Radio detection of cosmic rays with LOFAR … and beyond

Katie Mulrey

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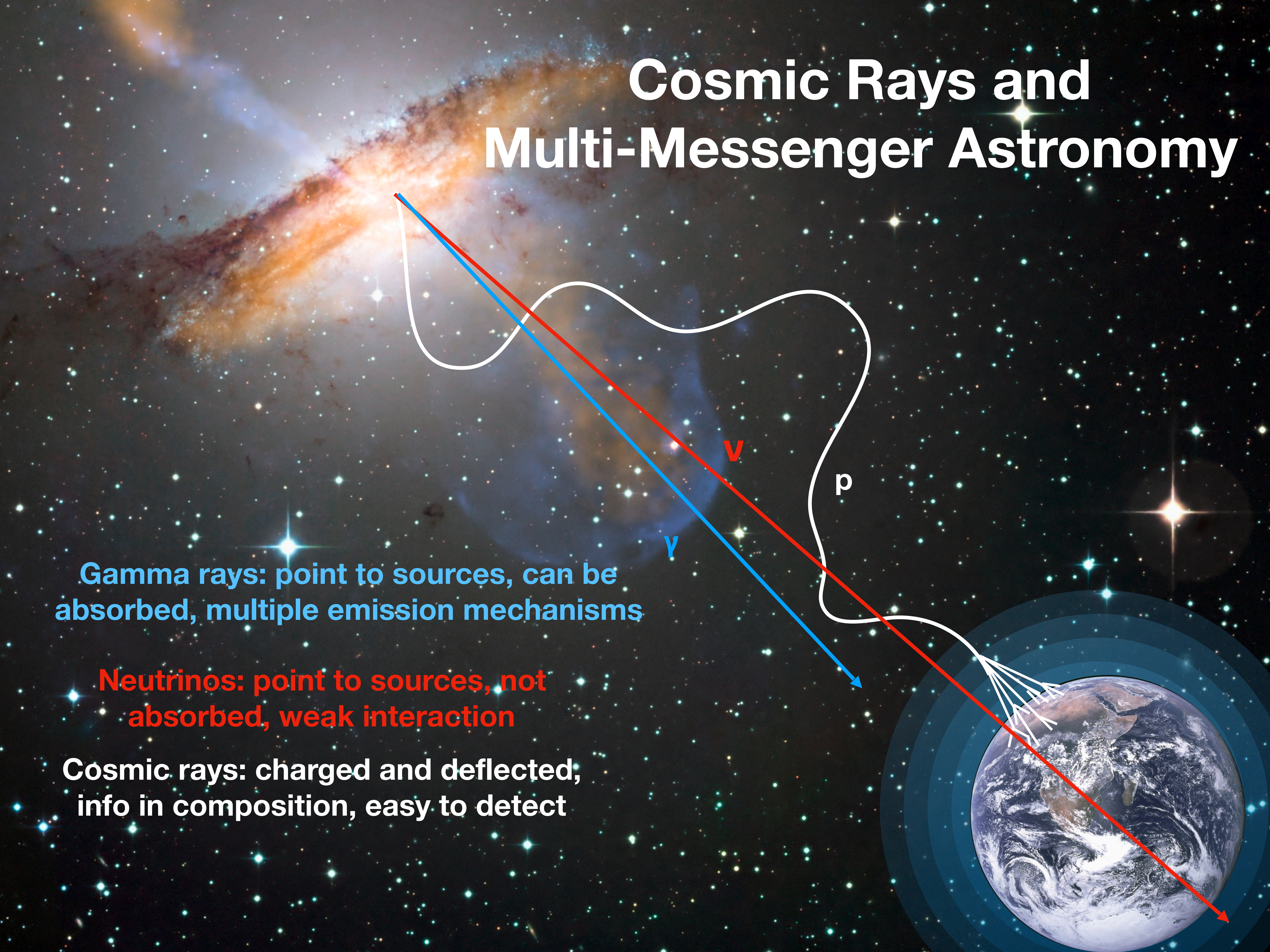
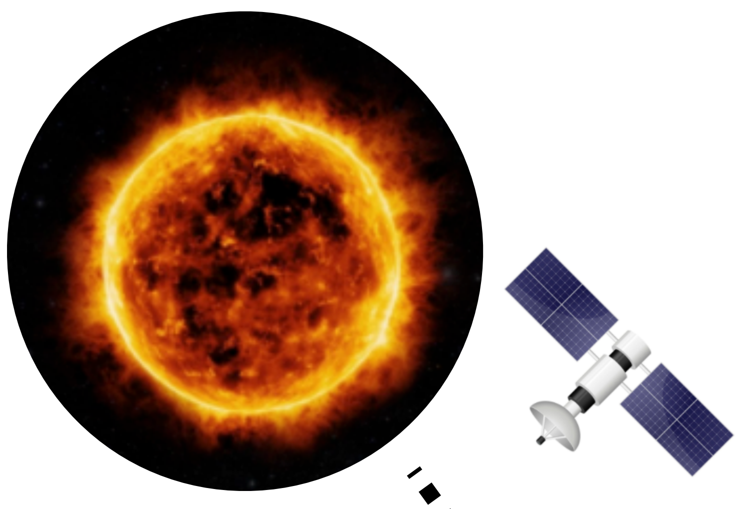
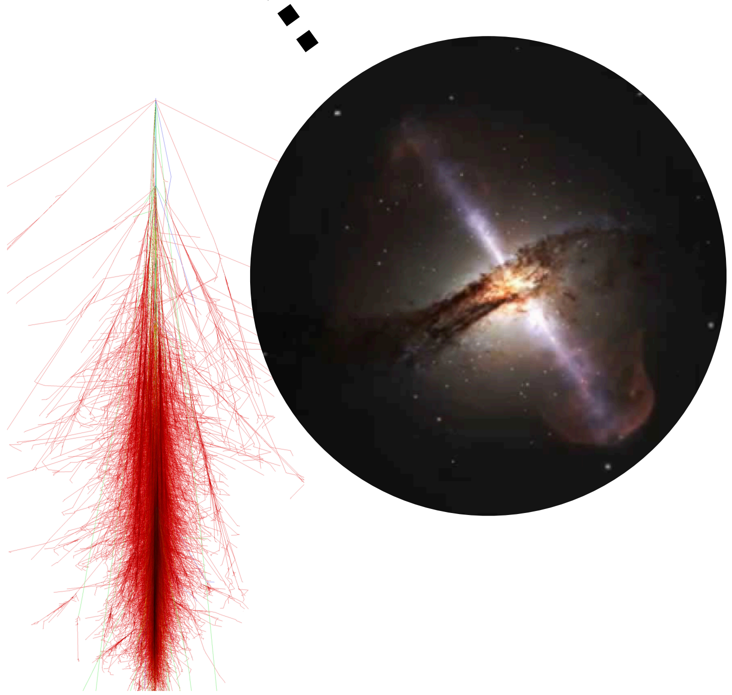
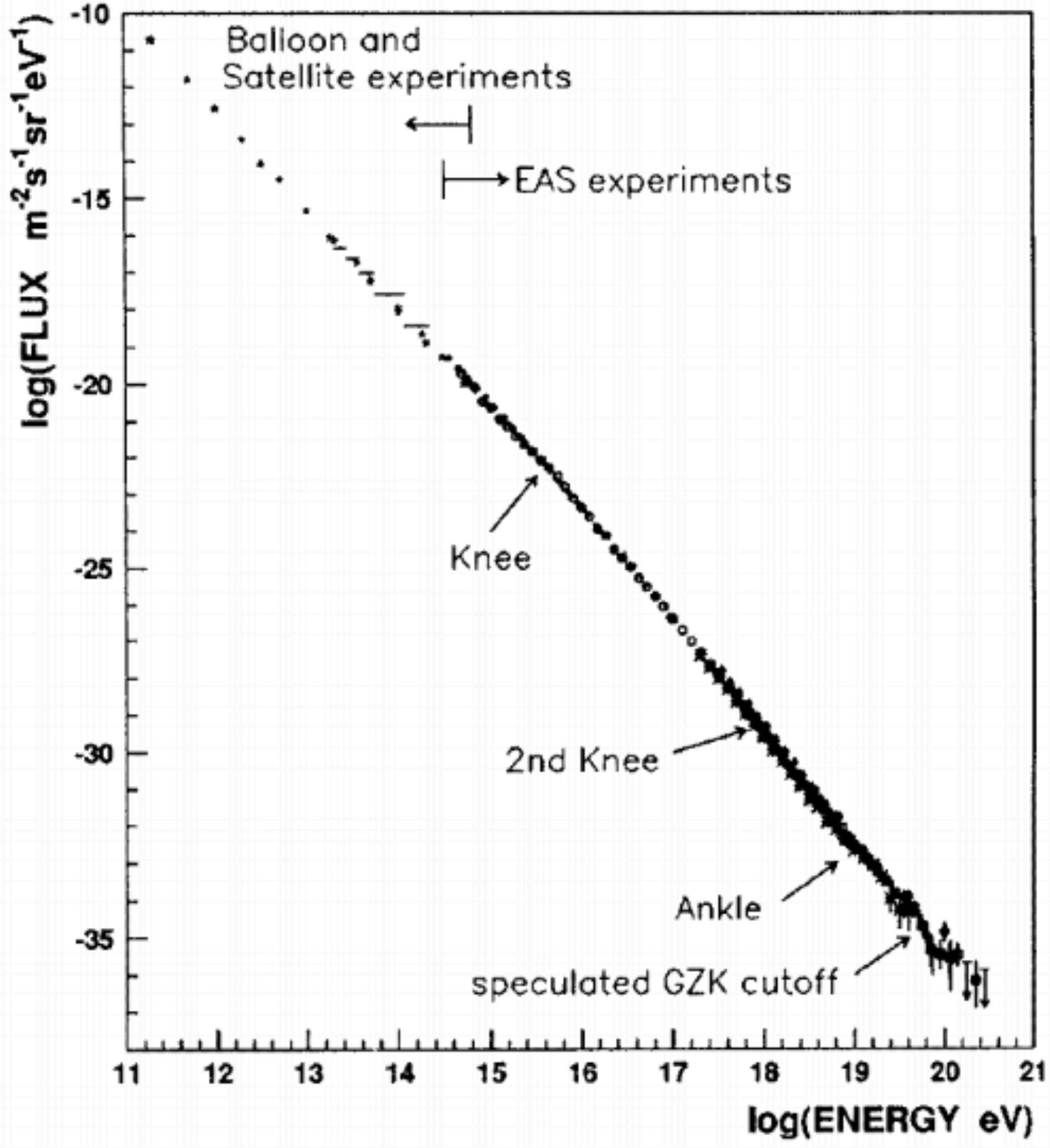

Cosmic Rays and
Multi-Messenger Astronomy
ν
p
γ
Gamma rays: point to sources, can be absorbed, multiple emission mechanisms
Neutrinos: point to sources, not absorbed, weak interaction
Cosmic rays: charged and deflected, info in composition, easy to detect

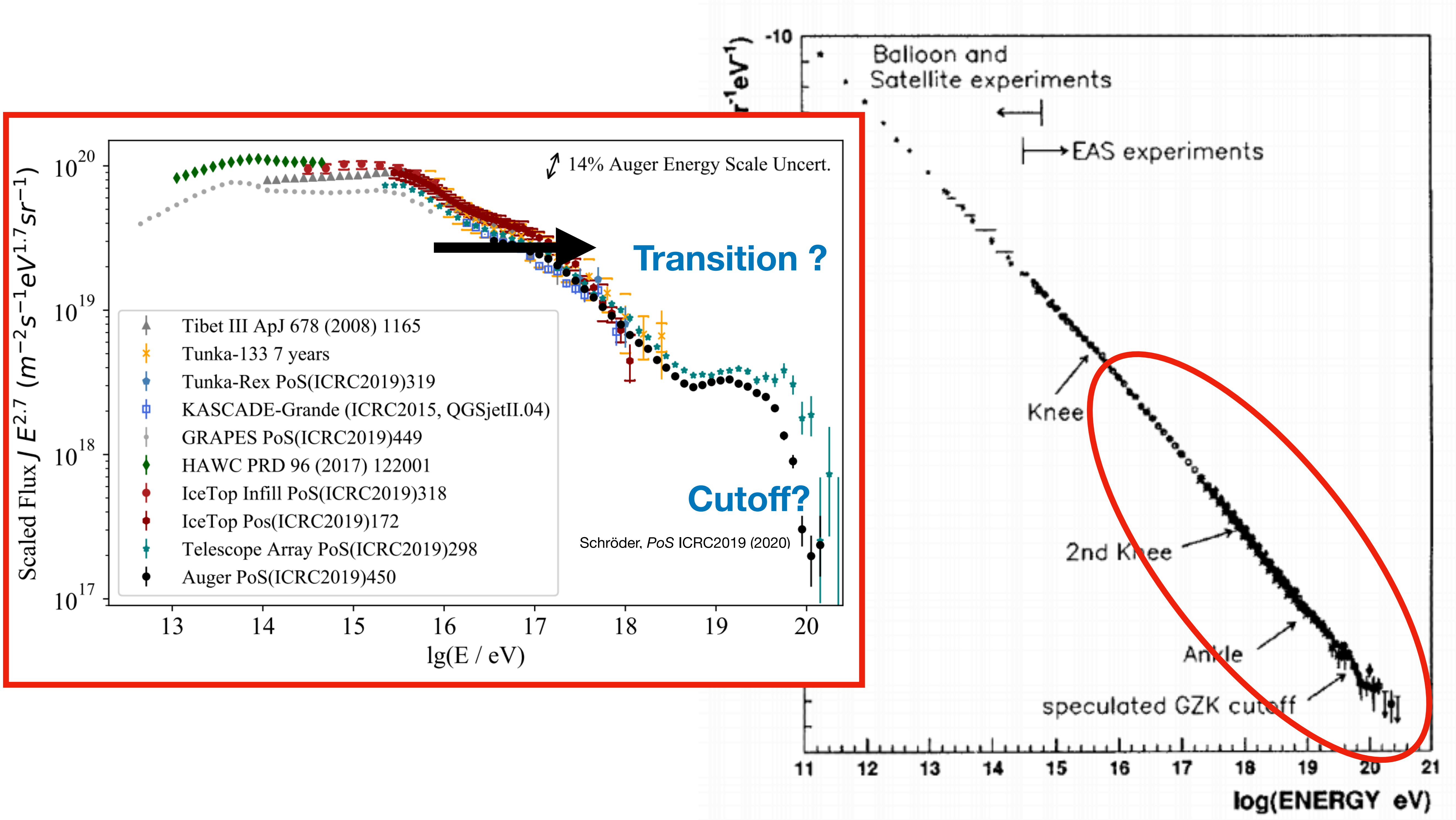
Where do cosmic rays come from?







Where do cosmic rays come from?



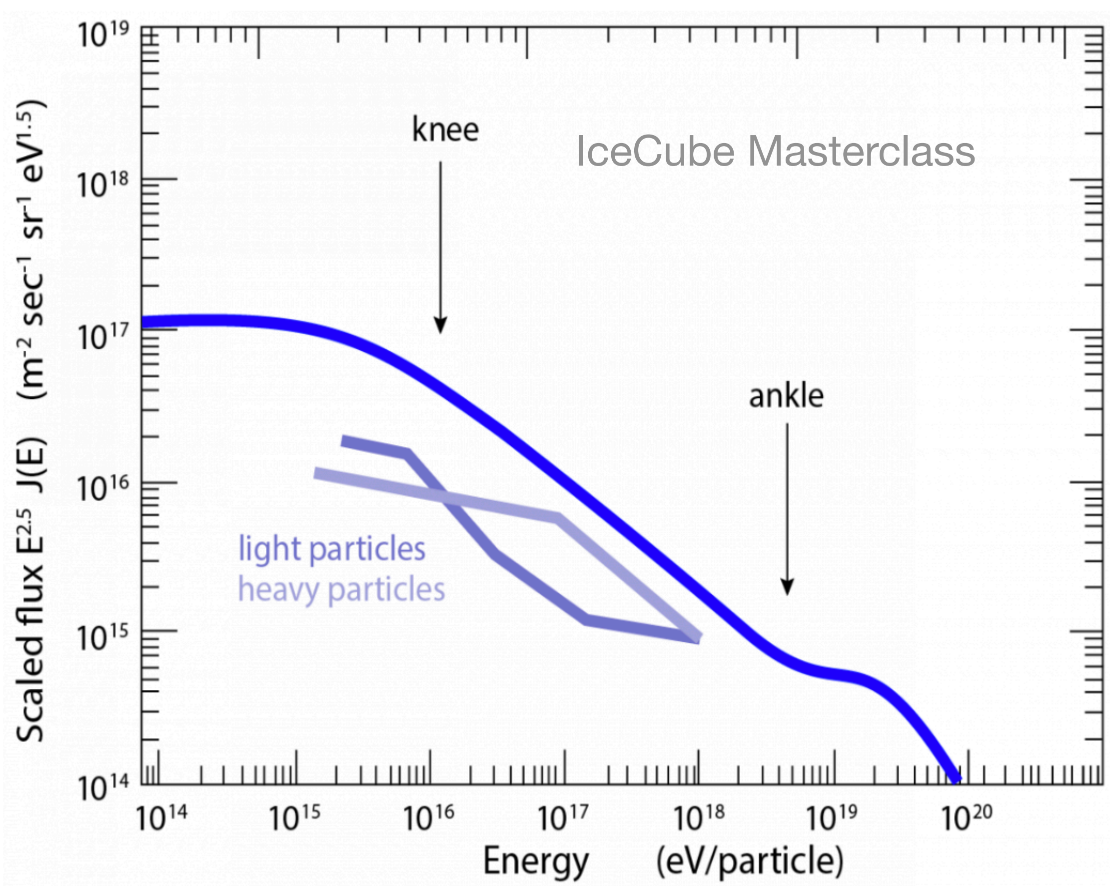
Where do cosmic rays come from?

Galactic: SNR ? → **Extragalactic: AGN ?**

Hillas criterion:

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

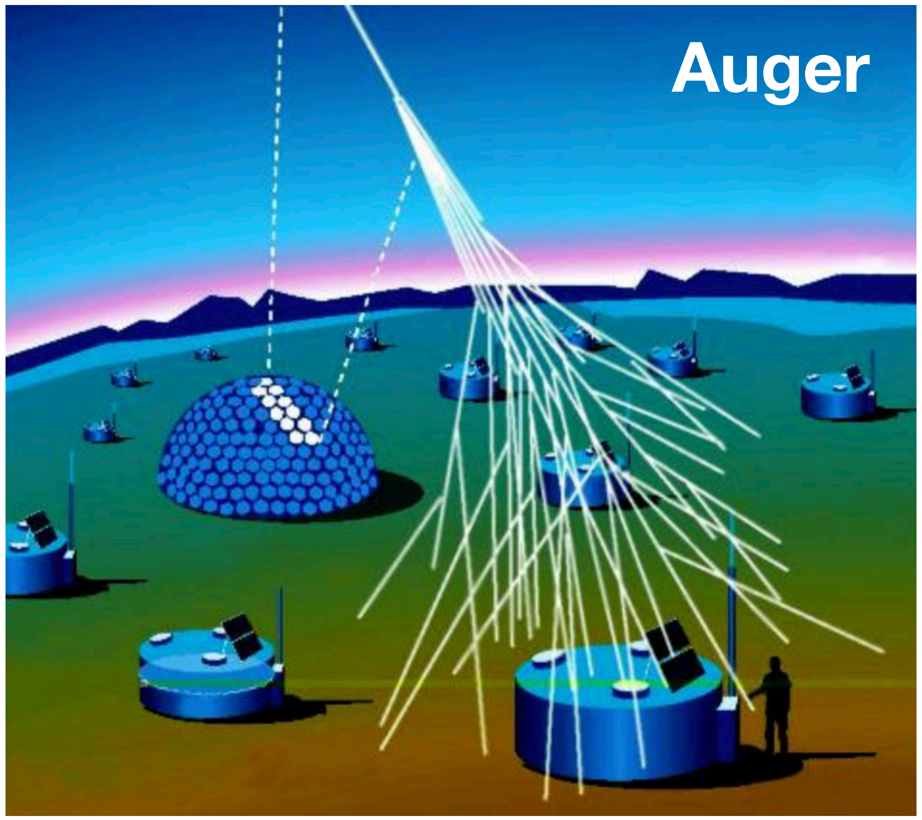
$$E_{Fe,\ max} = 26 \times E_{p,max}$$

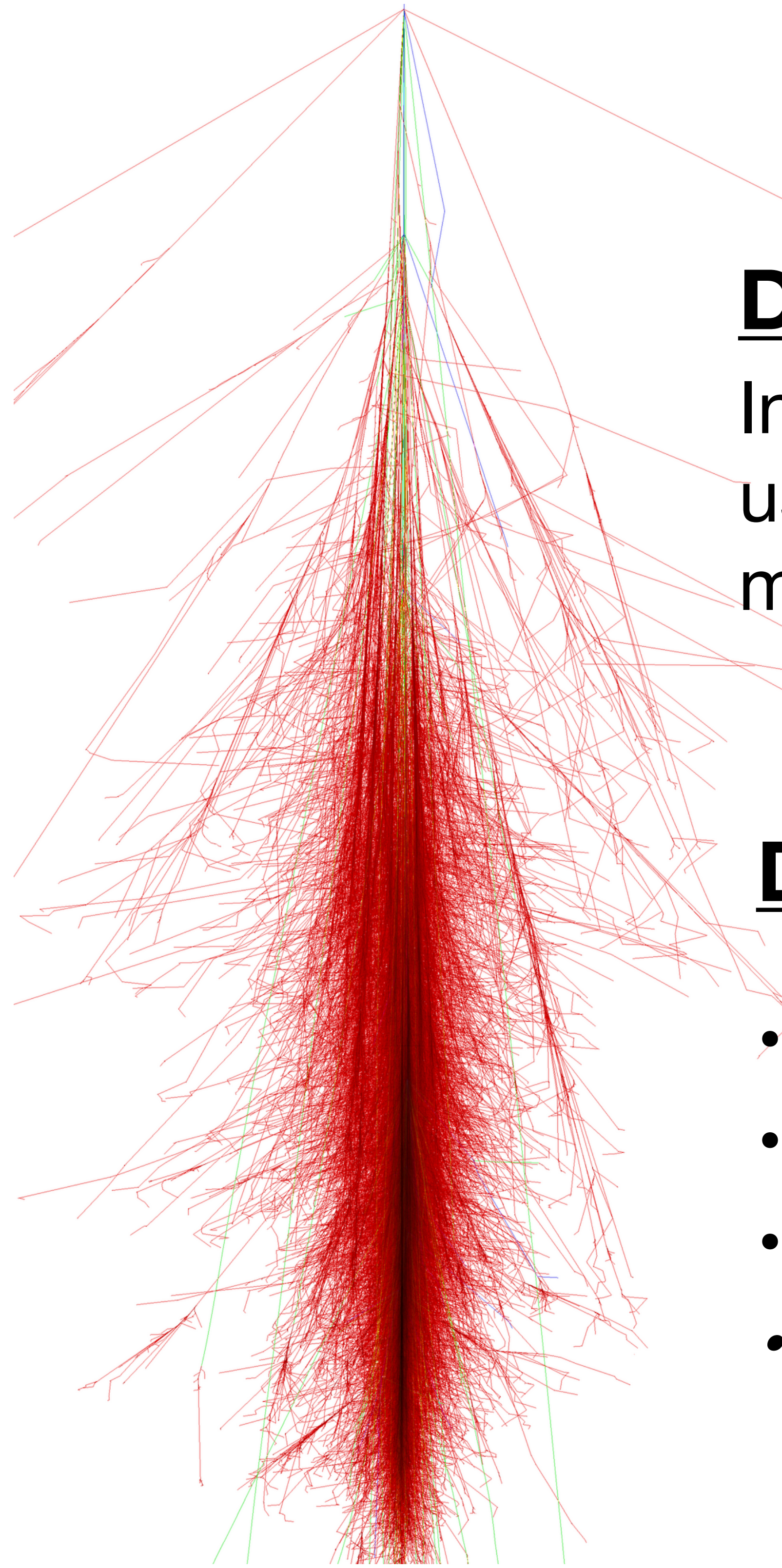


- Below 10^{19} eV, can't point directly to sources
- Transition to heavier composition indicates the maximum source energy is reached

To answer this question, we need to determine the *energy* and *composition* of cosmic rays.

Detecting comic-ray air showers





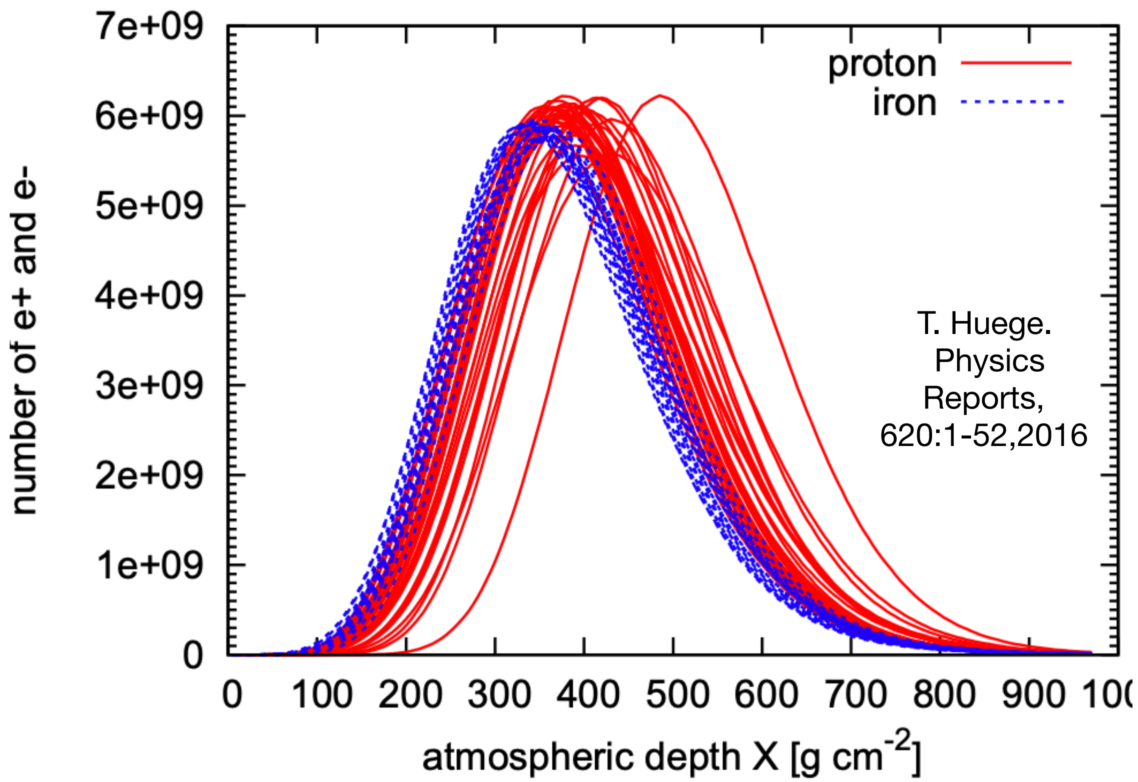
Detection Strategy

Instrument a wide area or use a large target to maximize effective area.

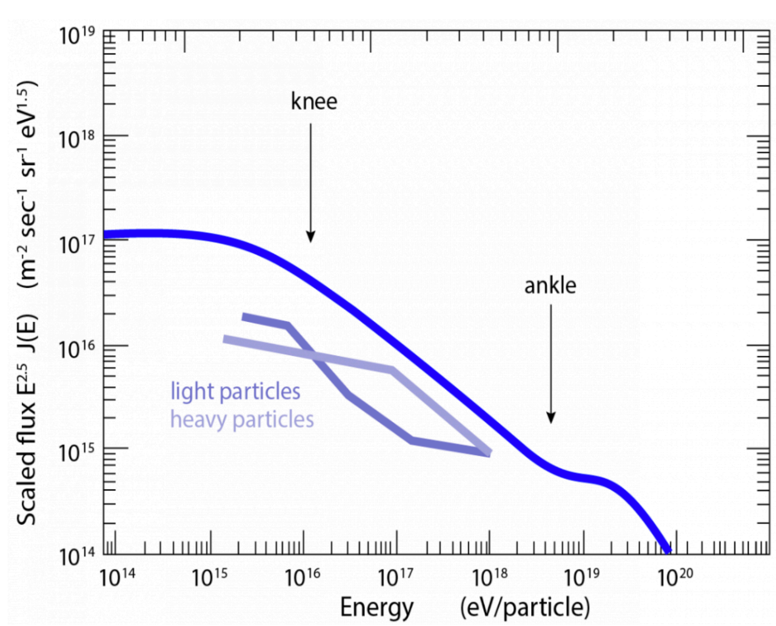
Detection Methods

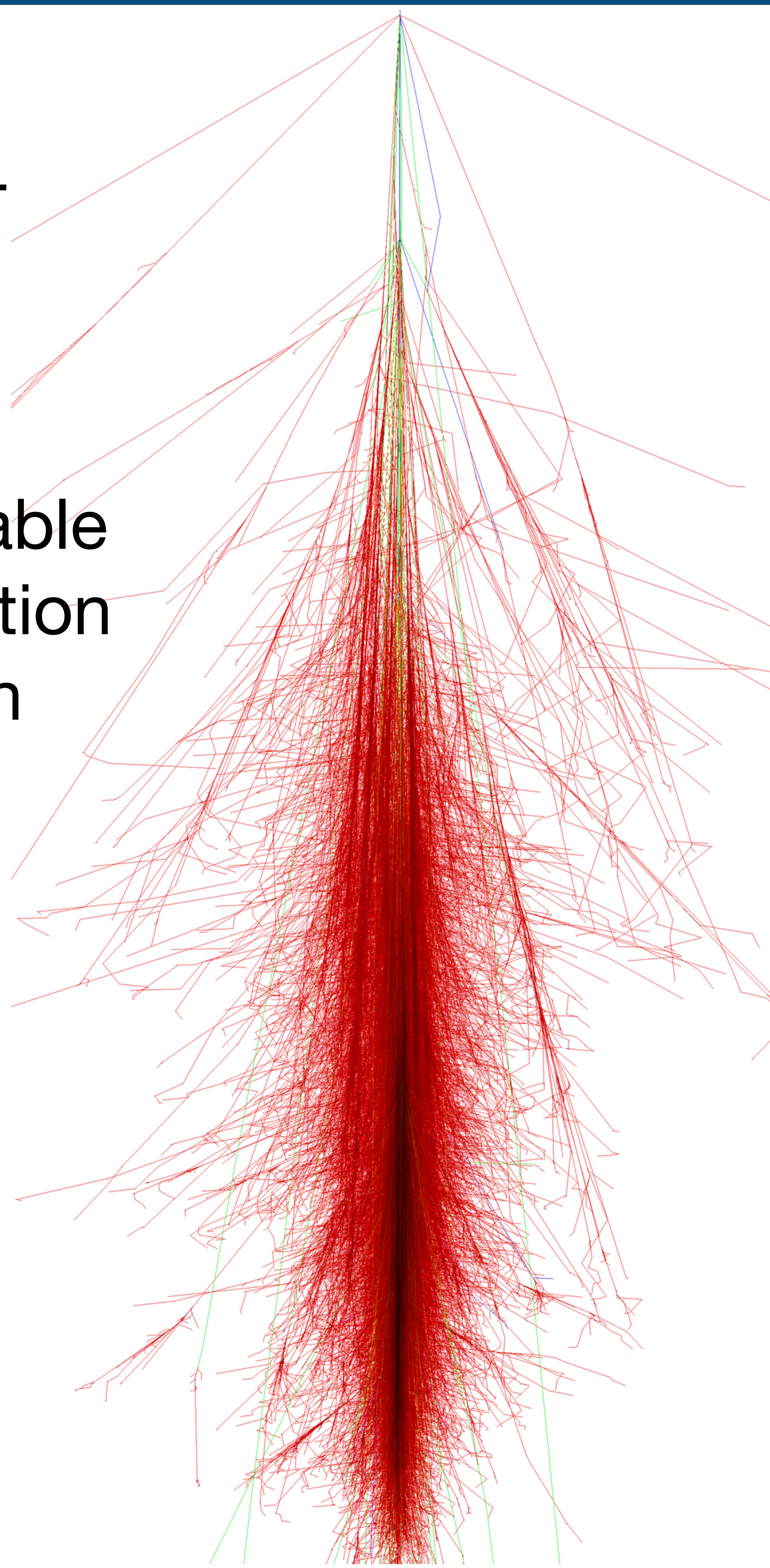
- Particles
- Fluorescence
- Cherenkov light
- ***Radio***

Detecting comic-ray air showers

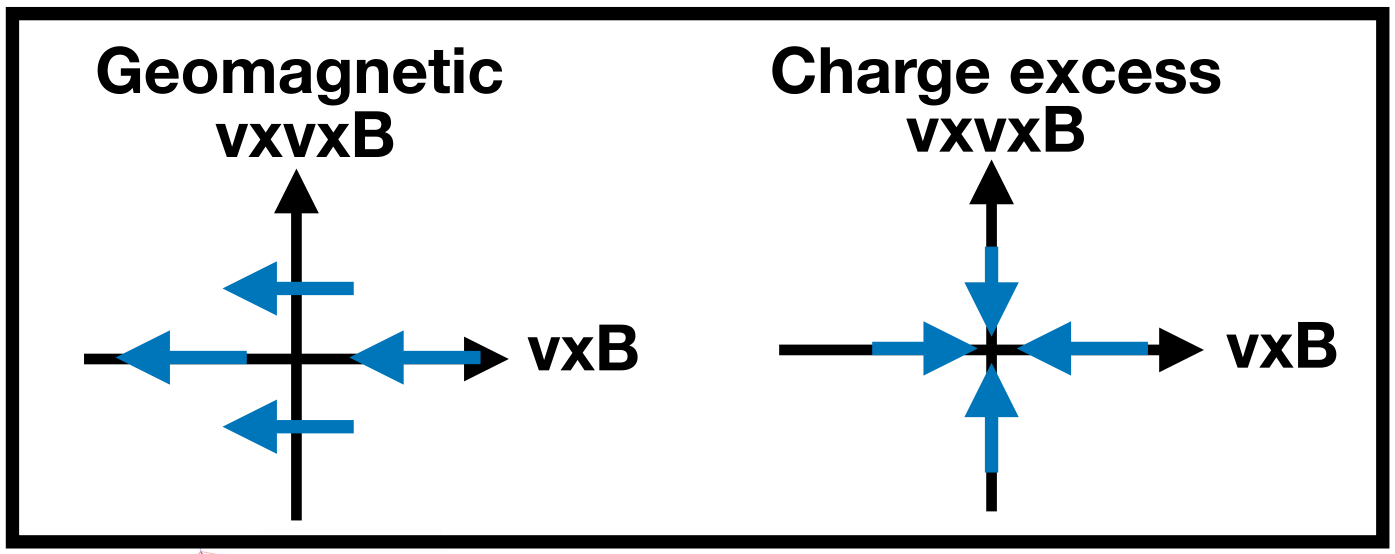


- Indirect detection- can't determine composition
- **X_{max}** is an observable that gives information about composition



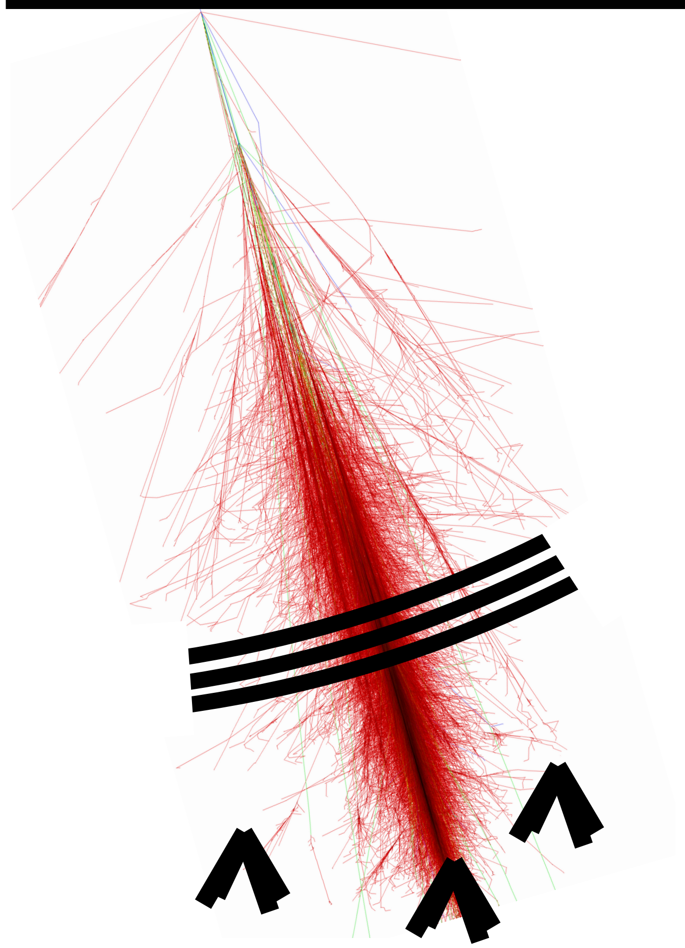


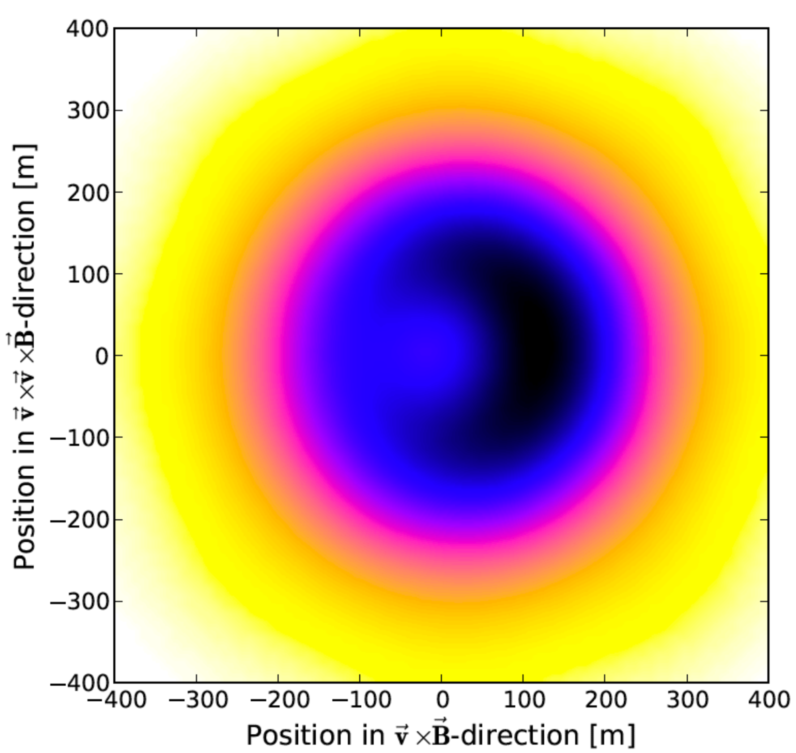
Radio Emission



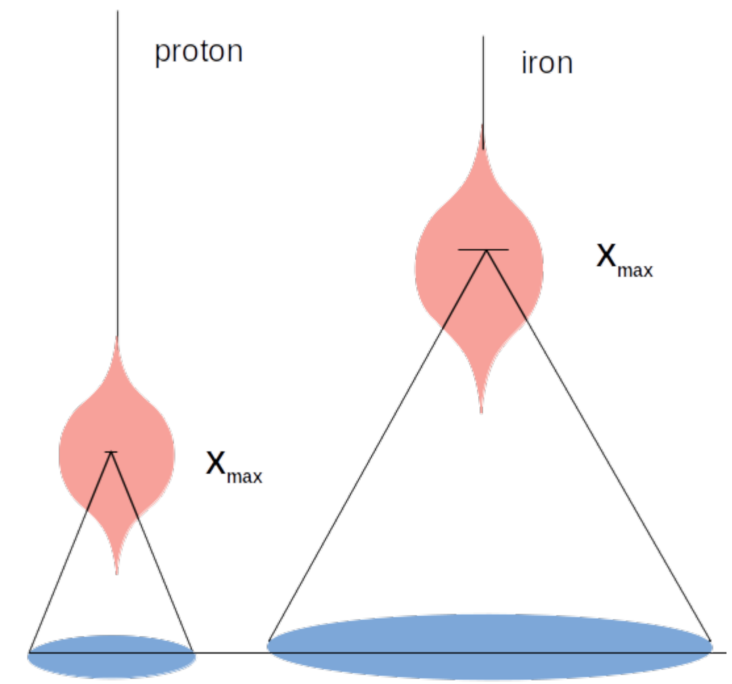
- Generated in the electromagnetic components of the air shower
- Radiation pattern, signal strength, and pulse shapes contain information about shower development

