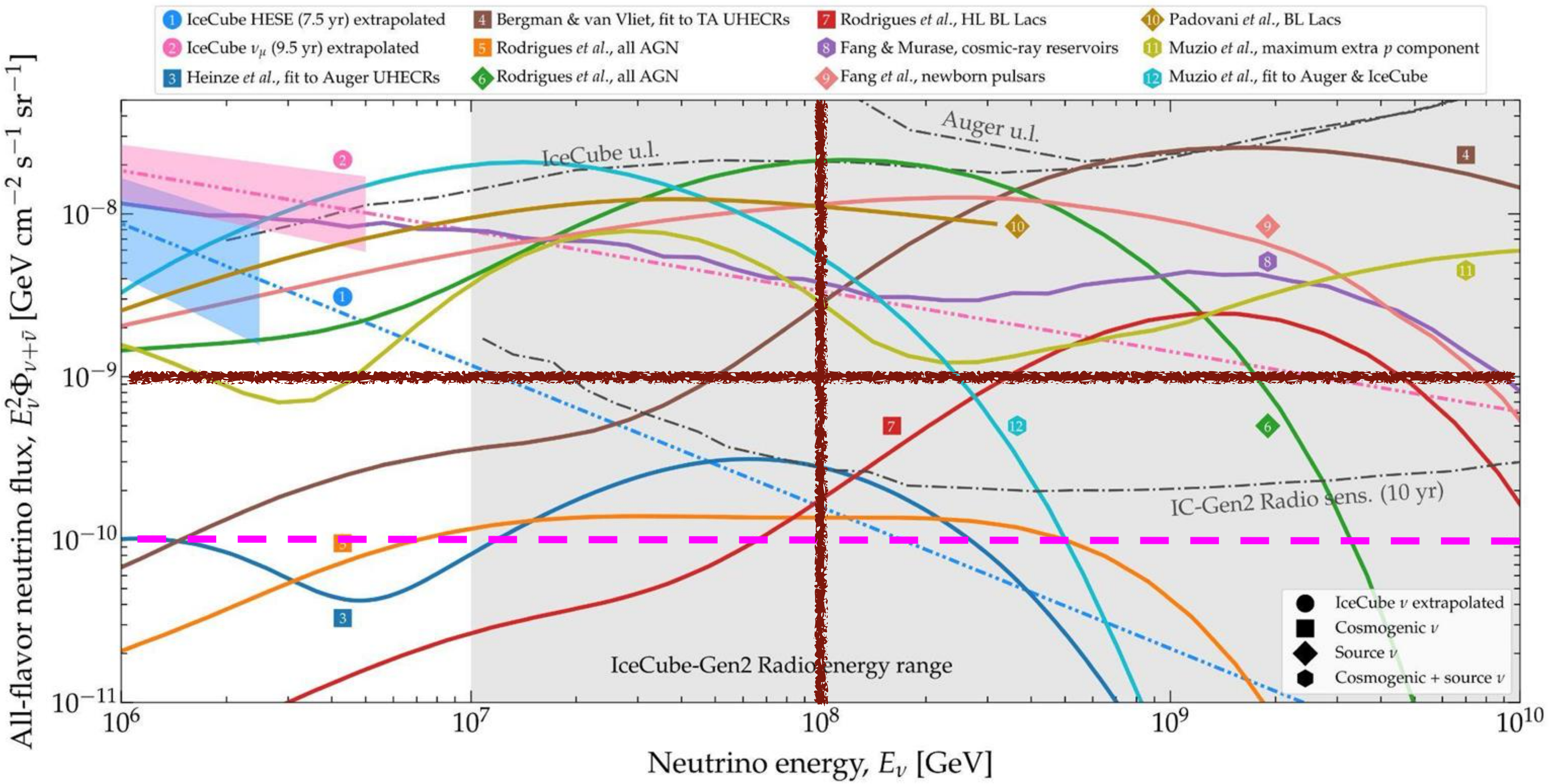
# Targeting 100-PeV Tau Neutrino Detection with an Array of Phased & High-Gain Autonomous Antennas

**Stephanie Wissel**

ARENA 14 June 2024 Chicago

Andrew Zeolla, Cosmin Deaconu, Valentin Decoene, Kaeli Hughes, Zachary Martin, Katharine Mulrey, Austin Cummings for the BEACON Collaboration, Rafael Alves Batista, Aurélien Benoit-Lévy, Mauricio Bustamante, Pablo Correa, Valentin Decoene, Arsène Ferrière, Marion Guelfand, Tim Huege, Kumiko Kotera, Olivier Martineau, Kohta Murase, Valentin Niess, Jianli Zhang, for the GRAND Collaboration, Oliver Krömer, Kathryn Plant, Frank G. Schroeder

# 100 PeV Tau Neutrino Target Sensitivity



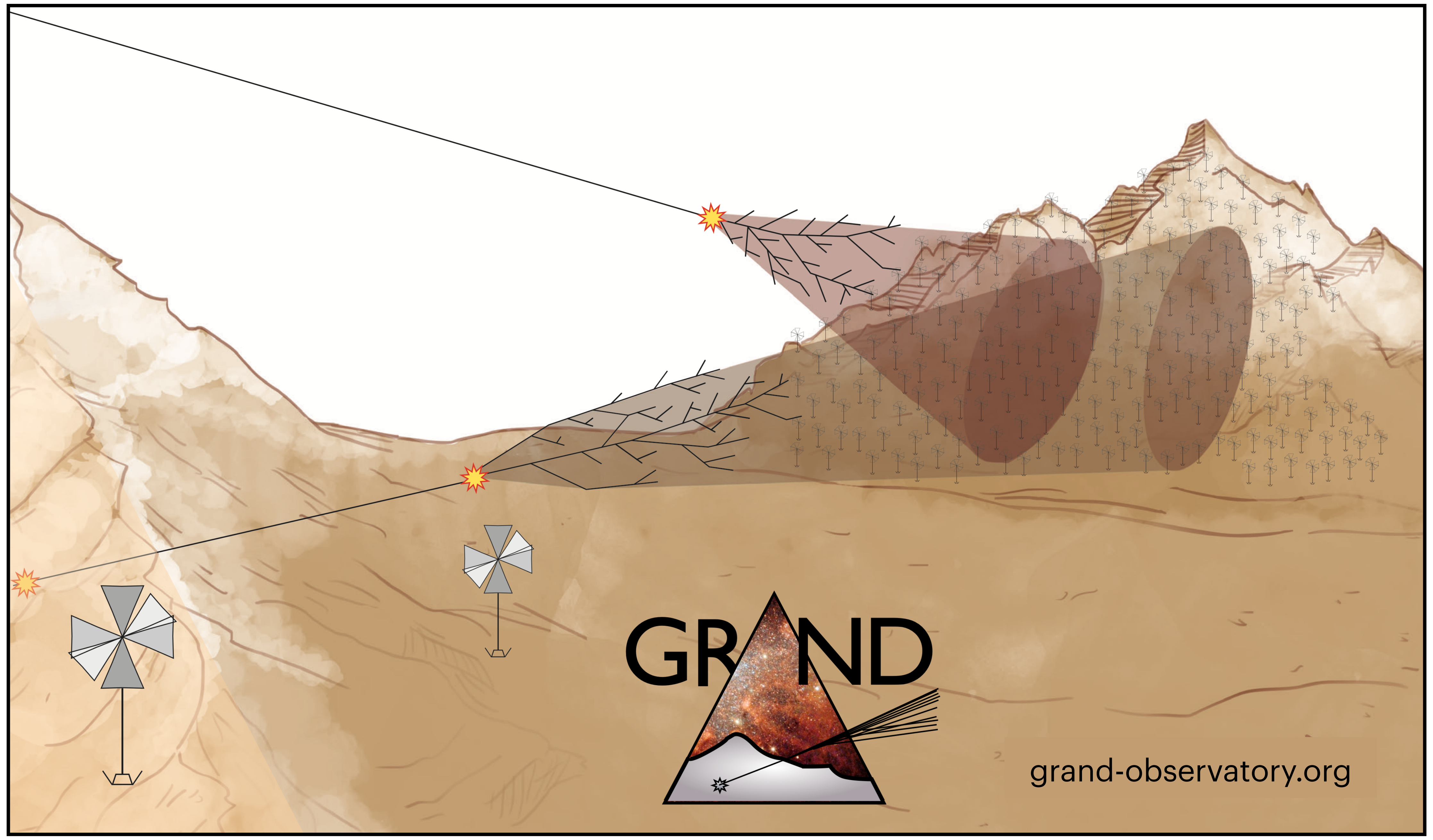

Valera, Bustamante, Glaser arXiv:2210.03756

- Target discovery instrument in 5-10 years
- Reach diffuse sensitivity $10^{-9}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ at 100 PeV
- Target large FoV & lower energy scale where flux is higher (even though lower exit probability)

# Radio Detection of Tau Neutrinos

Whitepaper:
GRAND Collaboration
arXiv:1810.09994

## GRAND Concept

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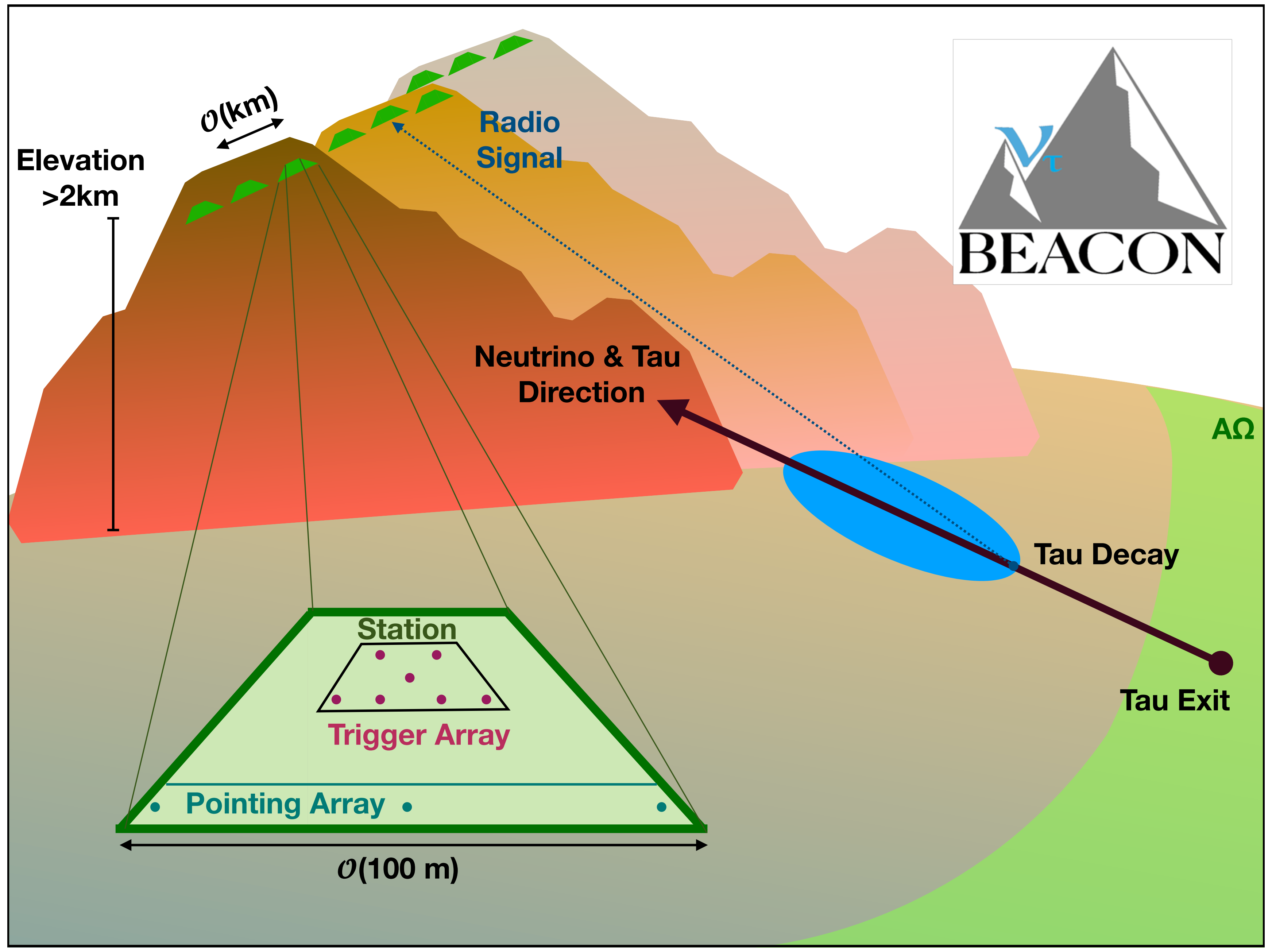


Design study:
BEACON Collaboration
JCAP 2020
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See also TAROGE-M
https://arxiv.org/pdf/2207.10616

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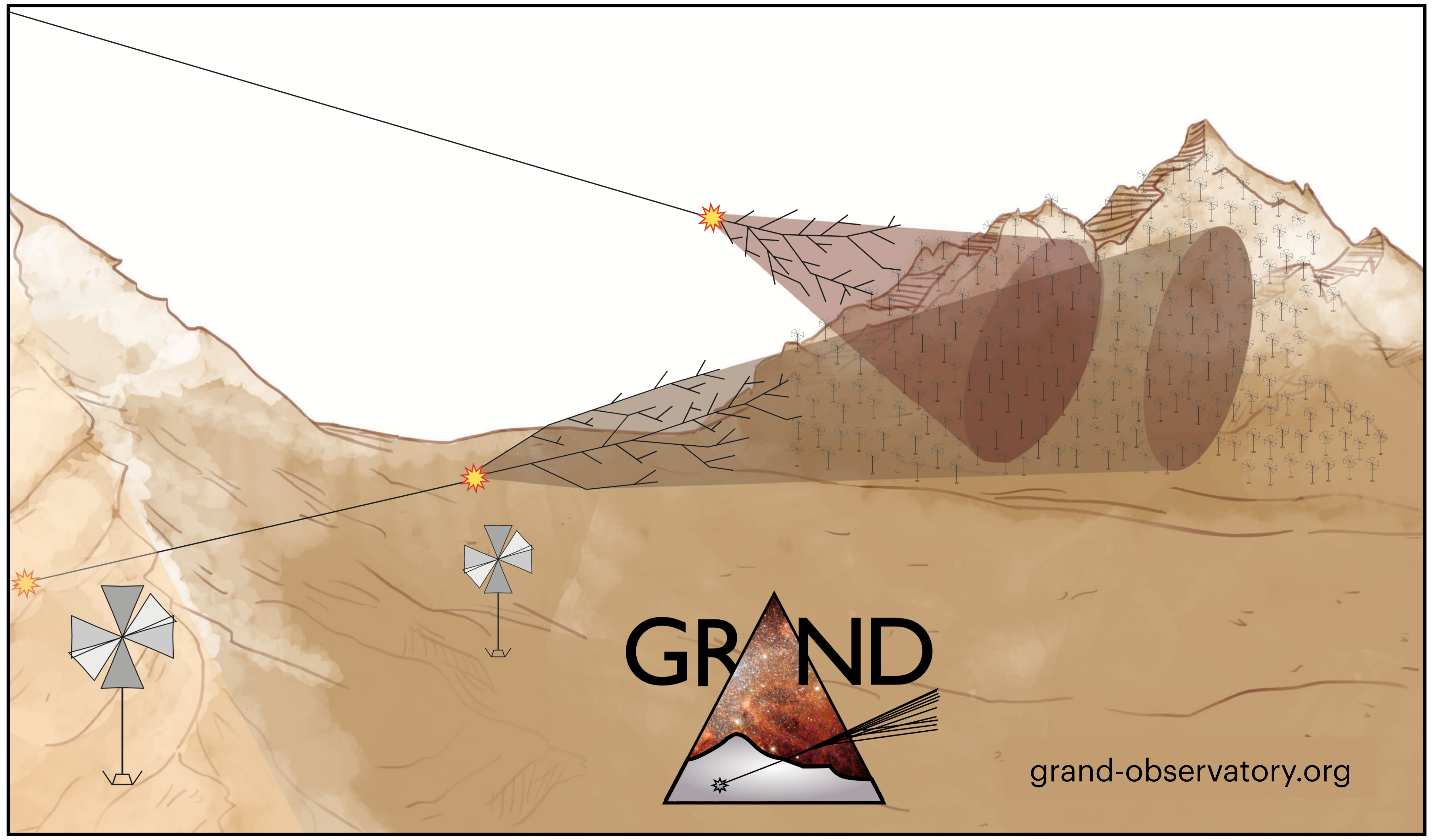


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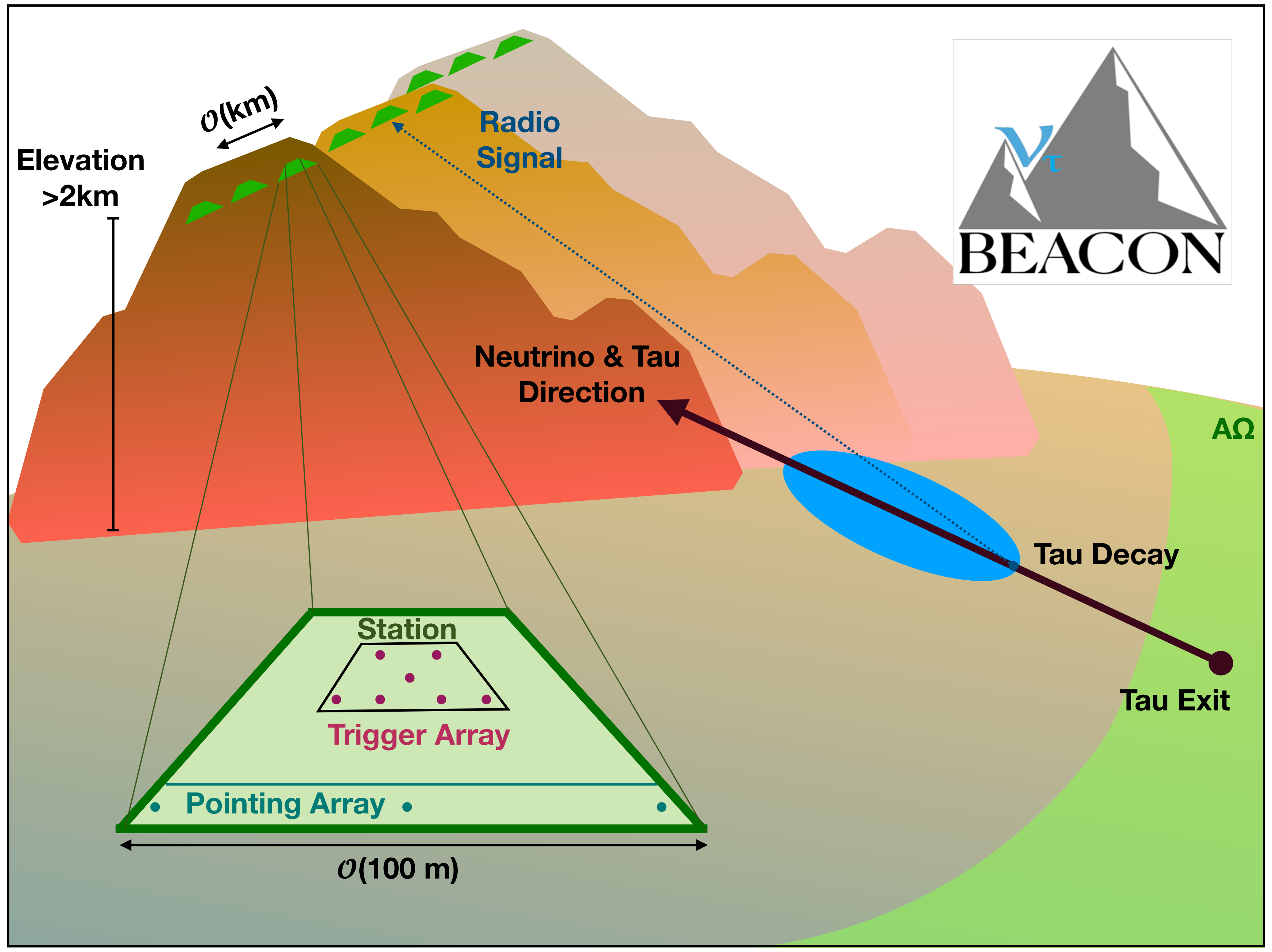


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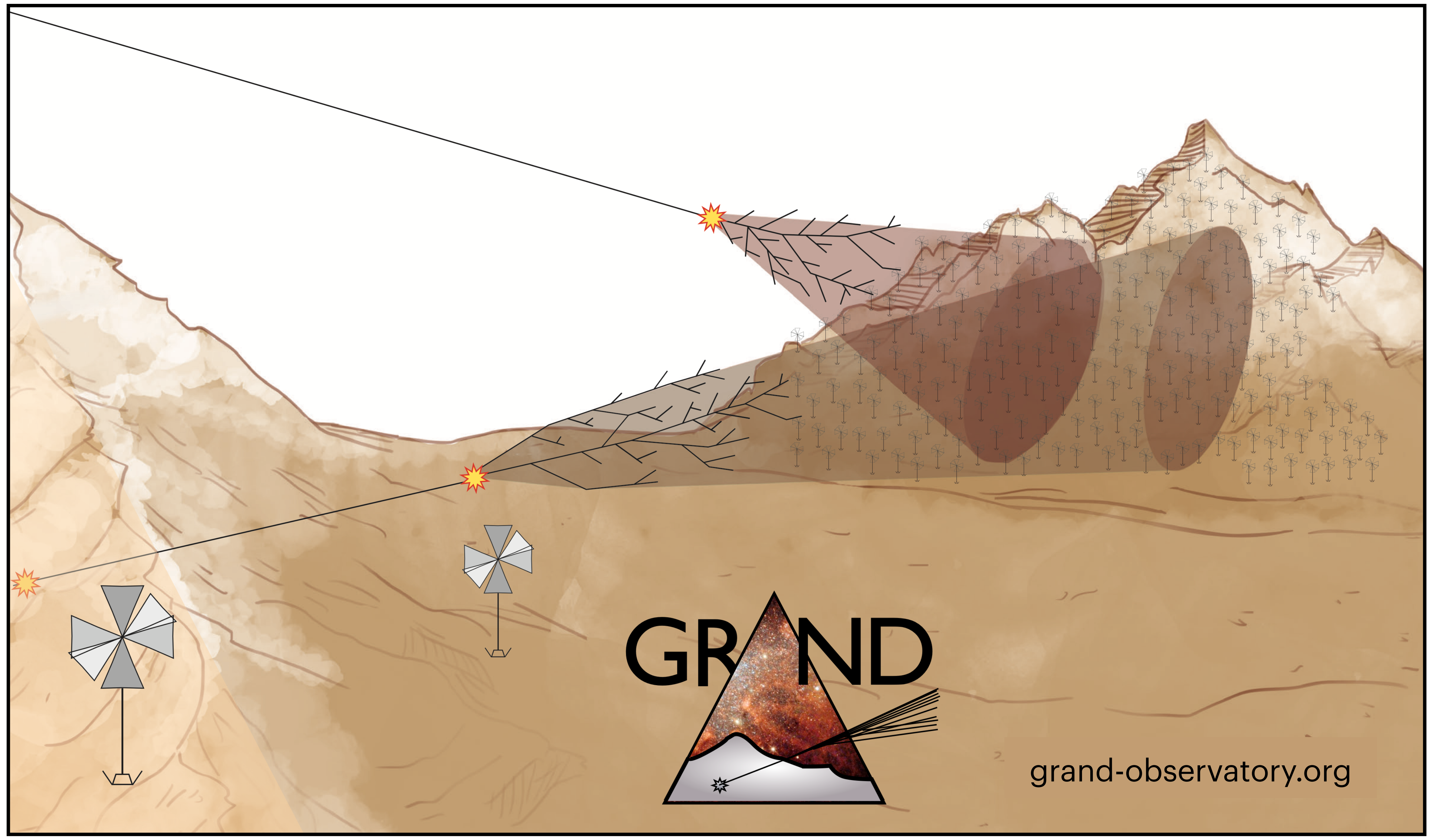


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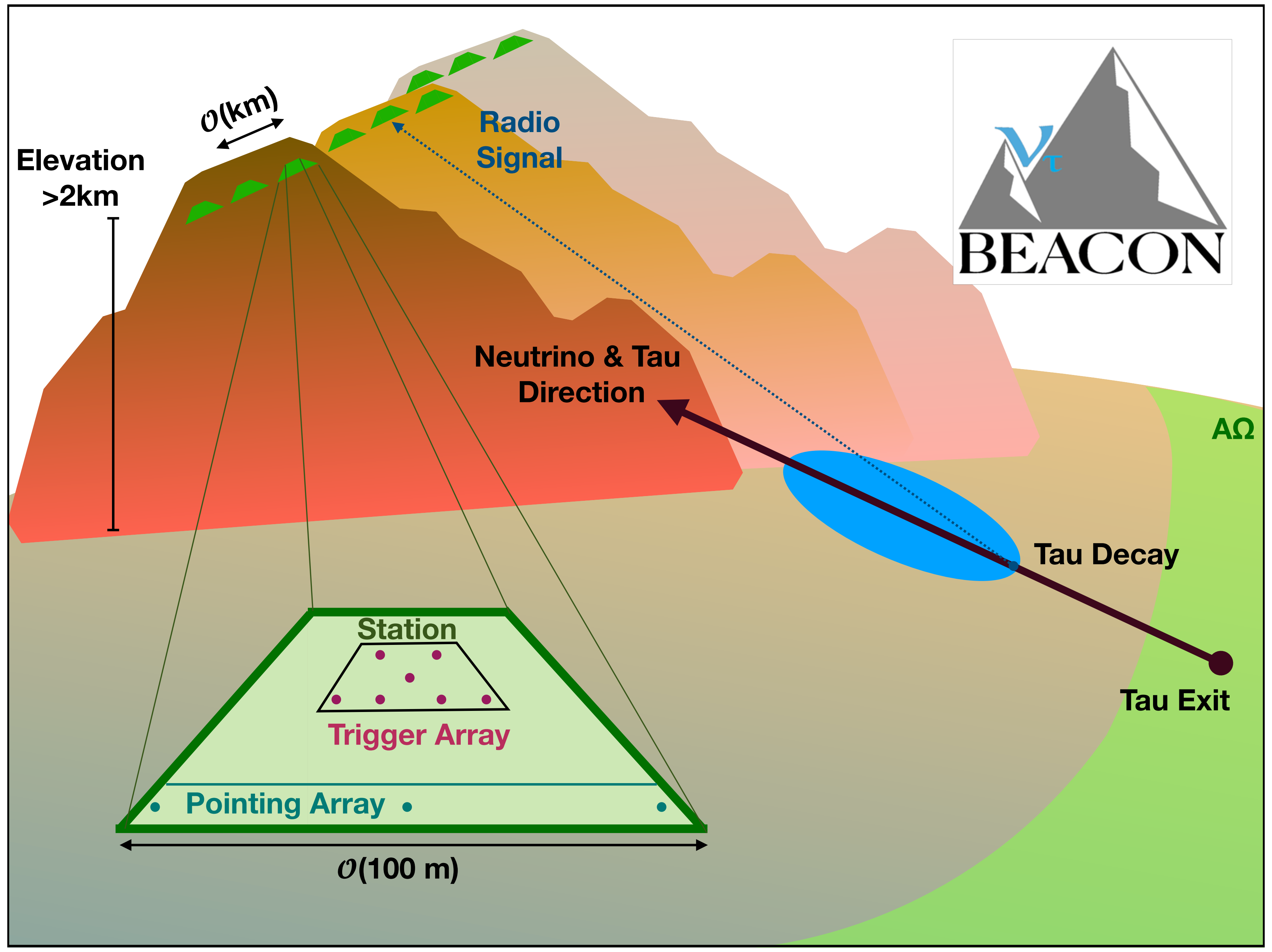


