



# IMAGING ATMOSPHERIC RADIO TELESCOPE

Anne Timmermans, Sebastian A. Mueller  
Juan Ammerman-Yebra, Harm Schoorlemmer

# SIMULATING AN IART OVERVIEW

## Gamma ray detection

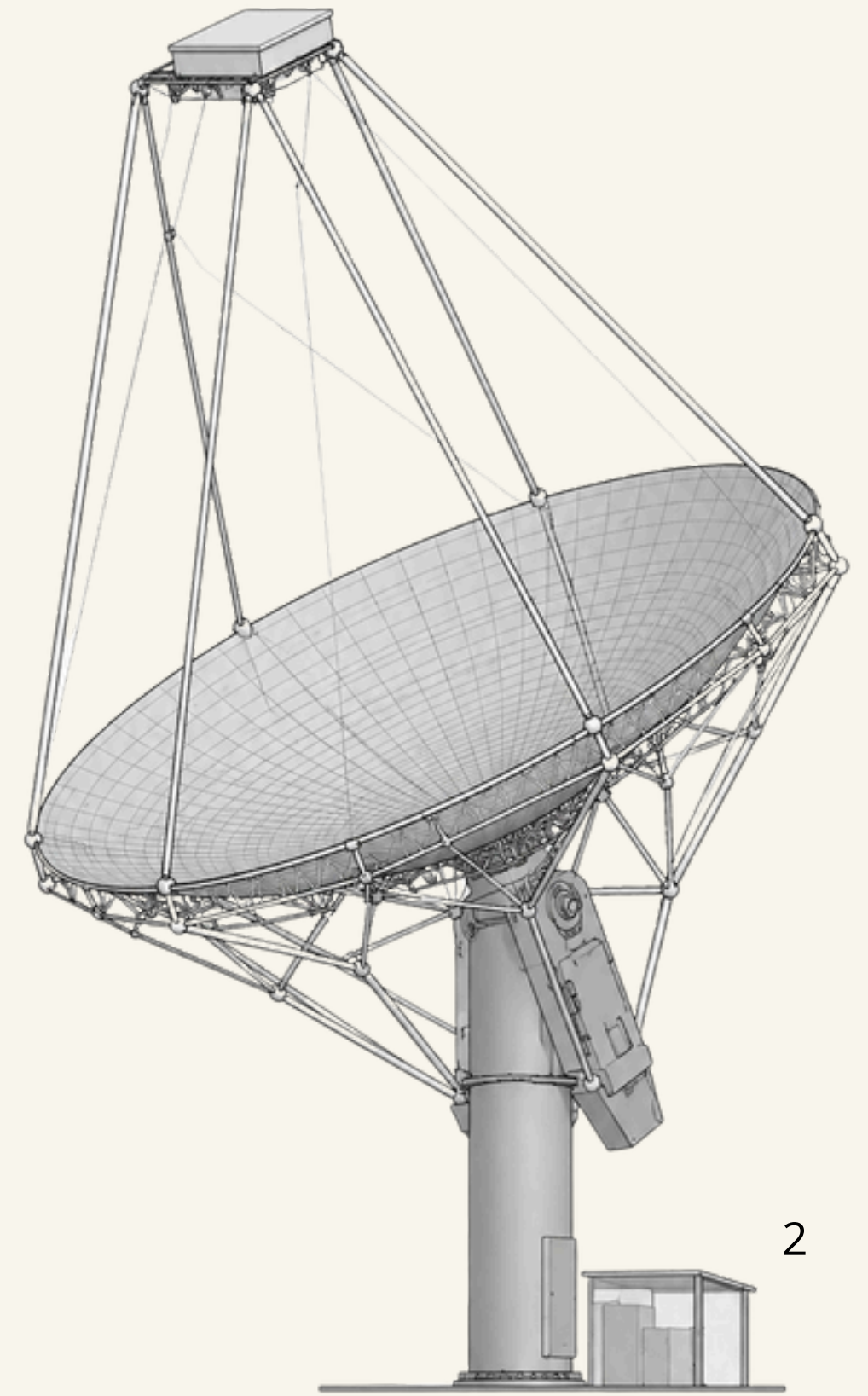
Motivation and background

## Simulation

How (well) does the simulation work?

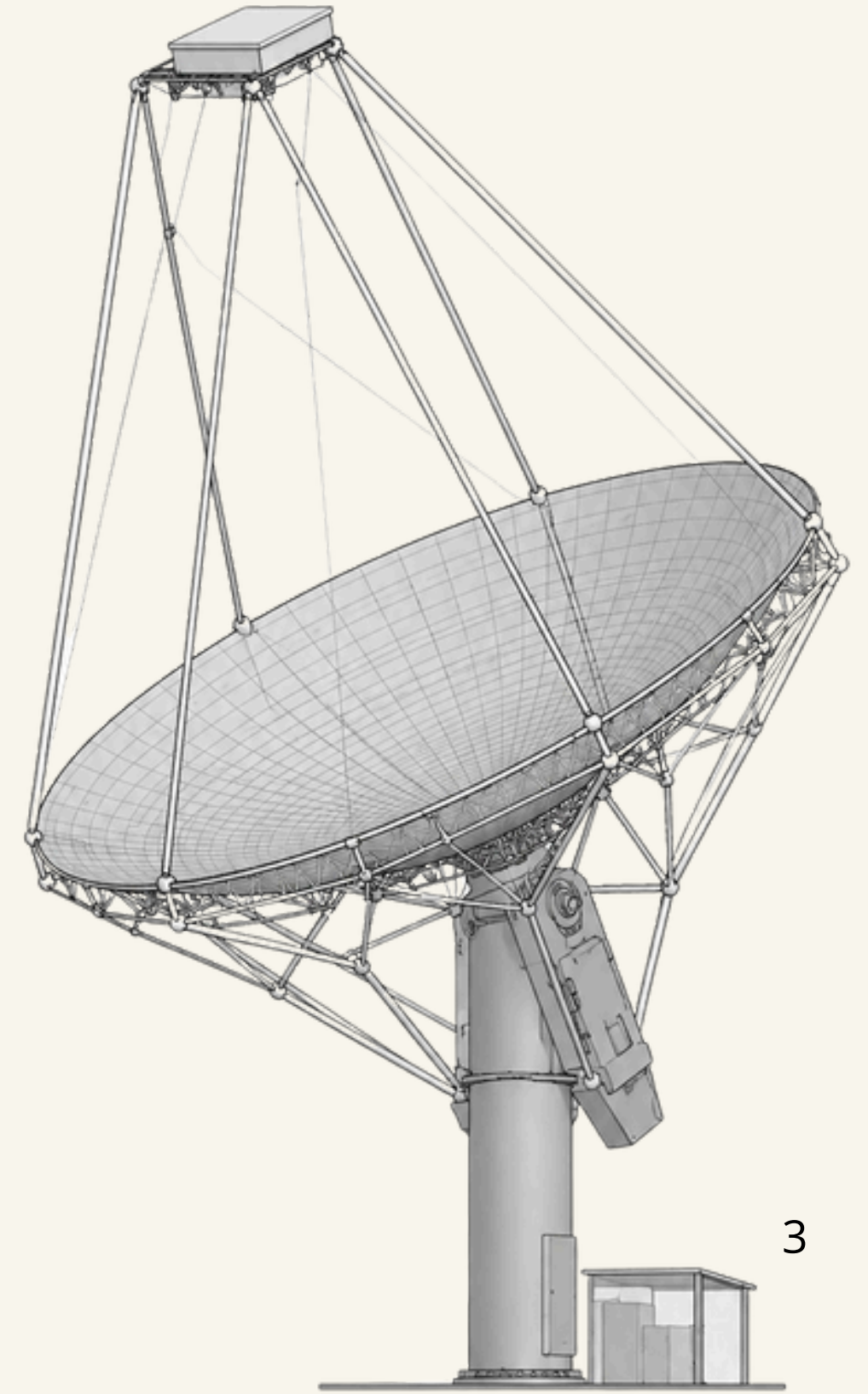
## Air shower images

Results with air shower simulations



# SIMULATING AN IART OVERVIEW

**Gamma ray detection**  
Motivation and background



# INTRODUCTION TO GAMMA-RAY DETECTION

## Why?

- Probe for origin of (galactic) cosmic rays
- Cosmic ray acceleration processes
- Dark matter searches

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- High resolution of  $\sim 0.1^\circ$
- Good gamma-hadron separation
- Low duty cycle  $\sim 12\%$

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## Radio

- Low Frequency ( $< 500$  MHz)  
→ Auger, TURBO, RNO-G ...
- High Frequency ( $\sim$  GHz)  
→ AMBER, CROME, MIDAS
- High duty cycle  $\sim 100\%$

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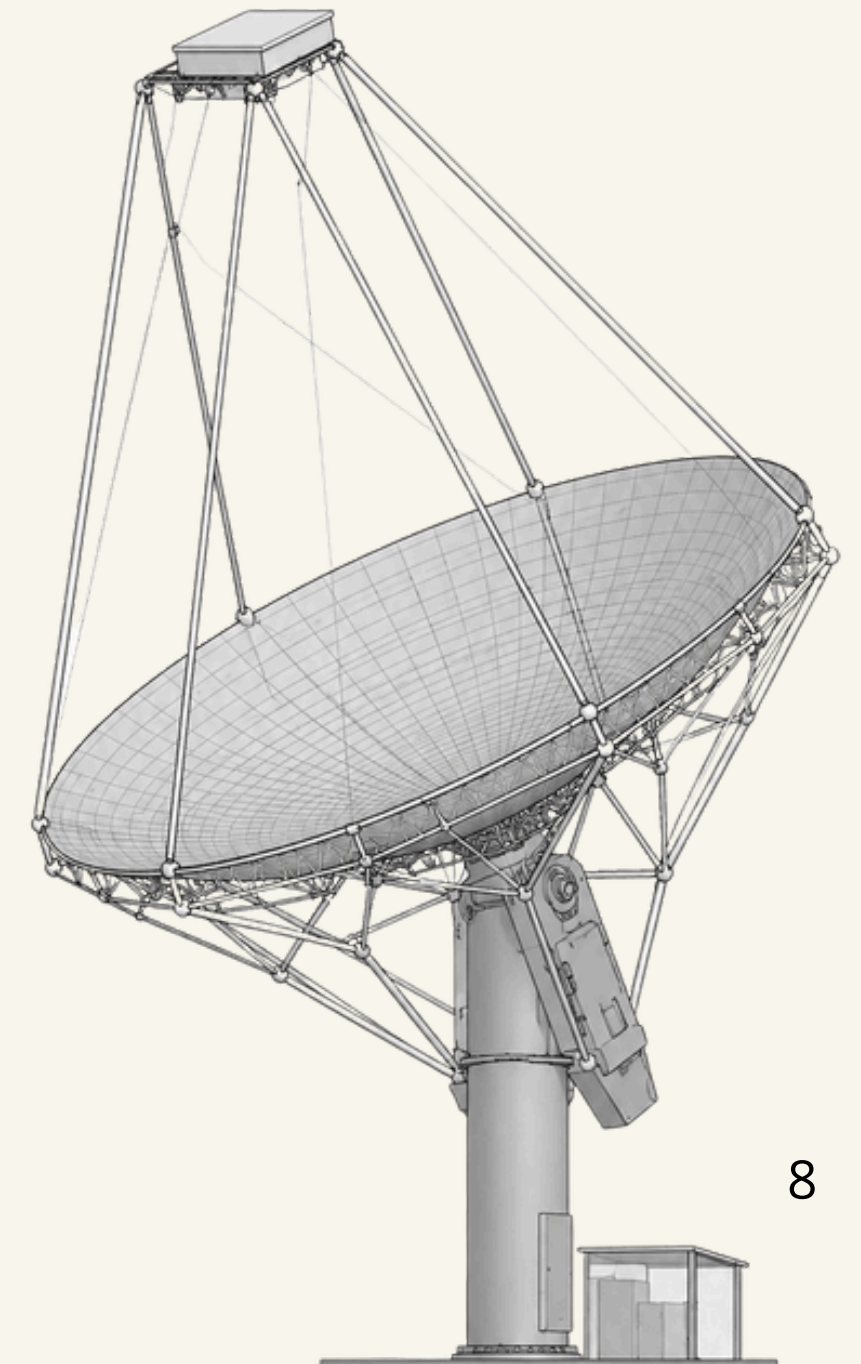
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## Gamma ray detection

Motivation and background

## Simulation

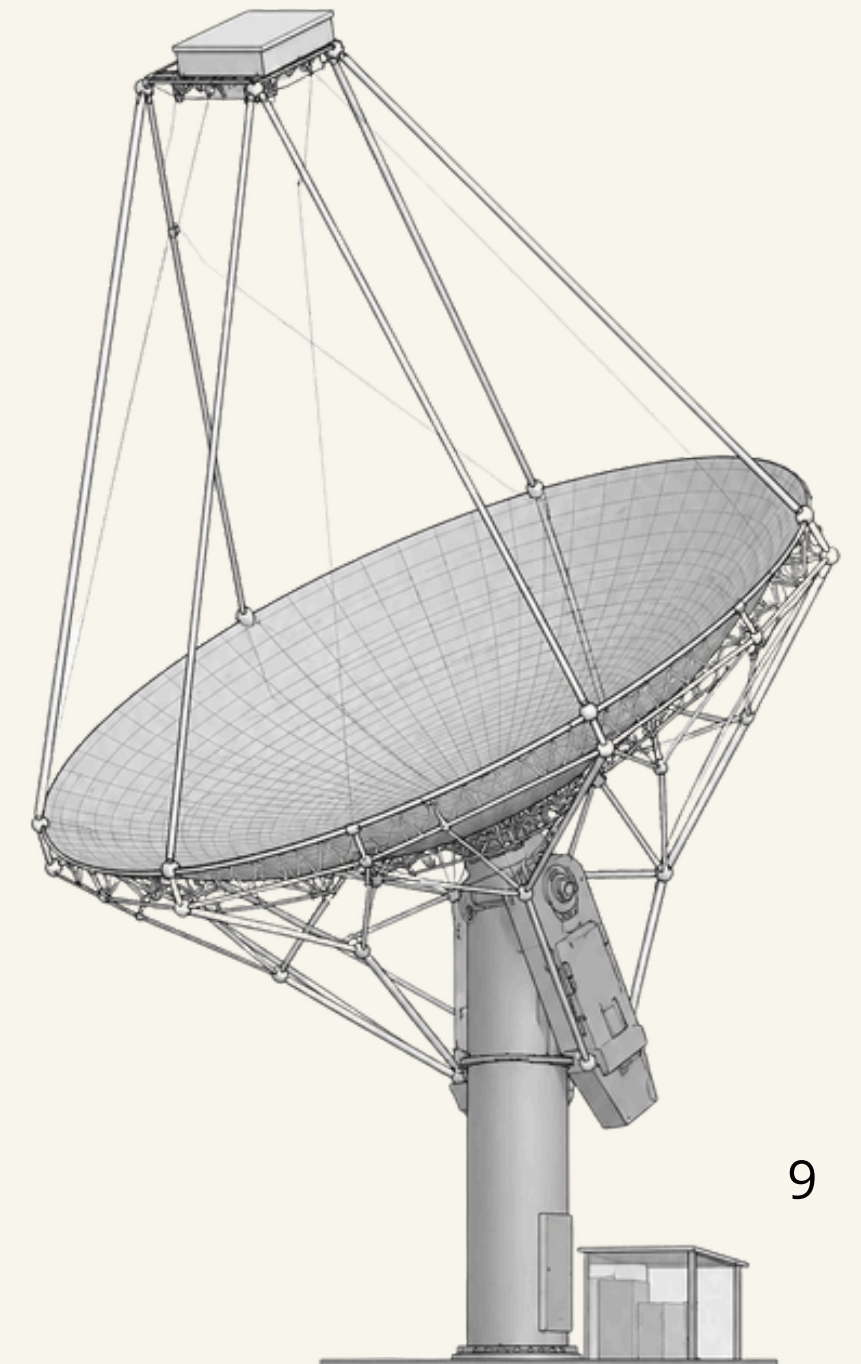
How (well) does the simulation work?



# IART SIMULATION

## Huygens principle

Every point on a wavefront acts as a source of secondary wavelets. The final field is the superposition of all contributions.



