EISCAT SCIENCE EXAMPLES: D-REGION RESEARCH CHEMICAL EFFECT ON OZONE BY PULSATING AURORA

ISR SUMMER SCHOOL
24–30 July 2016, Sodankylä

Esa Turunen[1,3], Antti Kero[1], Pekka T. Verronen[2], Yoshizumi Miyoshi[3], Shin-ichiro Oyama[3], Shinji Saito[3]

[1]Sodankyla Geophysical Observatory, University of Oulu, Finland
[2]Earth Observation, Finnish Meteorological Institute, Helsinki, Finland.
[3]Institute of Space-Earth Environmental Research, Nagoya University, Japan

Does Space Weather affect Climate?

PHOTO: AURORA AT SODANKYLÄ, FINLAND ON 02.04.2016 AT 24:00

ISEE Nagoya university Institute for Space-Earth Environmental Research

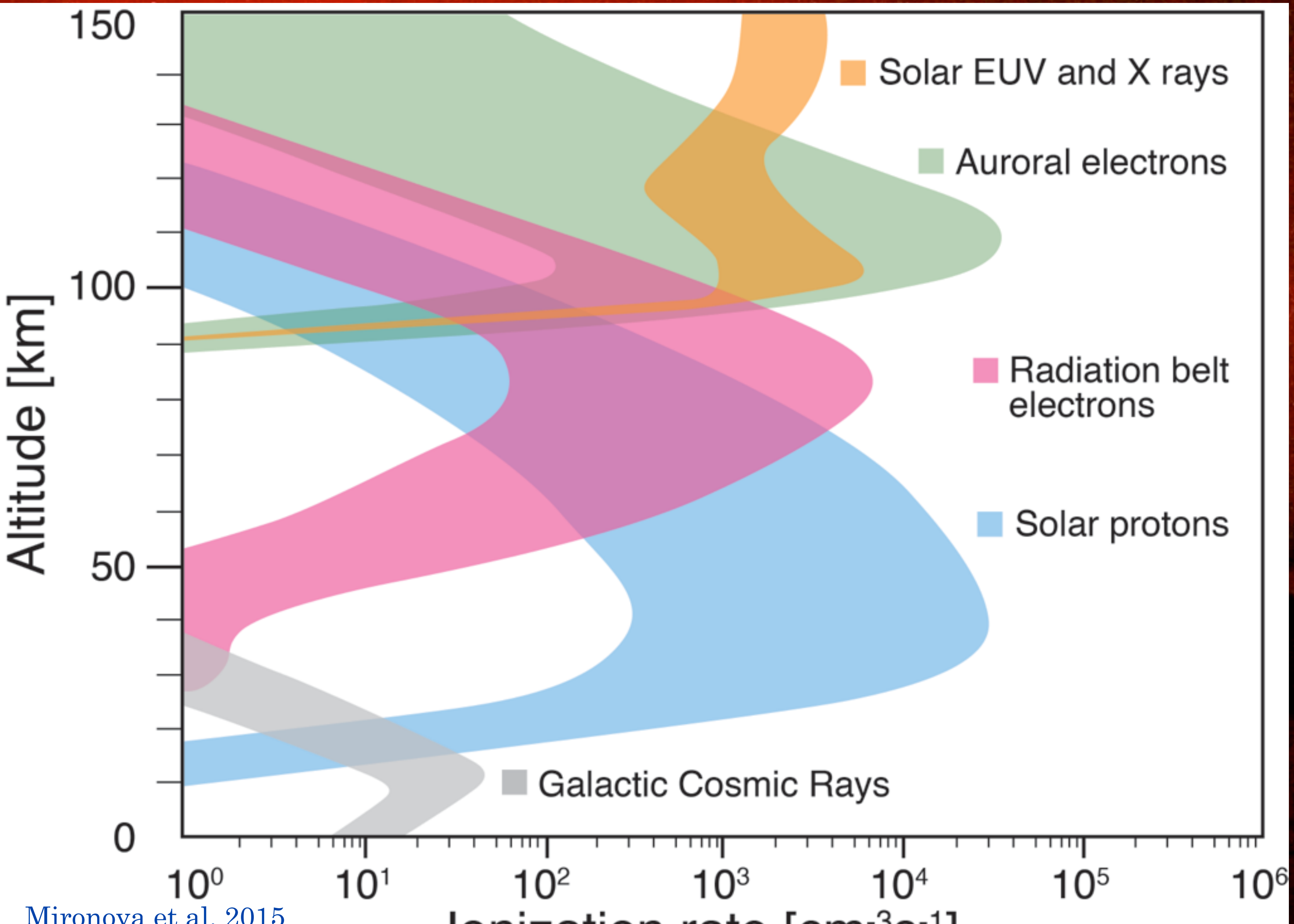
Finnish Meteorological Institute

Sodankylä Geophysical Observatory
University of Oulu

Interestingly:

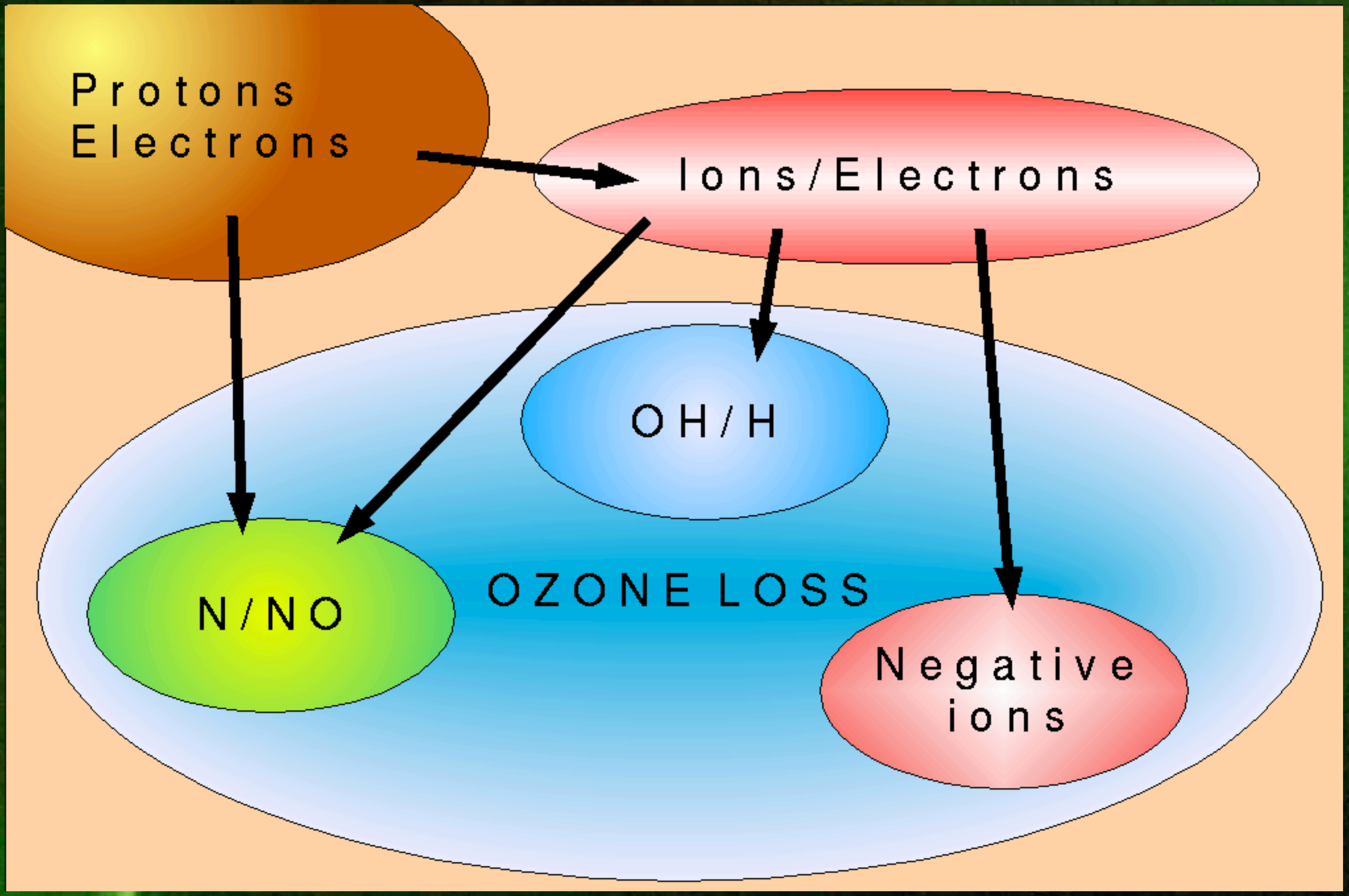
Degree of ionisation is very low in the upper atmosphere, specially in the mesosphere-lower thermosphere region

