



European Research Council

Cosmic ray composition measurements with LOFAR

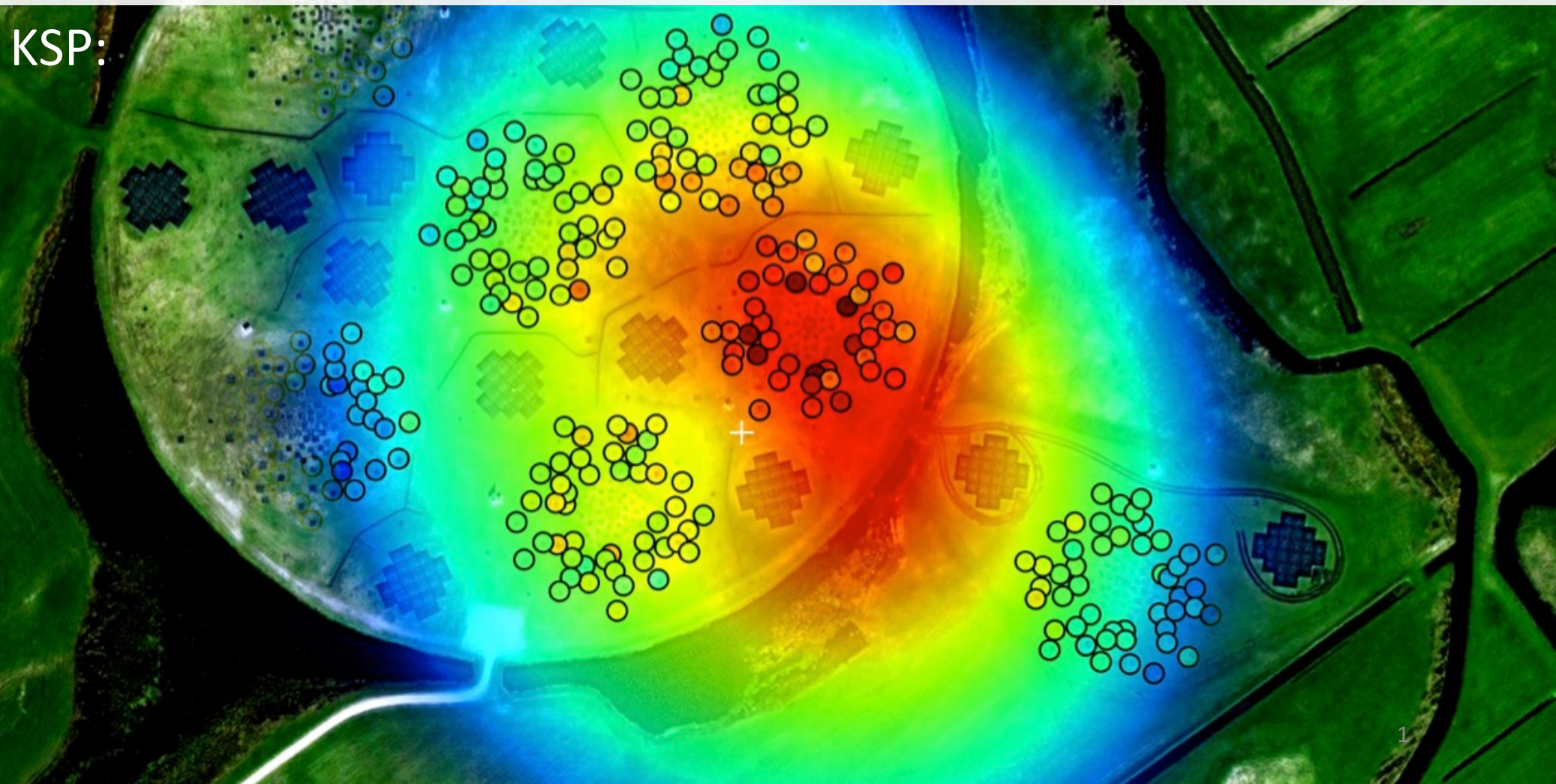
Stijn Buitink for the LOFAR Cosmic Ray KSP



International Cosmic Ray Conference, Madison, July 25 2019

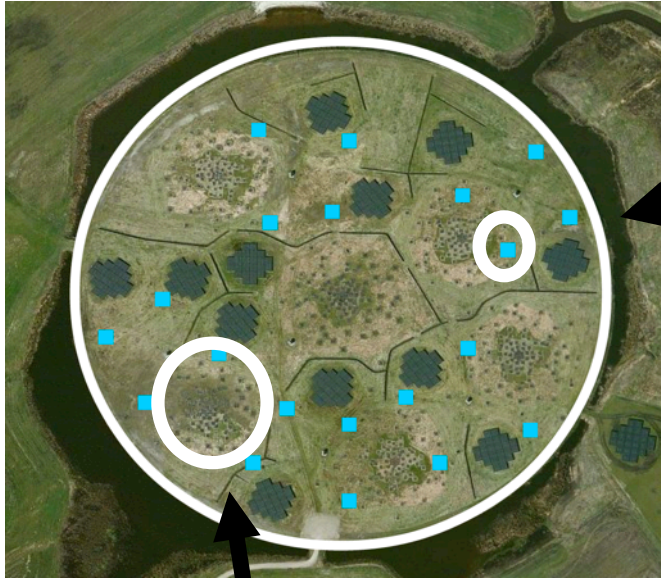
The LOFAR CR KSP:

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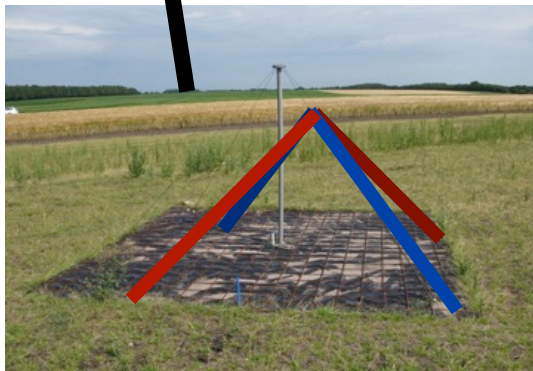


Cosmic Ray Detection at LOFAR

300 m



- LOFAR Radboud Array
- scintillator detectors
- Provides trigger for antenna readout

