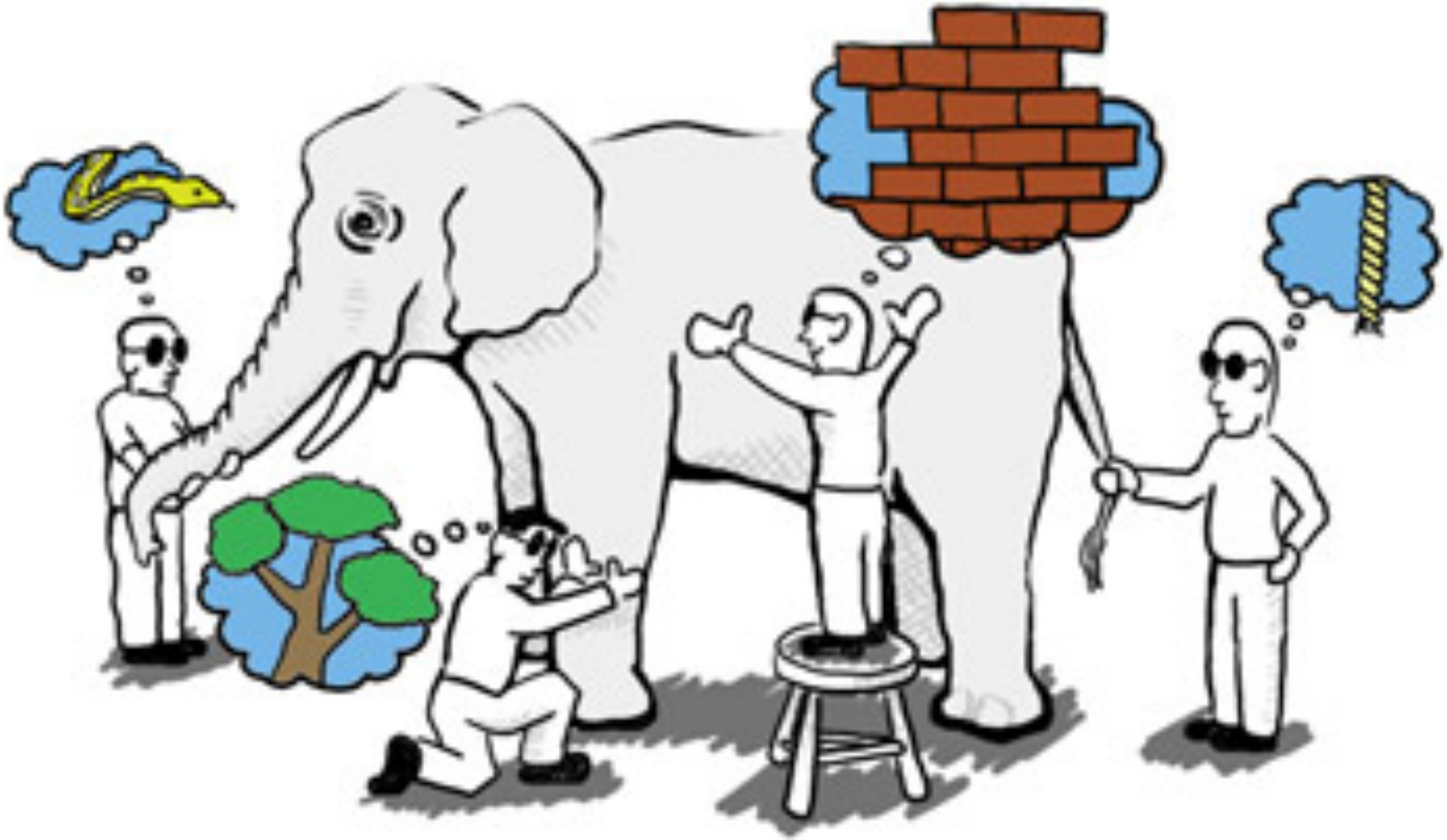
Interpreting ISR Data

From data plots to physics

Ian McCrea, STFC RAL, UK
(with thanks to Mike
Lockwood)



Introduction

Having a data plot is not the same as knowing what is going on.

Your goal is not just to take some data, but to do some interpretation.

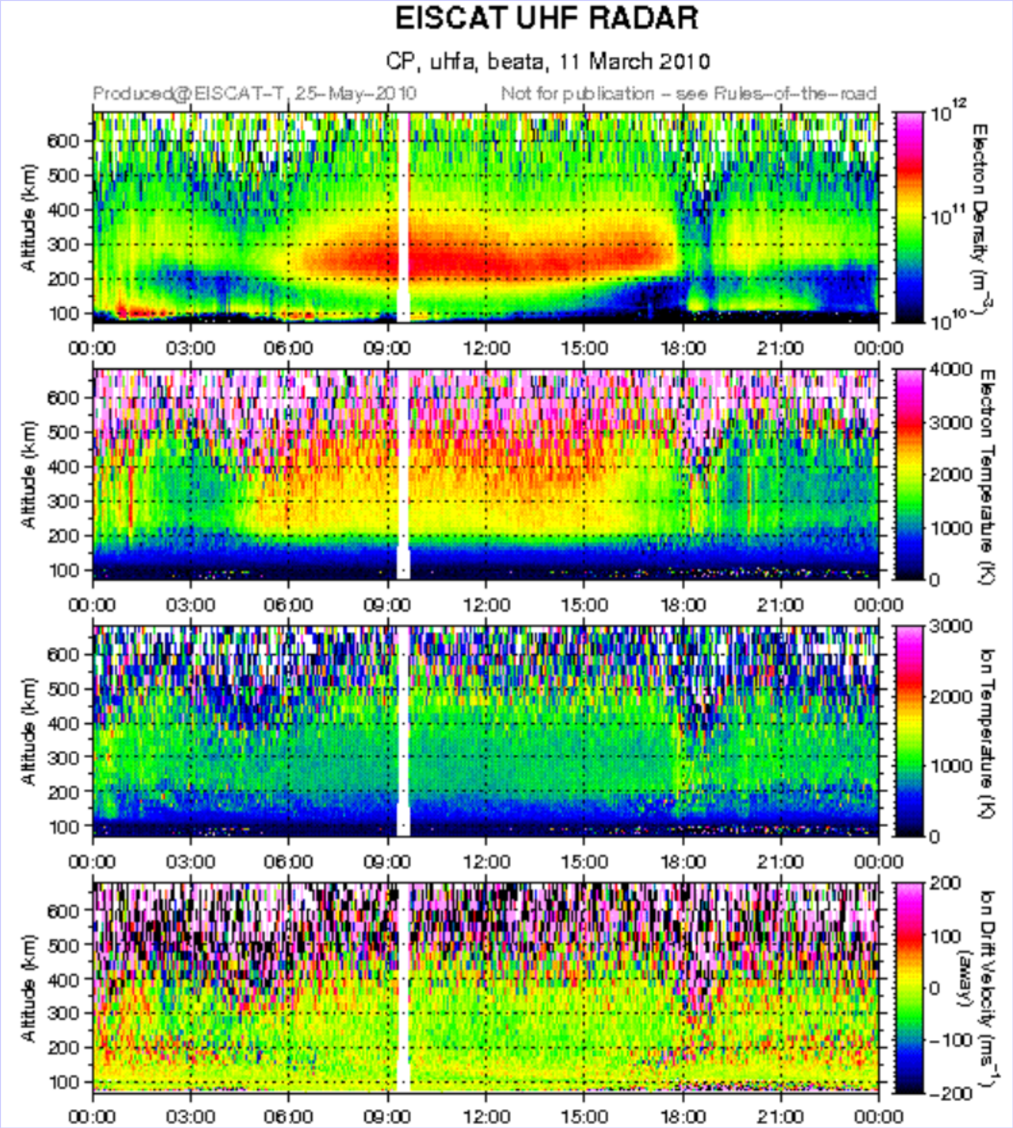
- (1) What you see depends on where and how you look
- (2) Parameters in ISR data can be ambiguous
- (3) Knowing some physics helps you make sense of the data
- (4) Combining with data from other instruments gives better context