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- Simplified, inexpensive autonomous antenna design
- Imaging of shower → good reconstruction and can be used in trigger
- RFI rejection (also demonstrated on OVRO-LWA)
- Timing sync demo-ed to be good enough to with AERA-style beacons
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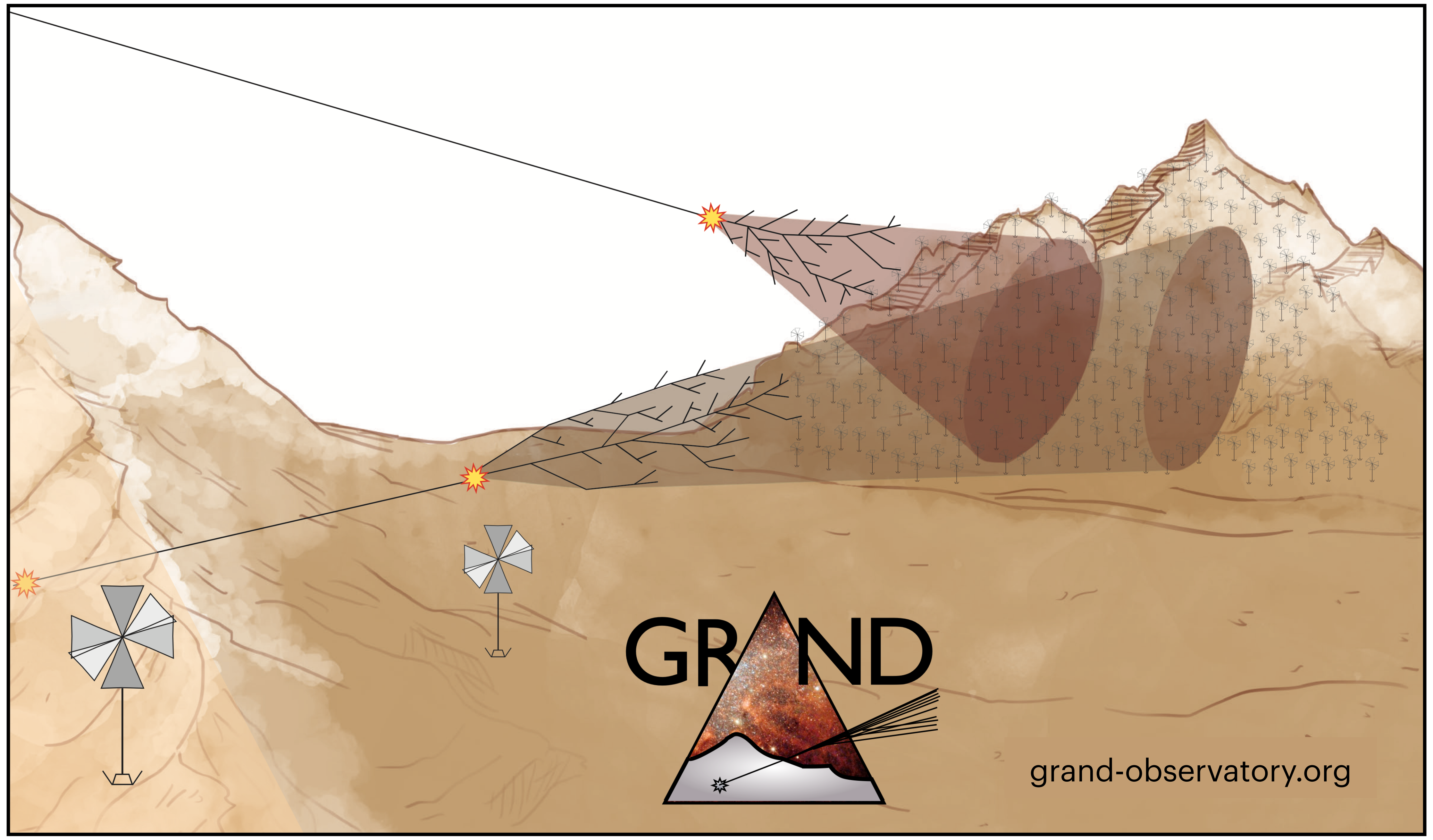


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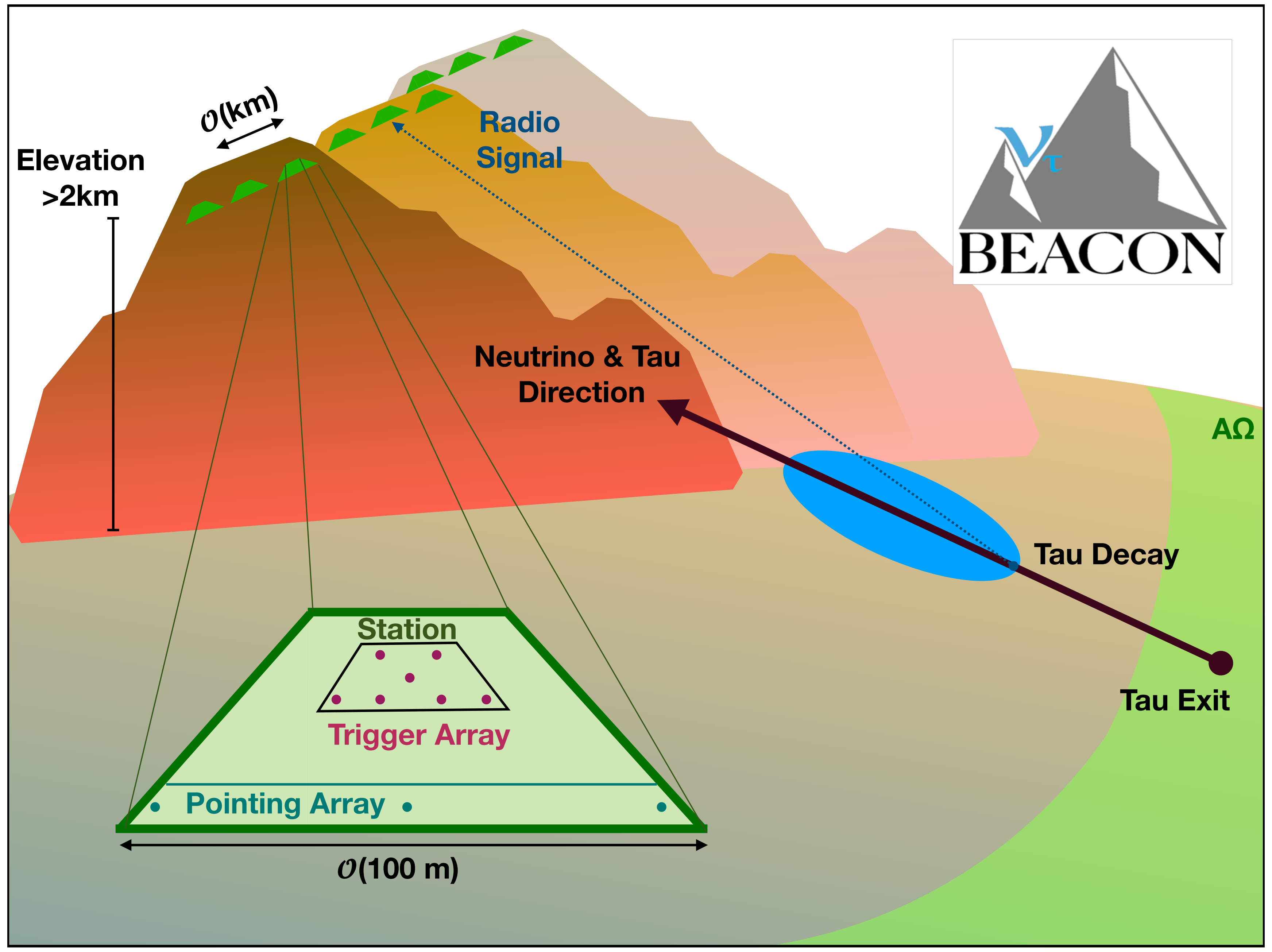


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- Efficient due to phasing (fewer channels, lower thresholds)
- Phasing allows for lower trigger thresholds, tunable beams at the horizon, and directional rejection of noise
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- High elevation increases the single station effective area at high energies

# Radio Detection of Tau Neutrinos

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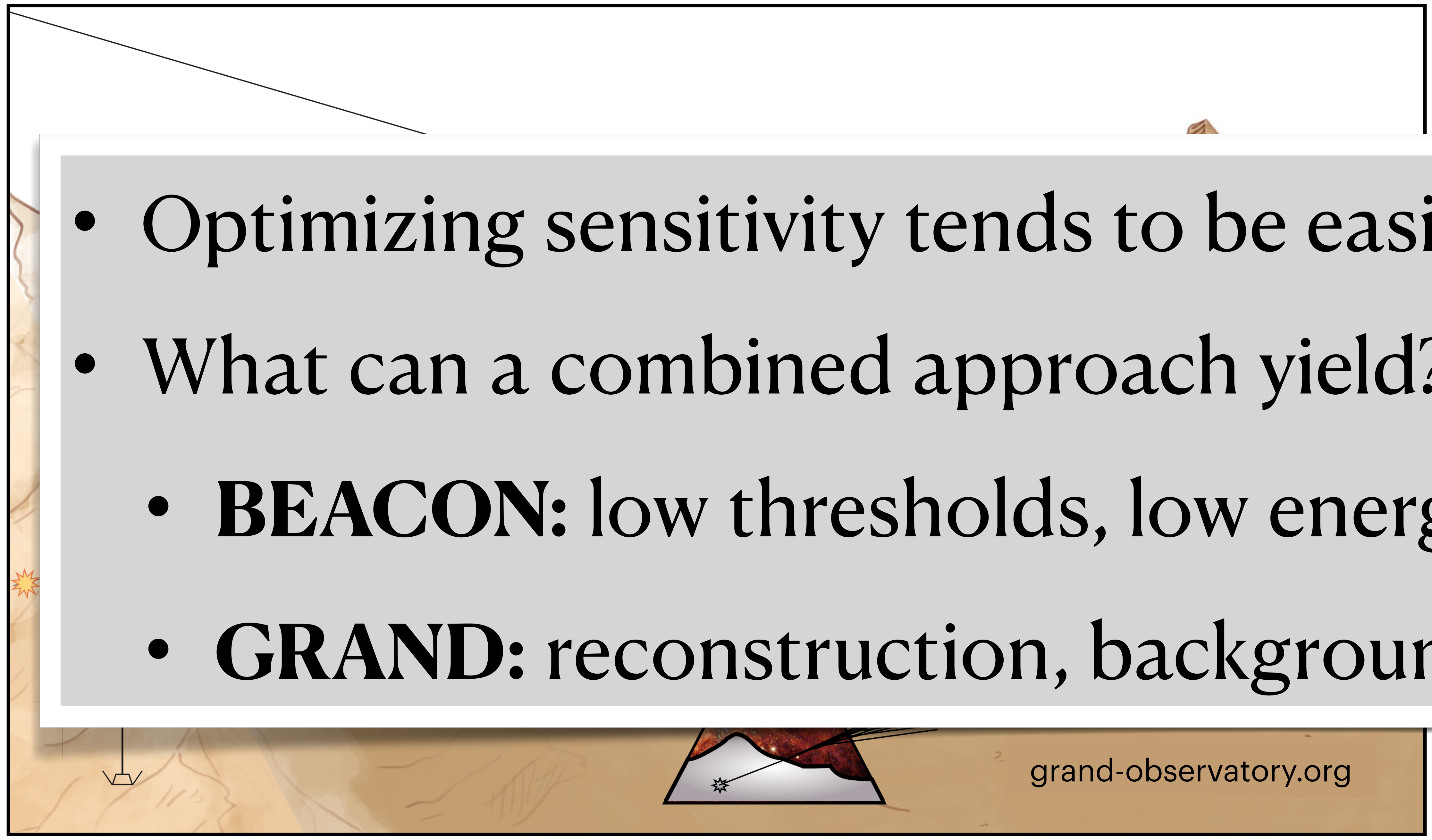


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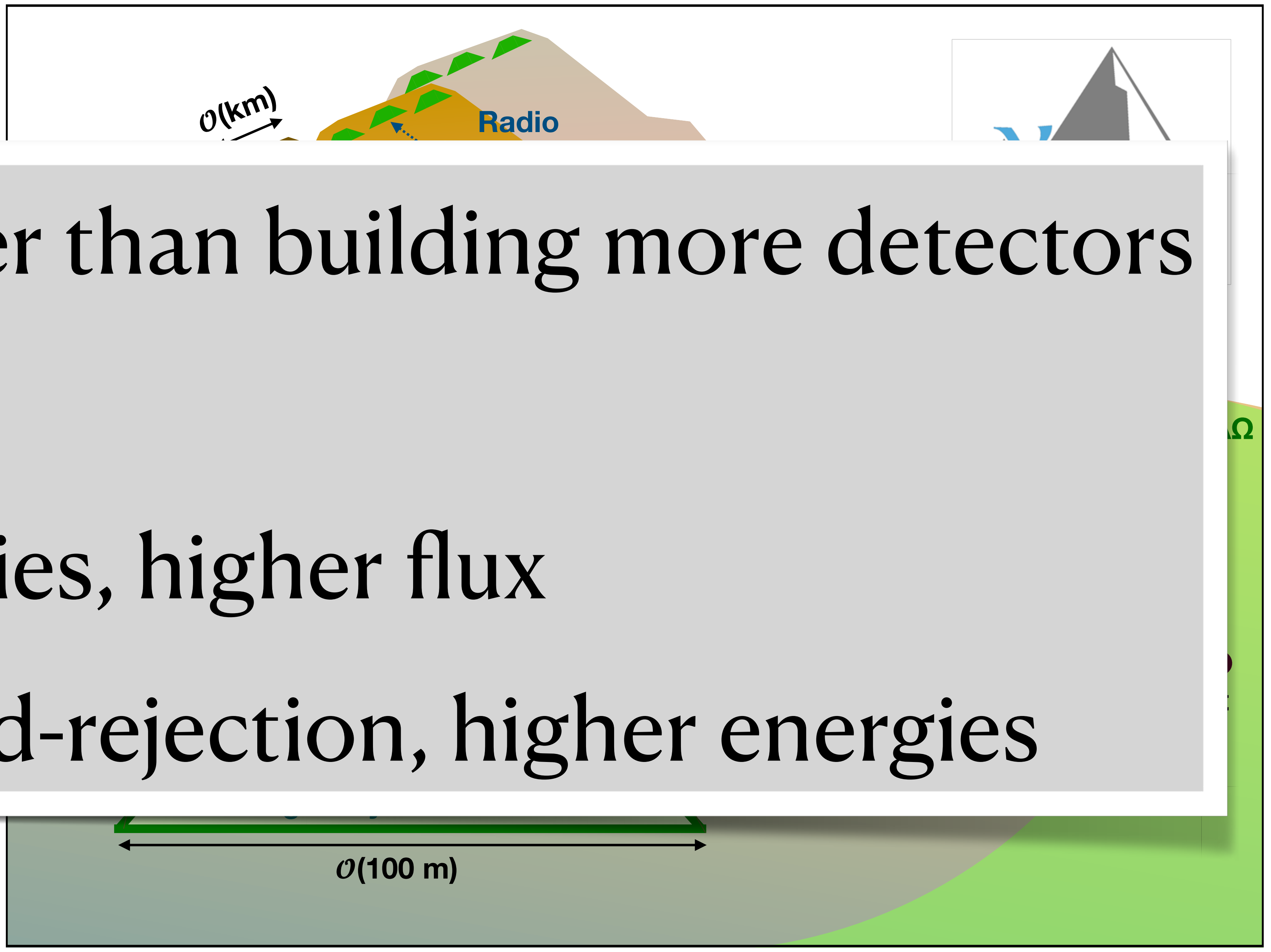


- Optimizing sensitivity tends to be easier than building more detectors
- What can a combined approach yield?
  - **BEACON:** low thresholds, low energies, higher flux
  - **GRAND:** reconstruction, background-rejection, higher energies

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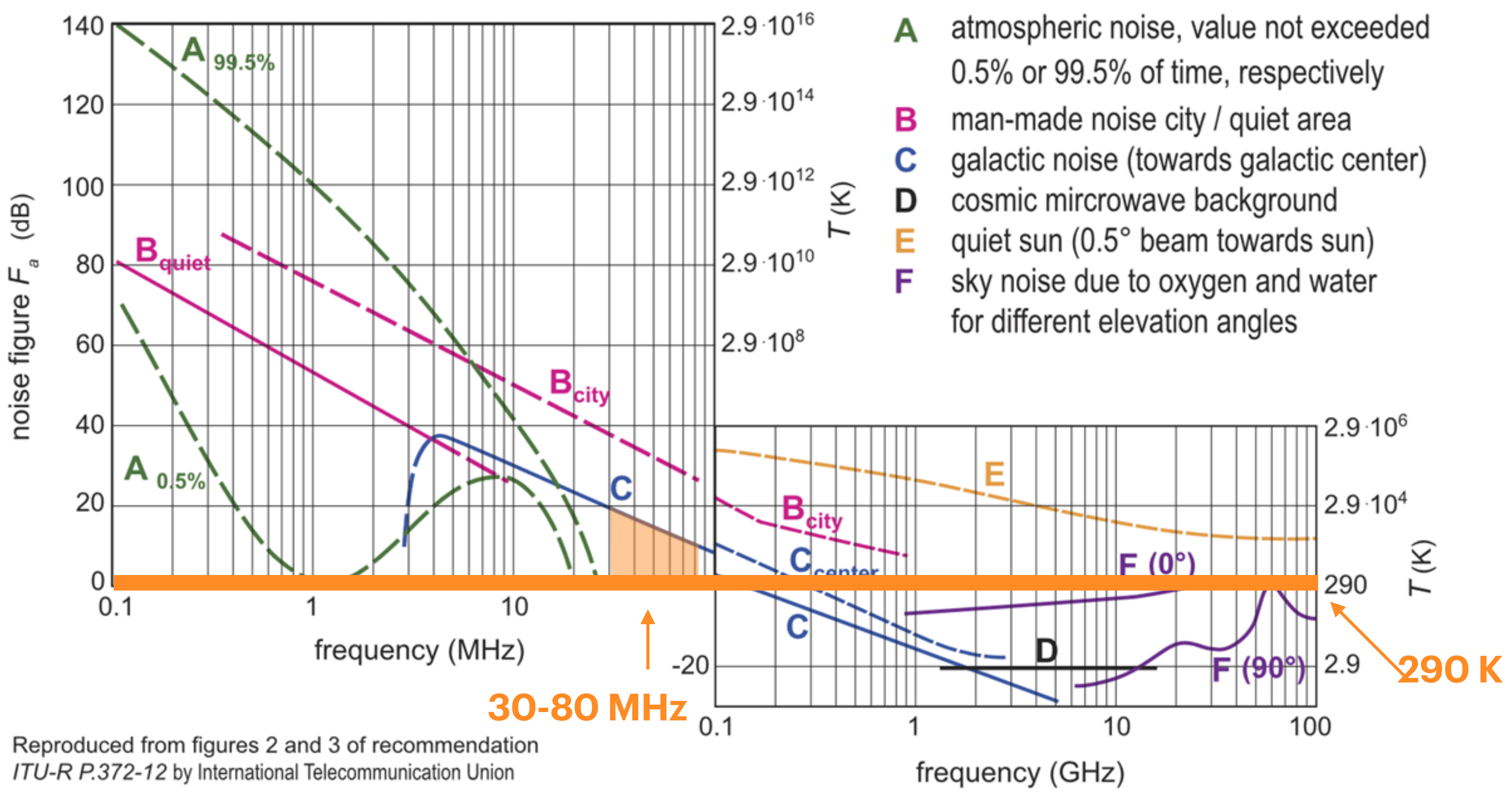
# Design Considerations

## Targeting 100 PeV and a Factor of 10+ Improvement in Sensitivity

- **Elevation:** High enough for large aperture, but low enough for peak sensitivity at 100 PeV
- **Phased Trigger:** Combine signal from N antennas → SNR grows as $\sqrt{N}$

See also Wissel JCAP 2020 arXiv:2004:12718

- **Antenna Beams & Temperature:**
  - **Phased Array:** 30-80 MHz dipoles with phased beams
  - **Sparse Array:** High-gain autonomous antennas




Reproduced from figures 2 and 3 of recommendation *ITU-R P.372-12* by International Telecommunication Union

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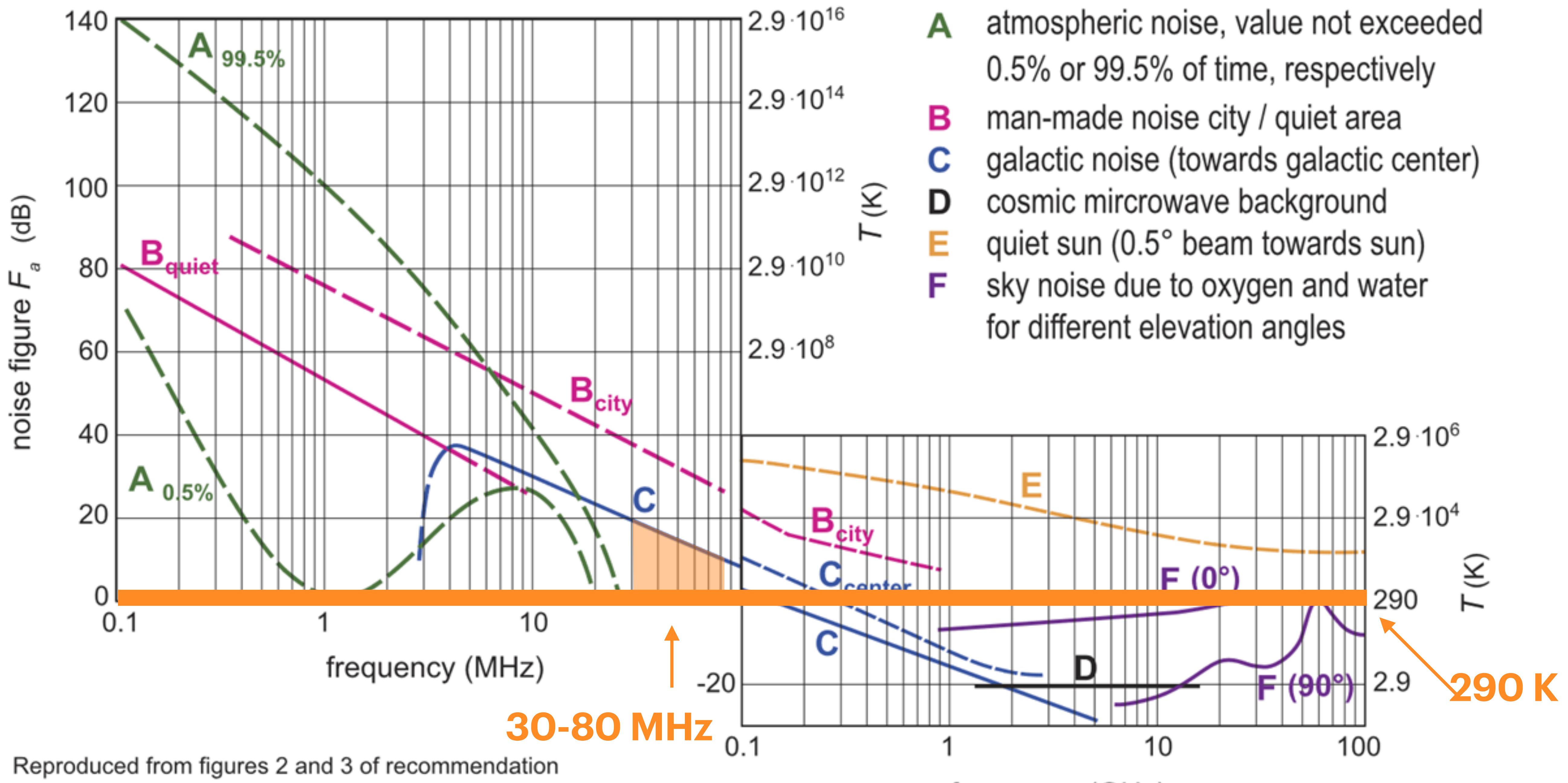


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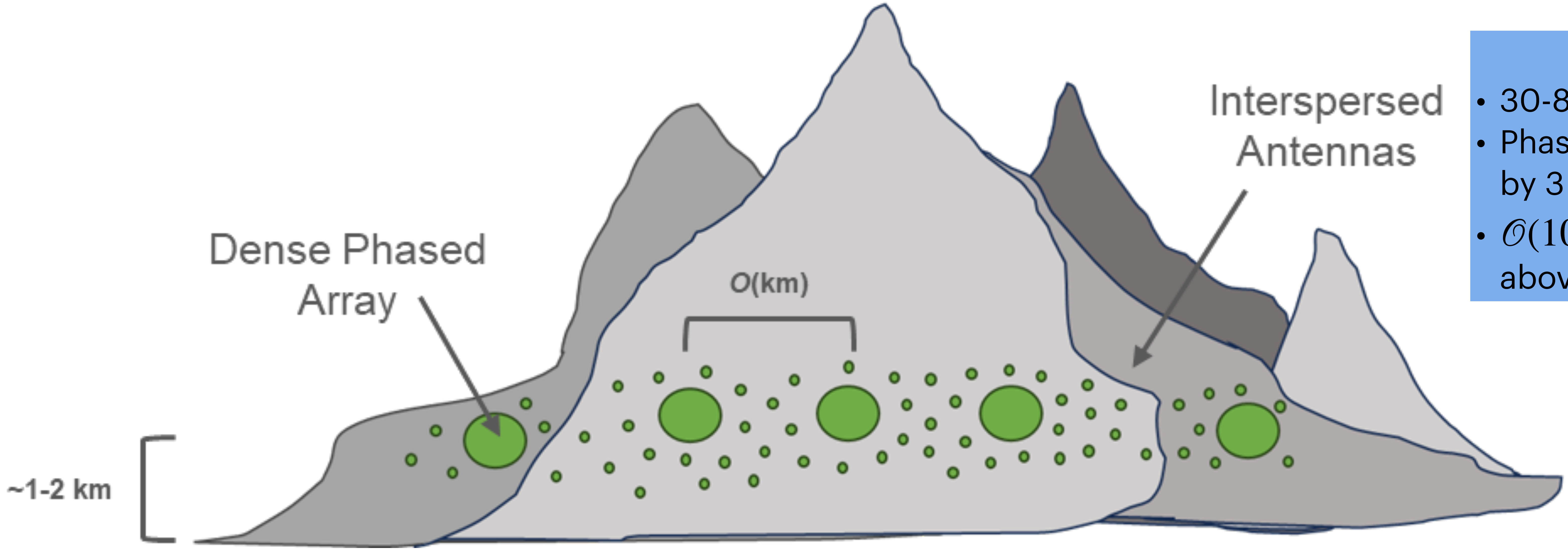
$$T_{ant} = (r + (1-r)\mathscr{F})T_{gal} + (1-r)T_{ground} + T_{sys}$$