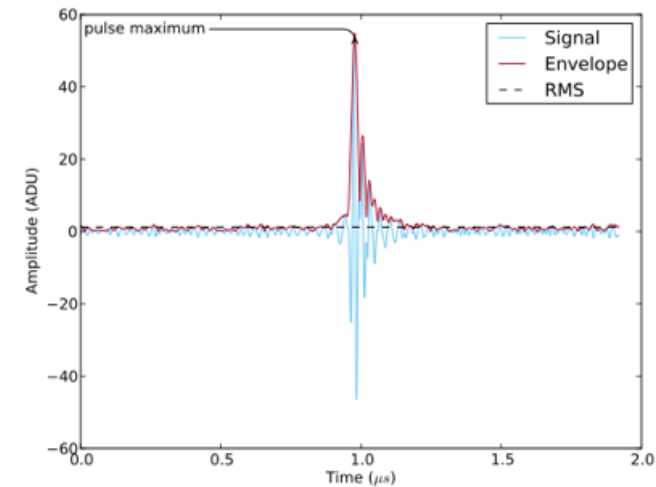


6 LBA stations (6 x 48 antennas)
+ stations outside Superterp

trigger

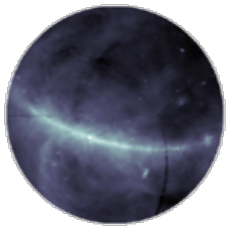
buffer

2 ms read-out



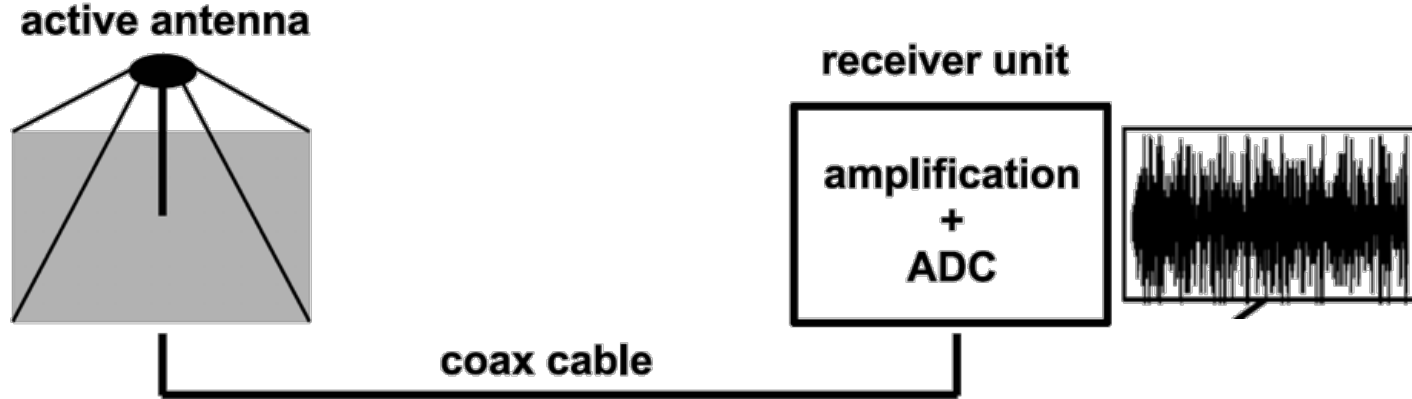
offline analysis

- RFI cleaning
- direction reconstruction
- antenna pattern unfolding

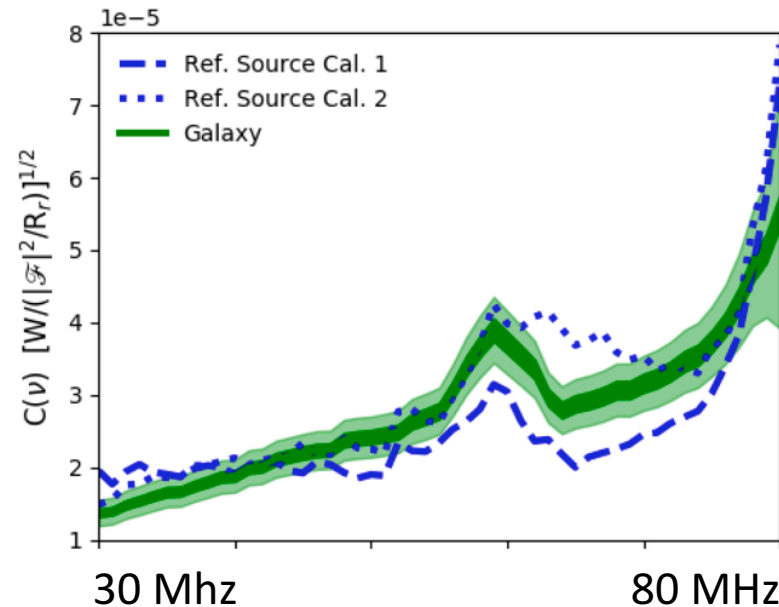


LFmap