Here we will show some practical examples of how simple processes can look quite different, depending on what kind of experiment you are running.

Always remember:

- The data can depend strongly on the design of the experiment
- The ISR technique can be prone to both systematic and random errors
- If the data look unusual – be suspicious!
- Eliminate possible sources of error before you publish your new discovery!

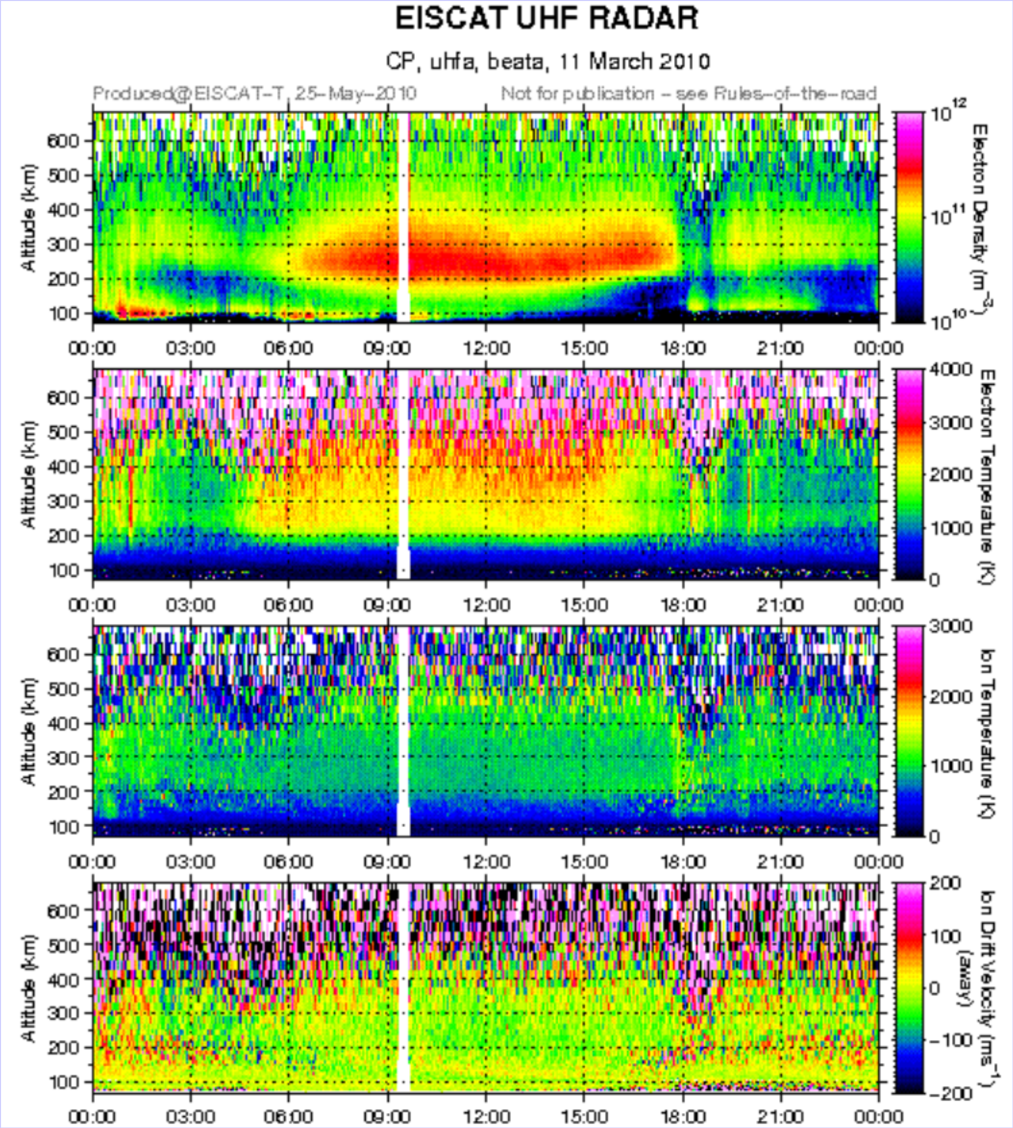
A simple EISCAT data set



CP1: Field-aligned data

- Electron Density Ne (m^{-3})
- Electron Temperature (K)
- Ion Temperature (K)
- Line-of-sight ion velocity (ms^{-1})

