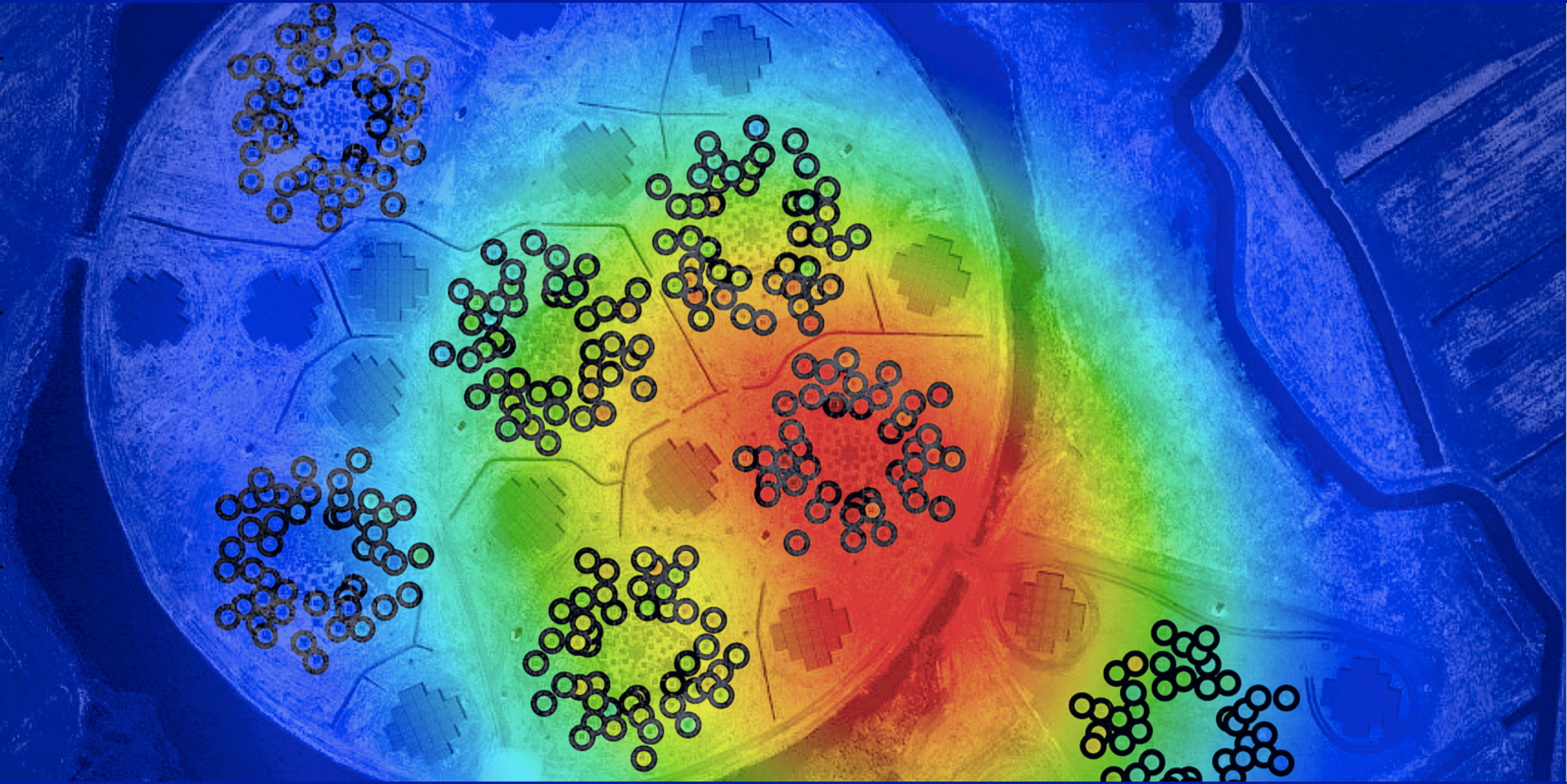
# The atmospheric refractive index and radio emission from extensive air showers



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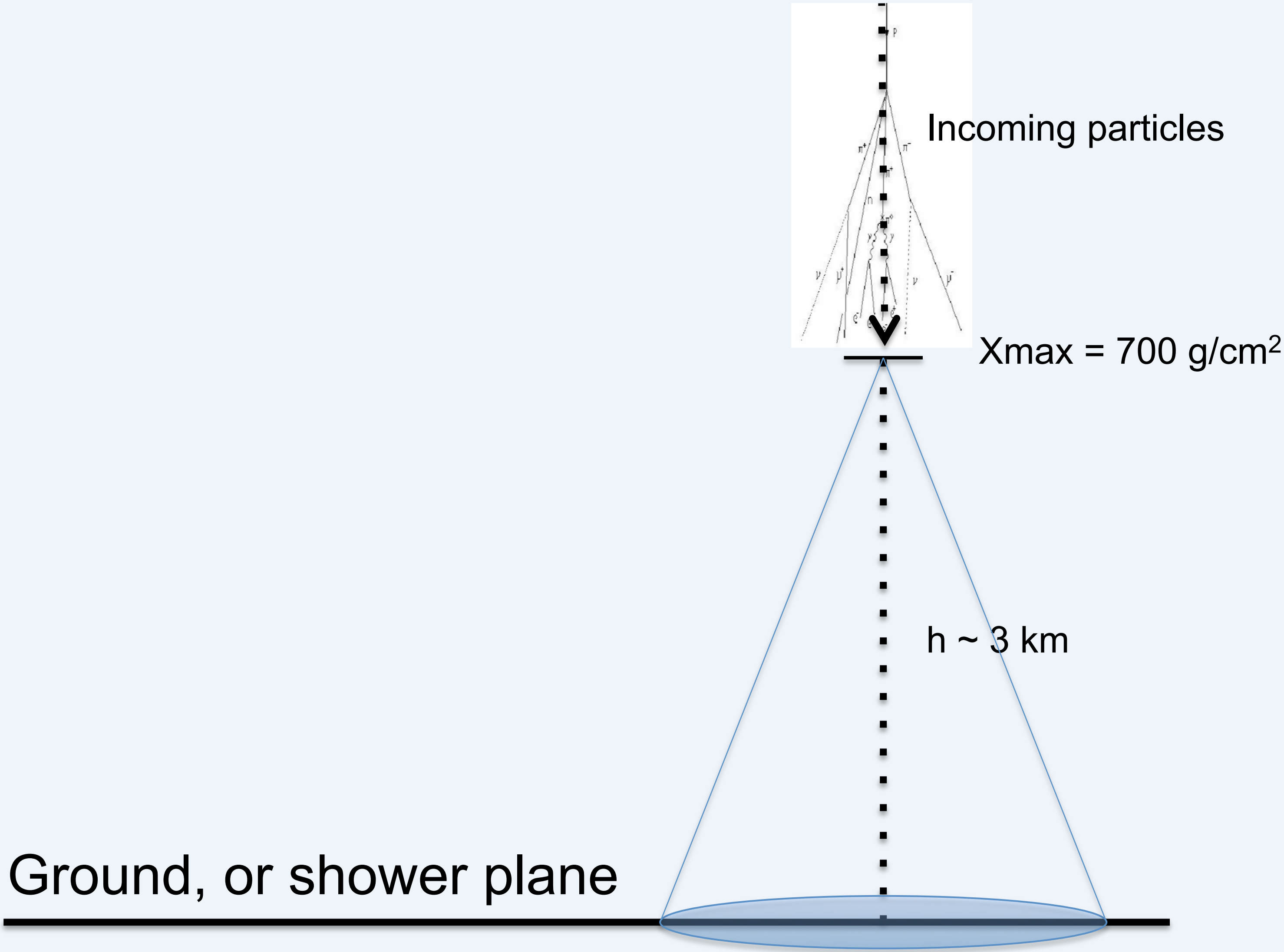
# Simplified air shower footprint on the ground