X_{max} & energy

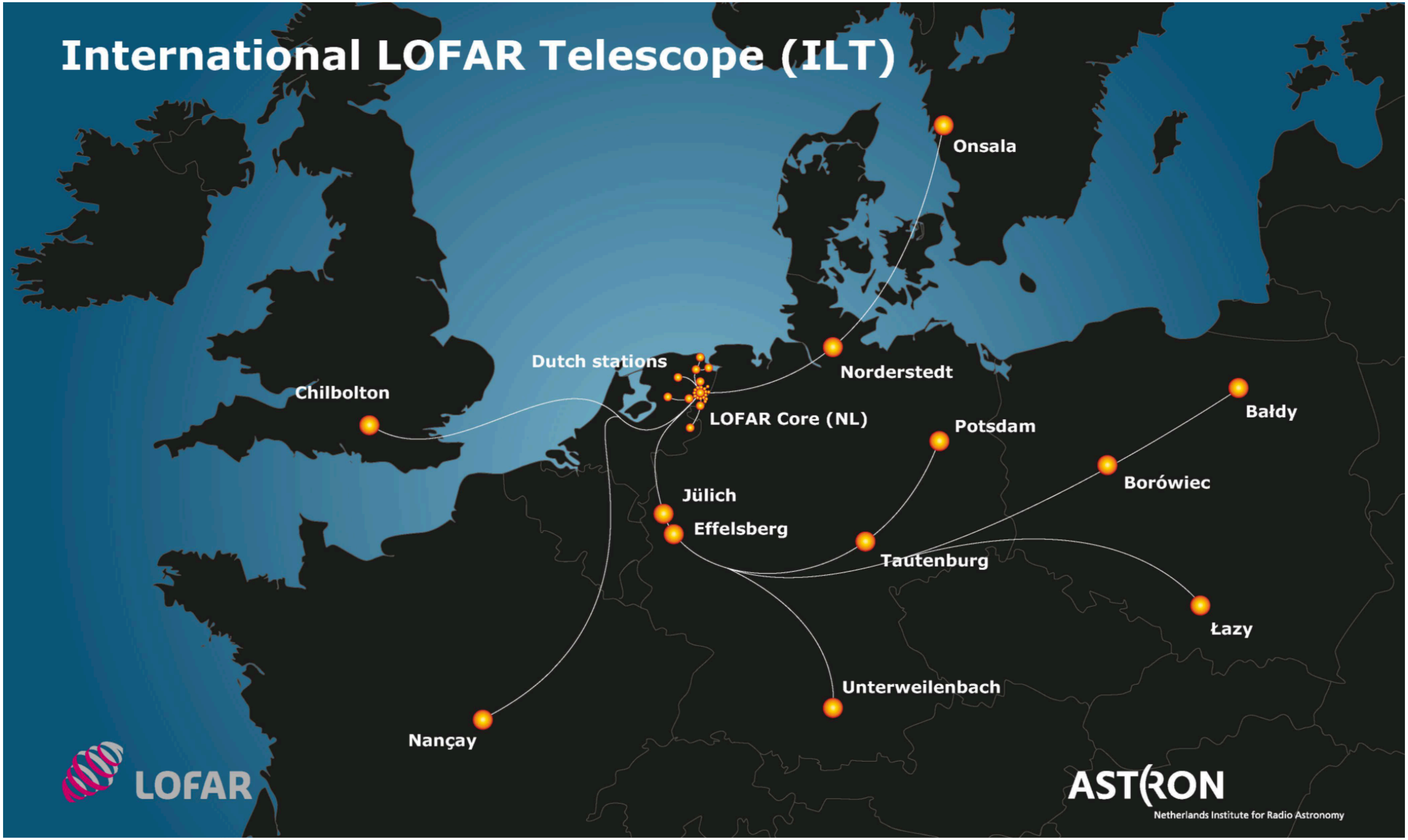




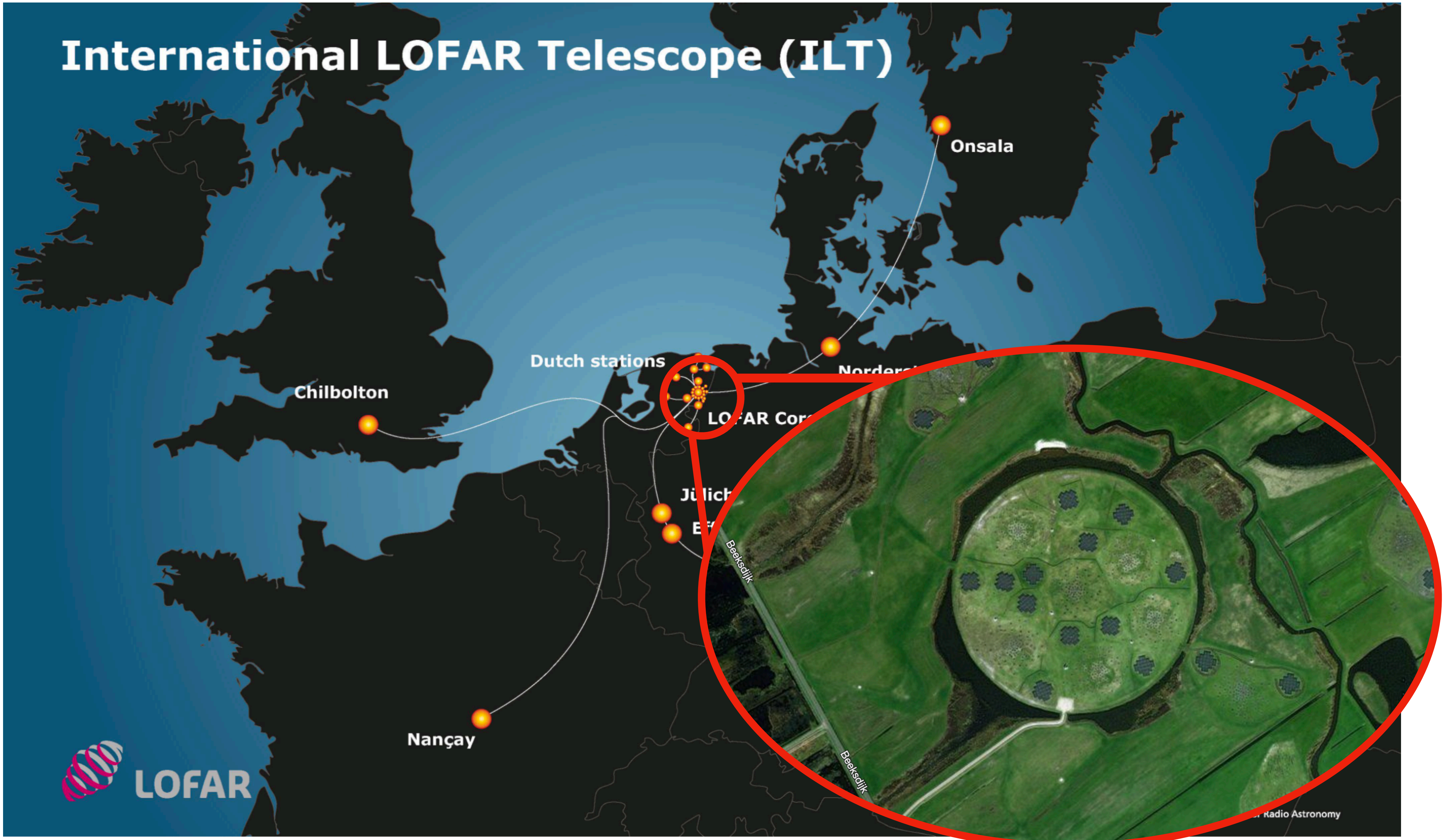
A. Nelles et al., Astropart. Phys. 60, 13 (2015)



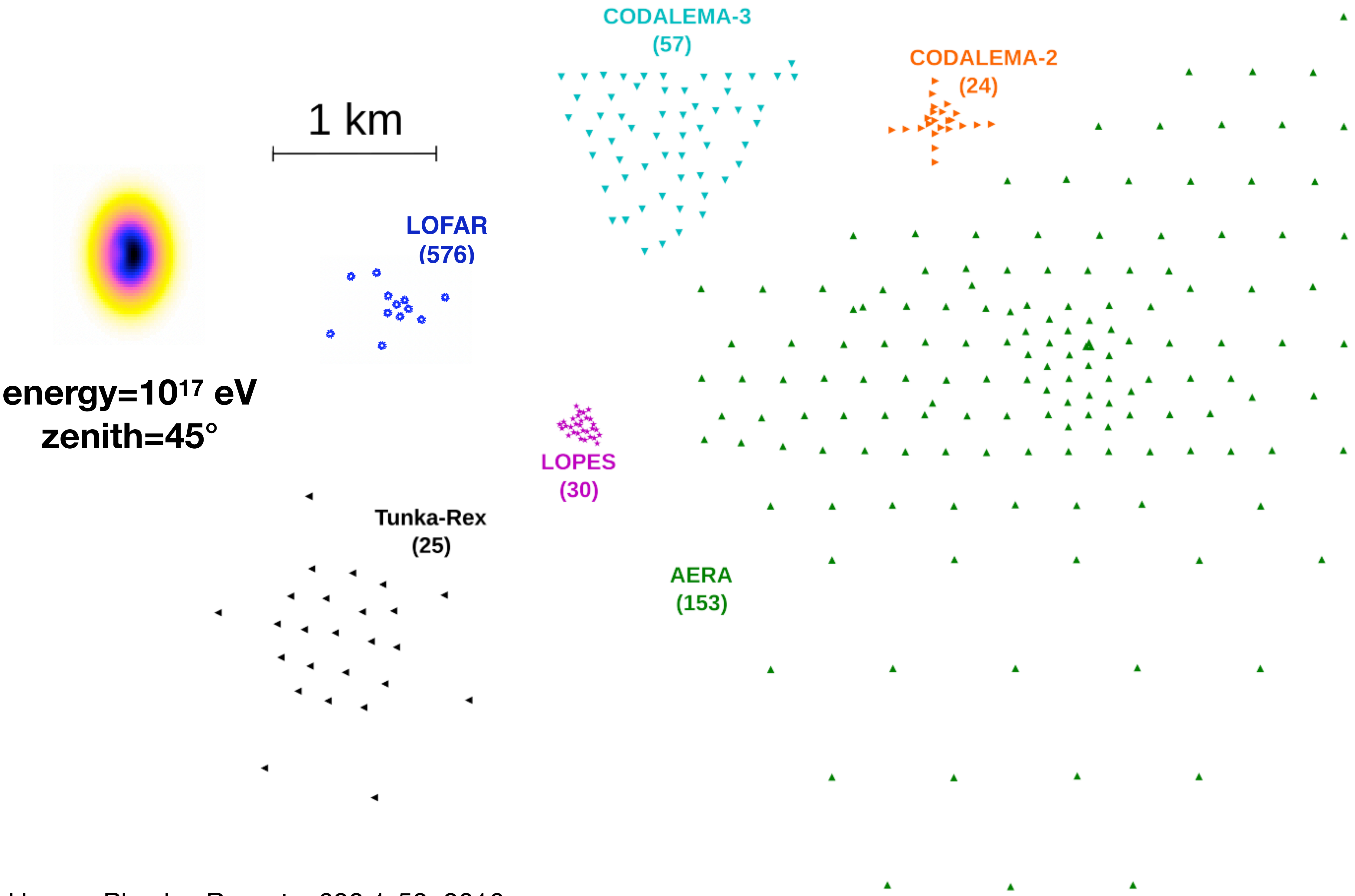
Low Frequency ARray



Low Frequency ARray



Radio Detection Experiments



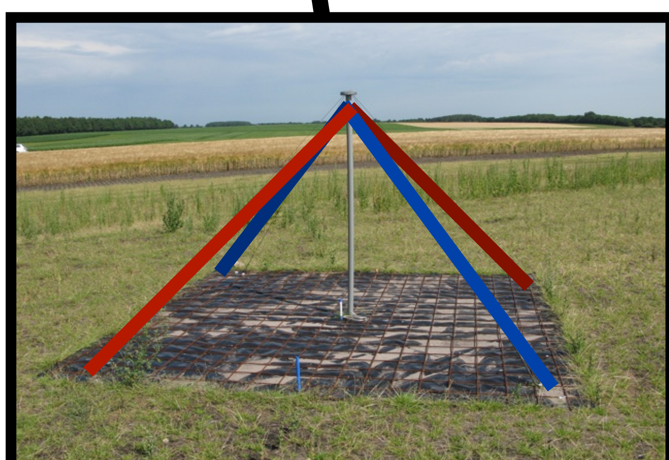
T. Huege. Physics Reports, 620:1-52, 2016.

Cosmic Ray Detection at LOFAR

300 m

- LOFAR Radboud Array (LORA) scintillators
- Provides trigger for antenna readout

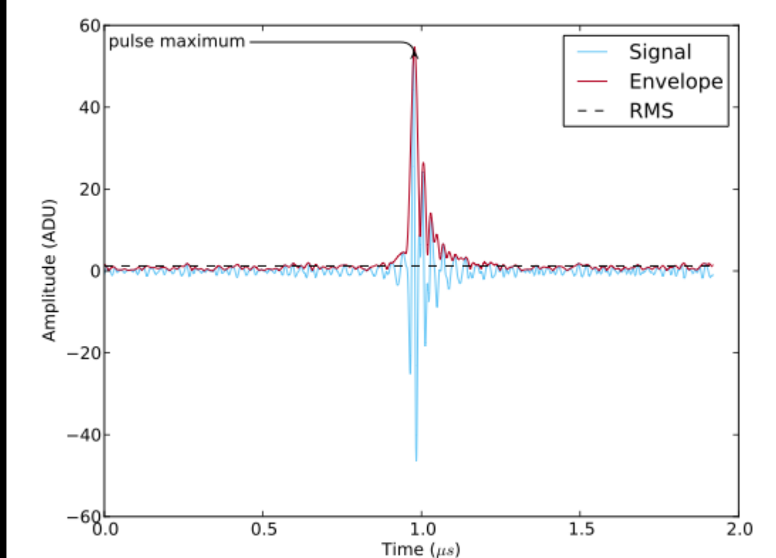
trigger



buffer

2 ms read-out

offline analysis

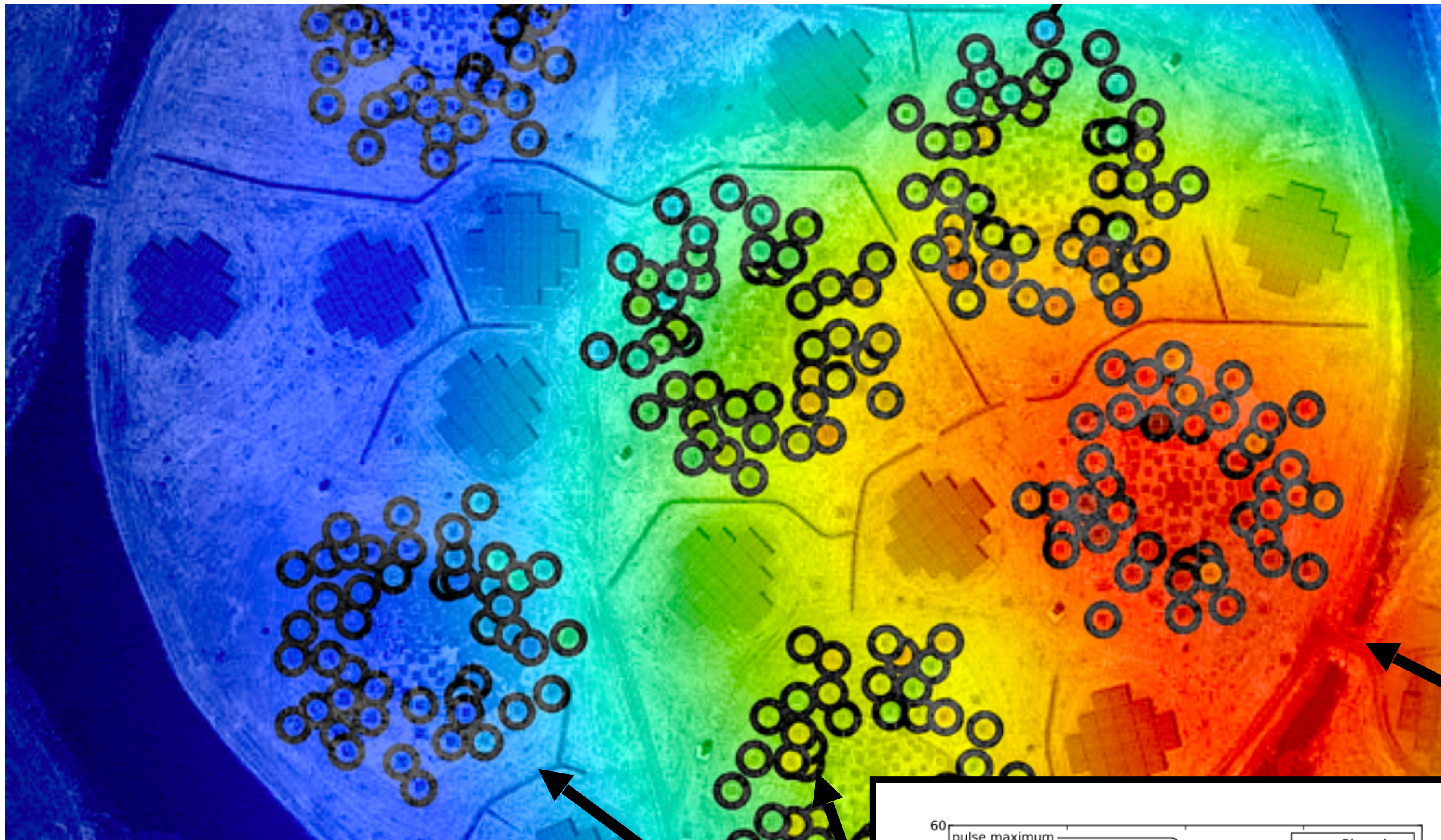


- RFI cleaning
- direction reconstruction
- antenna pattern unfolding
- calibration

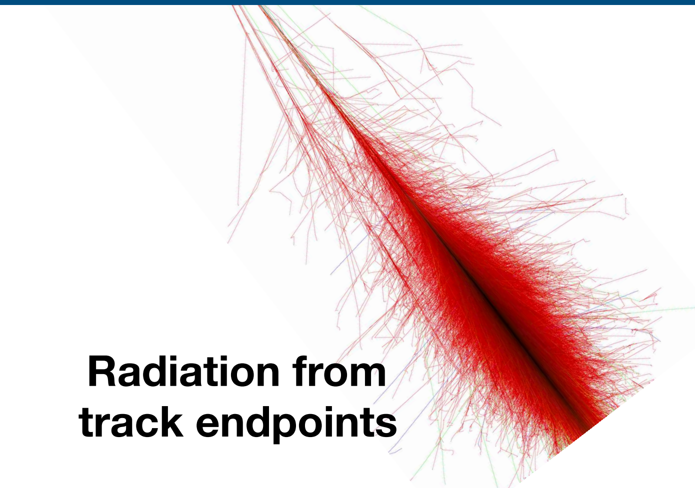
P. Schellart et al., A&A 560, 98 (2013)

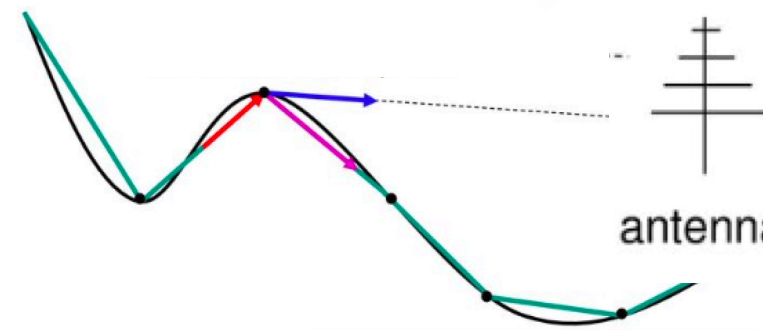
6 LBA stations (6 x 48 antennas)
+ stations outside Superterp, 30-80 MHz

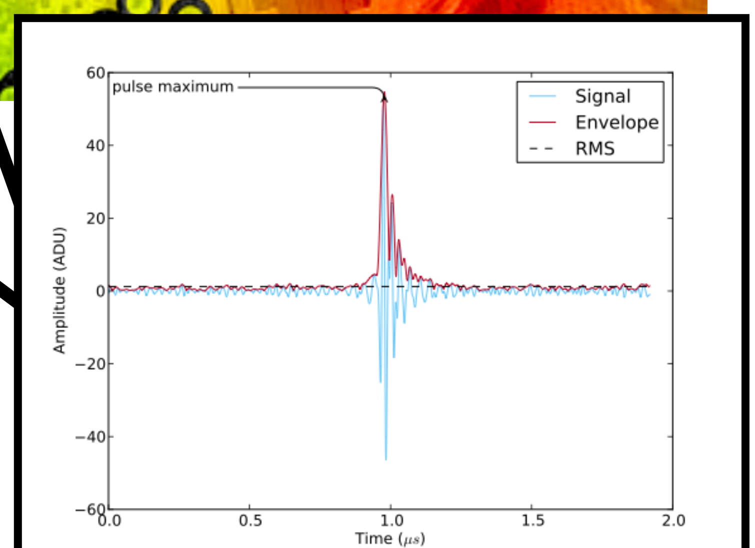
Event Analysis



SB et al. PRD 90 082003 (2014).







<u>LOFAR data</u>

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

<u>CoREAS simulation</u>

- no assumptions about emission
- independent of hadronic models

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

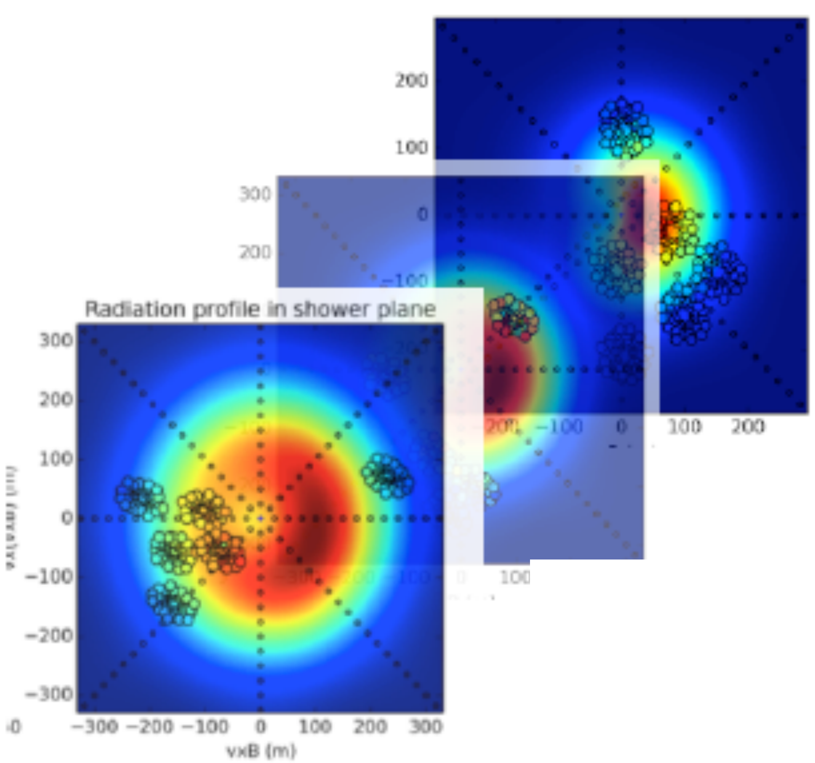
Event Analysis

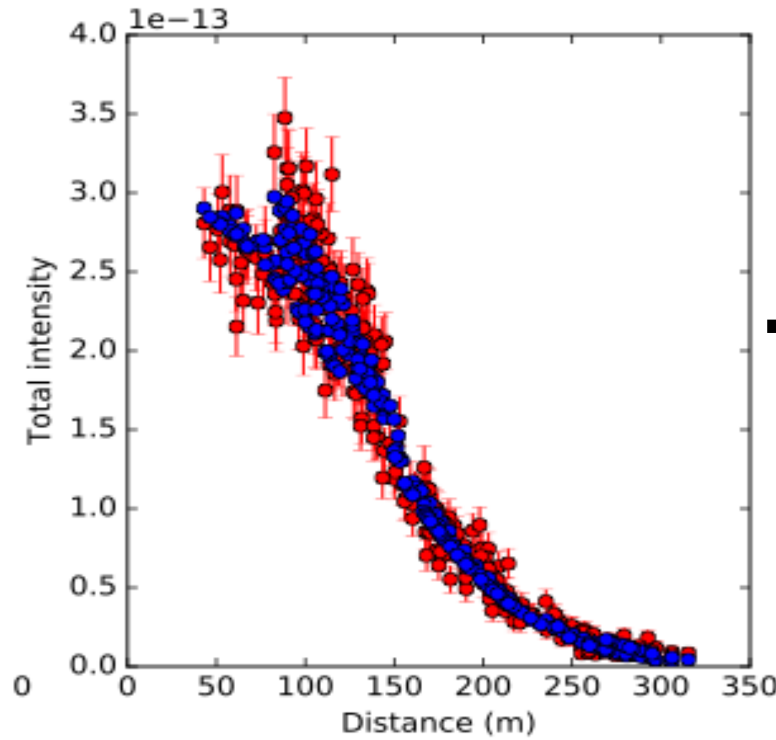
- Simulate ~30 P and Fe showers with realistic atmosphere and known arrival direction (natural distribution of X_{max})
- Calculate reduced χ^2 for each simulation
- Parabola fit determines event X_{max}
- Resolution < 20 g/cm^2
- Systematic uncertainties < 9 g/cm^2

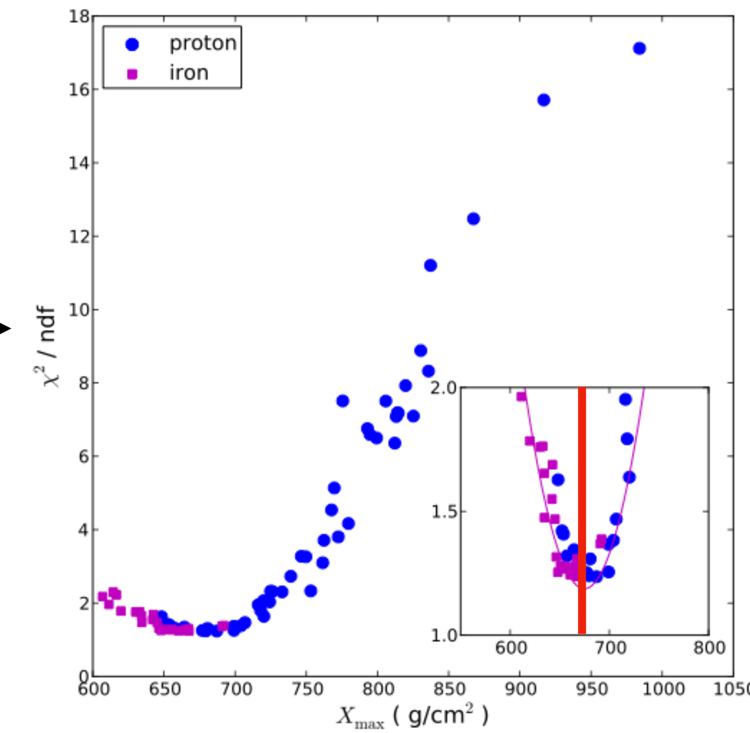
$$\chi^2_{\text{radio}} = \sum_{\text{antennas}} \left(\frac{P_{\text{ant}} - f_r^2 P_{\text{sim}} (x_{\text{ant}} - x_0, y_{\text{ant}} - y_0)}{\sigma_{\text{ant}}} \right)^2$$

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

Free parameters: energy and core position







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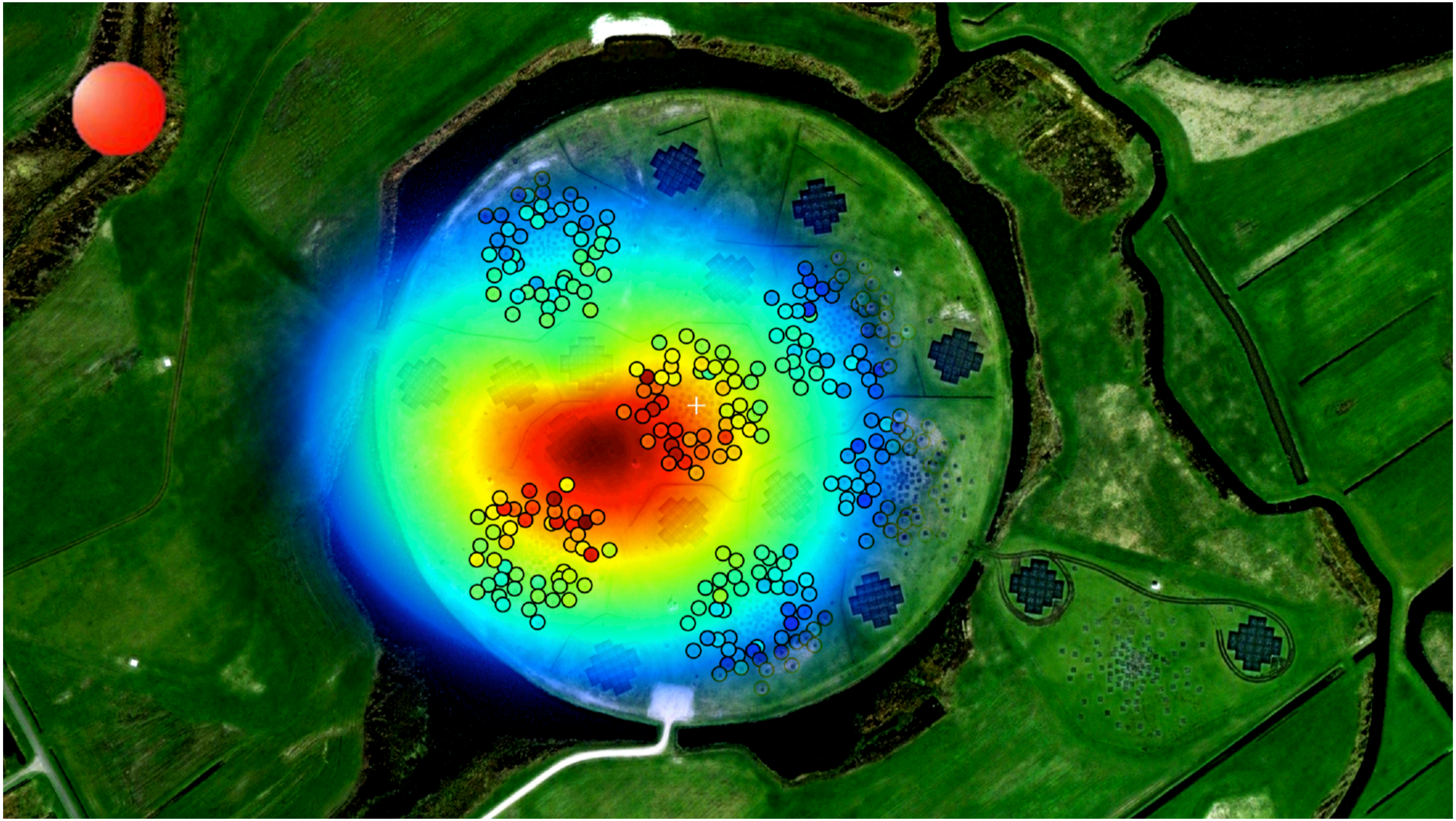

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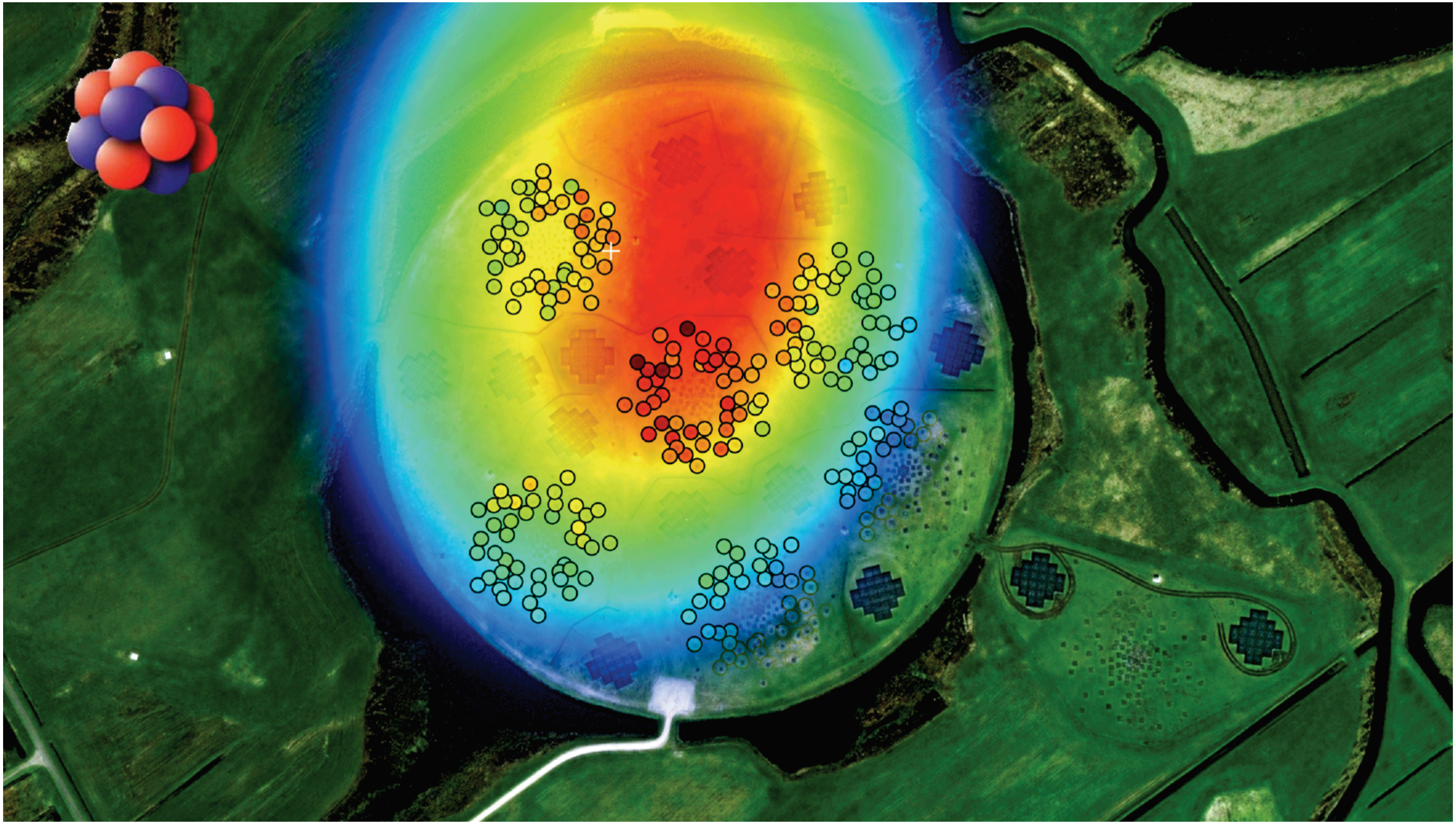
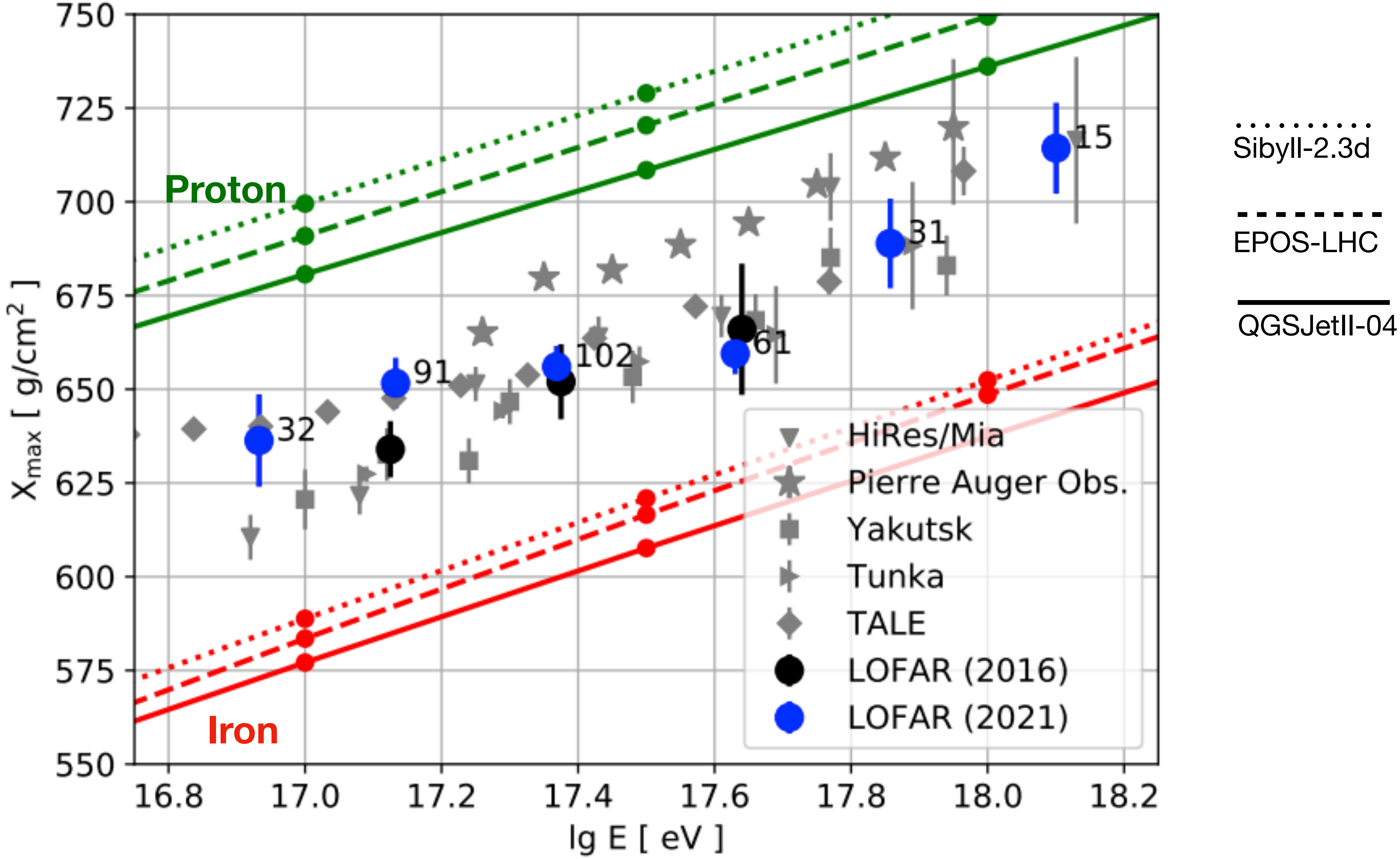


