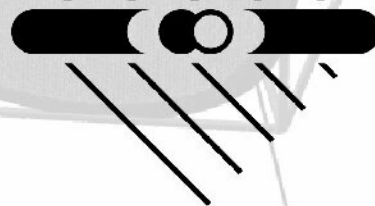


Advancing the atmospheric Cherenkov-method to detect gamma-rays with one Giga electron Volt

Sebastian Achim Mueller

Max-Planck-Institute for Nuclear Physics

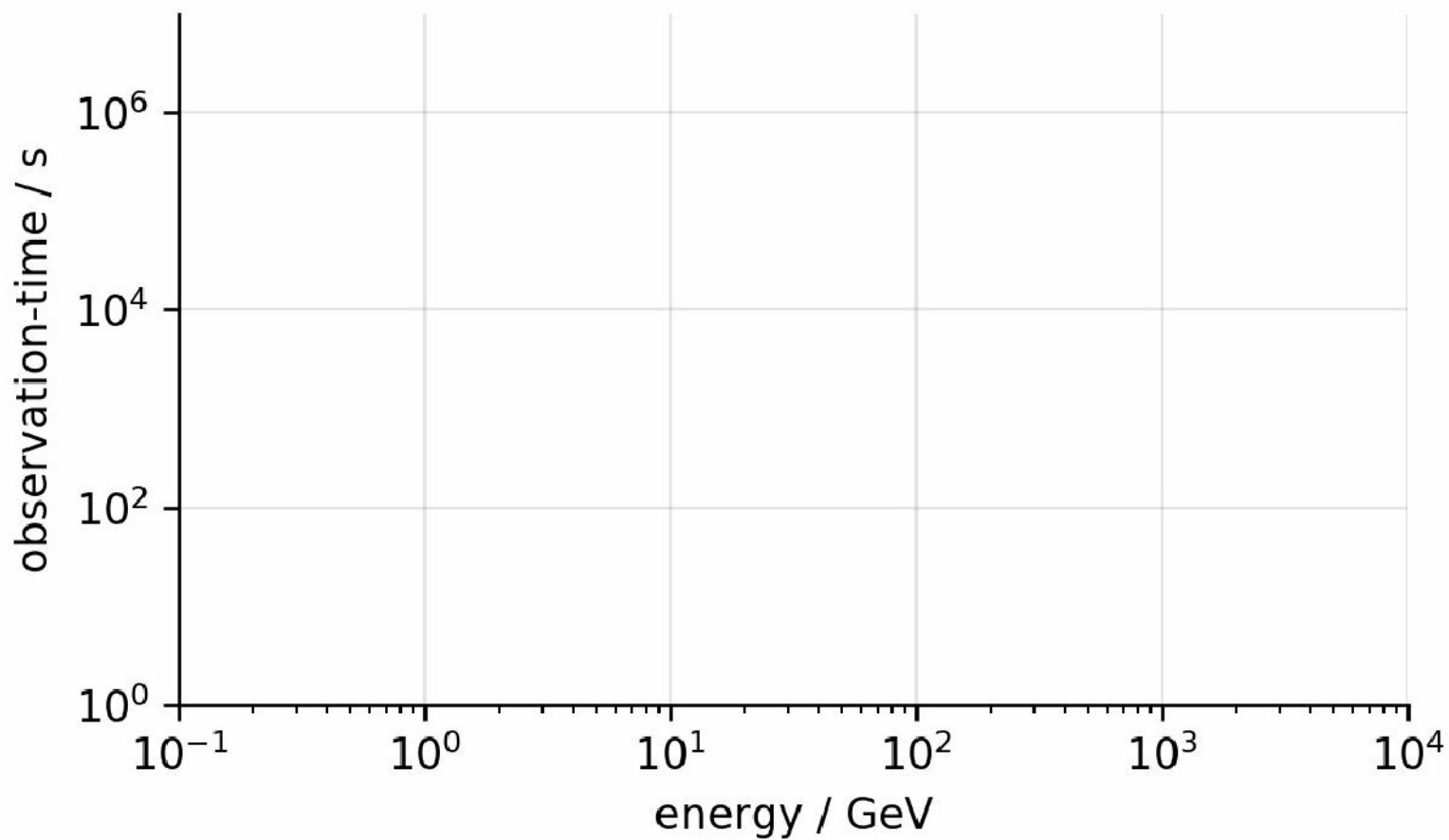
sebastian-achim.mueller@mpi-hd.mpg.de



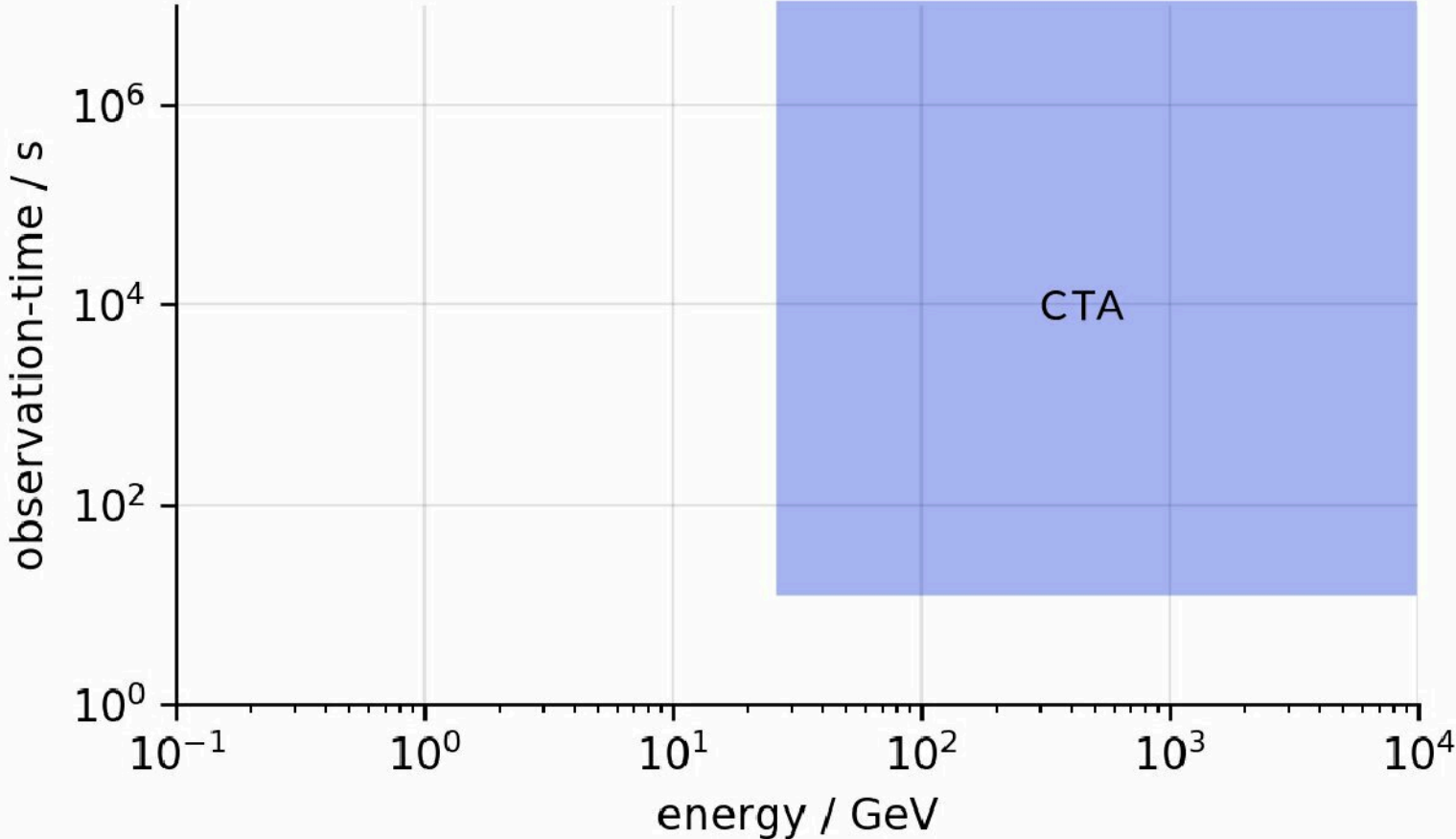
γ 2022

7th Heidelberg International Symposium on
High Energy Gamma-Ray Astronomy
Barcelona, July 4-8 2022

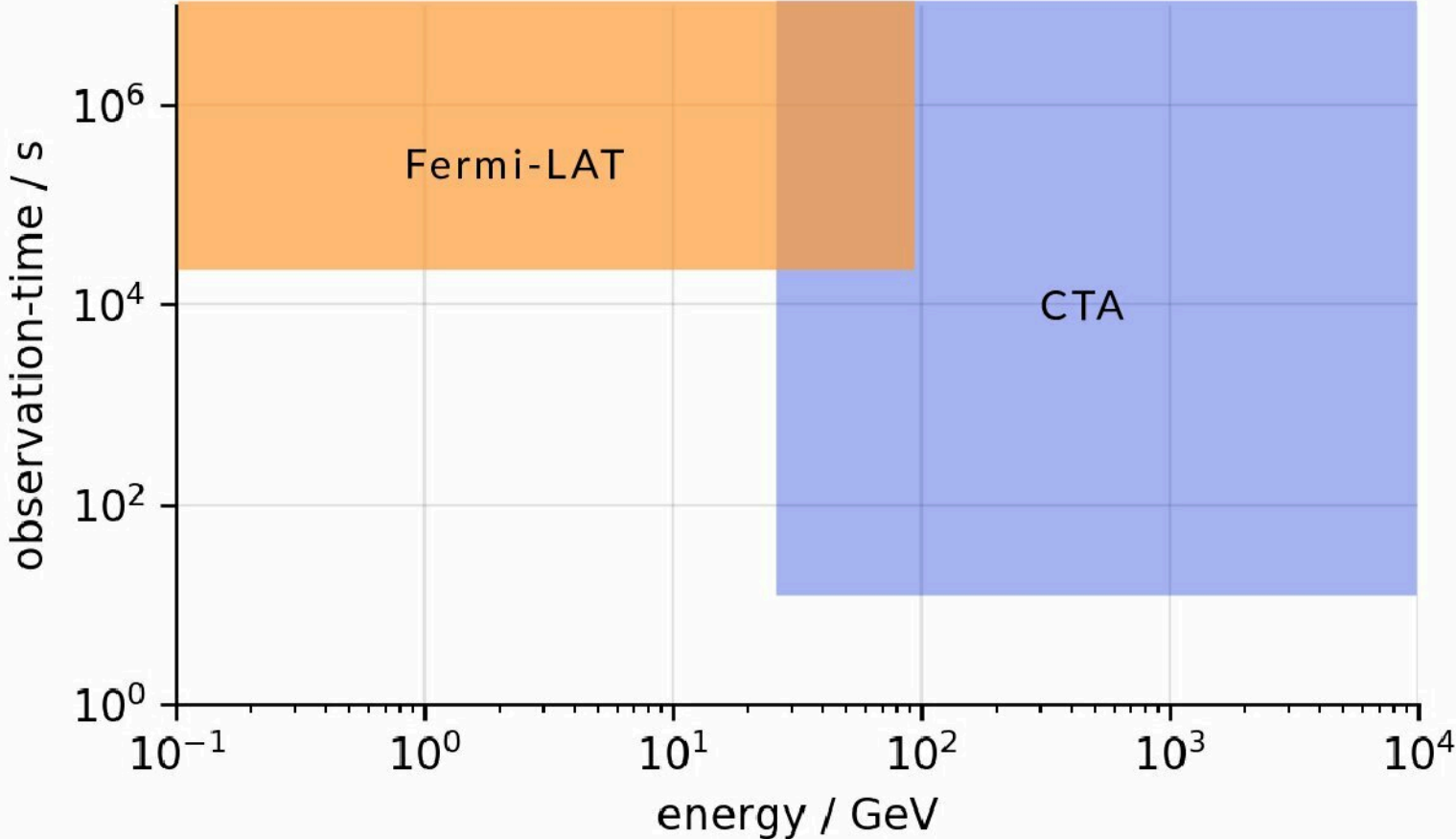
Explore Timing



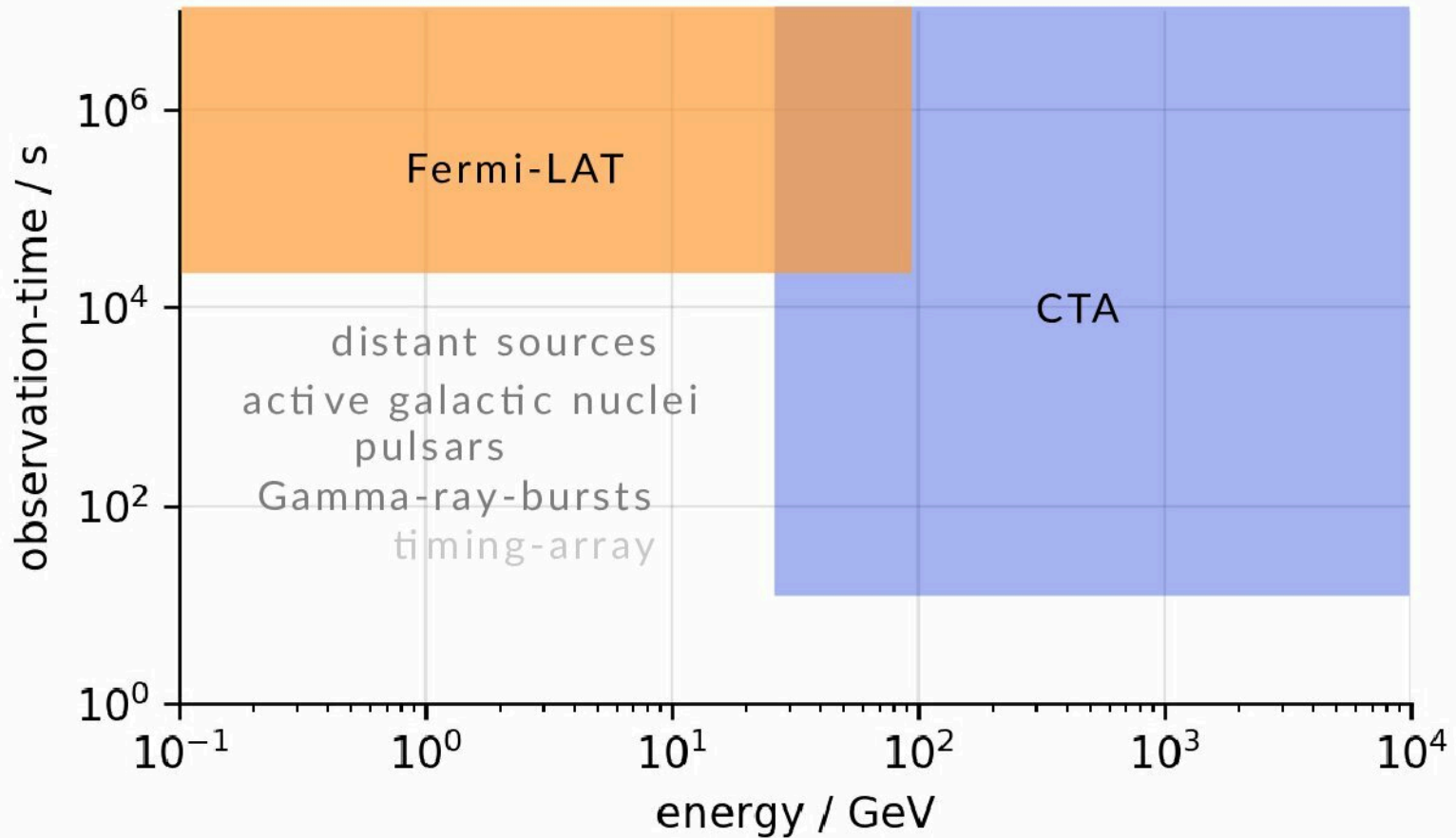
Explore Timing



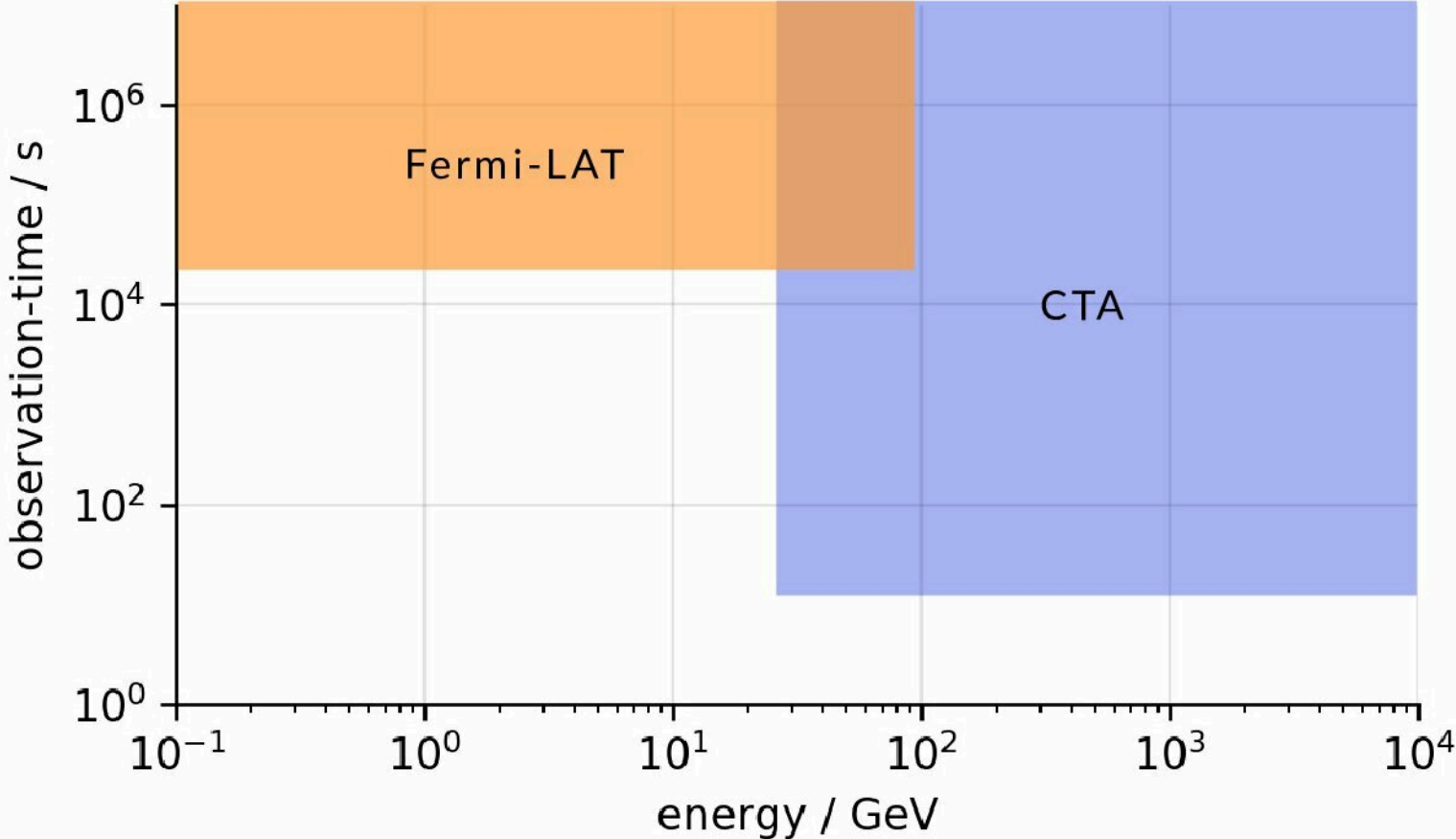
Explore Timing

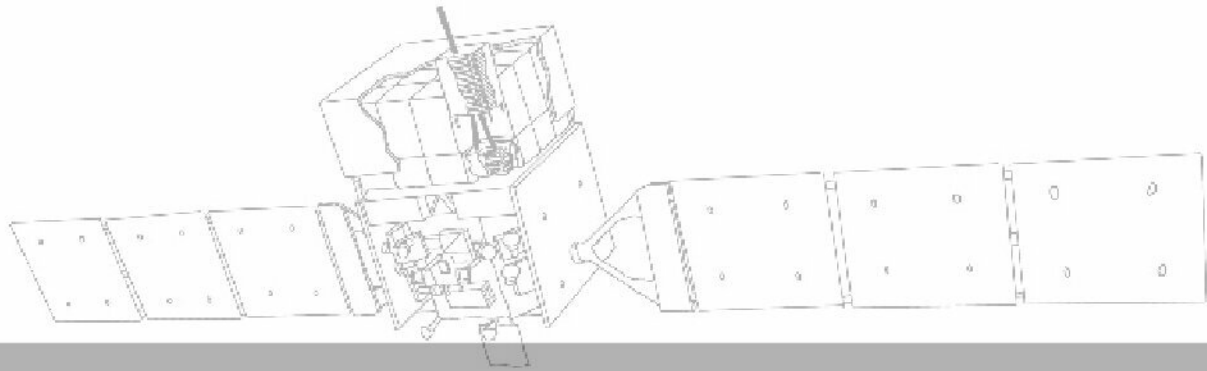


Explore Timing



Explore Timing





Today



Credit: <https://www.mpi-hd.mpg.de/hfm/HESS/>

Directly in Space



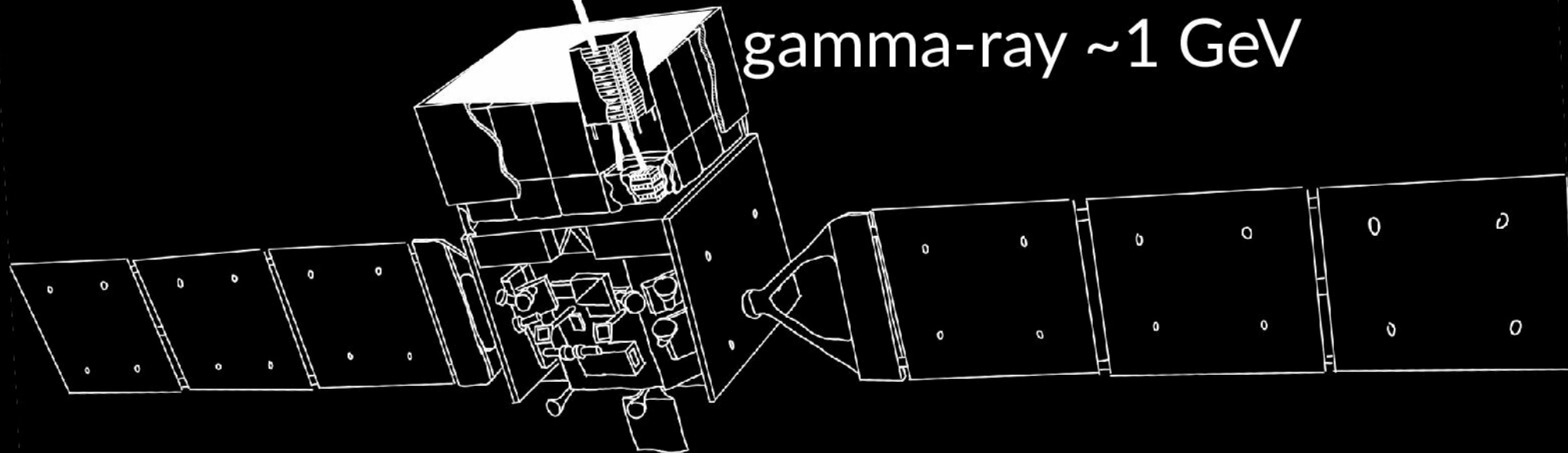
Directly in Space



Directly in Space



Directly in Space



gamma-ray ~1 GeV

$\sim 1 \text{ m}^2$

Indirectly in Atmosphere



Indirectly in Atmosphere

gamma-ray ~ 100 GeV



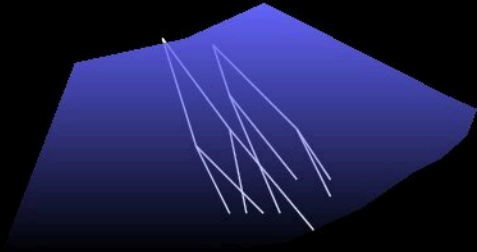
Indirectly in Atmosphere



gamma-ray ~ 100 GeV



Indirectly in Atmosphere

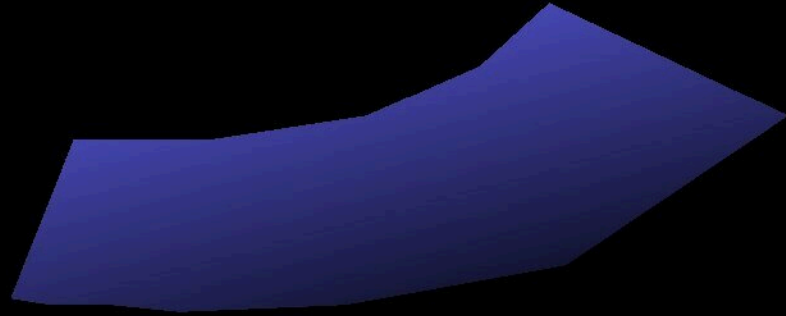


gamma-ray ~ 100 GeV



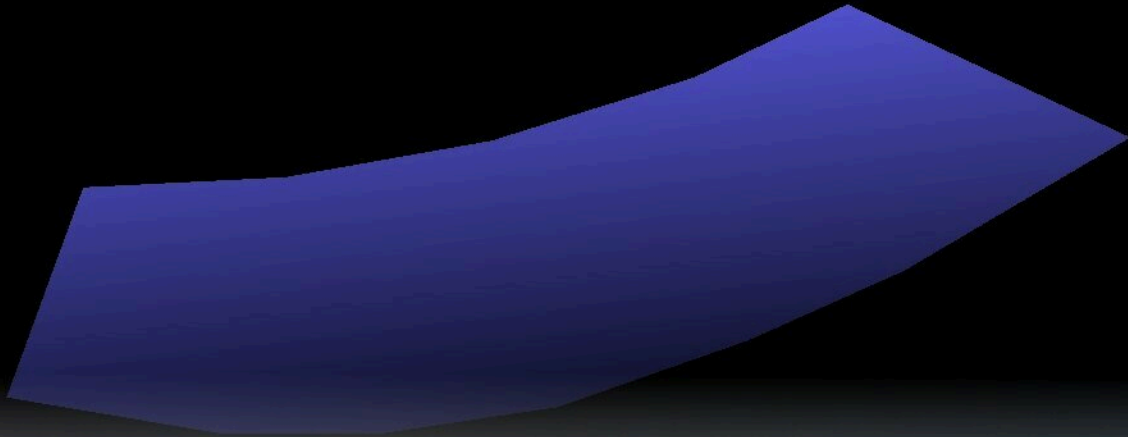
Indirectly in Atmosphere

gamma-ray ~ 100 GeV



Indirectly in Atmosphere

gamma-ray ~ 100 GeV



Indirectly in Atmosphere

gamma-ray ~ 100 GeV



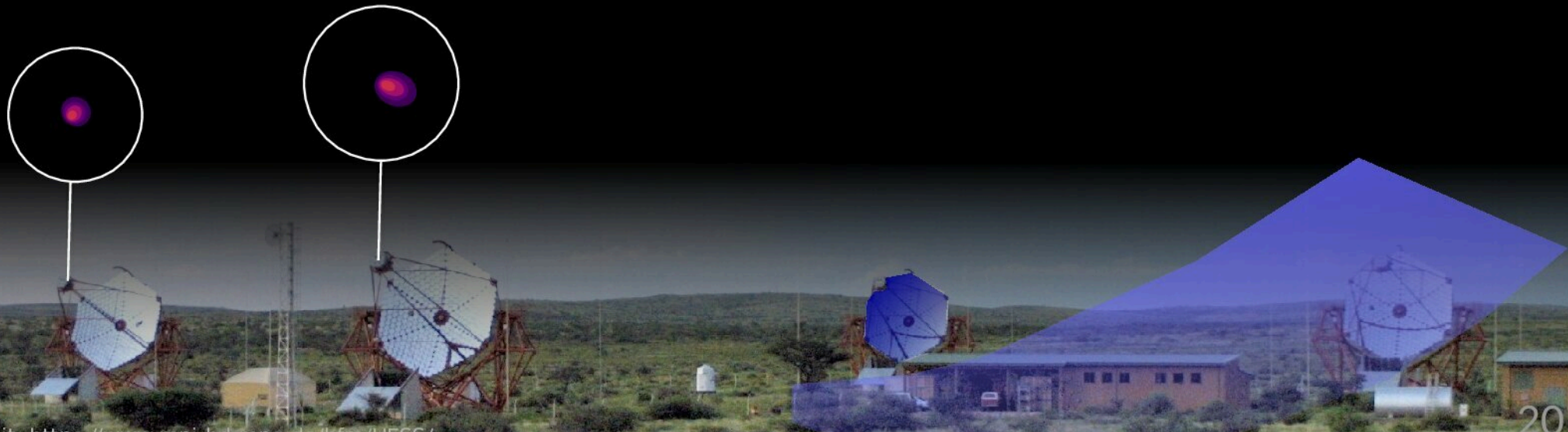
Indirectly in Atmosphere

gamma-ray ~ 100 GeV



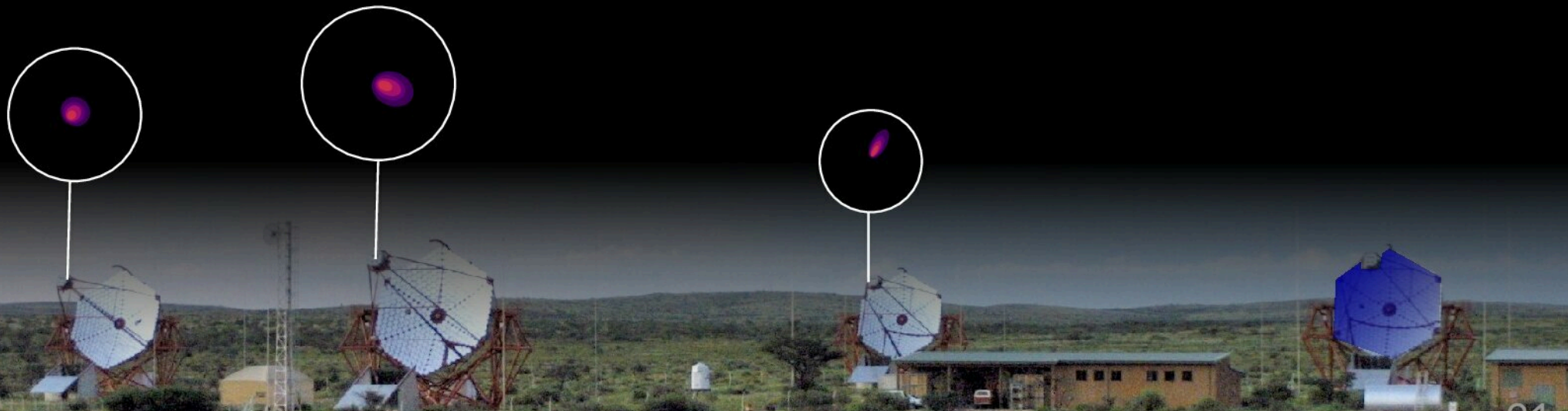
Indirectly in Atmosphere

gamma-ray ~ 100 GeV



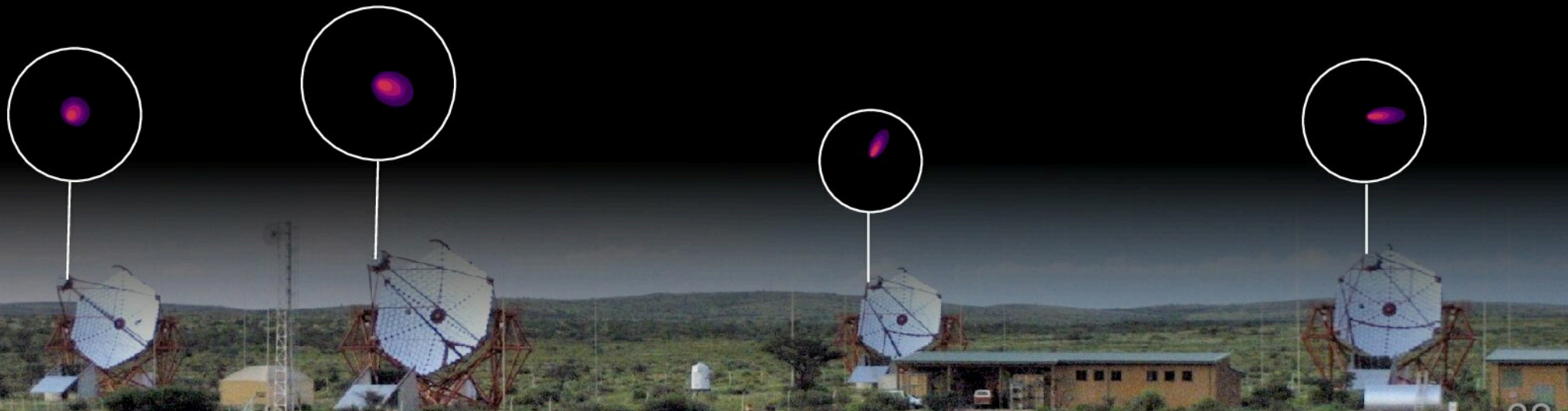
Indirectly in Atmosphere

gamma-ray ~ 100 GeV



Indirectly in Atmosphere

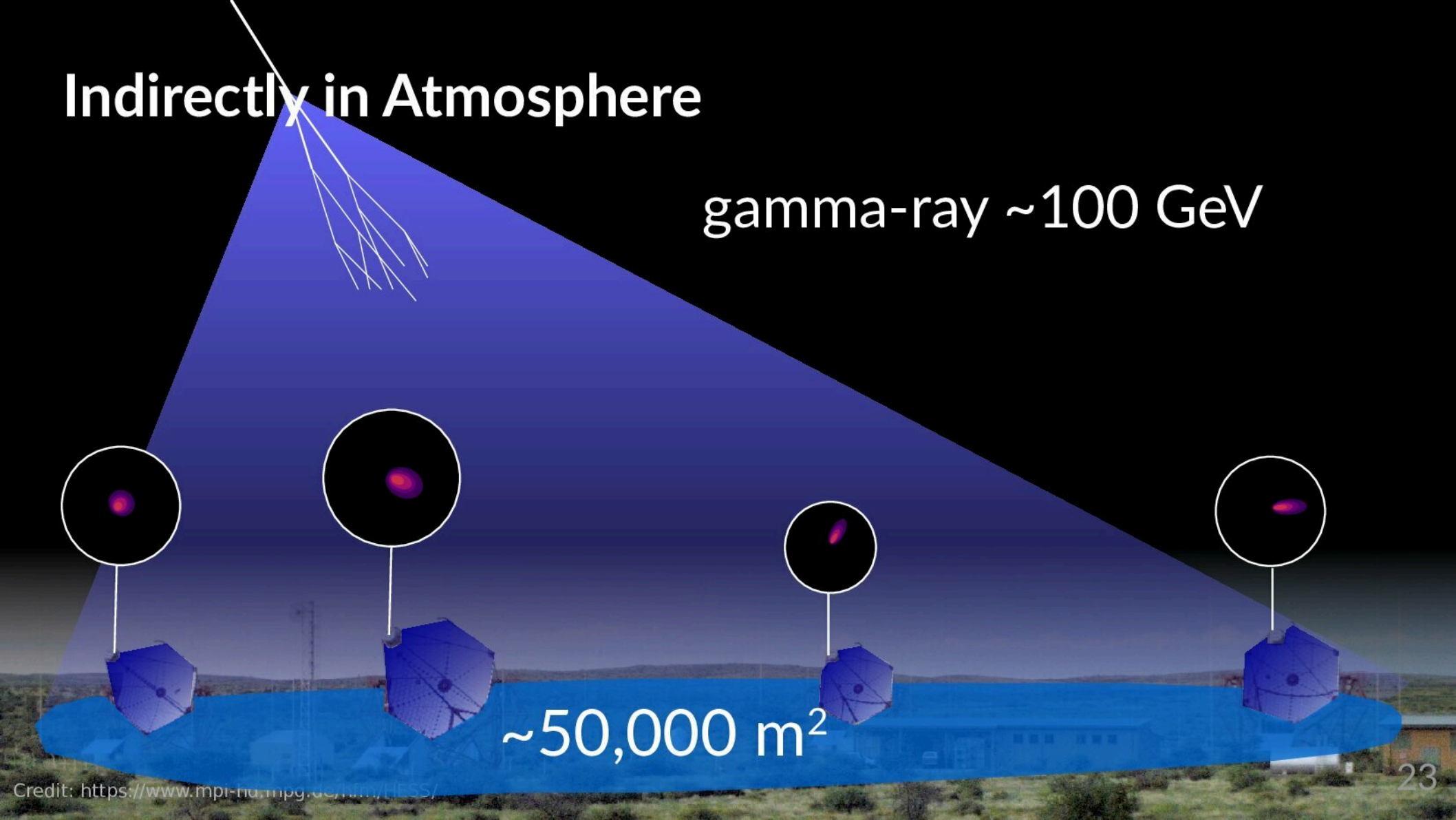
gamma-ray ~ 100 GeV



Indirectly in Atmosphere

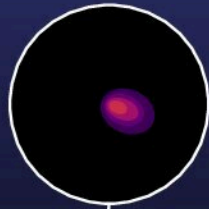
gamma-ray ~ 100 GeV

$\sim 50,000$ m²



Indirectly in Atmosphere

gamma-ray ~ 10 GeV

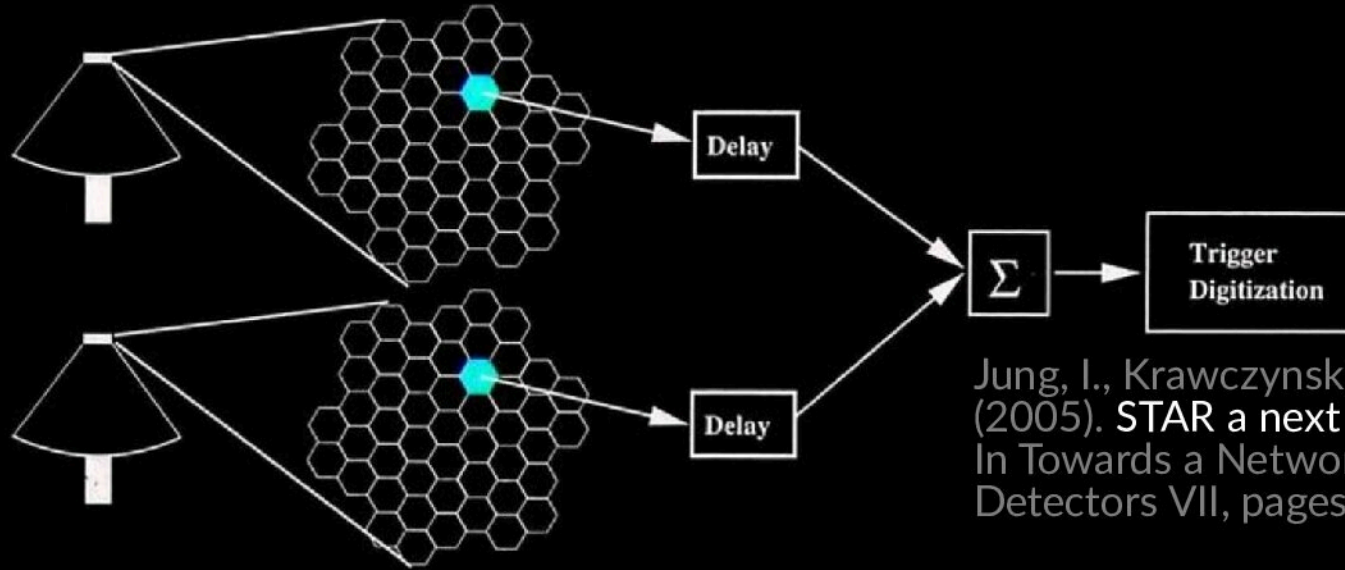


Indirectly in Atmosphere

gamma-ray ~ 1 GeV



Centralized Trigger



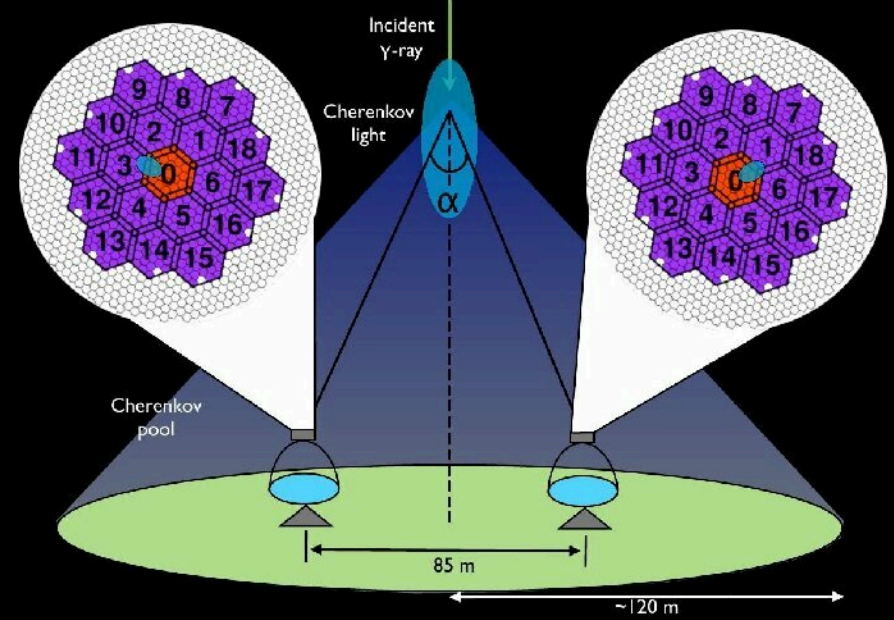
Jung, I., Krawczynski, H., Buckley, J., and Falcone, A. (2005). STAR a next generation Cherenkov telescope. In Towards a Network of Atmospheric Cherenkov Detectors VII, pages 463–6.



Centralized Trigger

López-Coto, R., Mazin, D., Paoletti, R., Bigas, O. B., and Cortina, J. (2016).

The Topo-Trigger: A new concept of stereo trigger system for imaging atmospheric Cherenkov telescopes. *Journal of Instrumentation*, 11(04):P04005.



Large Telescope

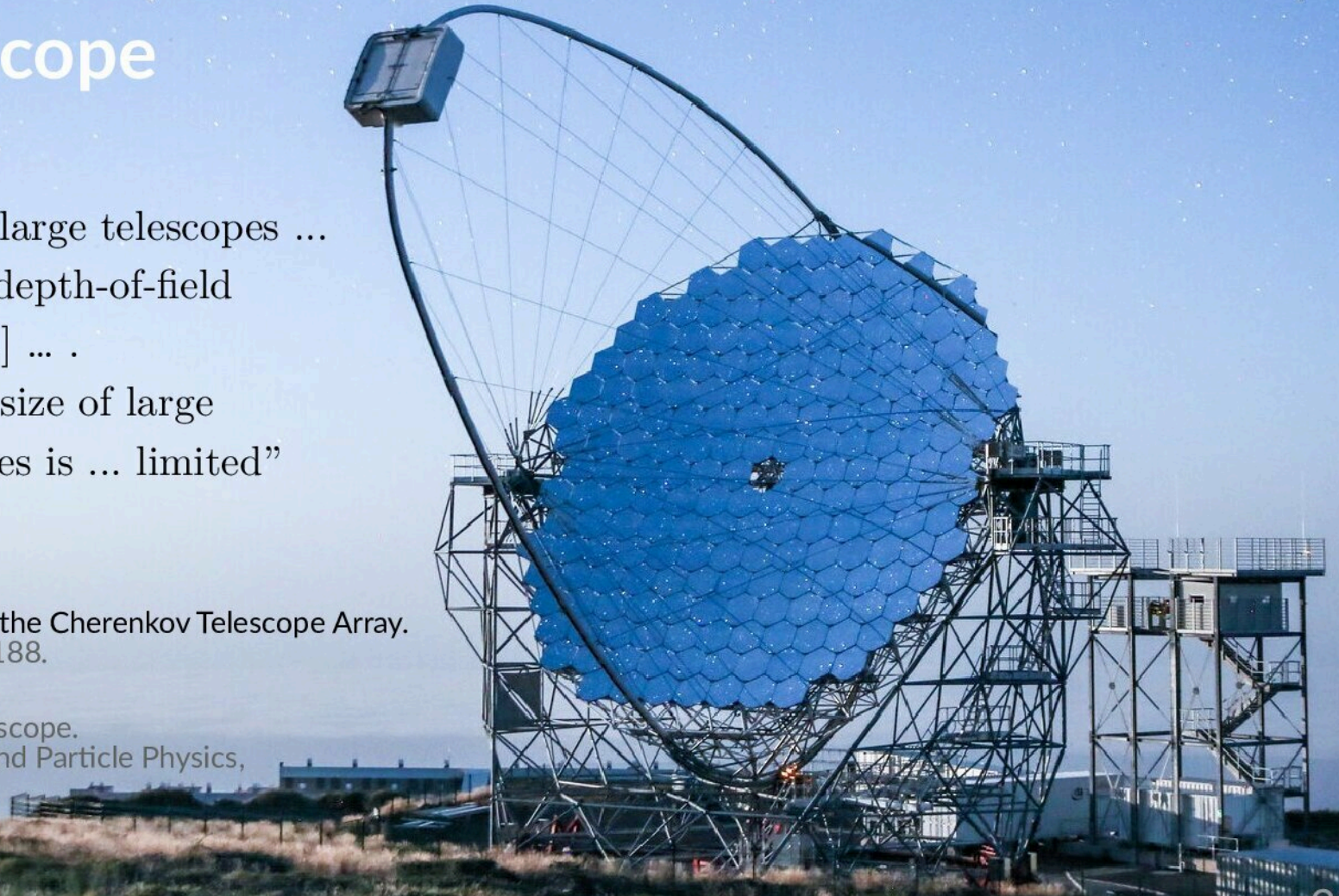


Large Telescope

“... a problem with large telescopes ...
is the very limited depth-of-field
[Hofmann, W. 2001]
(Thus,) The useful size of large
Cherenkov-telescopes is ... limited”

Bernlohr, K. et al. (2013).
Monte Carlo design studies for the Cherenkov Telescope Array.
Astroparticle Physics, 43:171-188.

Hofmann, W. (2001).
How to focus a Cherenkov telescope.
Journal of Physics G: Nuclear and Particle Physics,
27(4):933-939.



A.Biland, ETHZ, 22.Jan.1999



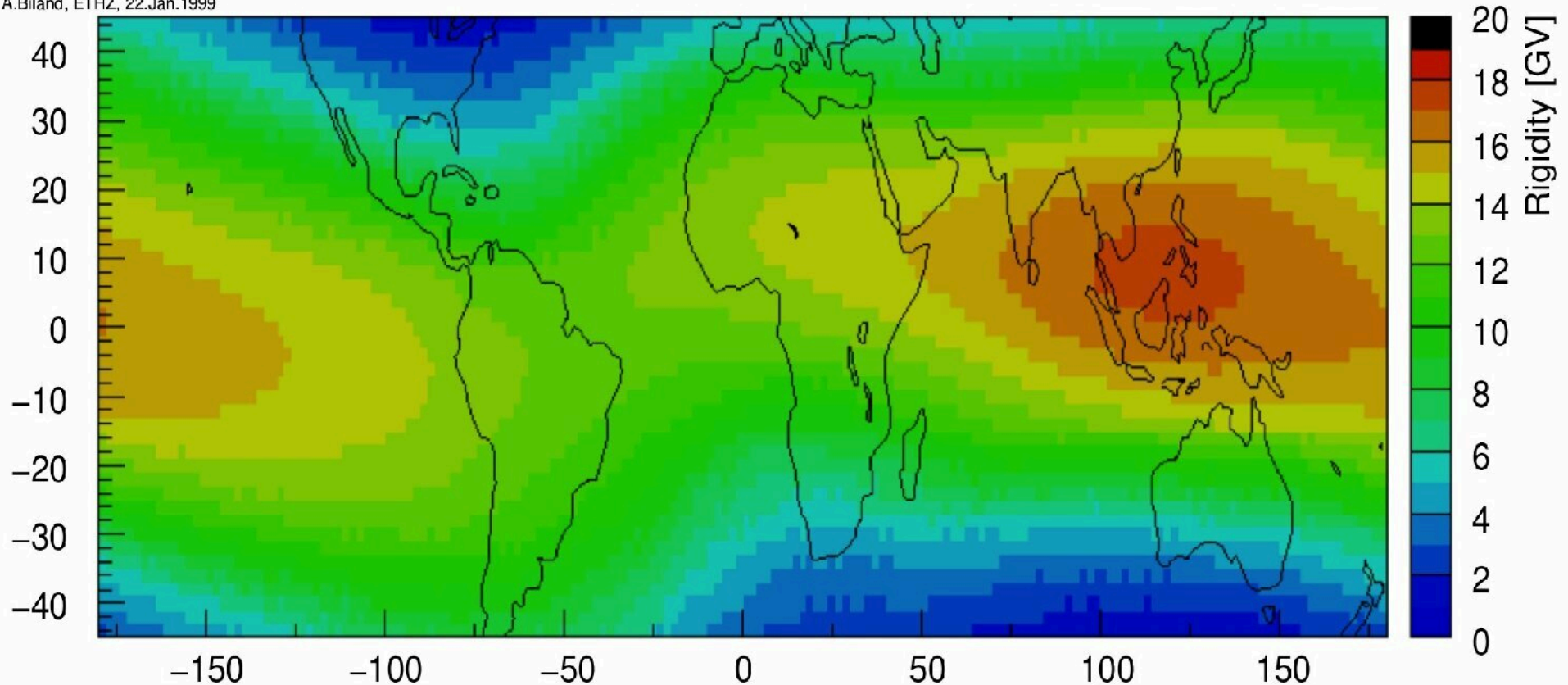
Sneaking Below the Geomagnetic Cutoff



Geomagnetic Cutoff for Radially Arriving Cosmic-Ray Particles

Geomagnetic Cutoff

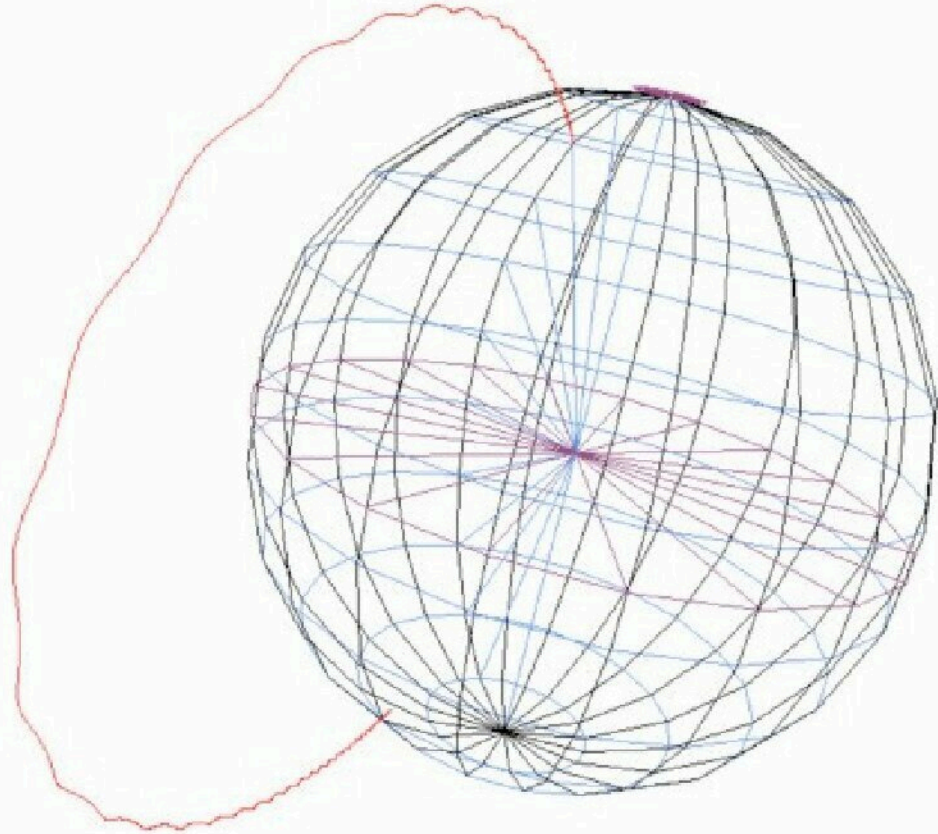
A.Biland, ETHZ, 22.Jan.1999



Geomagnetic Cutoff for Radially Arriving Cosmic-Ray Particles

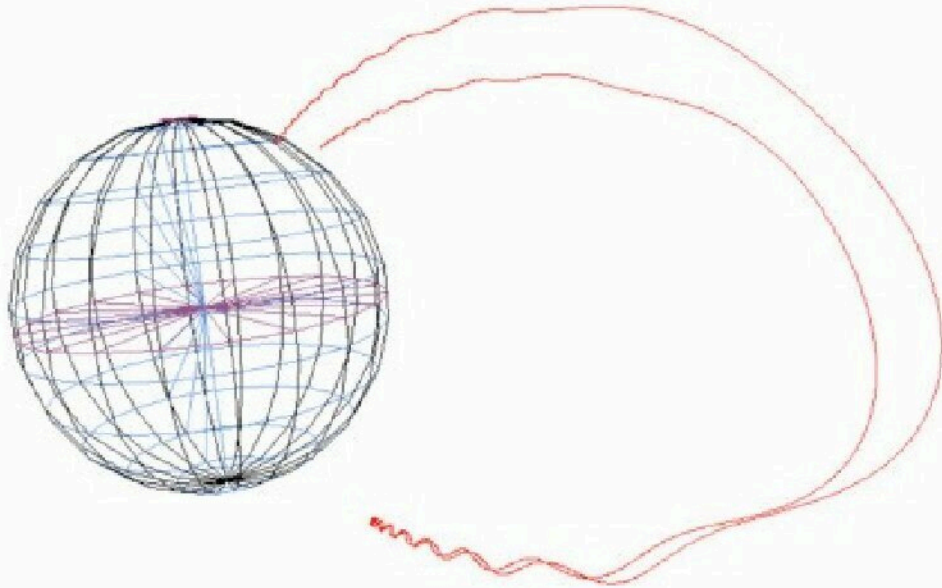
Adrian Biland, ETH Zurich, 1999

Geomagnetic Cutoff



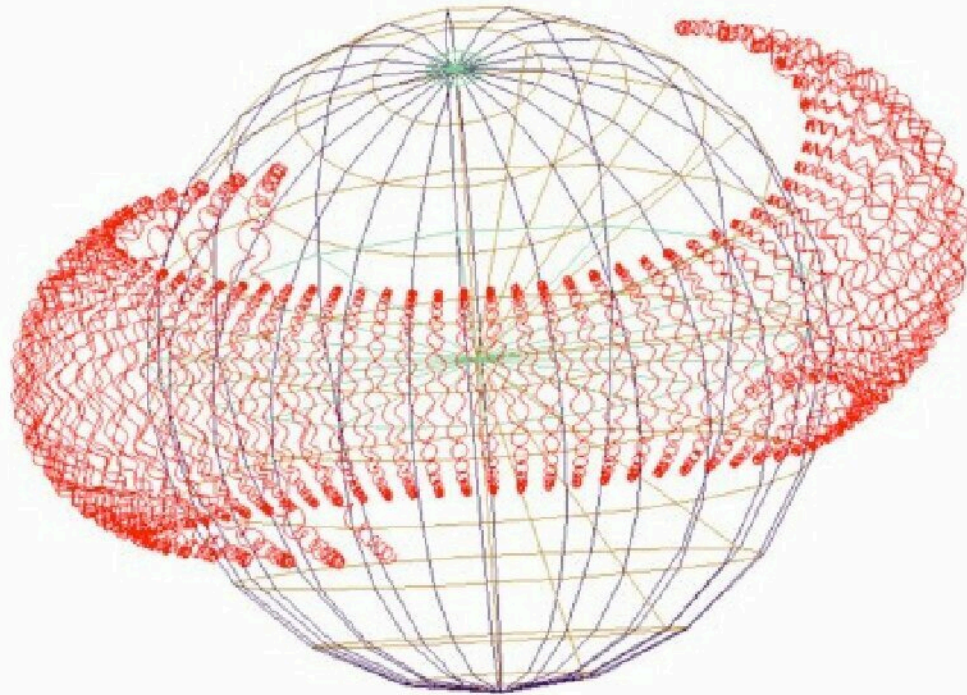
no-bounce

Geomagnetic Cutoff



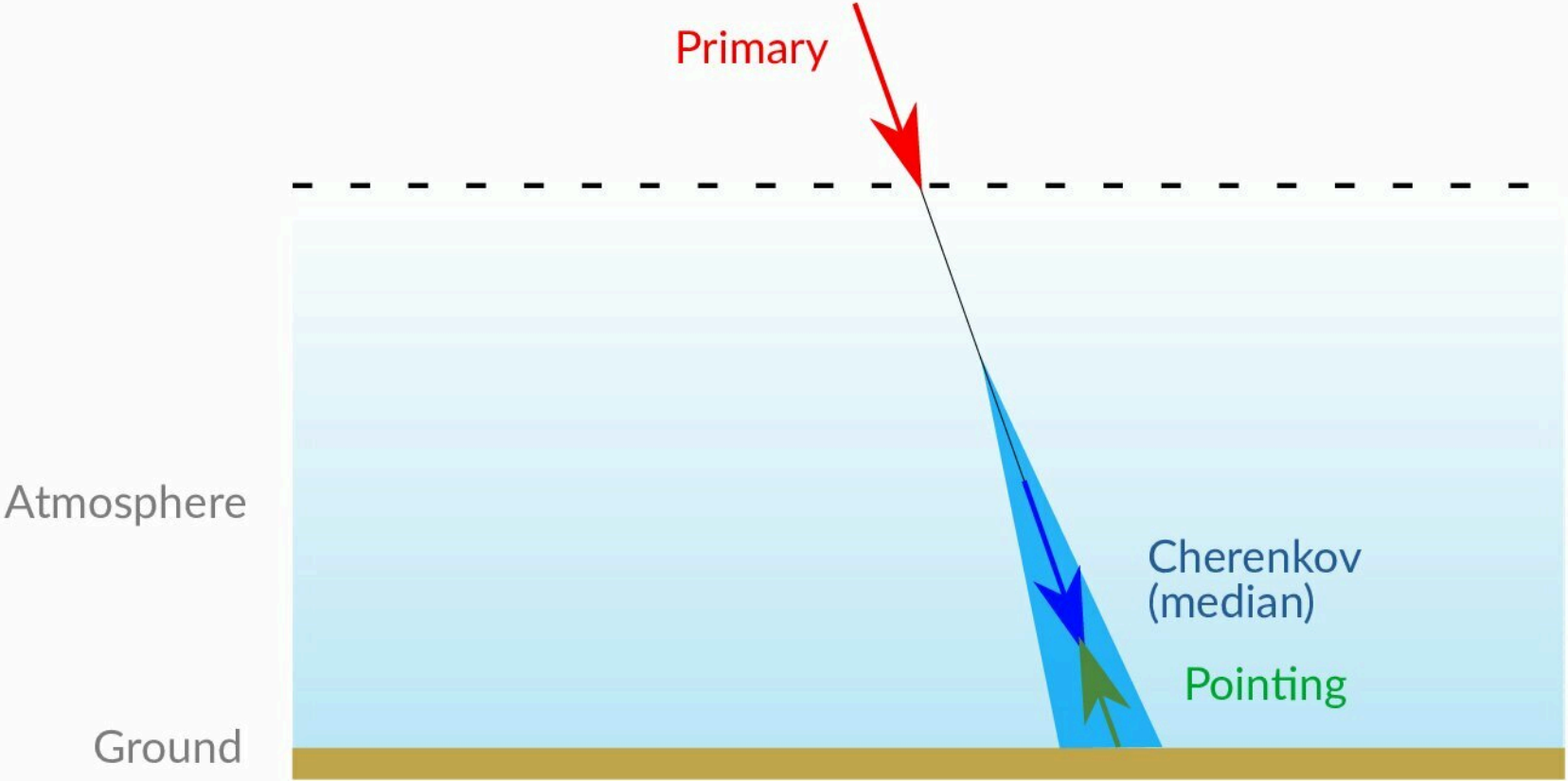
one-bounce

Geomagnetic Cutoff



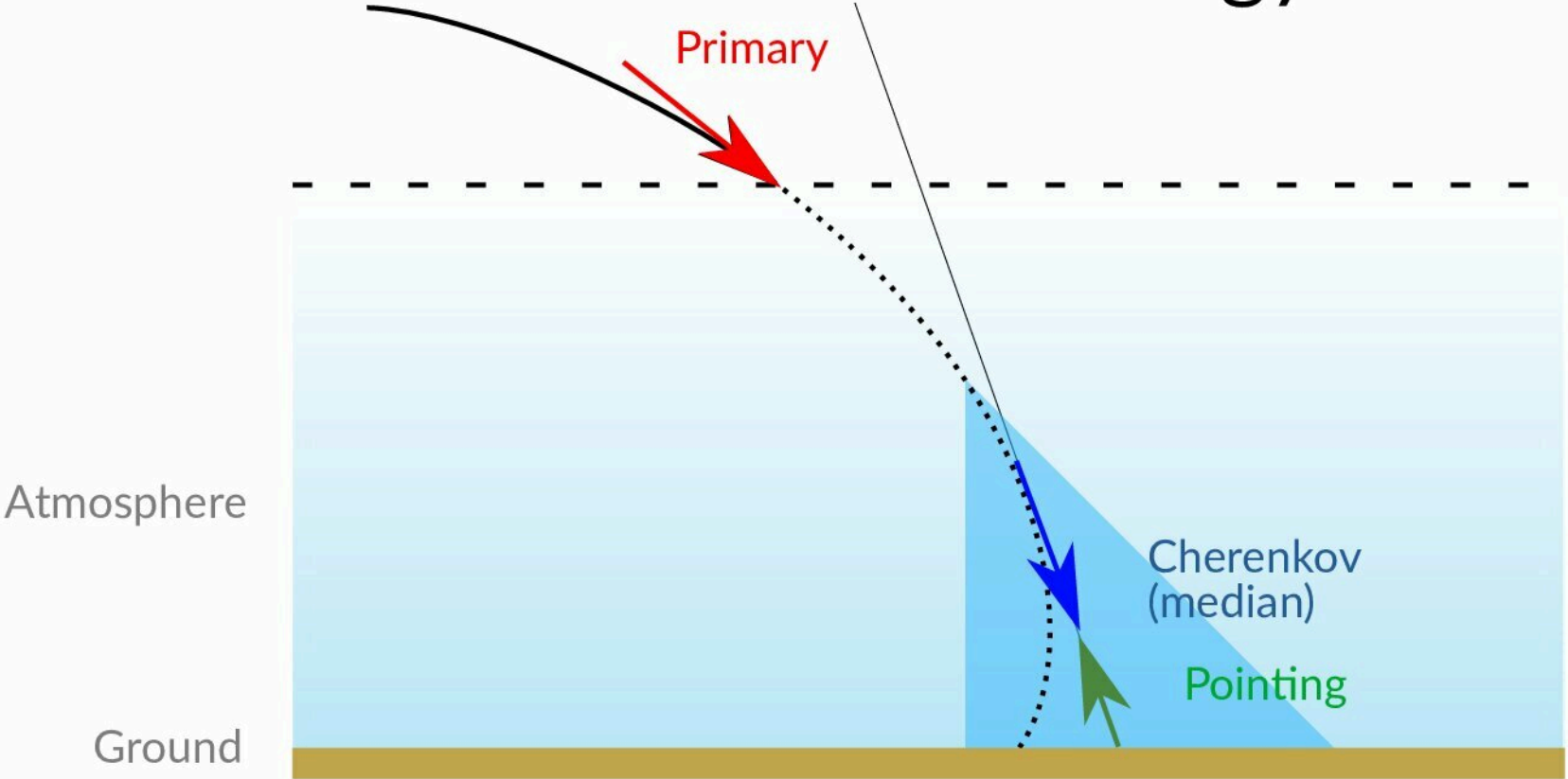
multi-bounce

Deflection of shower



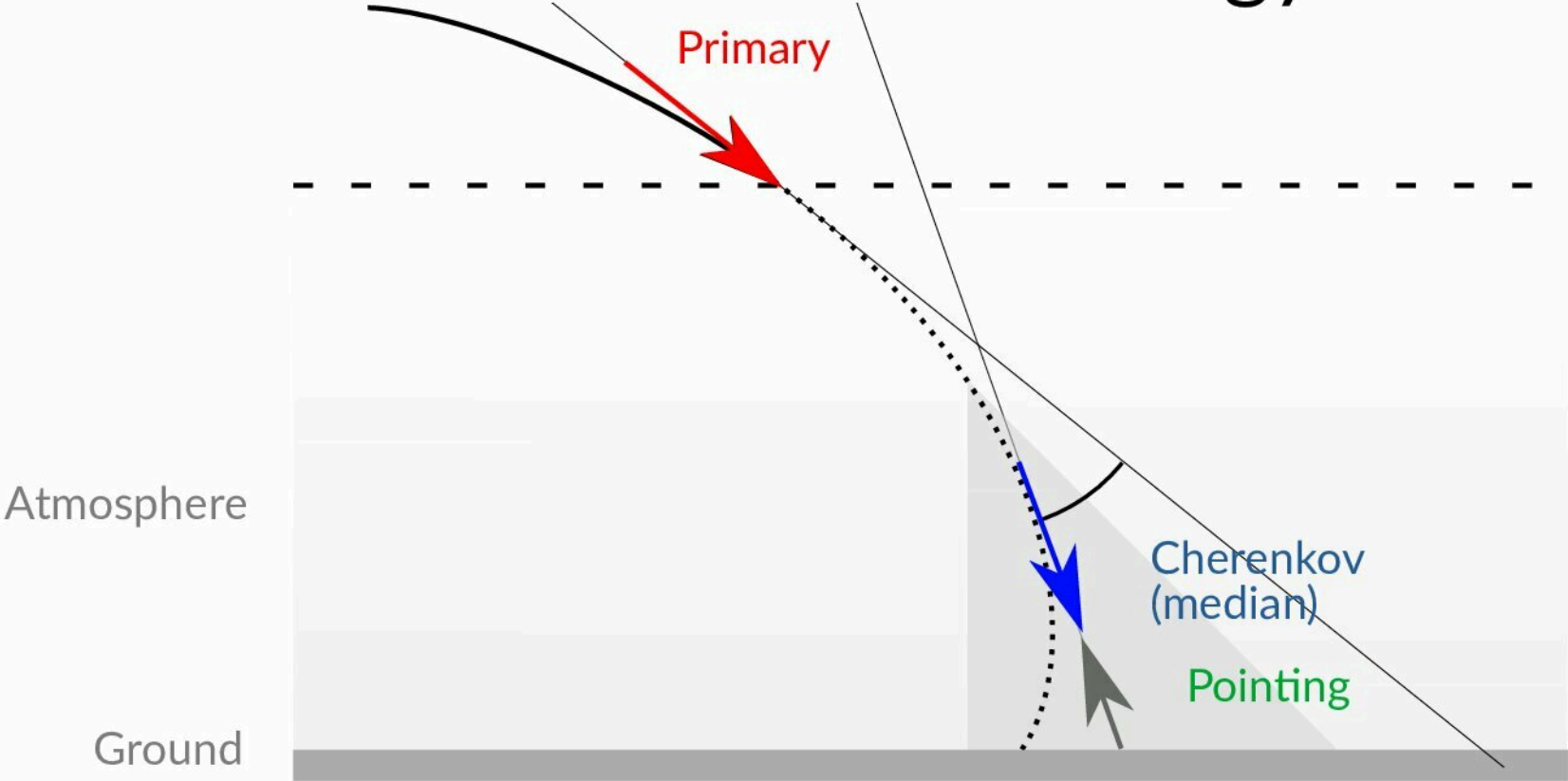
Deflection of shower

Energy < 20 GeV



Deflection of shower

Energy < 20 GeV



Deflection of shower Helium

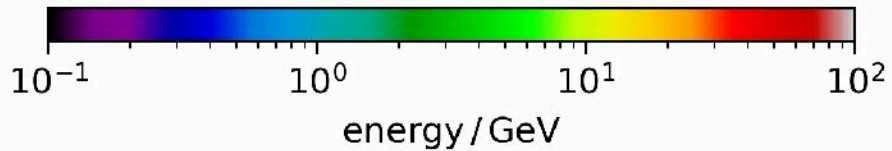


Gamsberg, Namibia

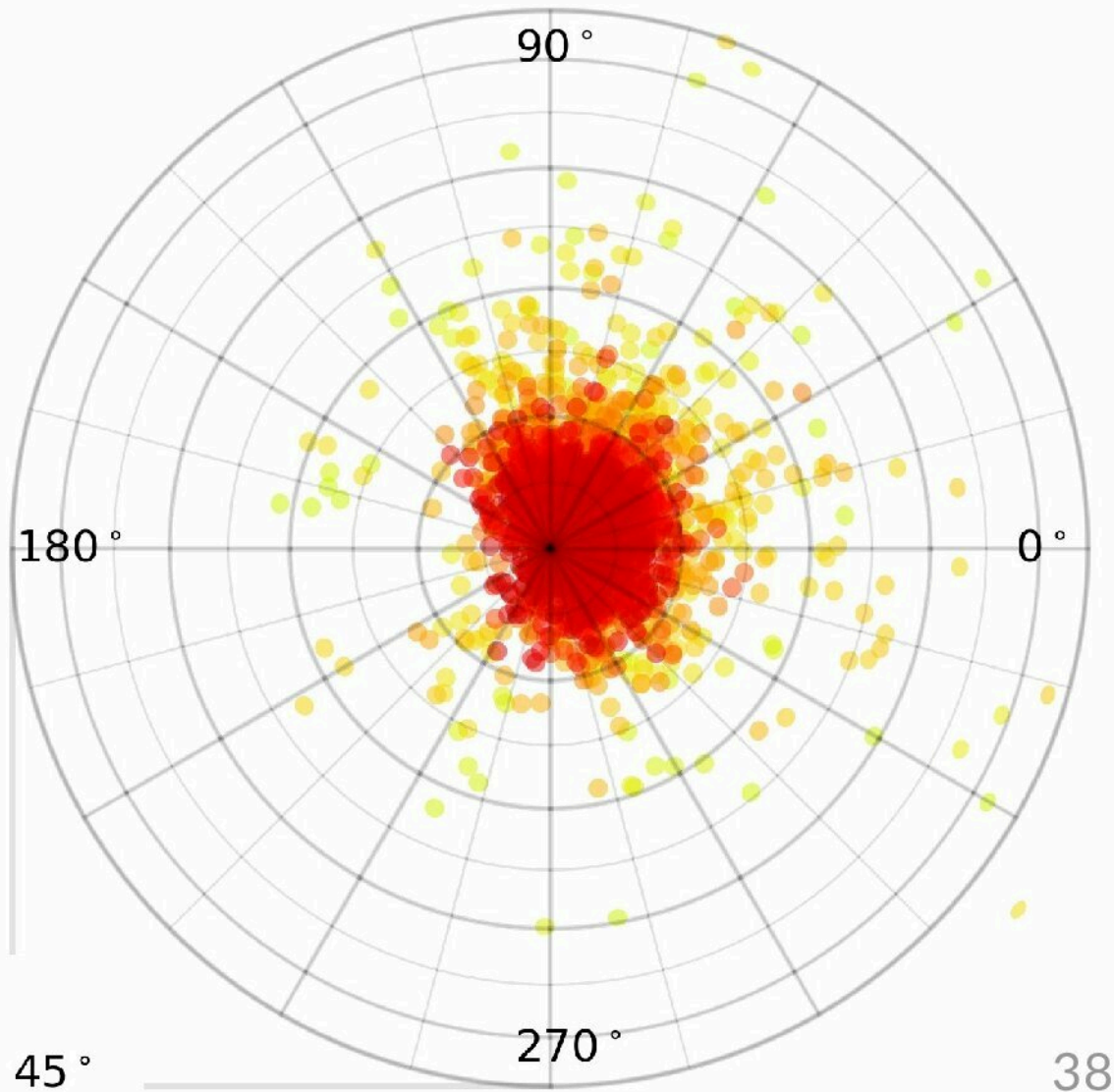
horizontal: 12.5uT

vertical: -25.9uT

2300m a.s.l.



Direction of primary to get
Cherenkov-light from zenith.



Deflection of shower Proton

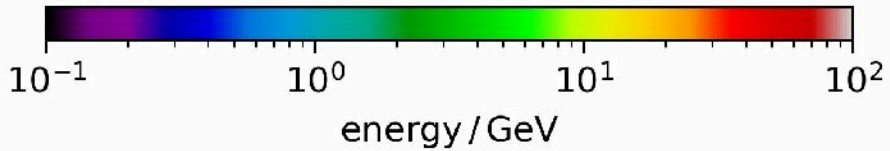


Gamsberg, Namibia

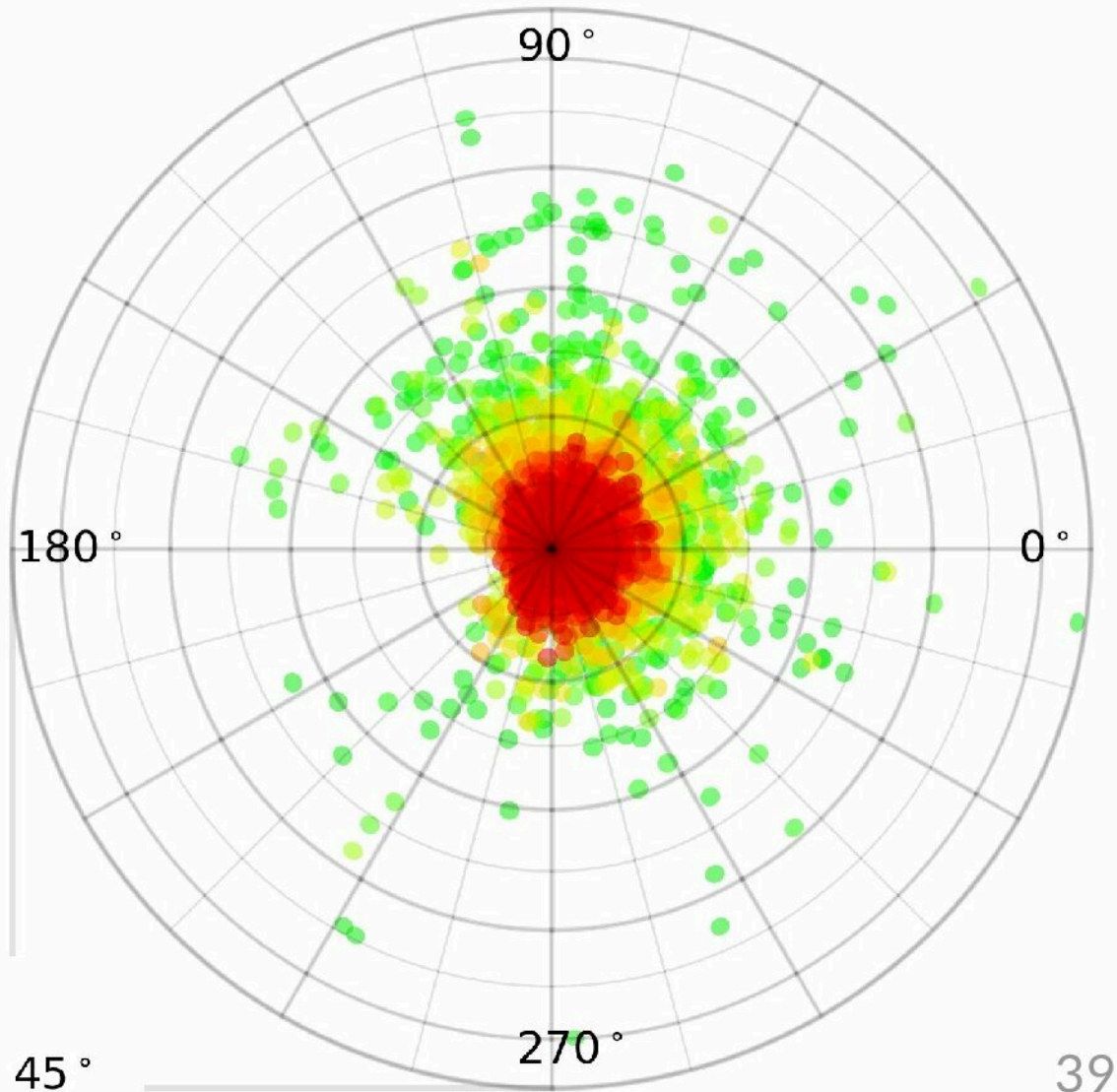
horizontal: $12.5\mu\text{T}$

vertical: $-25.9\mu\text{T}$

2300m a.s.l.



Direction of primary to get
Cherenkov-light from zenith.



Deflection of shower Electron

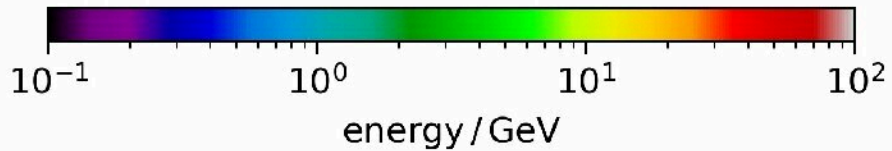


Gamsberg, Namibia

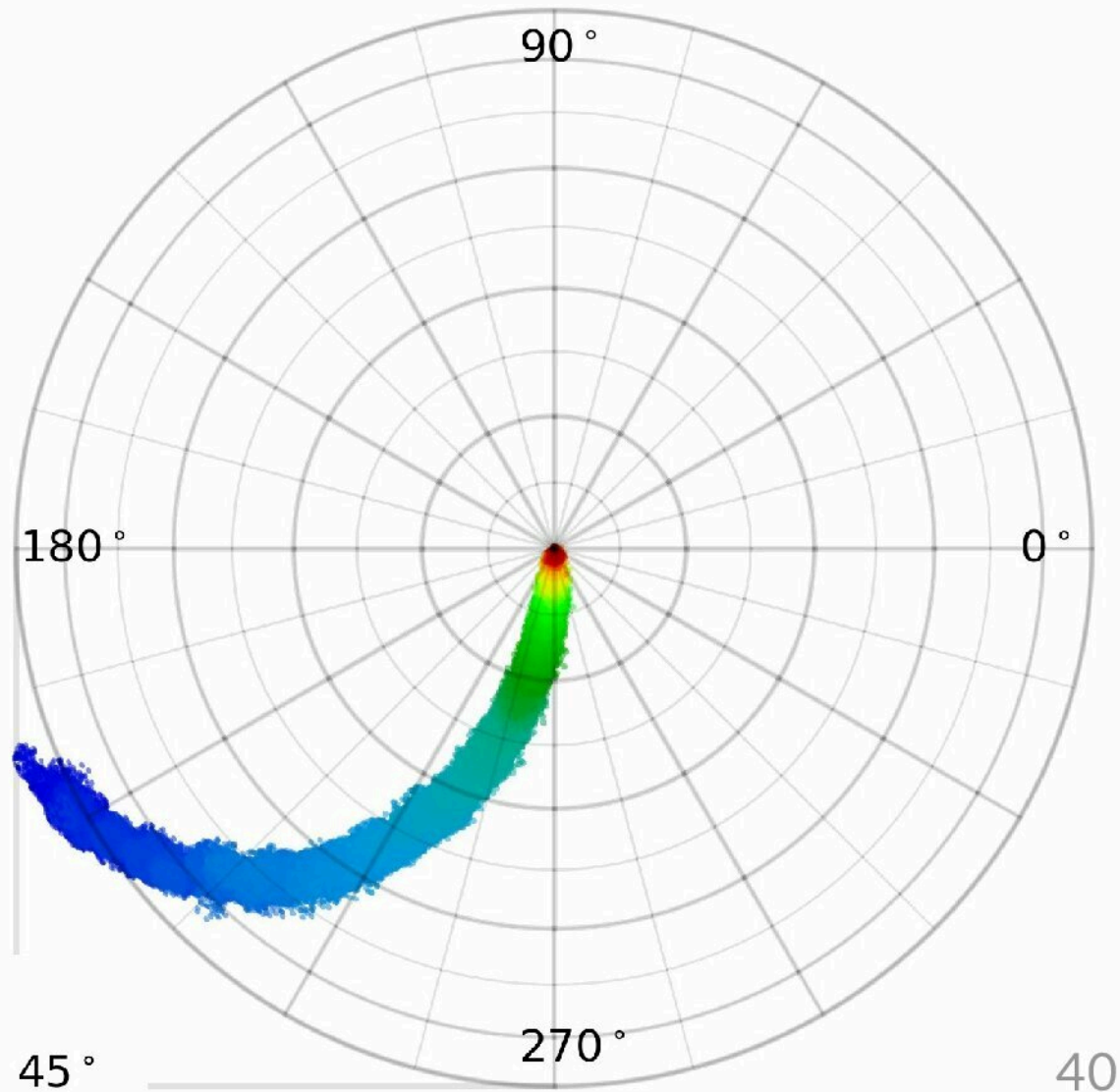
horizontal: 12.5uT

vertical: -25.9uT

2300m a.s.l.



Direction of primary to get
Cherenkov-light from zenith.



Deflection of shower

Gamma-ray

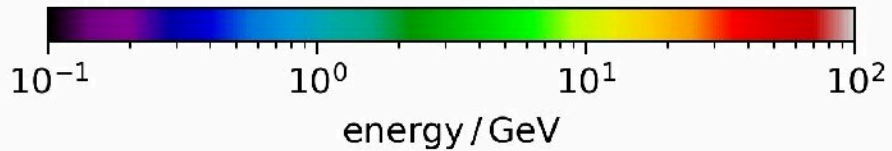


Gamsberg, Namibia

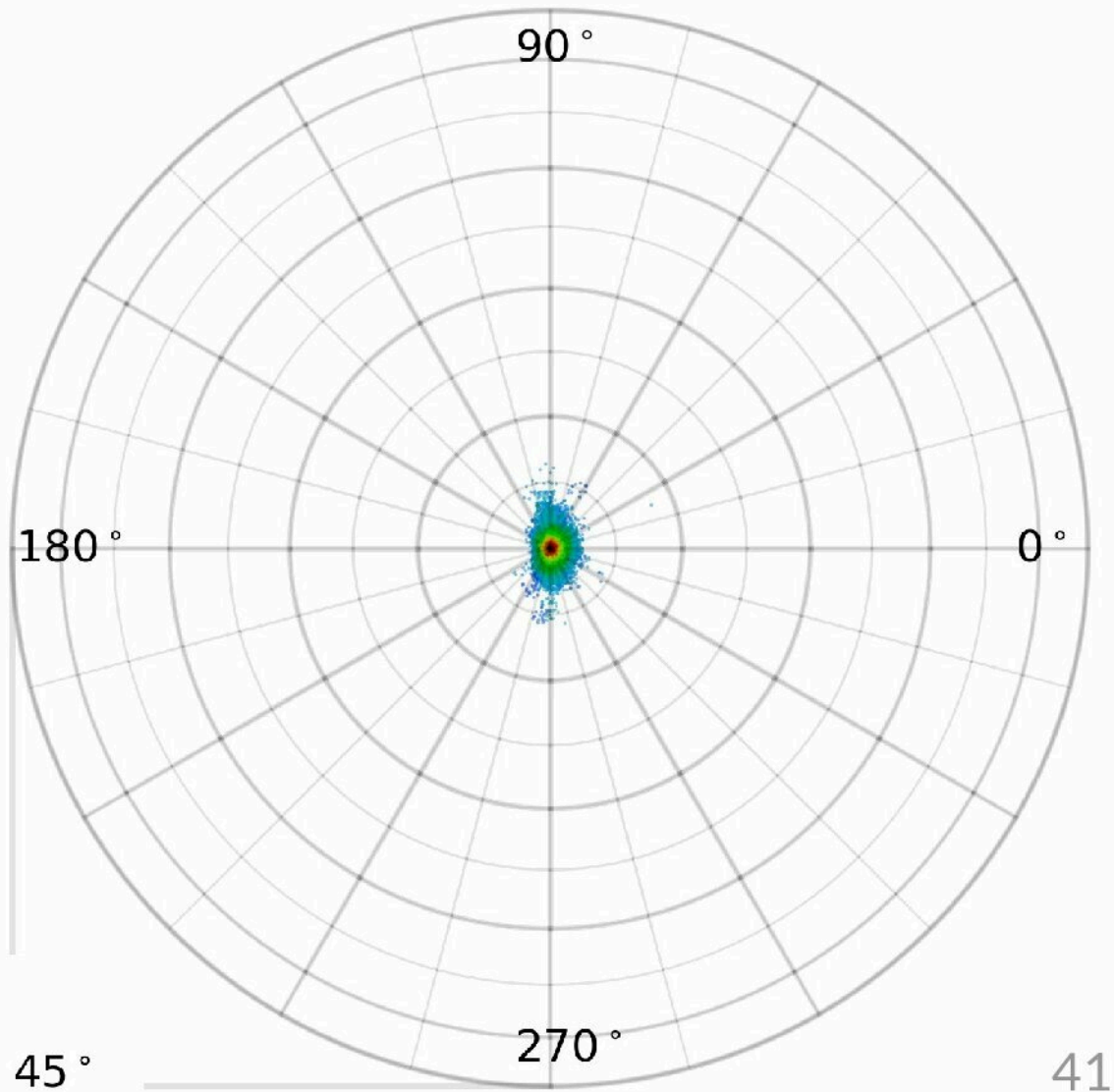
horizontal: 12.5uT

vertical: -25.9uT

2300m a.s.l.



Direction of primary to get
Cherenkov-light from zenith.



Deflection of shower Gamma-ray

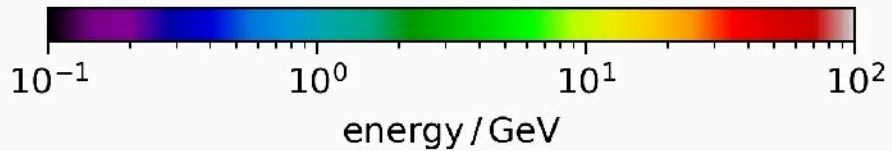


Gamsberg, Namibia

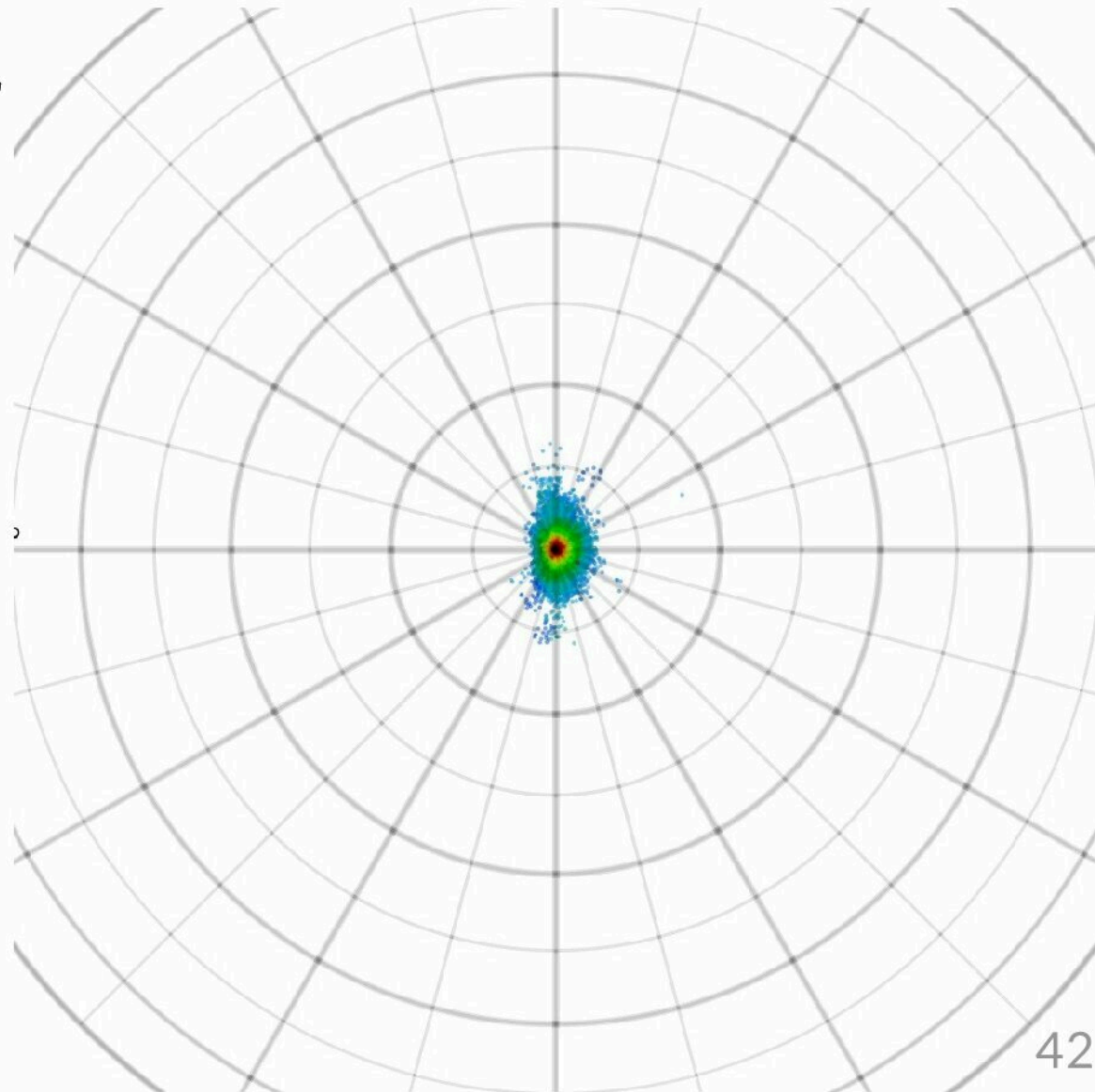
horizontal: 12.5uT

vertical: -25.9uT

2300m a.s.l.



Direction of primary to get
Cherenkov-light from zenith.



Deflection of shower Gamma-ray

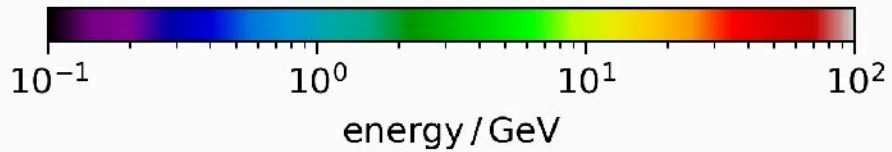


Gamsberg, Namibia

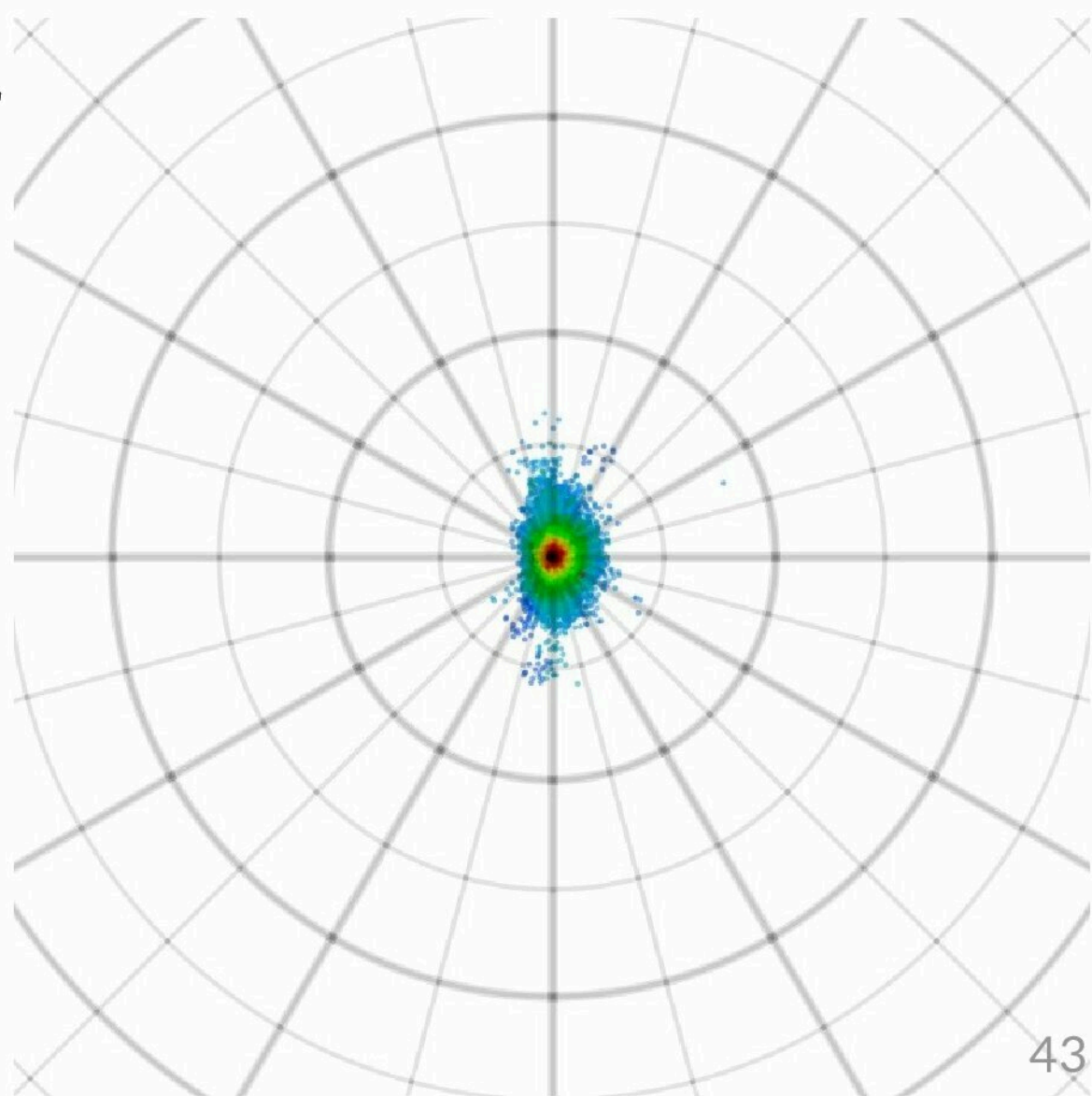
horizontal: 12.5uT

vertical: -25.9uT

2300m a.s.l.



Direction of primary to get
Cherenkov-light from zenith.



Deflection of shower Gamma-ray

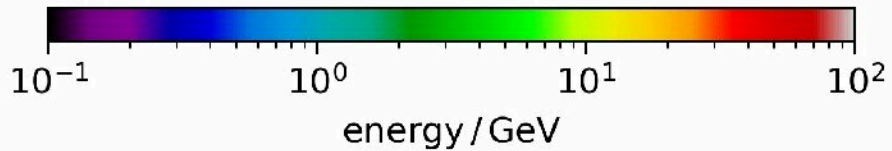


Gamsberg, Namibia

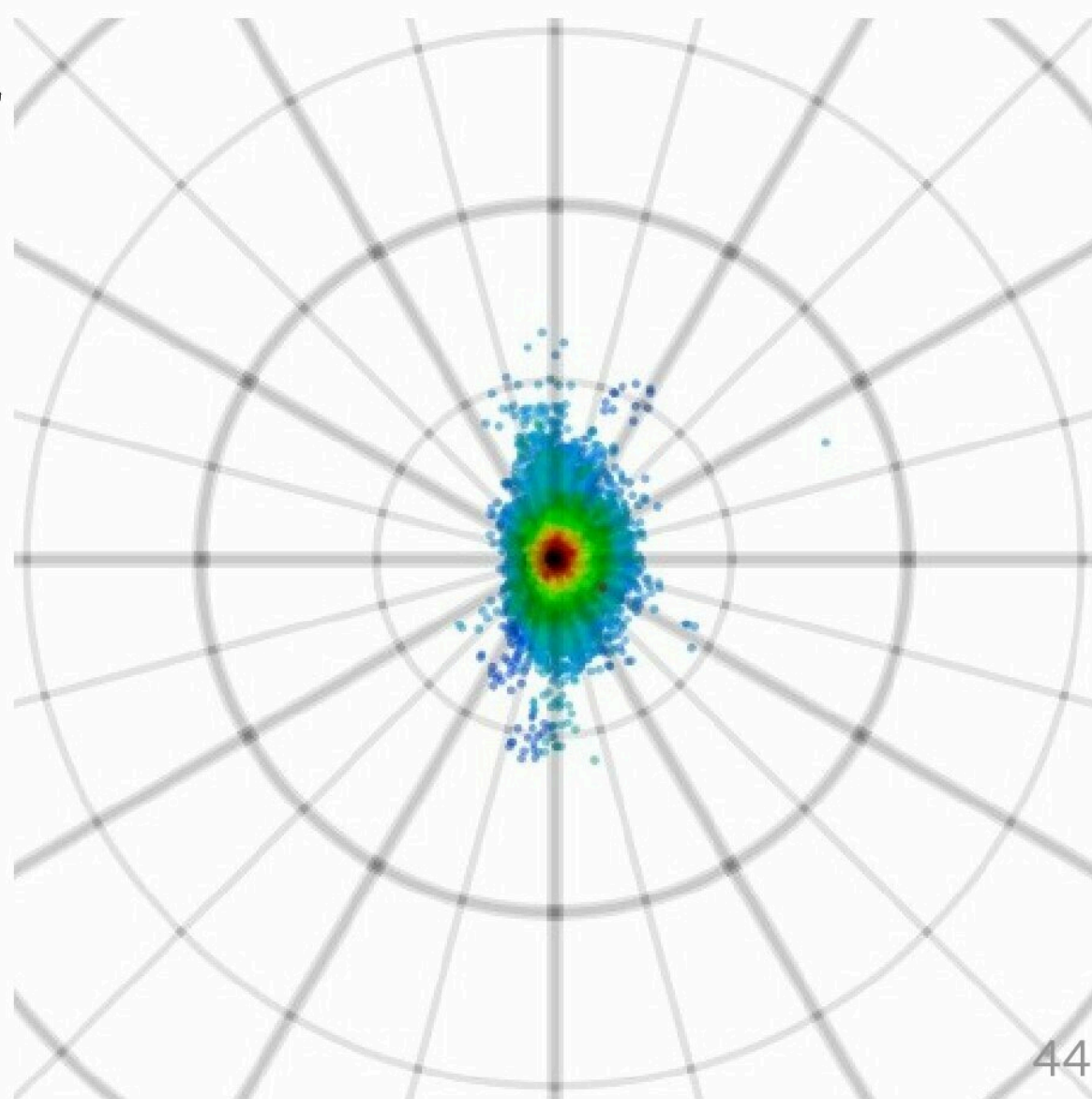
horizontal: 12.5uT

vertical: -25.9uT

2300m a.s.l.



Direction of primary to get
Cherenkov-light from zenith.



Deflection of shower

Gamma-ray

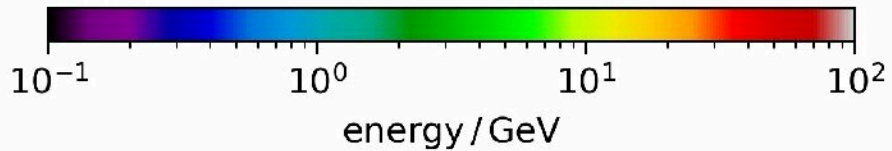


Gamsberg, Namibia

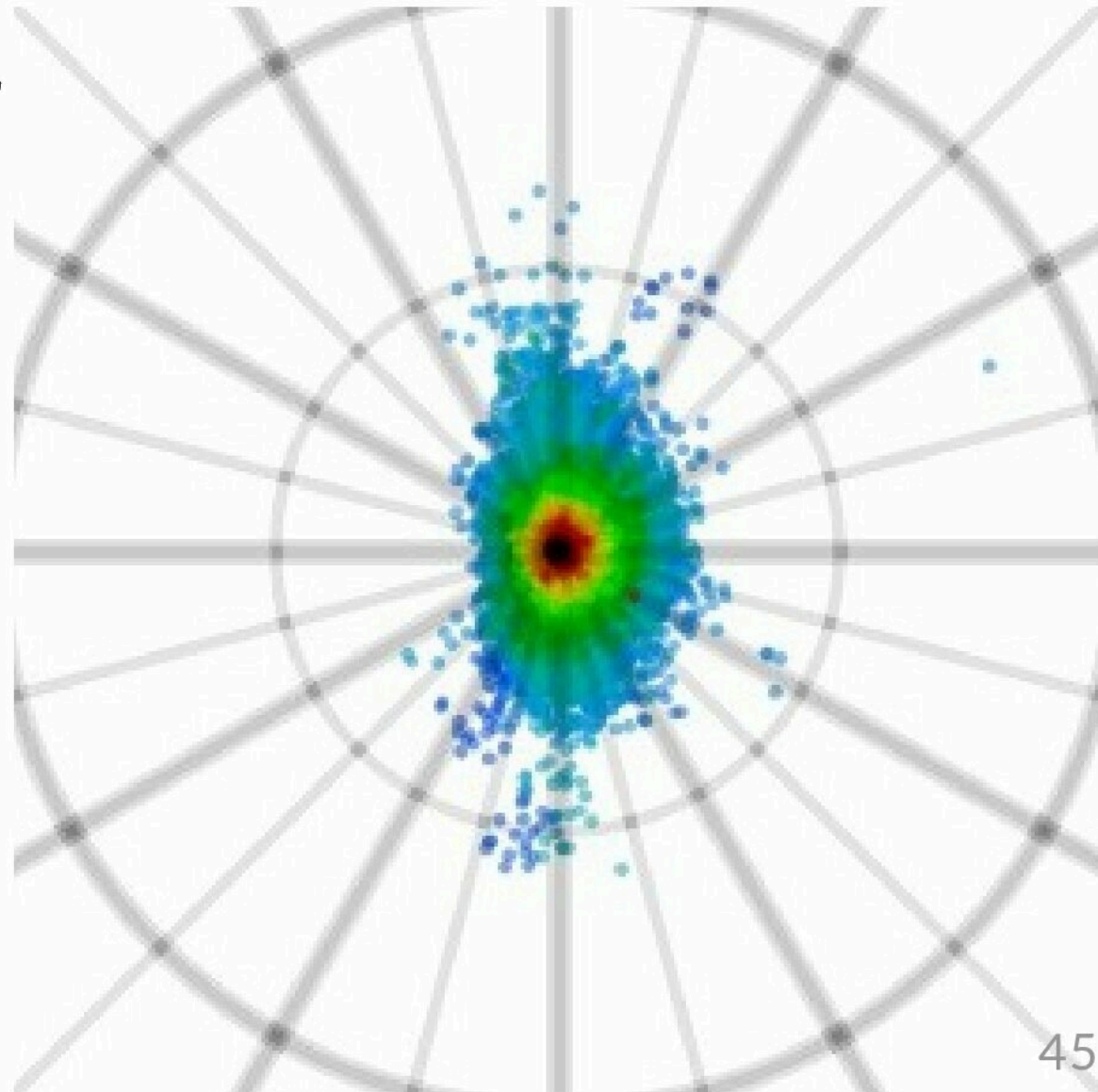
horizontal: 12.5uT

vertical: -25.9uT

2300m a.s.l.



Direction of primary to get
Cherenkov-light from zenith.



Deflection of shower

Gamma-ray

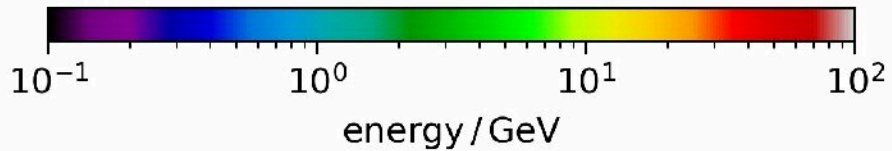


Gamsberg, Namibia

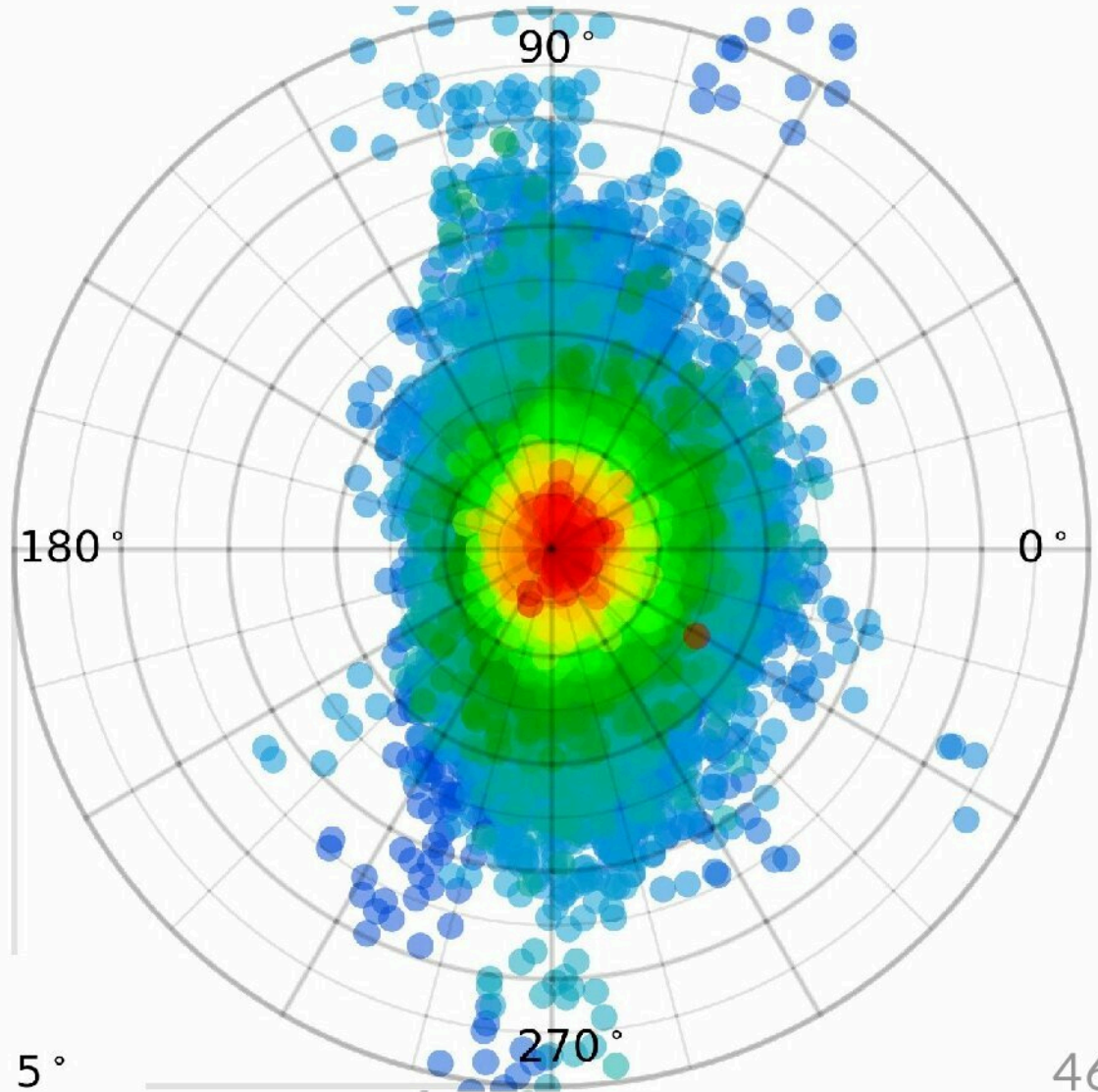
horizontal: 12.5uT

vertical: -25.9uT

2300m a.s.l.



Direction of primary to get
Cherenkov-light from zenith.



Deflection of shower

Gamma-ray

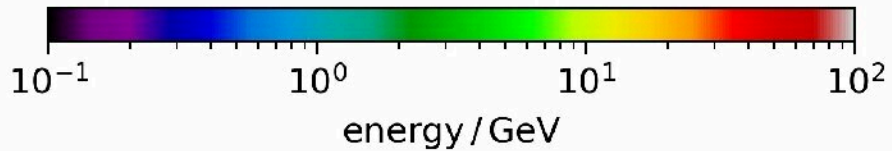


Chajnantor, Chile

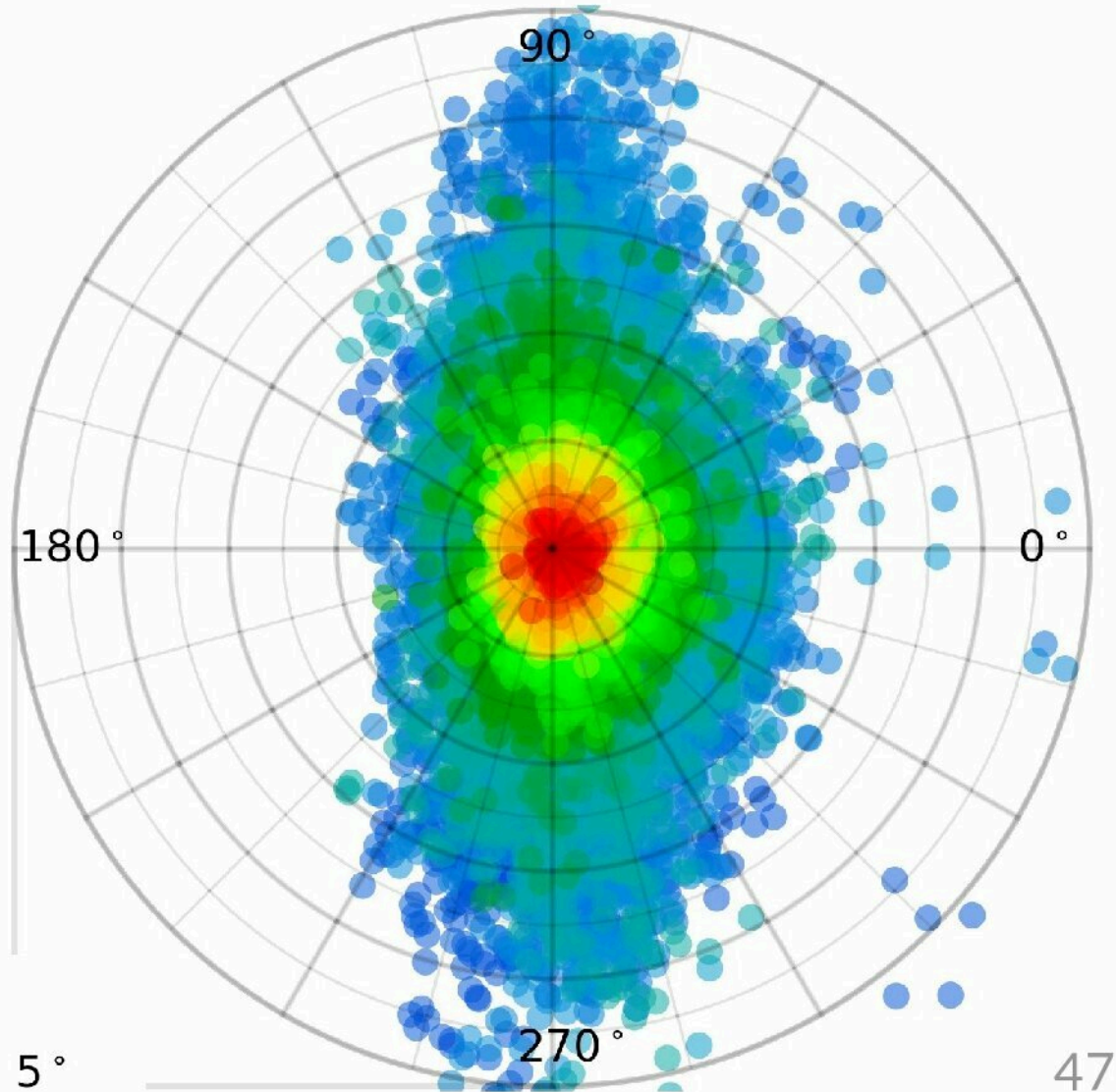
horizontal: 20.8uT

vertical: -11.4uT

5000m a.s.l.



Direction of primary to get
Cherenkov-light from zenith.



Deflection of shower

Gamma-ray

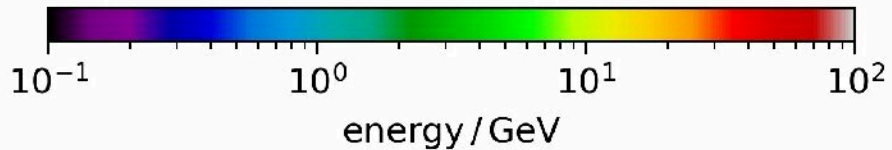


Roque, La Palma

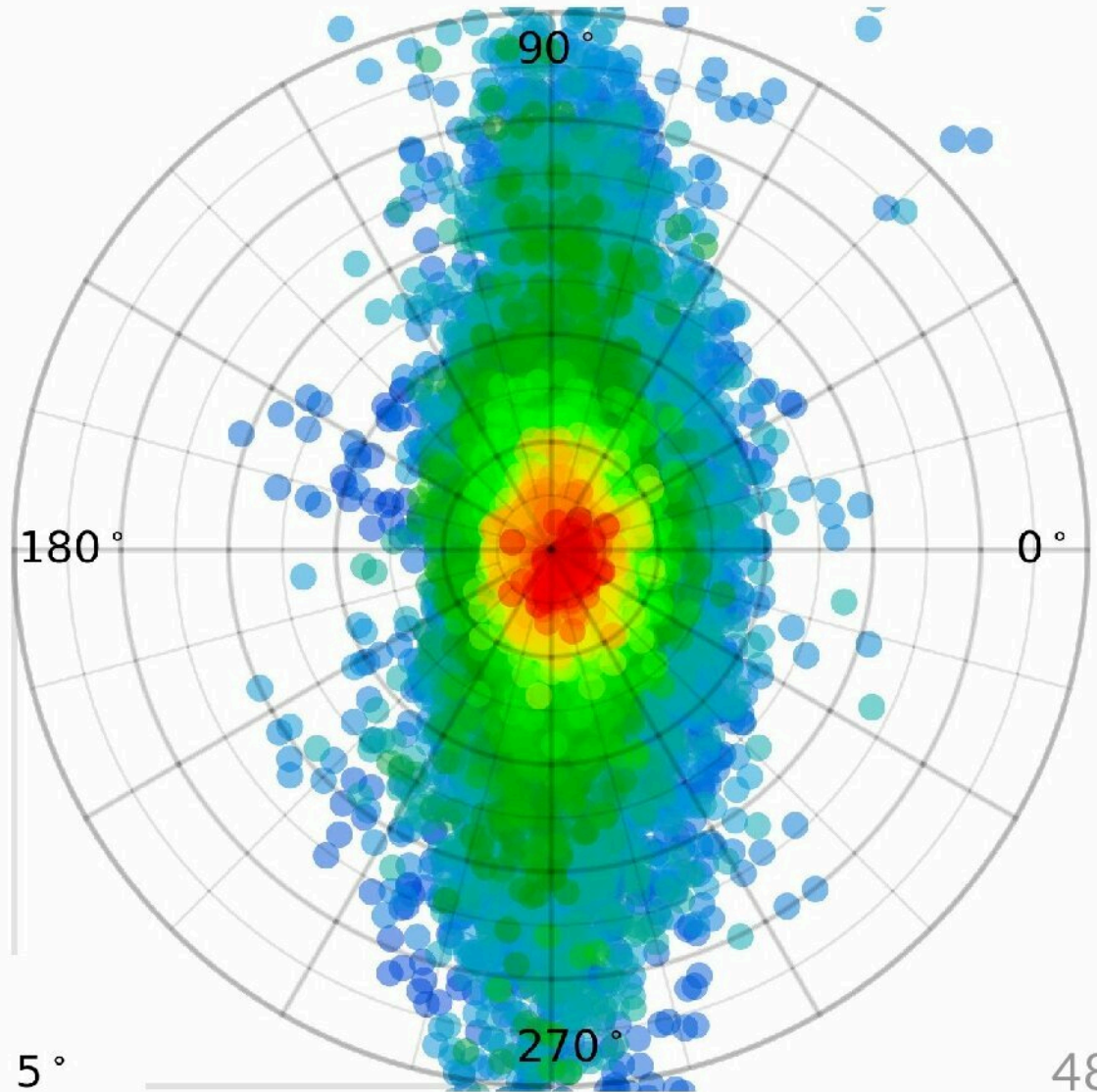
horizontal: 30.4uT

vertical: -23.8uT

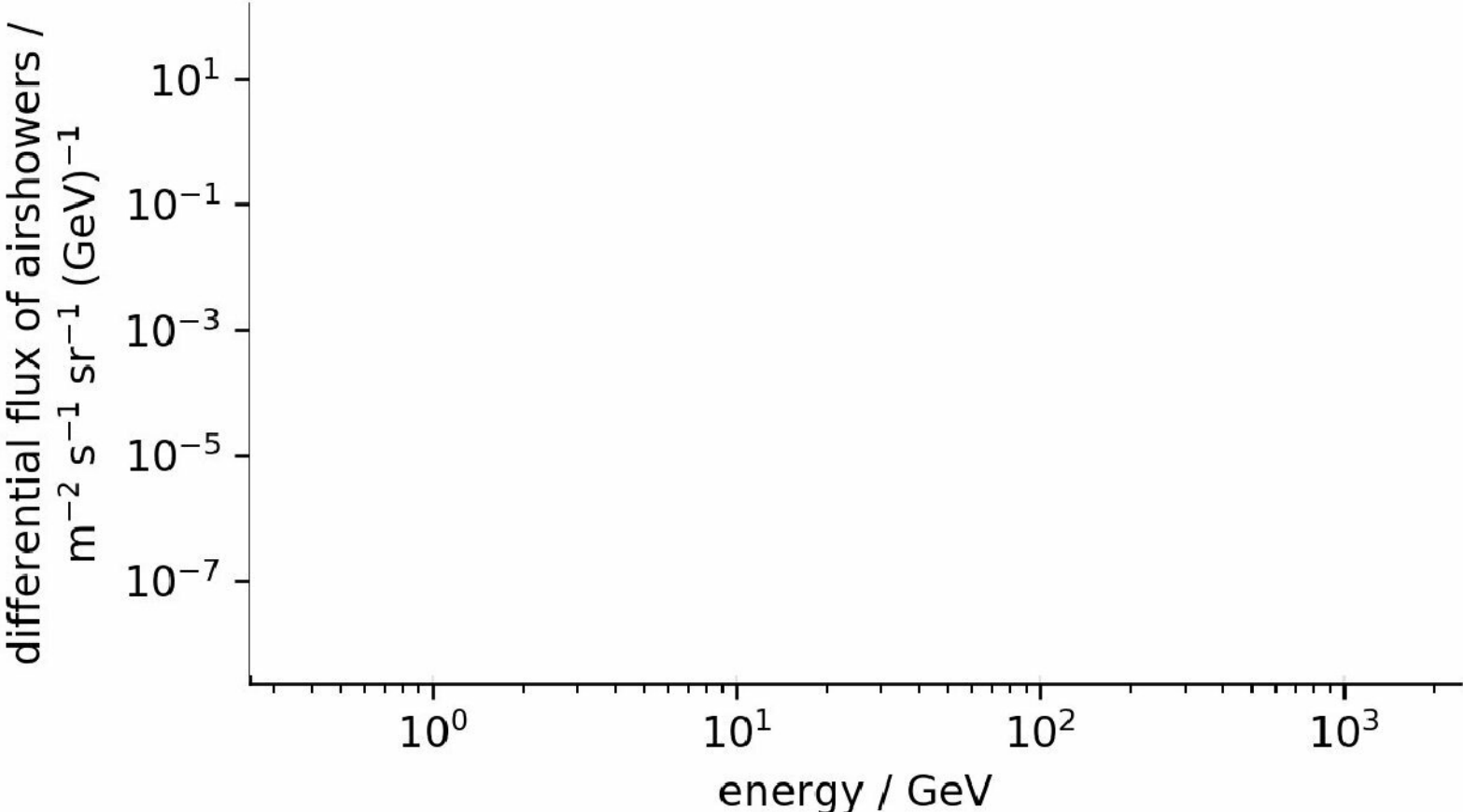
2200m a.s.l.



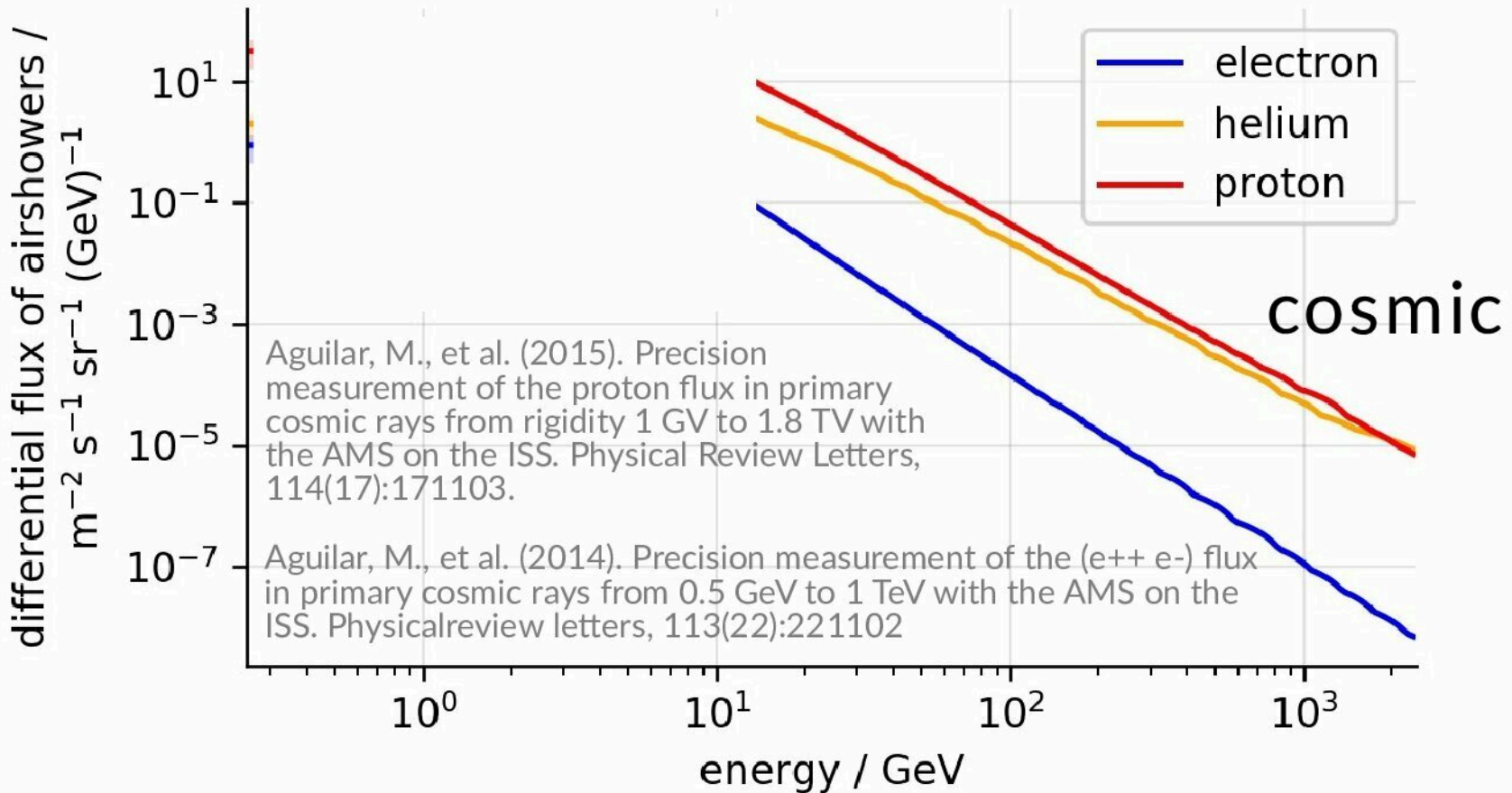
Direction of primary to get
Cherenkov-light from zenith.



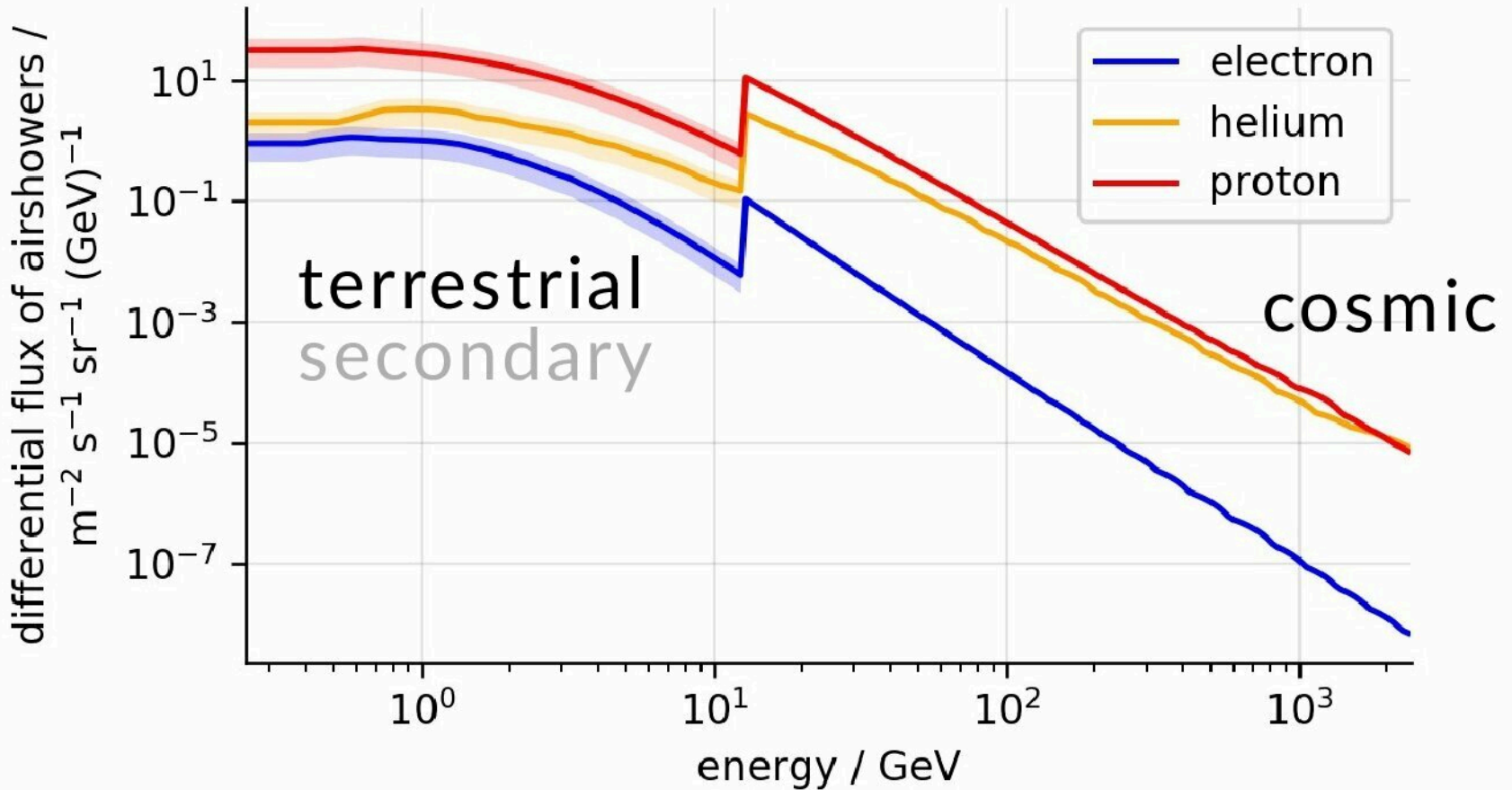
Background from Airshowers



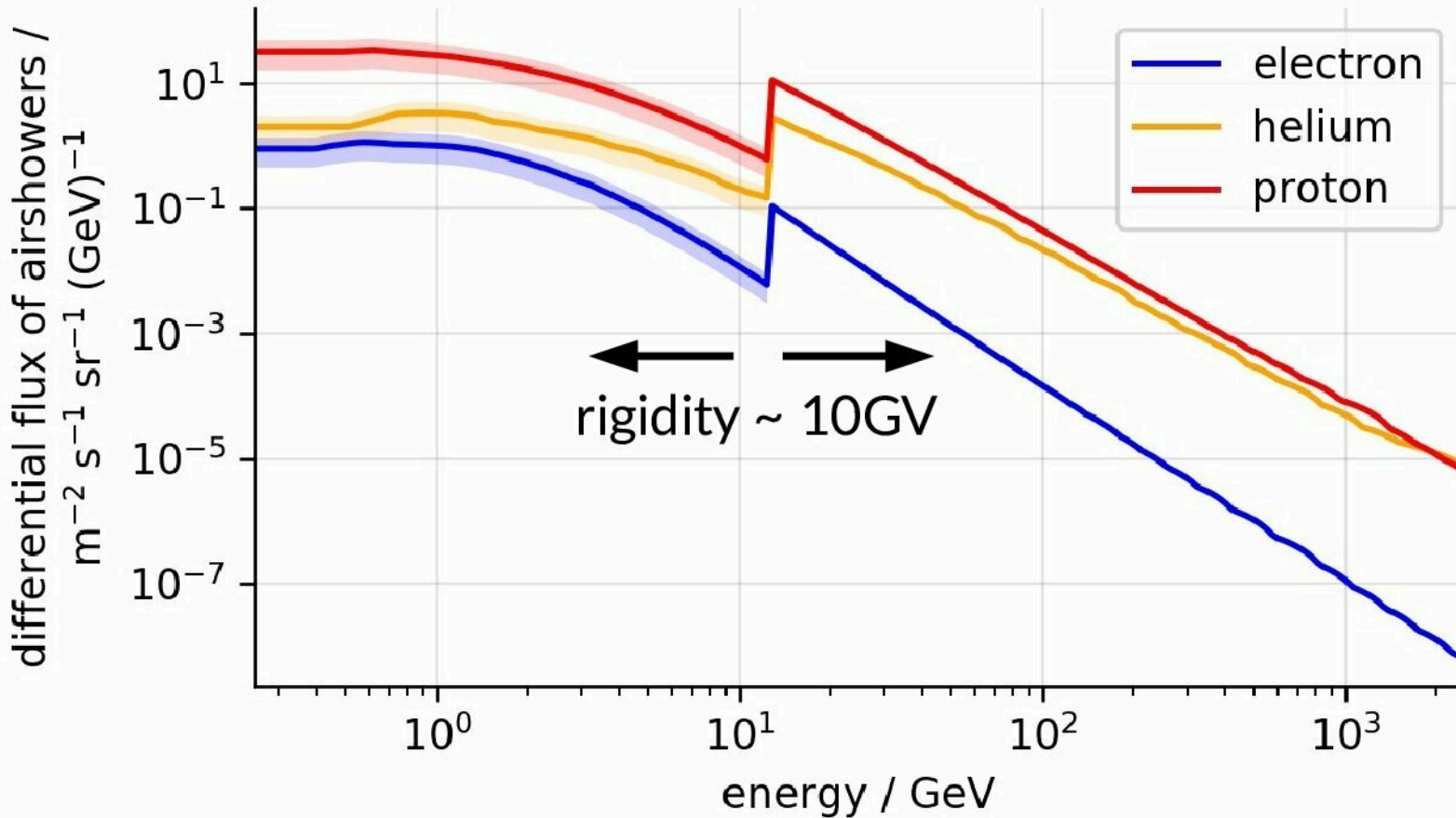
Background from Airshowers



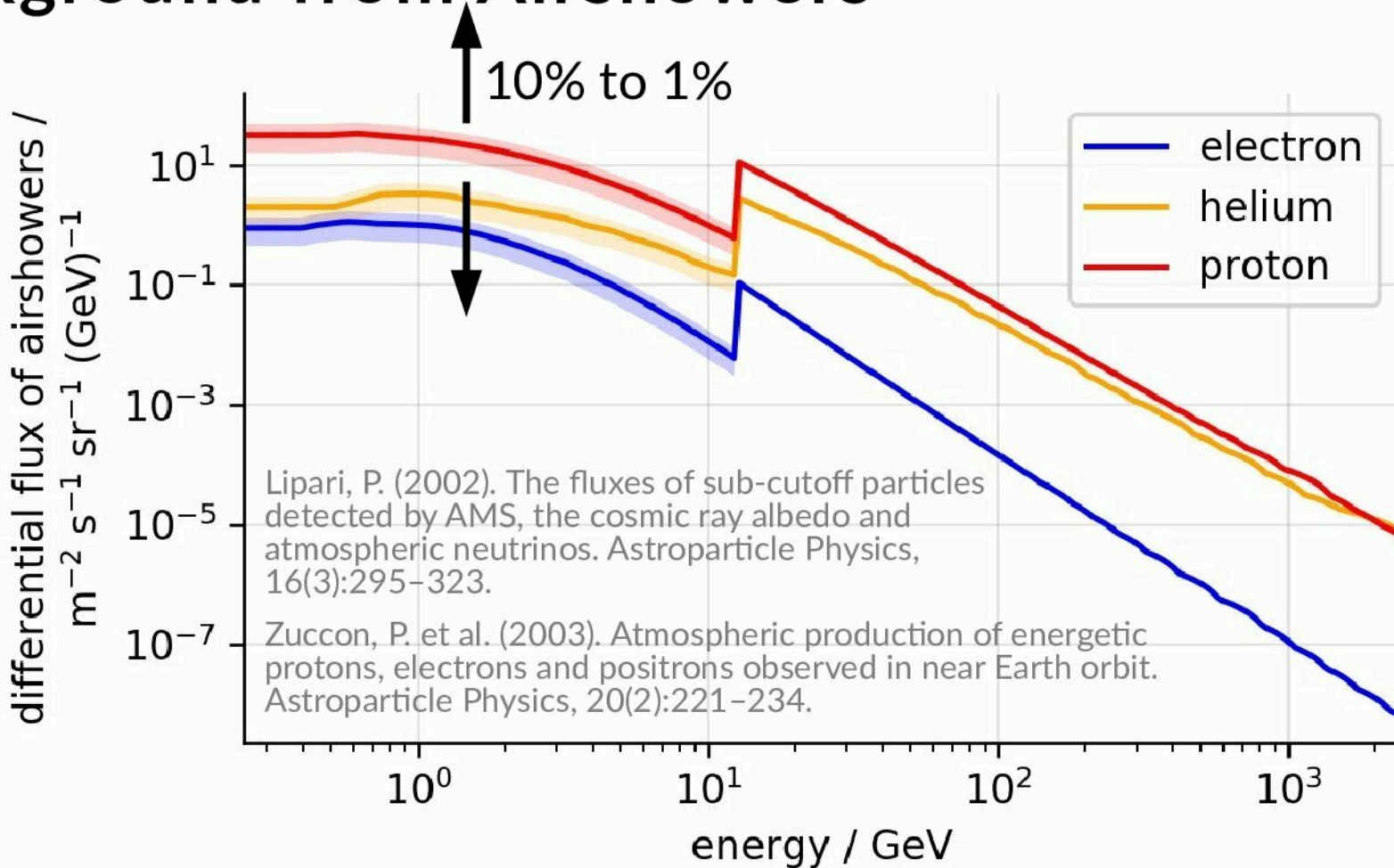
Background from Airshowers



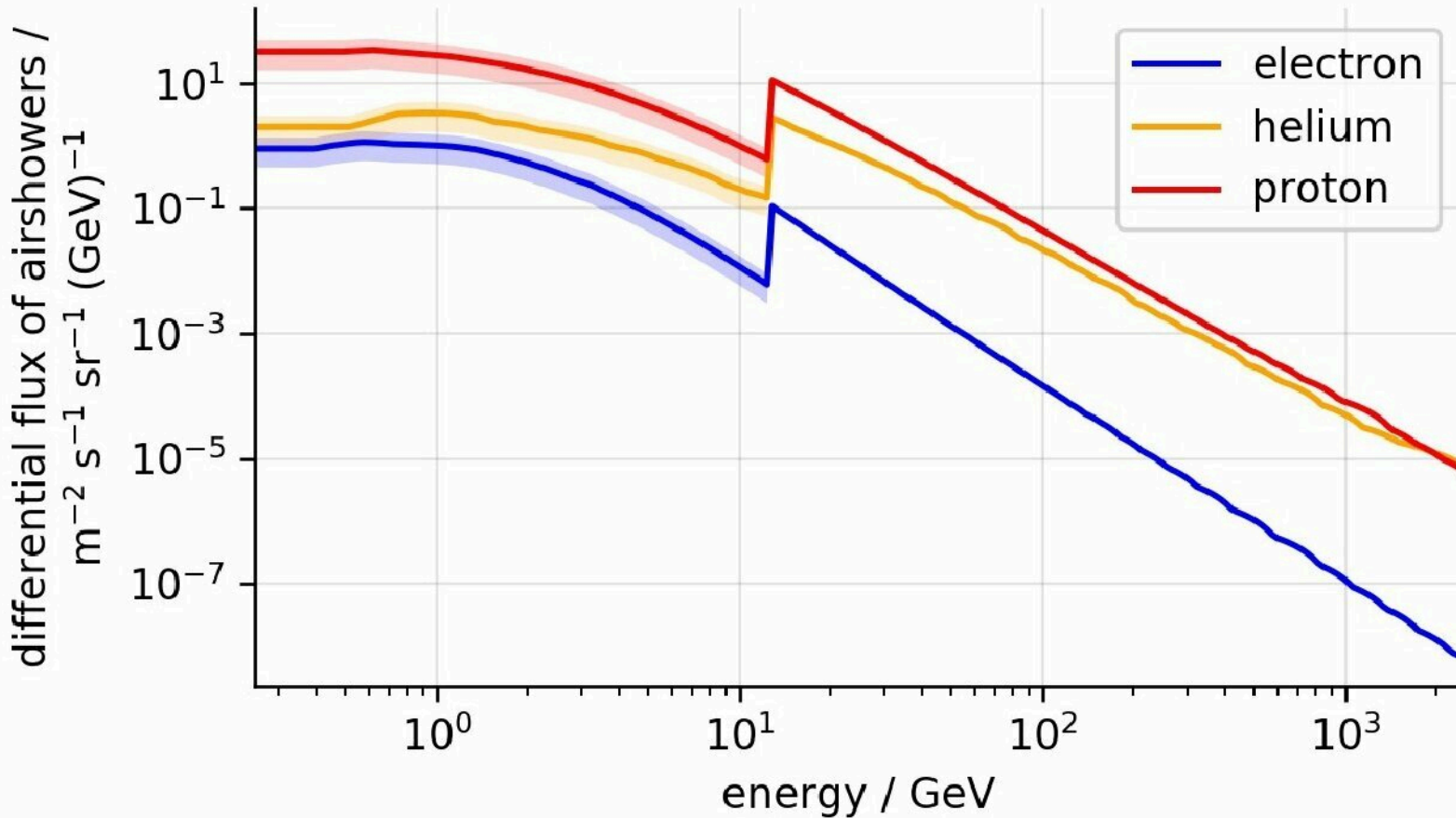
Background from Airshowers

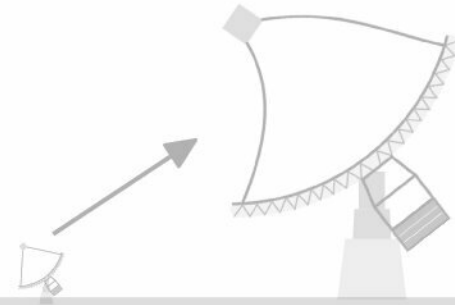


Background from Airshowers

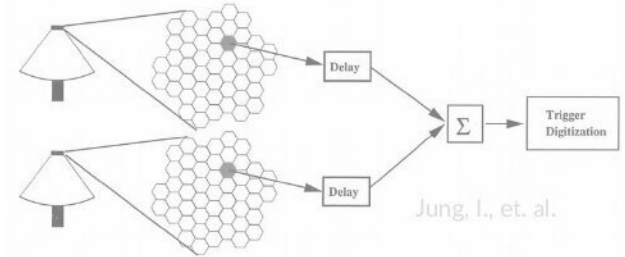
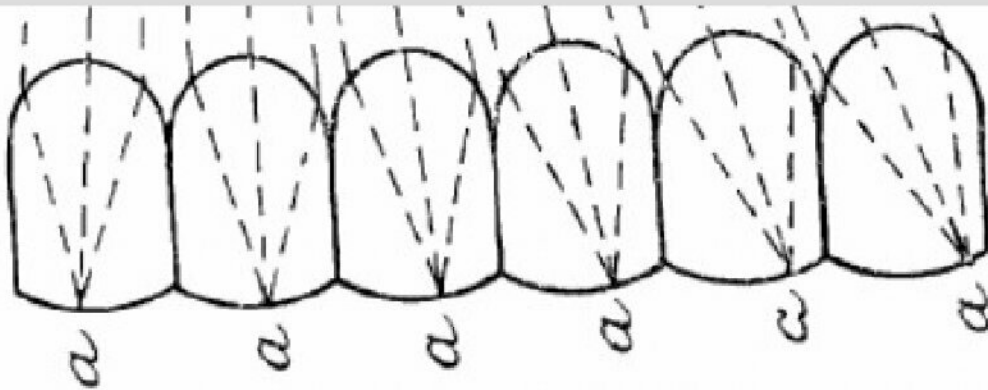


Background from Airshowers





Plenoptic Perception



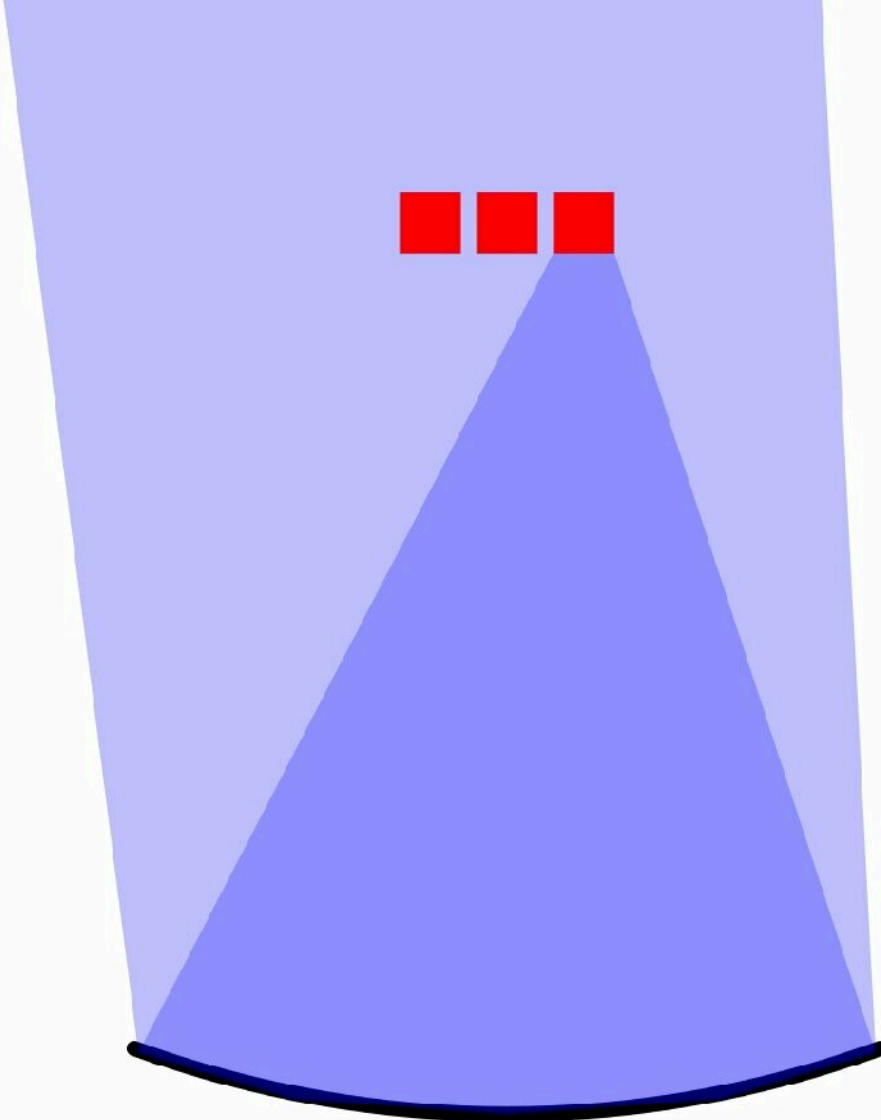
Plenoptics

Telescope



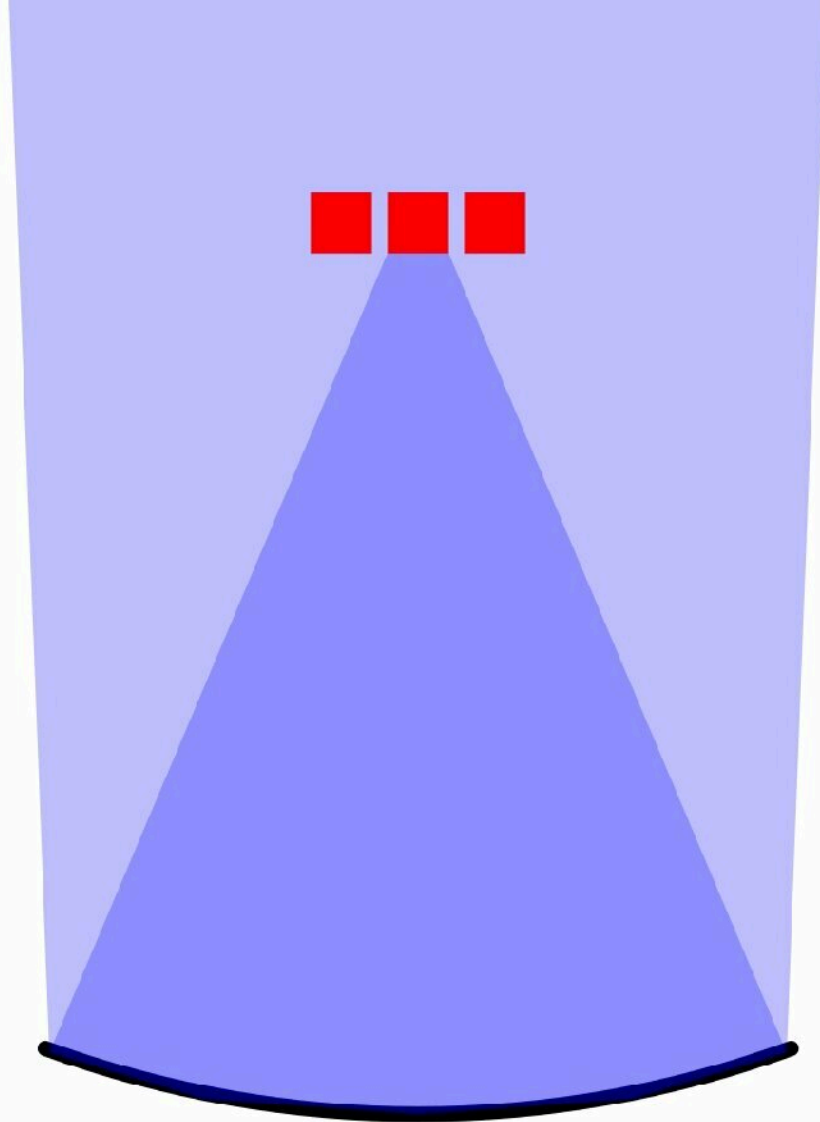
Plenoptics

Telescope



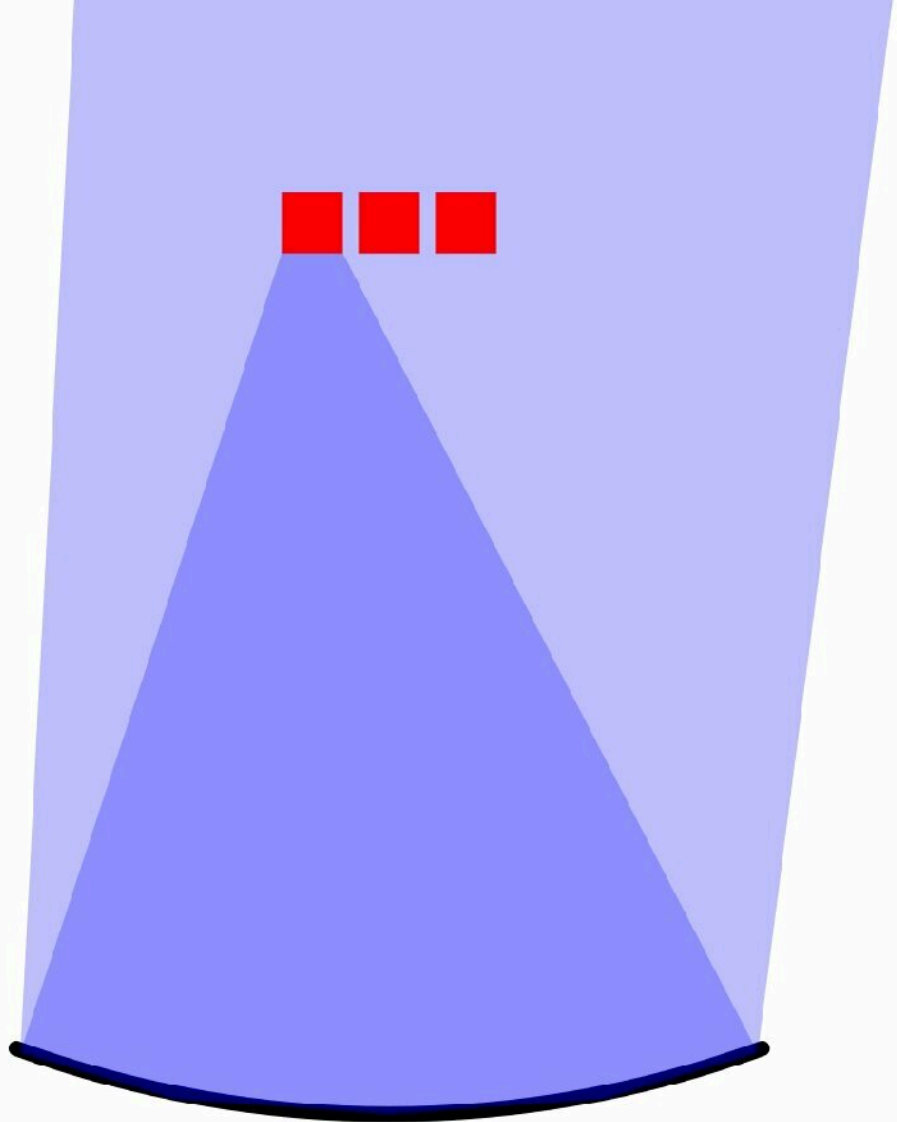
Plenoptics

Telescope



Plenoptics

Telescope



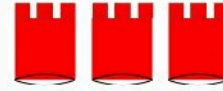
Plenoptics

Telescope



Plenoptics

Telescope
Plenoscope



ÉPREUVES RÉVERSIBLES

823

donc un large faisceau qui converge vers A (voir *fig. 1*) : c'est un faisceau large, puisqu'il a pour base toute la plaque sensible, ou du moins toute la partie de cette plaque d'où le point A était visible (¹).

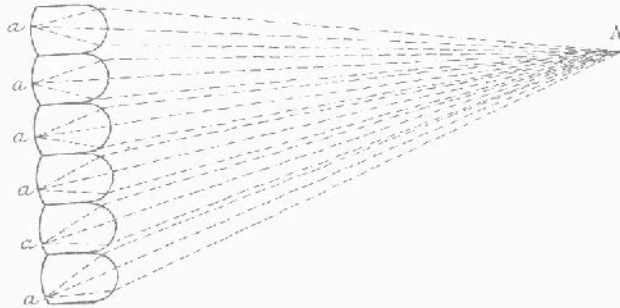


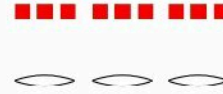
Fig. 1.

Par M. G. Lippmann, (1908),
Epreuves reversibles donnant la sensation du relief,
Phys. Theor. Appl. 7, p.821-825



Plenoptics

Plenoscope



ÉPREUVES RÉVERSIBLES

823

donc un large faisceau qui converge vers A (voir *fig. 1*) : c'est un faisceau large, puisqu'il a pour base toute la plaque sensible, ou du moins toute la partie de cette plaque d'où le point A était visible (¹).

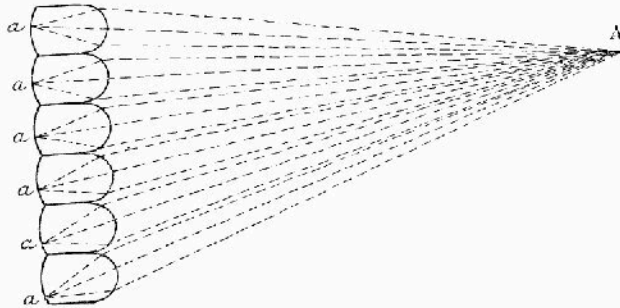


Fig. 1.

Par M. G. Lippmann, (1908),
Epreuves reversibles donnant la sensation du relief,
Phys. Theor. Appl. 7, p.821-825



Plenoptics

Plenoscope

ÉPREUVES RÉVERSIBLES

823

donc un large faisceau qui converge vers A (voir fig. 1) : c'est un faisceau large, puisqu'il a pour base toute la plaque sensible, ou du moins toute la partie de cette plaque d'où le point A était visible (1).

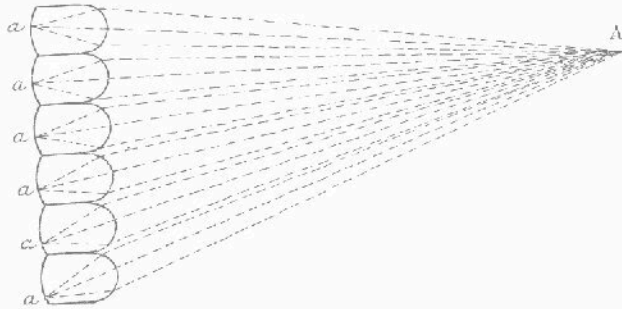
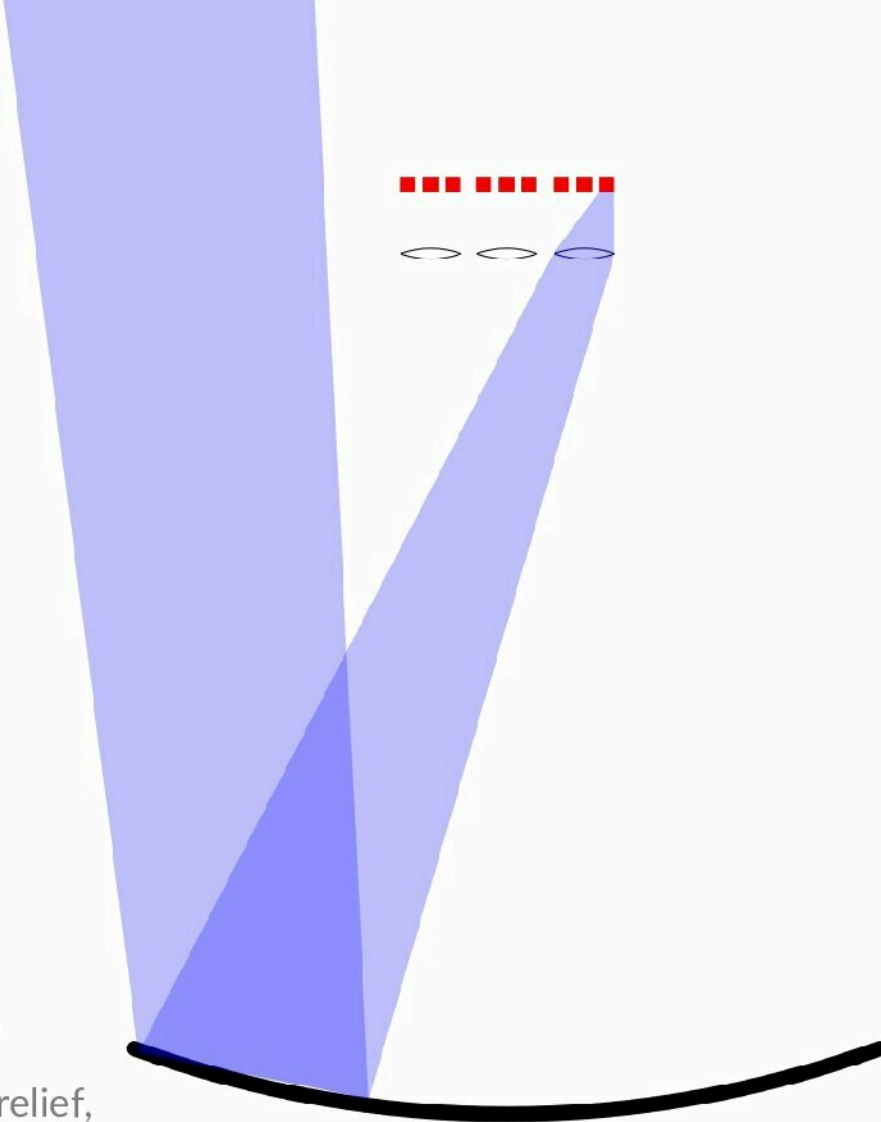


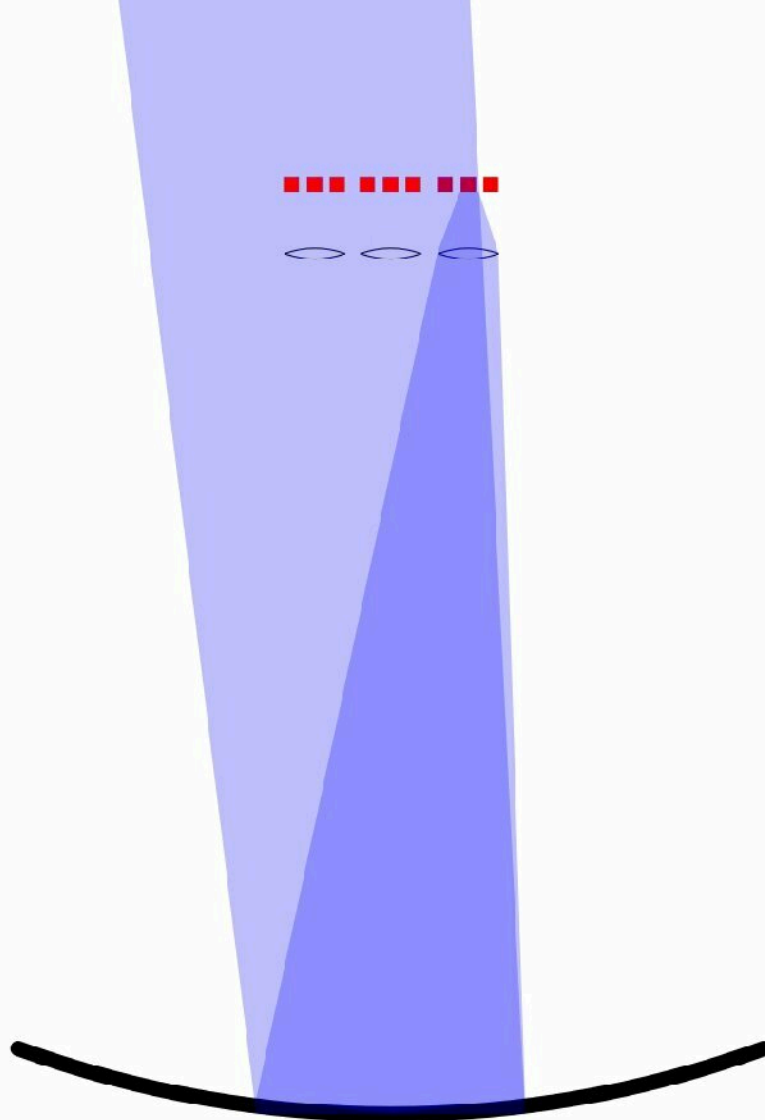
Fig. 1.

Par M. G. Lippmann, (1908),
Epreuves reversibles donnant la sensation du relief,
Phys. Theor. Appl. 7, p.821-825



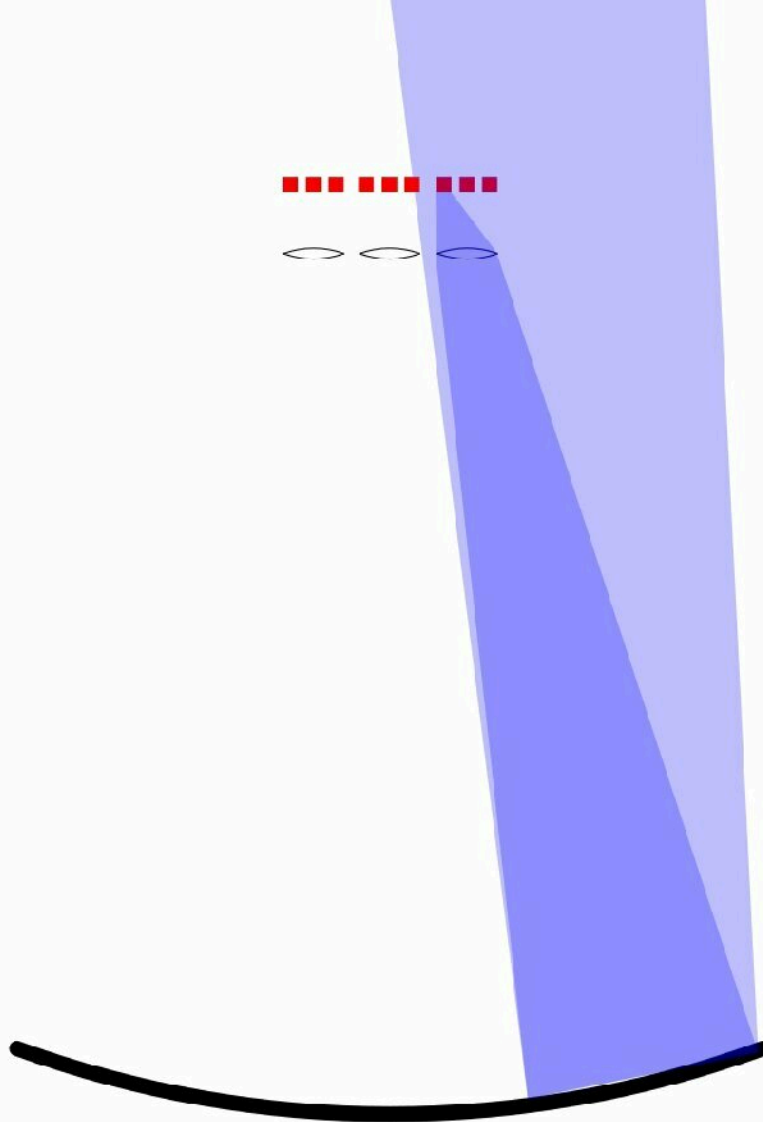
Plenoptics

Plenoscope



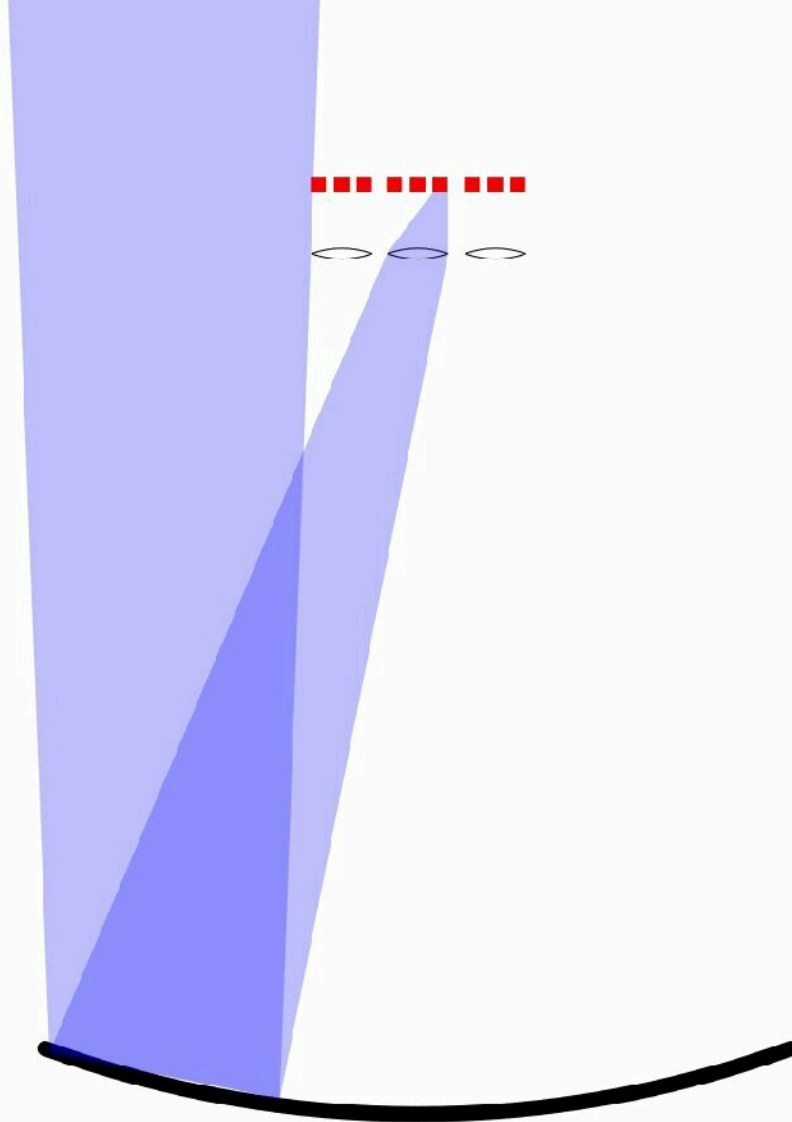
Plenoptics

Plenoscope



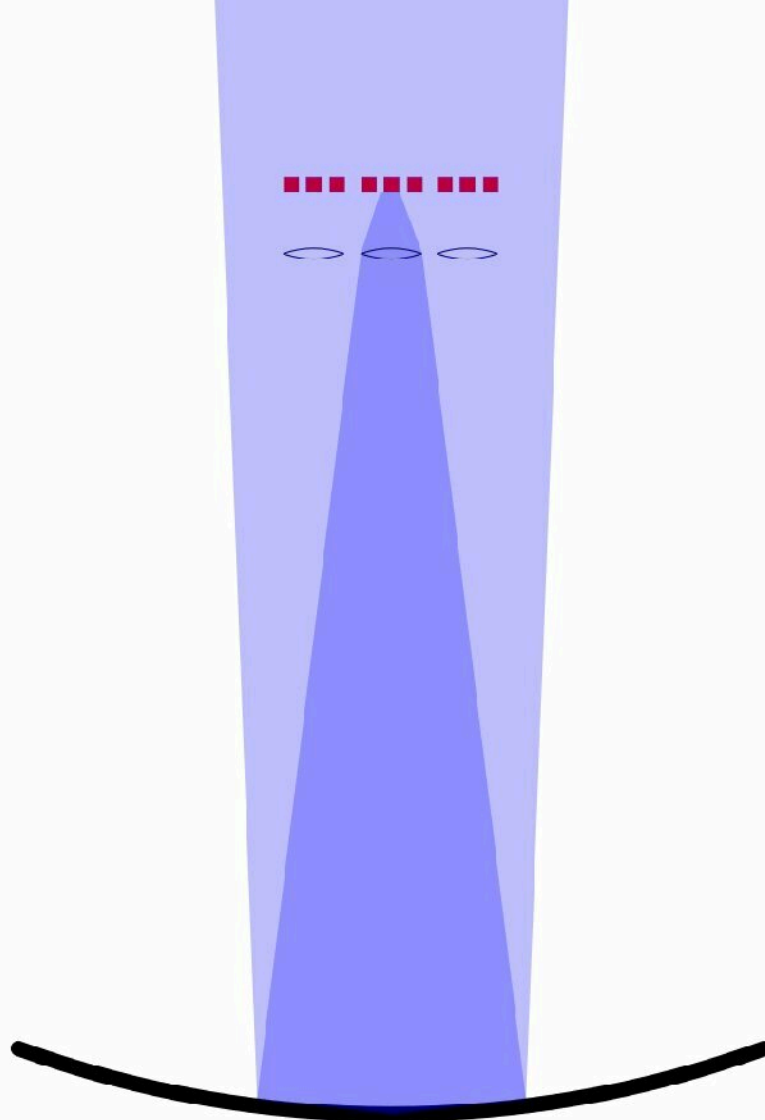
Plenoptics

Plenoscope



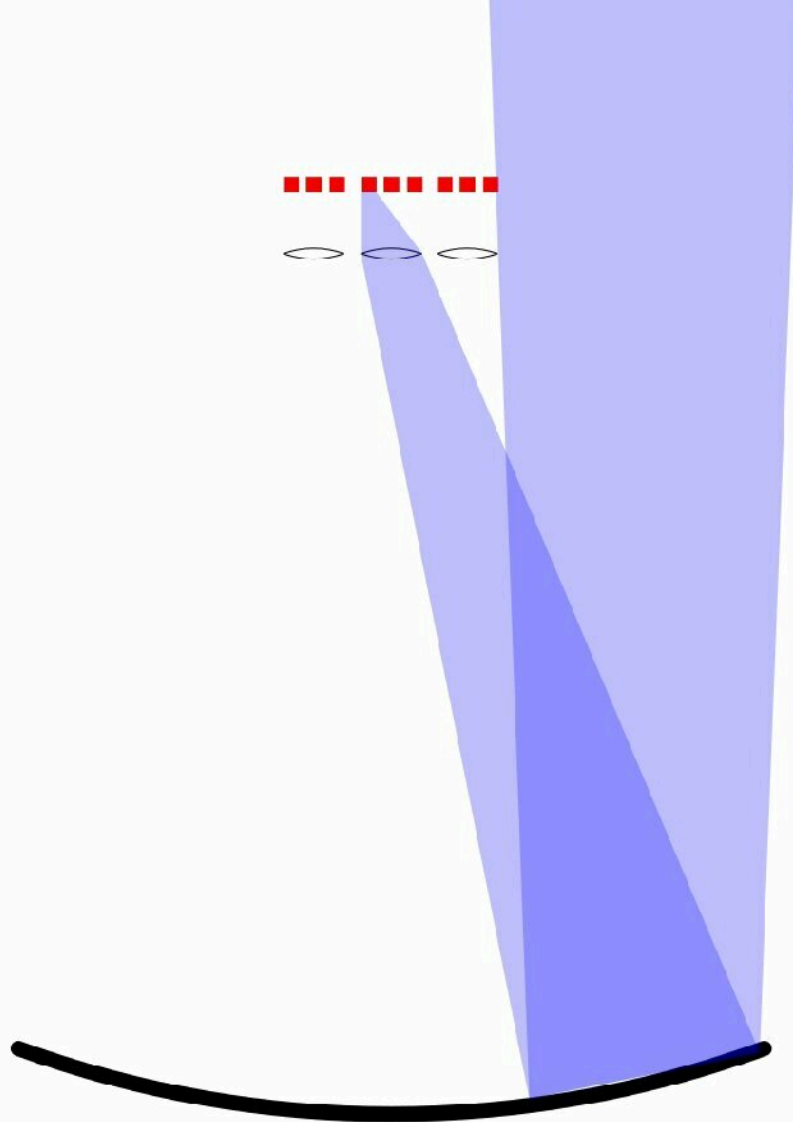
Plenoptics

Plenoscope



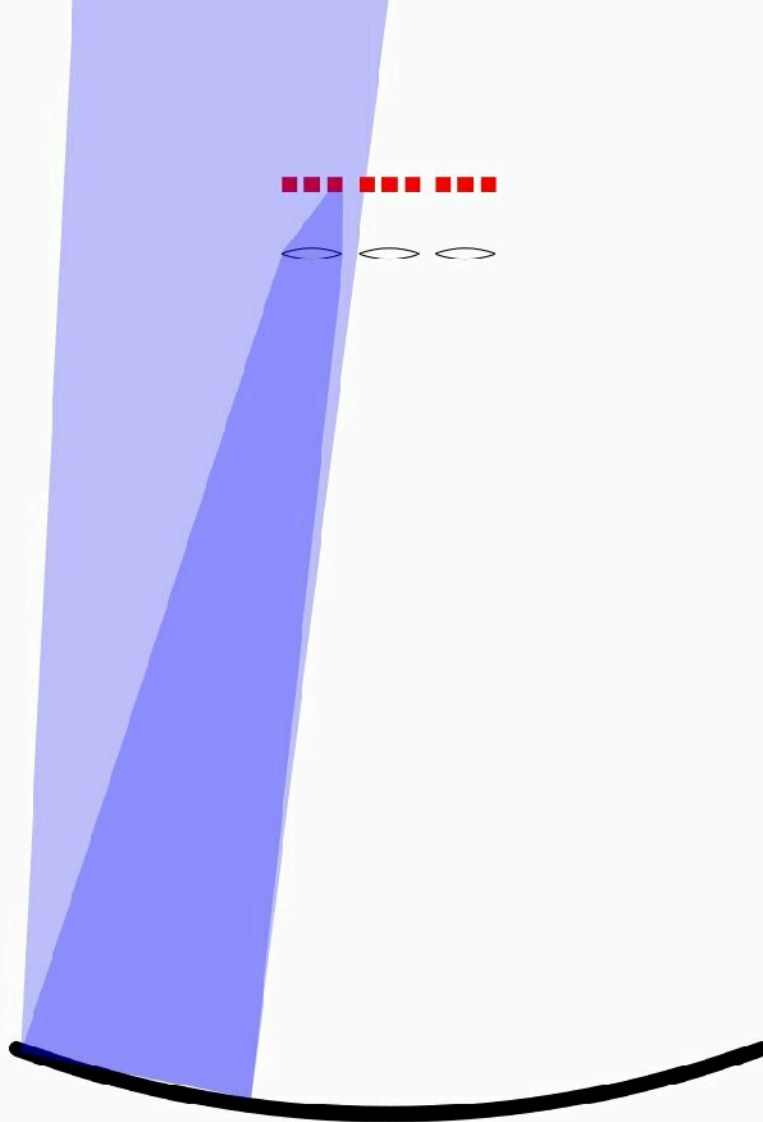
Plenoptics

Plenoscope



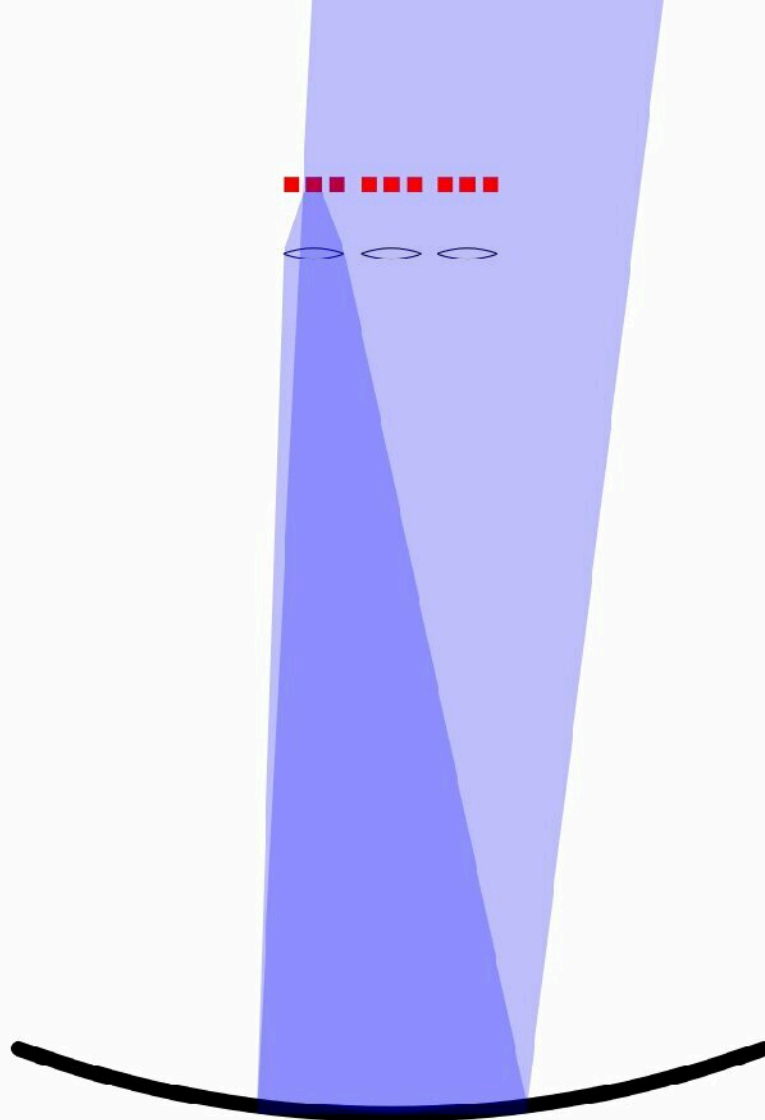
Plenoptics

Plenoscope



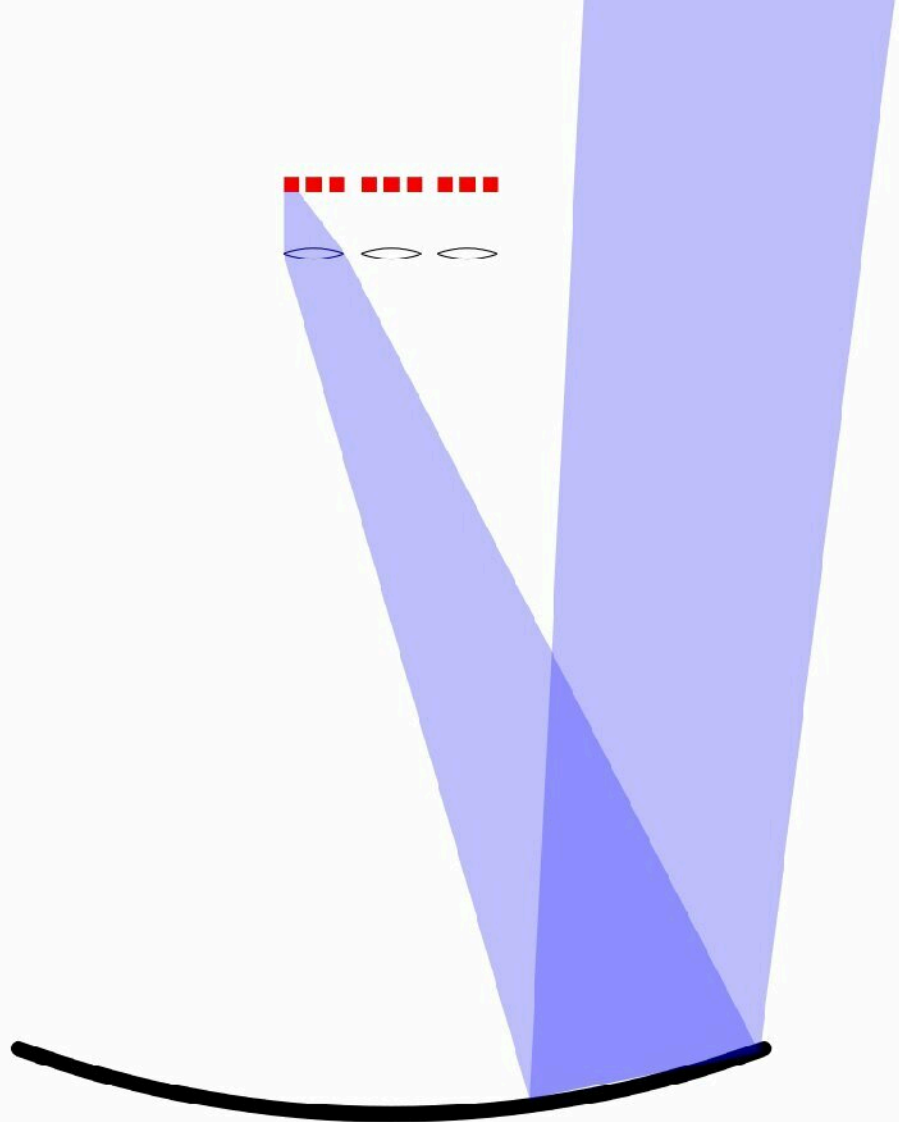
Plenoptics

Plenoscope



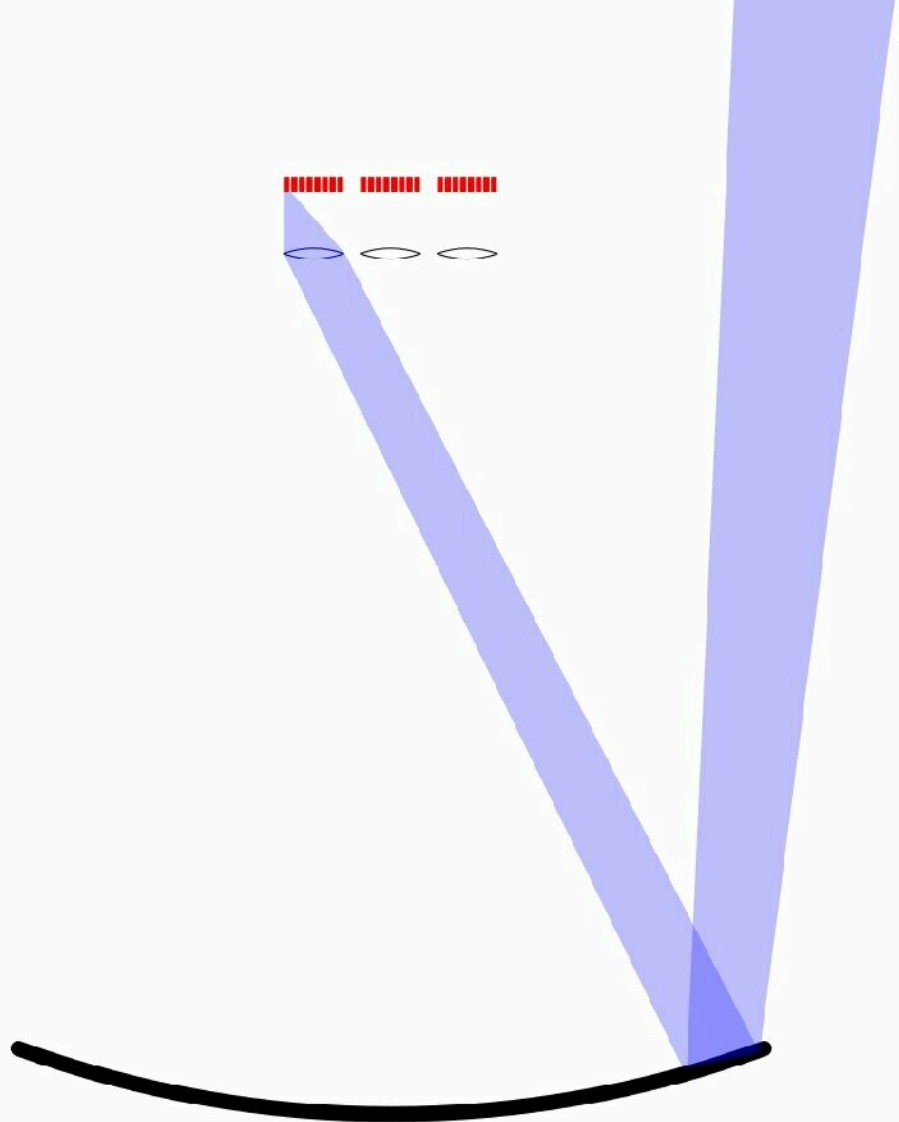
Plenoptics

Plenoscope



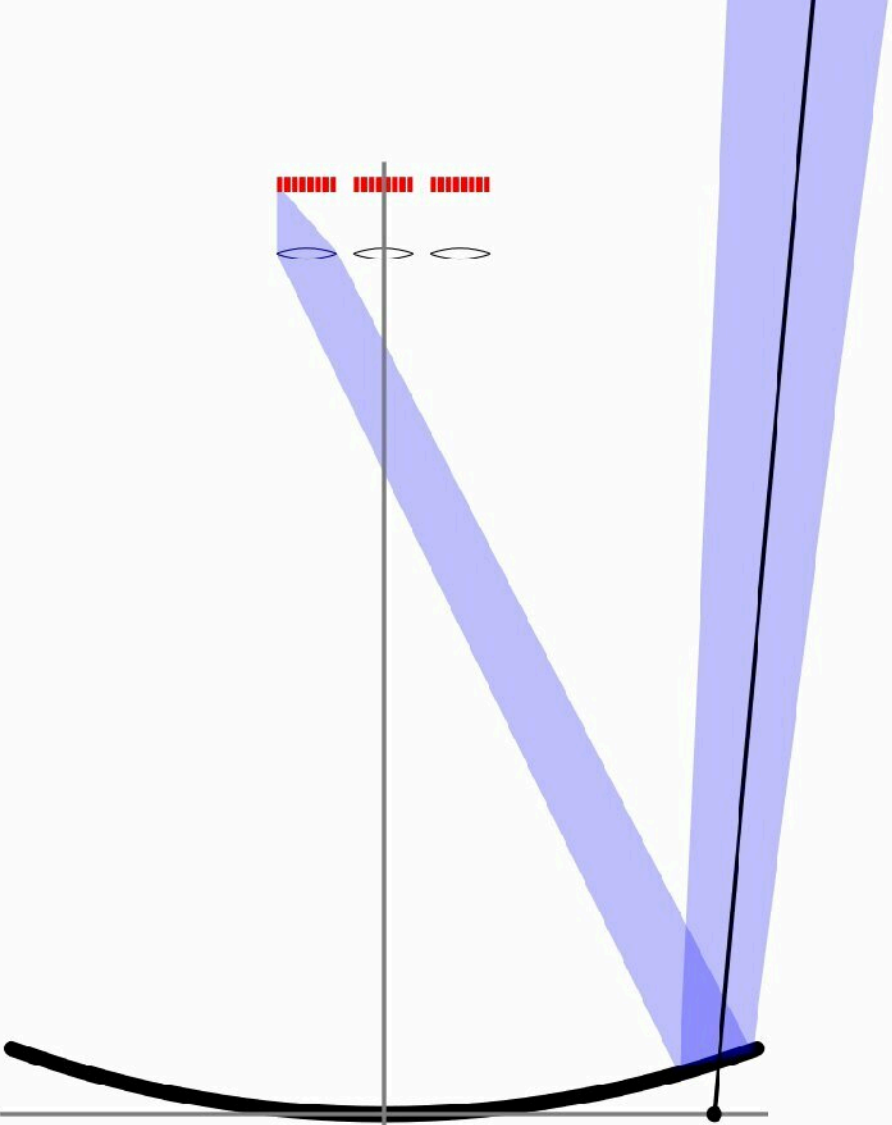
Plenoptics

Plenoscope



Plenoptics

Plenoscope
thin lens

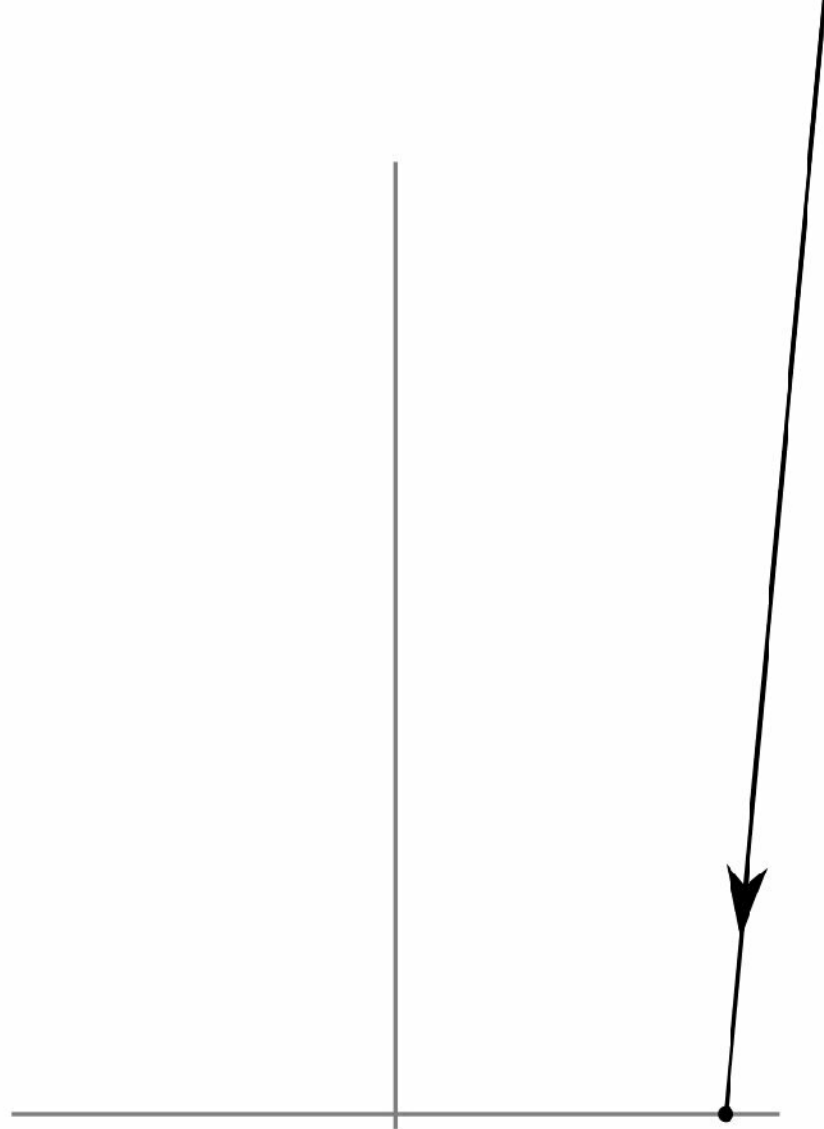


Plenoptics

thin lens

$$\frac{1}{\text{focal-length}} = \frac{1}{\text{depth}} + \frac{1}{\text{image-distance}}$$

Equations: arXiv:1904.13368 (astro-ph)



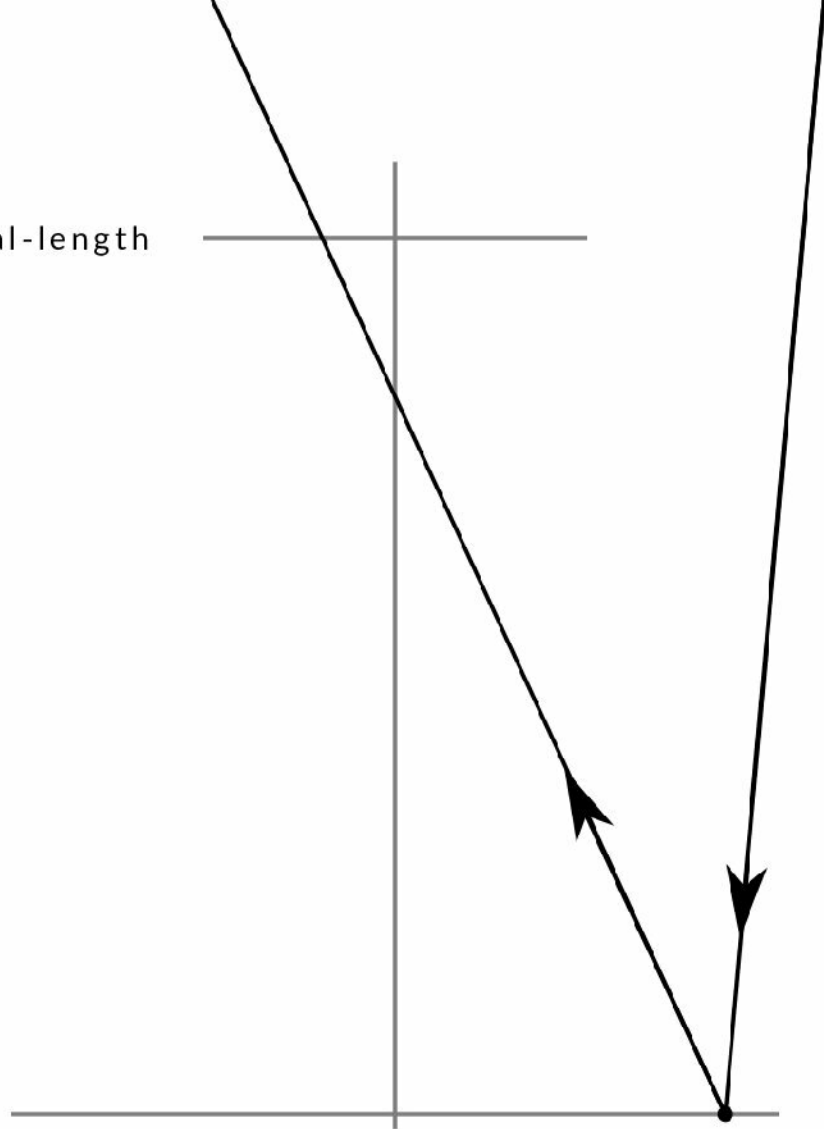
Plenoptics

thin lens

$$\frac{1}{\text{focal-length}} = \frac{1}{\text{depth}} + \frac{1}{\text{image-distance}}$$

Equations: arXiv:1904.13368 (astro-ph)

focal-length

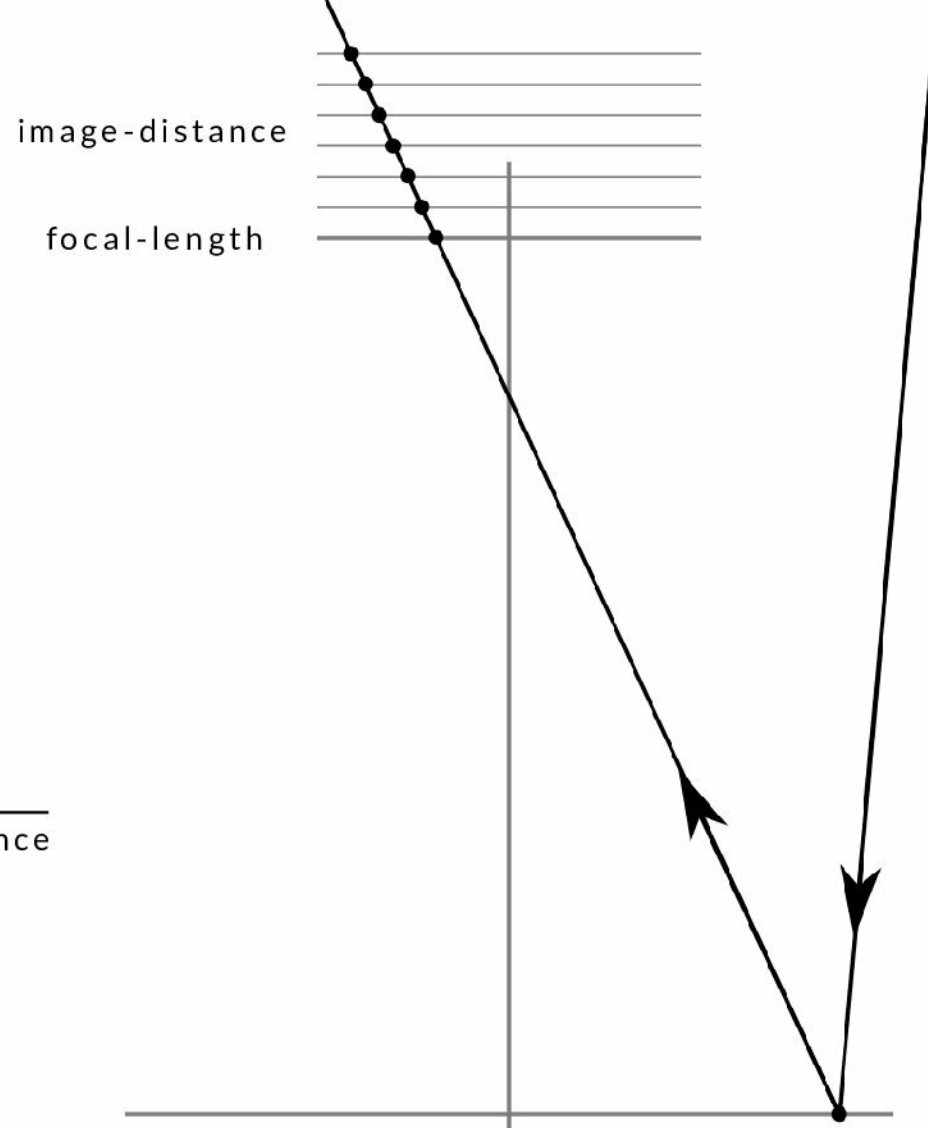


Plenoptics

thin lens

$$\frac{1}{\text{focal-length}} = \frac{1}{\text{depth}} + \frac{1}{\text{image-distance}}$$

Equations: arXiv:1904.13368 (astro-ph)

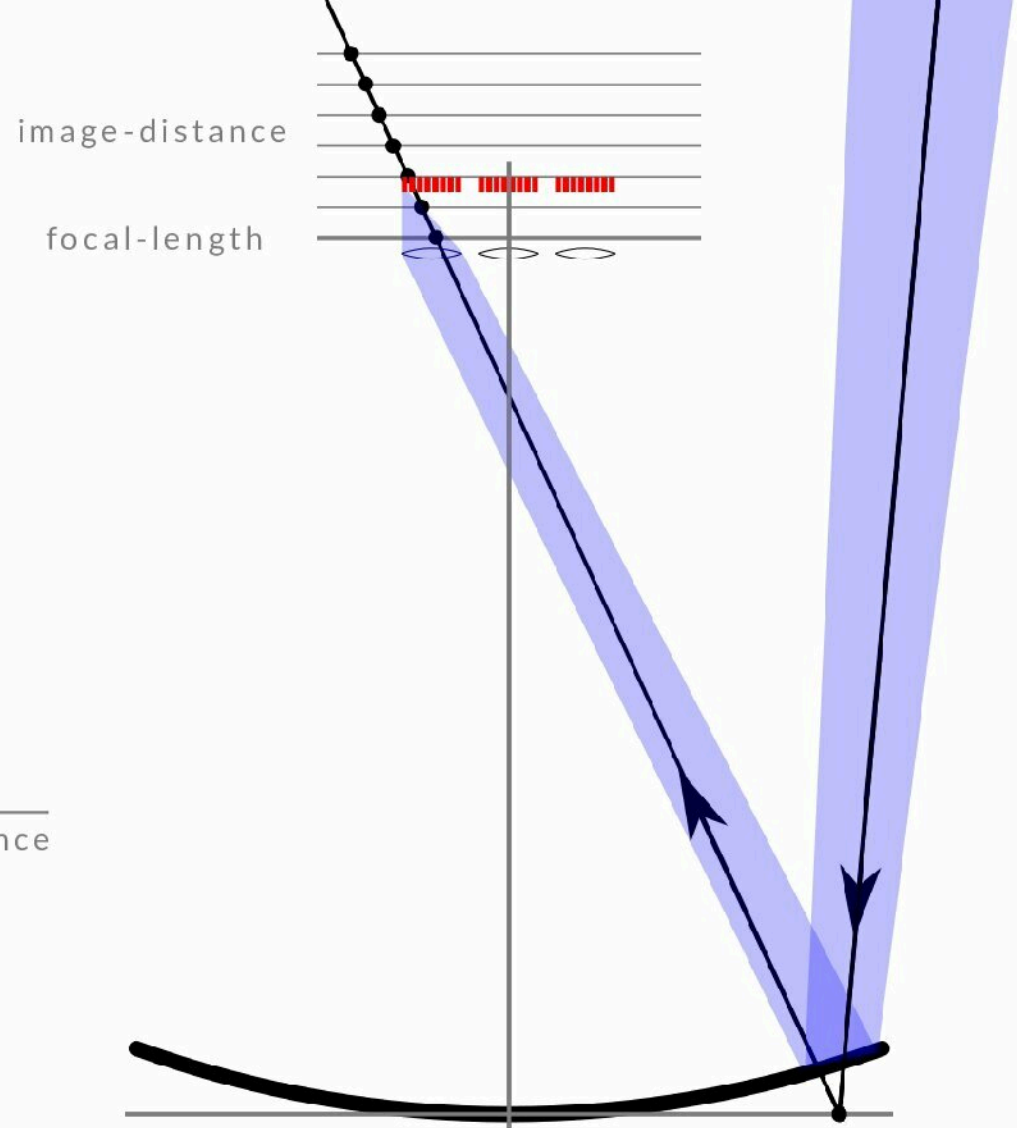


Plenoptics

Plenoscope
thin lens

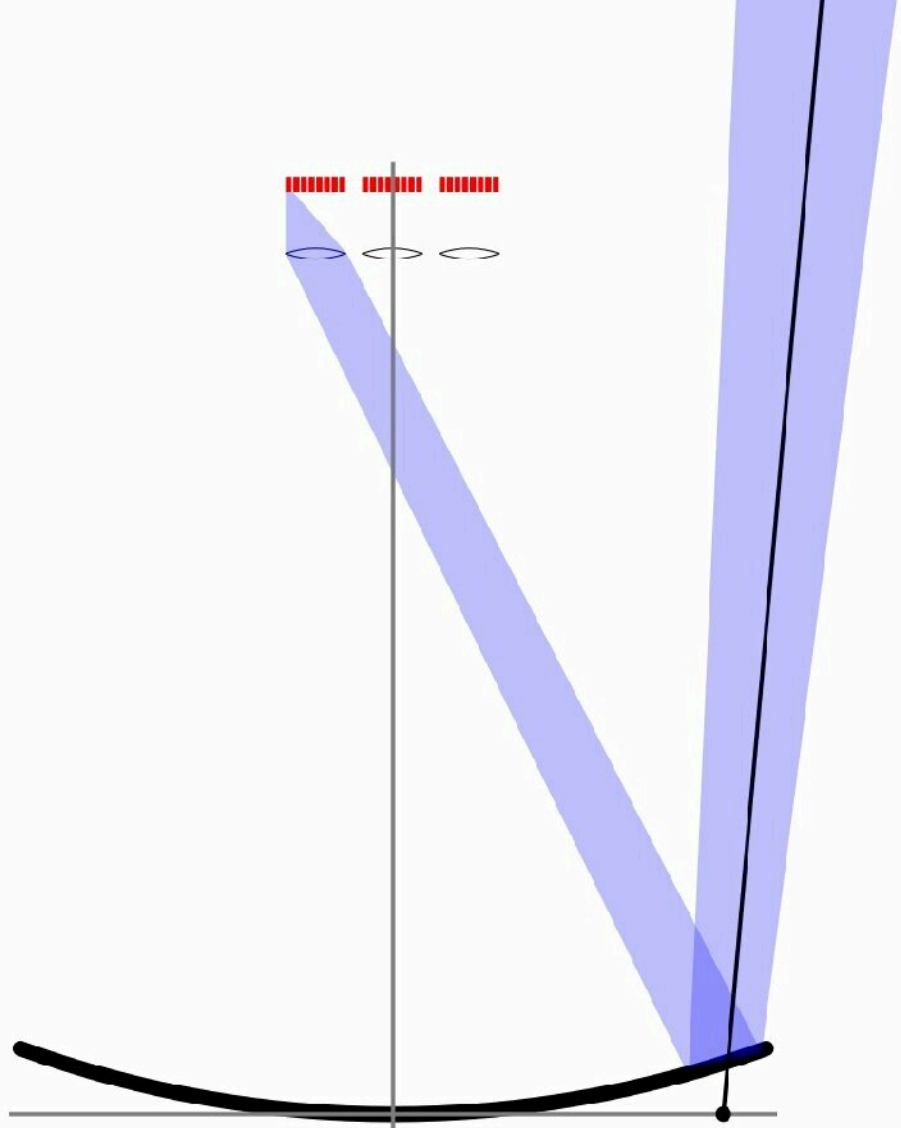
$$\frac{1}{\text{focal-length}} = \frac{1}{\text{depth}} + \frac{1}{\text{image-distance}}$$

Equations: arXiv:1904.13368 (astro-ph)



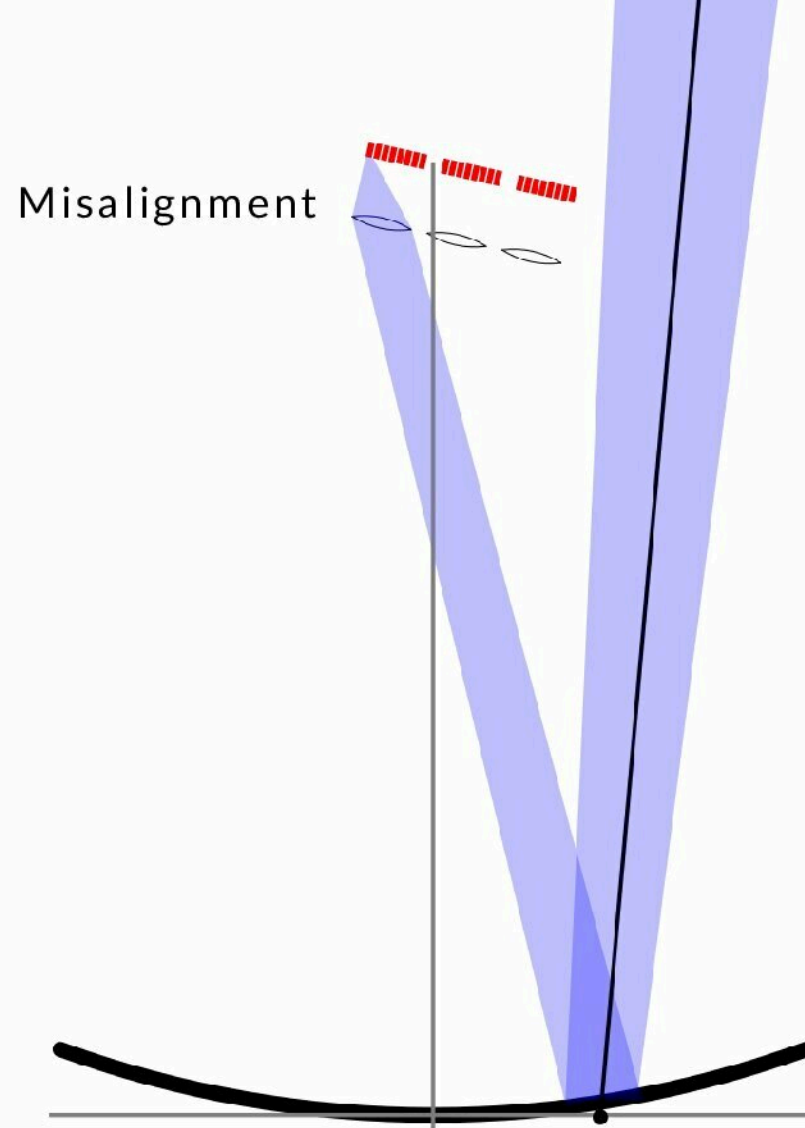
Plenoptics

Plenoscope



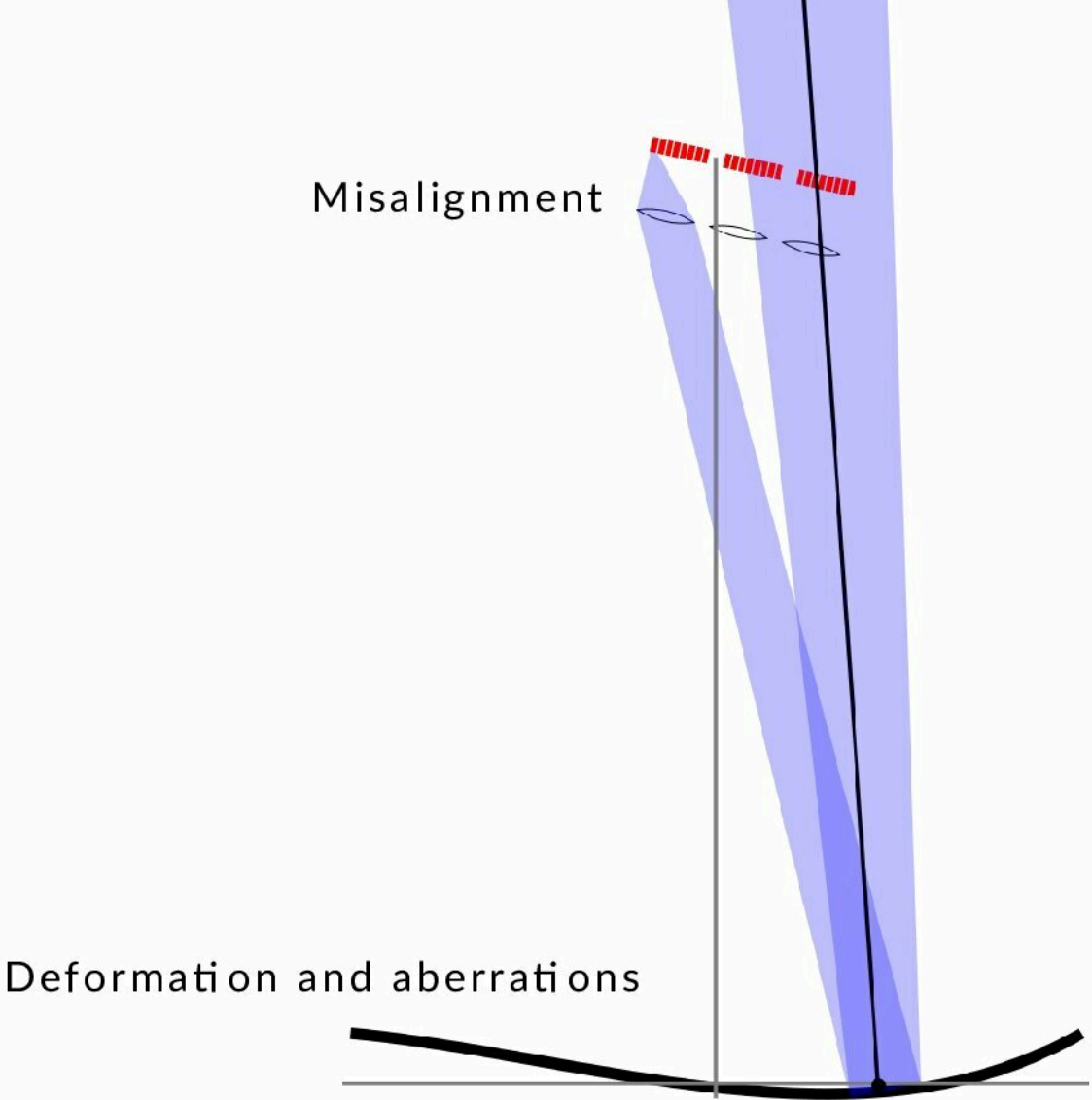
Plenoptics

Plenoscope



Plenoptics

Plenoscope

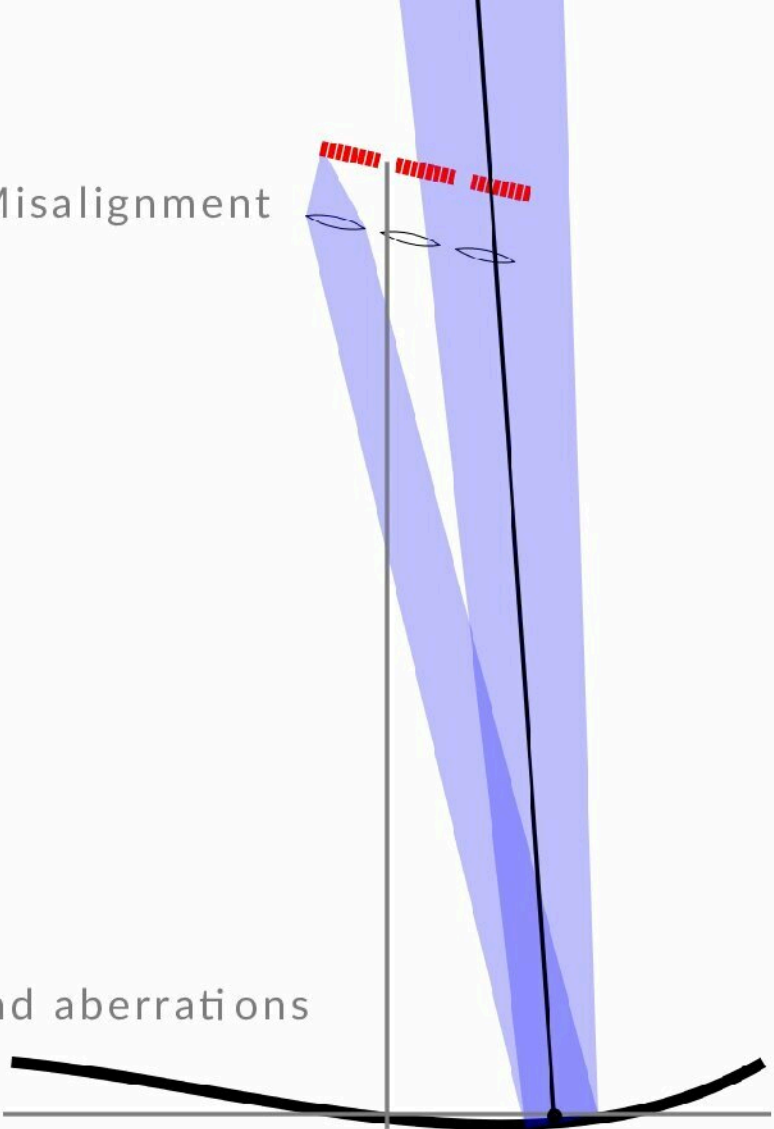


Plenoptics

Plenoscope
thin lens

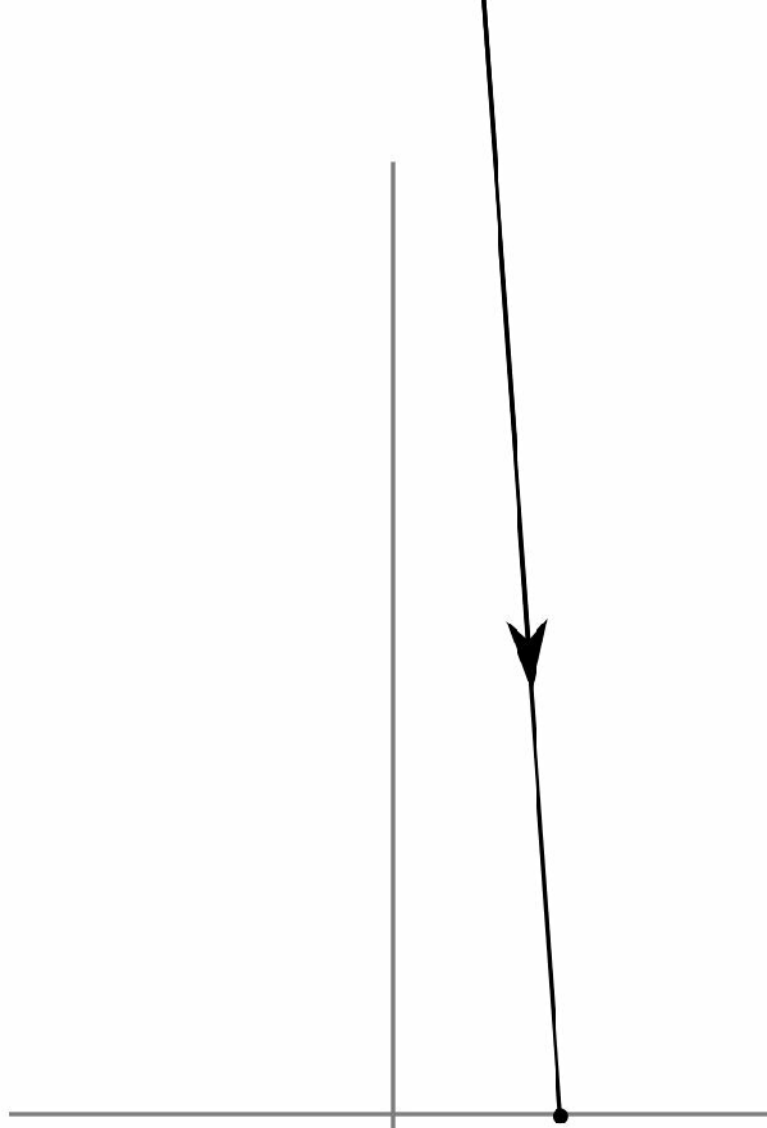
Deformation and aberrations

Misalignment



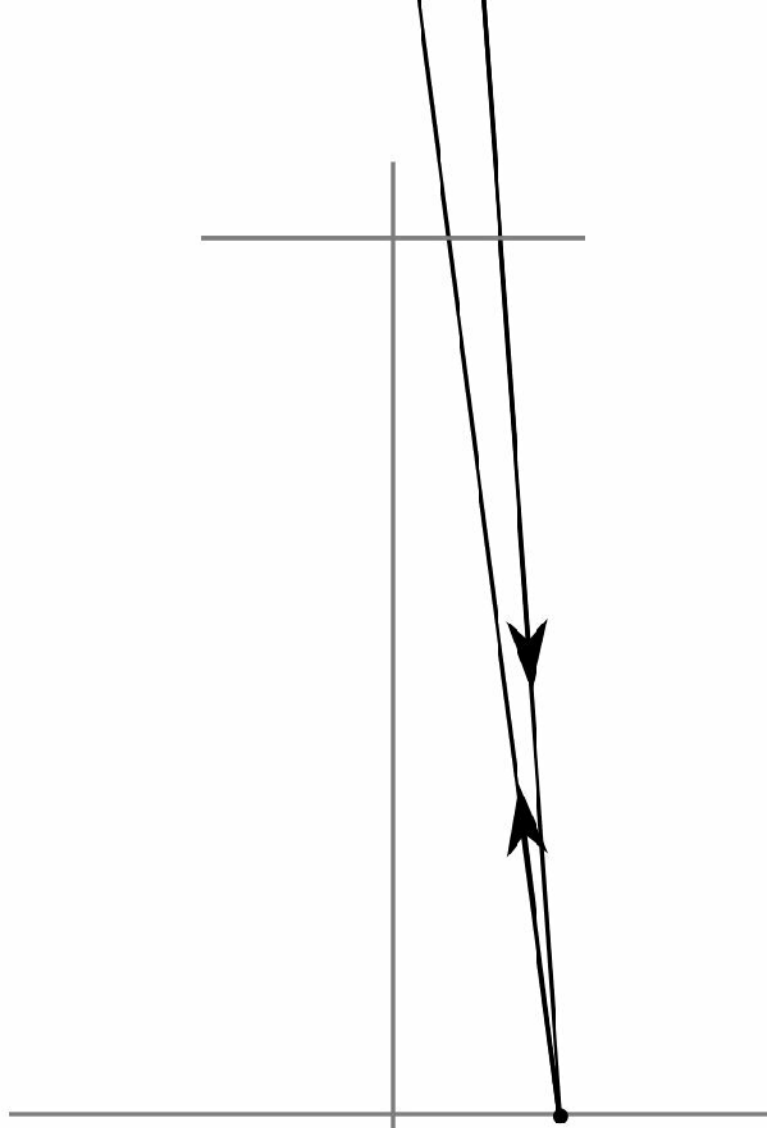
Plenoptics

thin lens



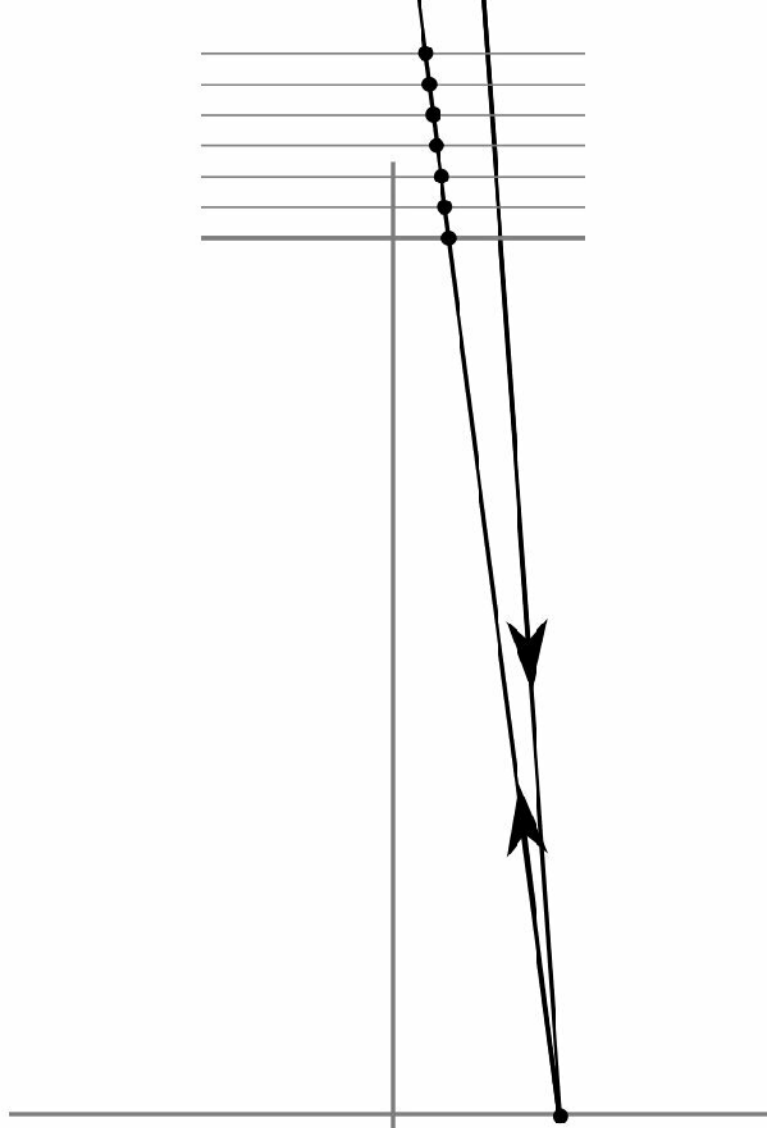
Plenoptics

thin lens



Plenoptics

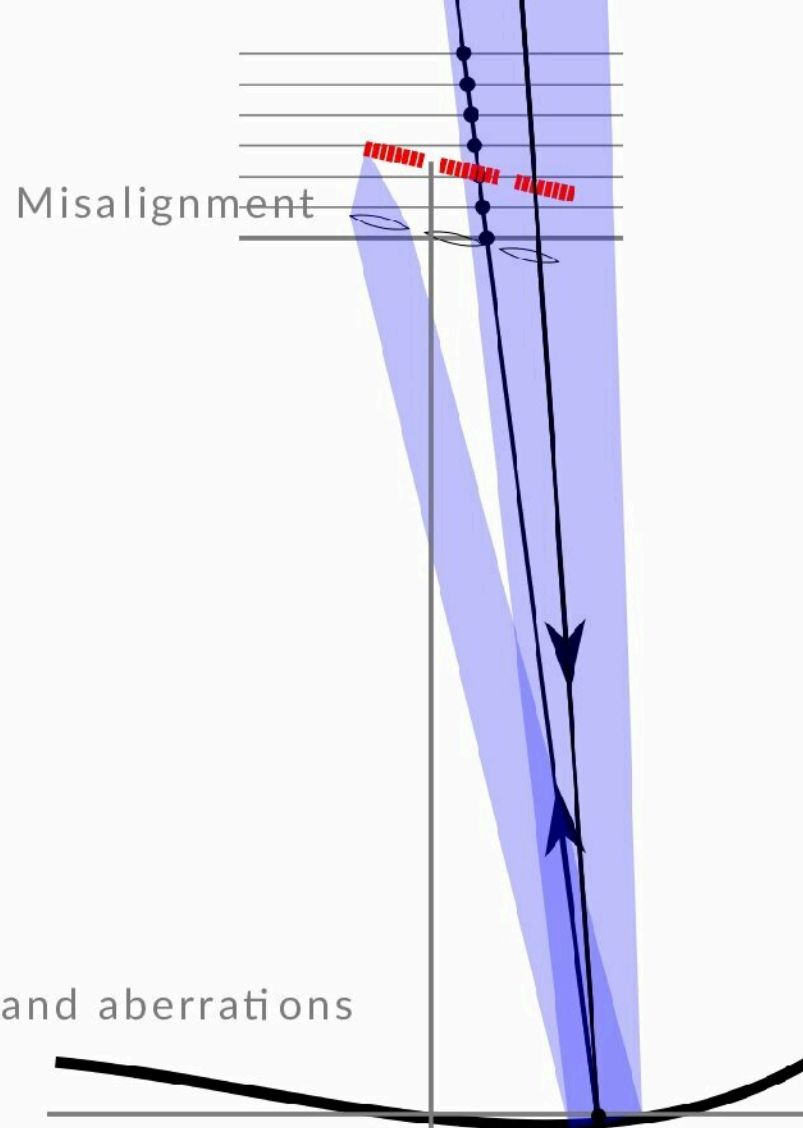
thin lens



Plenoptics

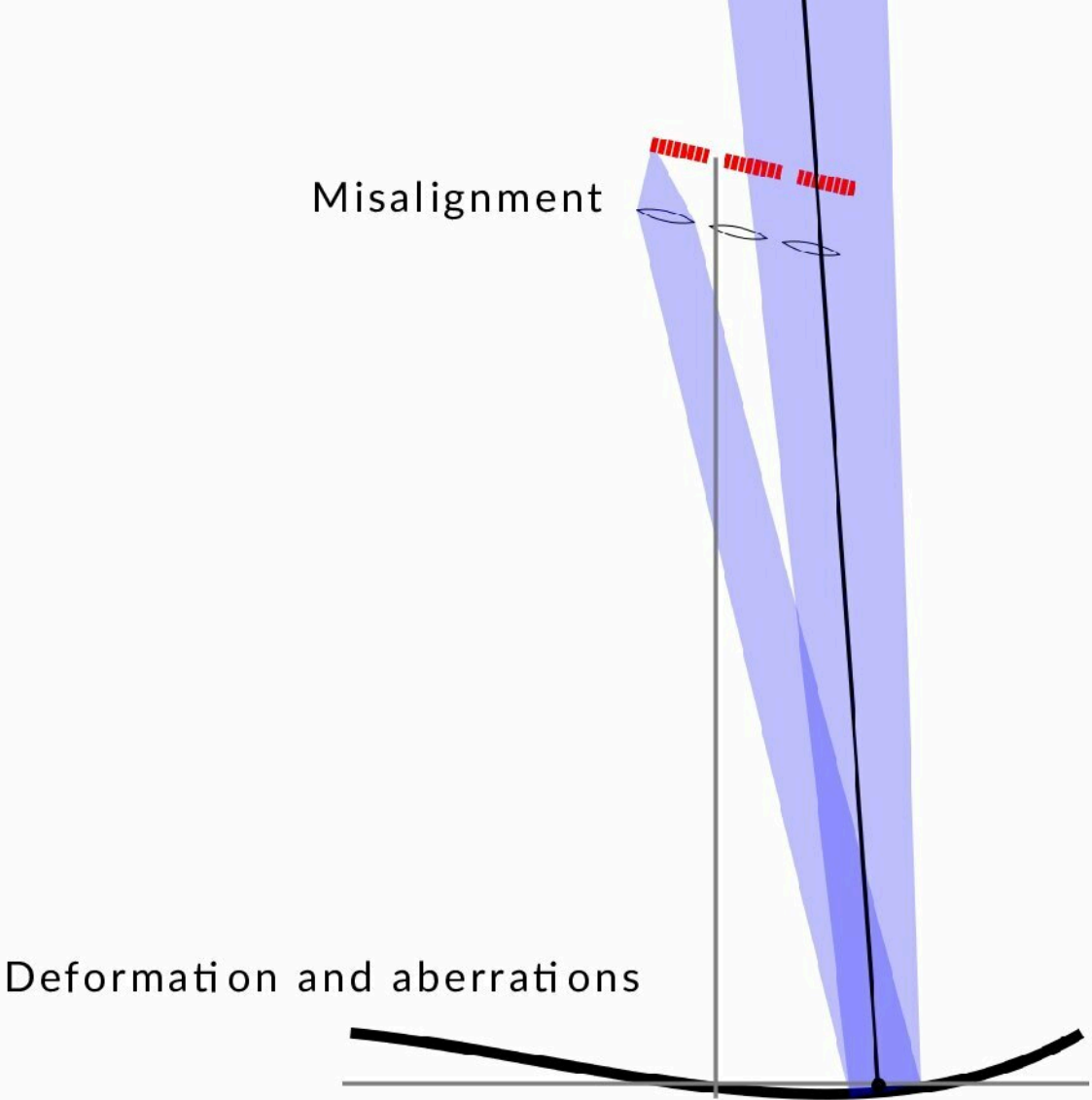
Plenoscope
thin lens

Deformation and aberrations



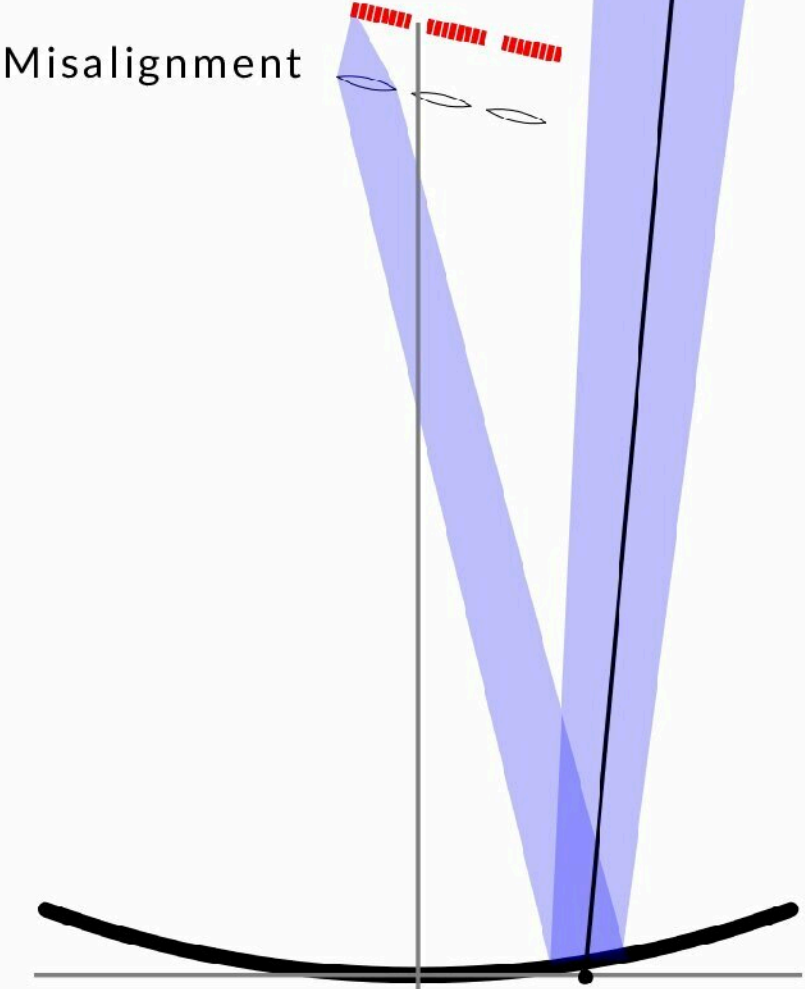
Plenoptics

Plenoscope



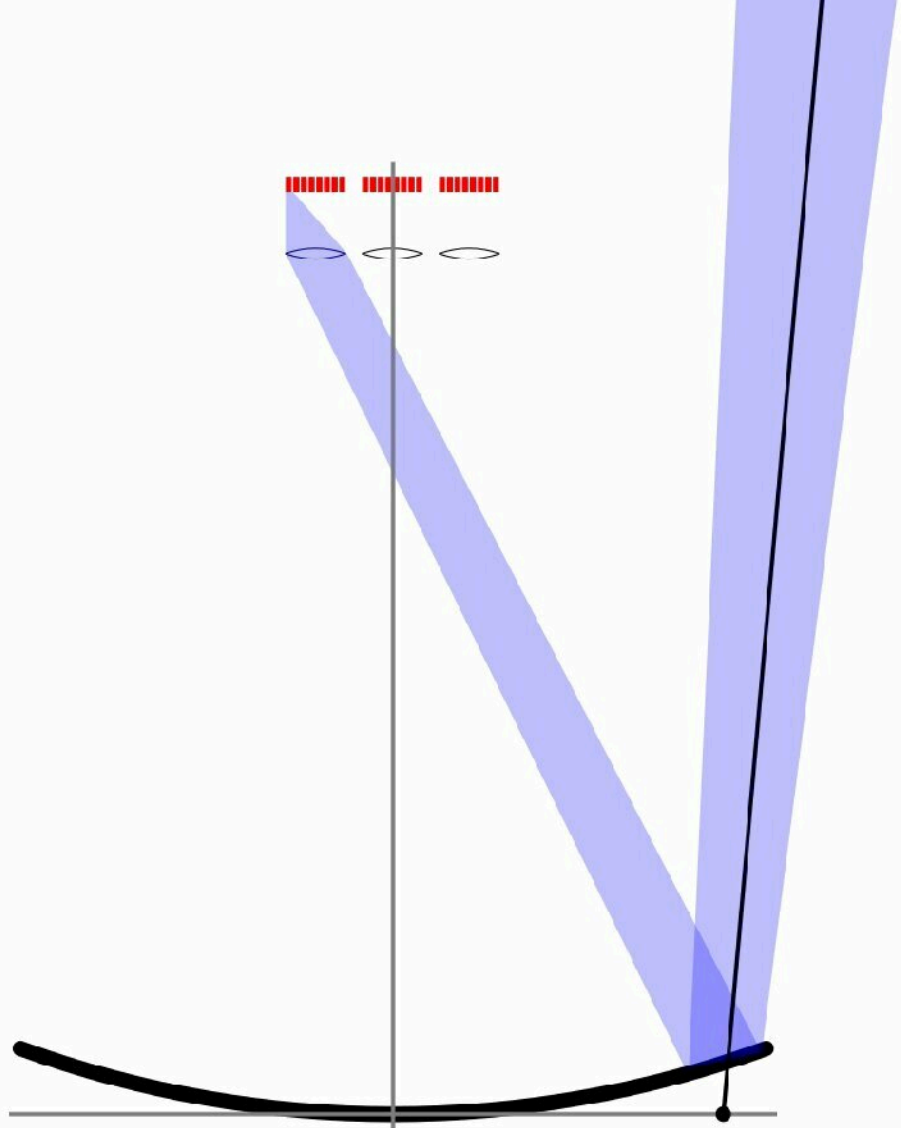
Plenoptics

Plenoscope



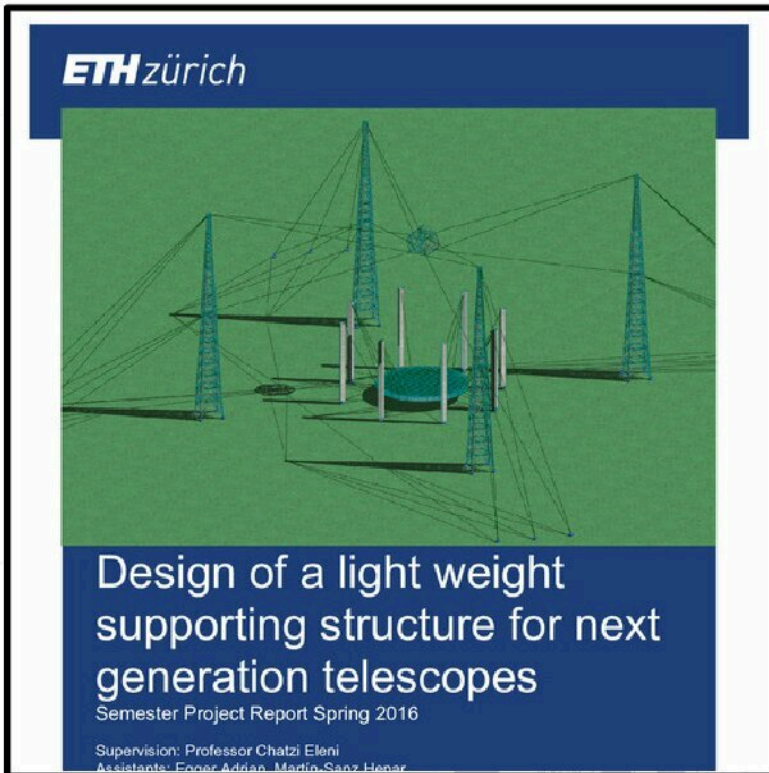
Plenoptics

Plenoscope

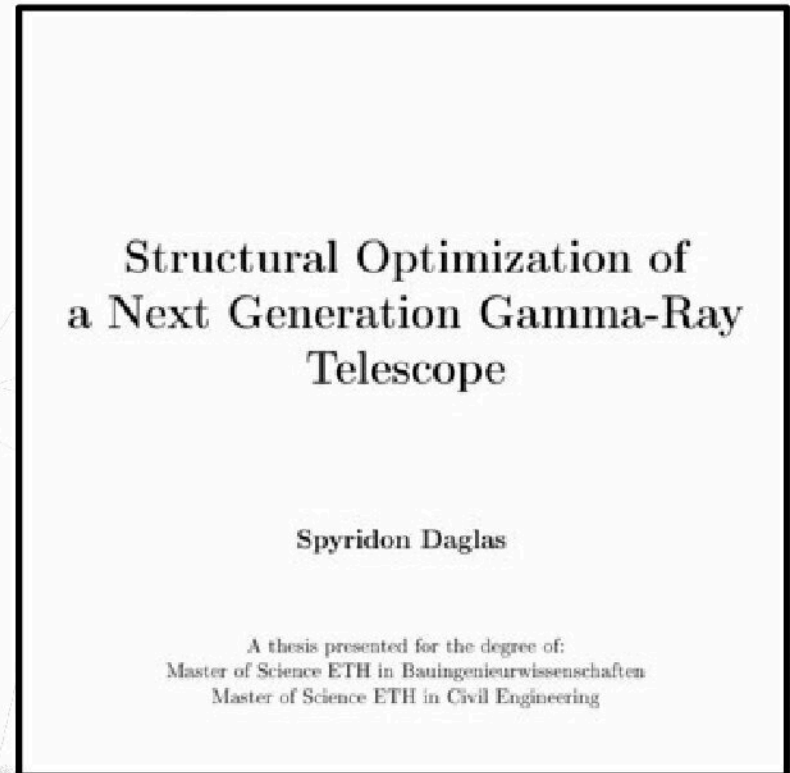




C H E R E N K O V - P L E N O S C O P E

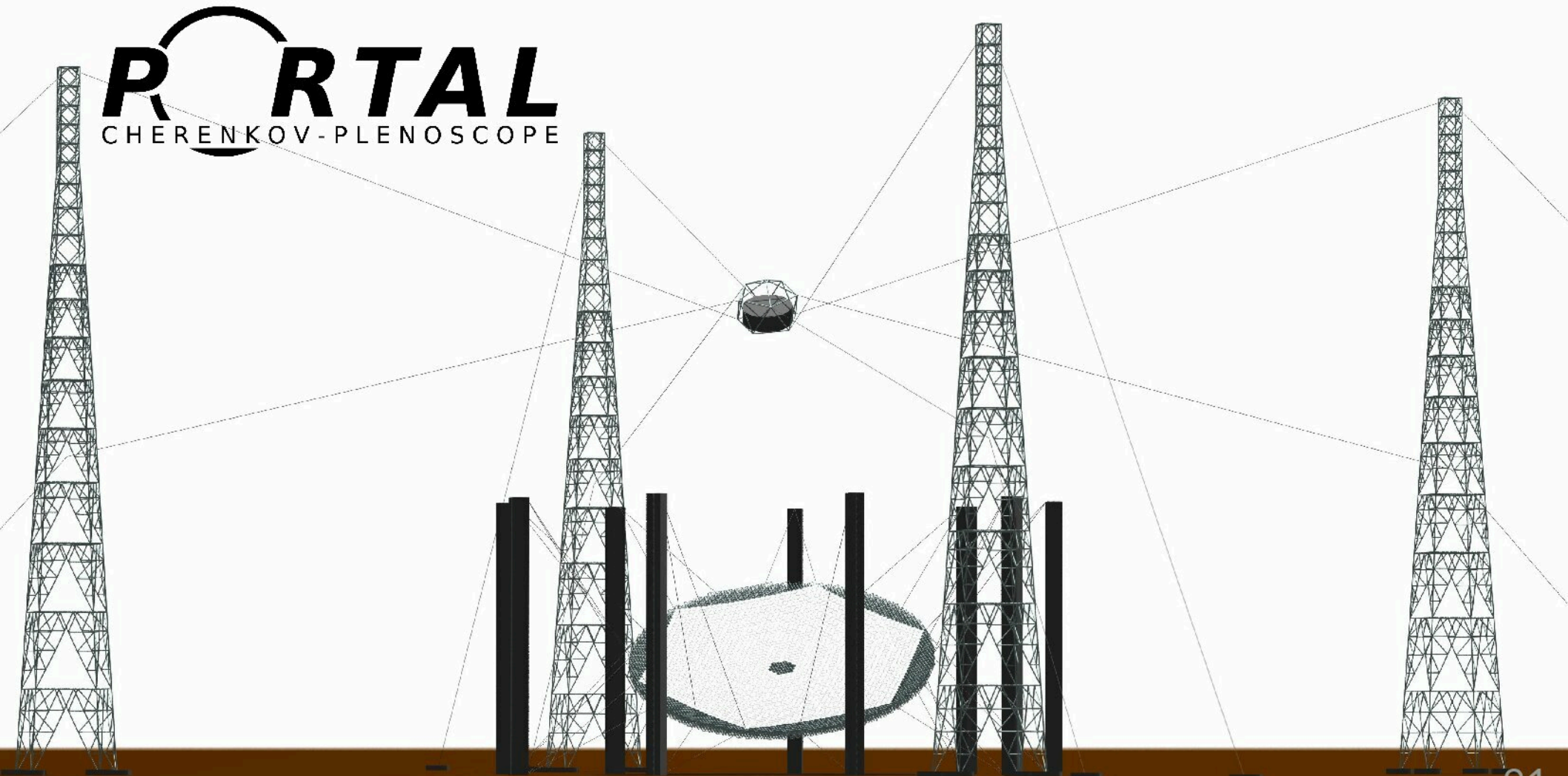


Georgios Zinas and Spyridon Daglas
Report (2016)



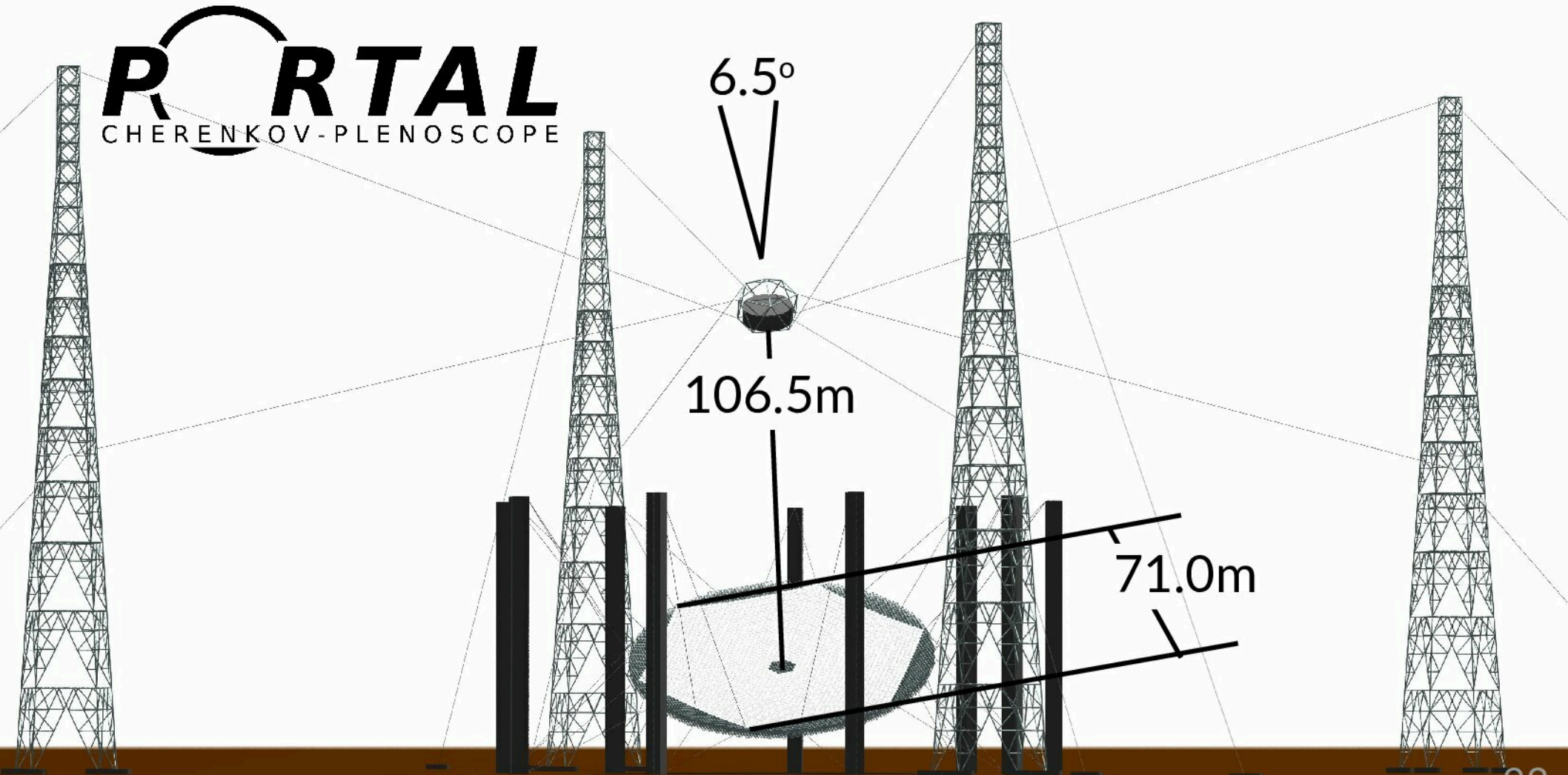
Spyridon Daglas
Master-thesis (2017)
in **Civil Engineering**

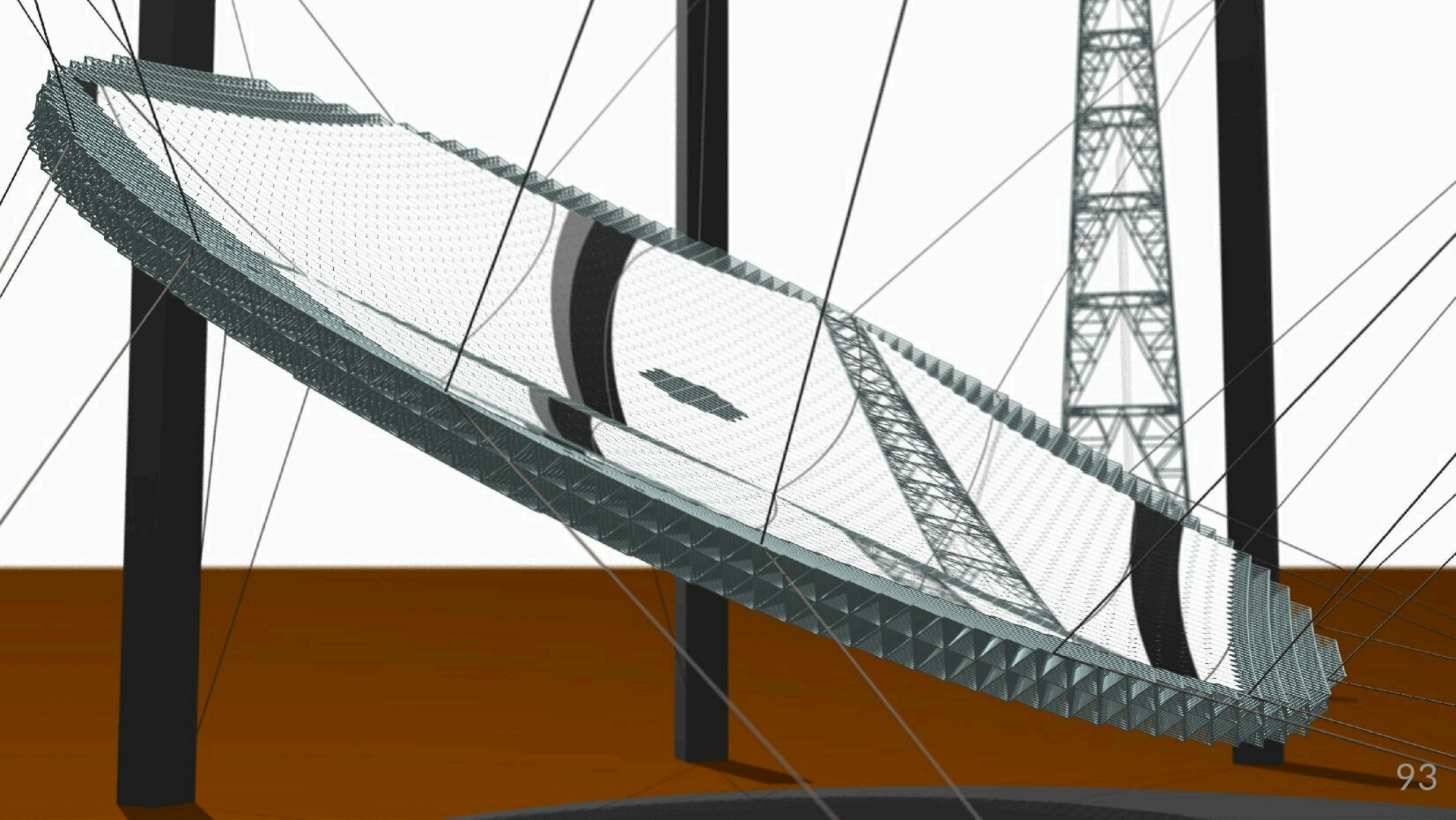
PORTAL CHERENKOV-PLENSCOPE

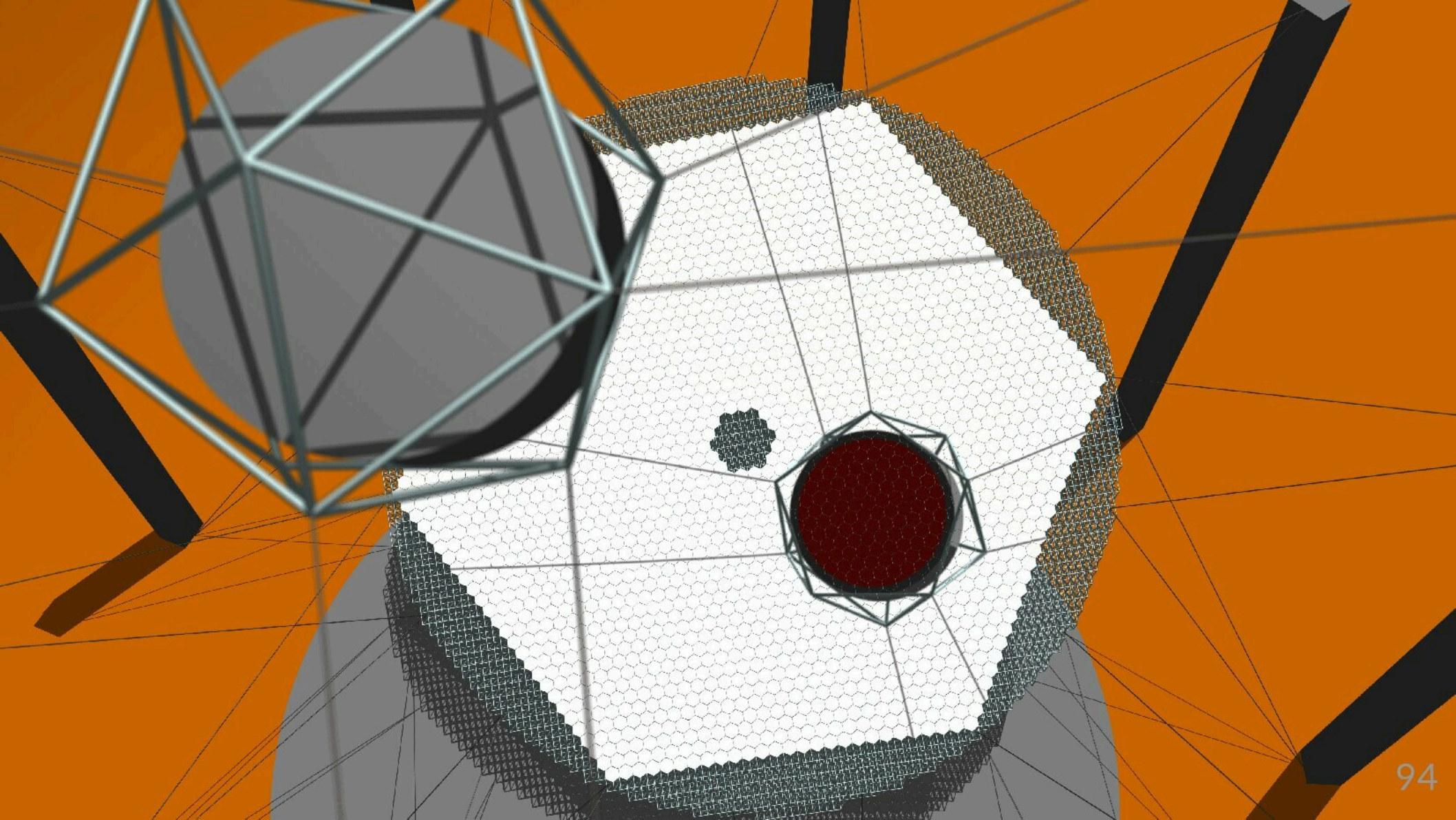


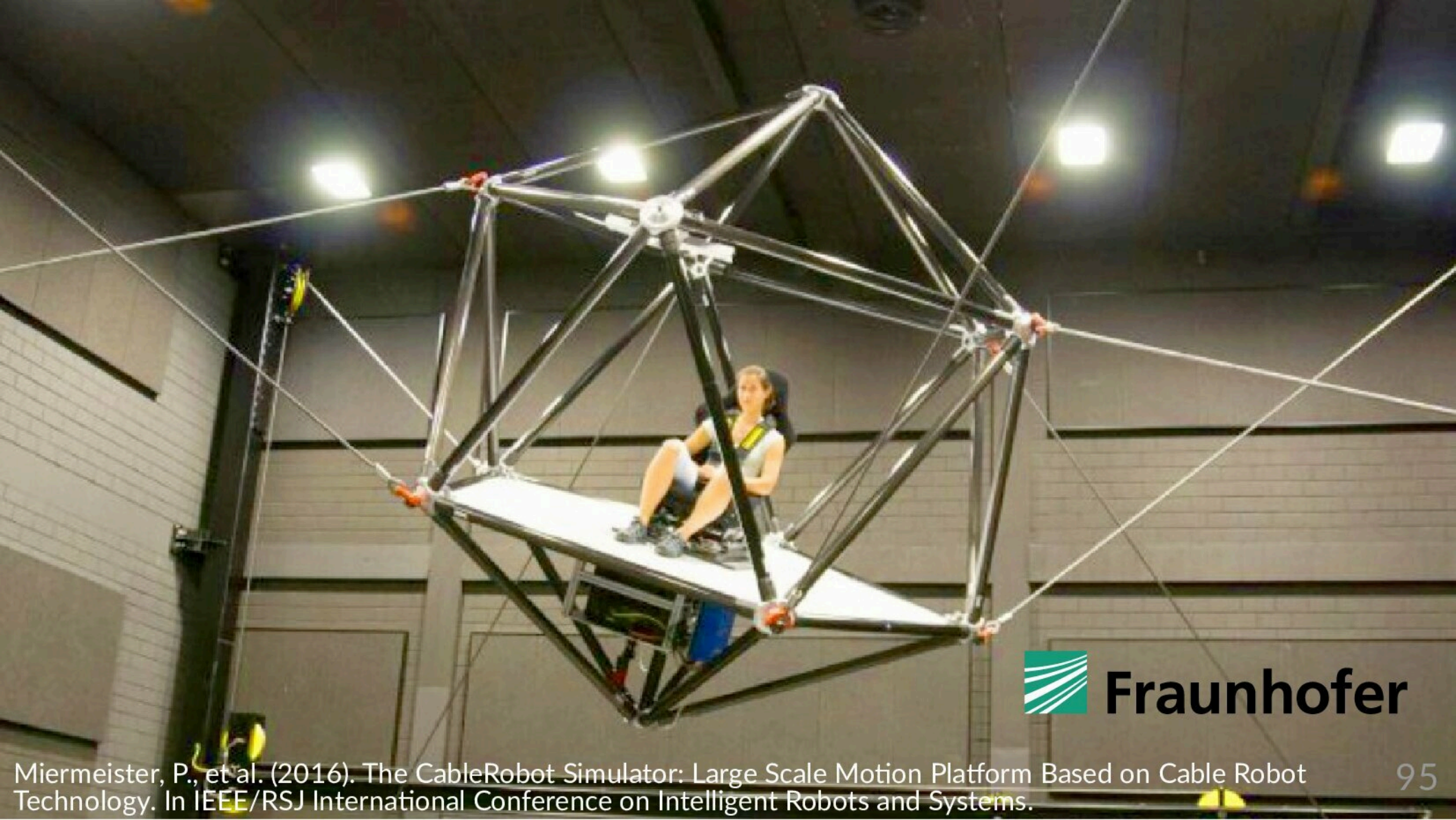
RORTAL

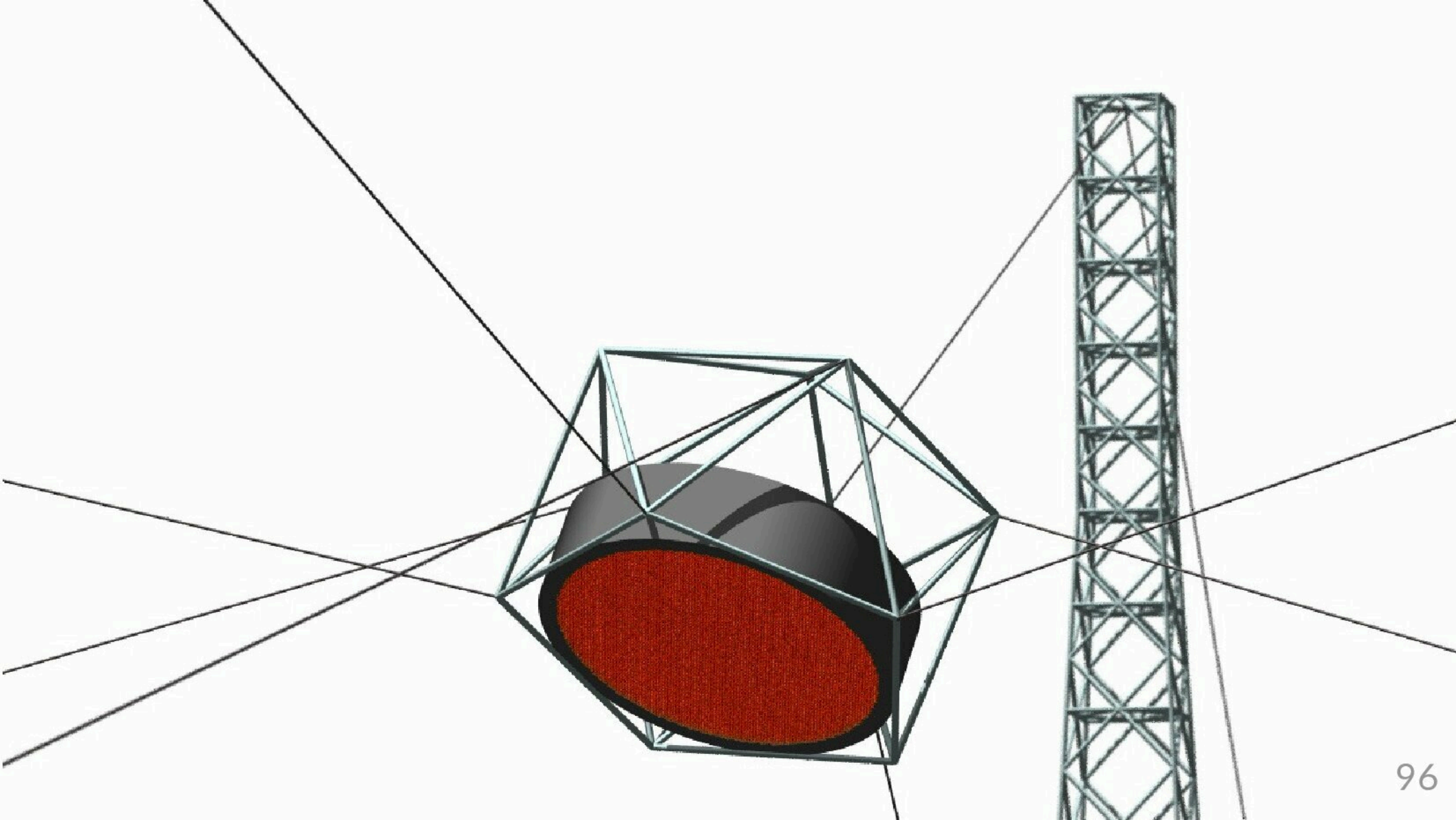
CHERENKOV-PLENSCOPE



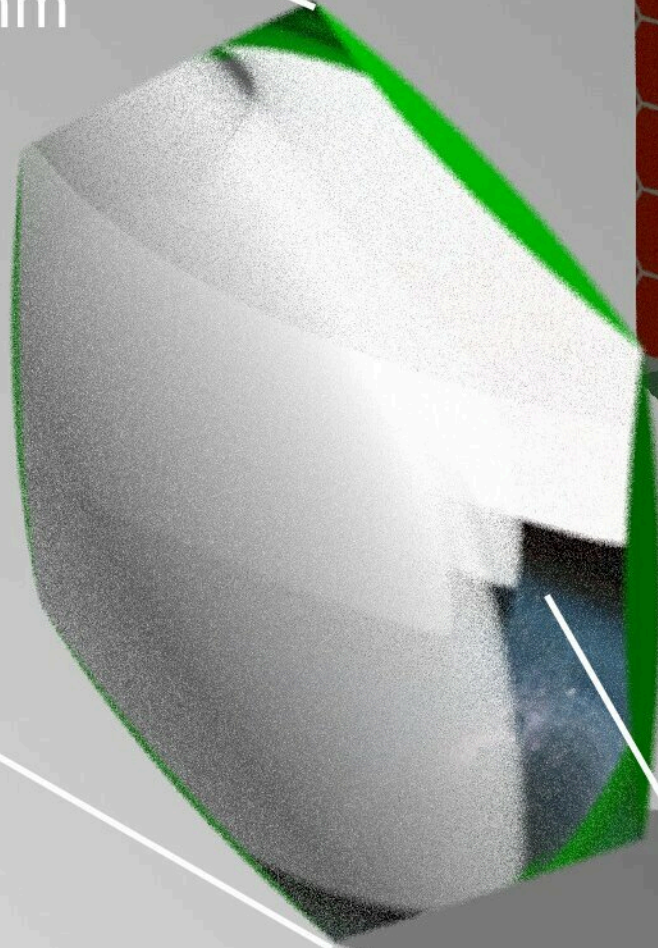








143mm



Lens

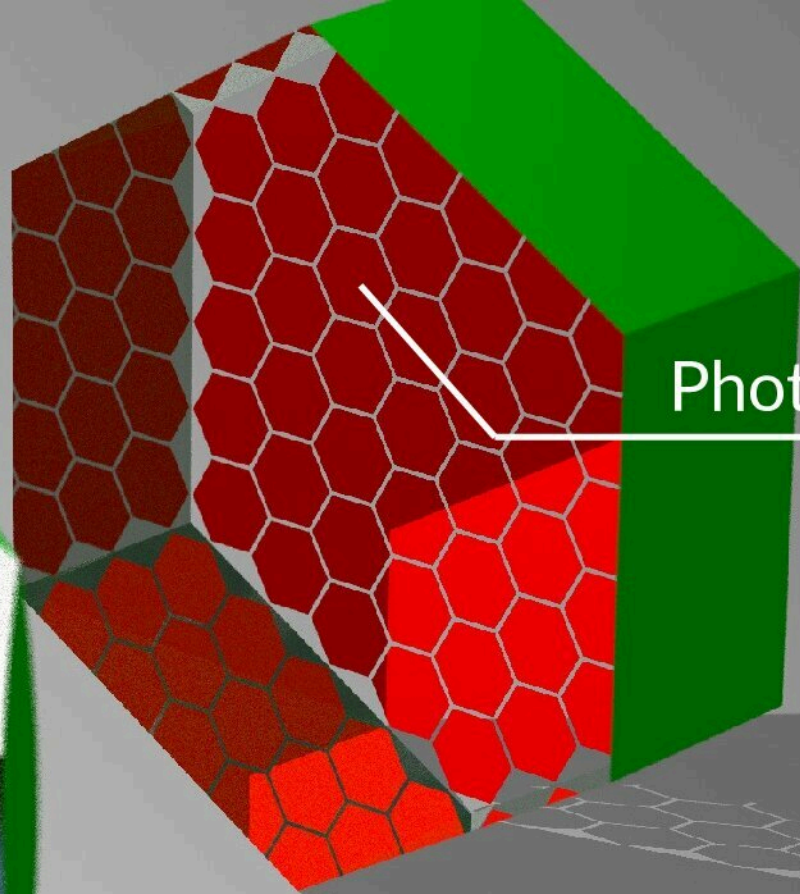
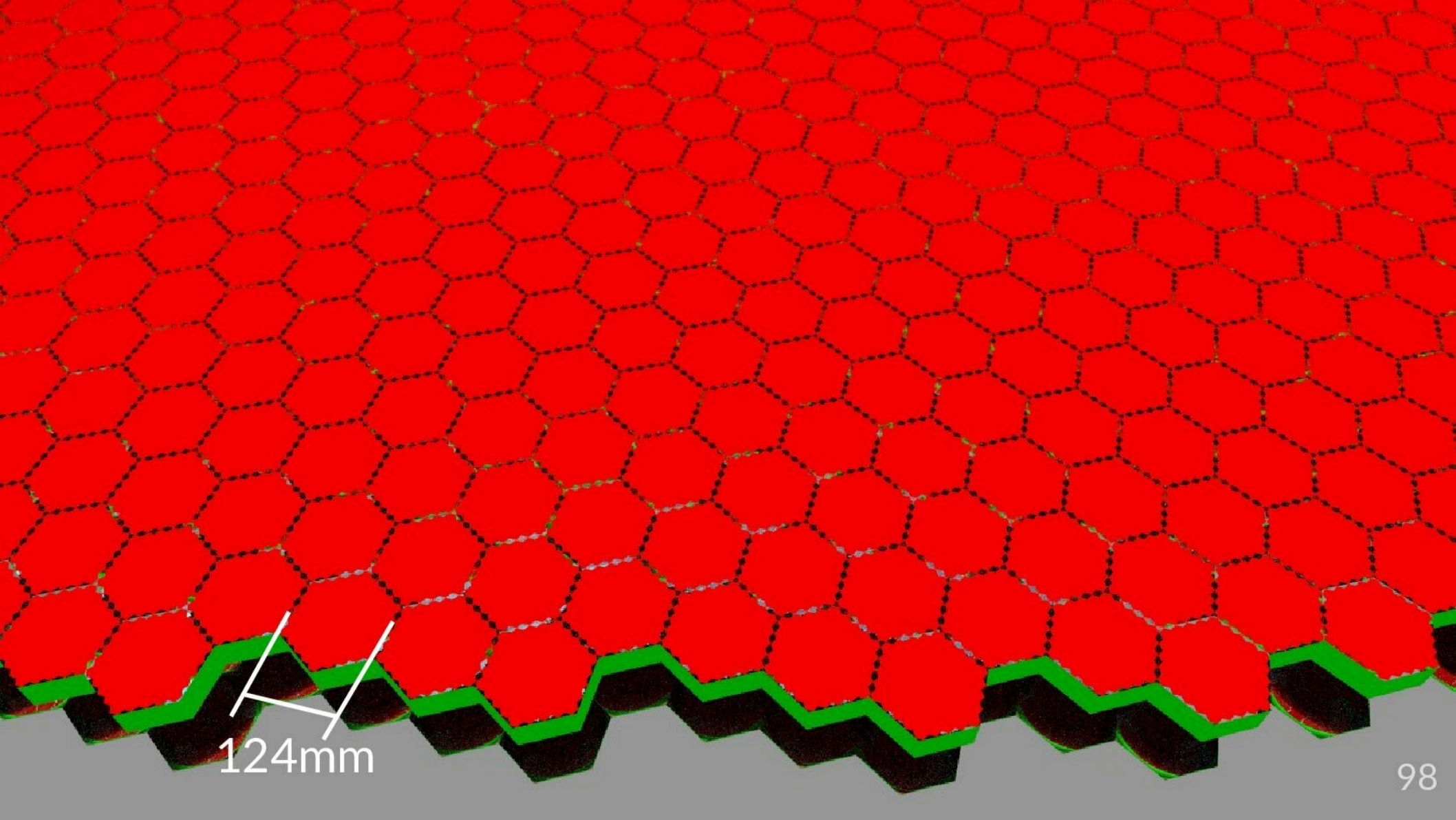
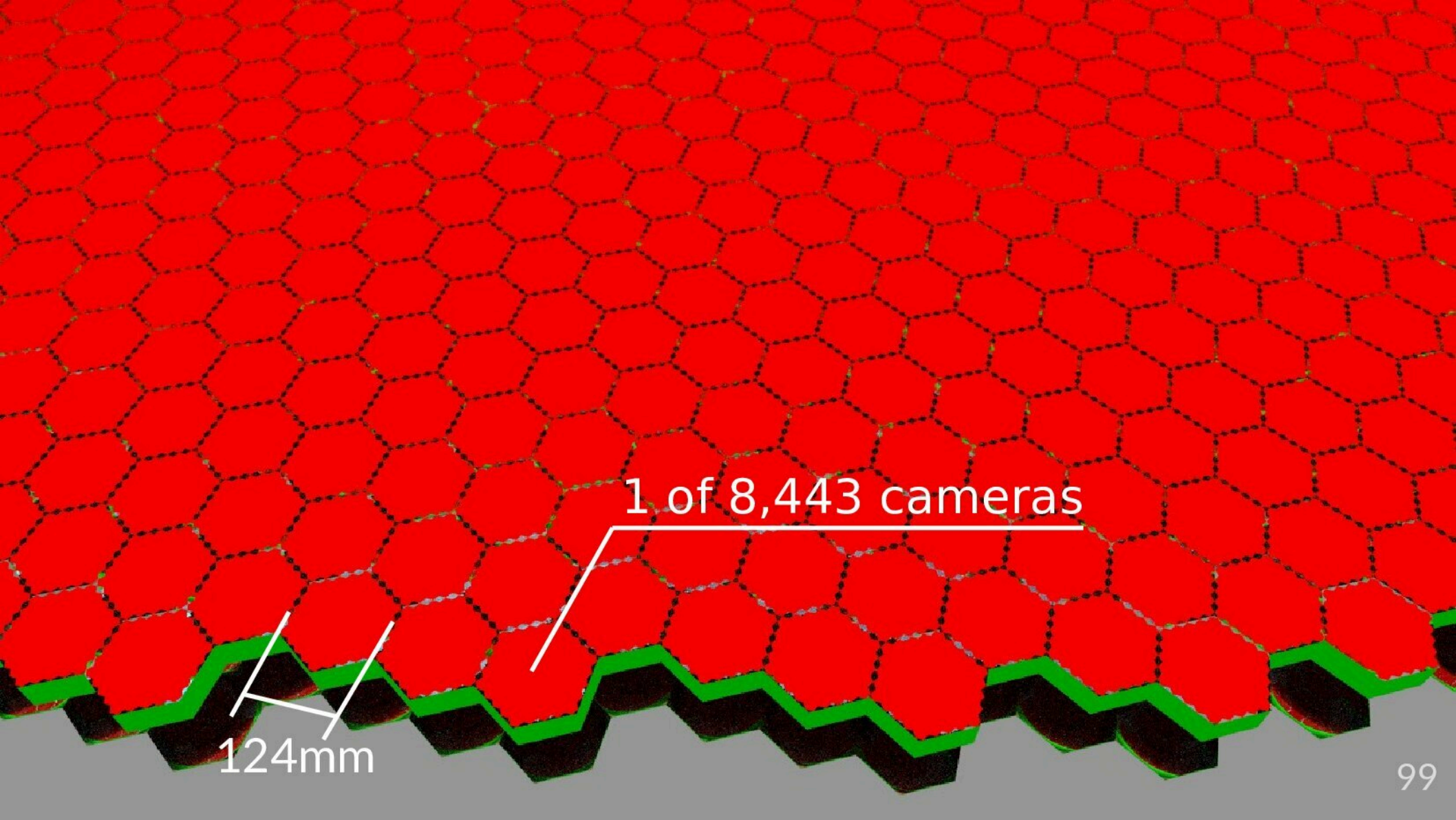


Photo-sensors

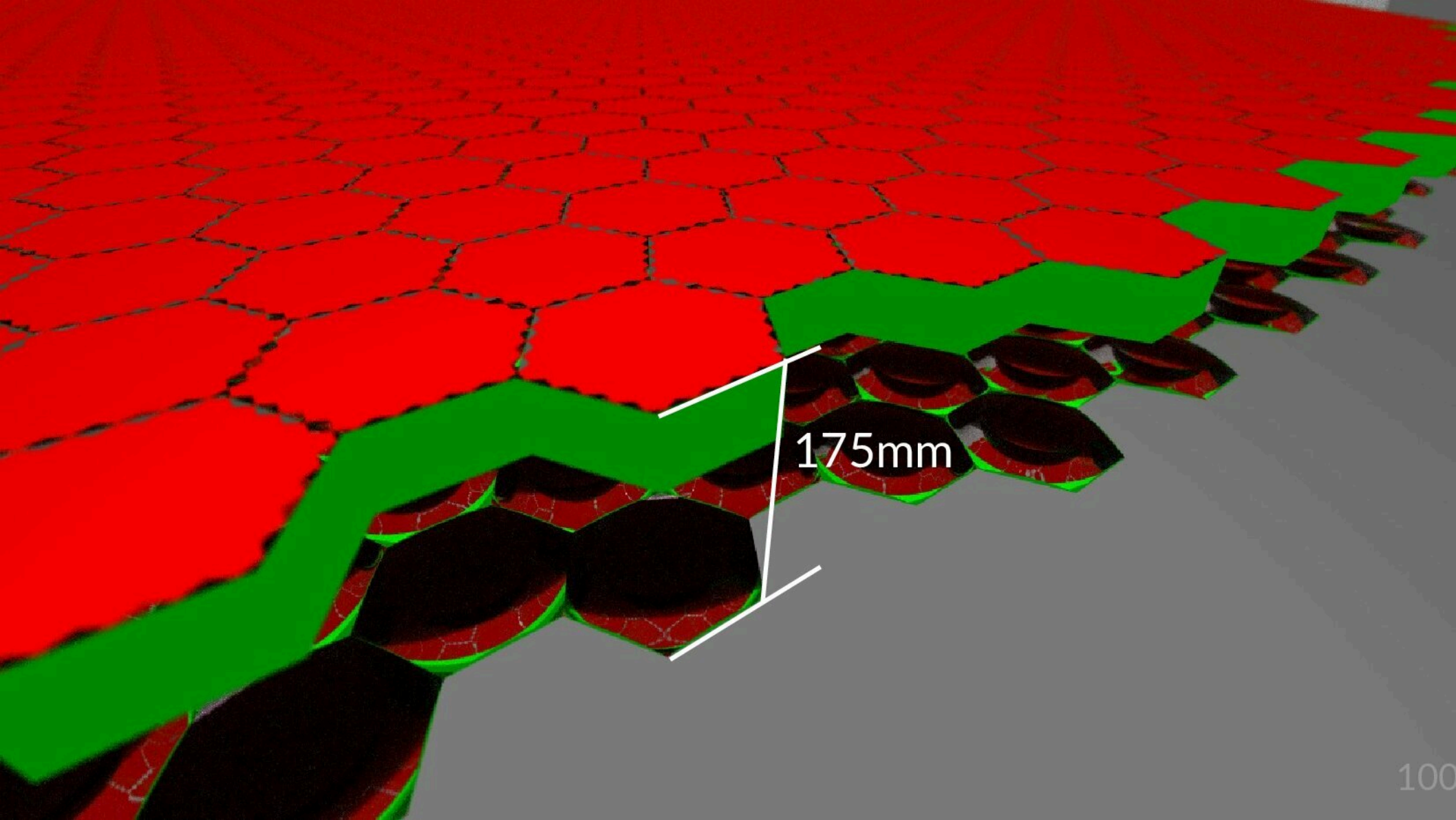


124mm



1 of 8,443 cameras

124mm



175mm

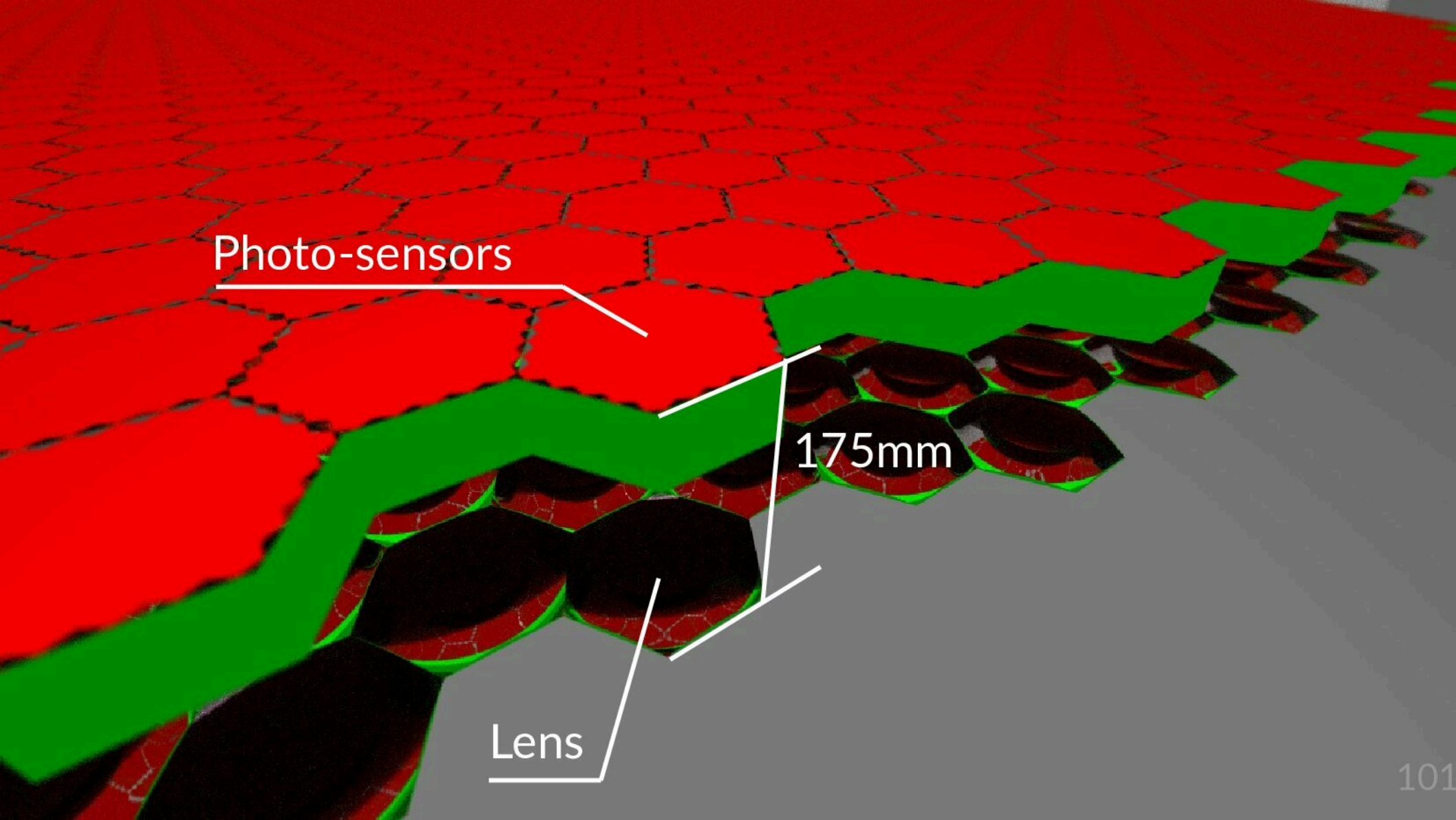
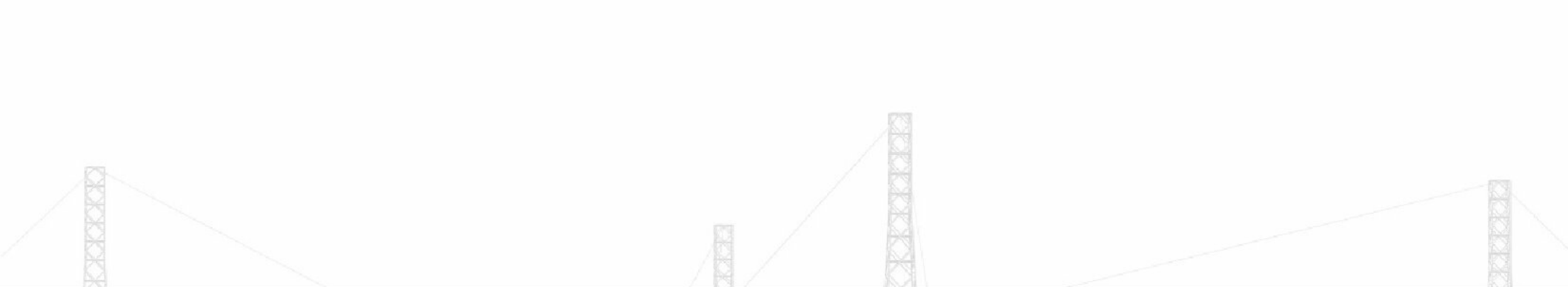