Normally < 10^{-6}

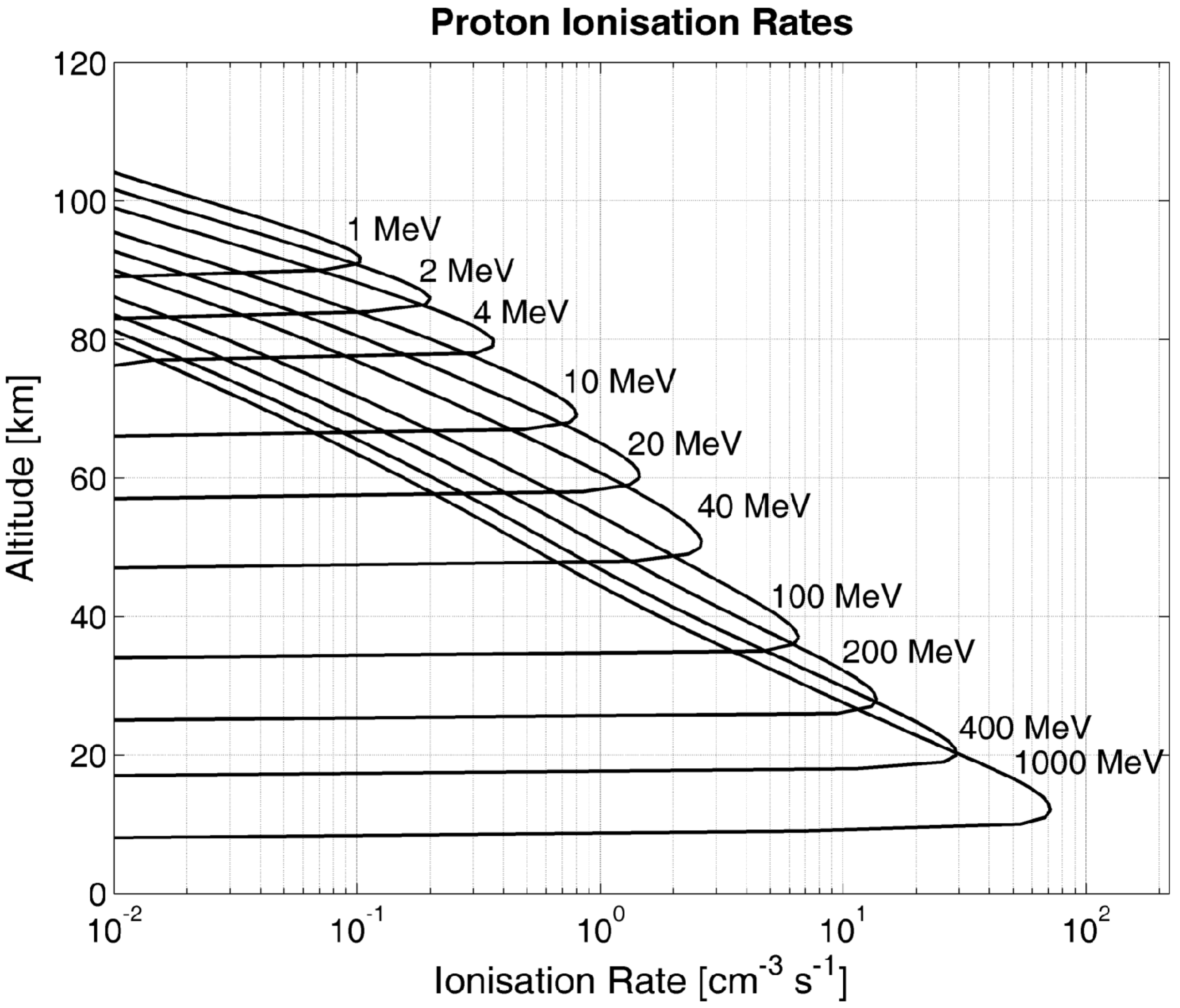


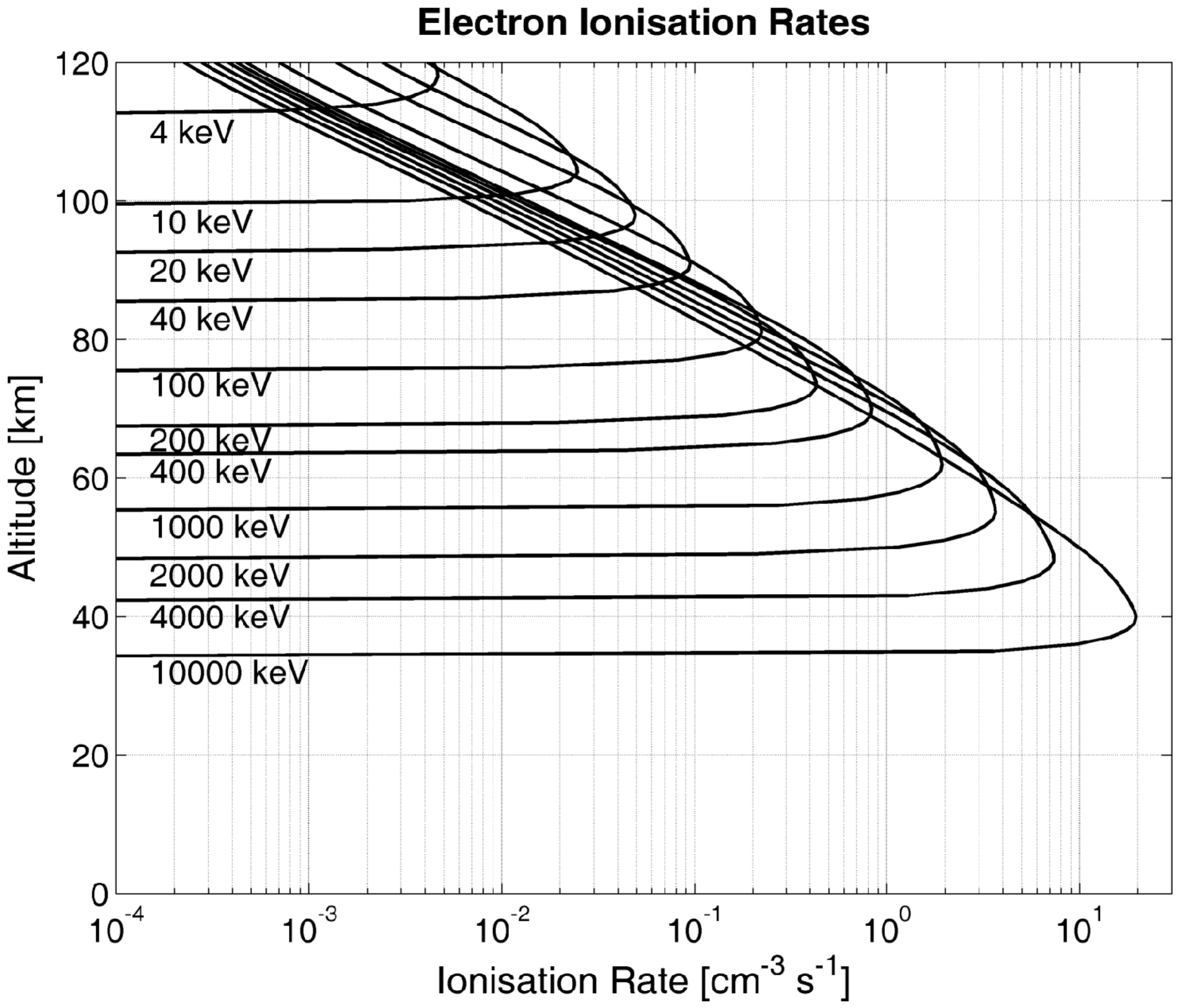
Mironova et al. 2015
adapted from Baker

However, similarily as trace gases affect the atmospheric properties, also coupling of ion and neutral chemistry turns out to be important.



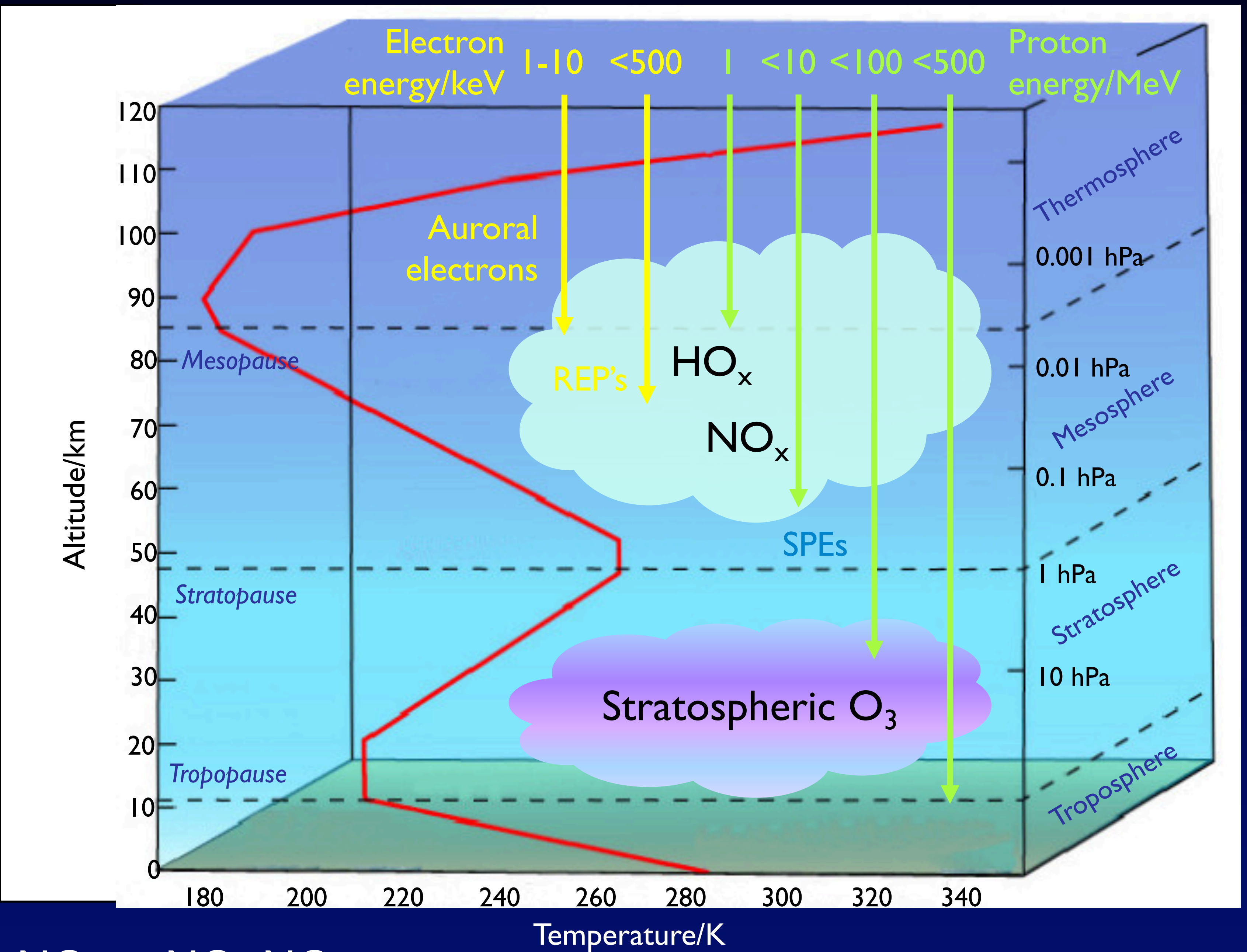
High-energy particles penetrate deep into the atmosphere





From Turunen et al., 2008

The impact of particle precipitation on neutral atmosphere



Particle precipitation

↓

Production of NO_x and HO_x

↓

Destruction of mesospheric and upper stratospheric O_3

↓

Change in radiation balance of mesosphere & stratosphere

↓

Stratosphere-troposphere coupling

↓

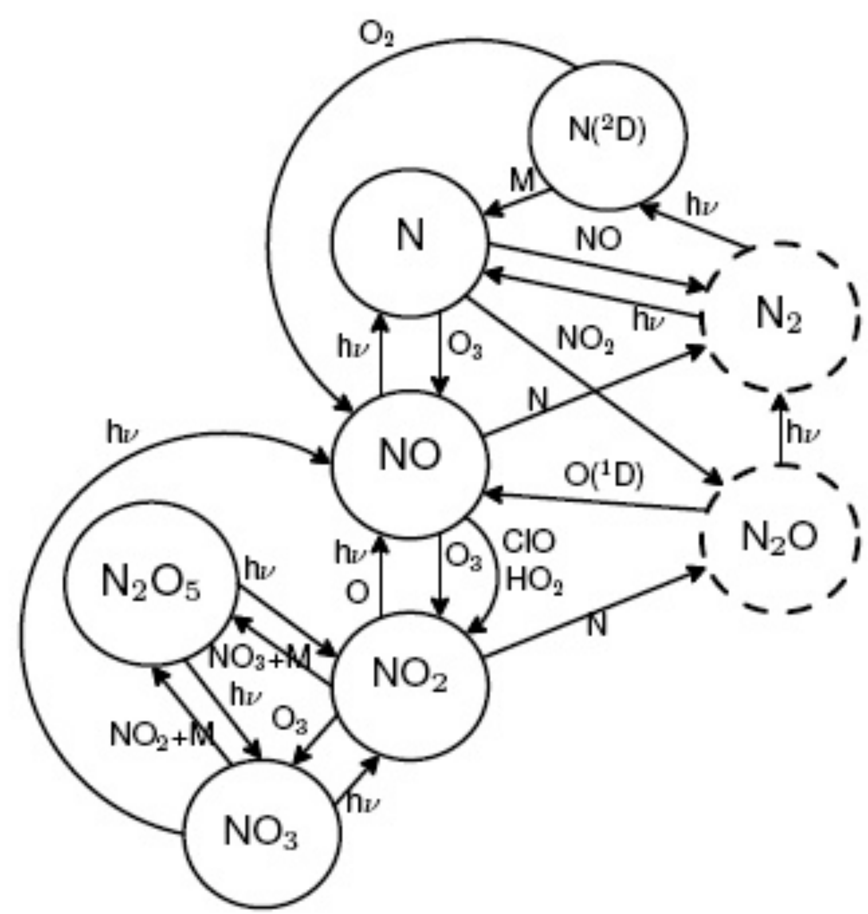
“Climate?”

NOx = NO, NO_2
NOy = NOx + many other N species
HOx = H, OH, HO_2

figure by C. Rodger

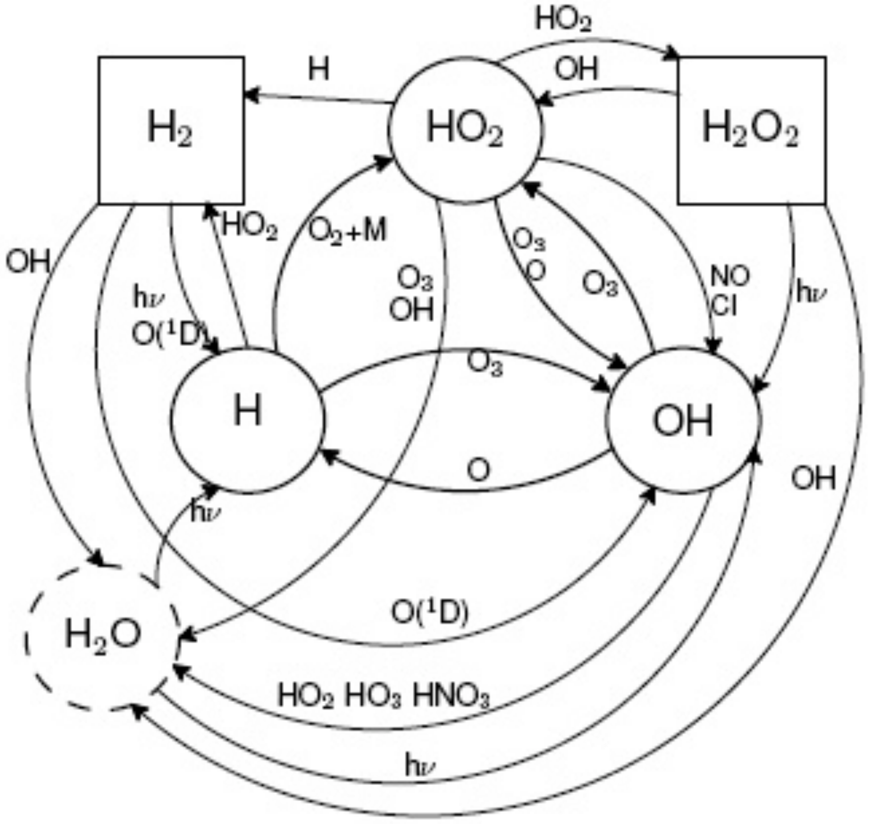
Odd nitrogen

- $NO_x = N + NO + NO_2$
- Simply in lower thermosphere
  - $N(^2D)+O_2$->NO+O
  - $N(^4S)+O_2$->NO+O
  - $NO+N(^4S)$->N_2+O
  - NO+hv->$N(^4S)$+O
  - in stratosphere
    - $N_2O+O(^1D)$->2NO
- lifetime order of 1 day
- absence of sunlight
  - absence of mesospheric O
  - NO, NO2 extremely long-lived
    - polar night



Odd hydrogen

- $HO_x = H + OH + HO_2$
- created also by ion chemistry in mesosphere and upper stratosphere
- short-lived
- in-situ destruction of O_3



Energetic Particle Effects on the Atmosphere

Charged particles precipitate in the polar areas producing HO_x and NO_x in mesosphere and stratosphere

- HO_x ($H + OH + HO_2$)
- Short lifetime
- HO_x cycle upper-stratosphere – lower-mesosphere

$$OH + O_3 \rightarrow HO_2 + O_2$$
$$HO_2 + O \rightarrow OH + O_2$$
$$\text{Net: } 2O_x \rightarrow 2O_2$$

