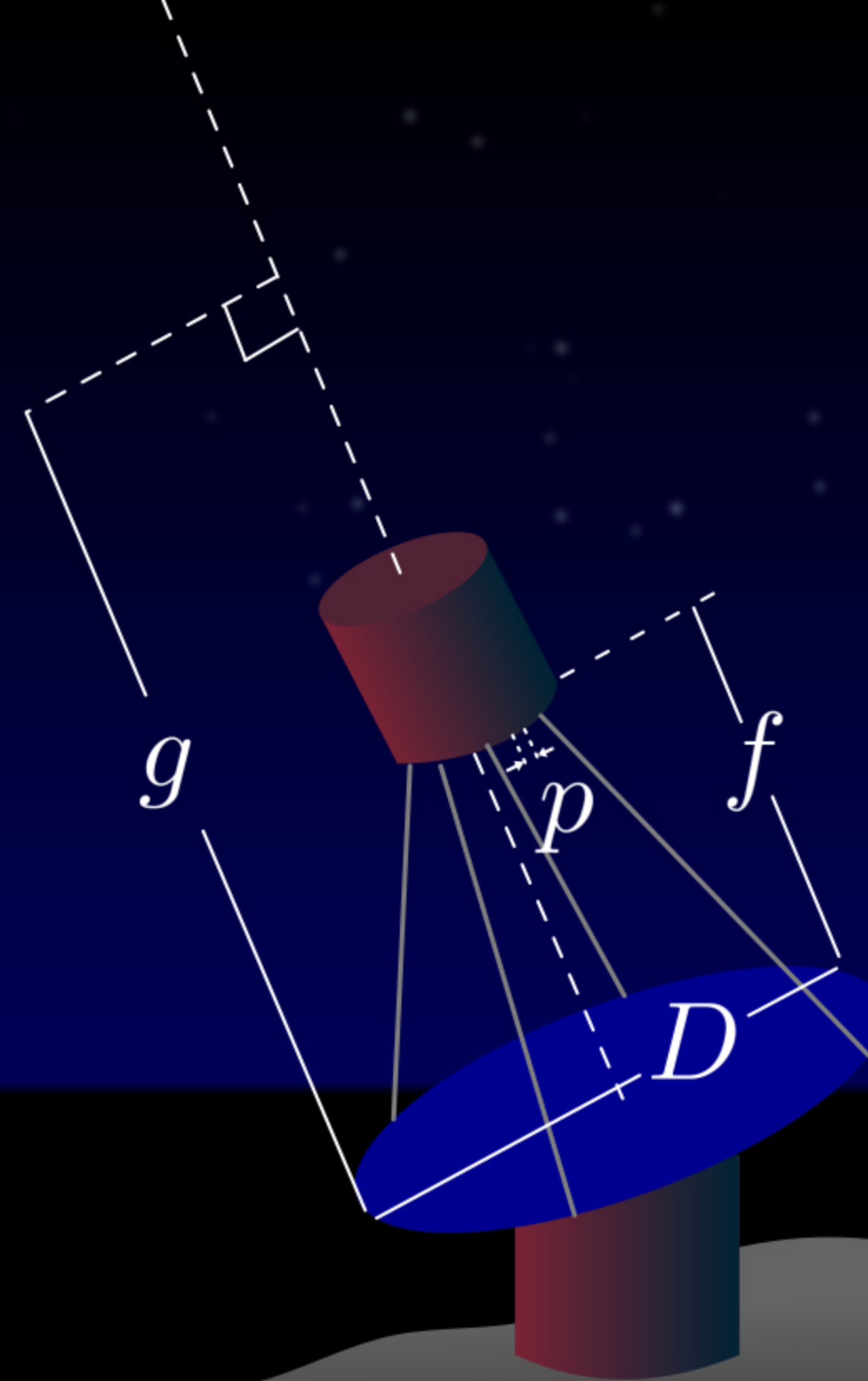
Monte Carlo design studies for the Cherenkov Telescope Array

Astroparticle Physics, vol.43 p.171-188



Limits of Telescopes

depth-of-field



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



K. Bernloehr et al. 2013

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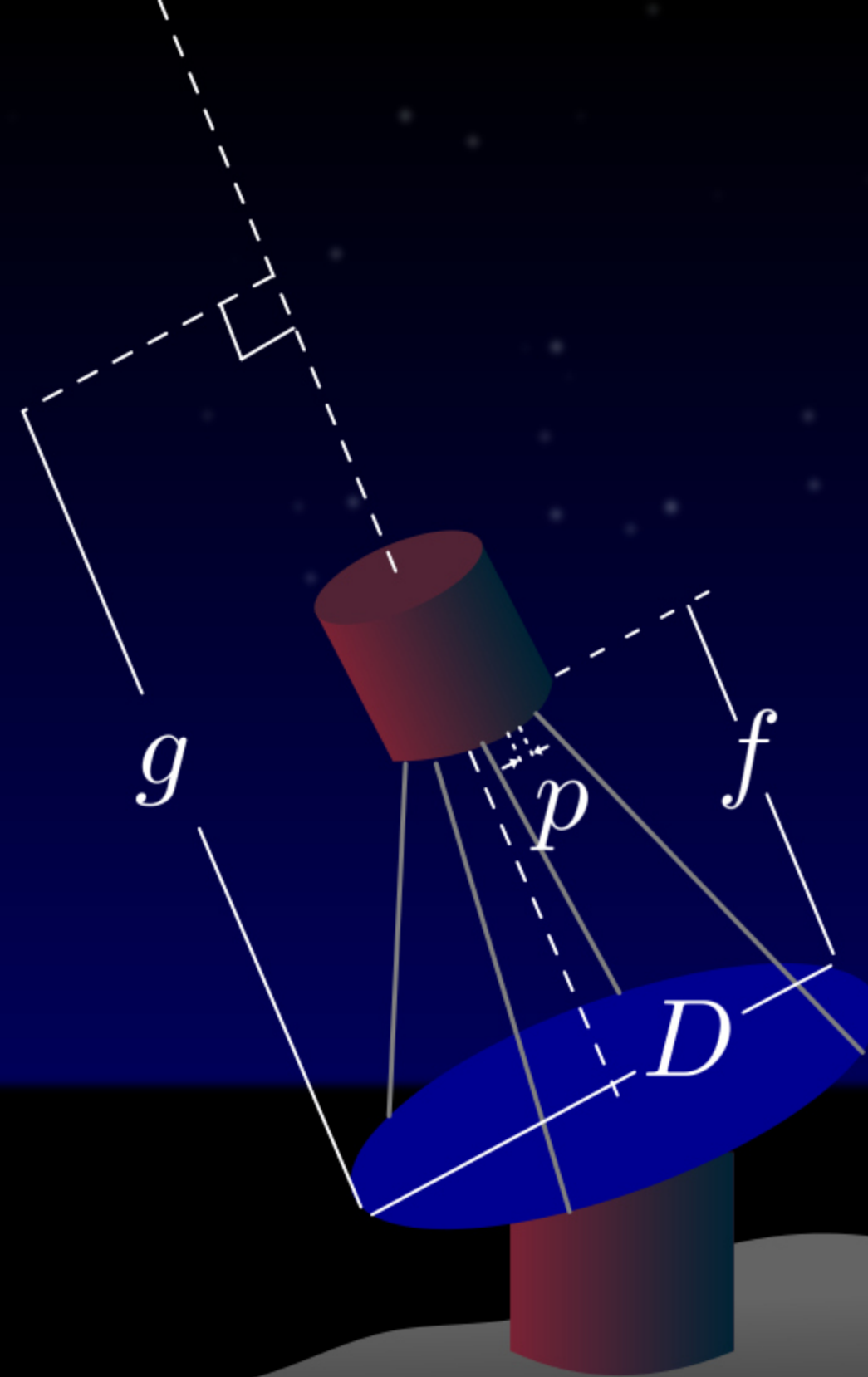
Astroparticle Physics, vol.43 p.171-188

Limits of Telescopes

depth-of-field

$$D = 71 \text{ m}$$

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



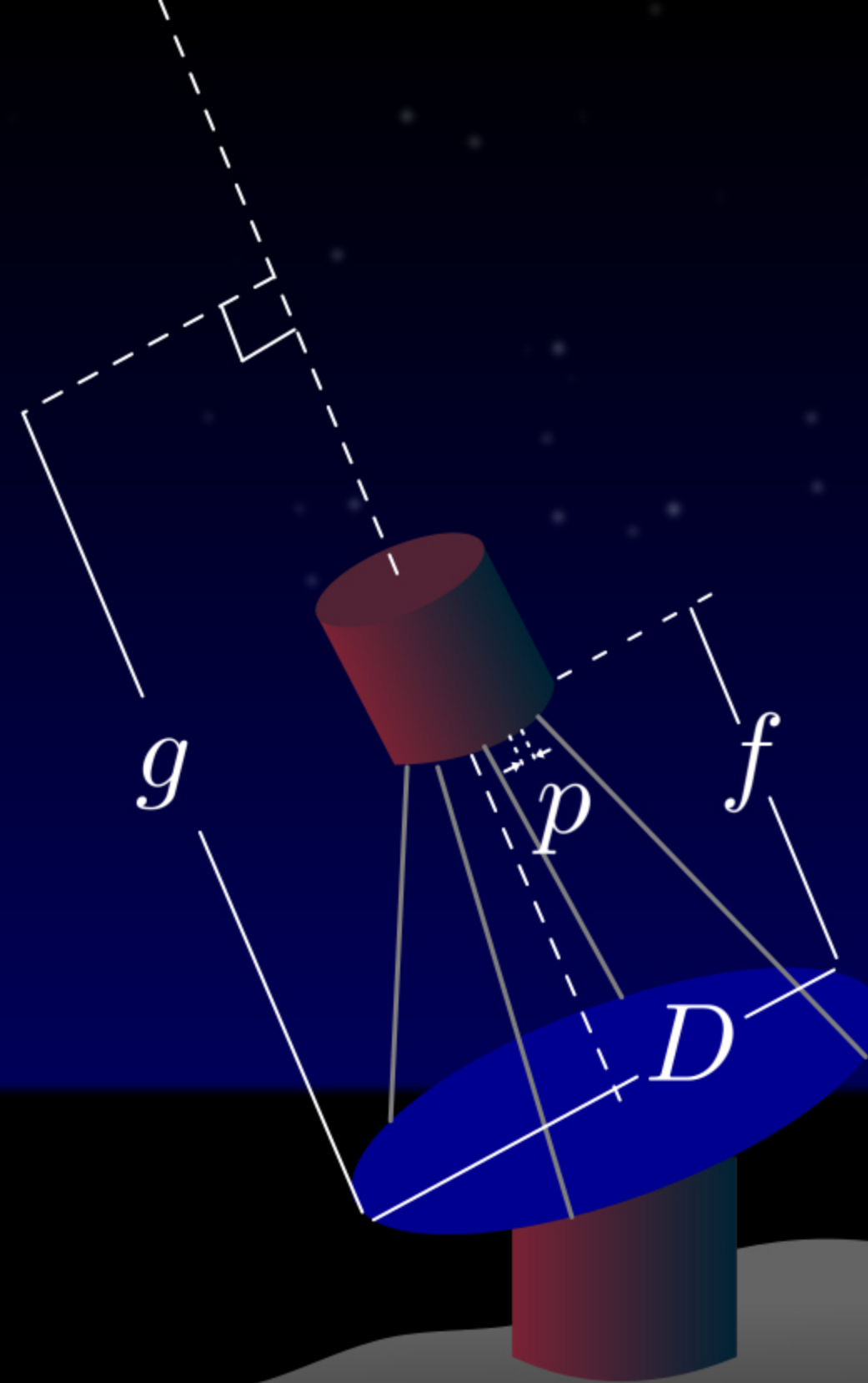
Limits of Telescopes

depth-of-field

$$D = 71 \text{ m}$$

$$f/D = 1.5$$

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



Limits of Telescopes

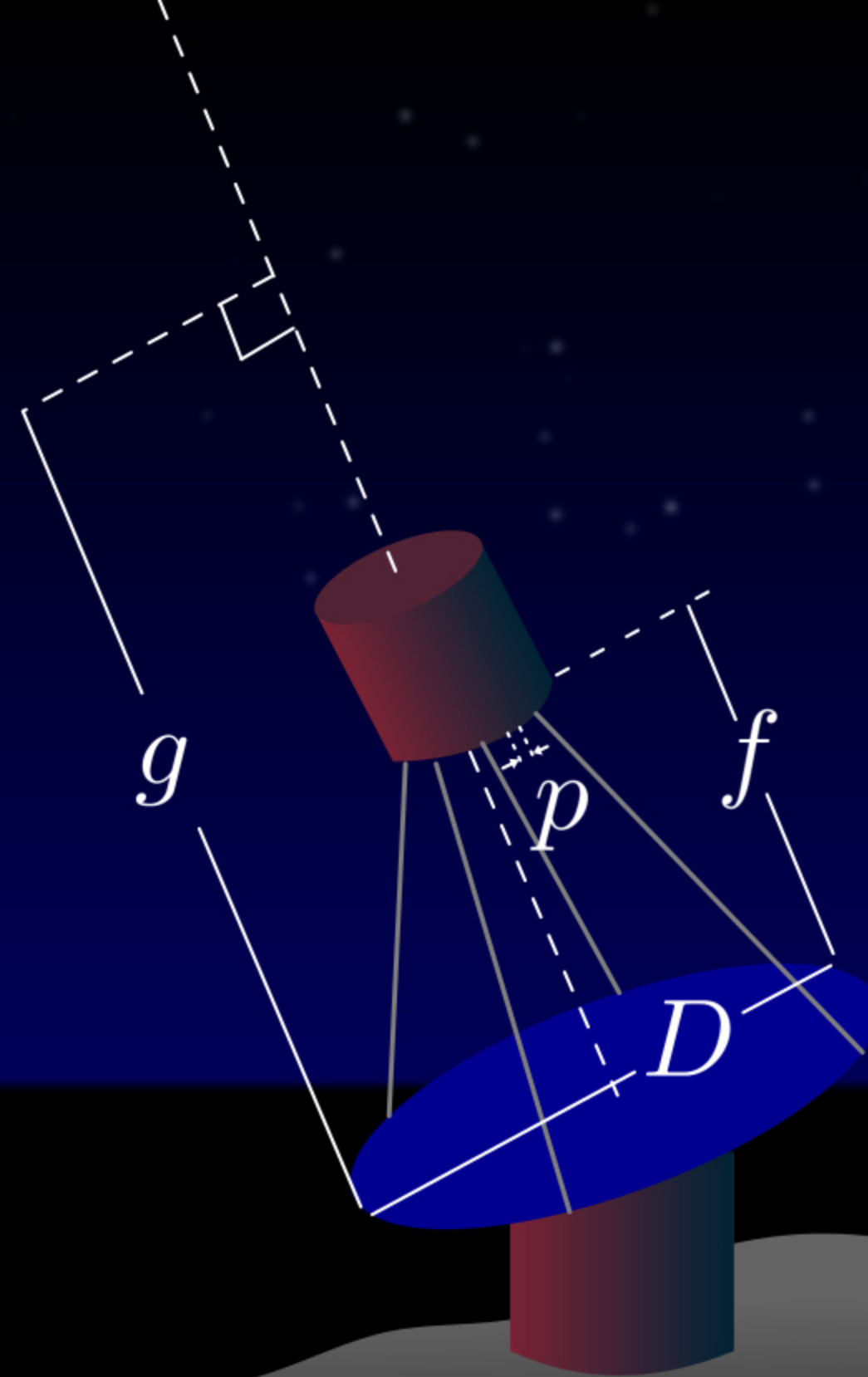
depth-of-field

$$D = 71 \text{ m}$$

$$f/D = 1.5$$

$$p = 124 \text{ mm } (0.067^\circ)$$

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



Limits of Telescopes

depth-of-field

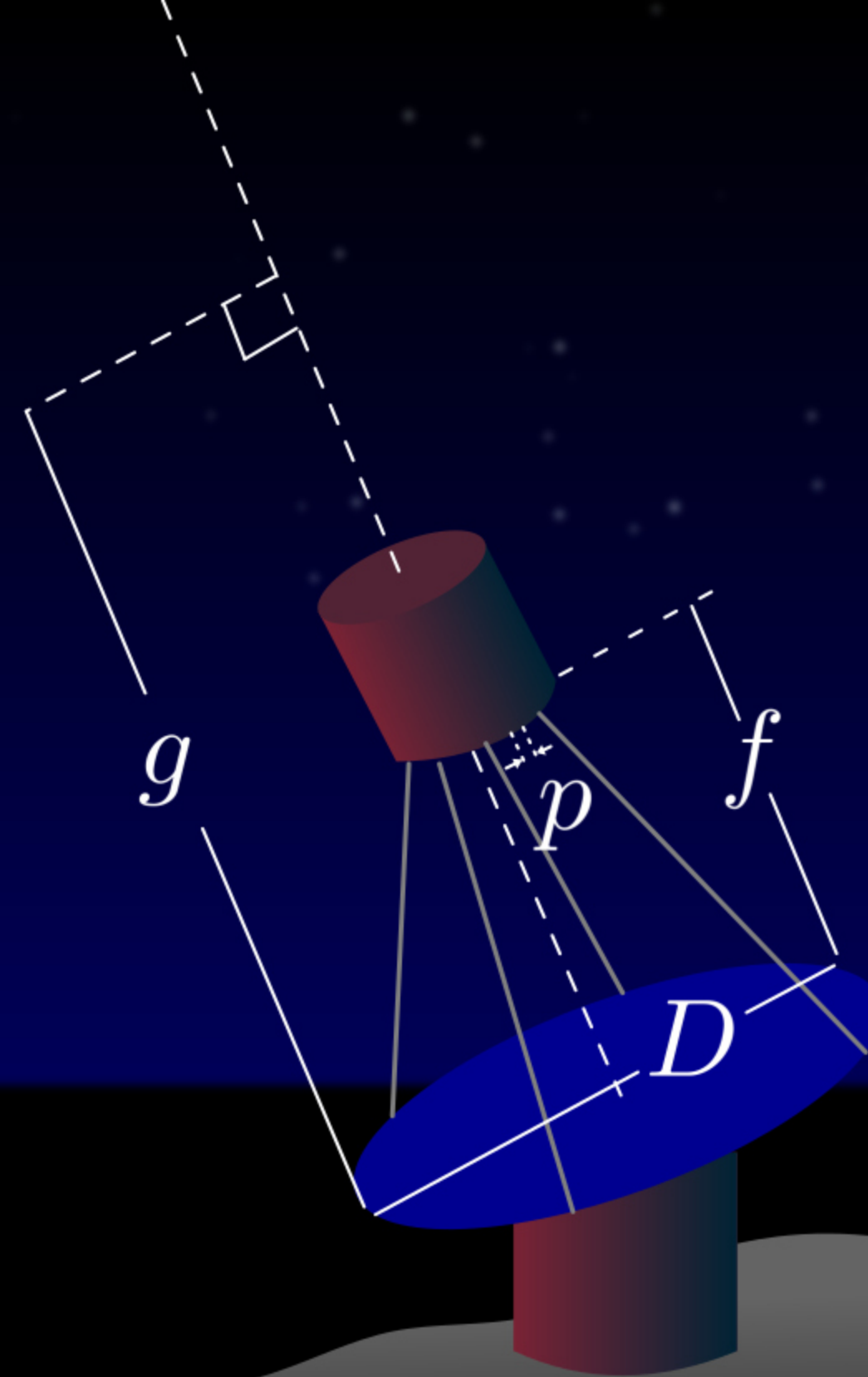
$$D = 71 \text{ m}$$

$$f/D = 1.5$$

$$p = 124 \text{ mm } (0.067^\circ)$$

$$g = 10 \text{ km}$$

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



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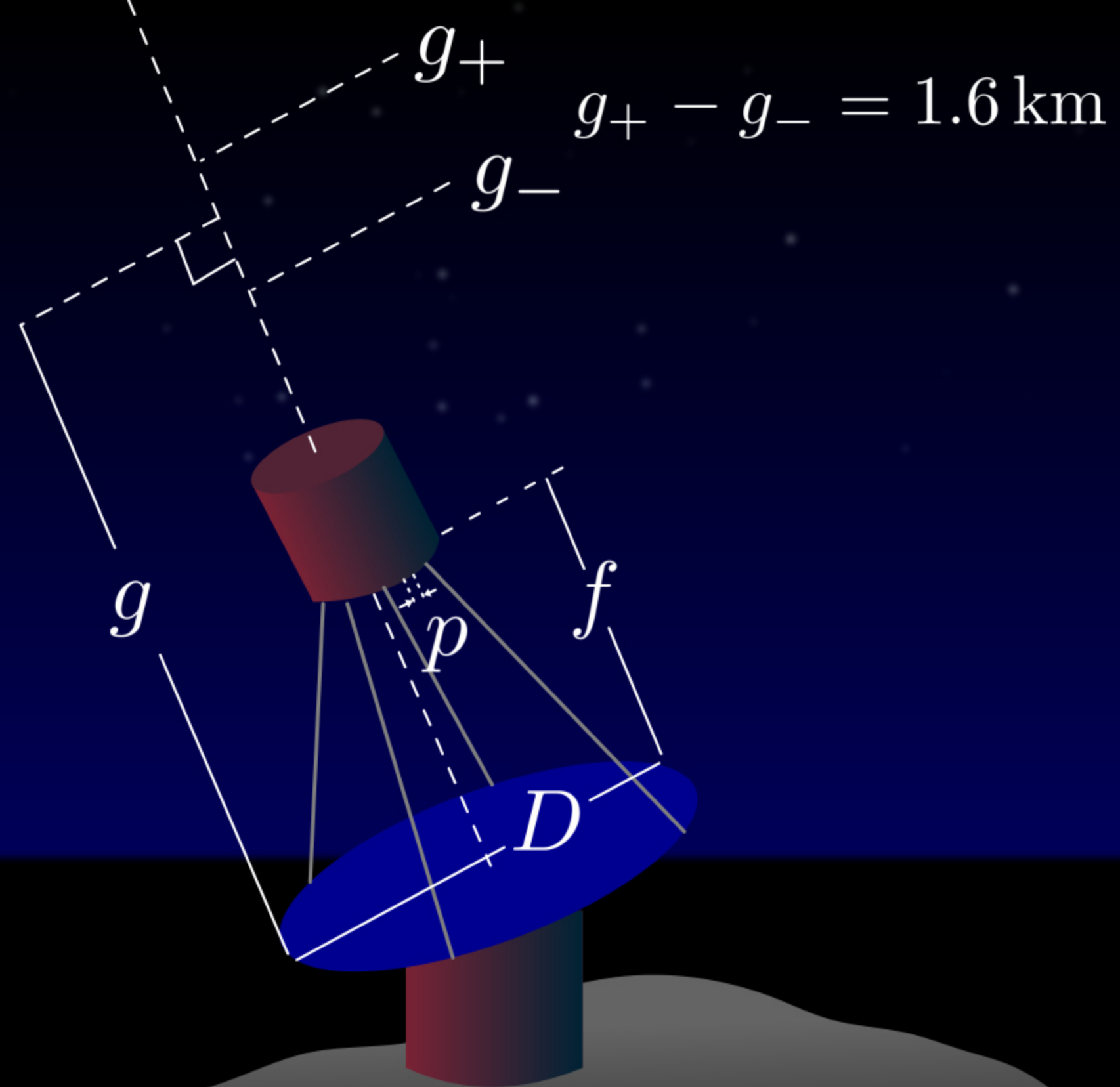
$$D = 71 \text{ m}$$

$$f/D = 1.5$$

$$p = 124 \text{ mm } (0.067^\circ)$$

$$g = 10 \text{ km}$$

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



Motivation



Motivation

depth-of-field

aberrations



Motivation

deformations and misalignments

depth-of-field

aberrations



Motivation

deformations and misalignments

depth-of-field



Motivation



Motivation



Motivation



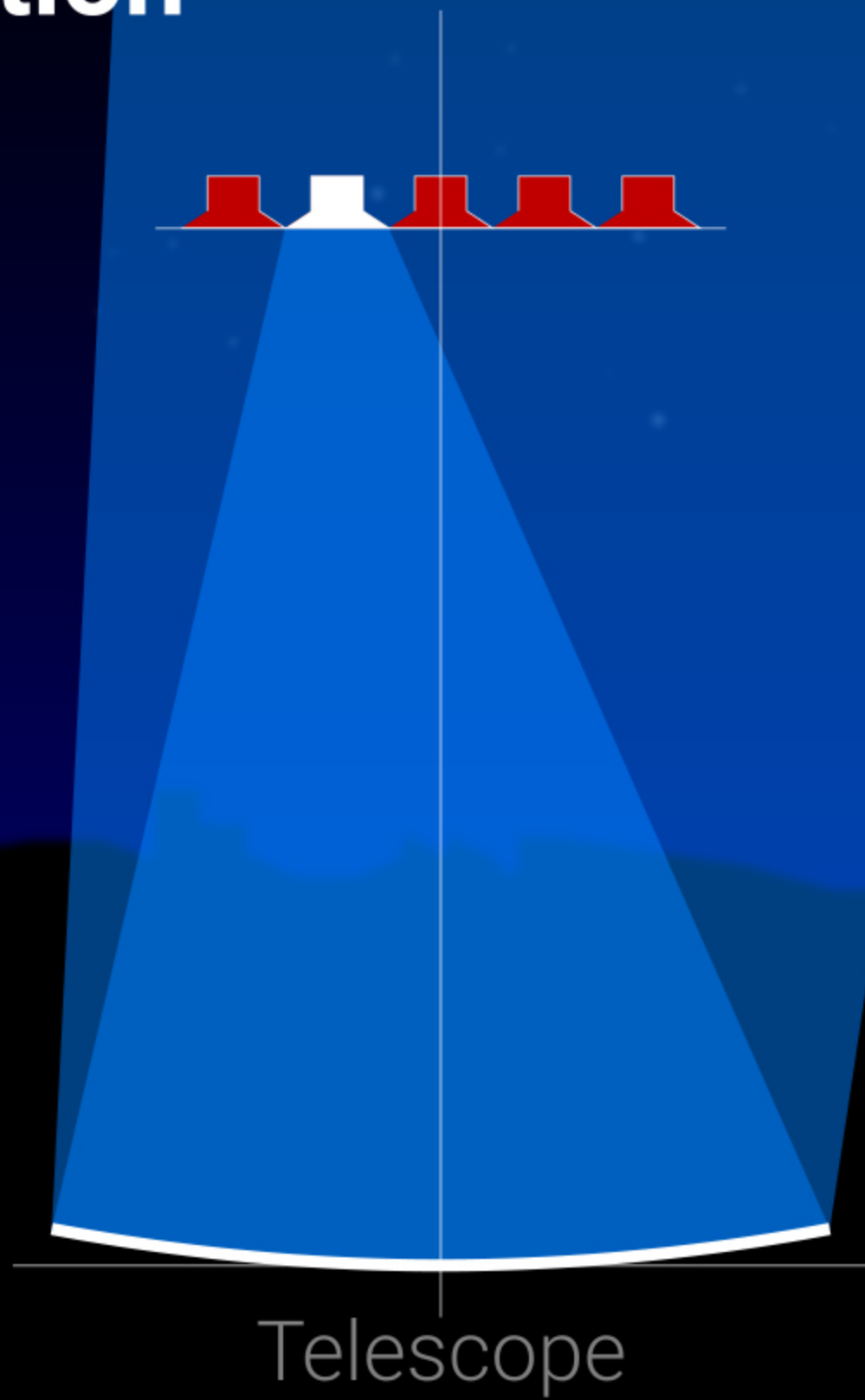
Motivation



Motivation



Motivation



Motivation



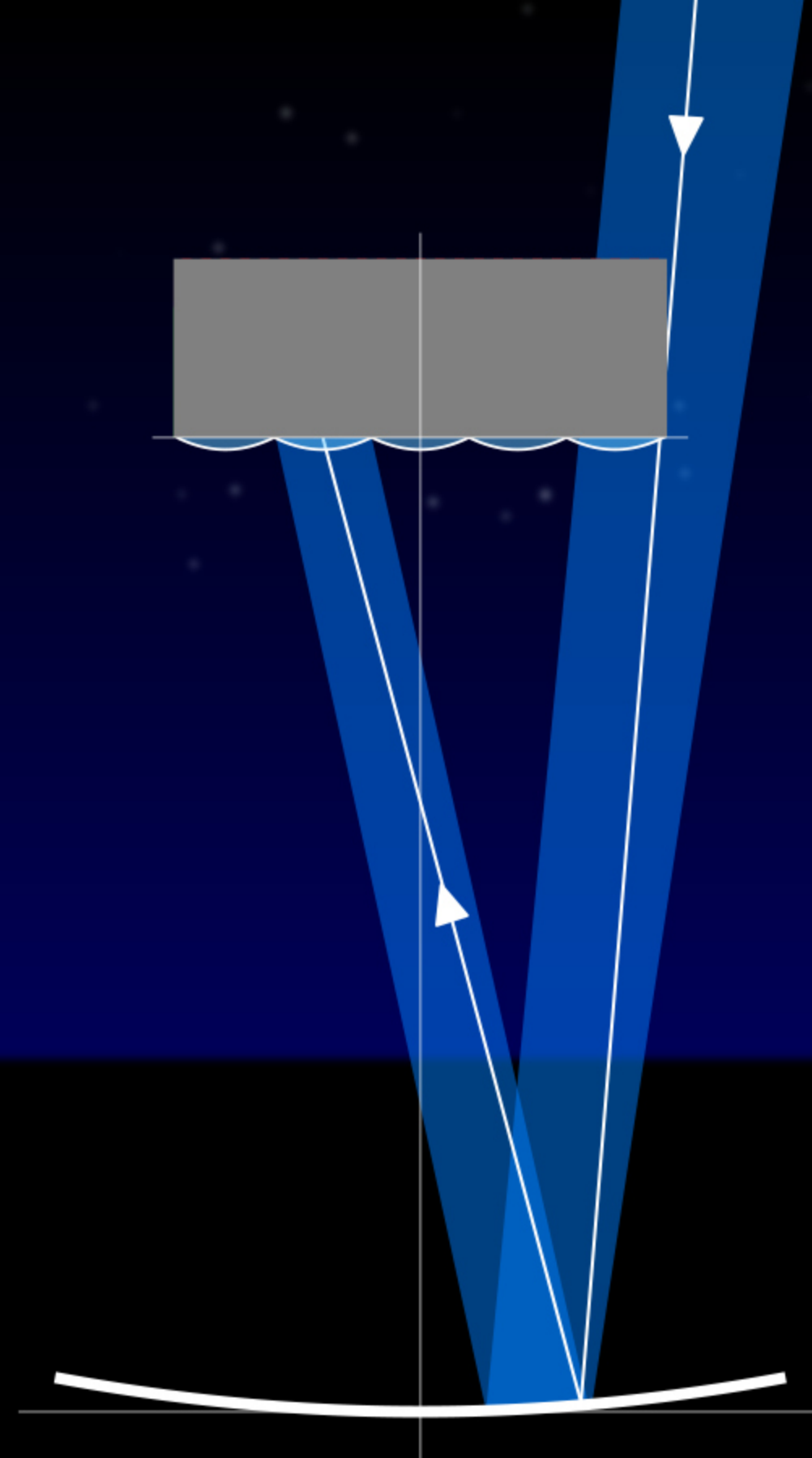
Motivation



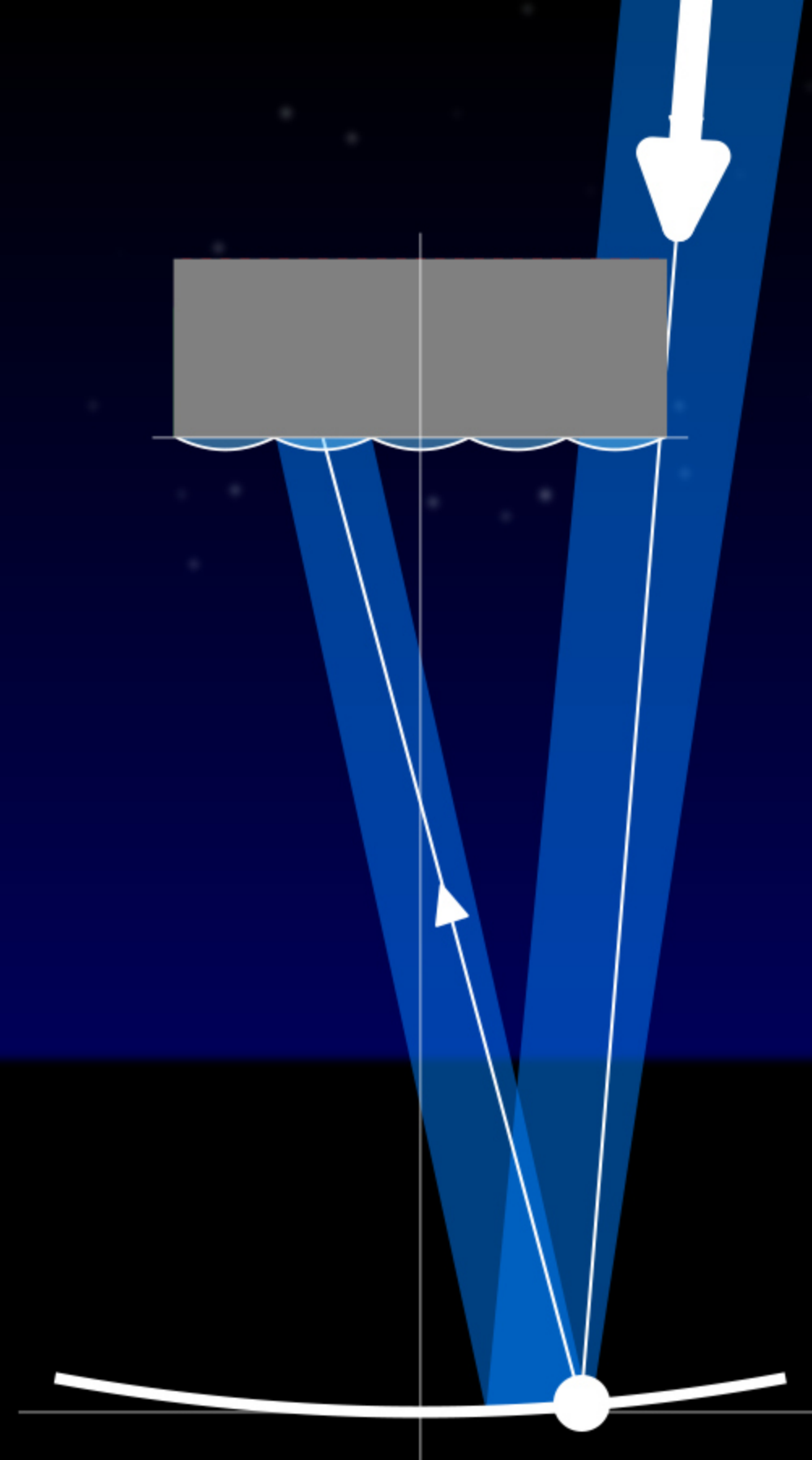
Motivation



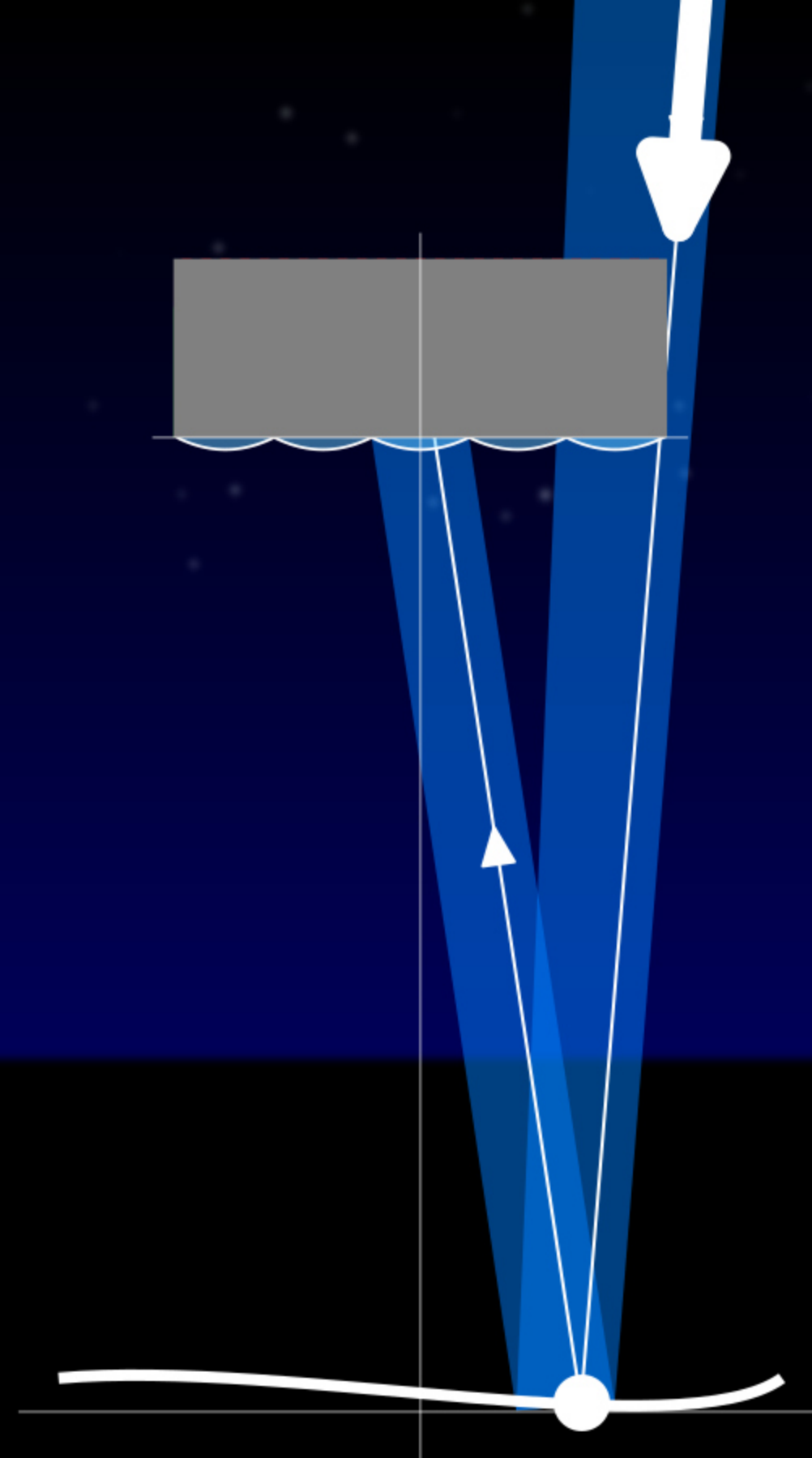
Motivation



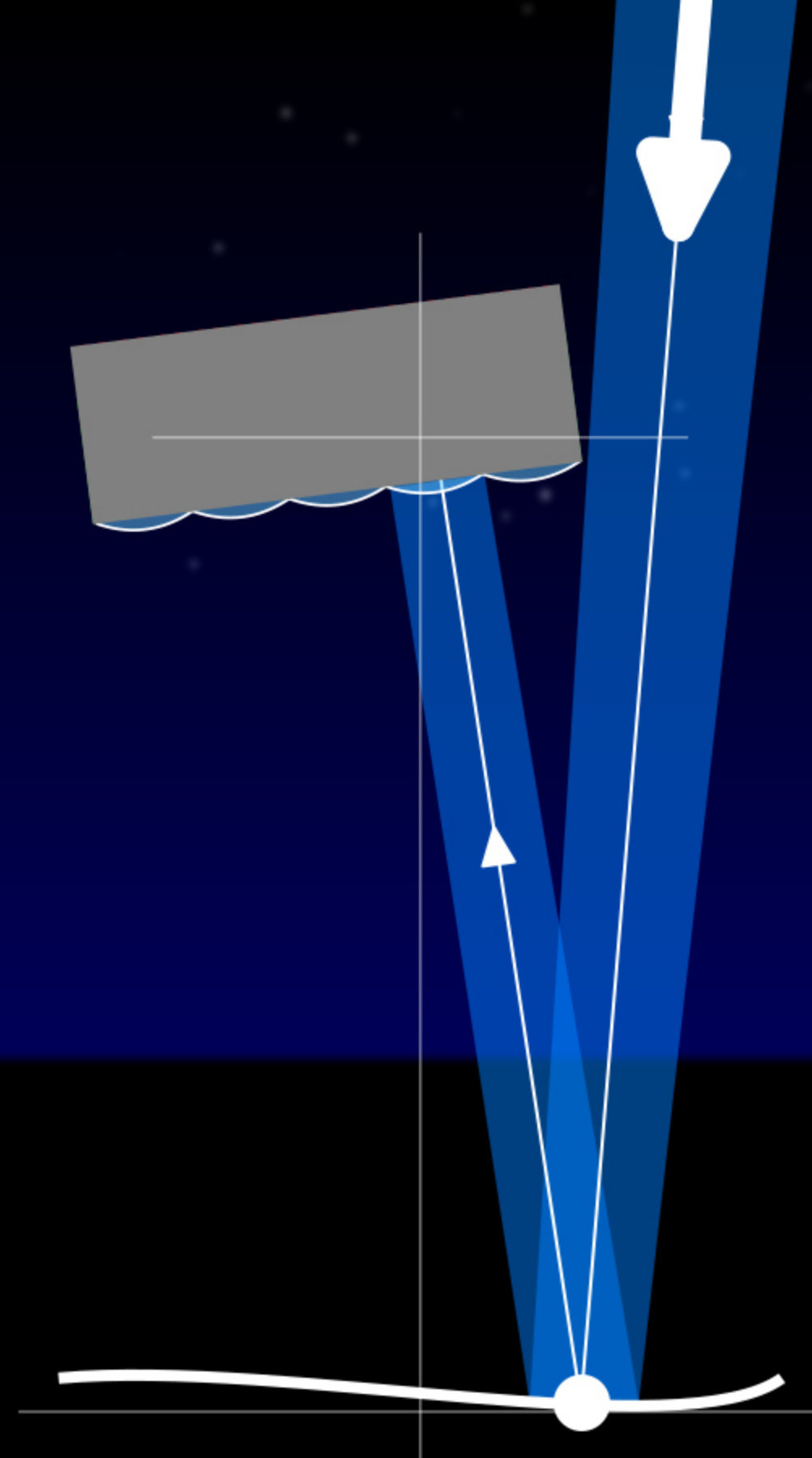
Motivation



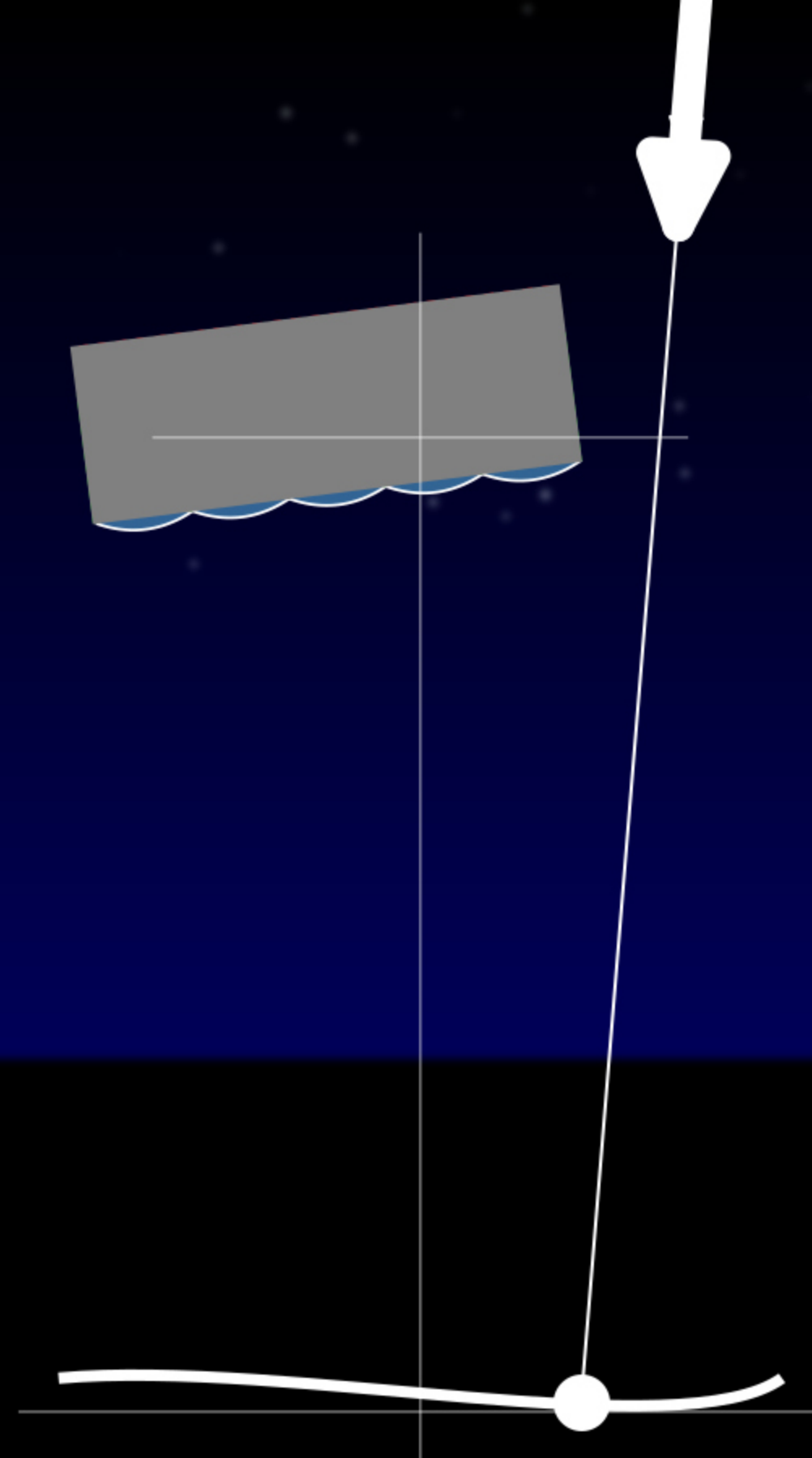
Motivation



Motivation



Motivation



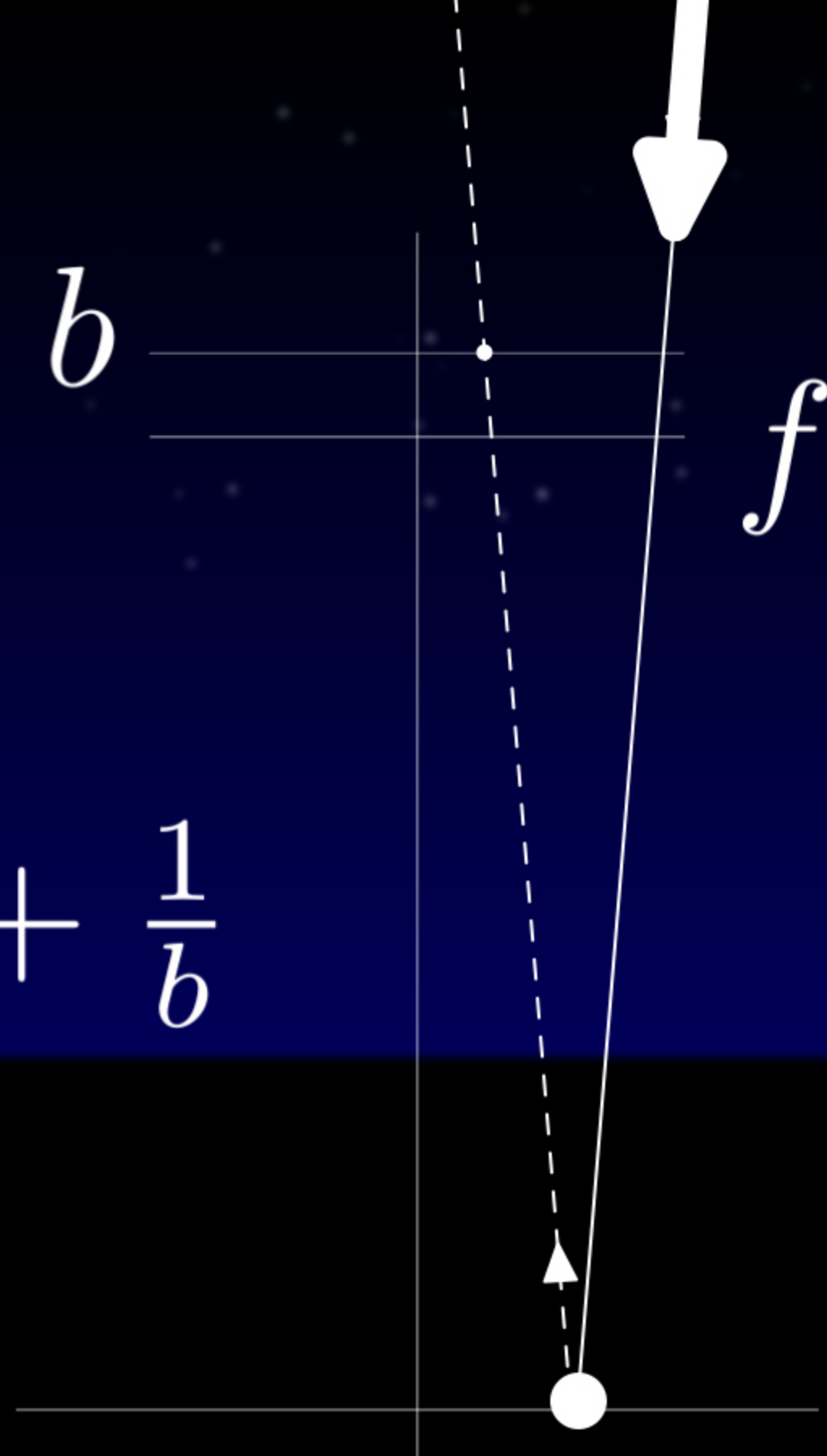
Motivation



Motivation



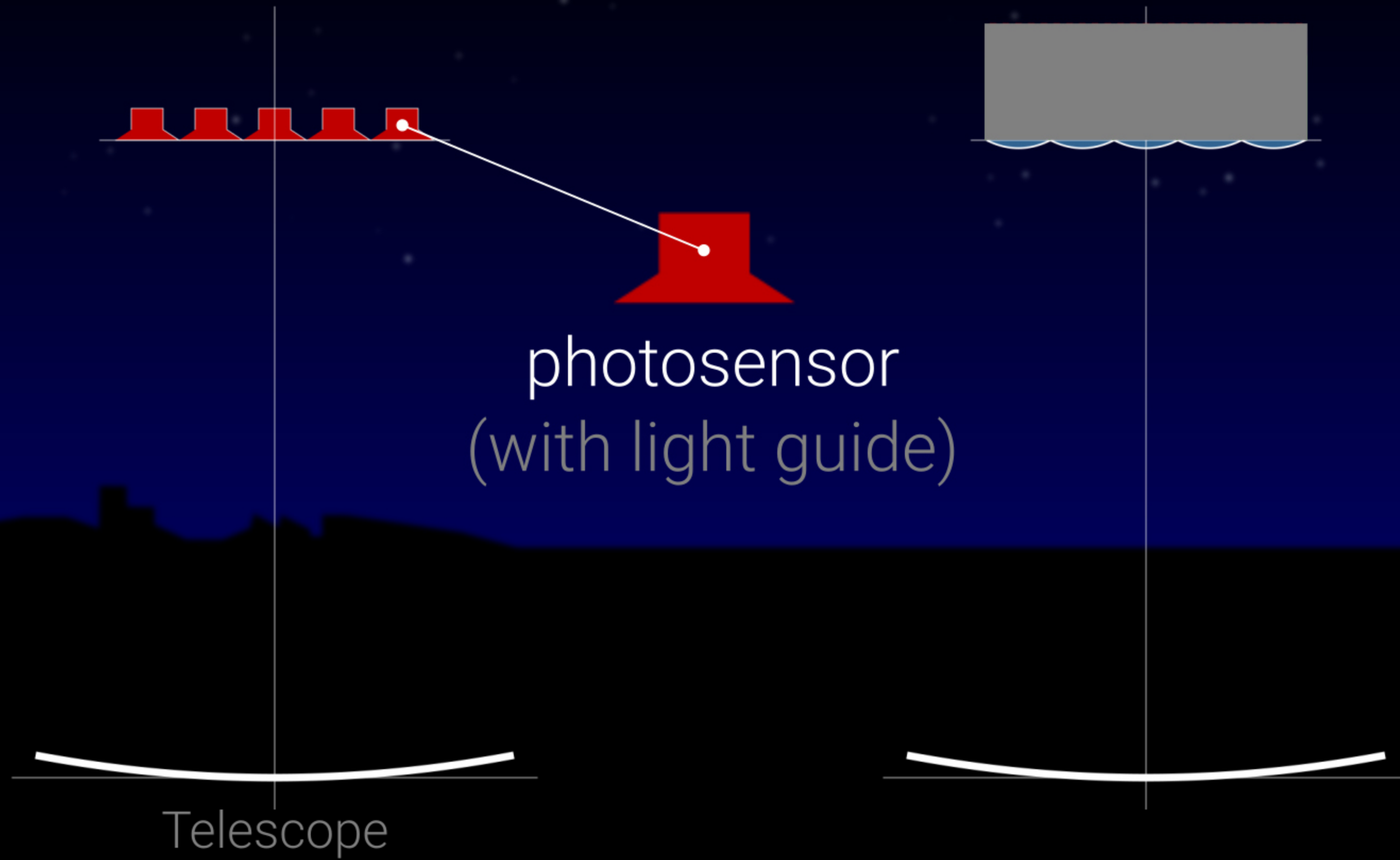
$$\frac{1}{f} = \frac{1}{g} + \frac{1}{b}$$



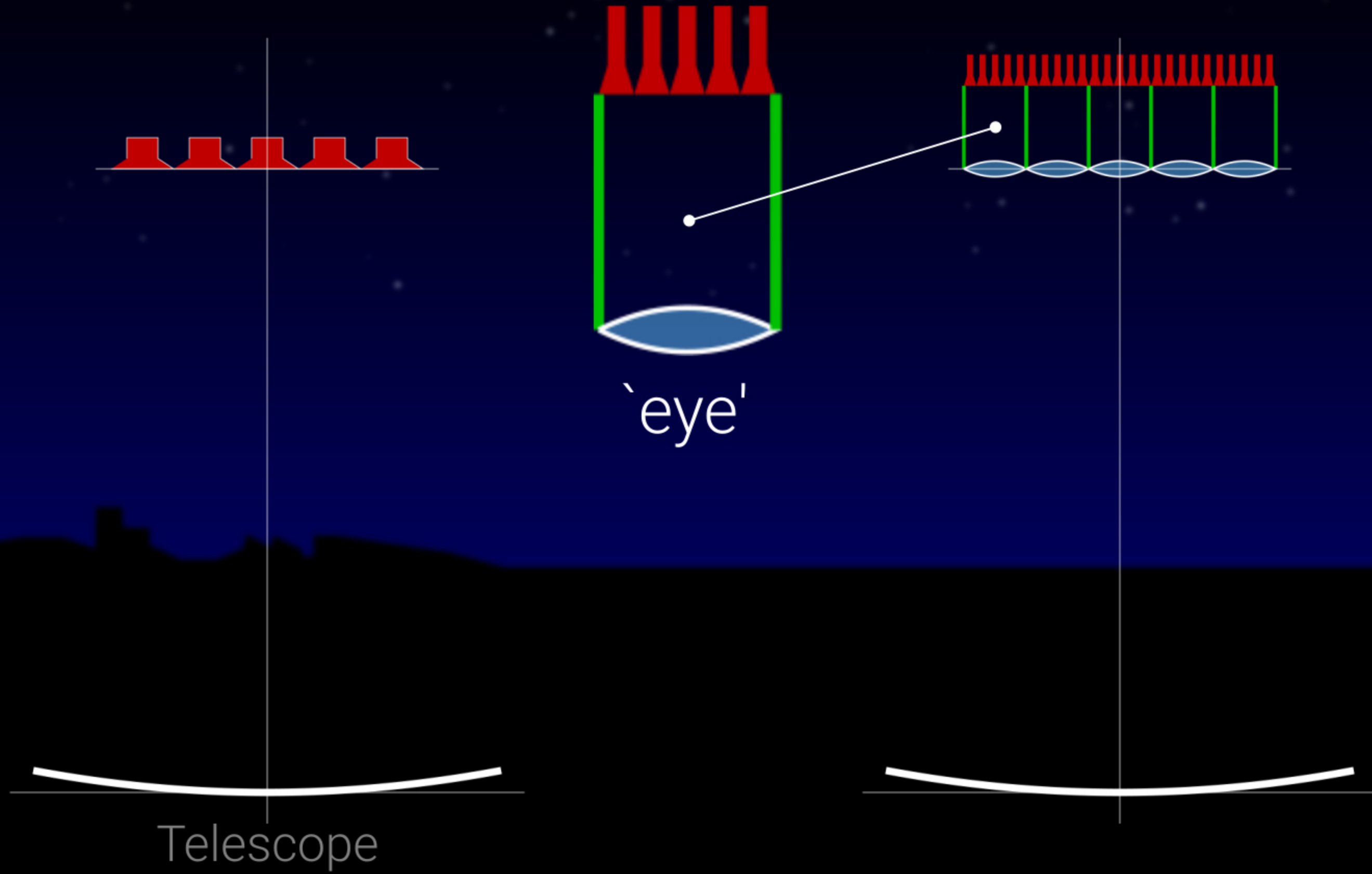
Optics



Optics



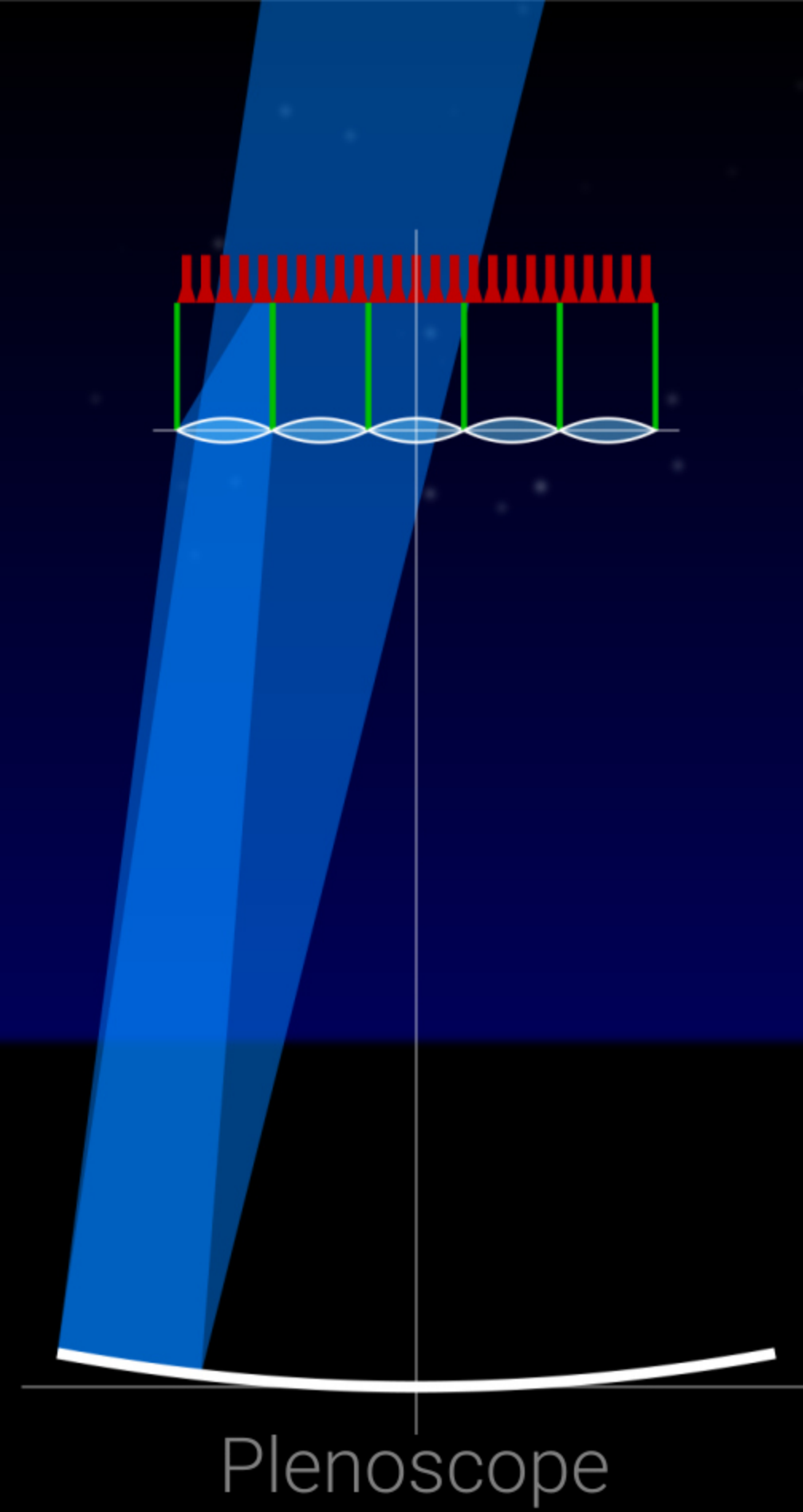
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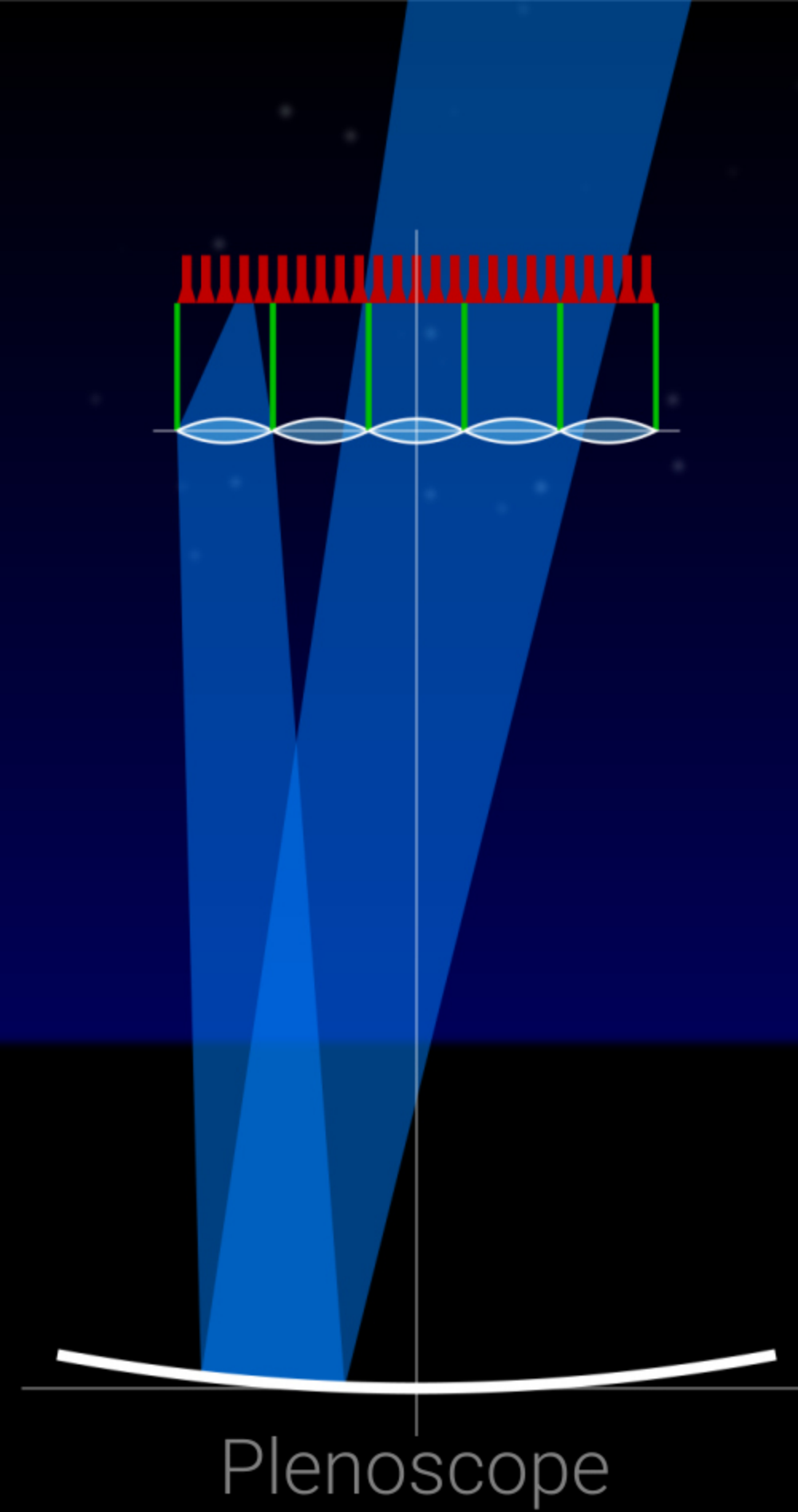
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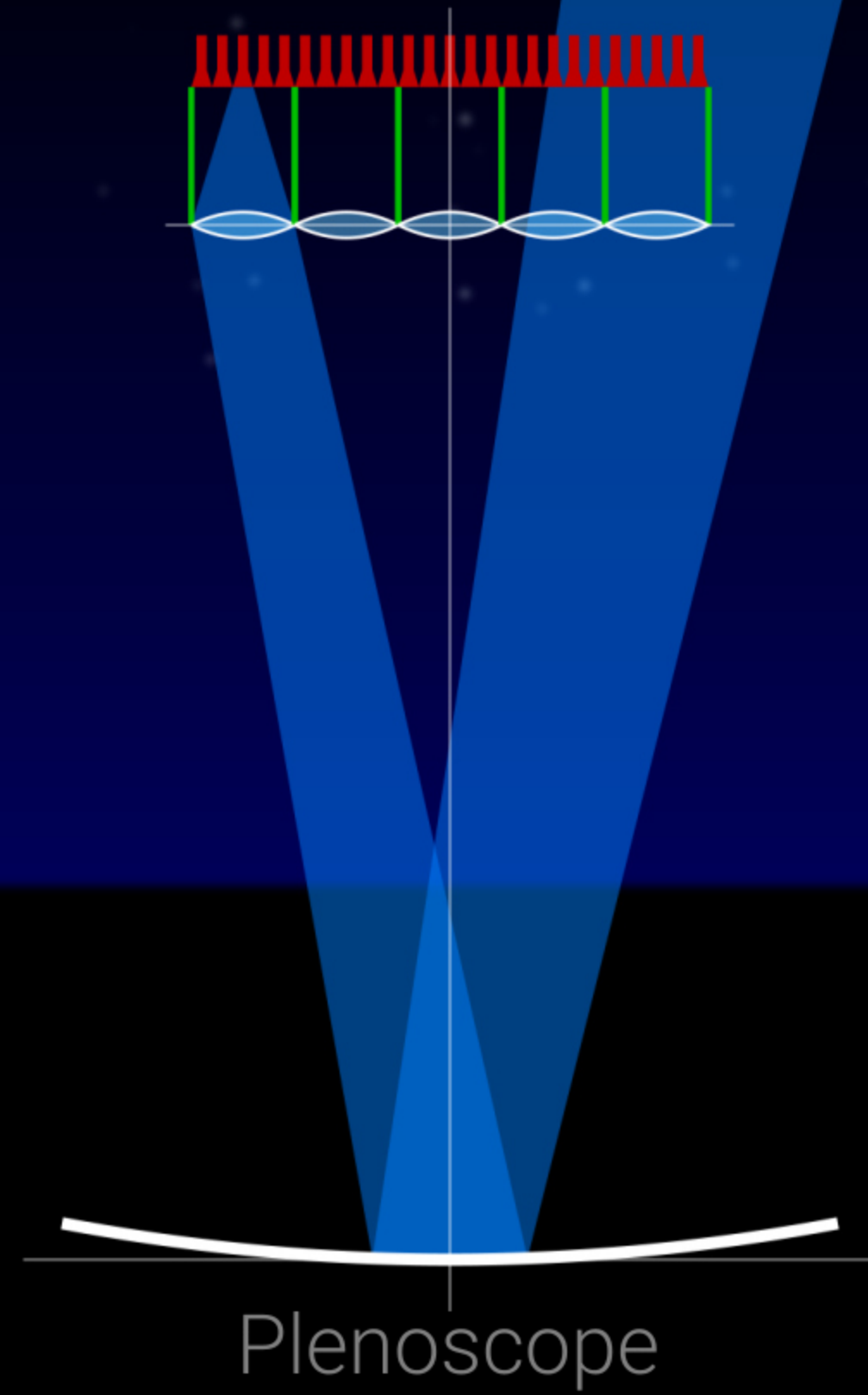
Optics



Optics



Optics



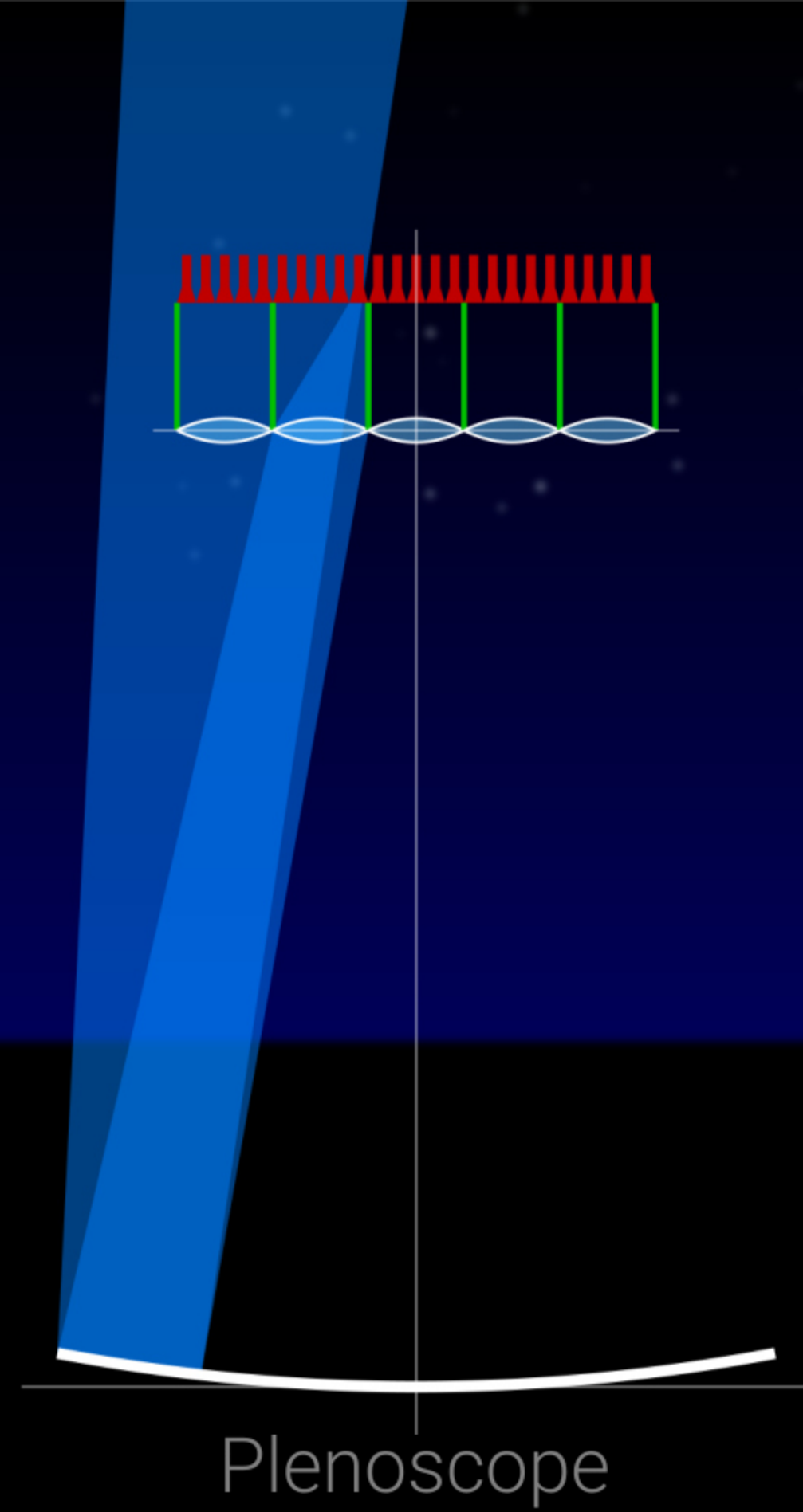
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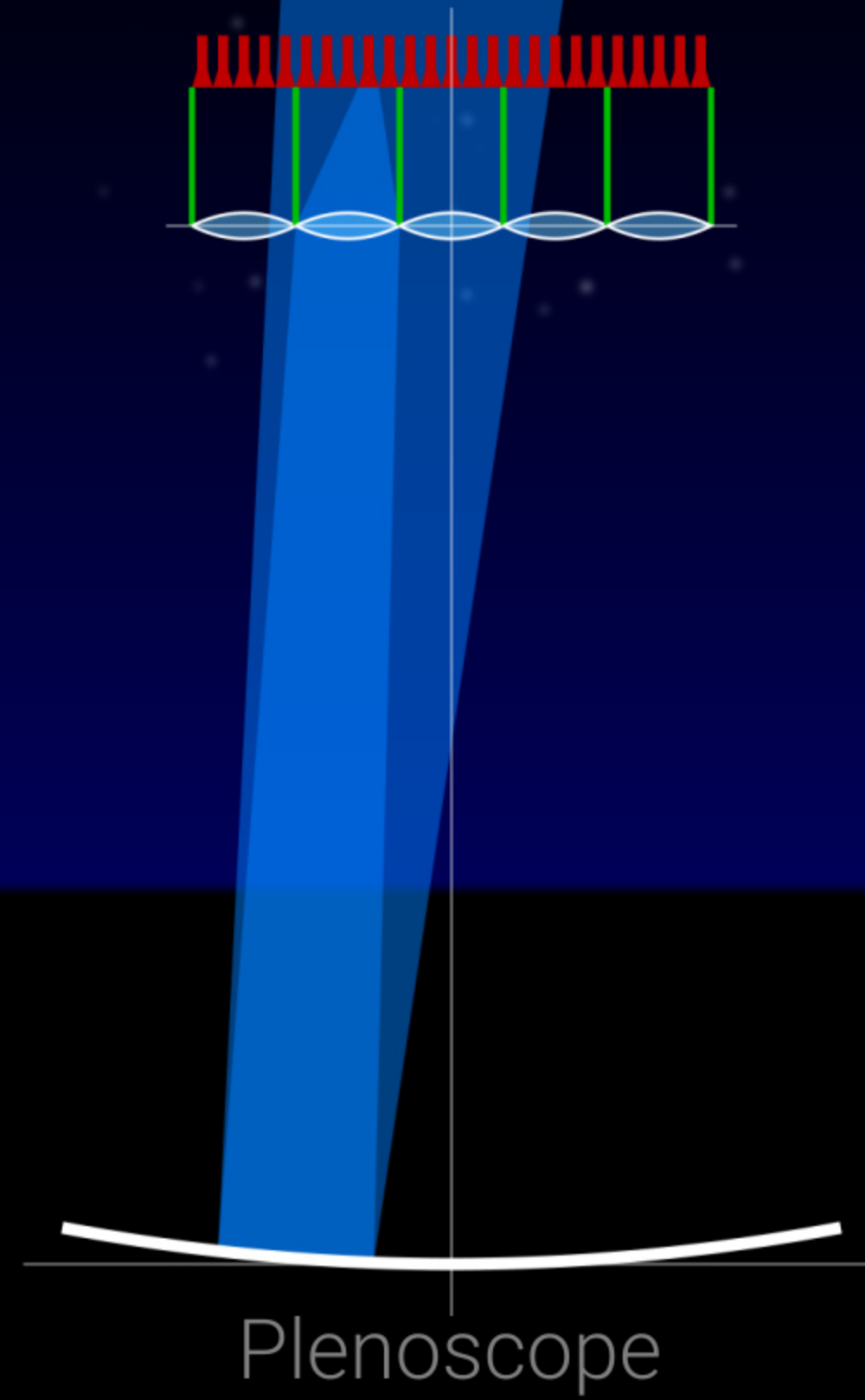
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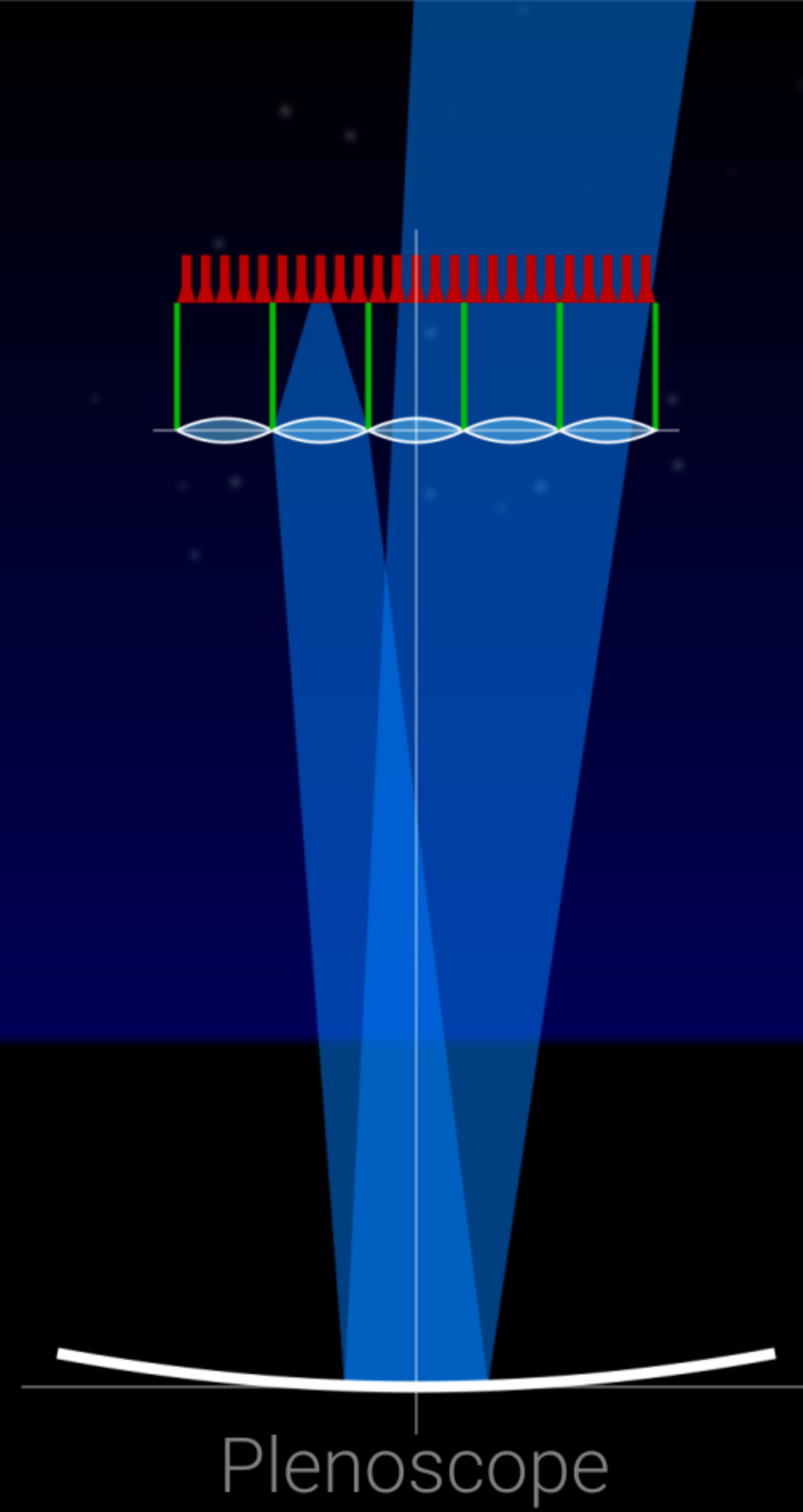
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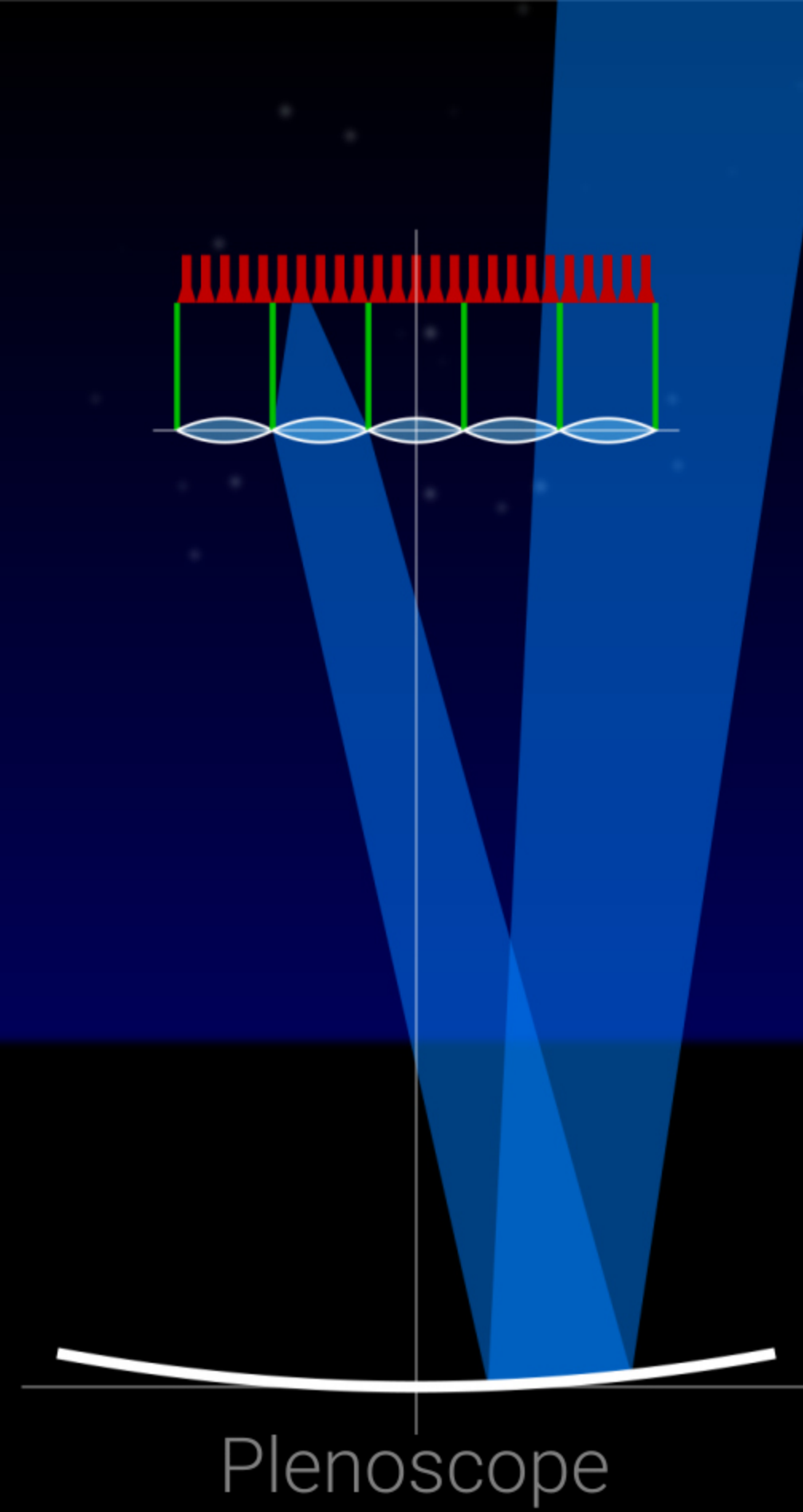
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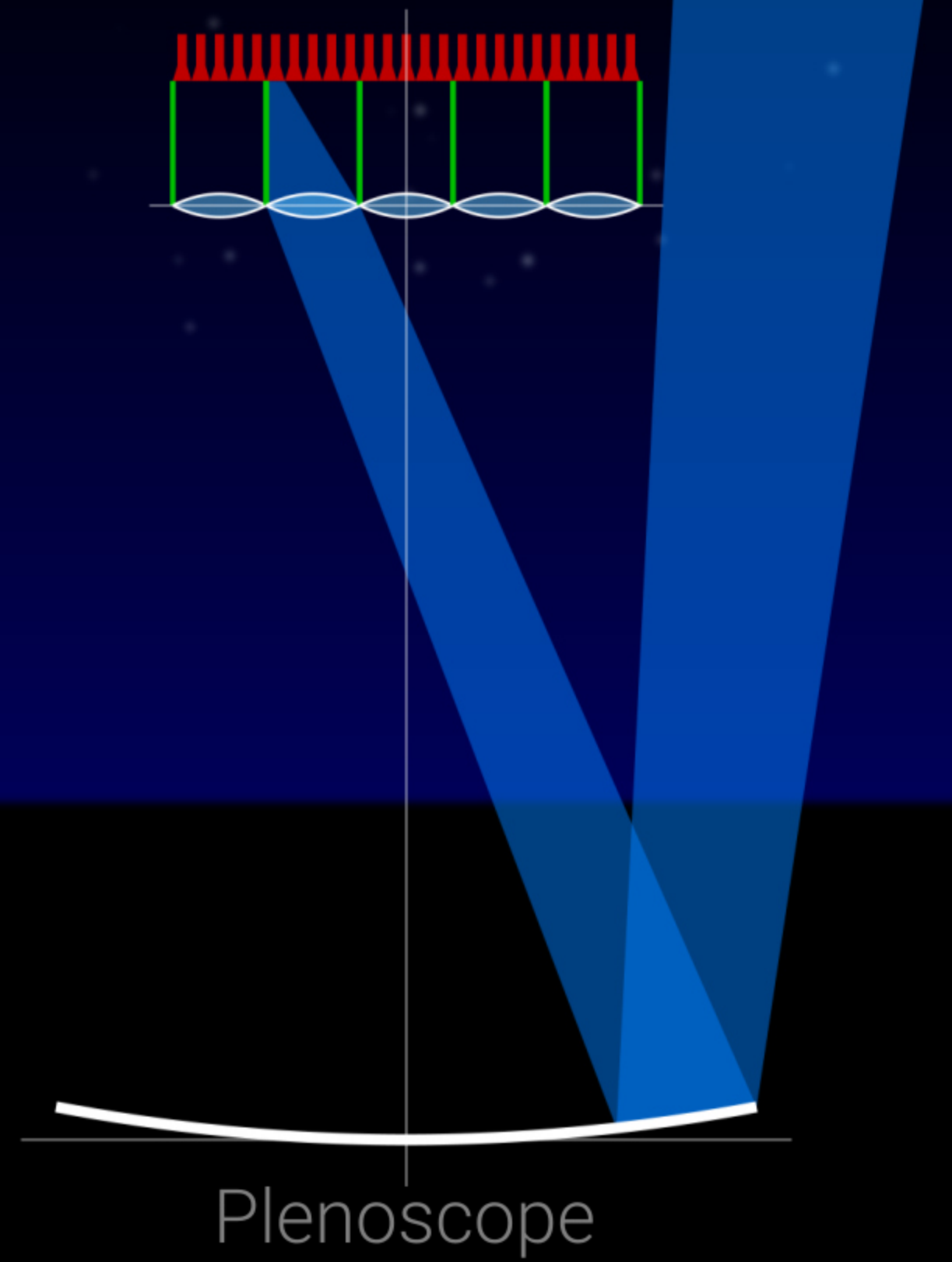
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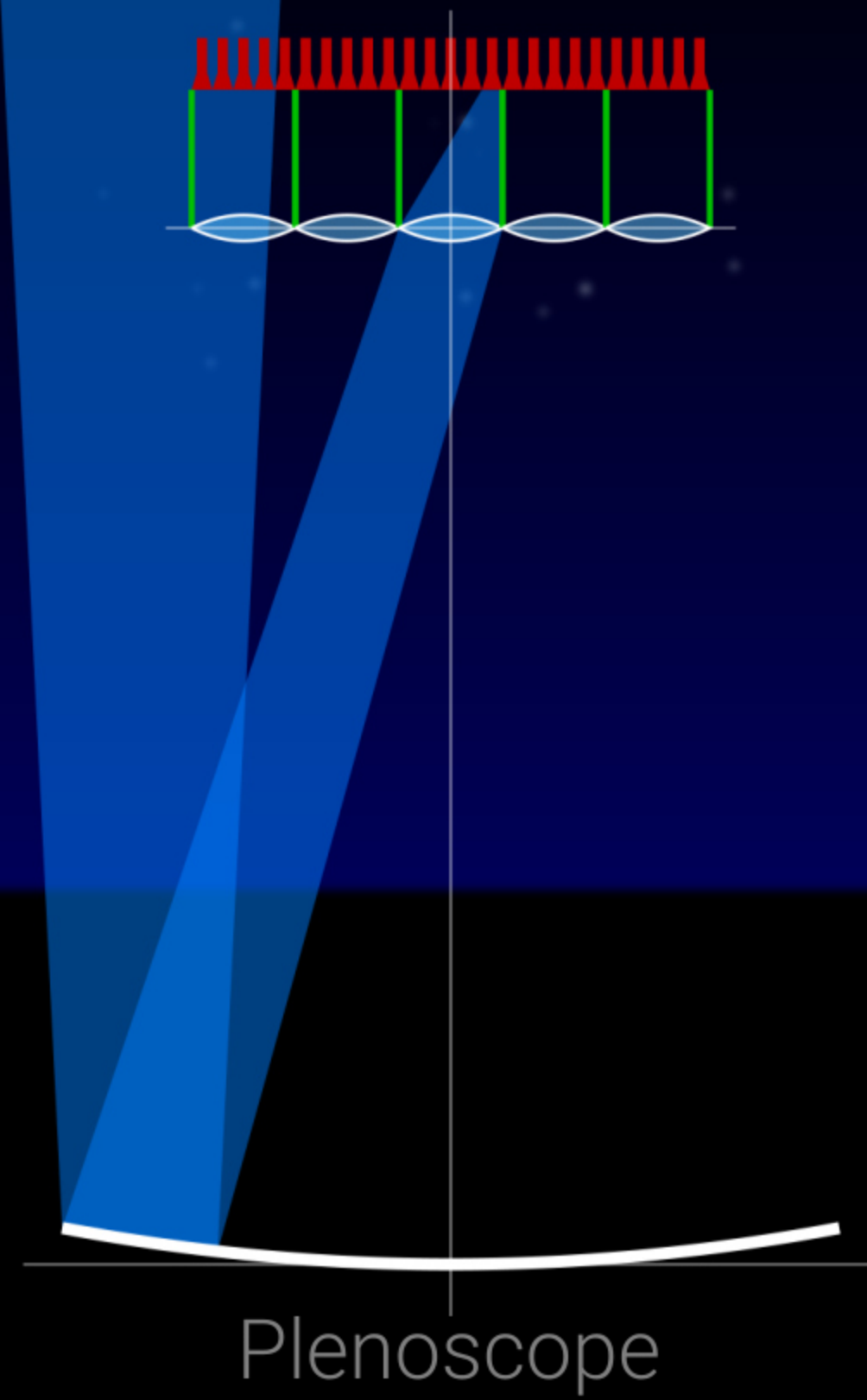
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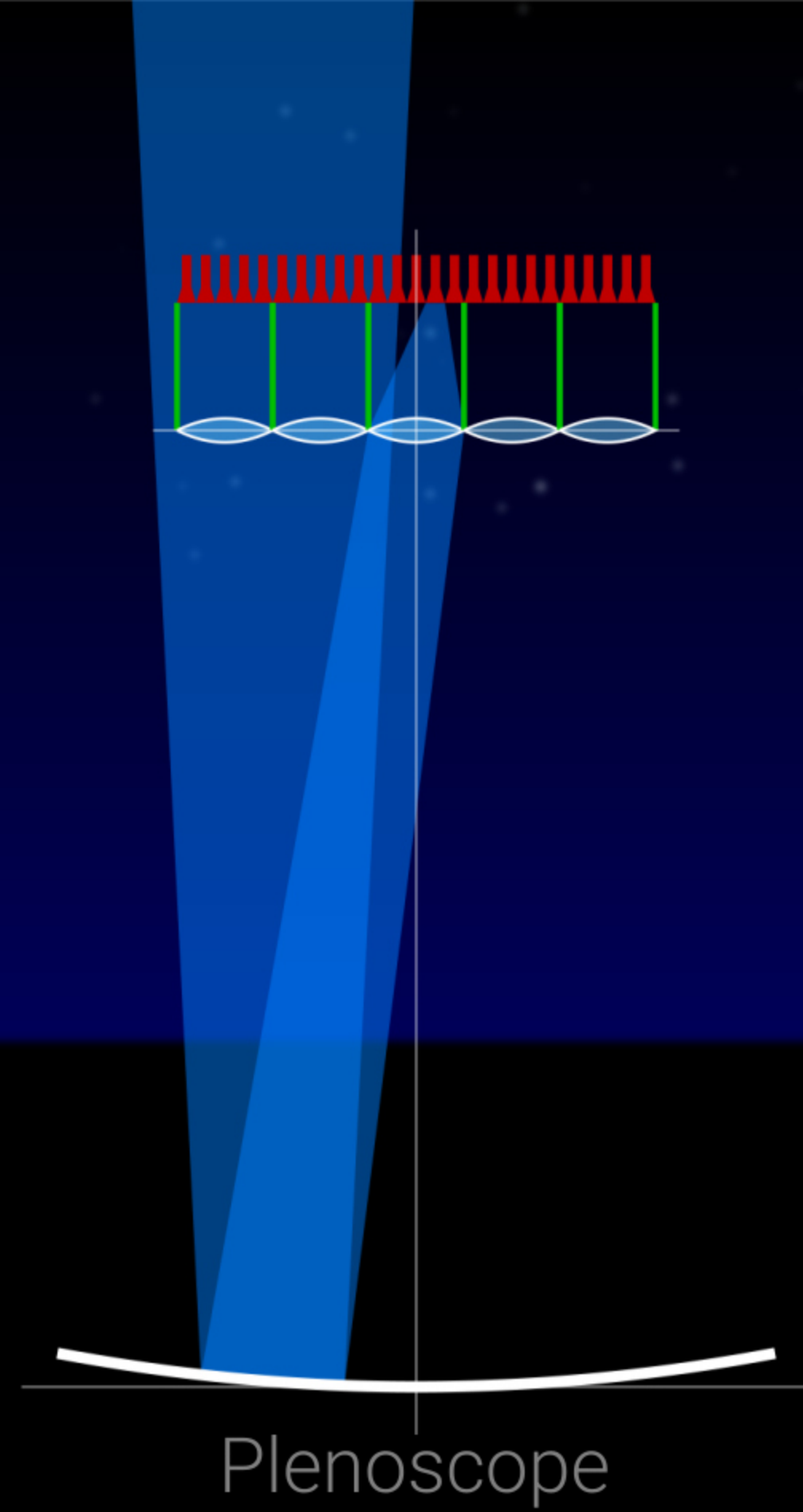
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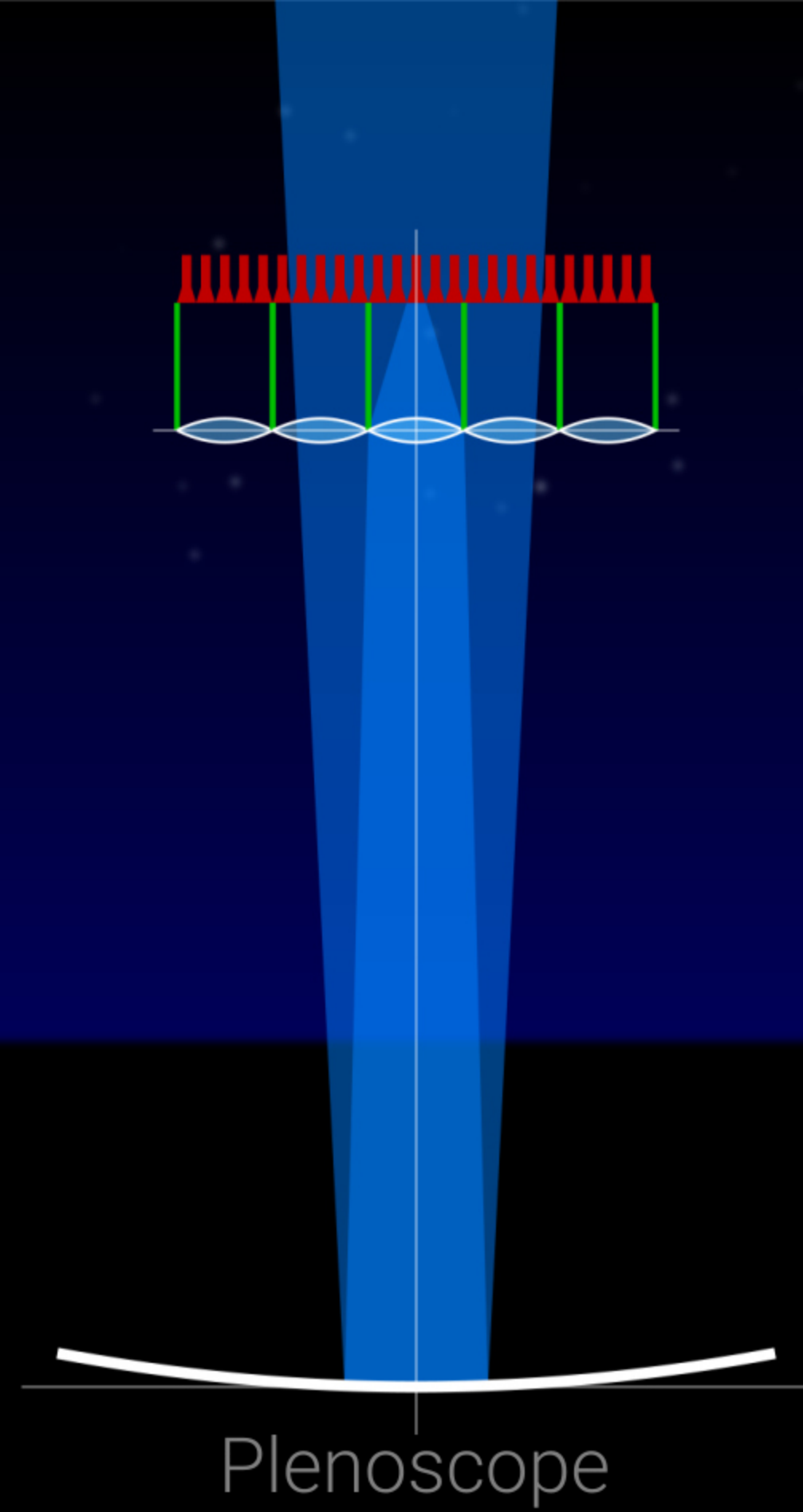
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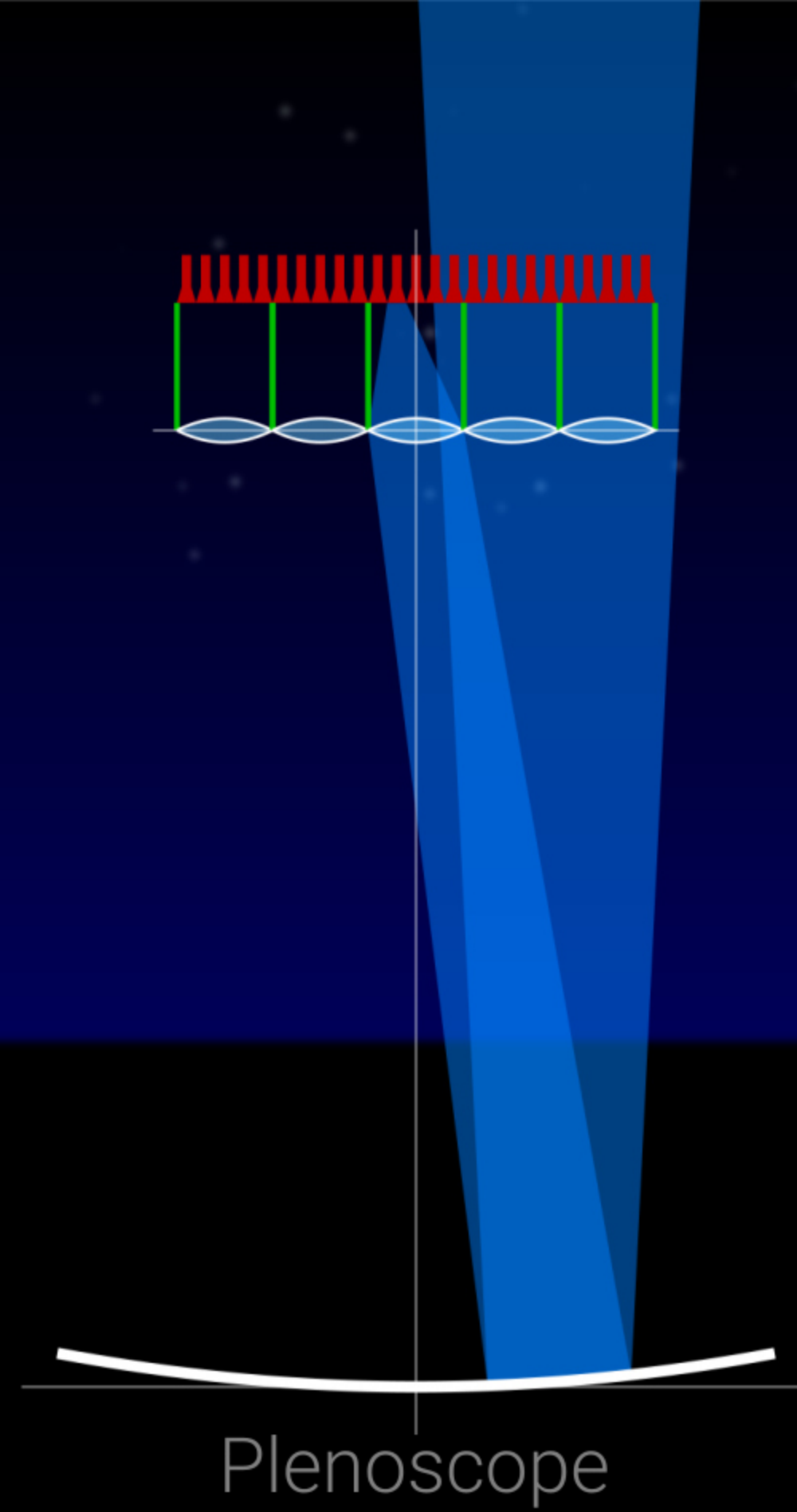
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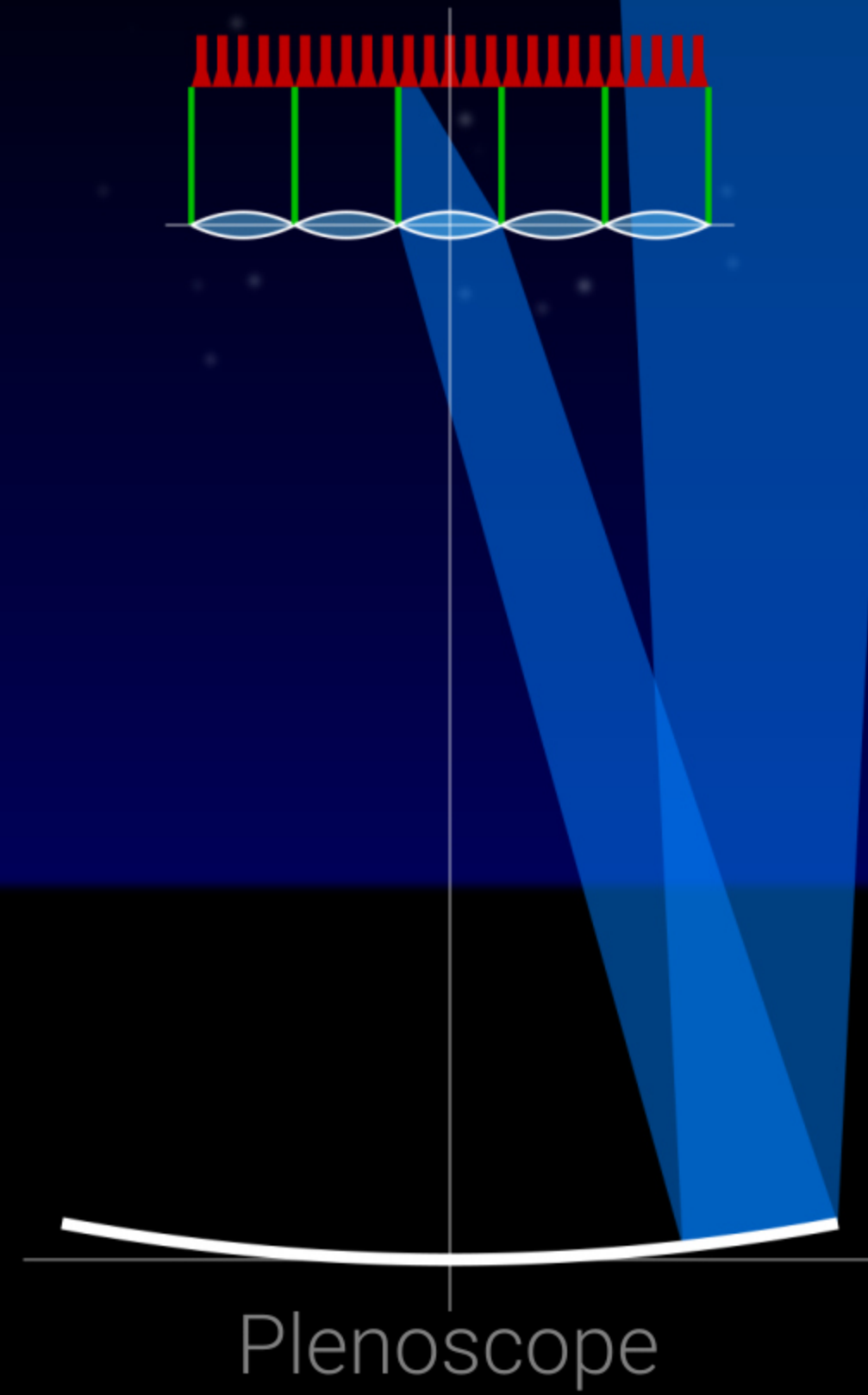
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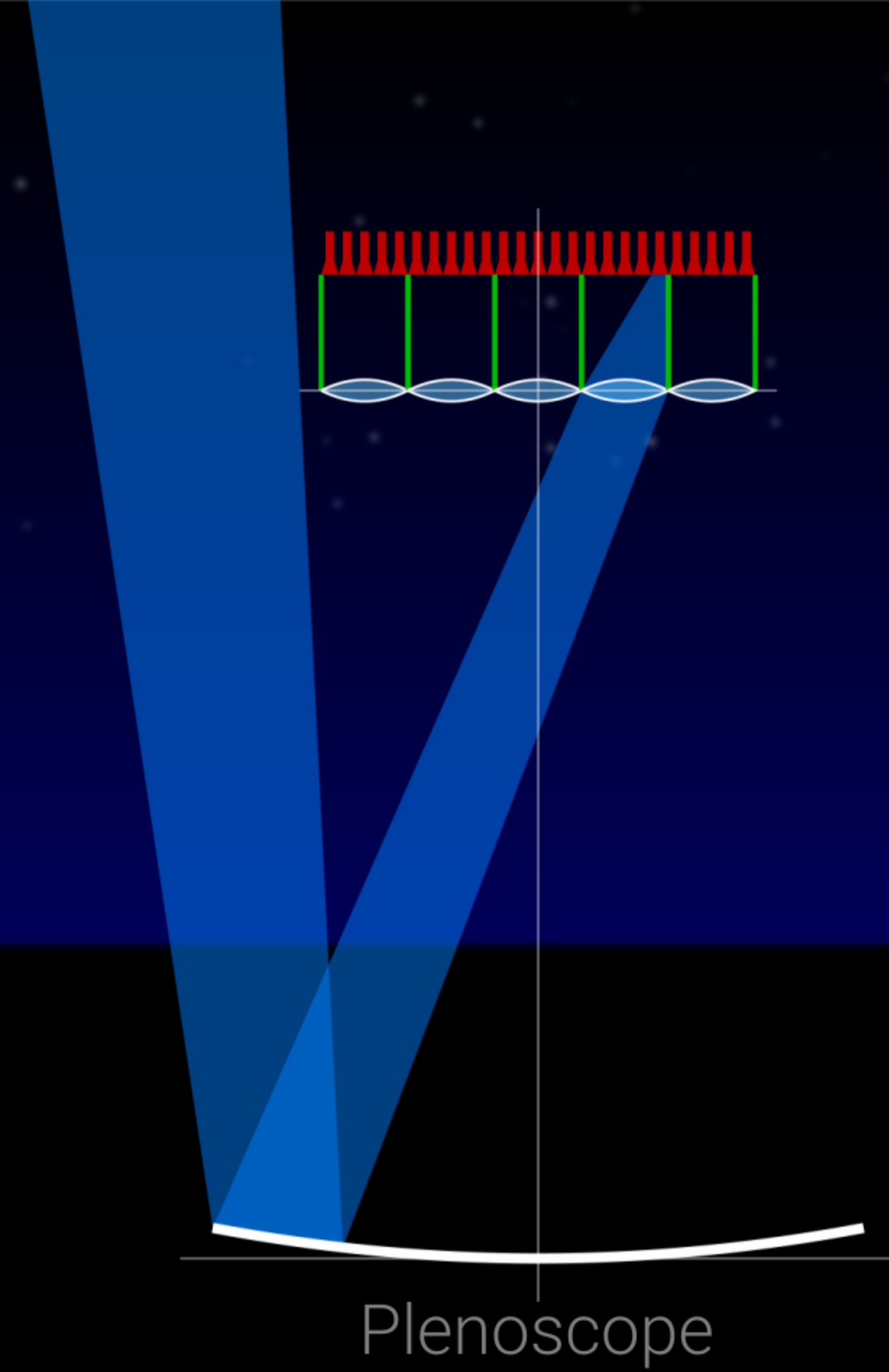
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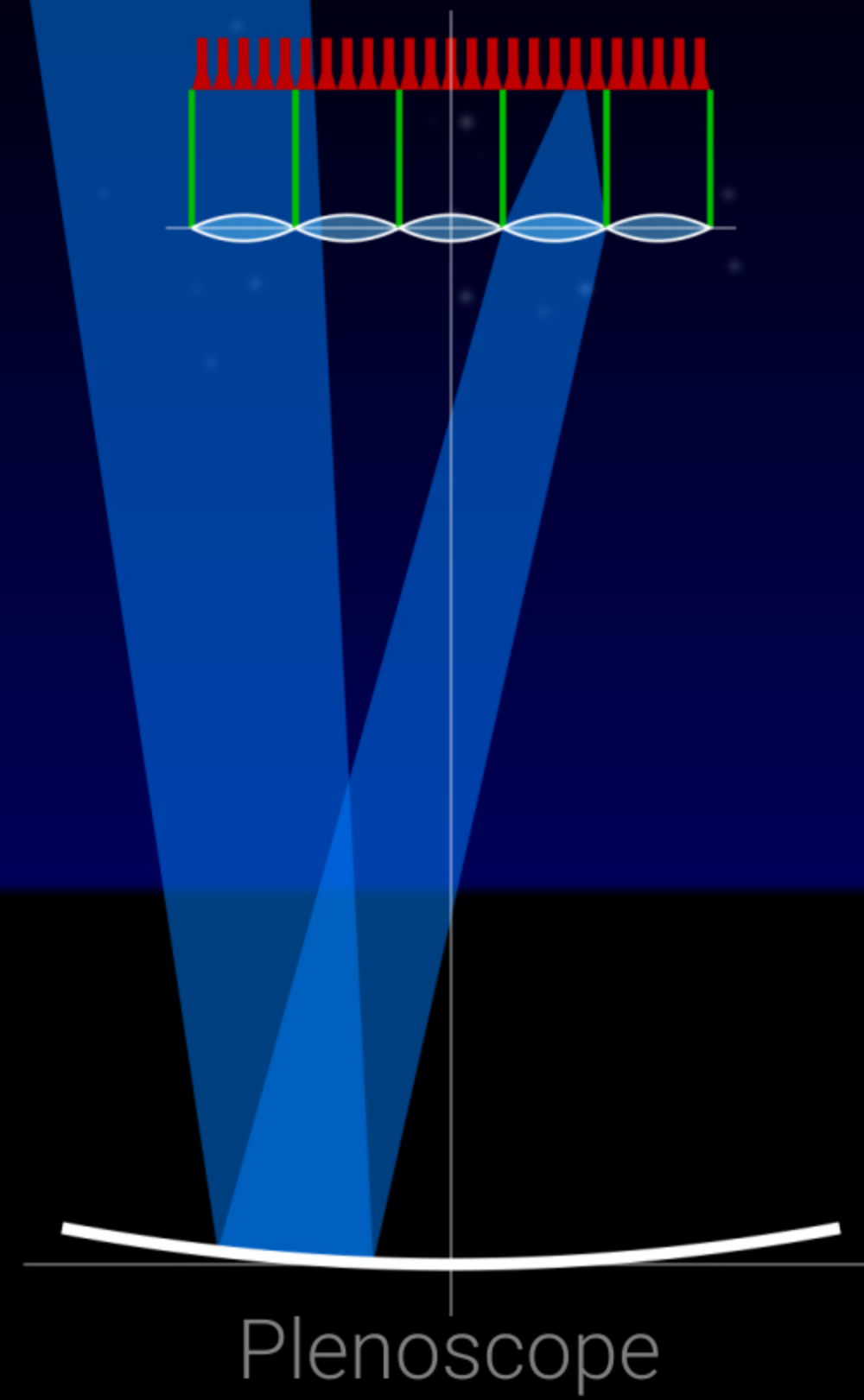
Optics