Incoming particles

Xmax = 700 g/cm$^2$

h ~ 3 km

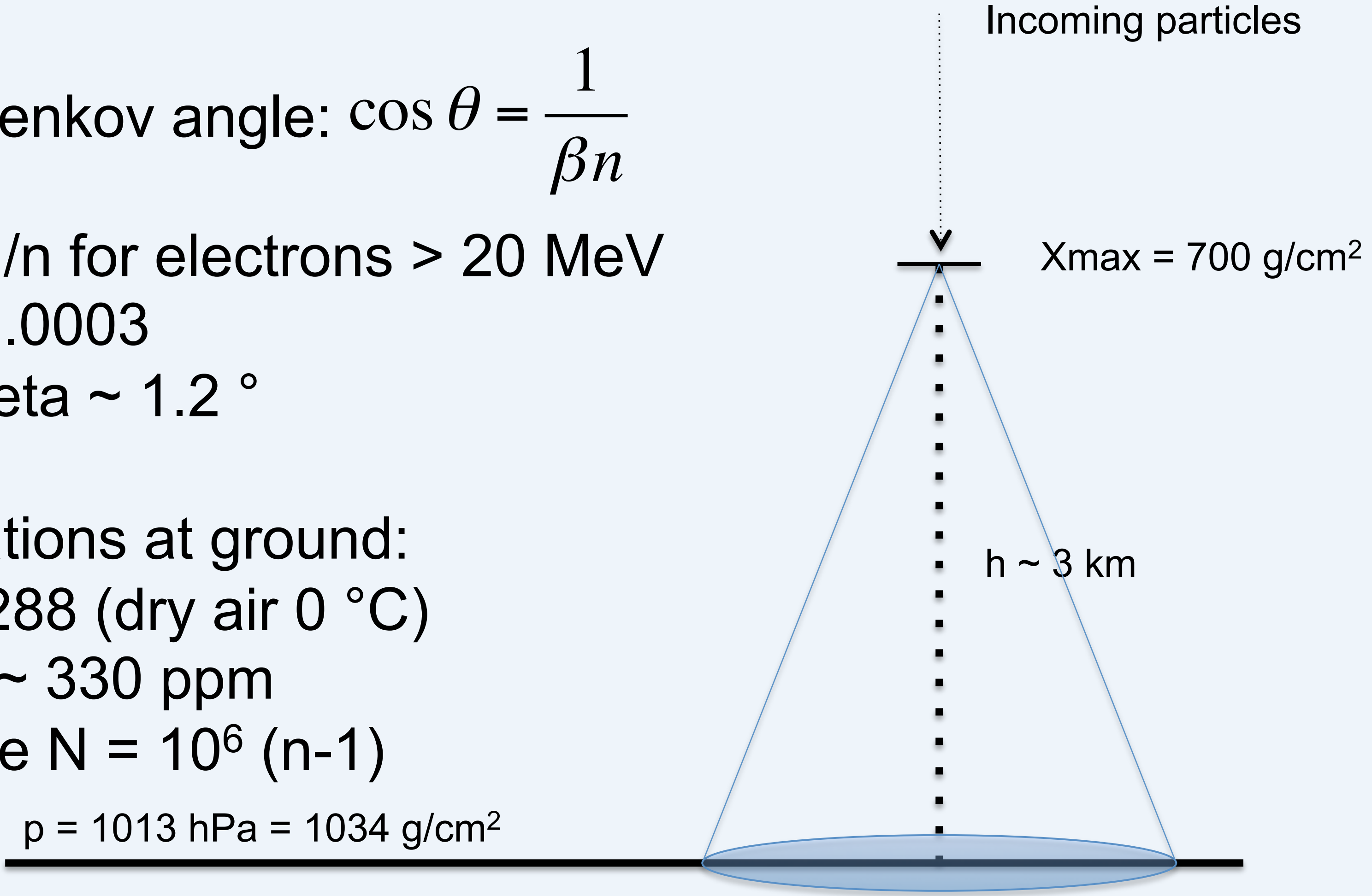
Ground, or shower plane

# Simplified air shower footprint on the ground

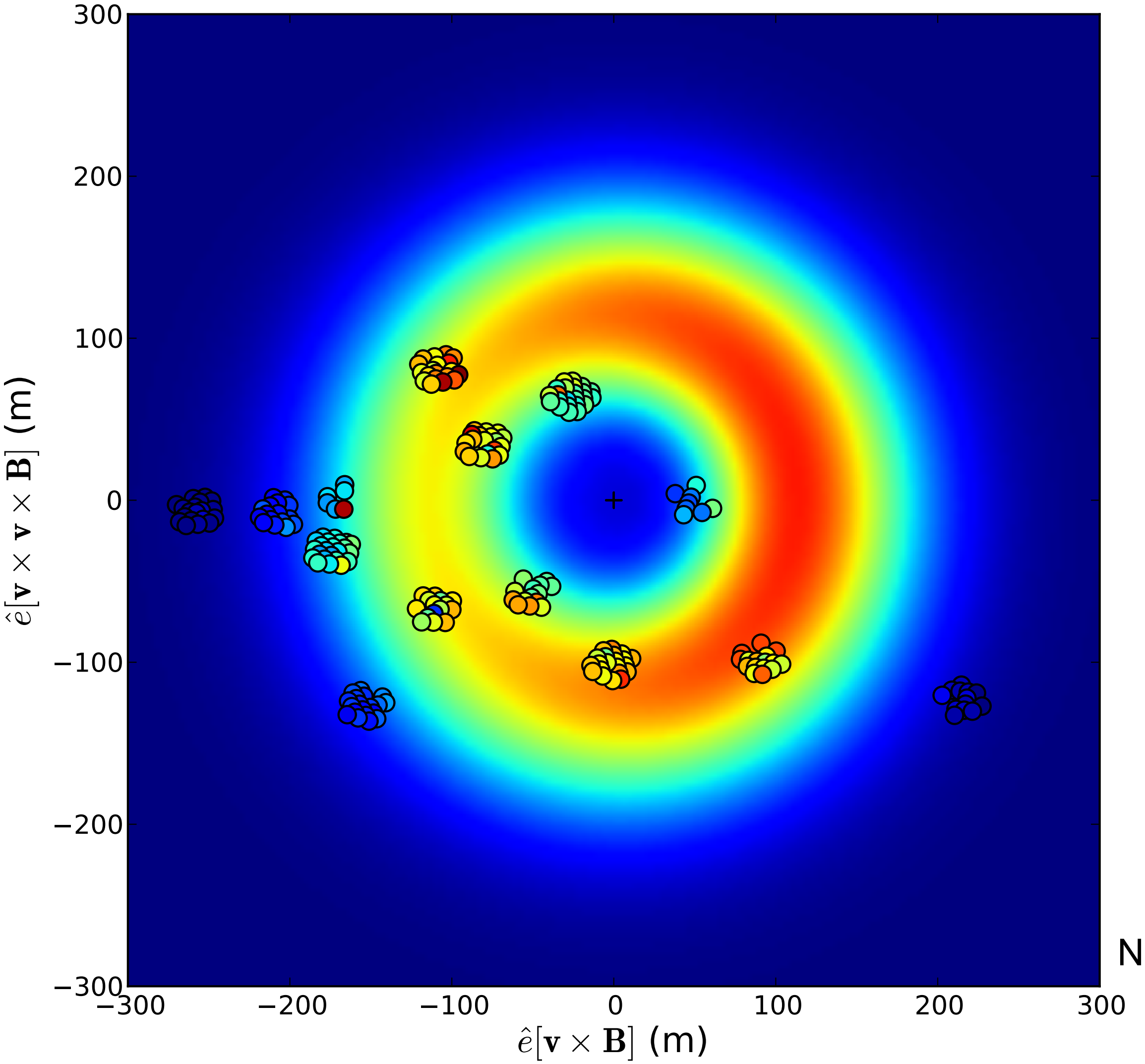
Cherenkov angle: $\cos\theta = \frac{1}{\beta n}$

$\beta > 1/n$ for electrons > 20 MeV
$n \sim 1.0003$
-> theta ~ 1.2 °