Ionpair production → water cluster ion production and -reactions → HO_x

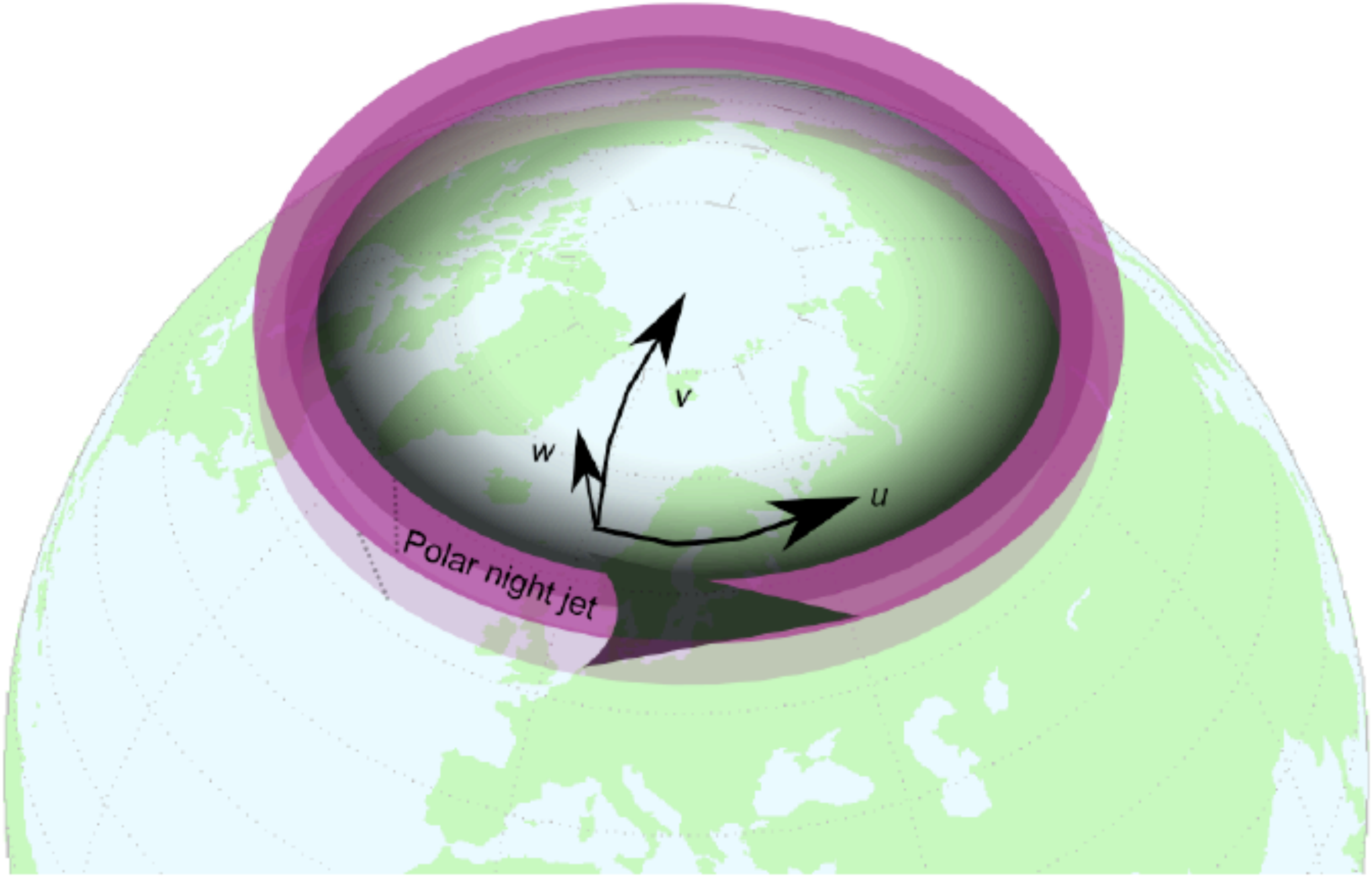
- NO_x ($N + NO + NO_2$)
- Loss: photodissociation → long lived during night → transported to stratosphere and lower latitudes
- NO_x cycle, upper-stratosphere

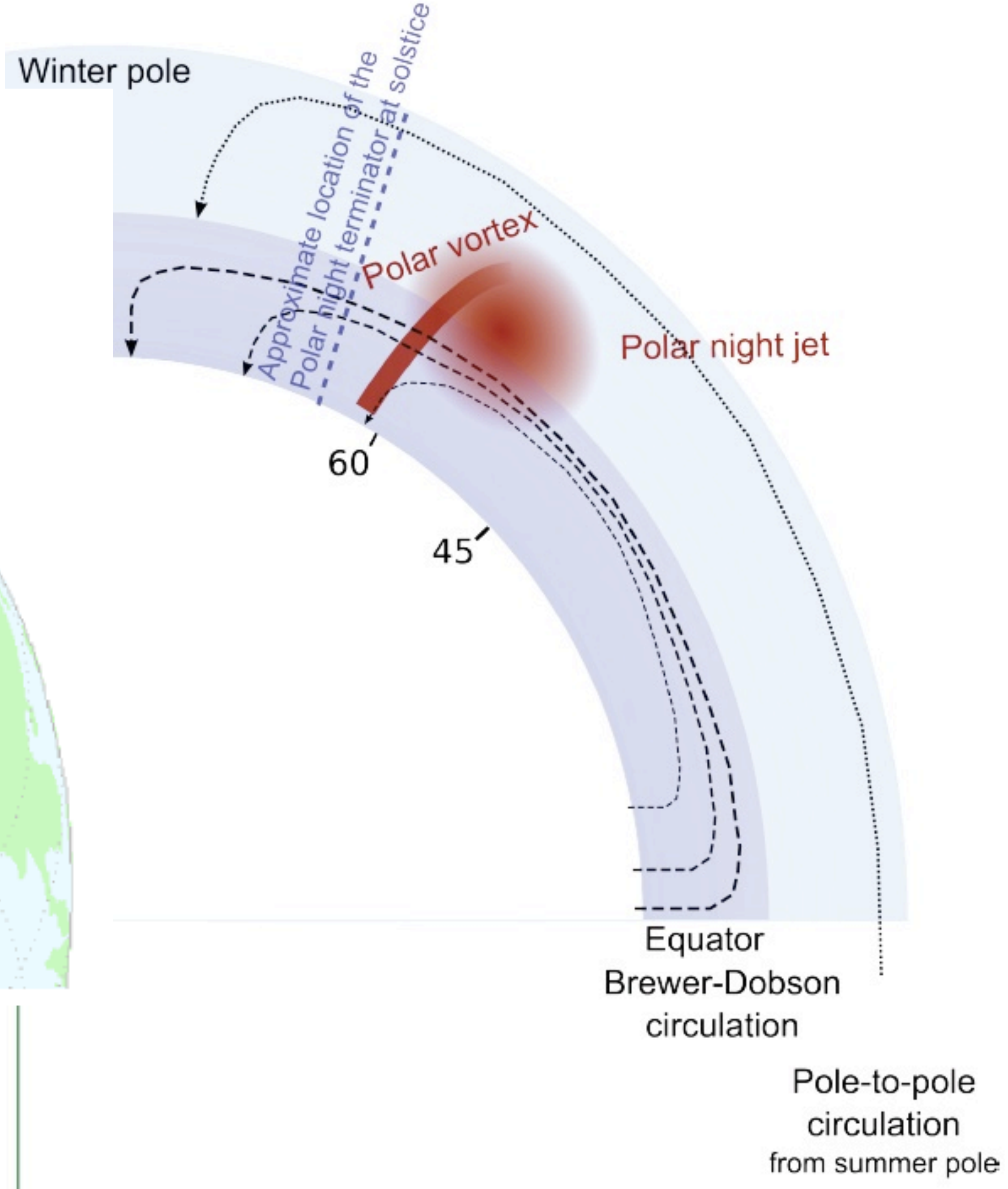
$$2(NO + O_3) \rightarrow 2(NO_2 + O_2)$$
$$NO_2 + h\nu \rightarrow NO + O$$
$$NO_2 + O \rightarrow NO + O_2$$
$$\text{Net: } 2O_3 \rightarrow 3O_2$$

p, $e^* + N_2$ → ion-chemistry → NO_x

Polar vortex

- Normally at 60° N
- Isolates the air in the polar area from rest of the atmosphere, 16km - mesosphere.





(from A. Seppälä)

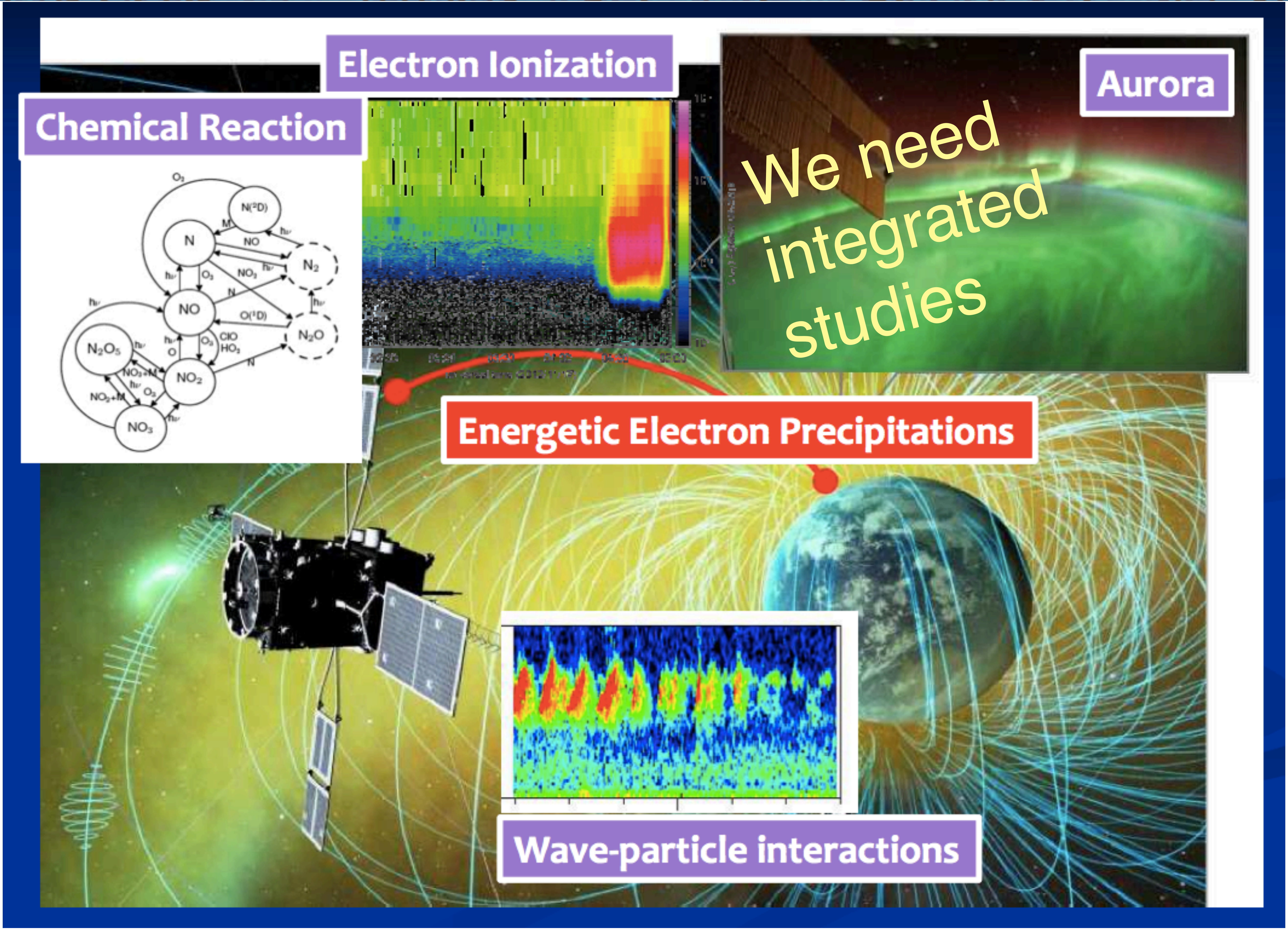
CHAMOS

Chemical Aeronomy in the Mesosphere and Ozone in the Stratosphere

CHAMOS.FMI.FI

Image: SOHO (ESA & NASA)

Geospace Environment <-> Atmosphere



Pulsating Aurora

FAST VARIATIONS IN AURORAL EMISSIONS

- Flickering aurora 3-15 Hz, up to 45 Hz (Dahlgren et al., 2014)
- Pulsating aurora 2-20 sec, often with 3 Hz modulation

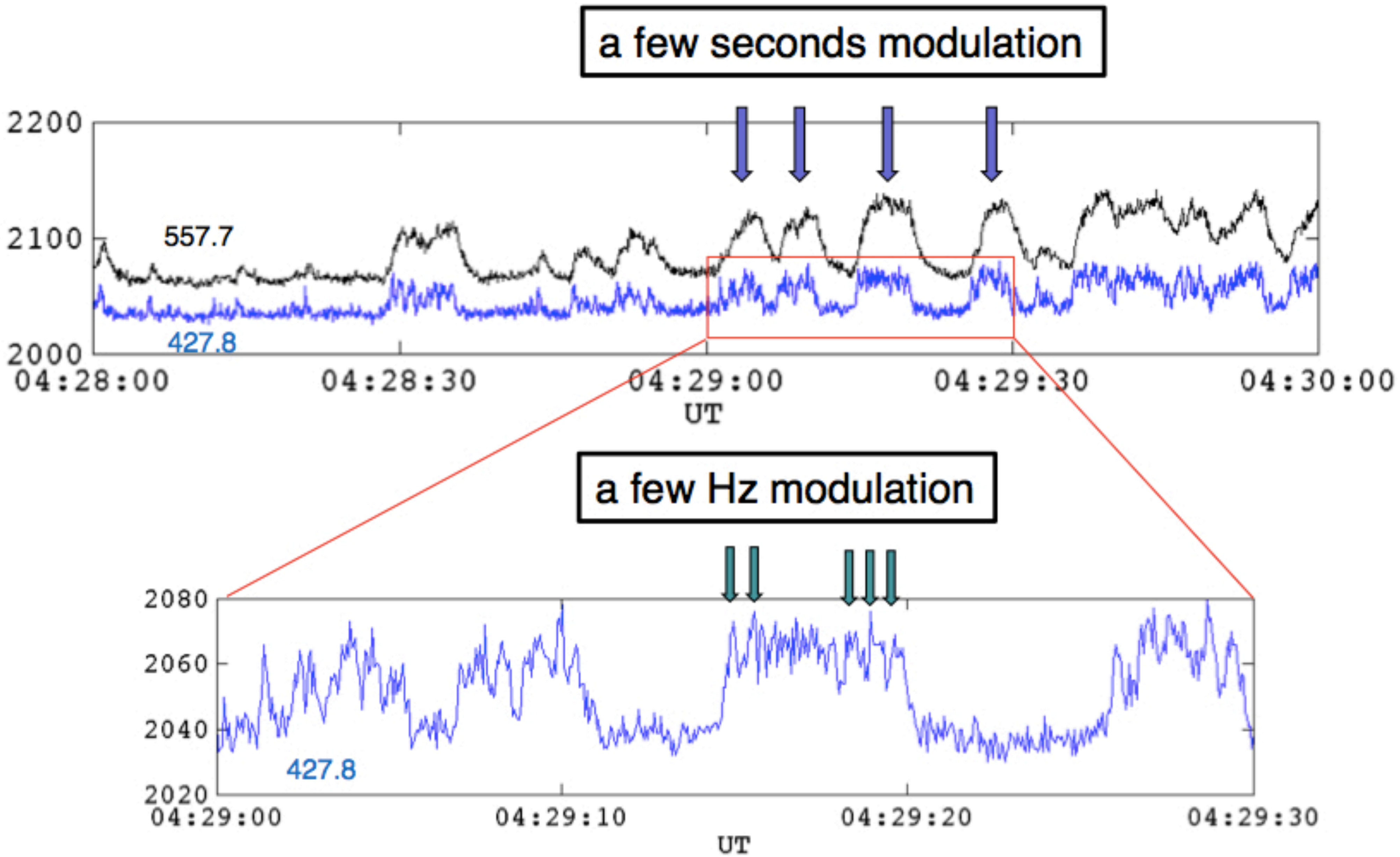
EMPHASIS OF RESEARCH SO FAR:

- What is the cause of pulsations?
- How do different frequencies coexist?
- How do thin structures relate to patches?
- etc.