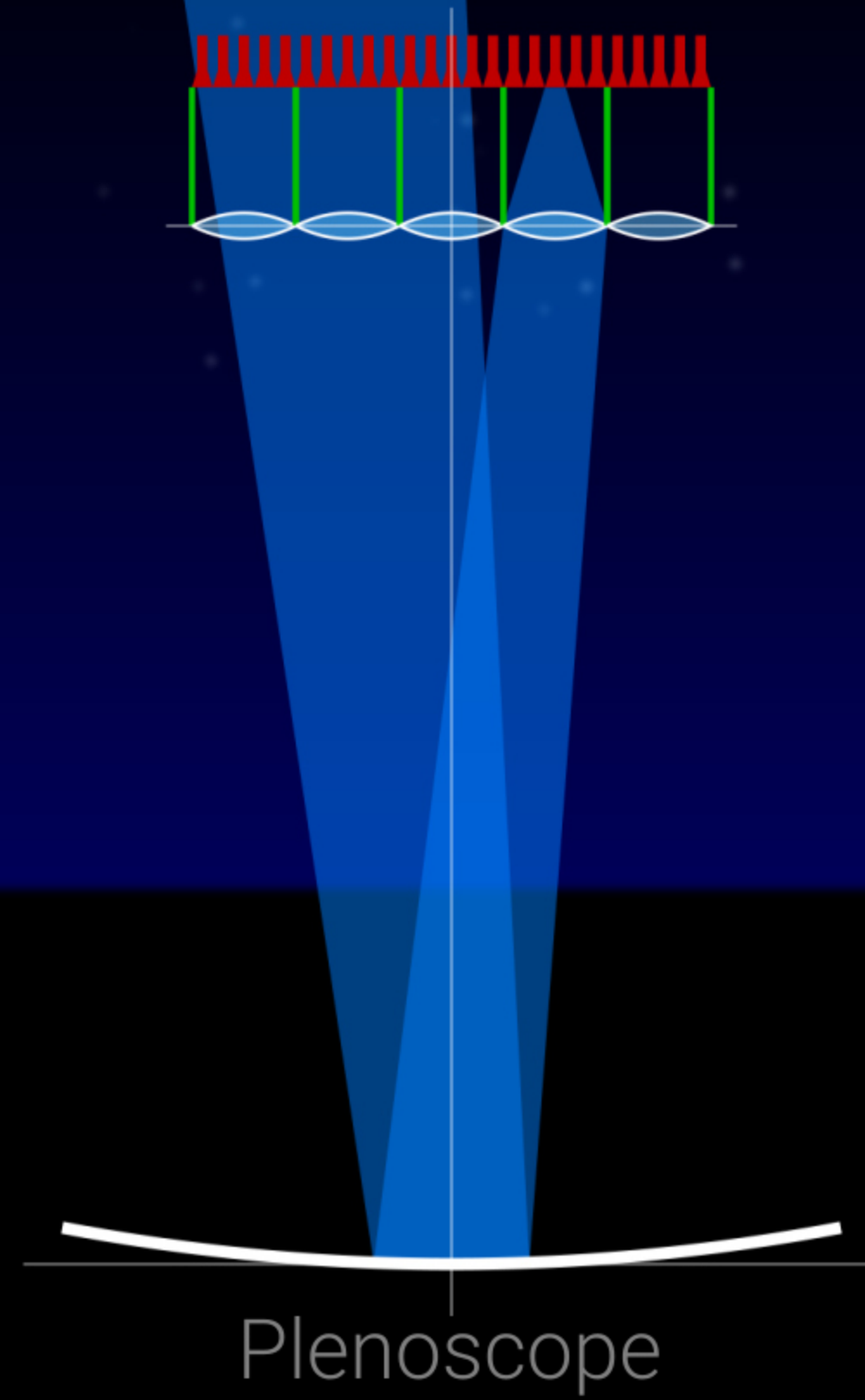
Optics



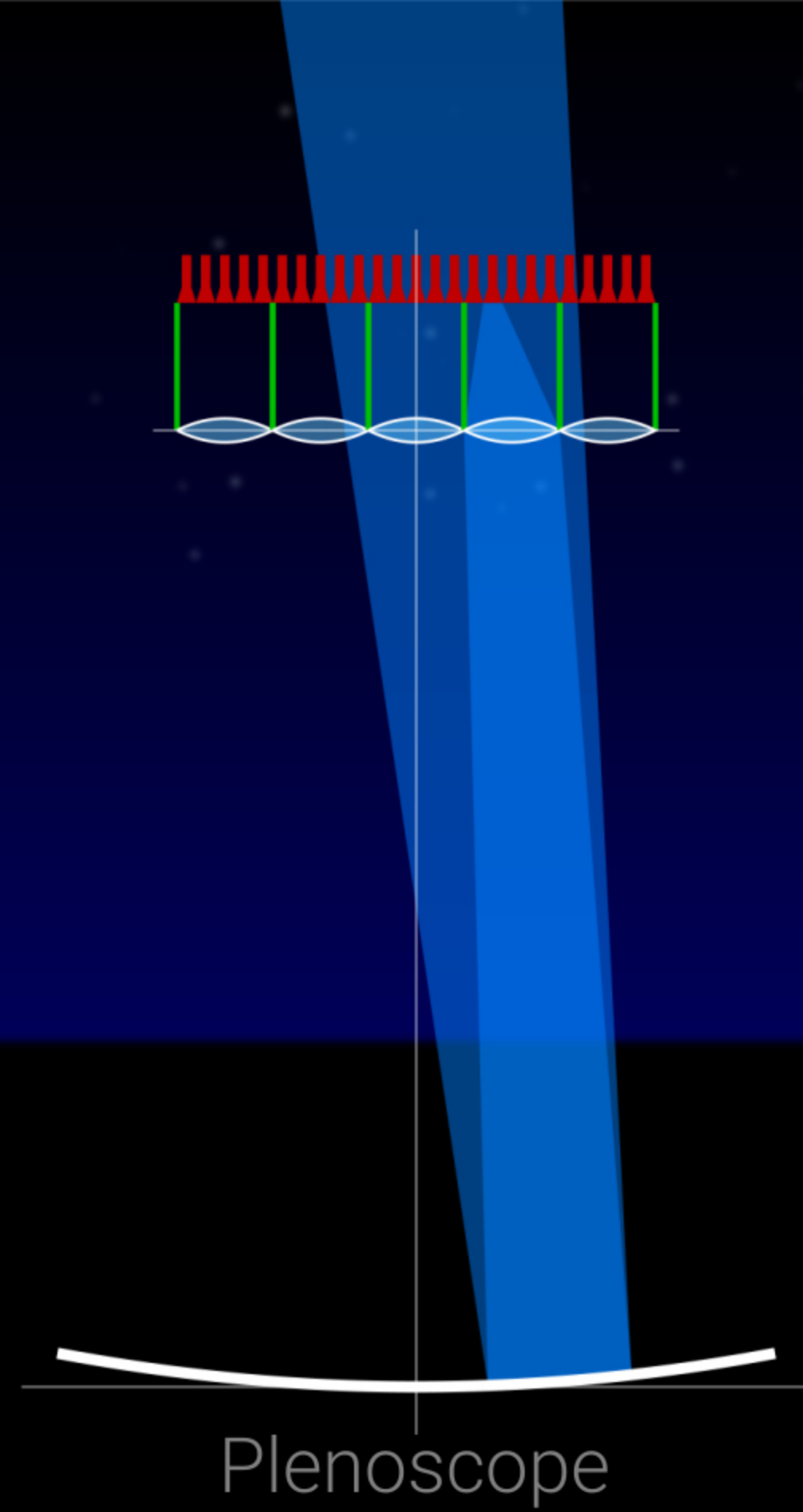
Optics



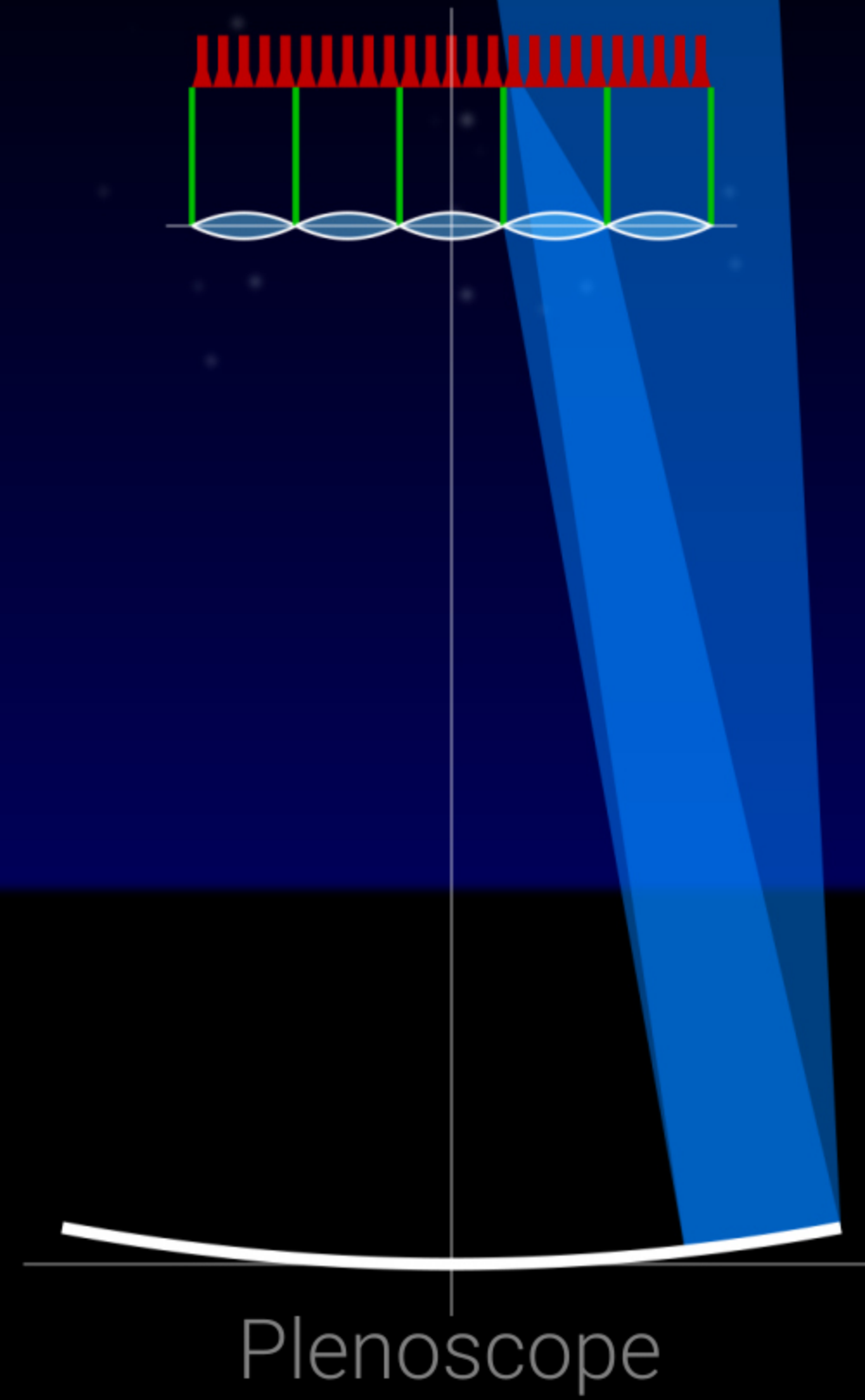
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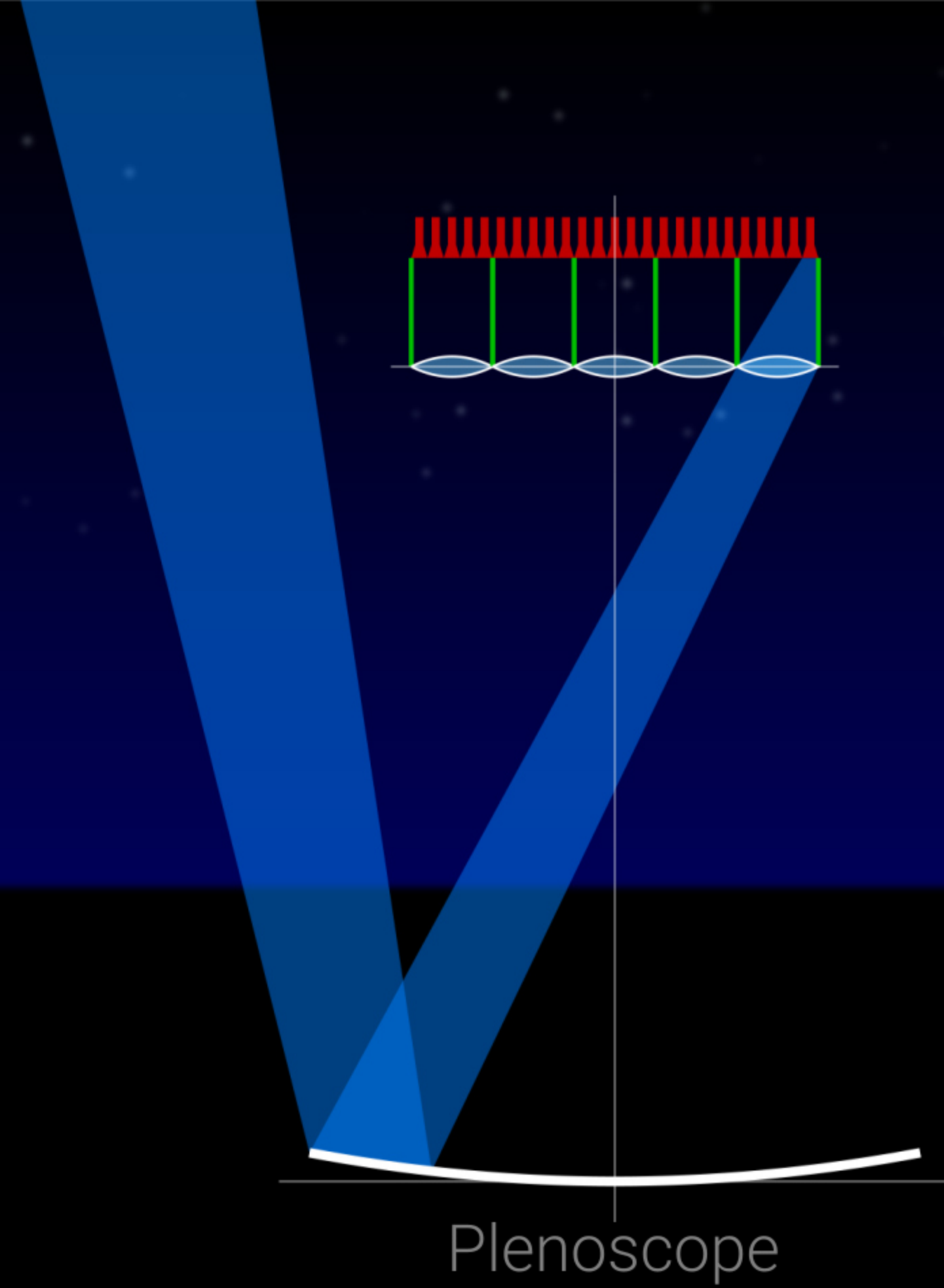
Optics



Optics



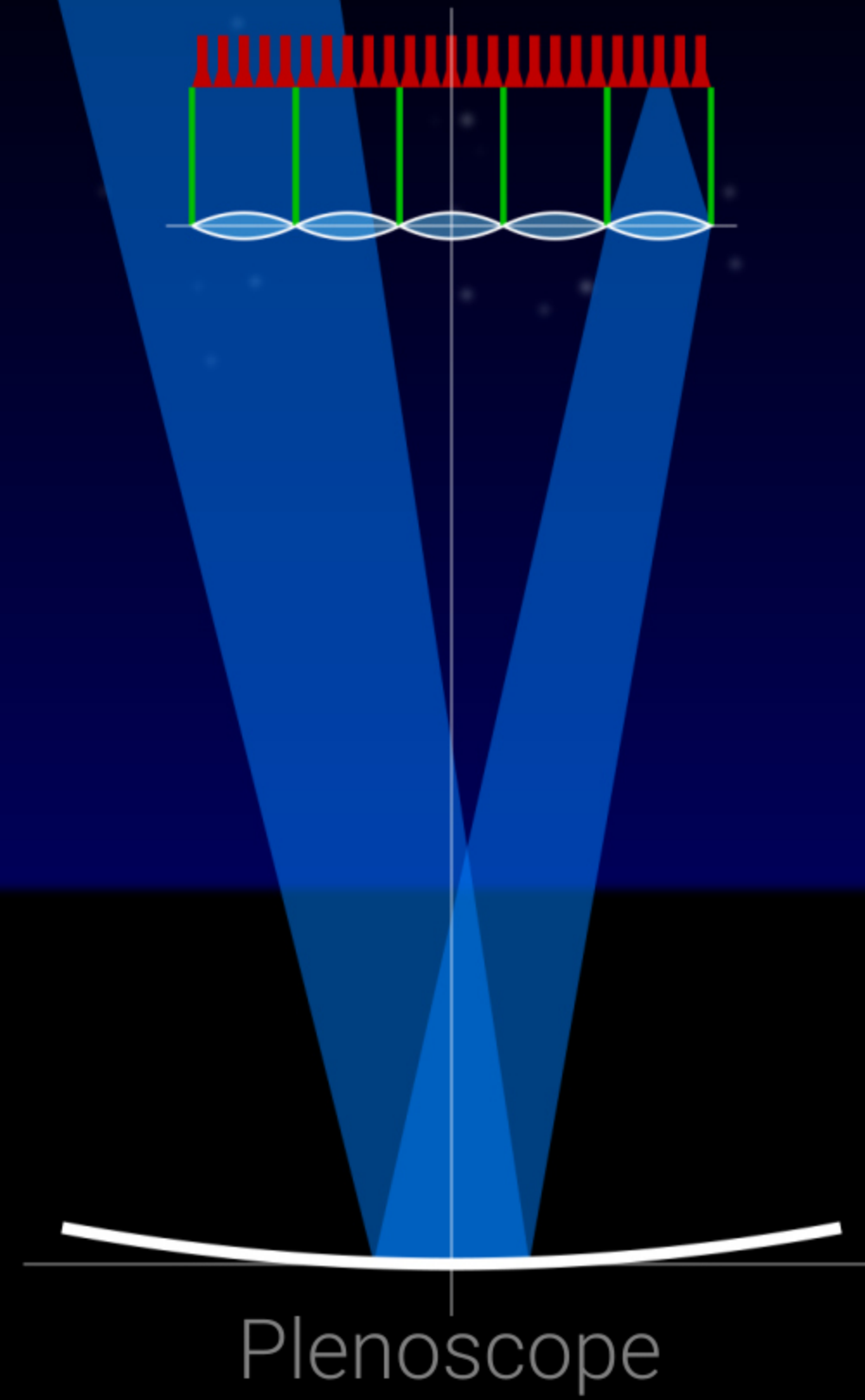
Optics



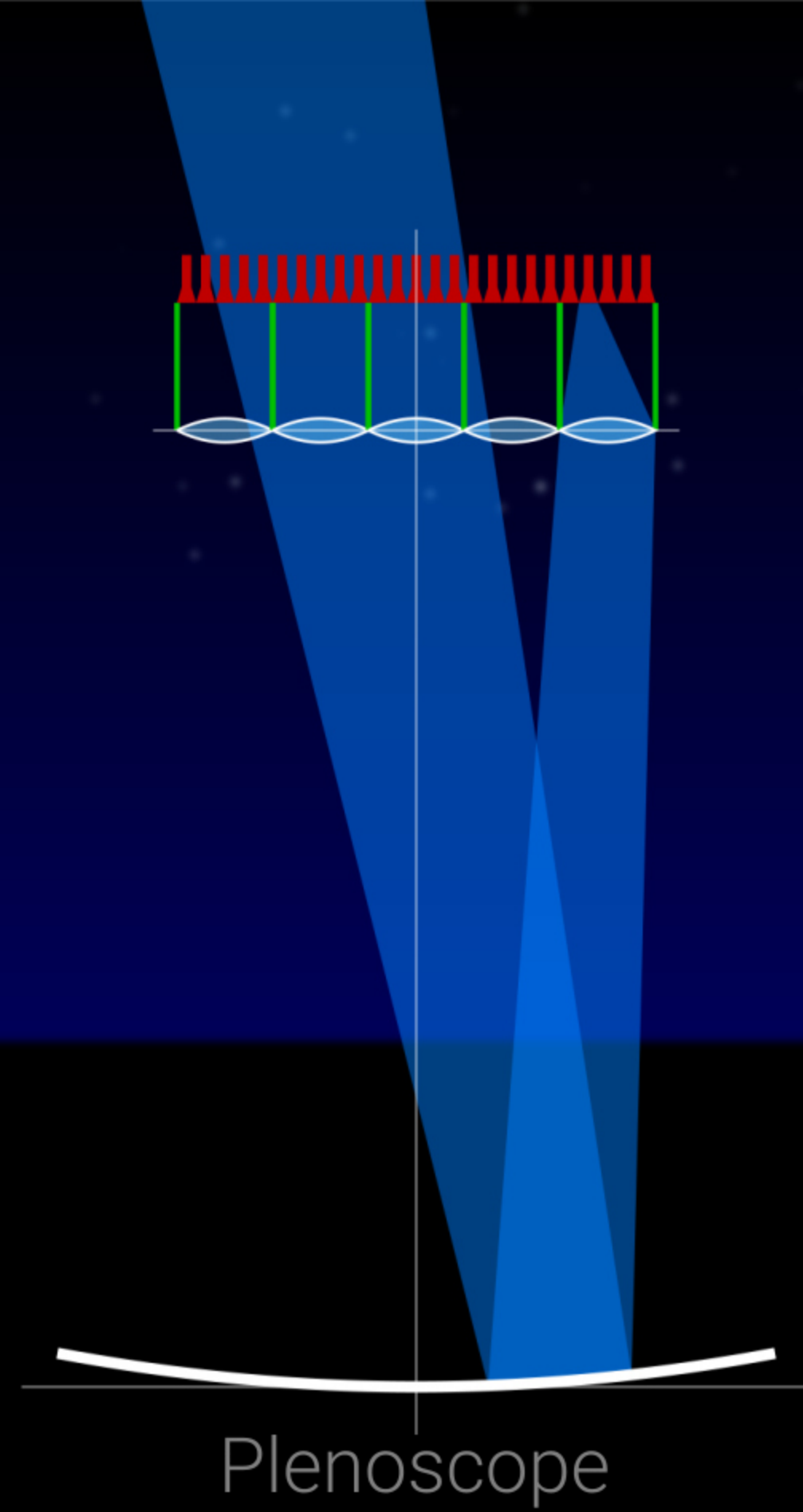
Optics



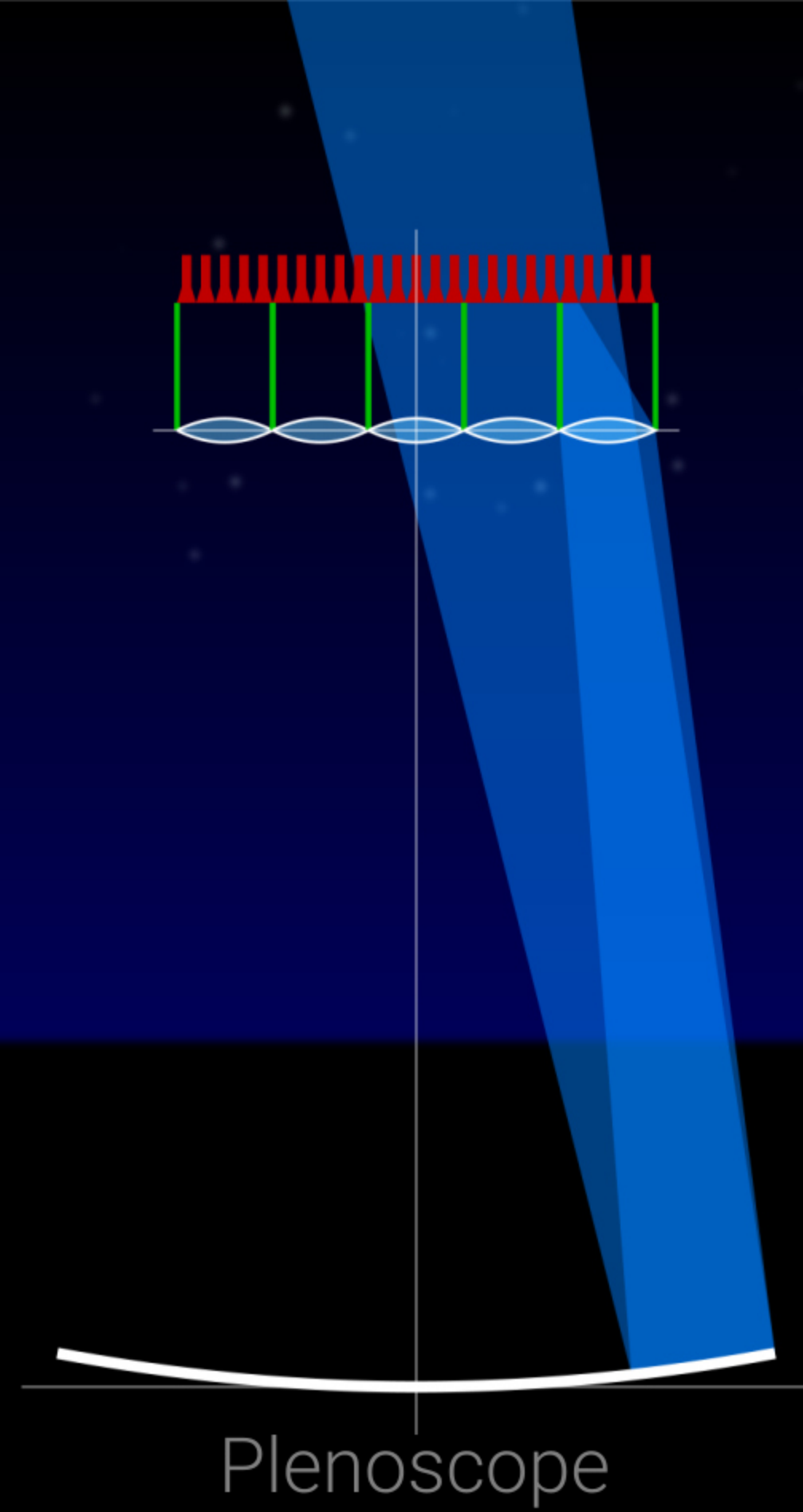
Optics



Optics



Optics

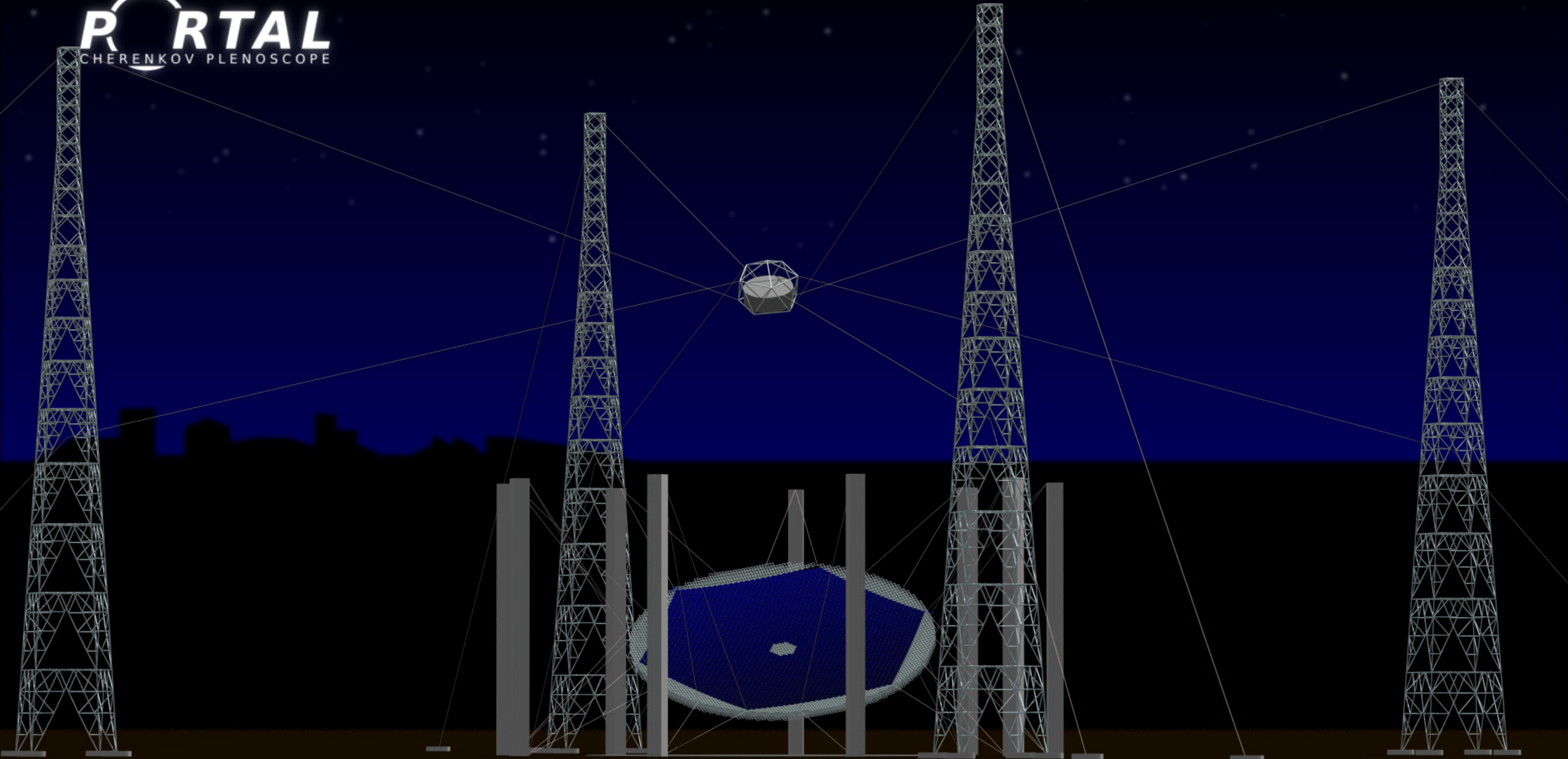


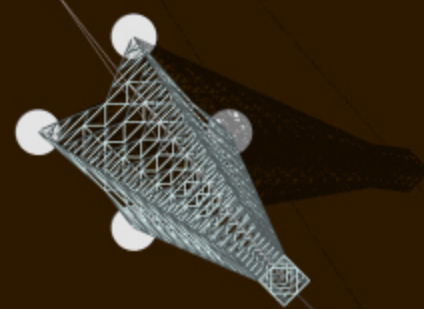
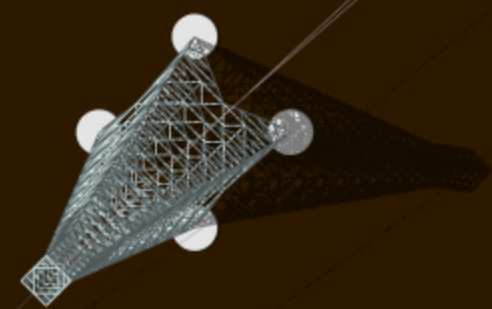
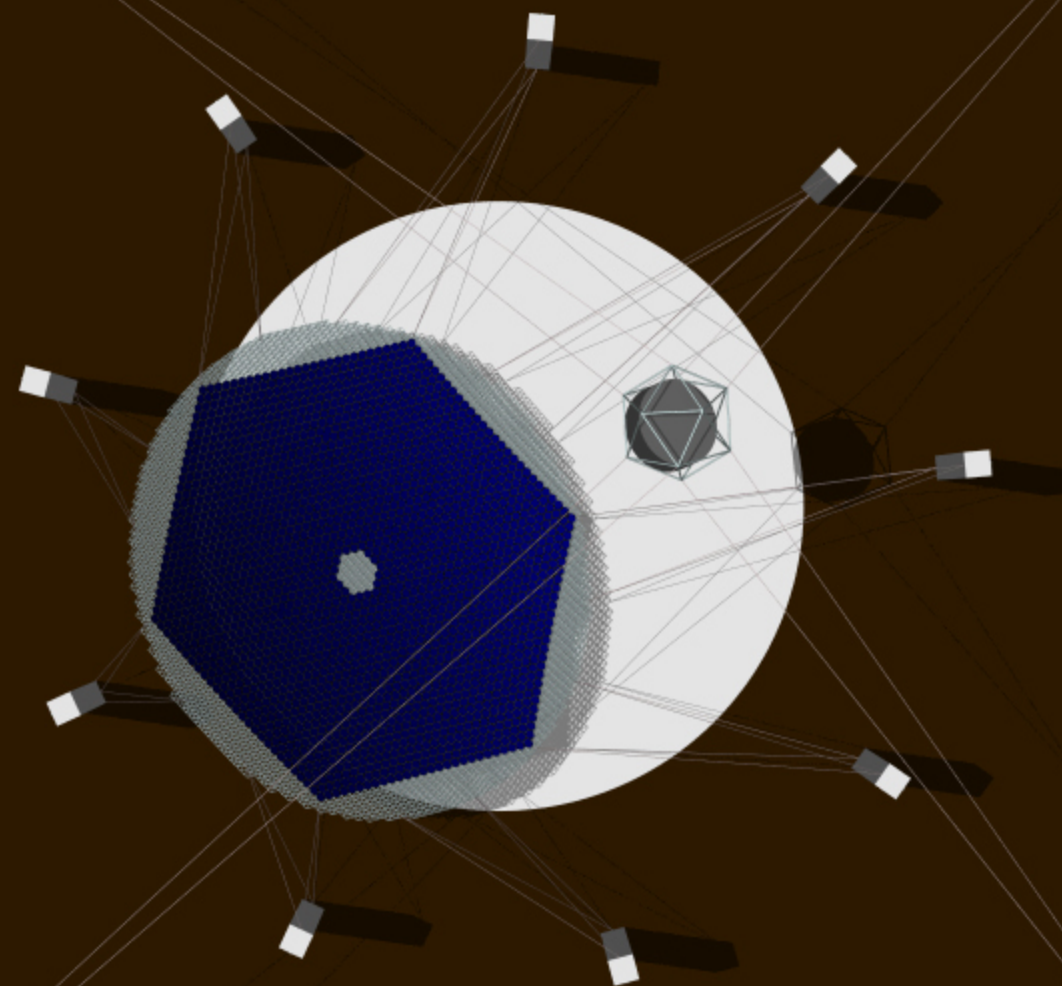
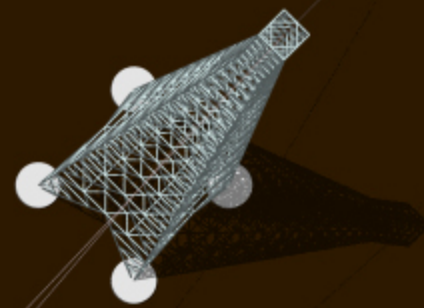
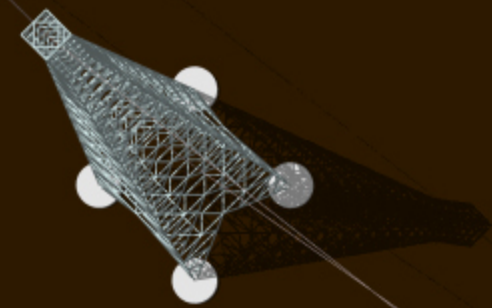
PORTAL

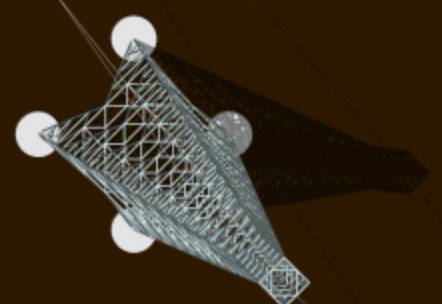
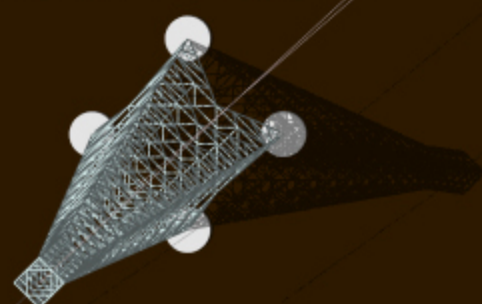
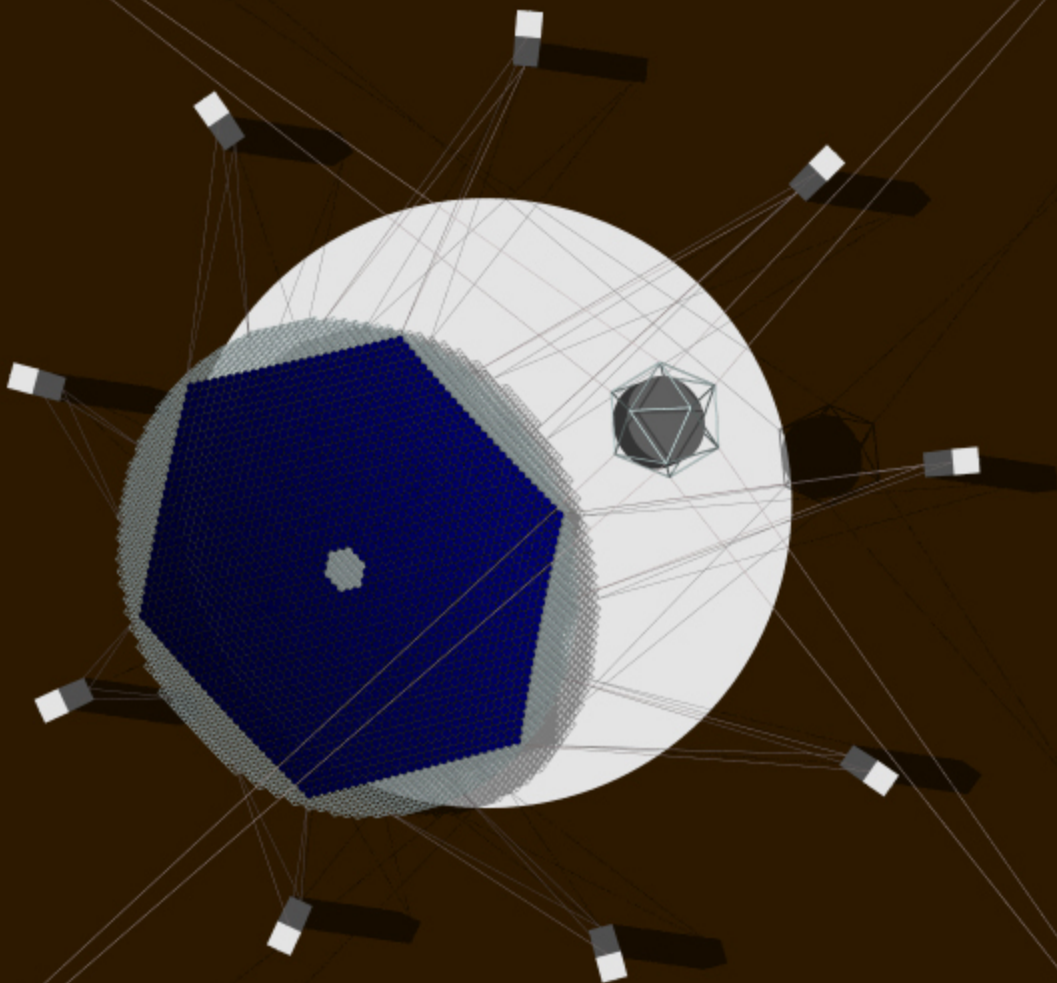
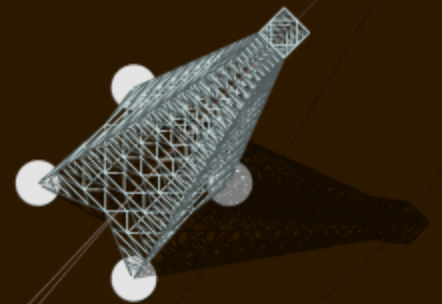
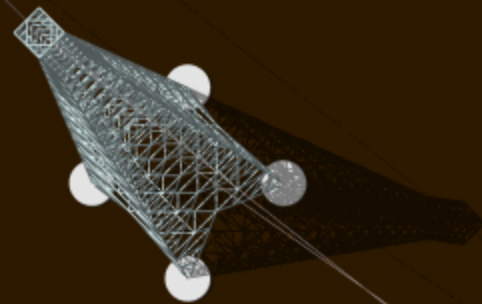


PORTAL

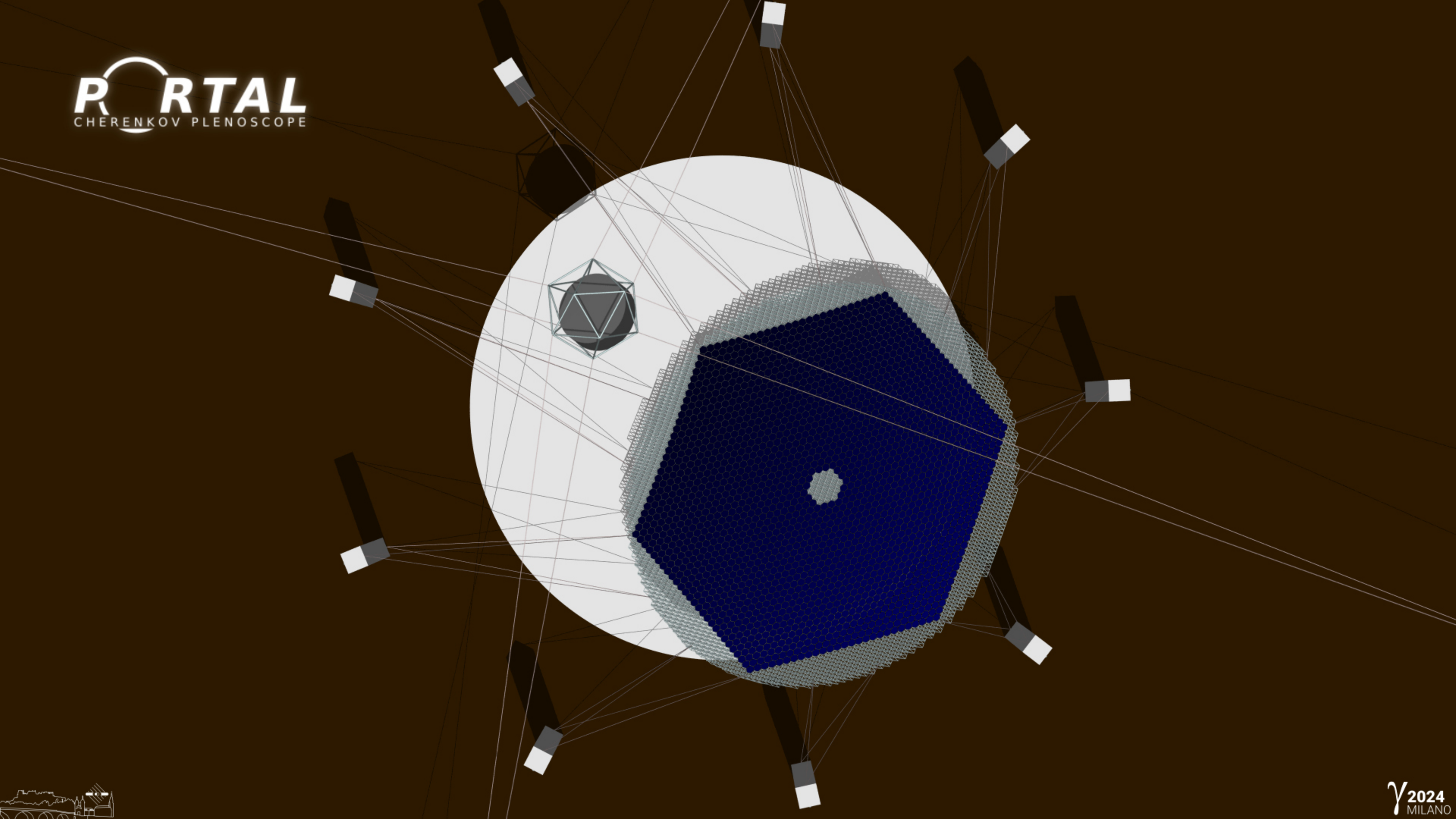
CHERENKOV PLENOSCOPE





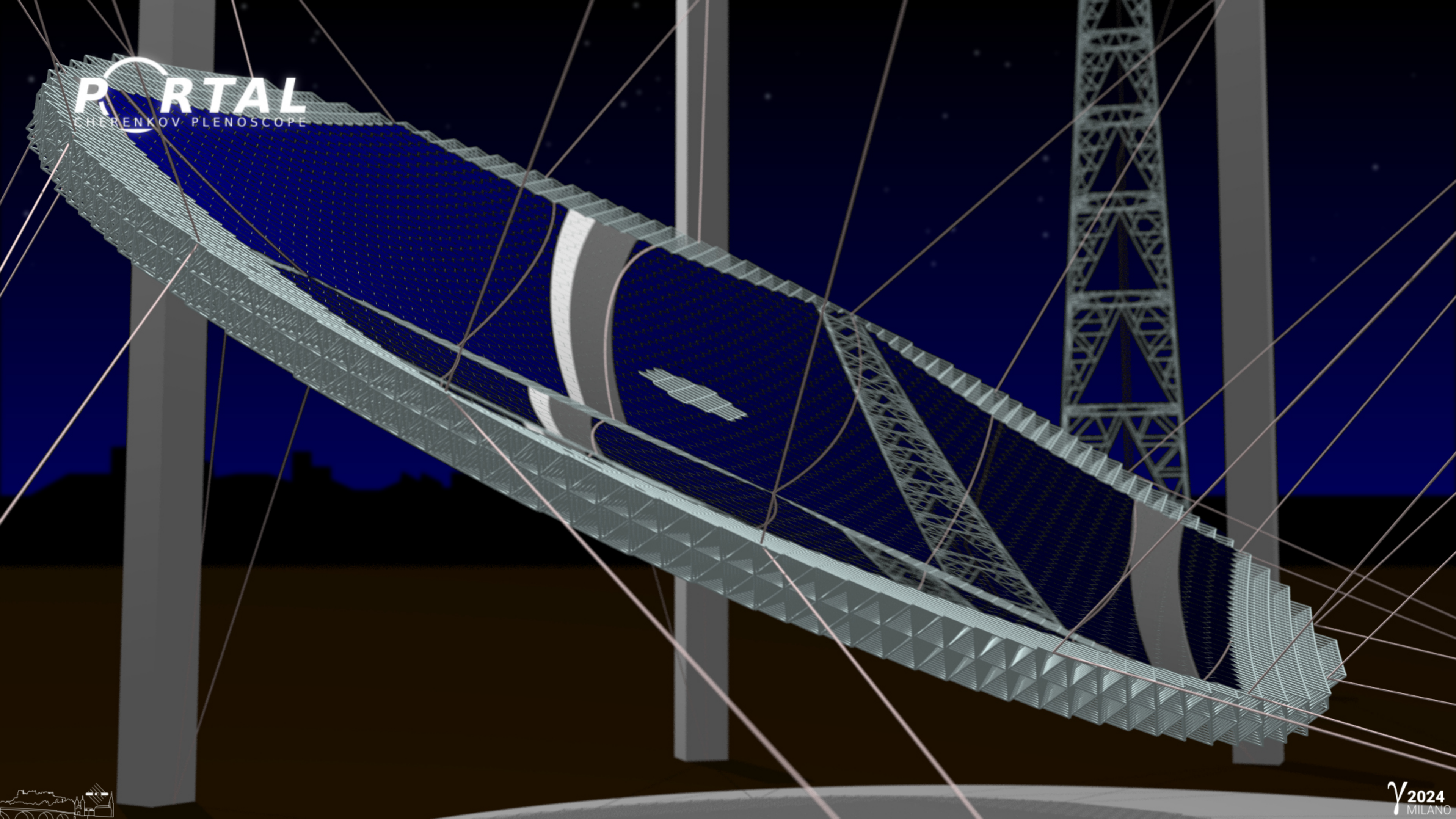


Philipp Miermeister et al. 2016
(Fraunhofer IPA, MPI bio. Cybernetics, Korea University)
The CableRobot Simulator: Large Scale Motion Platform Based on Cable Robot Technology
International Conference on Intelligent Robots and Systems
Daejeon, Korea



PORTAL

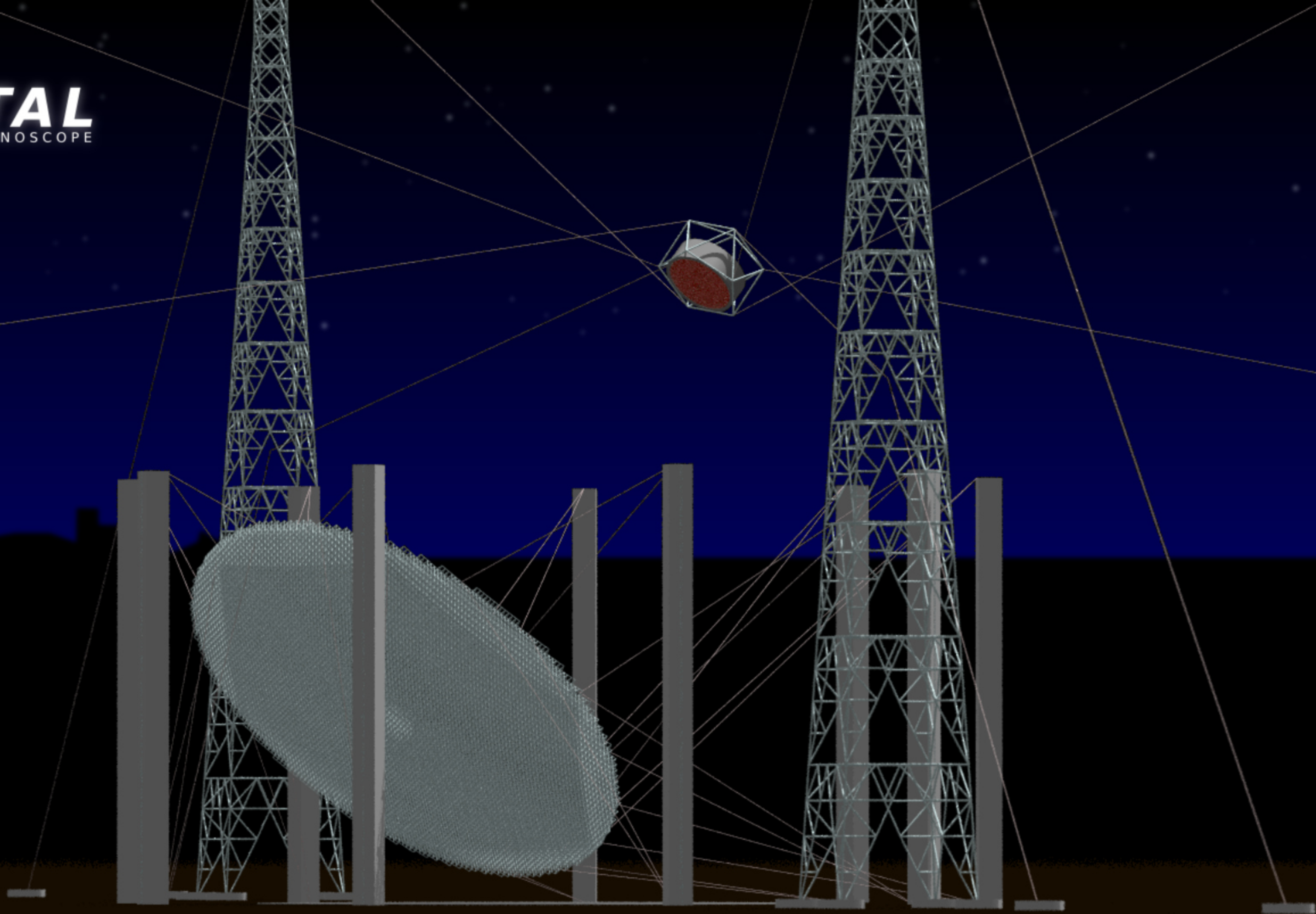
CHERENKOV PLENOSCOPE



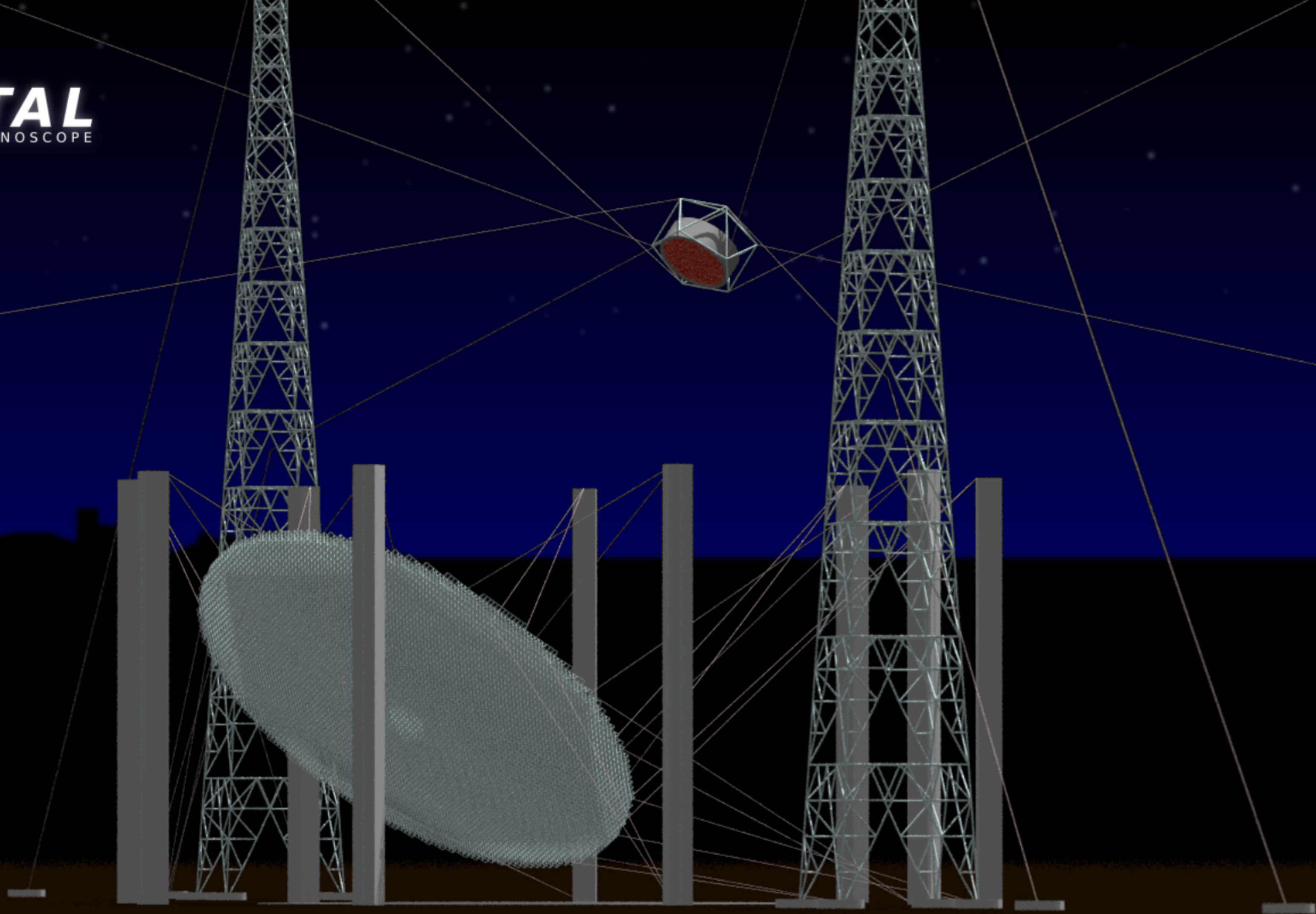
71 m

$f = 106.5 \text{ m}$

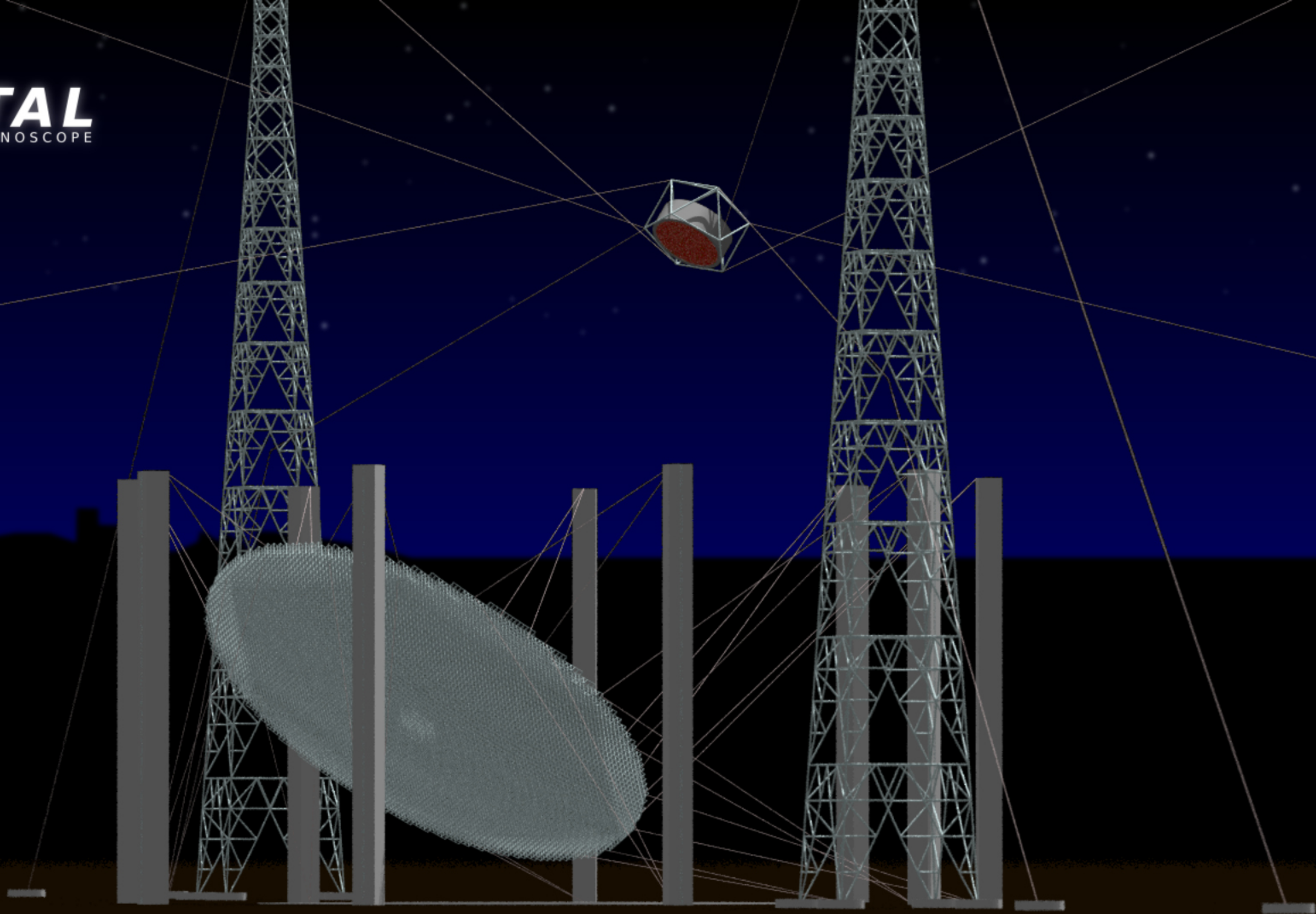
PORTAL
CHERENKOV TELESCOPE



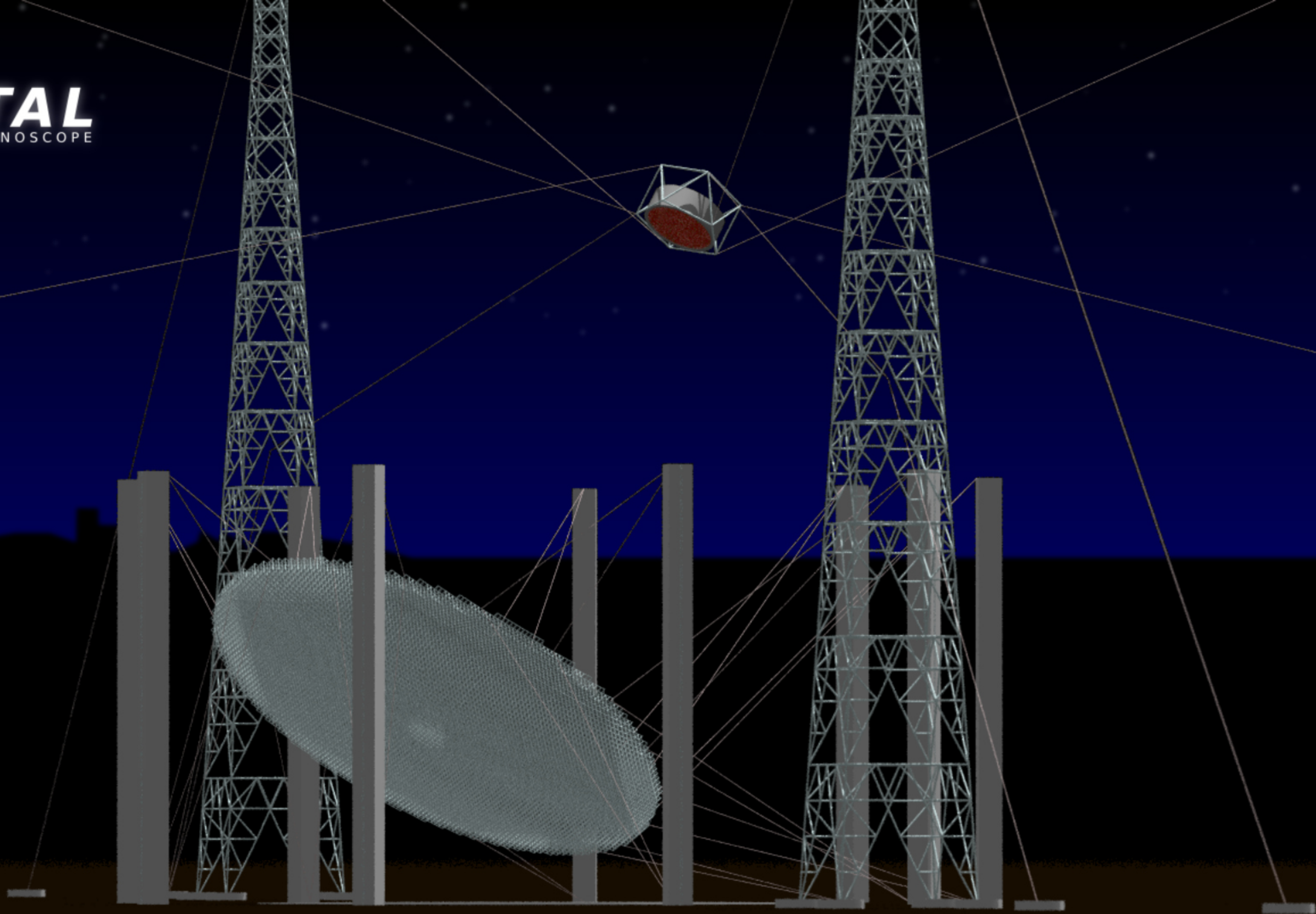
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CHERENKOV TELESCOPE



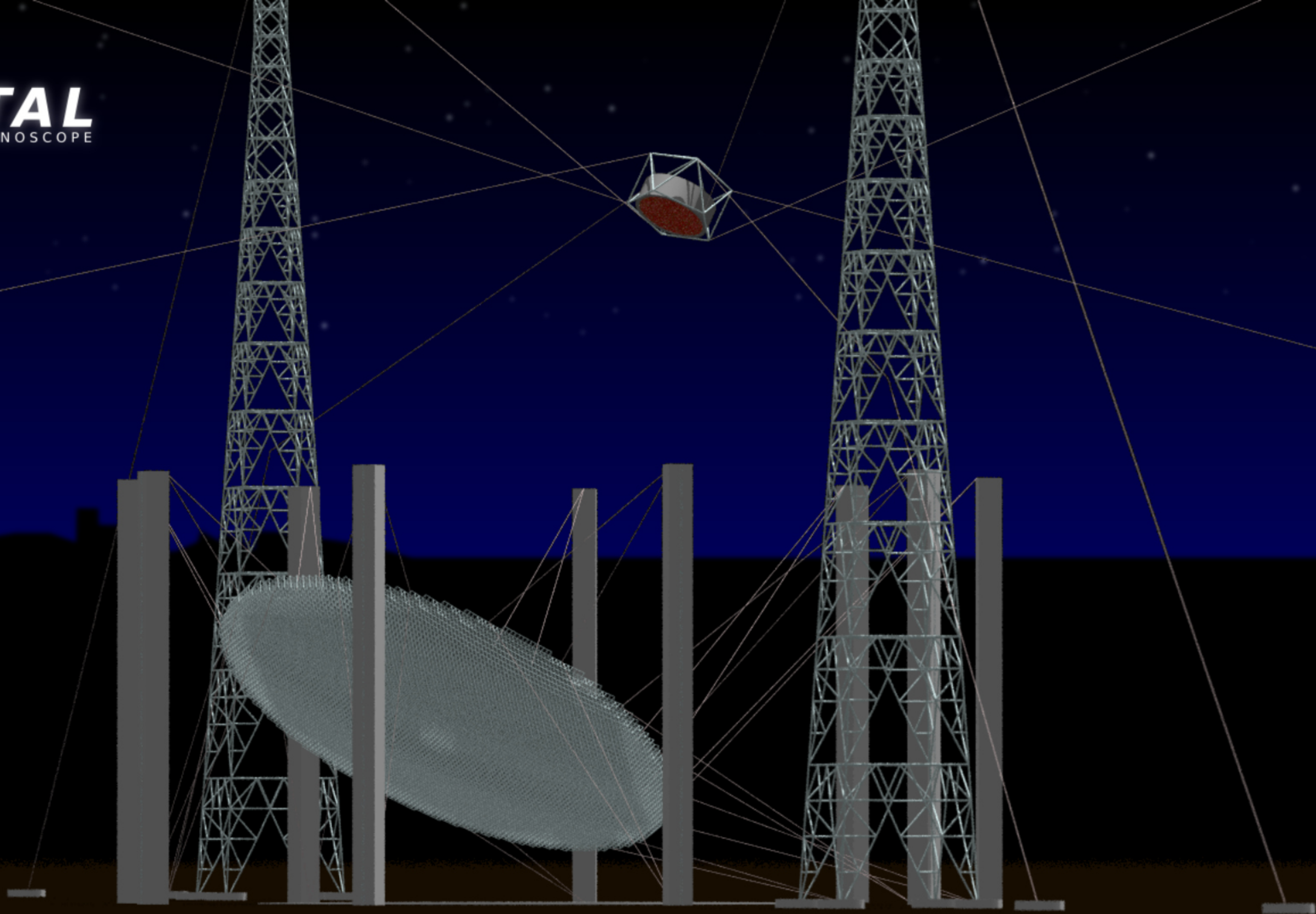
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CHERENKOV TELESCOPE



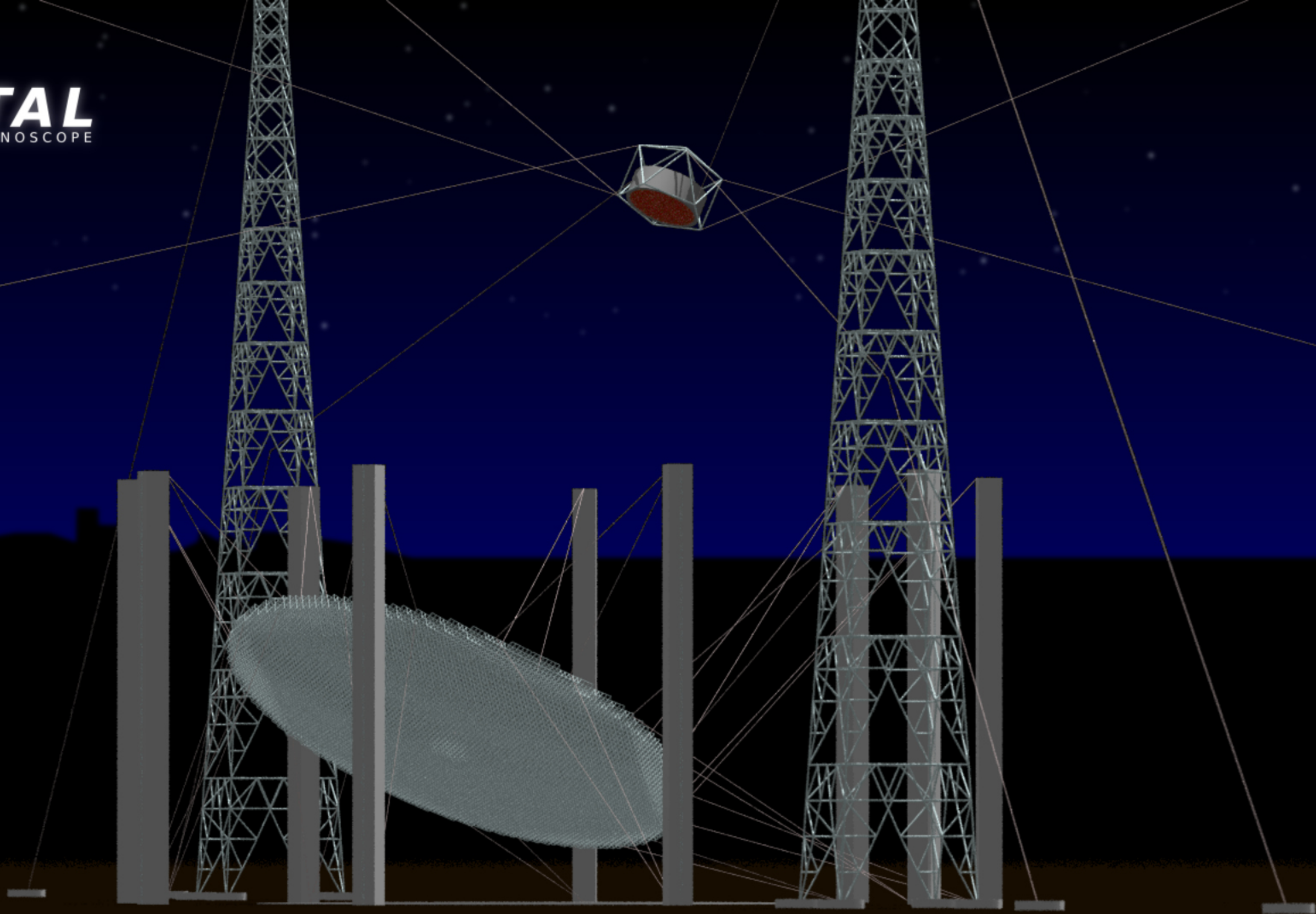
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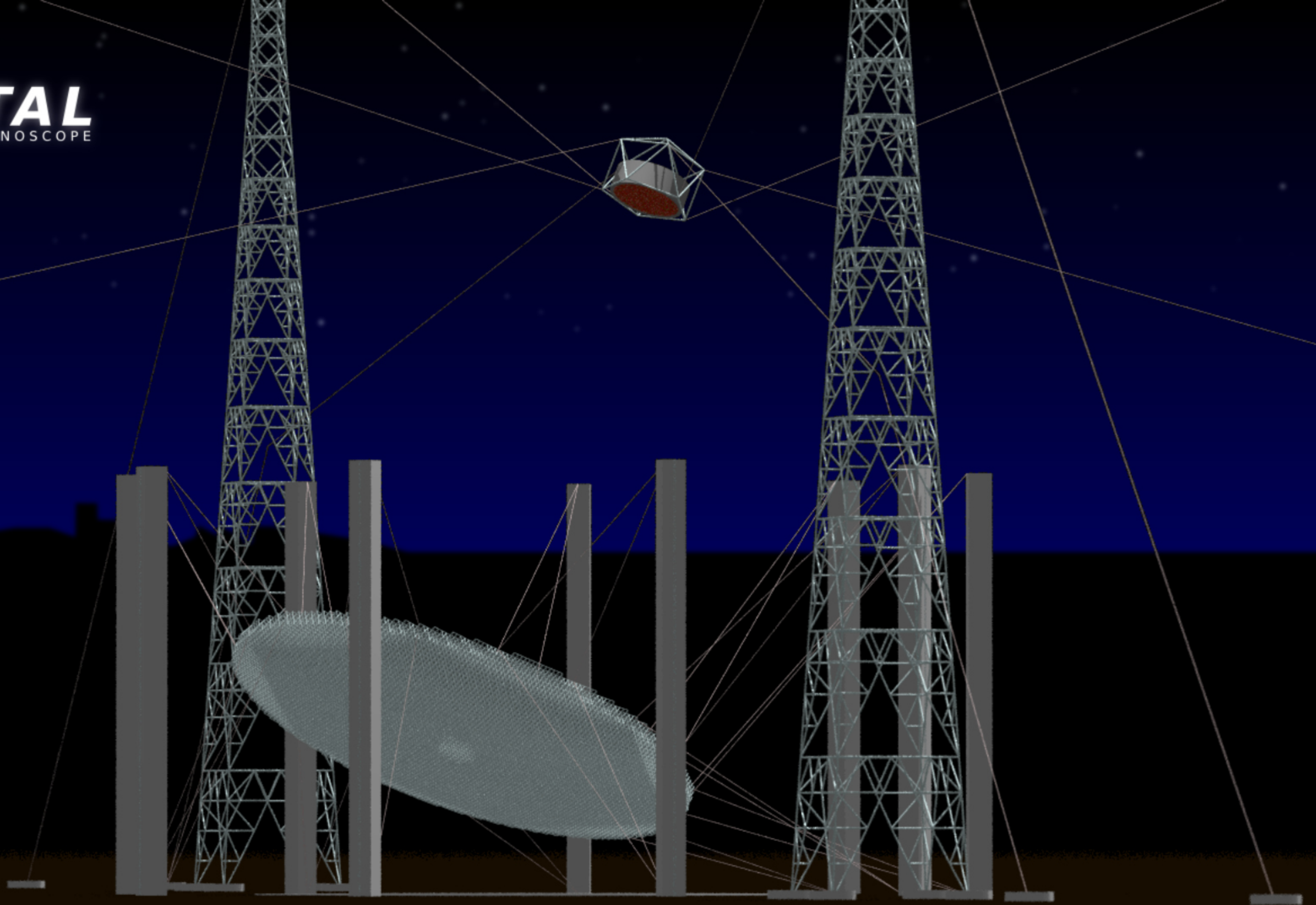
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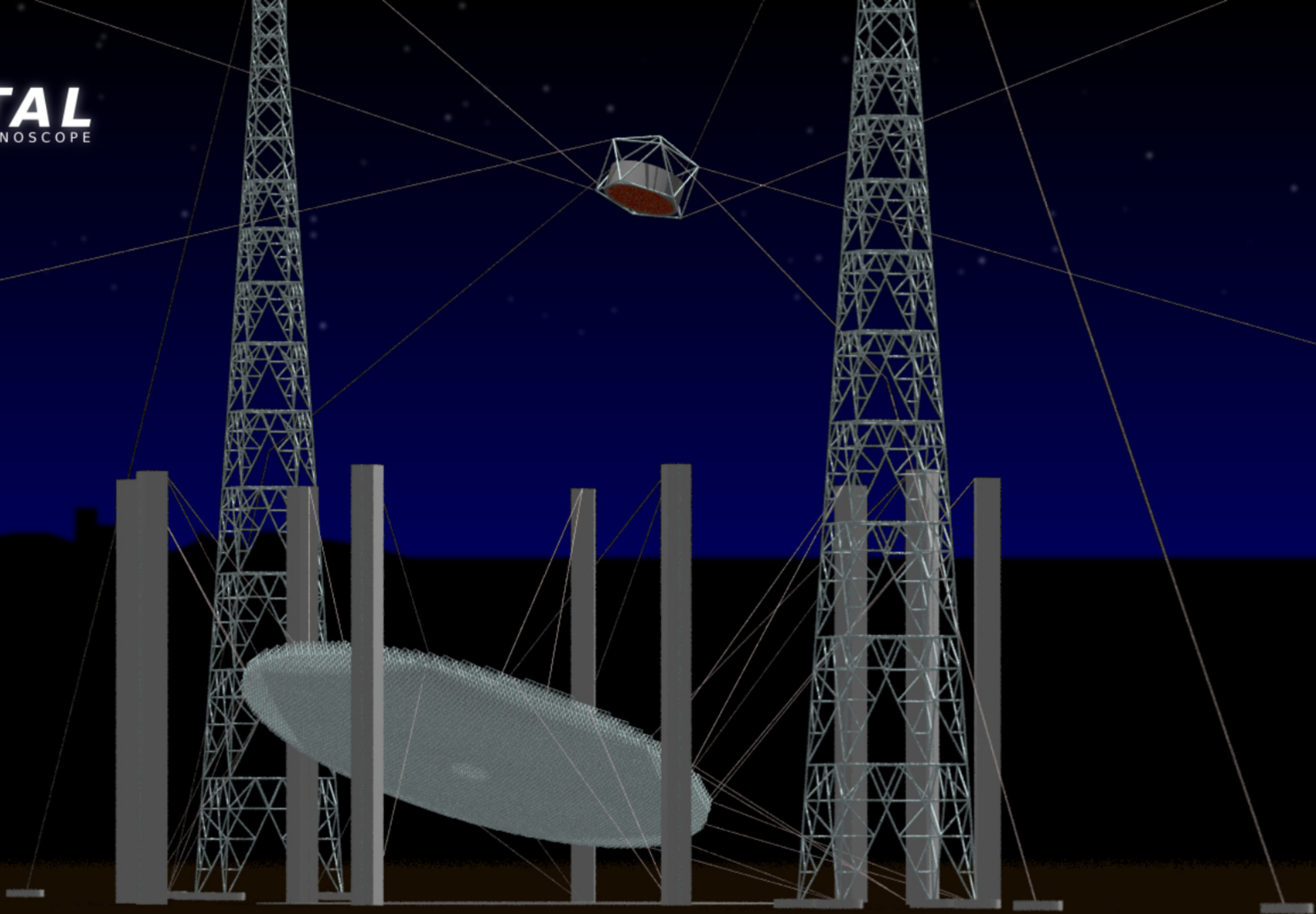
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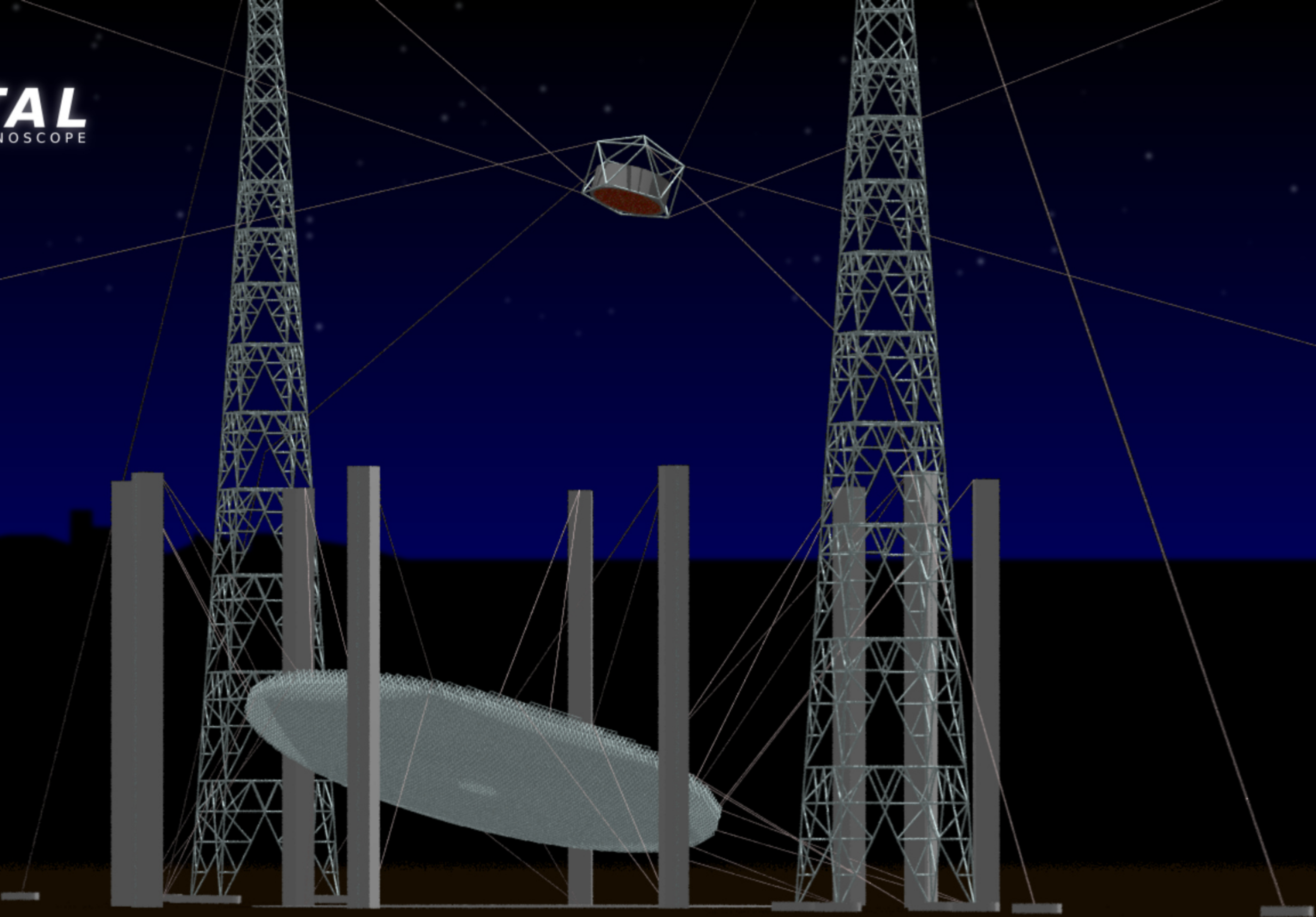
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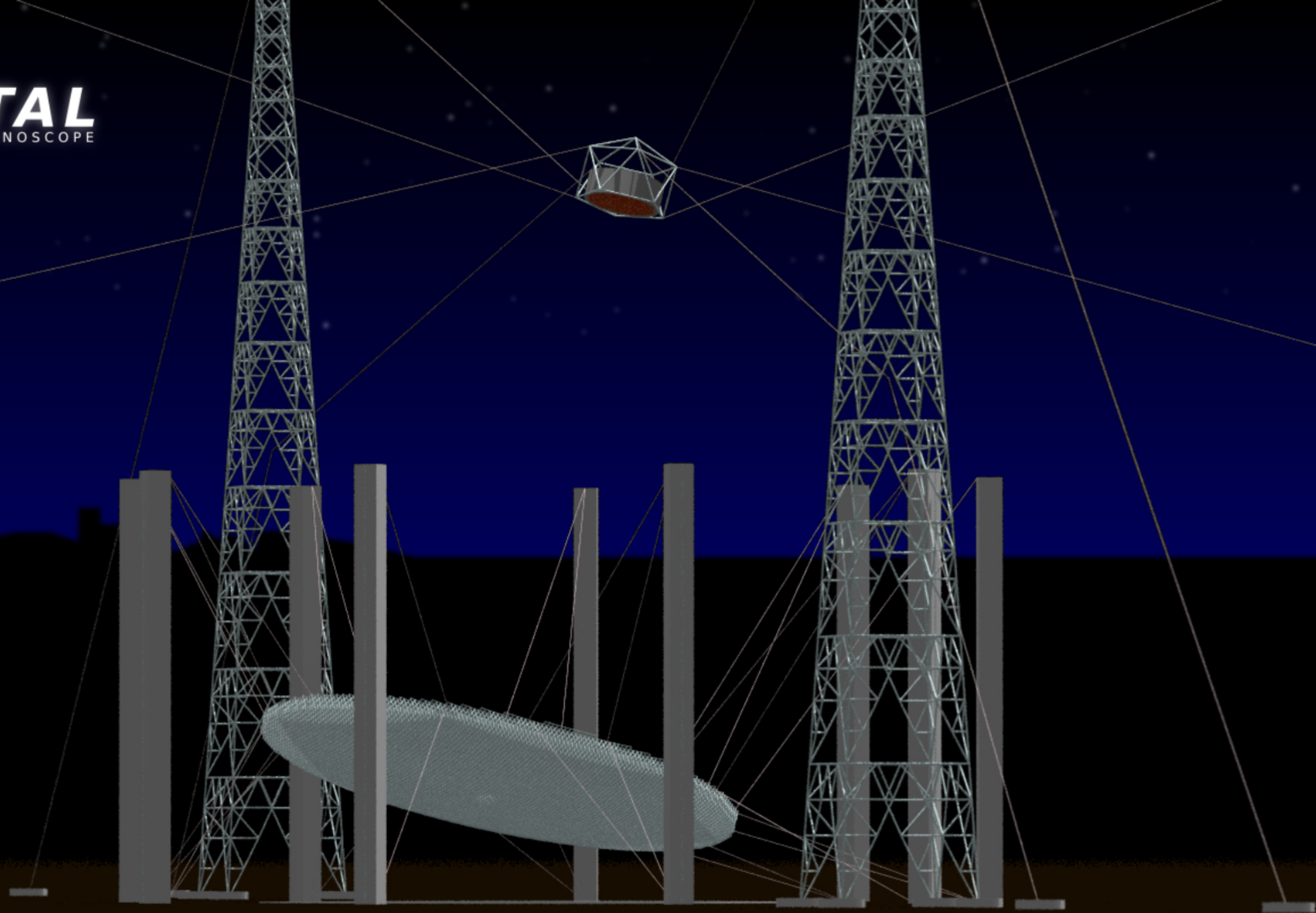
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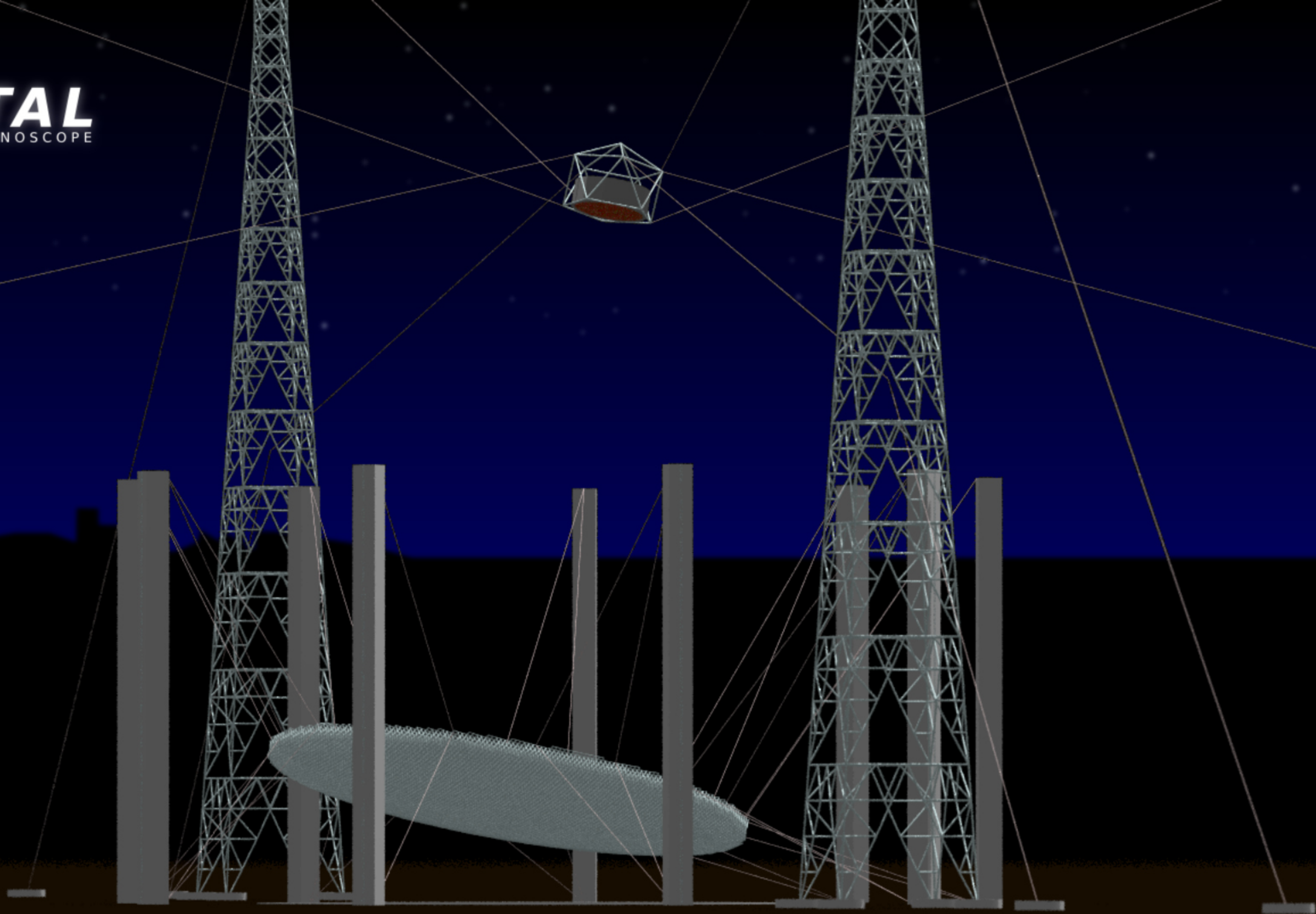
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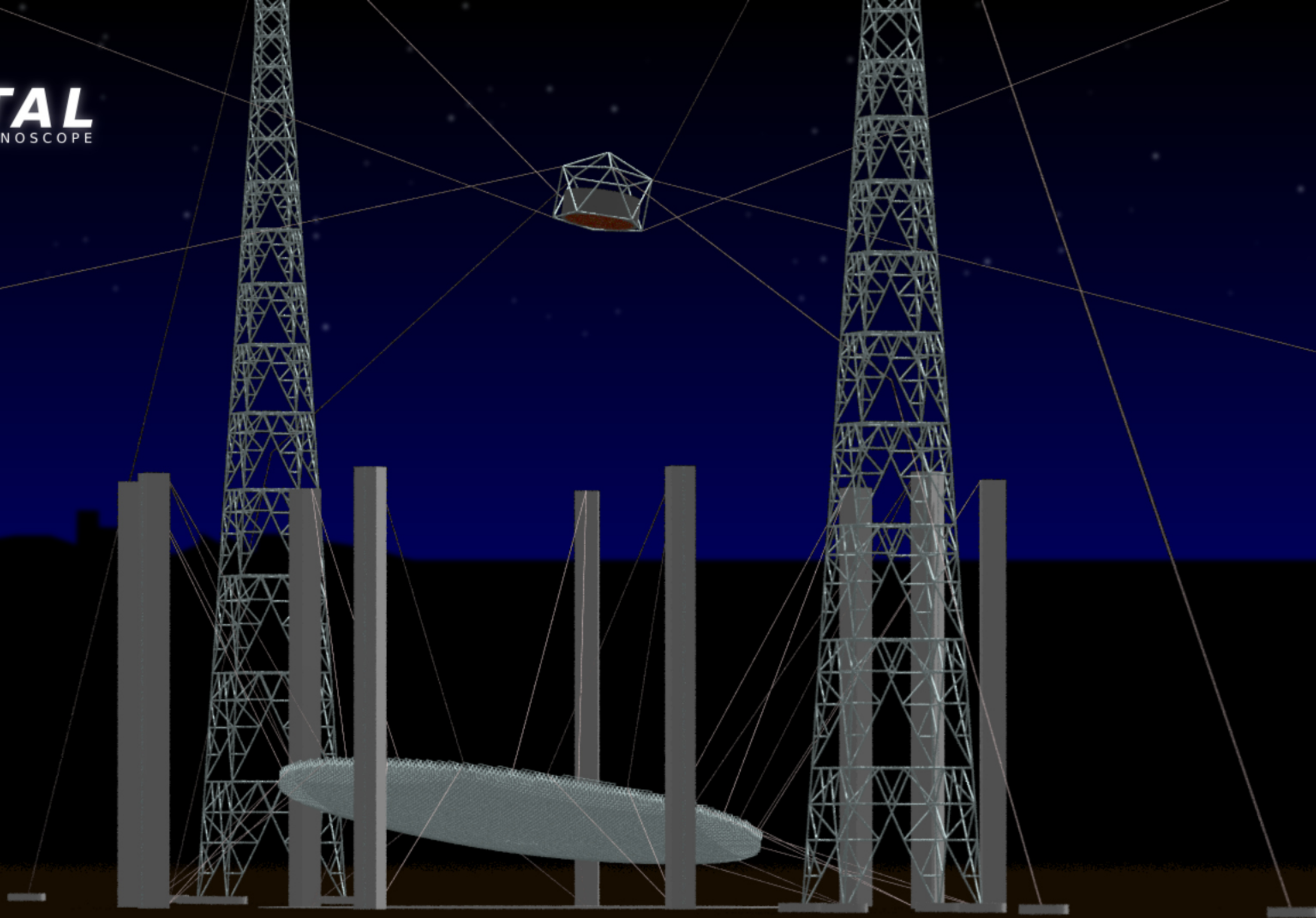
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CHERENKOV TELESCOPE