# IART SIMULATION

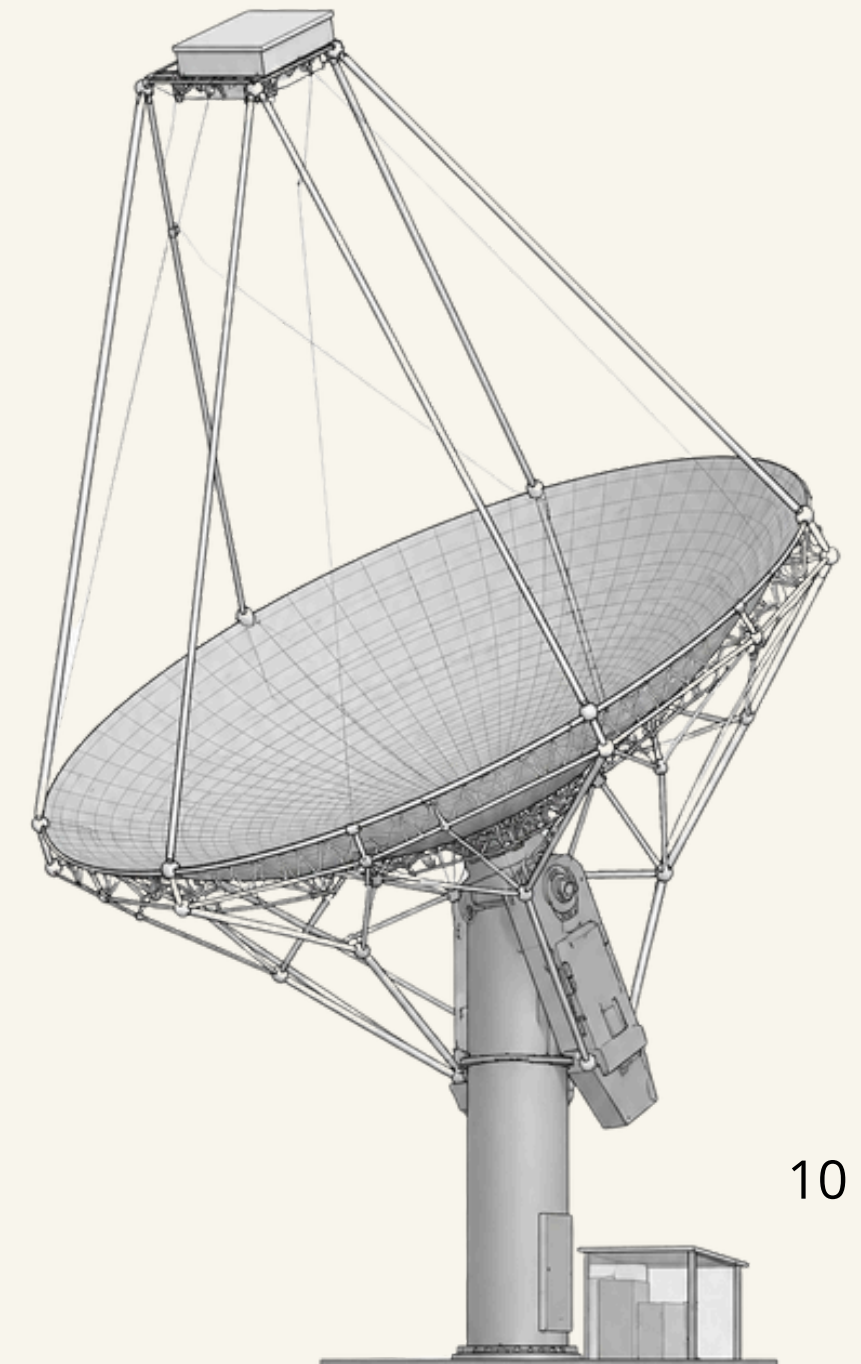
1

A source of radio signal  
*MC simulation or test source*



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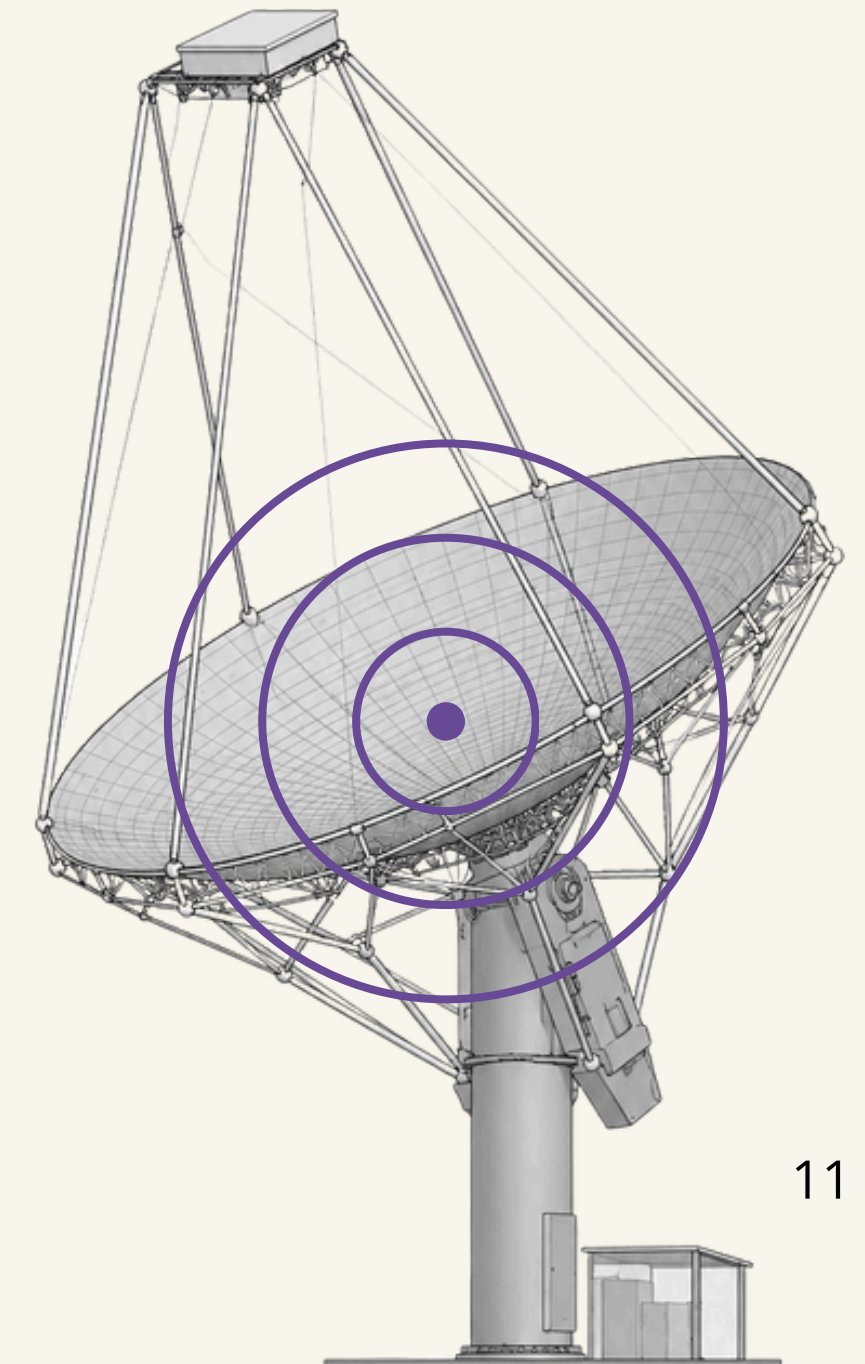
# IART SIMULATION

1

**A source of radio signal**  
*MC simulation or test source*

2

**Probe field on the mirror and reflect**  
*Reflection according to Huygens principle*



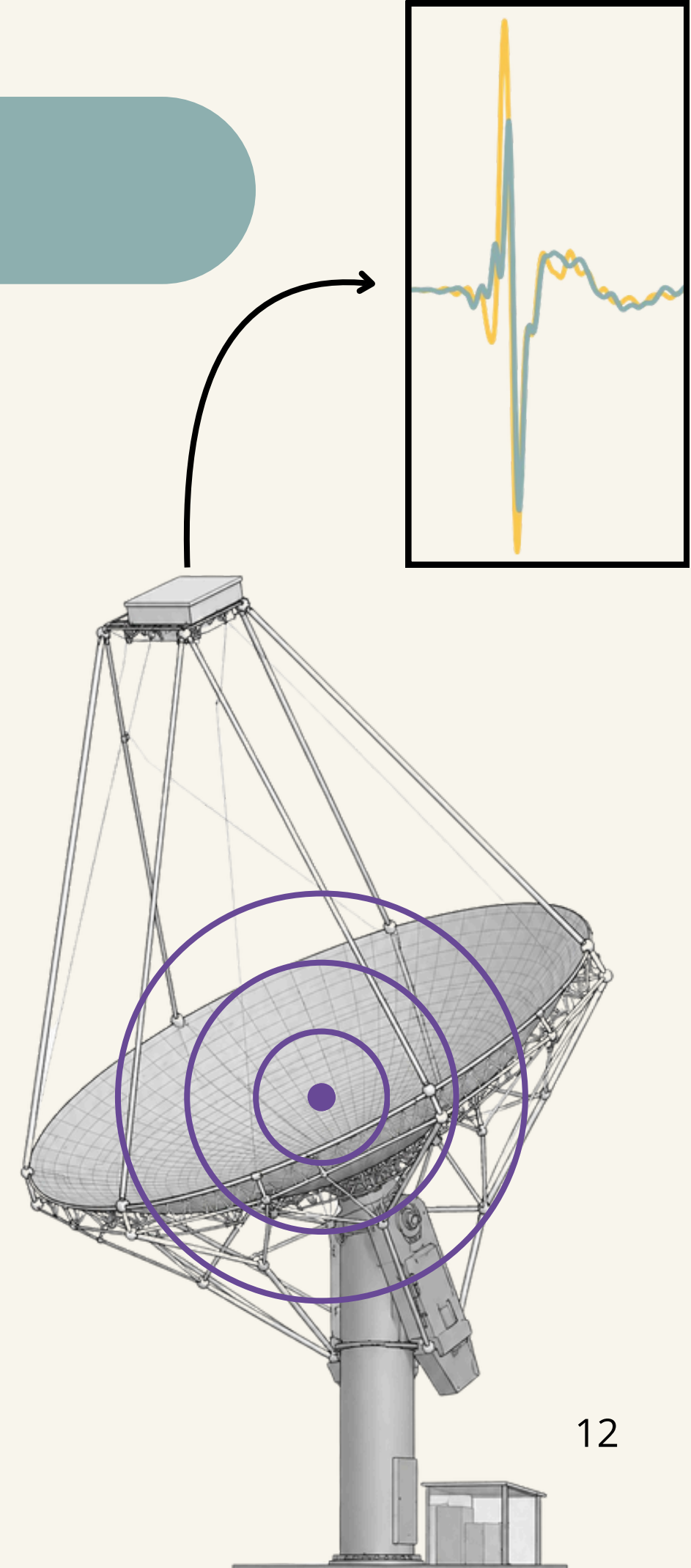
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# IART SIMULATION

- 1** A source of radio signal  
*MC simulation or test source*
- 2** Probe field on the mirror and reflect  
*Reflection according to Huygens principle*
- 3** Collect fields in each camera pixel  
*Total field in each pixel is the superposition of all contributions*

**Huygens principle**  
Every point on a wavefront acts as a source of secondary wavelets. The final field is the superposition of all contributions.