Composition Results



Corstanje et al. 2021. arXiv:2103.12549v1

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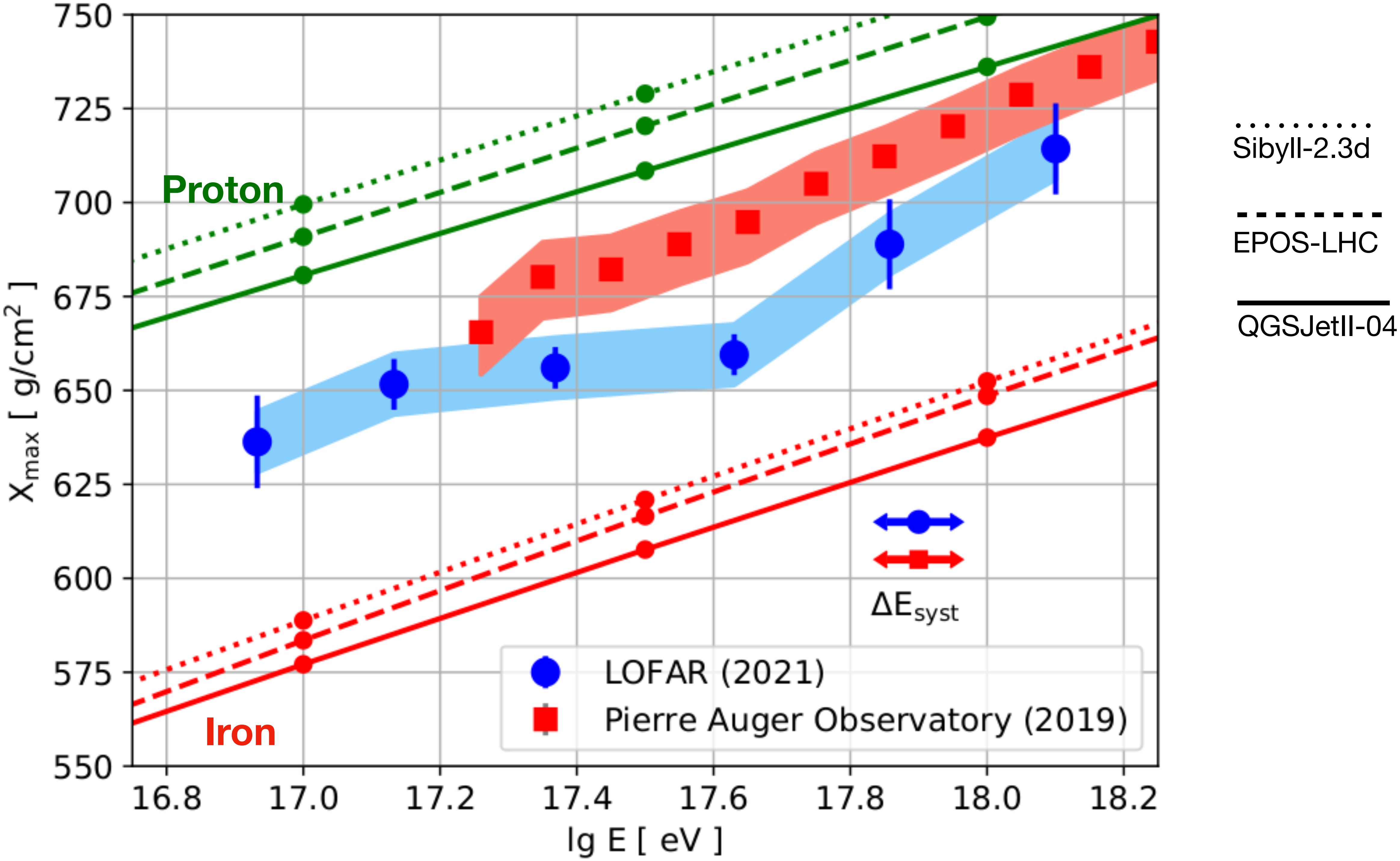
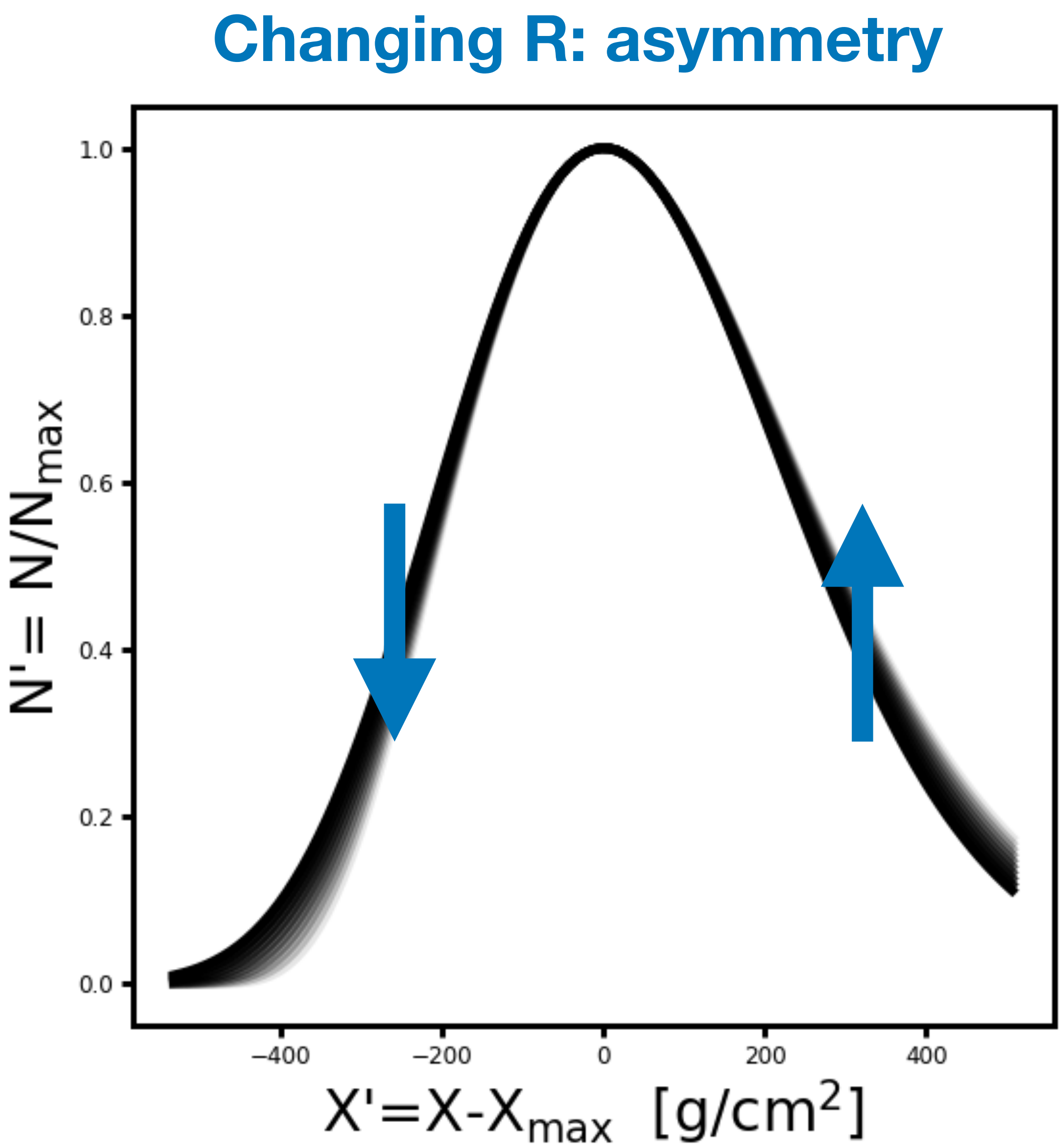
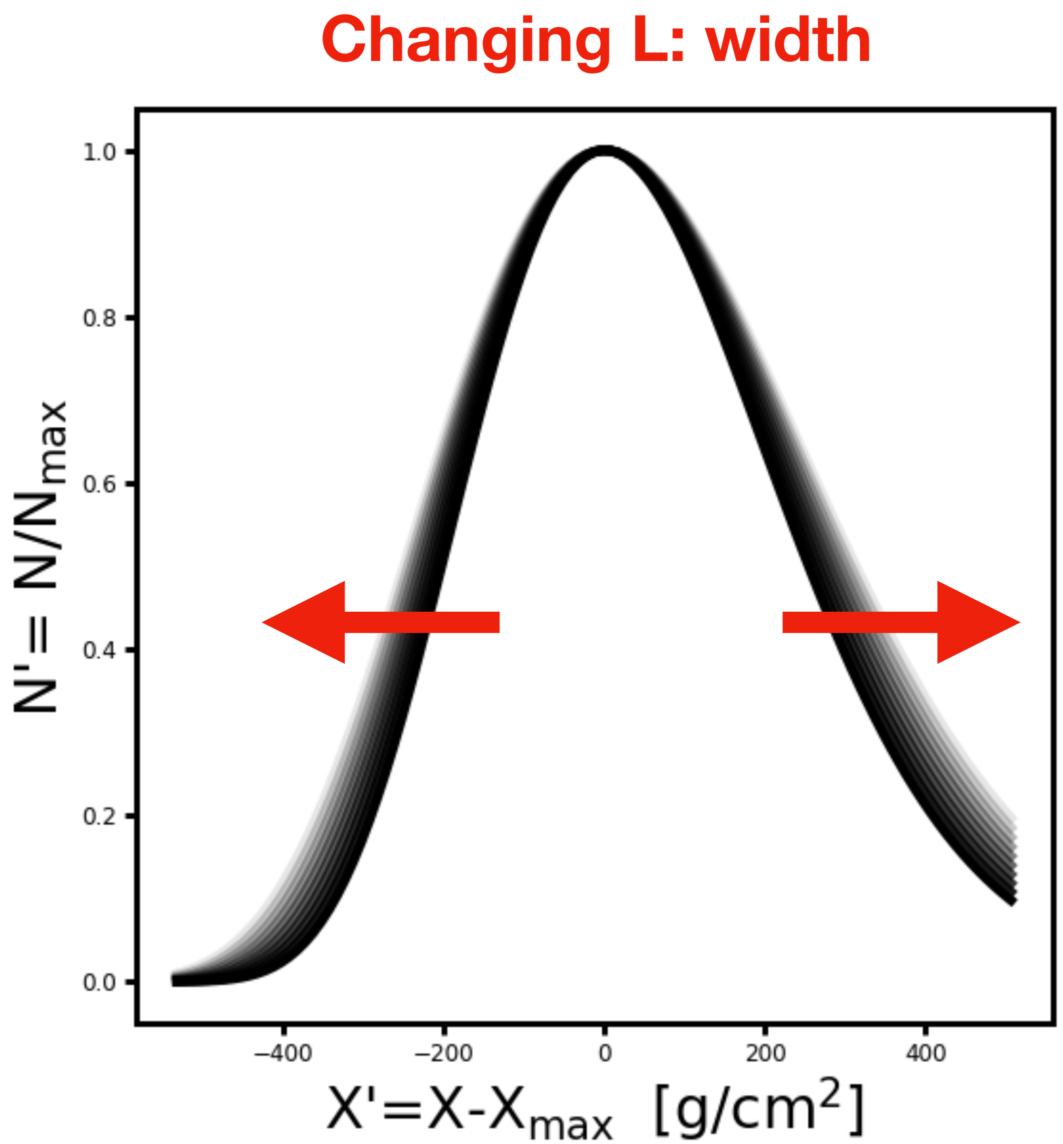


Corstanje et al. 2021. arXiv:2103.12549v1

Beyond X_{max}

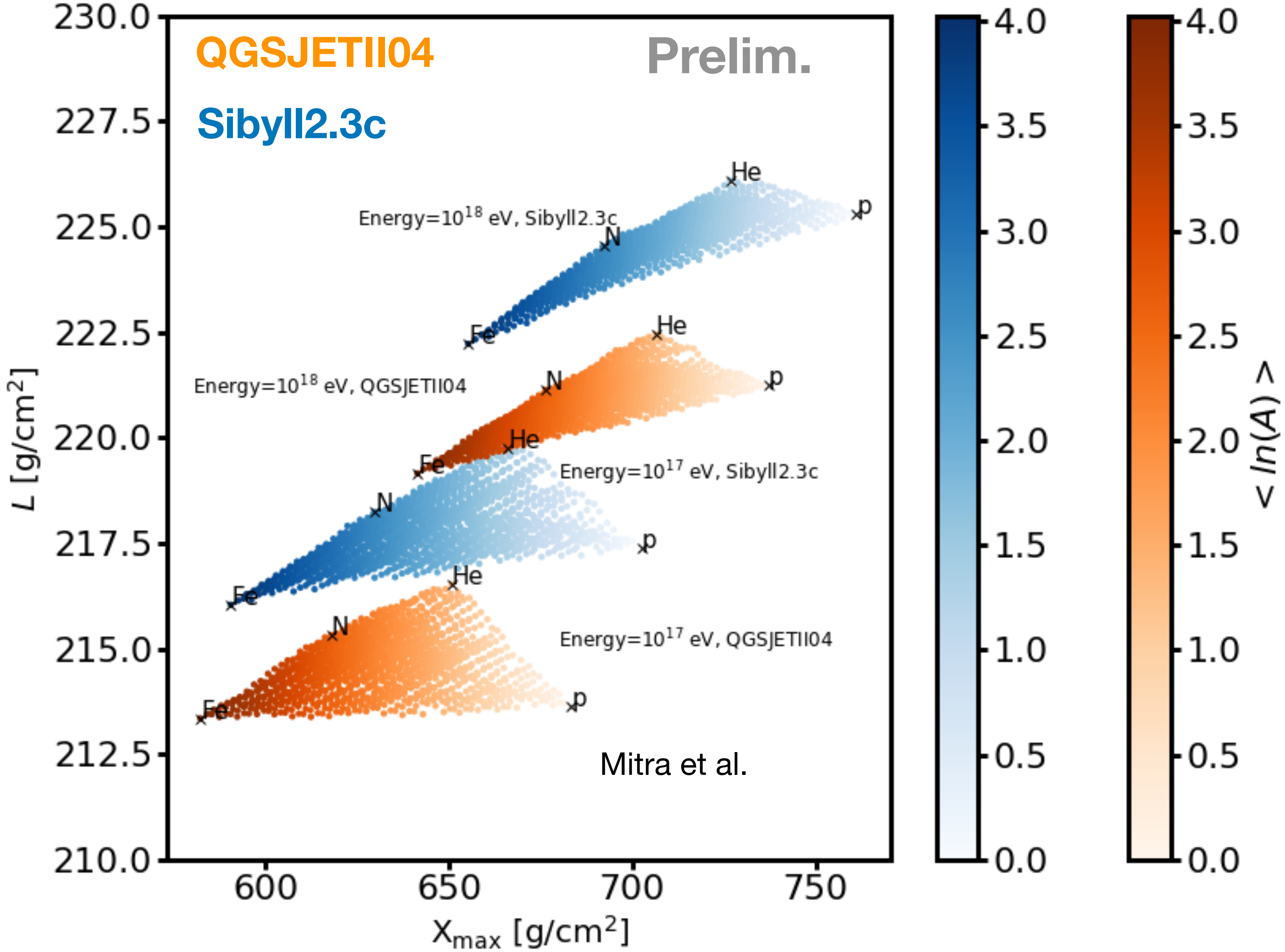
$$N' = (1 + \frac{RX'}{L})^{R^{-2}} \exp\left(\frac{-X'}{LR}\right)$$





From P. Mitra

Beyond X_{max}



$$\langle ln(A) \rangle = f_p \ln(1) + f_{He} \ln(4) + f_N \ln(14) + f_{Fe} \ln(56)$$

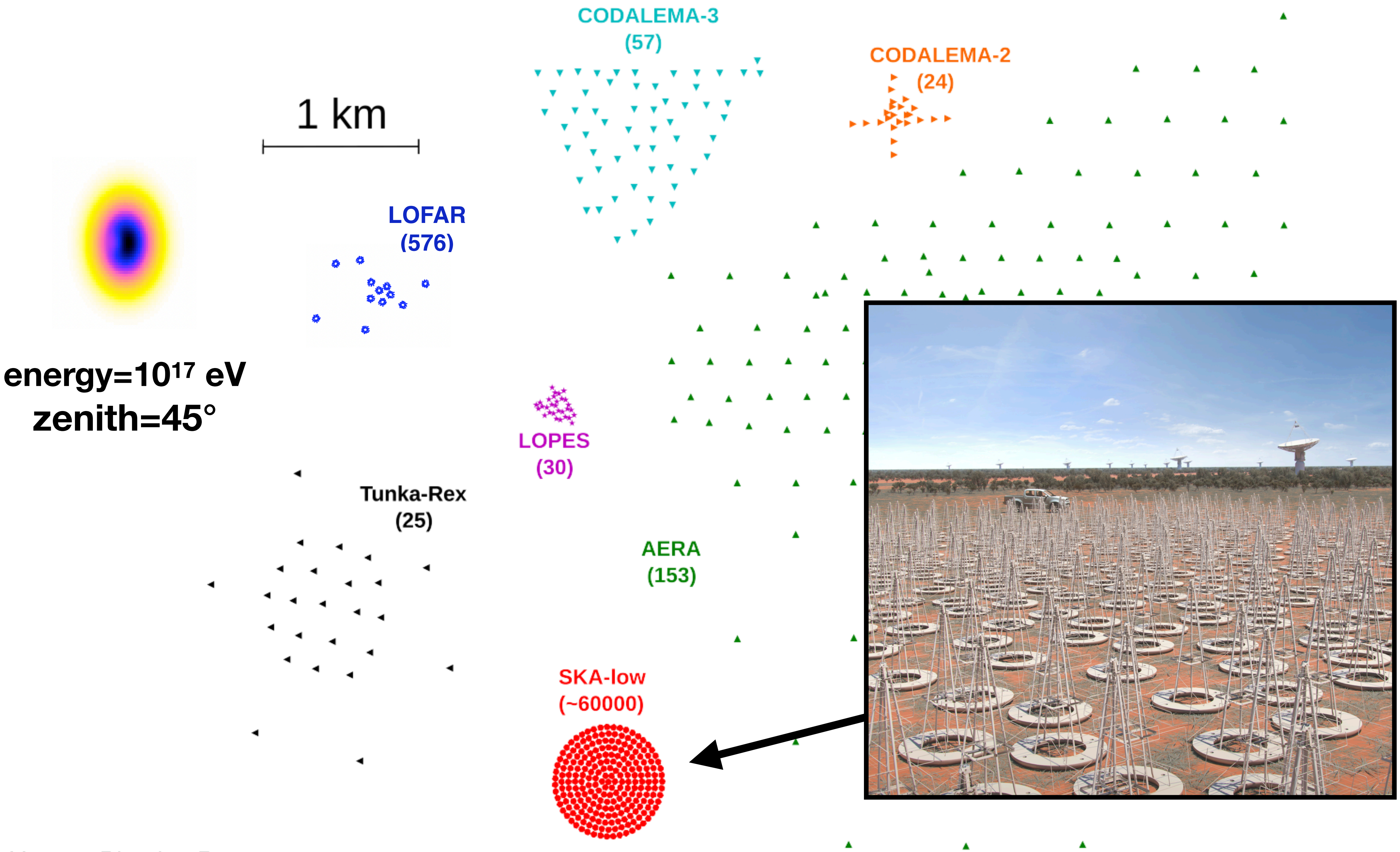
- 5000 CONEX showers for each combination
- Studying L and X_{max}/R together yields more info about composition and hadronic interaction model

Can the composition be better determined by including L in the fit?

- Determining L requires sensitive measurements

From P. Mitra

Radio Detection Experiments

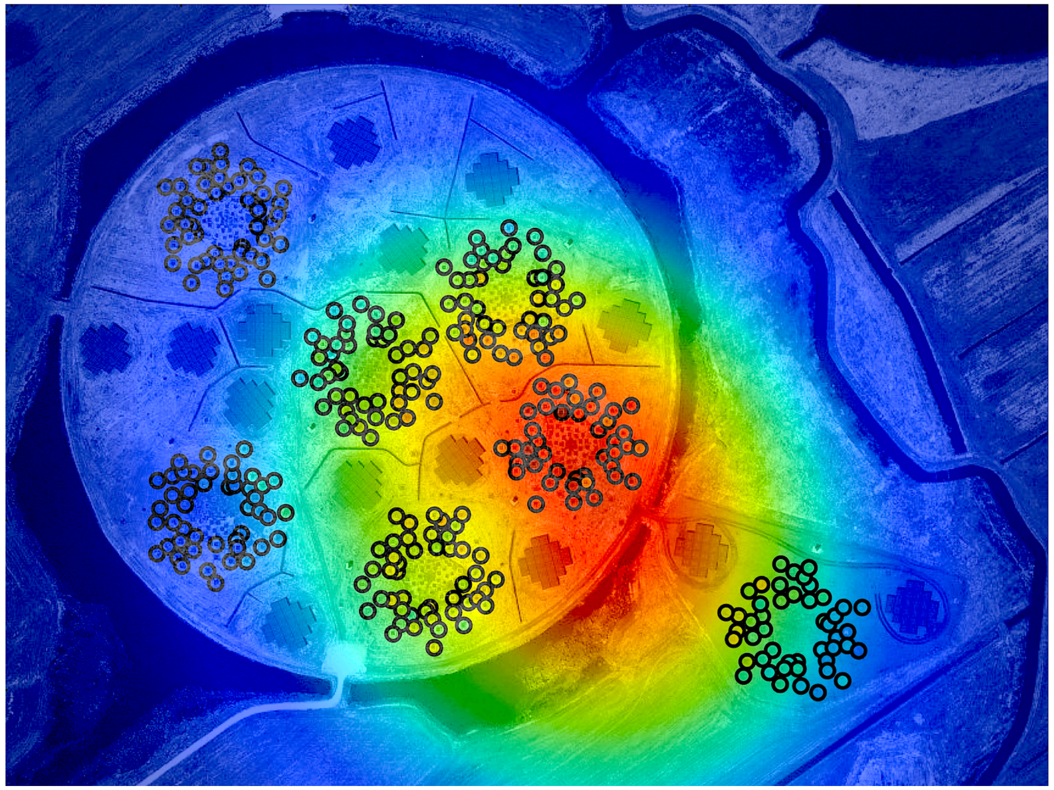


T. Huege. Physics Reports, 620:1-52, 2016.

Radio Detection Experiments

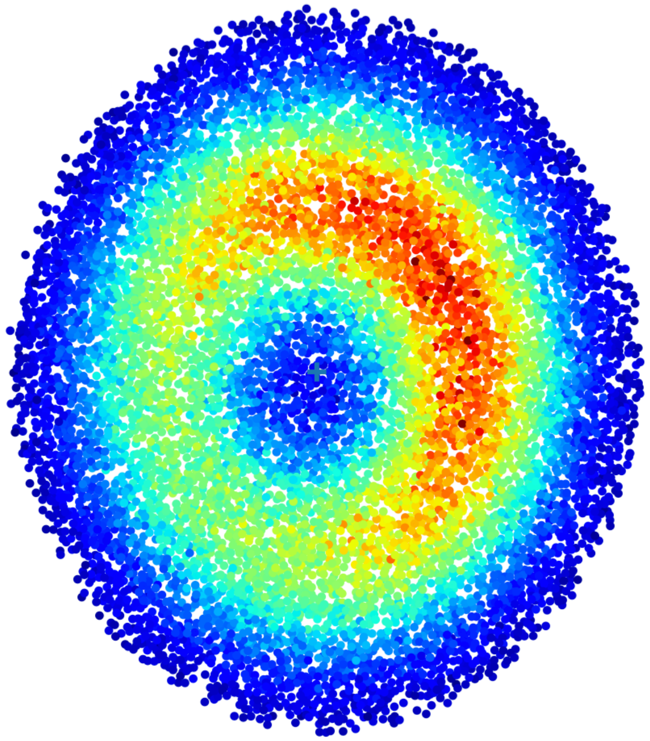
LOFAR

- X_{max} resolution: 20 g/cm^2
- Energy resolution: 9%
- Core resolution: 3-10 m
- Northern hemisphere



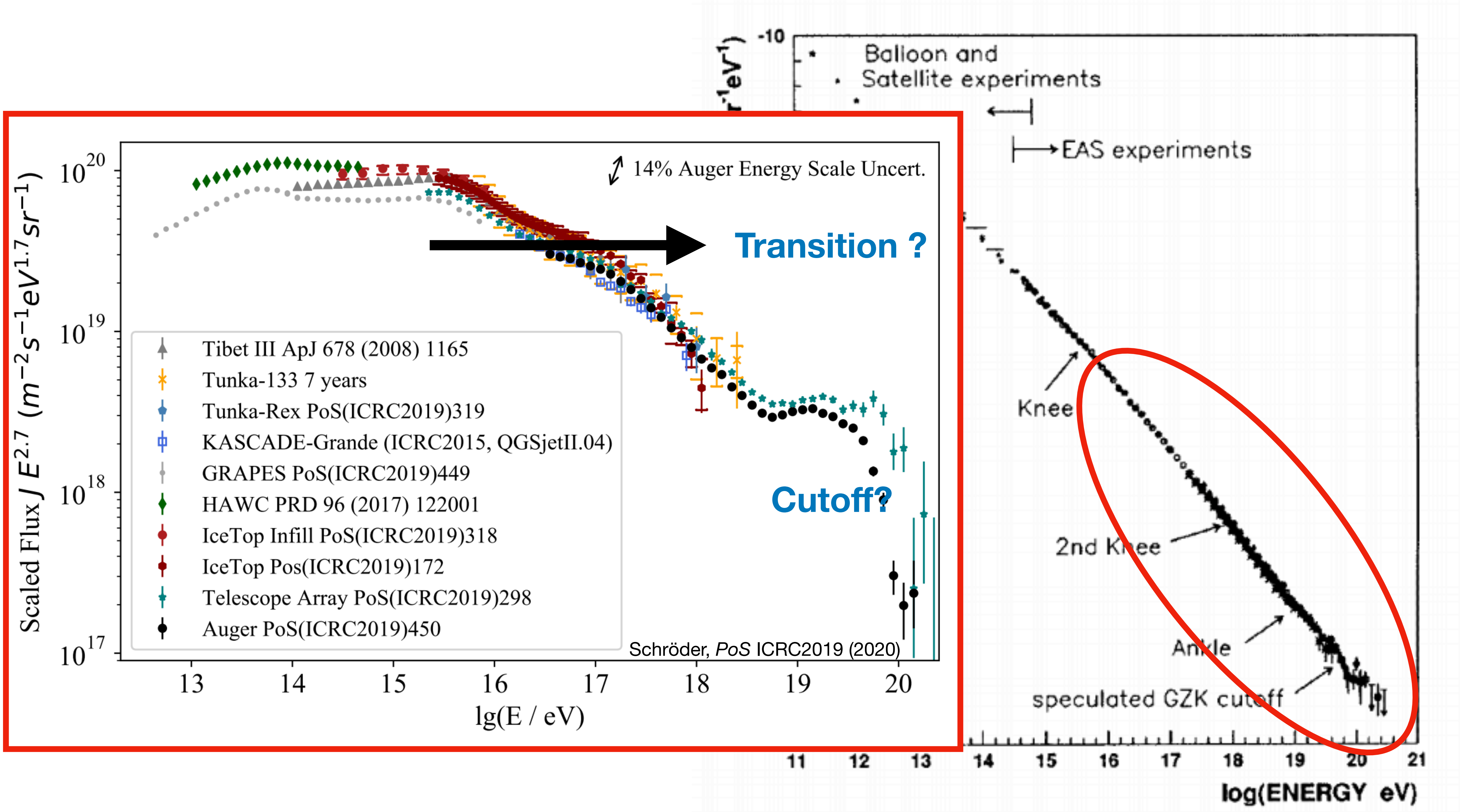
SKA

- X_{max} resolution: 6-8 g/cm^2
- Energy resolution: 3%
- Core resolution: 50 cm
- Southern hemisphere



Coming online soon …

Where do cosmic rays come from?



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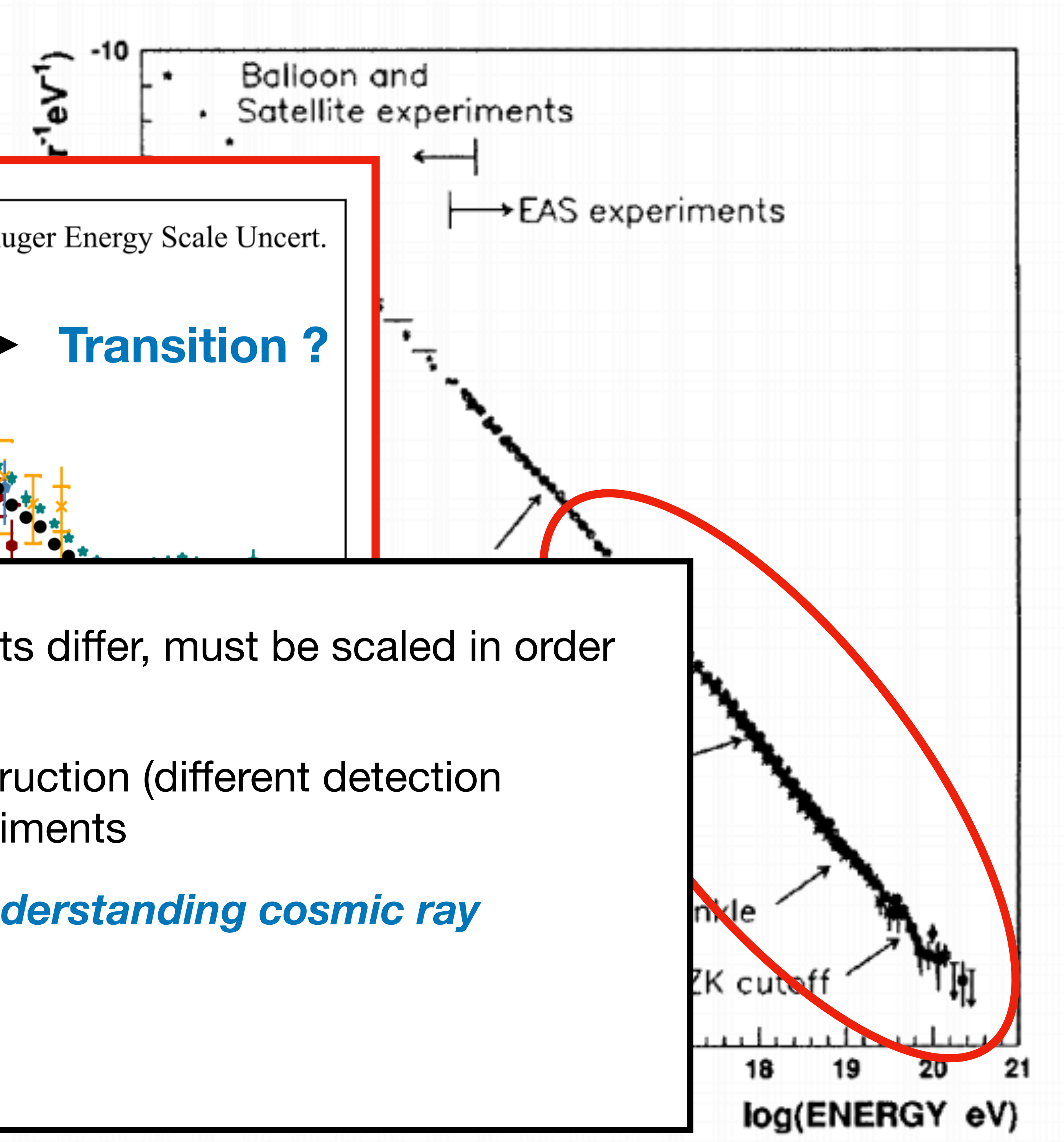
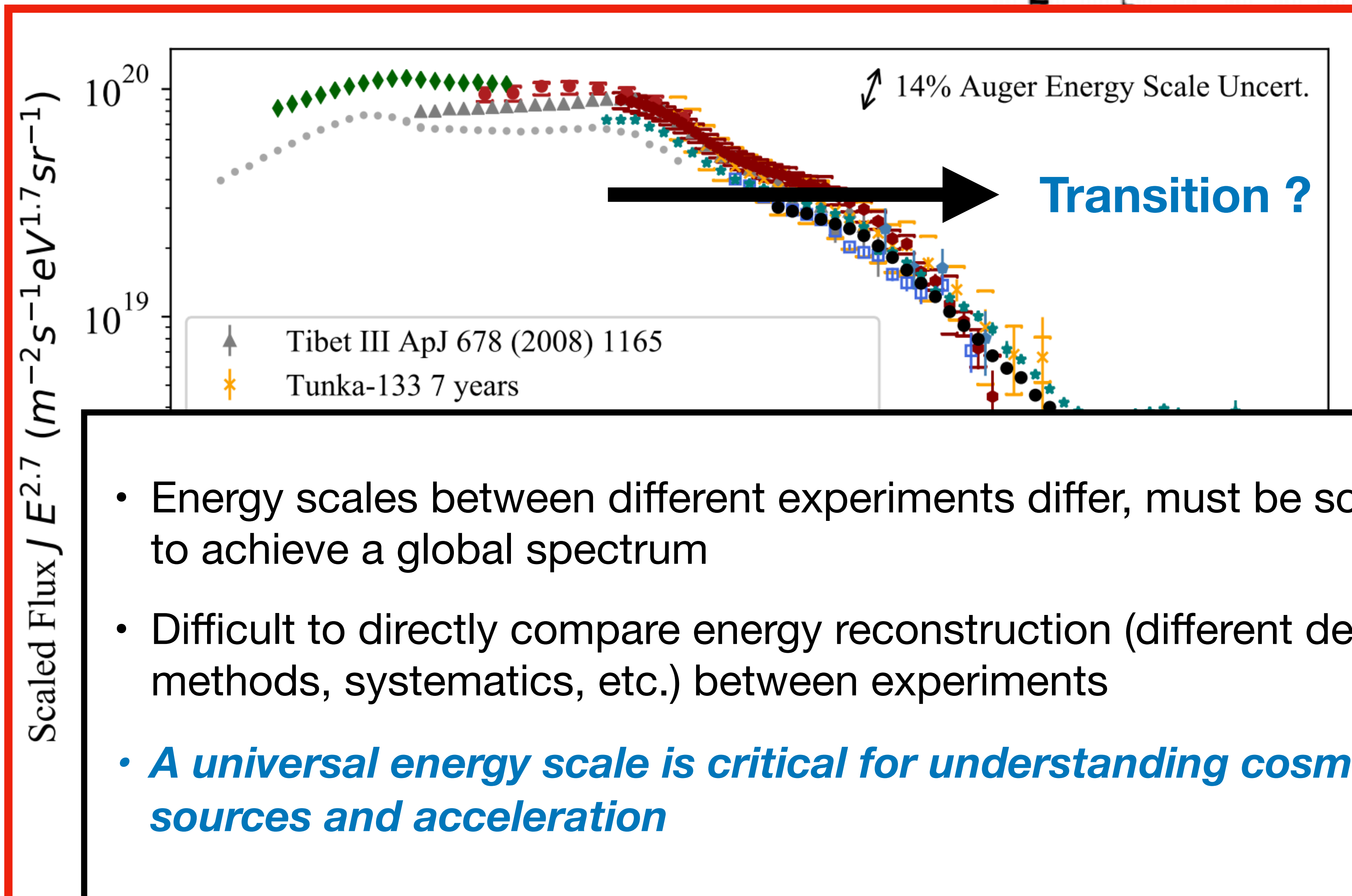
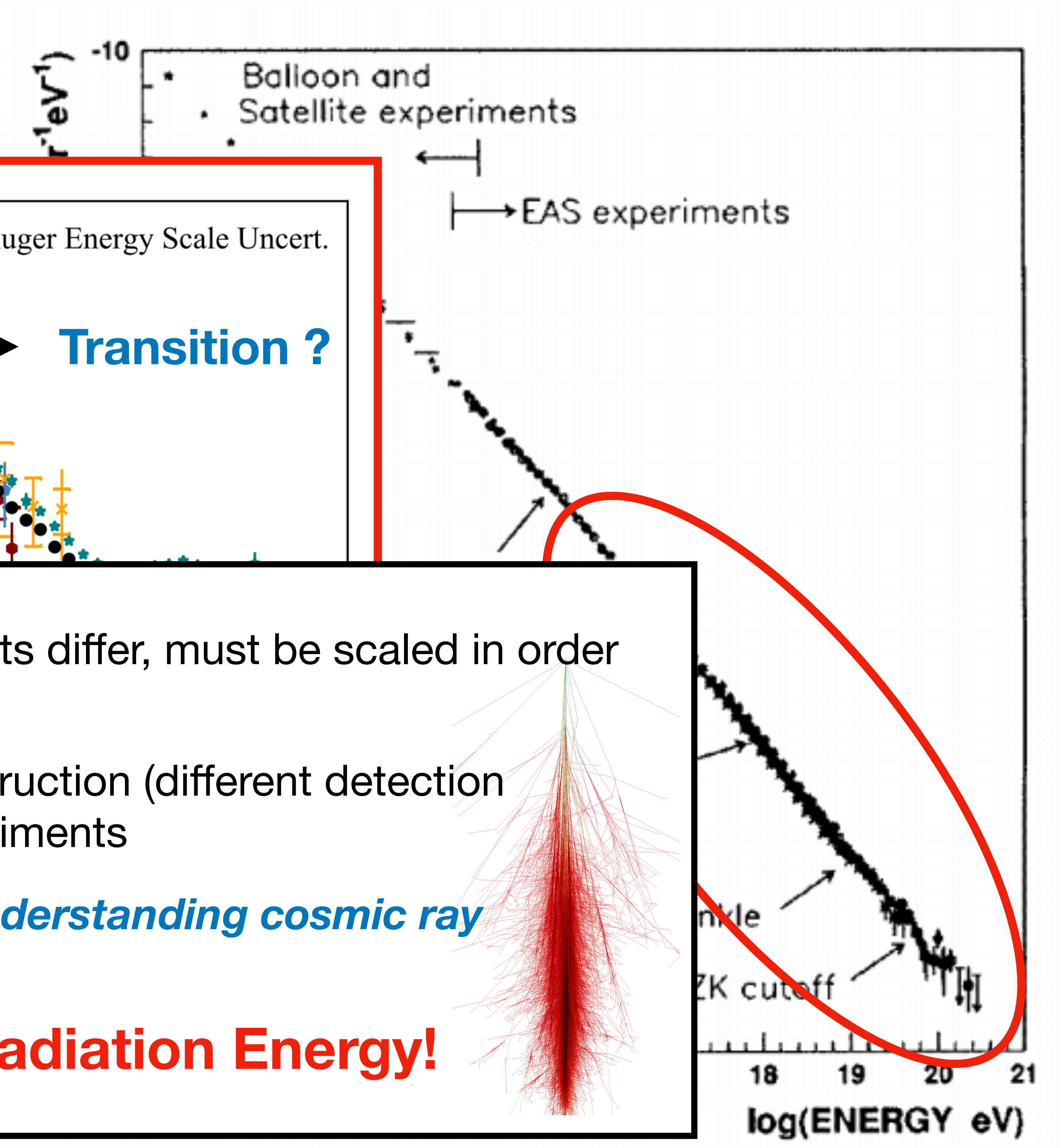
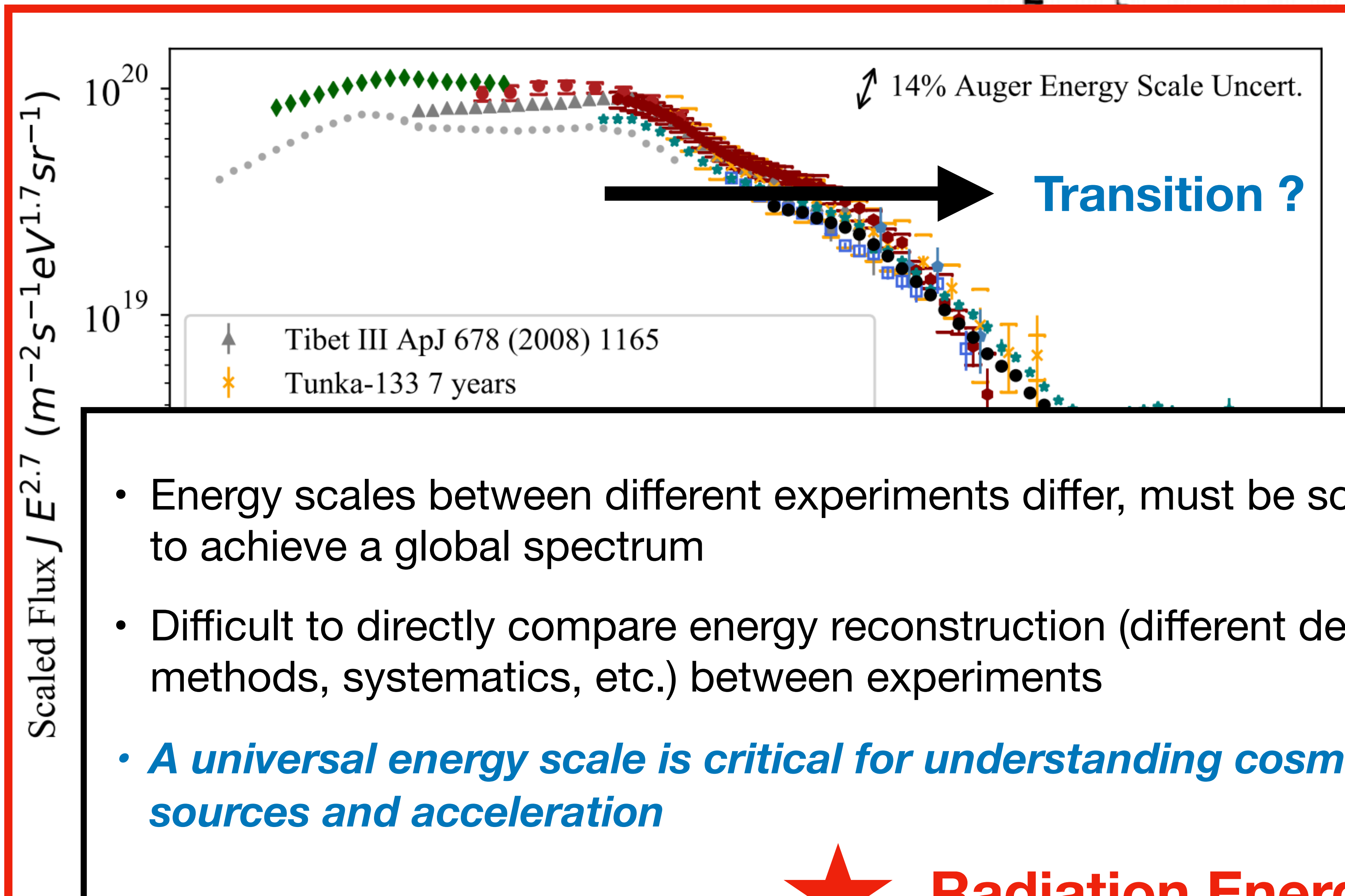




