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Status of SWGO TURBO:

The Southern Wide-field
Gamma-ray Observatory The Utility for Radio
Beam-formed Observations

interferometric radio
detection of air
showers

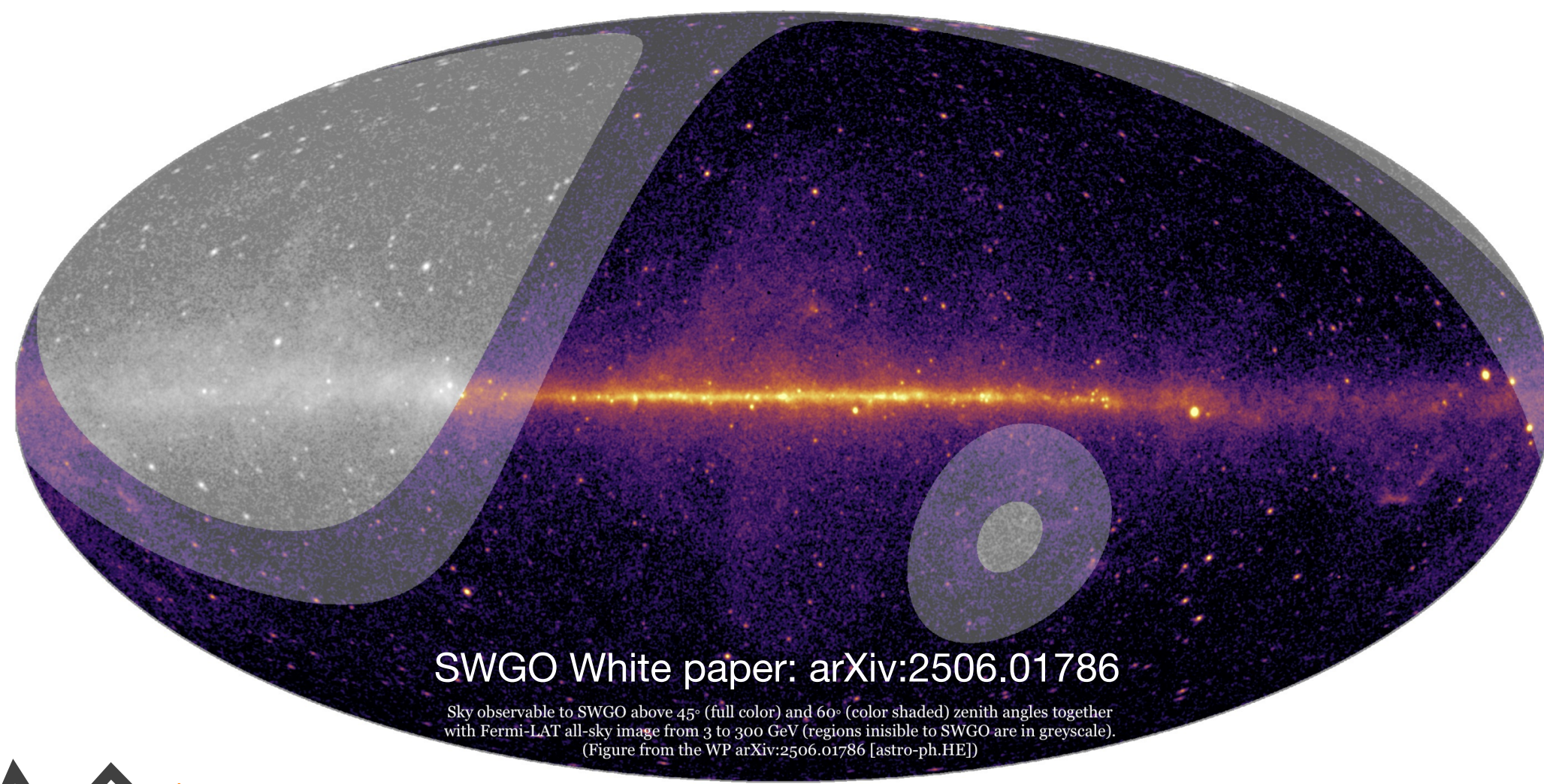
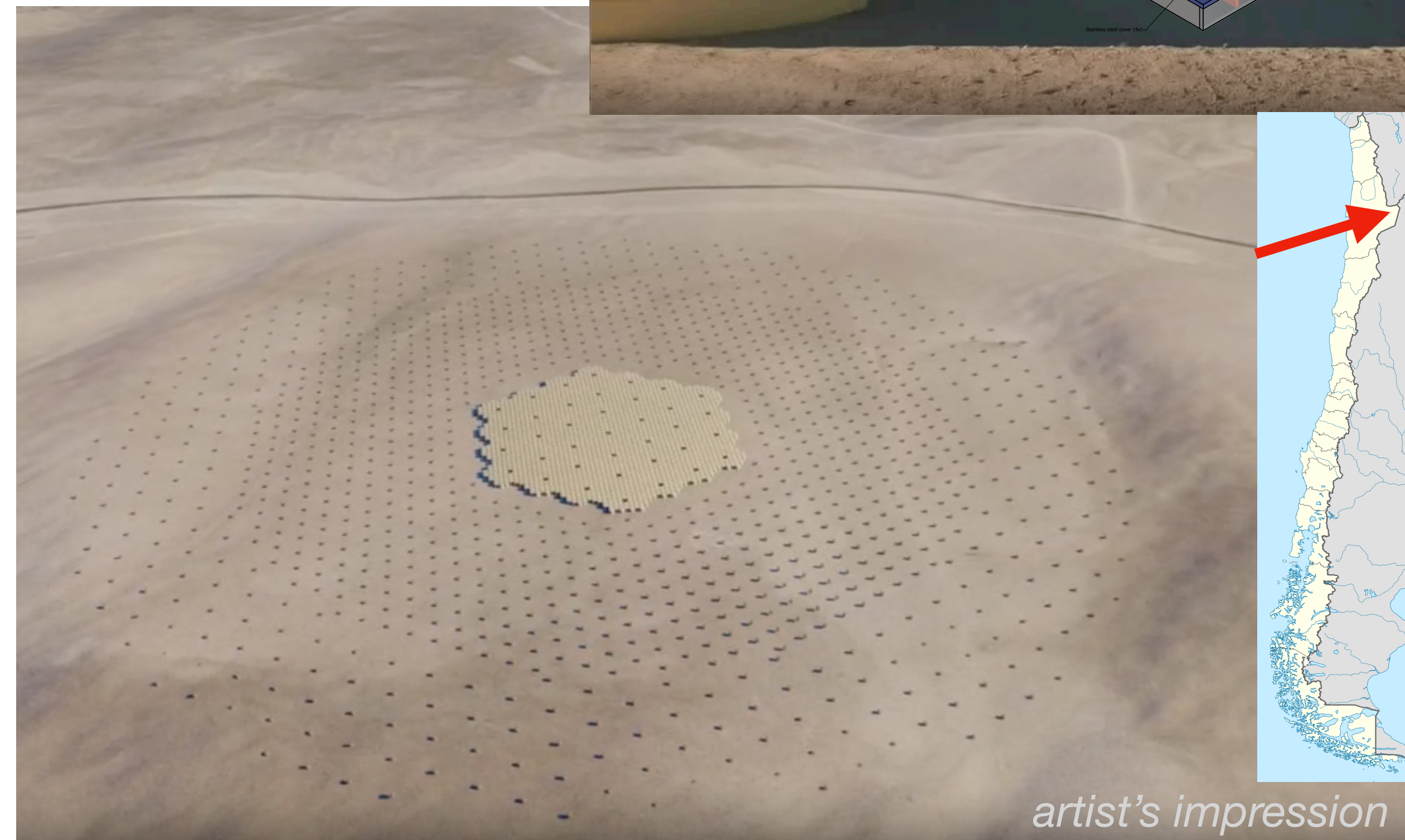
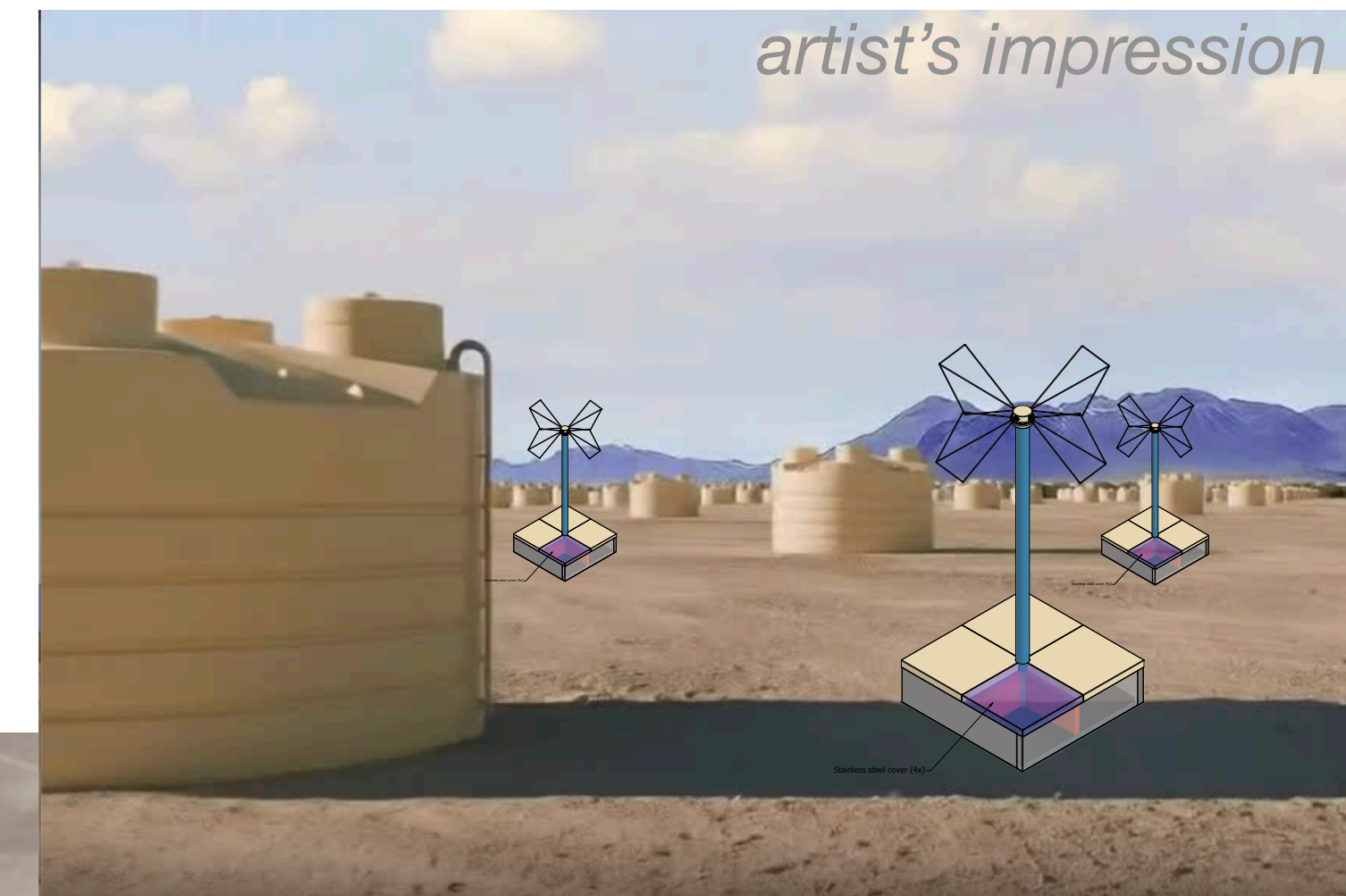
Bjarni Pont,
for the SWGO Collaboration

ARENA
Karlsruhe
June 9, 2026

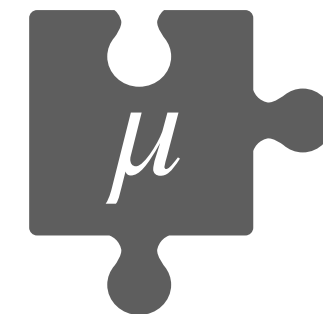
Pampa la Bola, Atacama, Chile

- **Southern Wide-field Gamma-ray Observatory**
 - No wide-view γ -observatories in the South!
 - North: HAWC/LHAASO
- Survey: new sources, TeV Halo's, Micro-quasars,...
- Transients: AGNs, GRBs, follow-up (KM3NeT/GW)
- ~100GeV to **PeV photon** detection
- Detailed **air shower** observations

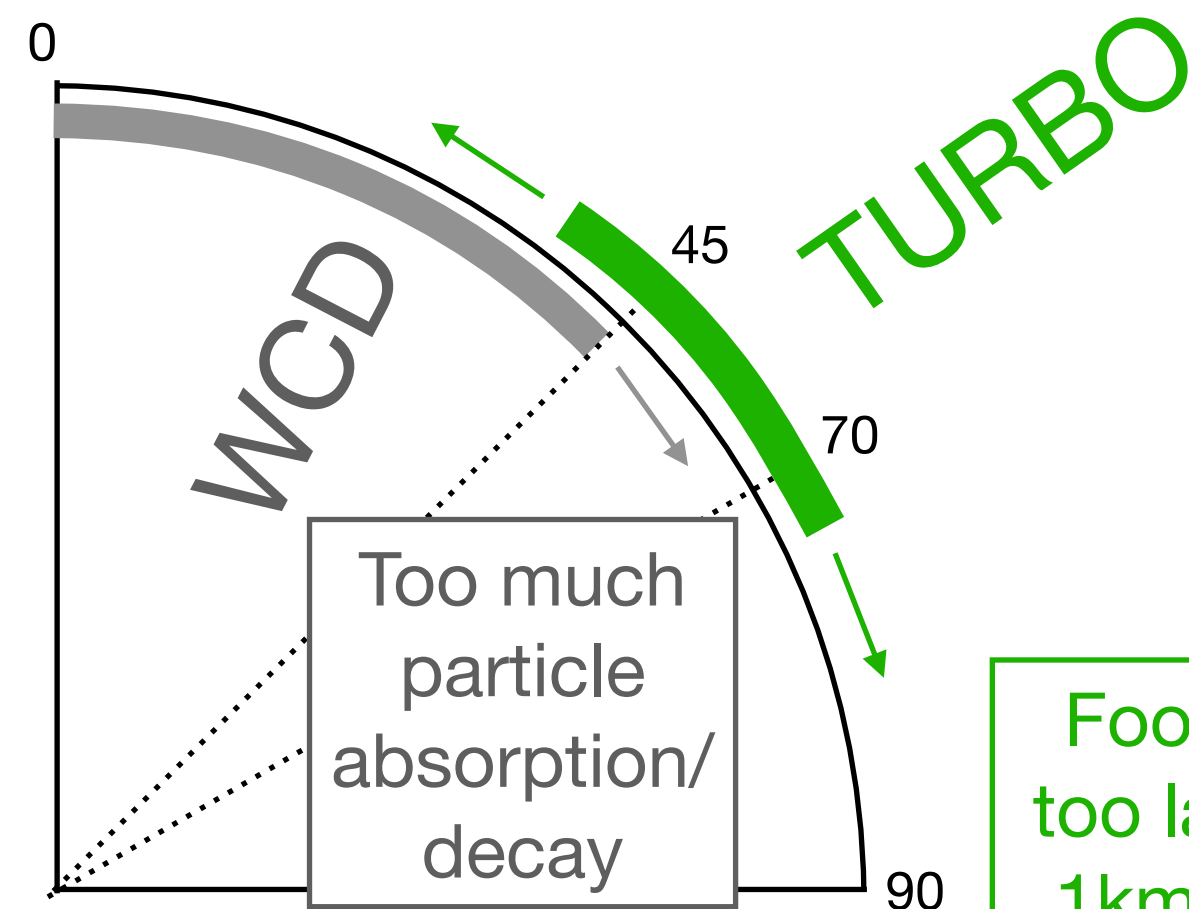
- 4770m altitude
- Atacama desert, Chile (near ALMA)
- Area: ~1km²
- ~ 3000-5000 WCD
- ~ 800 radio antennas



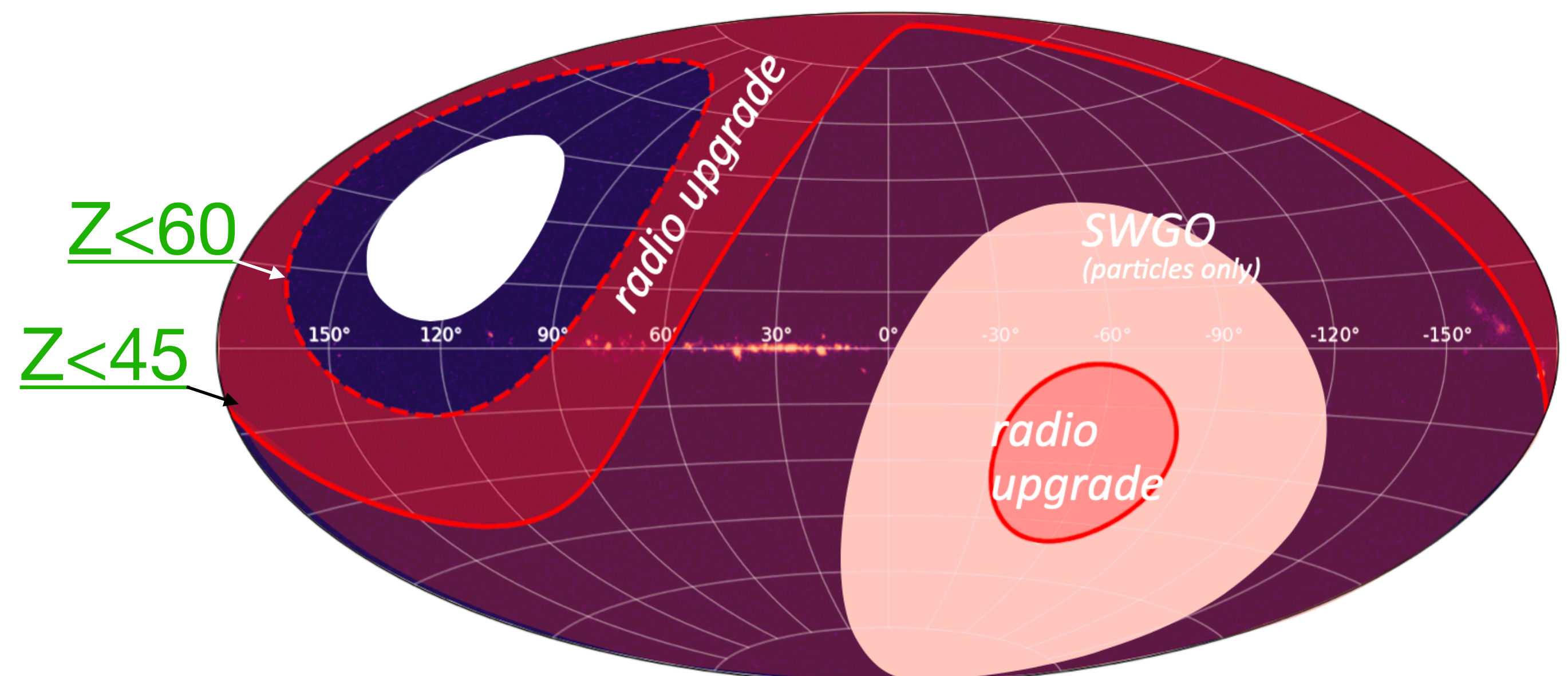
- **Gammas** at $>\text{PeV}$
 - Extend **sky coverage**: $Z=45-70$
 - Improved **pointing**: $<0.1\text{deg}$ angular resolution
- **Charged particles** PeV-EeV (Methods demonstrated at Auger at EeV energies)
 - **Energy** scale
 - Longitudinal profile from **interferometry** (X_{max} , etc.)
 - **Hybrid** observations $\rightarrow$ studying hadr. interactions, ...



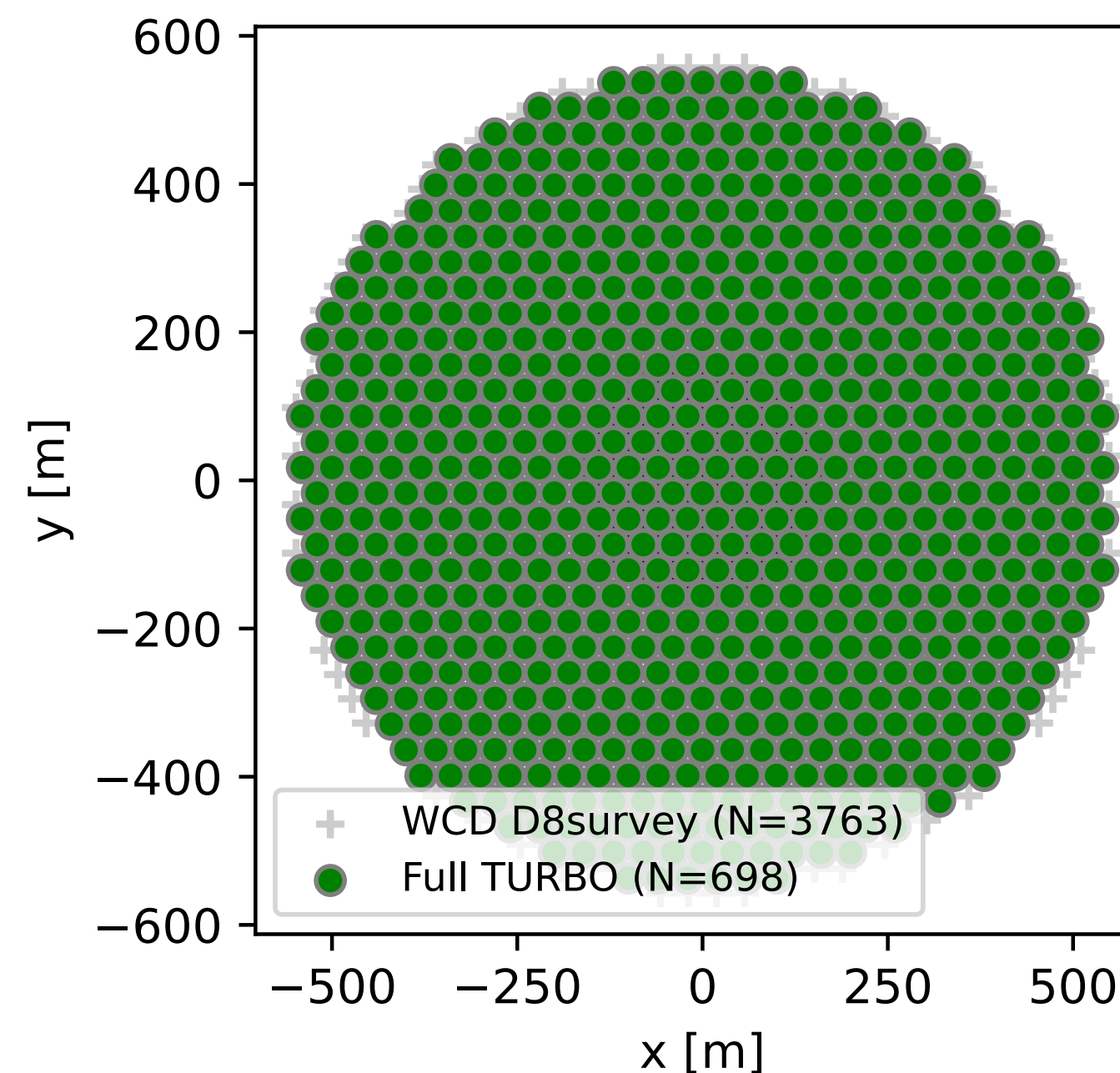
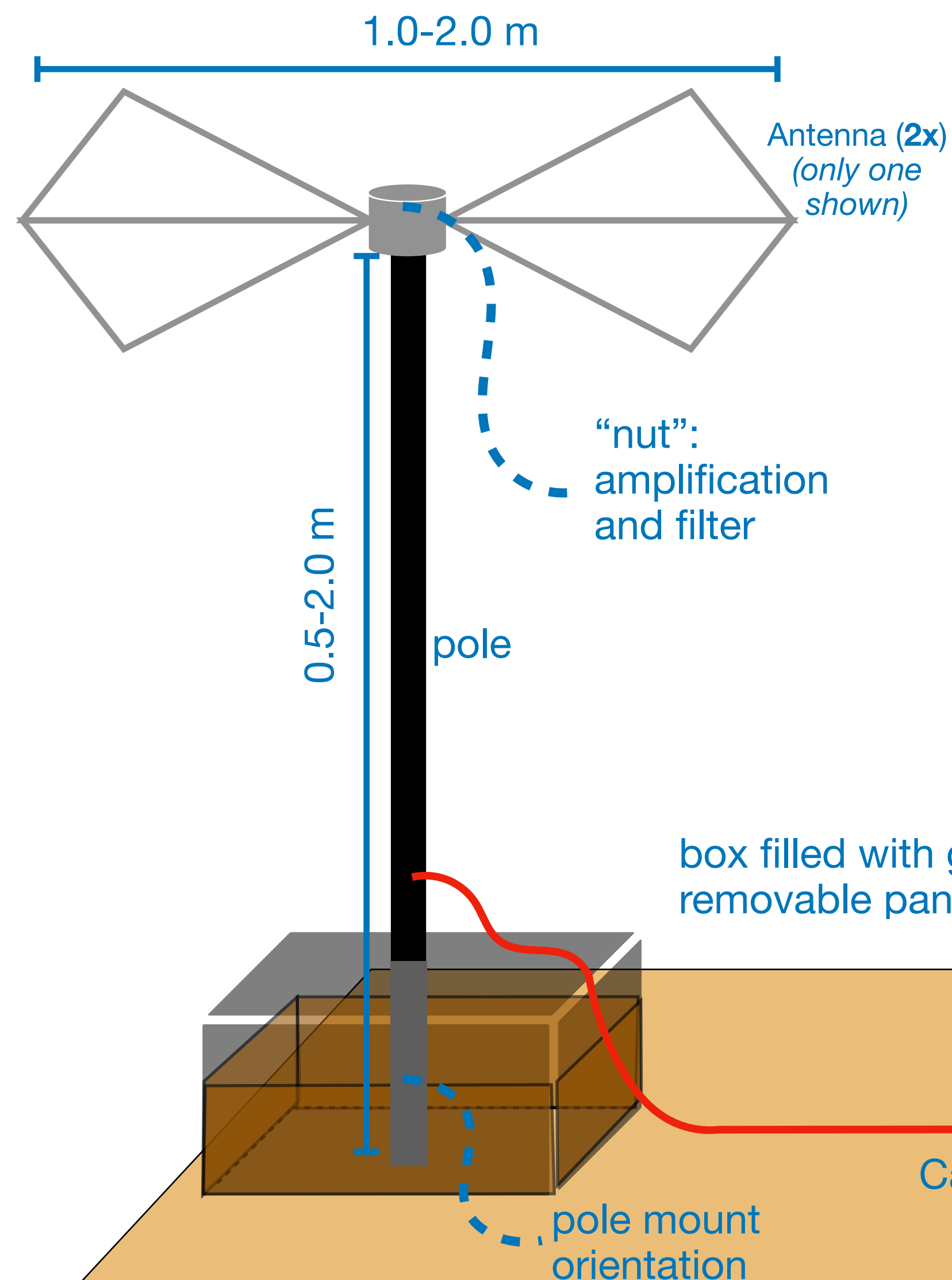
- Footprints too small
- X_{max} in ground



Footprints
too large for
1km² array

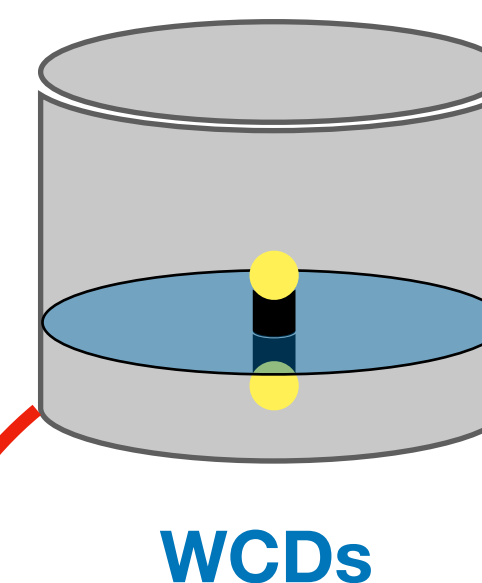


Conceptual design

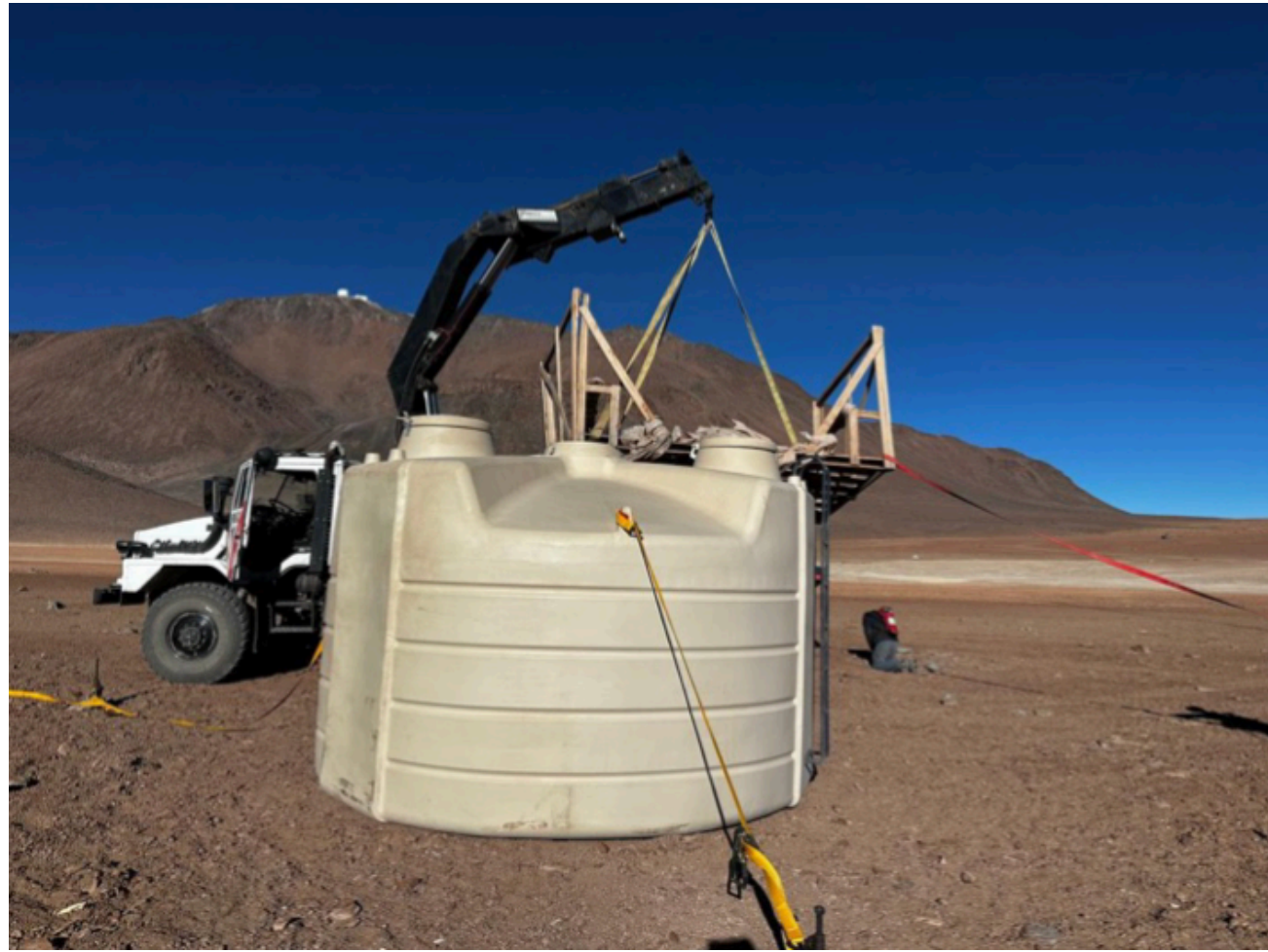


- Based on *horizon antenna*
- ~700-800 stations
- Uniform grid (1km²)
- Integrated **within** SWGO (shared timing!)
- Frequency band: 50-200MHz

Field node:
7 antenna
X tanks



Breaking ground: Now

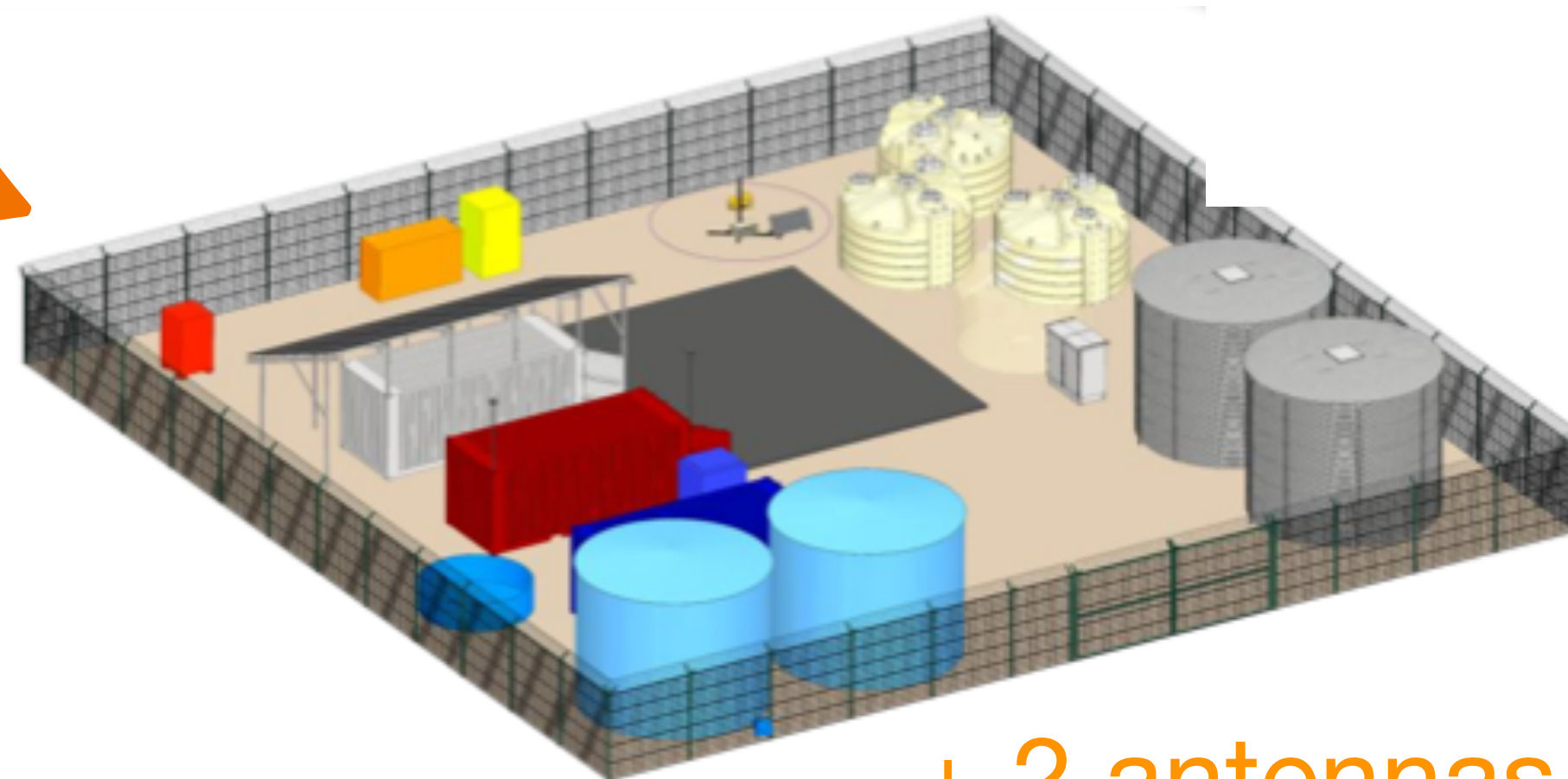


Engineering Array: 2027 - “2030”

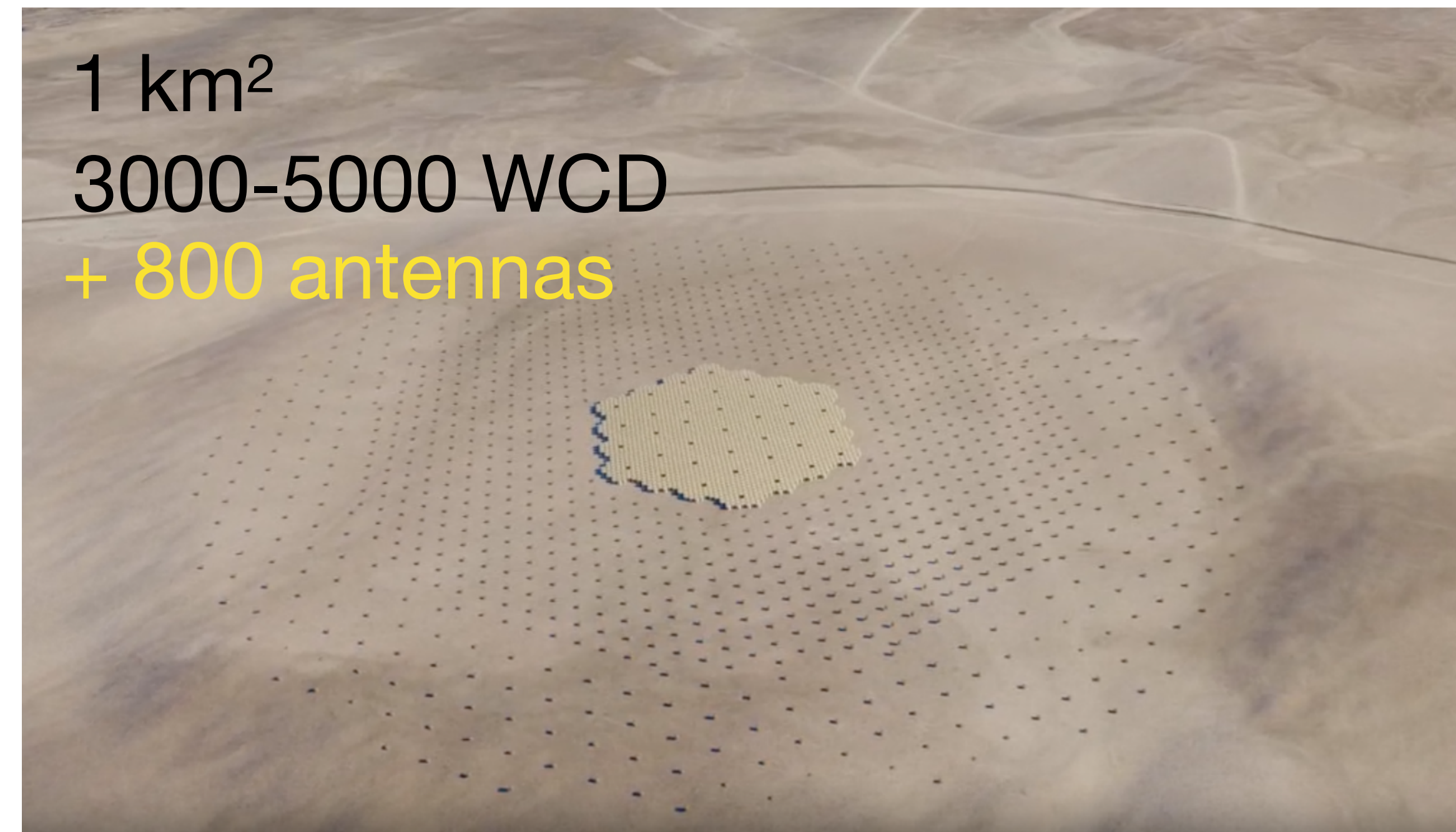
Various WCD
+ ~50 antennas

Full Array: “2030” -

Pathfinder: 2026

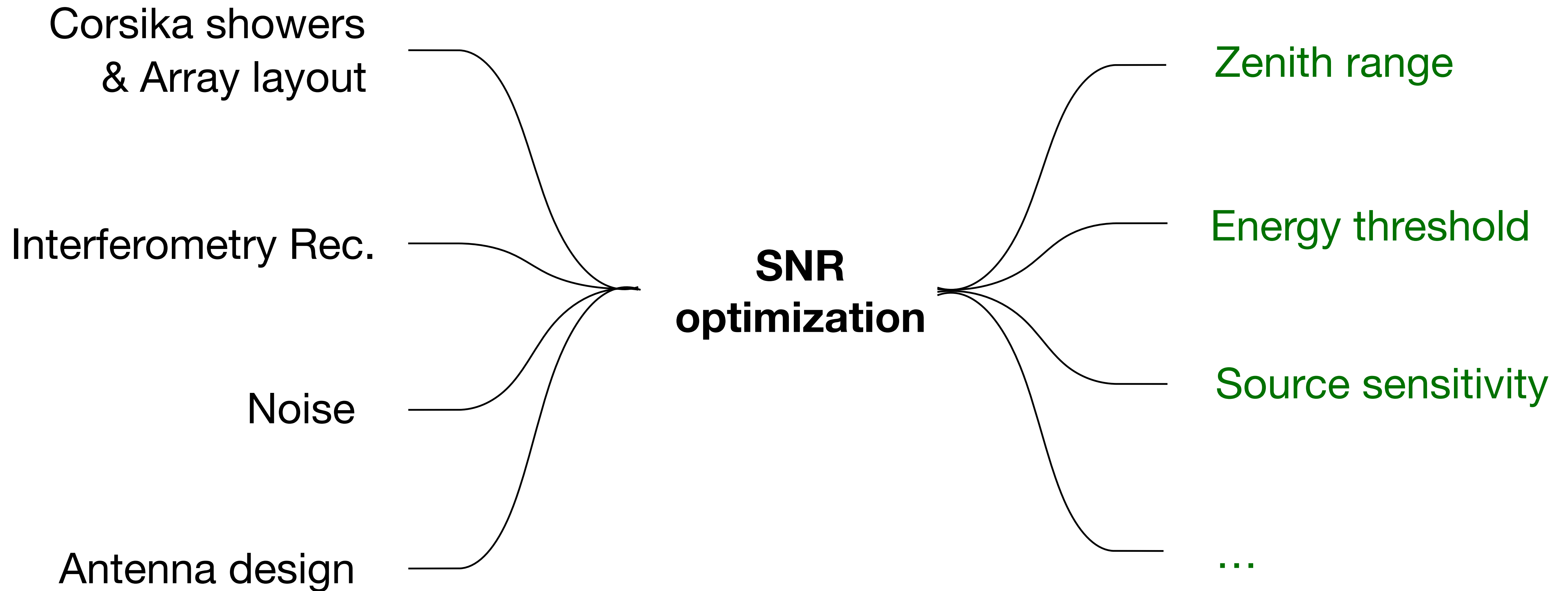


+ 2 antennas



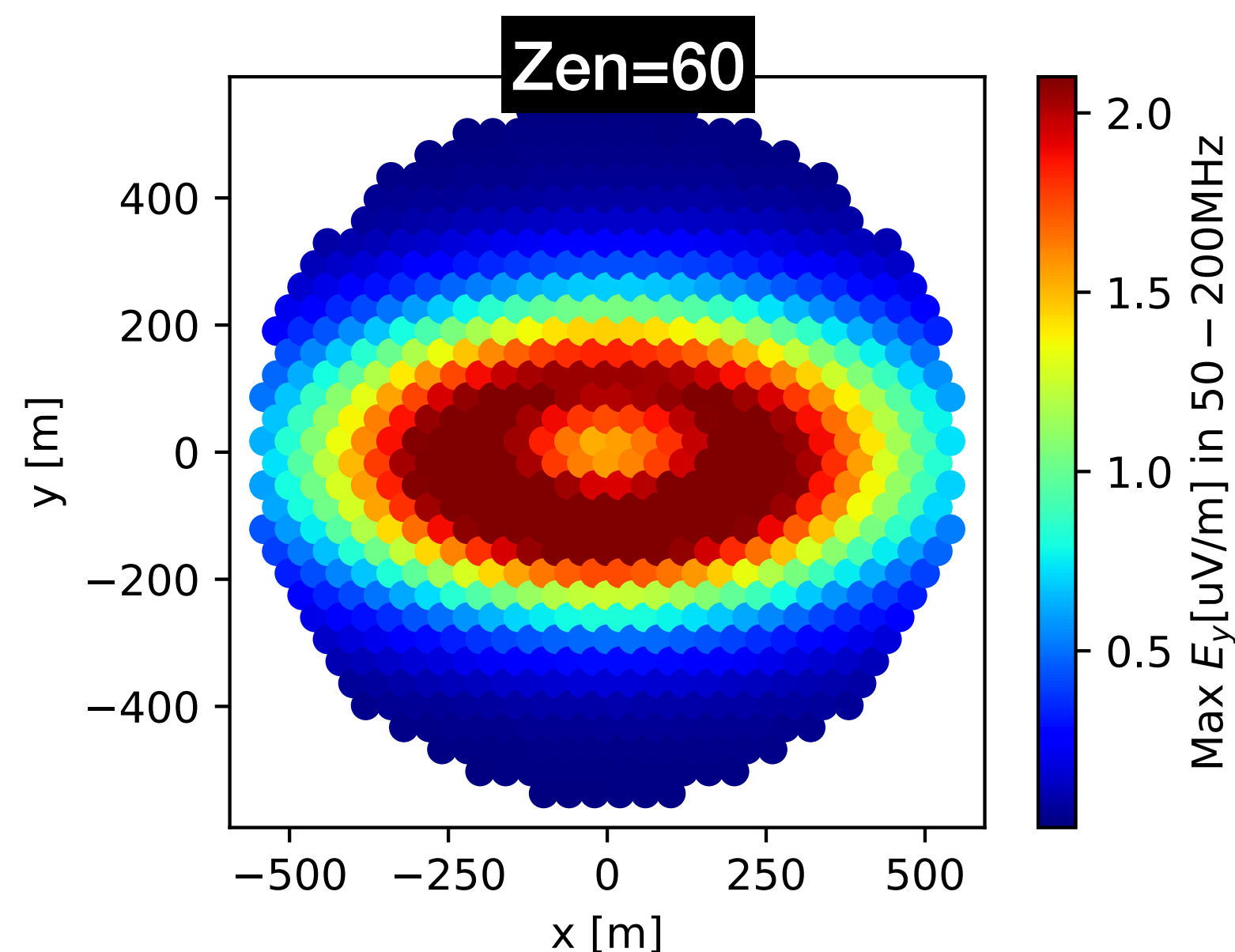
1 km²
3000-5000 WCD
+ 800 antennas

The idea of this talk



- Array: N=698, triangular grid, 40m spacing, filling SWGO area.
- Corsika/CoREAS simulations of radio signals at antenna positions*.
 - **Energy:** 1,10,100 PeV
 - Range of **Zenith** and **Azimuth**
 - **Primary:** gamma

1PeV gamma (ground plane, $A_{\text{corsika}}=0$, no noise)



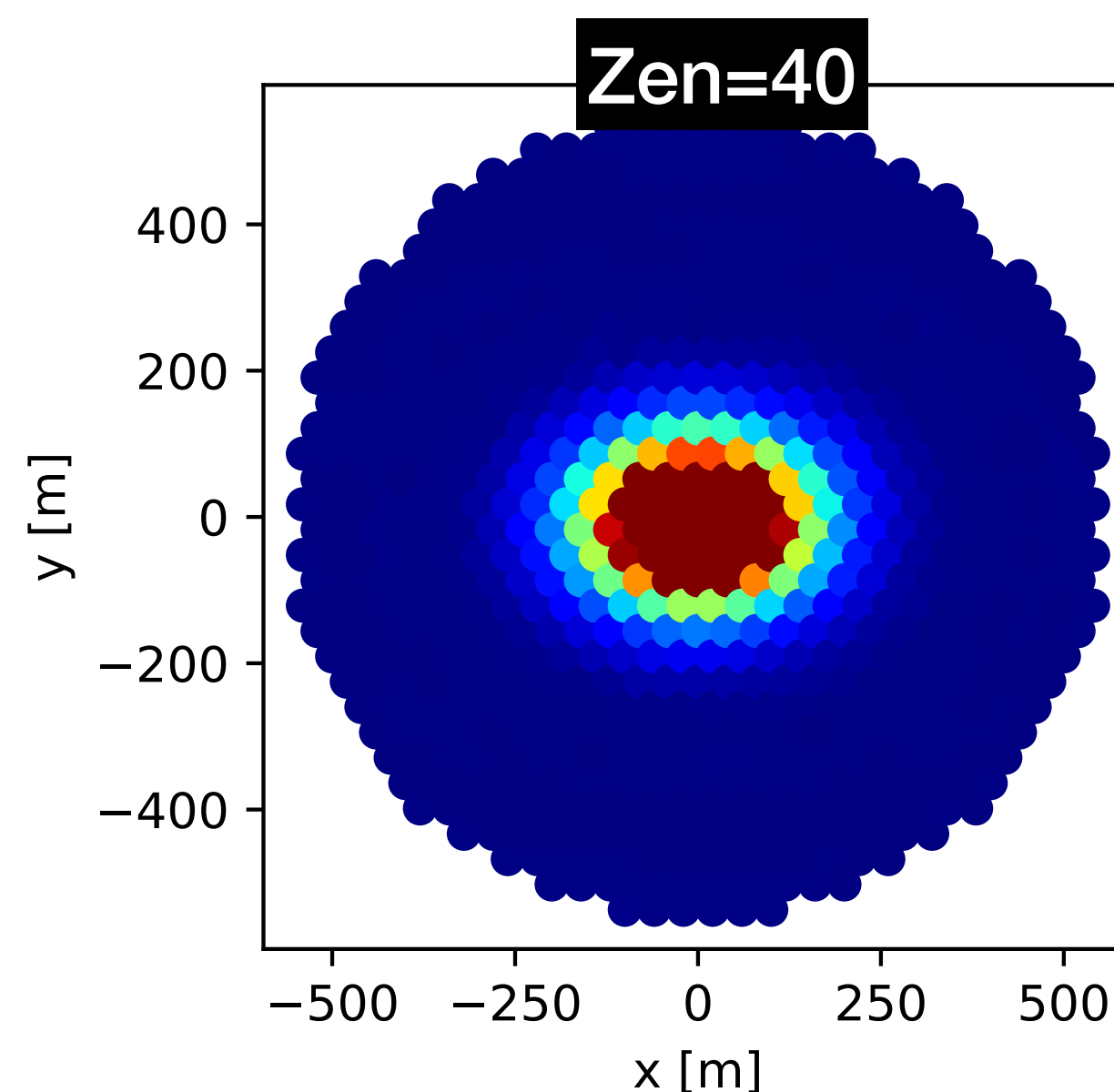
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Goal:
“What **Zen range** and
what **E threshold**?”

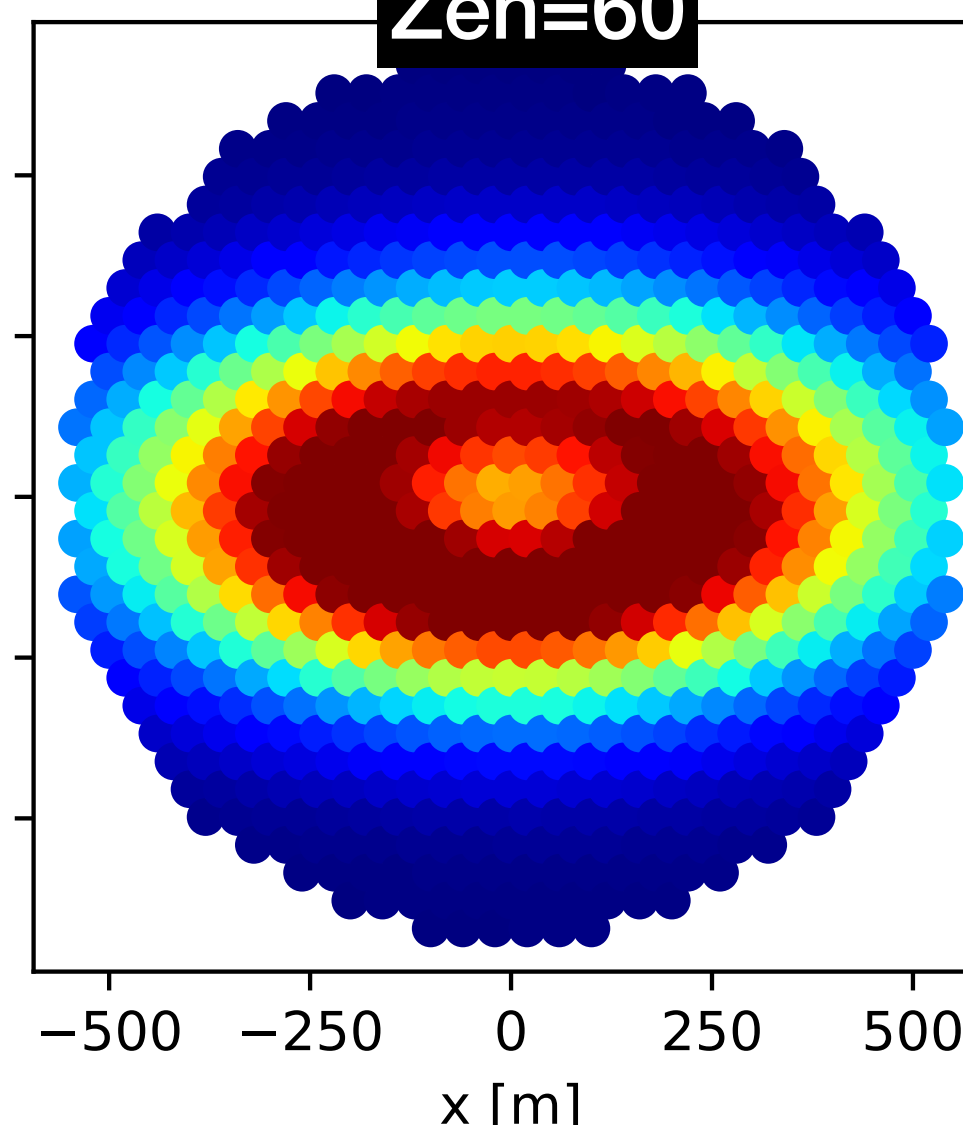
1PeV gamma (ground plane, $A_{\text{corsika}}=0$, no noise)

<— Zen

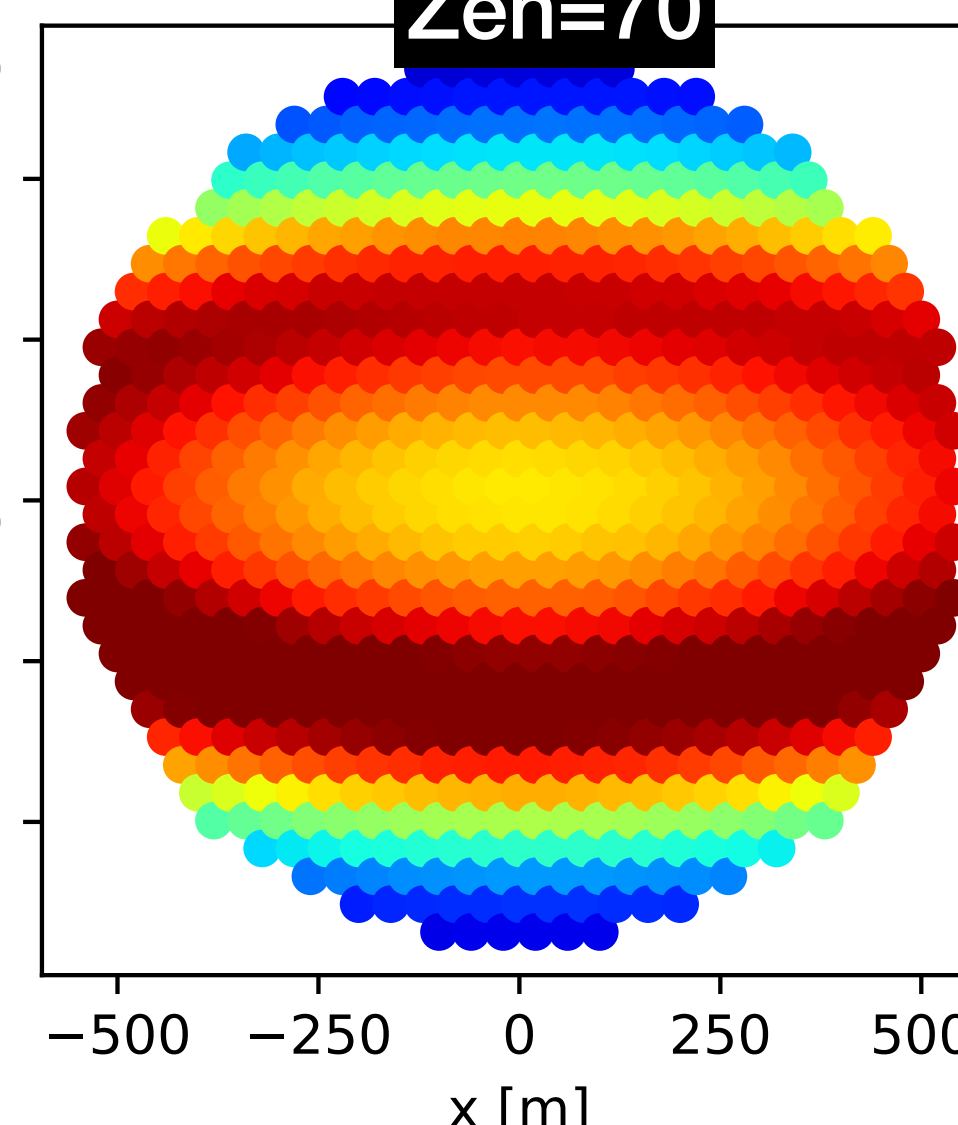
Too small



Zen=60



Zen=70



Zen—>

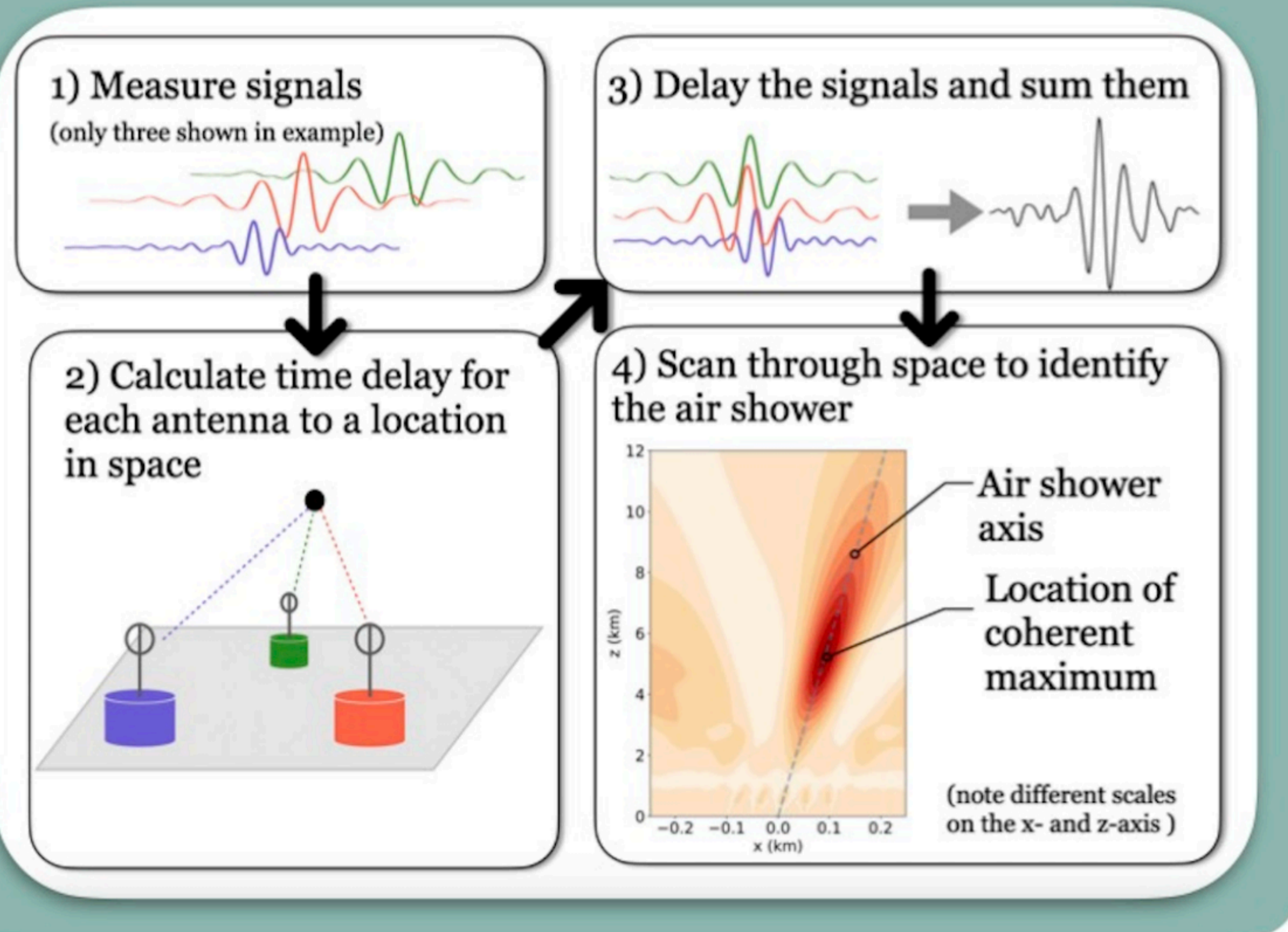
Too big

Max E_y [uV/m] in 50 – 200MHz

ASIRA

Method

[ICRC2023]



[see also talk by Pim on Thursday]

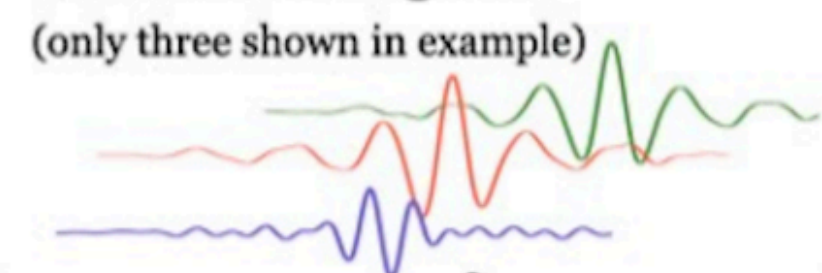
- [ASIRA]*: **A**ir **S**hower Interferometric **R**econstruction **A**lgorithm
 - ‘**Imaging**’ of the longitudinal profile
 - Potential for energy, $X_{\max}$, shower physics, ...
 - Needed for TURBO: “Digging into the noise floor”

ASIRA

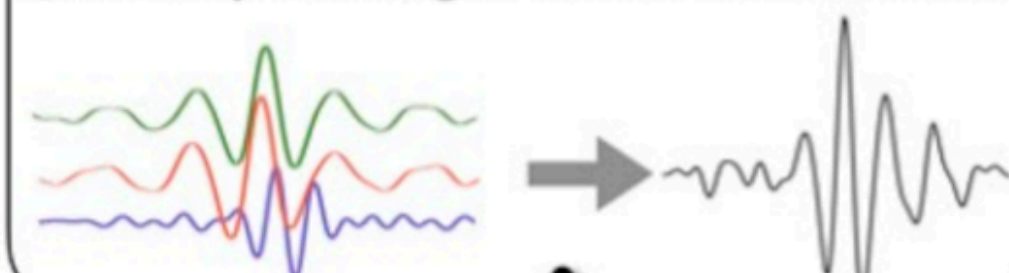
Method

[ICRC2023]

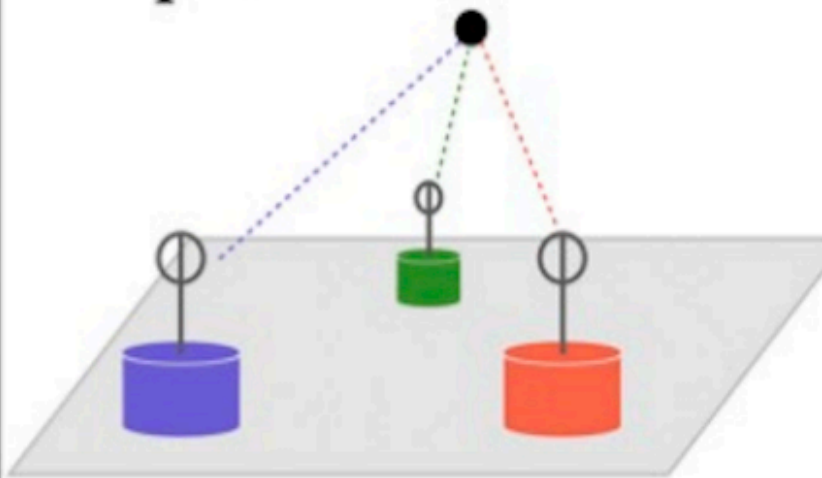
1) Measure signals (only three shown in example)



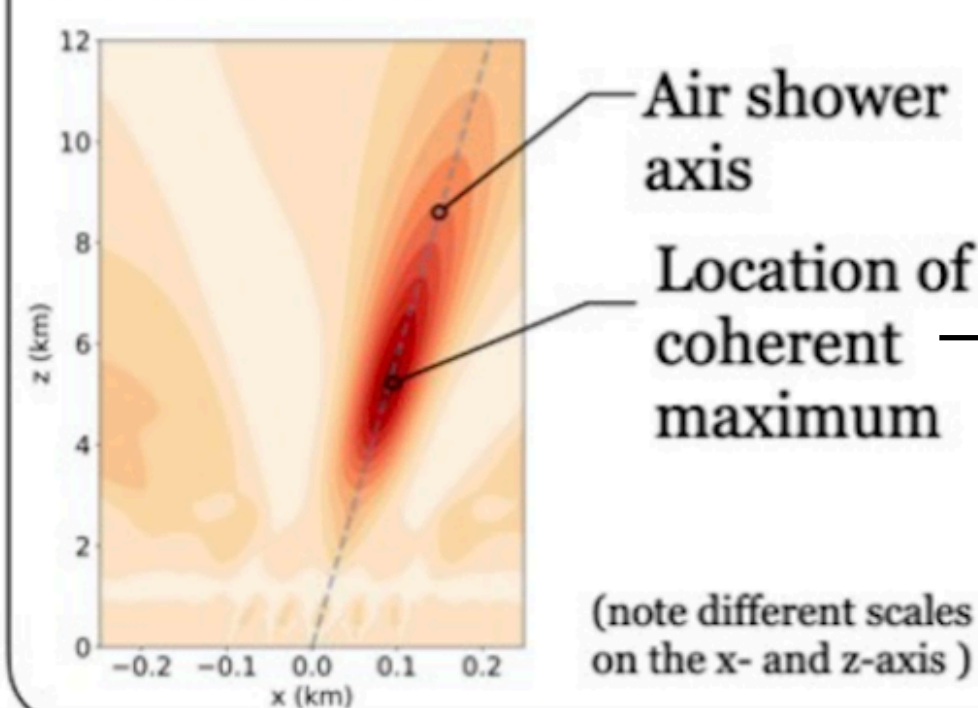
3) Delay the signals and sum them



2) Calculate time delay for each antenna to a location in space

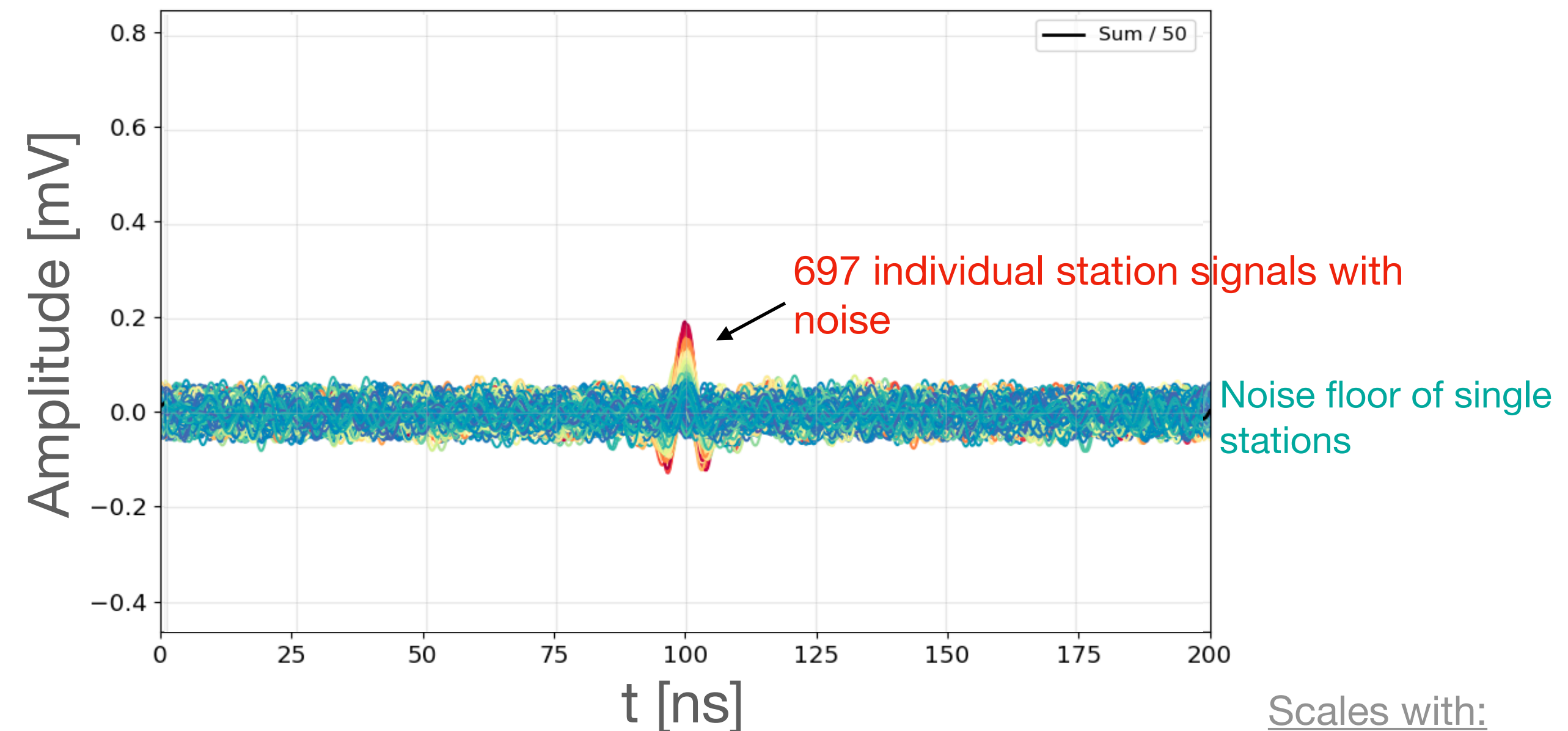


4) Scan through space to identify the air shower



[see also talk by Pim on Thursday]

Example: 100PeV gamma, $Z=60$, GSM08 galactic noise



Scales with:

- Coherent total **signal** at X_{RIT} $\sim N_{stations}$
- Approximate **noise** (galactic dominated):
 - $RMS\ noise \approx (25\ uV/m\ per\ station) * \sqrt{N_{stations}} \sim \sqrt{N_{stations}}$

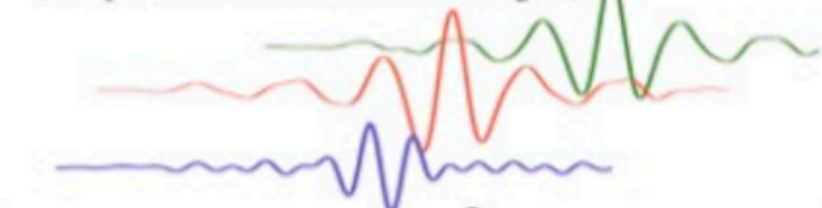
ASIRA

Method

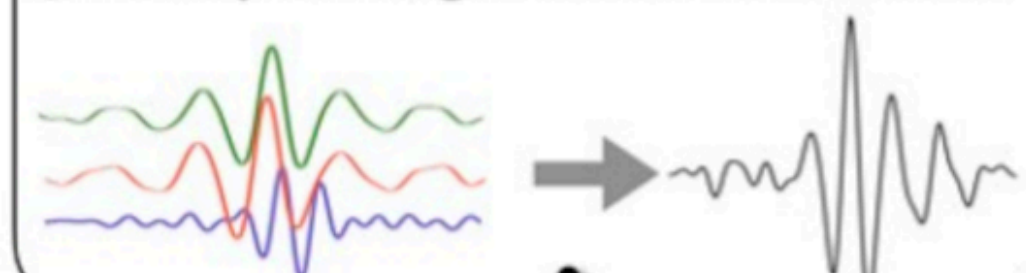
[ICRC2023]

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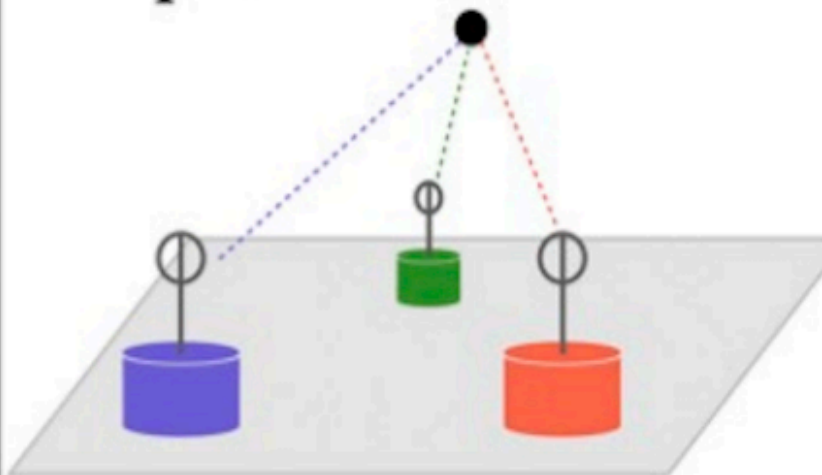
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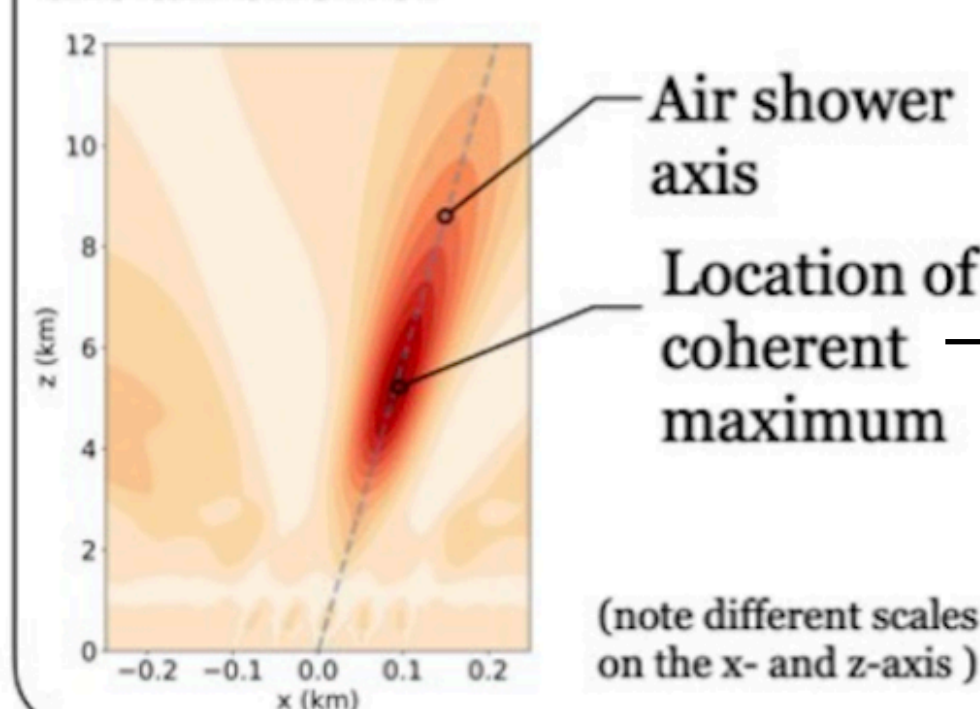
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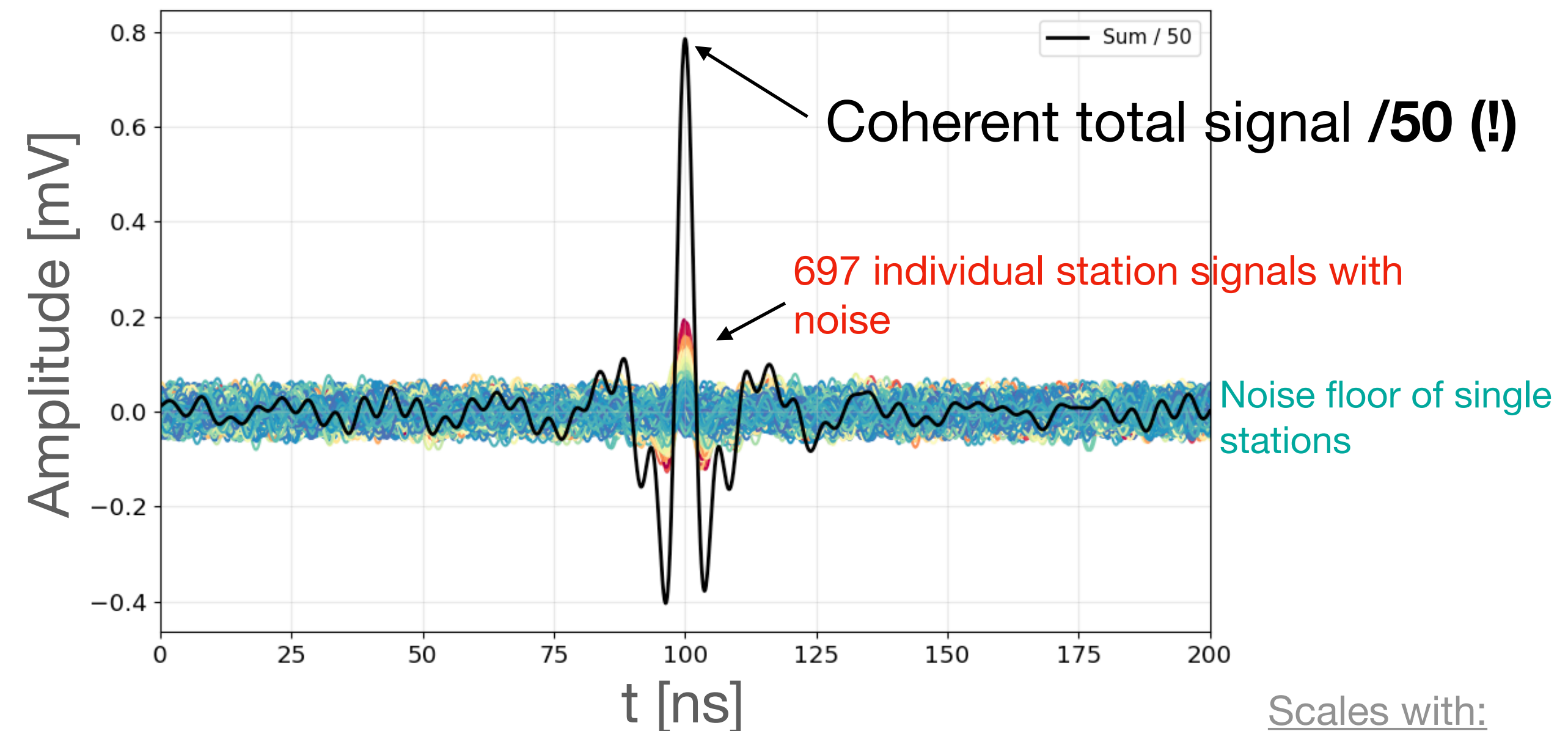


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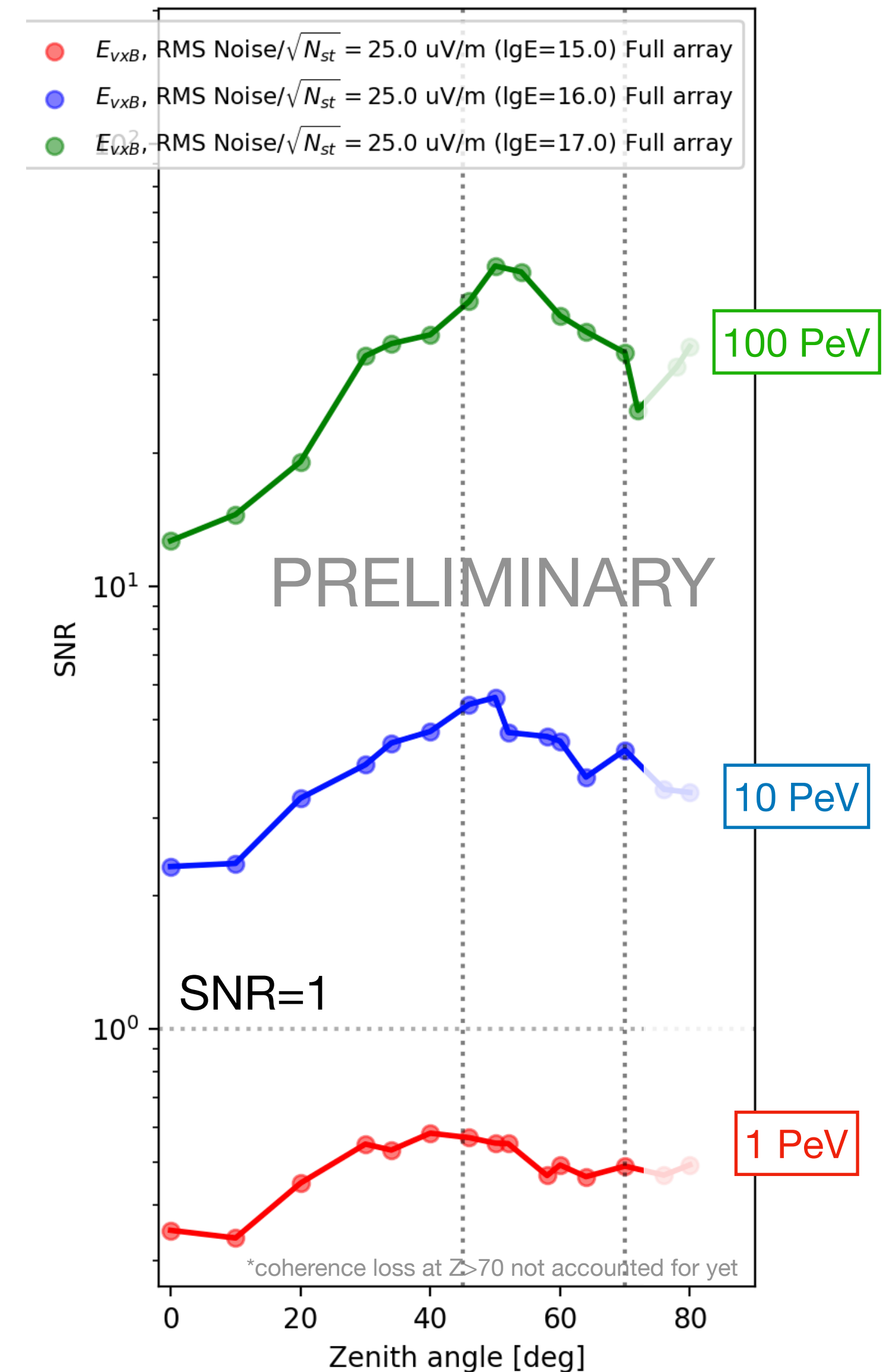
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- Approximate **noise** (galactic dominated):
 - $\text{RMS noise} \approx (25 \text{ uV/m per station}) * \sqrt{N_{\text{stations}}} \sim \sqrt{N_{\text{stations}}}$

Expectations of SNR vs {Z,E}

- **SNR** = $E_{\text{tot,coherent}} / \text{RMS}(E_{\text{noise}})$
- Station cutoff at ~ 1.4 Cherenkov radii

- $\rightarrow$ good reconstructions from 5-10PeV (?)
- $\rightarrow$ Performance peaking beyond $Z=45$

Goal:
“What **Z**en range and
what **E** threshold?”



- **SNR** = $E_{\text{tot,coherent}} / \text{RMS}(E_{\text{noise}})$
- Station cutoff at ~ 1.4 Cherenkov radii

- $\rightarrow$ good reconstructions from 5-10PeV (?)
- $\rightarrow$ Performance peaking beyond $Z=45$

Goal:
“What **Zen range** and
what **E threshold**?”

- To study further [in progress]:

Optimizations

- Try station layouts
- **Vary antenna design**
- frequency band cuts?

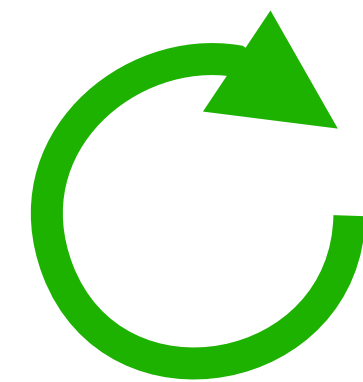
Systematics

- Partial footprints
- Azimuth variation

Noise:

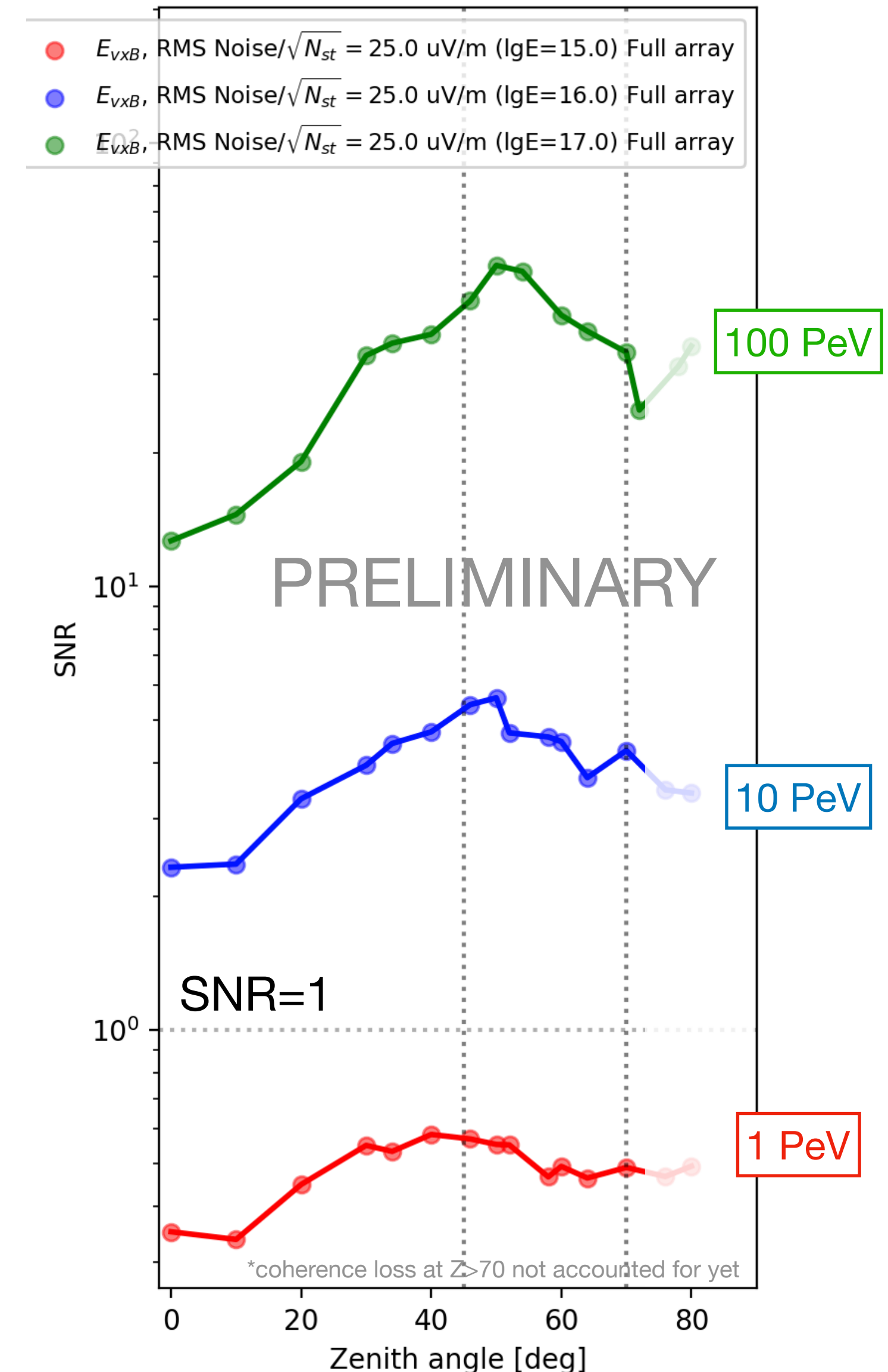
- System noise
- Signal chain losses
- **Background sky (LST)**

Boost signal

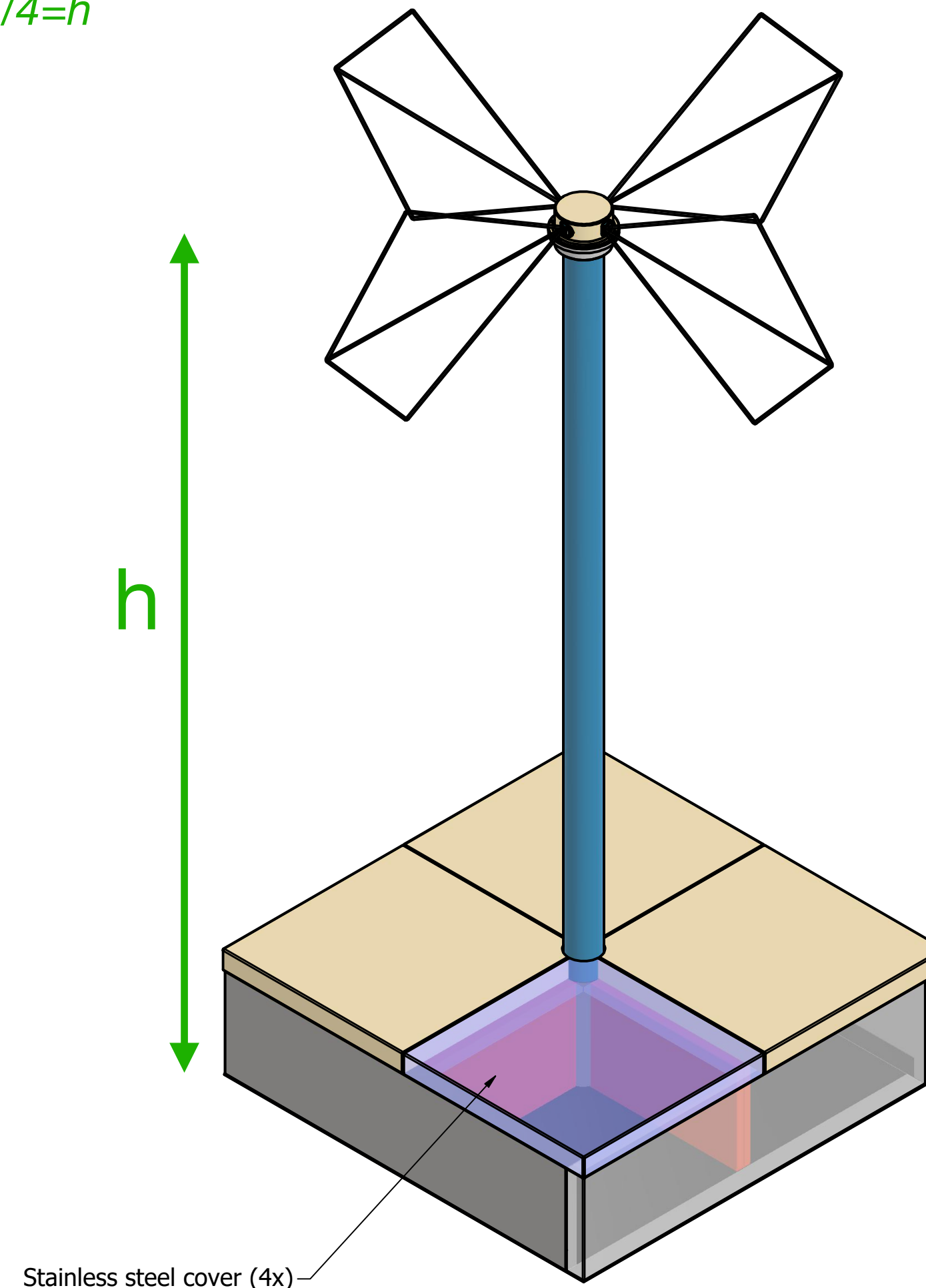
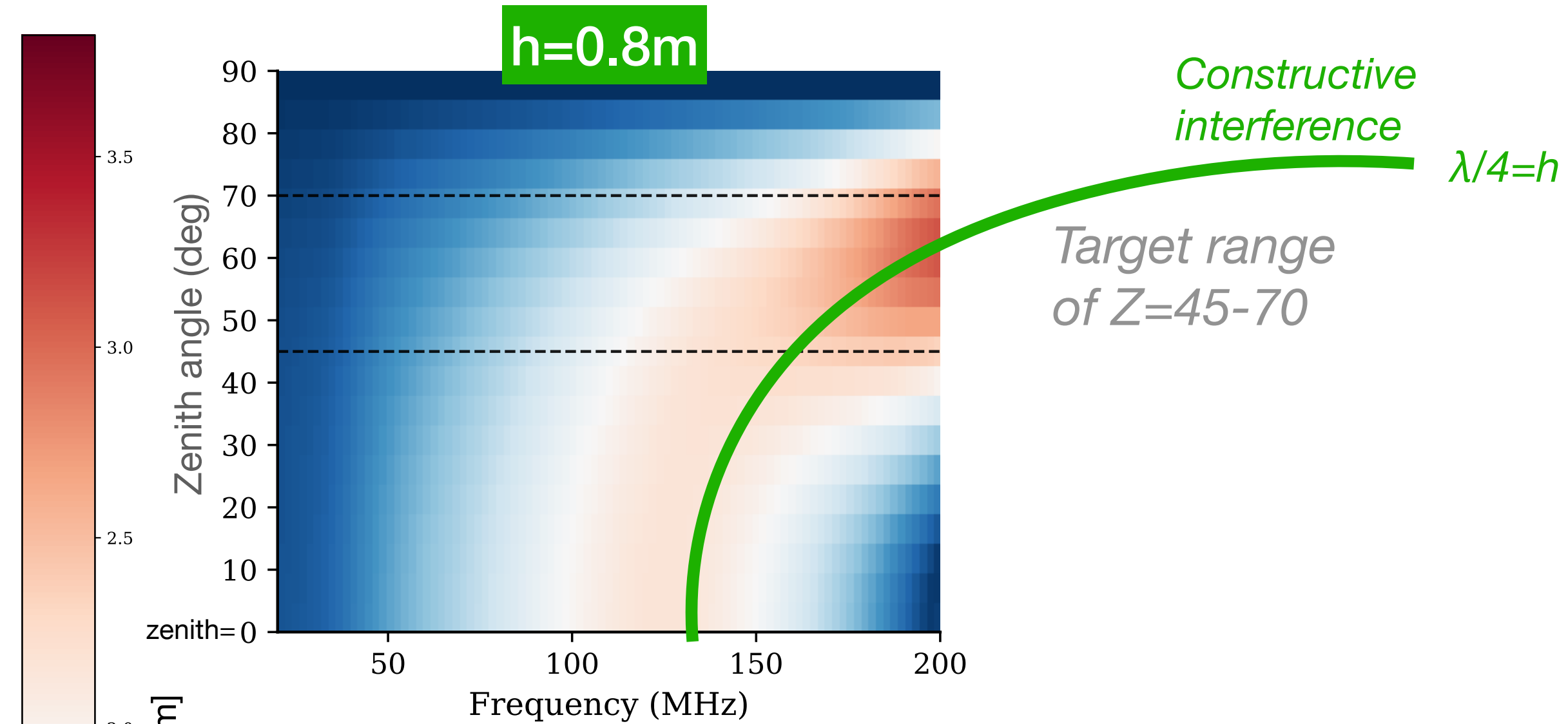


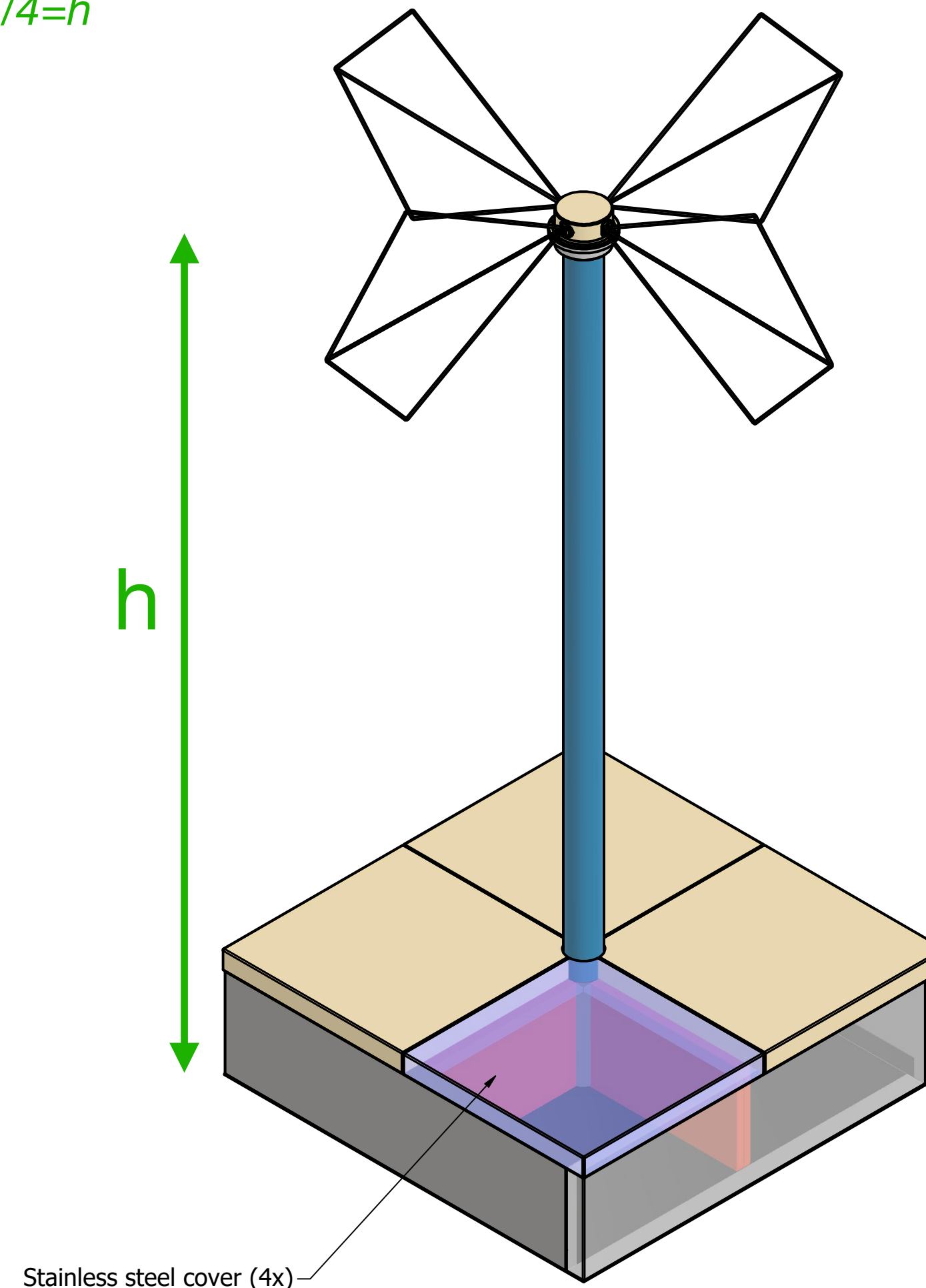
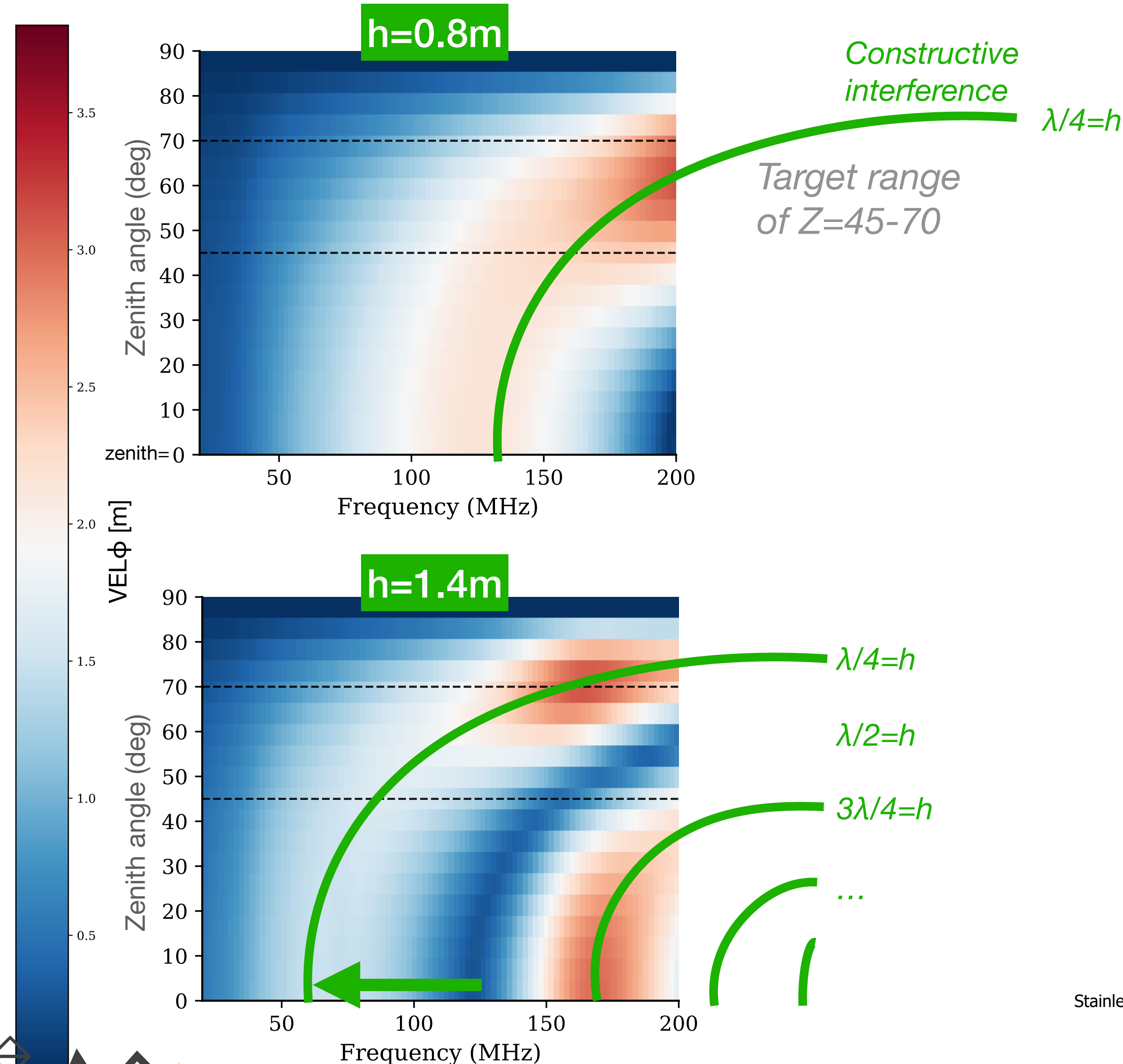
Suppress noise

“Dig deeper into the noise”



Antenna optimization



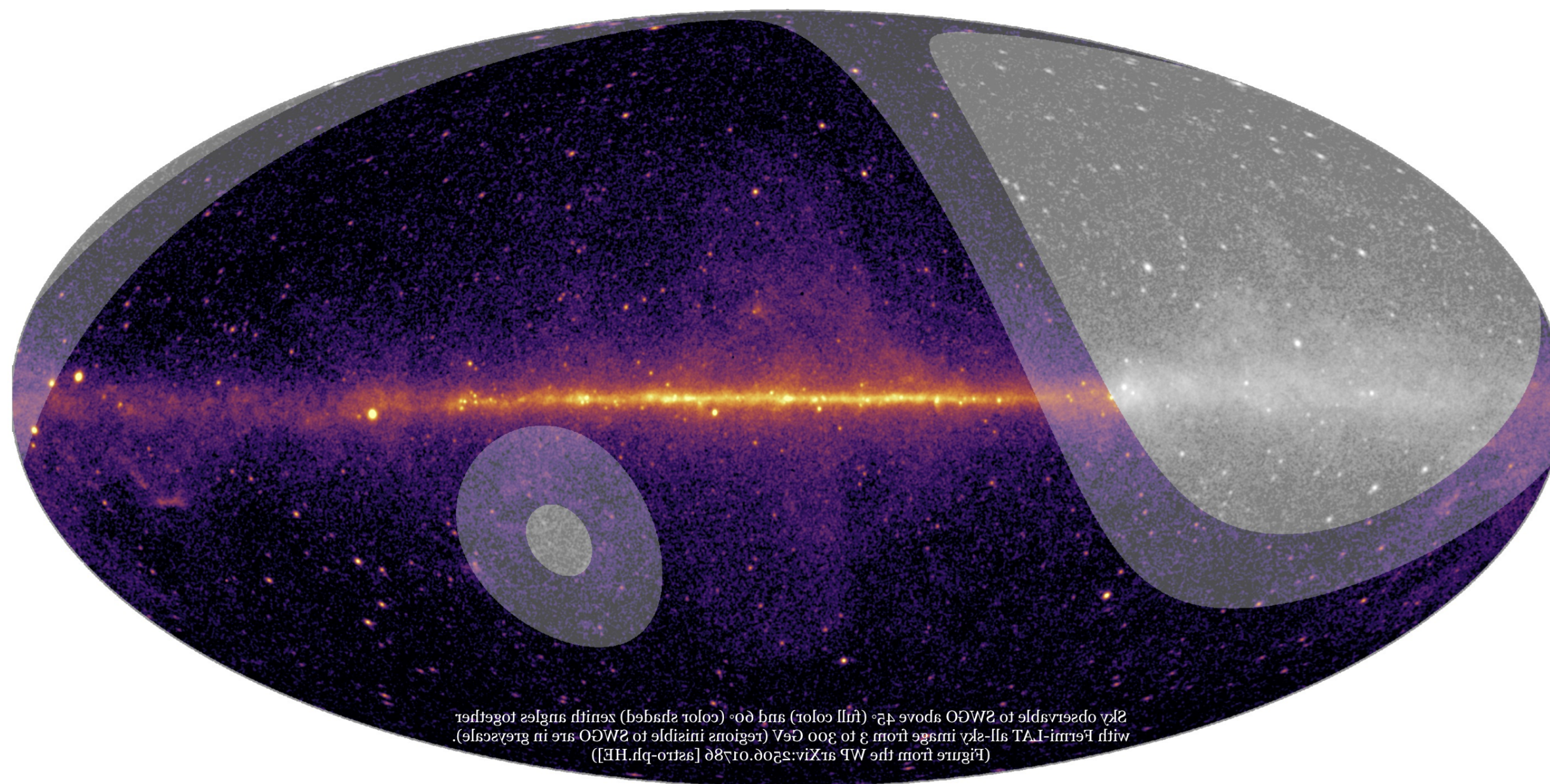


Mast height (h)

Also vary:
reflecting mesh, width,
orientation, rotation, tilt, ...

Signal

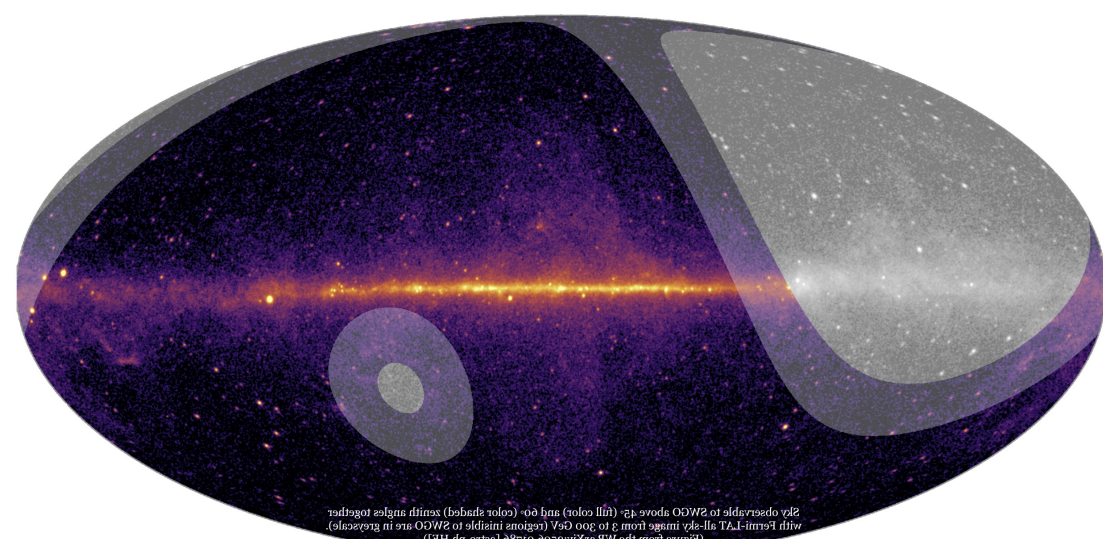
Fermi <TeV gamma sky
[SWGO FOV]



- + extending WCD beyond Zen>45
- + gamma source locations (l,b)

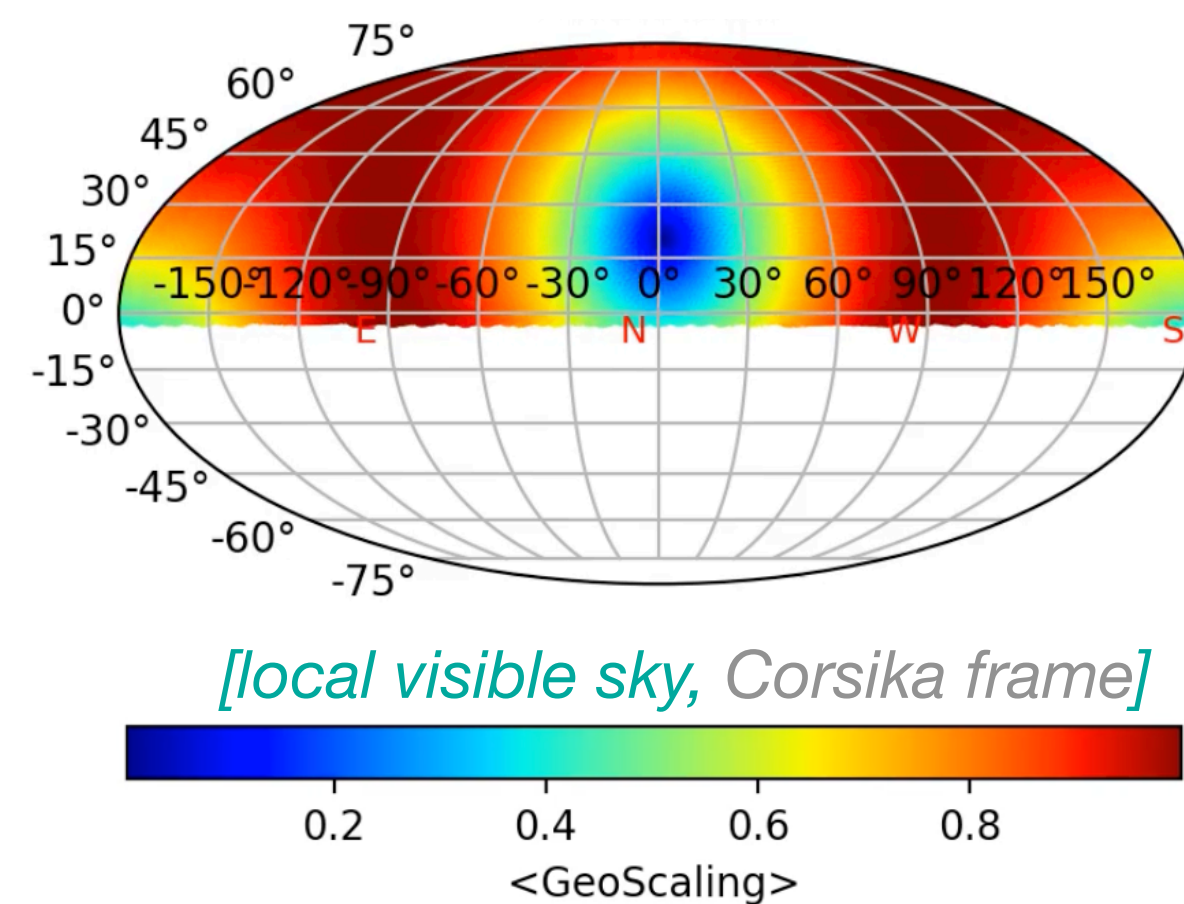
Signal

Fermi <TeV gamma sky
[SWGO FOV]



[Galactic sky]

$E_{\text{geo}} \sim |v \times B|$



[local visible sky, Corsika frame]

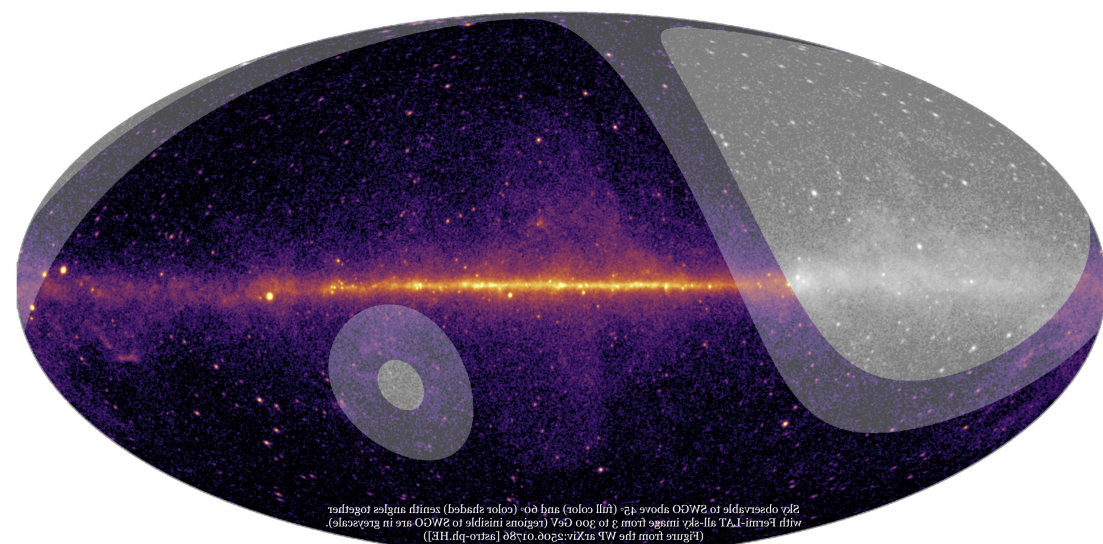
- + extending WCD beyond Zen>45
- + gamma source locations (l,b)

- + $E_{\text{geo}}(f)$ slope depends on distance to core

Signal

!Example antenna design!

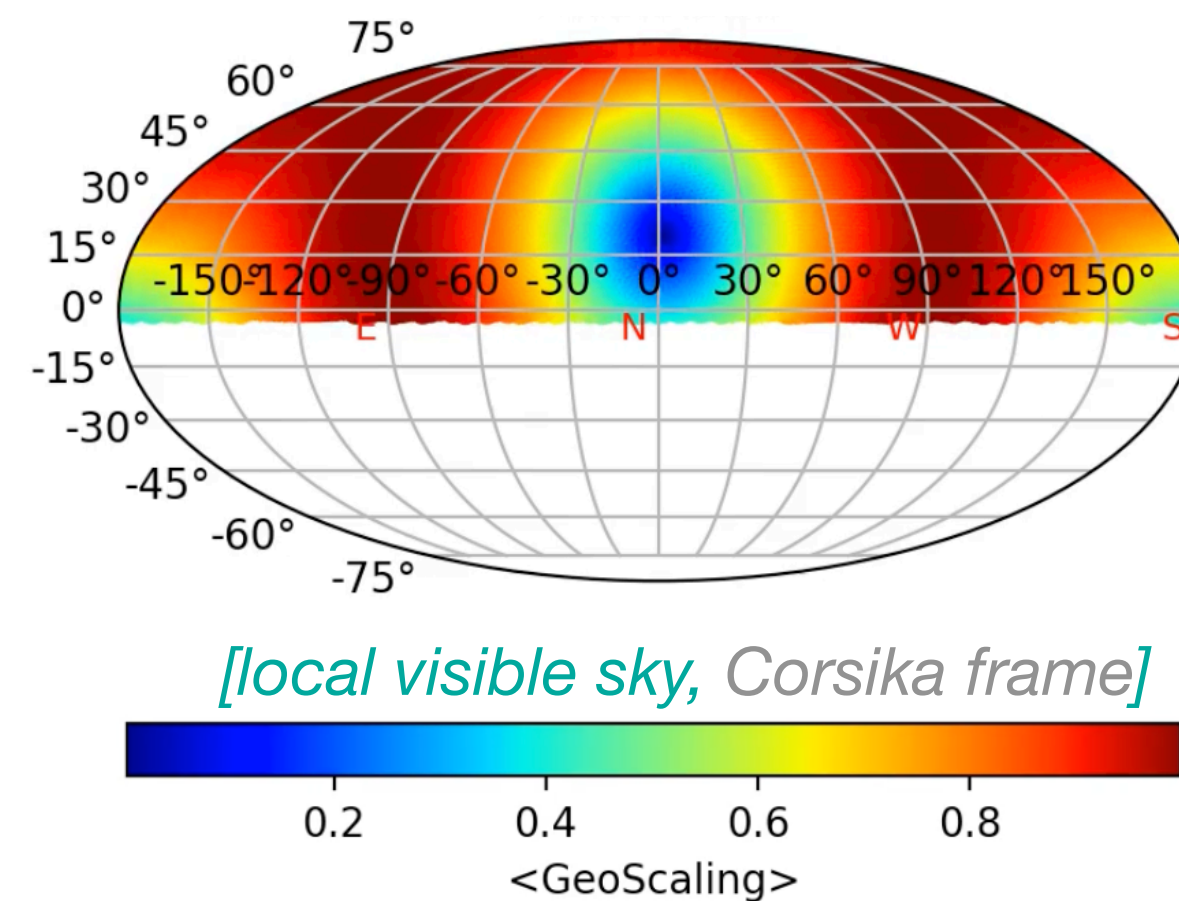
Fermi <TeV gamma sky
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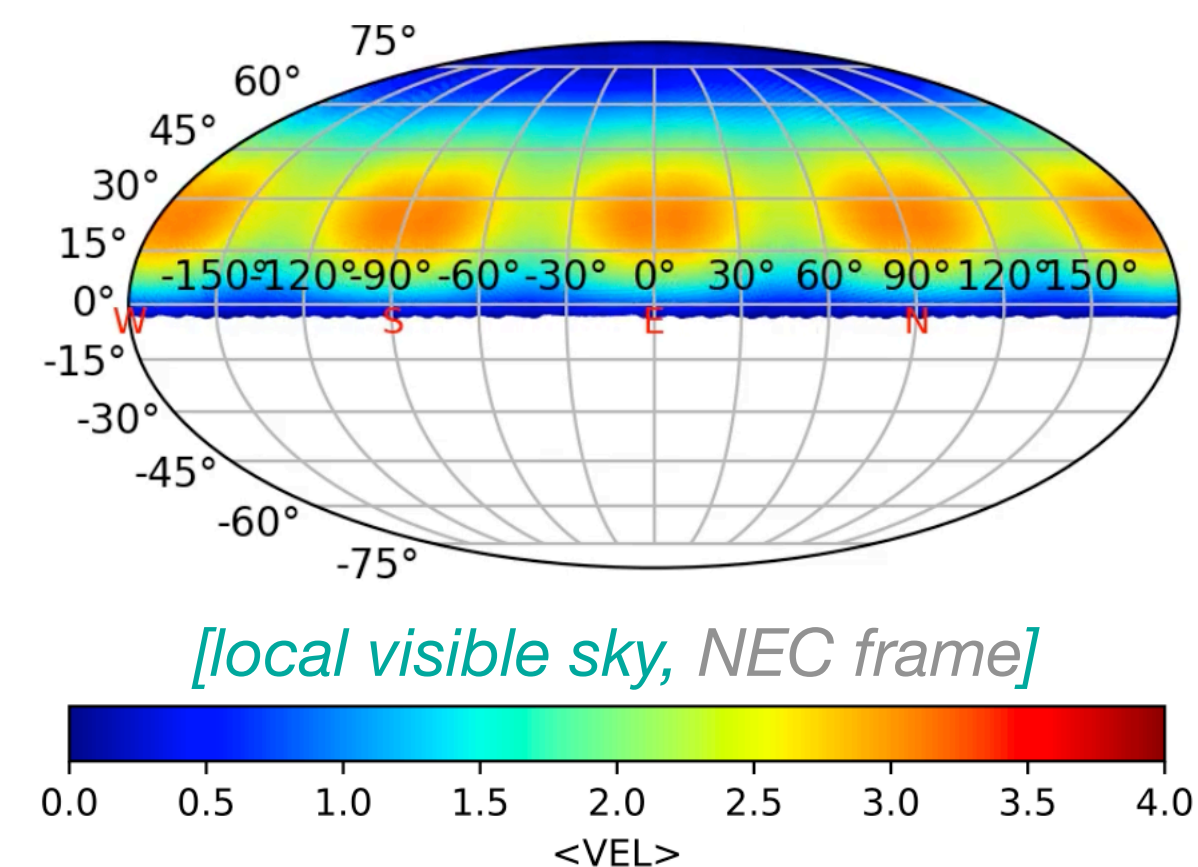
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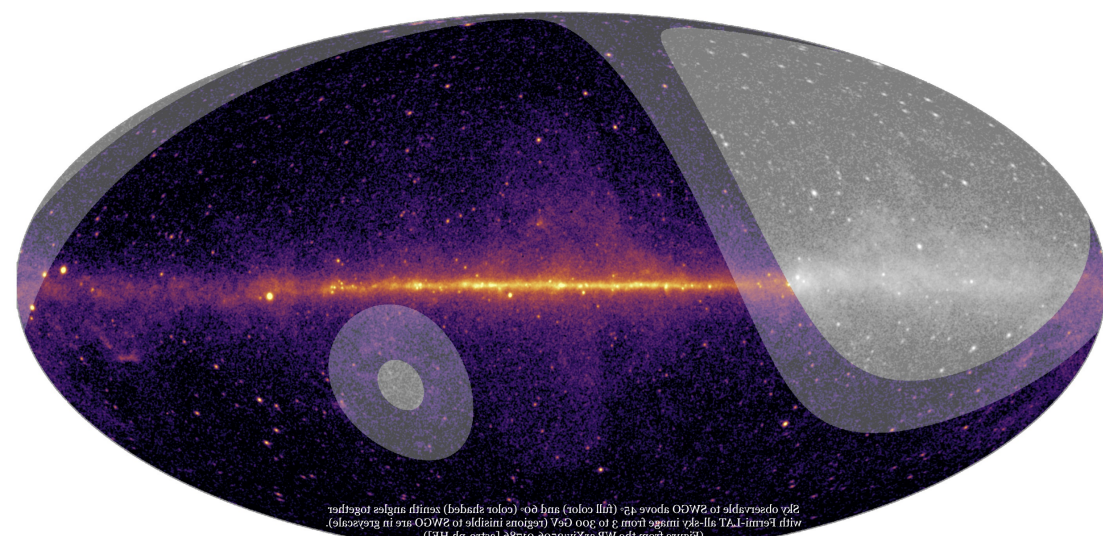
Total VEL [f=200MHz]



- + Signal(f): some point in $Z=[45-70]$
- > vary **antenna** design(f) to:
- Optimize signal (f)

Signal

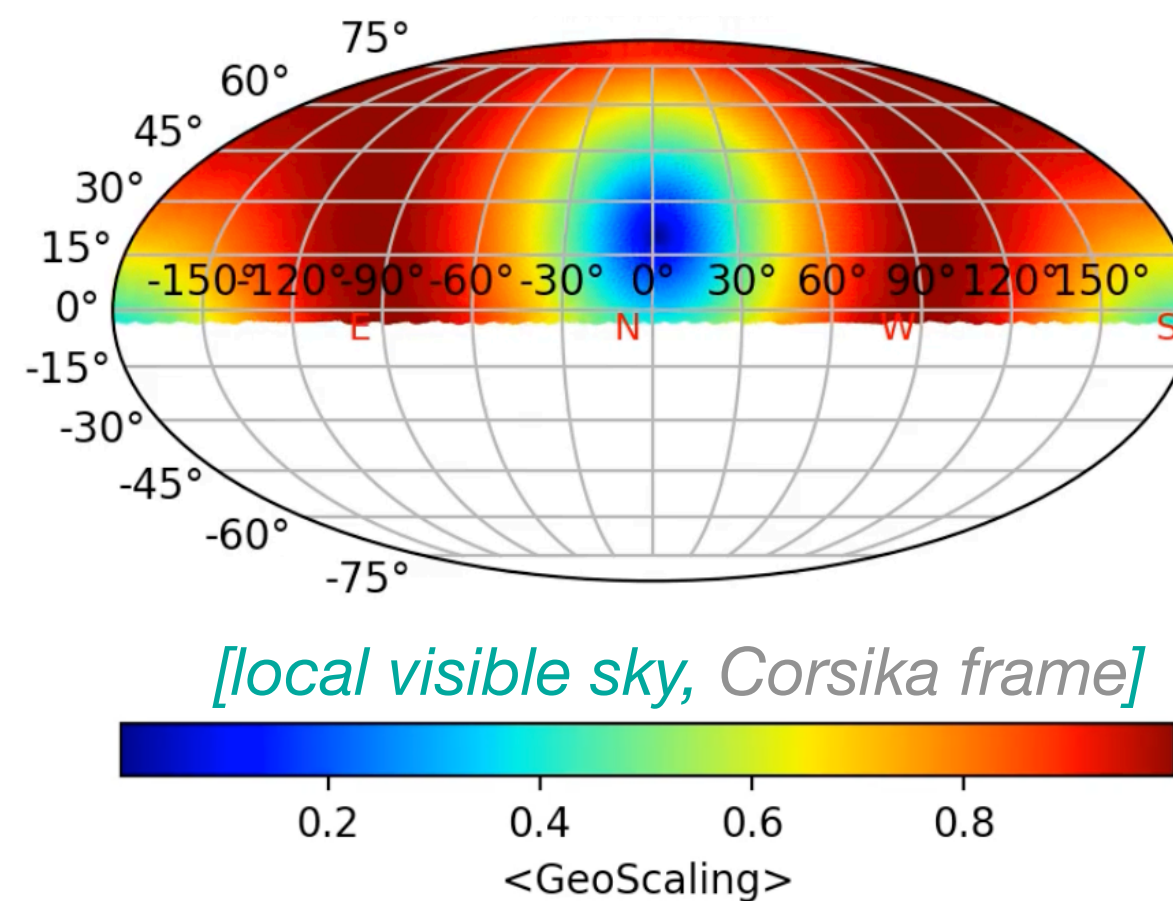
Fermi <TeV gamma sky
[SWGO FOV]



[Galactic sky]

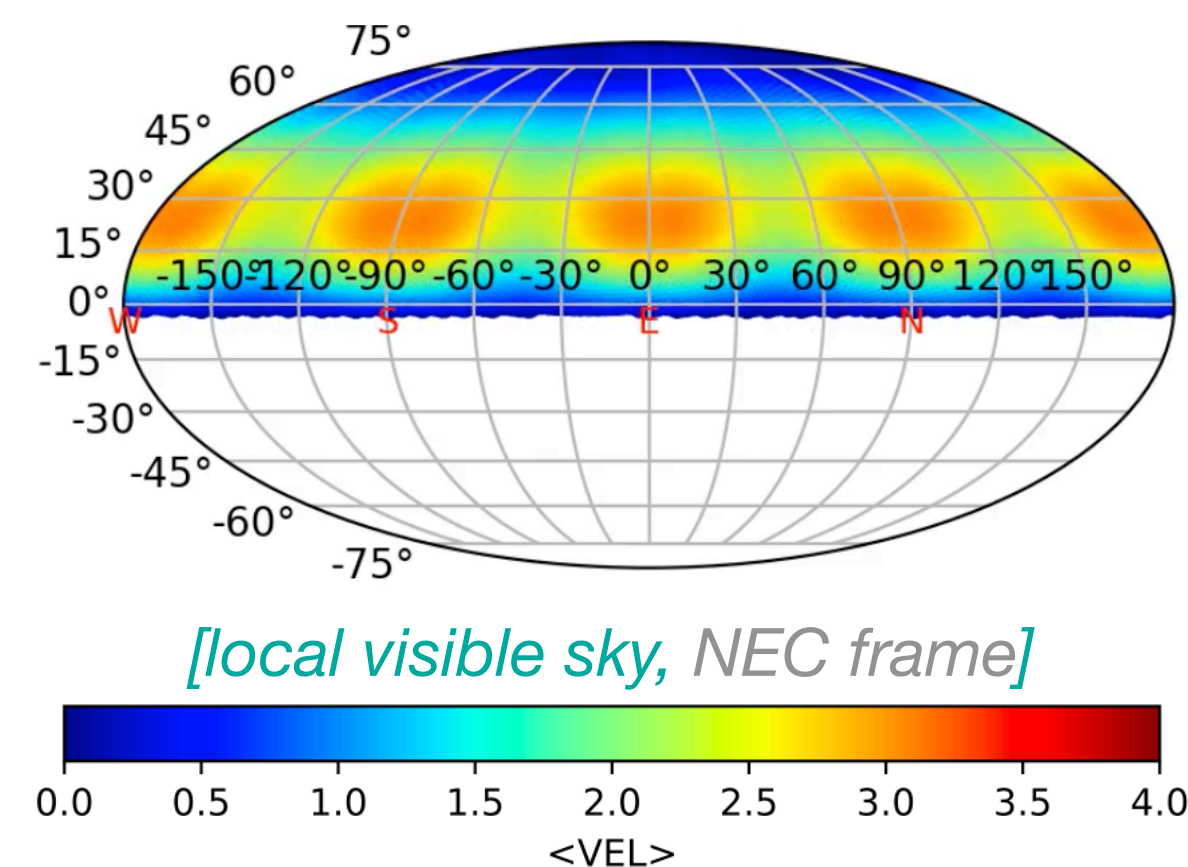
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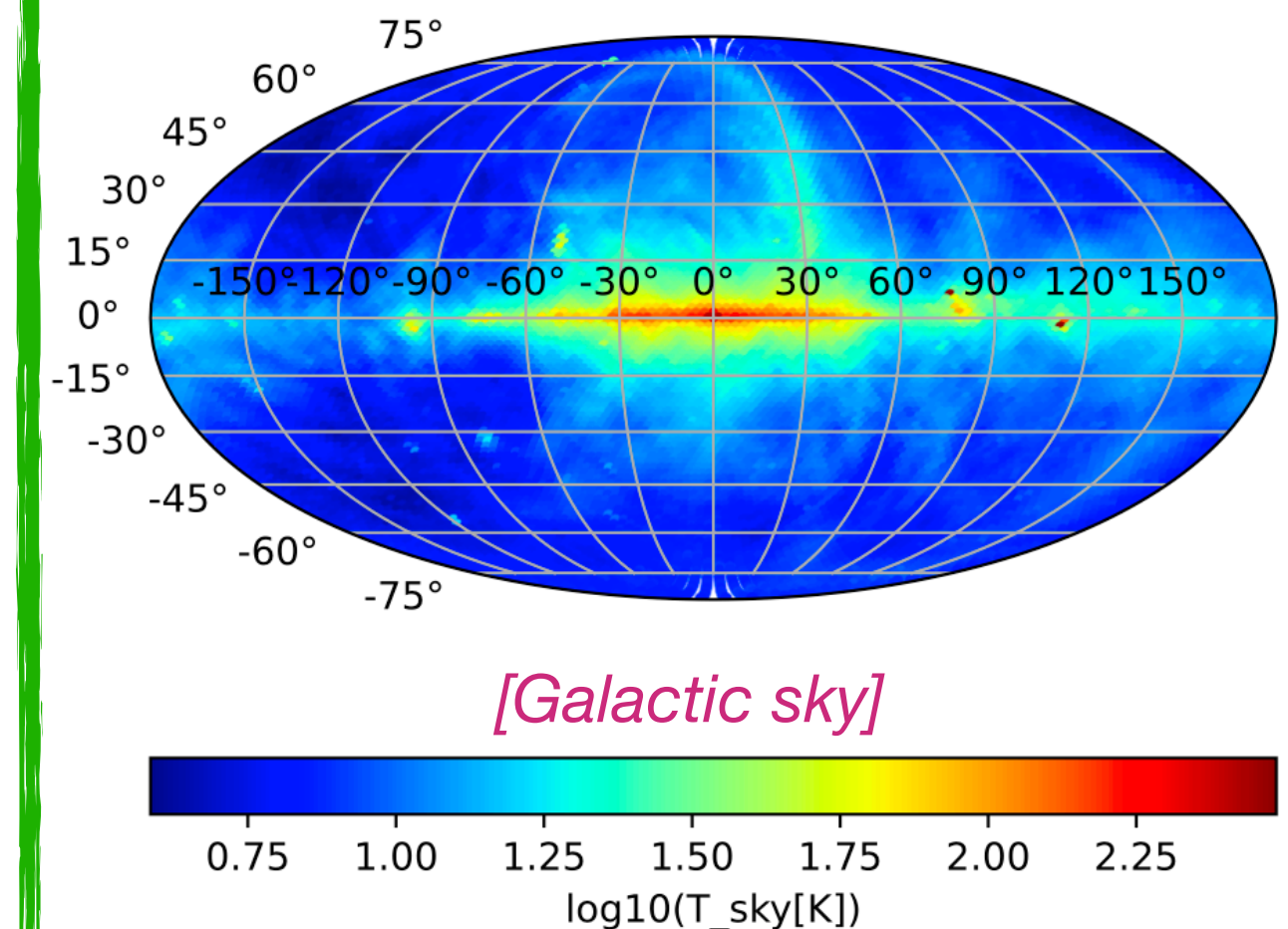
Total VEL [f=200MHz]



- + Signal(f): some point in $Z=[45-70]$
- + Noise(f): **entire** visible sky
- > vary **antenna** design(f) to:
 - Optimize signal (f)
 - Suppress bright $T_{\text{sky}}(f)$

Noise

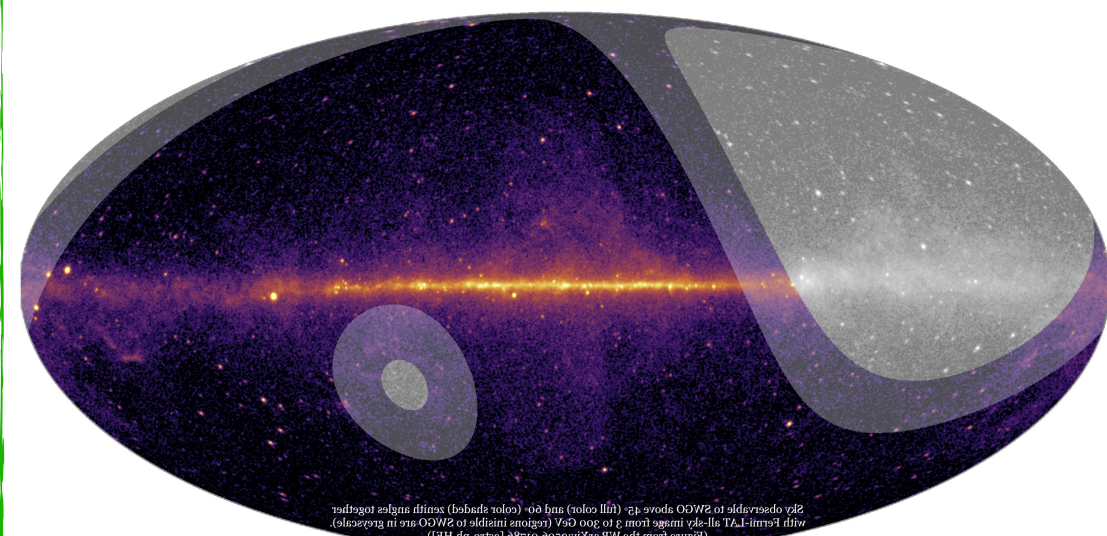
Radio sky noise [GSM08,f=200MHz]



- + depends on frequency
- + depends on time (LST)

Signal

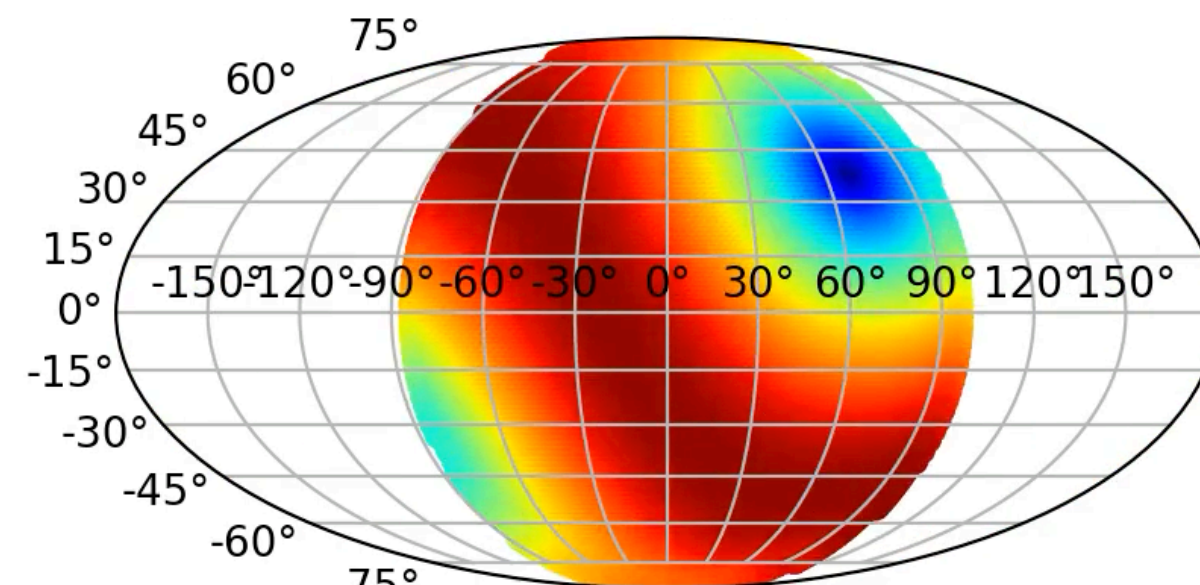
Fermi <TeV gamma sky
[SWGO FOV]



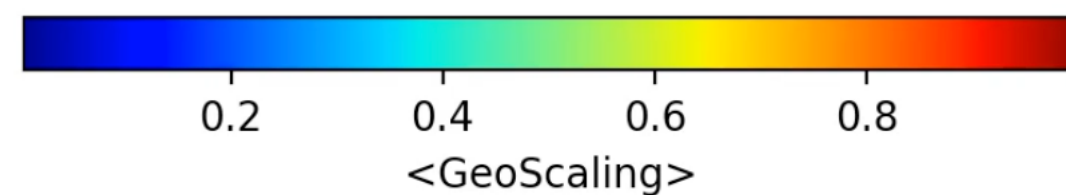
[Galactic sky]

- + extending WCD beyond Zen>45
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$E_{\text{geo}}(\text{LST}=22) \sim |v \times B|$



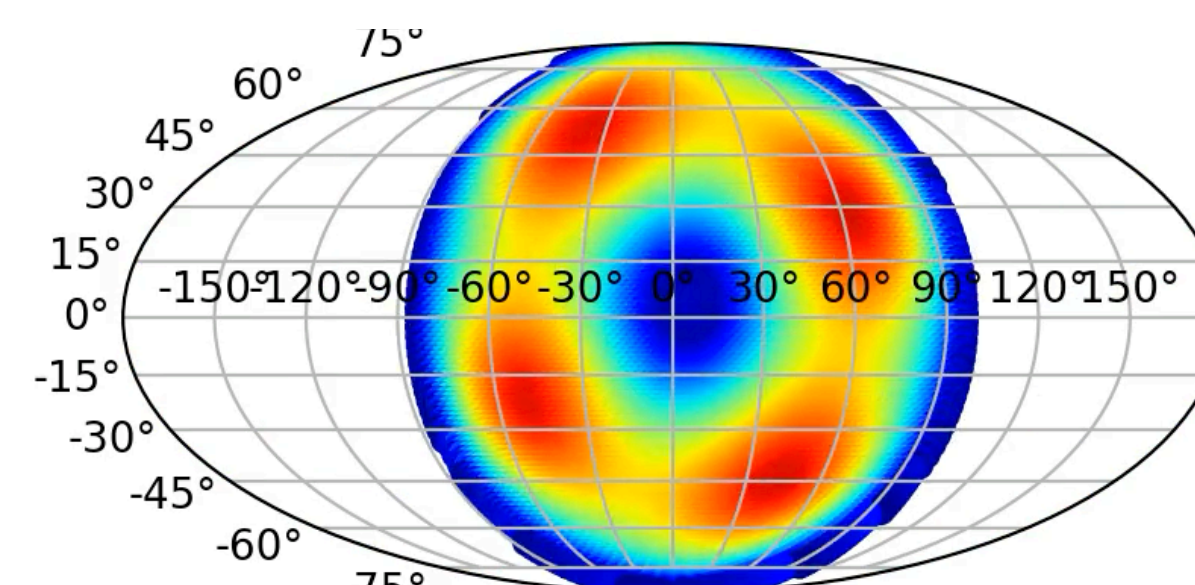
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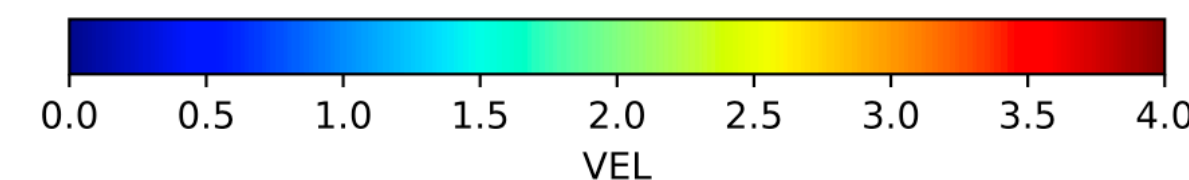
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Noise

Total VEL(LST=22) [f=200MHz]



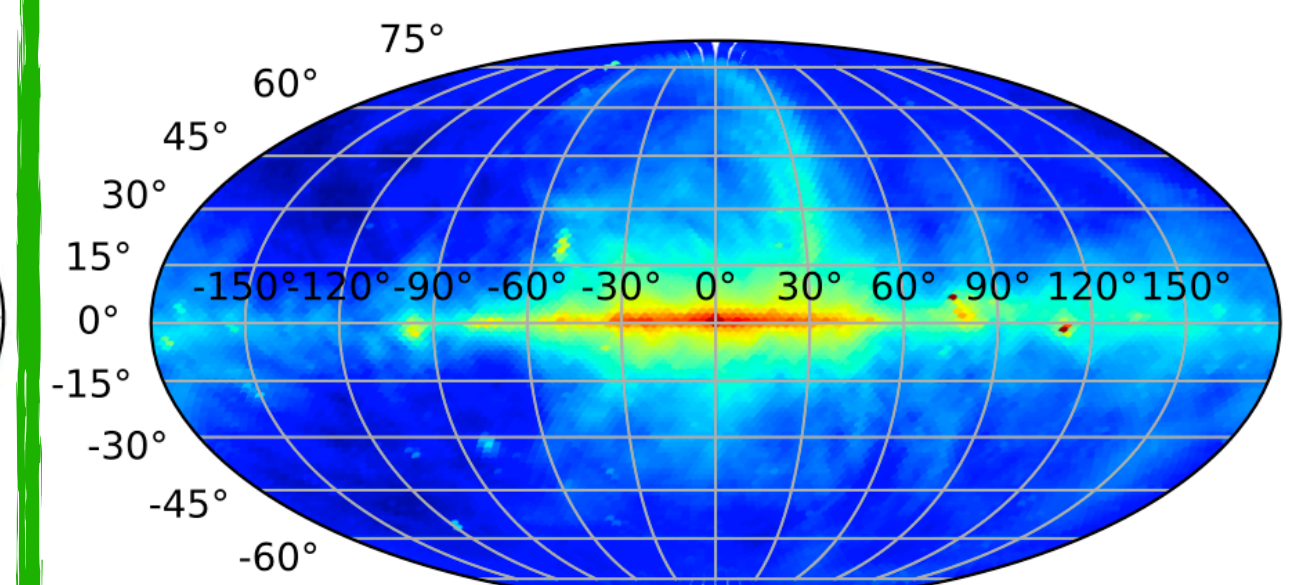
[Galactic sky]



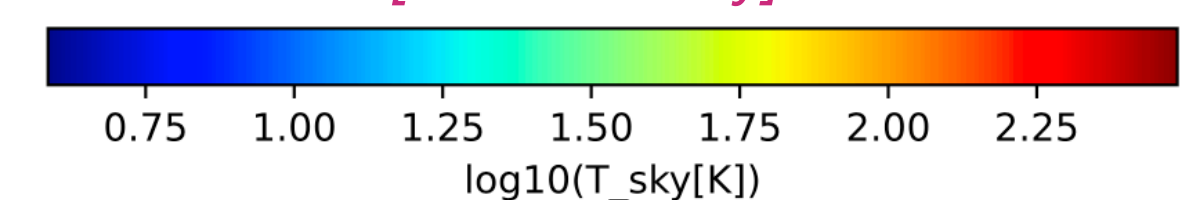
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Radio sky noise [GSM08,f=200MHz]



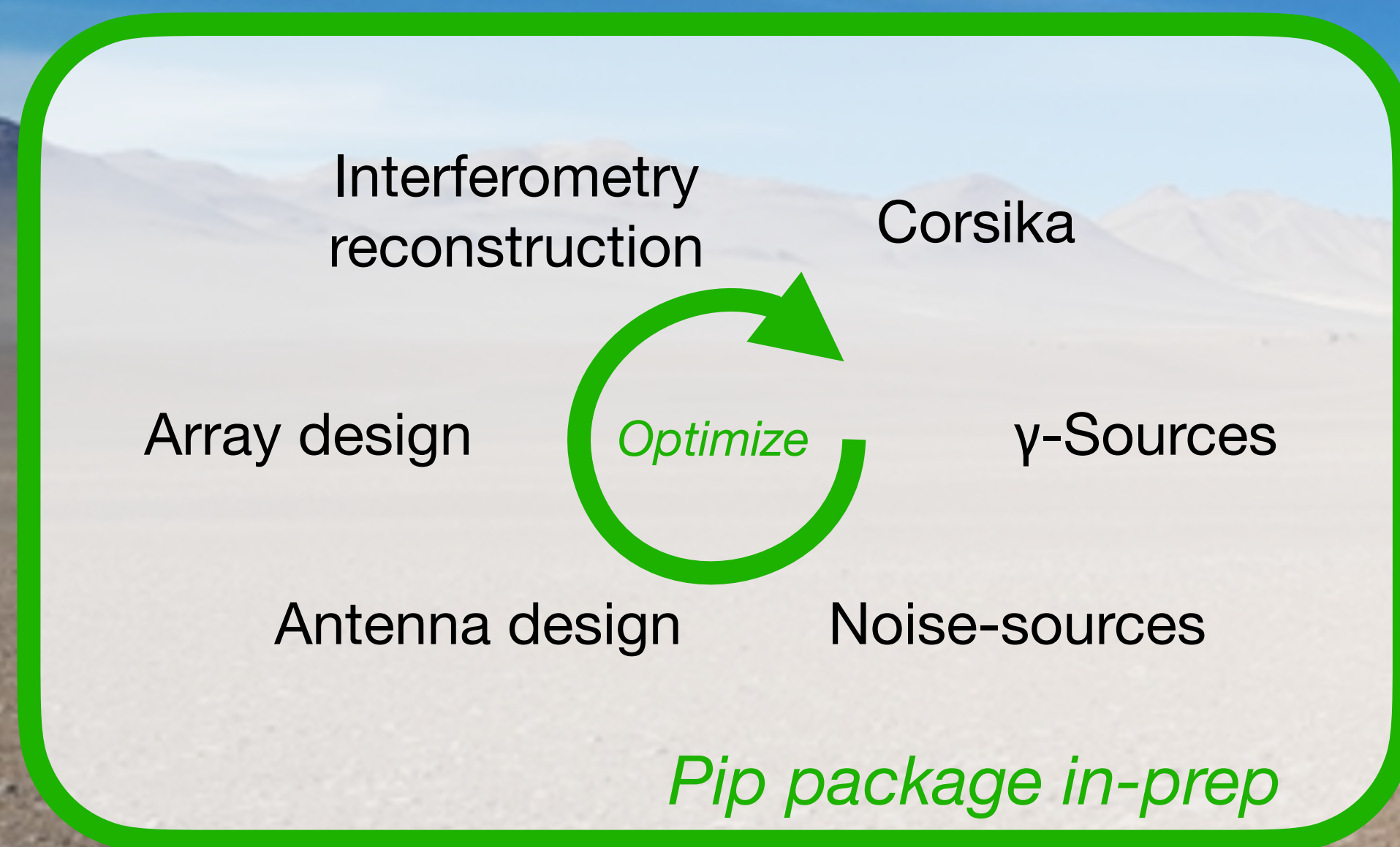
[Galactic sky]



- + depends on frequency
- + depends on time (LST)

Take home message

“Optimizing TURBO design for low energy threshold”
i.e. “Digging into the noise floor”



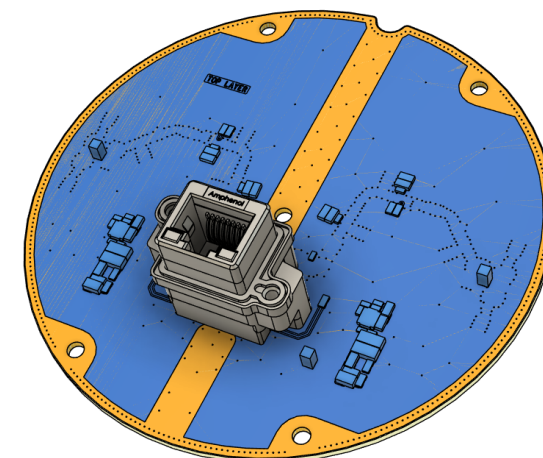
The author is funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Council Executive Agency. Neither the European Union nor the granting authority can be held responsible for them. This work is supported by ERC grant (CR-INTERFEROMETRY 101170979).

The “TURBO team”



Dániel Szálas-Motesiczky
(Electronics)

Prototype front-end board

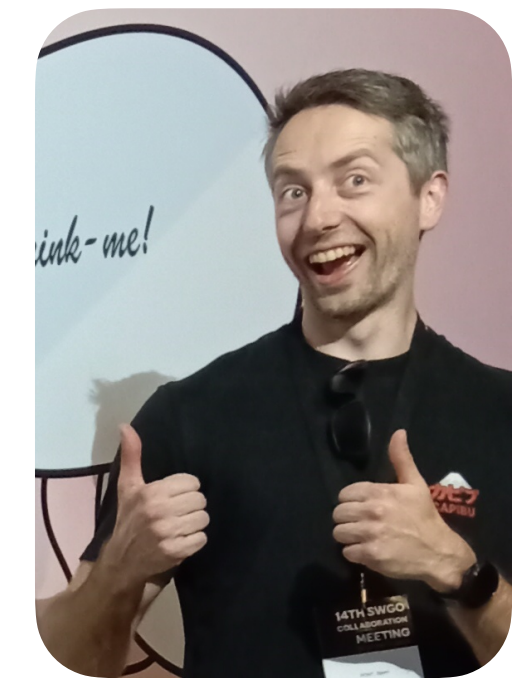
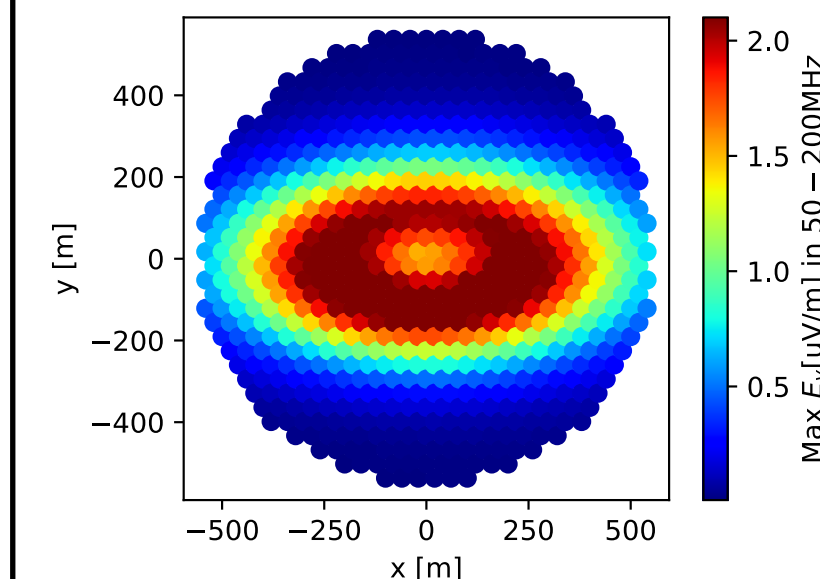


Harm Schoorlemmer
(“The boss”)



Funded by
the European Union

Gamma footprint

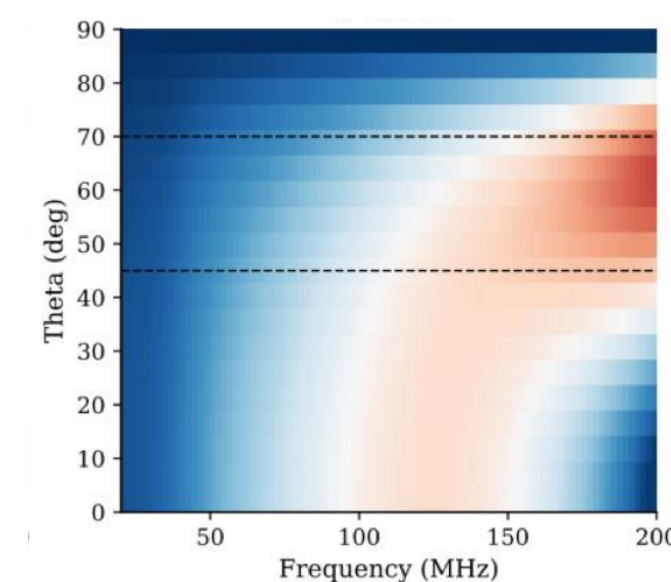
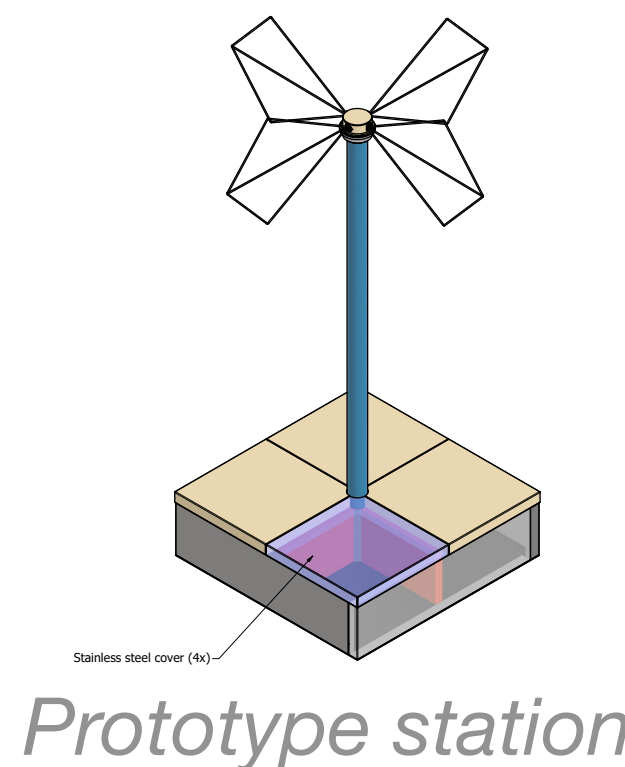


Bjarni Pont
(PostDoc)

“Optimizing Array Response”



Arno Engels
(Mechanical)



Antenna VEL

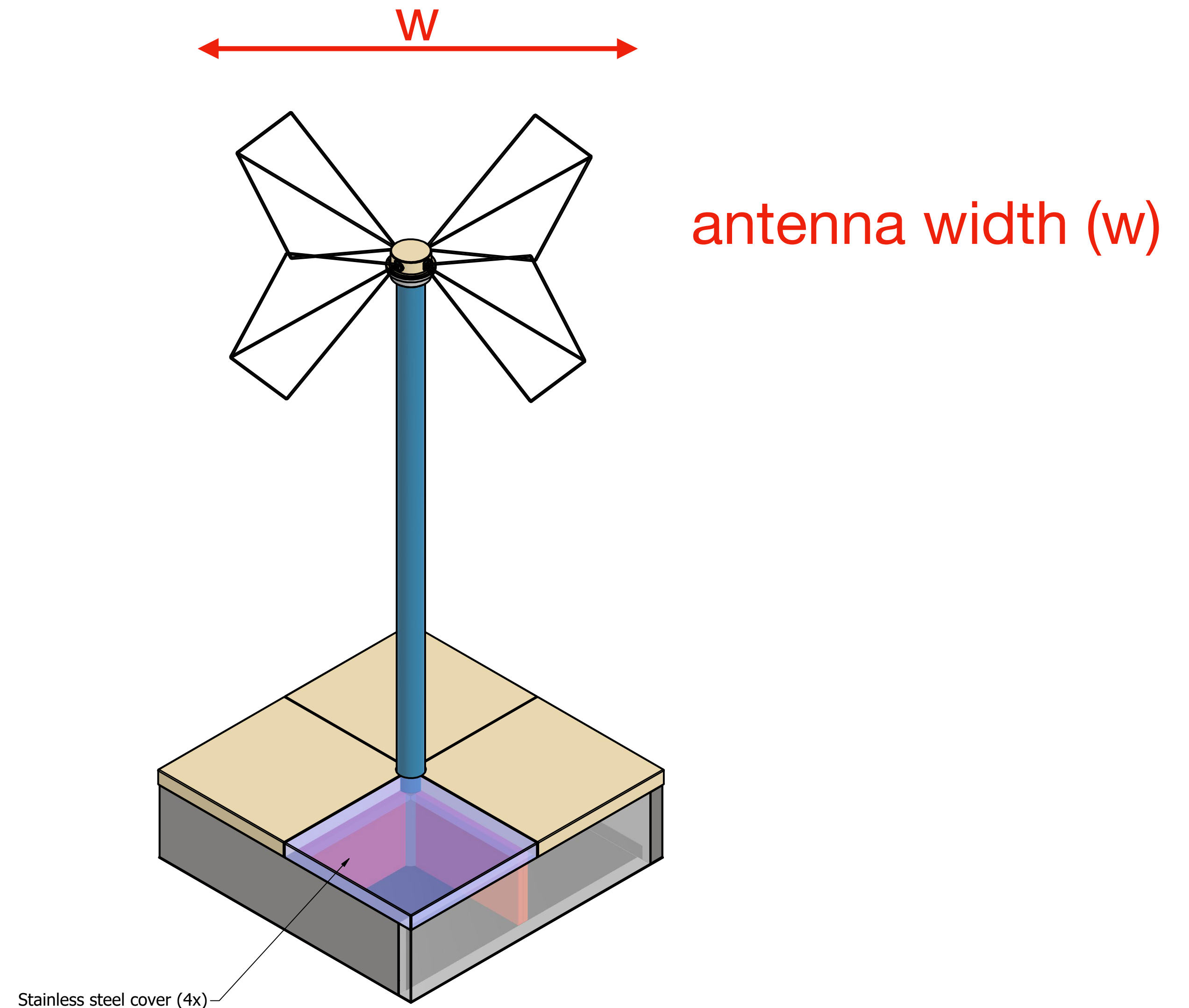
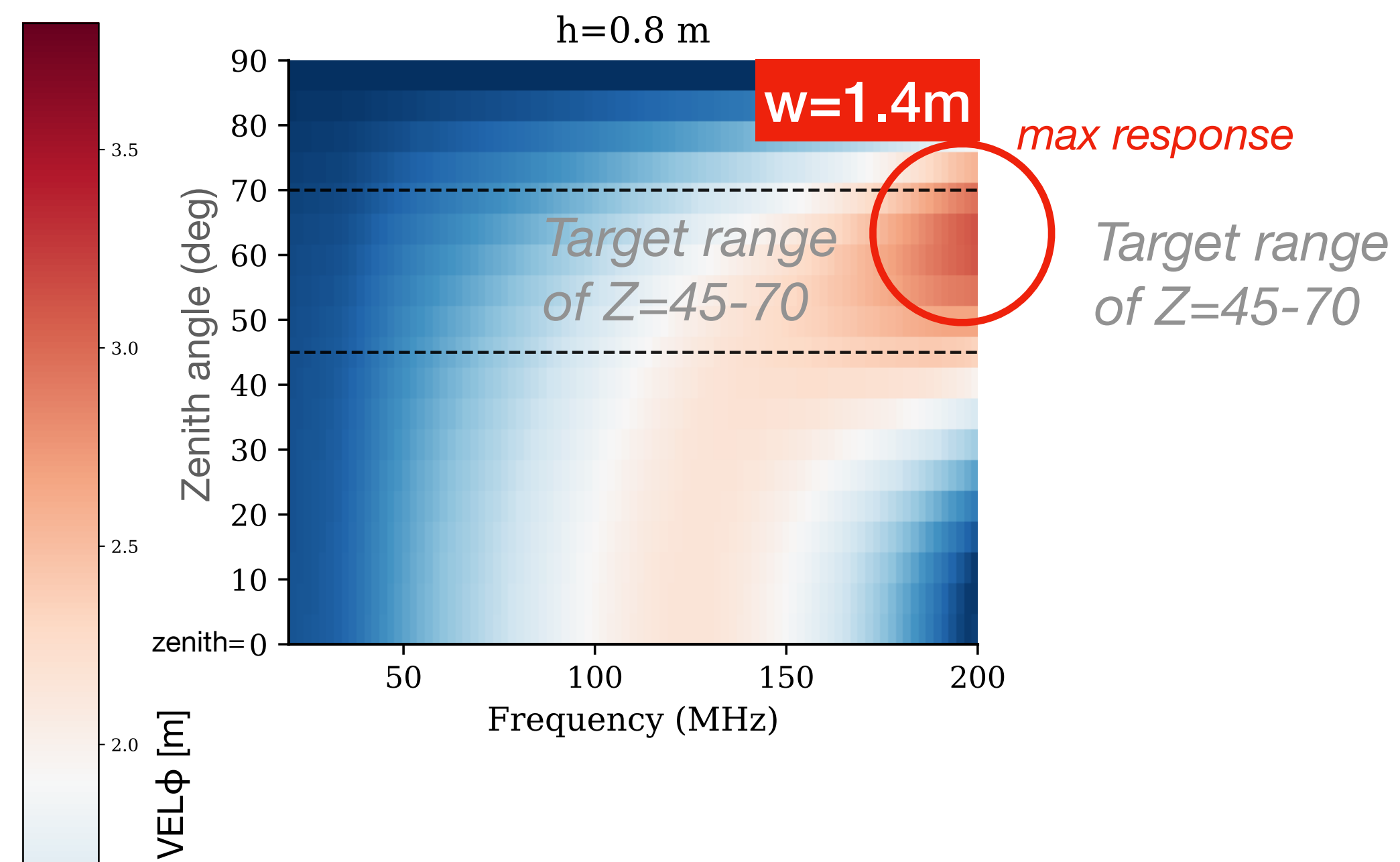


Lorenzo Casata
(PhD)

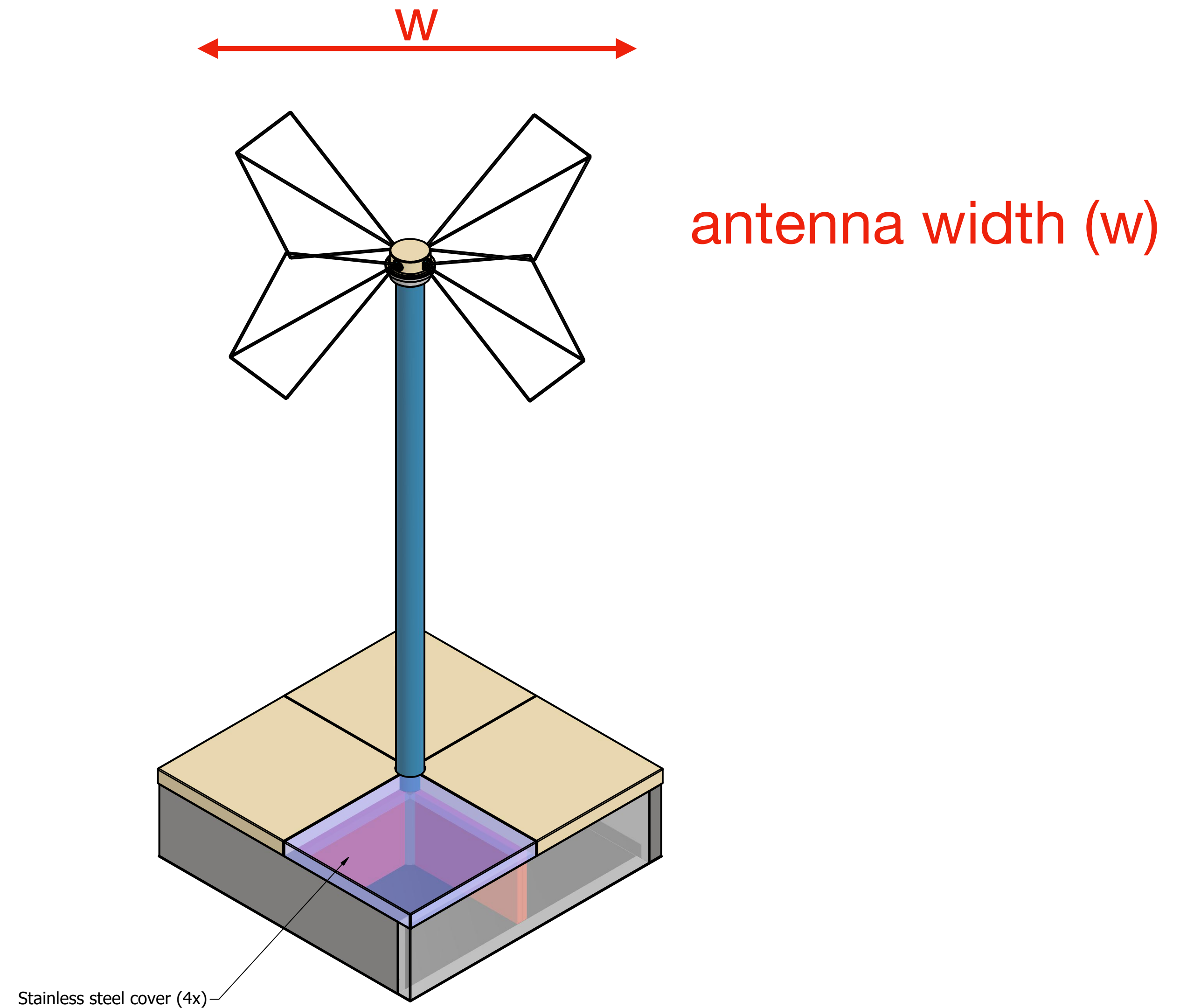
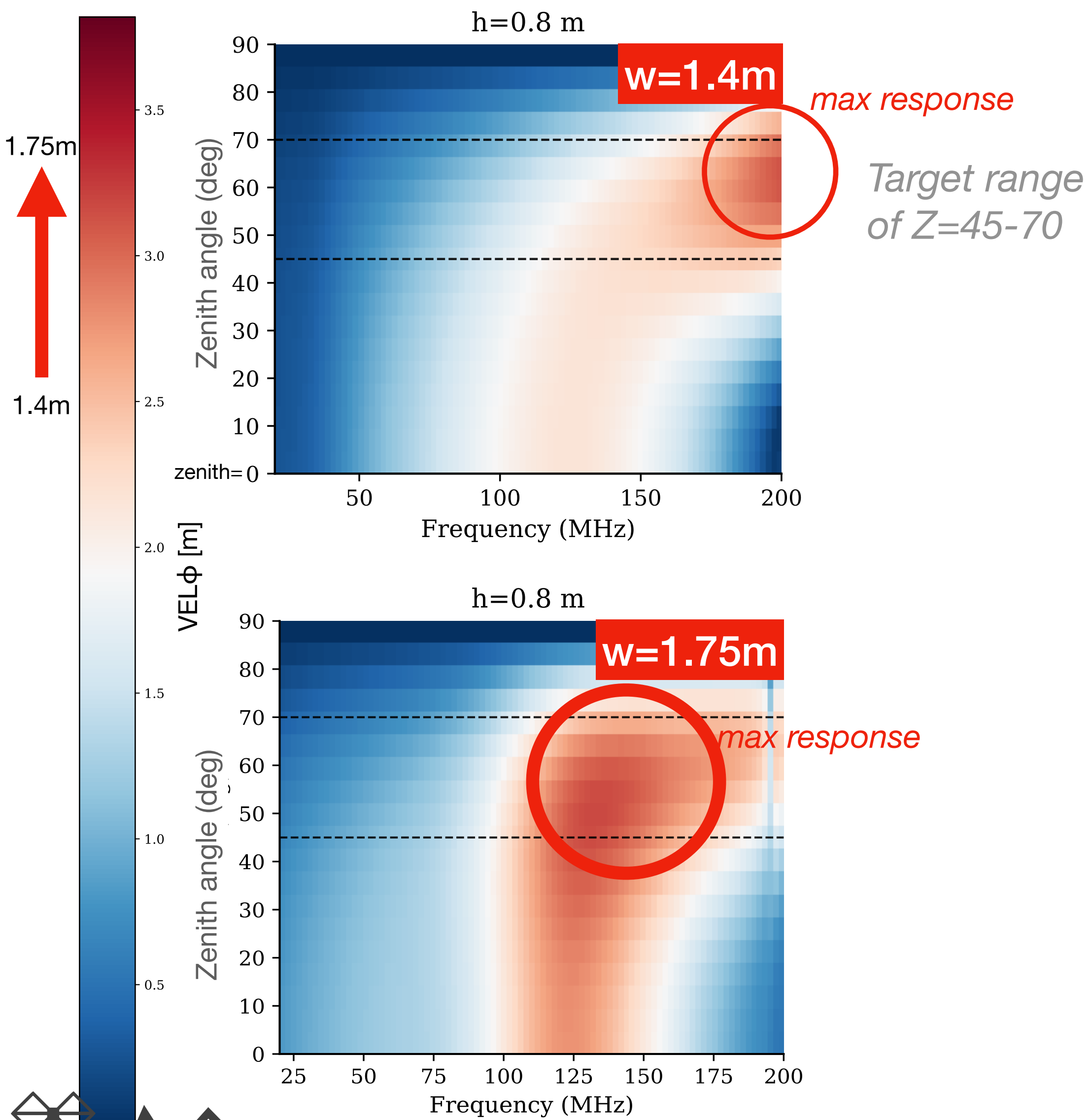
*“Optimizing Antenna/
Hardware Response”*

Backup

Antenna optimization



Antenna optimization

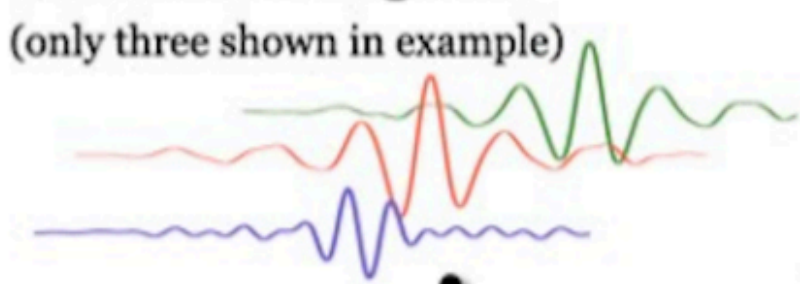


ASIRA

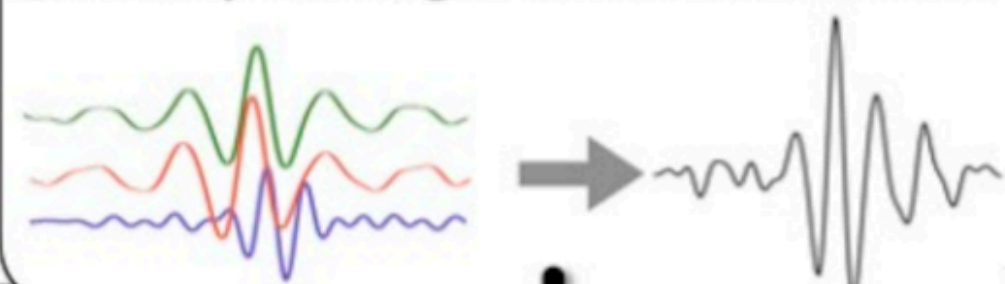
Method

[ICRC2023]

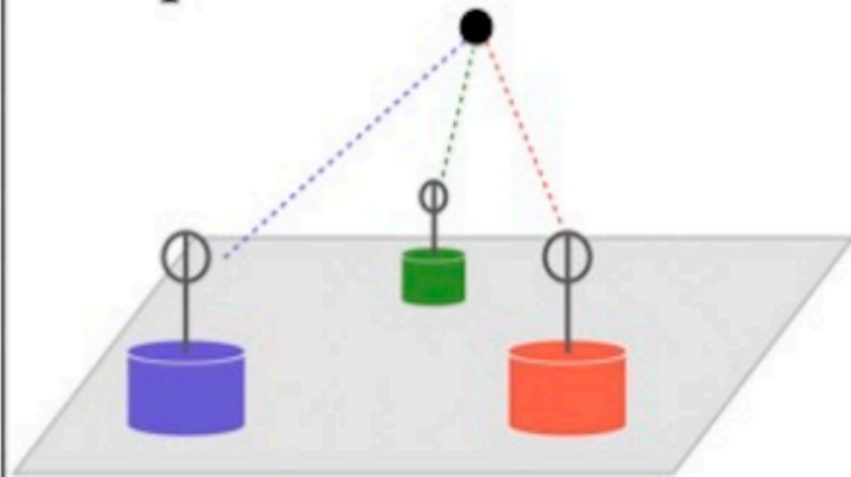
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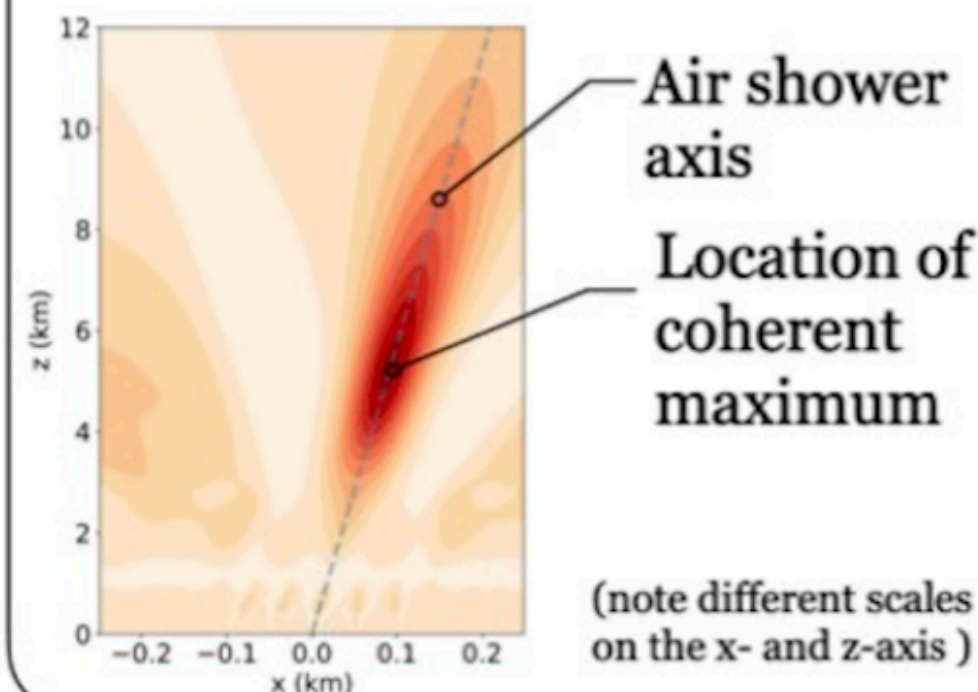
3) Delay the signals and sum them



2) Calculate time delay for
each antenna to a location
in space



4) Scan through space to identify
the air shower

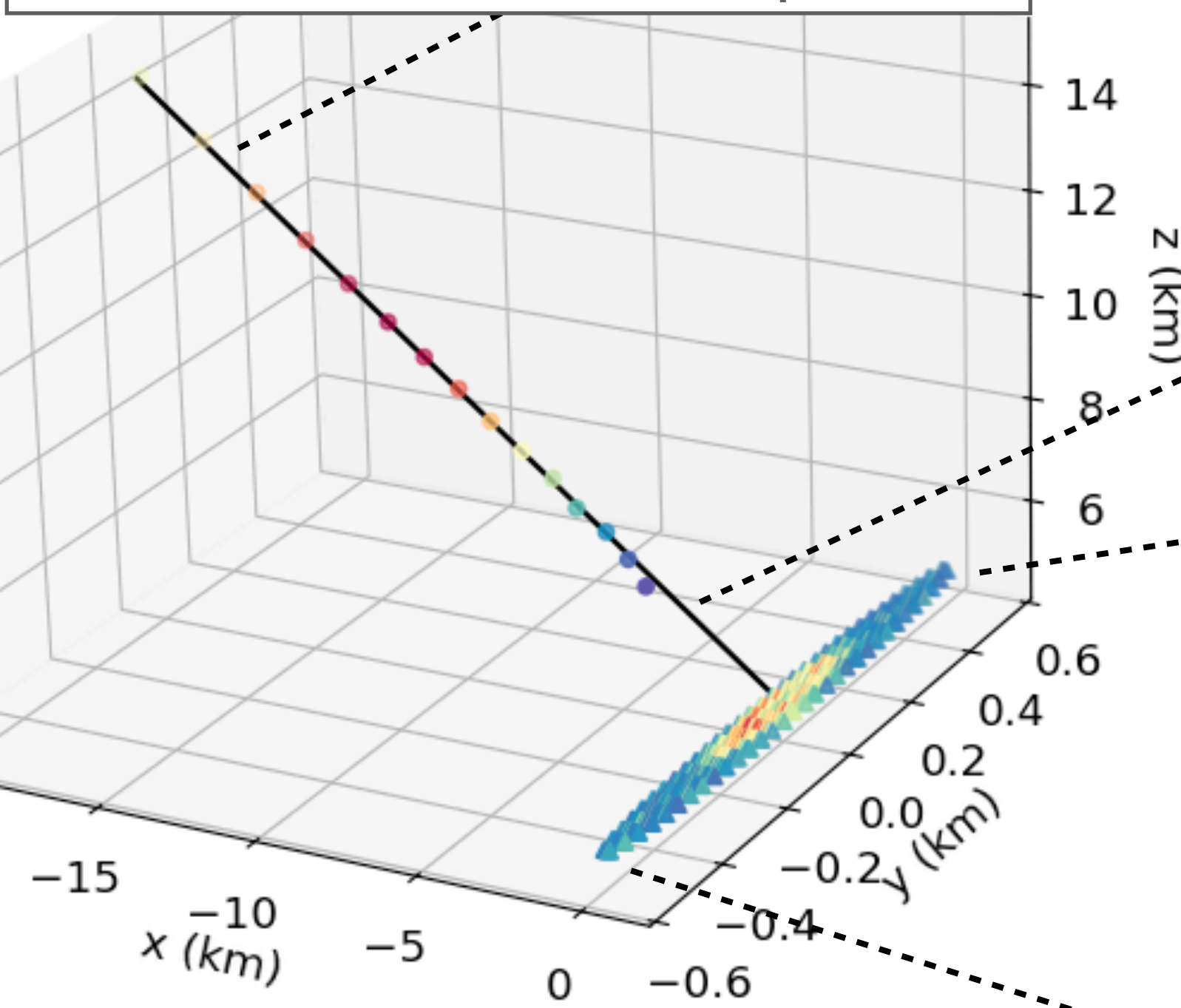


- [ASIRA]*: **A**ir **S**hower Interferometric **R**econstruction **A**lgorithm
 - ‘**Imaging**’ of the longitudinal profile
 - Potential for energy, $X_{\max}$, shower physics, ...
 - Needed: “Digging into the noise floor”
(single-station SNR of 1PeV gamma: ~ 0.1)
- Very accurate **axis reconstruction** potential:
 - AERA (Auger): ~ 0.25 deg (@ $\text{SNR} > 10$, $\lg E = 18$, $\langle N_{\text{st}} \rangle = 23$, $\delta_{\text{timing}} = 1 \text{ ns}$)
 - TURBO at 1-100 PeV energies: (δ =angular resolution w.r.t MC axis)
 - **w/o/ noise**: $\delta \sim 0.00\text{-}0.13$ deg
 - **w/ noise**: [...need to run the library].

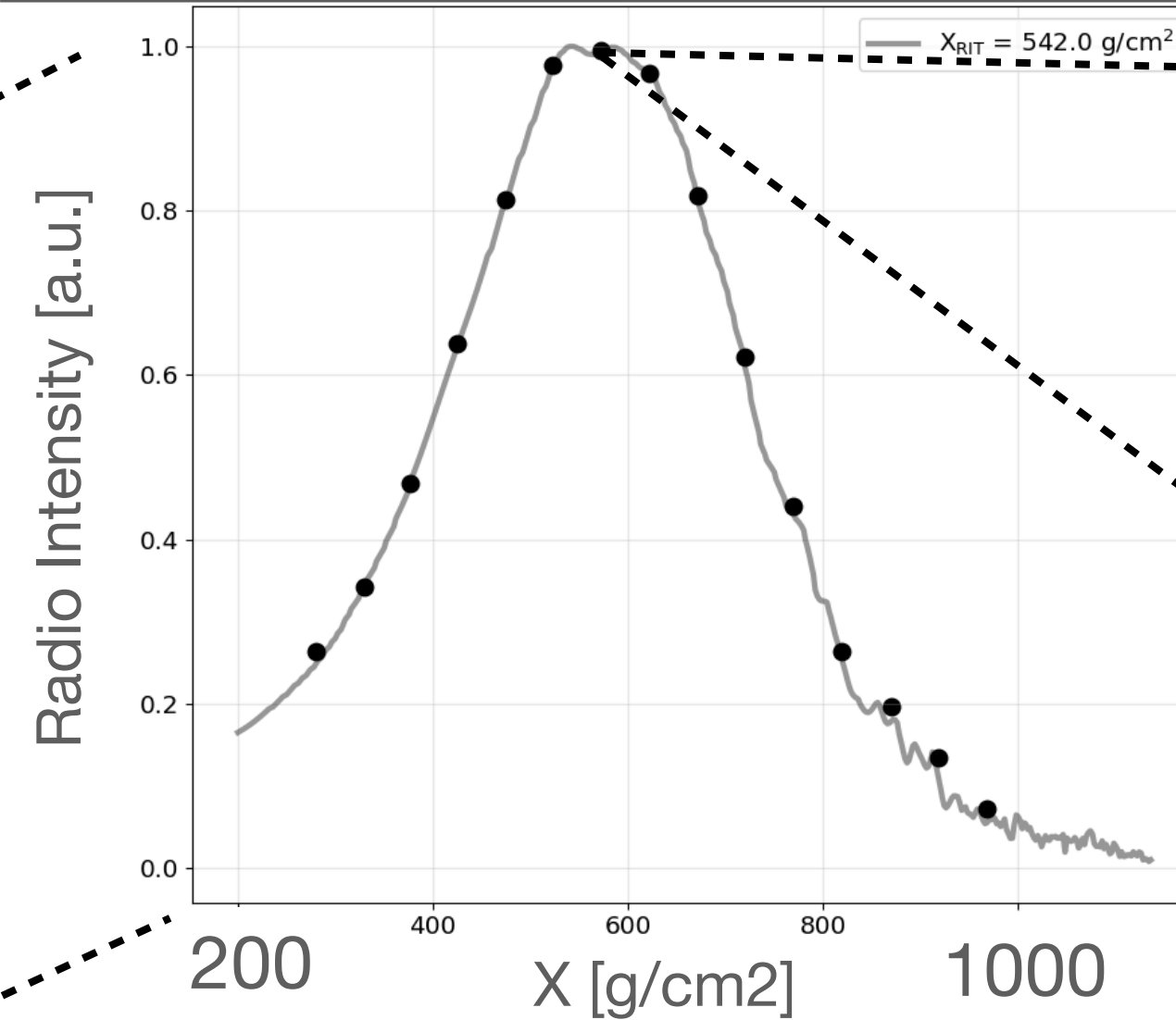
CoREAS: 100 PeV gamma
Z=60, A=0
GSM08 sky noise in $E_{\nu\chi B}$ (VEL unfolded)

→ MC axis rec: $\delta=0.03\text{deg}$

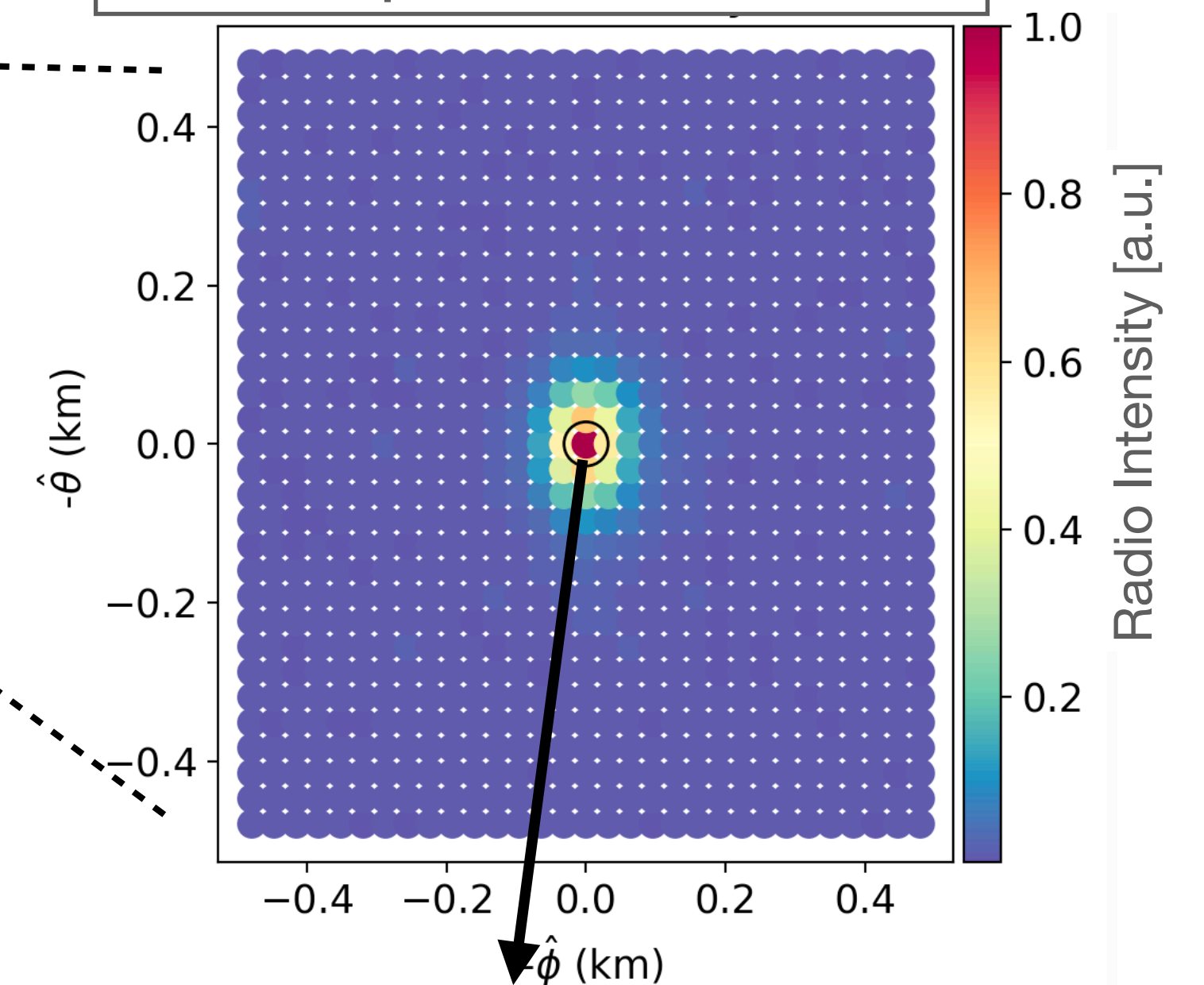
Shower axis and footprint



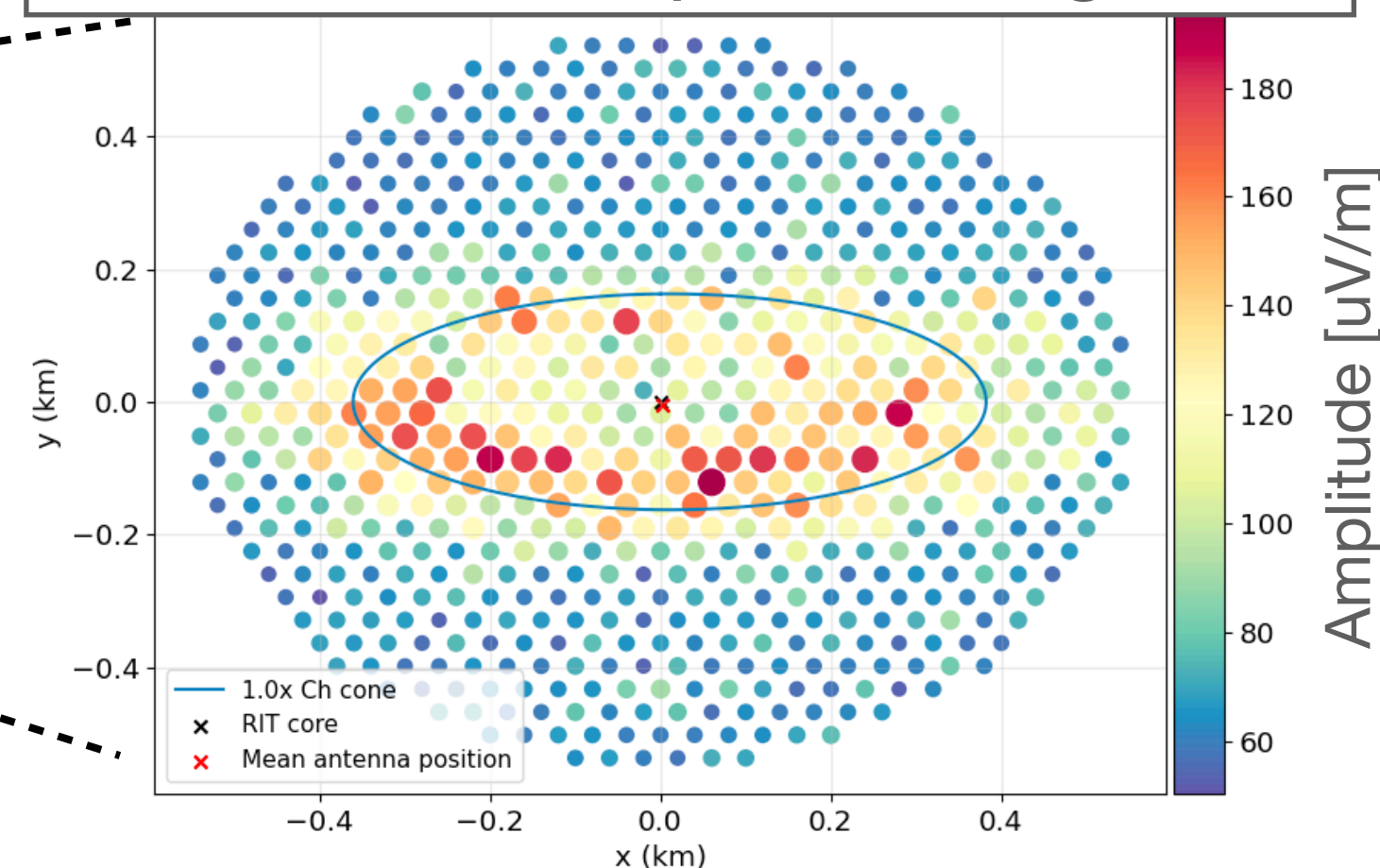
Longitudinal radio profile



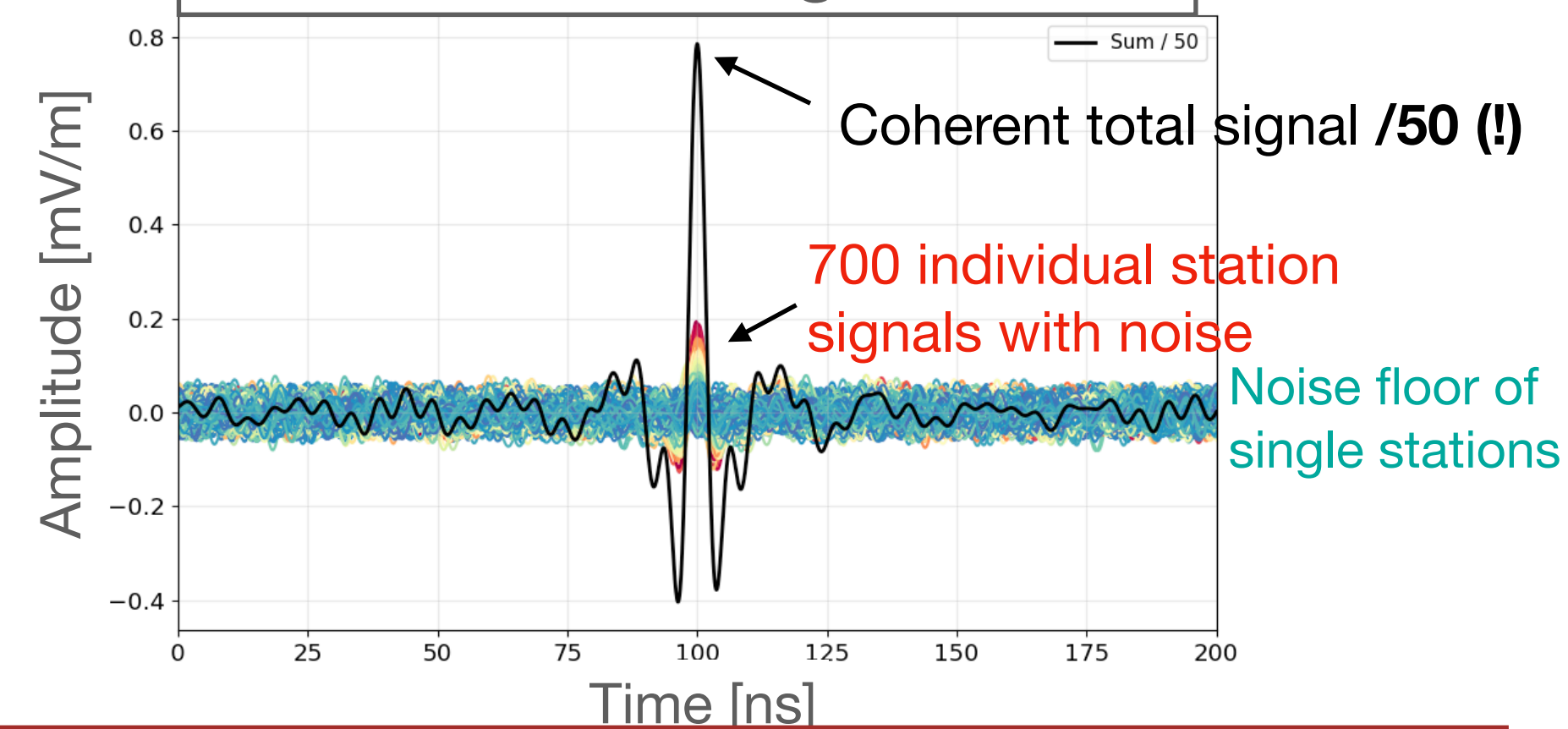
Shower plane slice at $X_{\max}$



Electric field amplitude at ground

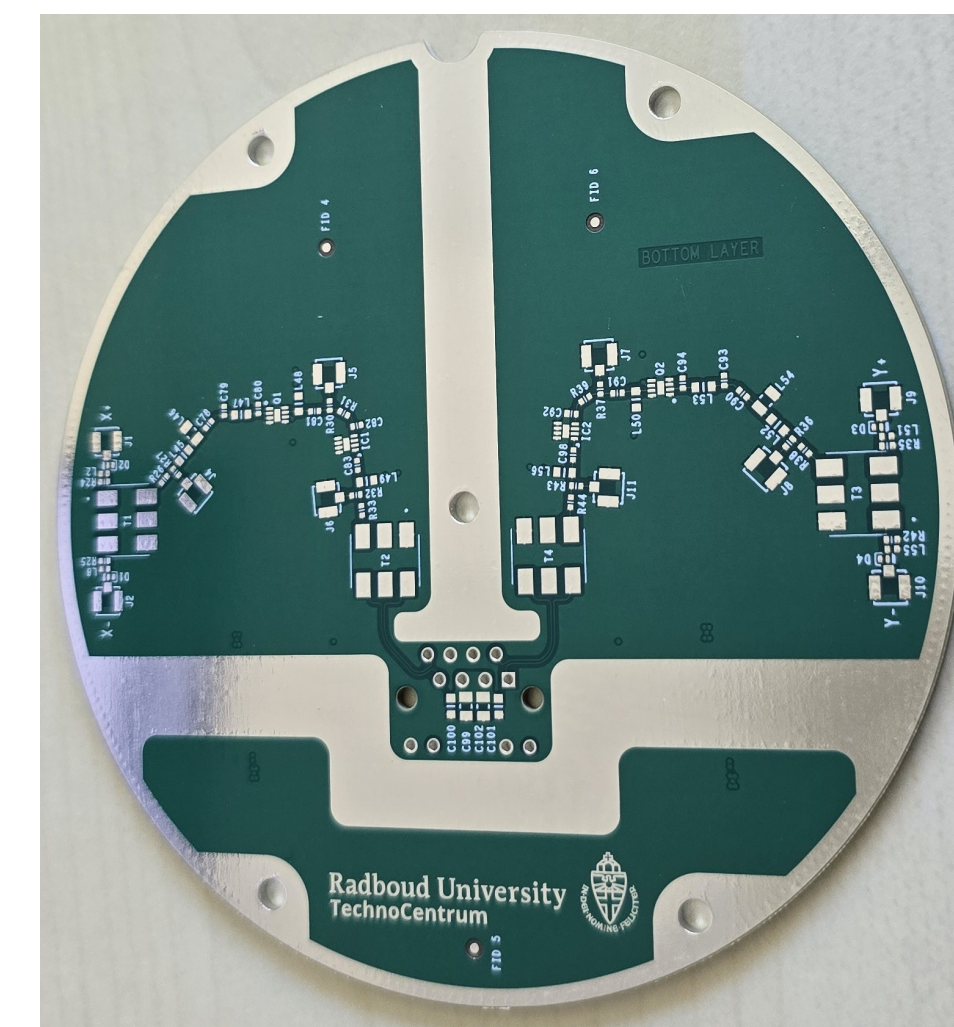
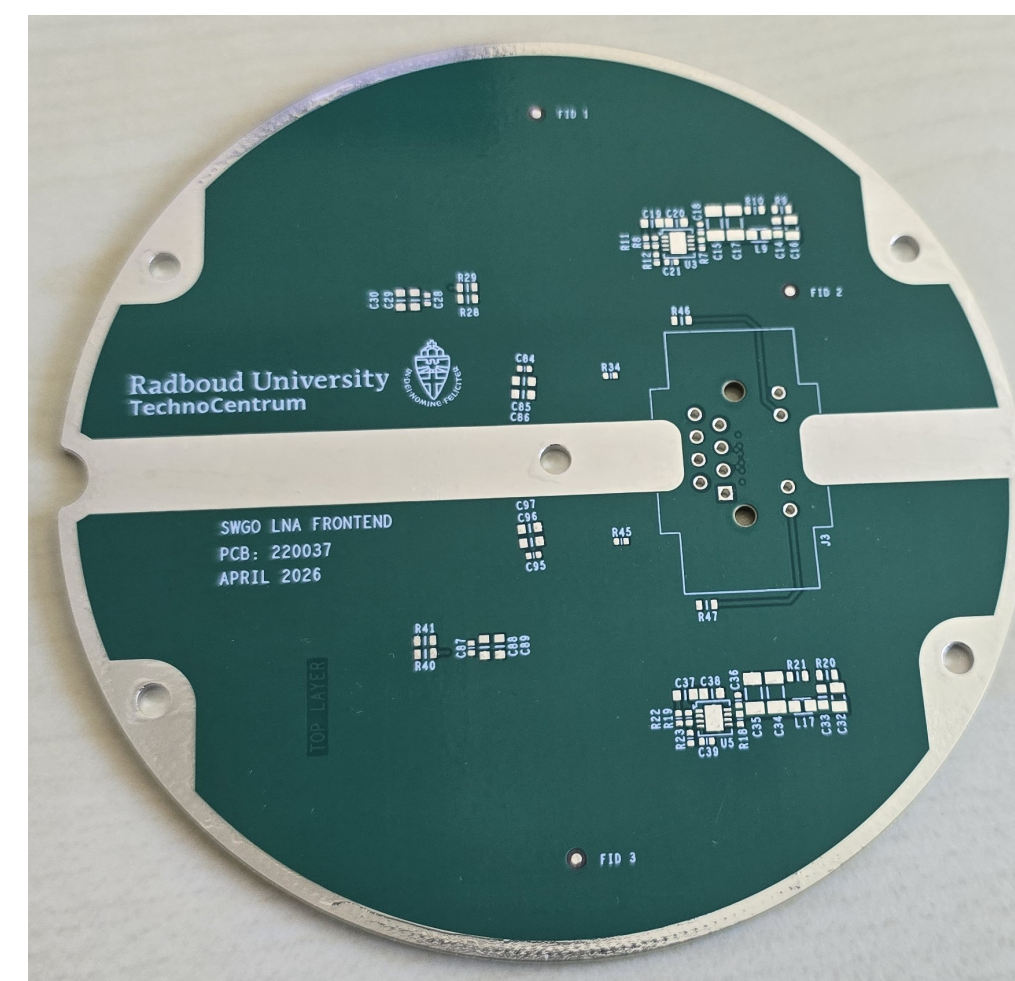
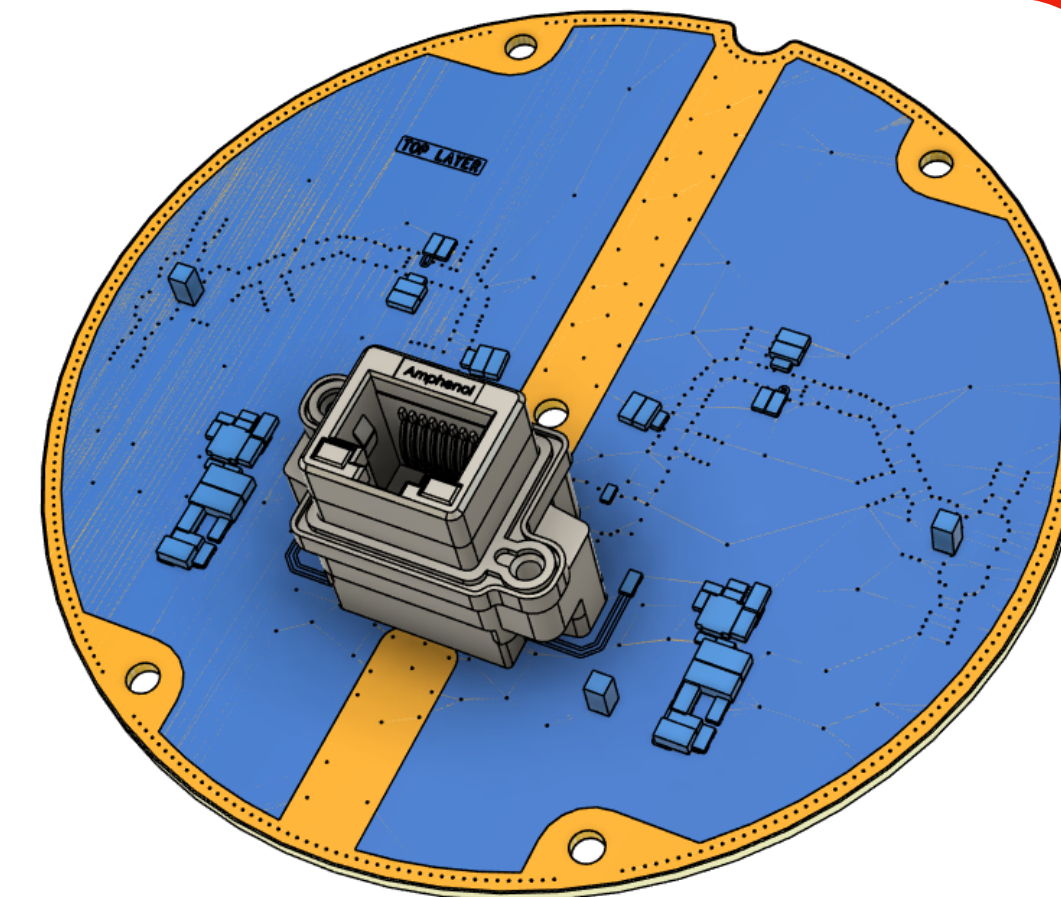
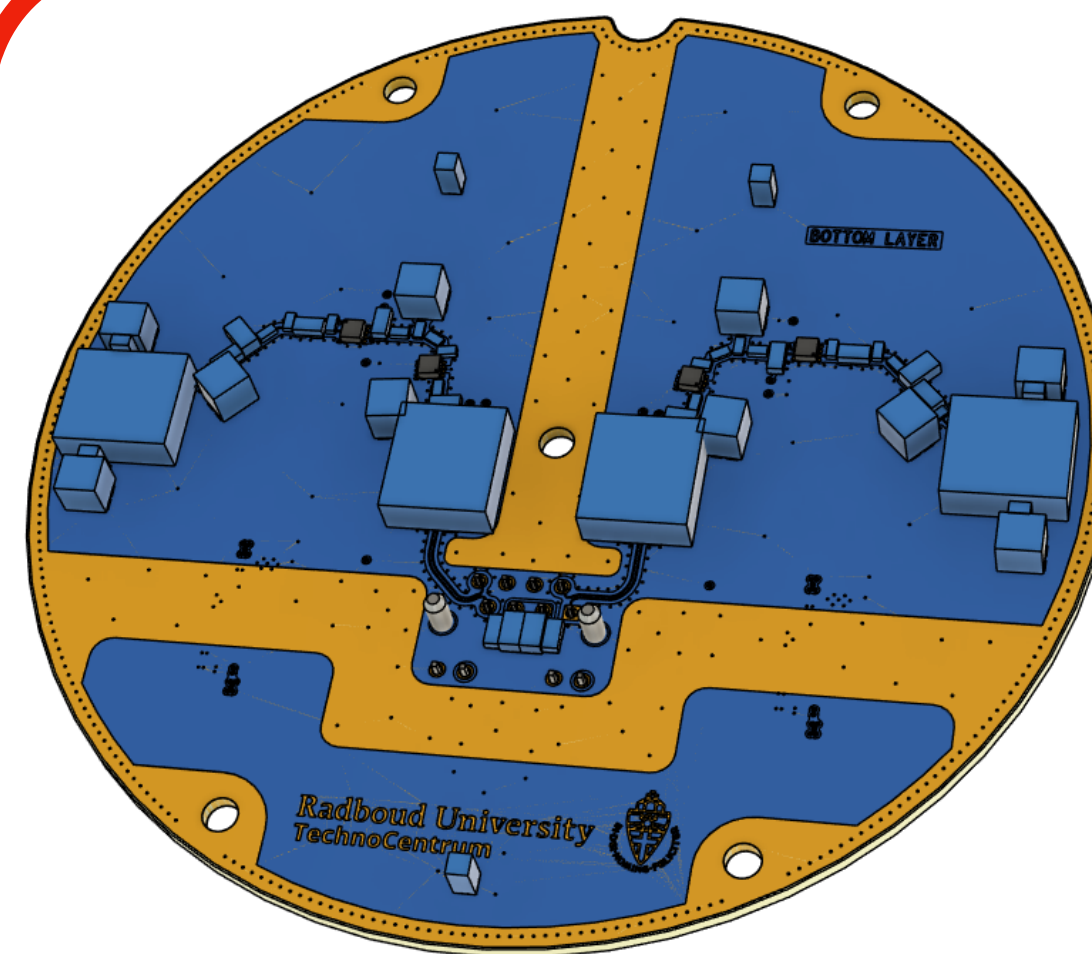
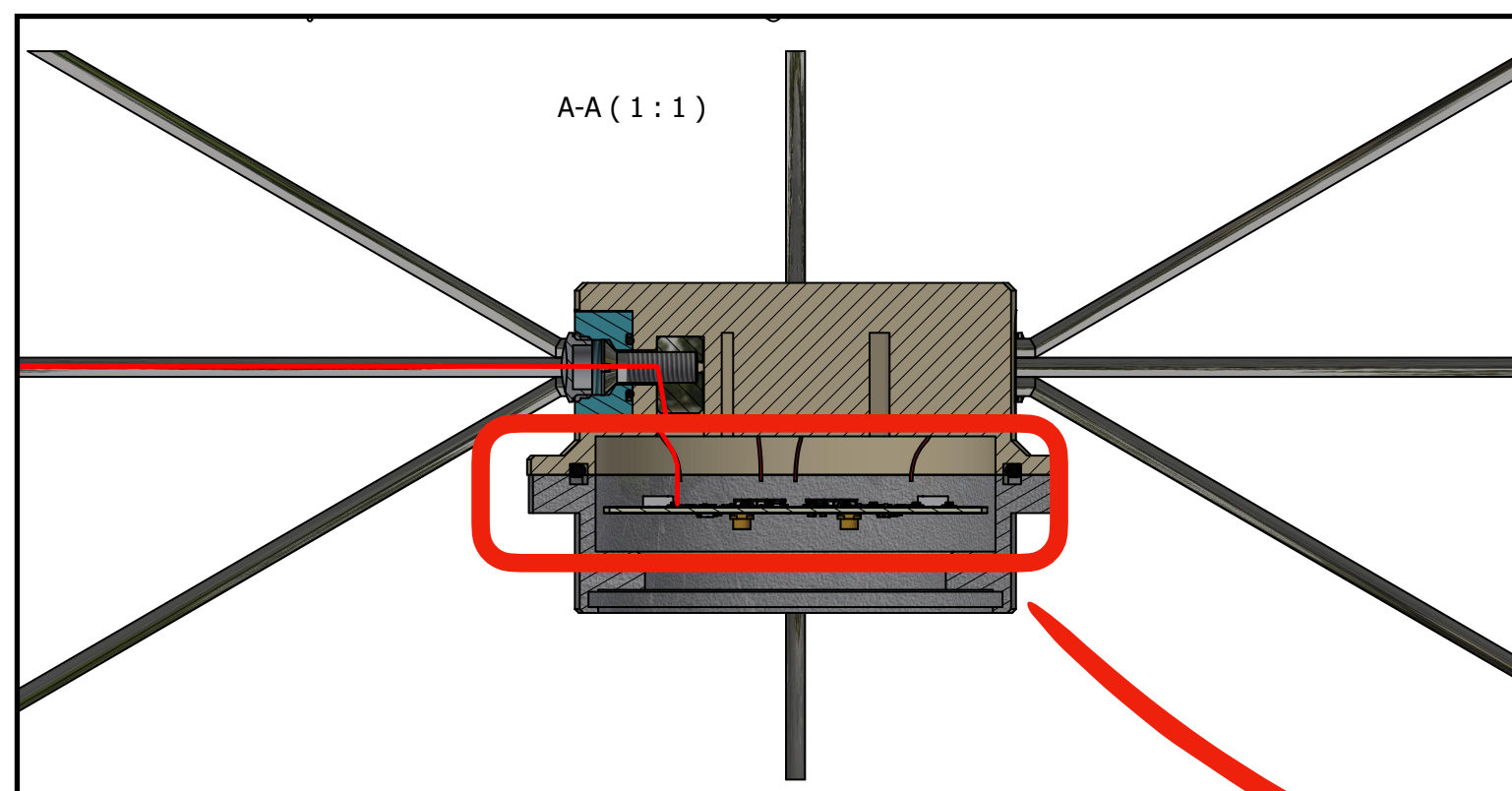


Coherent radio signal at X_{RIT}

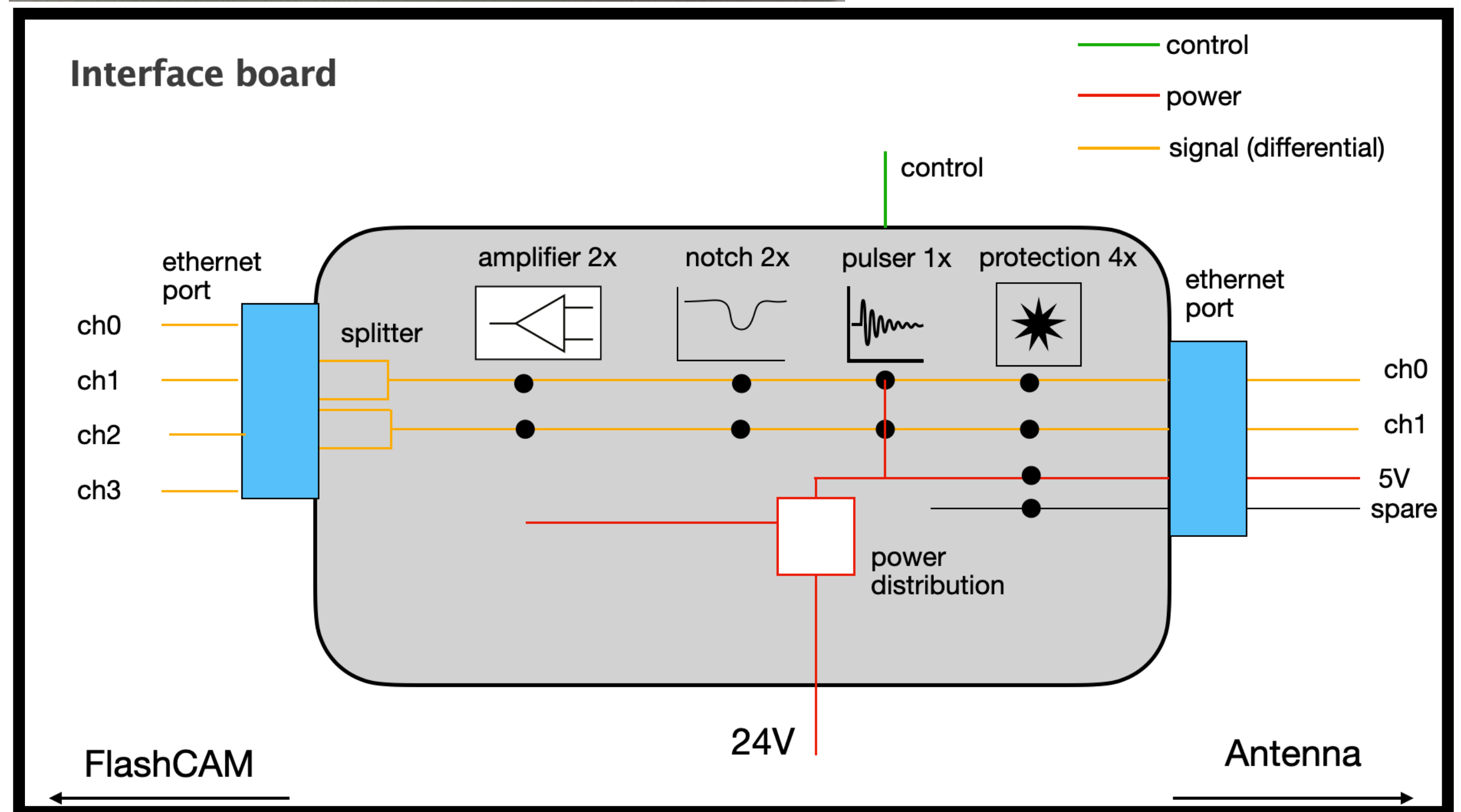


First iteration of design ready
and first PCBs produced

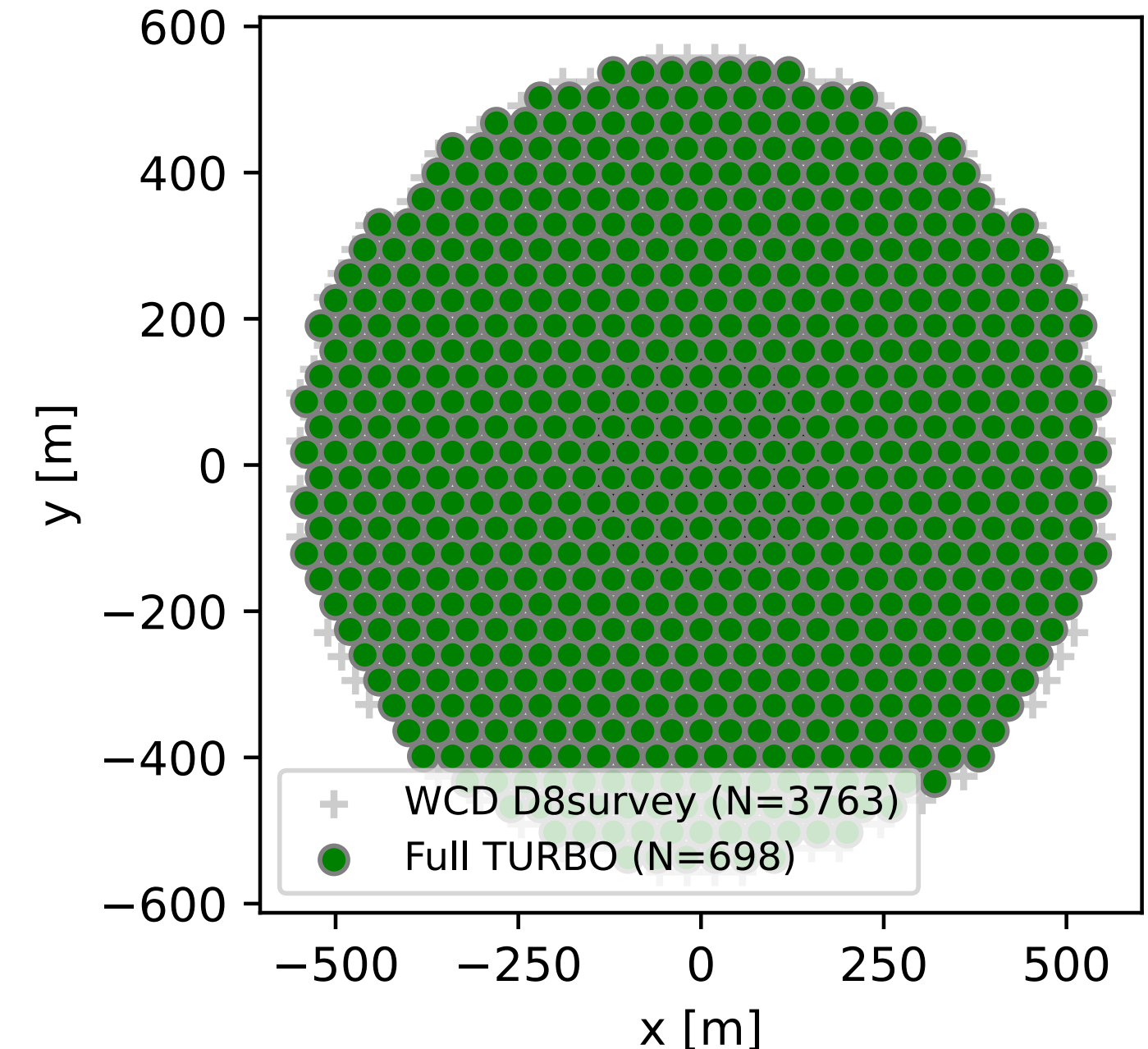
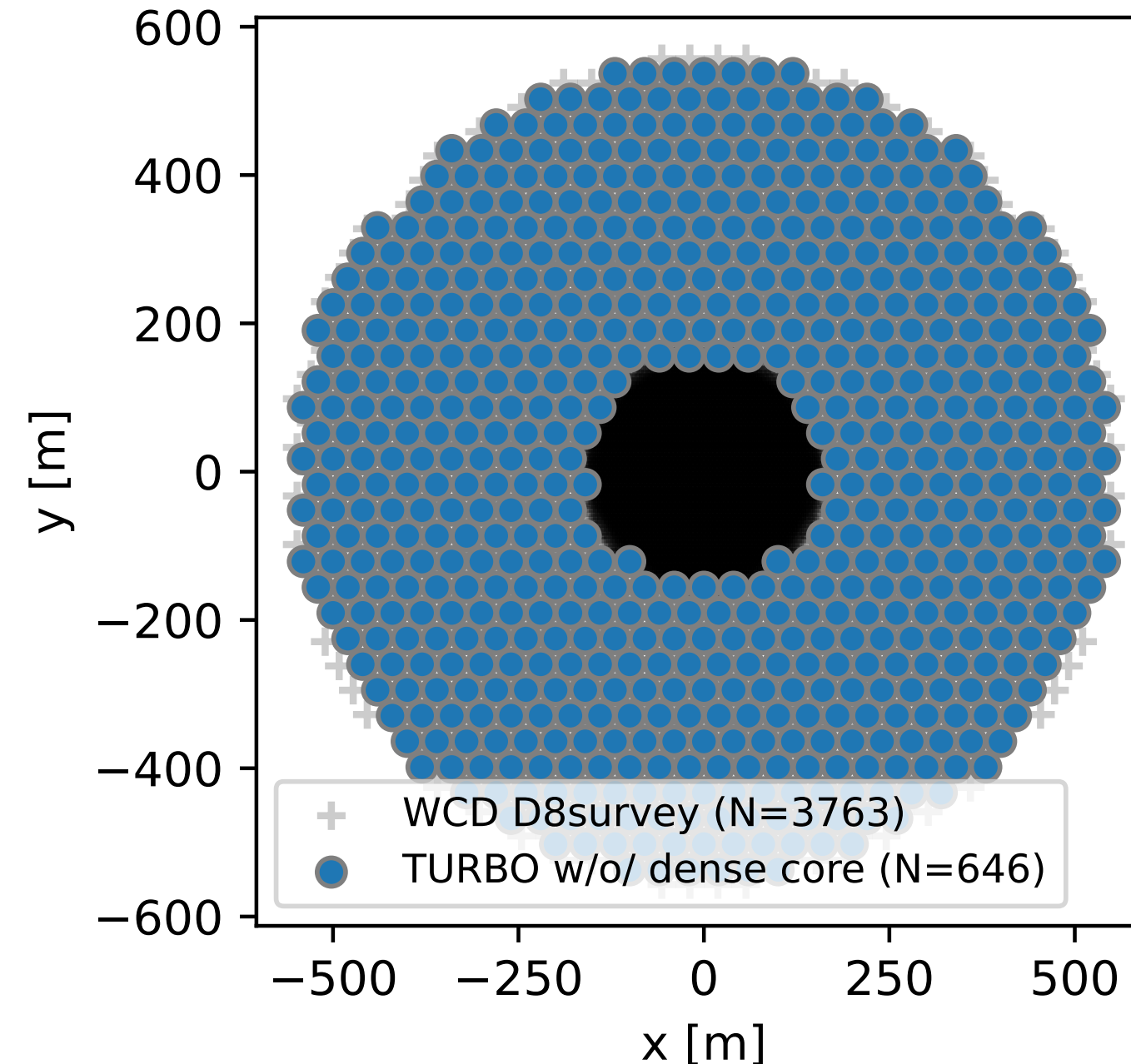
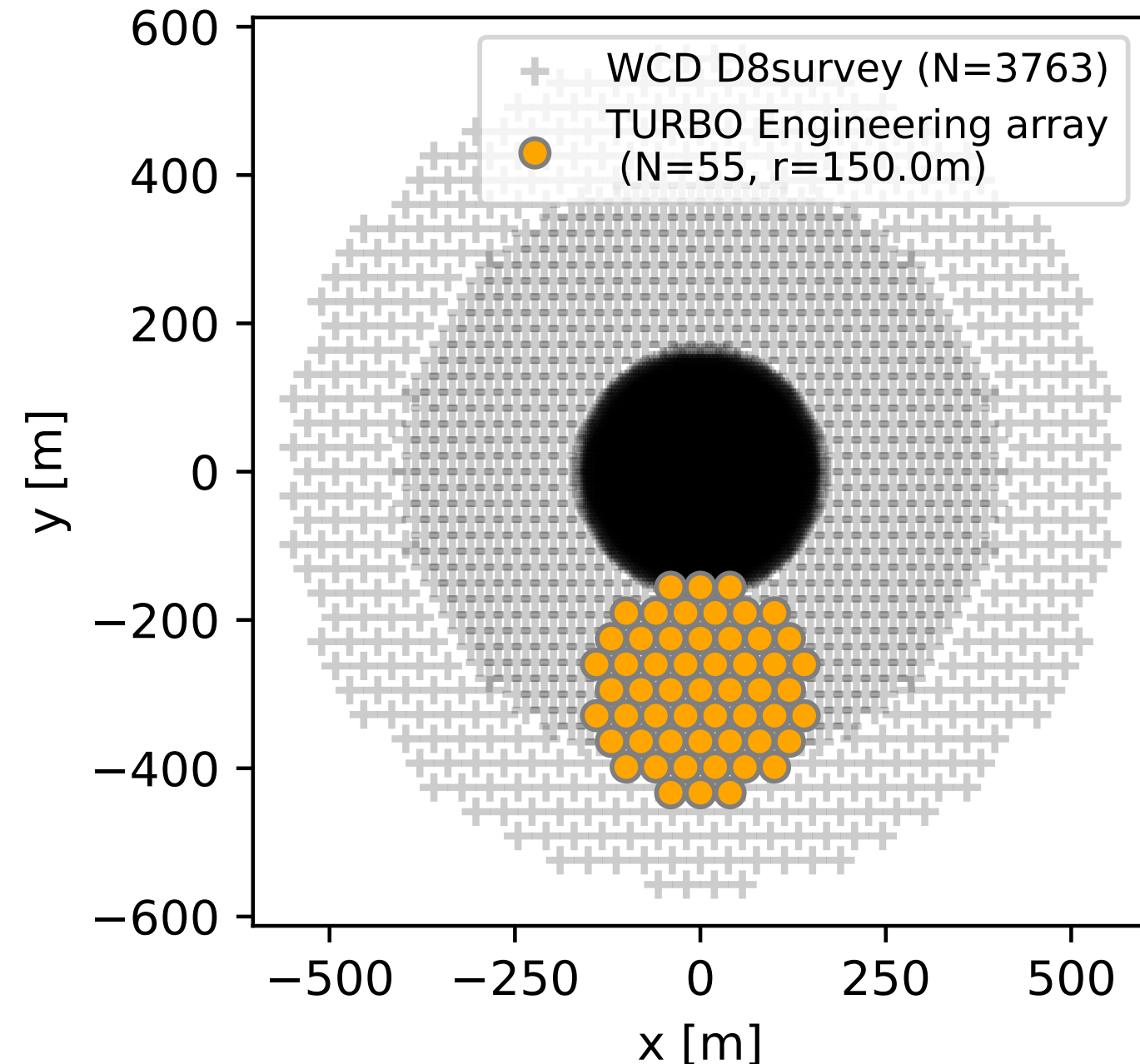
Currently populating the
boards for testing (coming
months)



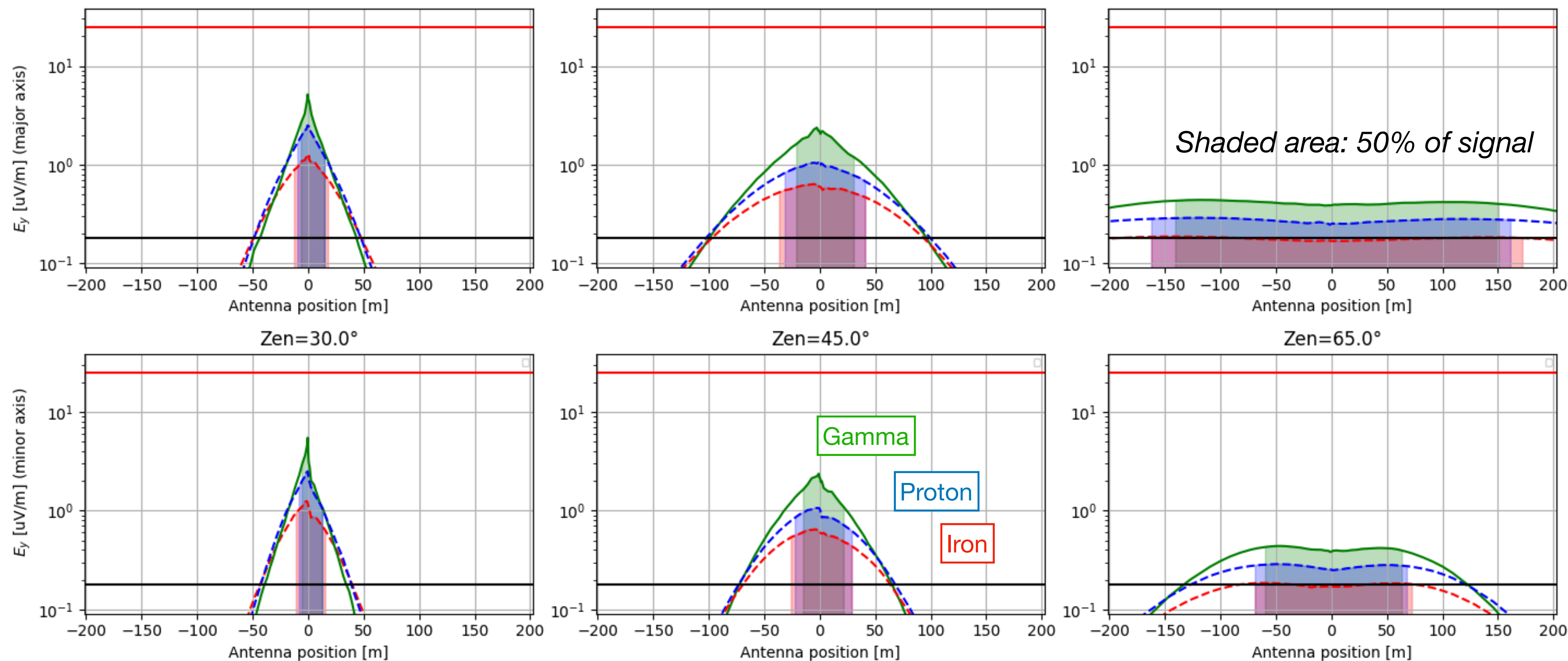
- Cable to antenna: Testing with 100m of CAT-7a cables
 - Advantage: shielding, standardized components, “cheap”, high-frequency performance. Less connectors.
 - To figure out: timing offset
- Testing usage of FlashCAM and modifications: on going.
- Conceptual design of interface board started => Will build upon the Phantom HV board design by MPIK.
- Interleaving of two channels with 2ns offset
=> 200MHz sampling & 200MHz band



- Placeholder SWGO layout
- TURBO layout
 - Regular triangular grid** (important for low interferometry biases)
 - Funding for **O(800) radio antennas**
 - Ideally following WCD spacing (minimizing RFI from WCD)
- TURBO Engineering Array** in outer array: **~50 antennas**
40m antenna spacing in WCD outer array: **~650 antennas**
- optional antennas on top of dense inner core(?): + ~50 antennas.**



1PeV footprint sizes (along semi-minor and semi-major axes)



- 10&100 PeV footprint sizes very similar because X_{max} is deeper resp.
- Amplitudes nearly scale with E_{γ}

Expectations of SNR

- Approximate **noise** (galactic dominated):
 - RMS noise = (25 uV/m per station) * sqrt(N_{stations})
- ASIRA: Coherent total **signal** at X_{max} vs {E, Zen}
- SNR** = $E_{\text{tot,coherent}} / \text{RMS}(E_{\text{noise}})$
(dynamic selection of stations for highest SNR)
- > good reconstructions from 5-10PeV ??
- Performance peaking beyond $Z=45$
- To study further [in progress]:

Optimizations

- Try station layouts
- Vary antenna design**
- frequency band cuts?

Systematics

- Partial footprints
- Azimuth variation

Noise:

- system noise
- Signal chain losses
- Background sky (LST)**