# SIMULATION VERIFICATION

**Point source 2**  
12.58 GHz

**Point source 1**  
10.69 GHz

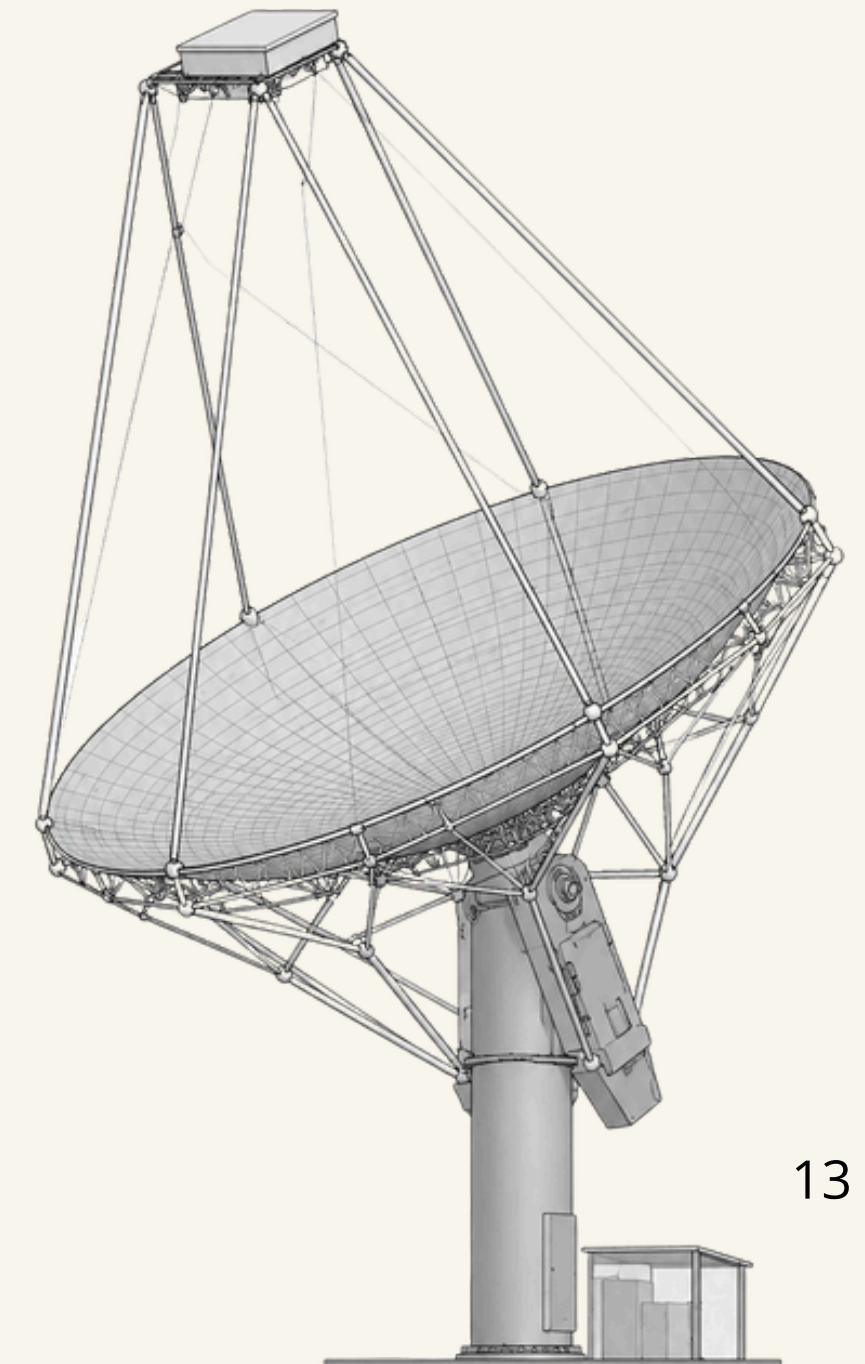


## Two simultaneous plane waves

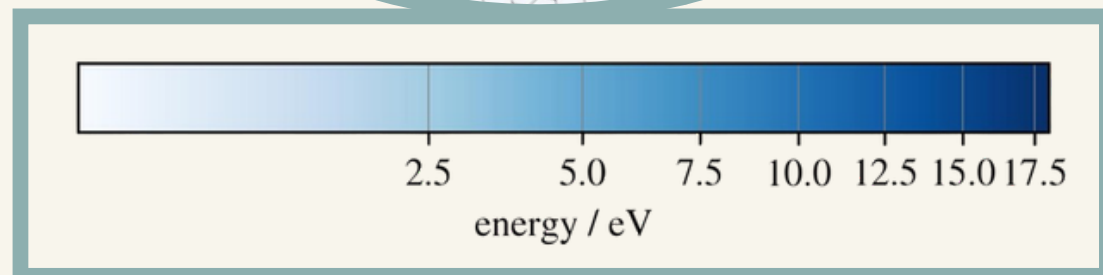
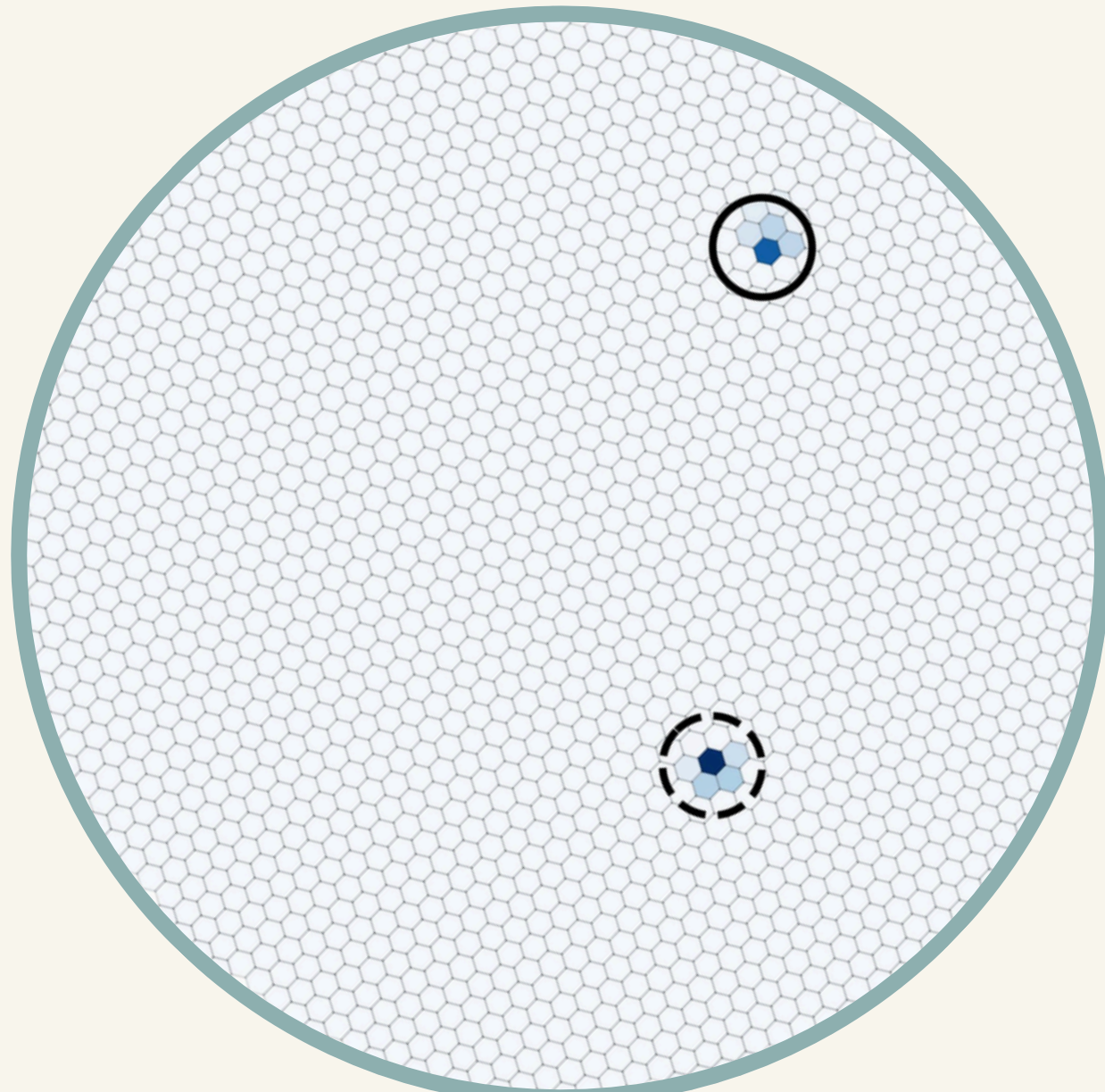
Plane waves differ in:

- Energy
- Polarization angle
- Frequency

→ **Test to disentangle them**



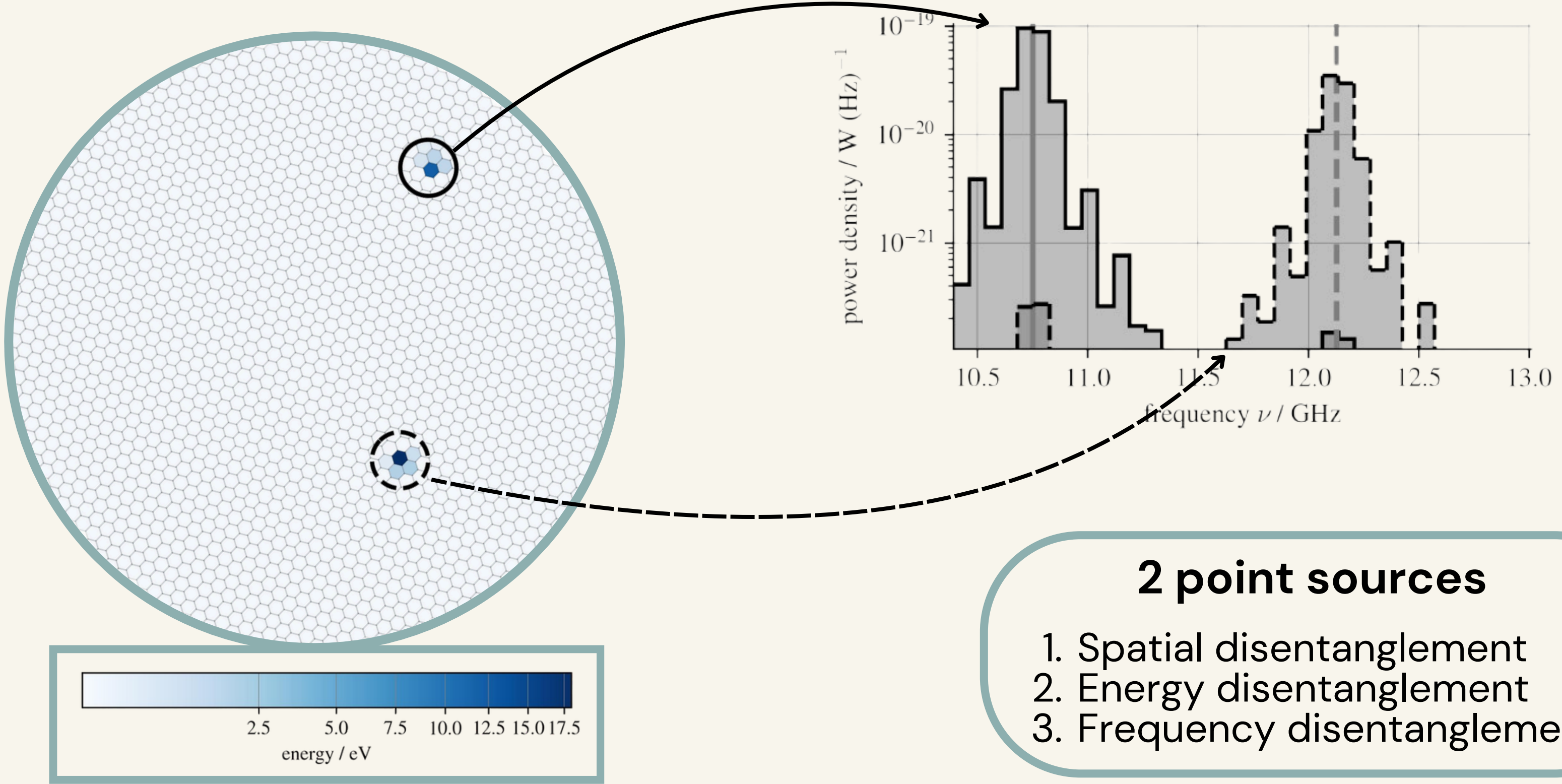
# SIMULATION VERIFICATION



## 2 point sources

1. Spatial disentanglement
2. Energy disentanglement

# SIMULATION VERIFICATION



# SIMULATING AN IART OVERVIEW

## Gamma ray detection

Motivation and background

## Simulation

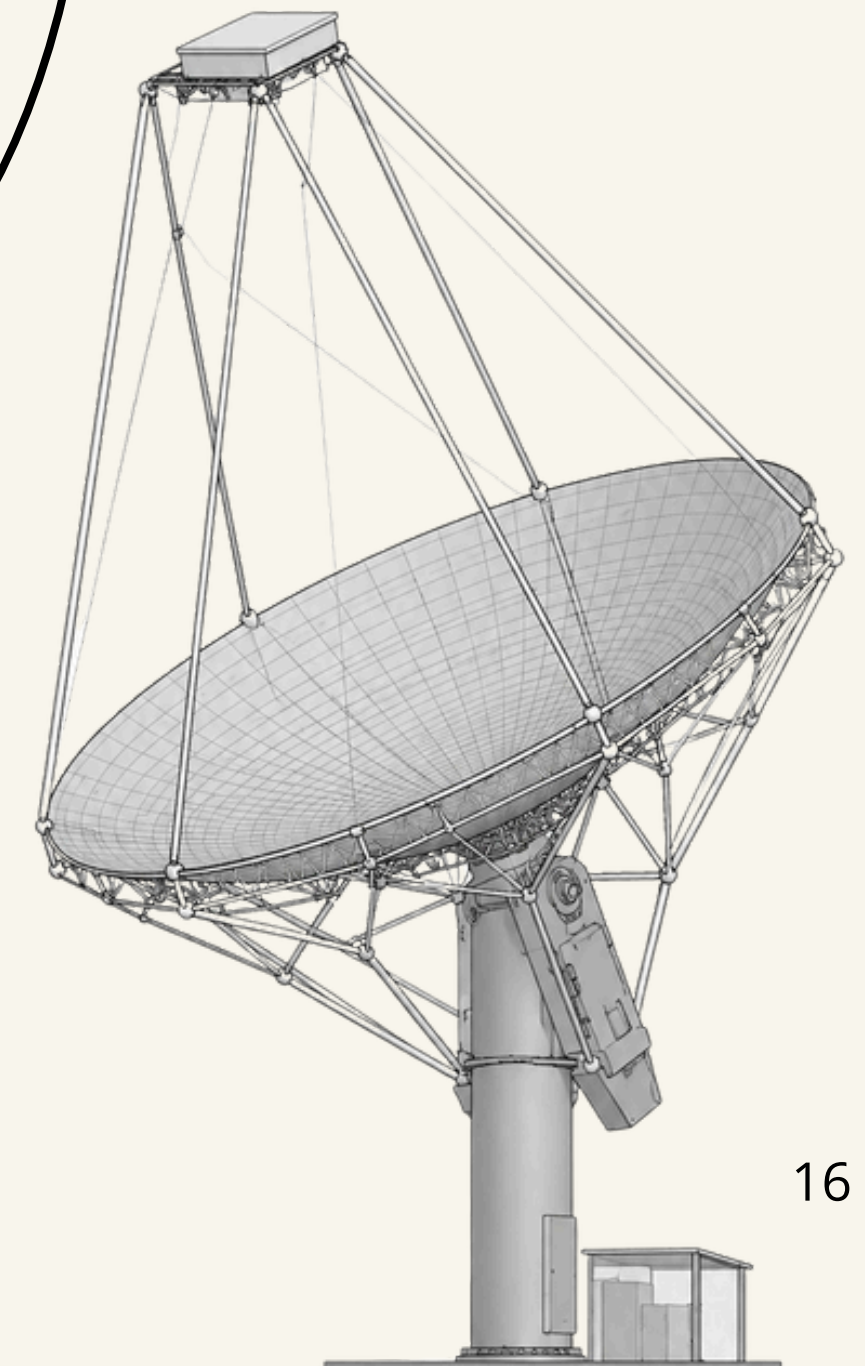
How (well) does the simulation work?

## Air shower images

Results with air shower simulations

You've all seen Juan Ammerman-Yebra's talk yesterday for a different simulation approach!

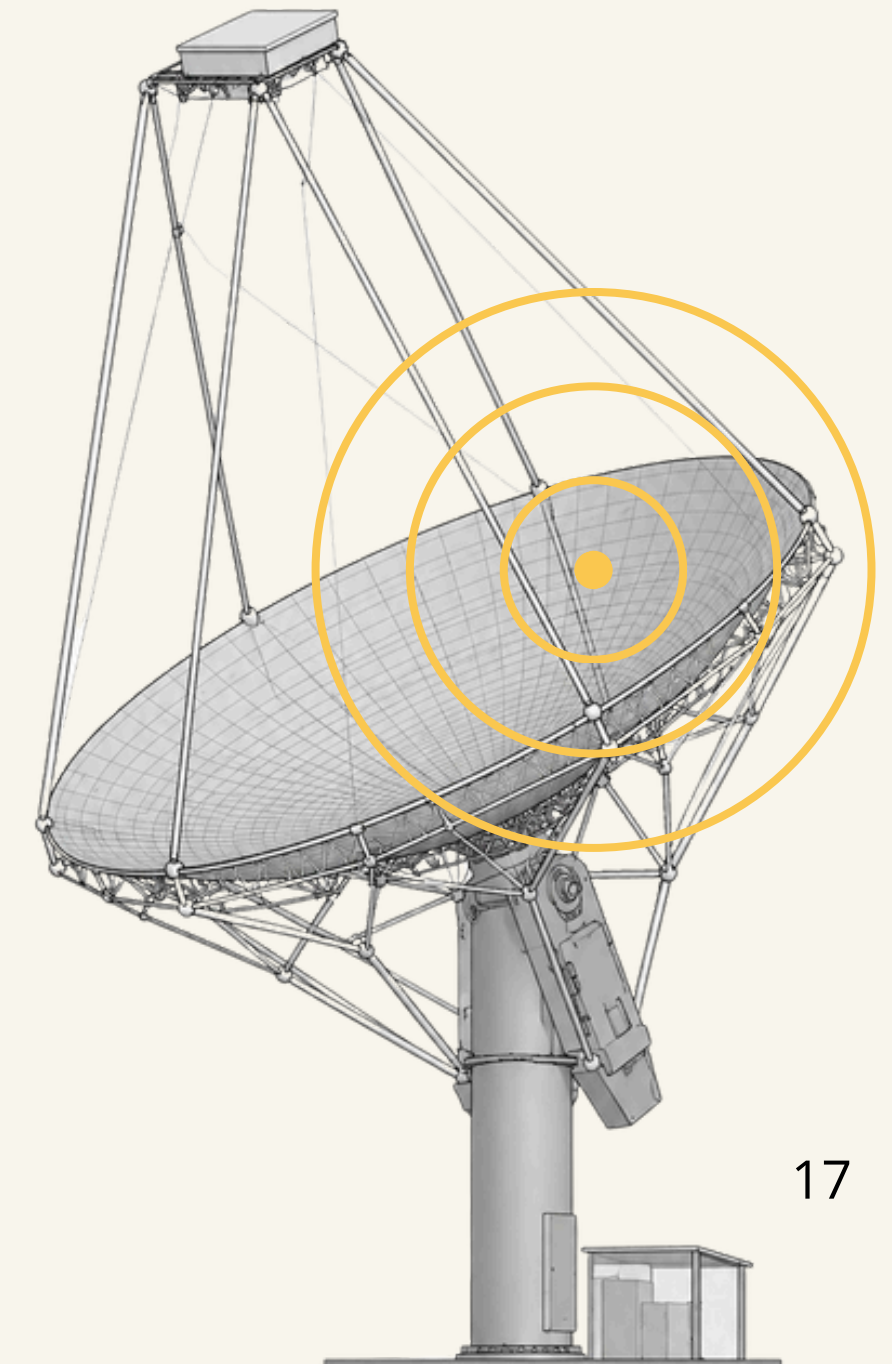
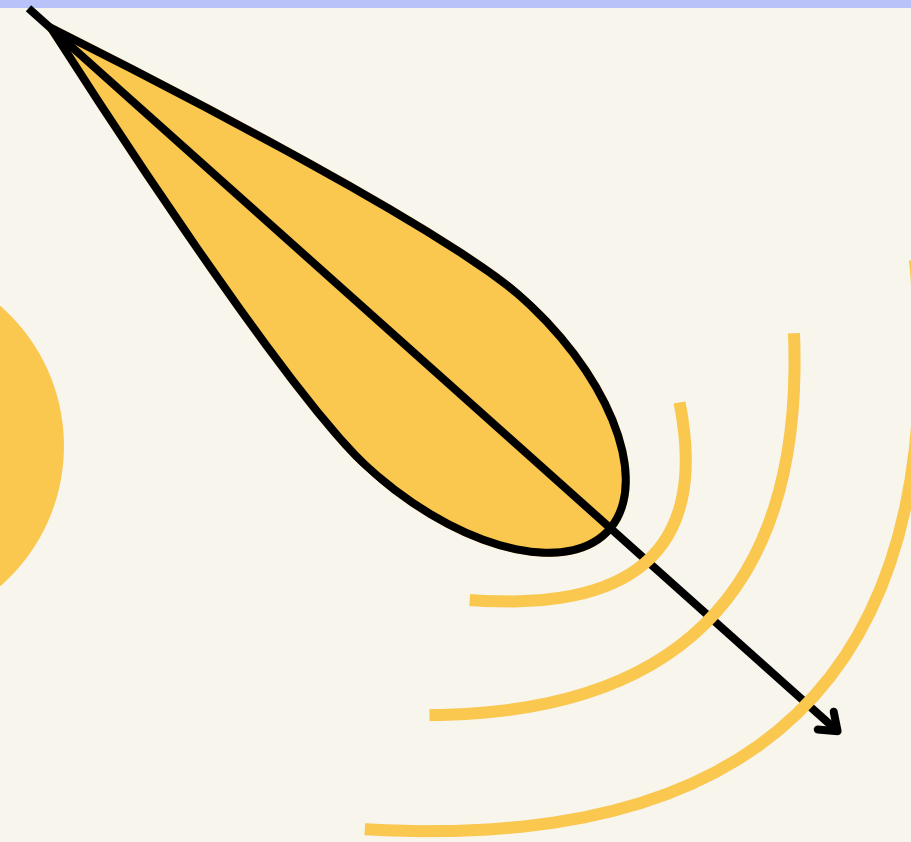
<https://indico.kit.edu/event/5380/contributions/22597/>



