# Detecting Cosmic Rays with LOFAR

## LOFAR Community Science Workshop 2019

Katie Mulrey for the CR KSP

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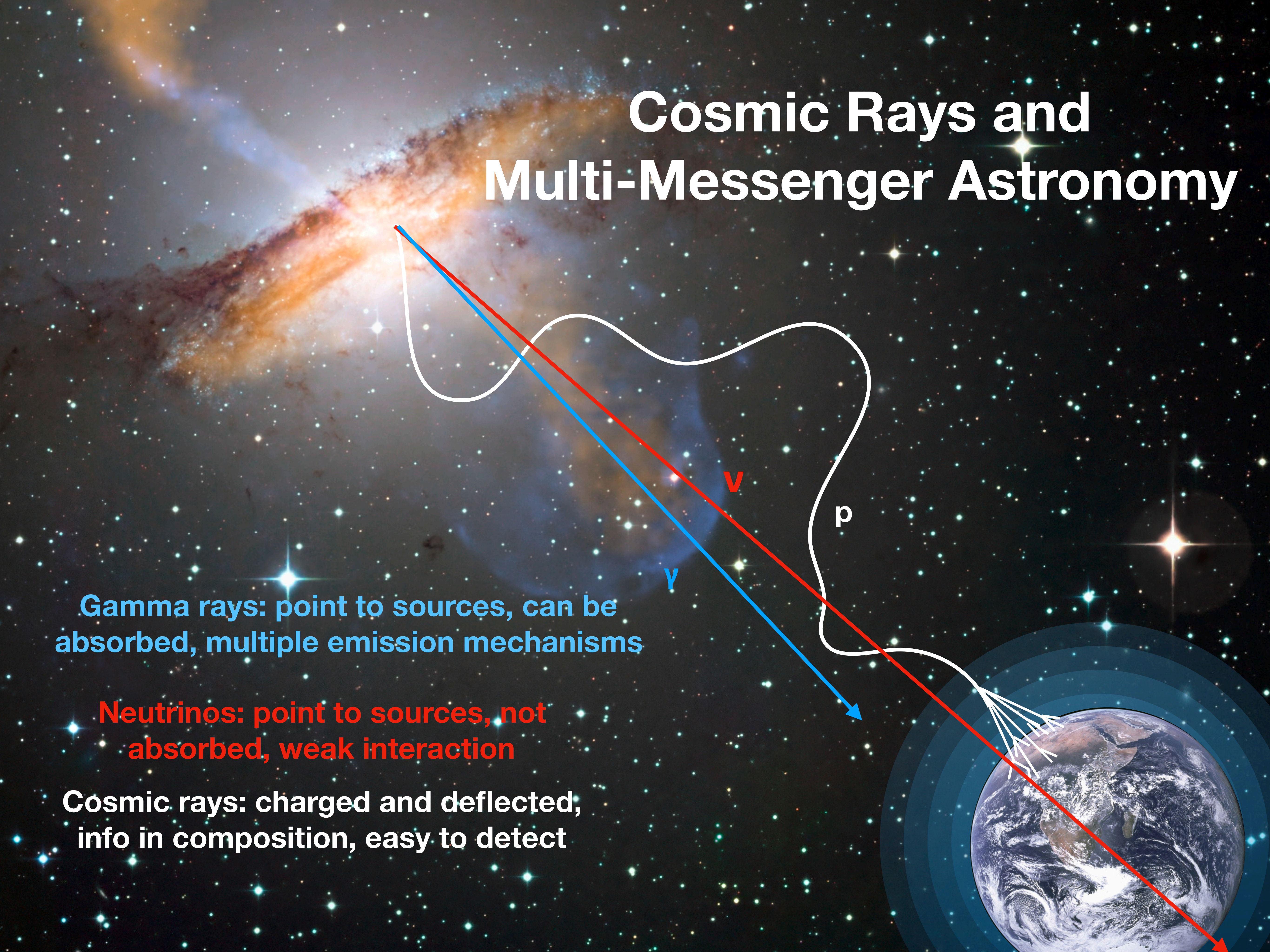
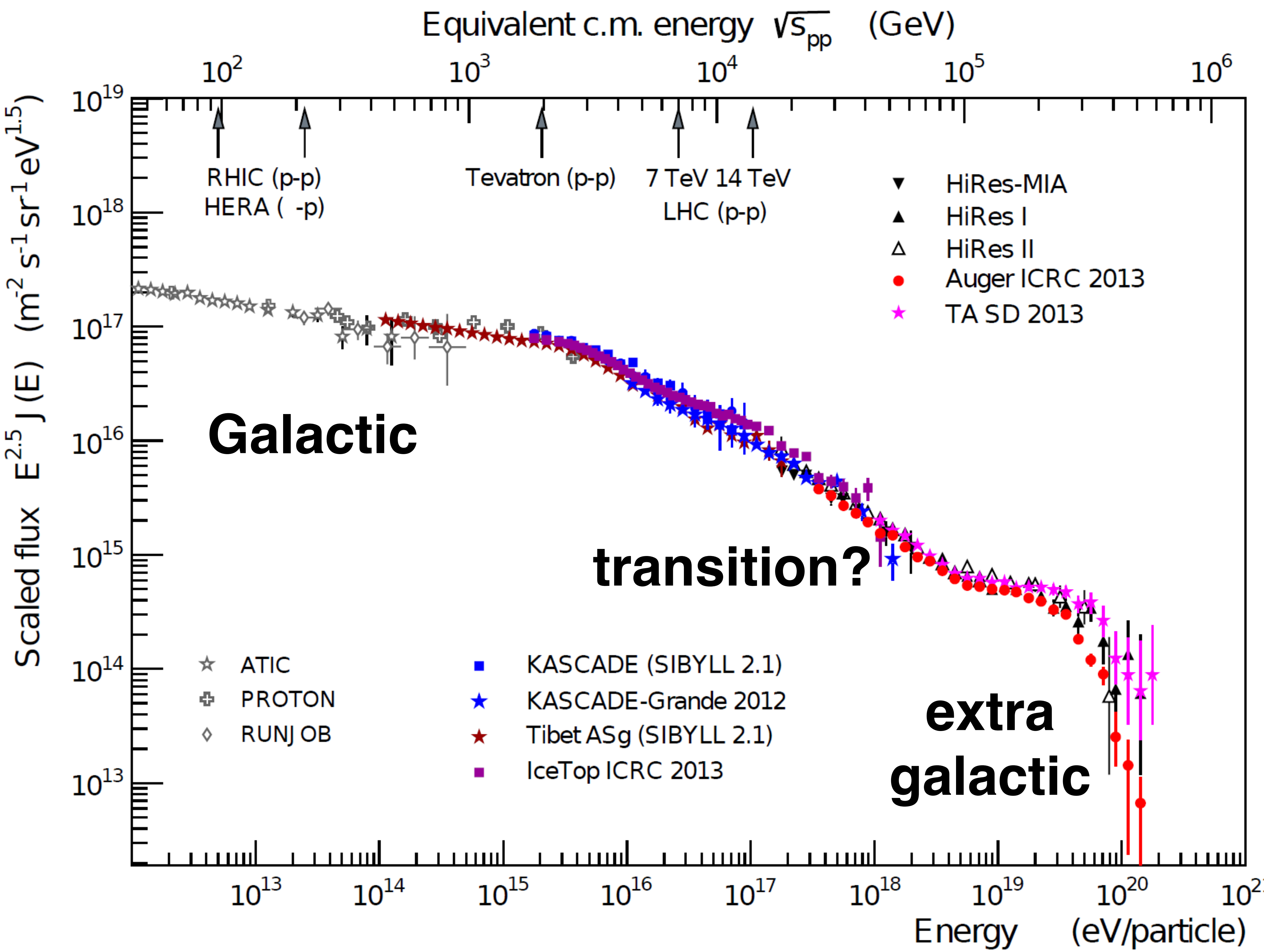
*kmulrey@vub.be


Cosmic Rays and
Multi-Messenger Astronomy
ν
p
γ
Gamma rays: point to sources, can be absorbed, multiple emission mechanisms
Neutrinos: point to sources, not absorbed, weak interaction
Cosmic rays: charged and deflected, info in composition, easy to detect

# Cosmic ray all-particle spectrum




G. Matthiae et al. New J. Phys 12 (2010)

# Cosmic ray energy & composition

**Galactic: SNR**

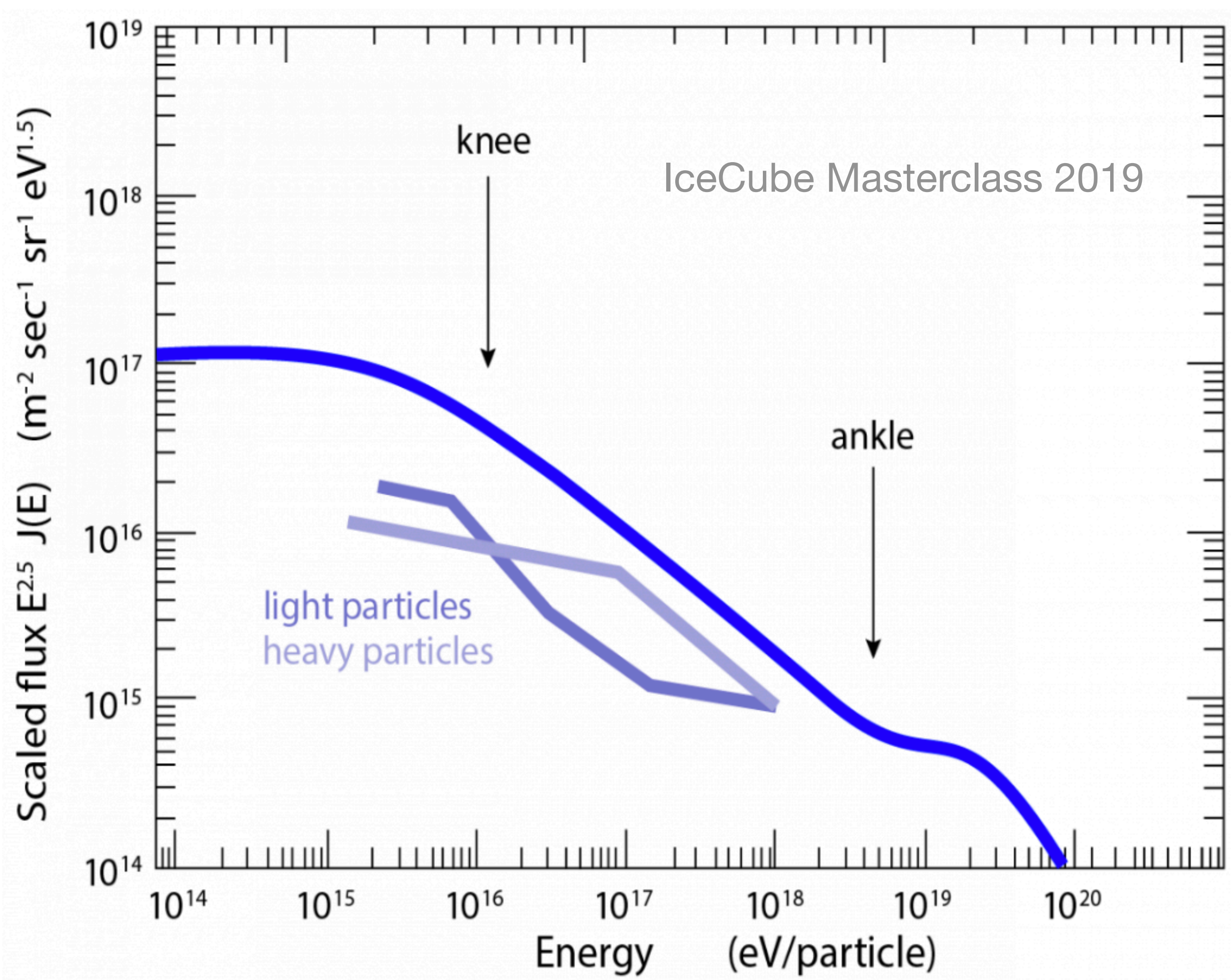
**Extragalactic: AGN**

**Hillas criterion**:

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

Max Energy

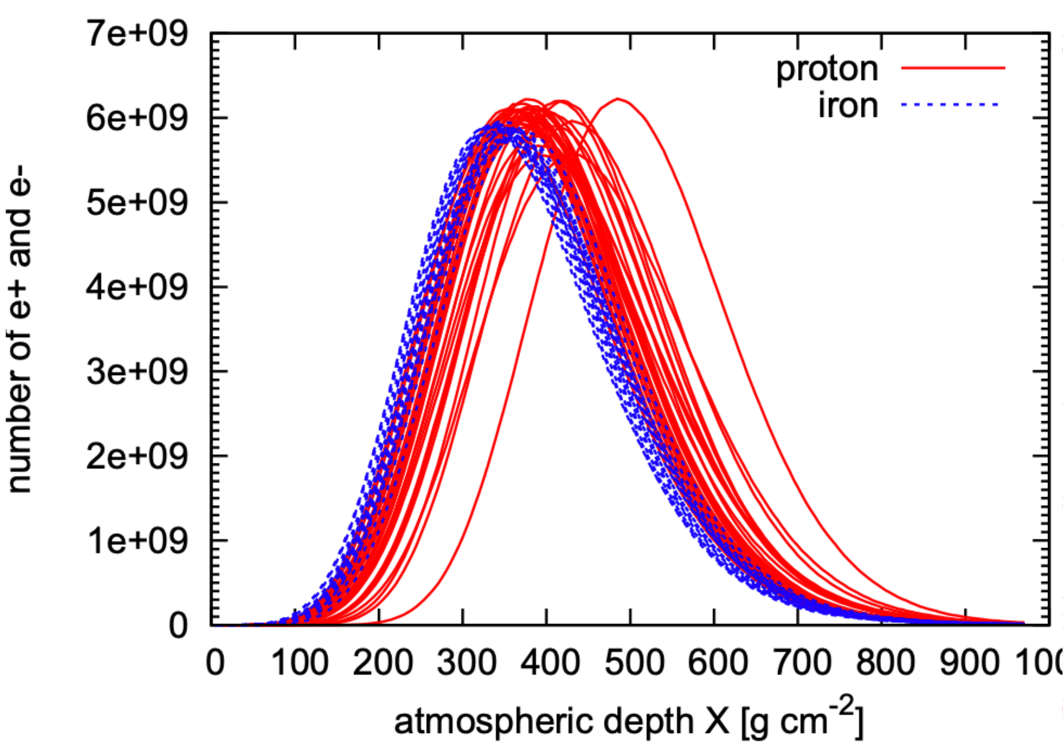
$$E_{Fe,\ max} = 26 \times E_{p,max}$$



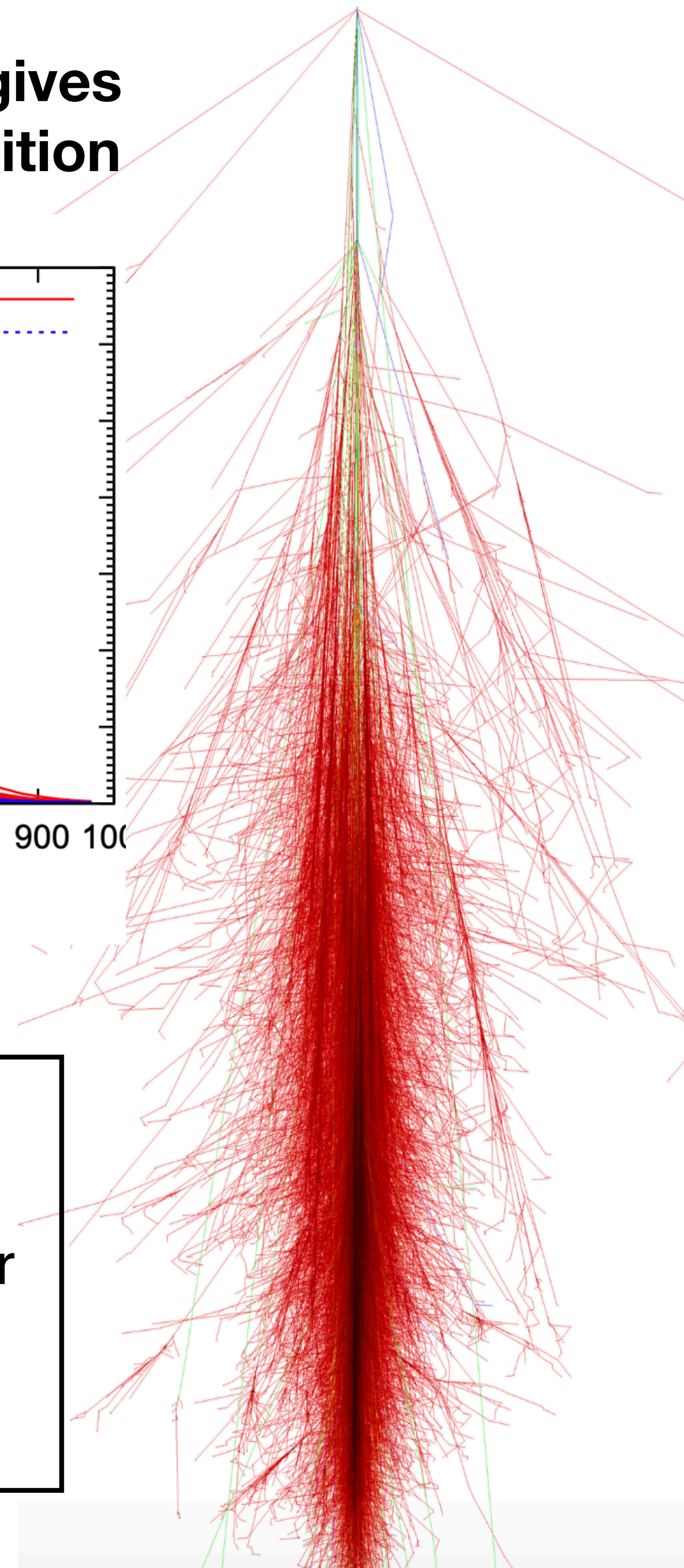

- Below $10^{19}$ eV, can't point directly to sources
- Use composition to understand origin
- **Transition to heavier composition indicates the maximum source energy is reached**

# Composition: Measuring $X_{max}$

**$X_{max}$ is an observable that gives information about composition**



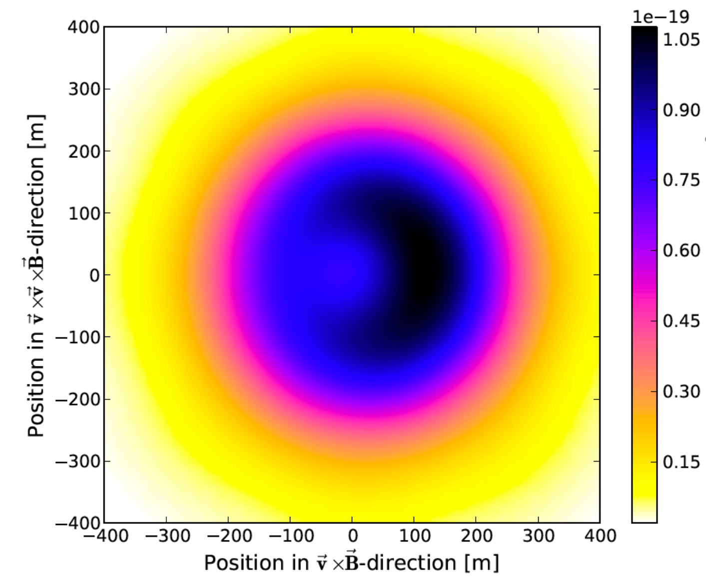

T. Huege. Physics Reports, 620:1-52,2016



## radio detection

nearly 100% duty cycle

LOFAR, AERA, Tunka




## electron/muon ratio

particles on ground,

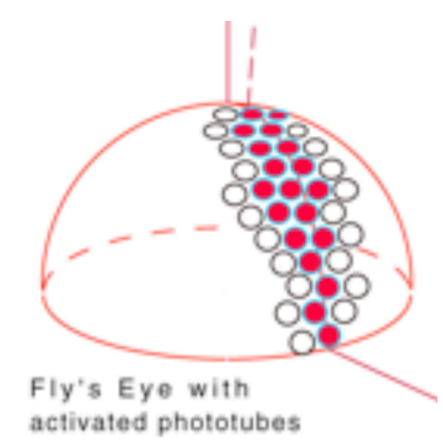
sensitive to shower-to-shower fluctuations

Kascade Grande, IceTop

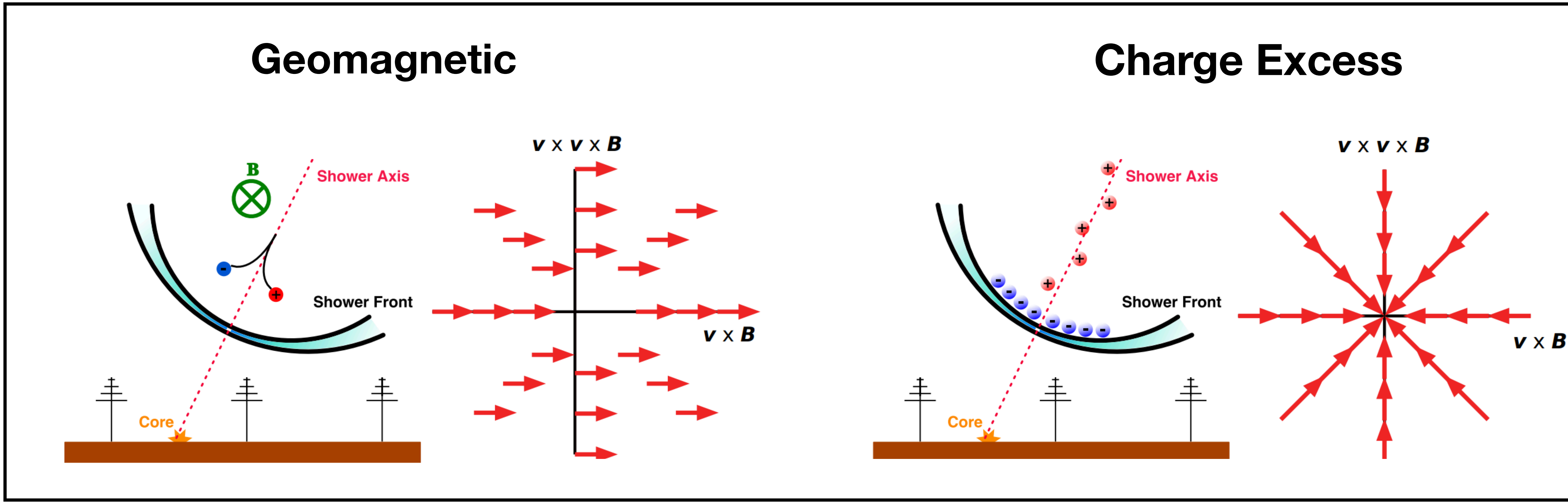
## fluorescence light

dark nights (<15% duty cycle)