$r$: sky fraction

$\mathscr{F}$: Fresnel coefficient of ground reflection

# A Hybrid Concept

## GRAND-BEACON




**Nominal:**

- 30-80 MHz frequency range
- Phased arrays: 1 km altitude, separated by 3 km, 24 channels (<200 m spacing)
- $\mathcal{O}(10)$ sparse antennas evenly spaced above and below 1 km

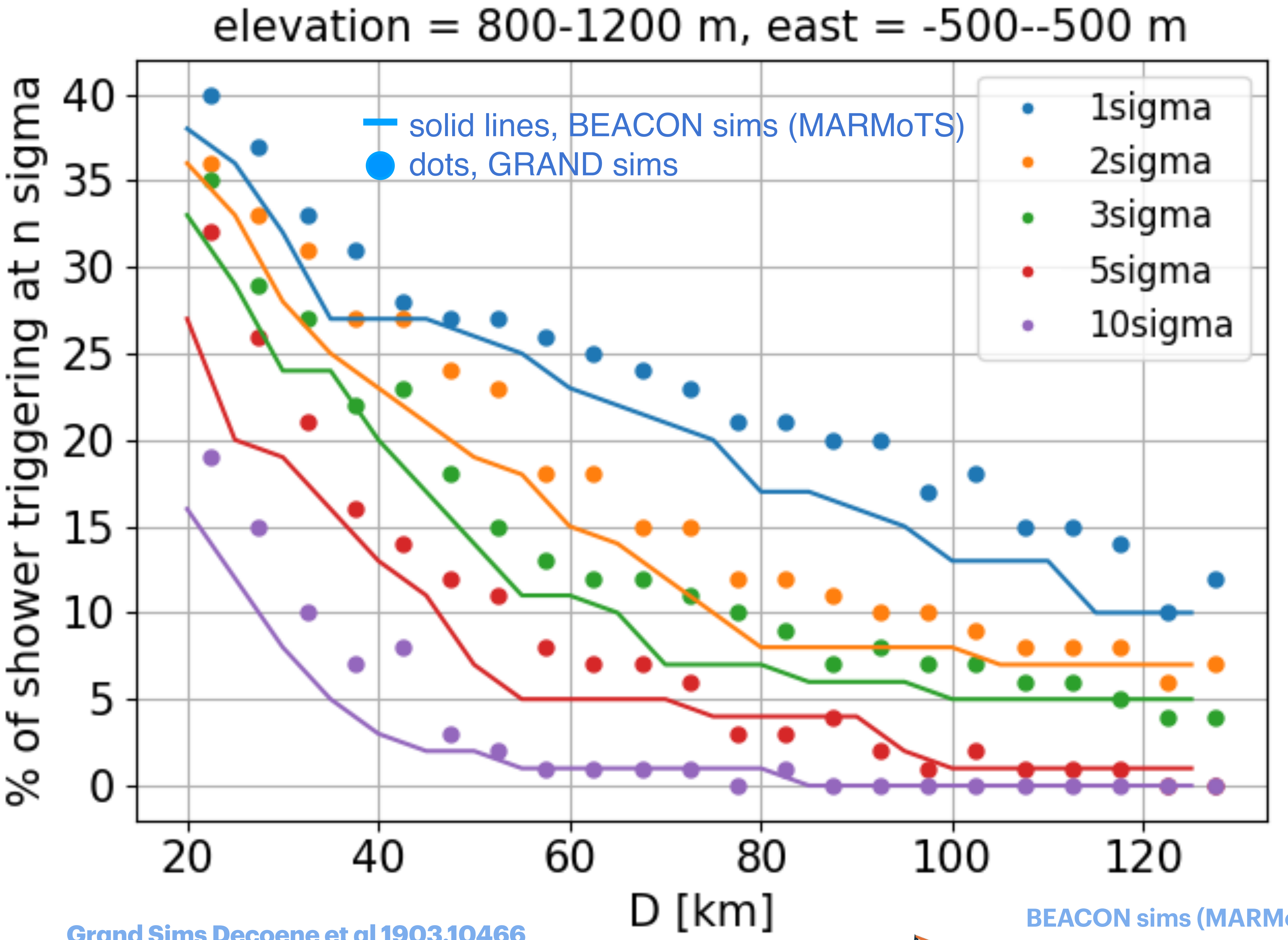
A. Zeolla

- **Trigger and Low-Energy Array:** Compact phased arrays lower energy threshold, allow for tunable beams at the horizon, and directional noise rejection; Low Frequency (eg 30-80 MHz) dipoles formed into higher gain beams
- **Reconstruction and High-Energy Array:** Single autonomous antennas for higher energies, long baselines for reconstruction, RFI rejection; High gain antennas

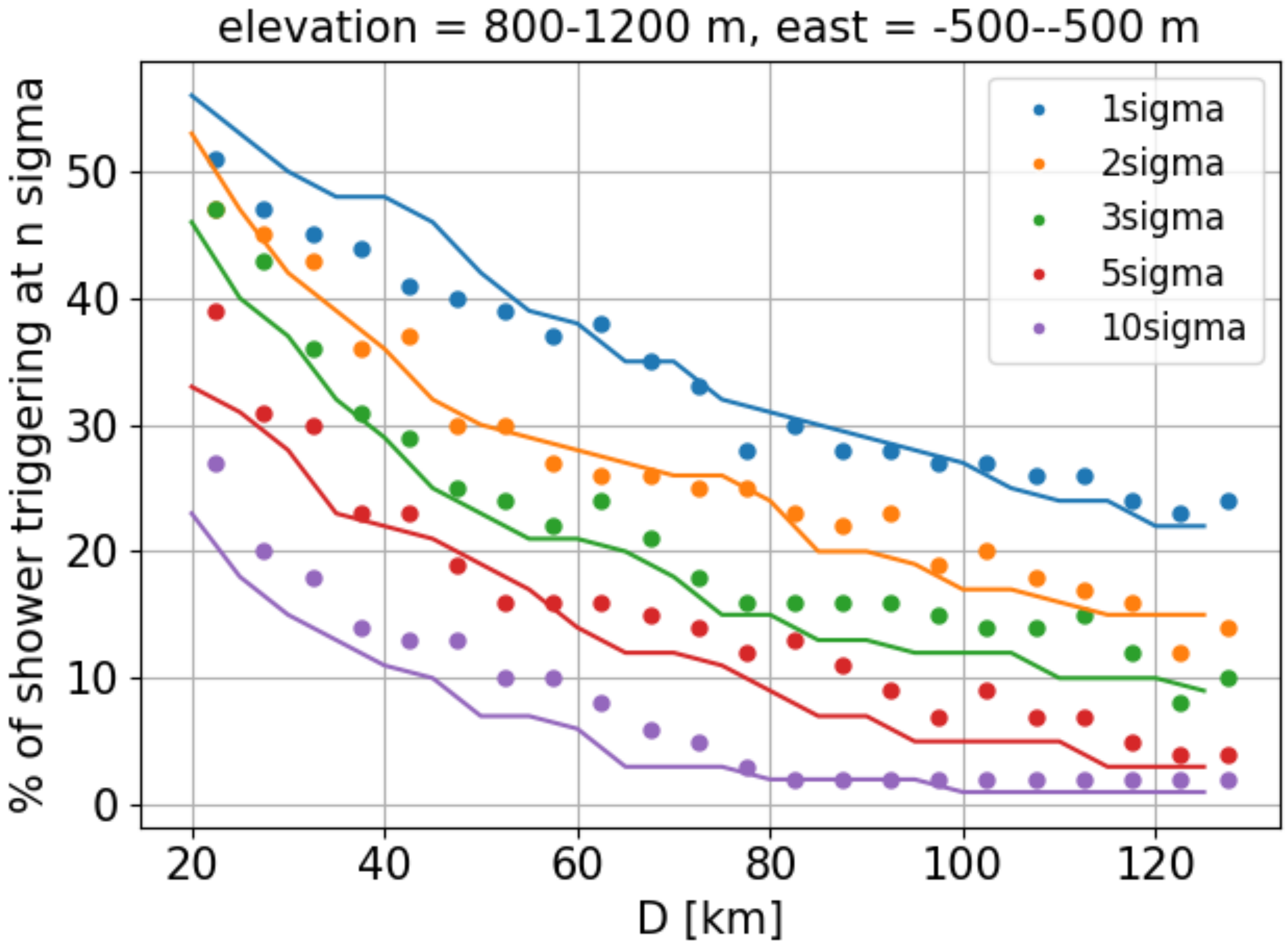
# GRAND & BEACON
# E-Field Trigger Simulations

- Bandwidth: 50-200 MHz
- Location: N 42.55°, E 86.68°
- Efield trigger with threshold $\sigma \times 22\ \mu\mathrm{V/m}$

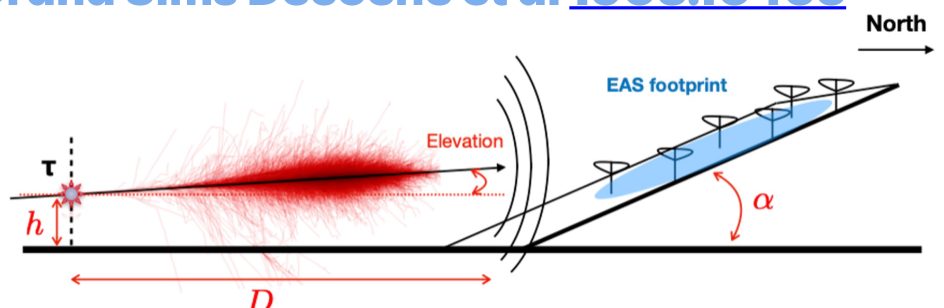
**$E_\nu$ = $10^{18}$ eV**



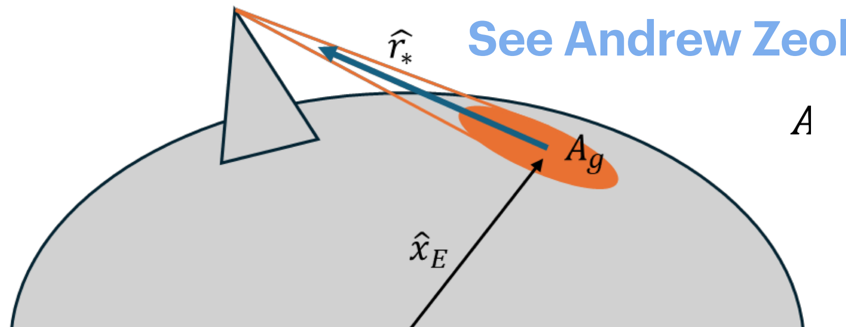

**$E_\nu$ = $10^{19}$ eV**




Grand Sims Decoene et al 1903.10466




BEACON sims (MARMoTS)
See Andrew Zeolla's talk



excellent agreement between 2 approaches

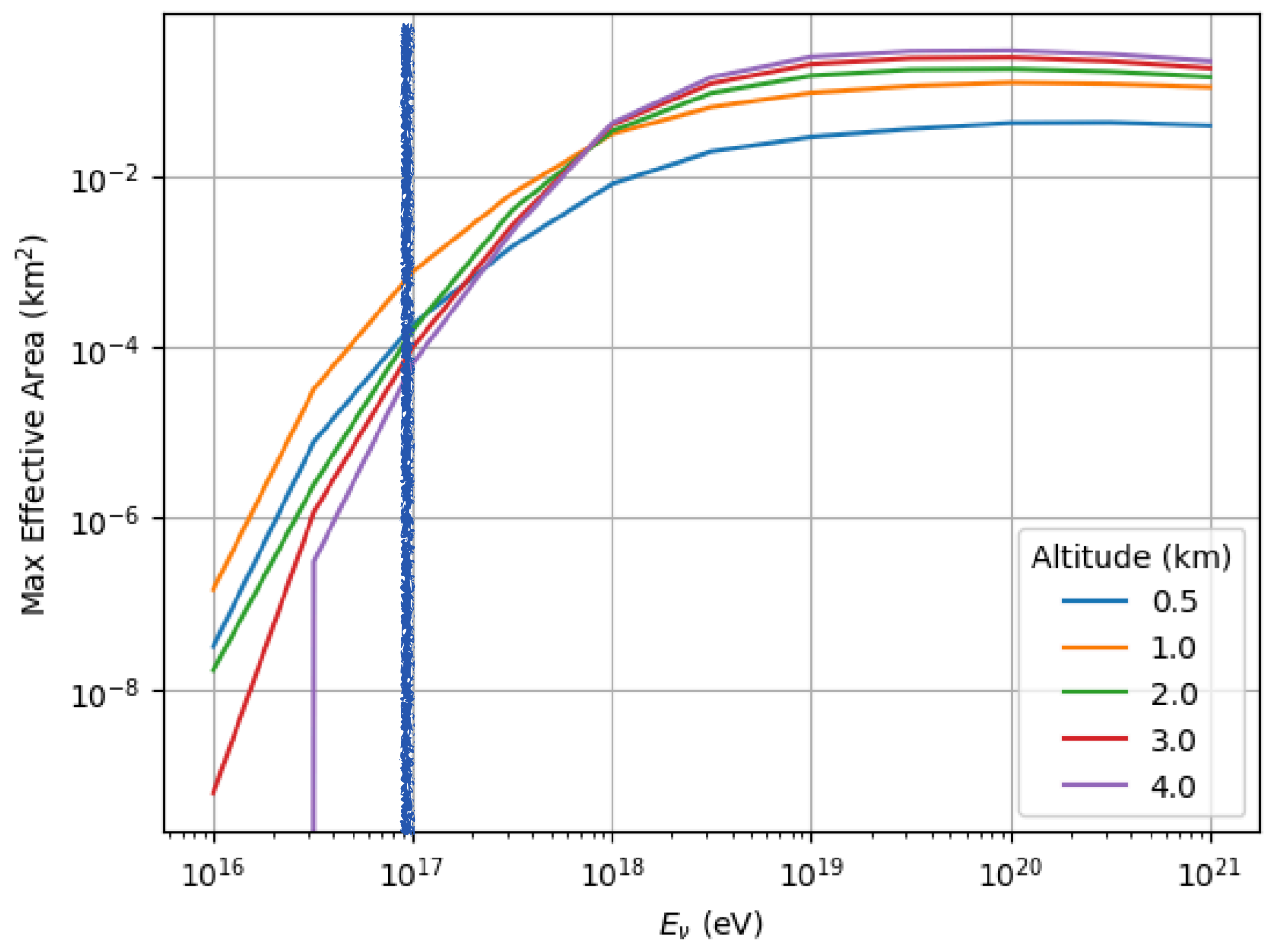
# Phased Array Peak Effective Areas

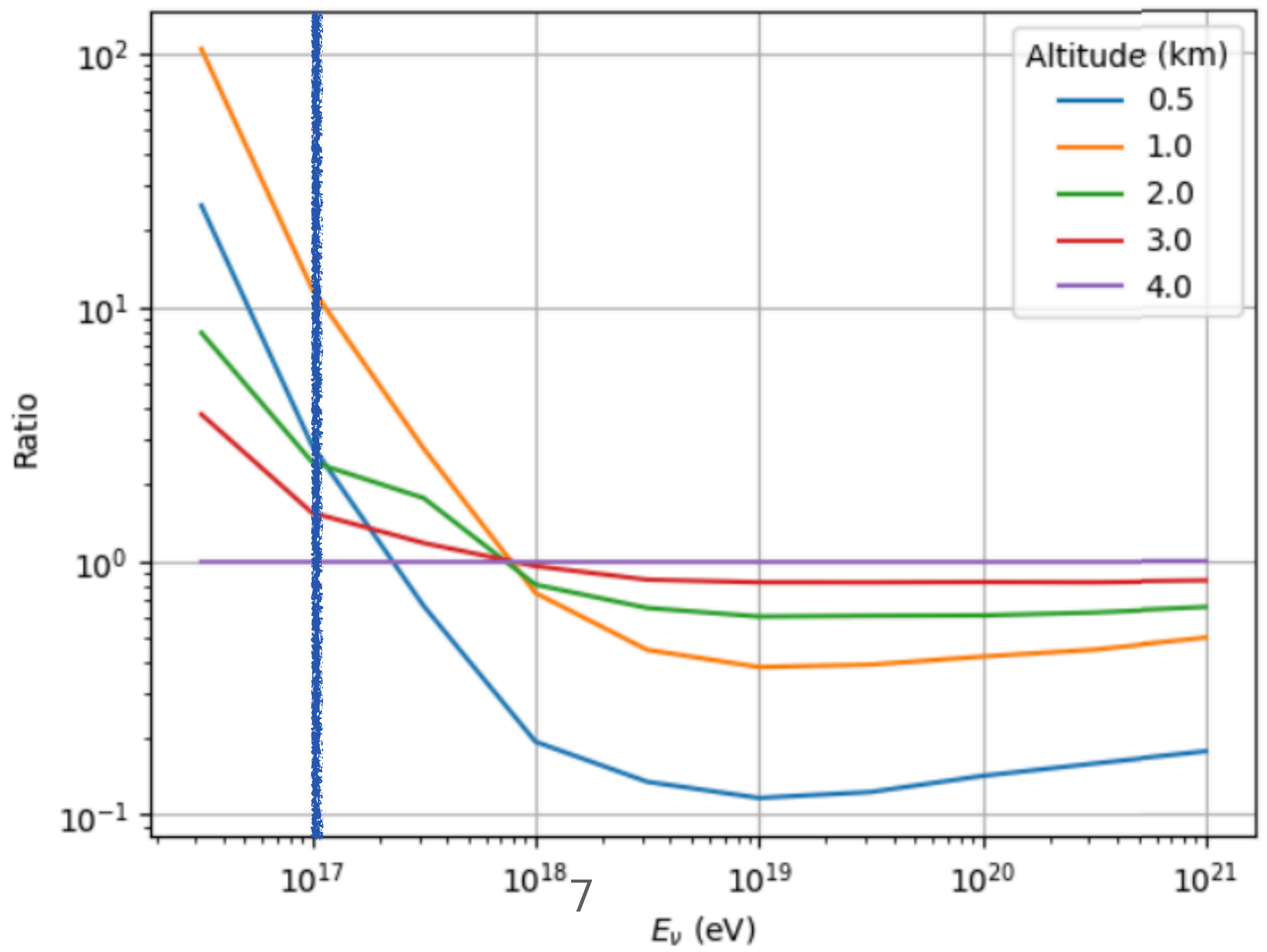
- Modestly high elevation: **1 km**
- Modest number of phased antennas: **25 antennas**
  - Effective area linear with gain of phased array (log of $N_{antenna}$)
- Beams will be tuned to cover the full annulus at horizon
  - Number of beams needed scales with beam gain
  - Needed FPGA resources likely will benefit from Moore's law

Simulated w/ MARMoTs by Andrew Zeolla (see his talk for more details on sims)

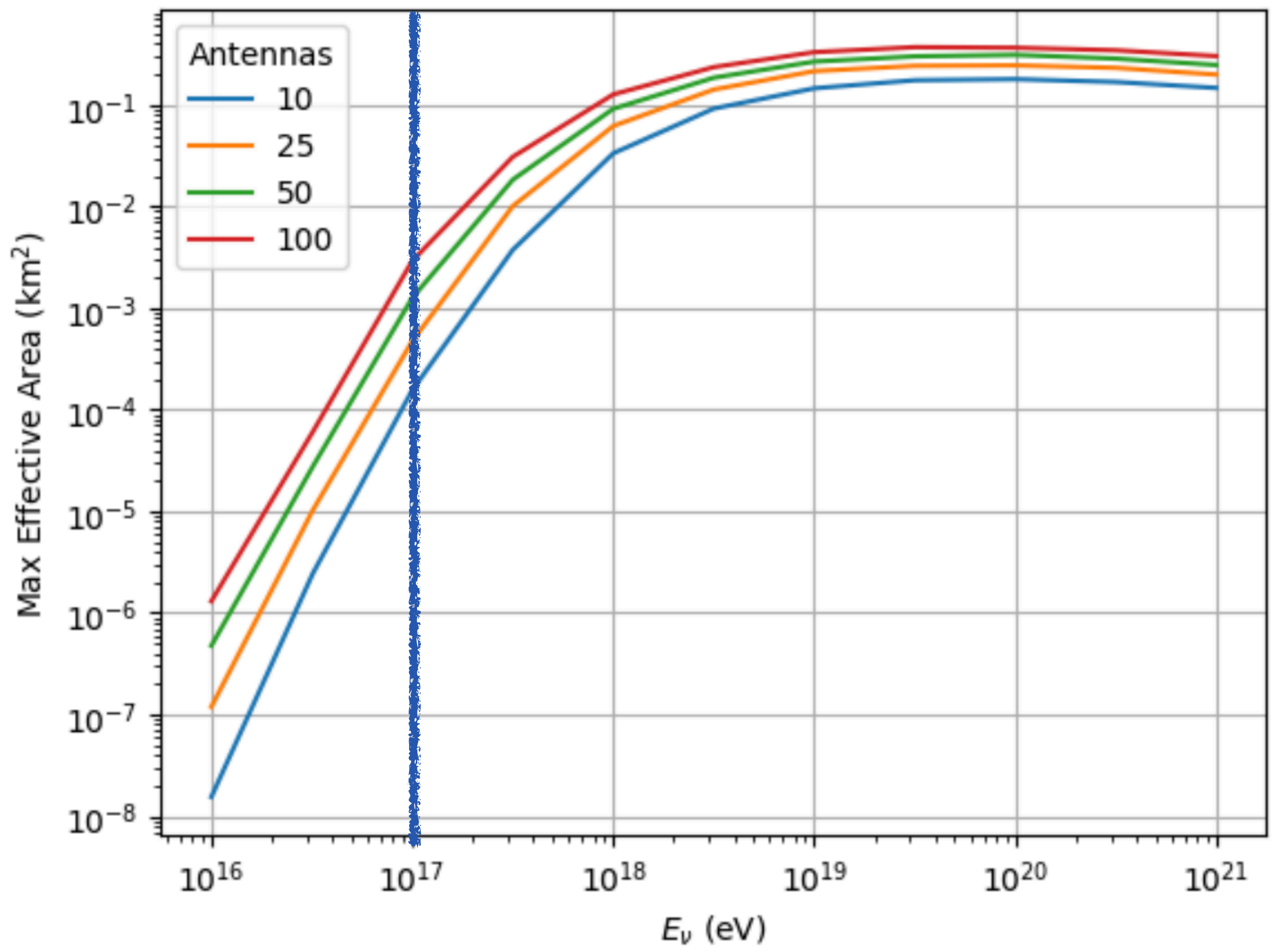
See also Wissel JCAP 2020 arXiv:2004:12718 for similar results

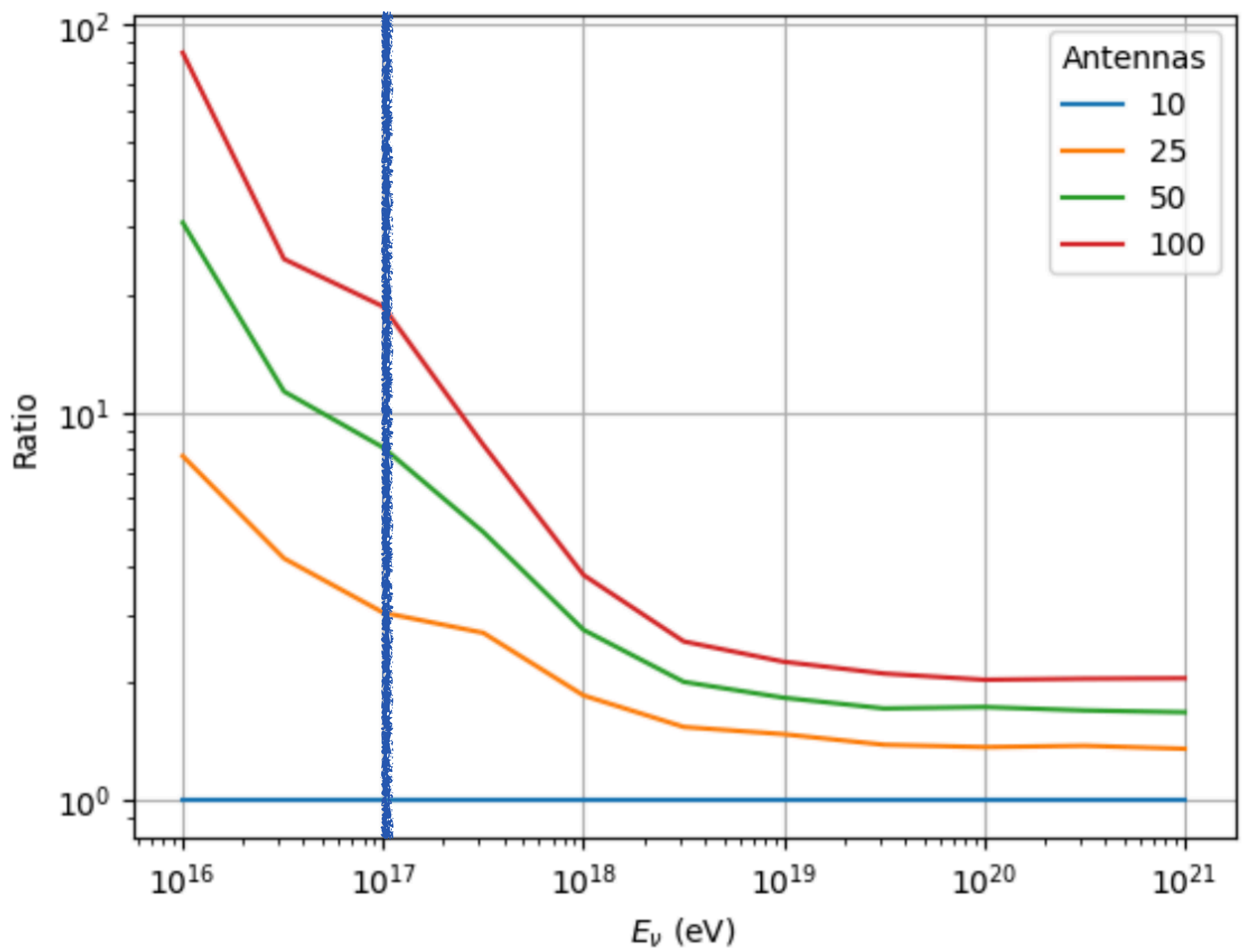
## Detector Elevation




## Number of Phased Antennas

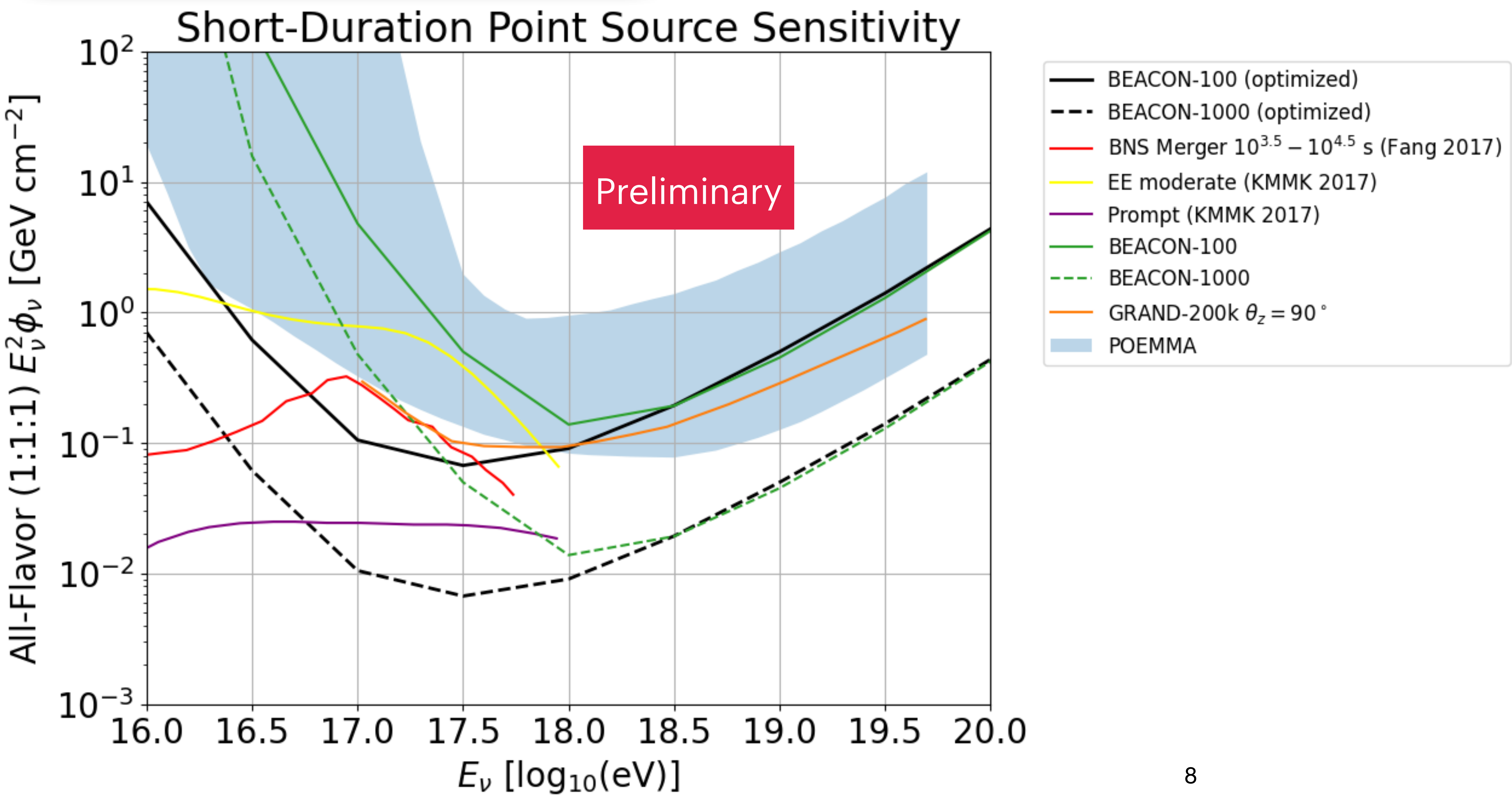


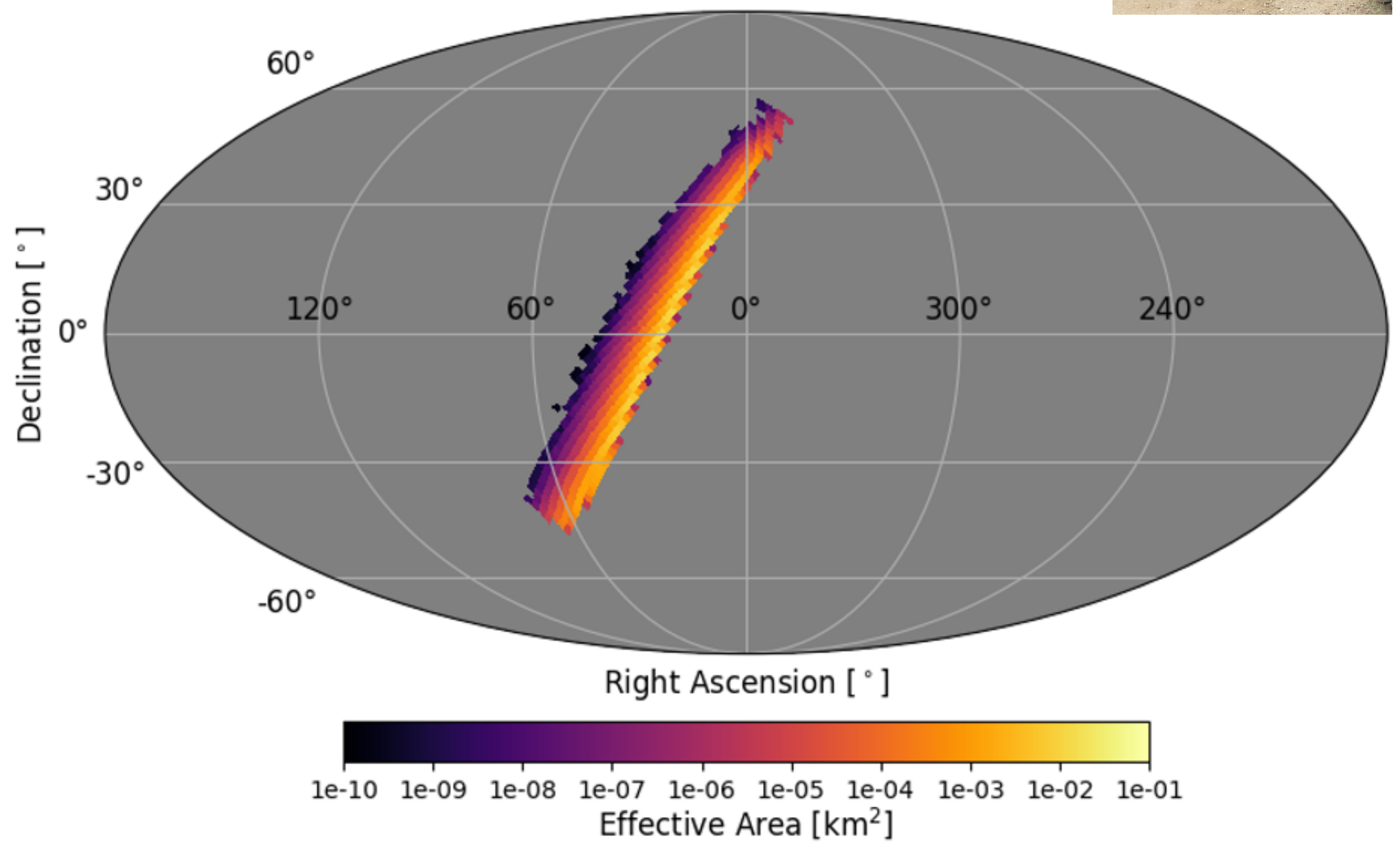
Phased array simulations with MARMoTS
See Andrew Zeolla's talk

# Phased Array - Optimistic Scenario

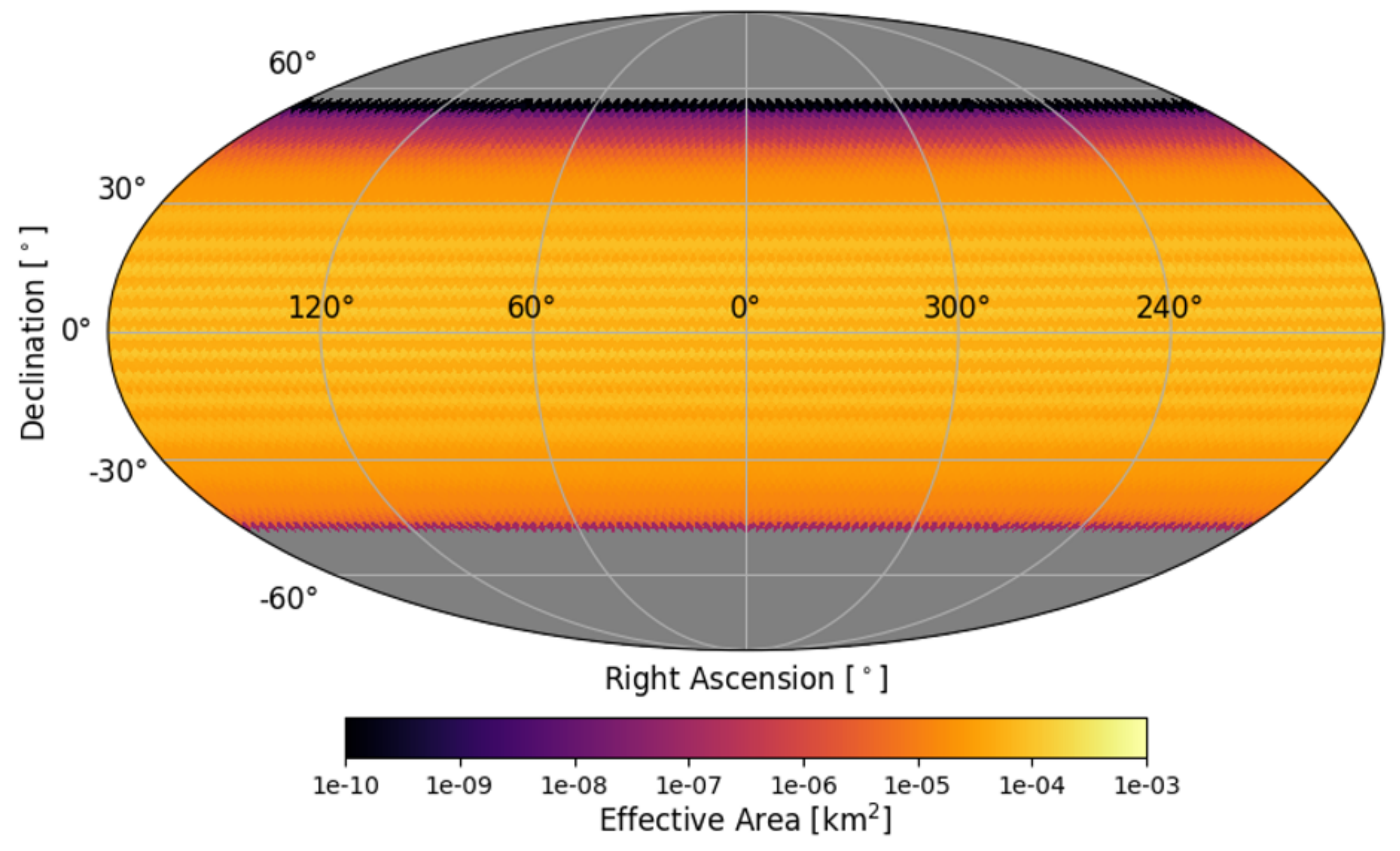
100 PeV Optimized:
- 24 antennas per station
- 1 km elevation
- 6 dBi gain, perfectly matched
- sky fraction 30%, Fresnel coeff. 0




## Instantaneous FoV




## Daily averaged FoV



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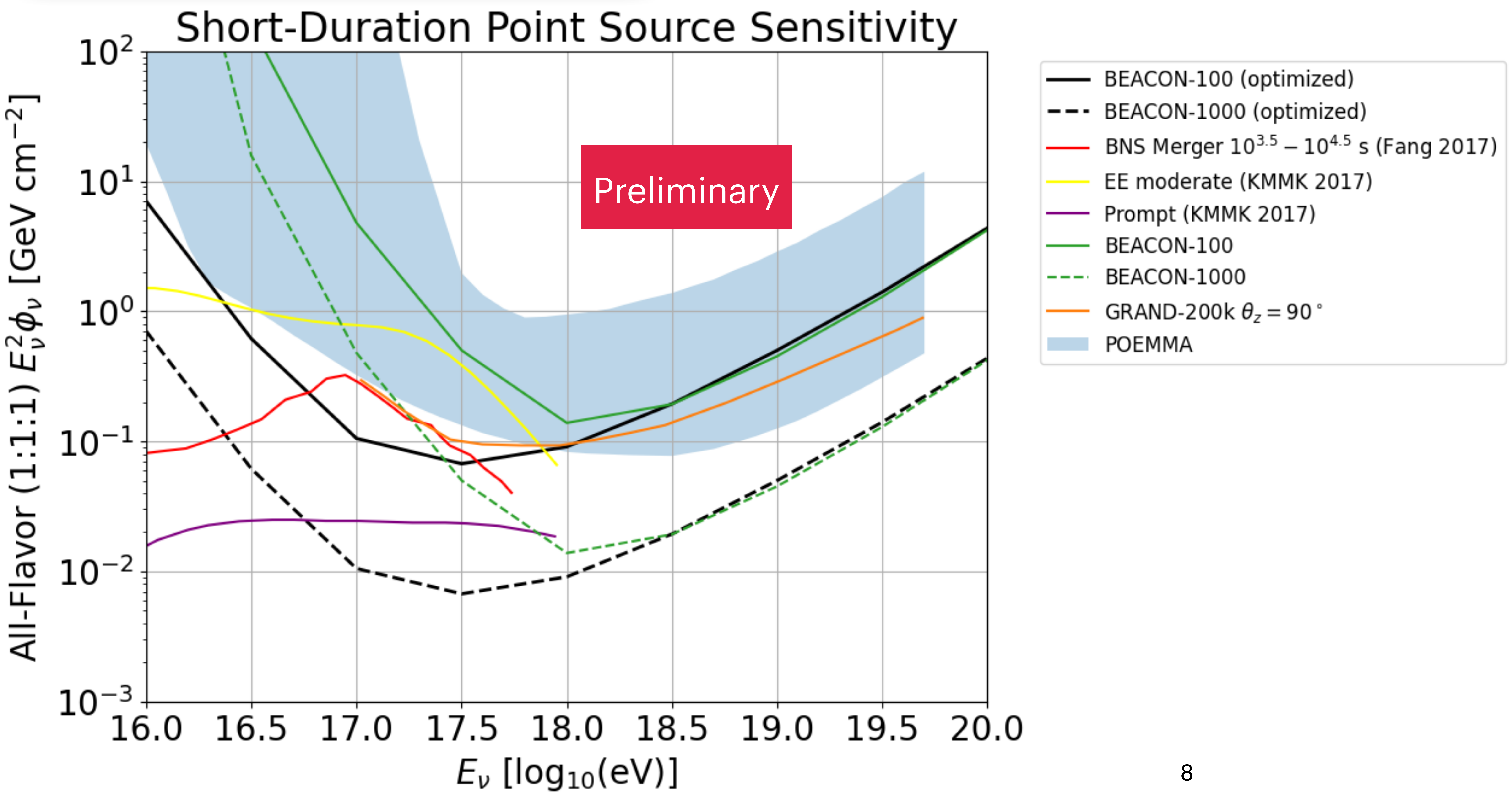
Antenna gain, beam width, sky fraction, Fresnel coefficients tied together in estimate of noise fraction in beam

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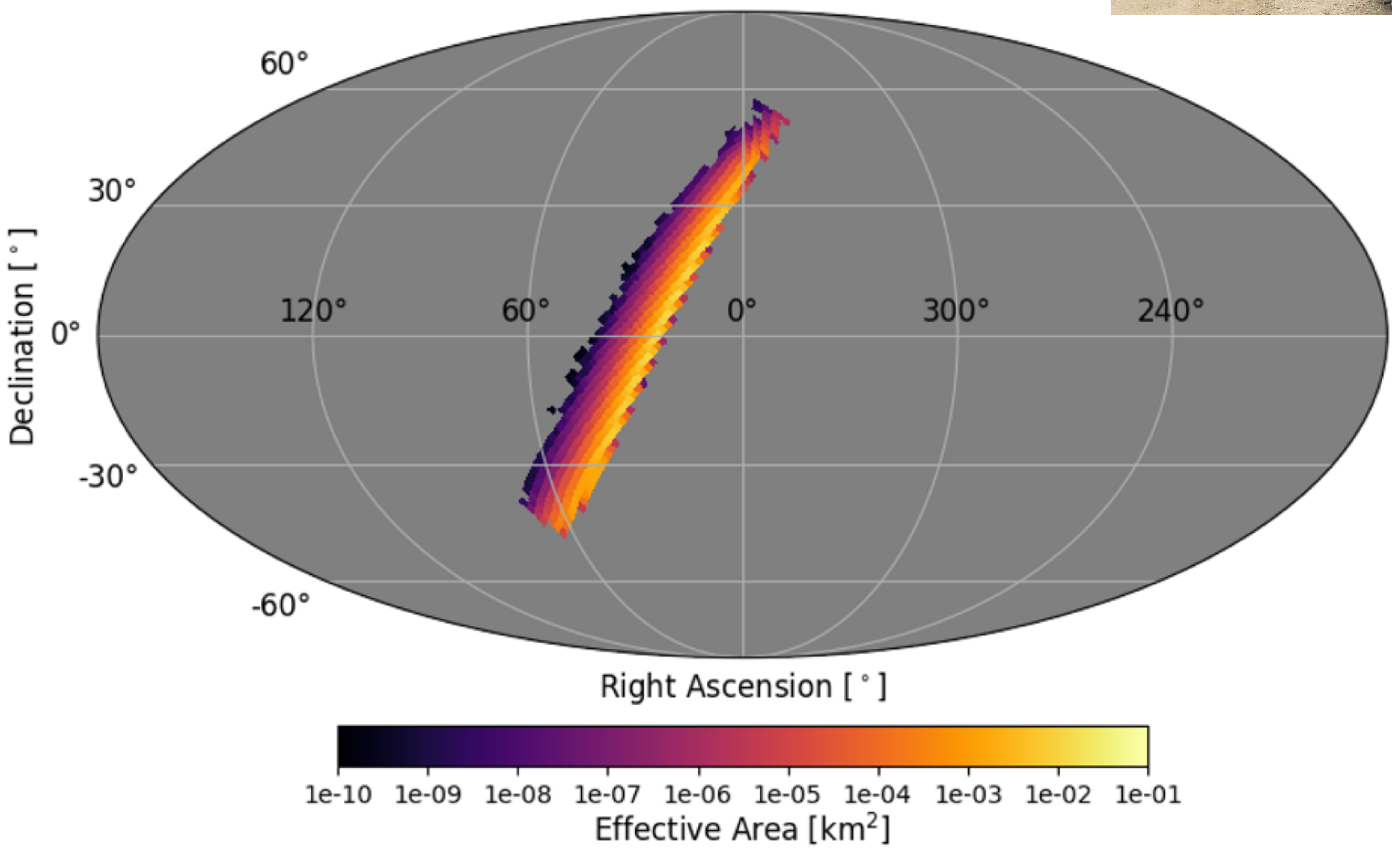


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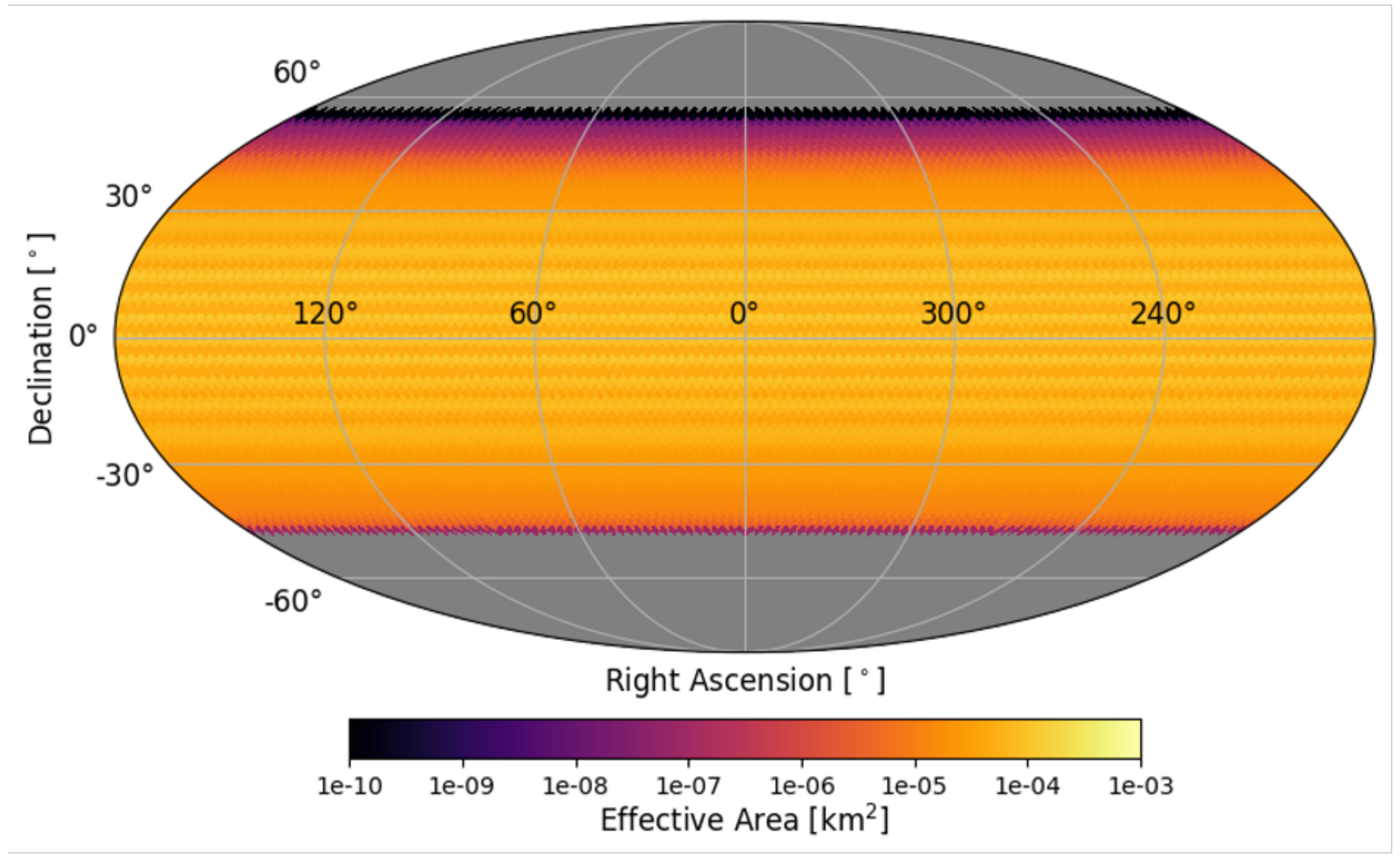

# Sparse Array

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  - Enables reconstruction of distance & energy
    → essential for CR/$\nu$ discrimination
  - To be verified with GRAND-BEACON layout + antenna design with noise present

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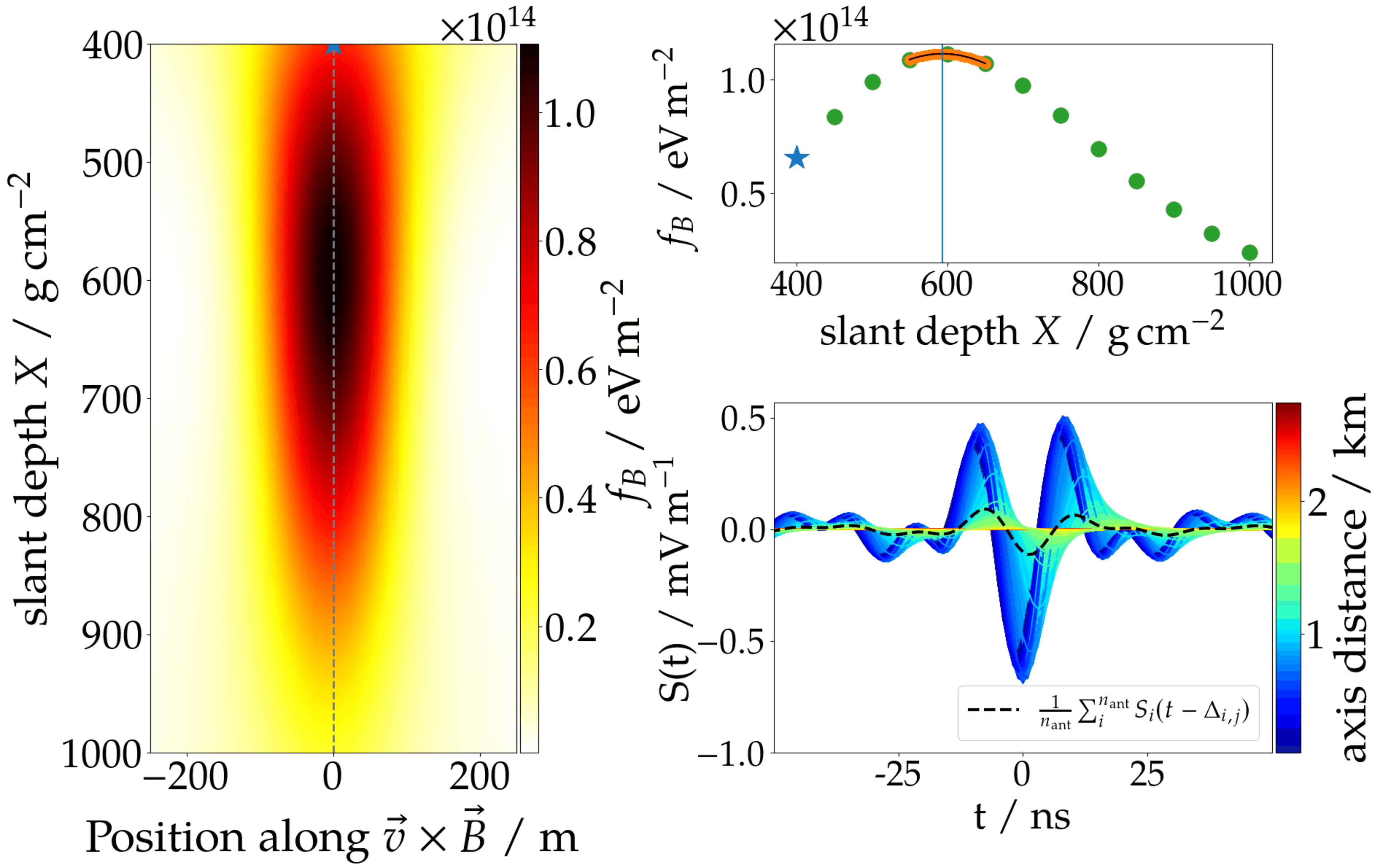


*Schoorlemmer & Carvalho arXiv:2006.10348*

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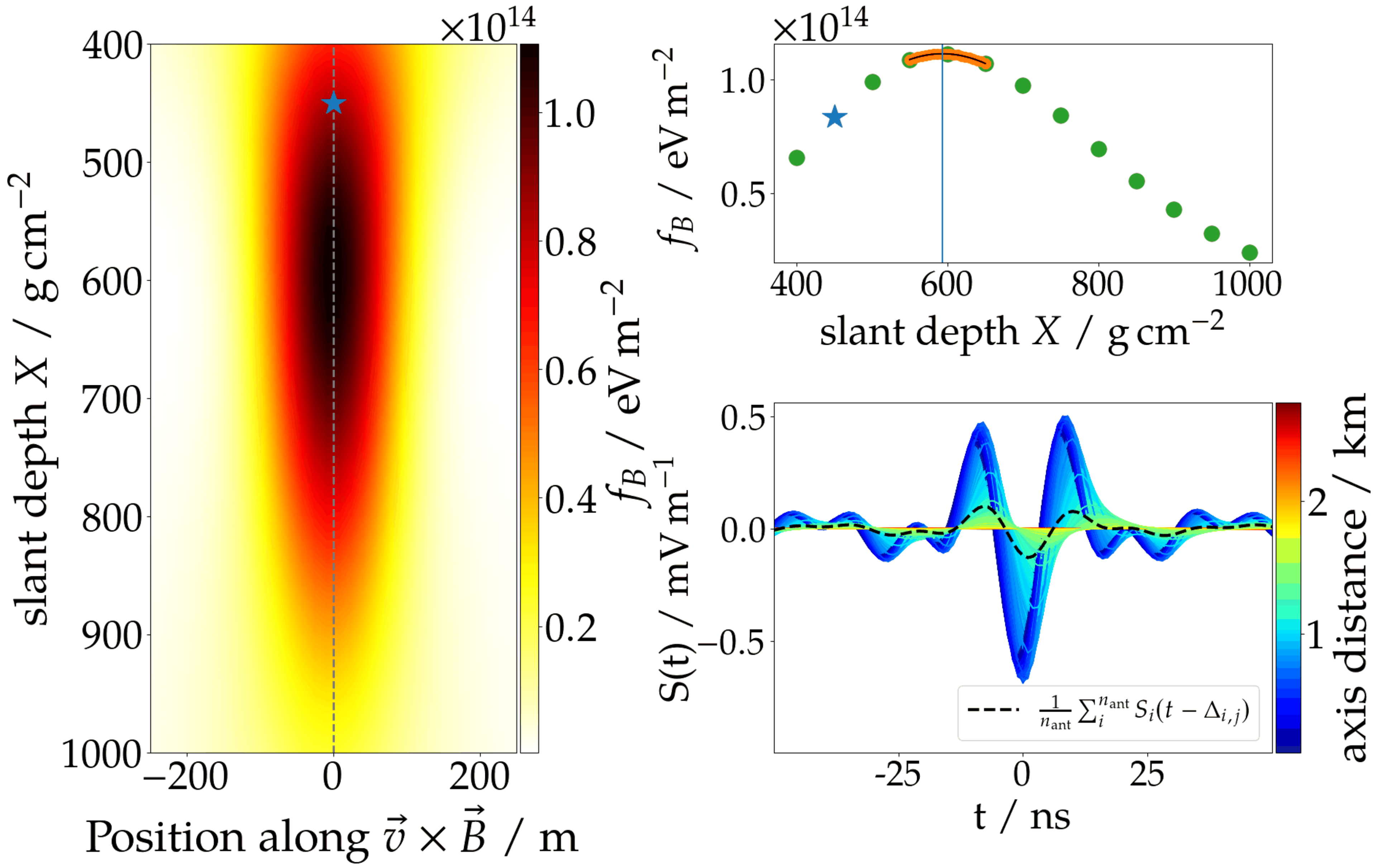


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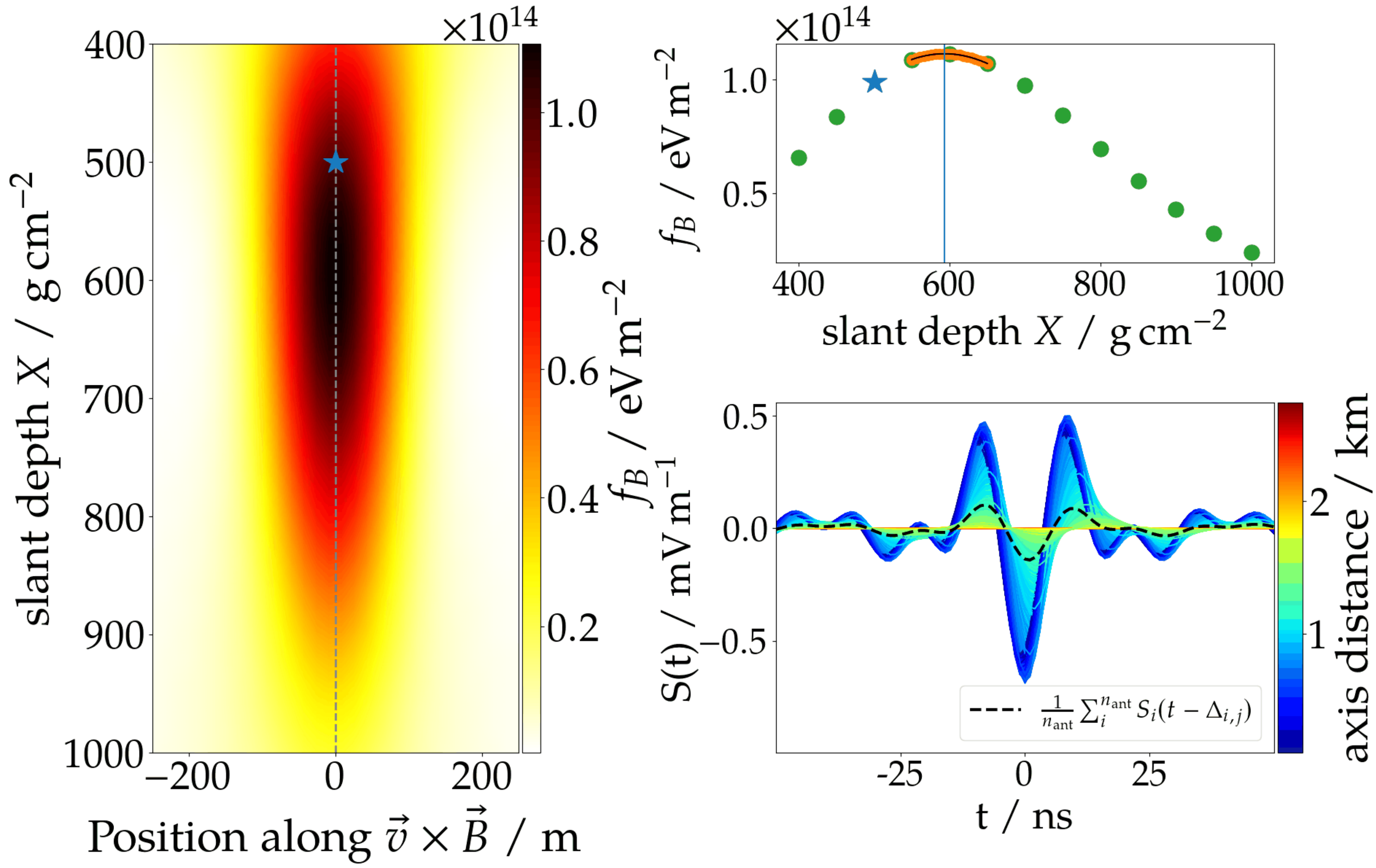


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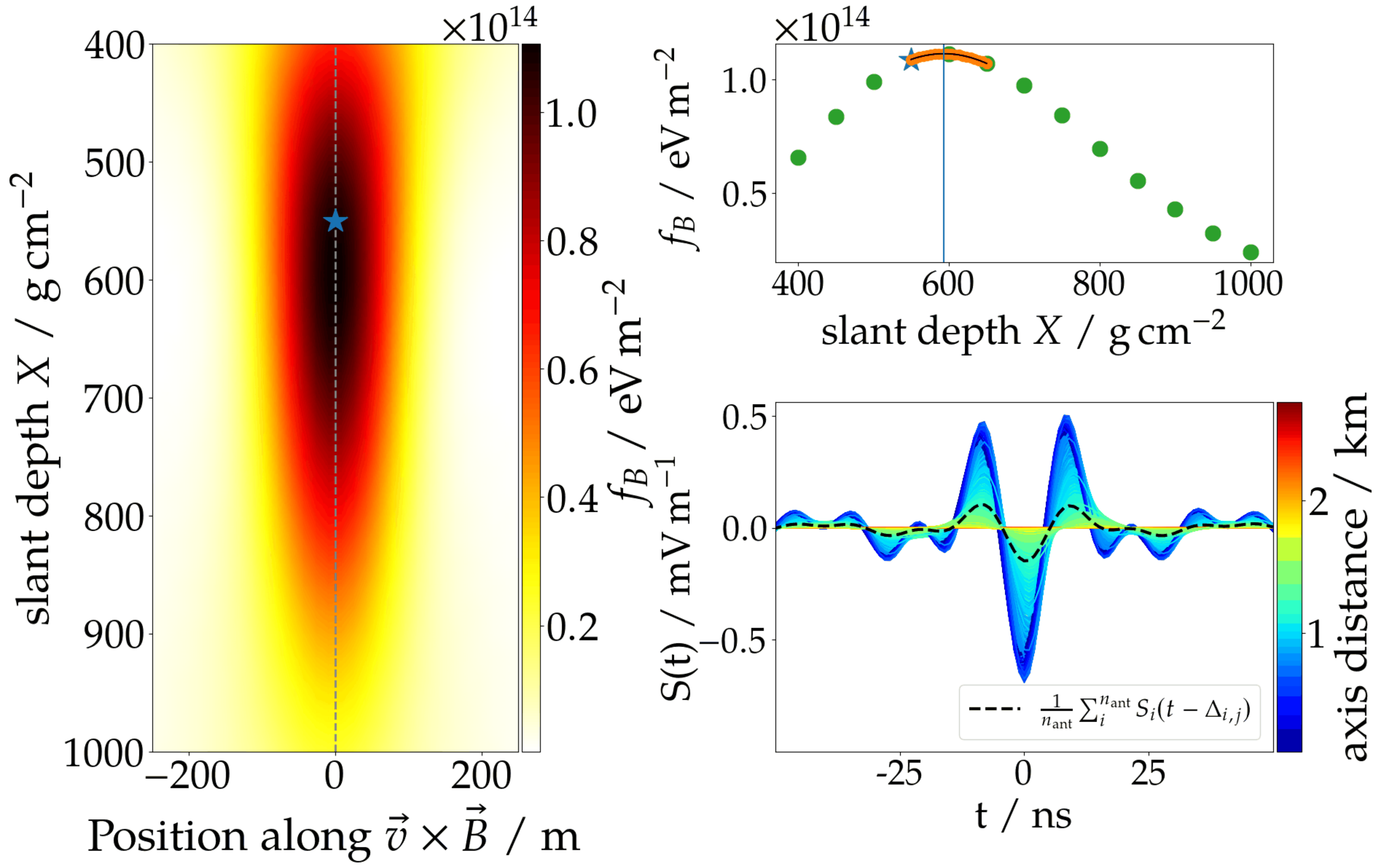


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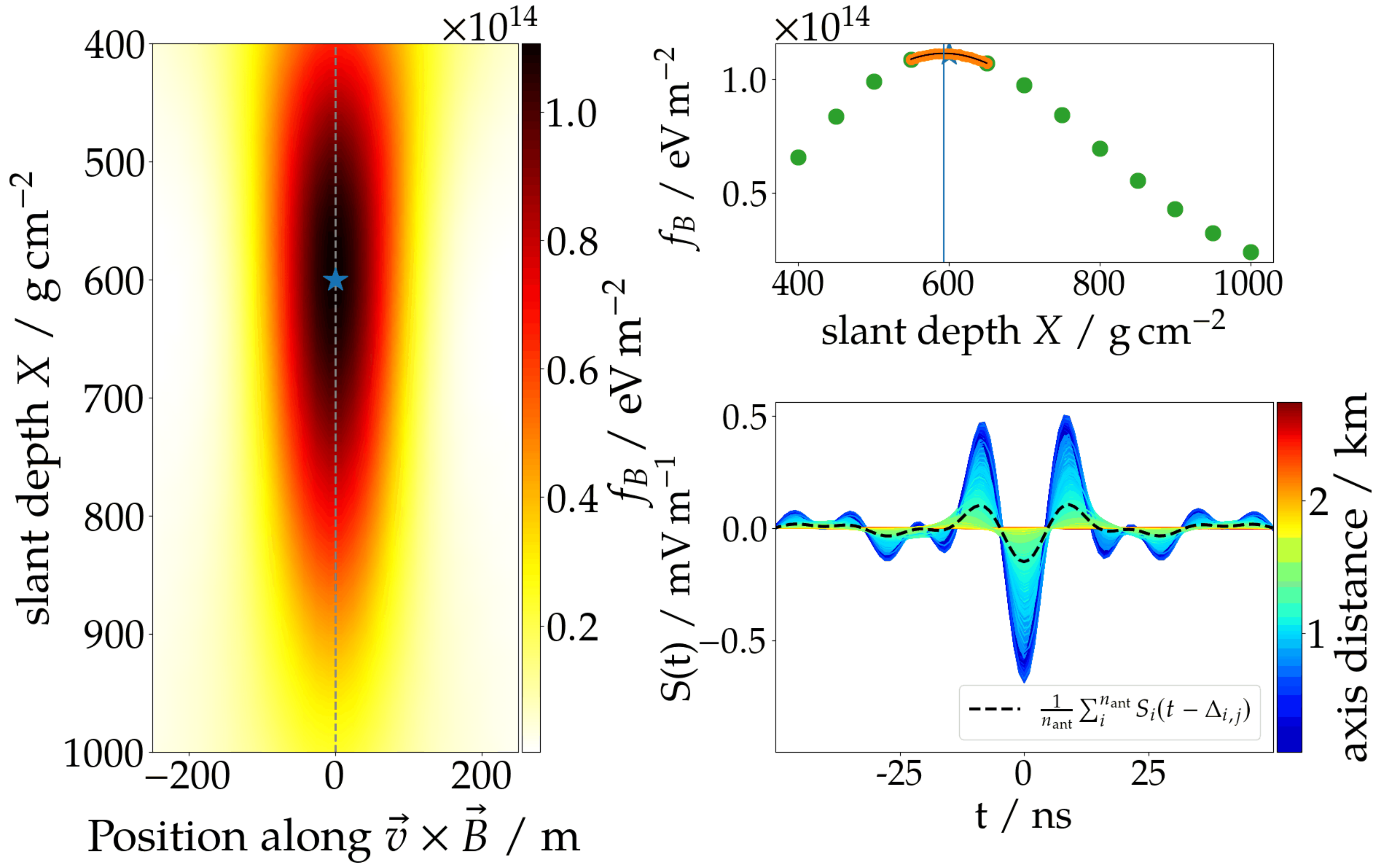


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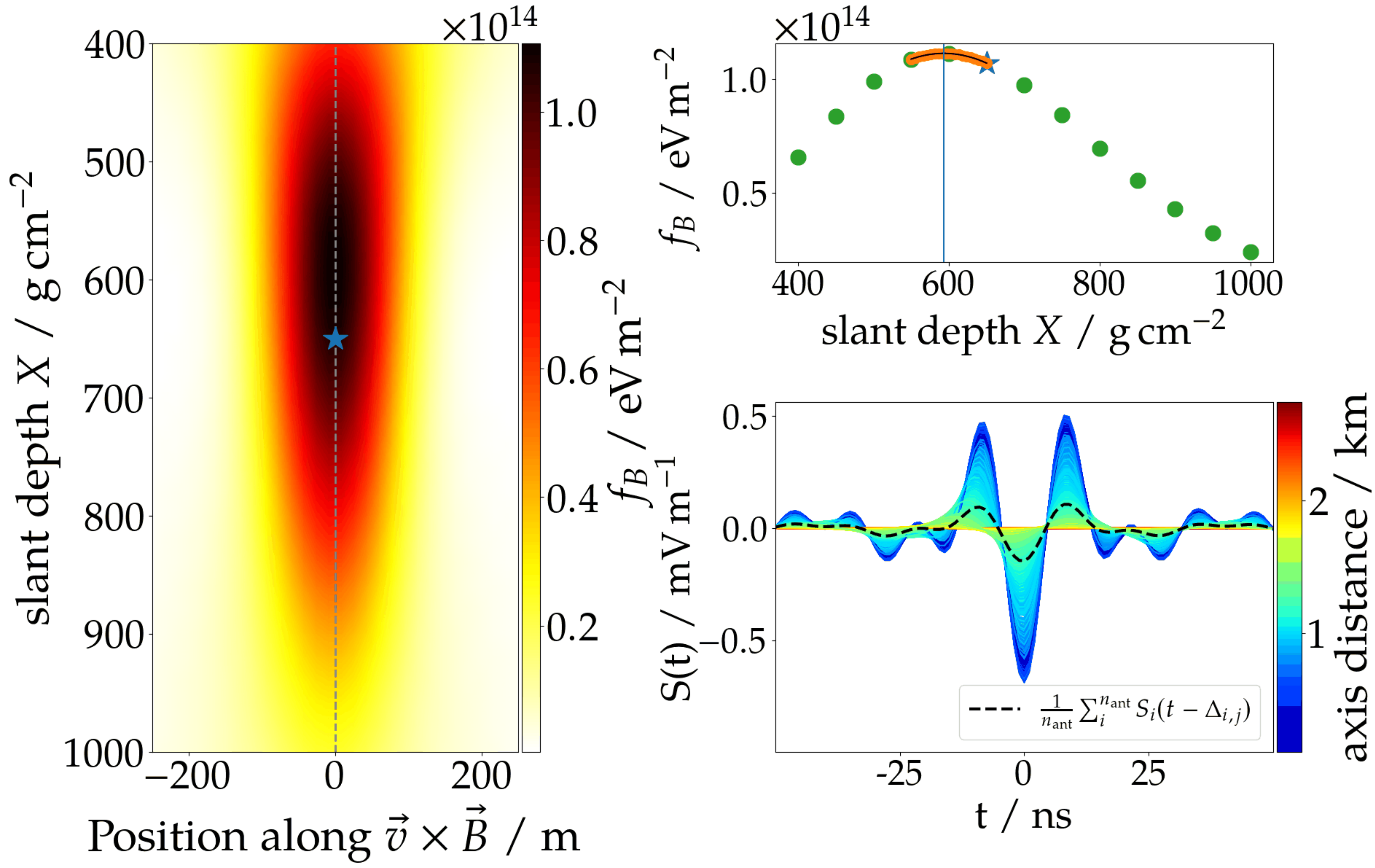


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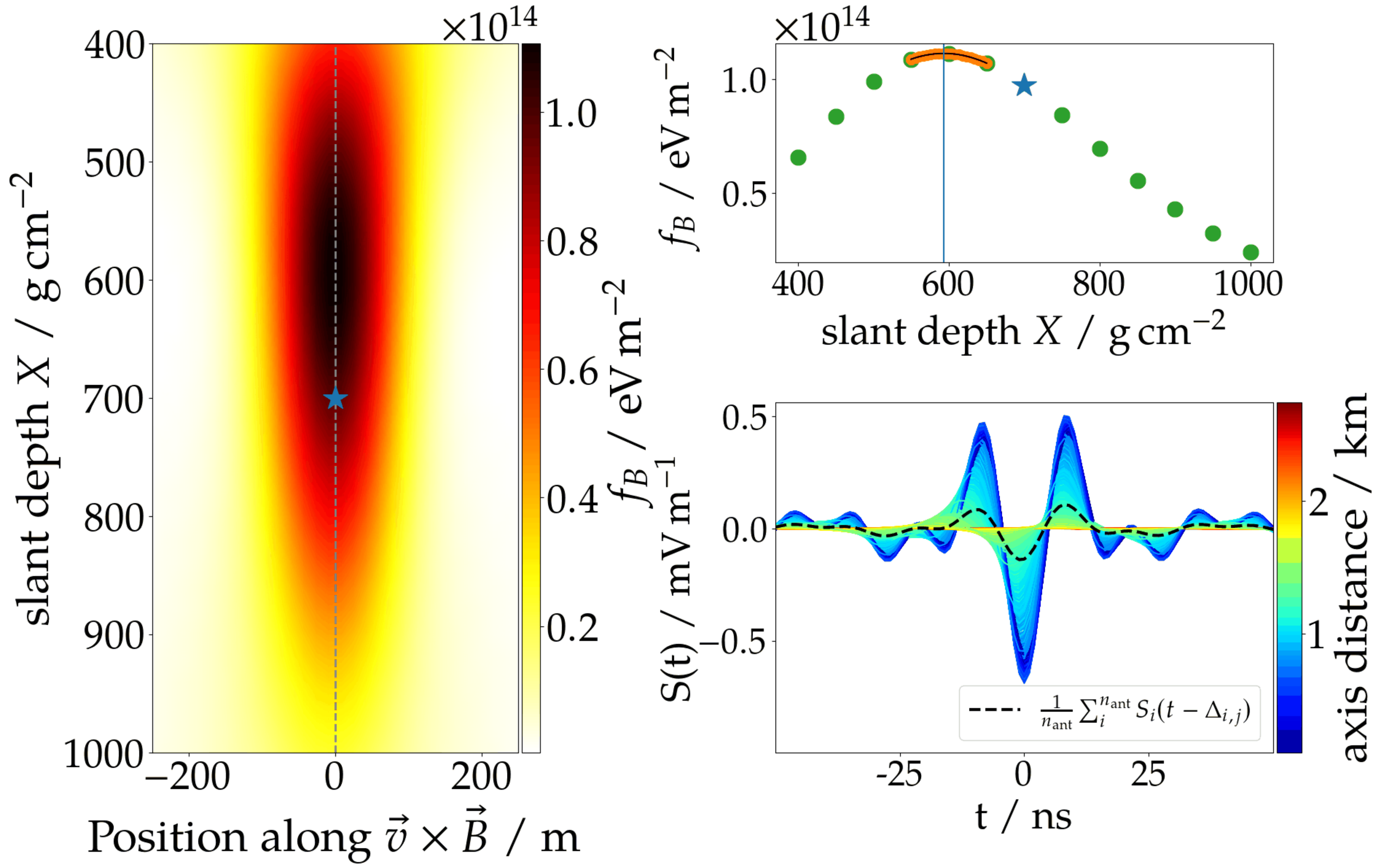


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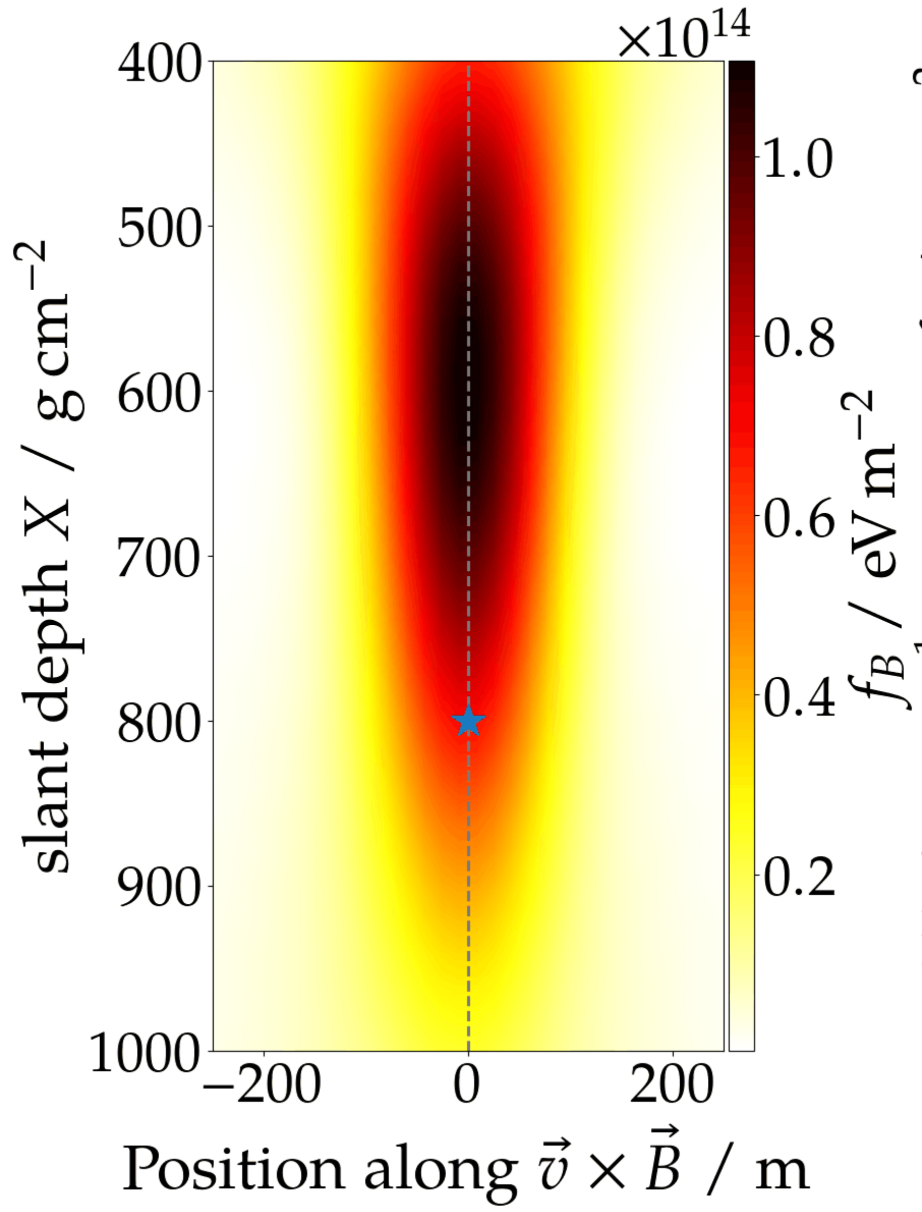


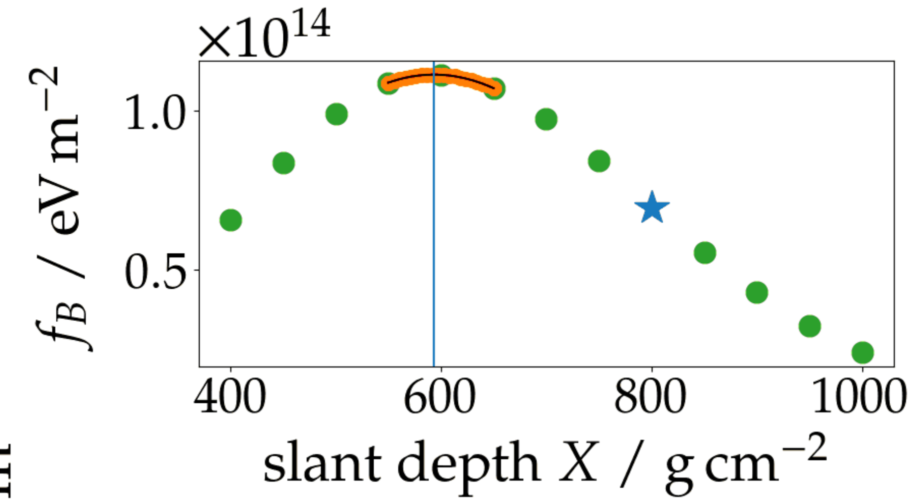


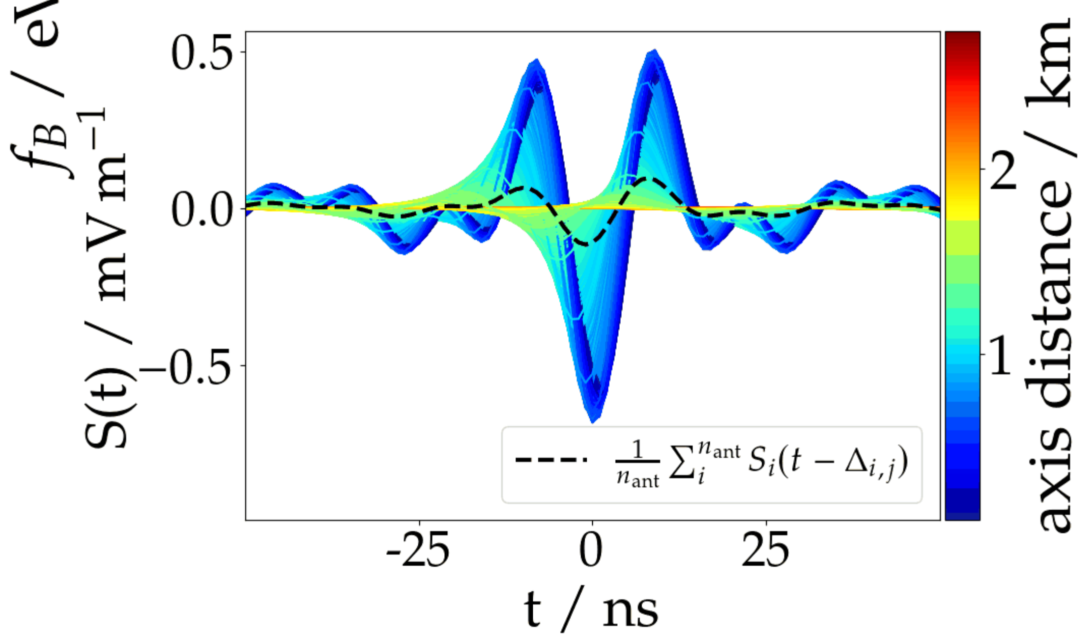


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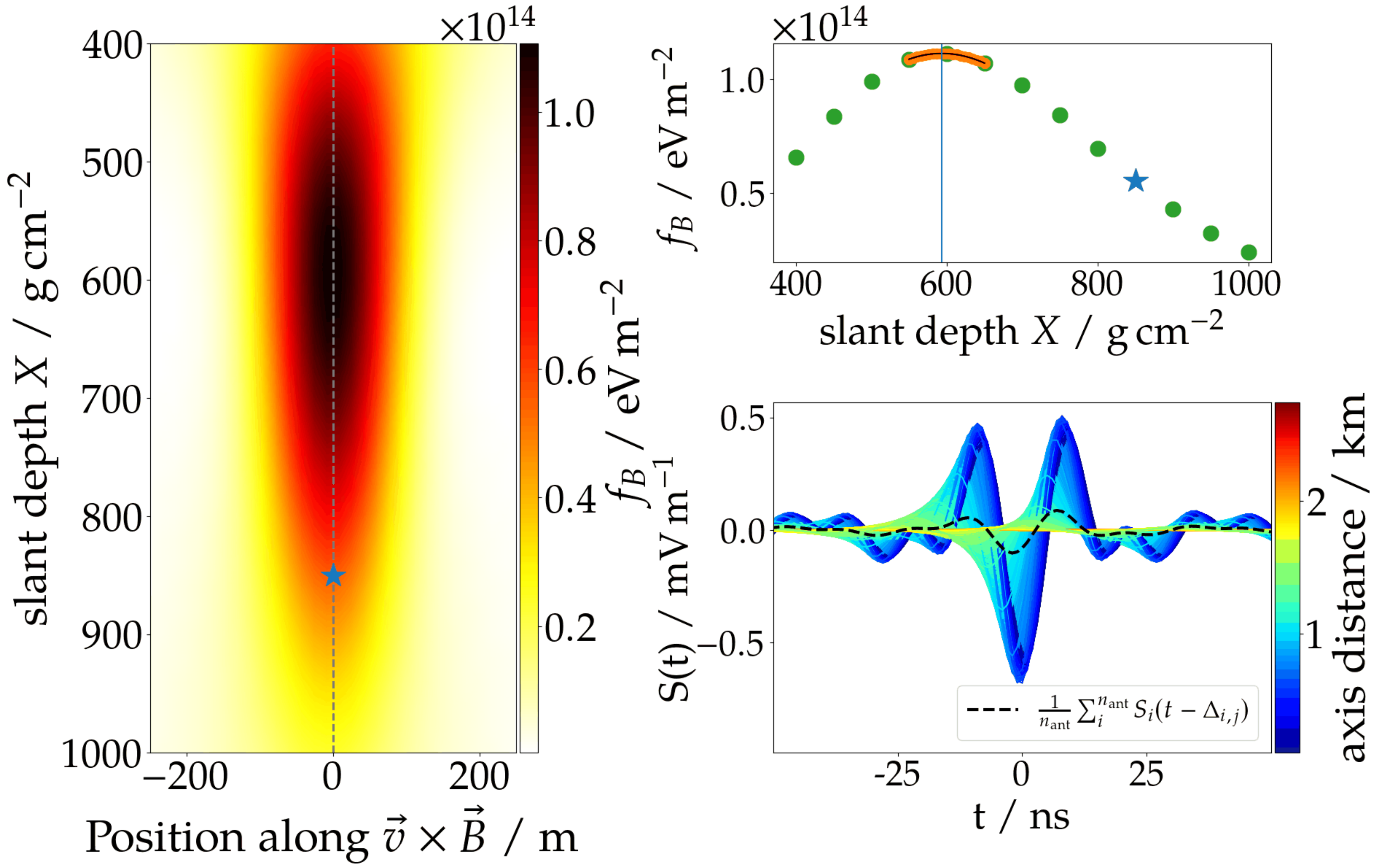


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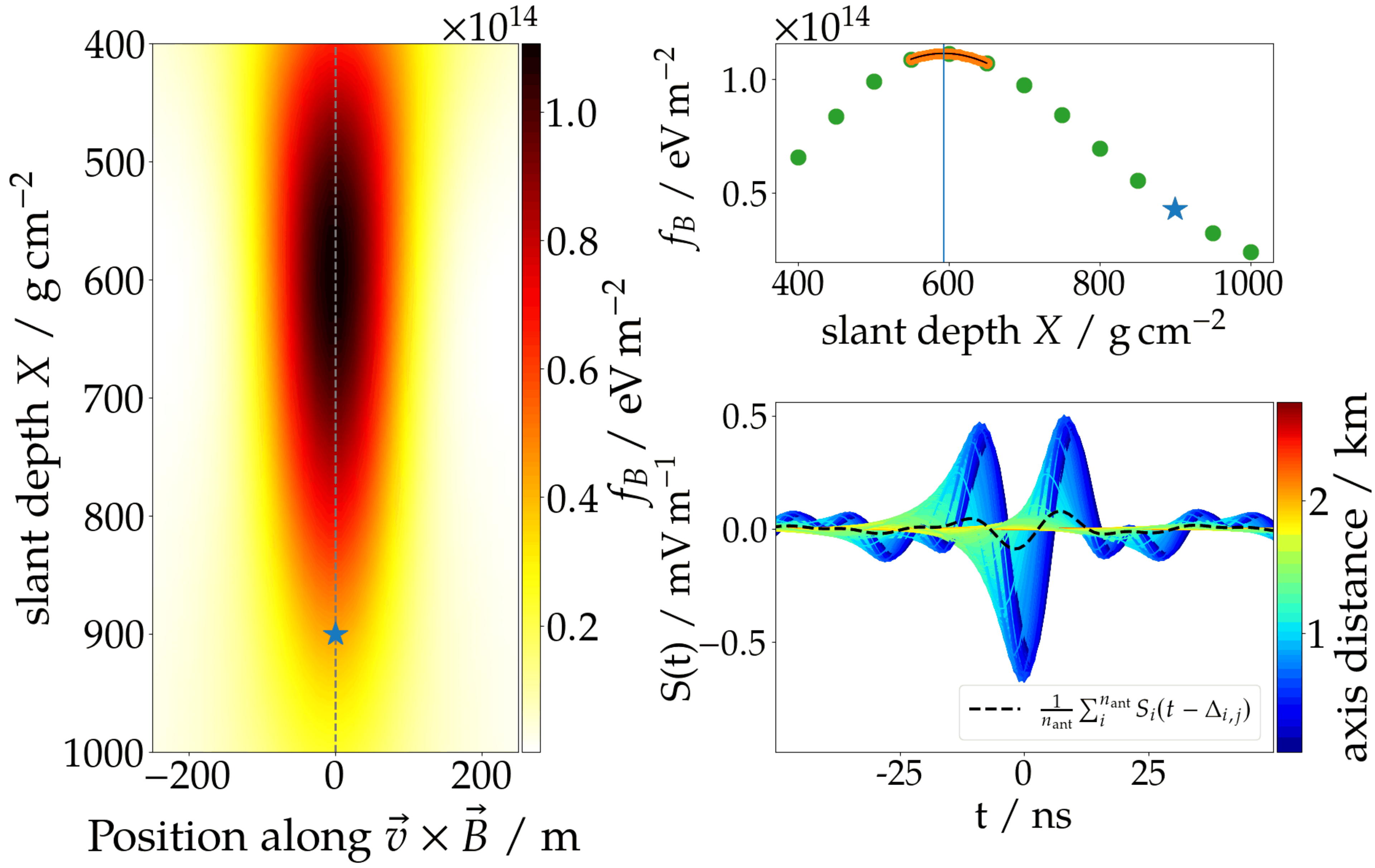


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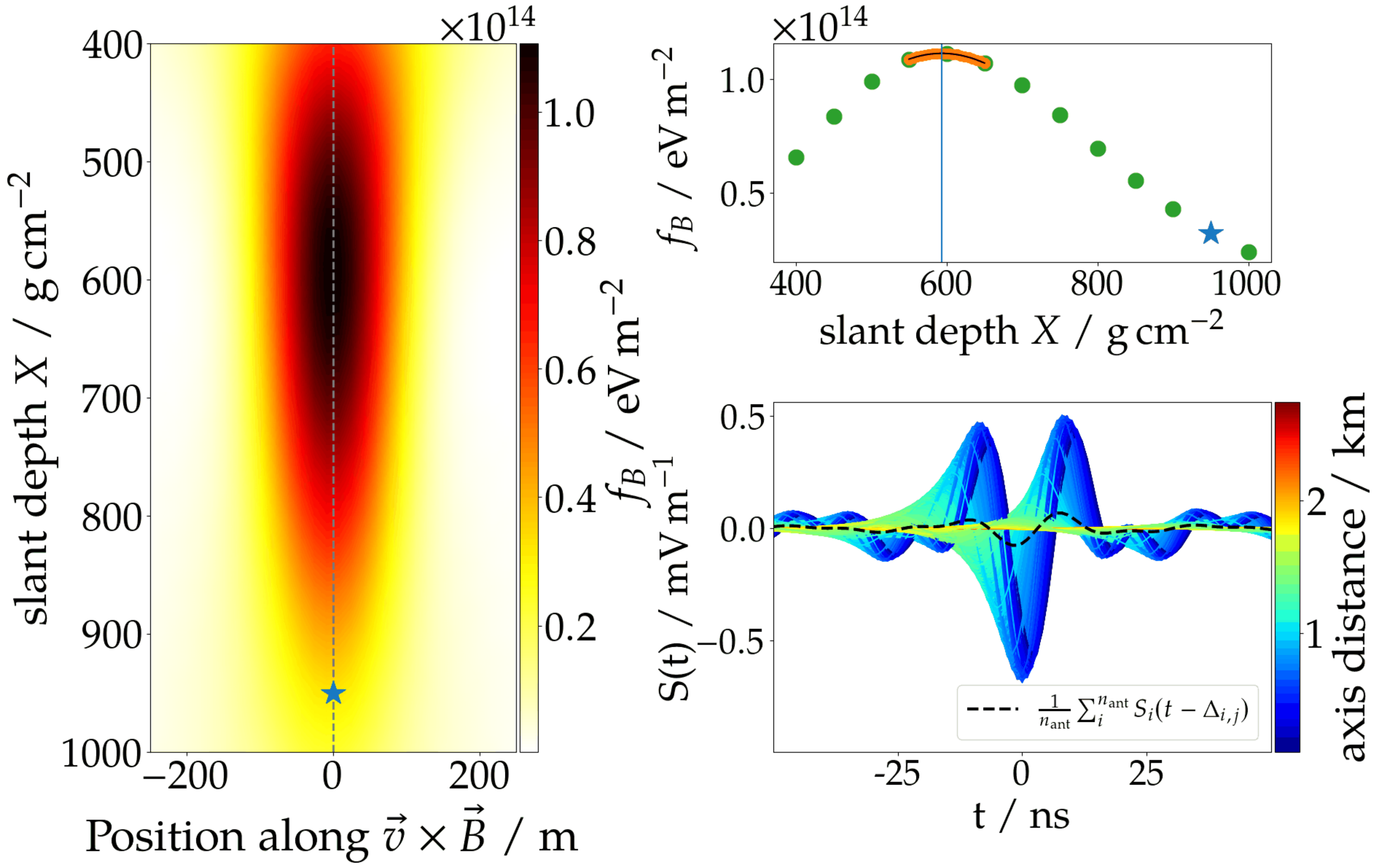


*Schoorlemmer & Carvalho arXiv:2006.10348*
*Schlüter & Huege arXiv:2102.13577*

# Sparse Array

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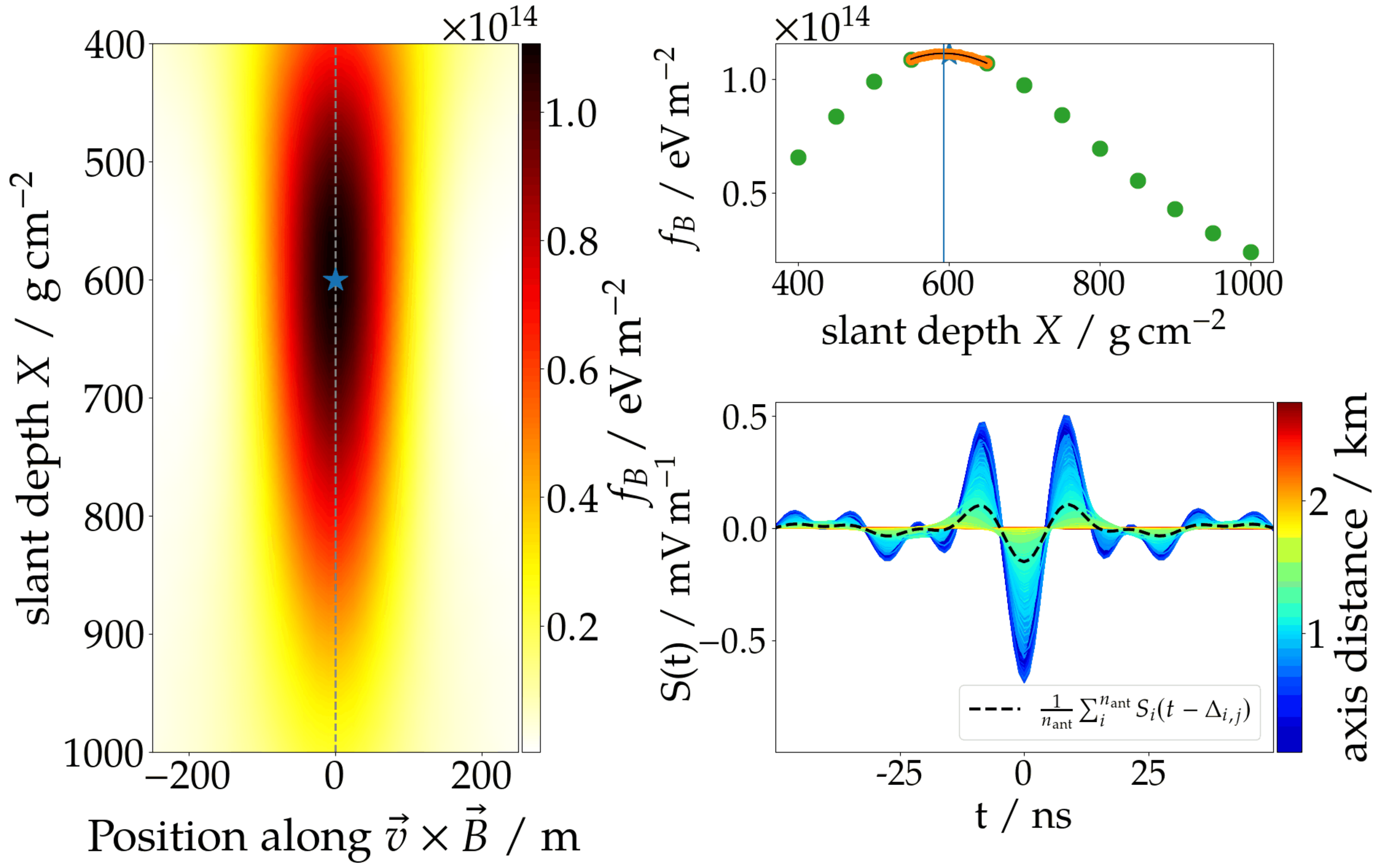


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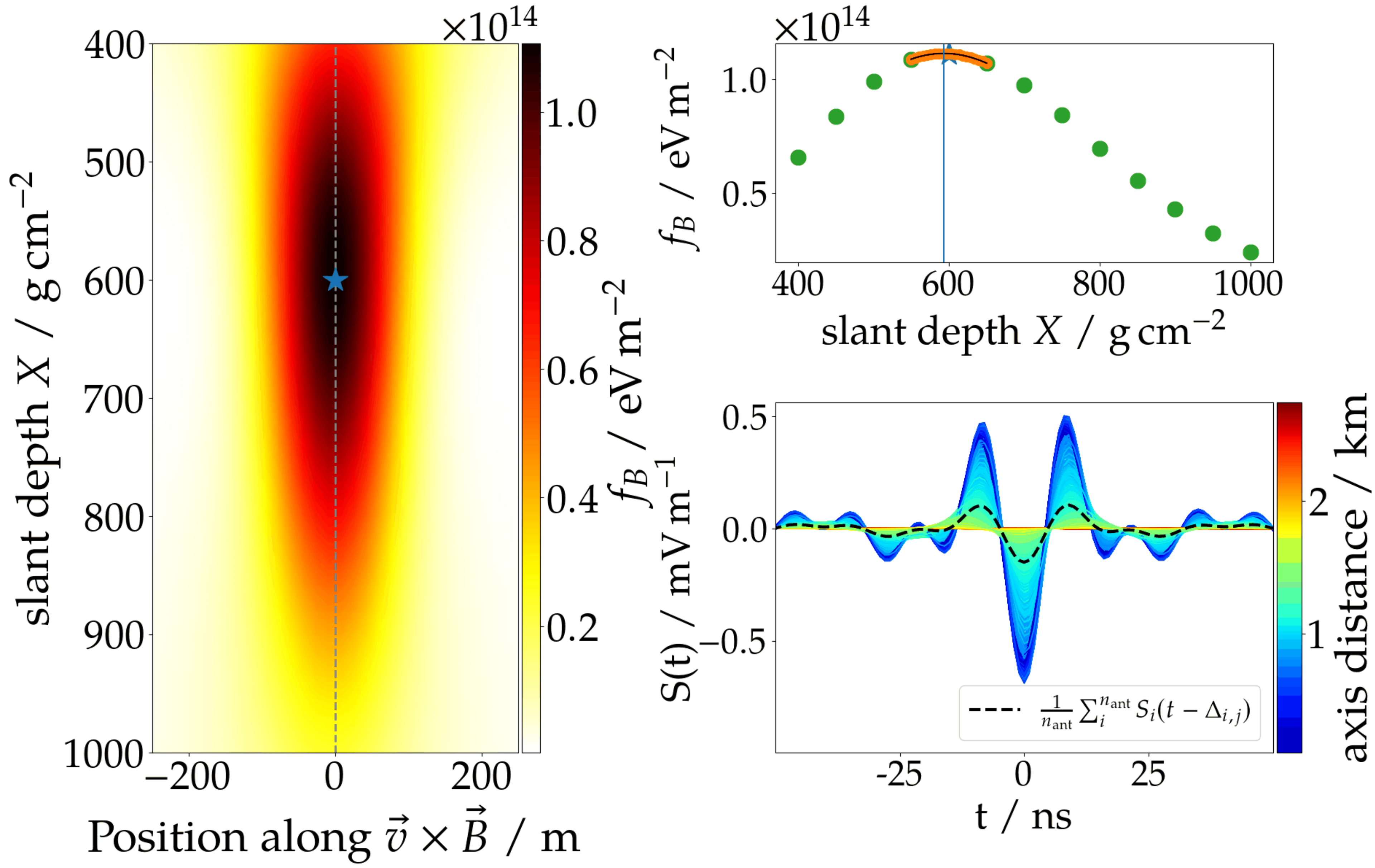


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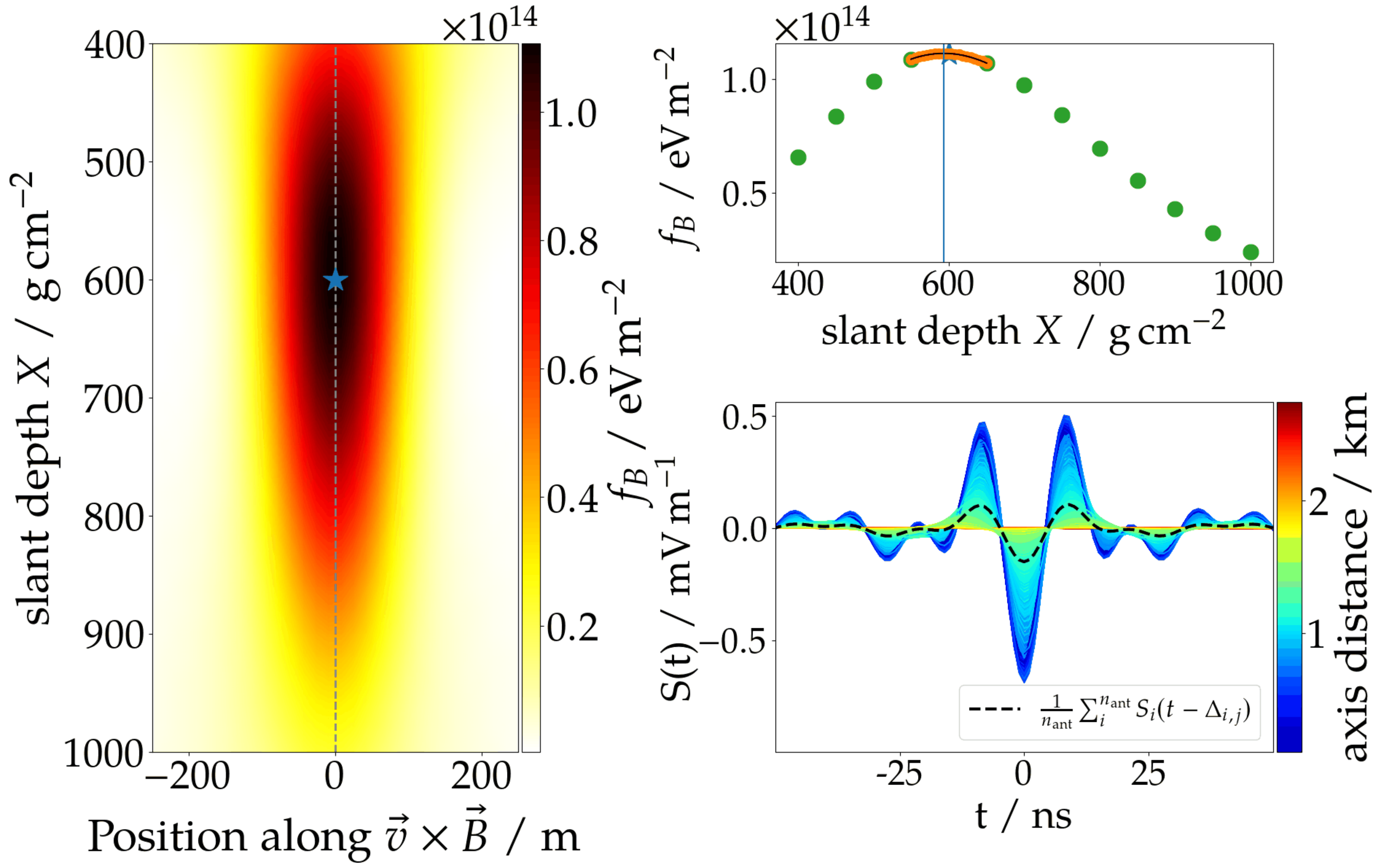


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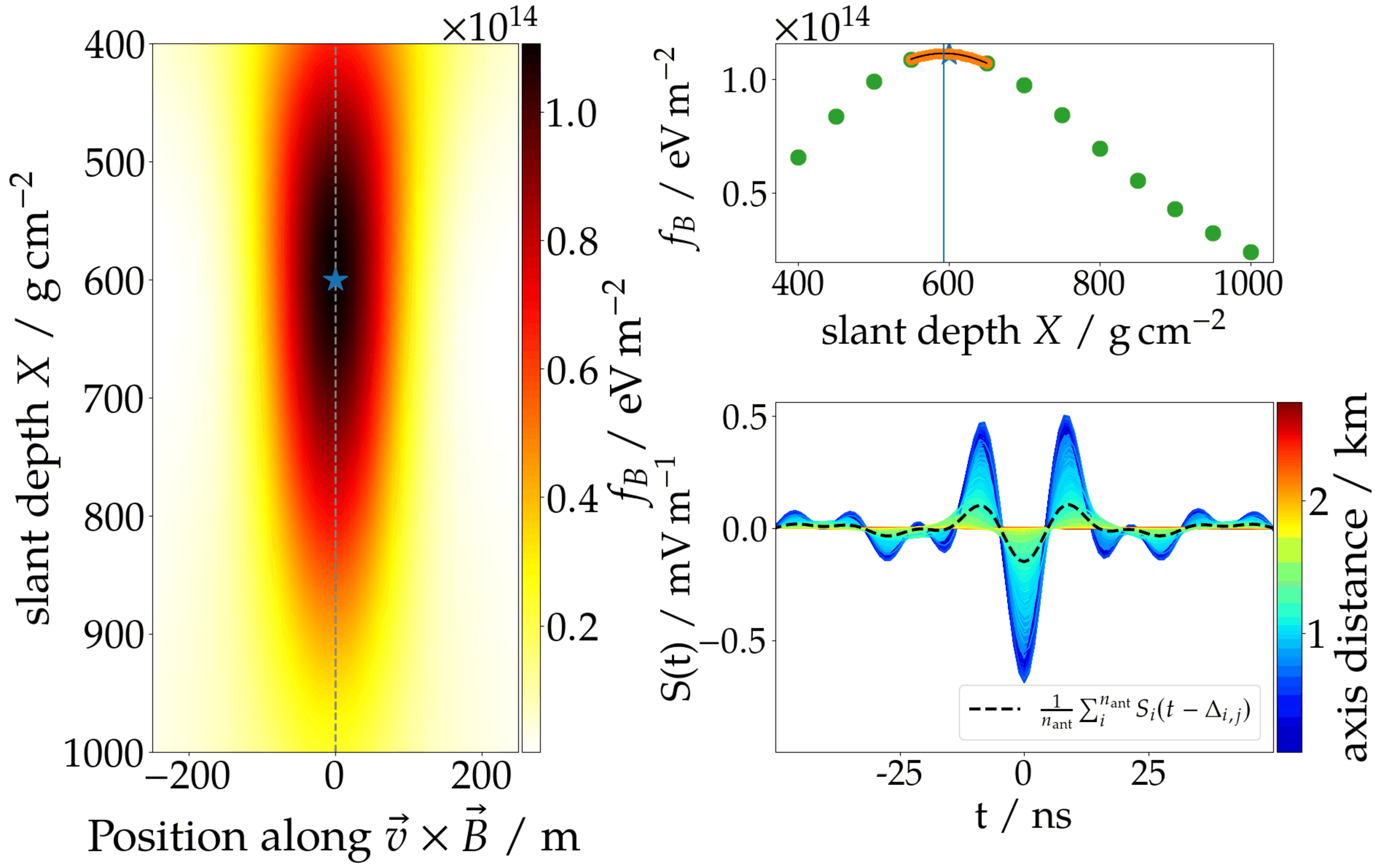


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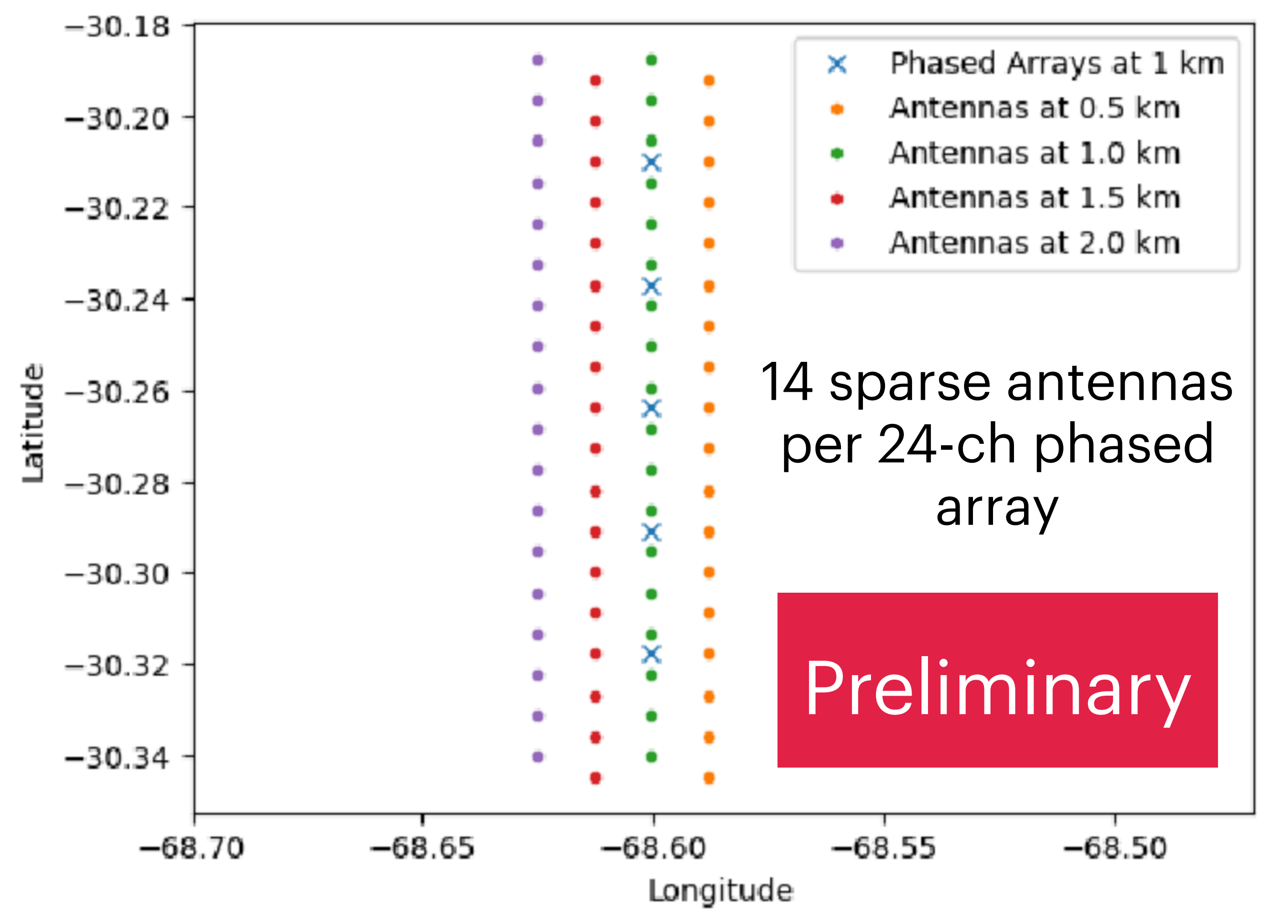
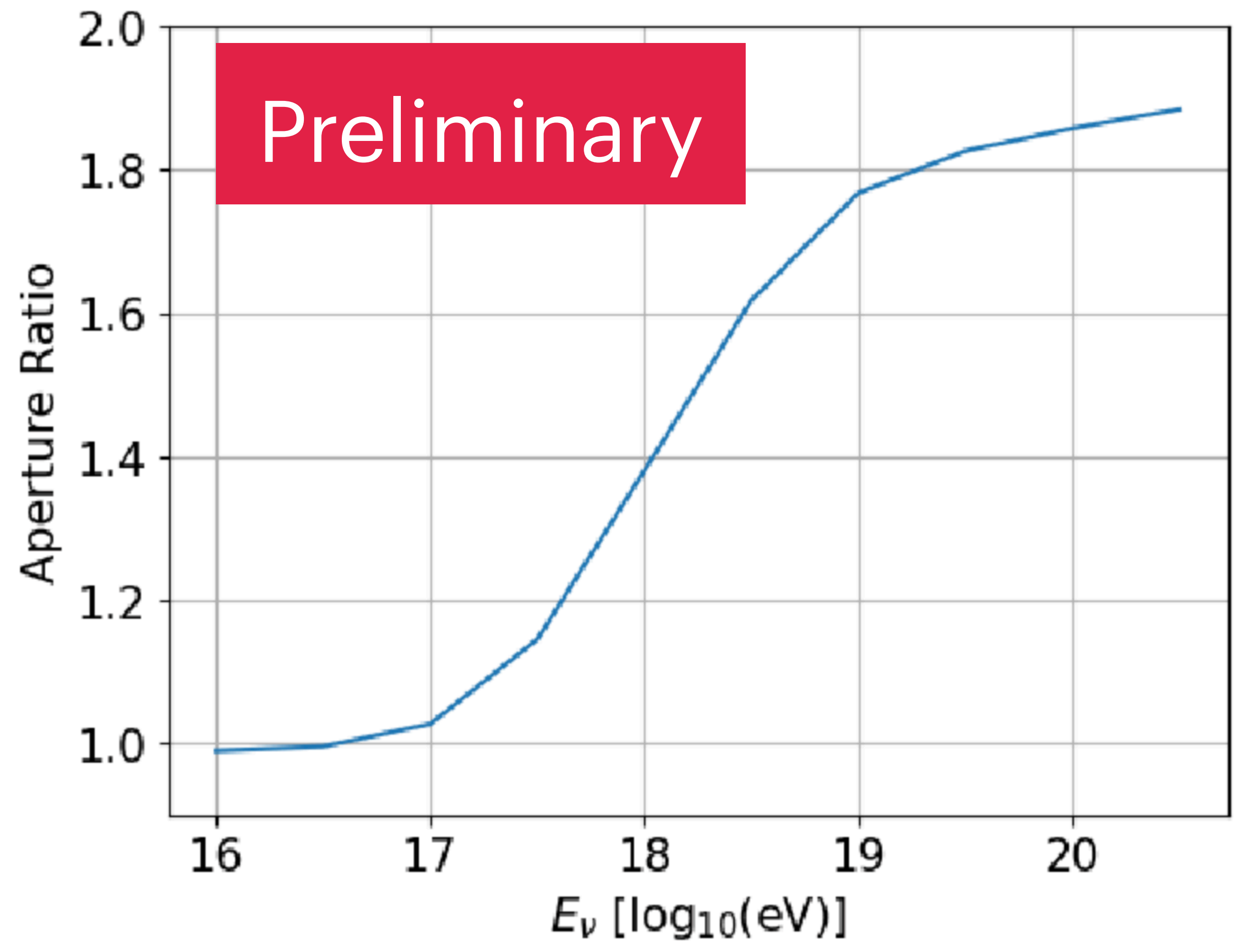



Horizon

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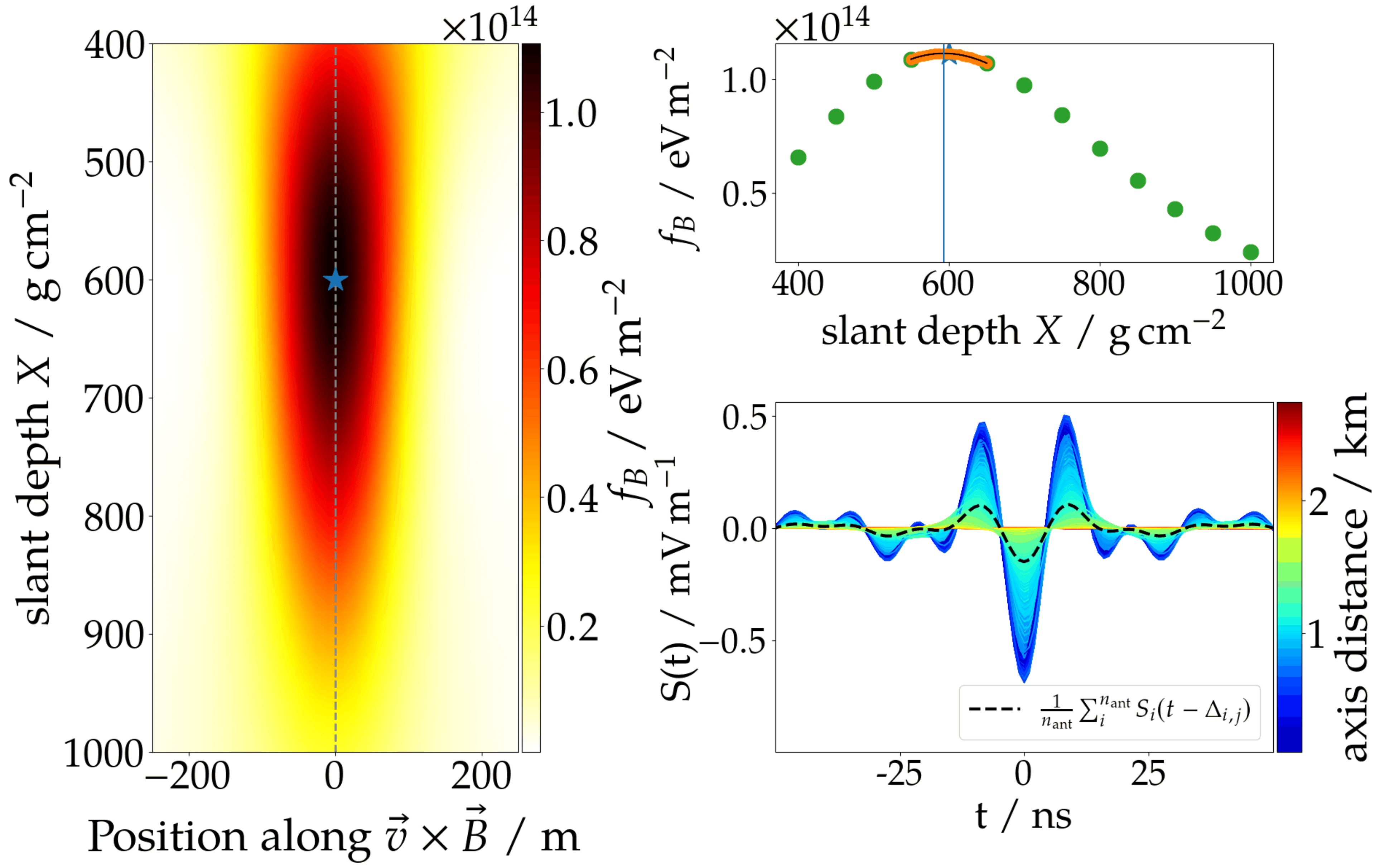


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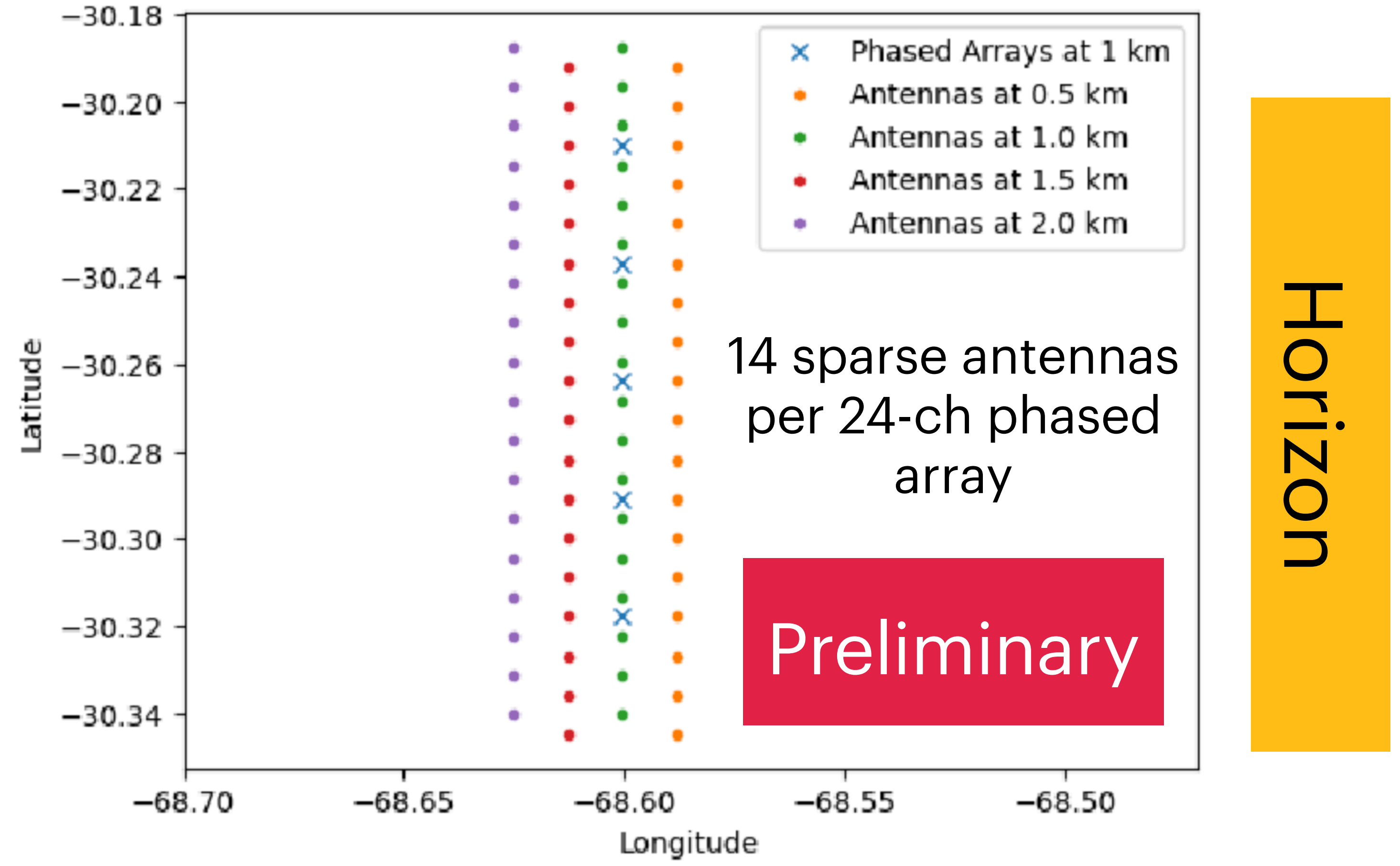


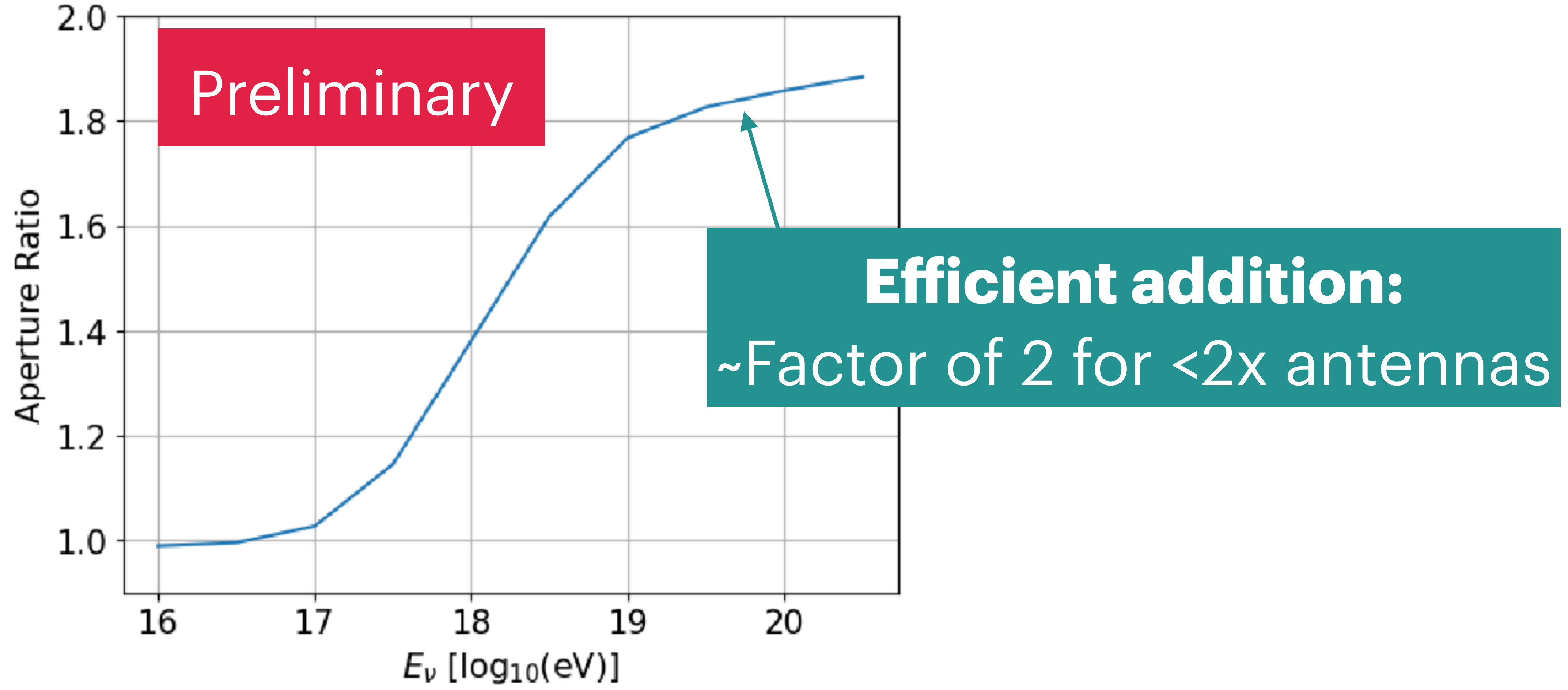


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# Antenna Design Examples

## Phased Array Dipoles

### Dual-Pol Short Dipoles

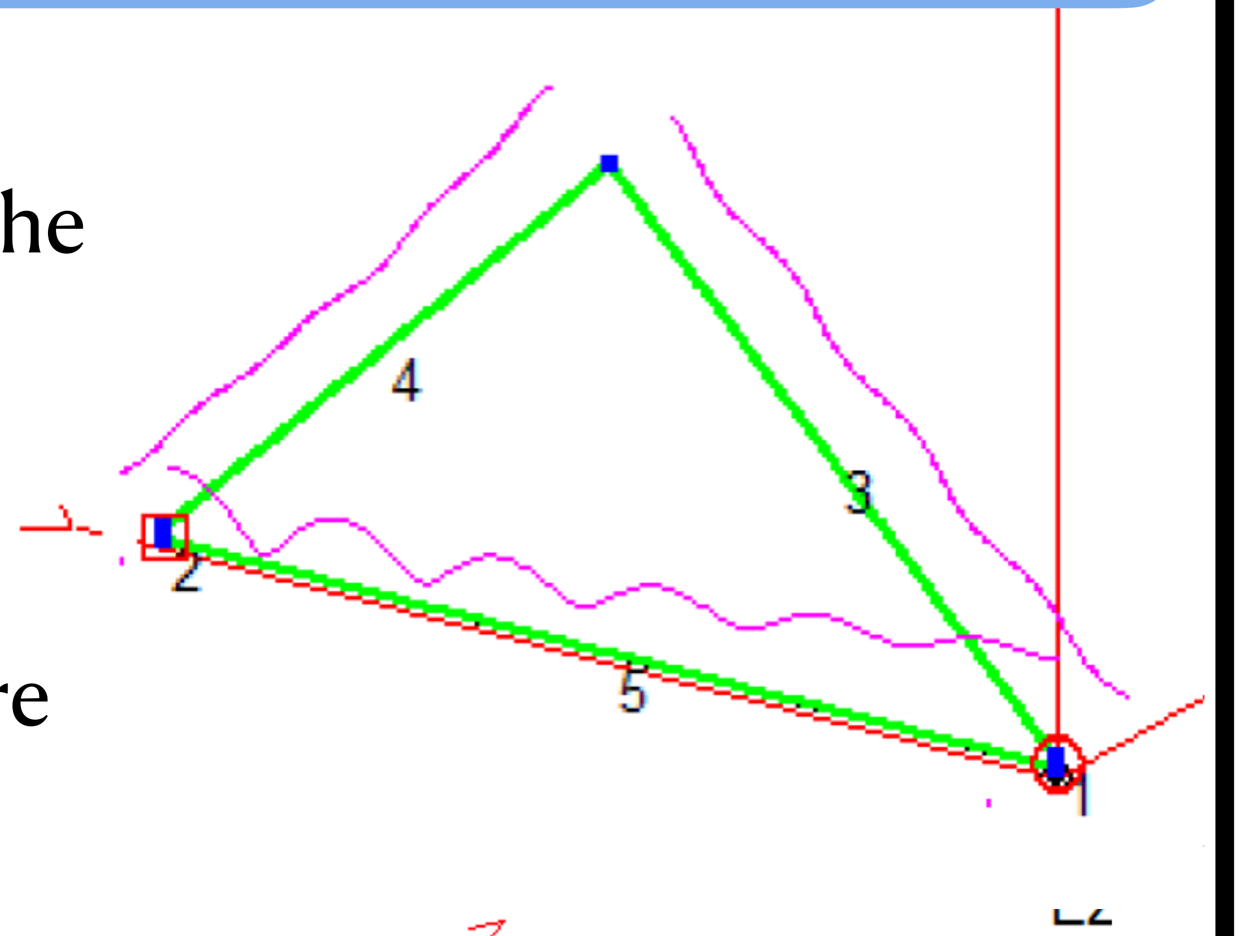
Dual-polarized electrically short dipoles, 4-5 m above ground

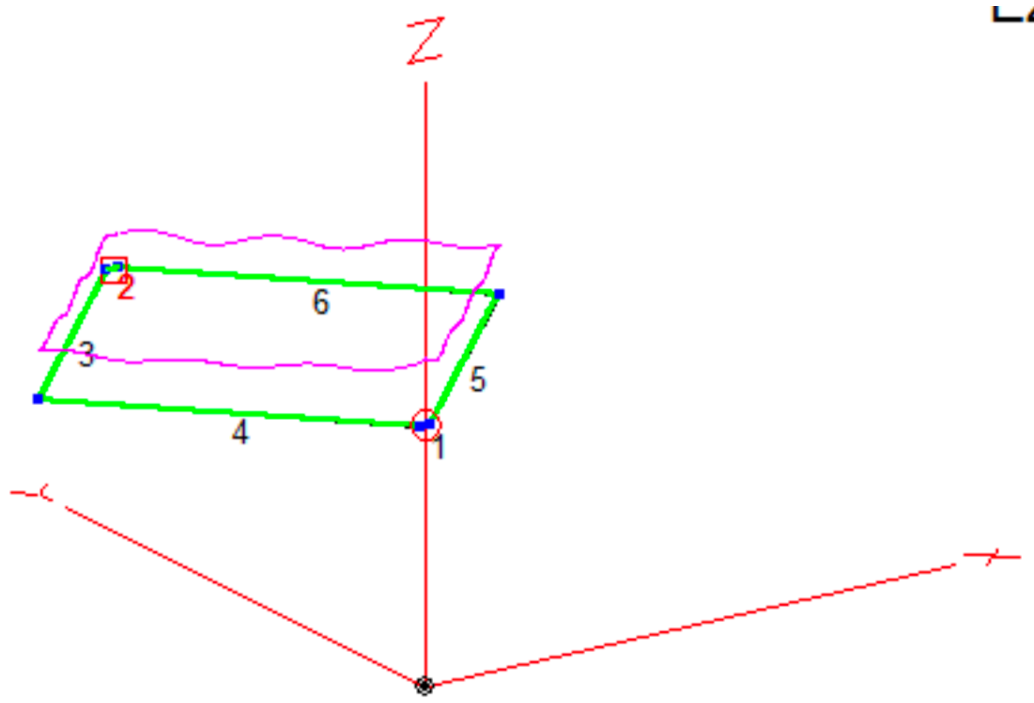
See Southall, et al. NIM-A 1048 167889 2023 2206.09660 and Zack Martin's talk

## Autonomous High Gain

### Rhombic Antennas

- **Goal:** high gain antennas pointed at the horizon
- Long wire in the shape of a rhombus
- Vpol: only one 5-m mast 10-m long wire
- Hpol: Rhombic antenna requires four 4-m masts
- LPDA may also work (but mechanical design challenge)
- Stacked SALLA antennas also an option



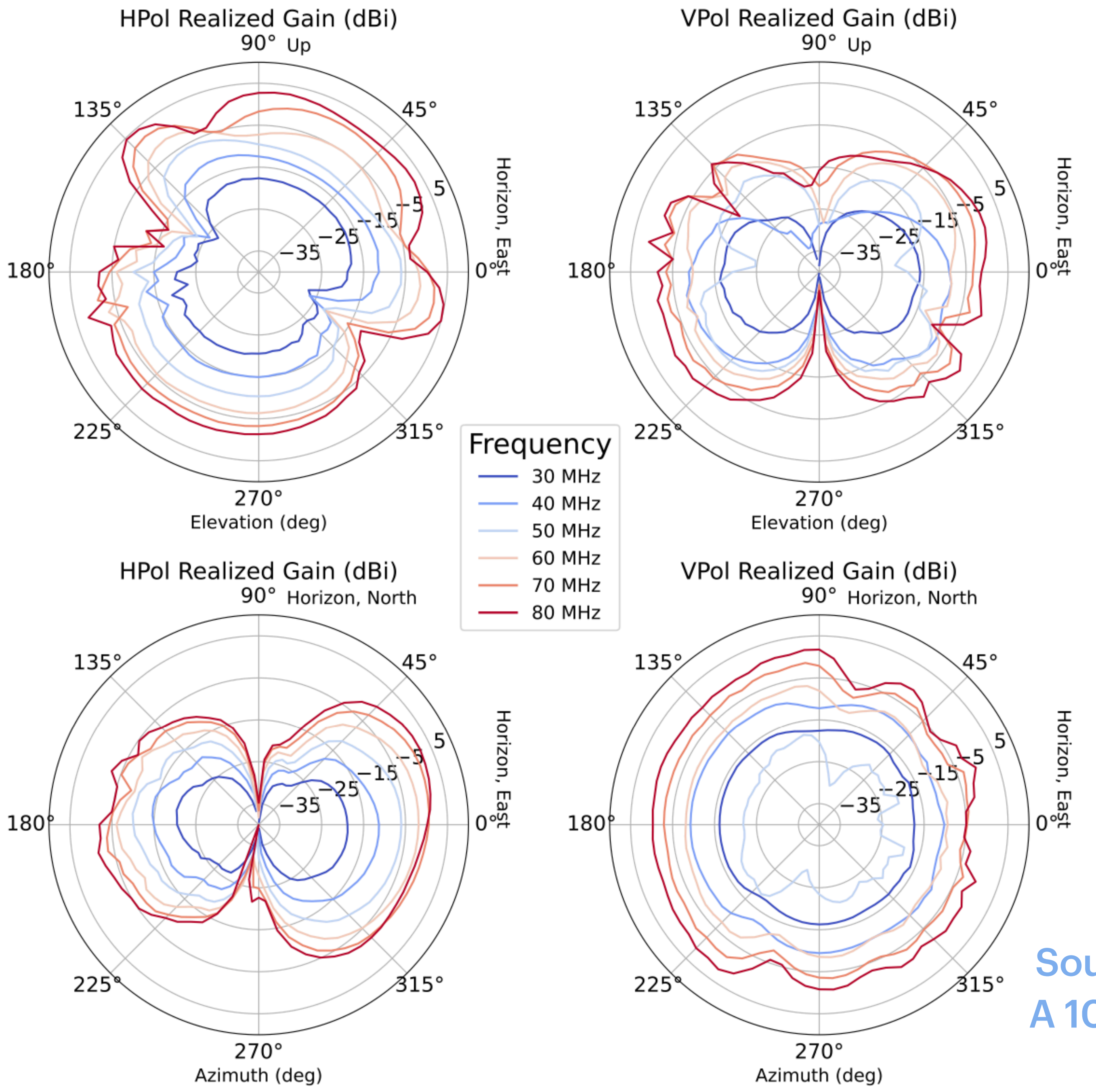
# Antenna Design Examples

## Phased Array Dipoles

### Dual-Pol Short Dipoles

Higher gain beams formed from lower gain antennas

**Realized Gain of a single antenna**



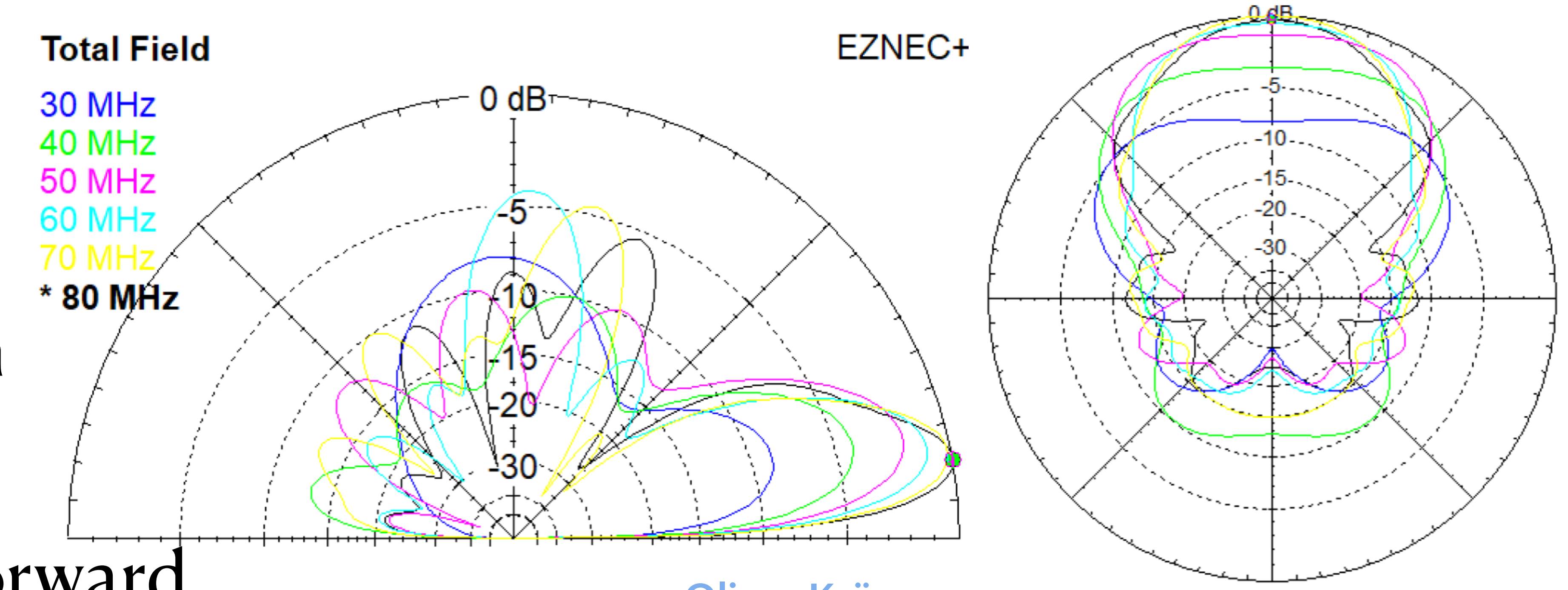

Southall, et al. NIM-A 1048 167889 2023 2206.09660

## Autonomous High Gain

### Rhombic Vpol

- Peak realized gain of 4.5 dBi
- On a 15° slope, main beam points to horizon
- Matching straightforward

**Directivity**

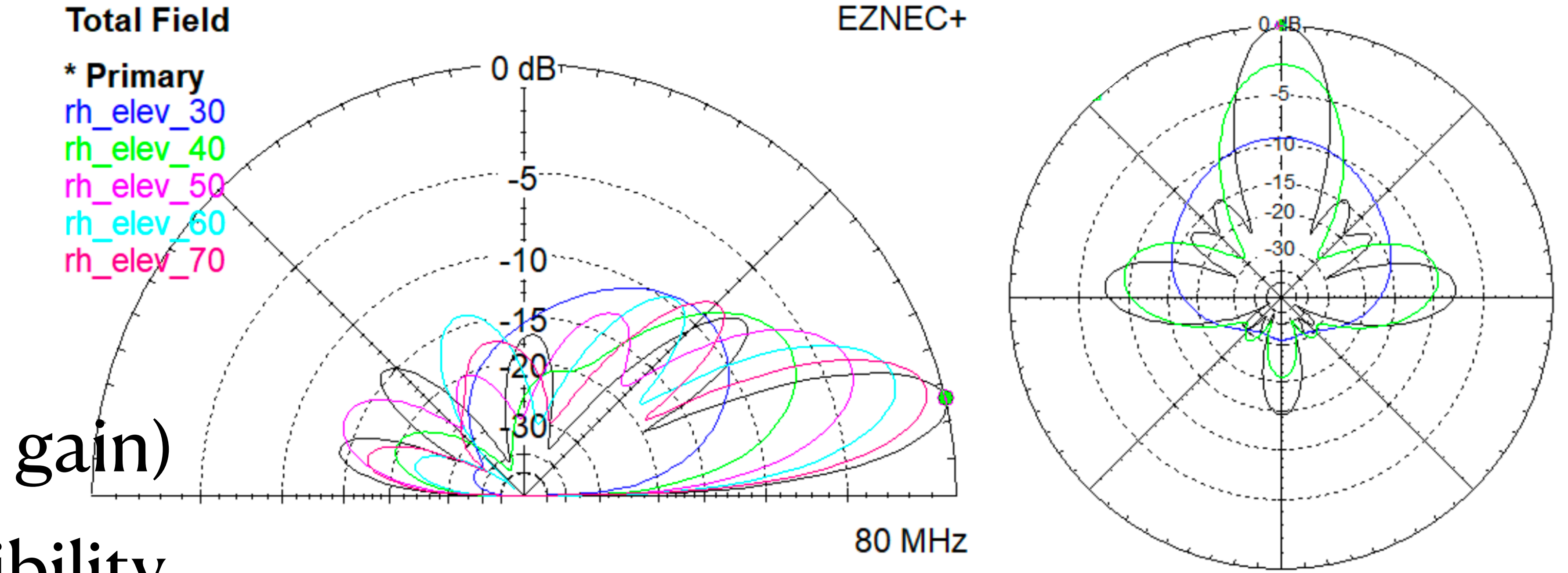



Oliver Krömer

### Rhombic Hpol

- Directivity good in direction of horizon
- Narrower beam 20° (peak 14 dBi realized gain)
- Not ideal but a possibility

**Directivity**




Oliver Krömer

# Conclusions

**GRAND-BEACON**

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## GRAND-BEACON


- **Combined approach can result in hybrid design with:**
  - **Phased arrays for low energies and low thresholds**
  - **Sparse autonomous antennas for reconstruction, CR/nu discrimination, & additional effective area at high energies**
  - **Background rejection from both sparse, long baseline array and directional masking with phasing**
  - Design based on collaborative workshop btwn GRAND & BEACON hosted at Penn State in January 2024
  - Ongoing work shows promise
    [good agreement between BEACON & GRAND sims, phased array triggering and elevation shows enhanced sensitivity at 100 PeV]

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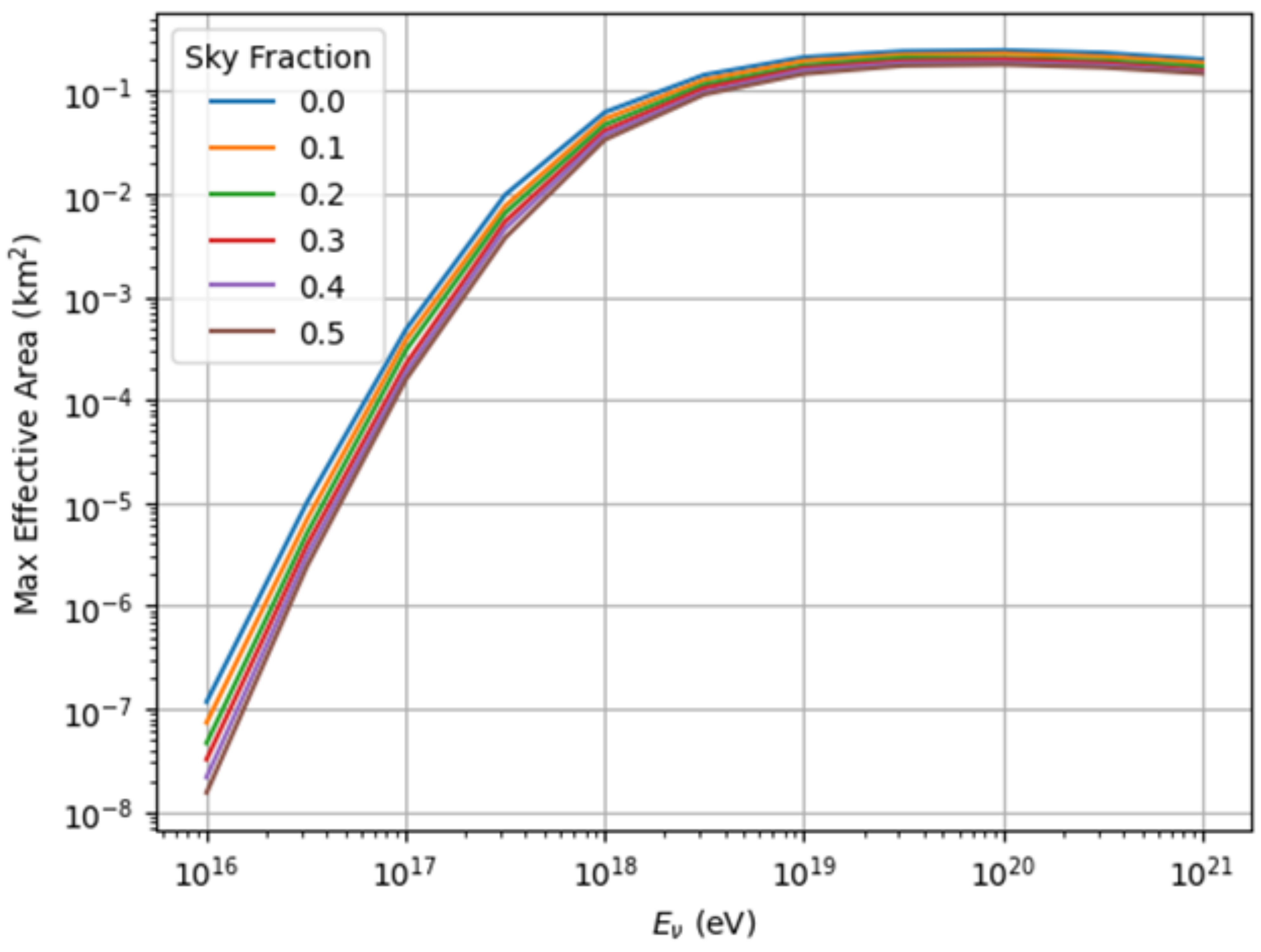
- **Can "tune" the sensitivity via careful selection of array parameters**
  - *Parameters:* elevation, sky noise fraction, phased & sparse array layouts, antenna beam and gain
- **Open questions:**
  - Further optimization into frequency range, antenna design, spacing...
  - Reconstruction performance & background rejection on low-threshold signals from phased array trigger
  - Impact of topography on phased array performance
  - Sky noise rejection with tuned antenna or phased beams. → Need measurements of sky noise when pointing at ground.

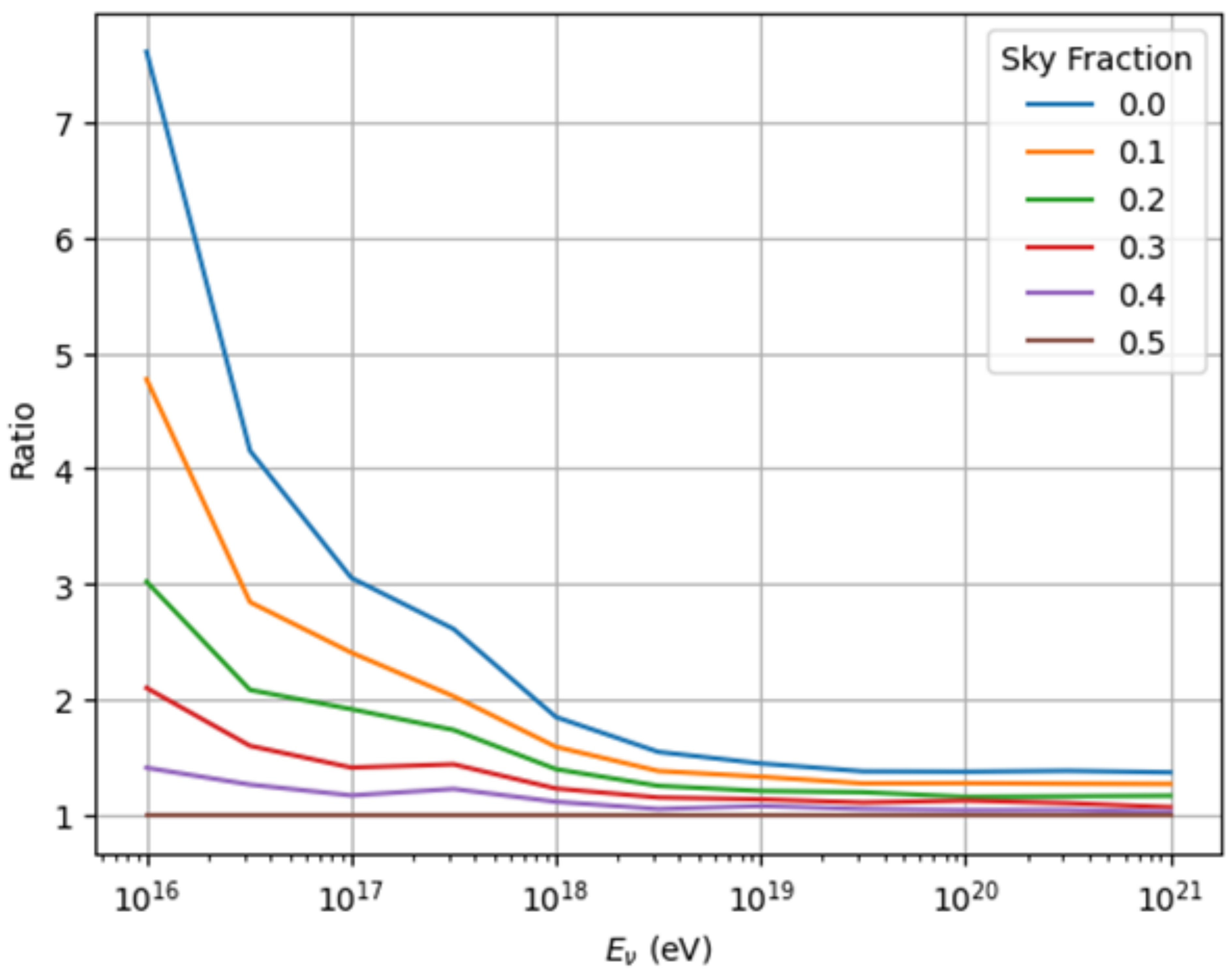
# Bonus Slides

# Sky Fraction

**Modest improvement**

- Fixed antenna gain (BEACON prototype), elevation, number of phased antennas

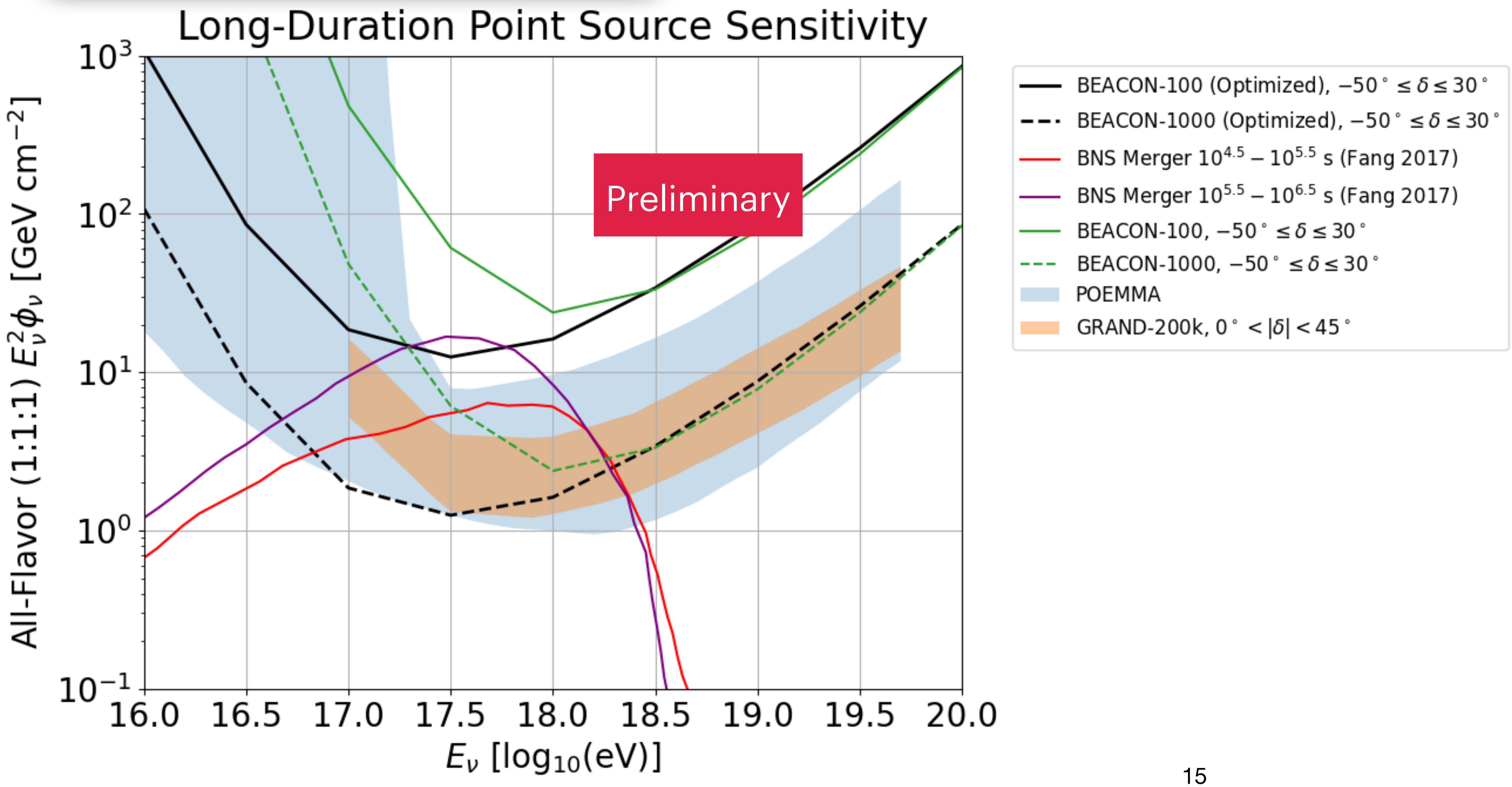


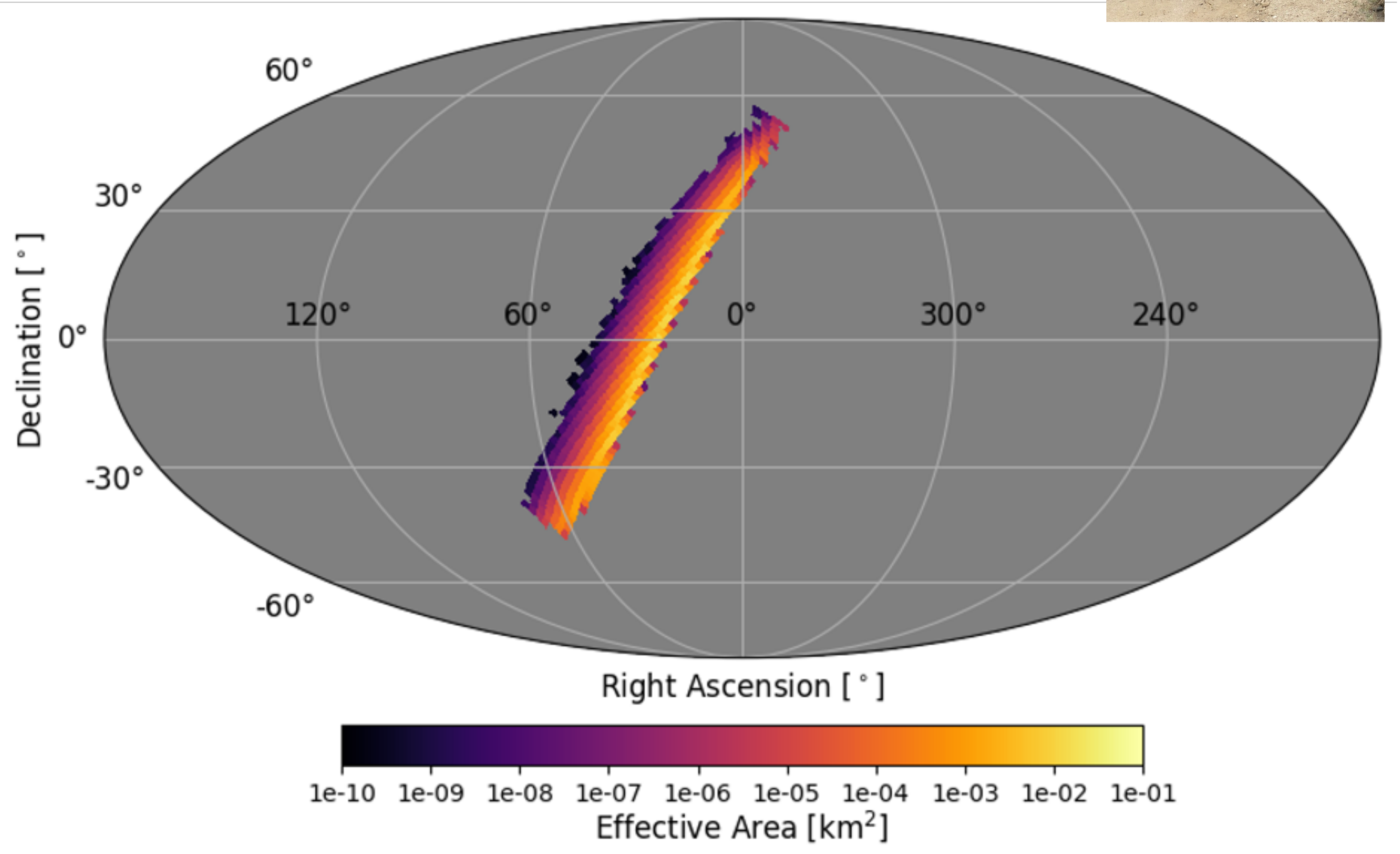
Phased array simulations with MARMoTS
See Andrew Zeolla's talk

# Phased Array - Optimistic Scenario

100 PeV Optimized:
- 24 antennas per station
- 1 km elevation
- 6 dBi gain, perfectly matched
- sky fraction 30%, Fresnel coeff. 0




## Instantaneous FoV




## Daily averaged FoV