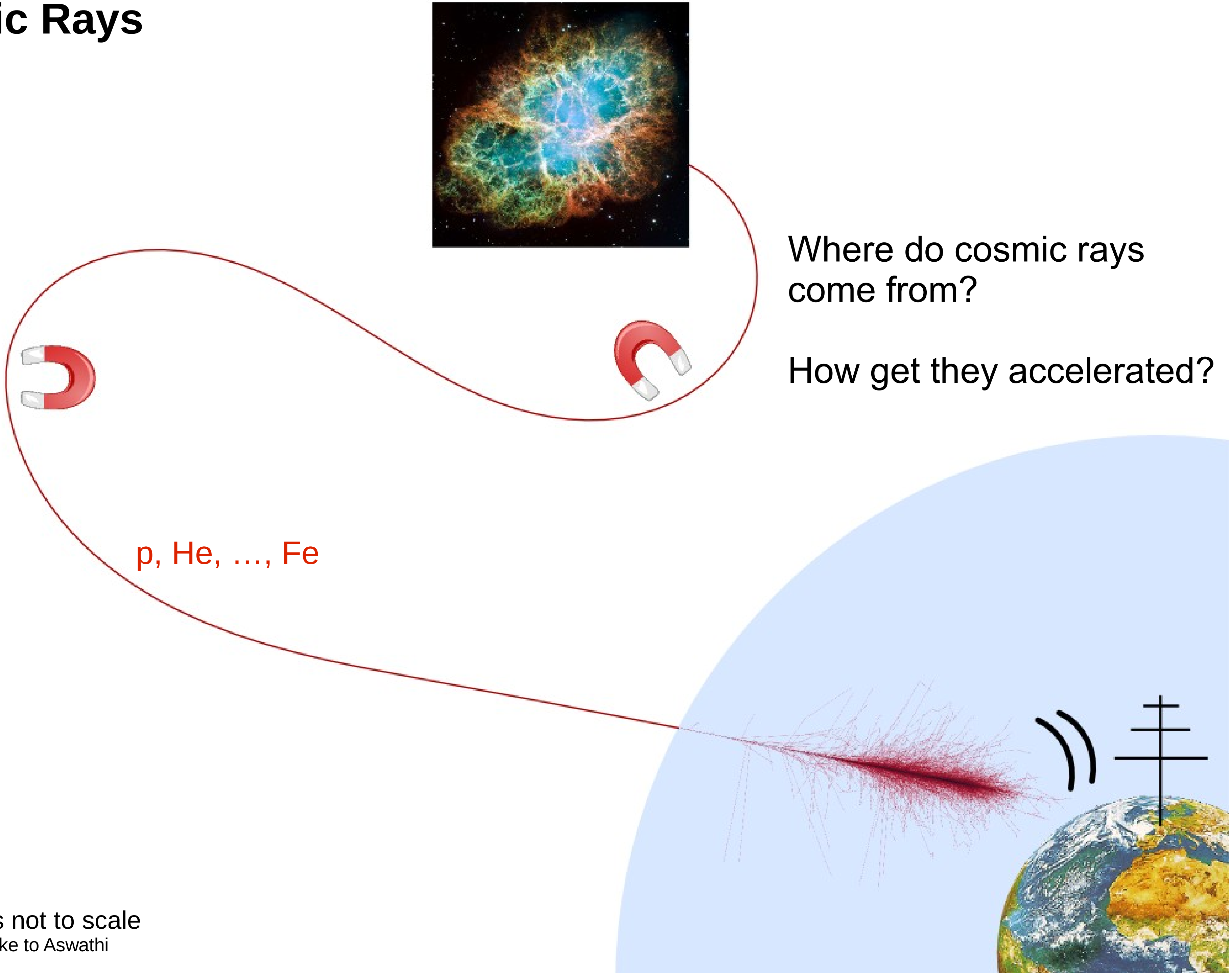
Karlsruhe Institute of Technology

Radio detection of air showers: Quo Vadis?

Anne Zilles (IEKP/IKP)

Cosmic Rays



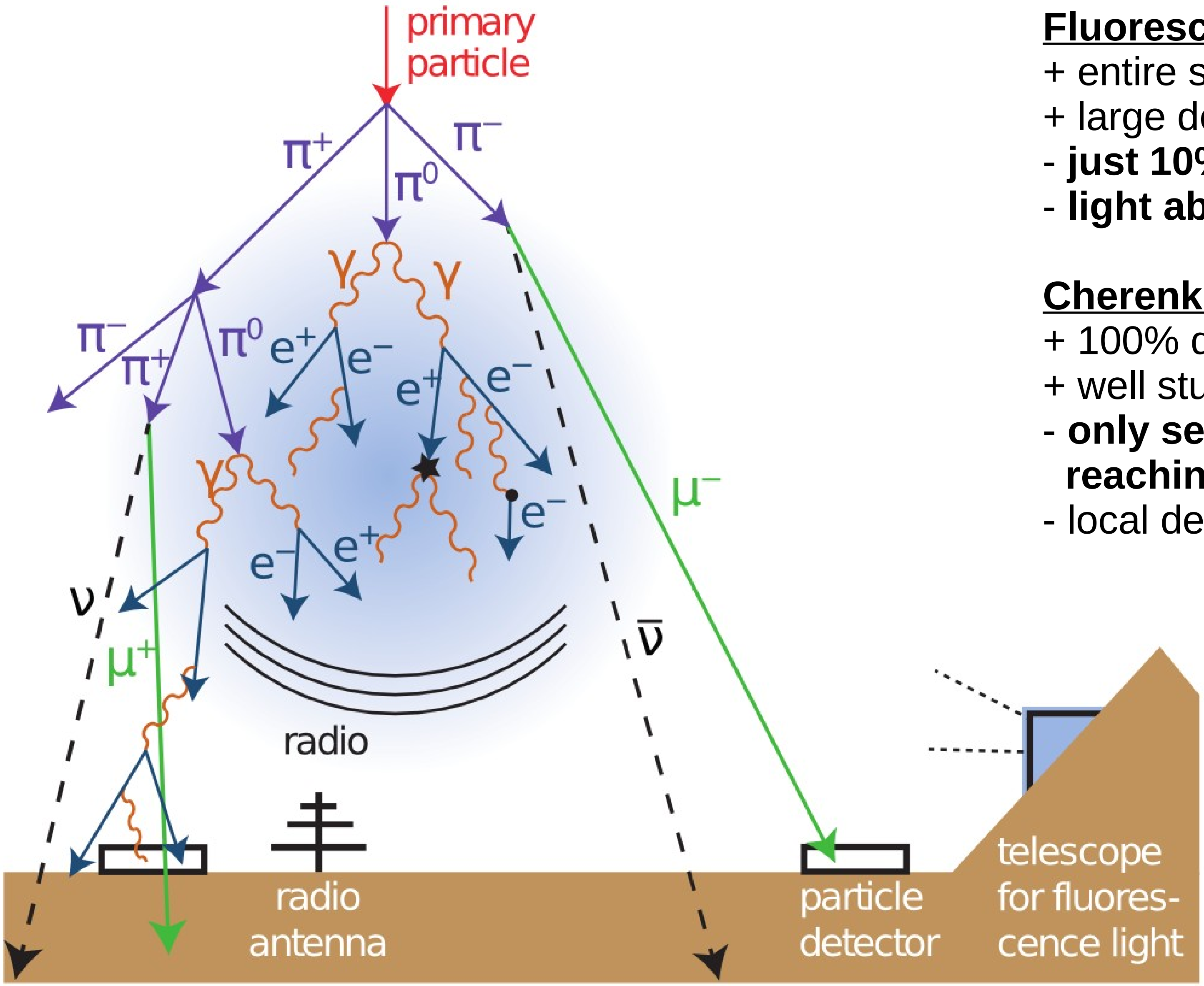
Where do cosmic rays come from?

How get they accelerated?

PS: Objects not to scale

Credit for the joke to Aswathi

Comparison to other detection techniques



[arXiv:1701.05496, modified]

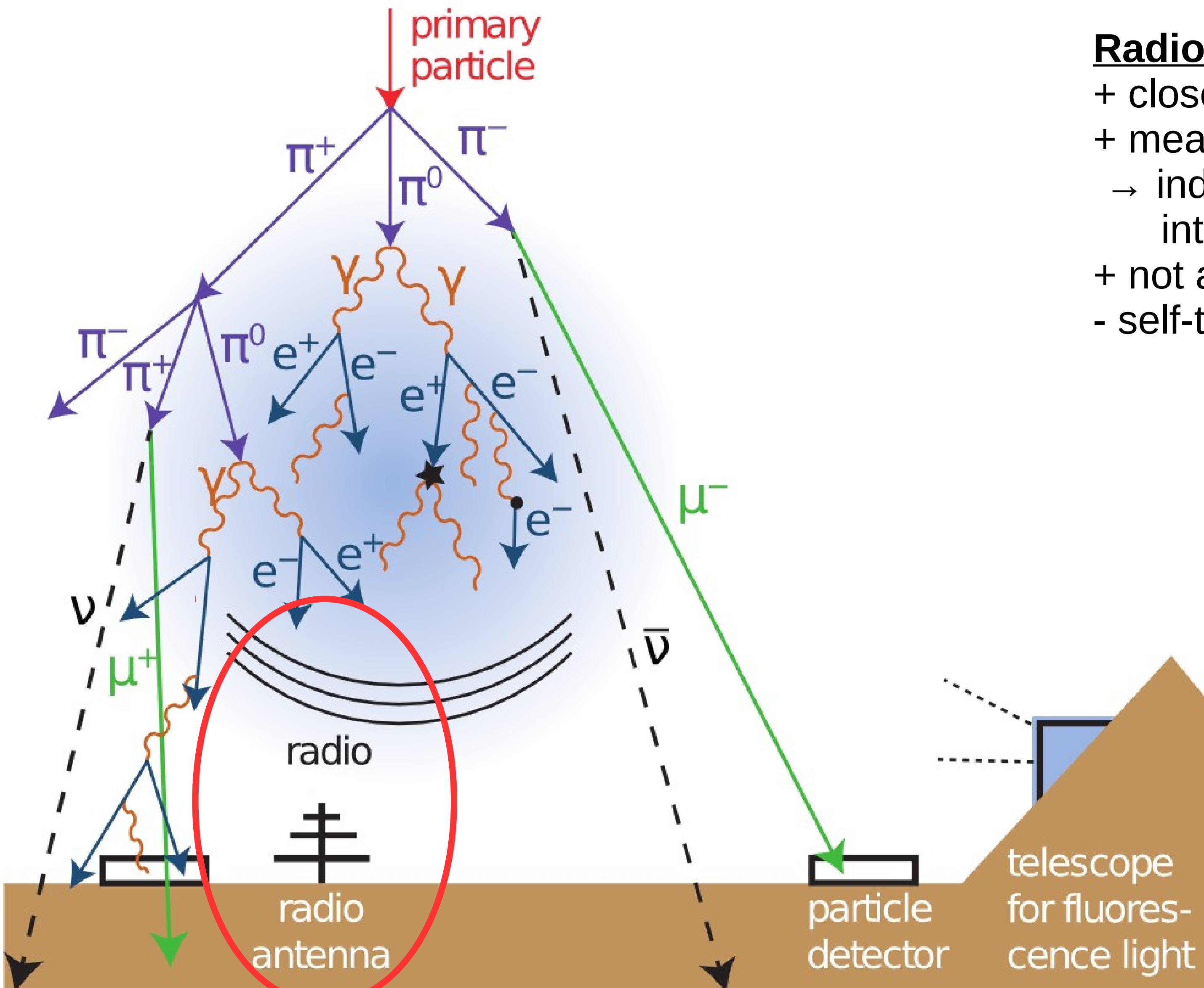
→ Joachim's poster
→ Francesca's talk

Fluorescence:
+ entire shower evolution
+ large detection volume
- **just 10% duty cycle**
- **light absorption by aerosols**

Cherenkov particle detectors:
+ 100% duty cycle
+ well studied
- **only sees particles reaching the ground**
- local detection only

→ Sarah's talk

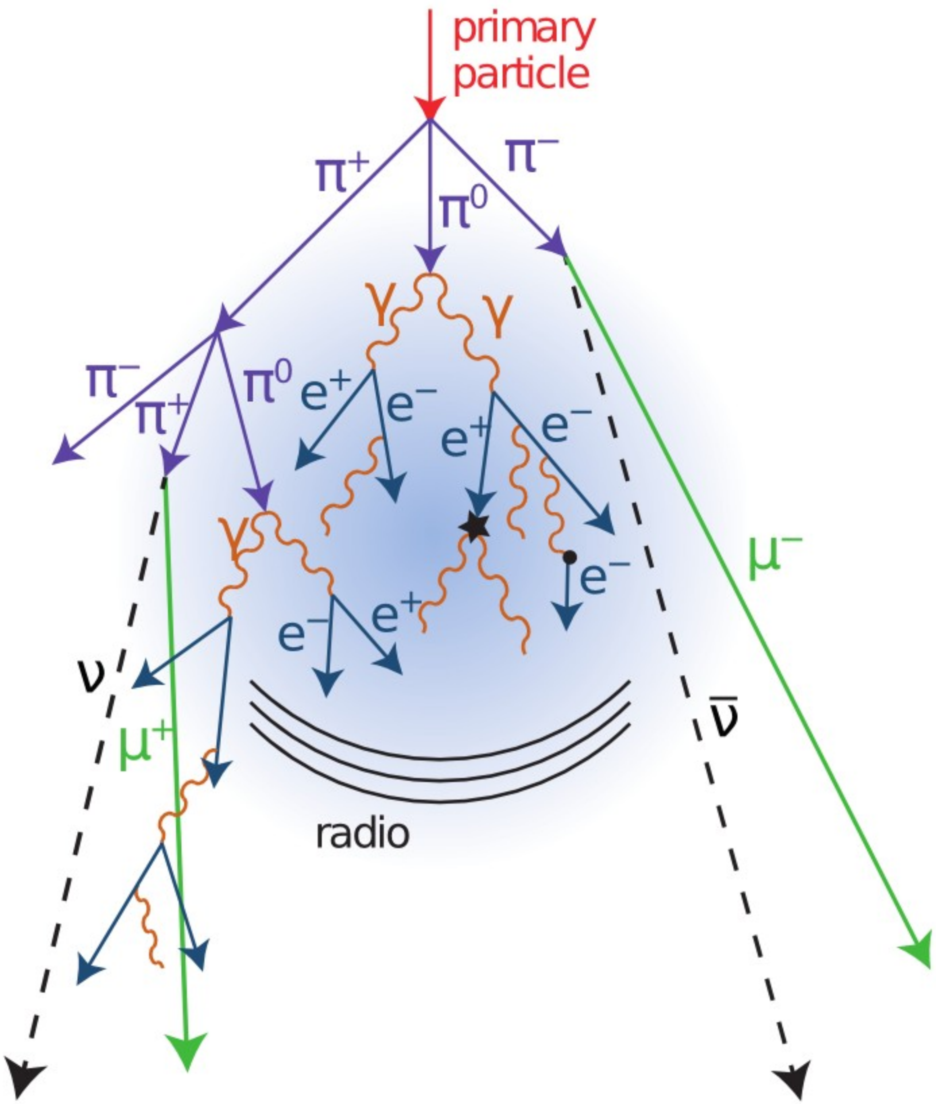
Comparison to other detection techniques