Pierre Auger Observatory



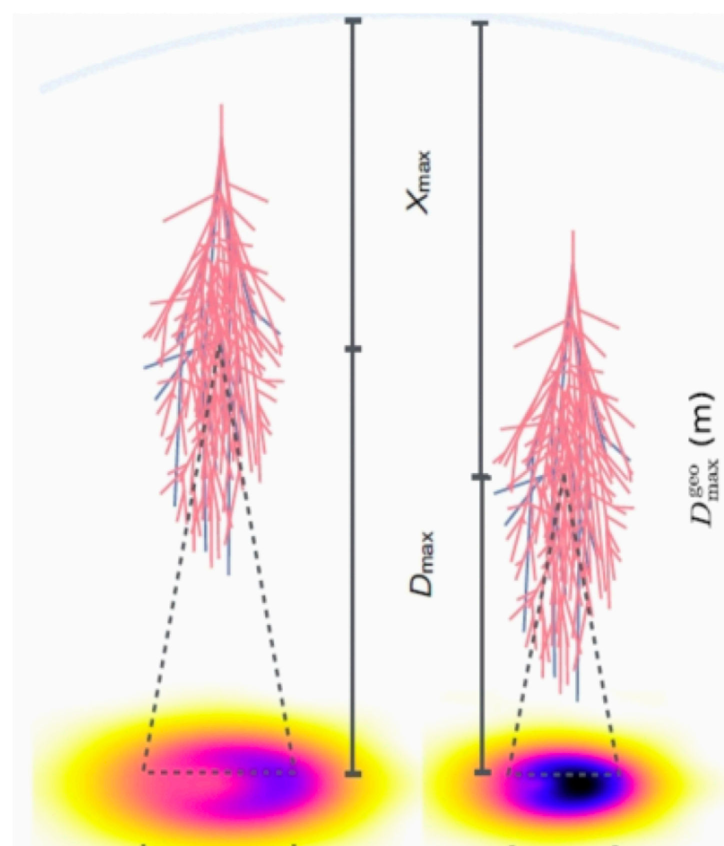
# Cosmic ray radio emission

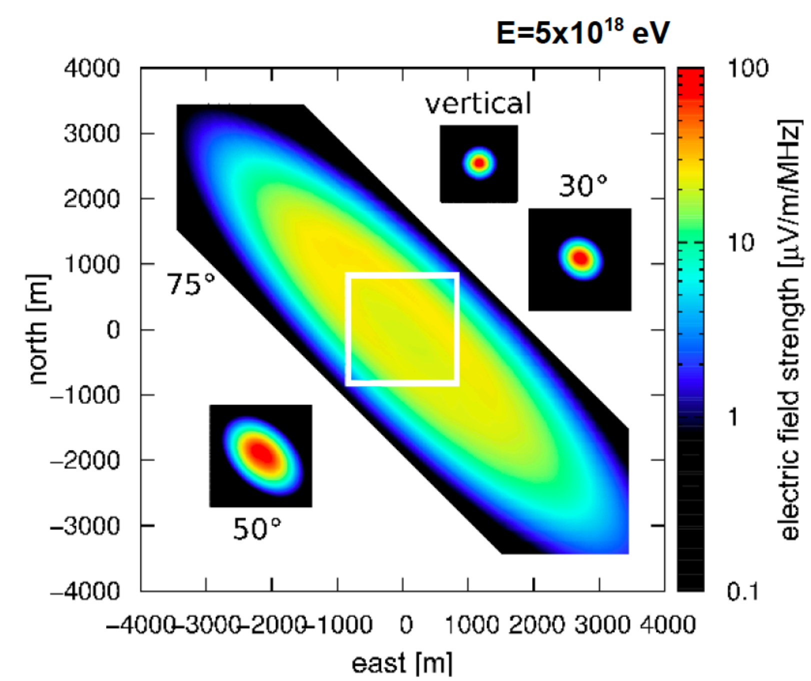



T. Huege. Physics Reports, 620:1-52, 2016

## Radiation Pattern:

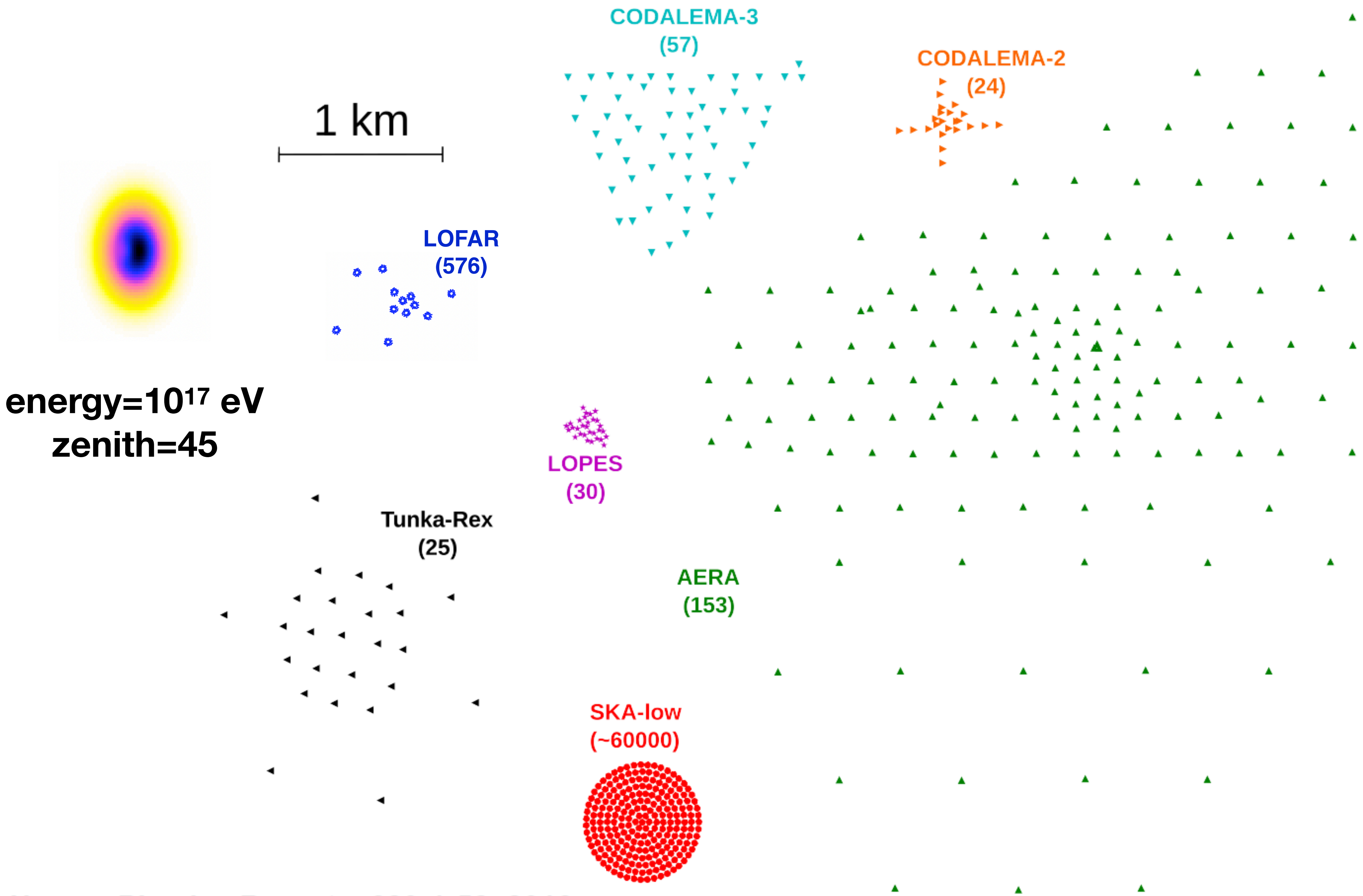
- Direction
- Magnetic Field
- Energy
- $X_{max}$
- Atmosphere




T. Huege. Physics Reports, 620:1-52, 2016

# Radio Detection Experiments




T. Huege. Physics Reports, 620:1-52, 2016

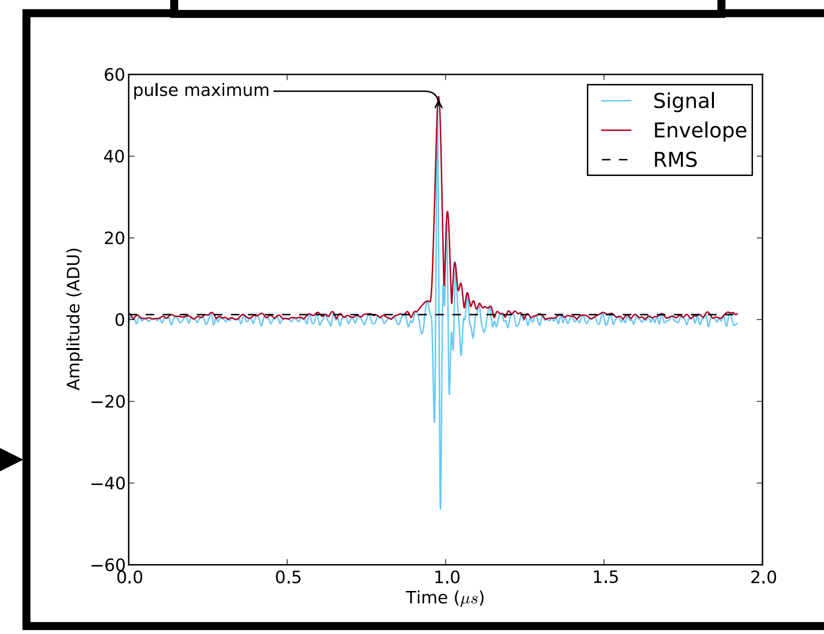
# Cosmic Ray Detection at LOFAR

300 m

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

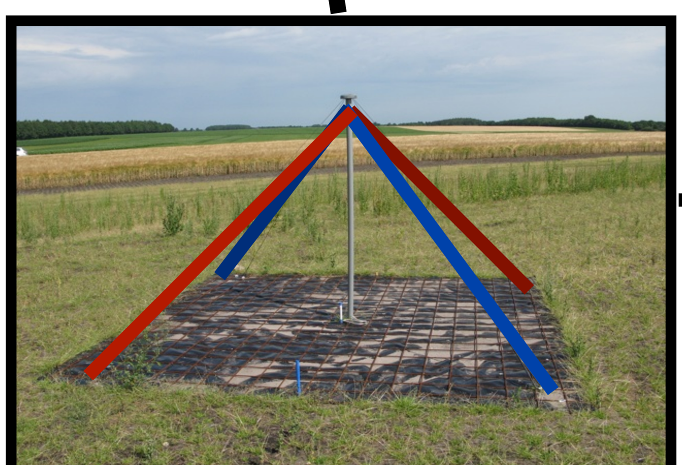
trigger

offline analysis




buffer

2 ms read-out



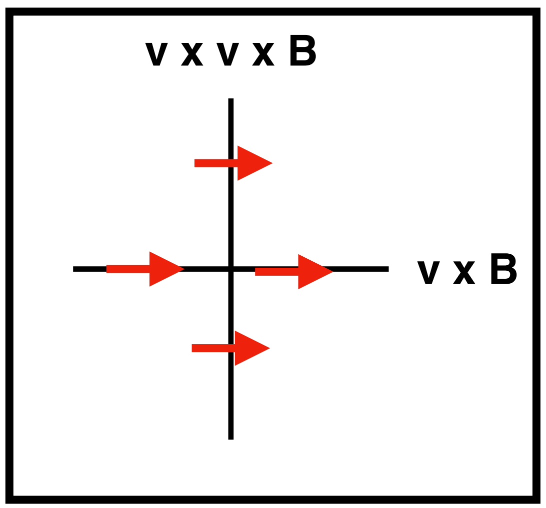
6 LBA stations (6 x 48 antennas)
+ stations outside Superterp

- RFI cleaning
- direction reconstruction
- antenna pattern unfolding
- calibration

P. Schellart et al., A&A 560, 98 (2013)

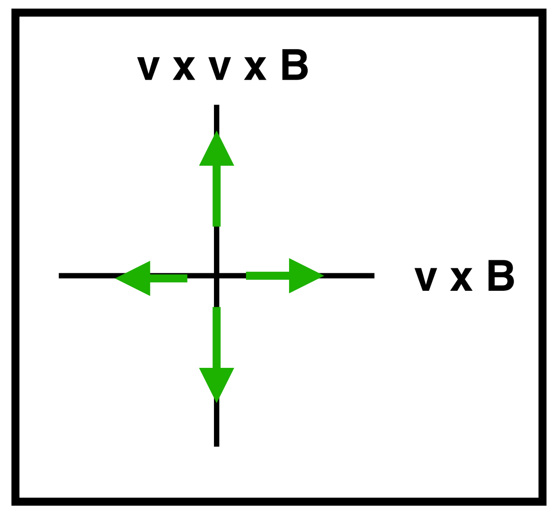
# Stokes Parameters

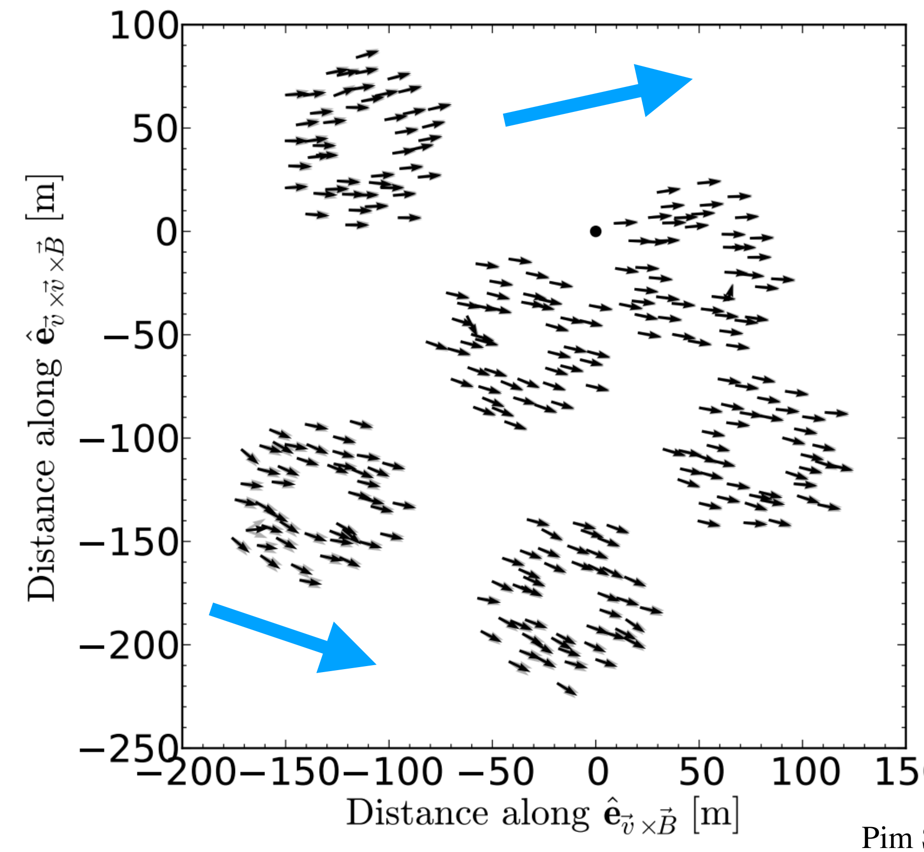
**Geomagnetic**



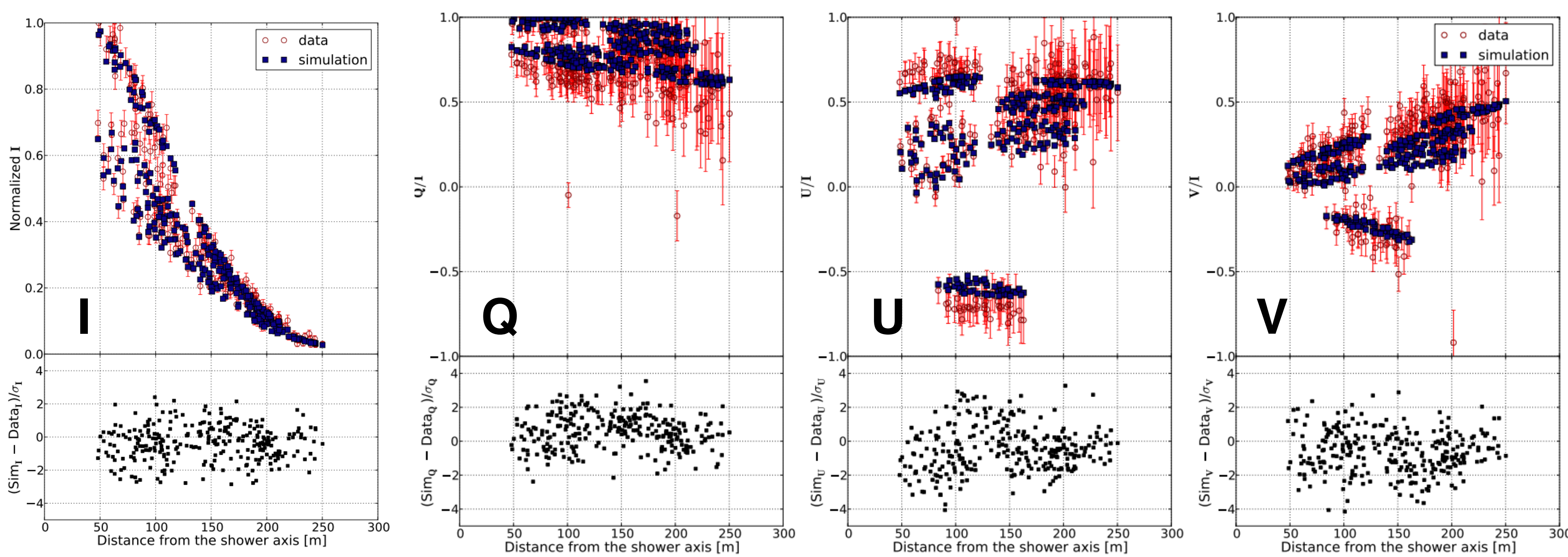

+

**Charge Excess**



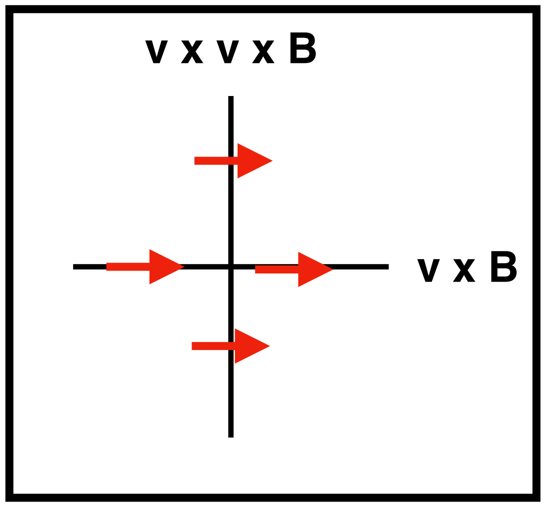

Pim Schellart et al.,
JCAP 10 14 (2014)




O. Scholten et al., PRD 94 1030101 (2016)

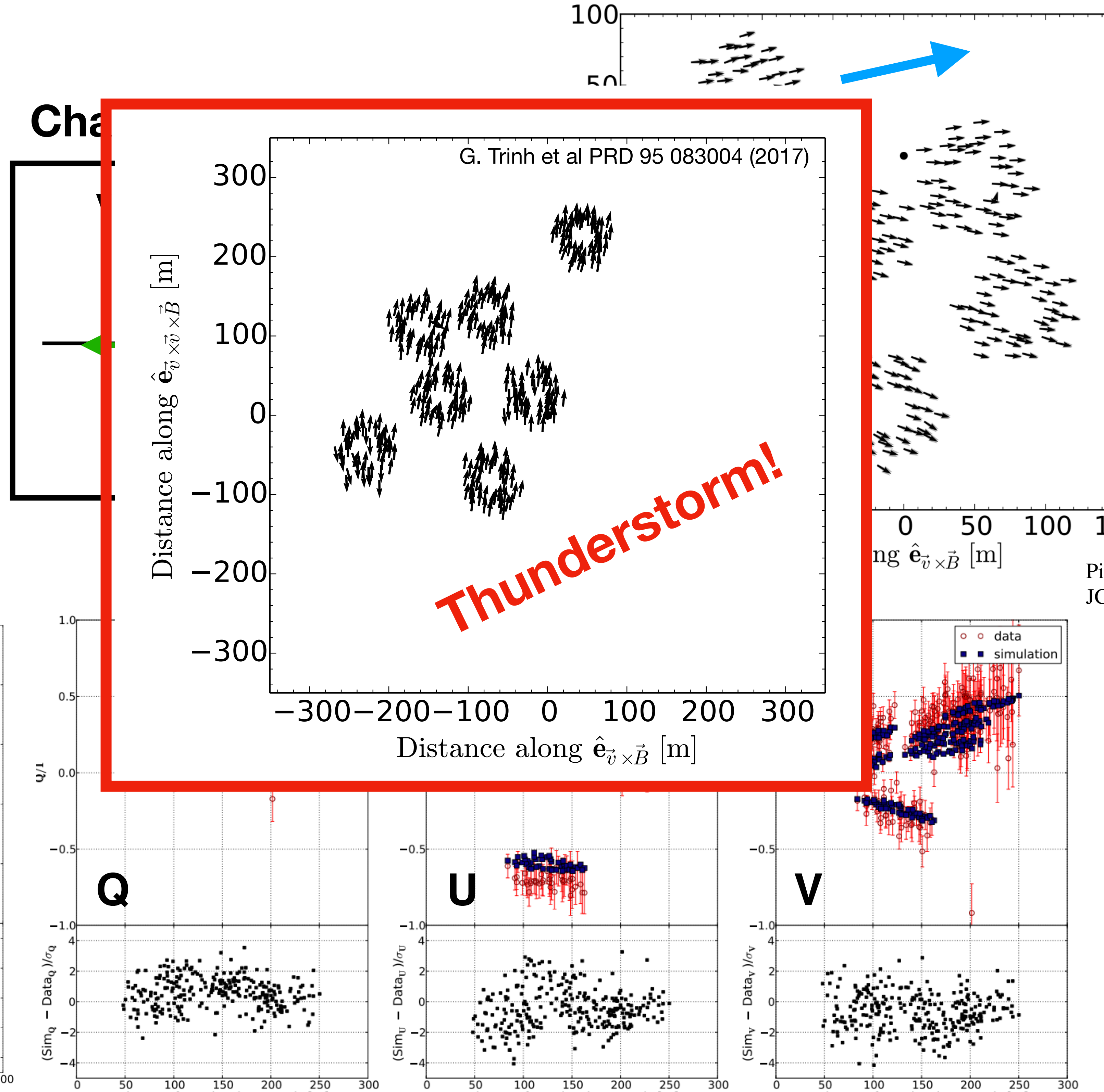
# Stokes Parameters

**Geomagnetic**

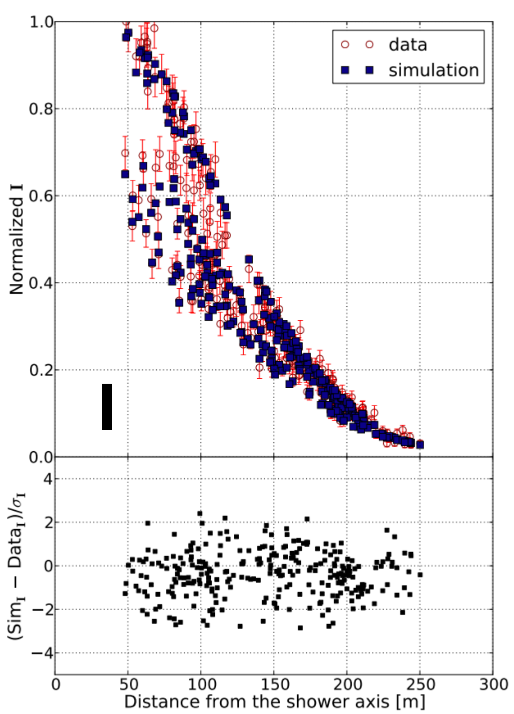



+

**Cha**

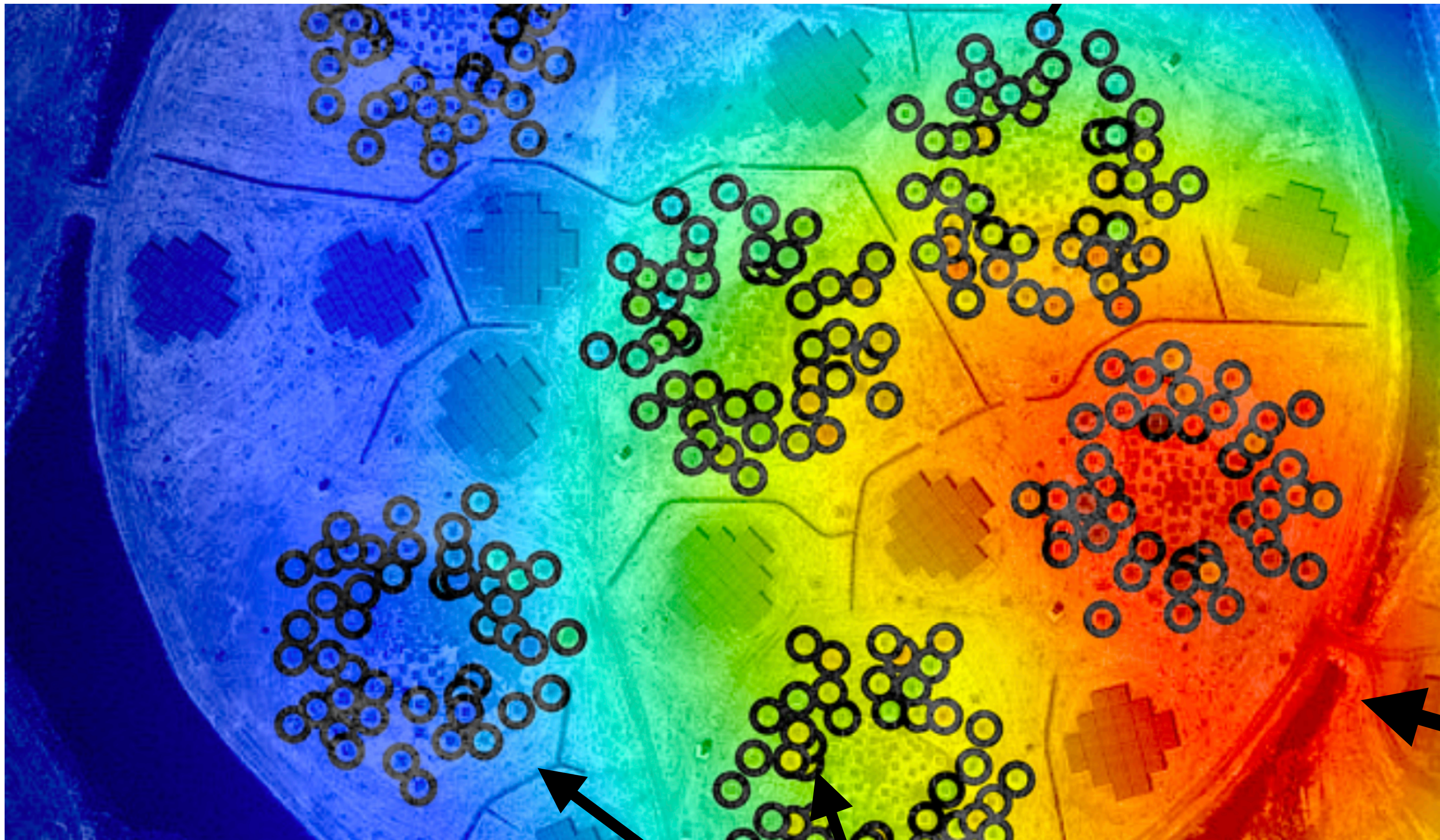



Pim Schellart et al., JCAP 10 14 (2014)