Less studied: Do Pulsating Aurora make chemical effects in the atmosphere?

pulsating aurora and its temporal variations

– typical, repeatable features



auroral emission intensity measured with a photometer (20 Hz sampling rate)

ISEE Nagoya university Institute for Space-Earth Environmental Research

Slide: S-I Oyama, EISCAT_3D User Meeting 2015

Model tool SIC, 20-150 km

Impact of precipitating particles and excess ionisation:

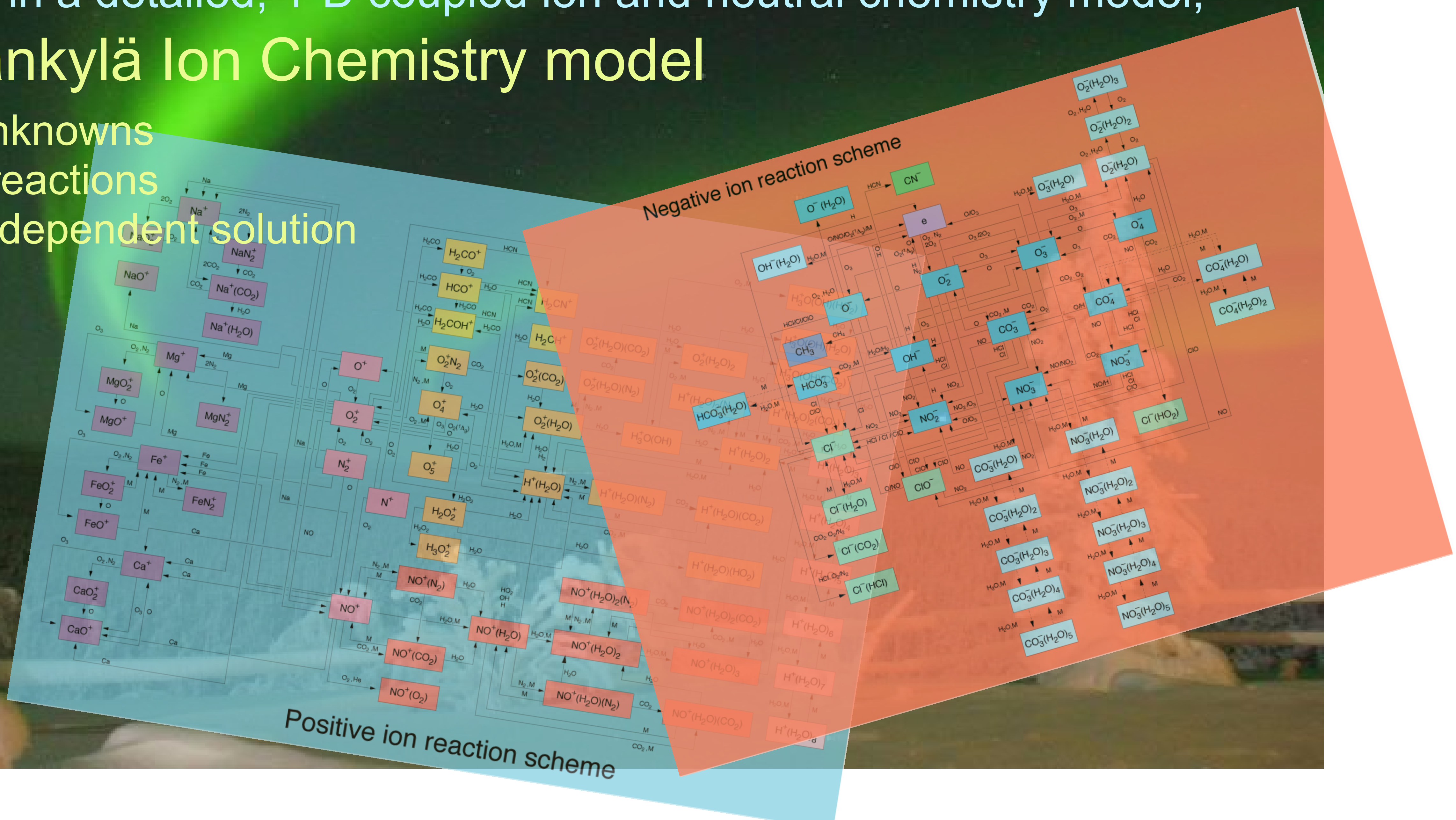
NO_x and HO_x generation,

effects on O_3

- in a detailed, 1-D coupled ion and neutral chemistry model,

Sodankylä Ion Chemistry model

- 80 unknowns
- 400 reactions
- time-dependent solution



Current version SICv8: positive ions

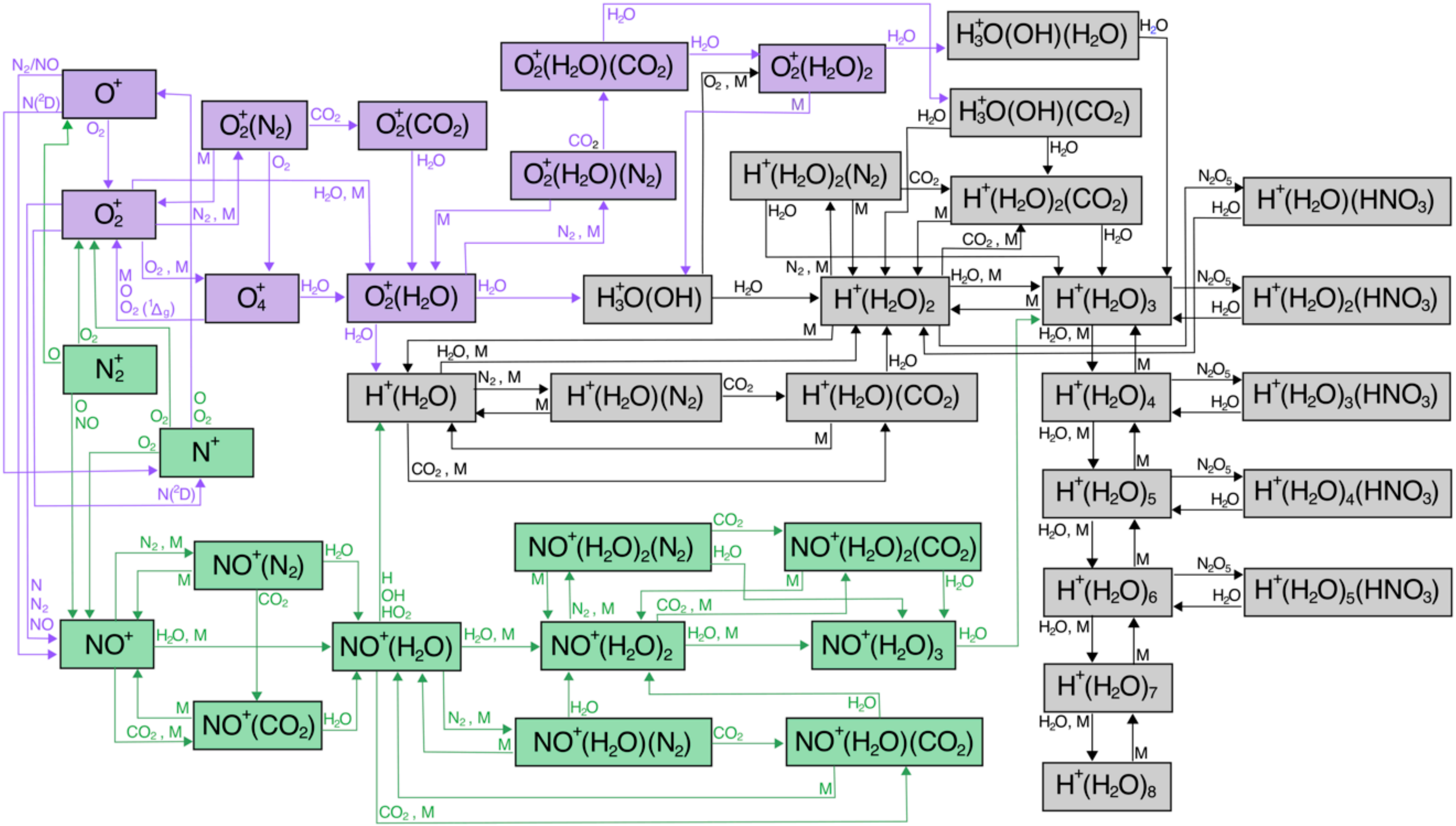


Figure: M. Andersson

Current version SICv8: negative ions

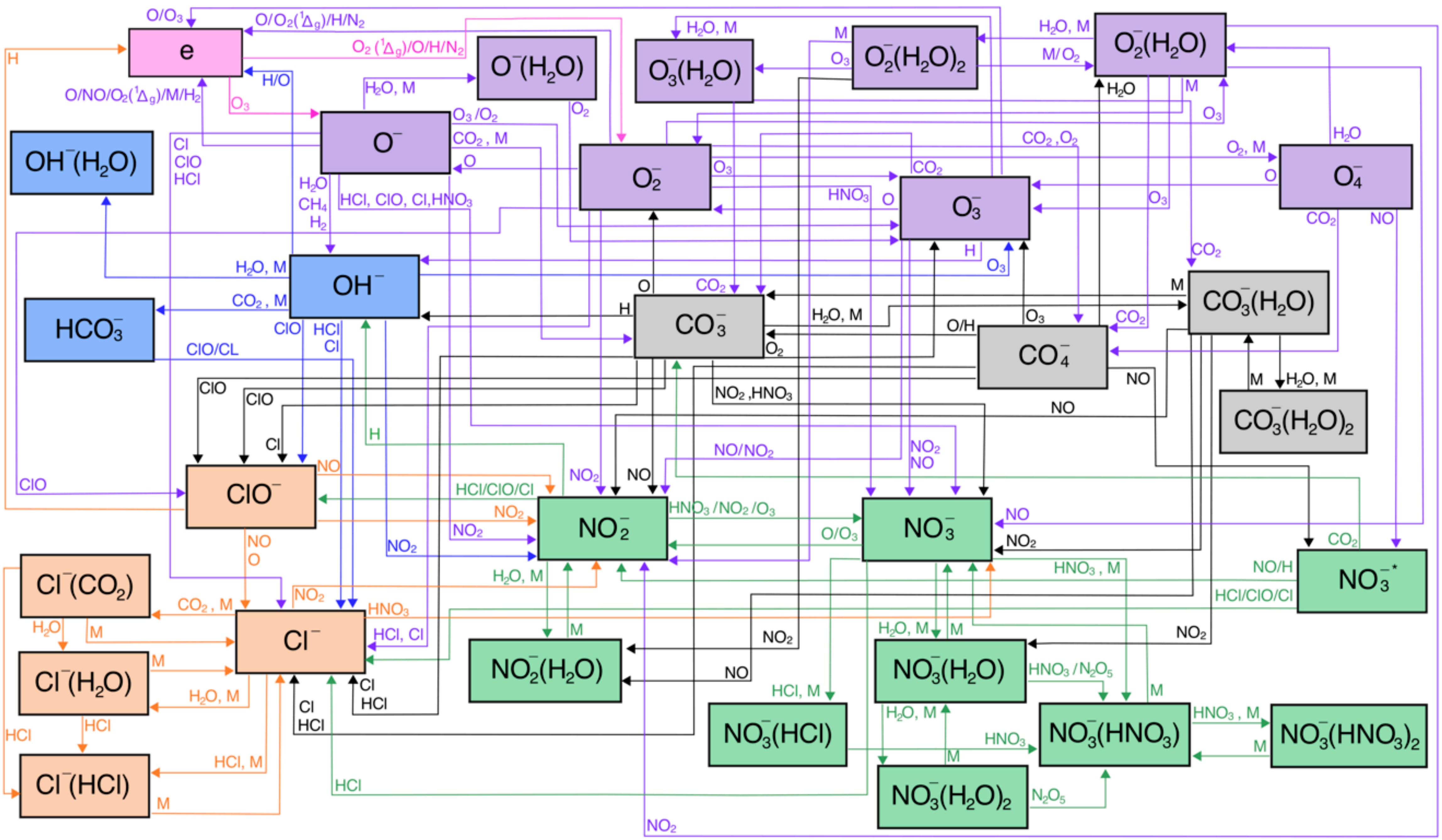


Figure: M. Andersson

Mathematical formulation

- Example for an earlier 55-ion version:

Continuity equation for ion i is (transport effects neglected):

$$\frac{\partial n_i}{\partial t} = P_i - n_i \cdot L_i \ ,$$ **where**

$$P_i = \sum_{production\,processes\,m} p_{im} \ , \quad L_i = \sum_{loss\ processes\,m} l_{im} \ .$$

Consider reaction $A^+ + B \rightarrow C^+ + D$.

For C^+: $p_{C^+m} = k[A^+][B]$ **and for** A^+: $l_{A^+m} = k[A^+][B]$.

Assume constant neutral concentrations: $p_{C^+m} = \Pi_{C^+m}\left[A^+\right]$, $l_{A^+m} = \Lambda_{A^+m}\left[A^+\right]$.

Continuity equation in matrix form is $$\frac{\partial \vec{N}}{\partial t} = \vec{F}\left(\vec{N}\right) = \Gamma\left(\vec{N}\right)\vec{N} + \vec{Q}\left(\vec{N}\right) .$$

Γ is a 55x55 matrix. Elements Π and Λ describe the production and loss rates of each ion. $\vec{N}$ is a vector containing the 55 unknown ion concentrations. $\vec{Q}$ is a vector which contains the constant primary ionization rates.