- Energy scales between different experiments differ, must be scaled in order to achieve a global spectrum
- Difficult to directly compare energy reconstruction (different detection methods, systematics, etc.) between experiments
- ***A universal energy scale is critical for understanding cosmic ray sources and acceleration***

Where do cosmic rays come from?





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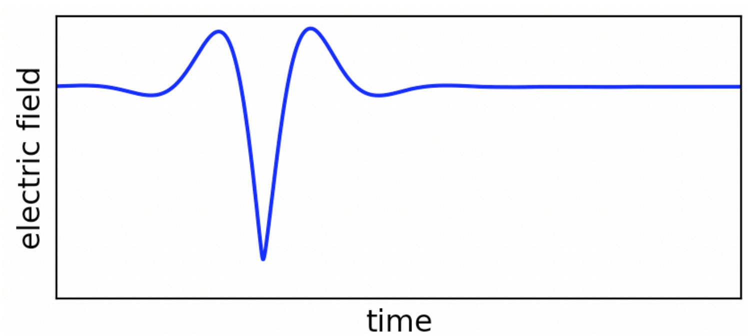
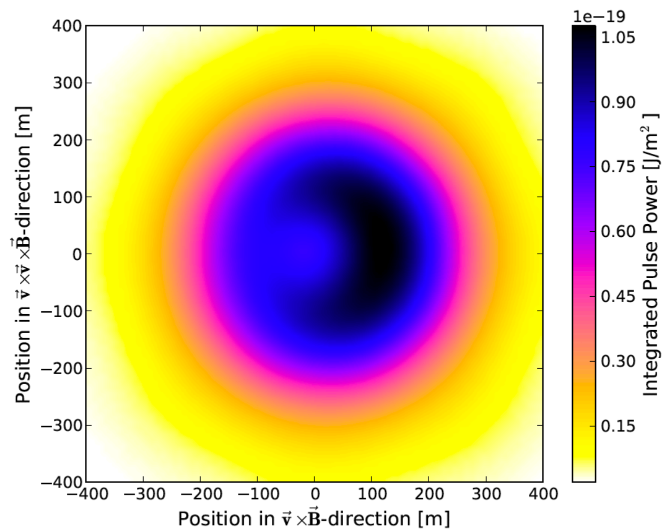
★ **Radiation Energy!**

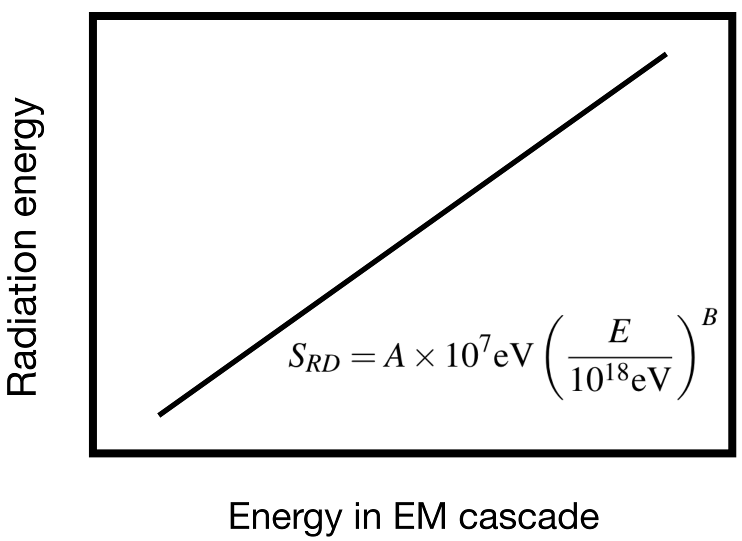
Radiation Energy

electric field → fluence | **fluence → radiation energy** | **radiation energy → EM energy**



$$f_{\vec{v}\times\vec{B}}(\vec{r}) = \varepsilon_0 c \Delta t \sum_i E^2_{\vec{v}\times\vec{B}}(\vec{r}, t_i)$$





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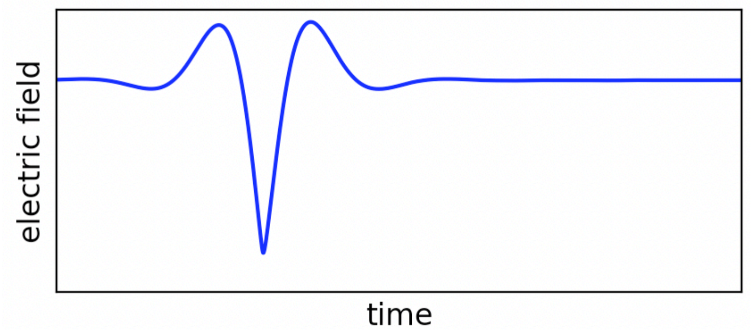
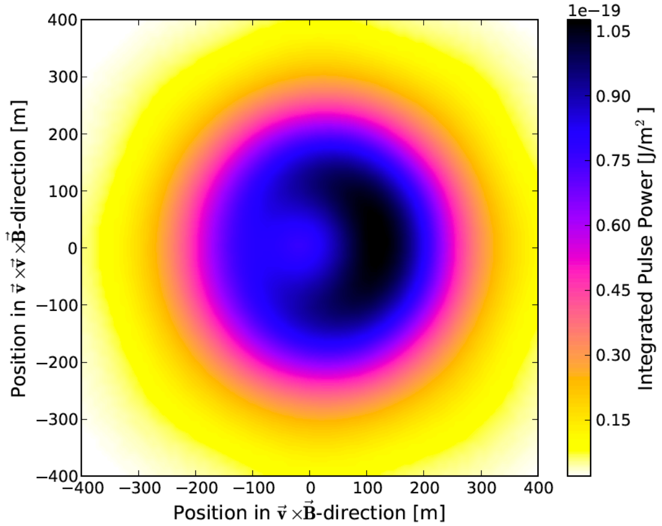
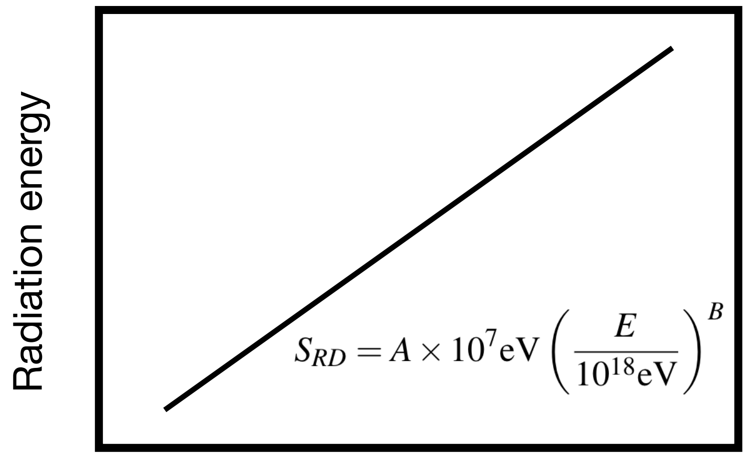






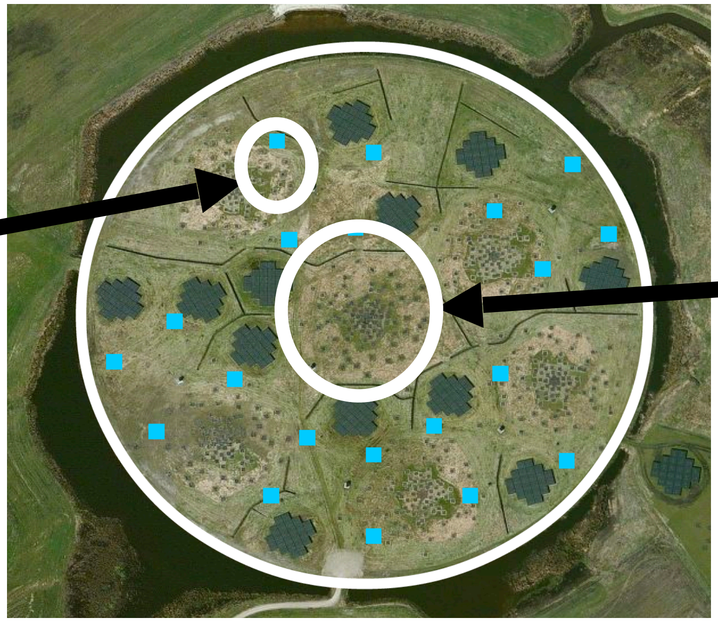
$$S_{RD} = \frac{E_{\mathrm{rad}}}{(a'^2 + (1 - a'^2))\sin^2\alpha\left(\frac{B_{\mathrm{Earth}}}{0.243\mathrm{G}}\right)^{1.8}}$$

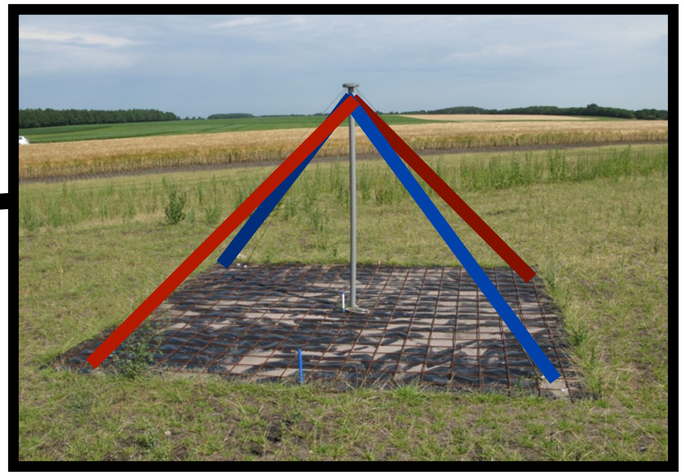
Corrected for local magnetic field
a = parametrization of the charge-excess fraction

Method from:
C. Glaser, et al. JCAP, 1609(09):024, 2016

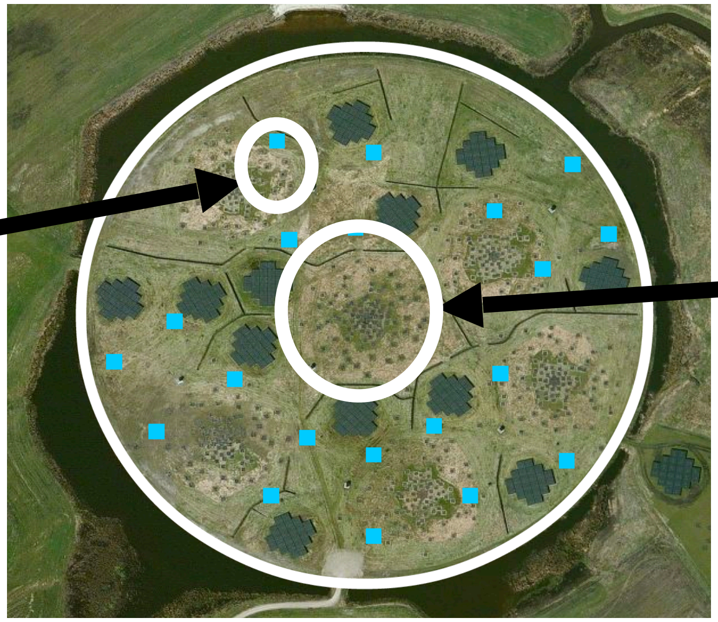
Corrected radiation energy is a universal quantity that can be directly compared between experiments

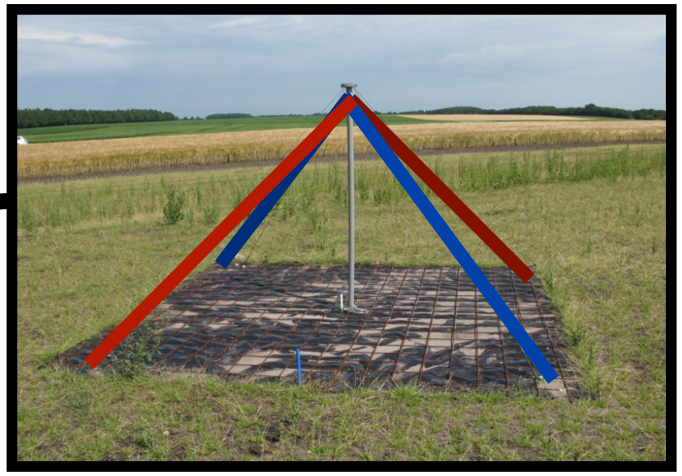
Energy Measurements



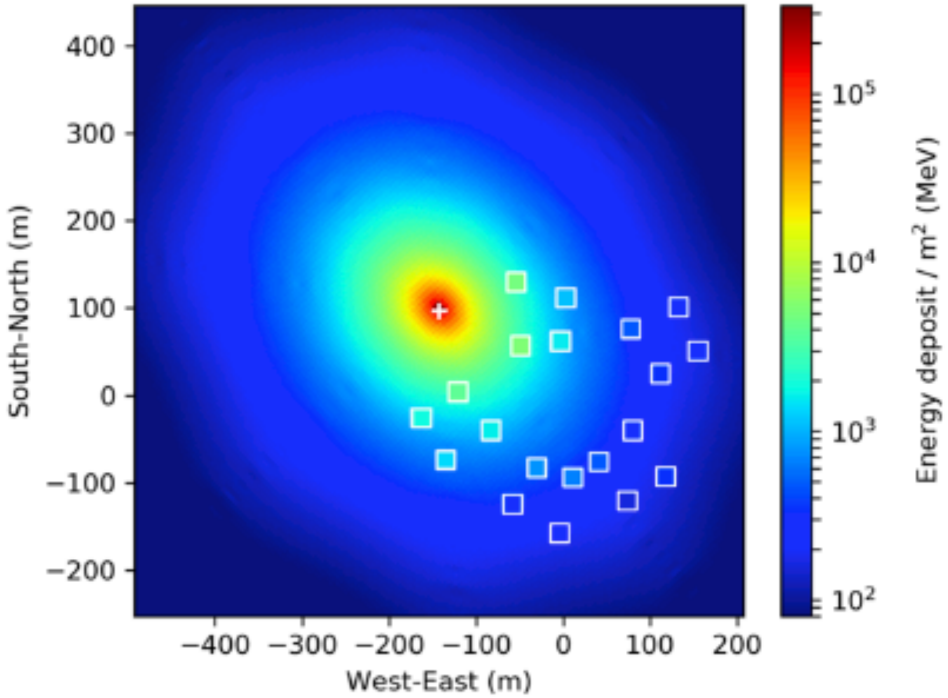


Energy Measurements





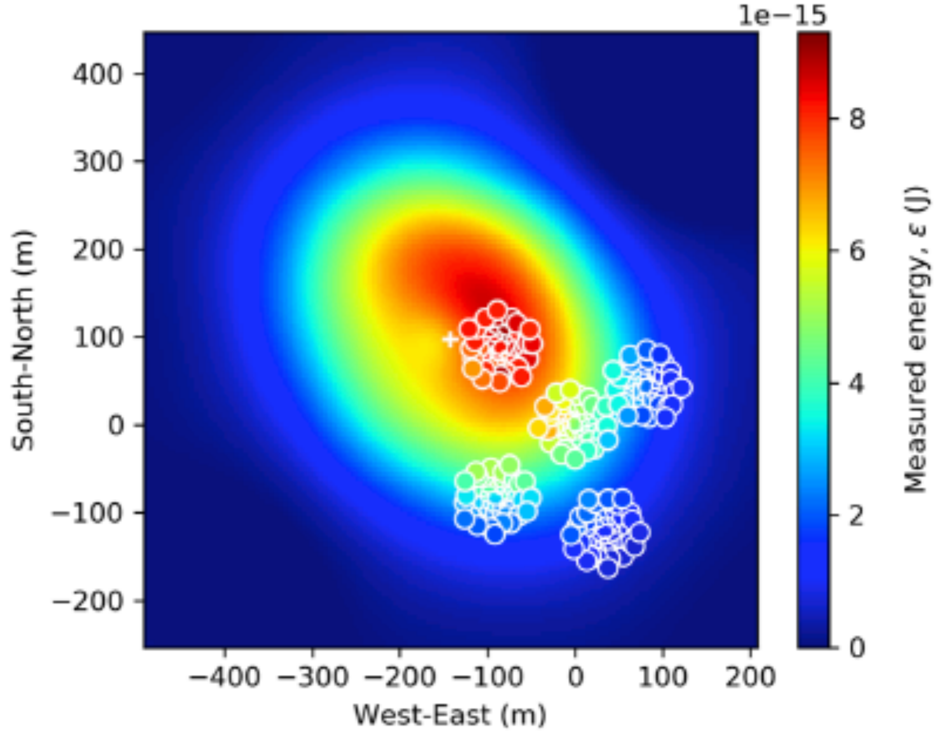
Particle footprint



$$\chi^2_{\text{particle}} = \sum_{\substack{\text{particle}\\ \text{detectors}}} \left(\frac{d_{\text{det}} - f_p d_{\text{sim}}}{\sigma_{\text{det}}} \right)^2$$

$$E_{\text{particle}} = f_p \times E_{\text{sim}}$$

Radio footprint



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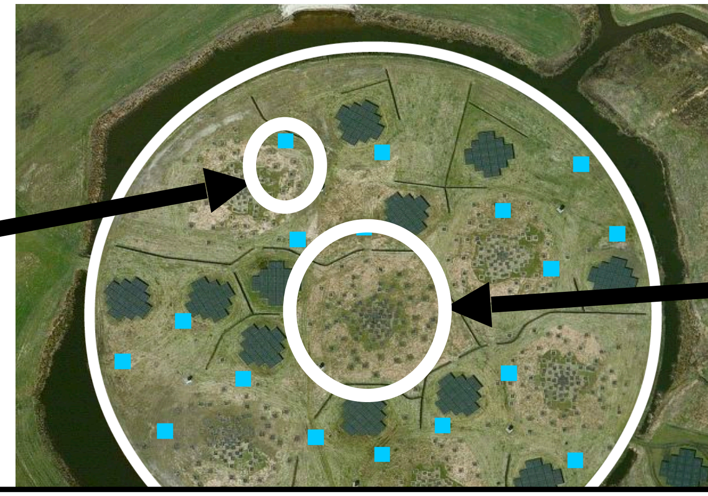
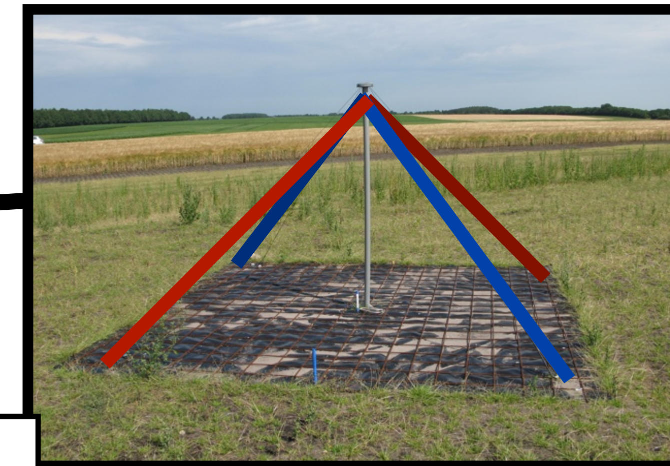
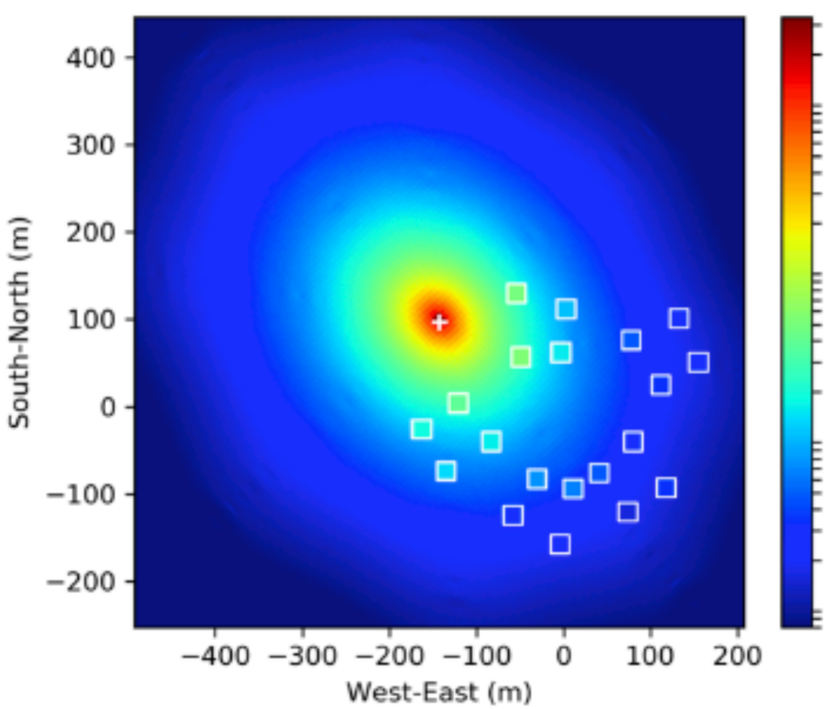
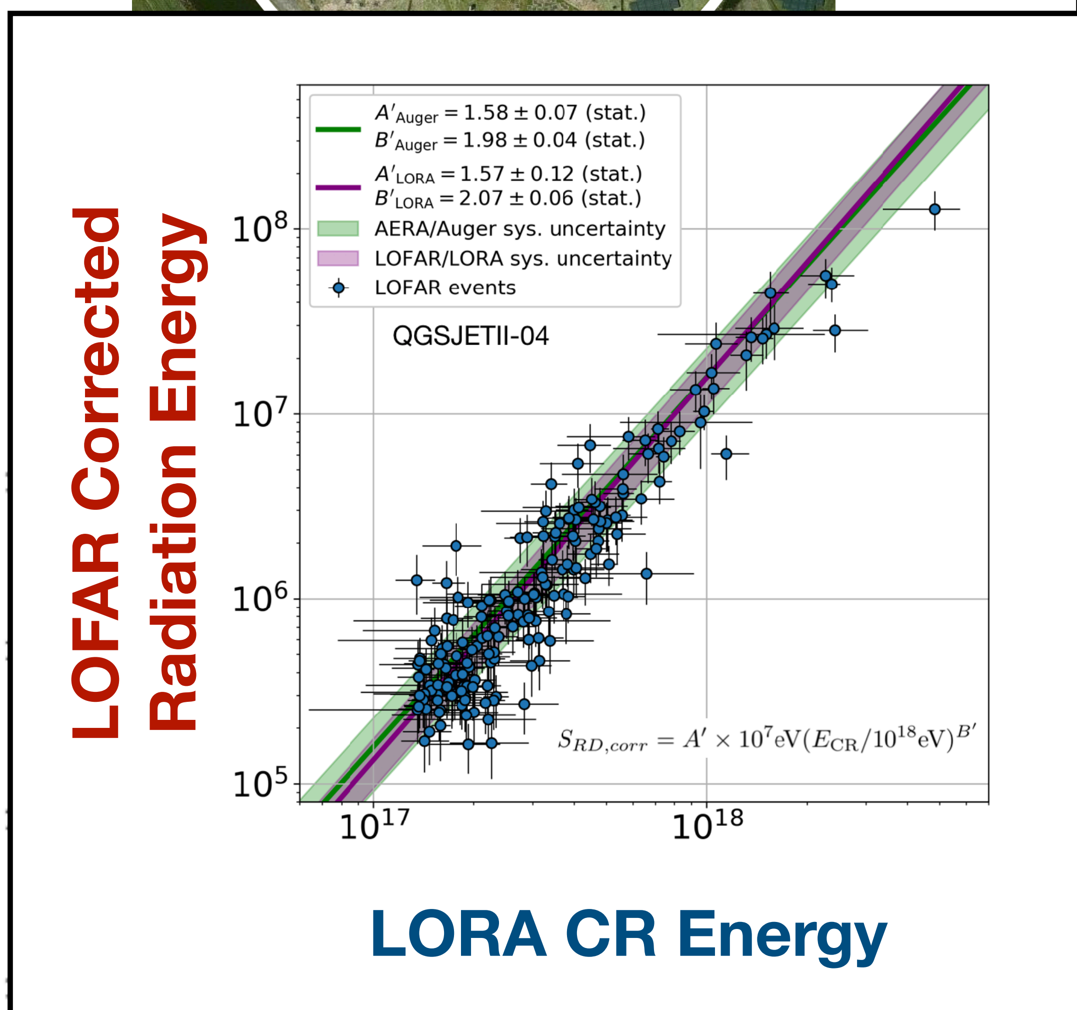


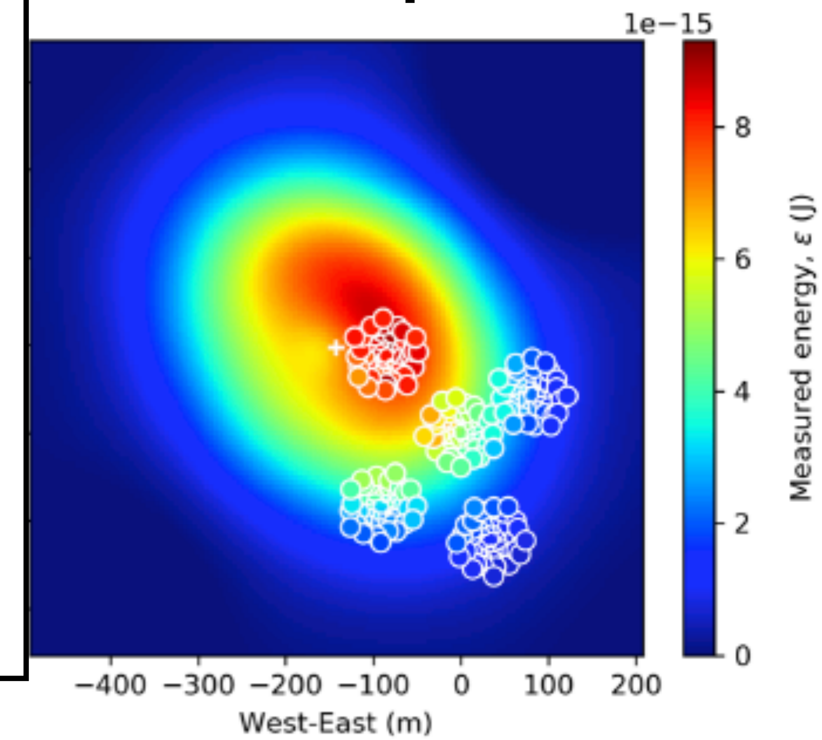


Particle footprint



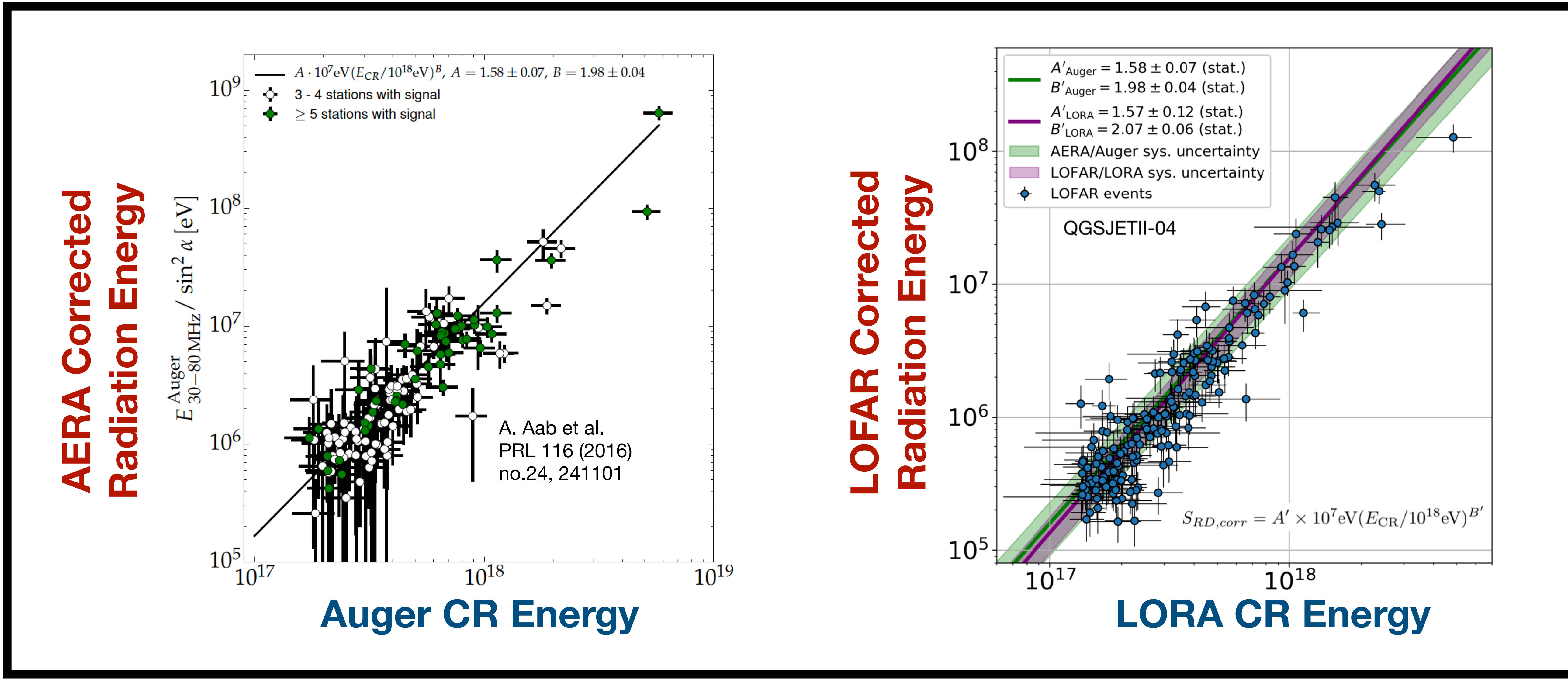


Radio footprint



Mulrey et al. JCAP 2020

Radiation Energy

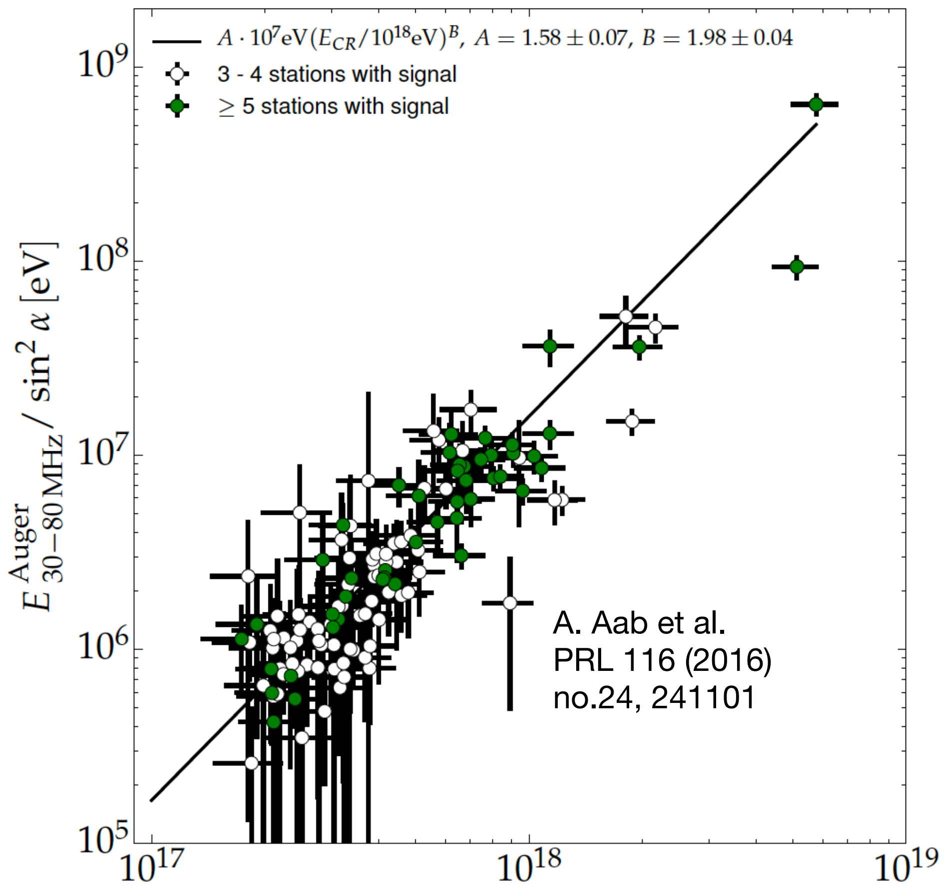


At a radiation energy of 1 MeV, the energy scales of Auger and LORA agree to within 6 ± 20 %