Variations at ground:
N = 288 (dry air 0 °C)
to N ~ 330 ppm
where $N = 10^6 (n-1)$



# Cherenkov ring at frequencies > 120 MHz

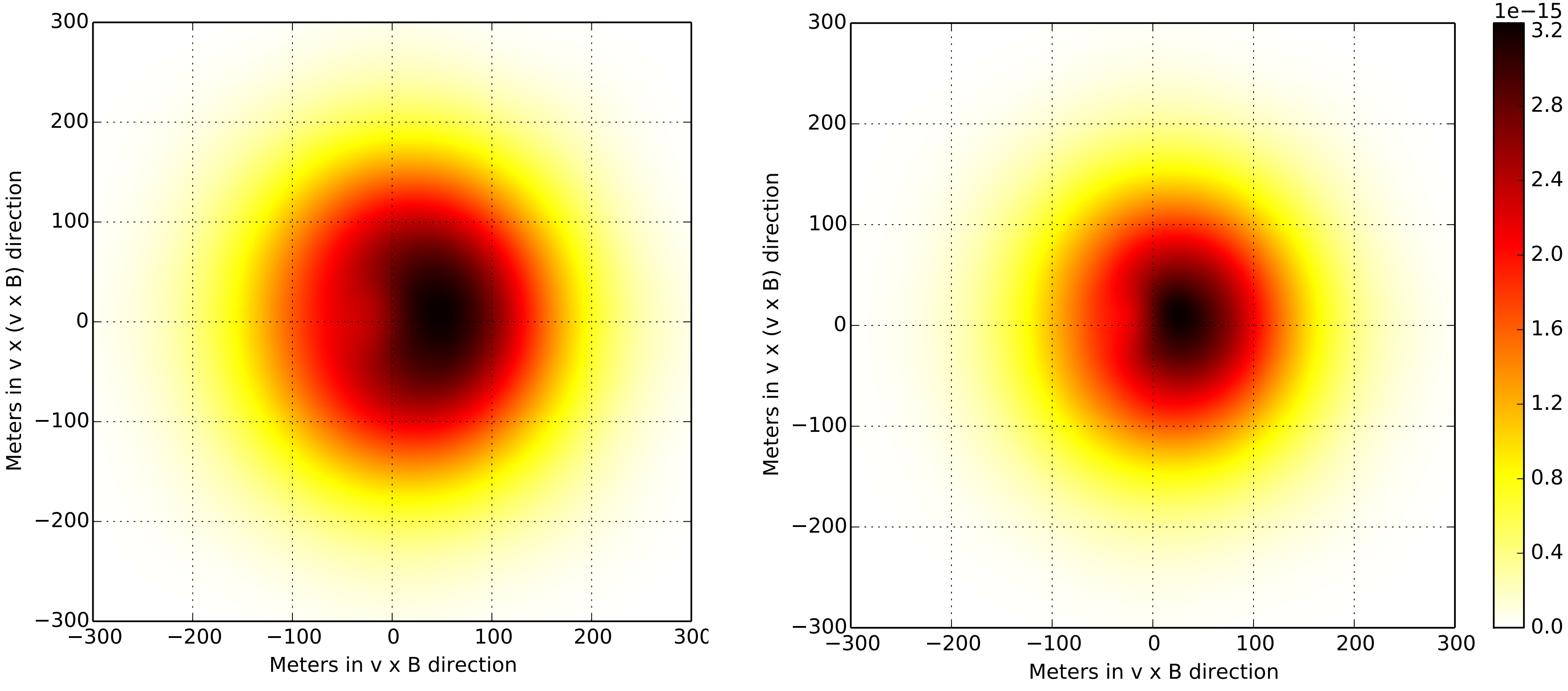


Simulation (CoREAS) with LOFAR HBA detection (circles)

Ring becomes sharper at higher frequencies

Nelles et al., Astropart. Phys 65 (2015)