# APPLICATION TO AIR SHOWER SIMULATIONS

## CORSIKA-CoREAS

Probe points on the mirror



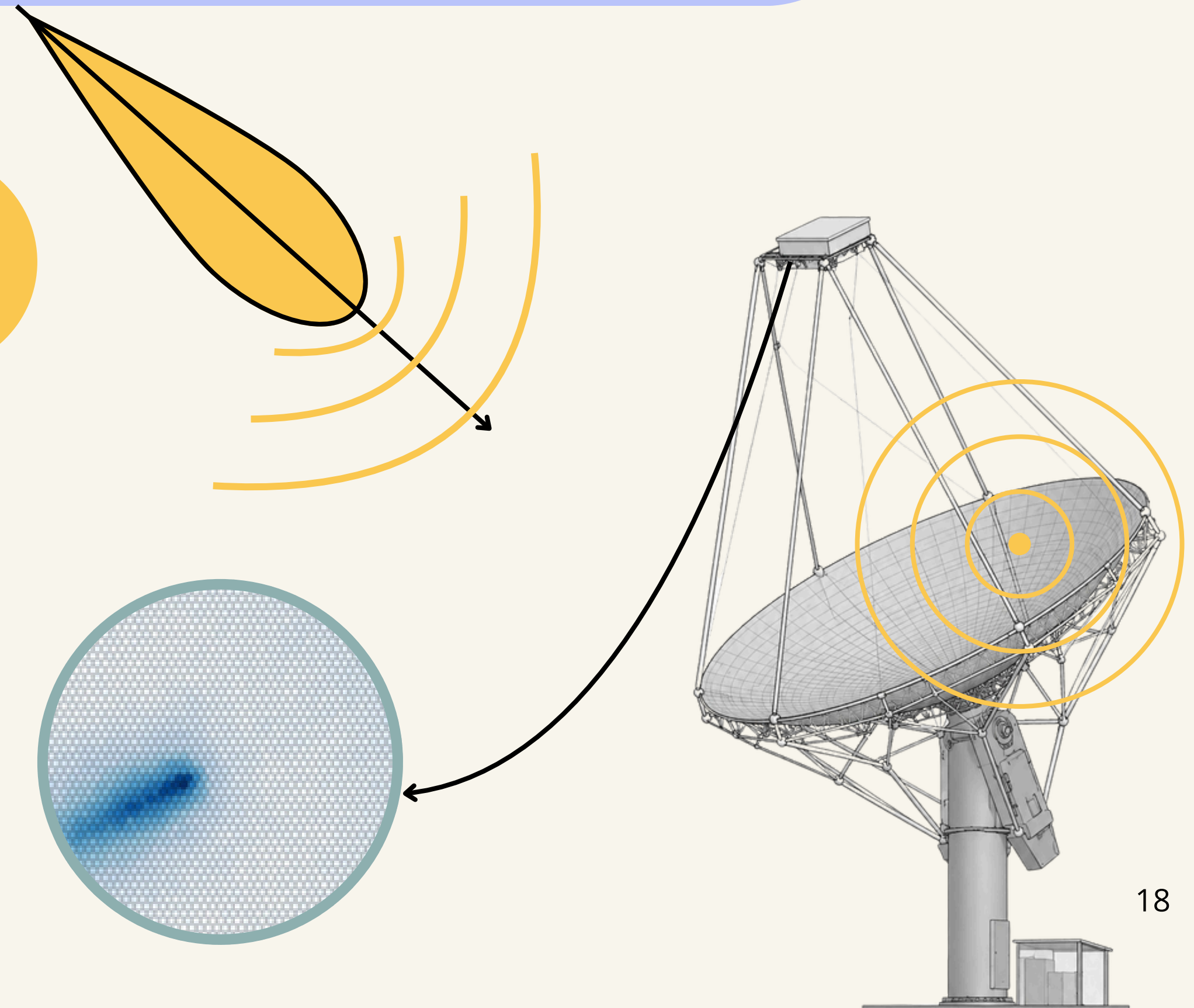
# APPLICATION TO AIR SHOWER SIMULATIONS

## CORSIKA-CoREAS

Probe points on the mirror

## IART simulation

Resulting waveforms in all pixels

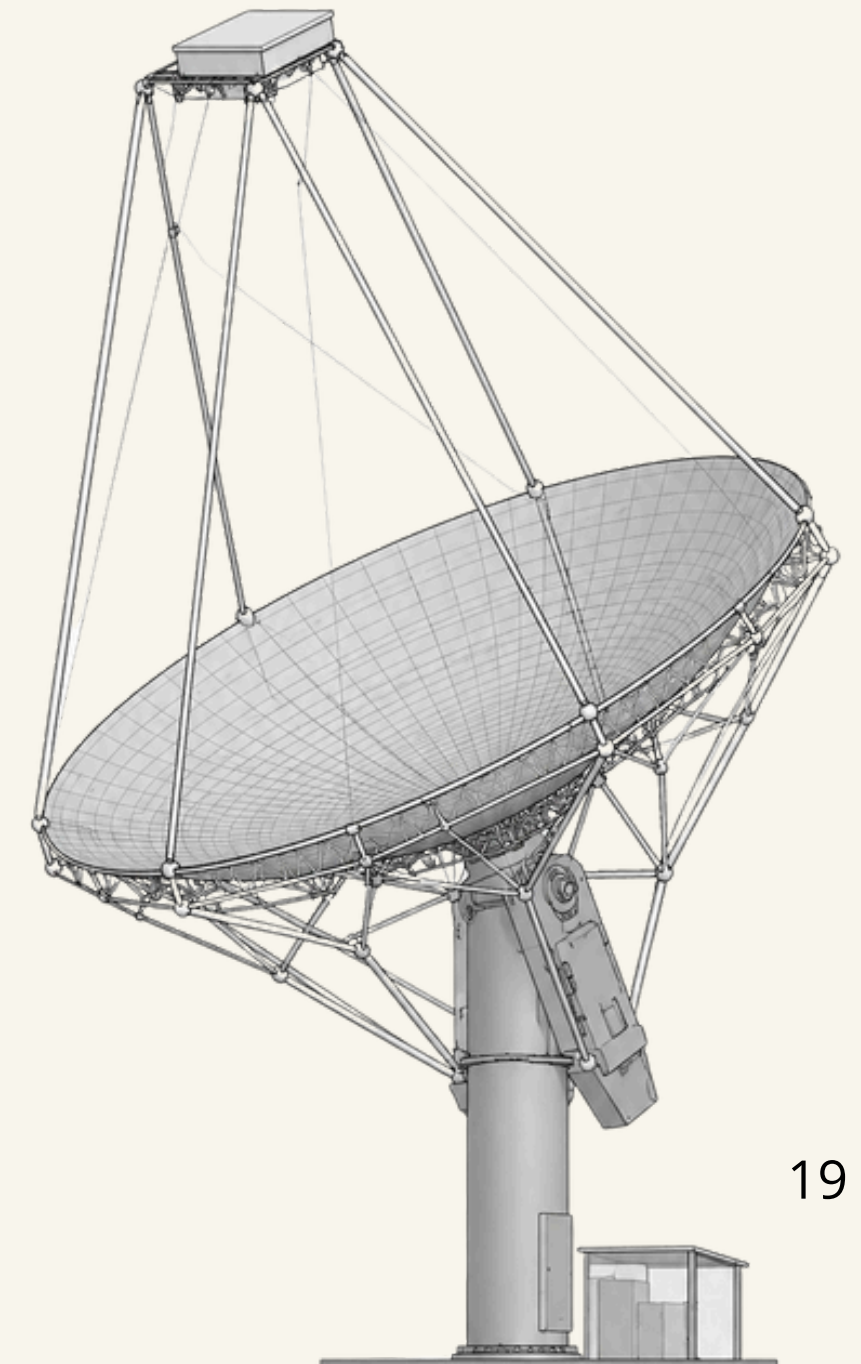


# SIMULATING AN IART OVERVIEW

## Air shower images

Results with air shower simulations

Different directions



# DIFFERENT DIRECTIONS

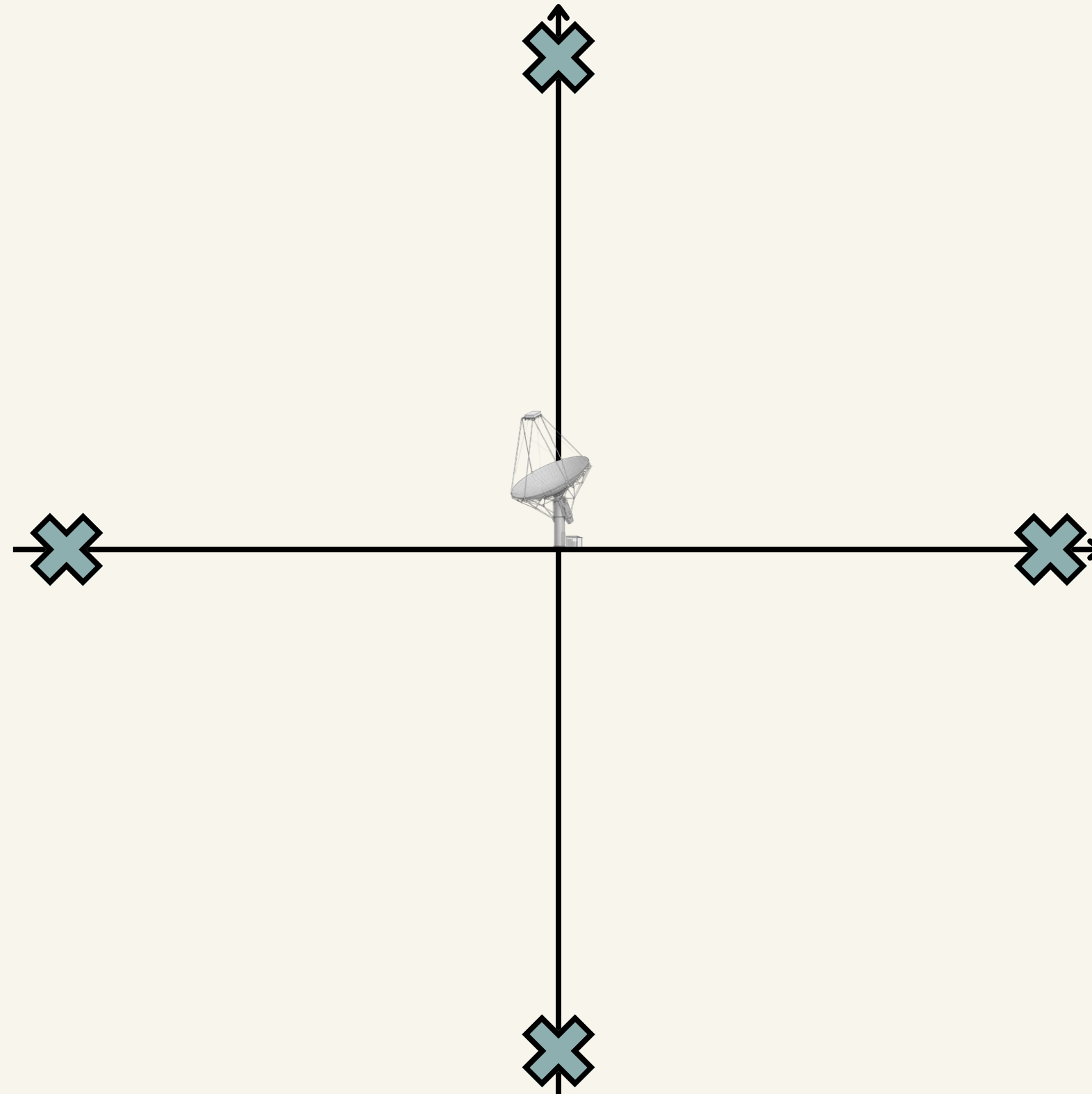
## Test if directional information is preserved

4 showers with:

- Gamma-ray
- Energy 1 TeV
- $\pm 100$  m EW/NS
- Zenith  $0^\circ$

Antenna's:

- 7 – 10 GHz  
Butterworth
- No noise



# DIFFERENT DIRECTIONS

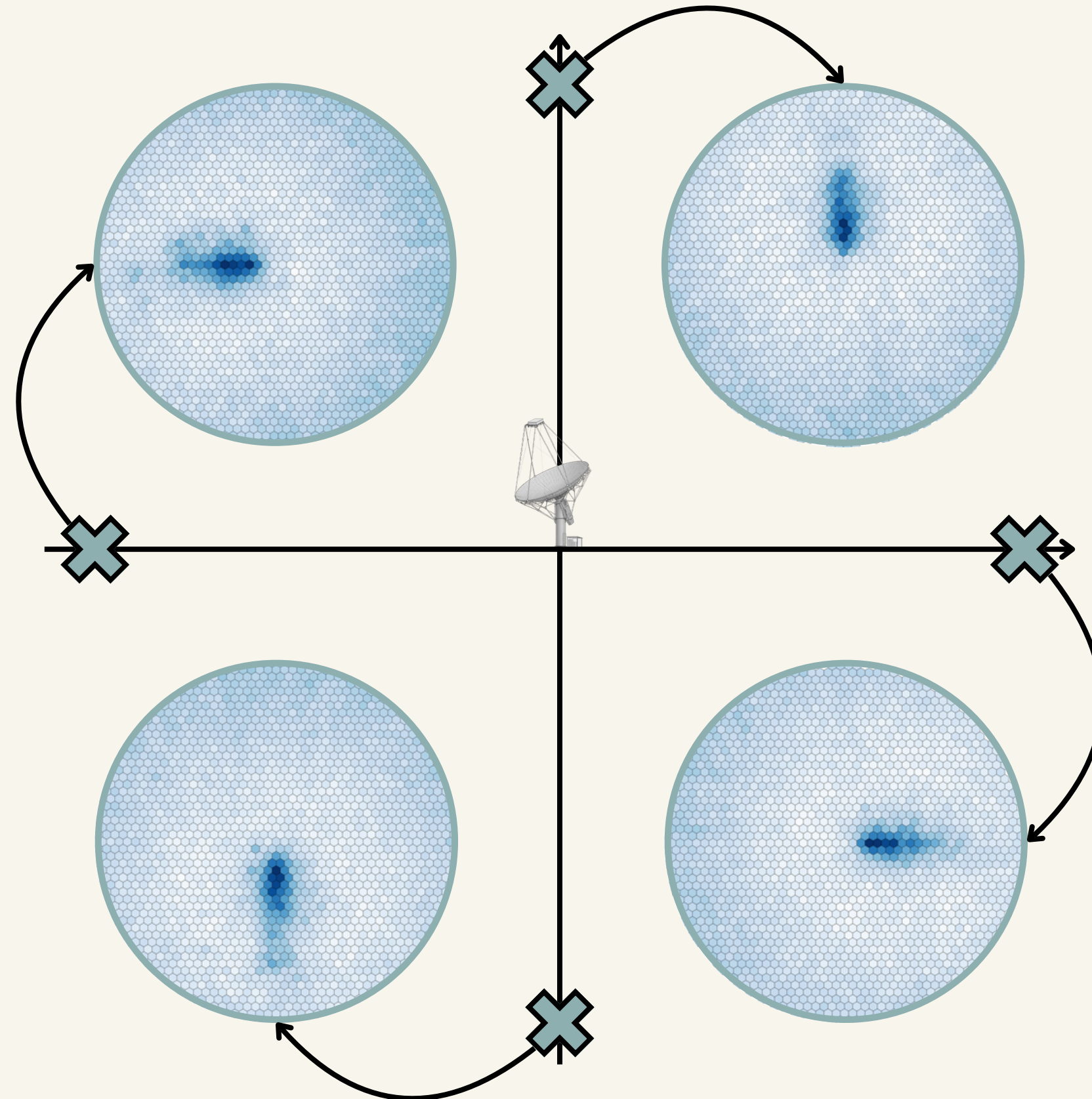
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**Directional information is correctly preserved**