A simple EISCAT data set

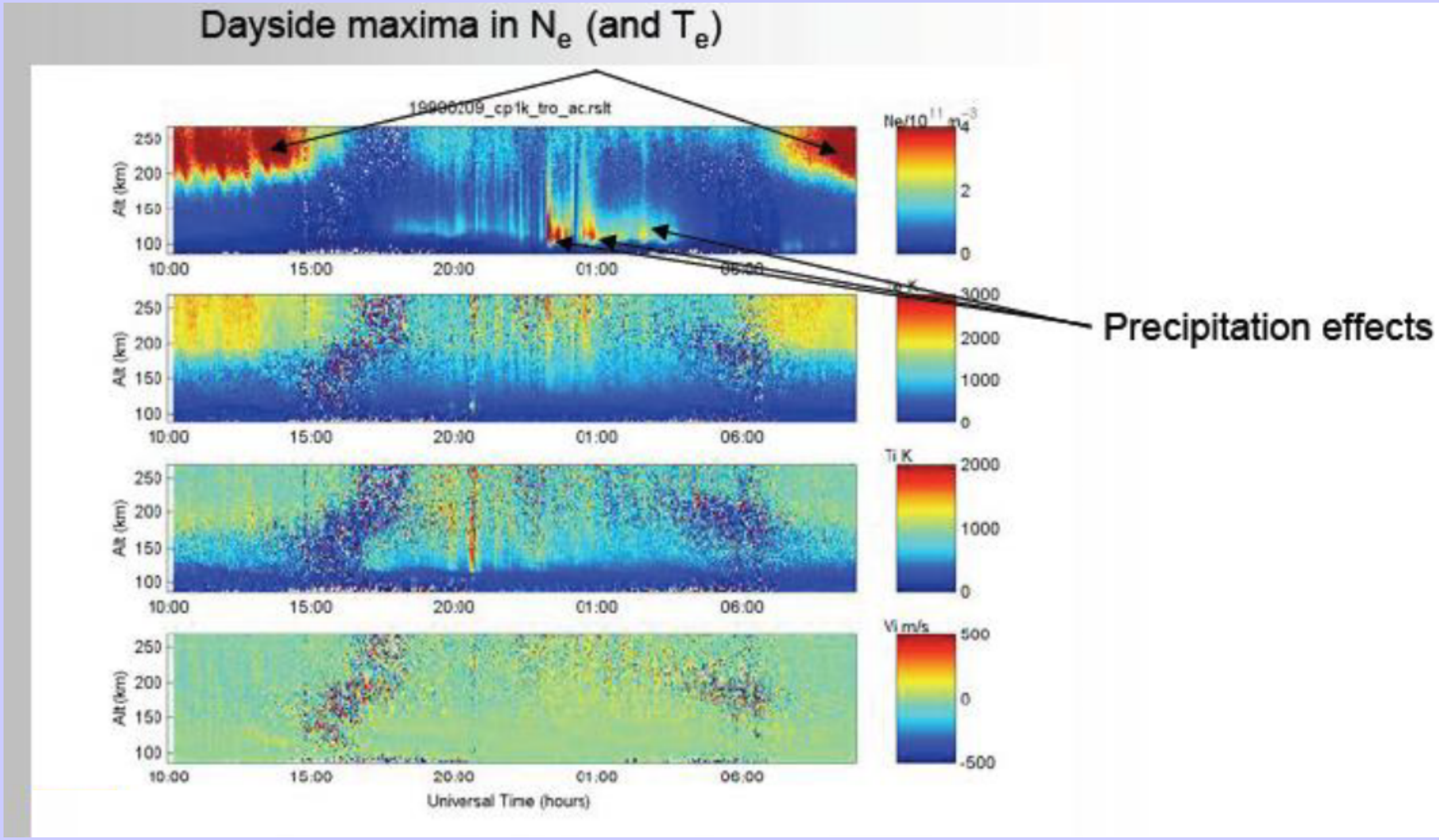


What can we see in this plot?

- The height structure of the E and F regions
- The diurnal variation of the ionosphere
- Aurora
- Electron and (maybe) ion heating
- Density troughs(?)
- Plasma blobs(?)
- Atmospheric tides(?)

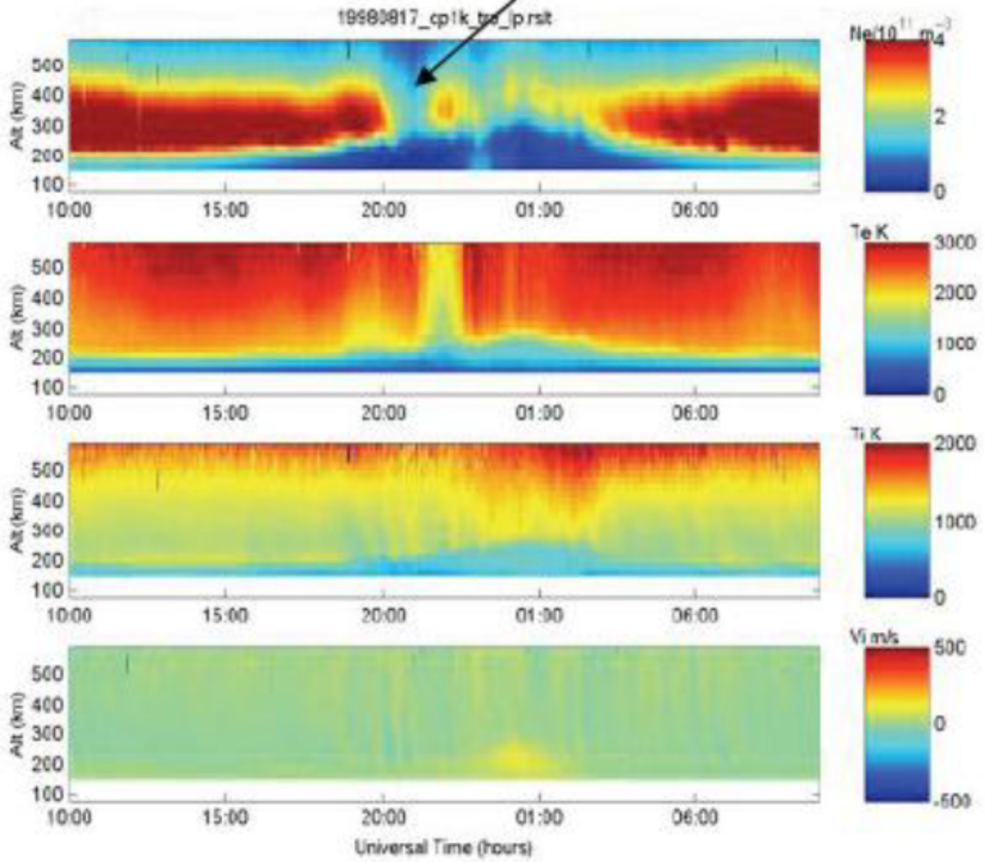
Generally it all makes sense!

More CP1 data (wintertime)