# Footprint at low frequencies, 30 – 80 MHz

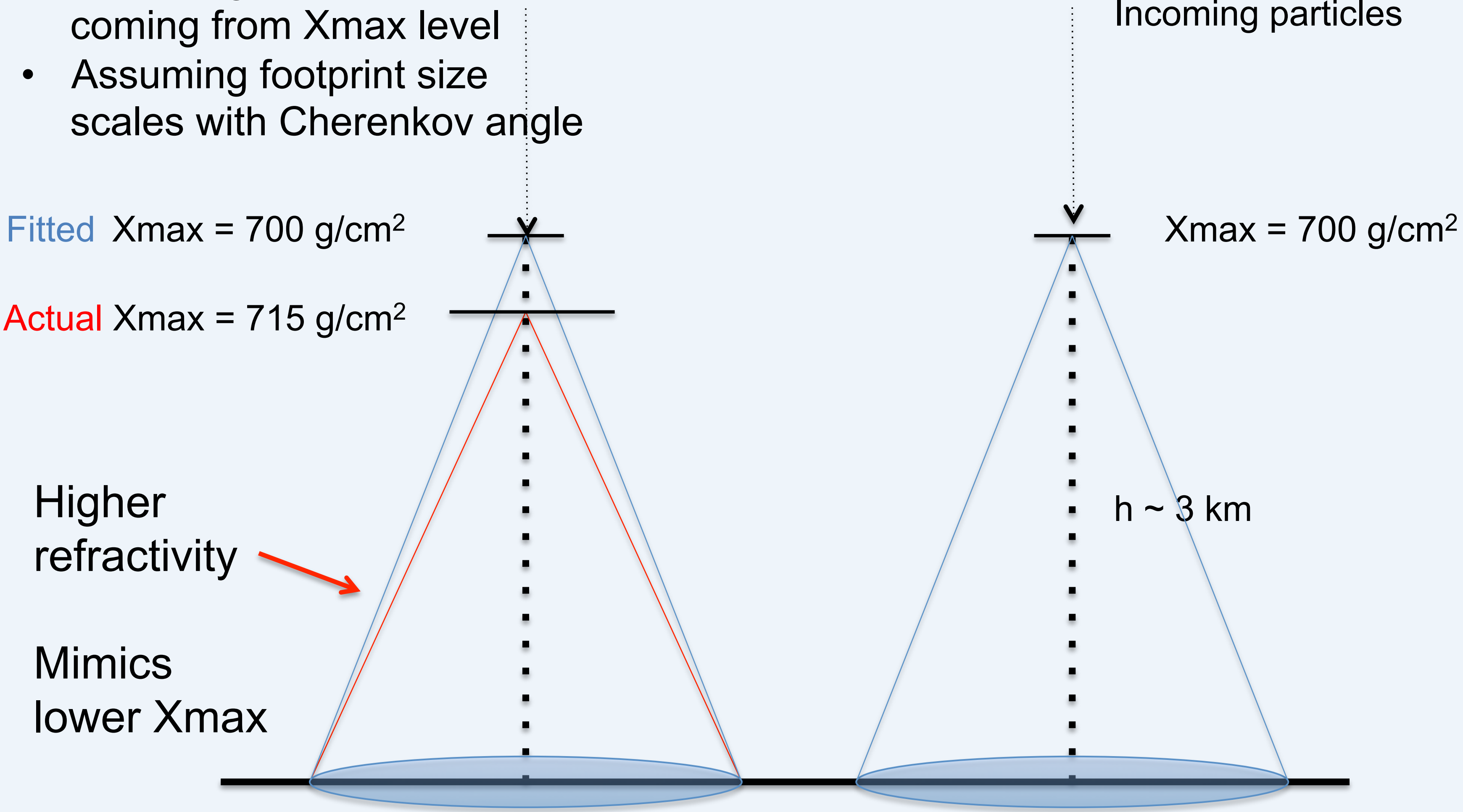

Xmax = 630 g/cm$^2$

Xmax = 700 g/cm$^2$

CoREAS simulated footprints of radio intensity

# The effect of variations in refractive index (simplified)

- Assuming all radiation coming from Xmax level
- Assuming footprint size scales with Cherenkov angle



Incoming particles

Fitted Xmax = 700 g/cm$^2$

Actual Xmax = 715 g/cm$^2$

Xmax = 700 g/cm$^2$

Higher refractivity

Mimics lower Xmax

h ~ 3 km

# Standard atmosphere (US/Intl.)

Constant temperature lapse rate:  L = 6.5 K / km

$p_0$ = 1013.25 hPa ( variable)

$T_0$ = 273.15 + 15 K ( “ )

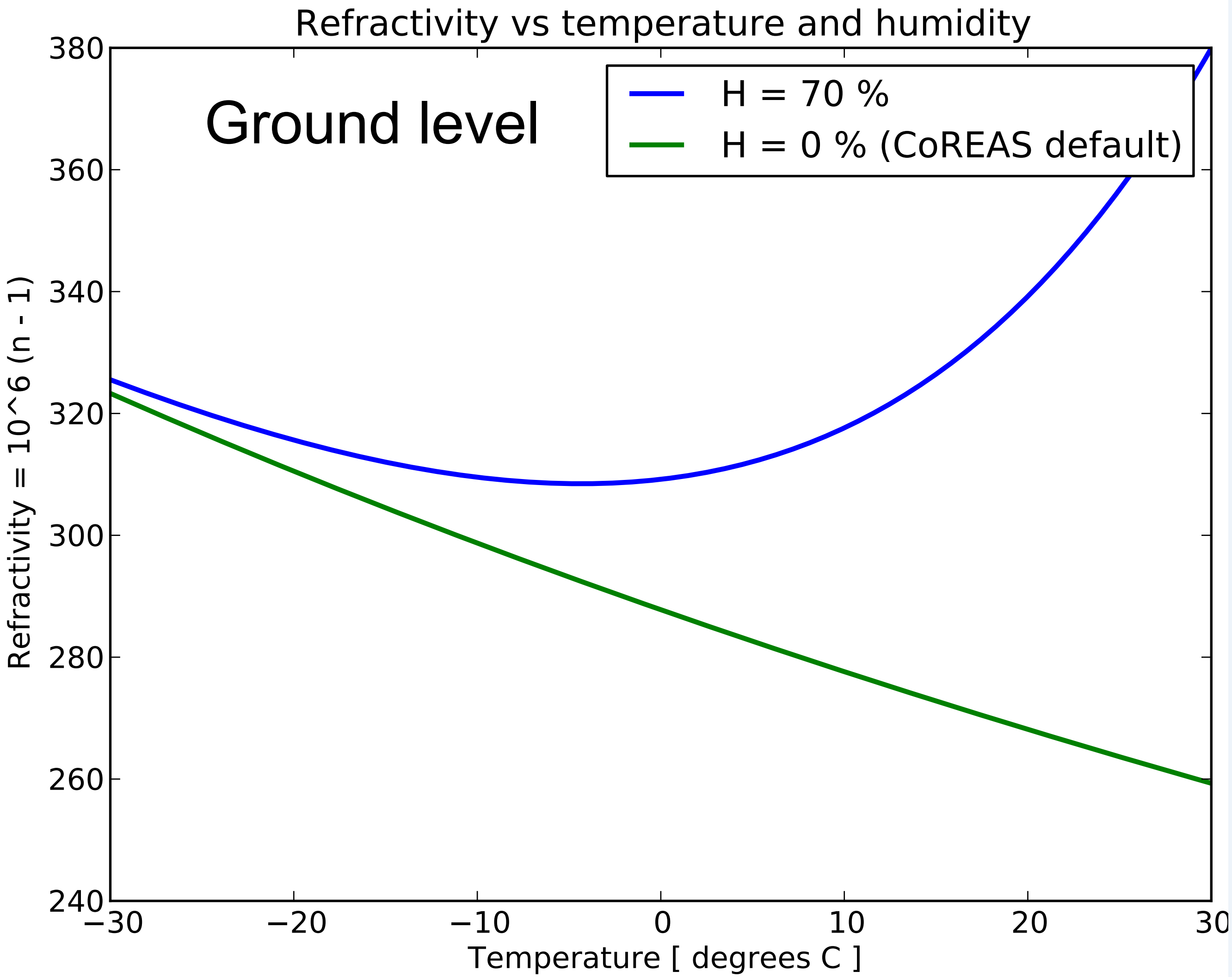
Then:

$$p = p_0 \left(1 - \frac{L}{T_0} h\right)^{\frac{gM}{RL}}$$

Refractivity N can be expressed as a function of pressure, temperature and (relative) humidity

- Different for radio vs IR/visible !
- Especially the water vapor contribution

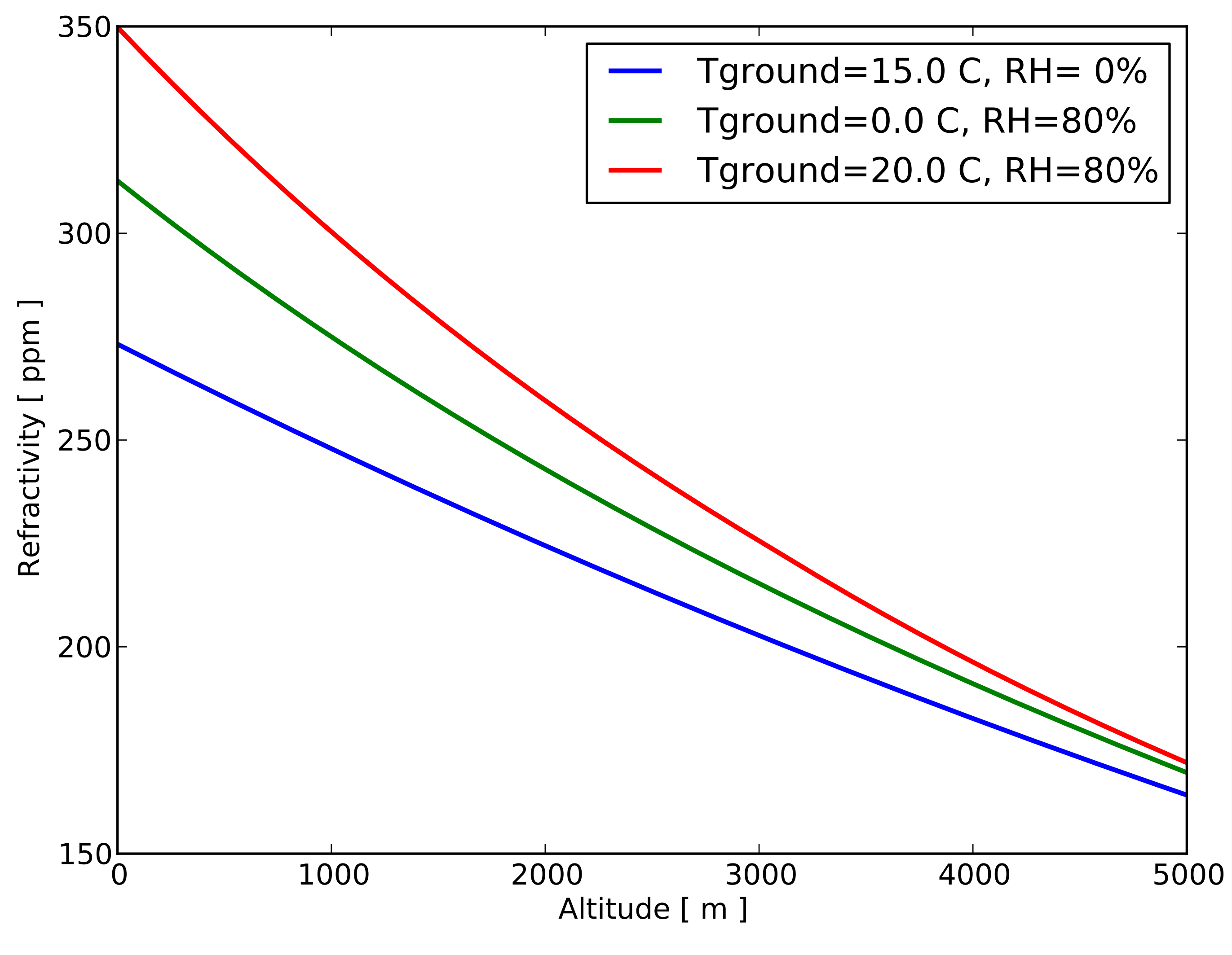
# Variations in refractive index



Refractivity proportional to density (dry) = green line

Absolute humidity independent of pressure

# Variations in refractive index

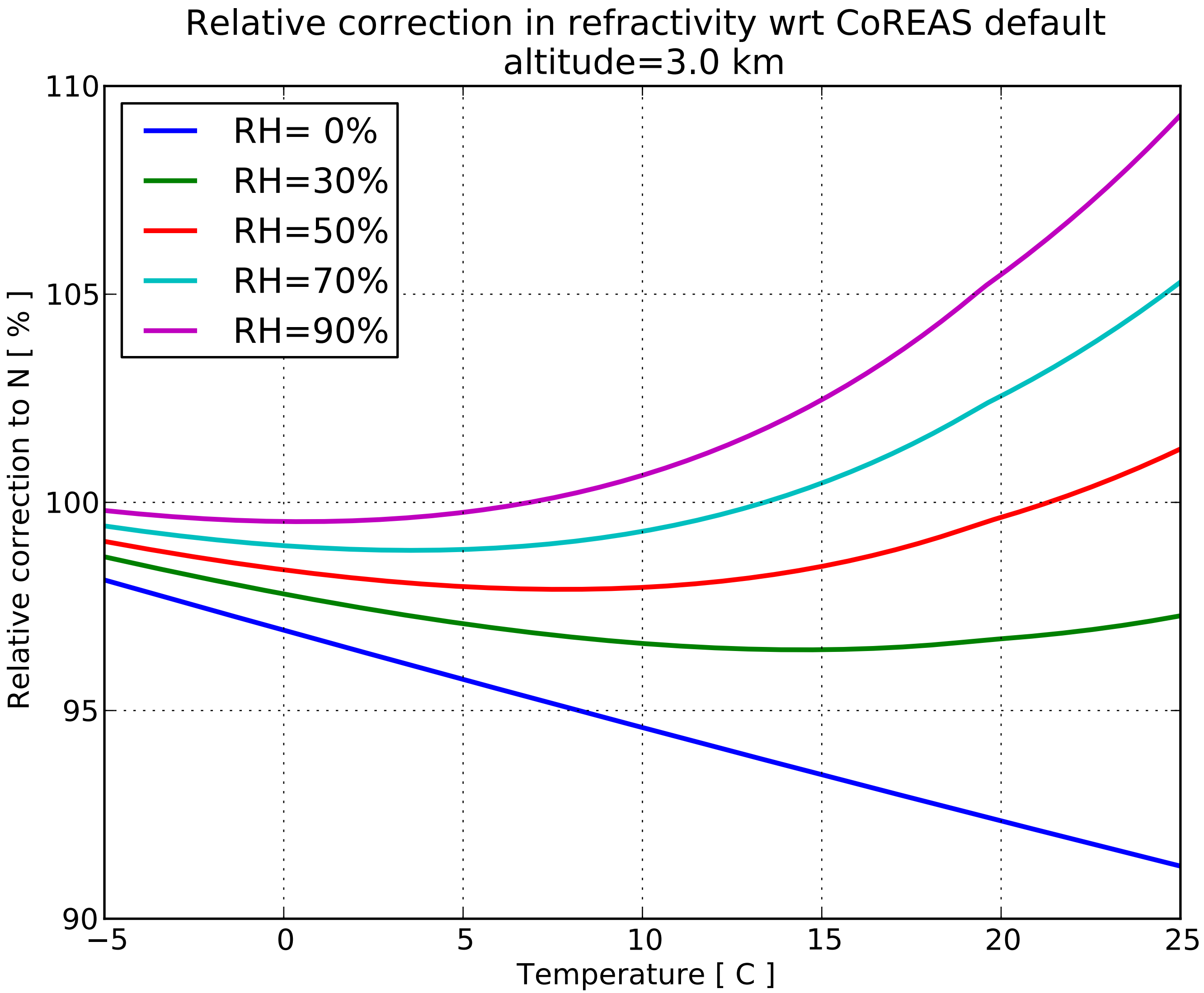


Humidity raises refractivity at all altitudes (radio)

Absolute humidity drops with altitude (colder)

Relative humidity (RH) assumed const

# Variations in refractive index



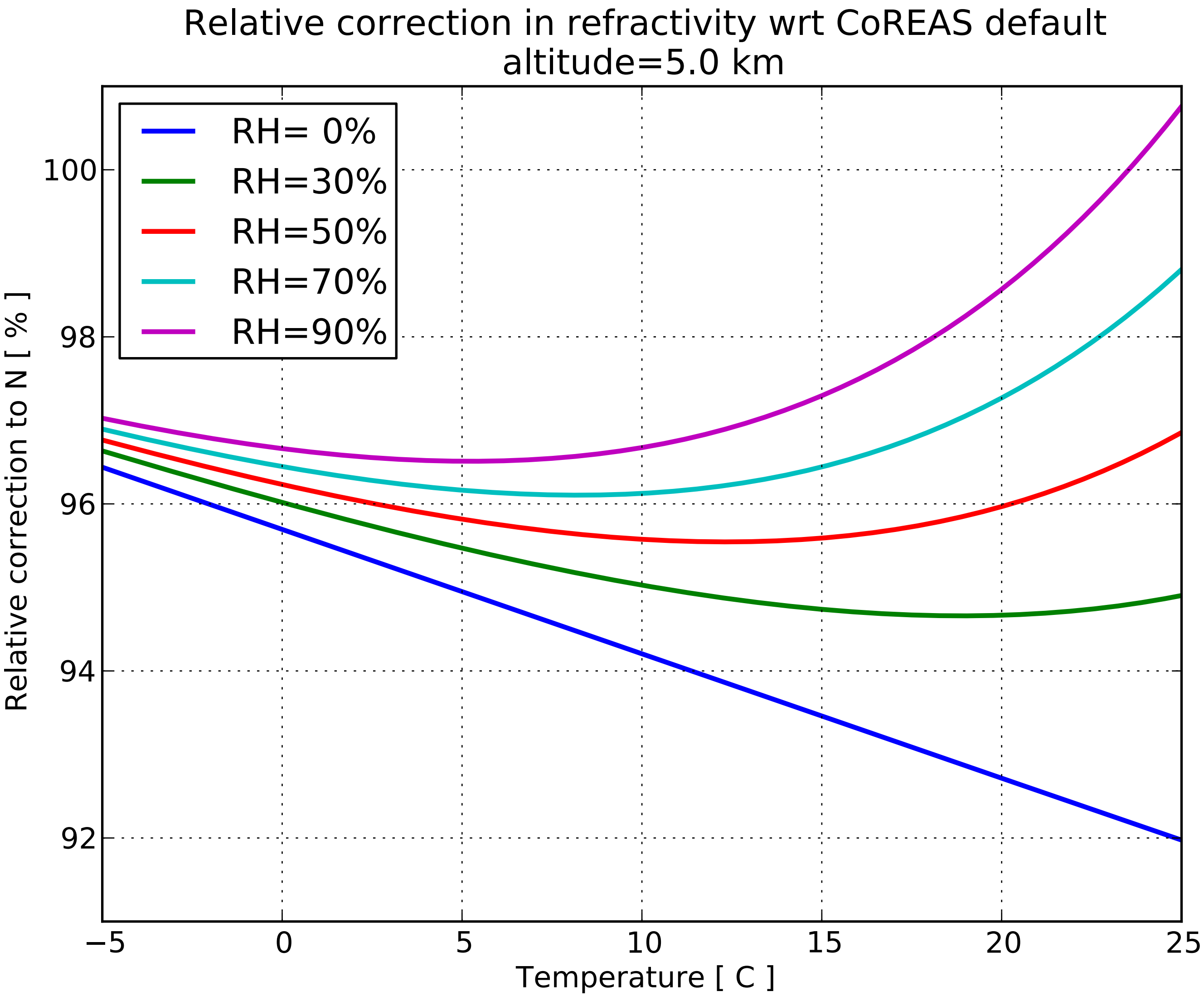
Percentage scaling of N

3 km up (zenith)

Versus ground temperature and relative humidity

RH assumed constant

# Variations in refractive index



Percentage scaling of N

5 km up
for ~45 ° shower

Systematically too low, ~ 4 %

- Cannot use one number for N at ground

# Effect of varying refractivity on Xmax measurements

- Use a fitting method as in composition analysis:

Normal N

50 simulated showers

10% higher N

50 simulated showers

take one as 'test shower'

('measured data')

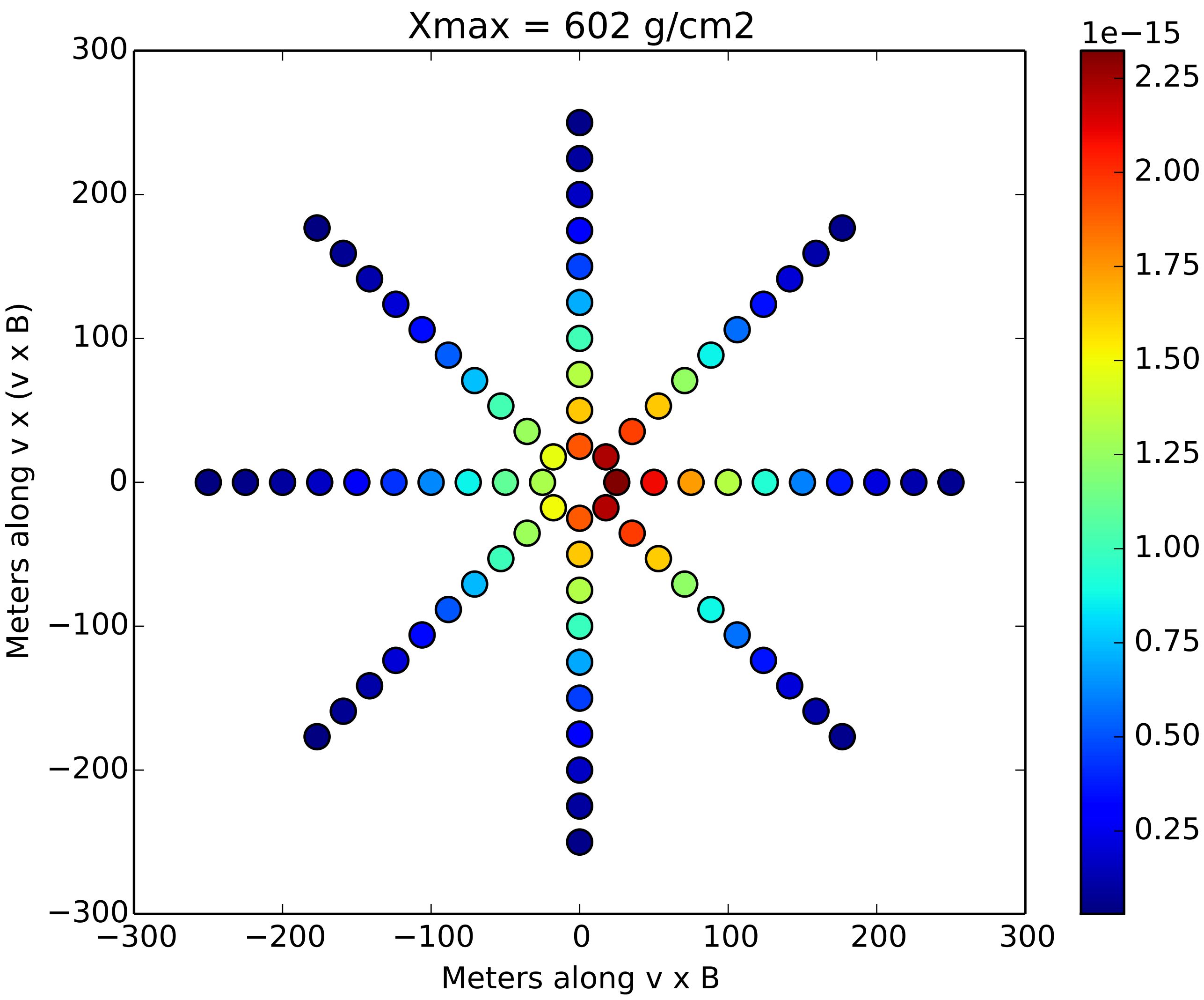
Fit 49 showers to the test shower

(lateral power distributions)

- Make plot of fit quality versus Xmax
- Minimum indicates best-fitting Xmax

Average offset over all 'test' showers

# Fitting shower LDF profiles

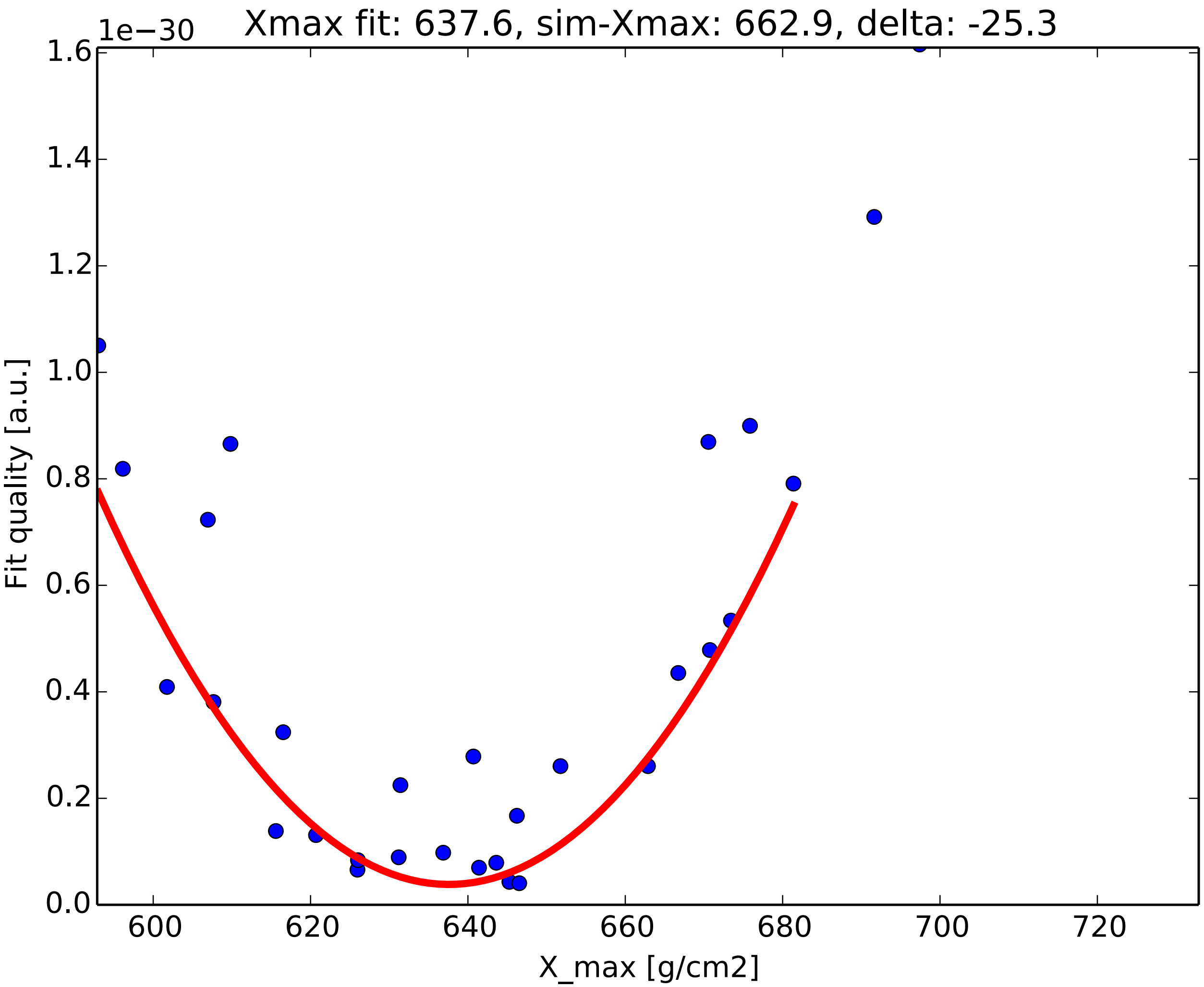


Compared antenna by antenna

Least-squares, MSE = fit quality

x 50

# Fitting Xmax

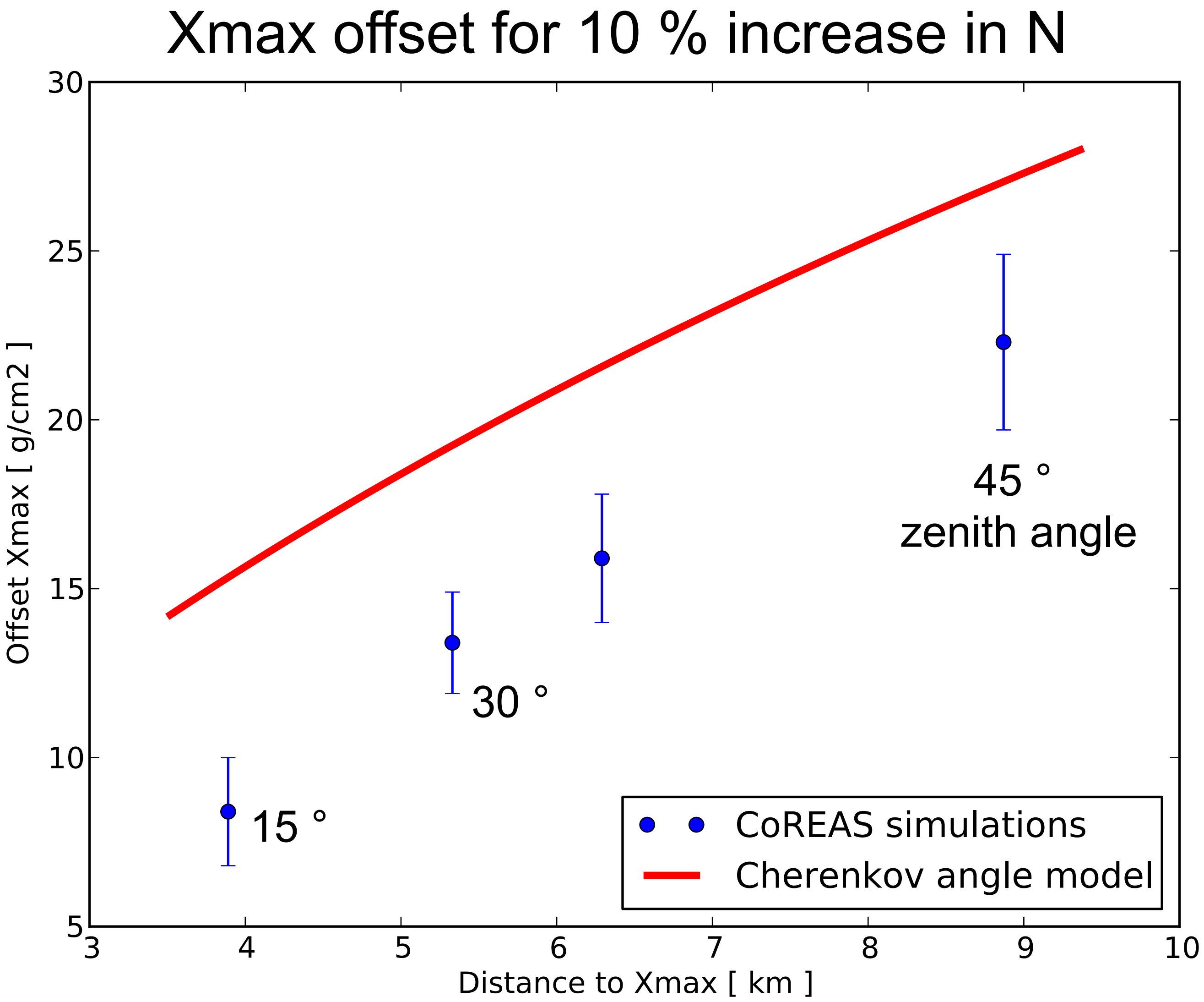


Parabolic fit, weights 1 / $y^2$ for emphasis on lower envelope

True Xmax is known (simulation)

Fitted Xmax measures the offset from varying refractivity

# Results



Rough model fits qualitatively

Up to ~ 25 % scaling

Cherenkov angle dependence only

Standard atmosphere

No free parameters!

Significant effect

cf. 16 g/cm$^2$ precision in composition analysis

# Conclusion

- Atmospheric refractivity is one of the major systematic uncertainties in determining Xmax
- Bias of 0.9 to 2.2 g/cm$^2$ per 1 % change in N
  - About 4 % variability realistic at Xmax level
- A simple model describes offsets qualitatively
  - Cherenkov angle scaling, standard atmosphere
- Not fully fixable through only ground level refractivity / one standard atmosphere
  - Would need CoREAS update, and use local weather data