K. Mulrey et al. JCAP (2020)

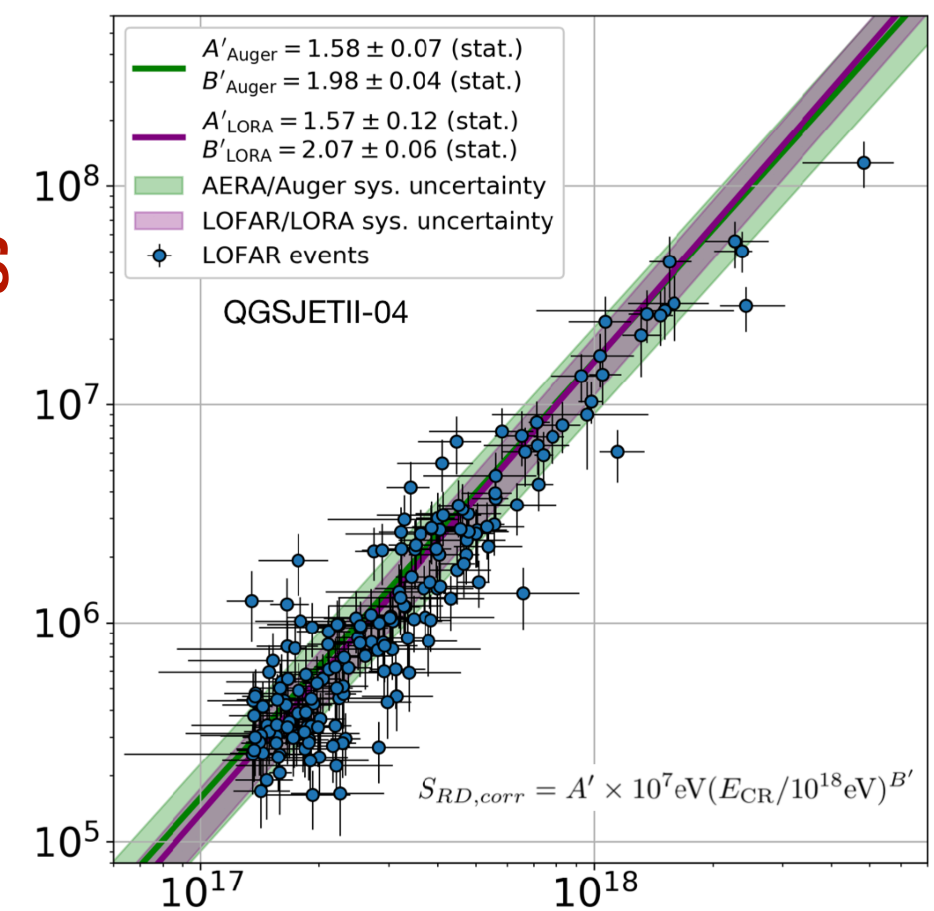
Radiation Energy

AERA Corrected Radiation Energy



Auger CR Energy

LOFAR Corrected Radiation Energy



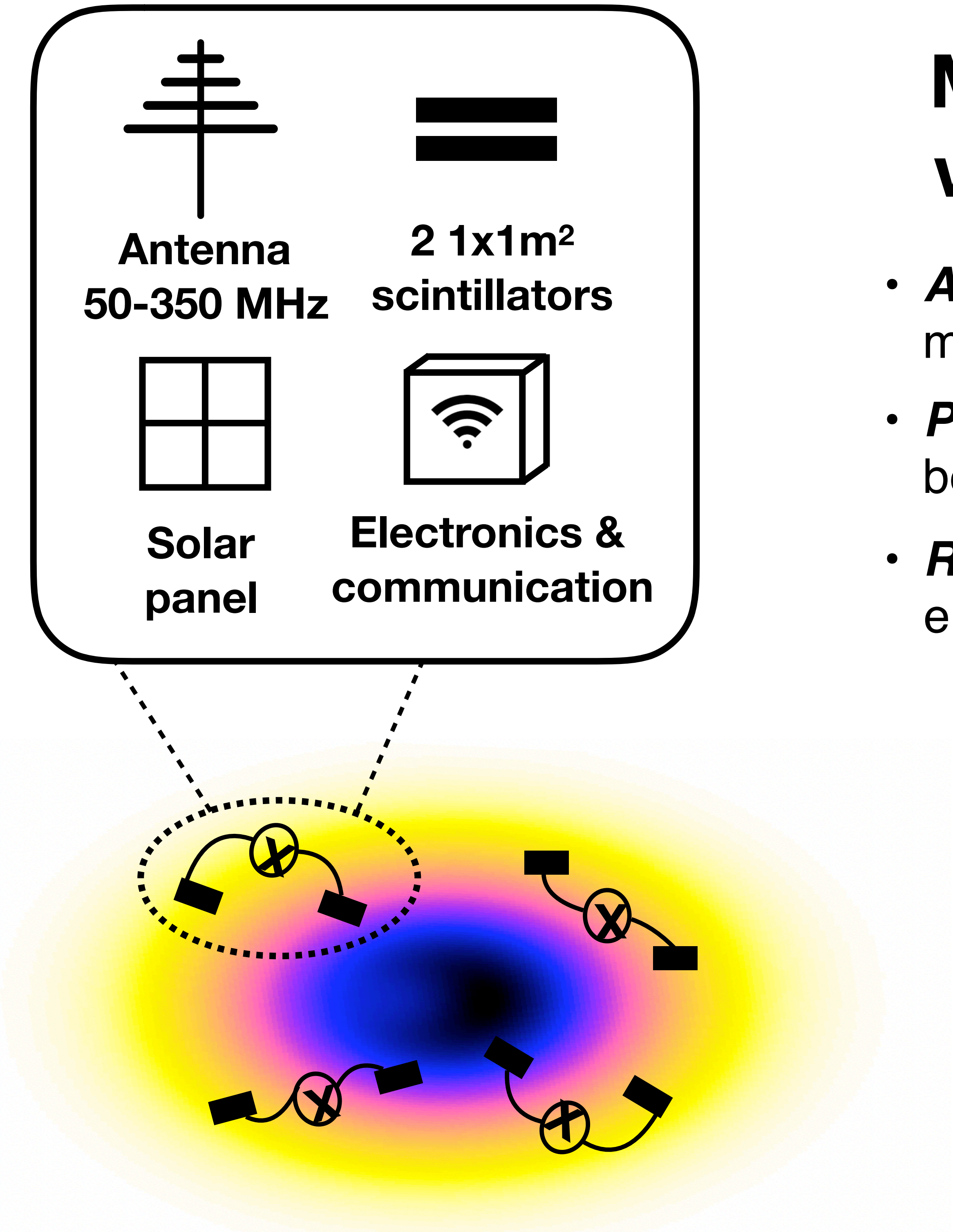
LORA CR Energy

At a radiation energy of 1 MeV, the energy scales of Auger and LORA agree to within 6 ± 20 %

Dominated by uncertainty on calibration / antenna.
How can we improve this?

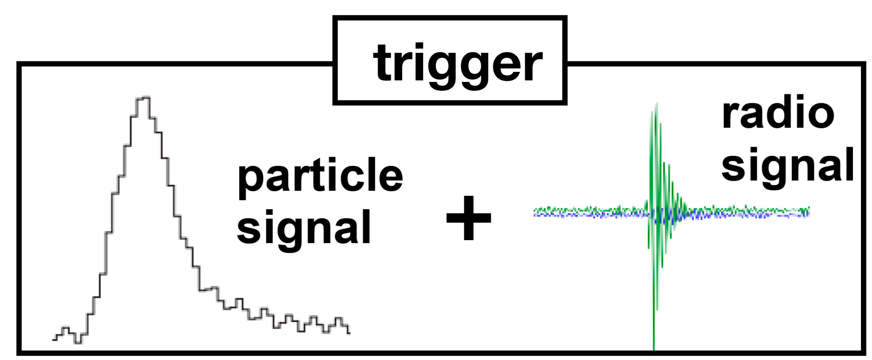
K. Mulrey et al. JCAP (2020)

Cross-calibration array



Measure the radiation energy with the same antenna array!

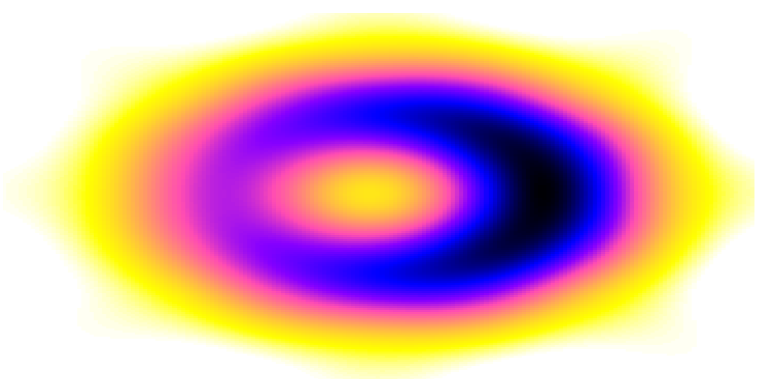
- ***Autonomous***: self triggering, independent energy measurement, no interference with main experiment
- ***Portable***: can be deployed at different sites, spacing can be adjusted to probe different energy regimes
- ***Result***: Quantify systematic differences between energy scales of the different experiments



Ensures a cosmic ray ✓
Strong radio signal ✓

Energy Reconstruction

1. Integrate fluence footprint to get radiation energy (2D LDF)

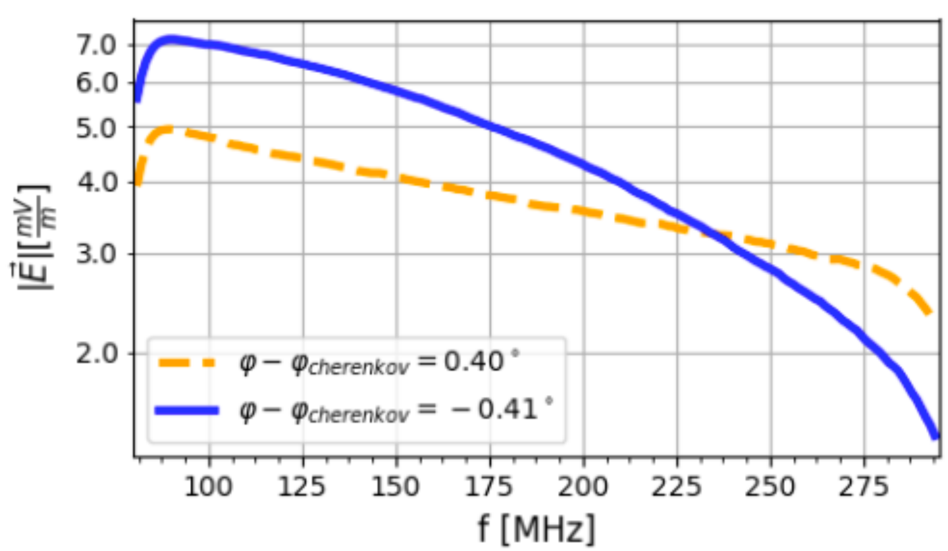


$$f = \varepsilon_0 c \left(\Delta t \sum_{t_1}^{t_2} |\vec{E}(t_i)|^2 - \Delta t \frac{t_2 - t_1}{t_4 - t_3} \sum_{t_3}^{t_4} |\vec{E}(t_i)|^2 \right)$$

A. Aab et al. PRL 116 (2016) no.24, 241101

- Only 5 stations- use direction/core info from host experiment
- Resolution ~20%

2. Use broadband spectral information (ARIANNA style)



$$\begin{pmatrix} \mathcal{E}_\theta \\ \mathcal{E}_\phi \end{pmatrix} = \begin{pmatrix} A_\theta \\ A_\phi \end{pmatrix} 10^{f \cdot m_f} \exp(\Delta j)$$

Corrected radiation energy

$$\frac{\sqrt{\Phi'_E}}{E_{shower}} = A \cdot \exp(-s \cdot (|m_f| \cdot \mathrm{GHz})^{0.8})$$

Welling et al. *JCAP* 10 (2019) 075

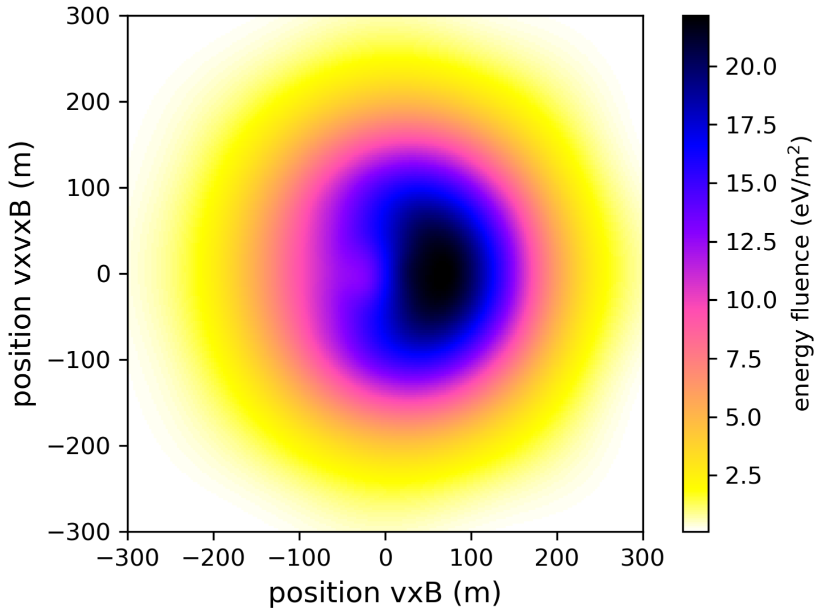
- Make use of spectral information to determine where you are w.r.t the Cherenkov cone
- Resolution ~15%

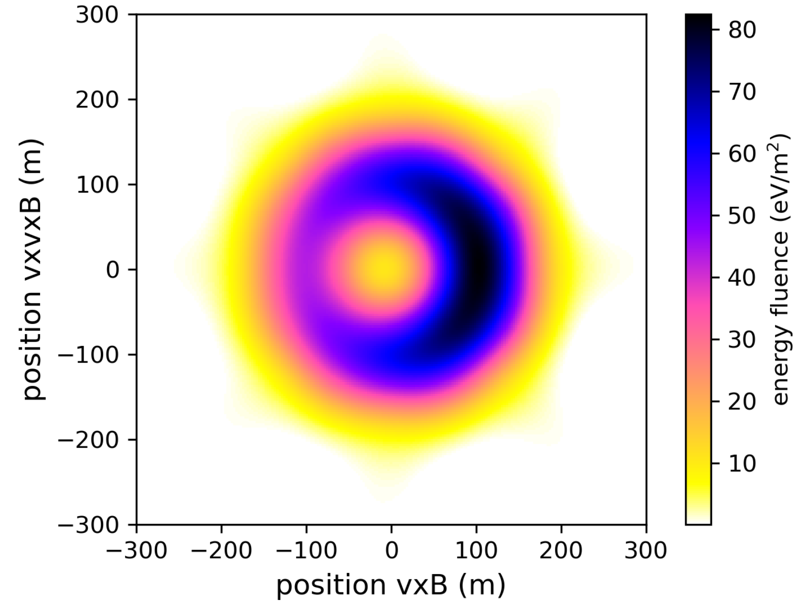
Cross-calibration array

30-80 MHz

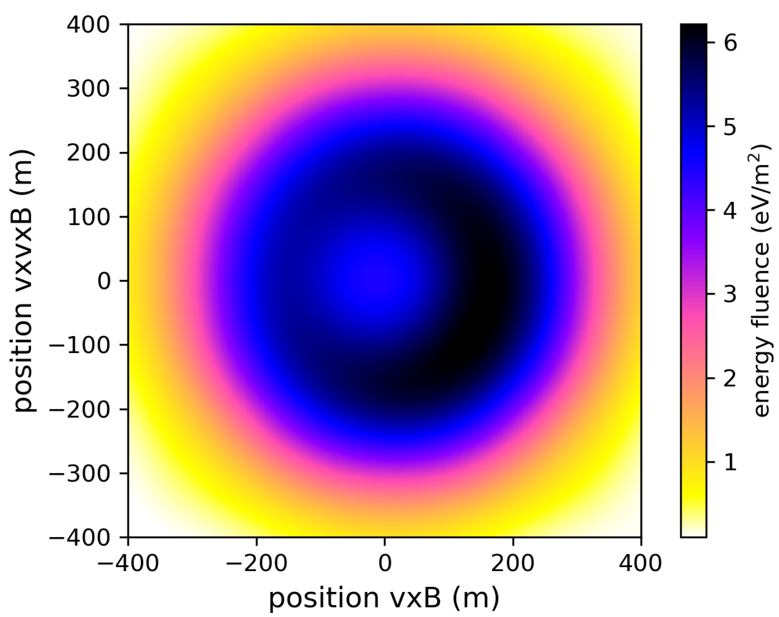
50-350 MHz

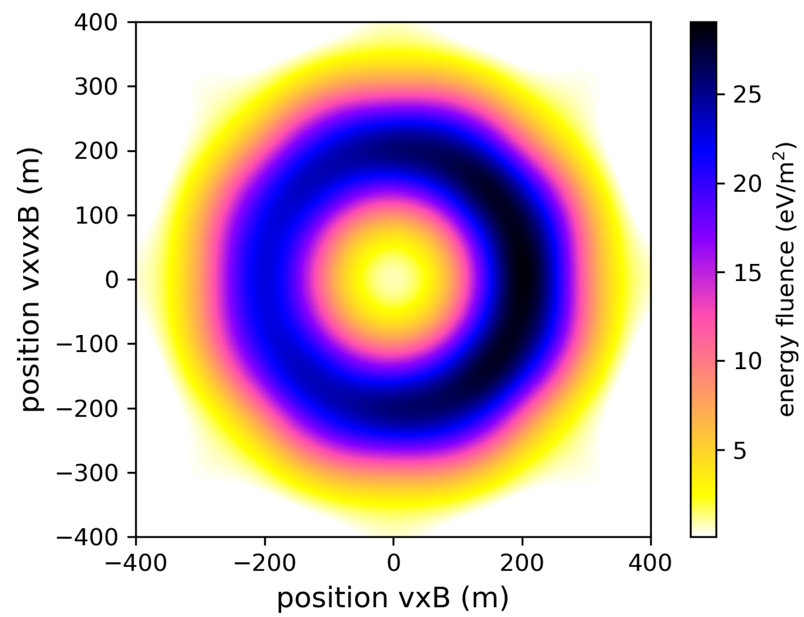
$$E = 3.5 \times 10^{17}\,\text{eV}$$
$$X_{\max} = 640\,\frac{\text{g}}{\text{cm}^2}$$
$$\theta = 33^\circ$$
$$D_{\max} = 604\,\frac{\text{g}}{\text{cm}^2}$$





$$E = 2.1 \times 10^{17}\,\text{eV}$$
$$X_{\max} = 673\,\frac{\text{g}}{\text{cm}^2}$$
$$\theta = 54^\circ$$
$$D_{\max} = 1159\,\frac{\text{g}}{\text{cm}^2}$$





Cross-calibration array

$$E = 3.5 \times 10^{17}\mathrm{eV}$$
$$X_{\mathrm{max}} = 640\frac{\mathrm{g}}{\mathrm{cm}^2}$$
$$\theta = 33^\circ$$
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$$E = 2.1 \times 10^{17}\mathrm{eV}$$
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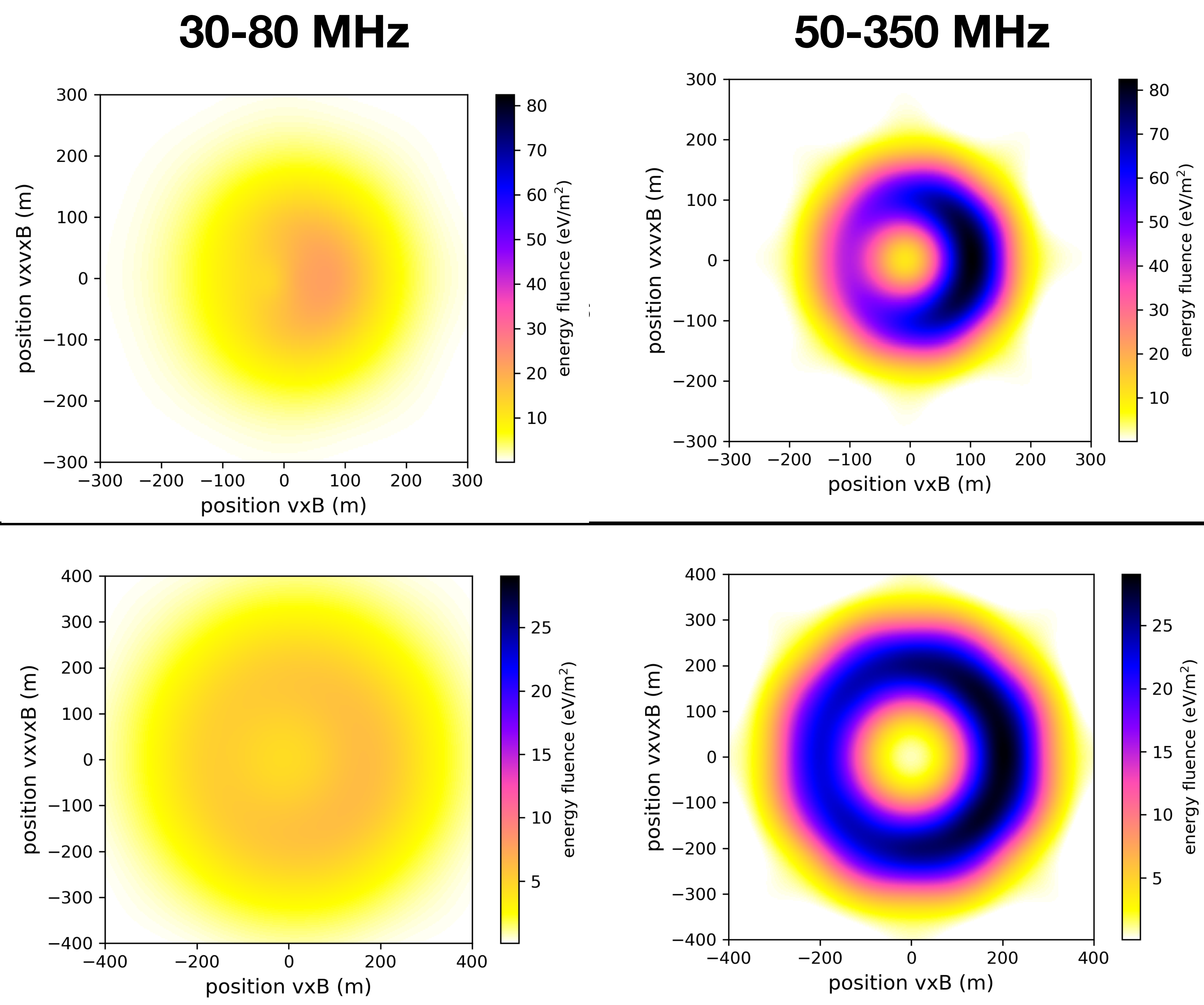
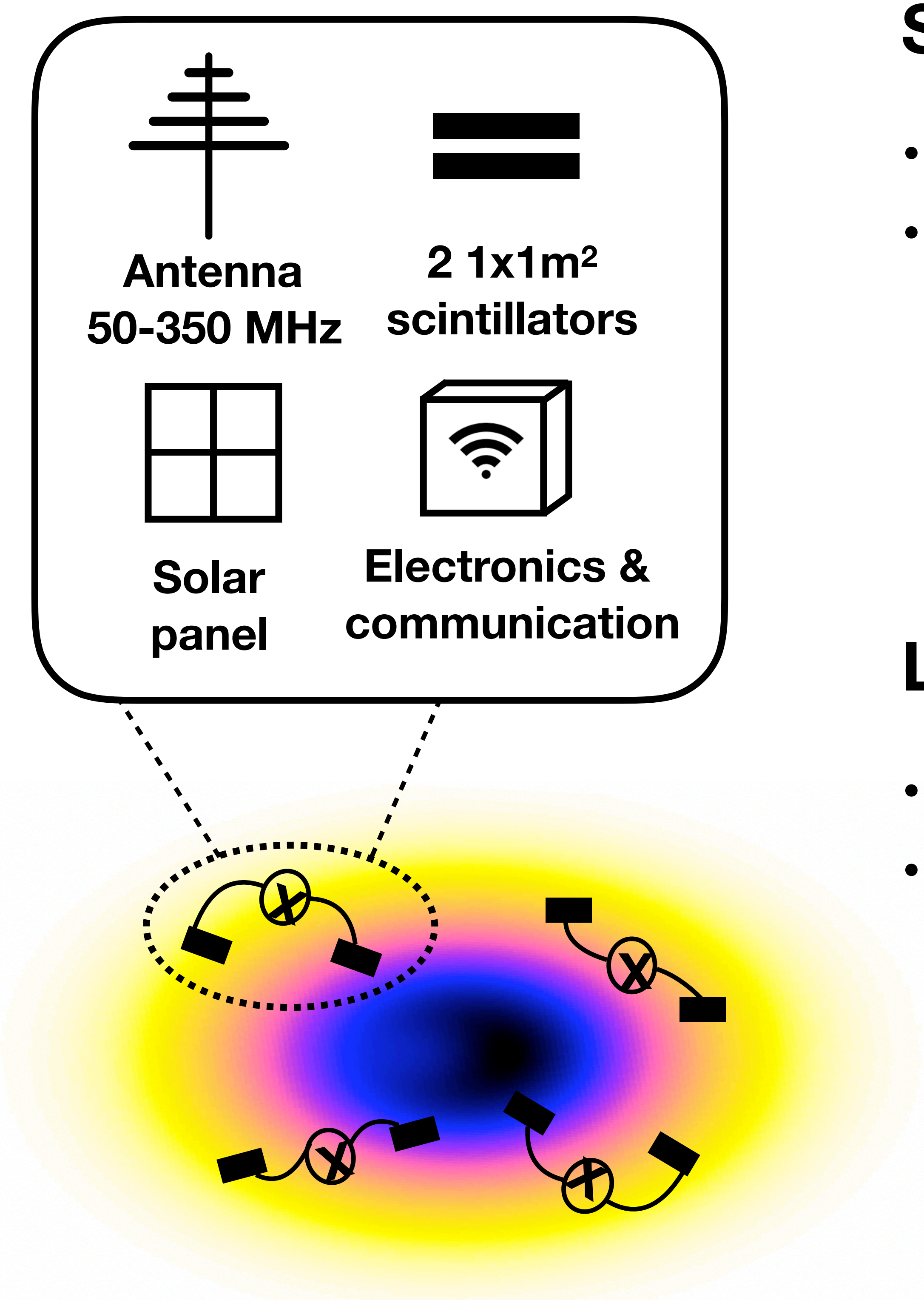
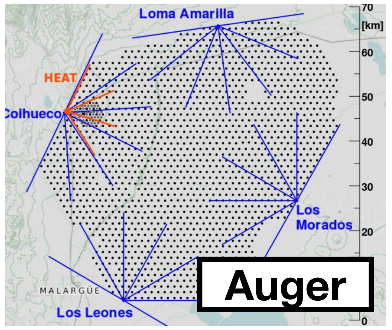


Cross-calibration array



Short Term

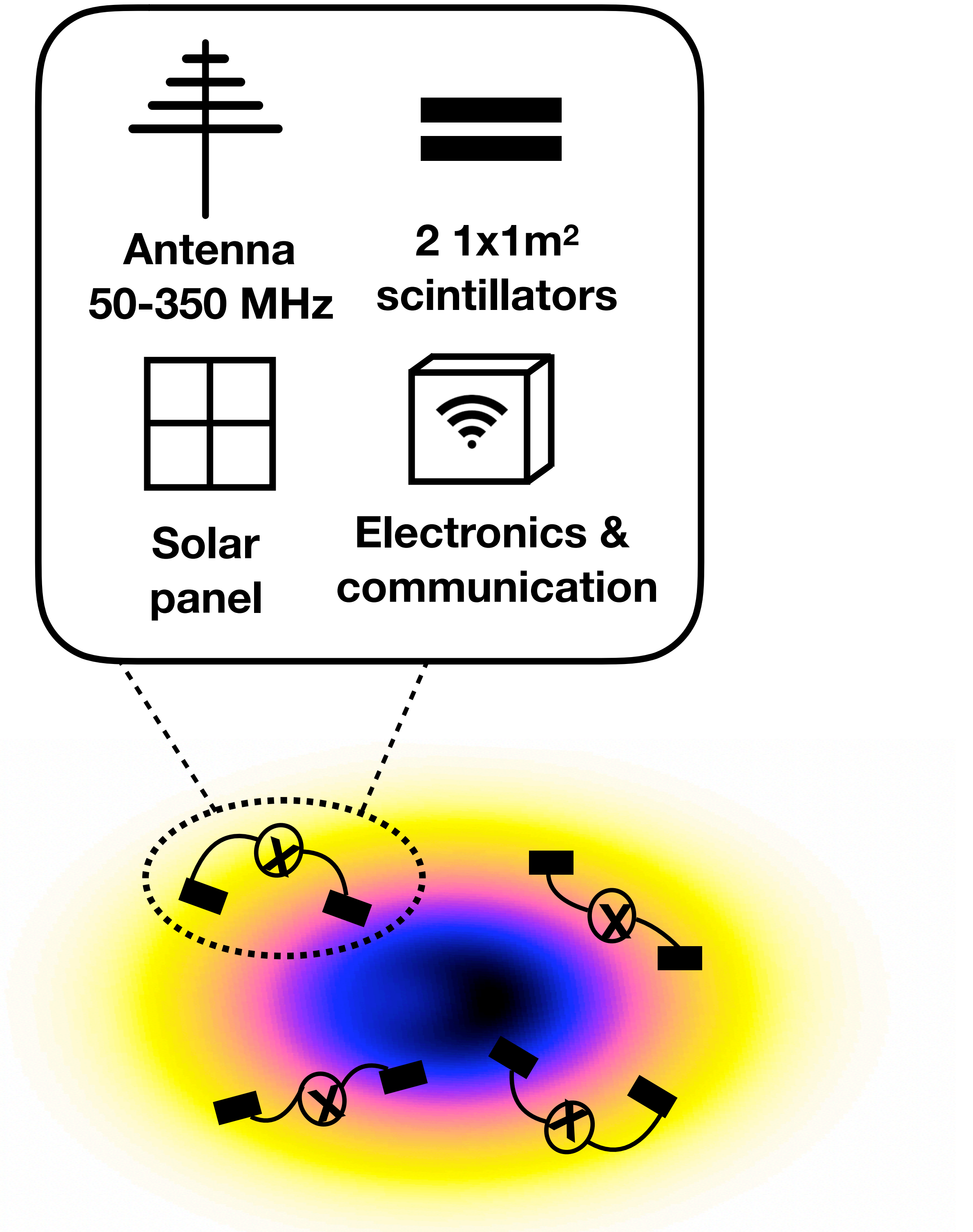
- Develop and deploy prototype array
- Develop techniques for broadband event reconstruction

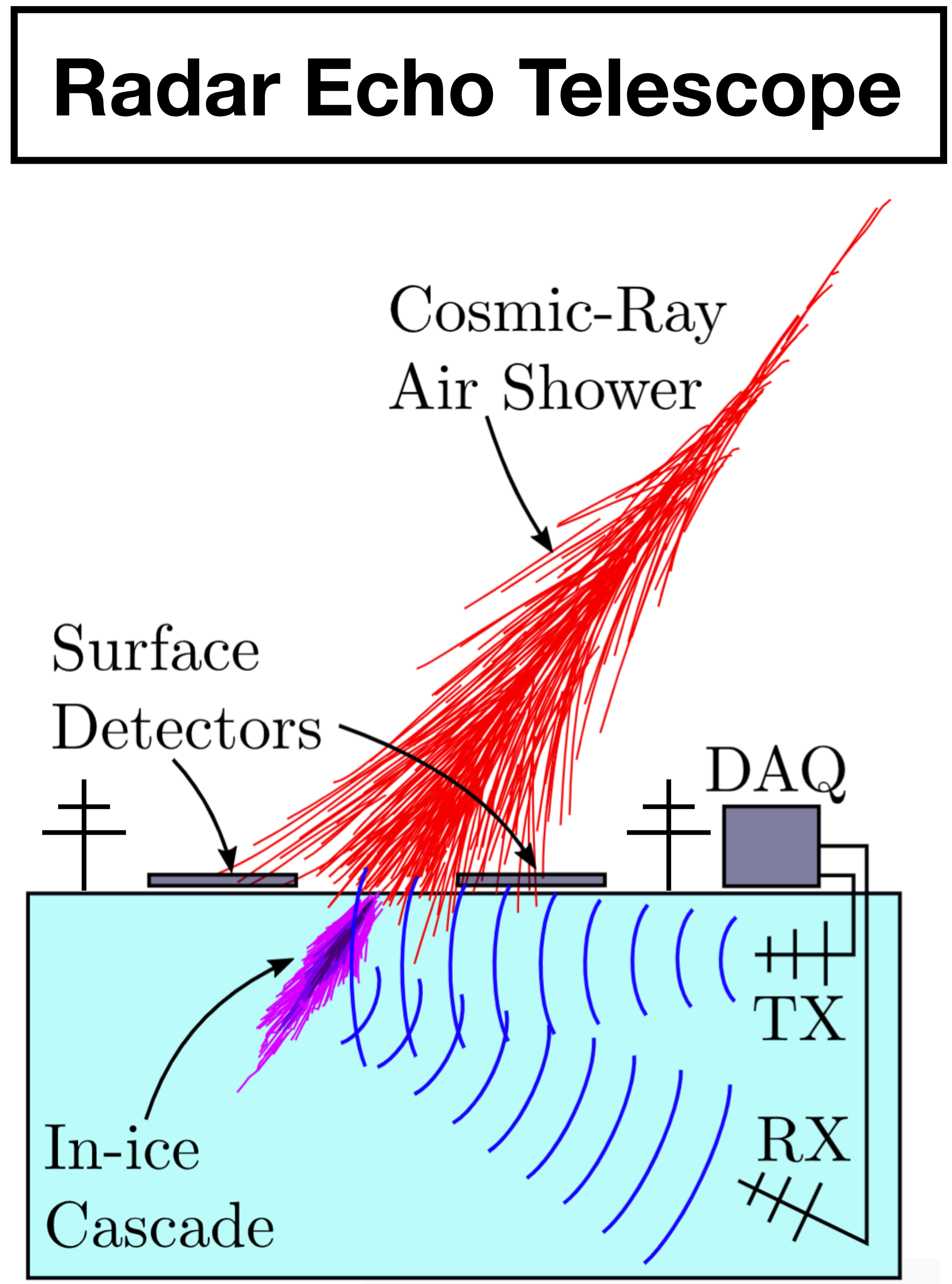


Long Term

- Include more stations to reach higher energies
- **Self-sustaining** program for use by other experiments

RET-CR Surface array





RET-CR
K. de Vries,
S. Prohira
et al.