Chemical equilibrium may be solved by setting $\frac{\partial n_i}{\partial t} = 0$ **.**

The set of equations is solved using the Newton-Raphson method. For details, see ***Turunen et al.., in STEP Handbook of Ionospheric Models, 1996.***

Starting from the equilibrium solution of the ion concentrations, we advance the concentrations in time, by taking small time steps according to the expression

$$\vec{N}_{n+1} = \vec{N}_n + \Delta t \left[\vec{F}(\vec{N}_n) + \left.\frac{\partial \vec{F}}{\partial \vec{N}}\right|_{\vec{N}=\vec{N}_n} \cdot \left(\vec{N}_{n+1} - \vec{N}_n \right) \right],$$

where the elements ϕ_{ij} **of the matrix**

$$\left.\frac{\partial \vec{F}}{\partial \vec{N}}\right|_{\vec{N}=\vec{N}_n}$$

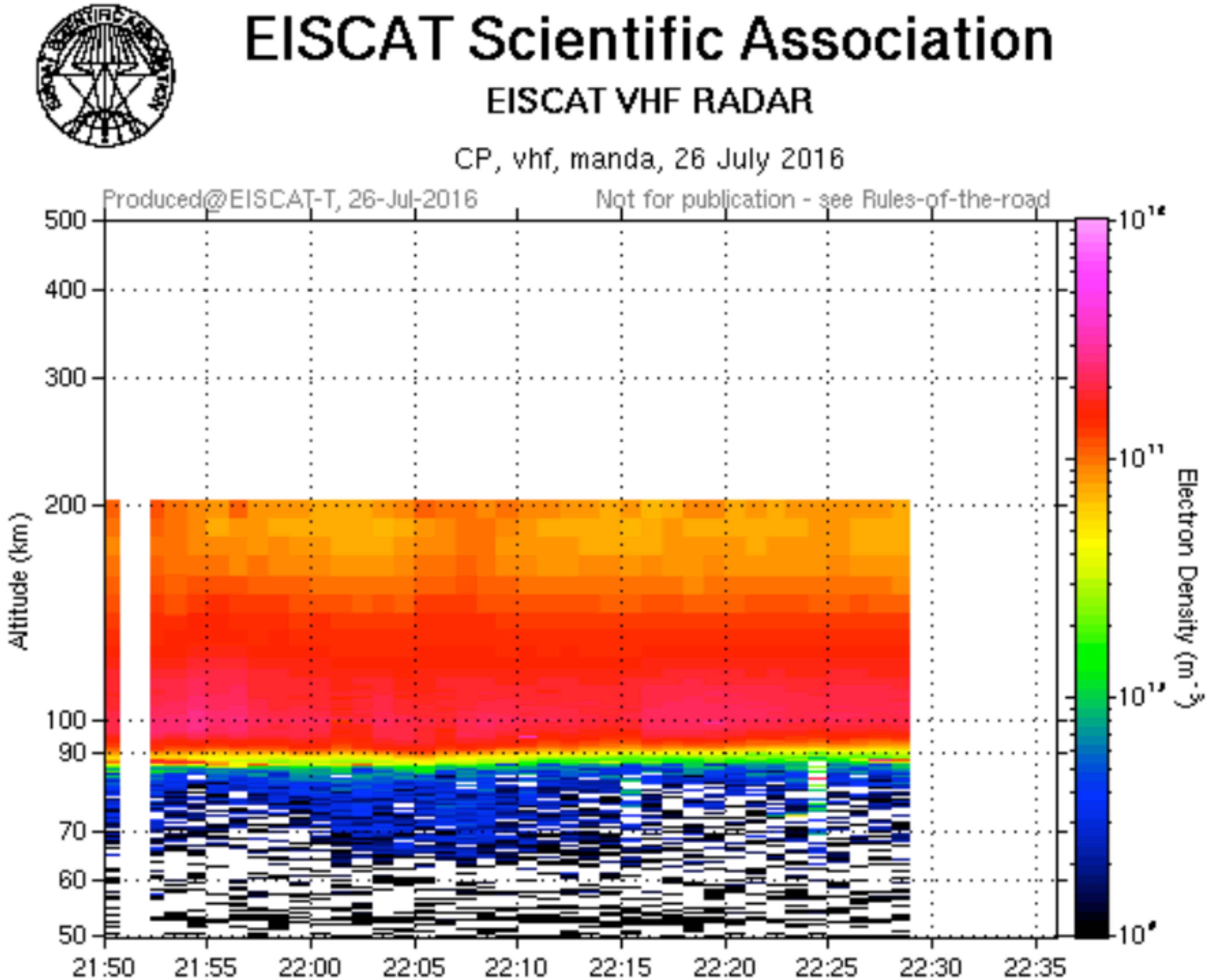
are the partial derivatives

$$\phi_{ij} = \left.\frac{\partial f_i}{\partial n_j}\right|_{\vec{N}=\vec{N}_n} .$$

The expression above is a set of linear equations, which has to be solved for each time step.

VHF Radar, Tromsø

Student exp 26.7.2016, ISR 2016 School

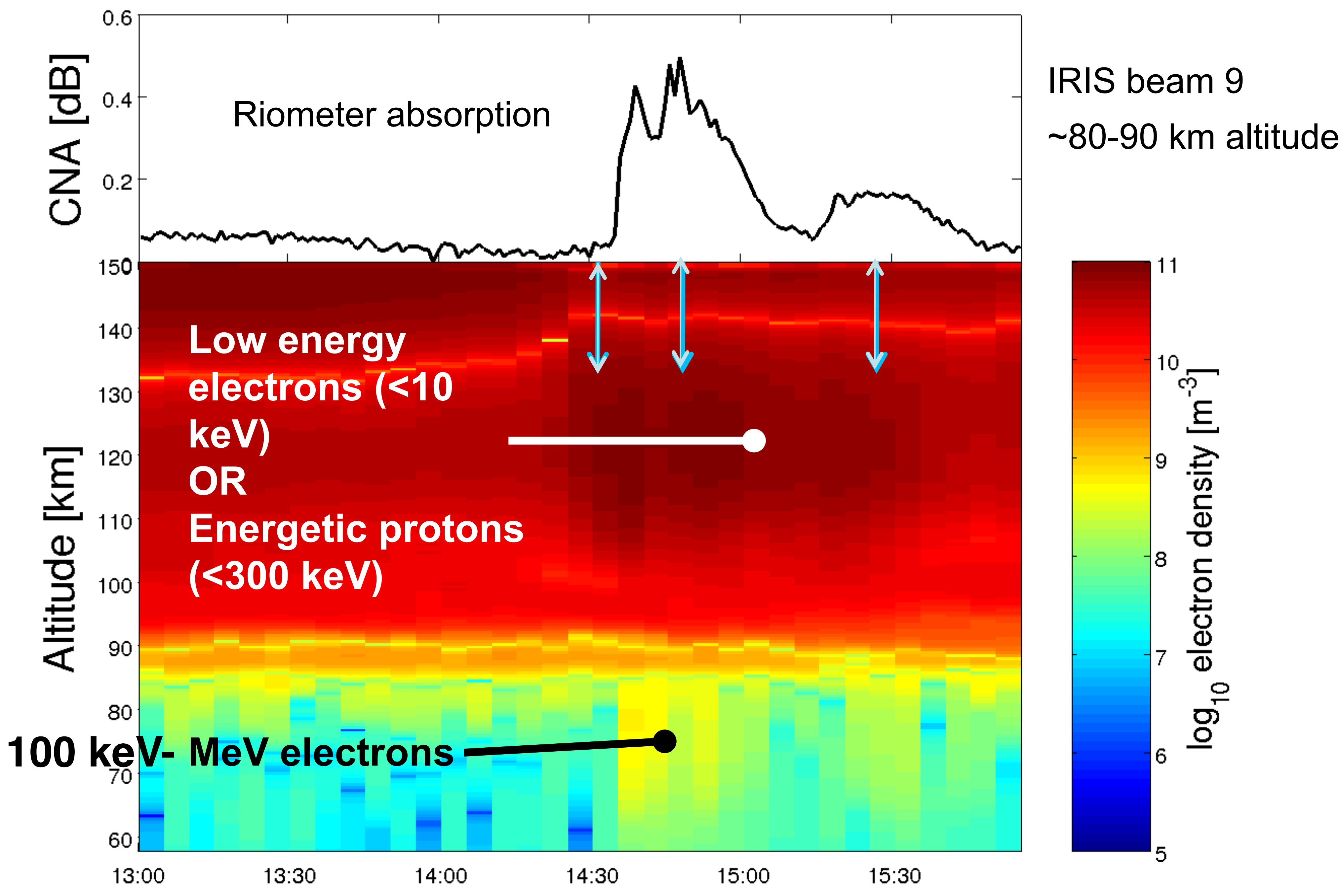


Enhancement of ionisation at 70-90 km altitude

Another manda experiment using EISCAT VHF:

Slide by M. Clilverd, presented in EISCAT_3D Users Meeting, Uppsala, 2012

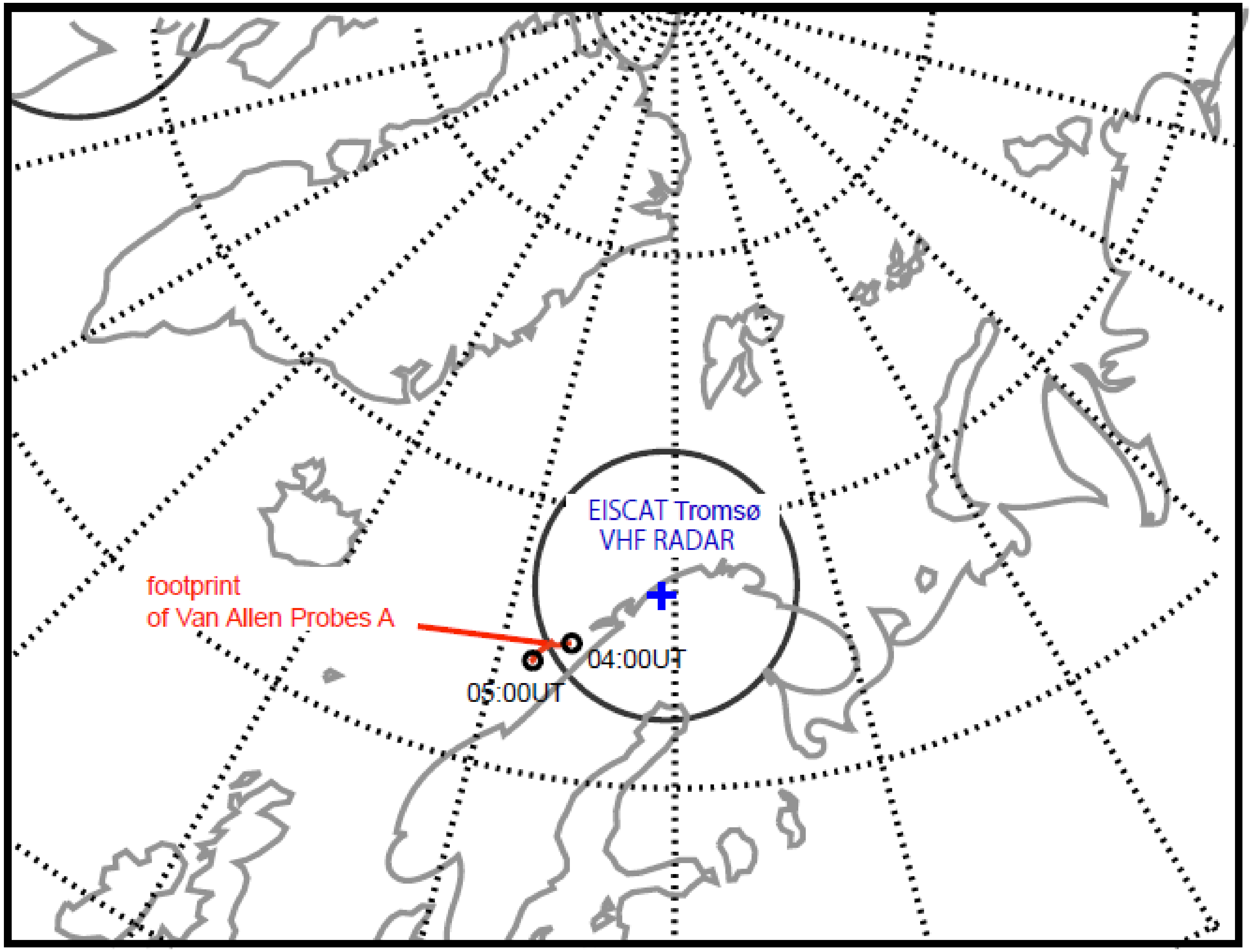
31 July 2009 – EISCAT VHF - MANDA



Thanks to Andrew Kavanagh

Yet another manda experiment using EISCAT VHF:

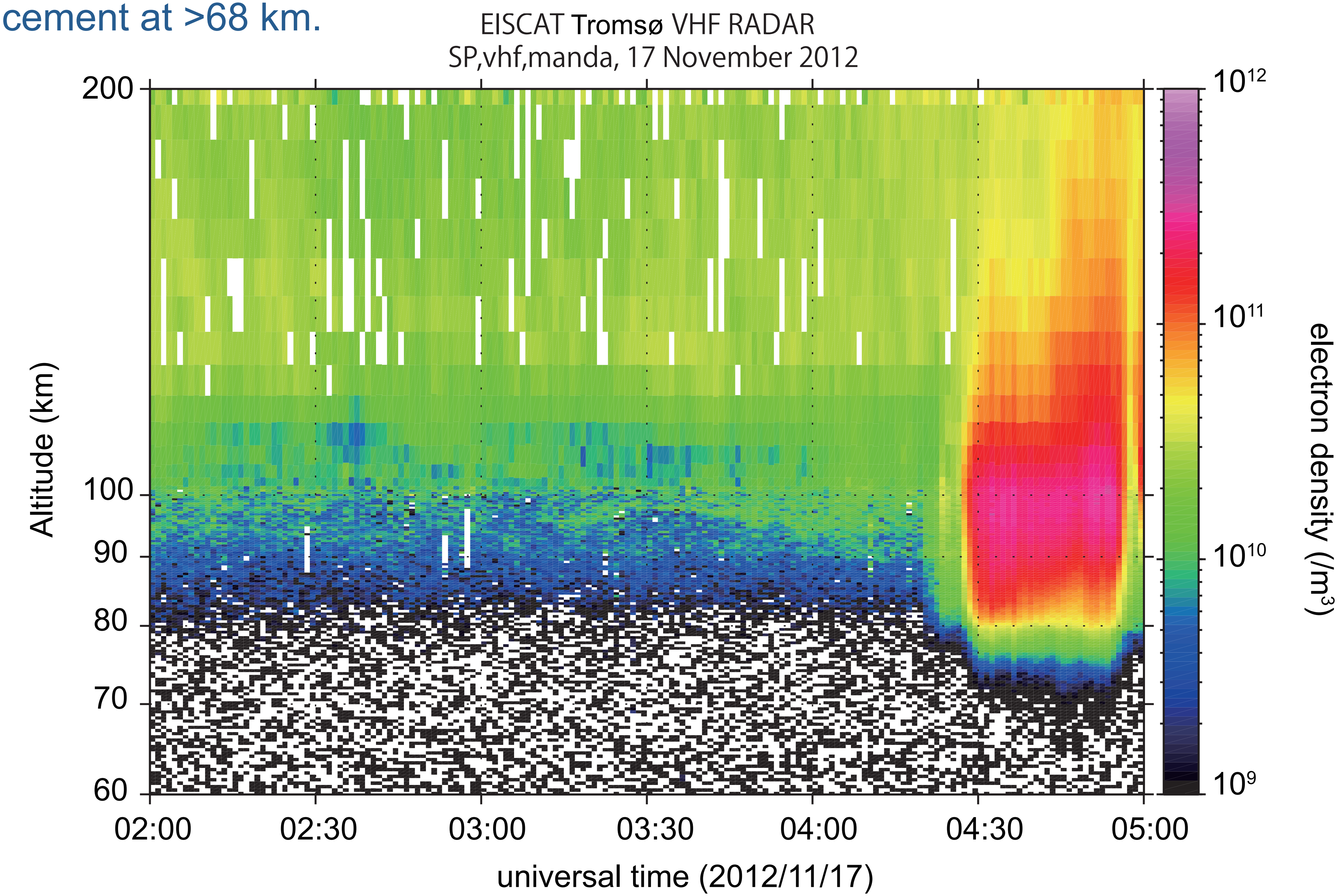
Geometry of observations: Van Allen Probe, with footprint overpassing Tromsø



17 NOVEMBER 2012

EISCAT RADAR, PULSATING AURORA *(MIYOSHI ET AL. 2015)*

A comparison of the electron density profiles for the periods both with and without the pulsating aurora reveals that the EISCAT VHF radar detected clearly electron density enhancement at >68 km.

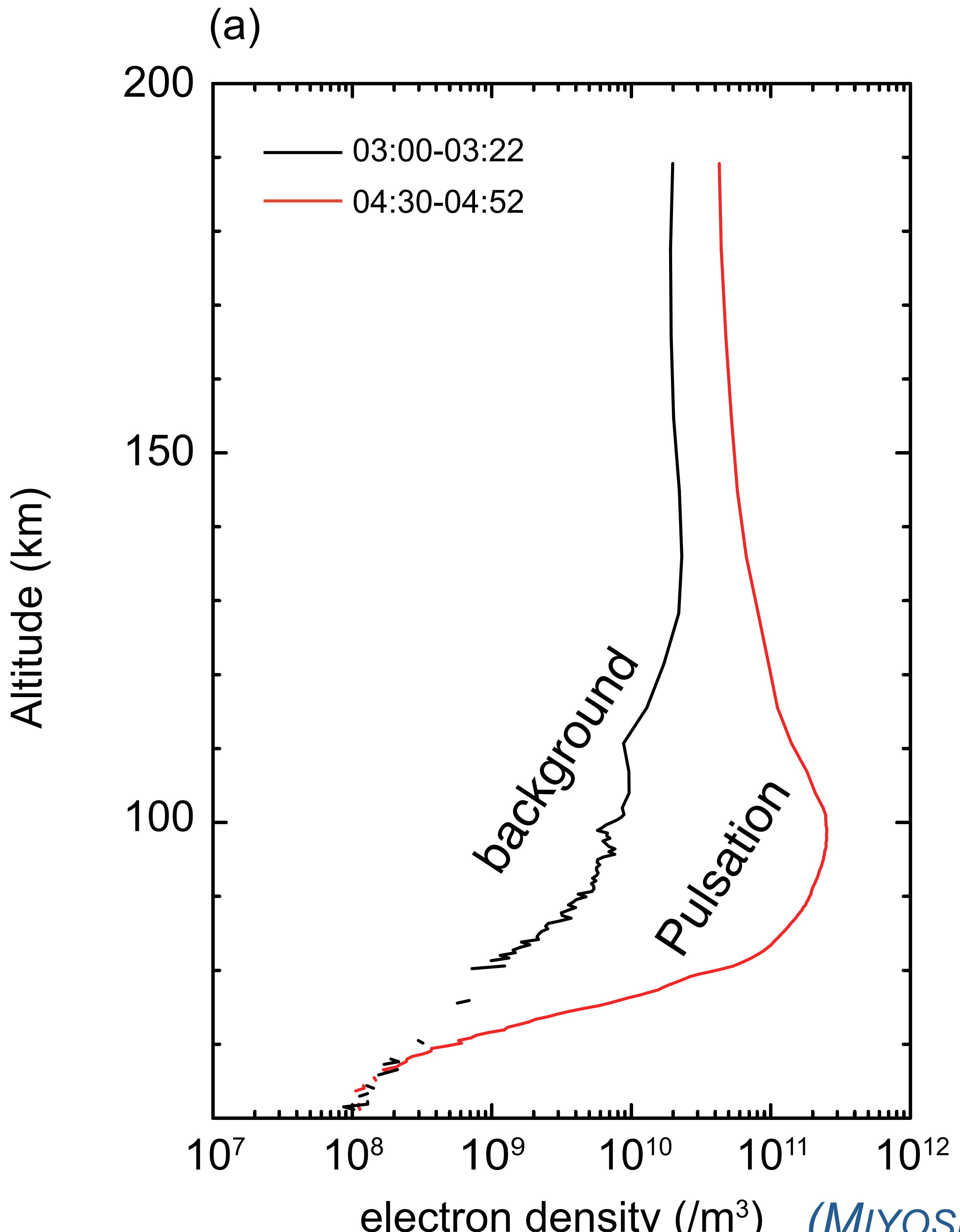


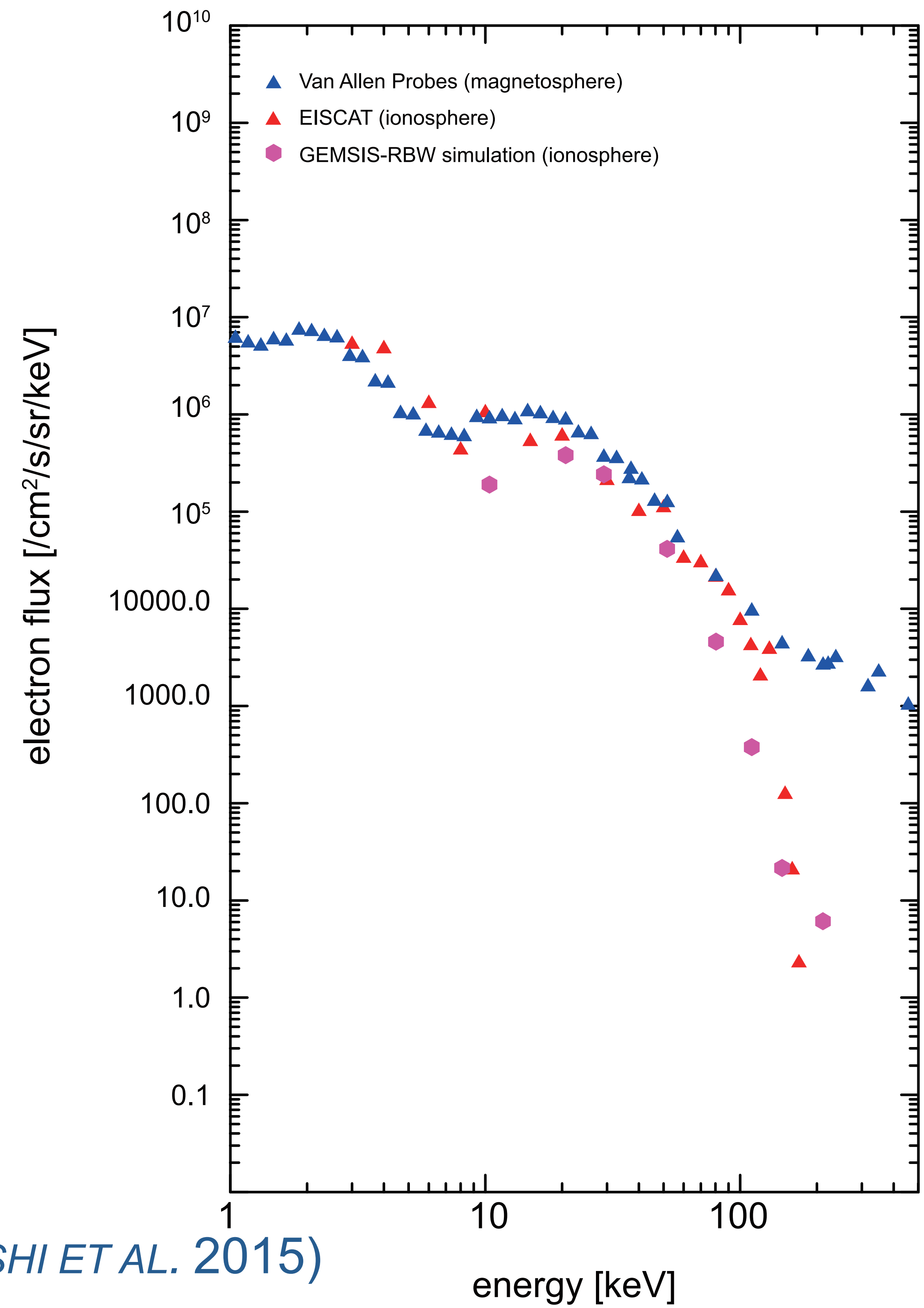
Nagoya university
Institute for Space-Earth Environmental Research

Finnish Meteorological Institute

Sodankylä Geophysical Observatory
University of Oulu

NE PROFILE CAN BE INVERTED TO ELECTRON SPECTRUM



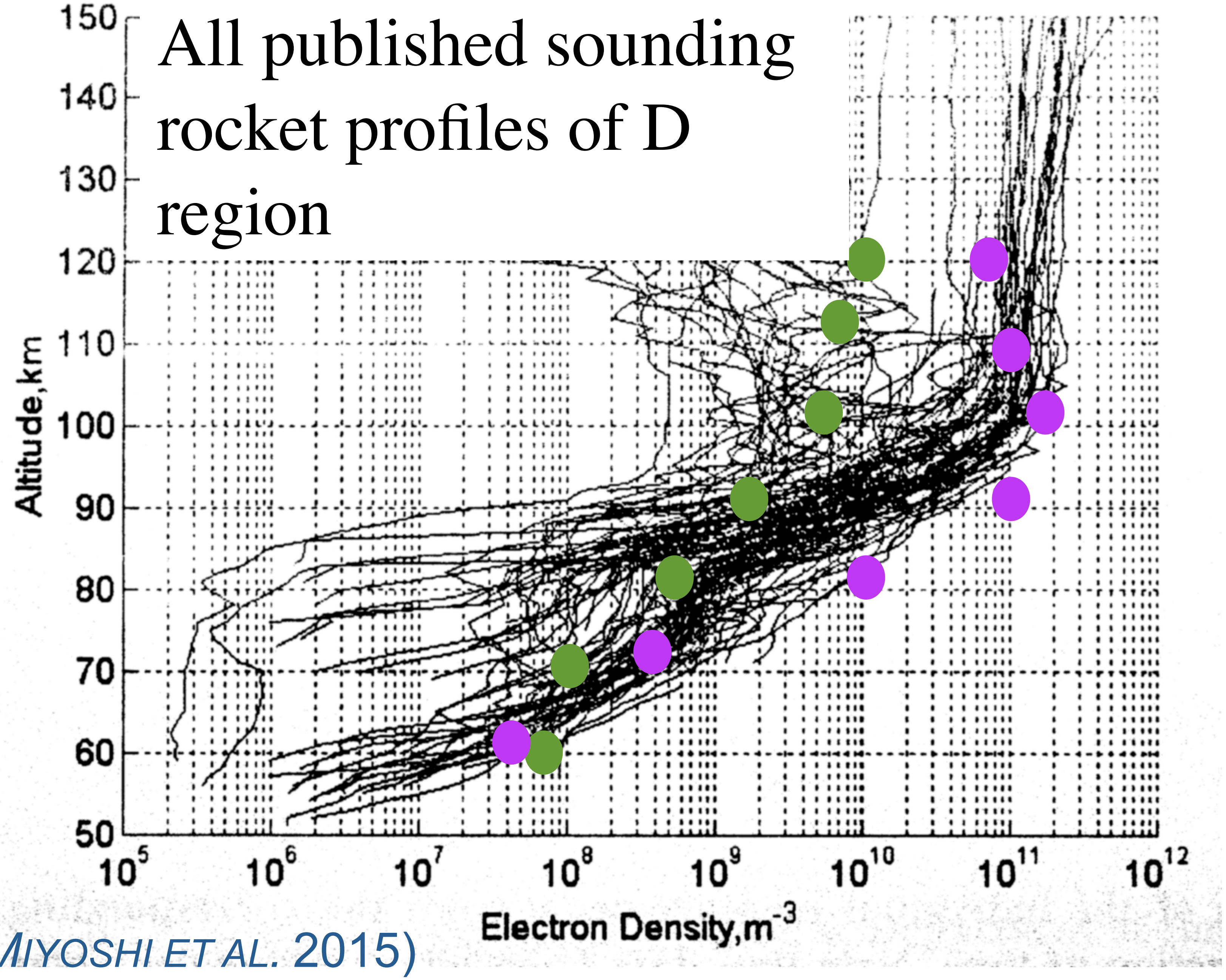


(MIYOSHI ET AL. 2015)