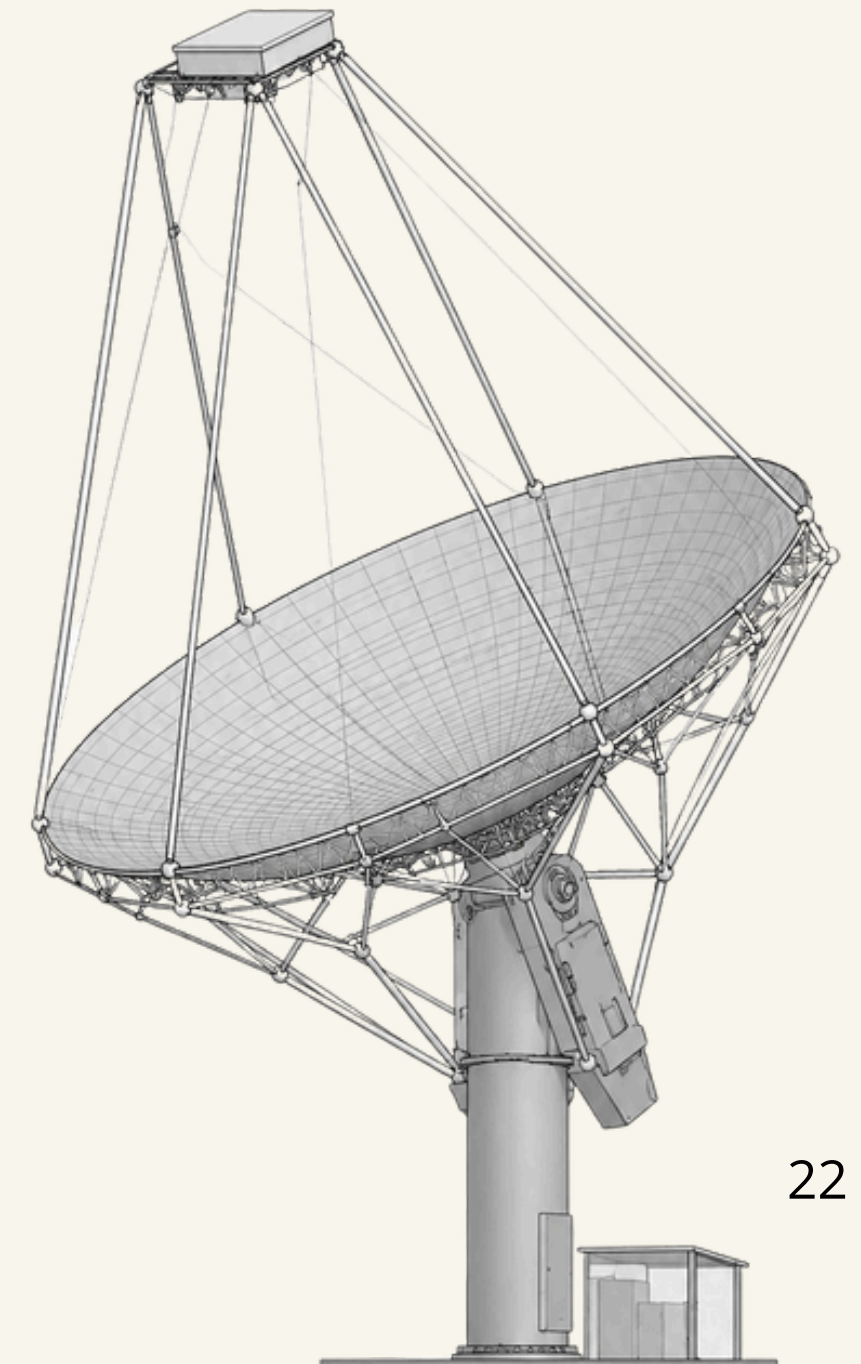
# SIMULATING AN IART OVERVIEW

## Air shower images

Results with air shower simulations

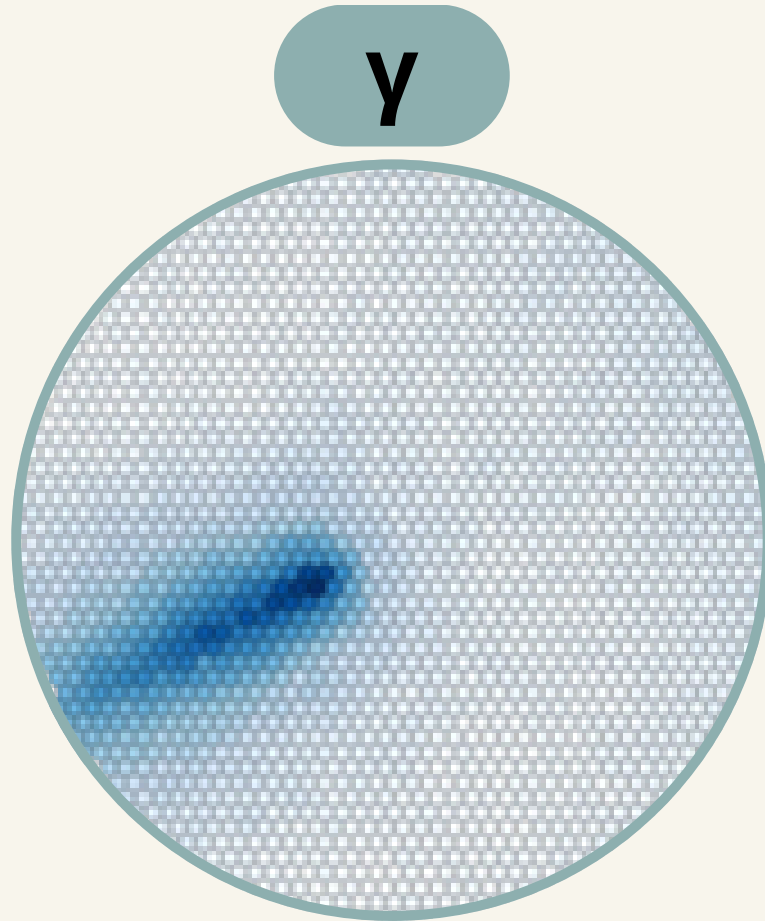
Different directions

Different primaries



# DIFFERENT PRIMARIES

10 TeV



## Test different primaries

Shower parameters:

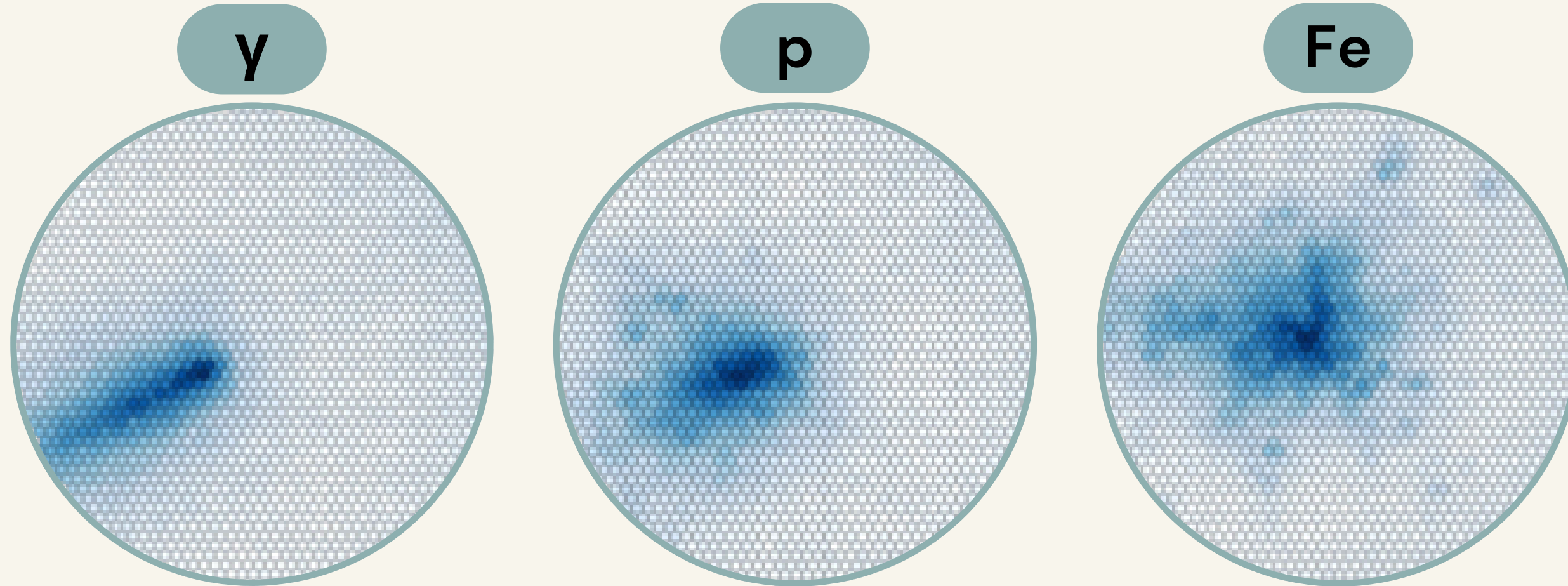
- Energy 10 TeV
- Core at (100, 50) m
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# DIFFERENT PRIMARIES

10 TeV



Fragmentation of EM  
shower component

## Test different primaries

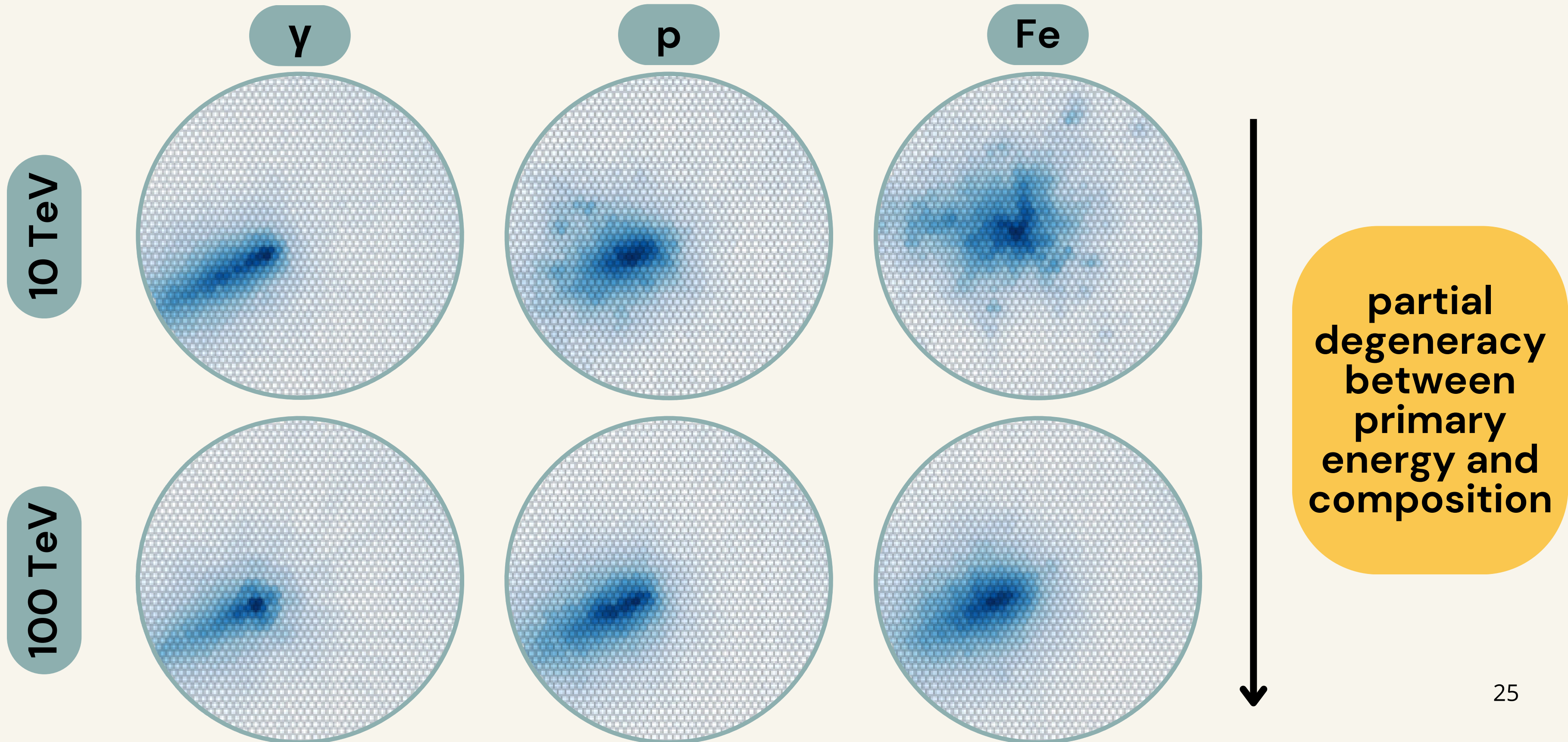
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# SIMULATING AN IART OVERVIEW

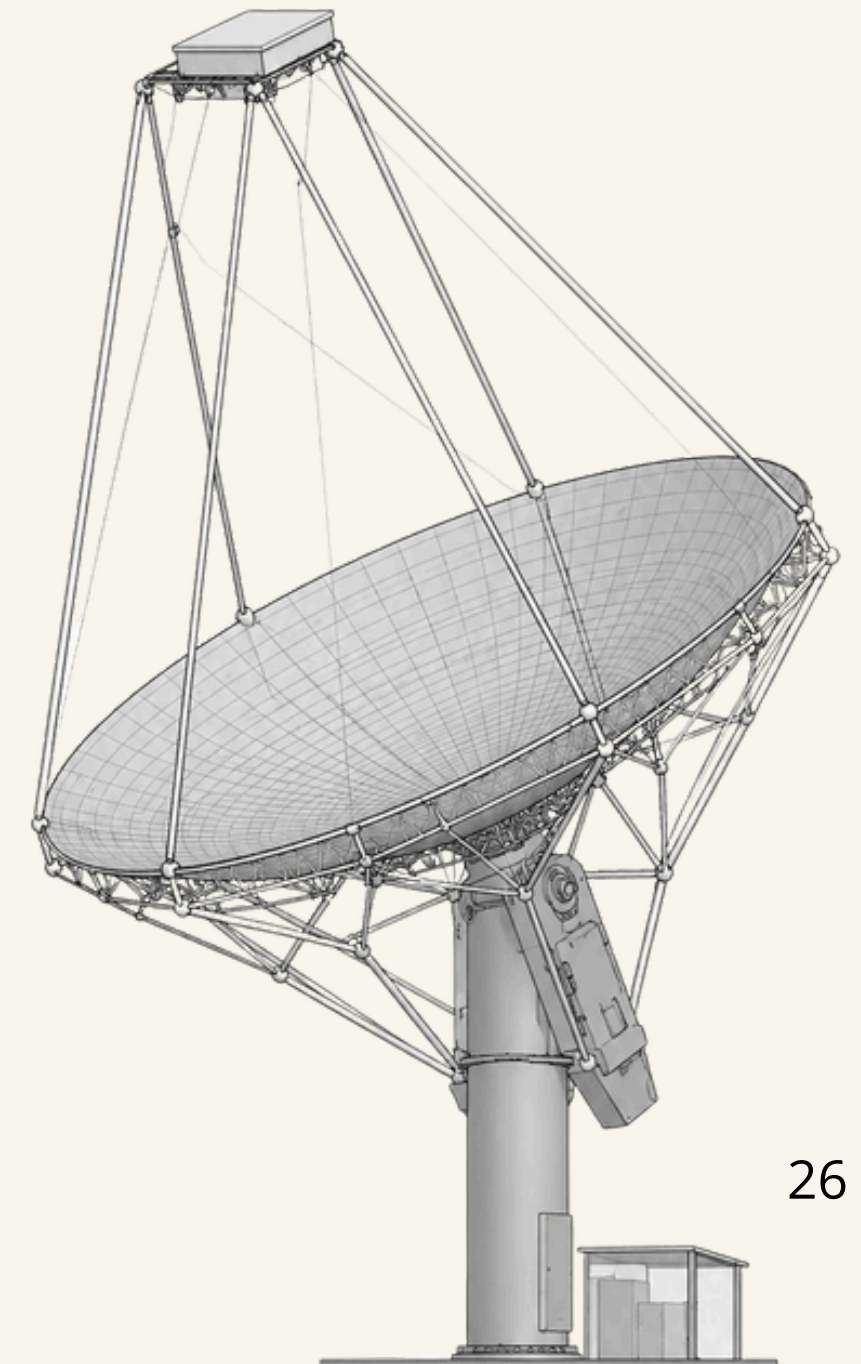
## Air shower images

Results with air shower simulations

Different directions

Different primaries

Different frequency bands



# DIFFERENT FREQUENCIES

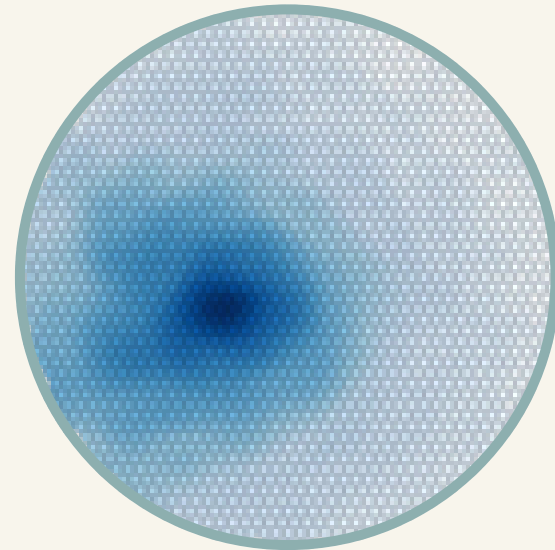
1-2 GHz

2-4 GHz

4-8 GHz

8-12 GHz

10 TeV

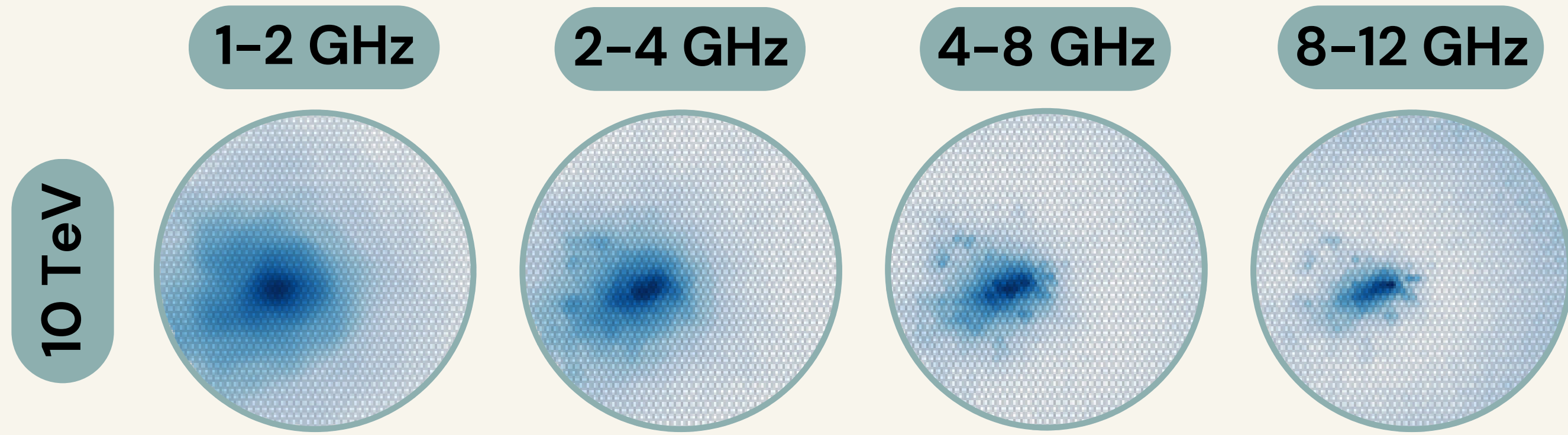


## Test different frequency bands

Shower parameters:

- Proton
- Energy 10 TeV
- Core at (100, 50) m
- Zenith 0°
- No noise

# DIFFERENT FREQUENCIES



**Decreasing coherence**

**Test different frequency bands**

Shower parameters:

- Proton
- Energy 10 TeV
- Core at (100, 50) m
- Zenith 0 °
- No noise

- Emission more concentrated around shower axis
- Fine-scale structures and sub shower contributions
- Lose some intensity

# **SIMULATING AN IART**

## **SUMMARY**

### **Simulation**

How (well) does the simulation work?

### **Air shower images**

Results with air shower simulations

# SIMULATING AN IART SUMMARY

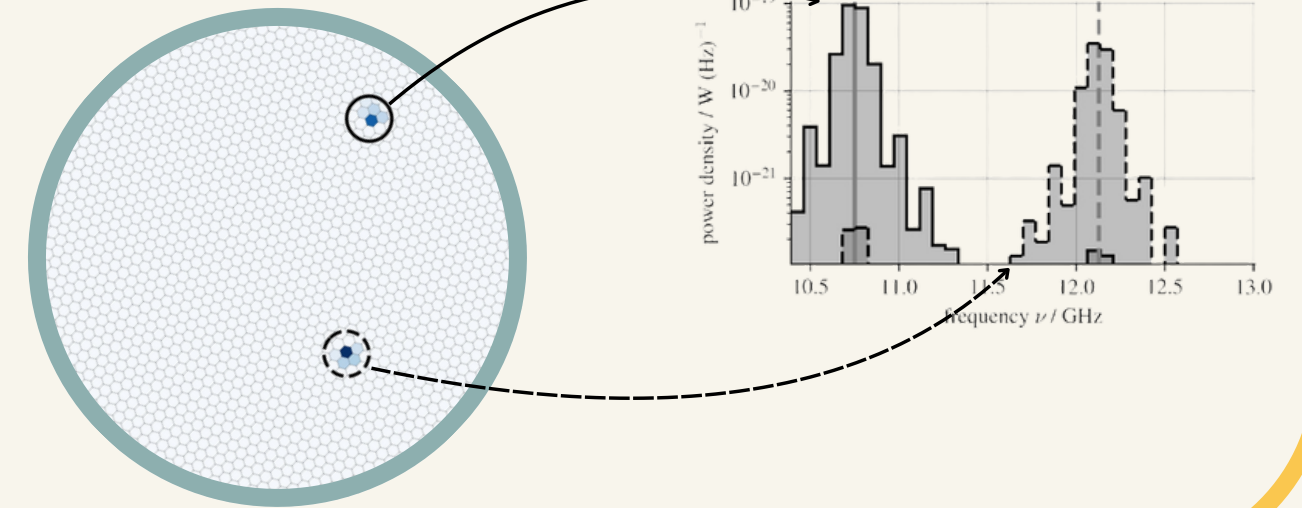
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Verification with 2  
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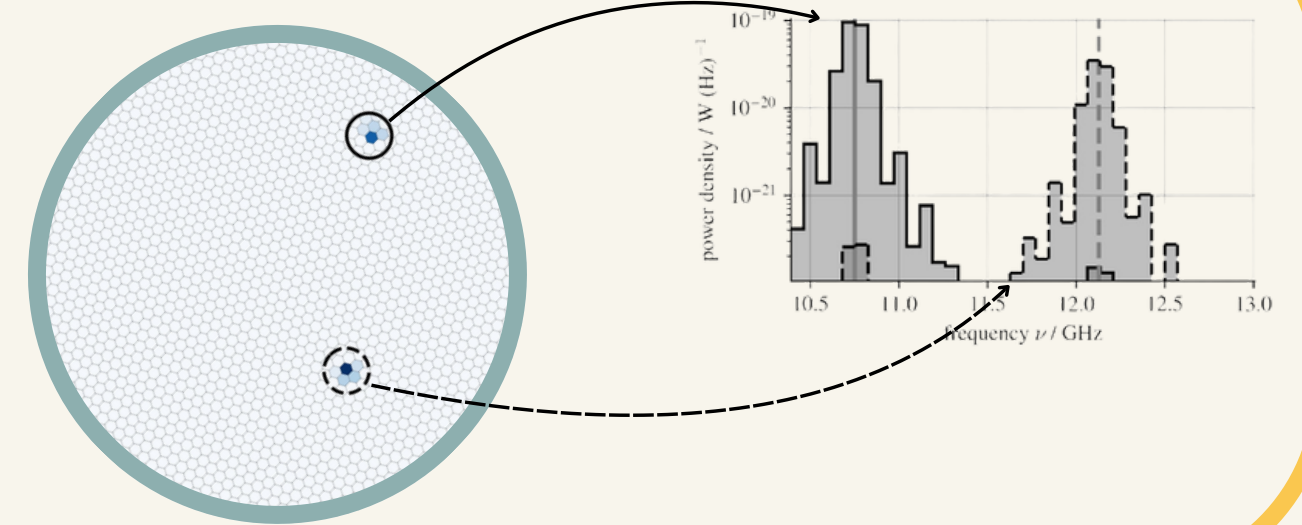


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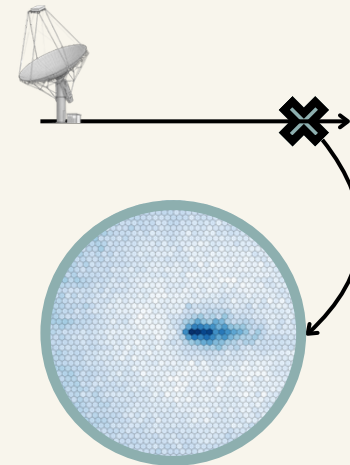
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Directional  
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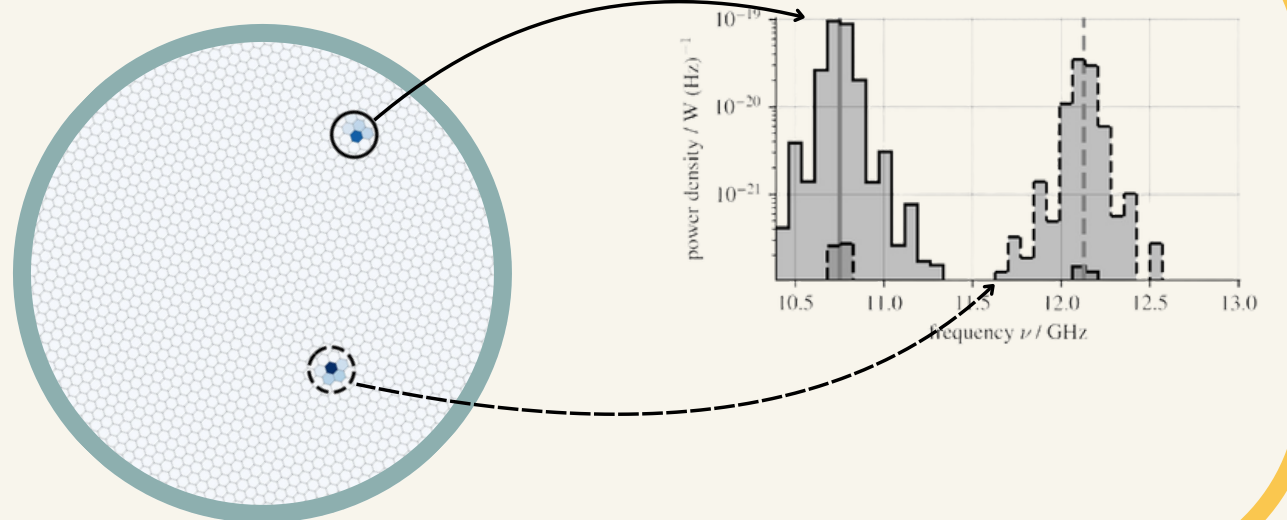
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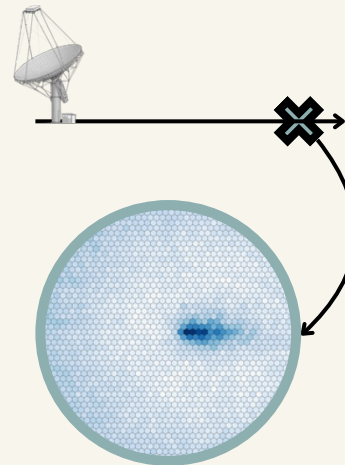
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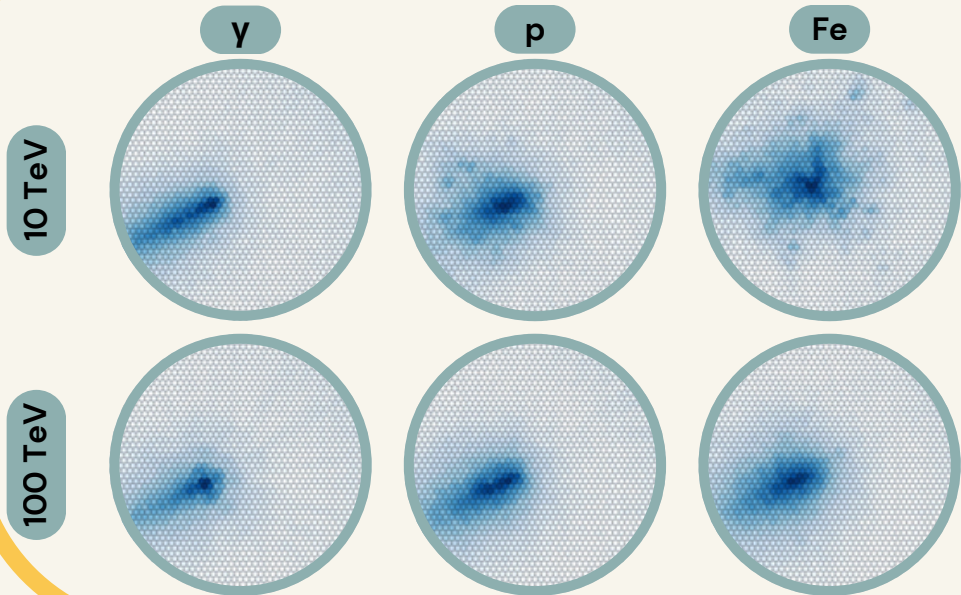
Verification with 2 plane waves



Directional information is correctly preserved



Fragmentation of EM shower component



partial degeneracy between primary energy and composition

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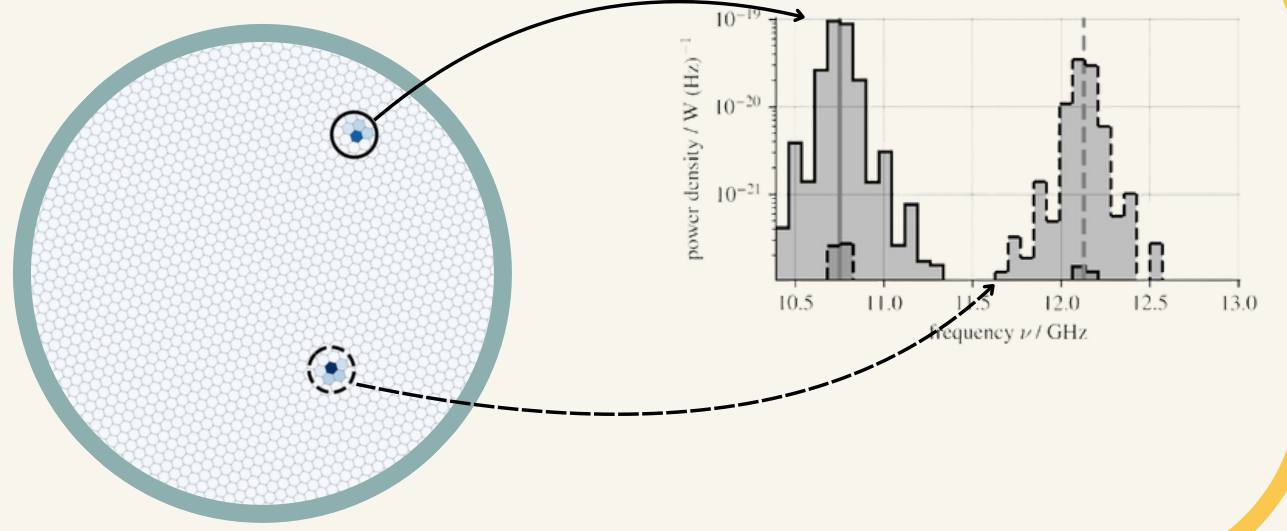
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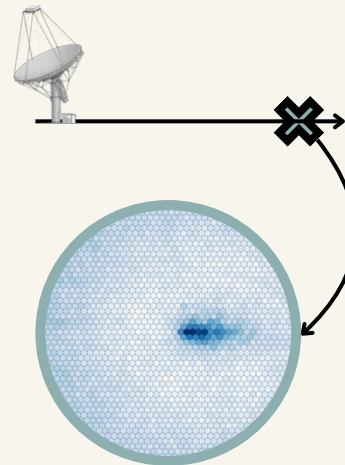
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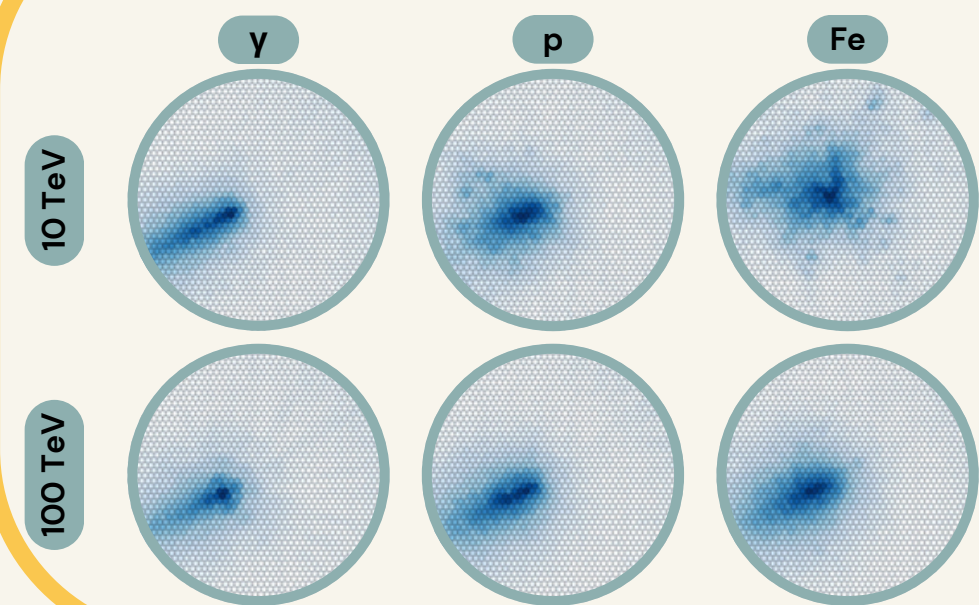
Verification with 2 plane waves



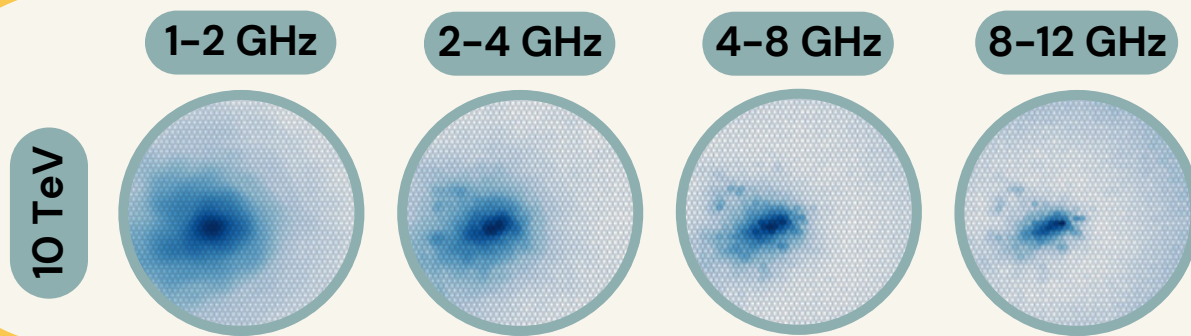
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Fragmentation of EM shower component



partial degeneracy between primary energy and composition



Decreasing coherence

# **SIMULATING AN IART**

## **NOTES**

## **NEXT STEPS**

# SIMULATING AN IART

## NOTES

## NEXT STEPS

### Telescope design

Here only one type of telescope is shown. Simulations have been done for three different sizes of telescopes.

Design of the telescopes was based on:

- Airy  
*Estimates the minimum mirror diameter which is required to potentially reach a specific angular resolution*
- Narrowing depth-of-field limits  
*Maximum useful mirror diameter before blurring*
- Atmospheric limits for radio (<25 GHz)

### Simulation verification

Not only done by 2 point sources.  
Also by ray tracing.

### No noise

The goal of this study was to show a proof of principle, not give a perfect estimate of the technique.

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## NEXT STEPS

### Realistic noise simulation & IRF

From back of the envelope calculations:

- E threshold ~ few PeV  
Dependent on:
  - Frequency band of antennas
  - Pixel size
  - Telescope structure

### Explore technical limitations

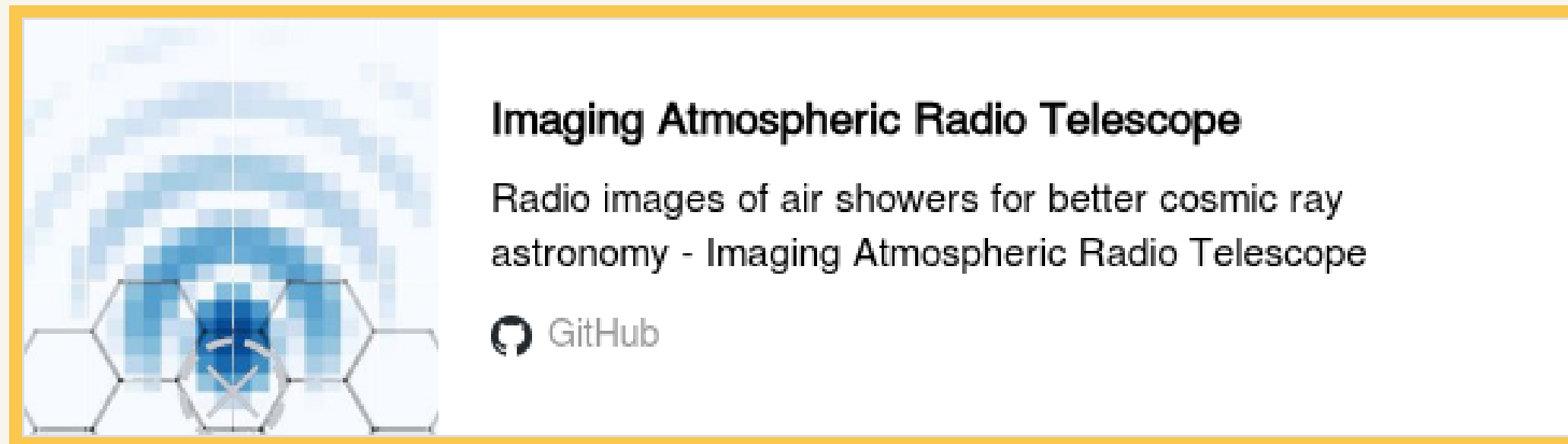
How do technical limitations influence the possibilities to reduce noise or enhance signal as much as possible?

### Look into different telescope lay-out

Broaden the look from IACT set-up to a more Trinity-like set-up for neutrino detection

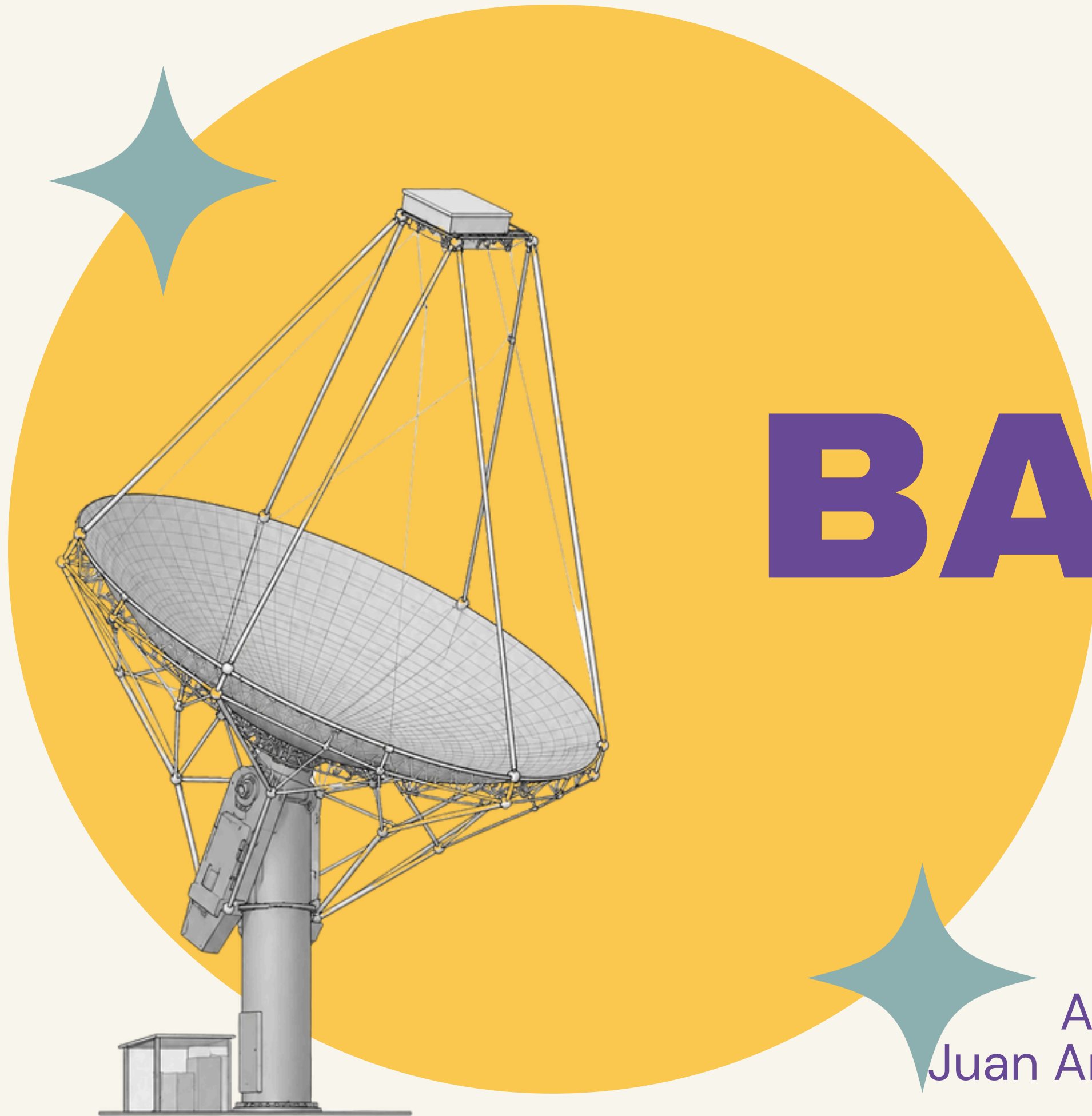
# SIMULATING AN IART

## GITHUB



The image shows a GitHub repository card for 'Imaging Atmospheric Radio Telescope'. On the left is a square thumbnail image showing a blue-toned radio image of an air shower with a hexagonal grid overlay. To the right of the thumbnail, the repository title 'Imaging Atmospheric Radio Telescope' is displayed in bold. Below the title is a descriptive sentence: 'Radio images of air showers for better cosmic ray astronomy - Imaging Atmospheric Radio Telescope'. At the bottom left of the card is the GitHub logo and the text 'GitHub'.

email: [anne.timmermans@mpi-hd.mpg.de](mailto:anne.timmermans@mpi-hd.mpg.de)



# BACK-UP

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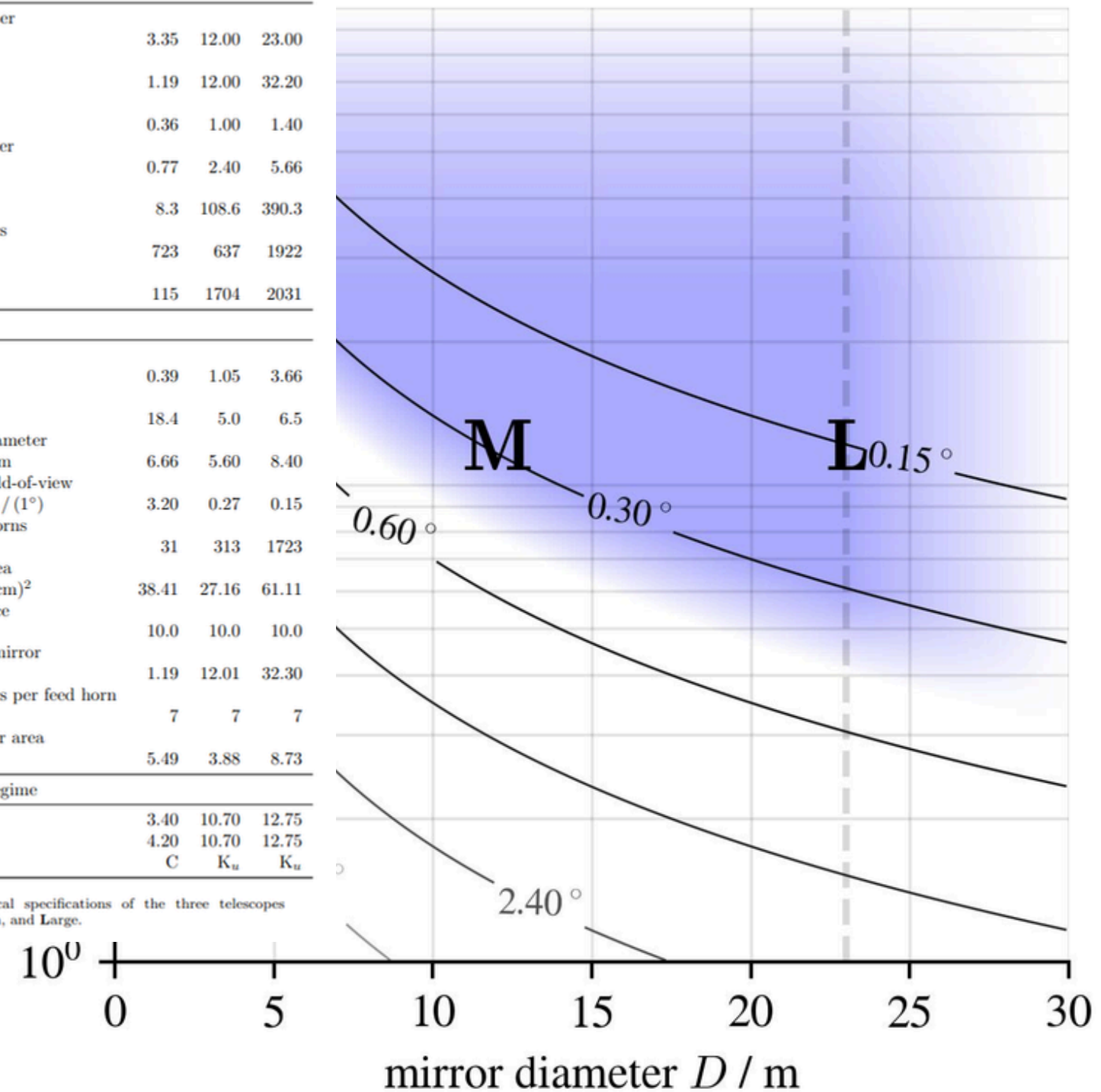
# TELESCOPE DESIGN

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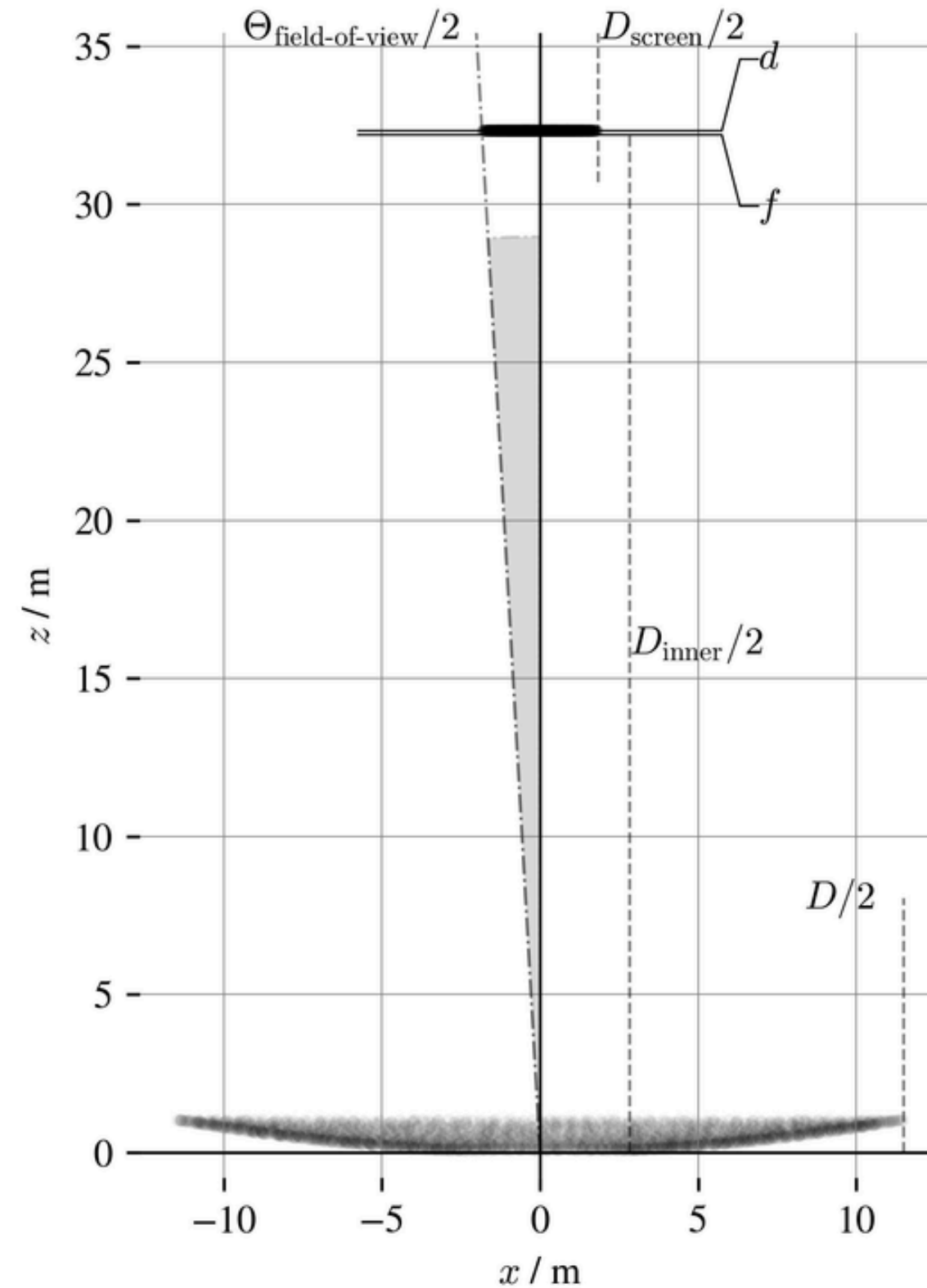
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- Narrowing depth-of-field limits  
*Maximum useful mirror diameter before blurring*
- Atmospheric limits for radio (<25 GHz)

Telescopes	C	M	L
<b>Mirror</b>			
outer diameter			
$D / \text{m}$	3.35	12.00	23.00
focal-length			
$f / \text{m}$	1.19	12.00	32.20
focal-ratio			
$f / D$	0.36	1.00	1.40
inner diameter			
$D_{\text{inner}} / \text{m}$	0.77	2.40	5.66
area			
$A_{\text{mirror}} / \text{m}^2$	8.3	108.6	390.3
num. scatters			
$M$	723	637	1922
scatter area			
$A_{\text{SM}} / (\text{cm})^2$	115	1704	2031
<b>Camera</b>			
diameter			
$D_{\text{camera}} / \text{m}$	0.39	1.05	3.66
field-of-view			
$\Theta_{\text{fov}} / (1^\circ)$	18.4	5.0	6.5
feed horn diameter			
$D_{\text{feed-horn}} / \text{cm}$	6.66	5.60	8.40
feed horn field-of-view			
$\Theta_{\text{feed-horn-full}} / (1^\circ)$	3.20	0.27	0.15
num. feed horns			
	31	313	1723
feed horn area			
$A_{\text{feed-horn}} / (\text{cm})^2$	38.41	27.16	61.11
focus distance			
$g / \text{km}$	10.0	10.0	10.0
distance to mirror			
$d / \text{m}$	1.19	12.01	32.30
num. scatters per feed horn			
$N$	7	7	7
scatter center area			
$A_{\text{SF}} / (\text{cm})^2$	5.49	3.88	8.73
<b>Frequency regime</b>			
$\nu_{\text{start}} / \text{GHz}$	3.40	10.70	12.75
$\nu_{\text{stop}} / \text{GHz}$	4.20	10.70	12.75
IEEE band	C	K <sub>u</sub>	K <sub>u</sub>

Table 2: Optical specifications of the three telescopes Crome, Medium, and Large.



# TELESCOPE DESIGN



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# WAIT... BUT WHY DOES IT WORK?

## Why the Huygens principle works:

- Traces sampled on the mirror contain directional information encoded in their relative phases and arrival times
- The Huygens propagation then acts like a coherent beamformer
- For each camera pixel the propagation delays compensate the phase gradient of the waves arriving from the corresponding direction, causing constructive interference
- Signals from other directions are not phase-matched and therefore interfere destructively, producing a much weaker response

# COMPARISON TO RAY-TRACING

## Energy conservation:

Huygens reproduces the ray-tracing prediction across the full field of view, with only small fluctuations. No systematic off-axis loss is observed as in the smaller telescopes.

## Point spread function (PSF):

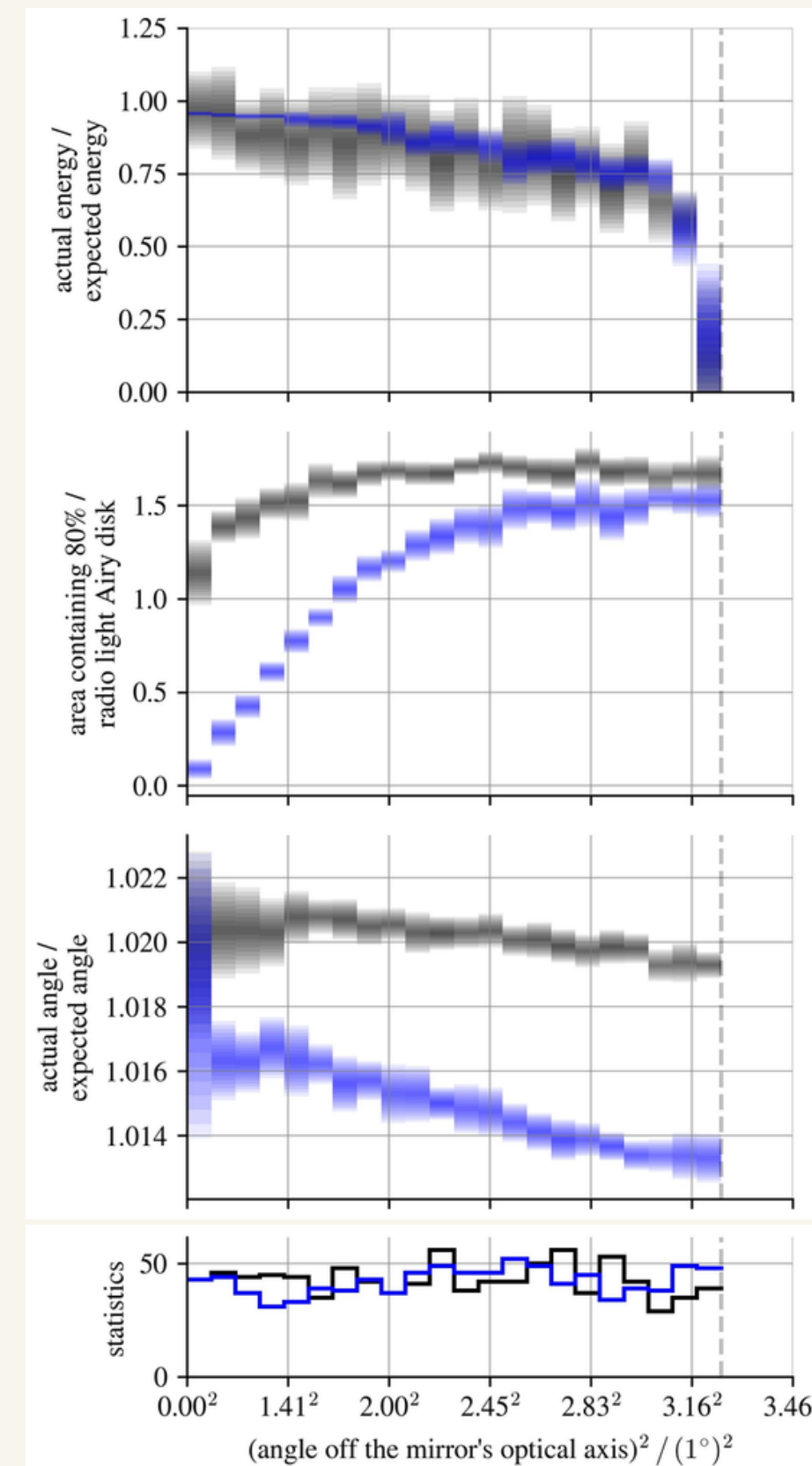
Near the optical axis, the Huygens PSF approaches the diffraction limit (Airy disk), demonstrating correct wave-optical behavior.

At larger field angles, the Huygens PSF grows due to mirror aberrations and approaches the ray-tracing prediction.

Thus, the Huygens method smoothly transitions from diffraction-dominated to aberration-dominated imaging.

## Distortion:

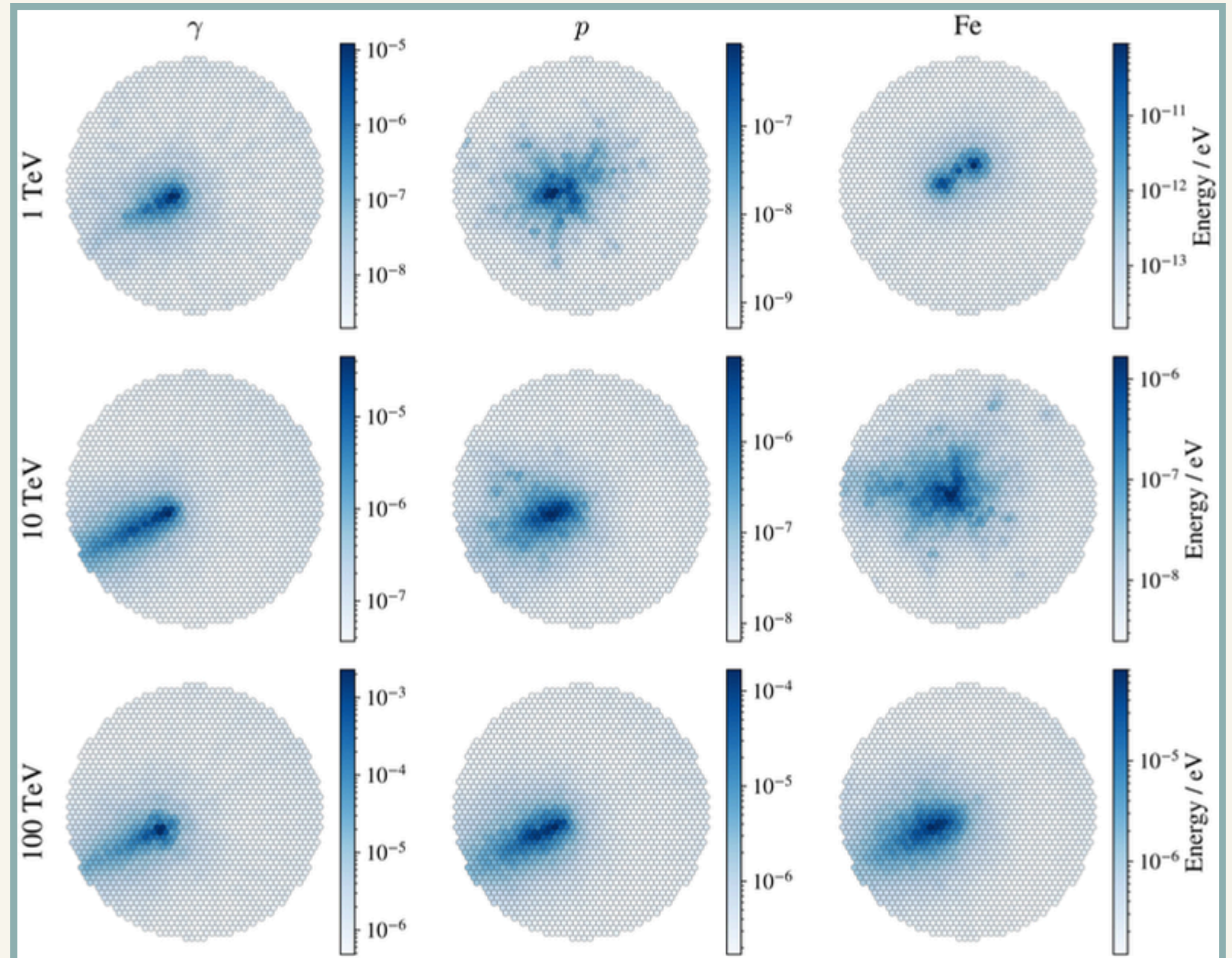
Both methods predict a small pincushion distortion. Huygens yields a distortion factor of approximately  $DIS=1.019$ , in close agreement with ray tracing, although it systematically predicts slightly smaller distortions.



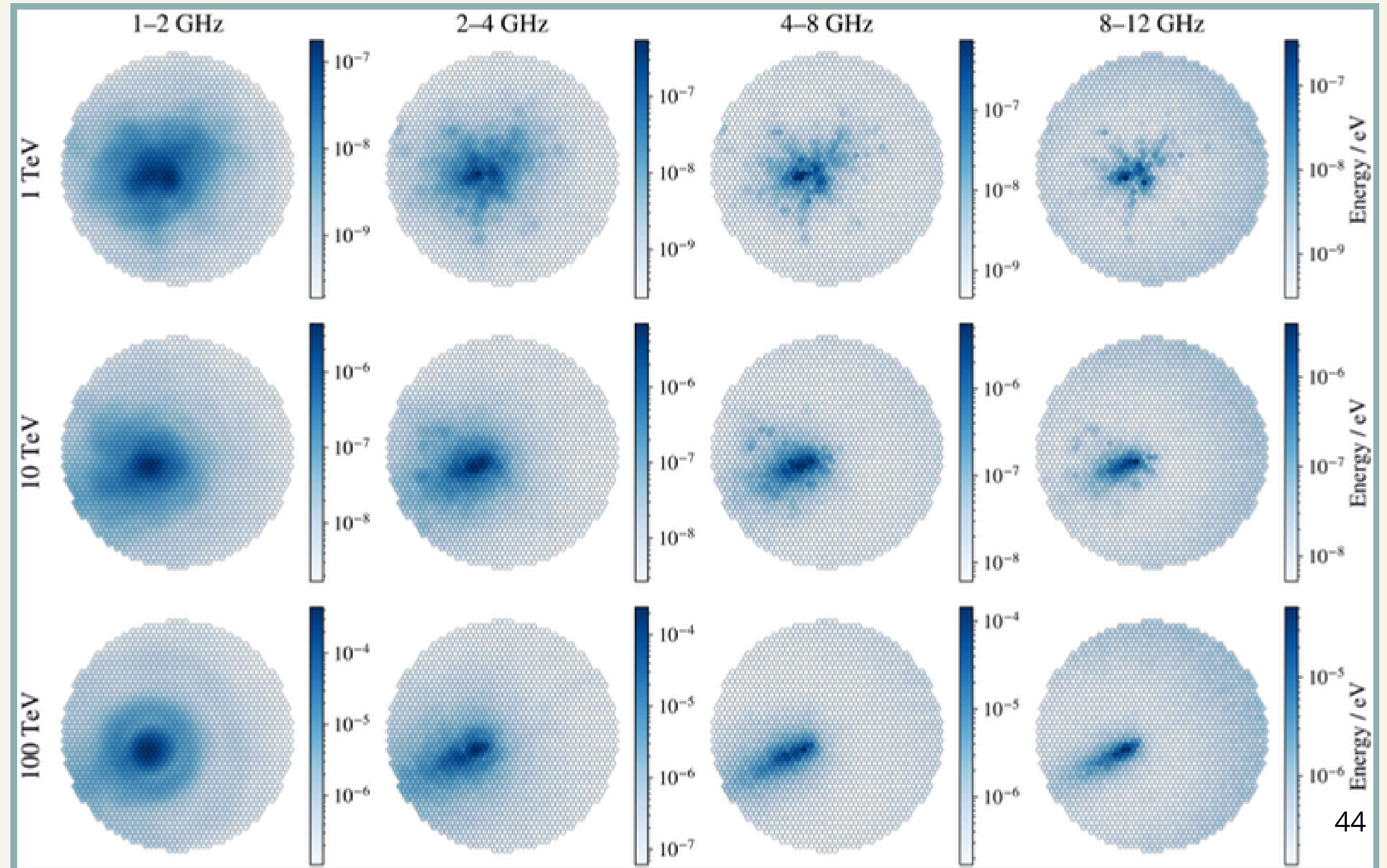
Ray-tracing

Simulation

# DIFFERENT PARTICLES



# DIFFERENT FREQUENCIES



# TRINITY-LIKE SET-UP?!