VUB prototype

Energy Cross Calibration array

SKALA antenna

CODALEMA electronics

KASCADE scintillators

DAQ

x 5 stations

RET-CR surface array

CODALEMA antenna

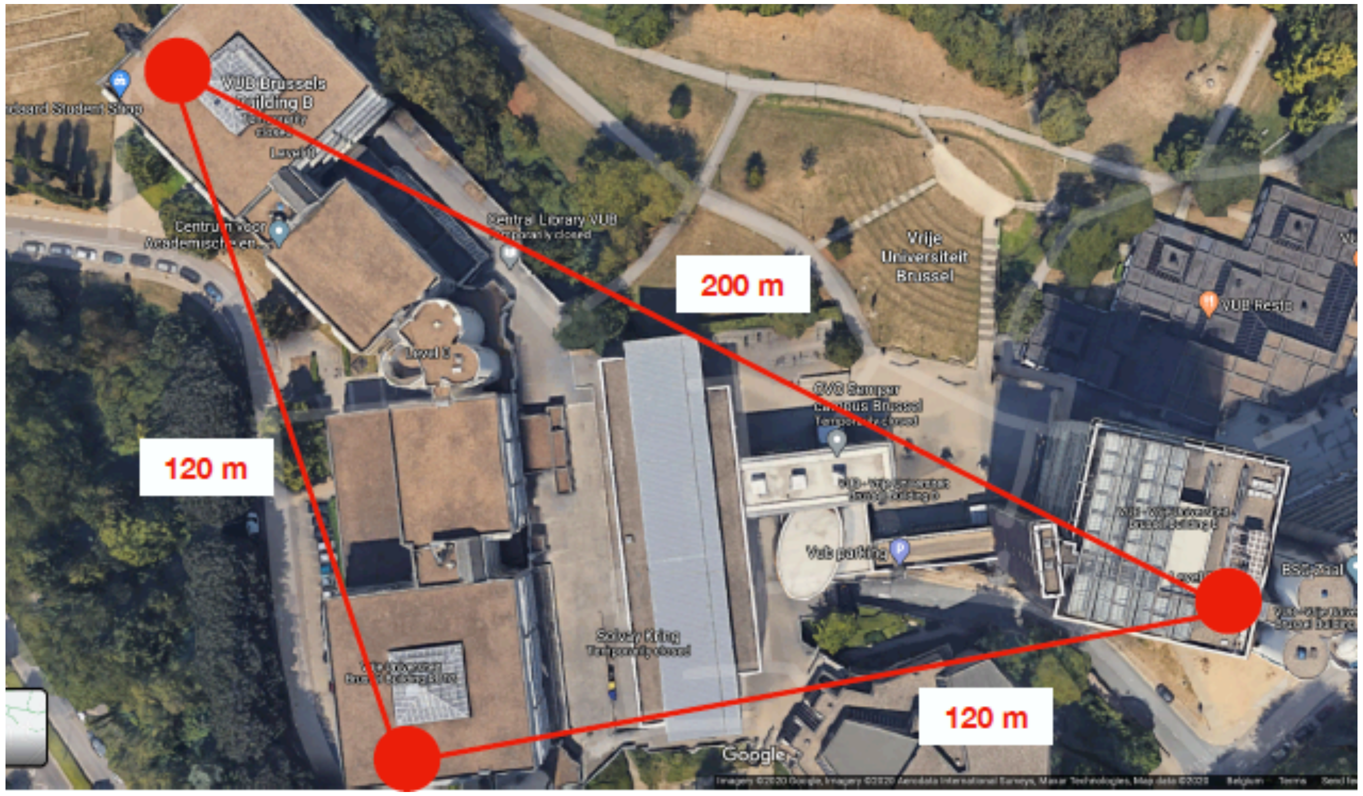
CODALEMA electronics

IceTop scintillators

DAQ

x 6 stations

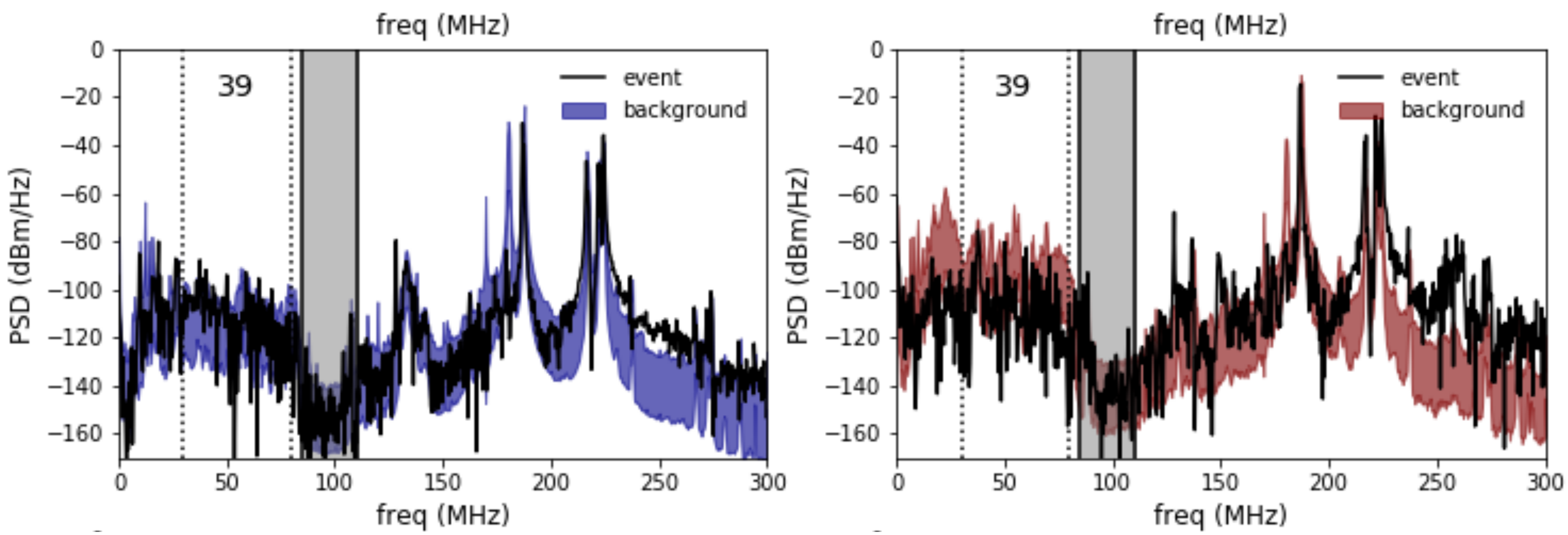
Prototype deployment at the VUB 2020-2021



VUB prototype

Krijn, Rose, Quique

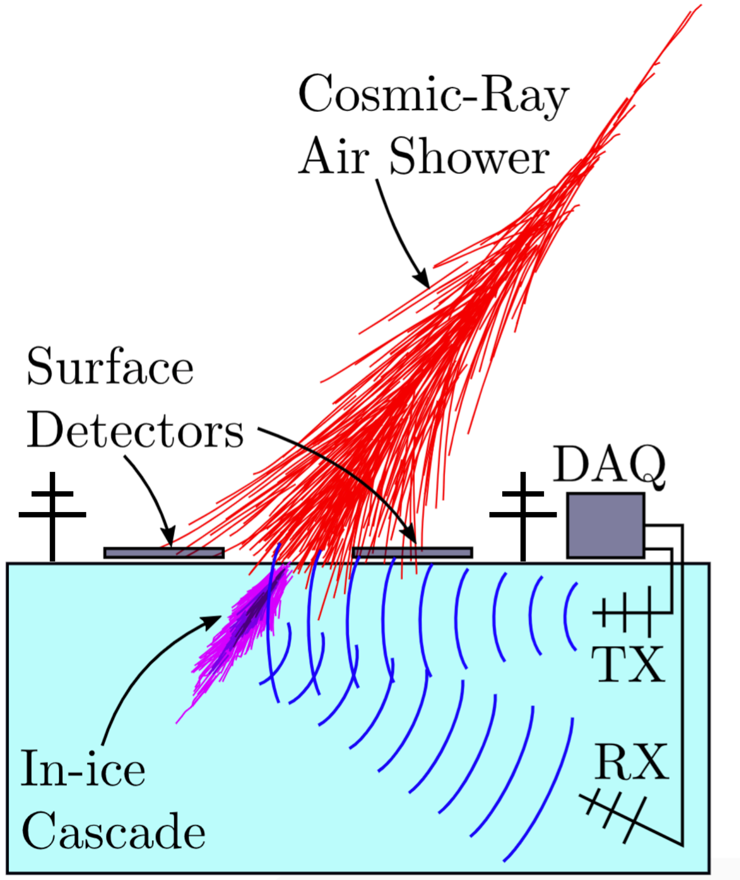
VUB prototype

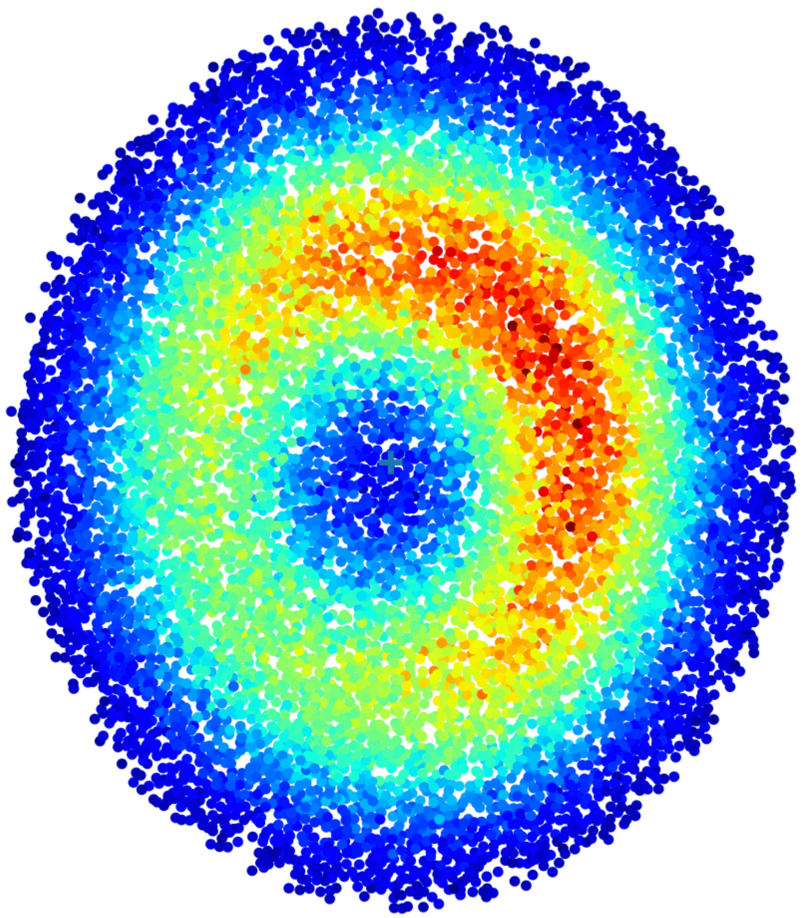


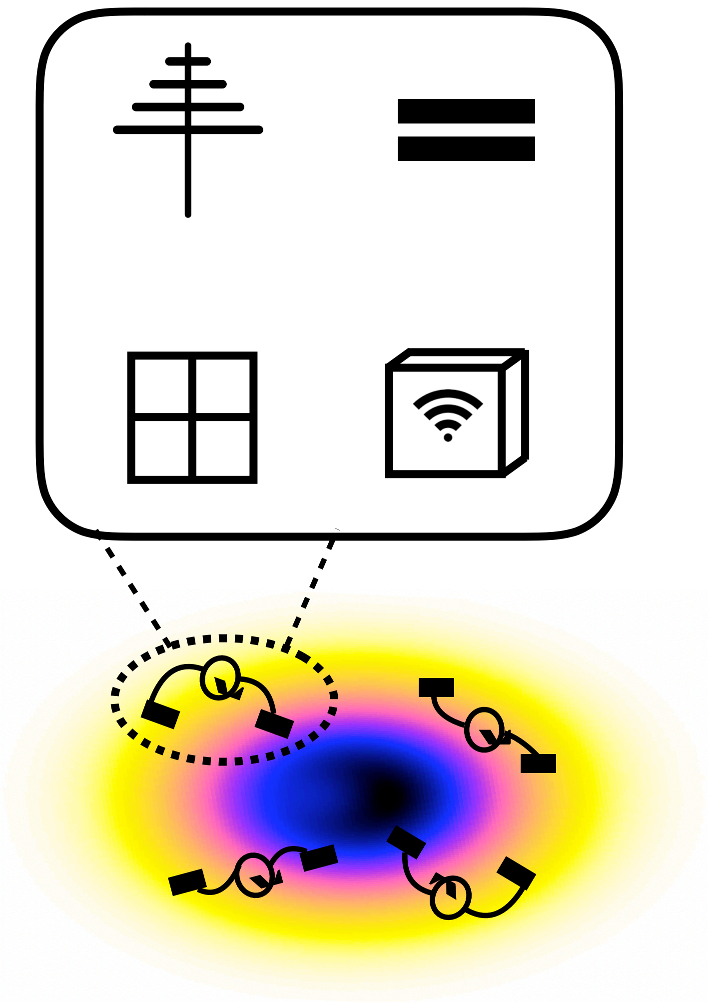
First CR data

Krijn, Rose, Quique

Radio detection of cosmic rays





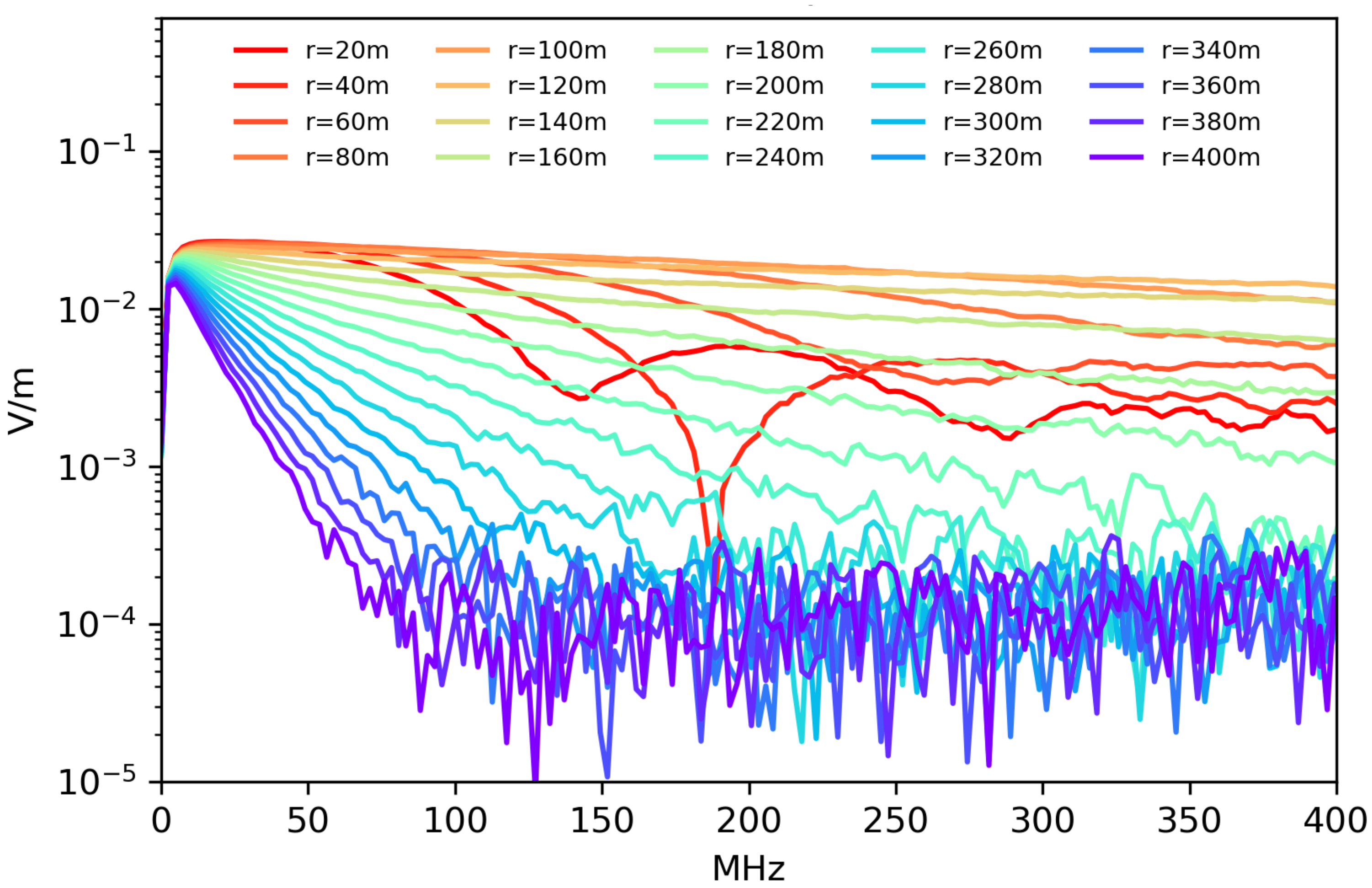


Questions?

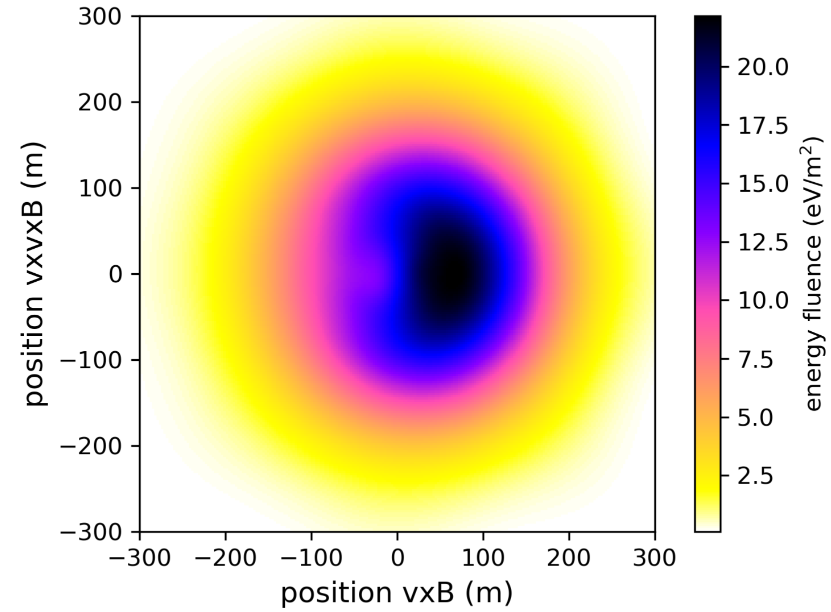
Extra

Energy Reconstruction

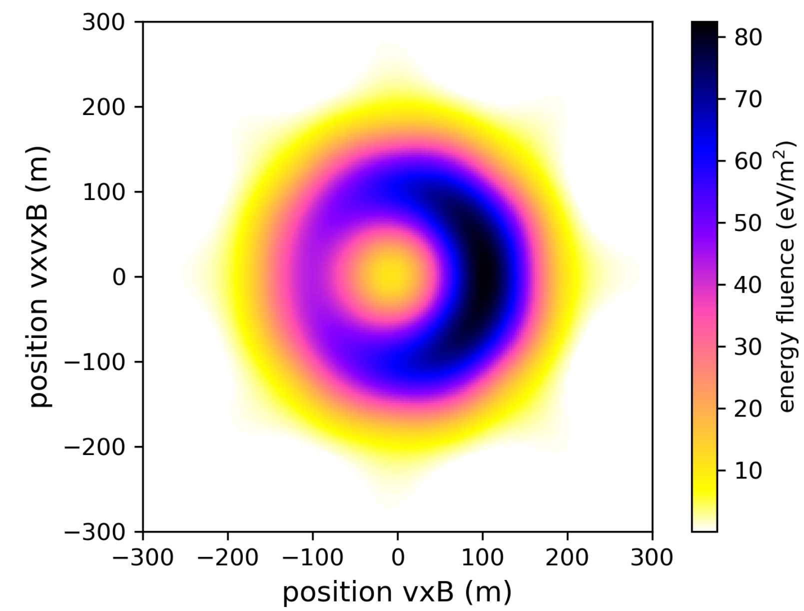
Geomagnetic signal on vxvxB arm
E~10^{17}eV
Xmax=640 g/cm²
zenith=33°



30-80 MHz

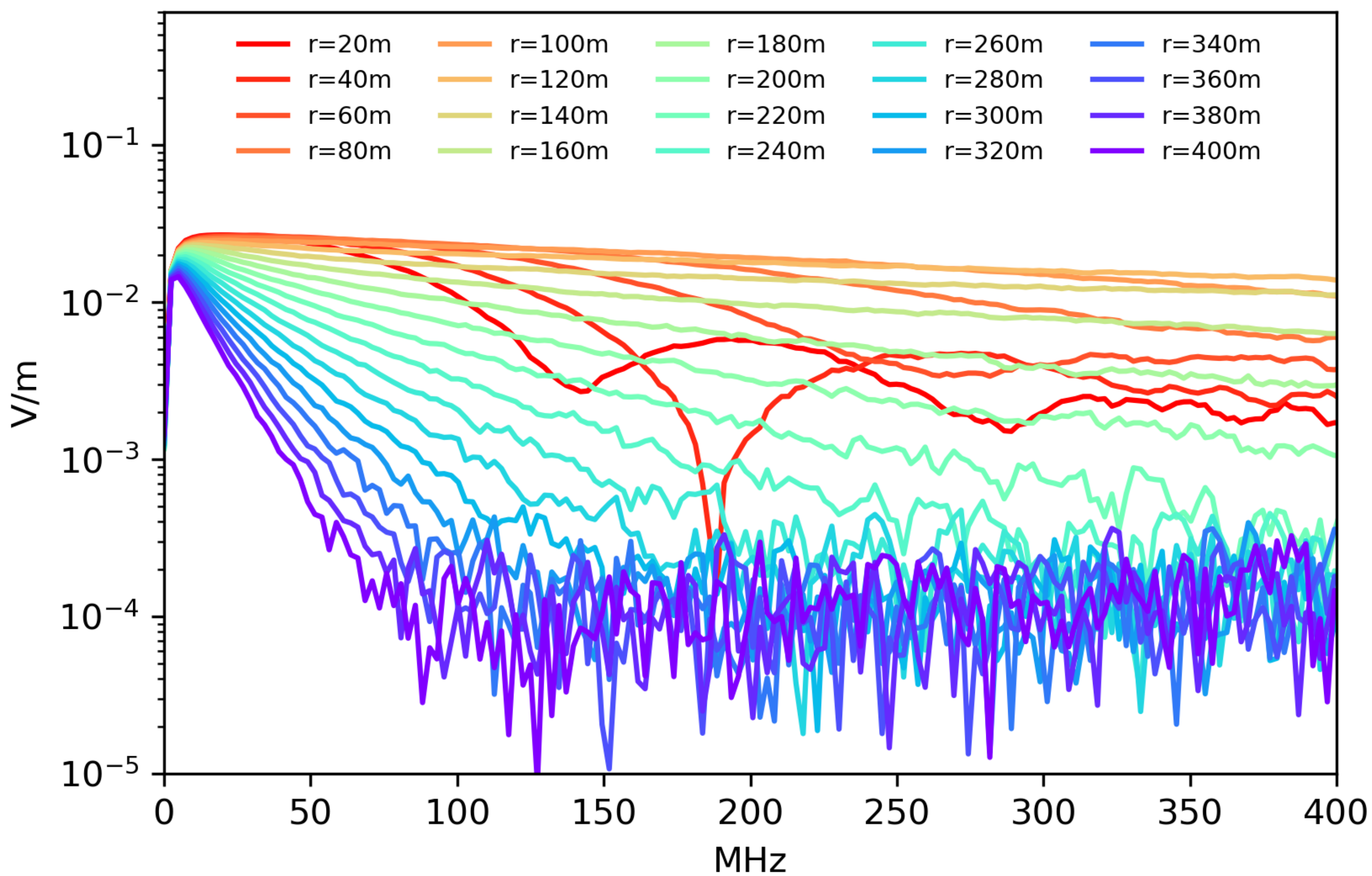


50-350 MHz



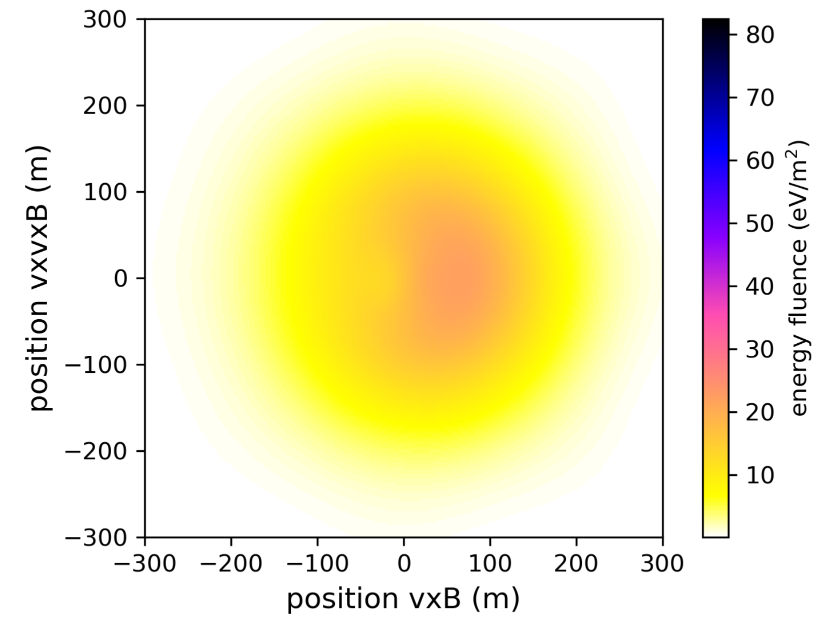
Energy Reconstruction

Geomagnetic signal on vxvxB arm
E~10^{17}eV
Xmax=640 g/cm^2
zenith=33°

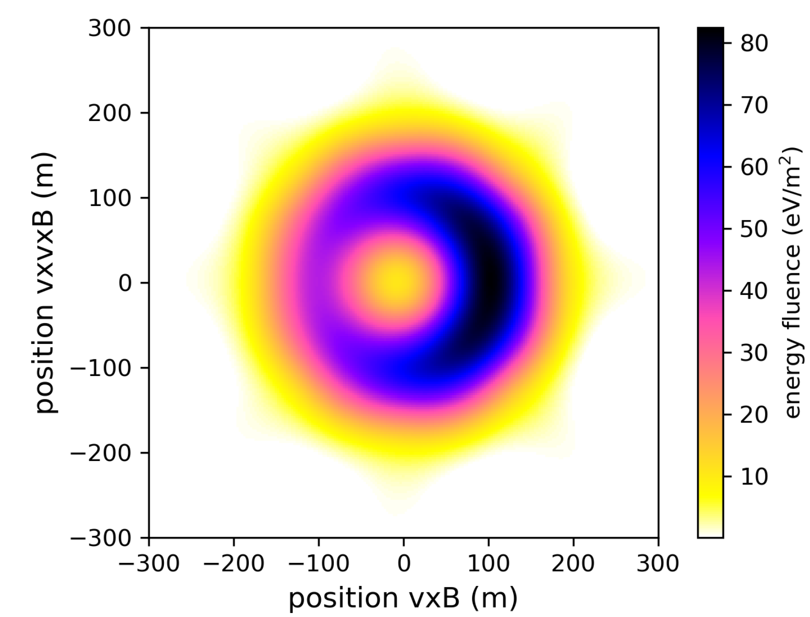


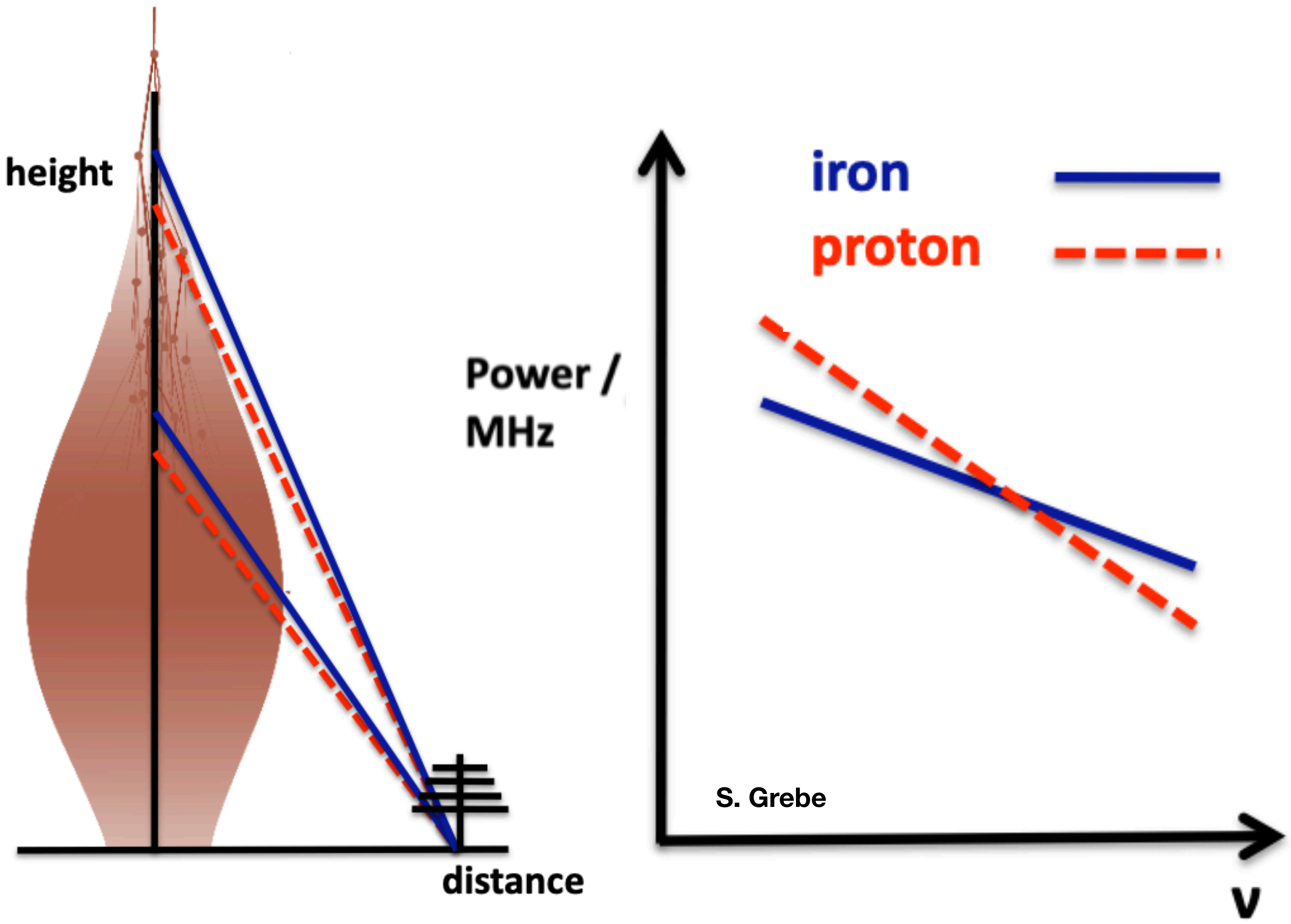
Energy reconstruction: work in progress

30-80 MHz

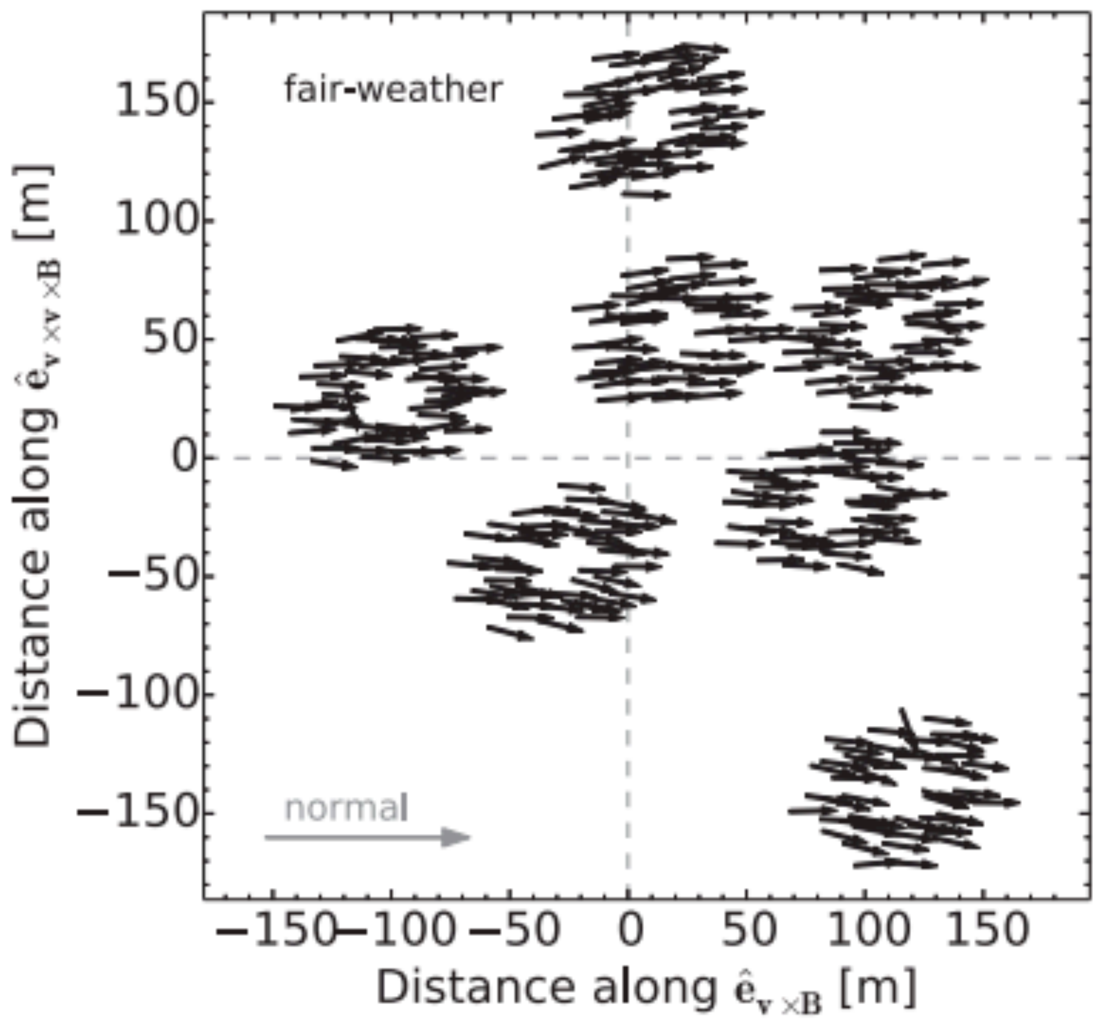


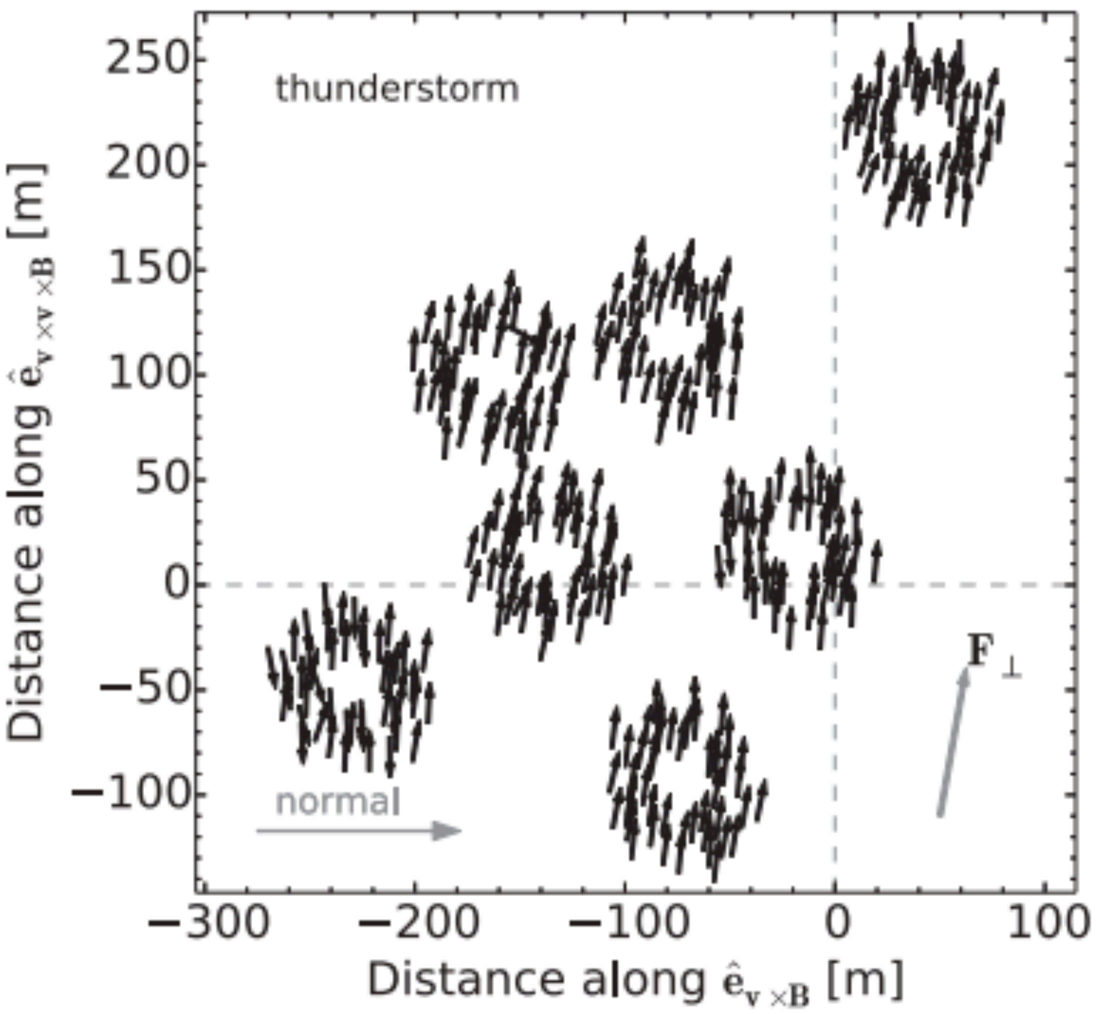
50-350 MHz

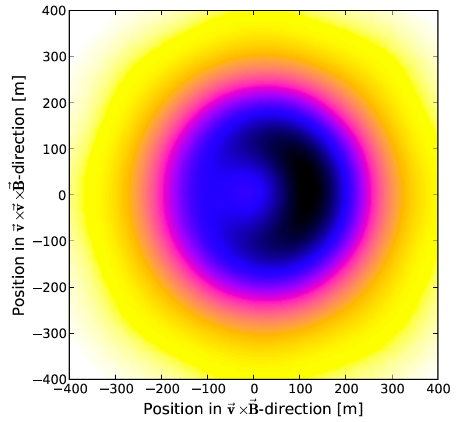



height
distance
Power /
MHz
iron
proton
S. Grebe
ν

Polarization

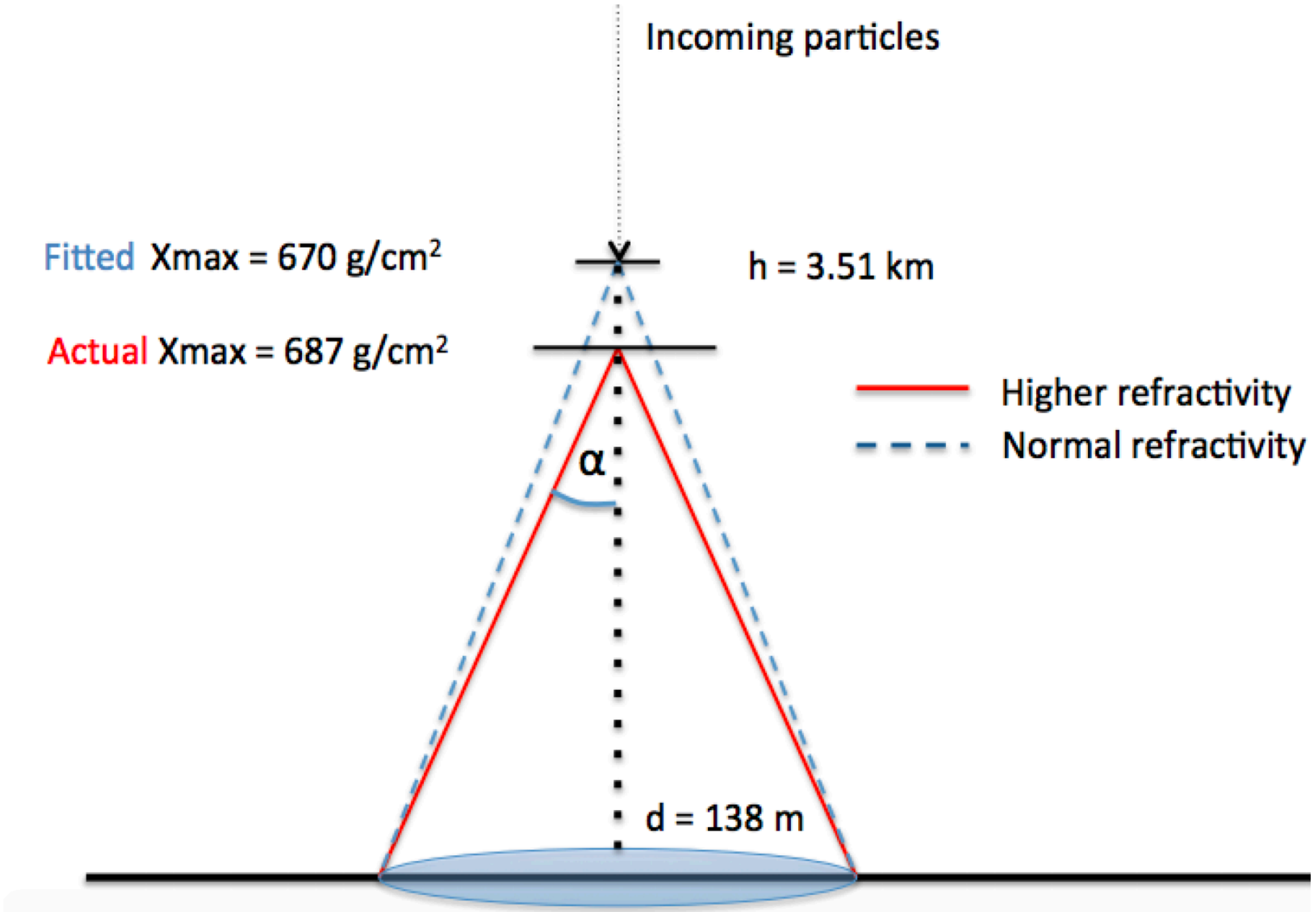






O. Scholten, et al. Phys. Rev. D 94 (2016) 103010

Atmospheric Corrections

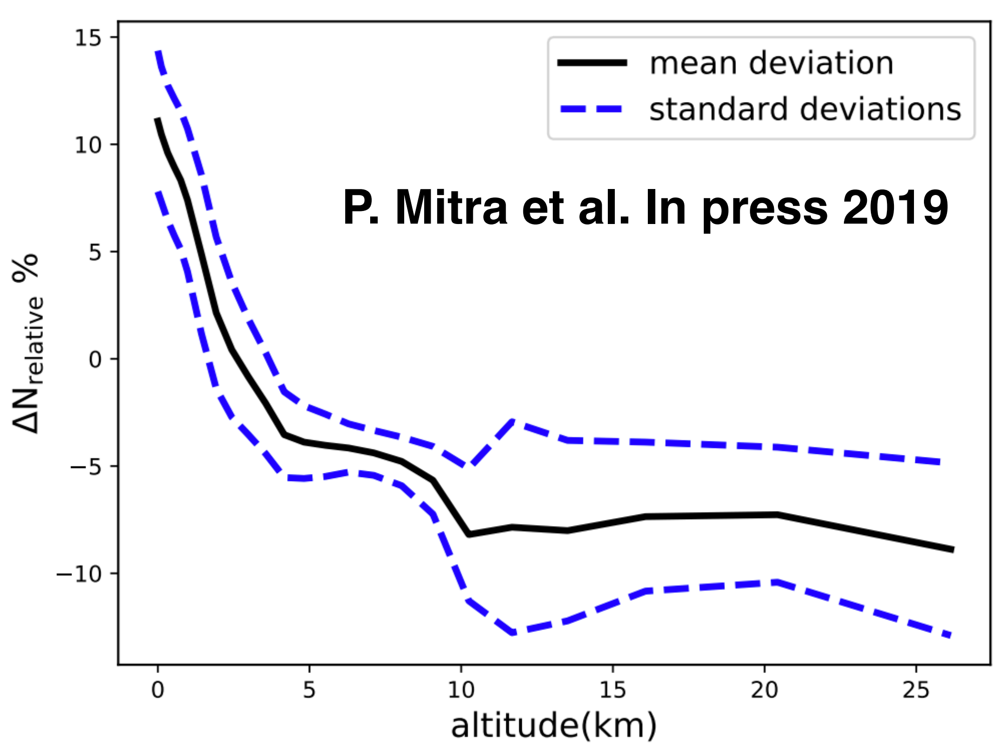


A. Corstanje Astropart.Phys. 89 (2017)

- Reduce systematic uncertainties on atmospheric conditions
- Previous: use density profile to do linear correction on Xmax

→ *Move to realistic GDAS atm*.