Variability of the lower ionosphere

- D-region variations
  - day/night
  - [NO] variability
  - electron precipitation
    - Aurora
    - Medium to high-energy electrons
    - Relativistic electrons
  - proton precipitation
    - solar proton events
  - X-rays
    - solar flares
    - bremsstrahlung
  - TLE's
    - sprites, blue jets, elves, gigantic jets
  - TGF's
  - Galactic gamma ray bursts

1-2 orders of magnitude < 80 km => HOx



(MIYOSHI ET AL. 2015)

● Pulsation

● Background

[from Friedrich and Torkar, 2001]

SIC MODEL WITH 1 MIN TIME RESOLUTION, FIT TO EISCAT NE

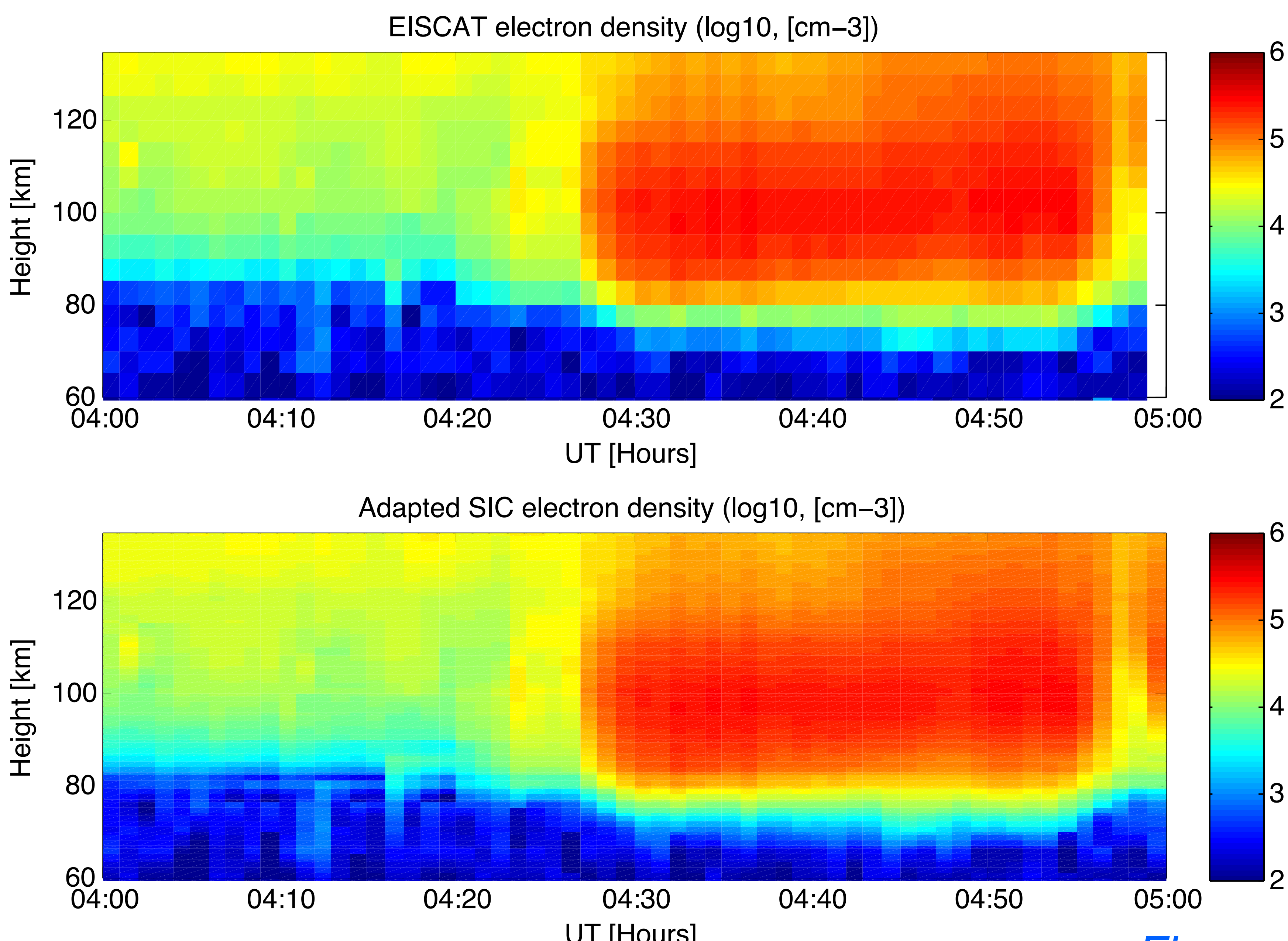


Figure by A. Kero, 2015

Inverting EISCAT Ne to Precipitating electron Spectrum

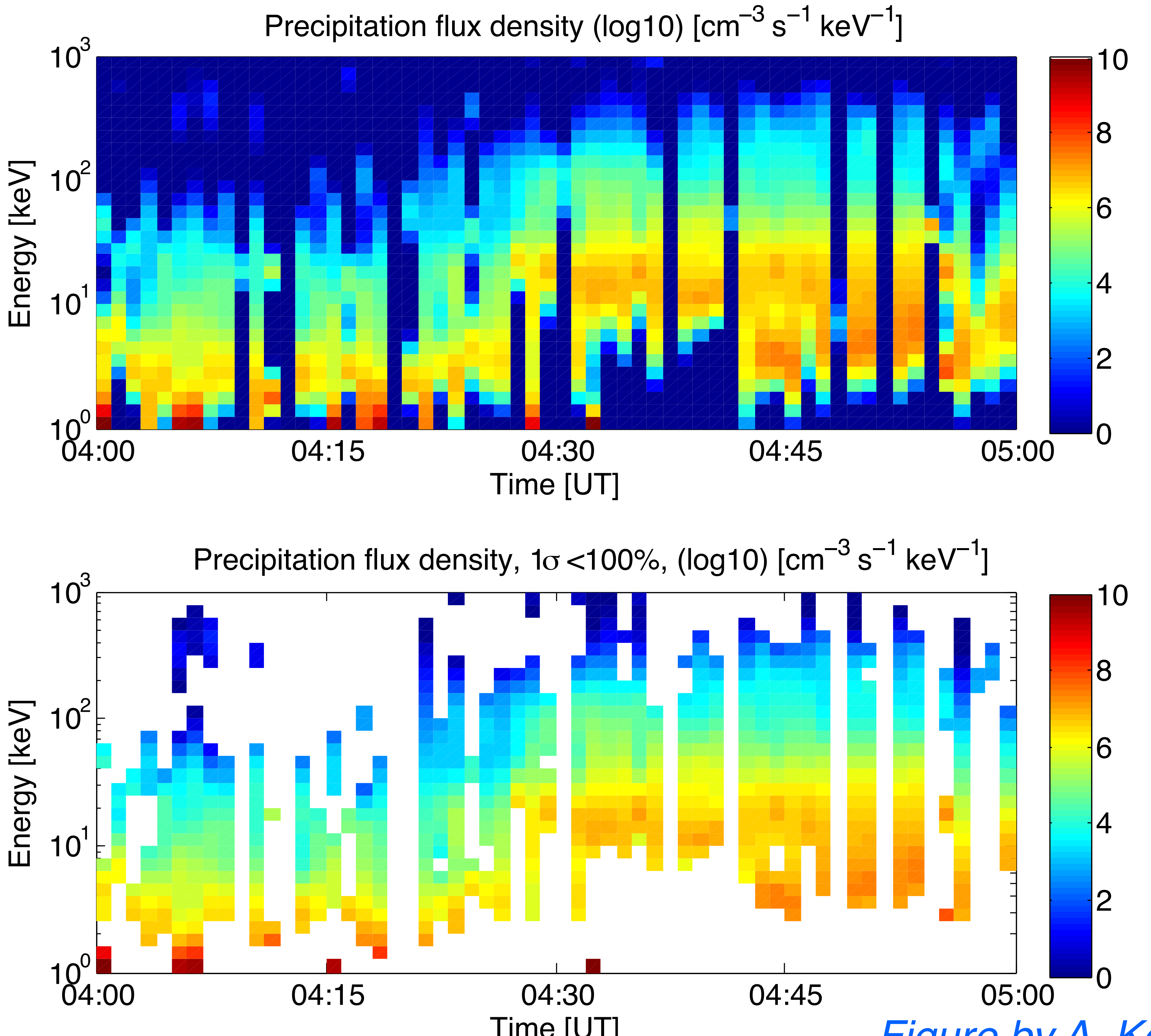


Figure by A. Kero, 2015

Nagoya university
Institute for Space-Earth Environmental Research

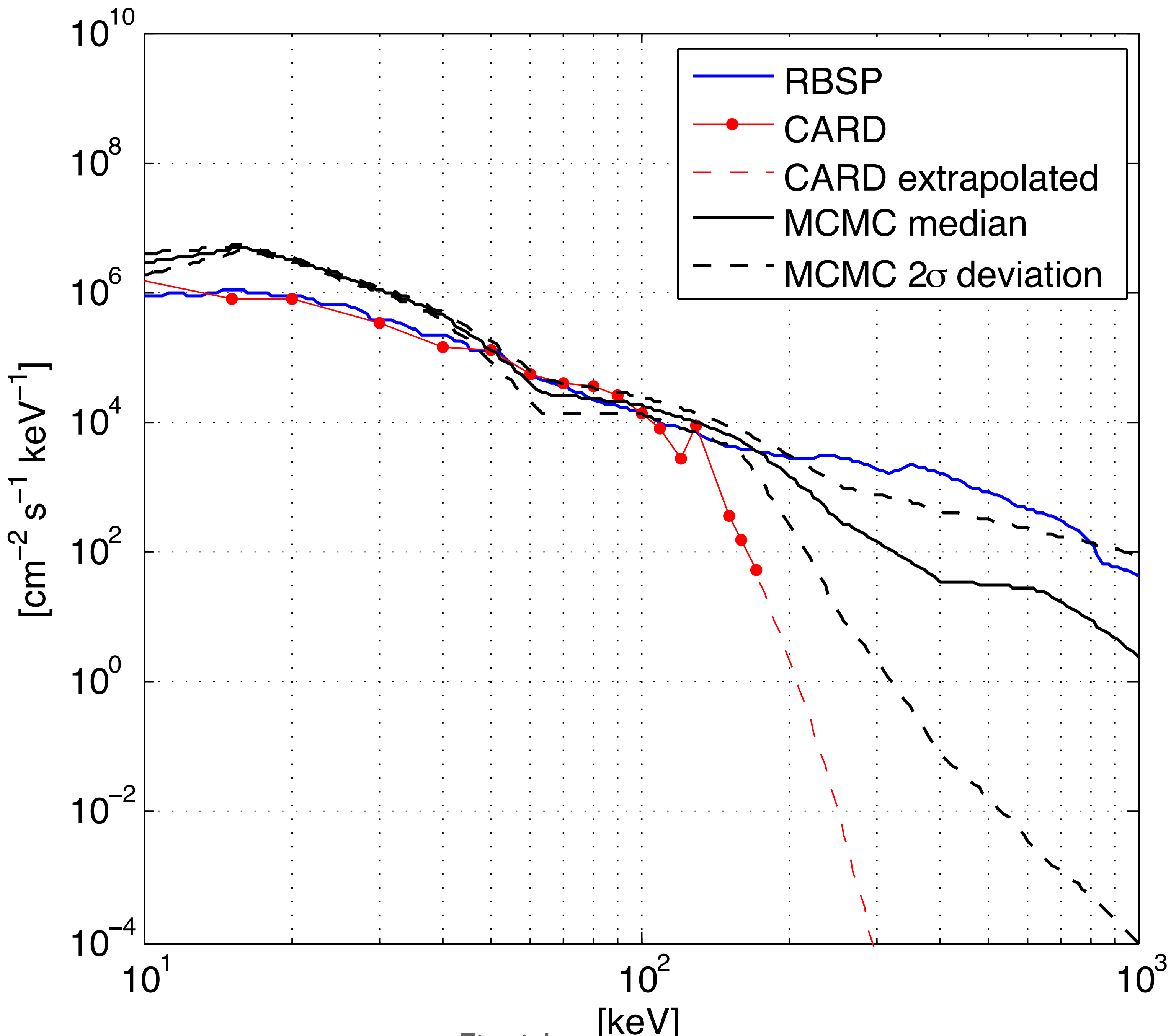
Finnish Meteorological Institute

Sodankylä Geophysical Observatory
University of Oulu

SIC MODEL: ELECTRON SPECTRUM AS INPUT

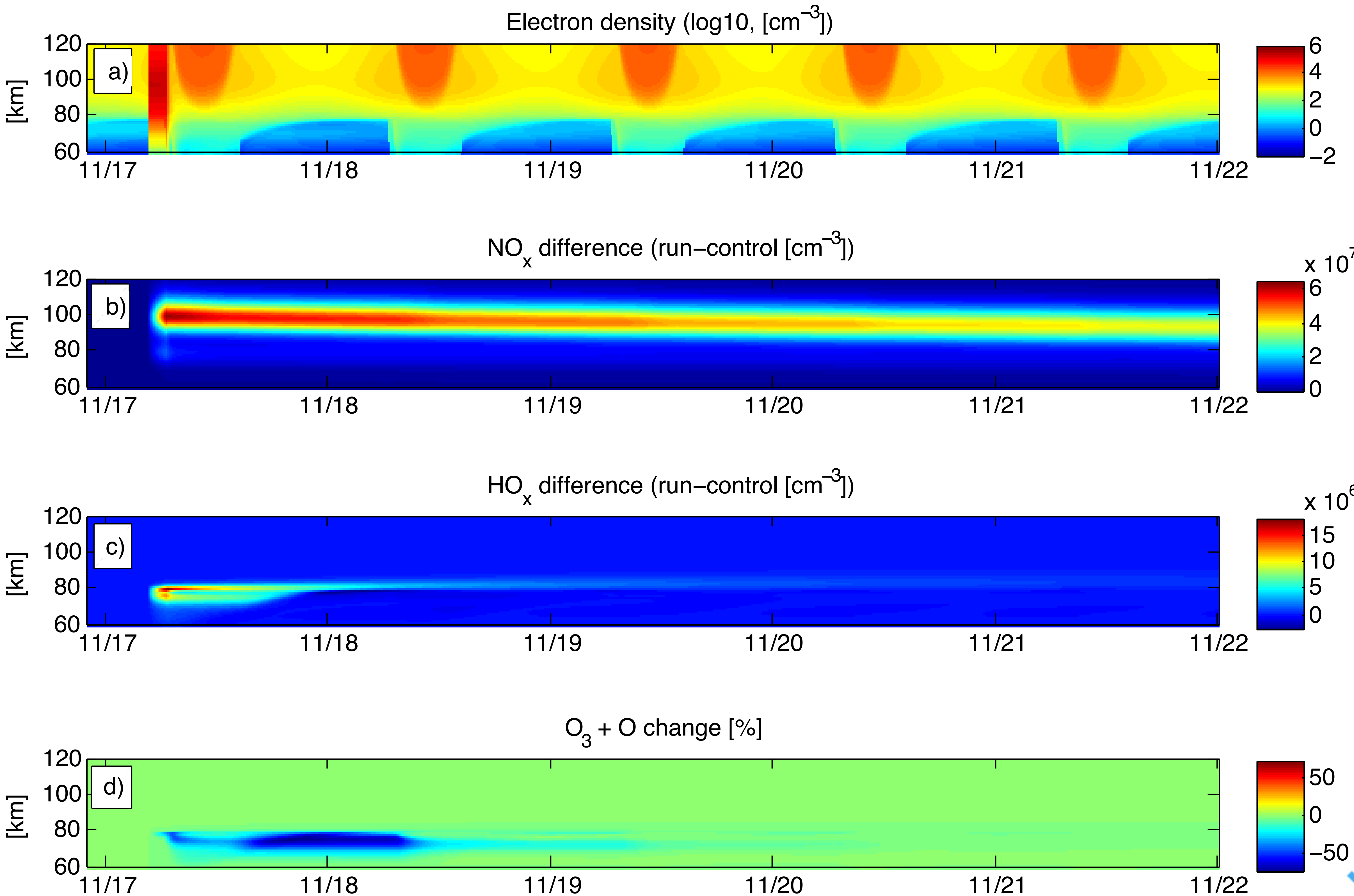
Note: the high energy tail of precipitating electron spectrum has large uncertainty due to large variance in EISCAT data at low altitudes