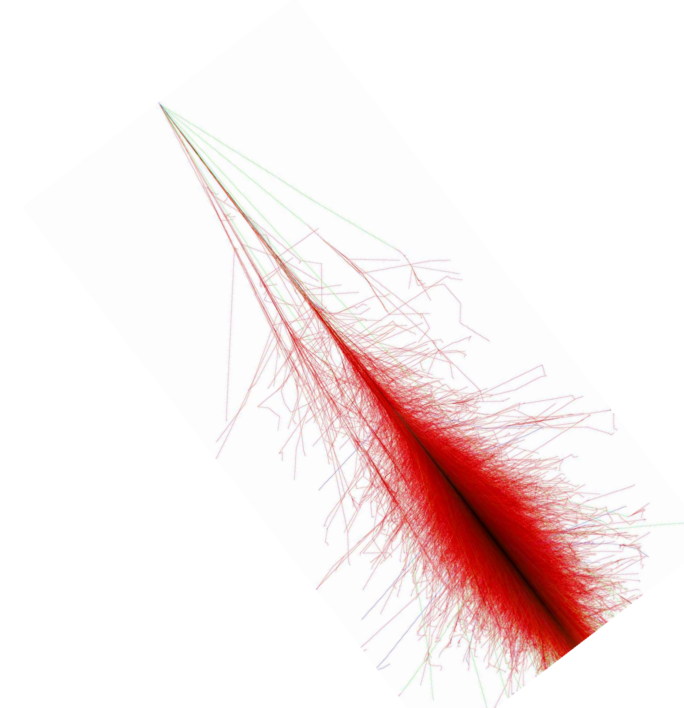


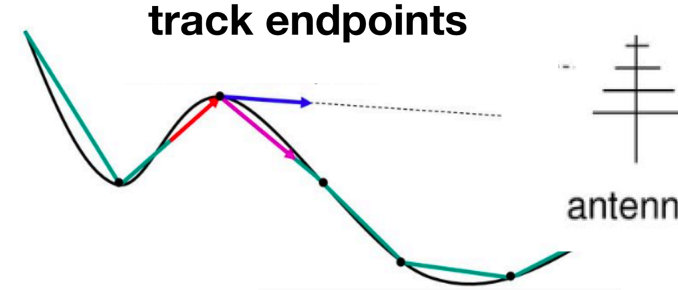

O. Scholten et al., PRD 94 1030101 (2016)

# Event Analysis



SB et al. PRD 90 082003 (2014).





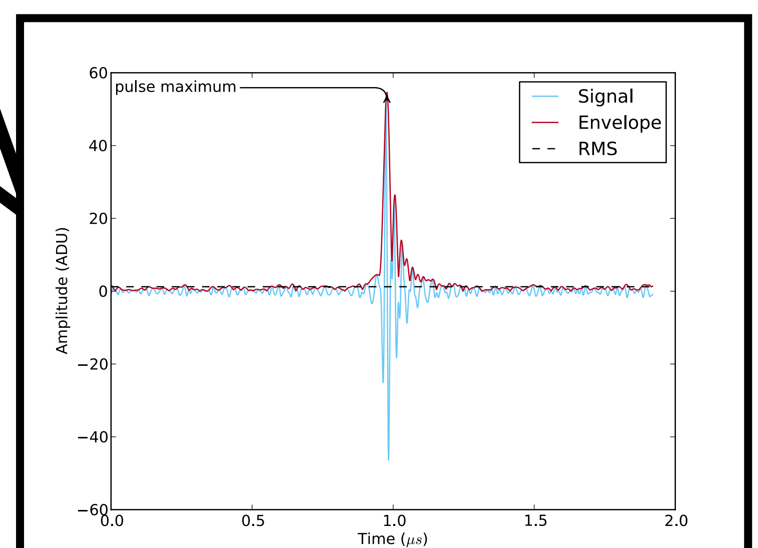

**<u>CoREAS simulation</u>**

- **no assumptions about emission**
- **independent of hadronic models**

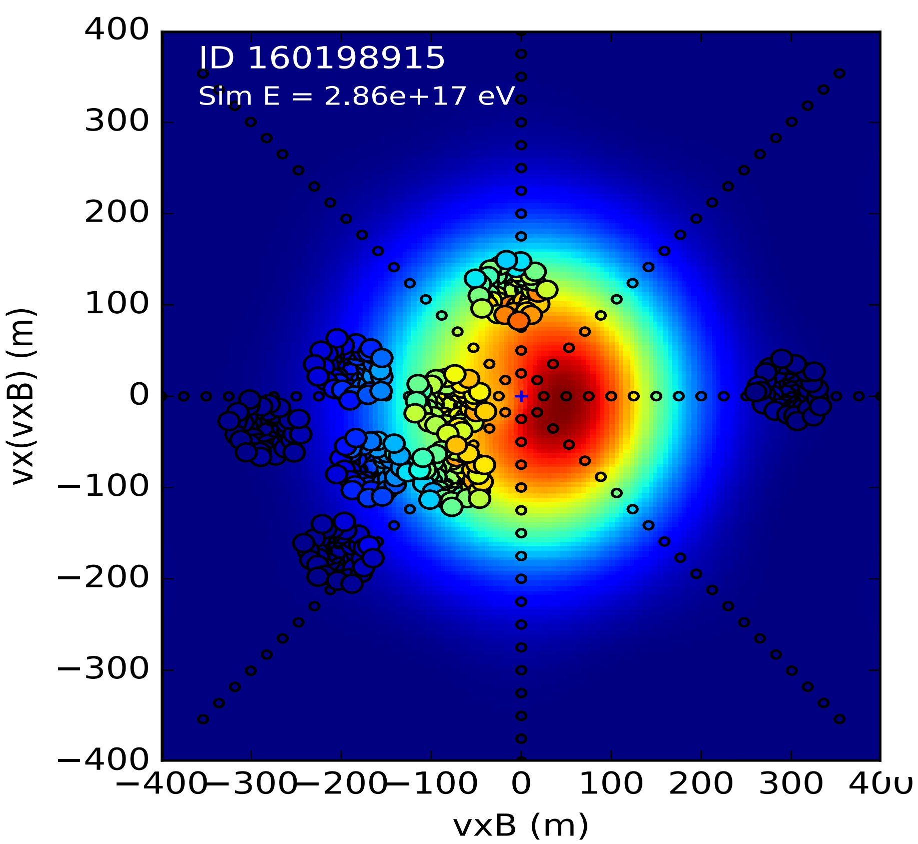
T. Huege et al. AIP Conf.Proc. 1535 (2013) no.1, 128

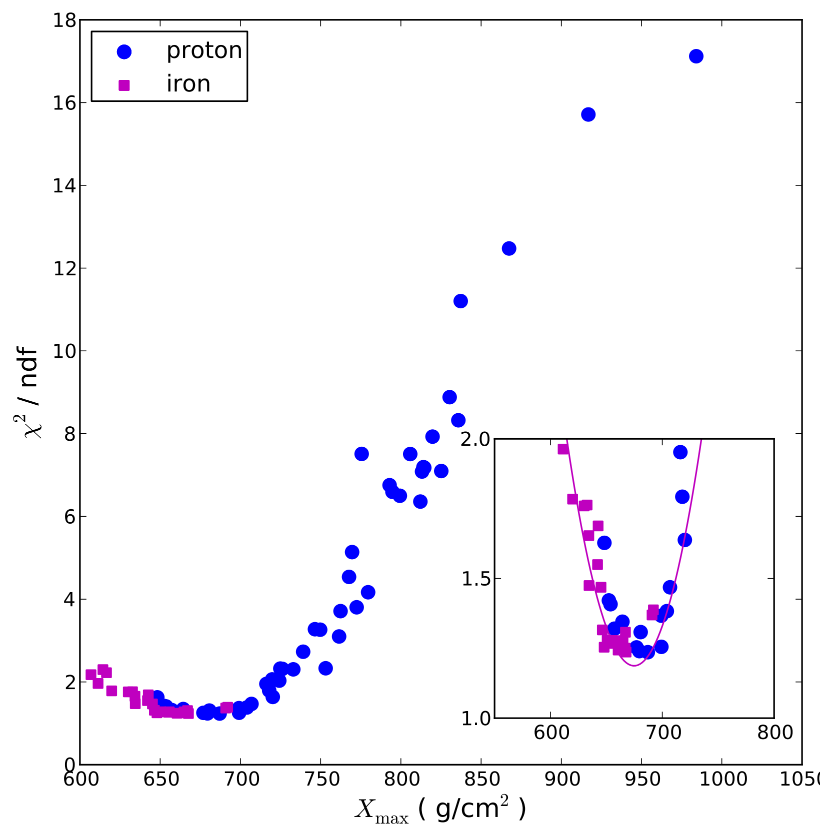
**<u>LOFAR data</u>**

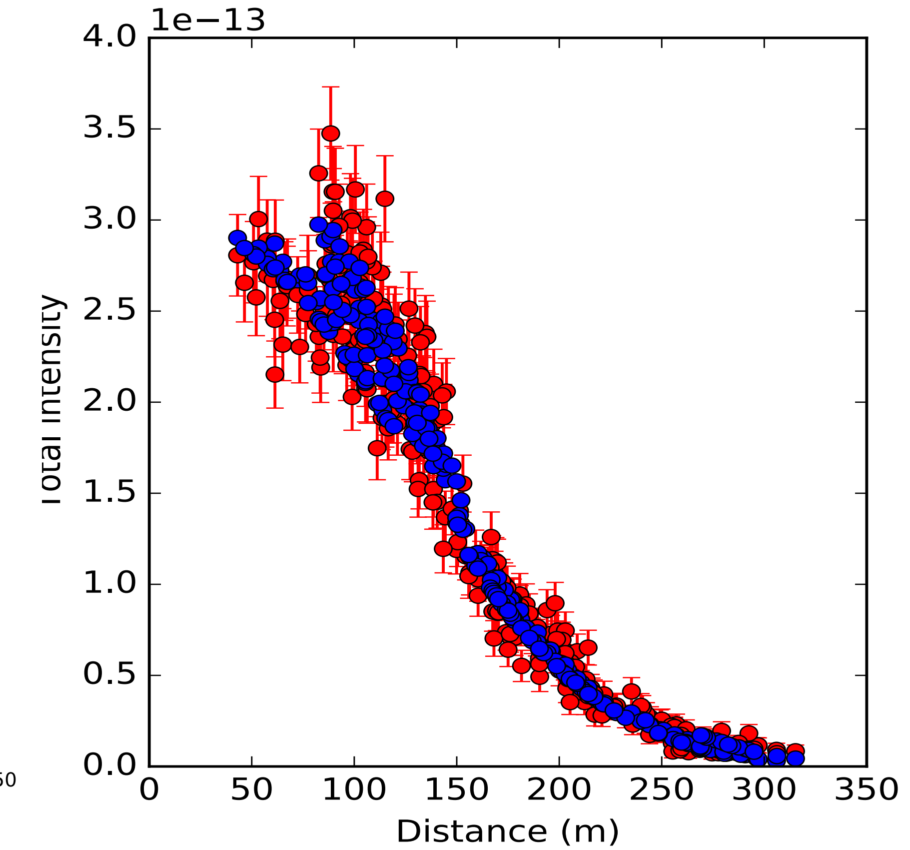
- **200-450 antennas / event**
- **Total power within 55ns of peak emission**



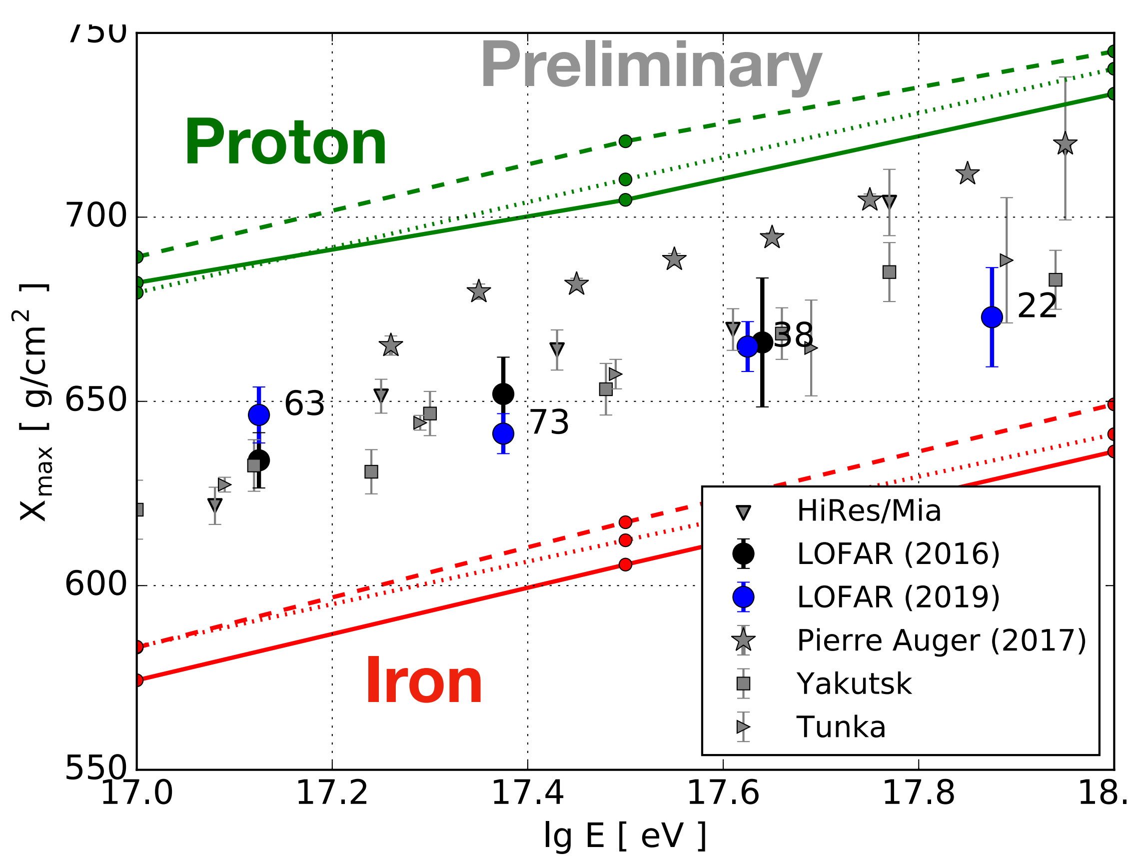
# Event Analysis



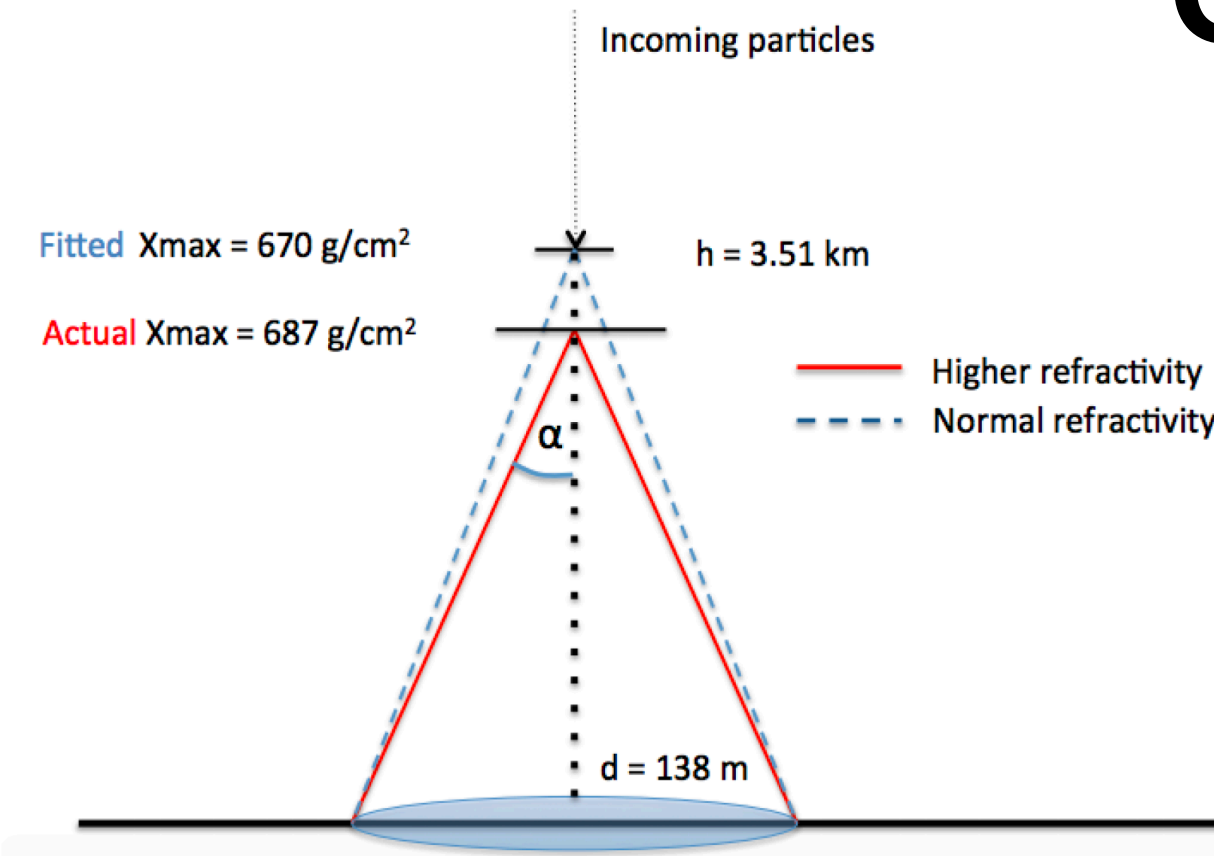




- Simulate proton and iron showers
- Power scales with energy²
- Calculate reduced $X^2$ for each simulation
- Parabola fit determines event $X_{max}$
- Resolution < 20 g/cm²
- Best fit (2016): 80% light particles (p+He) at $10^{17}$ -$10^{17.5}$ eV



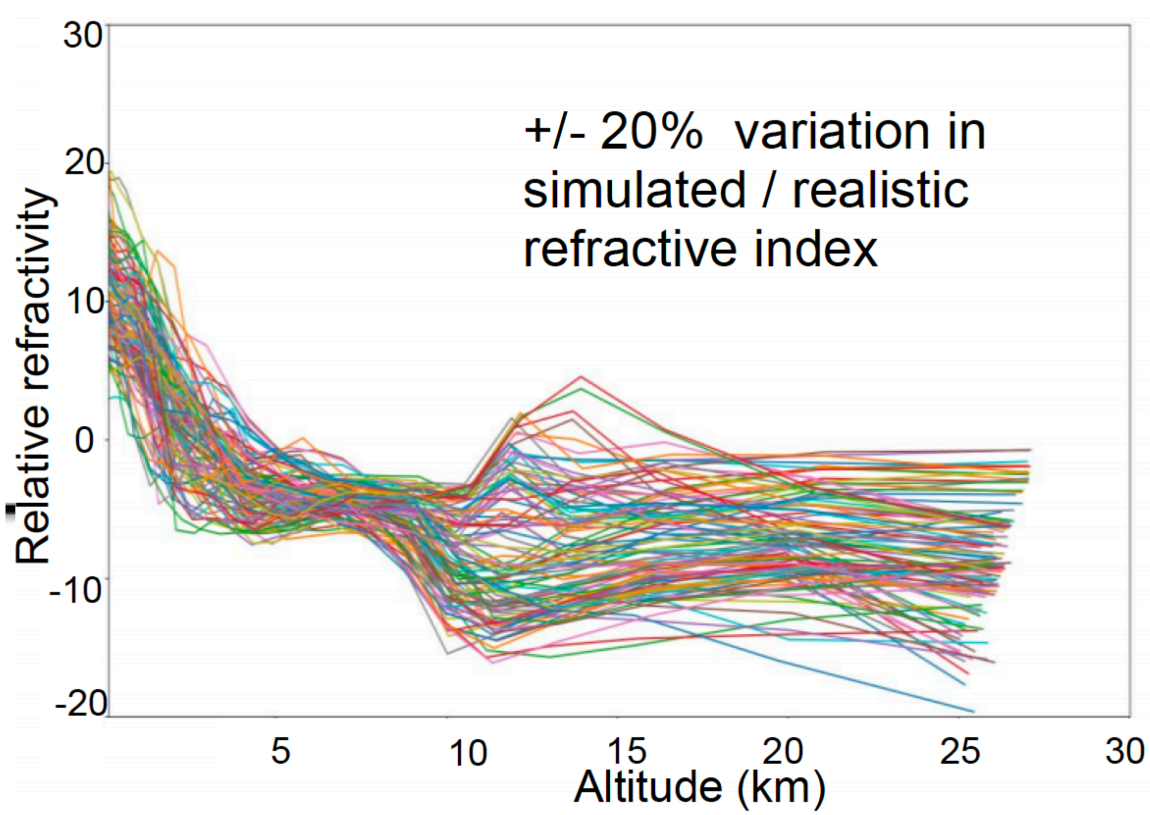

See talk by A. Corstanje

# GDAS Atmospheric Corrections

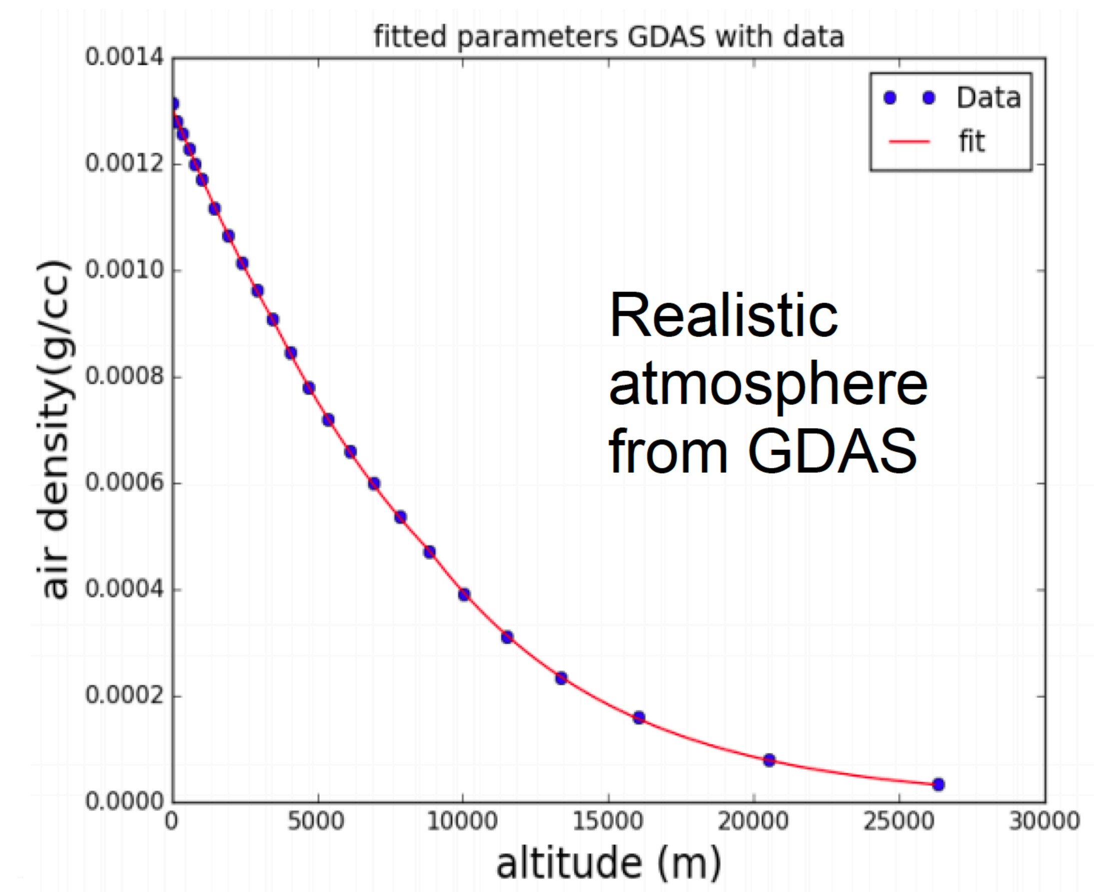



A. Corstanje Astropart.Phys. 89 (2017)

- **GDAS provides atmosphere measurements (temp, humidity, pressure)**
- **Any location (1°x1°), time (3-hourly)**
- **Integrated into simulations**
- **For extreme conditions, can shift $X_{max}$ up to 15 g/cm²**

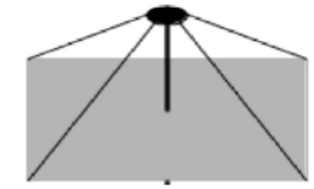


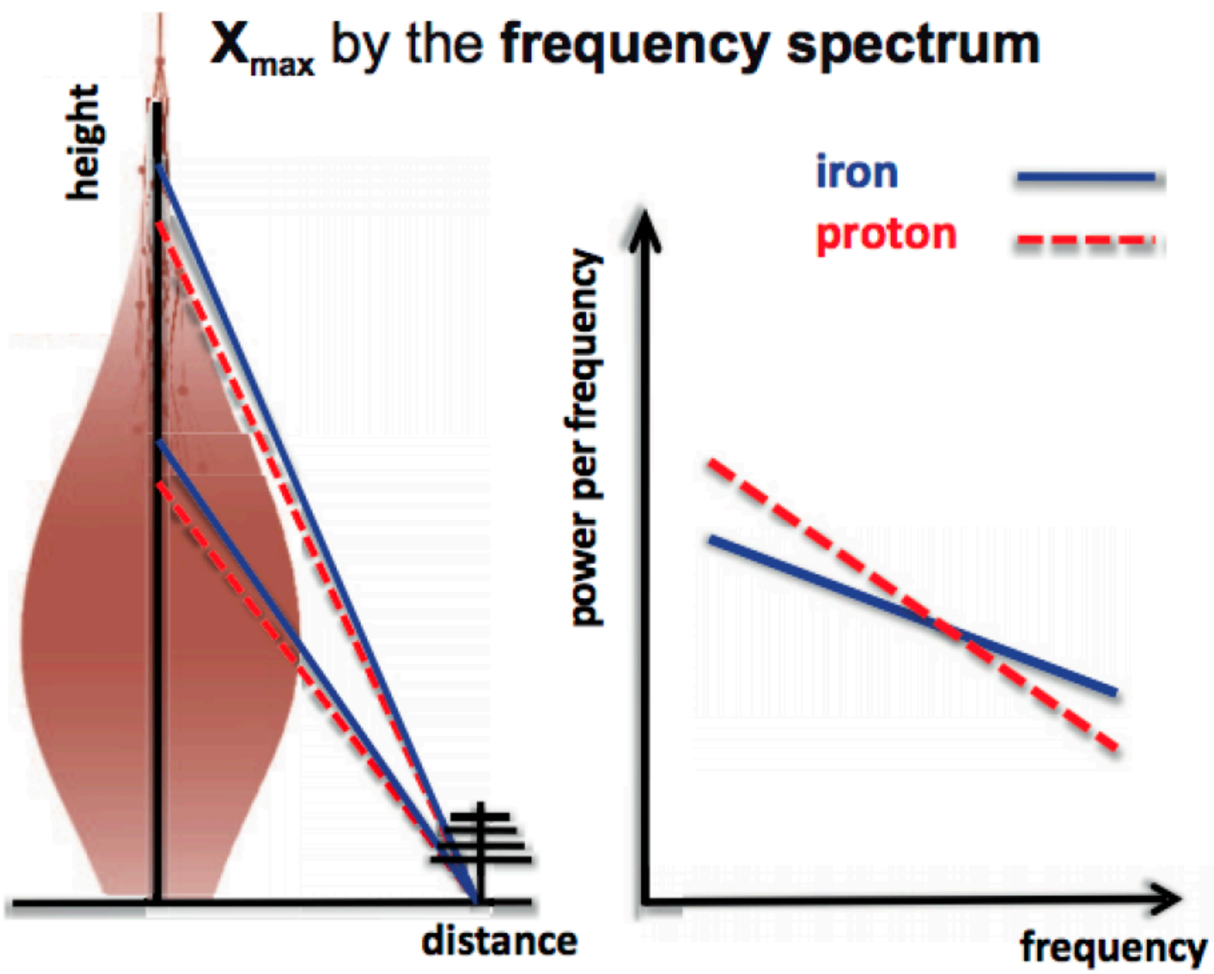

P. Mitra et al. PoS ICRC2017 (2018) 325



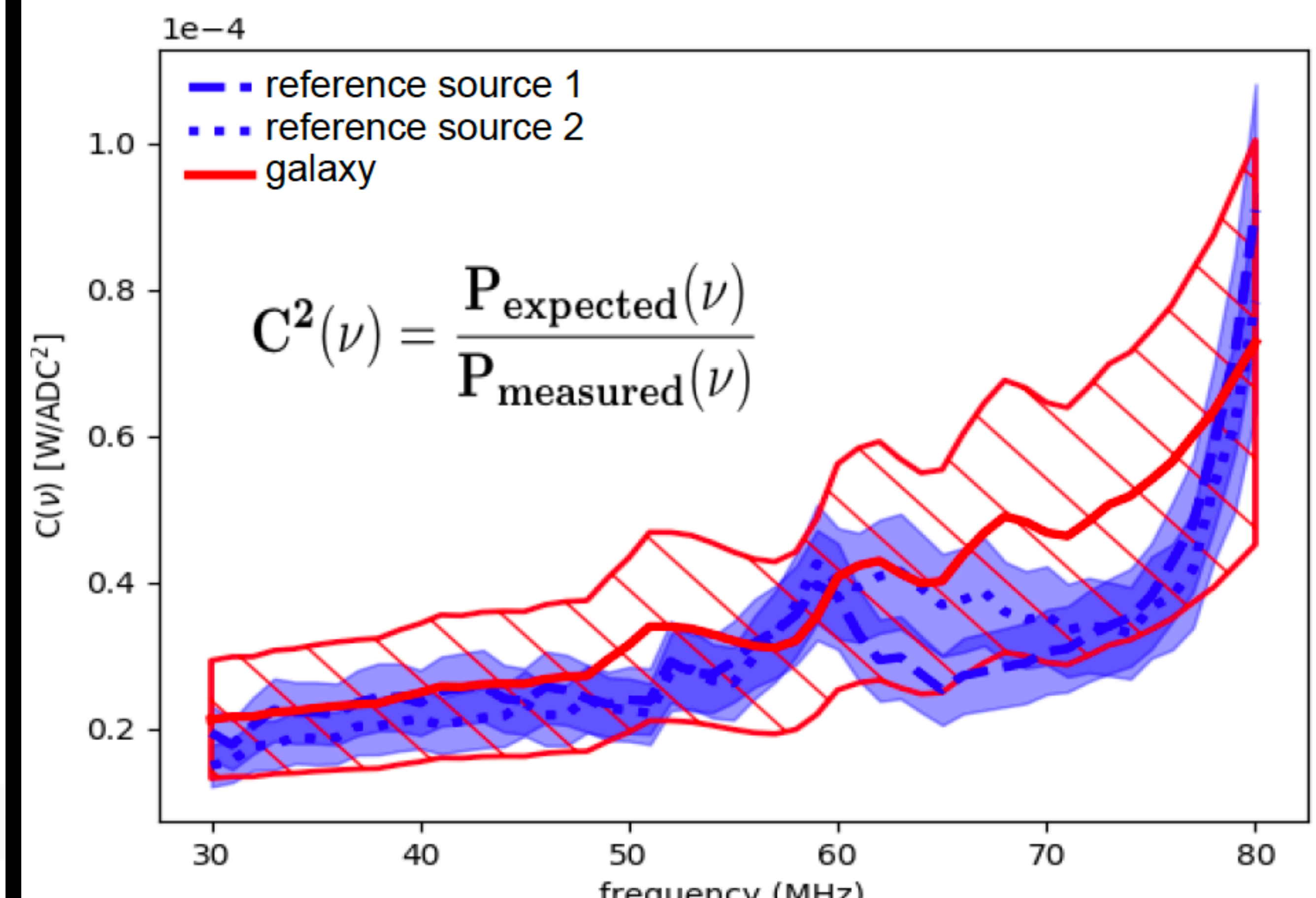
# Calibration

measured signal recorded in ADC counts ($P_m$) → voltage received at the antenna ($P_e$)






Schroeder, F. Prog.Part.Nucl.Phys. 93 (2017) 1-68



# Calibration

measured signal recorded in ADC counts ($P_m$)

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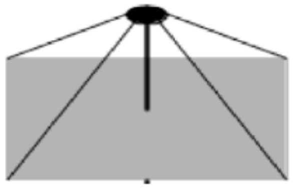


## 2 independent methods

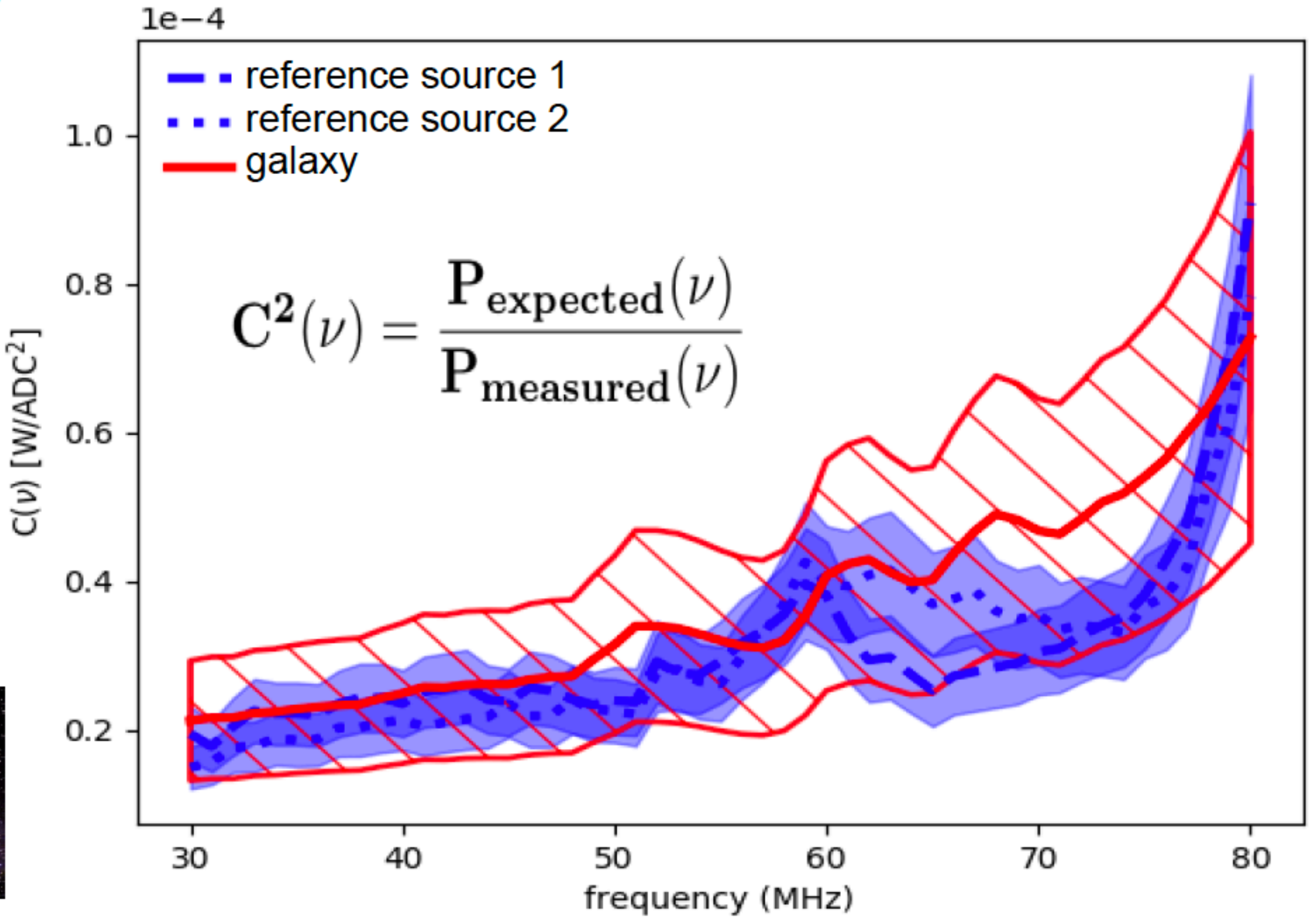
*Nelles, A. et al. 2015,Journal of Instrumentation, 10, P11005*

### 1. Reference Source

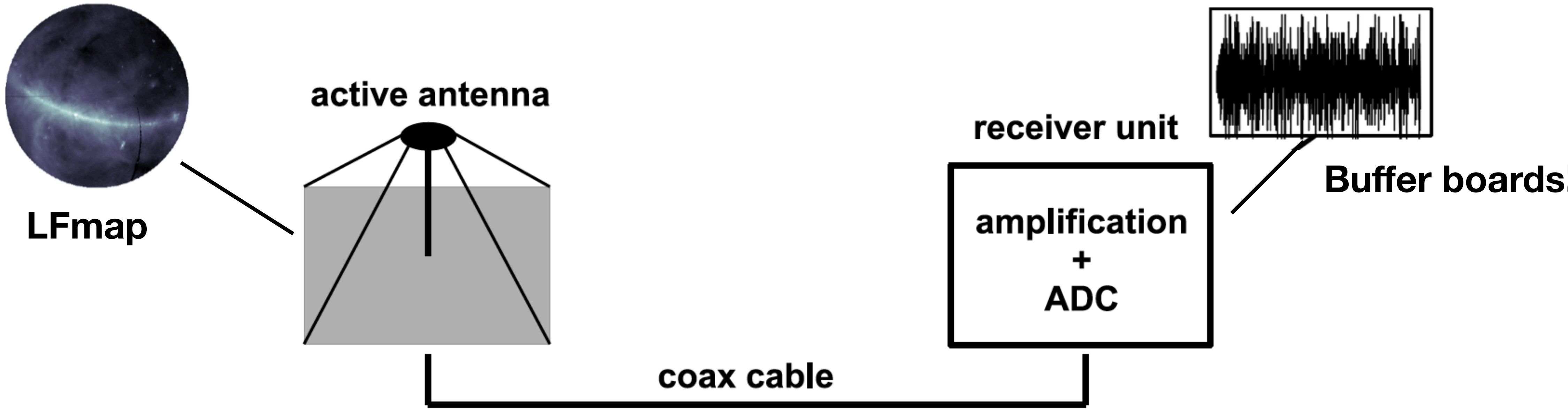
+ Angular response
- Relies on conflicting manufacturer data sheets
- Not easily repeatable

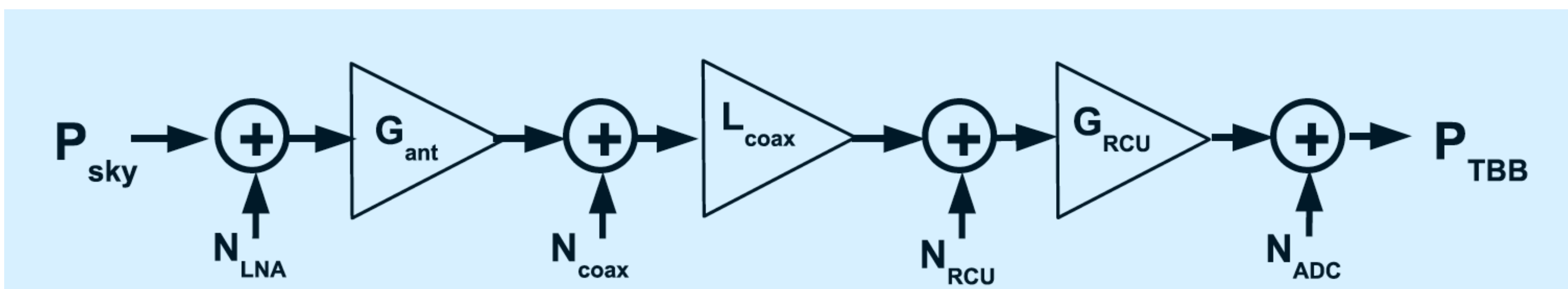
### 2. Galactic Emission

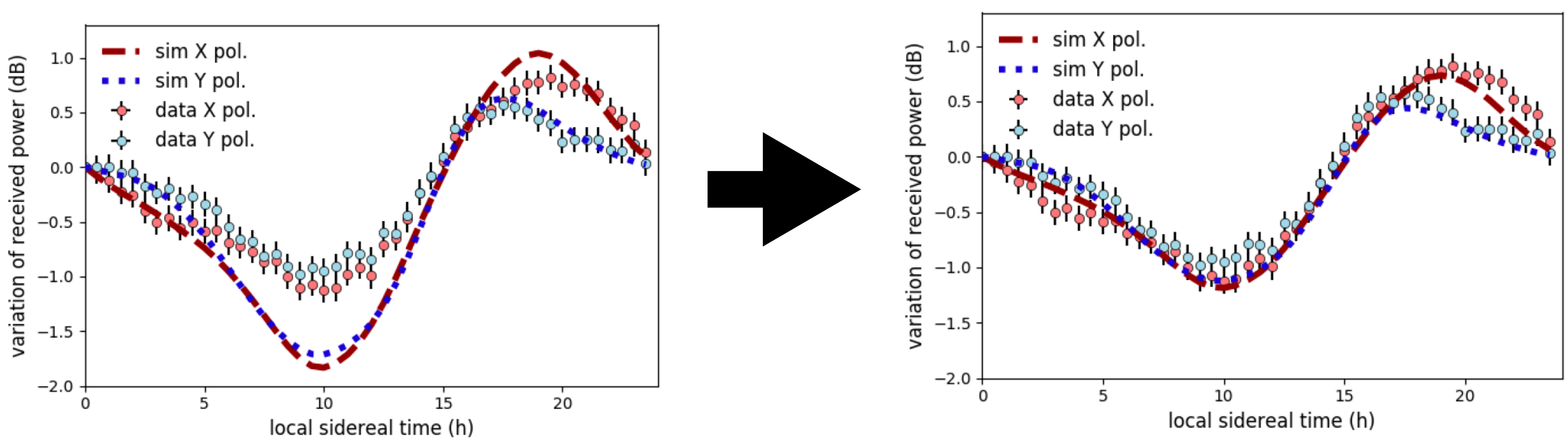
- Average over whole sky
+ Can be done anytime
- Large error bars due to electronic noise



# Calibration

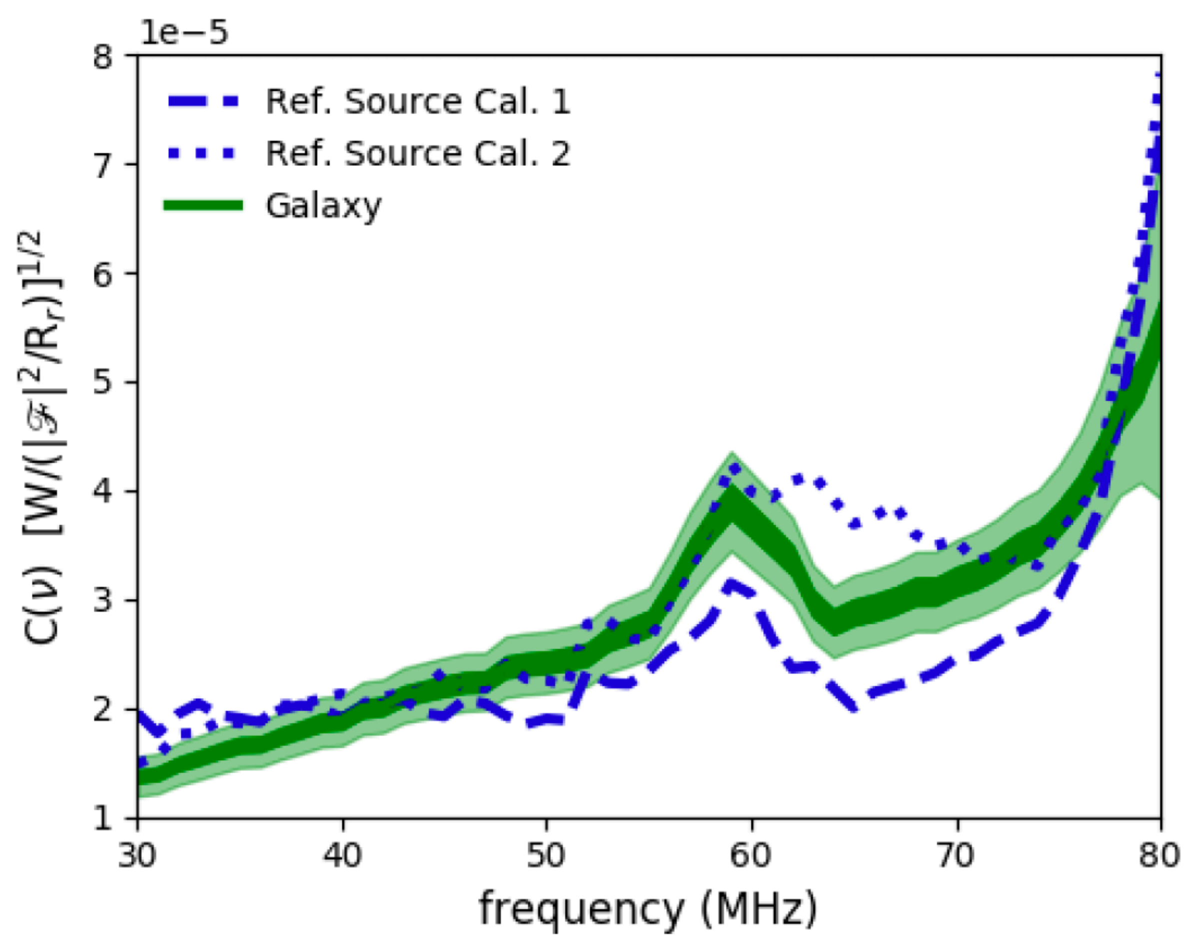


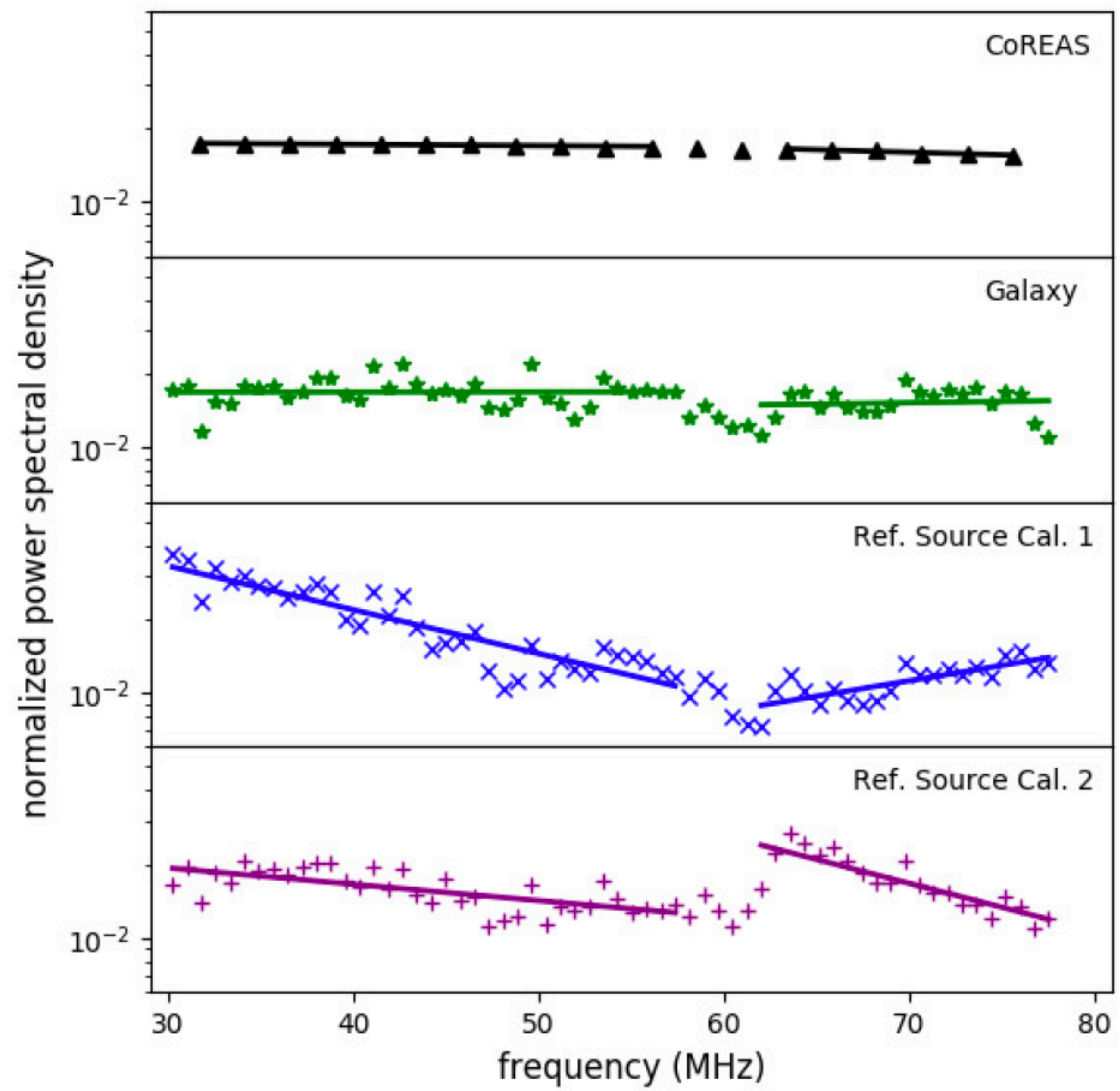



# Calibration

| 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** |



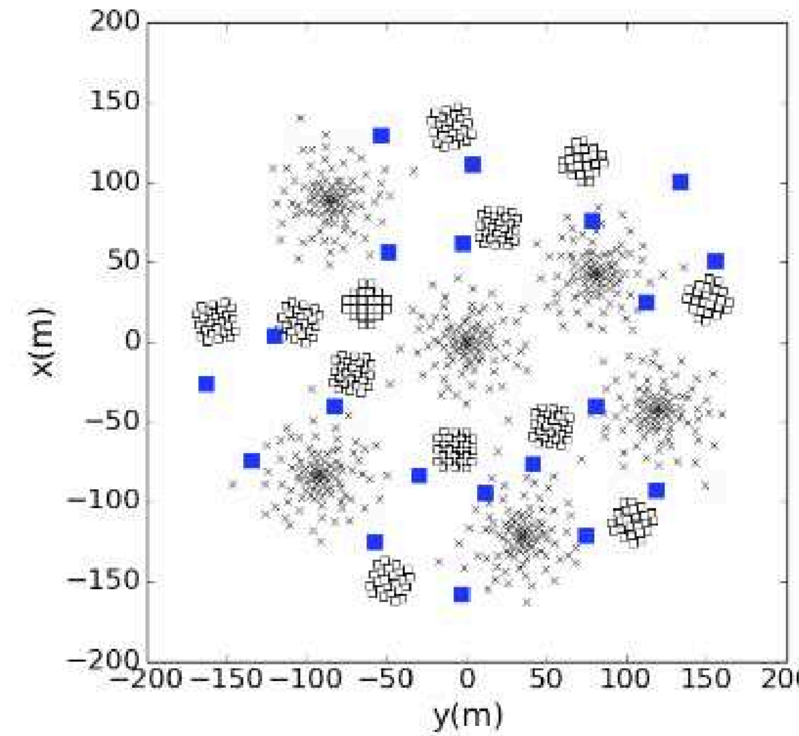




K. Mulrey et al. Astropart.Phys 111 (2019) 1-11.

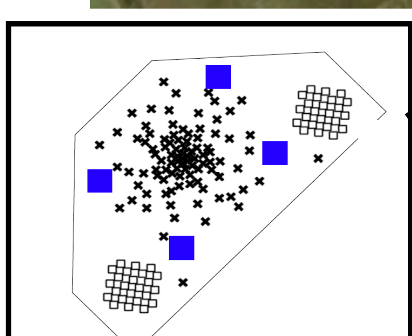
# LORA expansion

- Current cosmic-ray trigger is based on 20 scintillators on the superterp
- Expand by adding 20 scintillators at neighboring
- Expected 45% increase in events

**Current LORA**

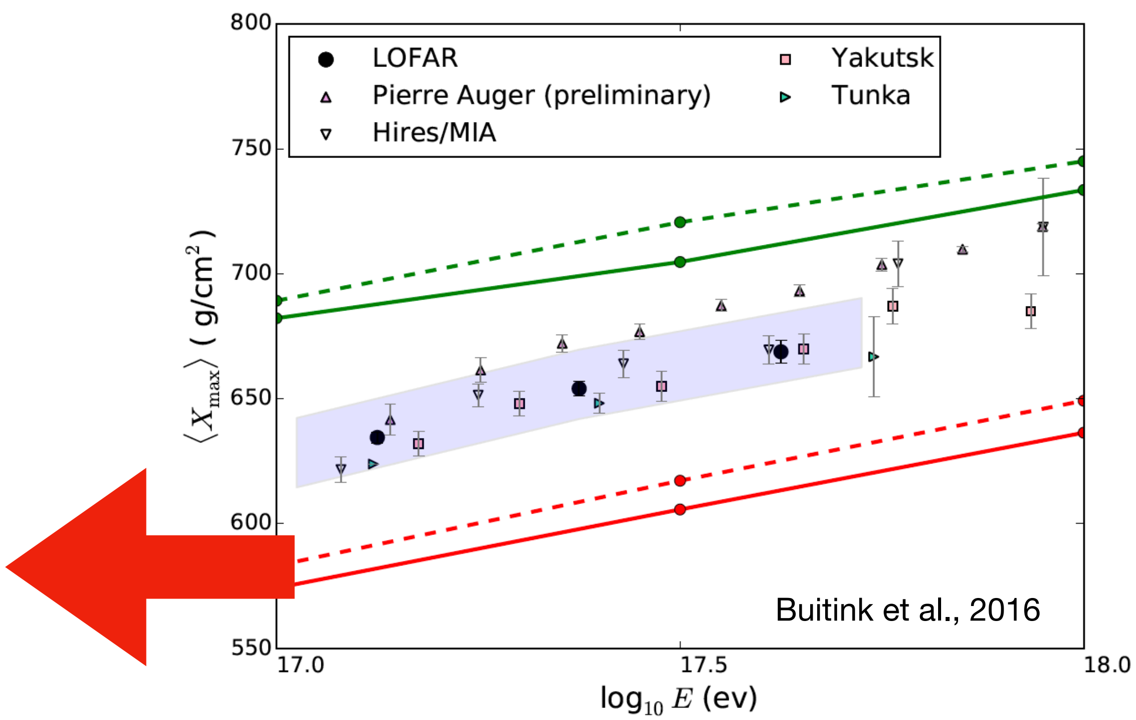


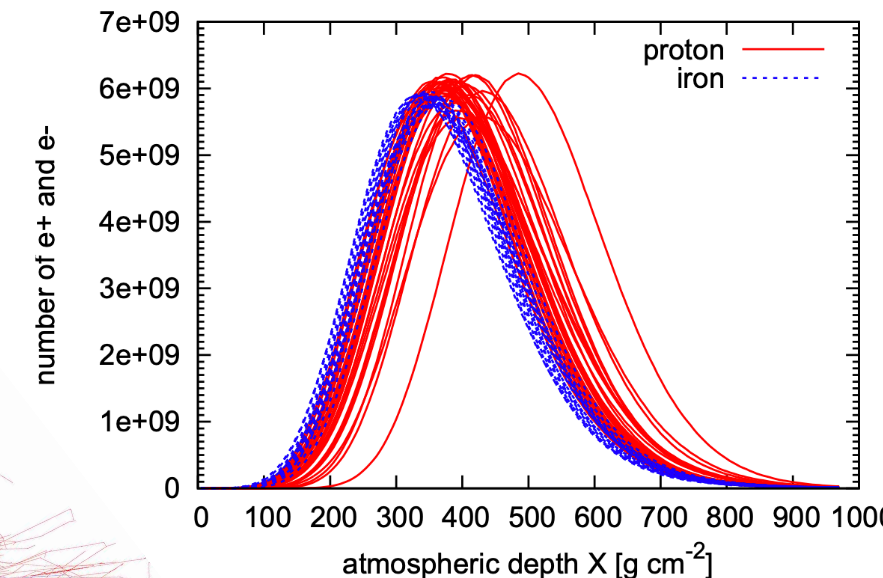


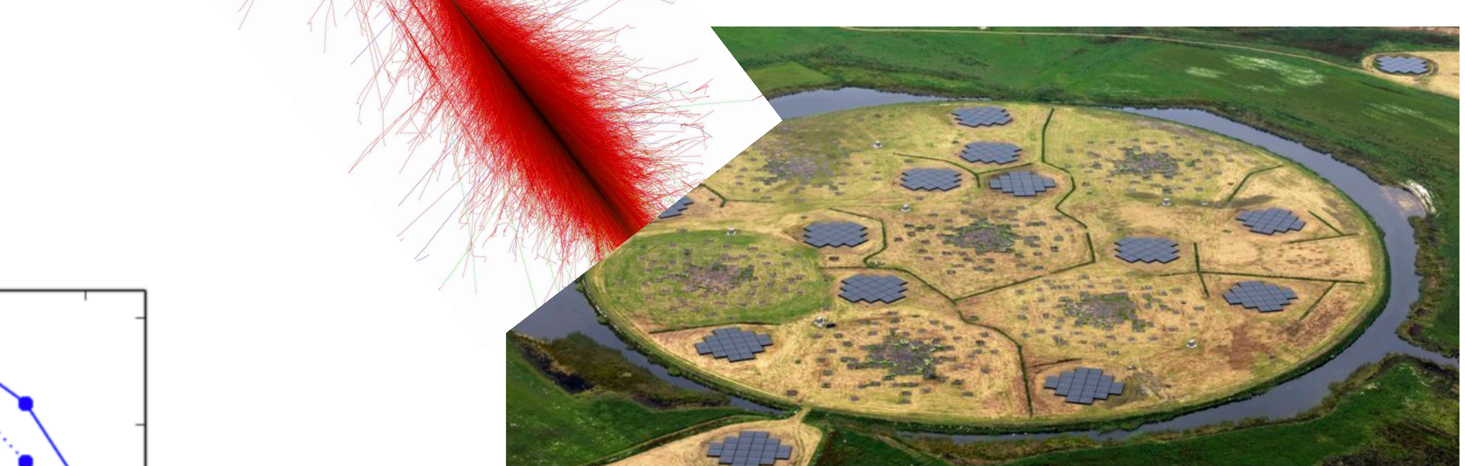


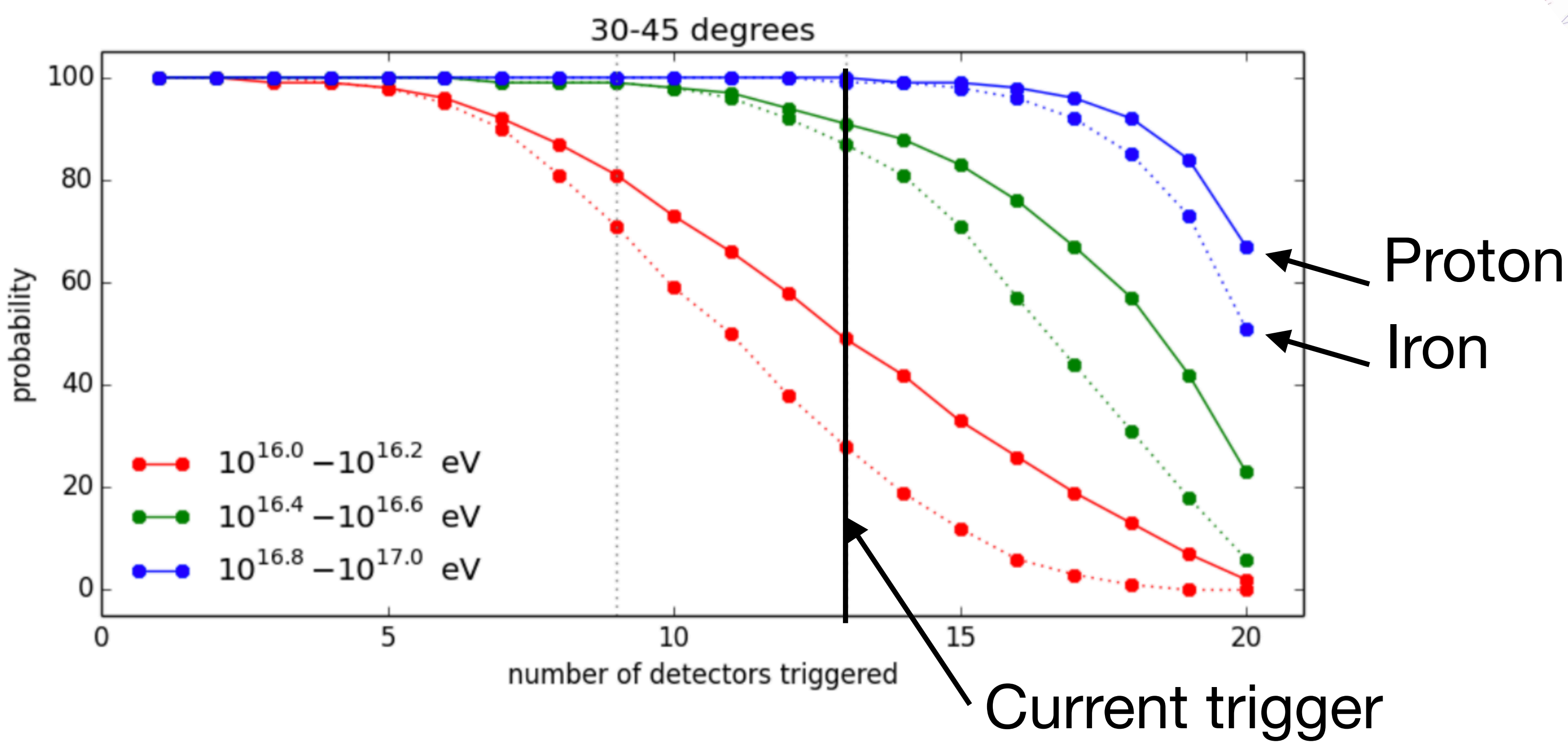
**Installation began spring 2018**

# Low Energy Extension: Hybrid Trigger



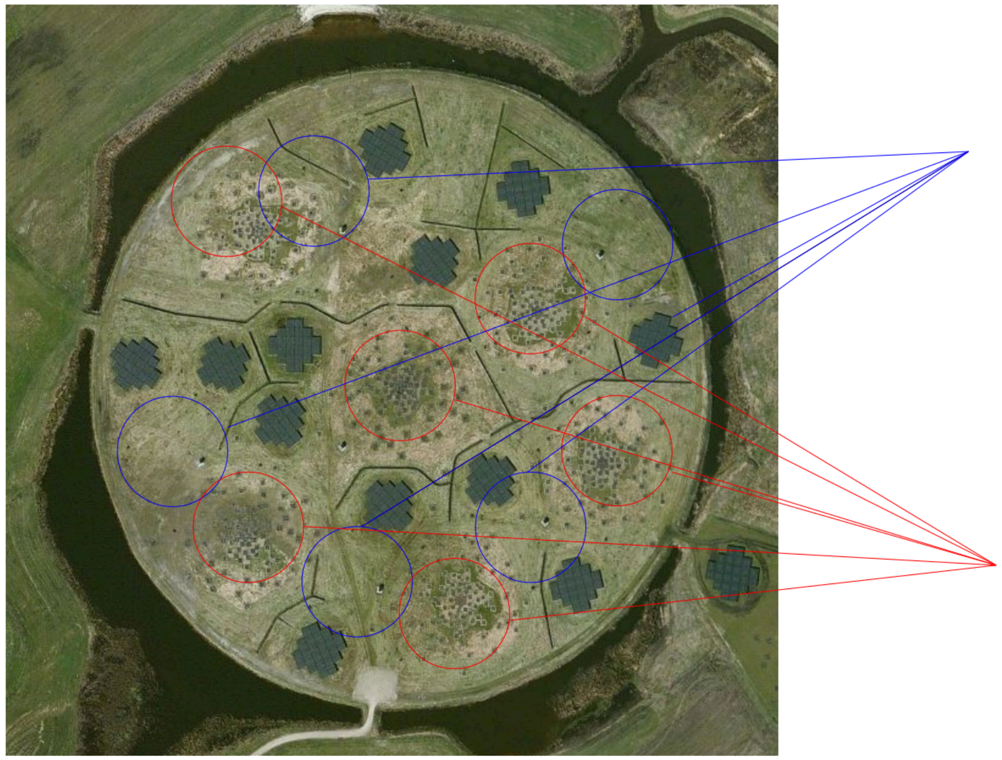



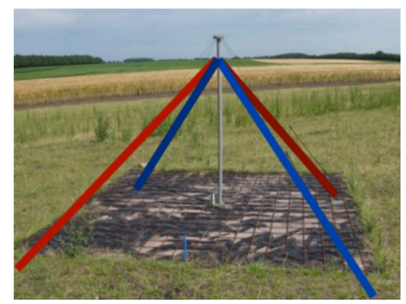



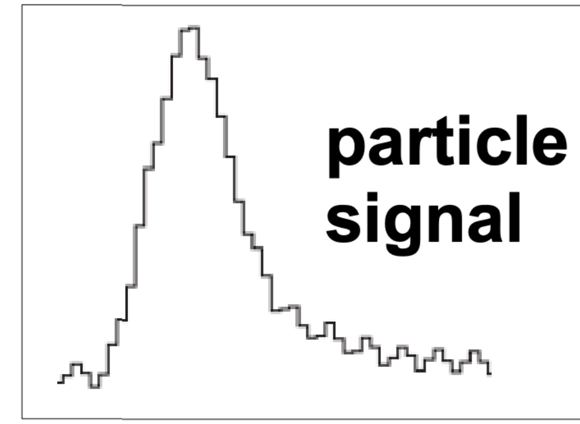


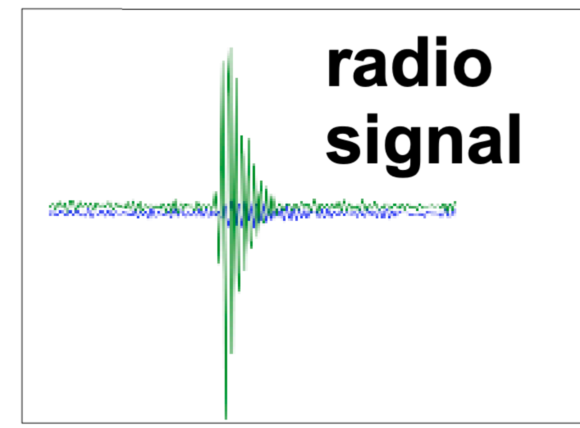

**All CR primaries must have same probability of triggering to remove bias**

# Hybrid Trigger








**Particle trigger**

- High rate with low trigger threshold
- Composition bias at low energies
+ Guaranteed cosmic ray

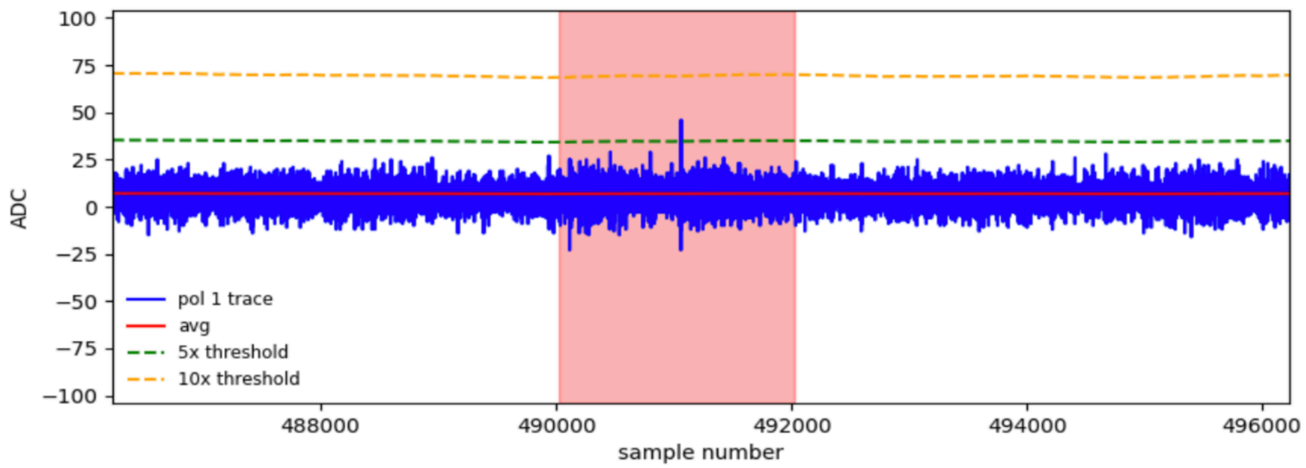
**Radio trigger**

- Flooded with RFI
+ Ensures a usable CR signal

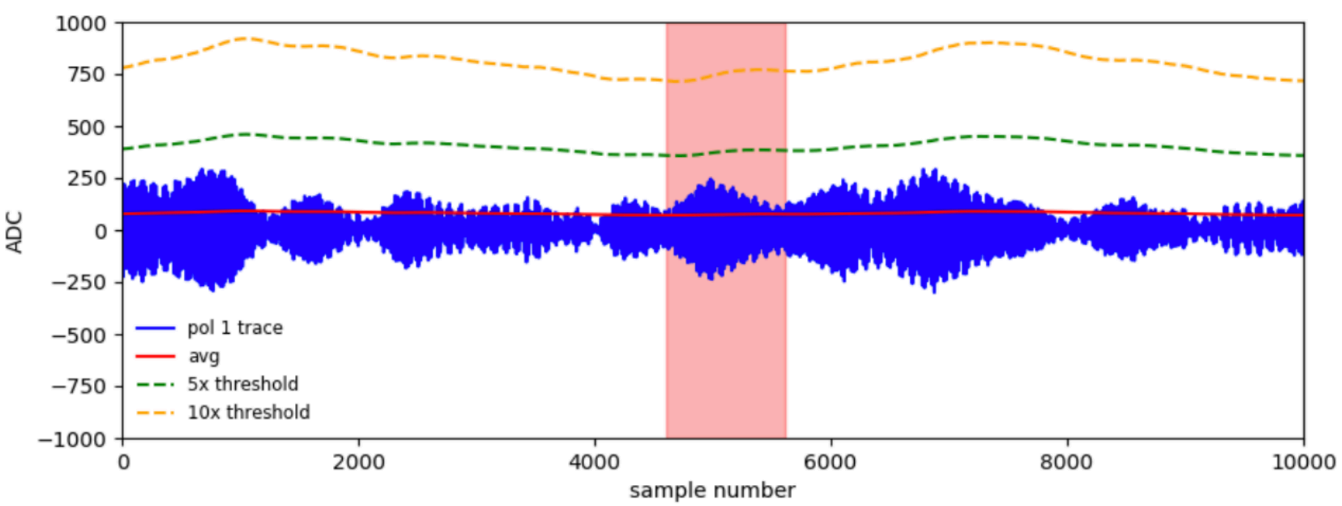
Cosmic ray
+
good radio signal
+
RFI rejection
+
Reduced trigger threshold

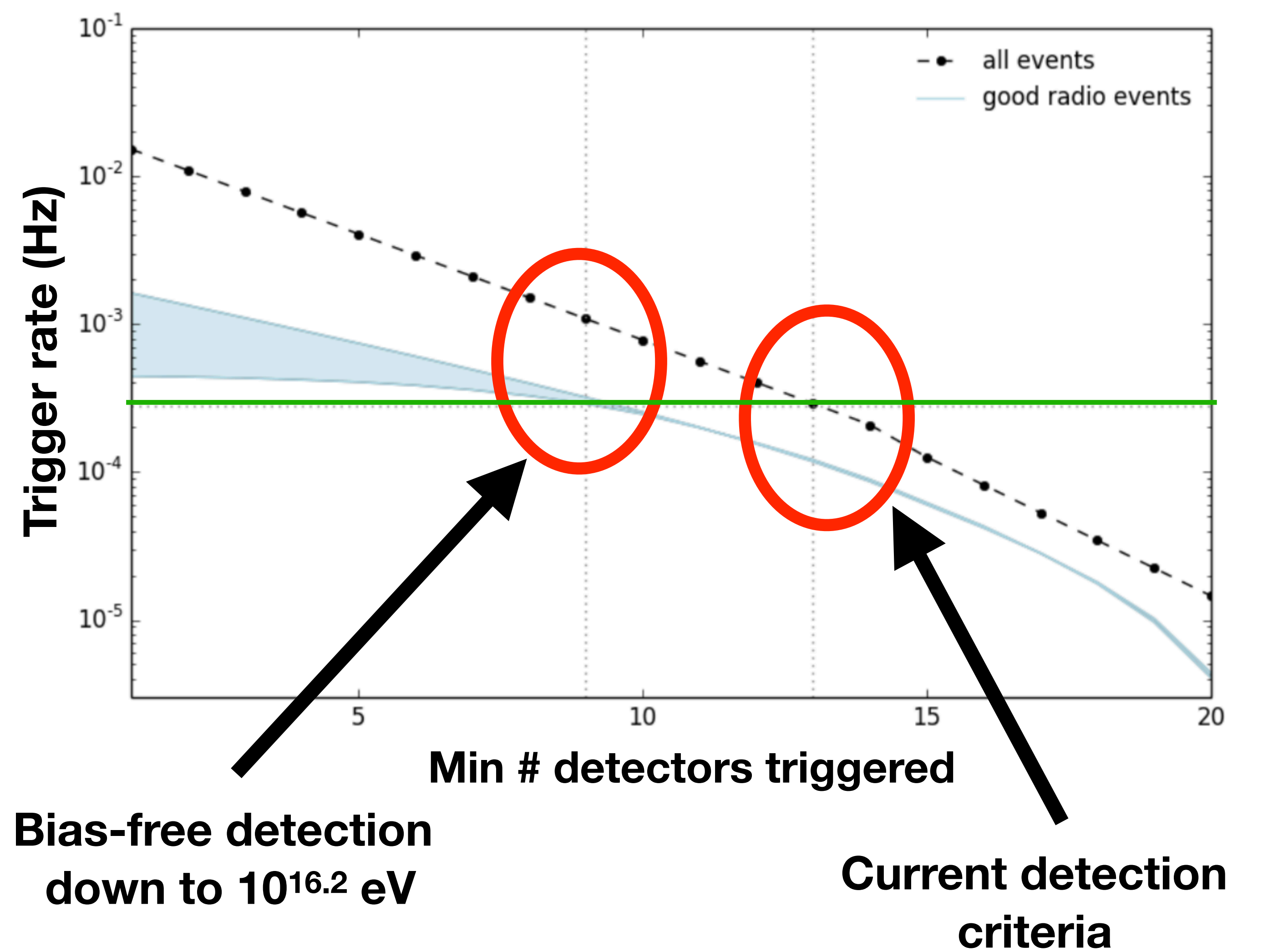
# Hybrid Trigger

CR detectable with radio

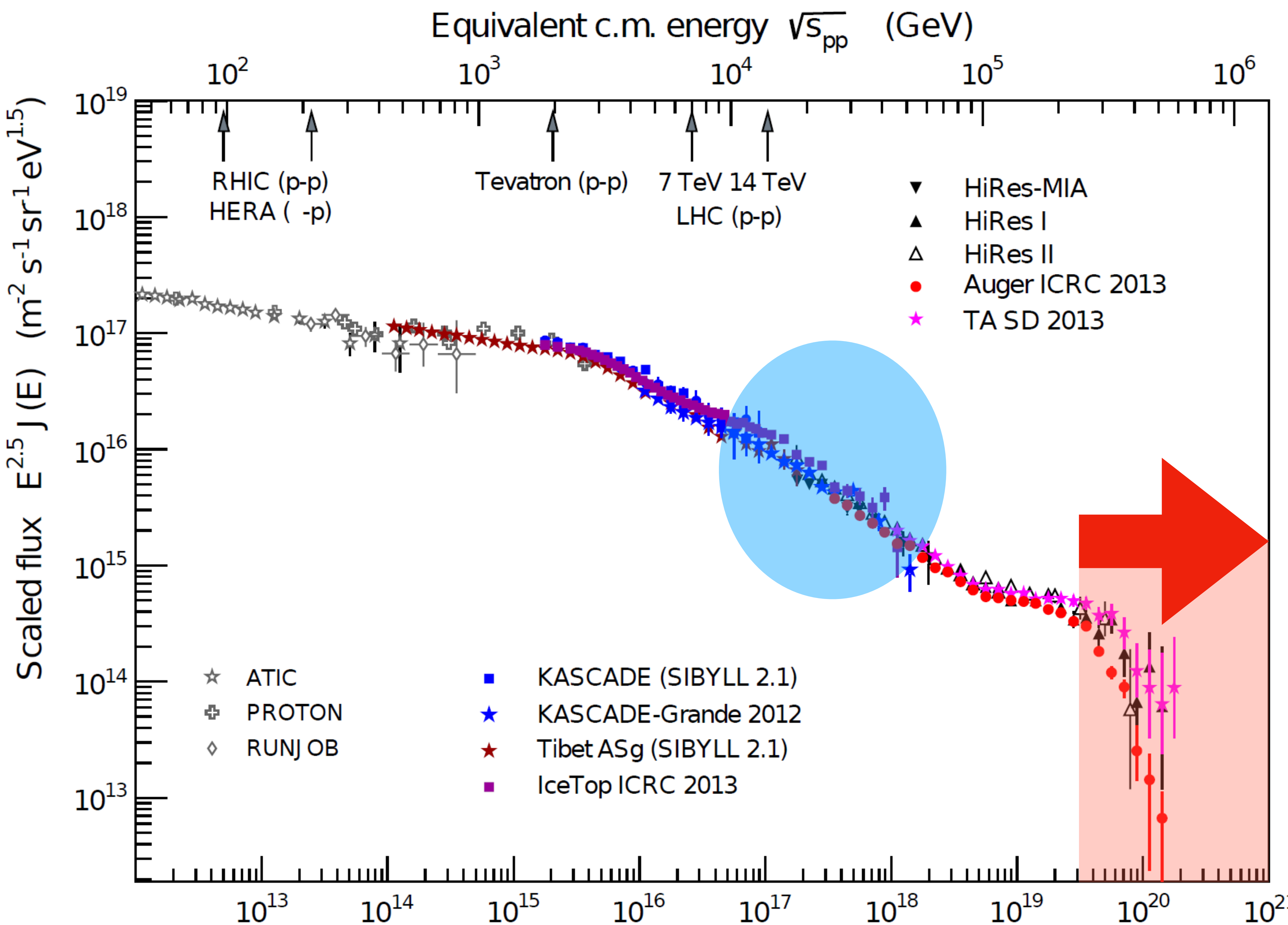



Event with high RFI



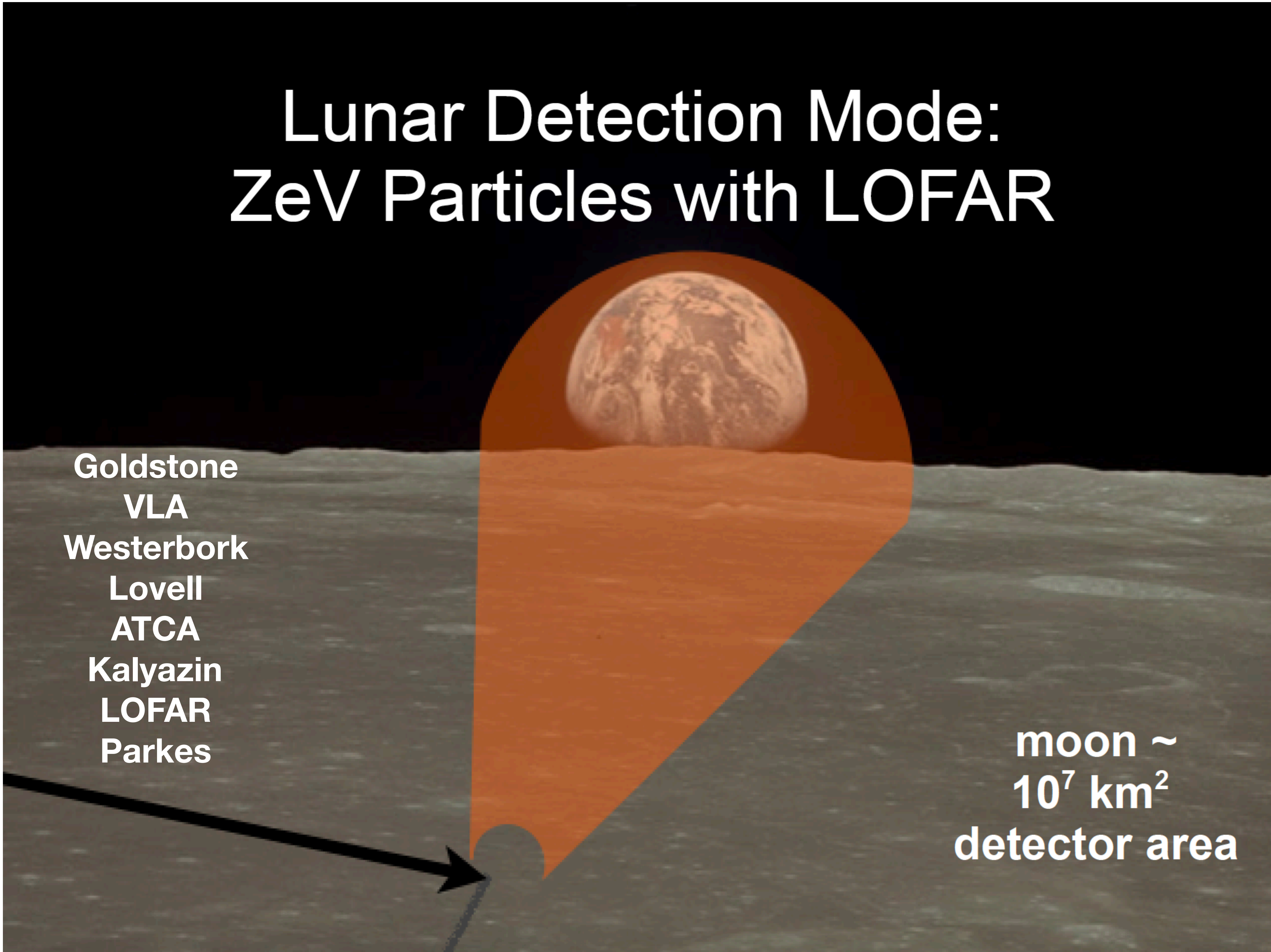




★ **Need access to existing radio trigger info in real time to form trigger**



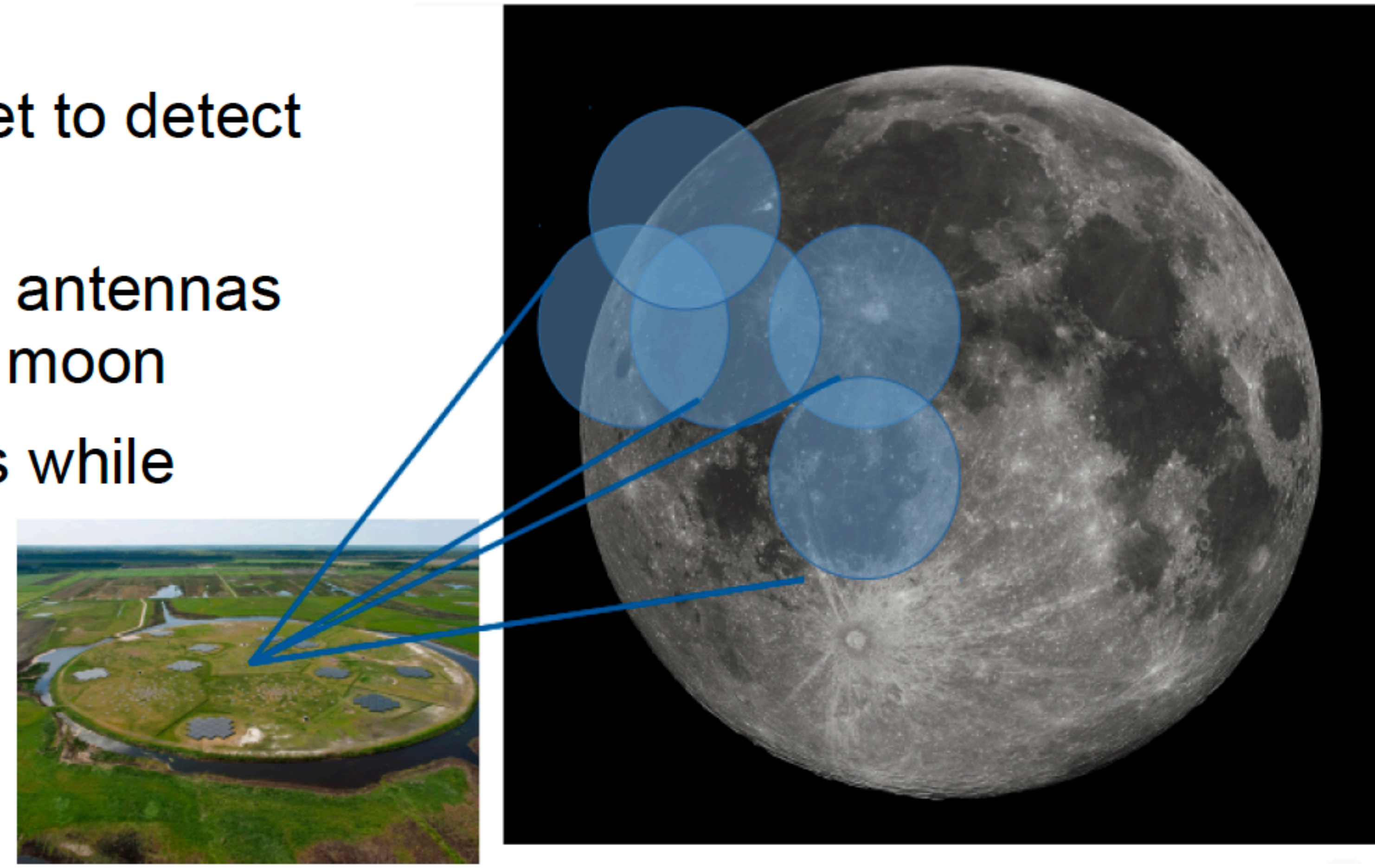

G. Matthiae et al. New J. Phys 12 (2010)

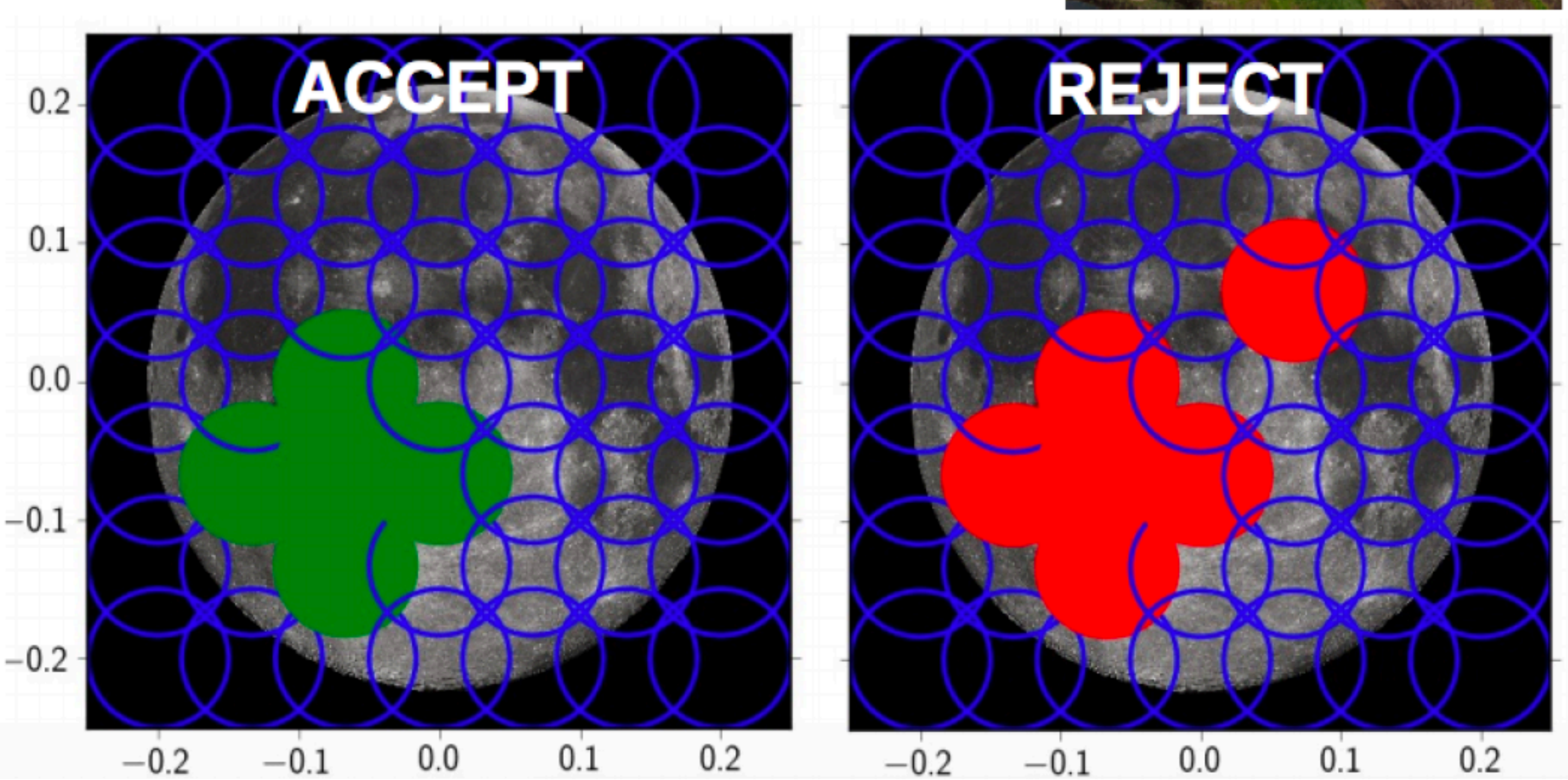
# Can we access the highest energy particles?


Lunar Detection Mode:
ZeV Particles with LOFAR
Goldstone
VLA
Westerbork
Lovell
ATCA
Kalyazin
LOFAR
Parkes
moon ~
$10^7$ km$^2$
detector area

# Lunar Detection Mode: NuMoon

- The moon provides large target to detect rare, highest energy particles
- Use high band (110-240 MHz) antennas to form multiple beams on the moon
- Search for nanosecond pulses while suppressing RFI





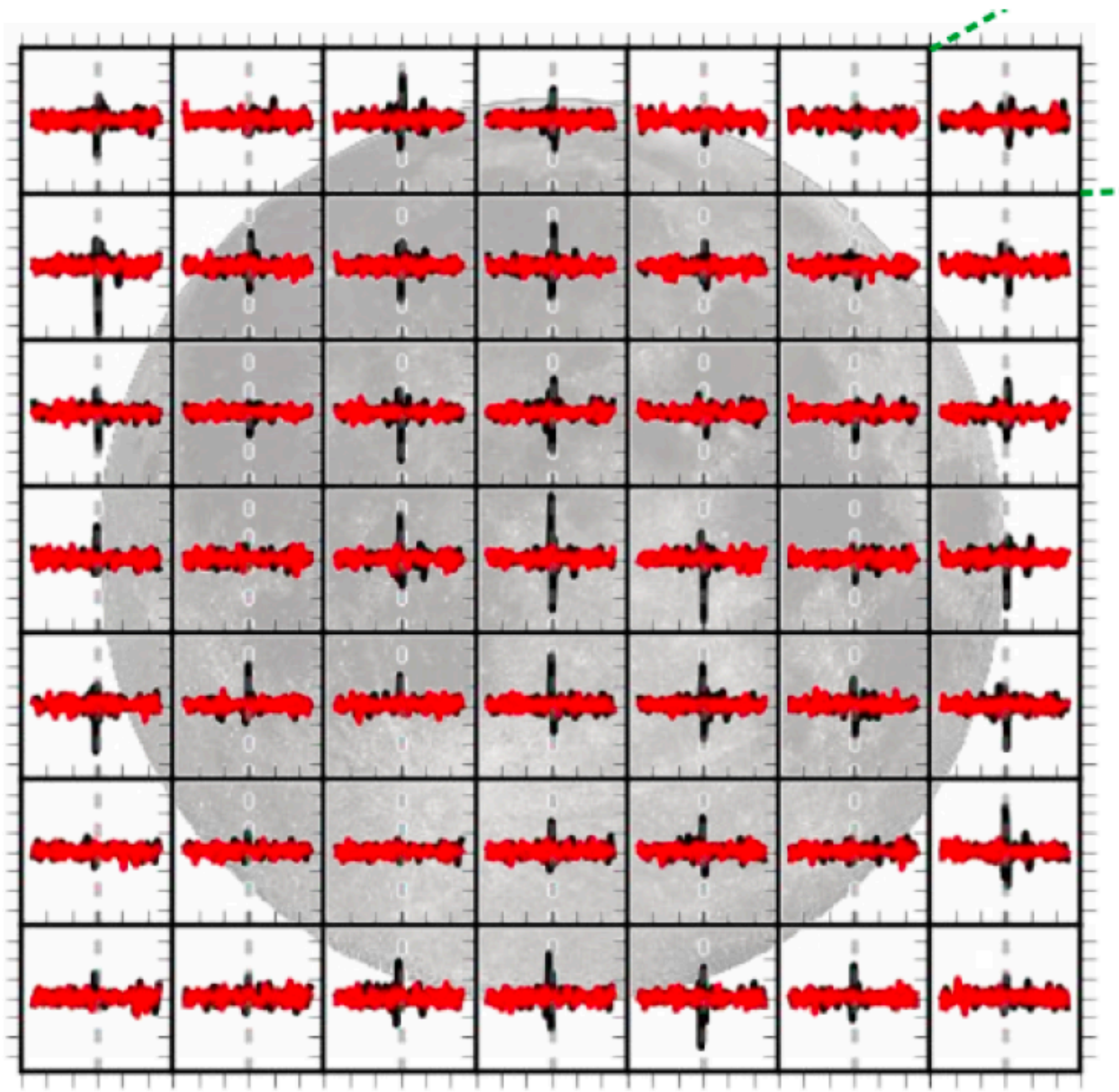

**<u>Challenges:</u>**

- Must trigger in real-time (5 s buffer)
- Signal is dispersed in ionosphere
- Only have access to processed signal

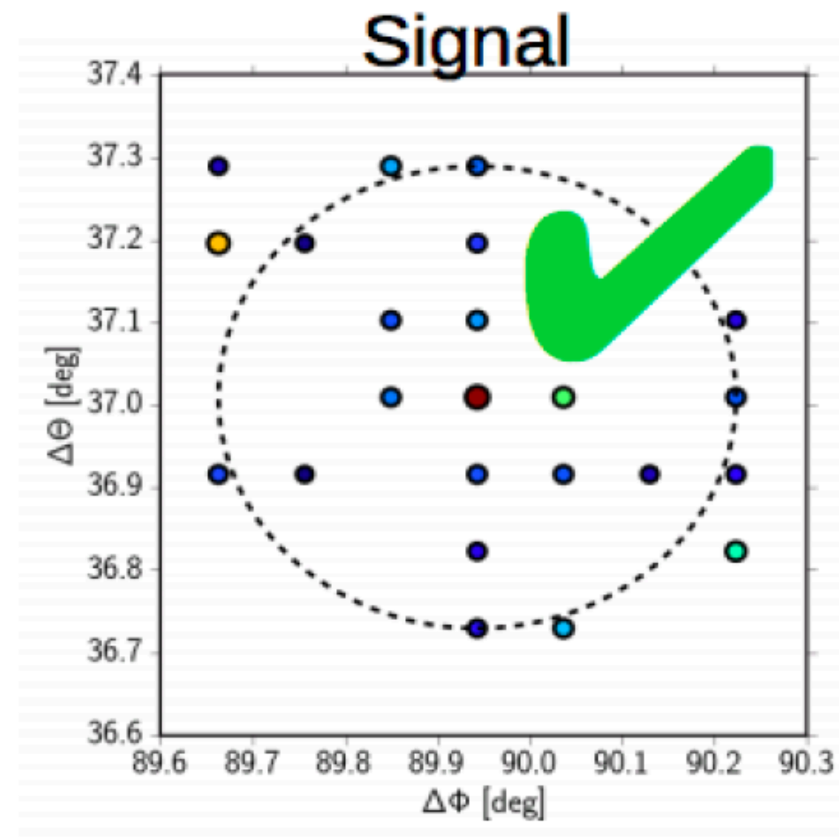
T. Winchen

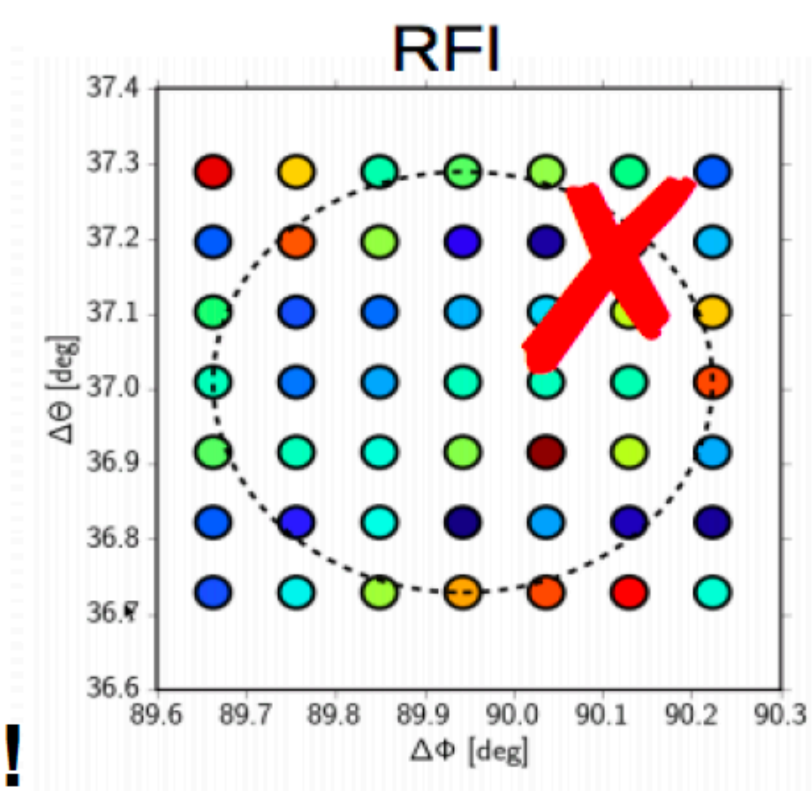
# Lunar Detection Mode: NuMoon

Simulated pulse from moon



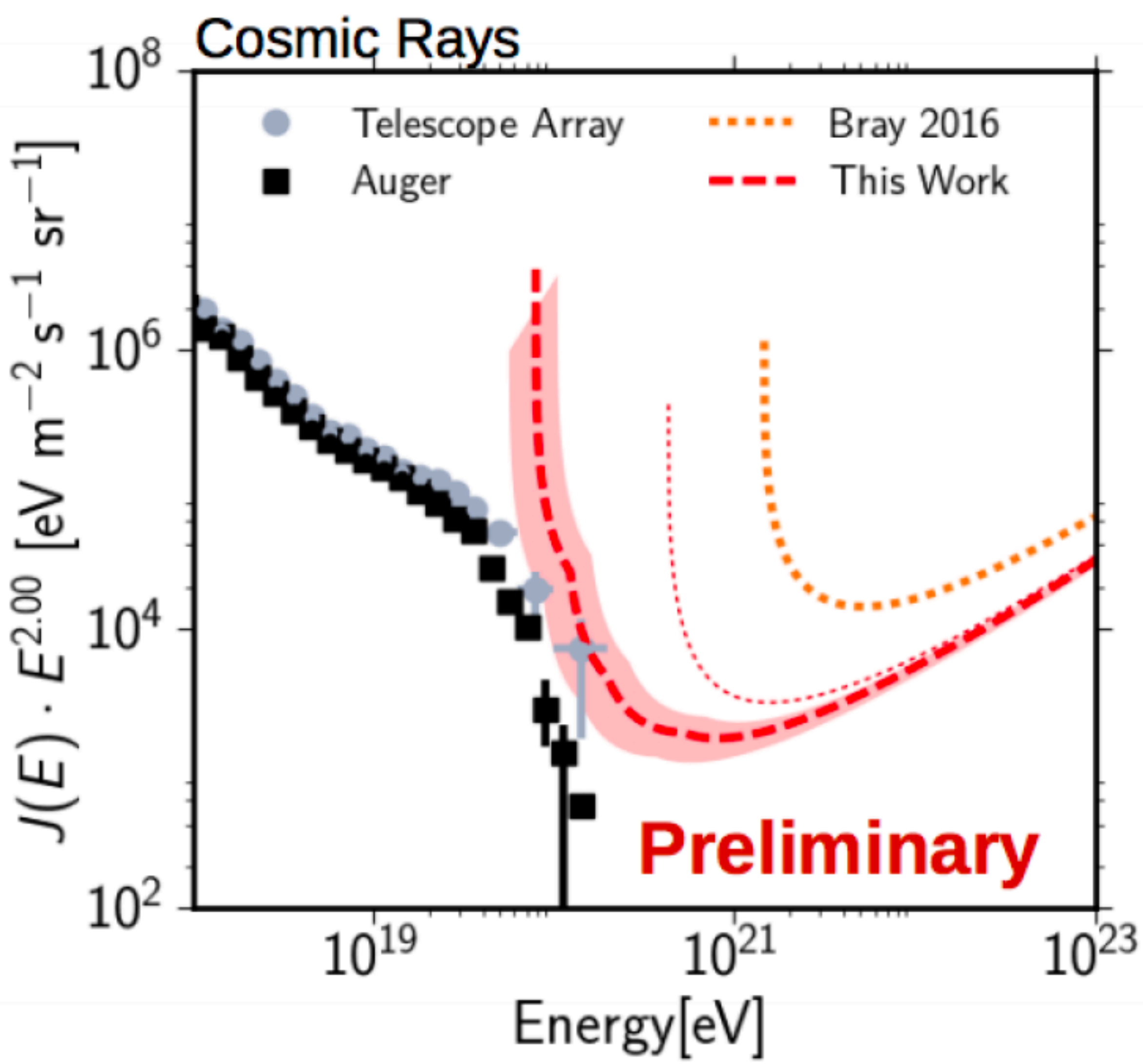
T. Winchen

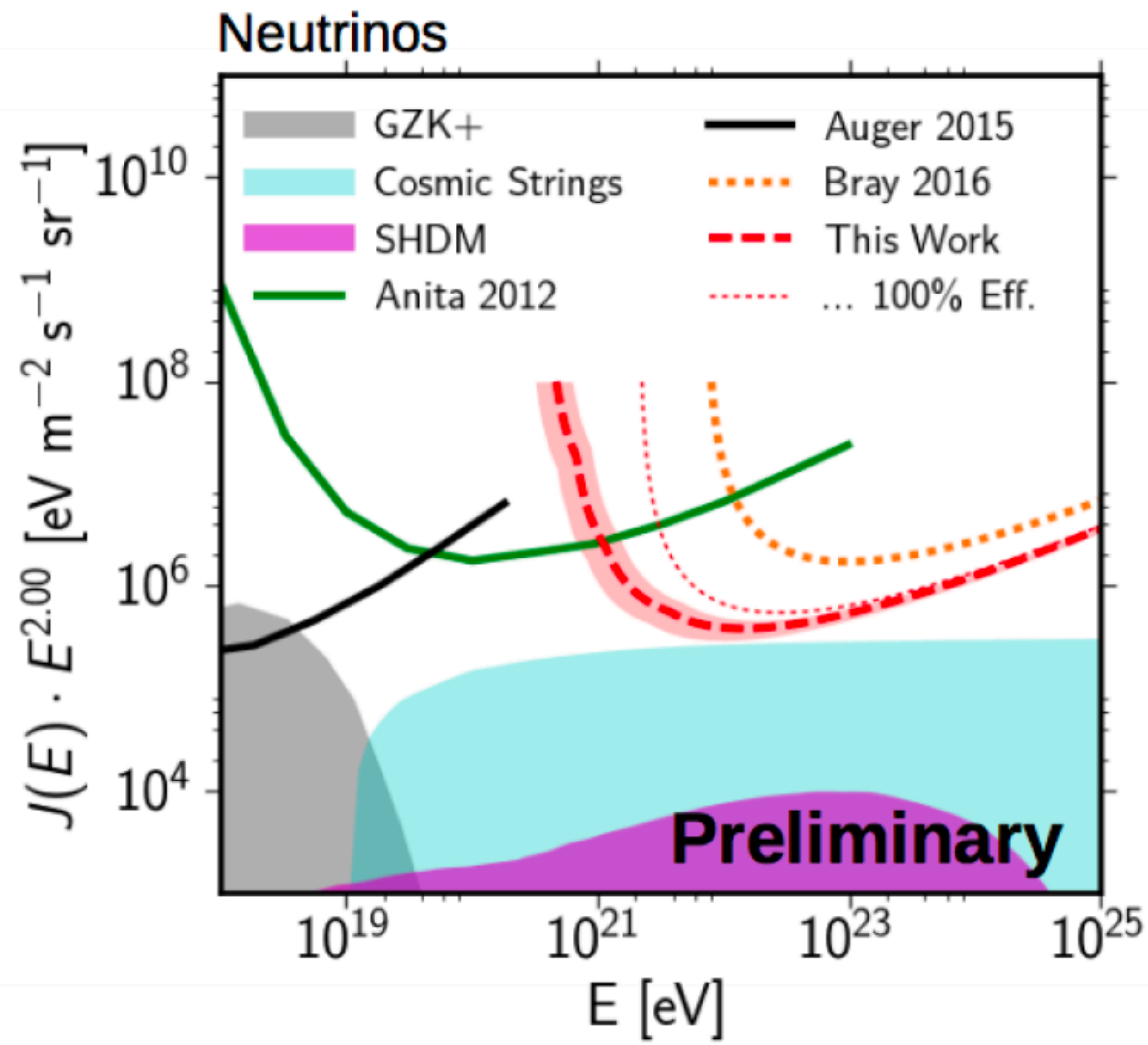



**Real time RFI rejection is possible!**

# Expected Sensitivity (200h)



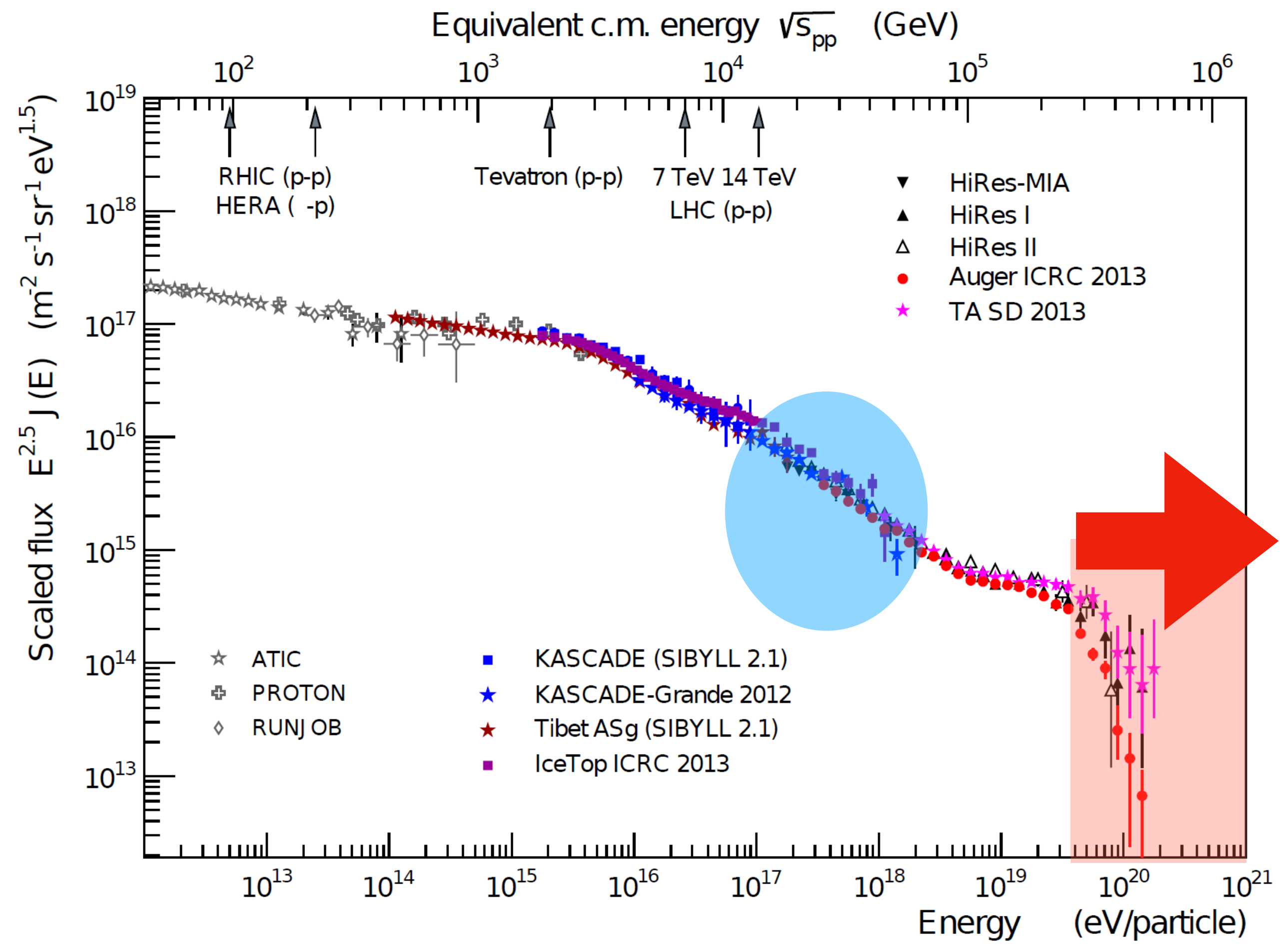



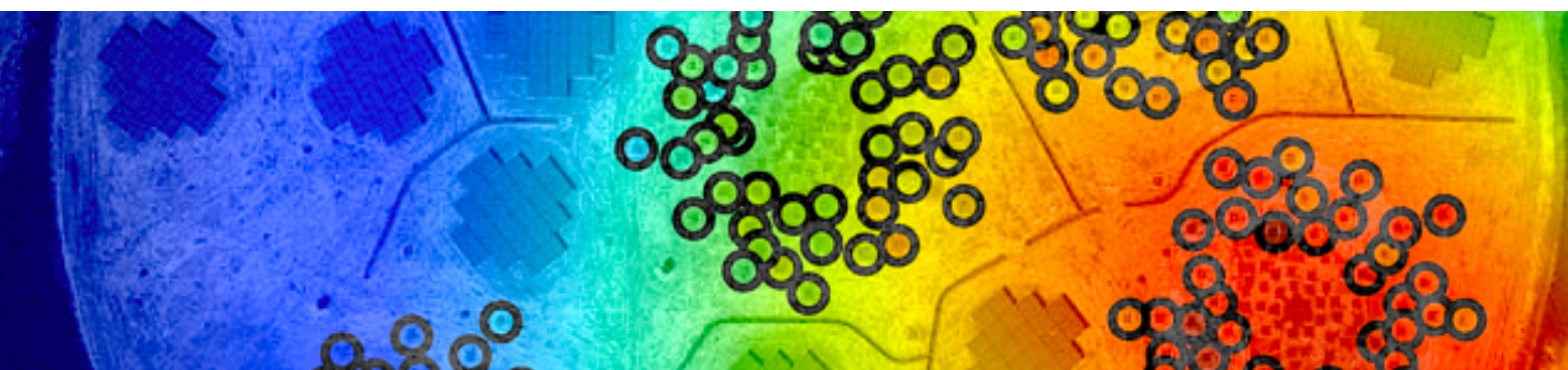

New sensitivity values:

- 5 stations instead of 24
- Increased bandwidth
- Reduced trigger threshold
- Full detection simulation
  (still relies on semi-analytical model for pulse escape from moon)

# Summary

- **LOFAR measures air showers with highest precision in radio**
- **$X_{max}$ reconstruction resolution competitive with fluorescence**
- **New atmospheric modelling & calibration**
- **Multiple Extensions (hybrid trigger + LORA)**
- **Lunar detection very promising (overlap with ground experiments!)**



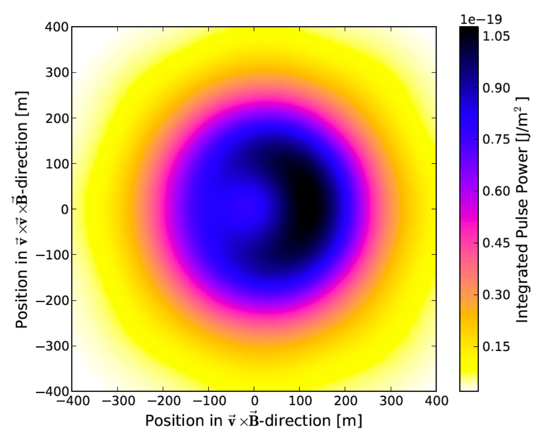
# Backup

# Calorimetric Energy Estimate

**Radio emission from cosmic rays provides a calorimetric energy measurement without uncertainties from hadronic models**

Glaser et al. JCAP 1609 (2016)

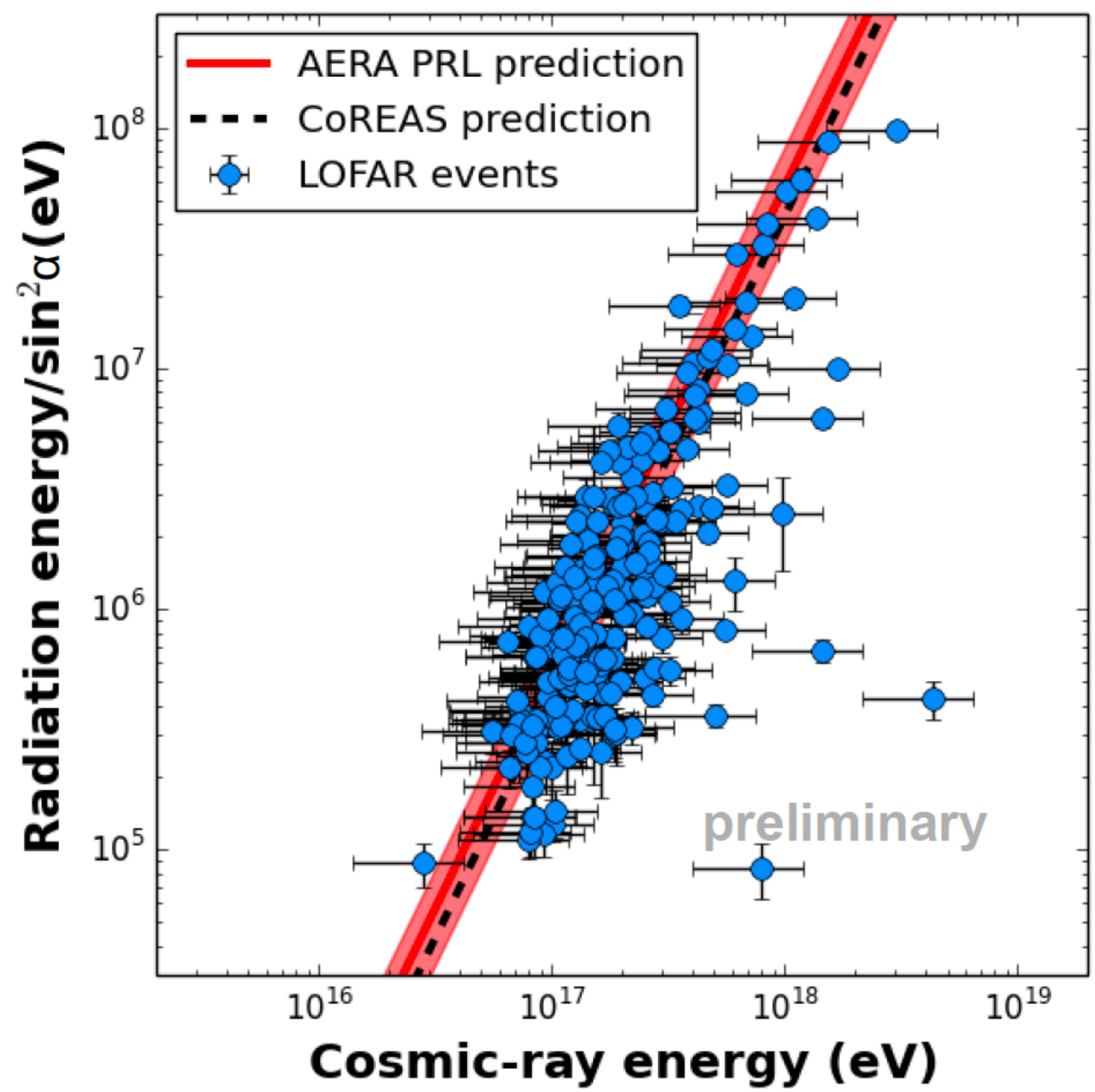
**Integrate fluence of radio footprint**




$$f = f_{\vec{v}\times\vec{B}} + f_{\vec{v}\times(\vec{v}\times\vec{B})}$$

$$S_{\mathrm{RD}} = \frac{1}{\sin^2\alpha} \int_{\mathbb{R}^2} f(\vec{r})\, \mathrm{d}^2\vec{r}$$

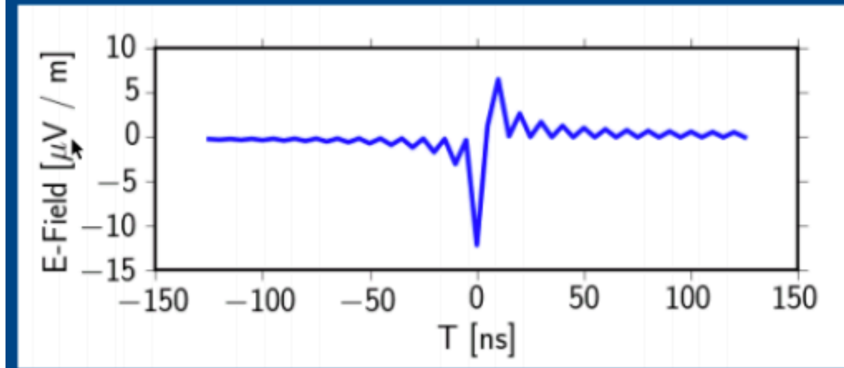
$$S_{\mathrm{RD}} = A \times 10^7\,\mathrm{eV}\,(E_{\mathrm{em}}/10^{18}\,\mathrm{eV})^B$$




Cosmic-ray energy given by the LORA particle detector energy reconstruction (NKG fitting method)

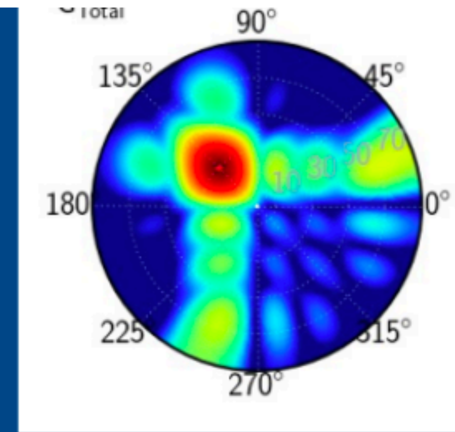
*T. Antoni et al., NIM A 513 (2003) 490.*

*S. Thoudam et al., Astroparticle Physics 73 (Jan., 2016) 34–43,*




Dispersion

*

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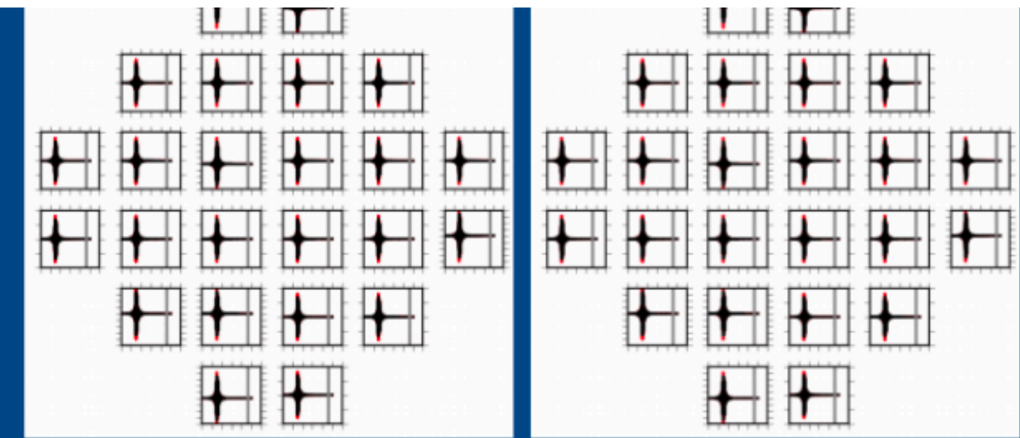


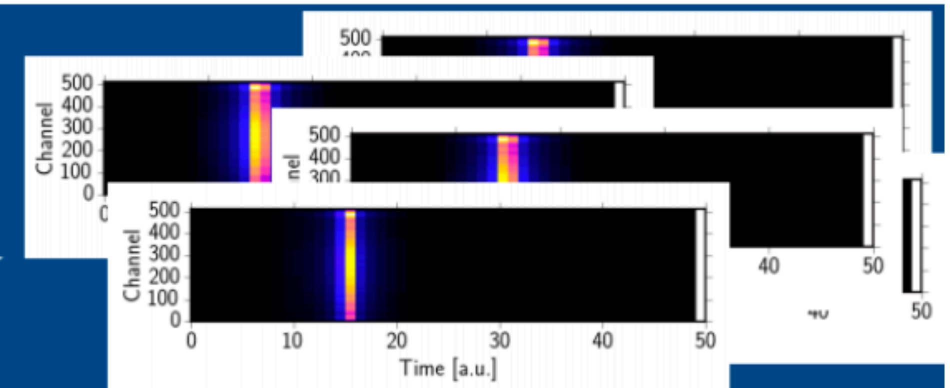
E-Field Pulse

Fold with tile gain-pattern

Voltage in Stations

## 2. Simulate Pre-Processing

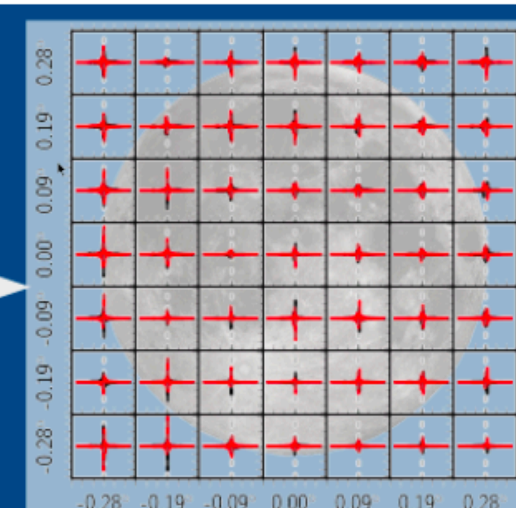
Voltage in Stations → PPF → *Other Filters* →




Station Beams

## 3. Online Analysis

Station Beam → PPF Inversion → De Dispersion →

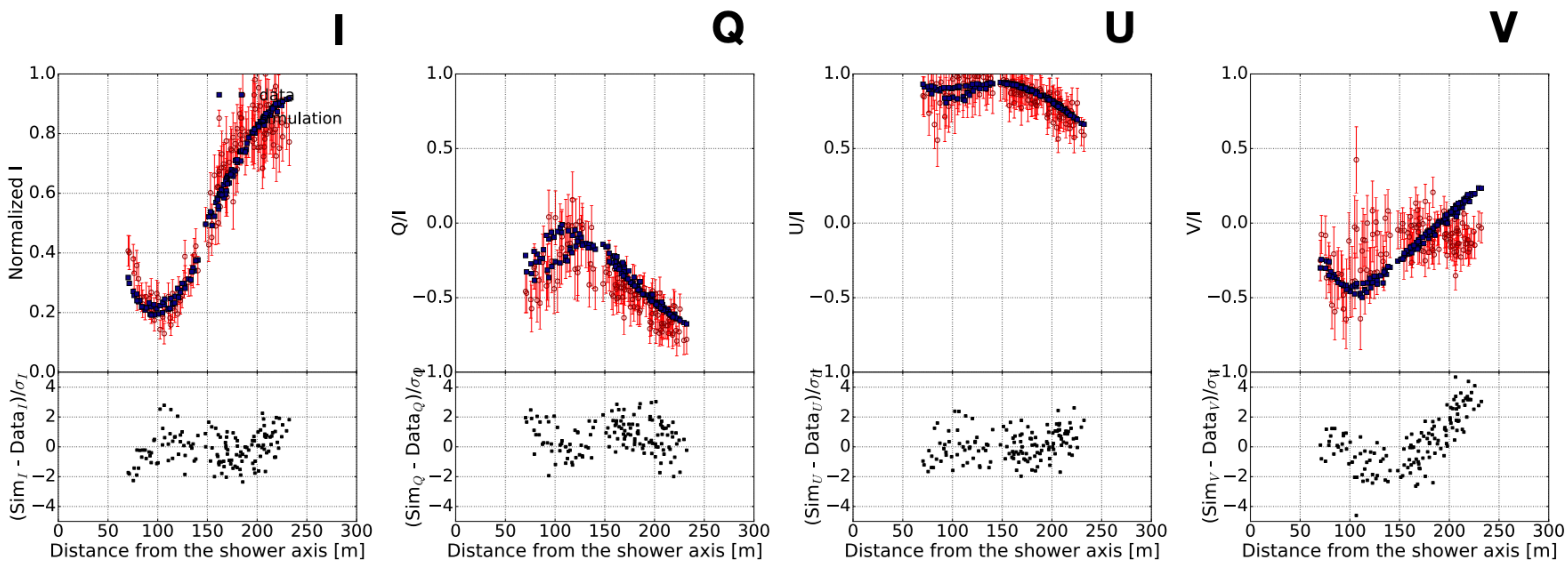


Analysis Beams on Moon

→ Trigger

T. Winchen

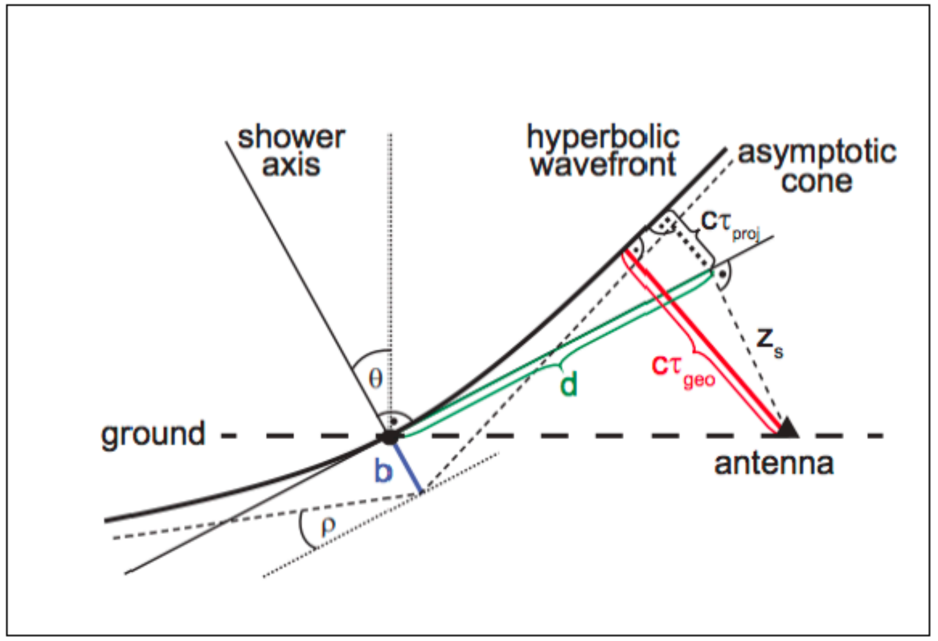
# Full Stokes polarisation & thunderstorms

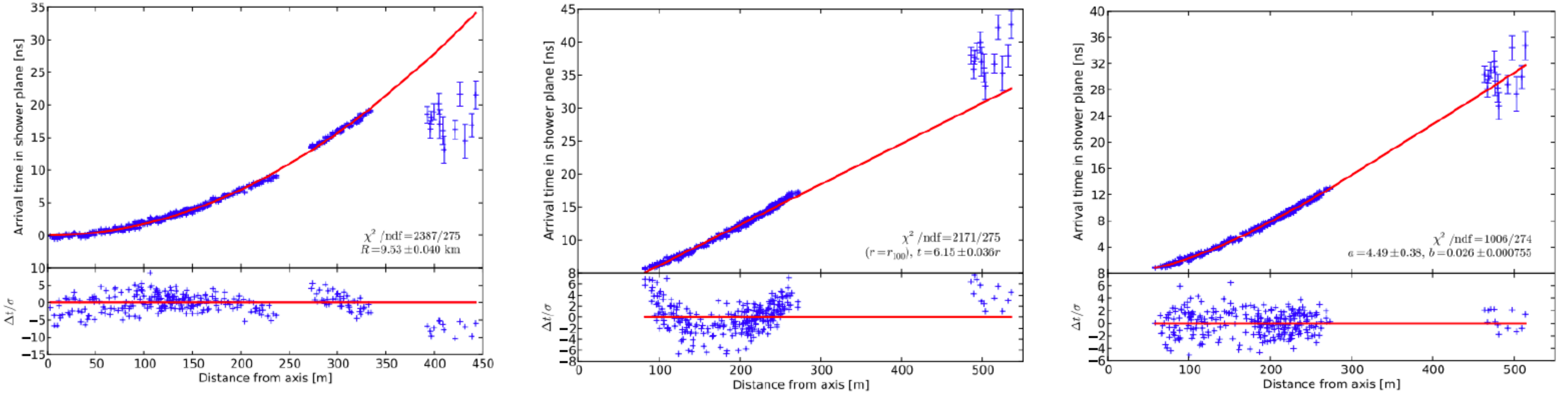



- Fair weather: small amount of circular polarisation confirmed by data
  O. Scholten et al., PRD **94** 1030101 (2016)

- **Thunderstorms**: strong signal in all Stokes parameters used to reconstruct atmospheric electric fields
  G. Trinh et al., PRD **95** 083004 (2017)

# Wavefront Shape




(c) Spherical fit

(b) Conical fit

(a) Hyperbolic fit

Corstanje, A. et al. Astropart.Phys. 61 (2015) 22-31

# Thunderstorm events

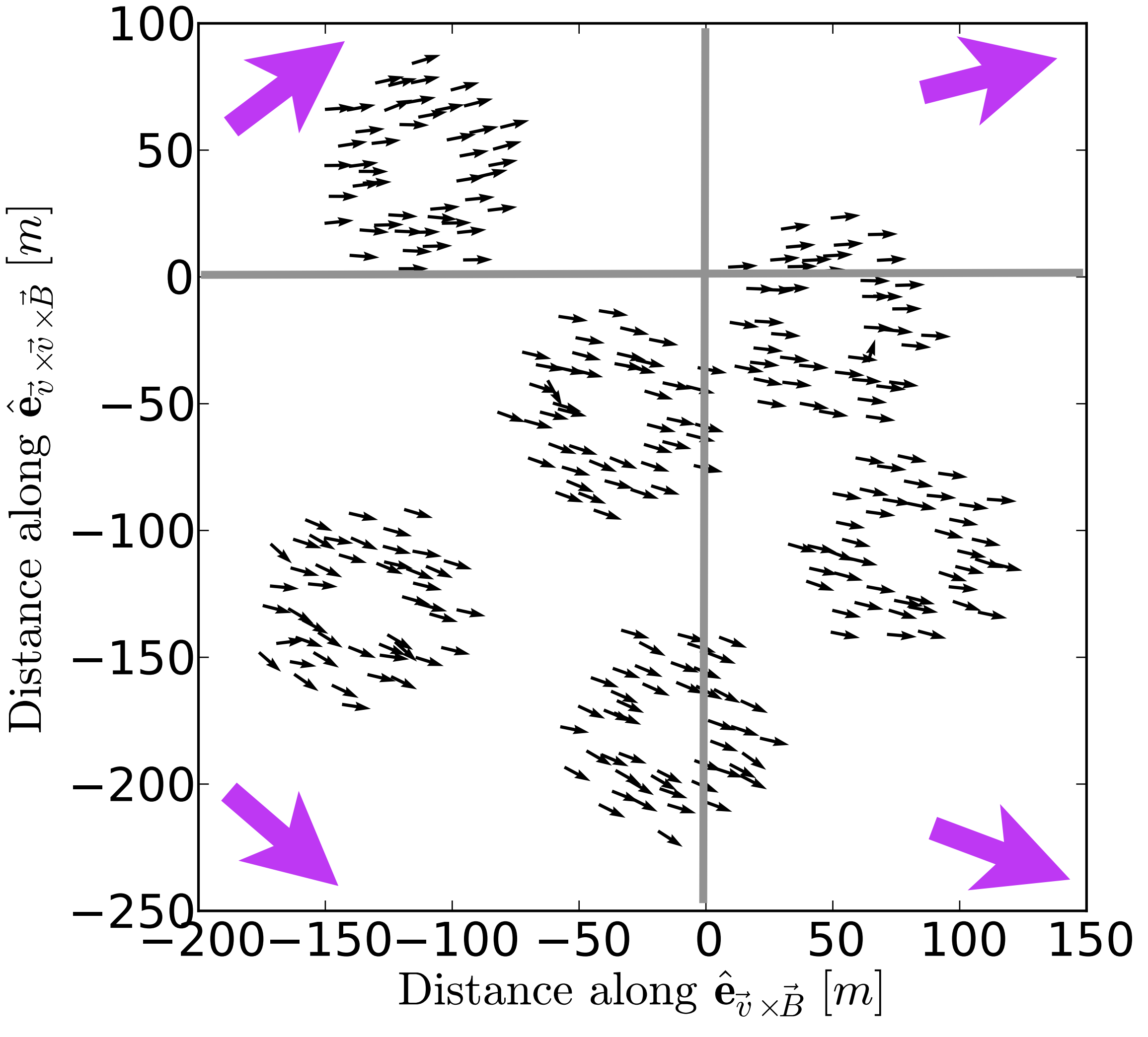
LOPES: Amplification in thunderstorms

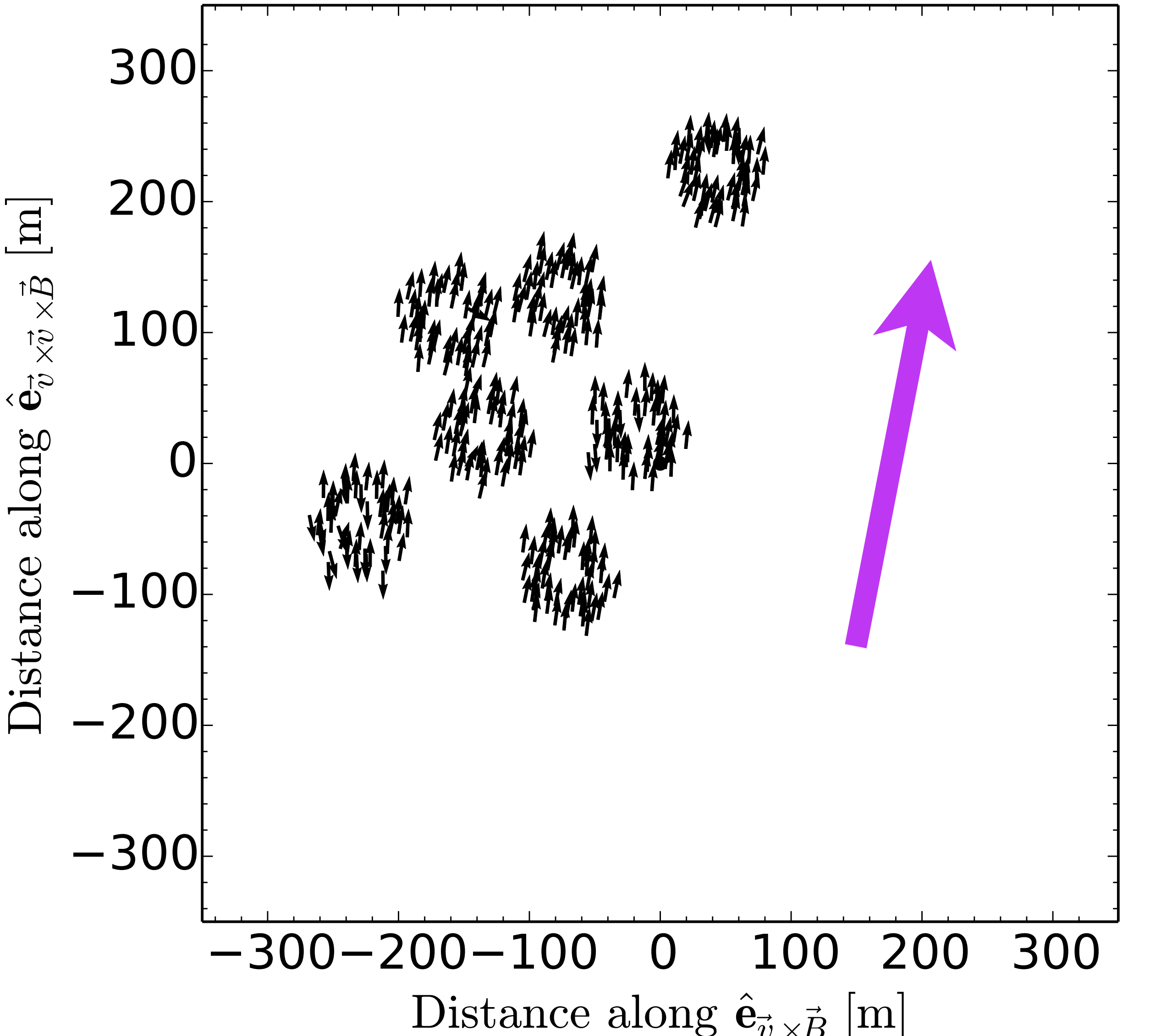
S.B. et al. A&A **467**, 385 (2007)

LOFAR: measure atmospheric E-field

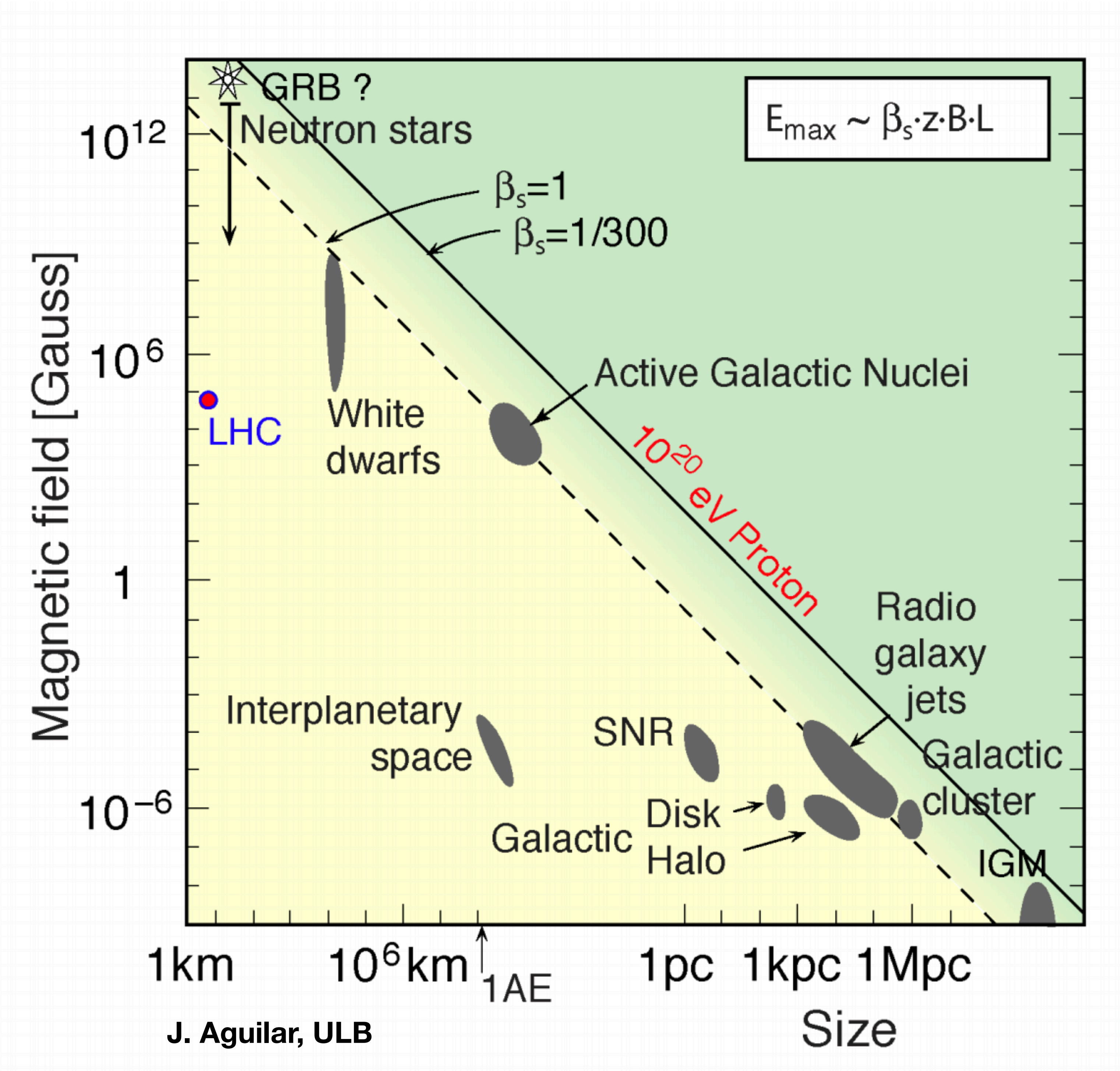
Schellart et al. PRL **114**, 165001 (2015)

Trinh et al. PRD **93**, 023003 (2016)



# Hillas Plot




$$E_{max} \simeq 10^{18}\text{eV}\; Z\, \beta \left(\frac{R}{\text{kpc}}\right)\left(\frac{B}{\mu\text{G}}\right)$$