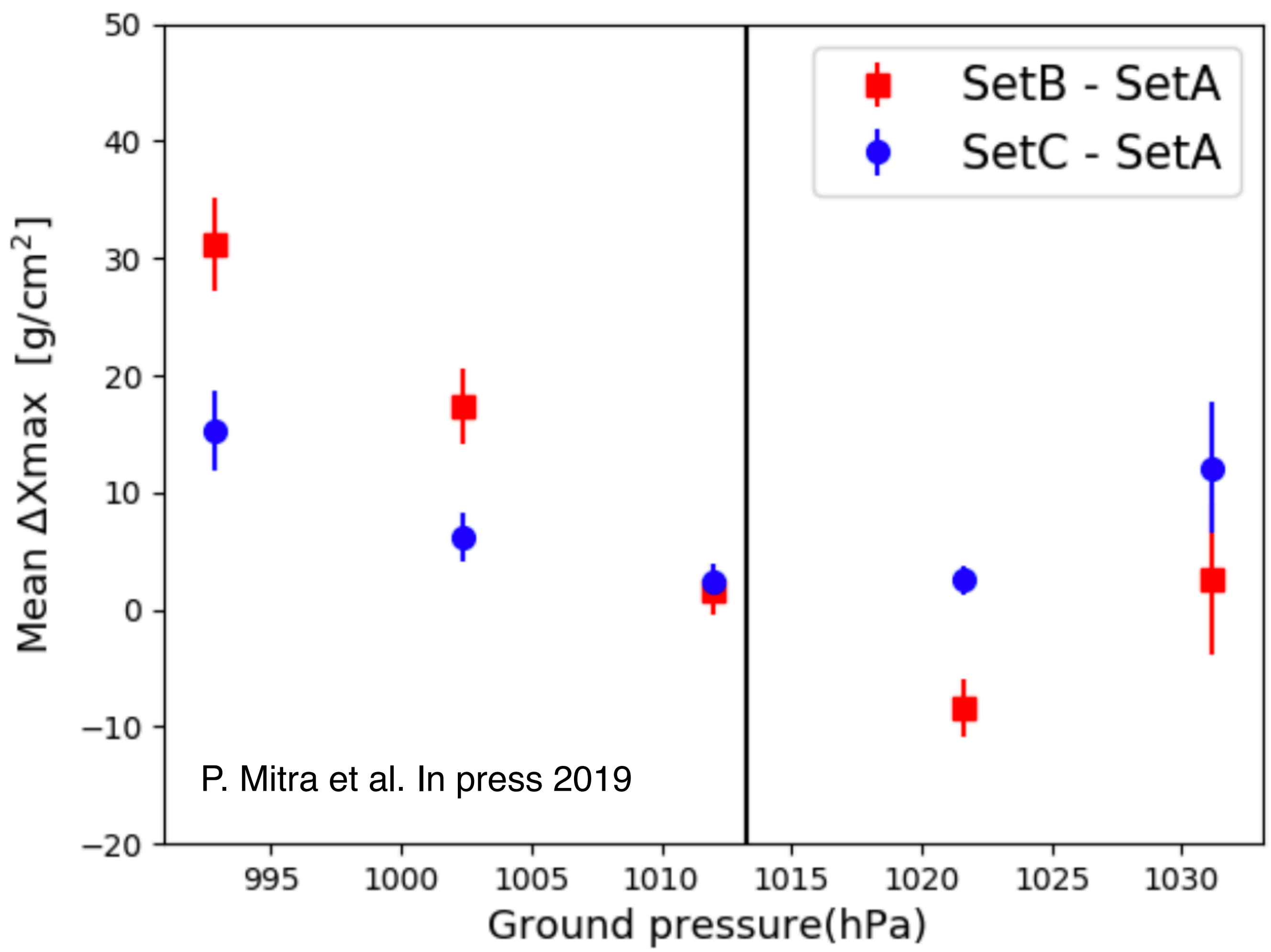
"Global Data Assimilation System"



- GDAS provides specific profiles for temperature, humidity, pressure
- Any location (1°x1°), time (3-hourly)

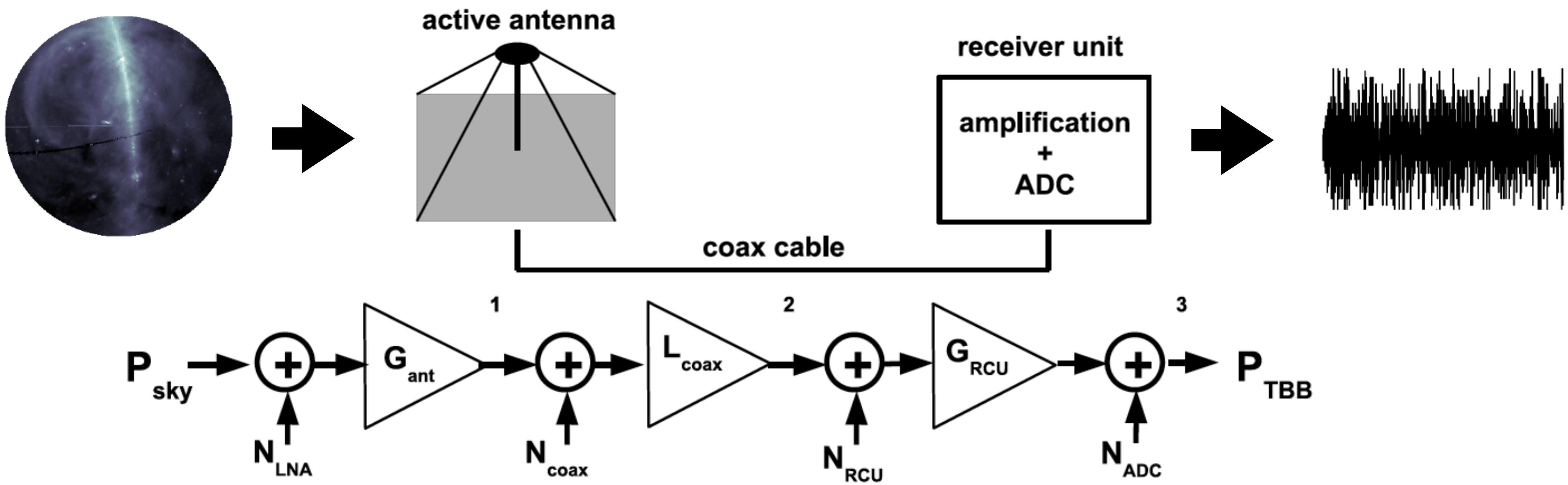
Atmospheric Corrections

- **New: implement density and refractivity directly into CORSIKA/CoREAS simulations**
- **Available as a standard option since CORSIKA 76300**
- **For extreme conditions, can shift X_{max} up to 15 g/cm²**



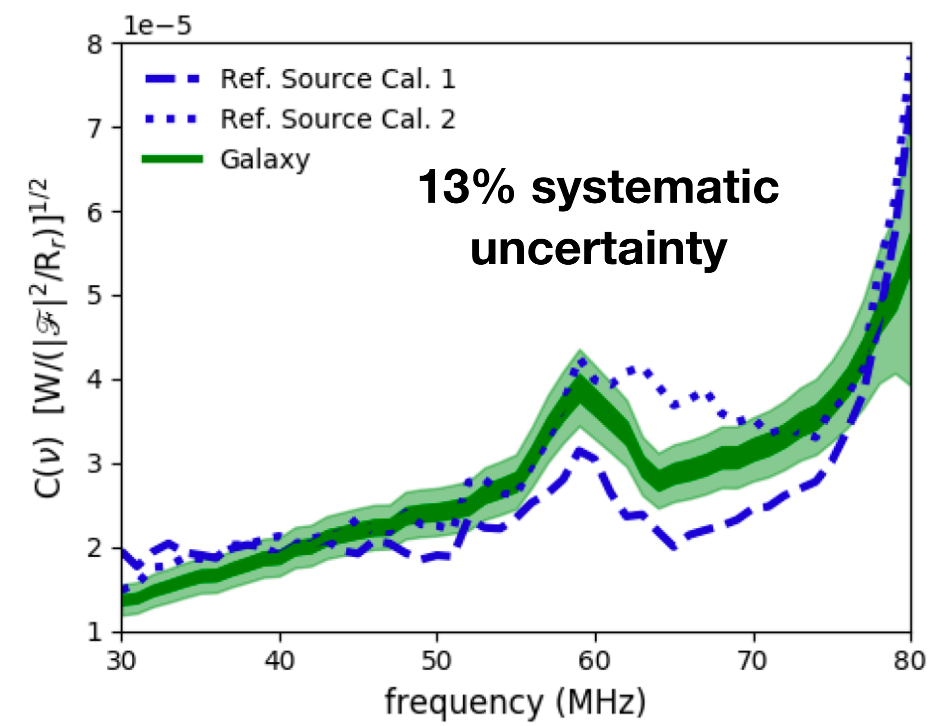
SetA: GDAS atmosphere
SetB: US Standard atmosphere
SetC: SetB + linear correction

Antenna Calibration



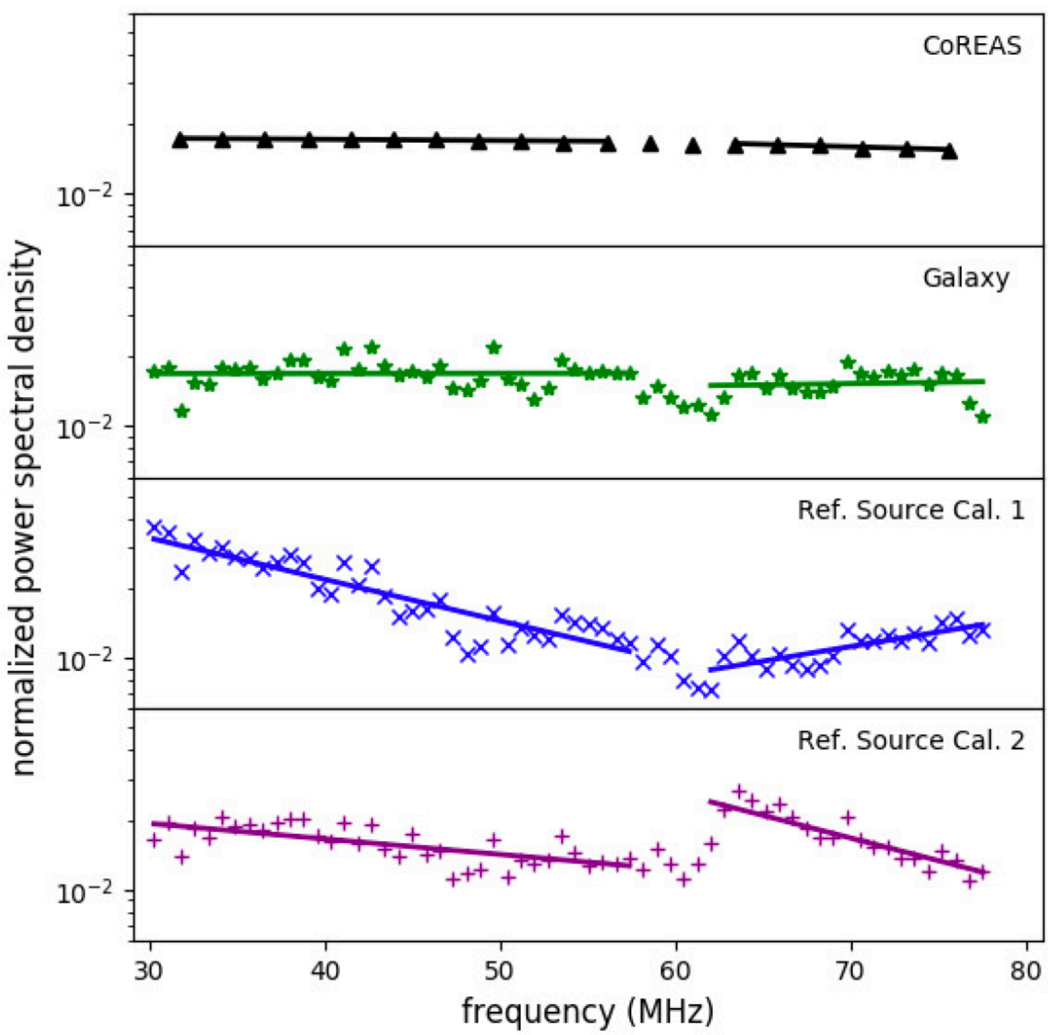
- ***Antenna calibration is critical for energy measurements and spectral analyses***

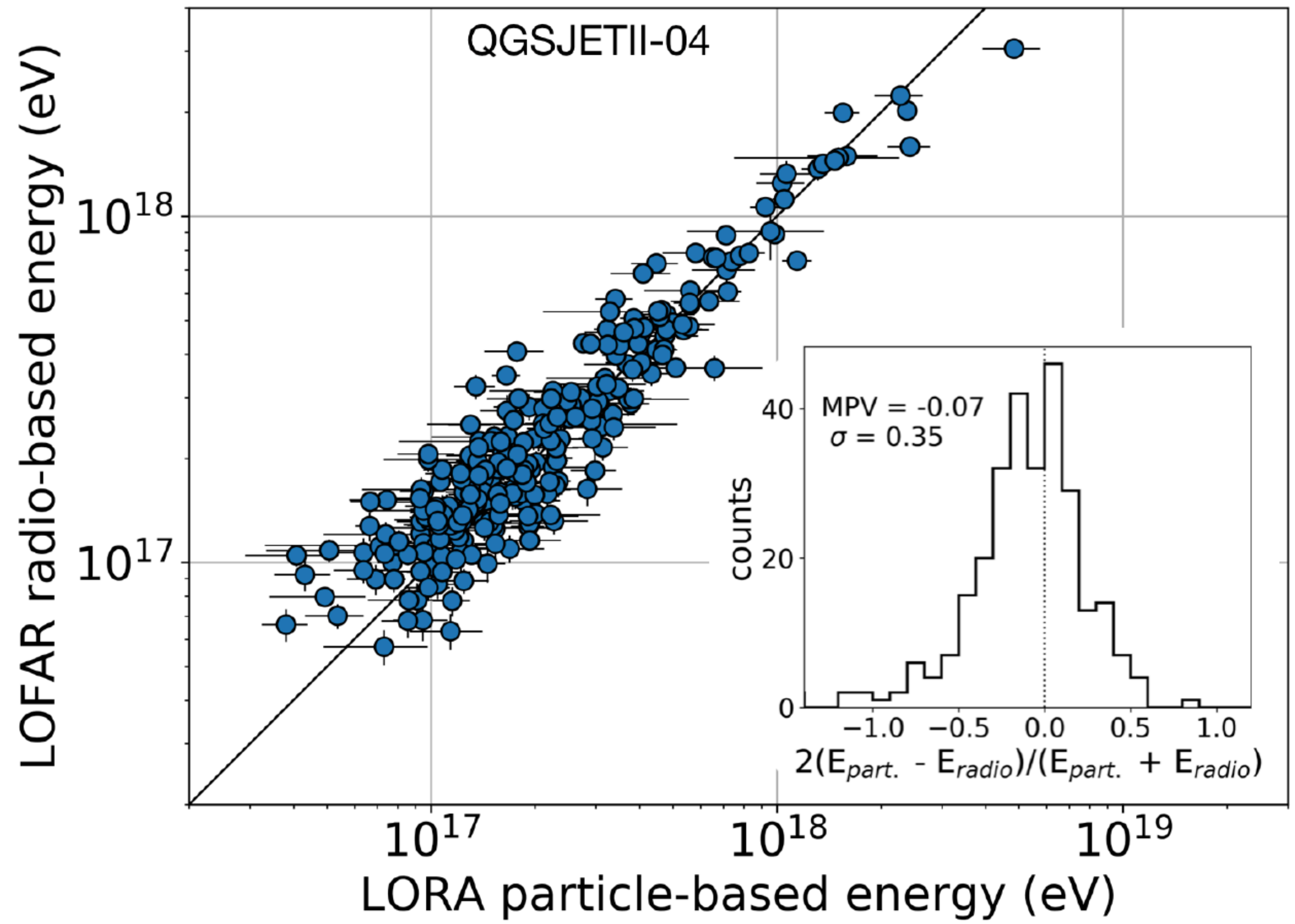
- Using galactic background AND model of the signal chain allows for the determination of the amplitude calibration



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

Antenna Calibration

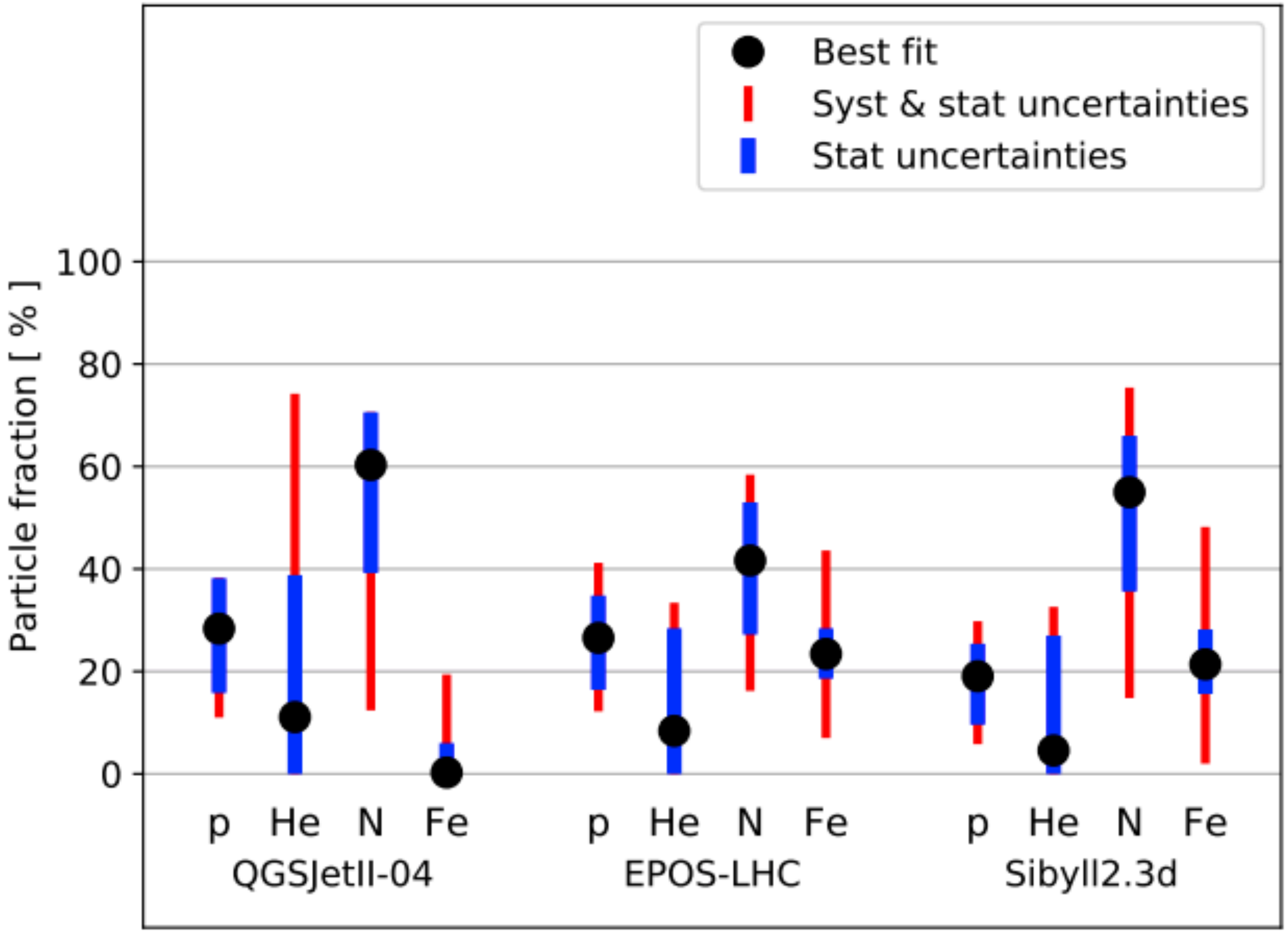




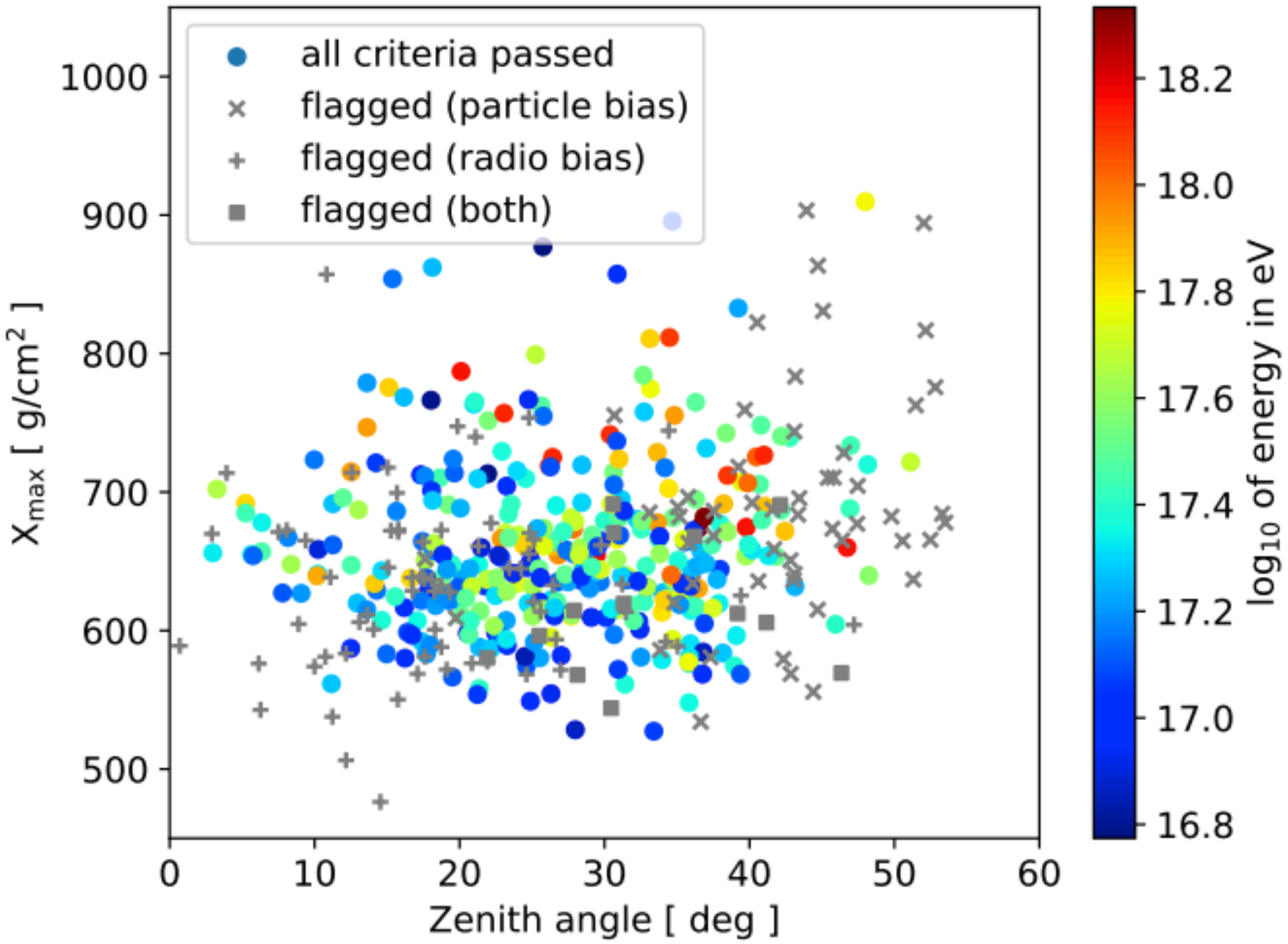
- Spectral shape shows good agreement between simulation and data

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

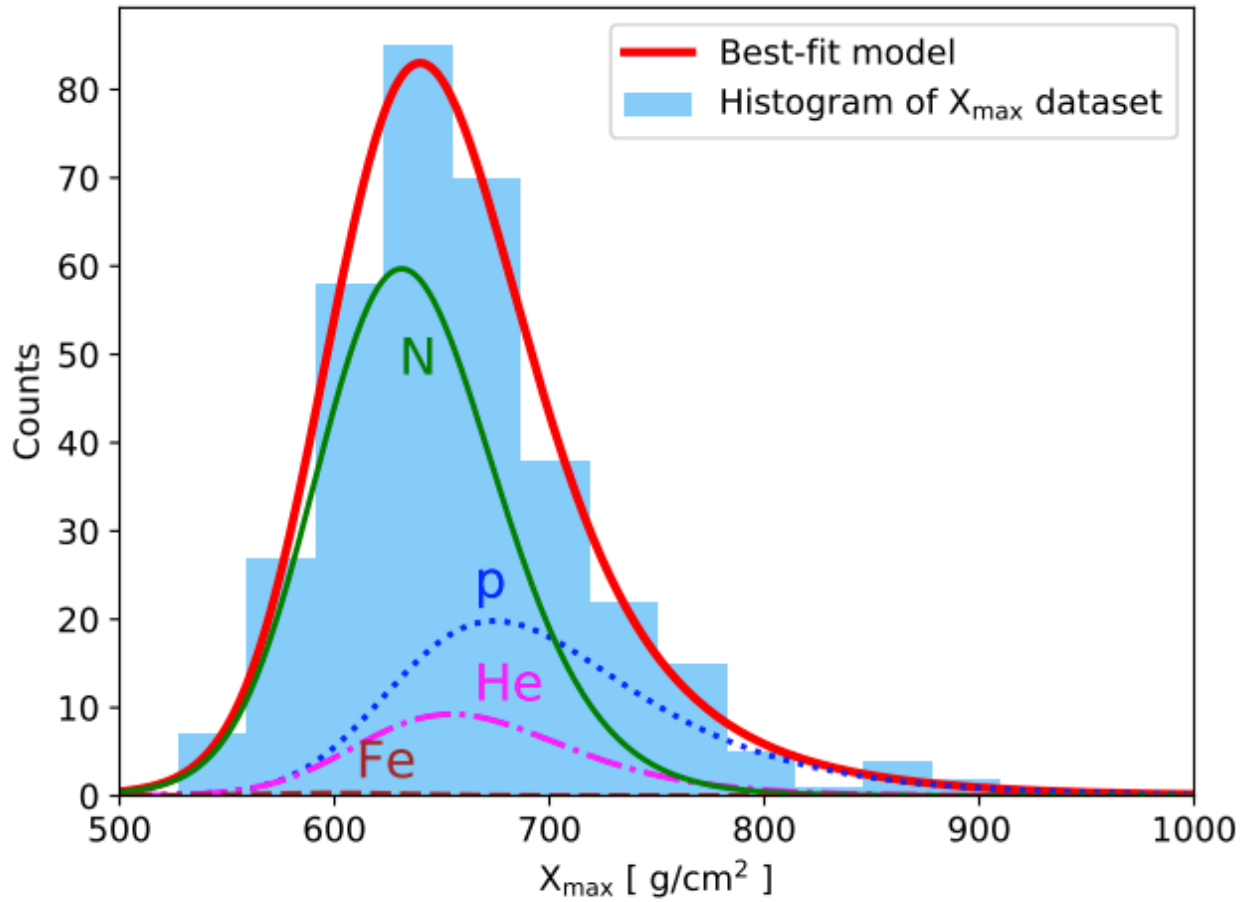
Absolute calibration makes radio-based energy scale possible



Best fit
Syst & stat uncertainties
Stat uncertainties
Particle fraction [%]
100
80
60
40
20
0
p He N Fe
QGSJetII-04
p He N Fe
EPOS-LHC
p He N Fe
Sibyll2.3d



all criteria passed
flagged (particle bias)
flagged (radio bias)
flagged (both)
X_{max} [g/cm^2]
Zenith angle [deg]
$\log_{10}$ of energy in eV



Best-fit model
Histogram of X_{max} dataset
N
p
He
Fe
Counts
X_{max} [g/cm^2]