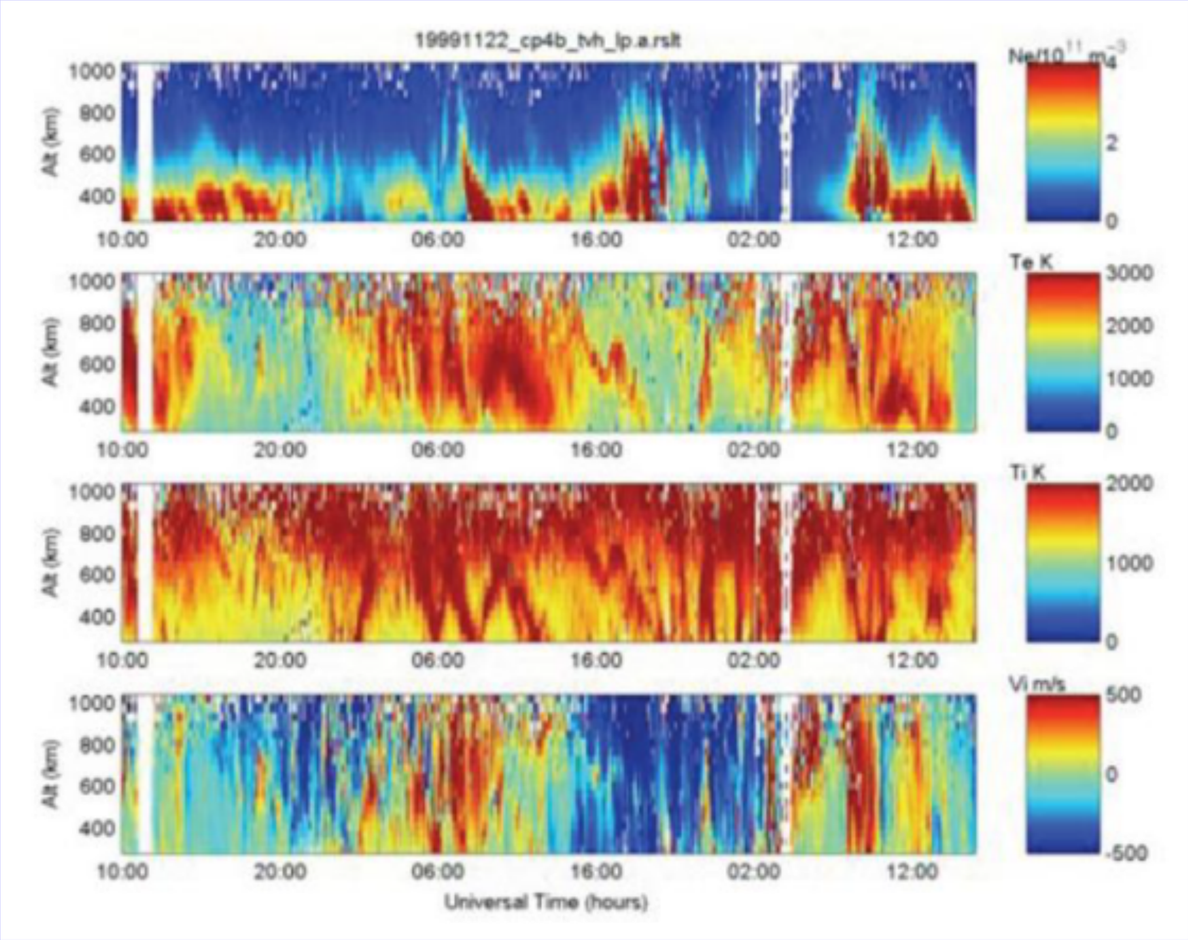
More CP1 data (summertime)

Nightside minima in N_e (and T_e)



Note T_e and, by electron ion conduction T_i are also much greater than in winter case

What about these data?



Electron number density, N_e (m^{-3})

Electron temperature, T_e (K)

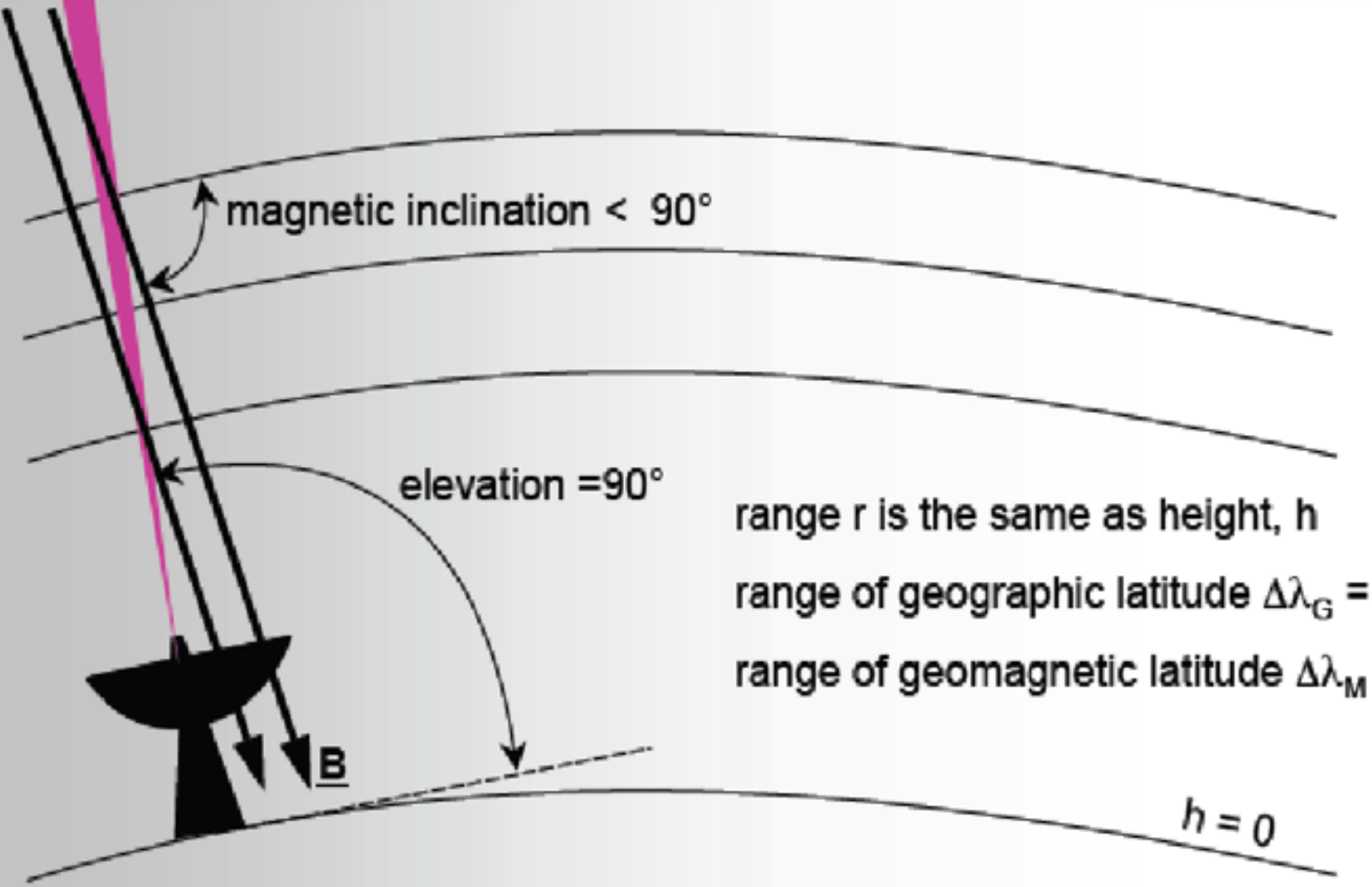
Ion temperature, T_i (K)

Line-of-sight velocity, V_{los} (ms^{-1})