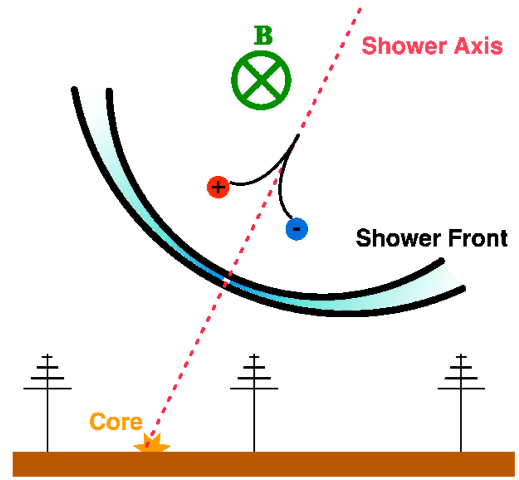
[arXiv:1701.05496, modified]

Radio detection:
+ close to 100% duty cycle
+ measure em. component
  → independent on hadronic interaction models
+ not absorbed by atmosphere
- self-triggering challenging

Air shower and emission of radio signal

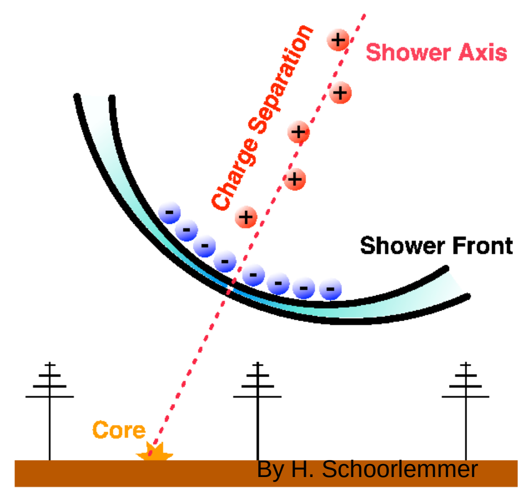


[arXiv:1701.05496, modified]



Geomagnetic effect:
Deflection of e^- and e^+ in Earth´s magnetic field
→ **time dependent transverse current**

~ 90%



Askaryan effect

→ **Time variation of net charge excess**

~ 10%

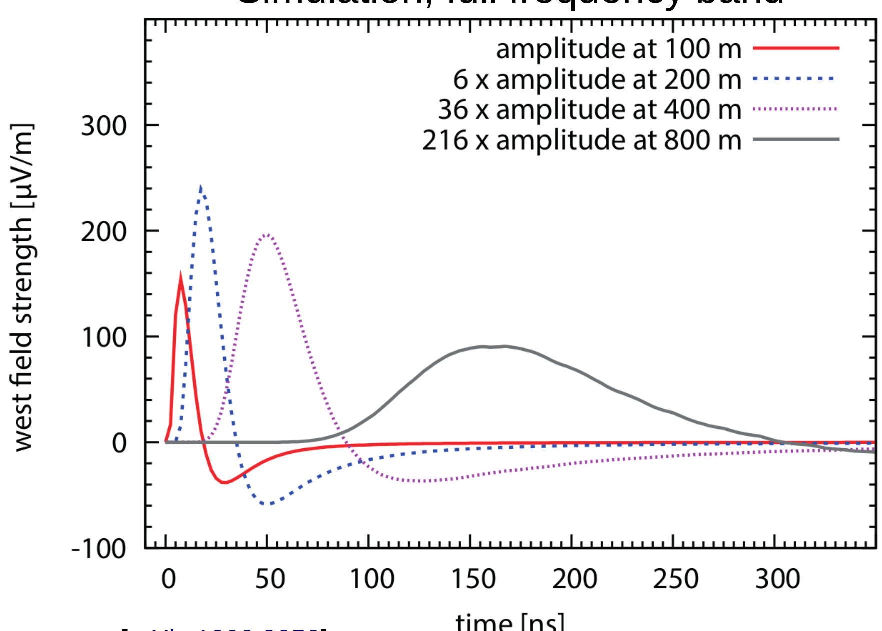
Radio pulses from air showers

Emitted signal: broad frequency spectrum
→ short in time → only contains few oscillations at each frequency

Shower front: ~ meters thick
→ amplified emission due to coherence at ~10-100MHz

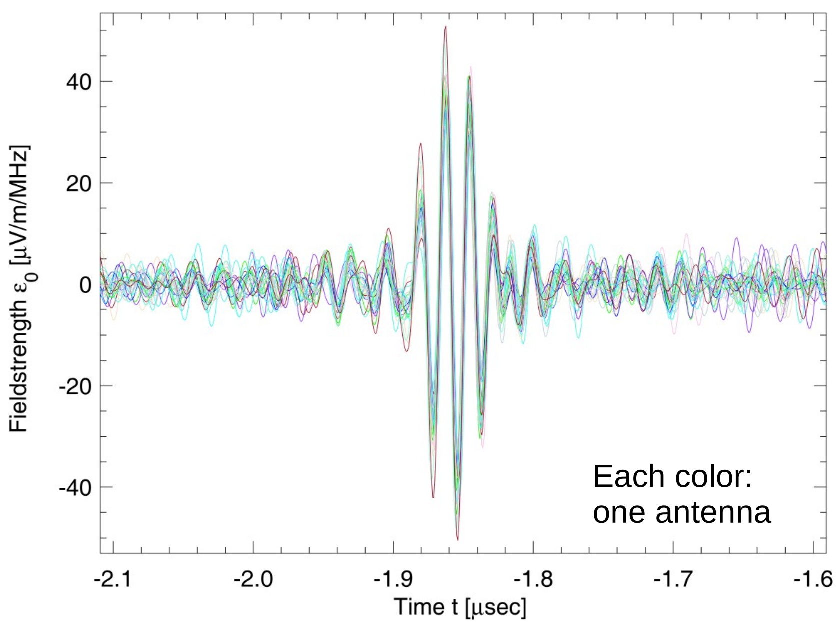
Typical bandwidth for measurements 30-80MHz
→ main information: amplitude and arrival time
→ more detailed information lost

Simulation, full frequency band



[arXiv:1202.3352]

Measurement, LOPES 43−74 MHz



[Nucl. Instr. and Meth. A 615 (2010) 277]

Radio detection of air showers:

Quo Vadis?

Radio detection of air showers:

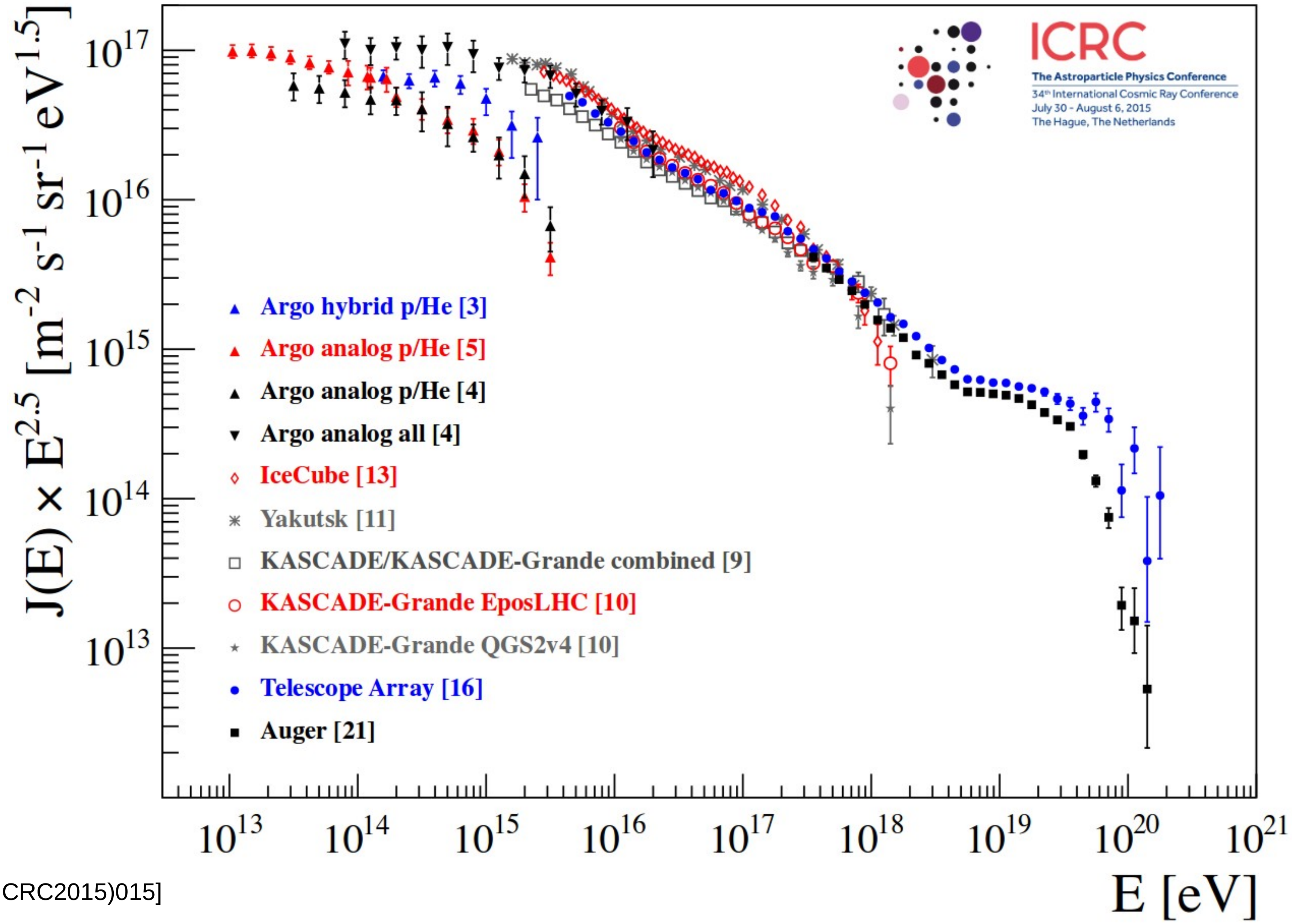
Quo Vadis?

Which physic's question can be answered with the help of radio detection?

My focus for this talk: mass composition of CRs

Energy spectrum of cosmic rays

Number of measured primaries in dependence of their energy:



[PoS(ICRC2015)015]

Energy spectrum of cosmic rays

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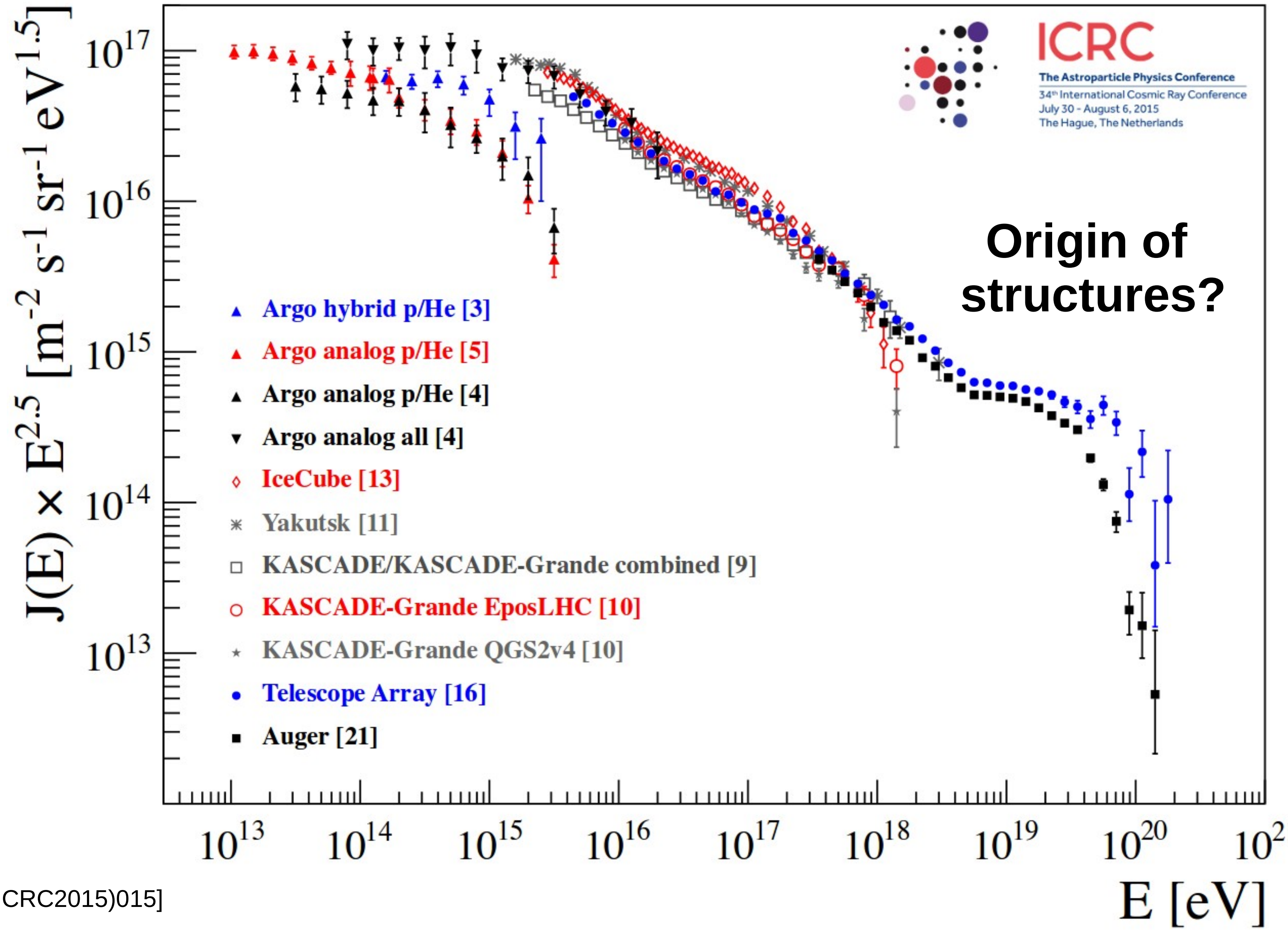

[PoS(ICRC2015)015]