Photo-sensors

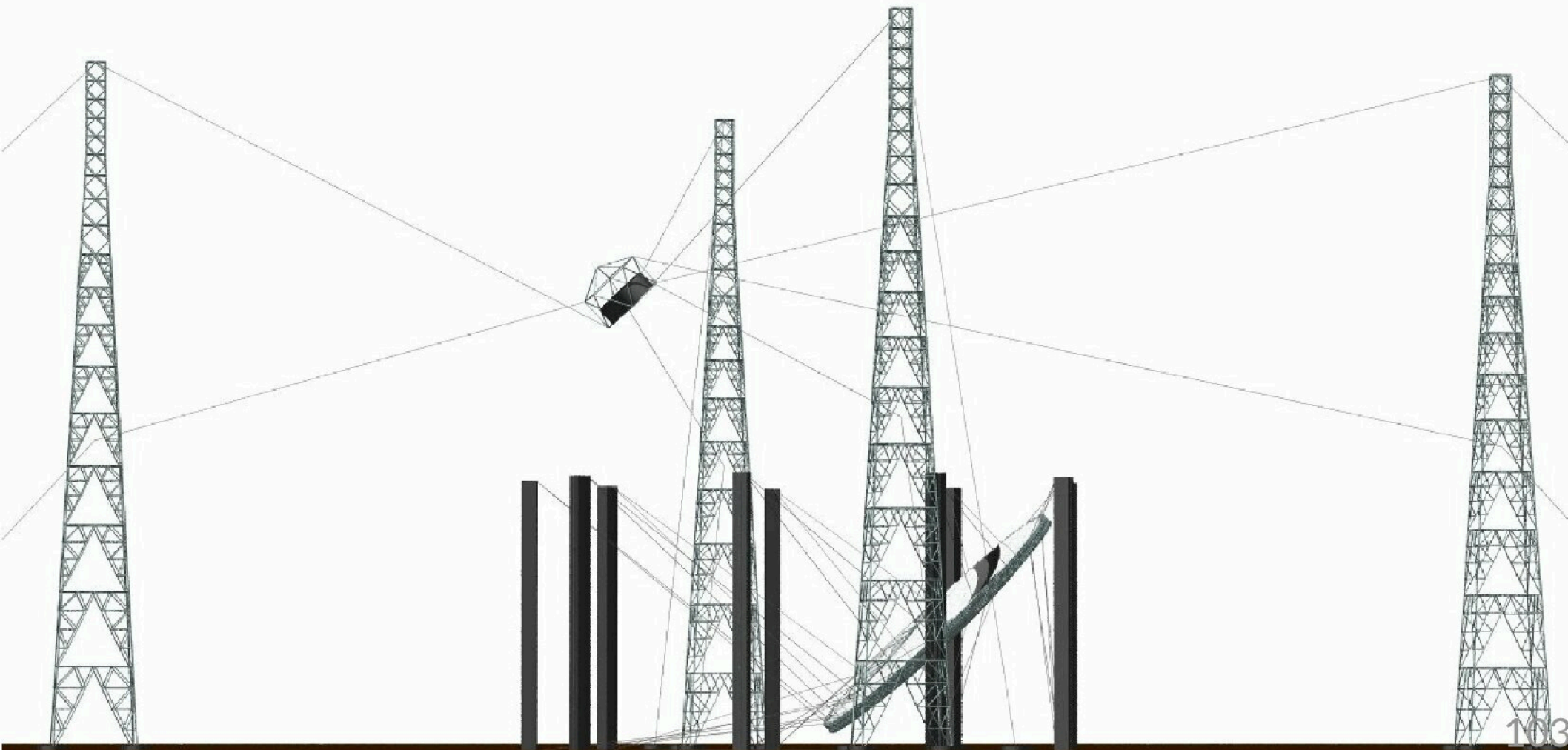
175mm

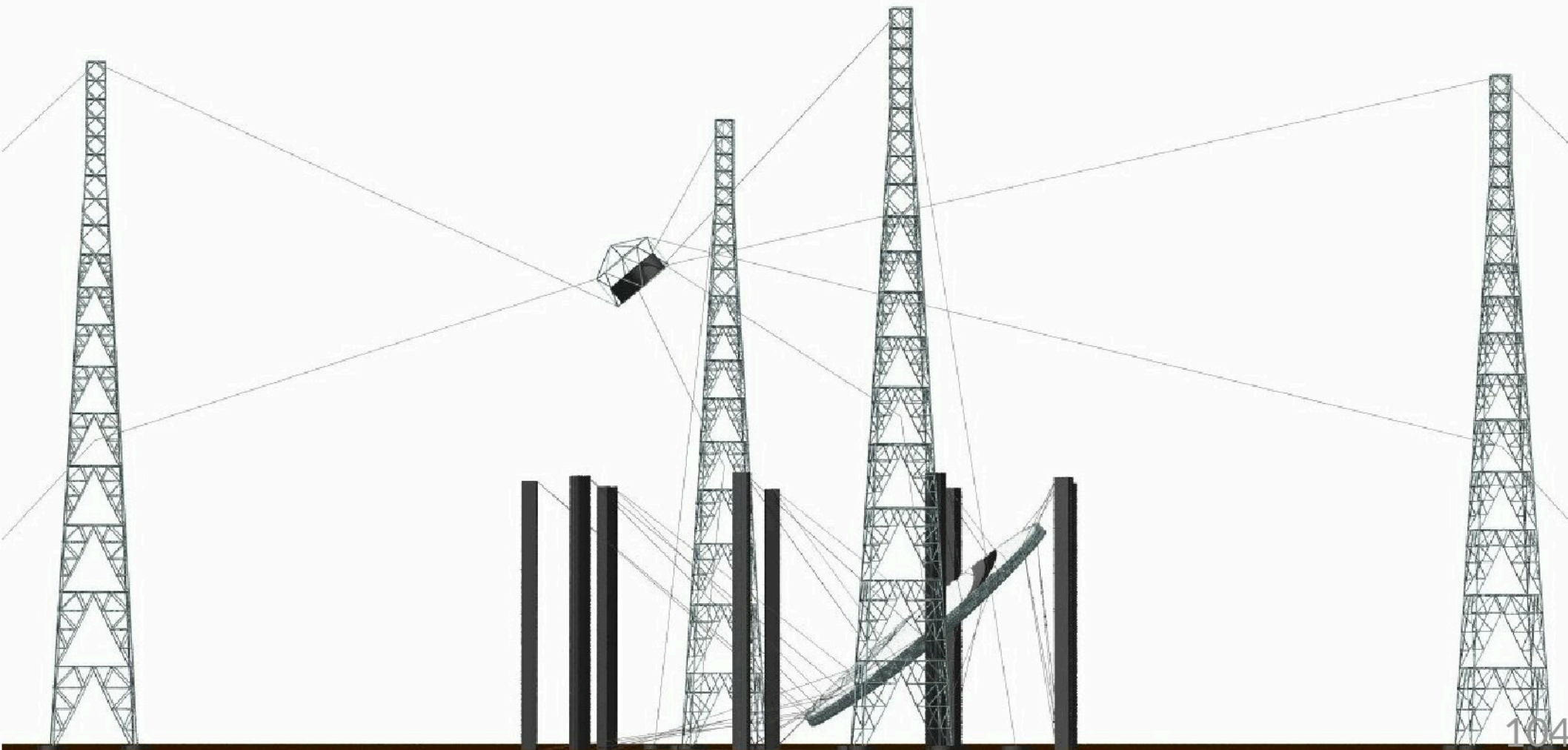
Lens

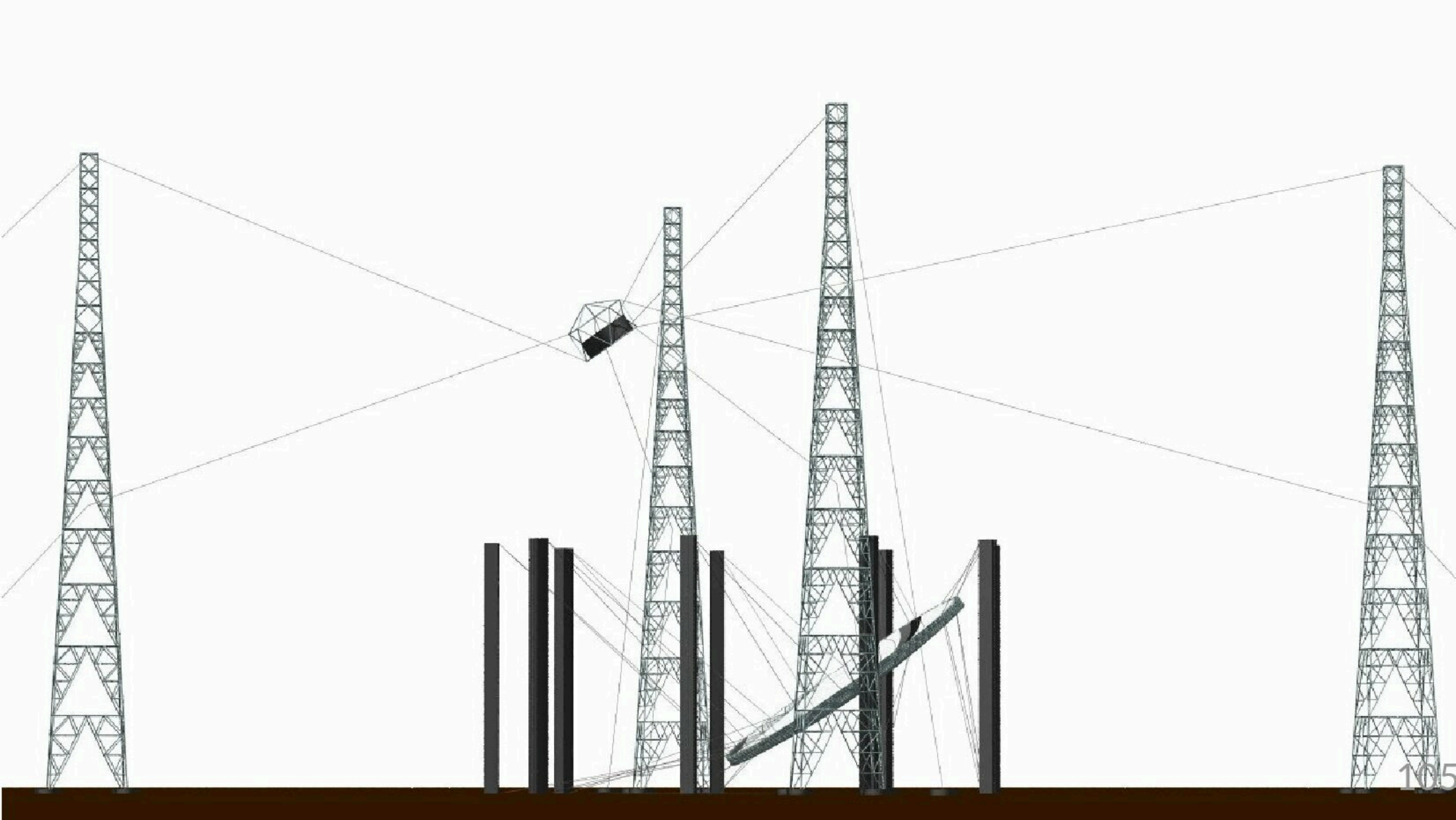


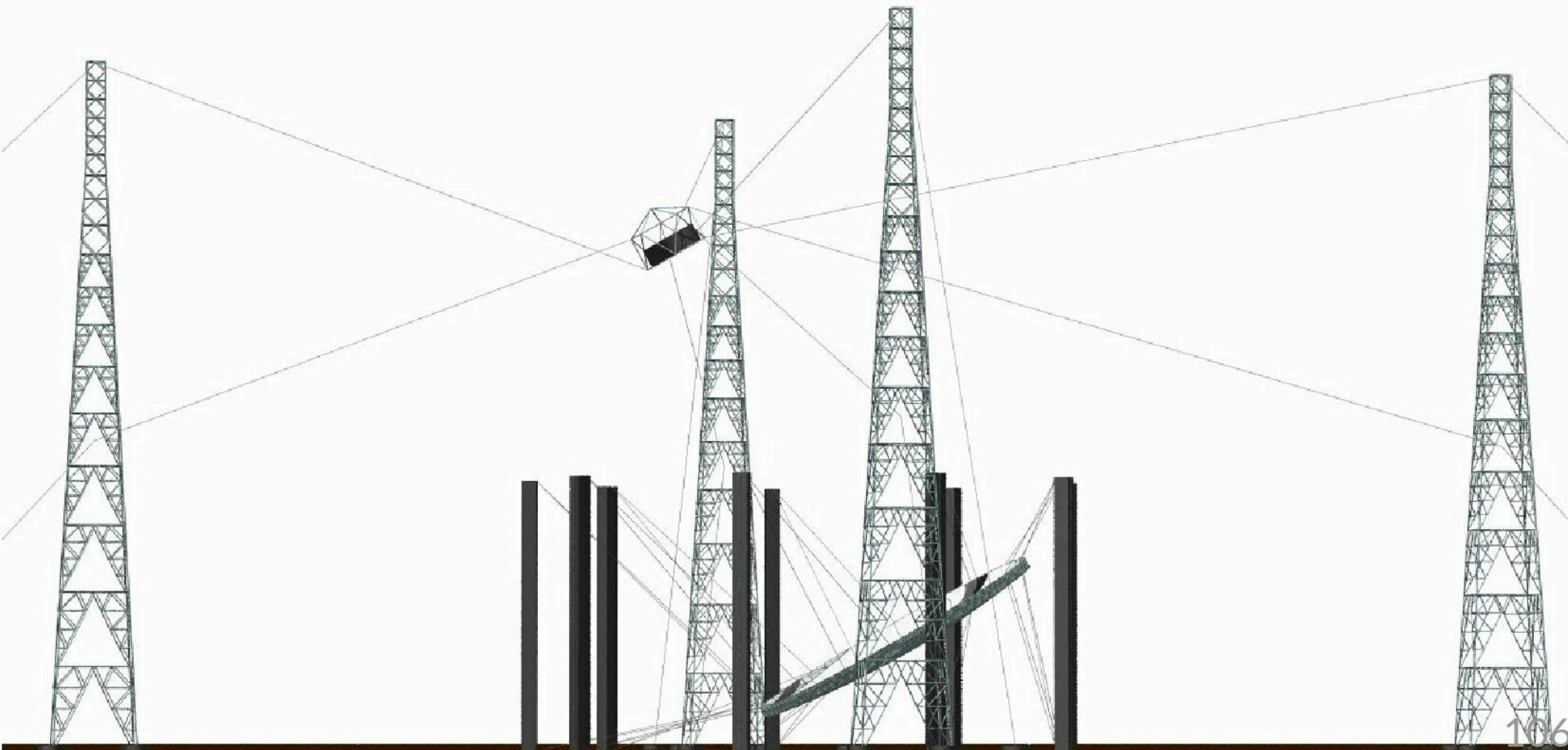
Pointing

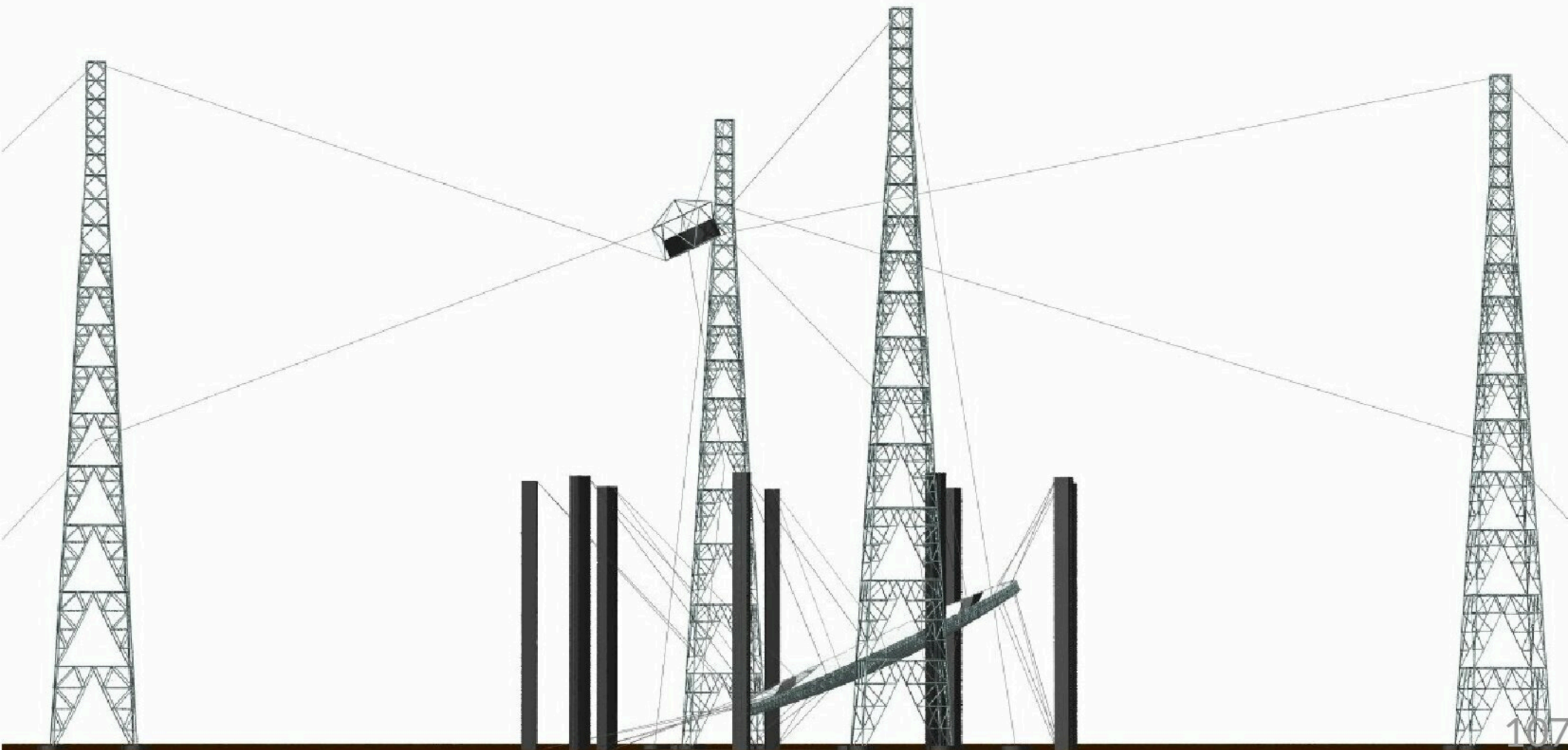


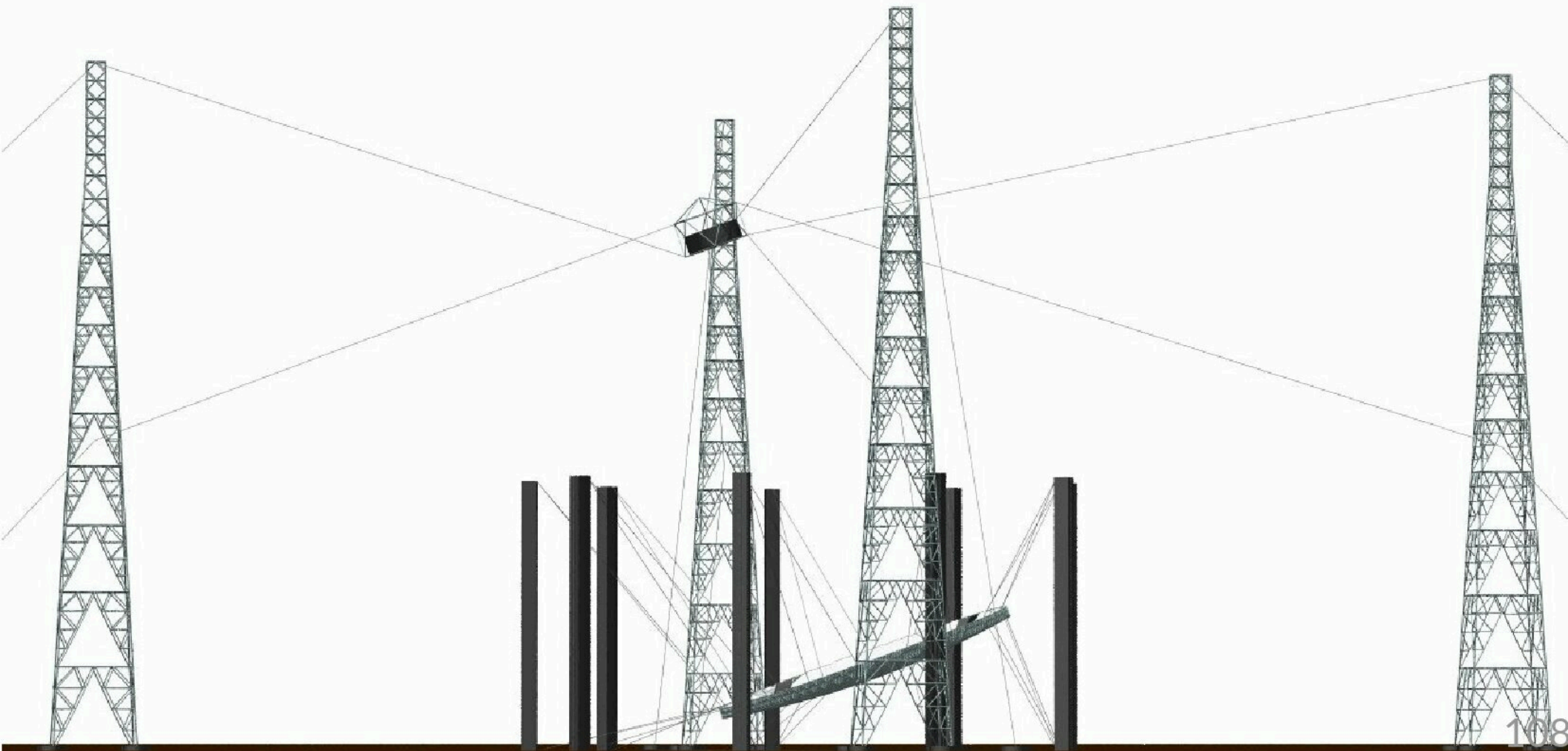


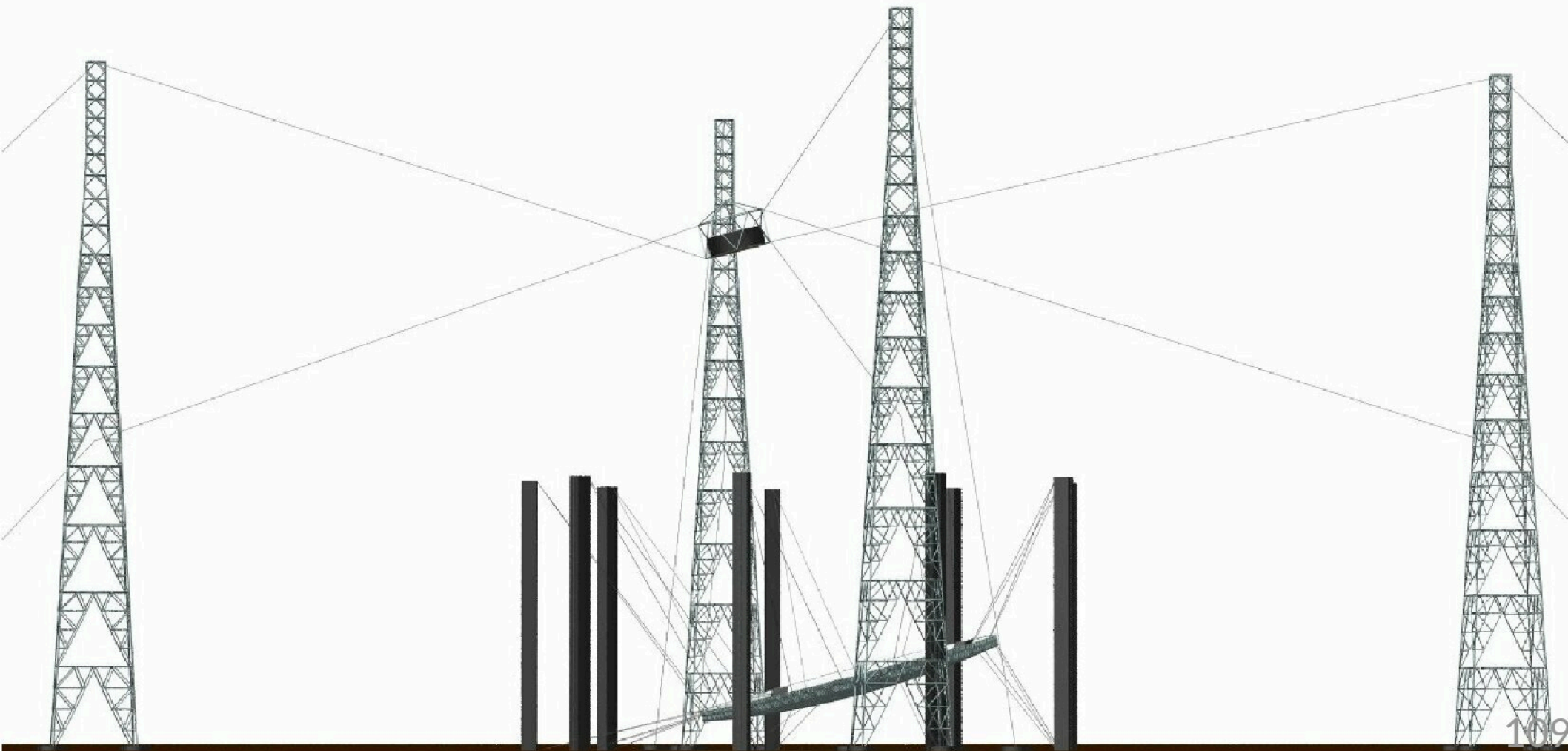


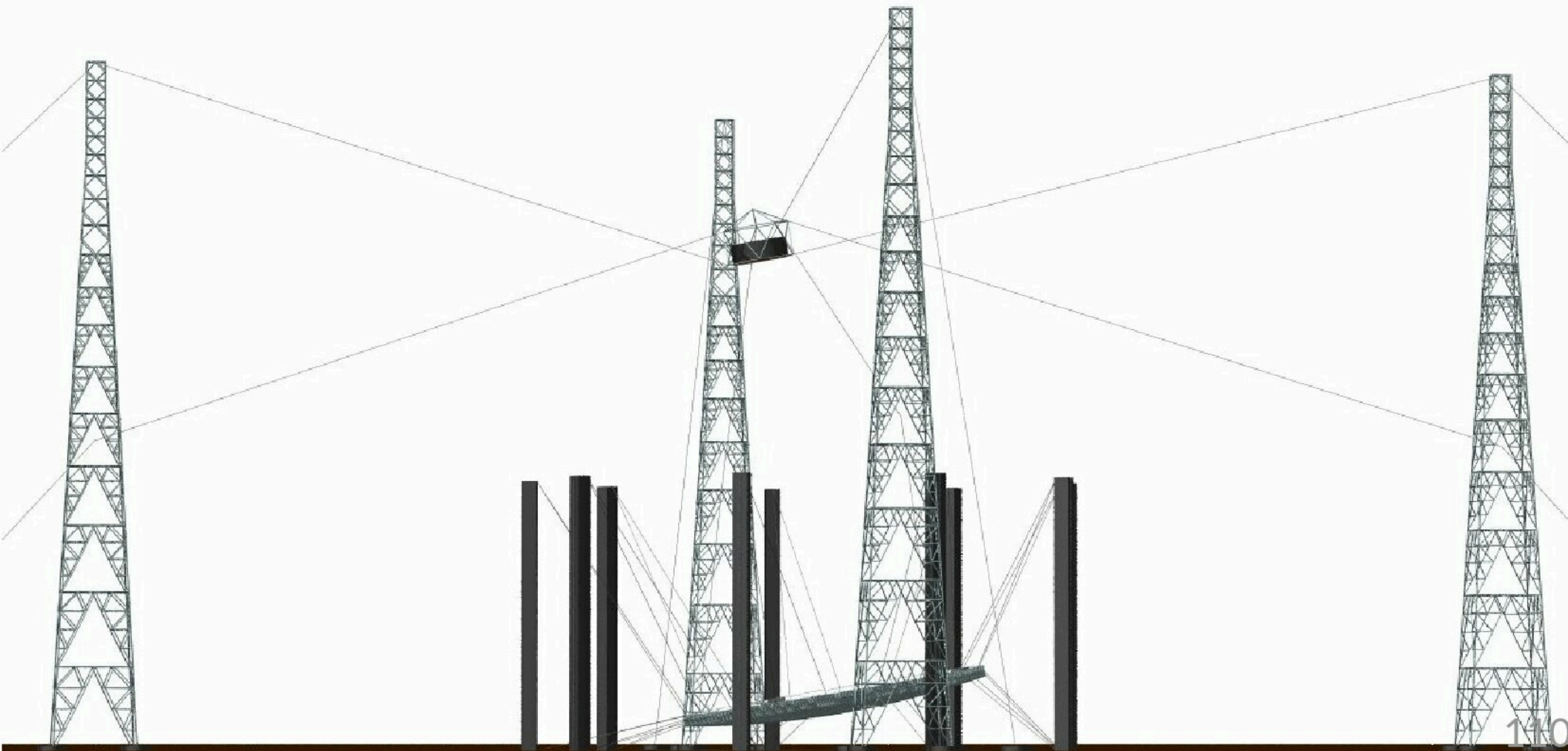


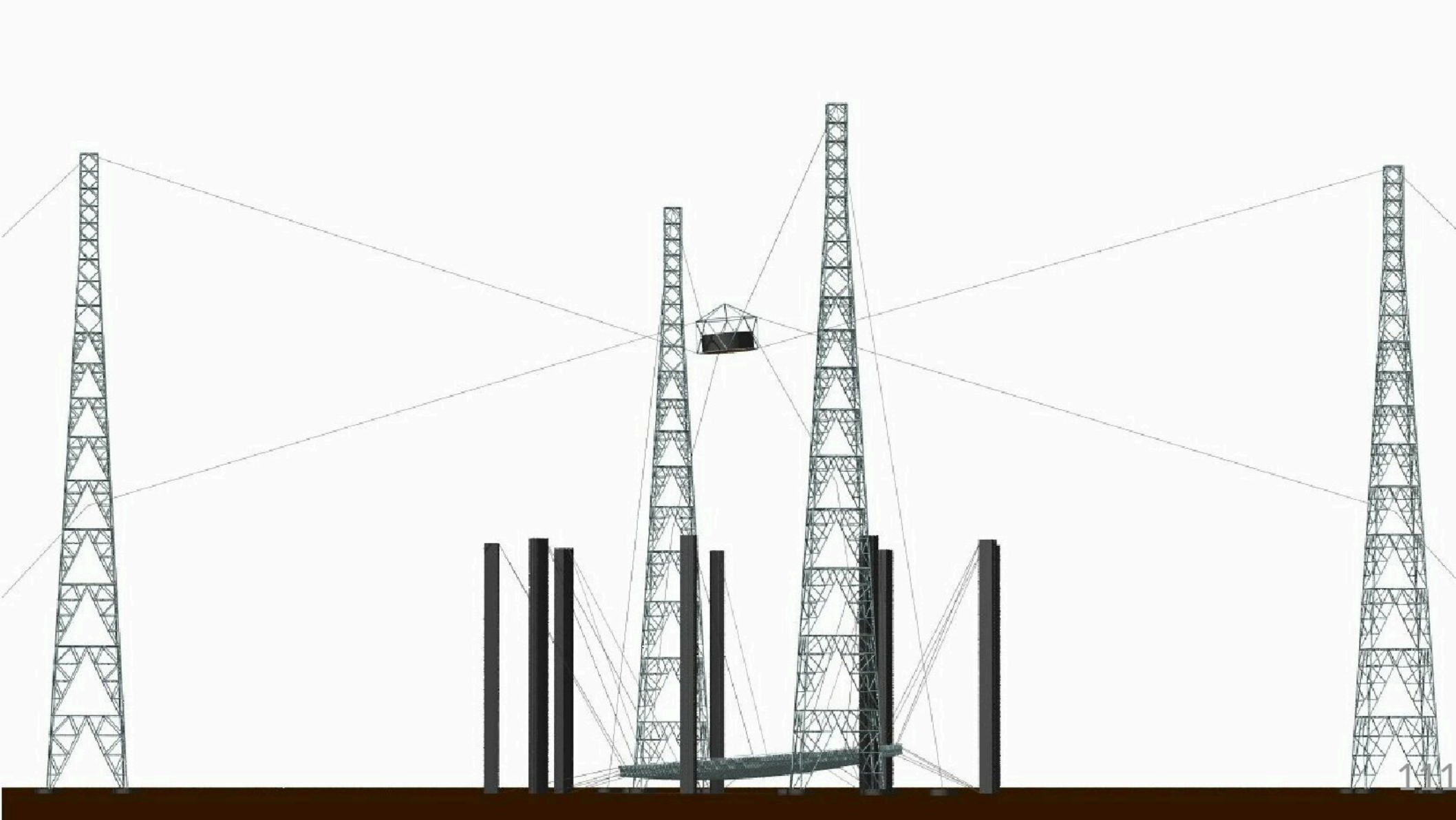


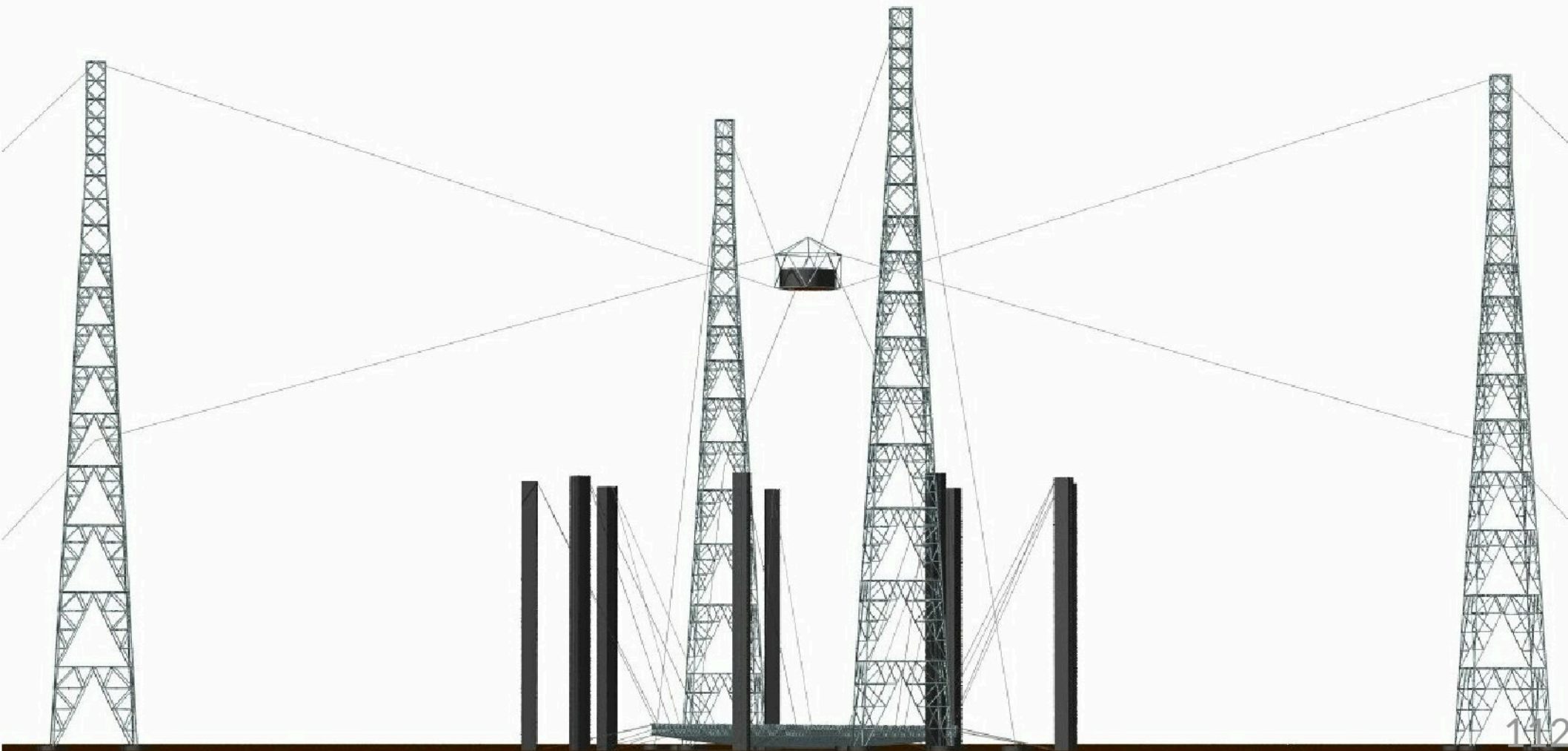


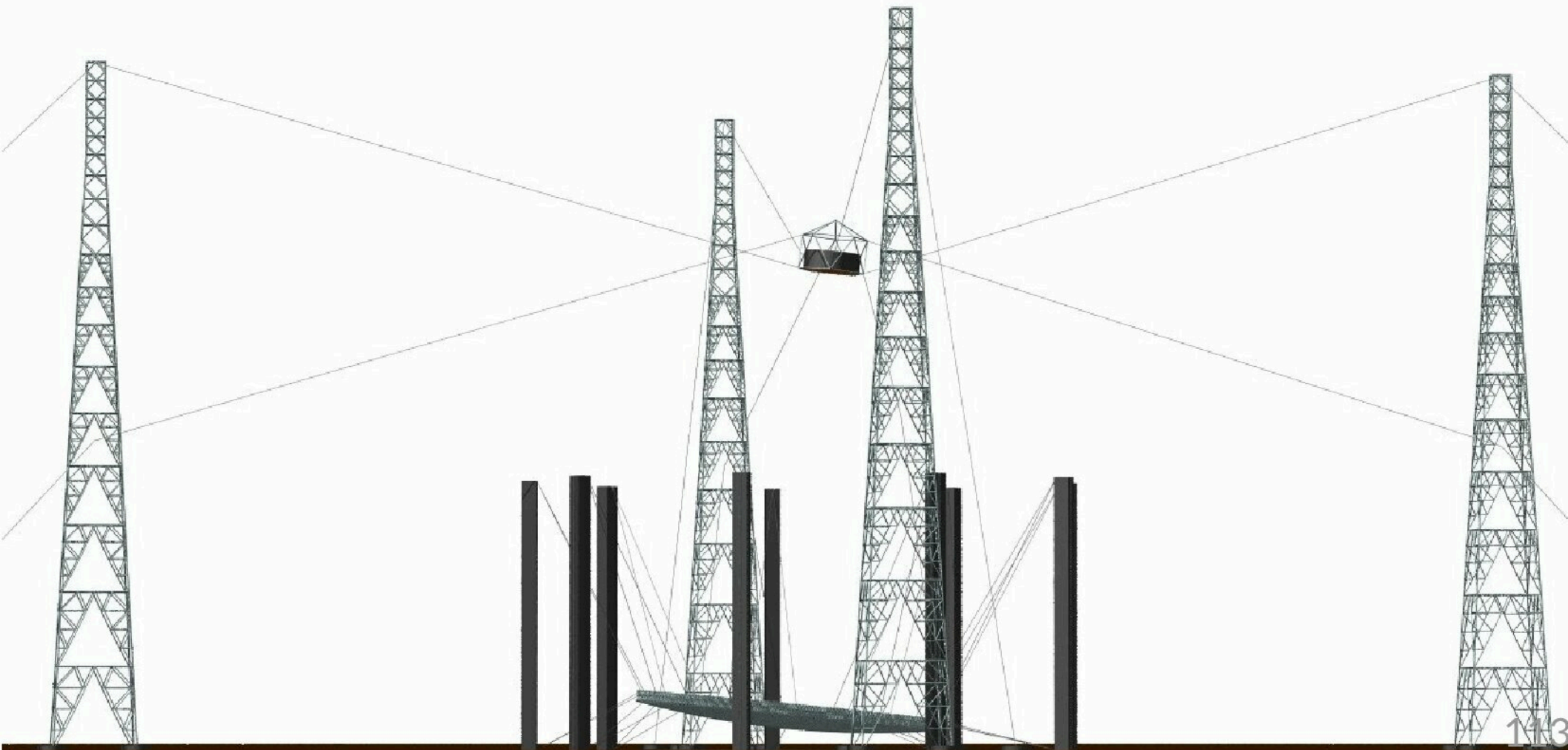


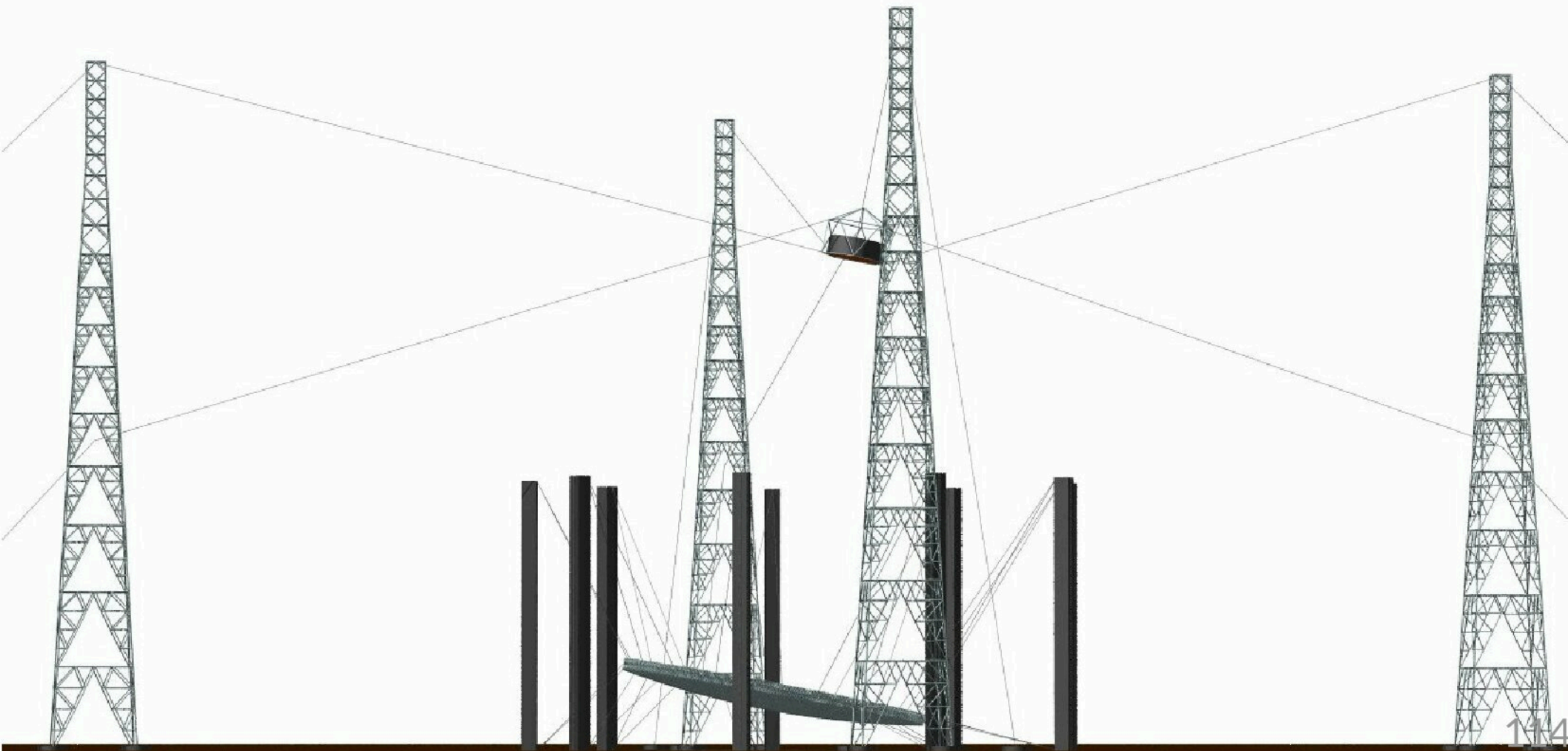


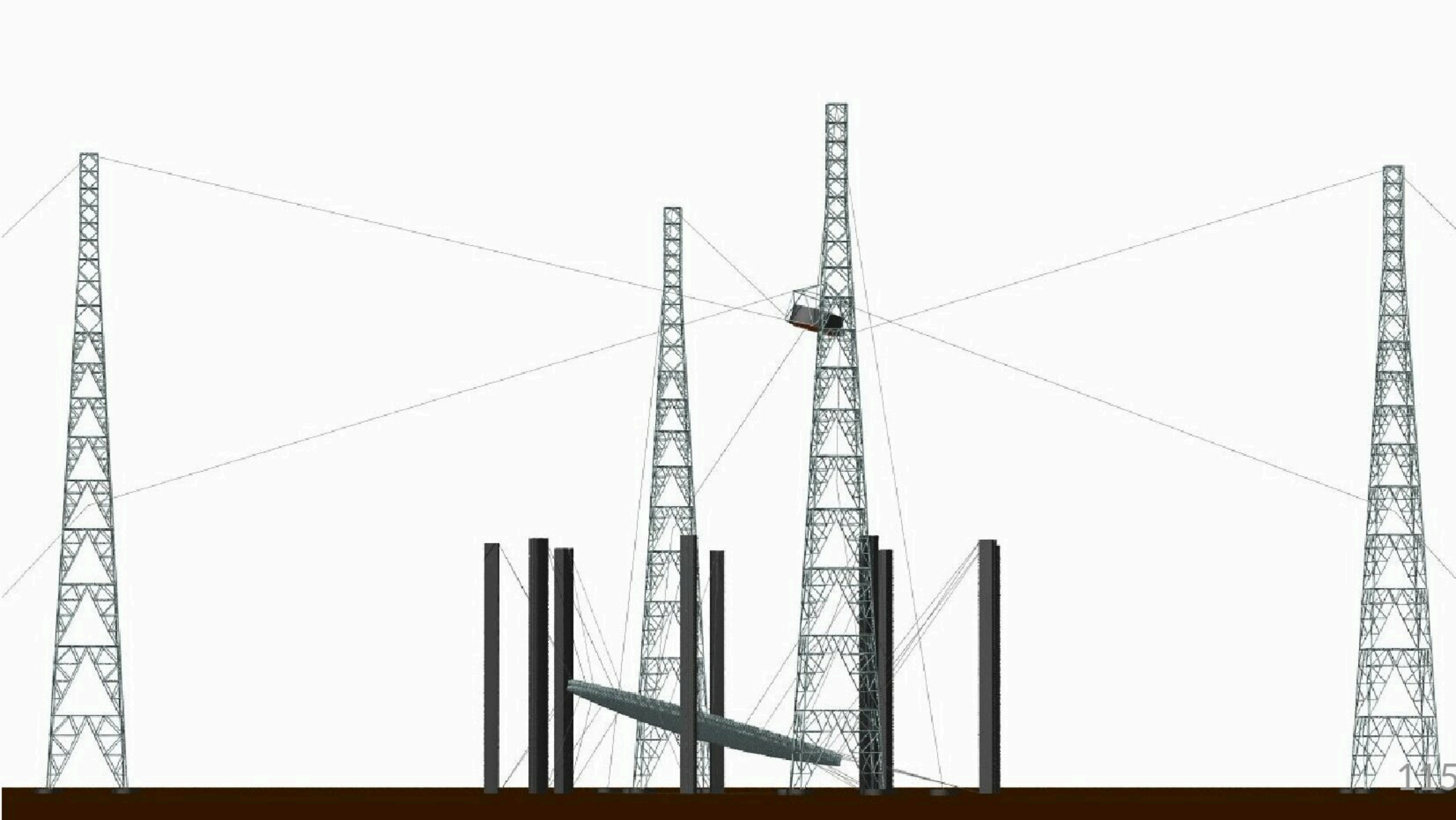


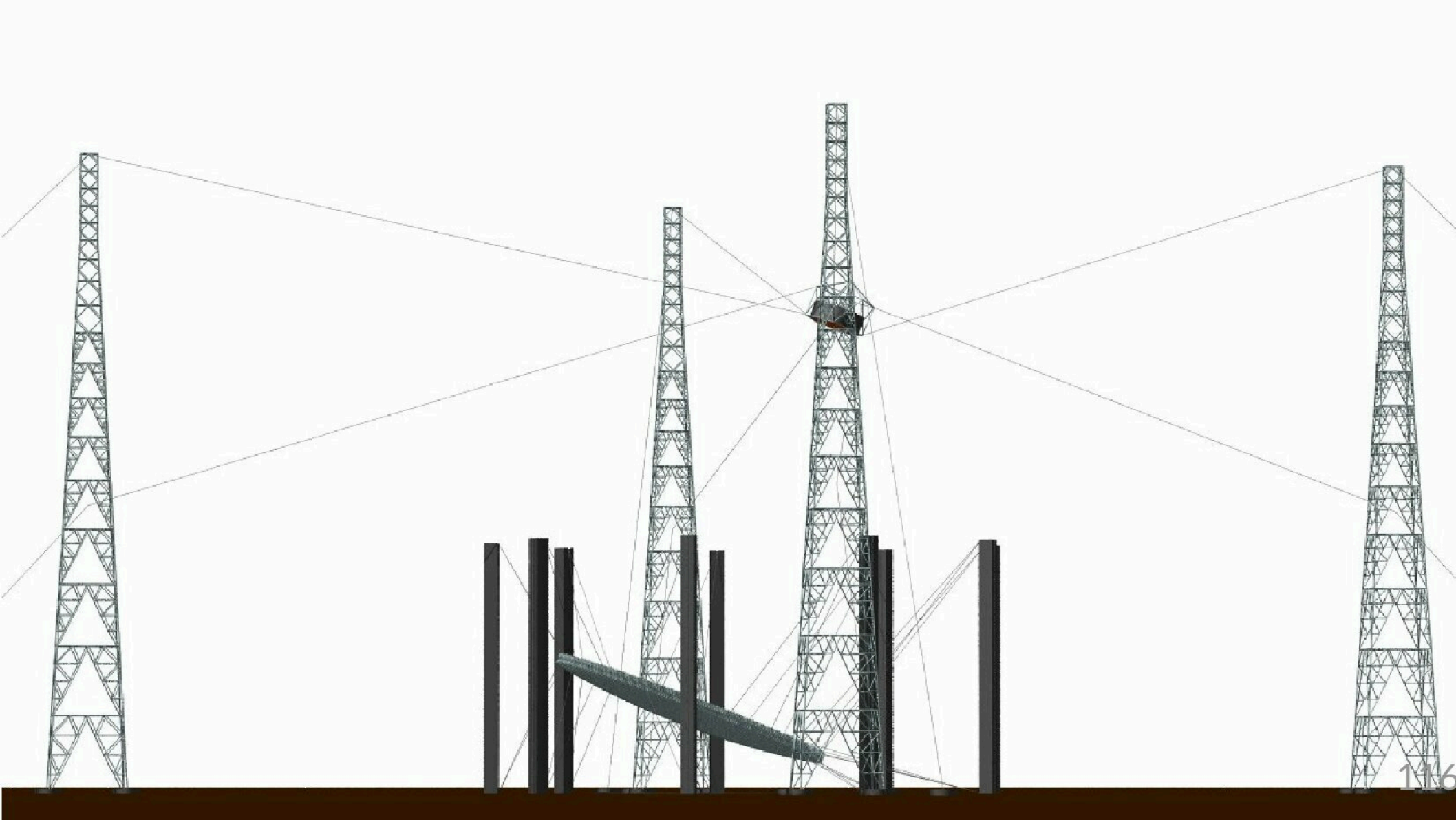


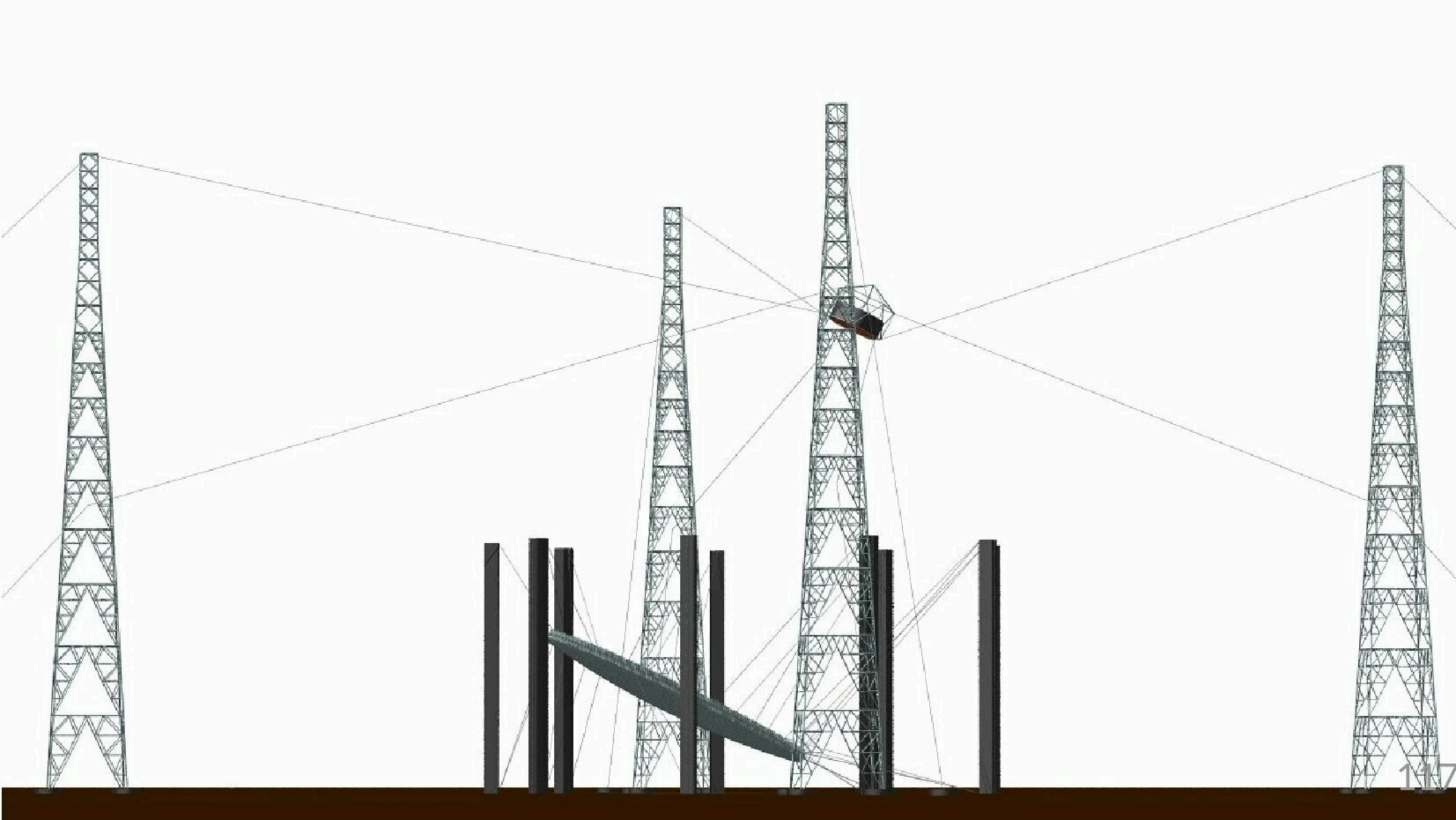


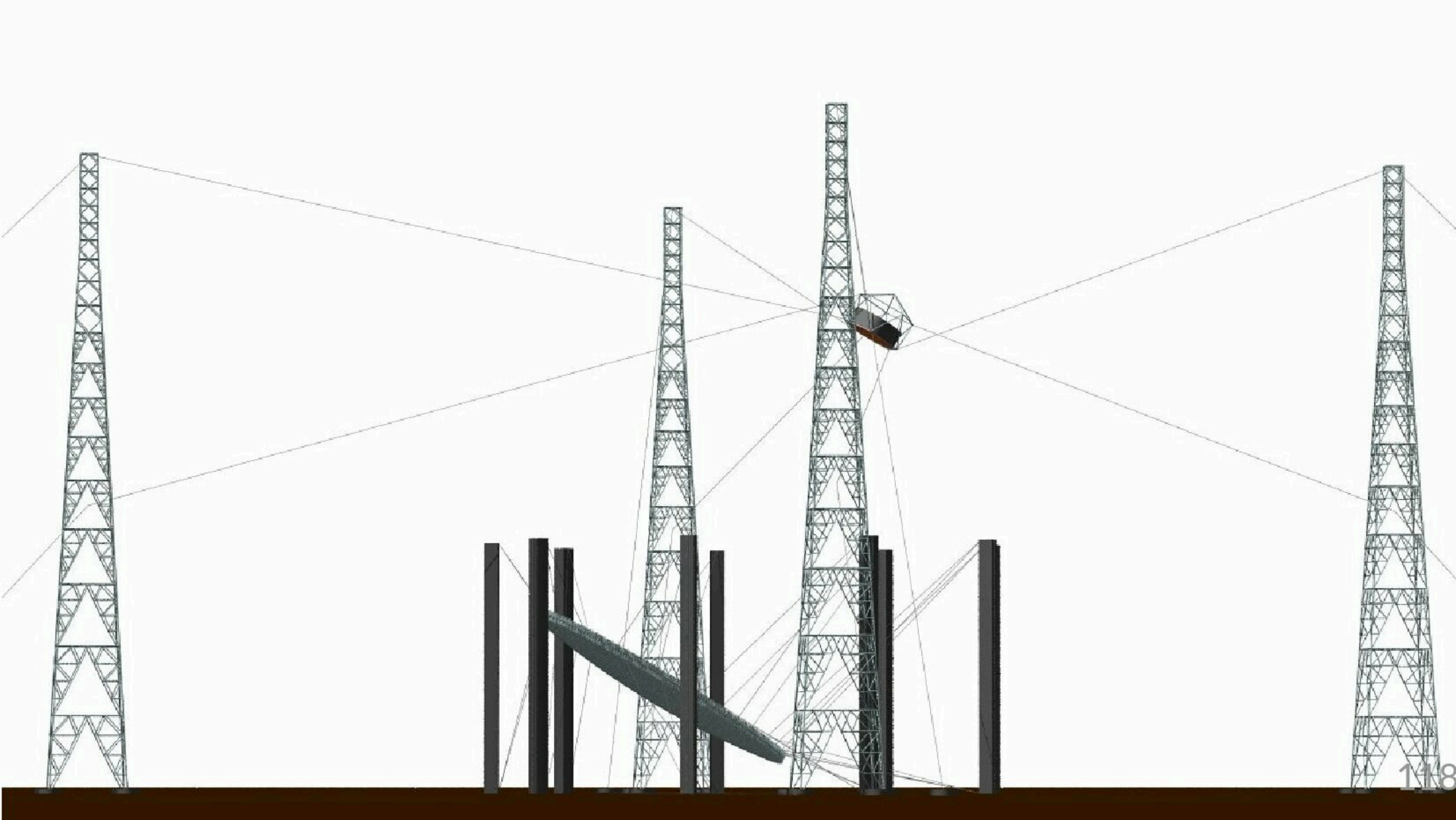


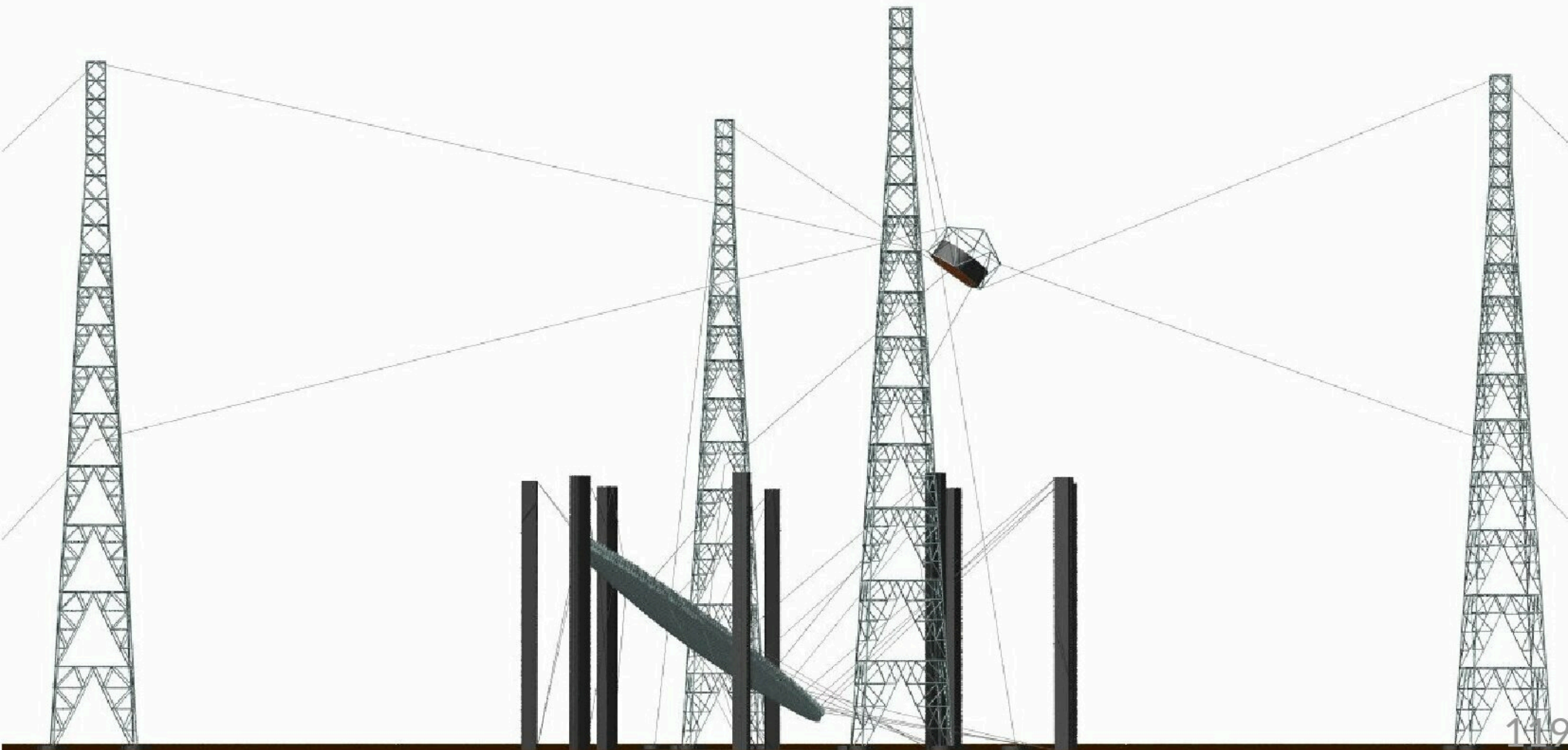


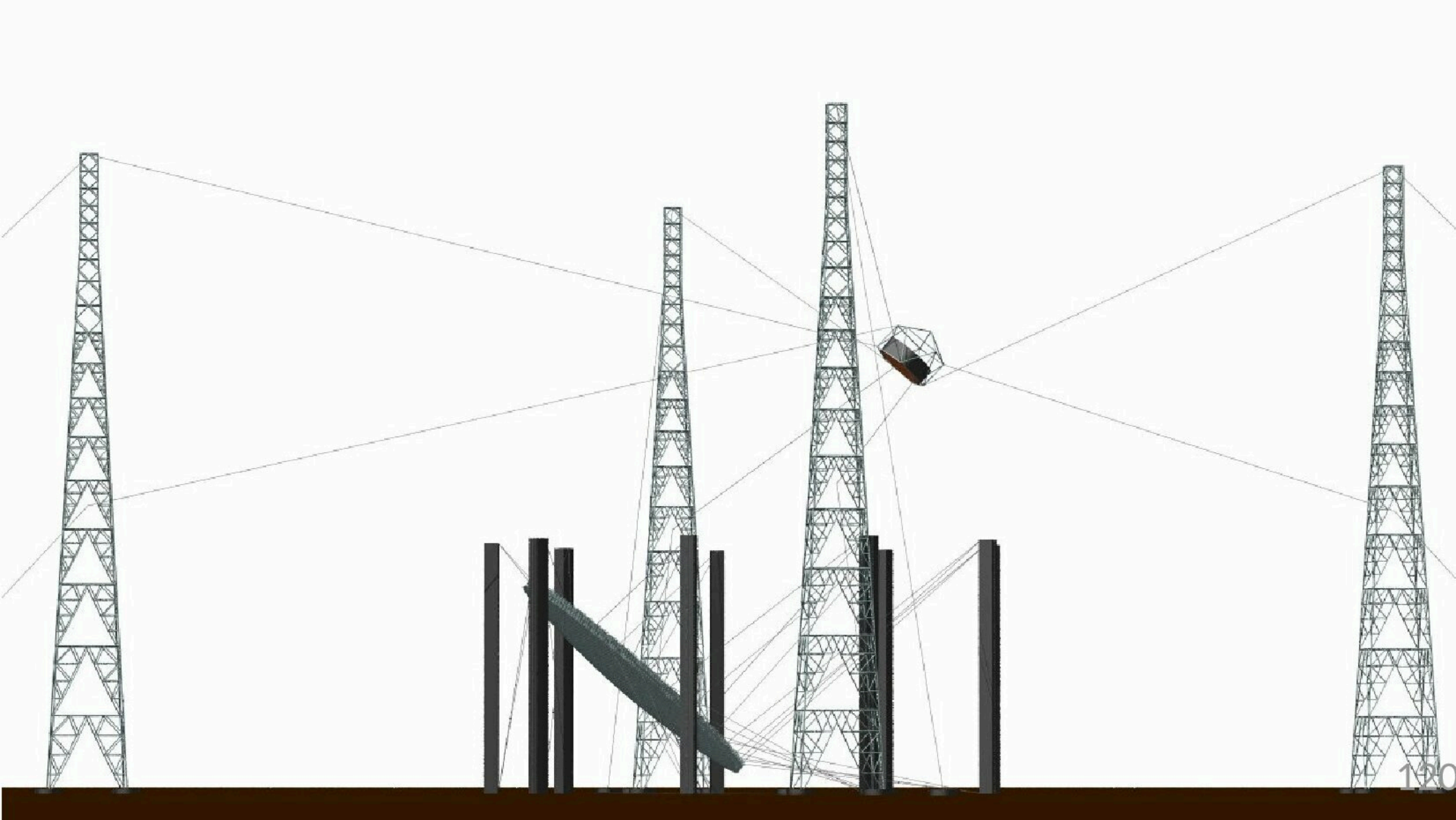


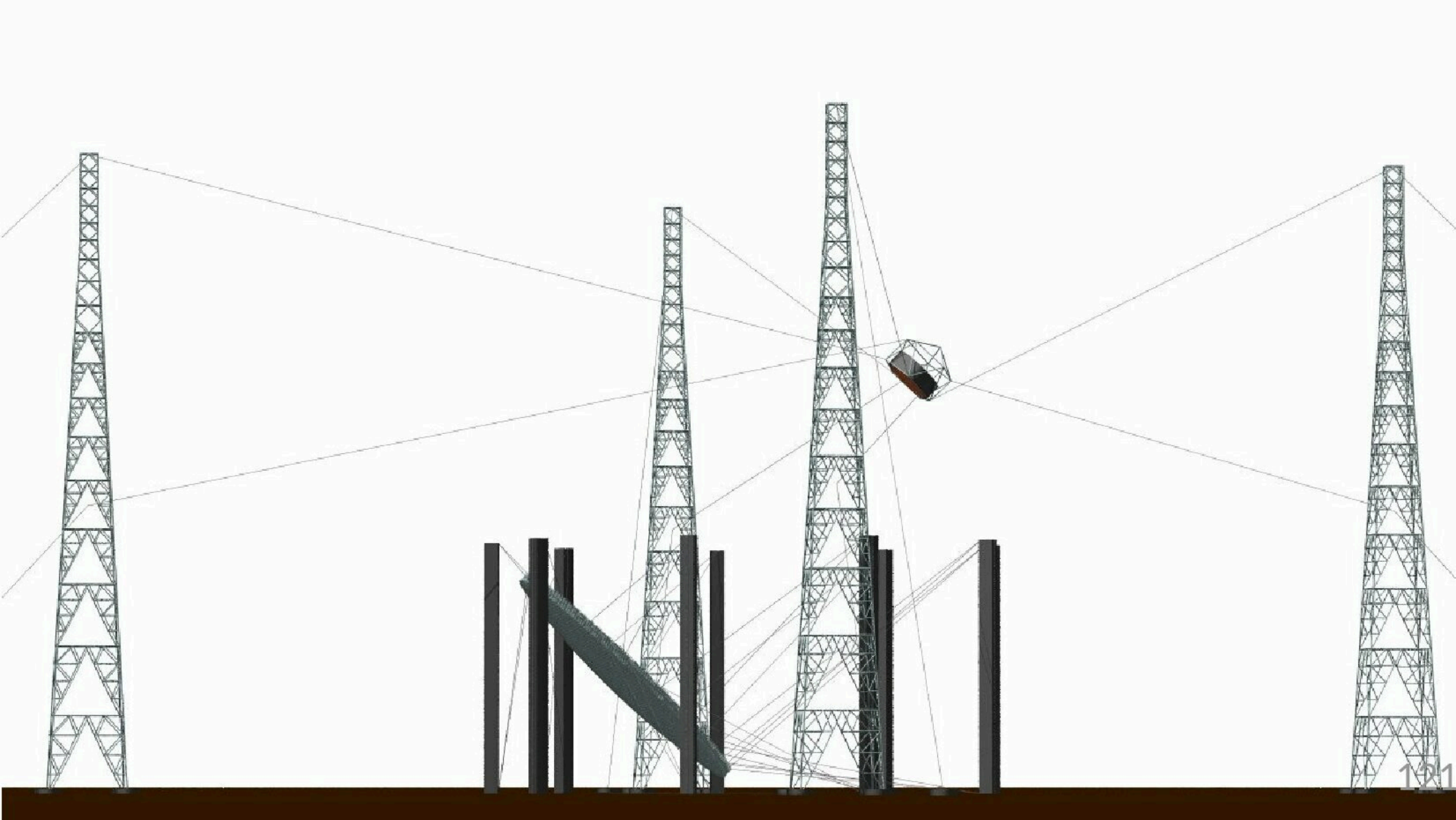




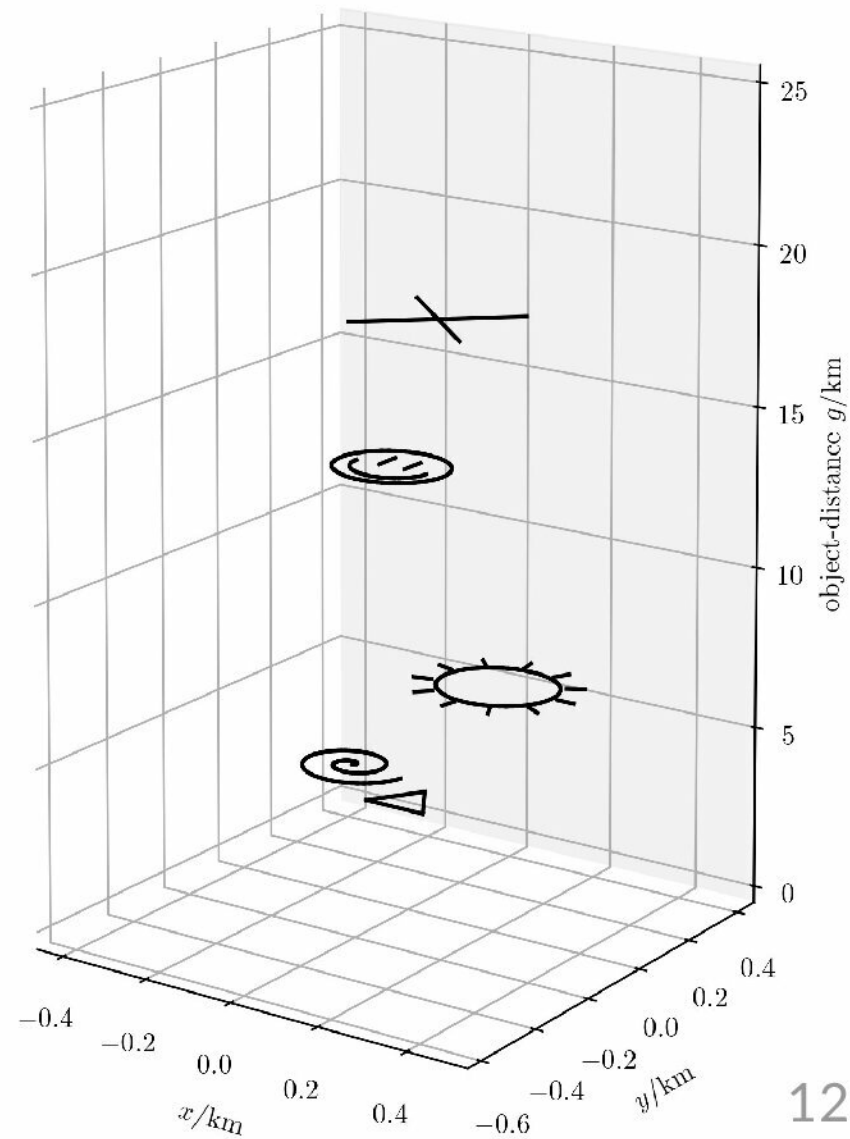


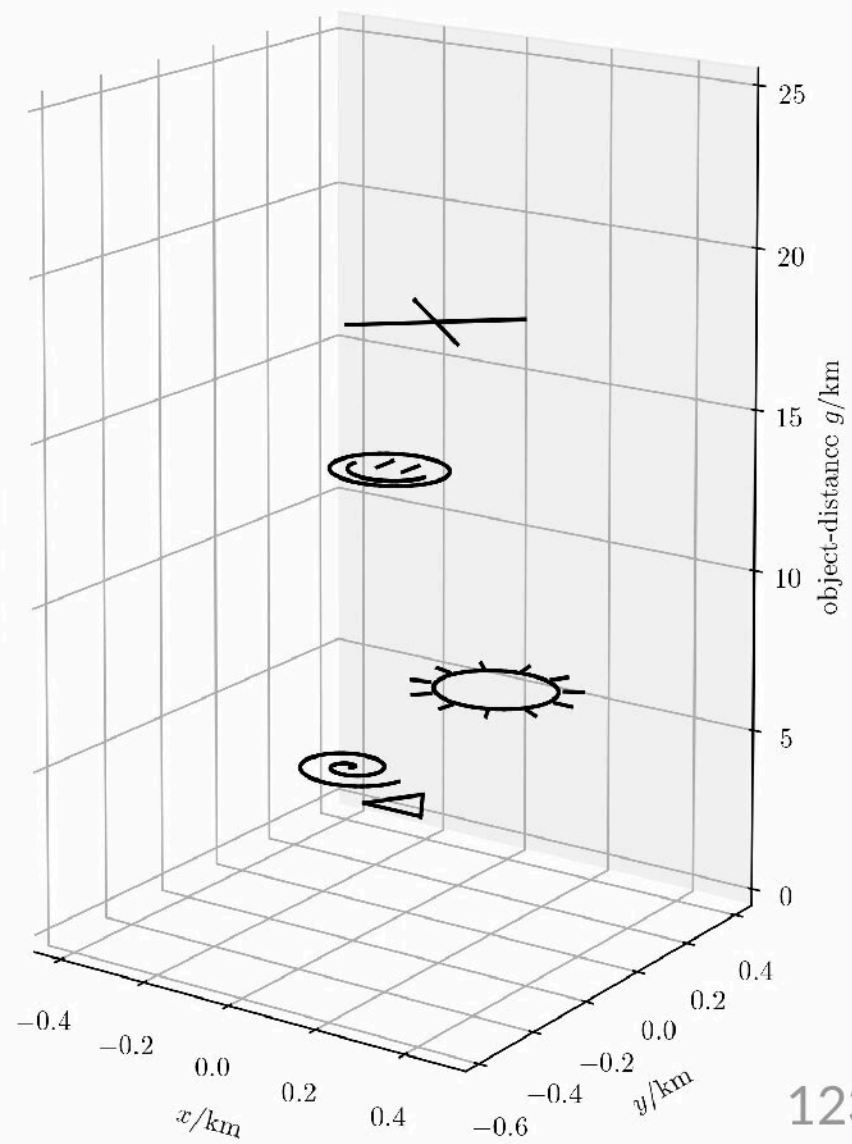
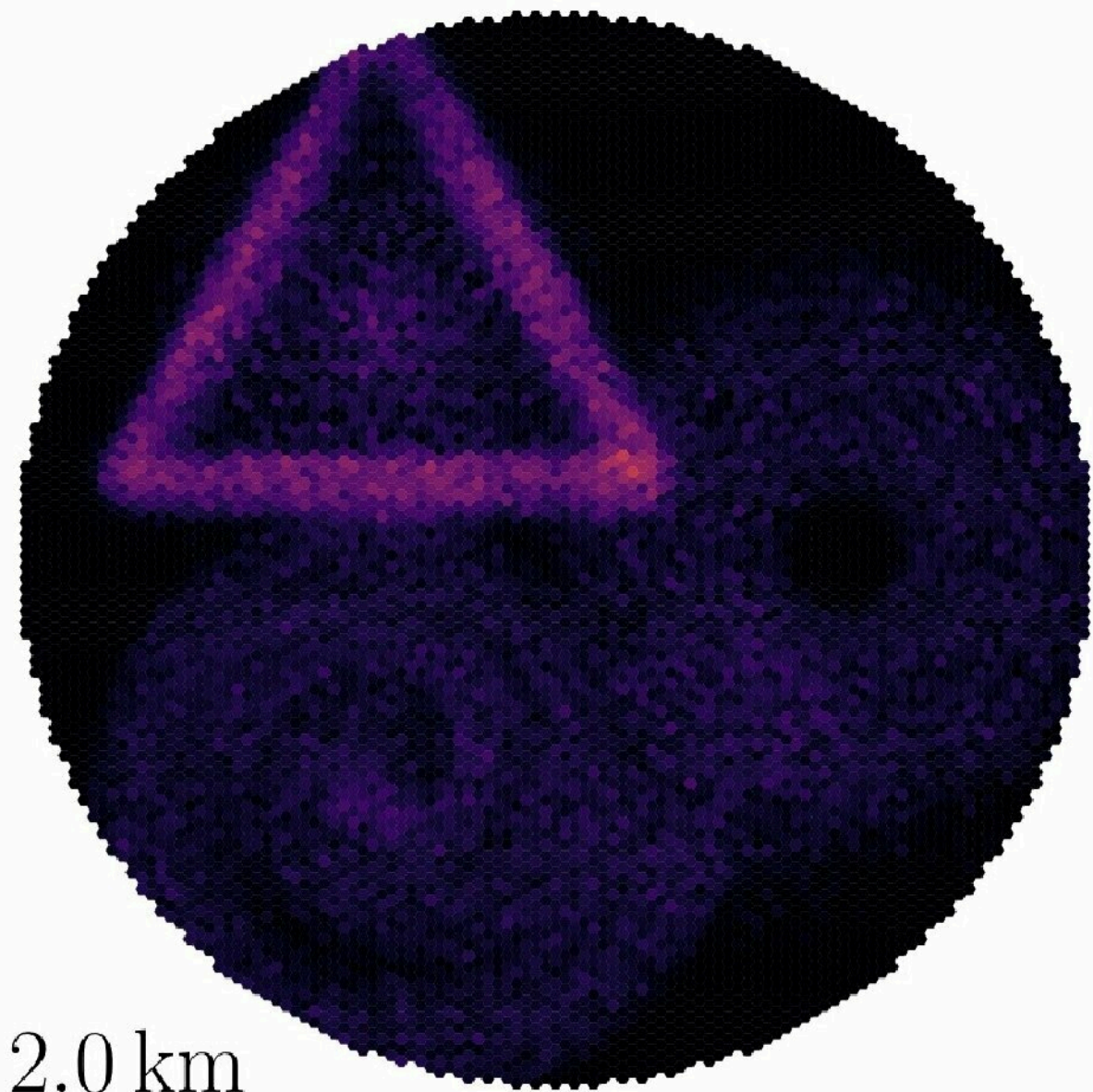


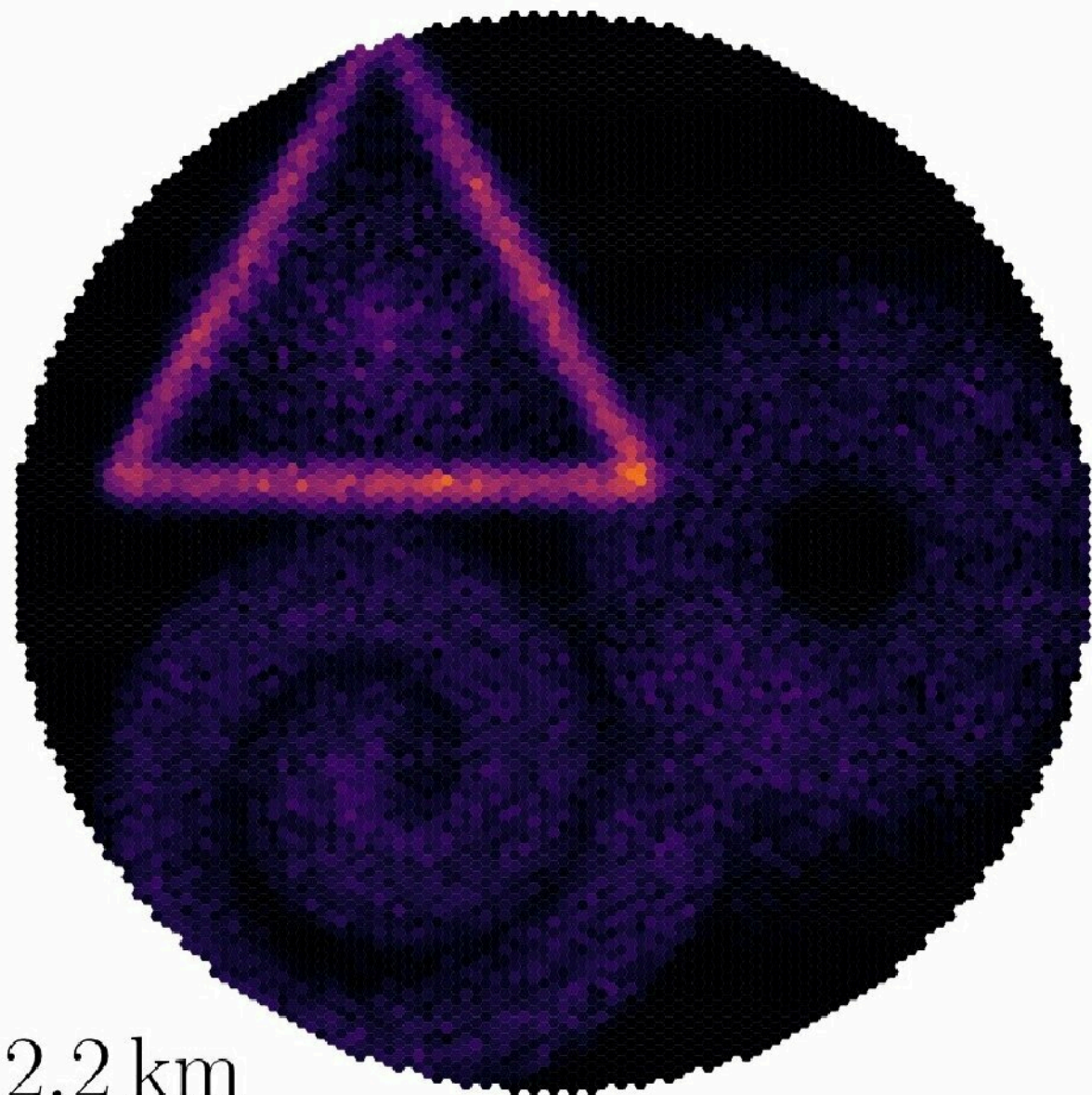




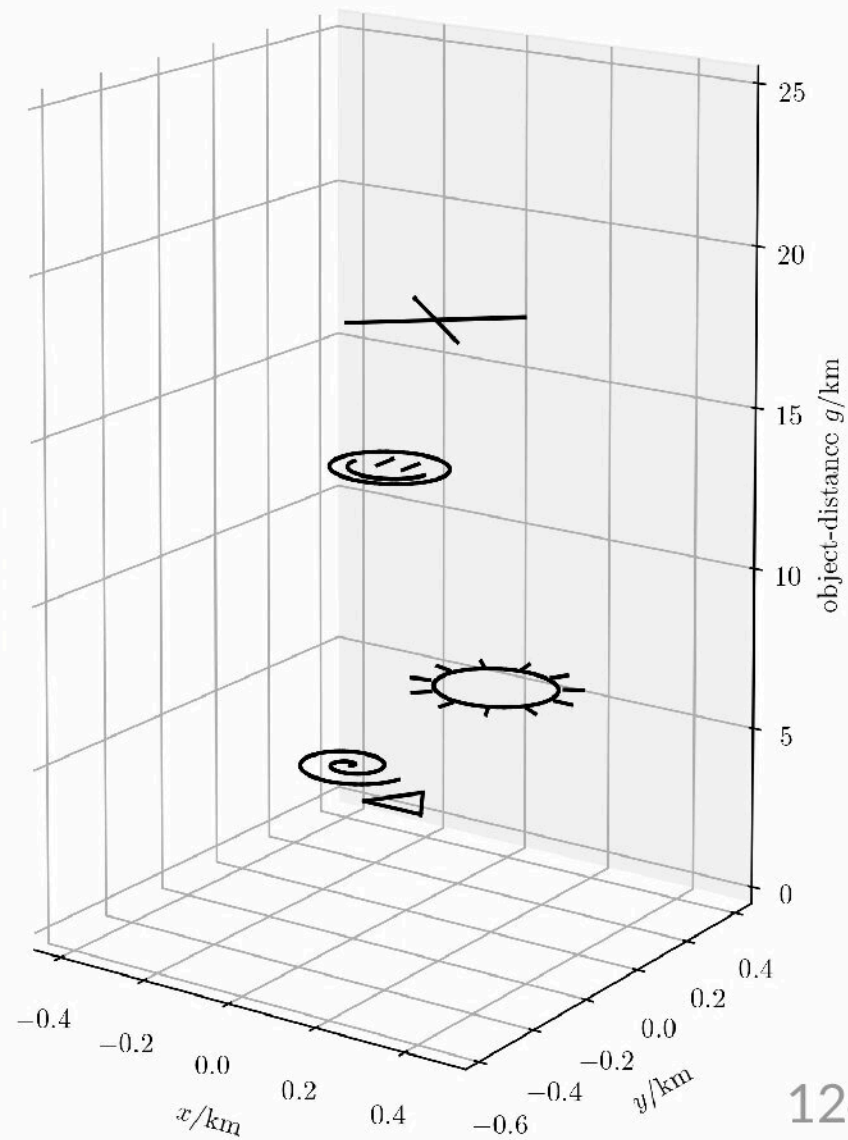
Phantom-Source

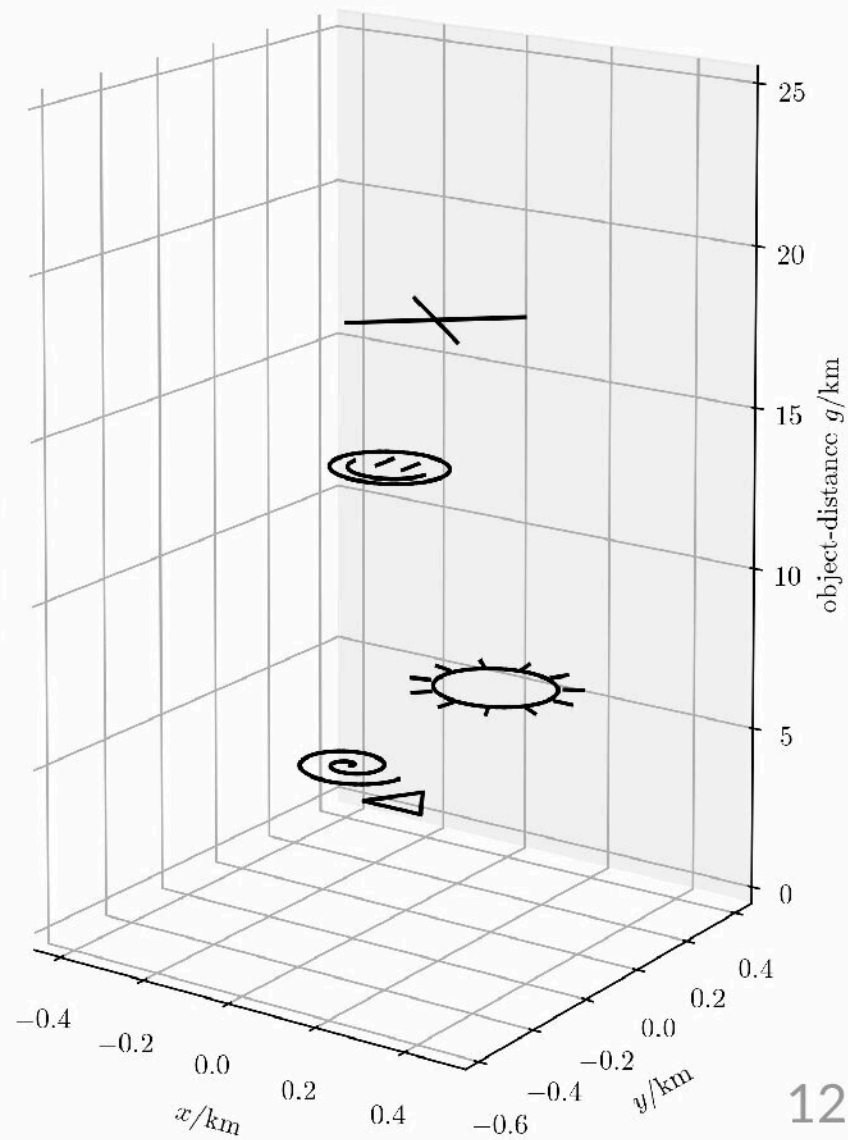
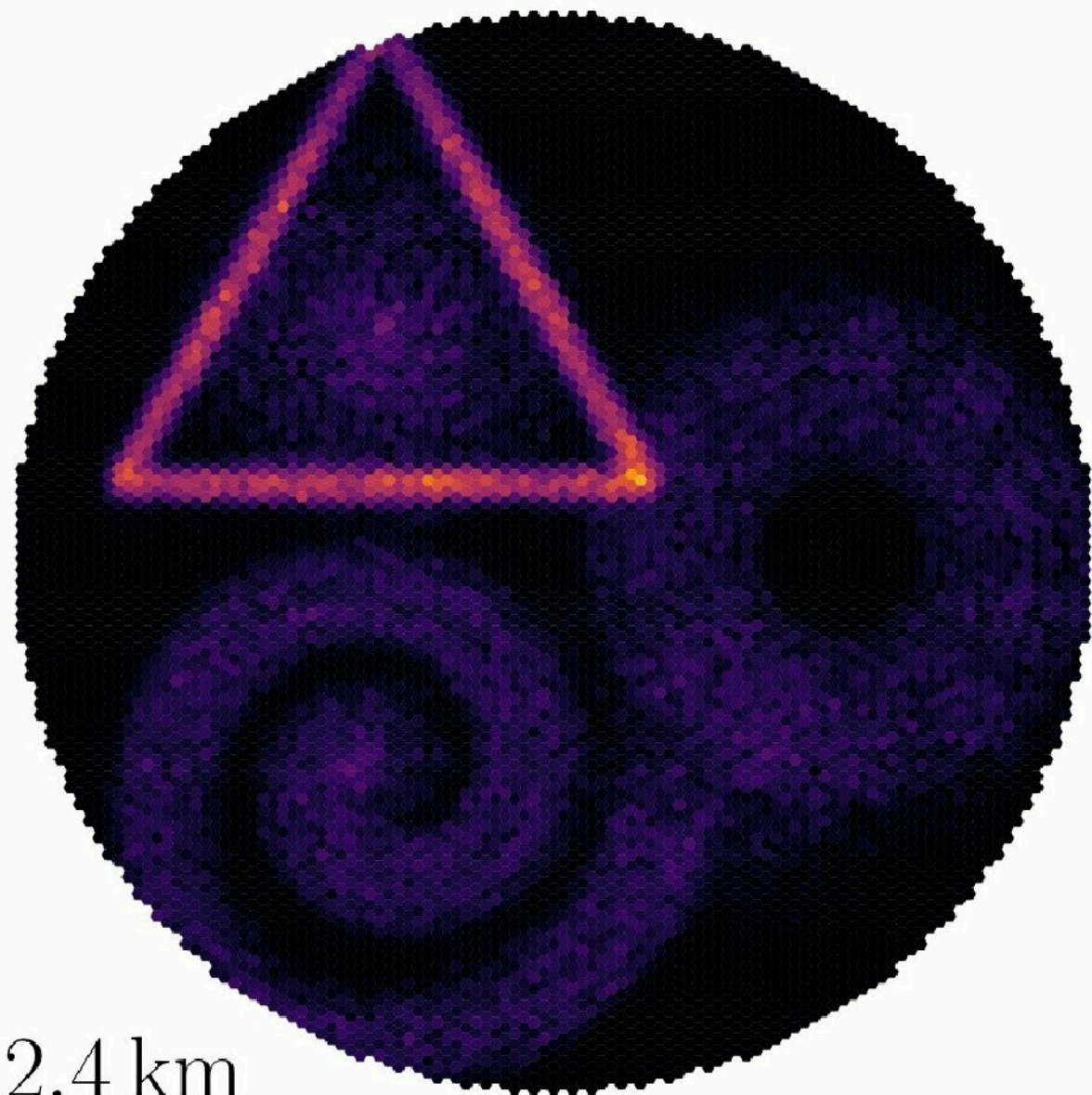


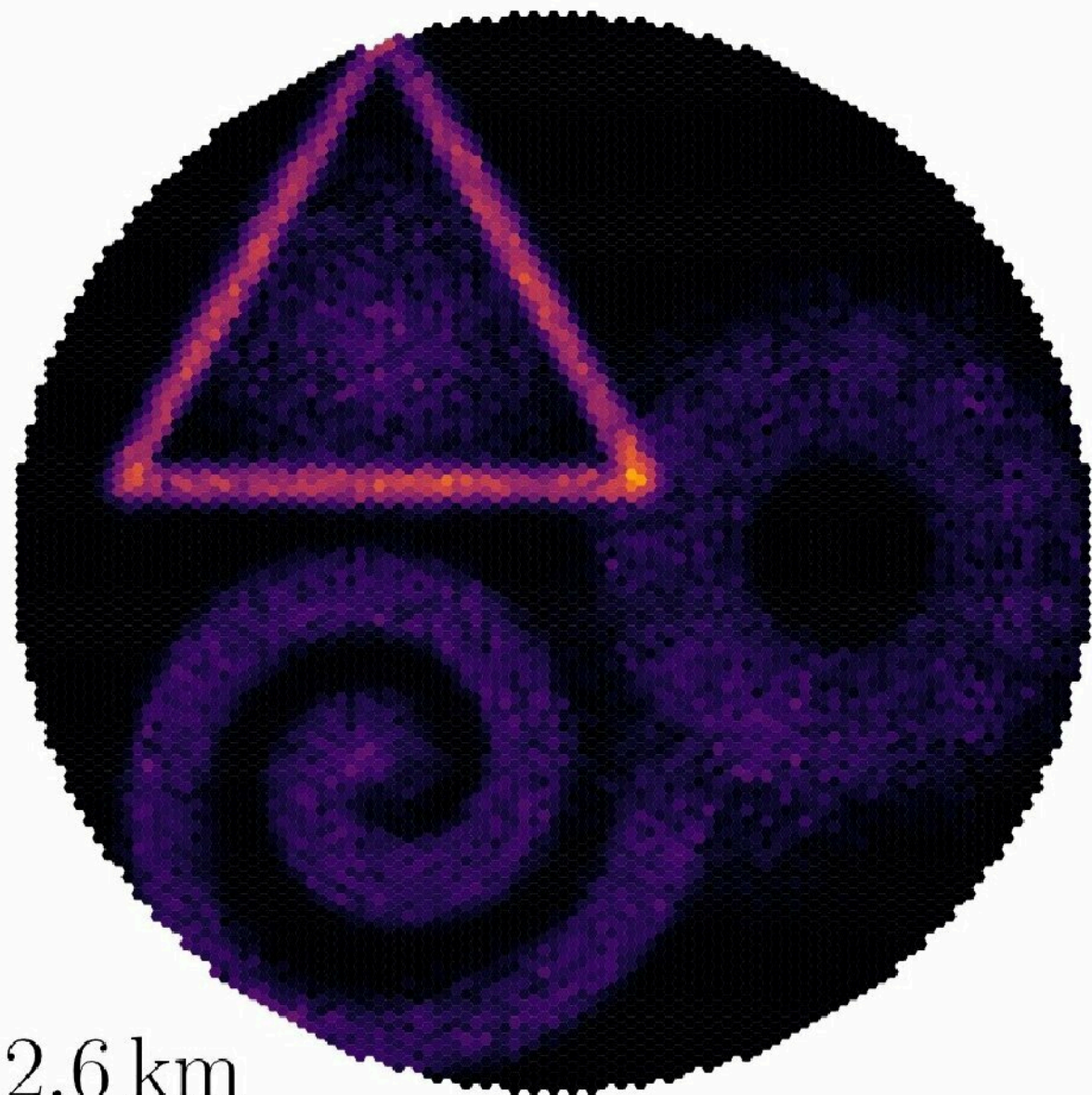




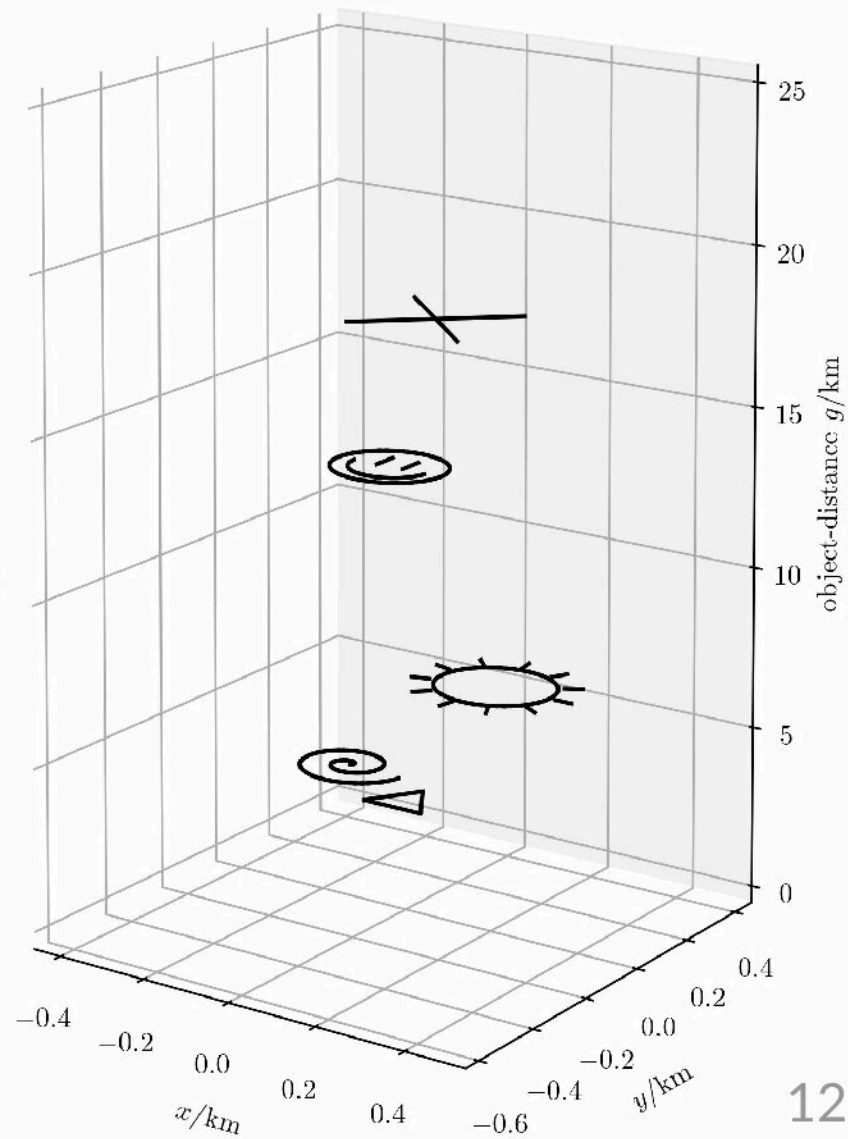
2.2 km

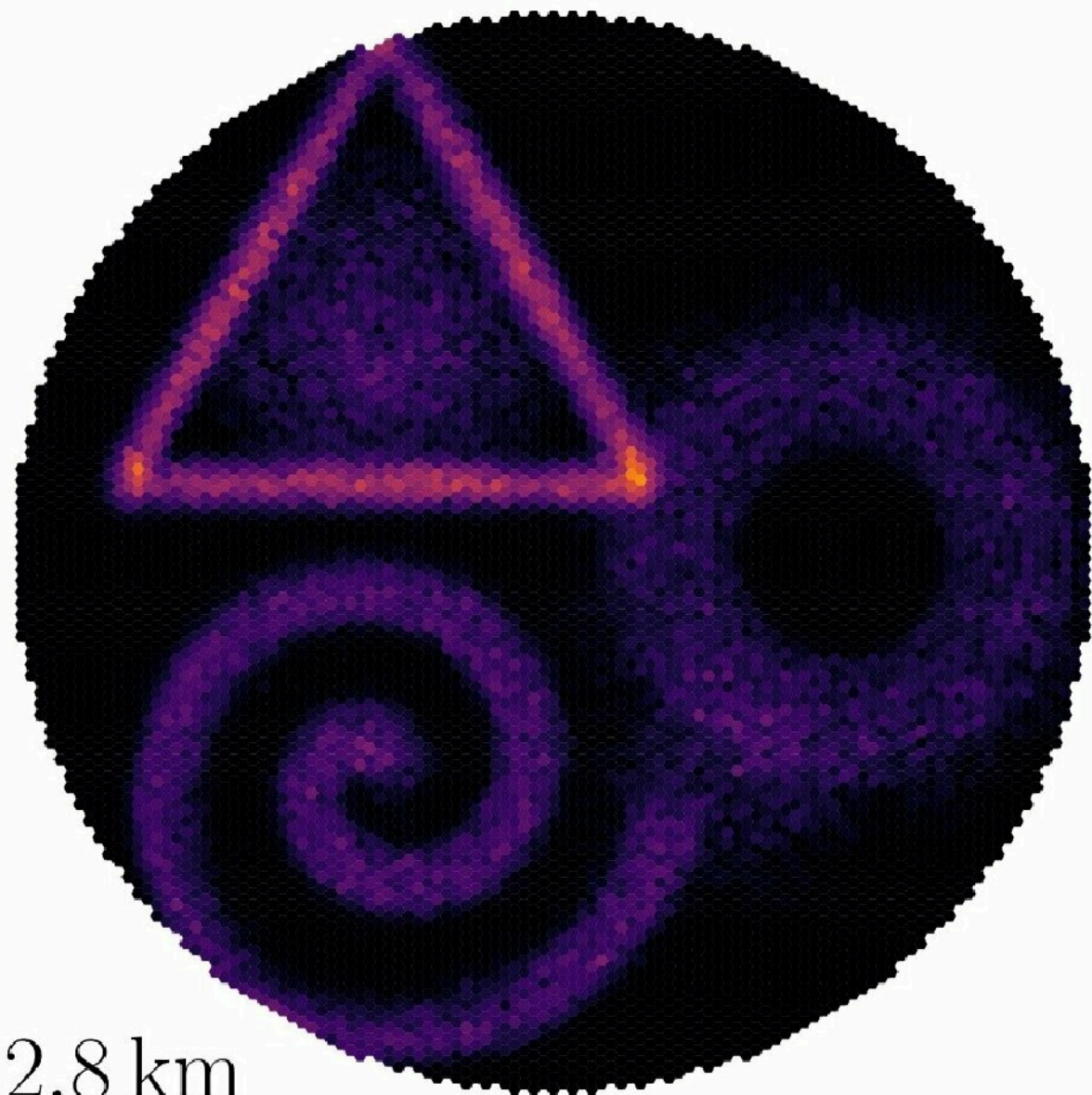




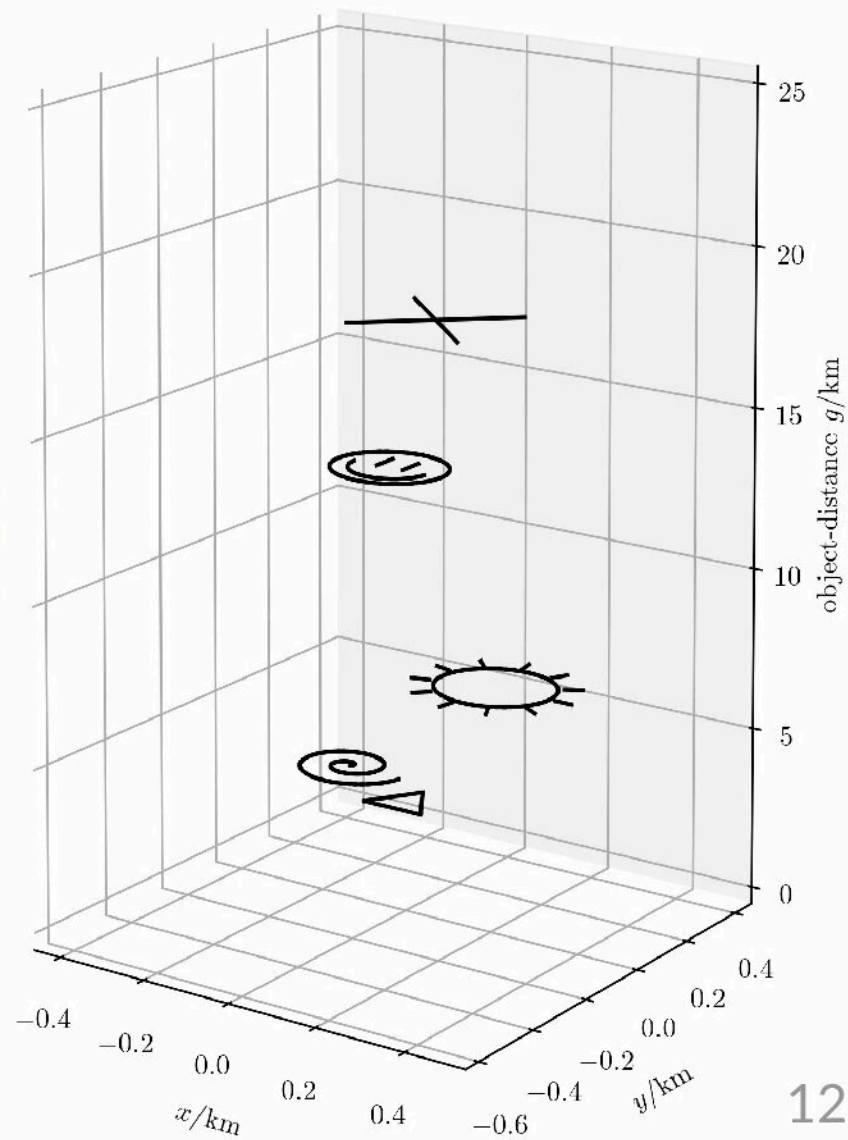


2.6 km

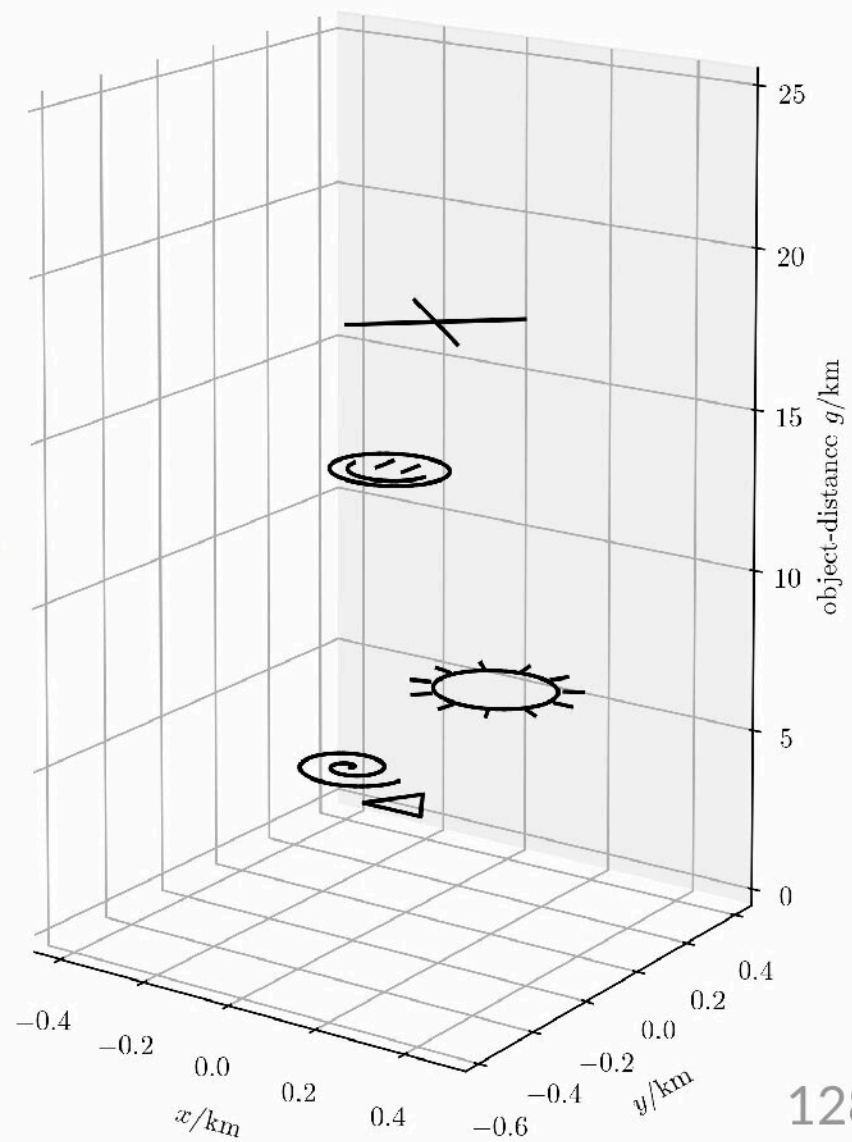
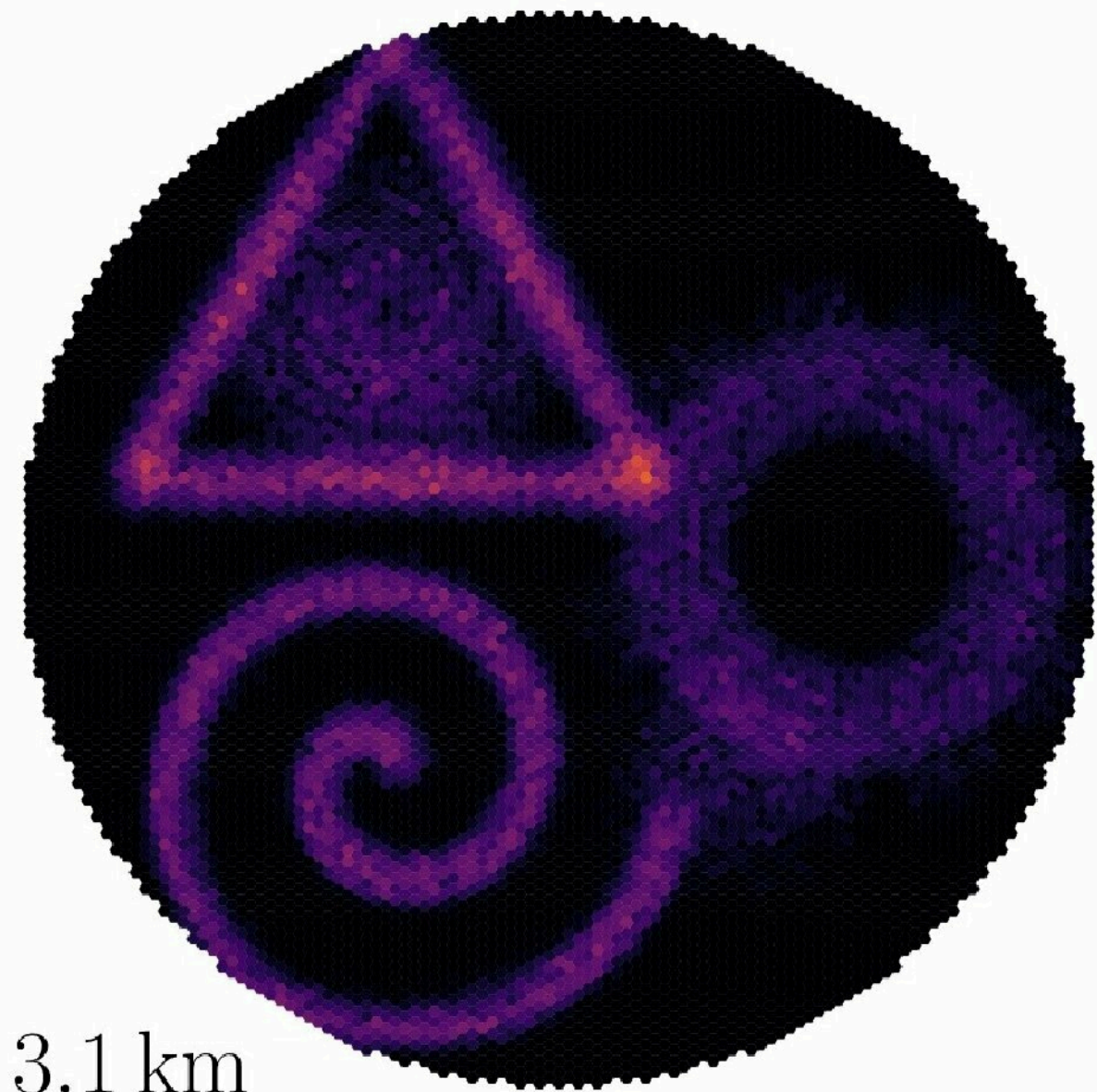


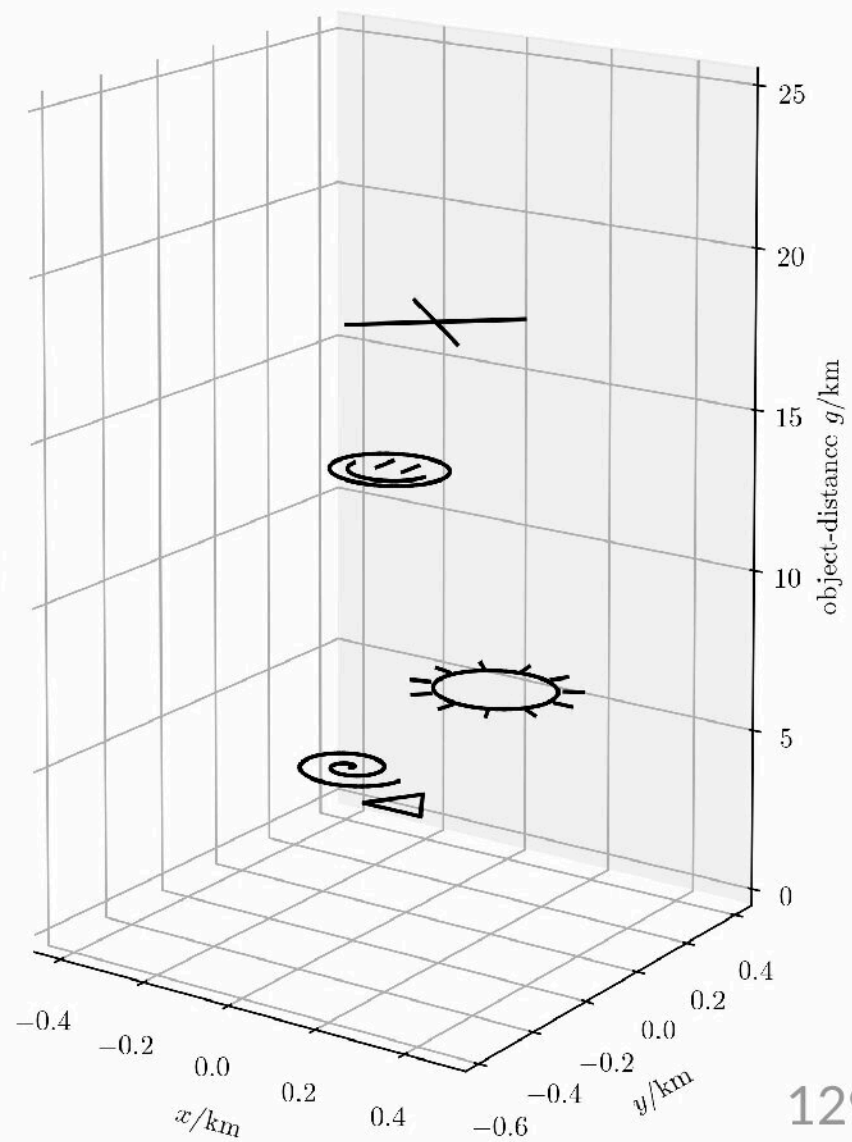
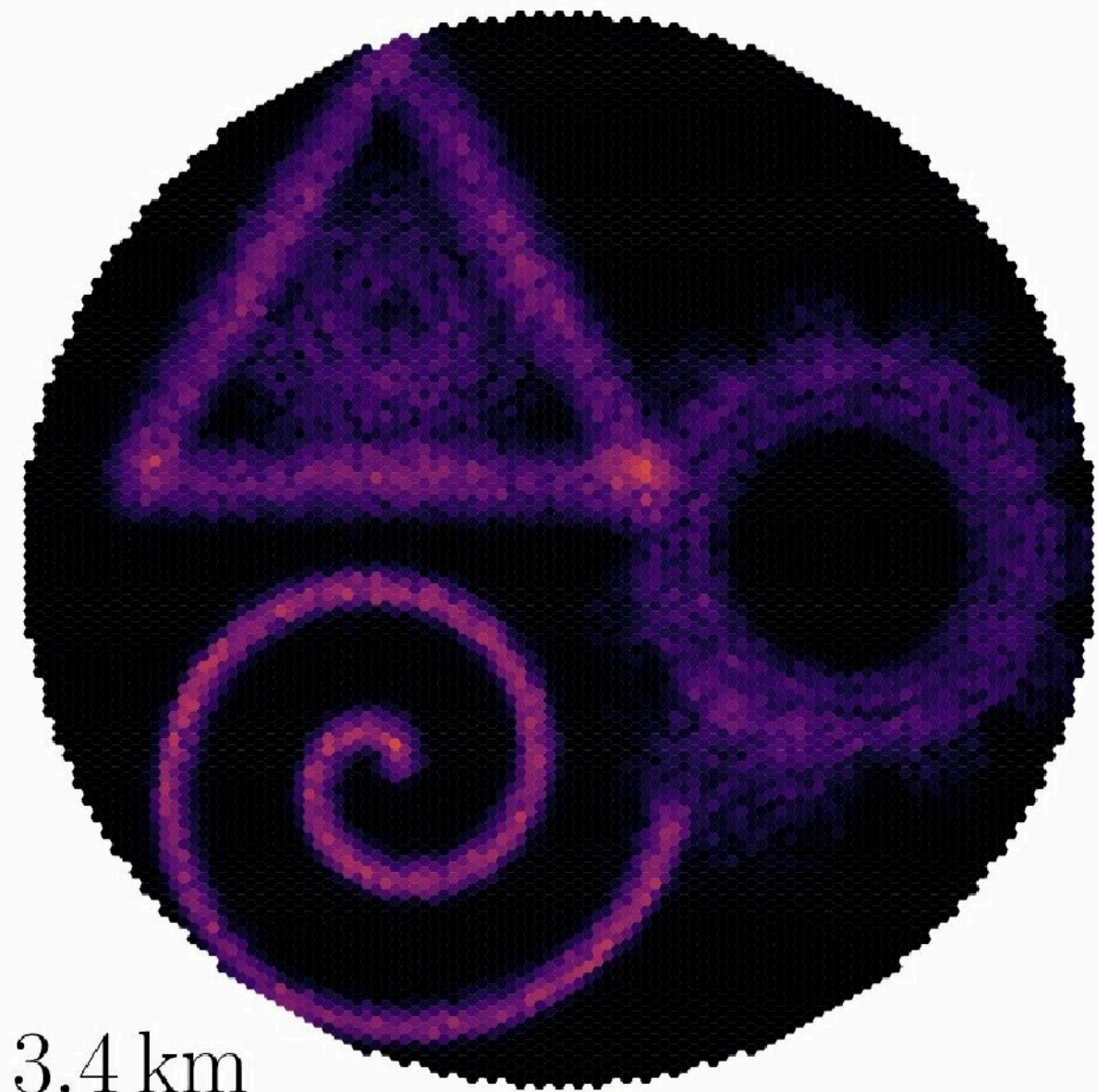


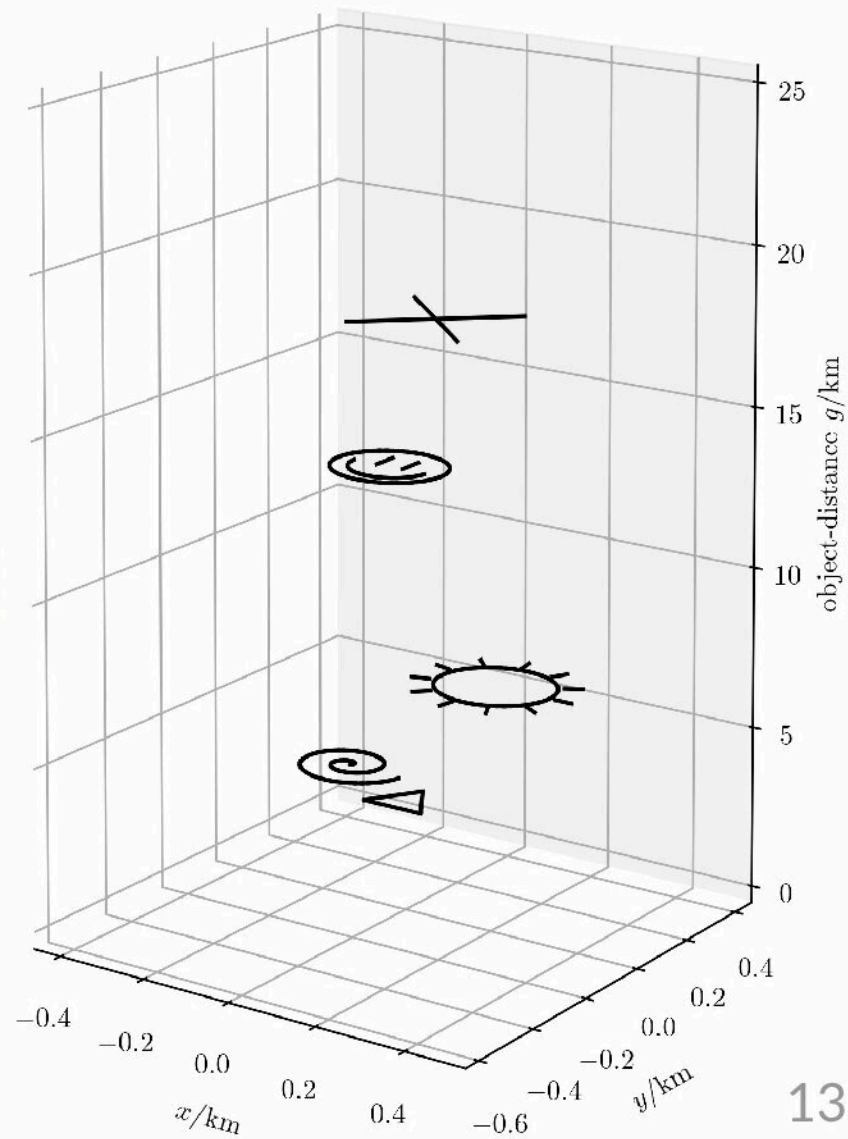
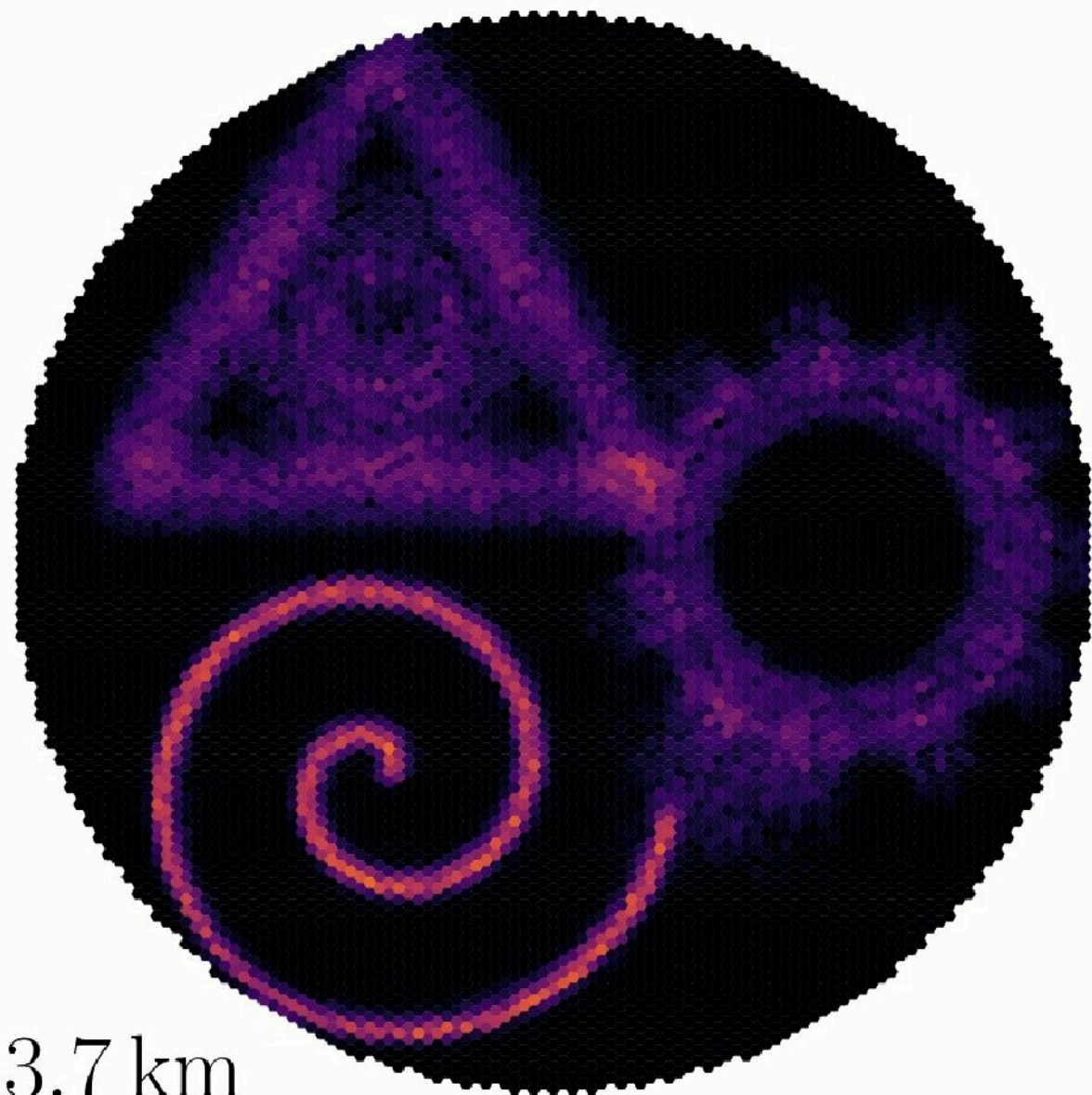
2.8 km

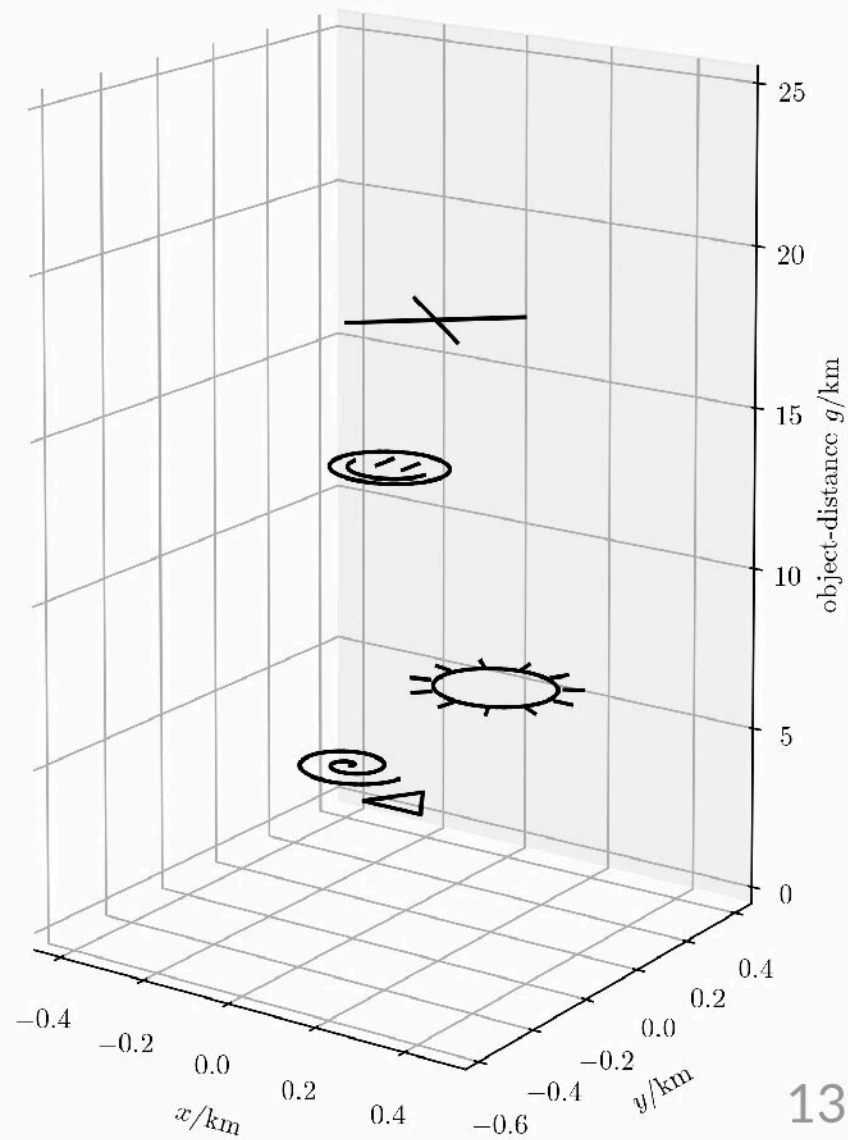
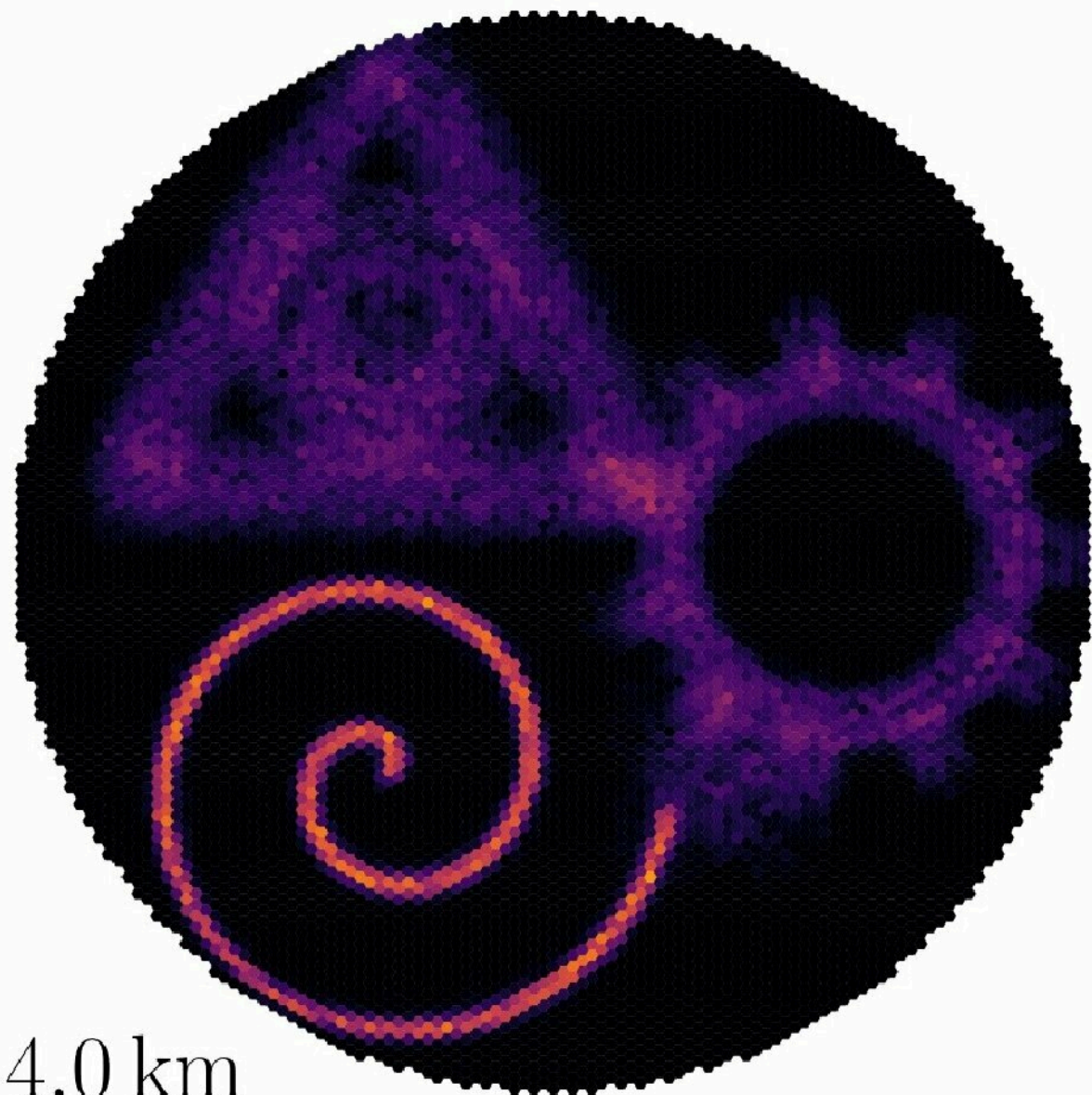


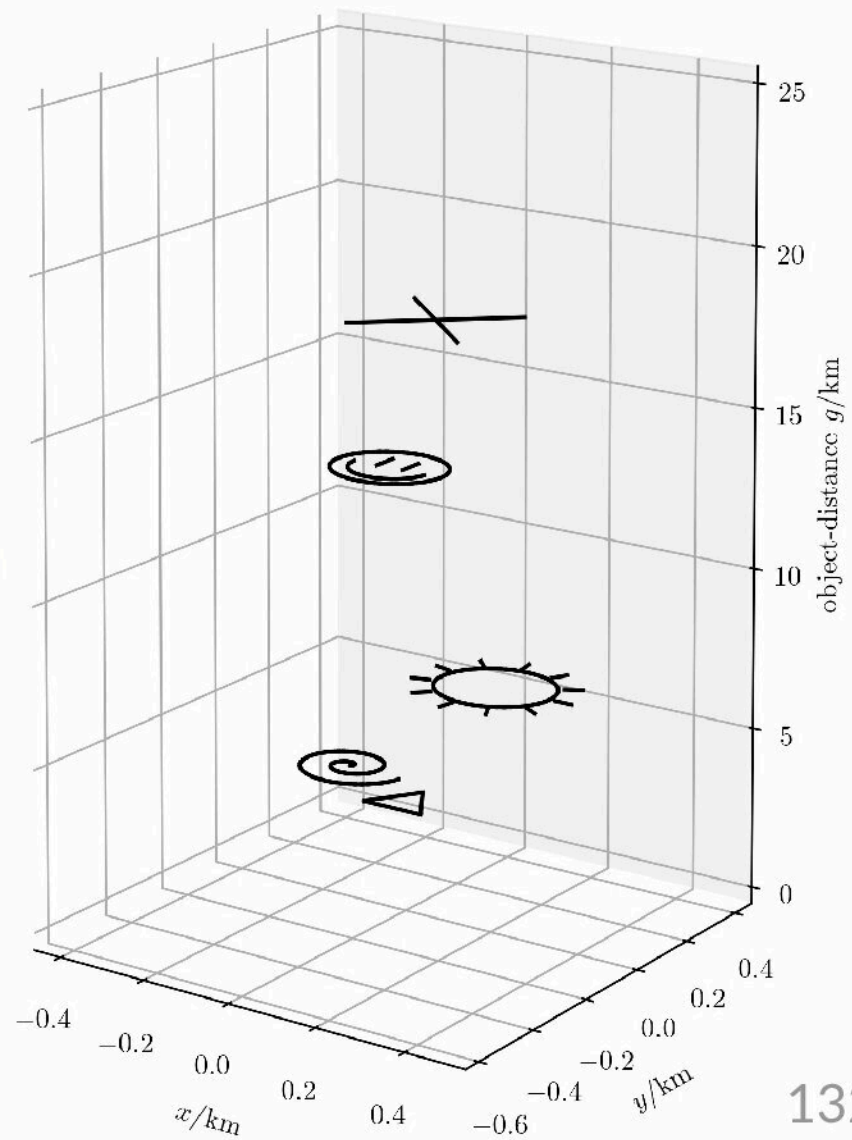
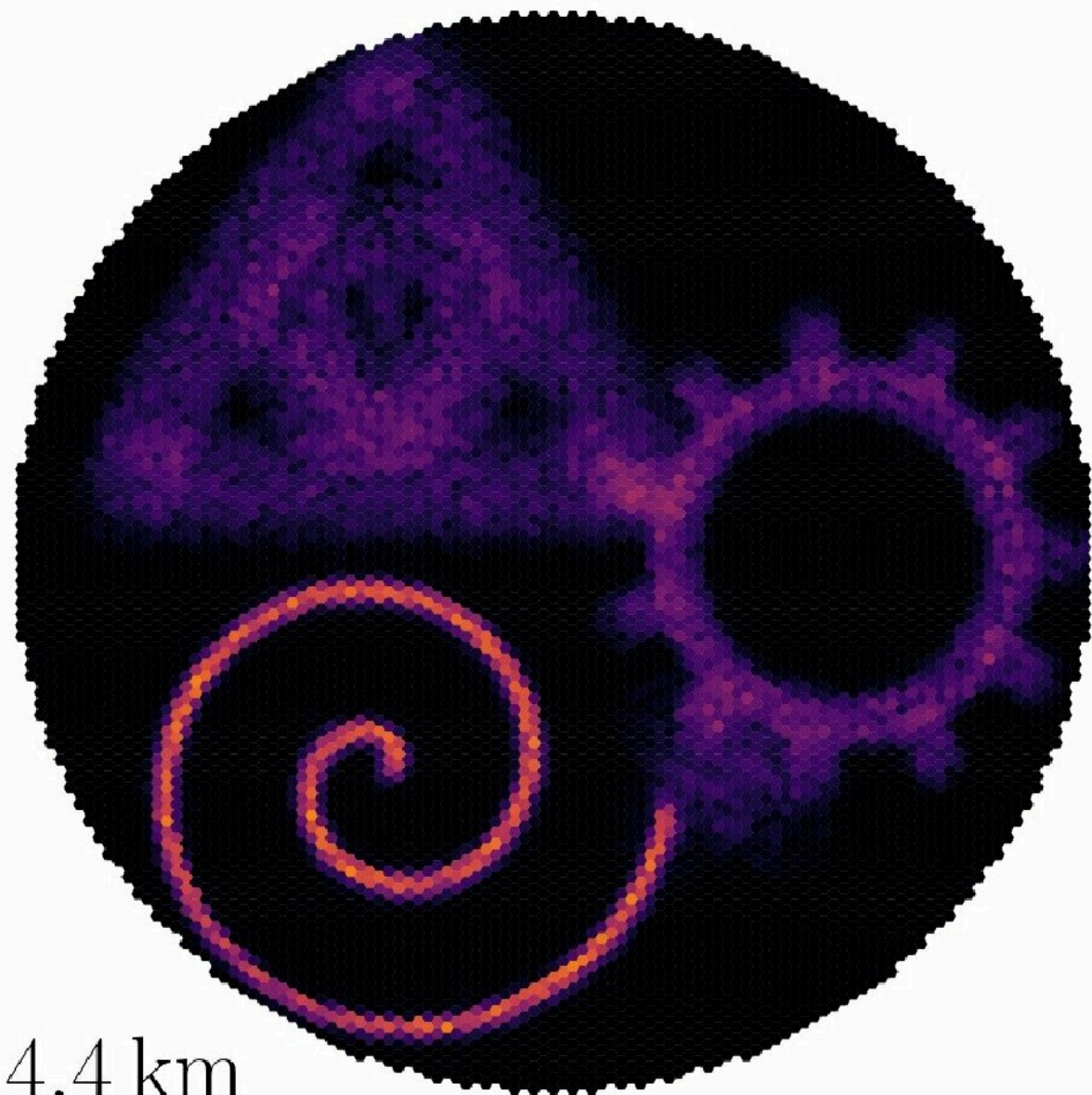
127

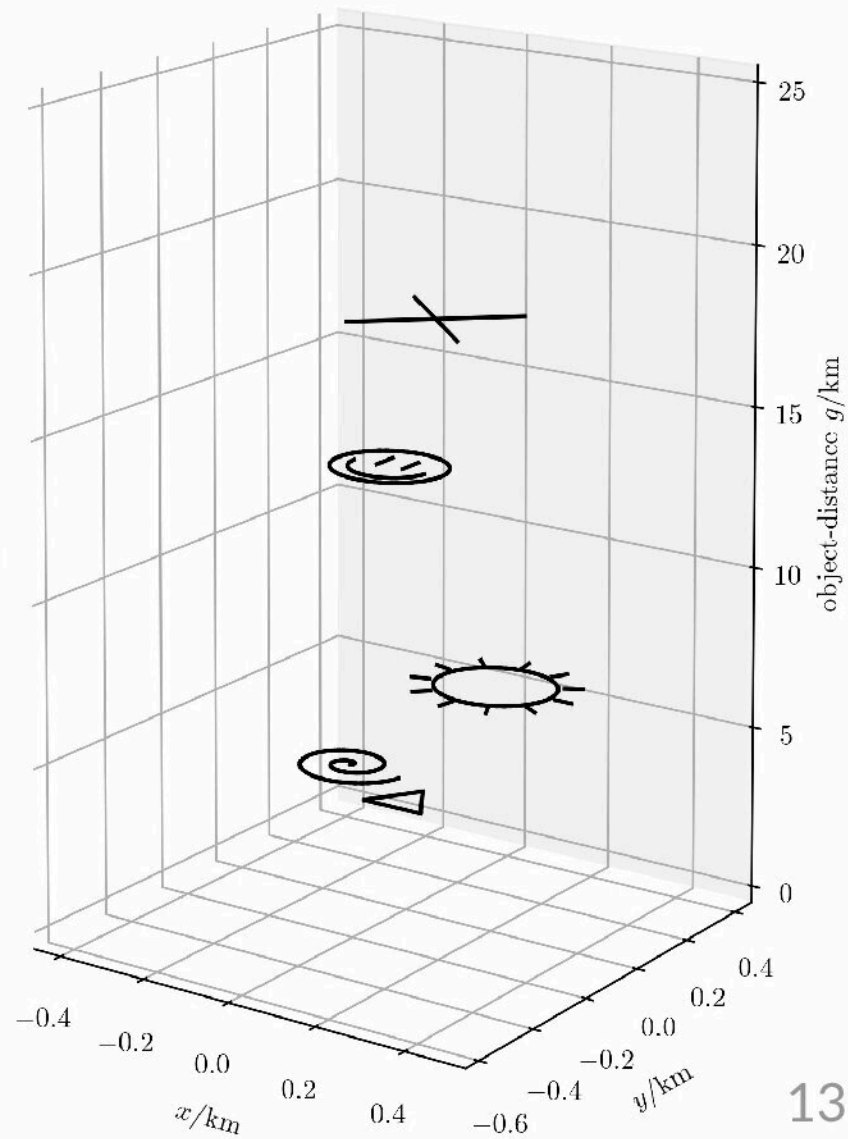
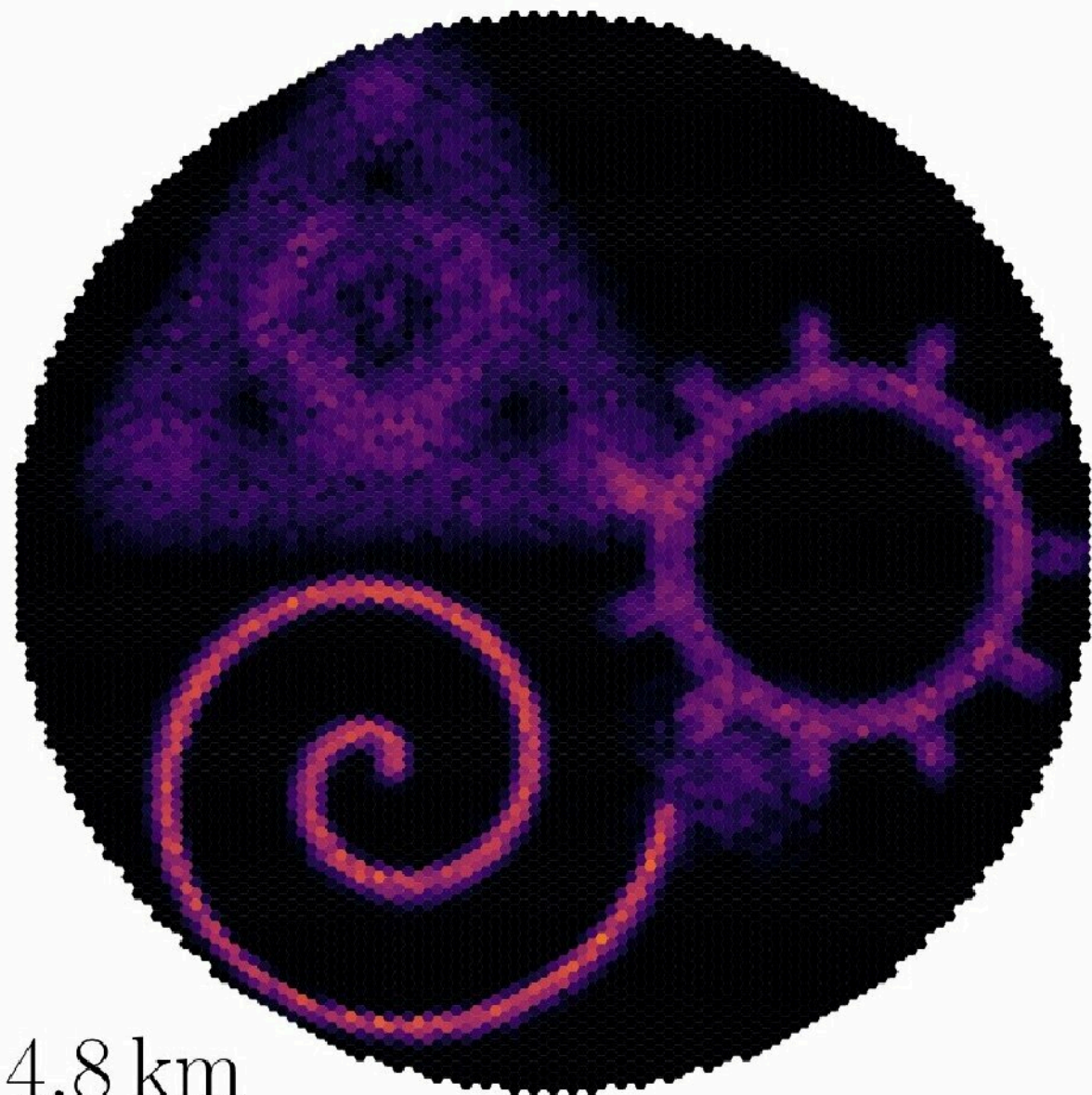


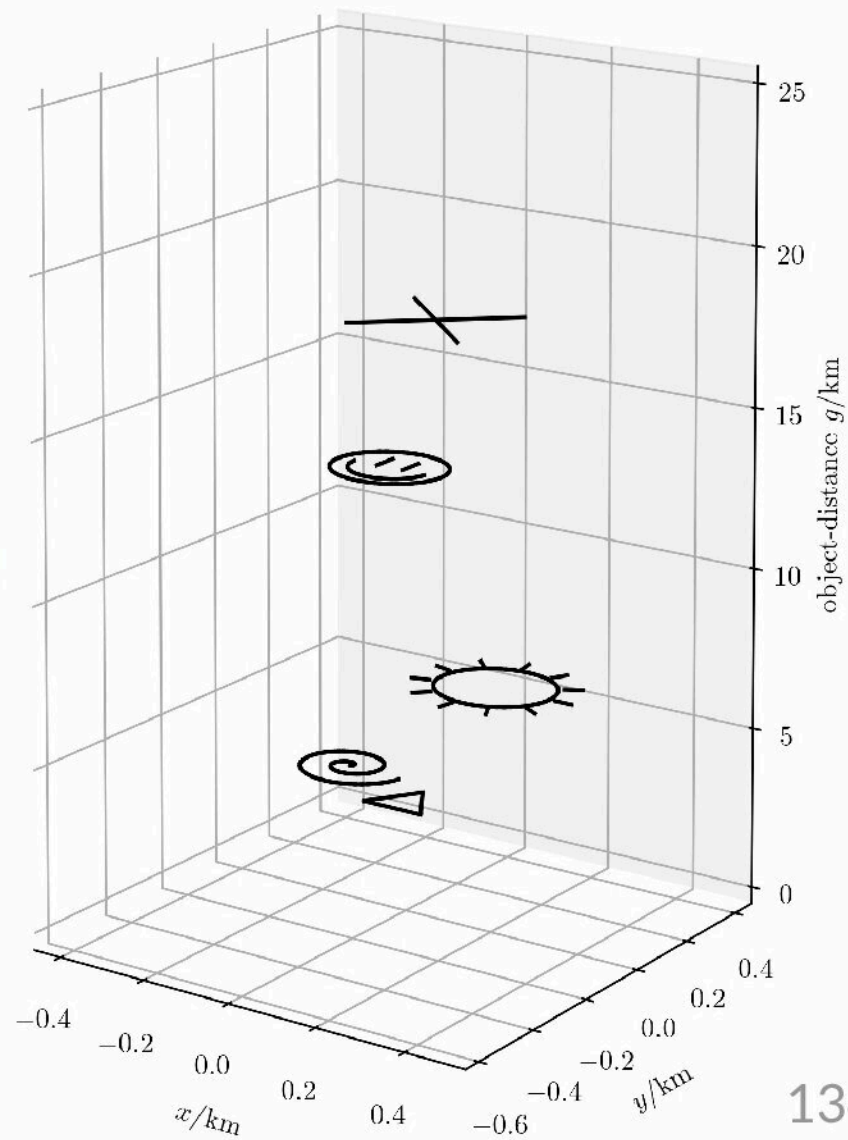
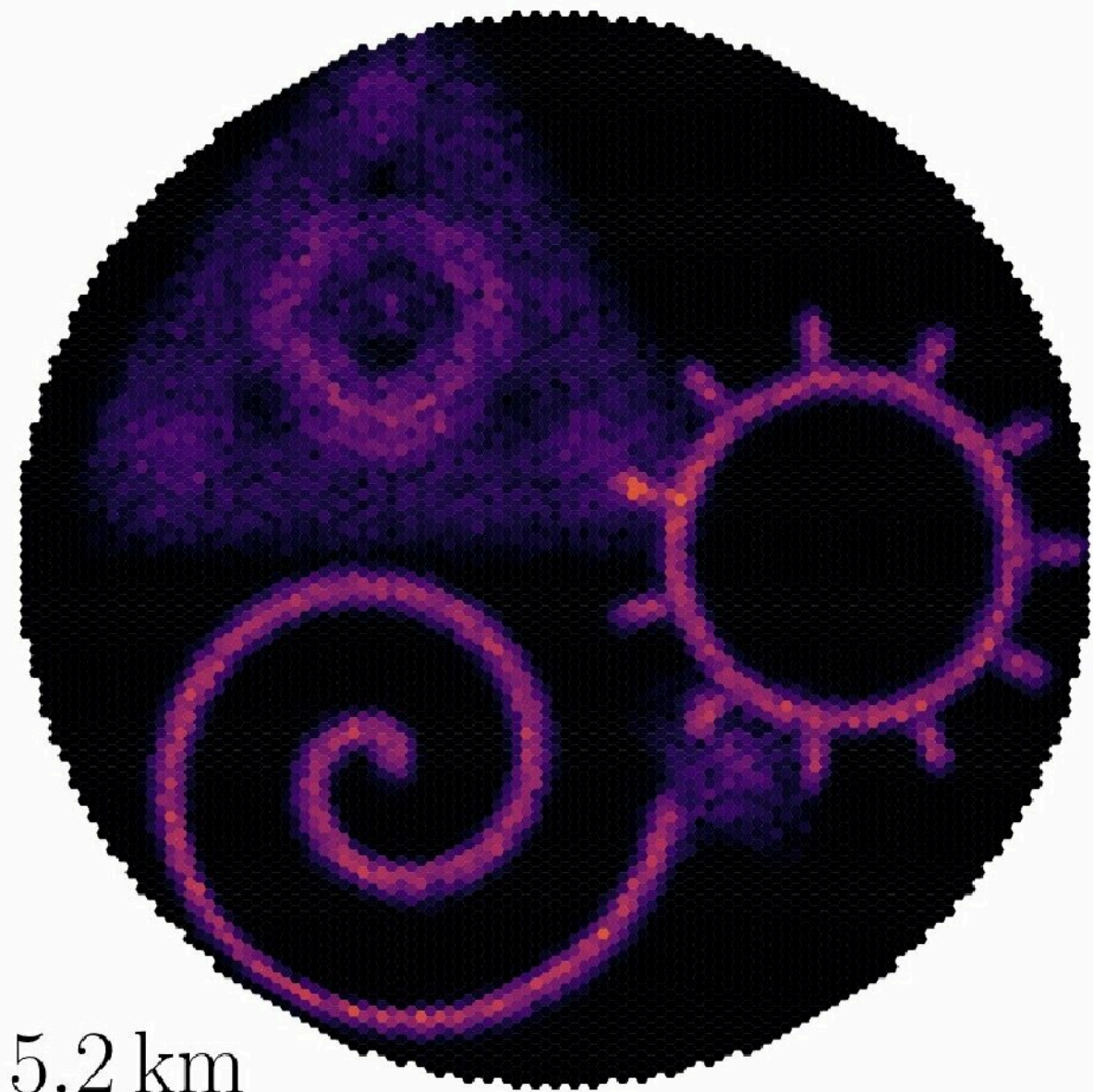


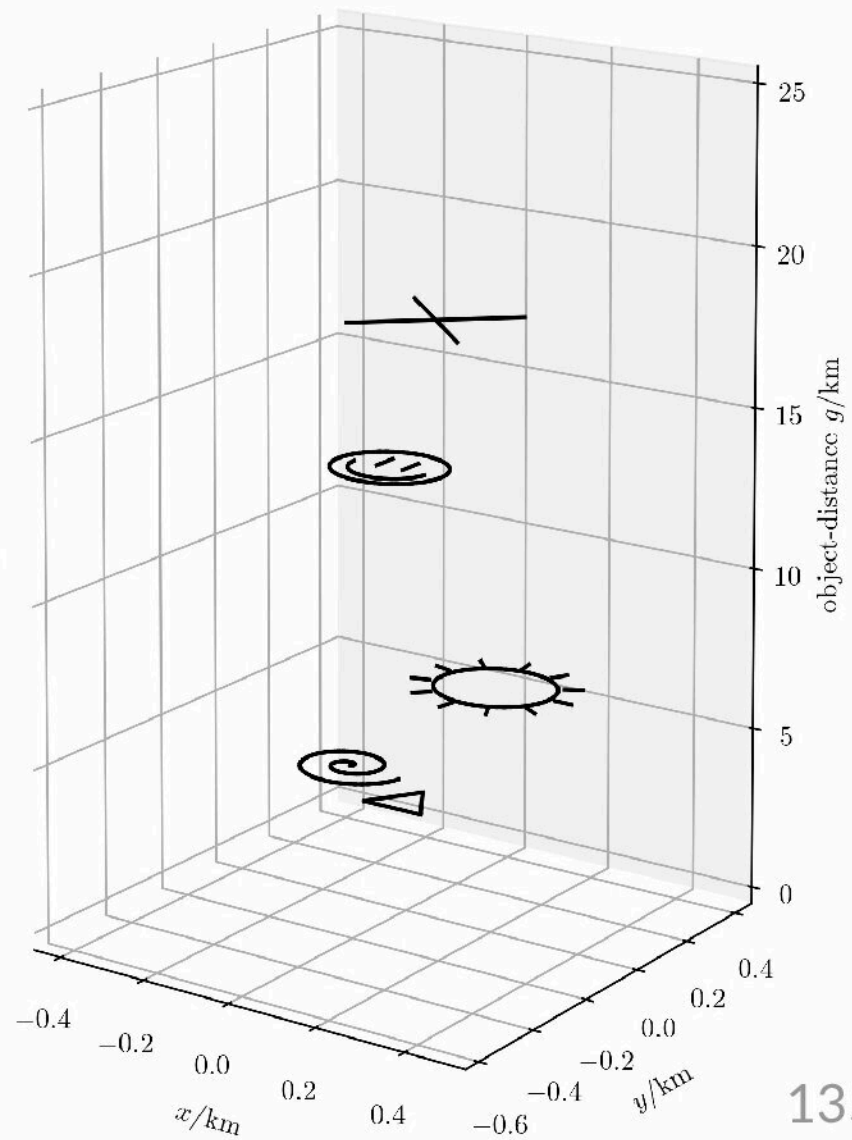
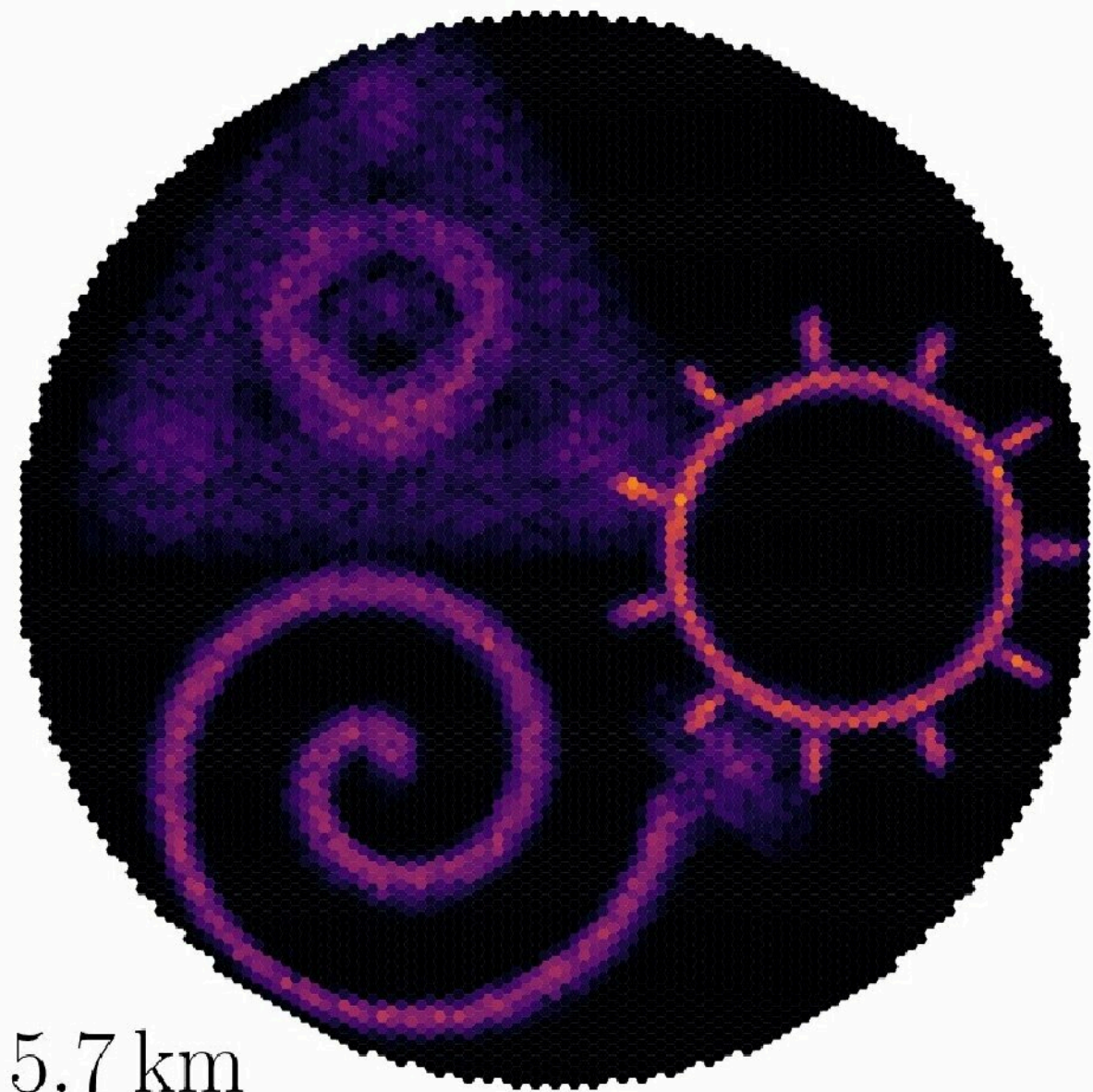


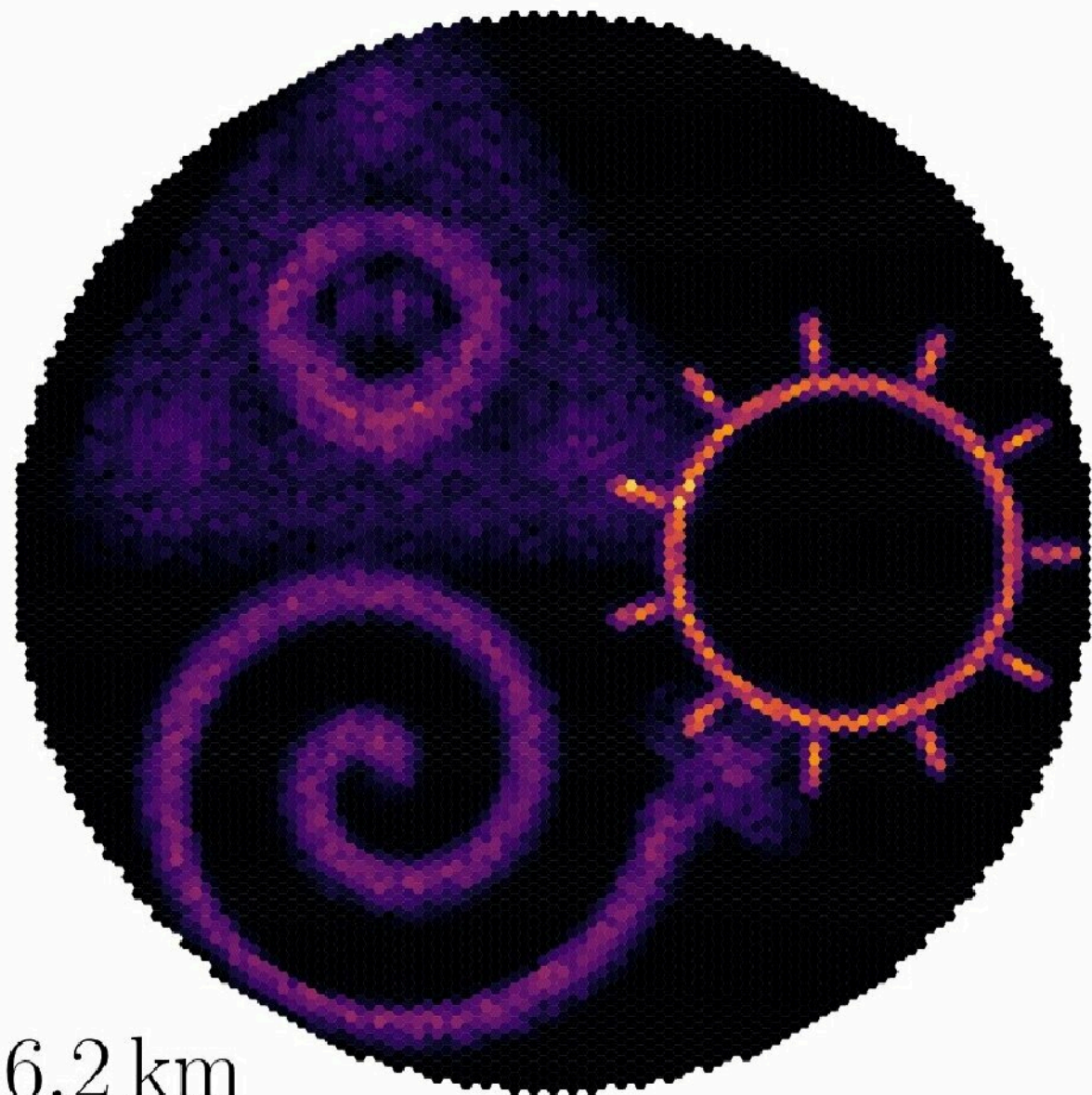




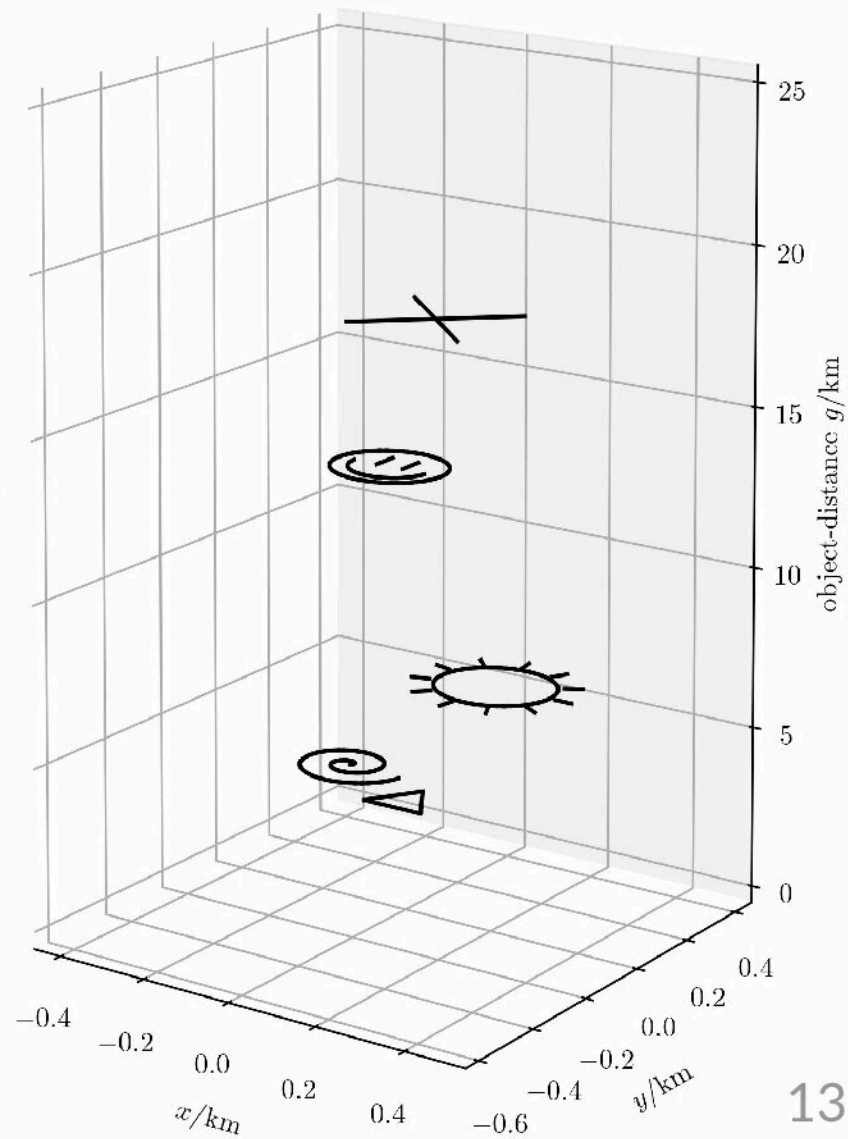


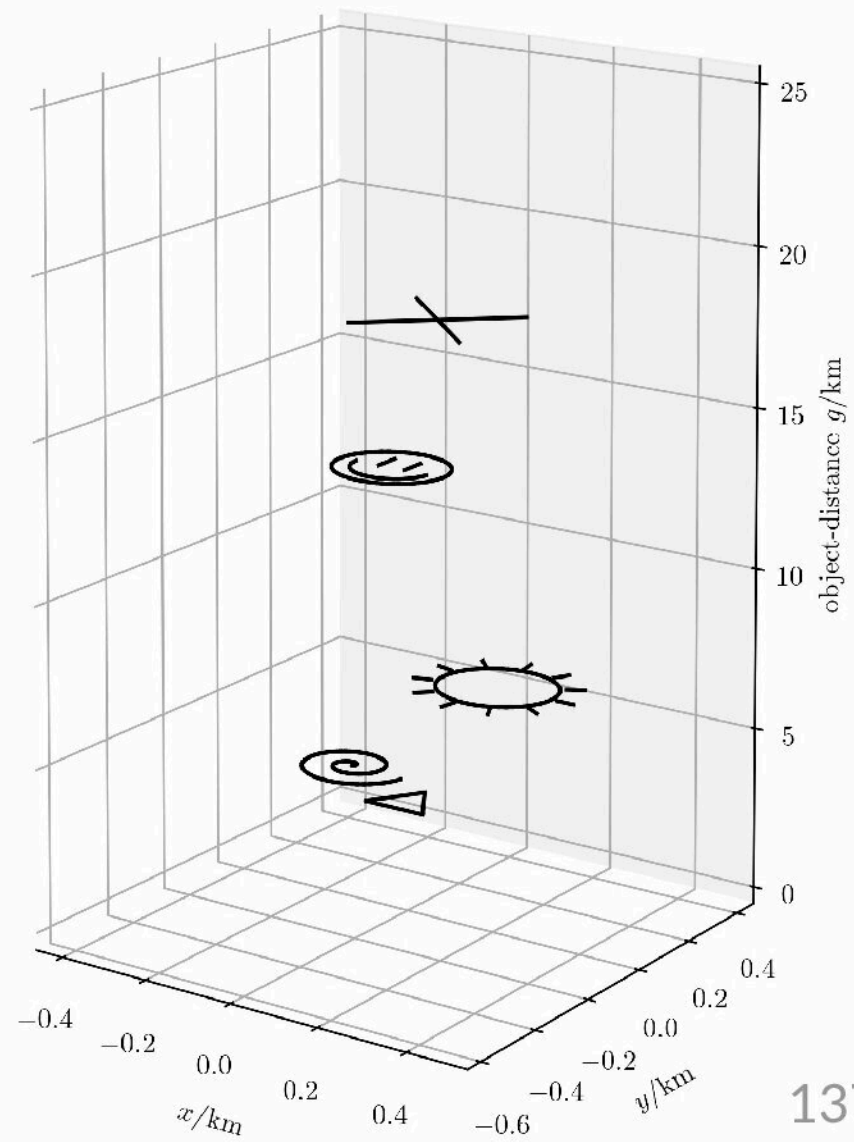
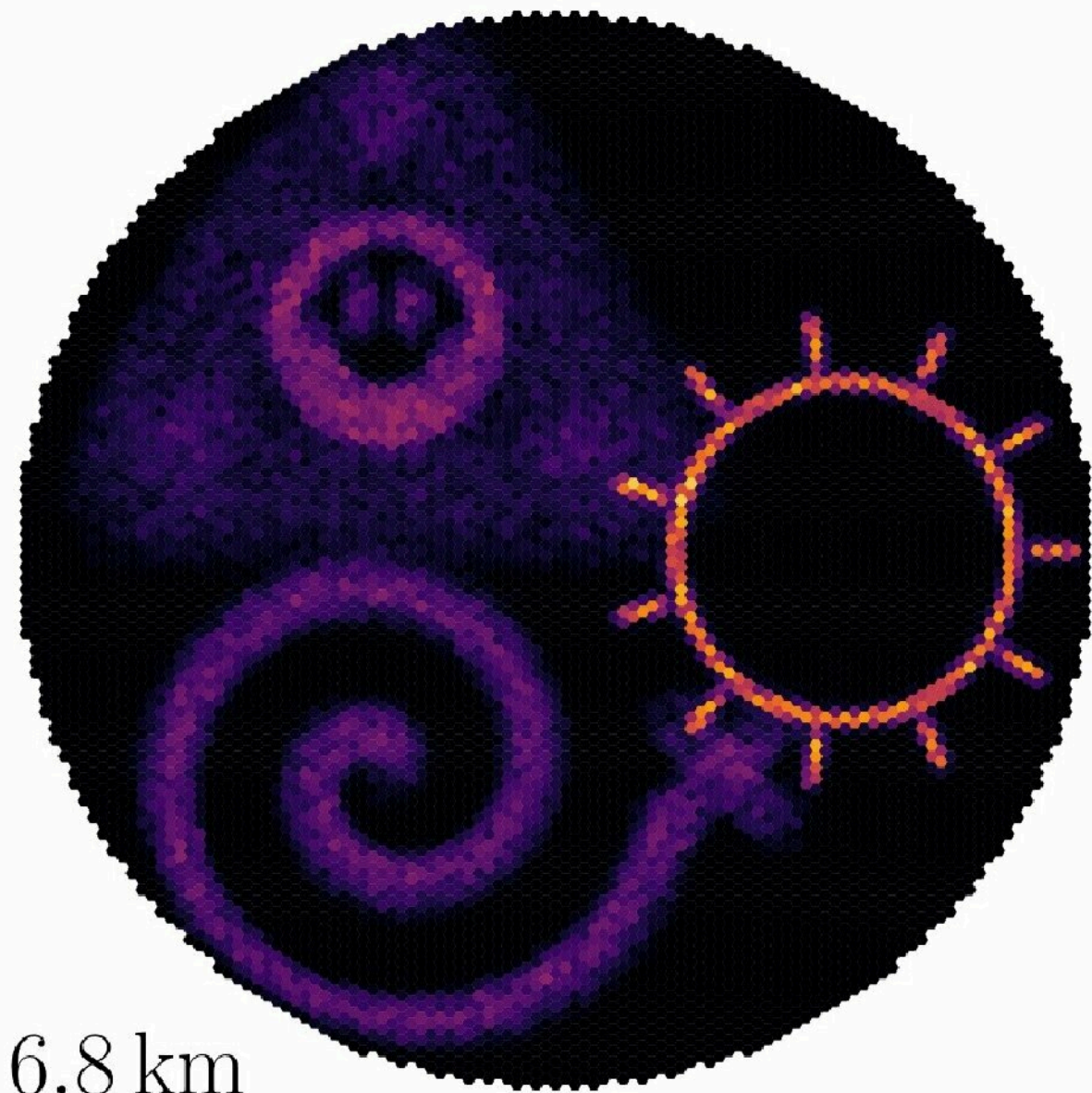


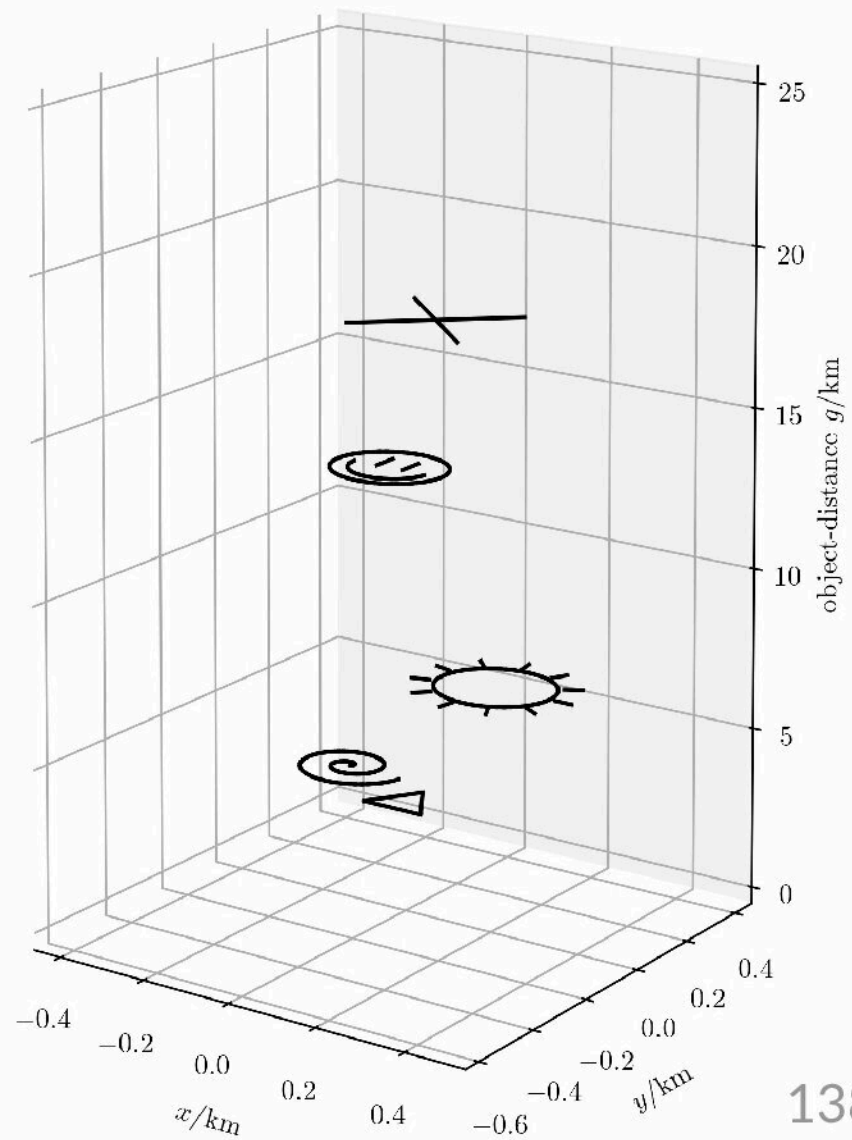
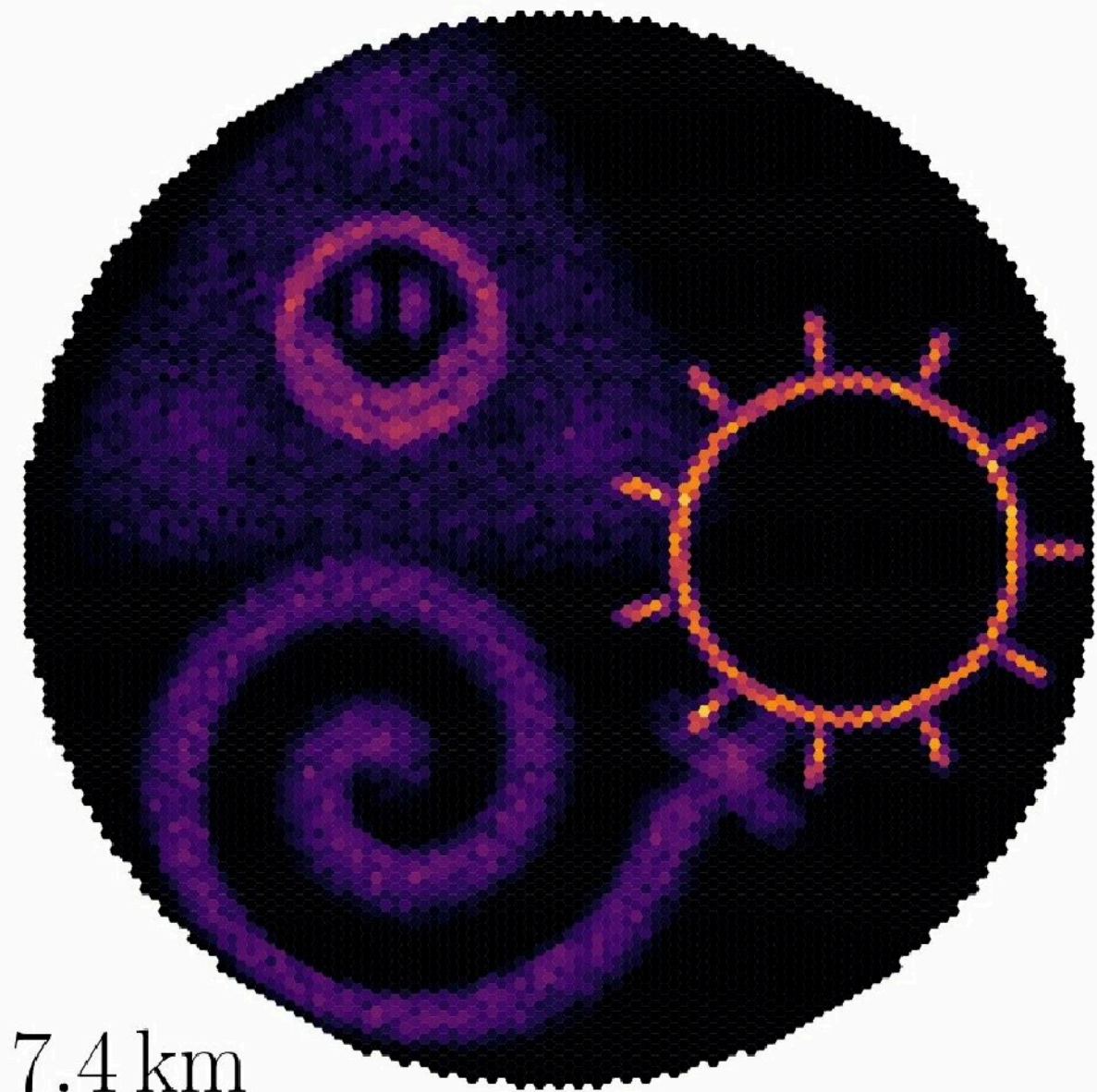


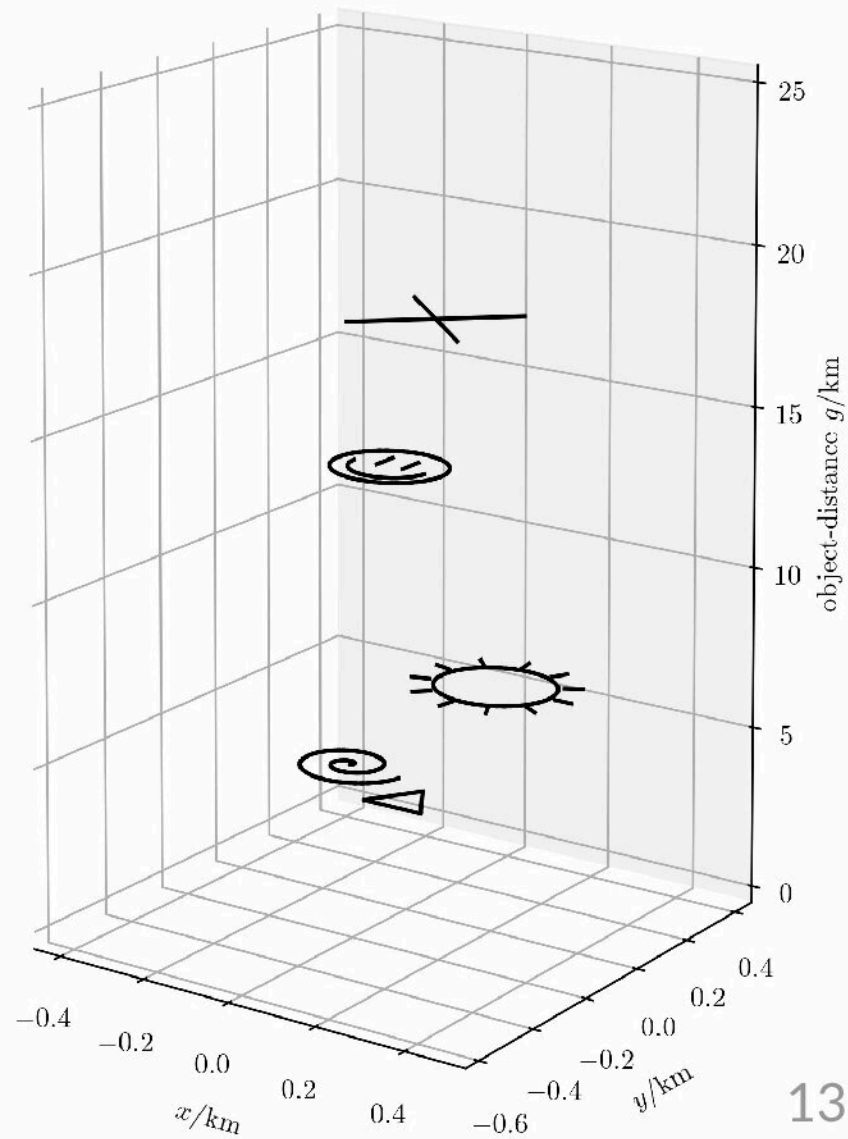
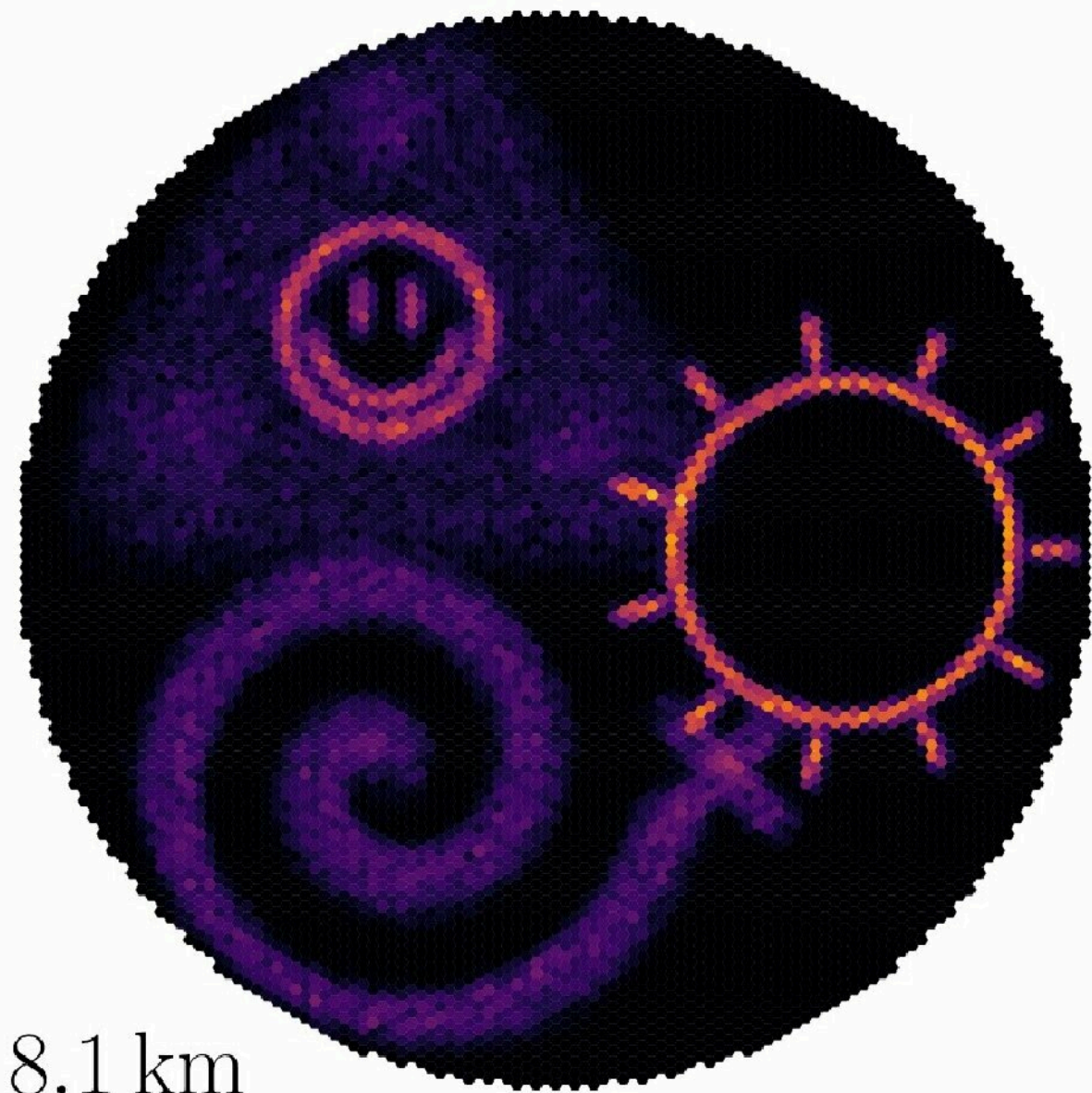


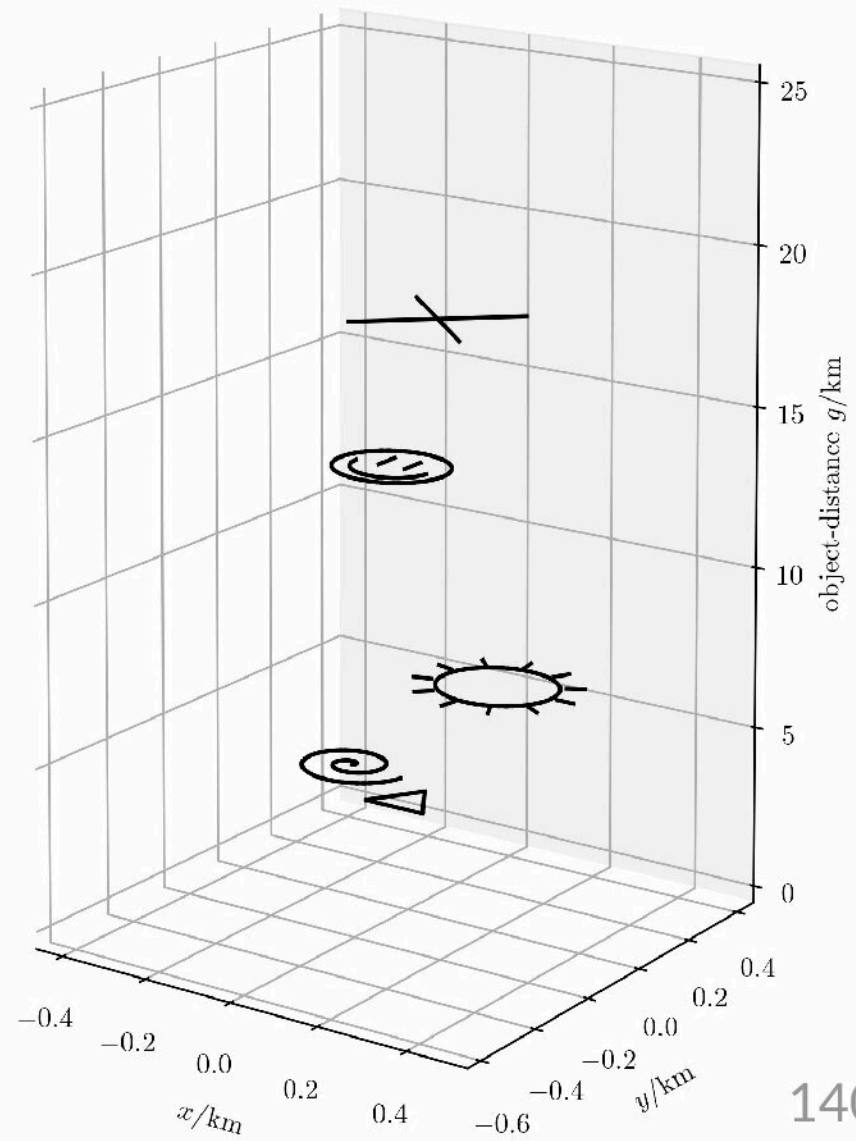
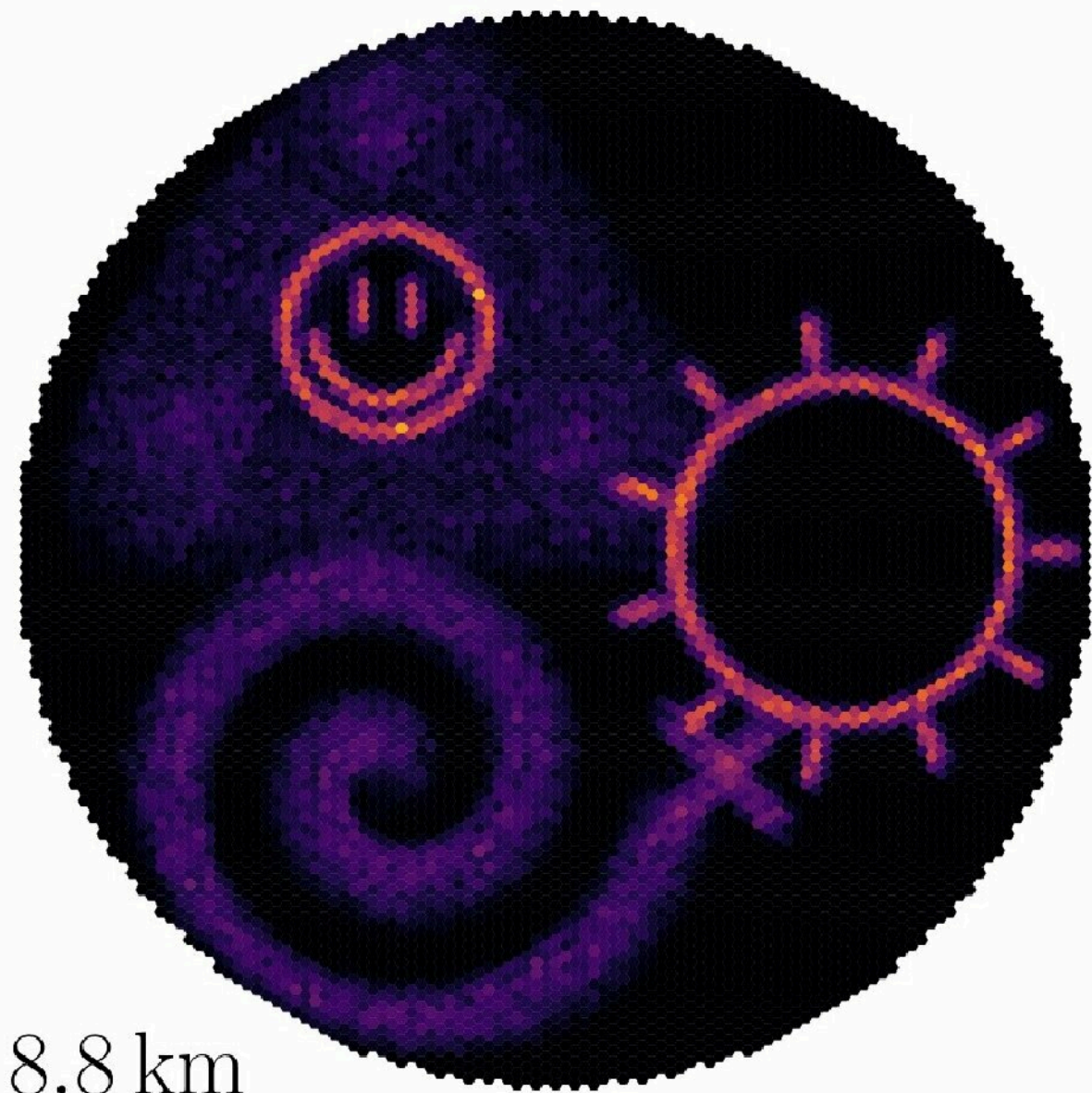
6.2 km

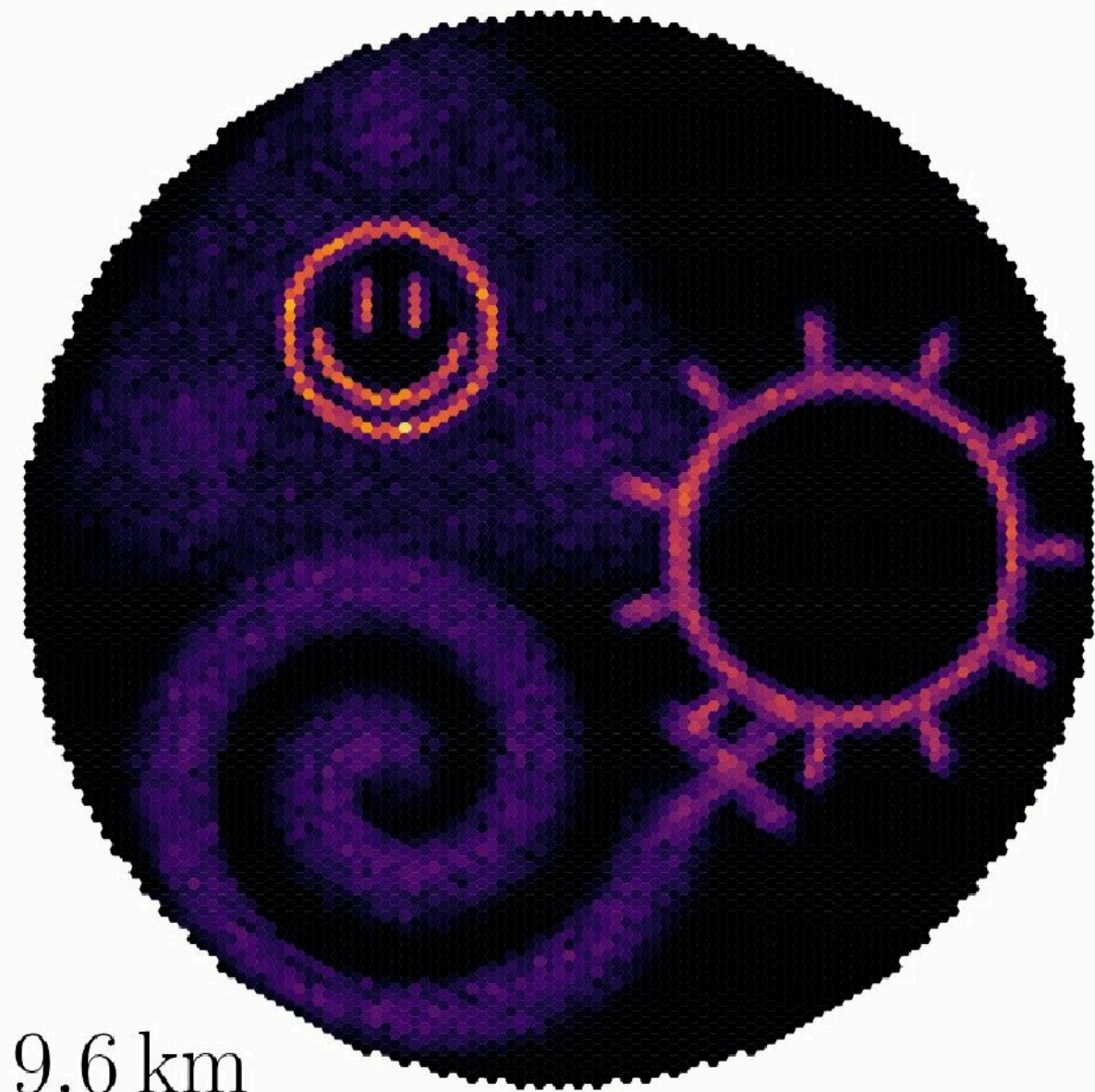




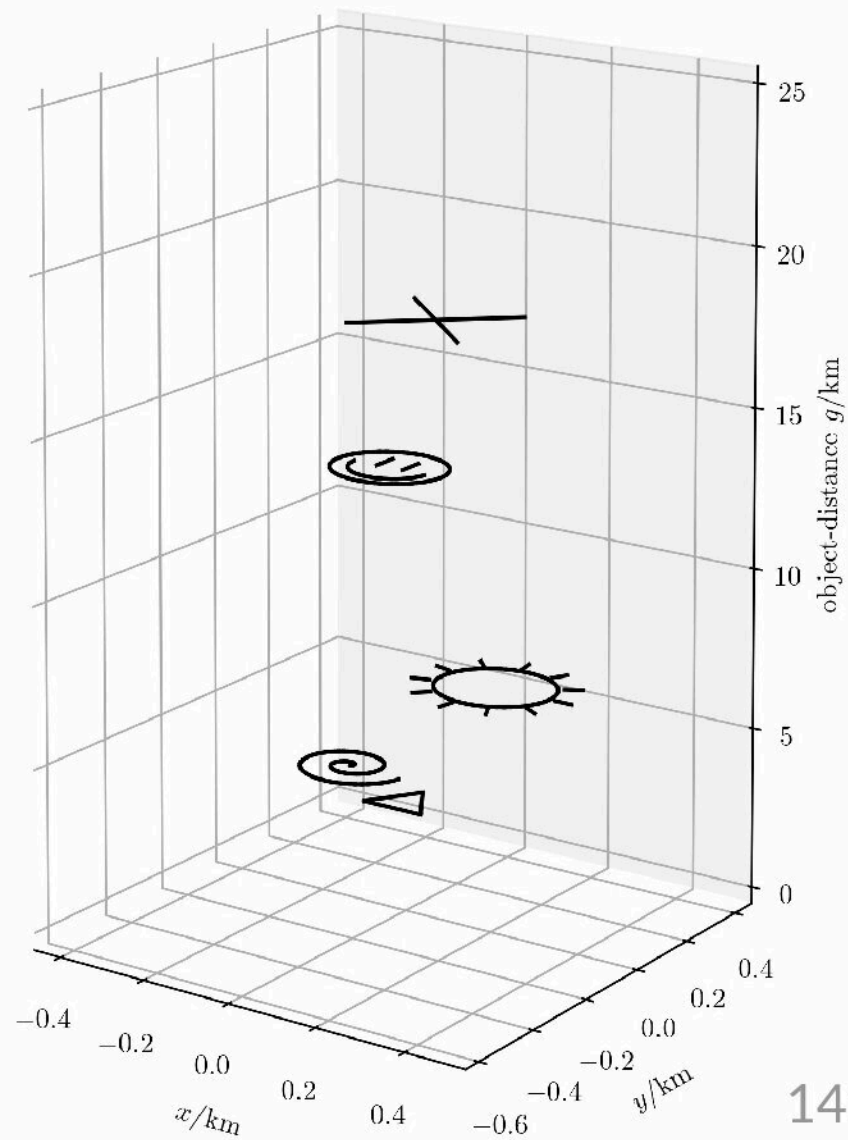




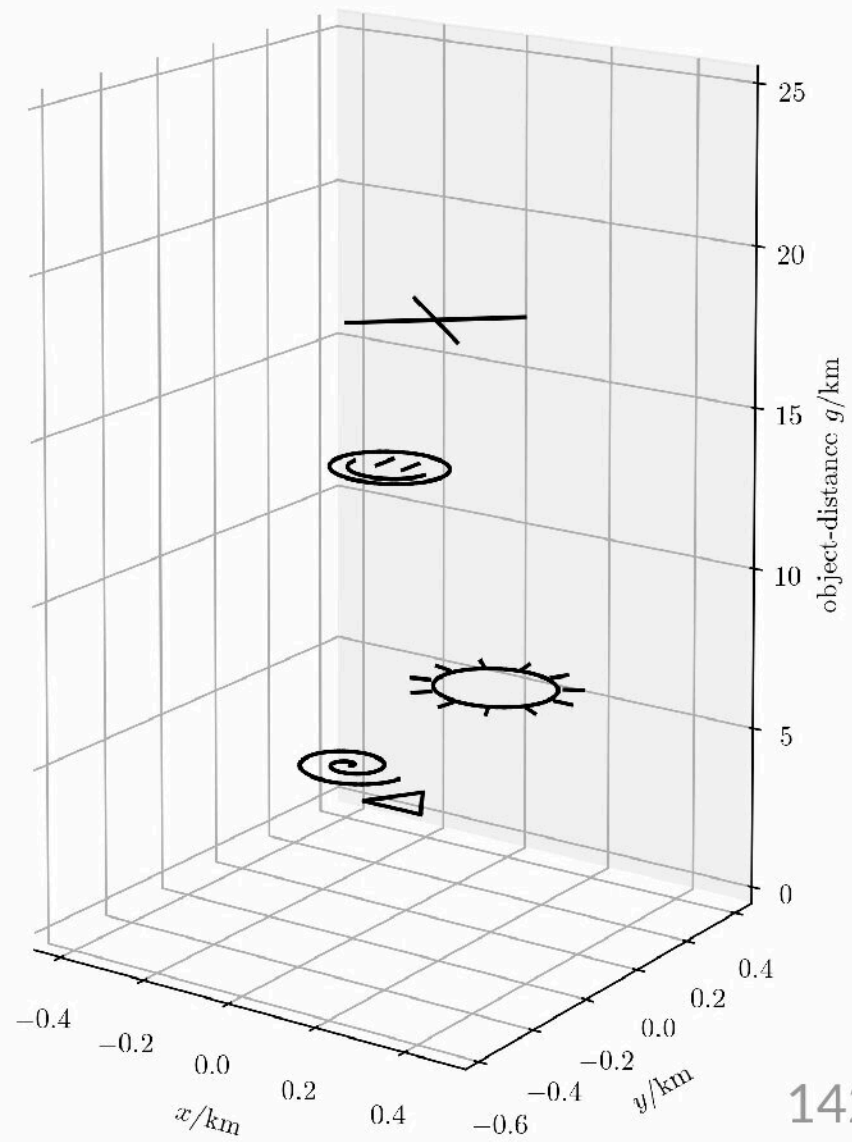
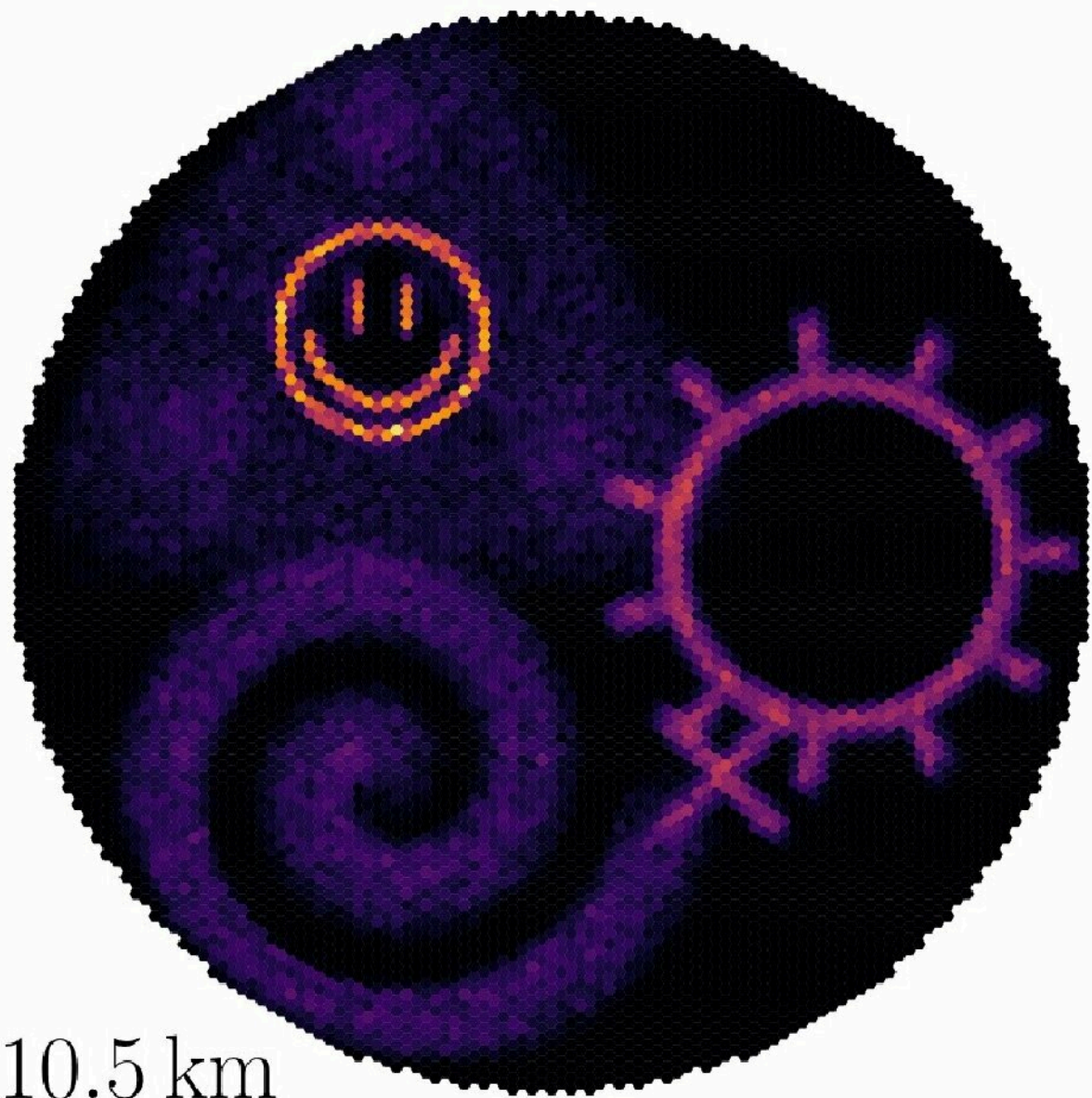


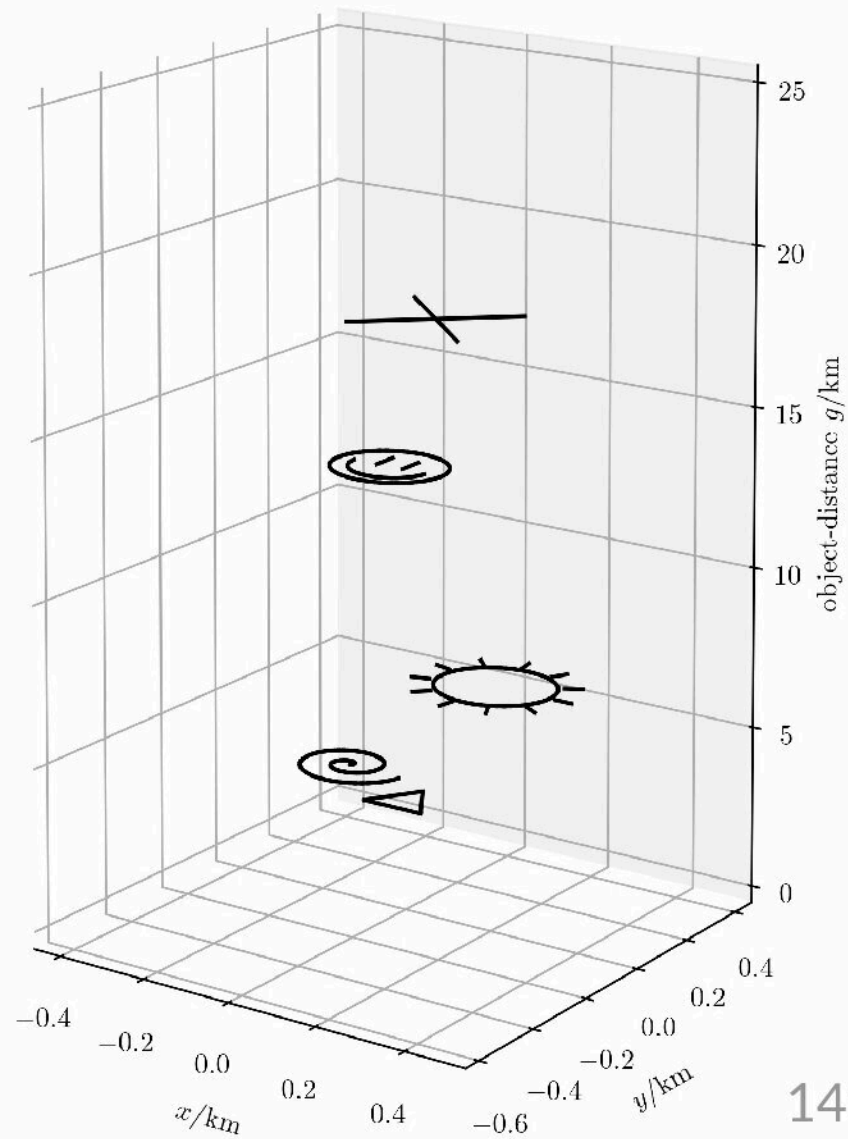
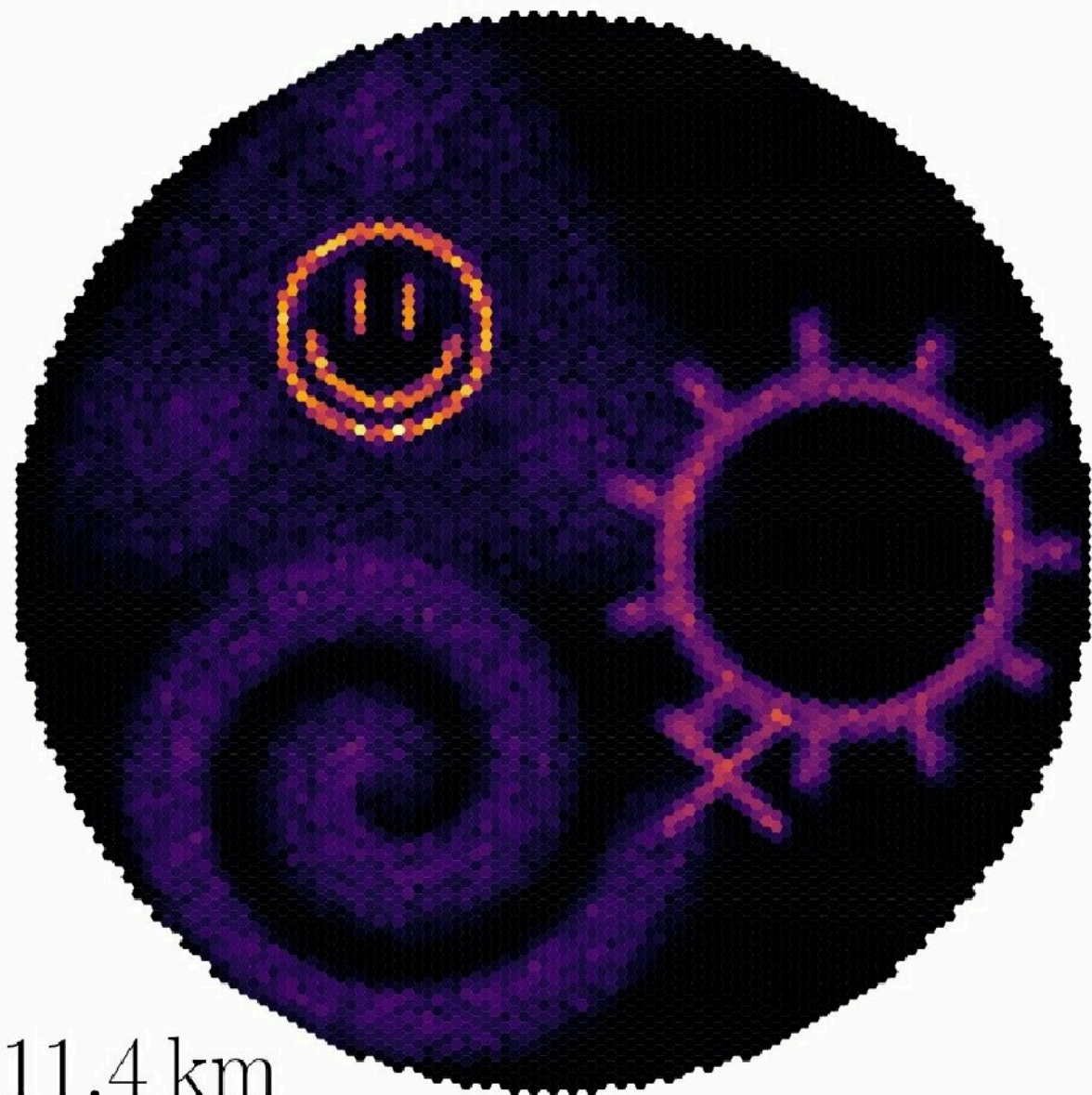


9.6 km

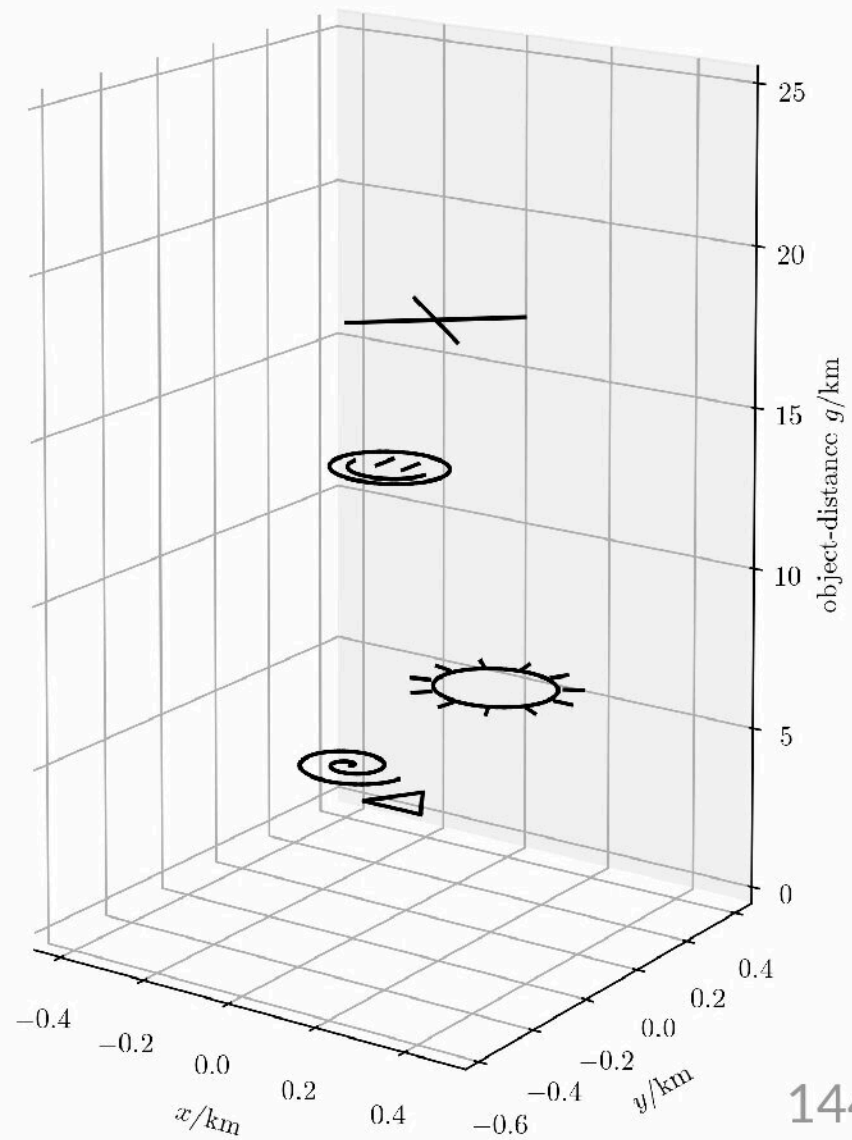
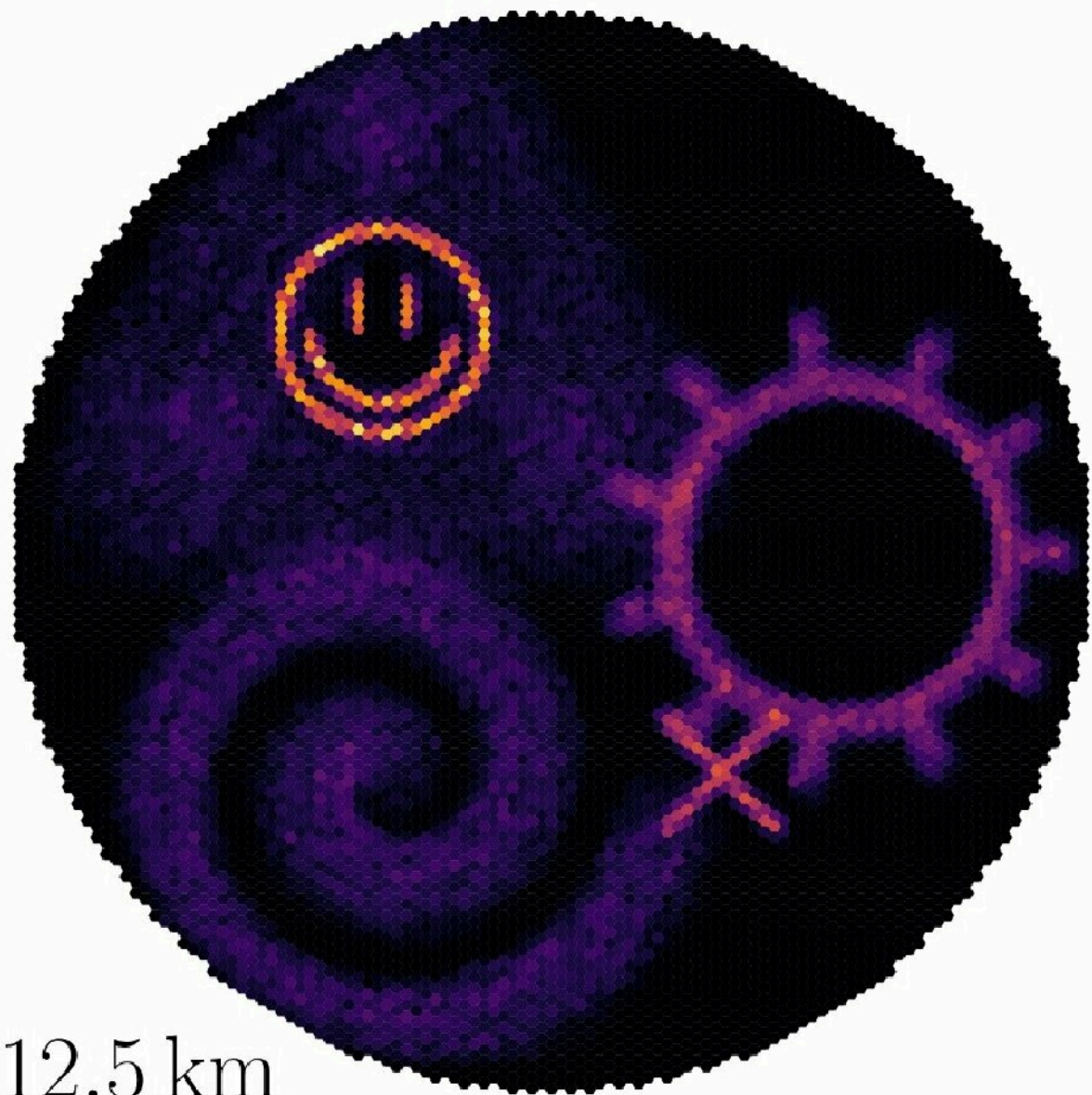


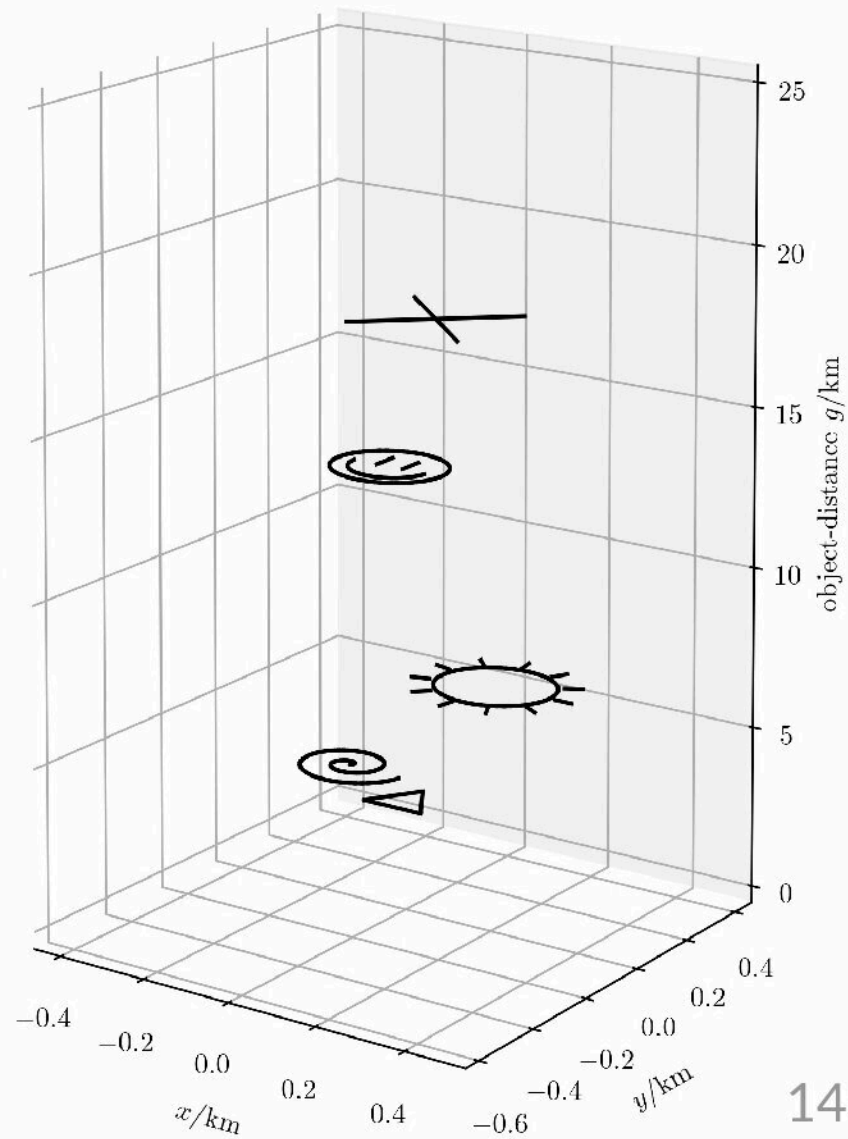
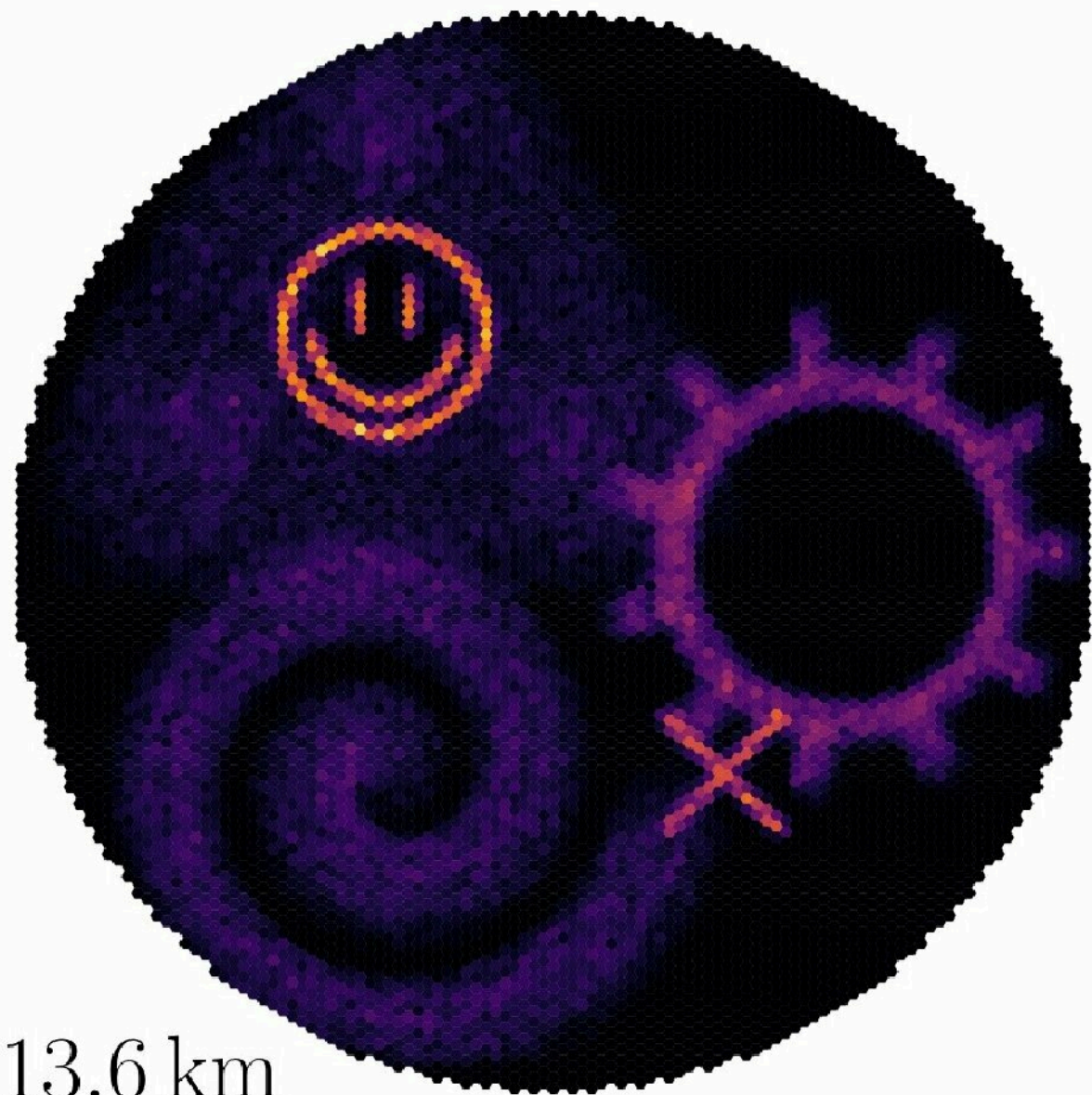
10.5 km



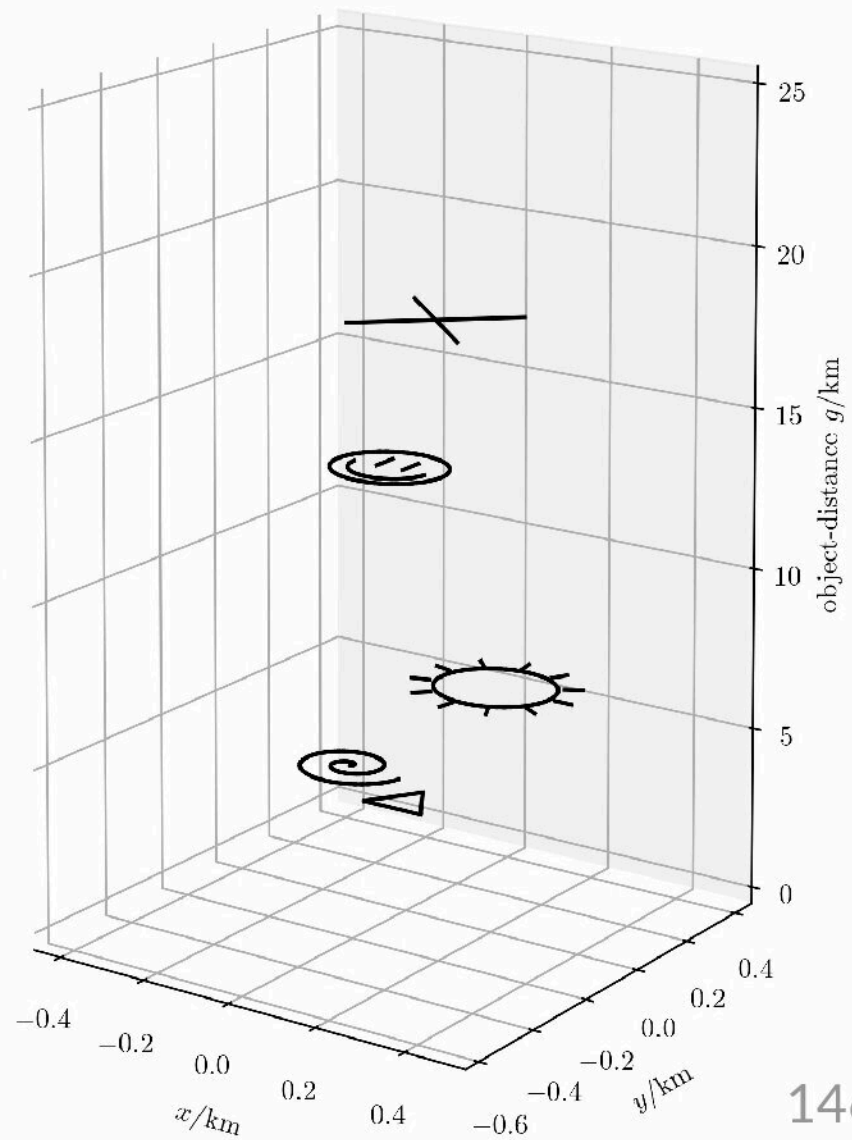
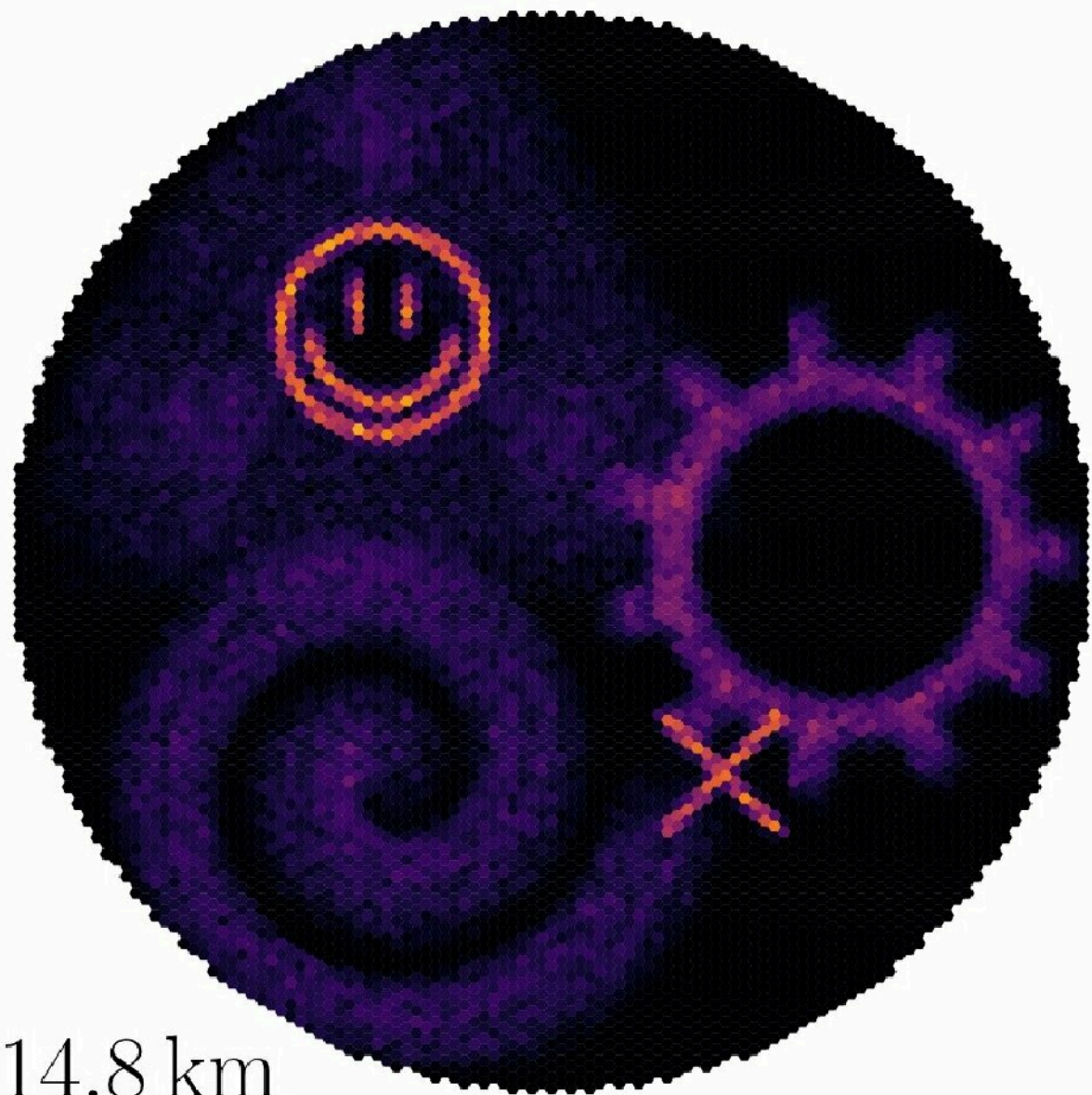


12.5 km

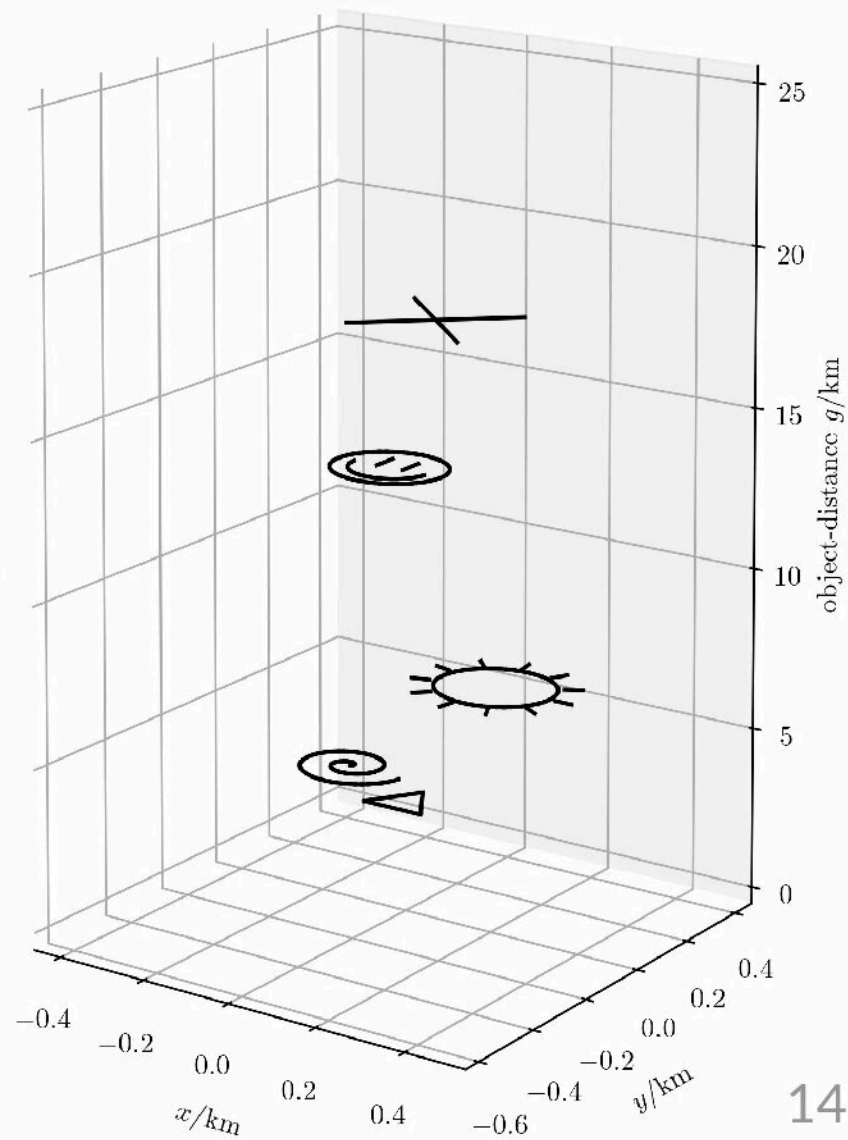
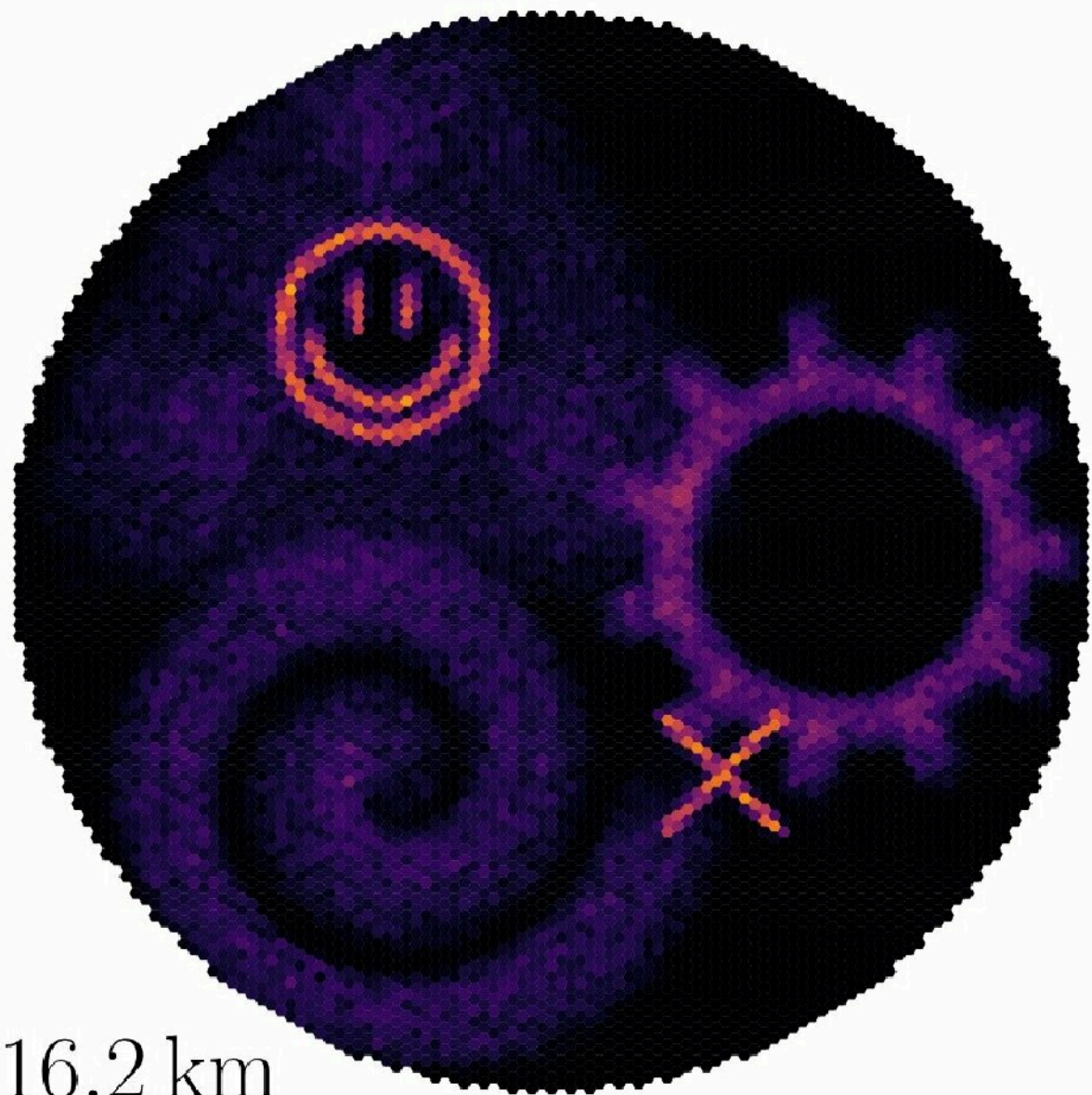


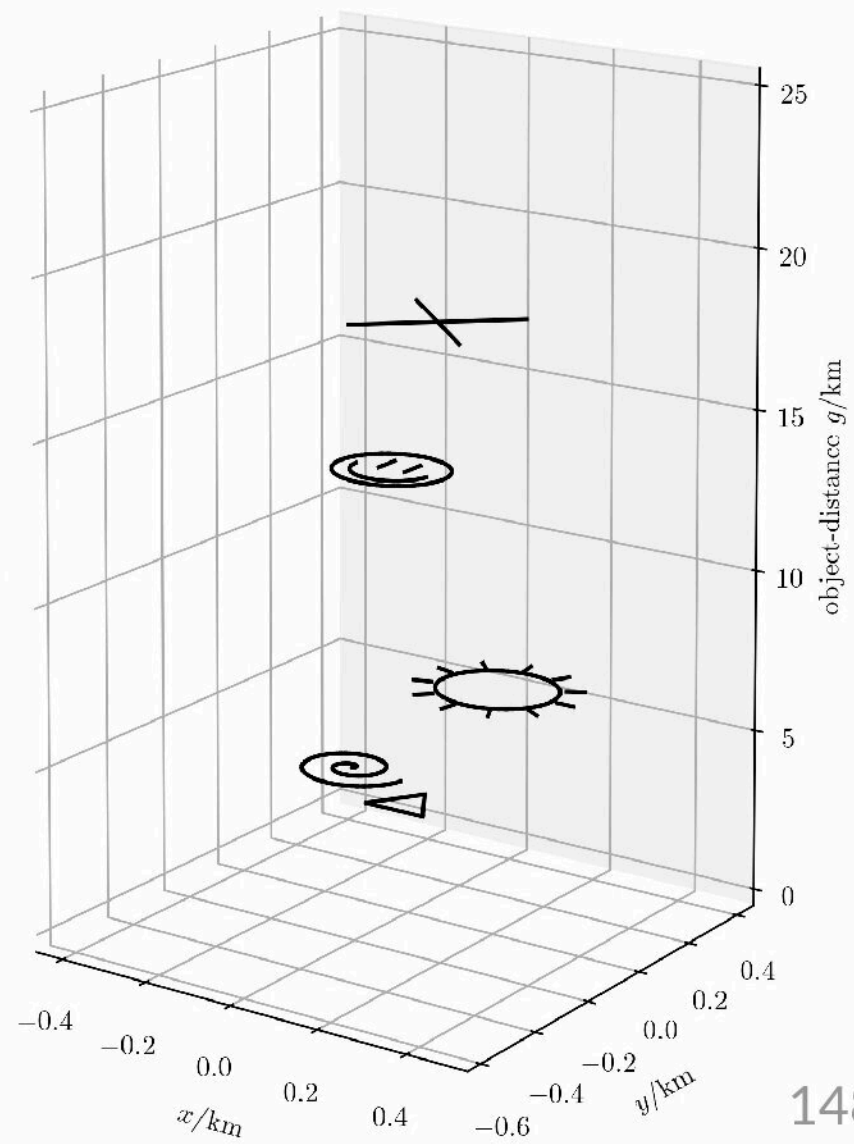
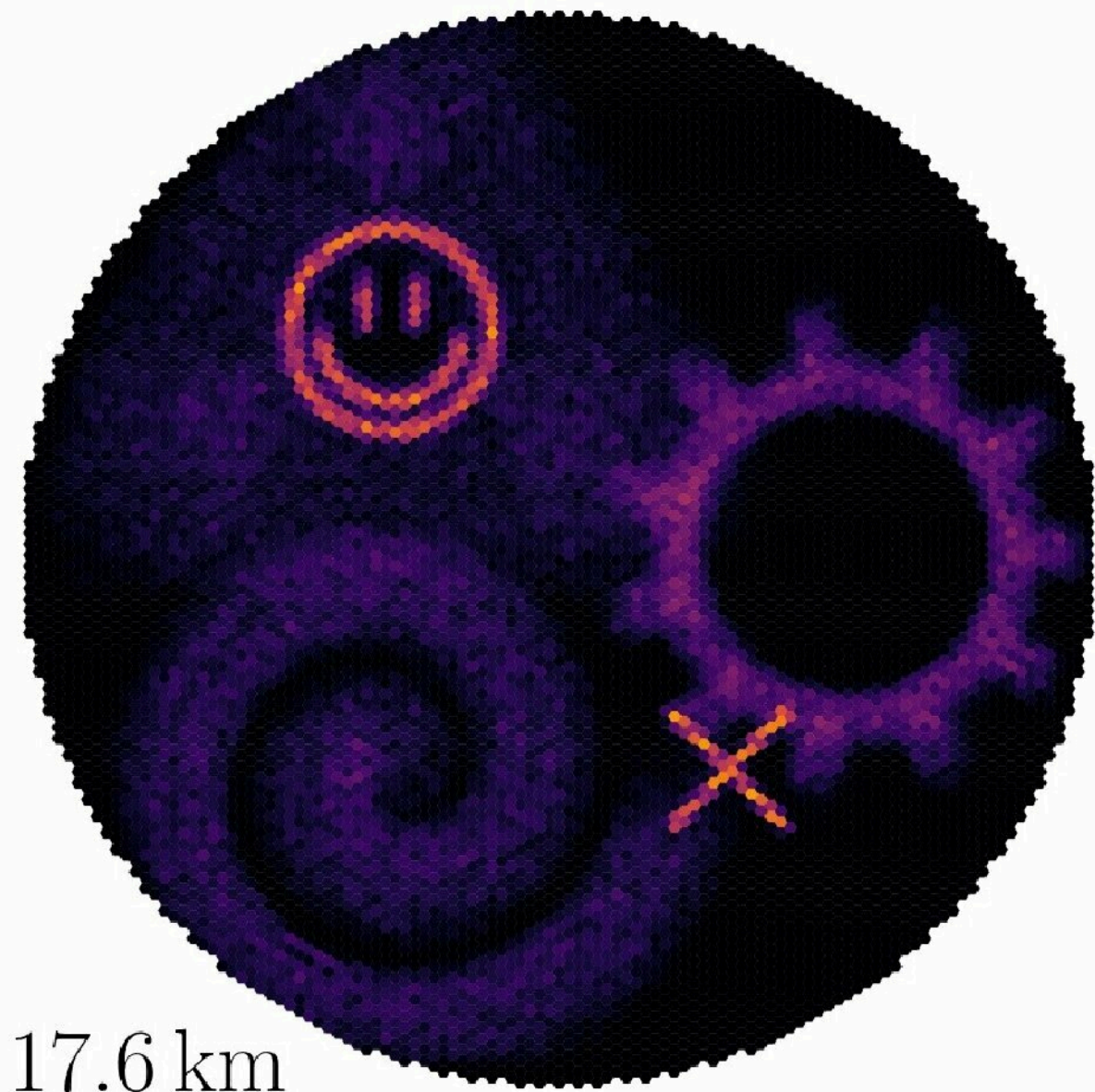


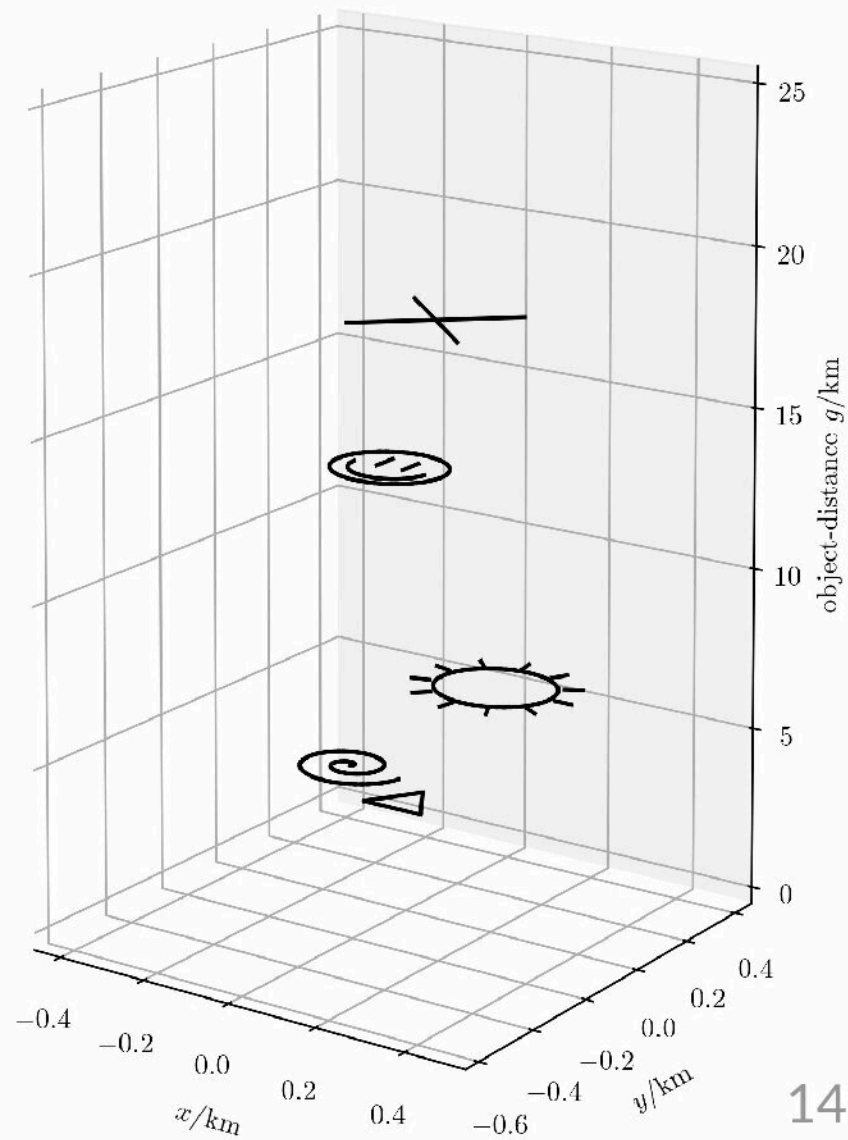
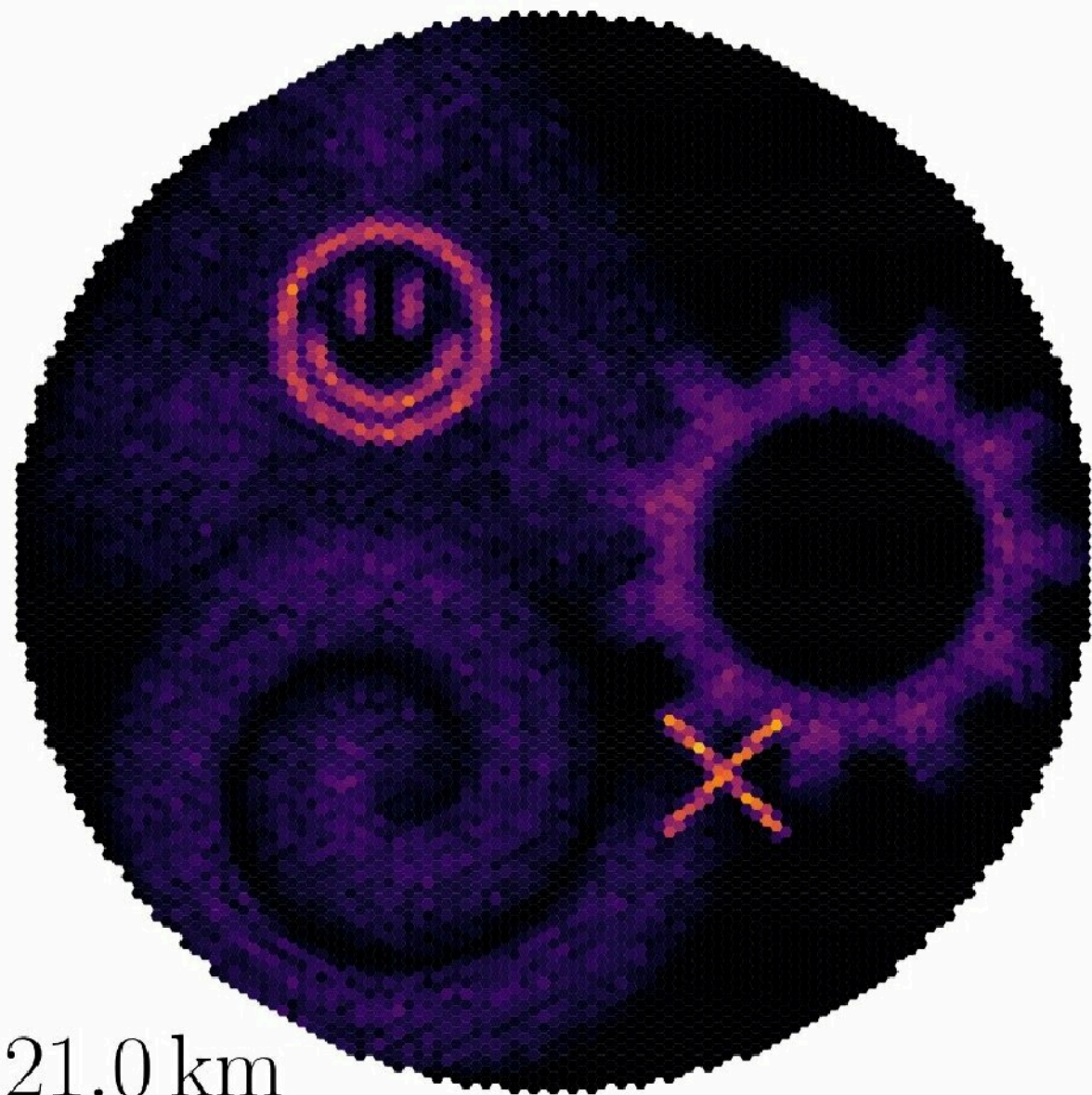
14.8 km

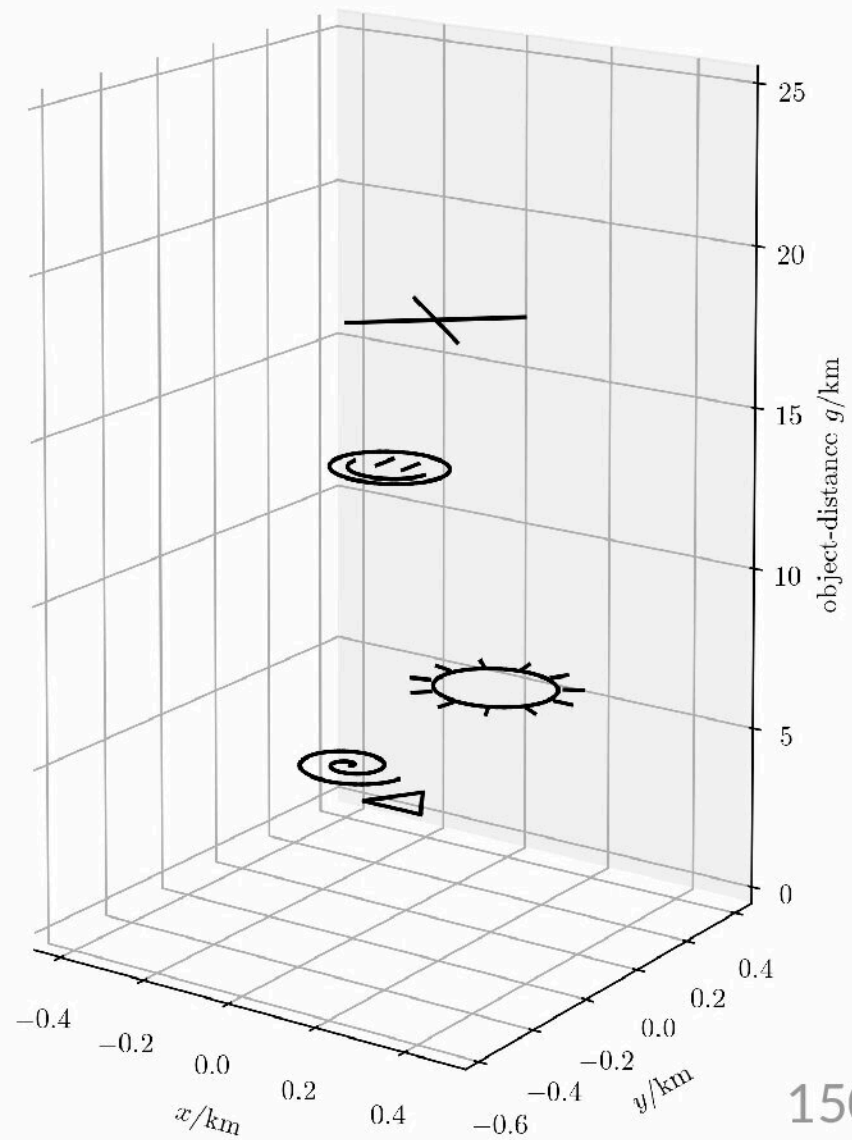
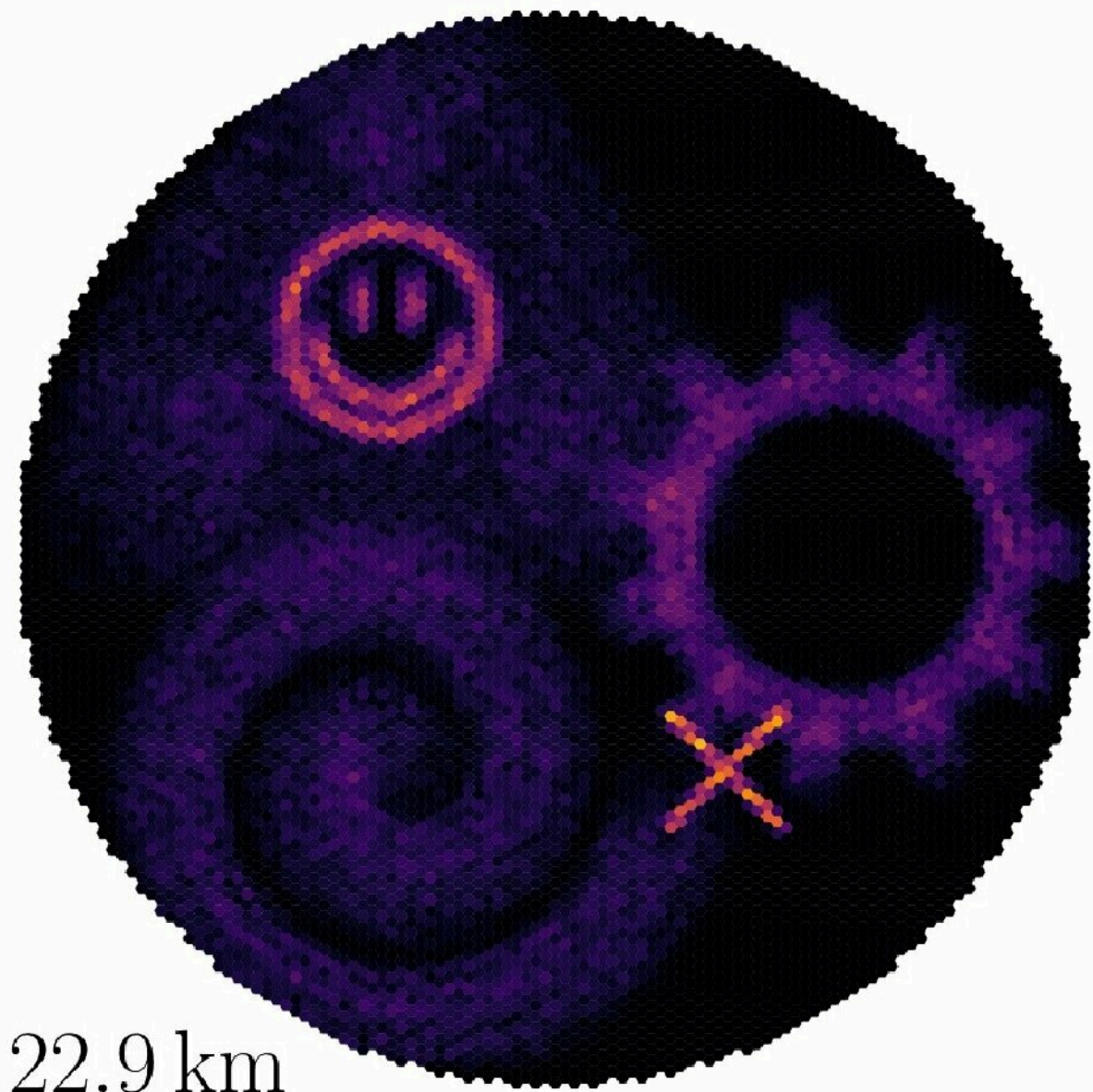


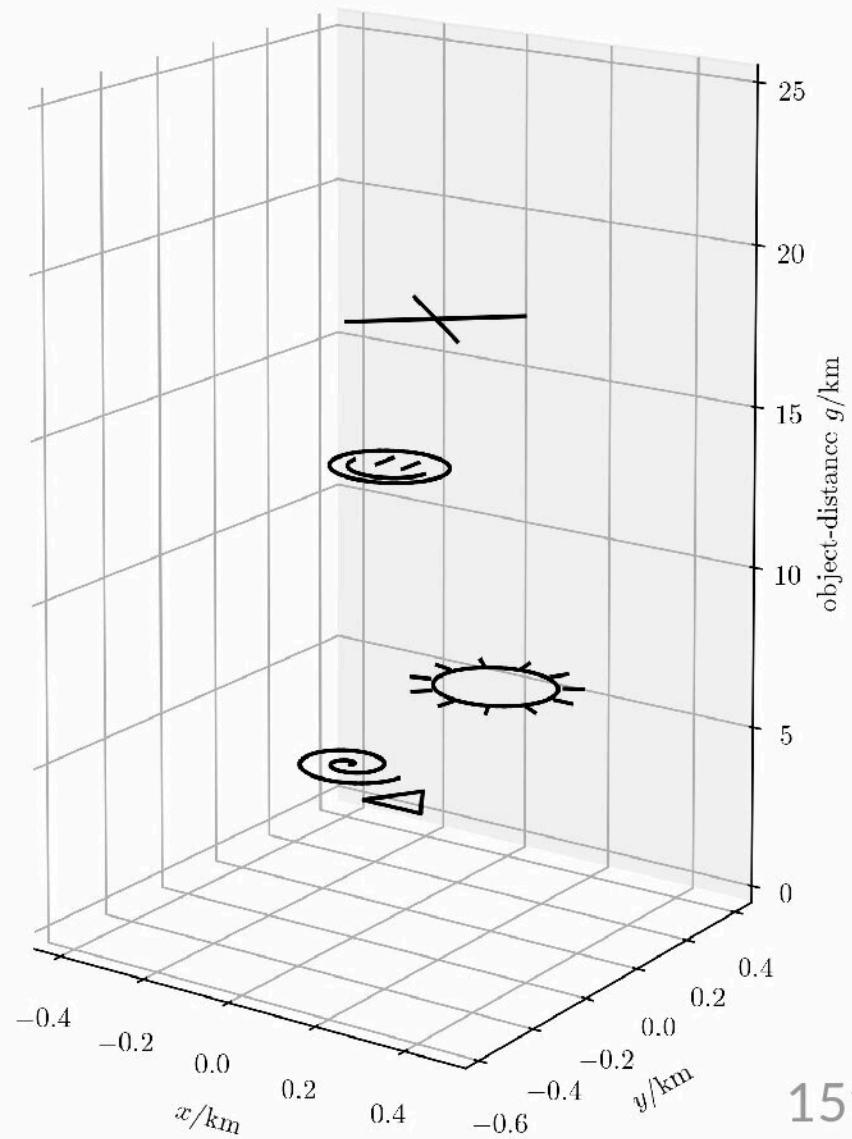
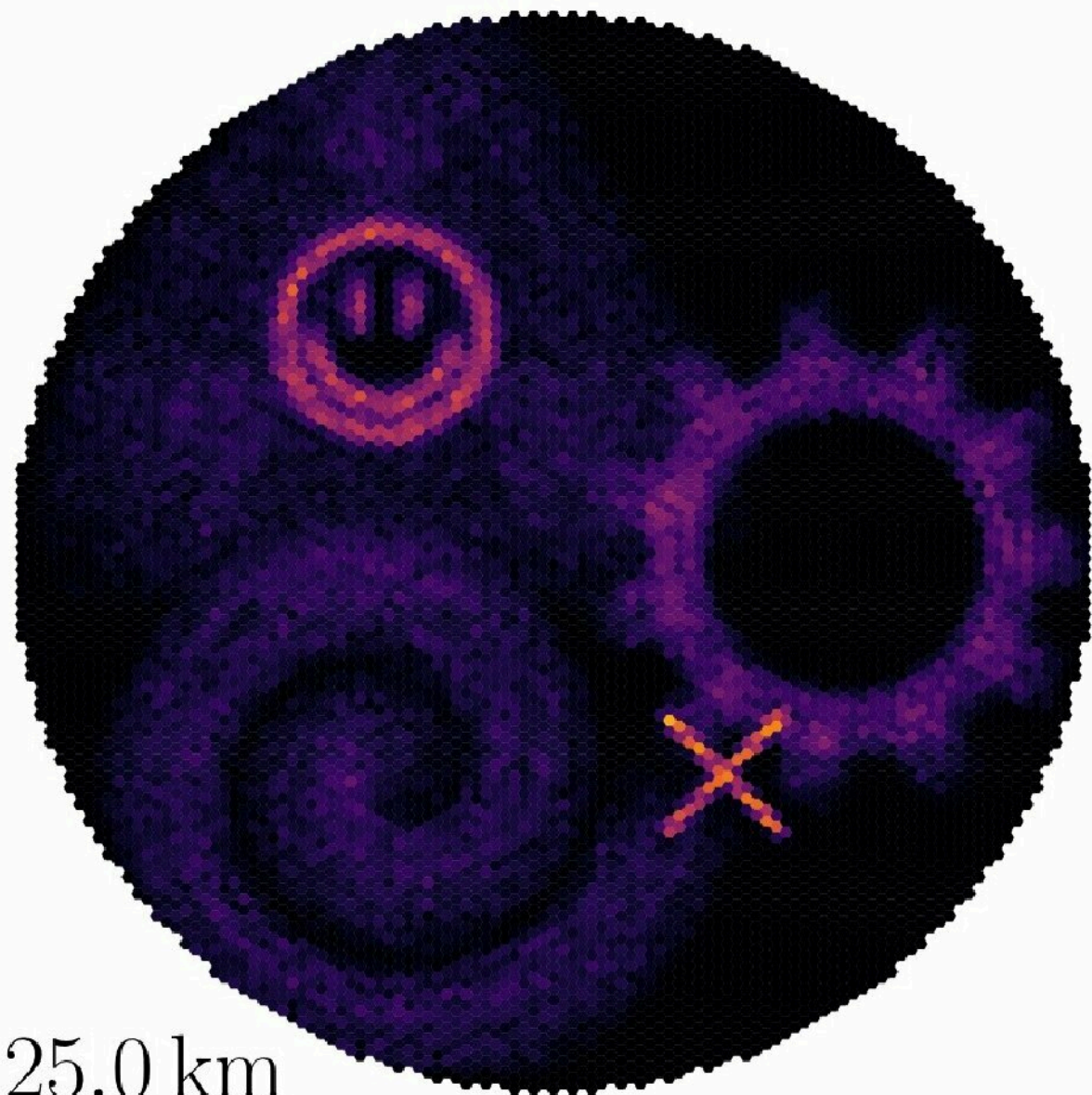
16.2 km

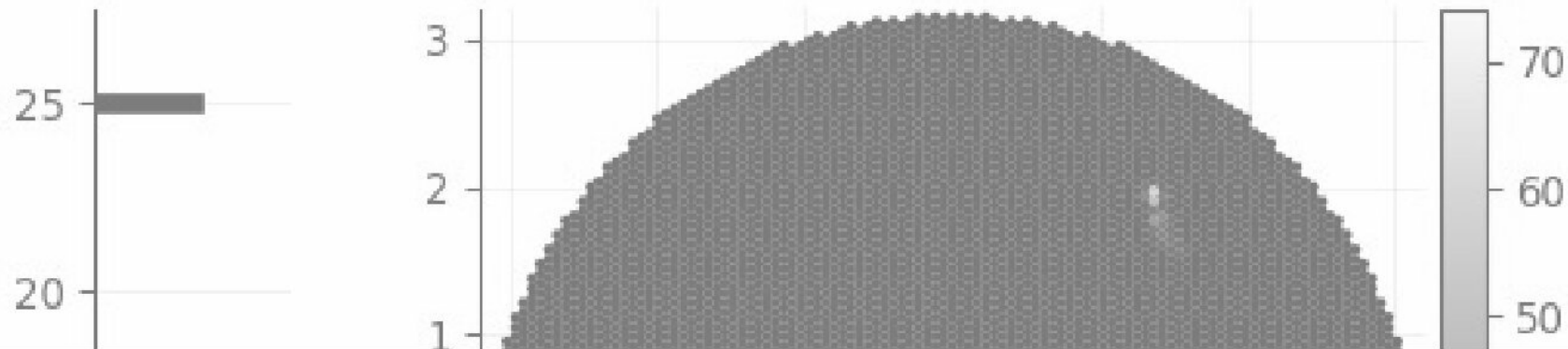




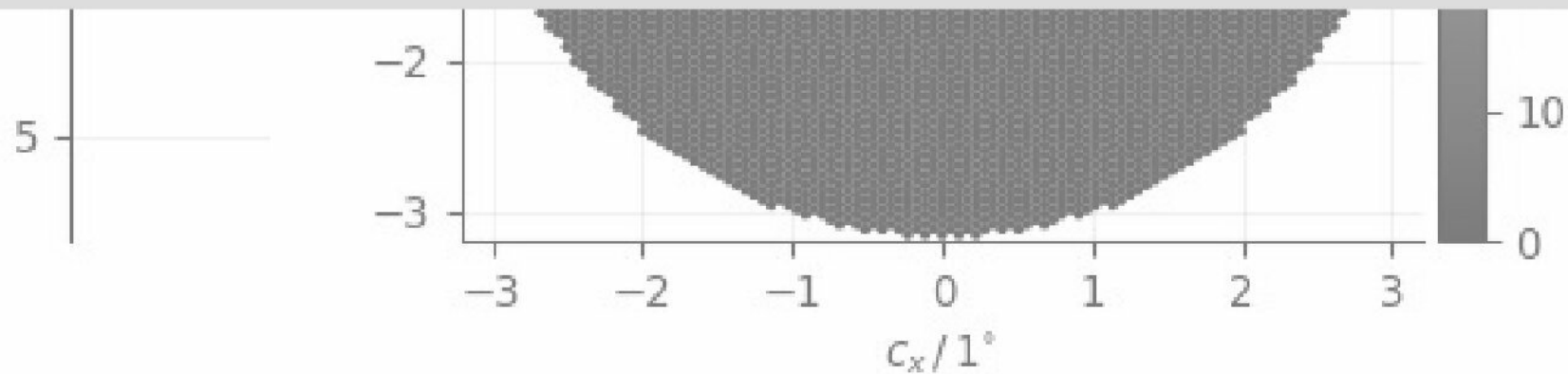


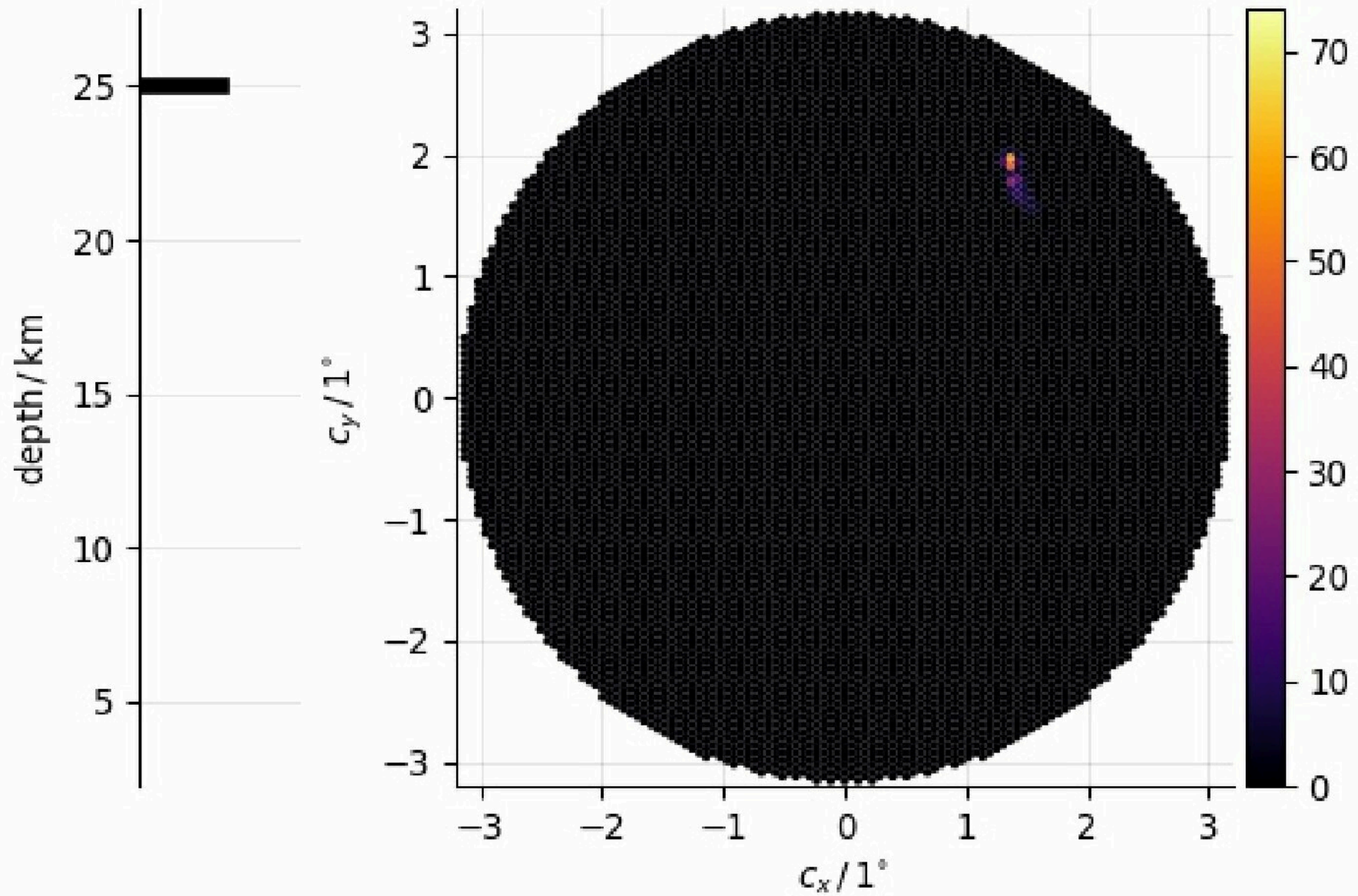


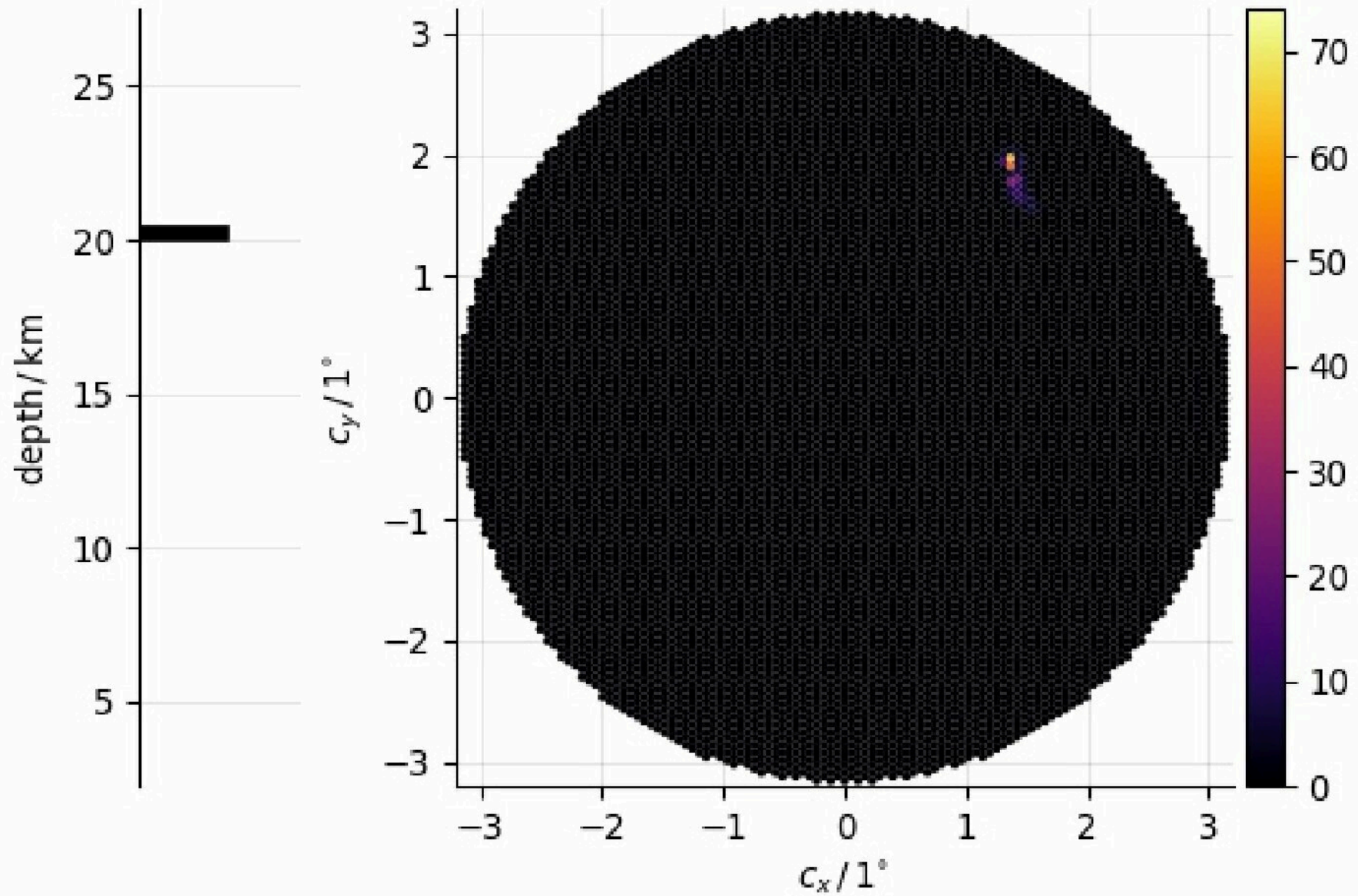


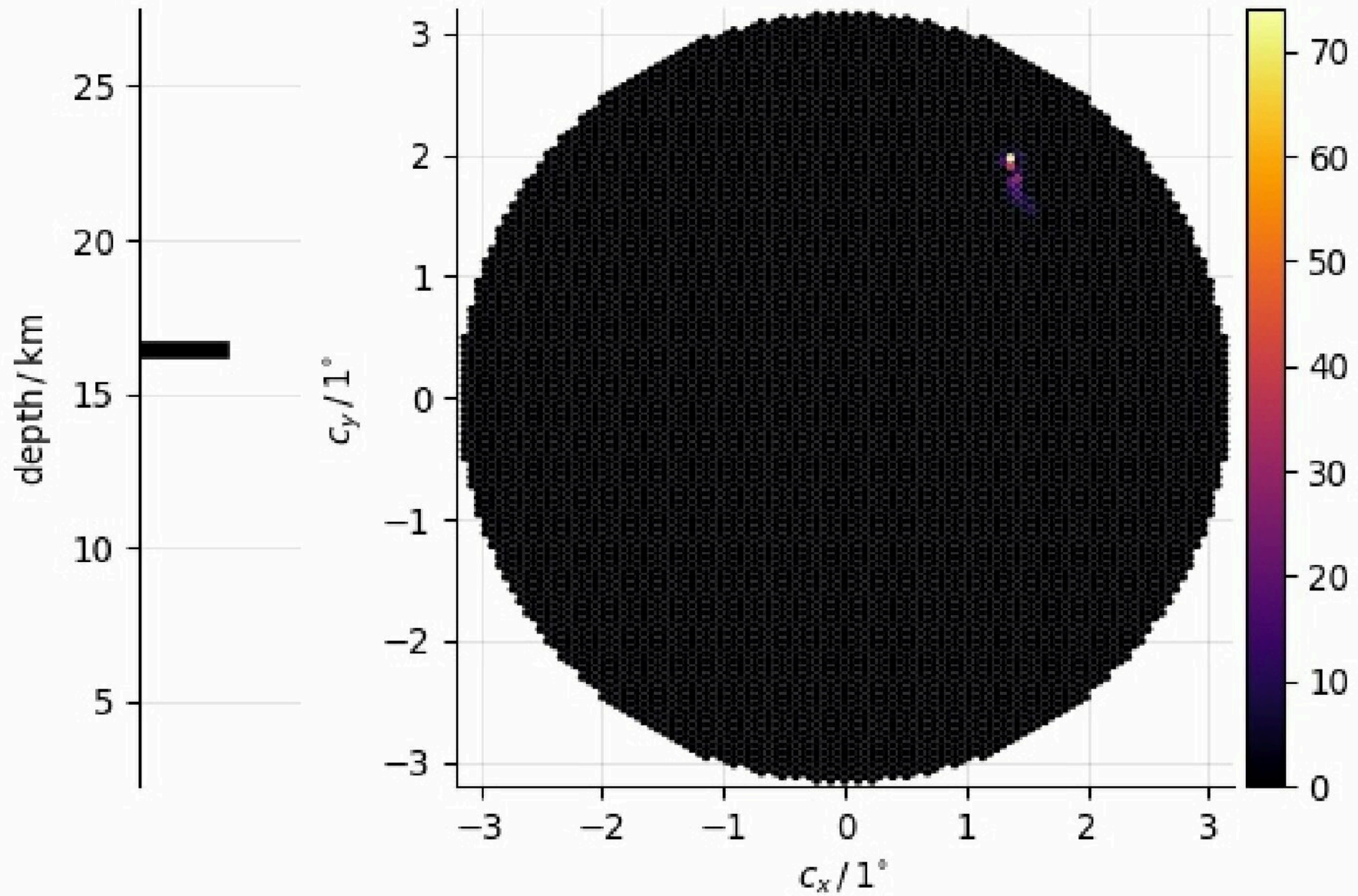


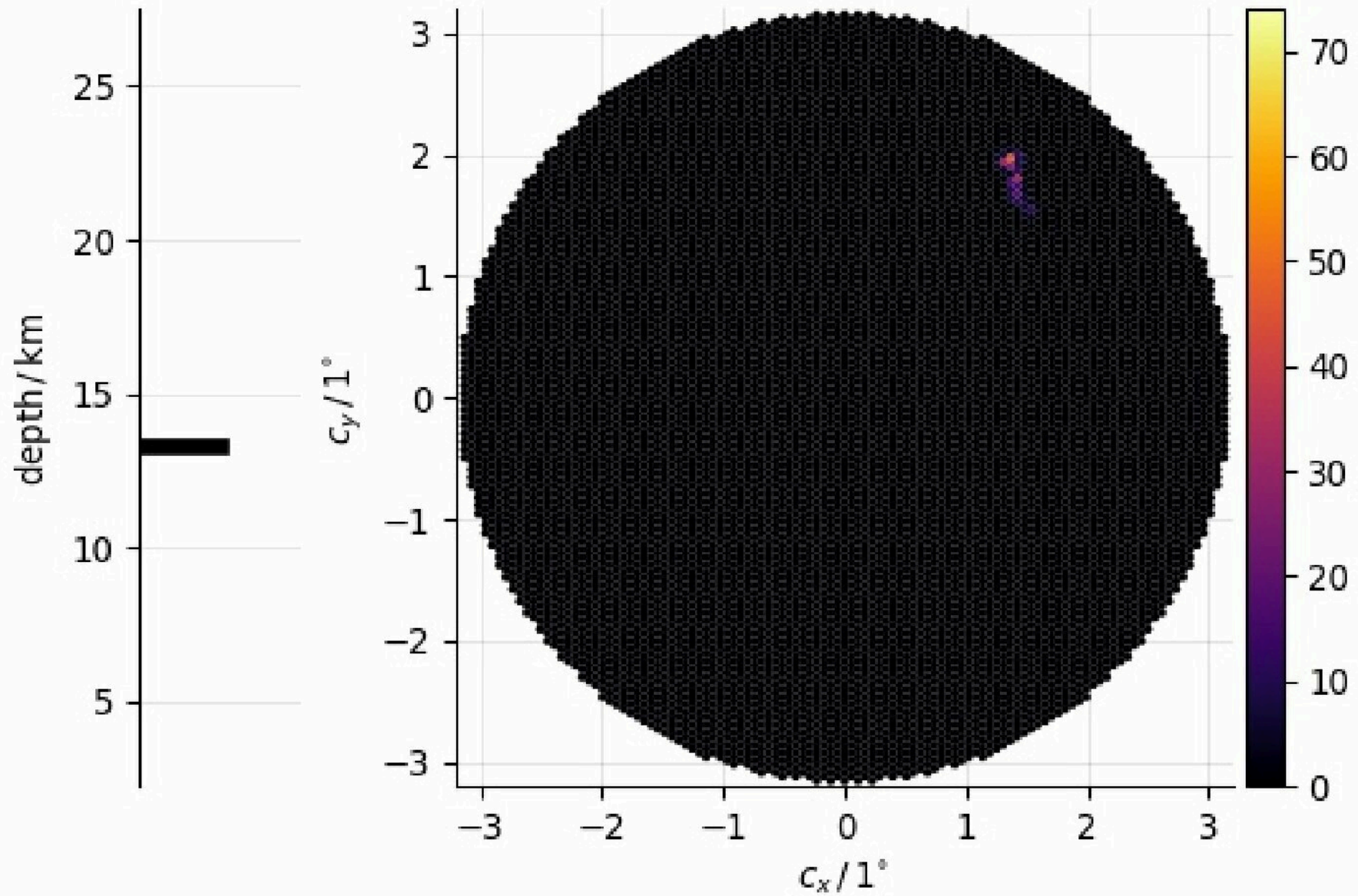
Gamma-showers below 5GeV

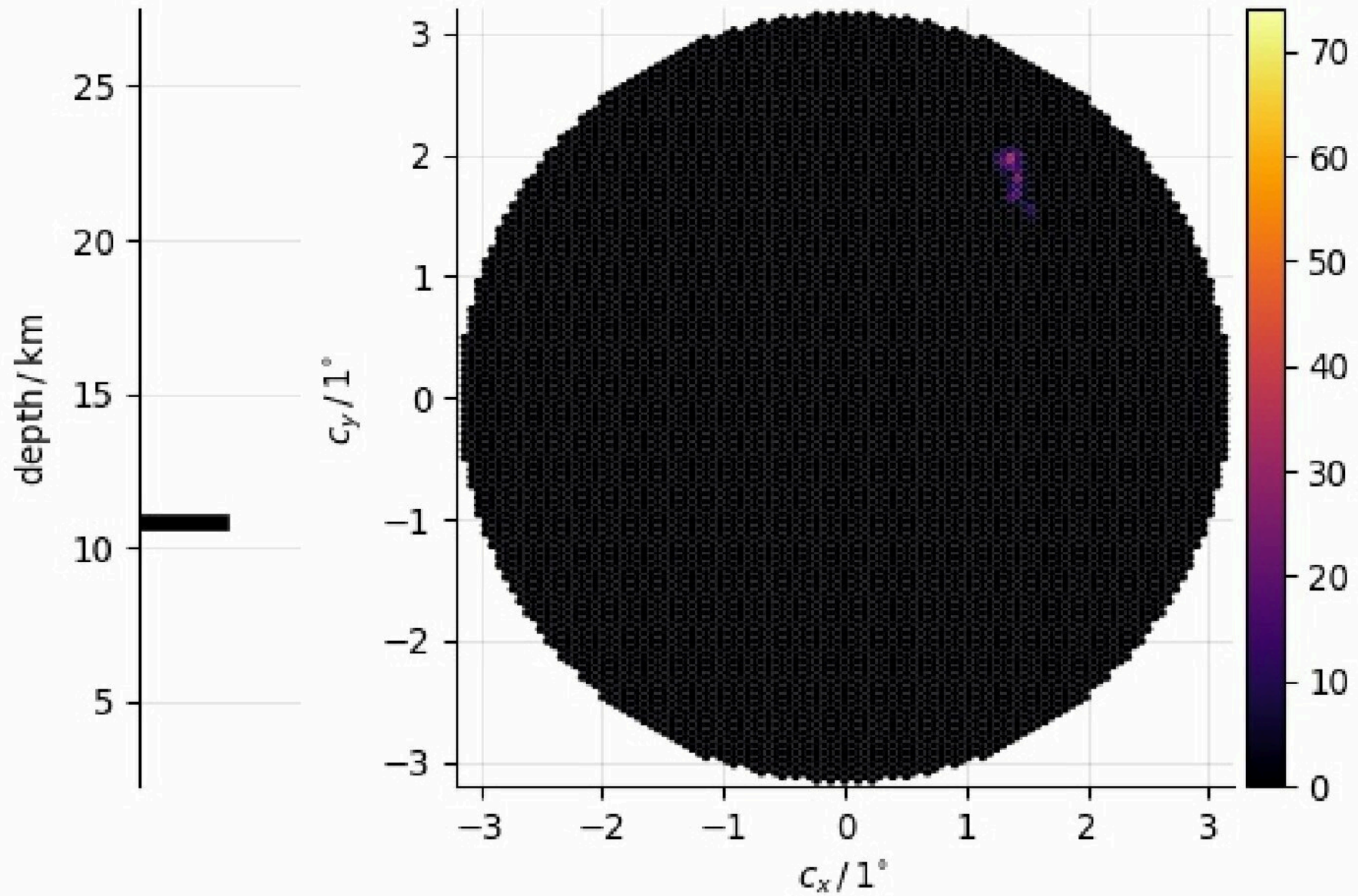


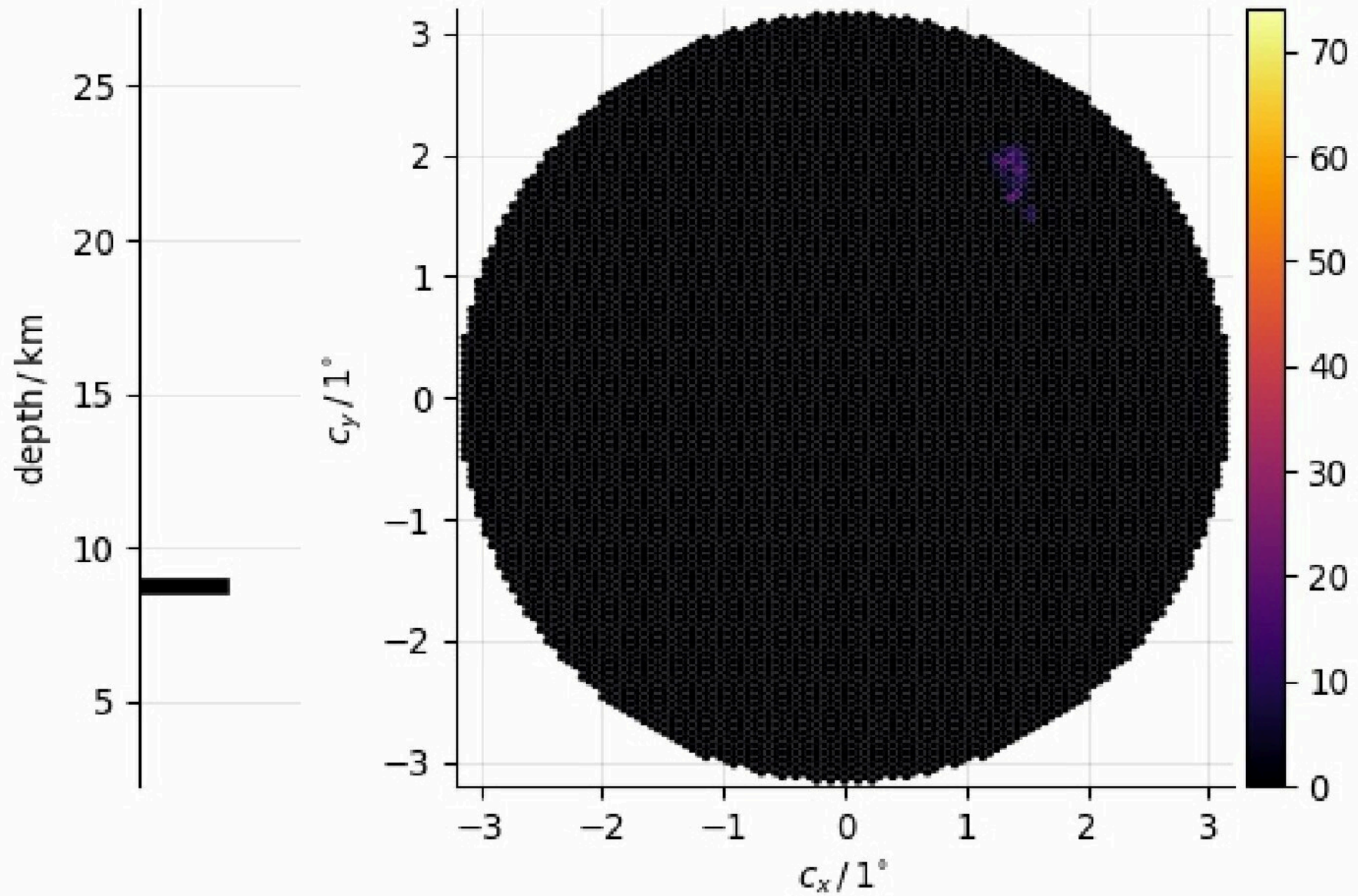


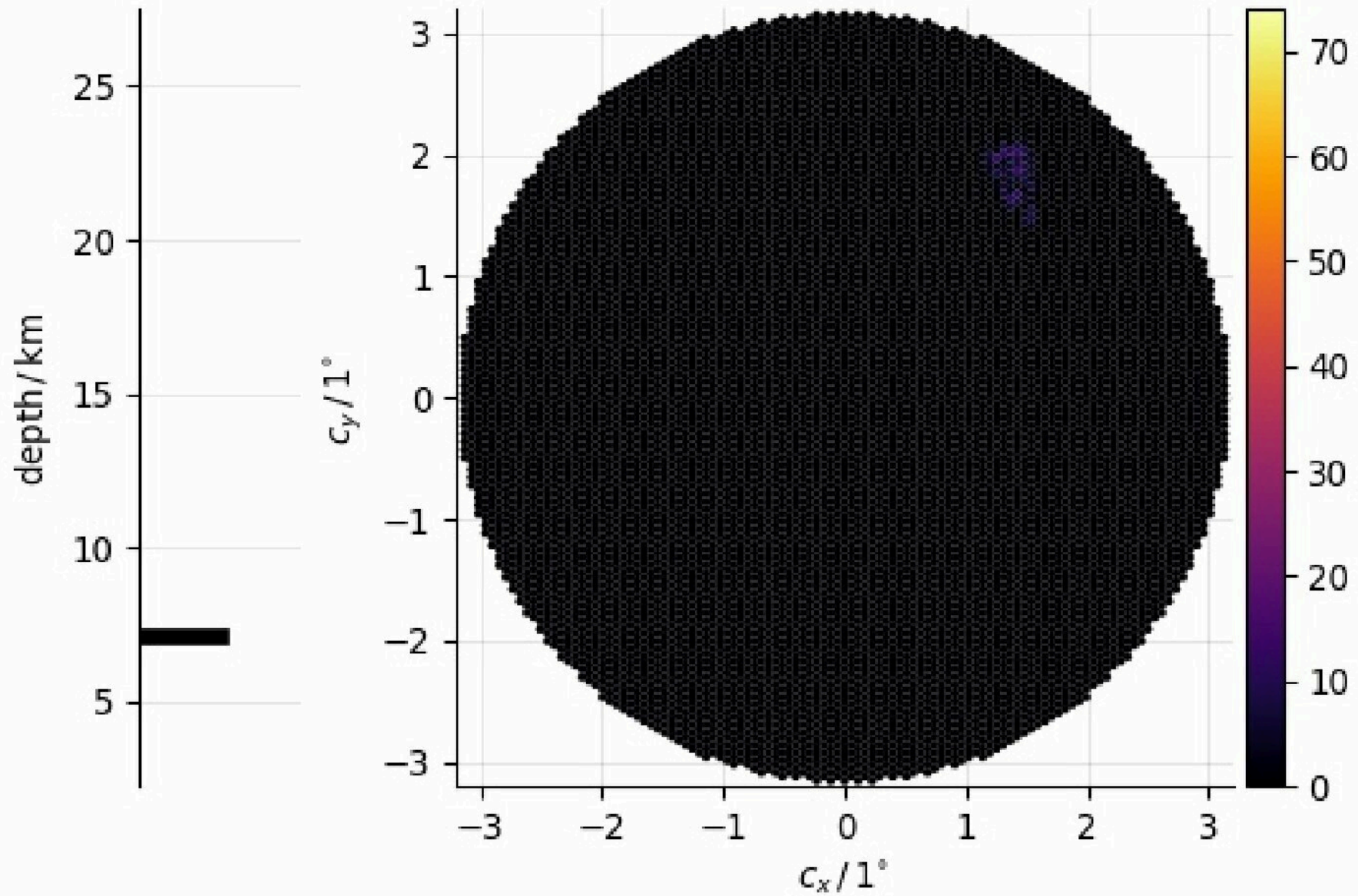


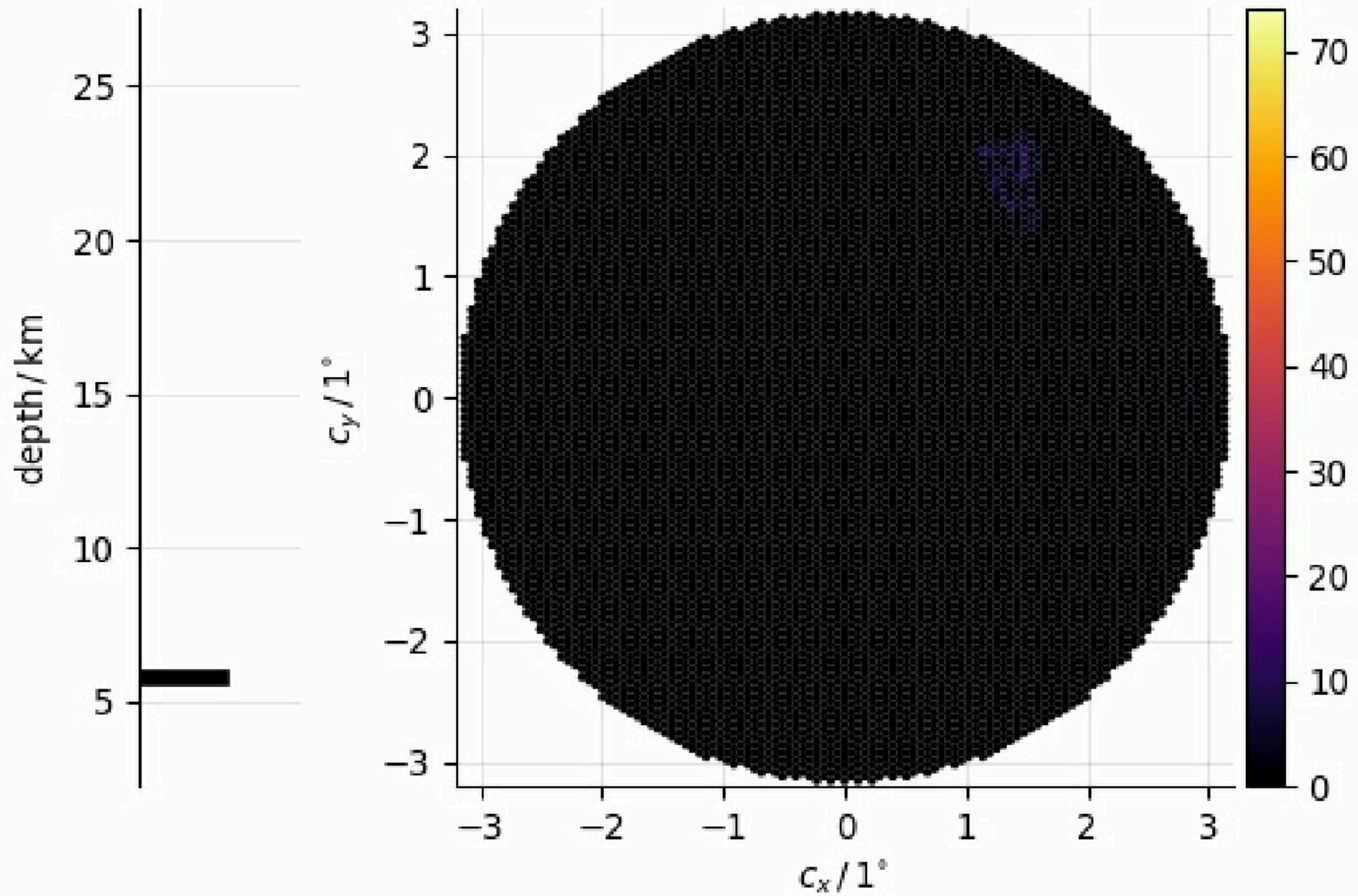


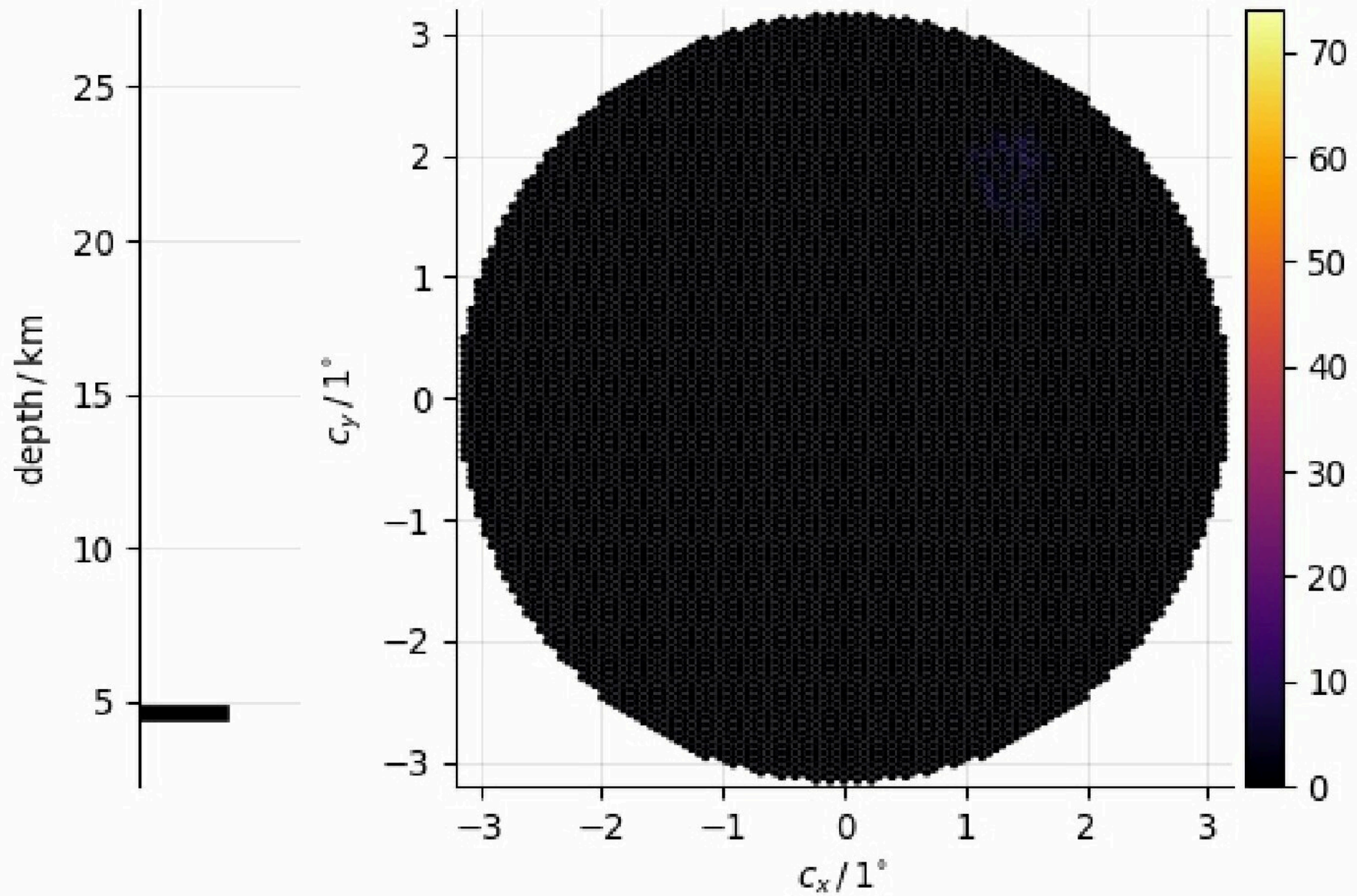


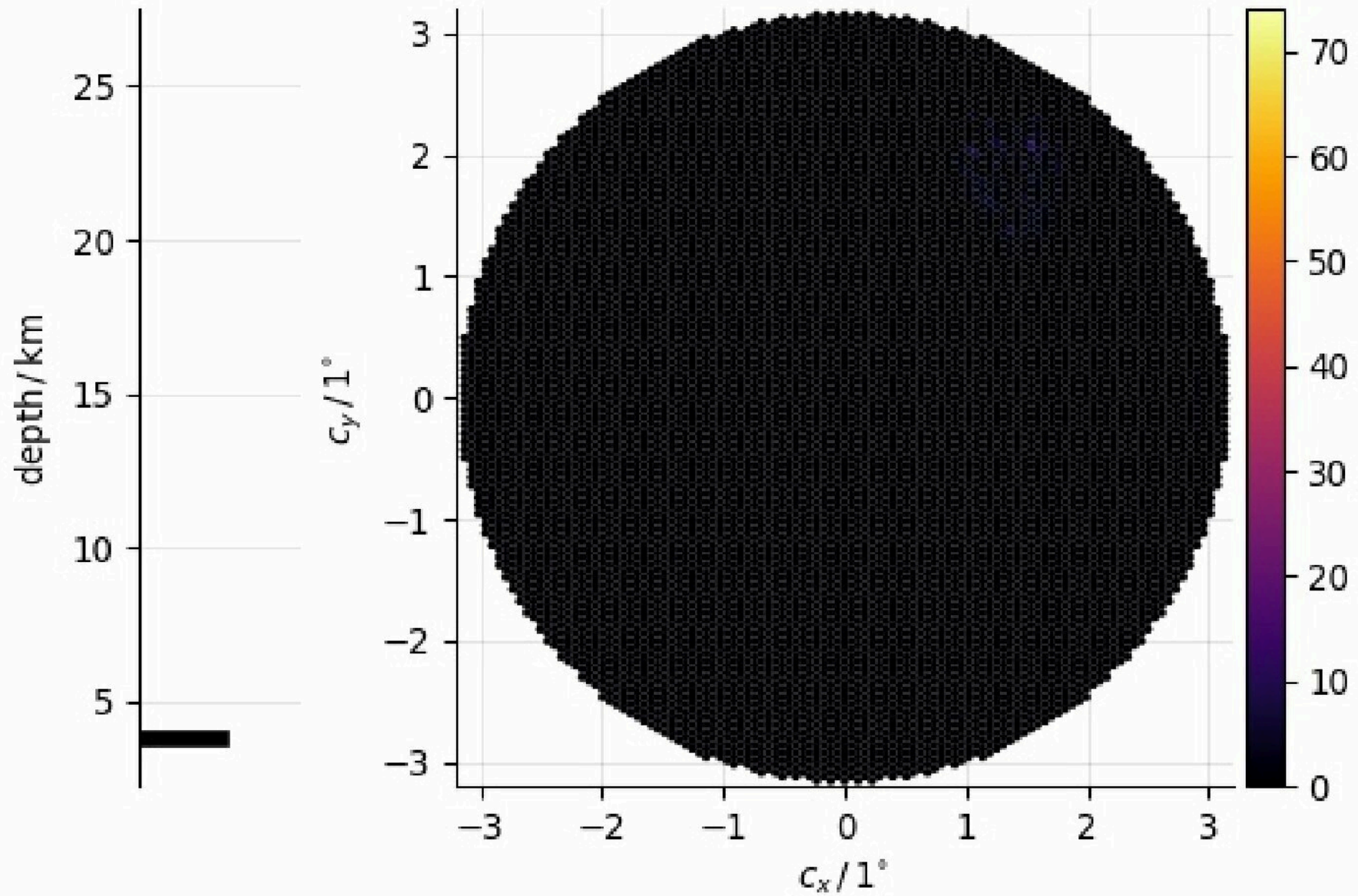


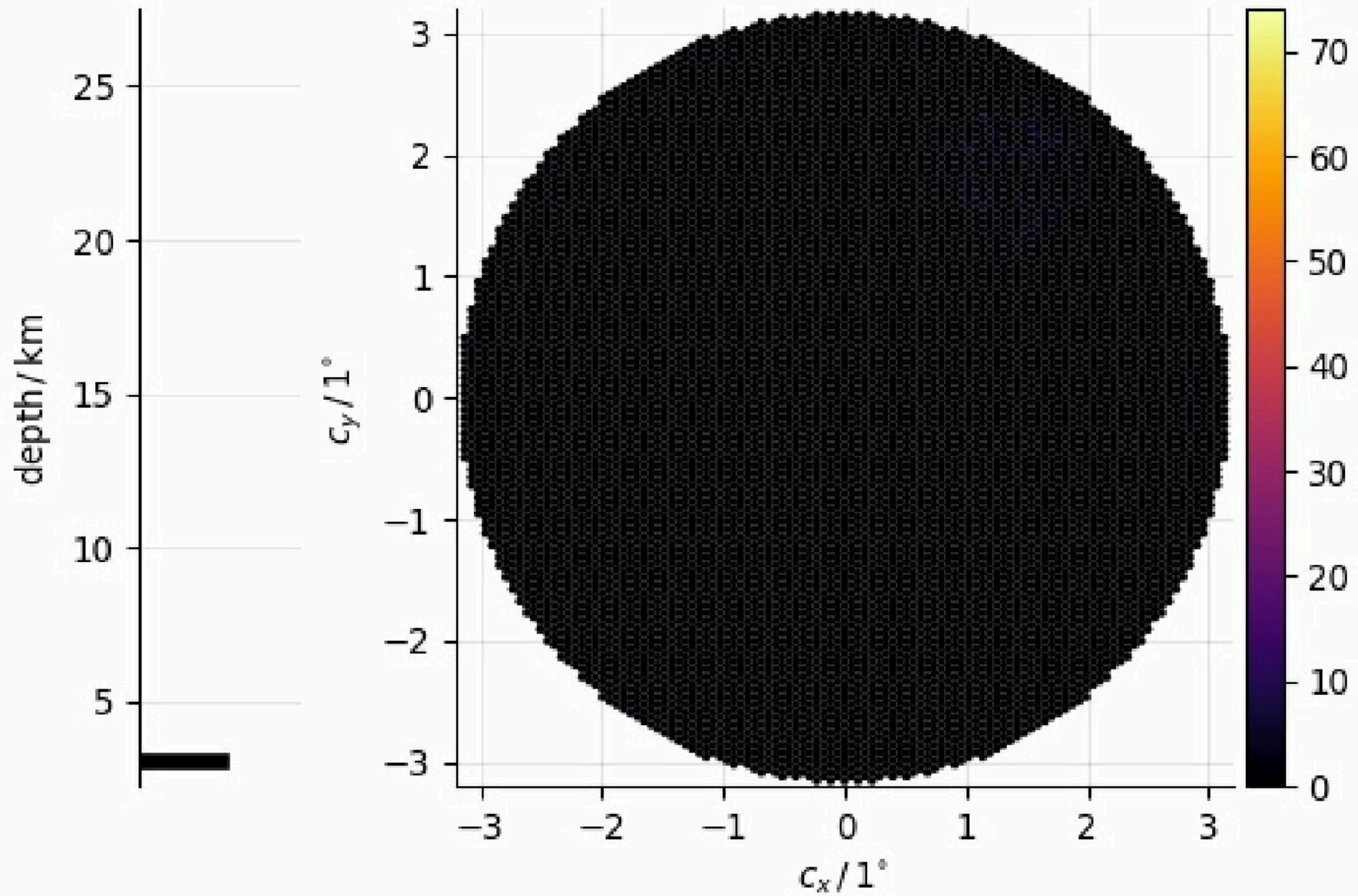


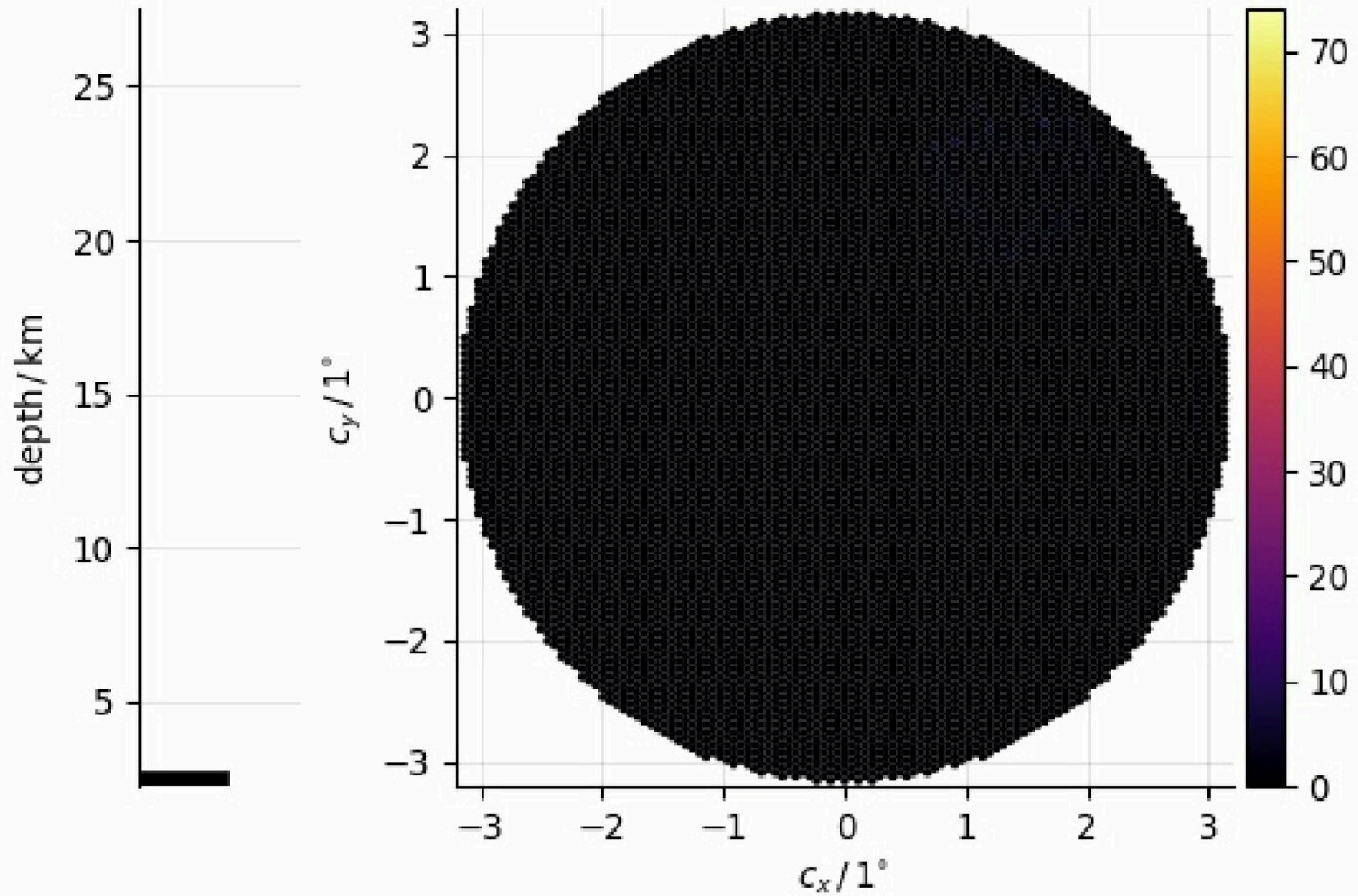


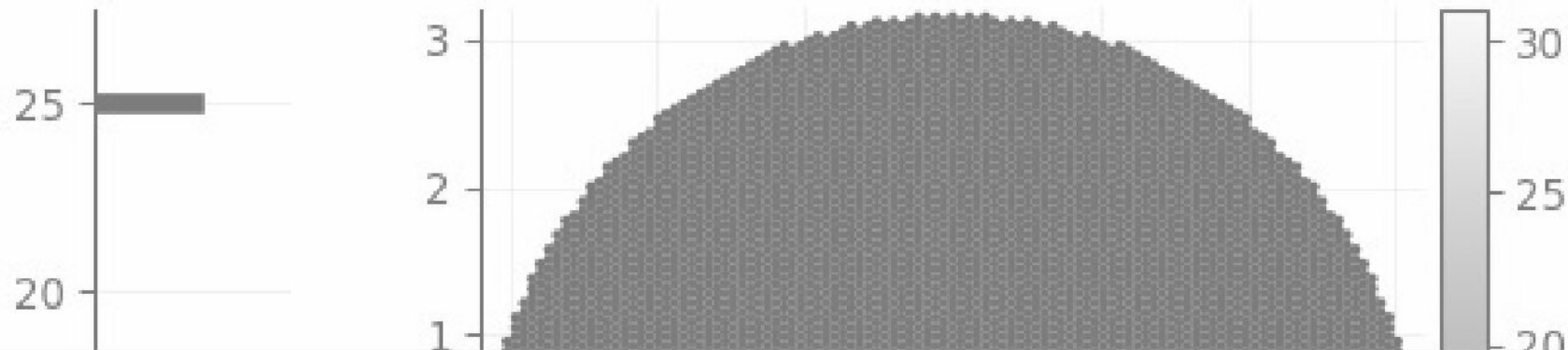




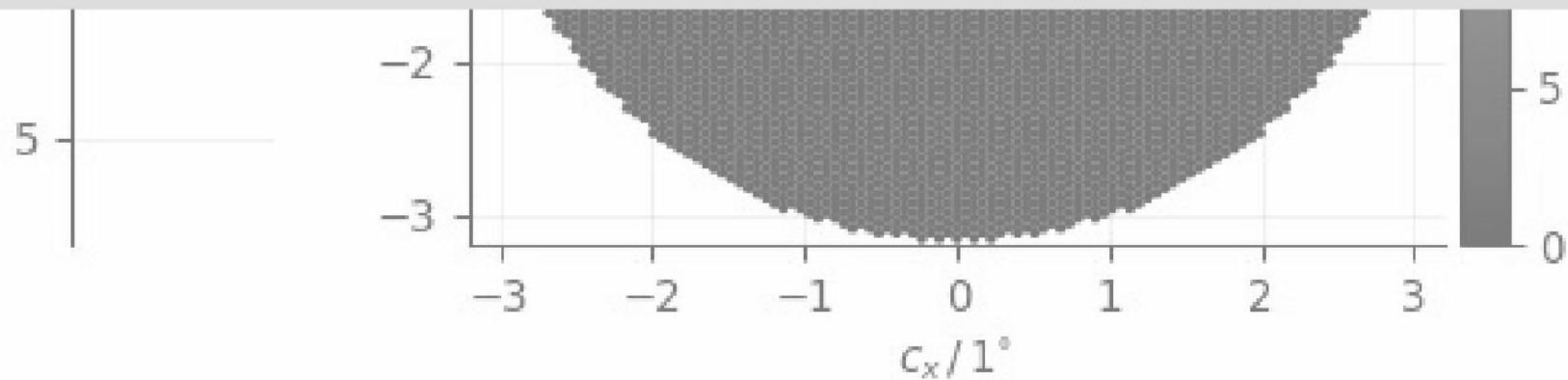


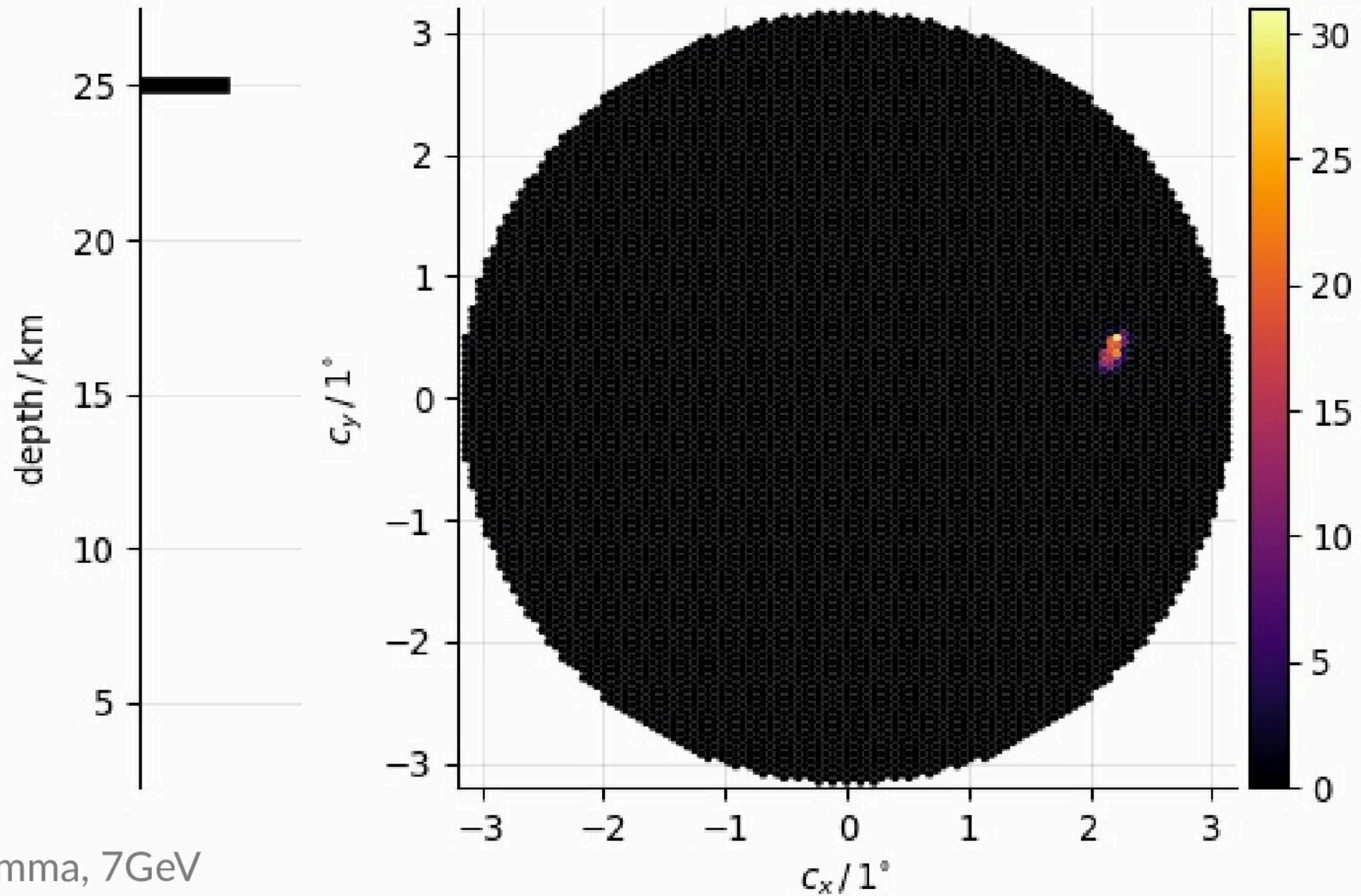




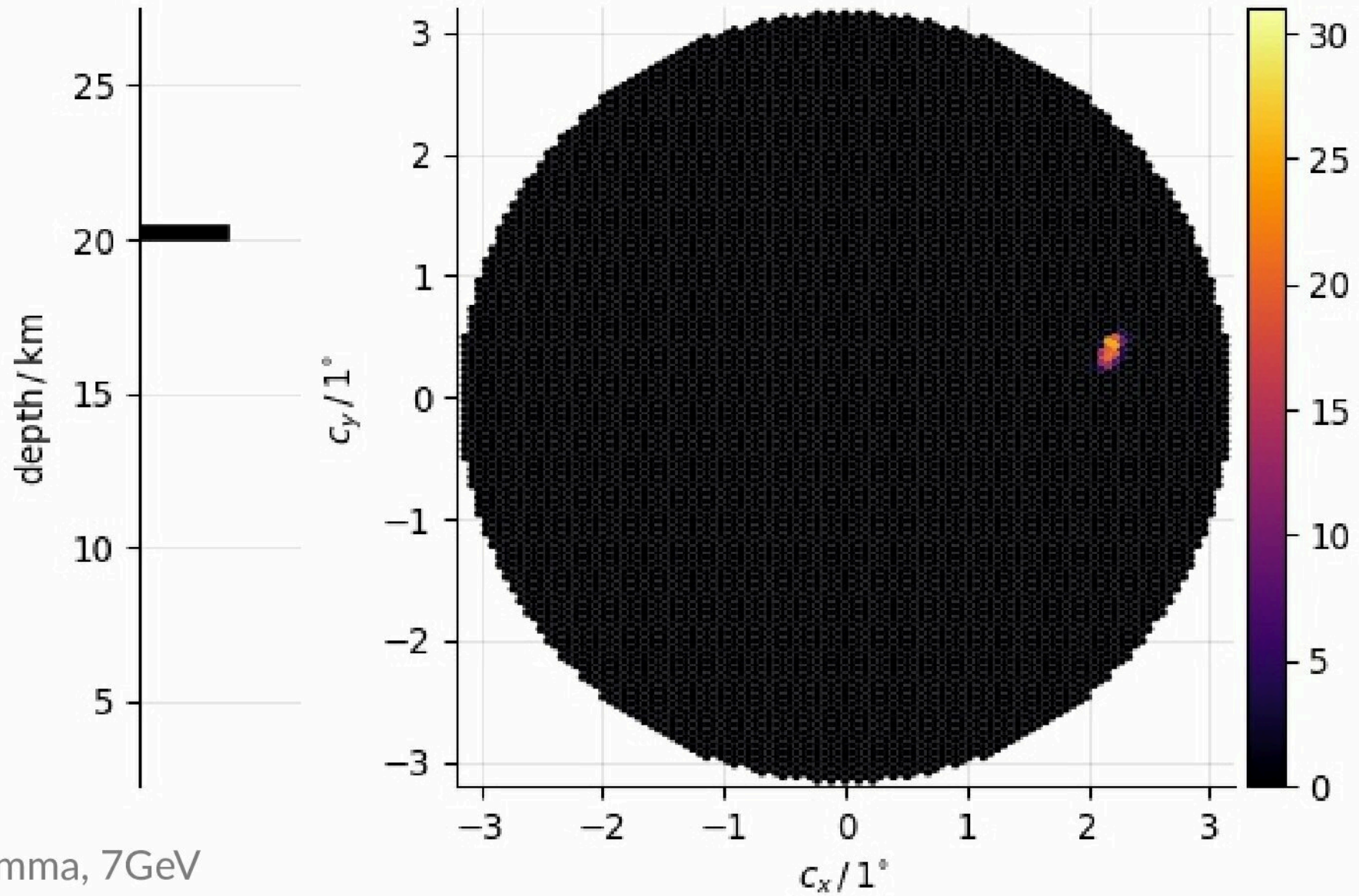


Gamma-showers above 5GeV

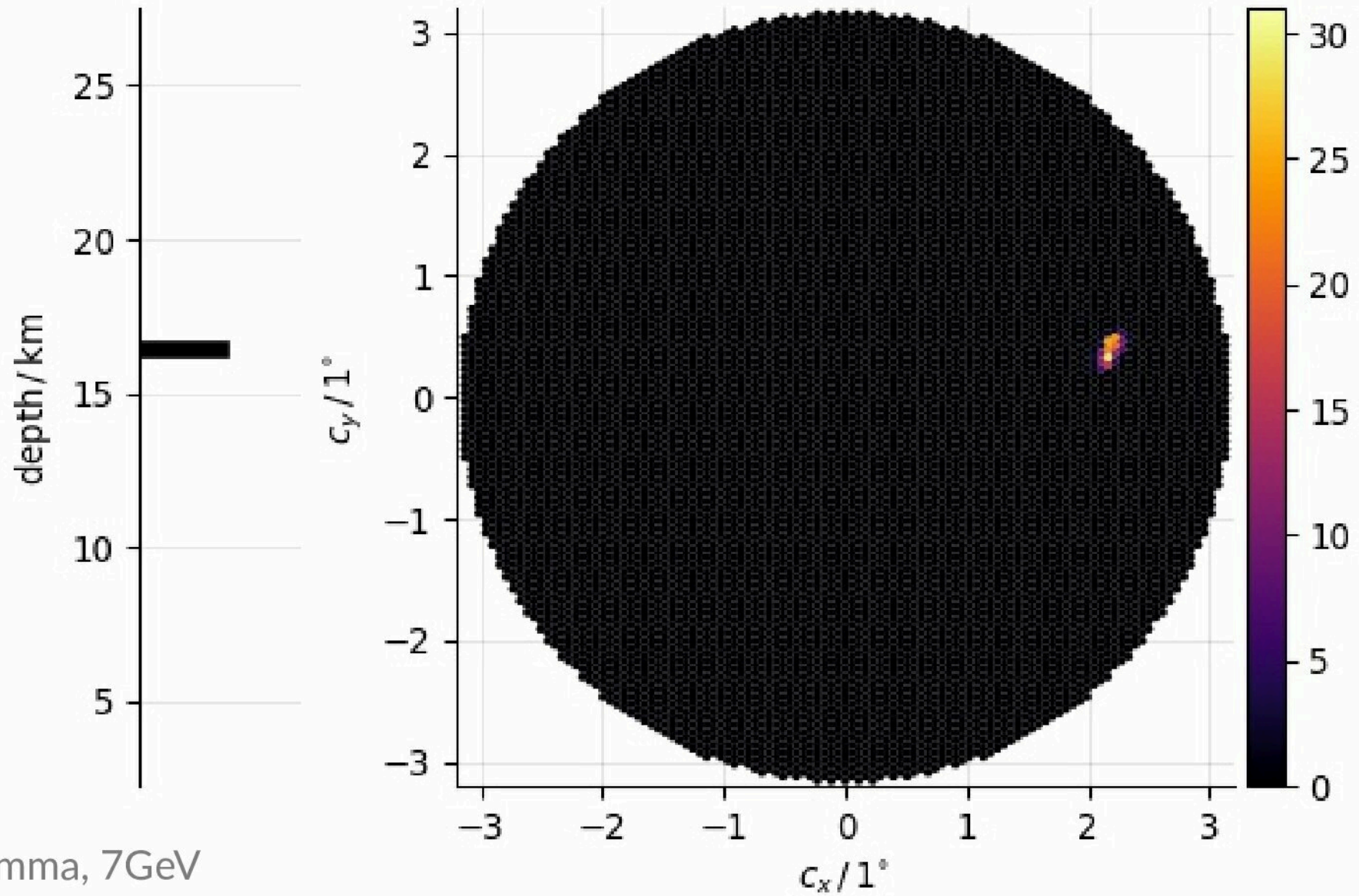




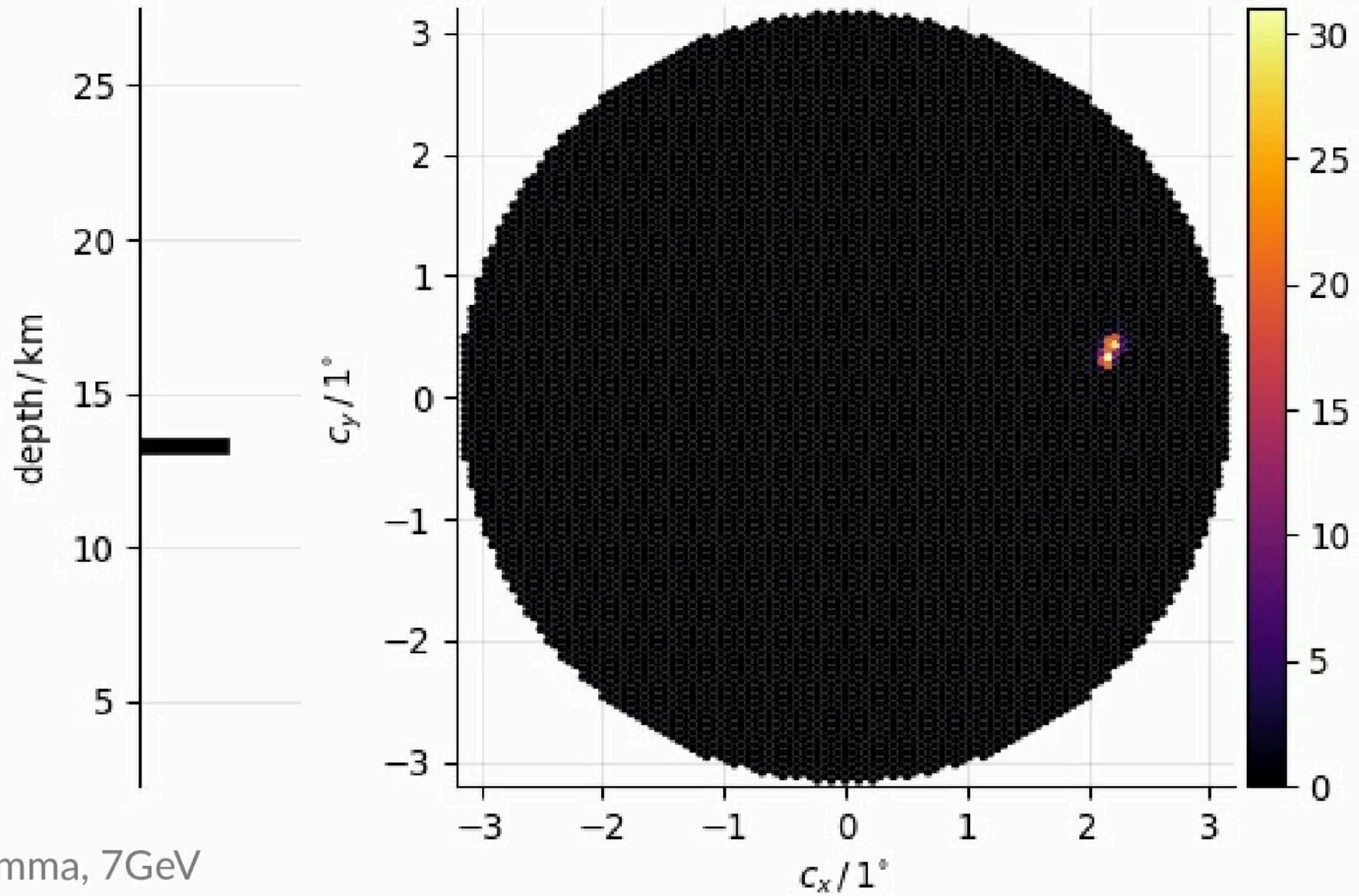
Gamma, 7GeV



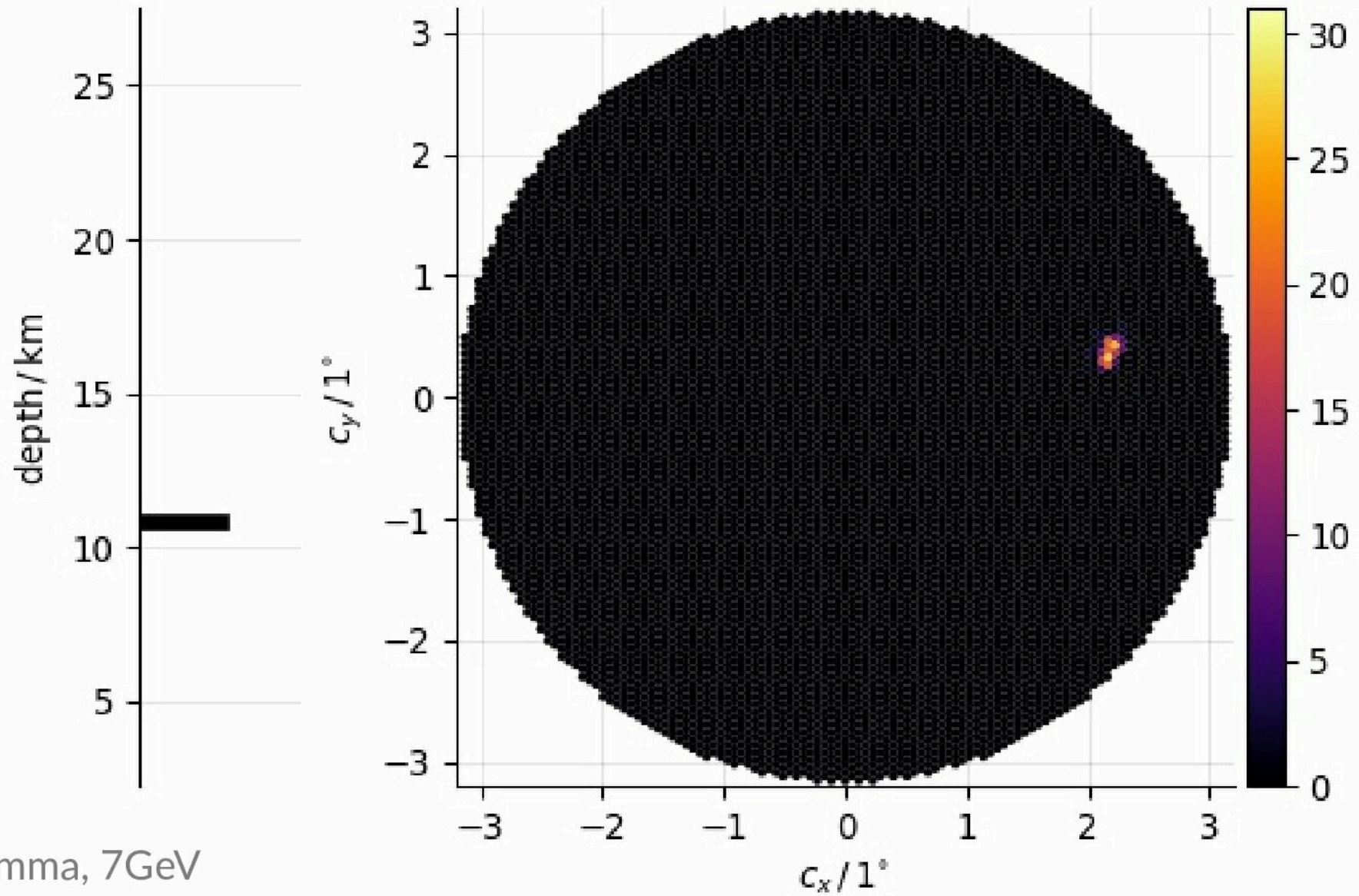
Gamma, 7GeV



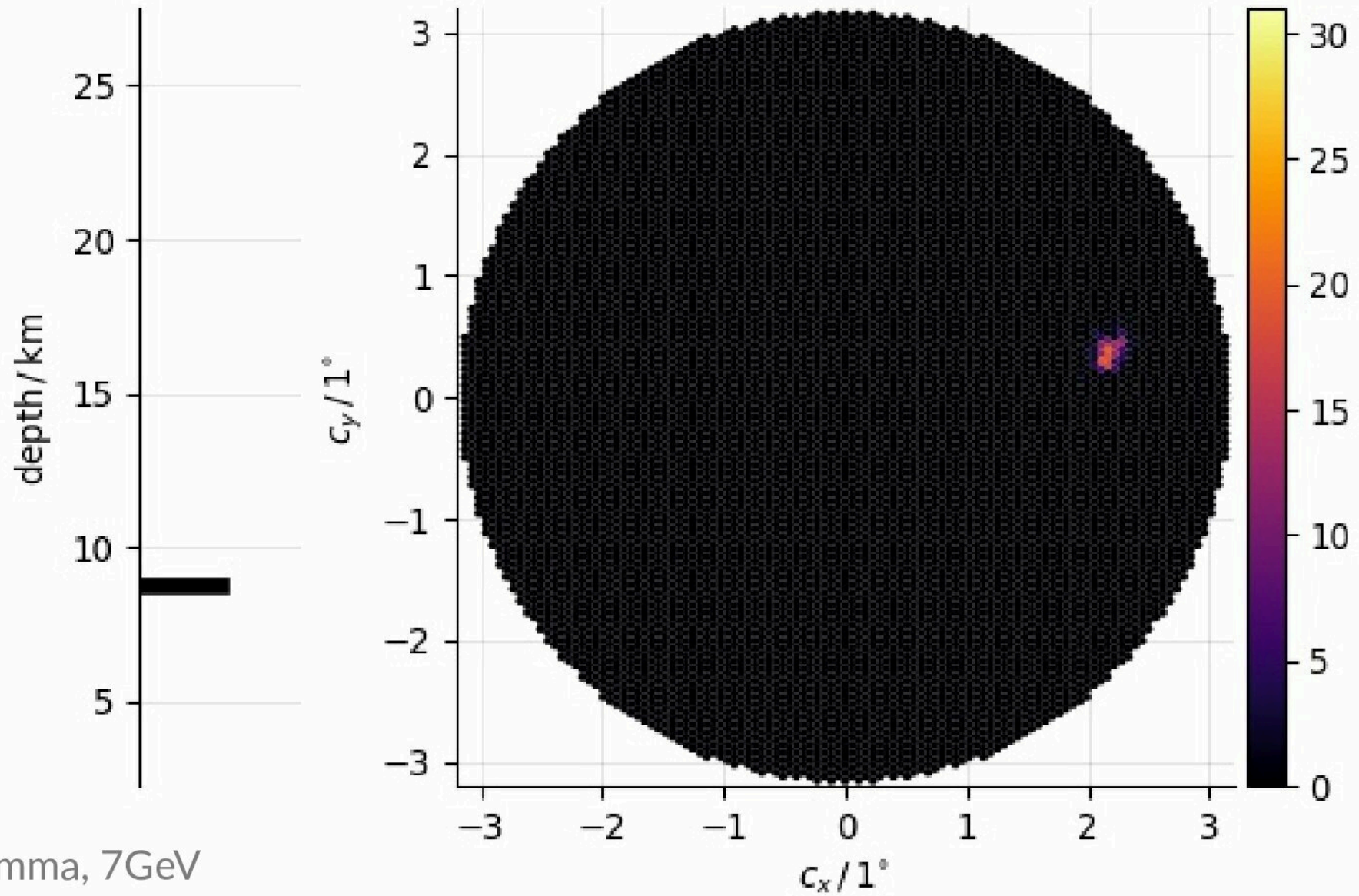
Gamma, 7GeV

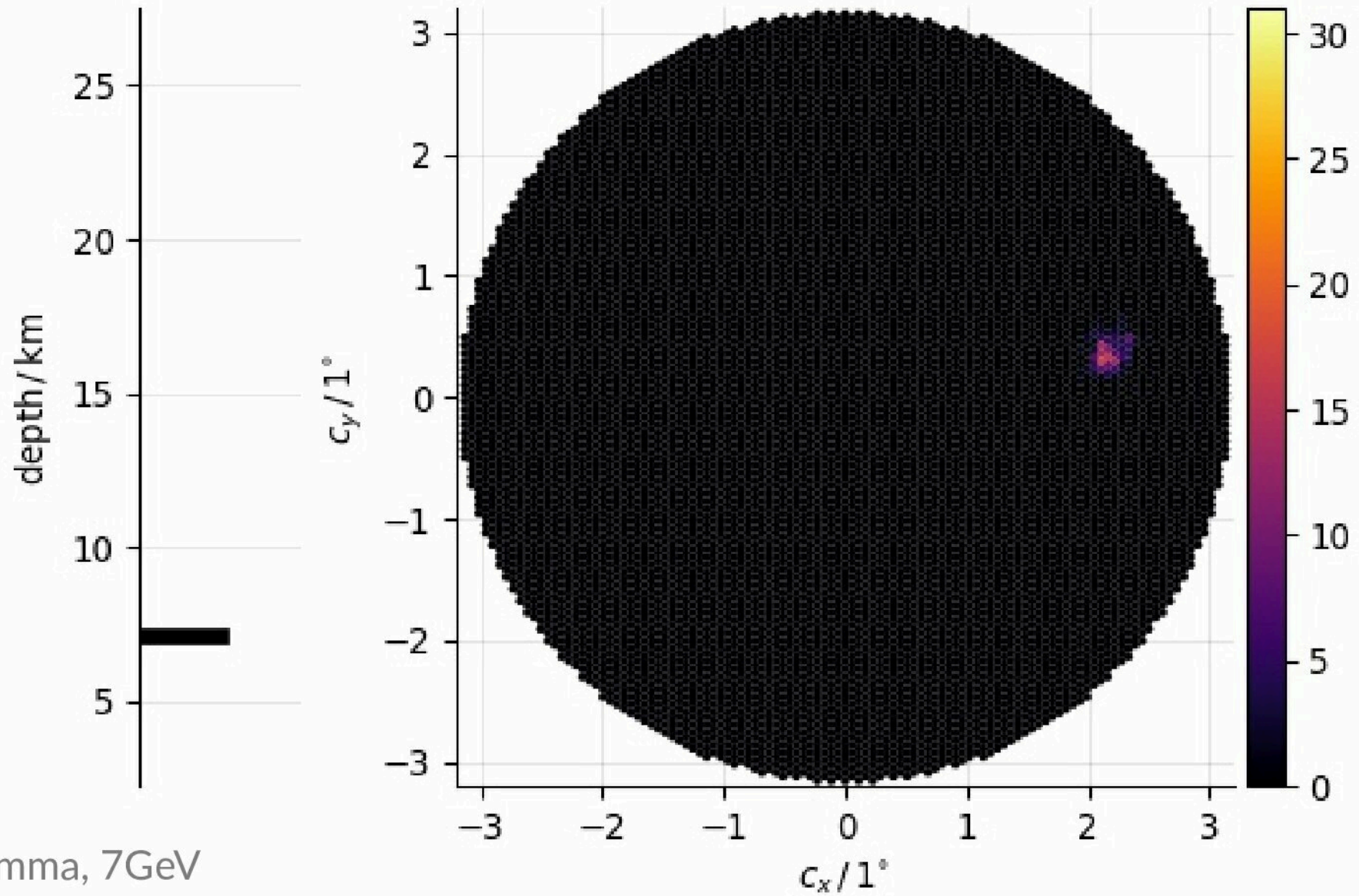


Gamma, 7GeV

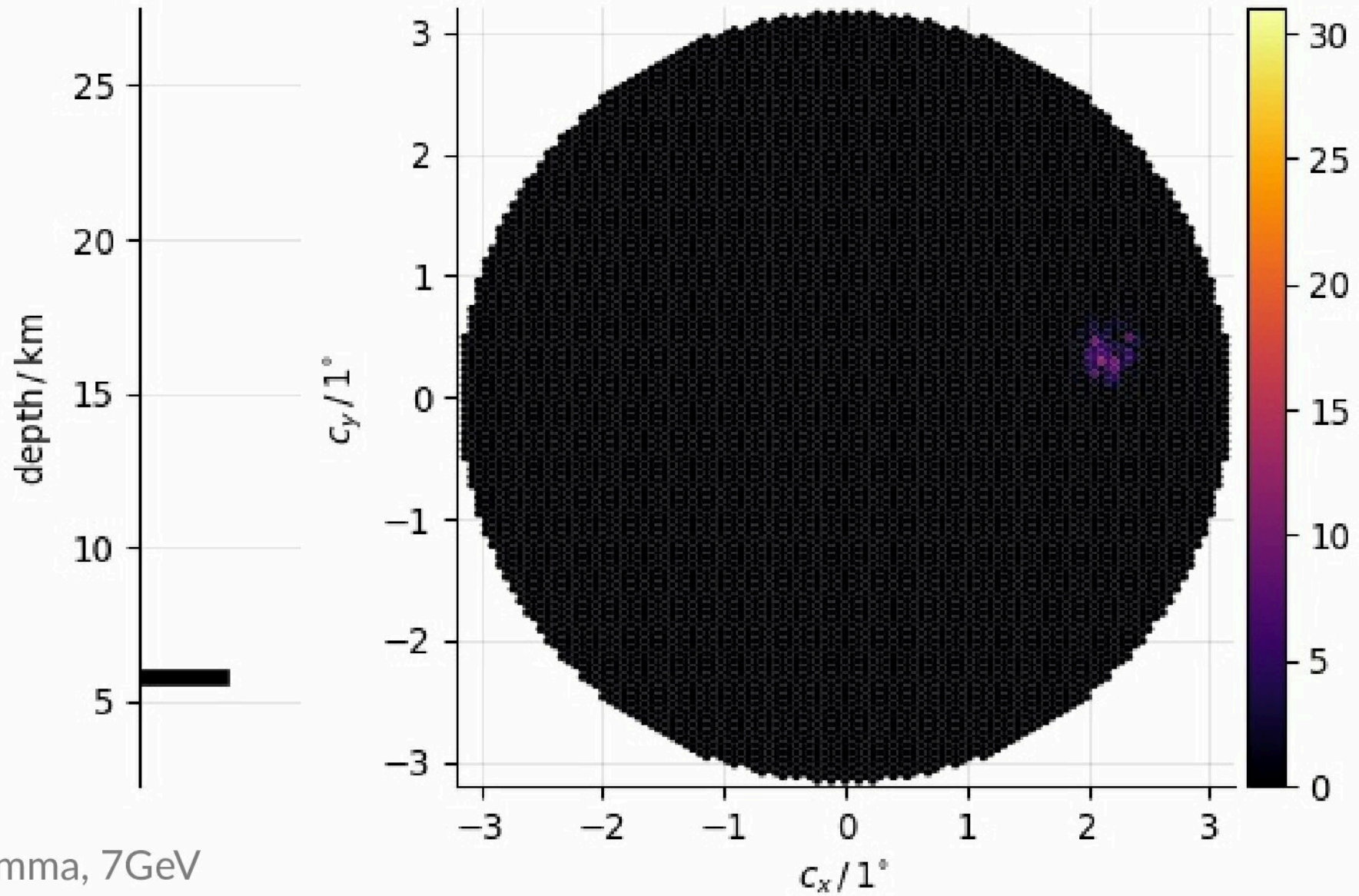


Gamma, 7GeV

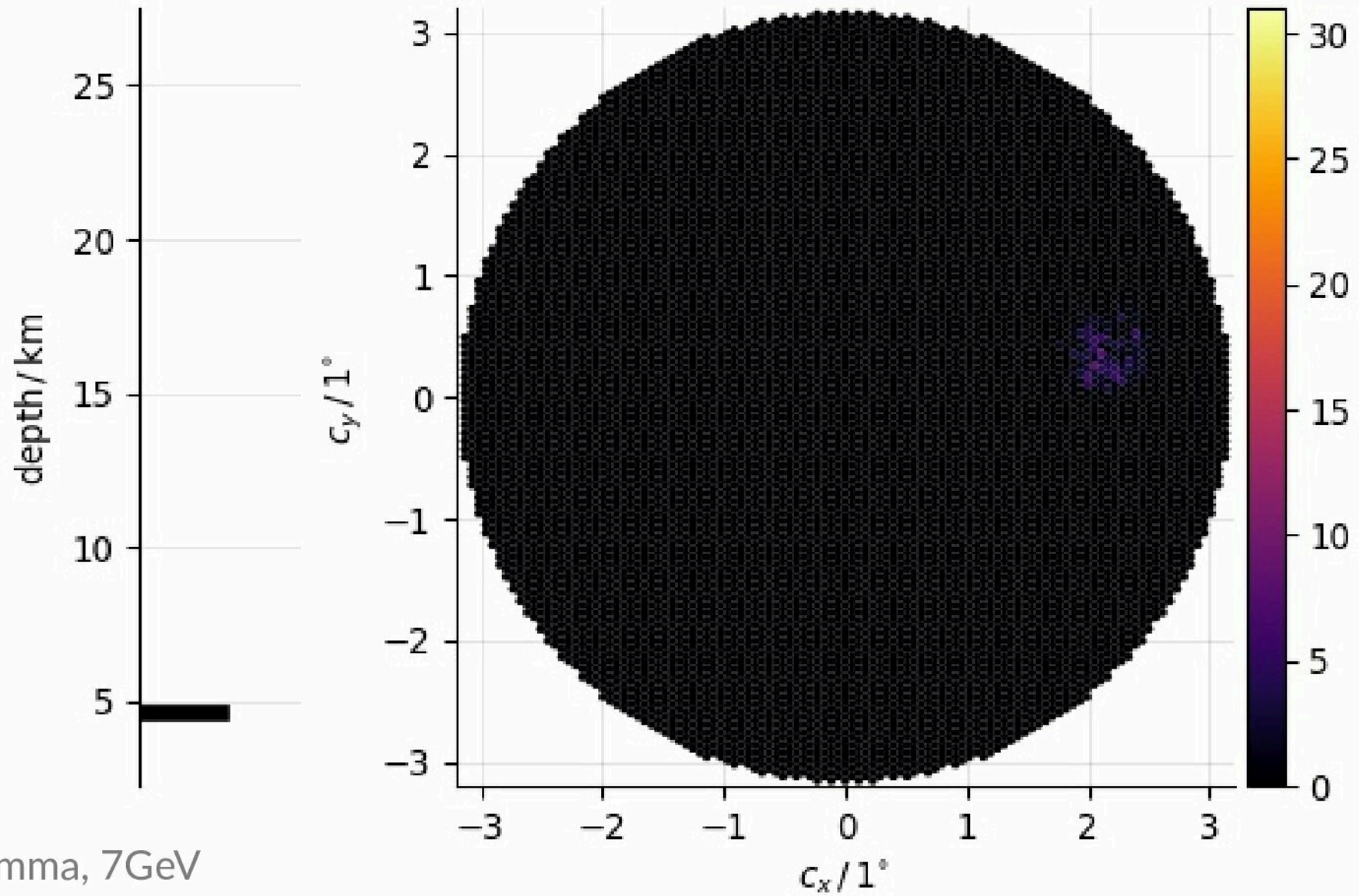




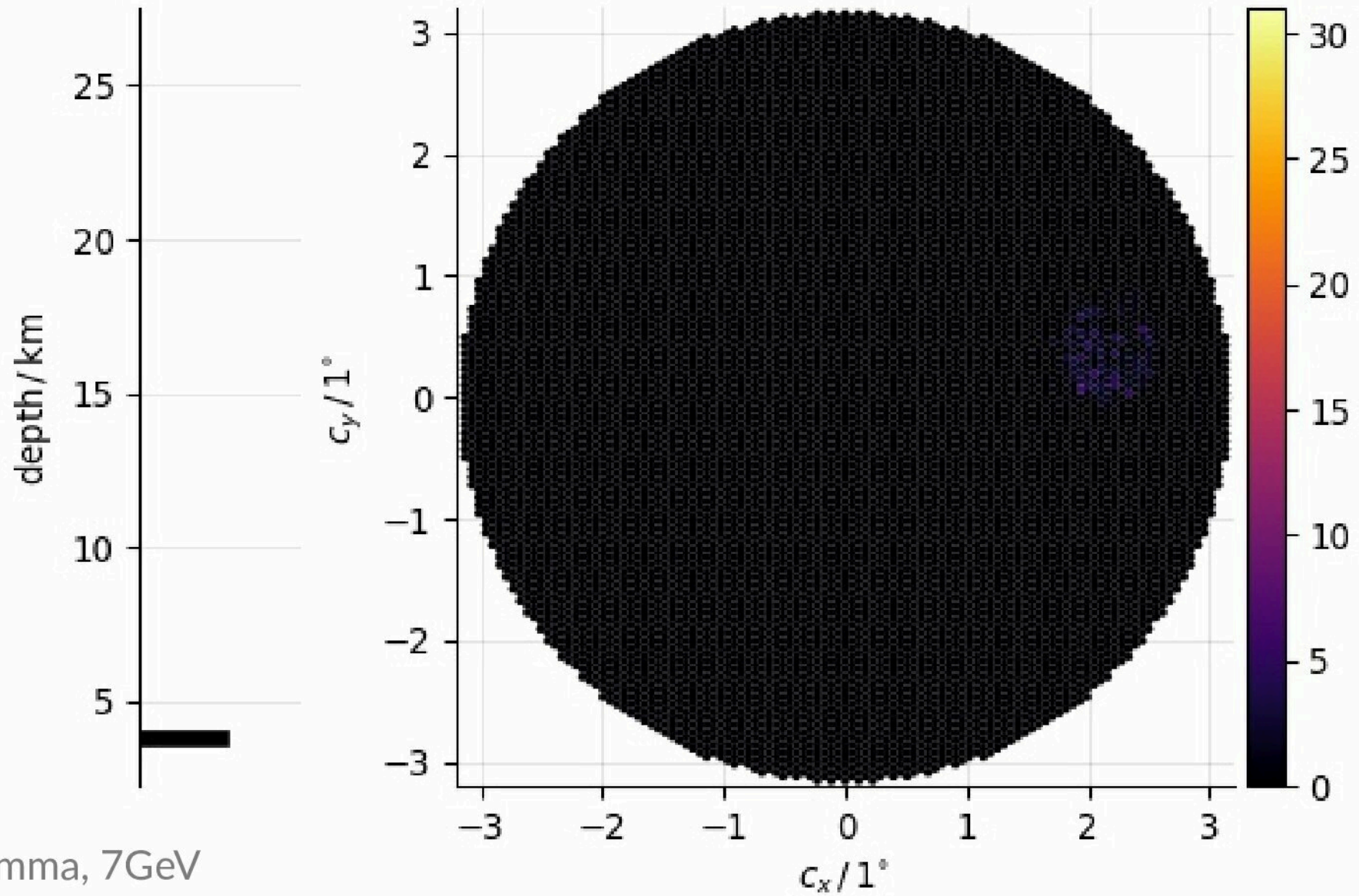
Gamma, 7GeV



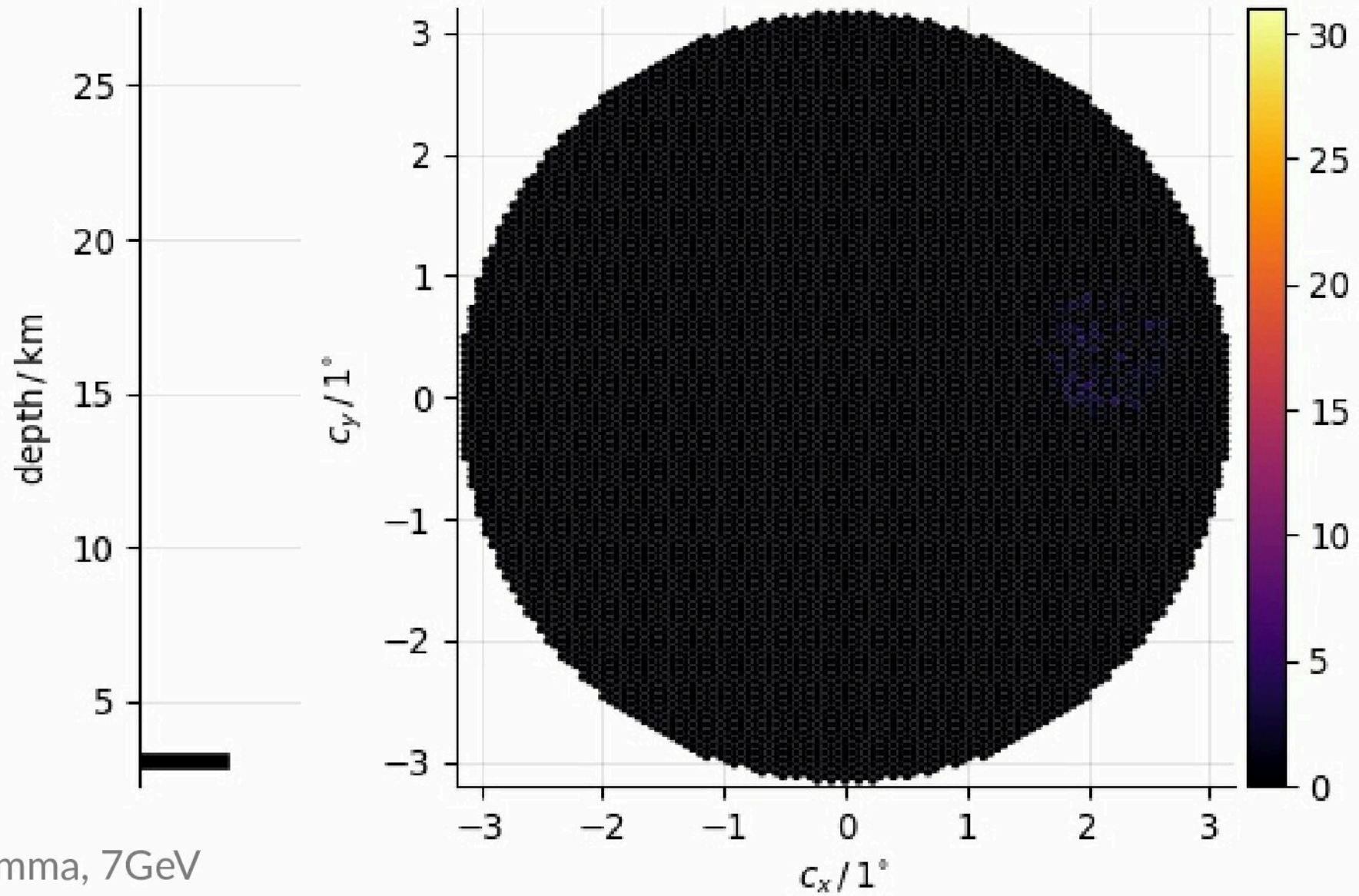
Gamma, 7GeV



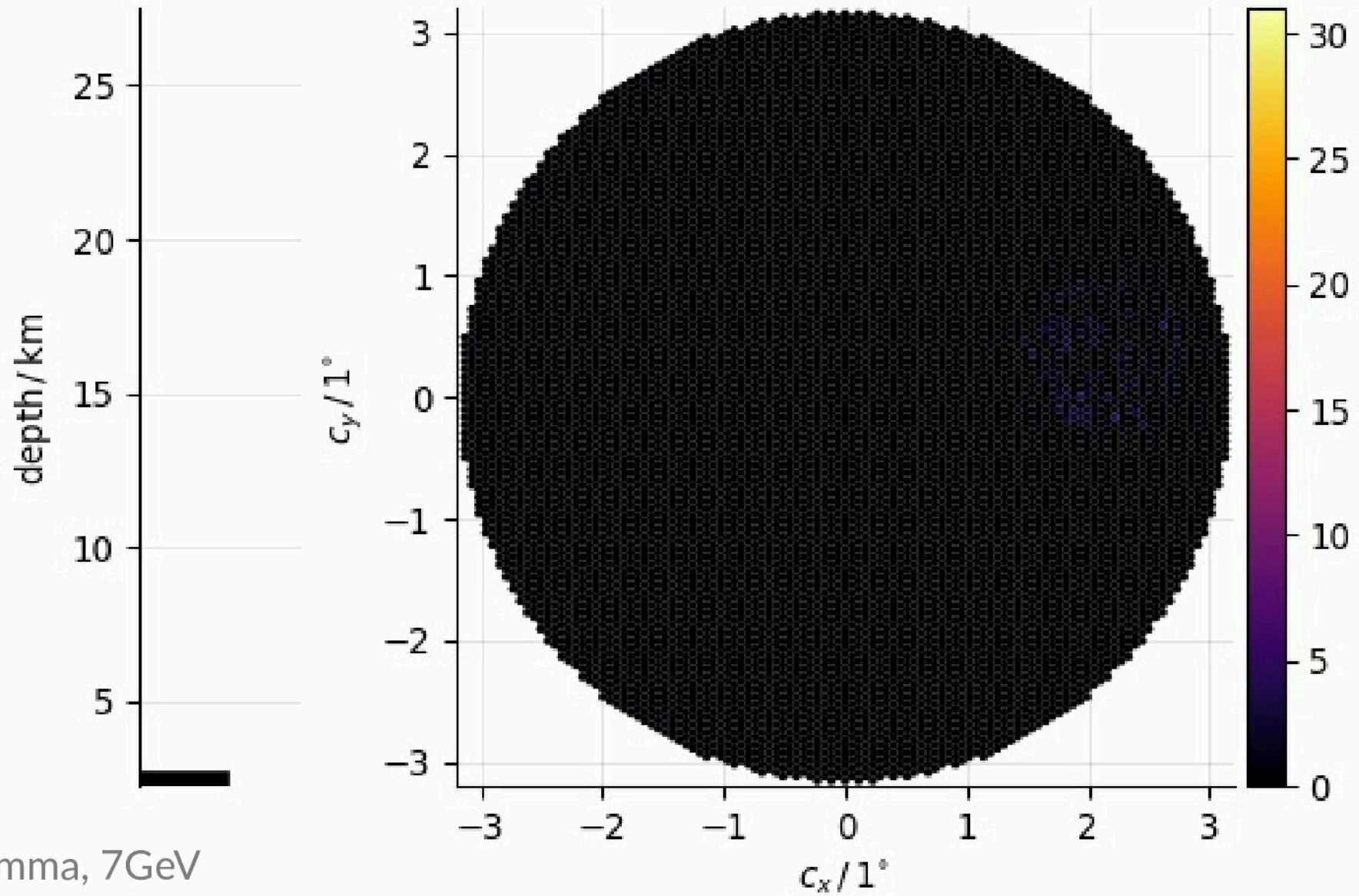
Gamma, 7GeV

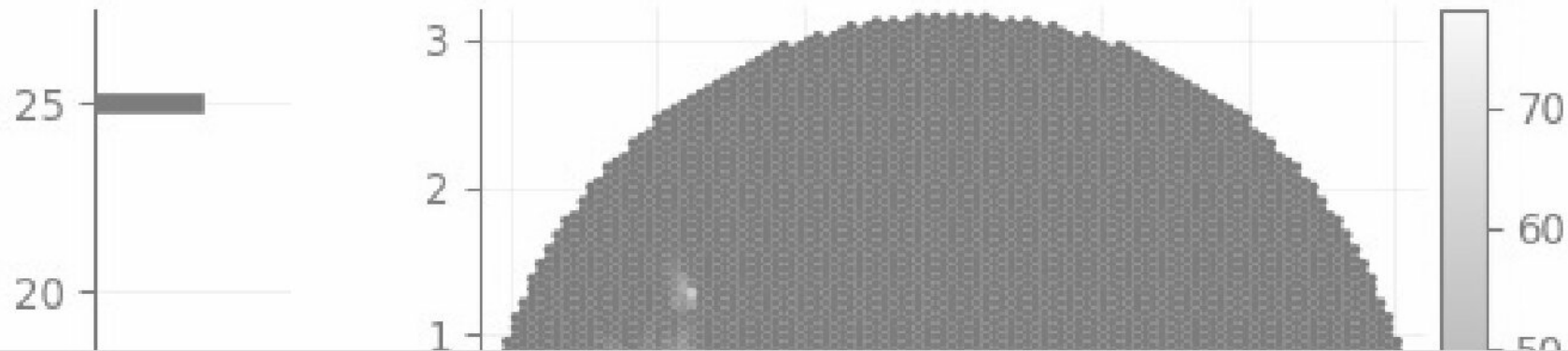


Gamma, 7GeV

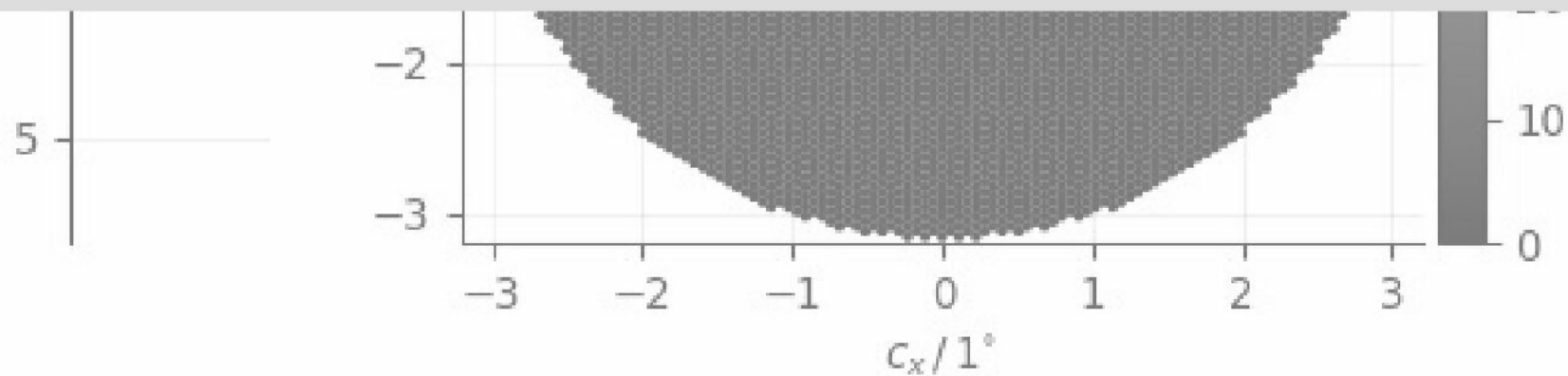


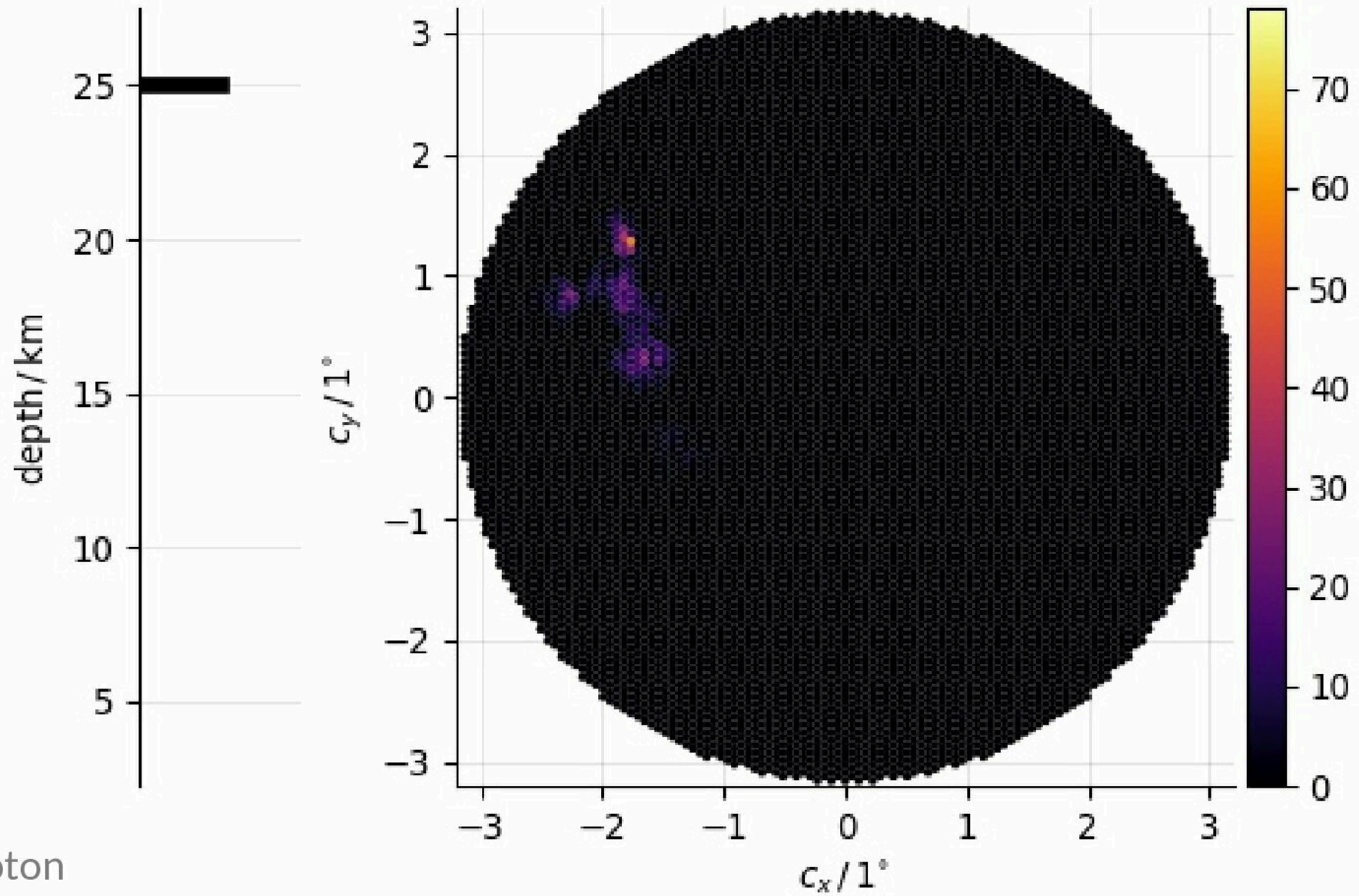
Gamma, 7GeV



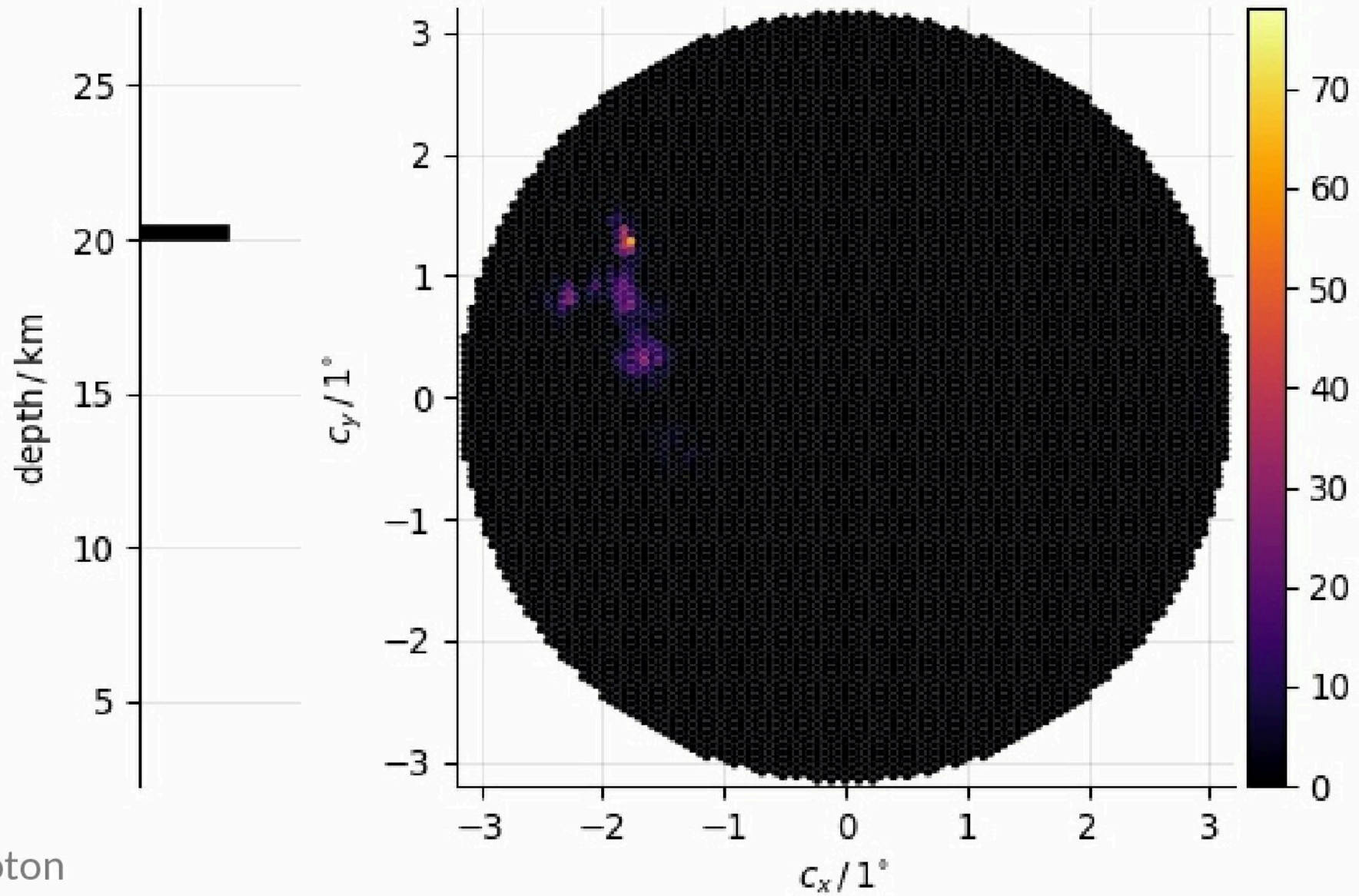


Proton-showers



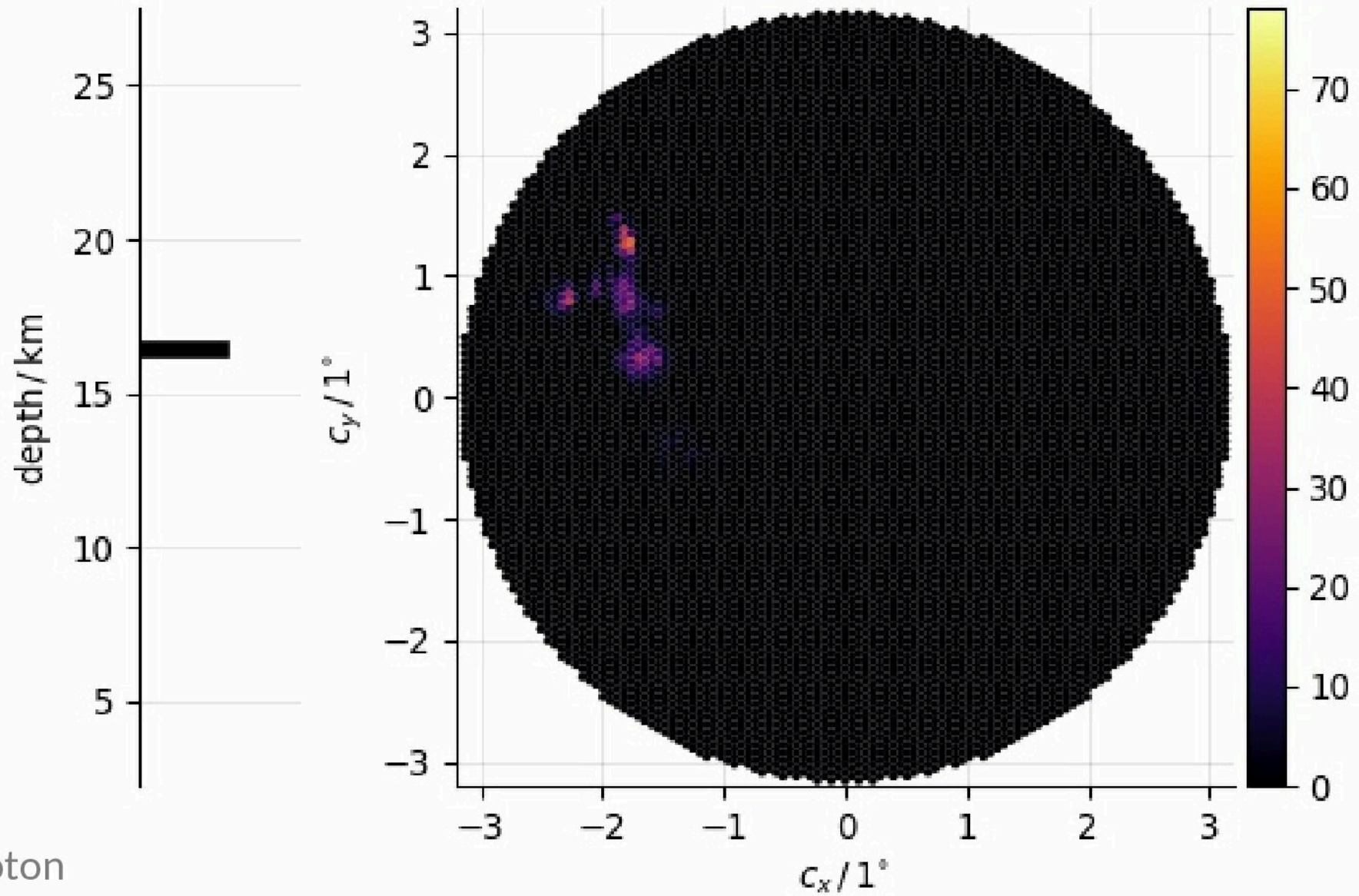


Proton

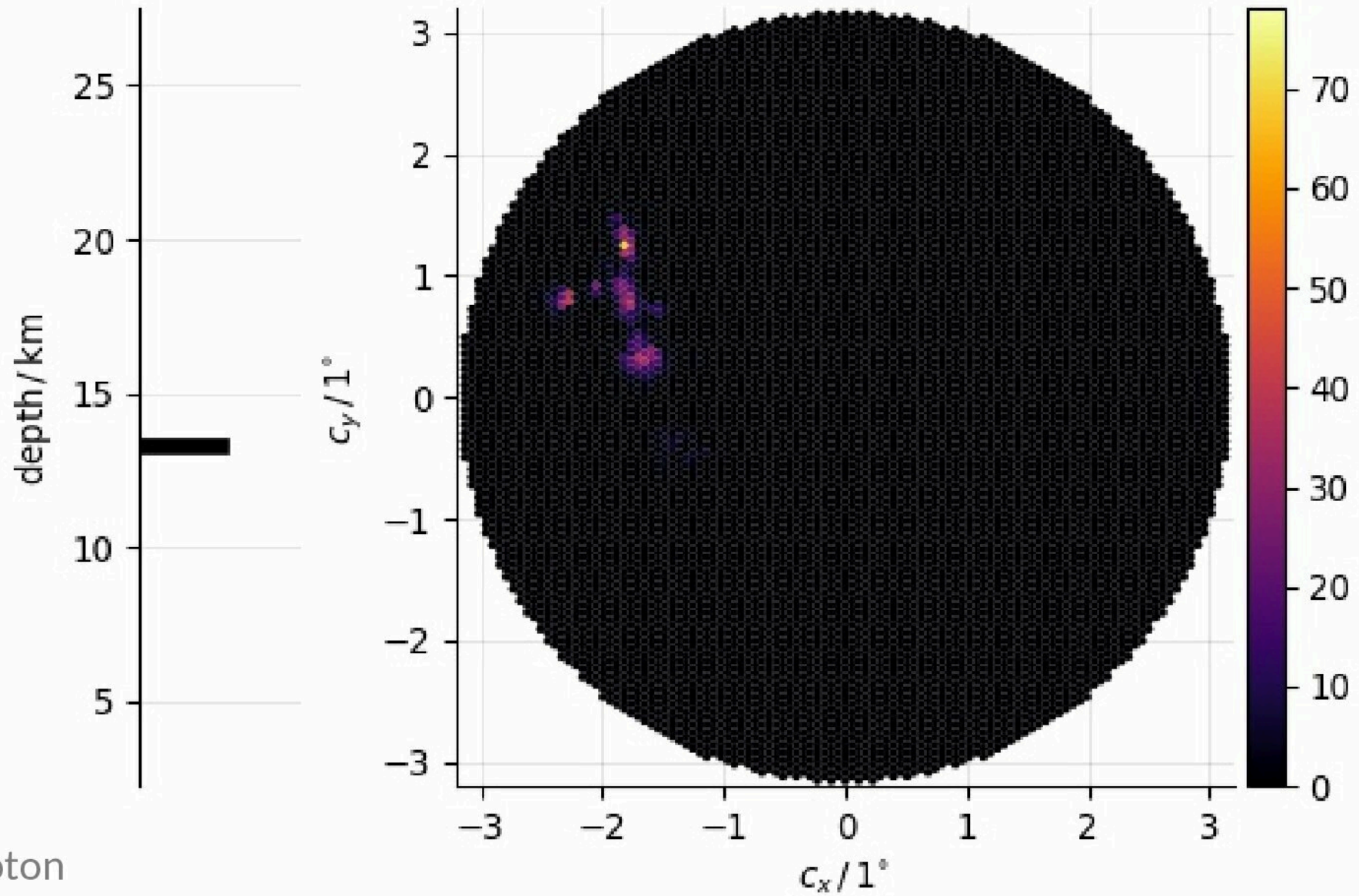


Proton

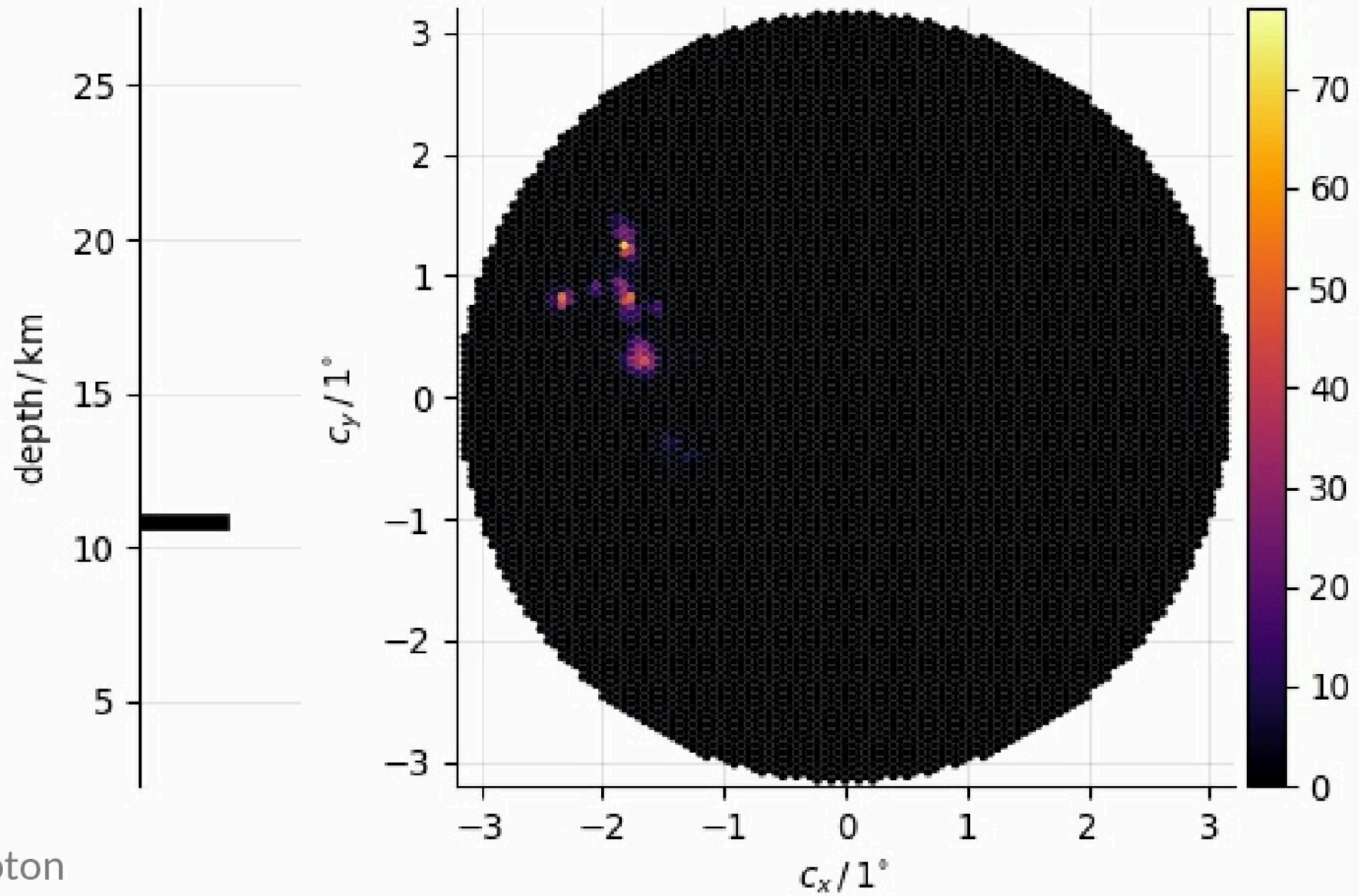
180



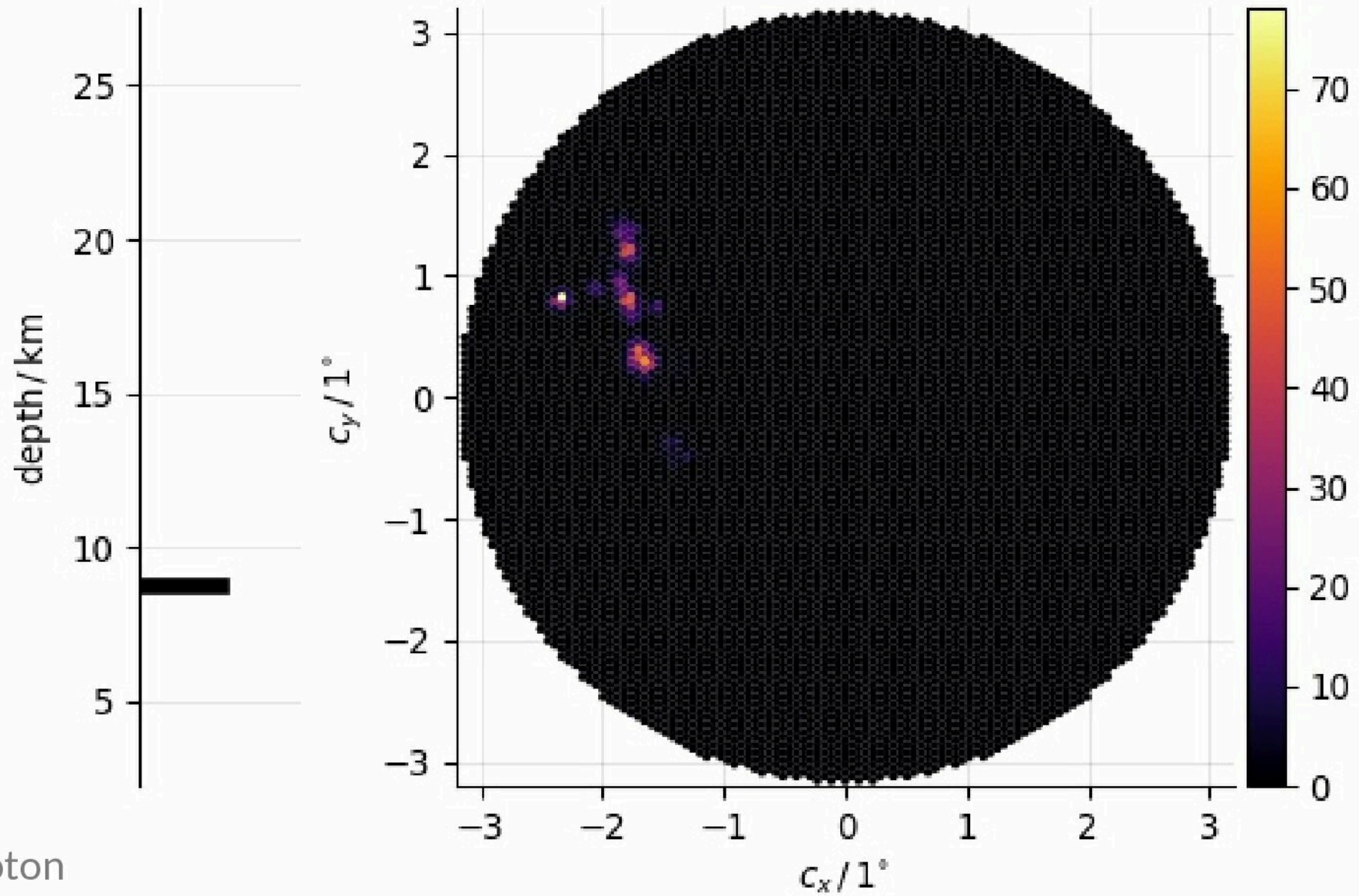
Proton



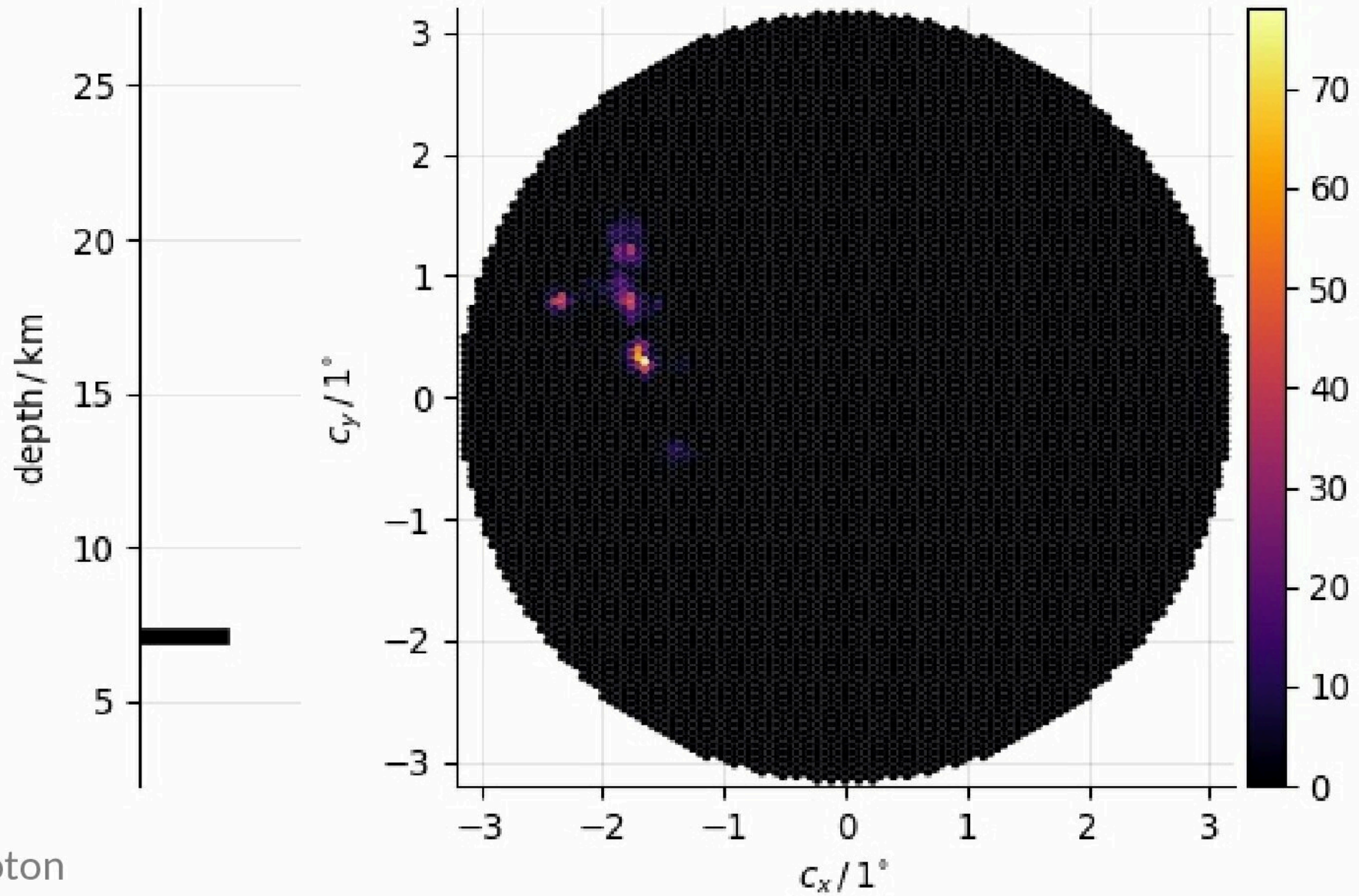
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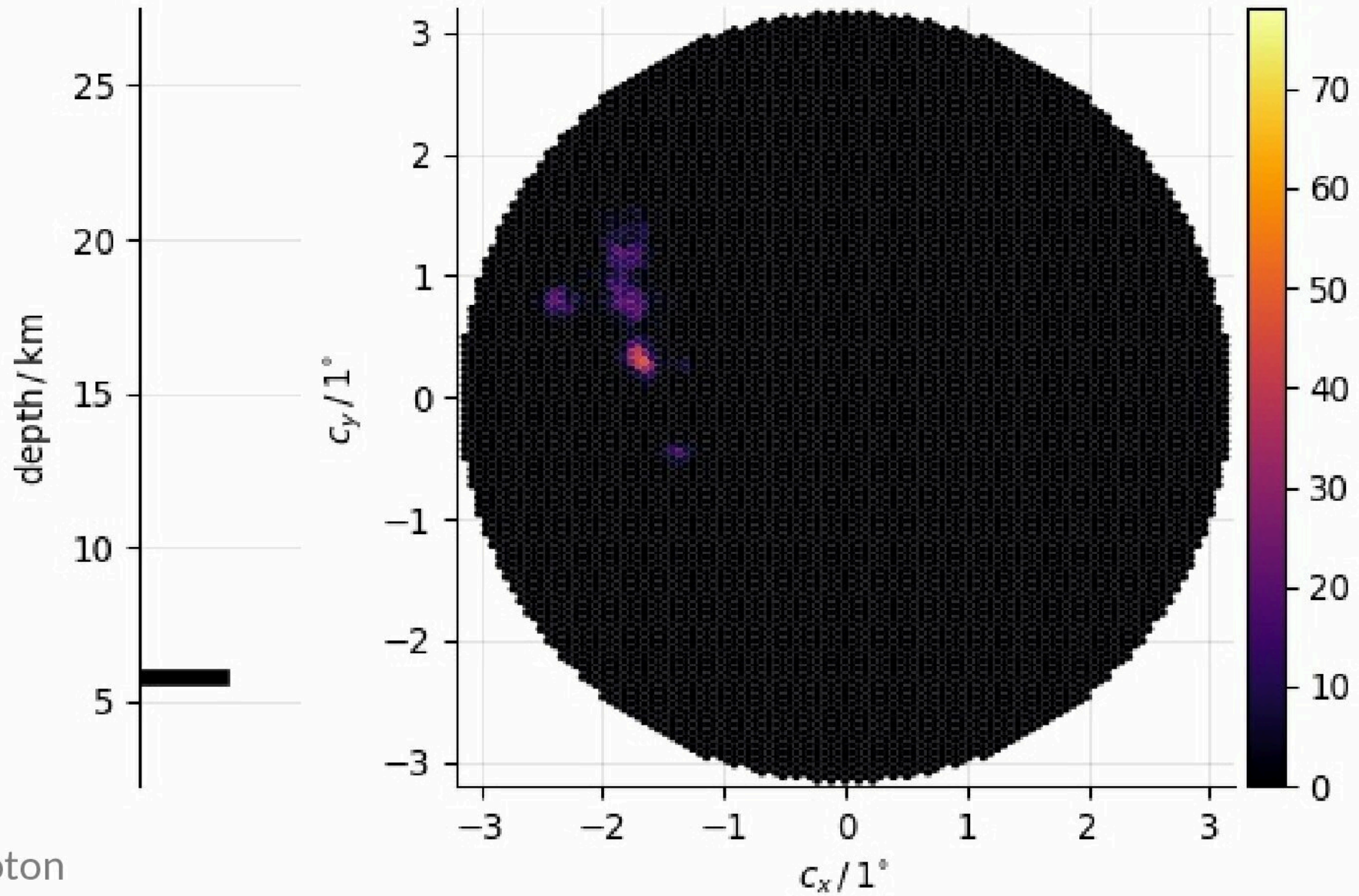
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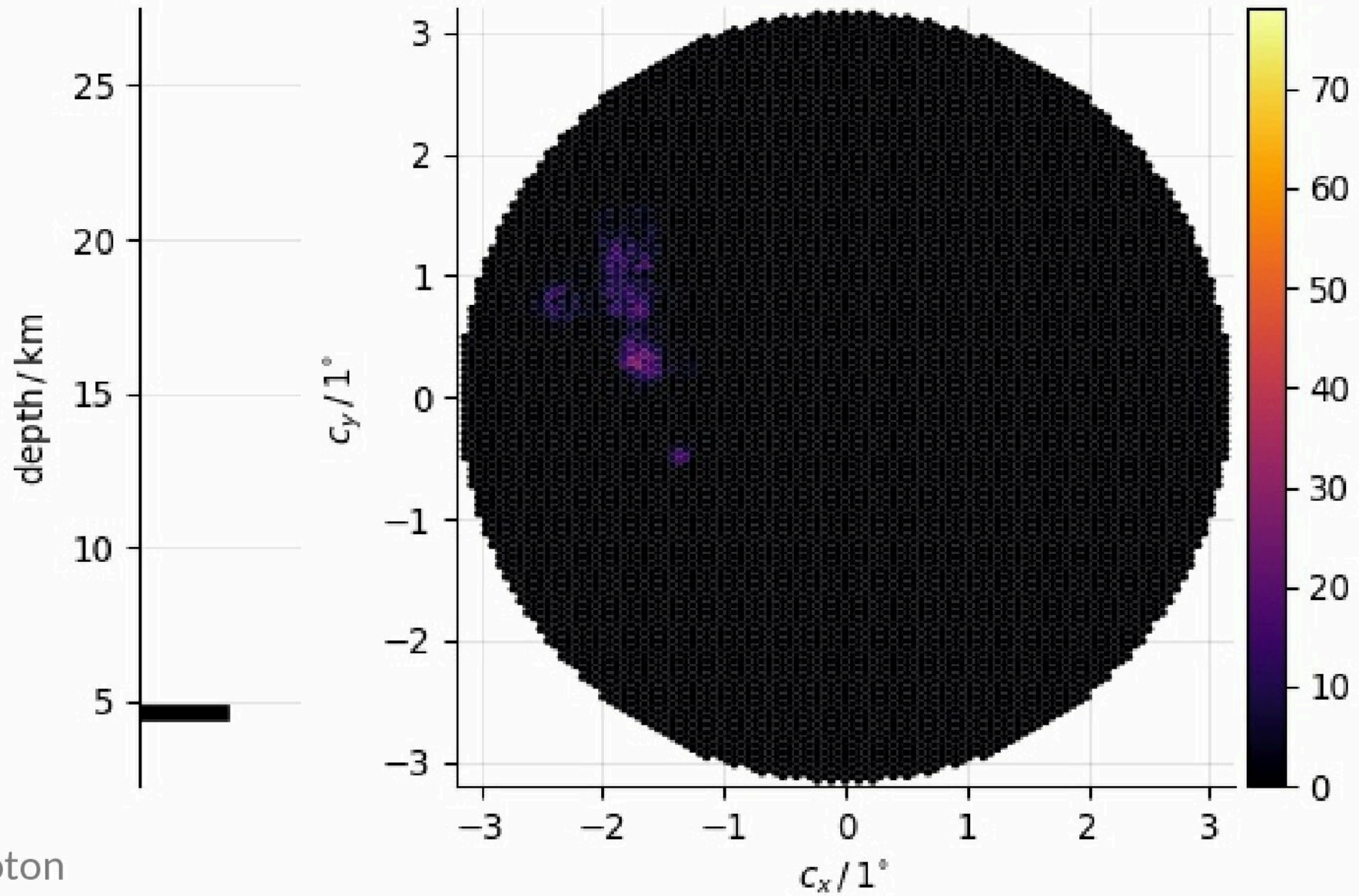
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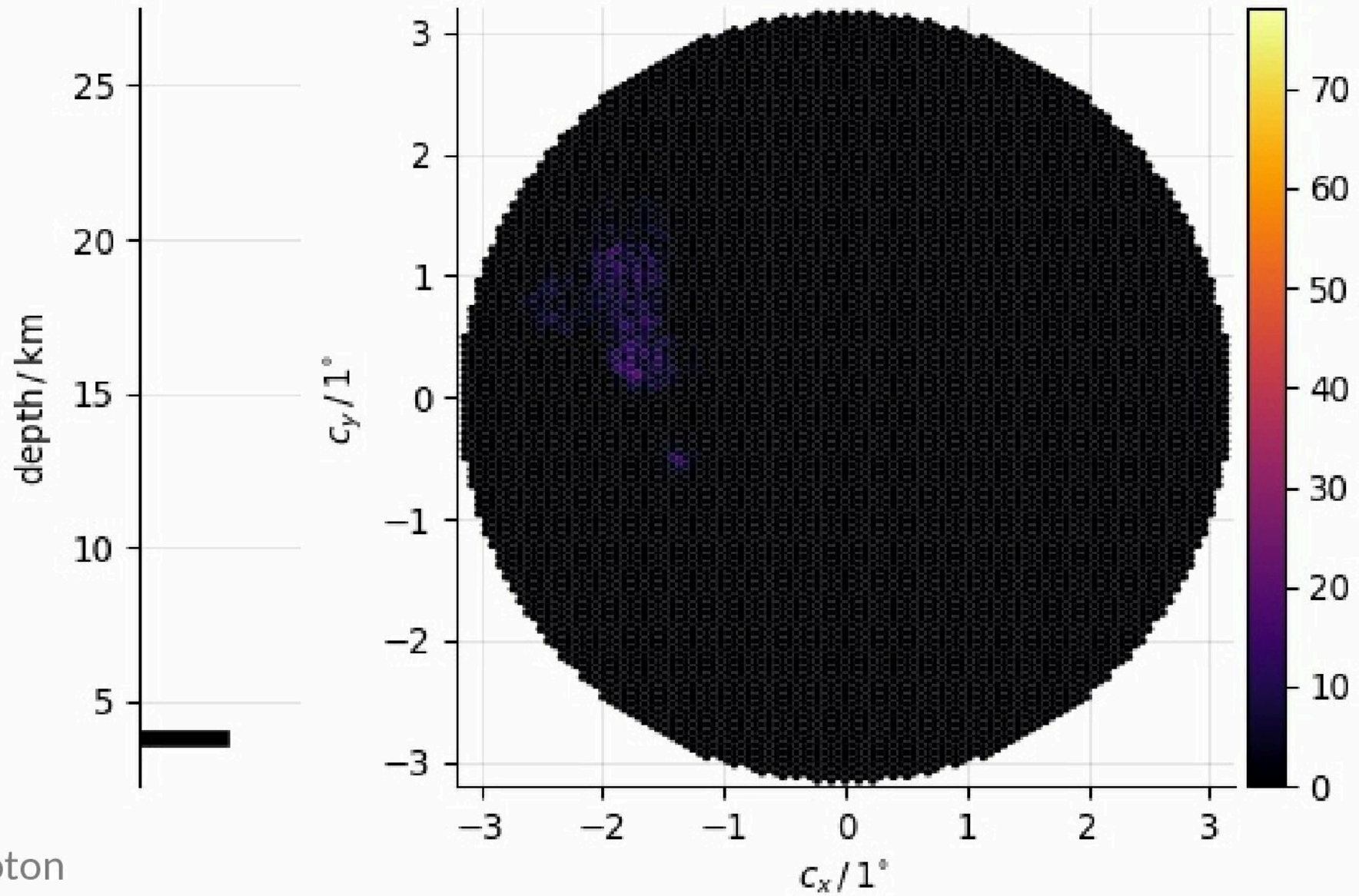
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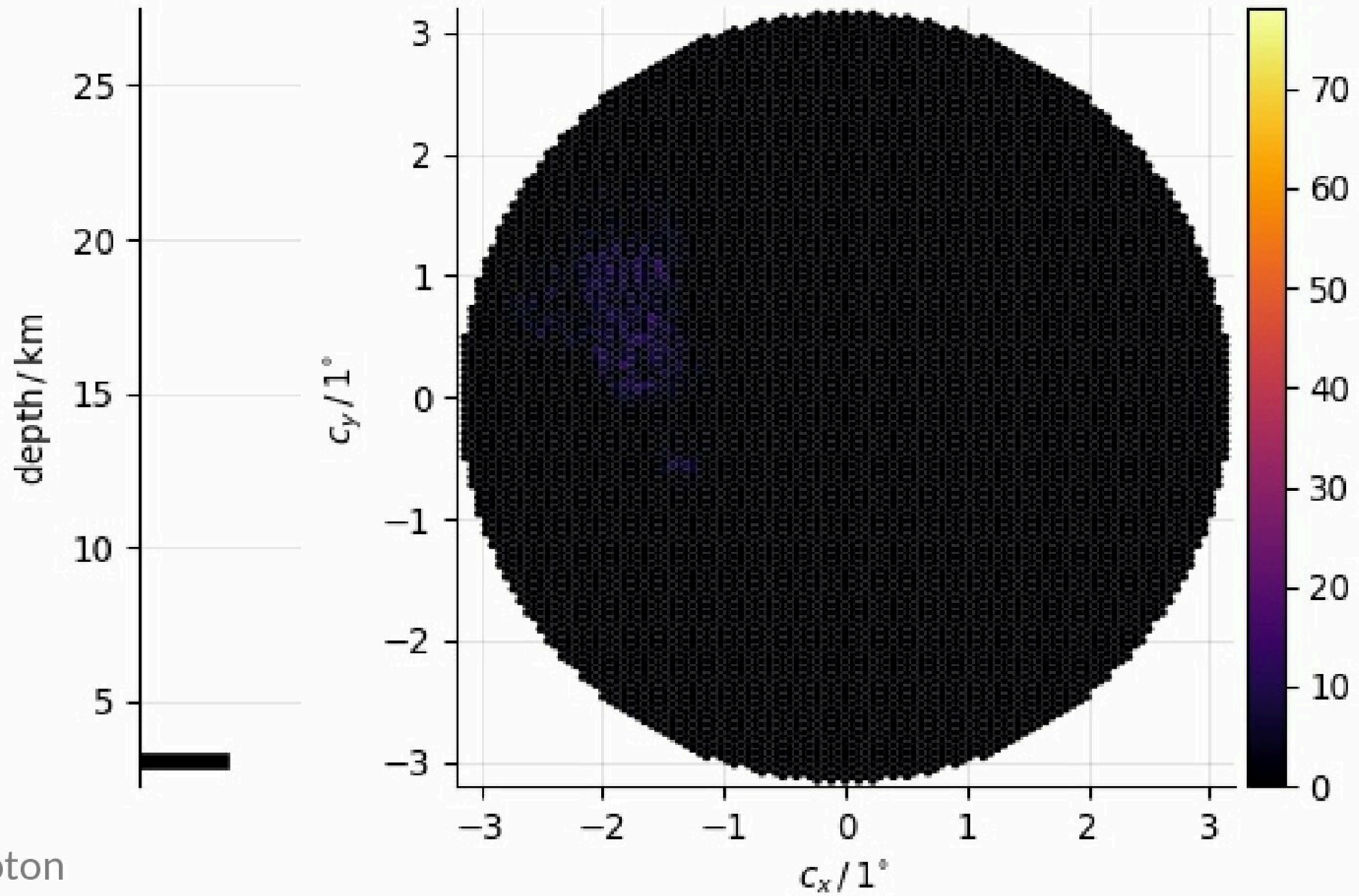
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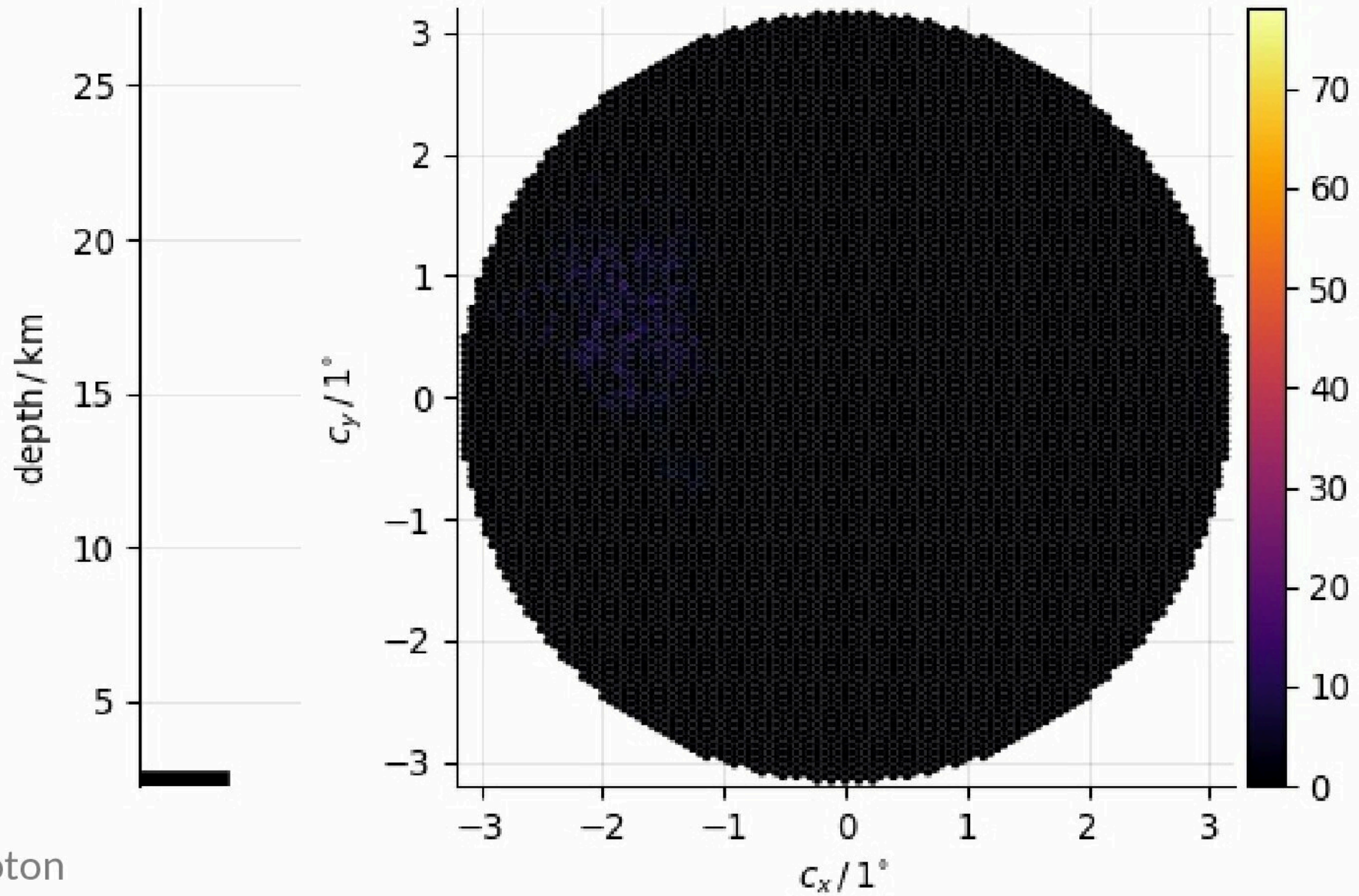
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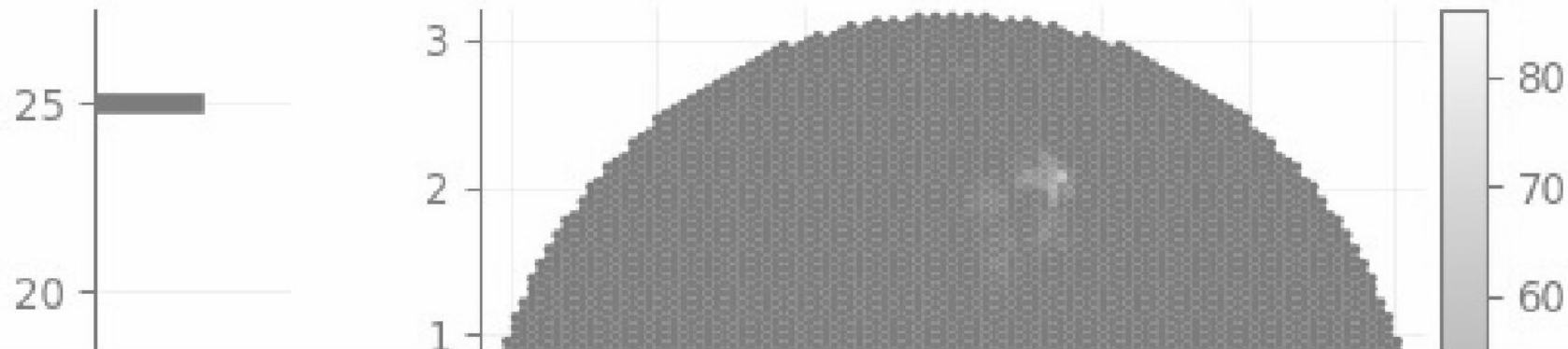
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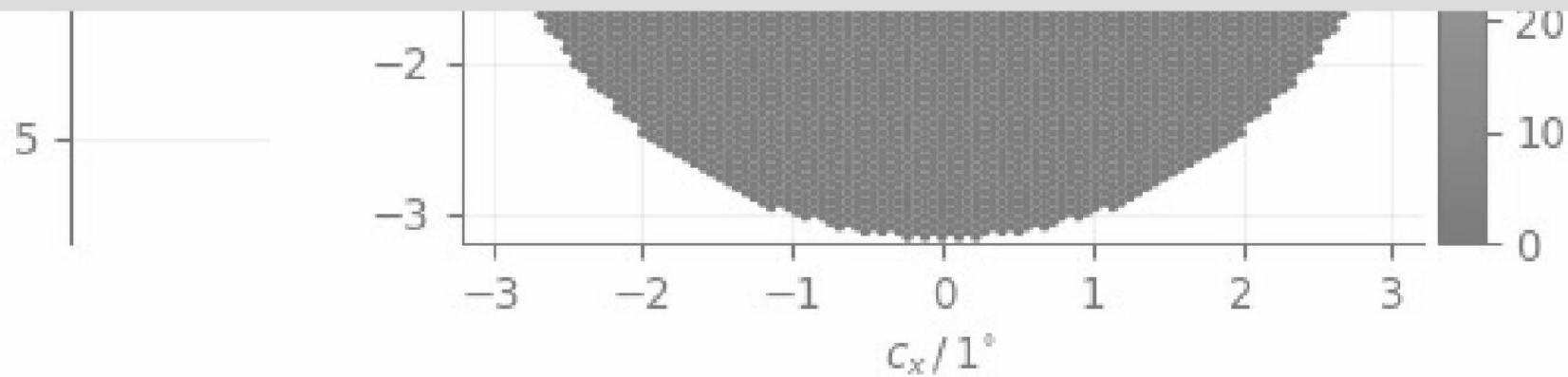
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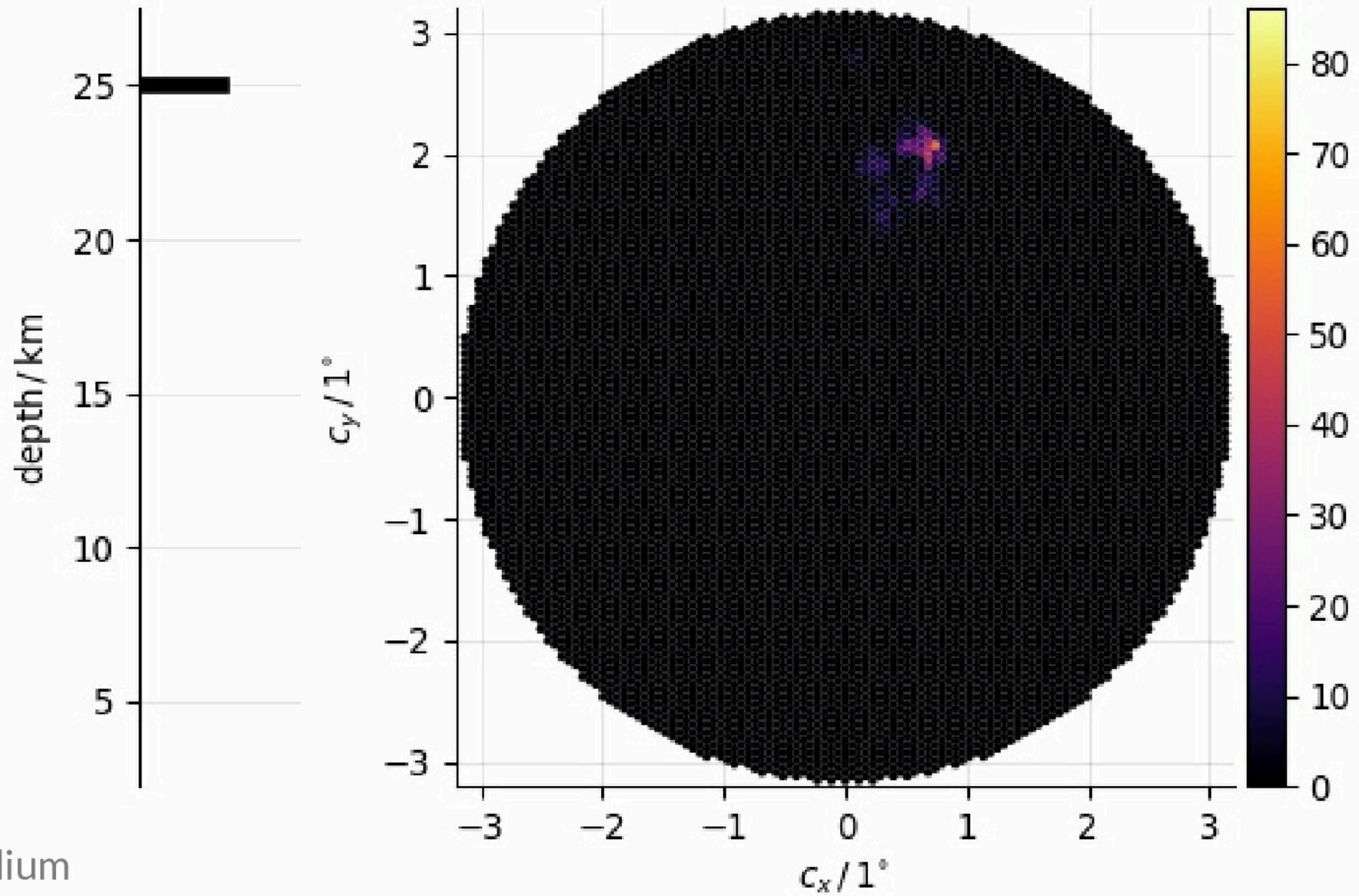


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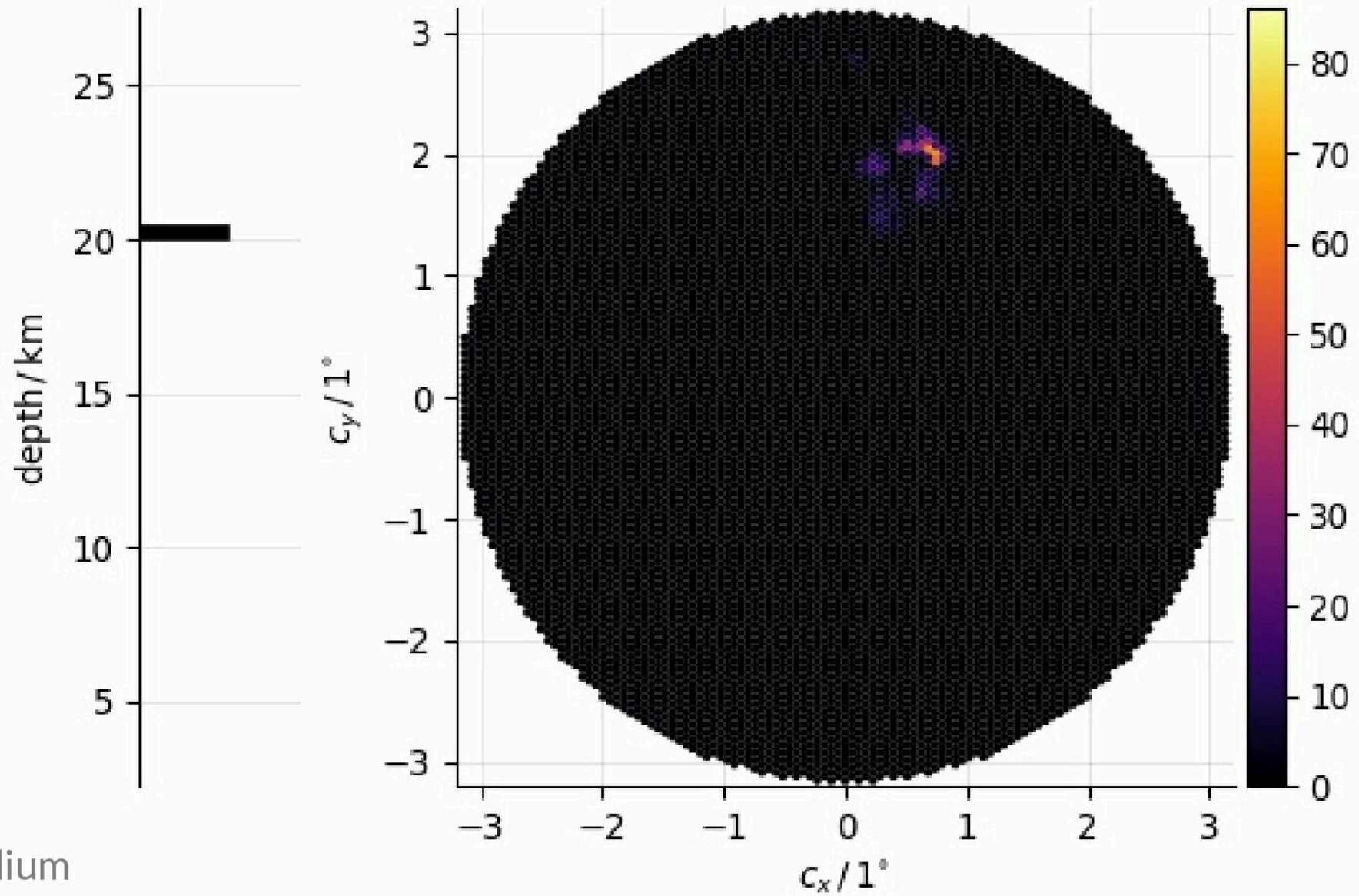


Helium-showers

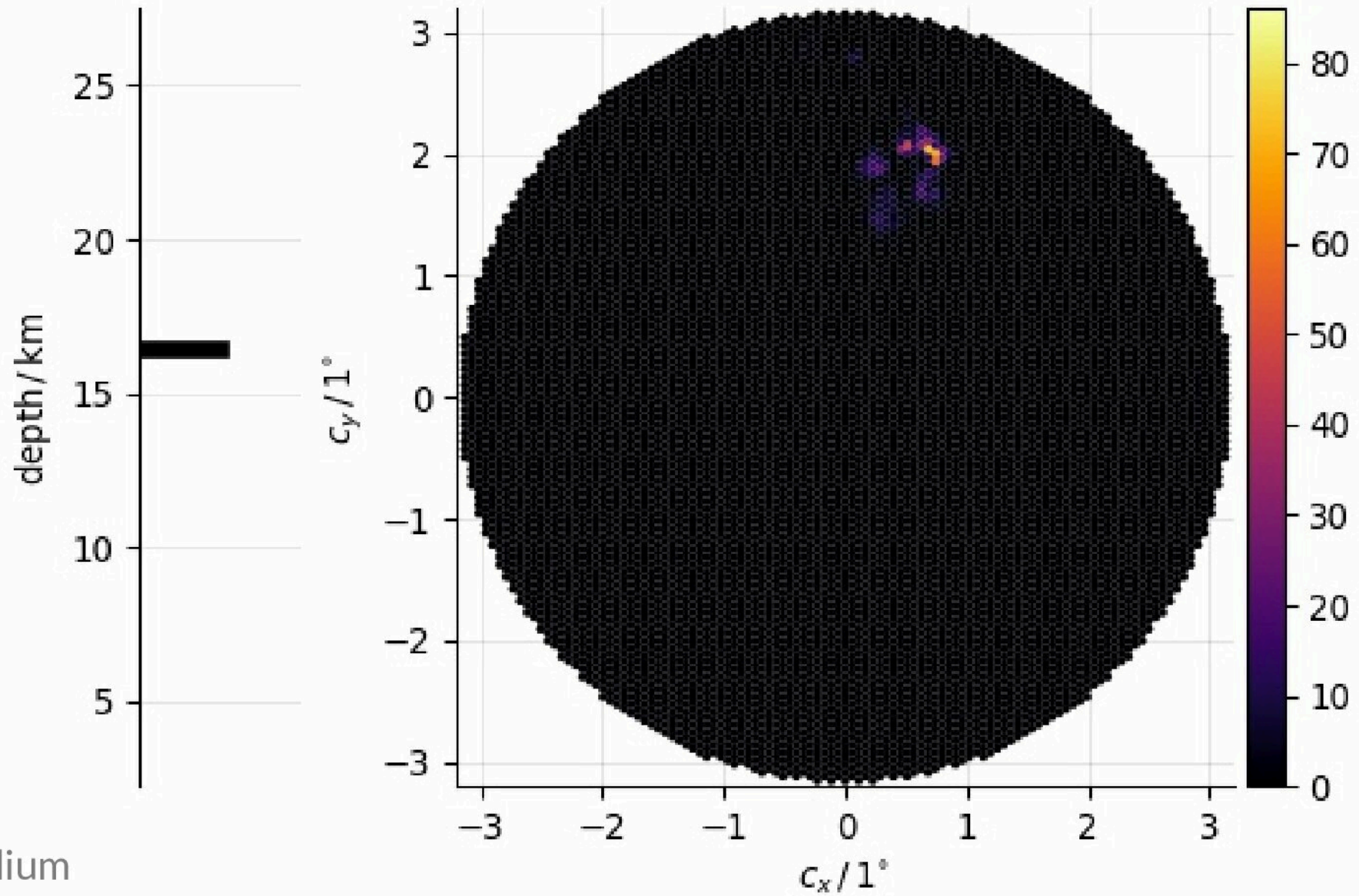




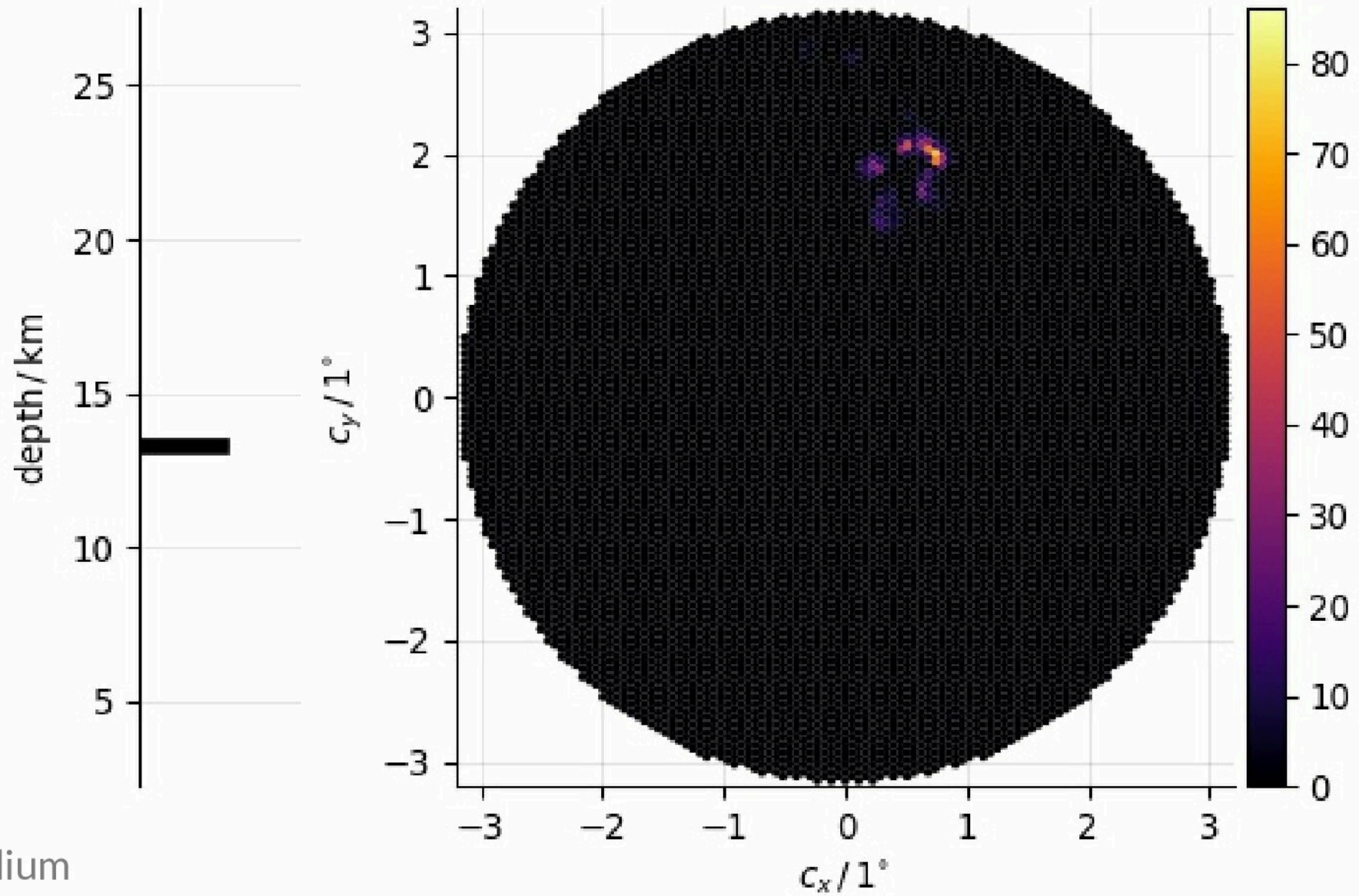
Helium



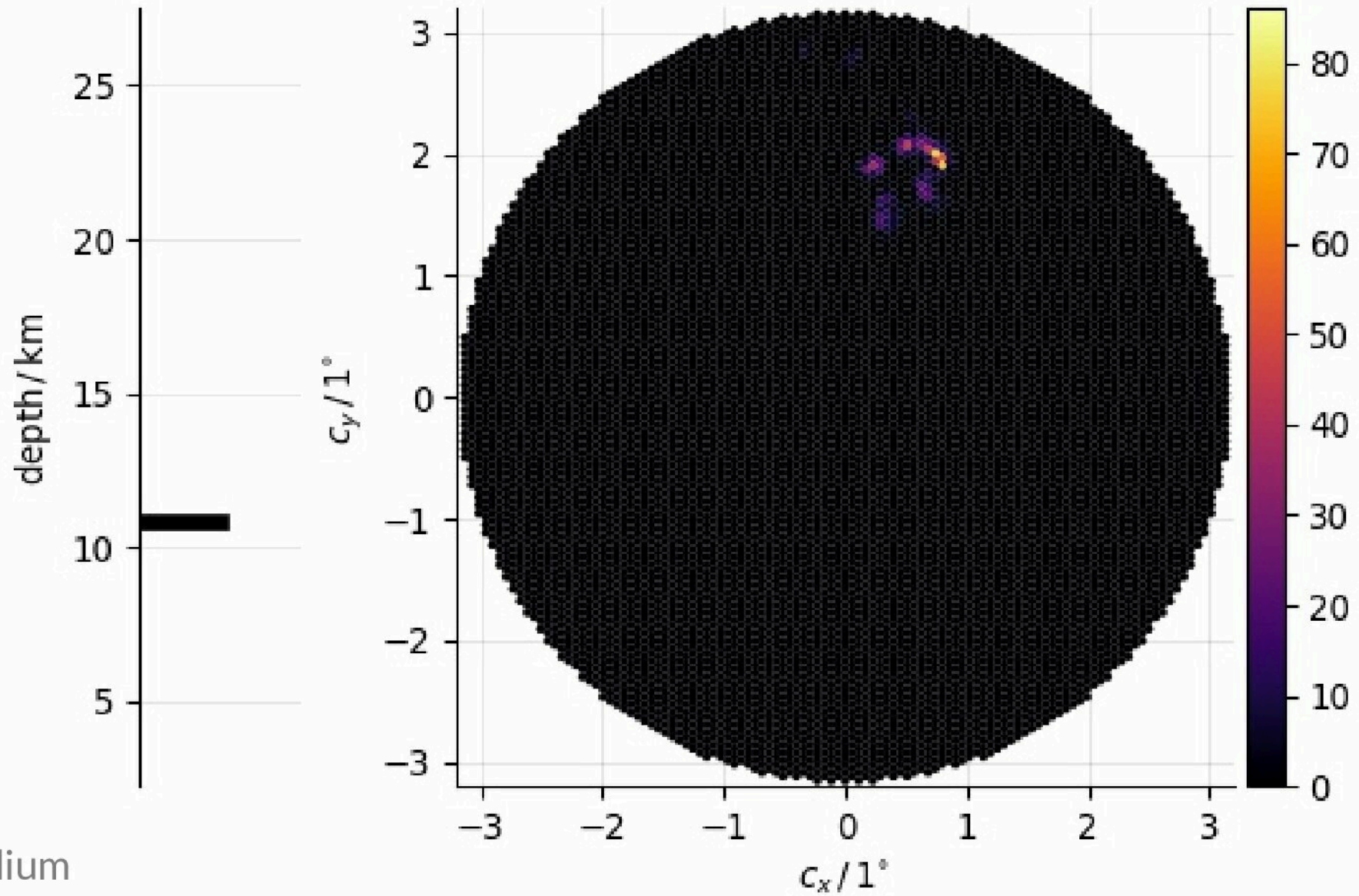
Helium



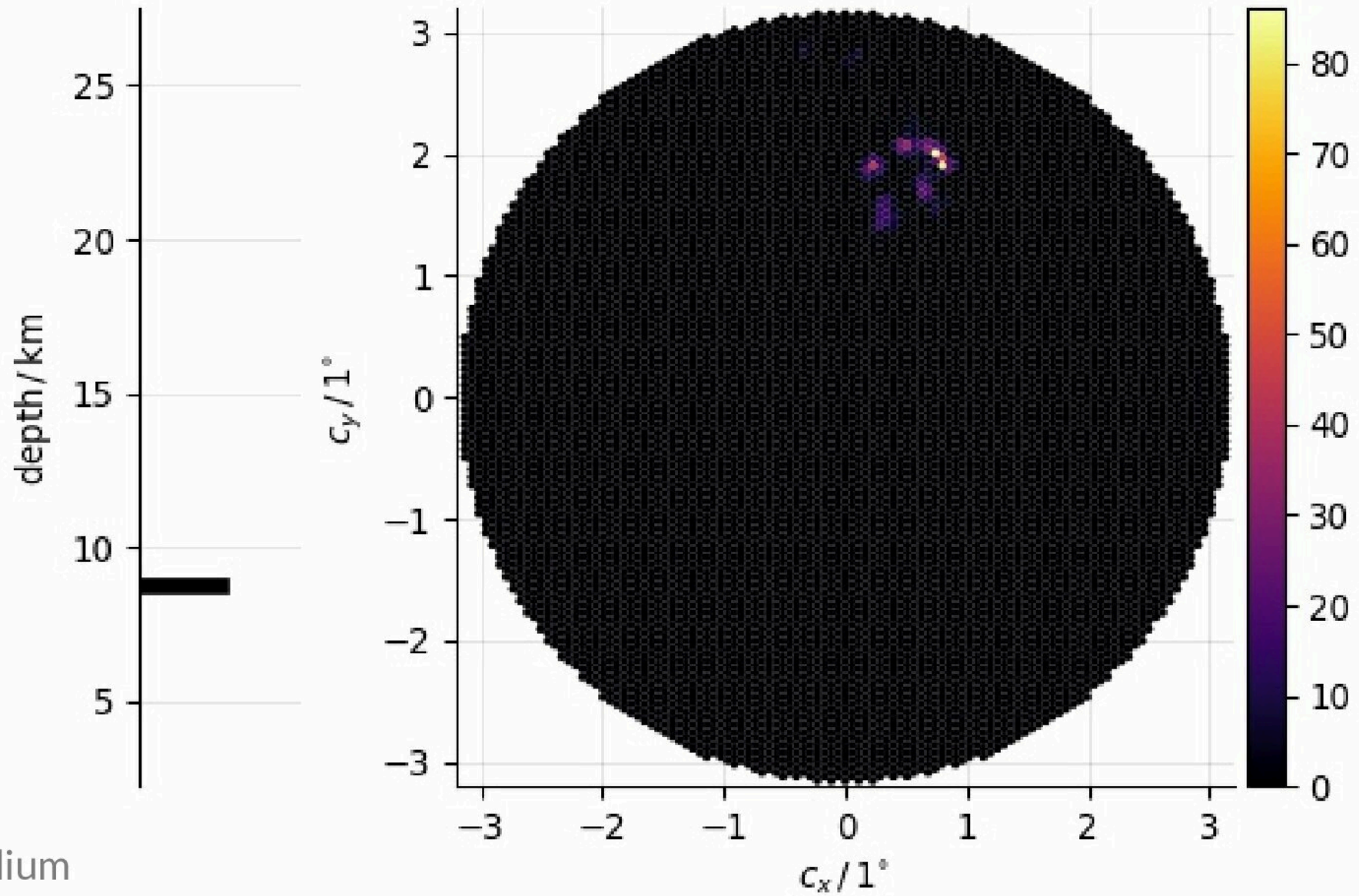
Helium



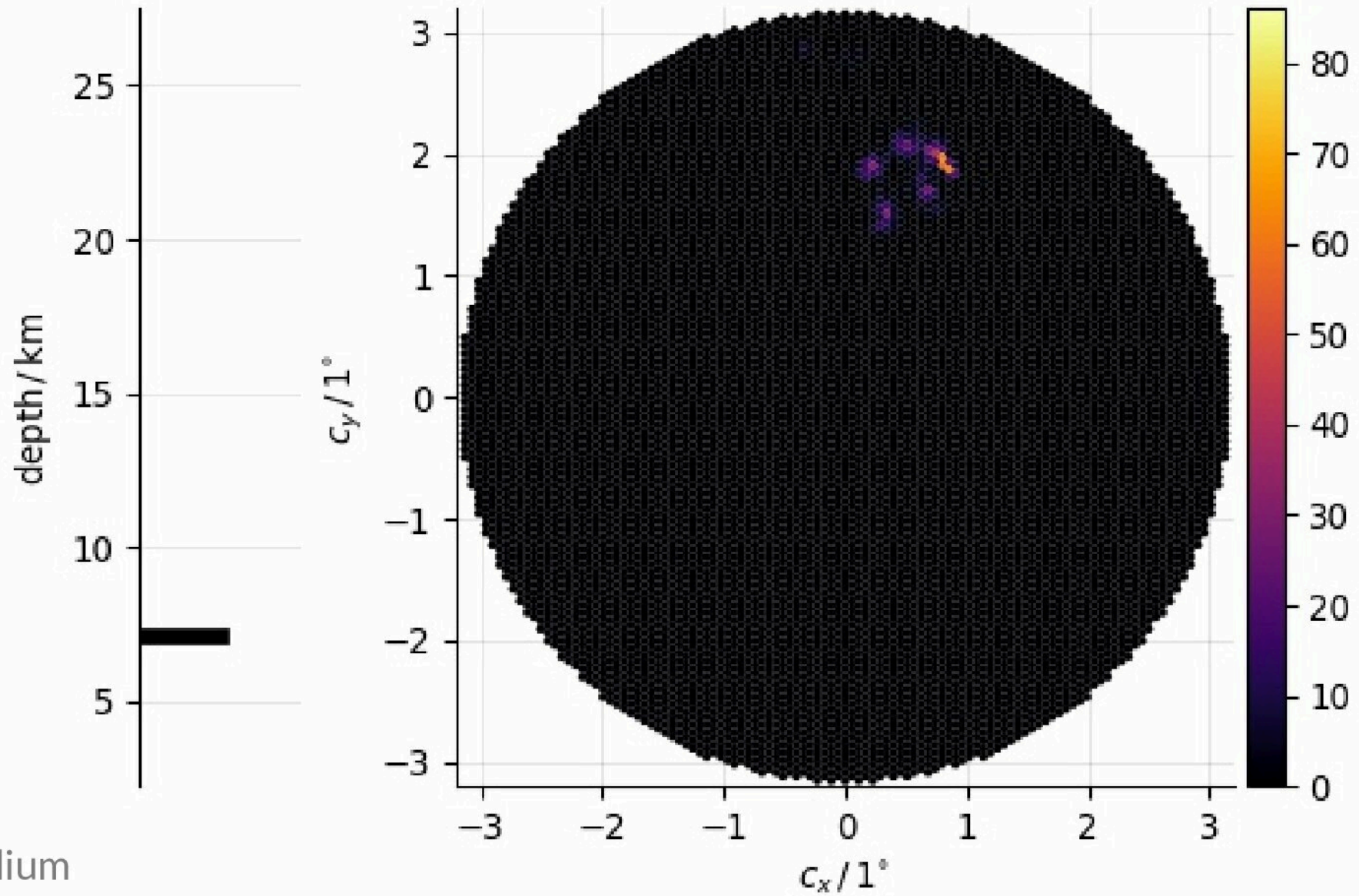
Helium

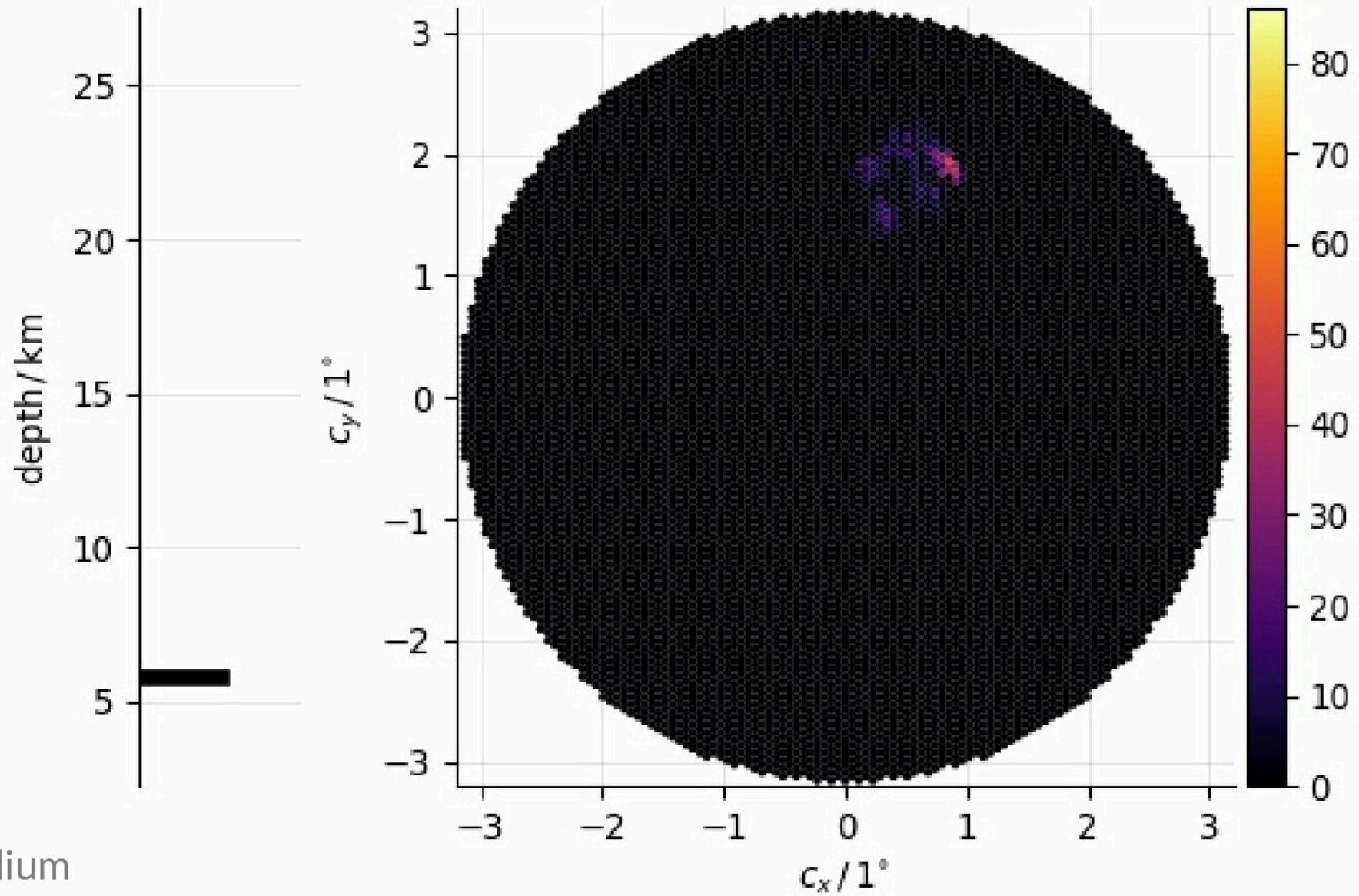


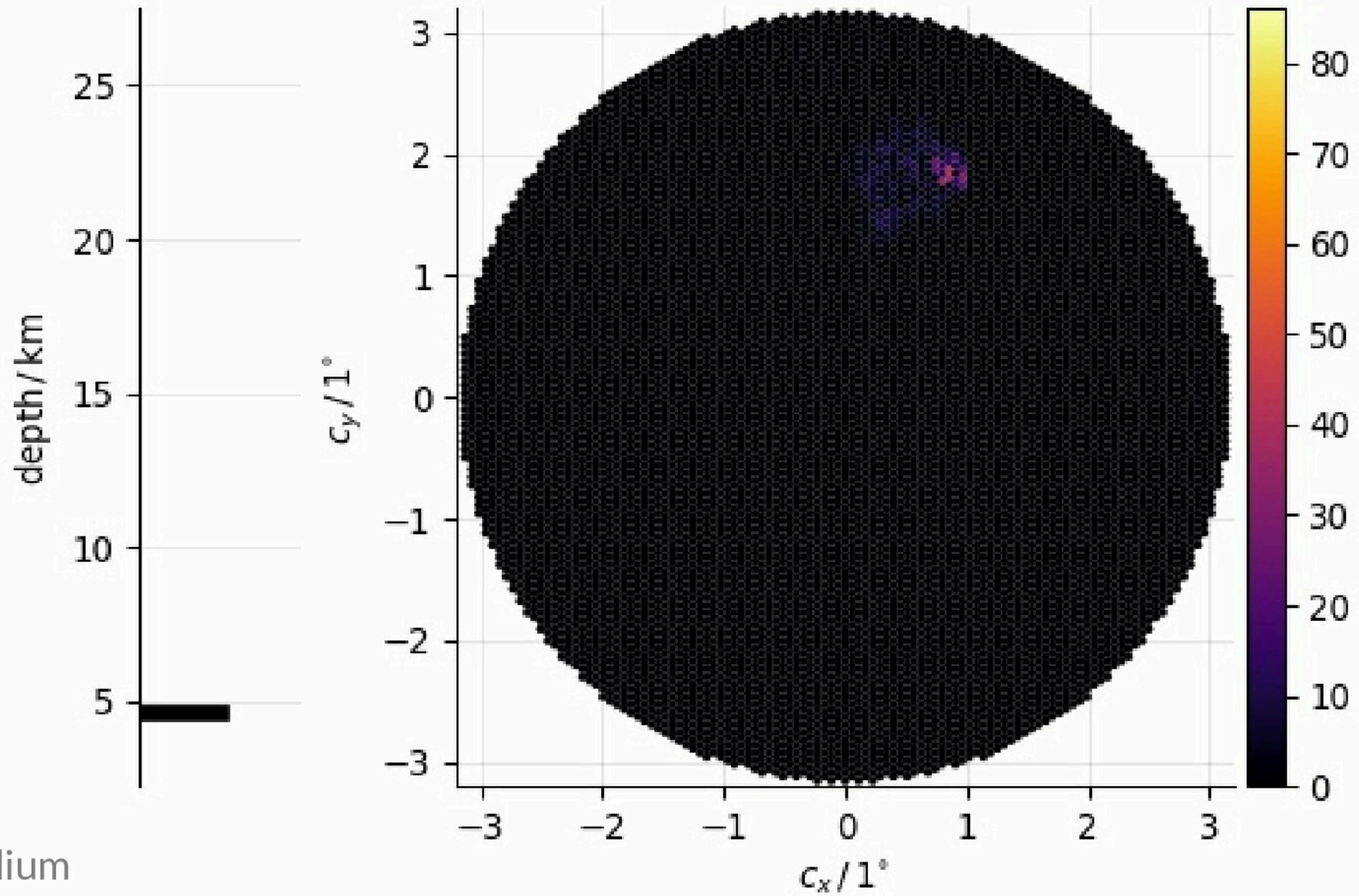
Helium



Helium

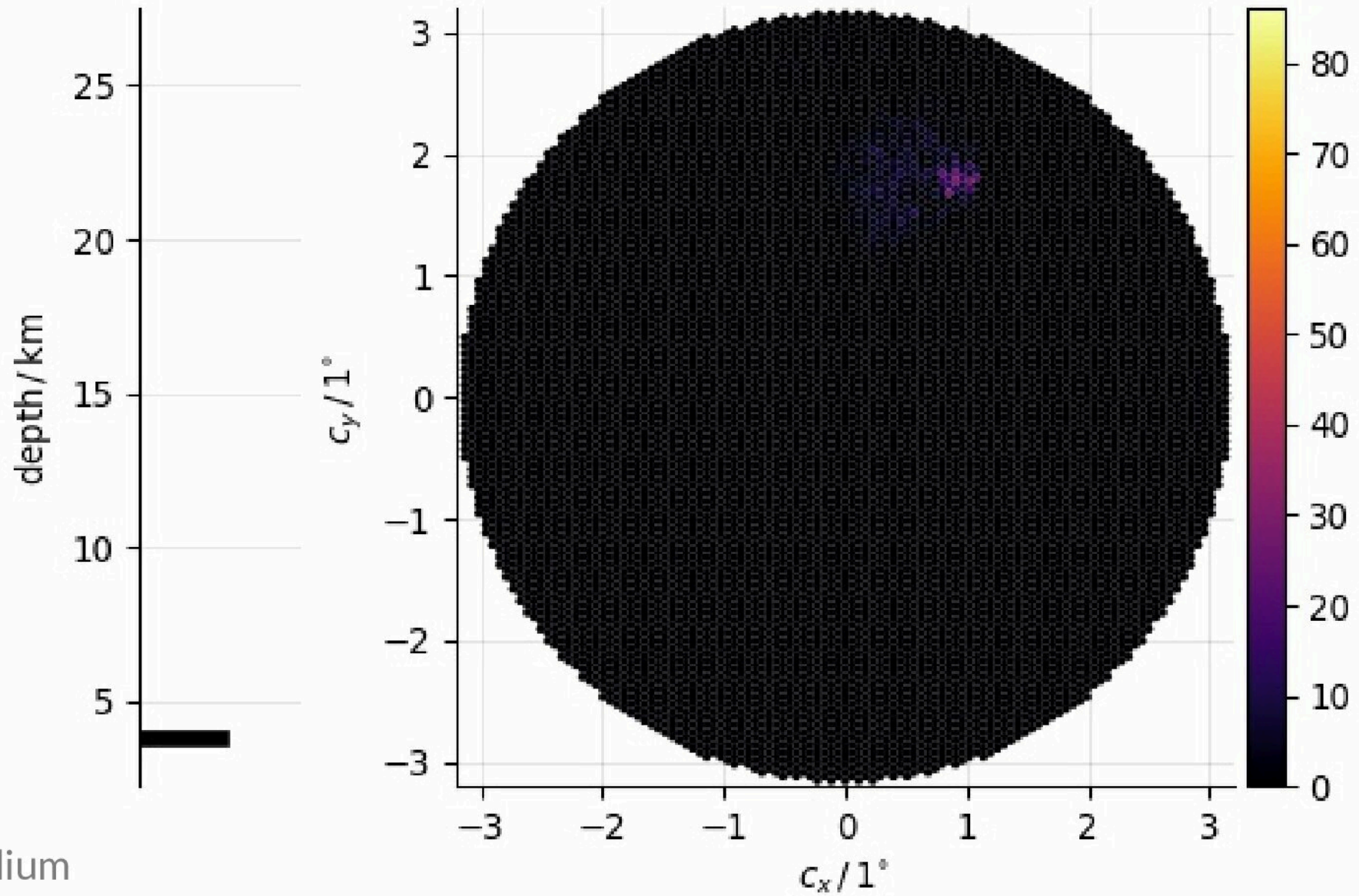


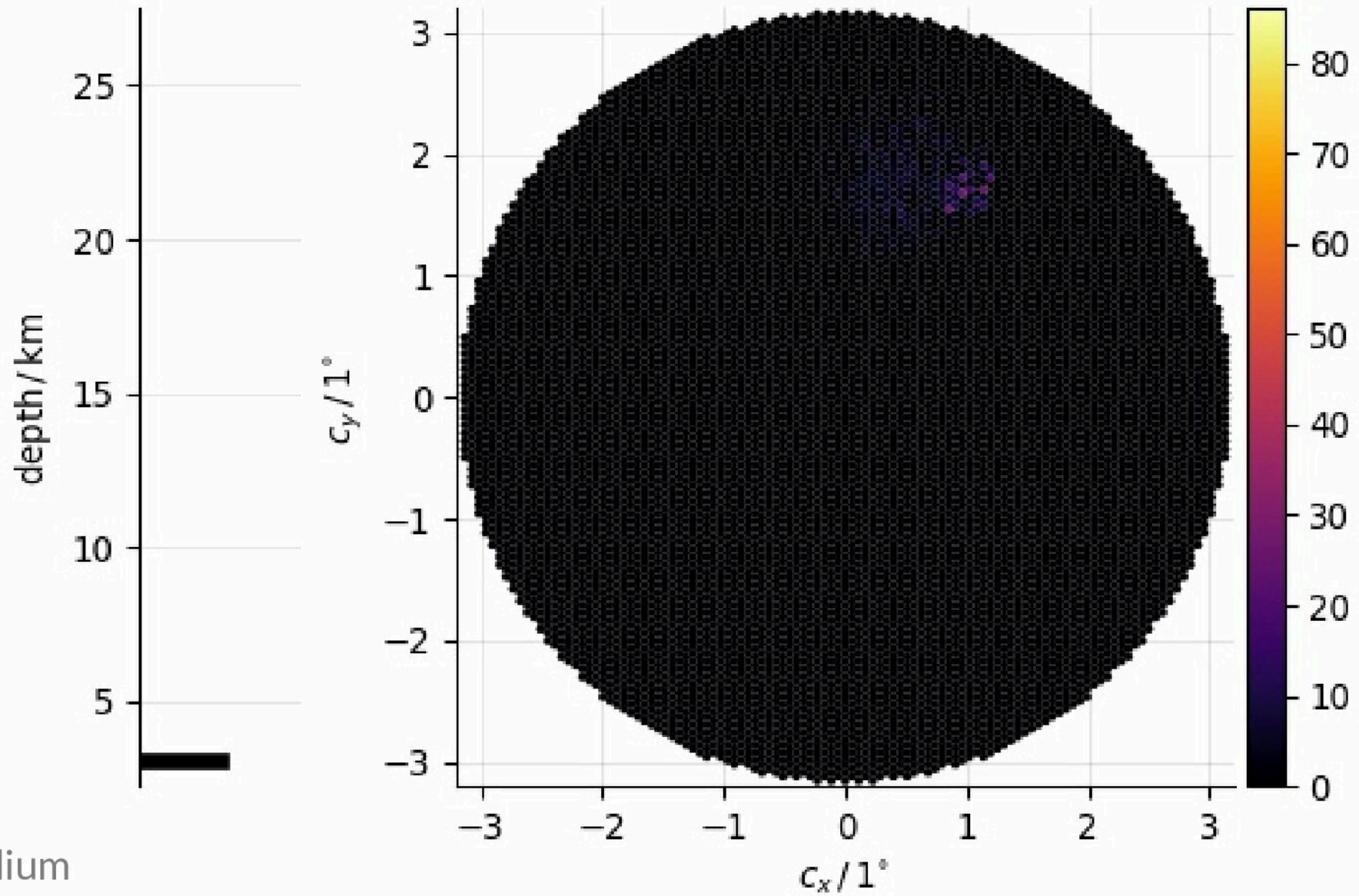


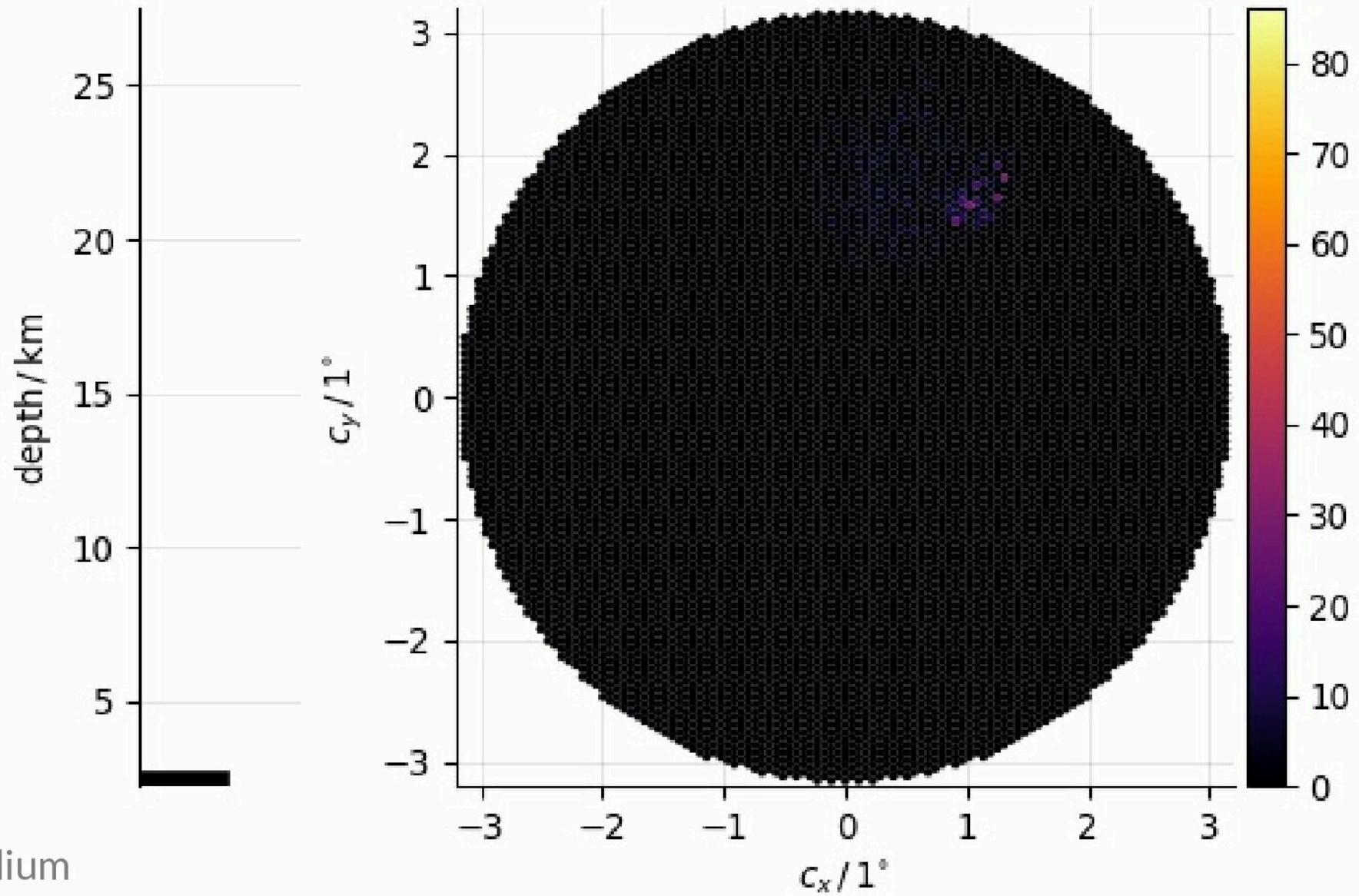


Helium

200



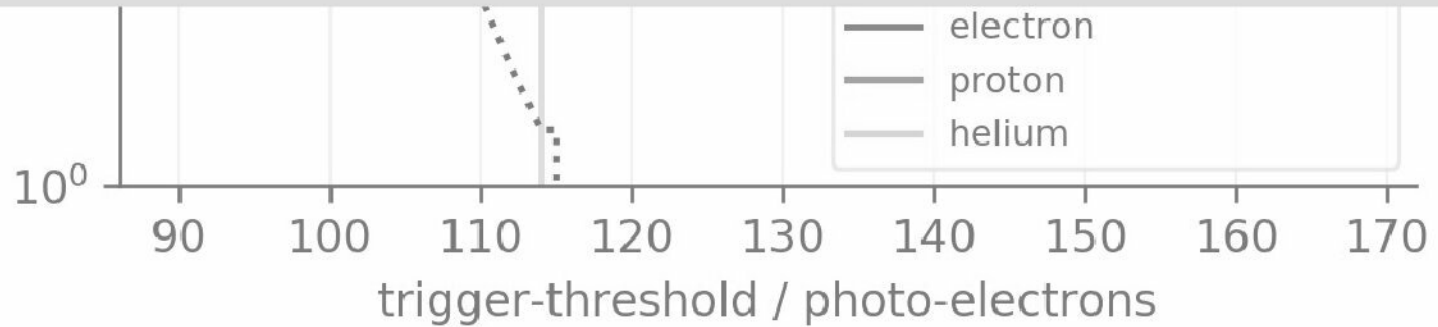




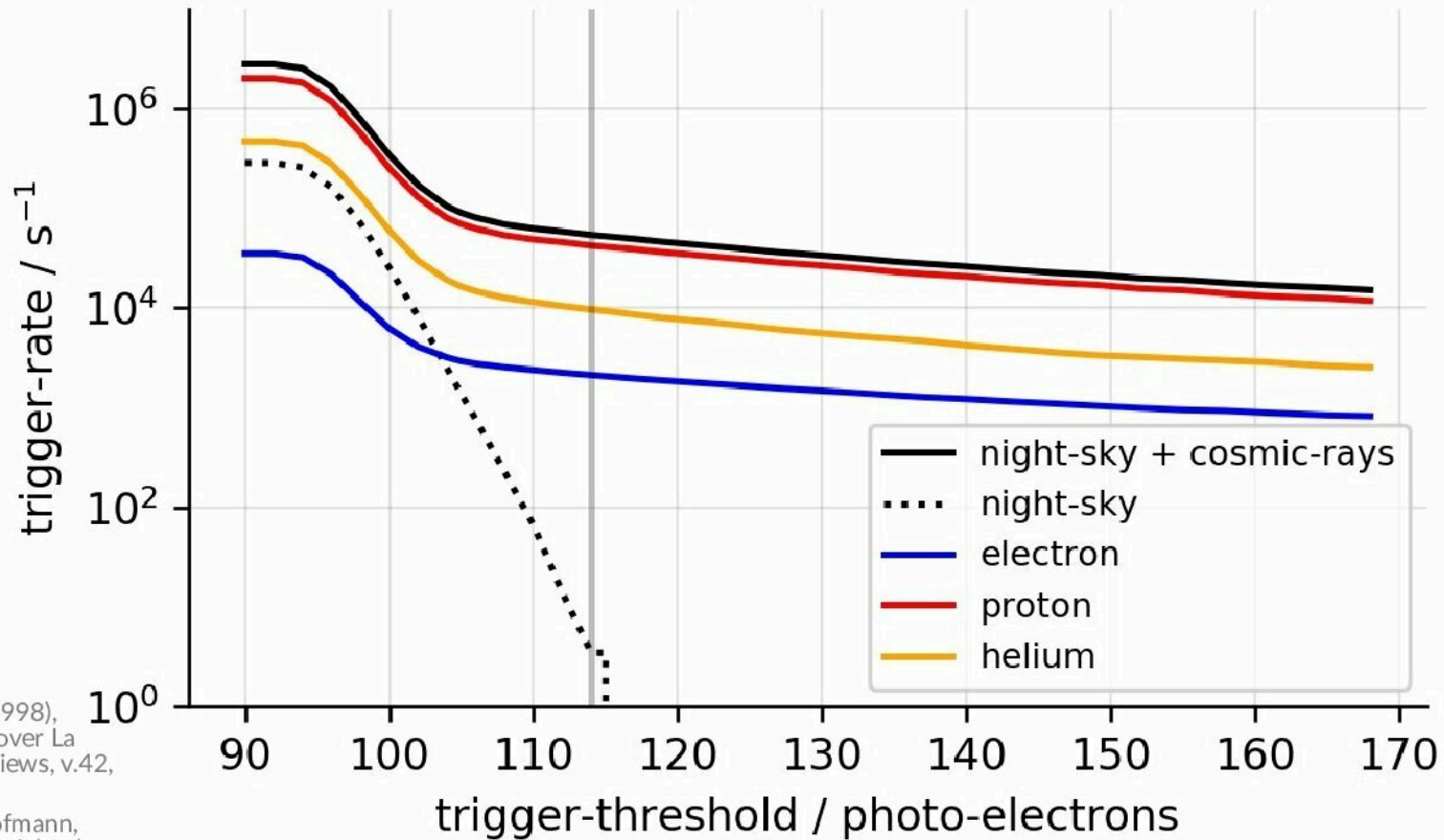
Helium



Performance (so far)



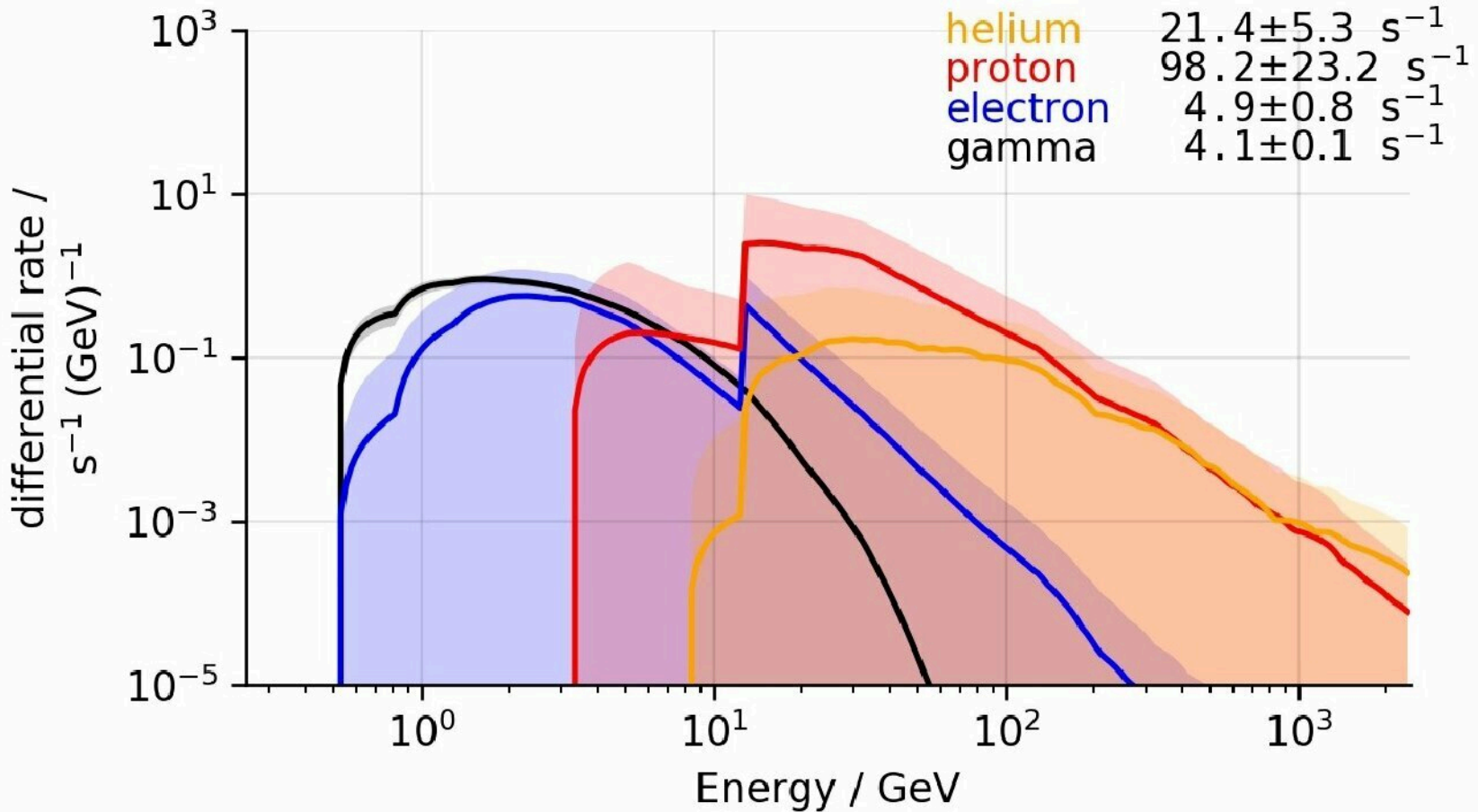
Performance, Rate-Scan



C.R. Benn and S.L. Ellison (1998),
Brightness of the night sky over La
Palma, New Astronomy Reviews, v.42,
n.6-8, p.503-507

S.Preuss, G.Hermann, W.Hofmann,
A.Kohnle (2002) Study of ... night sky
at La Palma and Namibia..., NIM-A,
v.481, p.229-240

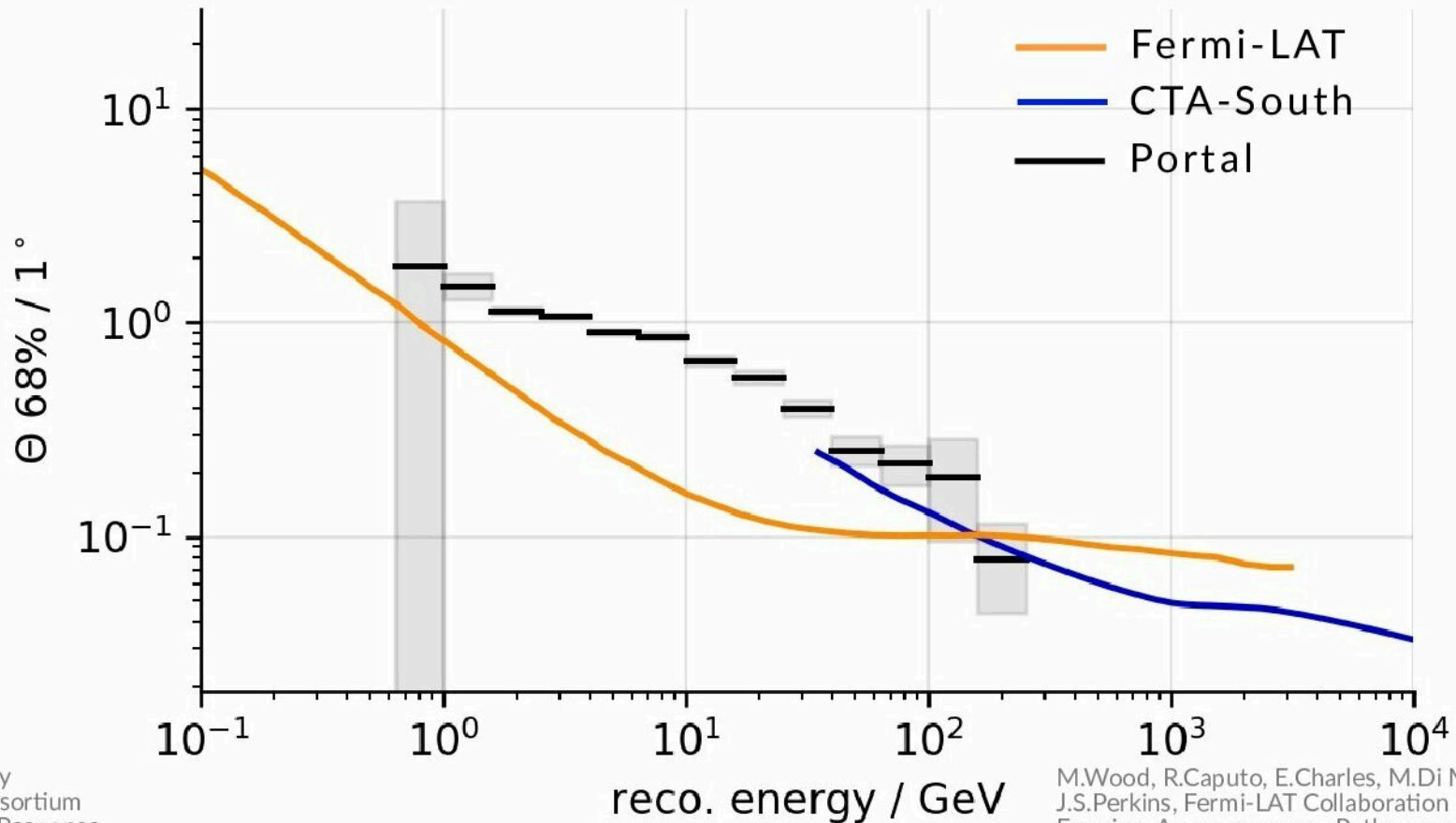
Performance, Rates on 3FGL J0534.5+2201



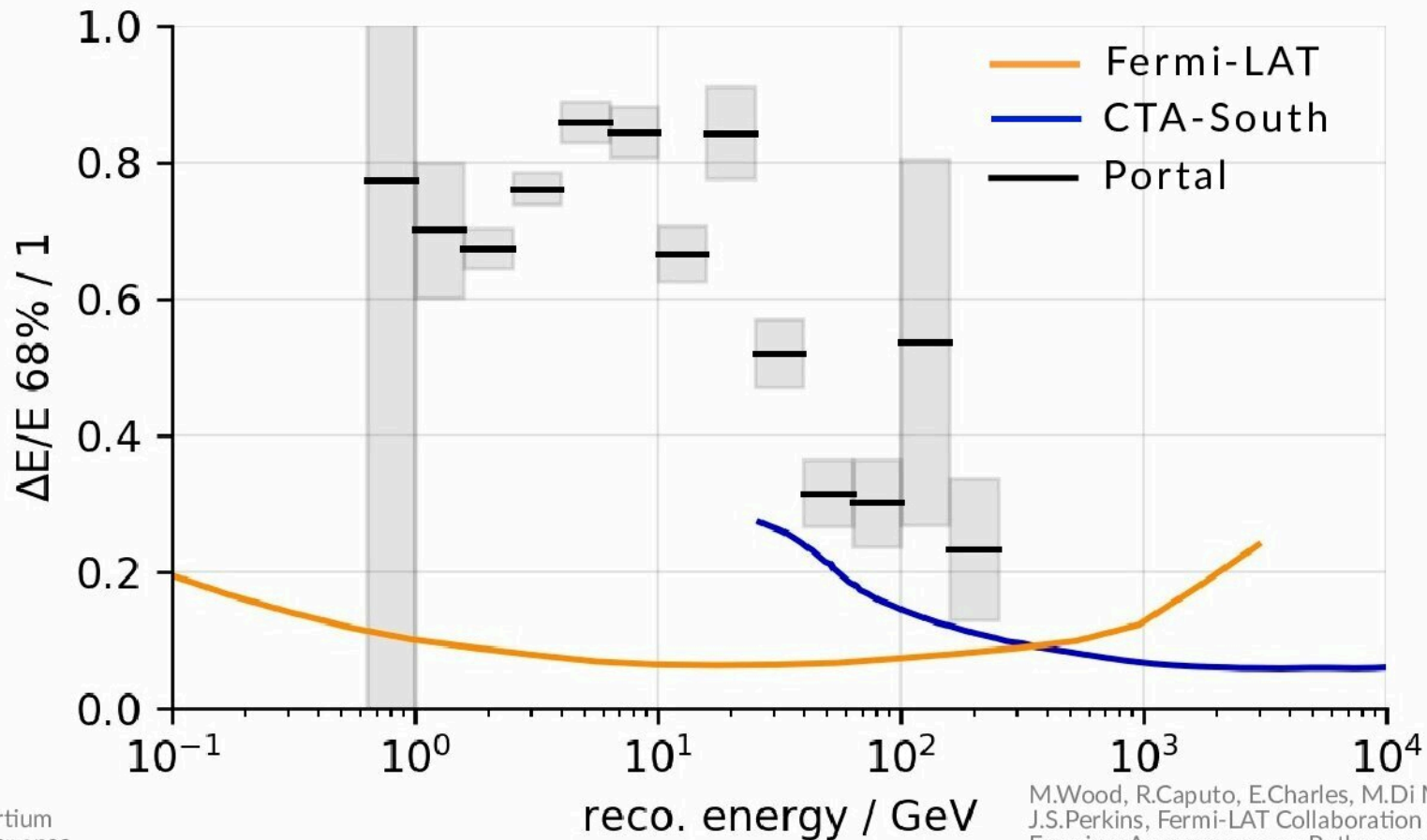
Performance, Gamma-Hadron-Separation

Not yet.

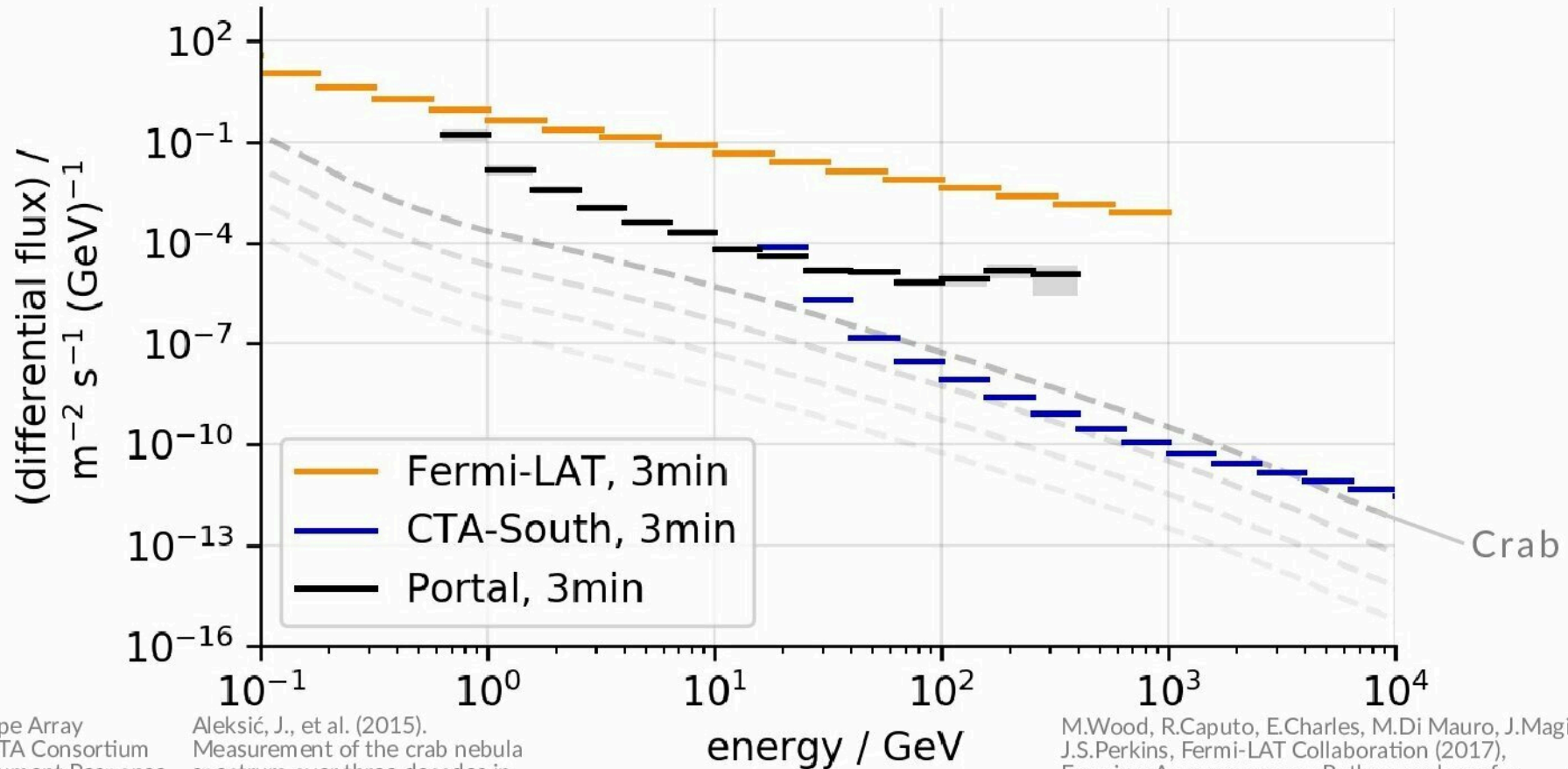
Performance, Direction



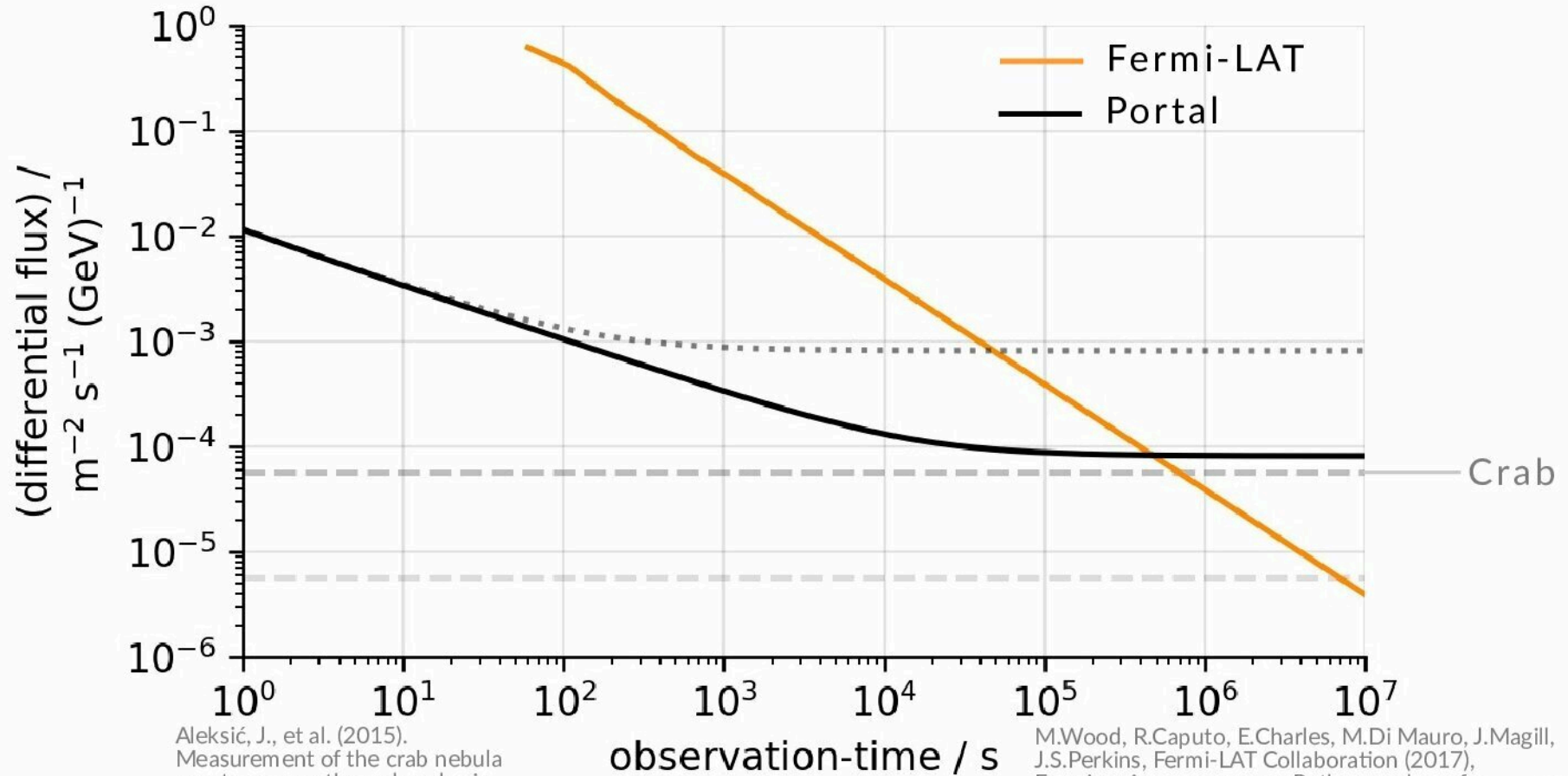
Performance, Energy



Performance, Sensitivity vs. Energy at 3min



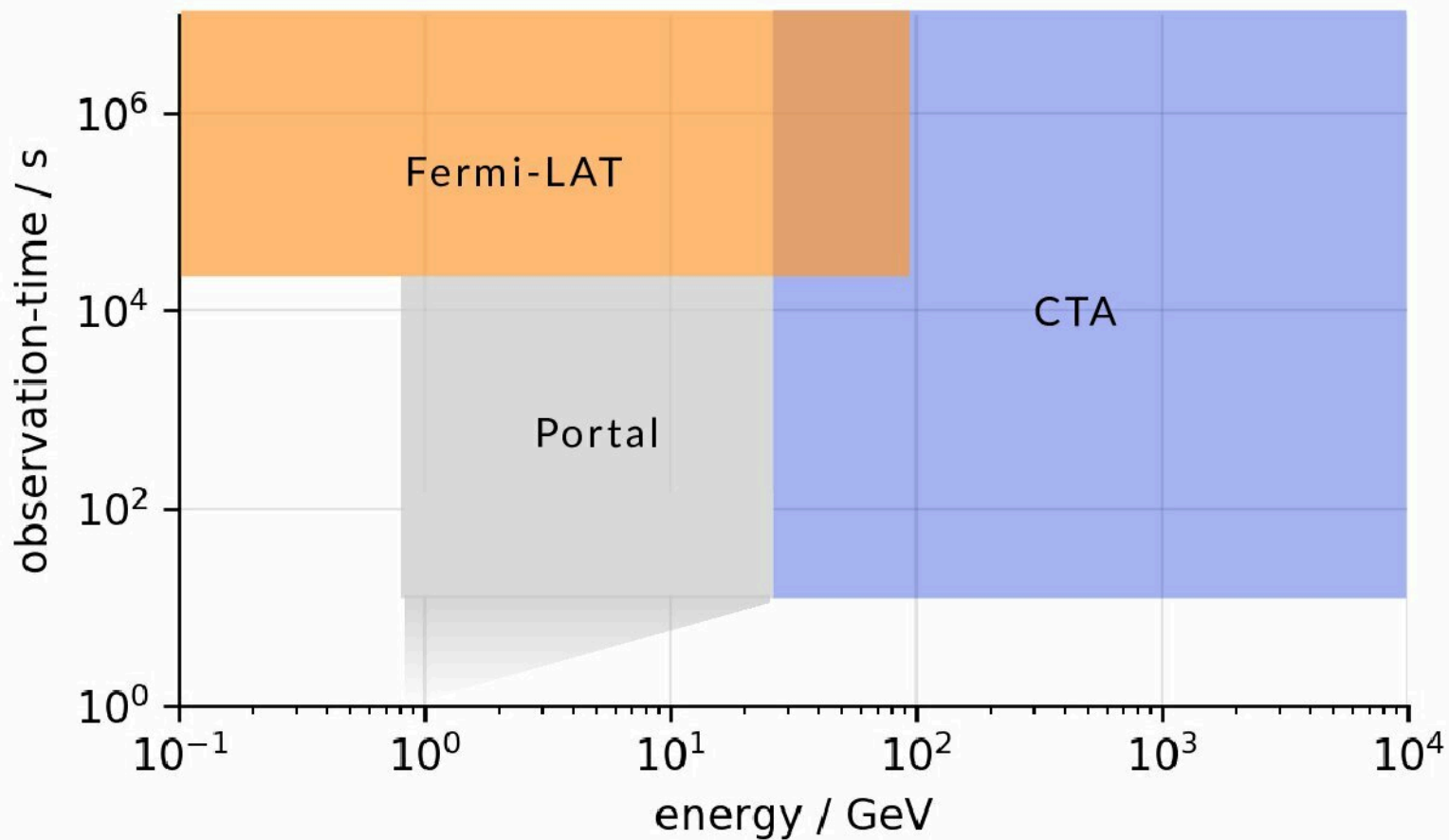
Performance, Sensitivity vs. Time at 2.5GeV



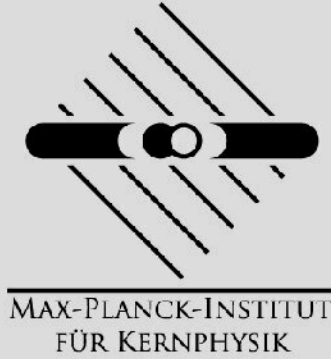
Aleksić, J., et al. (2015).
Measurement of the crab nebula
spectrum over three decades in
energy with the magic telescopes.
High Energy Astrophysics, 5:30–38.

M.Wood, R.Caputo, E.Charles, M.Di Mauro, J.Magill,
J.S.Perkins, Fermi-LAT Collaboration (2017),
Fermipy: An open-source Python package for
analysis of Fermi-LAT Data, Proc. 35th ICRC,
PoS(ICRC2017)824, IRF: P8R2_SOURCE_V6

Gamma-Ray-Timing-Explorer



Acknowledgment

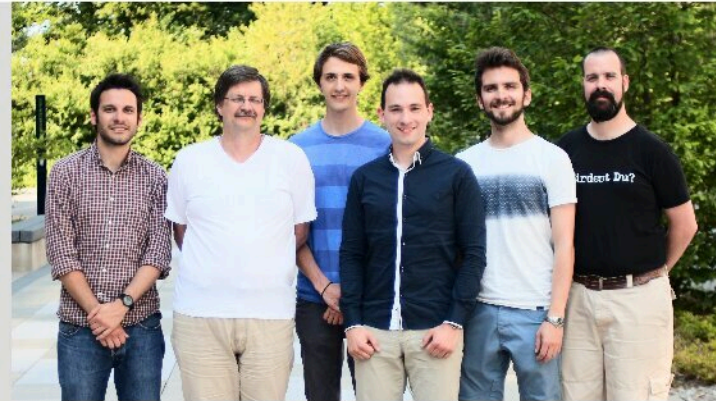


Werner Hofmann,
Jim Hinton

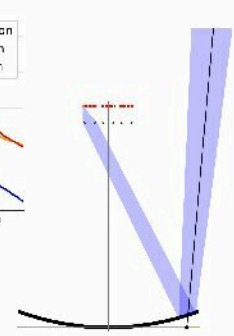
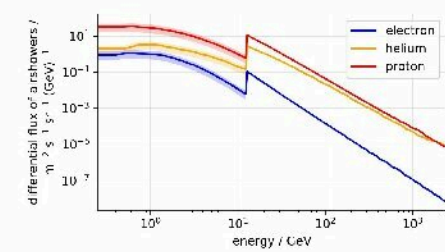
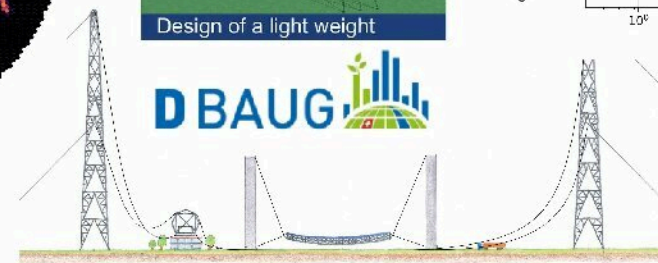
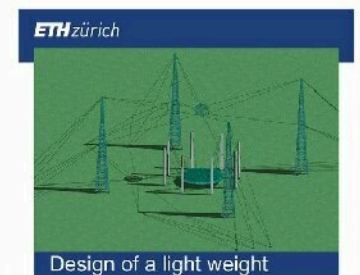
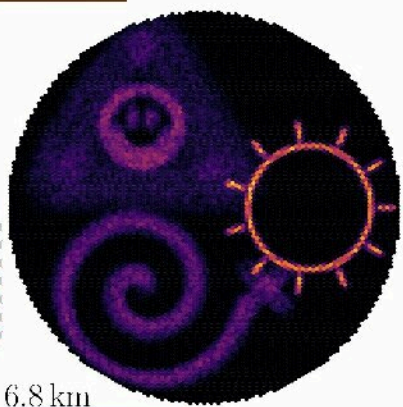
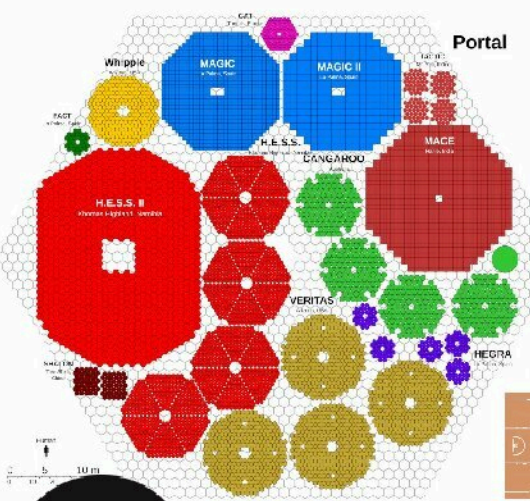
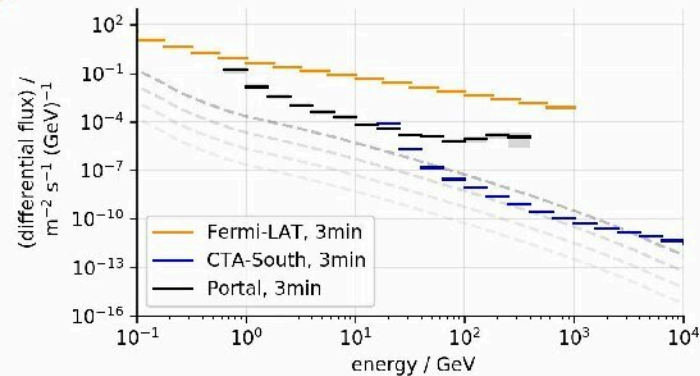
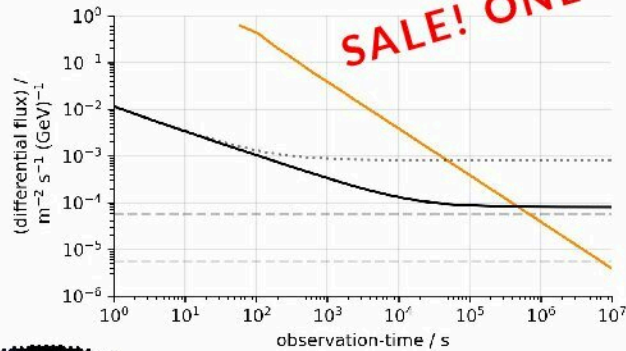
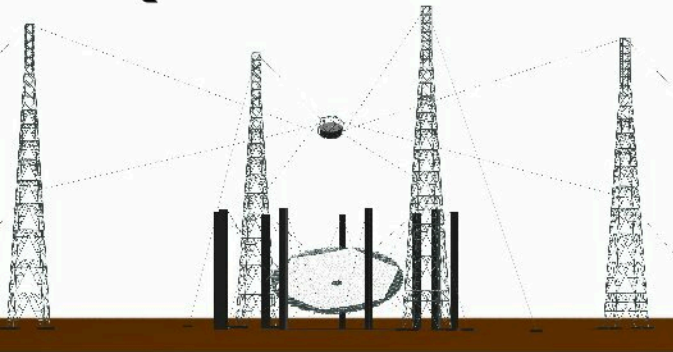


ETH zürich

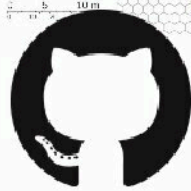
Adrian Biland, Felicitas Paus,
Max L. Ahnen, Dominik Neise,
Spyridon Daglas, Axel A. Engels,
Eleni Chatzi, Adrian Egger



Questions



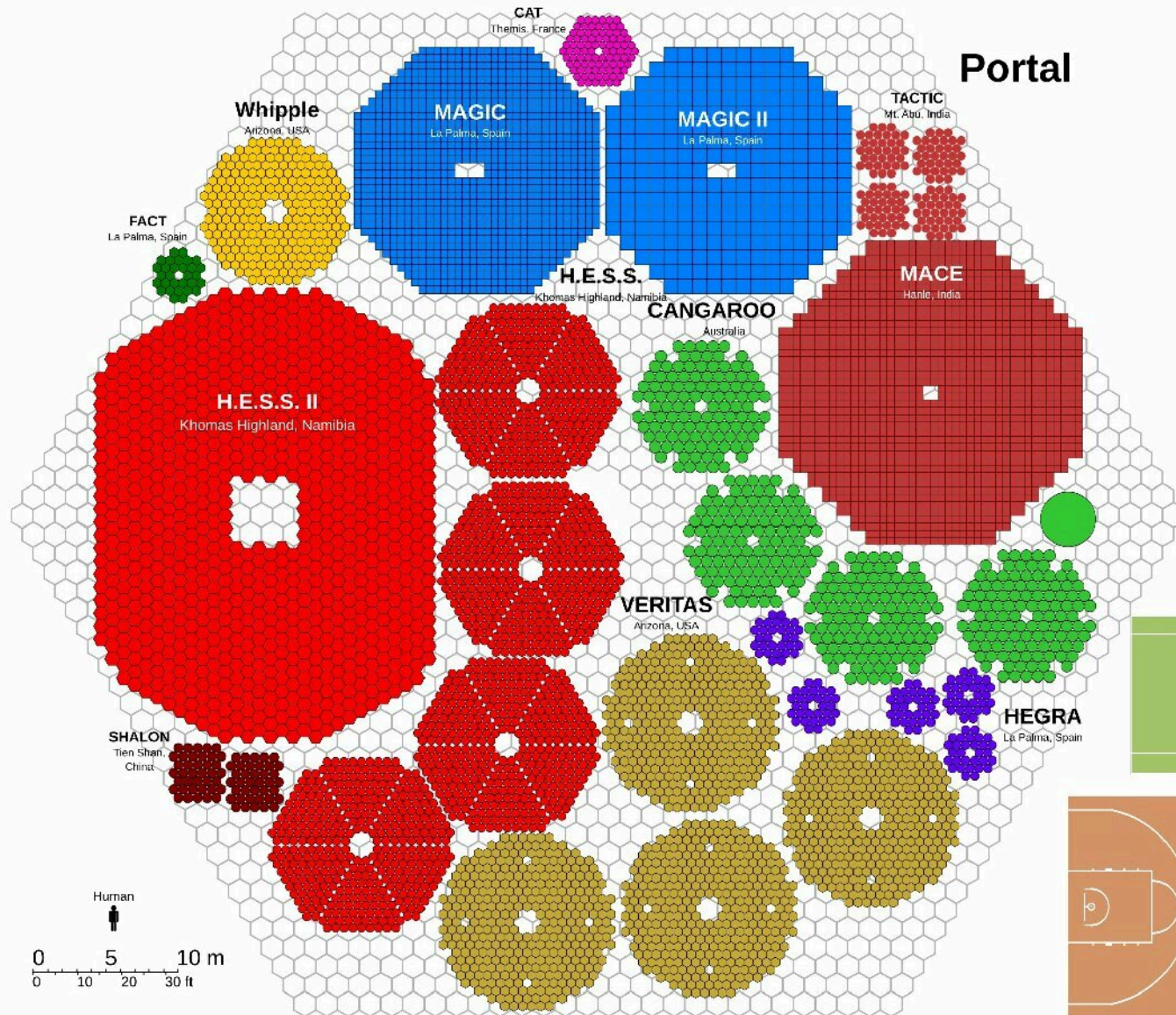
arXiv:1904.13368
(astro-ph)



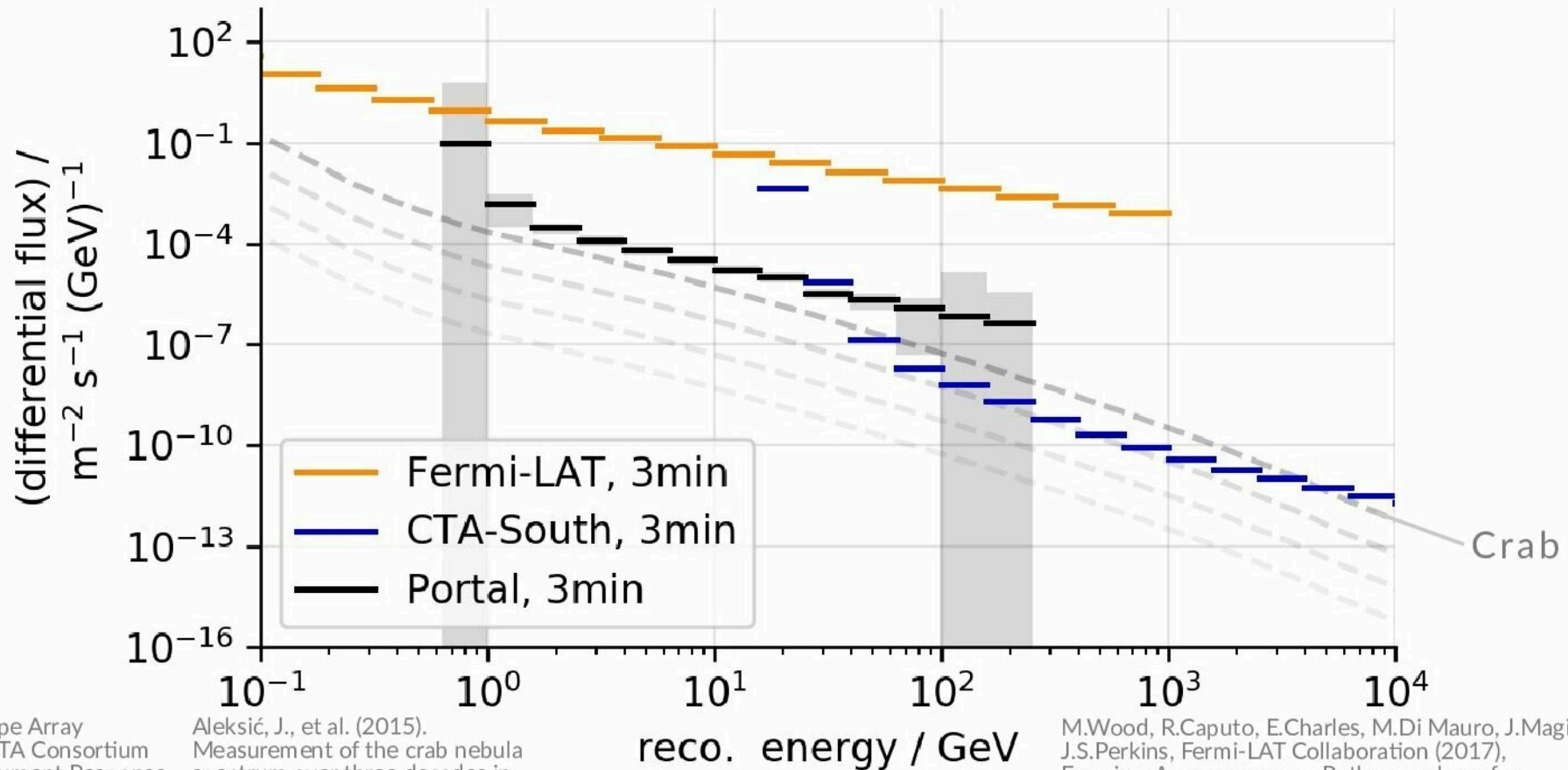
Go visit: <https://github.com/cherenkov-plenoscope>

Size

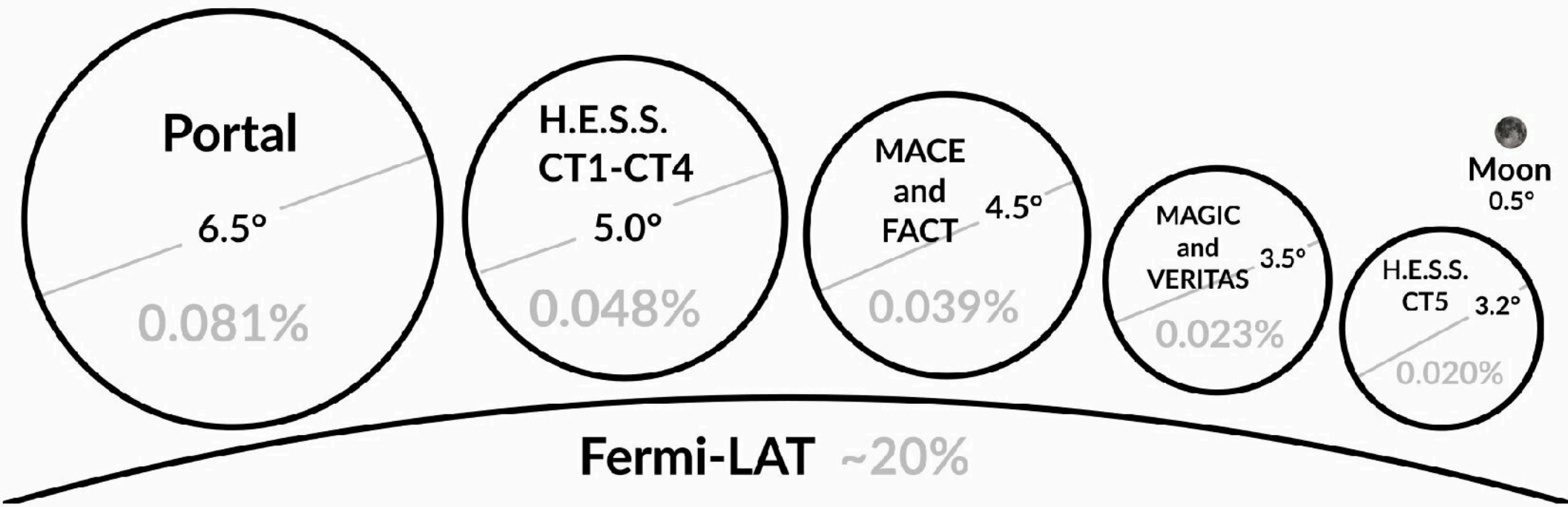
Portal



Performance, Sensitivity vs. Energy at 3min



Field-of-view



Costs Optics and Electronics

component	unit-costs	demand	cost / 10^6 EUR
Photo-sensors	5×10^5 EUR m^{-2}	115 m^2	57.5
Read-out-electronics	80 EUR channel ⁻¹	515,023 channels	41.2
Lenses	100 EUR lens ⁻¹	8,433 lenses	0.9
Mirror-facets	3×10^3 EUR m^{-2}	4174 m^2	12.5
Mirror-facet-actuators	10^3 EUR facet ⁻¹	2,087 facets	2.1
			114.2

Today: EUR ~ USD ~ CHF

Costs Total

	fraction / %	cost / 10 ⁶ EUR
Optics and electronics	51	114.2
Cable-robot-mount ¹	16	35.8
Central control-system ²	5	11.2
Project-engineering ²	5	11.2
Project-management ²	13	29.1
Site-infrastructure ²	10	22.4
	100	223.9

Today: EUR ~ USD ~ CHF

(1) Civil engineer Spyridon Daglas

(2) Adopted from reports by the European-Southern-Observatory (ESO)