Data from Turunen et al., JGR 2016, under review



SIC MODEL: O_3 REDUCTION BY PULSATING AURORA

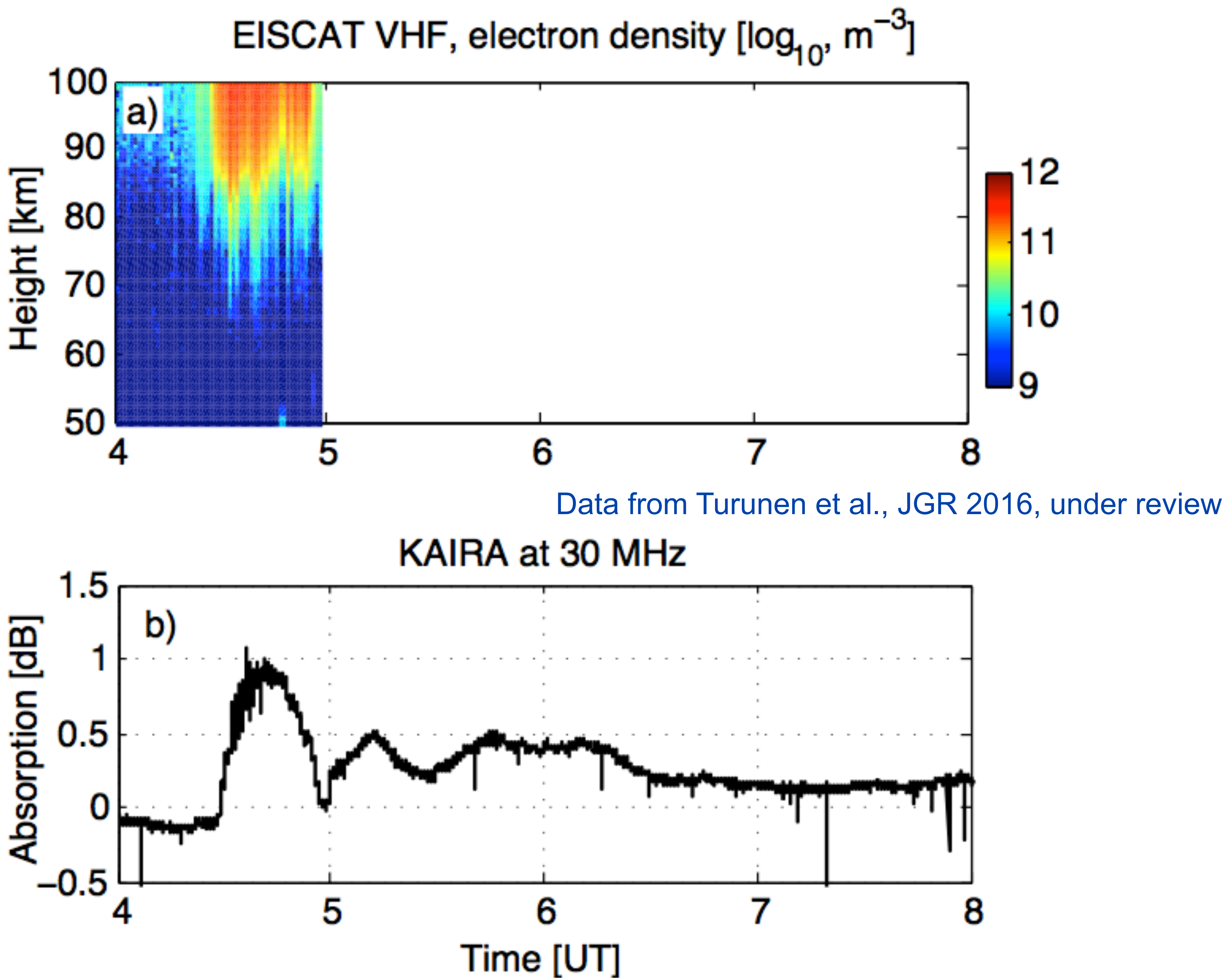
Data from Turunen et al., JGR 2016, under review



Nagoya university
Institute for Space-Earth Environmental Research

Finnish Date Meteorological Institute

Sodankylä Geophysical Observatory
University of Oulu



Nagoya university Institute for Space-Earth Environmental Research

Finnish Meteorological Institute

Sodankylä Geophysical Observatory University of Oulu

Pulsating Aurora -> Ozone Destruction

Data from Turunen et al., JGR 2016, under review

Spectrum in SIC	30 min	2h	dB
RBSP	-56%	-82%	2.5
MCMC median	-37%	-74%	1.5
MCMC lower 2σ	-25%	-63%	1.2
CARD	-14%	-48%	1.0

CONCLUSION OF THE STUDY

High-energy tail of the precipitating electron spectrum during pulsating aurora may cause significant variations in both odd nitrogen and odd hydrogen, causing consequent variations in odd oxygen.

For a single event and a modest estimate of the precipitating spectrum hardness, with 30 minutes duration of the forcing, we see mesospheric odd oxygen depletion of about 14% at 75 km.

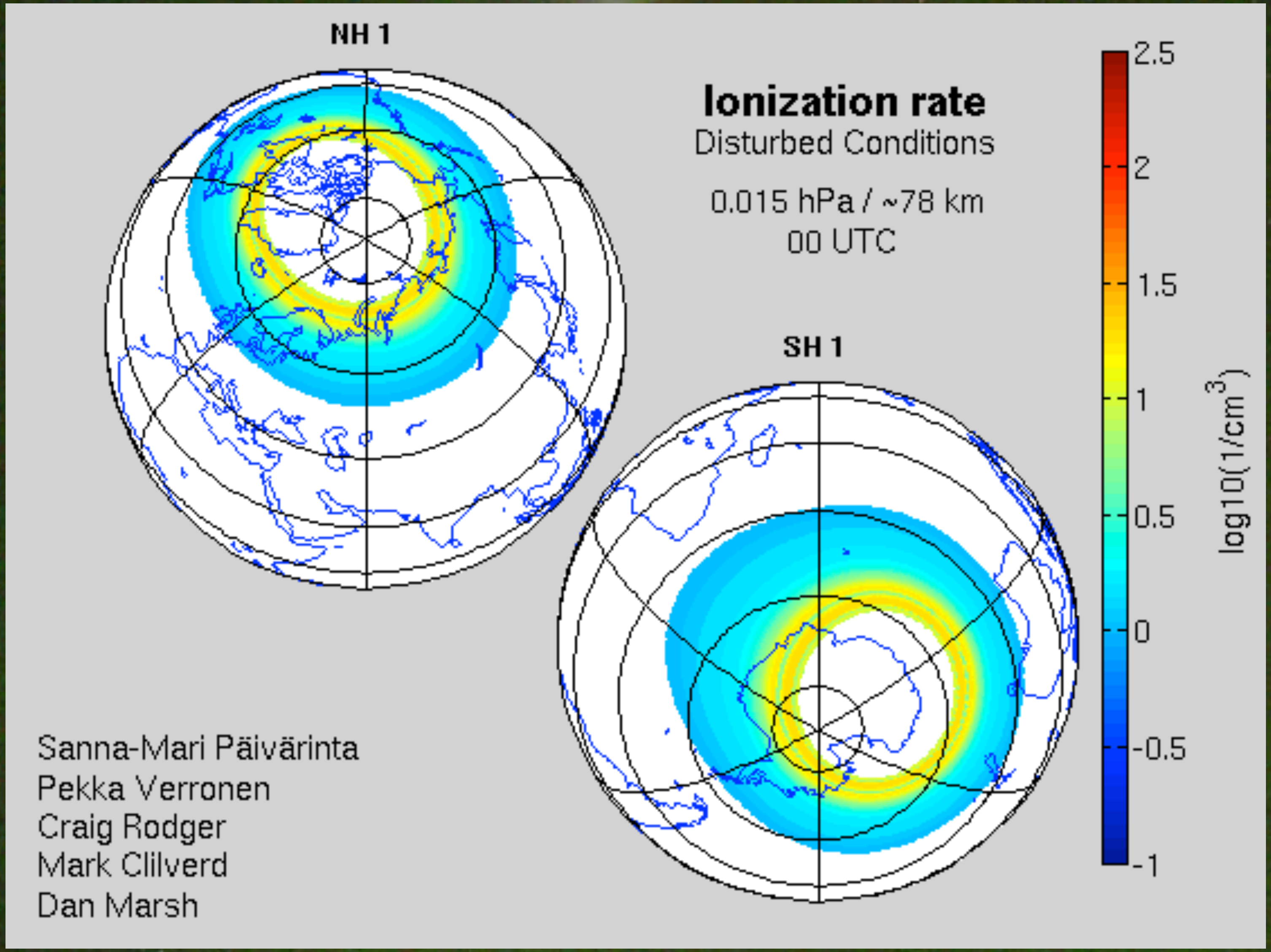
Harder high-energy tail of the precipitation, as for example shown by the results from our MCMC inversion, or longer duration of the event, as evidenced in our case by the KAIRA absorption data, **the odd oxygen depletion in the modeling reaches the level of several tens of percent.**

Odd oxygen variation due to a single event of pulsating aurora is in mesosphere at restricted altitude levels is similar to the quantitatively well-known effect by solar proton events.

Pulsating aurora are known to occur much more frequently than solar proton events, may last much longer than our modelled case and often cover spatially large regions.

This process should thus be considered when assessing the middle and upper atmospheric long-term variability and trying to understand the complex interactions between the geopace environment and the atmosphere.

Current satellites do not measure with enough accuracy and coverage the energy input by precipitating high-energy particles in lower ionosphere



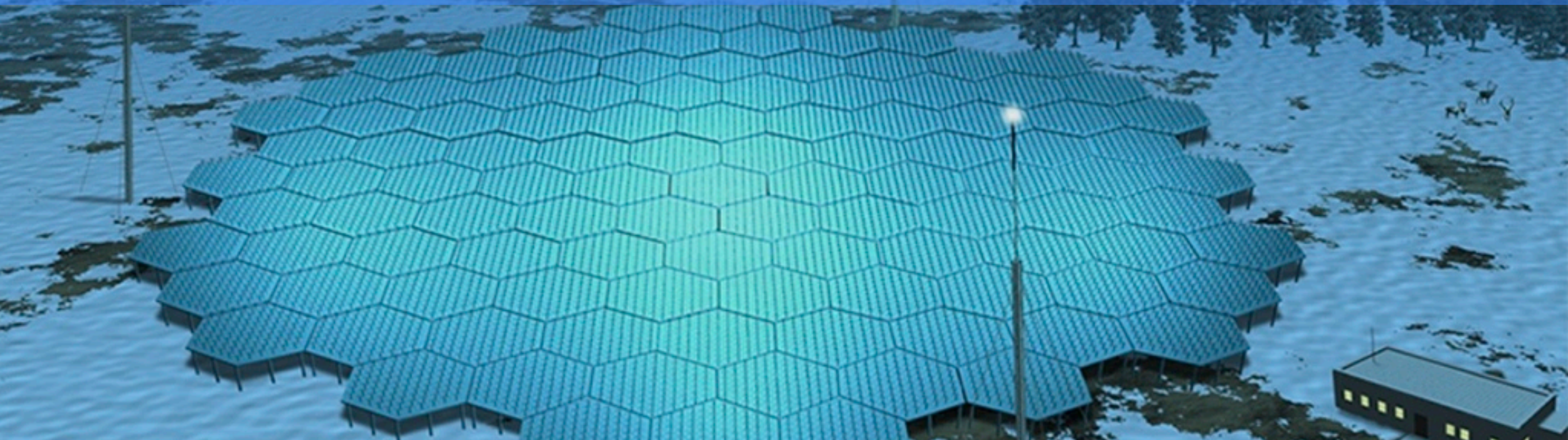
Ionization at 78 km estimated from POES satellite data:
200 days in Northern and Southern hemispheres *Credit: S.-M. Päivärinta FMI*

EISCAT_3D is in key position to support research on climate relevant dynamics of the whole atmospheric system.

EISCAT_3D will map real 3D electrodynamics.

Quantification of high-energy particle precipitation in 3D

Continuous wind measurements in 3D



Associate countries and institutes

Contributing affiliated countries: