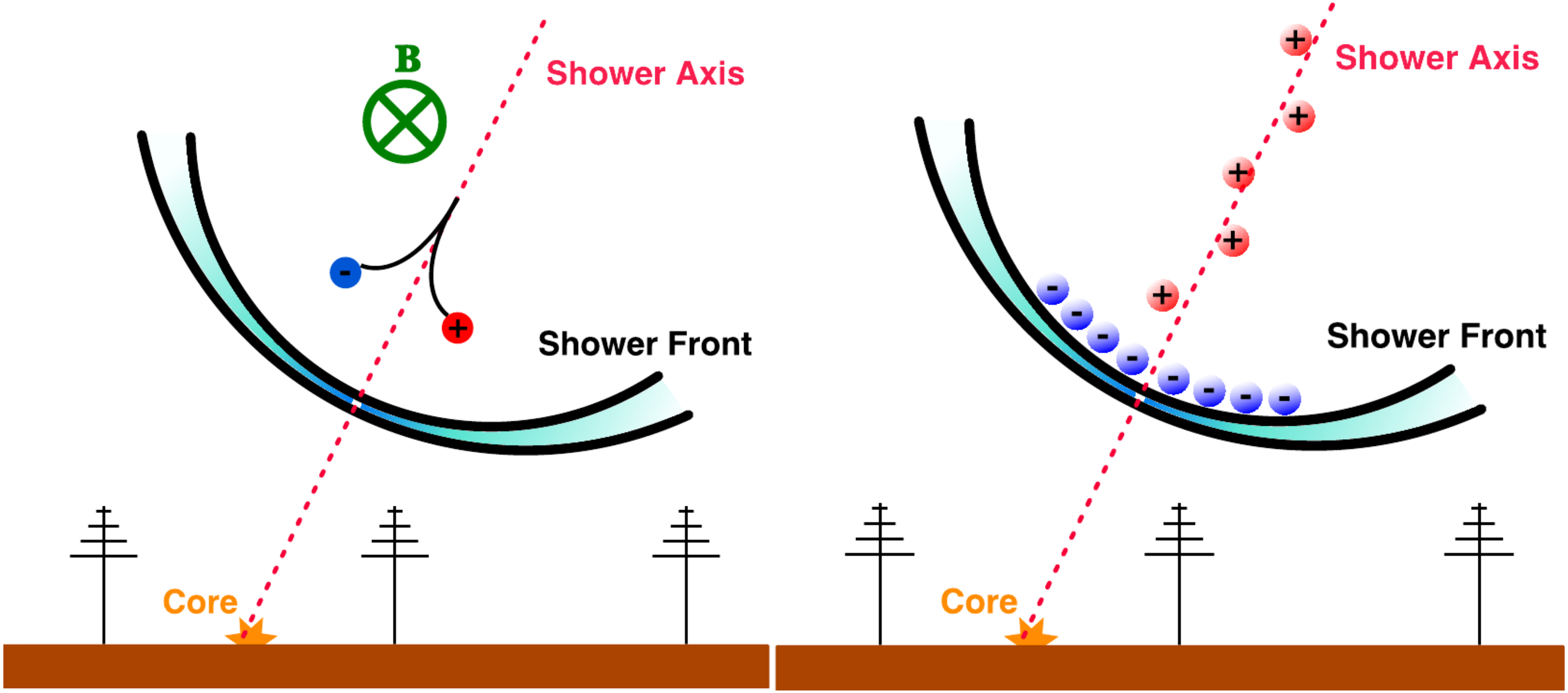
Tomographic imaging by radio emission of cosmic ray air showers using an information field theory approach

Institut für Kernphysik (IKP)

Radio analysis



Primary particle → air shower → radio pulse front

Standard observable: X_{max}, location of highest electron count

Radio analysis

- Current radio analysis: MCMC simulation:

$$p(t) = CoREAS(E_0, X_{max})$$

- Inference:

$$E_0, X_{max} = CoREAS^{-1}(p(t))$$

Radio analysis

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$$p(t) = CoREAS(E_0, X_{max})$$

- Inference:

$$E_0, X_{max} = \cancel{CoREAS^{-1}}(p(t))$$

CPU demand too high → χ^2 fit model functions

Tomography

- Inference problem involving a line-of-sight integral
- Many degrees of freedom
- Highly degenerate due to cancellation of terms and interference effects
- Simplest form: infer longitudinal development of radio-emitting component

$$N(X)|p(t)$$

Bayes Theorem

likelihood

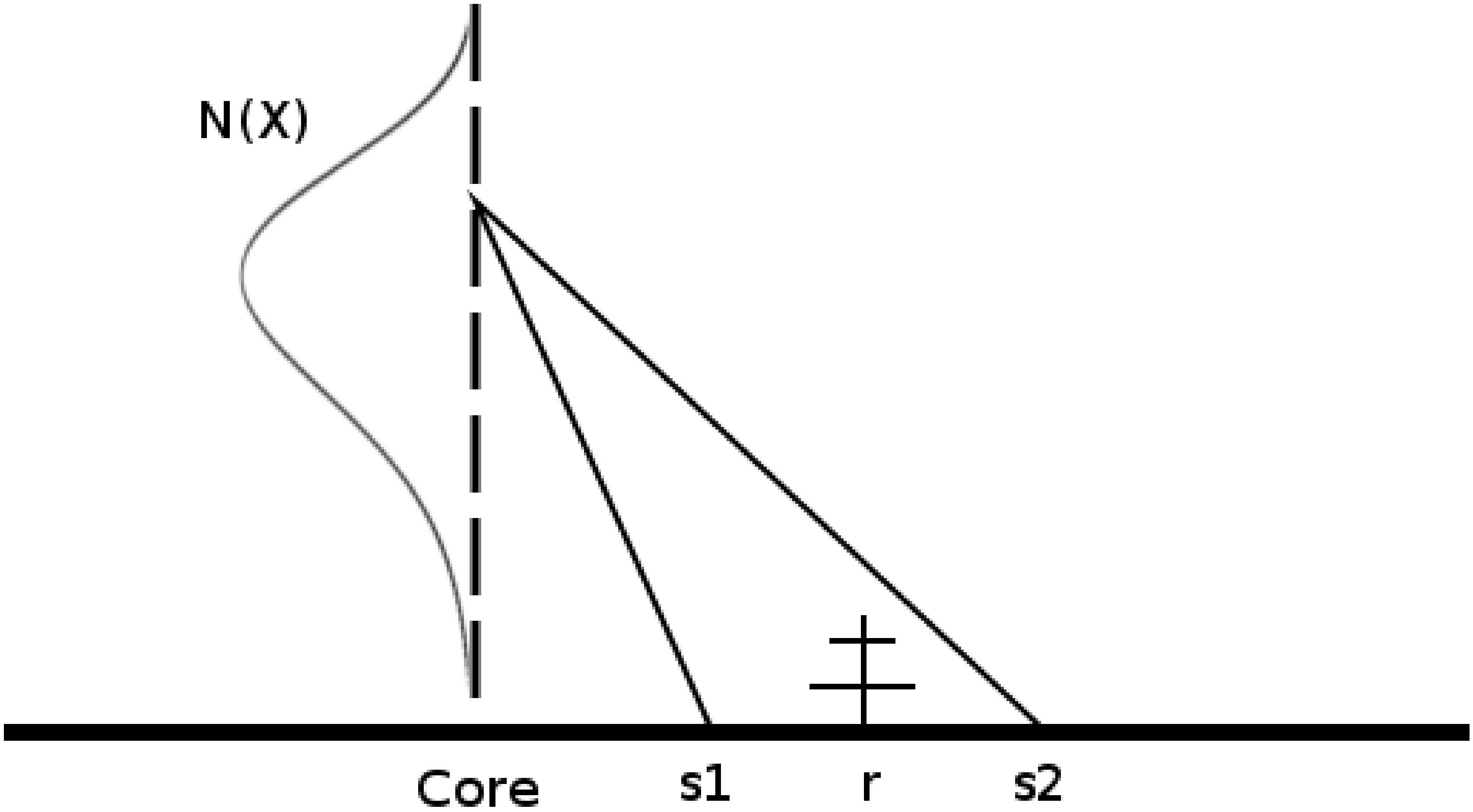
posterior $$P(N|p) = \frac{P(p|N) \cdot P(N)}{P(p)}$$ prior

evidence

- Mean of posterior = "result"
- Covariance of posterior = "uncertainty"
- Prior contains knowledge before taking data
- Likelihood = forward model

Forward Model

$$p(r) = f(p(s_1), p(s_2))$$



Forward Model

- Slice signal contribution by location of emitting particles
- Recombine slices with different weights

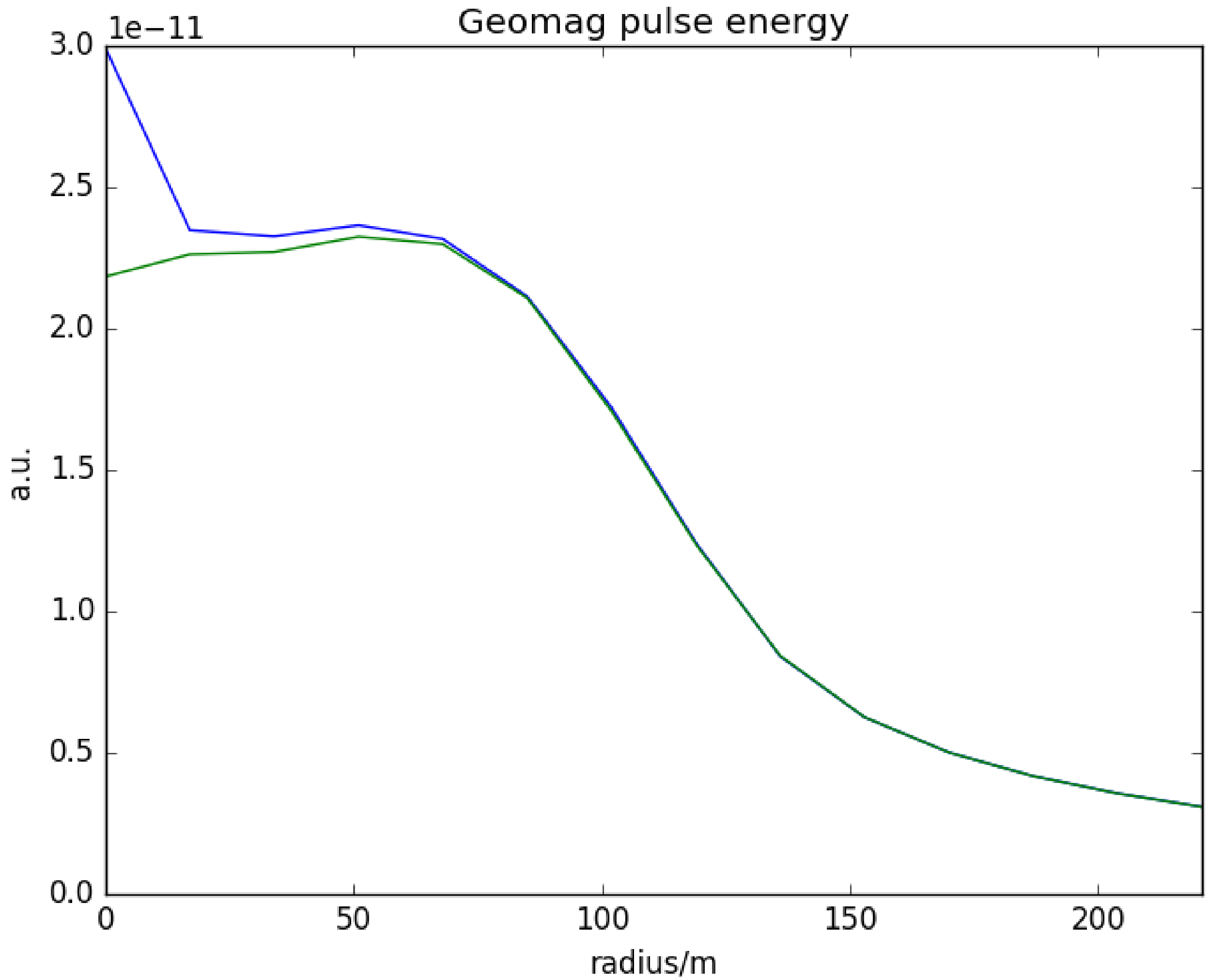
$$p(r) = \sum_X n(X) \cdot f\left(p(s_1, X), p(s_2, X)\right)$$

- Currently

$$n(X) = \frac{N_{target}(X)}{N_{template}(X)}$$

Pulse energy

10^{17}eV proton air shower, maximum ~18km above ground



Karlsruher Institut für Technologie

Forward Model

Ultimate goal: synthesis/lookup table for

- Primary energy
  - Power law scaling?
- Primary species
  - Separate templates necessary
- Longitudinal development N(X)
  - Lateral distribution necessary?
- Zenith, azimuth angles
  - Breaks correspondence between atmospheric depth and height
  - Asymmetric refractive index in shower plane
- Full 2D antenna field
  - Rotational symmetry sufficient?

Tomography

- Massive information loss along the line of sight
  - Requires good prior for reconstruction
  - Numerically highly unstable if undersampled
  - No existing instrument with enough data
  - Computationally demanding

- Further open questions:
  - Fast forward model (CoREAS too expensive to run iteratively, sampling unfeasible for SKA)
  - Viability of priors extracted from CoREAS
  - Unprecedented approach, overall viability not demonstrated

Thank you!

Questions?

Folientitel: Arial 26pt fett
2-zeilig: Arial 22pt fett

Untertitel: Arial 18pt fett
Auch mehrzeilig möglich.

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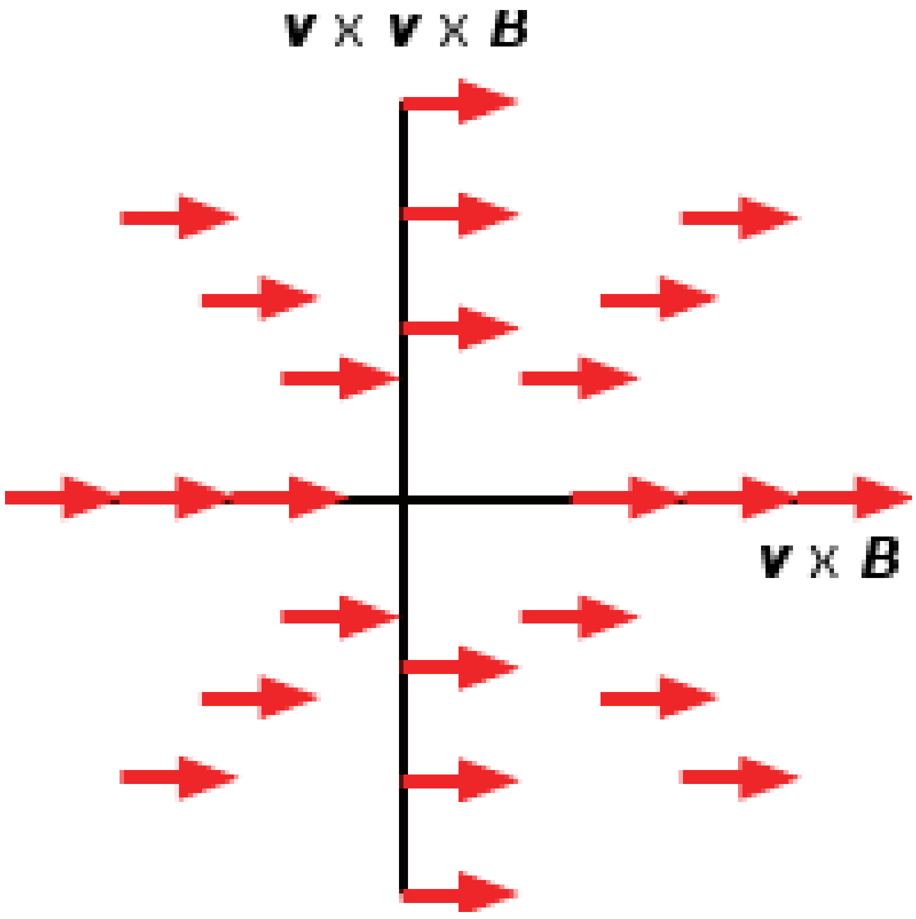
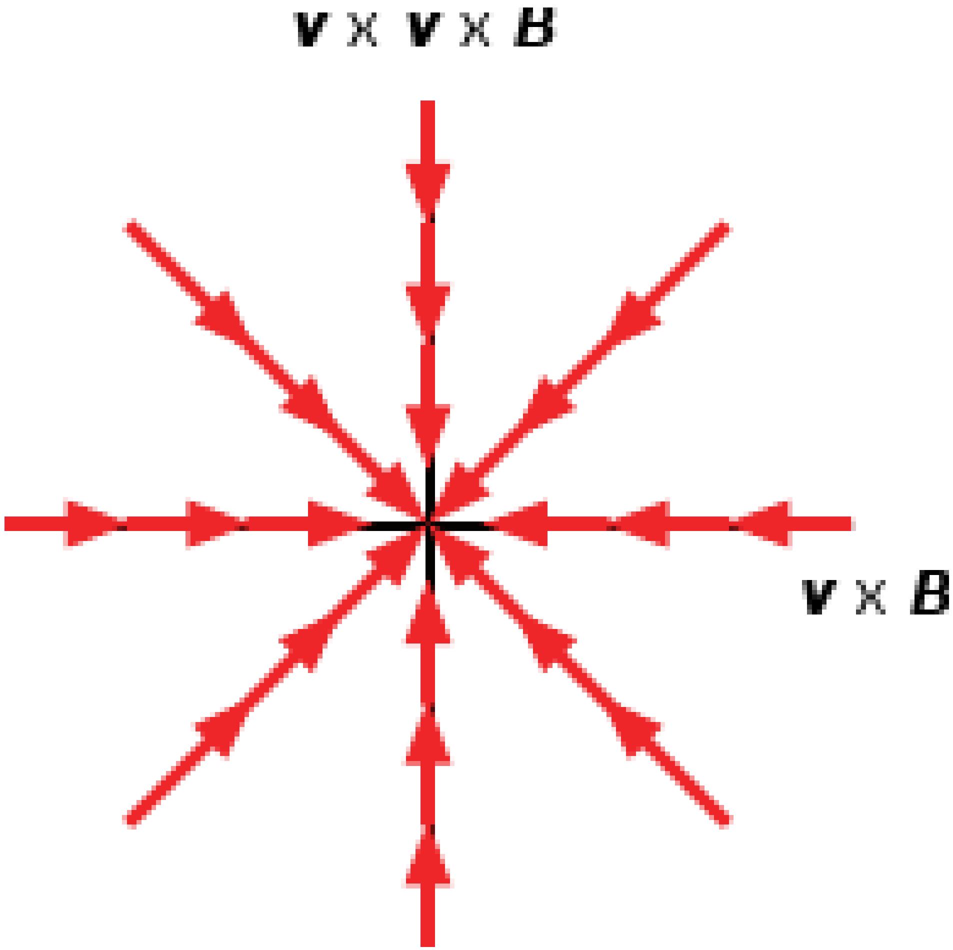
Radio Polarisation

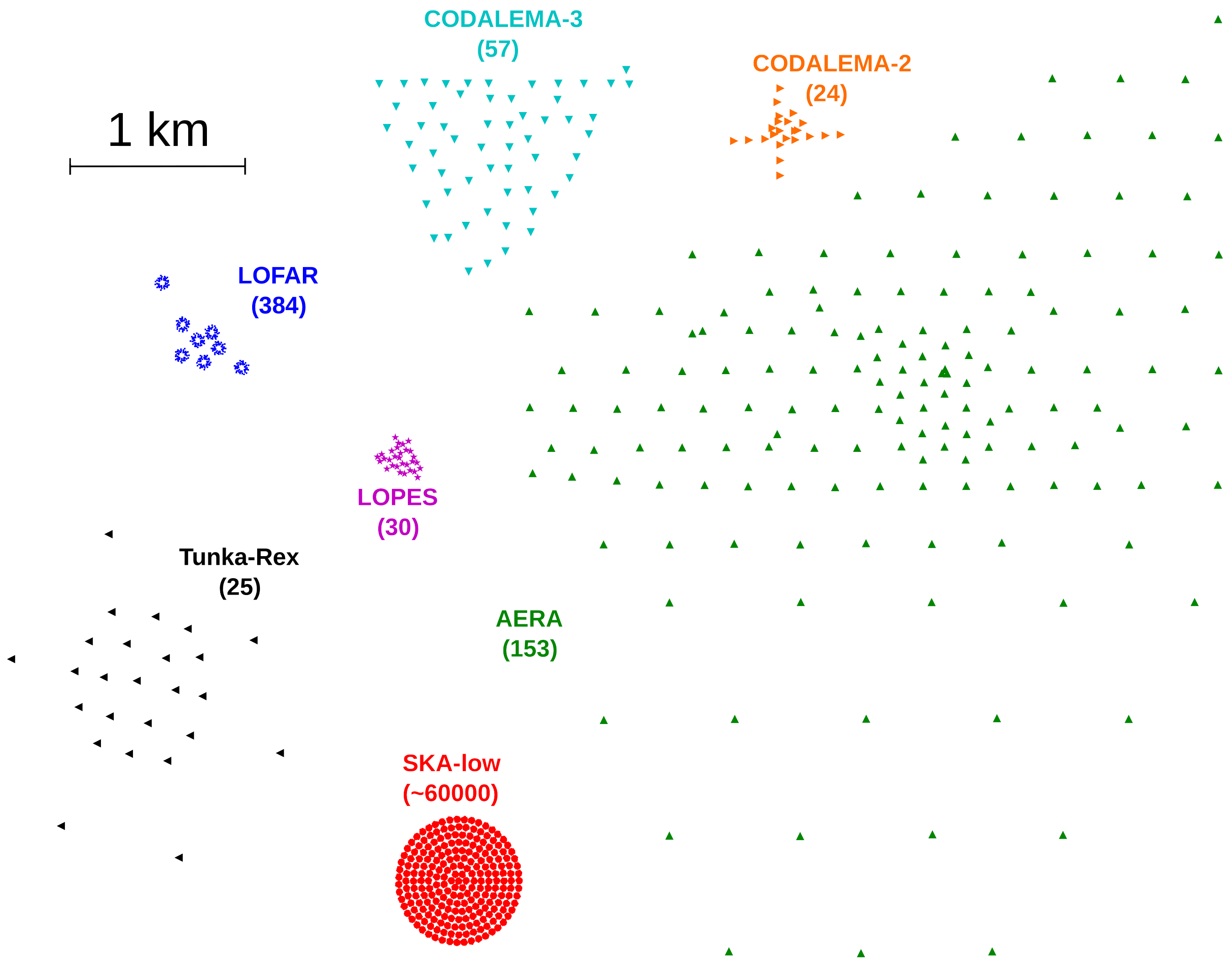


Geomagnetic



Charge Excess/Askaryan

Radio EAS Arrays



Forward Model

- CoREAS assumed accurate
- Simplified model derived from simulations matching abstract form

$$d = R(s) + n$$

where d = measured signal, s = (E, N, *etc.*),

n = measurement uncertainty, noise

Forward Model

- Interpolation of template pulses in Fourier space:
- Independent linear interpolation of amplitudes and phases

$$y = \left(1 - w(r)\right) \cdot y_1 + w(r) \cdot y_2$$

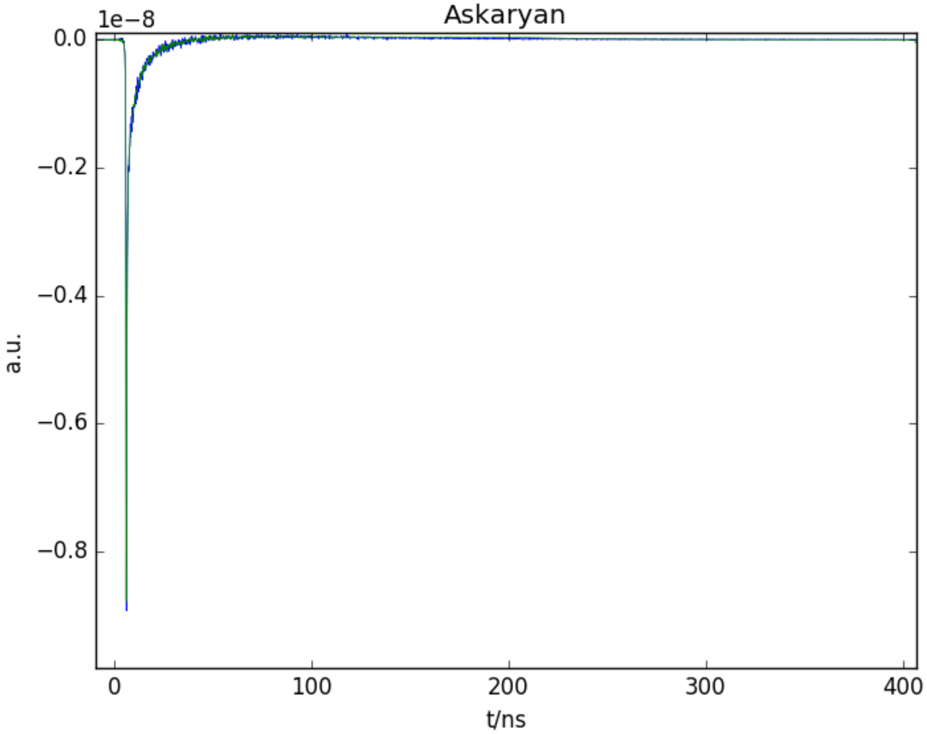
$$w(r) = \frac{r - s_1}{s_2 - s_1}$$

$$y = A, \phi$$

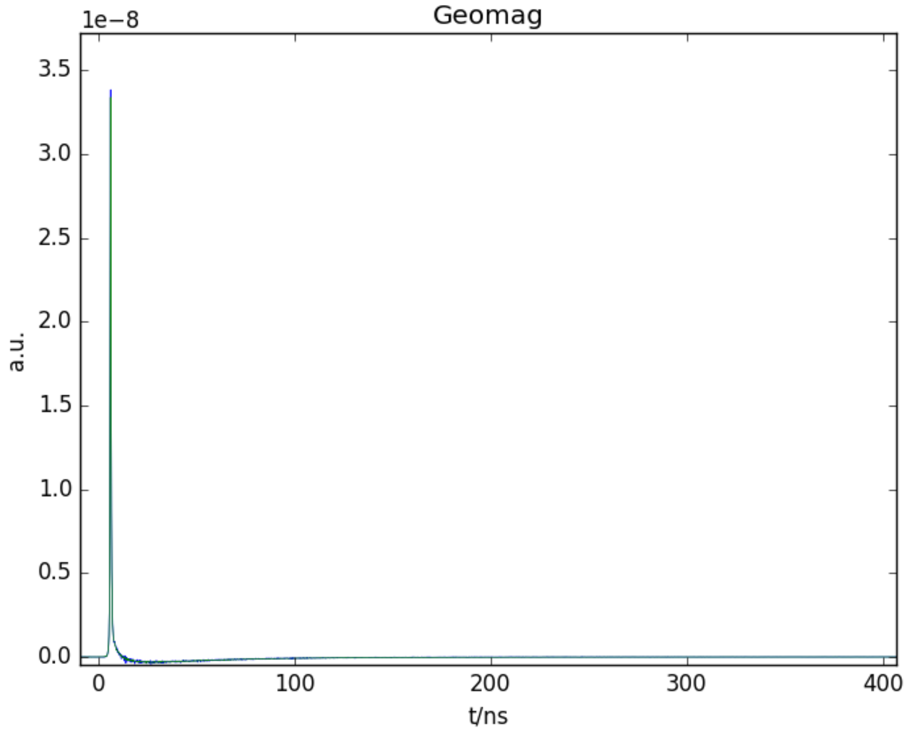
$$p = A \cdot e^{i\phi}$$

- Unfortunately not linear w.r.t. total pulse

Time series

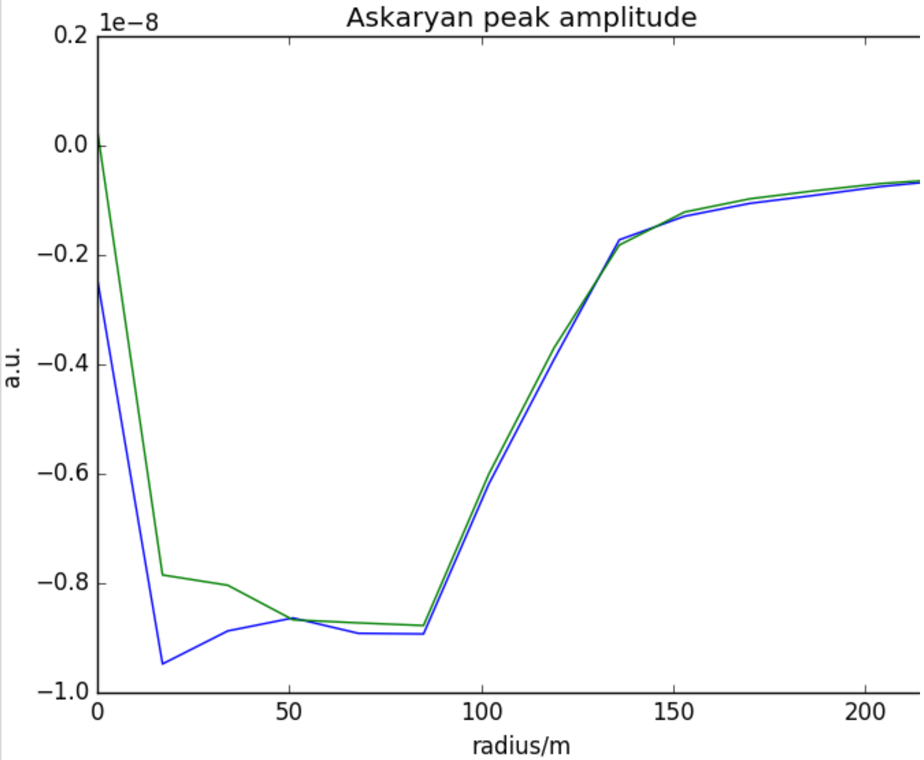


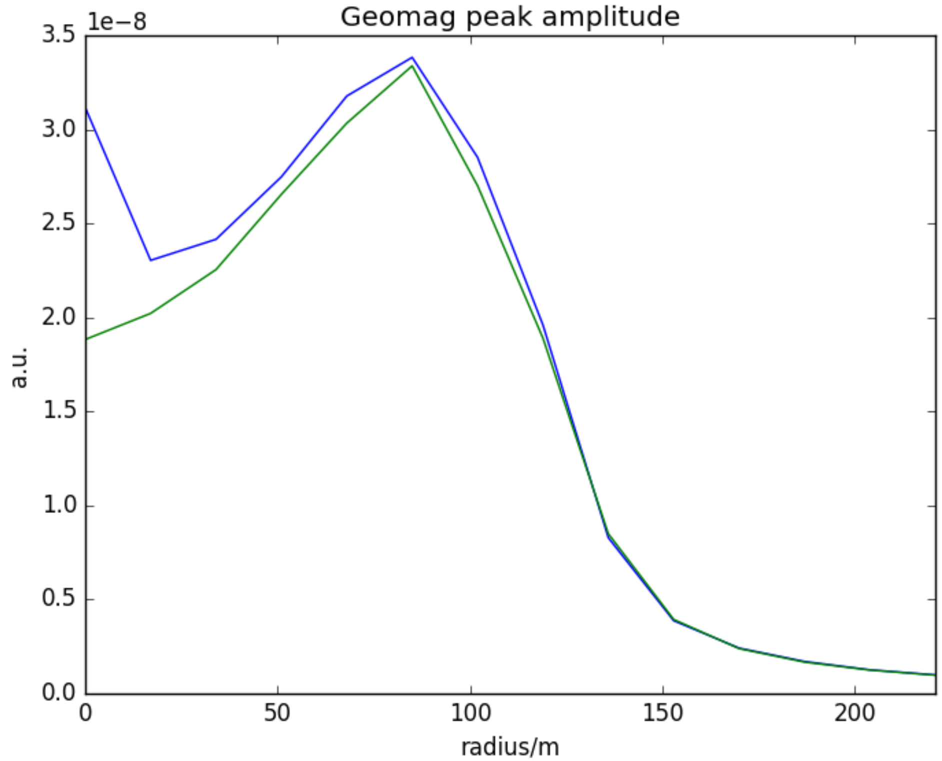
Askaryan
1e−8
0.0
−0.2
−0.4
−0.6
−0.8
a.u.
0
100
200
300
400
t/ns

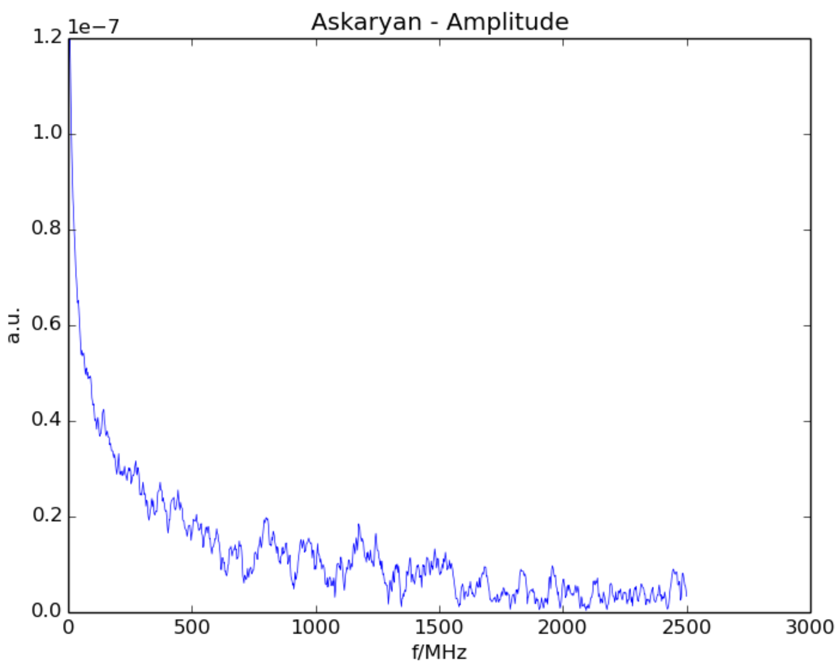


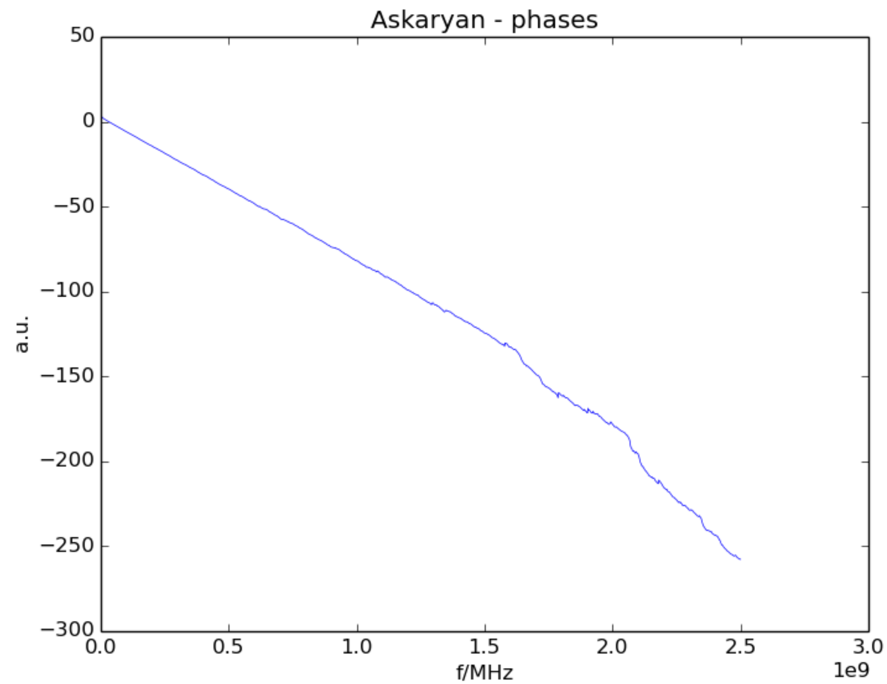
Geomag
1e−8
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
a.u.
0
100
200
300
400
t/ns

Peak height


Askaryan peak amplitude
1e−8
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
a.u.
0
50
100
150
200
radius/m


Geomag peak amplitude
1e−8
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
a.u.
0
50
100
150
200
radius/m


Askaryan - Amplitude
1e−7
1.2
1.0
0.8
0.6
0.4
0.2
0.0
a.u.
0
500
1000
1500
2000
2500
3000
f/MHz


Askaryan - phases
50
0
−50
−100
−150
−200
−250
−300
a.u.
0.0
0.5
1.0
1.5
2.0
2.5
3.0
1e9
f/MHz

Fourier rounding error