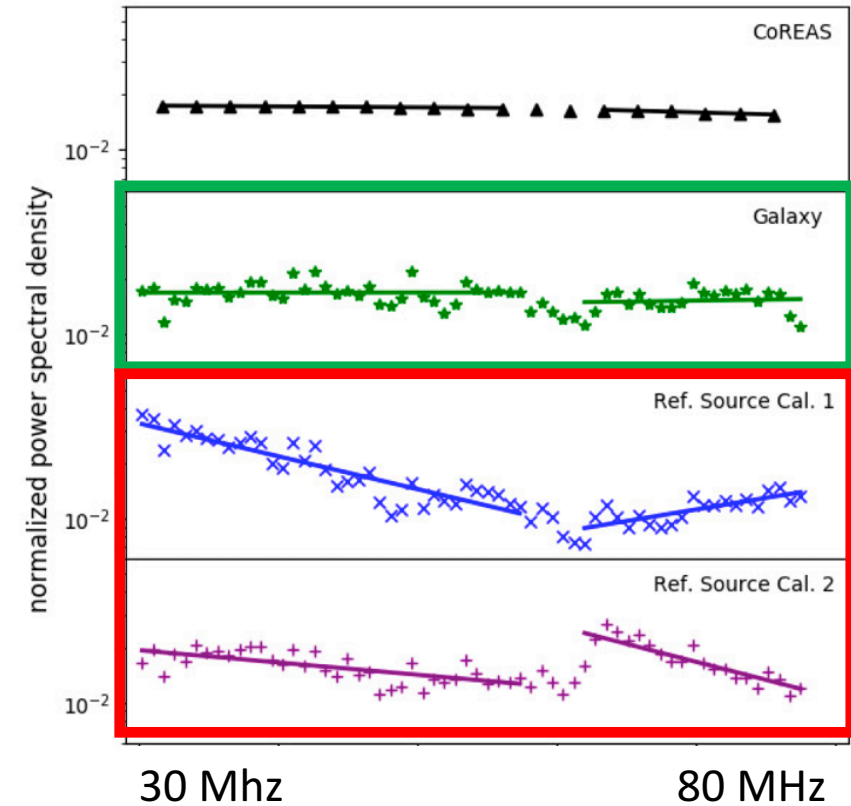
1. Improved frequency calibration



Systematic Uncertainty	Percentage
antenna model	2.5
sky model	11
electronic noise < 77 MHz	6.5
electronic noise > 77 MHz	20
total < 77 MHz	13



Galaxy vs reference source

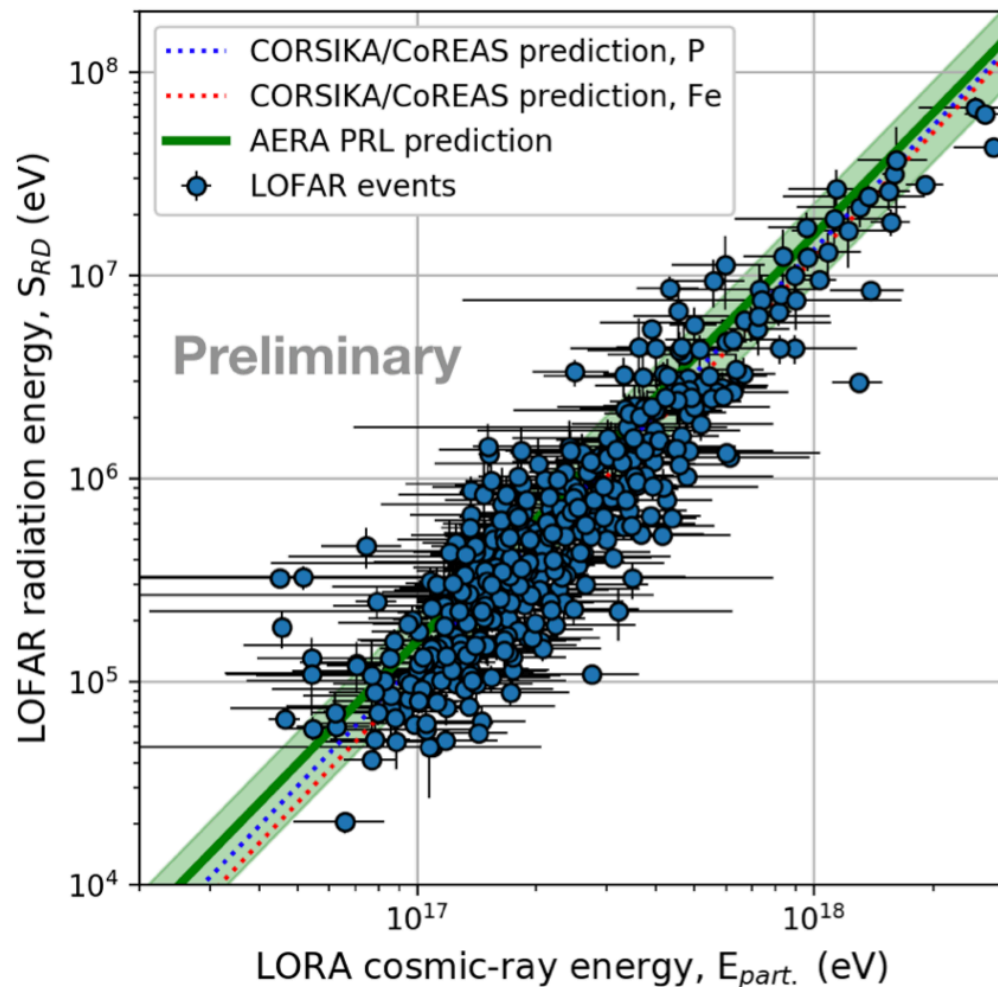


See talk Katie Mulrey on Saturday (CRI session 8) / K. Mulrey et al., Astropart.Phys 111 (2019) 1-11

