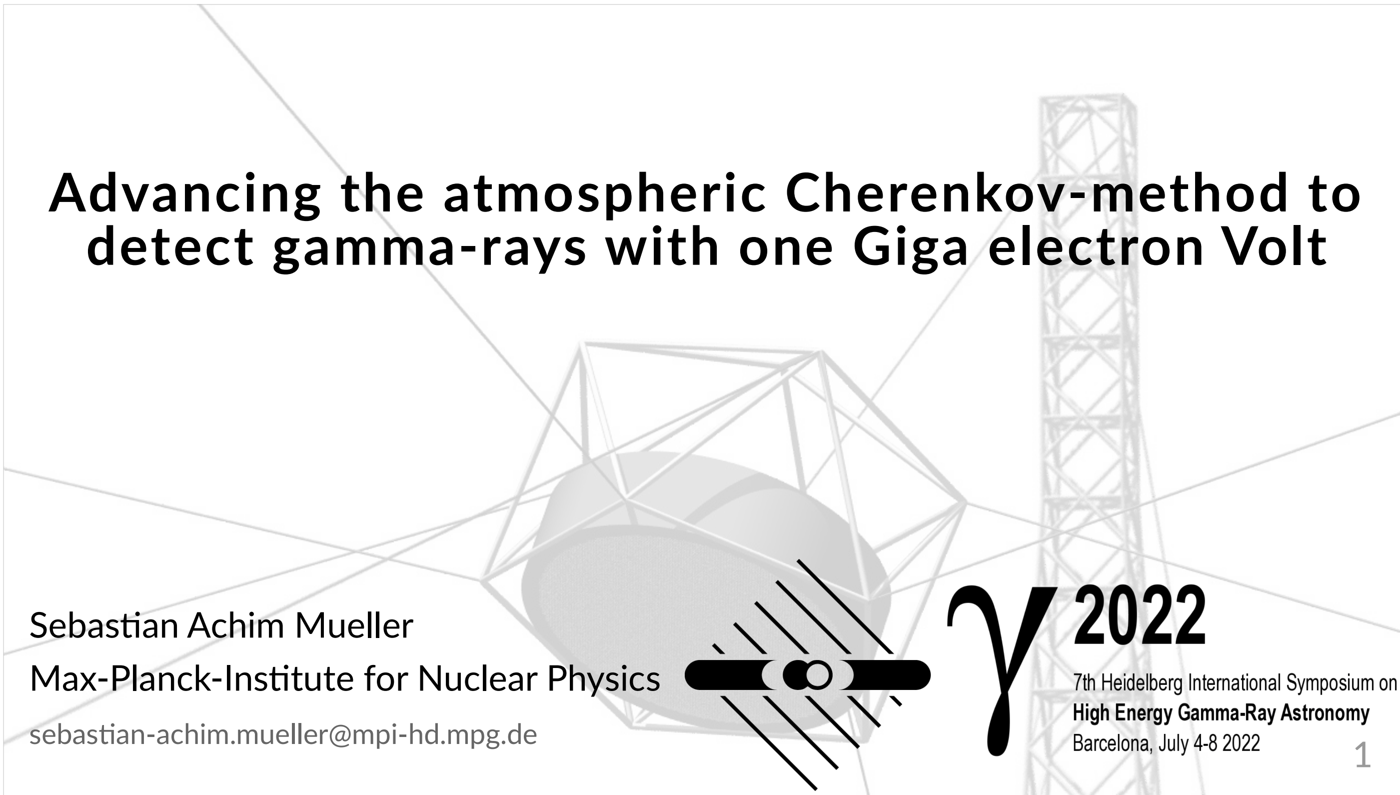
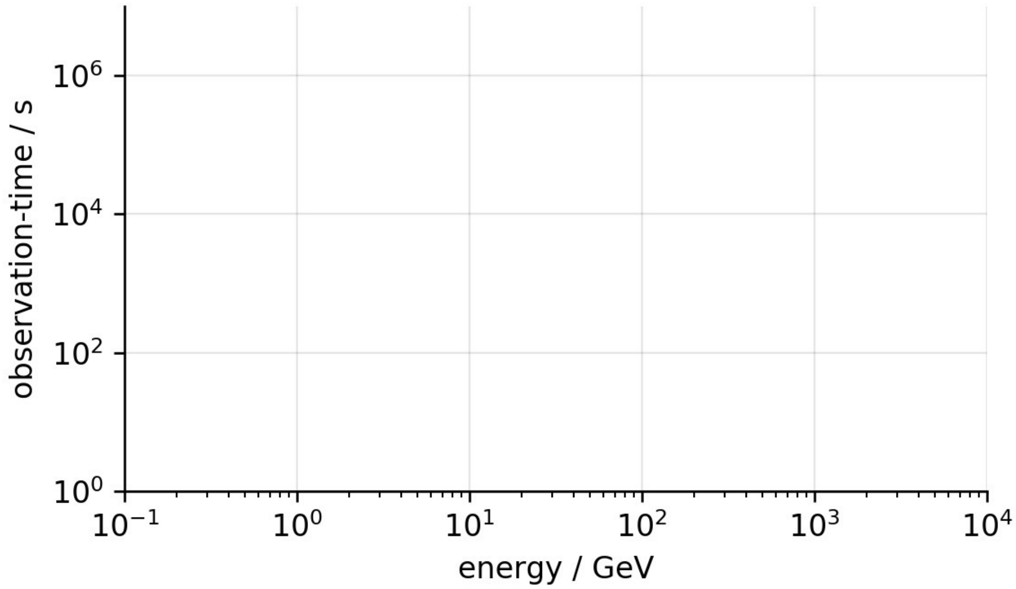


Advancing the atmospheric Cherenkov-method to detect Gamma-rays with one Giga electron Volt

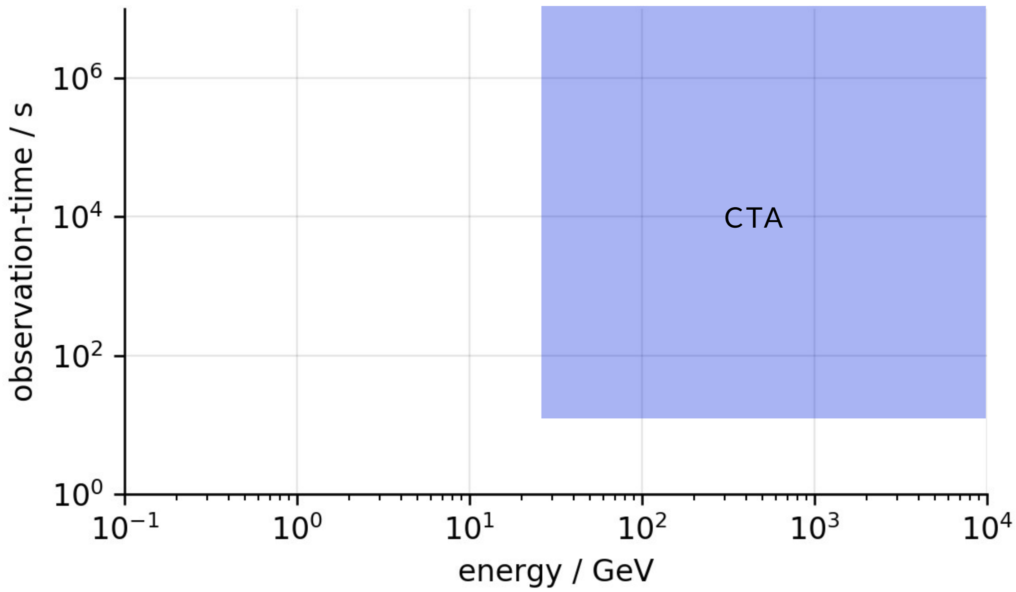
Explore Timing



One of the main motivations to advance the atmospheric Cherenkov-method is to explore timing.

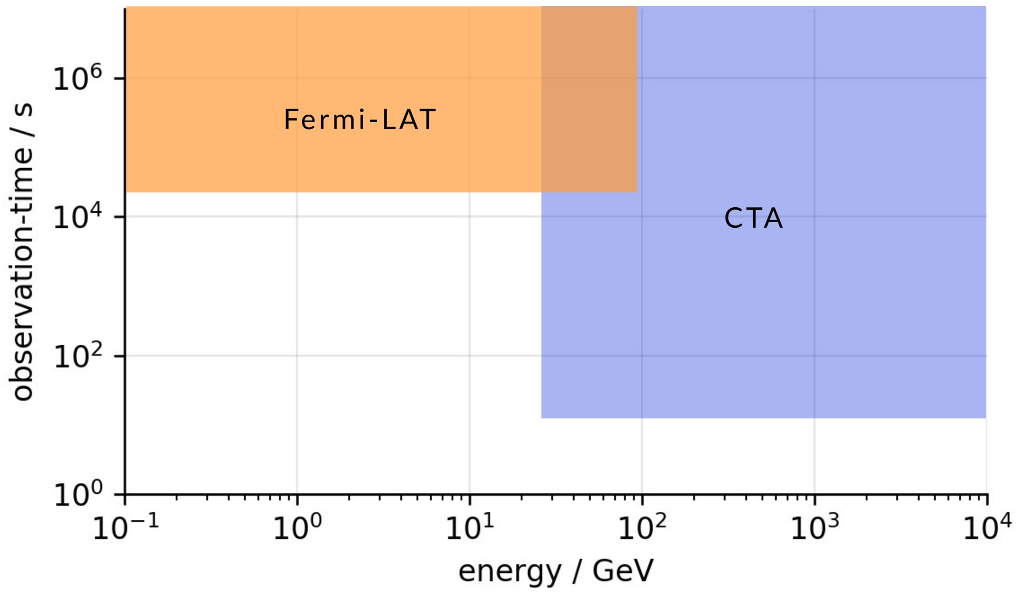
Oversimplified

Explore Timing



The atmospheric Cherenkov-method provides a good coverage down to about twentyfive giga electron Volts.

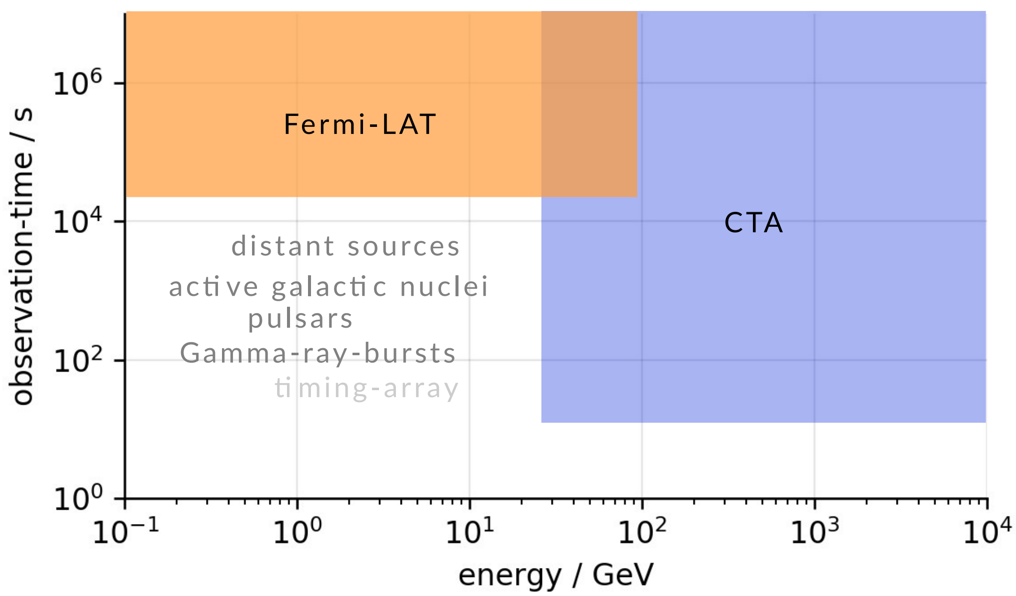
Explore Timing



4

And direct detection in space reaches down to far below one giga electron Volt, but takes quiet some time to even detect flares.

Explore Timing



5

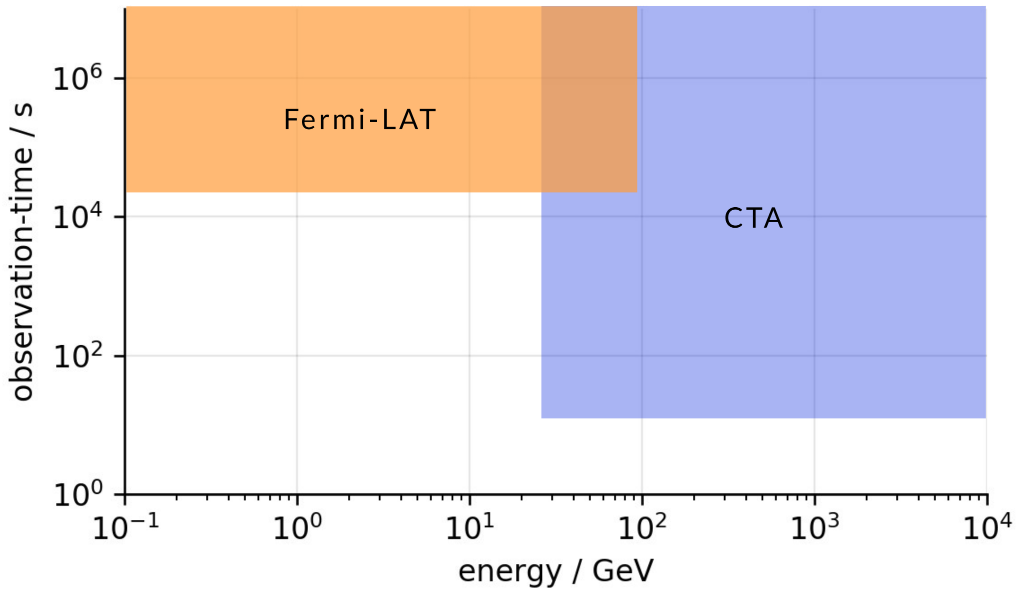
The remaining space here is of great interest.

Sources in cosmic distances, such as gamma-ray-bursts, have their high energetic gamma-rays absorbed by infrared light and only show up here.

Pulsars have their gamma-ray-emission cutoff at about ten giga electon Volt and therefore also only show up here.

And our understanding of active galactic nuclei always profited from the exploration of timing.

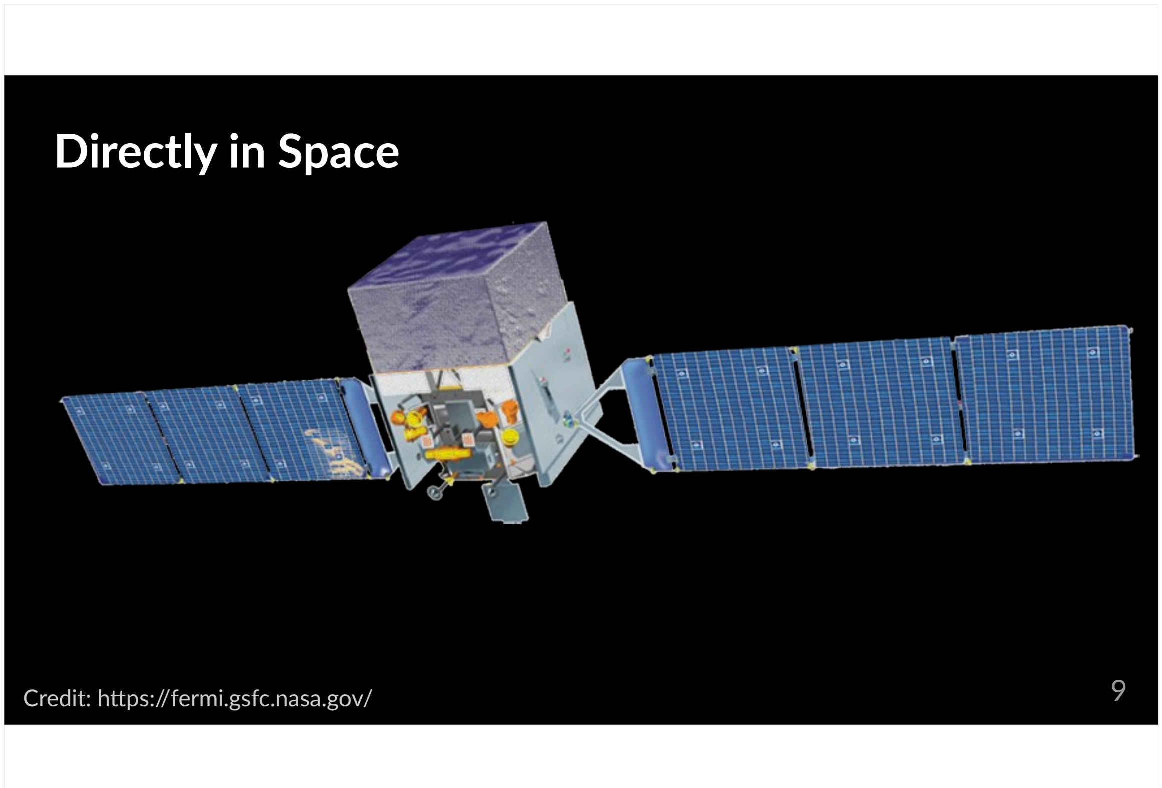
Explore Timing



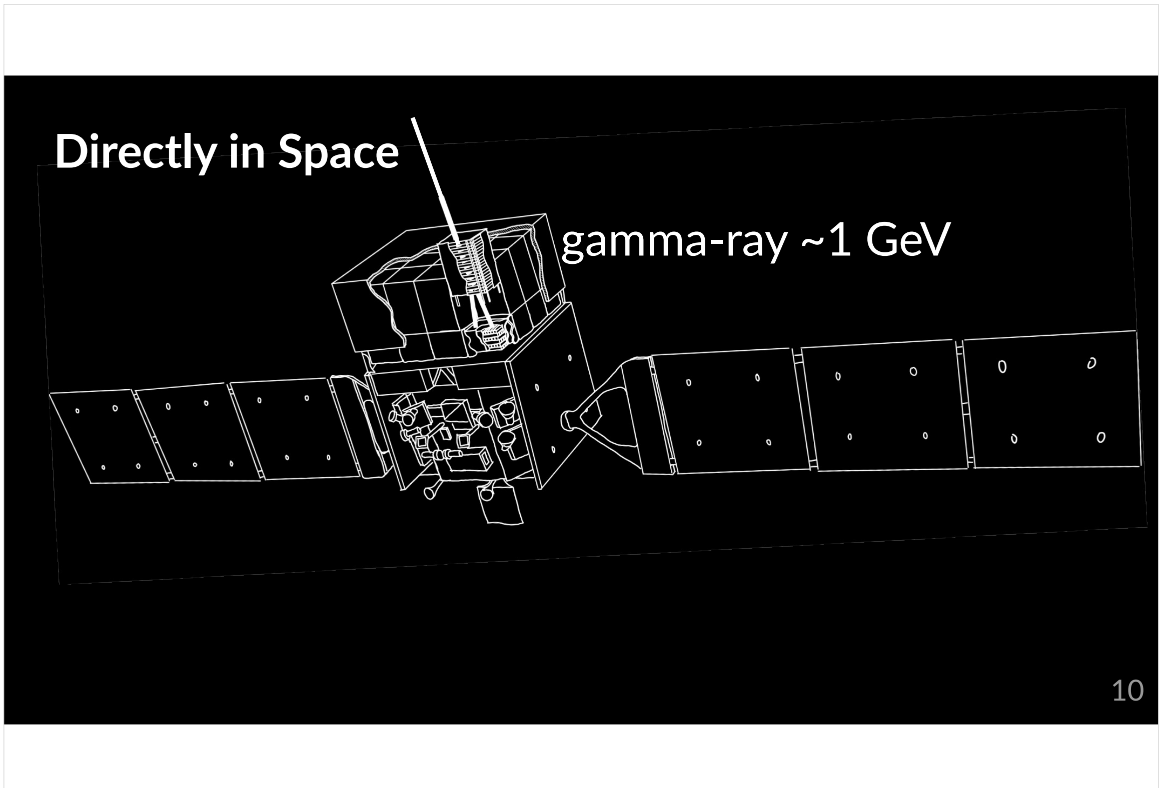
So what are the limitations

today?

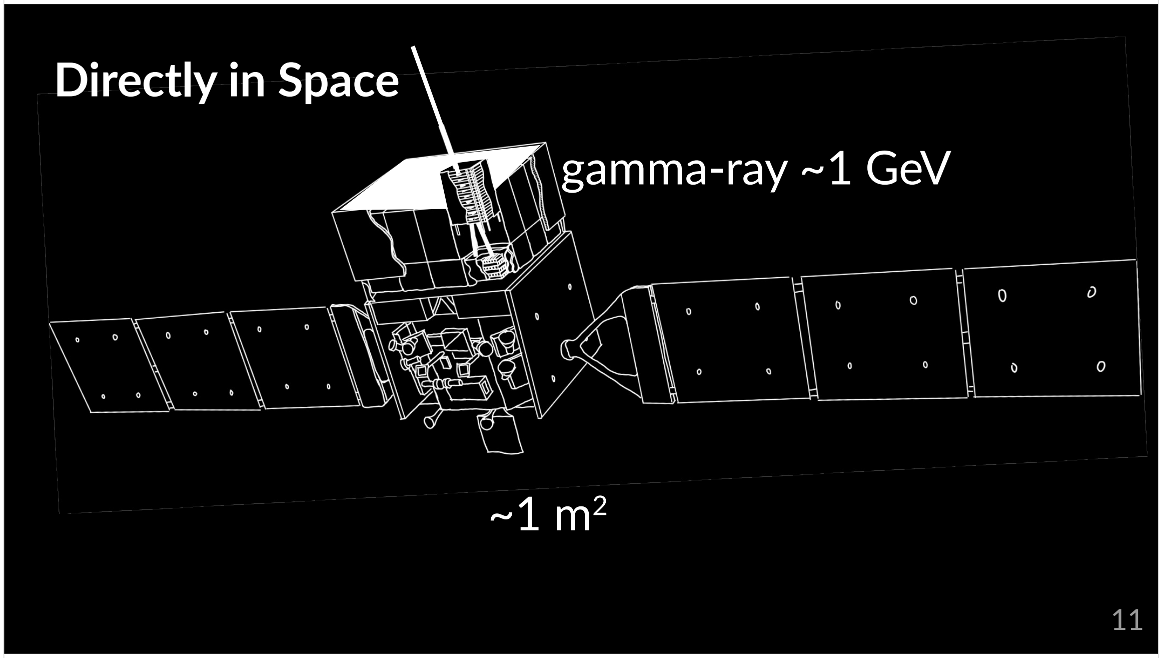
The detection-rate



of a satellite



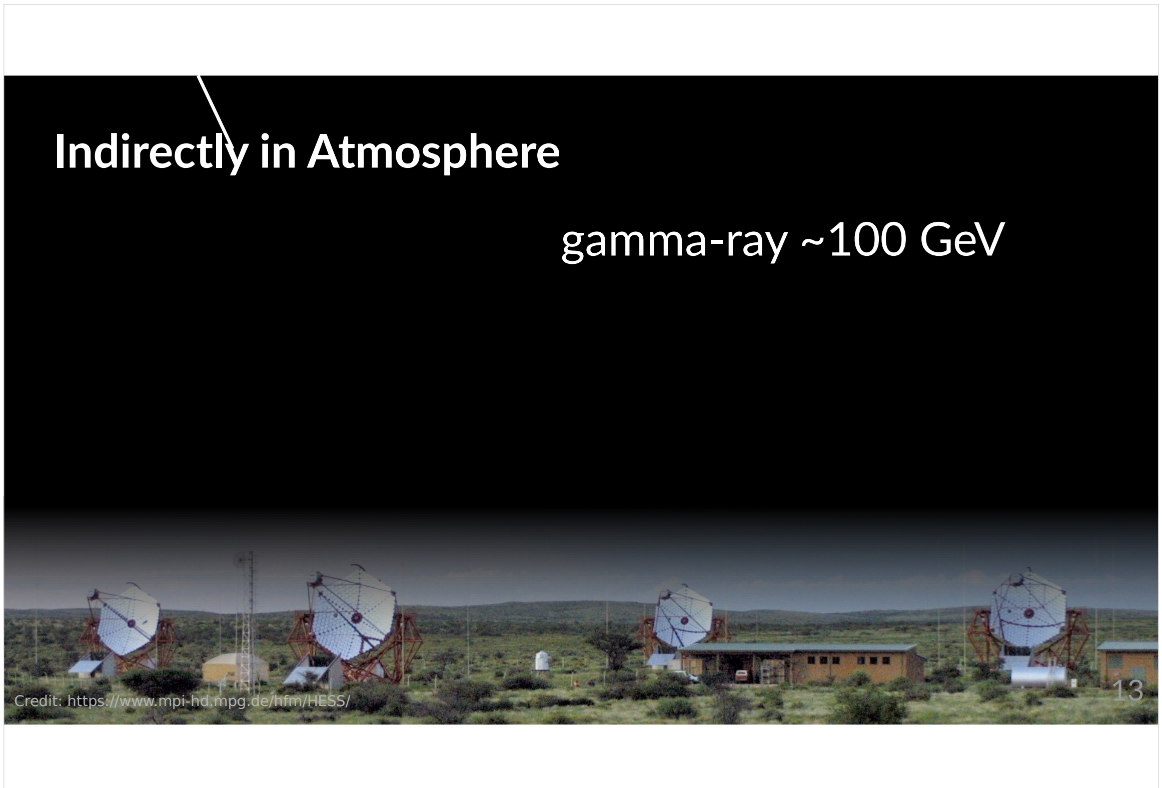
is limited by



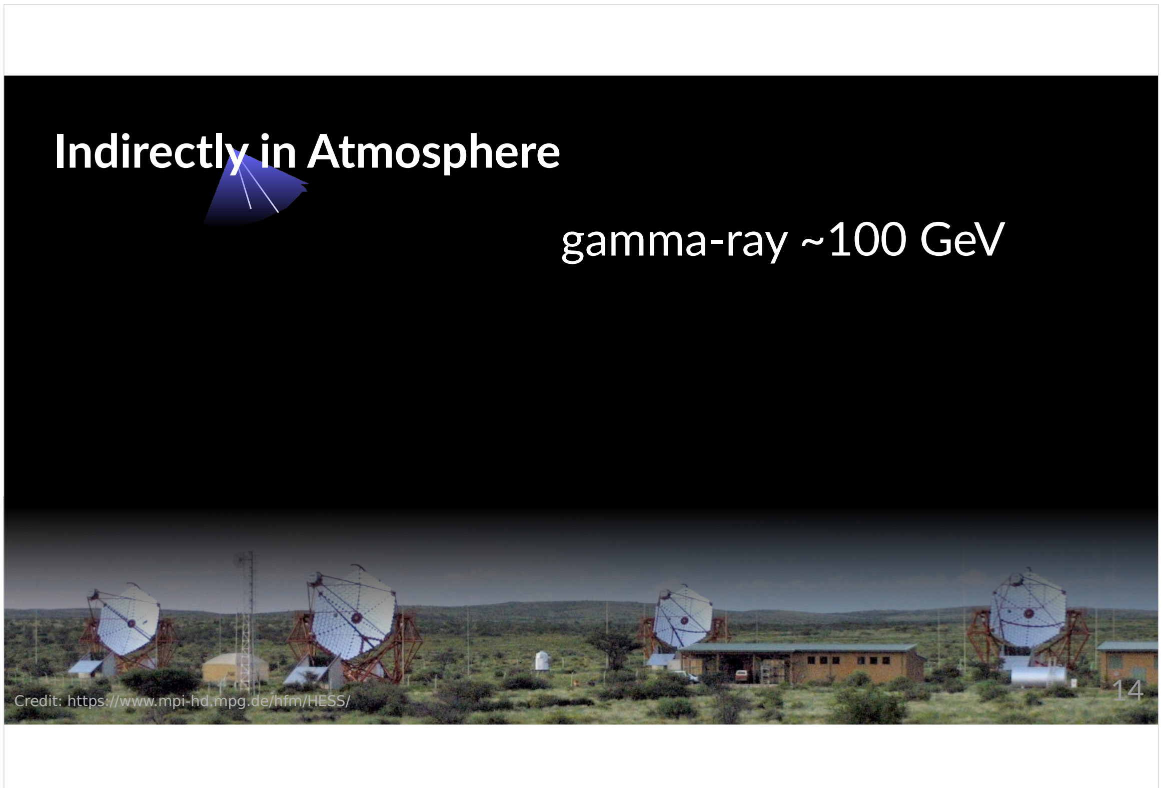
its small collection-area of about one square meter.

Indirectly in Atmosphere

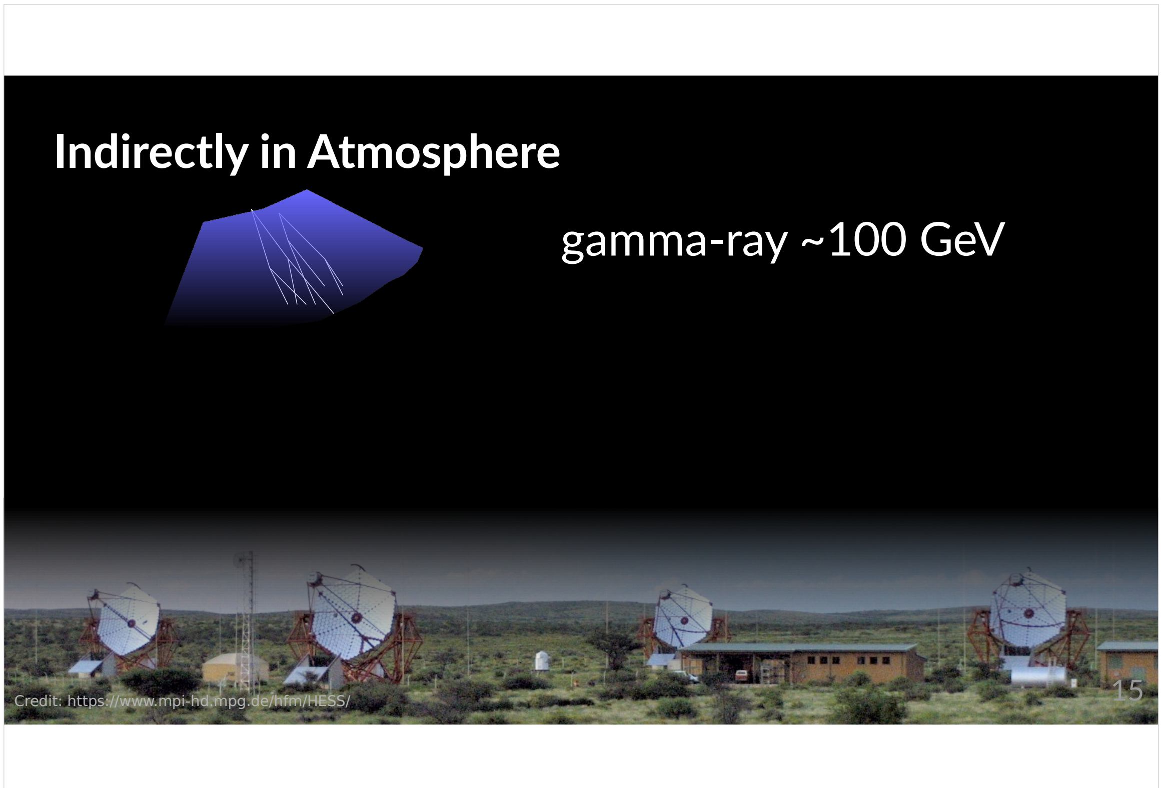
In contrast



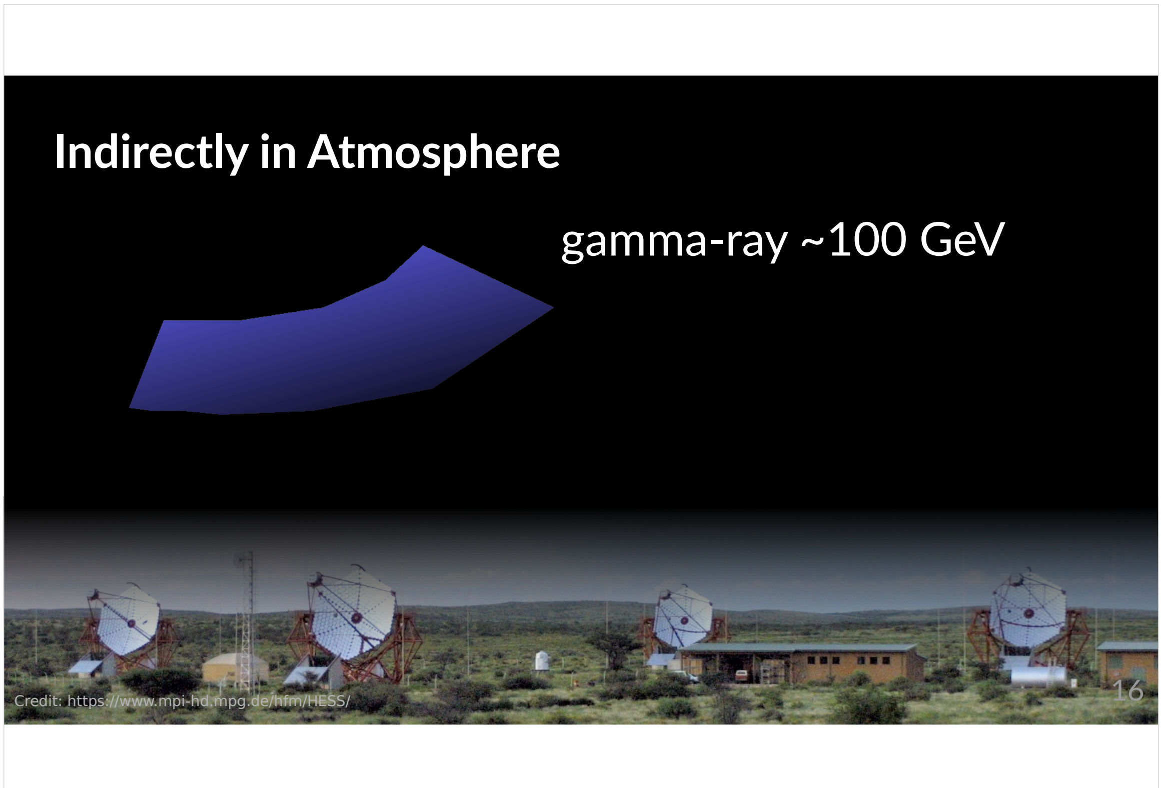
the effective collection-area



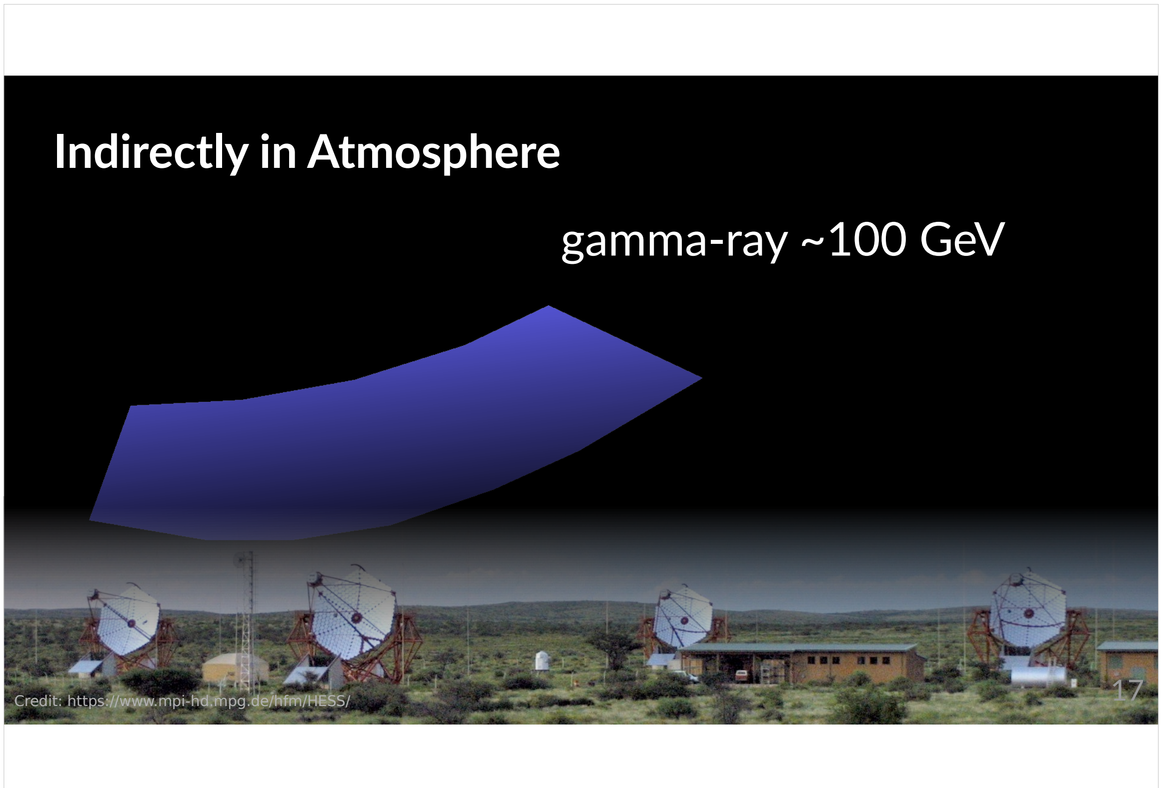
of the atmospheric Cherenkov-method


Indirectly in Atmosphere
gamma-ray ~100 GeV
Credit: https://www.mpi-hd.mpg.de/hfm/HESS/
15

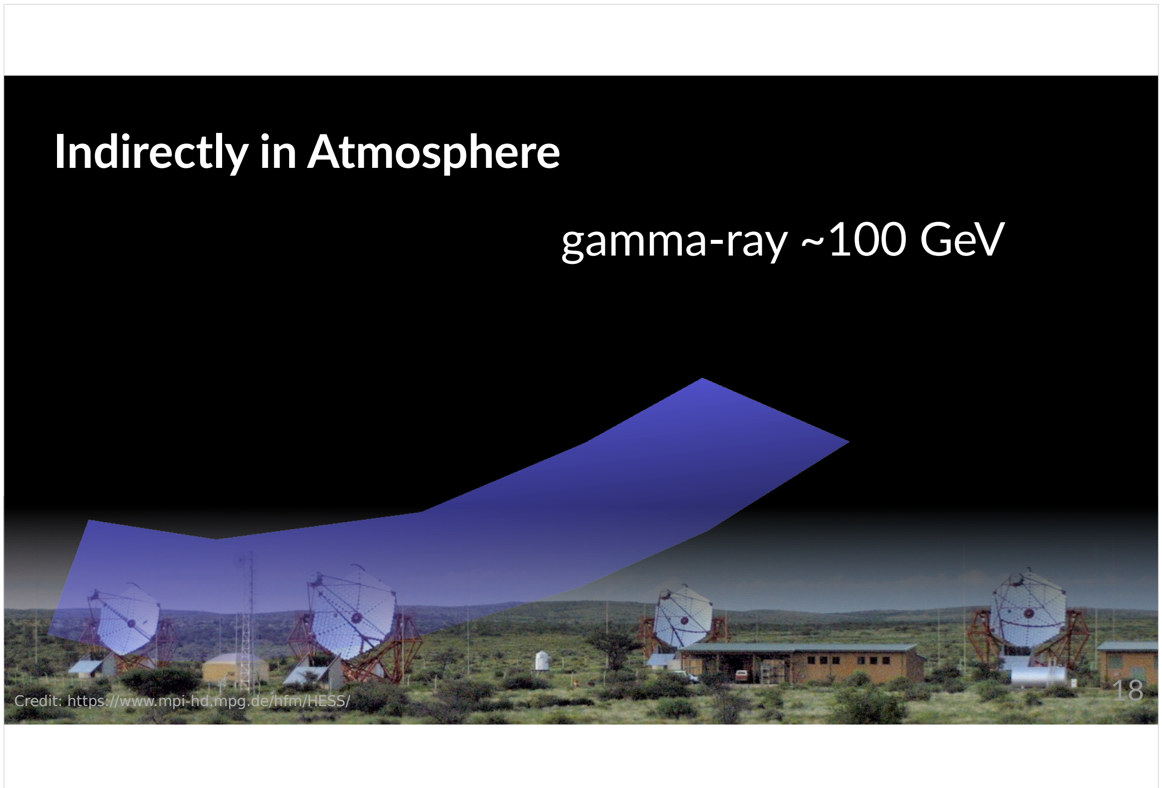
can be


Indirectly in Atmosphere
gamma-ray ~100 GeV
Credit: https://www.mpi-hd.mpg.de/hfm/HESS/
16

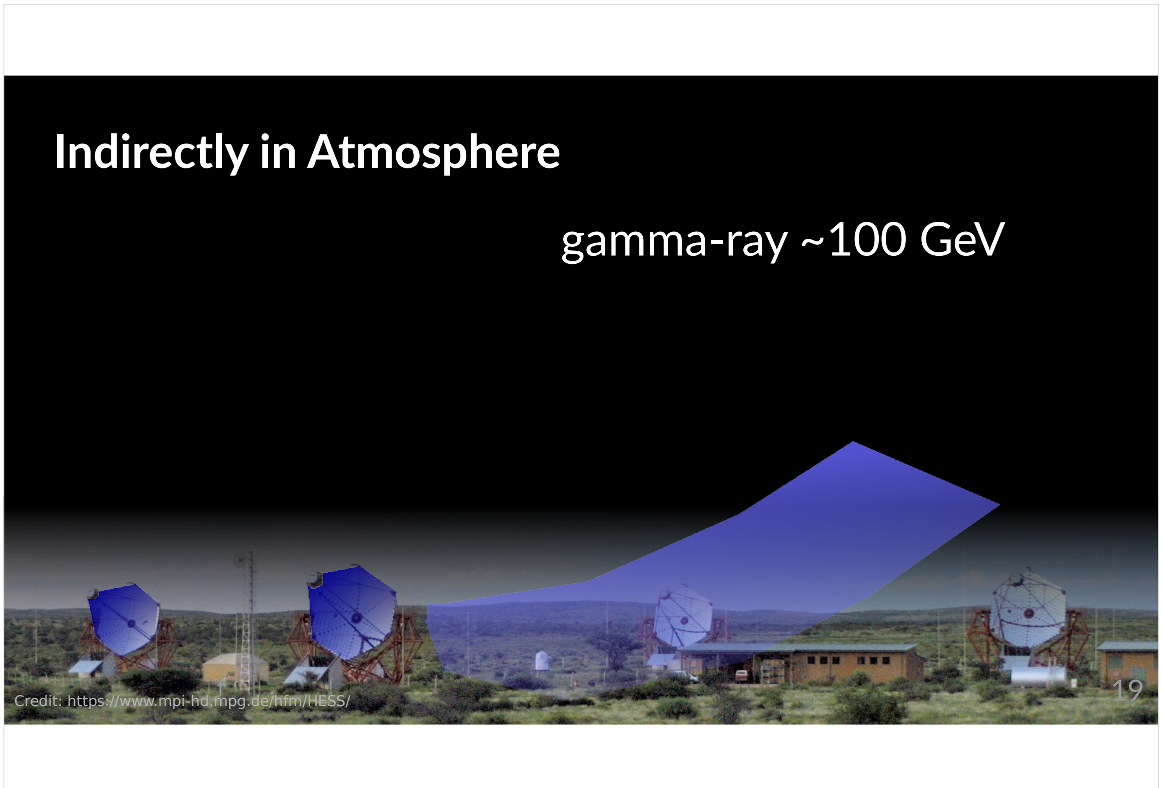
as large


Indirectly in Atmosphere
gamma-ray ~100 GeV
Credit: https://www.mpi-hd.mpg.de/hfm/HESS/
17

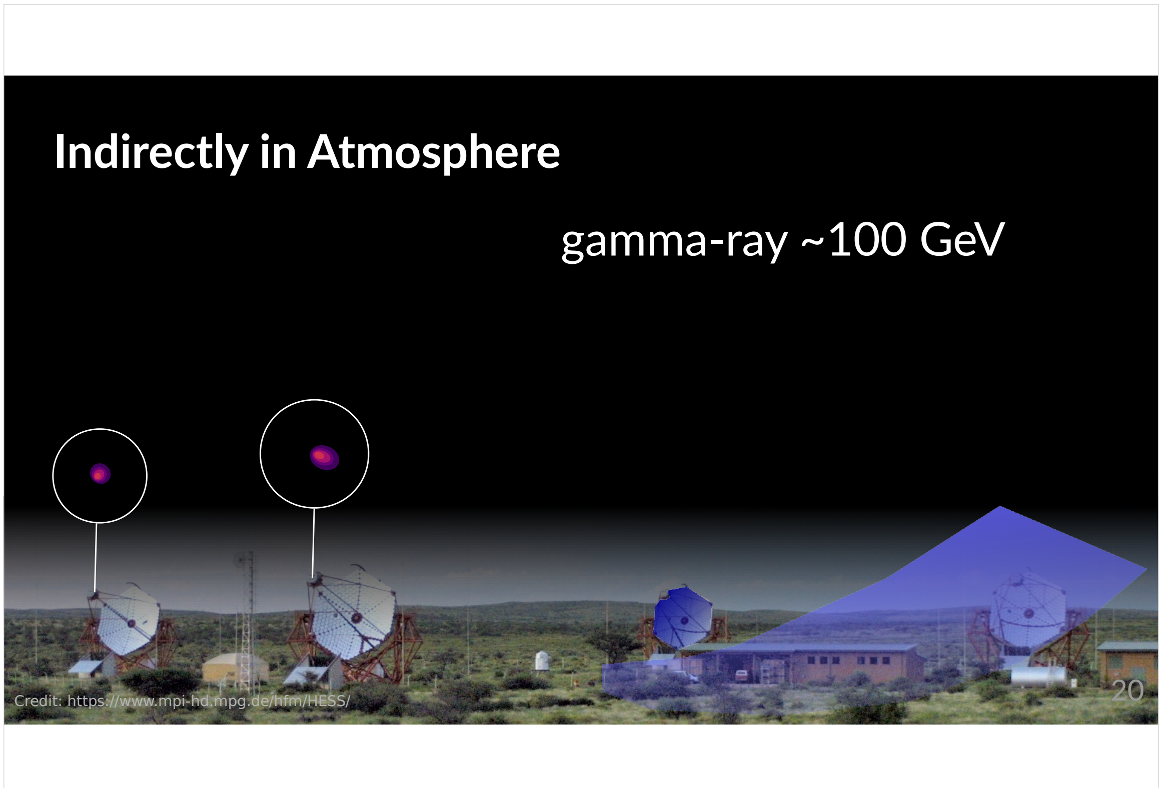
as the pool



of Cherenkov-light

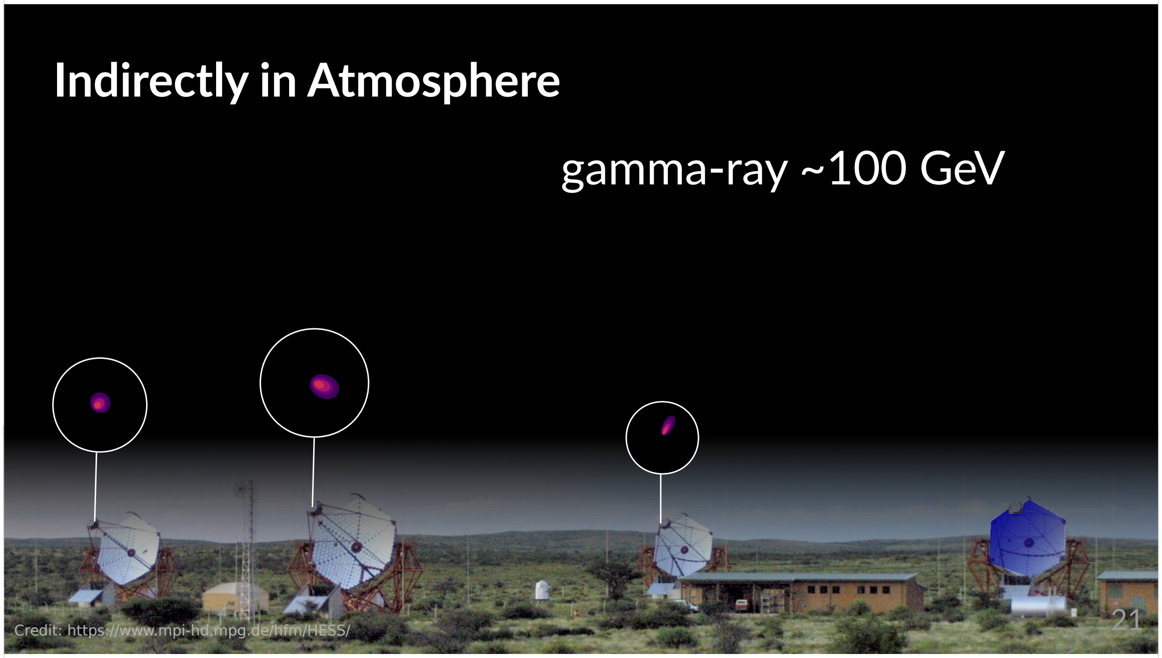

Indirectly in Atmosphere
gamma-ray ~100 GeV
Credit: https://www.mpi-hd.mpg.de/hfm/HESS/
19

on ground

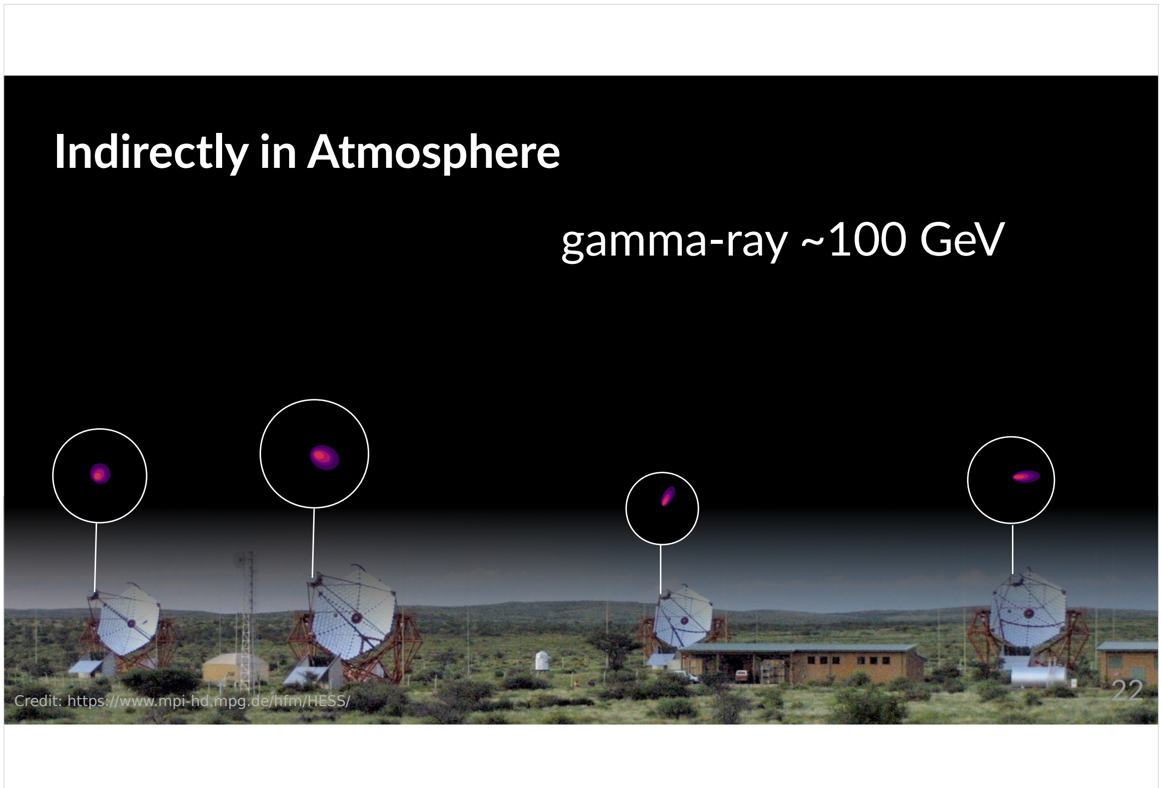


Indirectly in Atmosphere
gamma-ray ~100 GeV
Credit: https://www.mpi-hd.mpg.de/hfm/HESS/
20

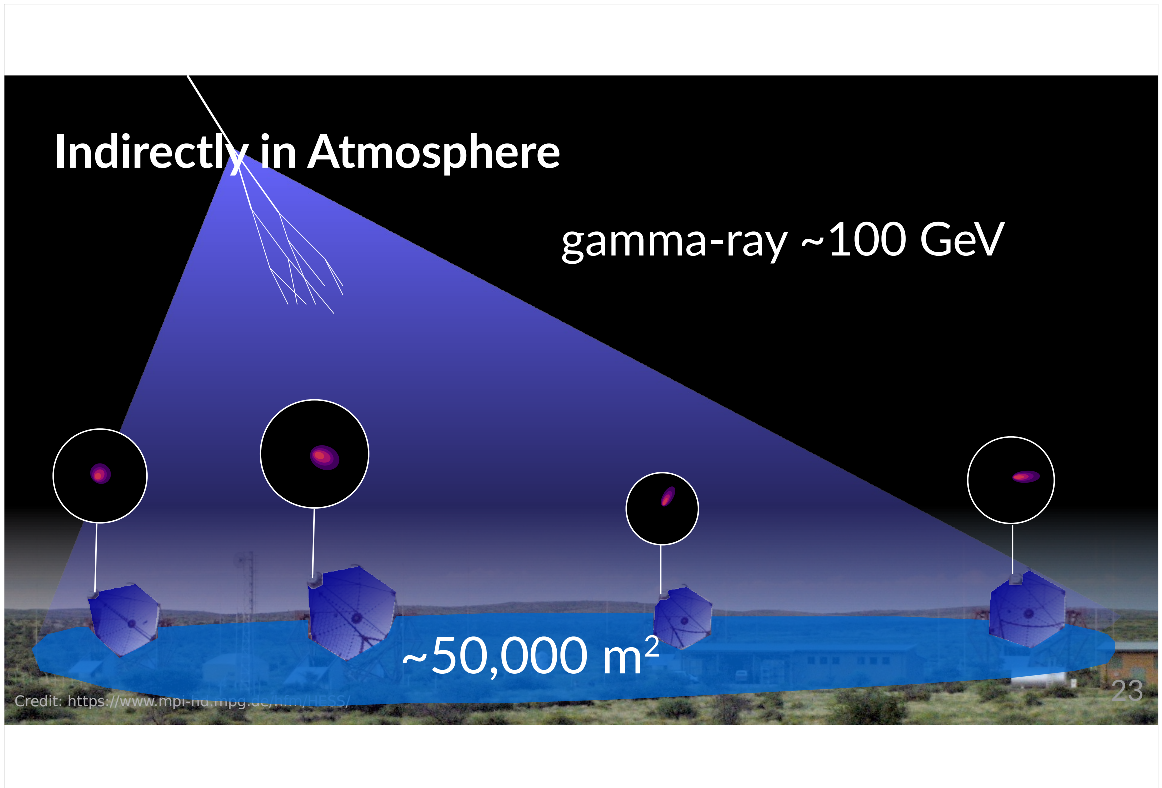
covering


Indirectly in Atmosphere
gamma-ray ~100 GeV
Credit: https://www.mpi-hd.mpg.de/hfm/HESS/
21

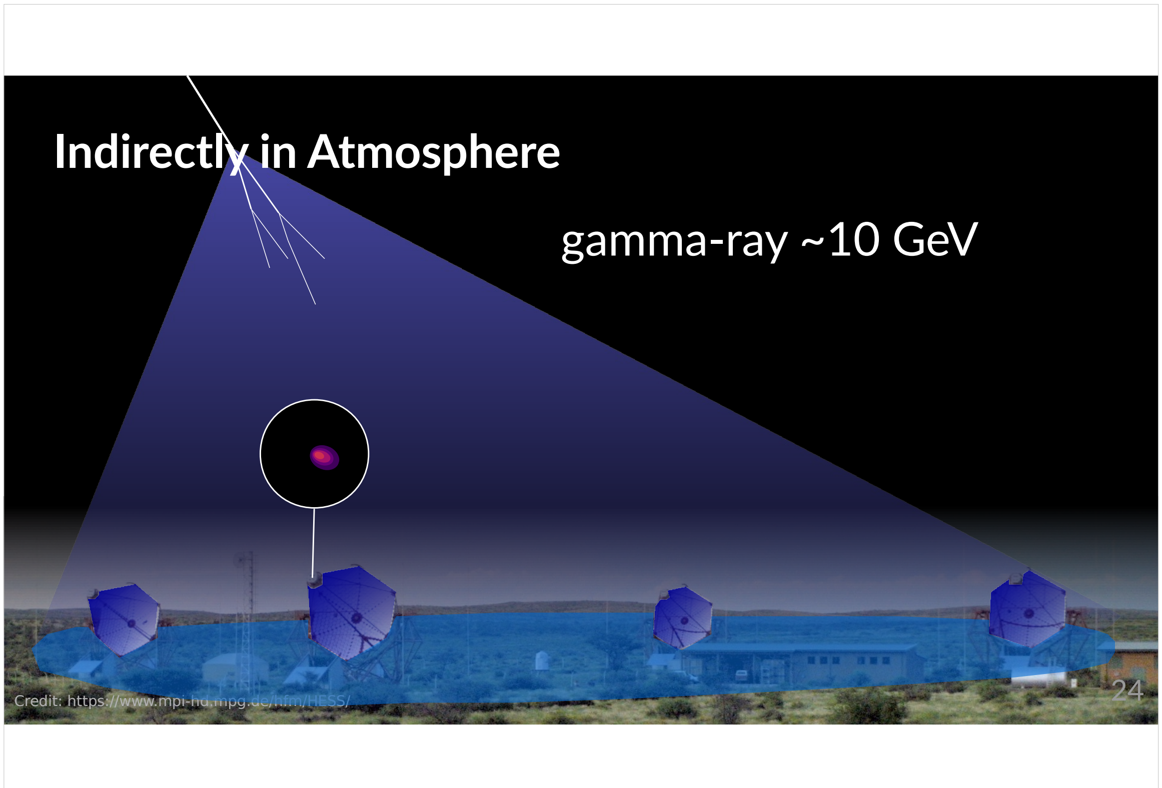
tens


Indirectly in Atmosphere
gamma-ray ~100 GeV
Credit: https://www.mpi-hd.mpg.de/hfm/HESS/
22

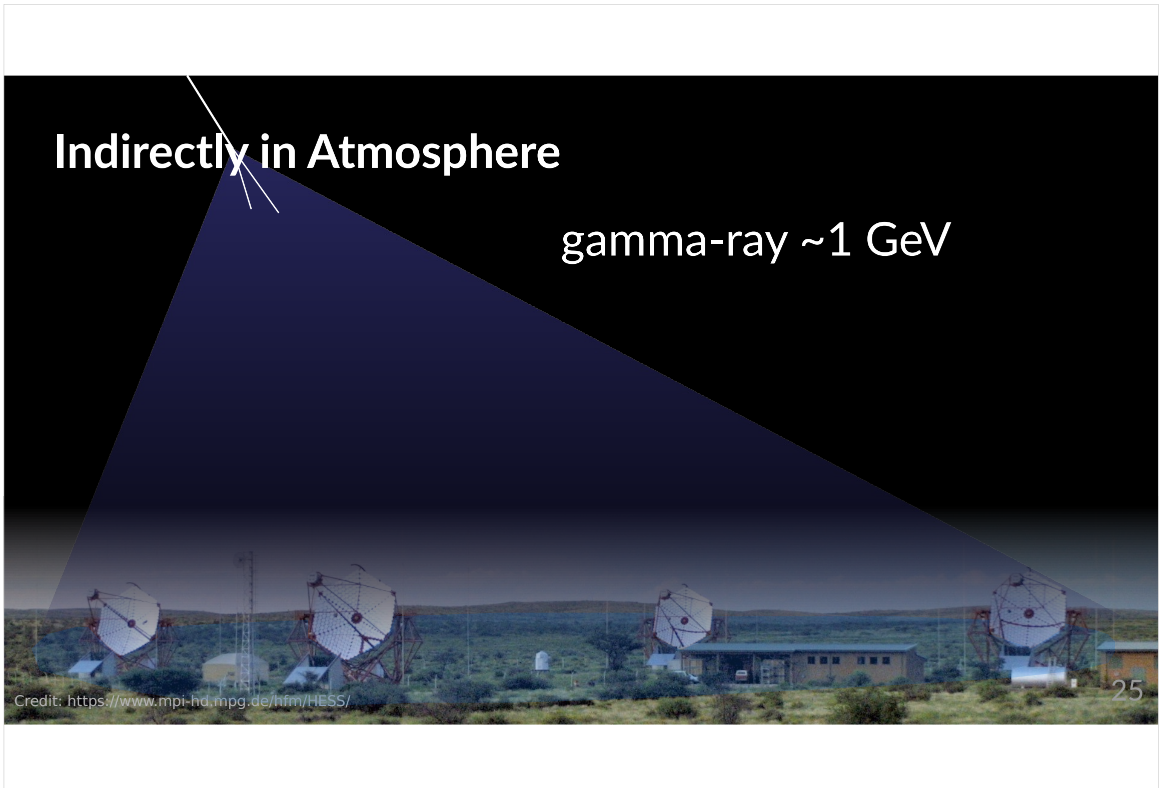
of



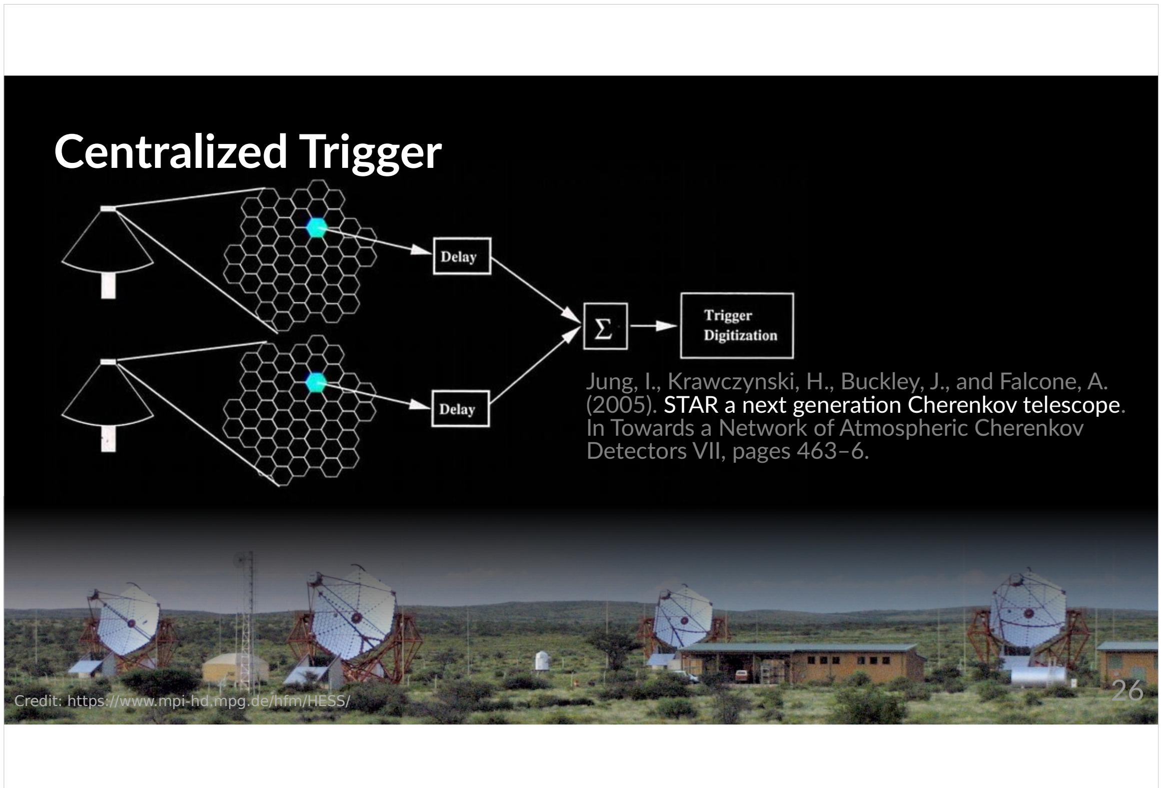
thousands of square meters.



But when the gamma-ray has less energy, there is less Cherenkov-light and the telescopes struggle to trigger.

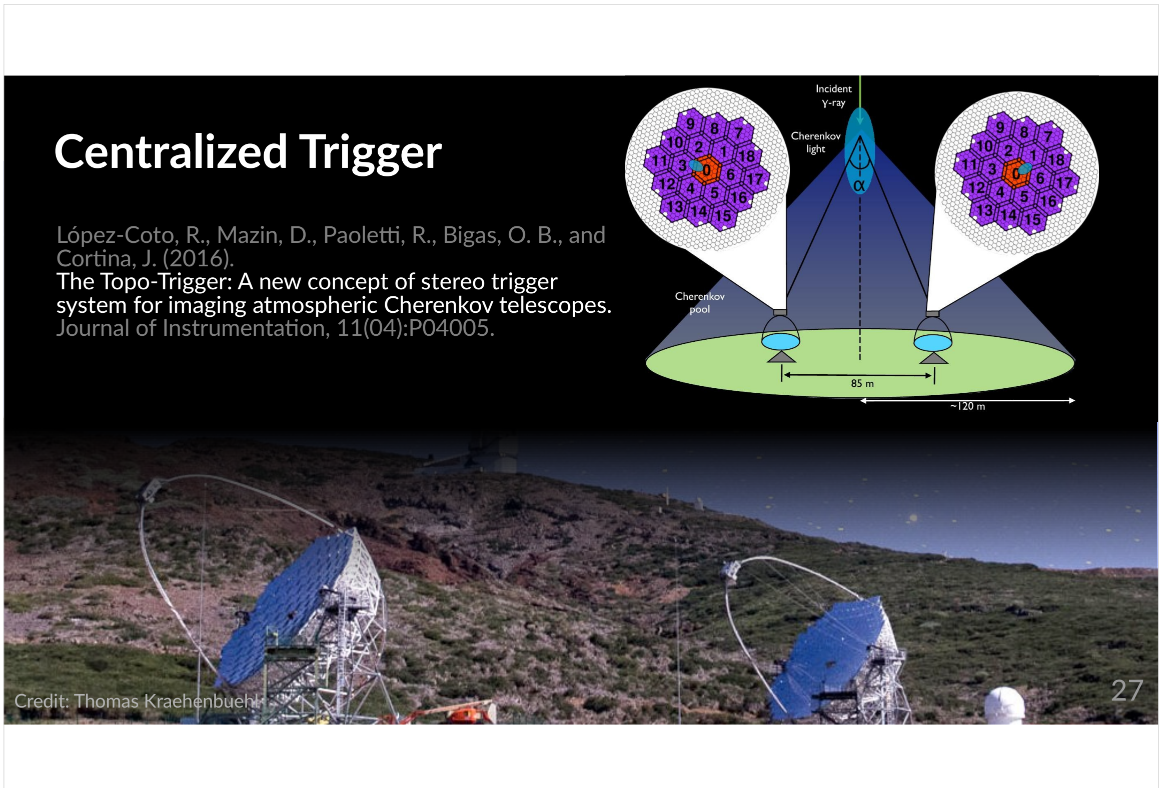


and eventually can not trigger at all.



Today there are two approaches to advance the atmospheric Cherenkov-method.

The first approach is to try making a centralized trigger for an array of telescopes.



But today, despite impressive progress, a centralized trigger remains a technological challenge.

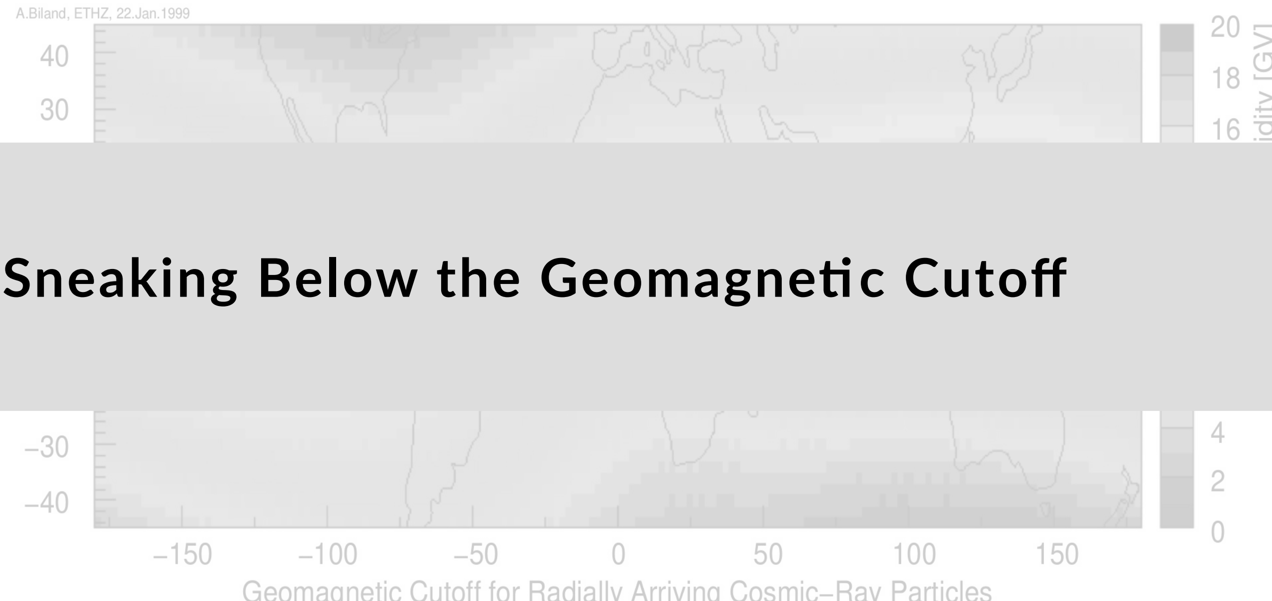
This is why the Cherenkov-Telescope-Array took the only approach left which is to build large telescopes.

But when we go even larger we find that:

A problem with large telescopes is the very limited depth-of-field.
And thus the useful size of large Cherenkov-telescopes is limited.

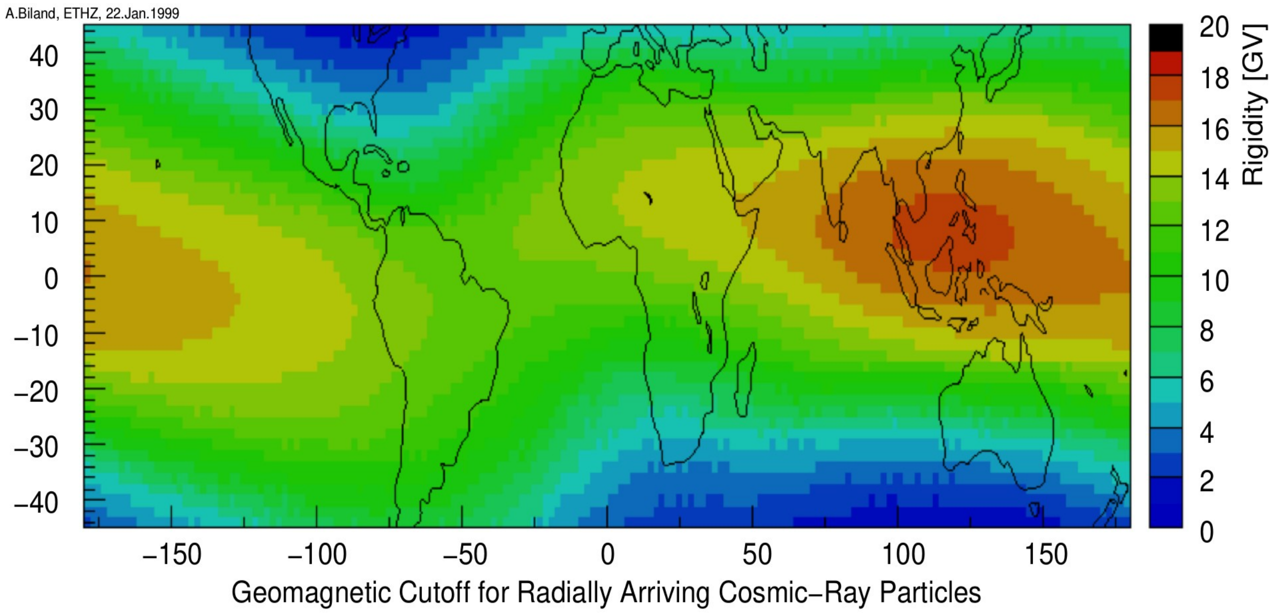
We will see an example later. (Phantom-source)

Sneaking Below the Geomagnetic Cutoff



Either way, any Cherenkov-method that will sneak below the geomagnetic cutoff will face a more complex background.

Geomagnetic Cutoff

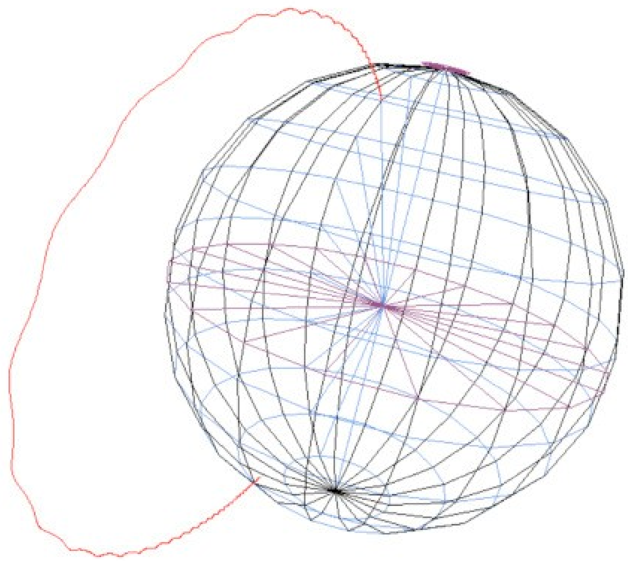


Adrian Biland, ETH Zurich, 1999

The geomagnetic cutoff prevents low energetic cosmic-rays from penetrating earth’s atmosphere.

Depending on the location, the energy, and the direction a low energy Cherenkov-instrument will not see showers induced by cosmic-rays

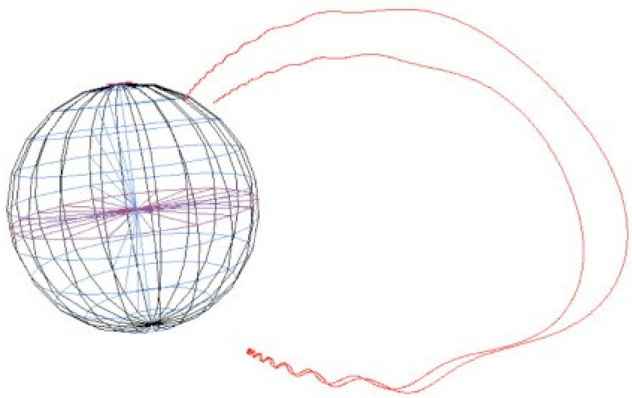
Geomagnetic Cutoff



no-bounce

simply because the required

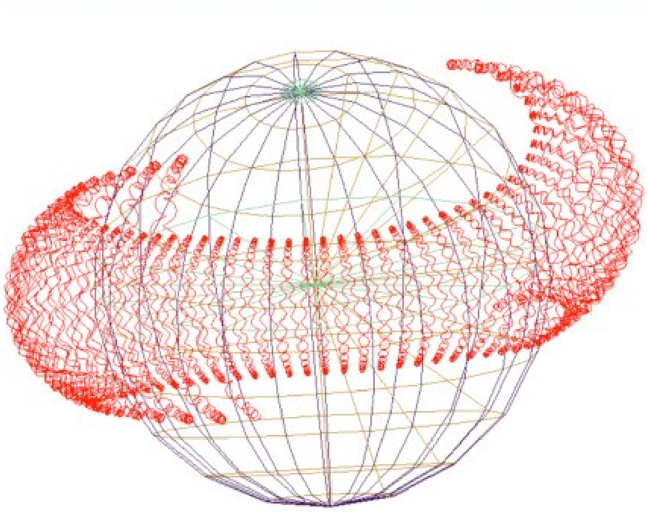
Geomagnetic Cutoff



one-bounce

trajectories

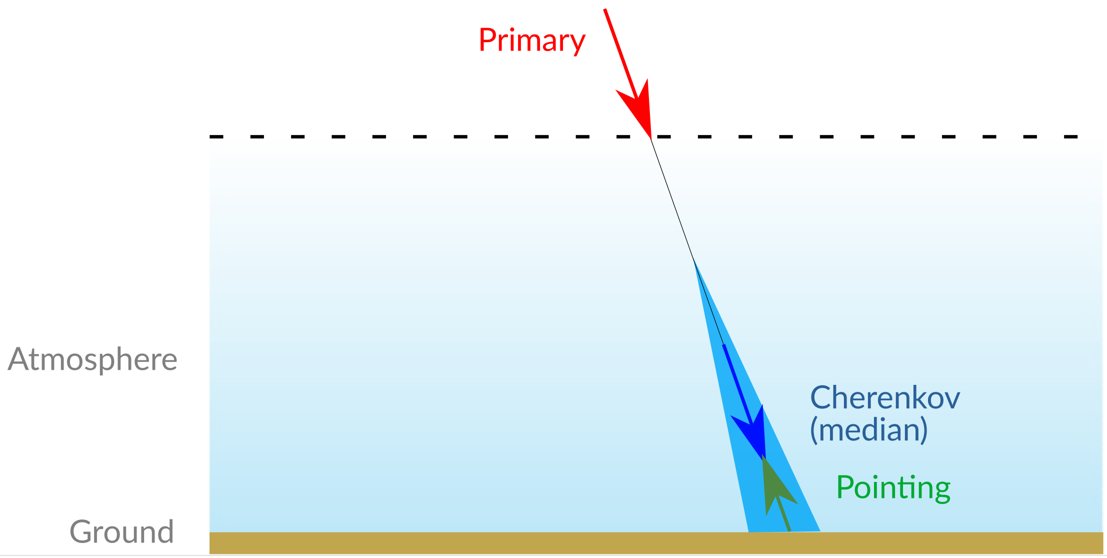
Geomagnetic Cutoff



multi-bounce

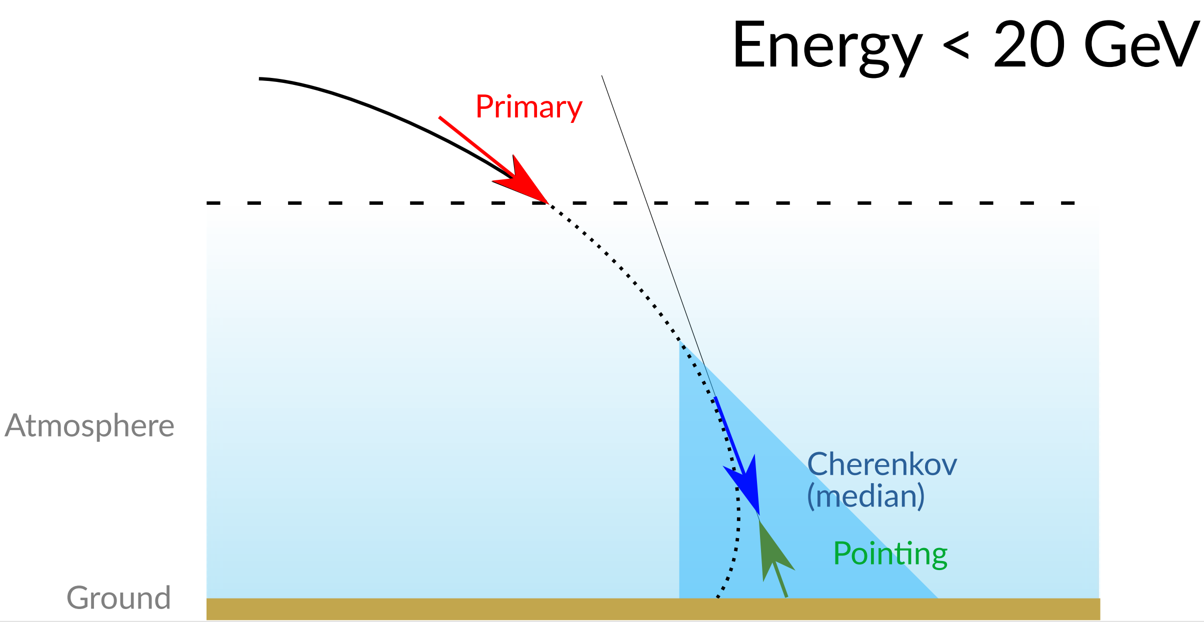
are blocked by the earth.

Deflection of shower



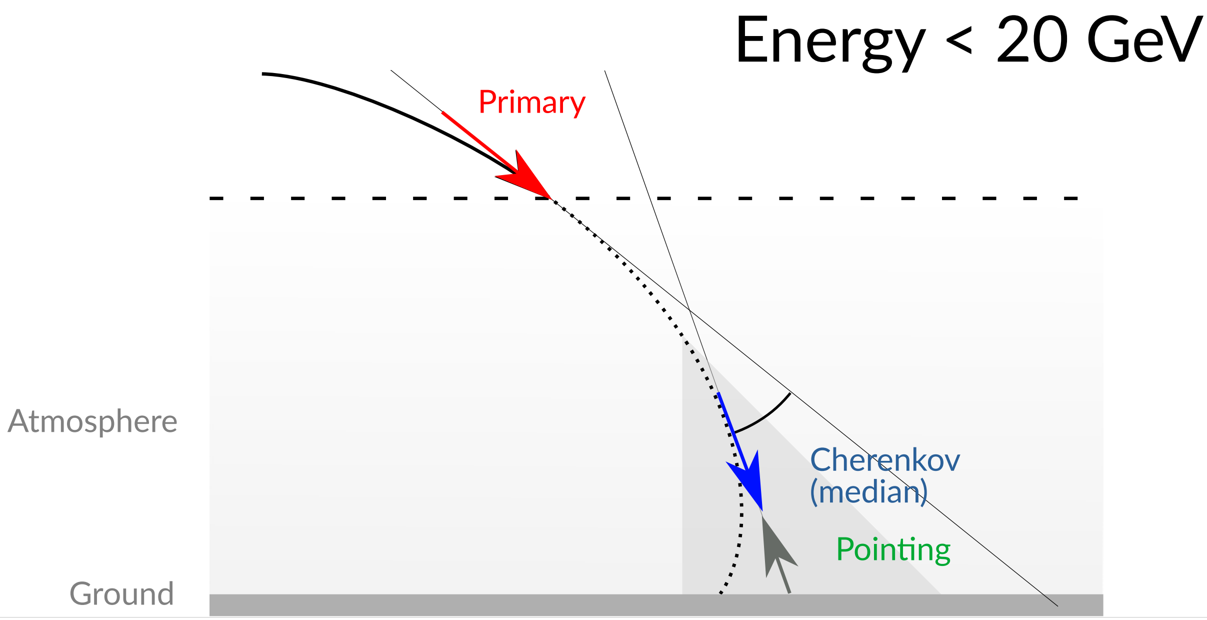
Further there is a deflection of the shower itself.

Deflection of shower

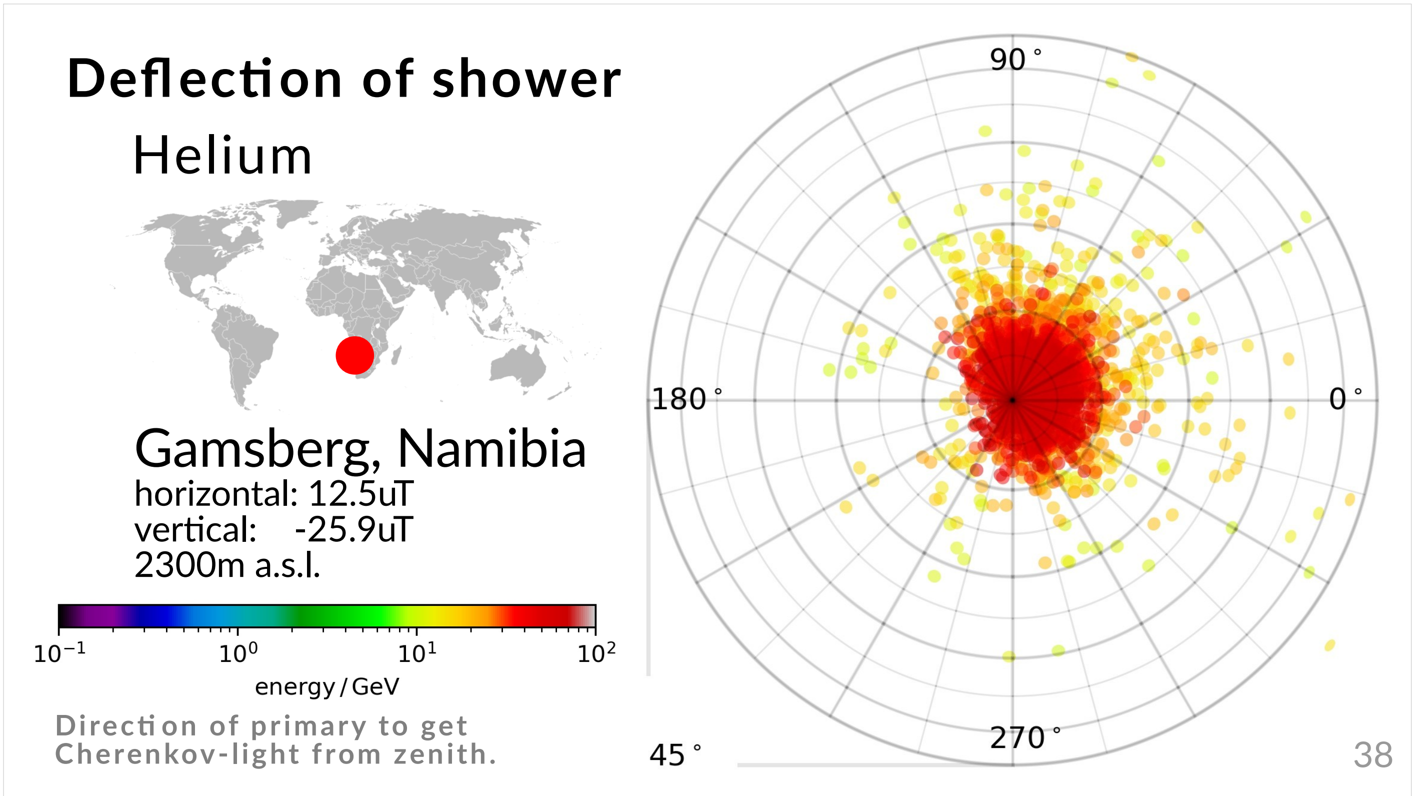


Below about twenty giga electron Volts earth's magnetic field deflects the shower noticeably.

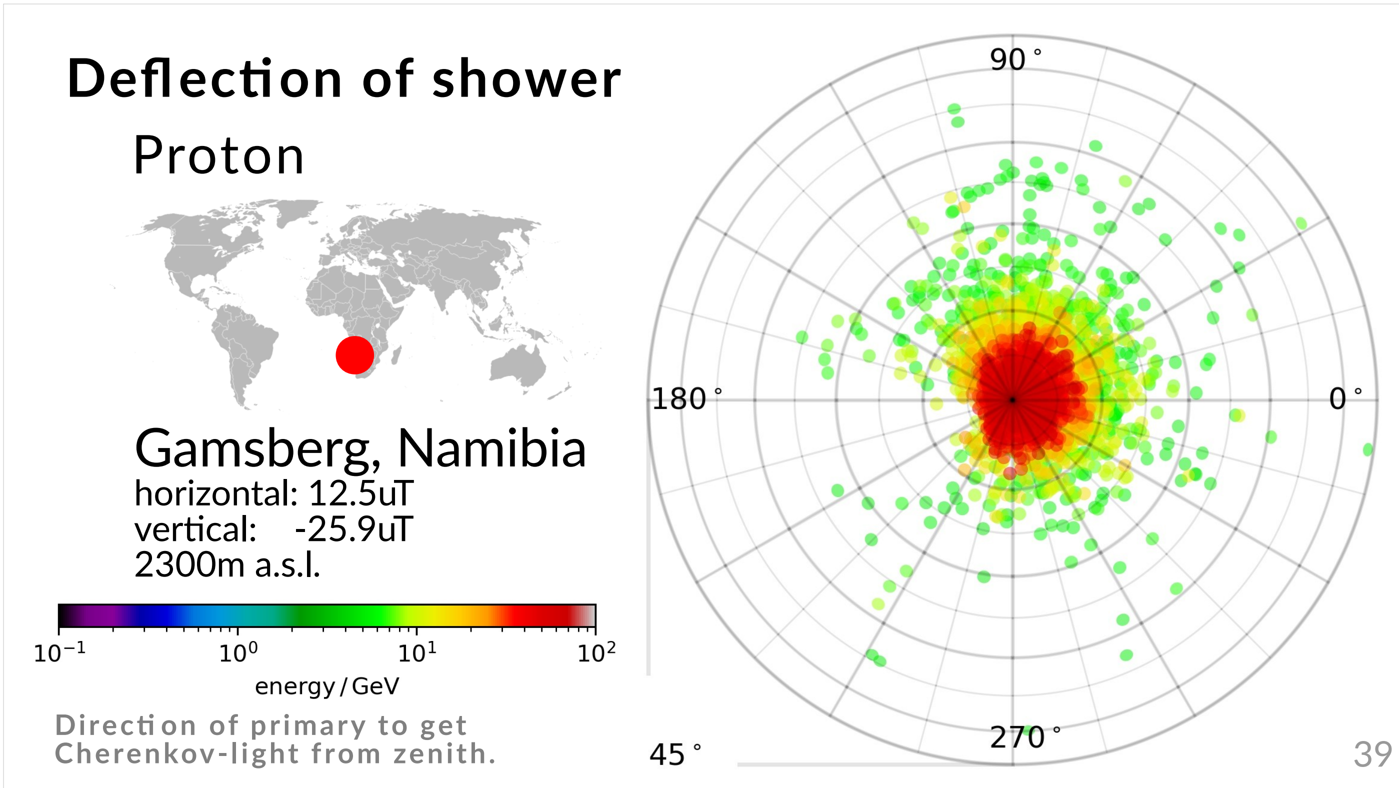
Deflection of shower



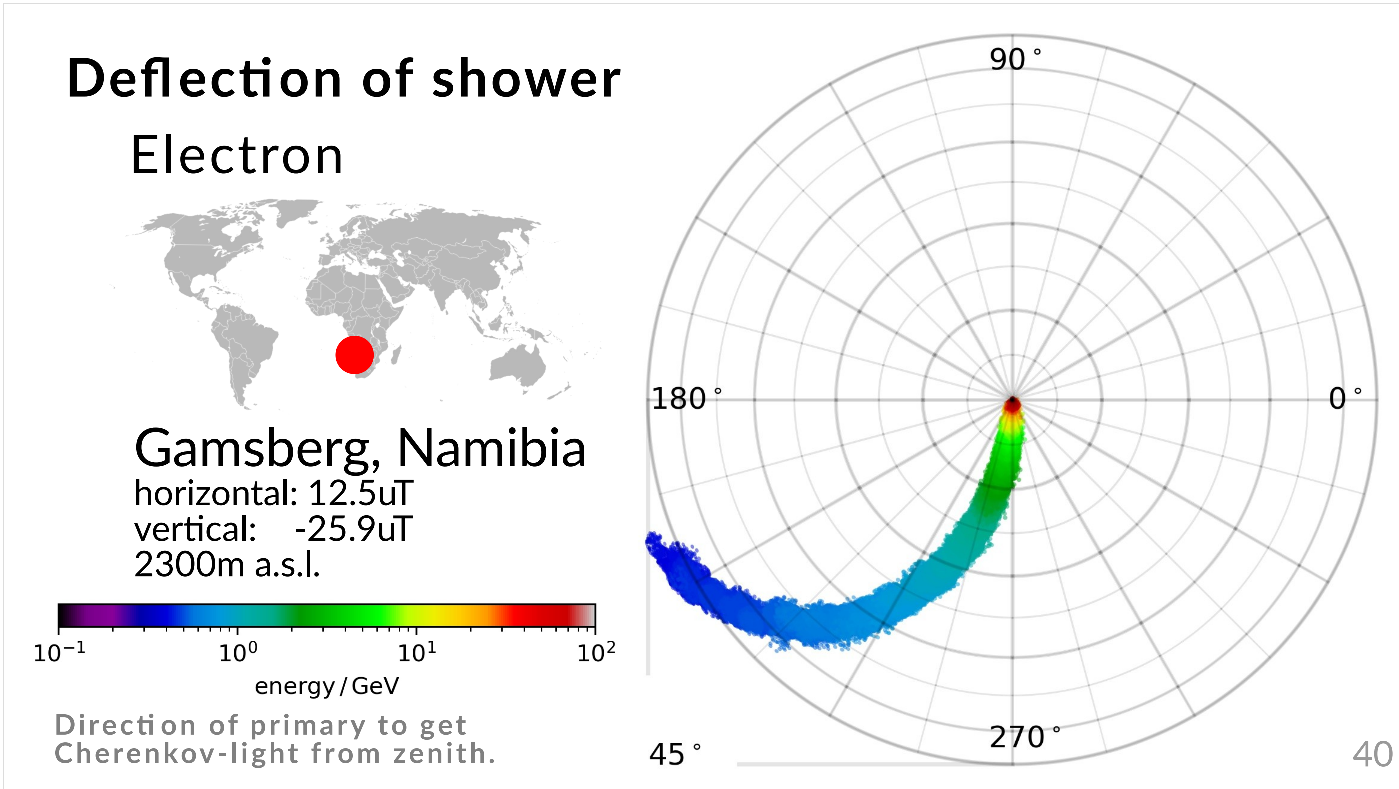
This raises the question from what direction do we have to through a cosmic-ray so that our instrument can see the Cherenkov-light?


Deflection of shower
Helium
Gamsberg, Namibia
horizontal: 12.5uT
vertical: -25.9uT
2300m a.s.l.
10^-1 10^0 10^1 10^2
energy / GeV
Direction of primary to get
Cherenkov-light from zenith.
90 °
180 °
0 °
270 °
45 °
38

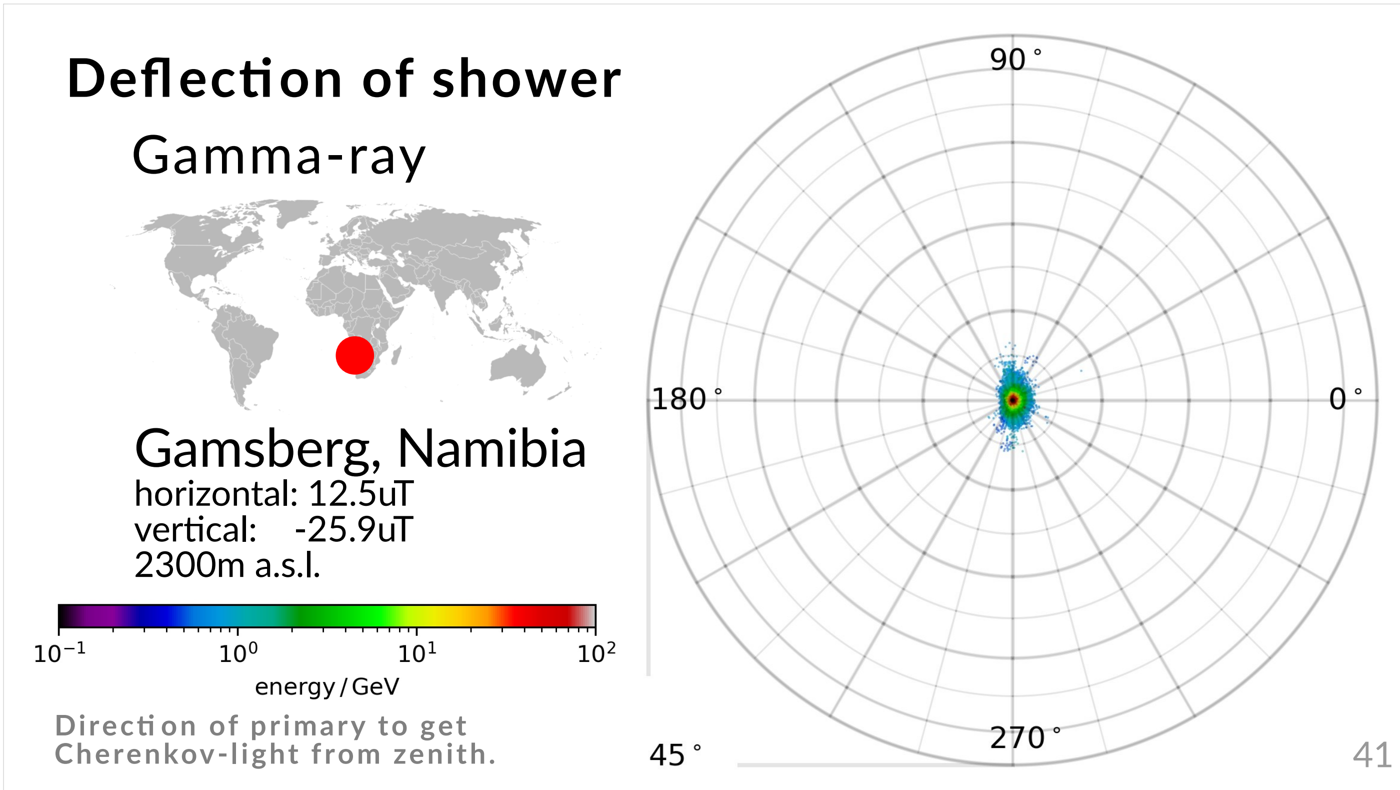
For Helium



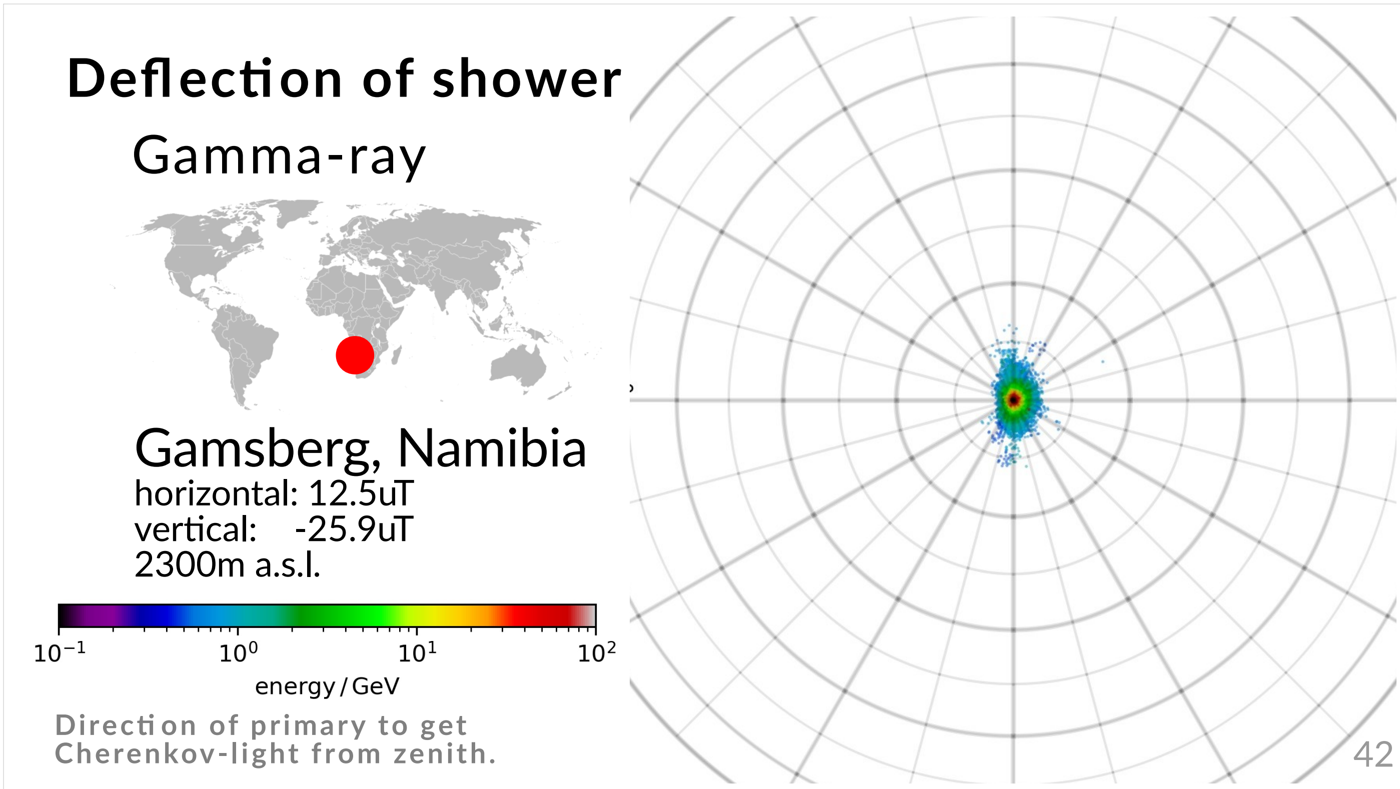
and the Proton this creates only small asymmetries.



But for leptons this deflection is so significant that there can be an additional cutoff.



This also effects our reconstruction of the gamma-ray's direction.

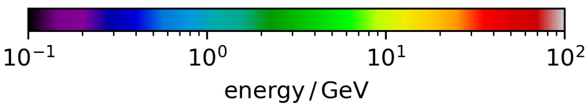


Let’s zoom in a bit

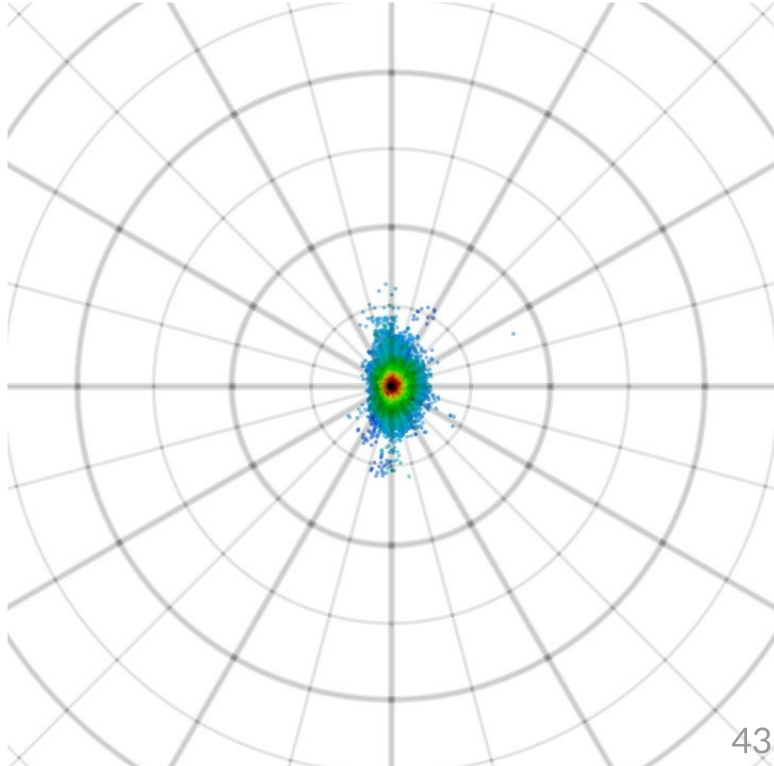
Deflection of shower

Gamma-ray

Gamsberg, Namibia
horizontal: 12.5uT
vertical: -25.9uT
2300m a.s.l.



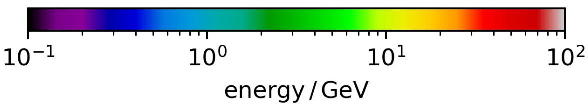
Direction of primary to get Cherenkov-light from zenith.



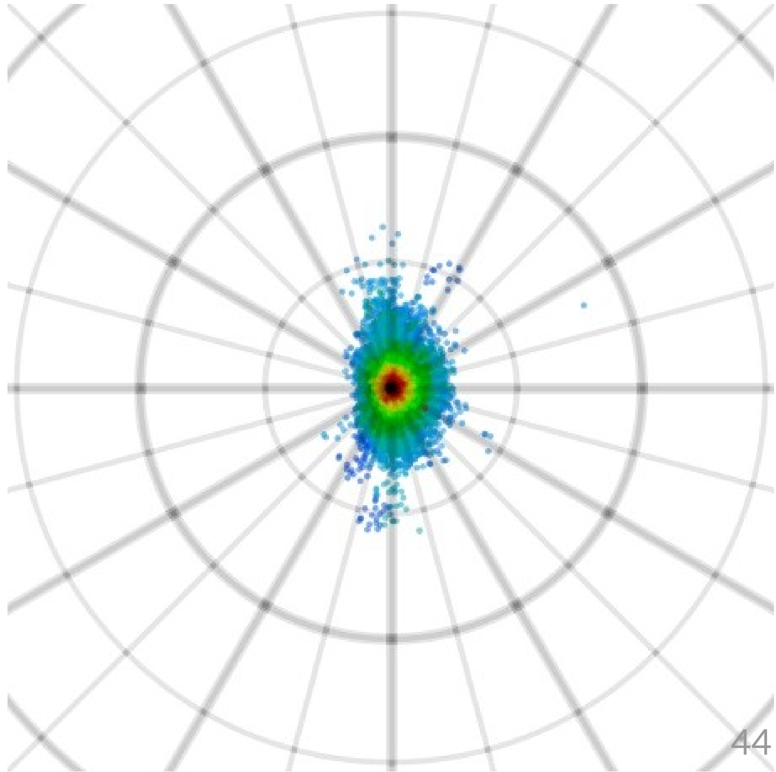
Deflection of shower

Gamma-ray

Gamsberg, Namibia
horizontal: 12.5uT
vertical: -25.9uT
2300m a.s.l.



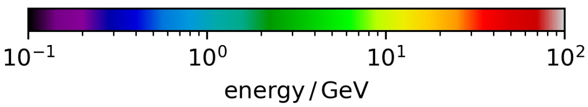
Direction of primary to get Cherenkov-light from zenith.



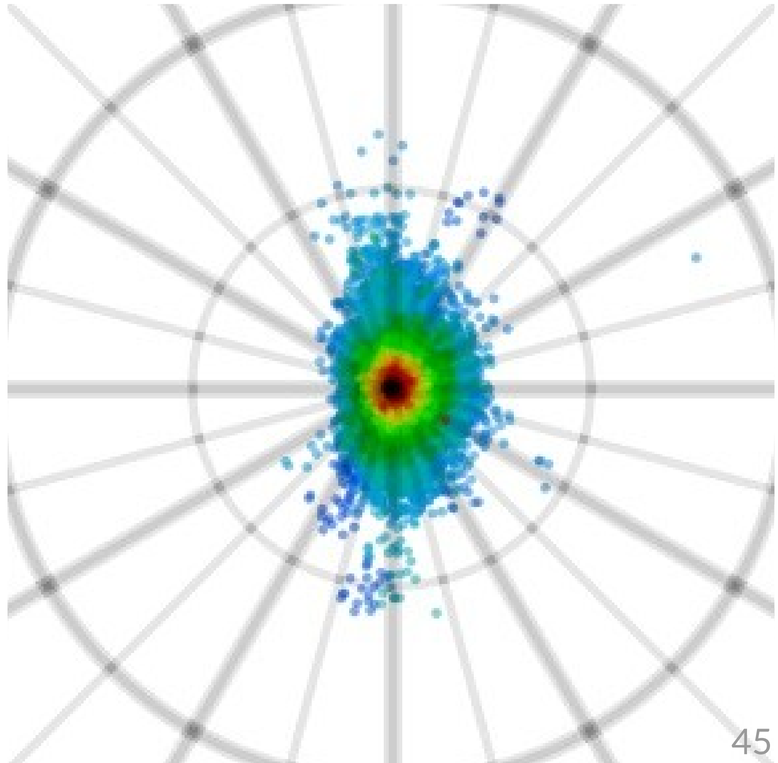
Deflection of shower

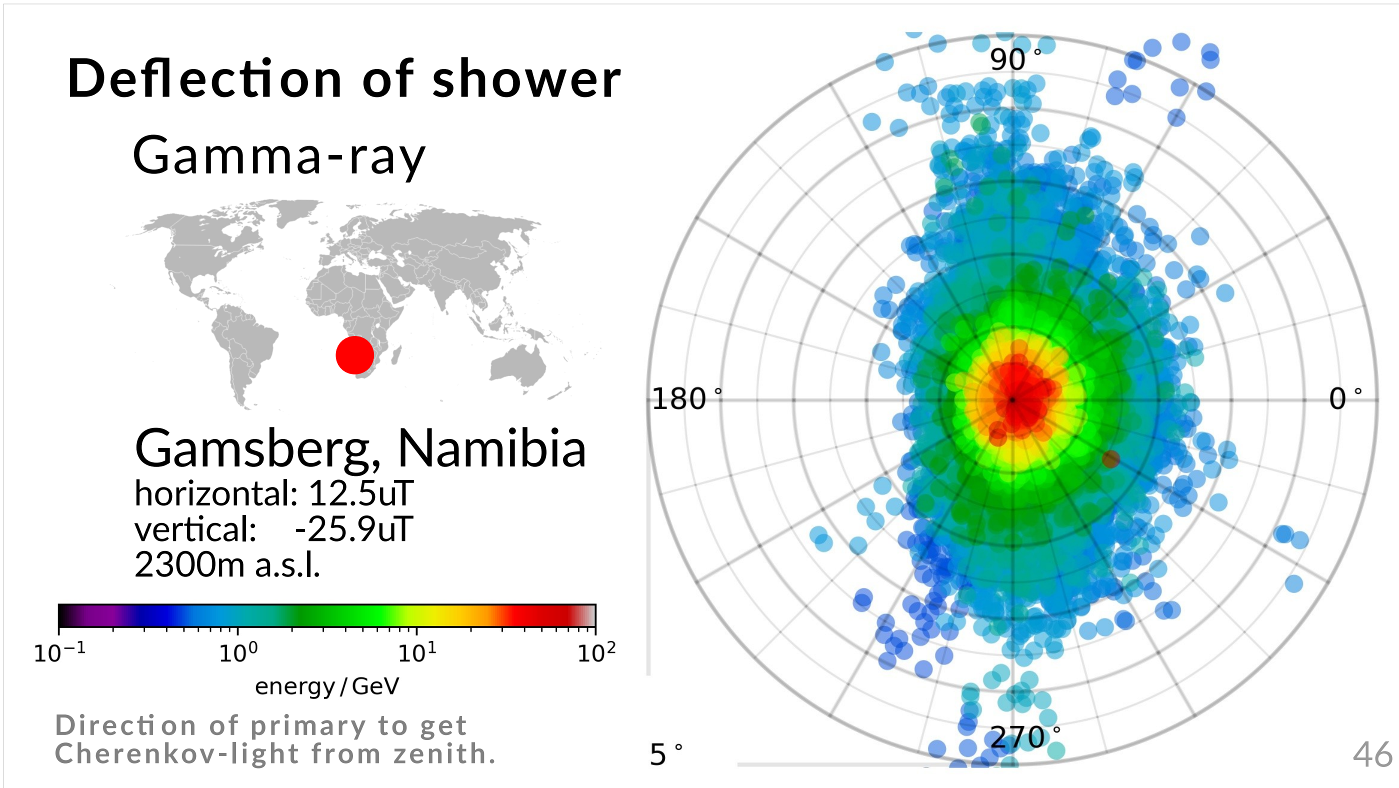
Gamma-ray

Gamsberg, Namibia
horizontal: 12.5uT
vertical: -25.9uT
2300m a.s.l.

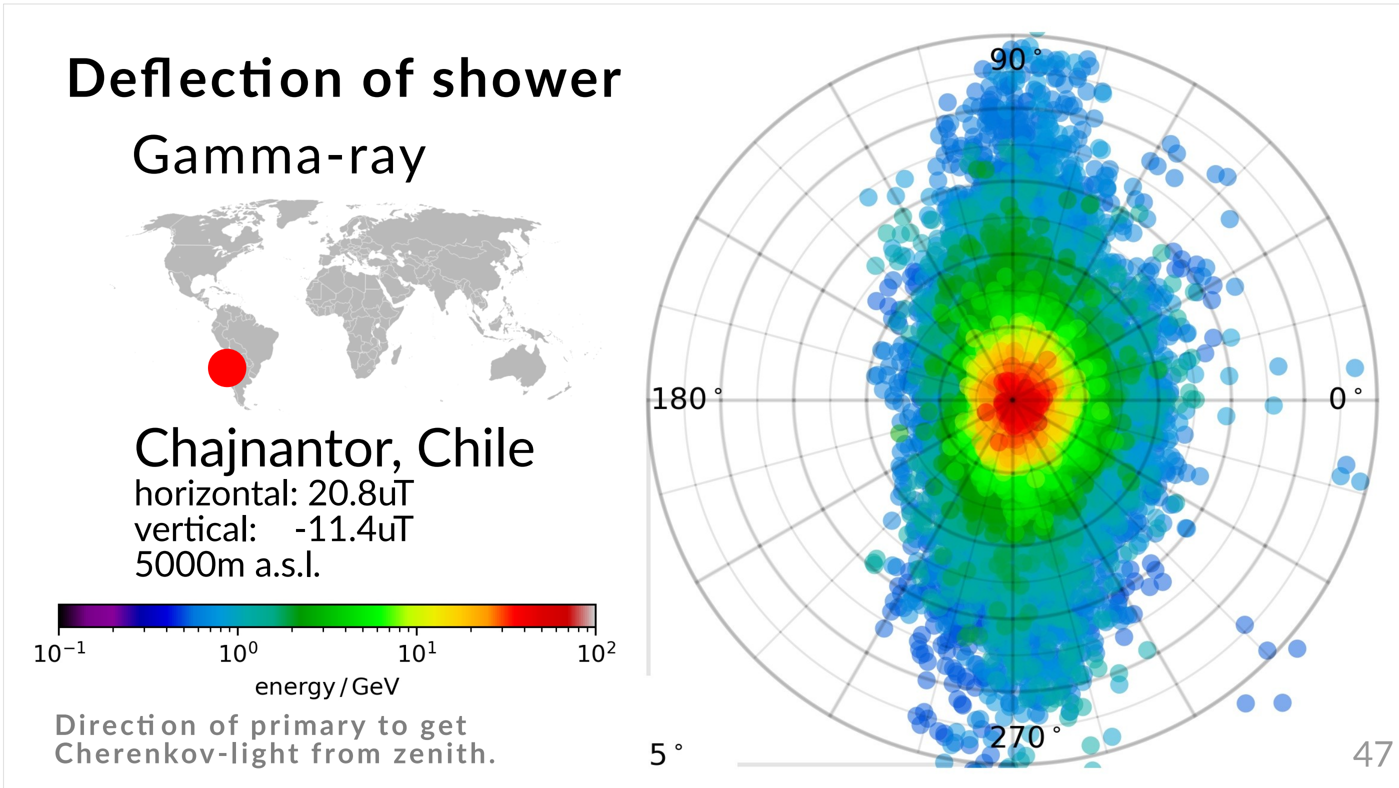


Direction of primary to get Cherenkov-light from zenith.

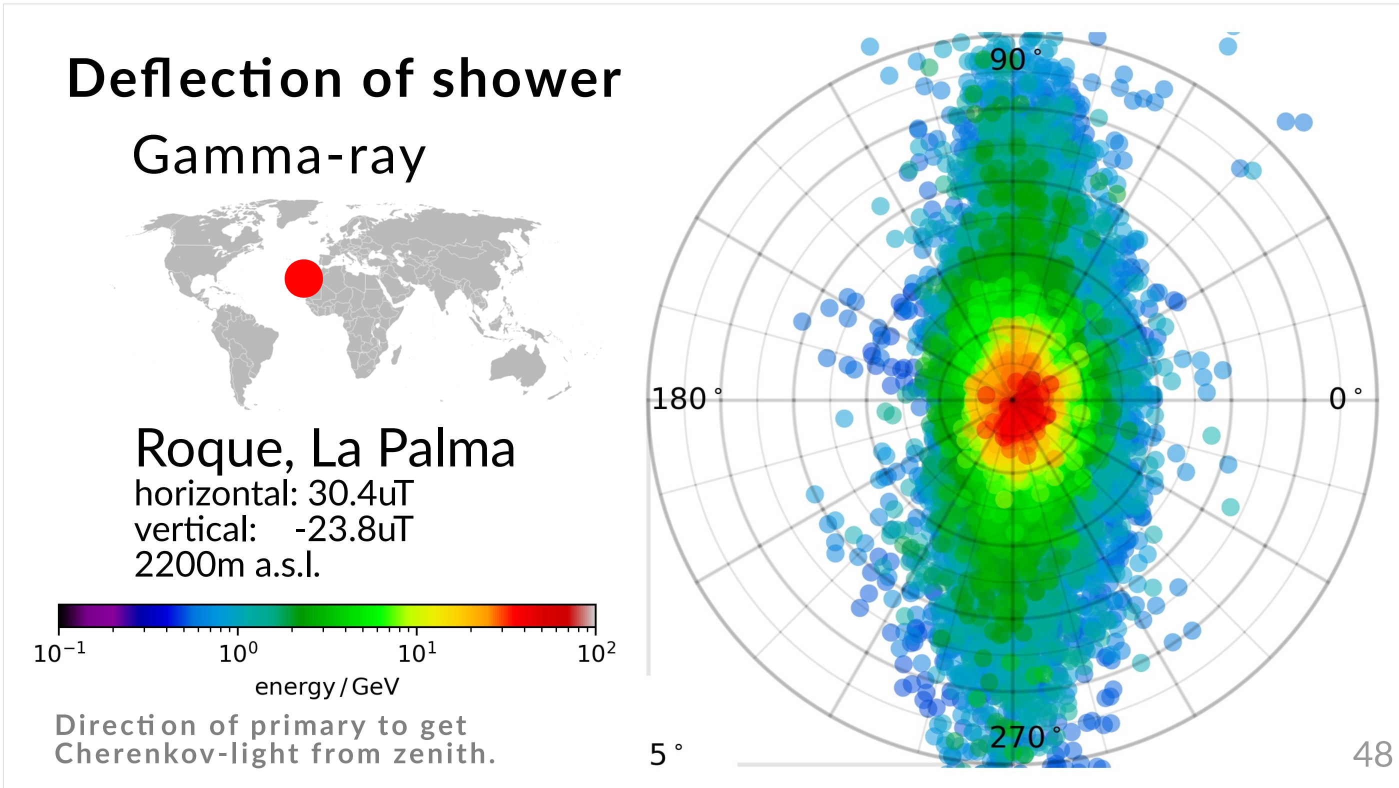




Most important here is the horizontal component of earth’s magnetic field.
The stronger the horizontal component becomes

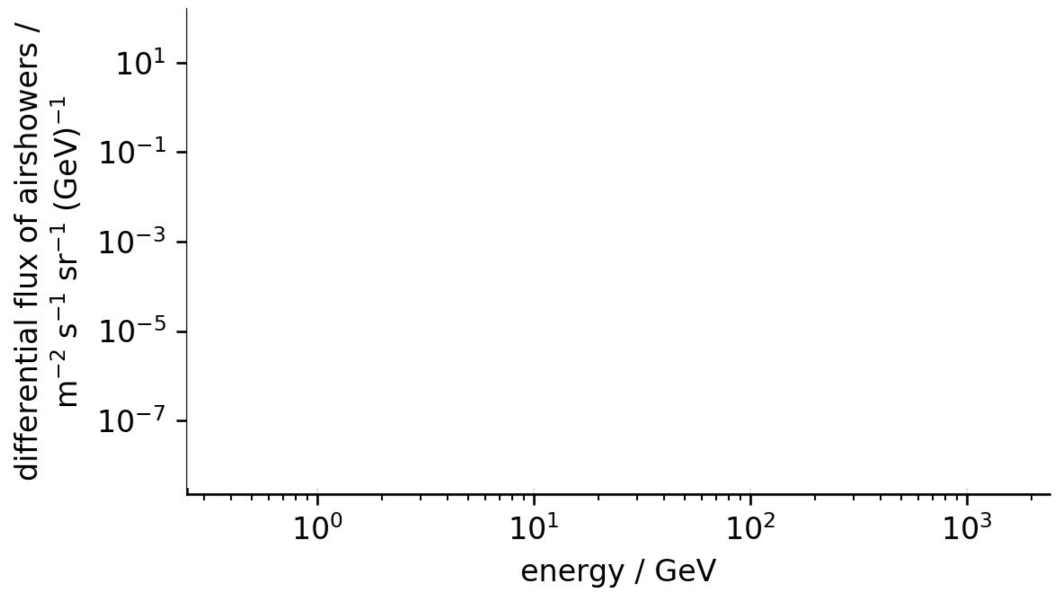

Deflection of shower
Gamma-ray
Chajnantor, Chile
horizontal: 20.8uT
vertical: -11.4uT
5000m a.s.l.
10^{-1}
10^{0}
10^{1}
10^{2}
energy / GeV
Direction of primary to get
Cherenkov-light from zenith.
90°
180°
0°
270°
5°
47

the larger



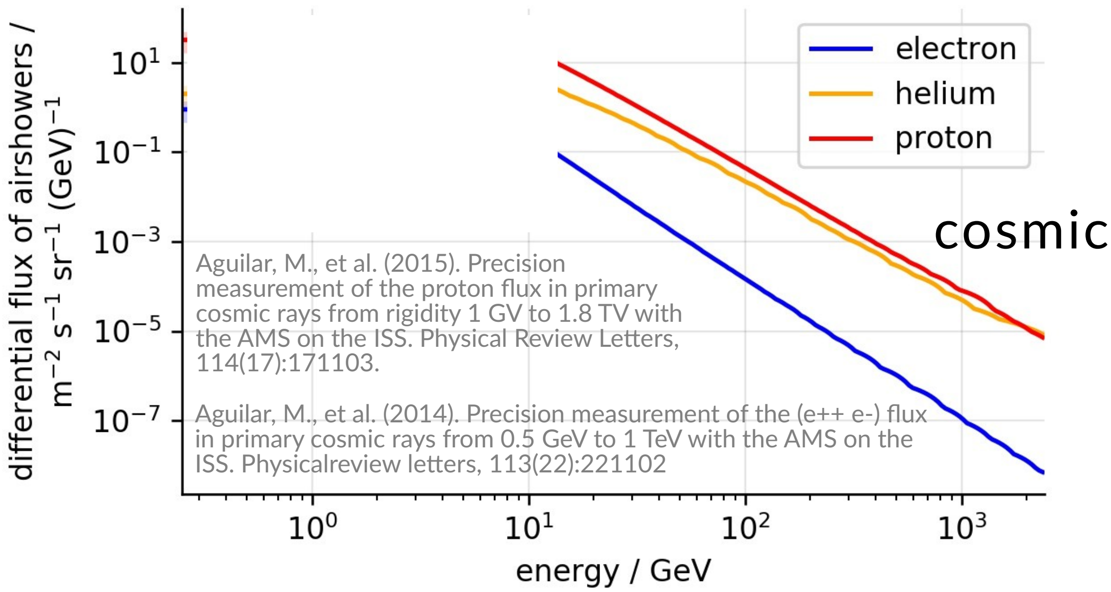
is the deflection

Background from Airshowers



How does this effect the background from airshowers?

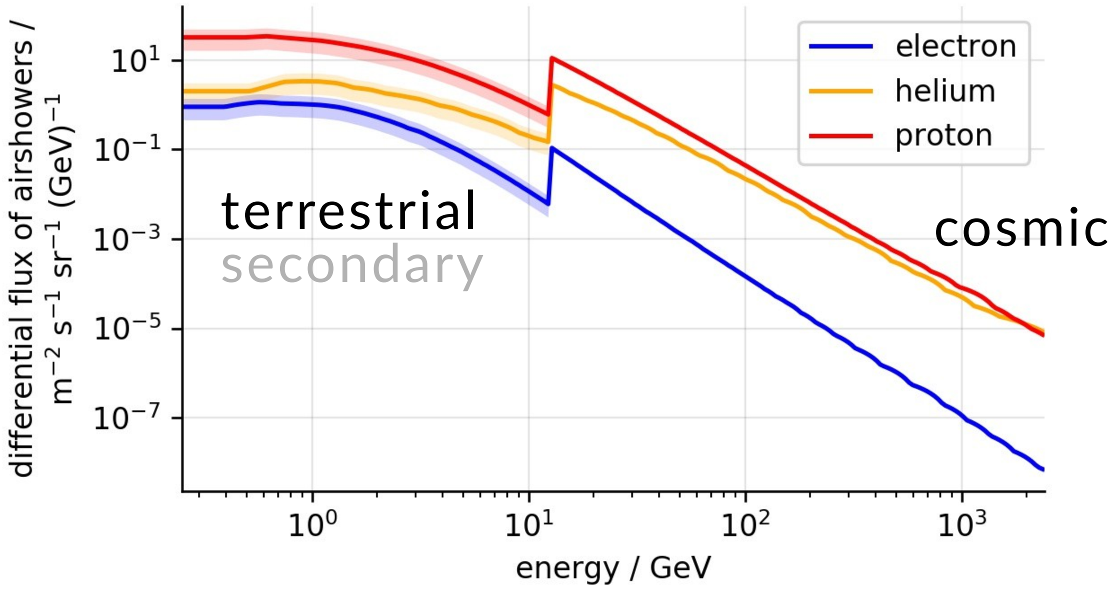
Background from Airshowers



50

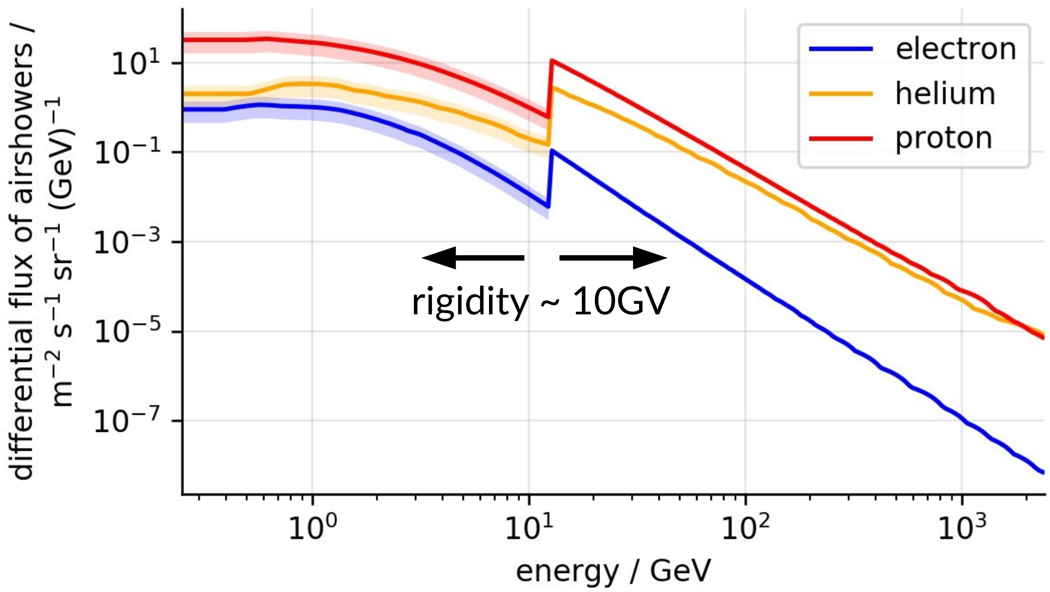
Above the geomagnetic cutoff, we have the usual cosmic-rays.

Background from Airshowers



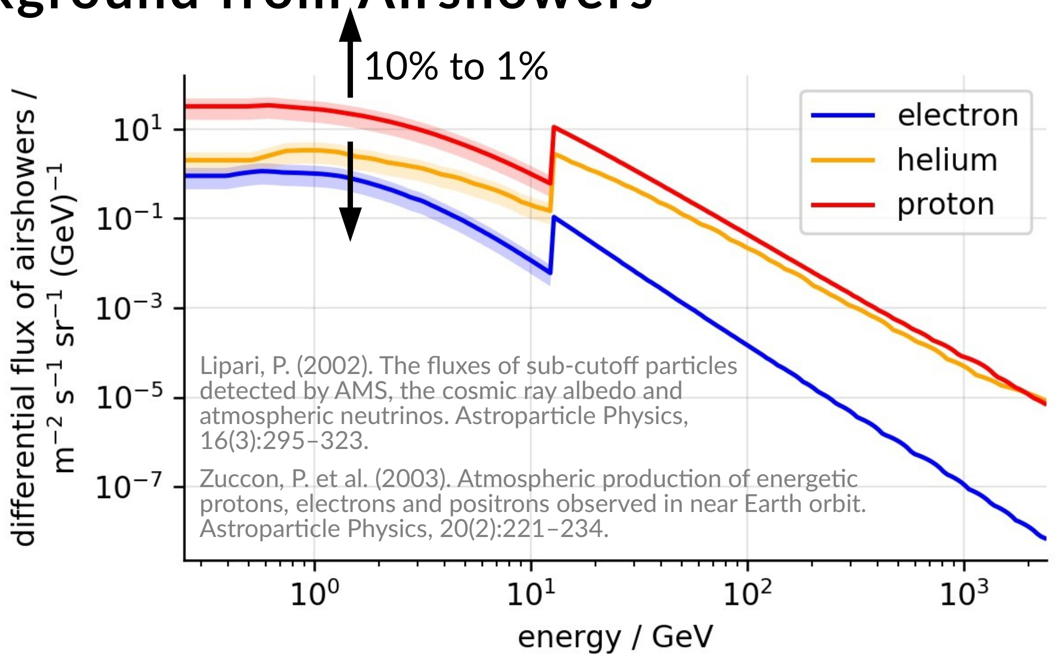
But below the geomagnetic cutoff we find showers induced by secondary, terrestrial particles.

Background from Airshowers



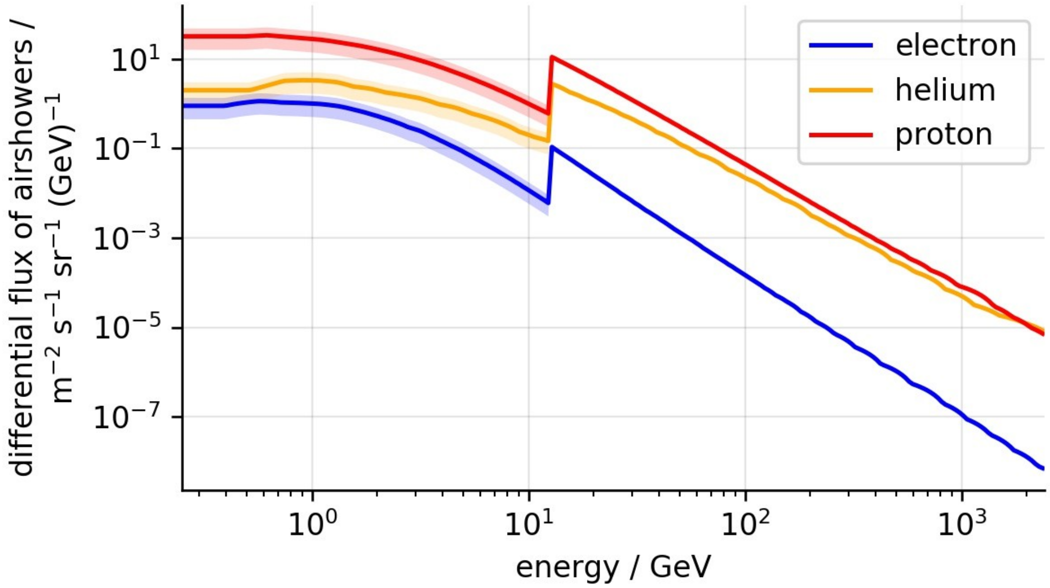
The cutoff rigidity depends on earth’s magnetic field.

Background from Airshowers

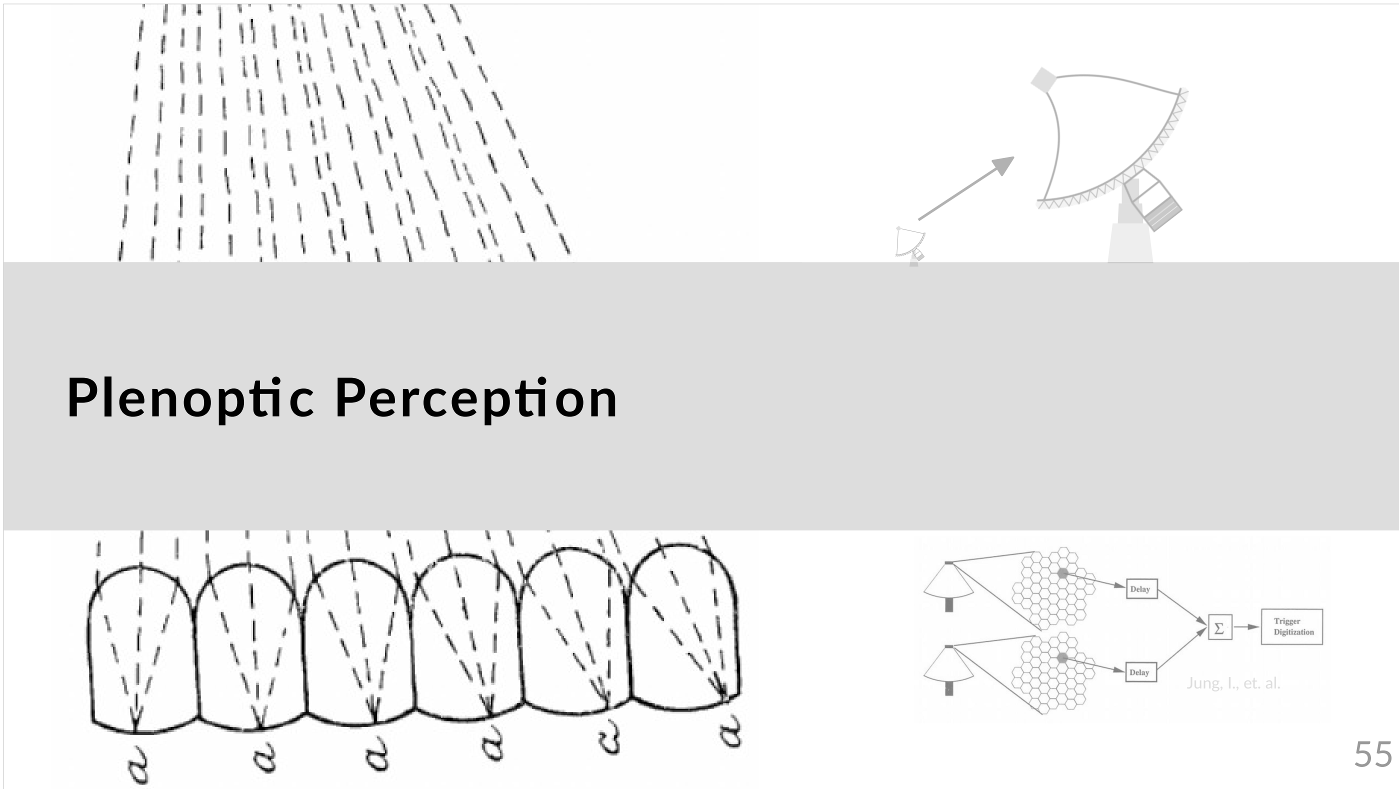


And the flux below the cutoff is estimated to be about one to ten percent of the initial cosmic-rays flux.

Background from Airshowers



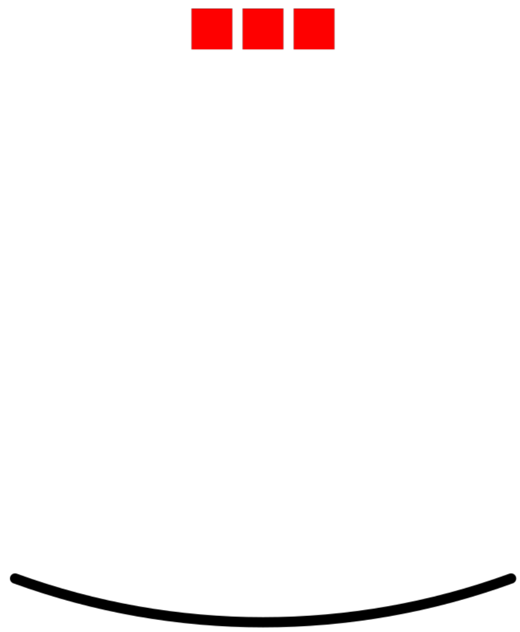
So any advance in the atmospheric Cherenkov-method will face a more complex background.



Now here is our proposal to advance the atmospheric Cherenkov-method using plenoptic perception to avoid the trigger-challenge and to resolve the limits of large telescopes.

Plenoptics

Telescope



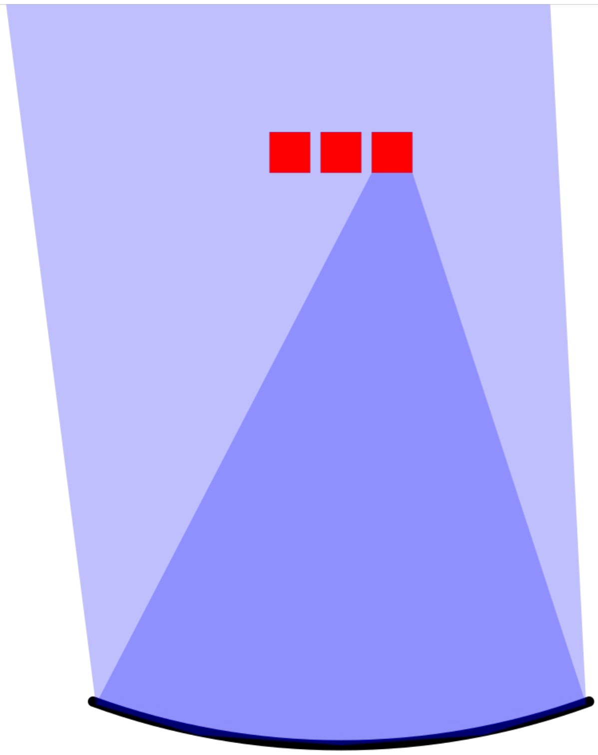
56

A telescope has a mirror and a sensor.

The sensor here is an array of red photo-sensors.

Plenoptics

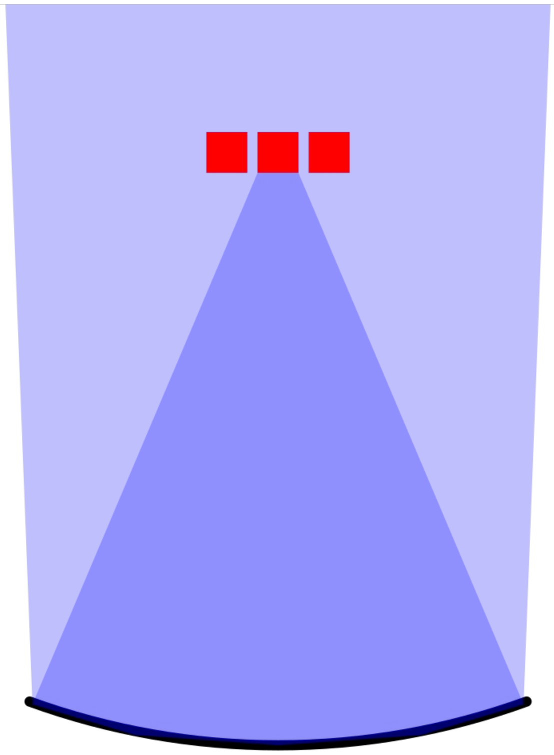
Telescope



Each photo-sensor samples a different beam of light.

Plenoptics

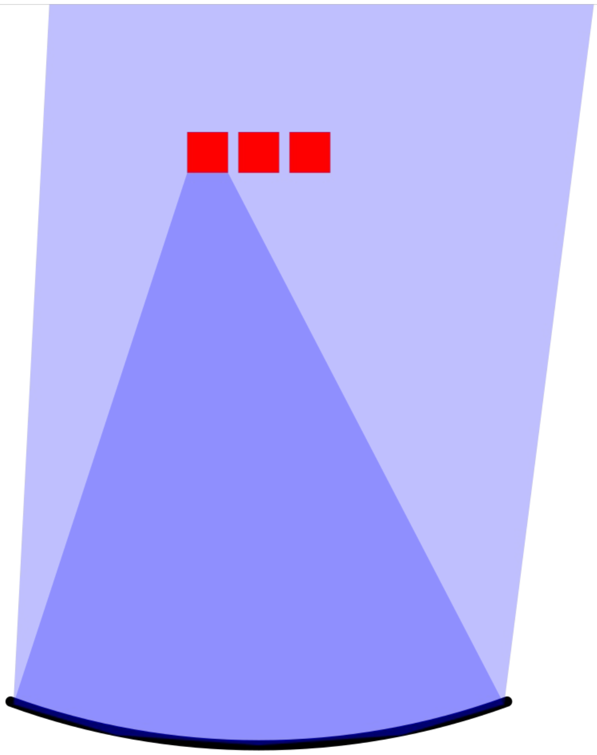
Telescope



Since the beams spread on the entire mirror

Plenoptics

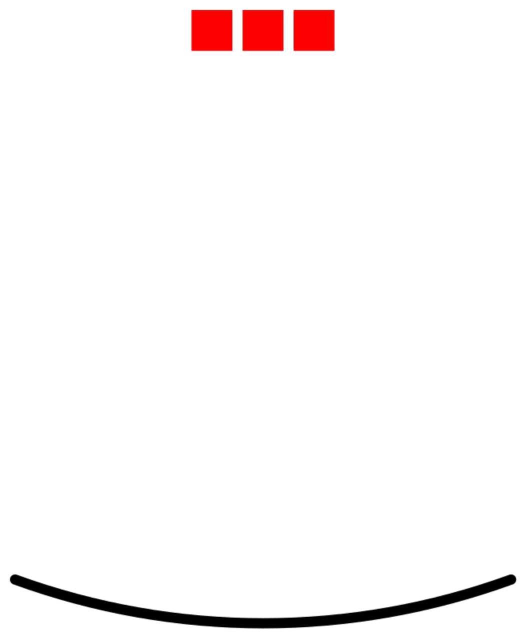
Telescope



The telescope can not measure the position where a photon is reflected on the mirror.

Plenoptics

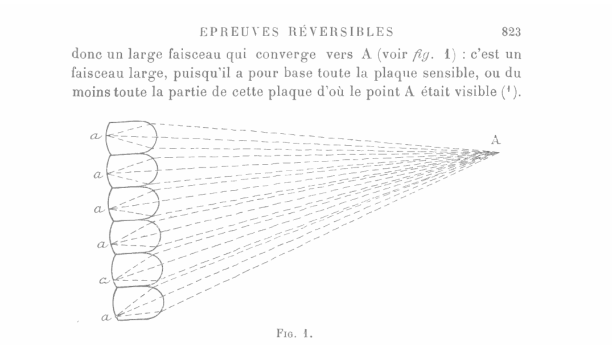
Telescope



Now we replace each photo-sensor with a camera

Plenoptics

Telescope
Plenoscope



EPREUVES 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).

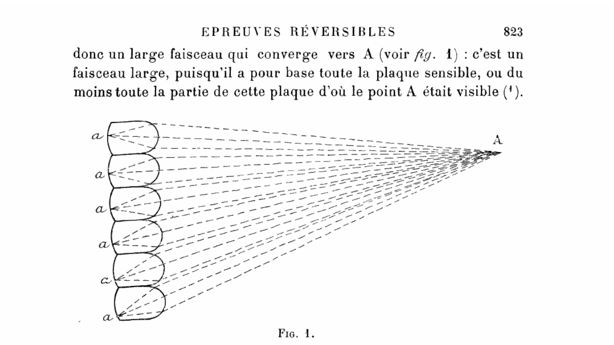
Fig. 1.

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

A camera is made of a lens and a __small__ array of photo-sensors.

Plenoptics

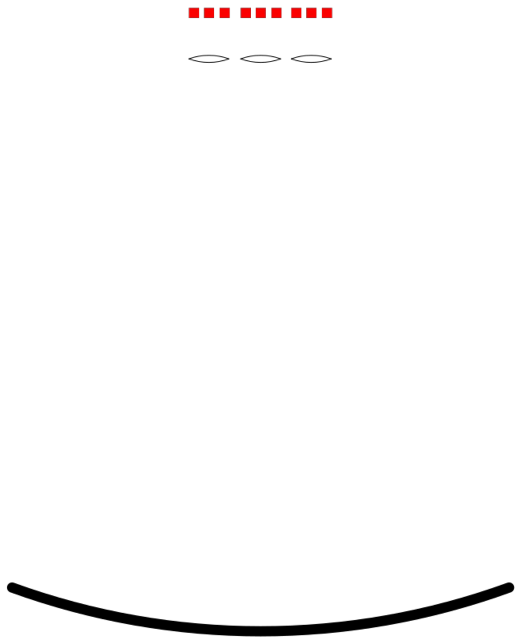
Plenoscope



EPREUVES 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.

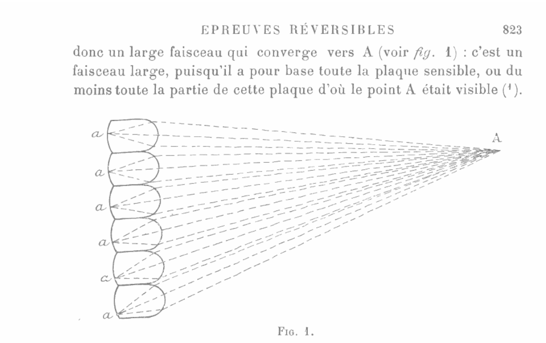


Par M. G. Lippmann, (**1908**),
Epreuves reversibles donnant la sensation du relief,
Phys. Theor. Appl. 7, p.821-825

Here are the lenses, and here the small arrays of photo-sensors. (pointing on it)

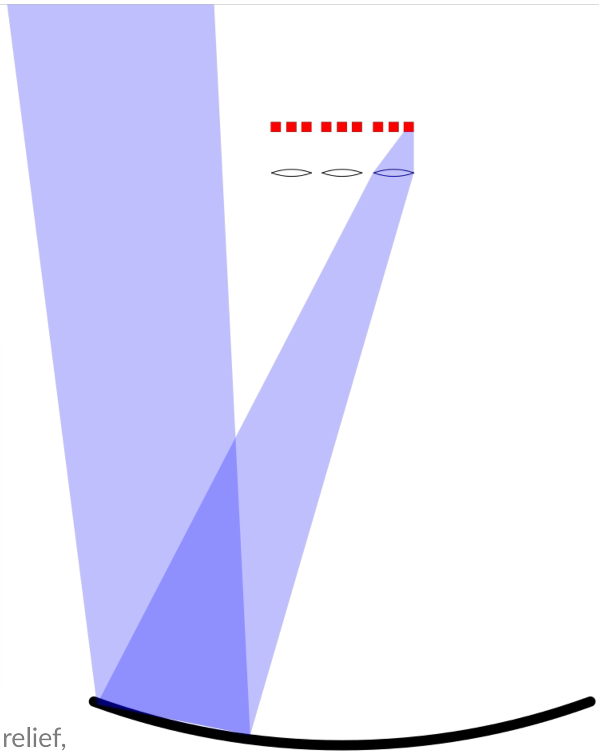
Plenoptics

Plenoscope


EPREUVES 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.

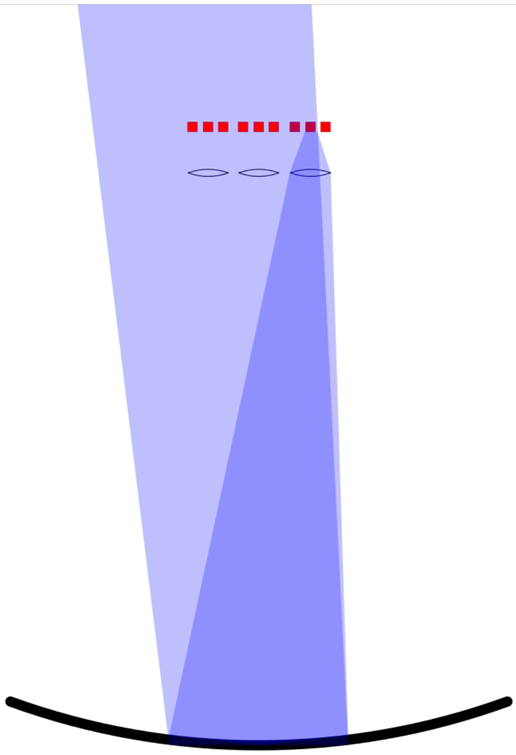


Par M. G. Lippmann, (**1908**),
Epreuves reversibles donnant la sensation du relief,
Phys. Theor. Appl. 7, p.821-825

Again each photo-sensor samples a beam of light

Plenoptics

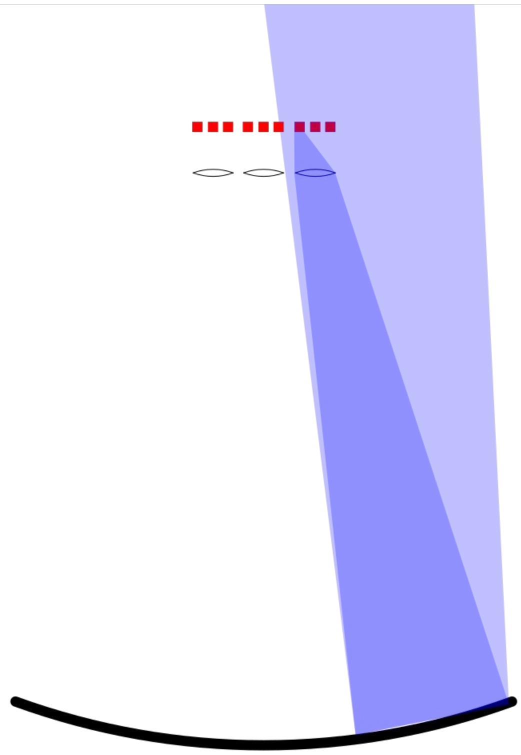
Plenoscope



but this time the beams do not spread on the entire mirror.

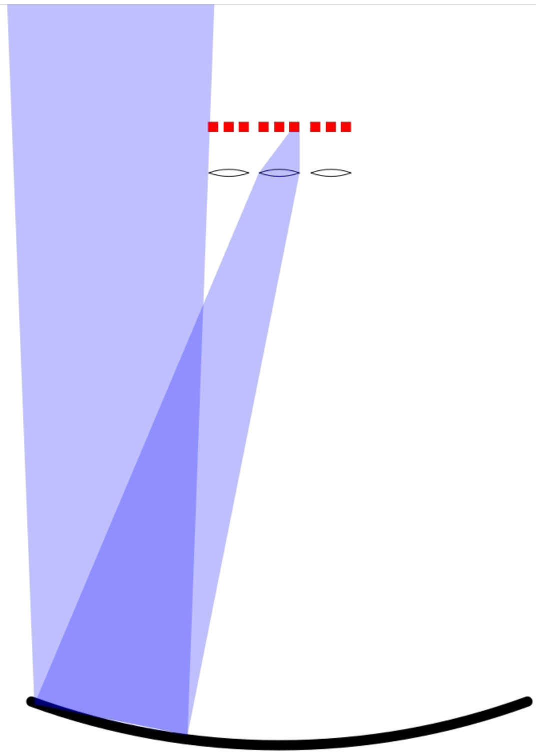
Plenoptics

Plenoscope



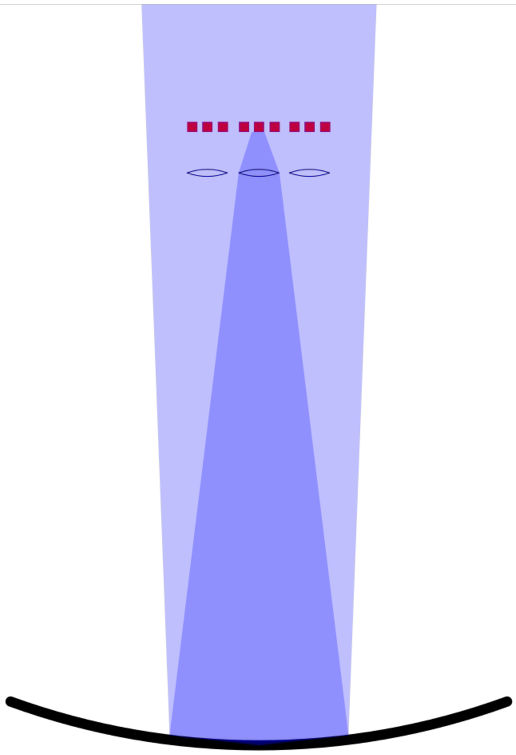
Plenoptics

Plenoscope



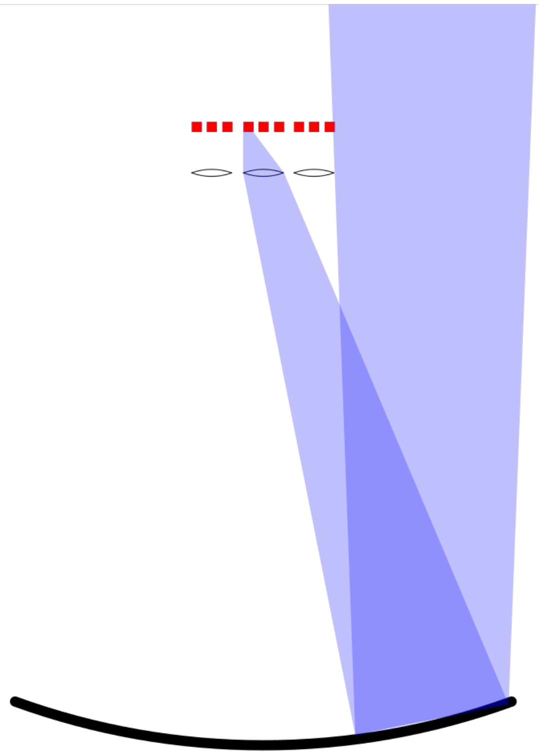
Plenoptics

Plenoscope



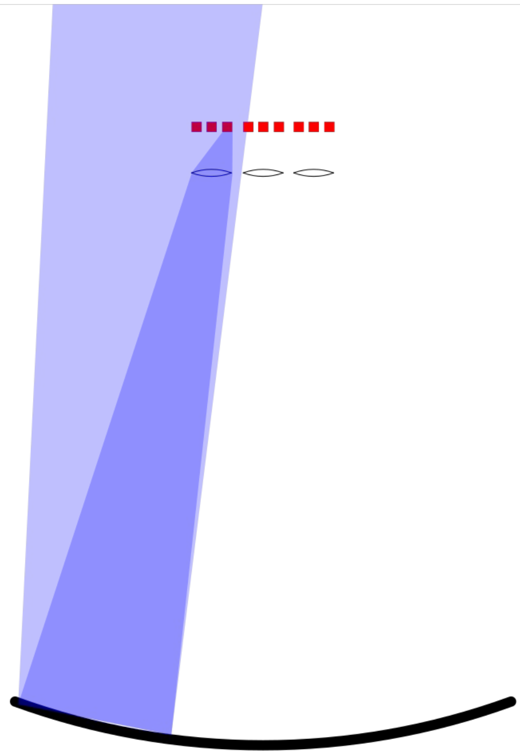
Plenoptics

Plenoscope



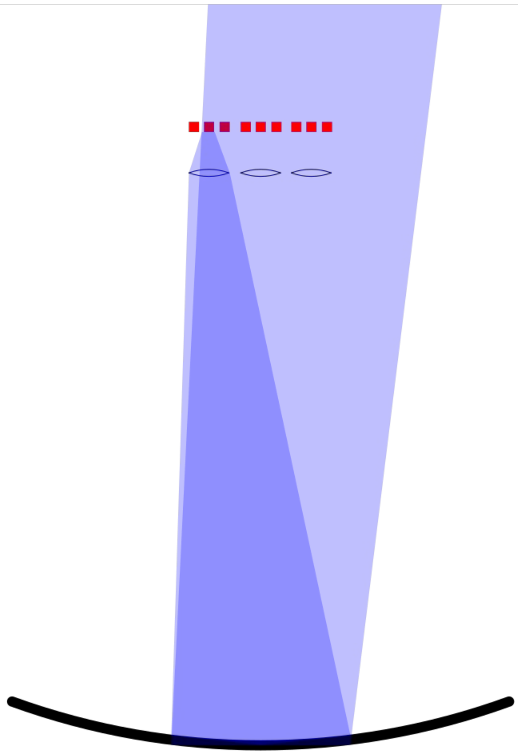
Plenoptics

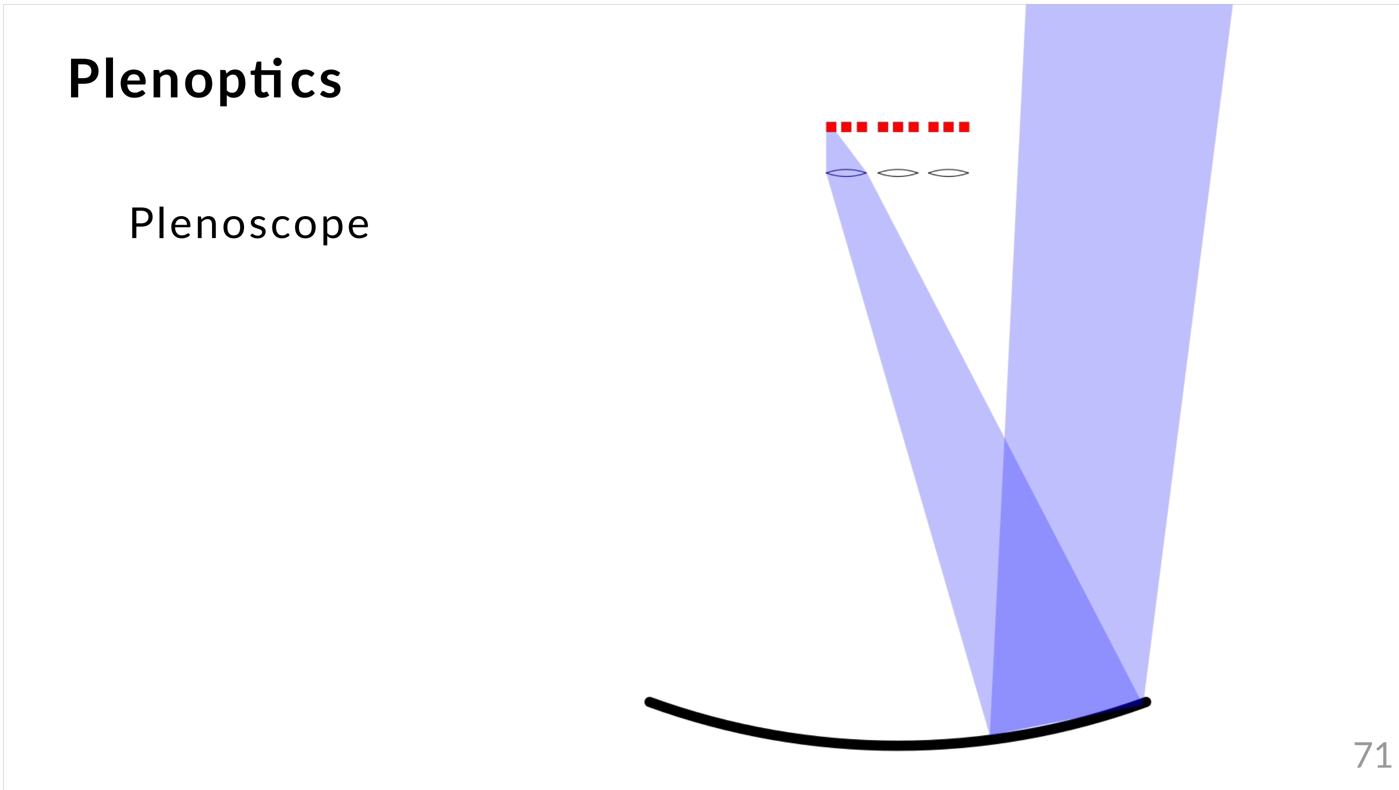
Plenoscope



Plenoptics

Plenoscope

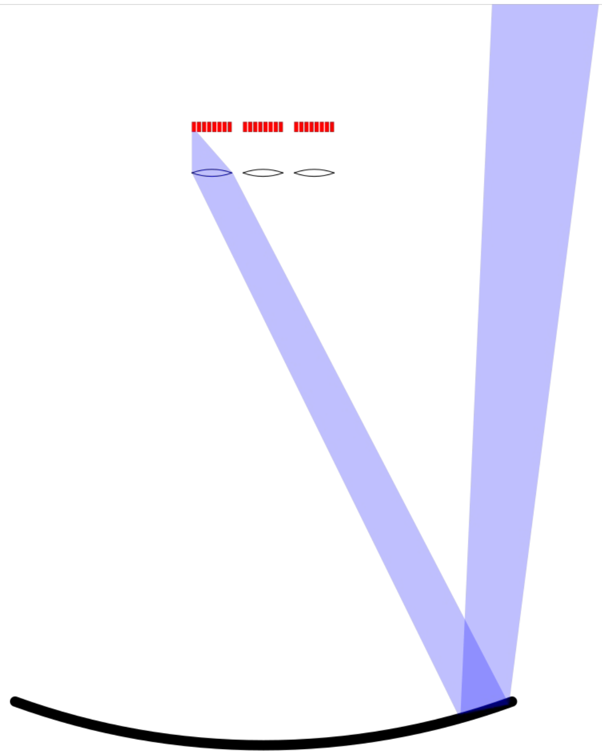




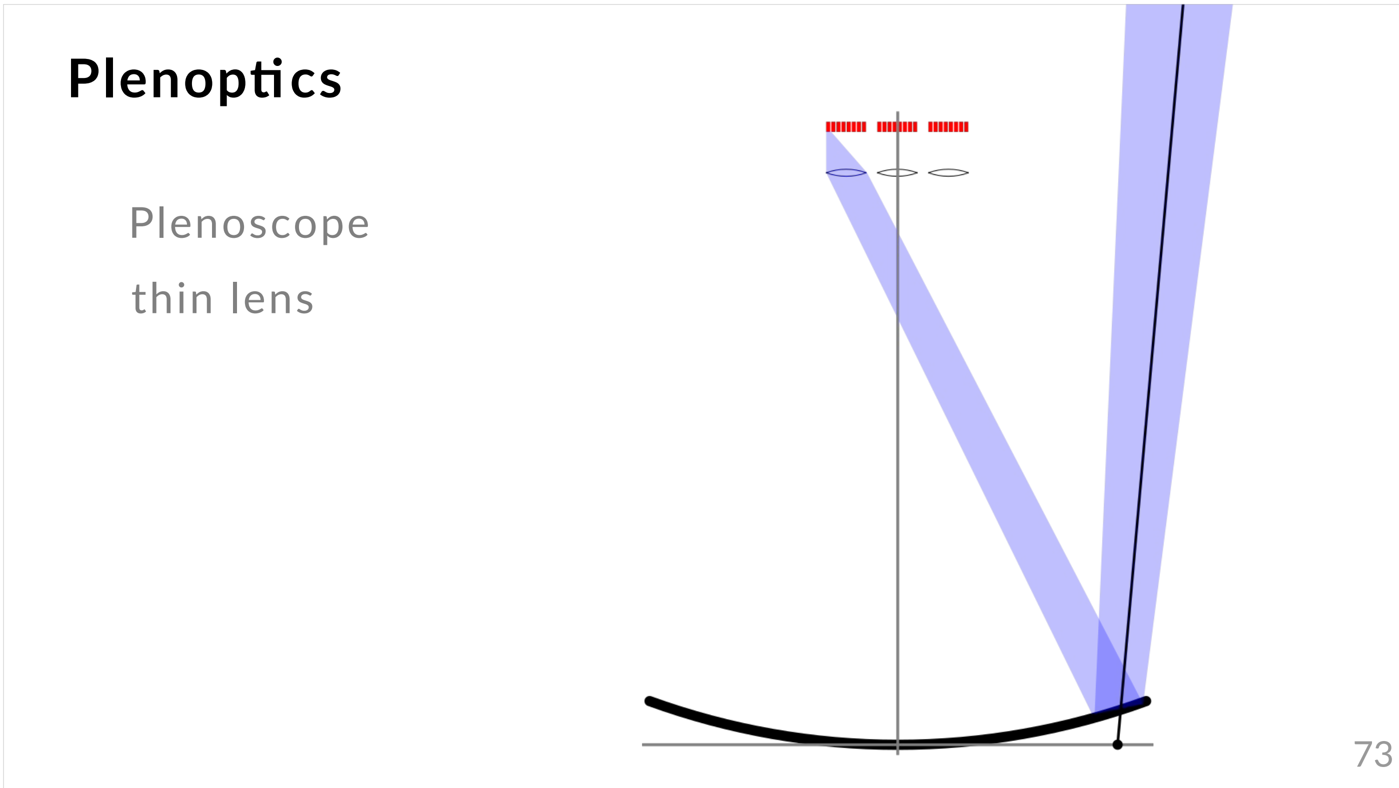
When we increase the density of photo-sensors inside the cameras,

Plenoptics

Plenoscope



the beams become so narrow



that they approximate the photons trajectories.

Now, the moment we measure the photons trajectories

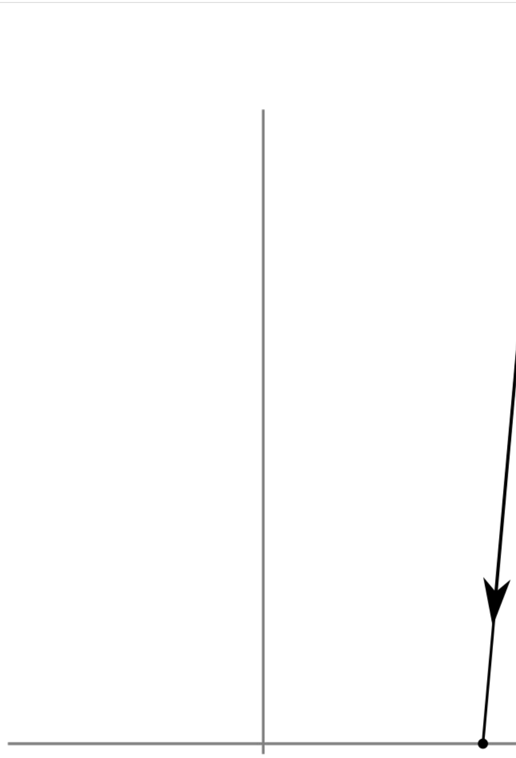
We can leave all the quirks and features of the hardware behind

Plenoptics

thin lens

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

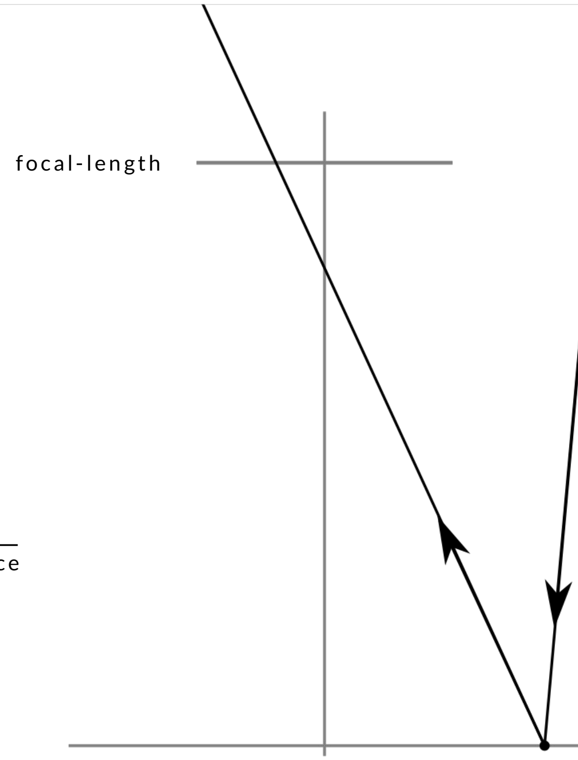
Equations: arXiv:1904.13368 (astro-ph)



and enter the 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)

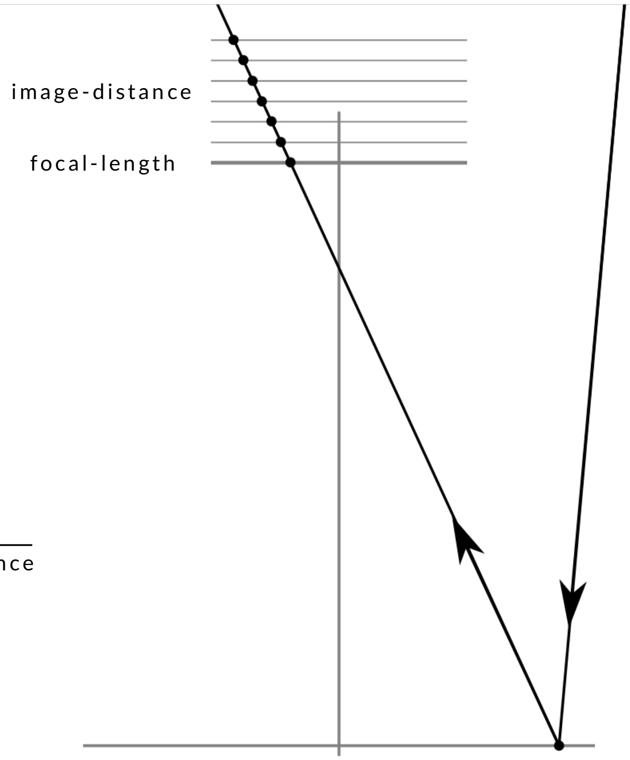
The thin-lens tells us where the photon will go after it passed the aperture's plane

Plenoptics

thin lens

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

Equations: arXiv:1904.13368 (astro-ph)



Now we are free to put virtual image-planes in any image-distance that our depth-driven heart desires.

This is where the imaging happens, here in the thin-lens, and not in a sensor that we can touch.

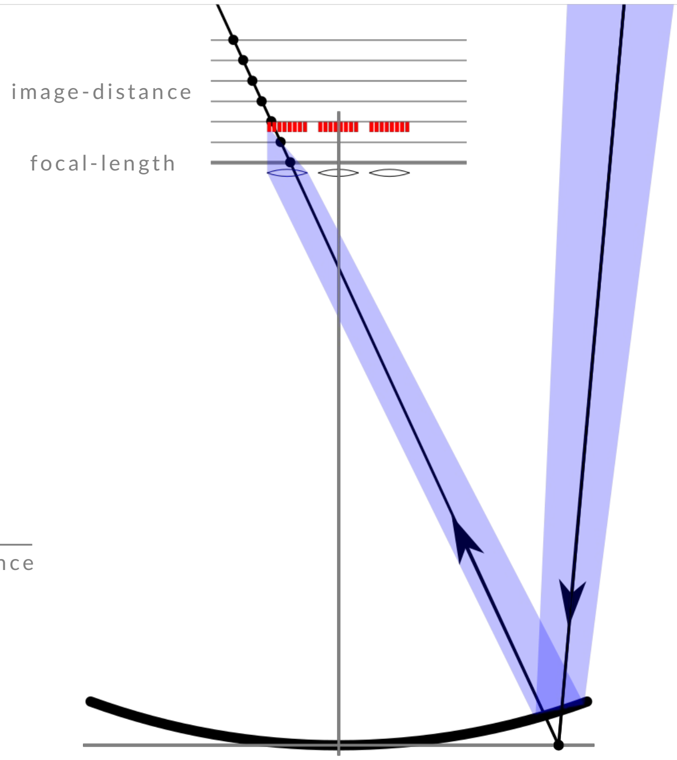
Plenoptics

Plenoscope

thin lens

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

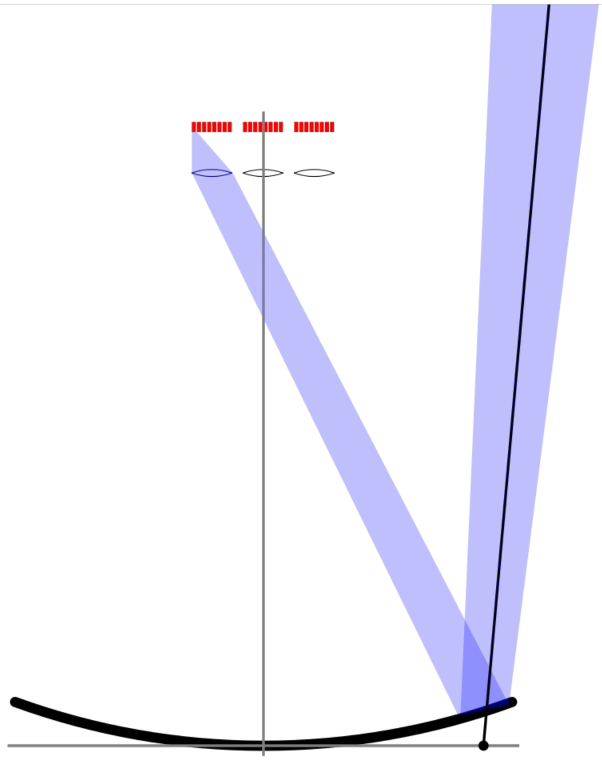
Equations: arXiv:1904.13368 (astro-ph)



Lets blend back to the plenoscope

Plenoptics

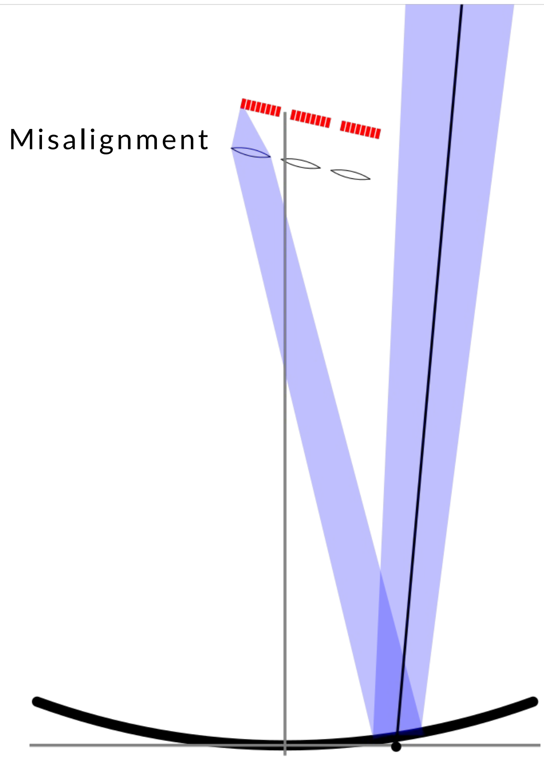
Plenoscope



and see what changes

Plenoptics

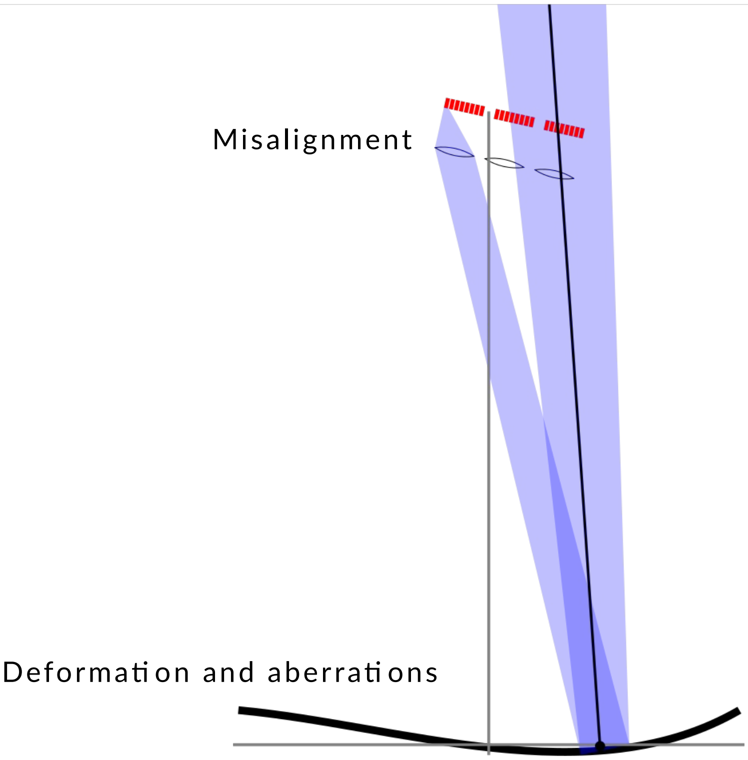
Plenoscope



when there is a misalignment

Plenoptics

Plenoscope

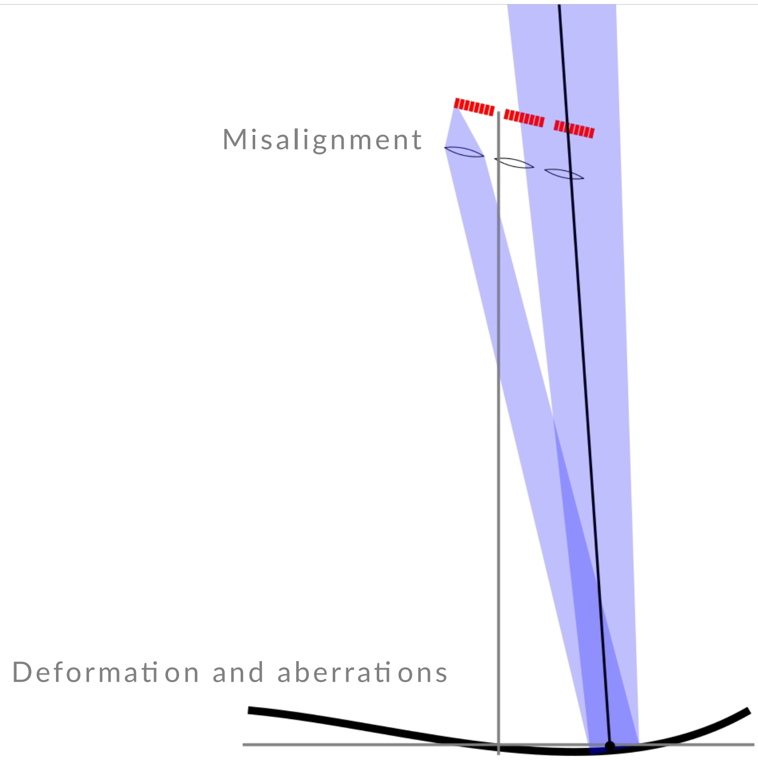


and a deformation

Plenoptics

Plenoscope

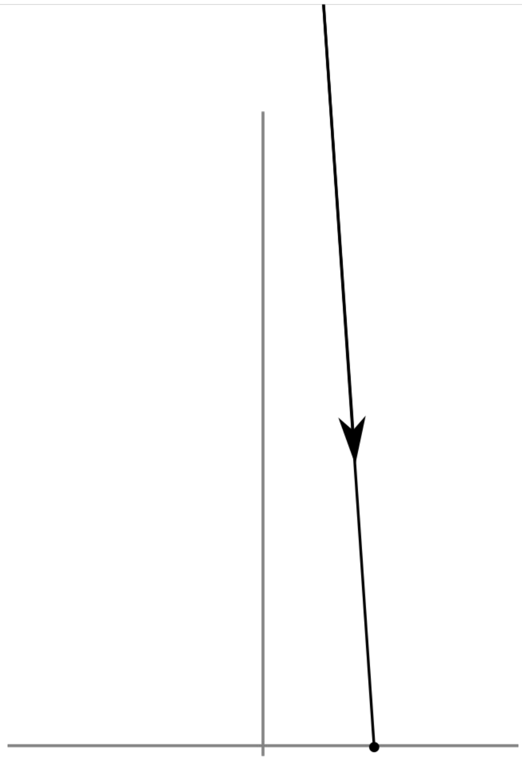
thin lens



Well, nothing.

Plenoptics

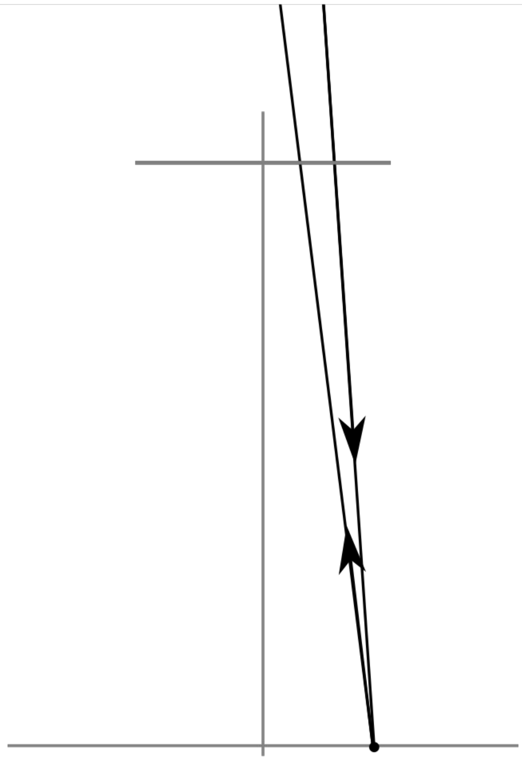
thin lens



Nothing changes. We still measure a trajectory.

Plenoptics

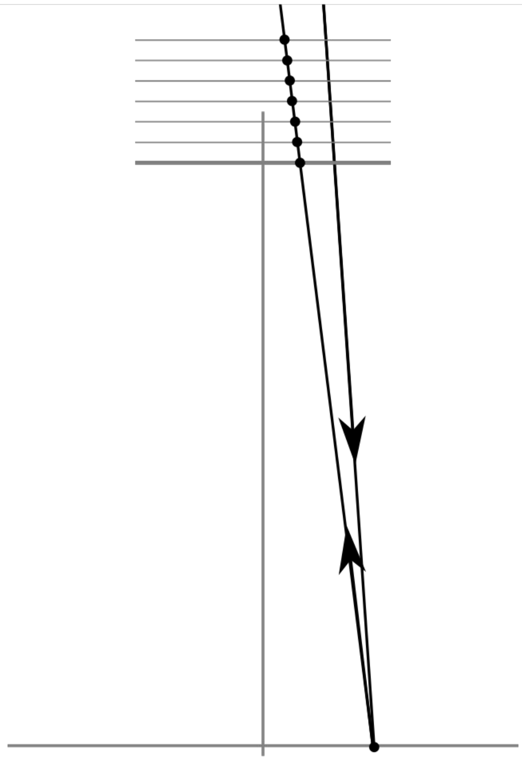
thin lens



We still use the thin-lens

Plenoptics

thin lens

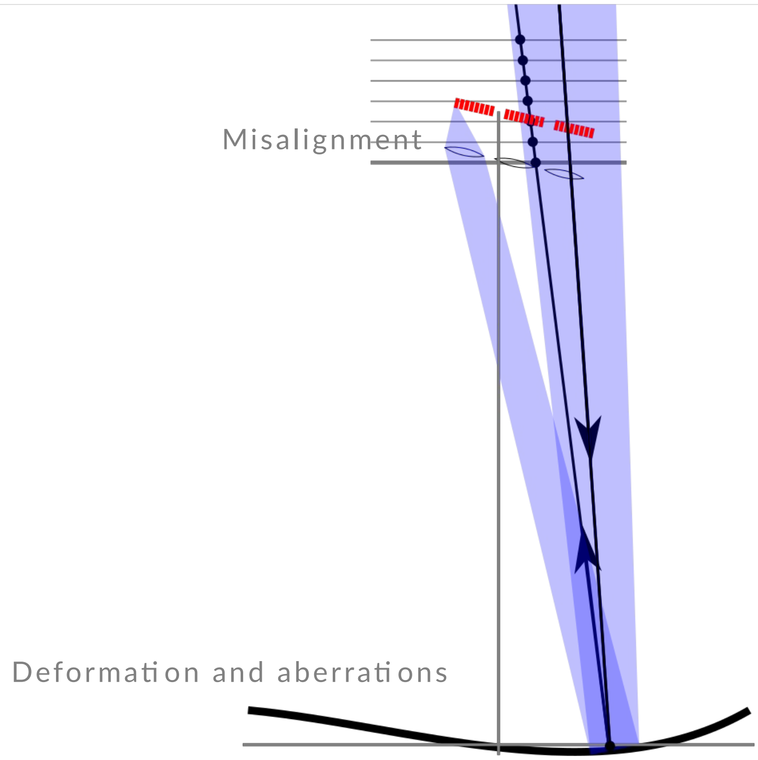


to do imaging.

Plenoptics

Plenoscope

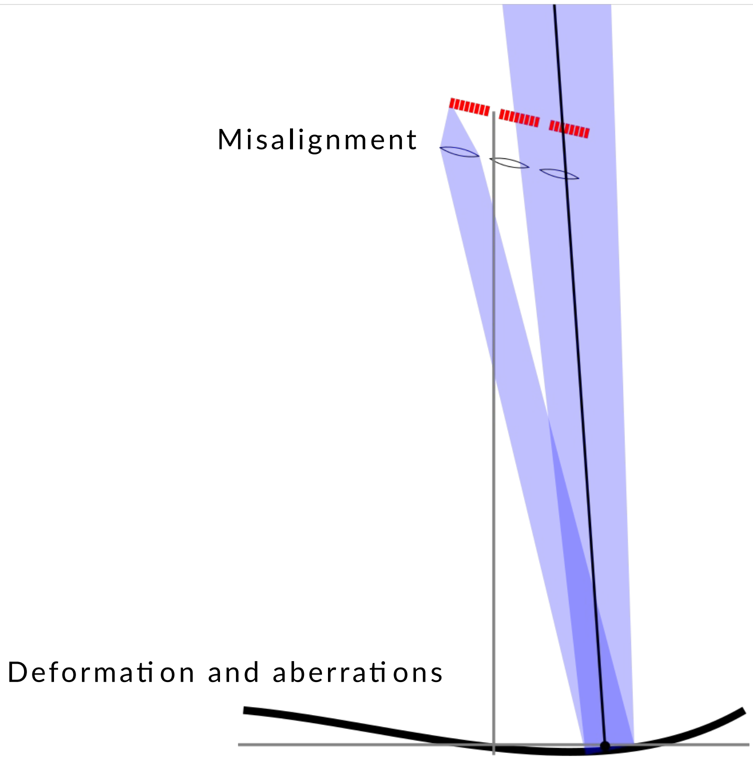
thin lens



And this way the plenoscope compensates

Plenoptics

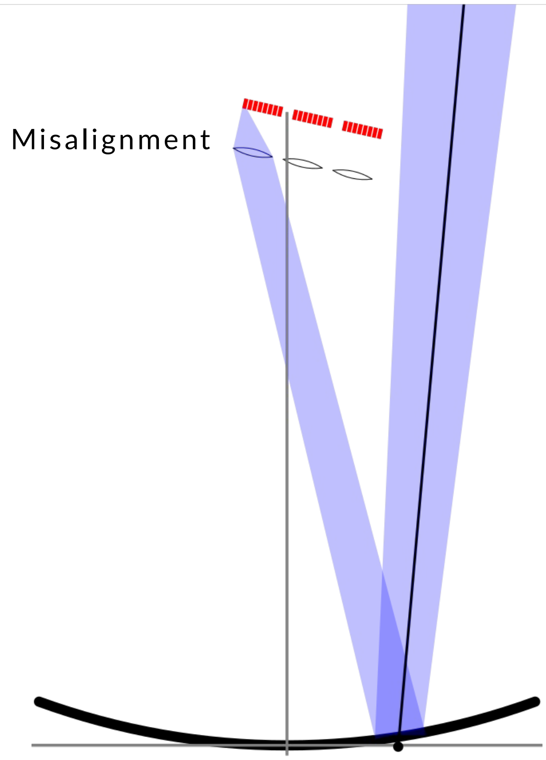
Plenoscope



Deformations and aberrations

Plenoptics

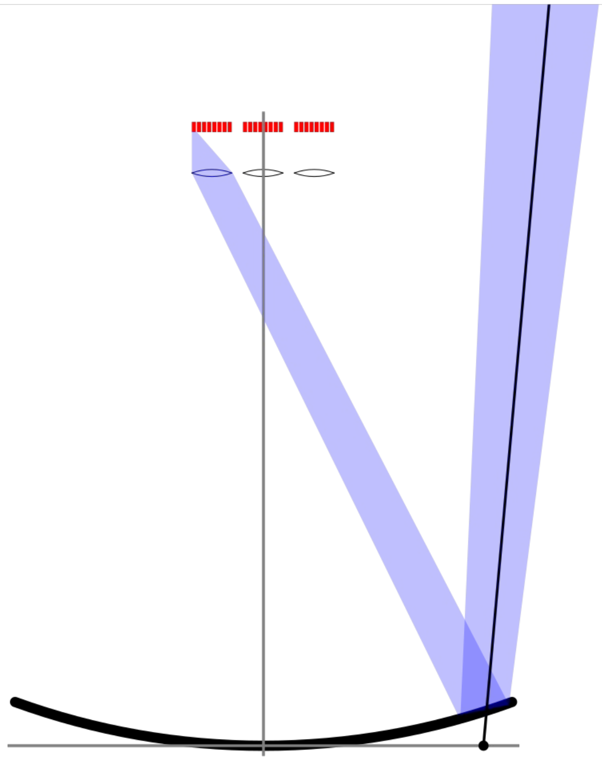
Plenoscope



as well as misalignments

Plenoptics

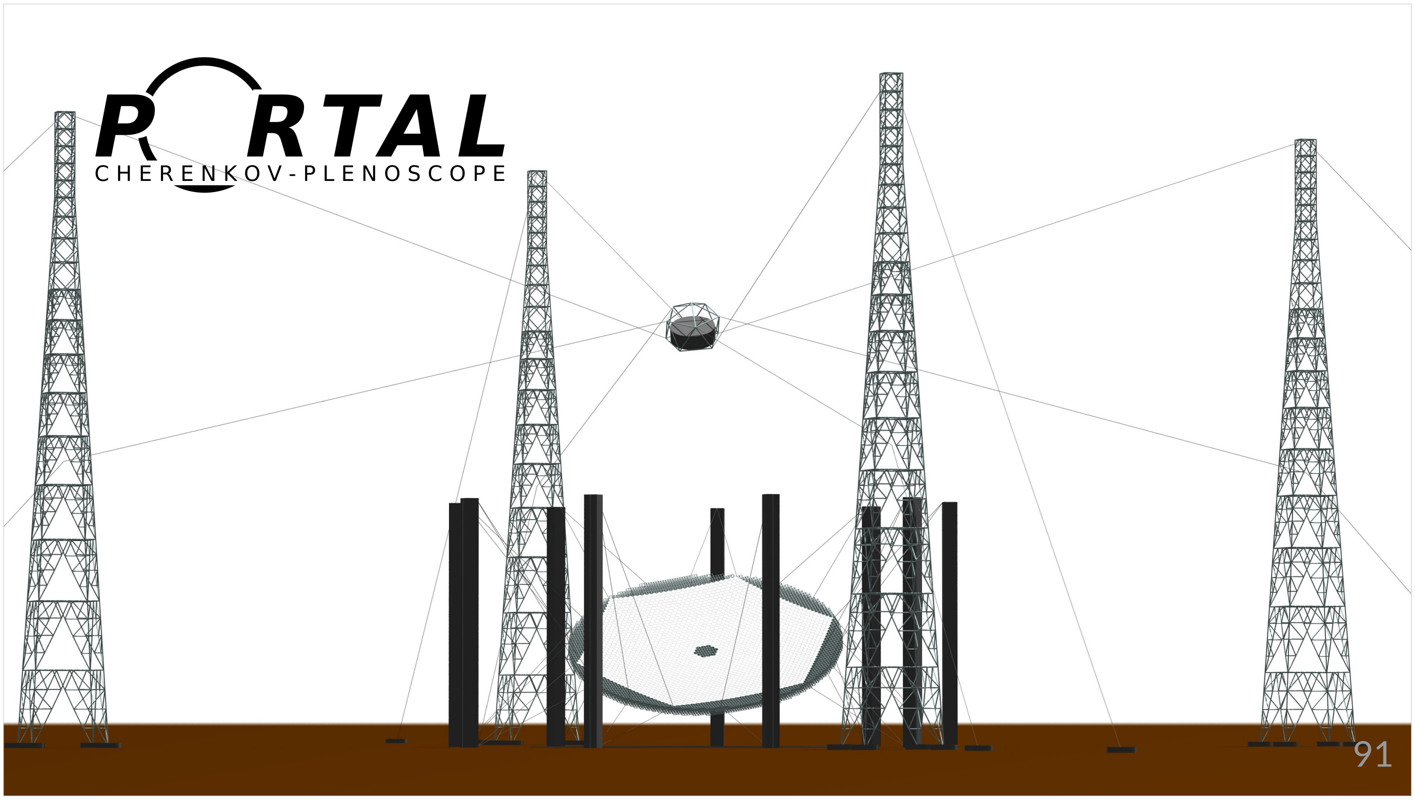
Plenoscope



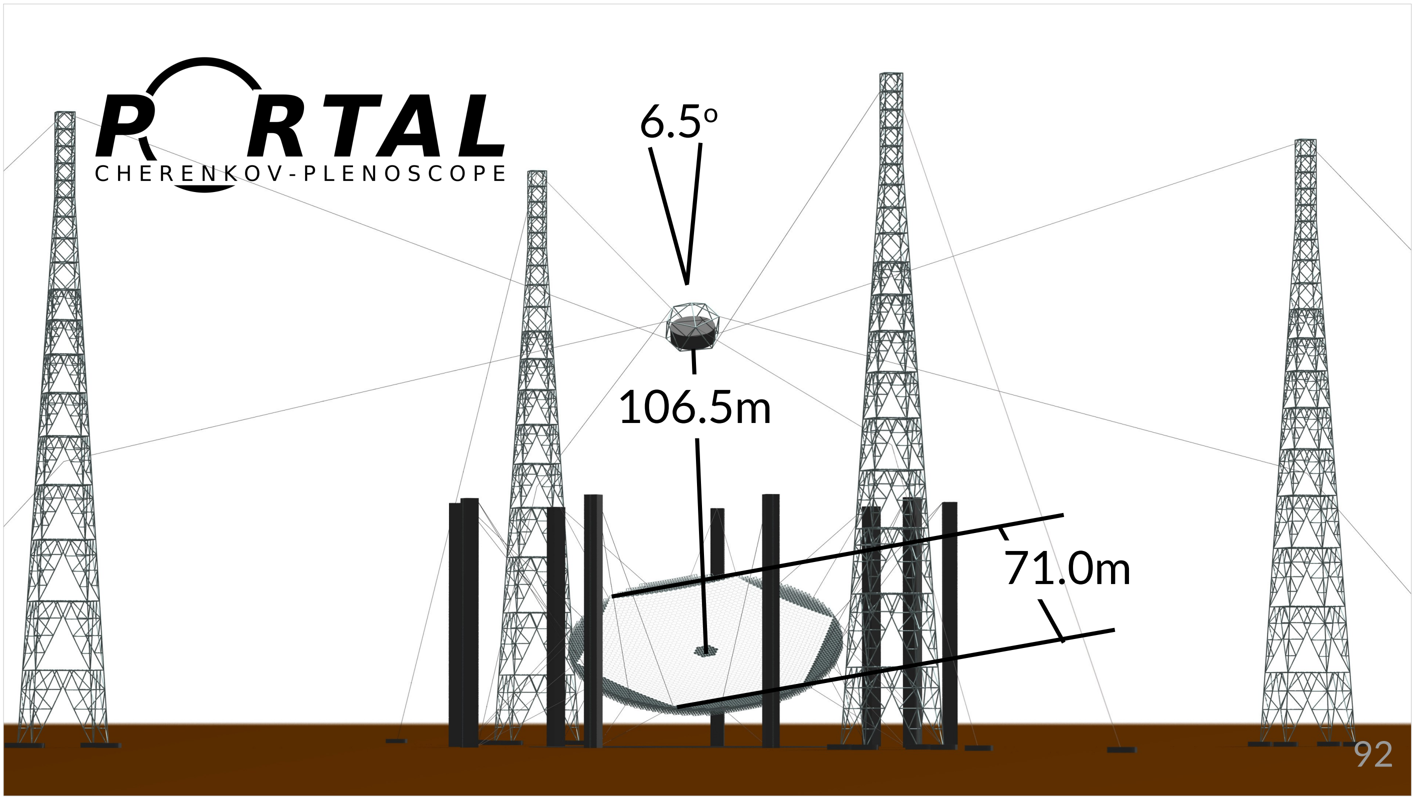
and turns a narrow depth-of-field into the perception of depth.

And in our proposal for the Cherenkov-plenoscope we take full advantage of these new possibilities.

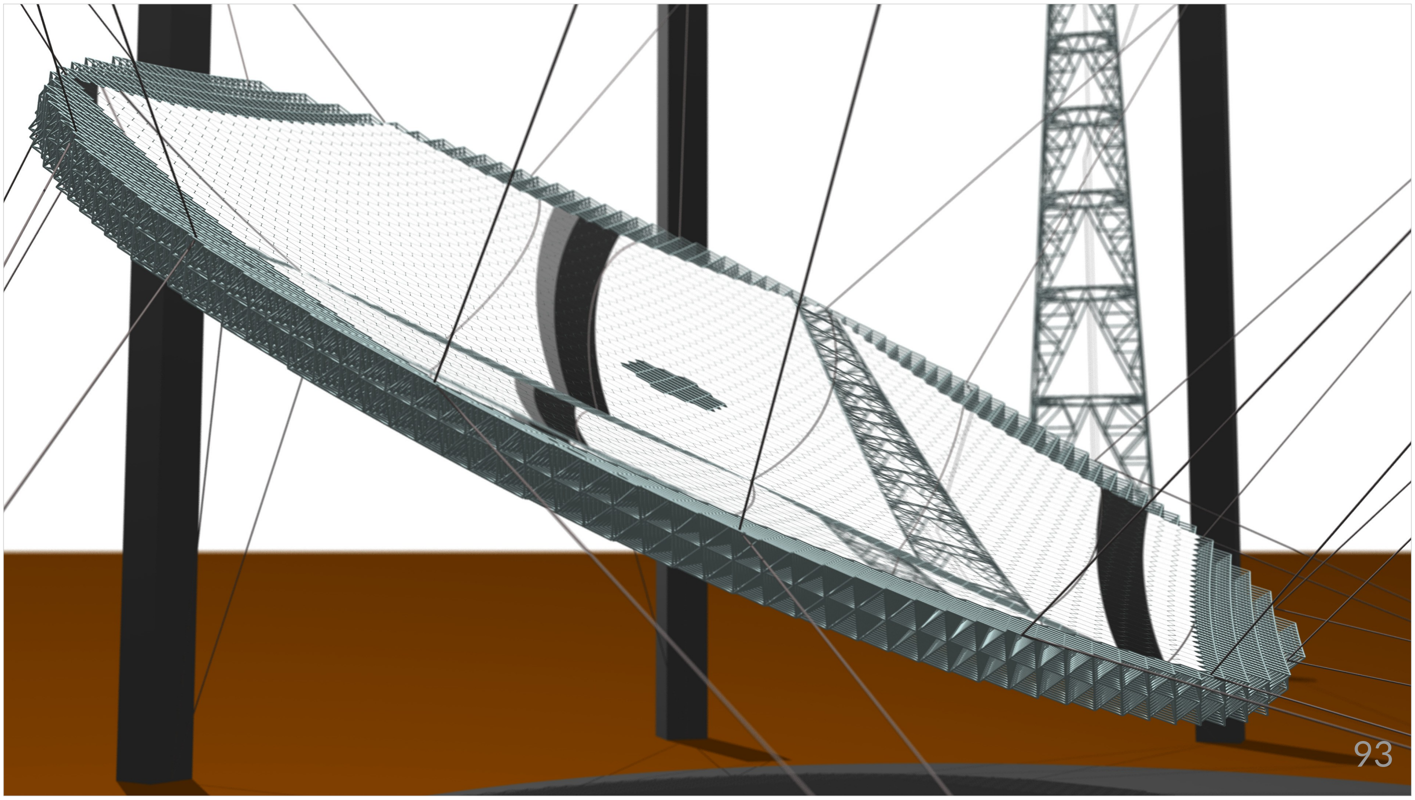
Together with ETH Zurich’s Department of Civil, Environmental and Geomatic Engineering



We propose Portal, a Cherenkov-plenoscope mounted on two cable-robots.

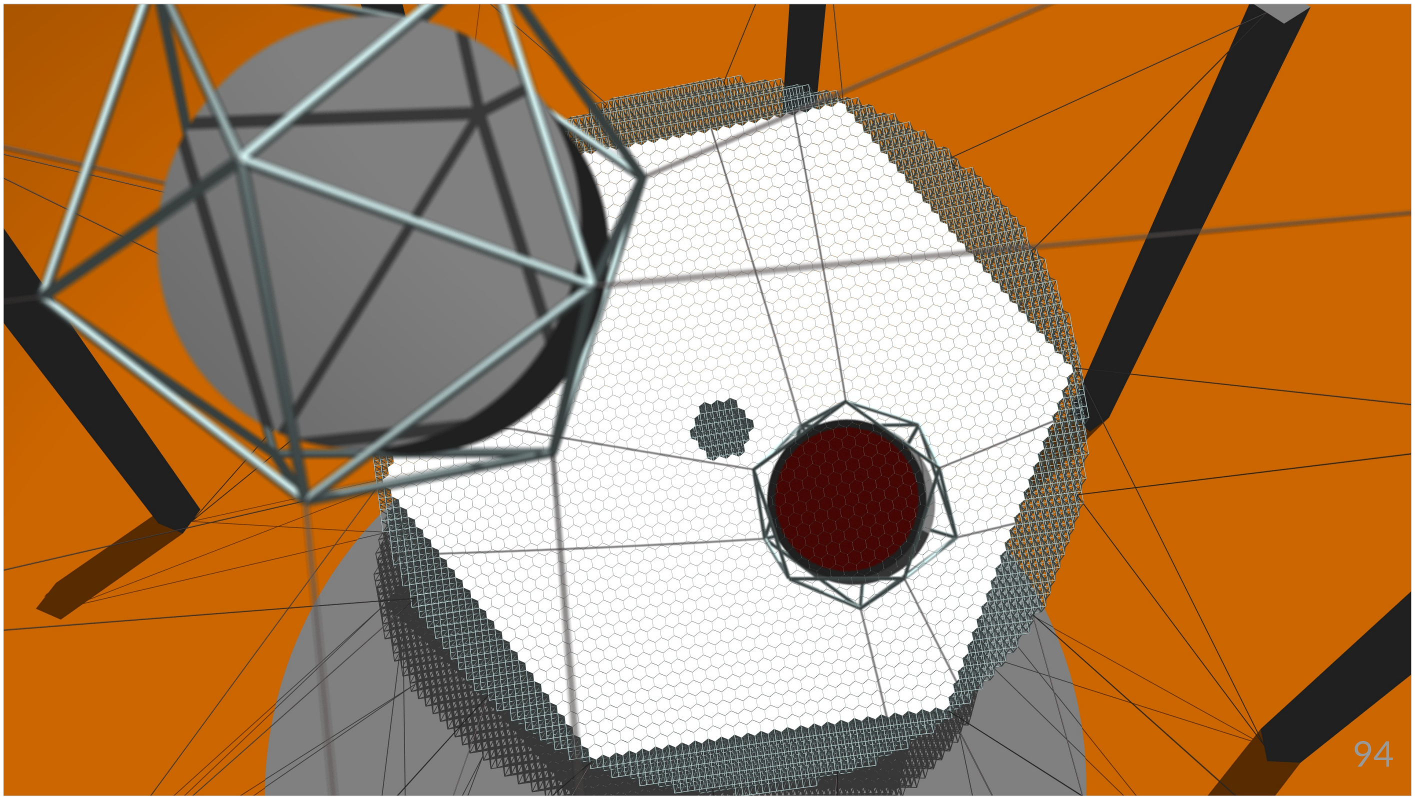


Portal is seventy one meters in diameter and has 106.5 meters focal-length.

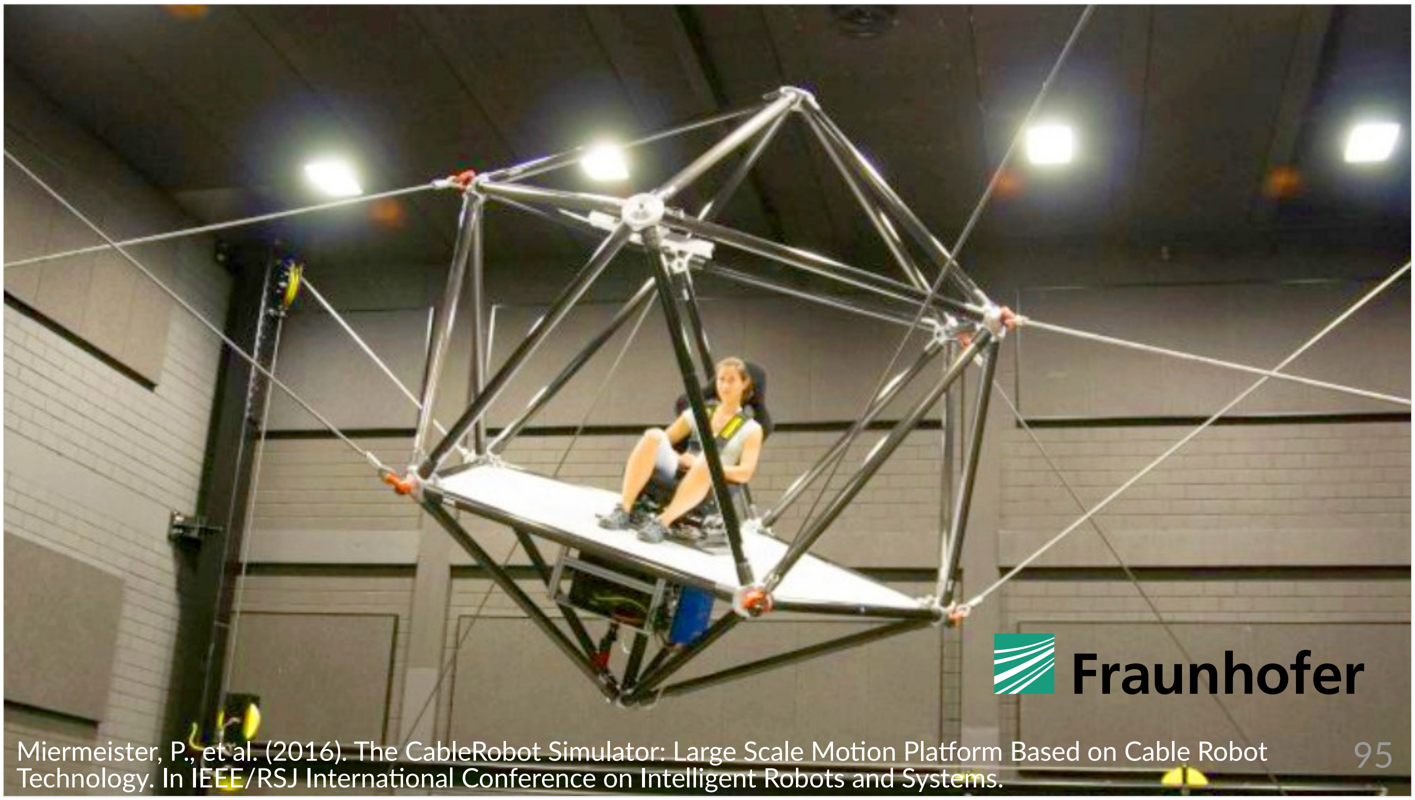


Portal’s mirror is mounted on a cable-robot suspended from concrete pillars and has a mass of about 180 tons.

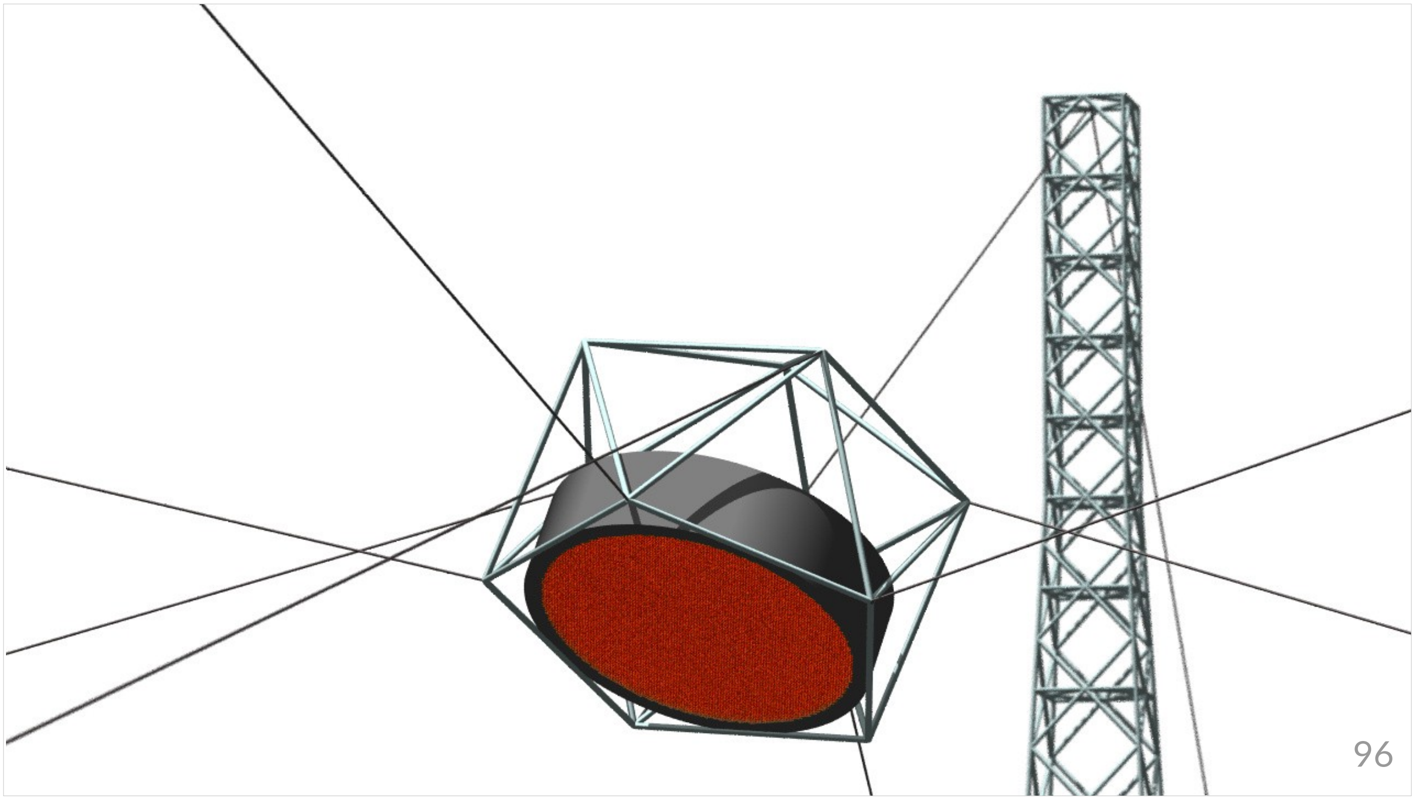
Structure of dish is 57.7t
Mirror-facets are 114t, 25.3kg m^{-2}, 4500m^2



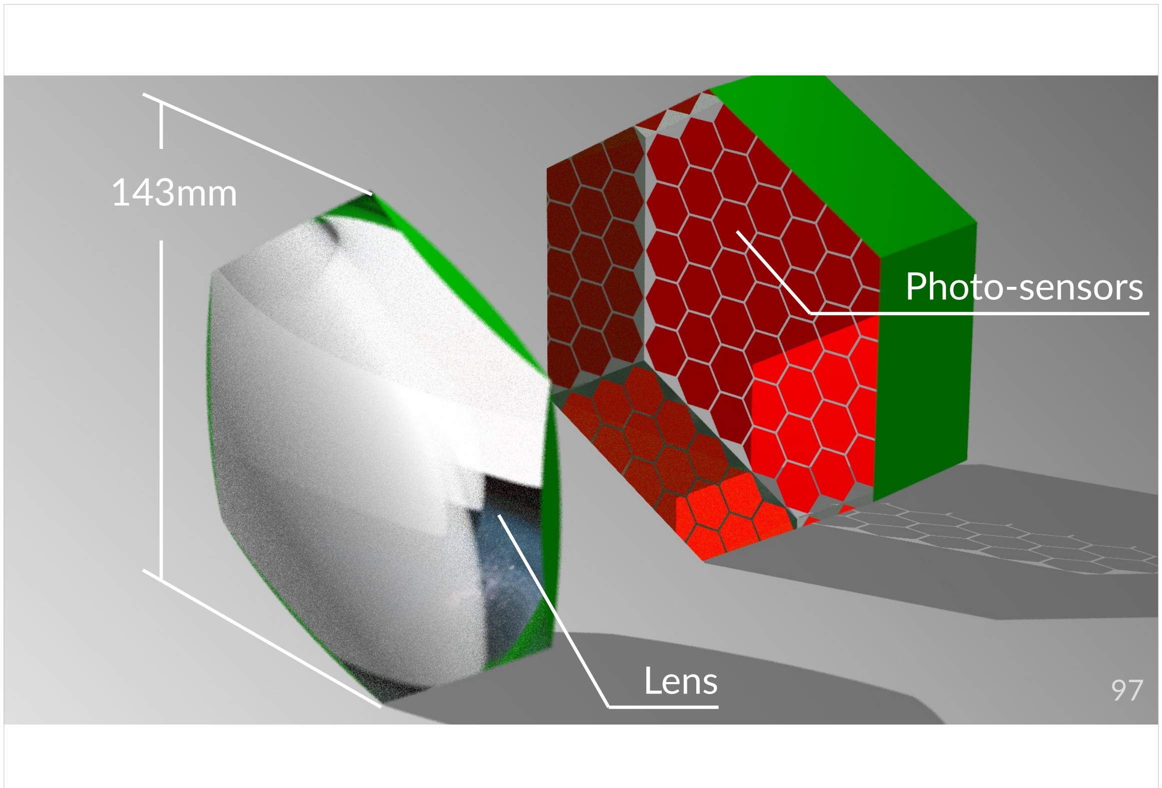
Portal’s light-field-sensor is mounted on an independent, second, cable-robot suspended from space-truss-towers.



and is inspired by Fraunhofer's cable-robot for motion-simulation.

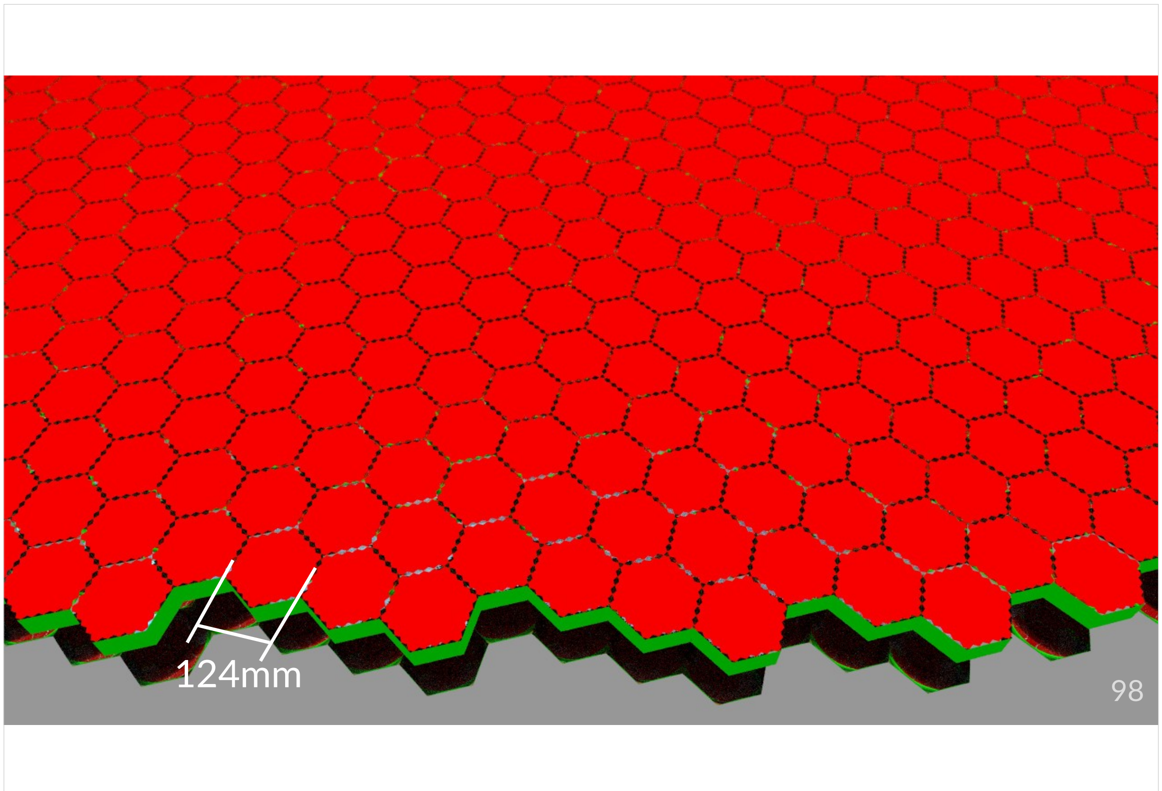


Looking through the lenses here, we can see the red photo-sensors.

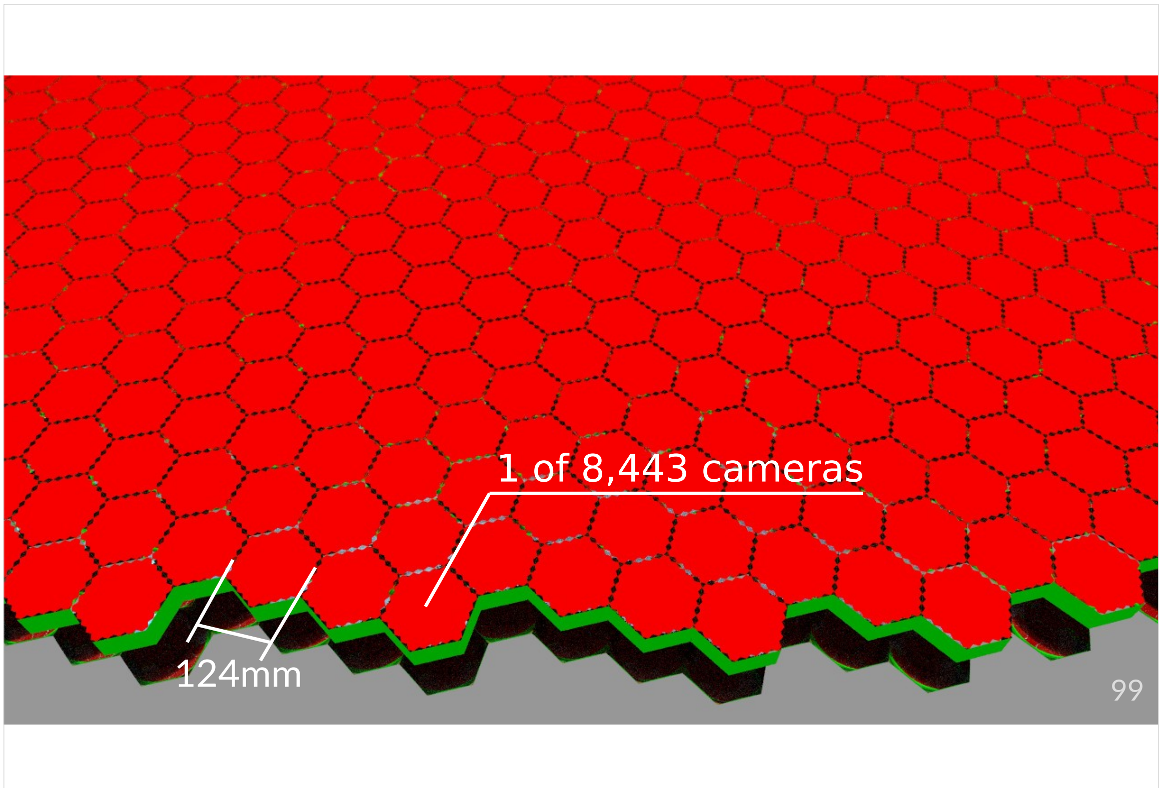


All optical surfaces of Portal are spherical.

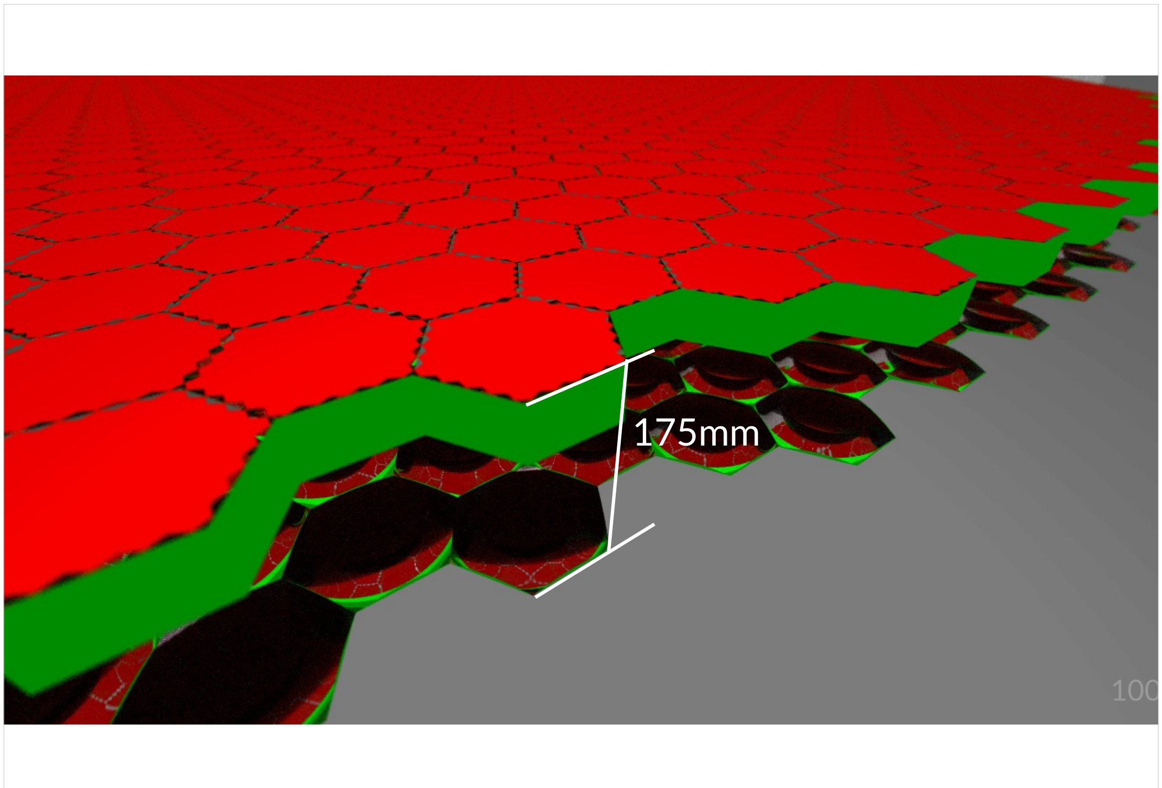
All cameras are identical,



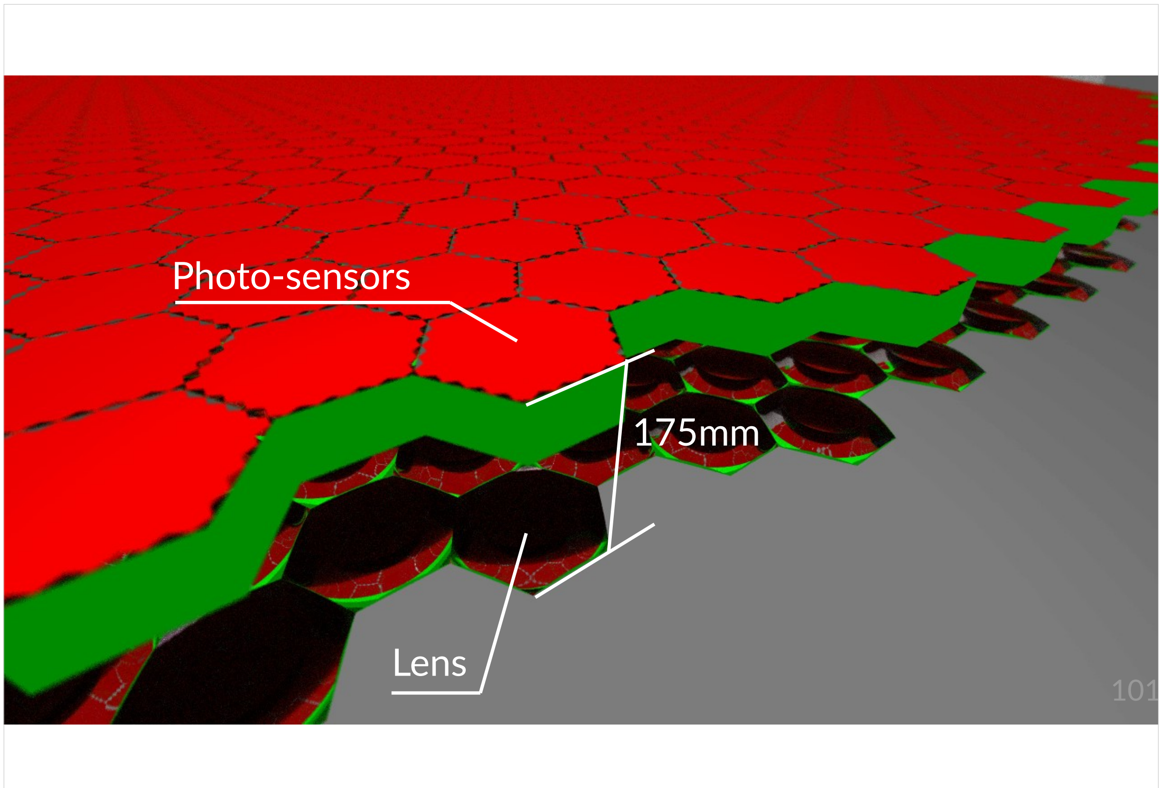
and densely



packed inside the light-field-sensor.

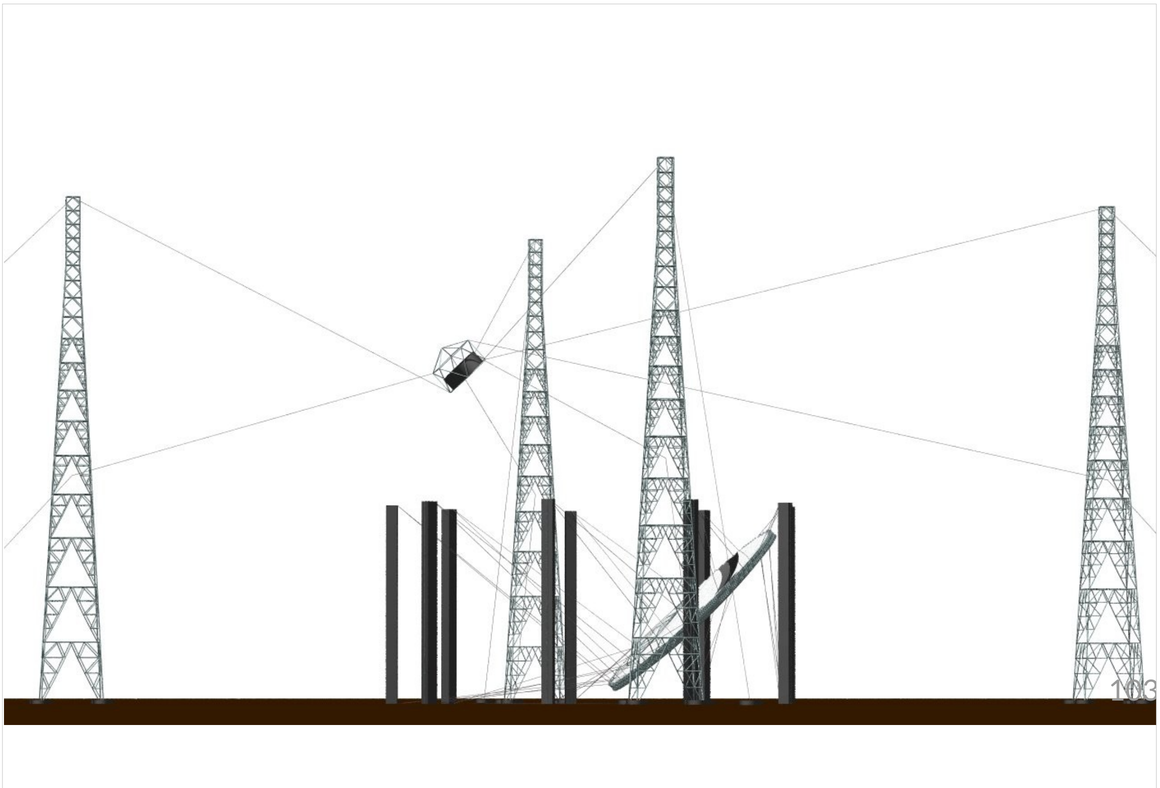


On the bottom we find the lenses,



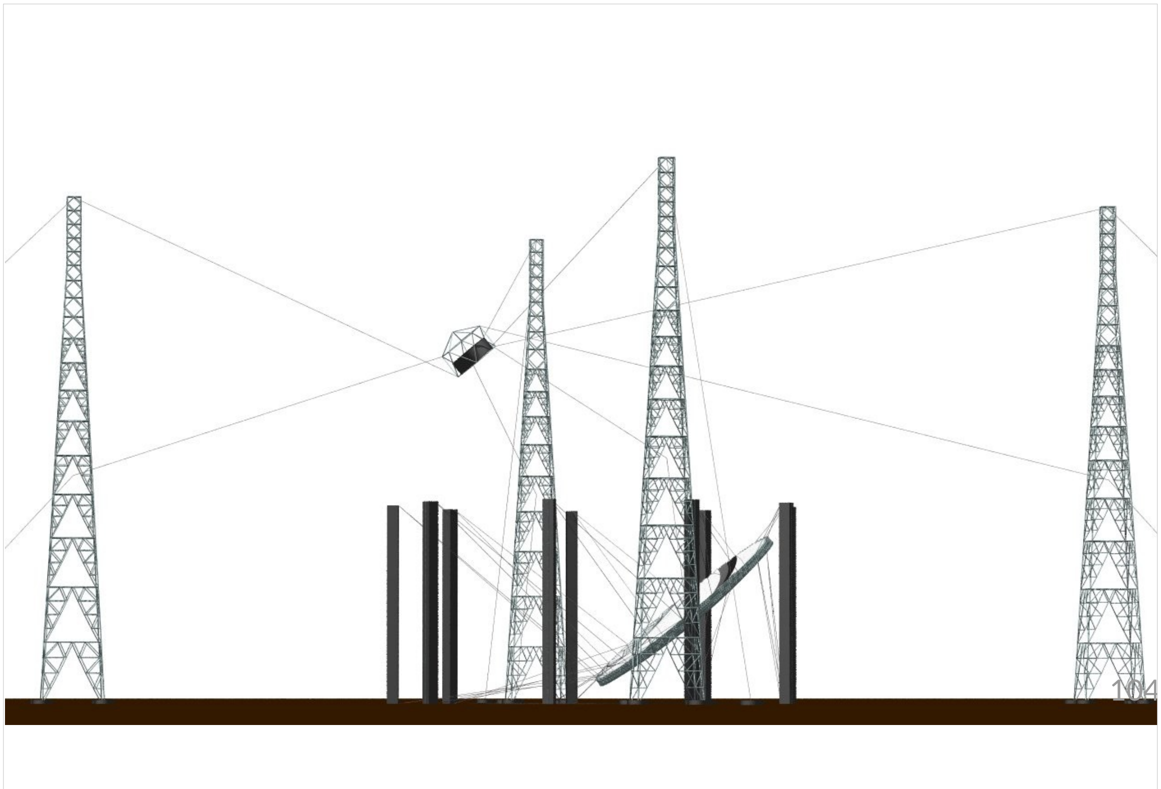
on top the photo-sensors.

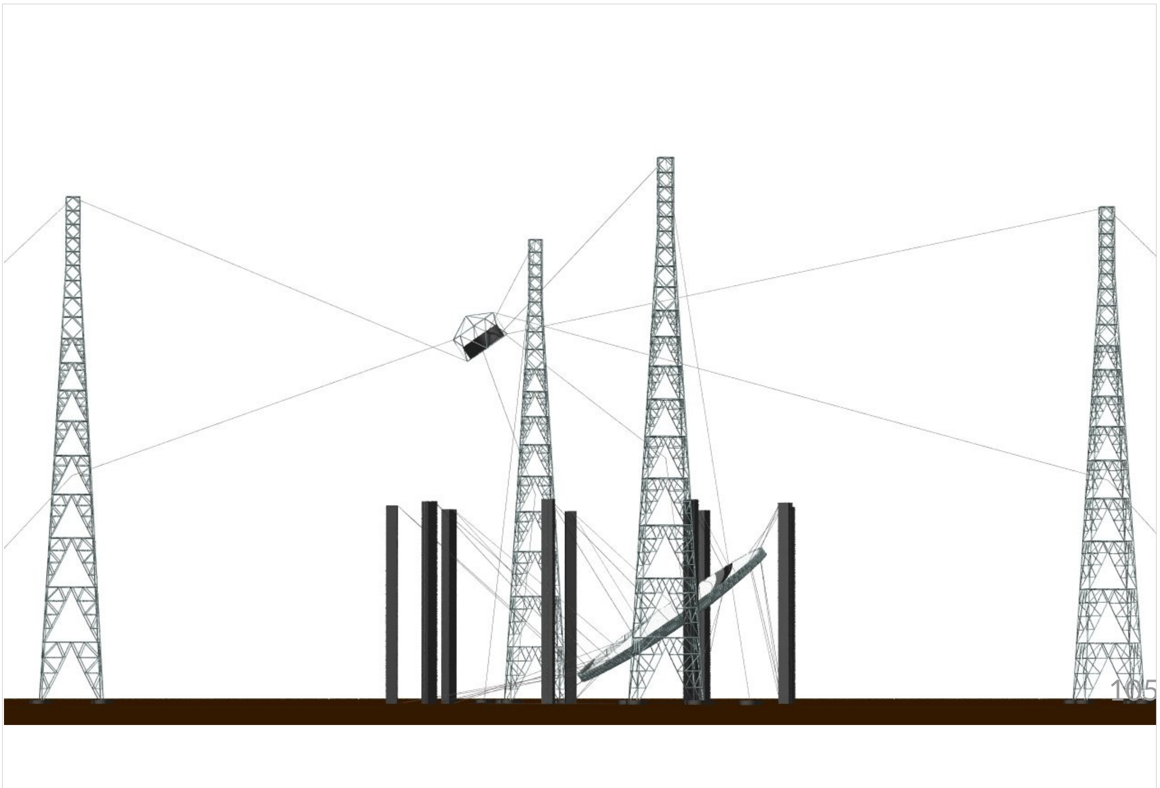
Pointing

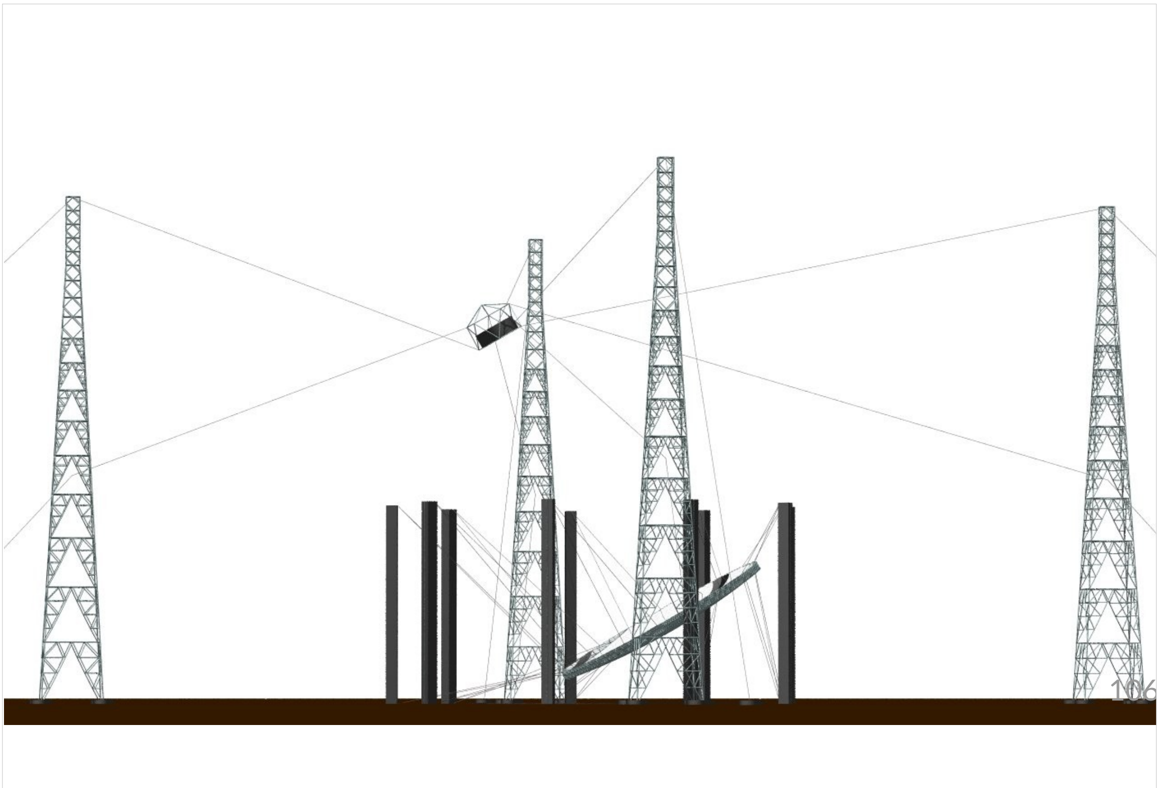


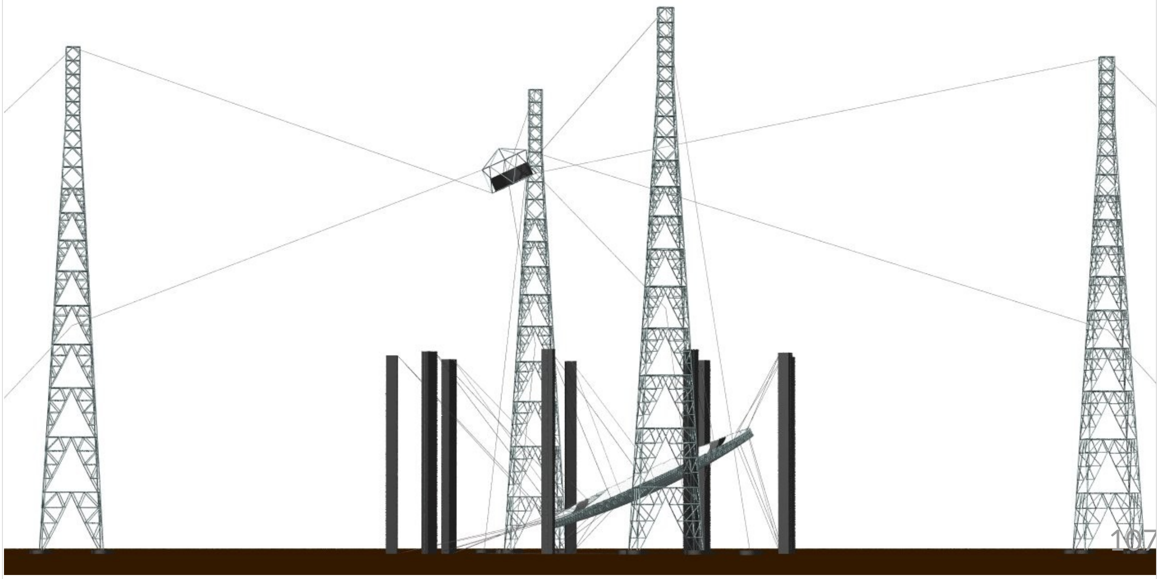
Portal’s cable-robot can point to zenith distances of up to forty five degrees.

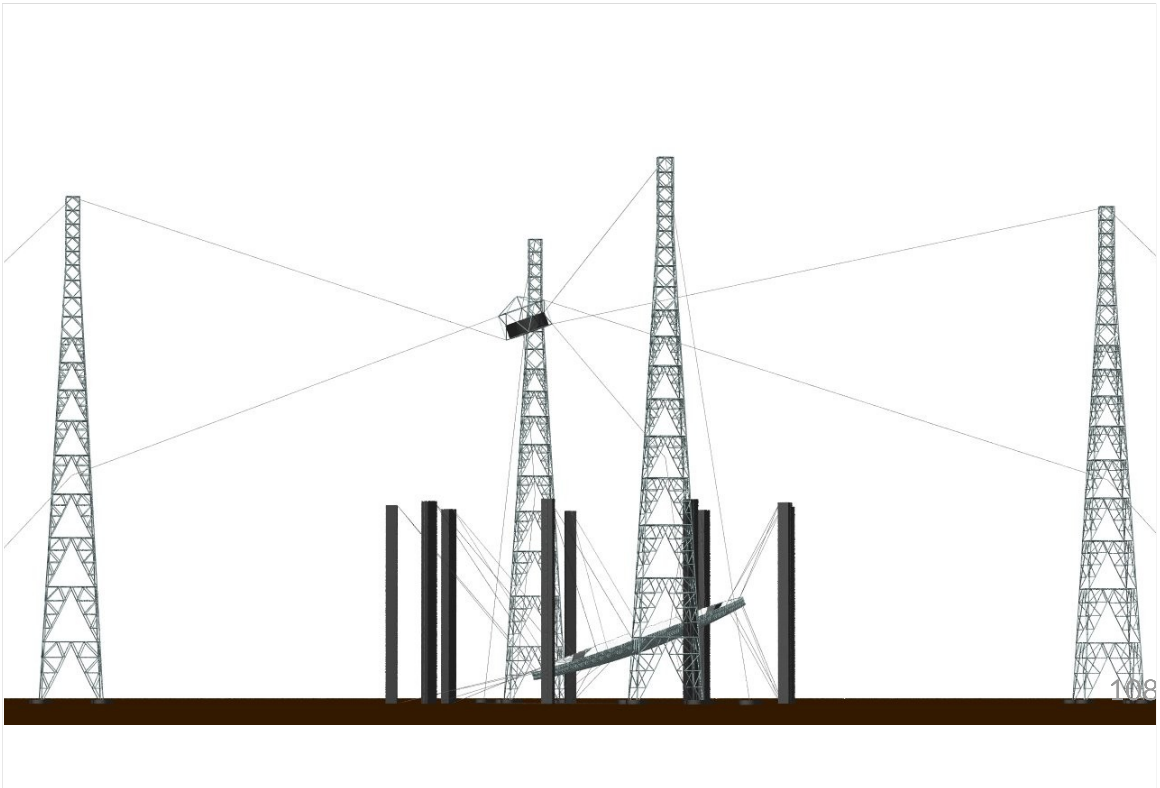
And unlike the altitude-azimuth-mount it has no near zenith singularities what makes it intrinsically faster for the hunt of transients.

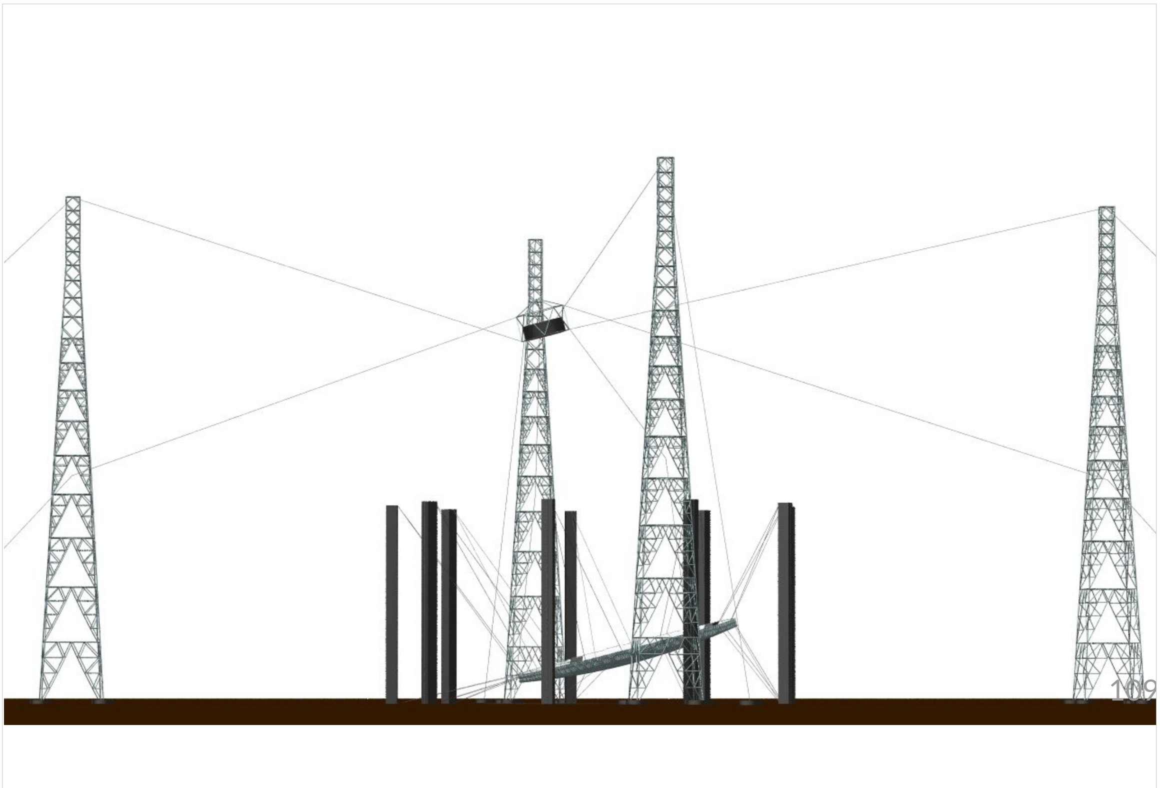


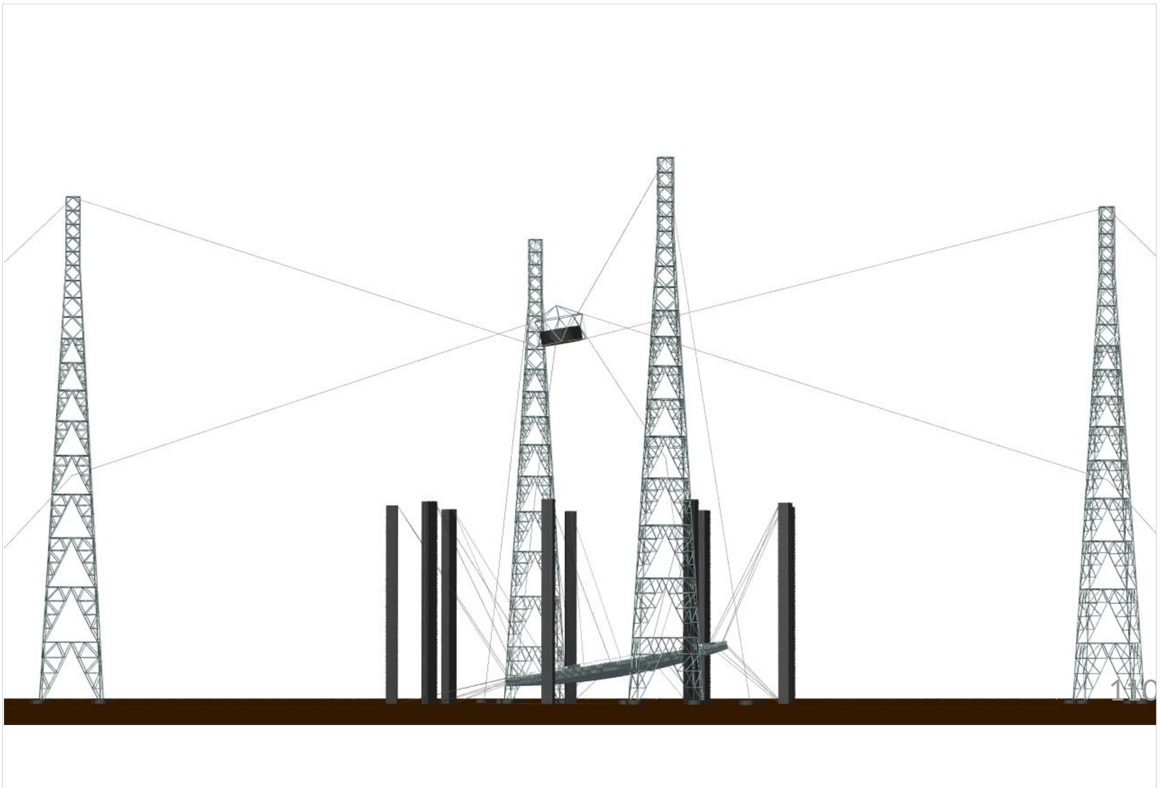


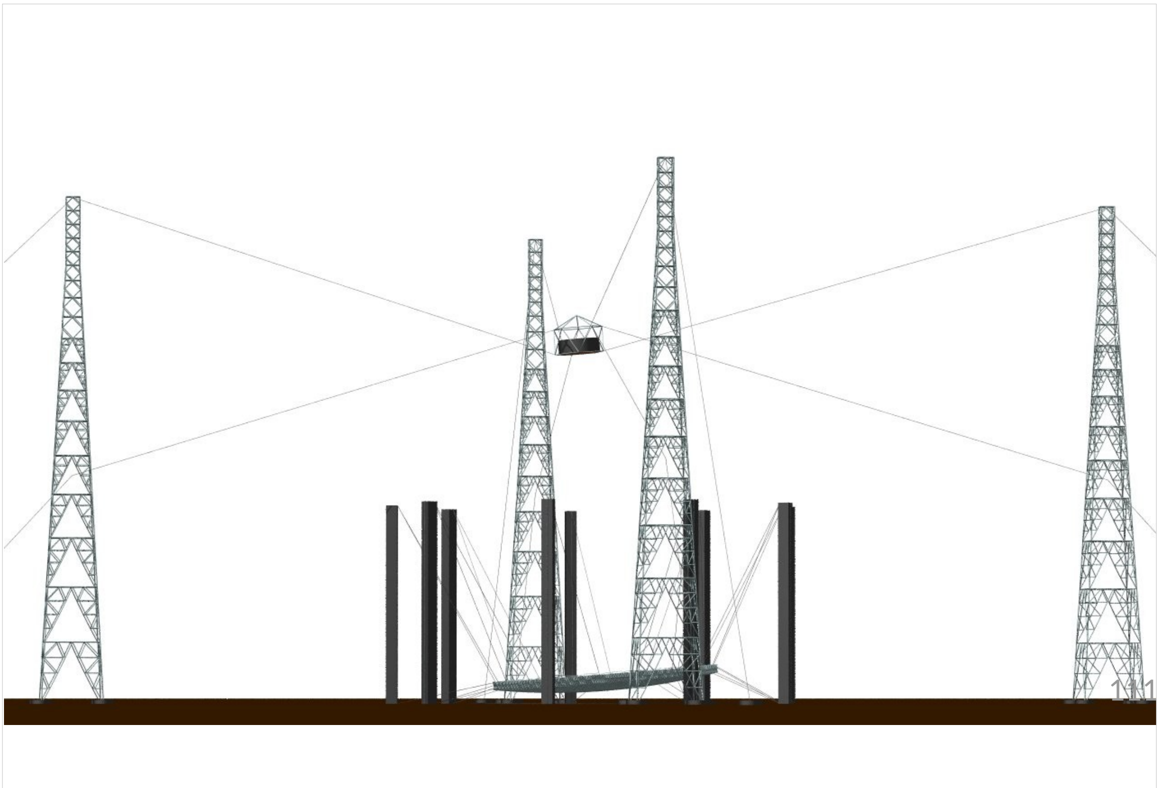


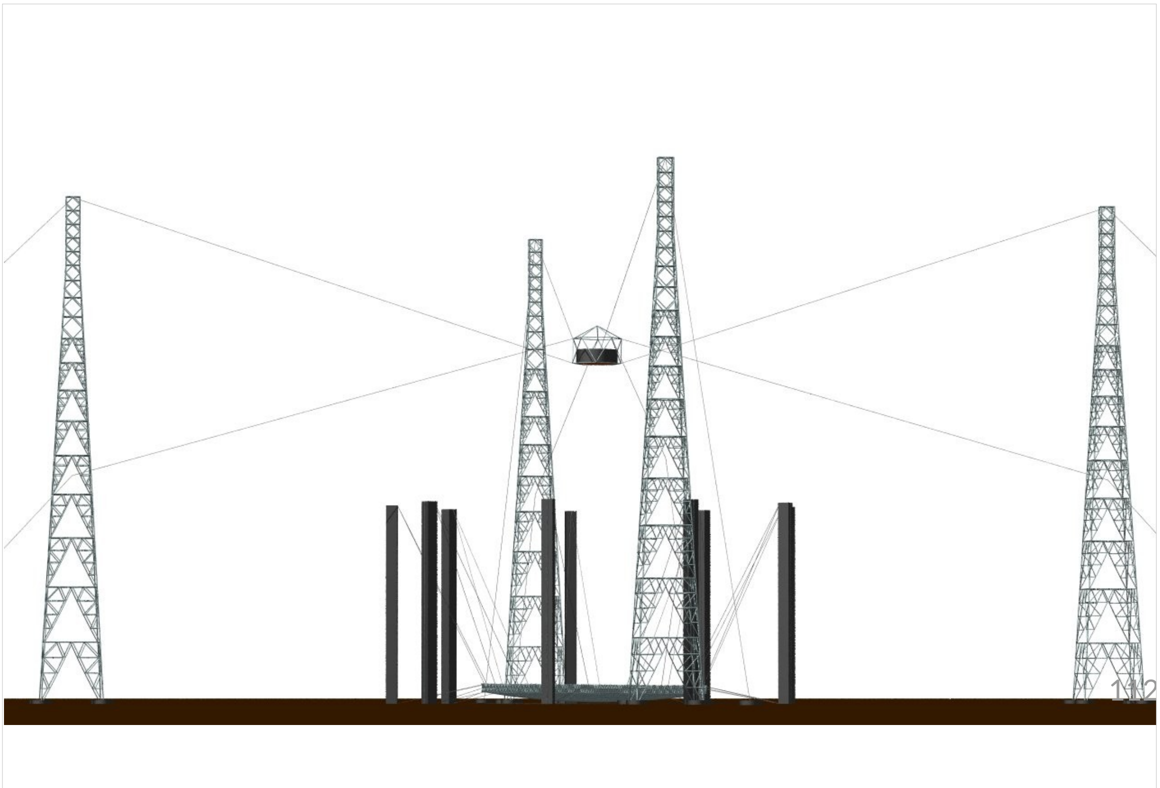


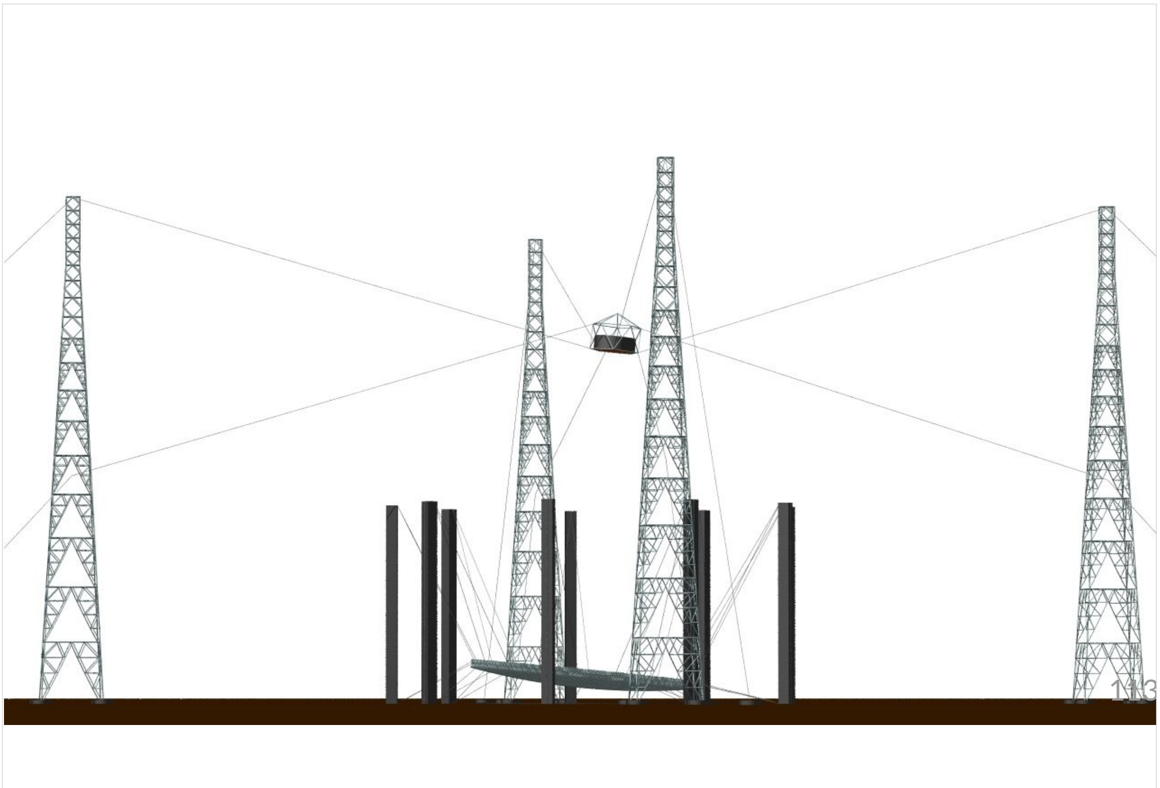


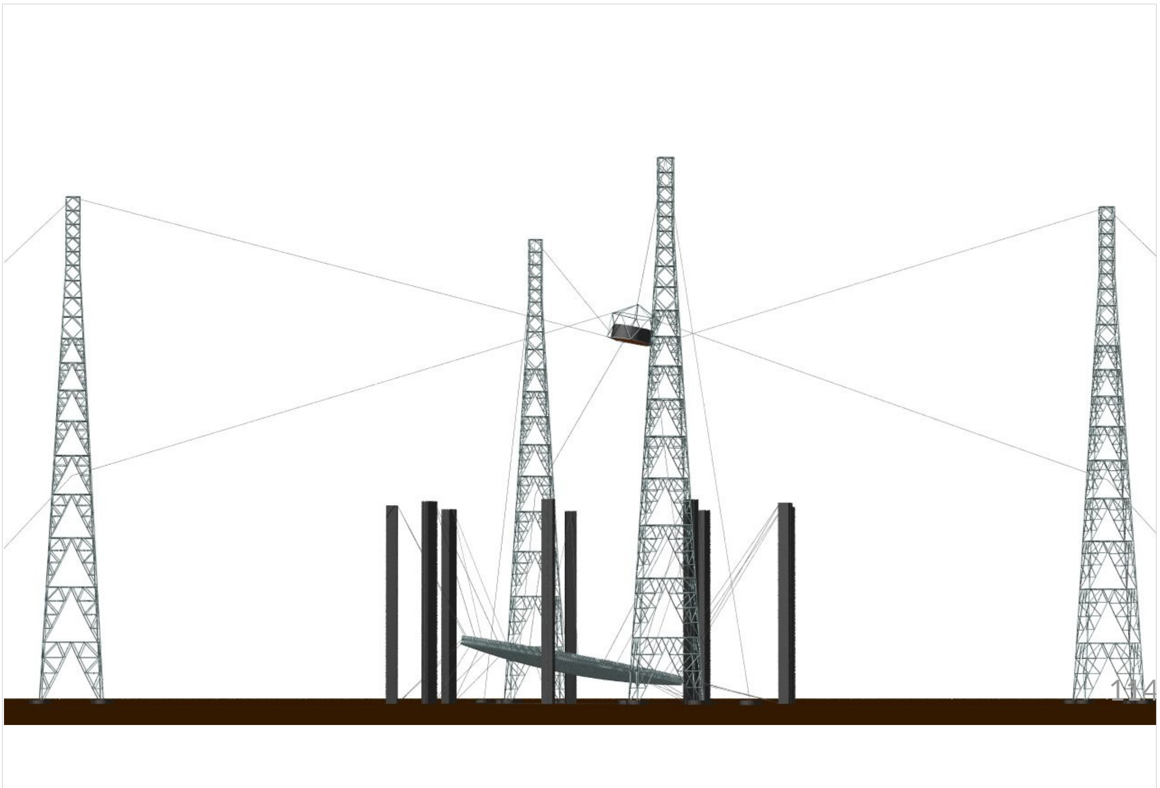


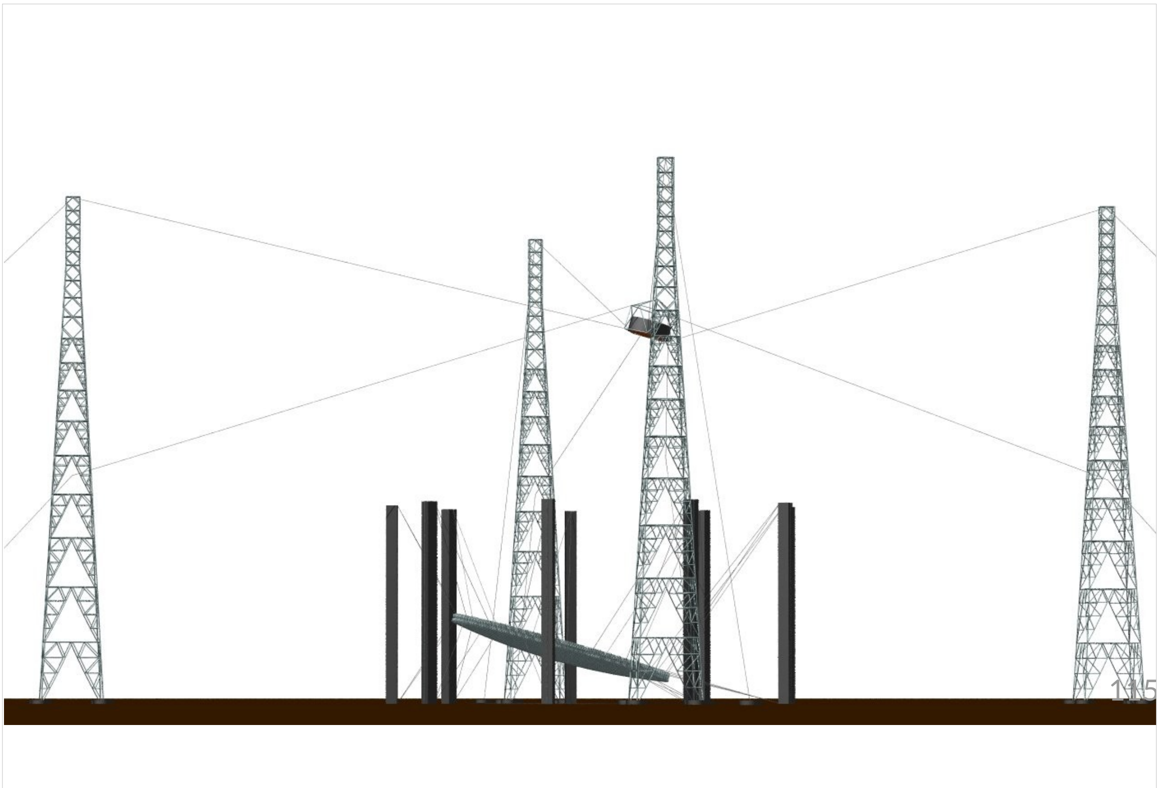


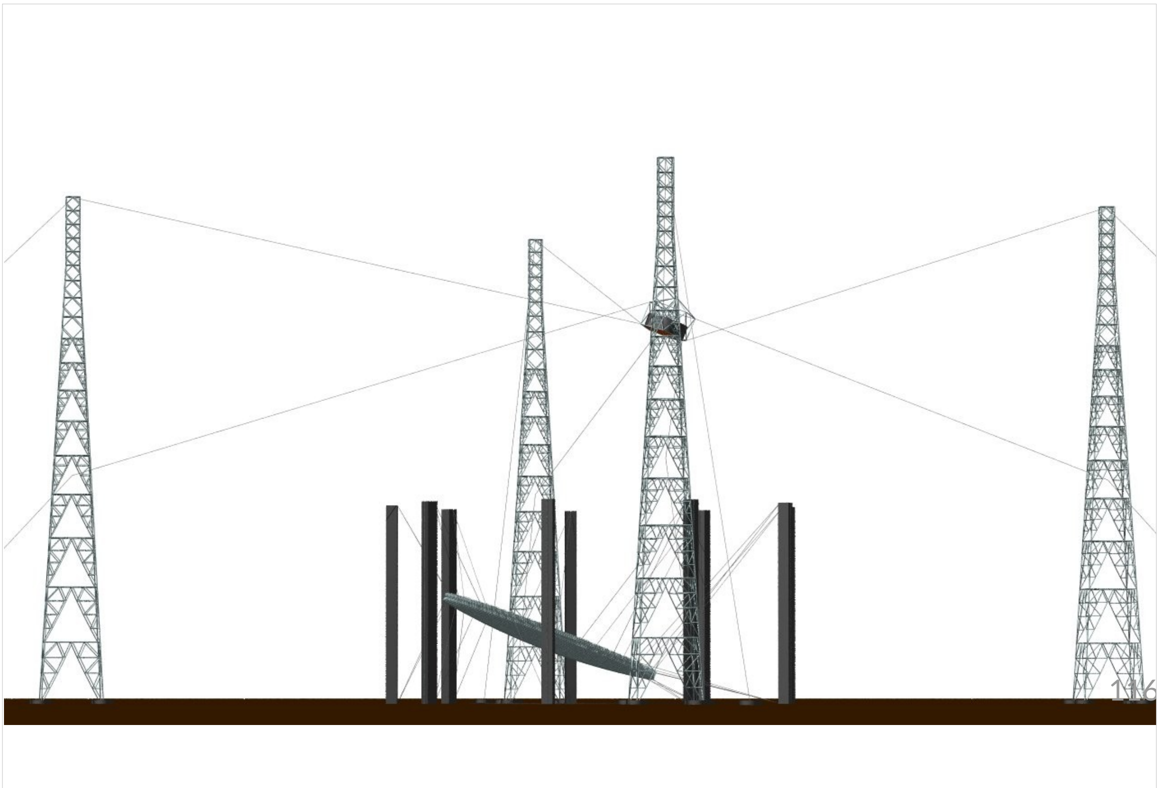


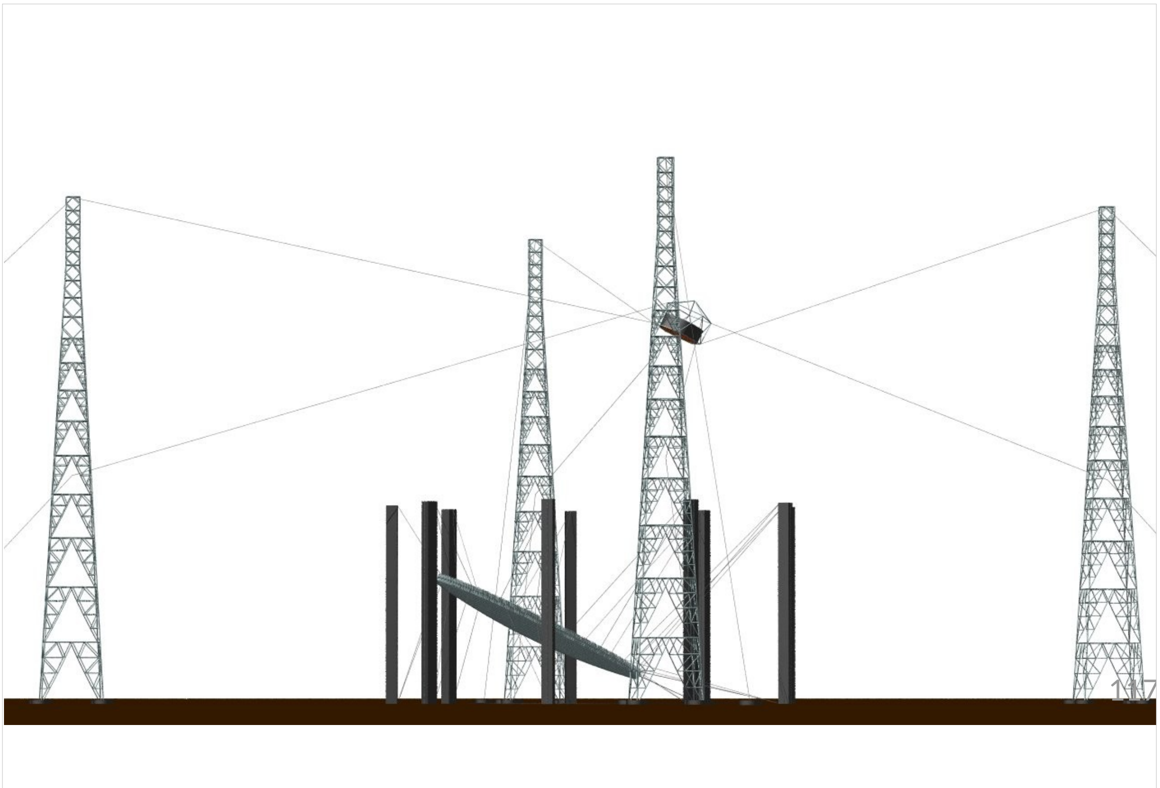


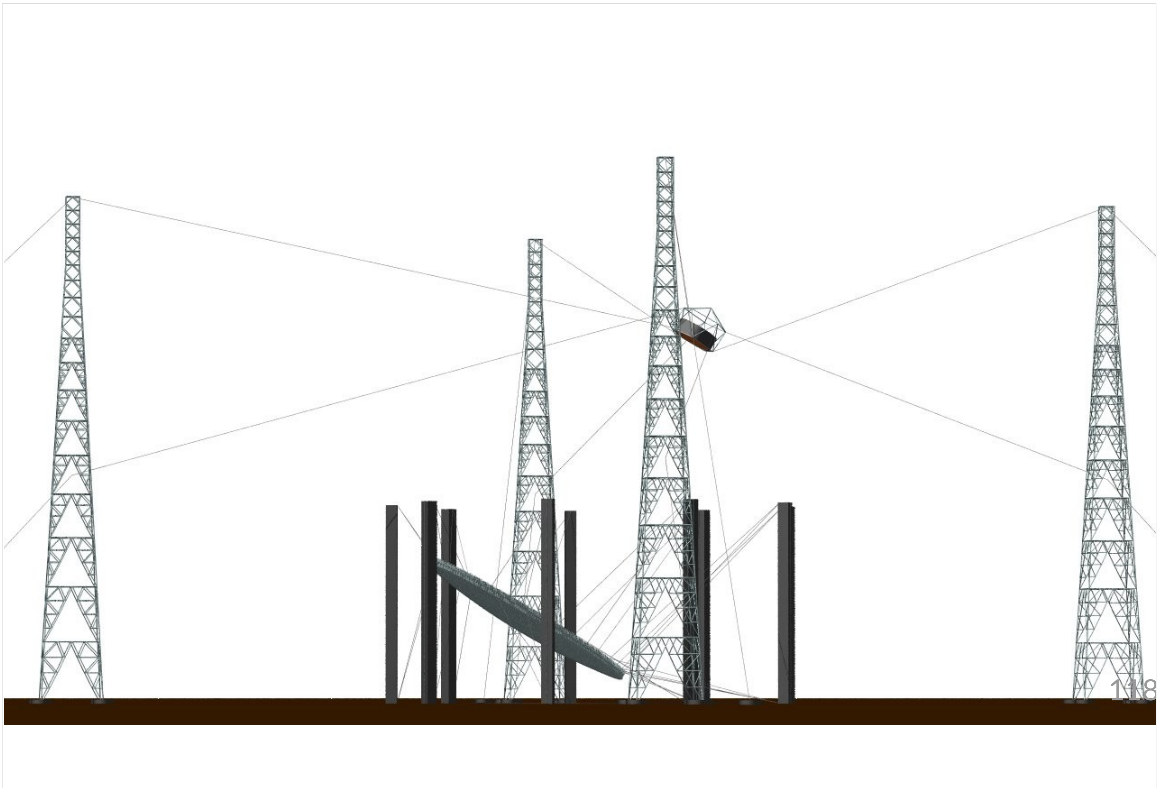


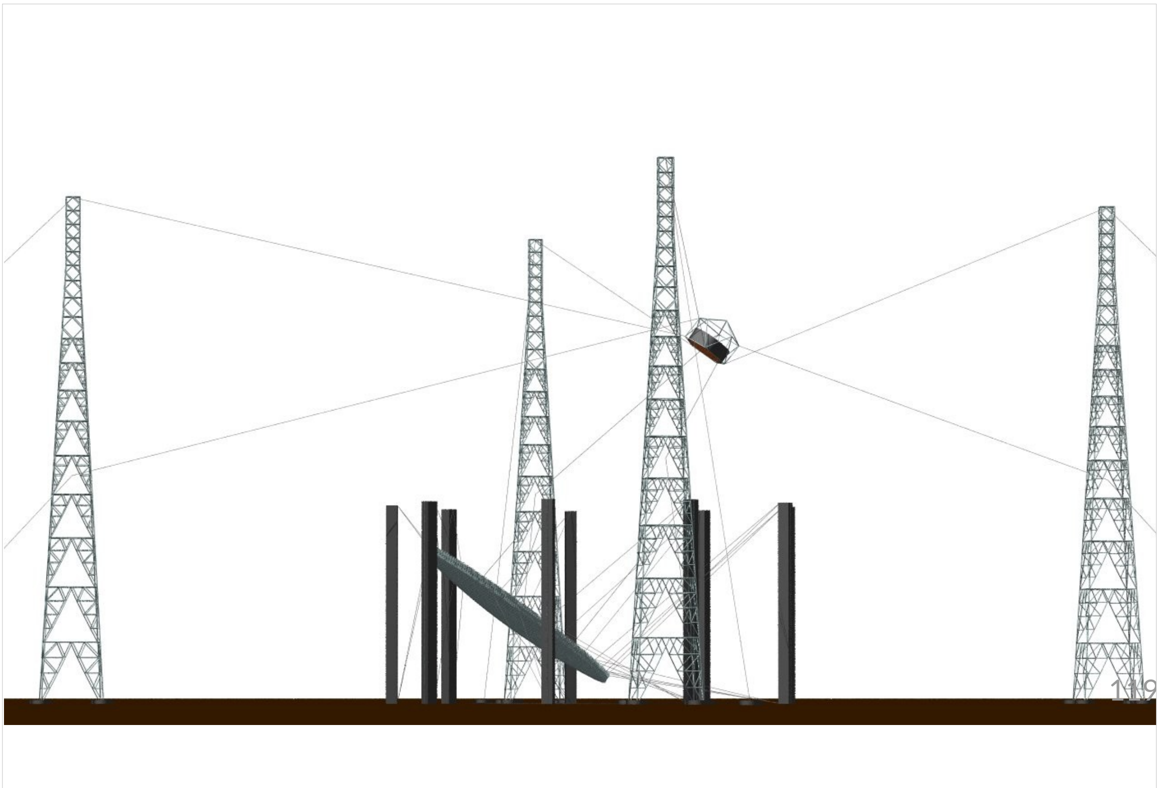


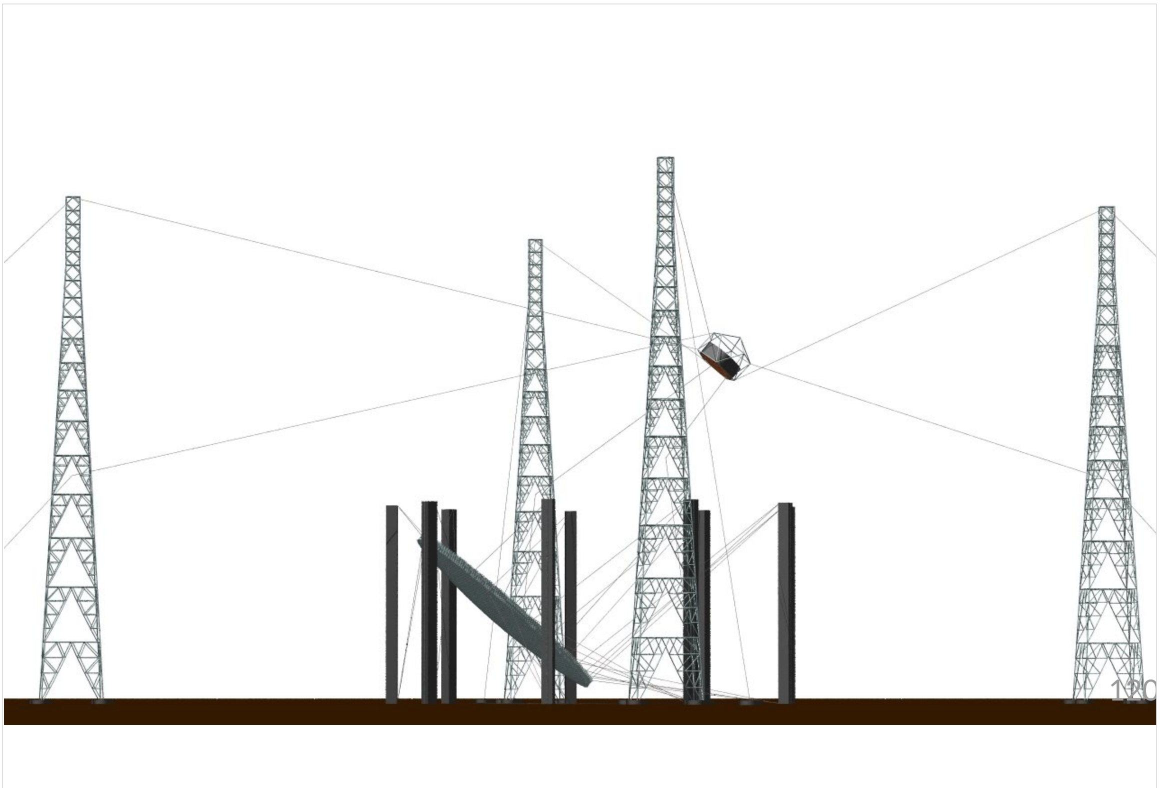


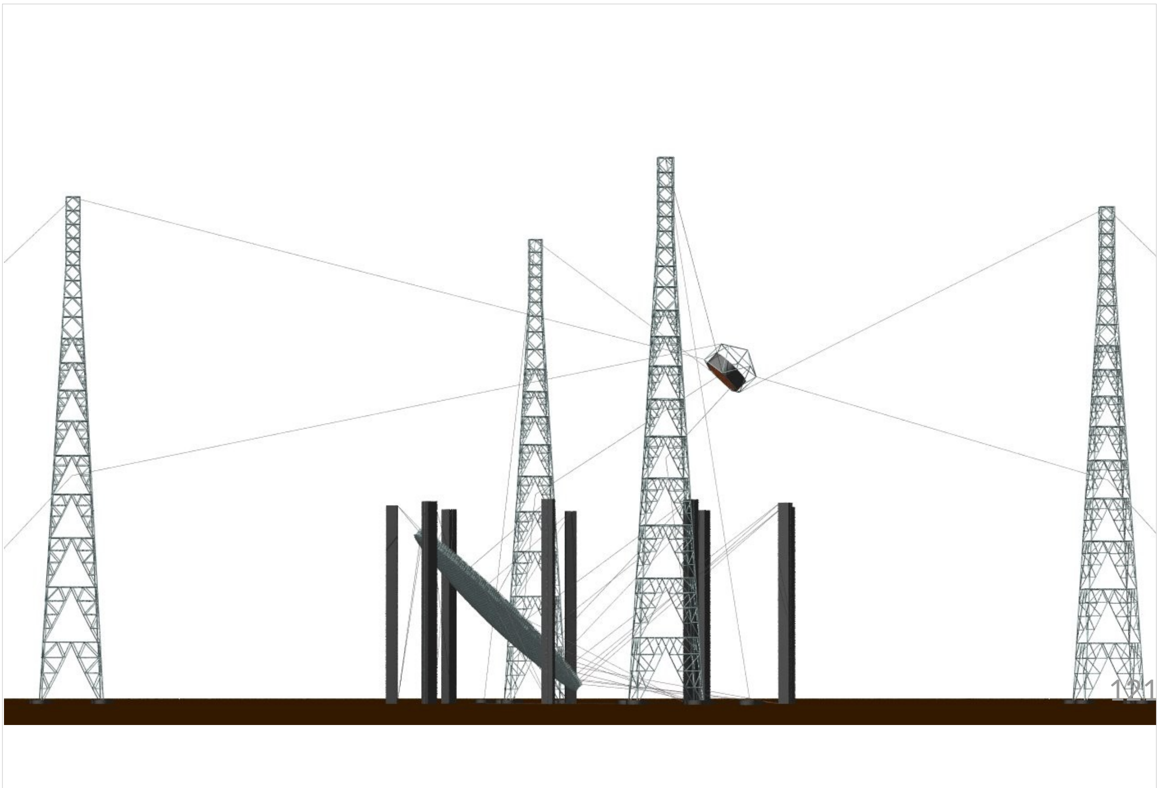




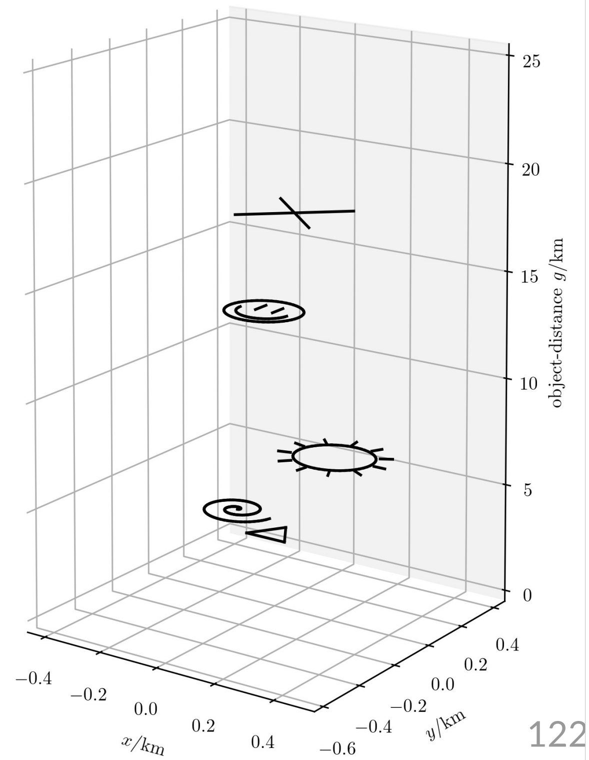




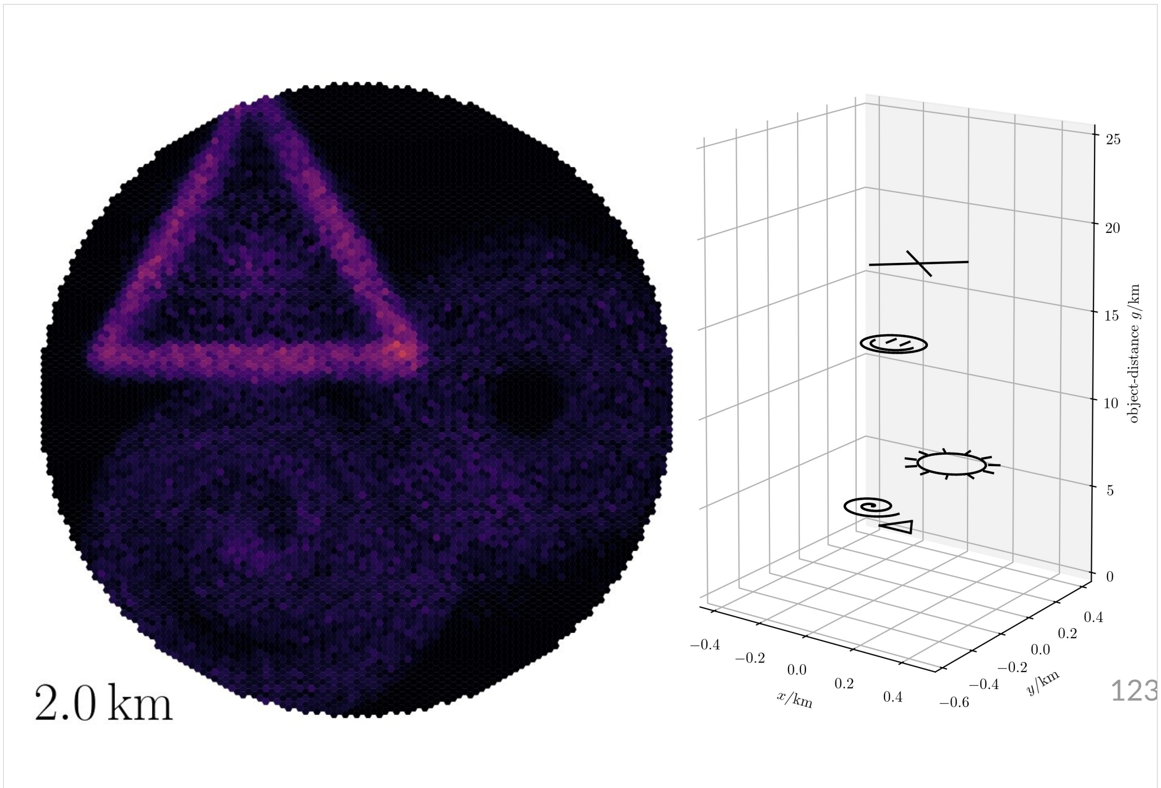




Phantom-Source

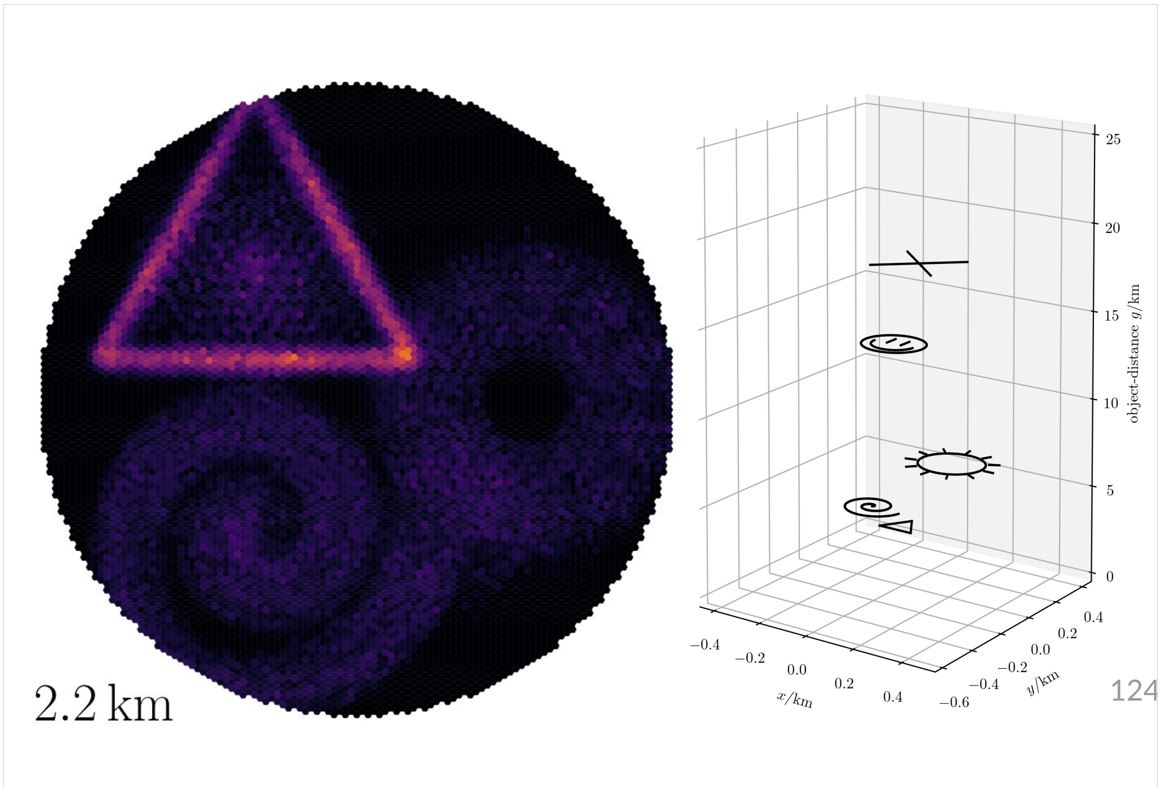


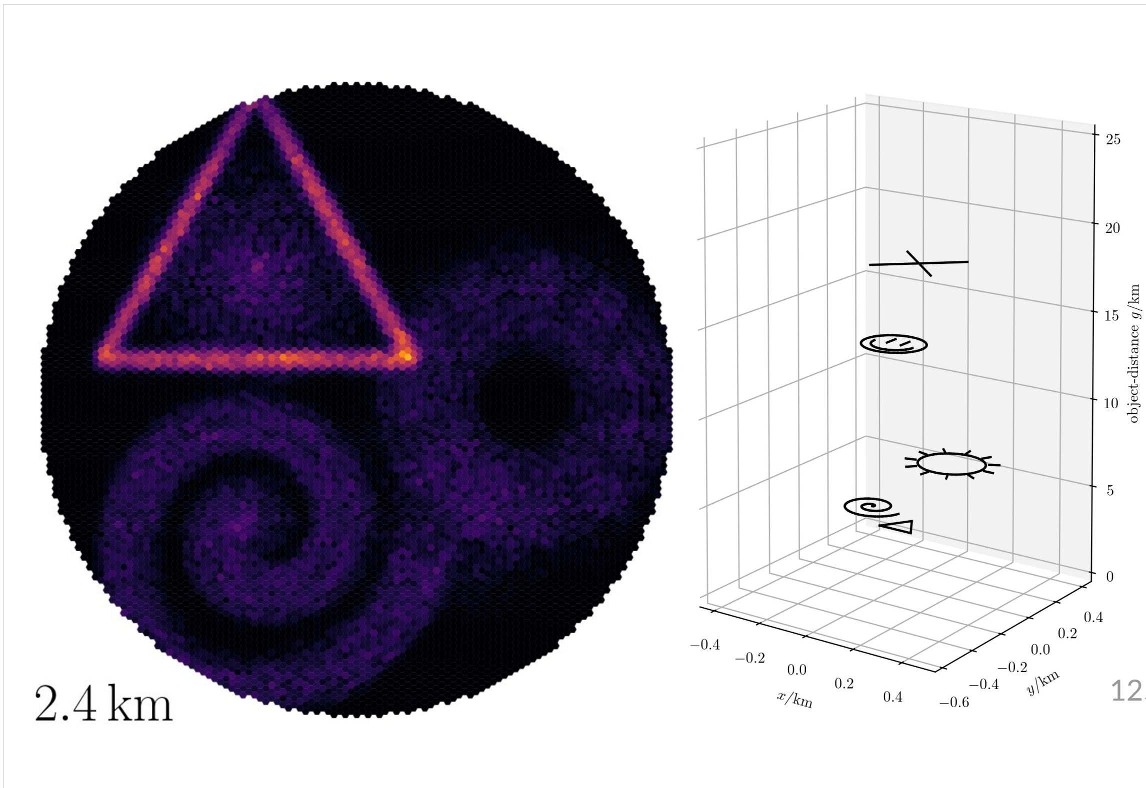
Now lets see Portal in action when observing a phantom-source.

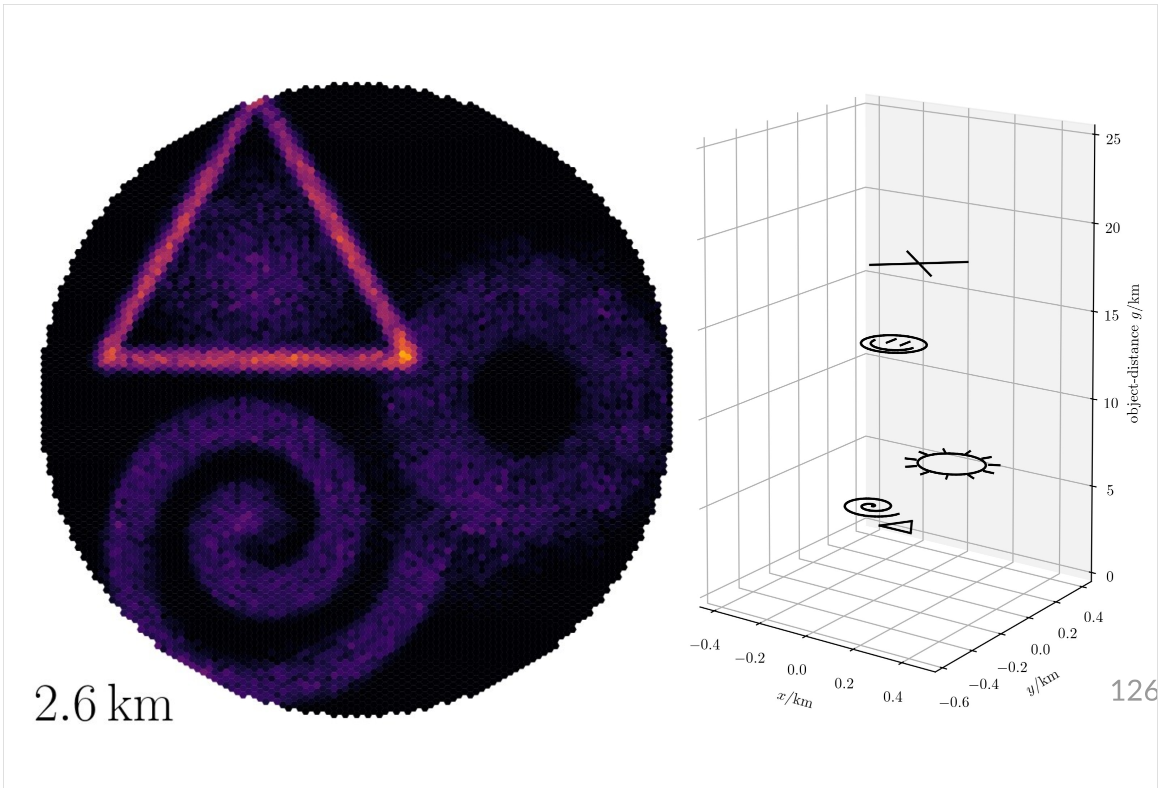


The Portal Cherenkov-plenoscope, measures the photons trajectories.
And the thin lens does the imaging.

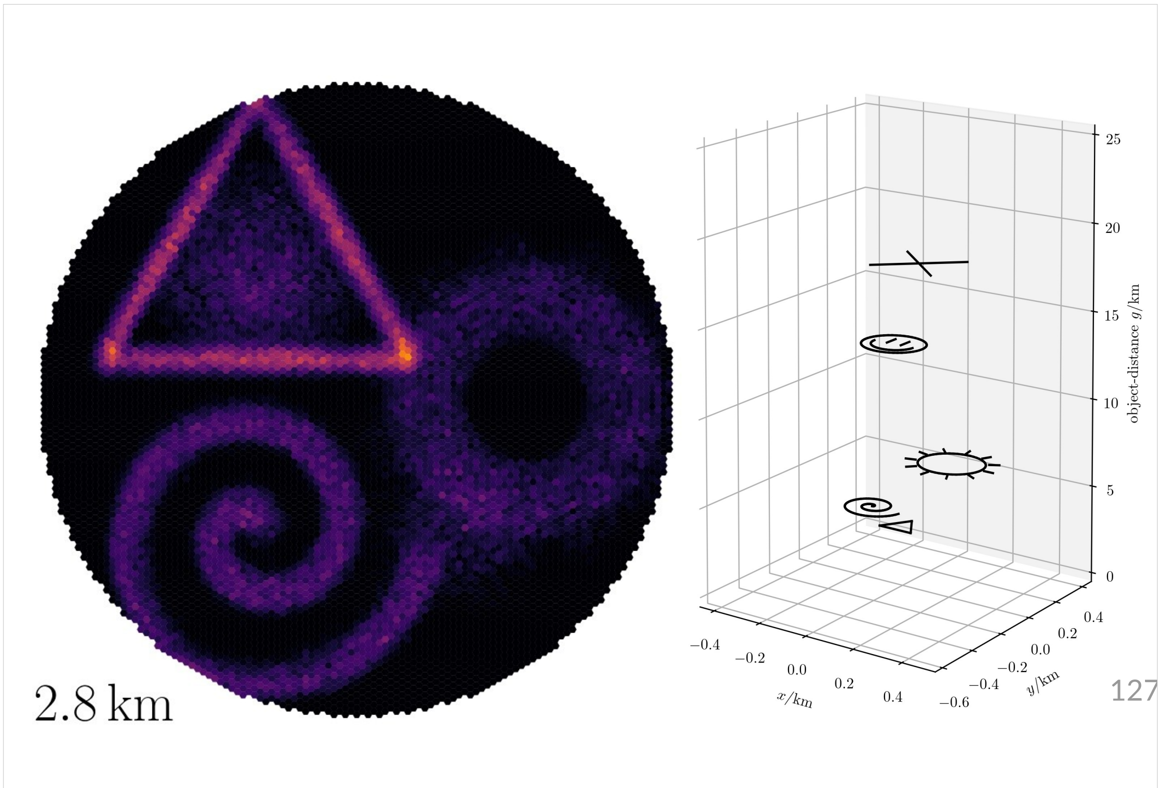
Here the depth is set to is two kilometers and we see the triangle.

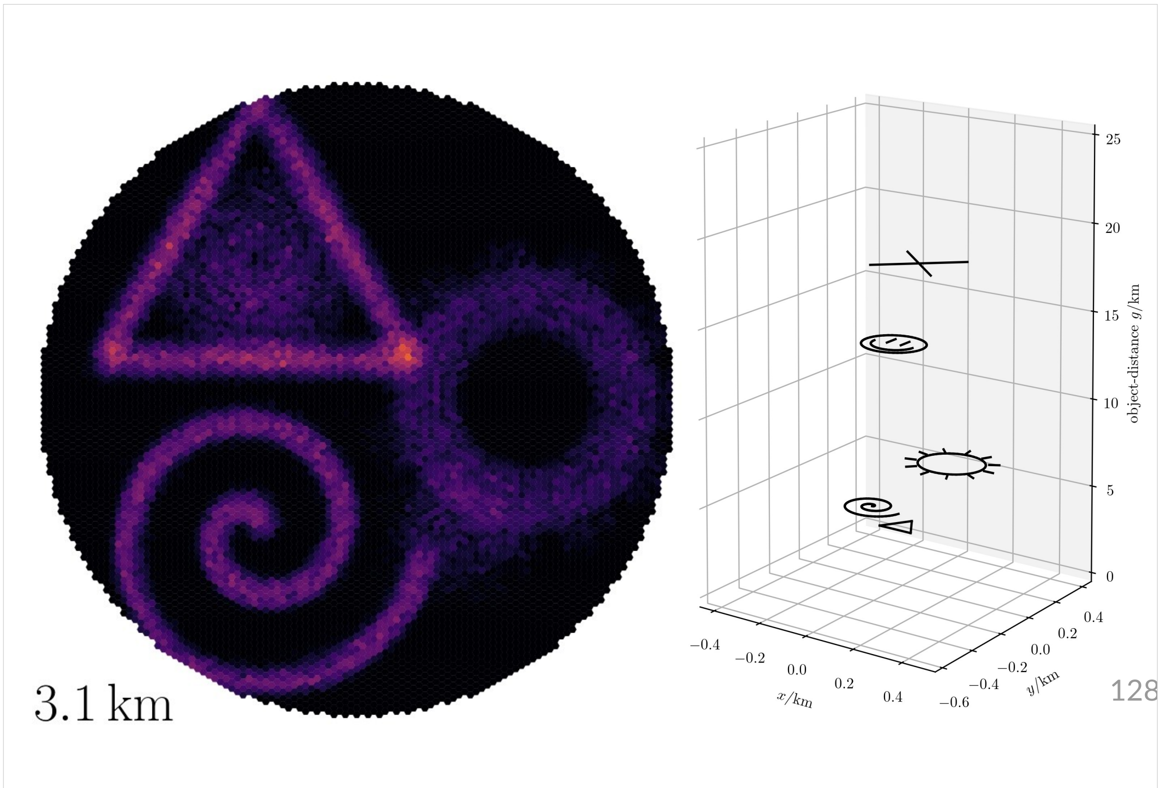

2.2 km
object-distance g/km
x/km
y/km
124

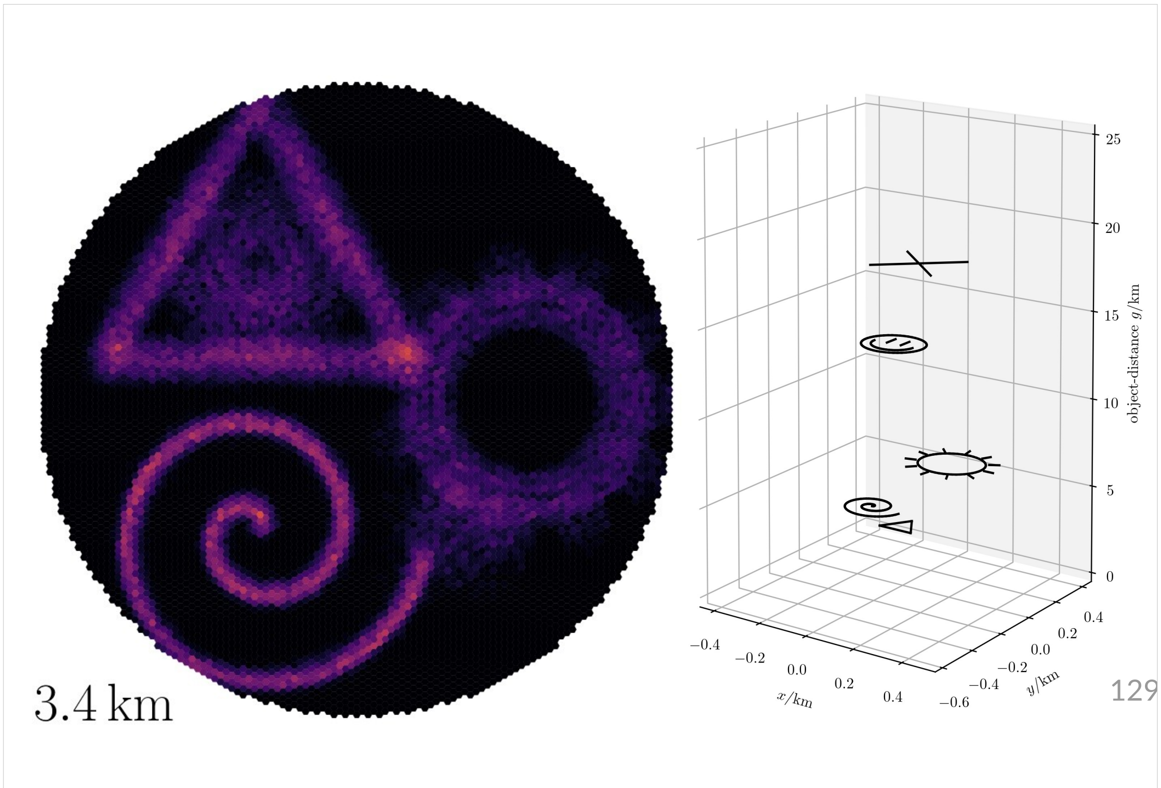

2.4 km
object-distance g/km
x/km
y/km
125

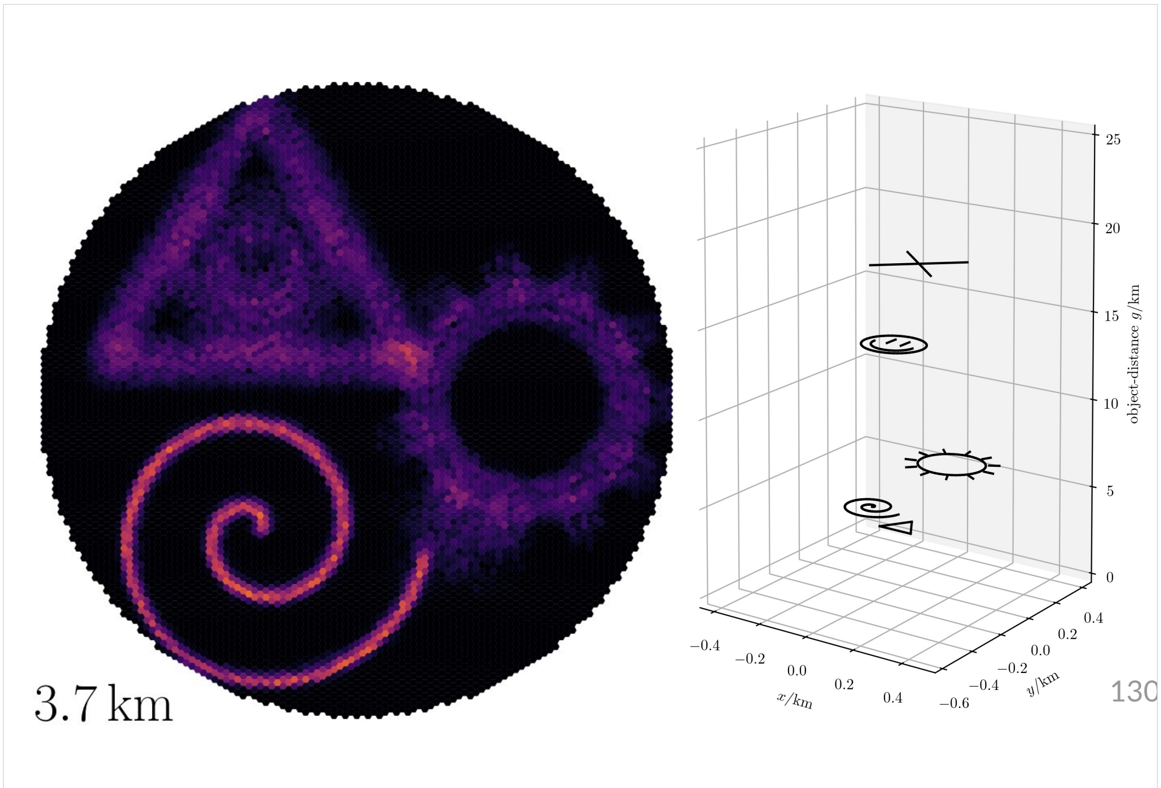


Looks like the triangle is in two point five kilometers depths.

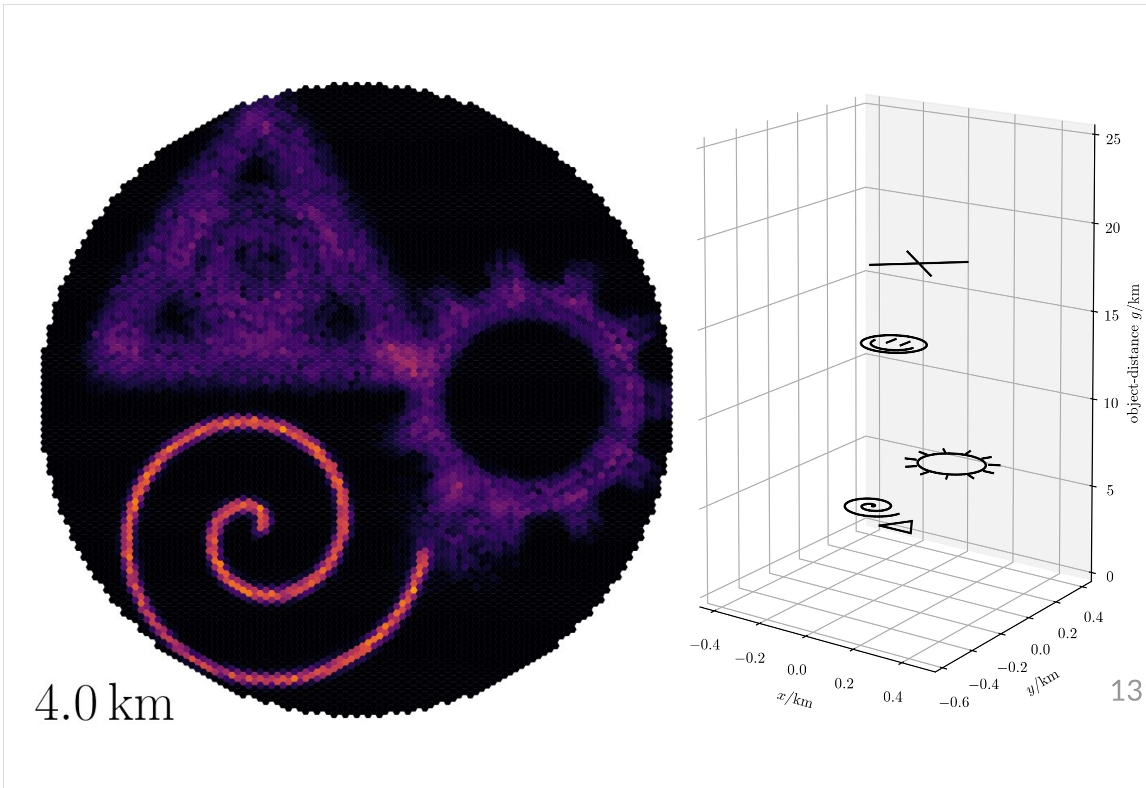

2.8 km
object-distance g/km
x/km
y/km


3.1 km
object-distance g/km
x/km
y/km
128

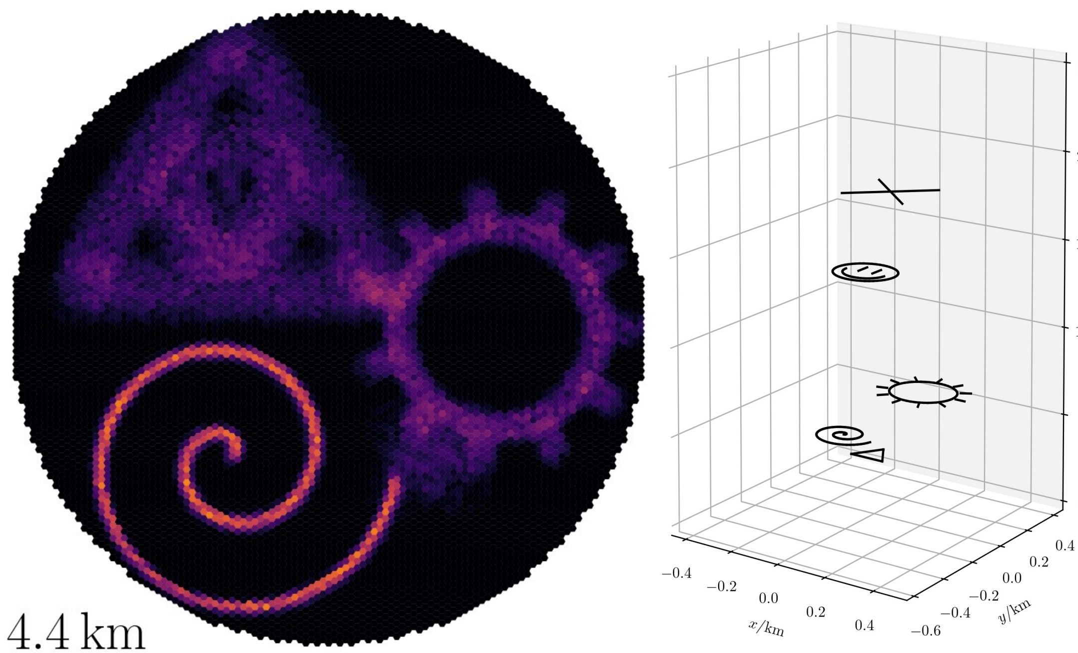

3.4 km
object-distance g/km
x/km
y/km
129



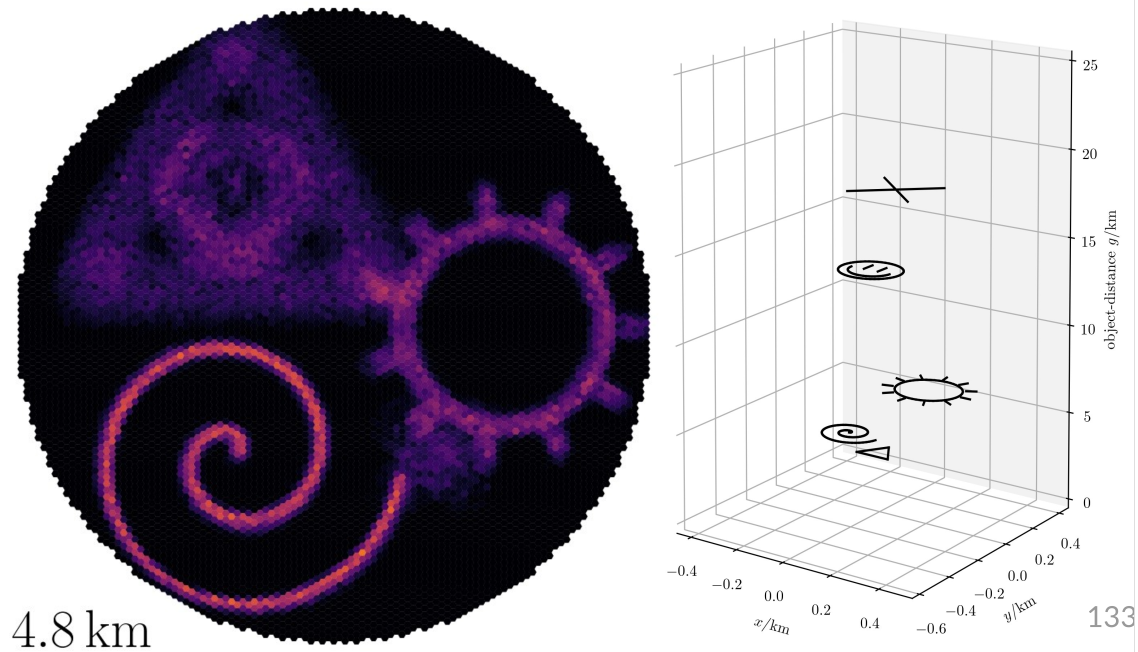
3.7 km
object-distance g/km
x/km
y/km
130

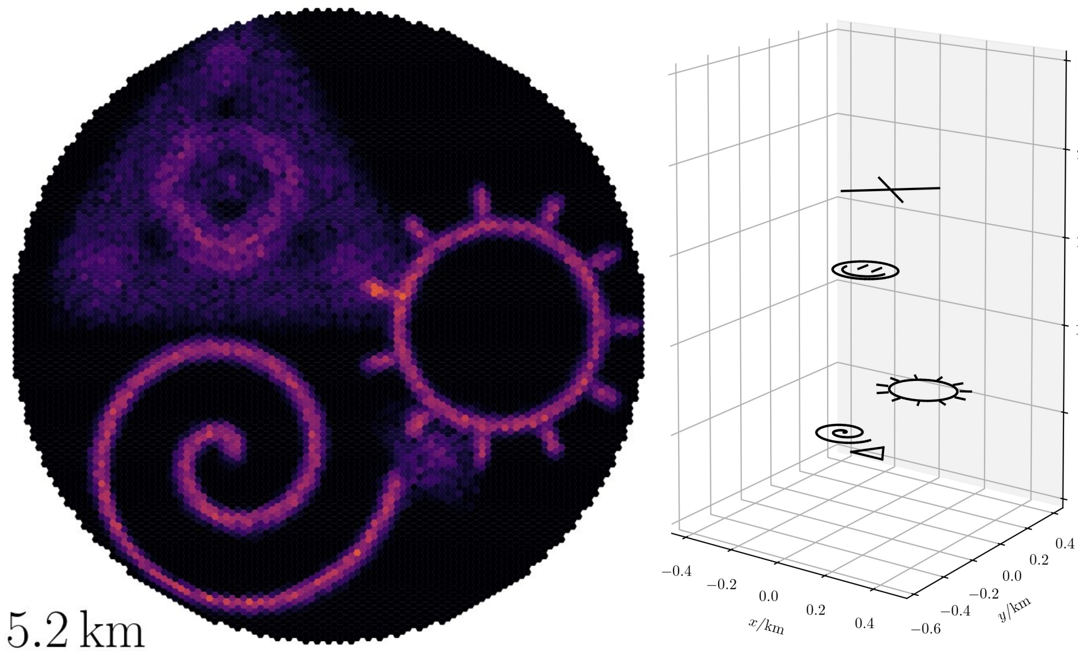


The spiral

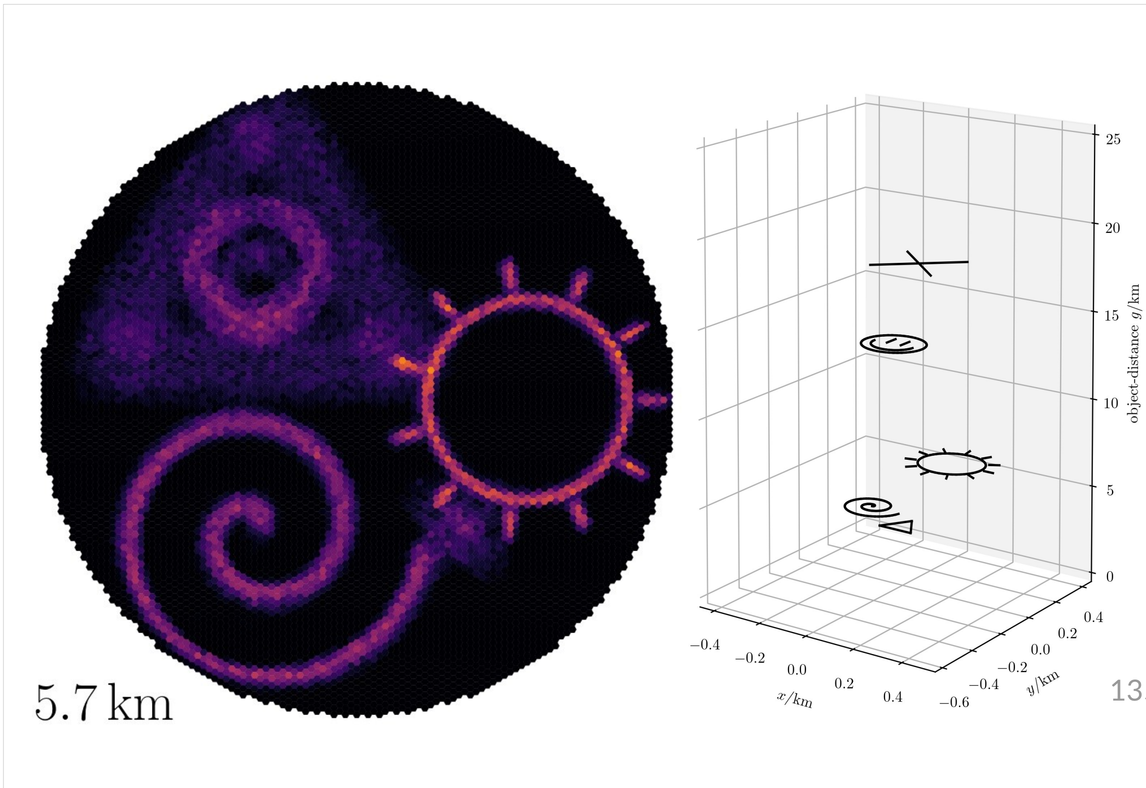

4.4 km
object-distance g/km
0
5
10
15
20
25
x/km
−0.4
−0.2
0.0
0.2
0.4
y/km
−0.6
−0.4
−0.2
0.0
0.2
0.4

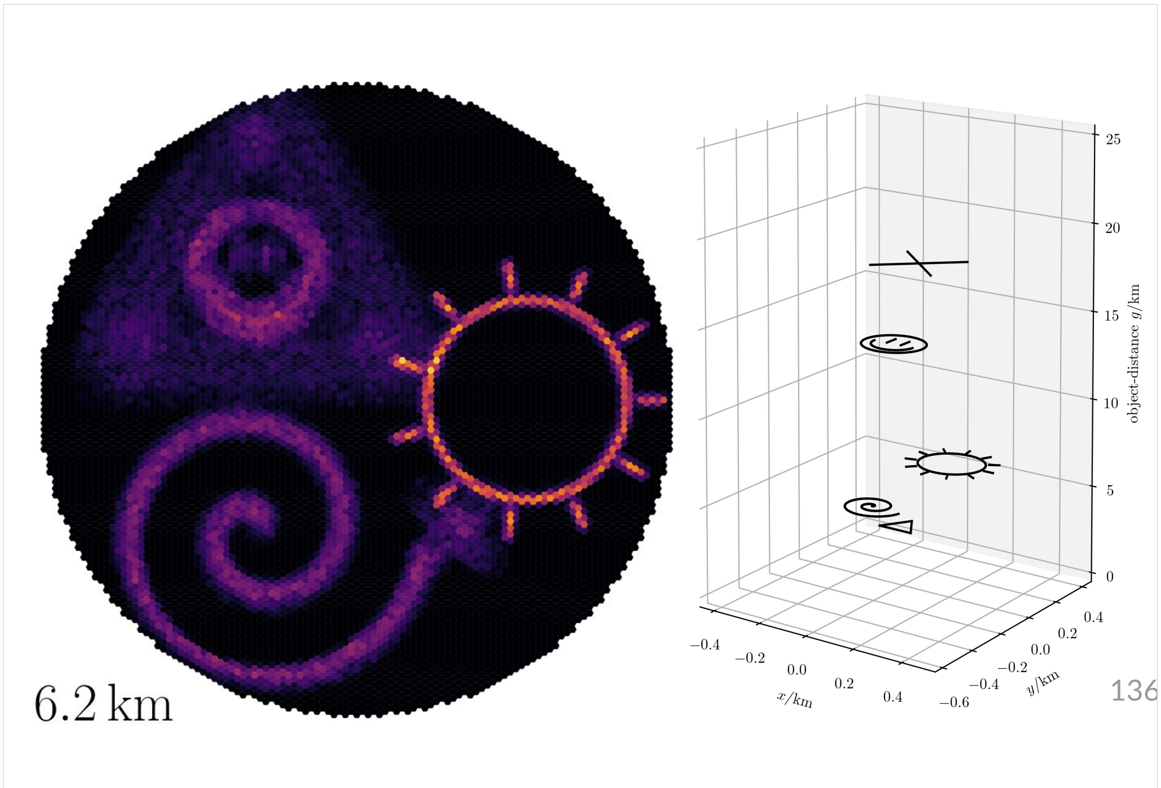
132


4.8 km
object-distance g/km
0
5
10
15
20
25
x/km
−0.4
−0.2
0.0
0.2
0.4
y/km
−0.6
−0.4
−0.2
0.0
0.2
0.4
133

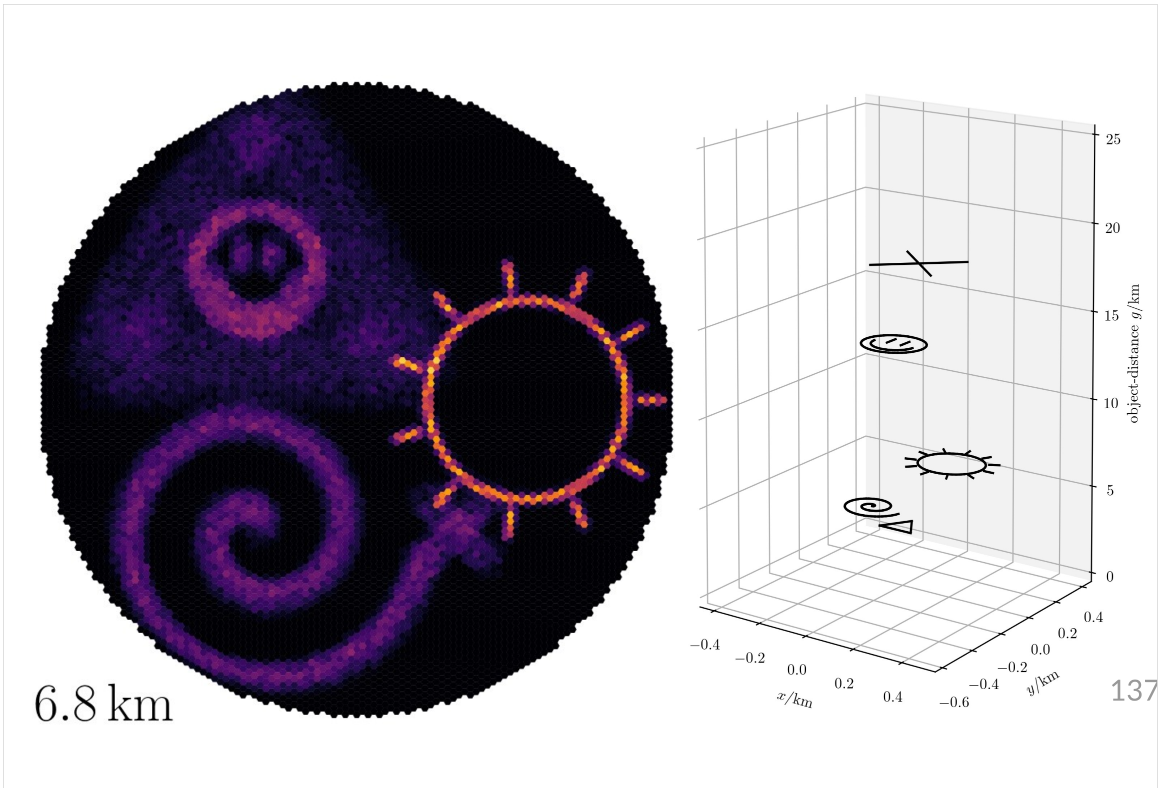

5.2 km
object-distance g/km
25
20
15
10
5
0
x/km
−0.4
−0.2
0.0
0.2
0.4
y/km
−0.6
−0.4
−0.2
0.0
0.2
0.4

134

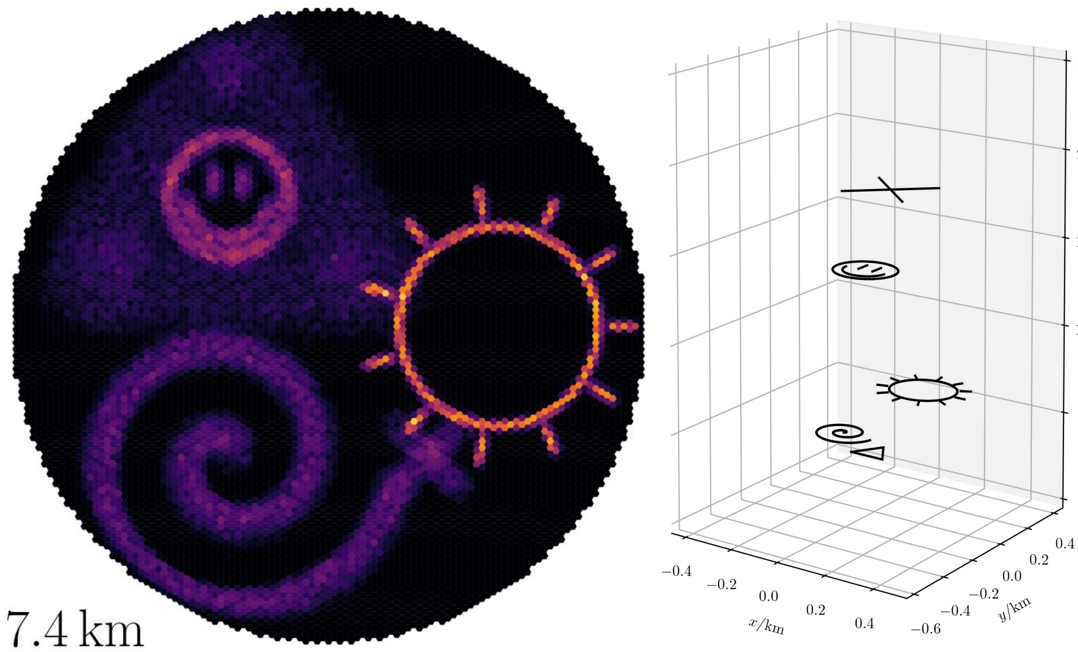

5.7 km
object-distance g/km
x/km
y/km
135



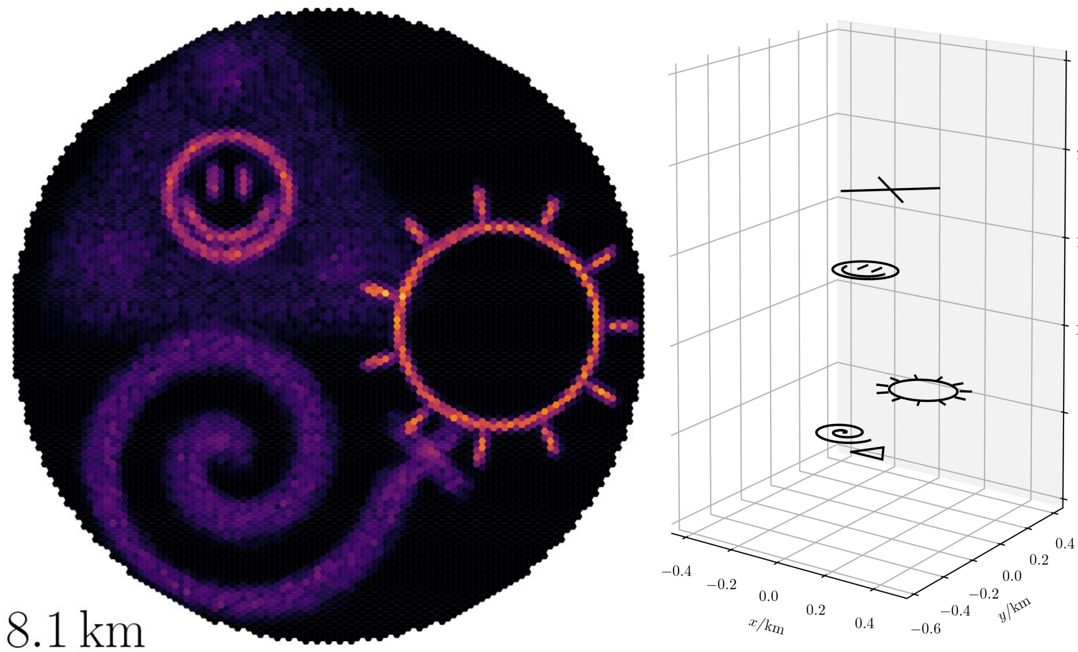
The sun-symbol



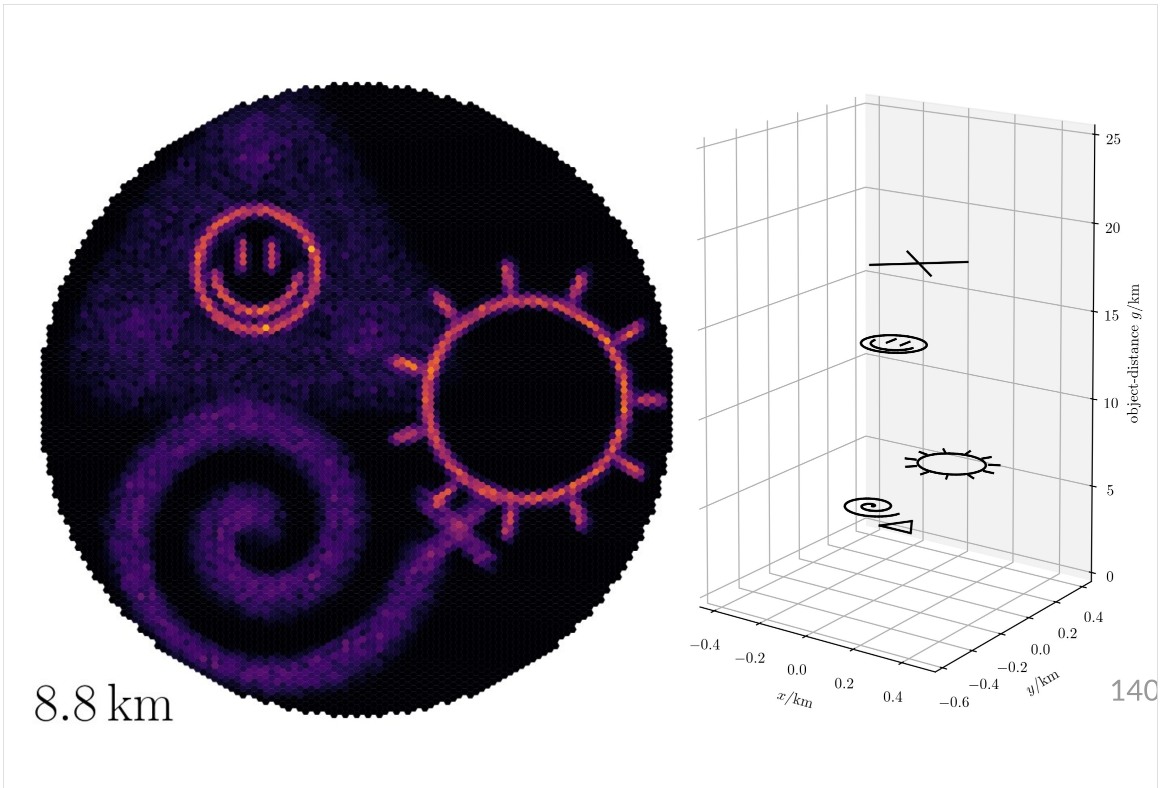
6.8 km
object-distance g/km
x/km
y/km
137

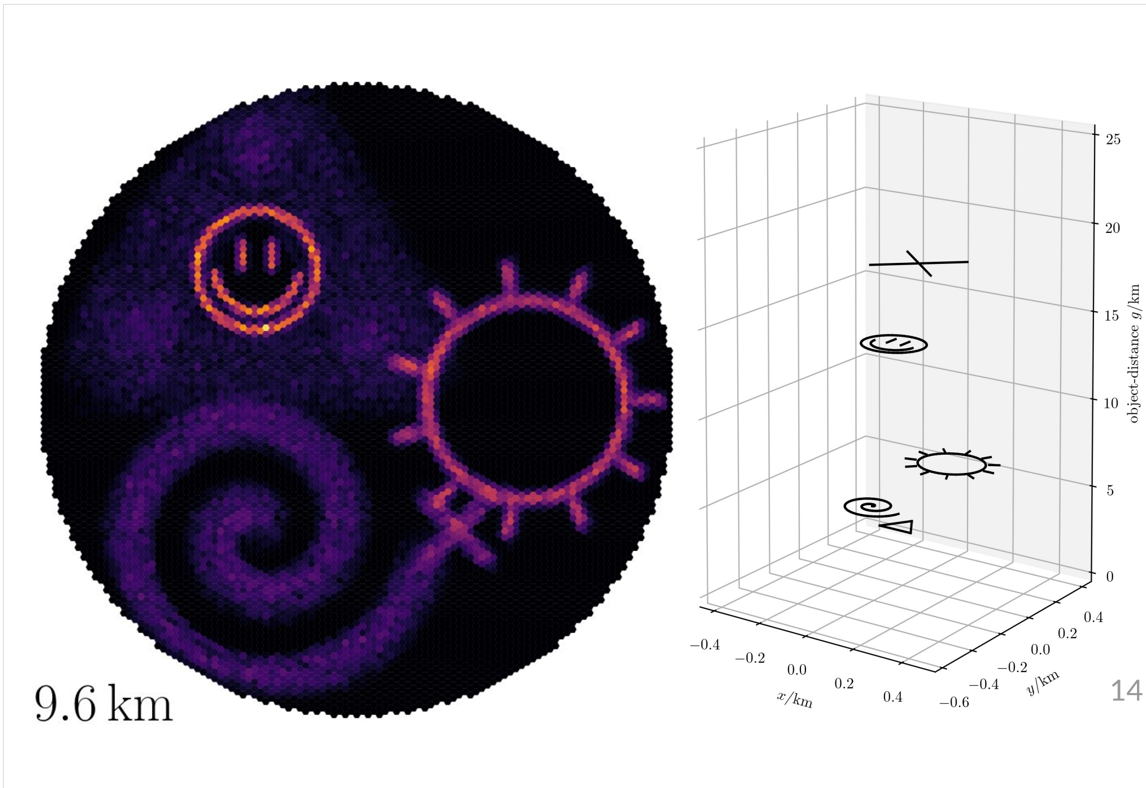

7.4 km
object-distance g/km
0
5
10
15
20
25
x/km
−0.4
−0.2
0.0
0.2
0.4
y/km
−0.6
−0.4
−0.2
0.0
0.2
0.4

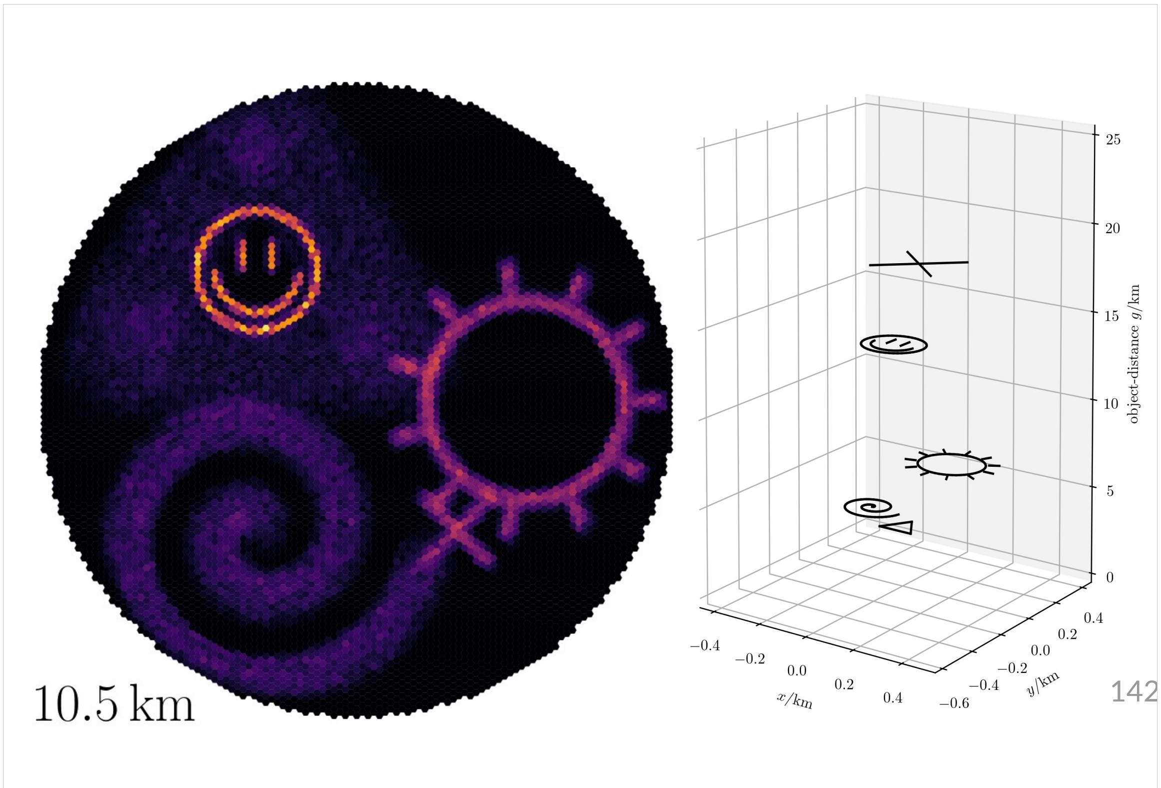
138


8.1 km
object-distance g/km
0
5
10
15
20
25
x/km
−0.4
−0.2
0.0
0.2
0.4
y/km
−0.6
−0.4
−0.2
0.0
0.2
0.4

139

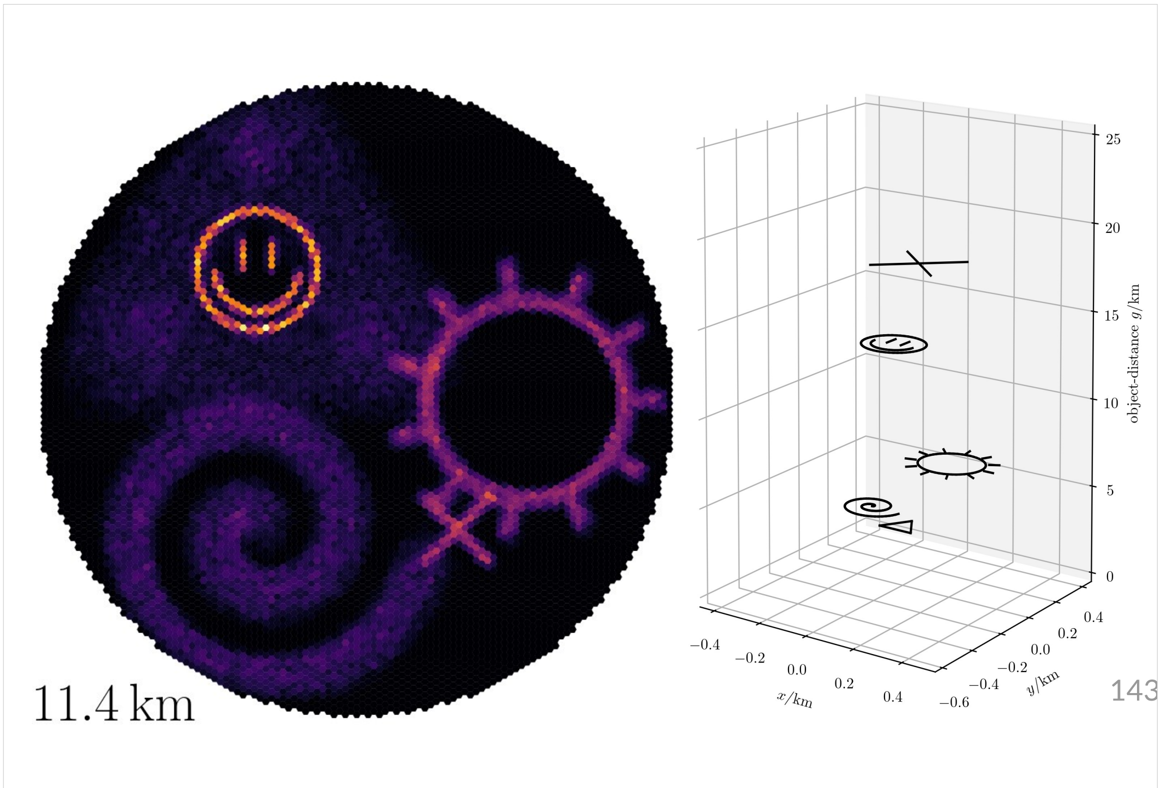

8.8 km
object-distance g/km
x/km
y/km
140


9.6 km
object-distance g/km
x/km
y/km
141



Ah a simley...

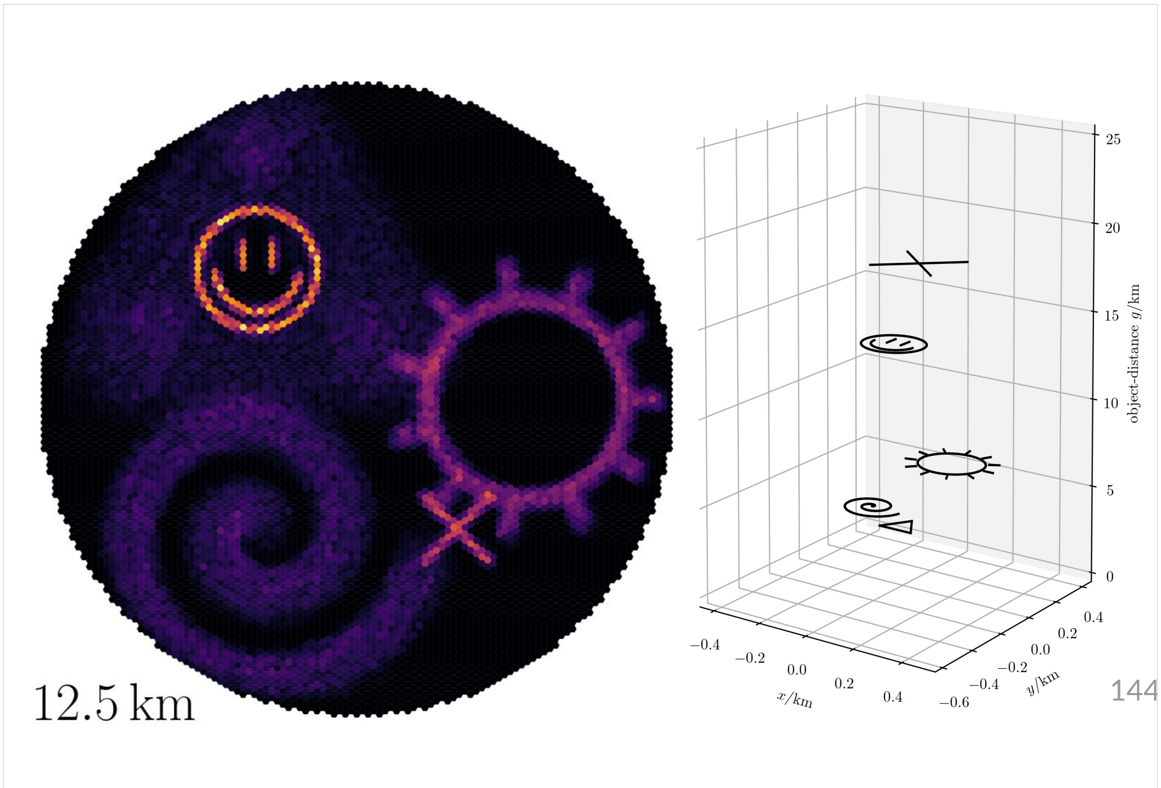
But, ... wait a minute!

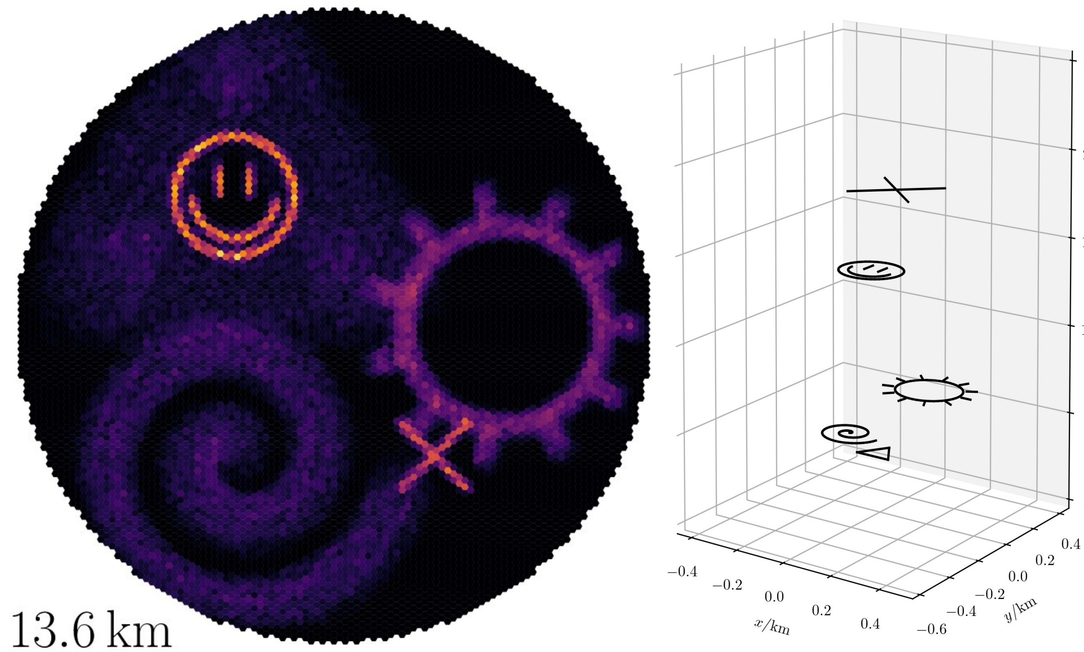


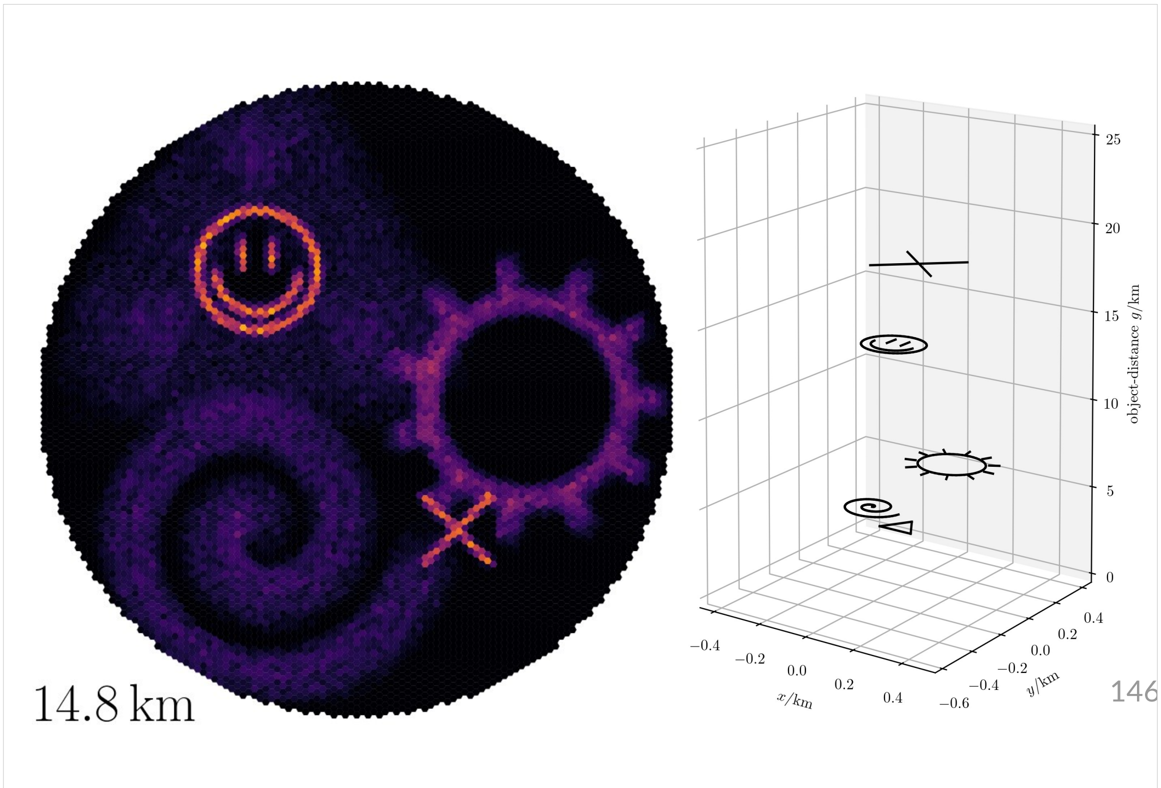
Where is the triangle?

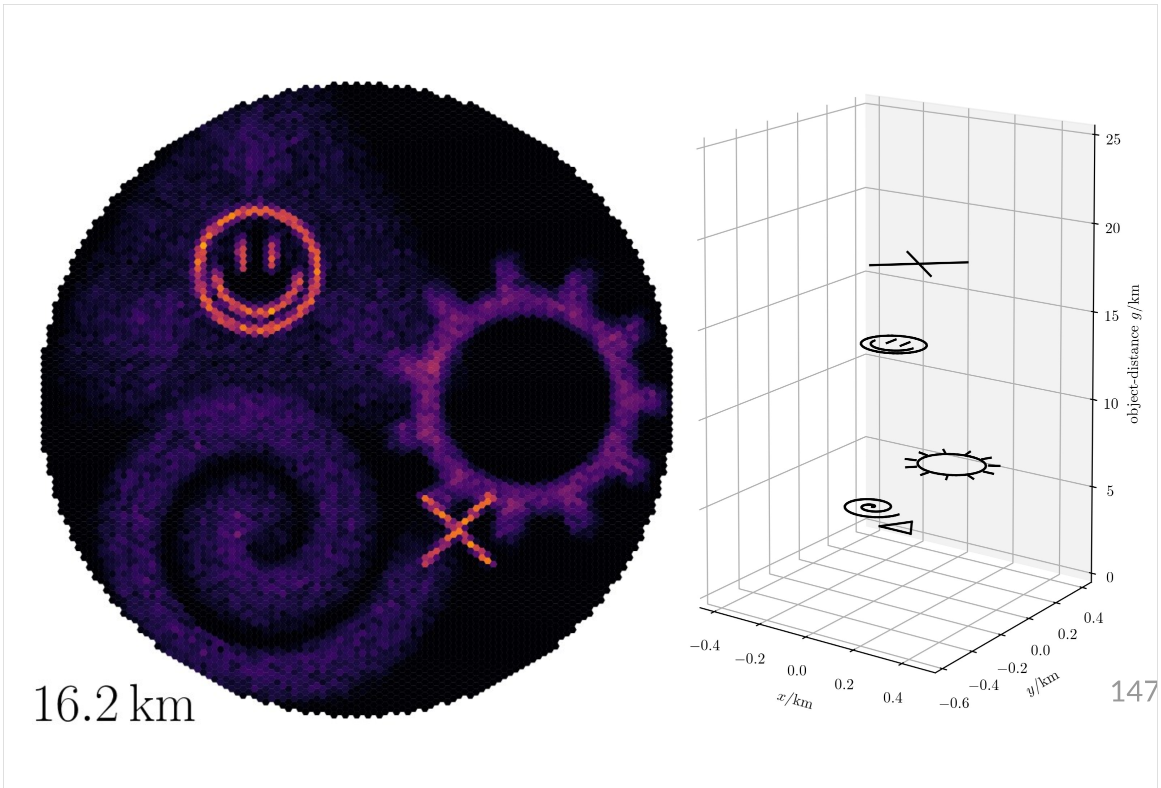
It is gone.

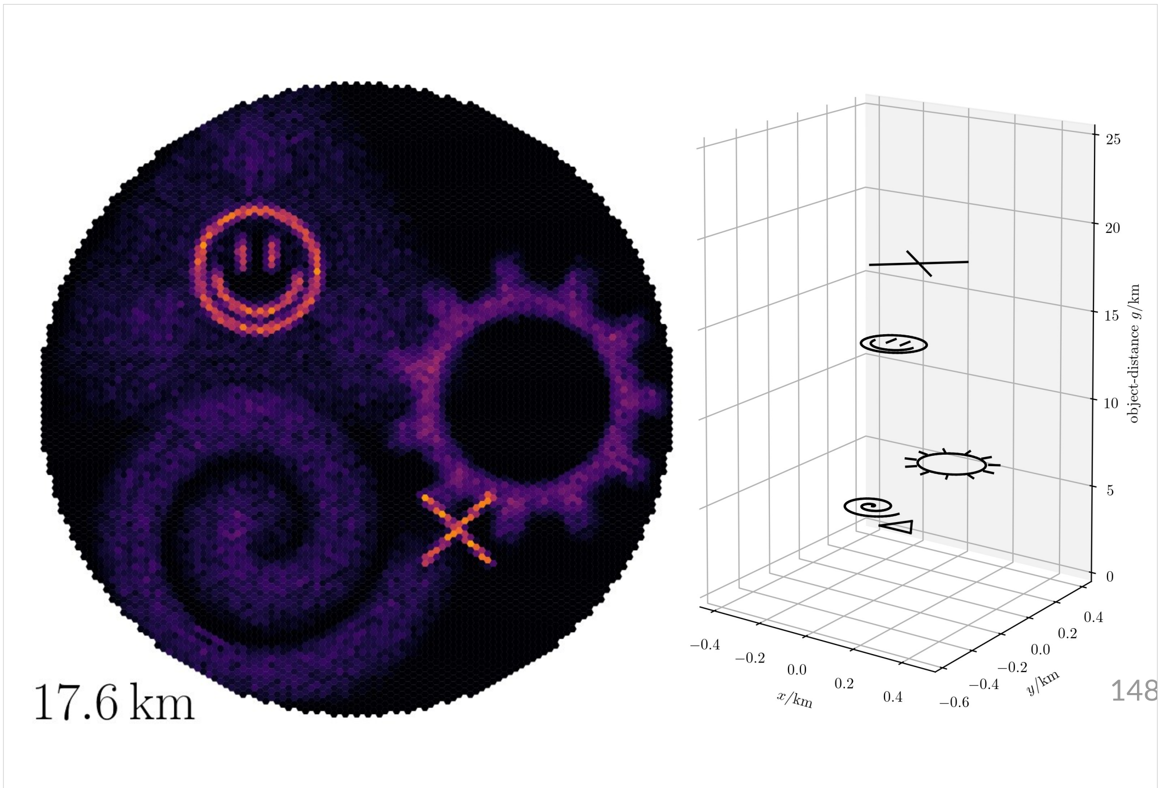
If this image was taken by a telescope, the narrow depth-of-field would have blurred the triangle so much that we would never have known about it.

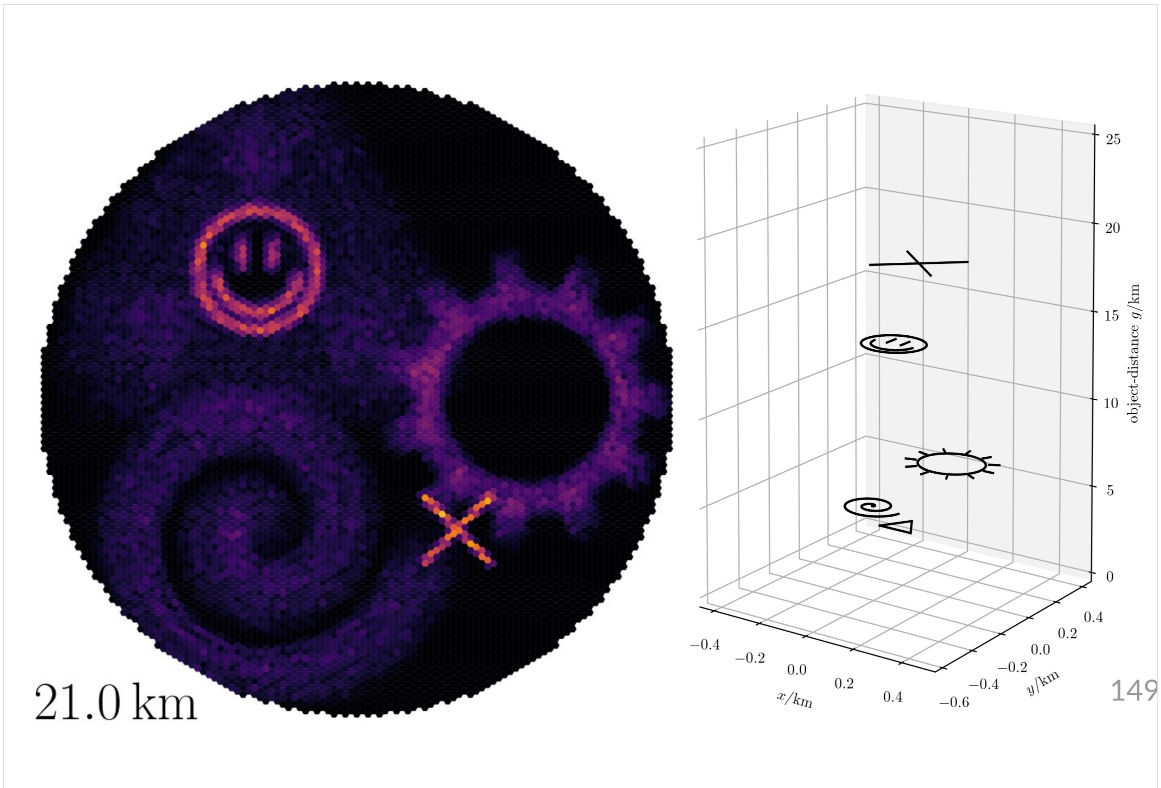

12.5 km
object-distance g/km
x/km
y/km
144

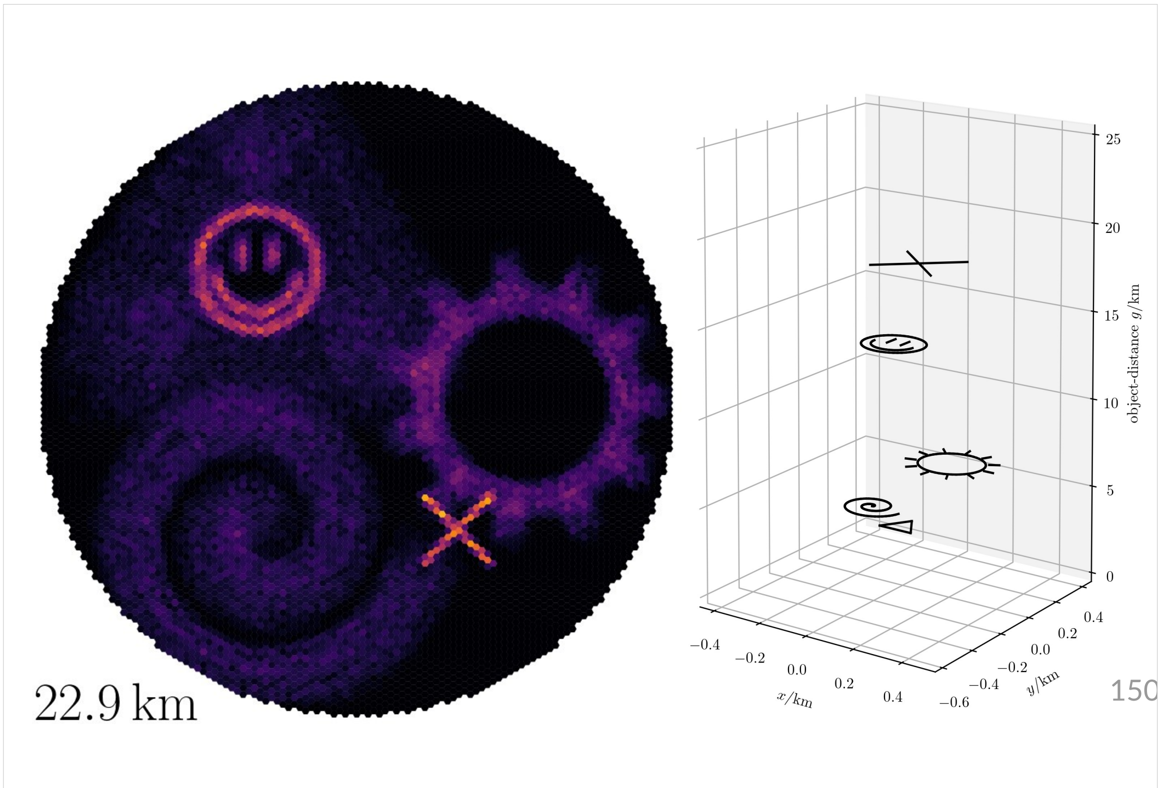

13.6 km
object-distance g/km
0
5
10
15
20
25
−0.4
−0.2
0.0
0.2
0.4
x/km
−0.6
−0.4
−0.2
0.0
0.2
0.4
y/km

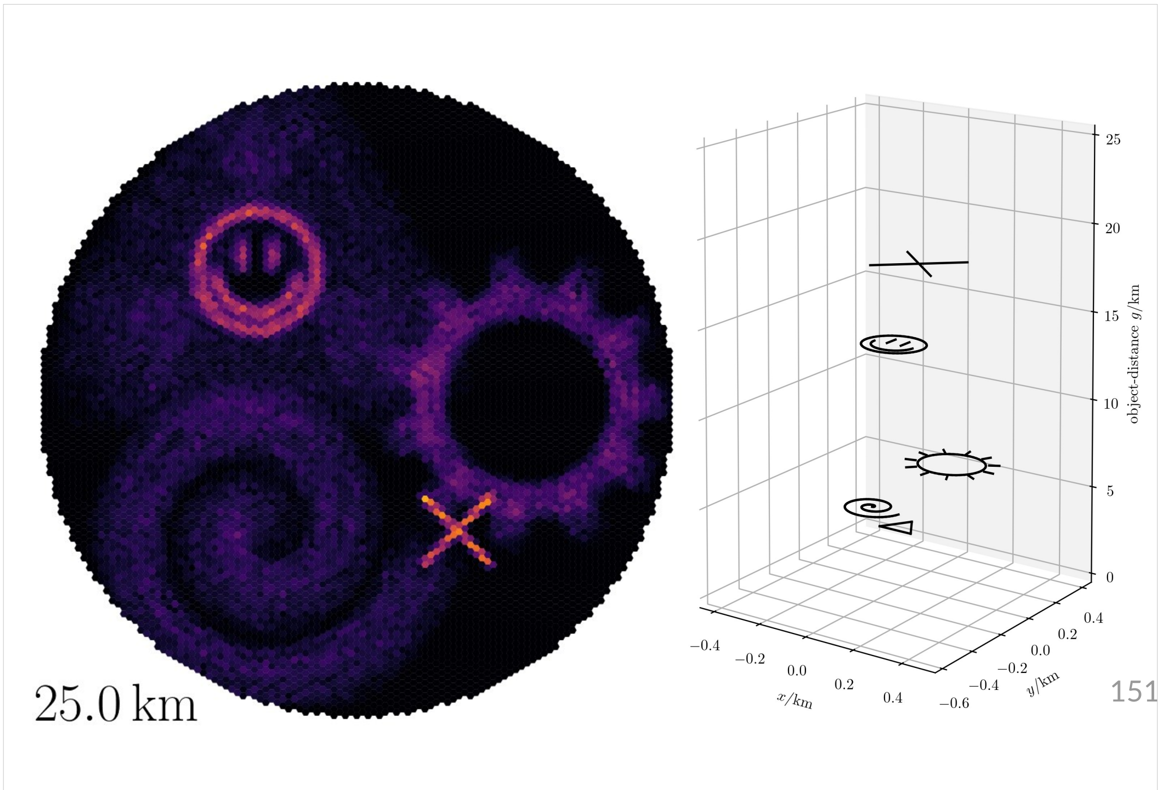

14.8 km
object-distance g/km
x/km
y/km
146


16.2 km
object-distance g/km
x/km
y/km
147


17.6 km
object-distance g/km
x/km
y/km
148


21.0 km
object-distance g/km
x/km
y/km
149


22.9 km
object-distance g/km
x/km
y/km
150

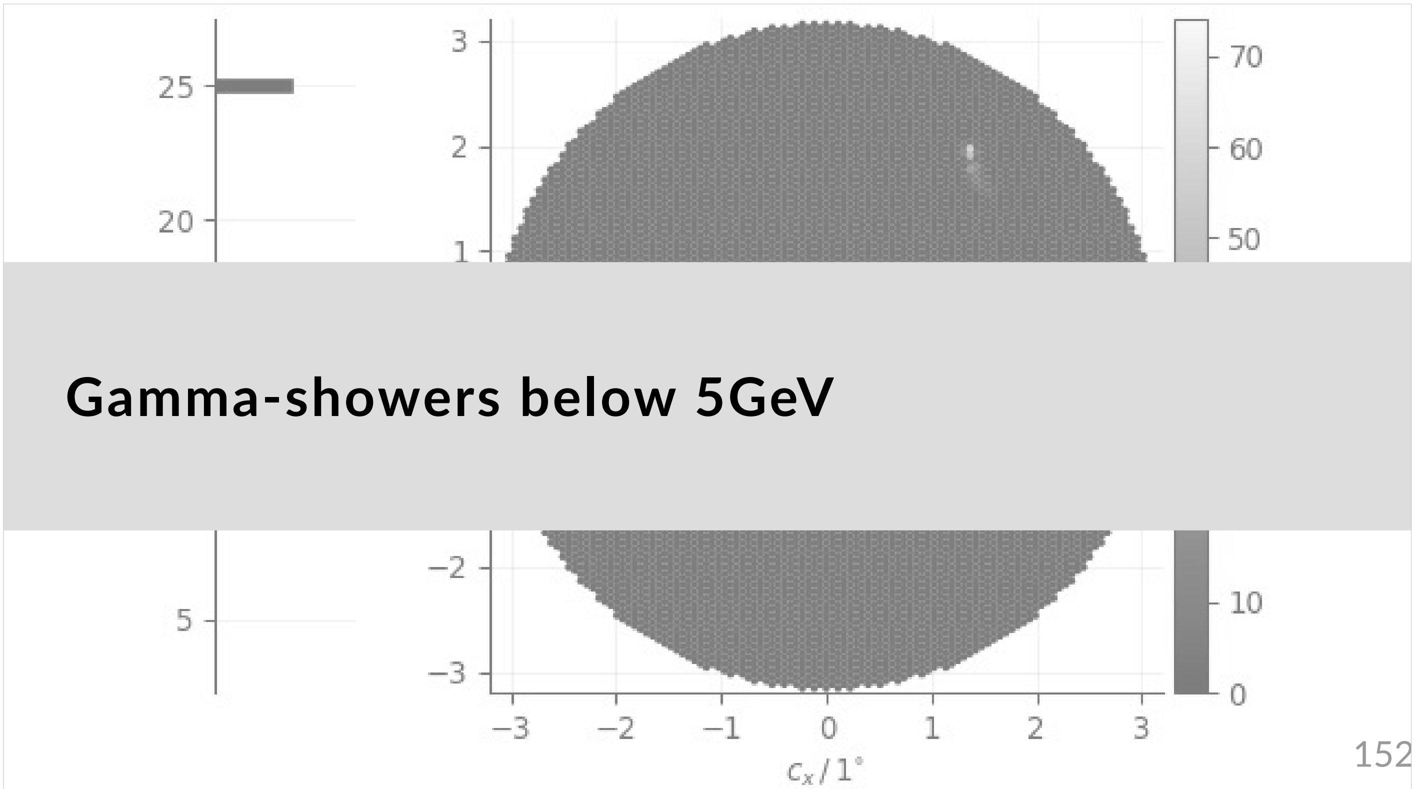


And the cross.

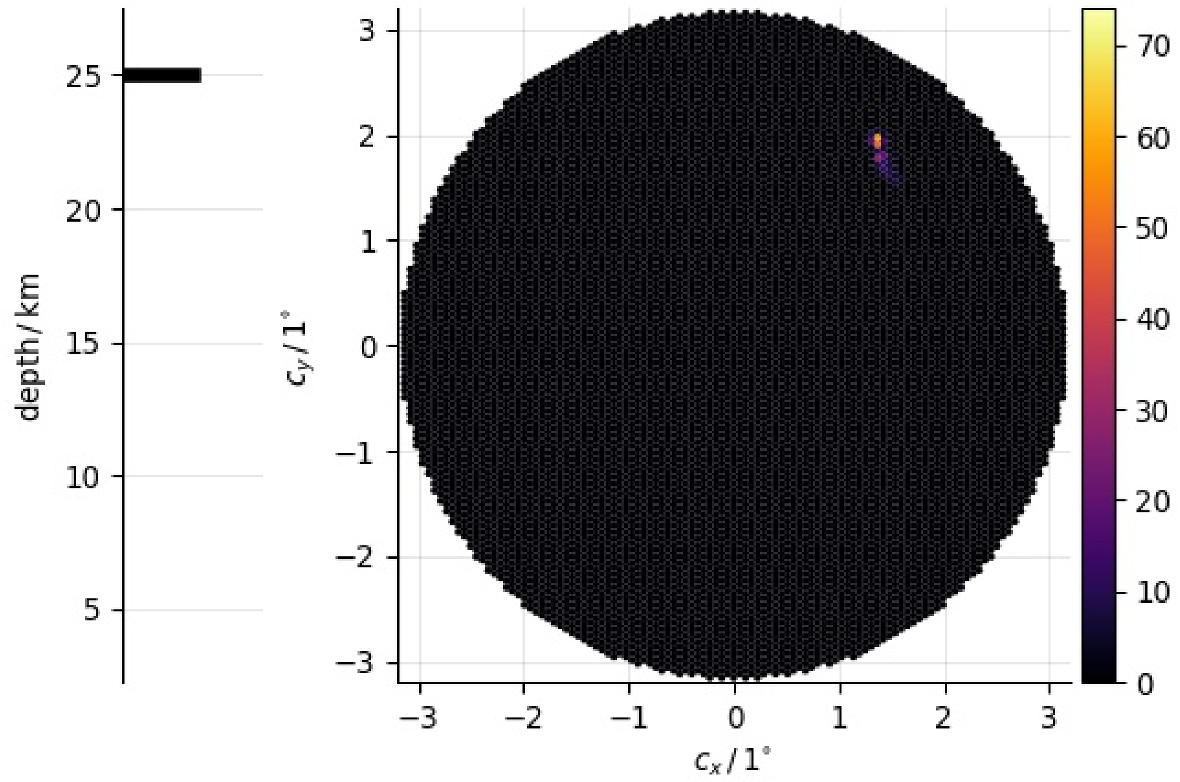
(Once more back and forth through the refocused images)

Note that there are no aberrations.

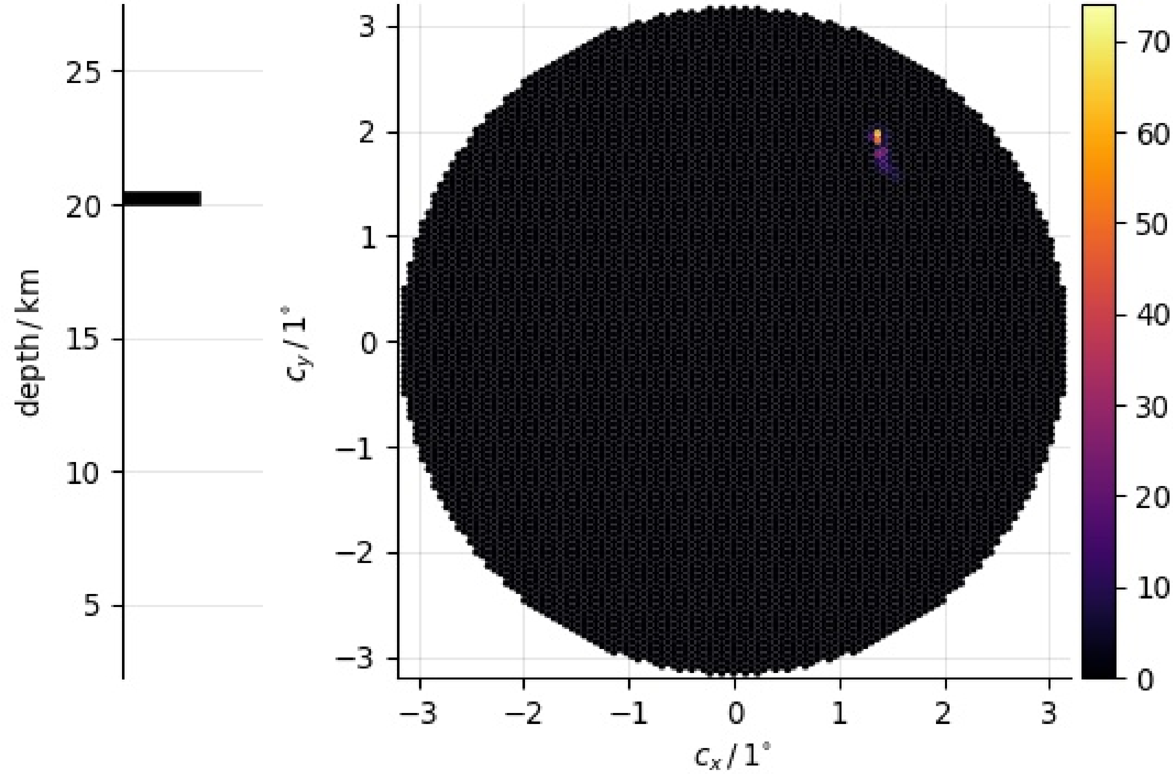
Note how the spiral and the sun-symbol look the same in the inner and outer regions of the field-of-view.



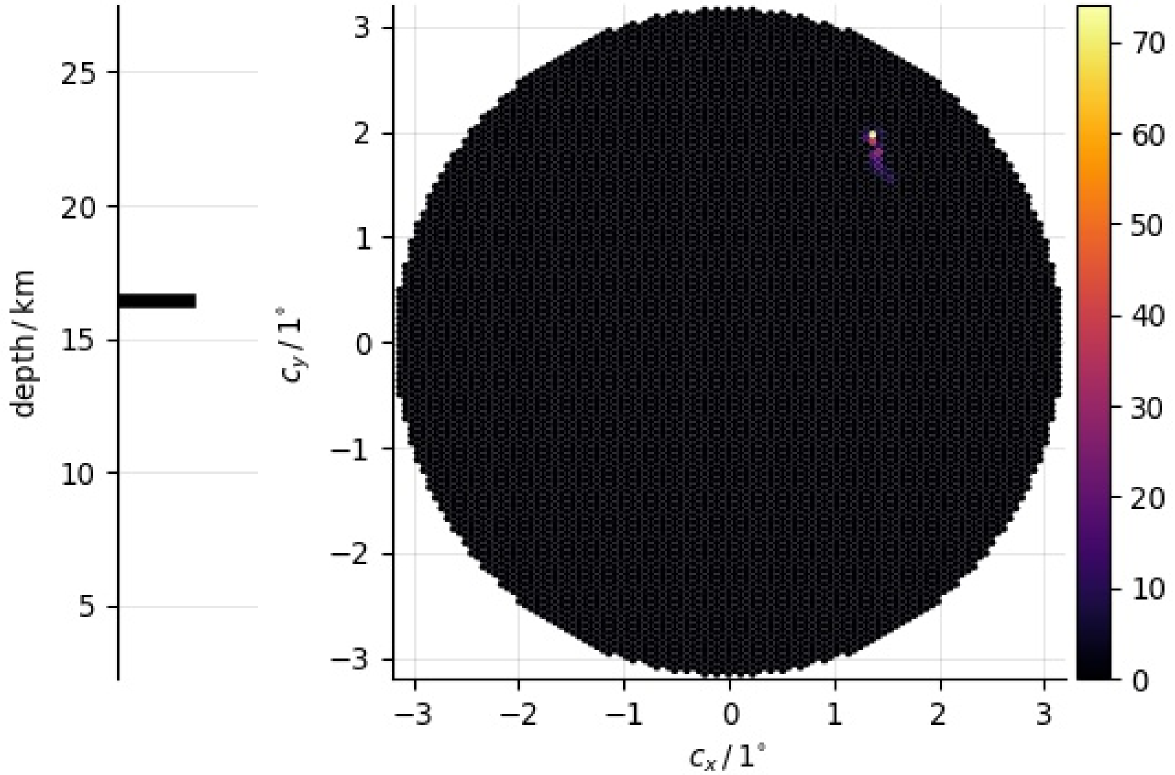
Lets also see some showers.



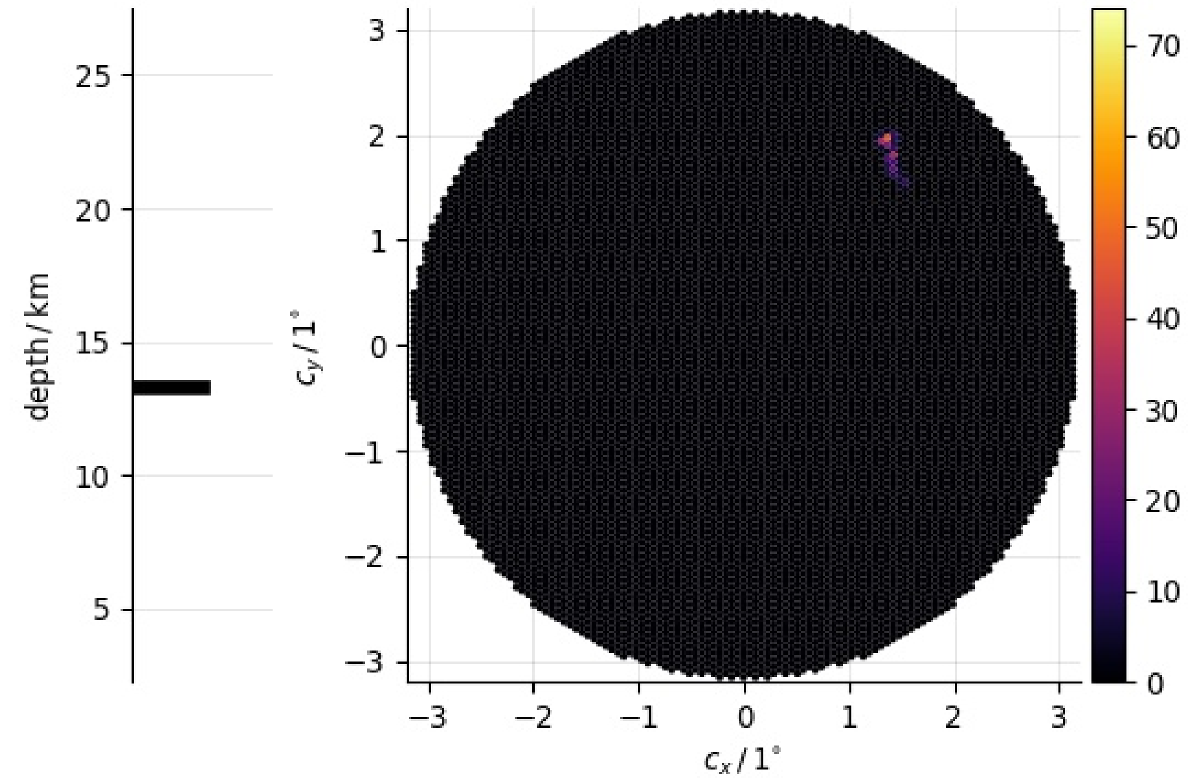
below five giga electron Volts we got mostly small blobs



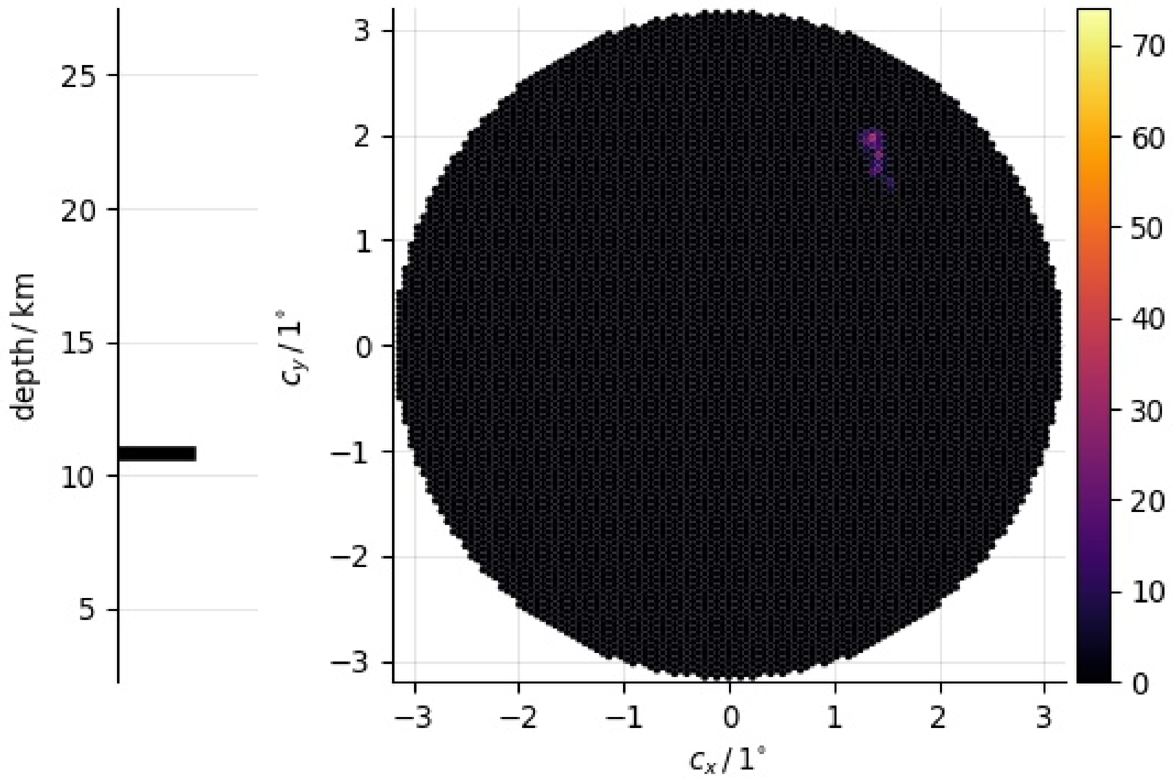
emitting light in a depth of more than fifteen kilometers



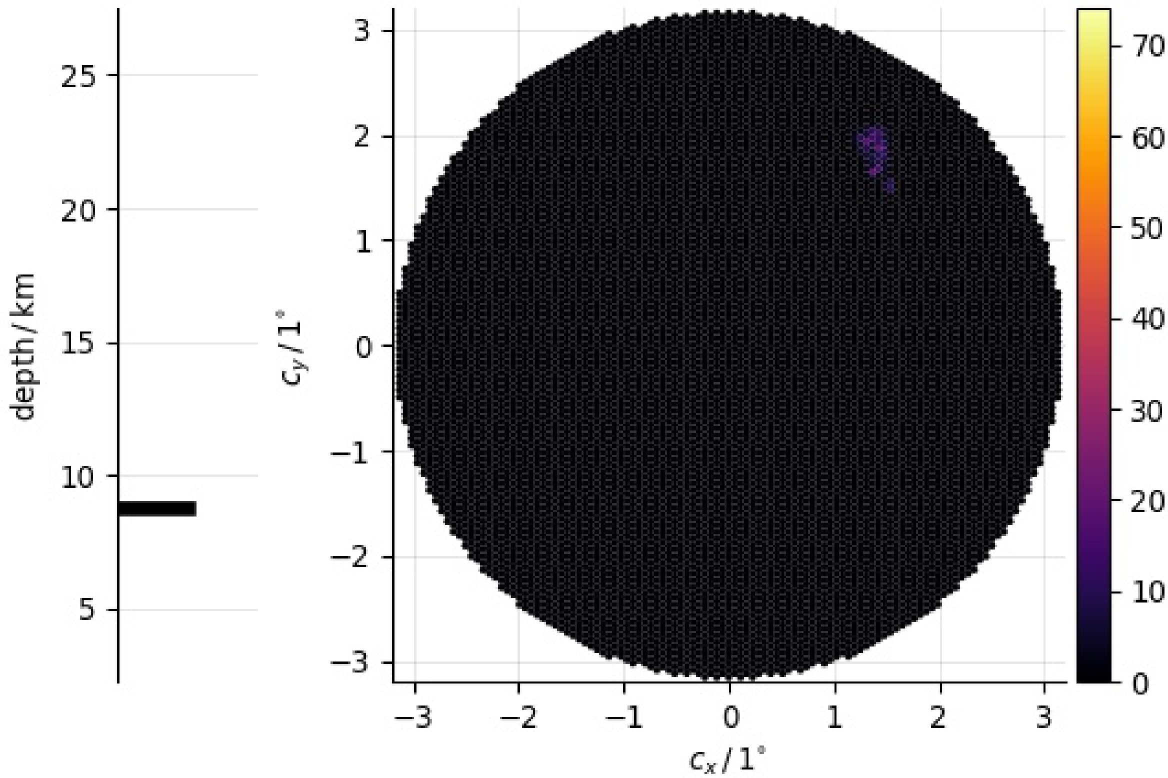
25
20
15
10
5
depth / km
3
2
1
0
−1
−2
−3
c_y / 1°
−3
−2
−1
0
1
2
3
c_x / 1°
70
60
50
40
30
20
10
0



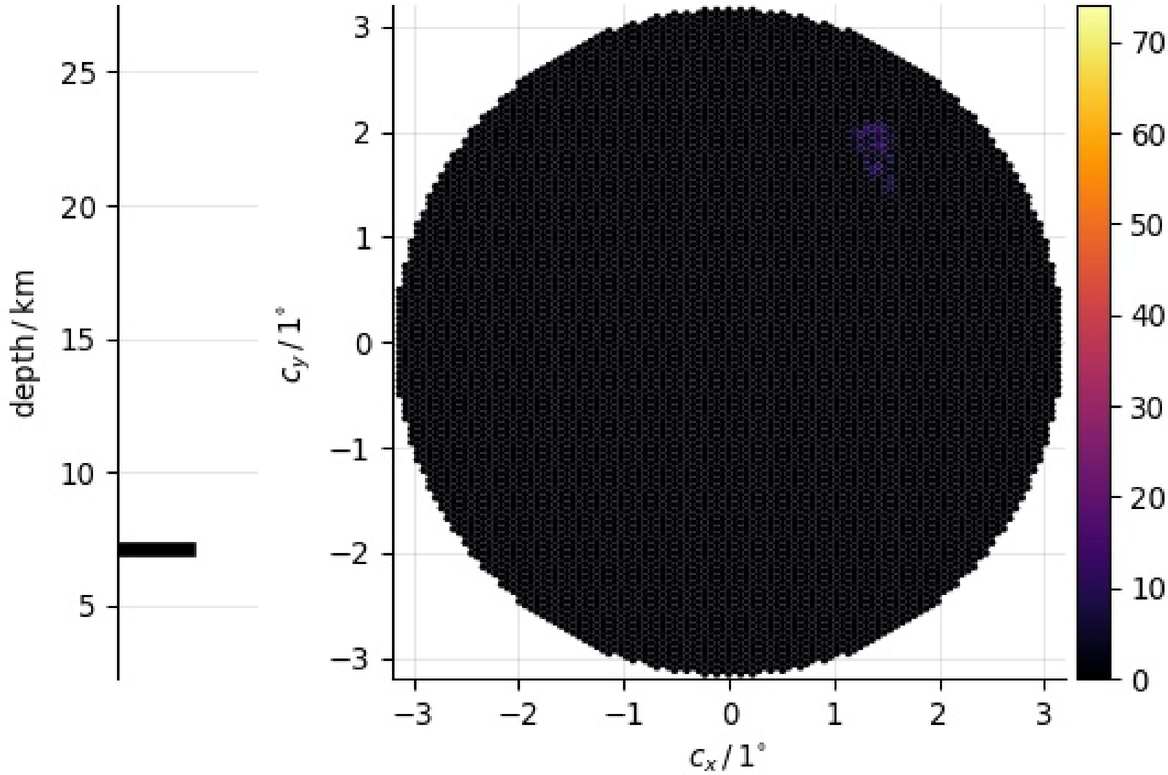
depth / km
25
20
15
10
5
c_y / 1°
c_x / 1°
3
2
1
0
−1
−2
−3
70
60
50
40
30
20
10
0



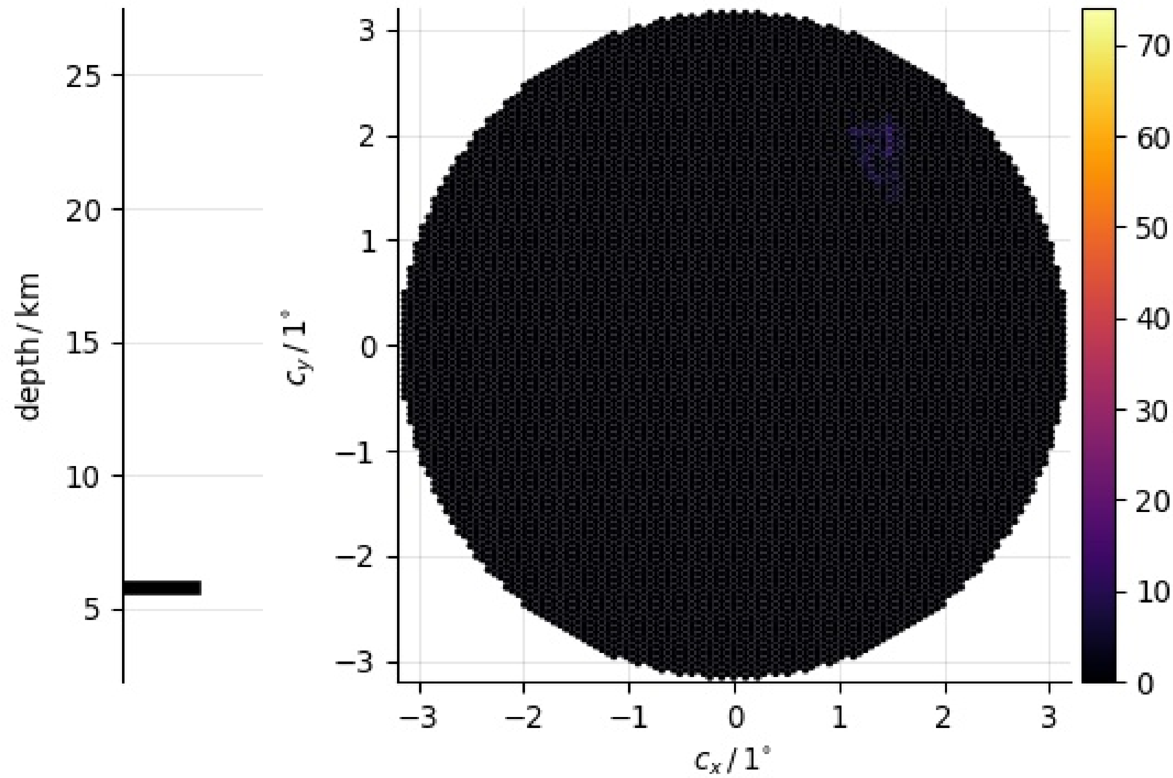
depth / km
25
20
15
10
5
c_y / 1°
3
2
1
0
−1
−2
−3
c_x / 1°
70
60
50
40
30
20
10
0

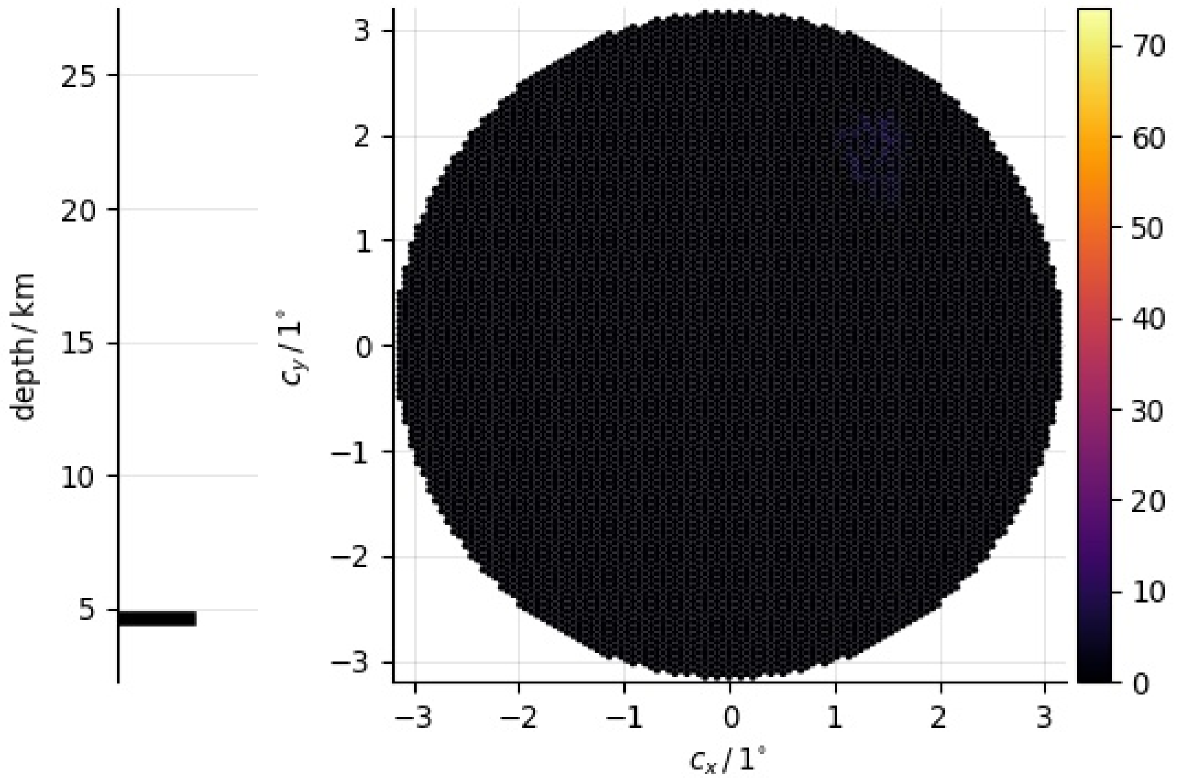


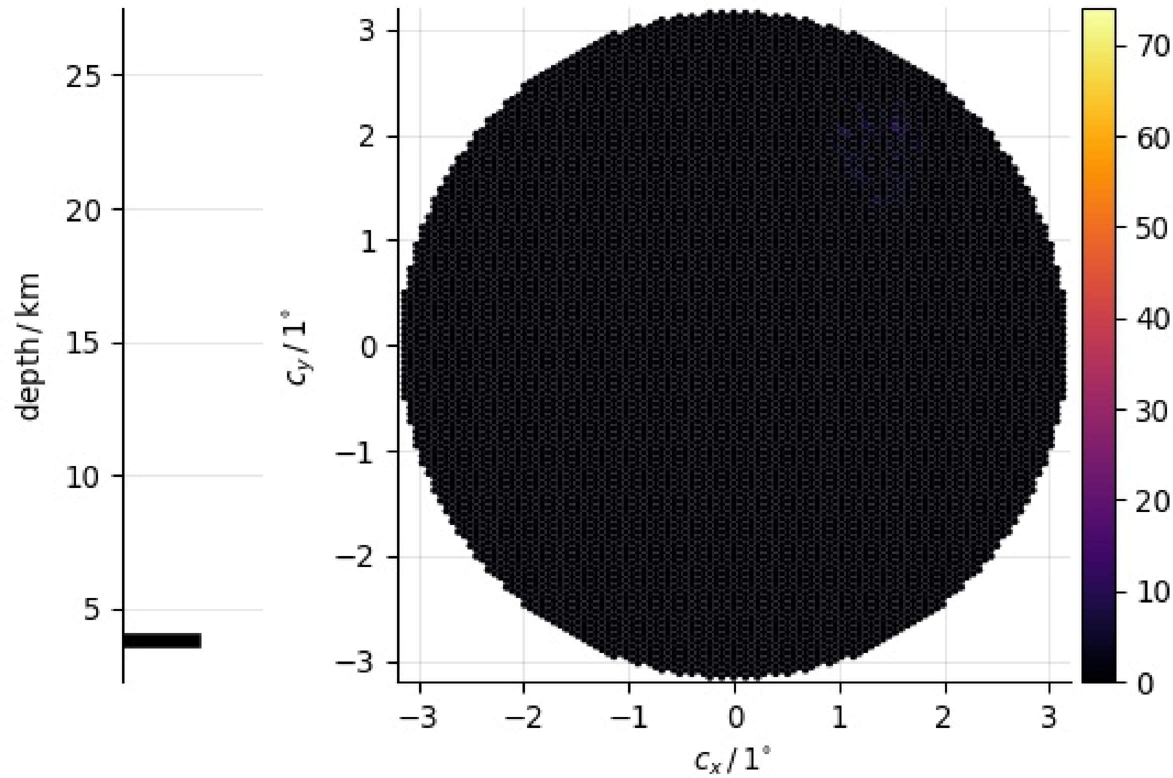
depth / km
25
20
15
10
5
c_y / 1°
c_x / 1°
−3
−2
−1
0
1
2
3
70
60
50
40
30
20
10
0

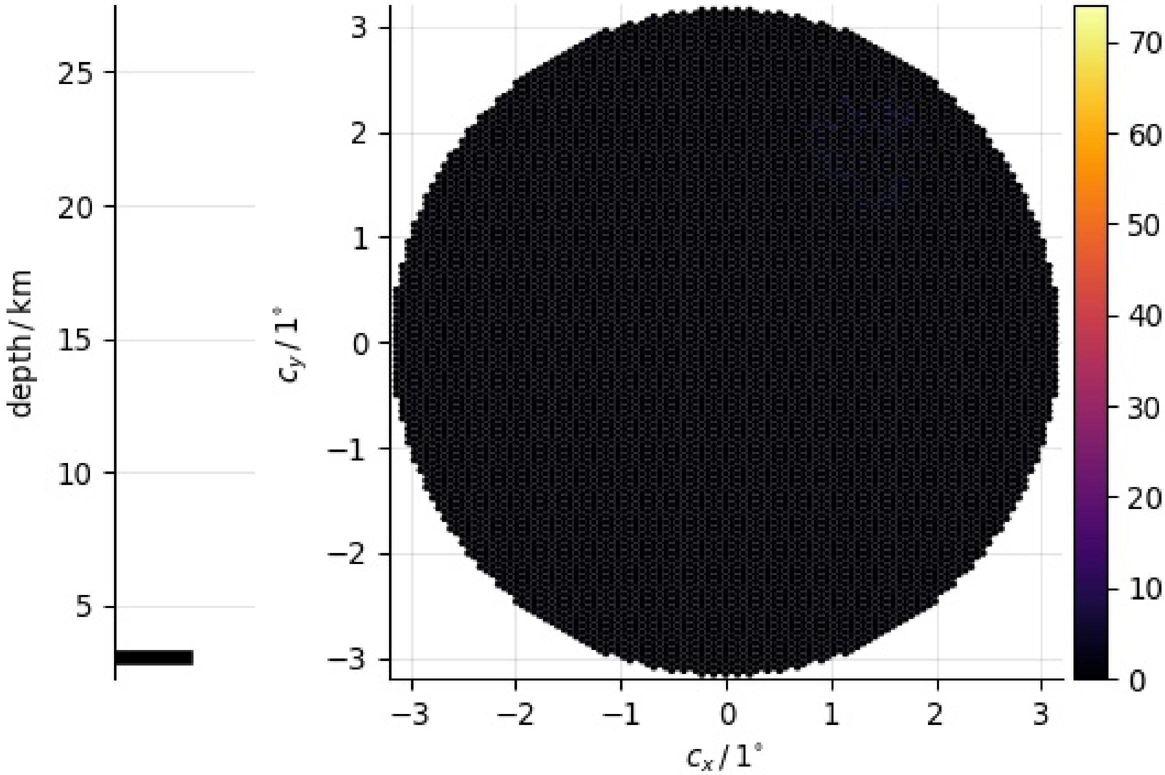


and no light below

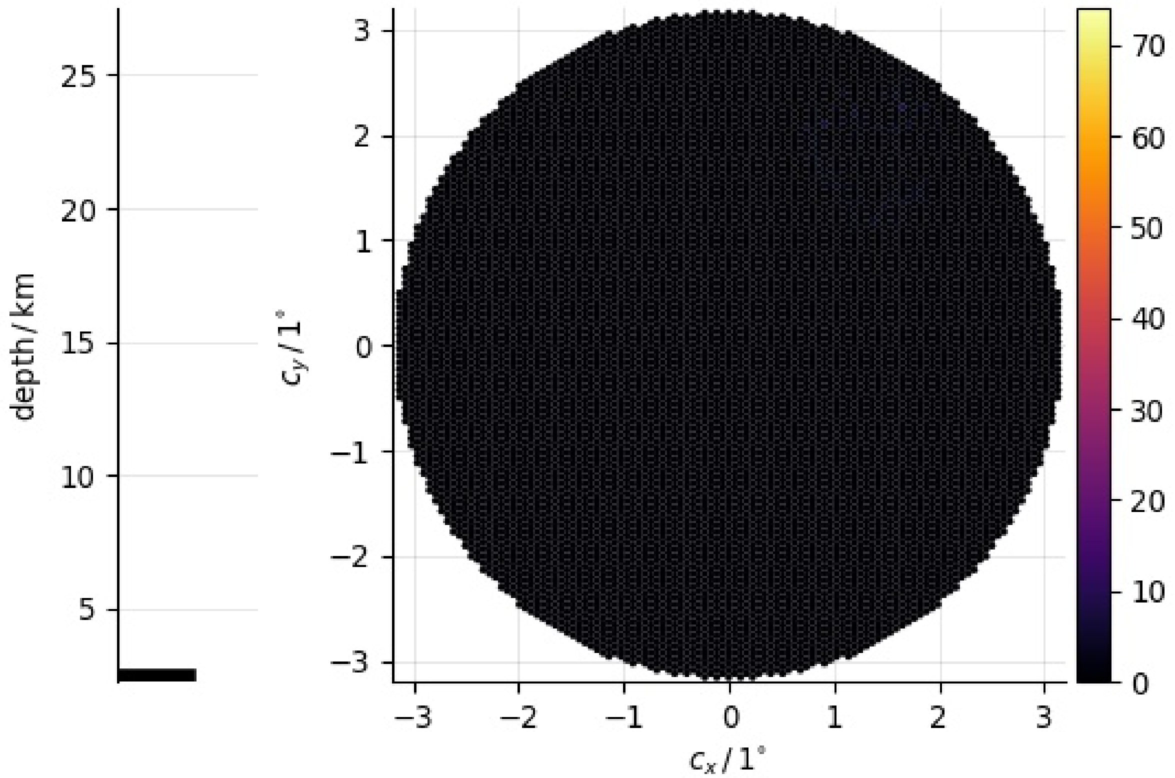

depth / km
25
20
15
10
5
c_y / 1°
3
2
1
0
−1
−2
−3
c_x / 1°
70
60
50
40
30
20
10
0


depth / km
25
20
15
10
5
c_y / 1°
3
2
1
0
−1
−2
−3
c_x / 1°
70
60
50
40
30
20
10
0

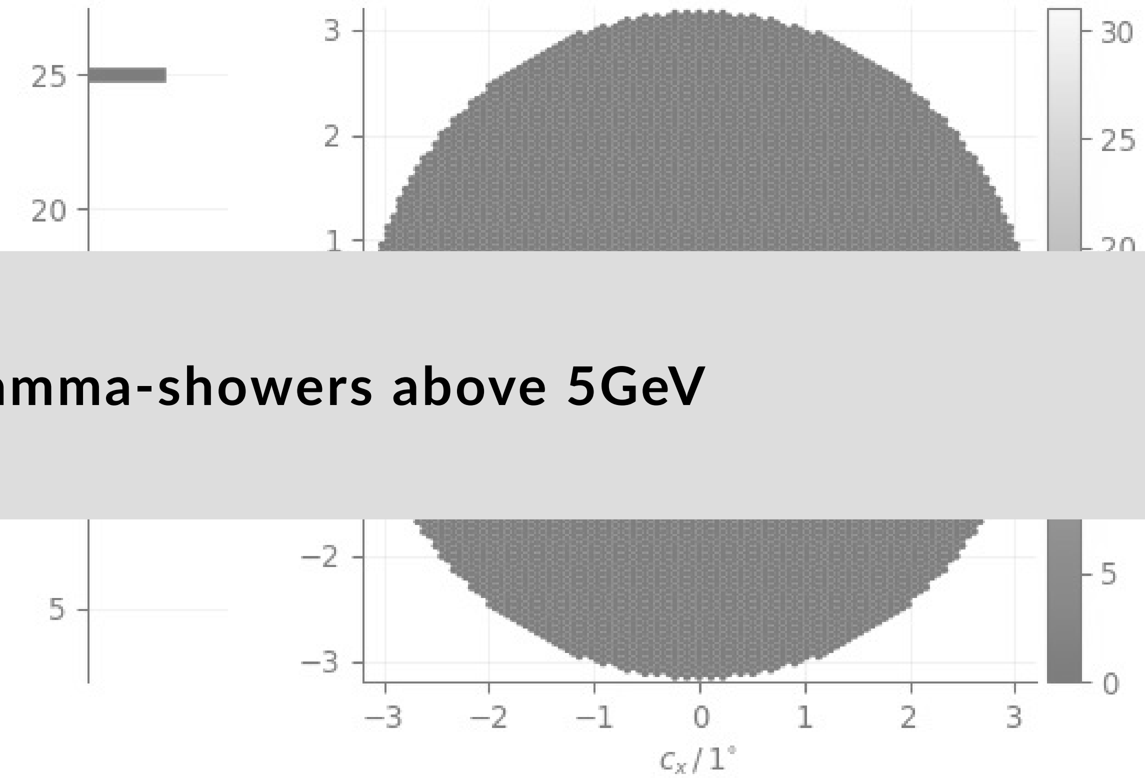

depth / km
25
20
15
10
5
c_y / 1°
c_x / 1°
3
2
1
0
−1
−2
−3
70
60
50
40
30
20
10
0

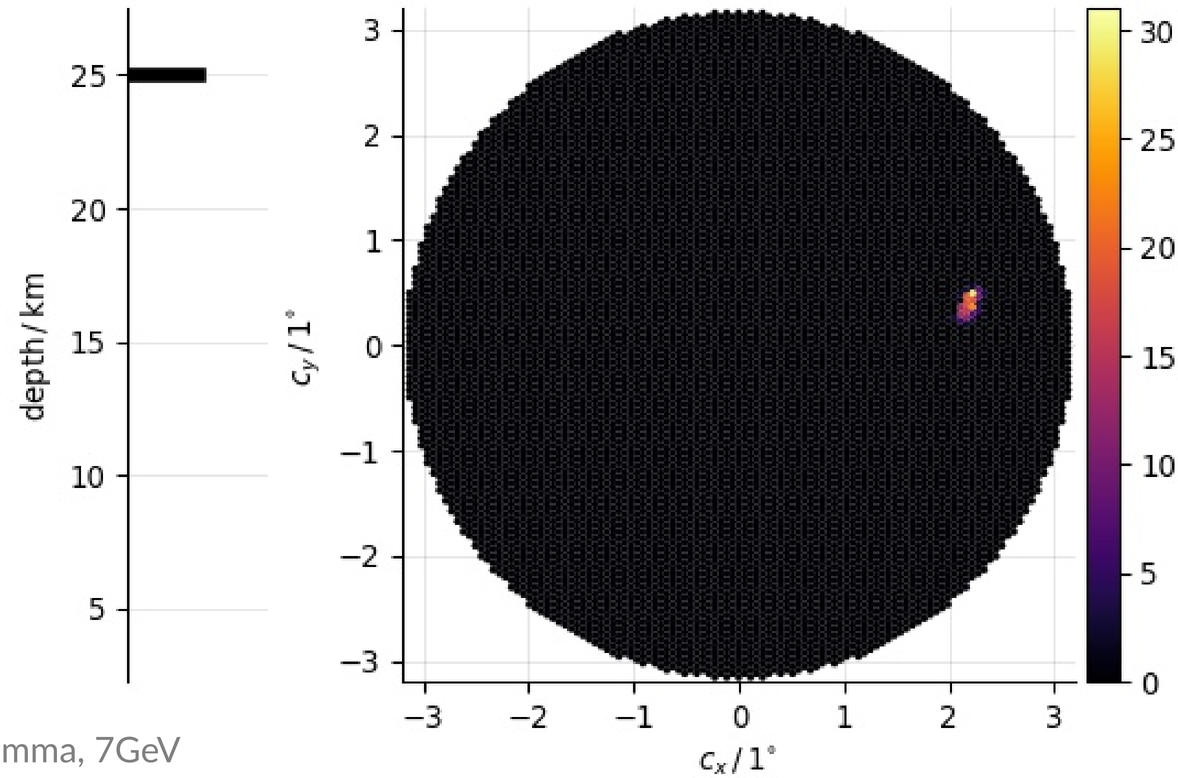


depth / km
25
20
15
10
5
c_y / 1°
3
2
1
0
−1
−2
−3
−3
−2
−1
0
1
2
3
c_x / 1°
70
60
50
40
30
20
10
0


depth / km
25
20
15
10
5
c_y / 1°
c_x / 1°
3
2
1
0
−1
−2
−3
70
60
50
40
30
20
10
0

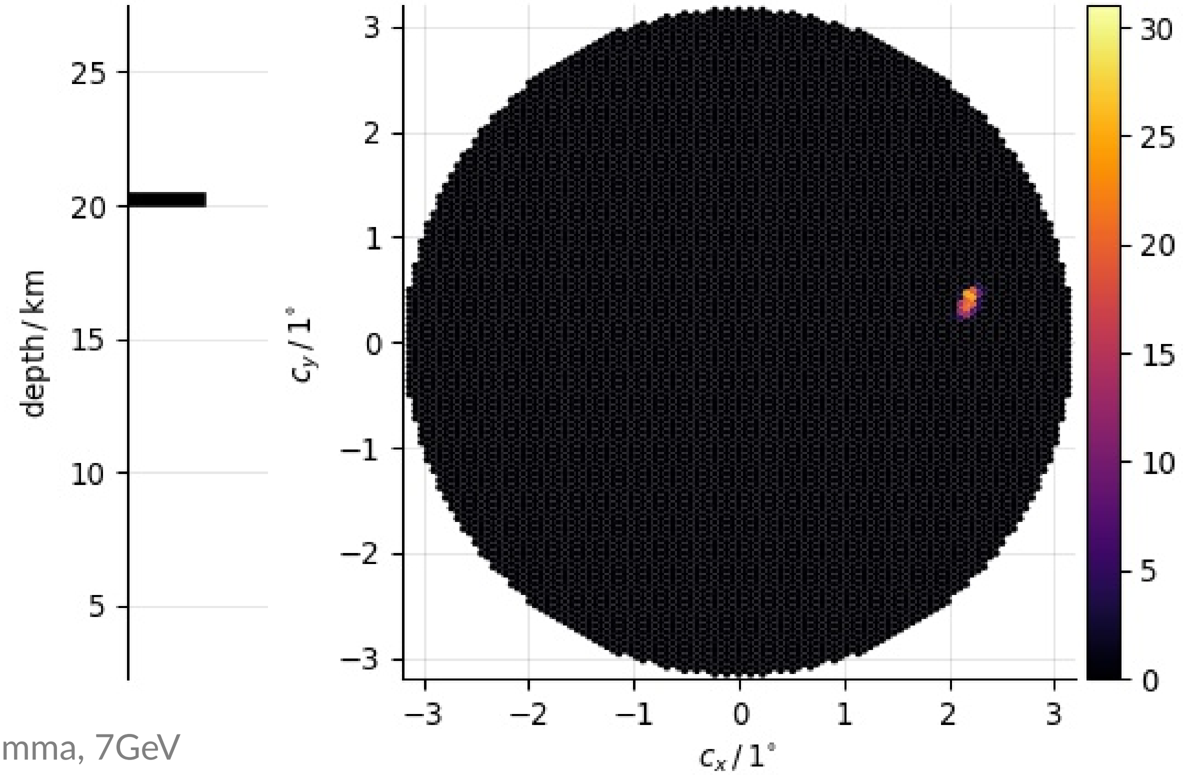
Gamma-showers above 5GeV



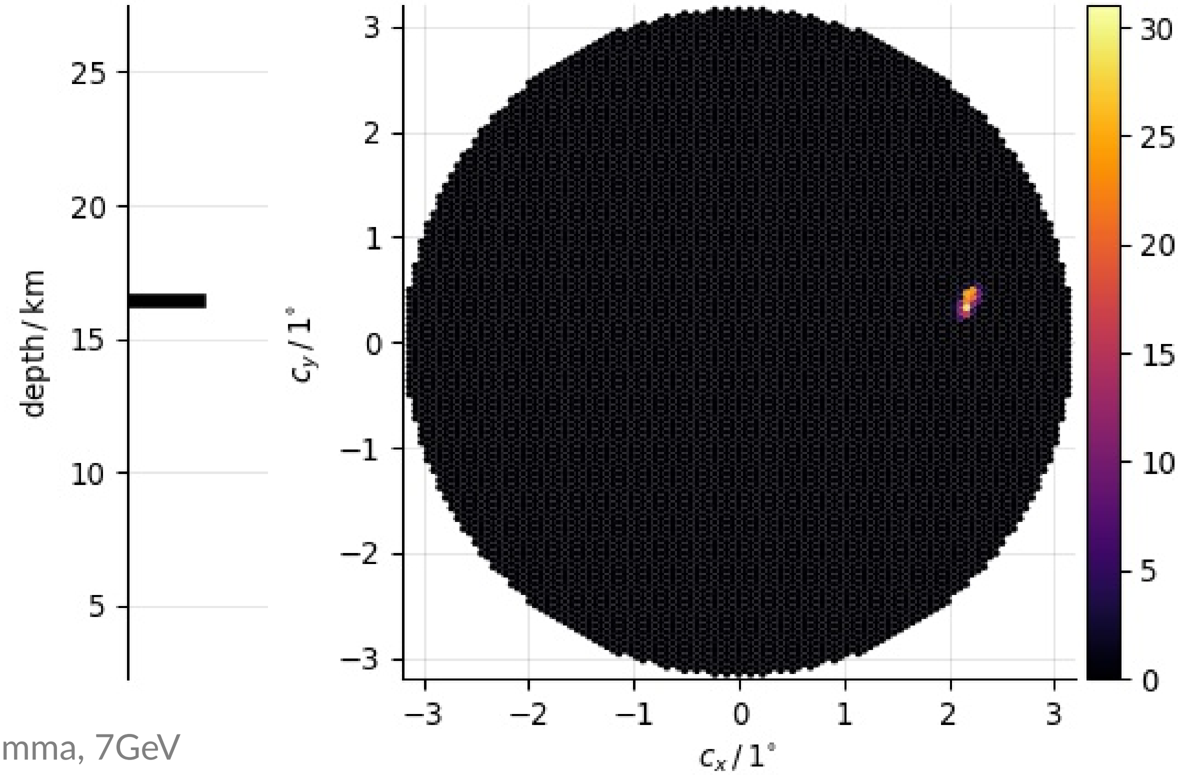


Gamma, 7GeV

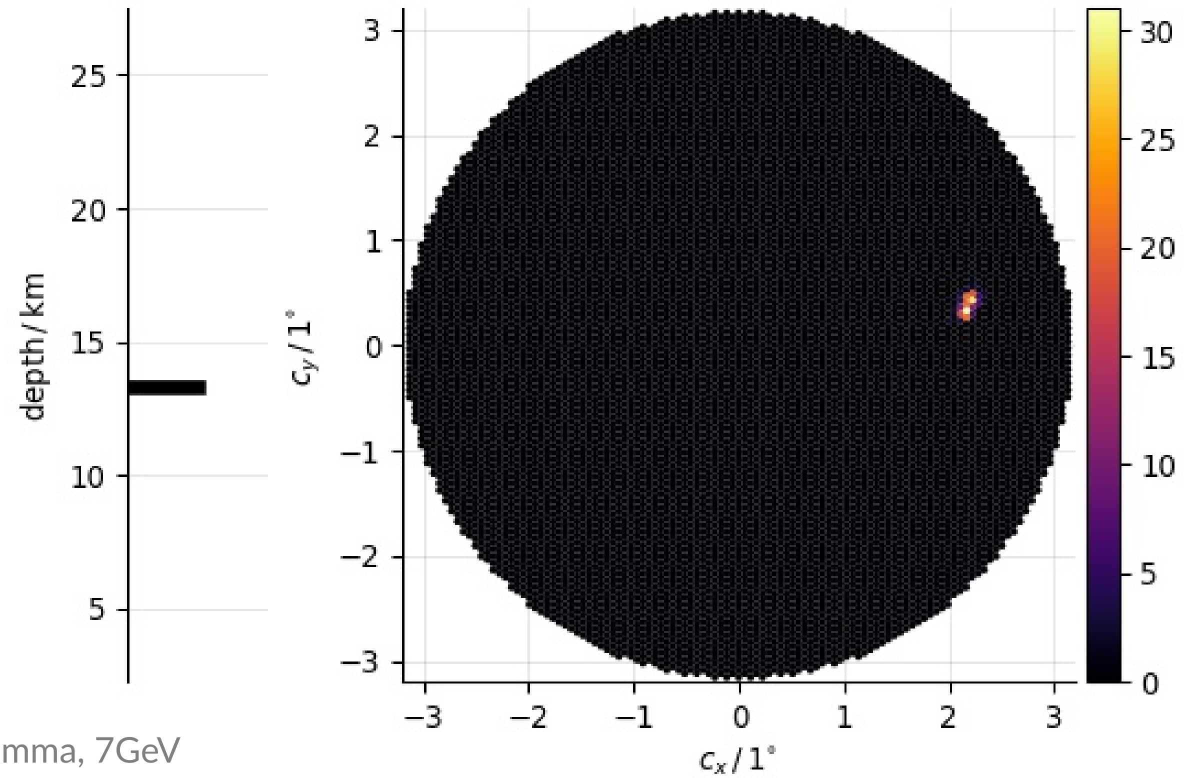
Above five giga electron volts we start to see an ellipse that shifts with depth.



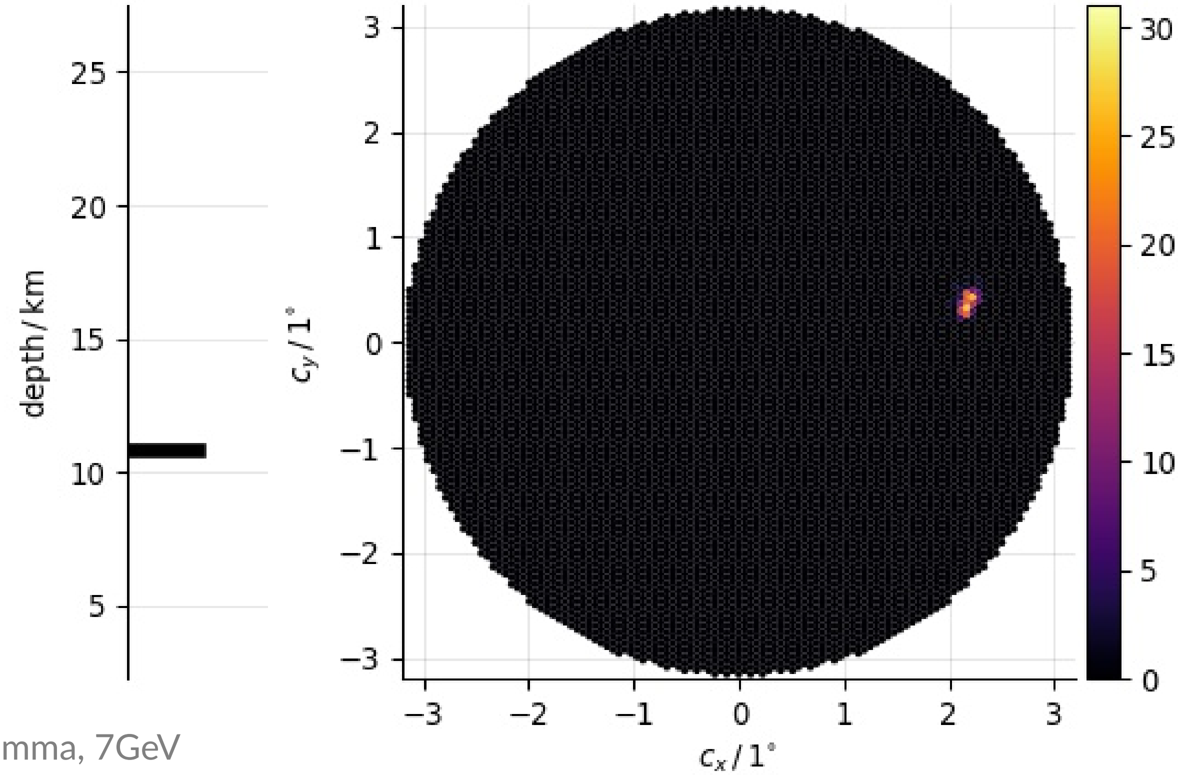
Gamma, 7GeV



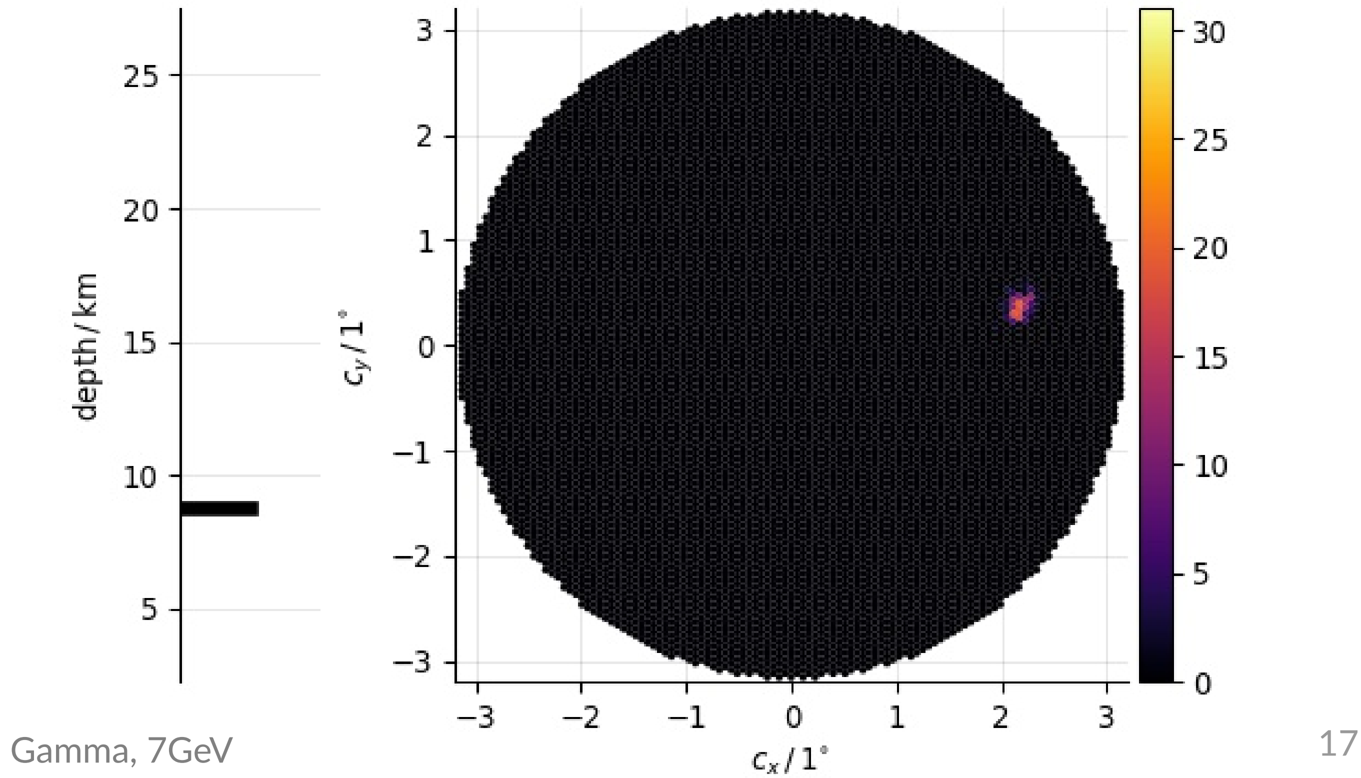
Gamma, 7GeV

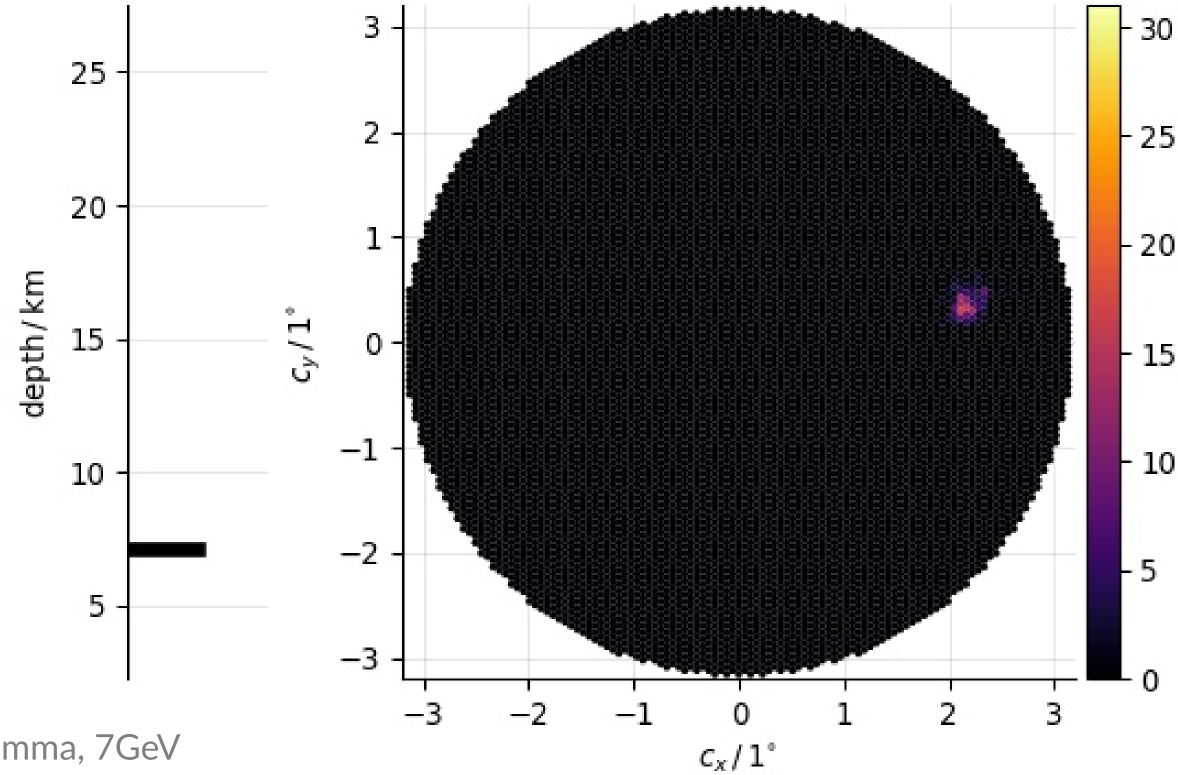


Gamma, 7GeV

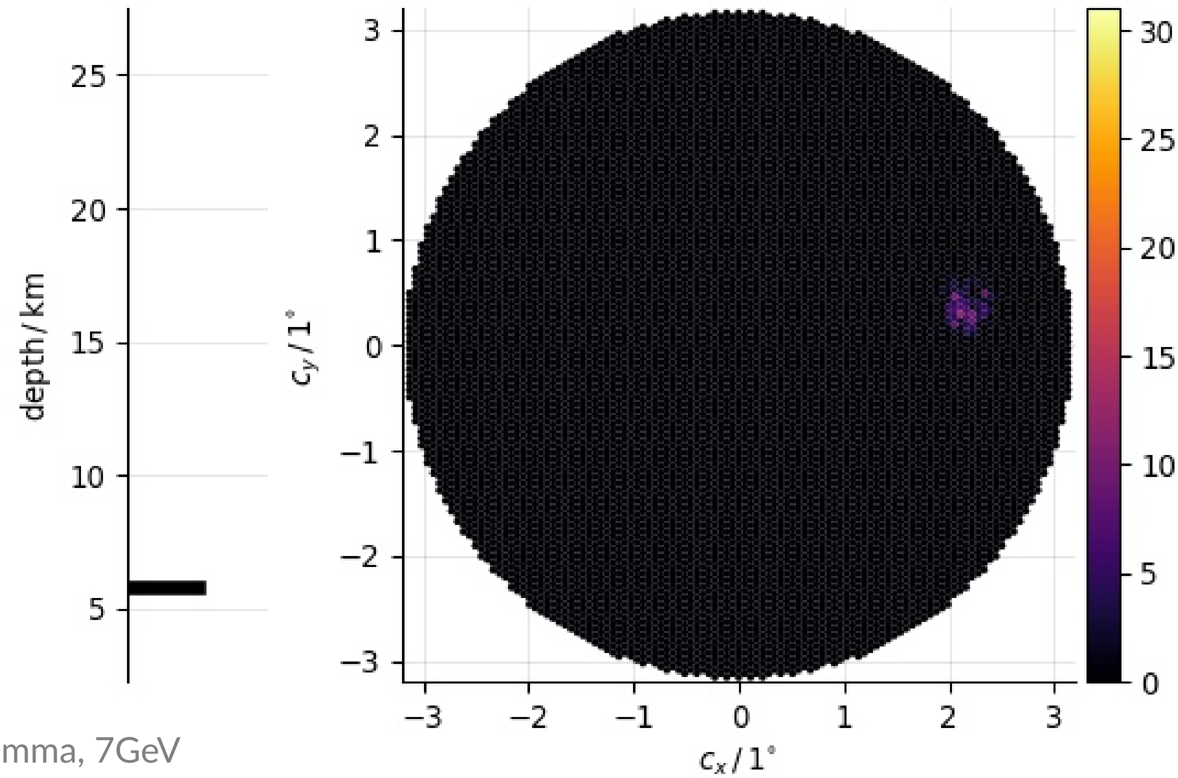


Gamma, 7GeV


depth / km
c_y / 1°
c_x / 1°
Gamma, 7GeV

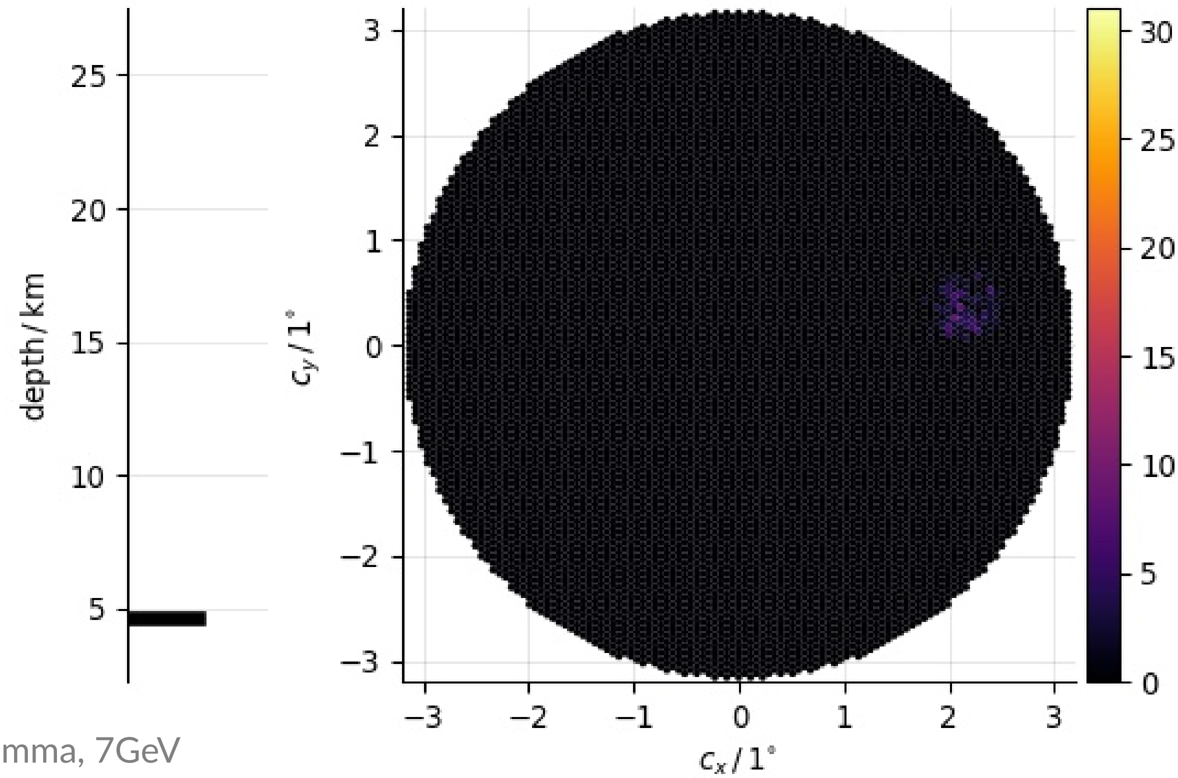


Gamma, 7GeV

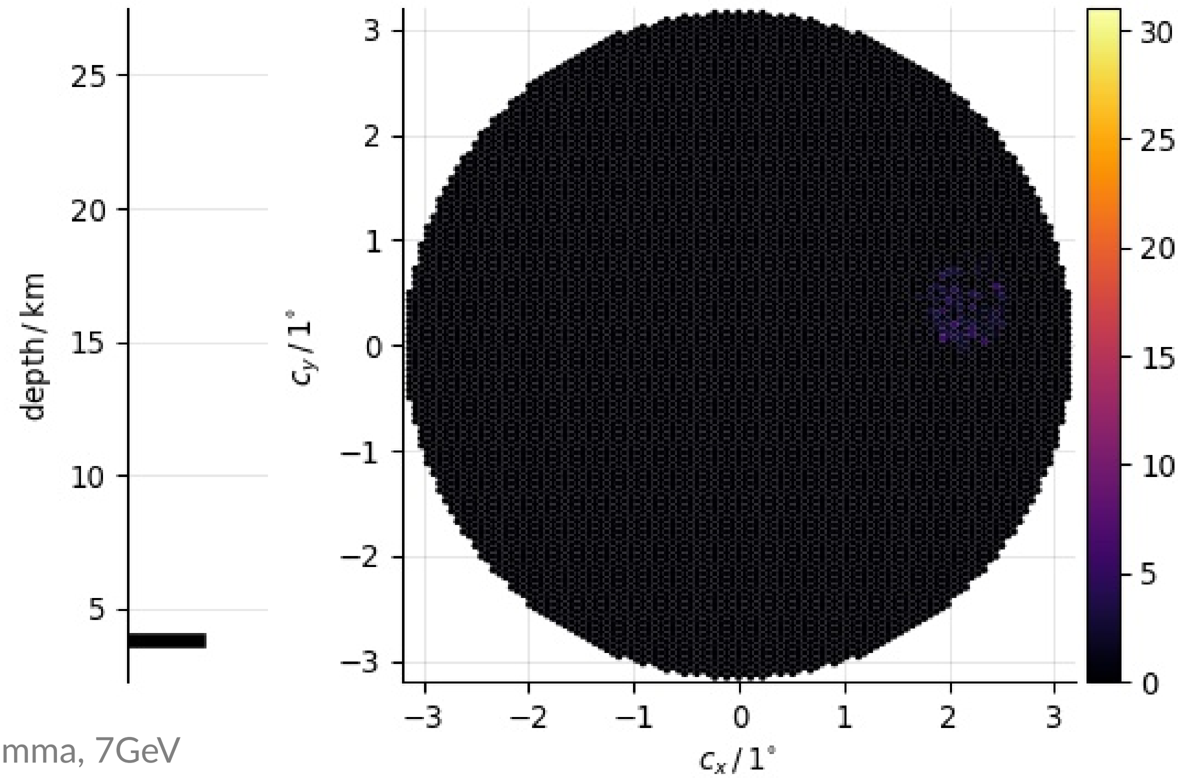


Gamma, 7GeV

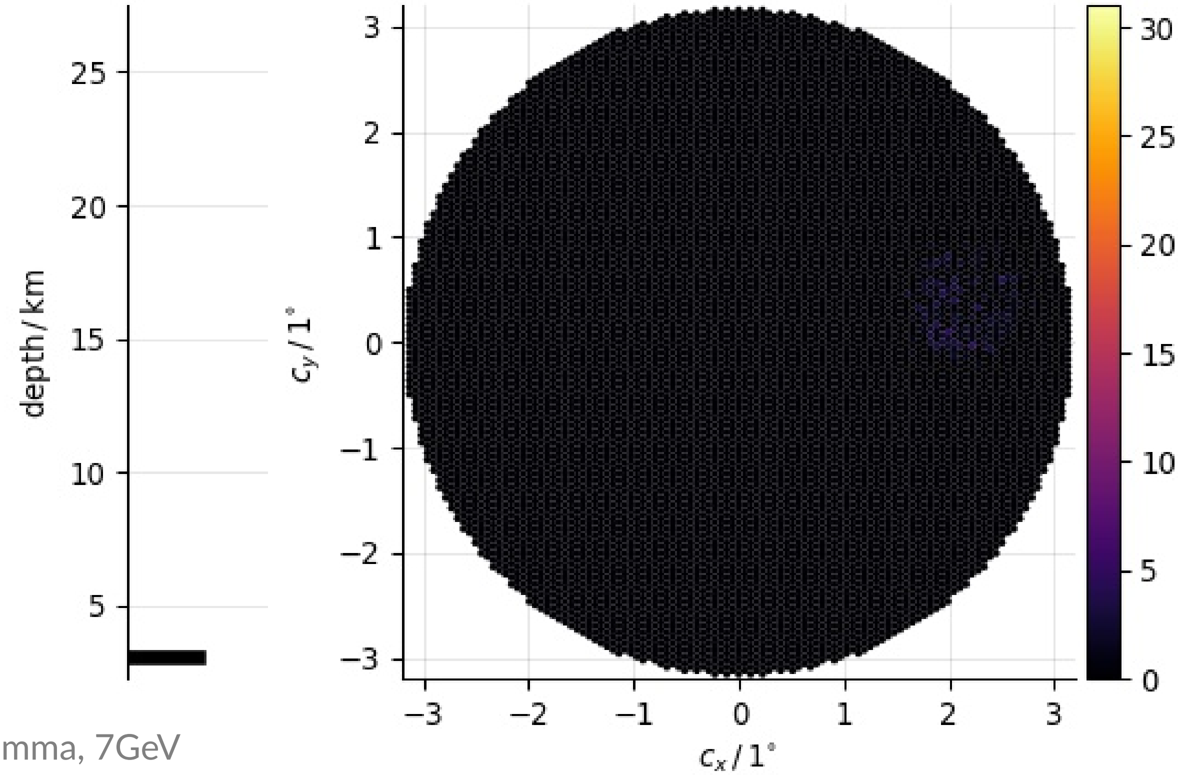
And again no light down here.



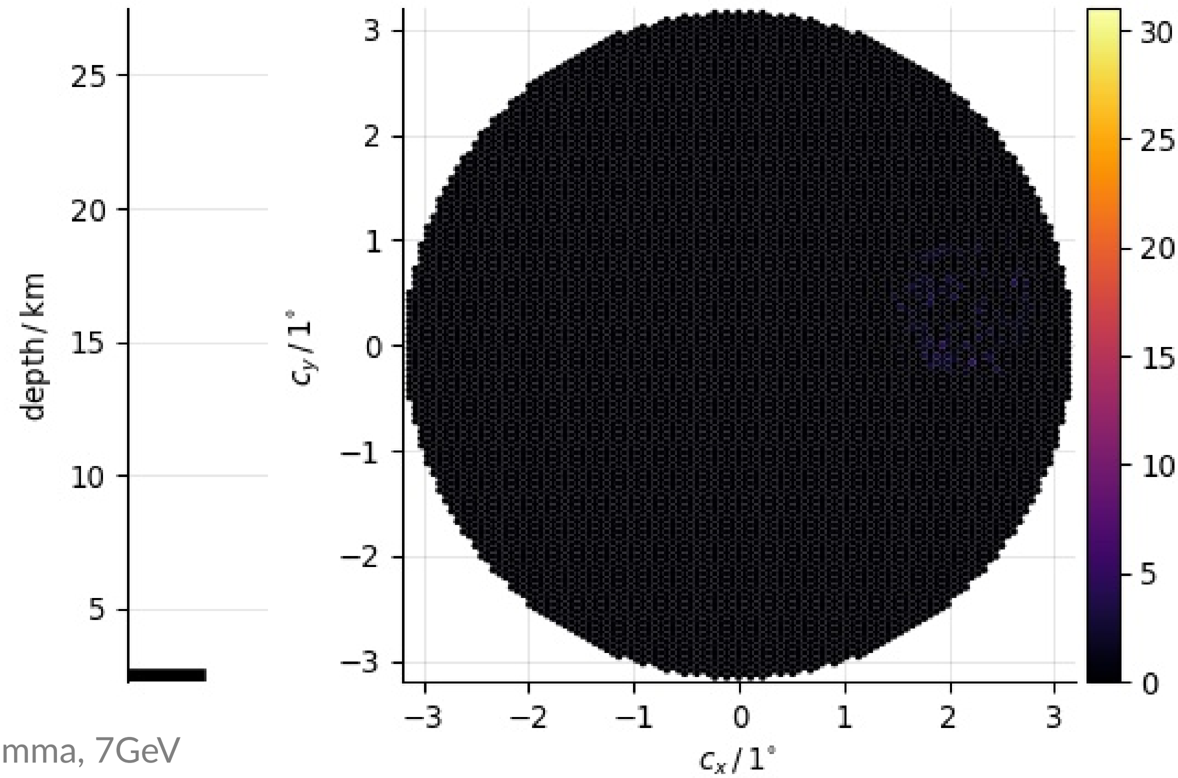
Gamma, 7GeV



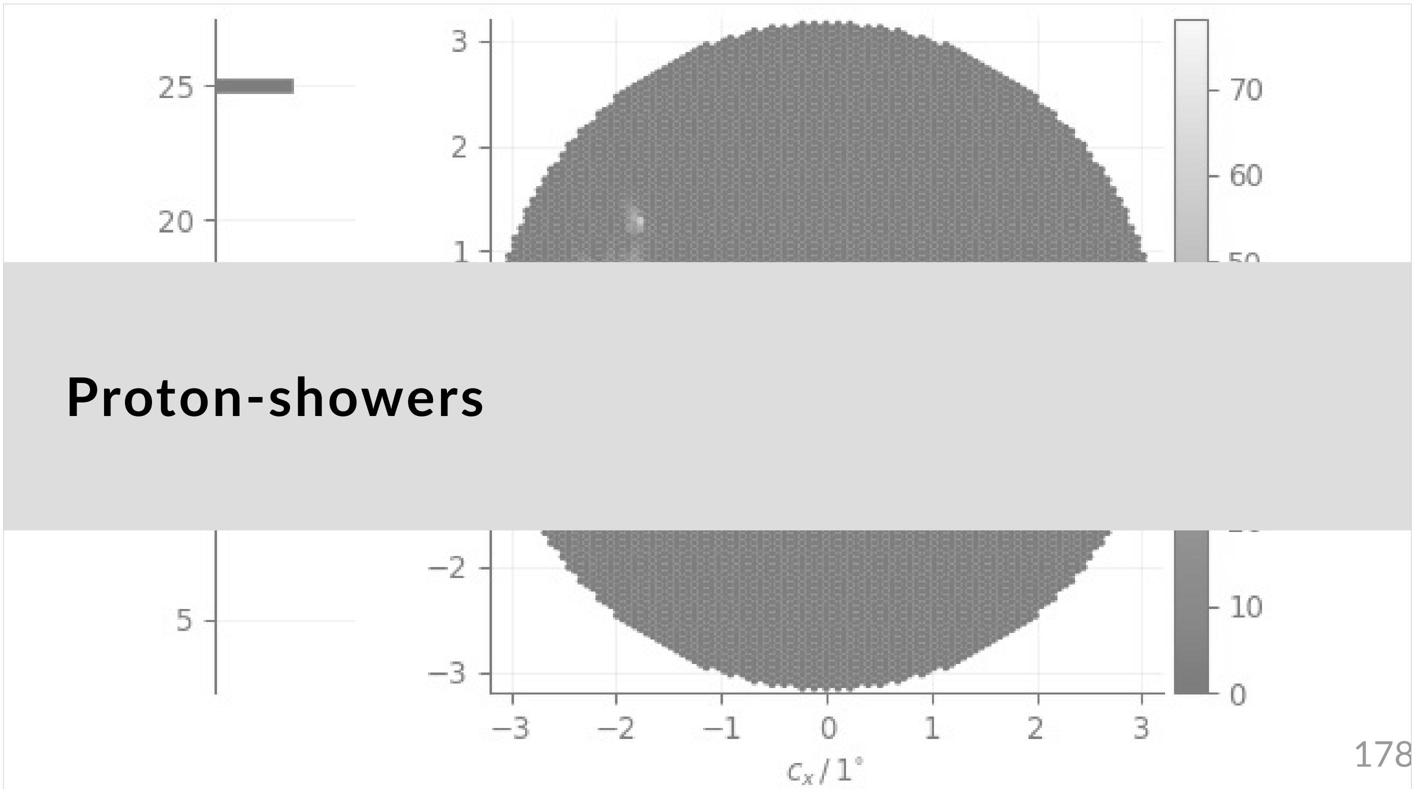
Gamma, 7GeV



Gamma, 7GeV

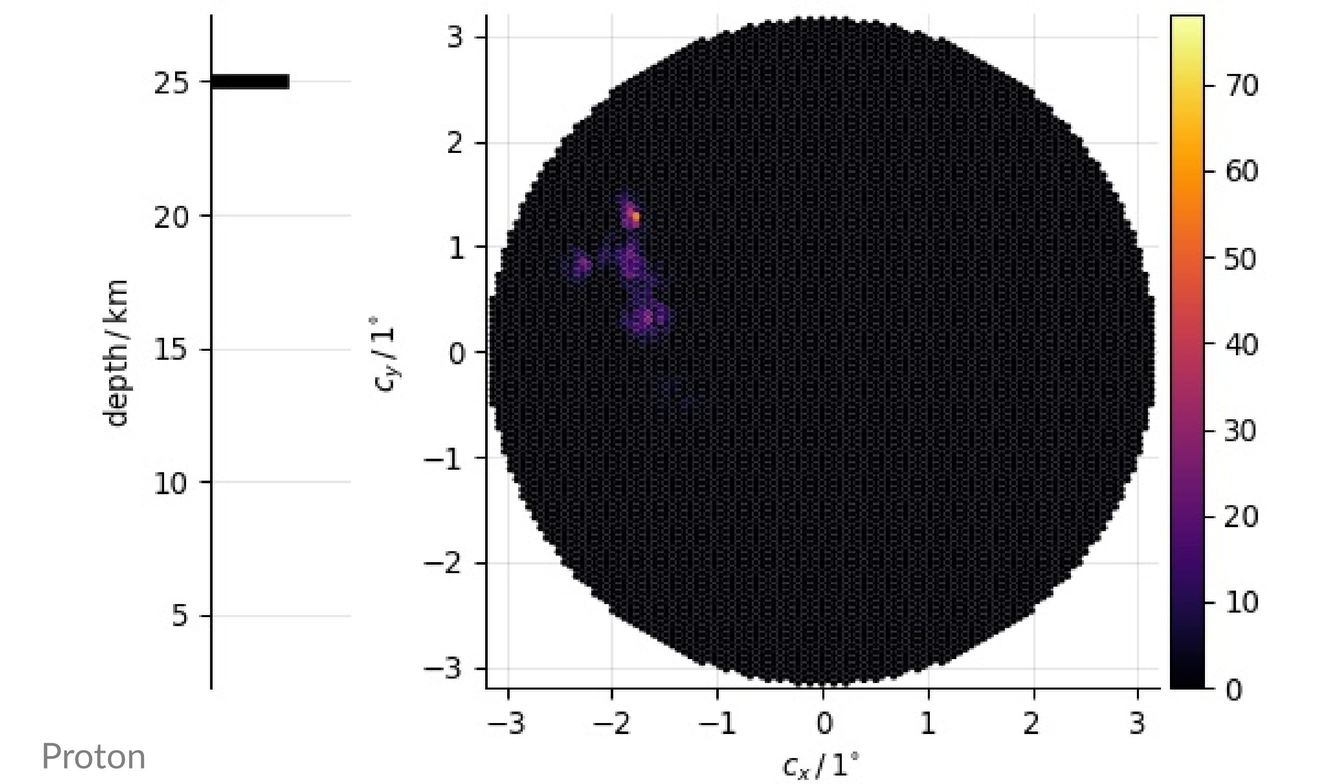


Gamma, 7GeV

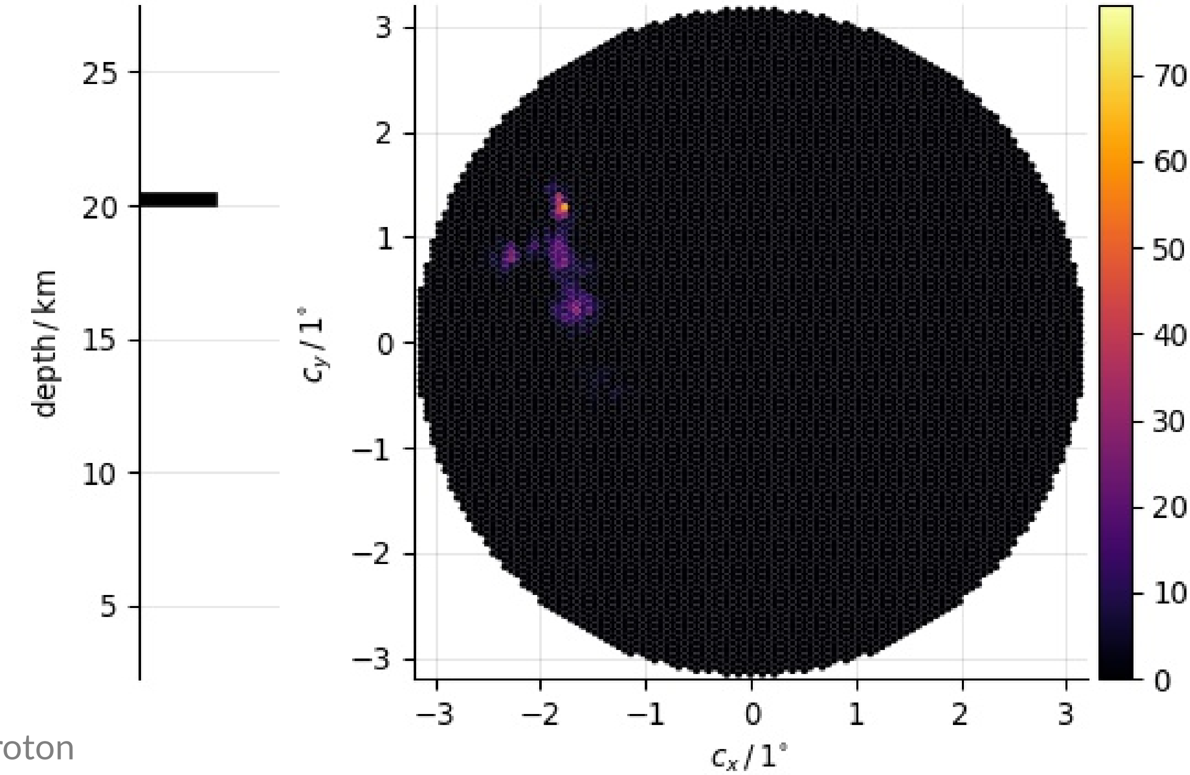


Proton-showers

And hadrons do

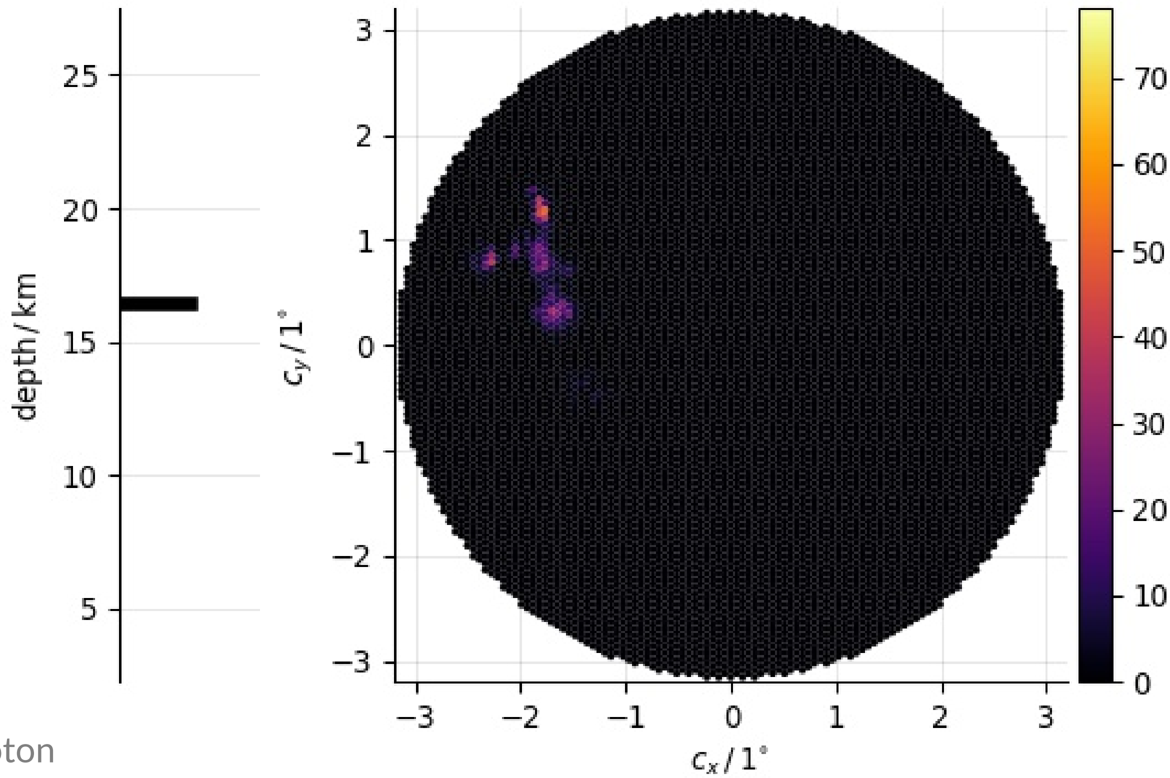


what hadrons do

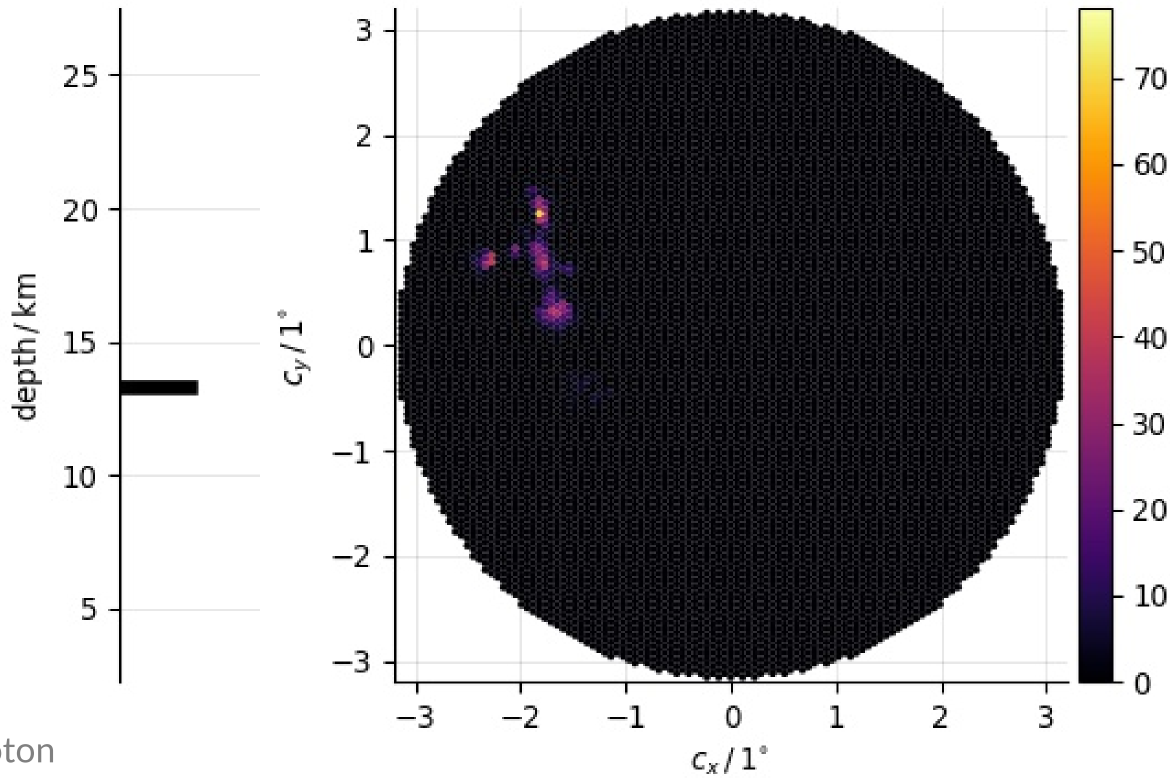


many jets with large transversal momentum

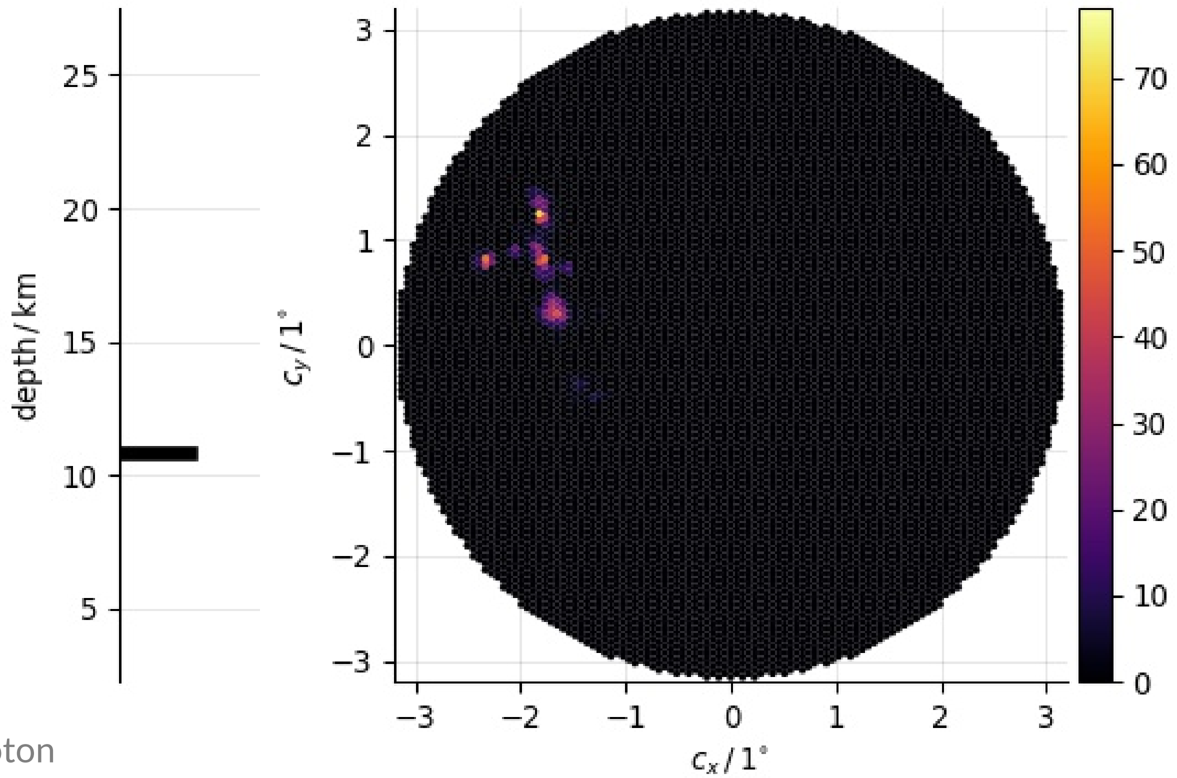
A first jet in 20km



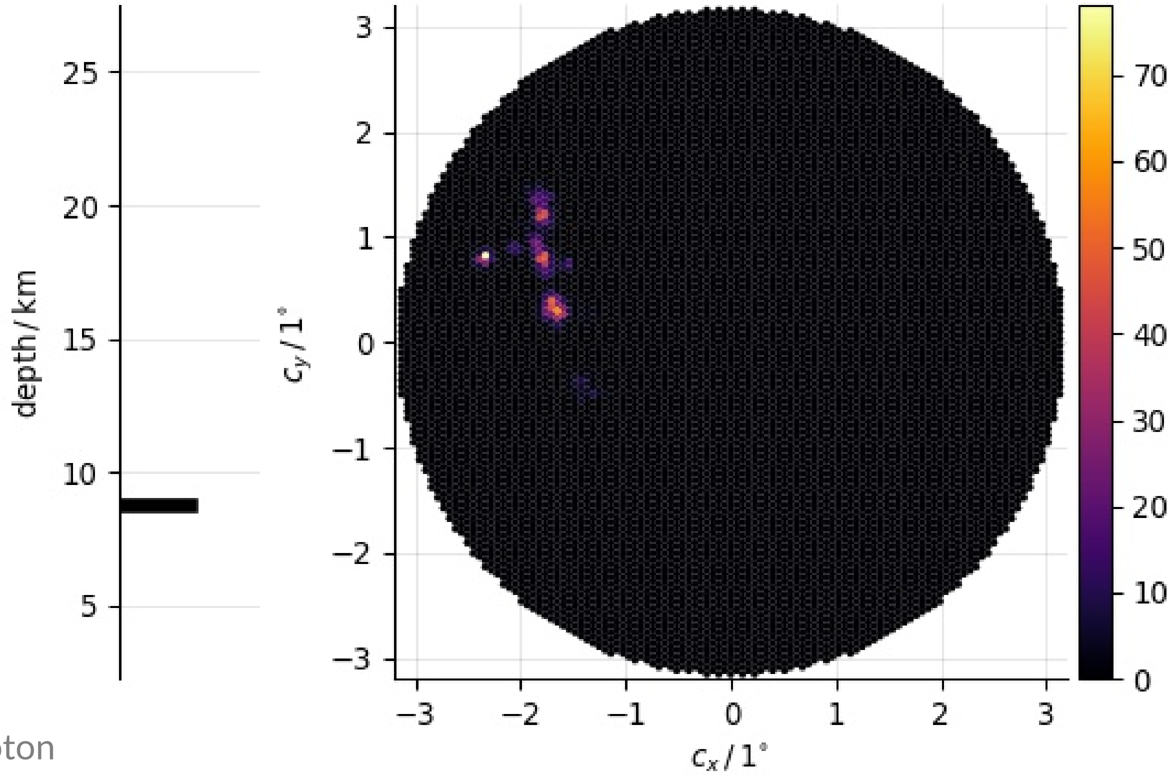
Proton


25
20
15
10
5
depth / km
3
2
1
0
−1
−2
−3
c_y / 1°
−3
−2
−1
0
1
2
3
c_x / 1°
70
60
50
40
30
20
10
0

Proton

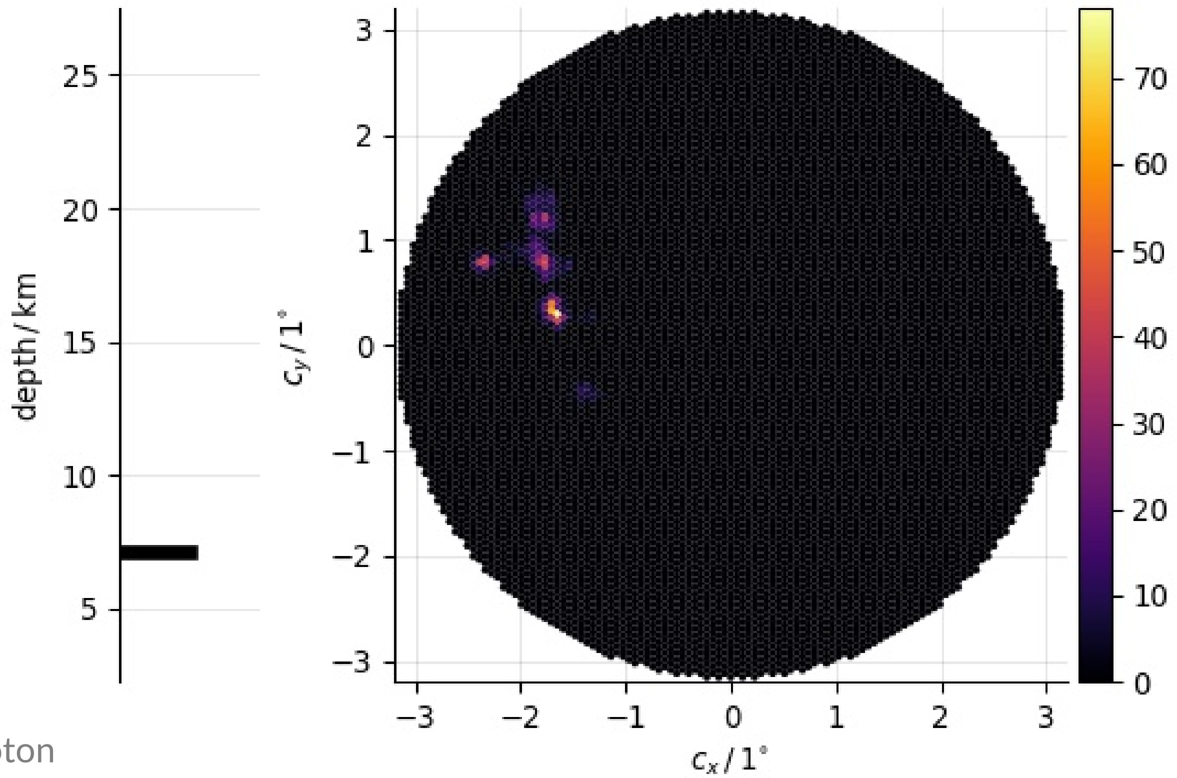


Proton



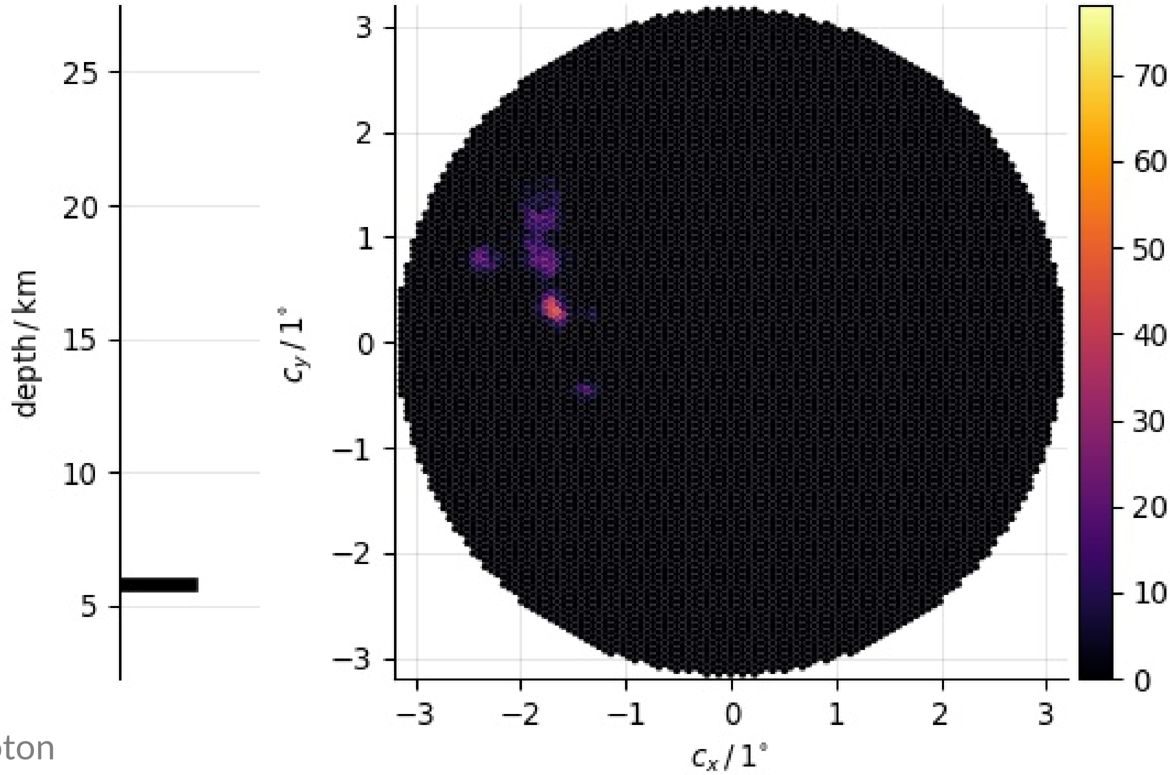
Proton

two jets here in 8km

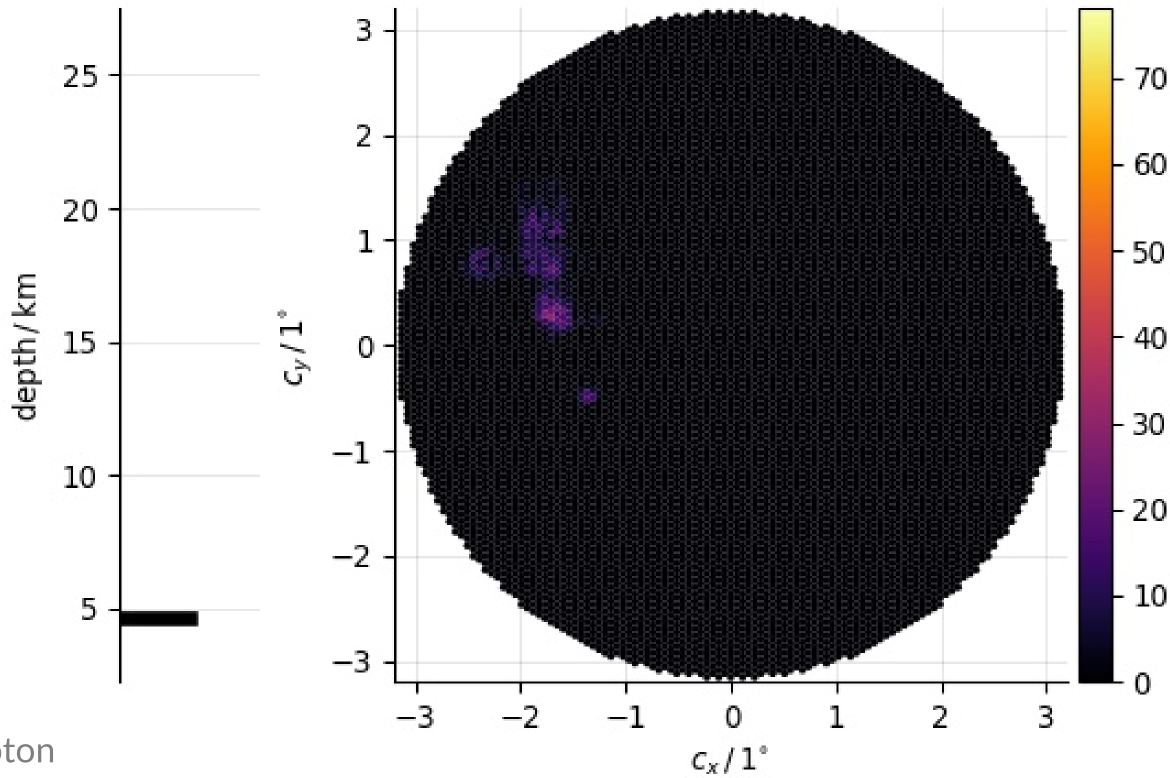


Proton

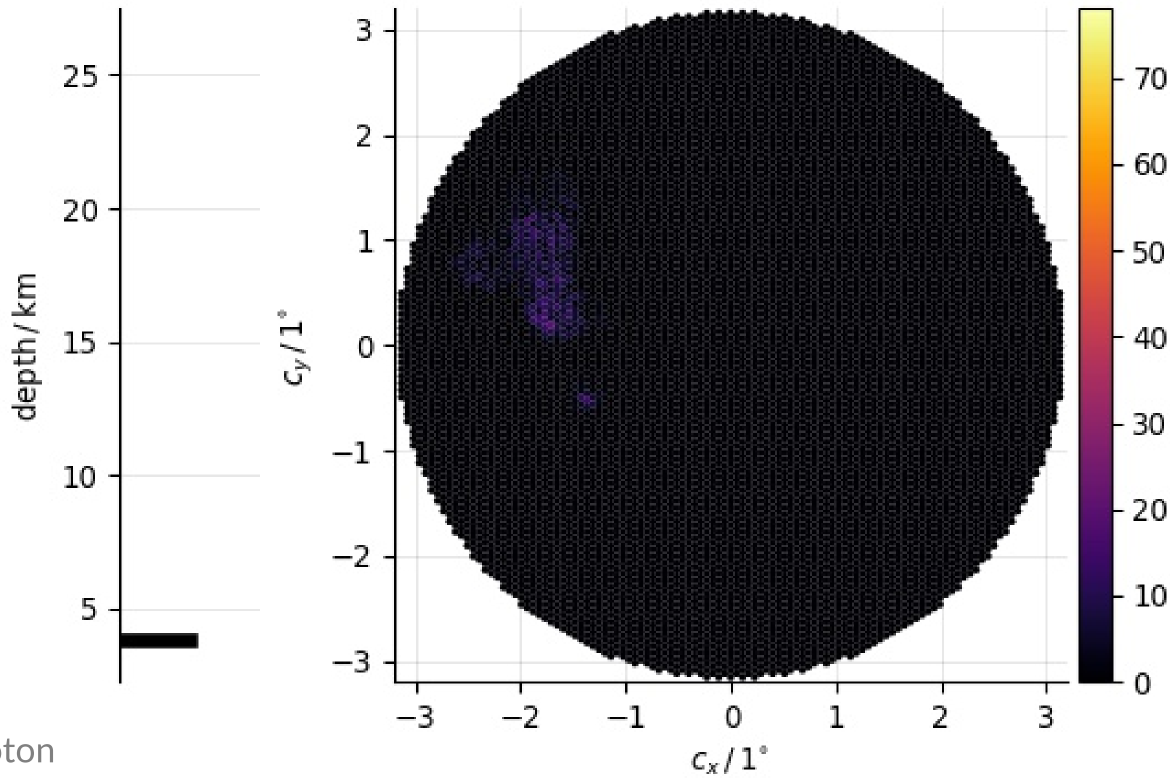
one big jet in 6km



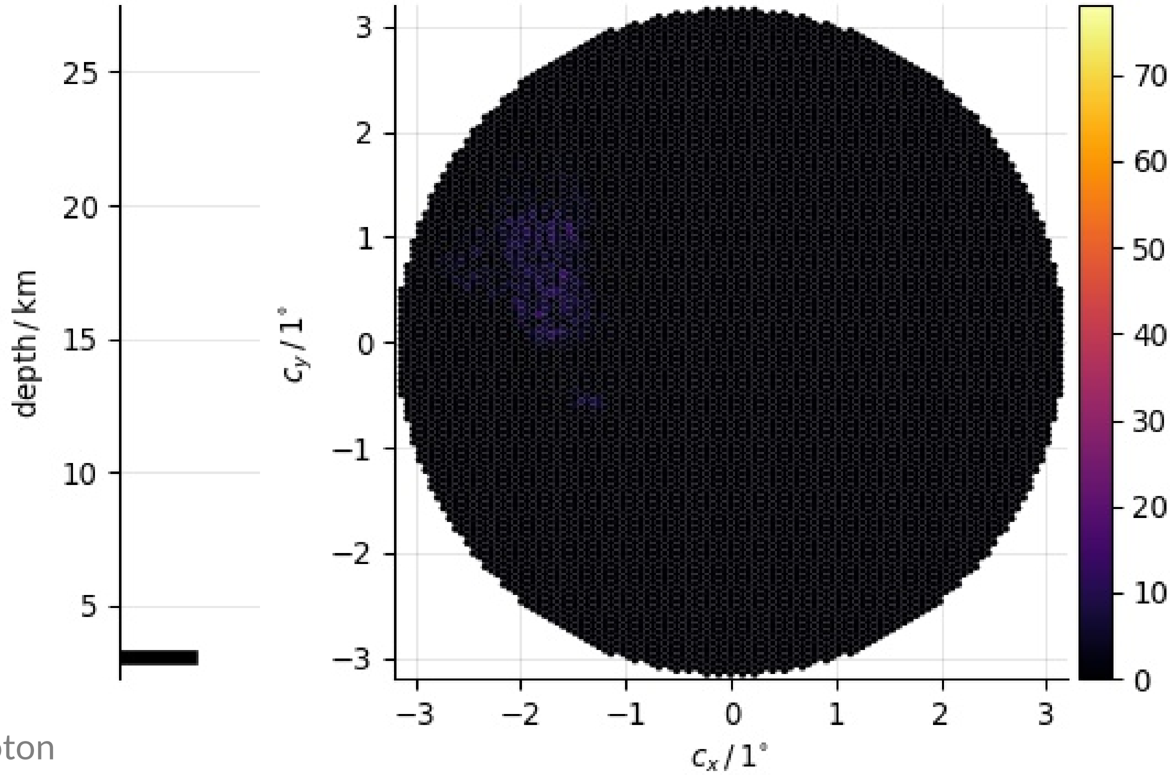
Proton



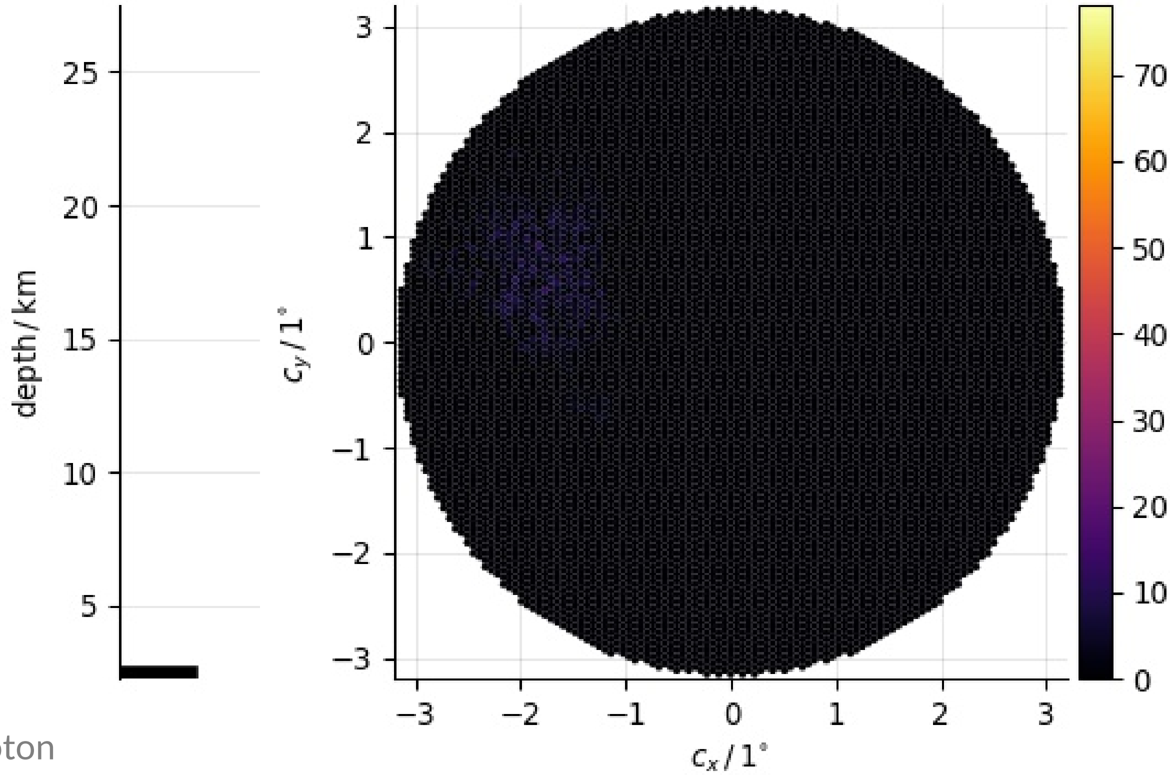
and a tiny one in 5km?



Proton

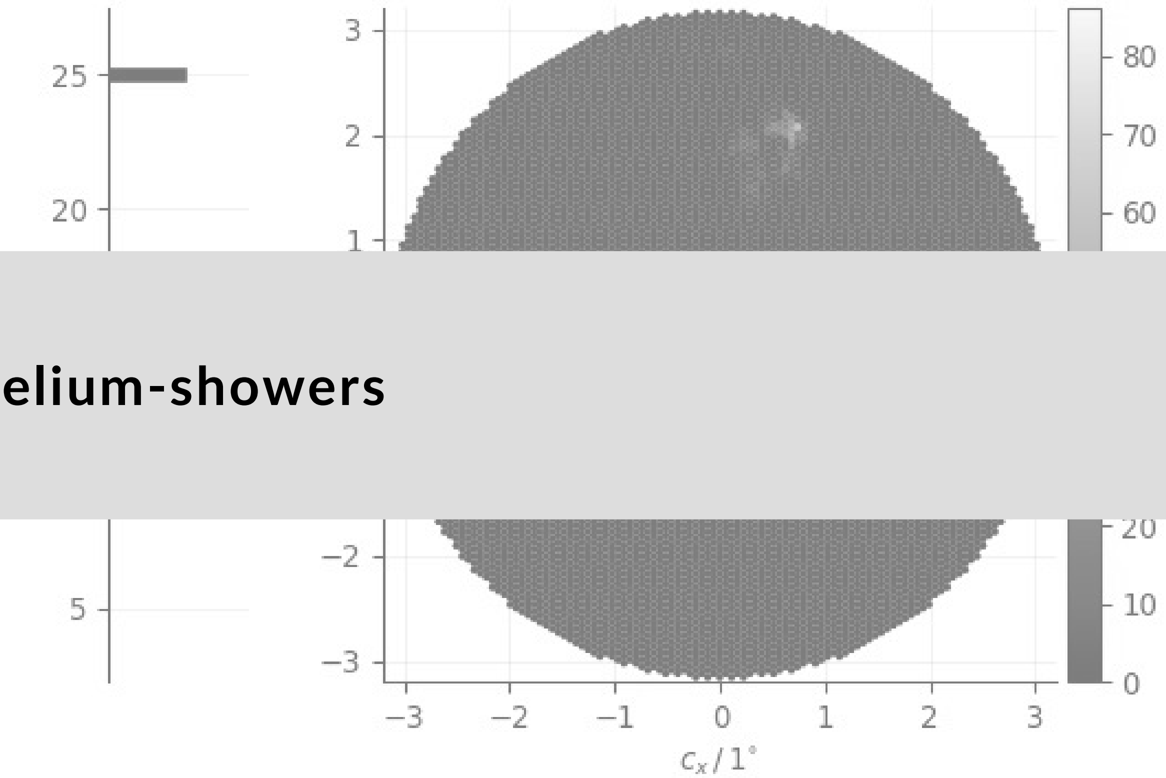


Proton

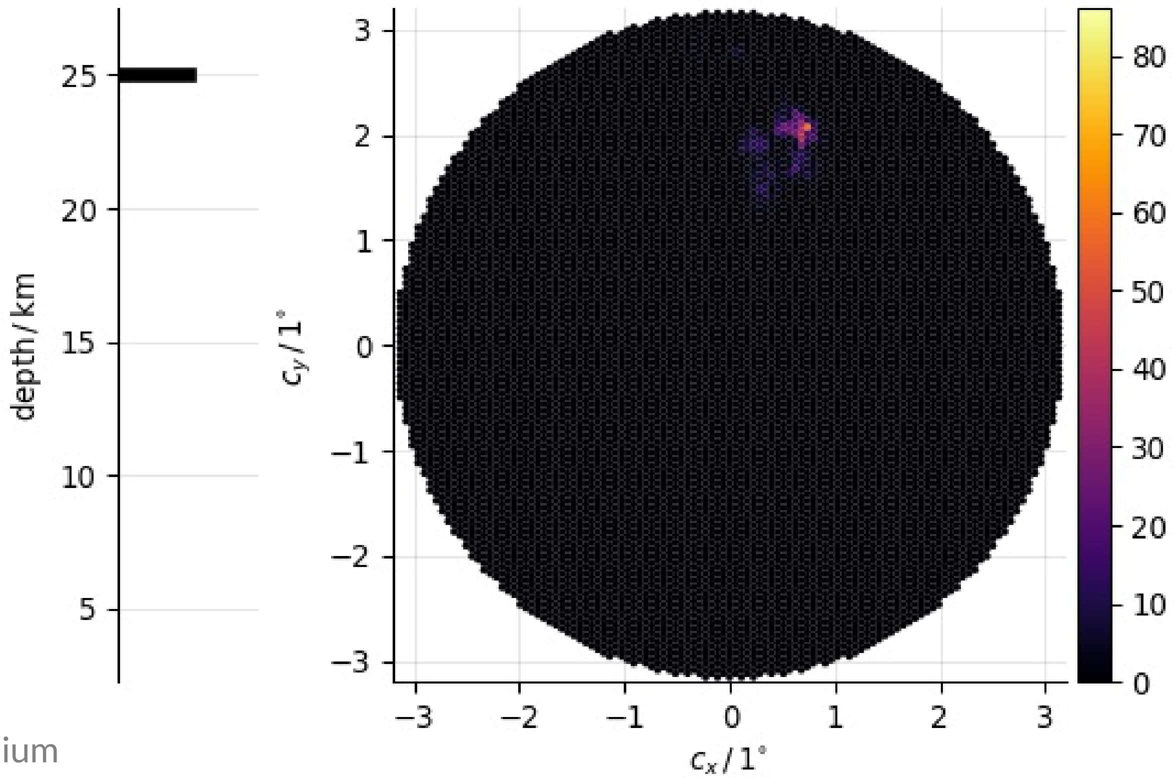

depth / km
25
20
15
10
5
$c_y / 1^\circ$
3
2
1
0
−1
−2
−3
$c_x / 1^\circ$
70
60
50
40
30
20
10
0

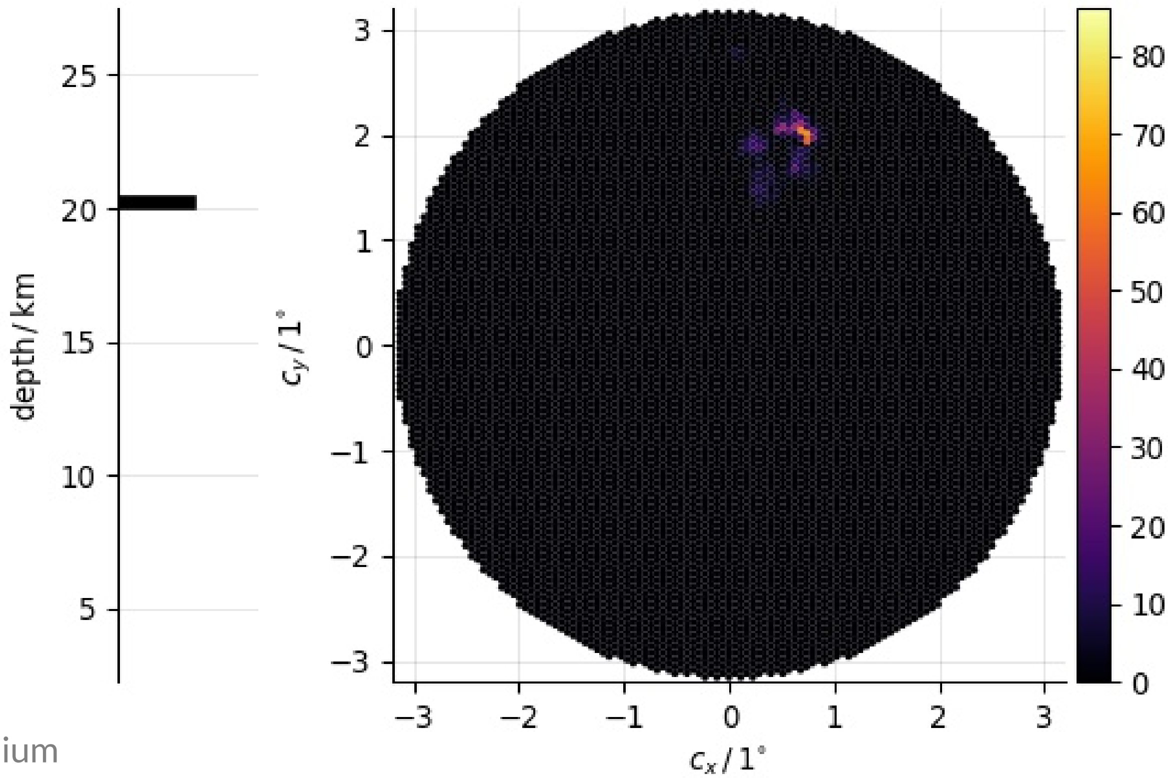
Proton

Helium-showers

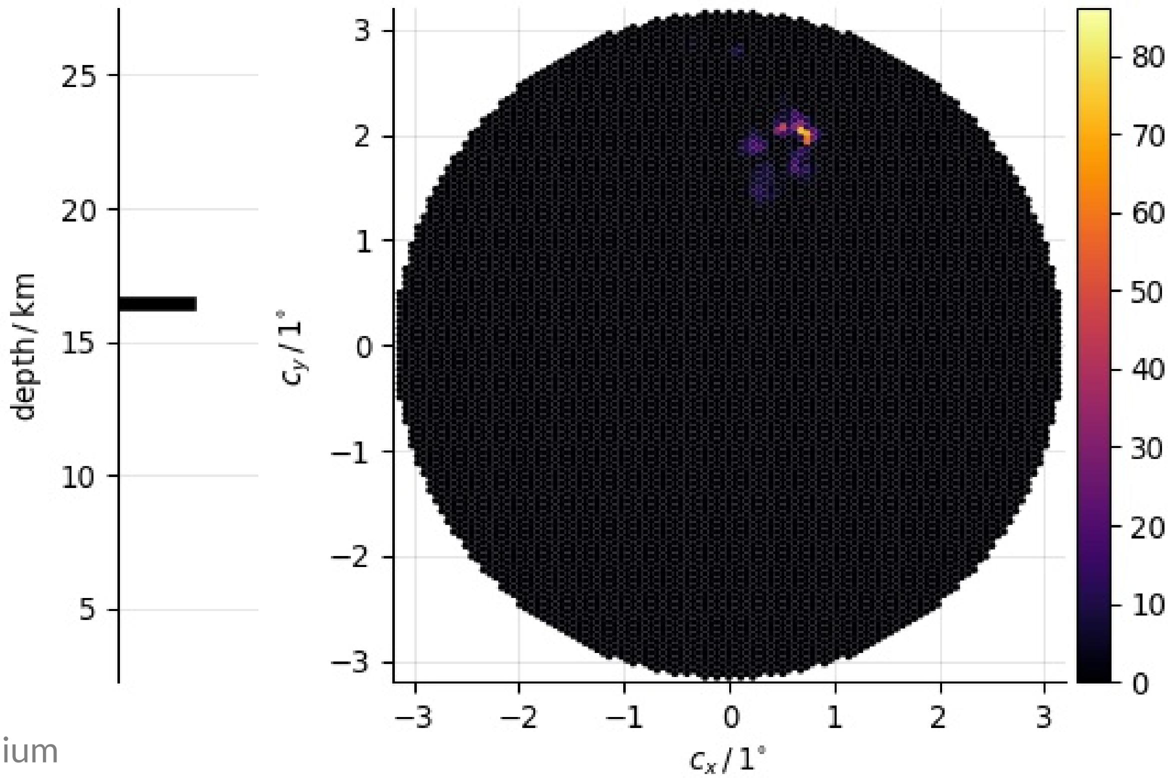


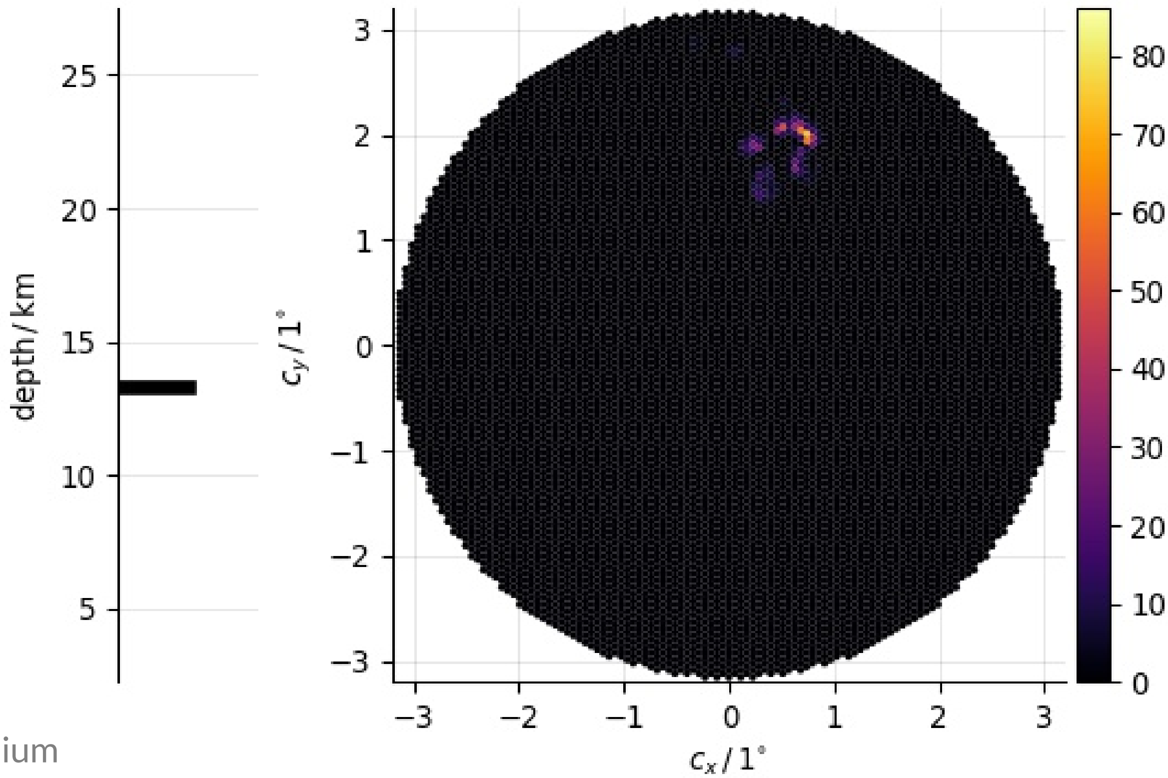
Ah Helium!

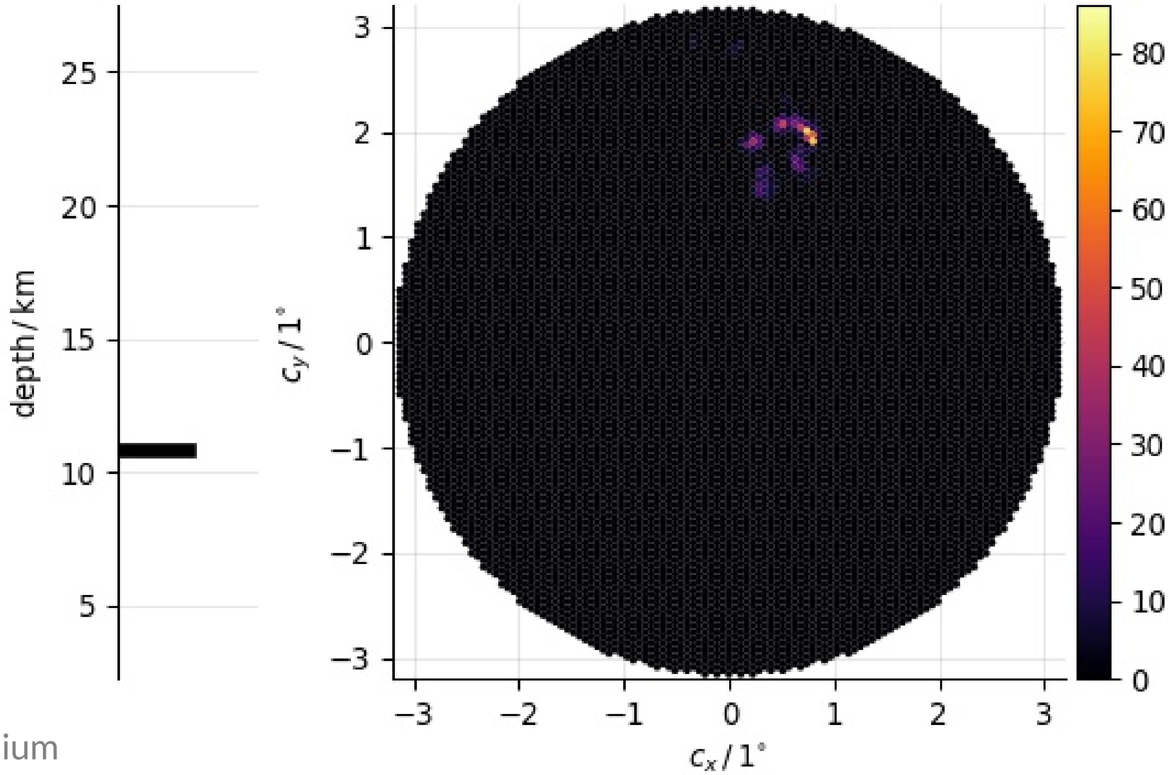

depth / km
25
20
15
10
5
c_y / 1°
c_x / 1°
3
2
1
0
−1
−2
−3
80
70
60
50
40
30
20
10
0

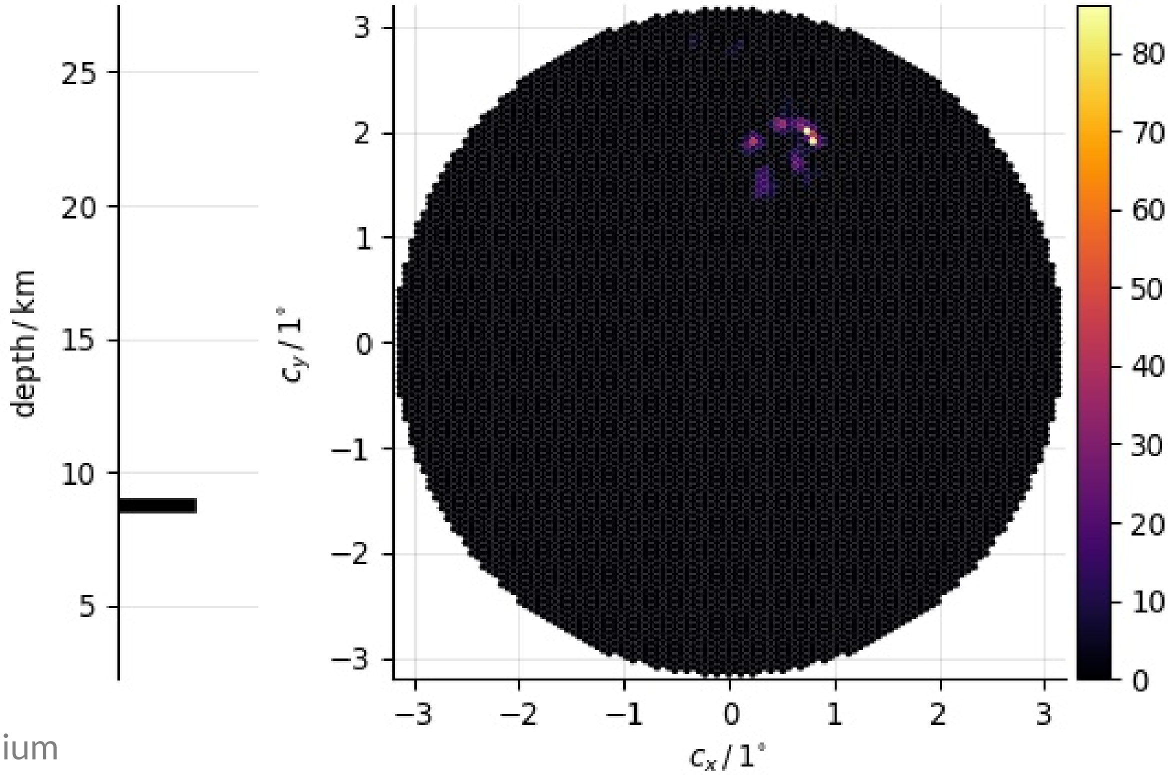


depth / km
25
20
15
10
5
c_y / 1°
3
2
1
0
−1
−2
−3
c_x / 1°
80
70
60
50
40
30
20
10
0


depth / km
25
20
15
10
5
c_y / 1°
c_x / 1°
3
2
1
0
−1
−2
−3
80
70
60
50
40
30
20
10
0

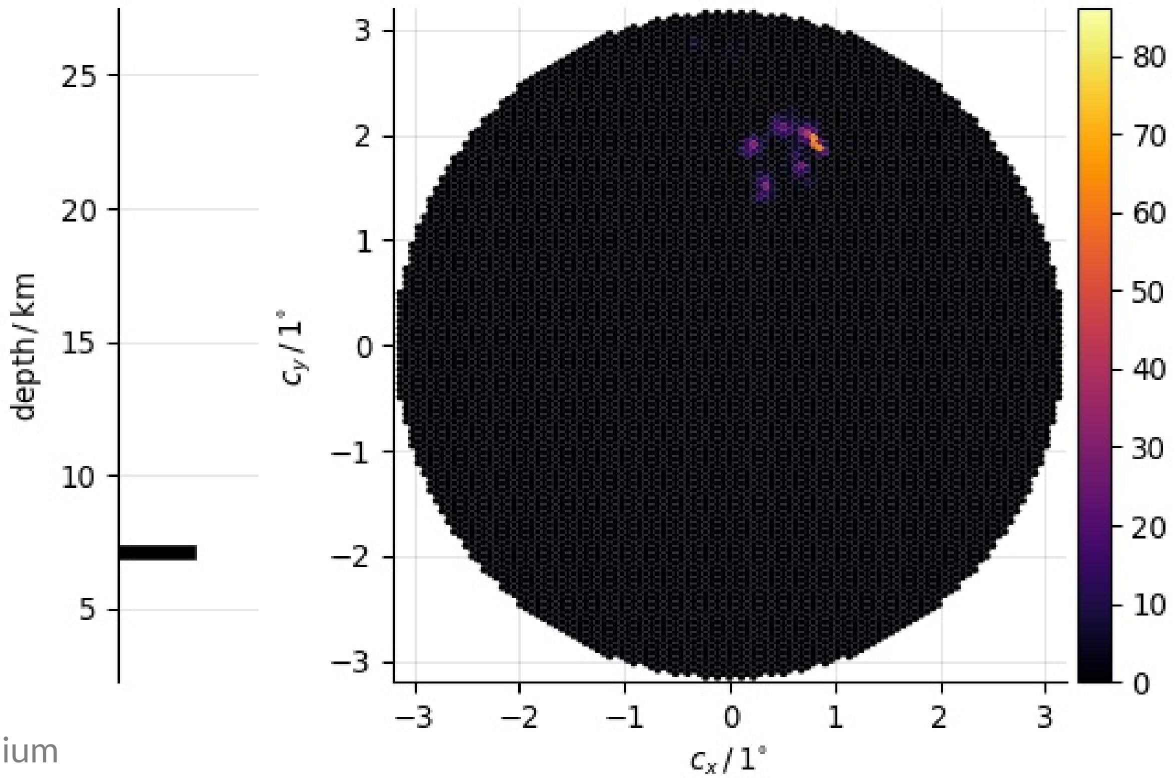

depth / km
25
20
15
10
5
c_y / 1°
3
2
1
0
−1
−2
−3
c_x / 1°
80
70
60
50
40
30
20
10
0


depth / km
25
20
15
10
5
c_y / 1°
c_x / 1°
3
2
1
0
−1
−2
−3
80
70
60
50
40
30
20
10
0



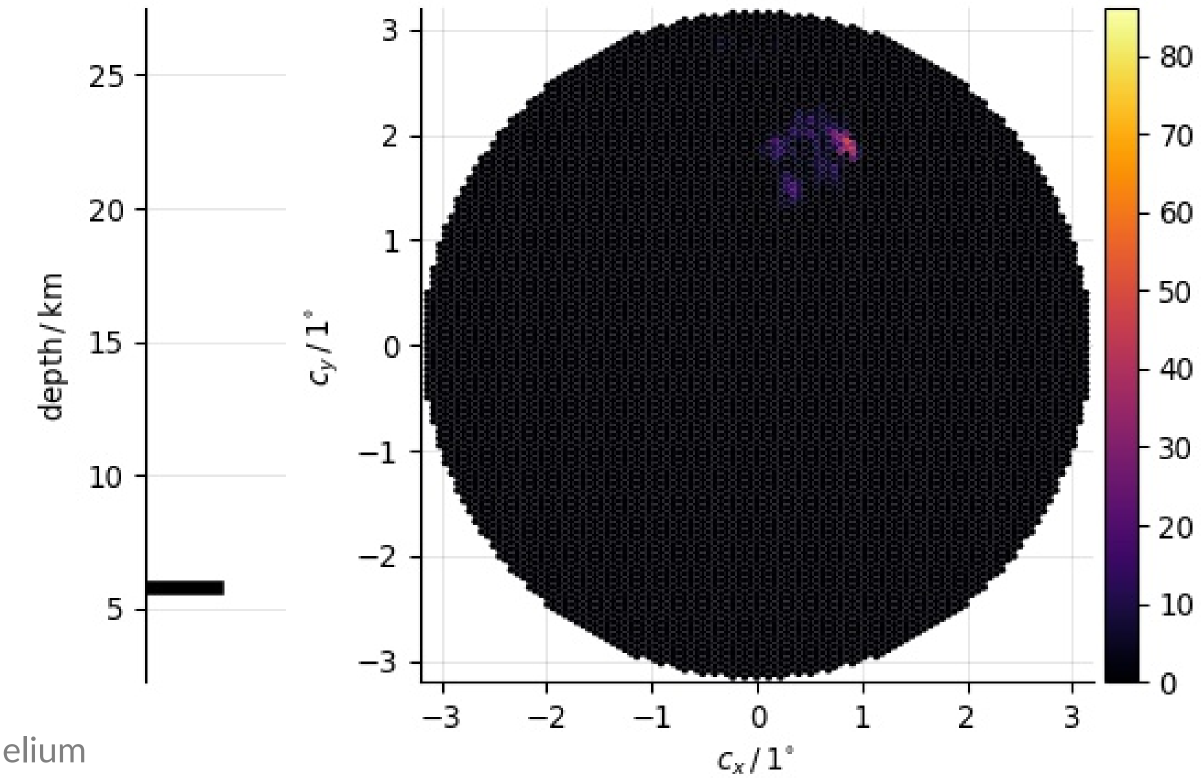
Helium

always a joy to see disintegrate.



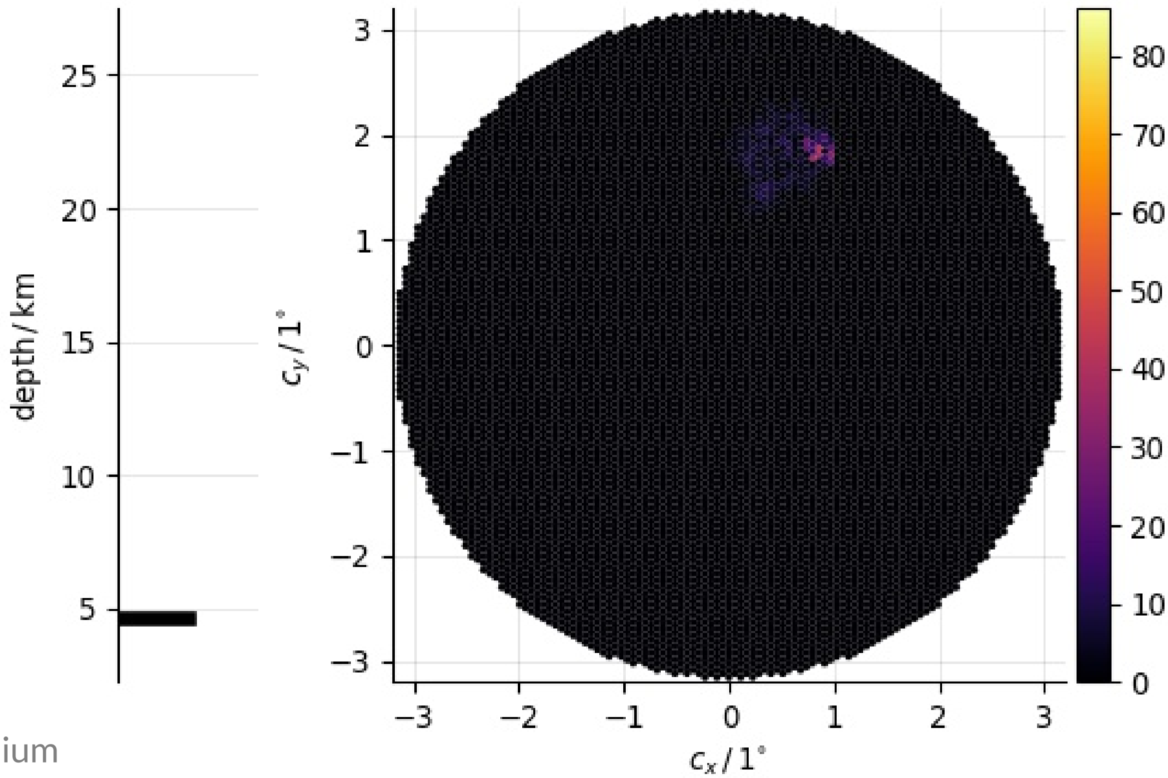
Helium

Four jets at about 8km

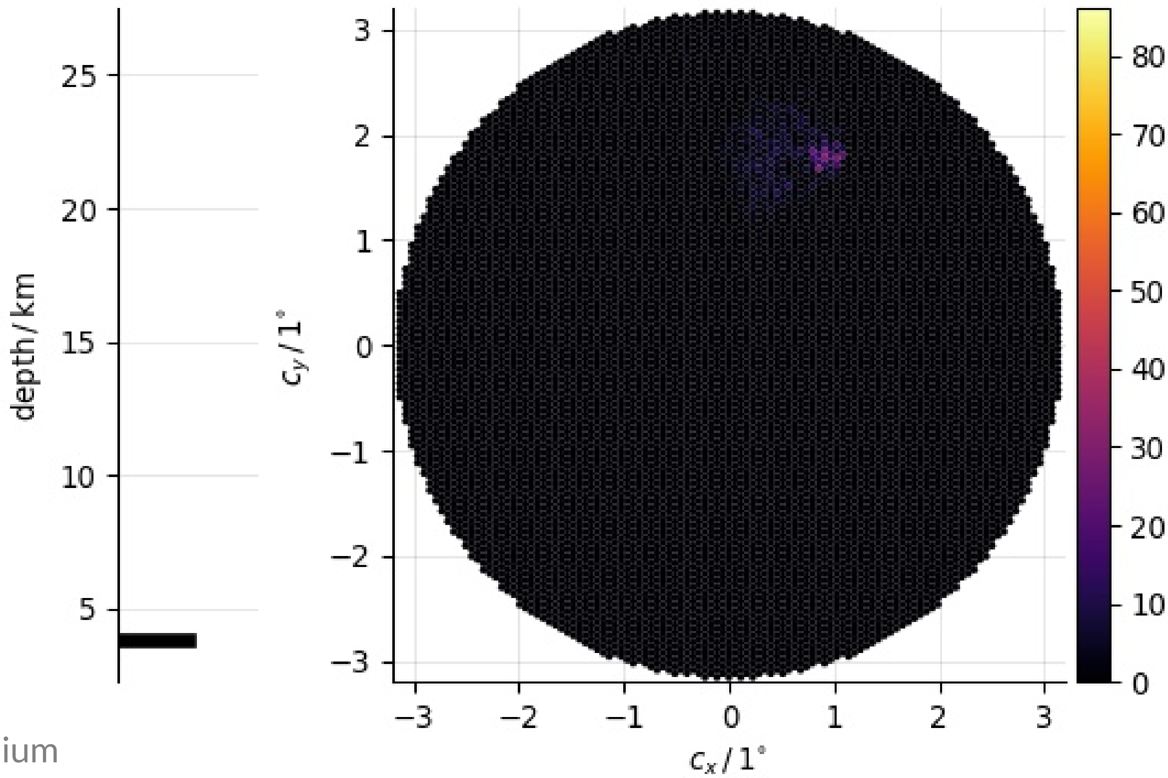


Helium

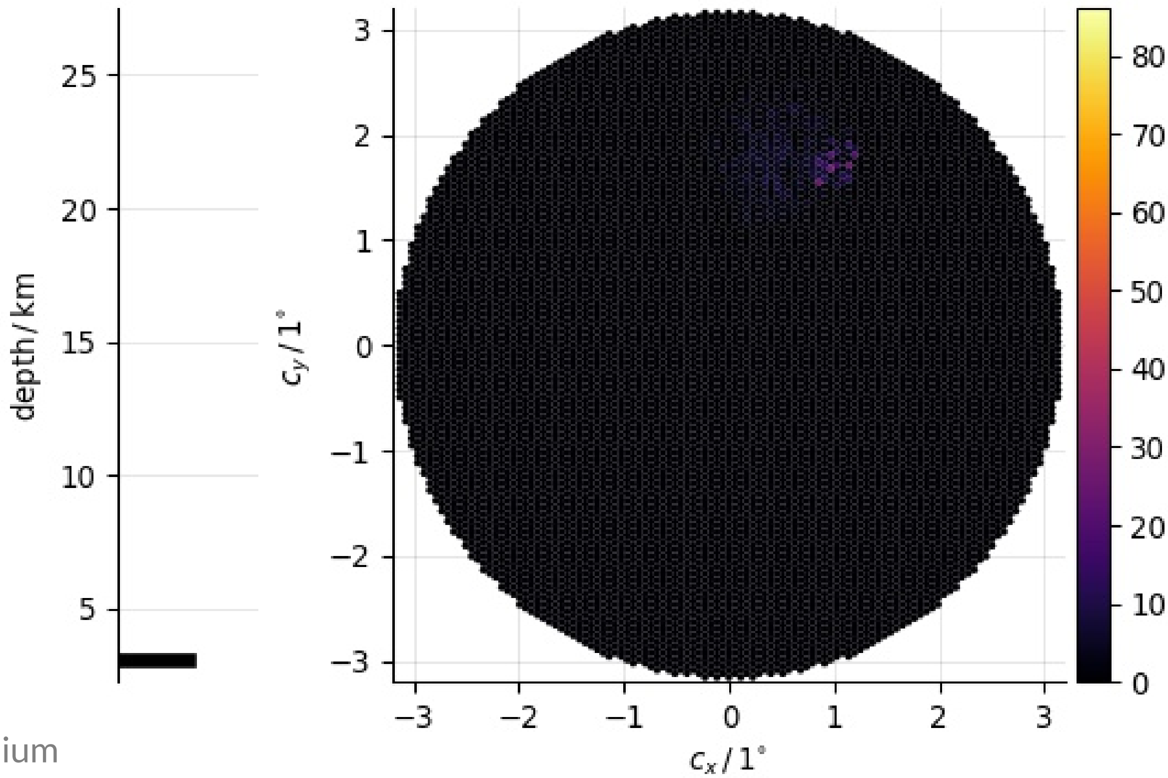
And a main jet going down from 16 to about 6km.

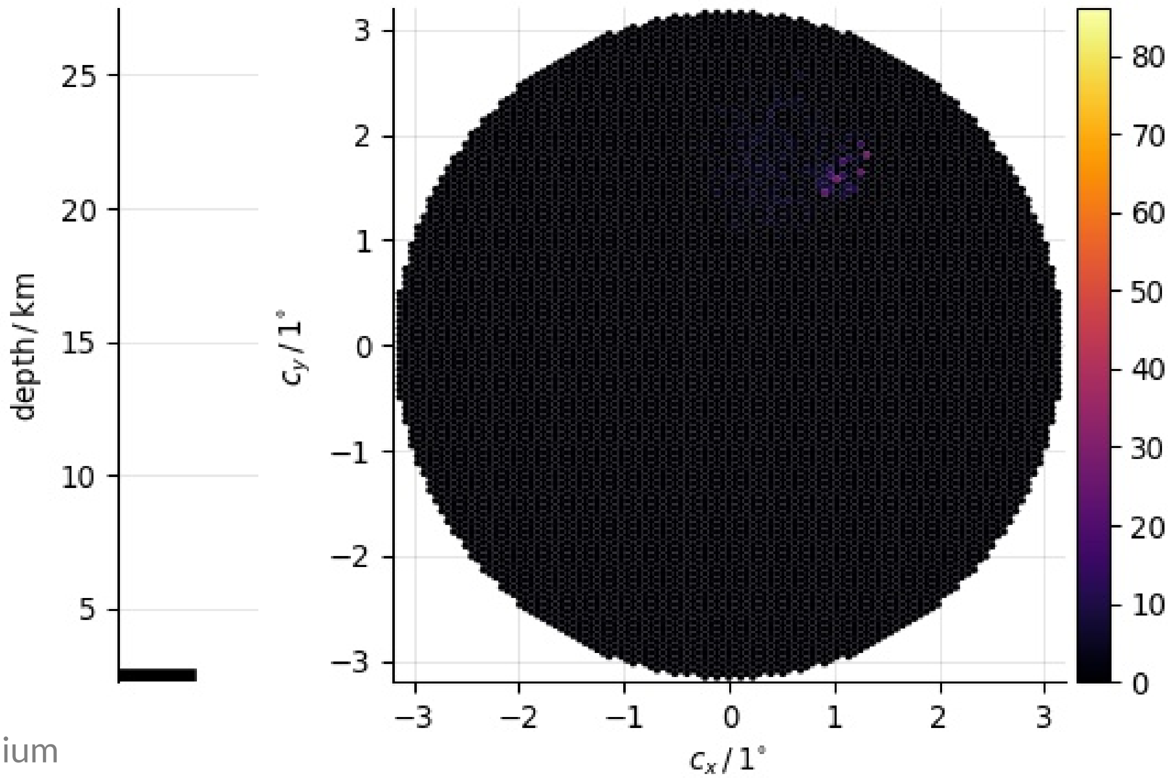


Helium

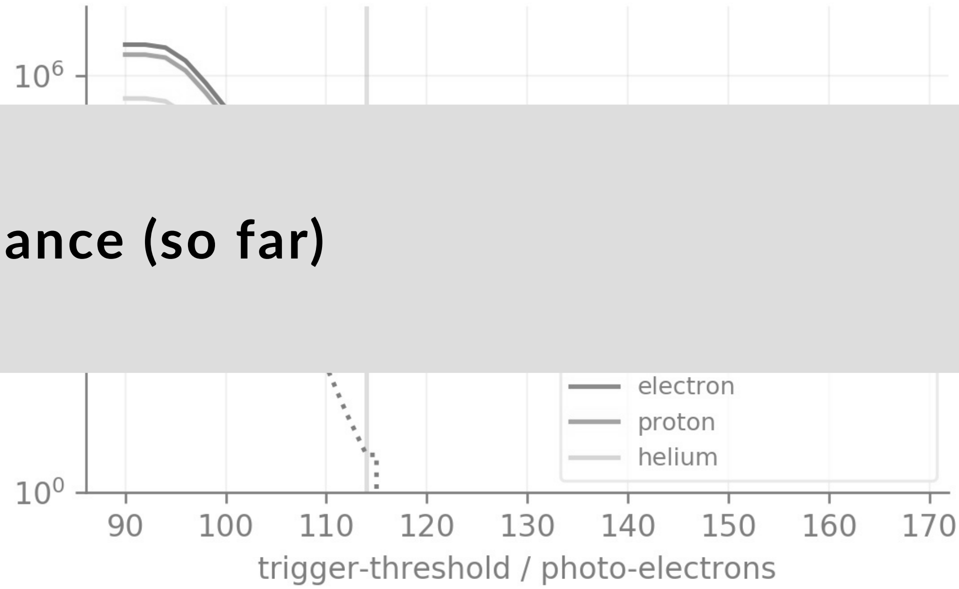


Helium


depth / km
25
20
15
10
5
c_y / 1°
c_x / 1°
3
2
1
0
−1
−2
−3
80
70
60
50
40
30
20
10
0



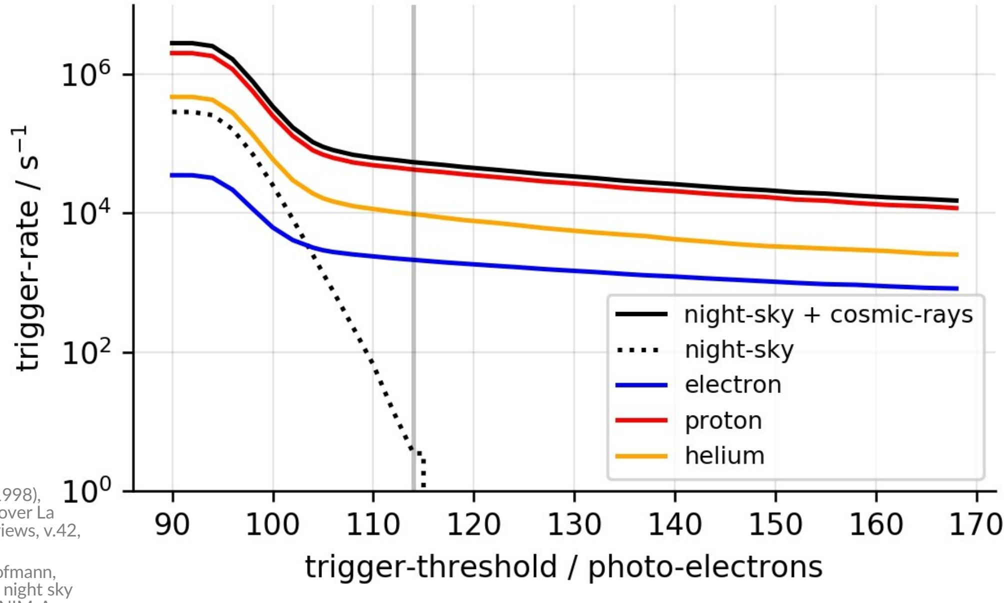
Helium



Performance (so far)

Performance

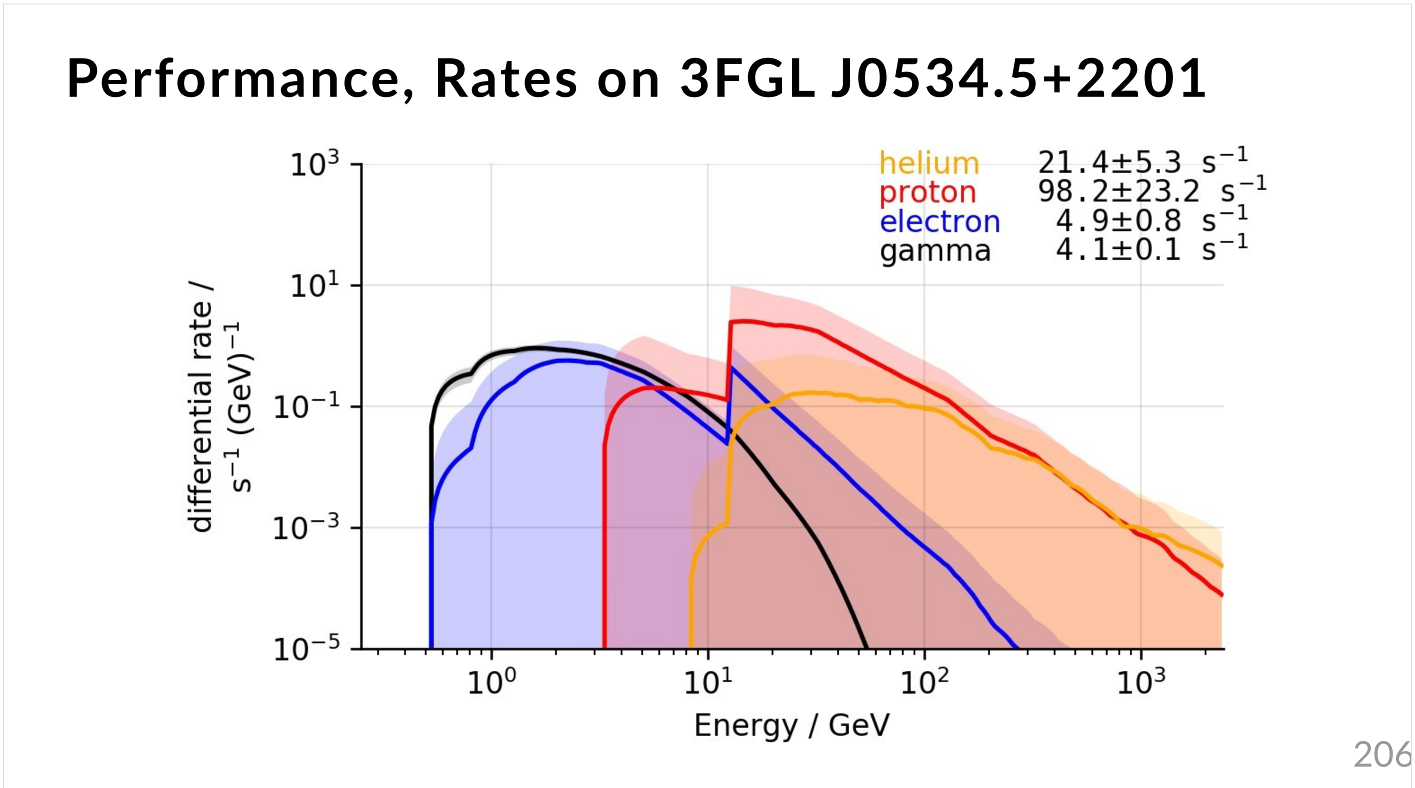
Performance, Rate-Scan



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

The trigger-threshold is set so that accidental triggers on the night sky are negligible.



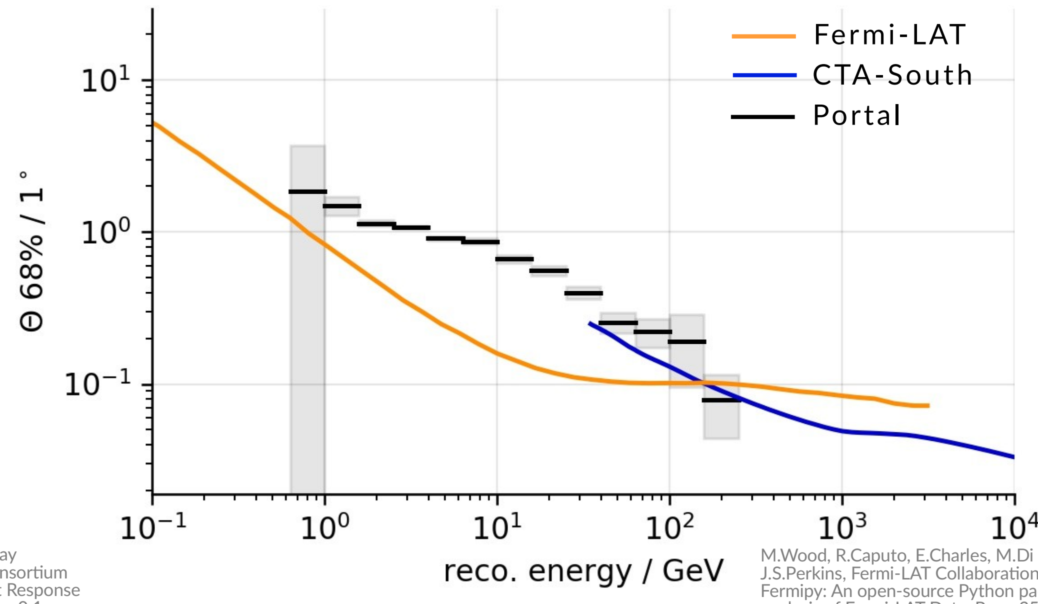
These are typical rates in the on-region.
You can see the geomagnetic cutoff.
The energy-threshold is at about two giga electron Volt.

Performance, Gamma-Hadron-Seperation

Not yet.

We do not have a gamma-hadron-seperation yet.

Performance, Direction

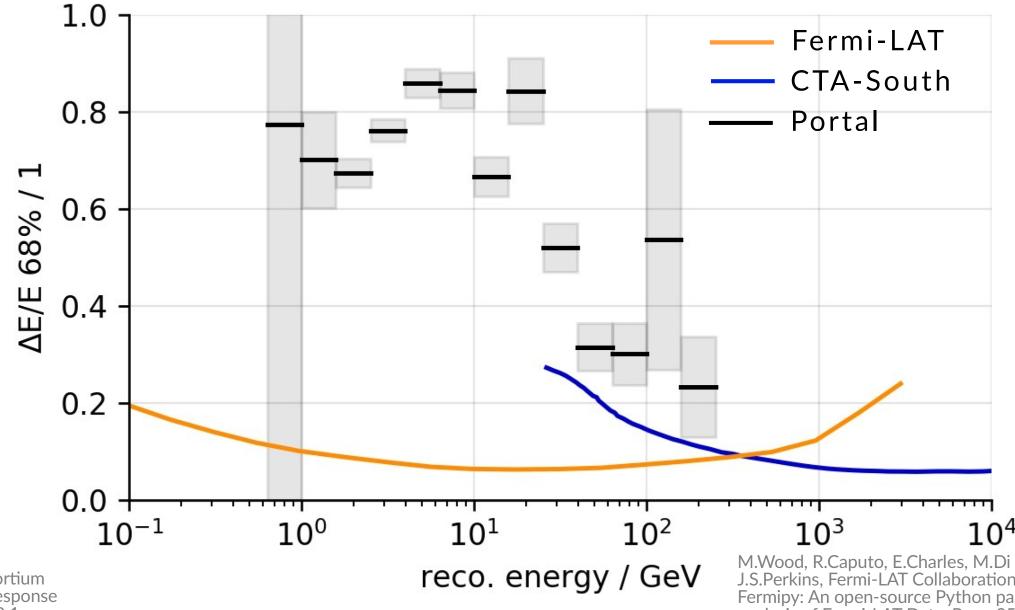


Cherenkov Telescope Array Observatory and CTA Consortium (2021). CTAO Instrument Response Functions - prod5 version v0.1, doi:10.5281/zenodo.5499840

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

Our current direction-resolution is a decent start I guess.

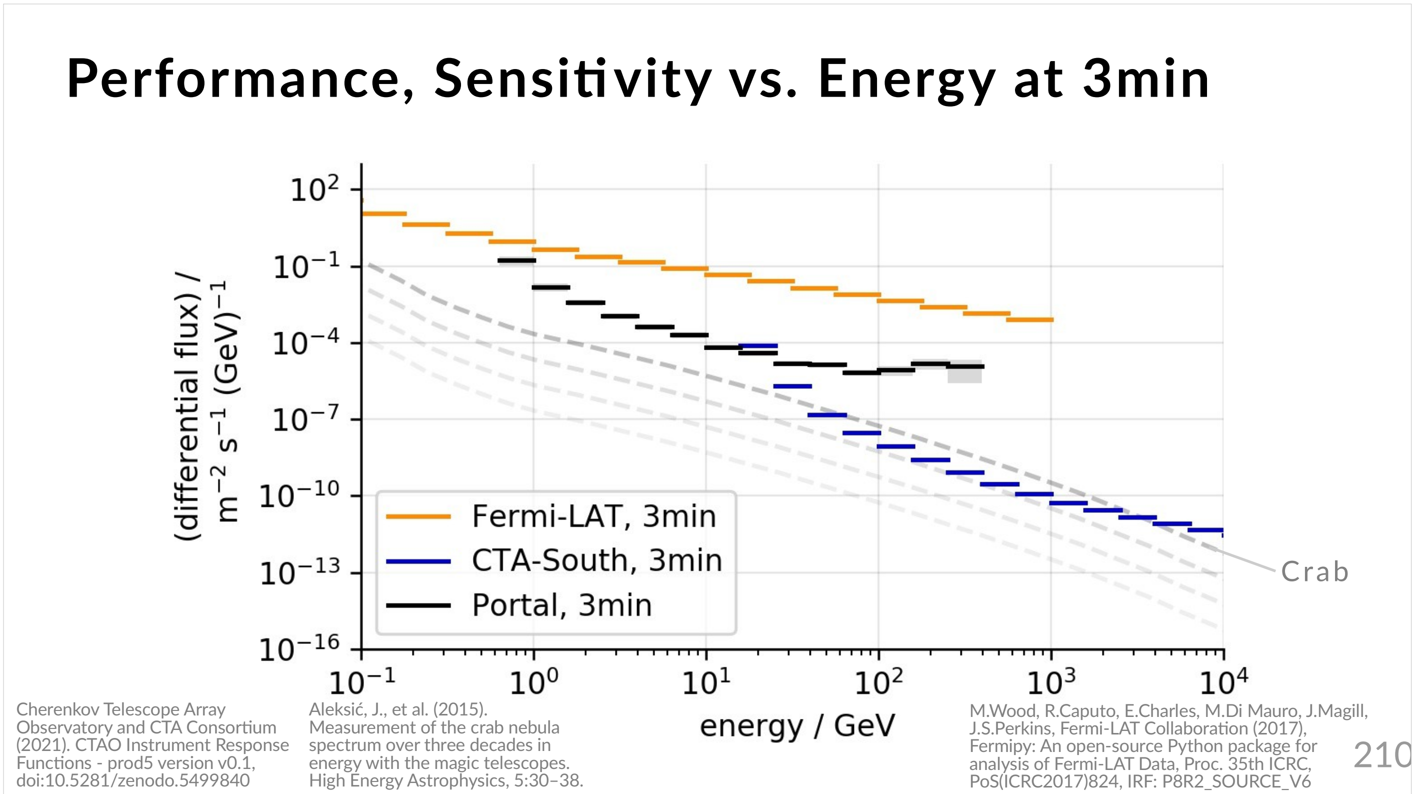
Performance, Energy



Cherenkov Telescope Array Observatory and CTA Consortium (2021). CTAO Instrument Response Functions - prod5 version v0.1, doi:10.5281/zenodo.5499840

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

Its definitely better than our current energy reconstruction.



Still this is our current differential flux sensitivity for an observation-time of three minutes.

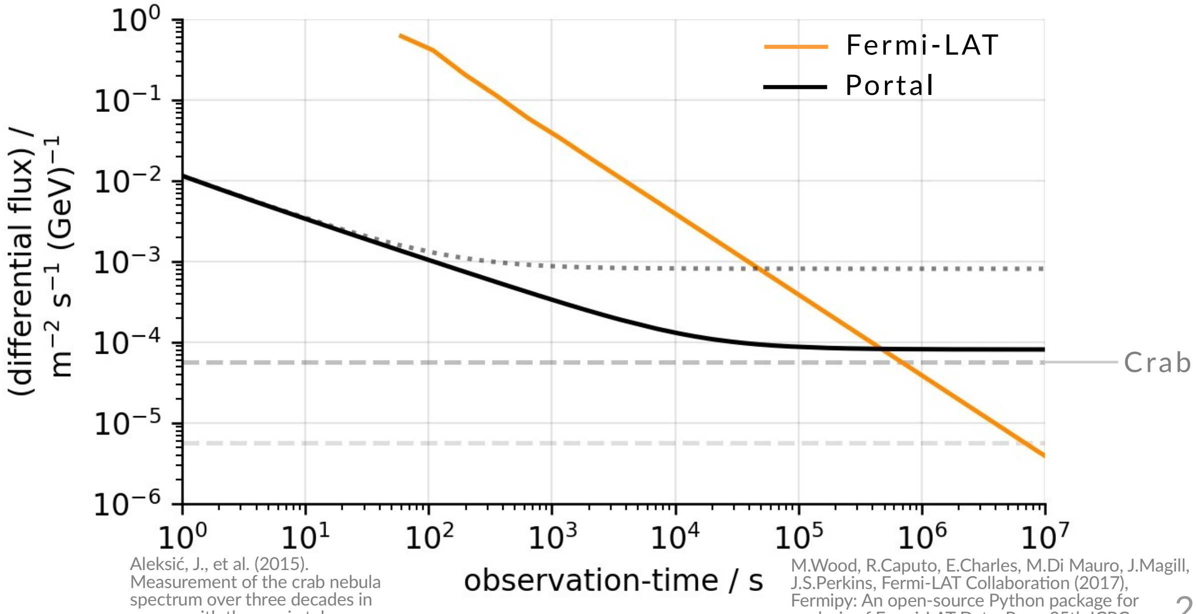
Here is Fermi in orange

Here is the southern Cherenkov-telescope-array

Here is the Portal Cherenkov-Plenoscope

Already now Portal takes over Fermi at about one giga electron Volt.

Performance, Sensitivity vs. Time at 2.5GeV

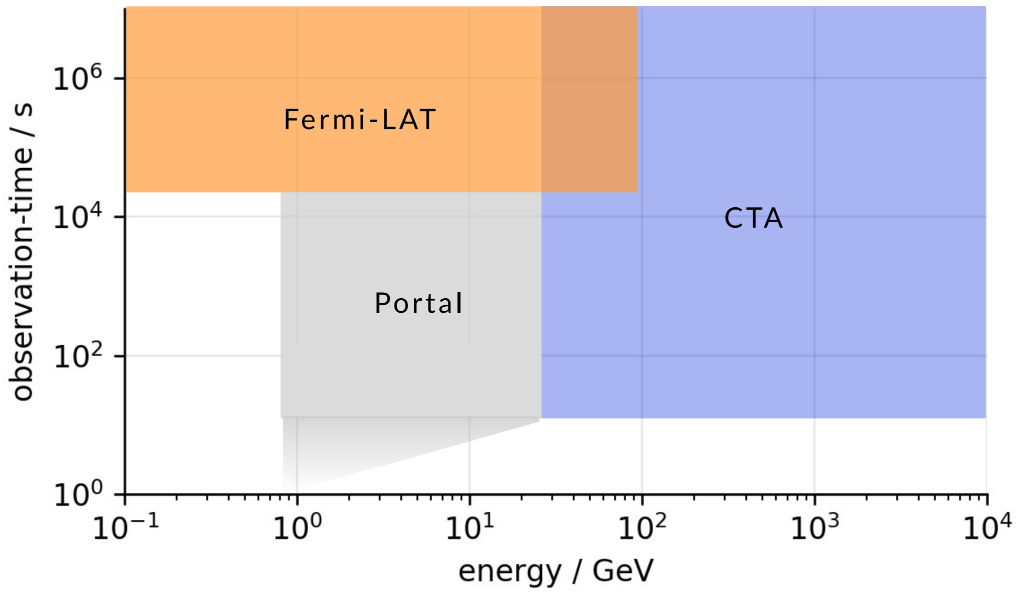


Aleksić, J., et al. (2015). Measurement of the crab nebula spectrum over three decades in energy with the magic telescopes. High Energy Astrophysics, 5:30–38.

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

Here is a closer look at the sensitivity at two point five giga electron Volts versus the observation-time.

Gamma-Ray-Timing-Explorer



So here you have it. We might have the opportunity to get a Gamma-ray-timing-explorer.

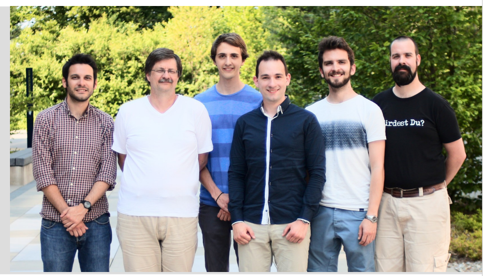
Acknowledgment

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

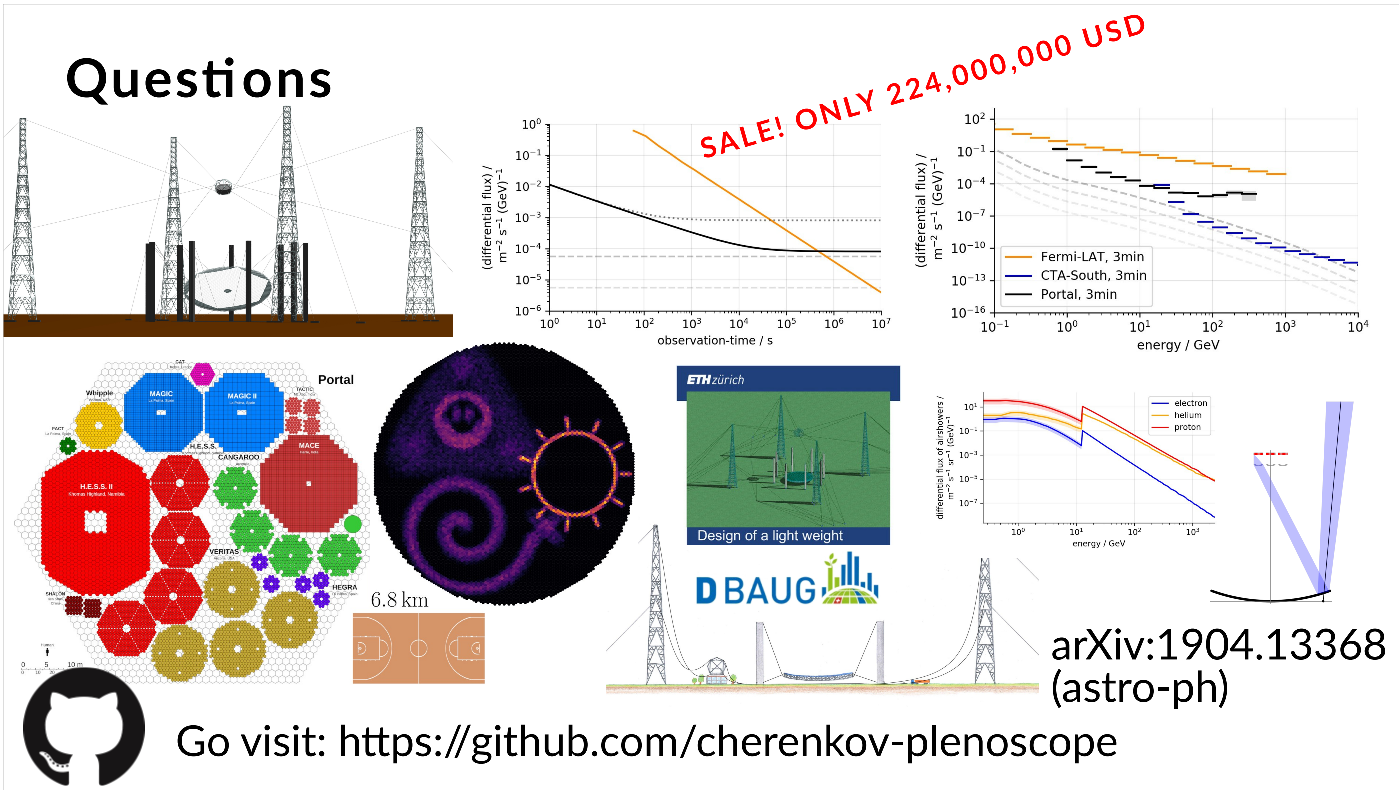
Werner Hofmann,
Jim Hinton

ETH zürich

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

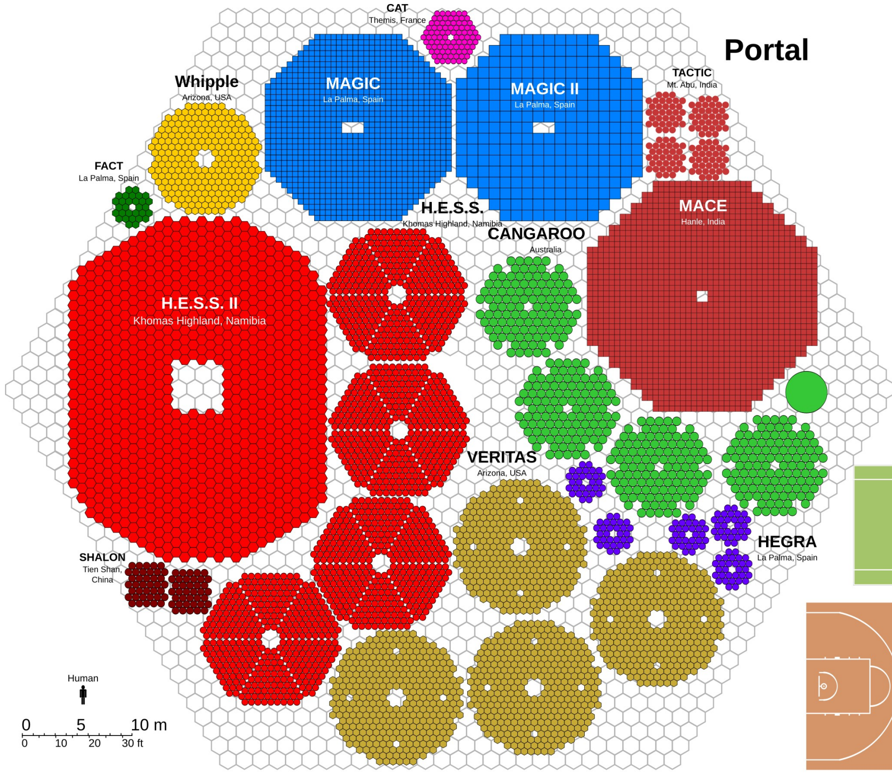


None if this would have been possible without the support of Felicitas Pauss, Adrian Biland, Jim Hinton and Werner Hofmann.

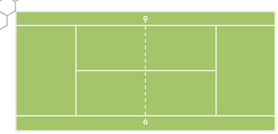


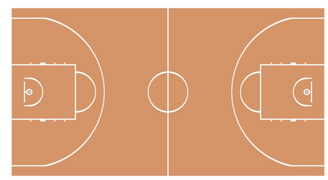
And know I am looking forward for your questions.

Size

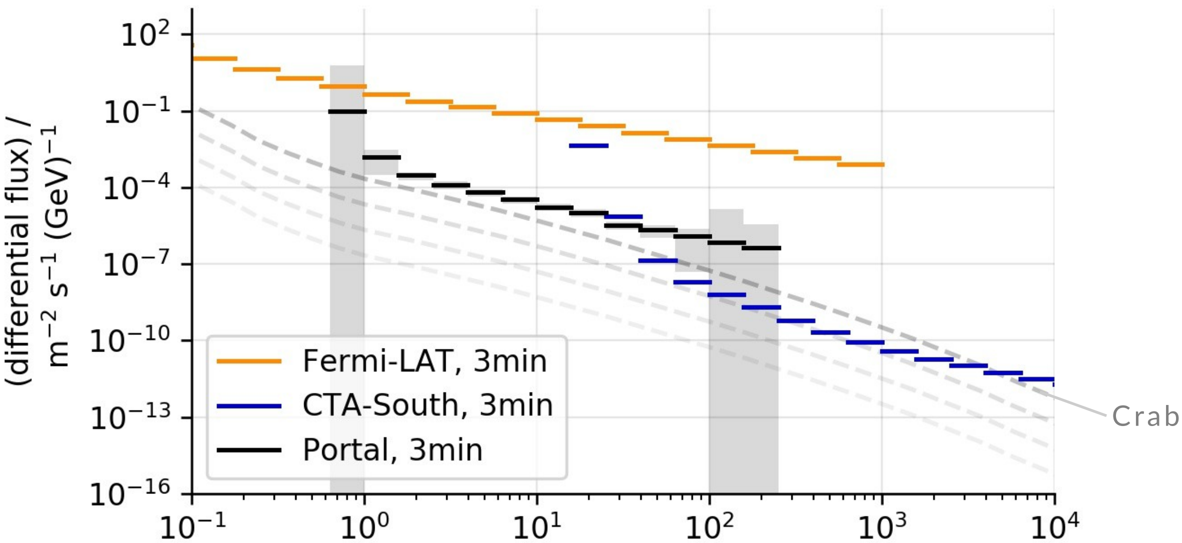

CAT
Themis, France
MAGIC
La Palma, Spain
MAGIC II
La Palma, Spain
Whipple
Arizona, USA
TACTIC
Mt. Abu, India
FACT
La Palma, Spain
H.E.S.S.
Khomas Highland, Namibia
CANGAROO
Australia
MACE
Hanle, India
H.E.S.S. II
Khomas Highland, Namibia
VERITAS
Arizona, USA
HEGRA
La Palma, Spain
SHALON
Tien Shan,
China
Human
0
5
10 m
0
10
20
30 ft

Portal





Performance, Sensitivity vs. Energy at 3min

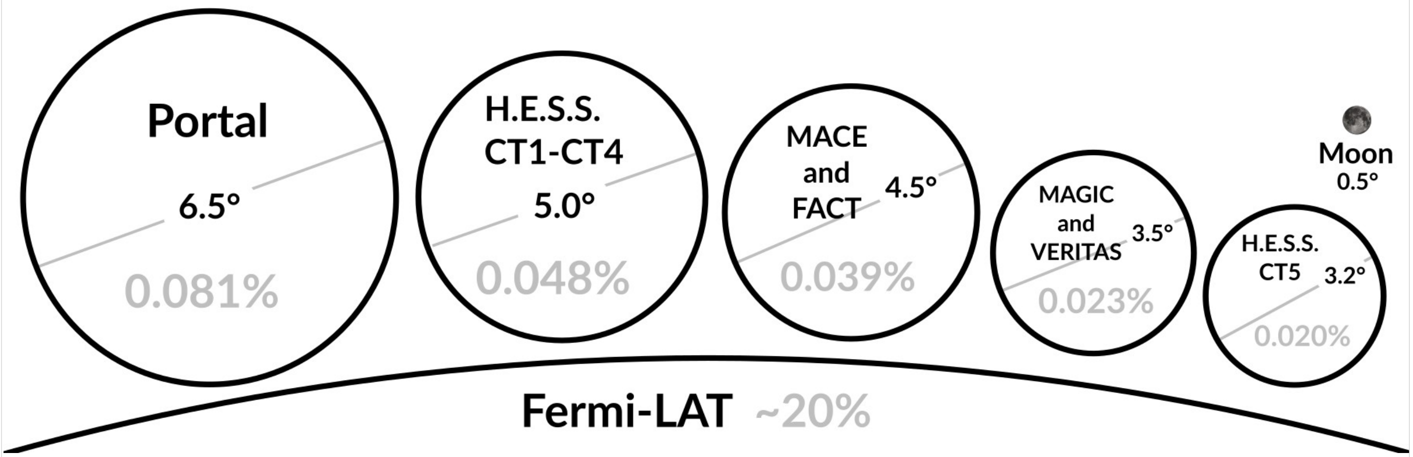


Cherenkov Telescope Array Observatory and CTA Consortium (2021). CTAO Instrument Response Functions - prod5 version v0.1, doi:10.5281/zenodo.5499840

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

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 Eurpean-Southern-Observatory (ESO)

These integration costs are based on studies by the european-southern-observatory for the construction of a telescope in harsh environments such as Atacama-desert.