Energy spectrum of cosmic rays

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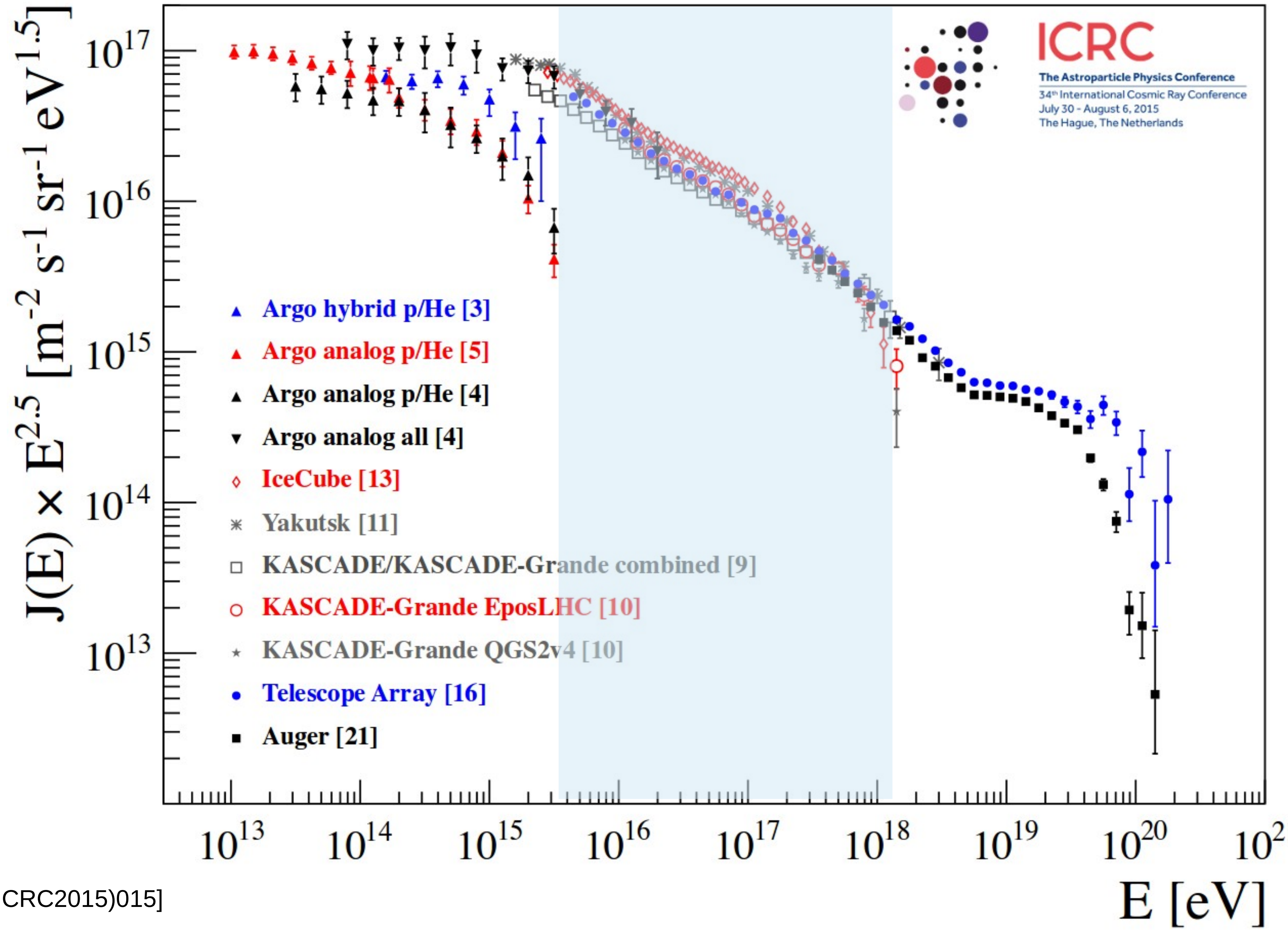
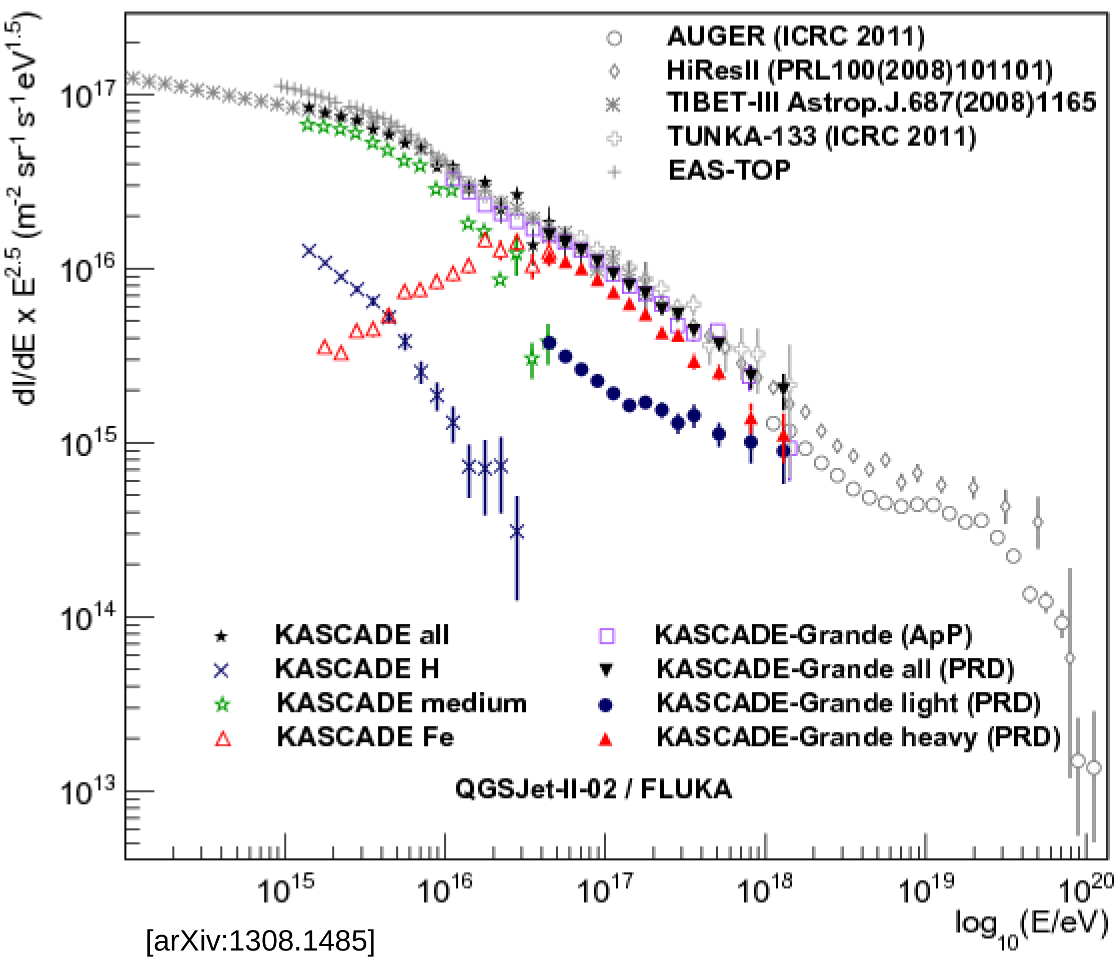


[PoS(ICRC2015)015]

Transition from galactic to extra-galactic

acceleration limit of galactic SN? → experimental check of elemental composition of CRs

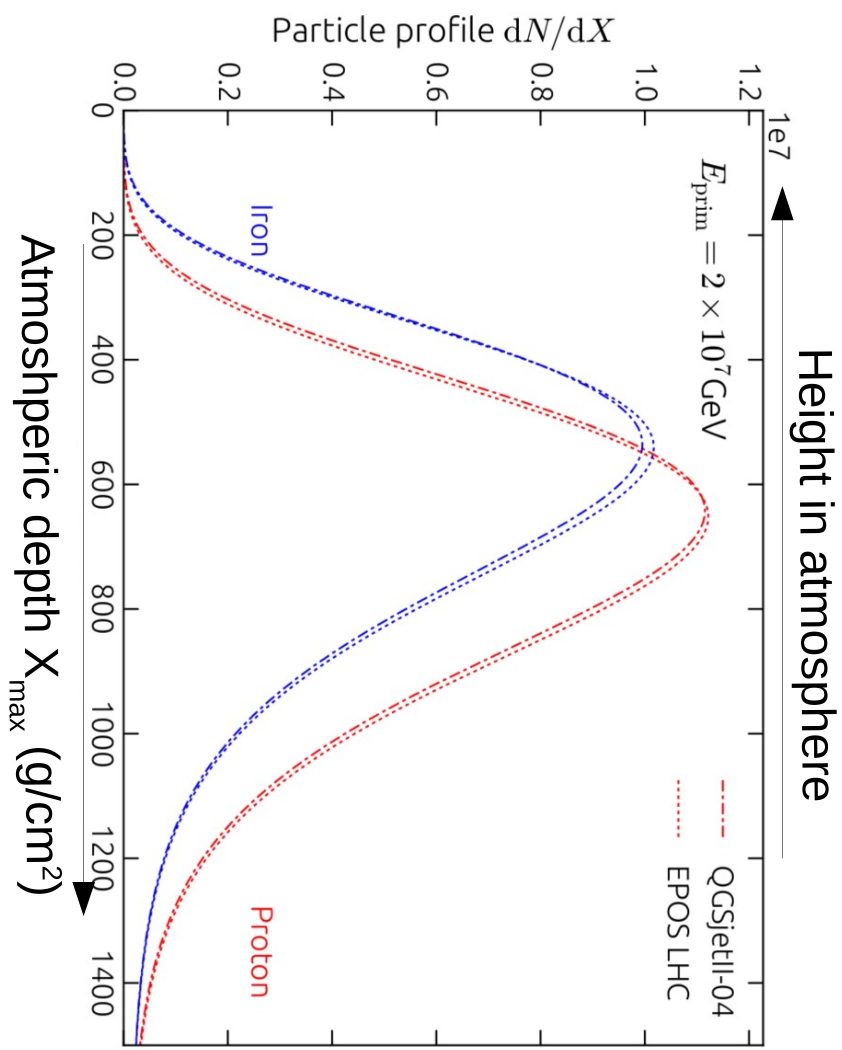


[arXiv:1308.1485]

Already roughly measured
→ need higher resolution

High-precision composition measurements in transition region
→ decompose
into individual elements
(p, He,…., Fe)

Identifying primary particle type: Separation of mass of CR by atmospheric depth



By Felix Riehn

→ **Methods based on statistics!**

Development of a heavy ion induced shower starts earlier

→ reaches the maximum number of particles earlier (low atmospheric depth) + more muons on ground

than is the case for proton induced showers of the same energy (high atmospheric depth)

Shower depth X_{max} = max. number of particles

Typically: $(X_{max,p} - X_{max,Fe}) \approx 100$ g/cm²

Best reconstruction uncertainty by Fluorescence detection technique: ~ 20 g/cm²

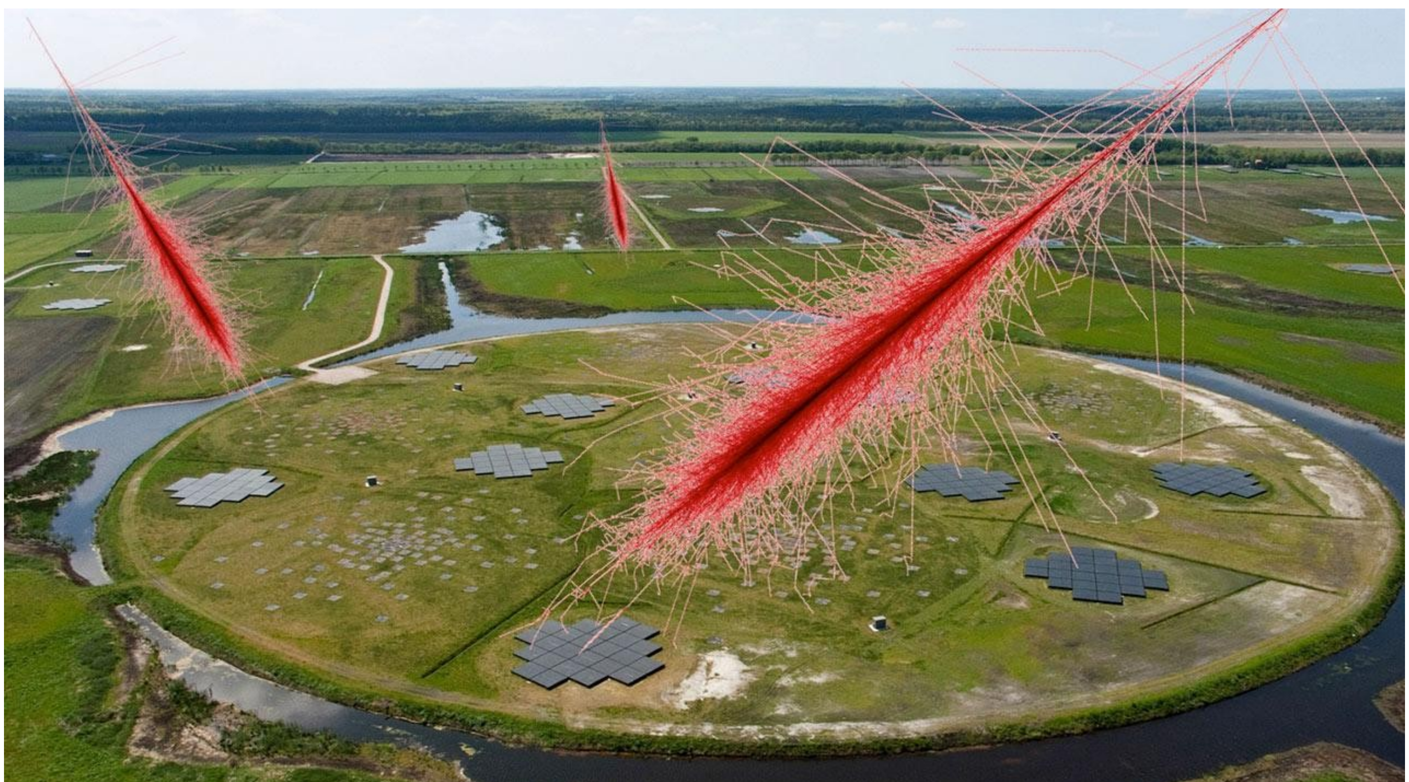
Low-Frequency Array (LOFAR)

Karlsruhe Institute of Technology

- Radio telescope located mainly in the Netherlands
- Astronomer's instrument also used for CR detection

LOFAR (7x48)

LOFAR core = “superterp” (300×300 m^2)



Low-band antenna, analyzed from 30-80MHz

Particle detector array (LORA) for triggering

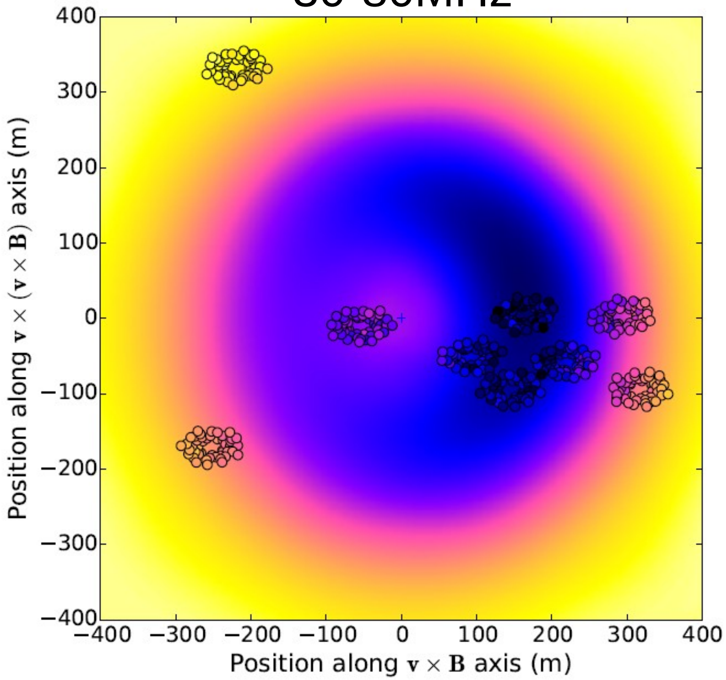
20 PD at 300×300 m^2

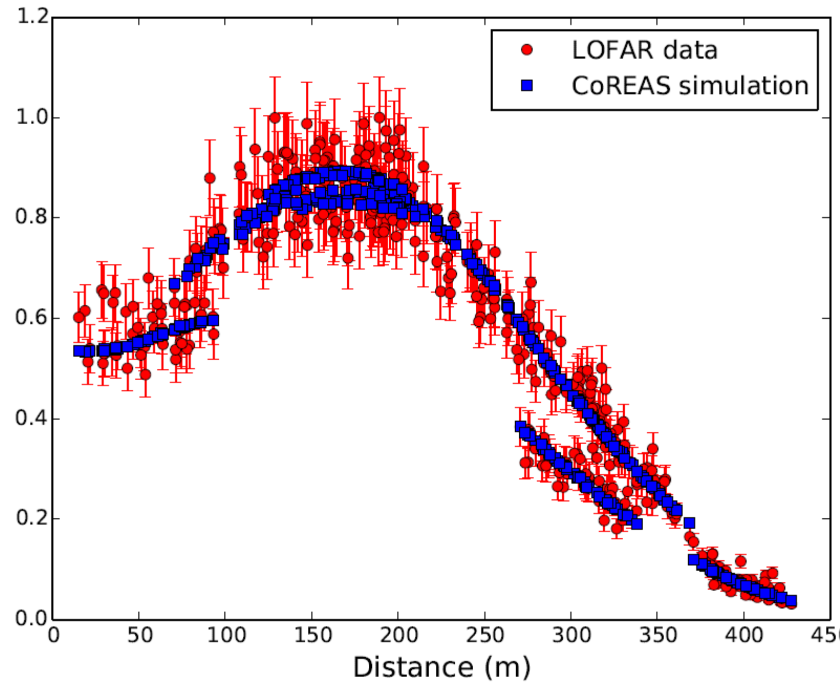
X_{max} reconstruction from LDF - LOFAR

Based on the well-understood emission mechanisms of the radio signal
→ simulations can described accurately the measured radio signal

LOFAR (7x48)

30-80MHz





Radio footprint in the shower plane:
Plane described by the direction of the shower and the Earth's magnetic field

Circles = measurements of LOFAR
Background = simulations

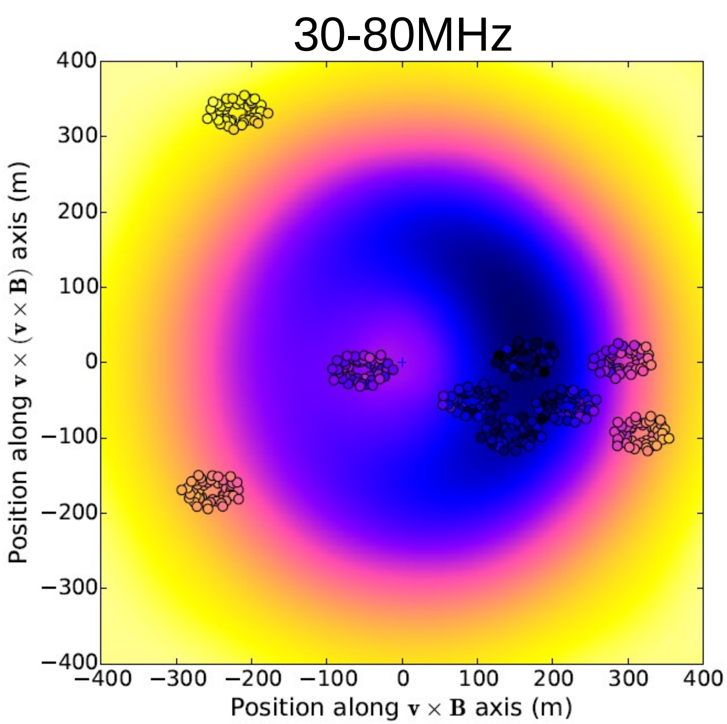
LDF = Lateral distribution function
Measured radio signal depend on the distance to the shower axis

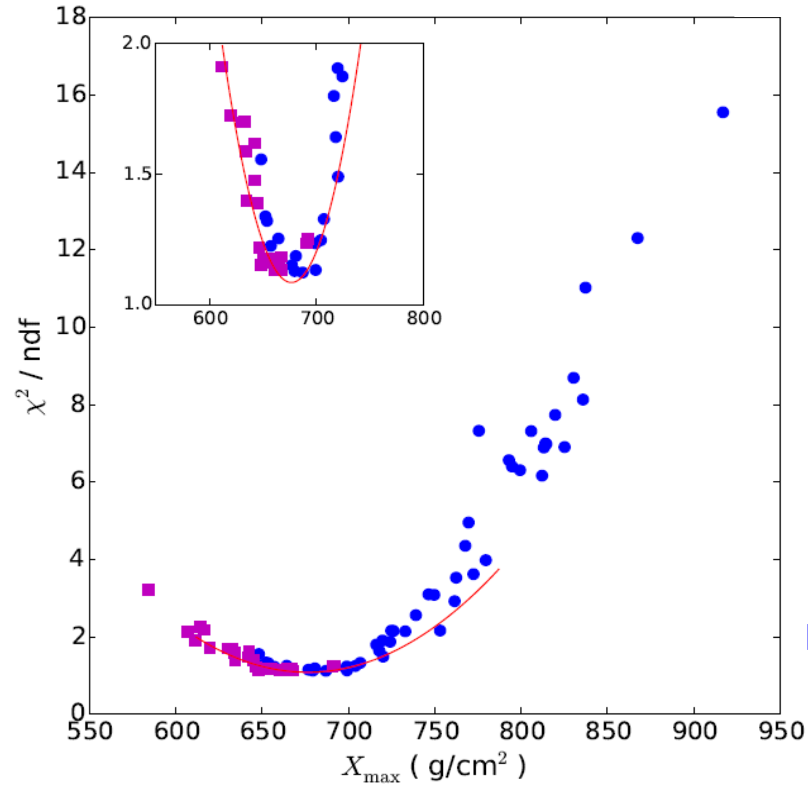
S. Buitink et al., Phys Rev D (2014), arXiv:1408.7001

X_{max} reconstruction from LDF - LOFAR

LOFAR (7x48)

Pick the one of many simulations describing data best





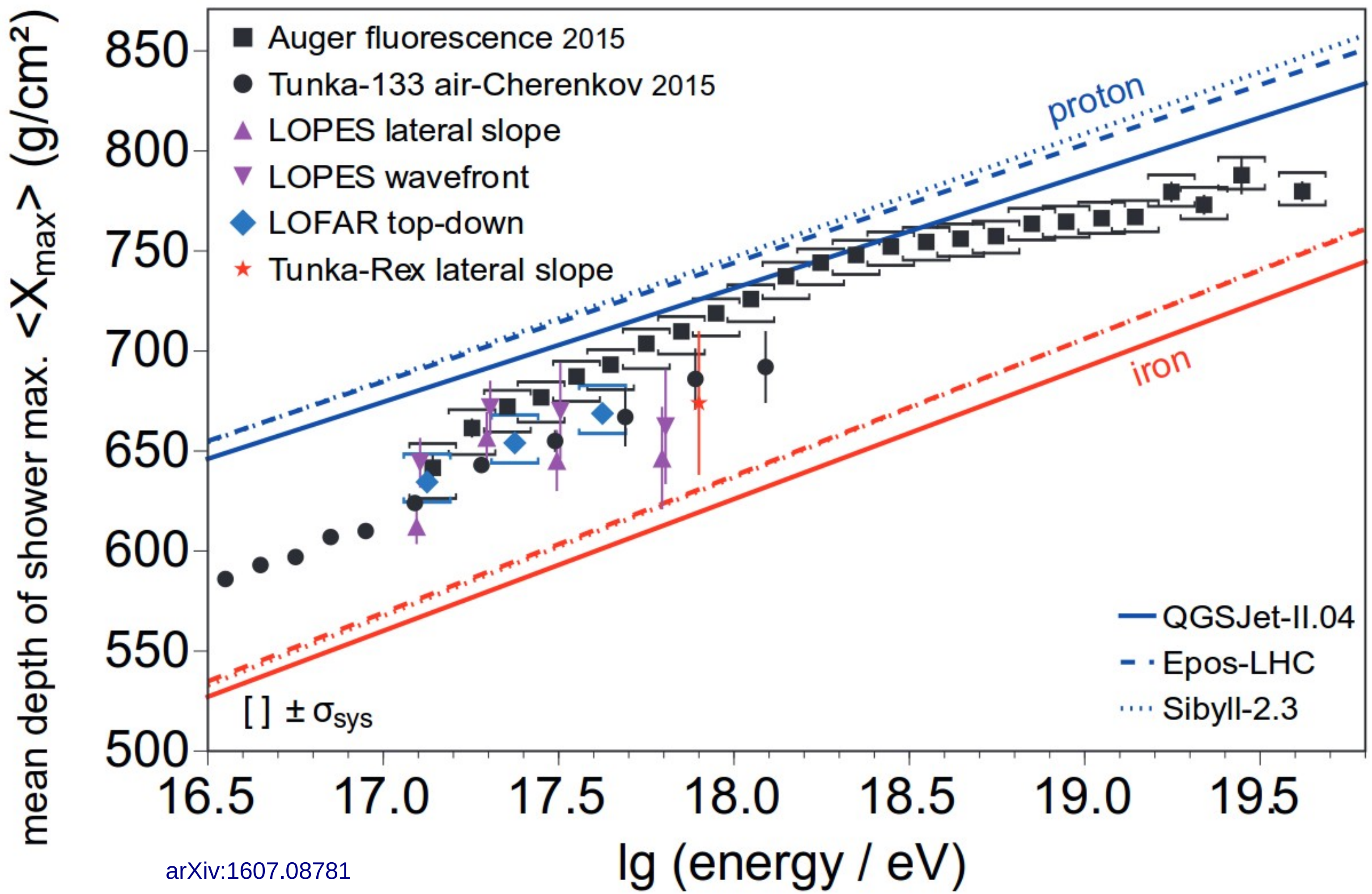
2d LDF fit to radio simulations yields mean X_{max} to ~17 g/cm²

- provided no unknown systematics: competitive with fluorescence

More: S. Buitink et al., Nature 531, 70 (2016)

Separation between proton and iron

Mass sensitivity of same order as particle detectors

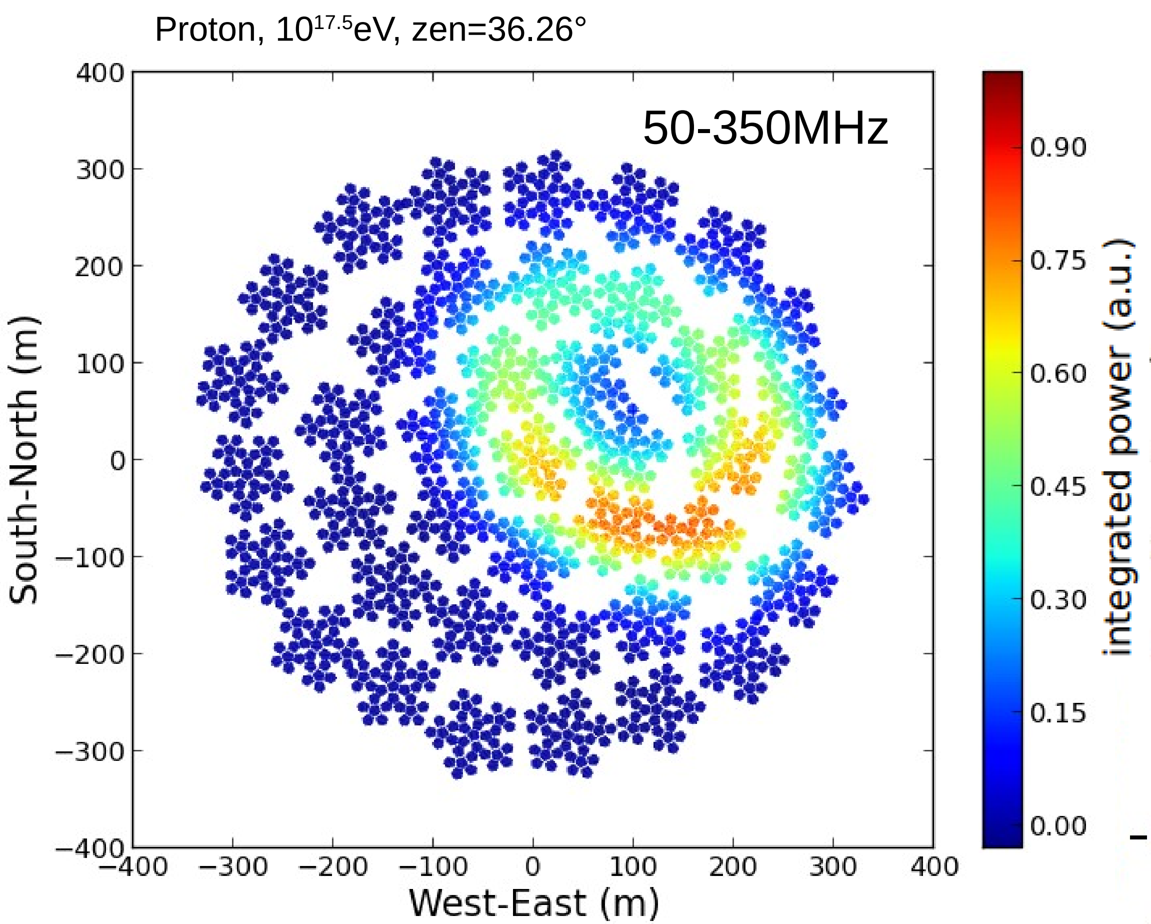


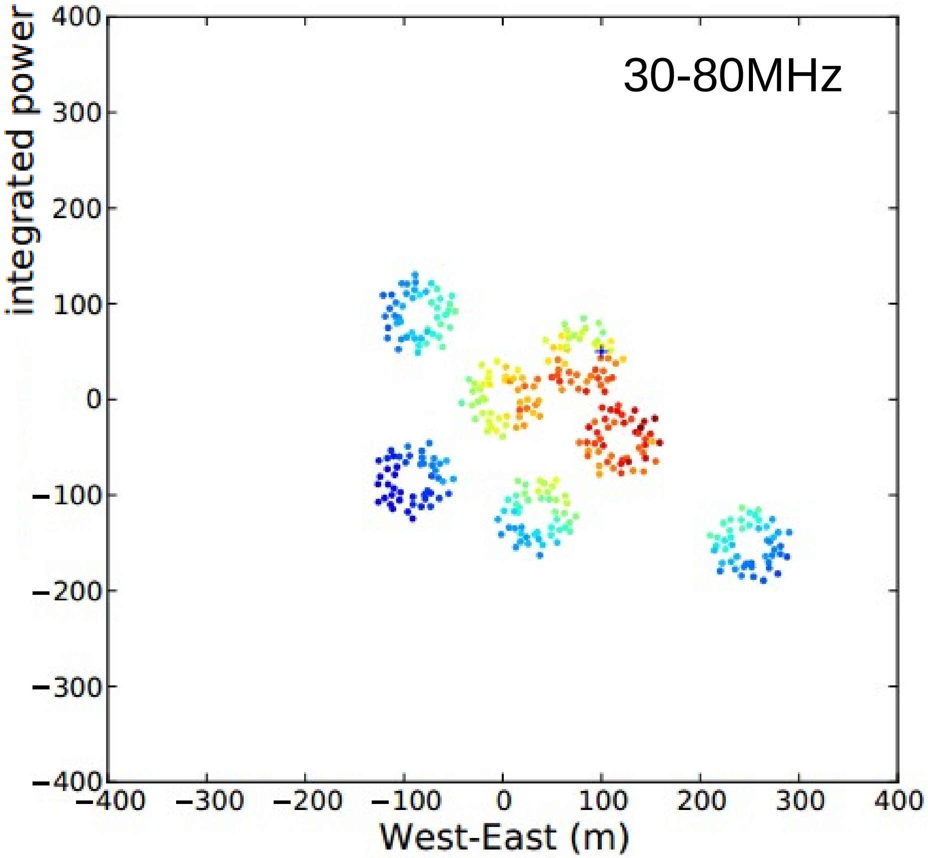
arXiv:1607.08781

Mass sensitivity of radio detection was also proven by LOPES [Phys. Rev. D 85 (2012) 071101]
Tunka-Rex [JCAP 01 (2016) 052]
...

SKA1-low - low frequency array stations

Located in West-Australia





- **~70,000 dipole antennas**
  in a circle of 750m diameter
- **bandwidth 50-350 MHz**
  (different part of radio signal)

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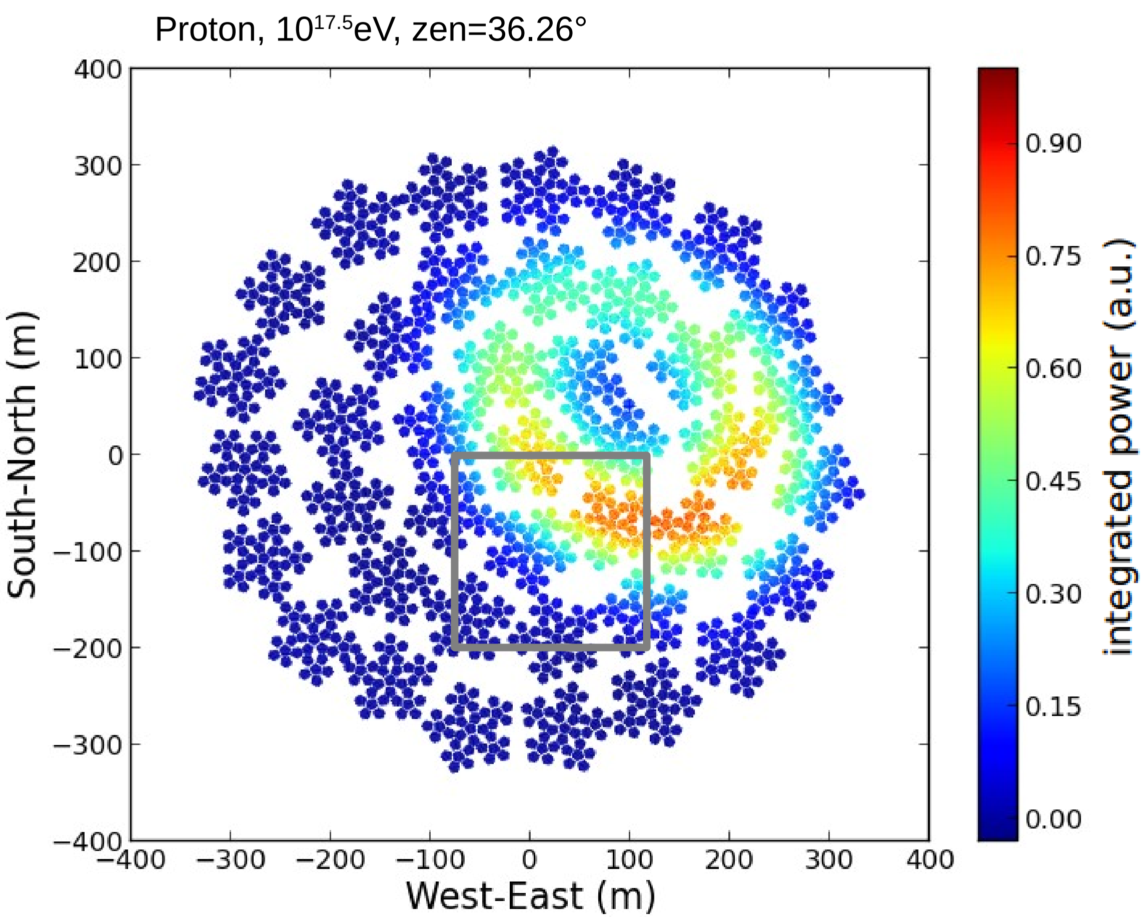

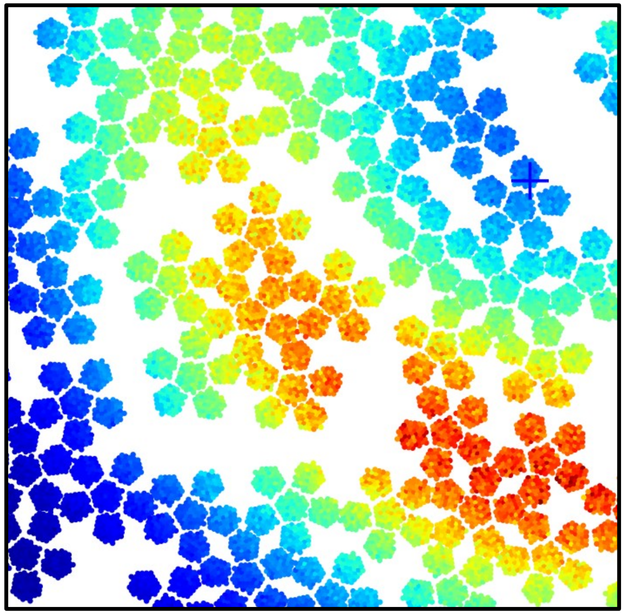

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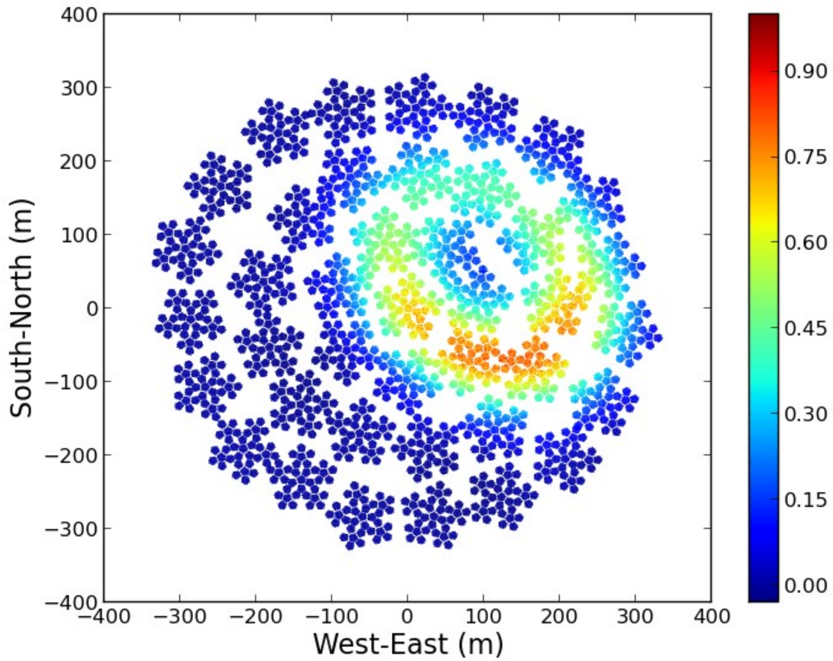
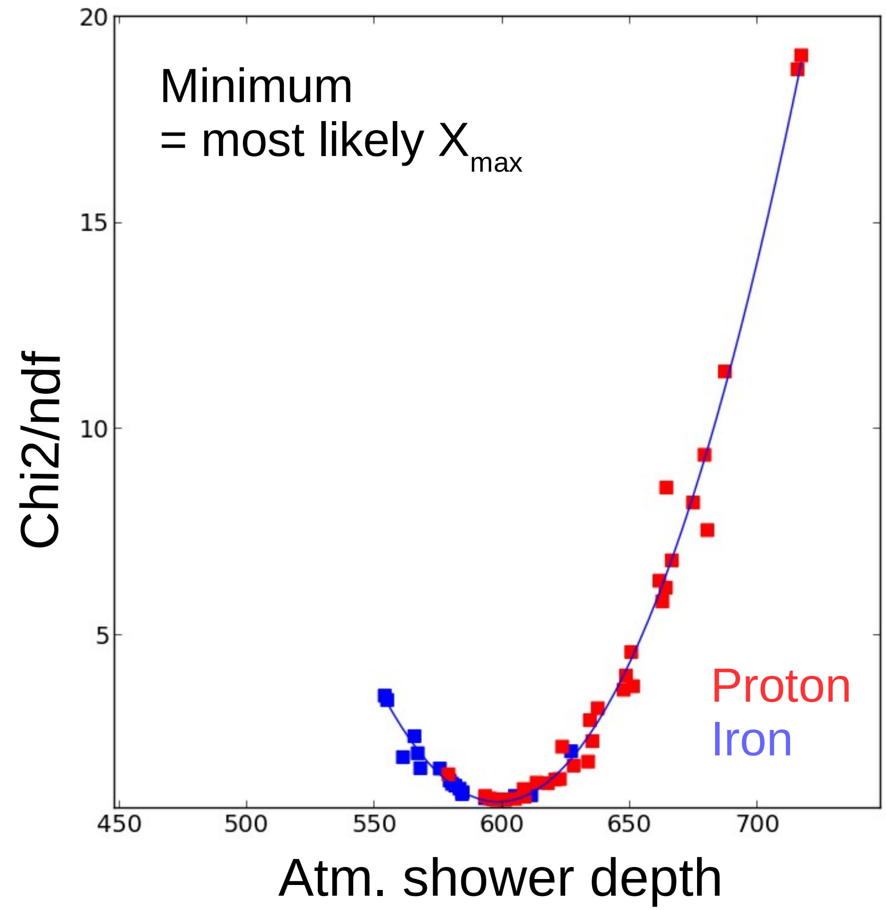
Measuring X_{max} with SKA-low



Adapting LOFAR-like method:
Pick the one of many simulations describing data best

First simulation study:
For air shower induced by primaries with E >= 10^{17}eV
→ $\Delta X_{max} < 10 g/cm^2$

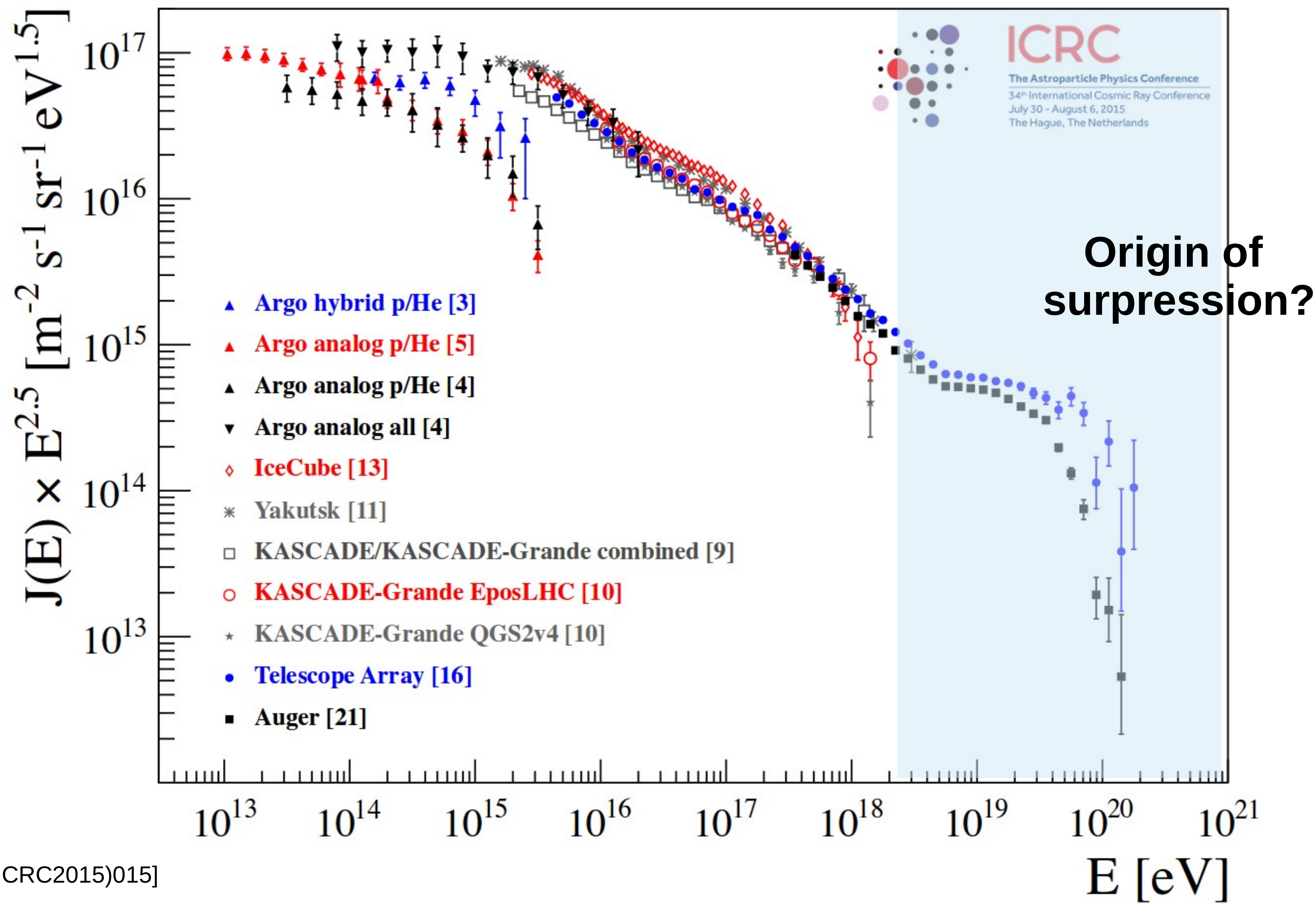
Proton, $10^{17.5}$eV, zen=36.26°



Decomposing possible?

Energy spectrum of cosmic rays

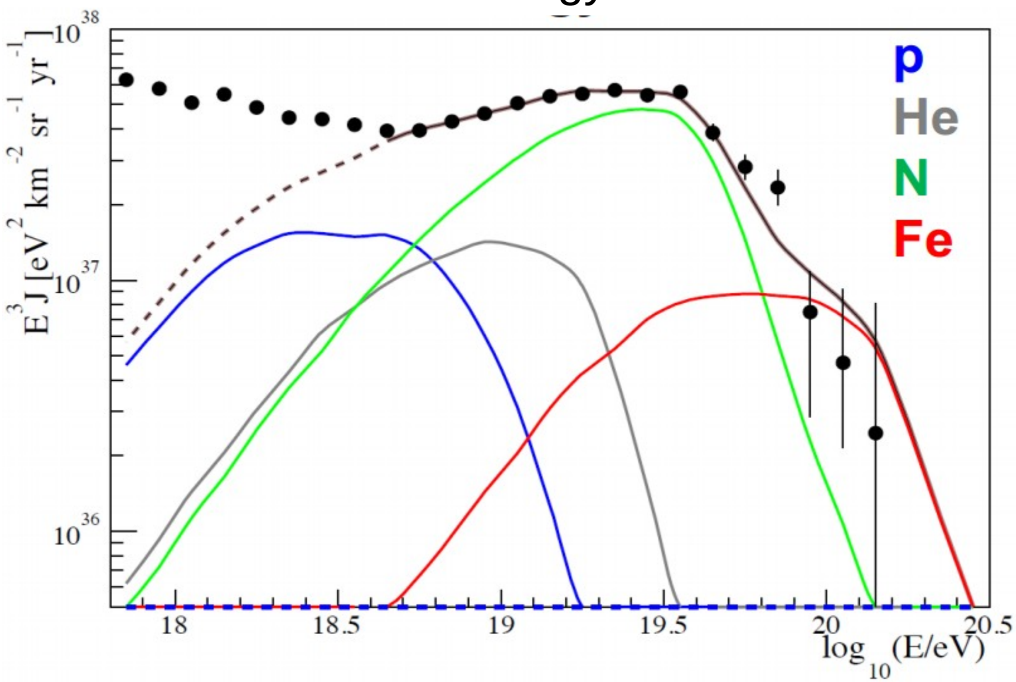
Number of measured primaries in dependence of their energy:



[PoS(ICRC2015)015]

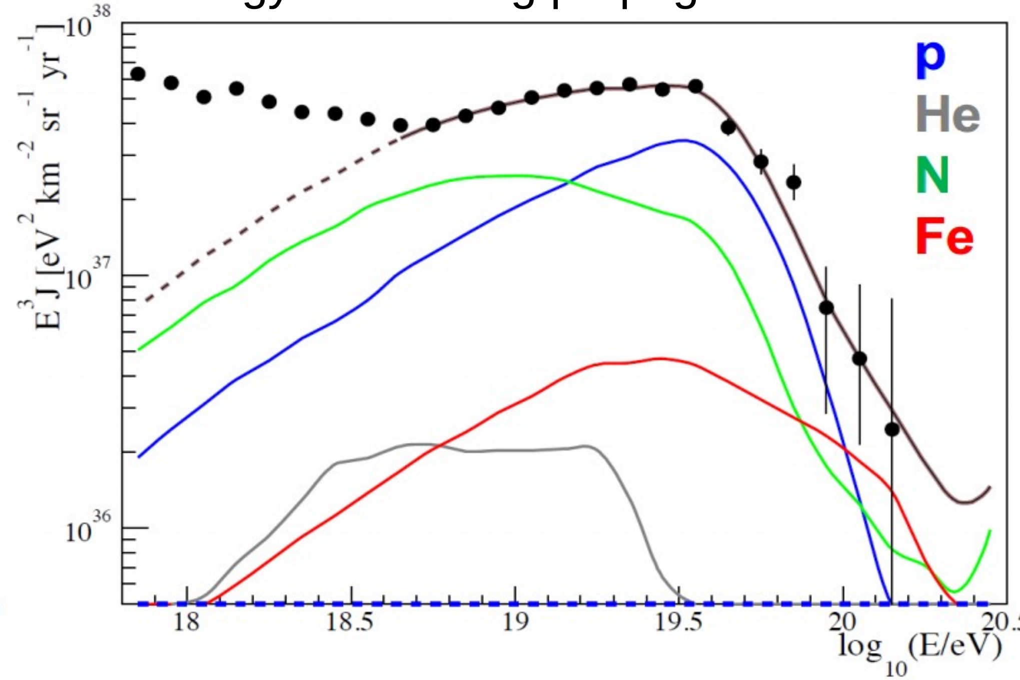
Origin of surpression? Separate masses!

Maximum energy of sources?



Cutoff first in proton spectrum,
then in He spectrum, ...

GZK cutoff?:
energy loss during propagation



Proton-dominated composition
at highest energies

Idea of slide adapted from F. Schroeder

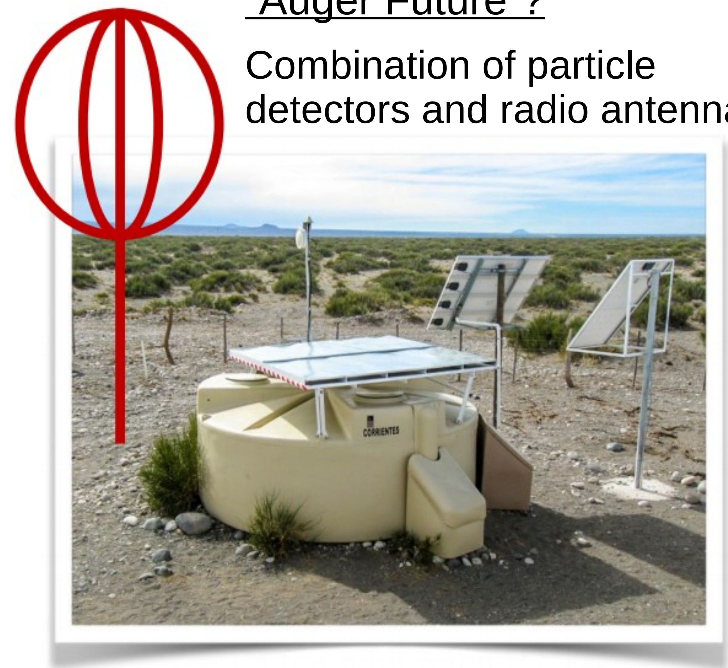
Inclined Air Showers

Increase statistic for UHECR:
Go to higher zenith angles!

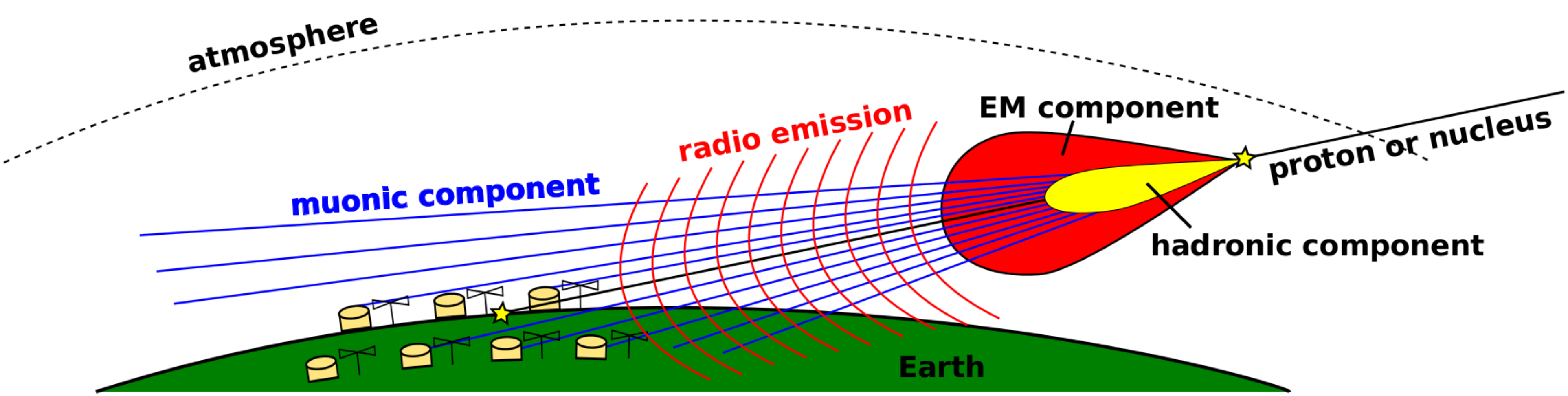
- Hadronic and electromagnetic component of shower absorbed → radio signal and muons left
- Earth's atmosphere transparent for radio signal (unlike for optical methods)
- Complementary information to muons
  - → better reconstruction of primary particle type
  - → add mass-sensitivity

<u>"Auger Future"?</u>

Combination of particle detectors and radio antennas

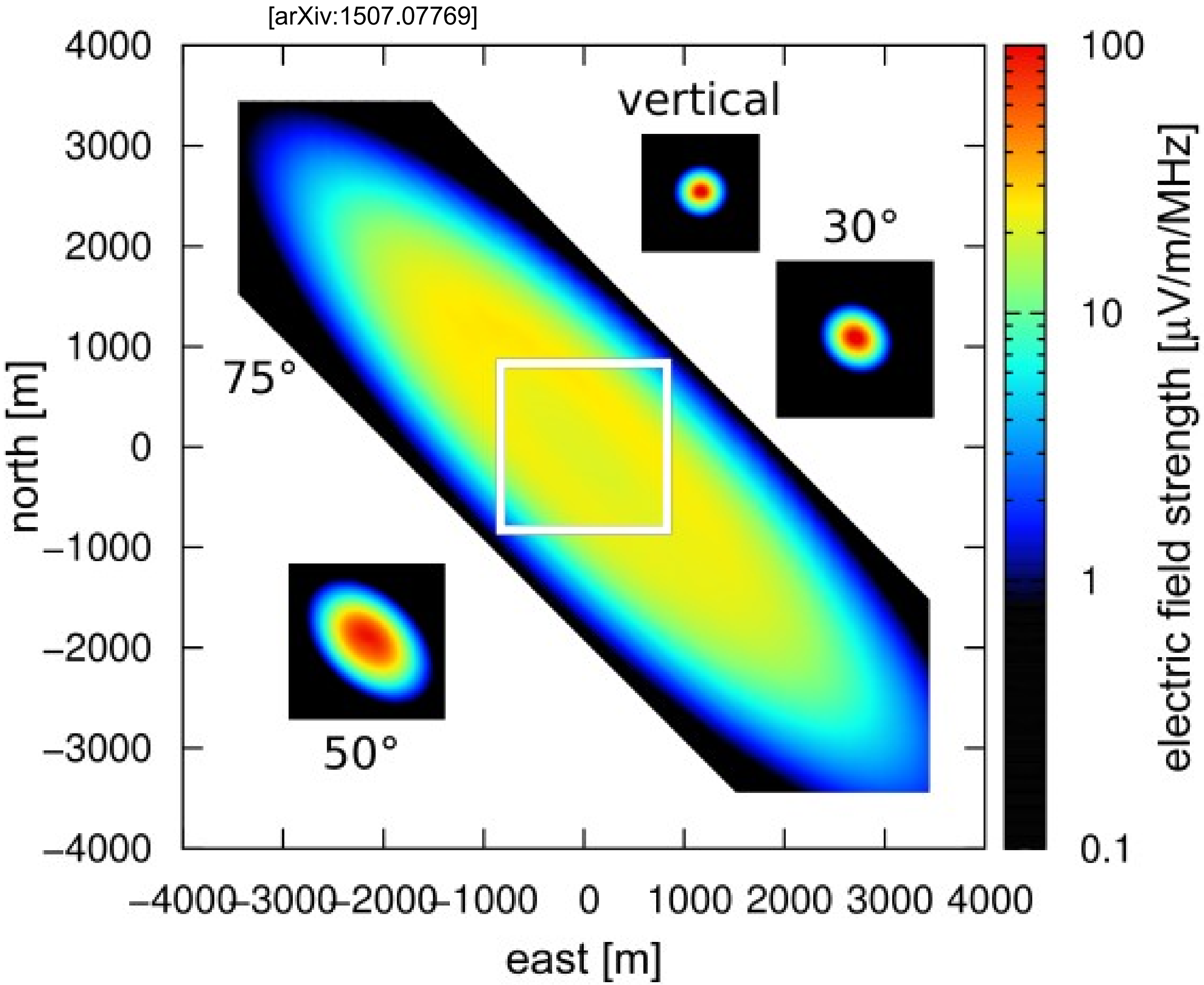


[F. Schroeder]



[E. Holt]

Inclined air showers: Huge footprints



- Simulated footprints of the radio emission of extensive air showers with an energy of 5×10^{18} eV
- Typical 30-80 MHz freq. band
- detection threshold: by Galactic noise ≈ 1-2 µV/m/MHz

+ Footprint becomes large
+ Detectable at distances of km

→ projection:
Antenna array with kms-spacing possible
- radio technique scalable to large areas
- large exposure for moderate costs

Neutrino detection: Horizontal air showers

Karlsruhe Institute of Technology

Looking for neutrinos beyond IceCube energies → <u>very large detection area</u> needed!

e.g. **cosmogenic neutrinos** (GZK neutrinos from the interaction of CR with CMB)

Several projects already on-going

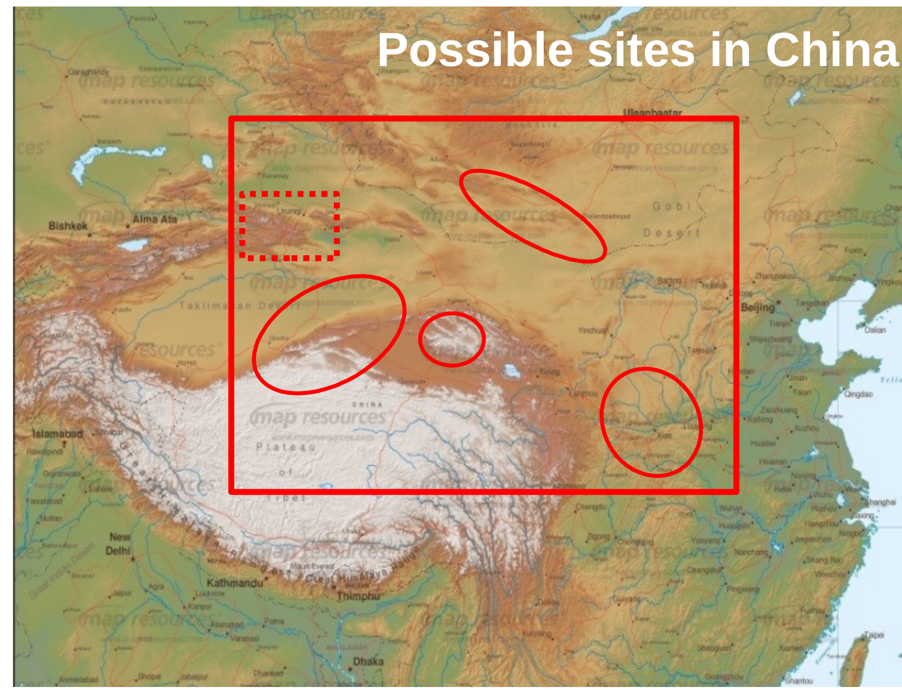
Neutrino detection: Horizontal air showers

Looking for neutrinos beyond IceCube energies → <u>very large detection area</u> needed!

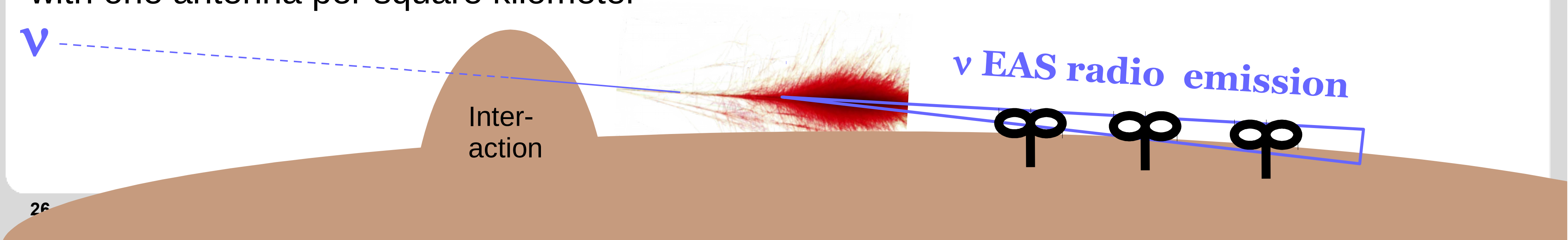
e.g. **cosmogenic neutrinos** (GZK neutrinos from the interaction of CR with CMB)

One future plan:

Giant Radio Array for Neutrino Detection
equip an area of roughly 200,000 km^2
with one antenna per square kilometer



[Olivier Martineau]



Summary

- Radio detection air showers well-established detection technique
- Emission of radio signal well-understood

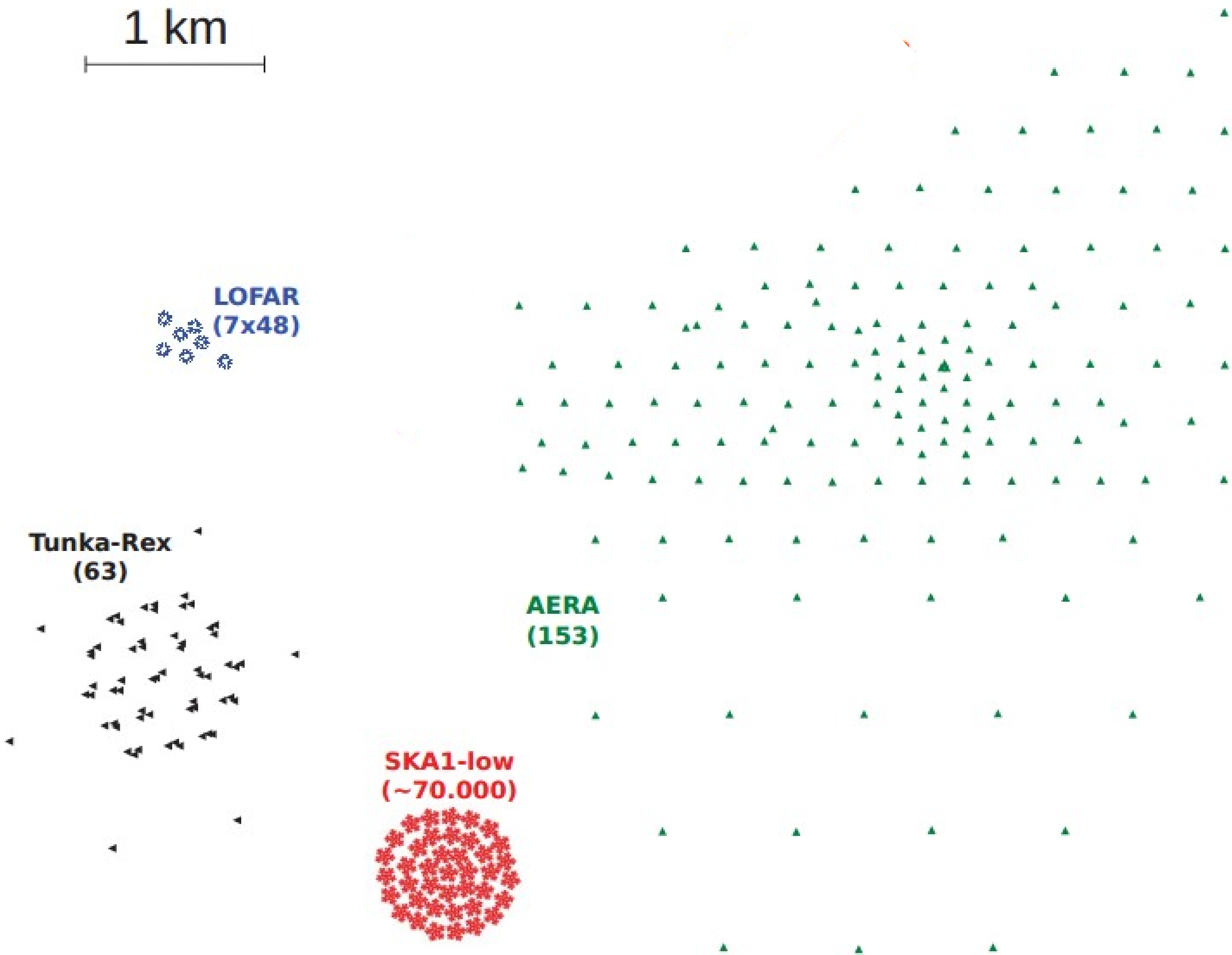
Quo vadis?
= Where can we profit the most by using the radio detection

→ Elemental composition of CRs in the transition region from Galactic to Extragalactic origin:
extreme precision measurements by dense radio arrays (SKA-low)

→ additional mass sensitivity for UHECR:
hybrid detection with particle detectors (Auger Future?)

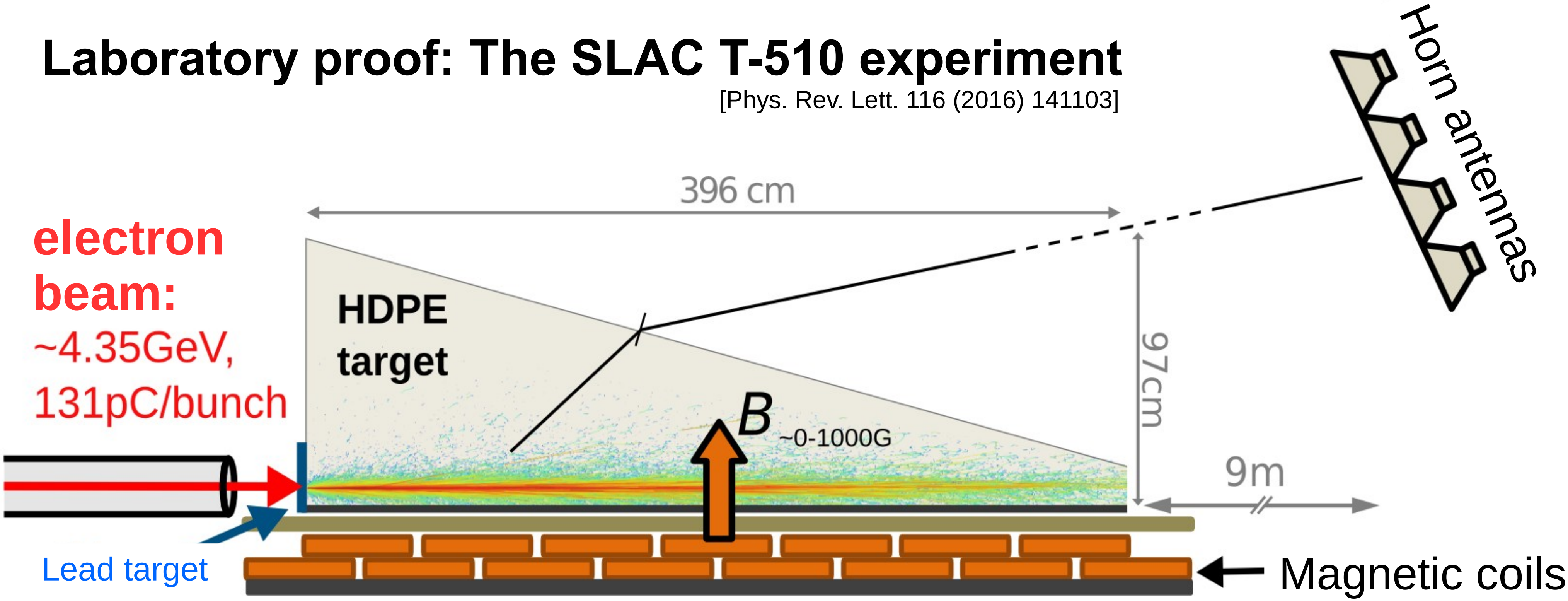
→ **neutrino detection**:
providing **large detection areas** covered by sparse radio arrays (GRAND)

backup

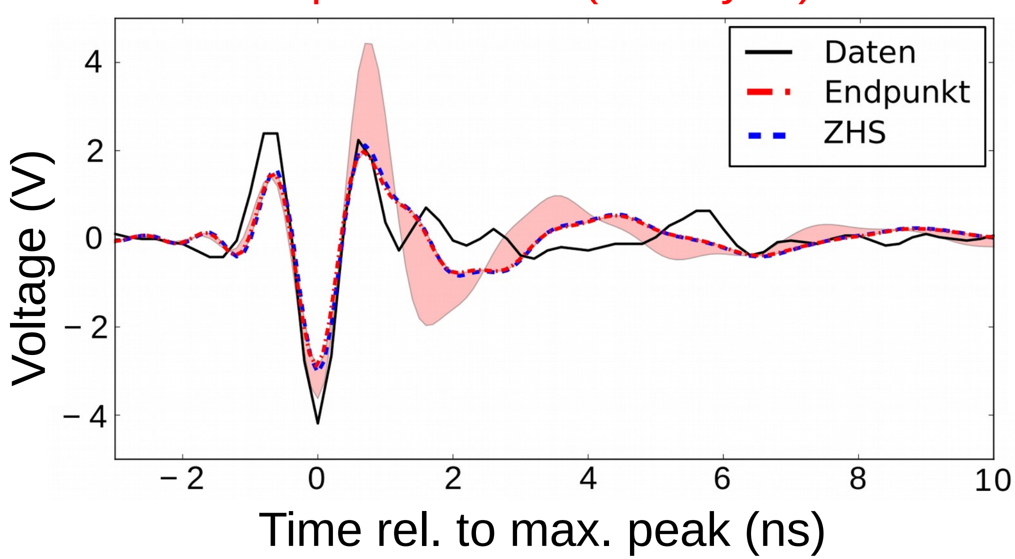

1 km
LOFAR
(7x48)
Tunka-Rex
(63)
AERA
(153)
SKA1-low
(~70.000)

Laboratory proof: The SLAC T-510 experiment

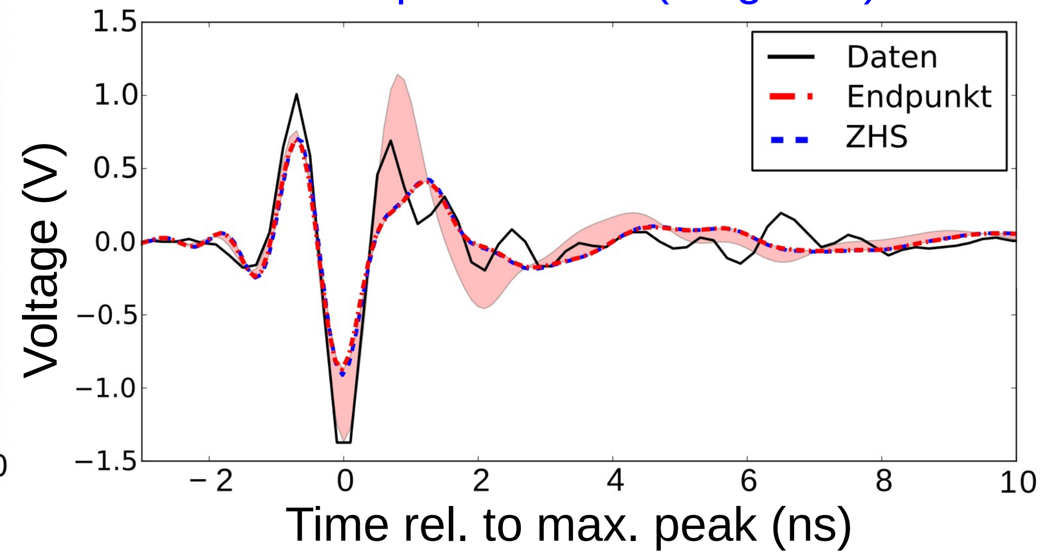
[Phys. Rev. Lett. 116 (2016) 141103]



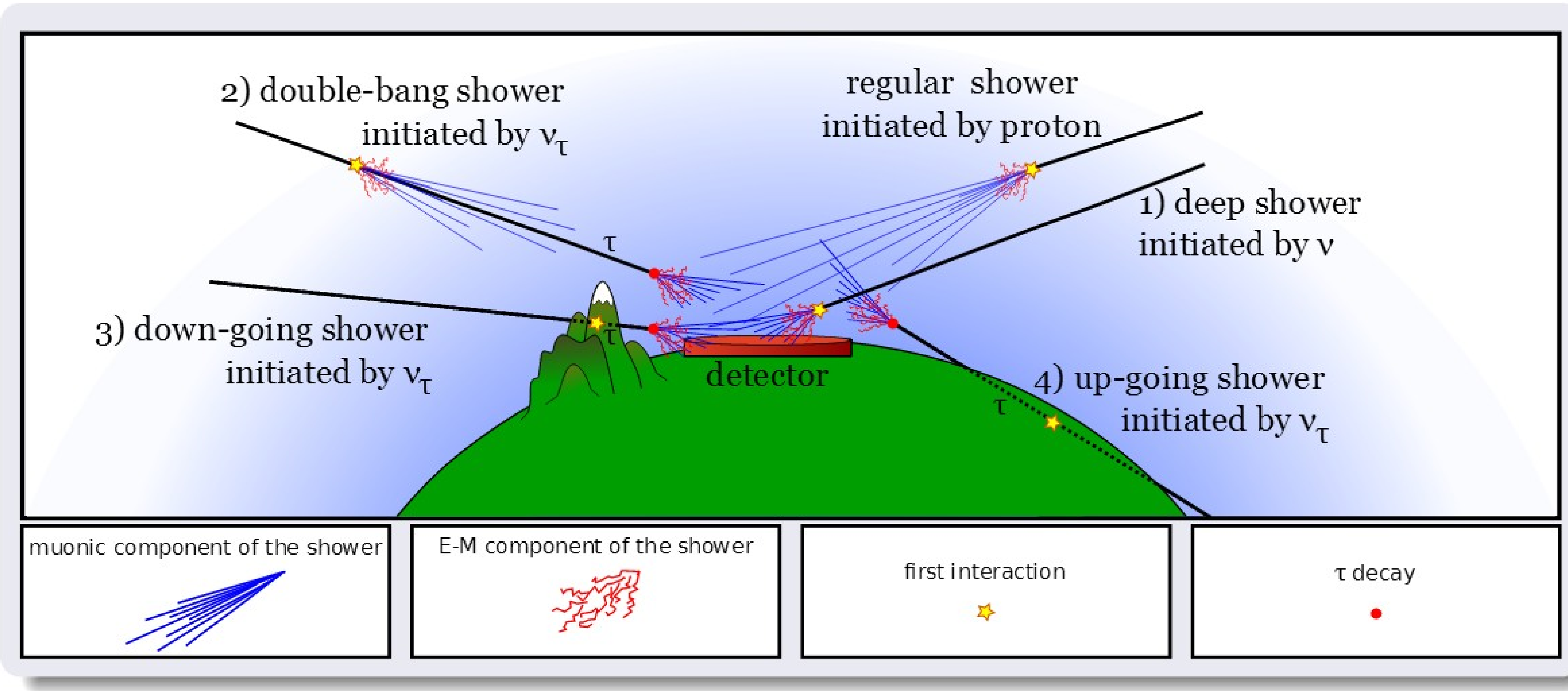
Vertical polarisation (Askaryan)



Horizontal polarisation (Magnetic)



Neutrino detection beyond IceCube energies



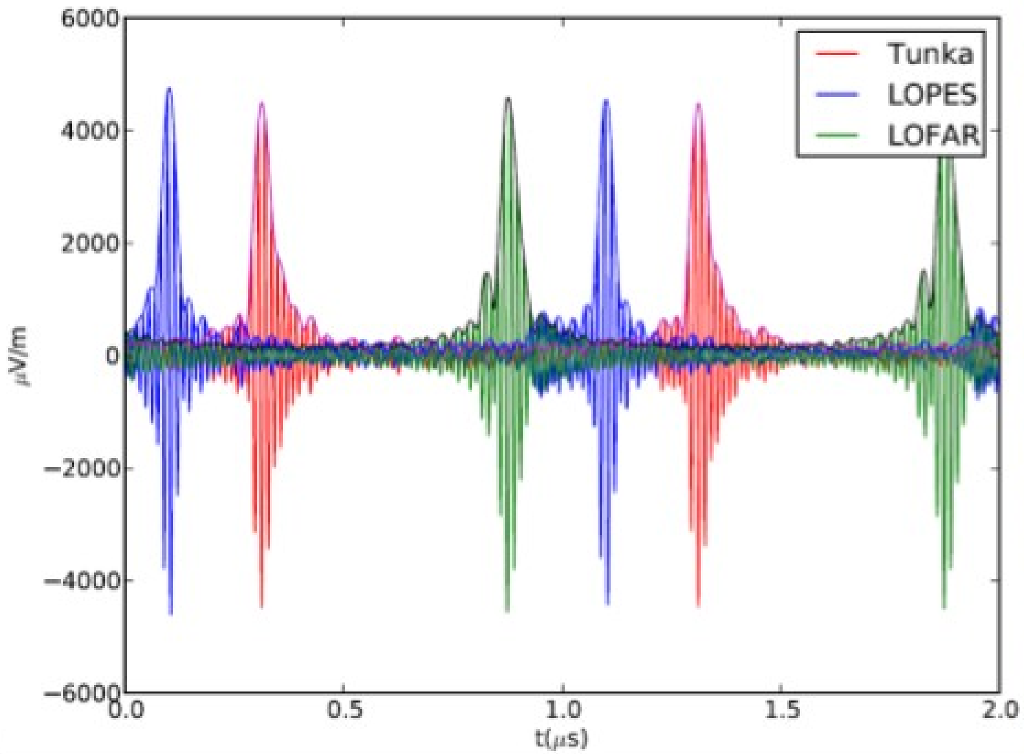
[From "UHE Neutrino searches with the Pierre Auger Observatory", Javier Tiffenberg]

→ Huge detection area needed → Radio (cheap)

Amplitude calibration

- Commercial reference source also used by LOPES and LOFAR

→ Common amplitude scale

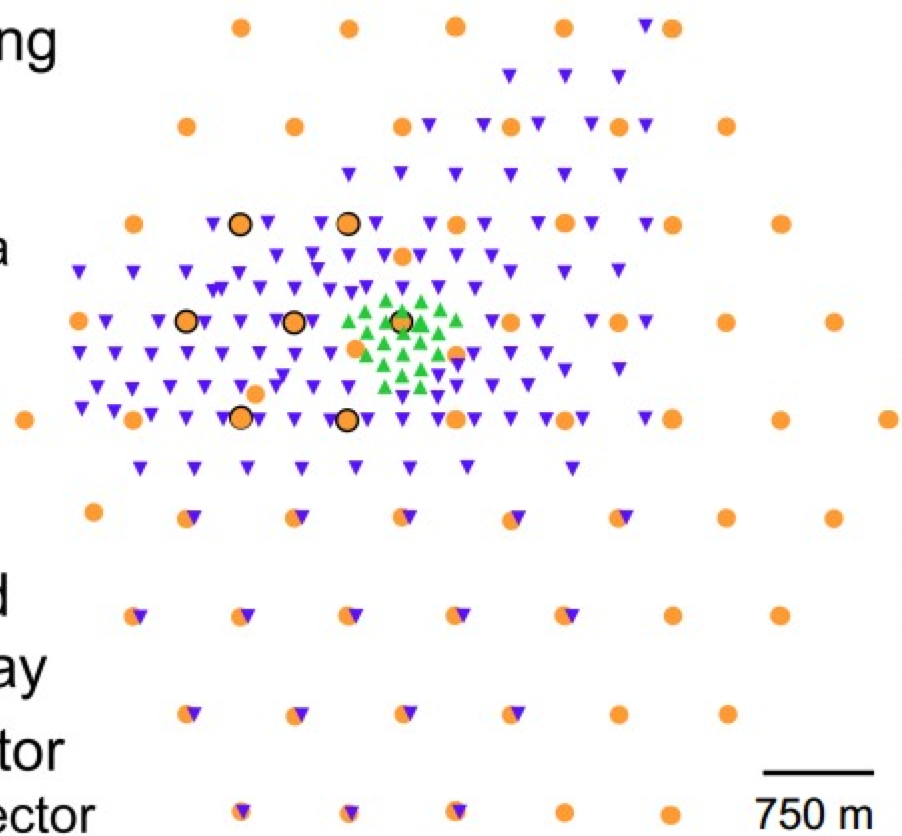


Auger Engineering Radio Array

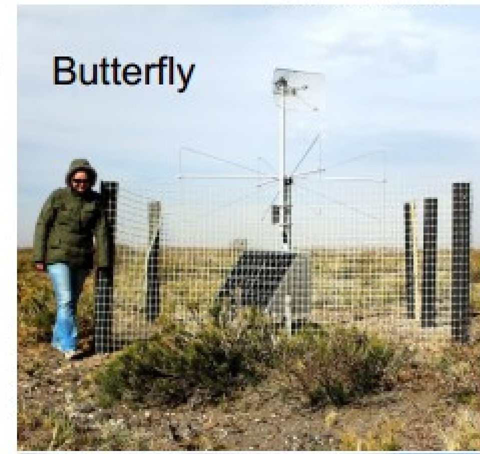
AERA
Auger Engineering Radio Array

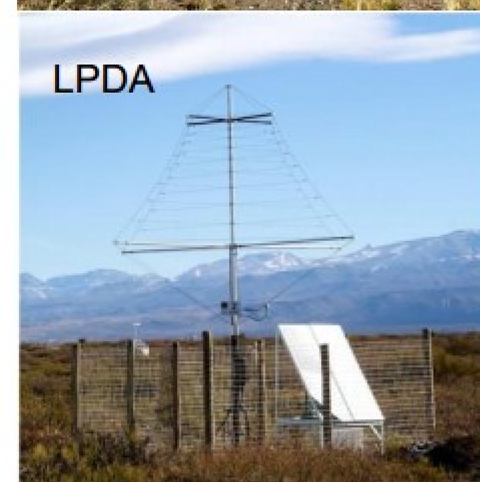
- 153 autonomous stations on 17 km²

Auger **E**ngineering **R**adio **A**rray
- ▲ LPDA antenna
- ▼ Butterfly antenna



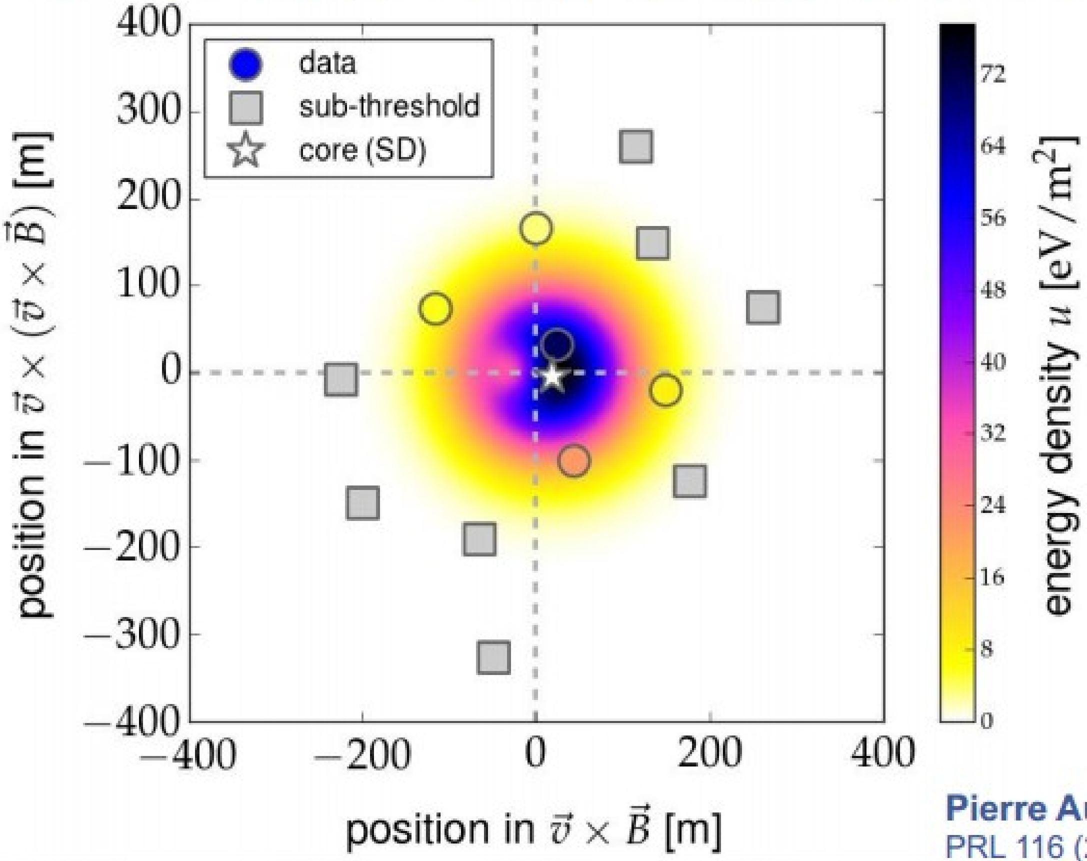
Auger **M**uon and **I**nfill **G**round **A**rray
- ● **S**urface **D**etector
- ○ with **M**uon **D**etector

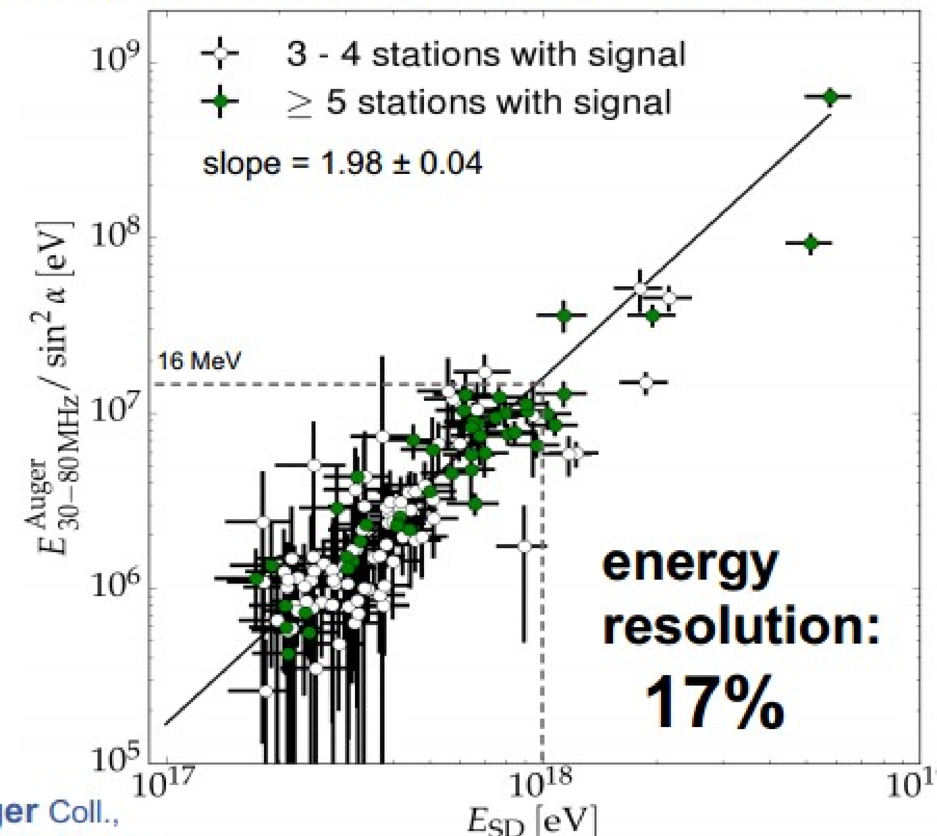




Energy reconstruction by AERA

- Total energy in radio signal scales quadratically with electro-mag. shower energy

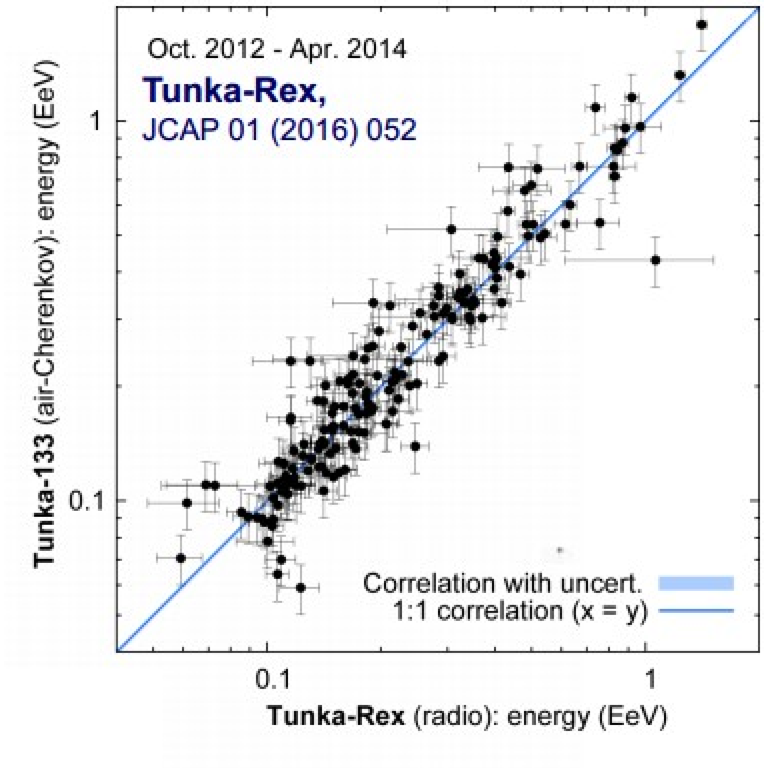




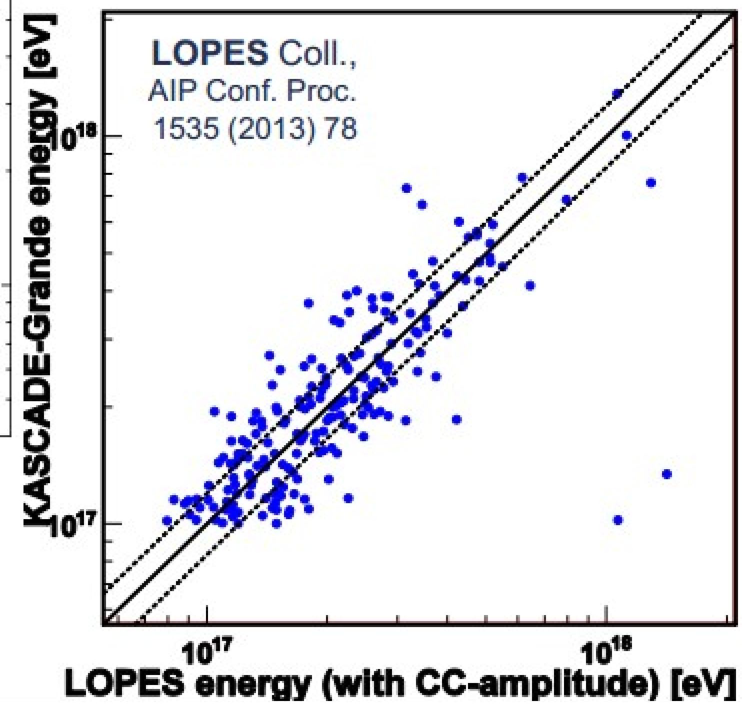
Pierre Auger Coll.,
PRL 116 (2016) 241101

Energy scaling of radio signal

precision by other experiments



+ several other experiments

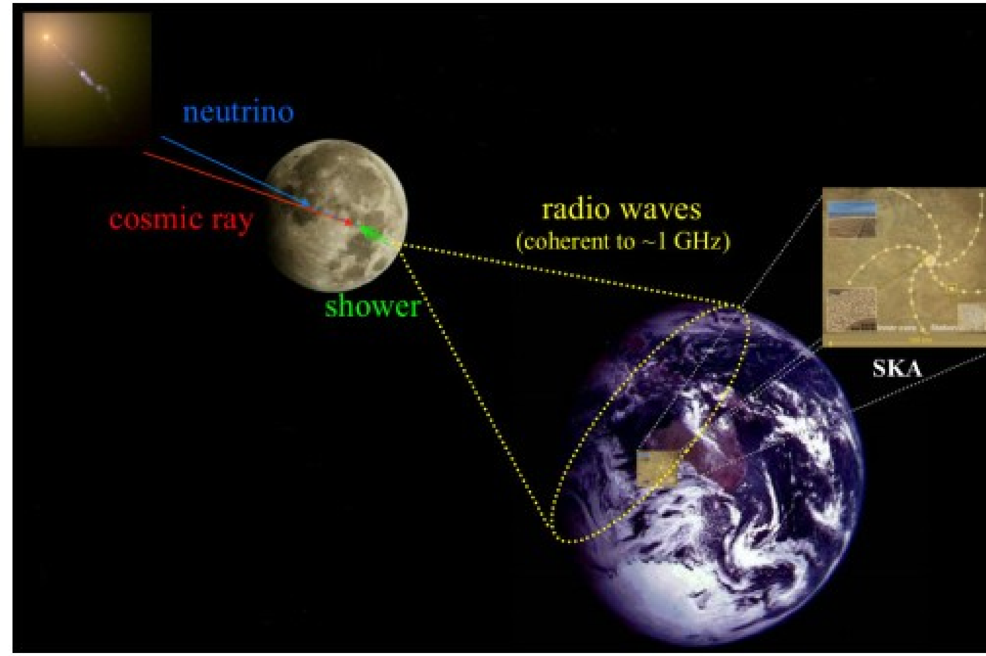


Atmospheric detection

Area ~ 1 km^2

Energy $\gtrsim 10^{17}$ eV

Lunar detection



Area $\sim 10^5$ km^2

Energy $\gtrsim 10^{20}$ eV