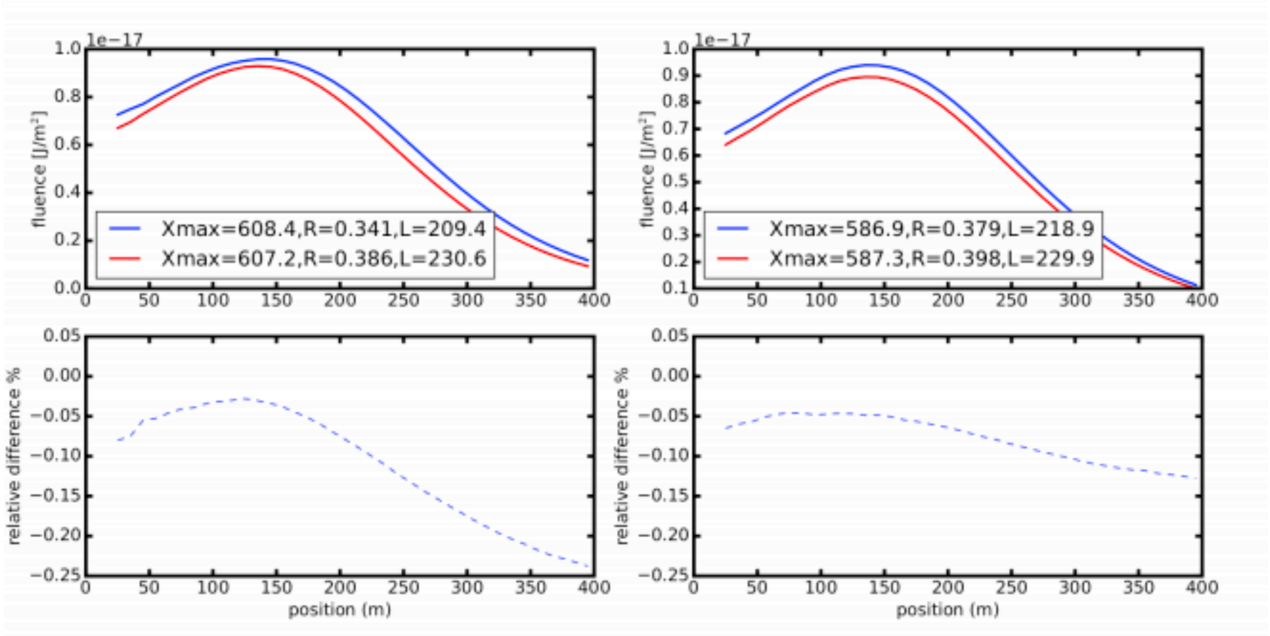


Figure 1.13: Category3: Radio fluence LDFs with similar X_{max}, different R, L

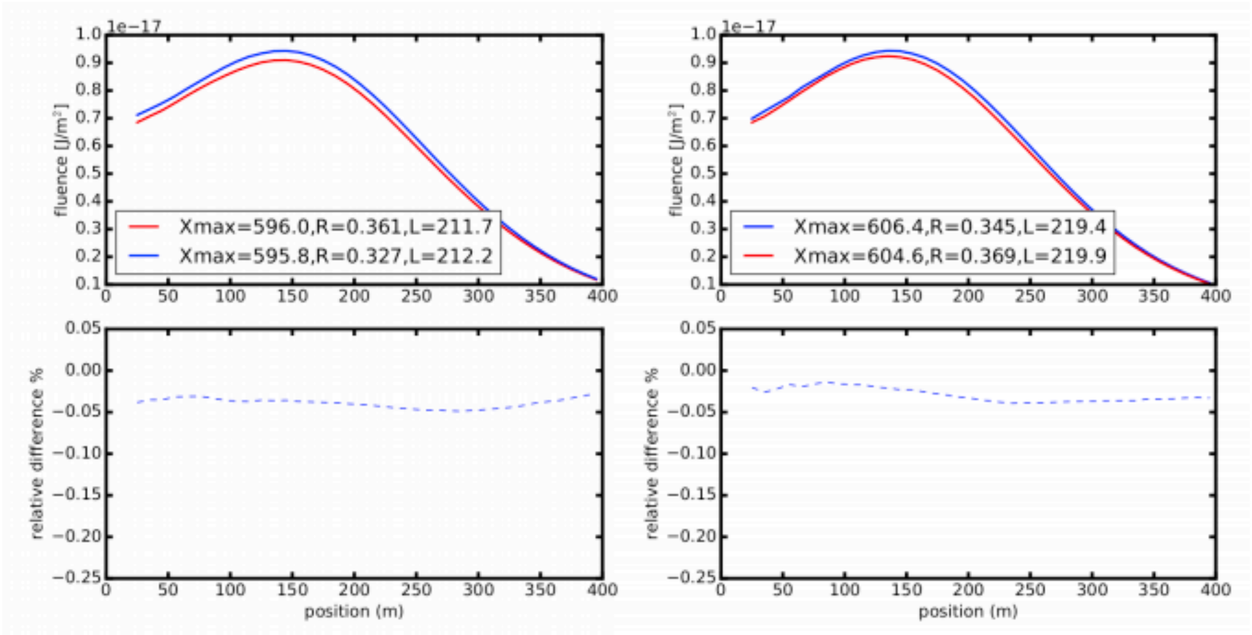
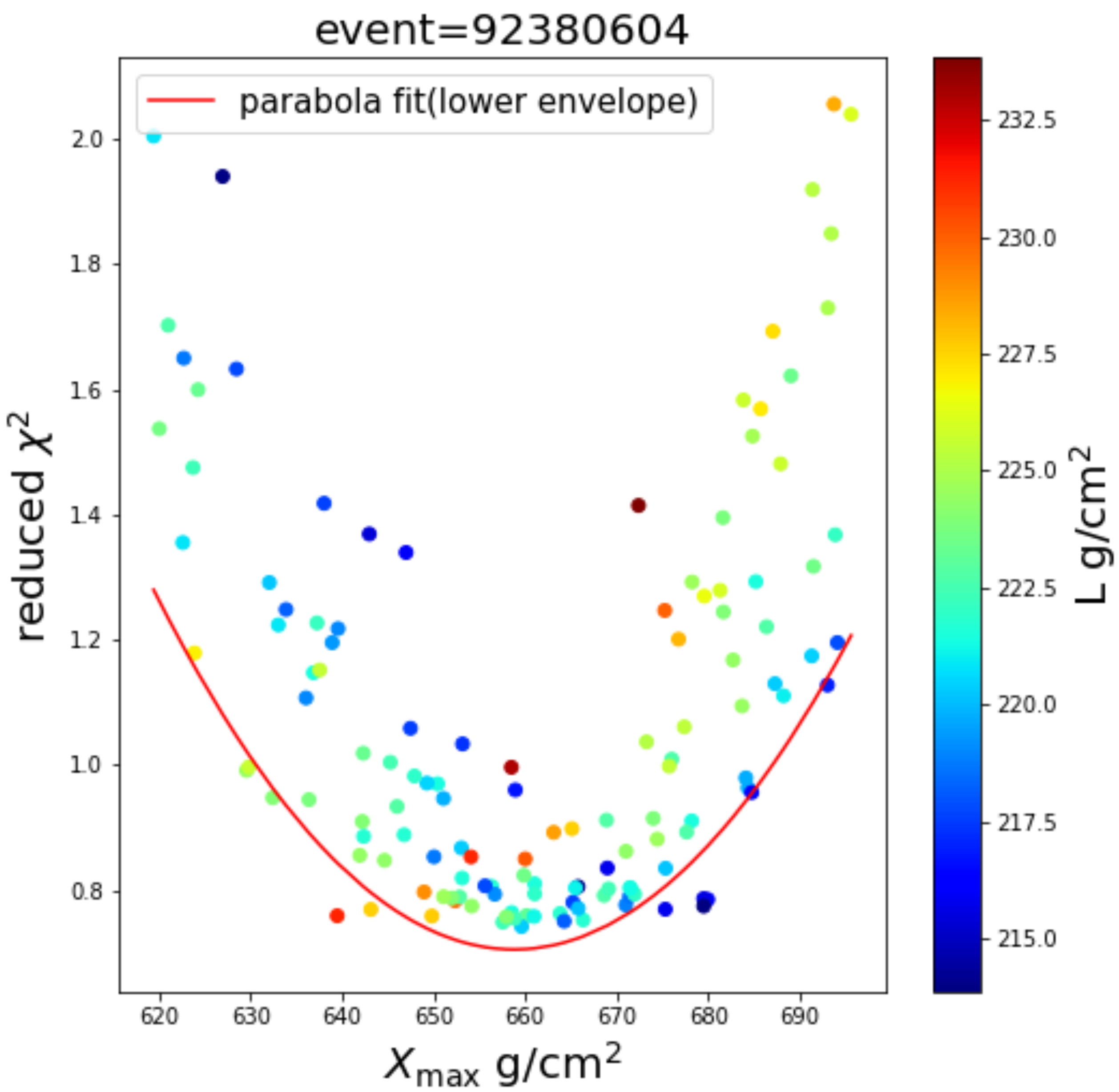
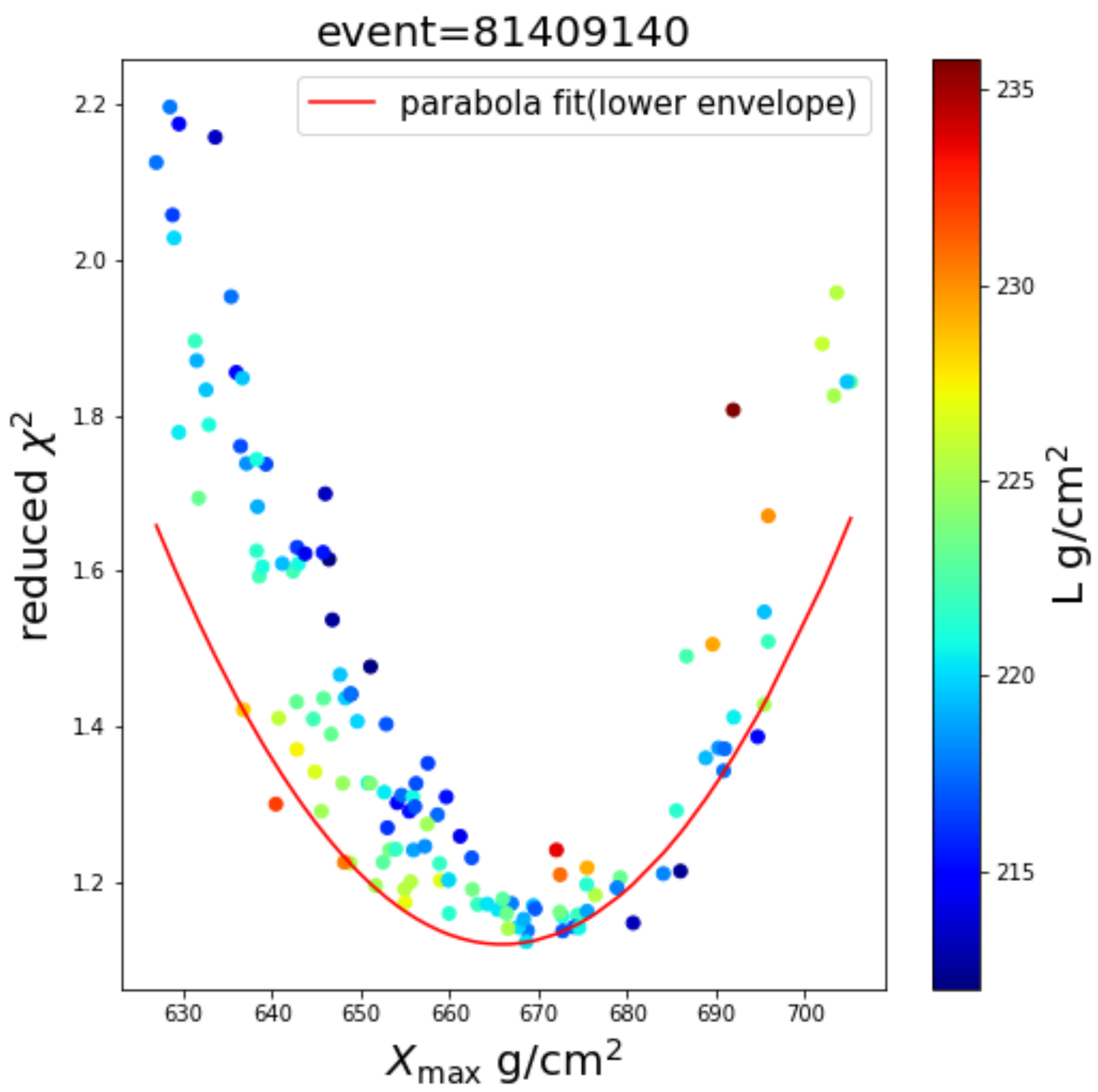


Figure 1.14: Category4: Radio fluence LDFs with similar X_{max}, L different R


event=92380604
parabola fit(lower envelope)
reduced χ^2
X_{max} g/cm^2
L g/cm^2


event=81409140
parabola fit(lower envelope)
reduced χ^2
X_{max} g/cm^2
L g/cm^2

Radio-based energy uncertainties

Uncertainty	Value
Event-by-event	
angular dependence of antenna model	5%
temperature dependence	negligible
reconstruction uncertainty	typically 9%
composition uncertainty	10 %
Total event-by-event	11% $\bigoplus$ reconstruction uncertainty
Absolute scale antenna calibration and system response	13%
hadronic interaction models	3%
radio simulation method	2.6%
Total absolute scale	13.6%

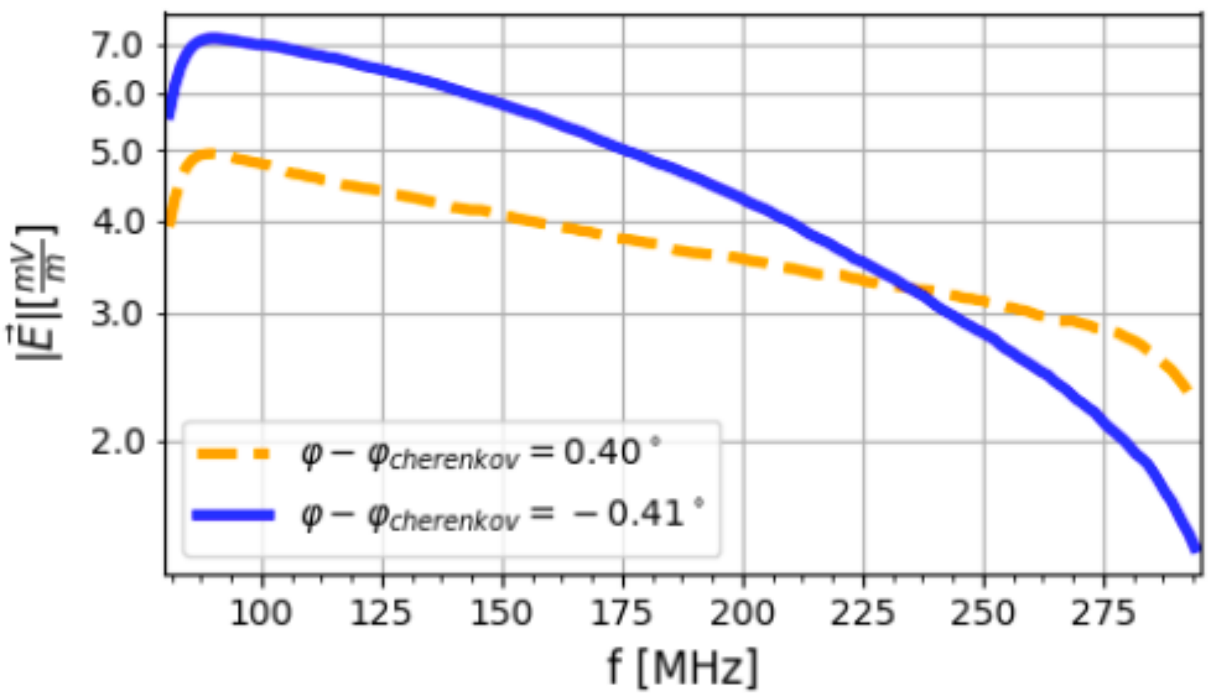
Particle-based energy uncertainties

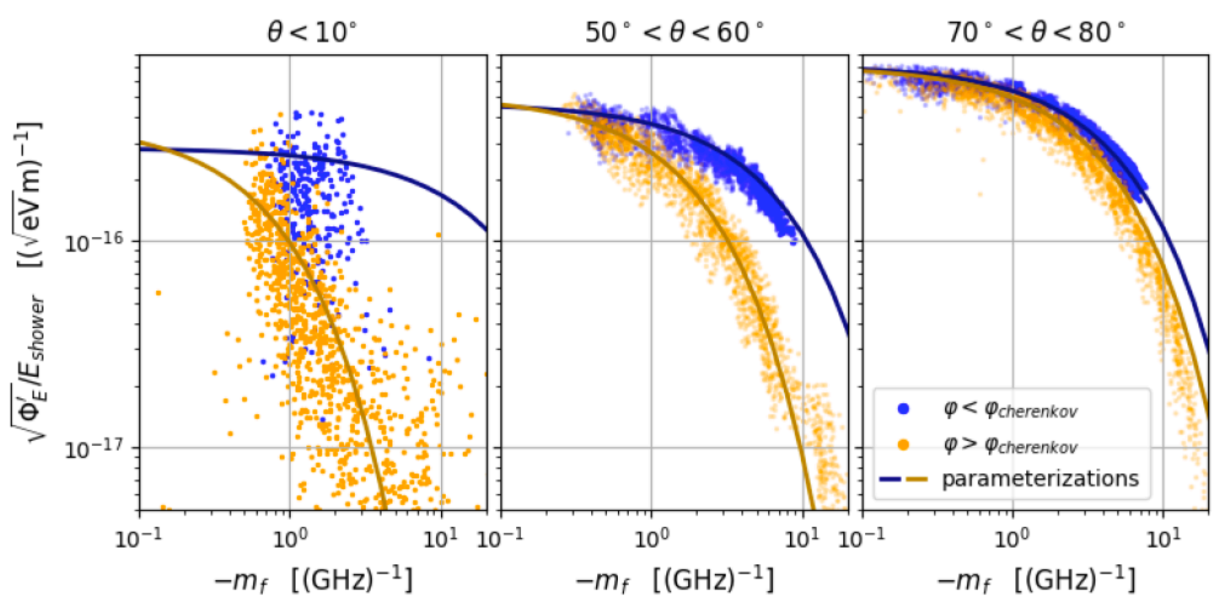
Uncertainty	Value
Event-by-event	
scintillator response variation	2.5%
reconstruction uncertainty	10 – 50%
composition uncertainty	2 – 30%
Total event-by-event	2.5% $\bigoplus$ reconstruction uncertainty $\bigoplus$ composition uncertainty
Absolute scale	
scintillator calibration	3%
hadronic interaction models	7%
Total absolute scale	7.6%

X_{max} uncertainties

	Syst. uncertainty	Added stat. unc.
Choice of hadronic interaction model	$5\,g/cm^2$	
Remaining atmospheric uncertainty	$\sim 1\,g/cm^2$	$\sim 2\,g/cm^2$
Five-layer atmosphere CORSIKA	$2\,g/cm^2$	$4\,g/cm^2$
Possible residual bias	$3.3\,g/cm^2$	
Curve fit for χ^2 optimum	$\leq 1\,g/cm^2$	
Total, added in quadrature	$7\,g/cm^2$	

Welling et al. *JCAP* 10 (2019) 075





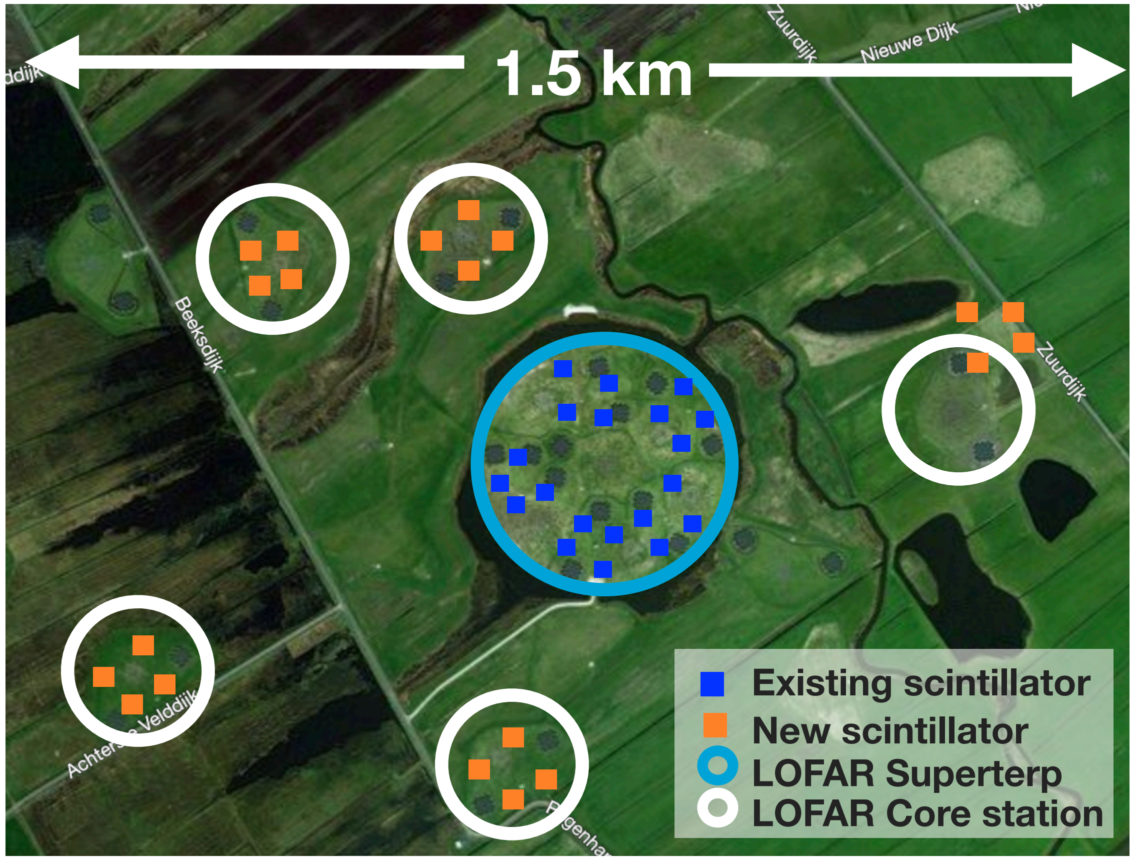
$$\begin{pmatrix} \mathcal{E}_\theta \\ \mathcal{E}_\phi \end{pmatrix} = \begin{pmatrix} A_\theta \\ A_\phi \end{pmatrix} 10^{f \cdot m_f} \exp(\Delta j)$$

Corrected radiation energy

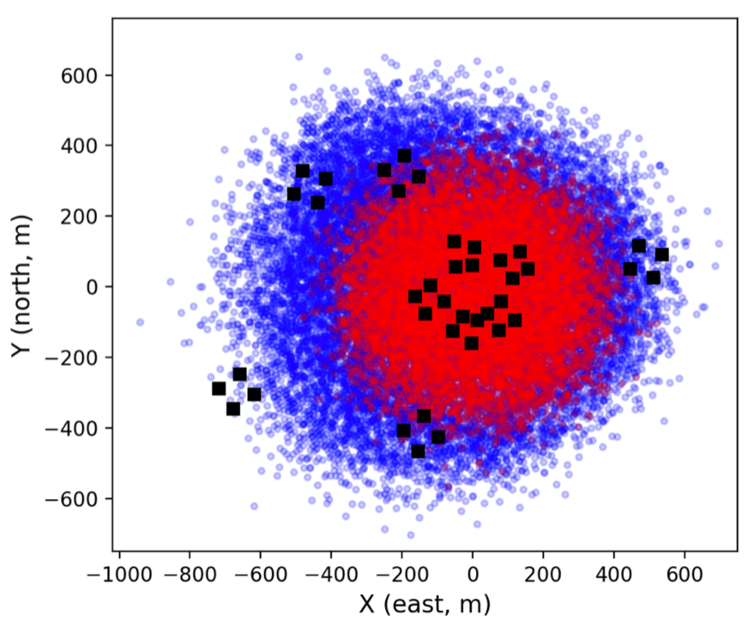
$$\frac{\sqrt{\Phi'_E}}{E_{shower}} = A \cdot \exp(-s \cdot (|m_f| \cdot \mathrm{GHz})^{0.8})$$

- Make use of spectral information to determine where you are w.r.t the Cherenkov cone
- Single antenna reconstruction?
- Resolution ~15%

Scintillator Array Extension

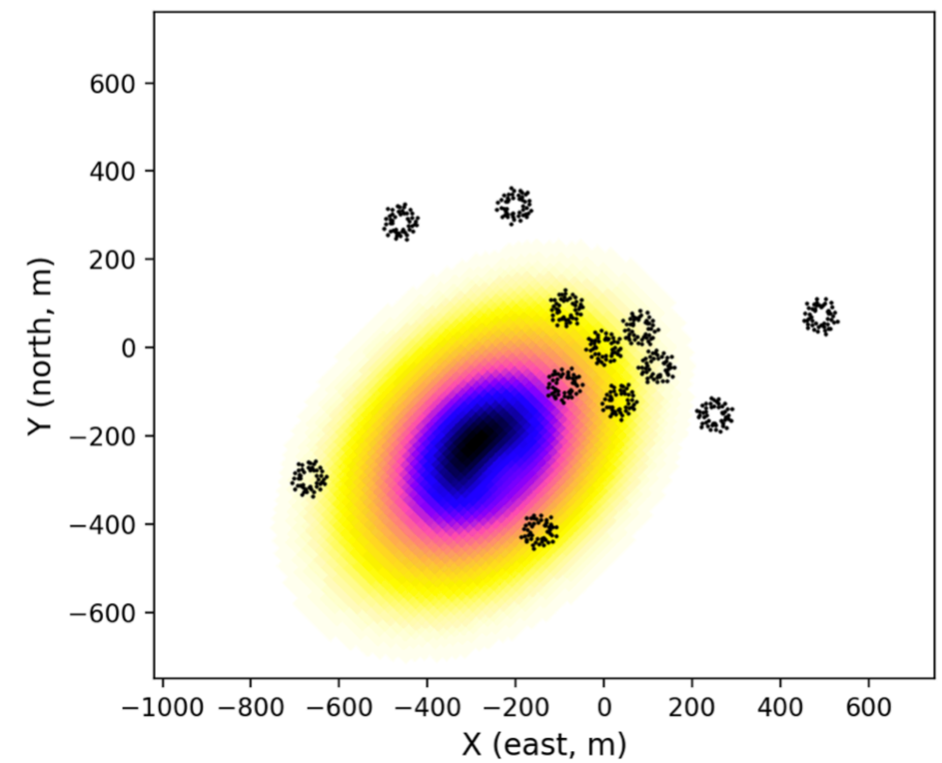


- **Current cosmic-ray trigger is based on 20 scintillators on the superterp**
- **Expand by adding 20 scintillators at neighboring stations**



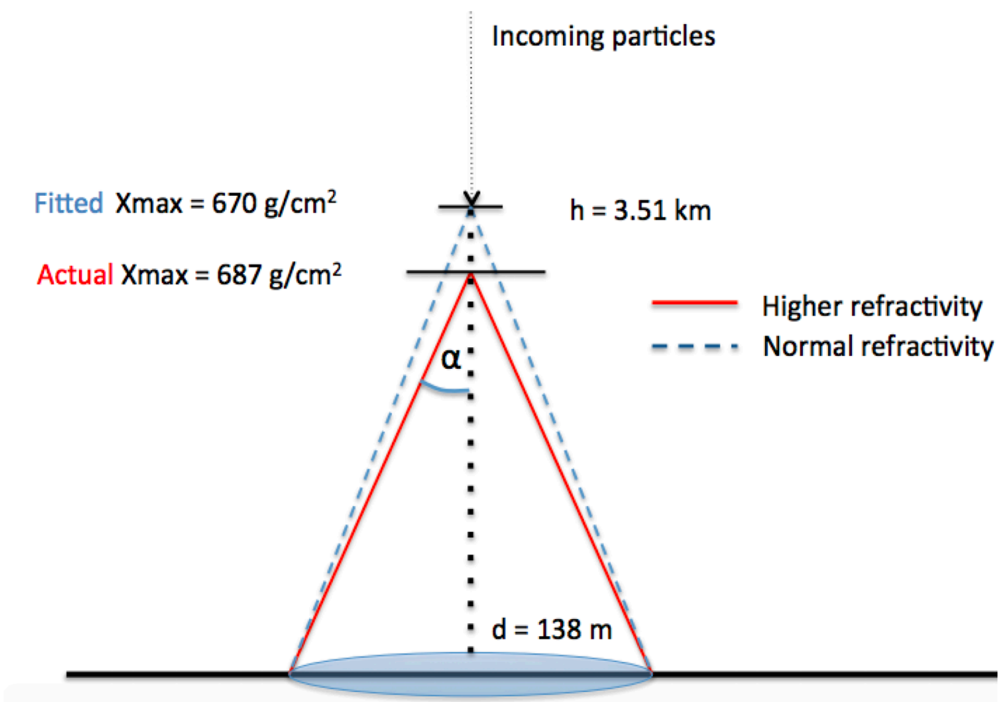
Simulated core positions

- Existing stations
- Expansion

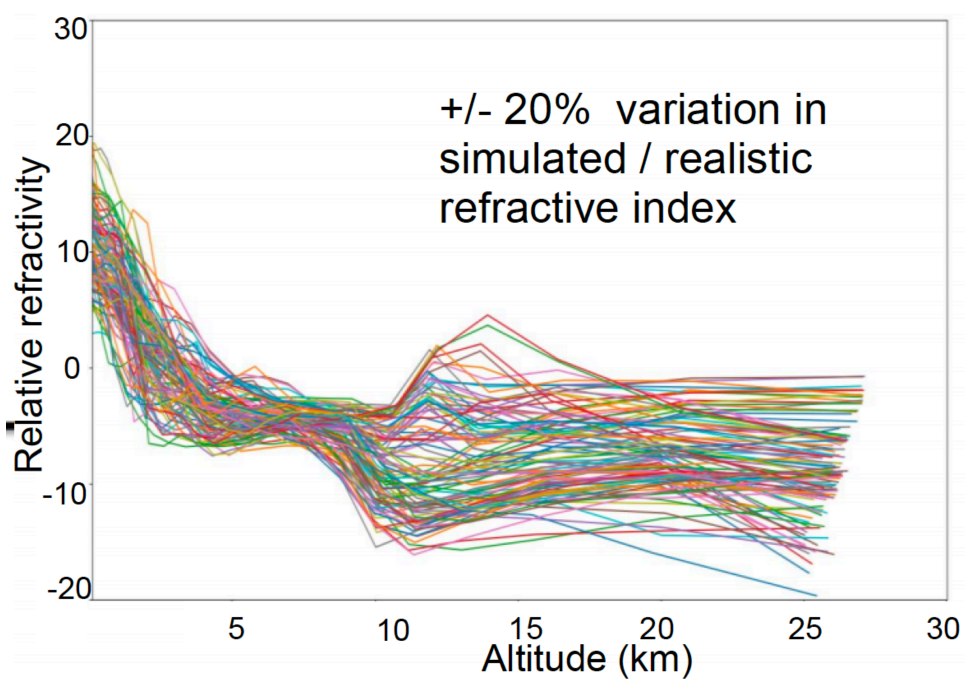


Triggering outside superterp:
Explore fringes of footprint

GDAS Atmospheric Corrections

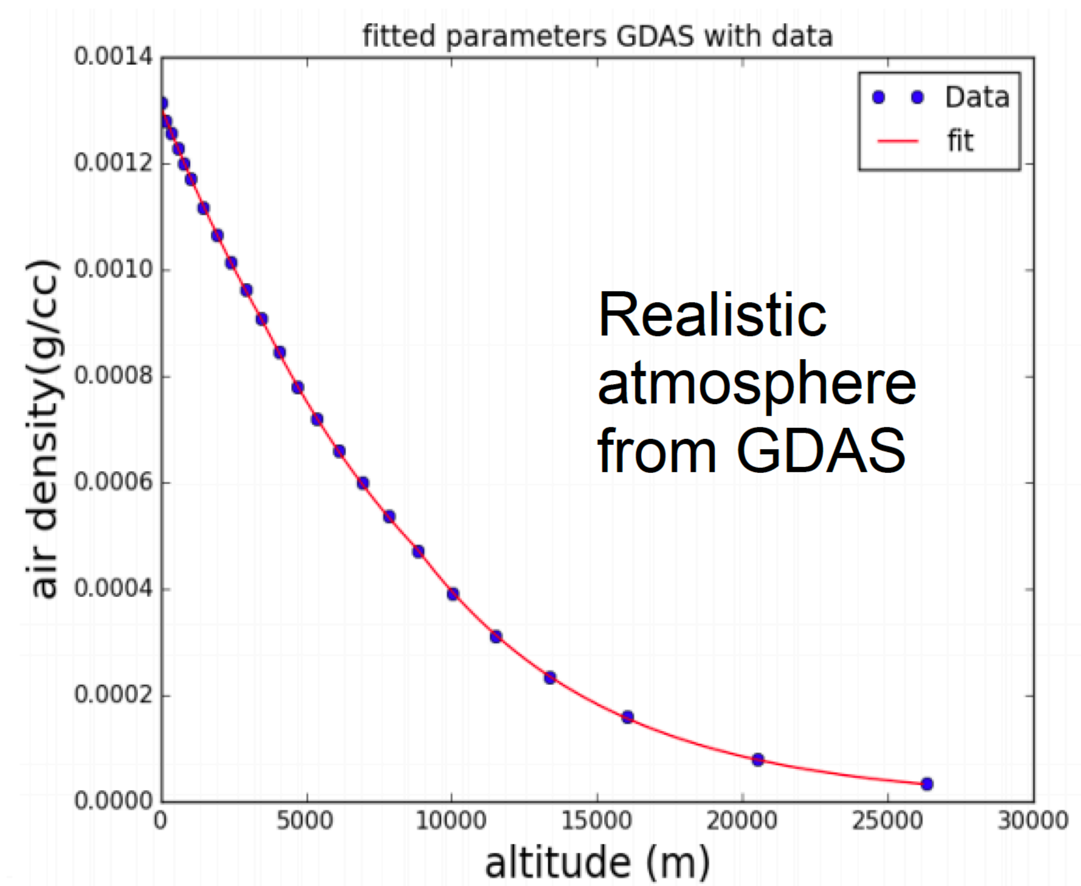


A. Corstanje Astropart.Phys. 89 (2017)

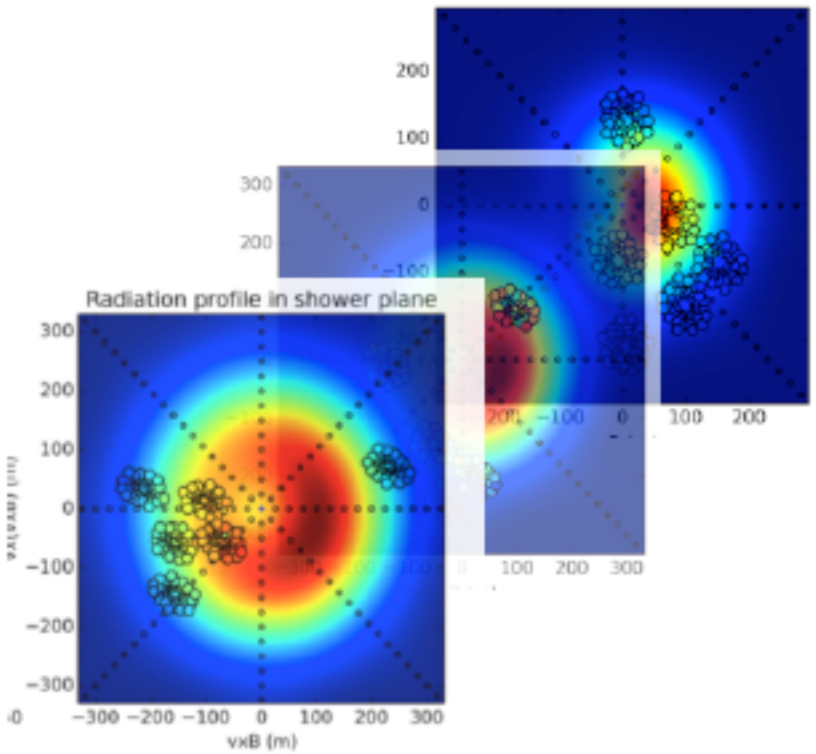


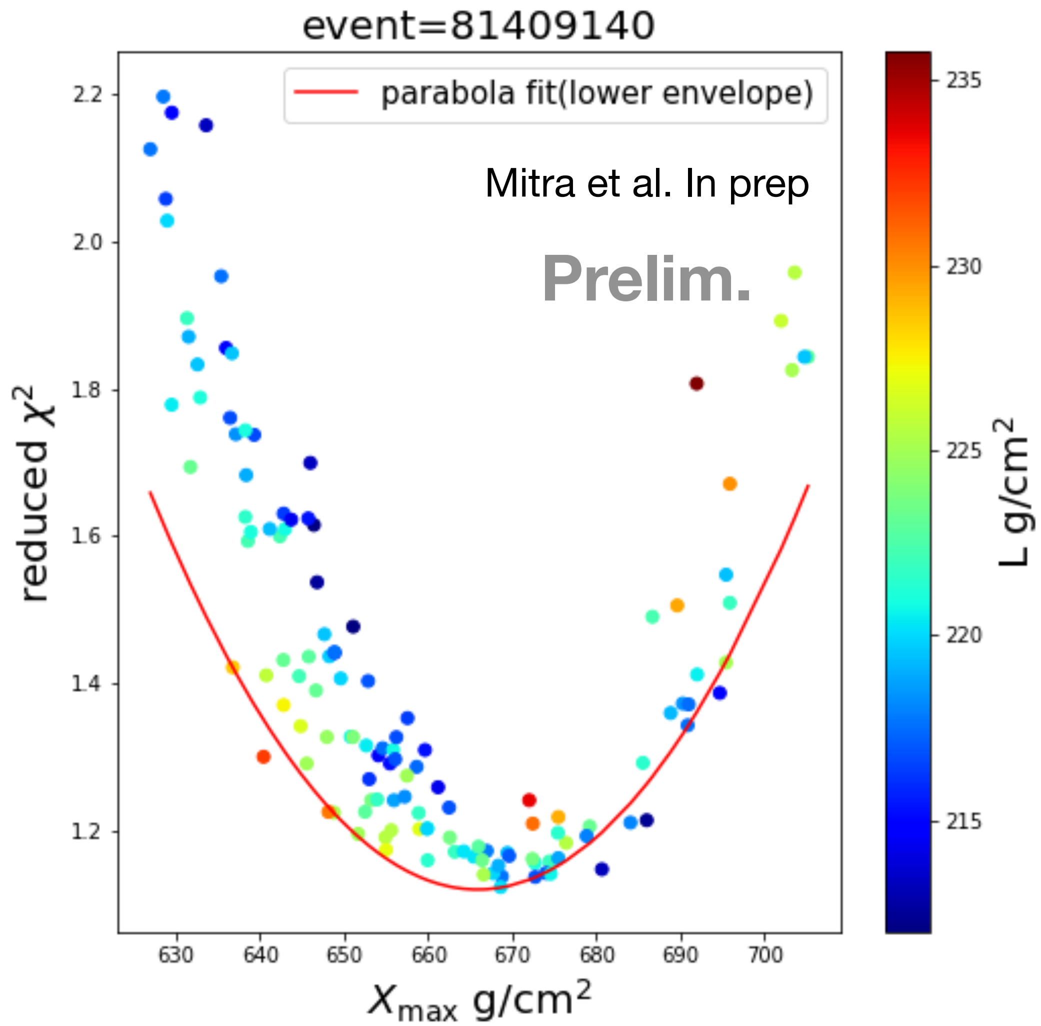
P. Mitra et al. PoS ICRC2017 (2018) 325

- **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**



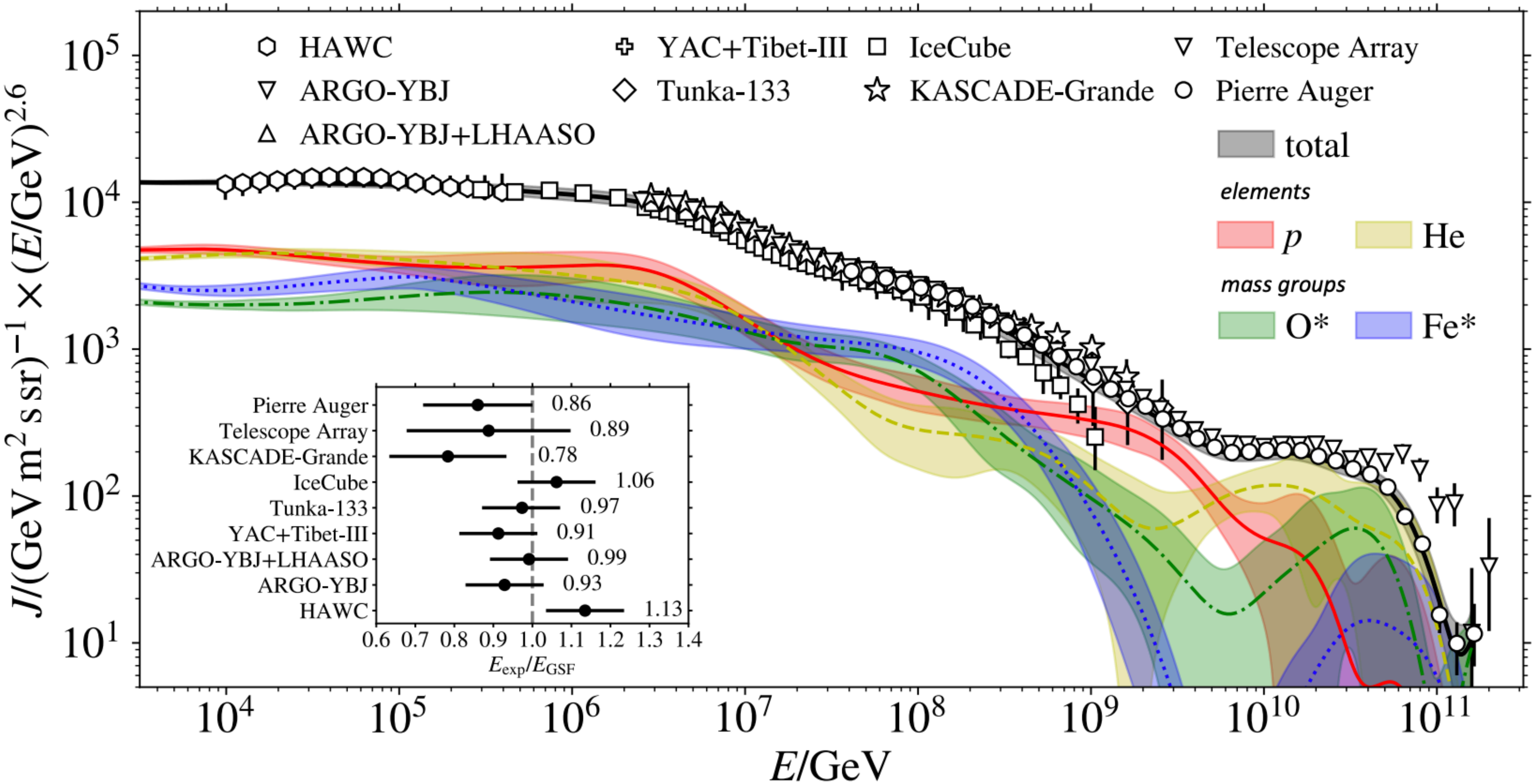
Beyond X_{max}





Can the composition be determined better by including L in the fit?

- Determining L requires sensitive measurements
- MC simulation-based reconstruction is limited by computation resources (MGMR3D)



H. Dembinski et al., PoS(ICRC2017)533