Changing Pointing Direction

Altitude and Pointing Direction

vertical, e.g. CP7, $(r / h) = 1$, $\Delta\lambda_G = 0$, $\Delta\lambda_M > 0$



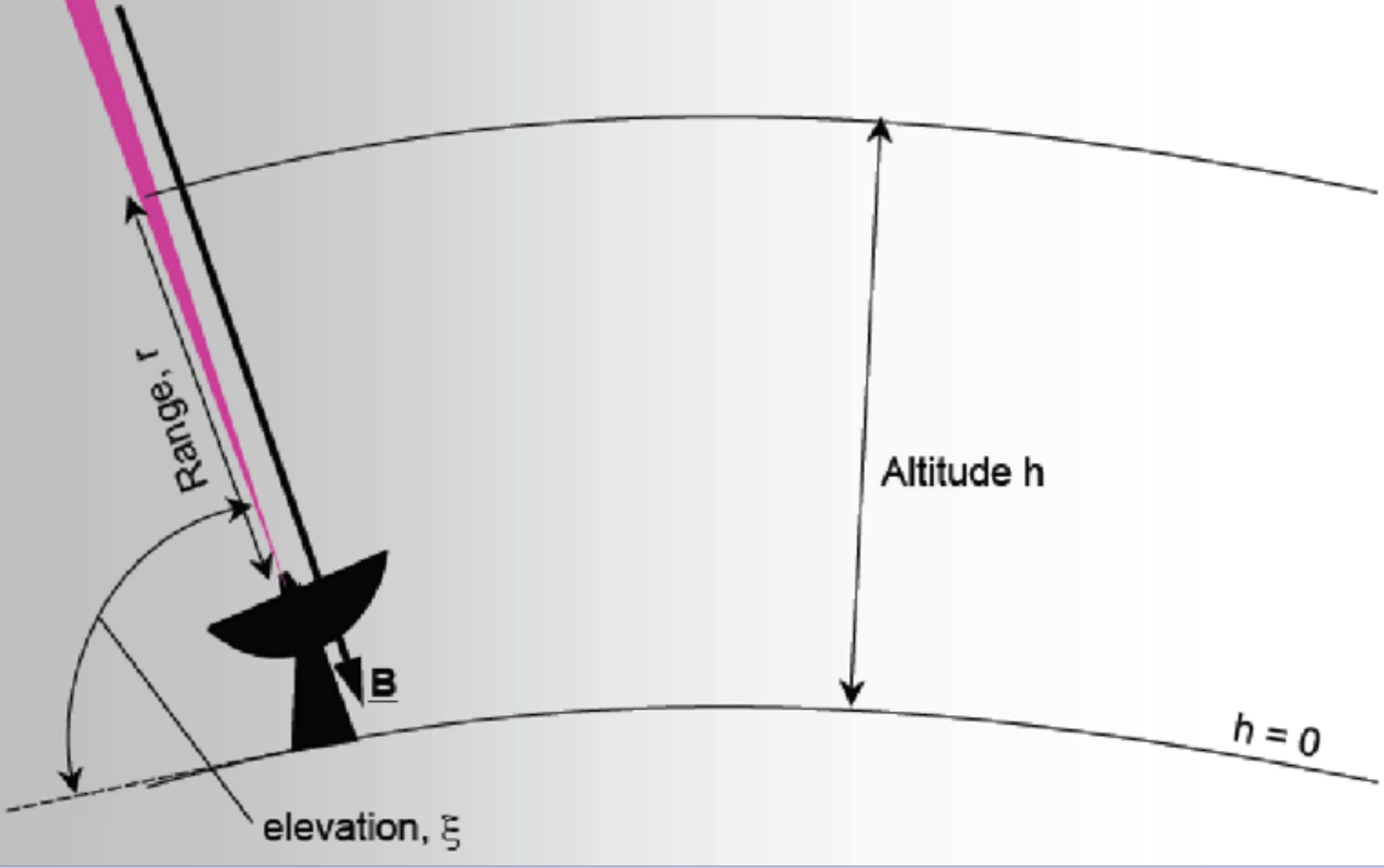
range r is the same as height, h

range of geographic latitude $\Delta\lambda_G = 0$

range of geomagnetic latitude $\Delta\lambda_M > 0$

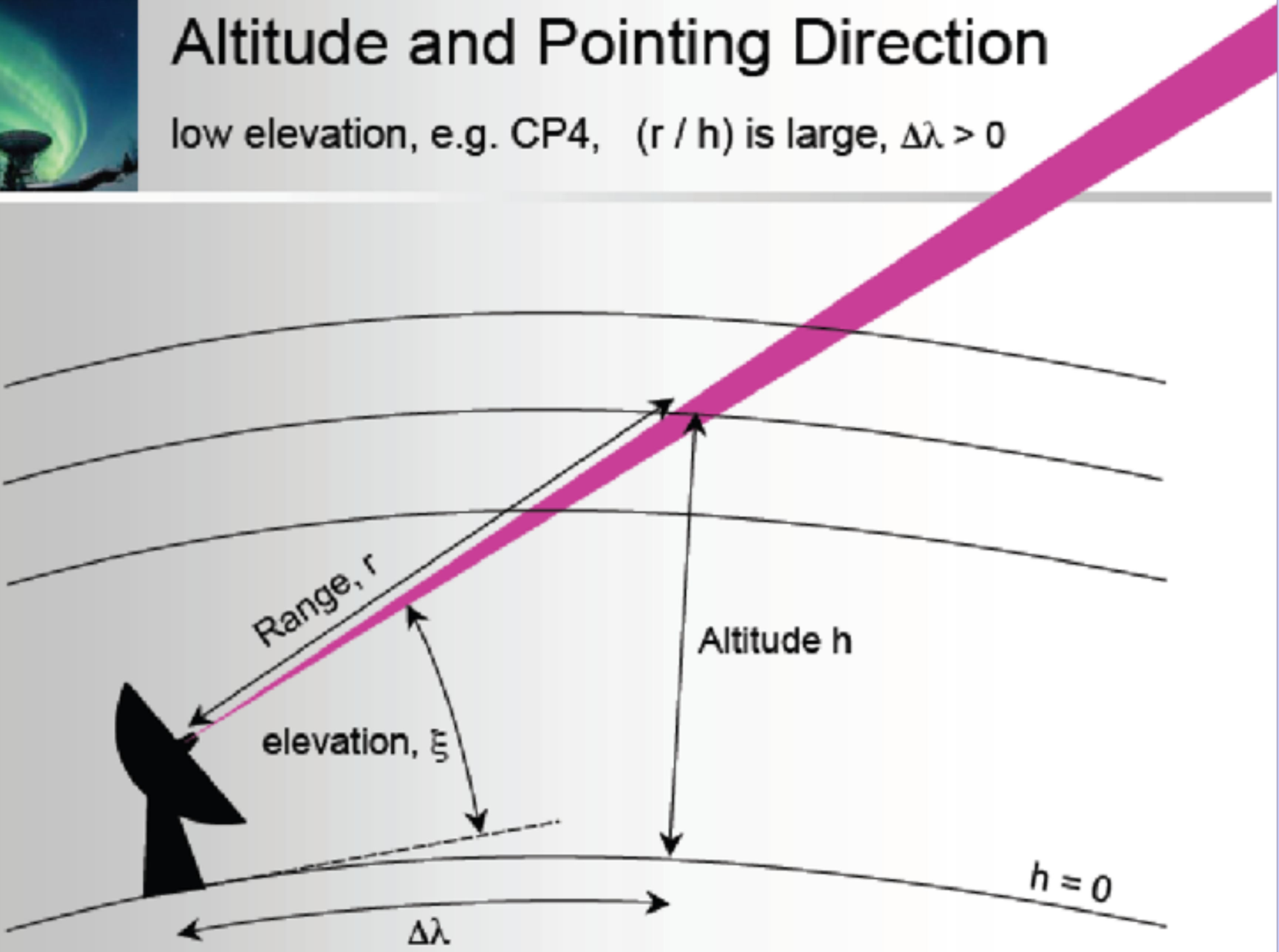
Altitude and Pointing Direction

Field-aligned, e.g. CP1, $(r / h) > 1$, $\Delta\lambda_M = 0$, $\Delta\lambda_G > 0$



Altitude and Pointing Direction

low elevation, e.g. CP4,   (r / h) is large, $\Delta\lambda > 0$



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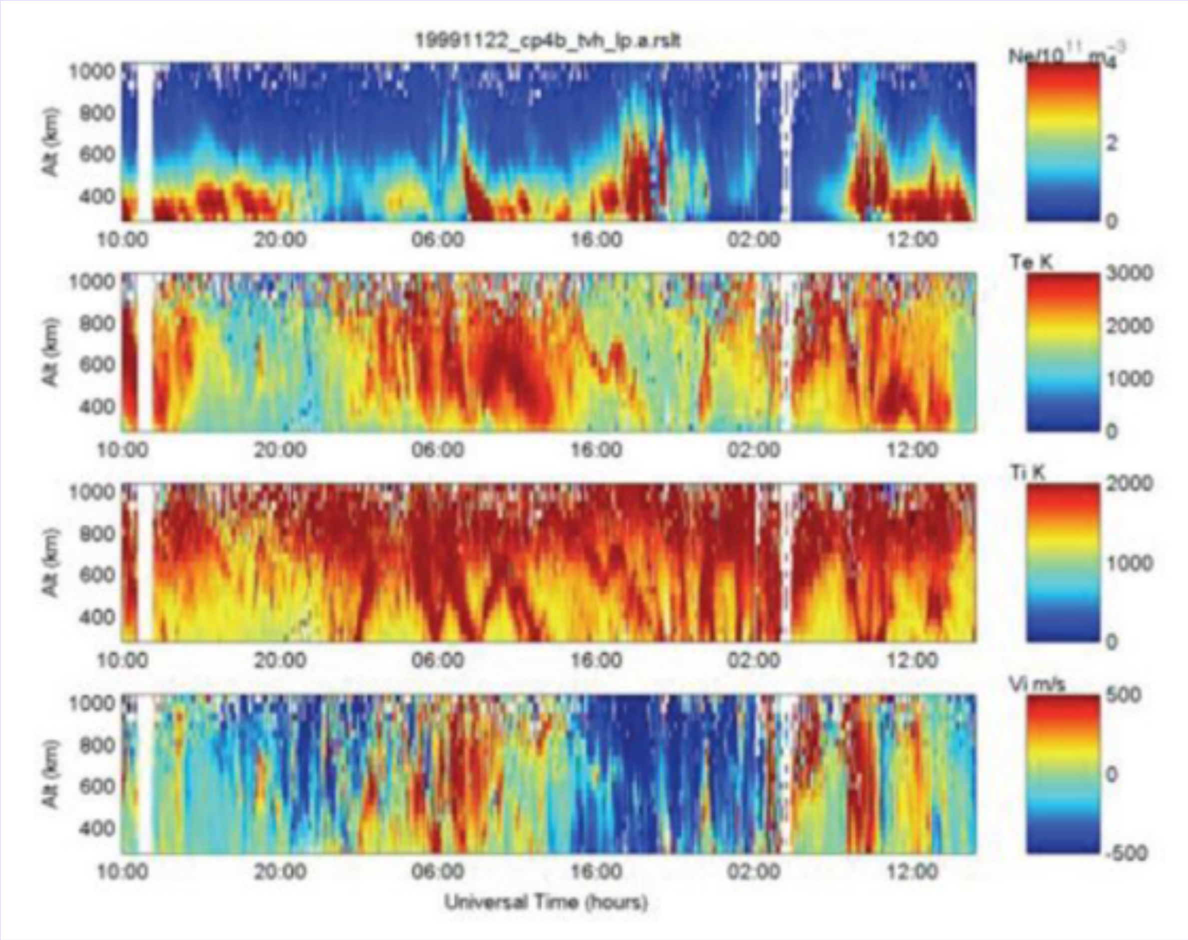

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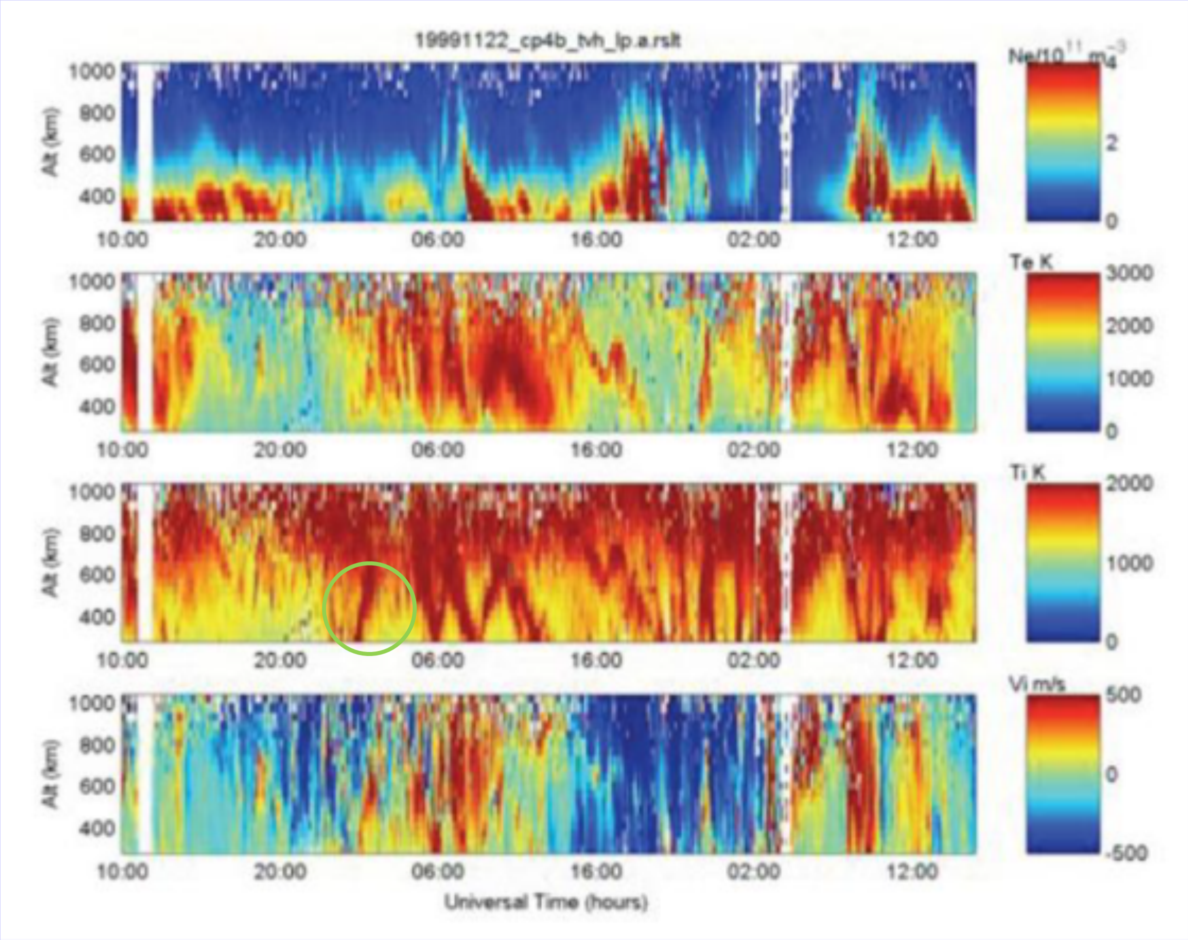

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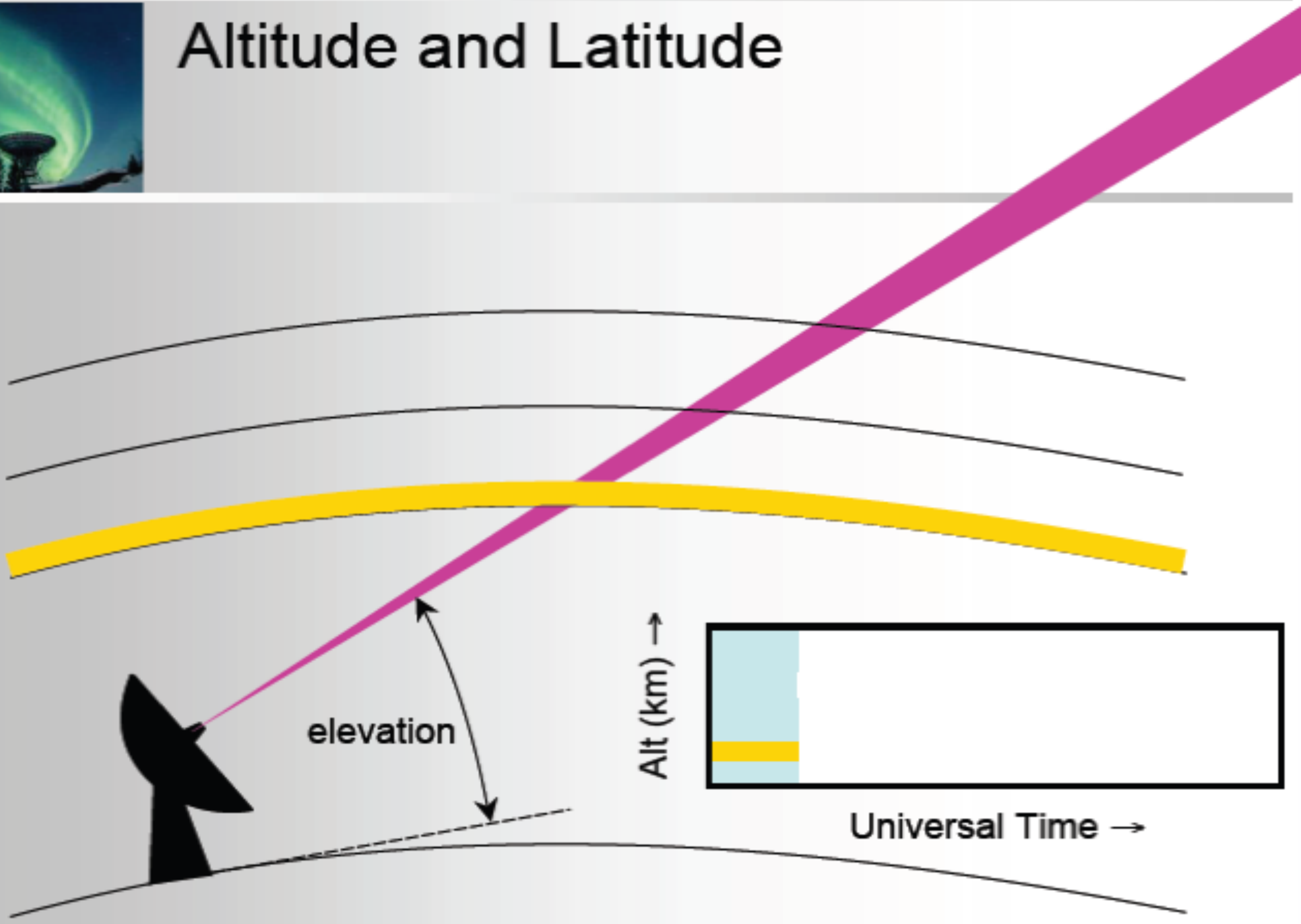

