# **Cosmic rays** with LOFAR 2.0

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WAN OVER



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### energy & composition

A. Corstanje et al 2021



### energy & composition + statistics

A. Corstanje et al 2021

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## energy & composition + statistics

A. Corstanje et al 2021

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Higher energies: need a bigger detector



Lower energies: need to control for detection biases



# LORA upgrade



### **Standard operation**

Keep trigger rate ~ 1/hour

(12/20 scintillators)



# LORA upgrade



#### 600 400 deposit (MeV) 200 10<sup>2</sup> y (m) × ×× 0 -200 10<sup>1</sup> -400 -600-500 500 0 x (m)

### **NEW** operation

### Keep trigger rate ~ 1/hour

(12/20 scintillators)



minimum number of detectors triggered

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# Hybrid Trigger

# What if we want to bring the trigger condition WAY down?











# Hybrid Trigger

#### **Monitor TBB level signal**

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### Can we probe this with LOFAR 2.0?



# **LOFAR 2.0**

- Continuous observation
- Simultaneous observation with low + high band antennas



30-80 MHz

50-350 MHz









30-80 MHz

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## Traditional event analysis

$$\chi^2_{\rm radio} = \sum_{\rm antennas} \left( \frac{P_{\rm ant} - (f_r^2) P_{\rm sim} (x_{\rm ant} - x_0) y_{\rm ant} - (y_0)}{\sigma_{\rm ant}} \right)^2$$

$$E_{\rm radio} = f_r \times E_{\rm sim}$$

Free parameters: energy and core position



### Can we measure this?

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# 110 simulated showers with same $X_{max}$ (within +/-0.5 g/cm2), different L, 50-100 MHz



### Can we measure this?

110 simulated showers with same  $X_{max}$  (within +/-0.5 g/cm2), different L, 50-100 MHz



 $L + 16 \text{ g/cm}^2 (R - 0.3) / 0.06$ 

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# How do we scale this up to handle 10x the events and many times more needed for LR analysis?



### **Template synthesis method**



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### **Template synthesis method**



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**Waveform interpolation** 





A. Corstanje, in prep

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### **Waveform interpolation**



 Interpolation algorithm to reconstruct the full pulse time series at any position in the radio footprint



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# **LOFAR 2.0**



Continuous observation: x10 events

- Simultaneous LBA + HBA
- Increased energy range
- Shower reconstruction beyond X<sub>max</sub>

### Plenty of new cosmic-ray science to do with LOFAR 2.0!

Backup



# **Shower imaging**





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### LOFAR event



- LOFAR data: First hint of radio reconstruction of L! for given X<sub>max</sub>, fit quality depends on L
- L-Xmax fit possible with LOFAR?
  LBA+HBA bandwidth would help!
- Important factors:
  - core fit precision (extended bandwidth helps)
  - homogeneous coverage (more events help)

Very promising analysis for LOFAR 2.0

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## Where do cosmic rays come from?



$$E_{max} \propto Z e B r$$

energy + composition

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