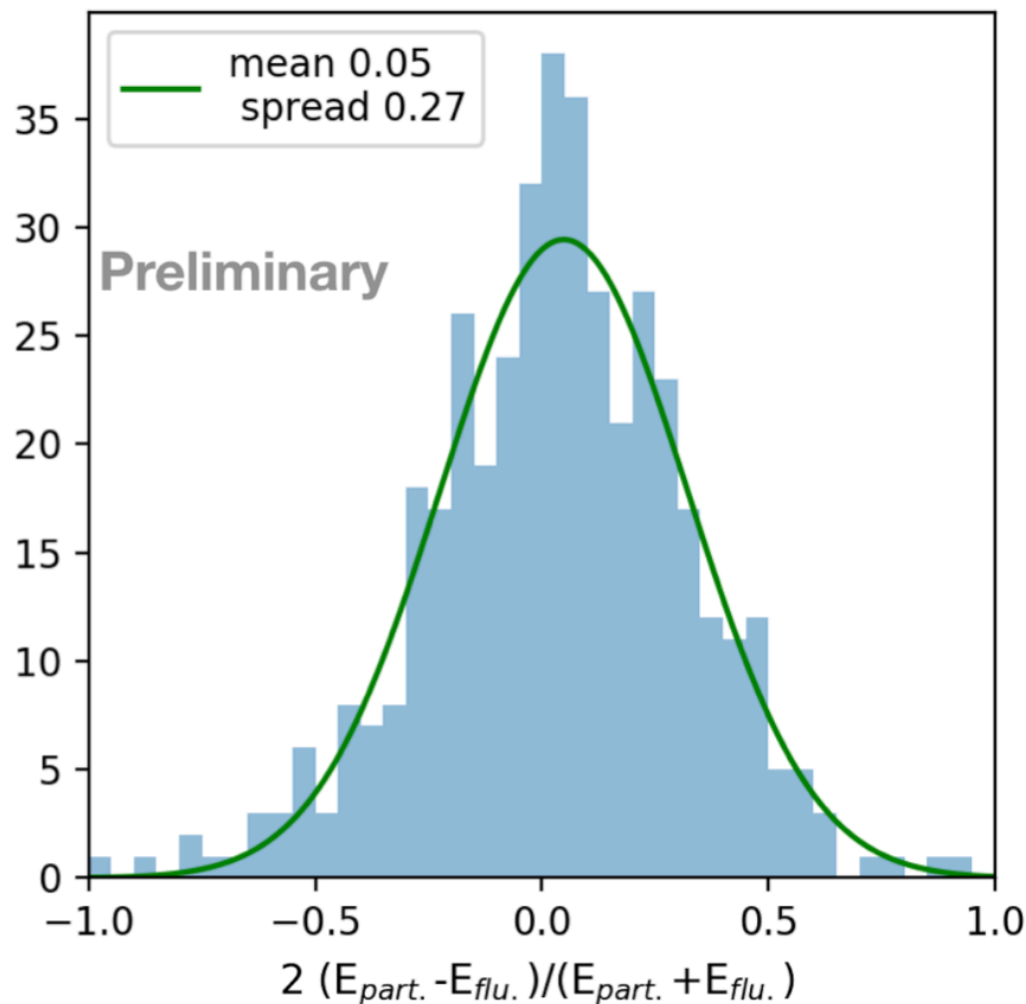
2. Absolute radio energy calibration

Systematic uncertainty on radio energy 14%

Radio antennas



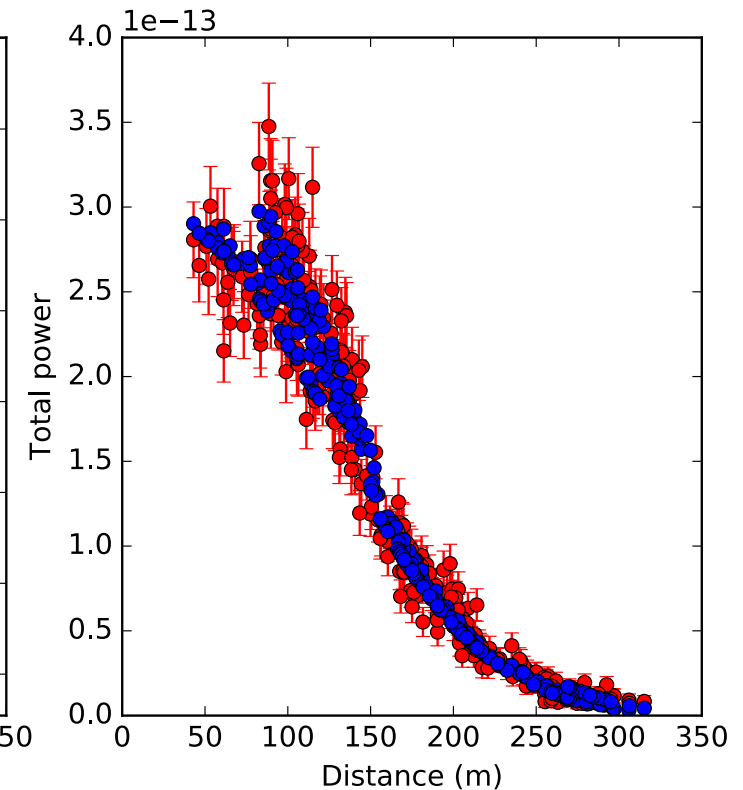
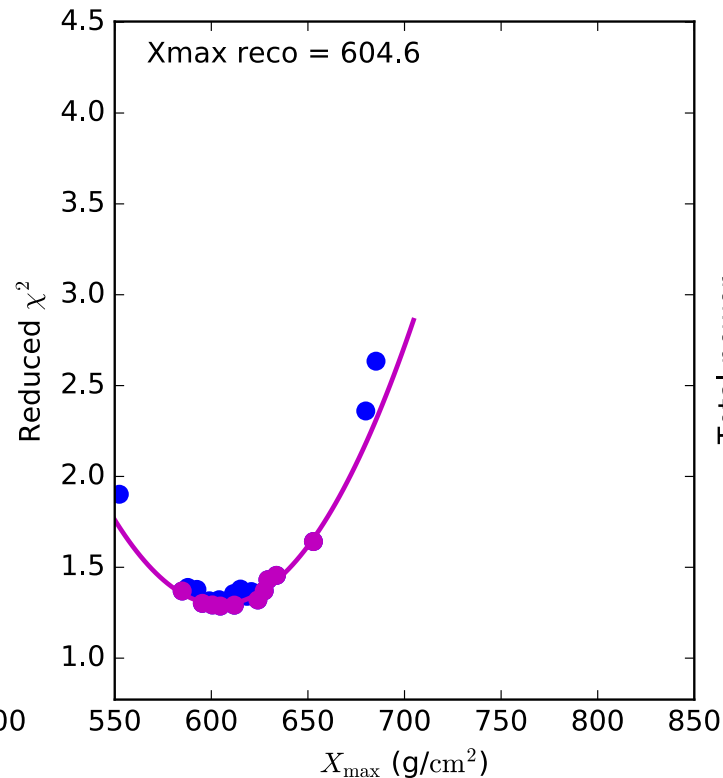
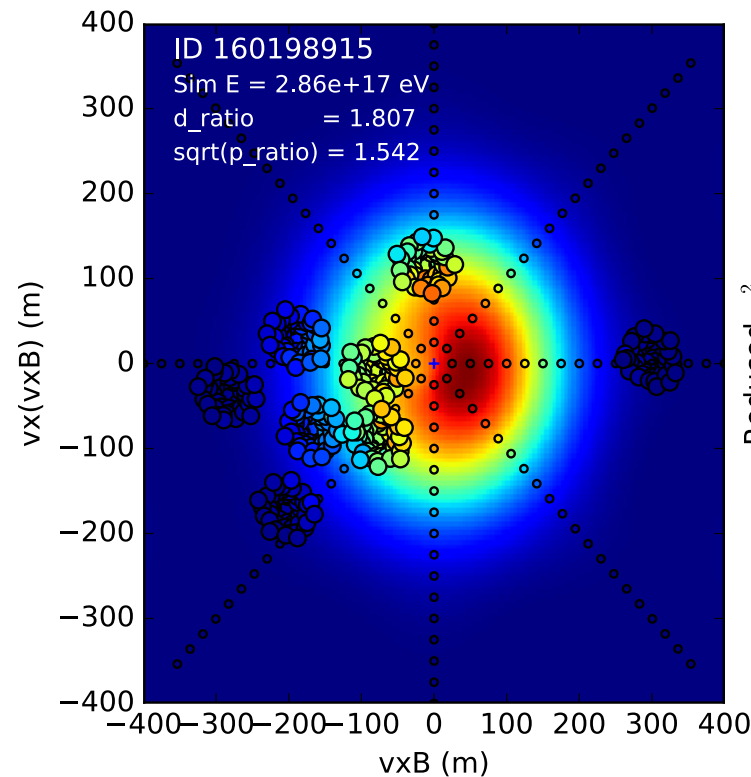
LORA scintillator array



See talk Katie Mulrey on Saturday (CRI session 8)

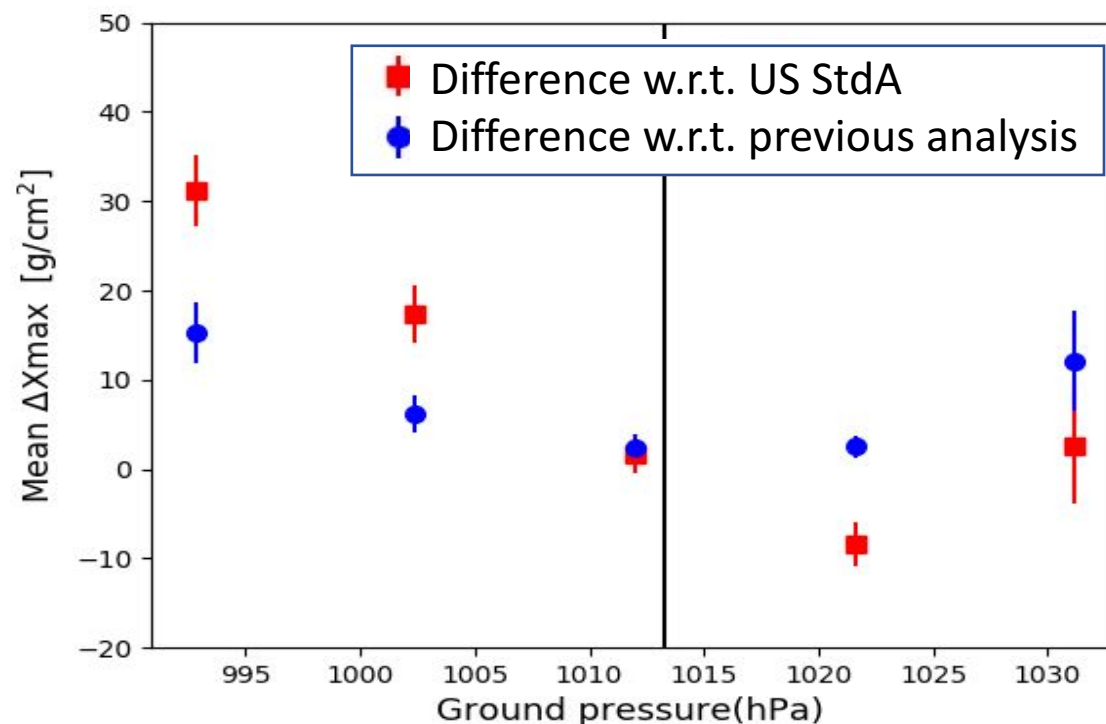
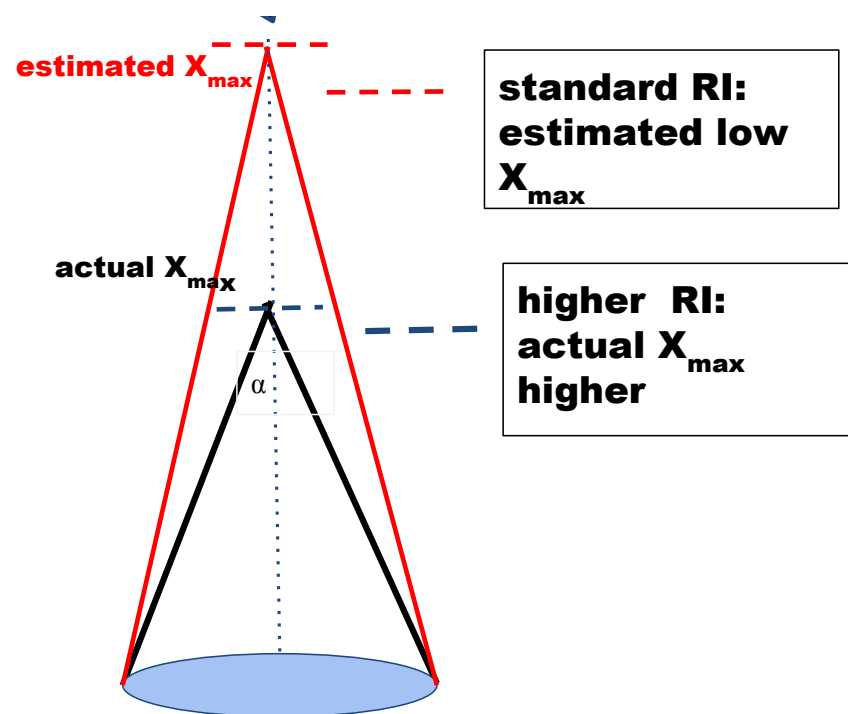
3. Xmax reconstruction now independent from particle detectors

- CoREAS: Simulate ~ 30 showers per event, spanning X_{\max} range
- Fit chi-squared as function of simulated X_{\max} : optimum
- State-of-the-art resolution of $< 20 \text{ g/cm}^2$
- Fit now uses only radio data



4. Matching footprints with event-specific atmospheres

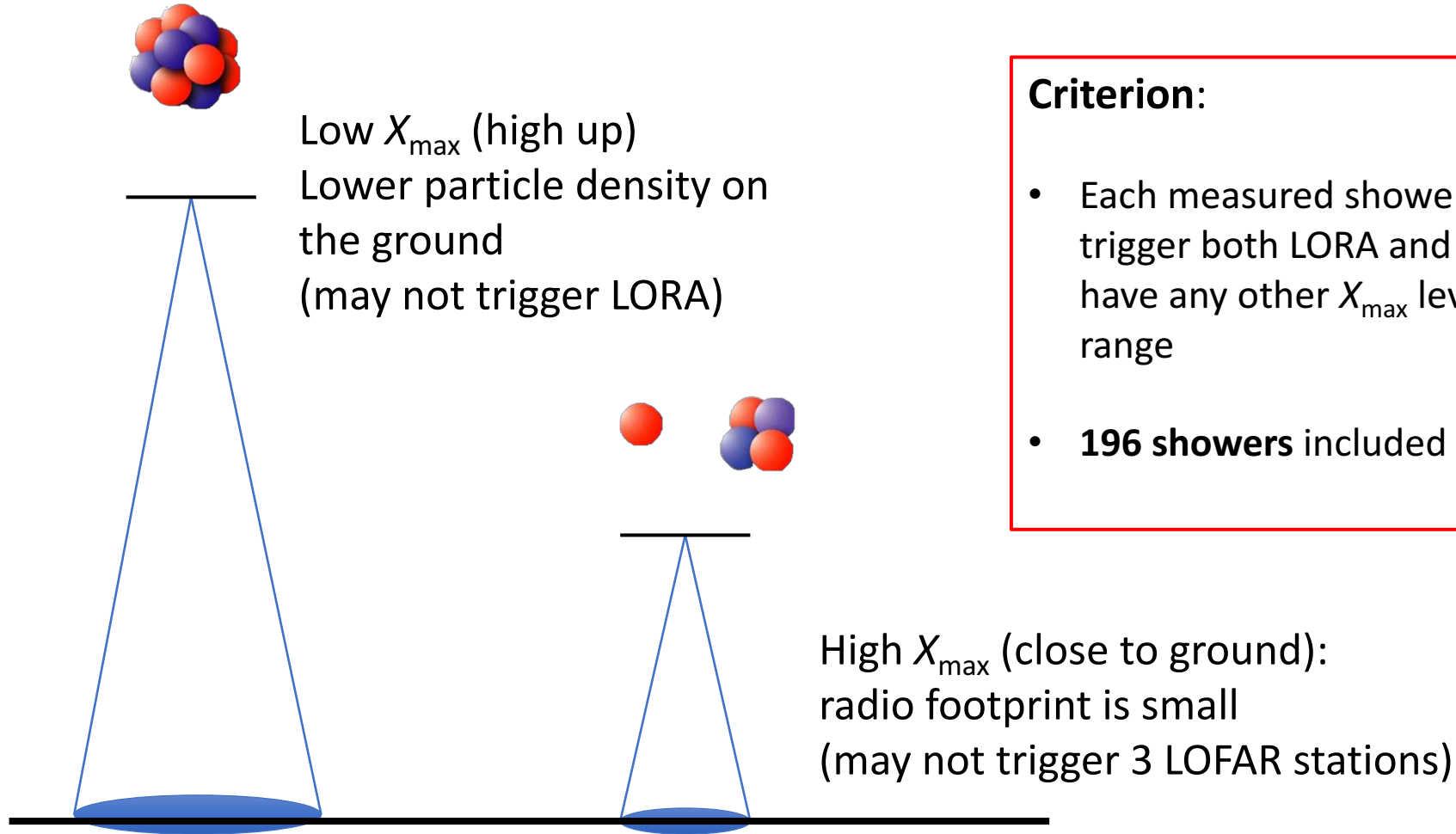
- Use GDAS to make atmospheric profile (density & index of refraction) for each shower
- 'gdastool' shipped with CORSIKA now!



- Previous analysis used linear correction for changing air pressure
- Residual errors of $\sim 15 \text{ g}/\text{cm}^2$ for days of very low air pressure

See poster Pragati Mitra on Tuesday Poster Session 3 (CRI)

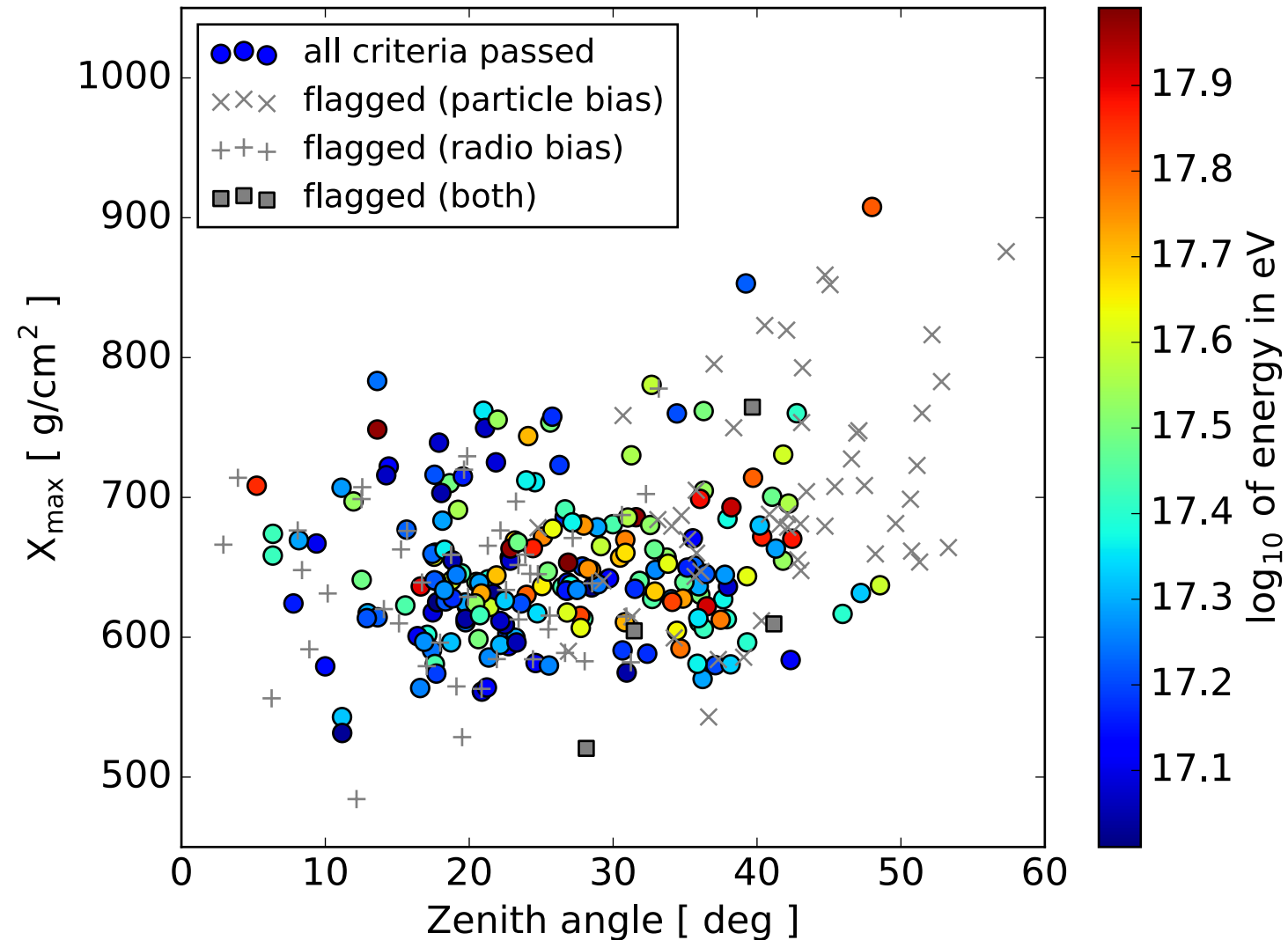
Avoiding a composition bias



Criterion:

- Each measured shower must be able to trigger both LORA and LOFAR, would it have any other X_{max} level within natural range
- **196 showers** included

Test for residual bias



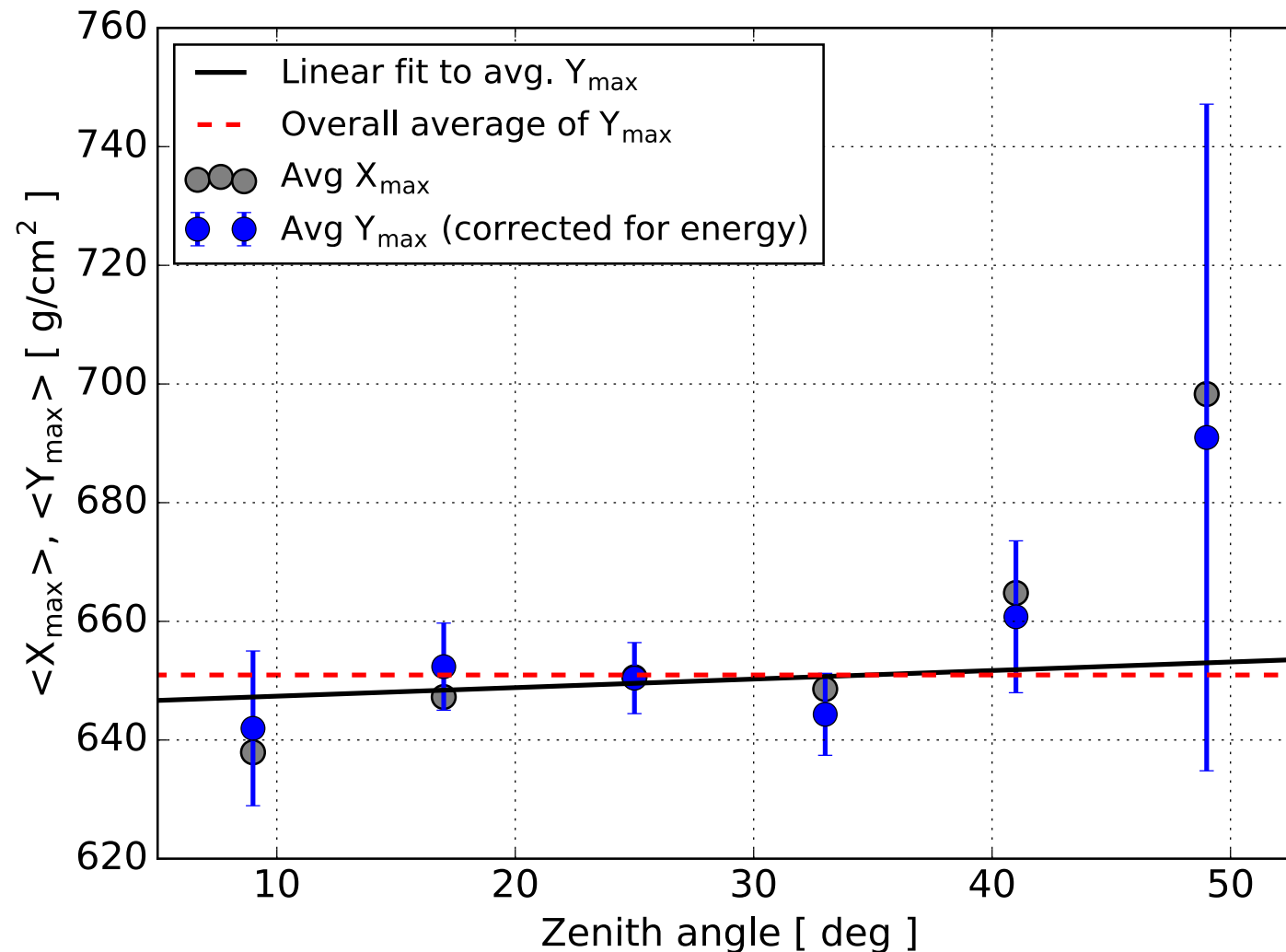
Particle flag removes mostly
inclined and deep events

*Higher altitude counterparts
(heavy nuclei) would not have
triggered LORA*

Radio flag removes mostly
vertical and shallow events

*Lower altitude counterparts (light
nuclei) would have a footprint
that is too small*

Test for residual bias

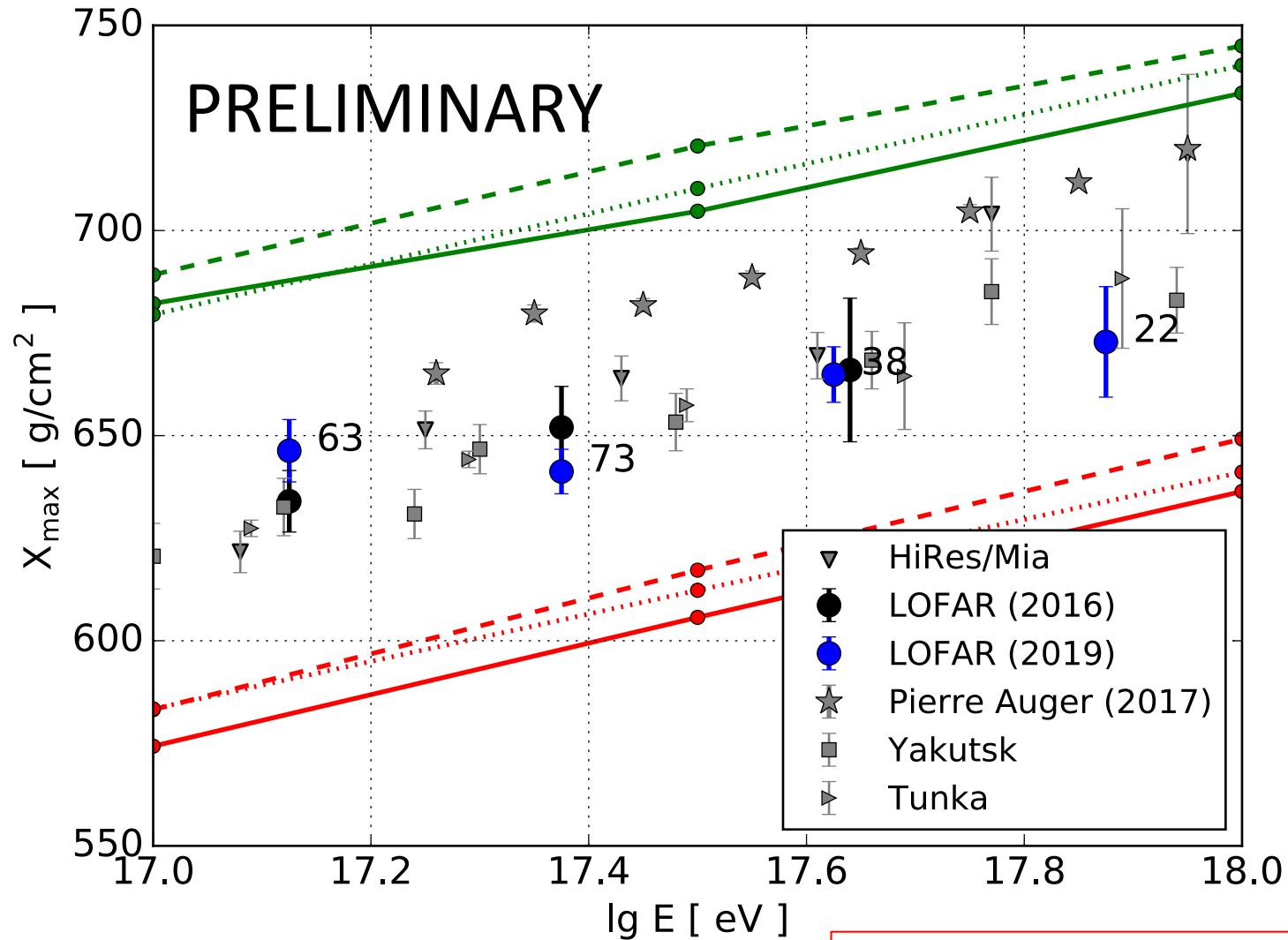


Slope of linear fit
 0.14 ± 0.4

- Consistent with zero

Constant fit: uncertainty
 3.2 g/cm^2

Results: average X_{\max} for 196 events



from A. Corstanje (2019), PhD thesis

Future: increasing statistics

- Added 20 scintillators at neighboring stations
- Expect 45% increase in events
- Lower energy threshold ($\sim 10^{16.5}$ eV)



First data fall 2019



- Hybrid trigger: trigger on particle + radio for bias-free composition down to at least $10^{16.5}$ eV
- LOFAR 2.0:
100% duty cycle
low band (30-80 MHz)
+ high band (110-190 MHz)

See poster Katie Mulrey on Tuesday Poster Session 3 (CRI)

Conclusions & outlook

Reducing systematic uncertainties [energy 14%, X_{\max} 7 g/cm²]



- 1. Improved frequency calibration ✓
- 2. Absolute radio energy ✓
- 3. X_{\max} reconstruction independent of particle detectors ✓
- 4. Event-specific GDAS atmospheres ✓
- 5. Investigate possible biases ✓ ...

Increasing statistics + lowering energy threshold



- 6. Expansion of LORA in progress: first data fall 2019
- 7. Hybrid trigger in progress
- 8. LOFAR 2.0 implementation of 100% duty cycle LBA+HBA: 2019-2023

Systematic uncertainties

	SYST	STAT
X_{\max} :		
• Choice of hadronic interaction model: (for X_{\max} reconstruction)	5 g/cm ²	
• Remaining uncertainty, atmosphere	~ 1 g/cm ²	2 g/cm ²
• Atmospheric uncertainty (5-layer Corsika):	2 g/cm ²	4 g/cm ²
• Possible bias, from $\langle X_{\max} \rangle$ vs zenith:	4 g/cm ²	
Total , added in quadrature:	7 g/cm²	
Energy:	14 %	10 %