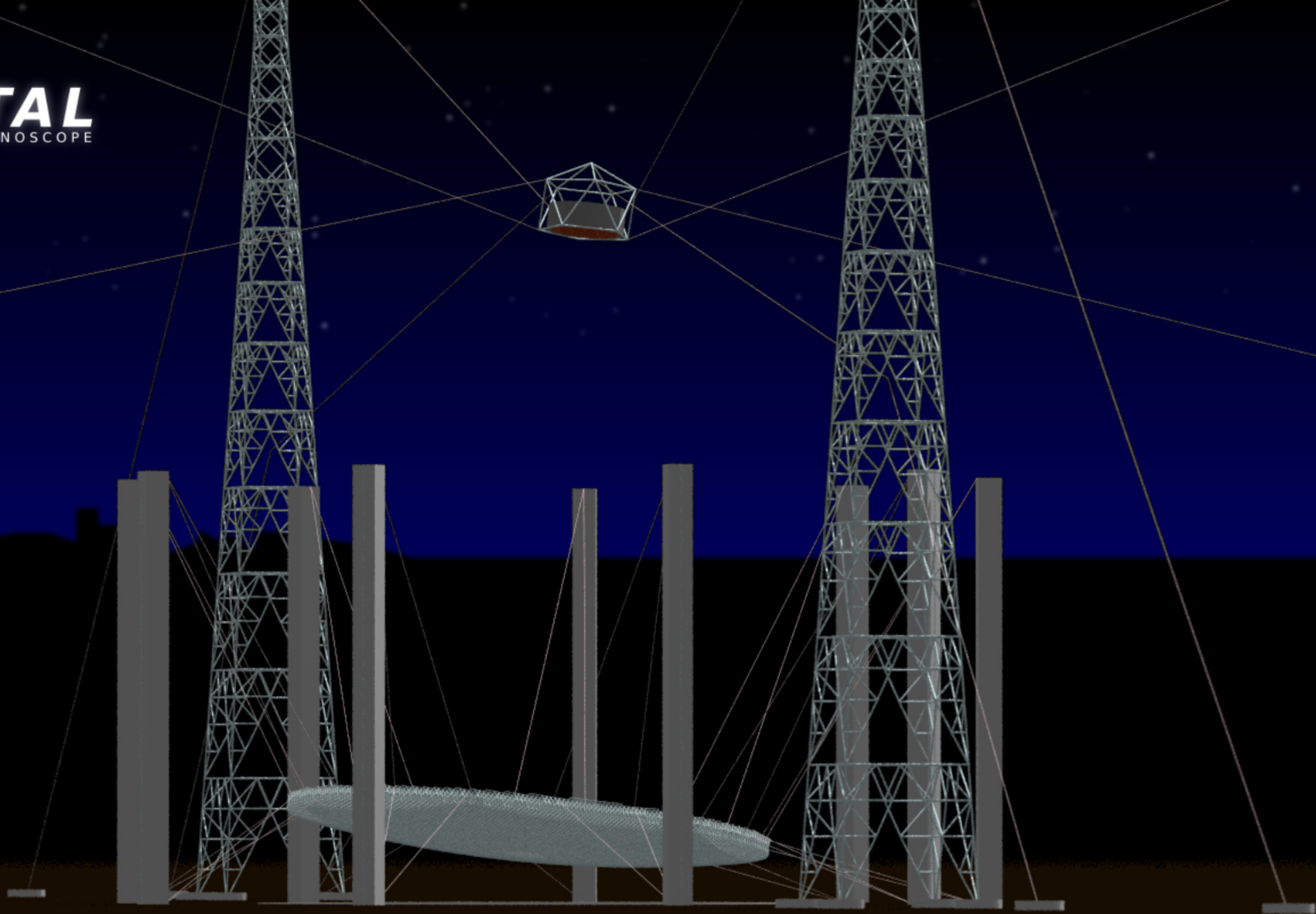
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CHERENKOV TELESCOPE



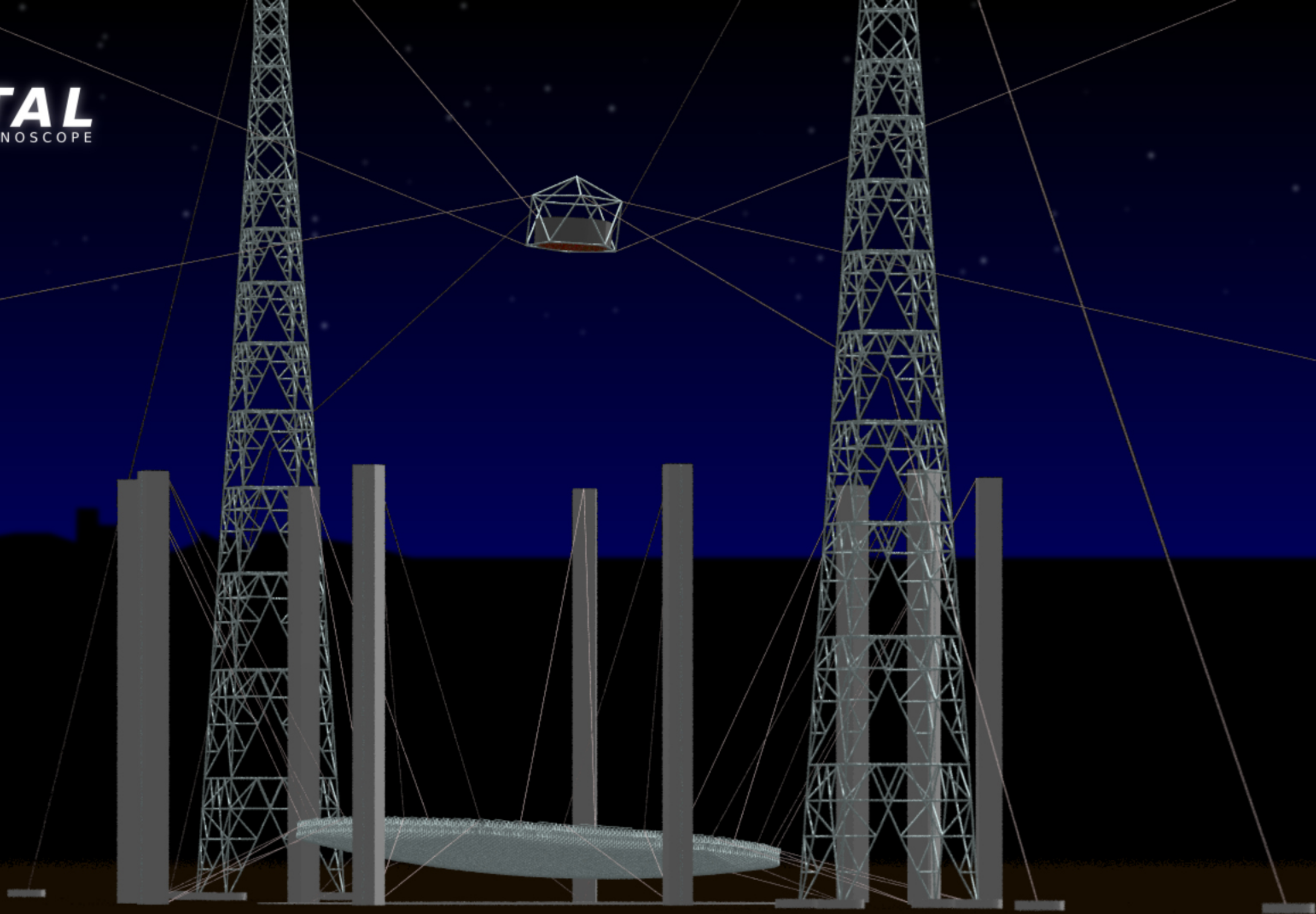
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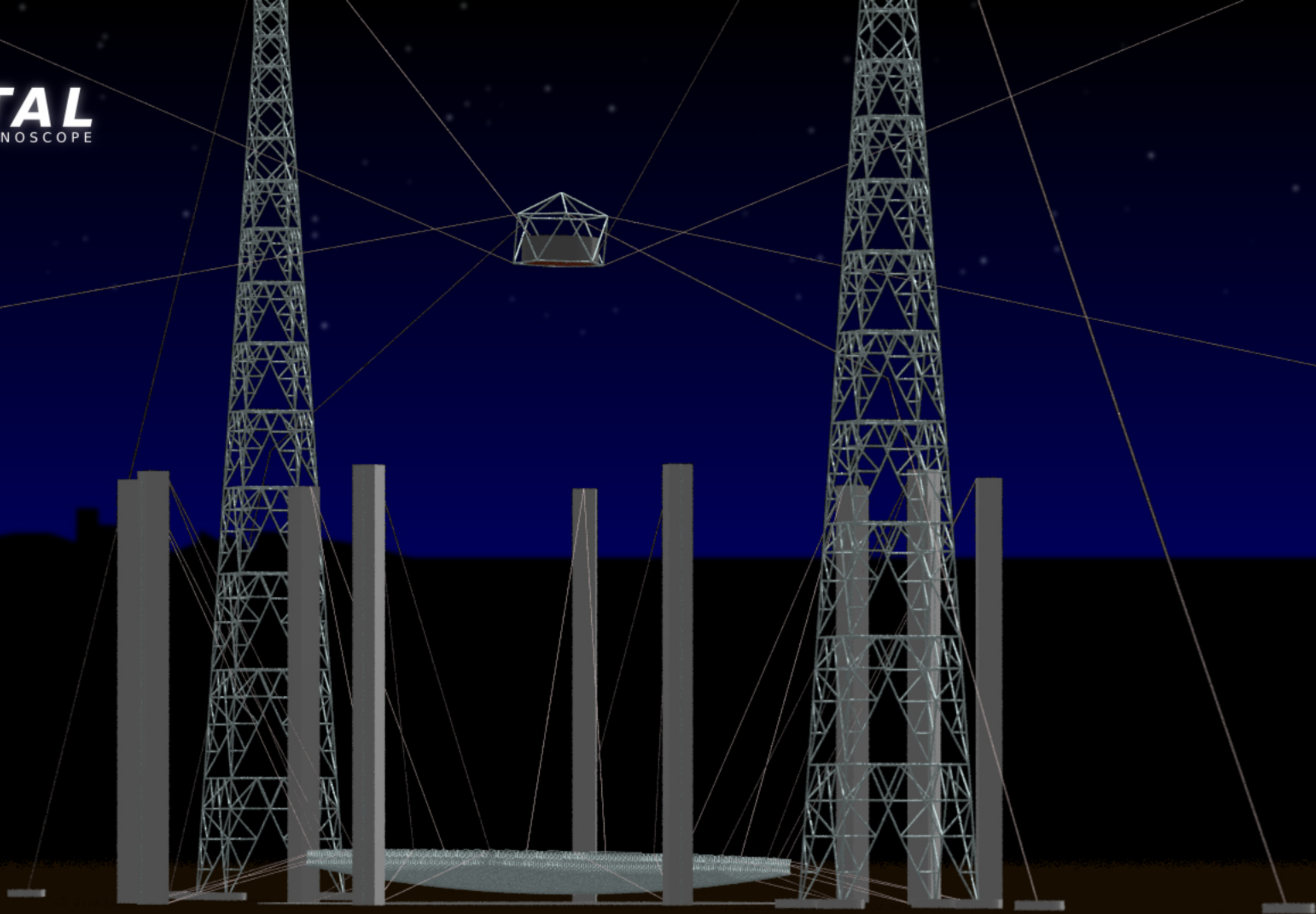
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CHERENKOV TELESCOPE



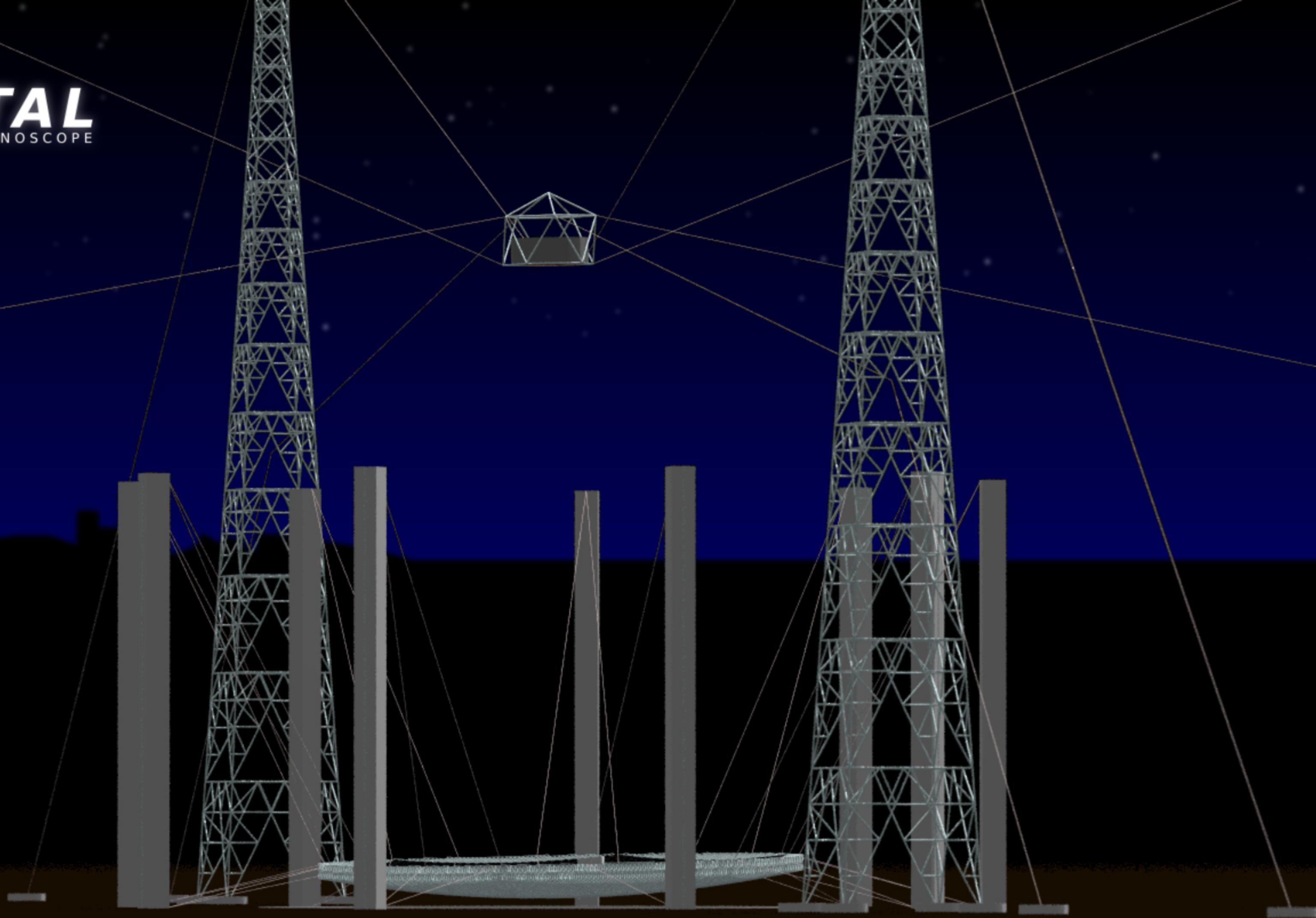
PORTAL
CHERENKOV TELESCOPE



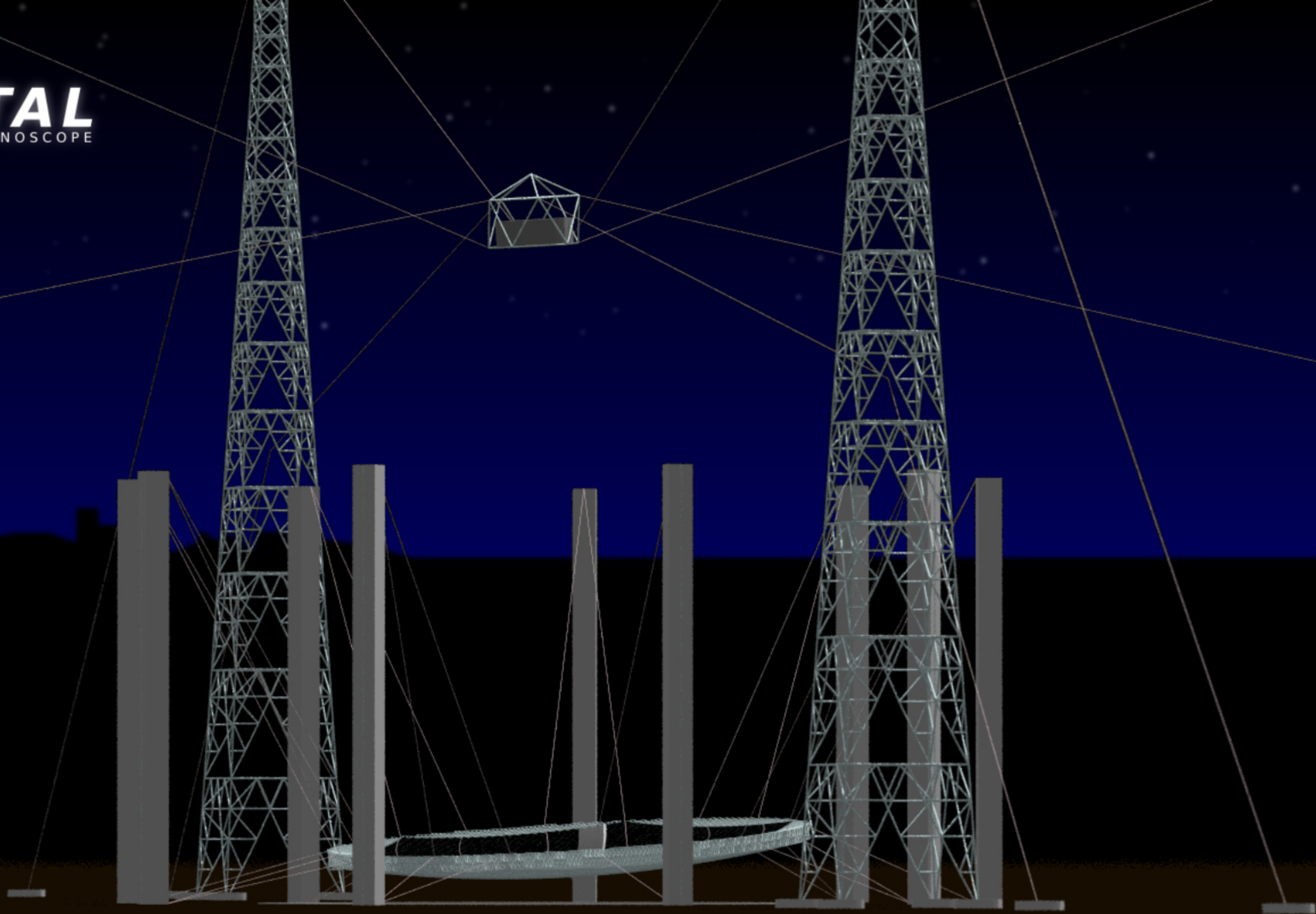
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CHERENKOV TELESCOPE



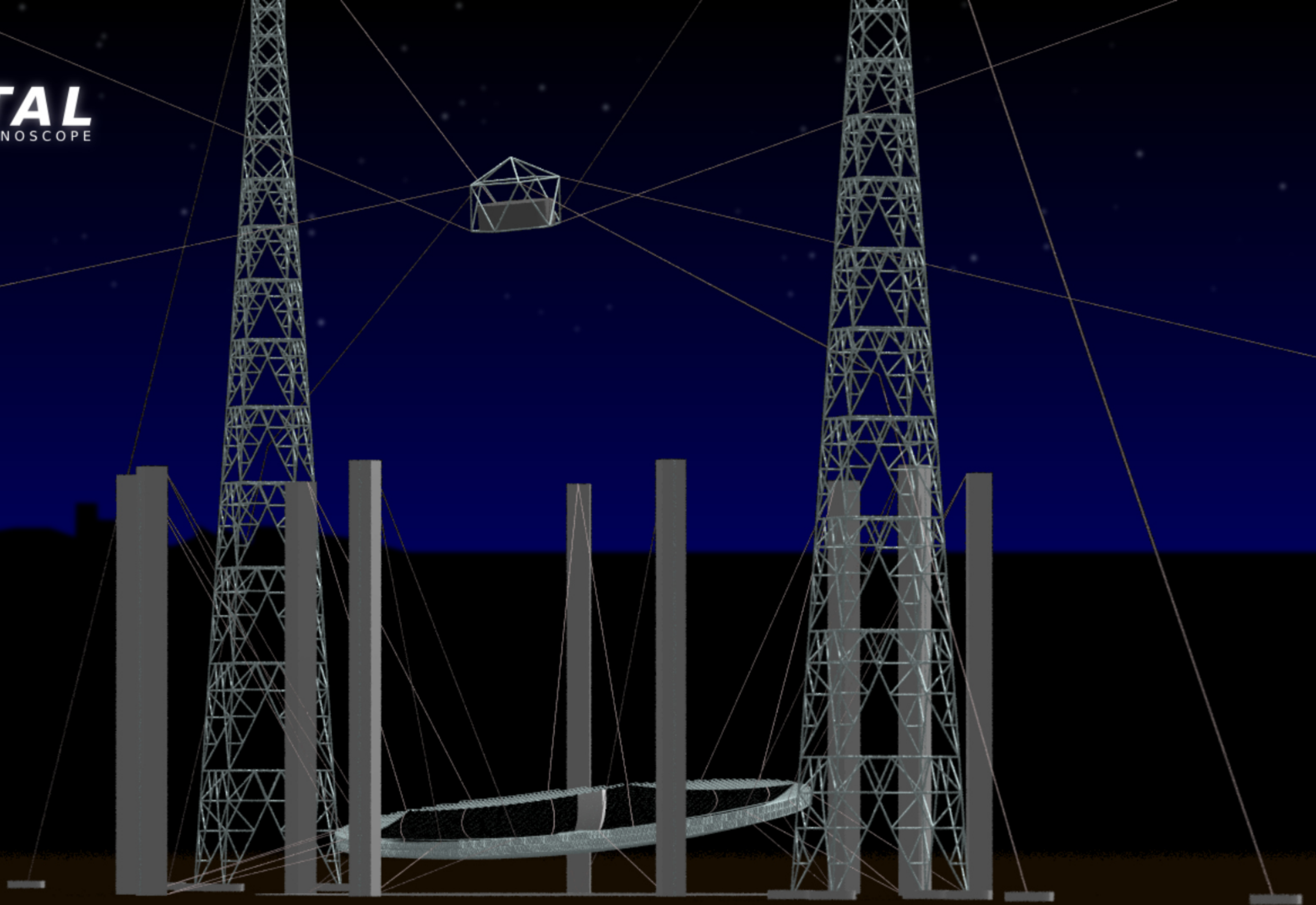
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CHERENKOV TELESCOPE



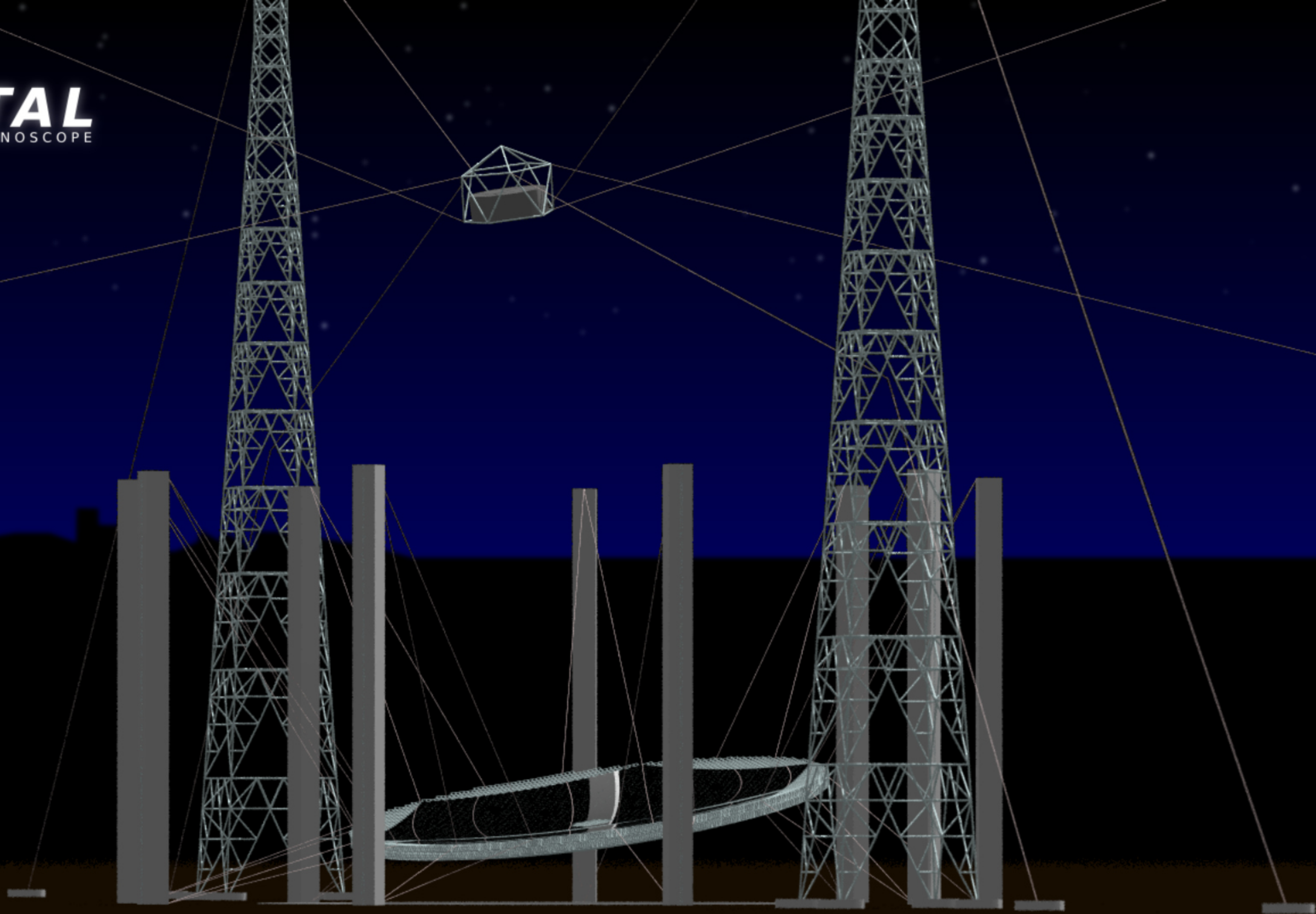
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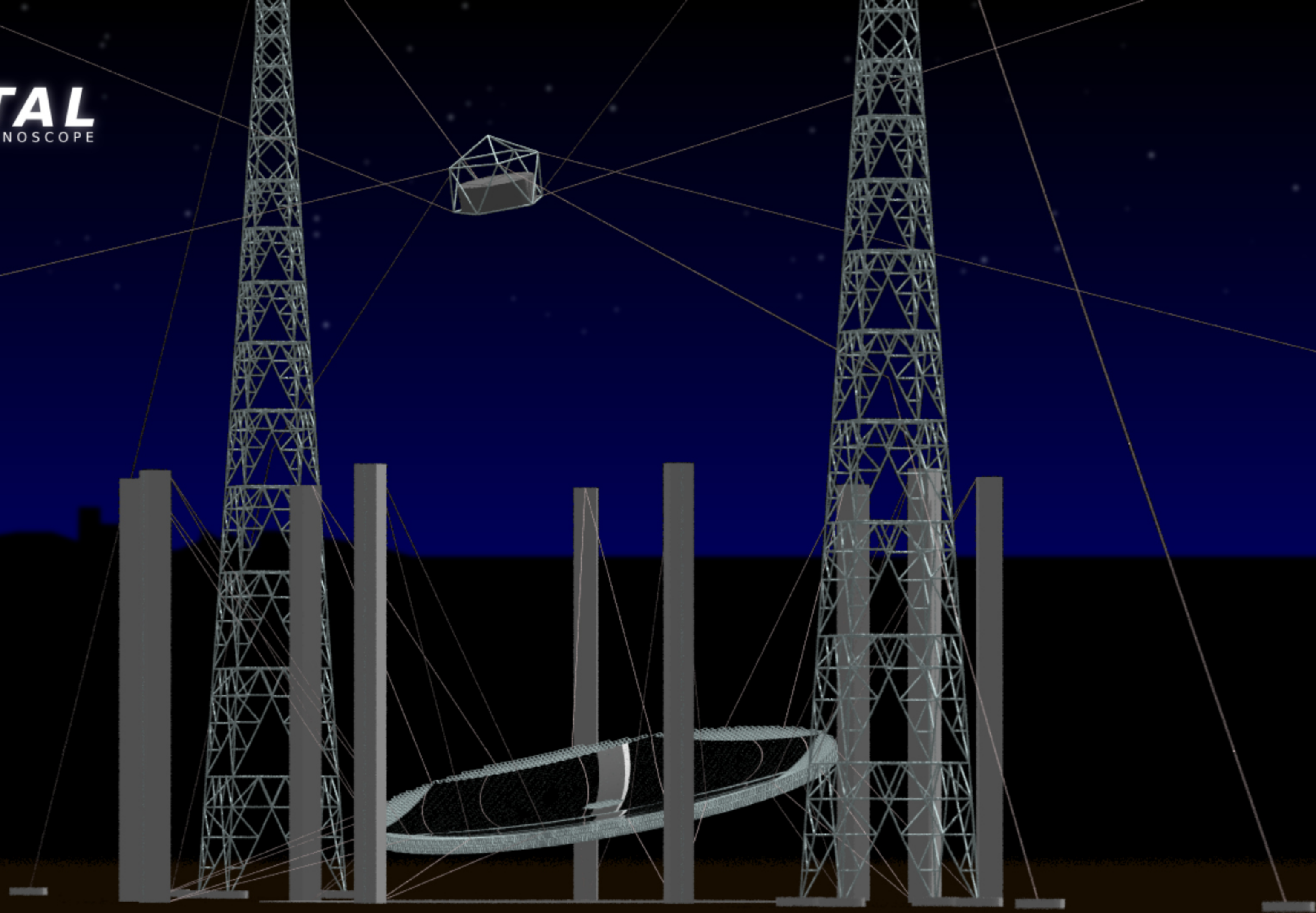
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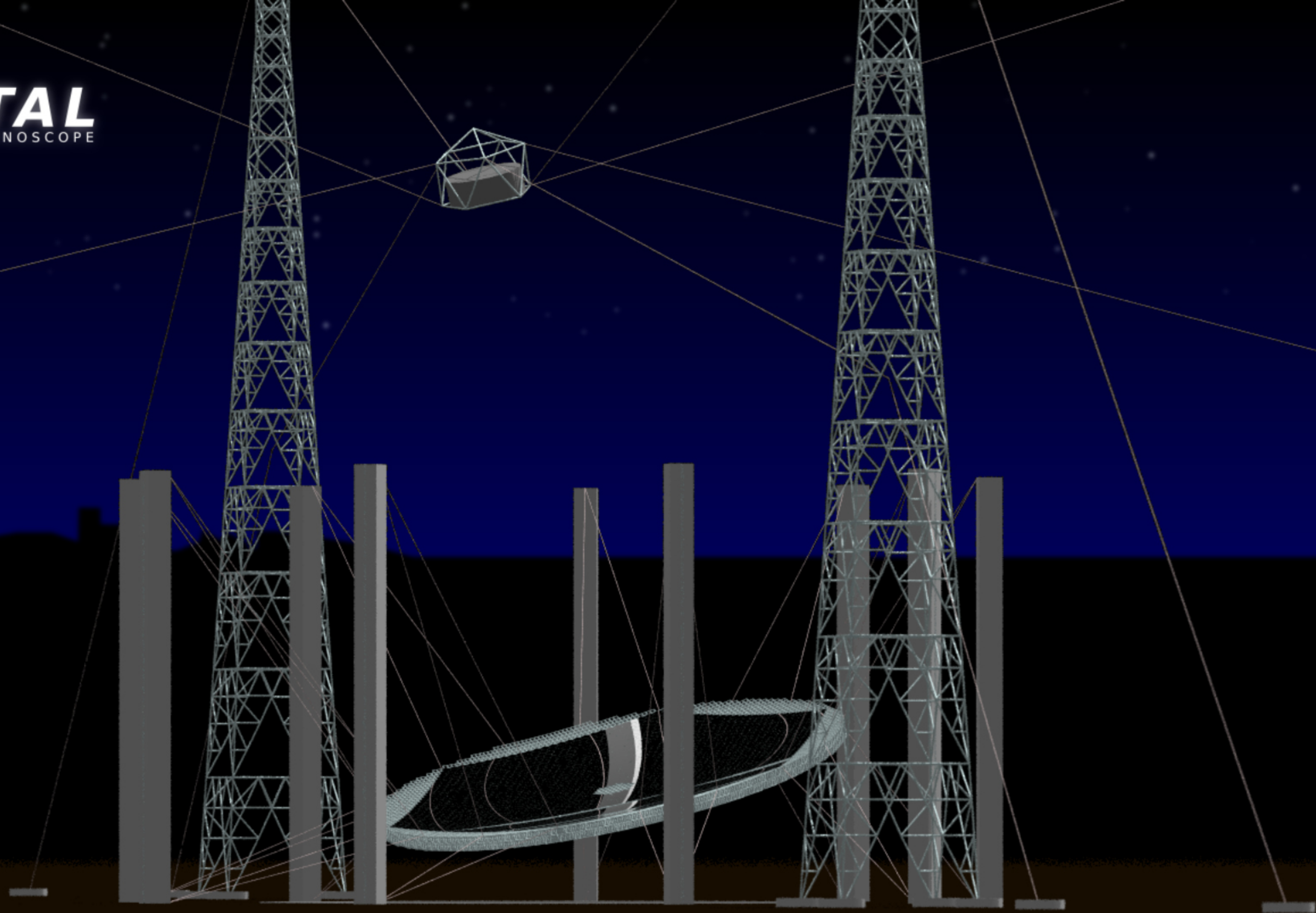
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CHERENKOV TELESCOPE



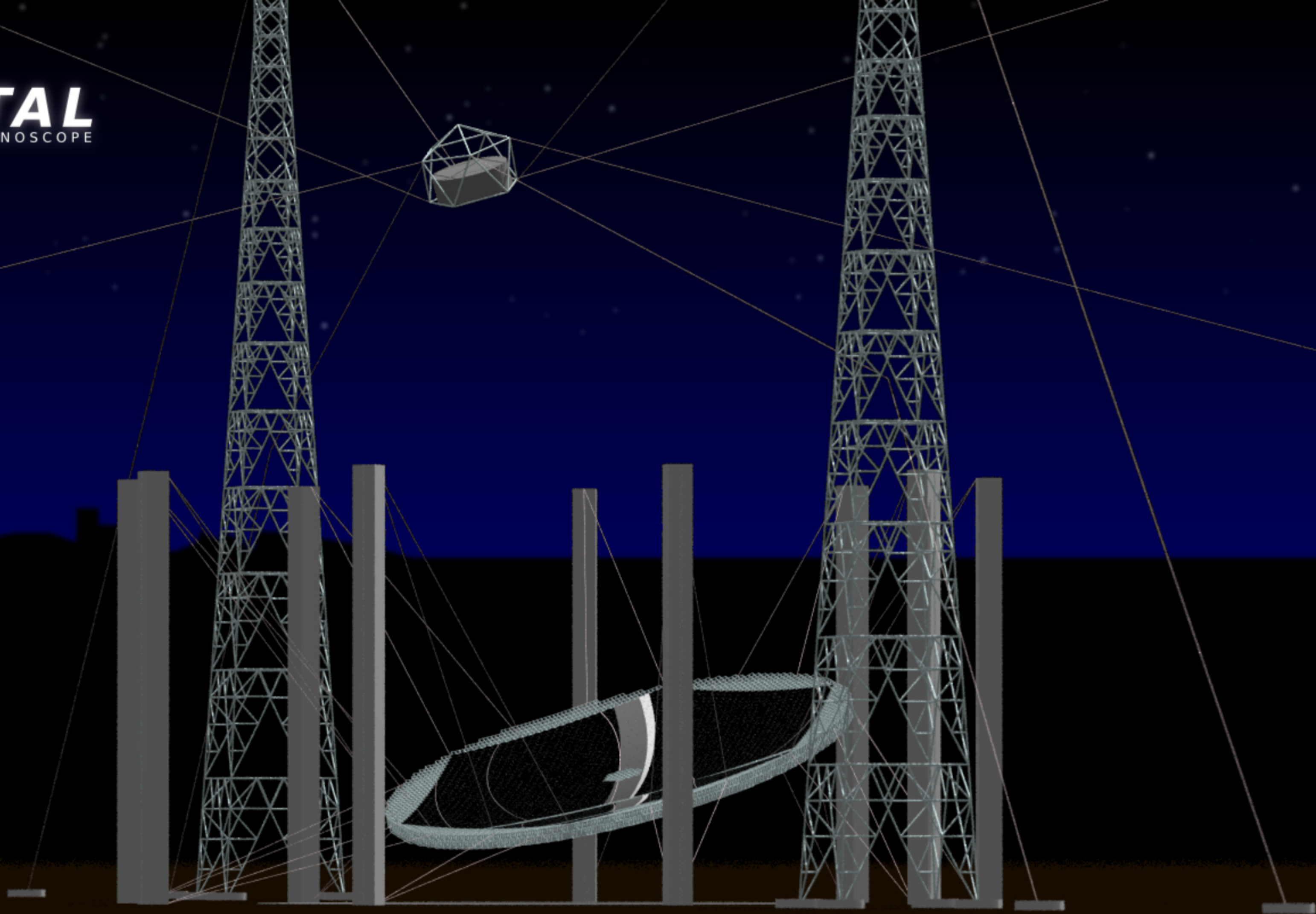
PORTAL
CHERENKOV TELESCOPE



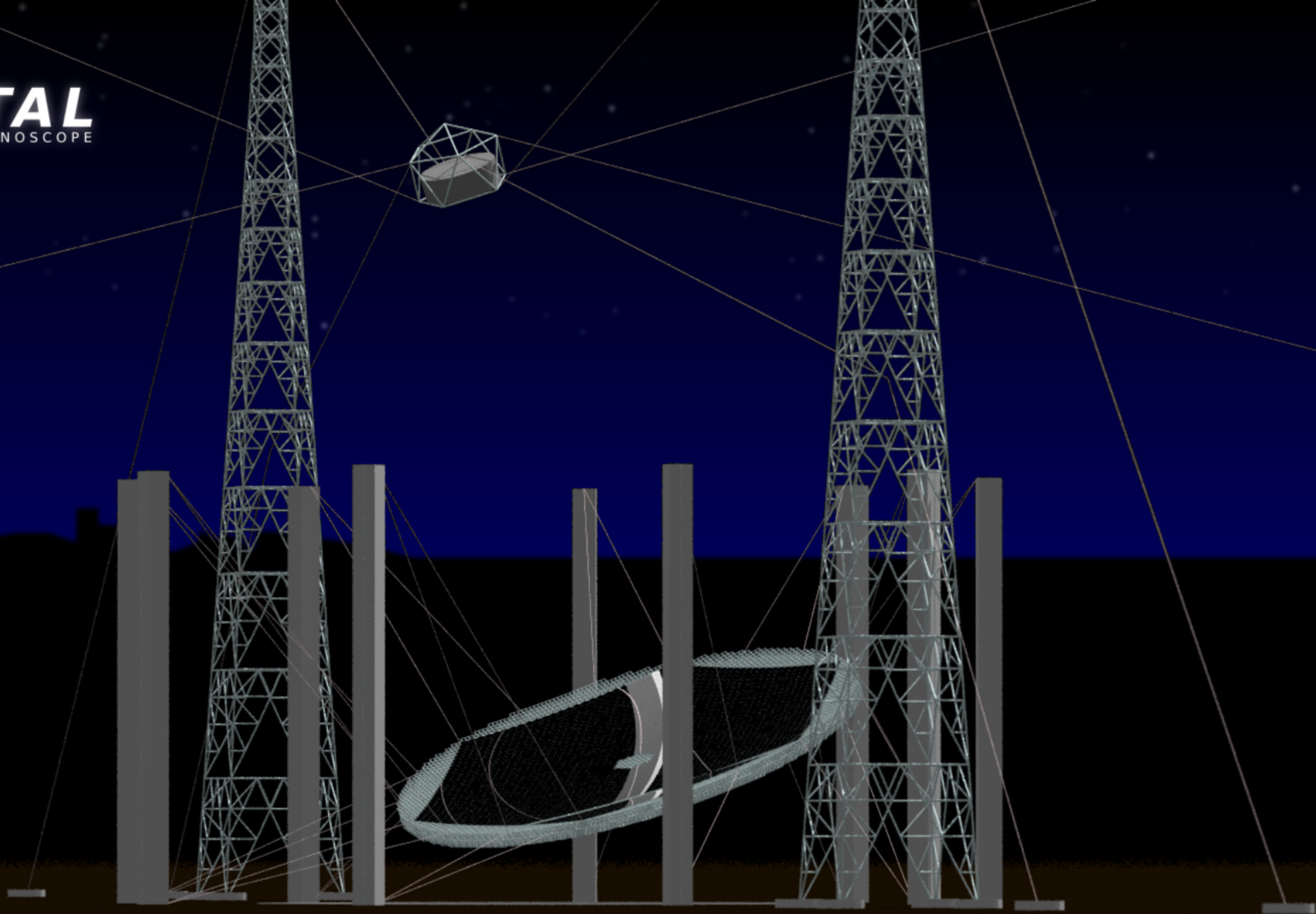
PORTAL
CHERENKOV PLENOSCOPE



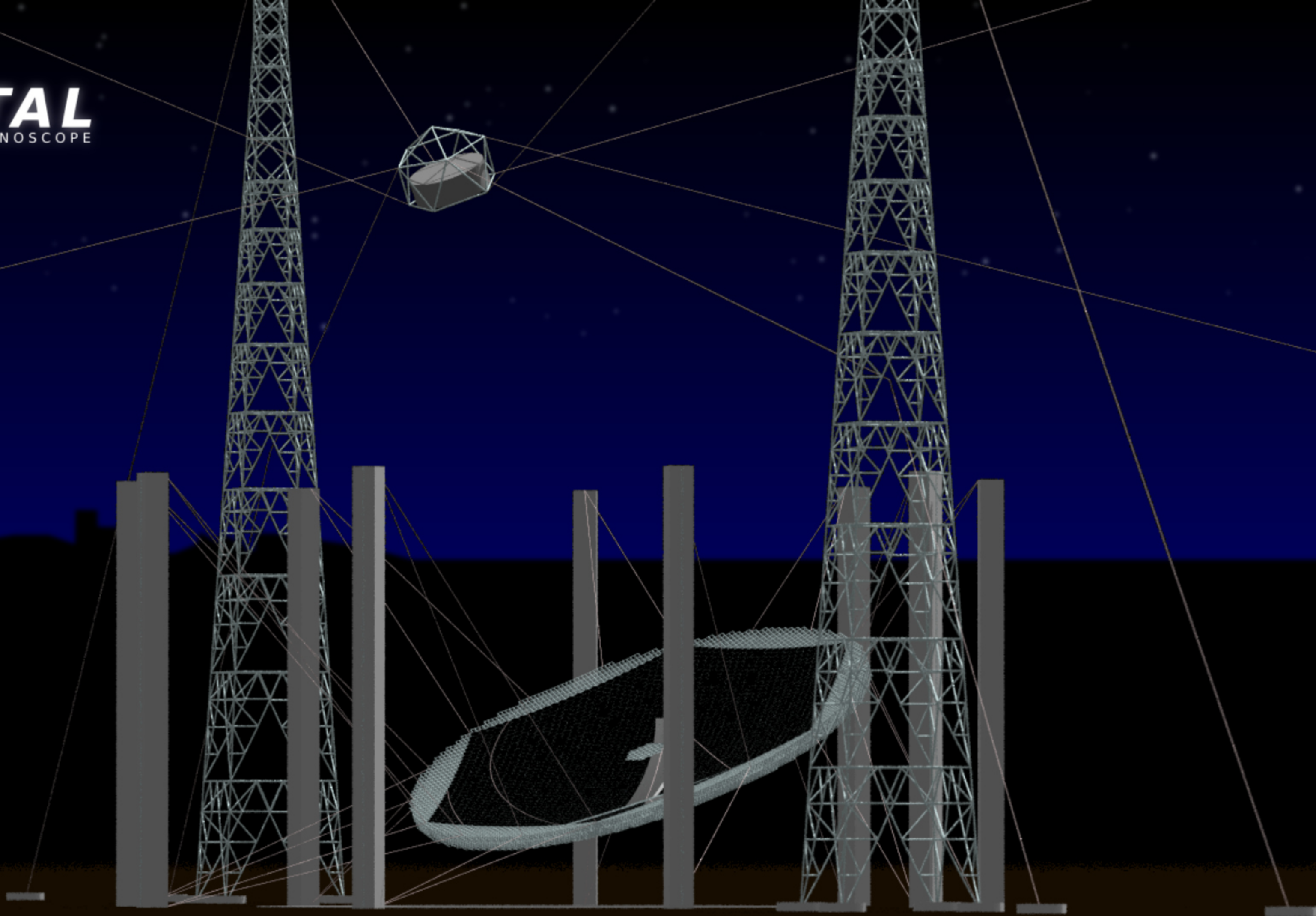
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CHERENKOV TELESCOPE



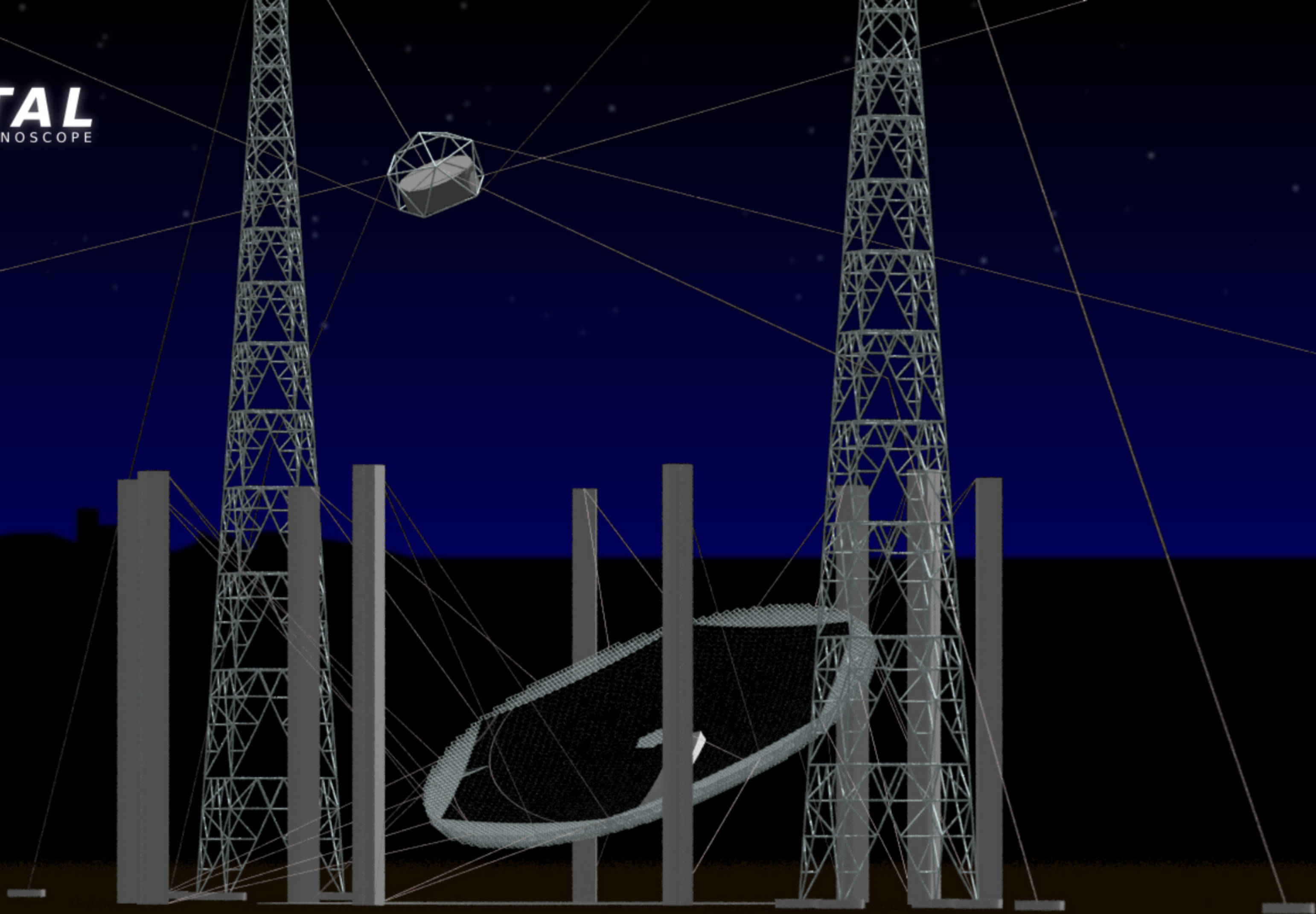
PORTAL
CHERENKOV TELESCOPE



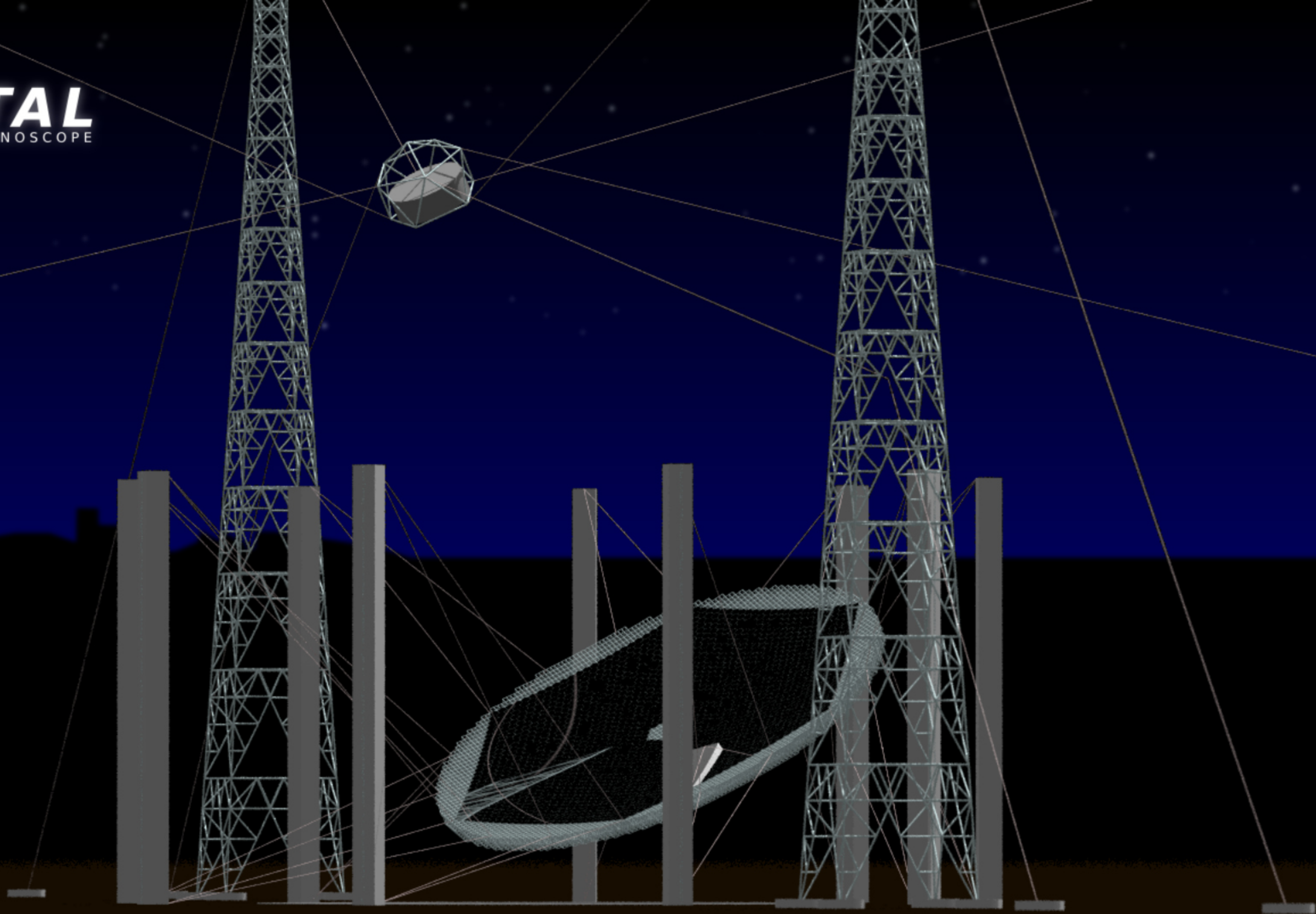
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CHERENKOV TELESCOPE



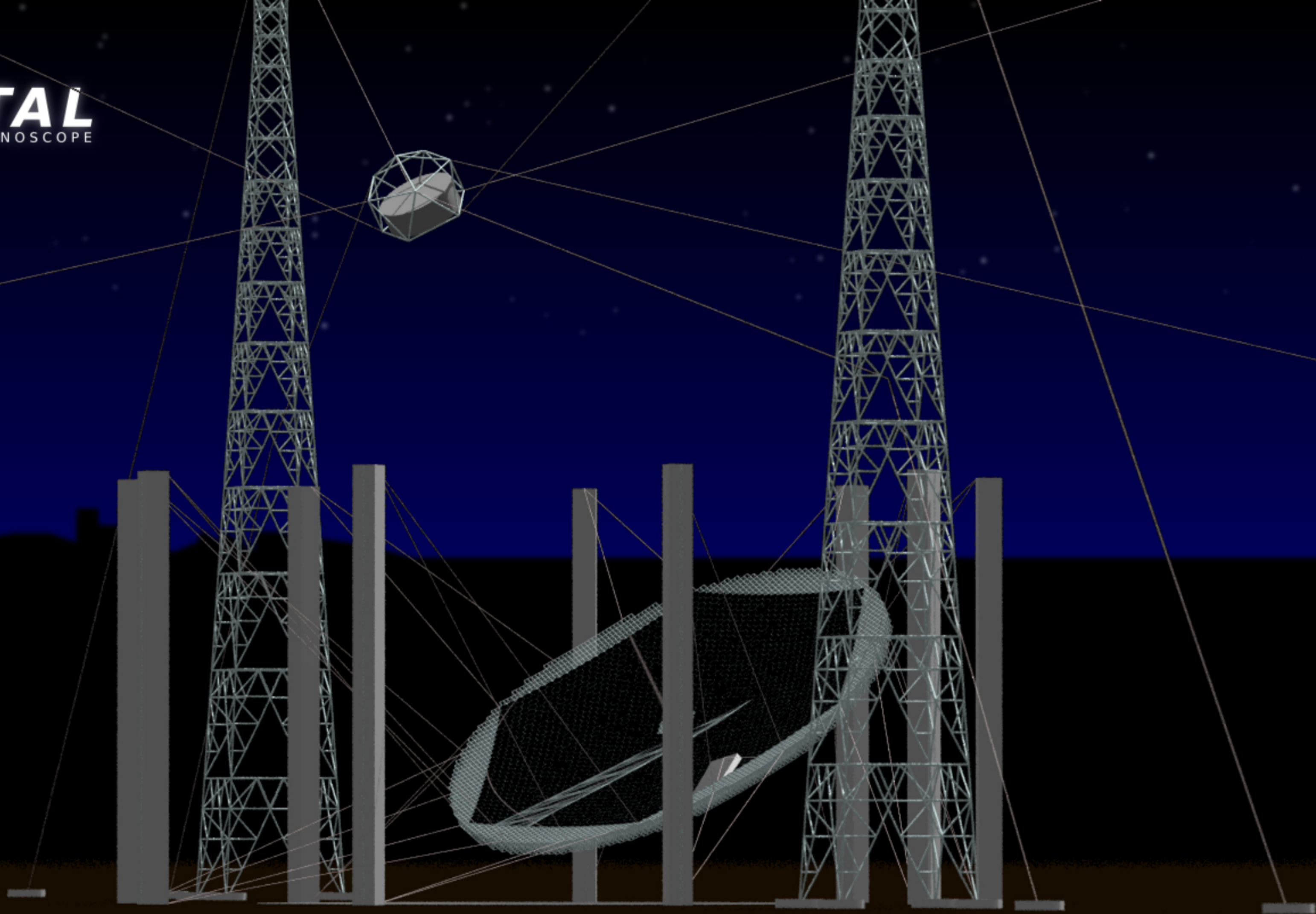
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CHERENKOV TELESCOPE



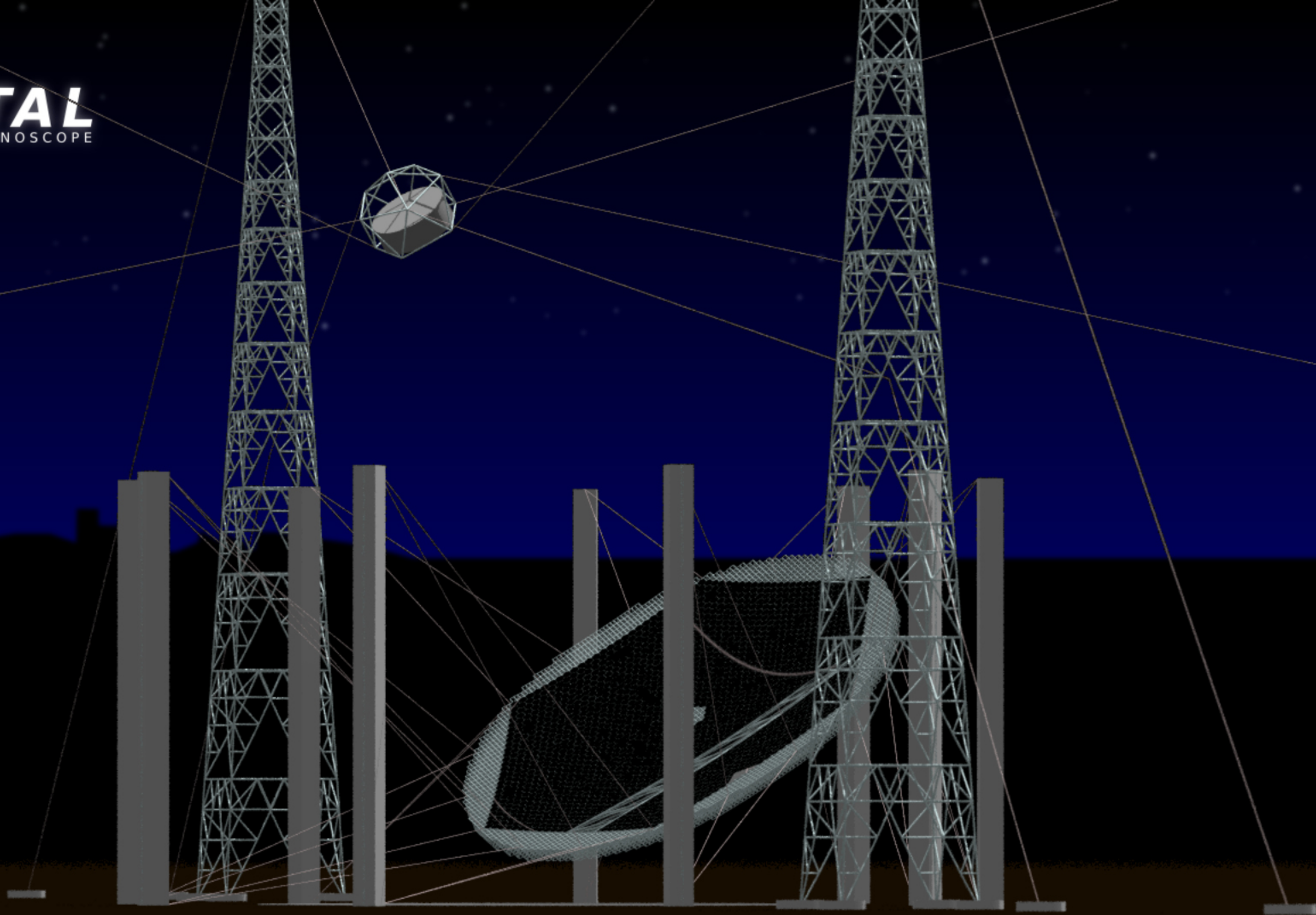
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CHERENKOV TELESCOPE



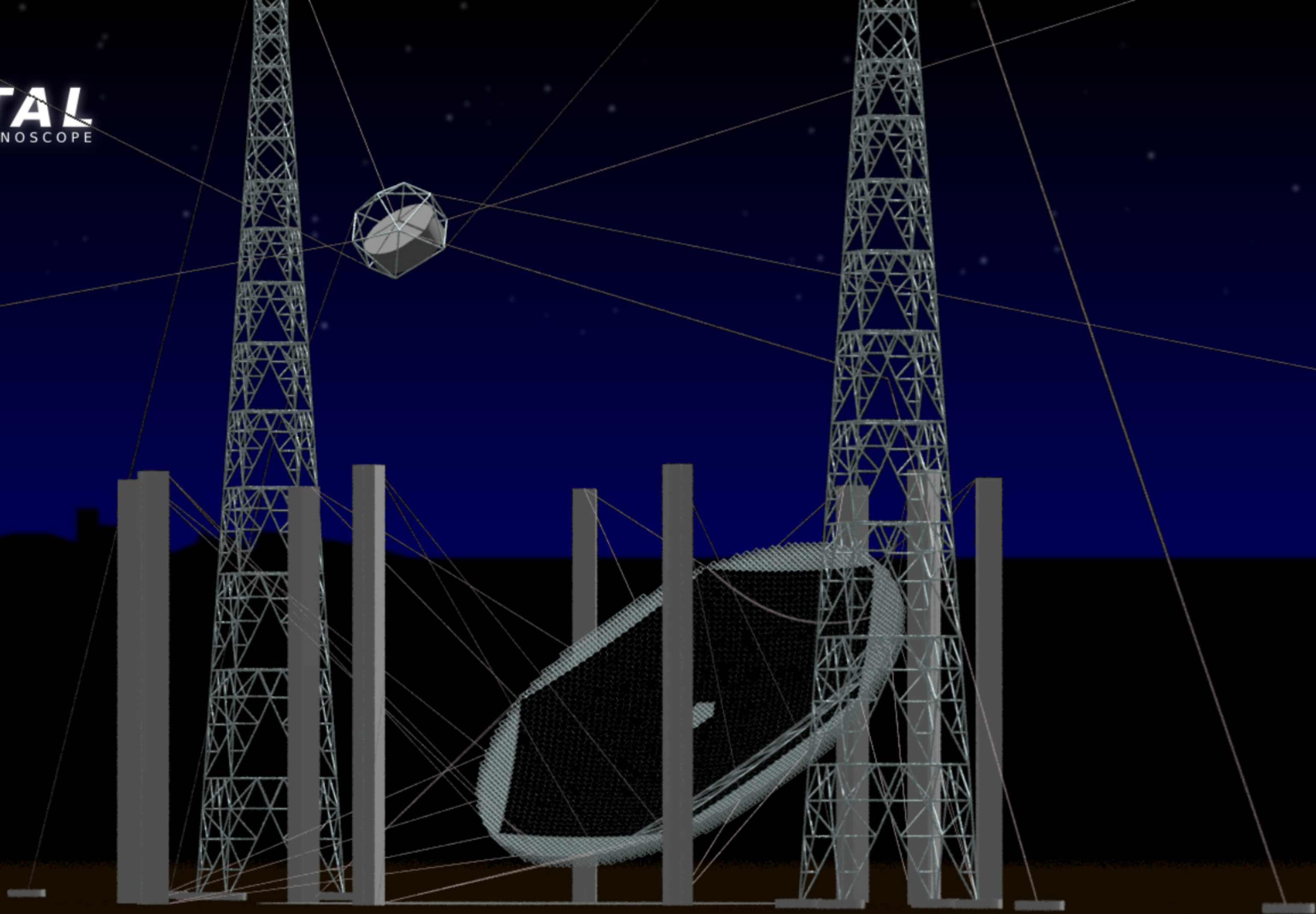
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CHERENKOV TELESCOPE



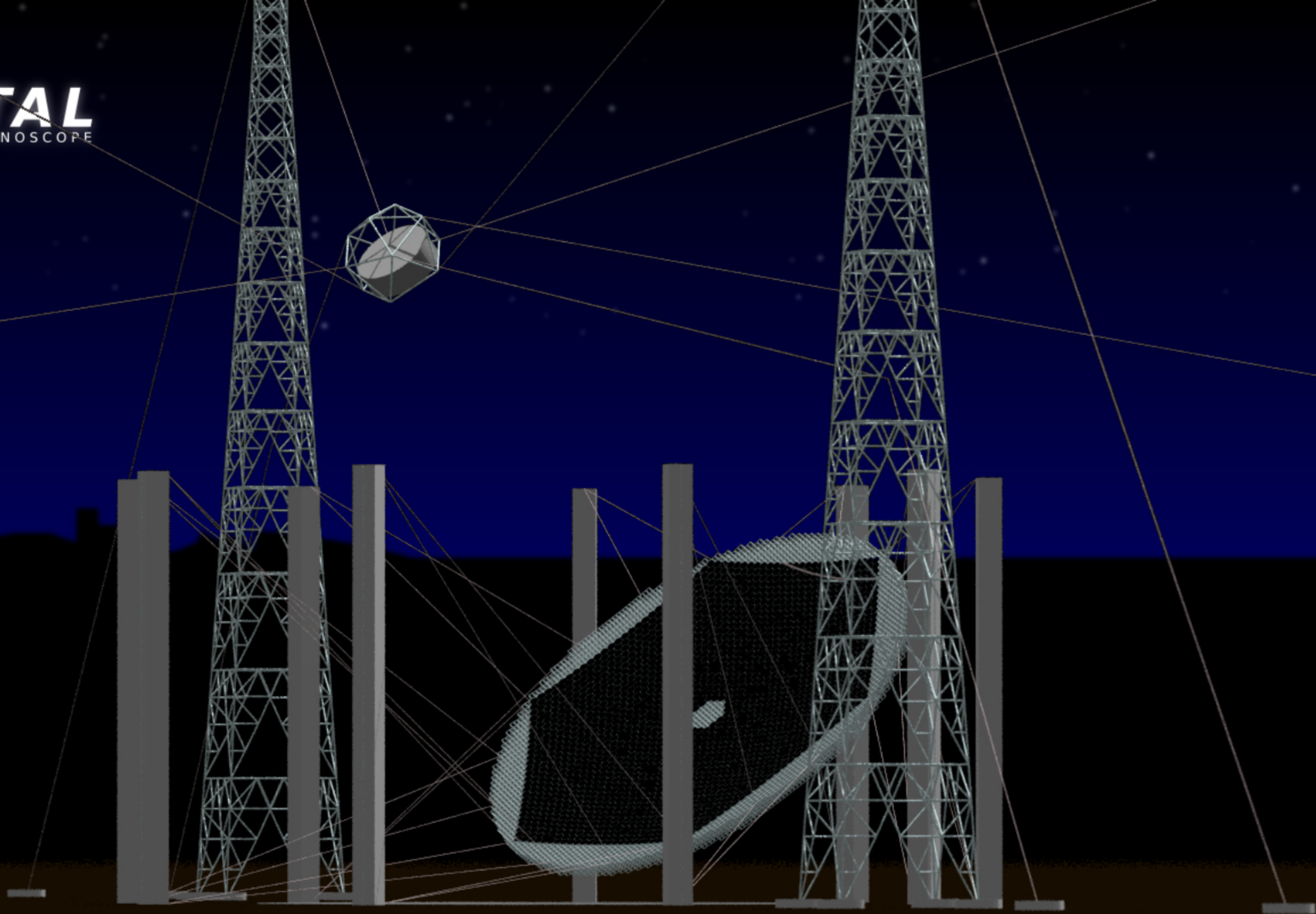
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CHERENKOV TELESCOPE

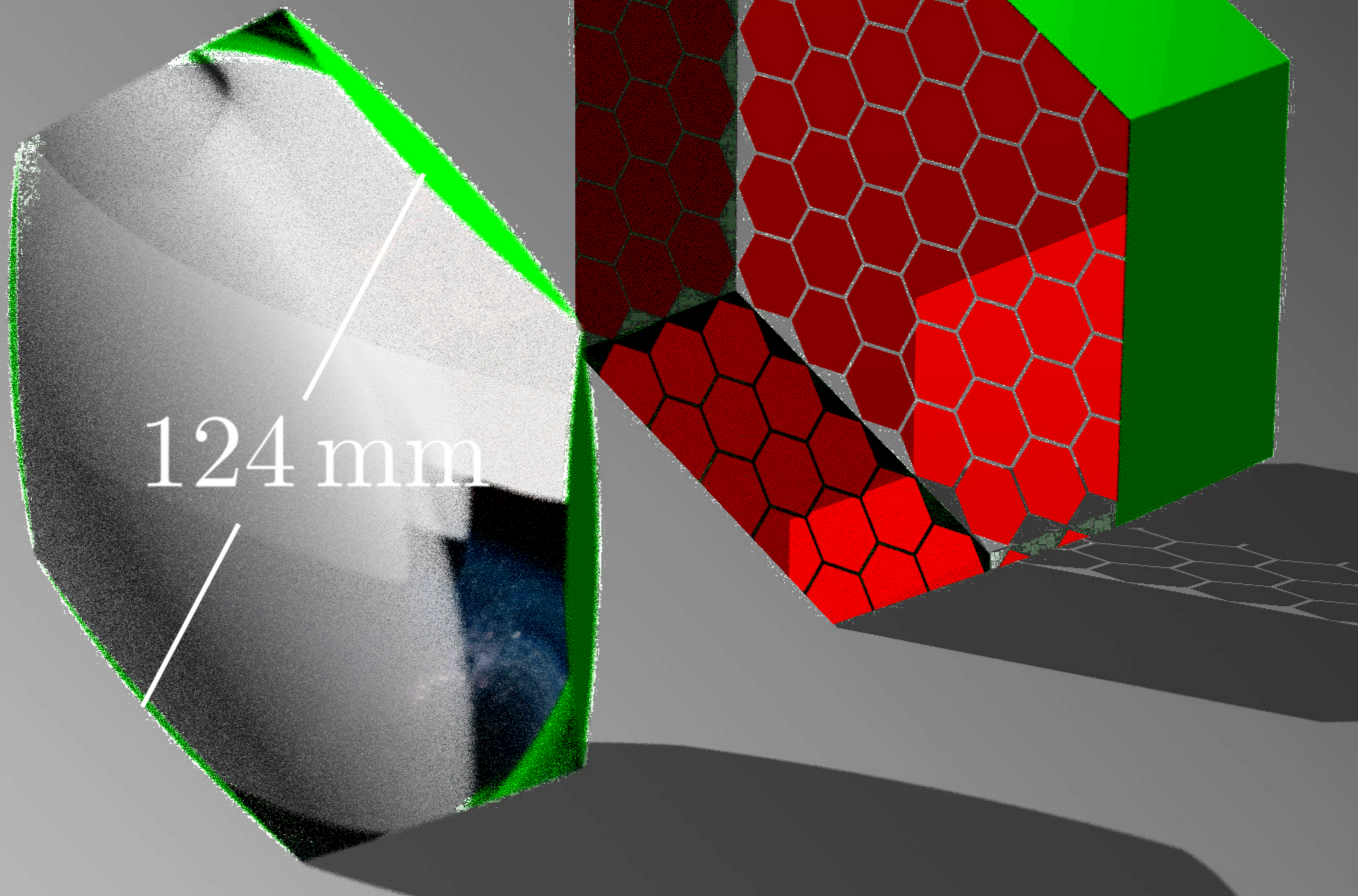


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CHERENKOV TELESCOPE



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6.5°
12.1 m

0.067°
124 mm

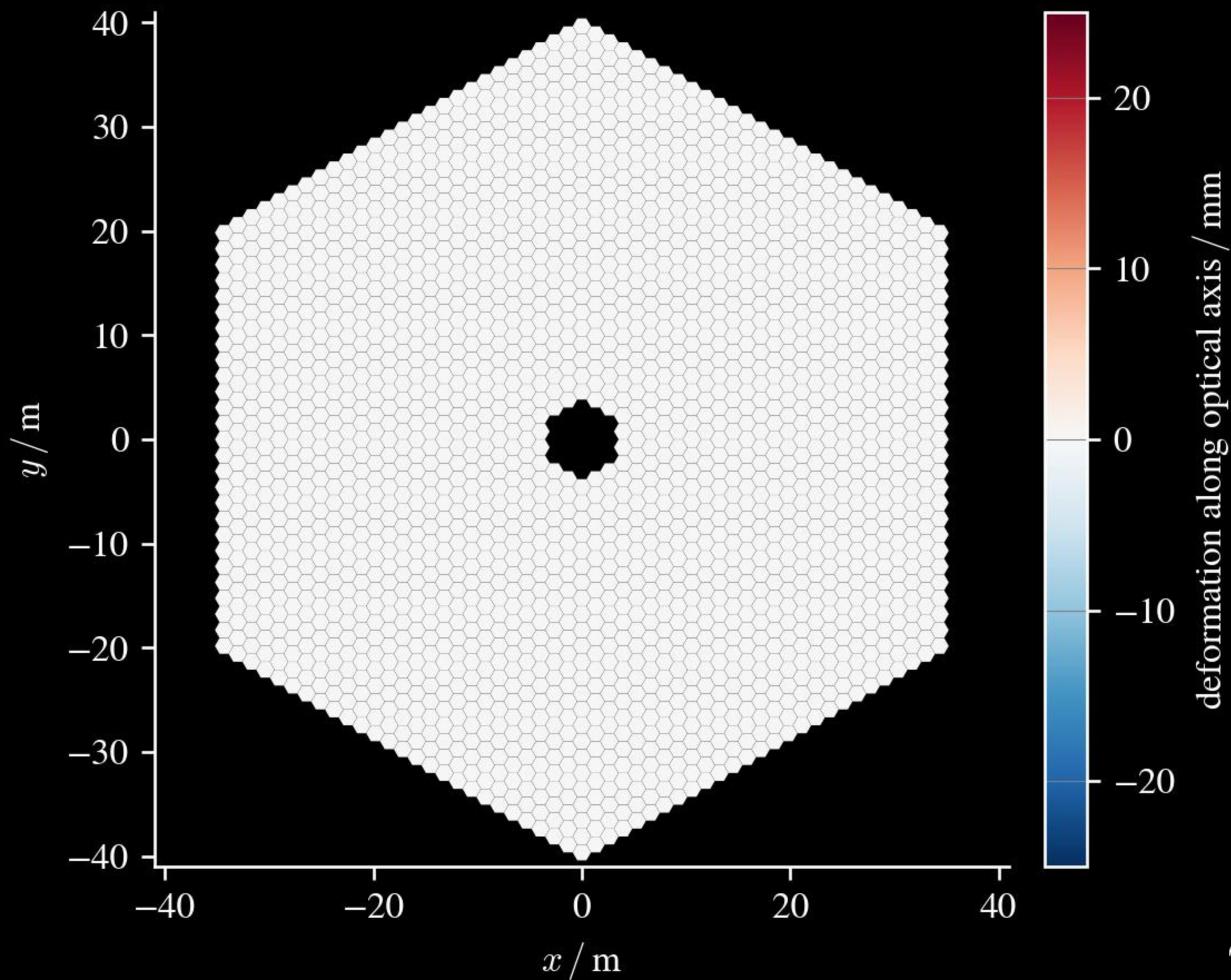
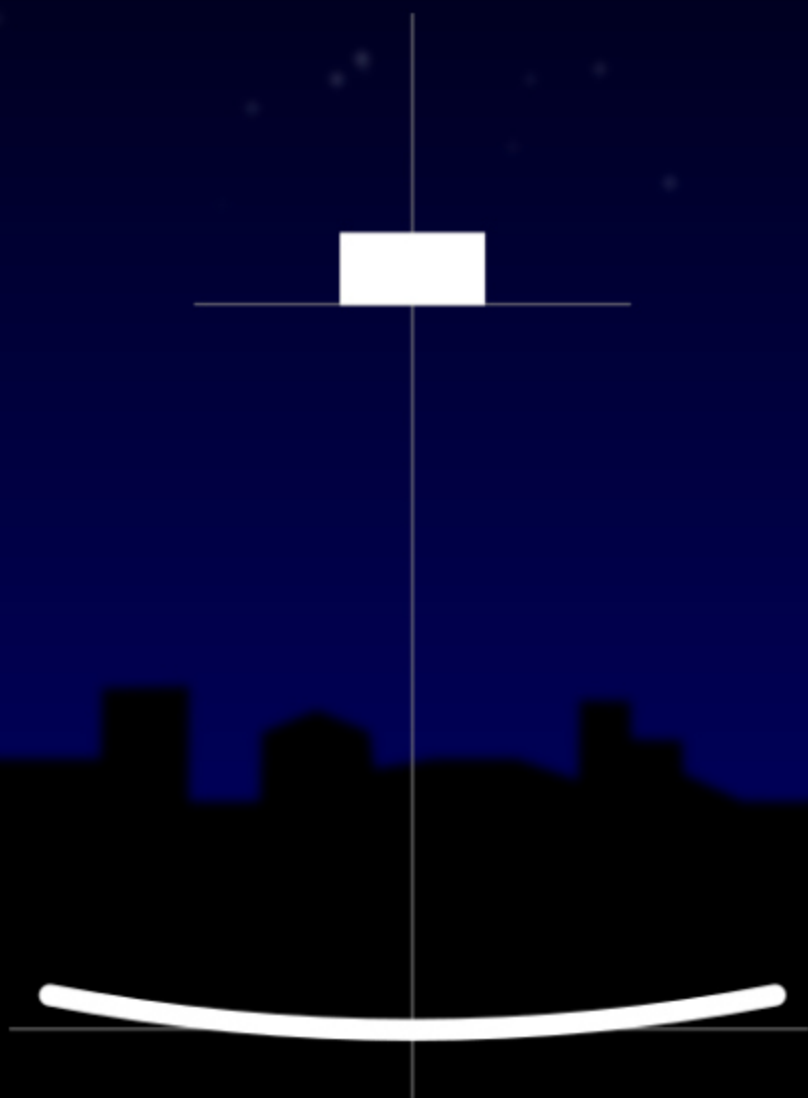
Optics

mirror deformations



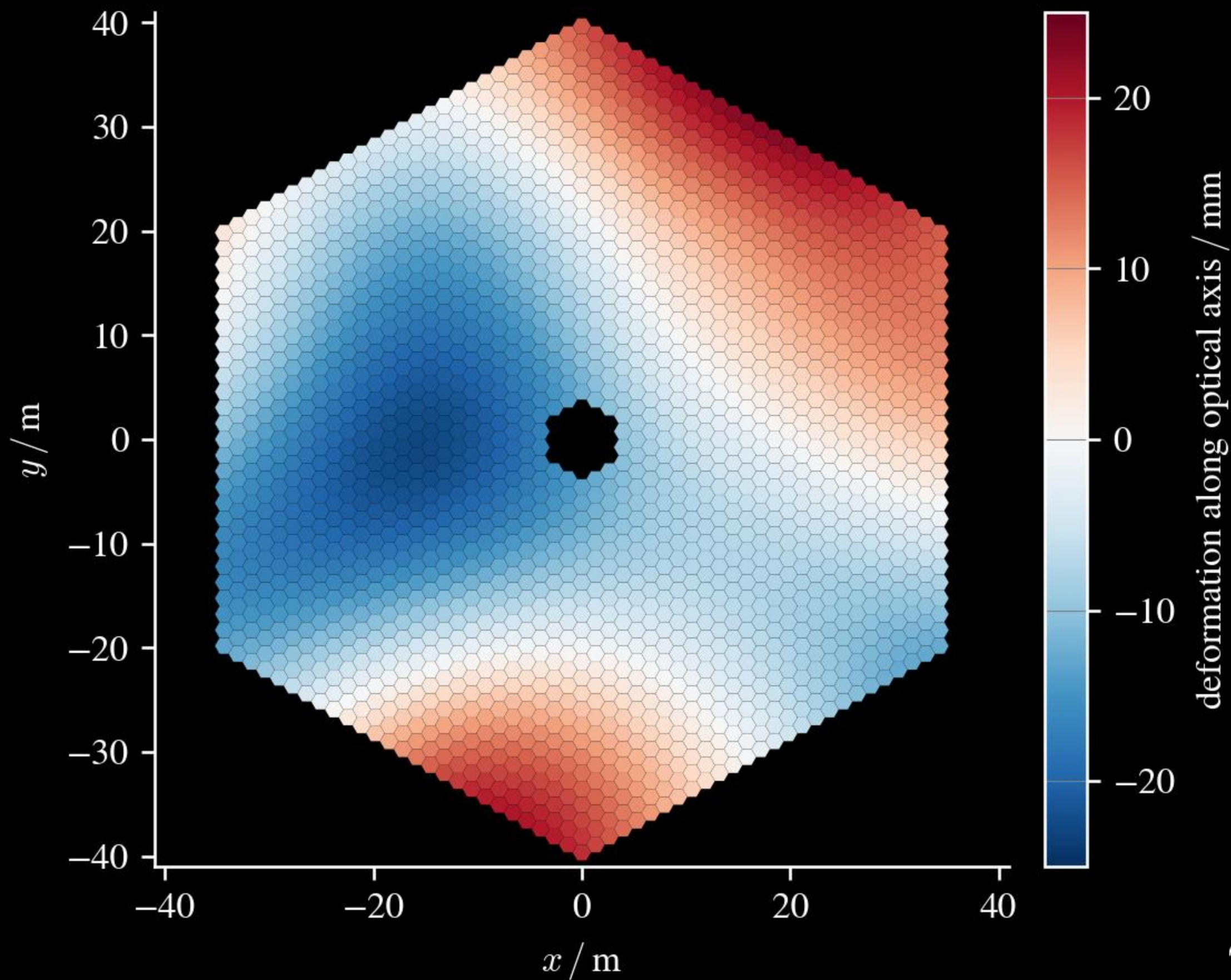
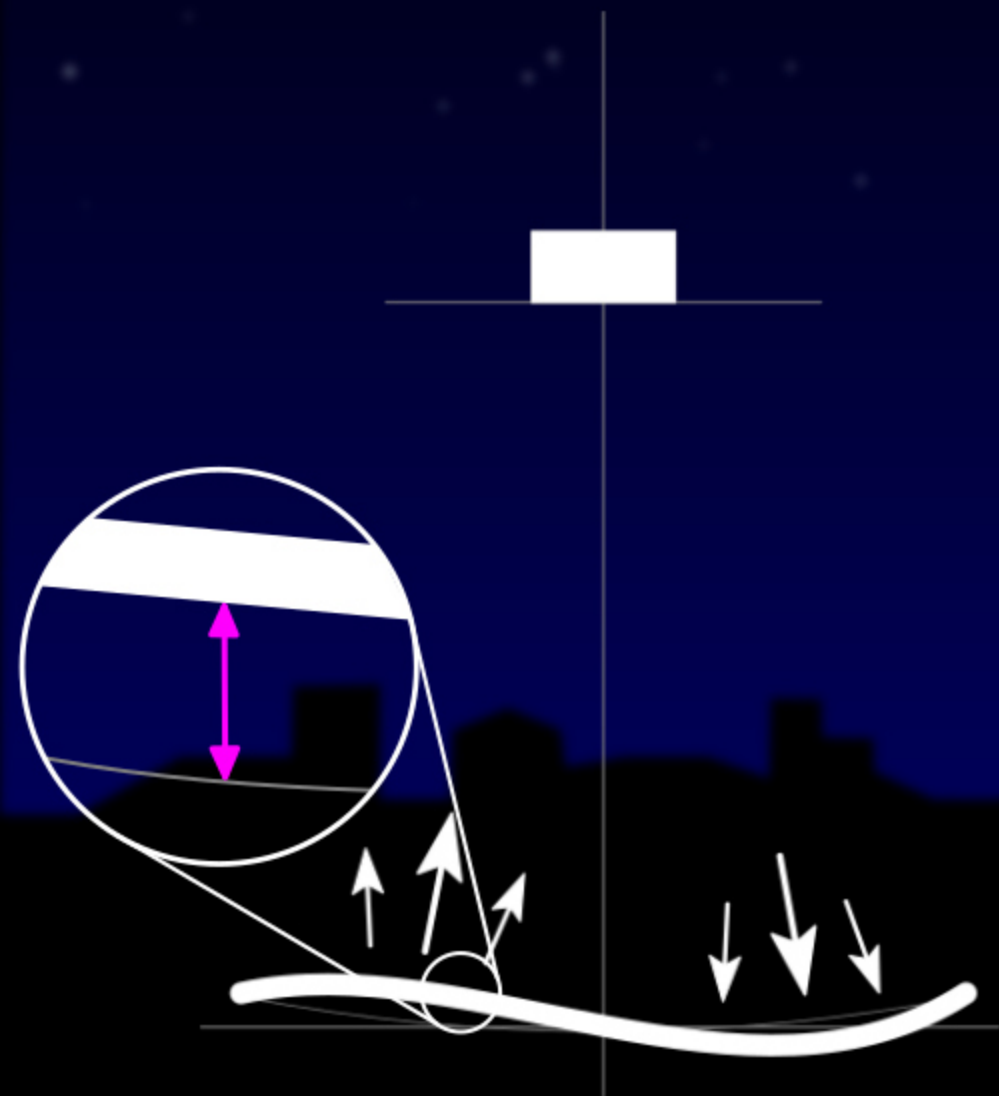
Optics

mirror deformations



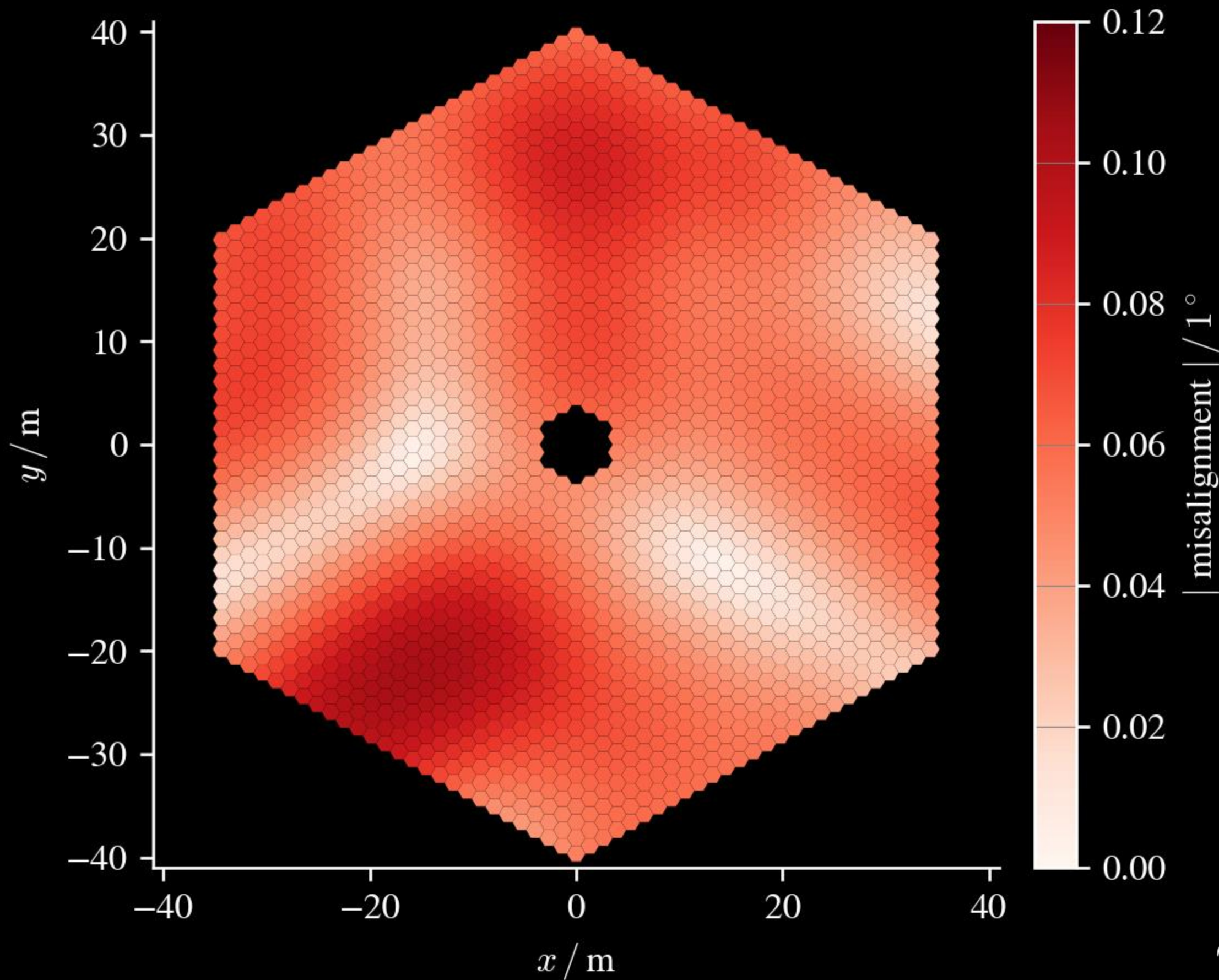
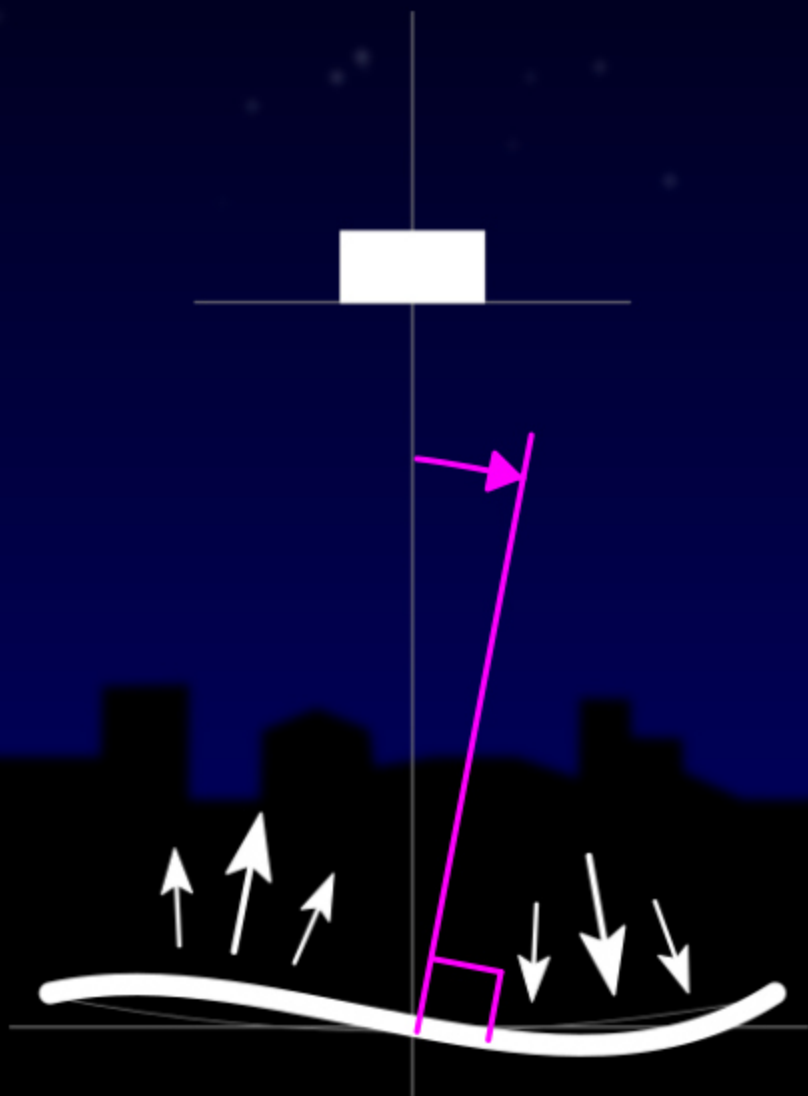
Optics

mirror deformations



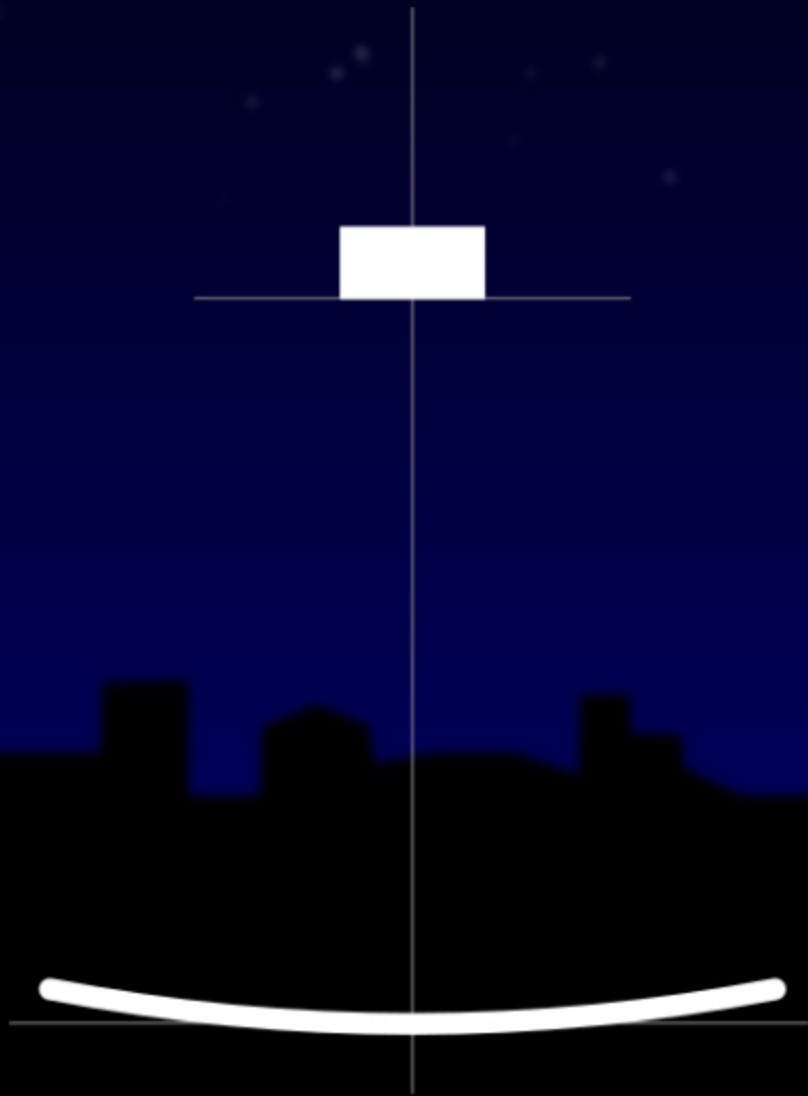
Optics

mirror deformations



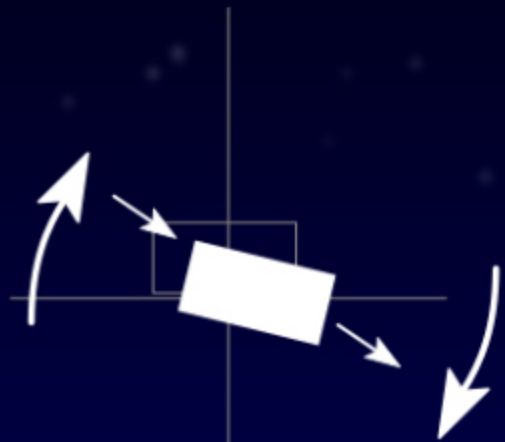
Optics

camera misalignment



Optics

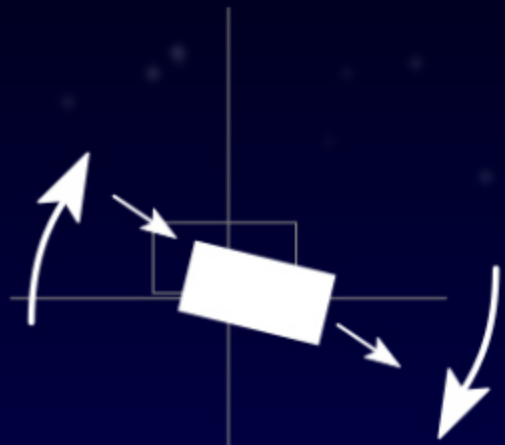
camera misalignment



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

Optics

camera misalignment



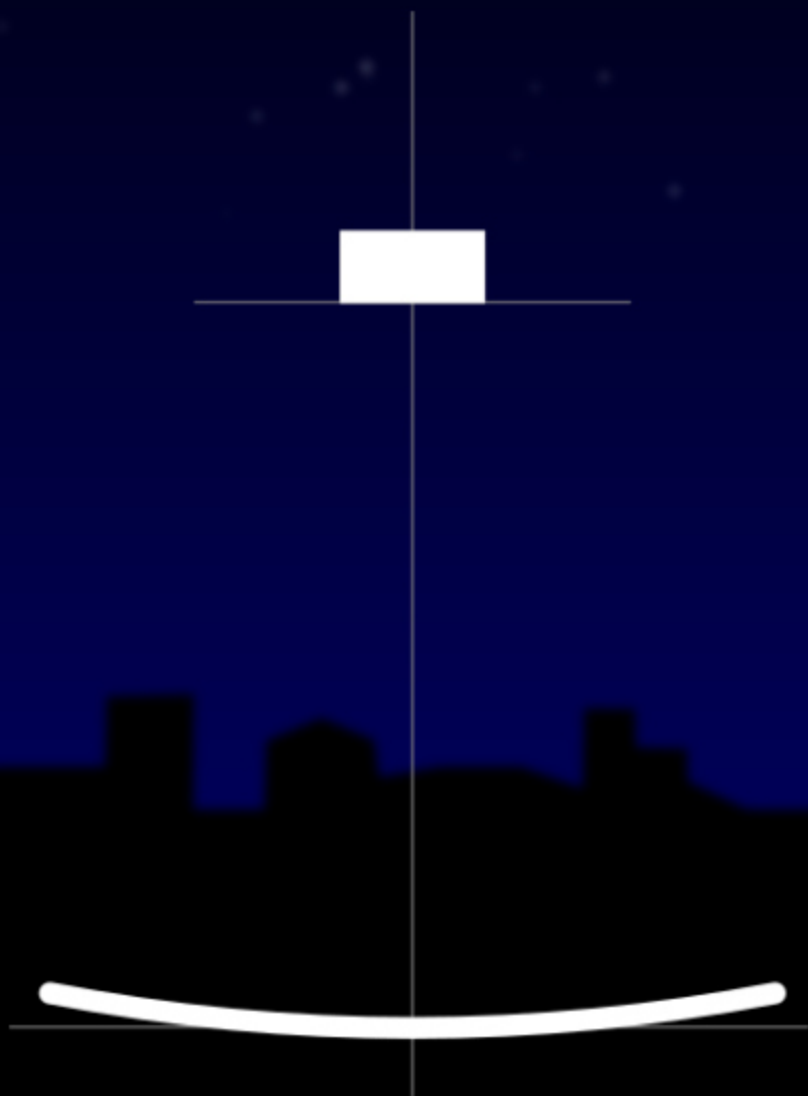
$$\begin{aligned}\text{Tait-Bryan-}xyz &= (1.0, 3.0, 5.0)^\circ \\ \text{translation-}xyz &= (-100, 200, -532.5) \text{ mm} \\ &= (-0.1, 0.2, -0.5)\%f\end{aligned}$$



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

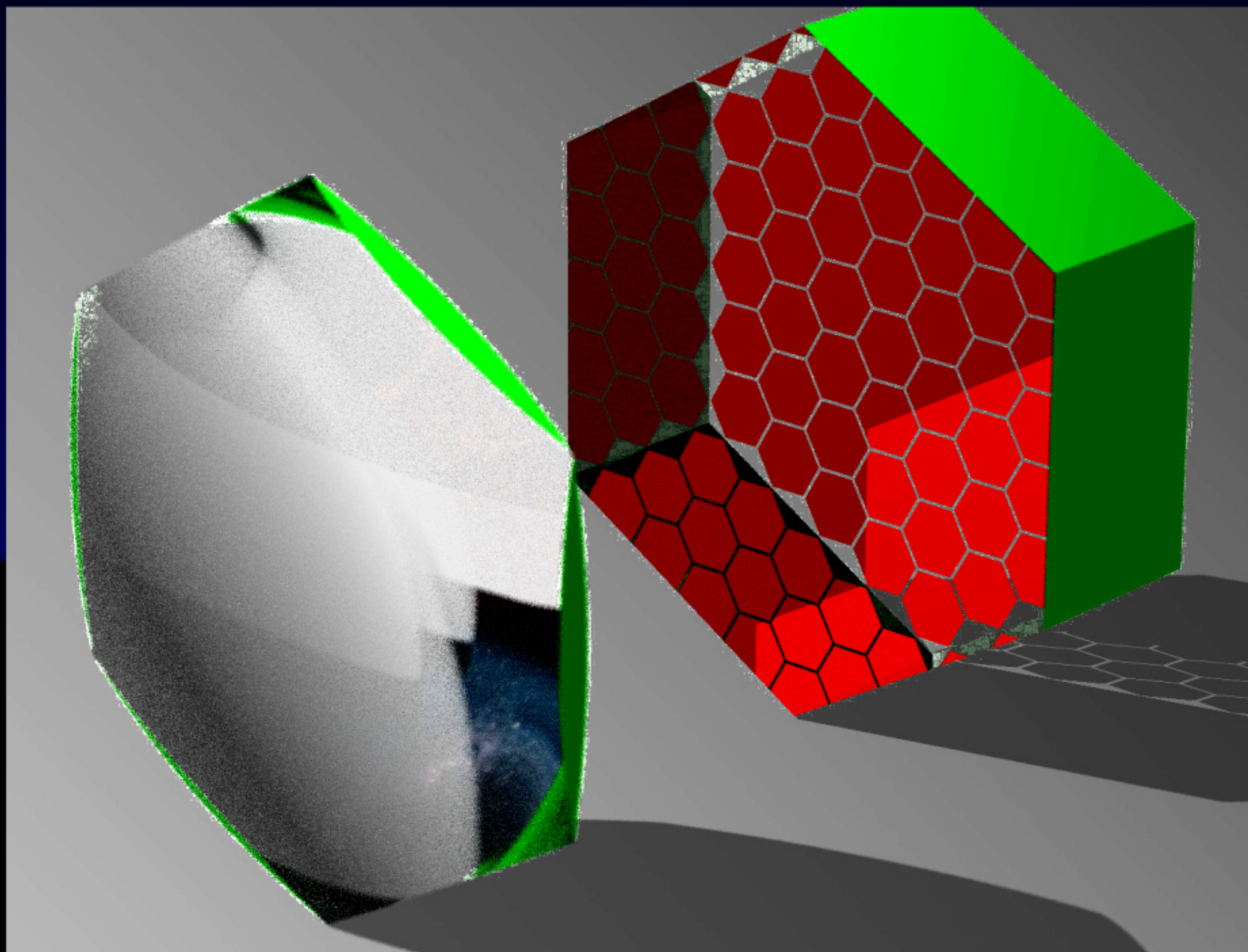
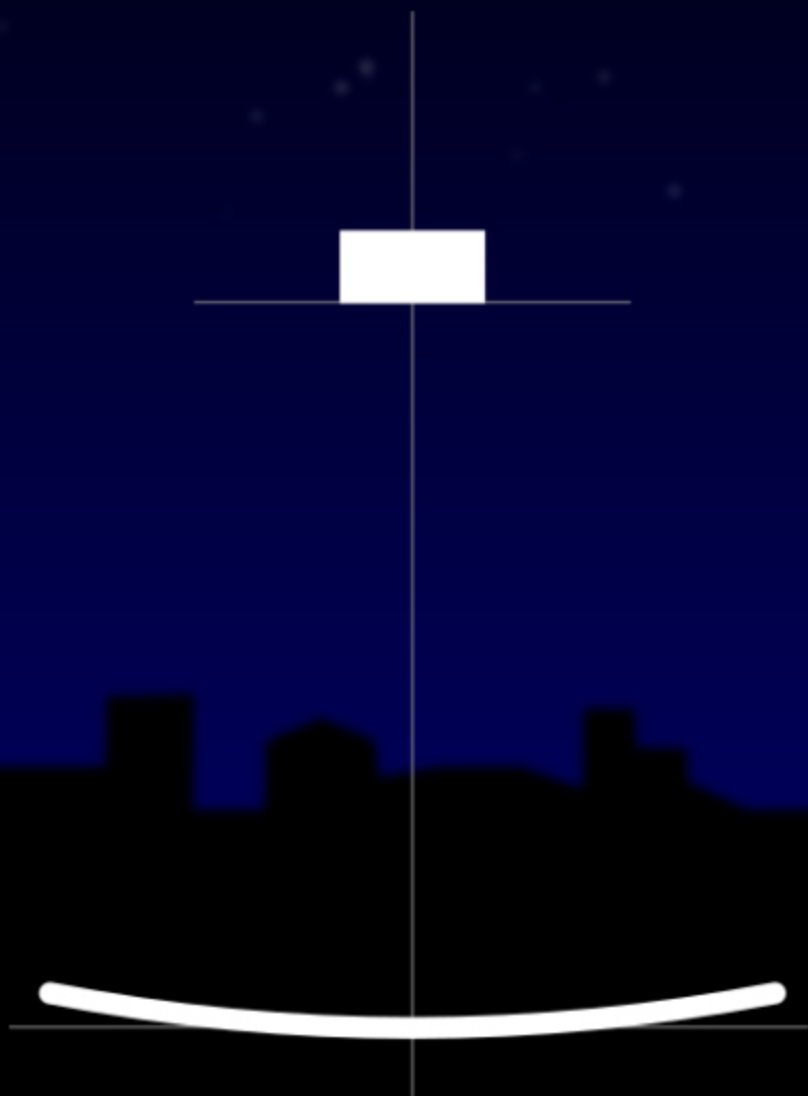
Optics

cameras



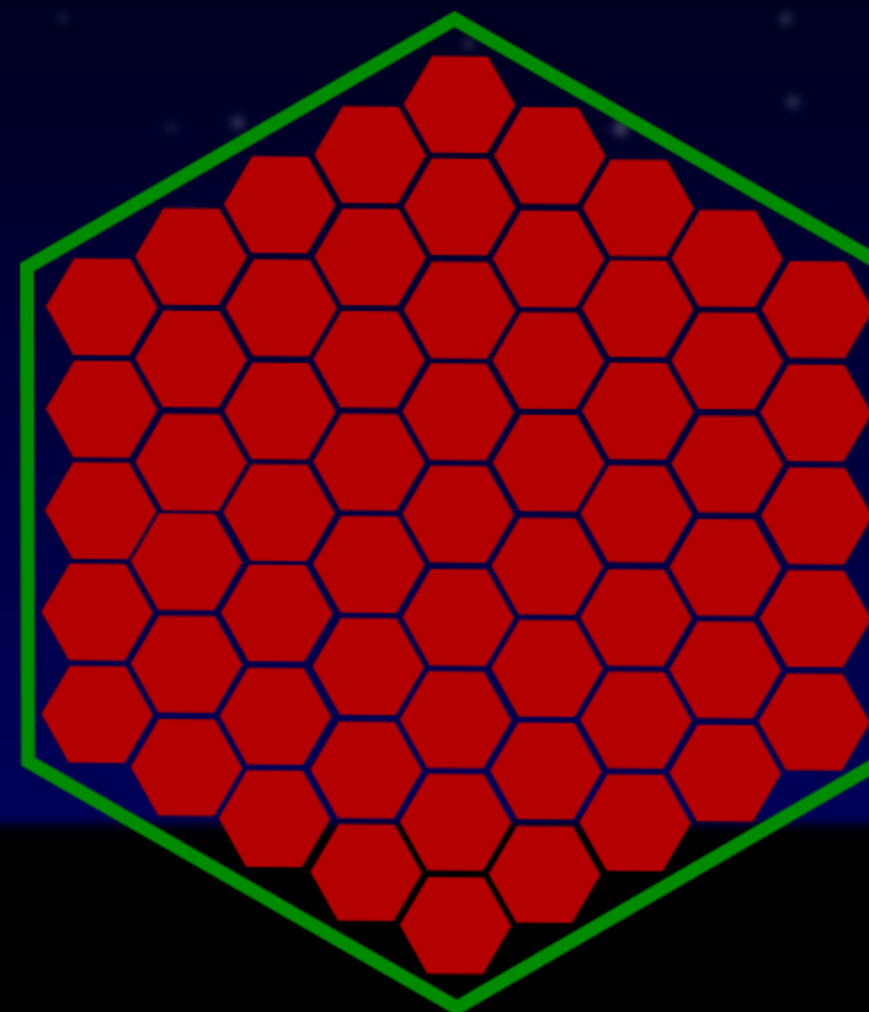
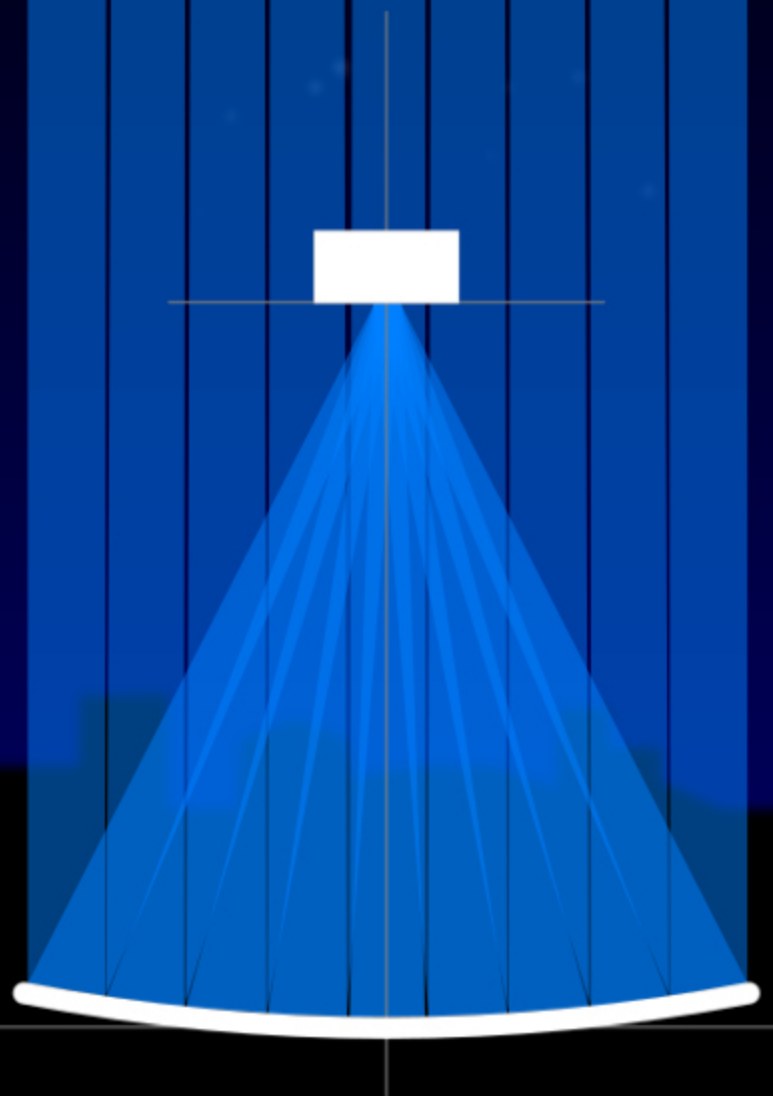
Optics

cameras



Optics

cameras

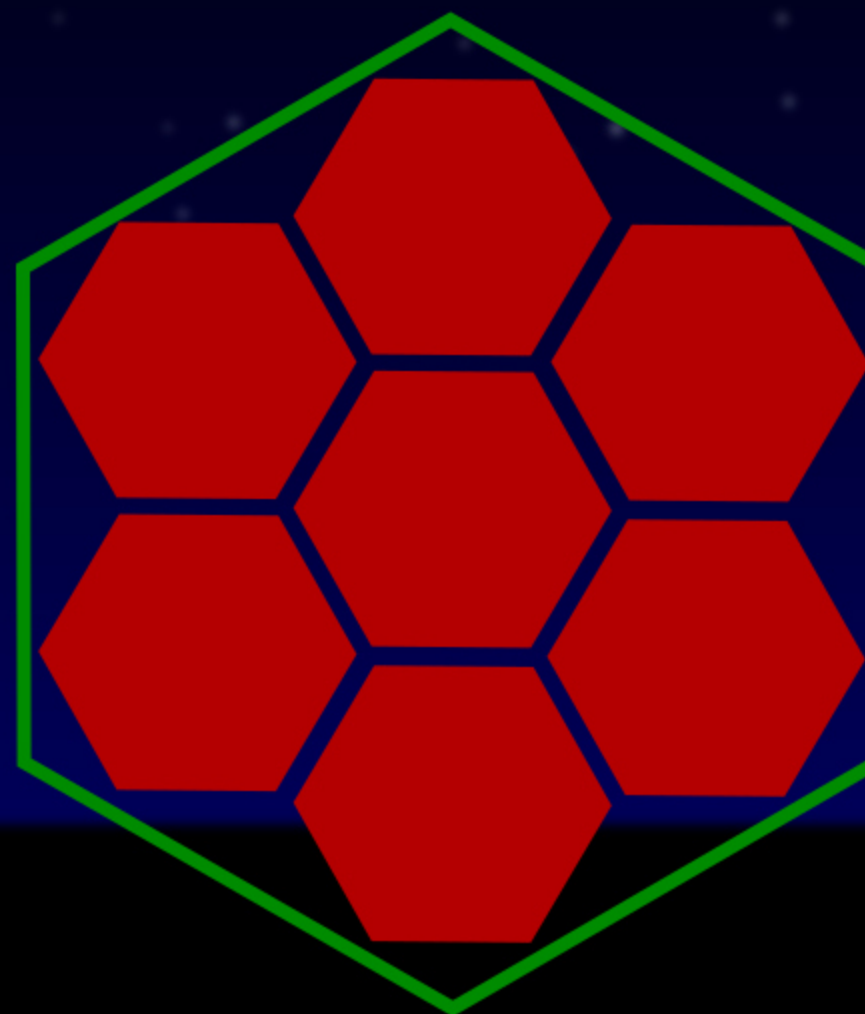
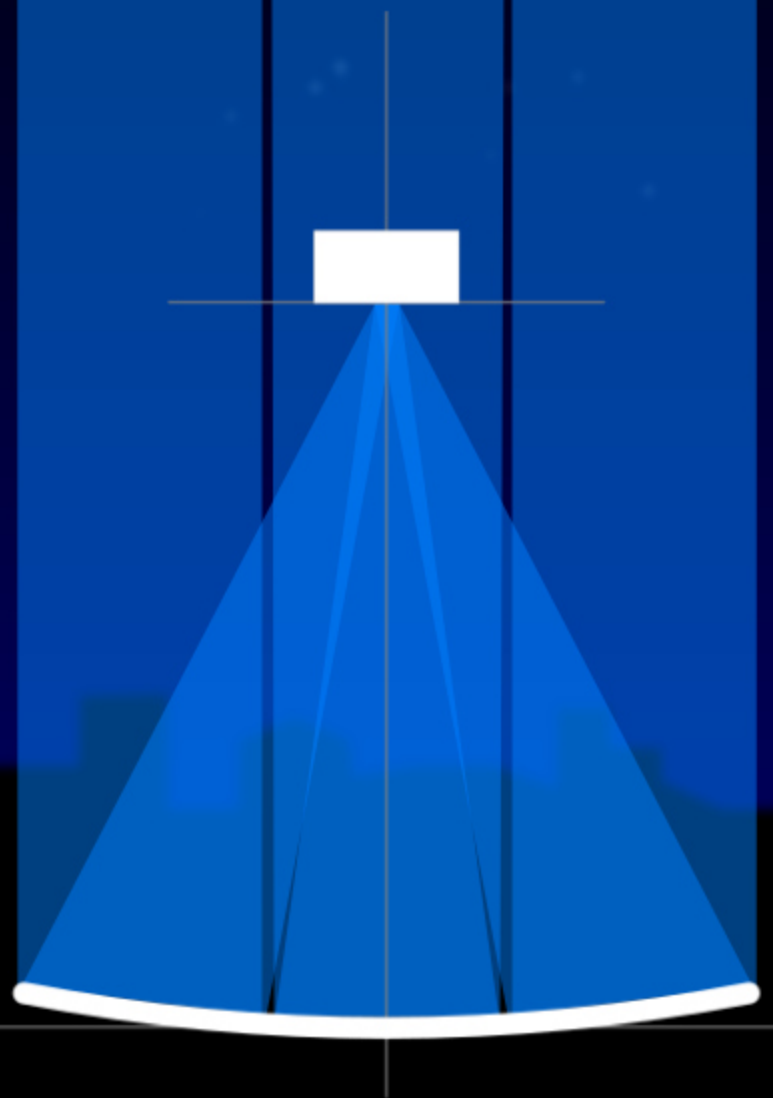


61 sample / mirror
(plenoscope)



Optics

cameras

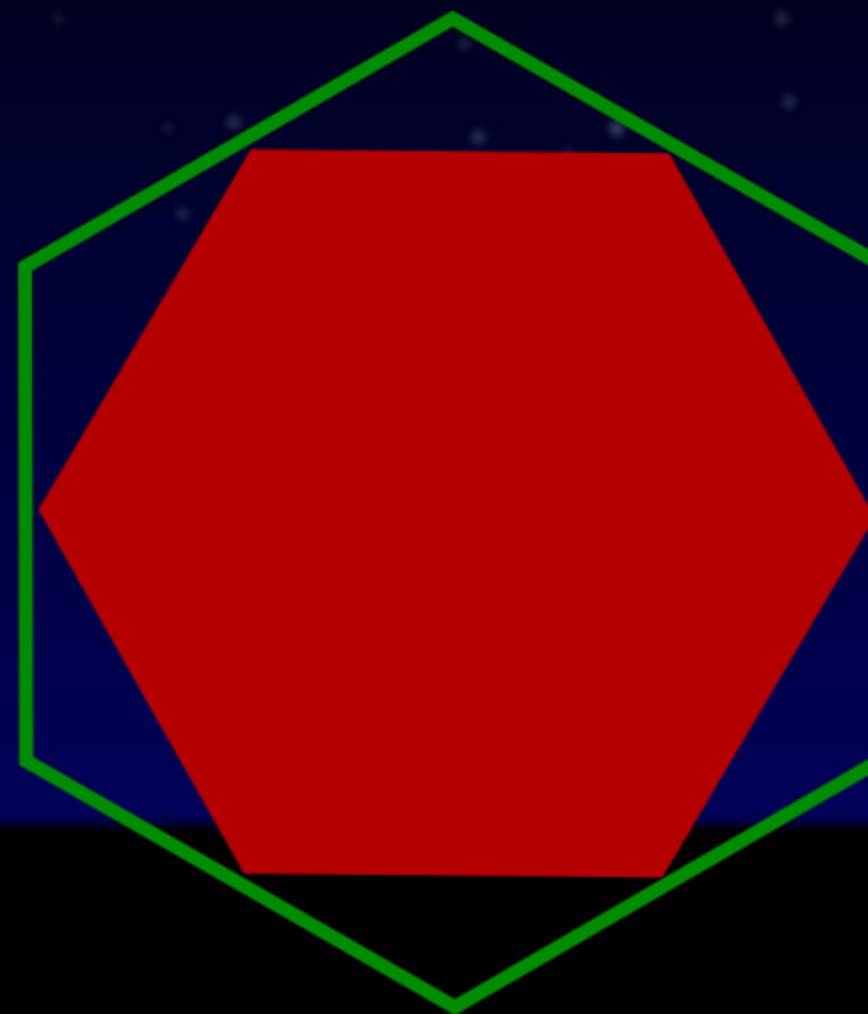
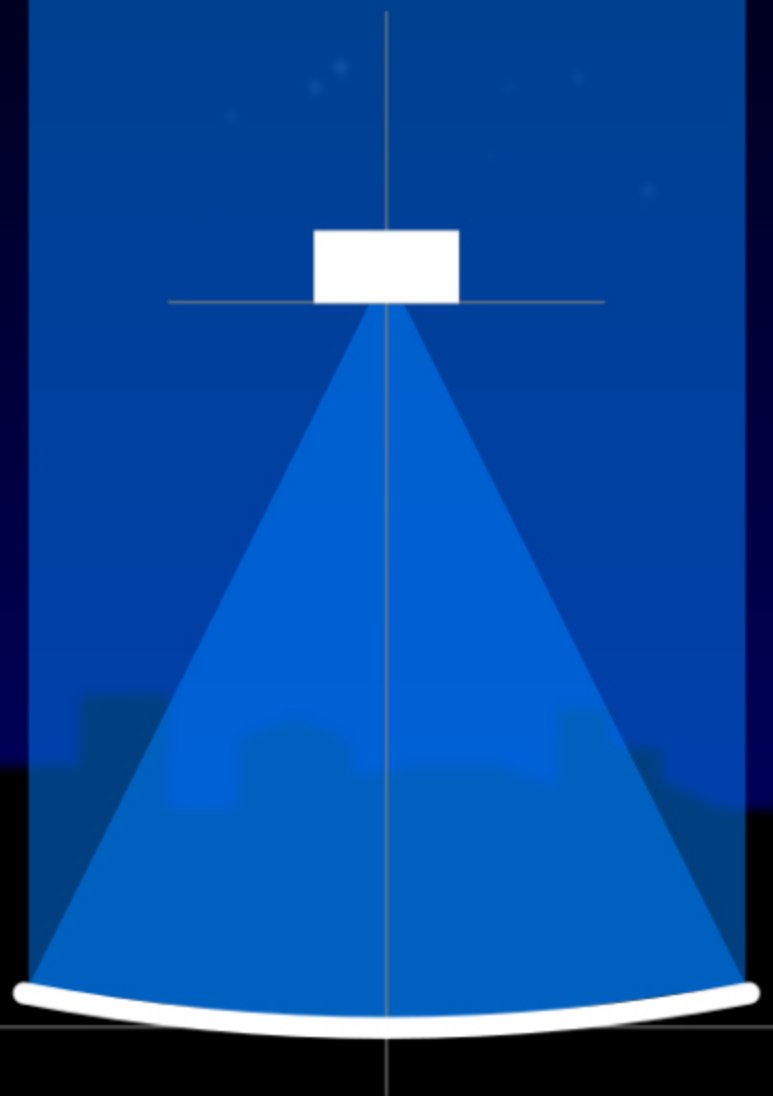


7 sample / mirror
(plenoscope)



Optics

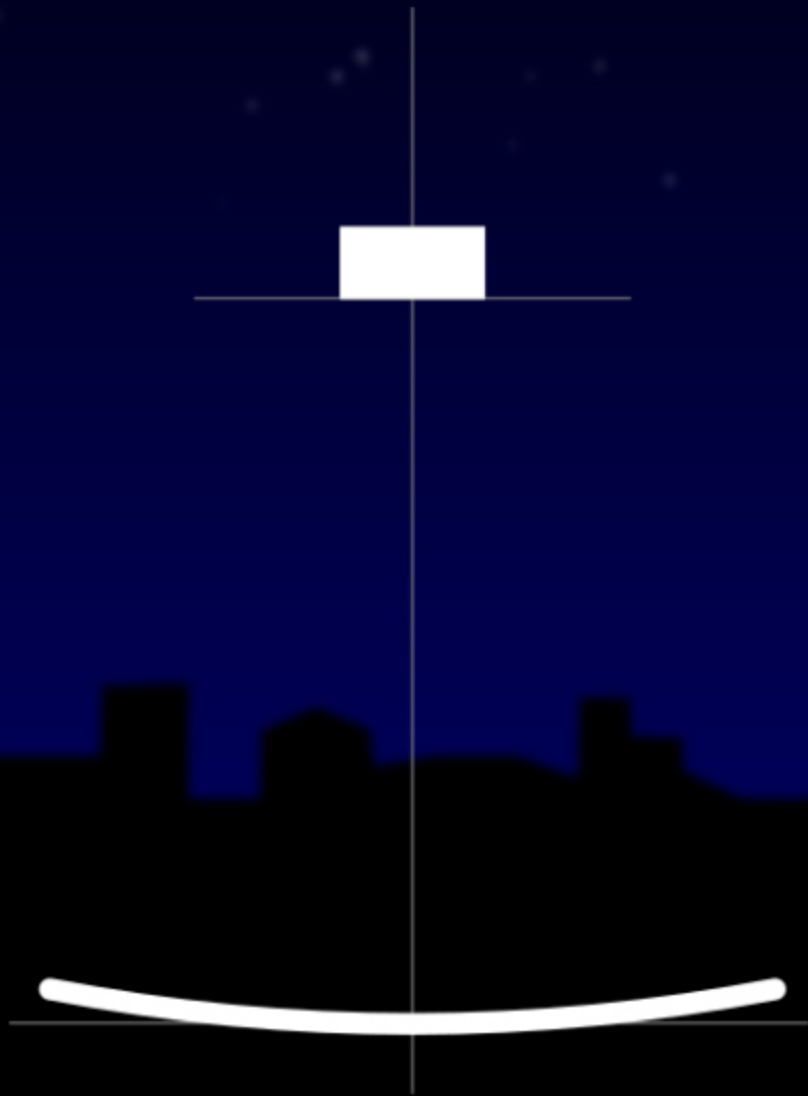
cameras



1 sample / mirror
(telescope)

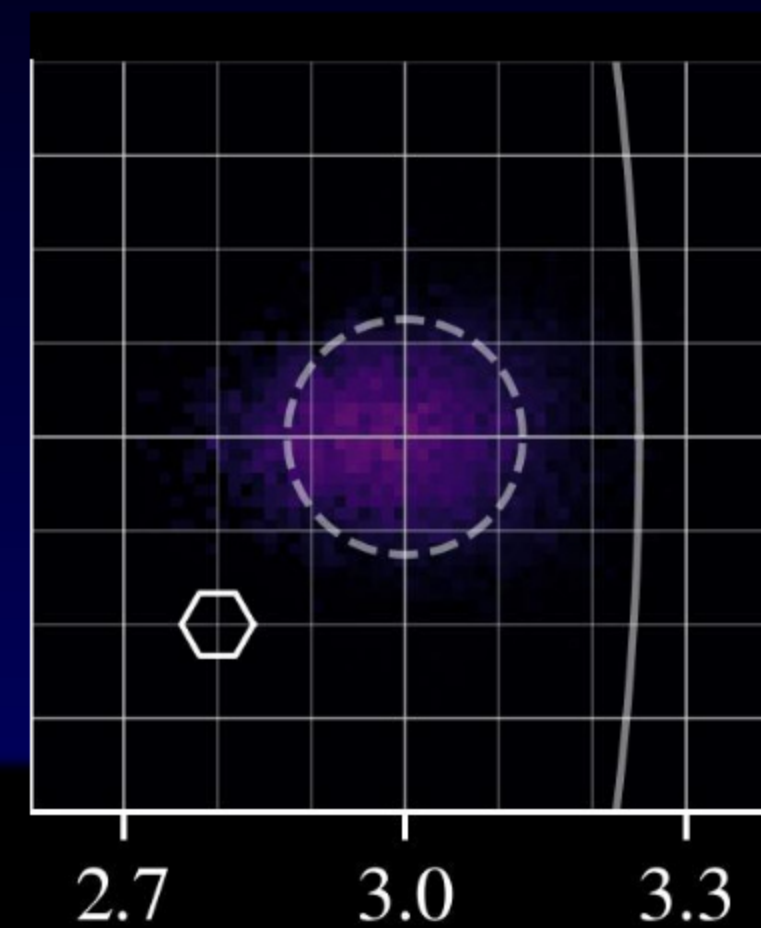
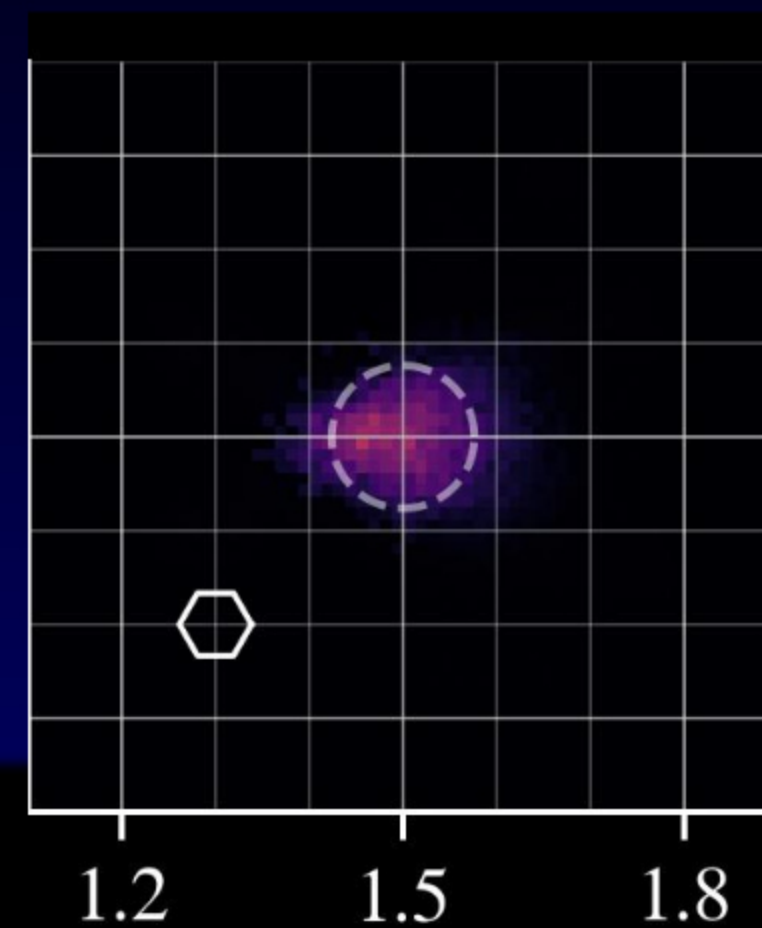
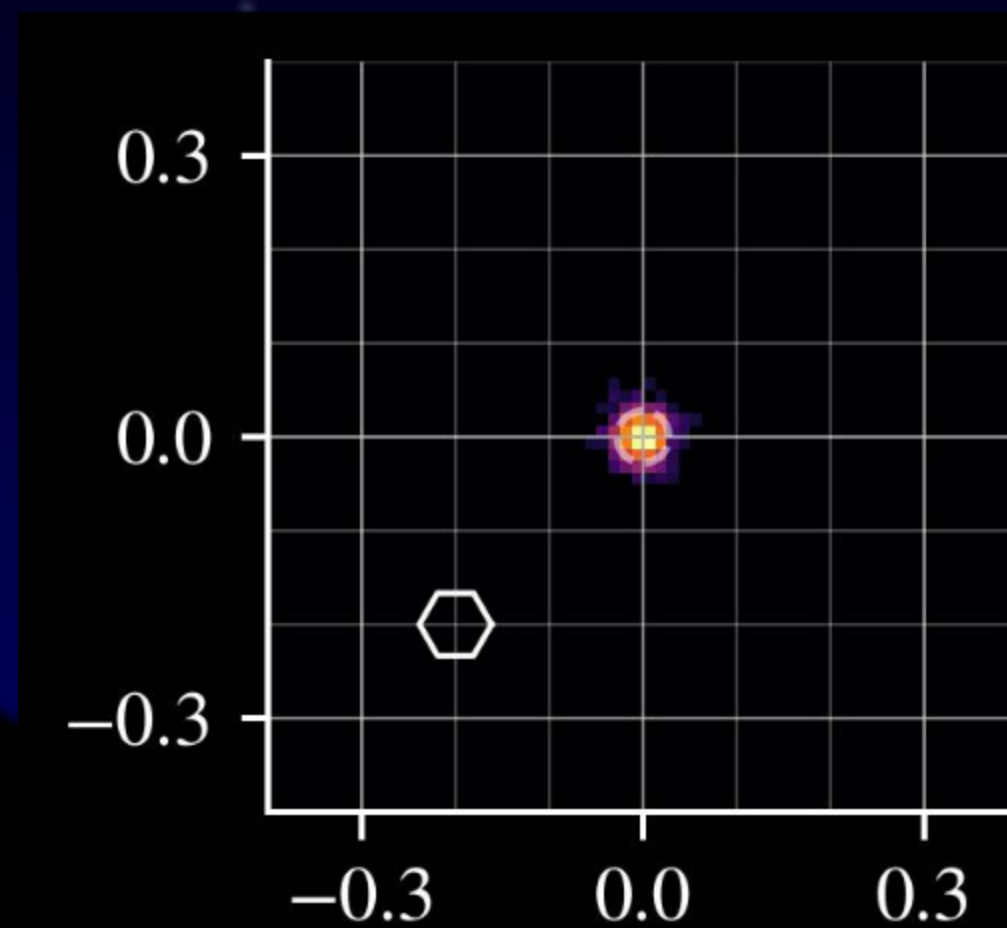
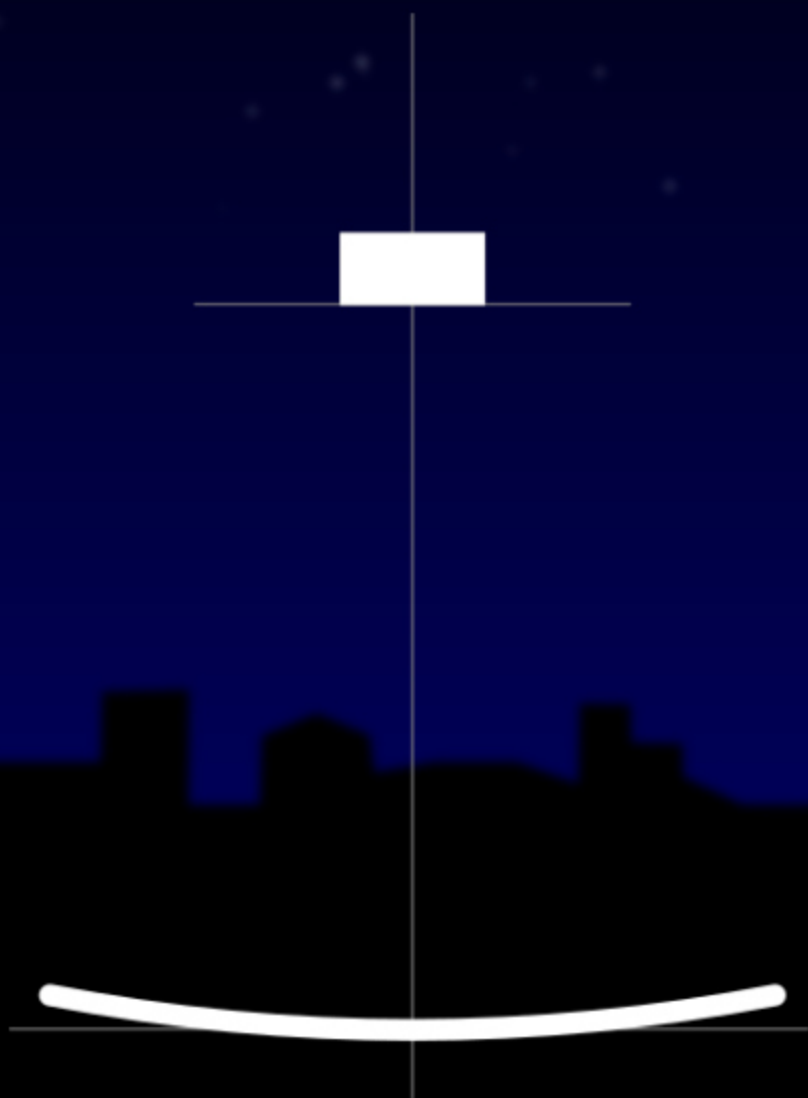
Optics

starlight performance



Optics

starlight performance

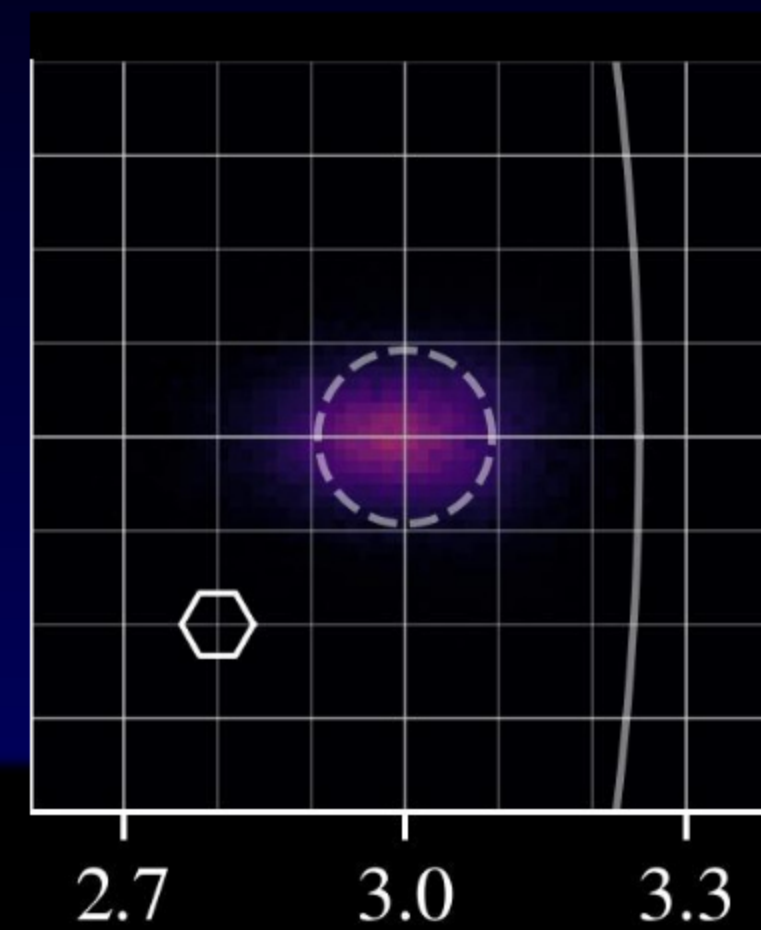
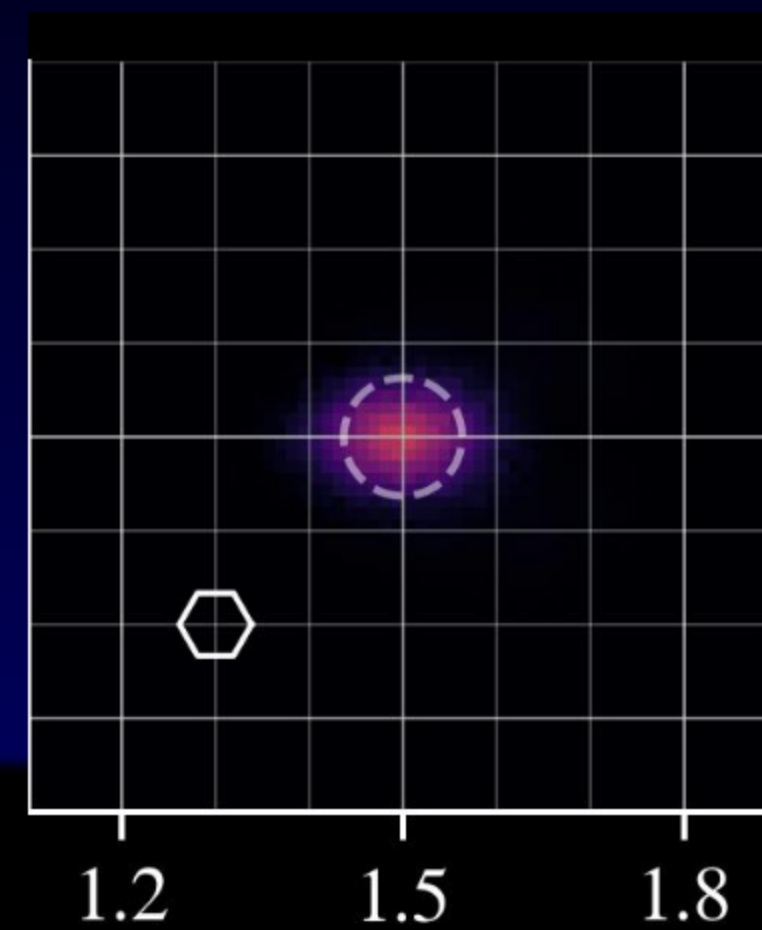
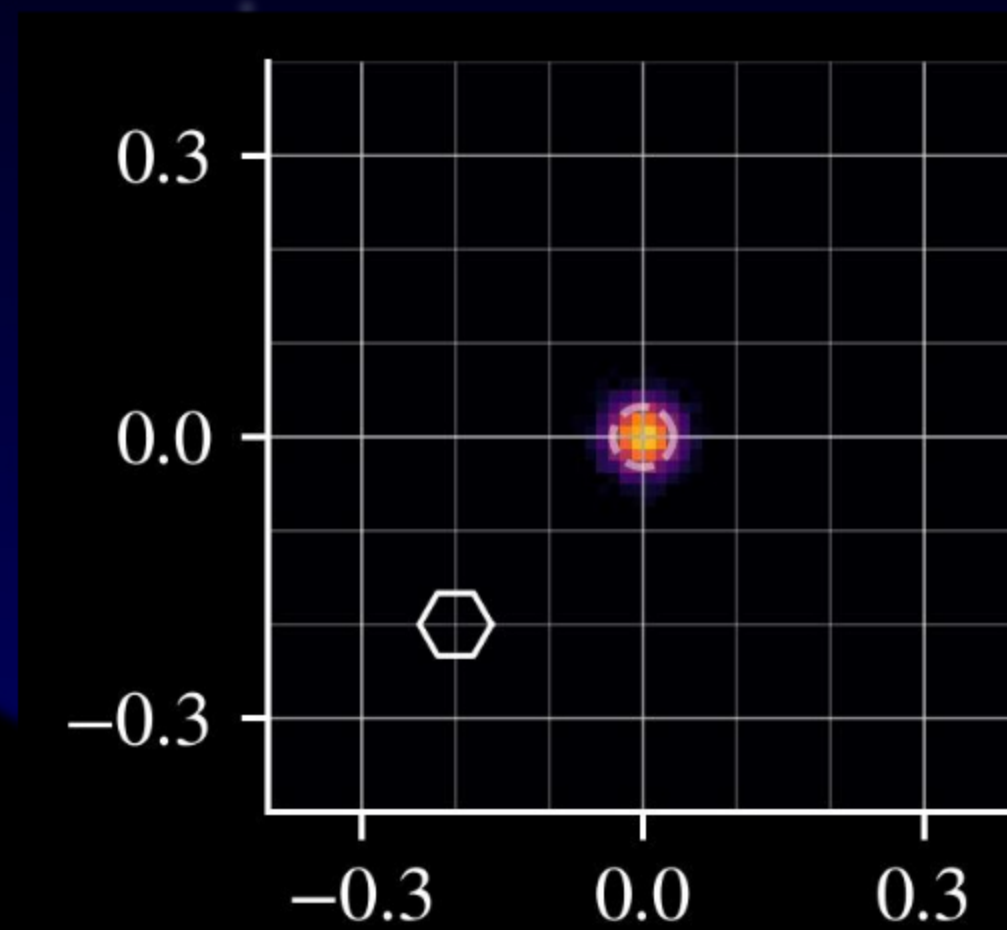
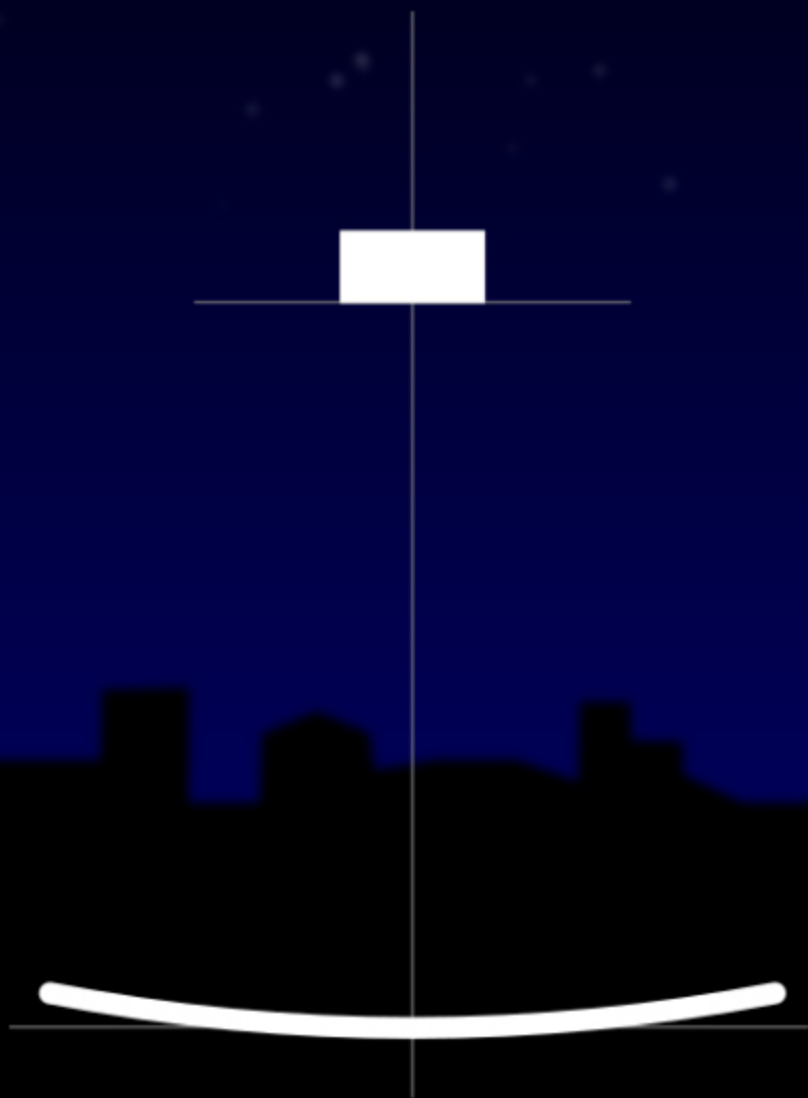


angle off the mirror's optical axis / (1°)



Optics

starlight performance

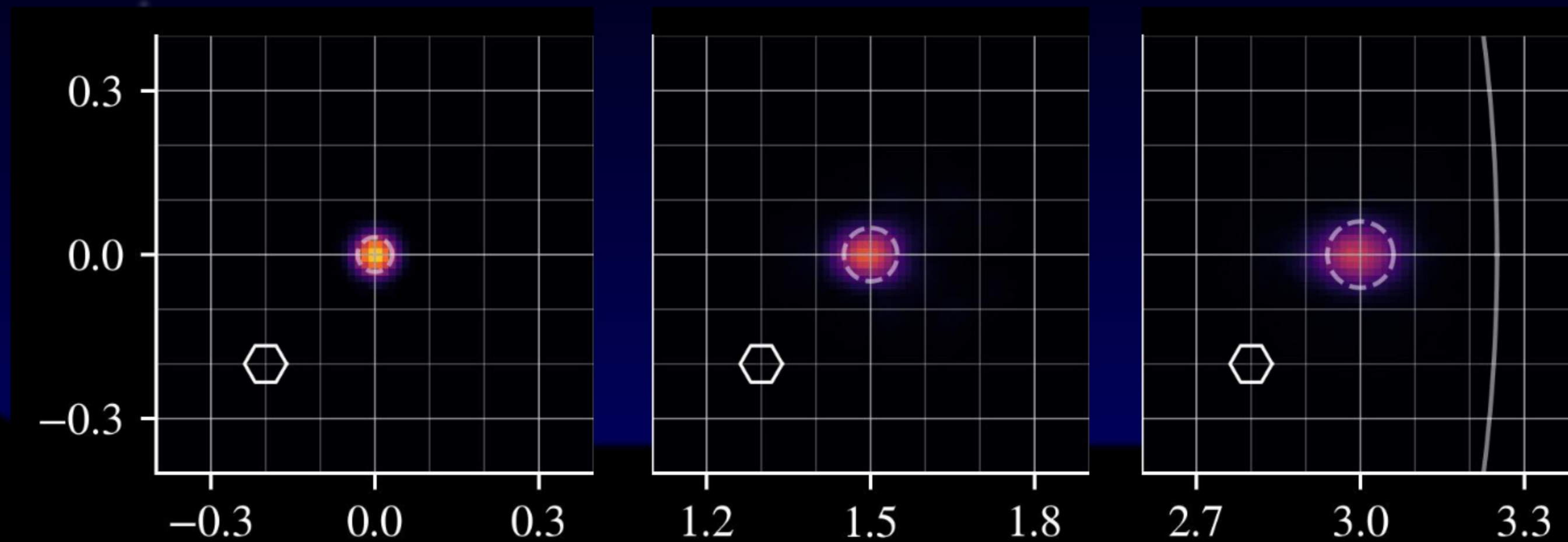
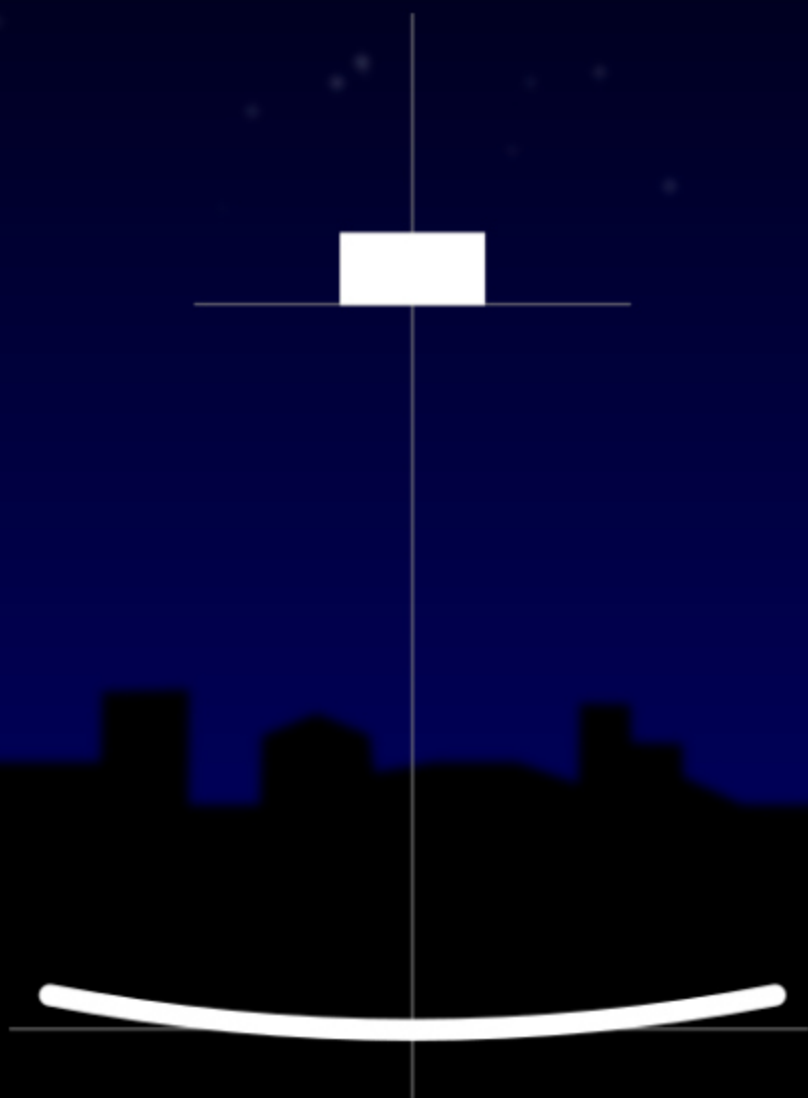


angle off the mirror's optical axis / (1°)



Optics

starlight performance

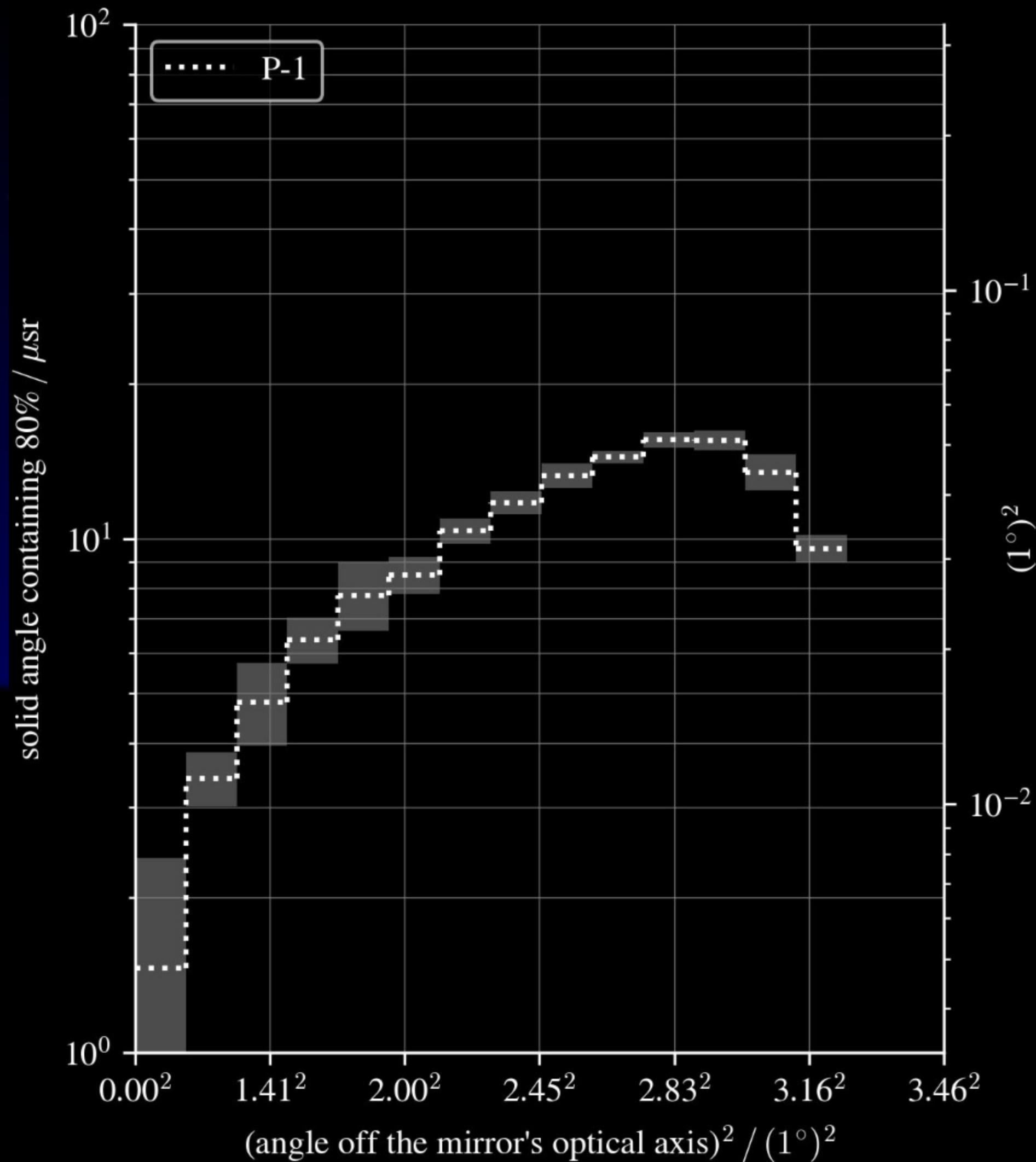
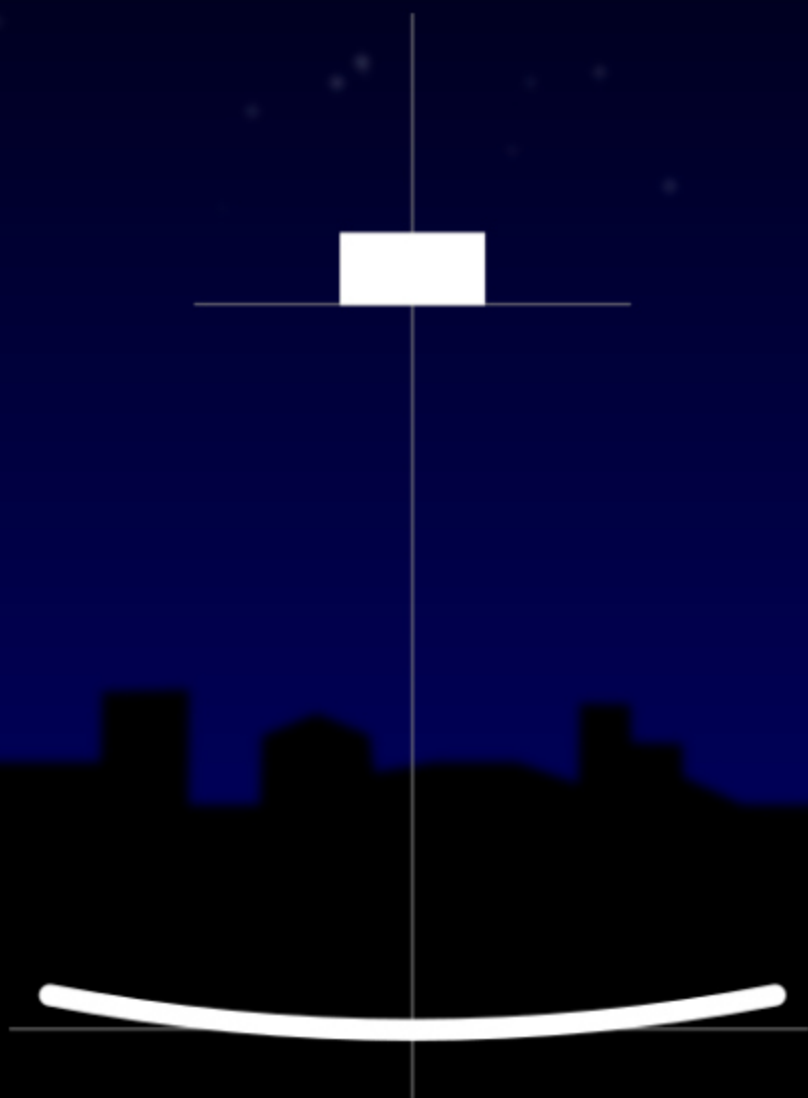


angle off the mirror's optical axis / (1°)



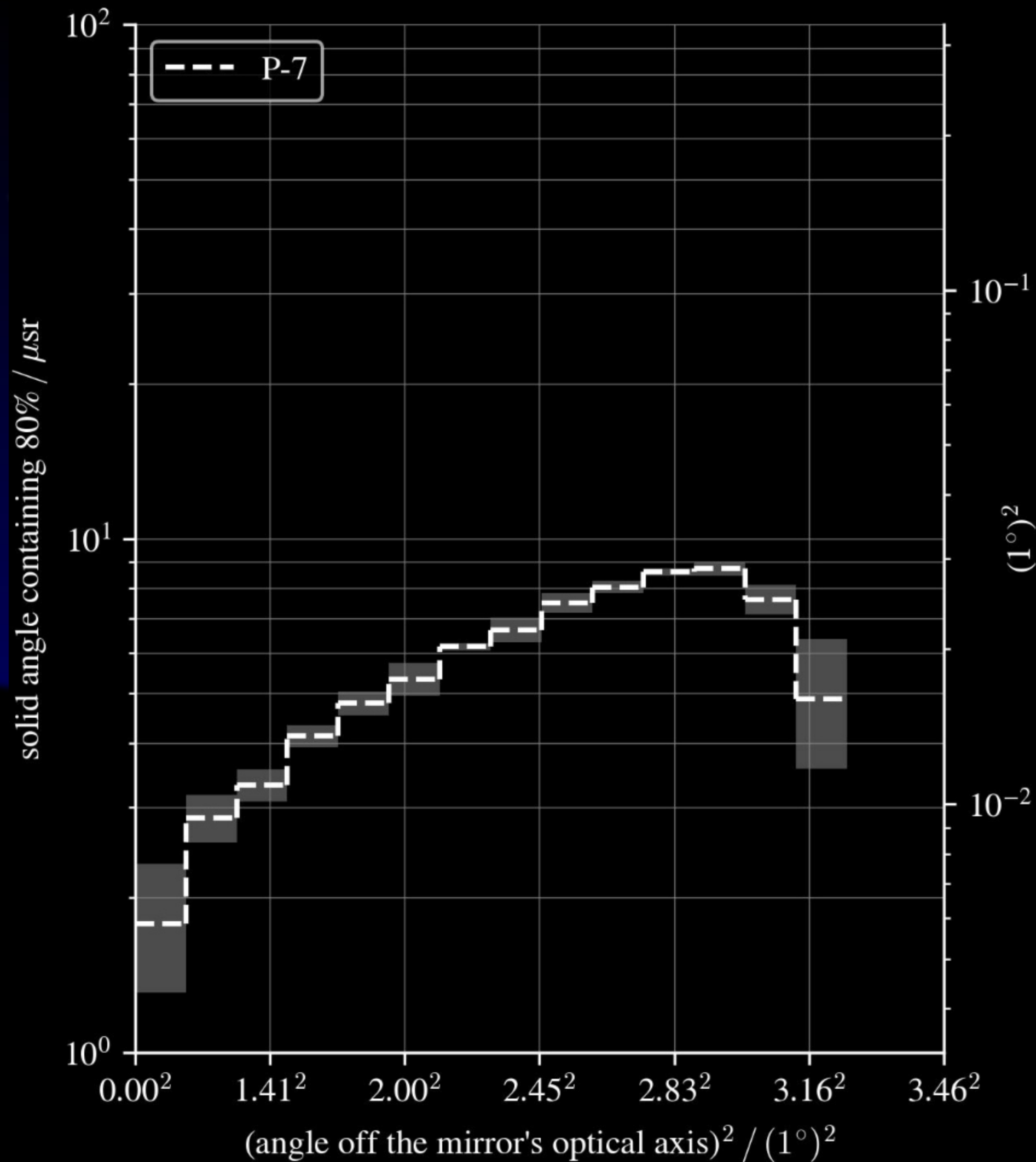
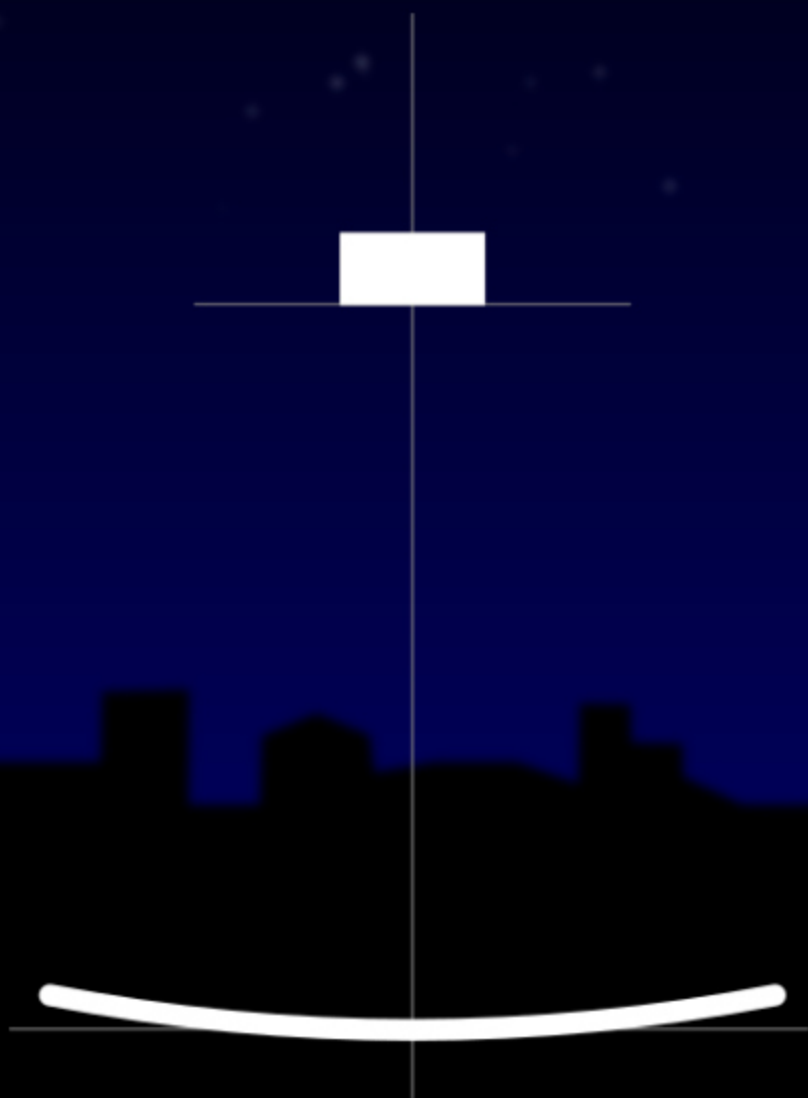
Optics

starlight performance



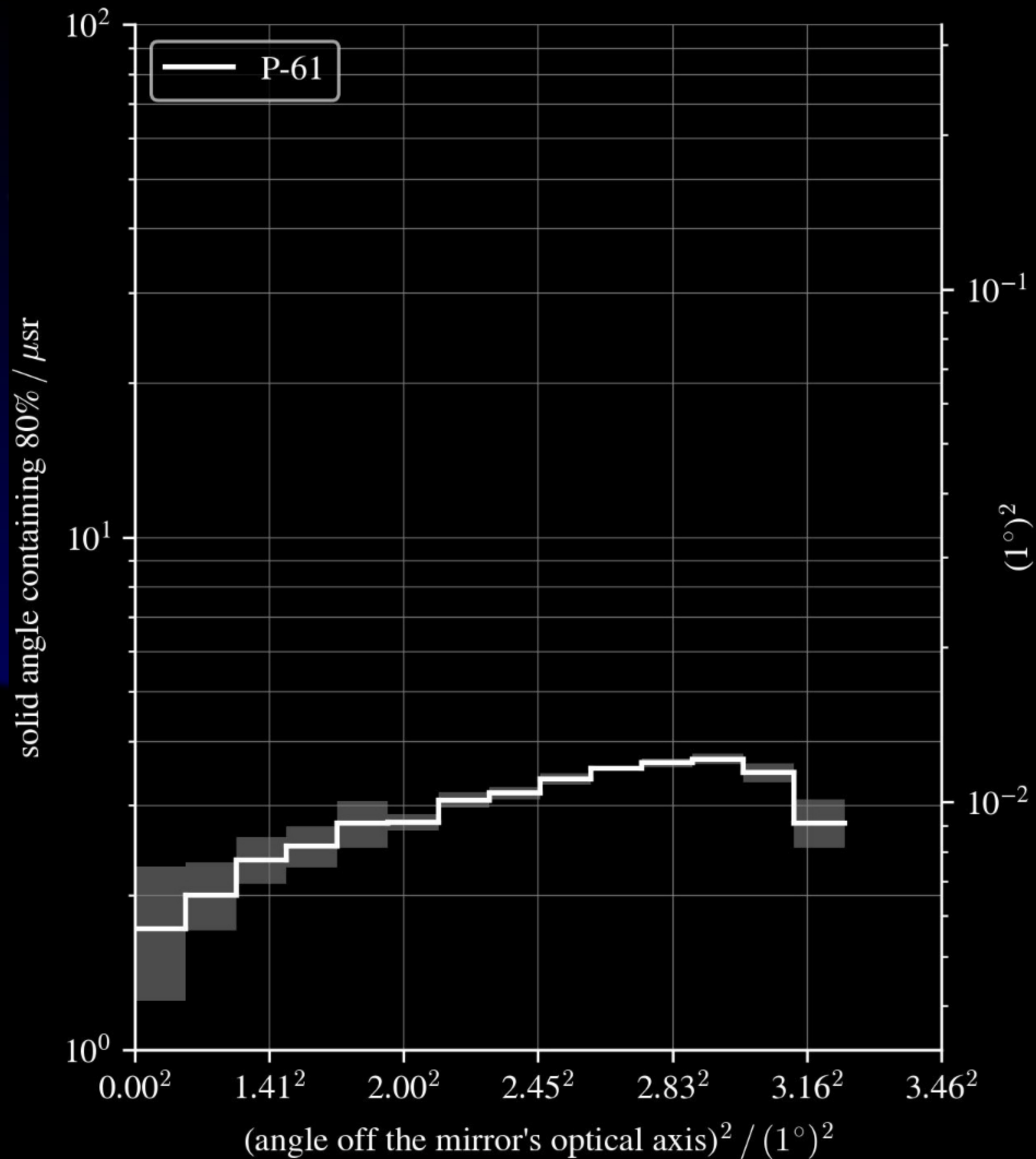
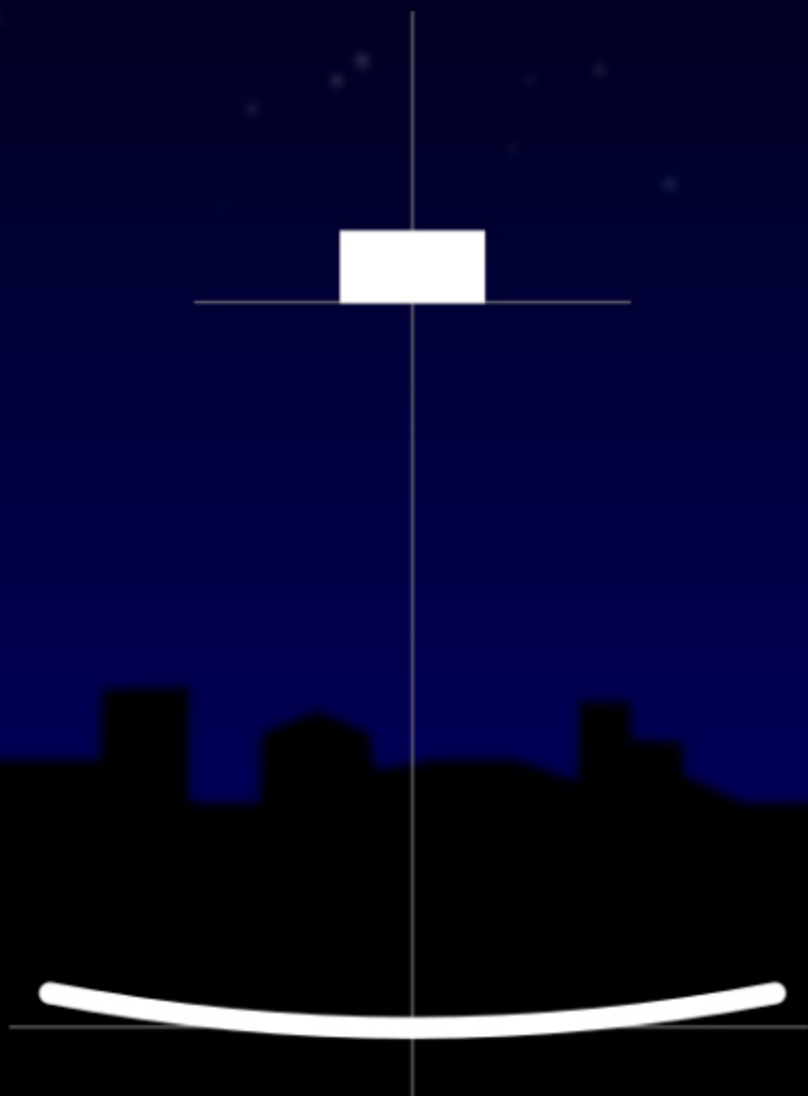
Optics

starlight performance



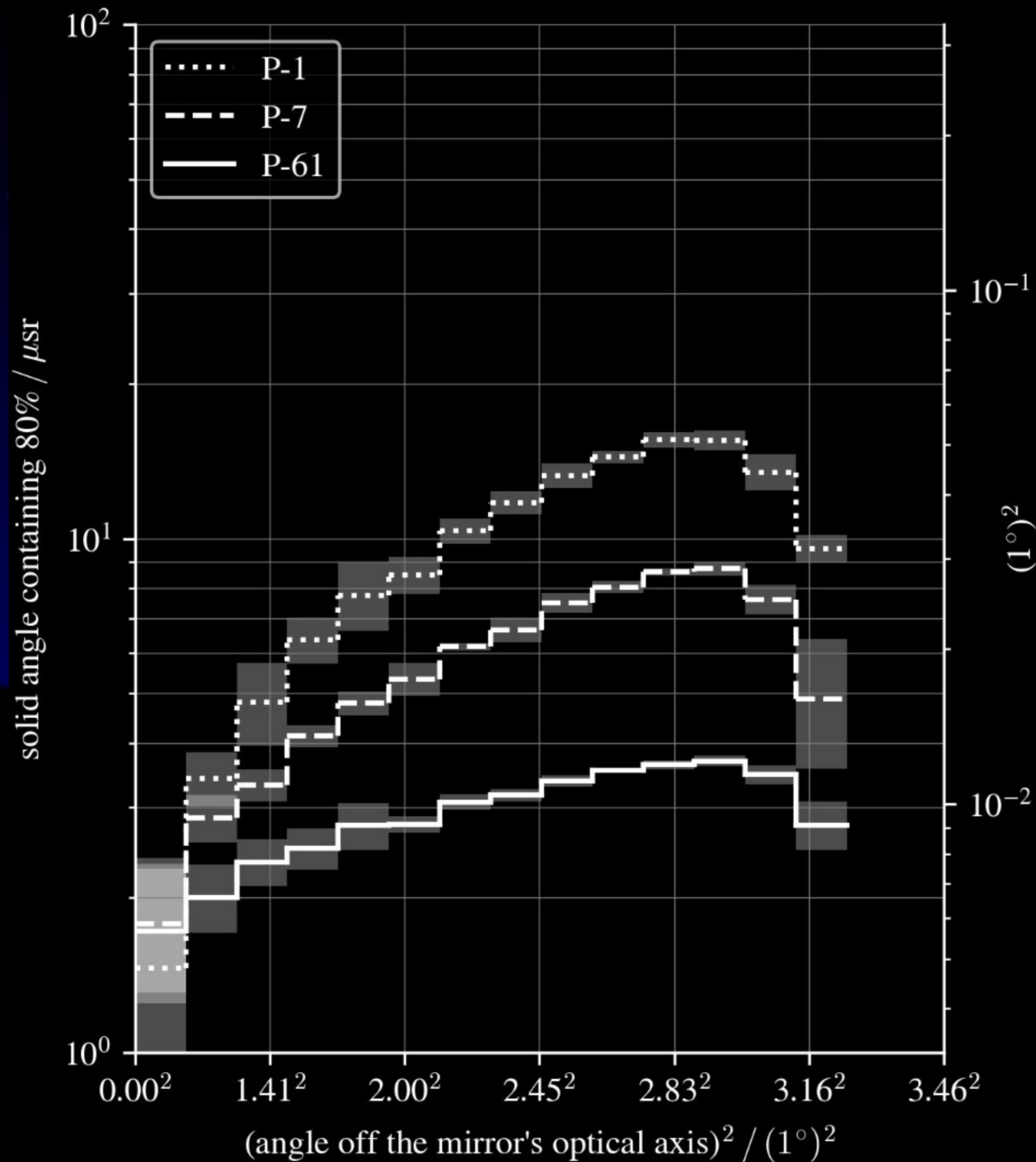
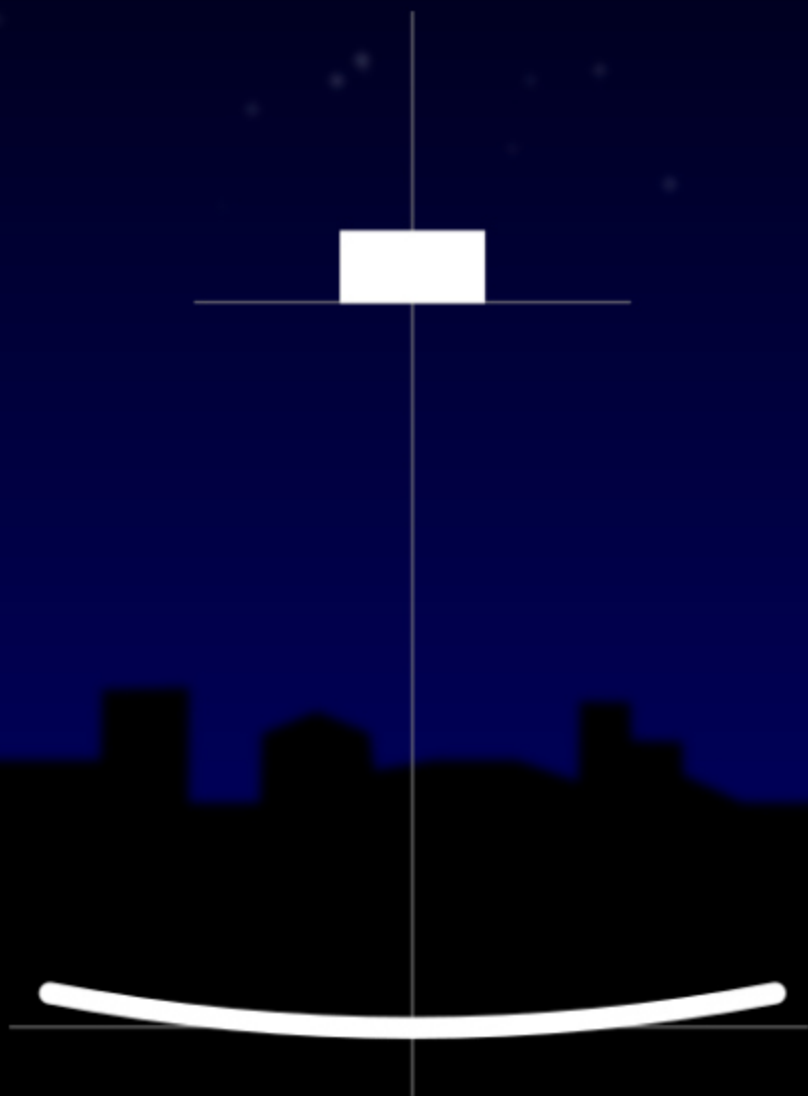
Optics

starlight performance



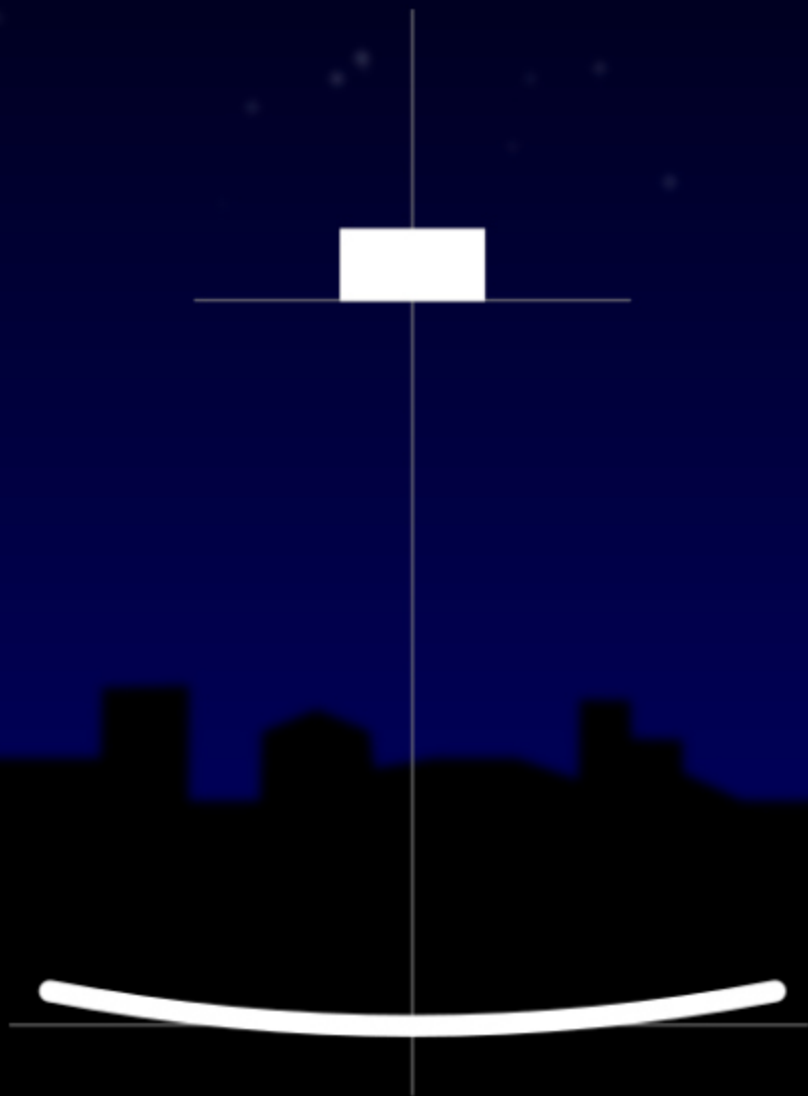
Optics

starlight performance



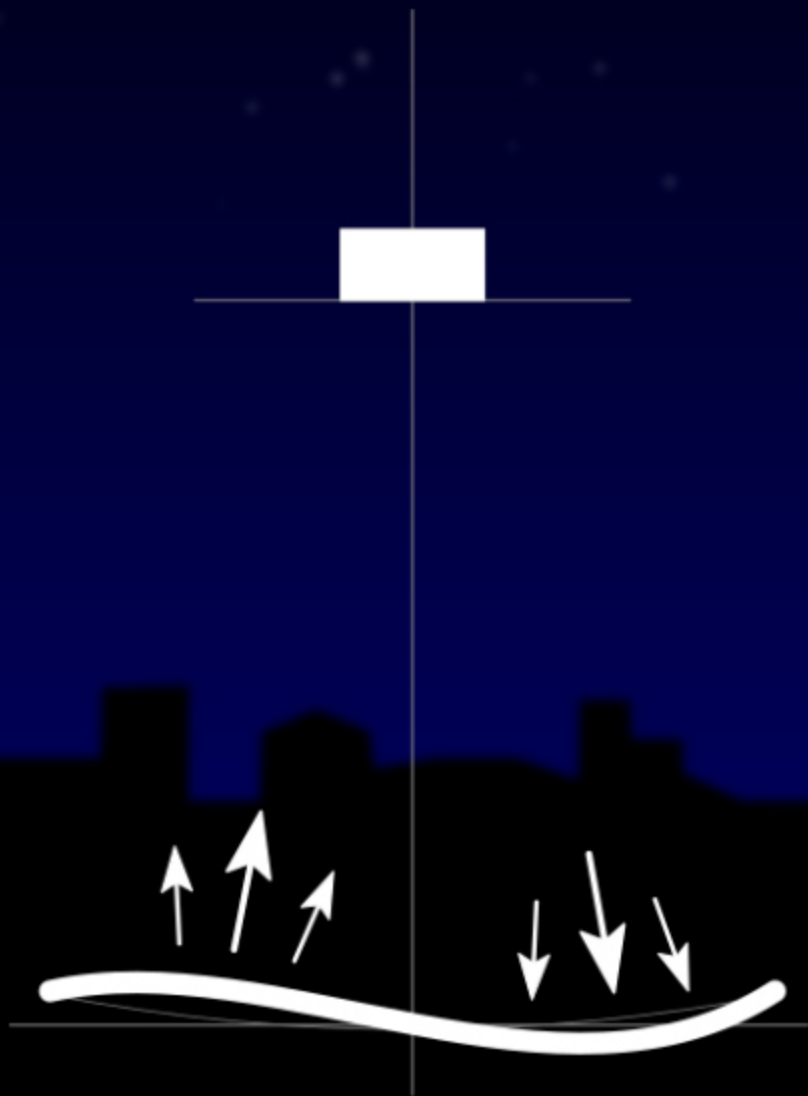
Optics

starlight performance



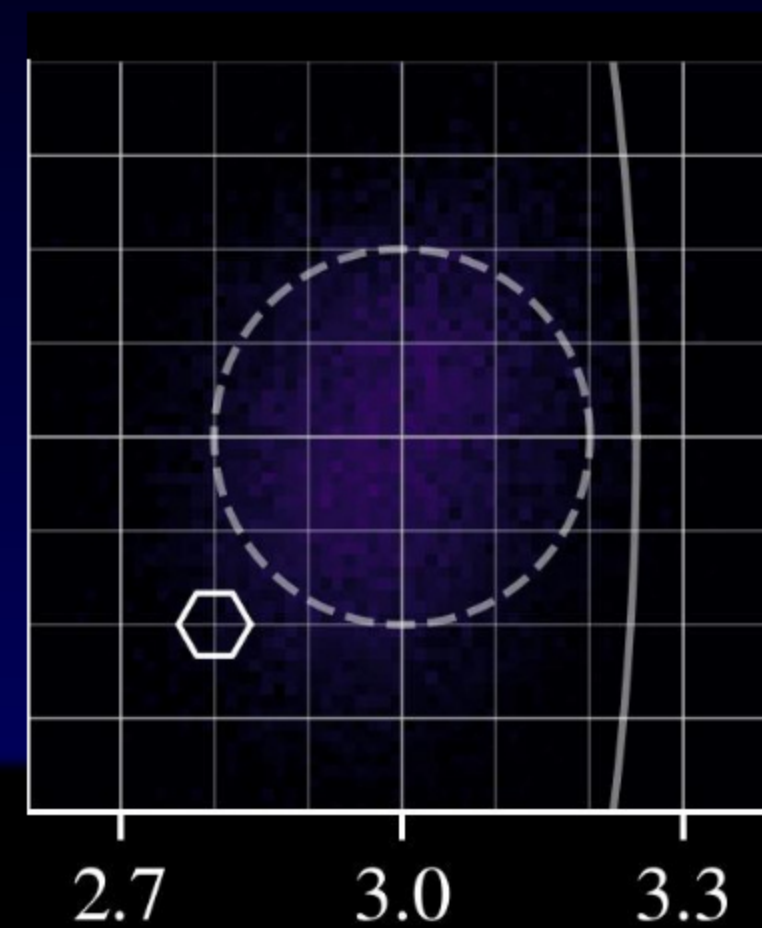
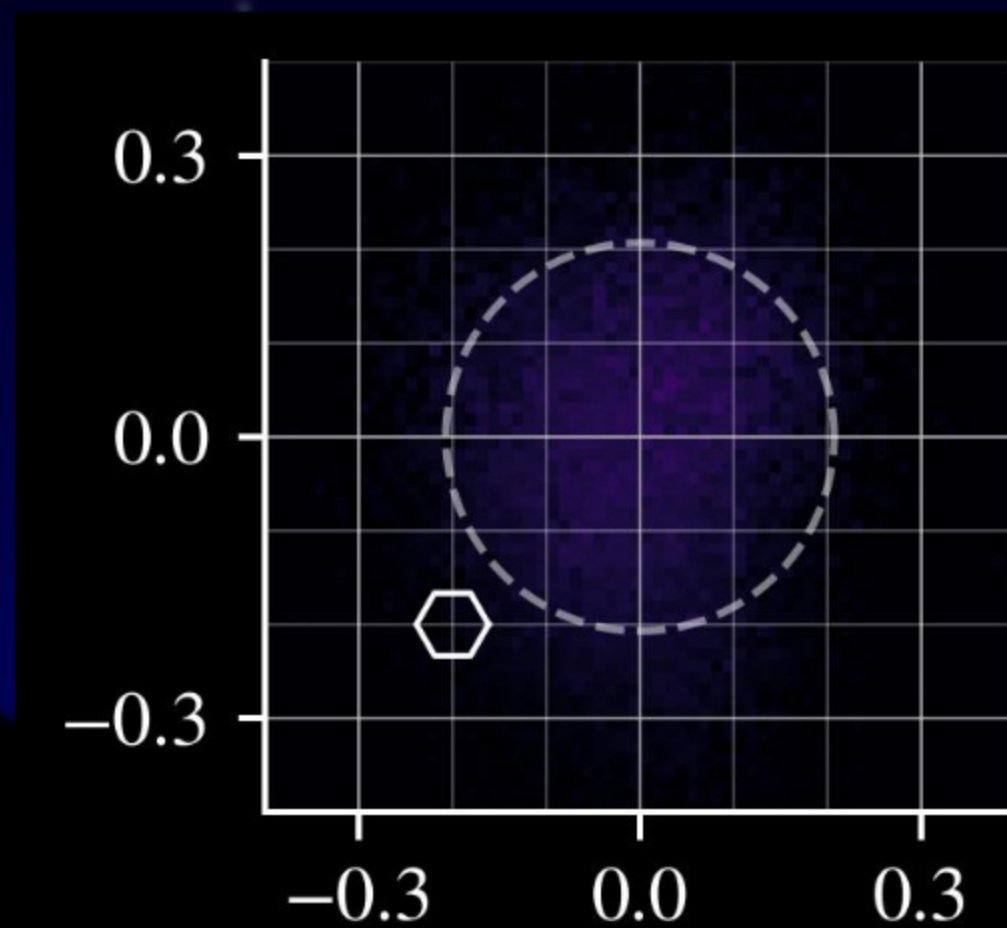
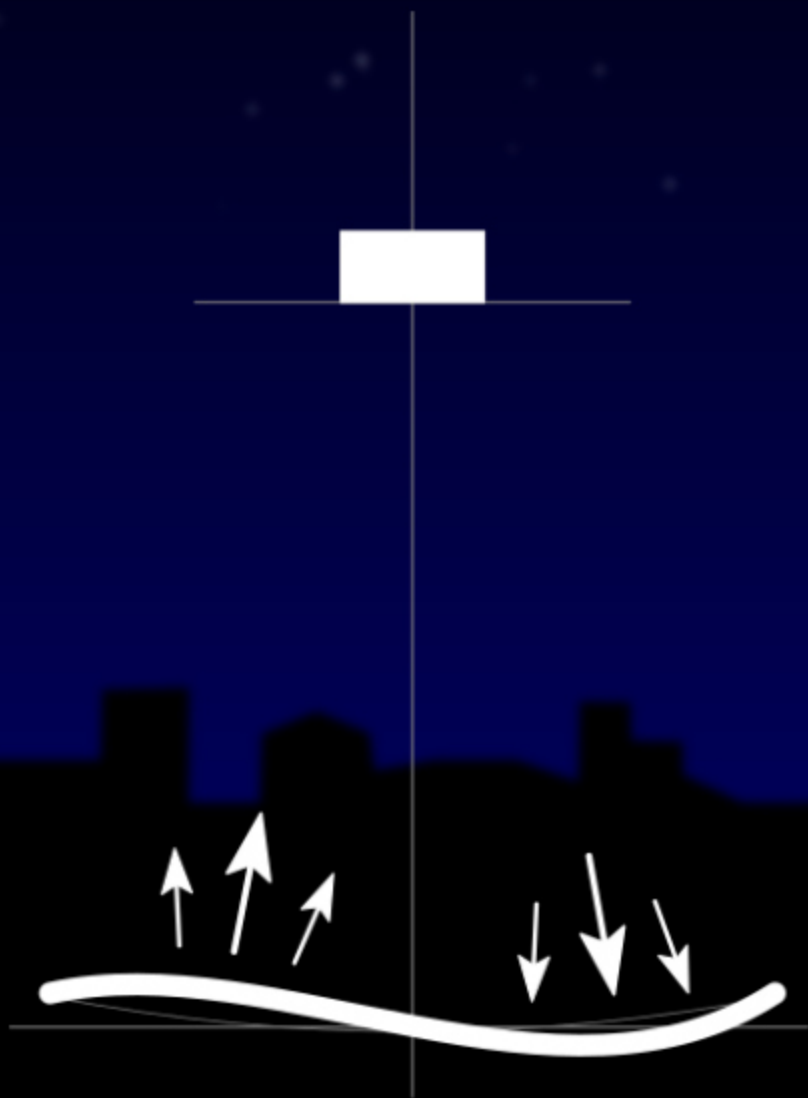
Optics

starlight performance



Optics

starlight performance

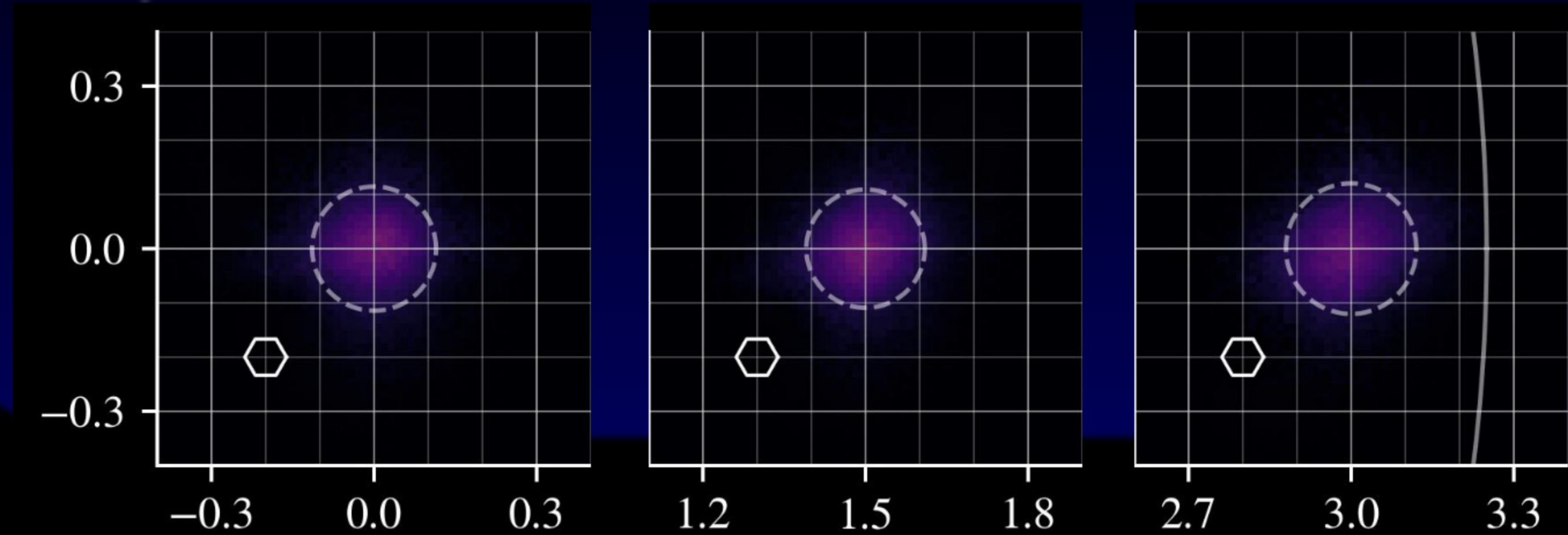
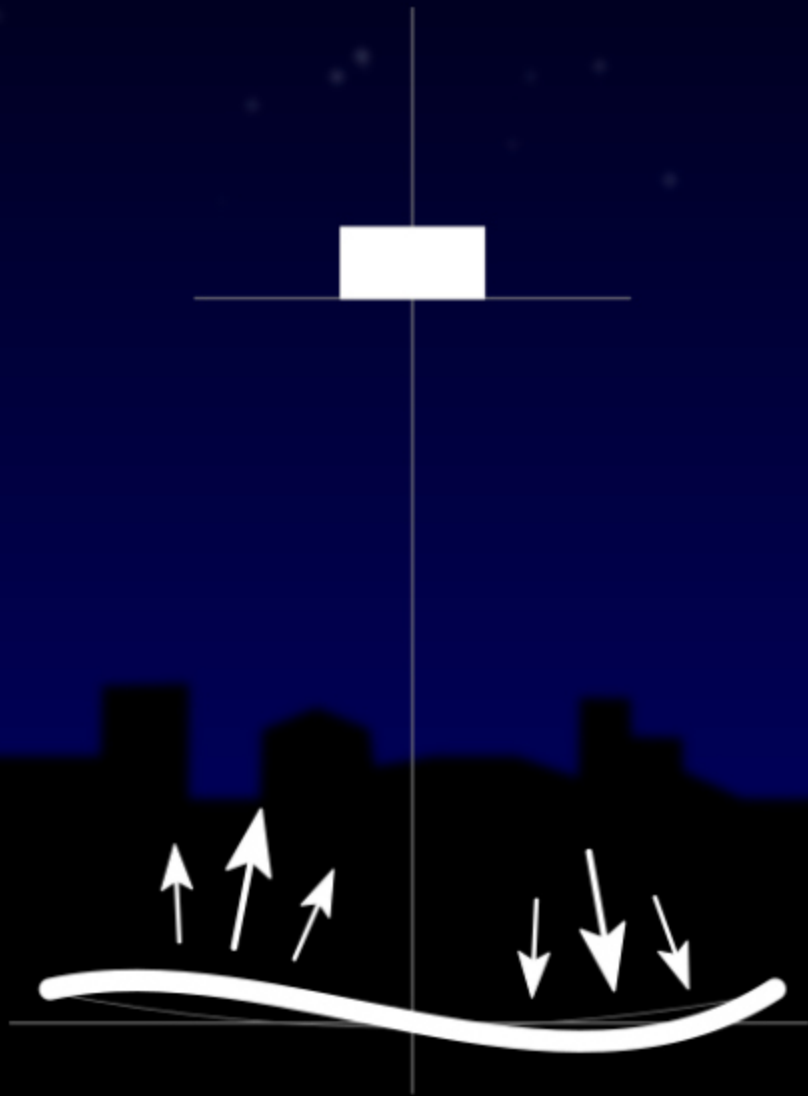


angle off the mirror's optical axis / (1°)



Optics

starlight performance

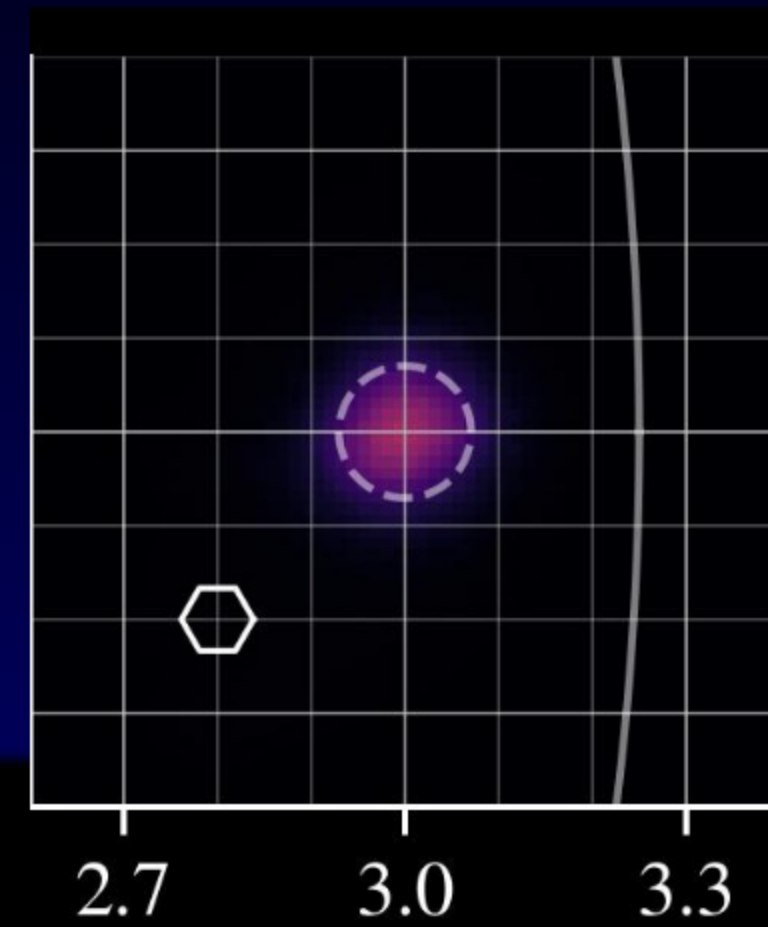
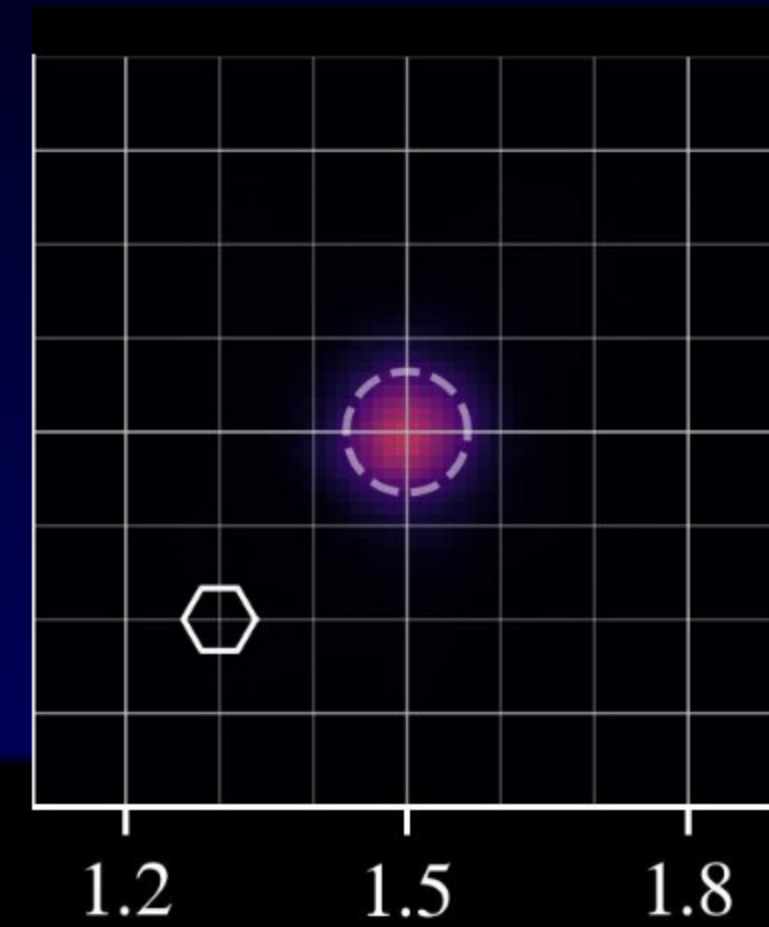
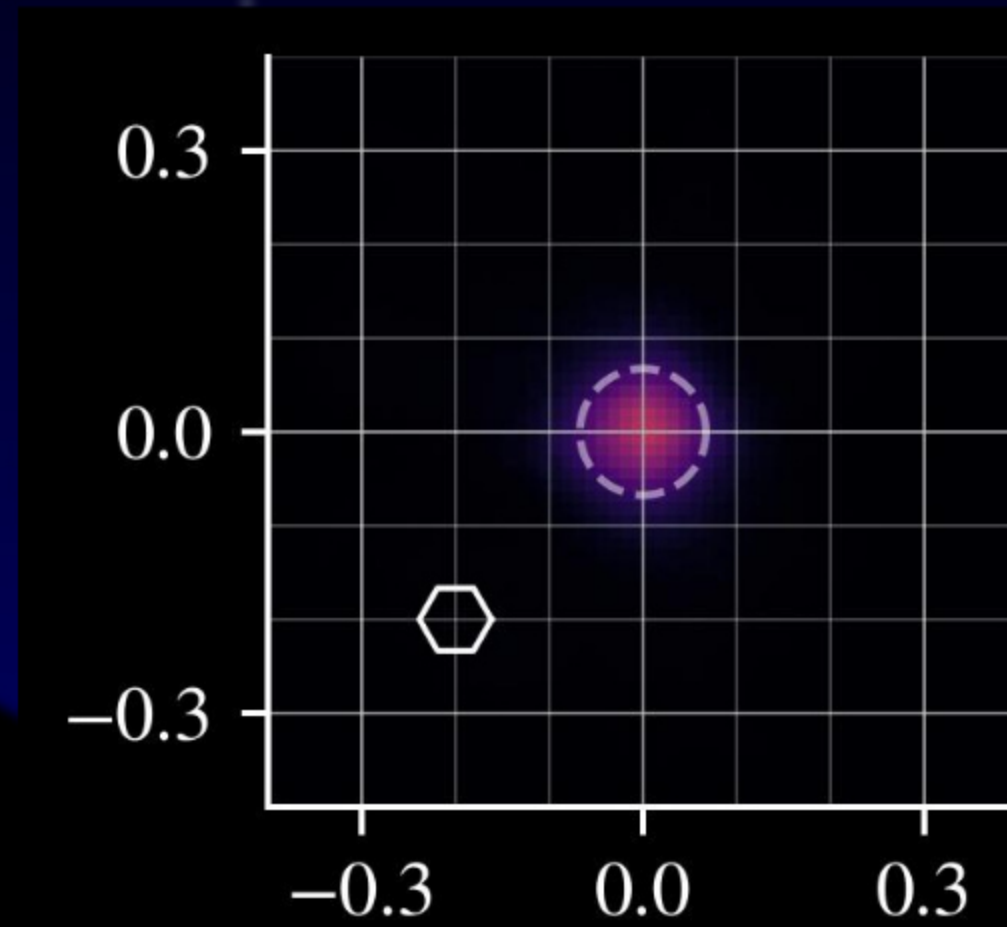
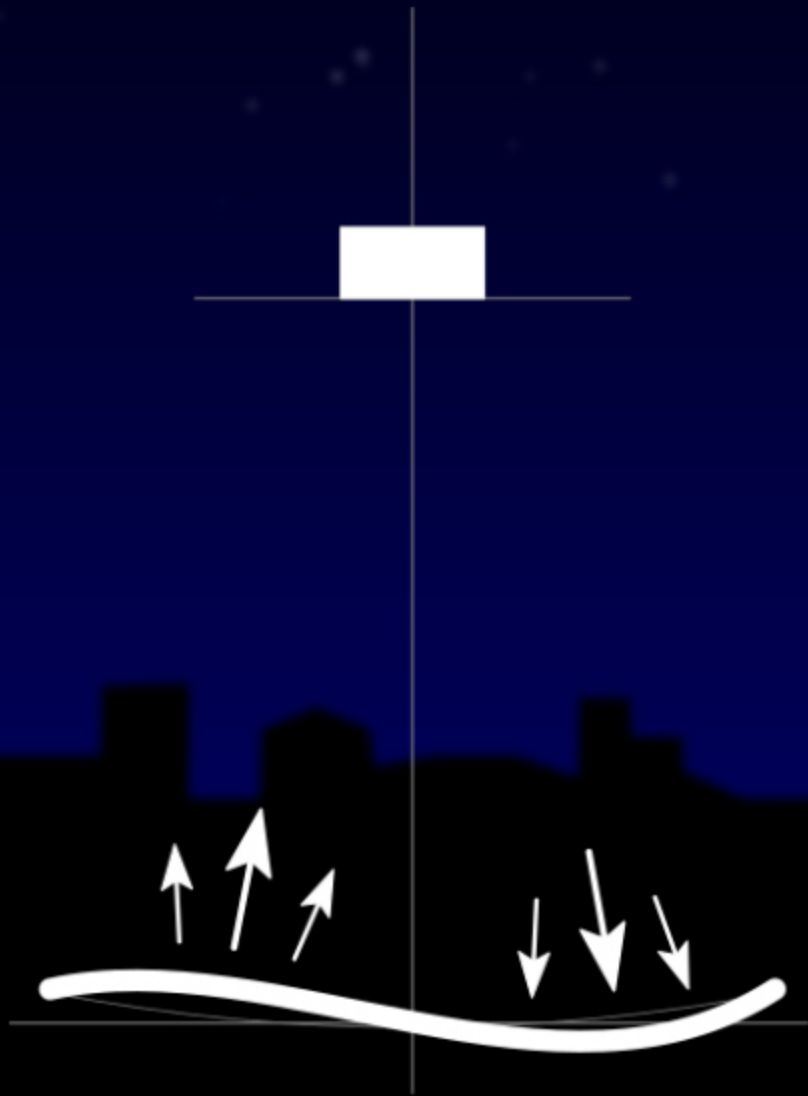


angle off the mirror's optical axis / (1°)



Optics

starlight performance

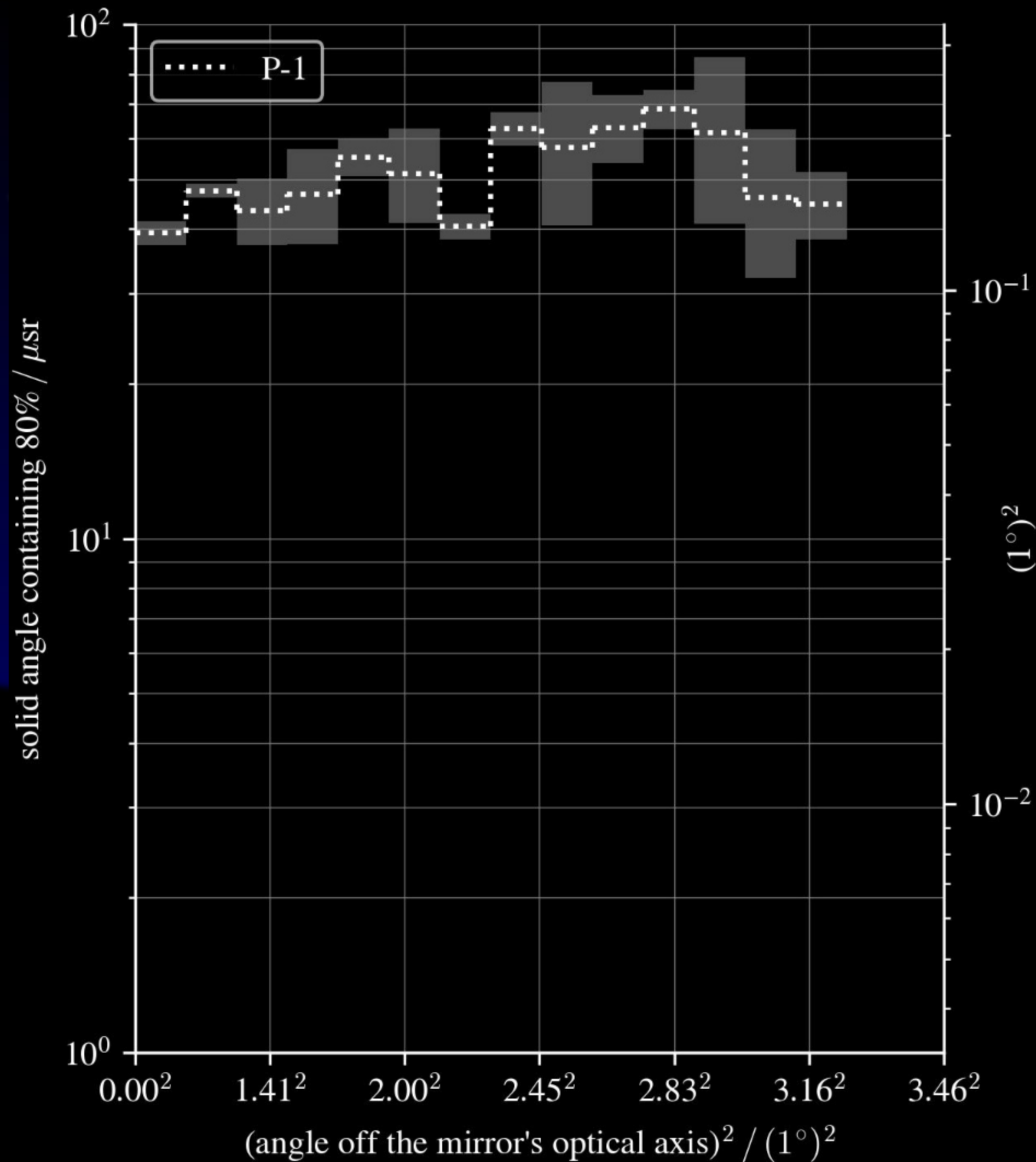
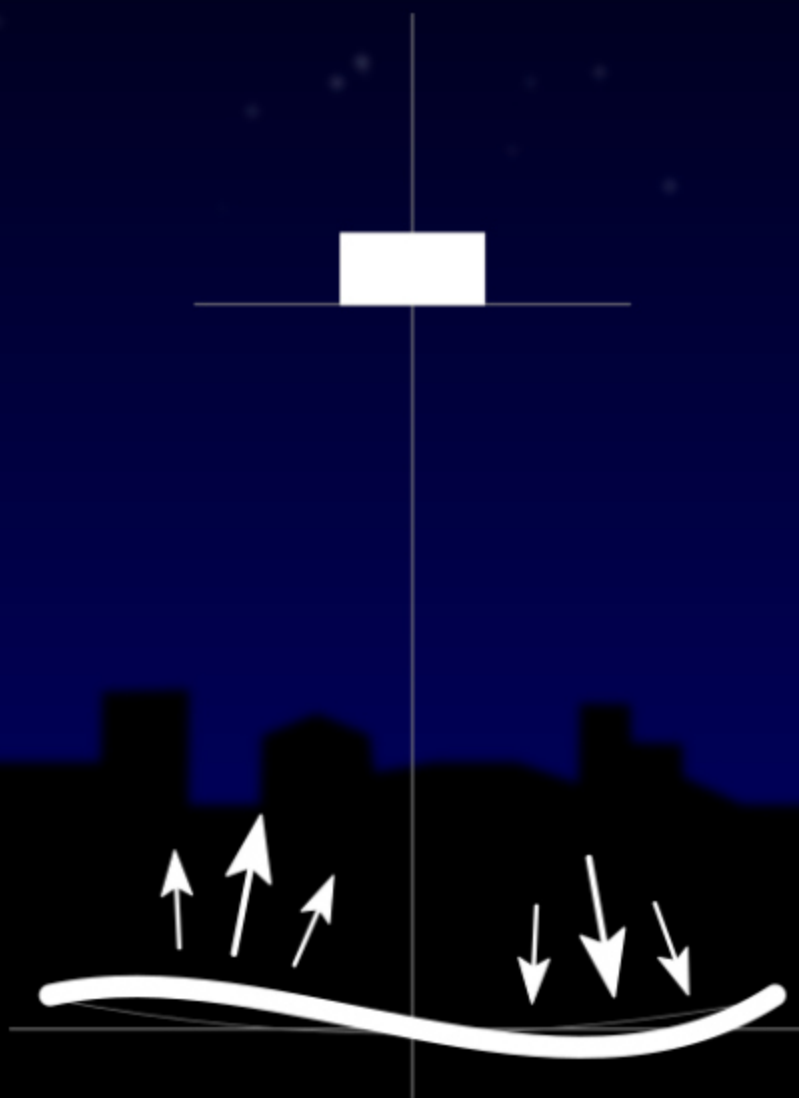


angle off the mirror's optical axis / (1°)



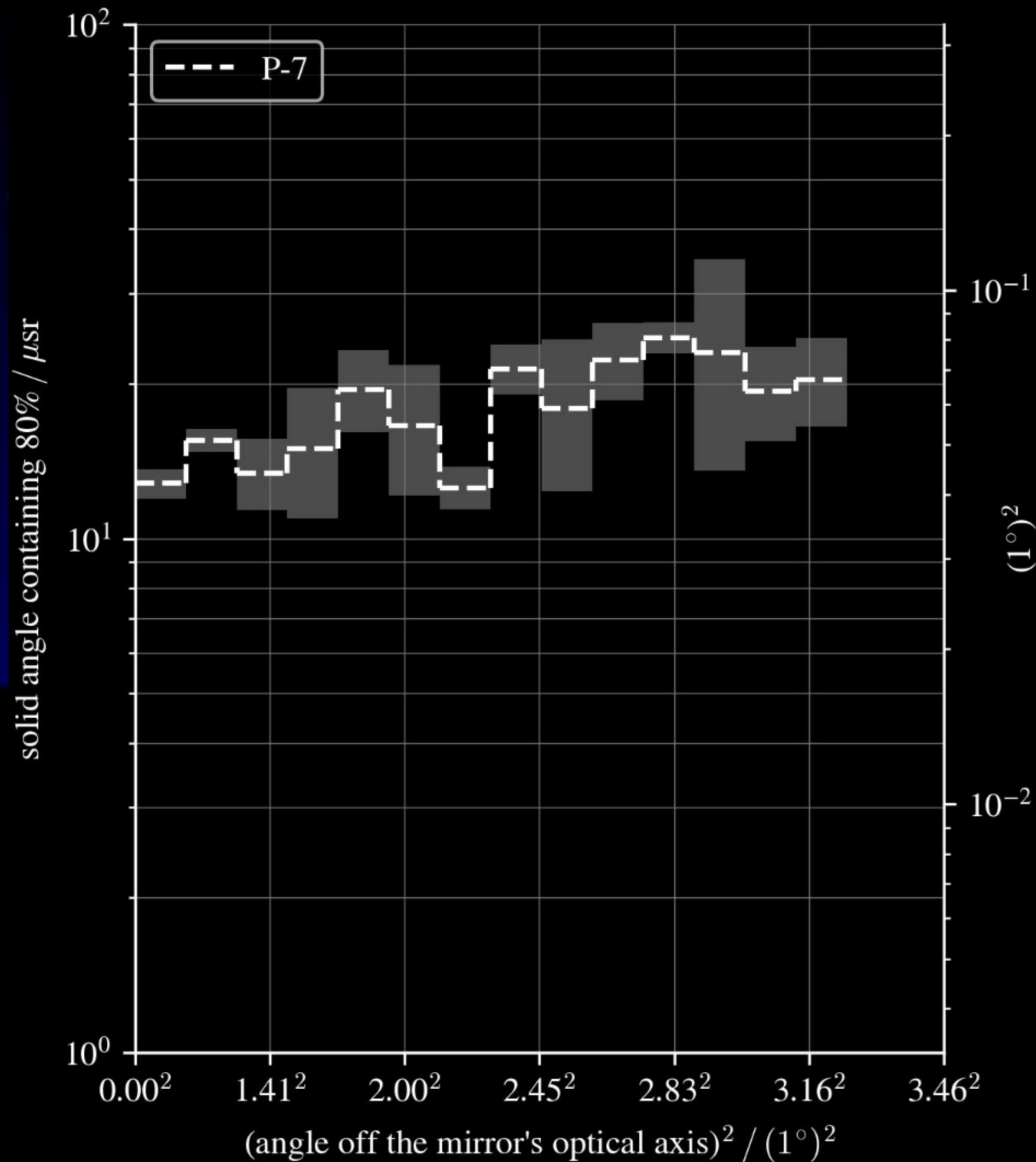
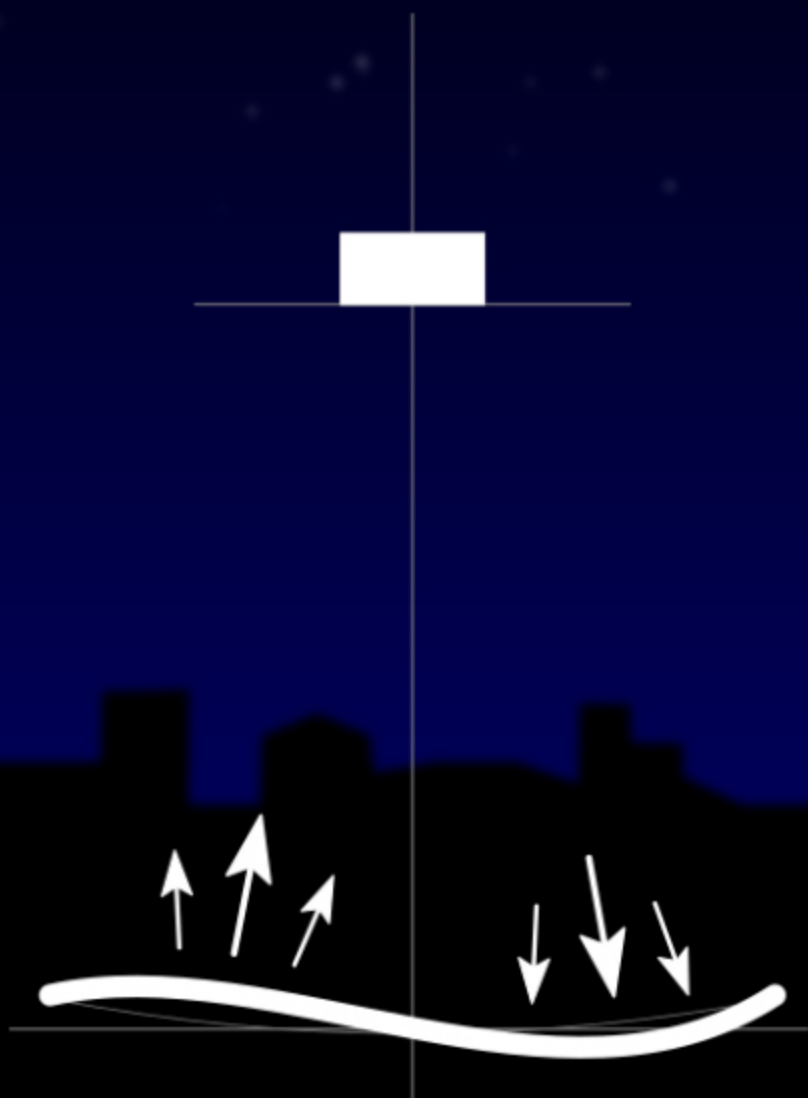
Optics

starlight performance



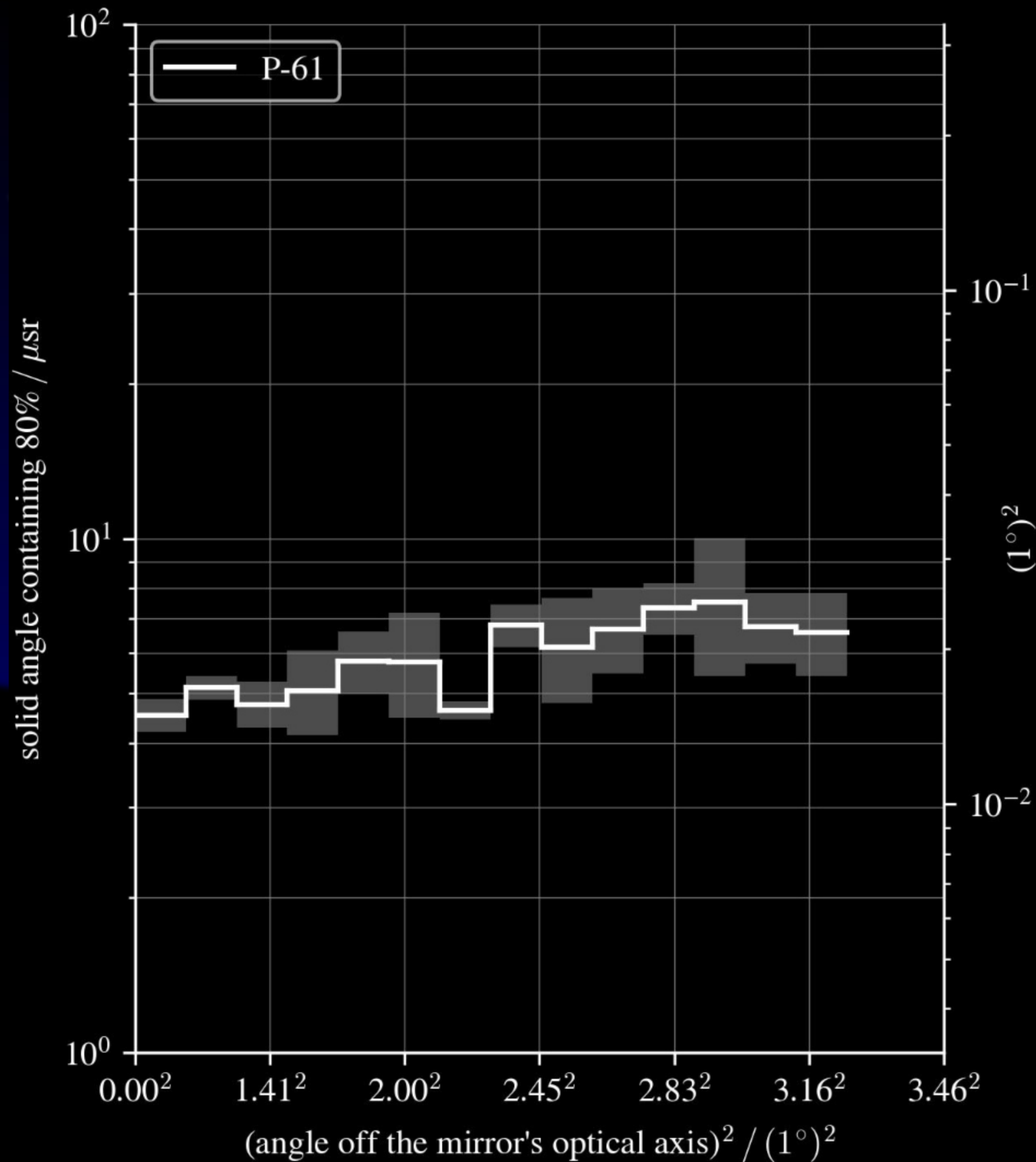
Optics

starlight performance



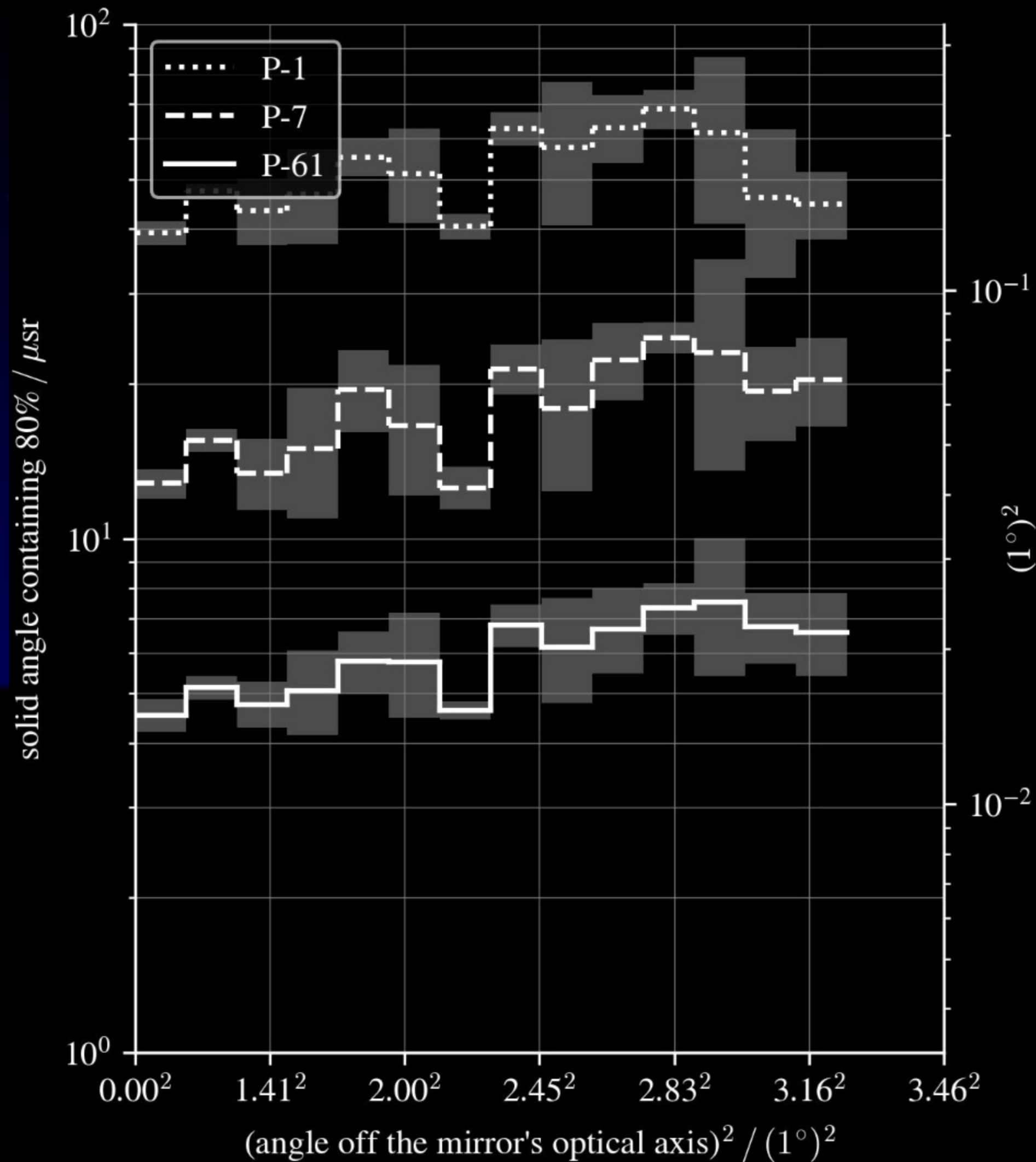
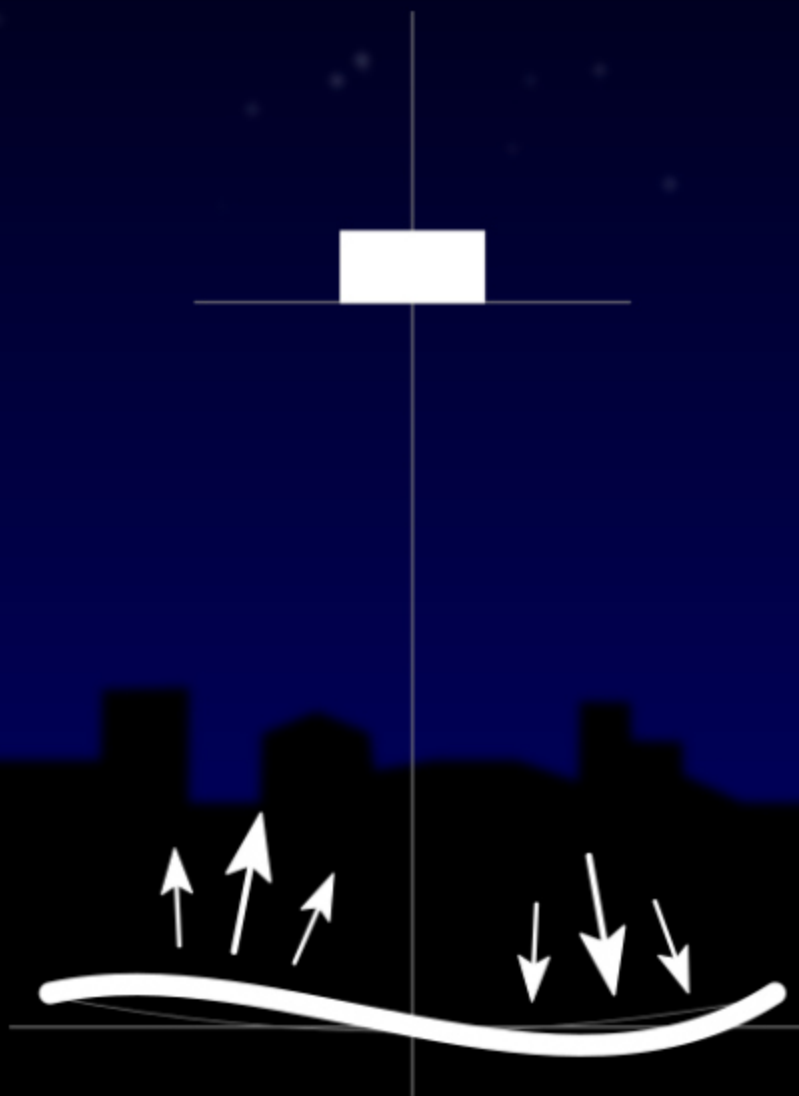
Optics

starlight performance



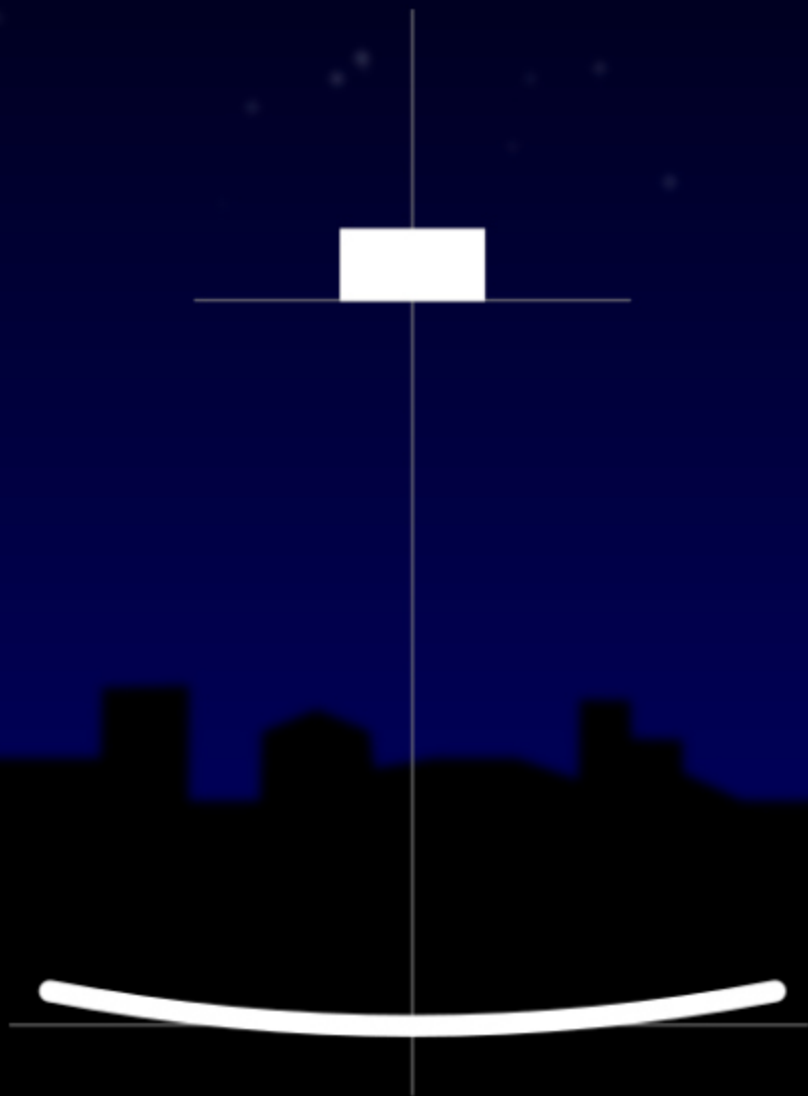
Optics

starlight performance



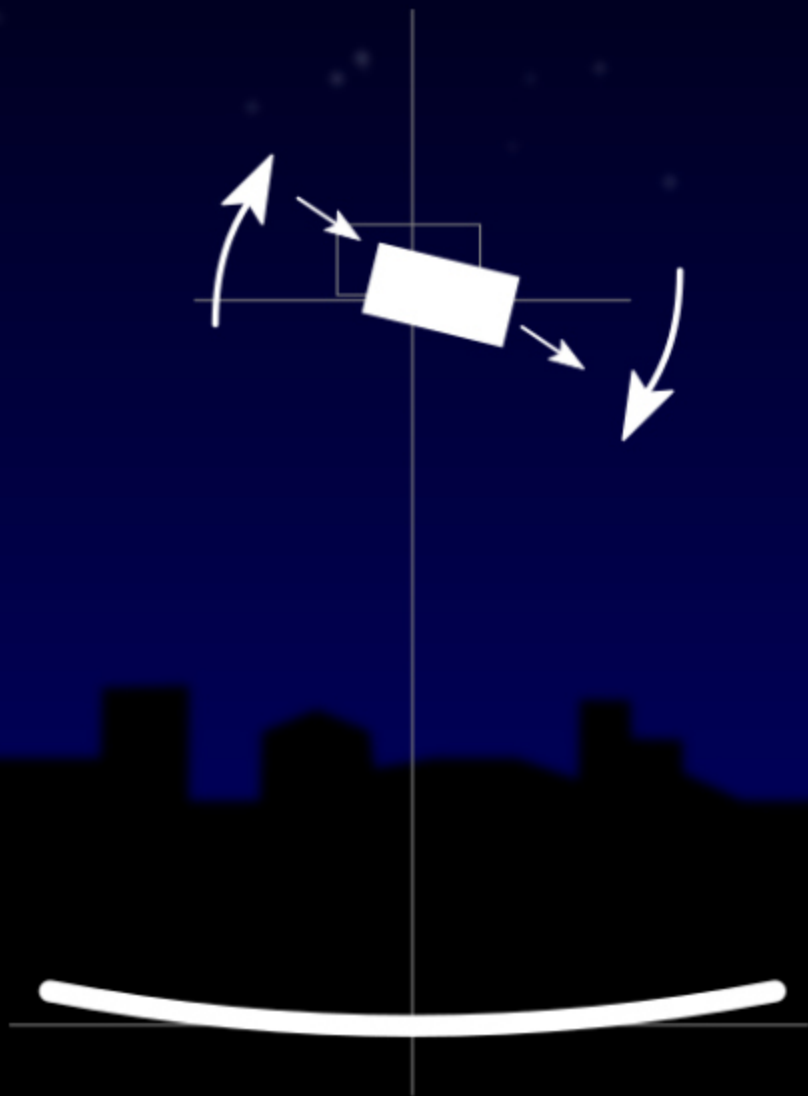
Optics

starlight performance



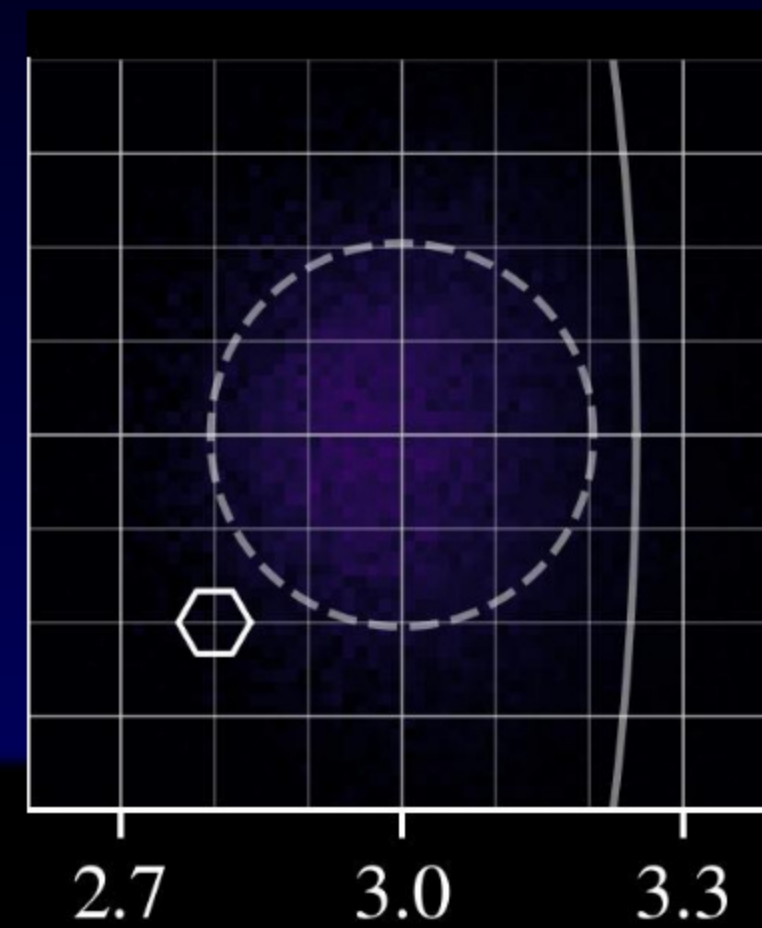
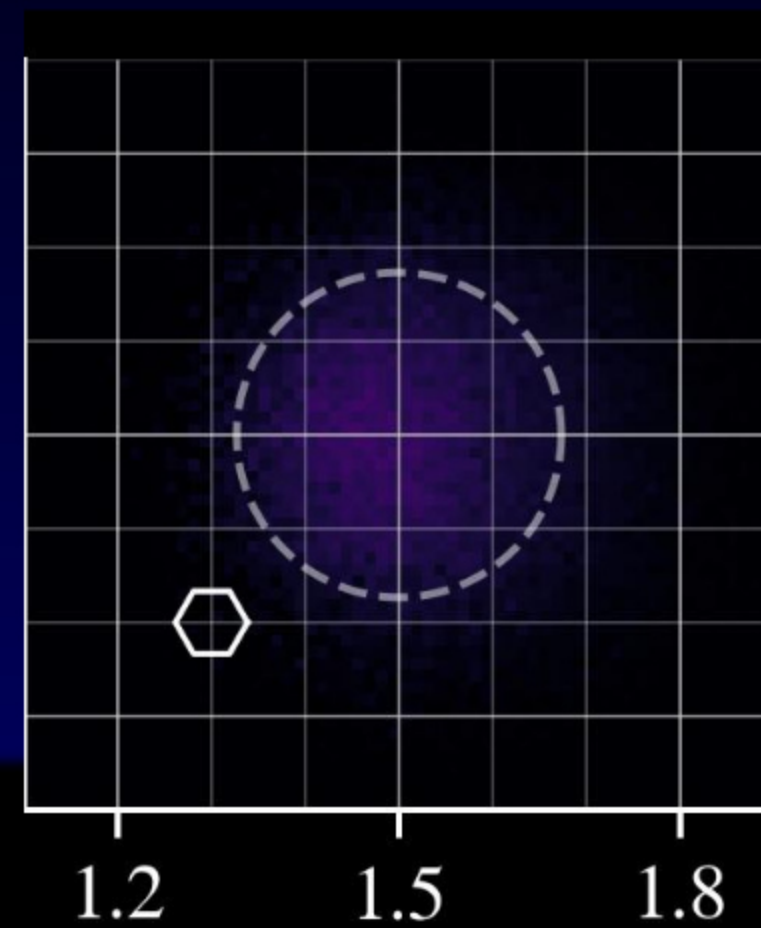
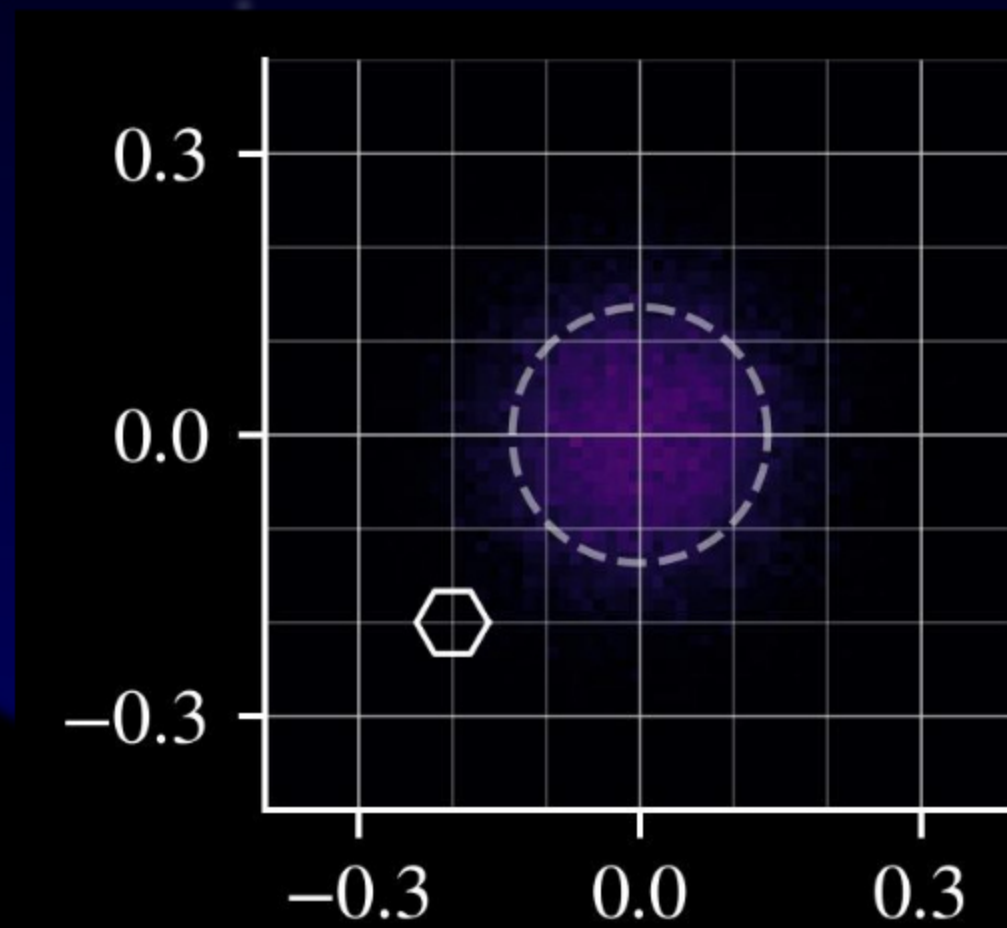
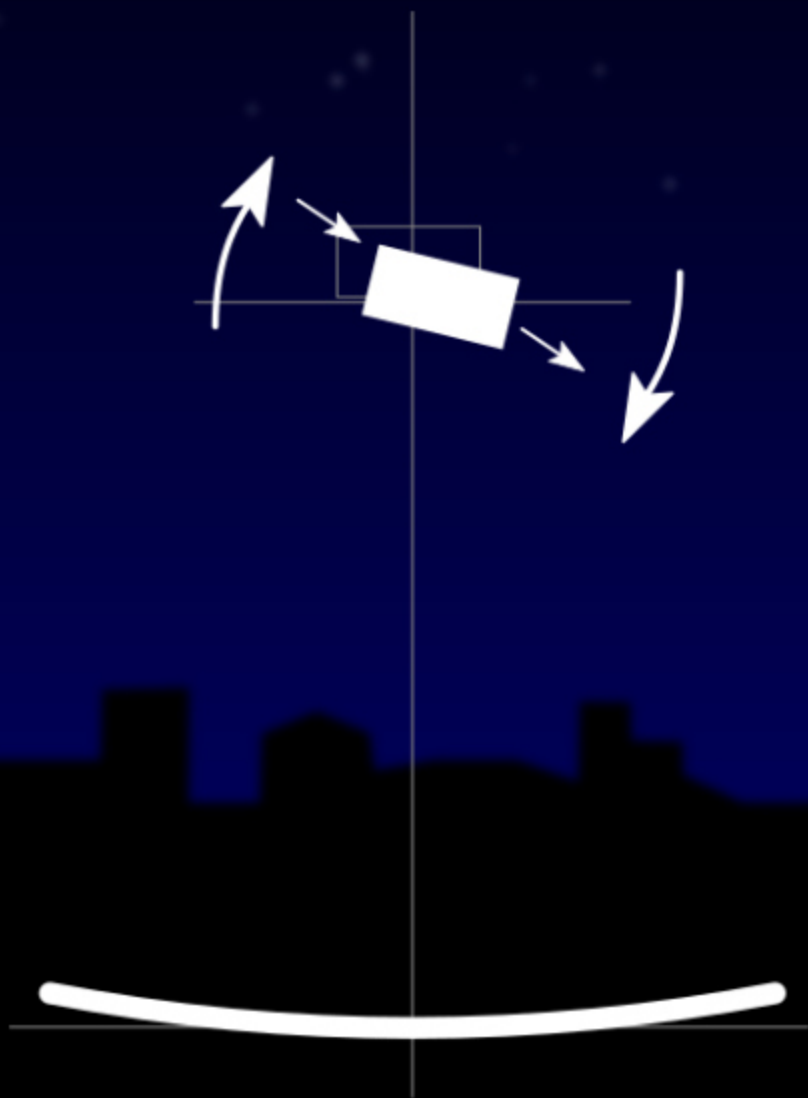
Optics

starlight performance



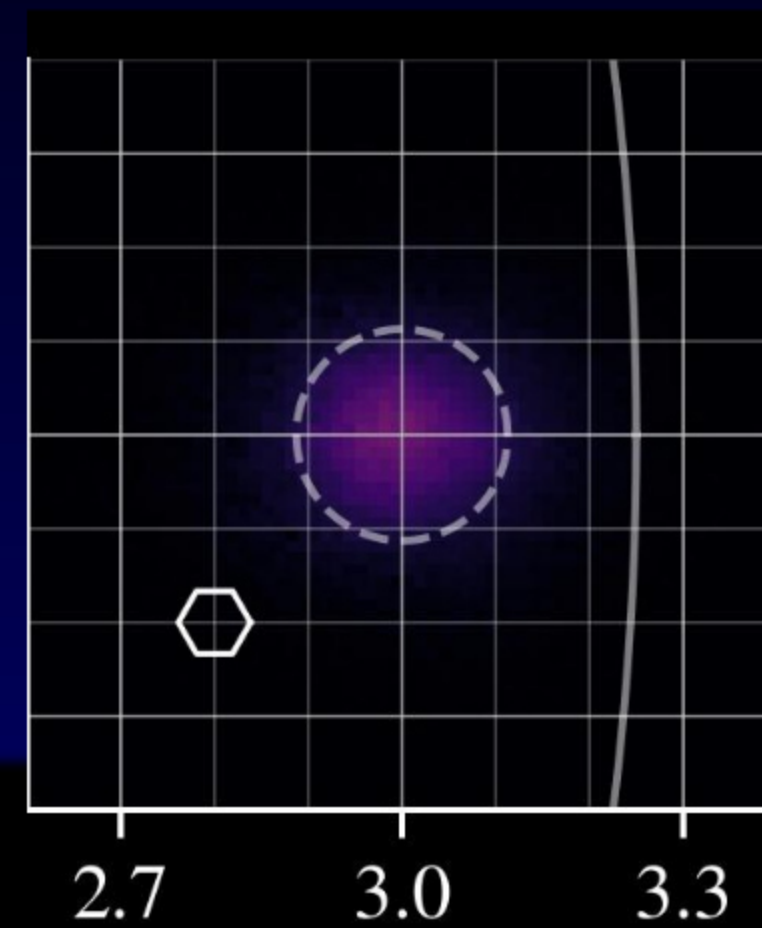
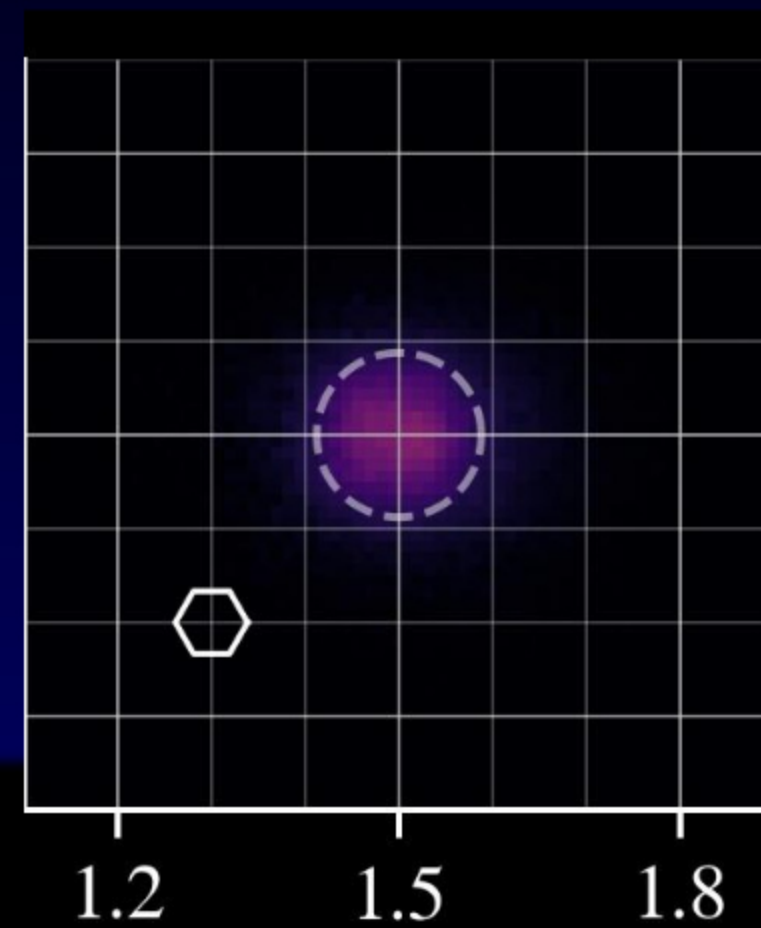
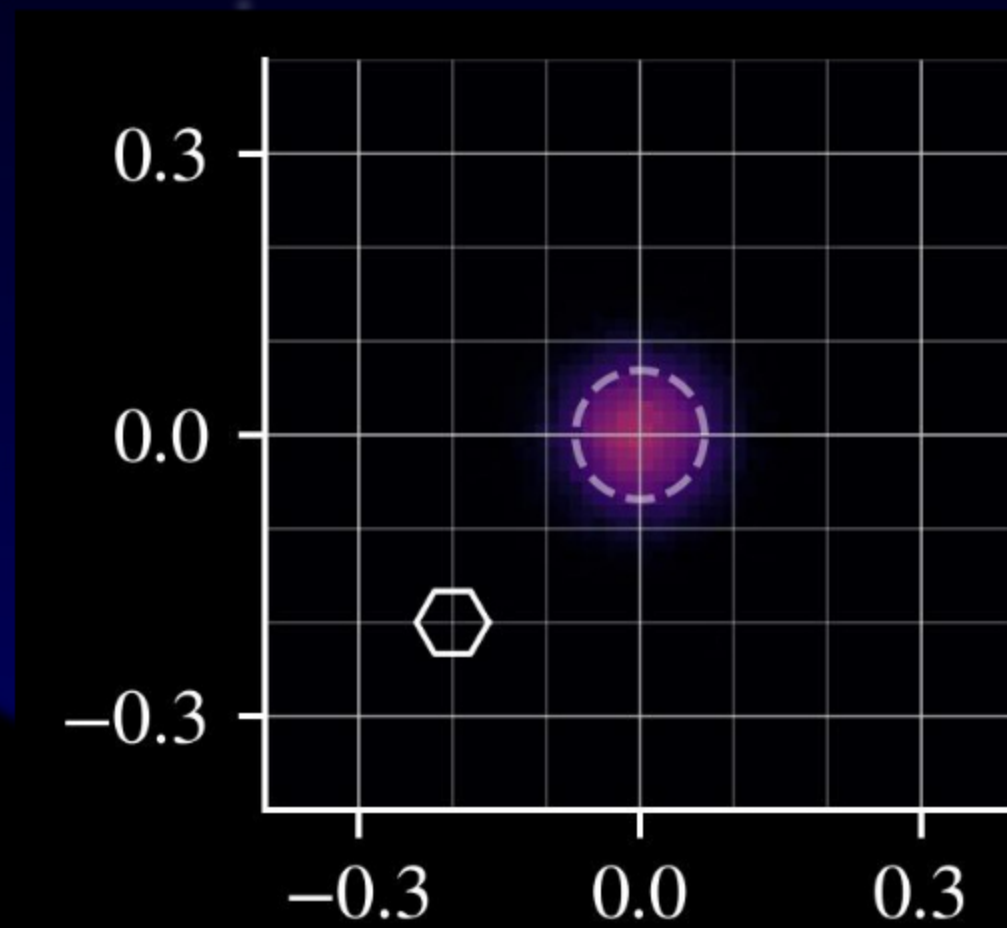
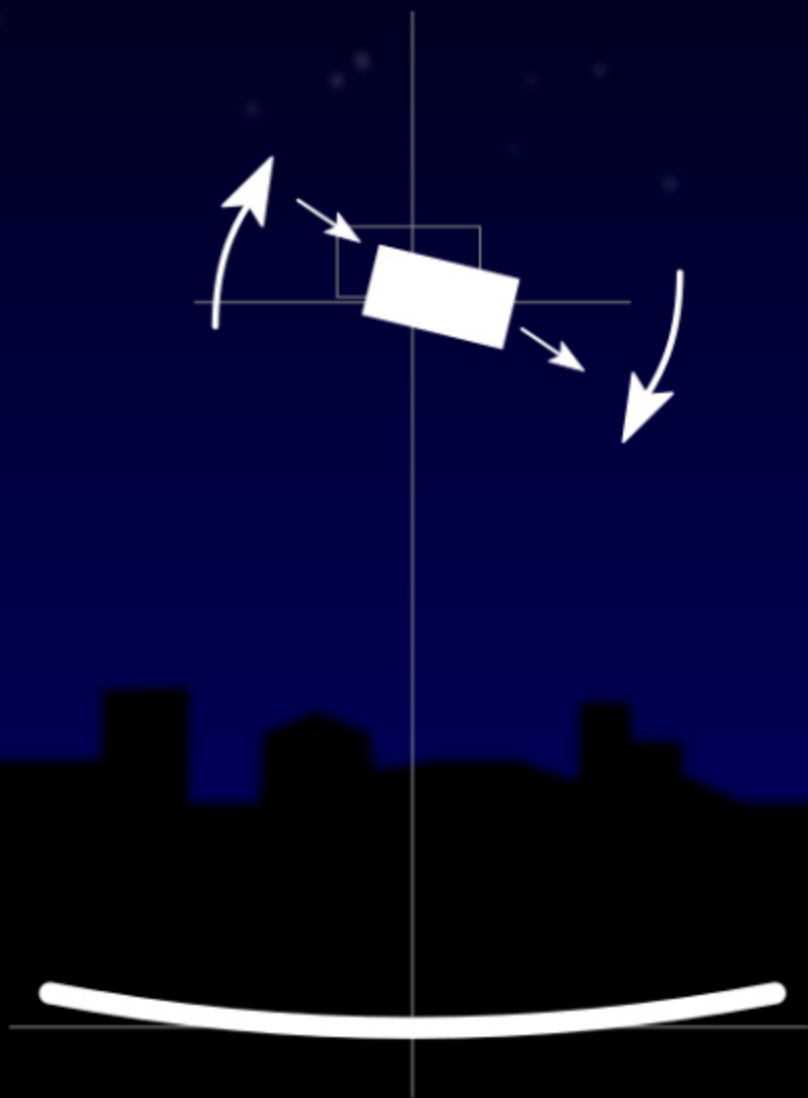
Optics

starlight performance



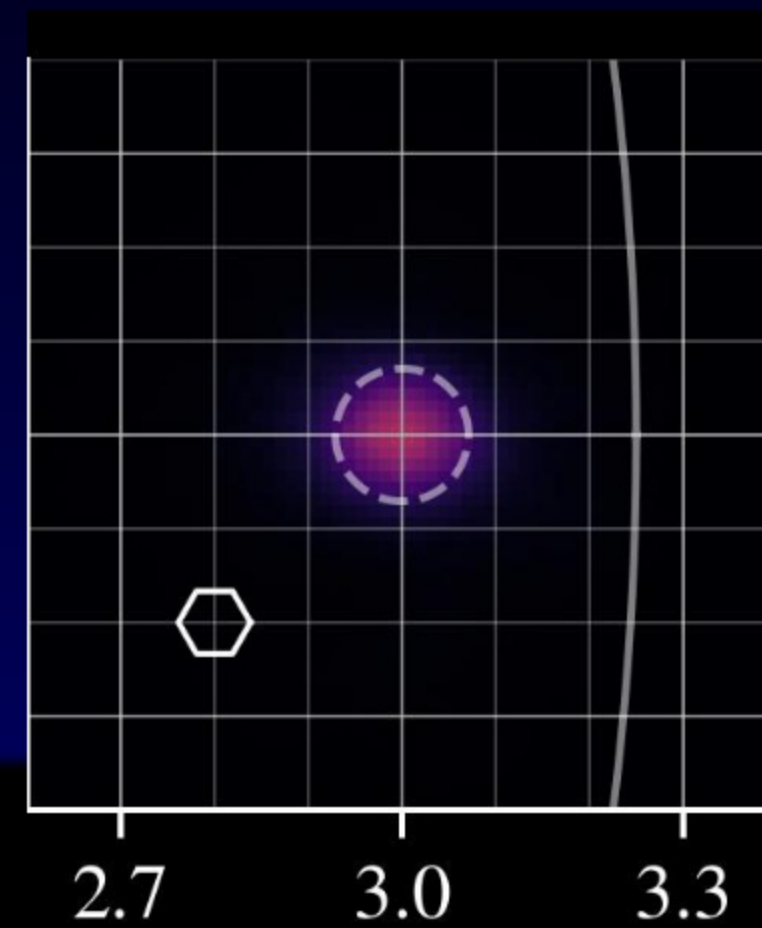
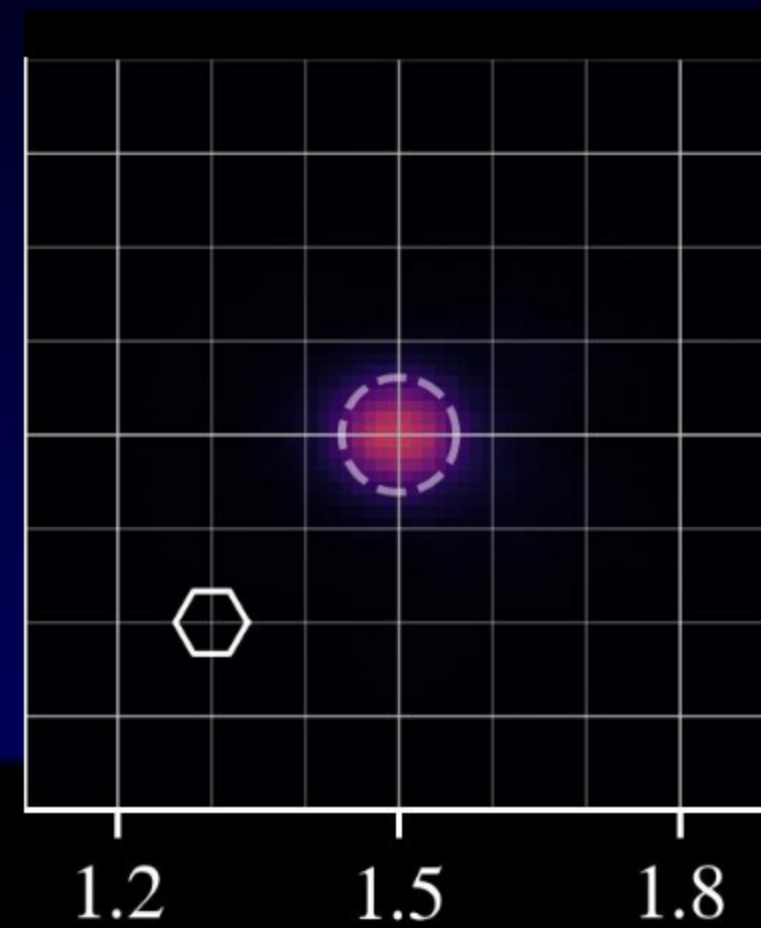
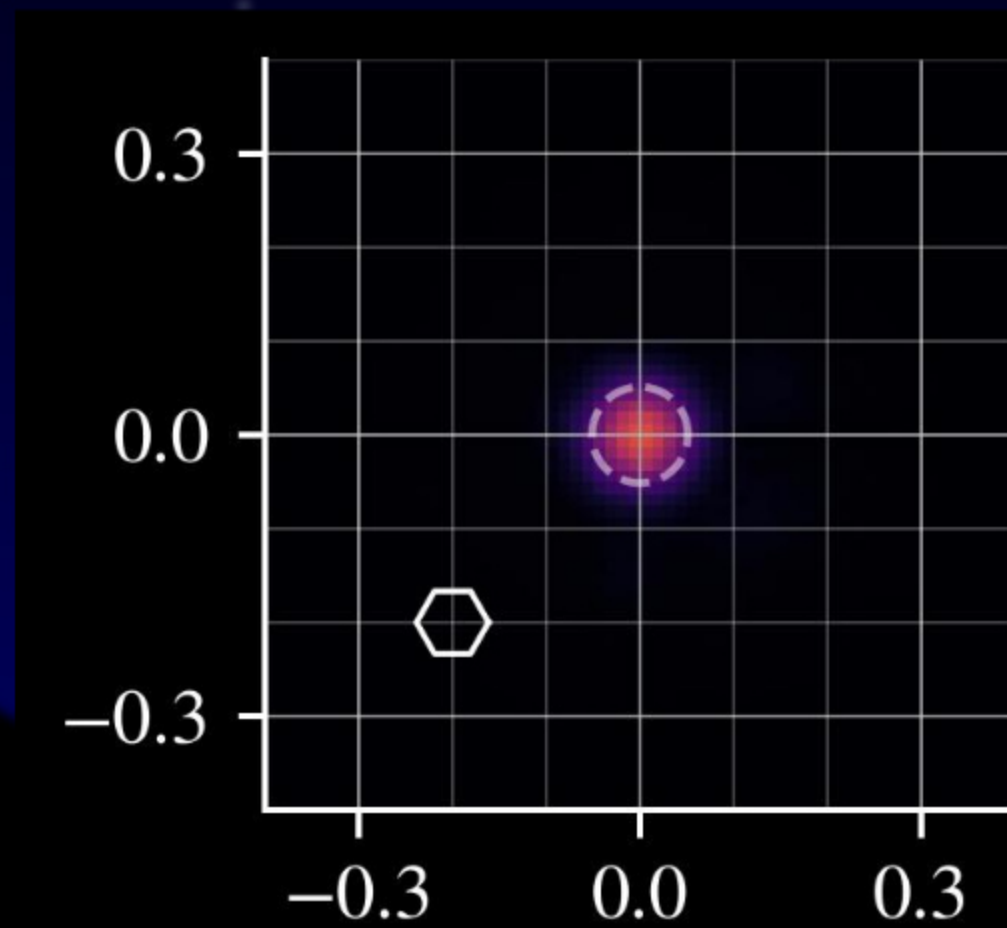
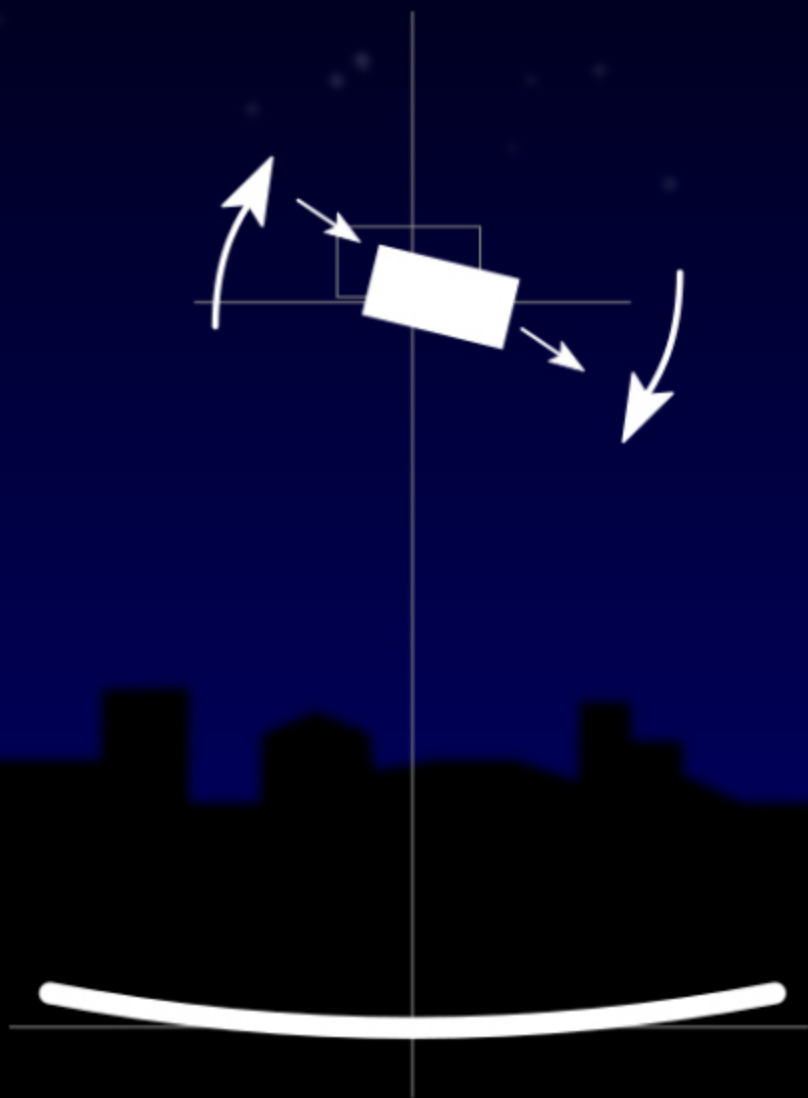
Optics

starlight performance



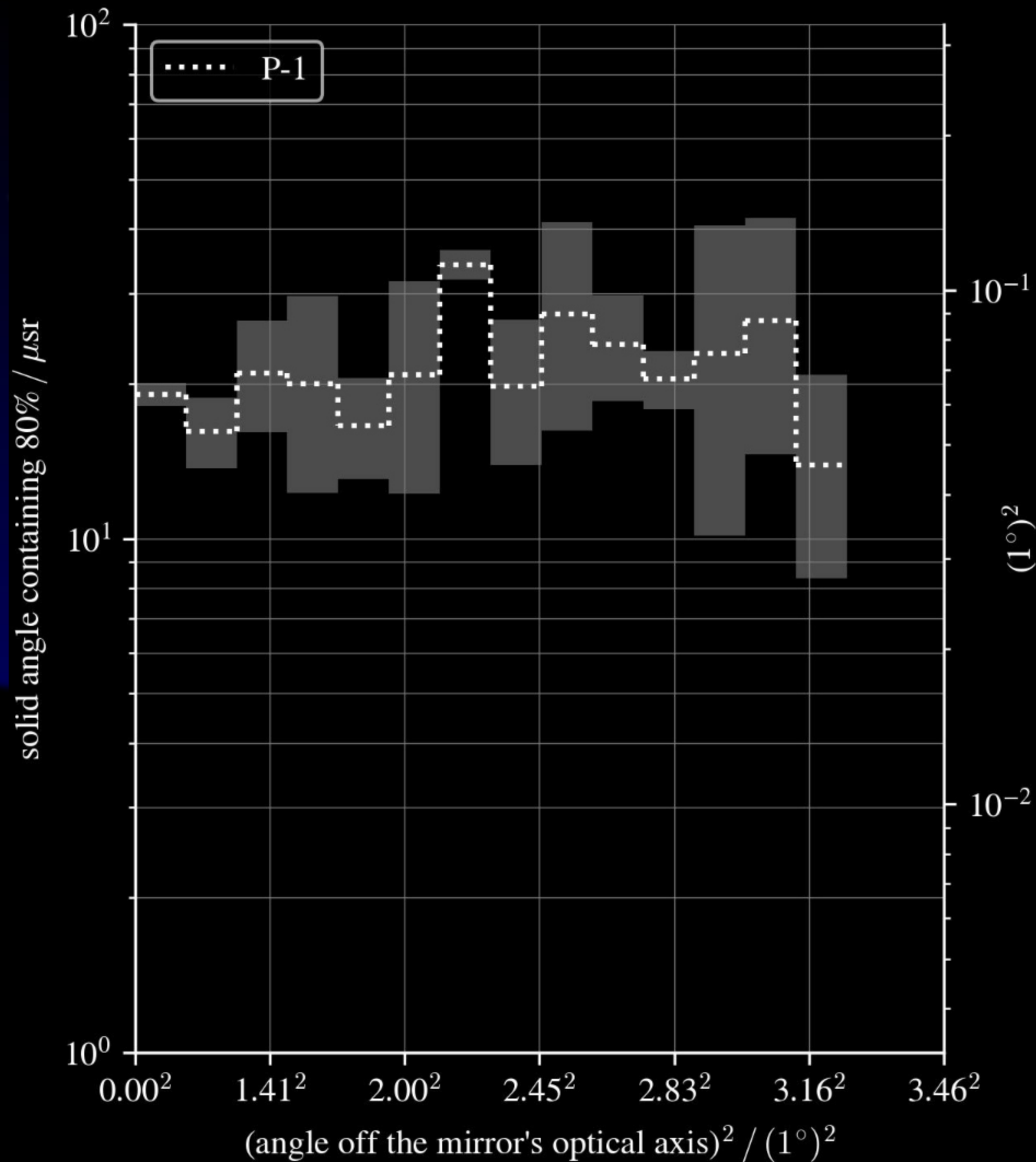
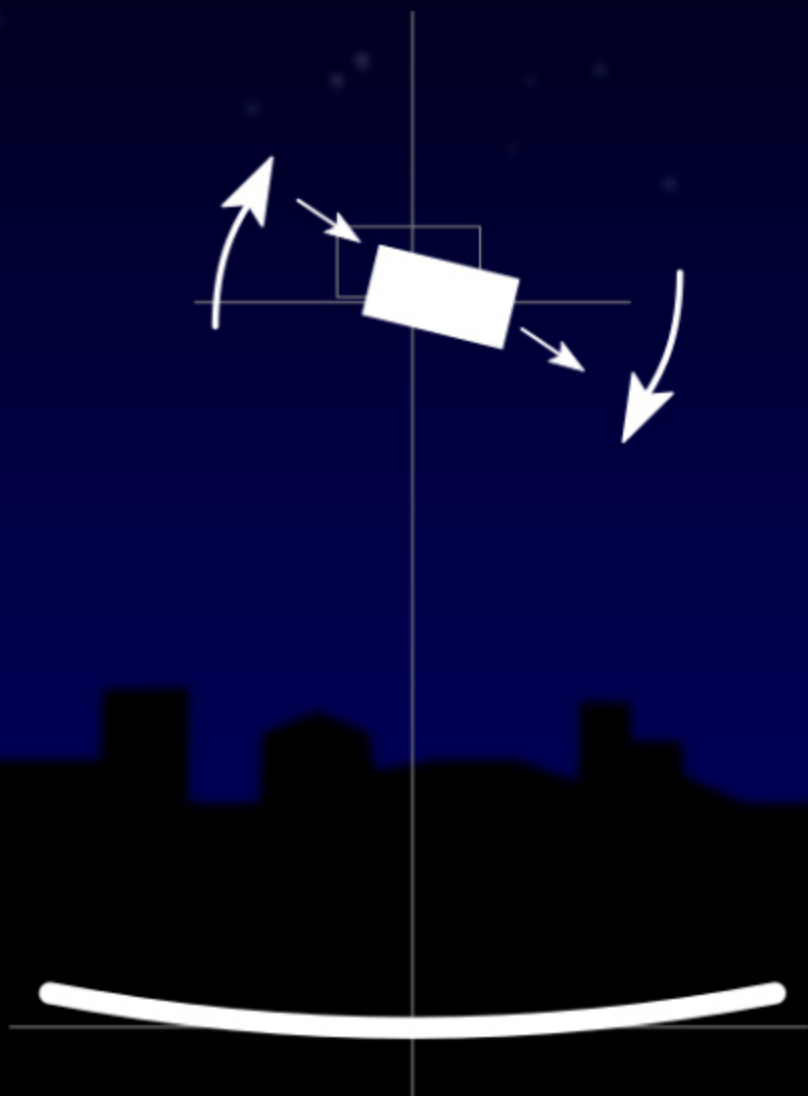
Optics

starlight performance



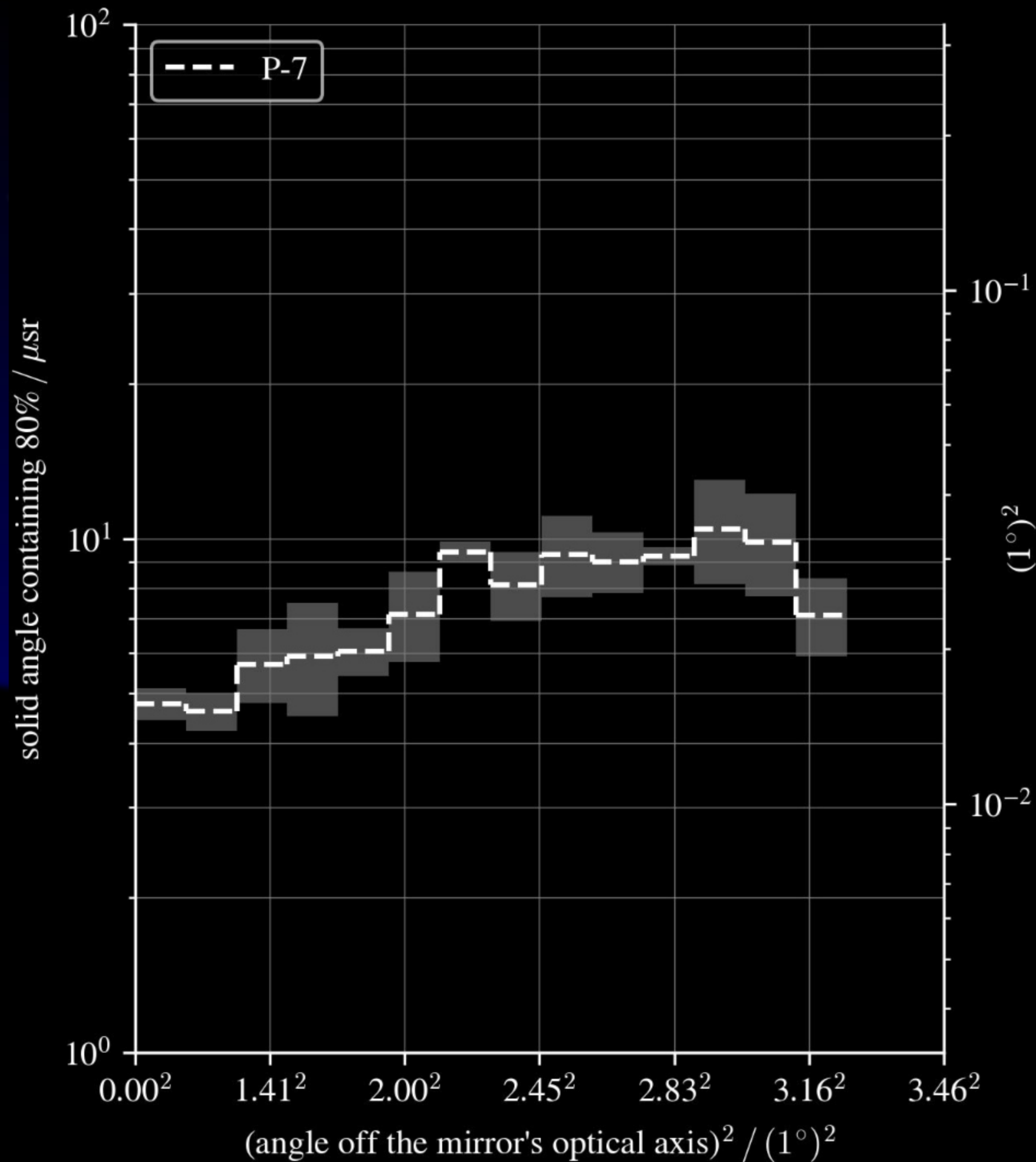
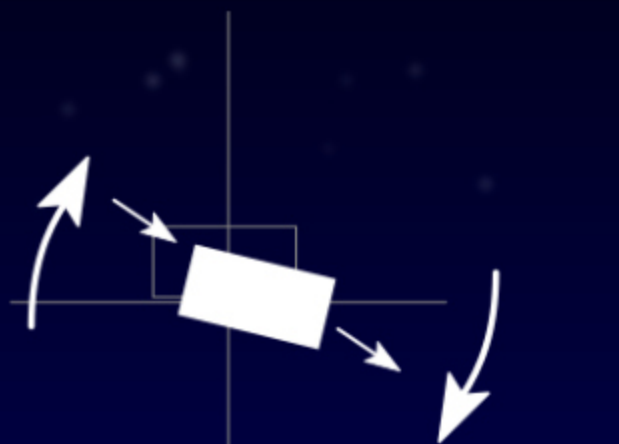
Optics

starlight performance



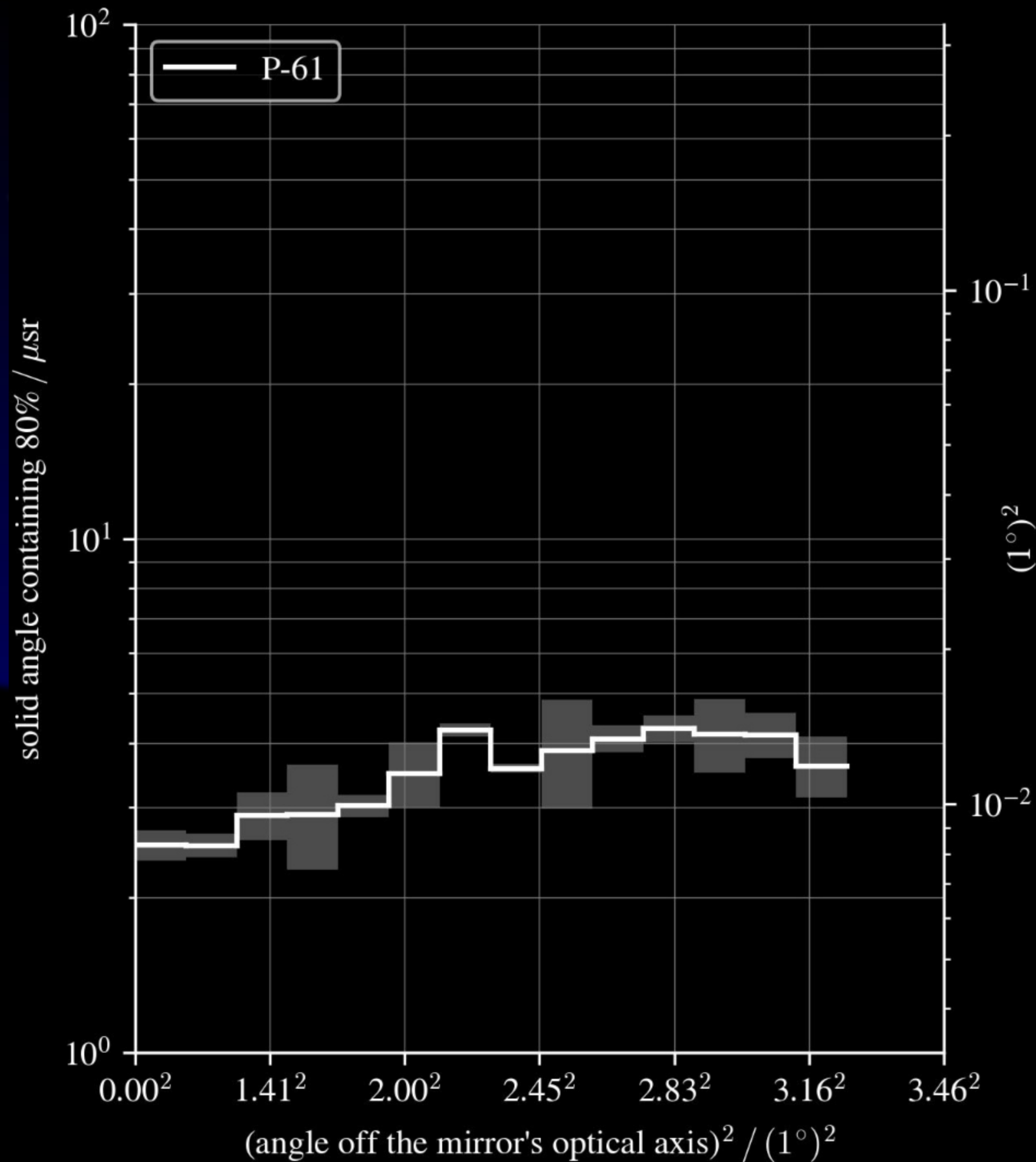
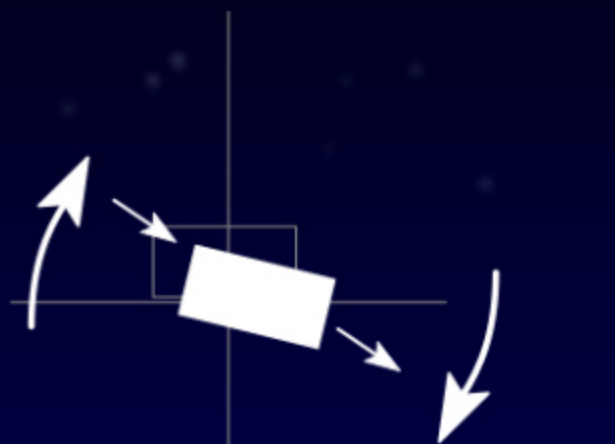
Optics

starlight performance



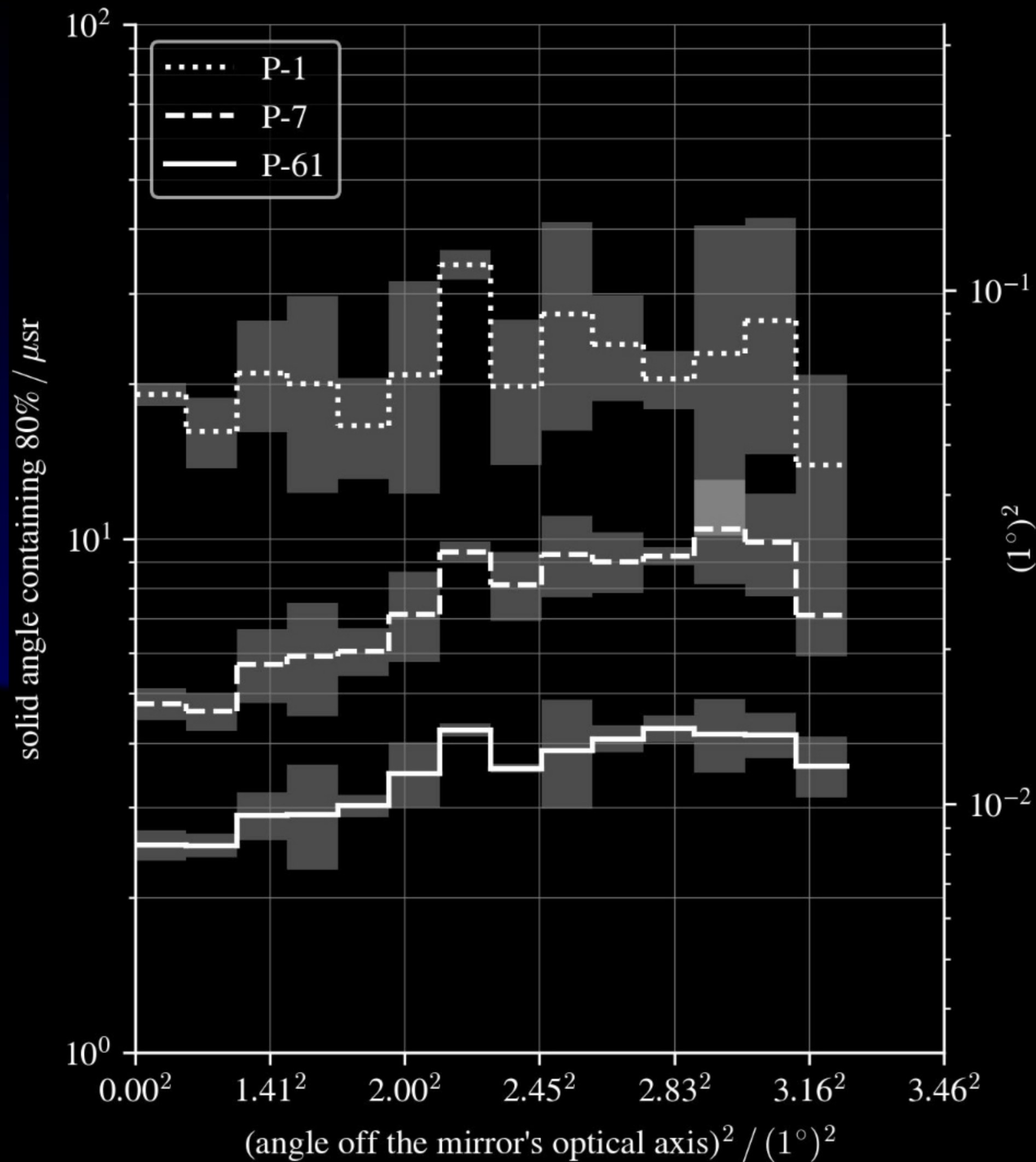
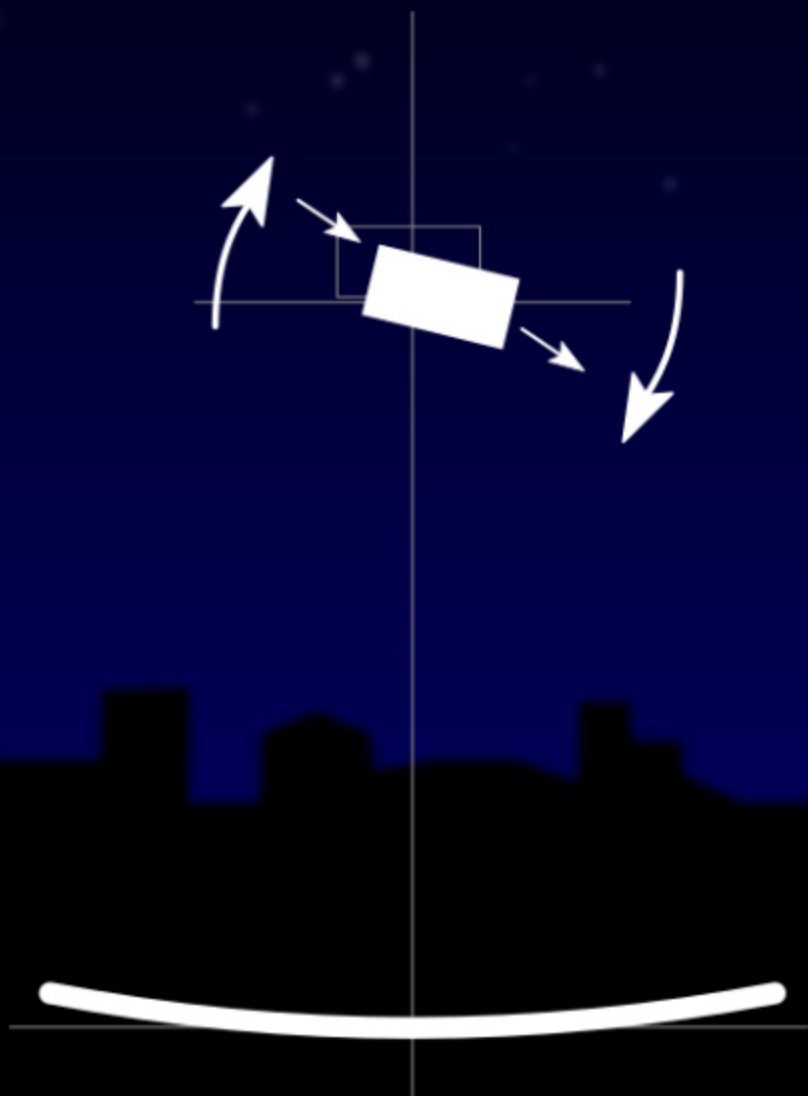
Optics

starlight performance



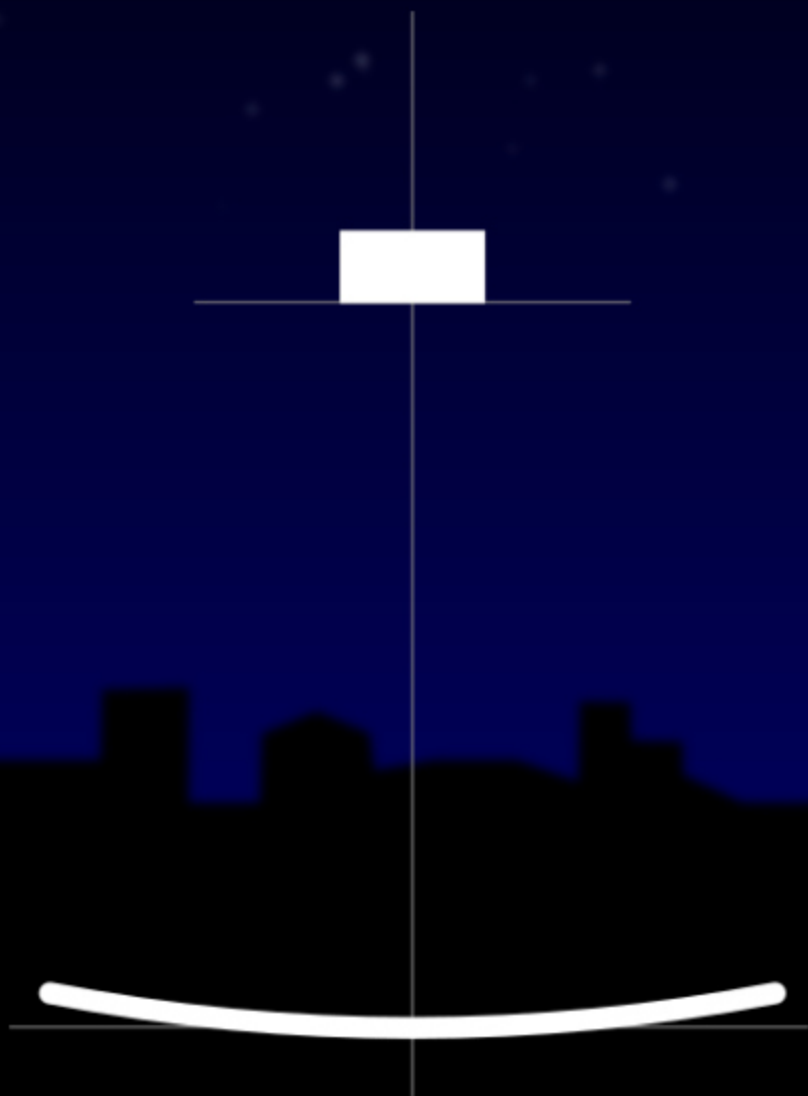
Optics

starlight performance



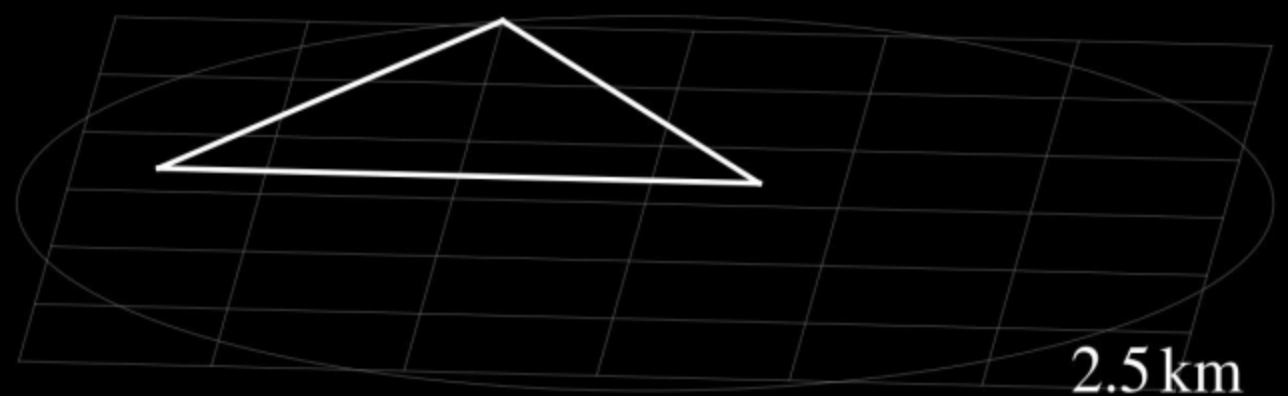
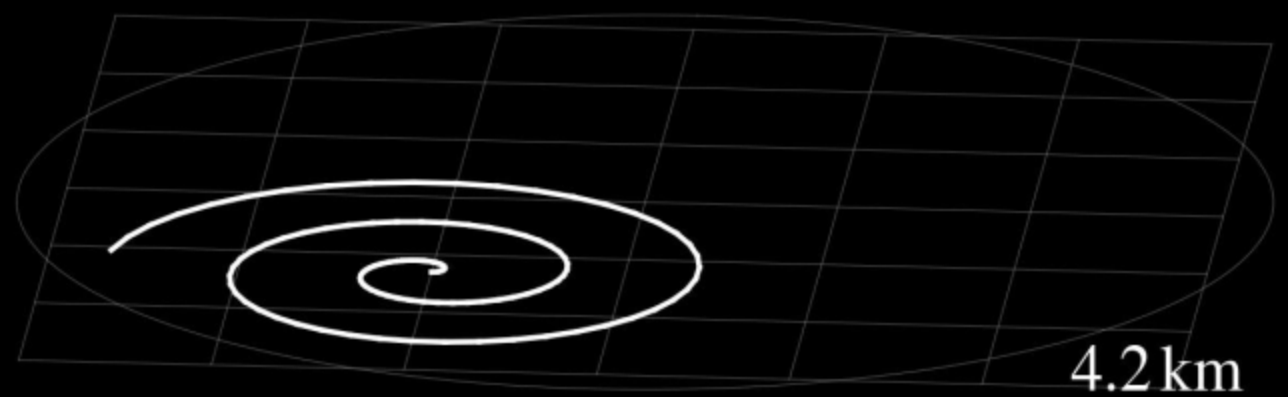
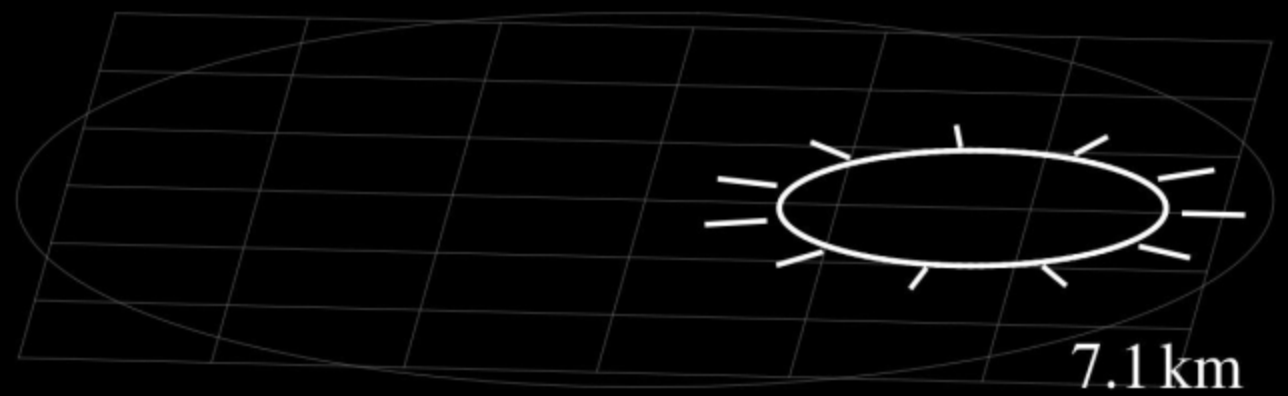
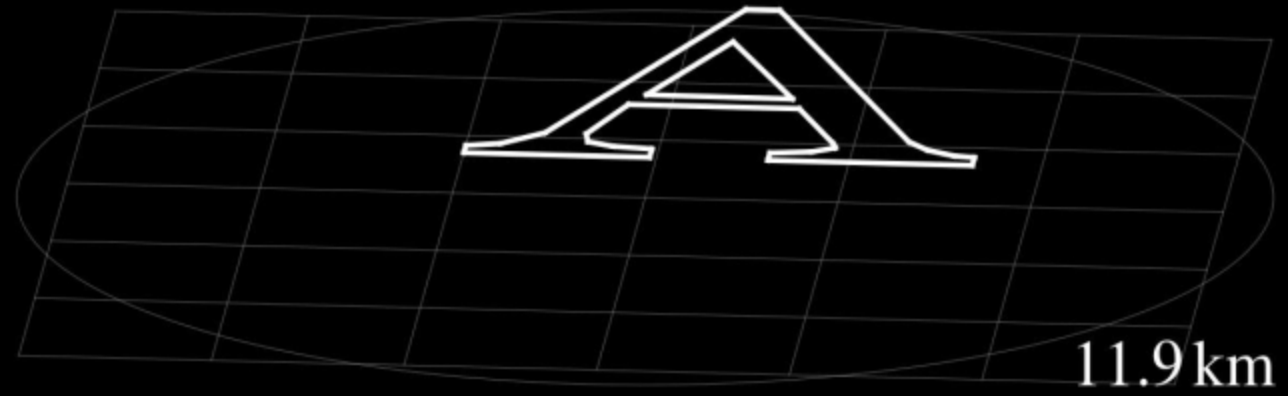
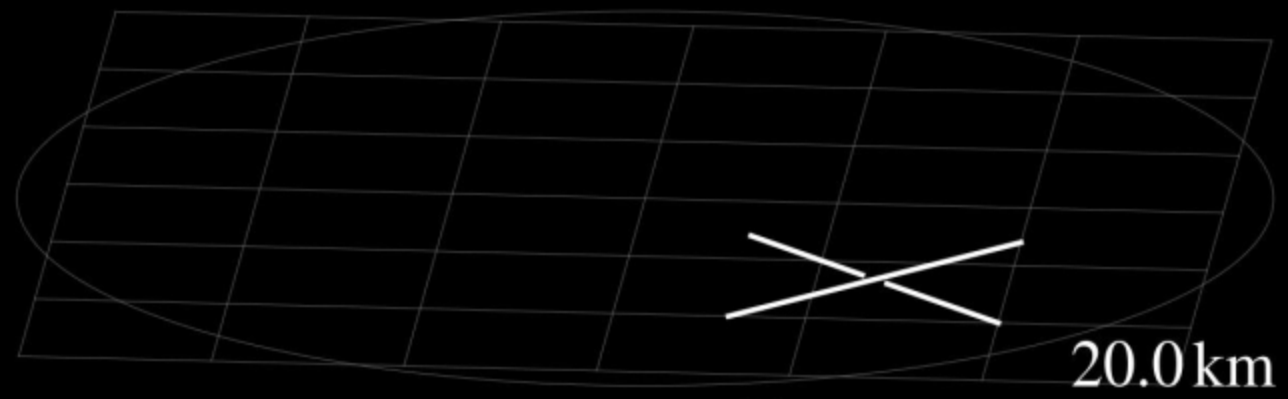
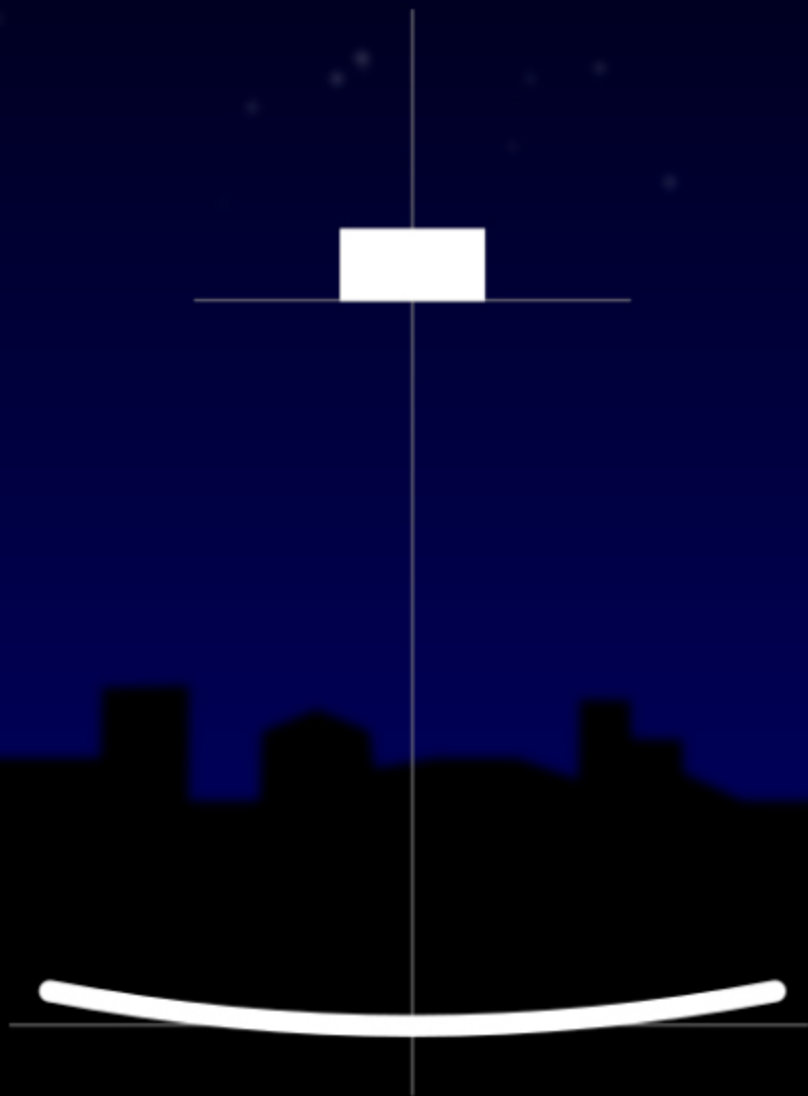
Optics

refocussing to any depth



Optics

refocussing to any depth

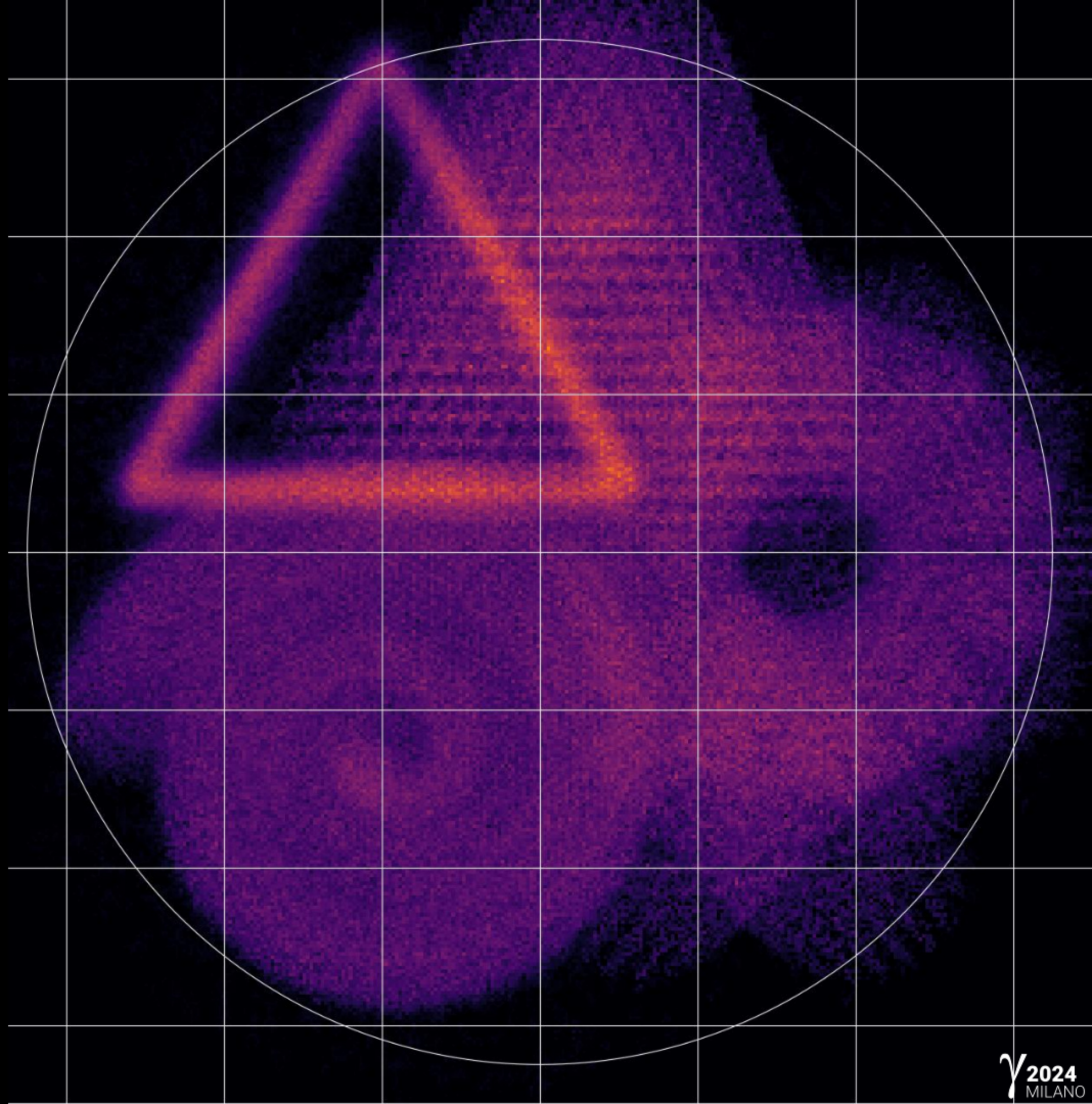
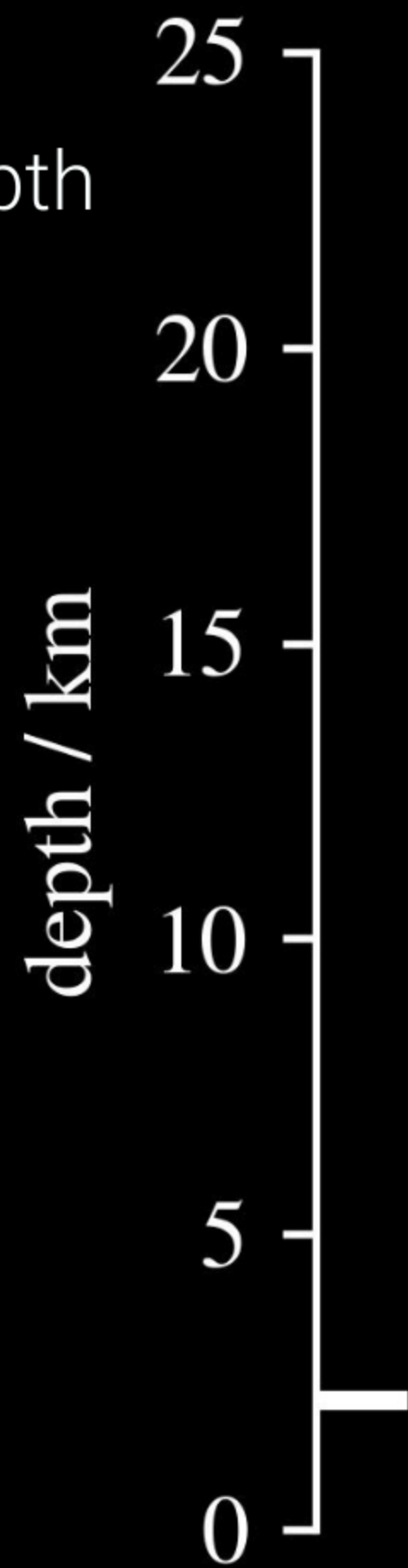


phantom in atmosphere



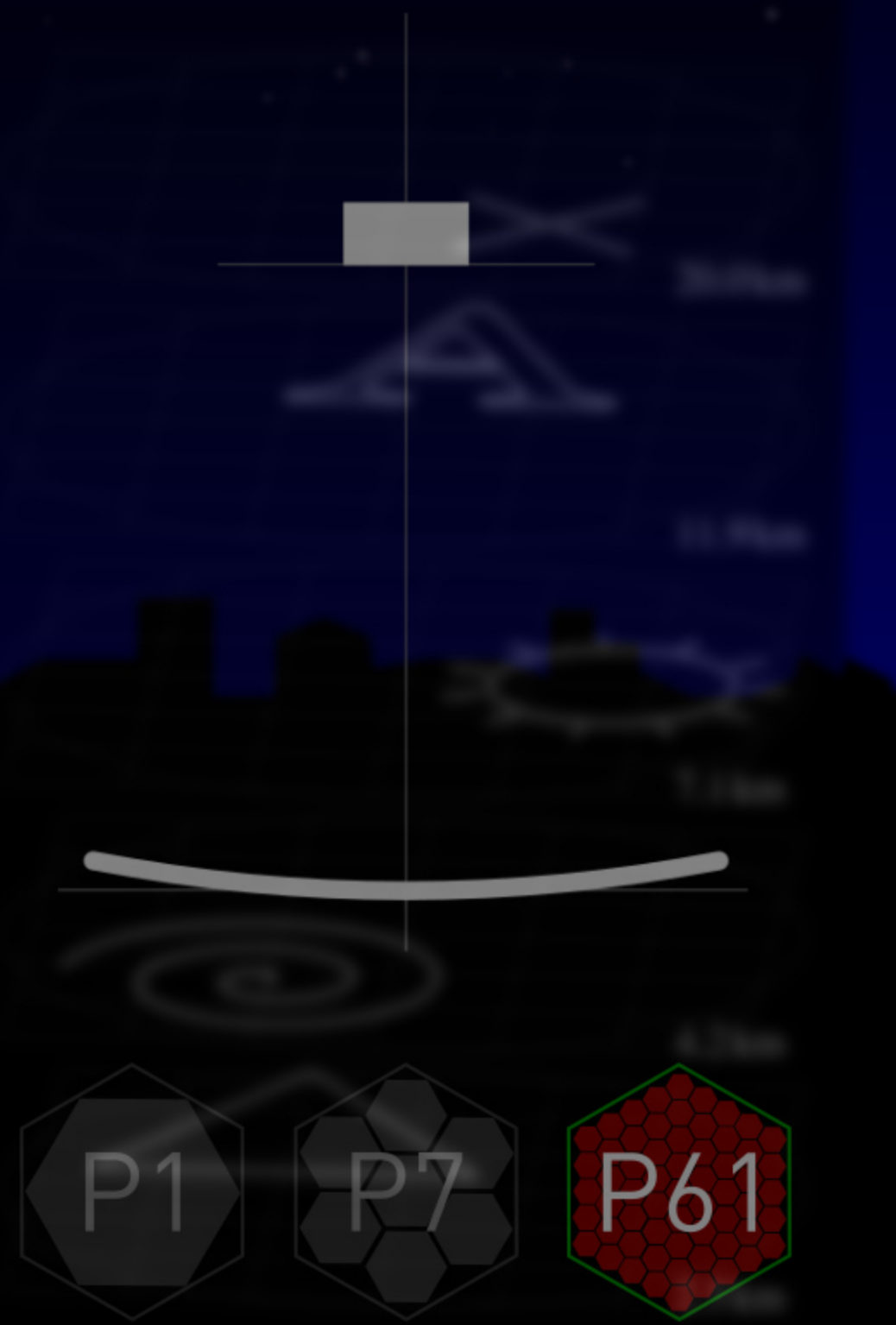
Optics

refocussing to any depth

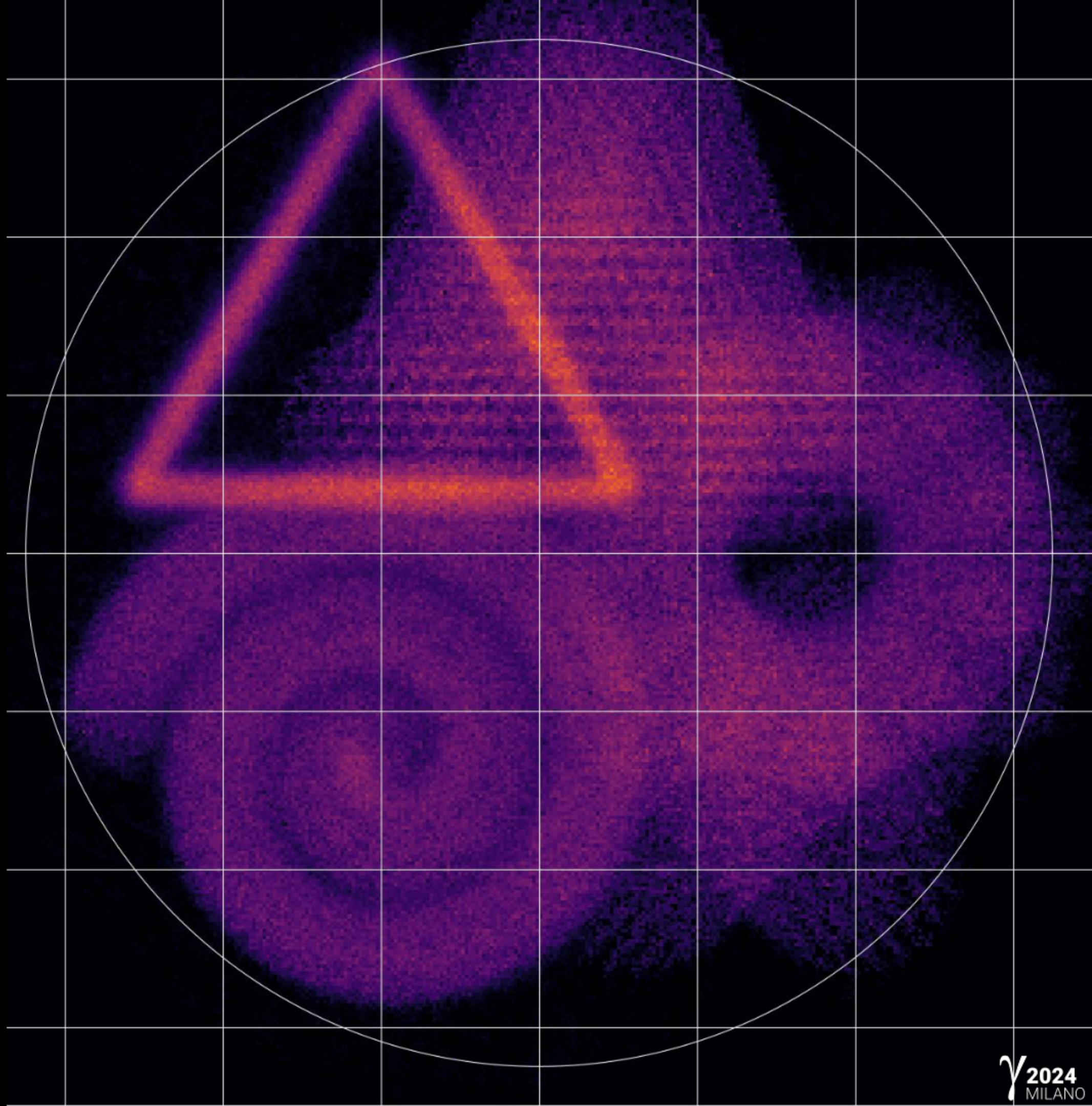
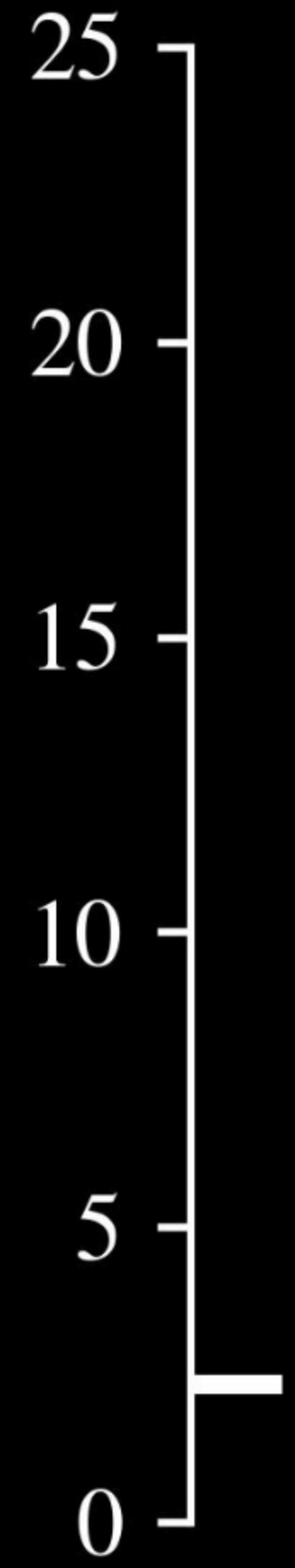


Optics

refocussing to any depth

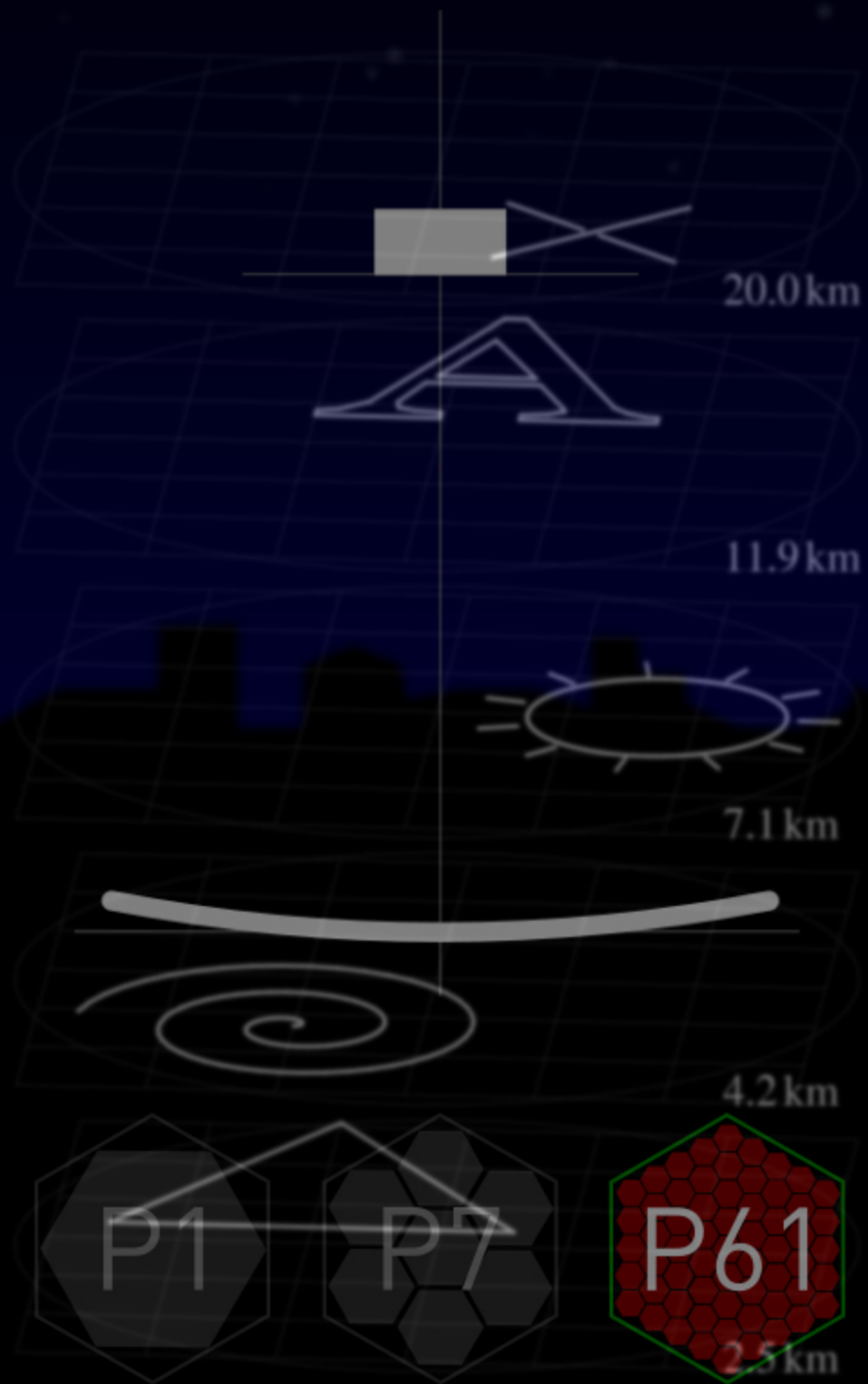


depth / km

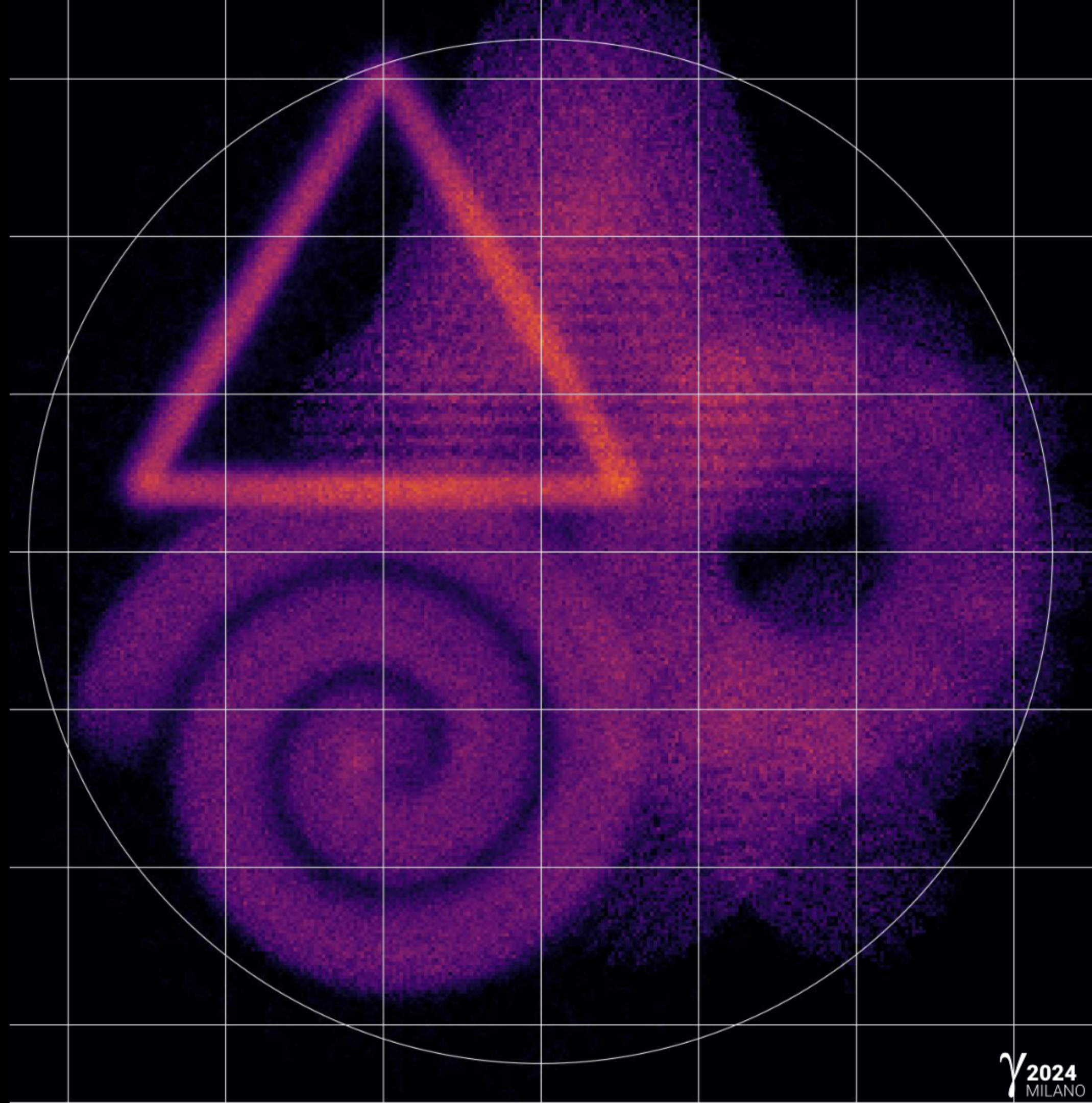
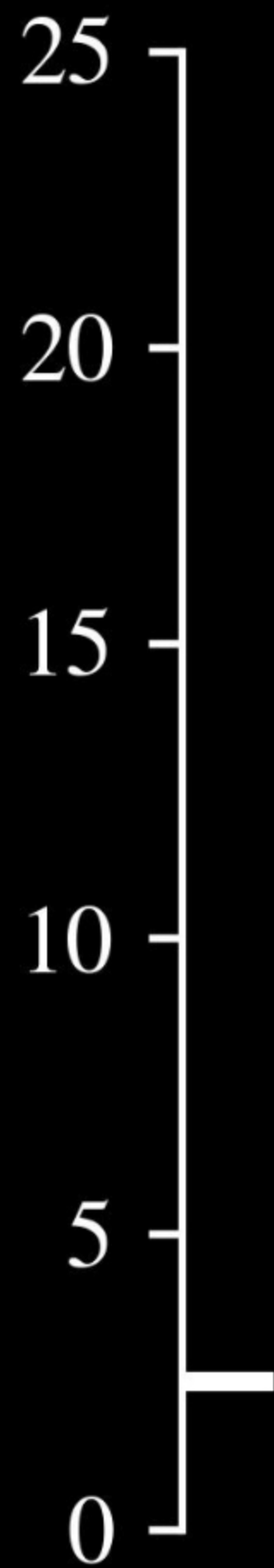


Optics

refocussing to any depth

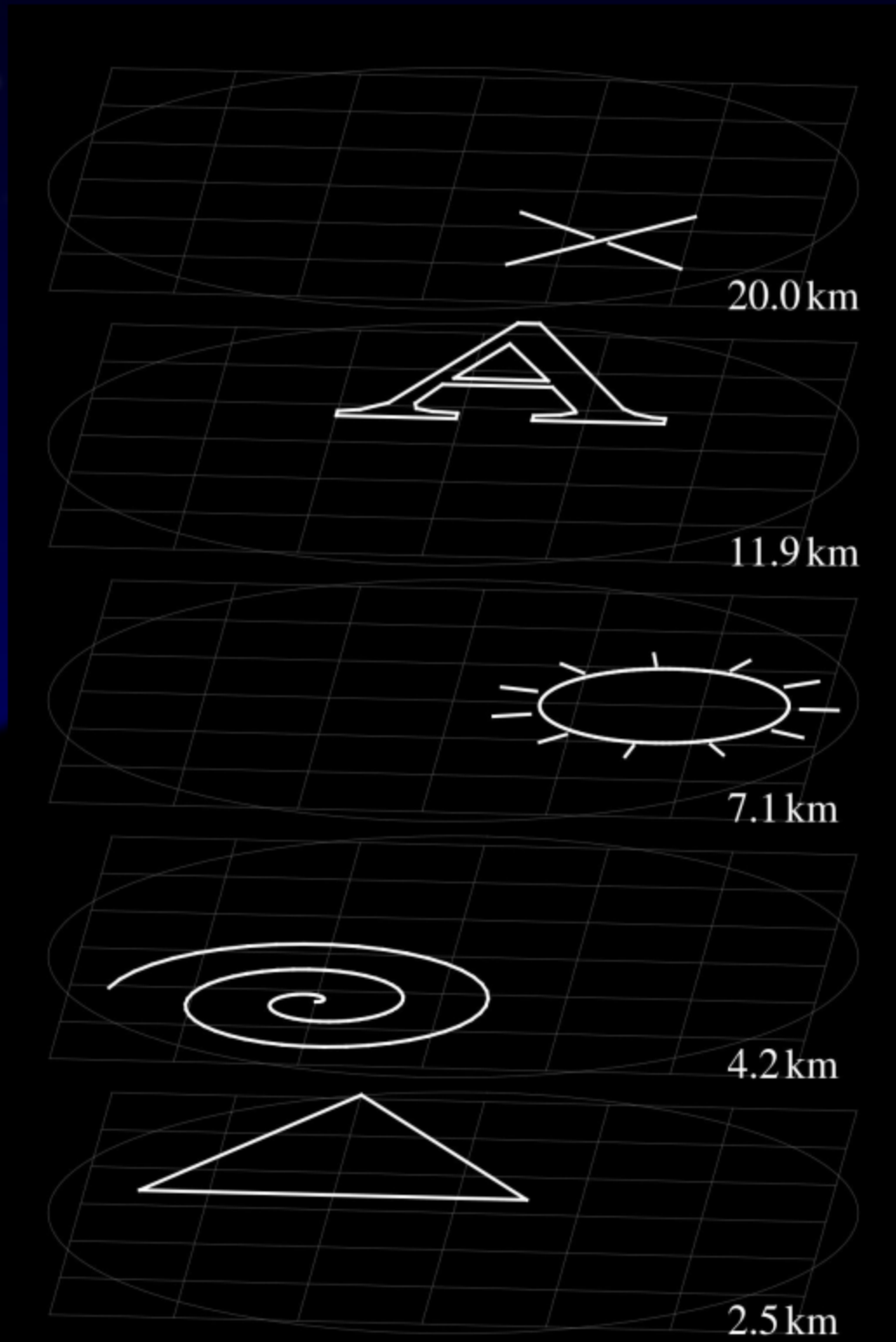


depth / km

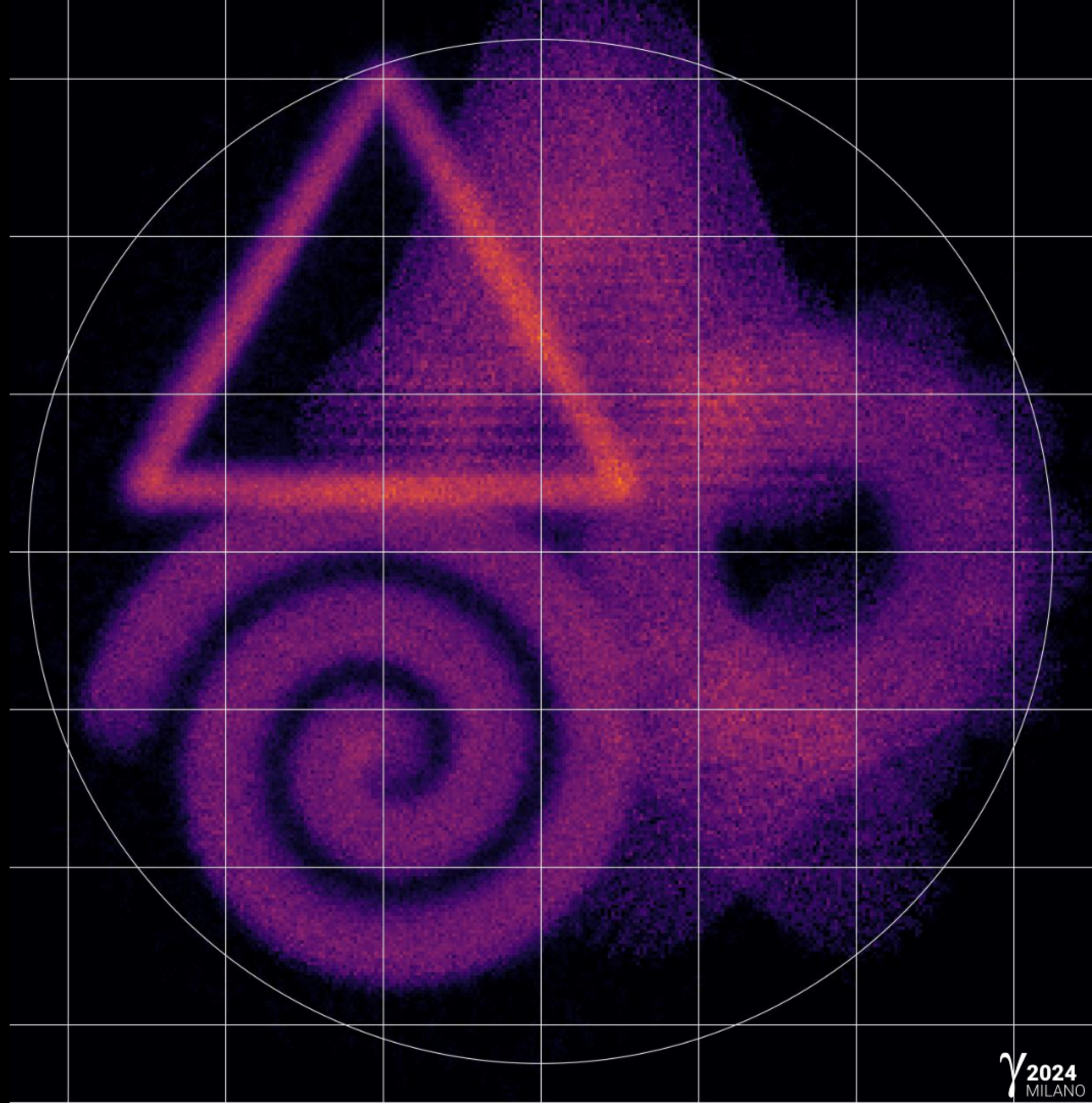
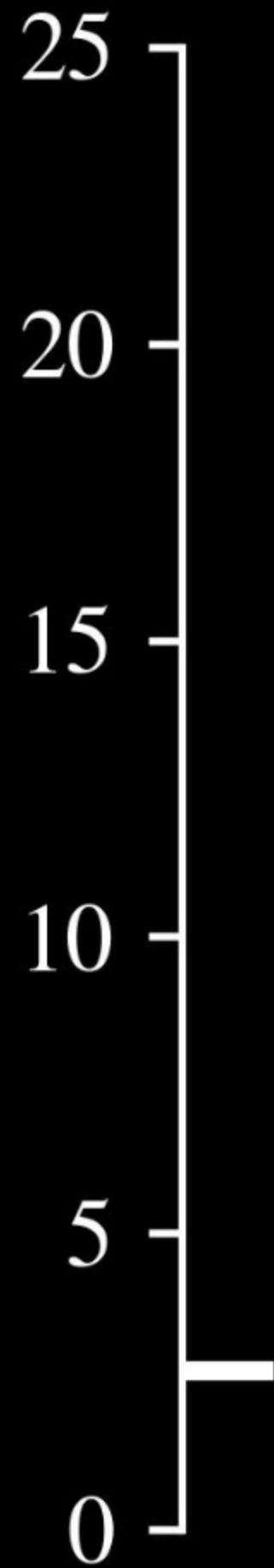


Optics

refocussing to any depth

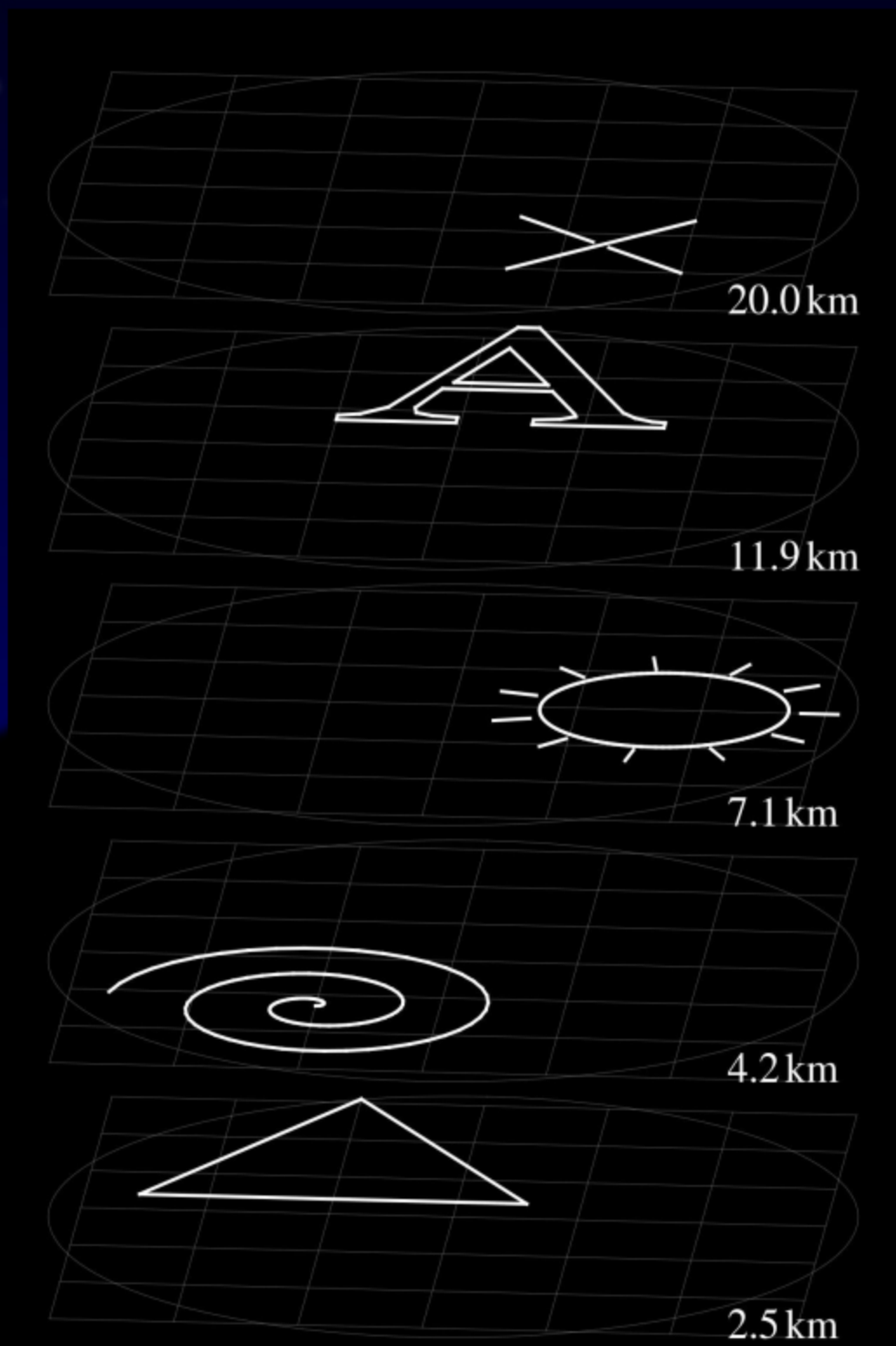


depth / km

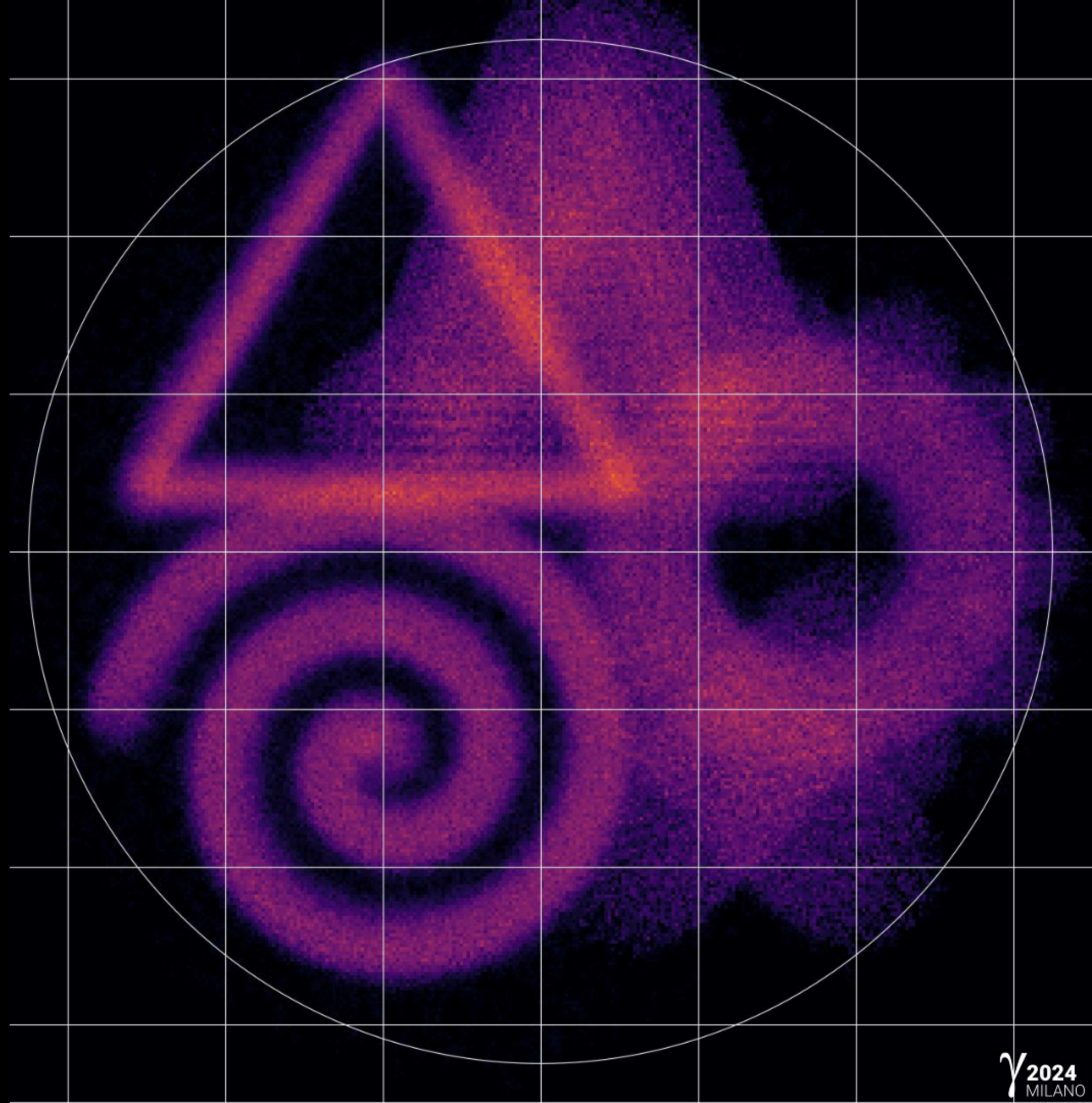
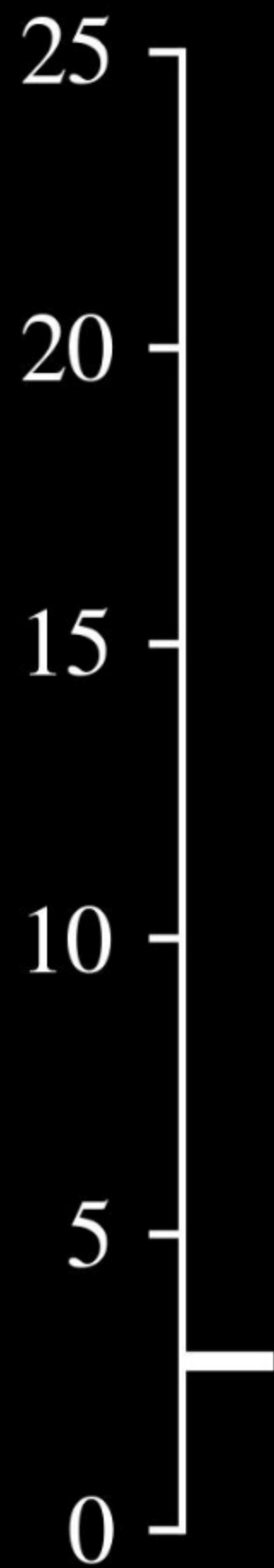


Optics

refocussing to any depth

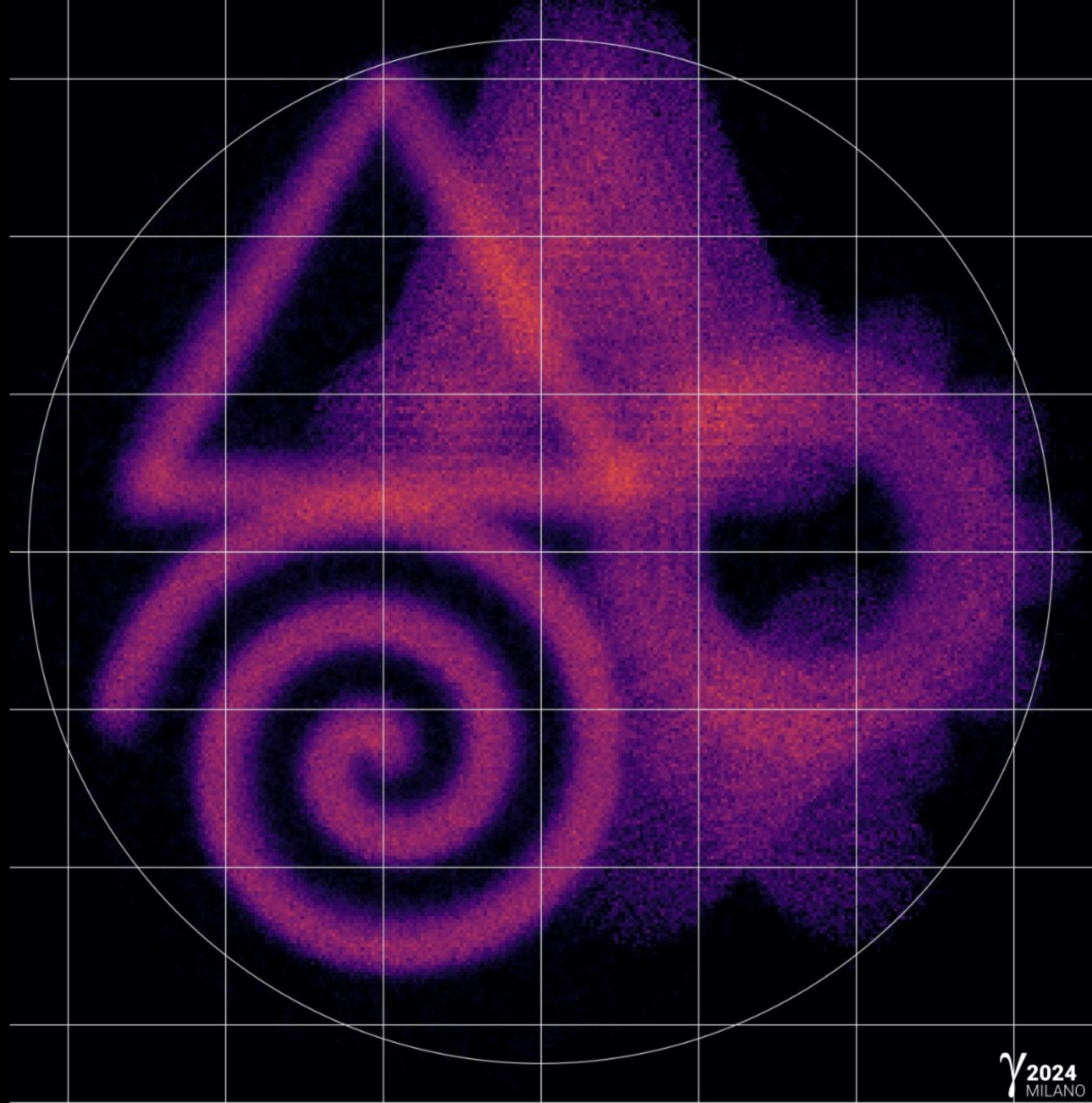
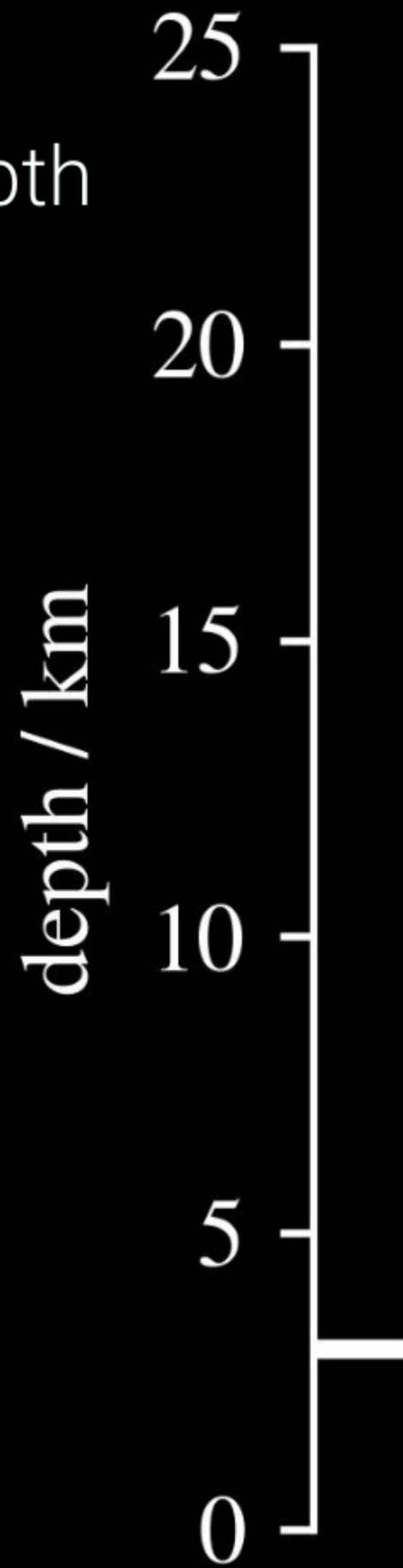
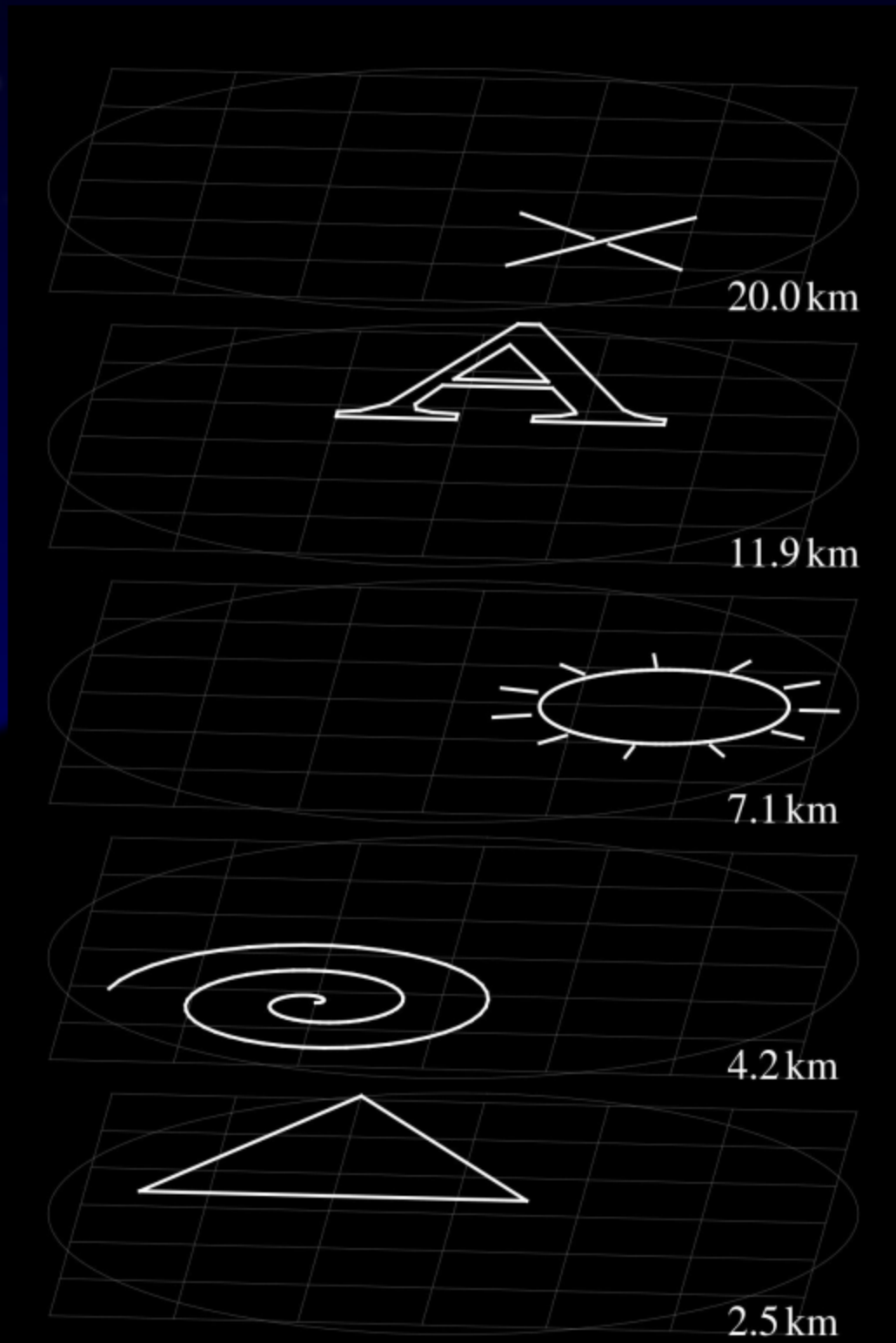


depth / km



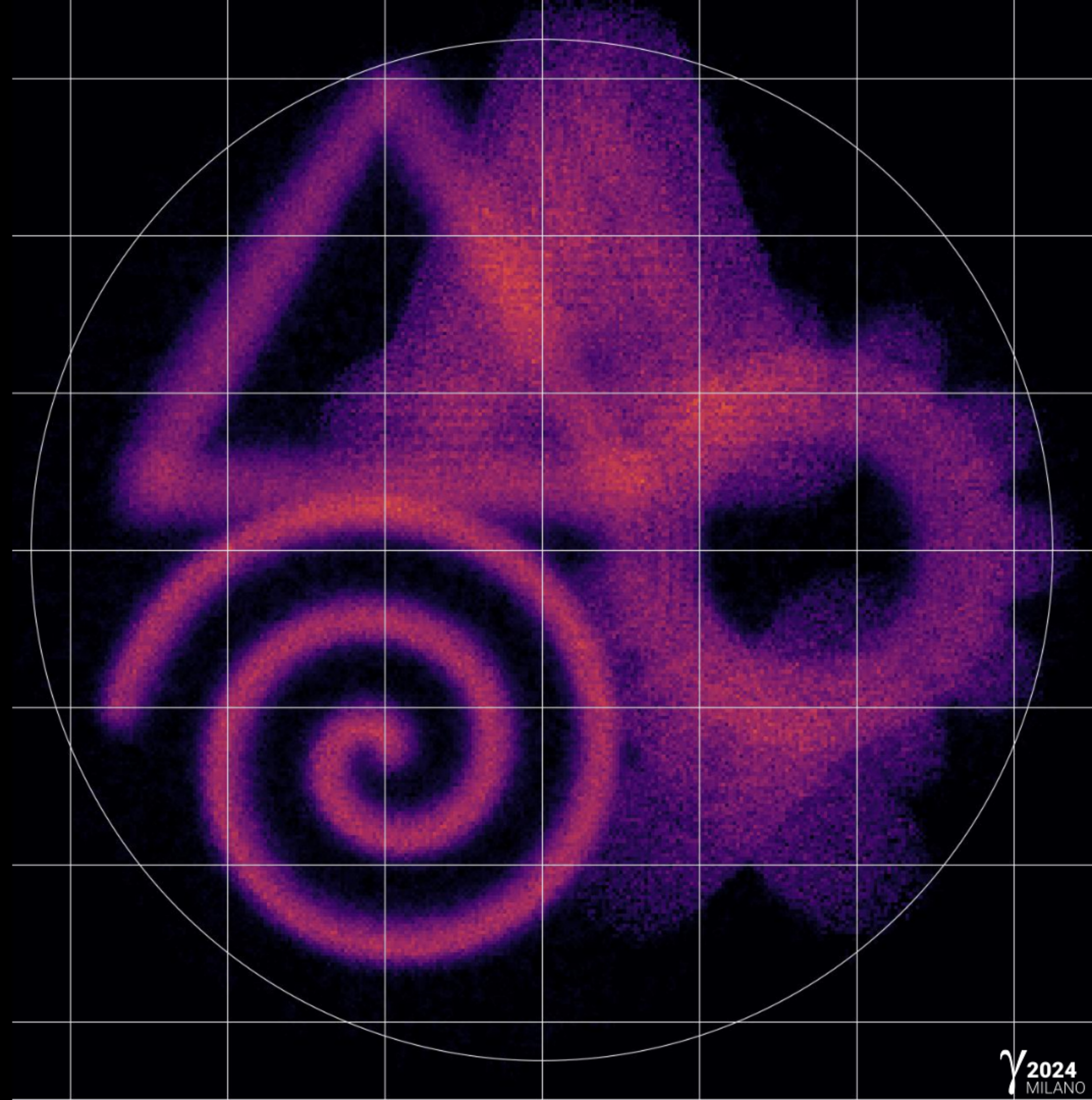
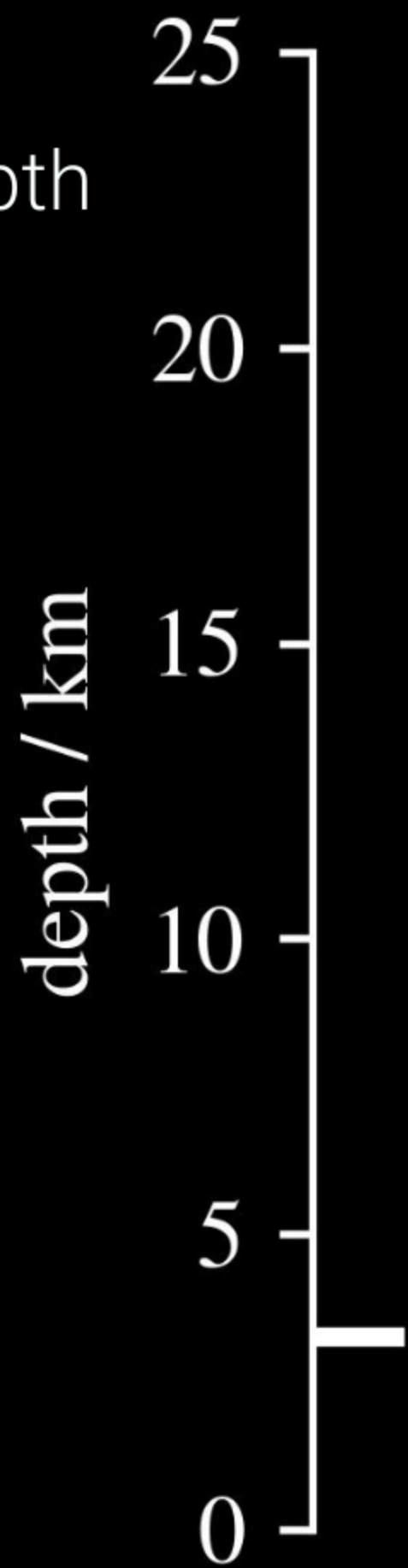
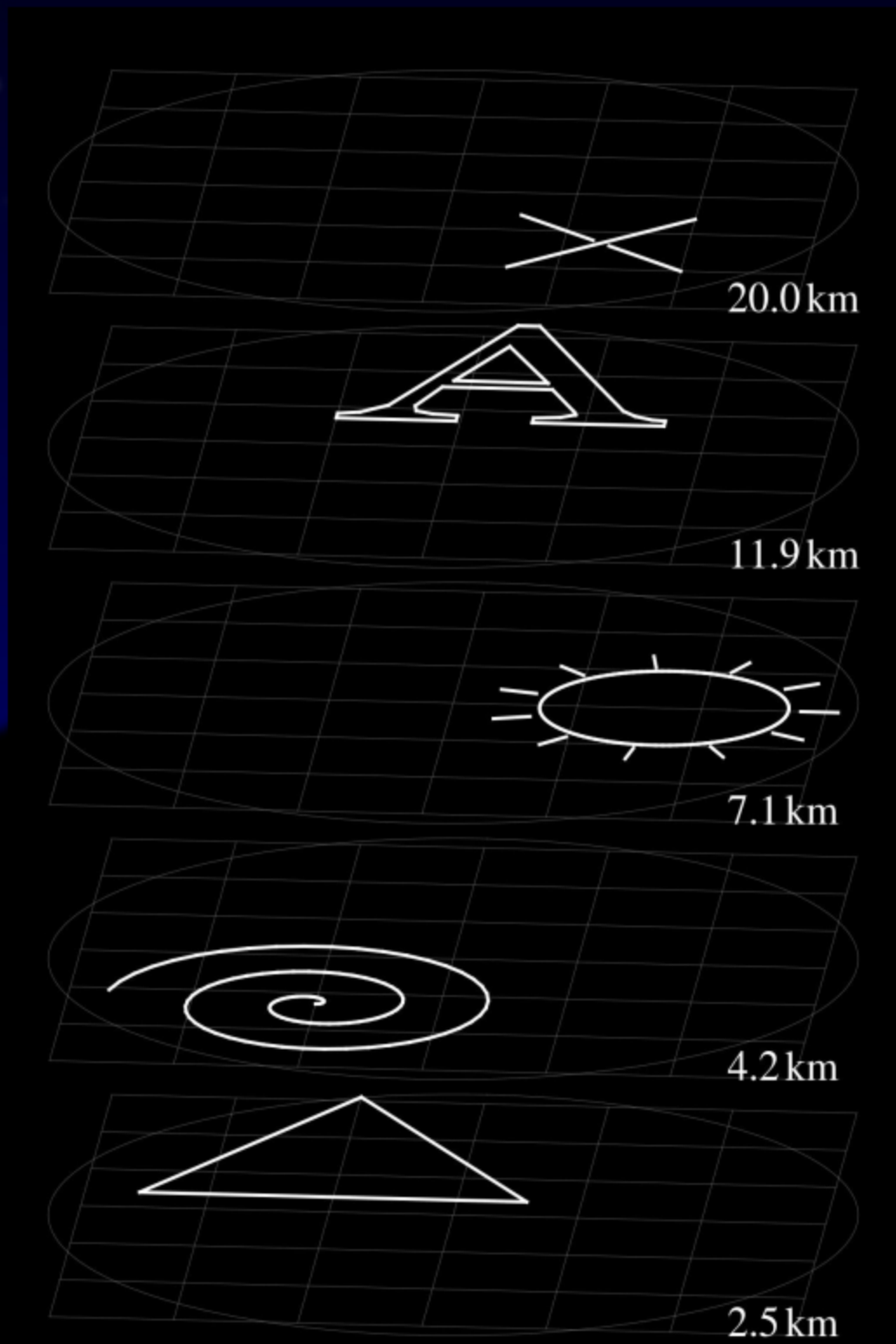
Optics

refocussing to any depth



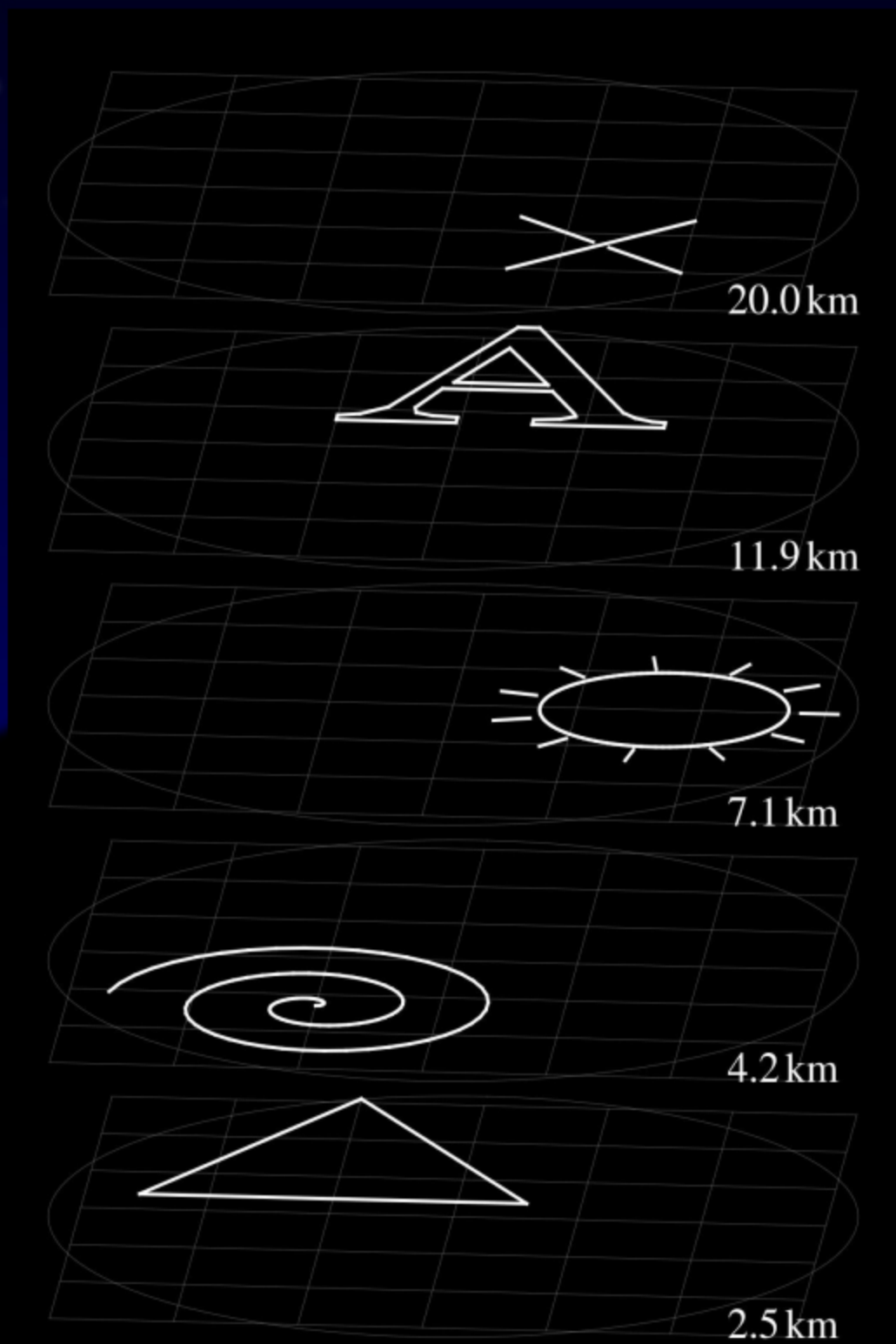
Optics

refocussing to any depth

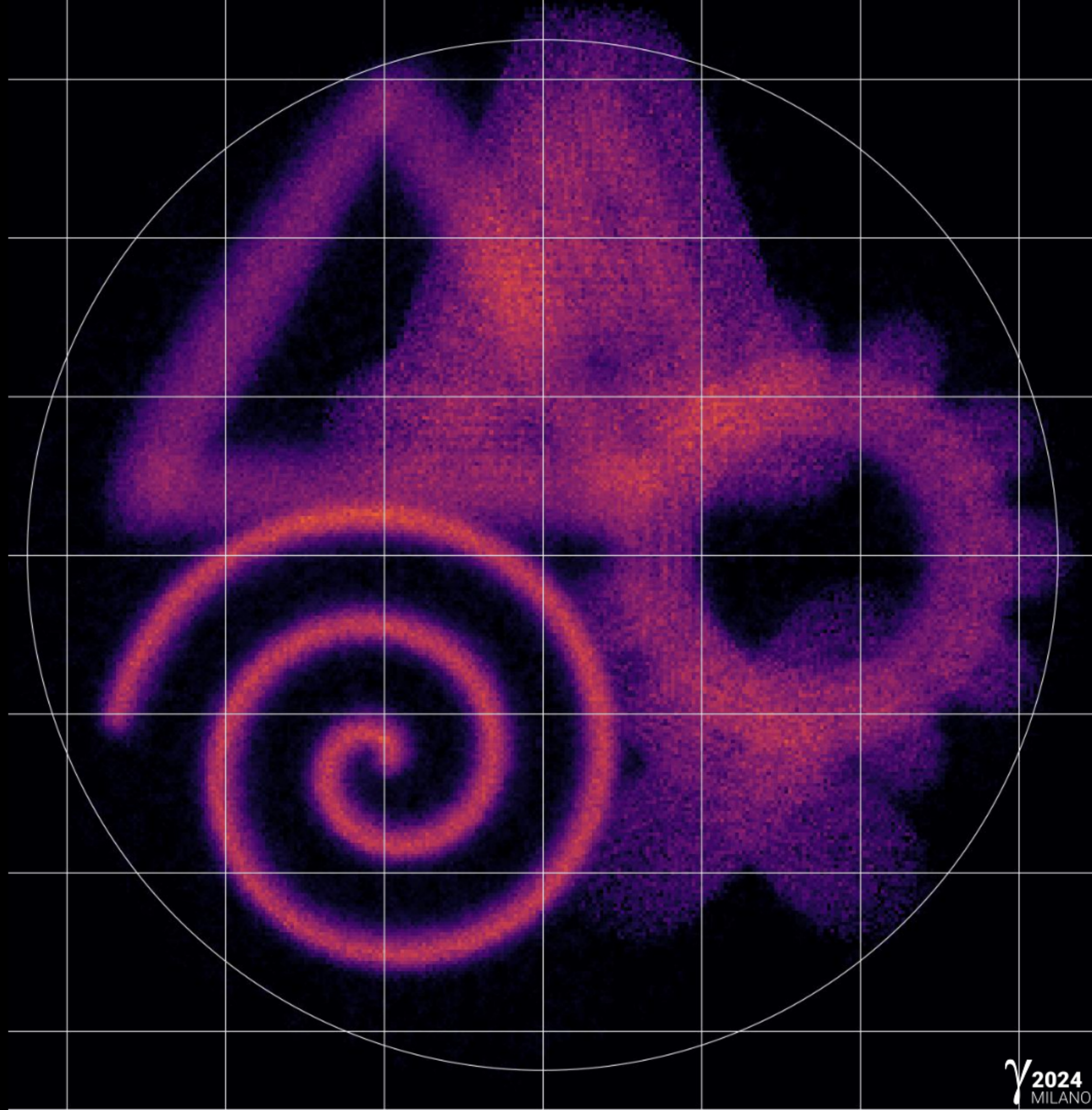
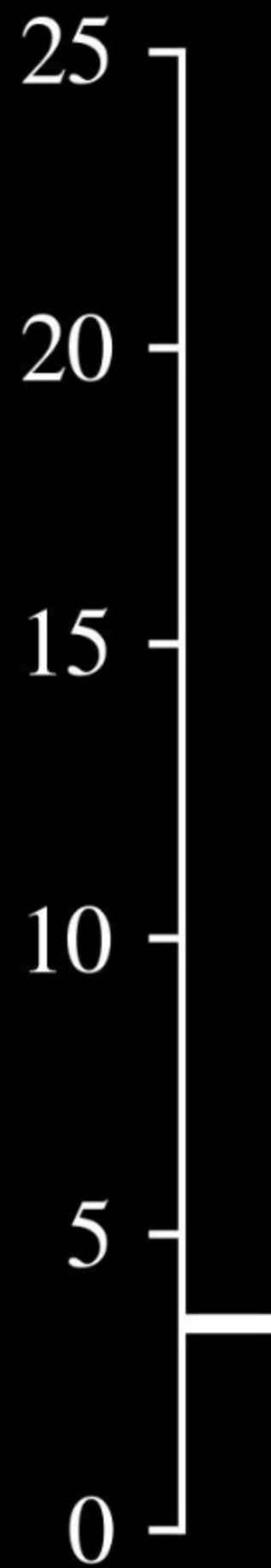


Optics

refocussing to any depth

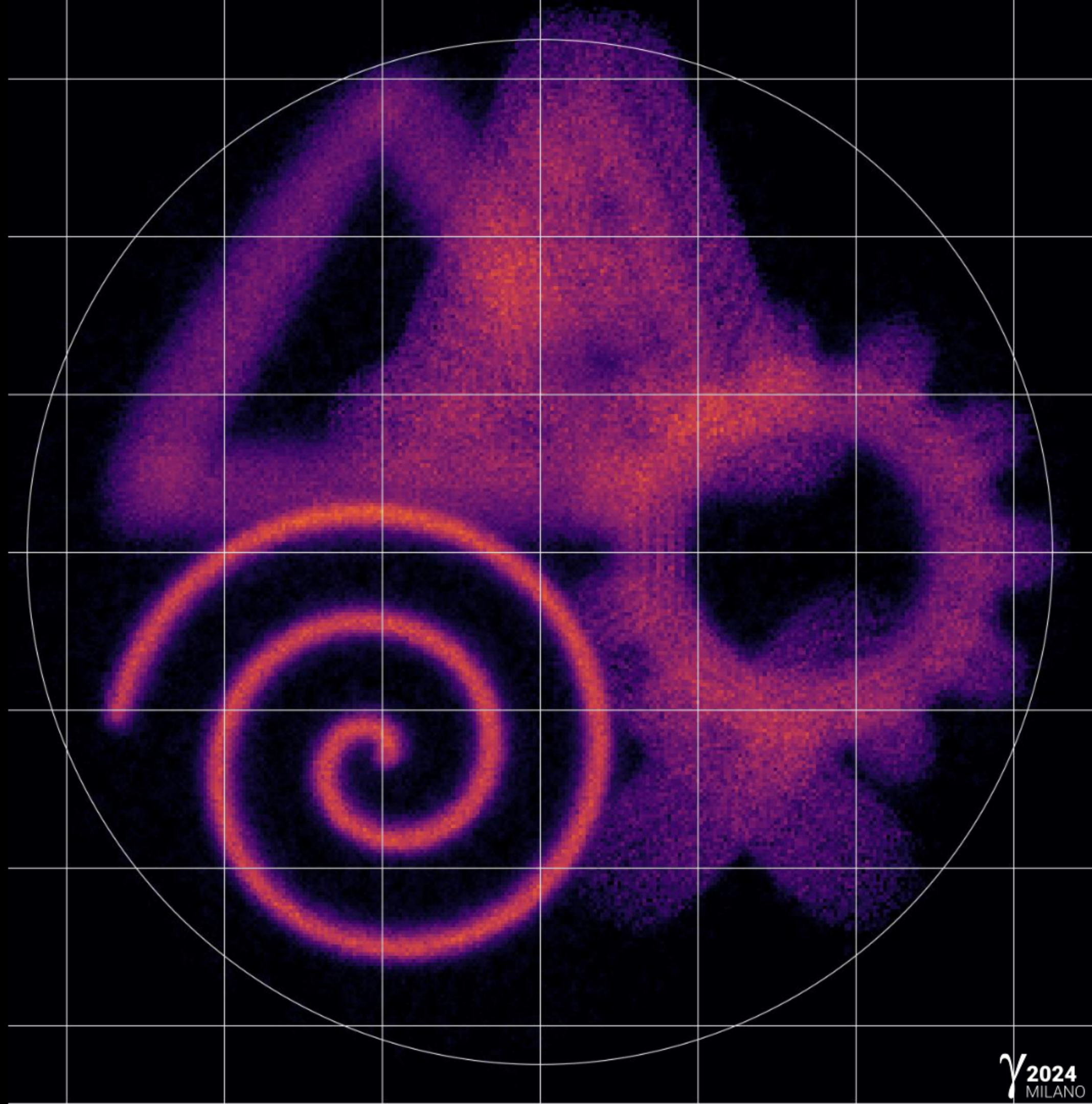
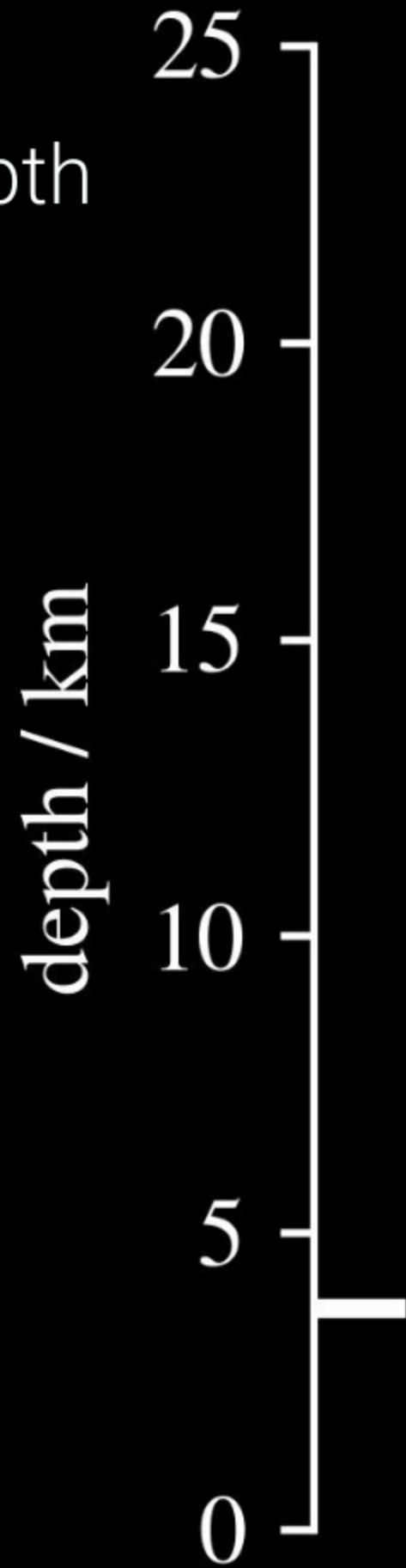
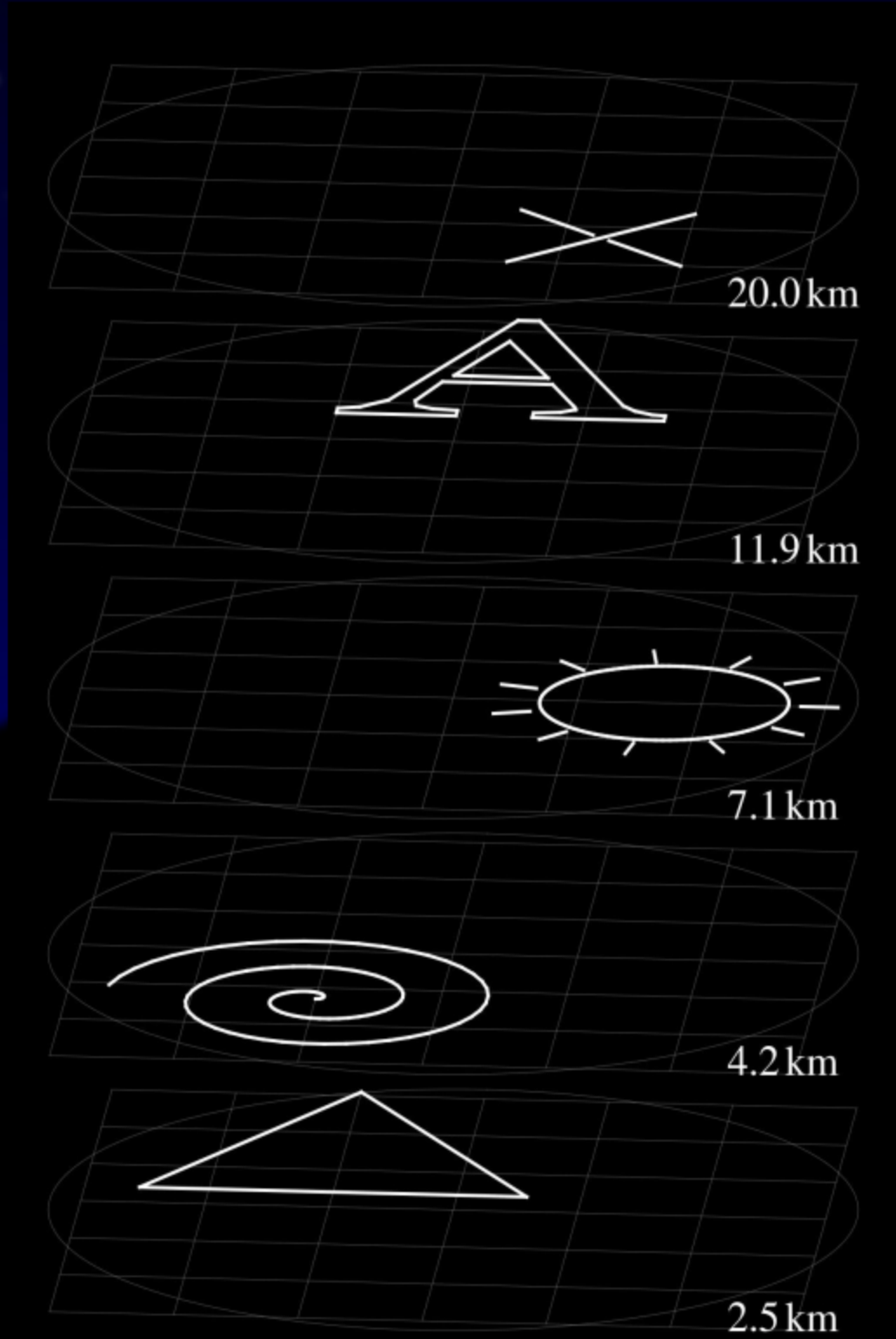


depth / km



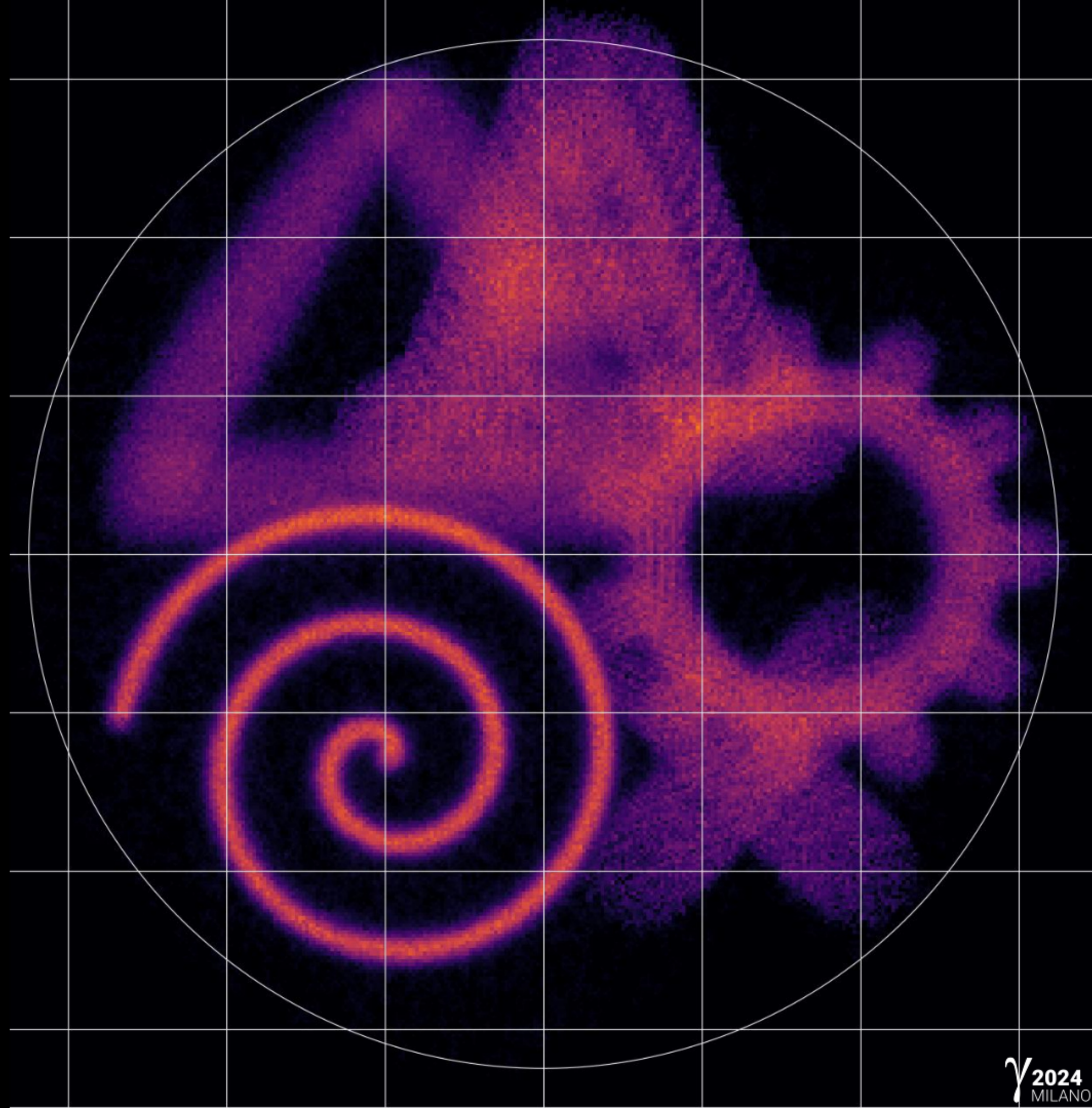
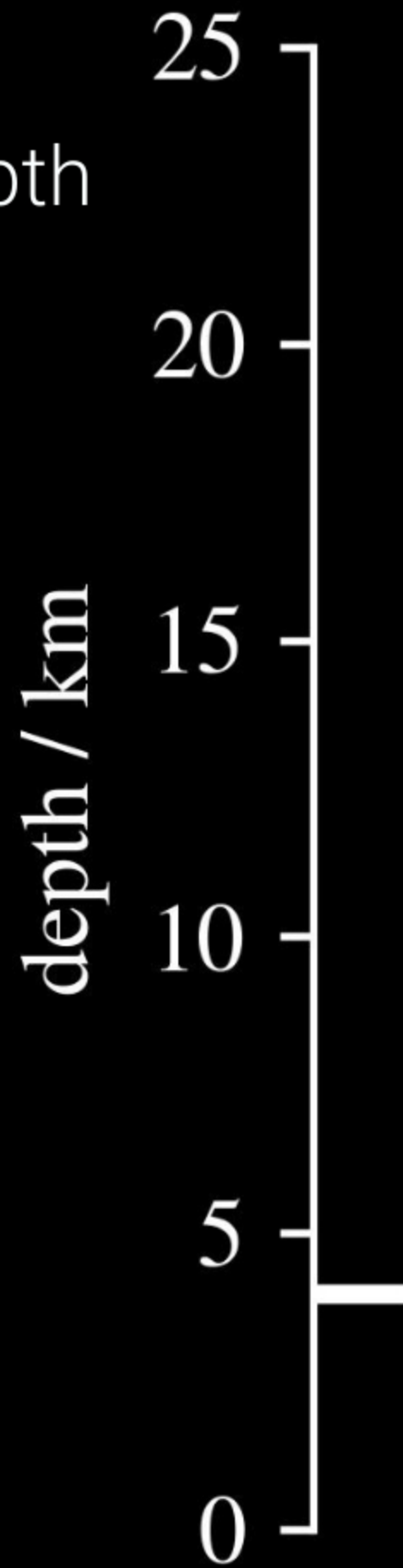
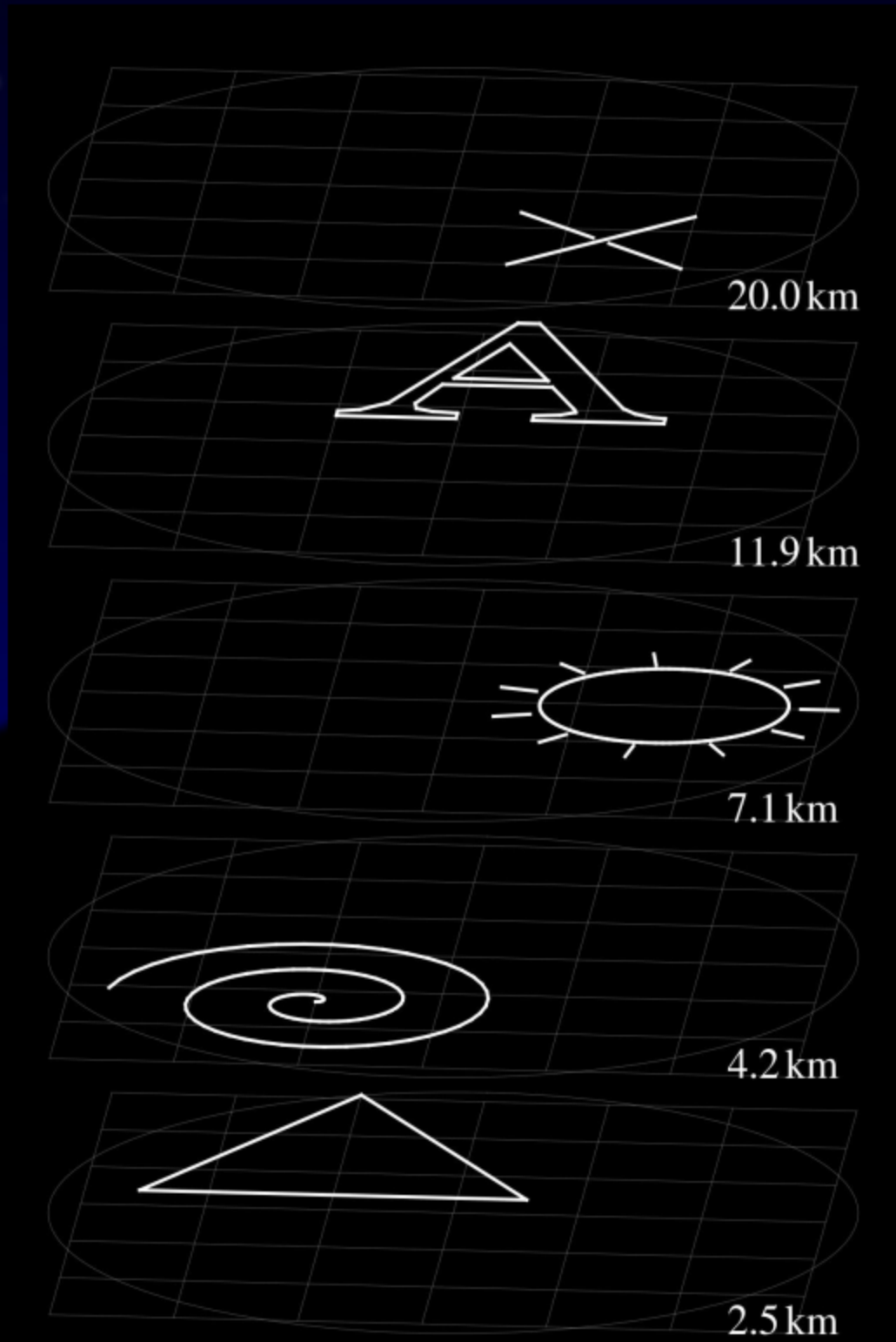
Optics

refocussing to any depth



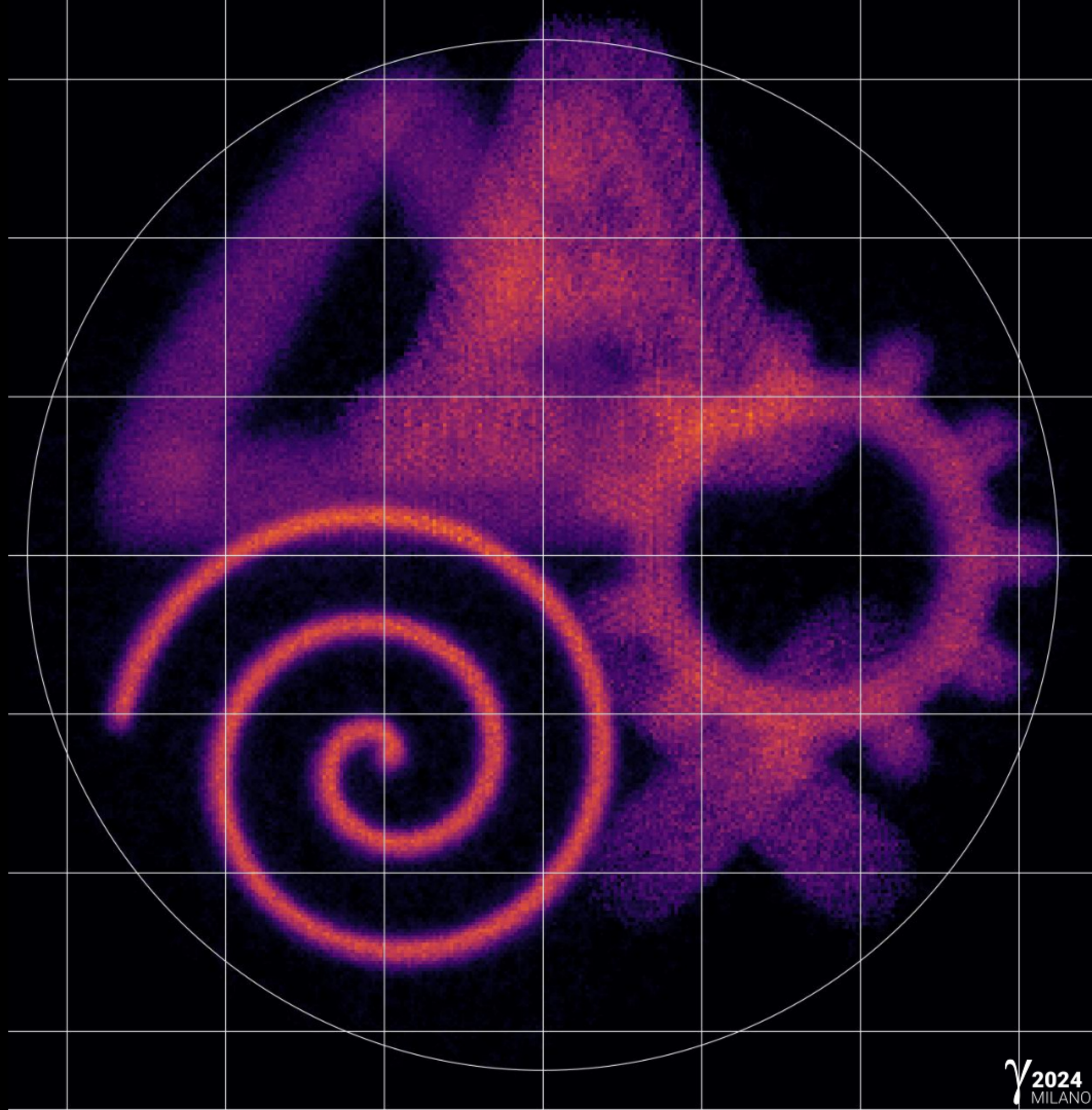
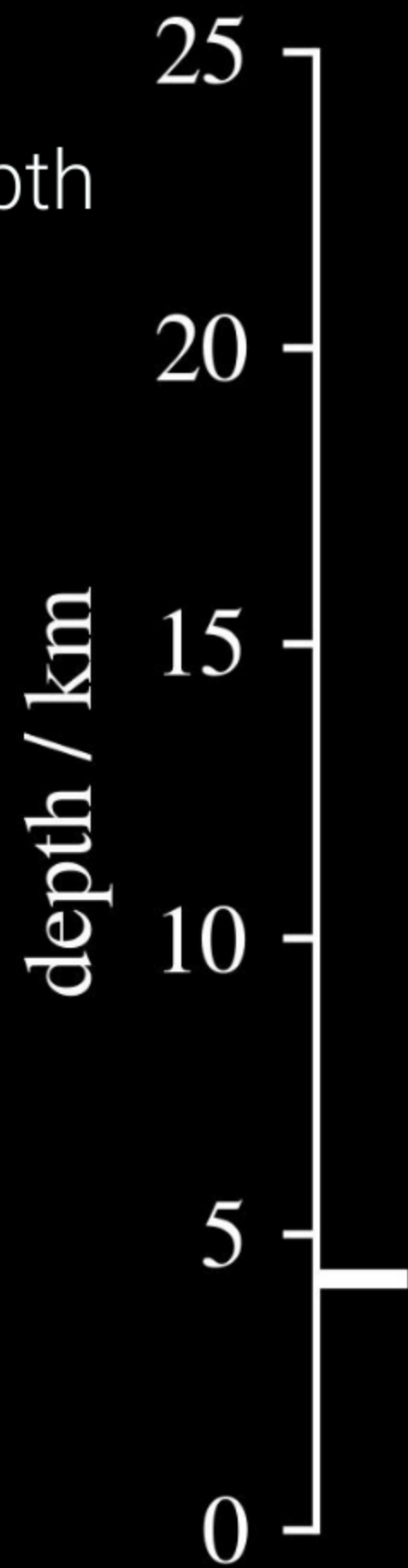
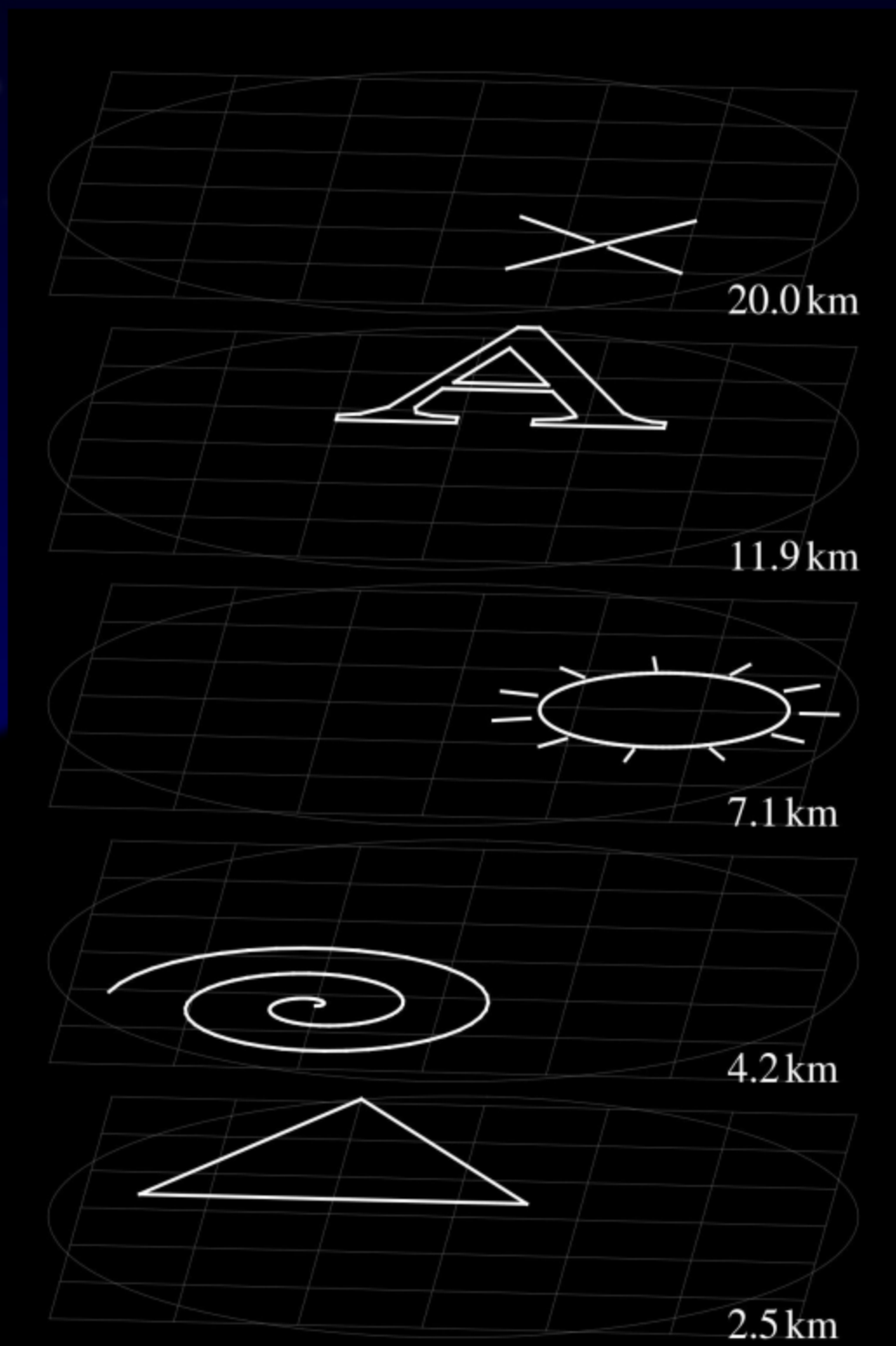
Optics

refocussing to any depth



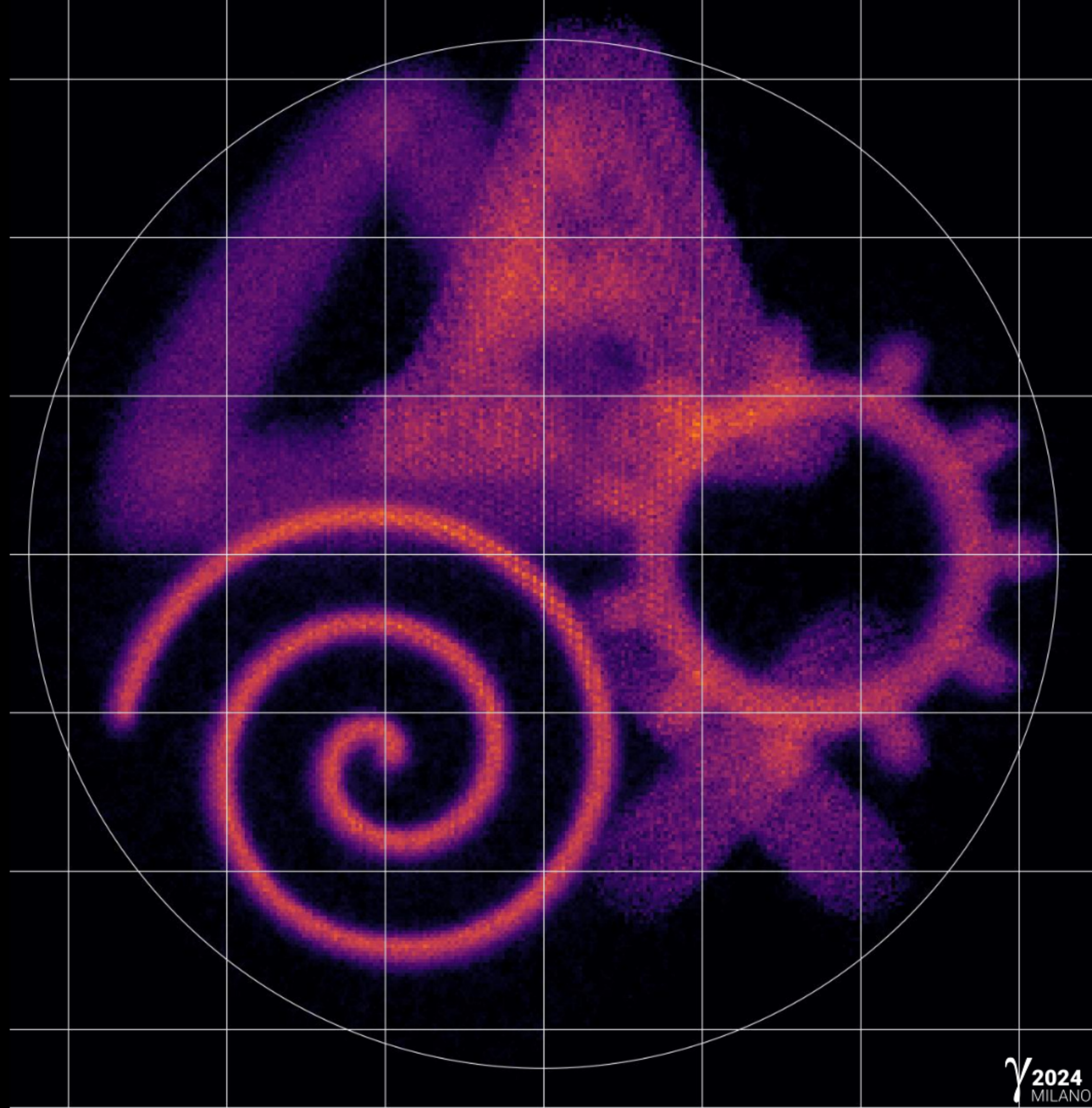
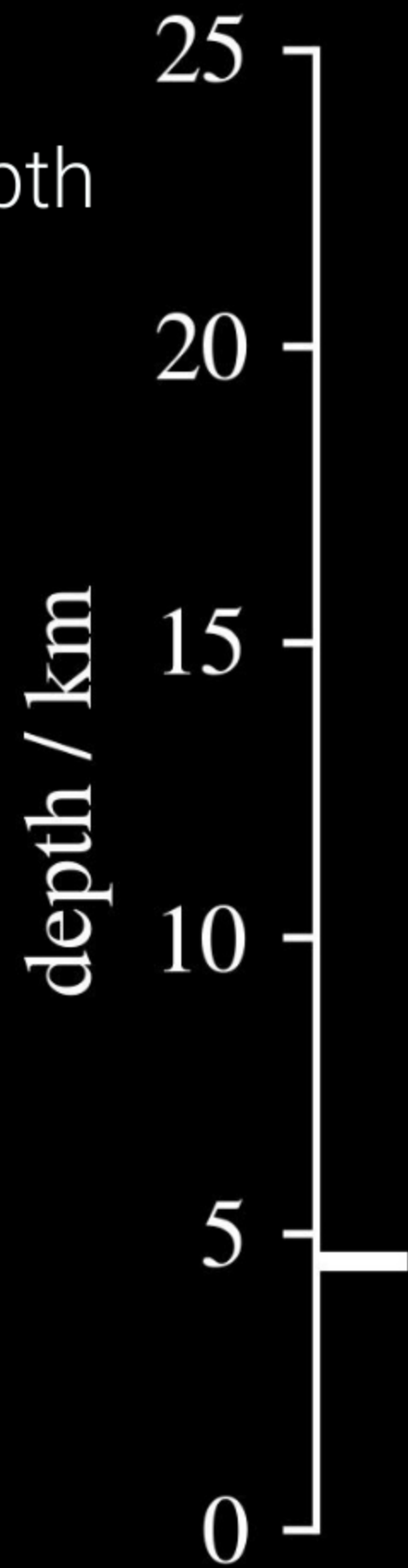
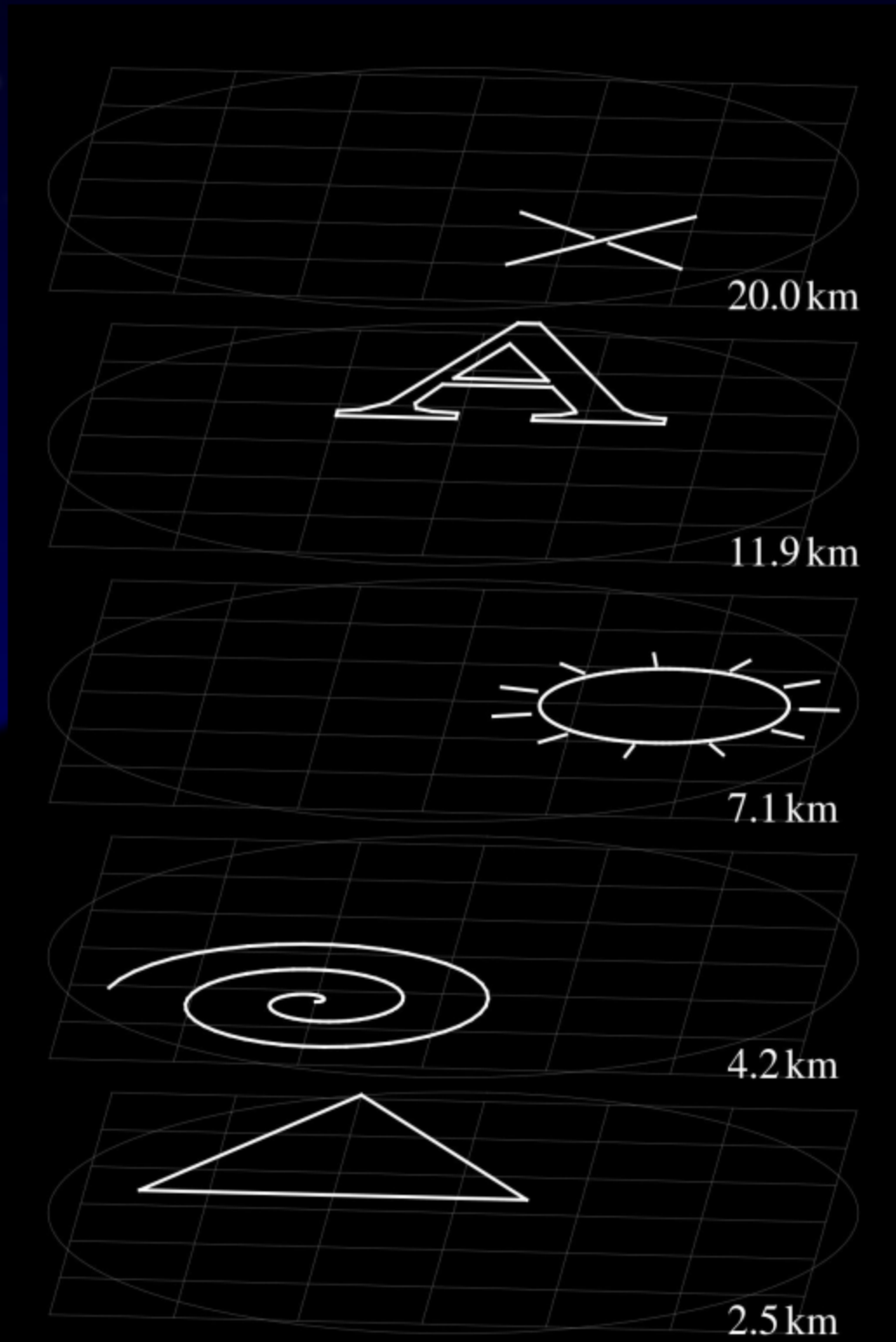
Optics

refocussing to any depth



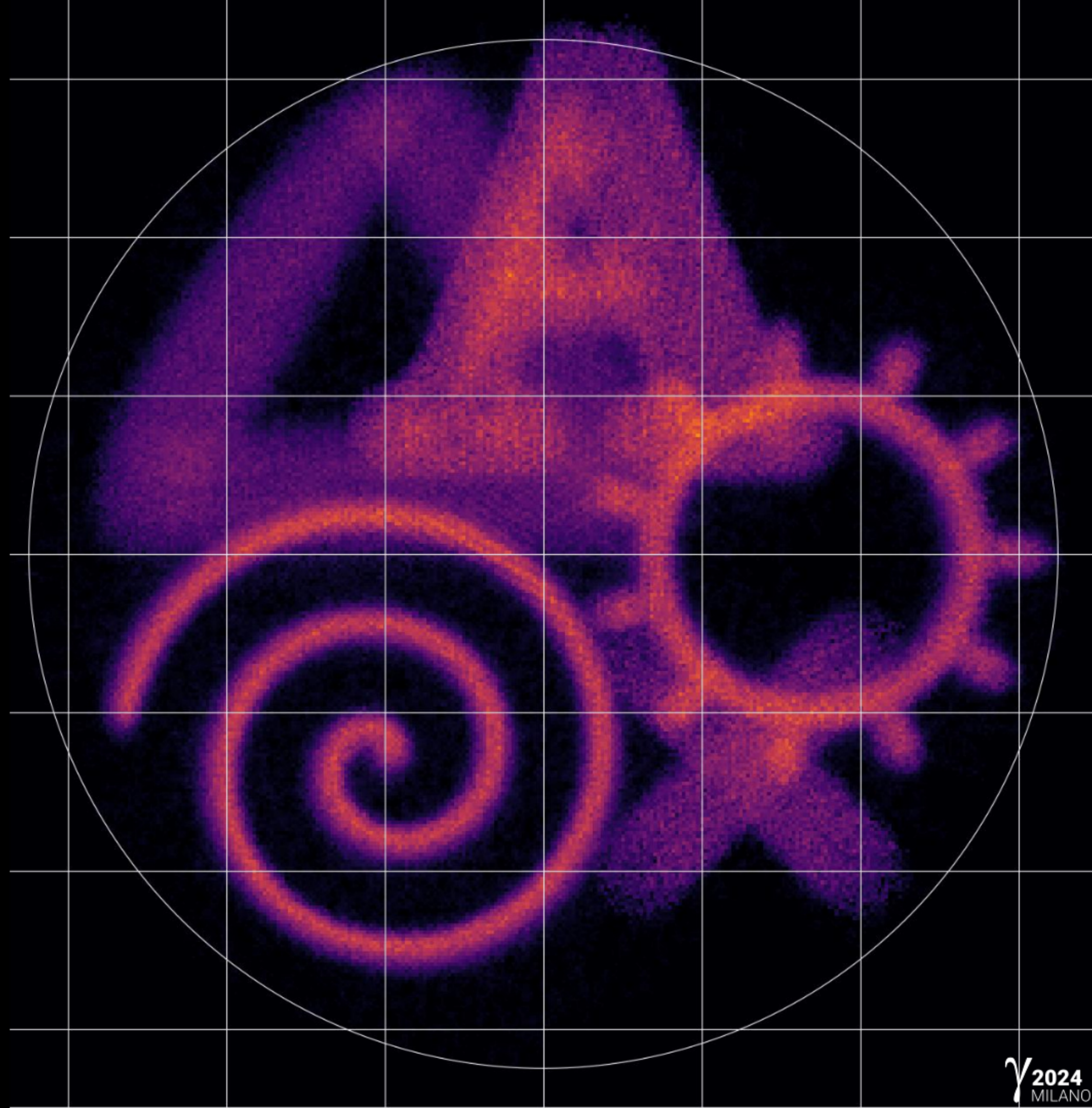
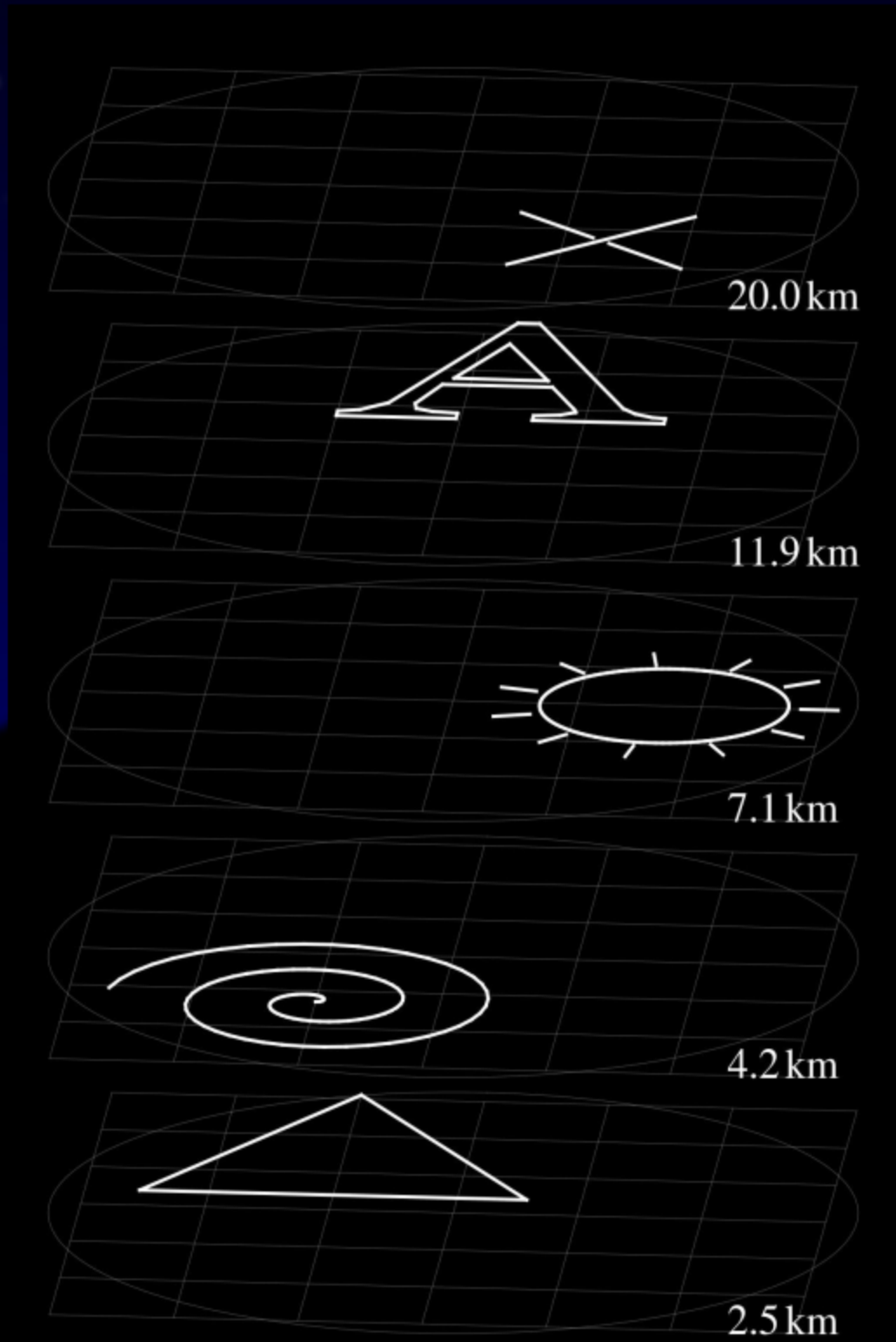
Optics

refocussing to any depth



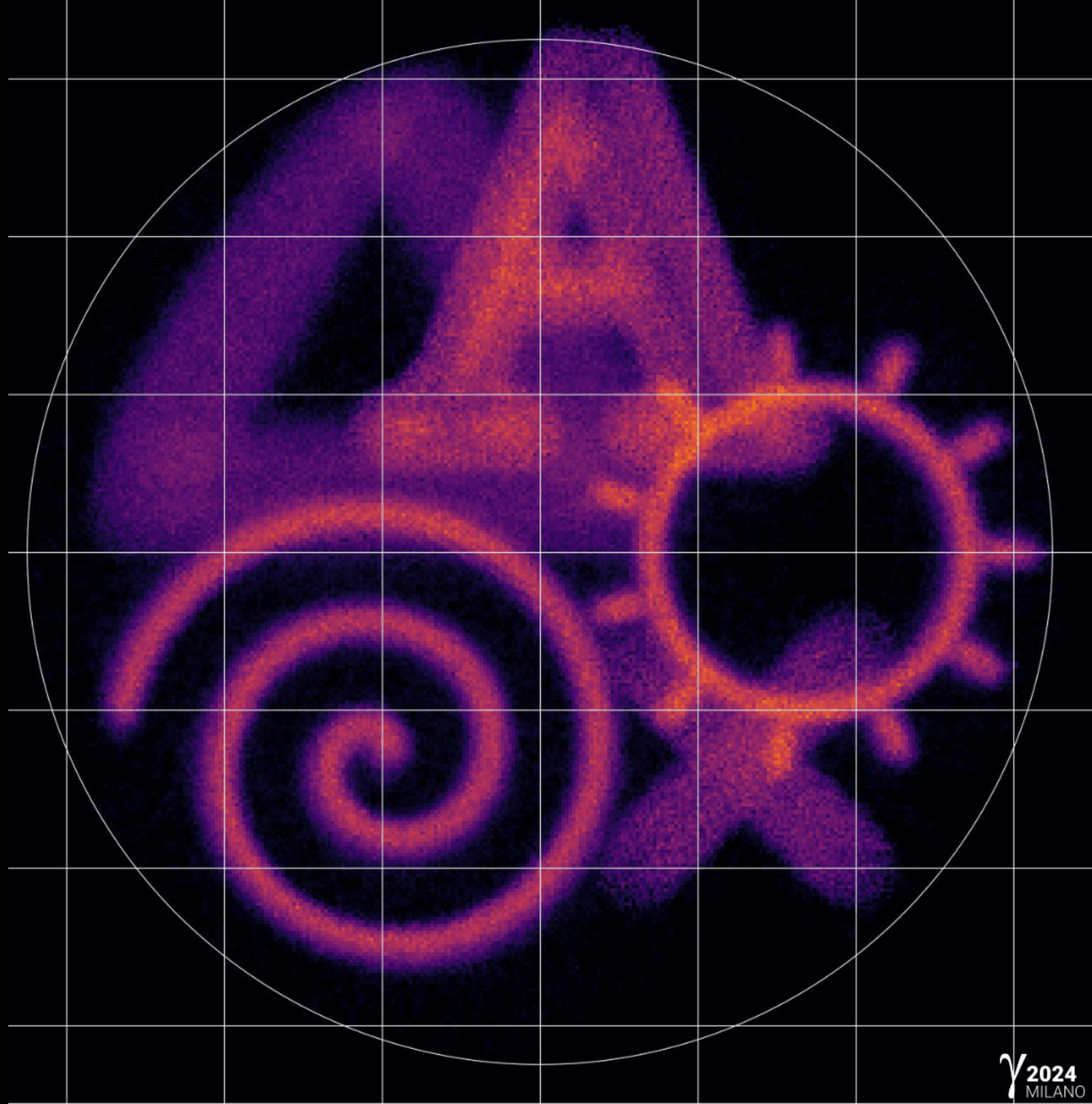
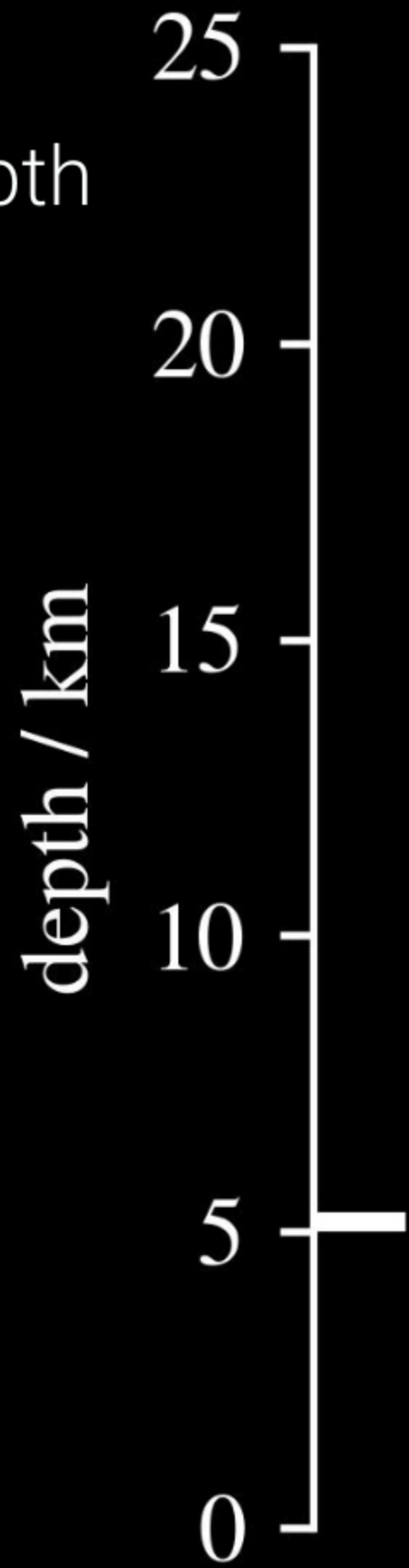
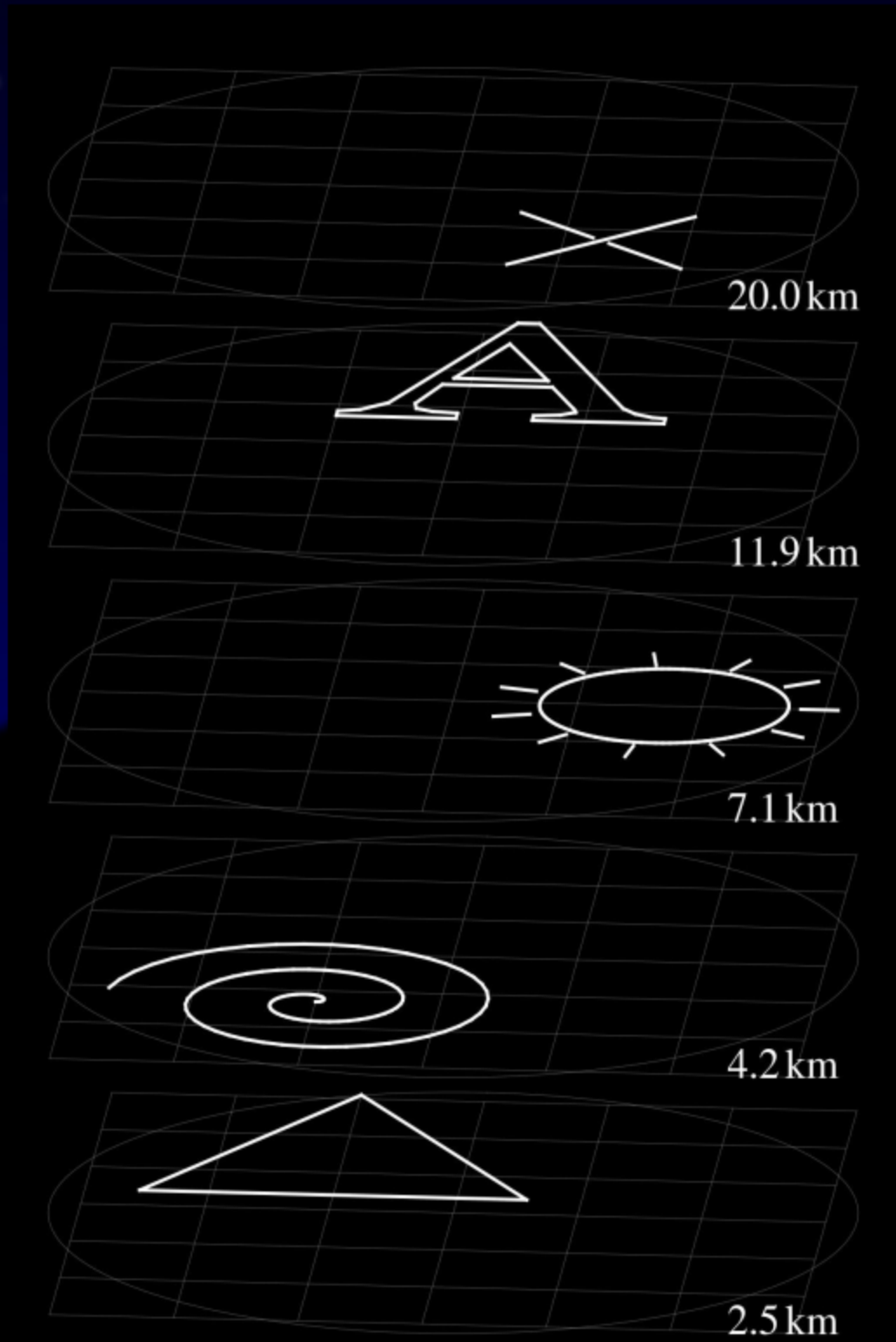
Optics

refocussing to any depth



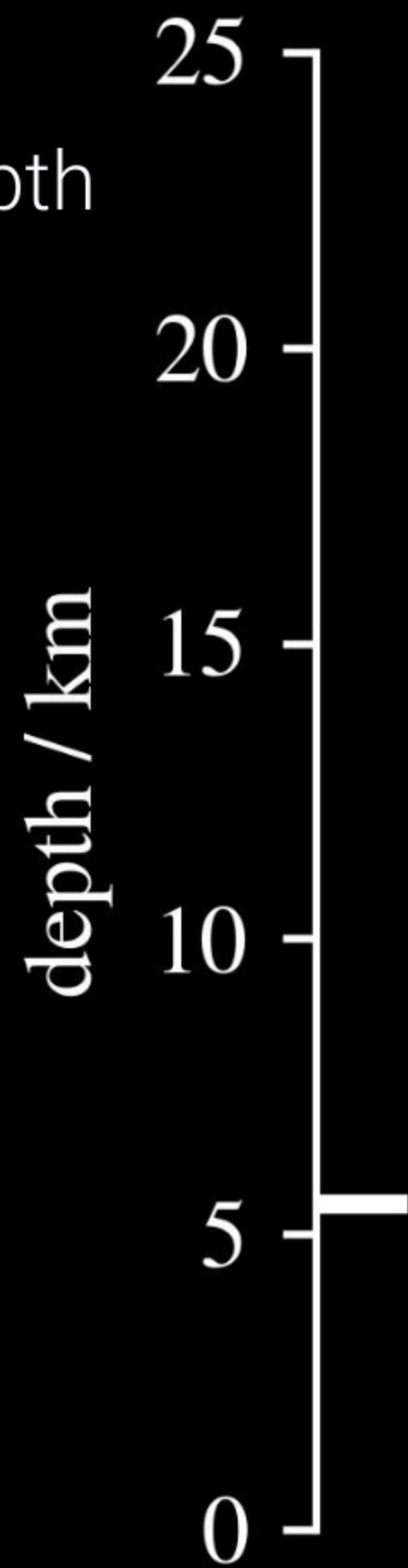
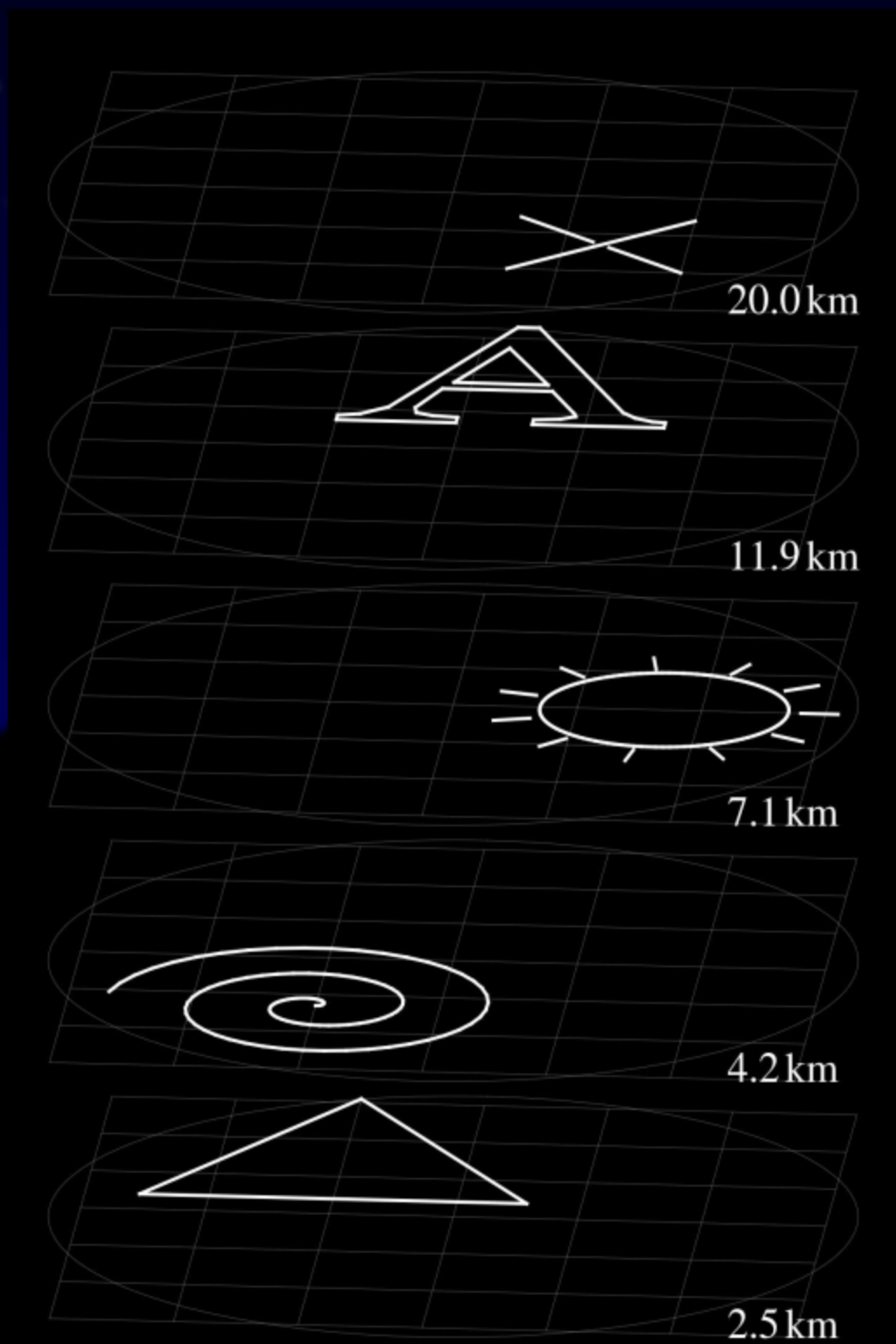
Optics

refocussing to any depth



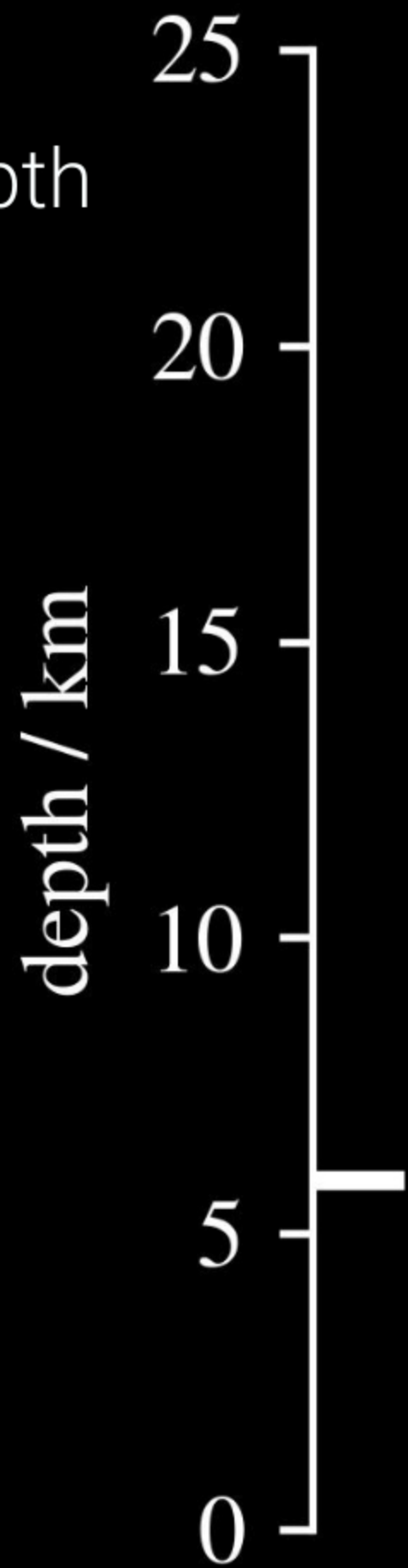
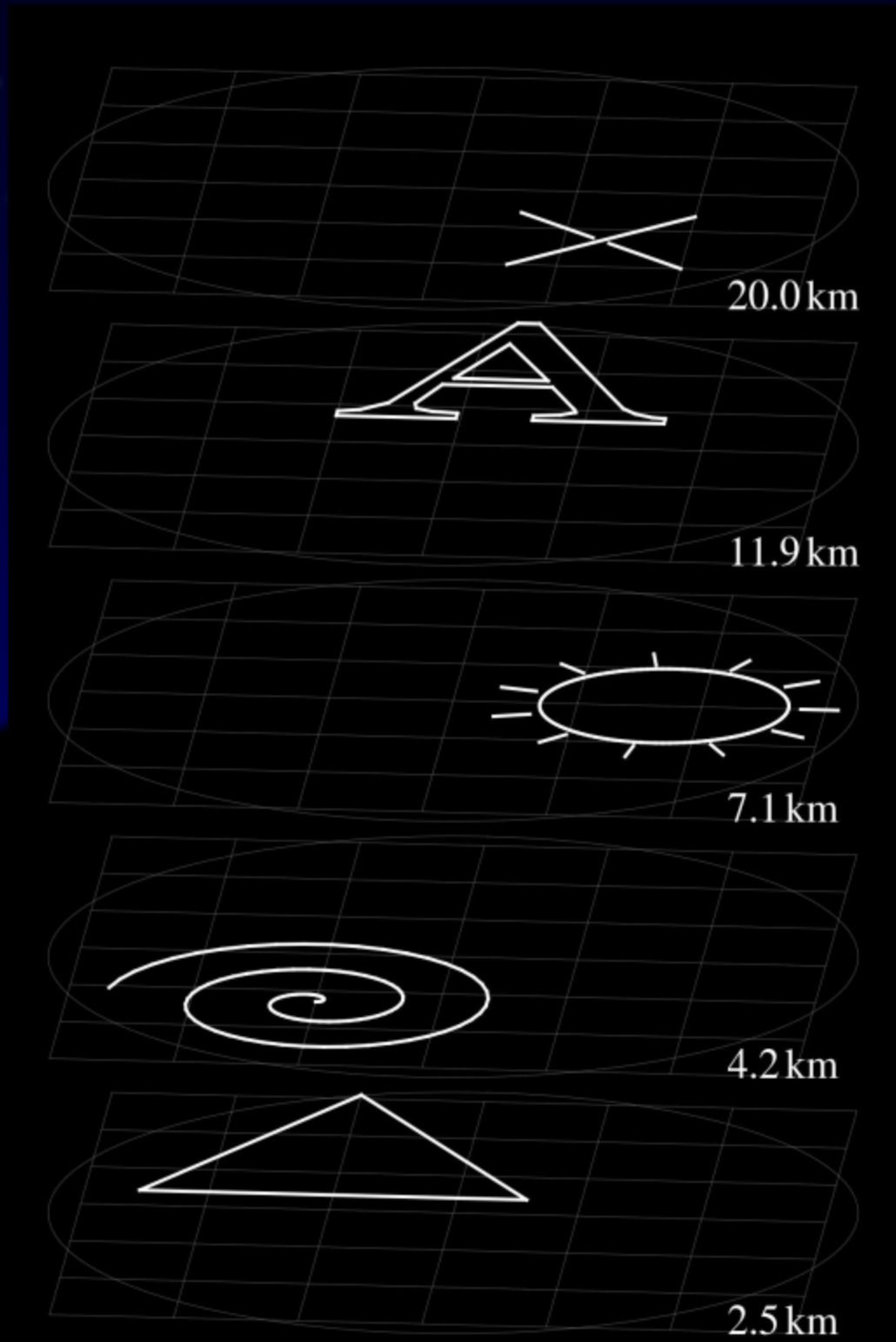
Optics

refocussing to any depth



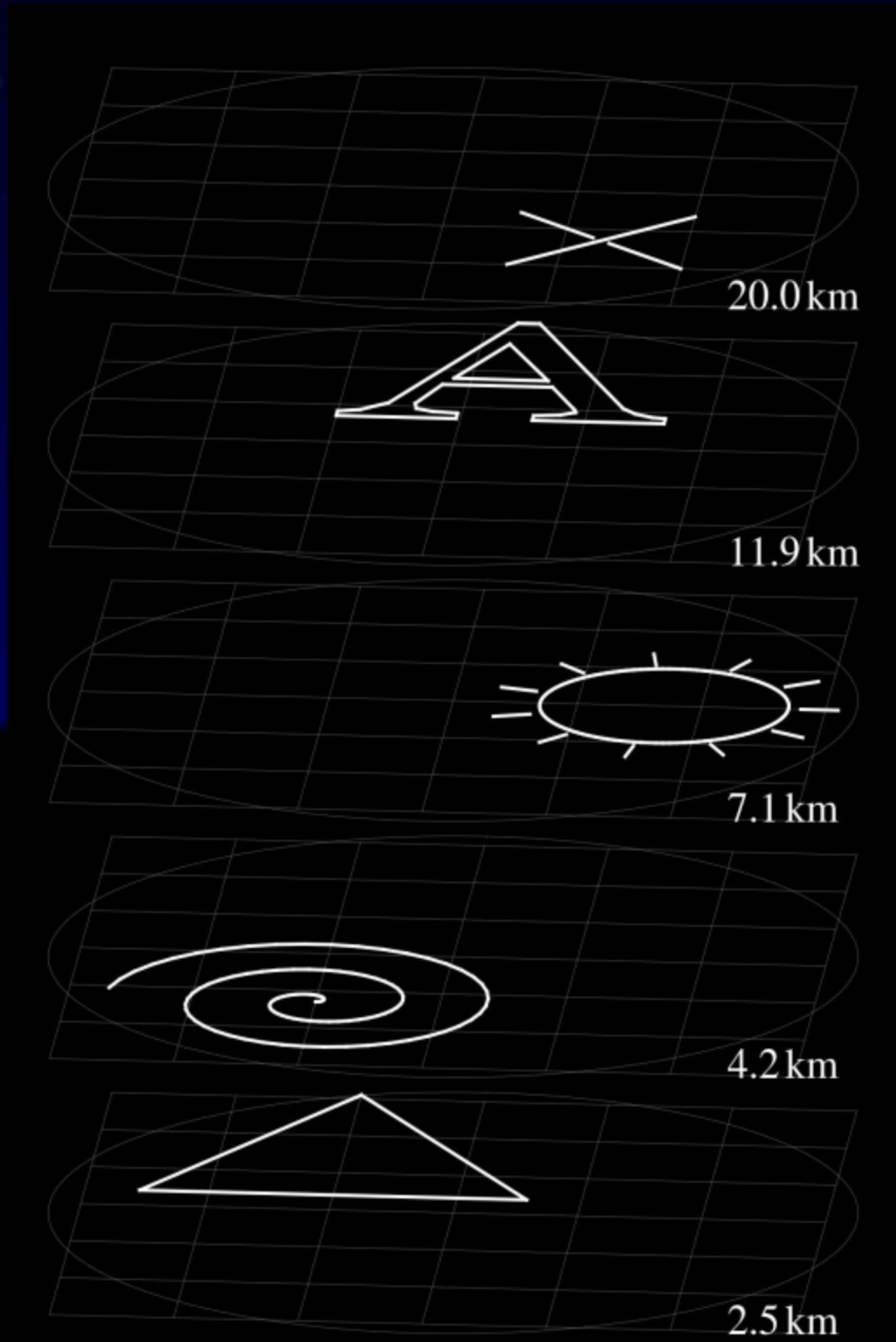
Optics

refocussing to any depth



Optics

refocussing to any depth



depth / km

25

20

15

10

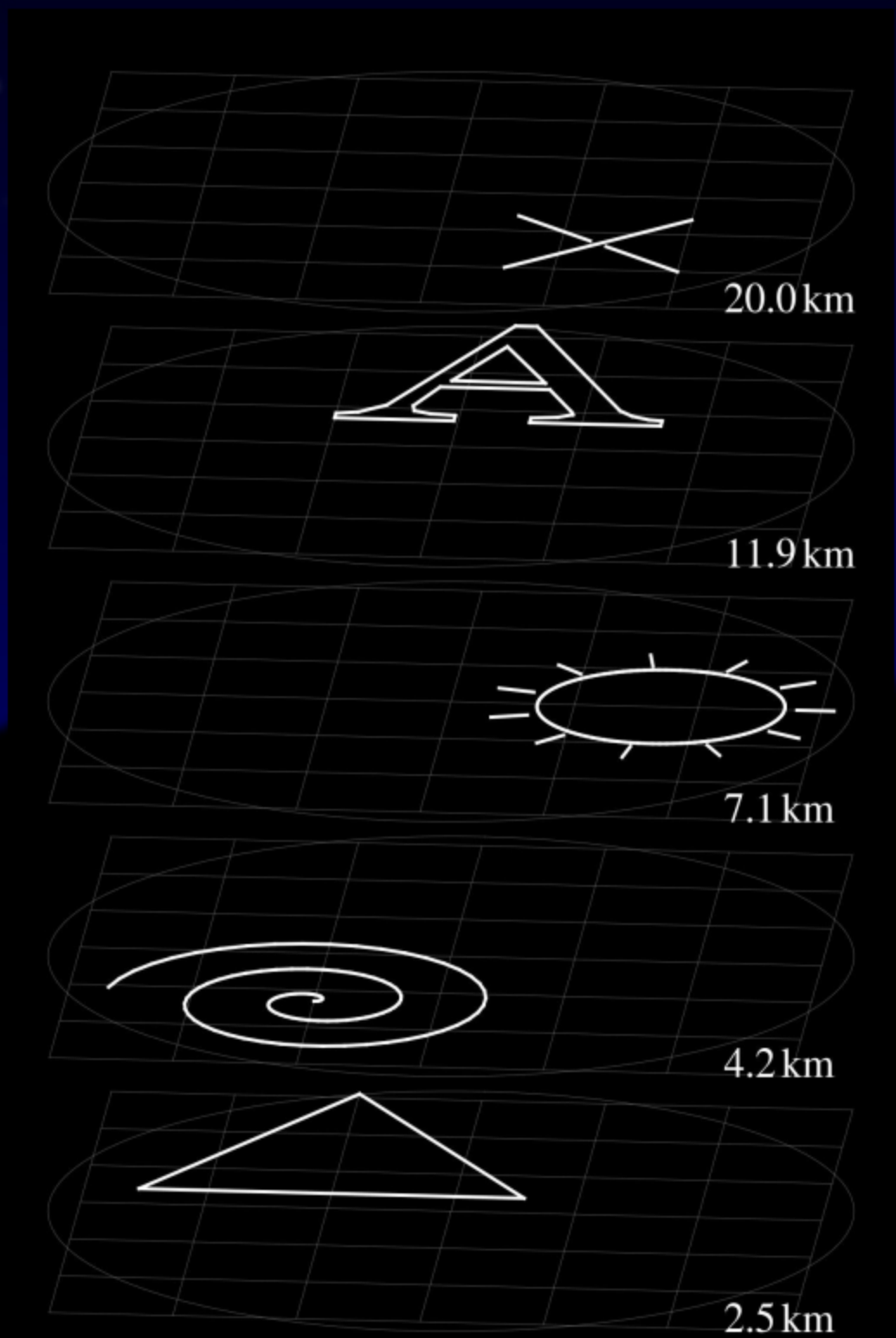
5

0



Optics

refocussing to any depth



depth / km

25

20

15

10

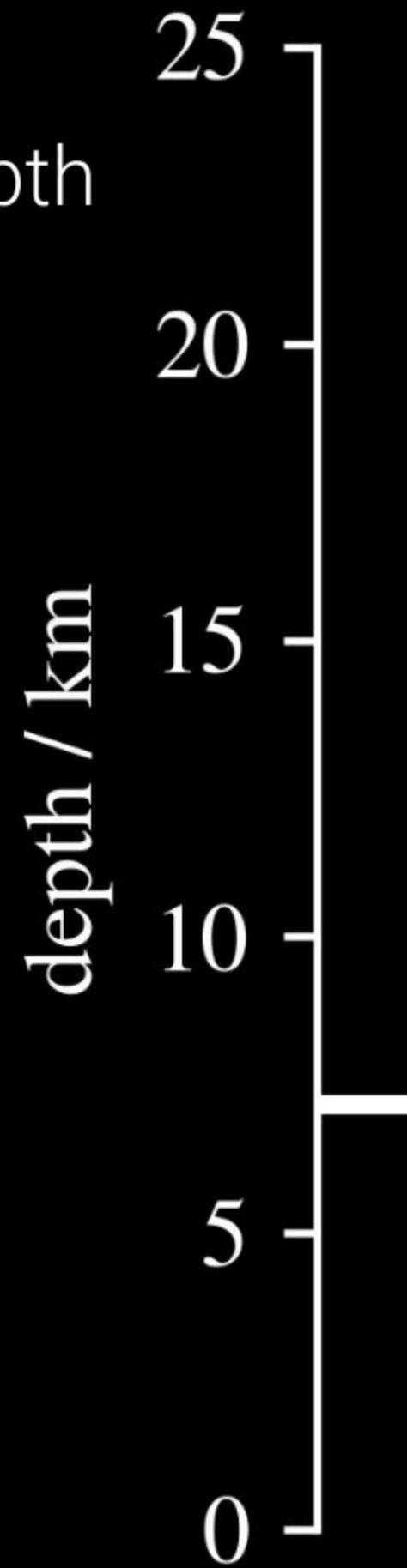
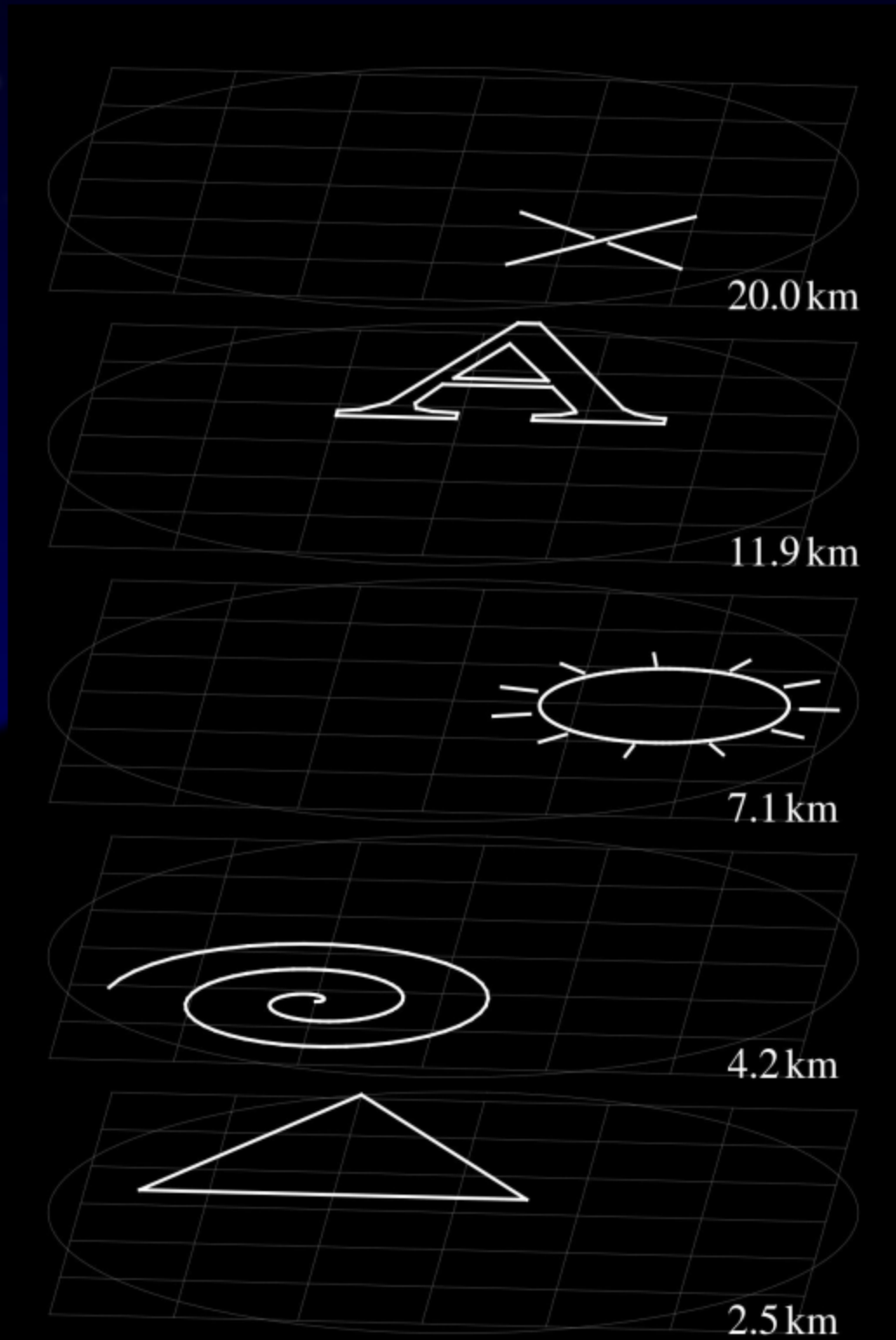
5

0



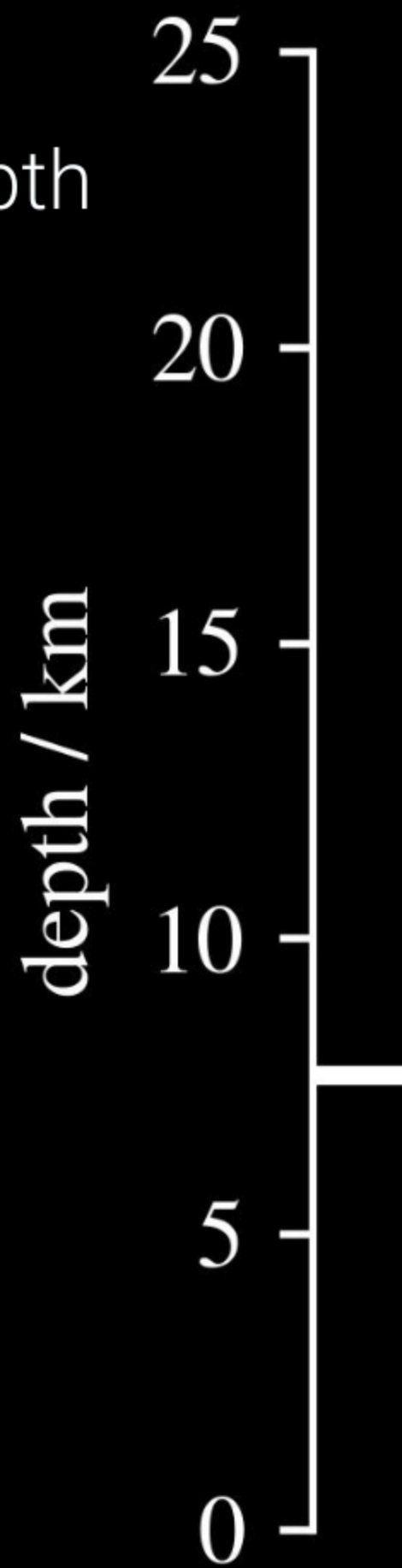
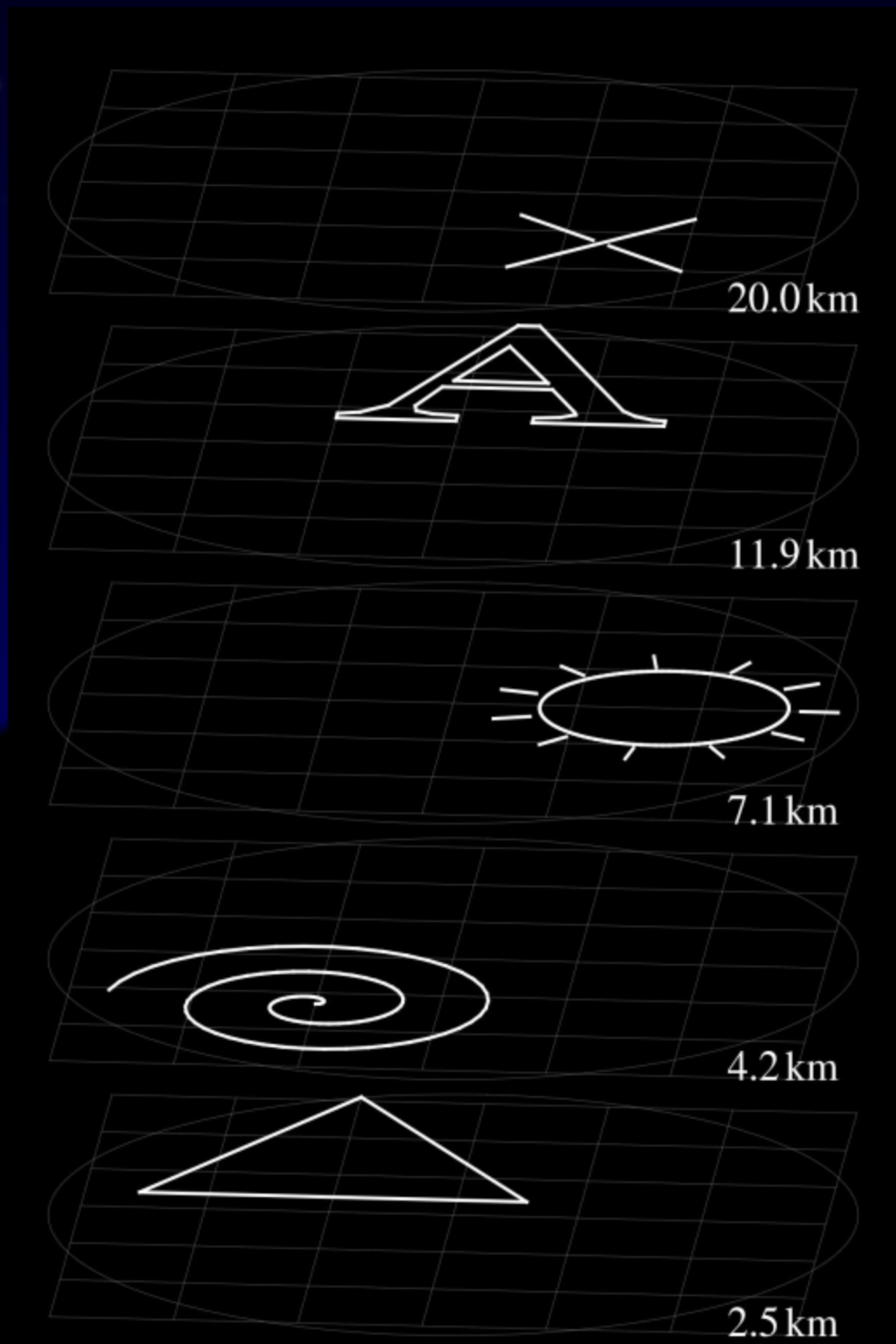
Optics

refocussing to any depth



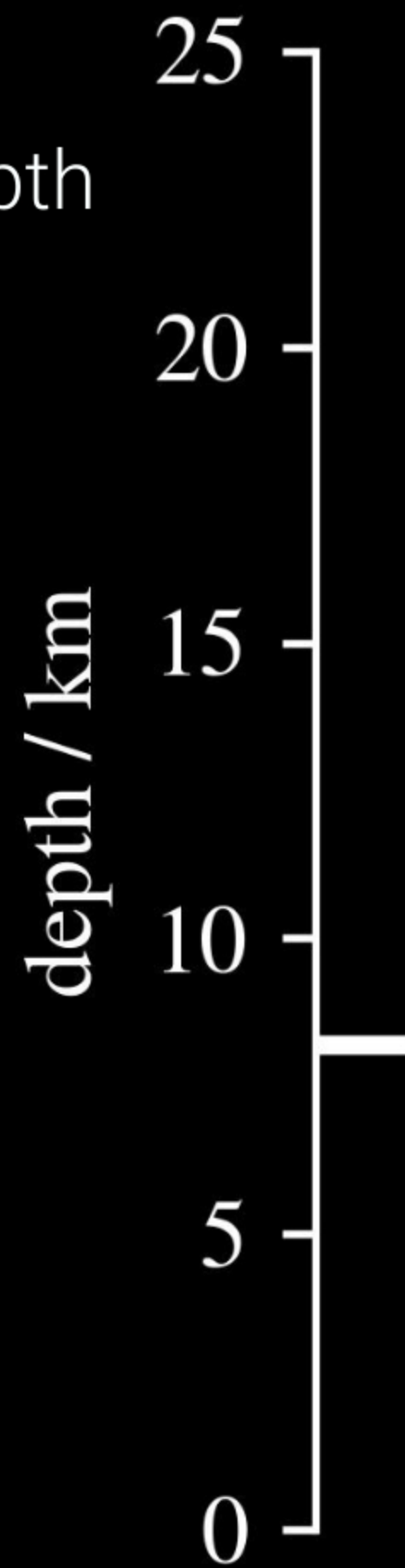
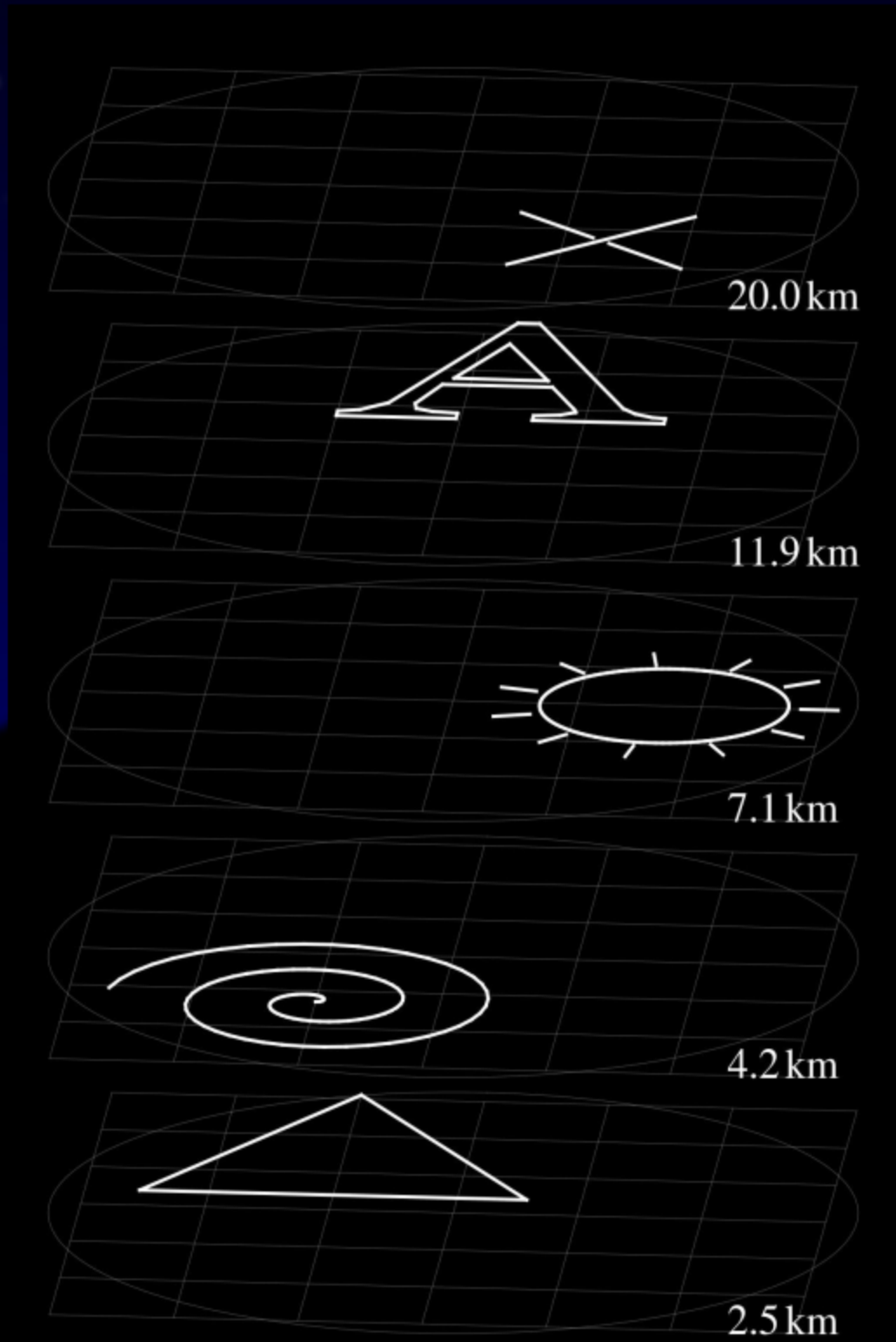
Optics

refocussing to any depth



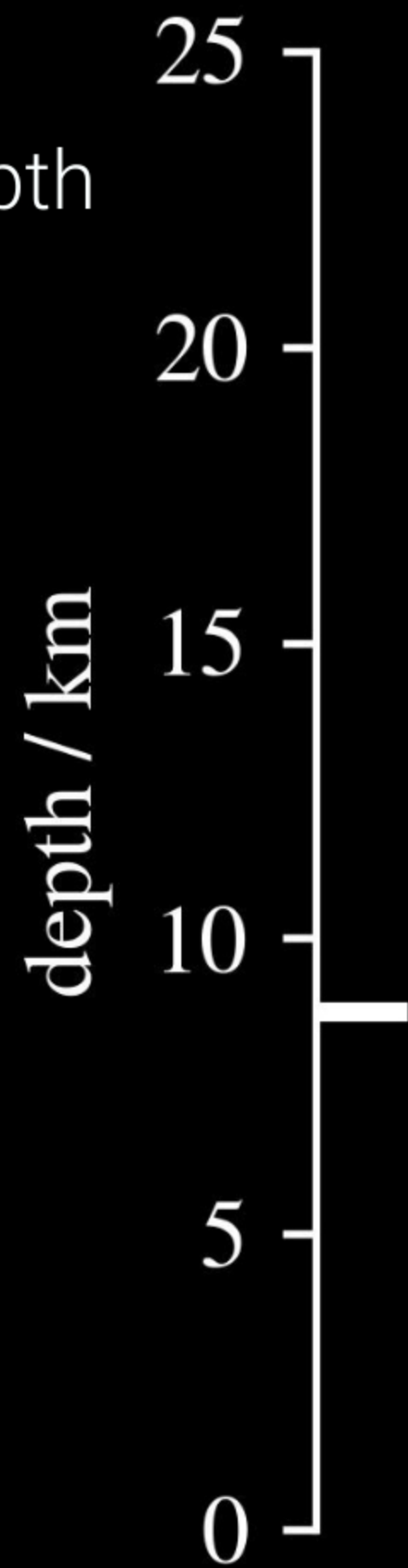
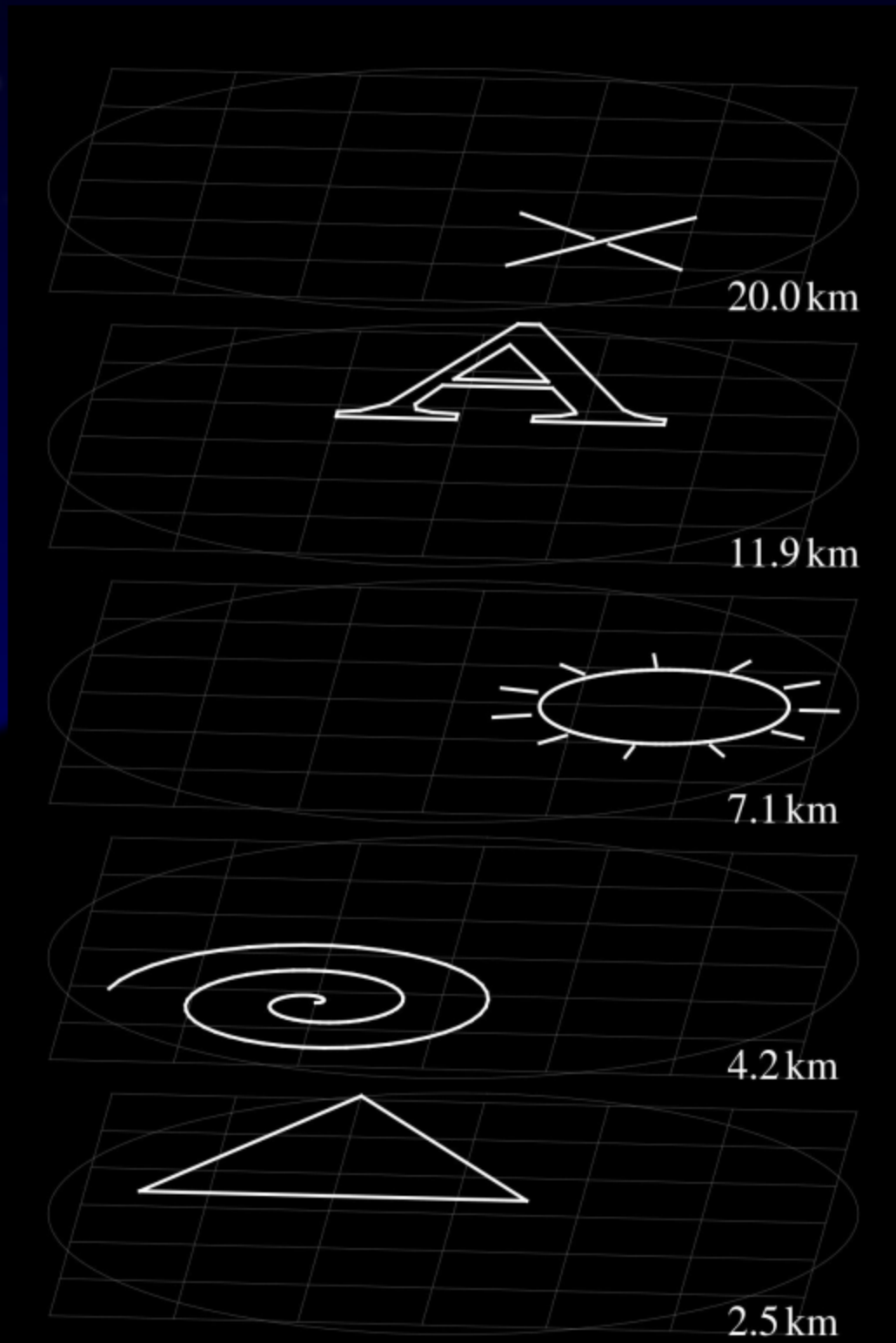
Optics

refocussing to any depth



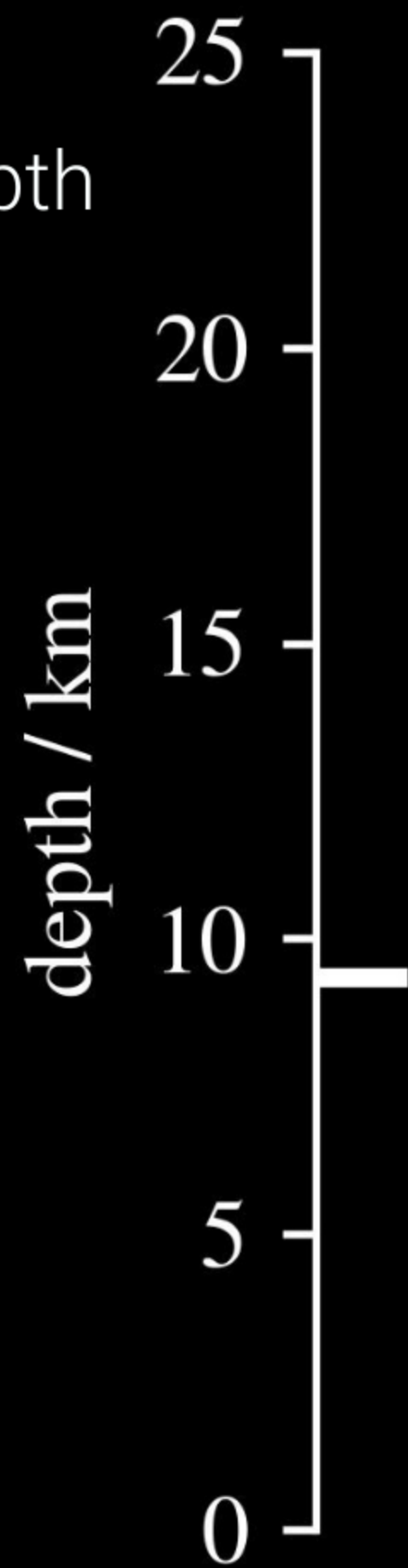
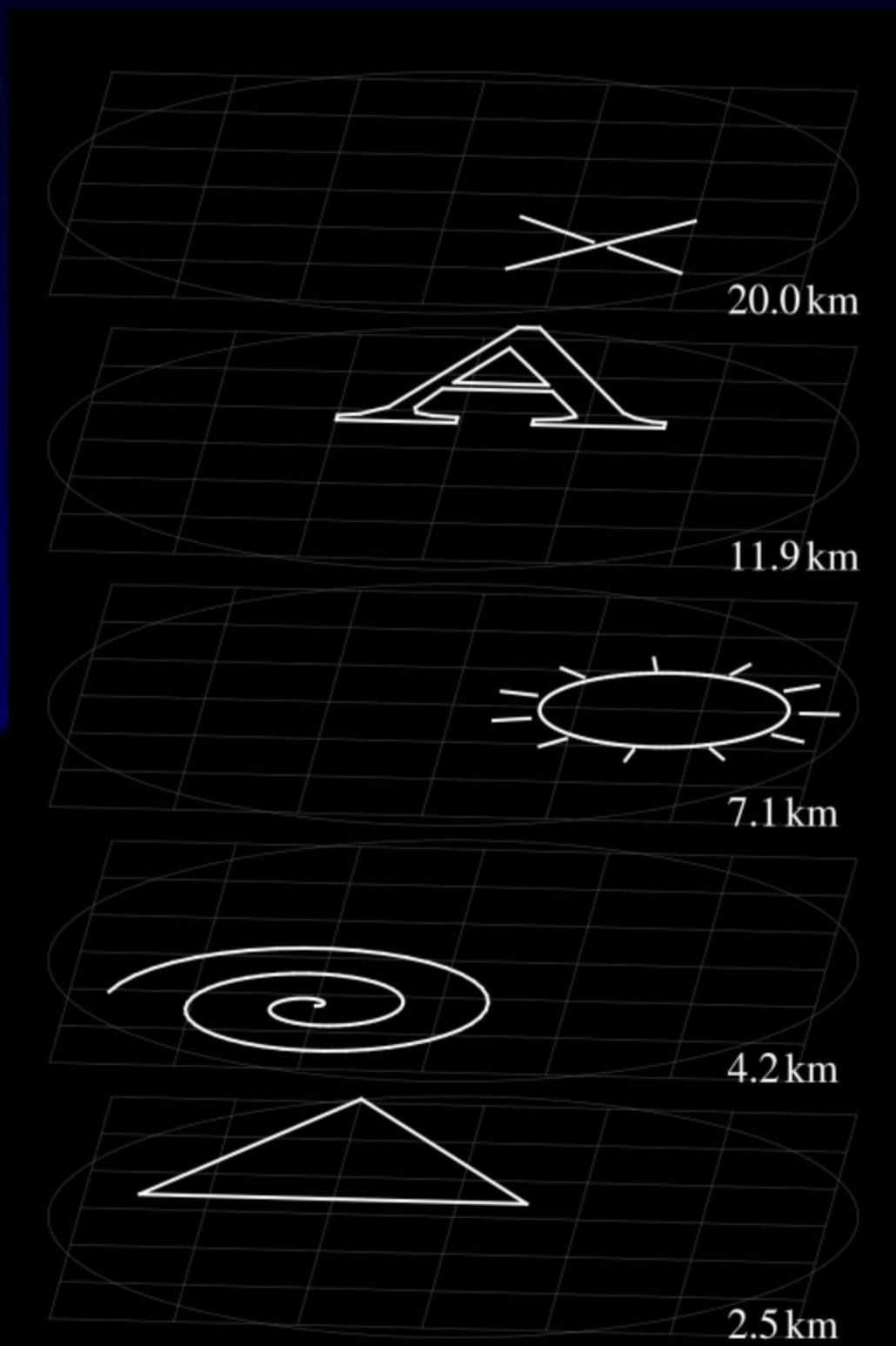
Optics

refocussing to any depth



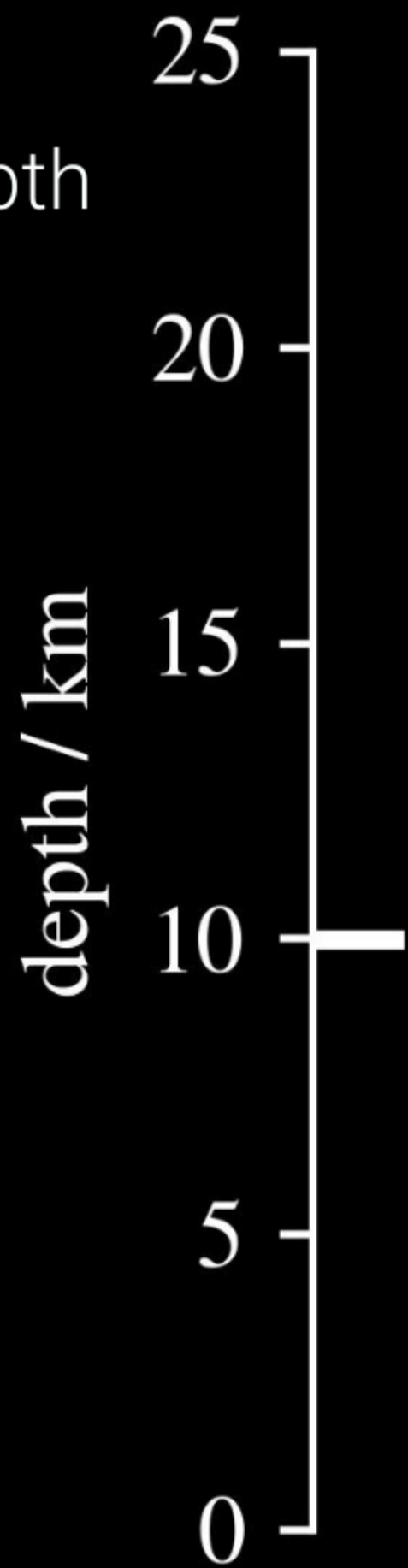
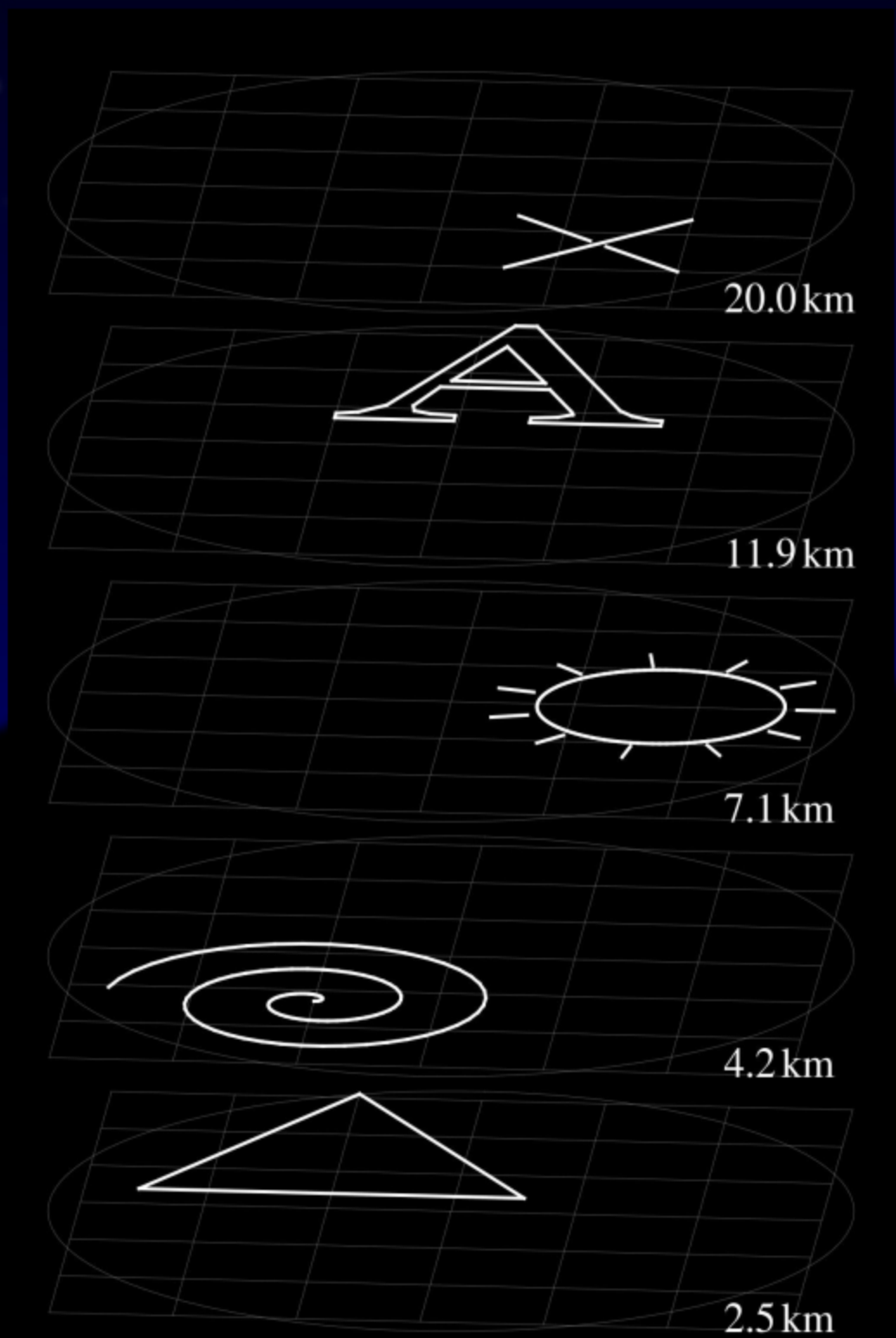
Optics

refocussing to any depth



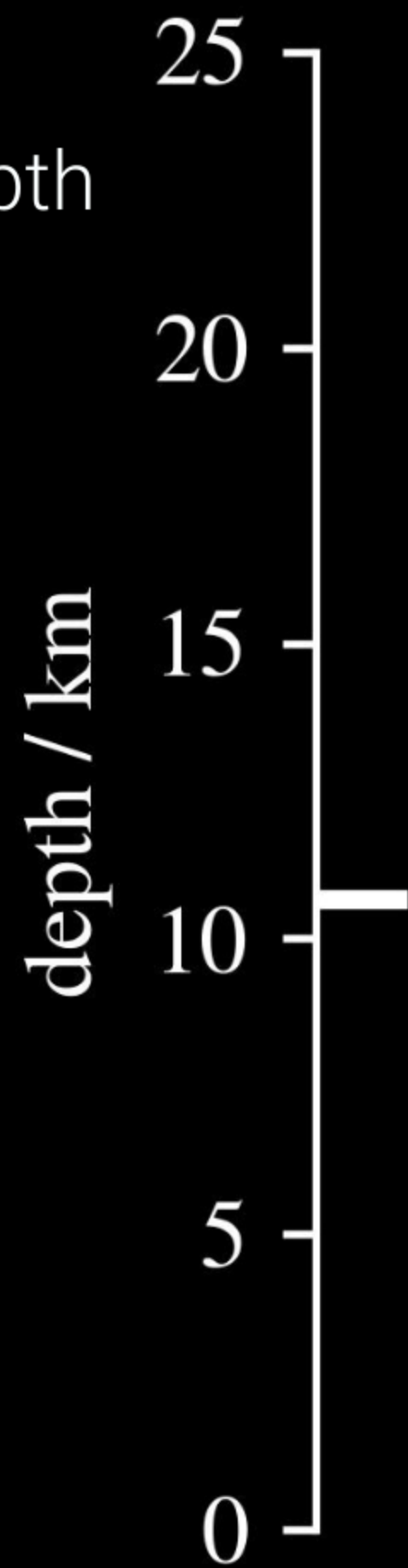
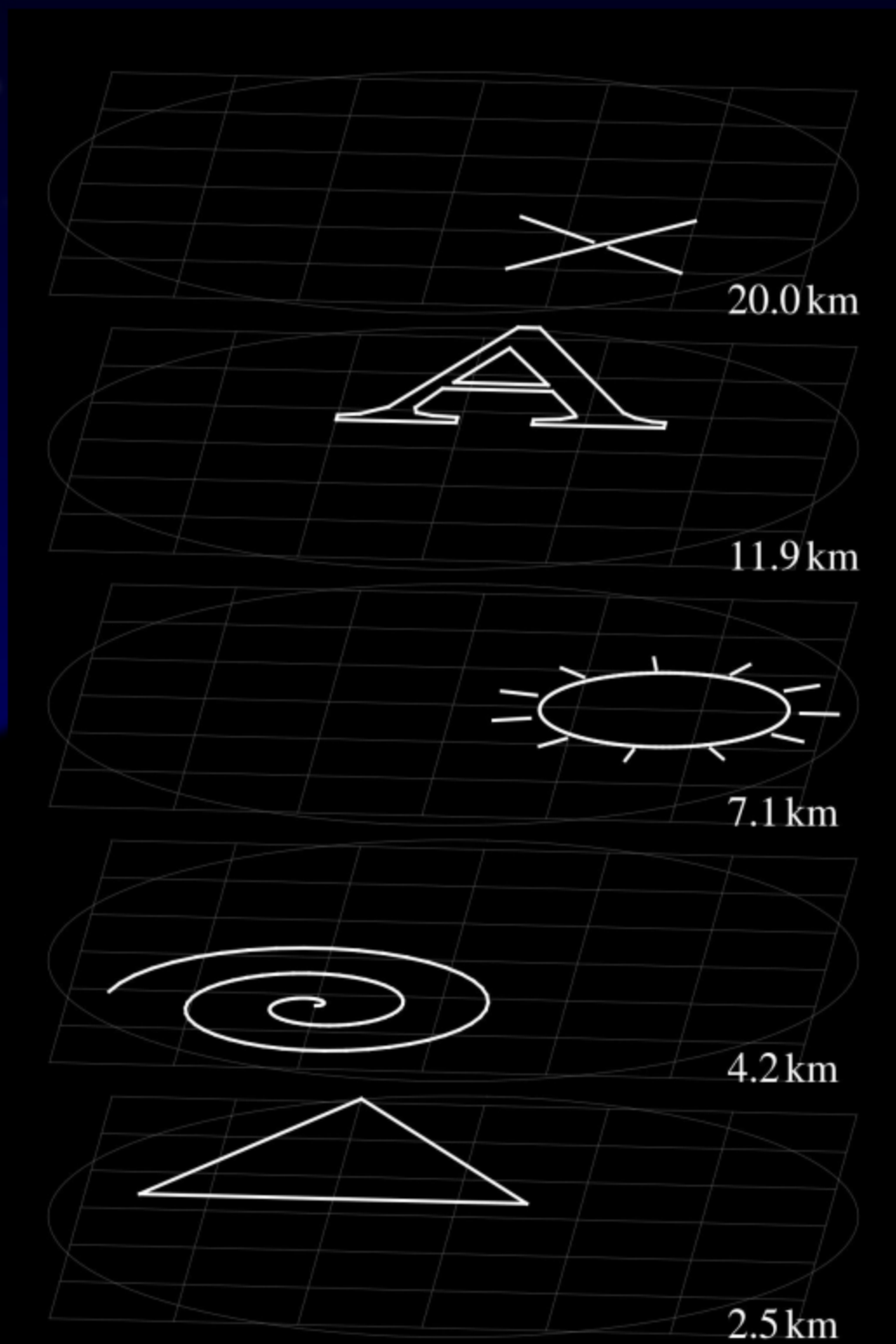
Optics

refocussing to any depth



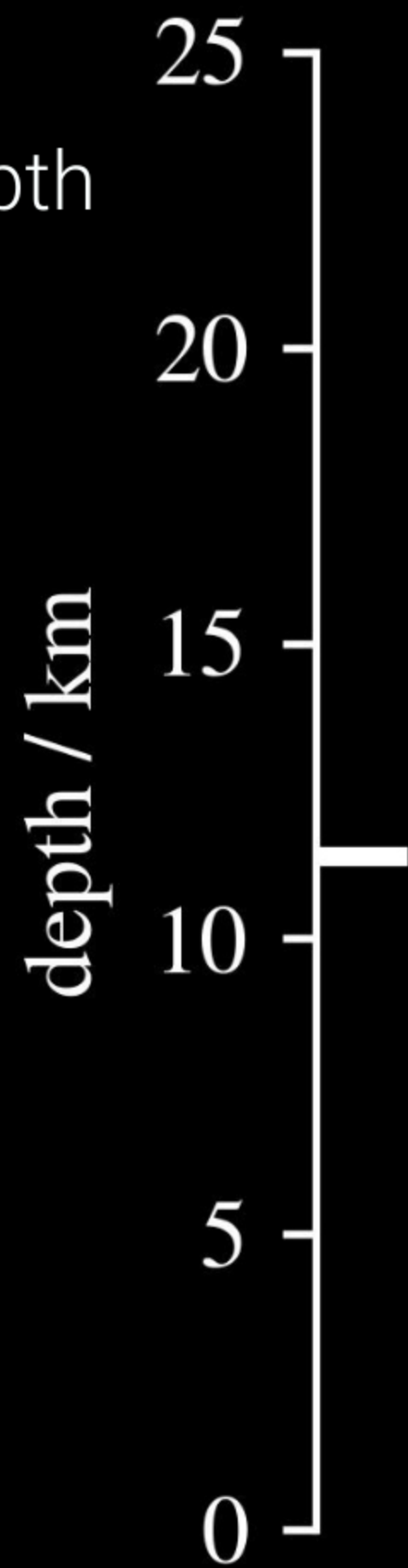
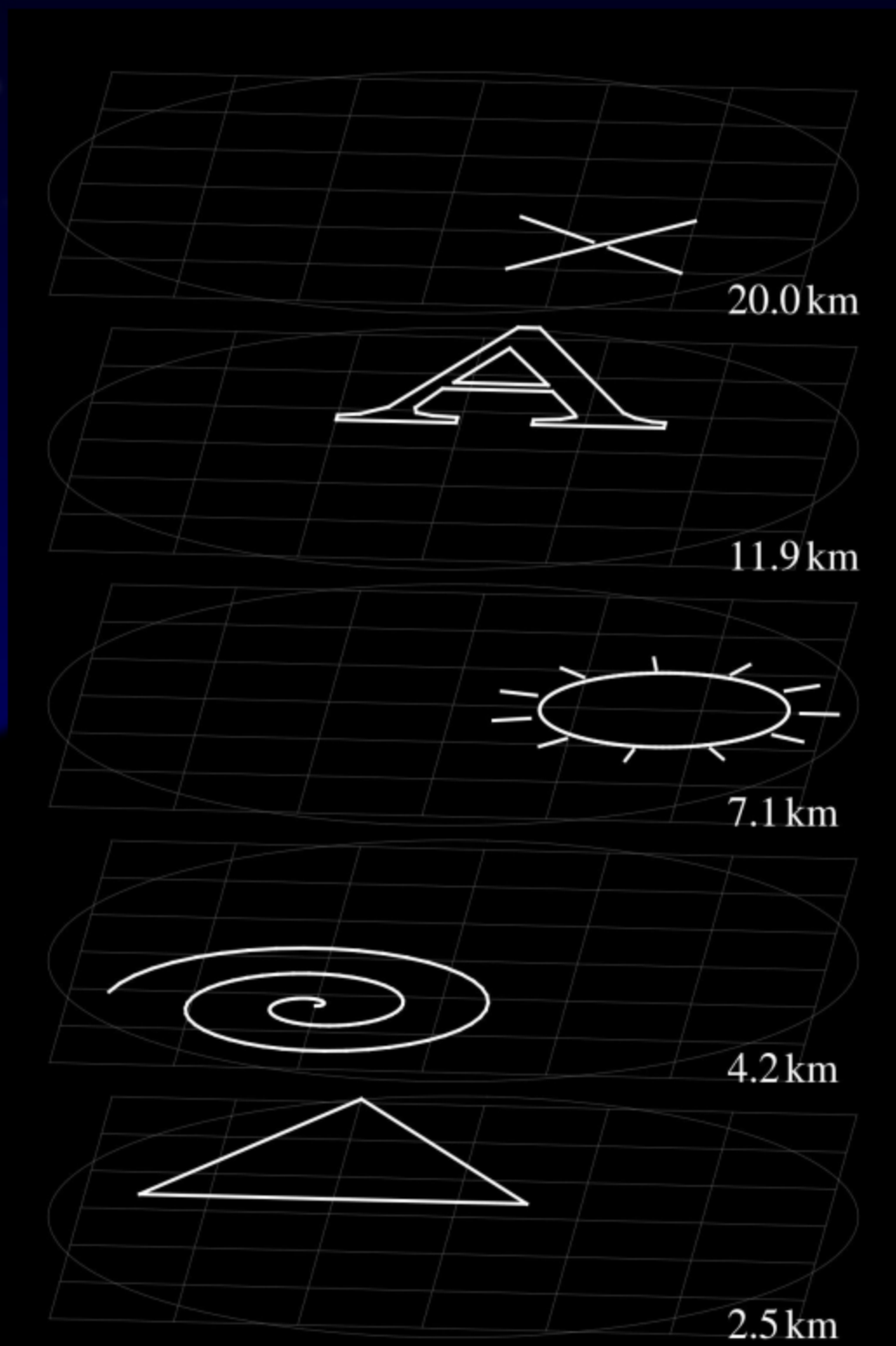
Optics

refocussing to any depth



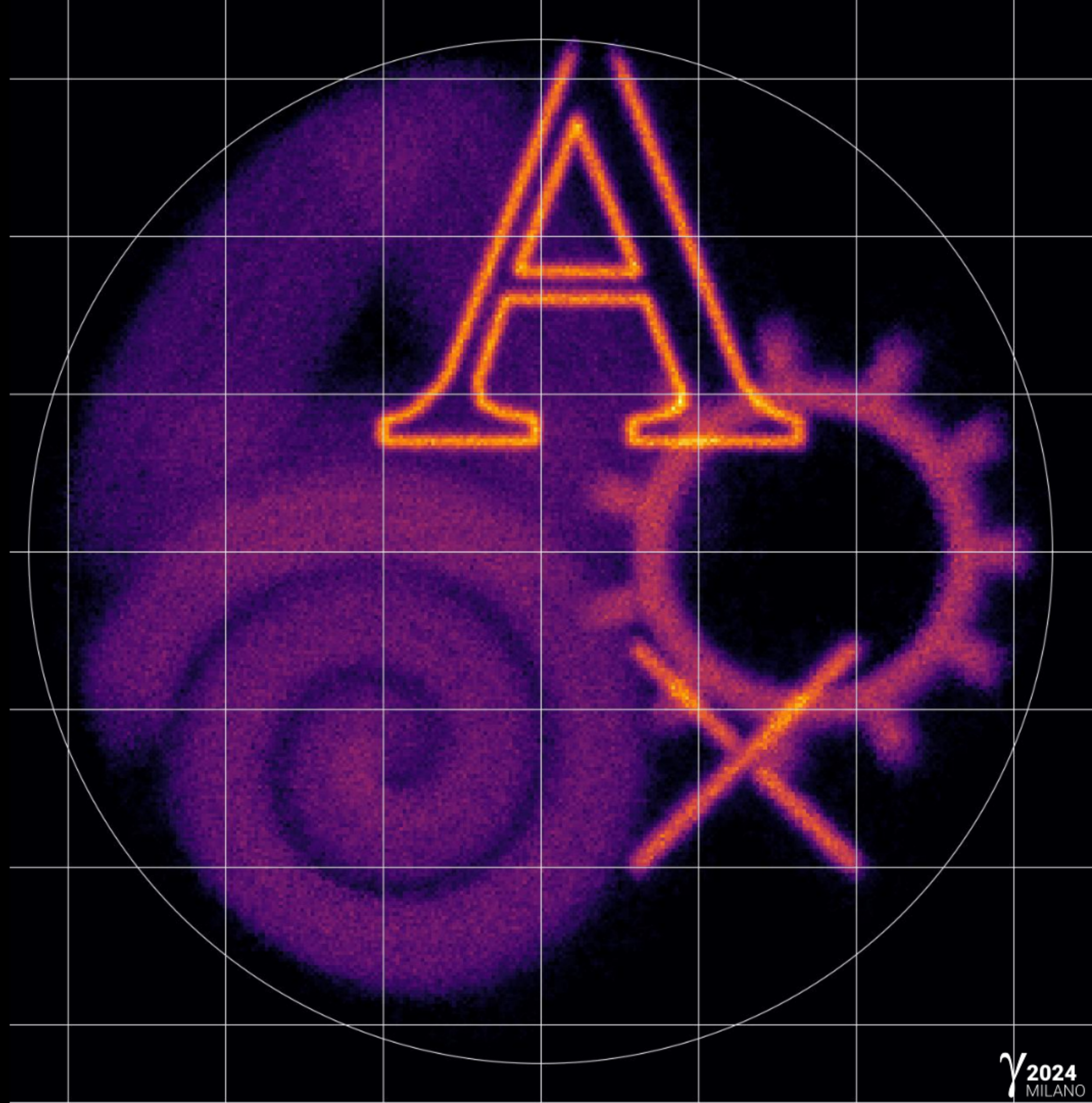
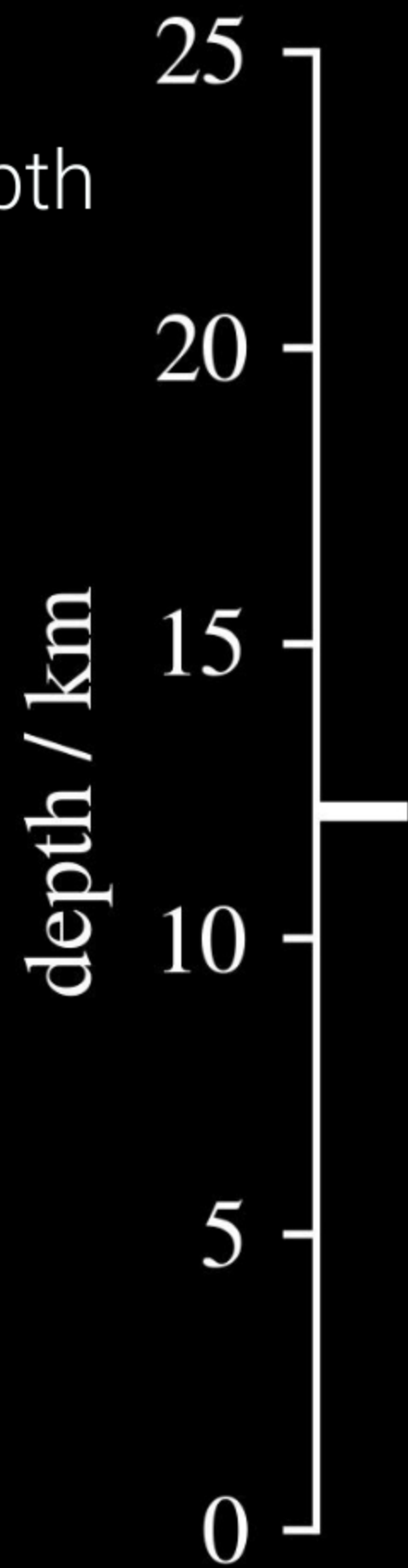
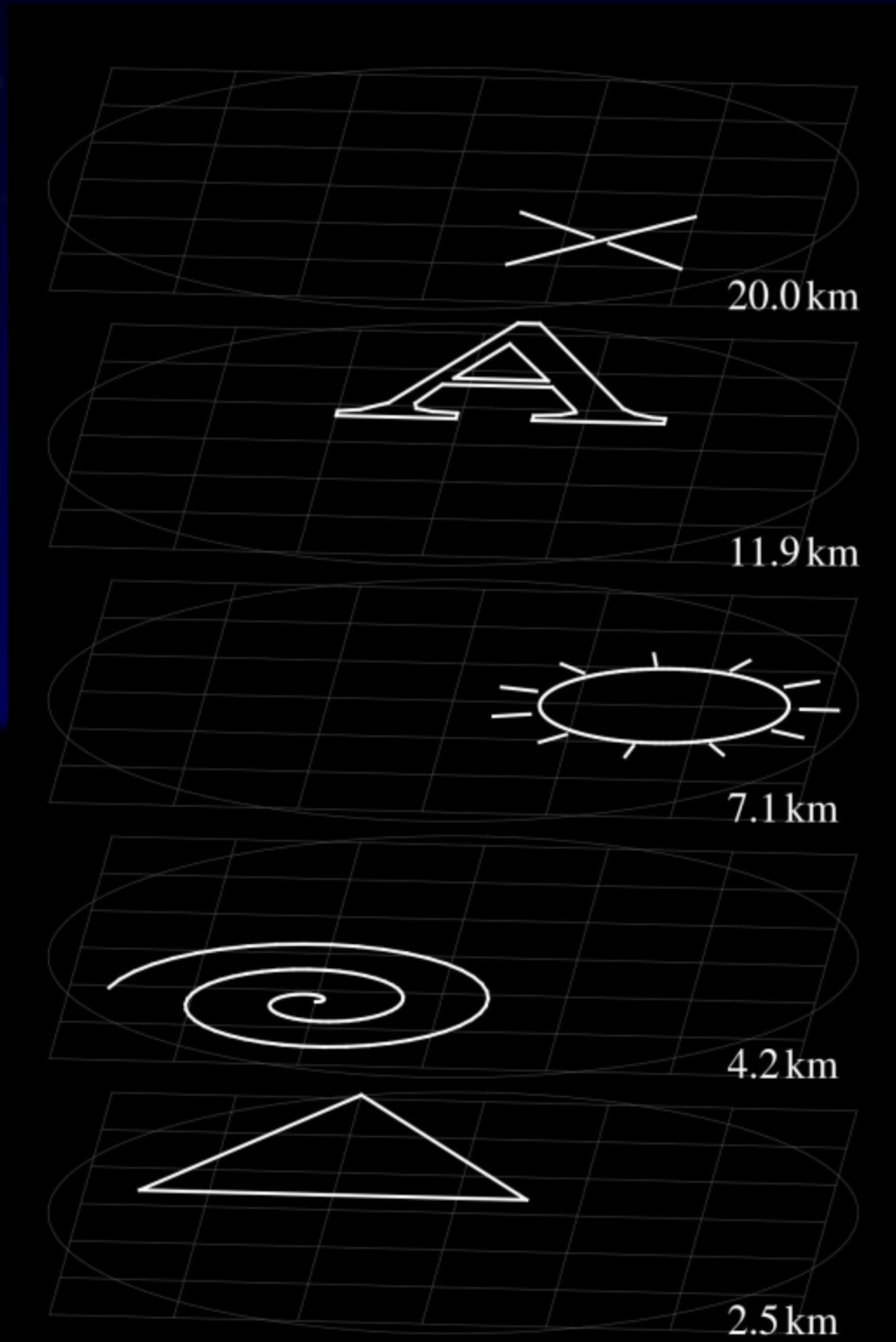
Optics

refocussing to any depth



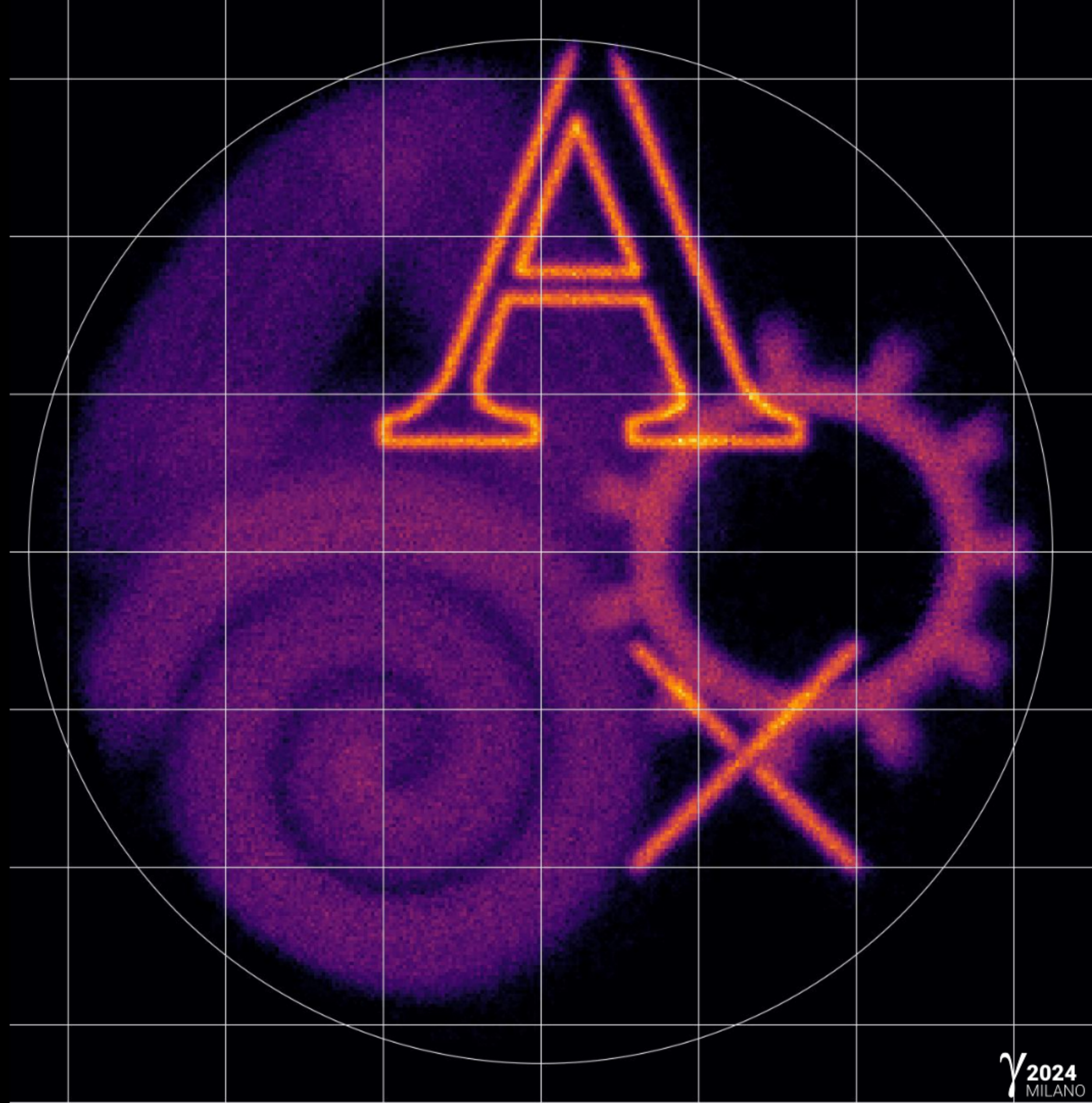
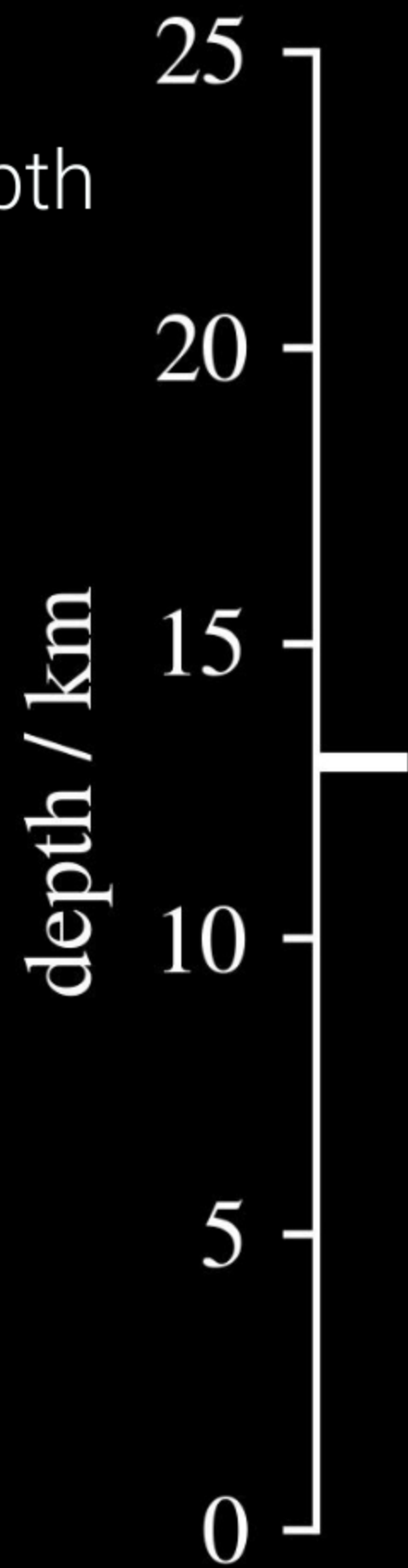
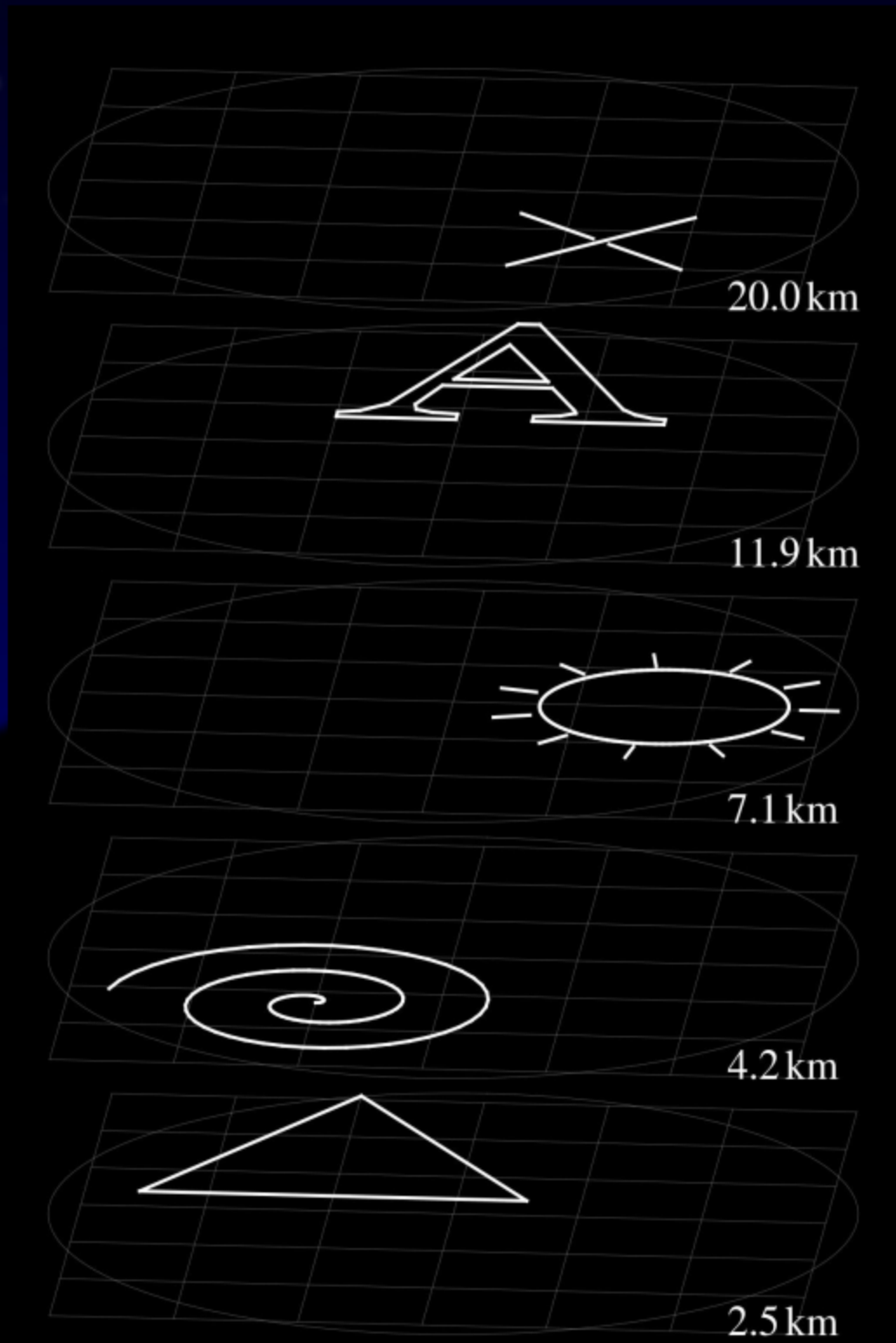
Optics

refocussing to any depth



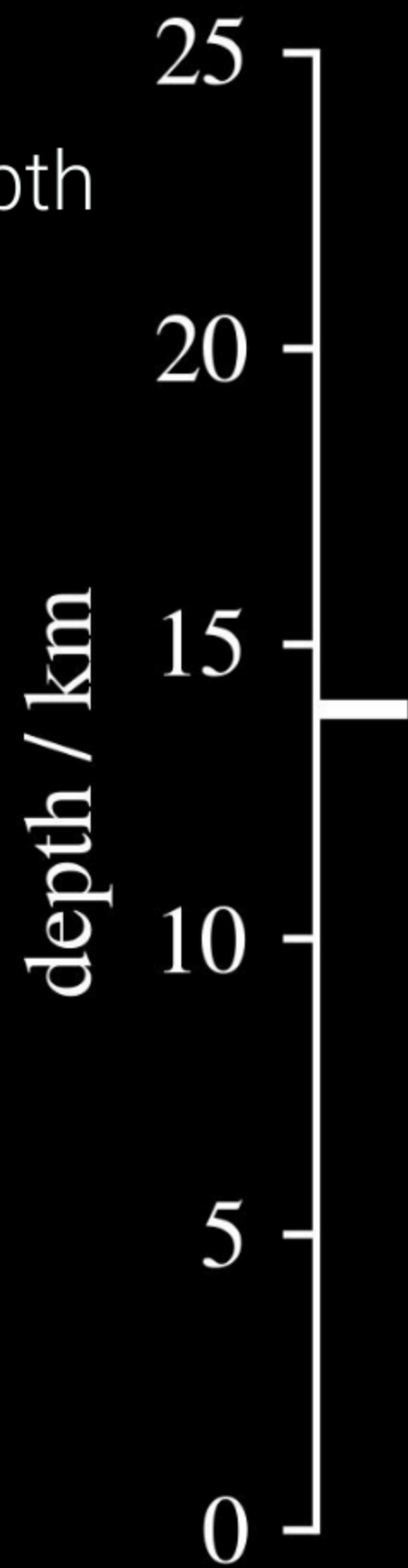
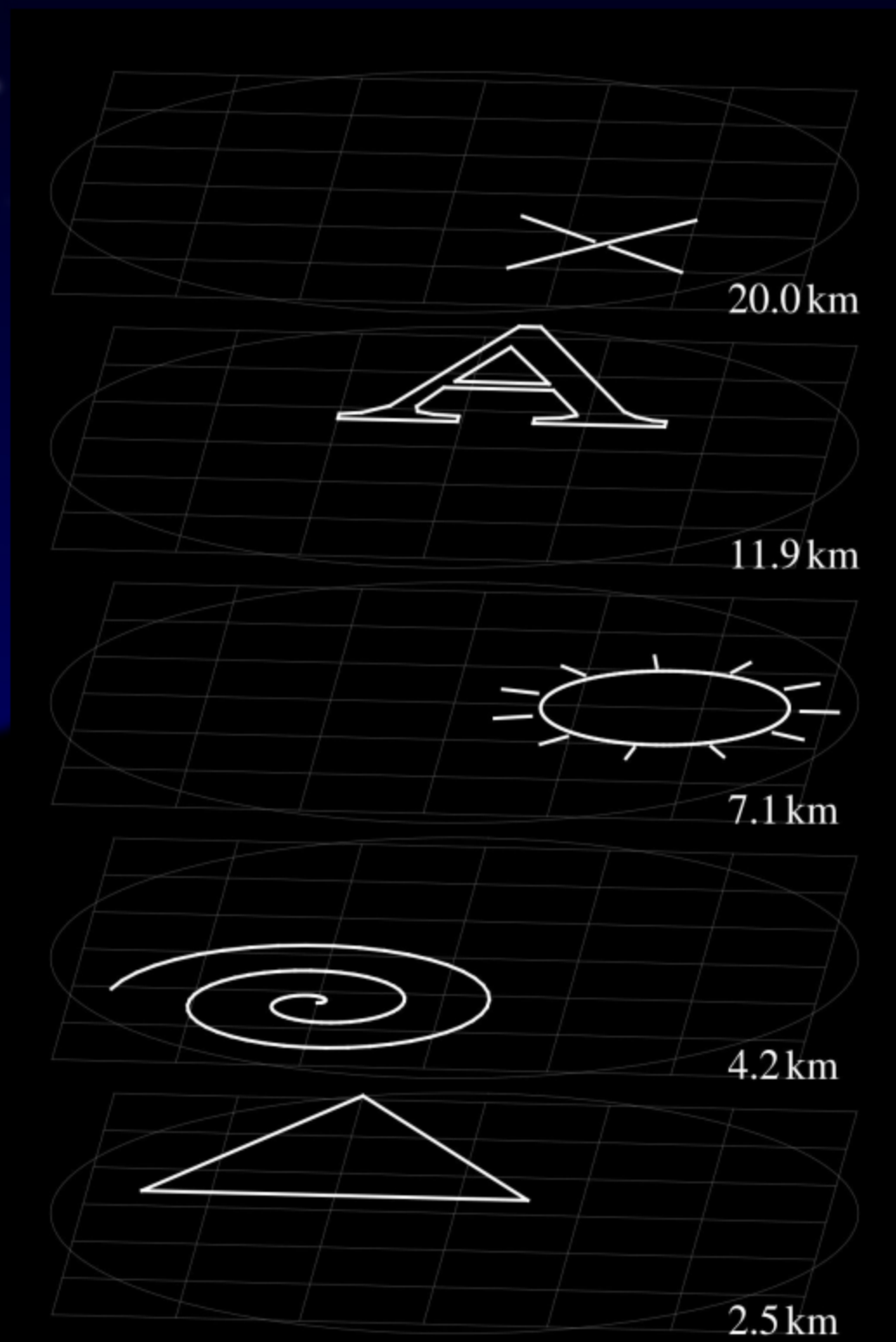
Optics

refocussing to any depth



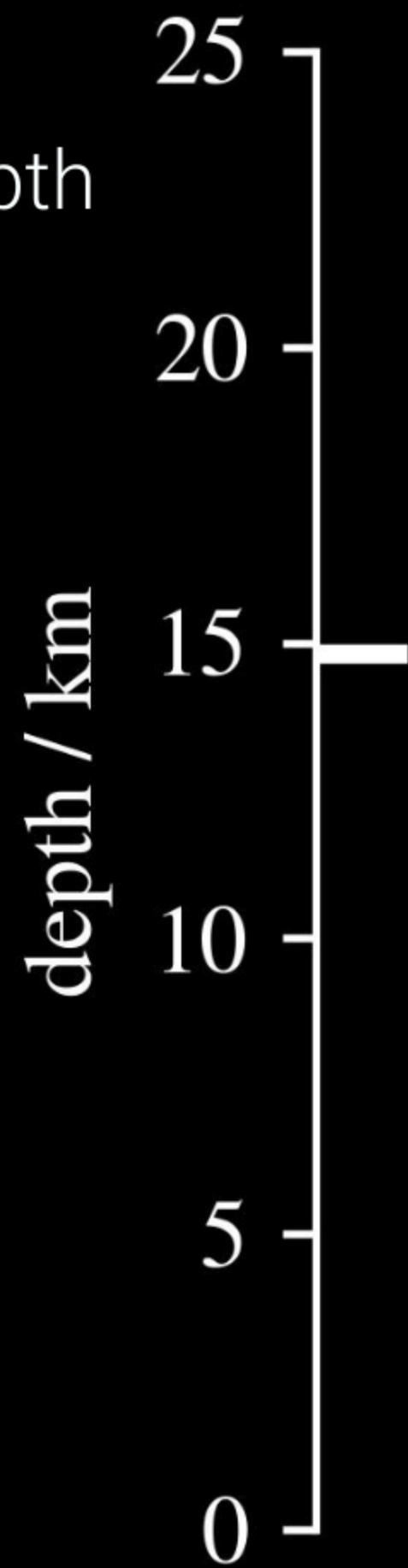
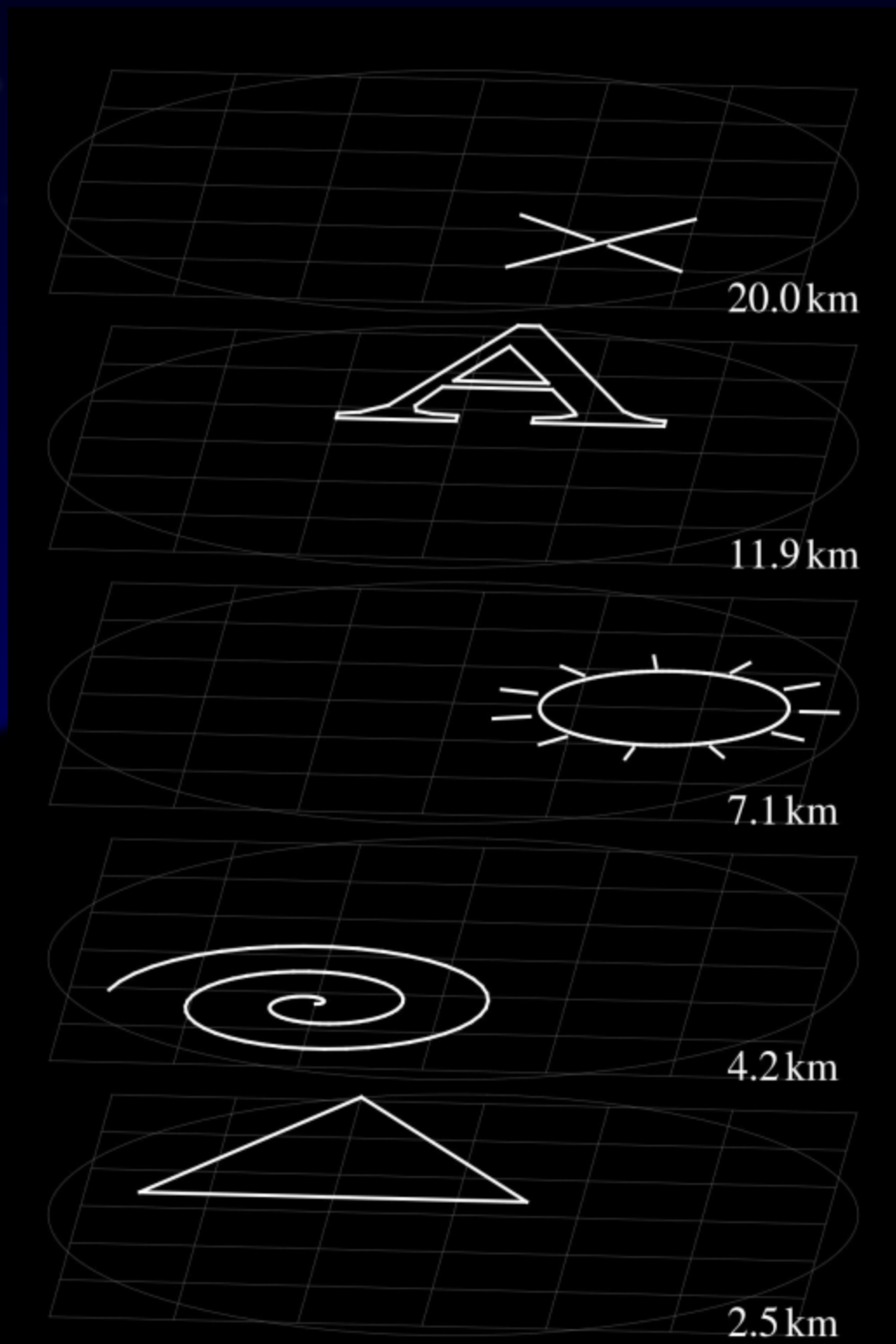
Optics

refocussing to any depth



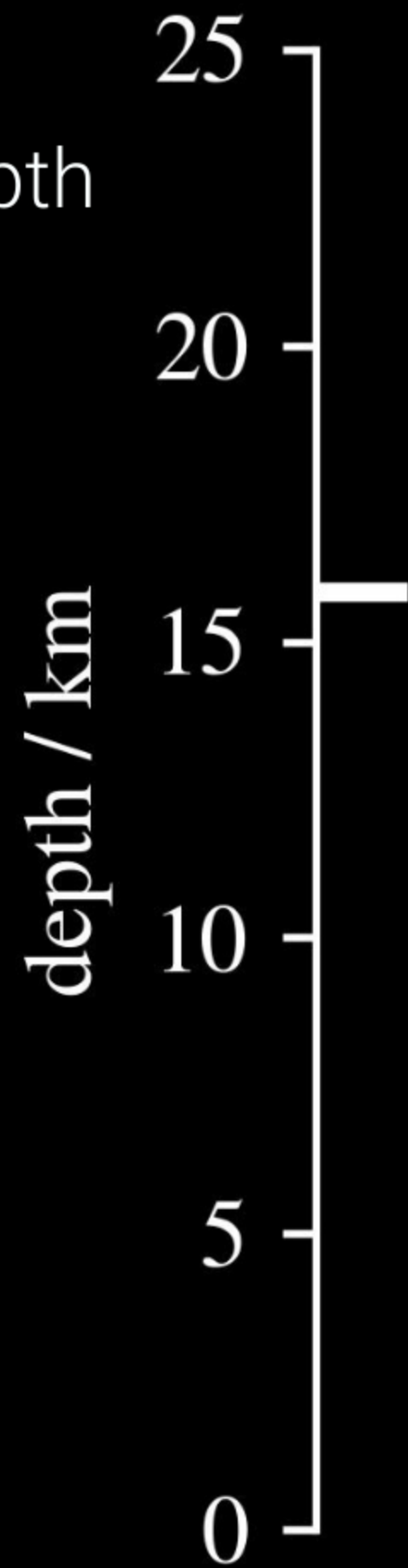
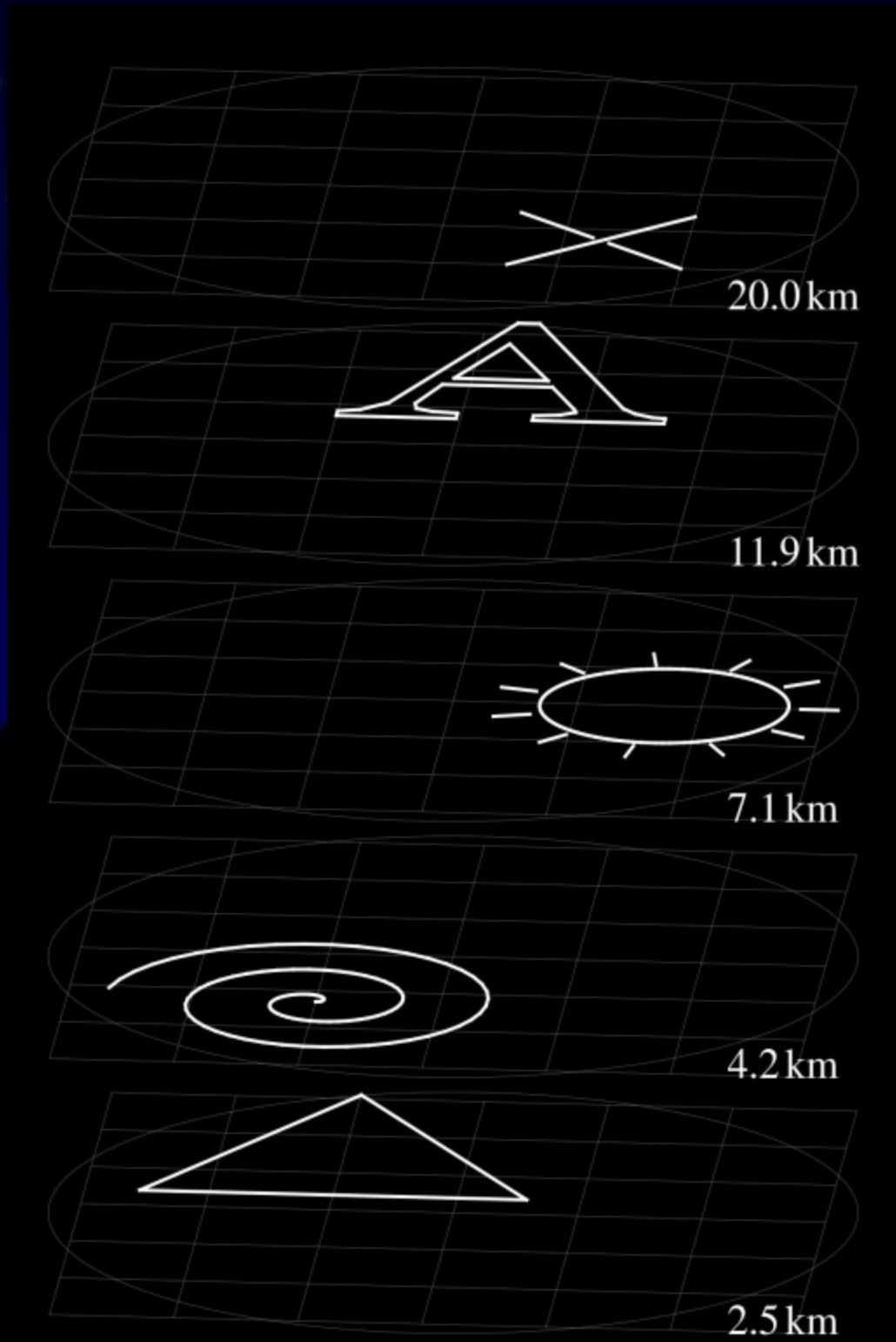
Optics

refocussing to any depth



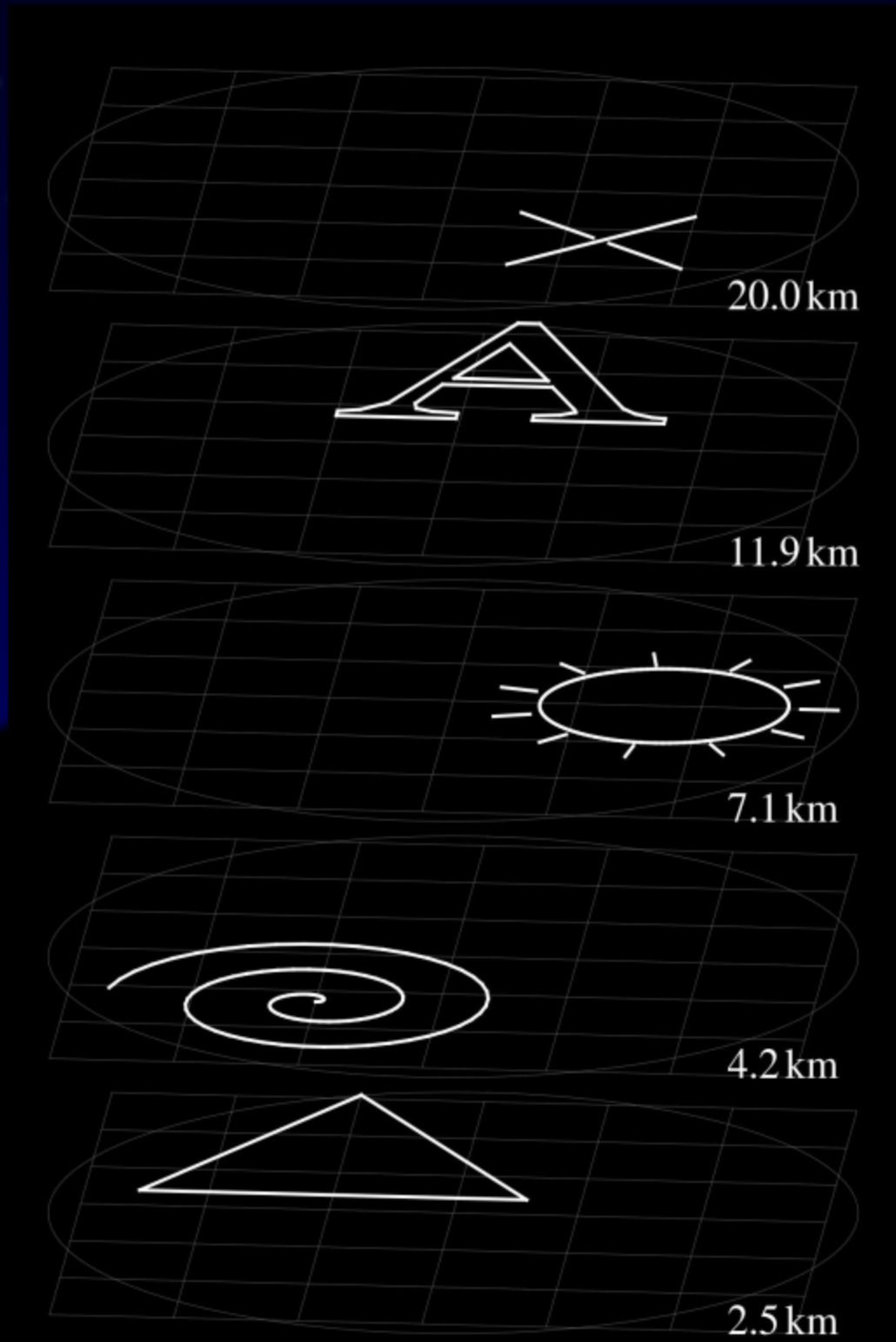
Optics

refocussing to any depth



Optics

refocussing to any depth



depth / km

25

20

15

10

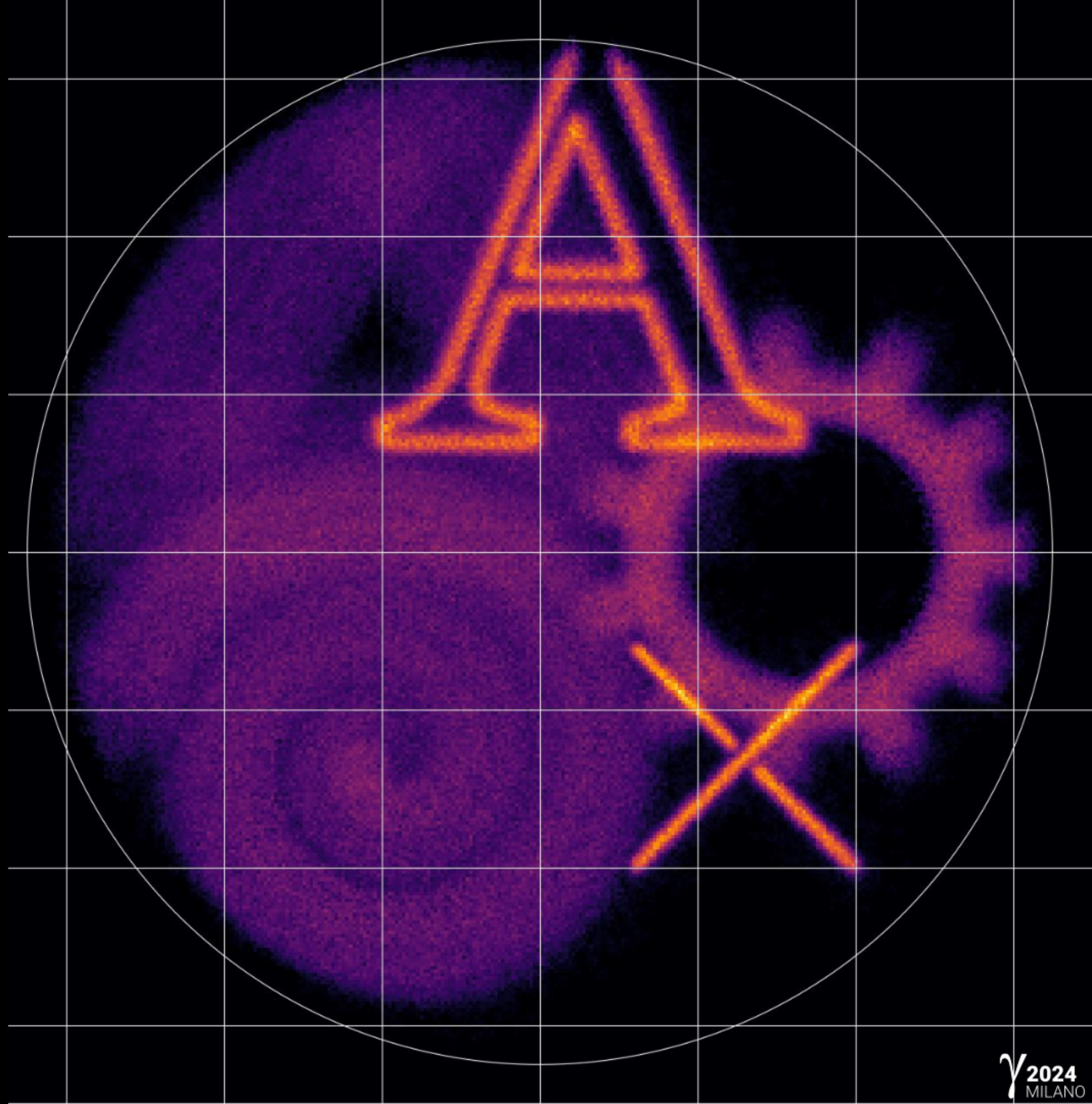
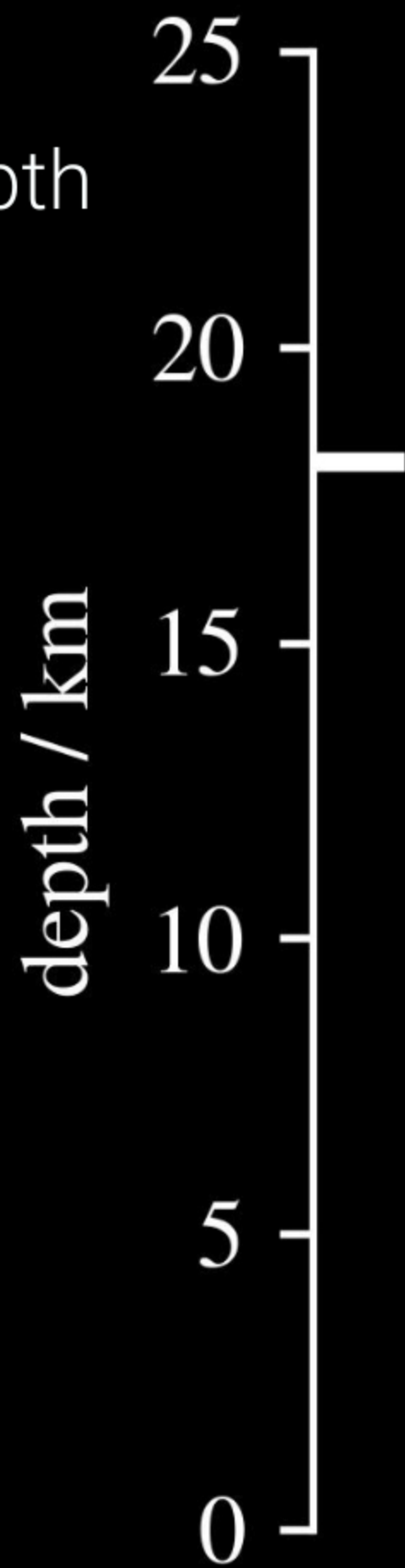
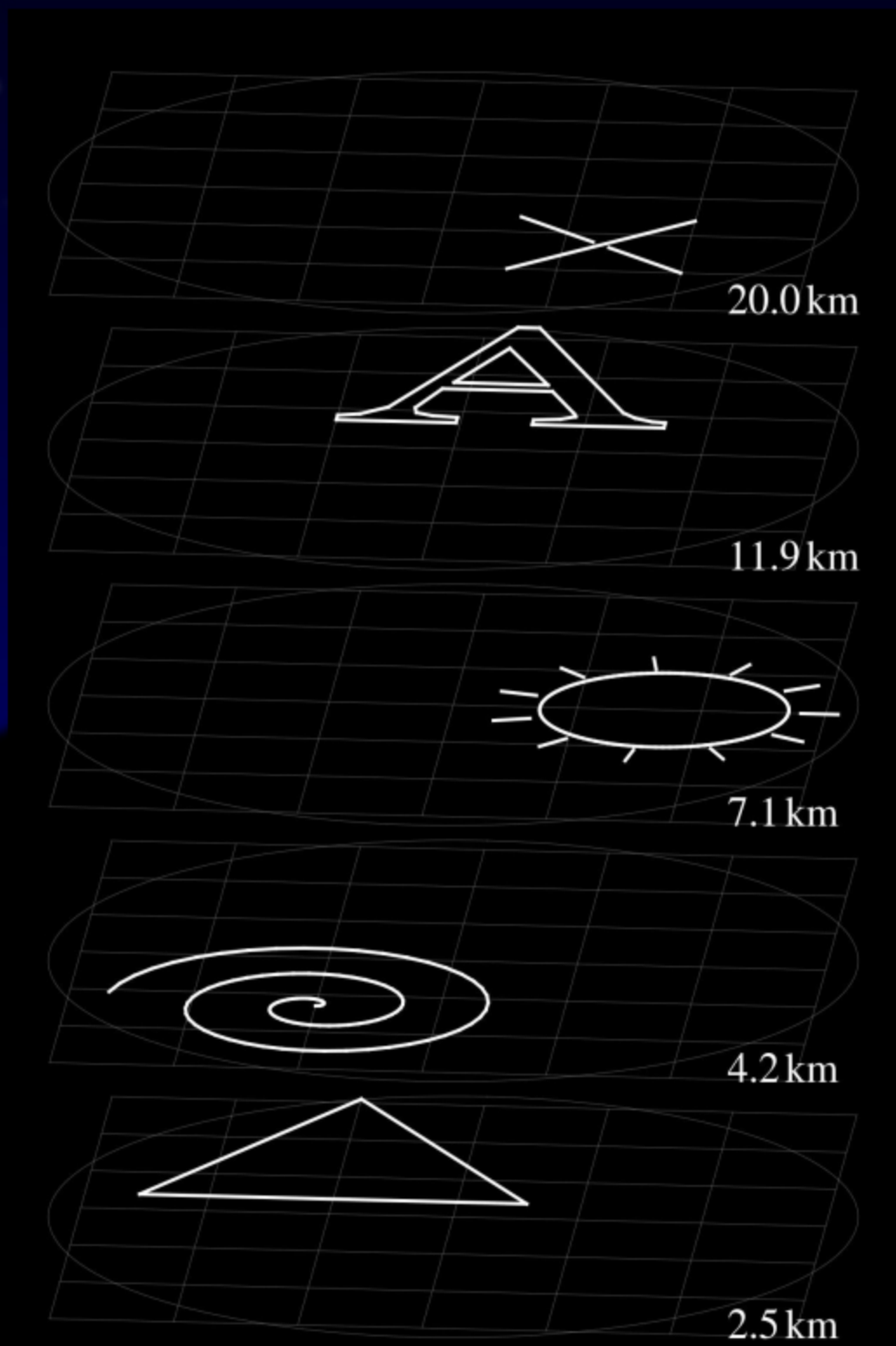
5

0



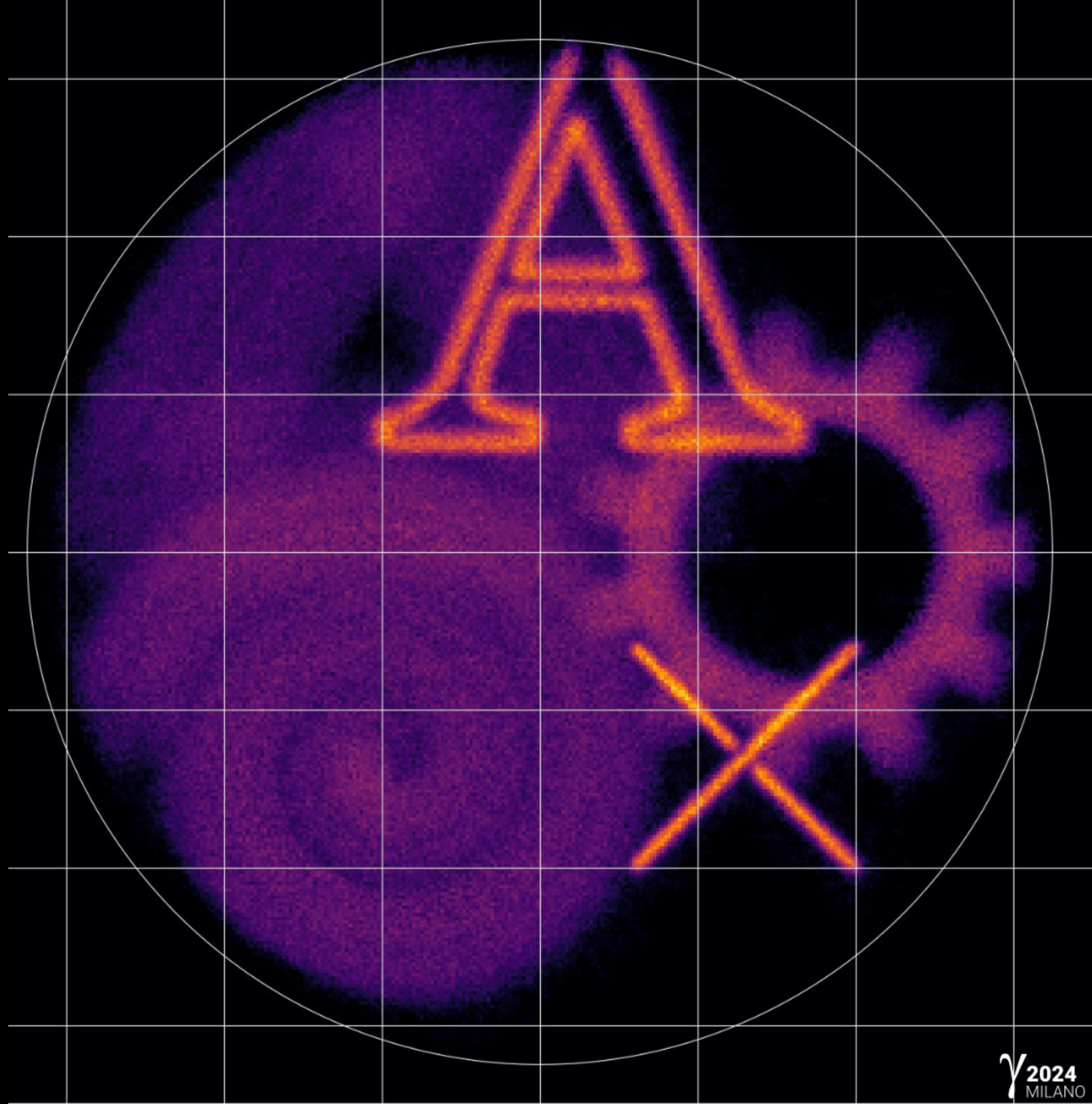
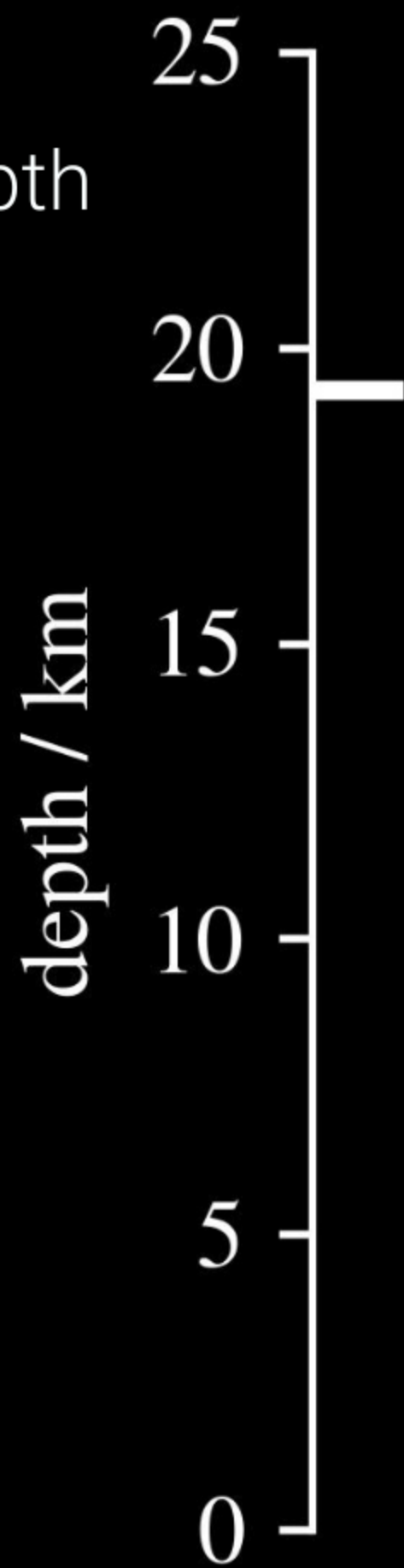
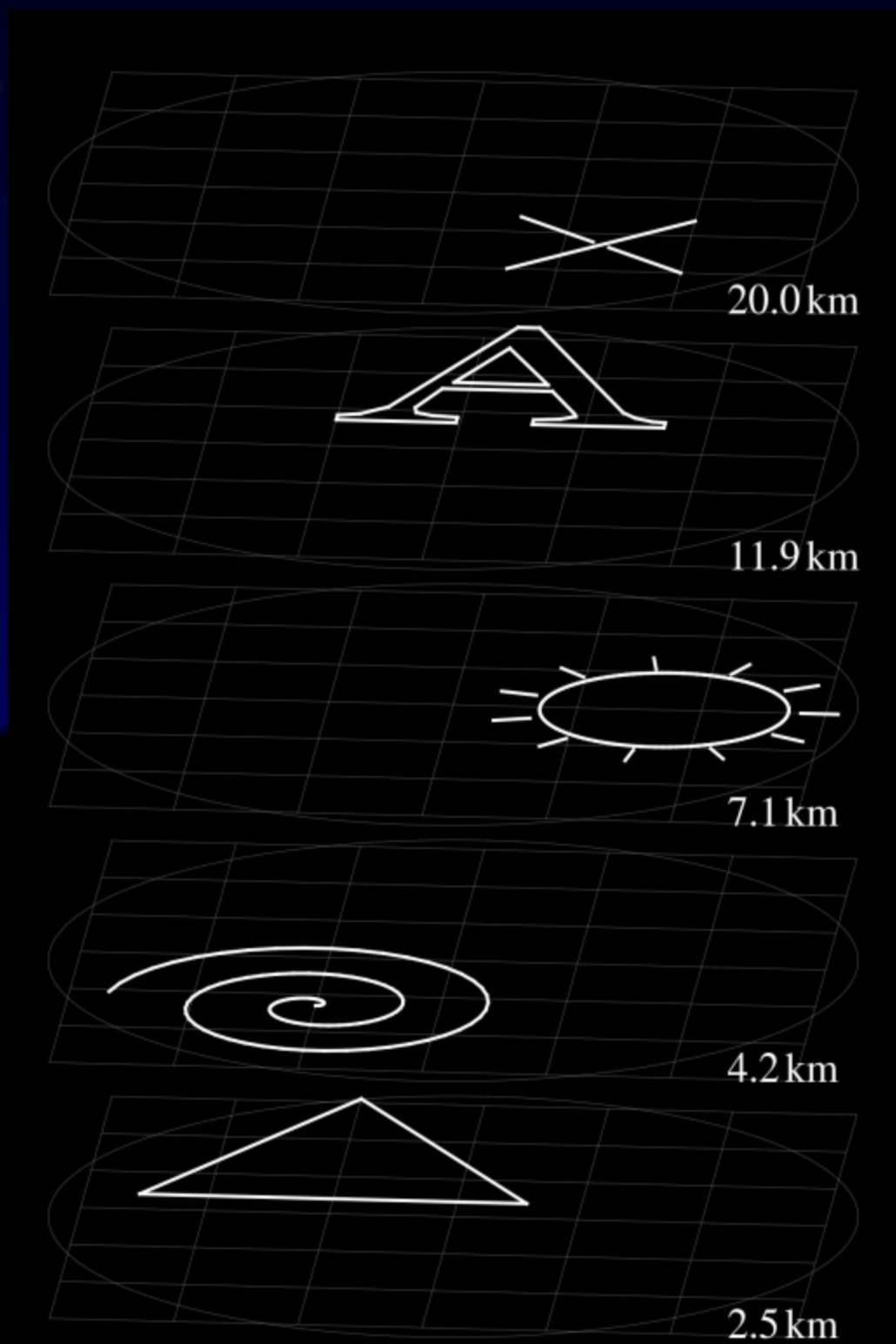
Optics

refocussing to any depth



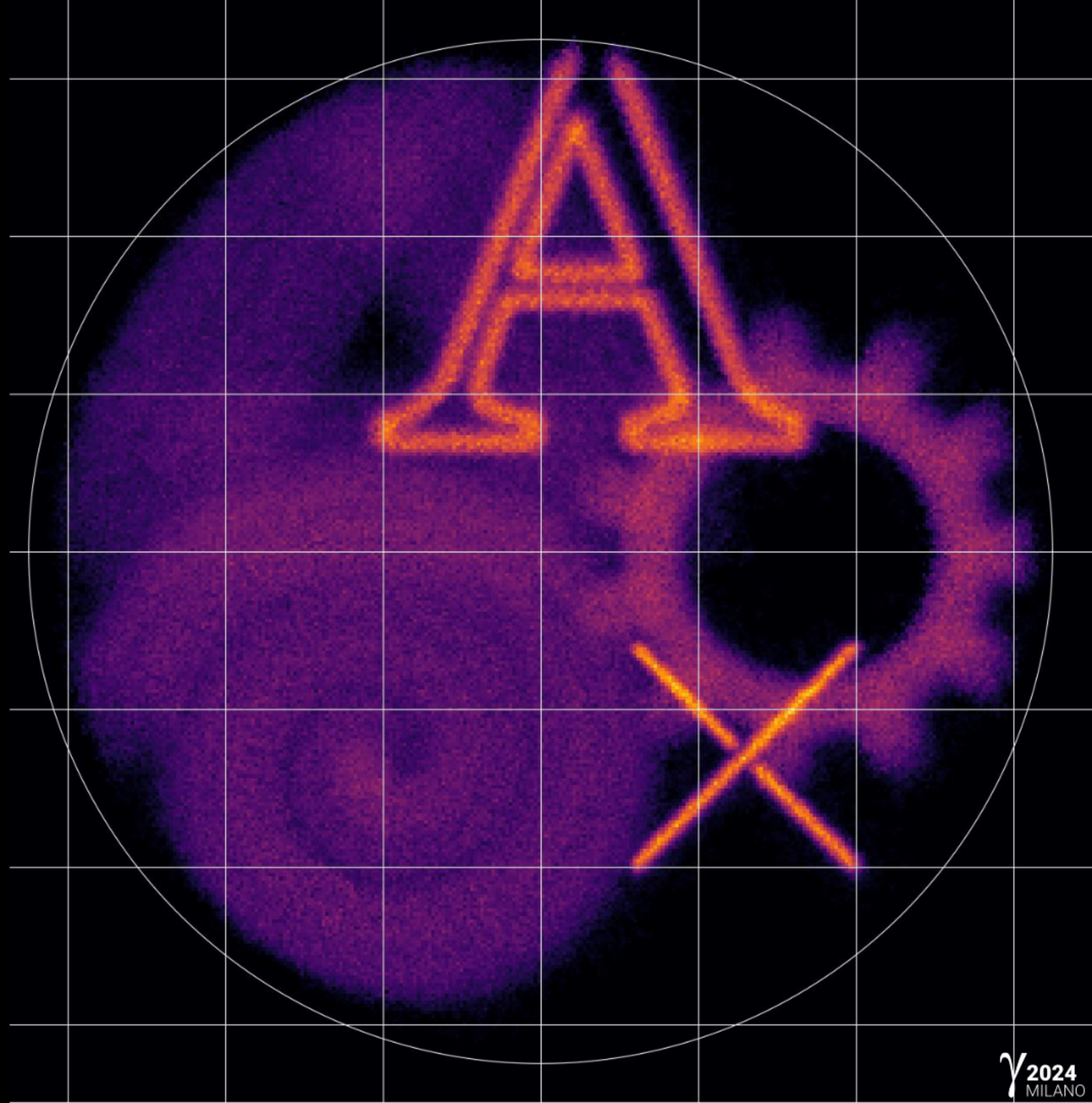
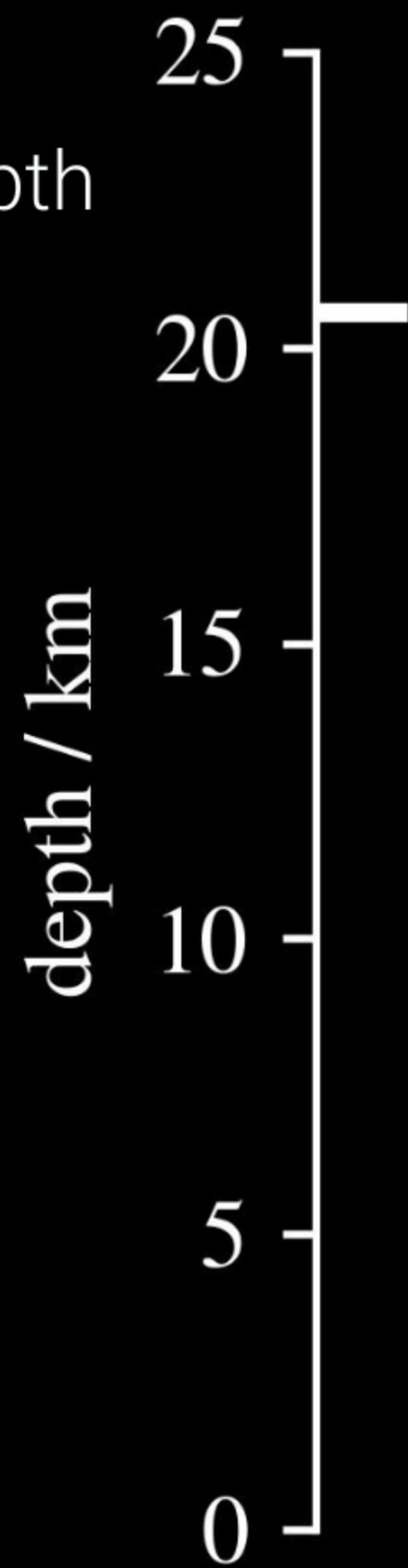
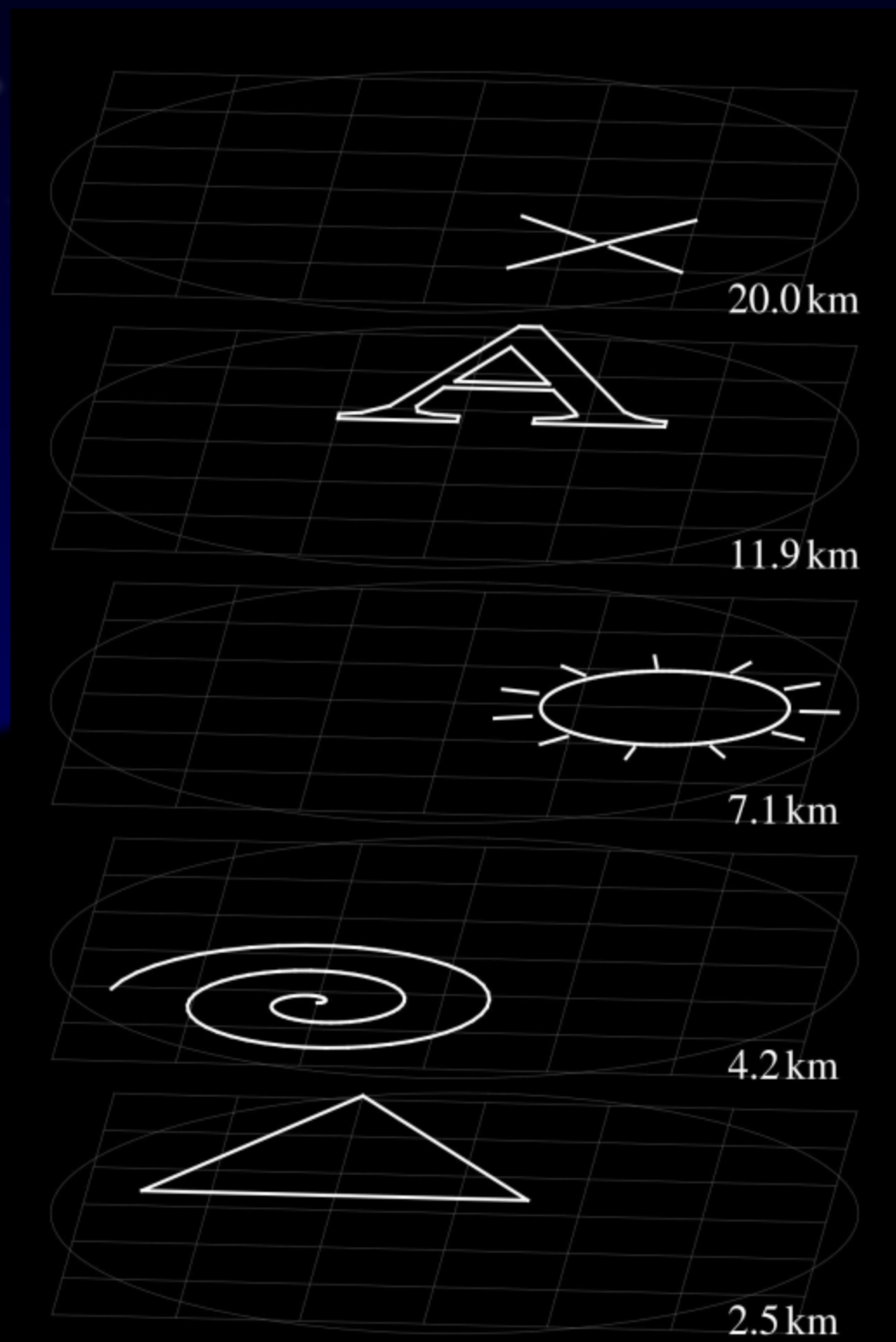
Optics

refocussing to any depth



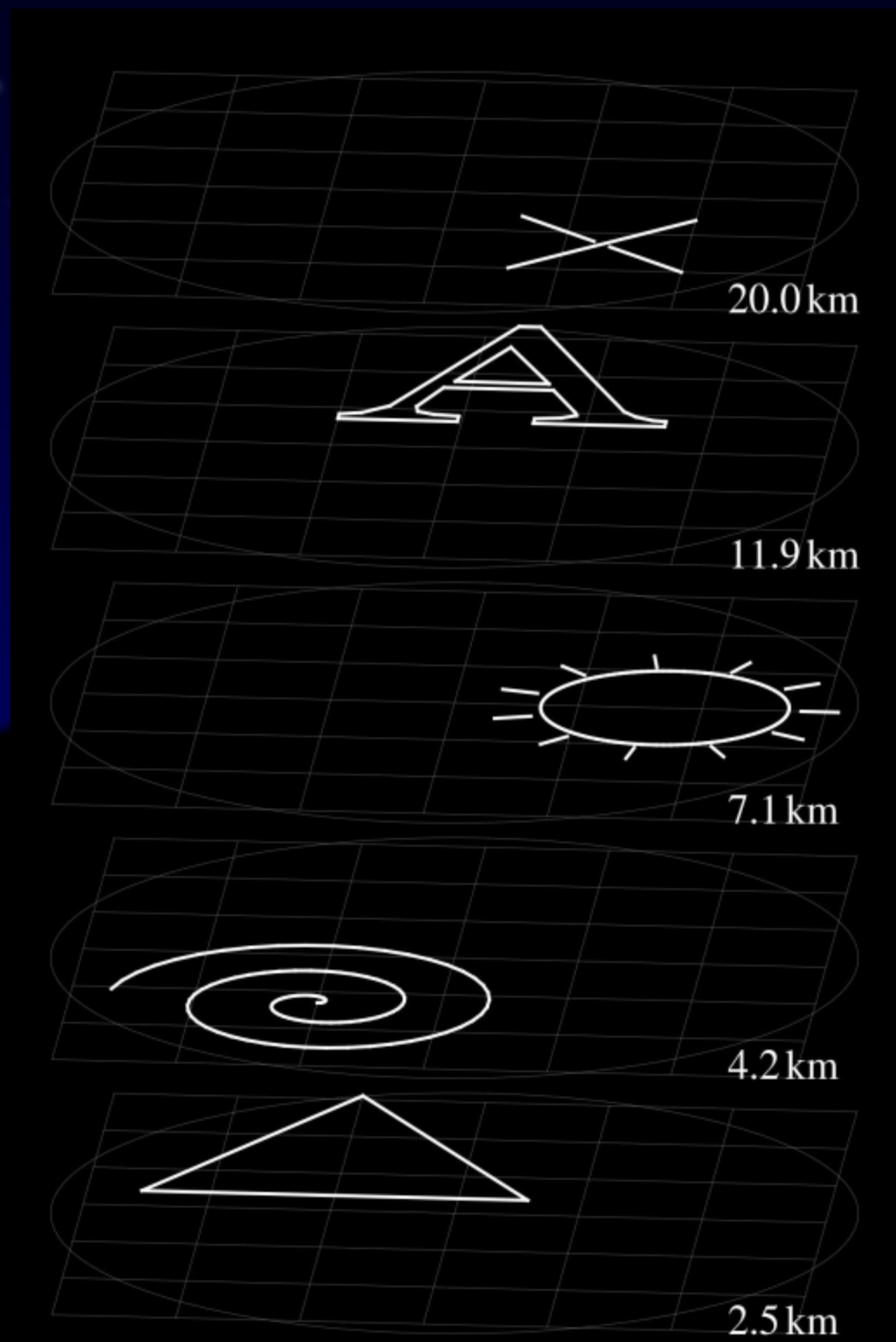
Optics

refocussing to any depth



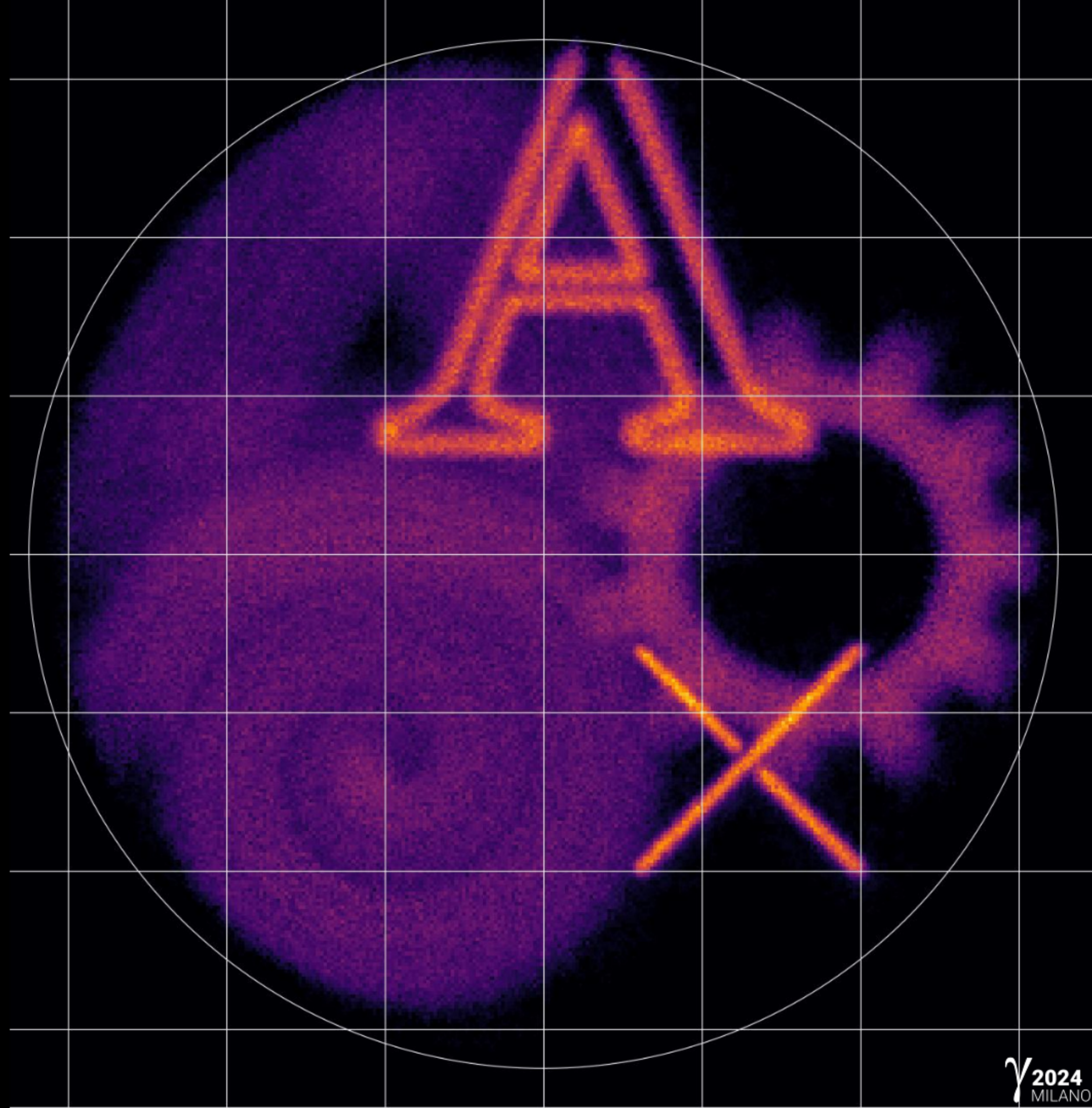
Optics

refocussing to any depth



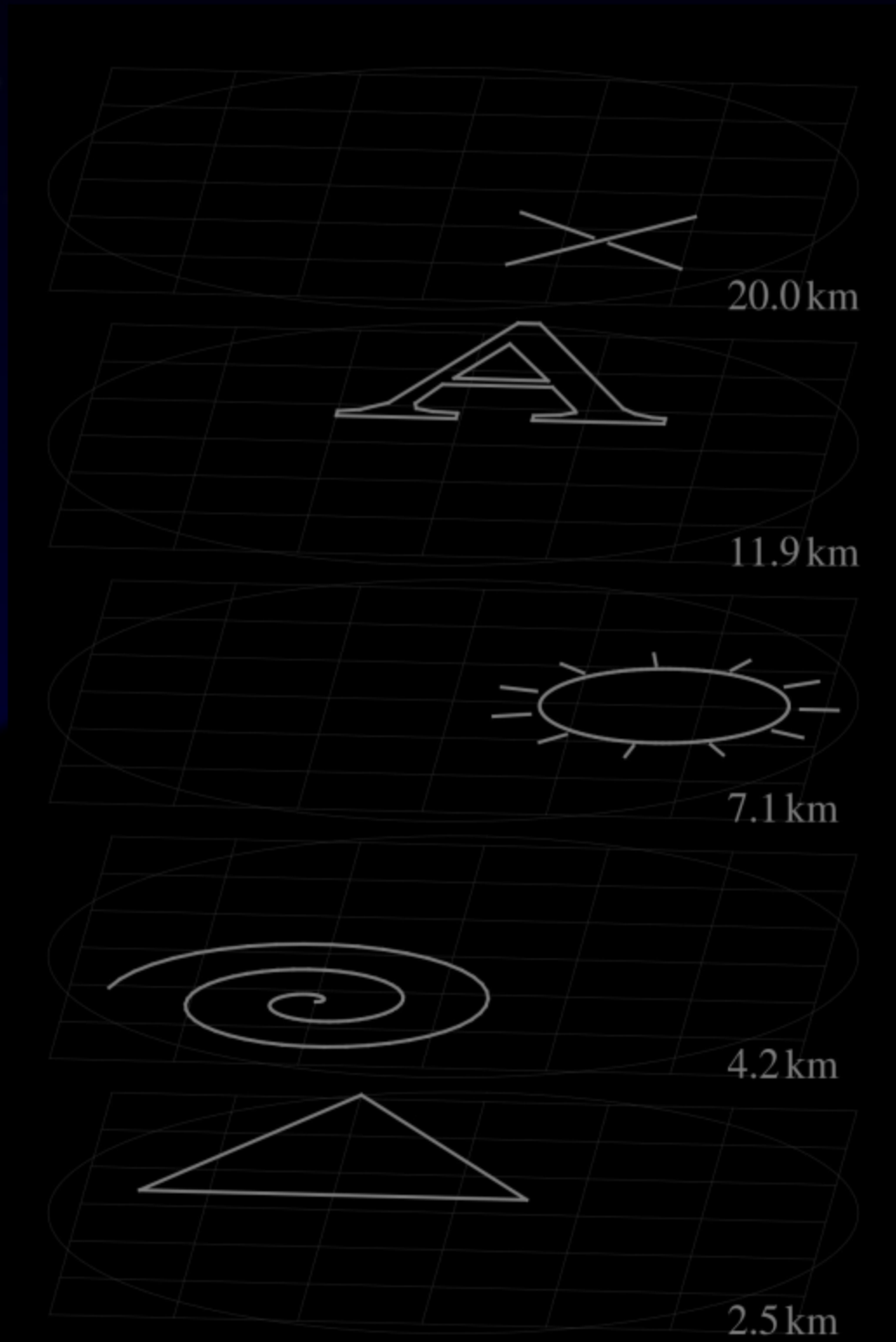
depth / km

25
20
15
10
5
0



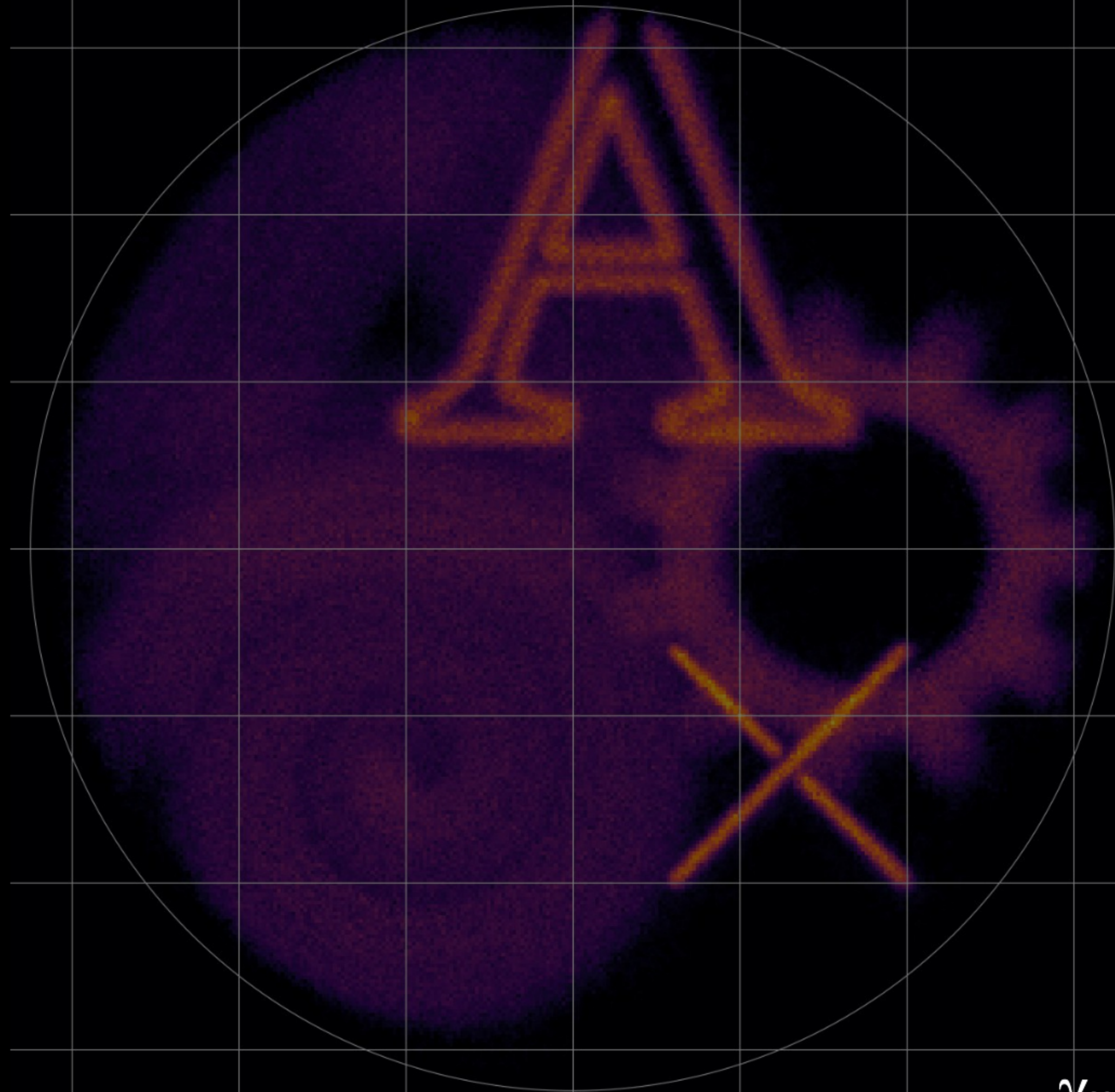
Optics

refocussing to any depth



depth / km

25
20
15
10
5
0



Conclusion



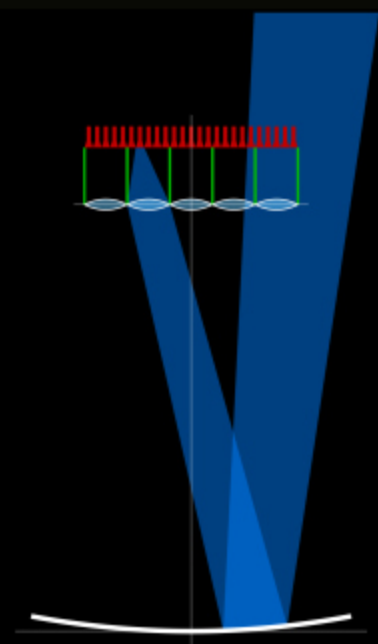
Conclusion

Cherenkov plenoscope



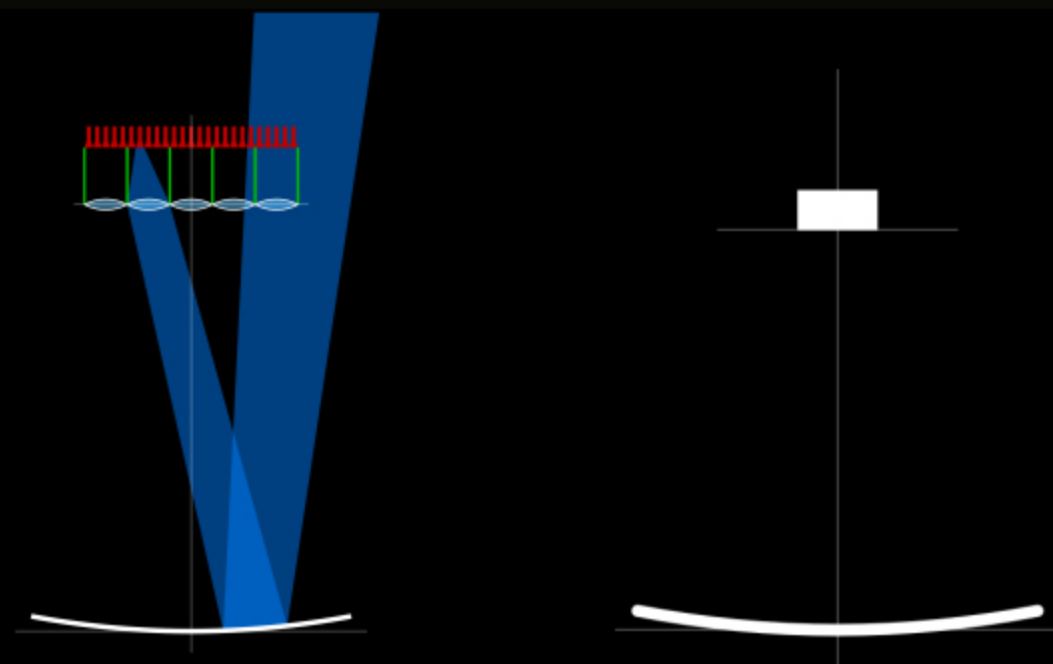
Conclusion

Cherenkov plenoscope



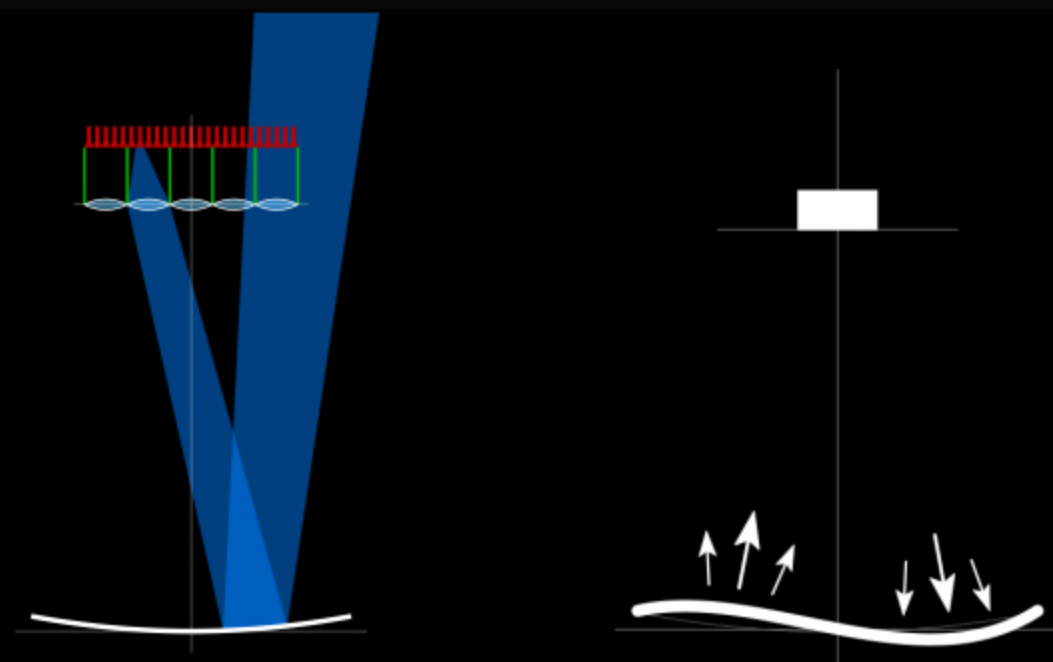
Conclusion

Cherenkov plenoscope



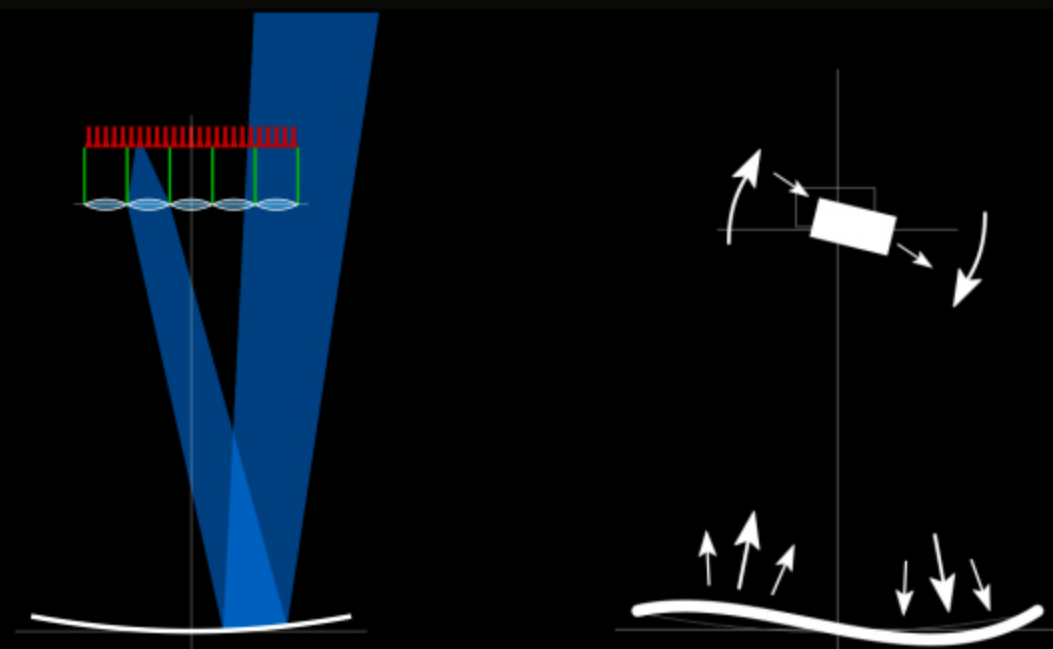
Conclusion

Cherenkov plenoscope



Conclusion

Cherenkov plenoscope



Conclusion

Cherenkov plenoscope