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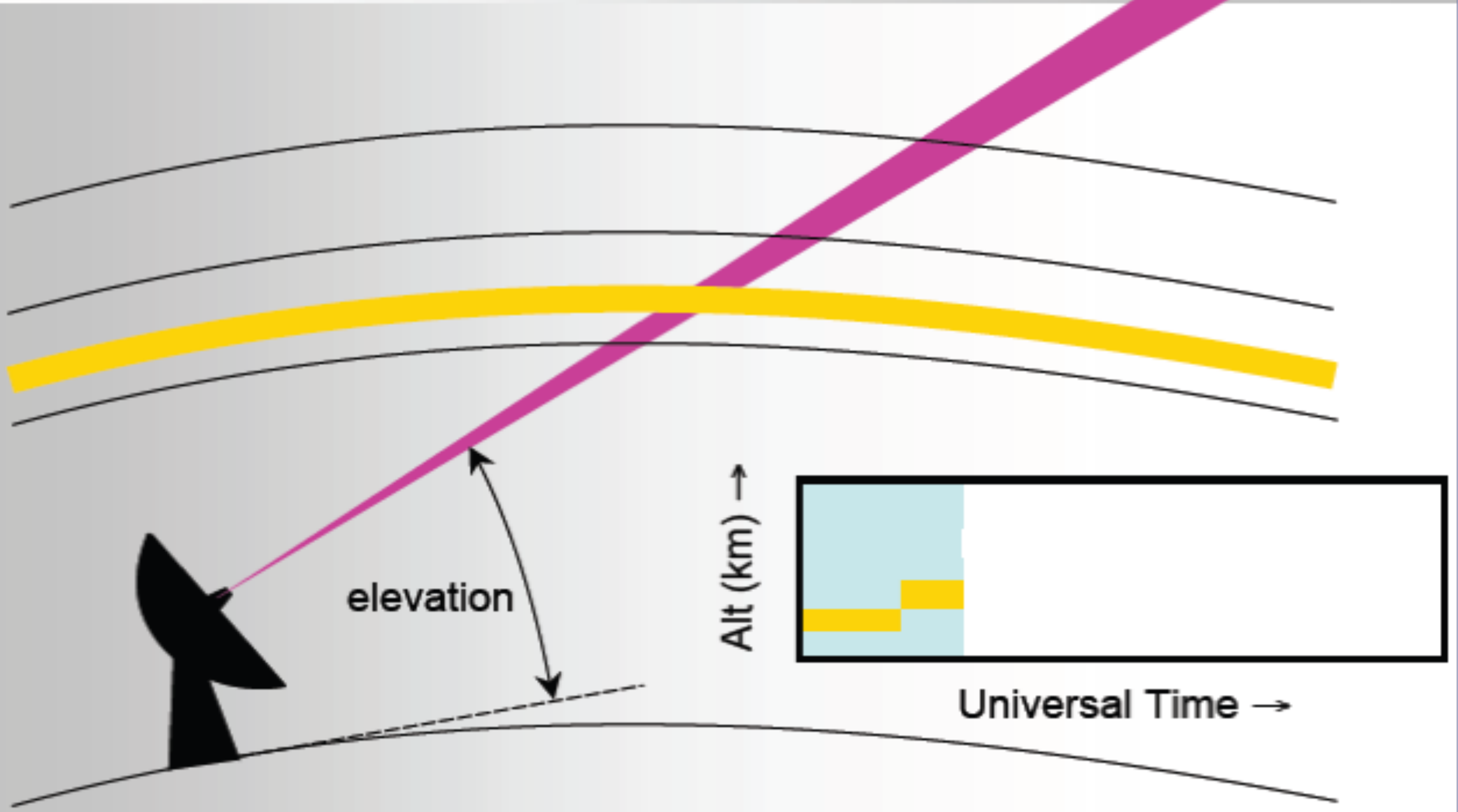

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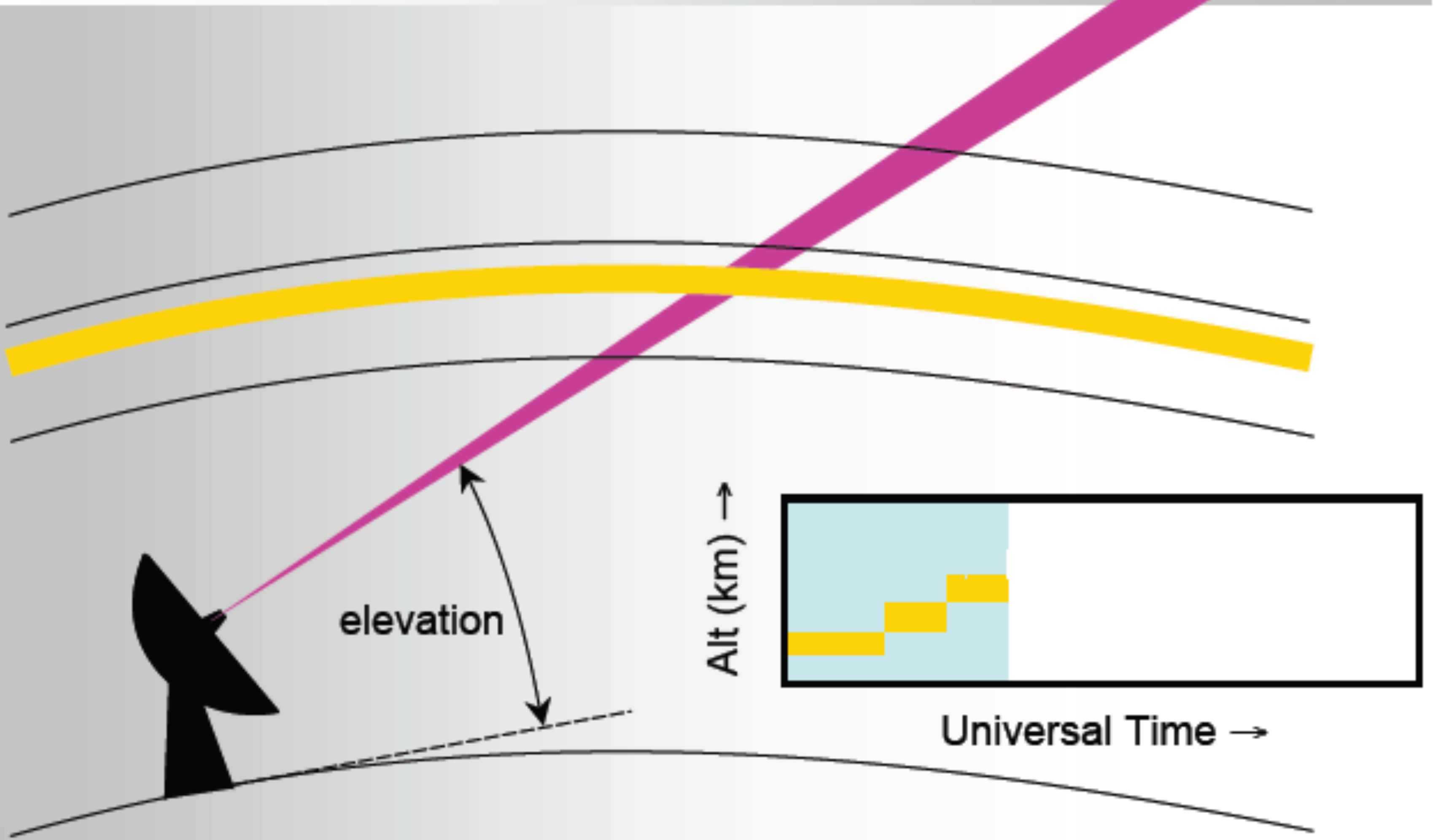

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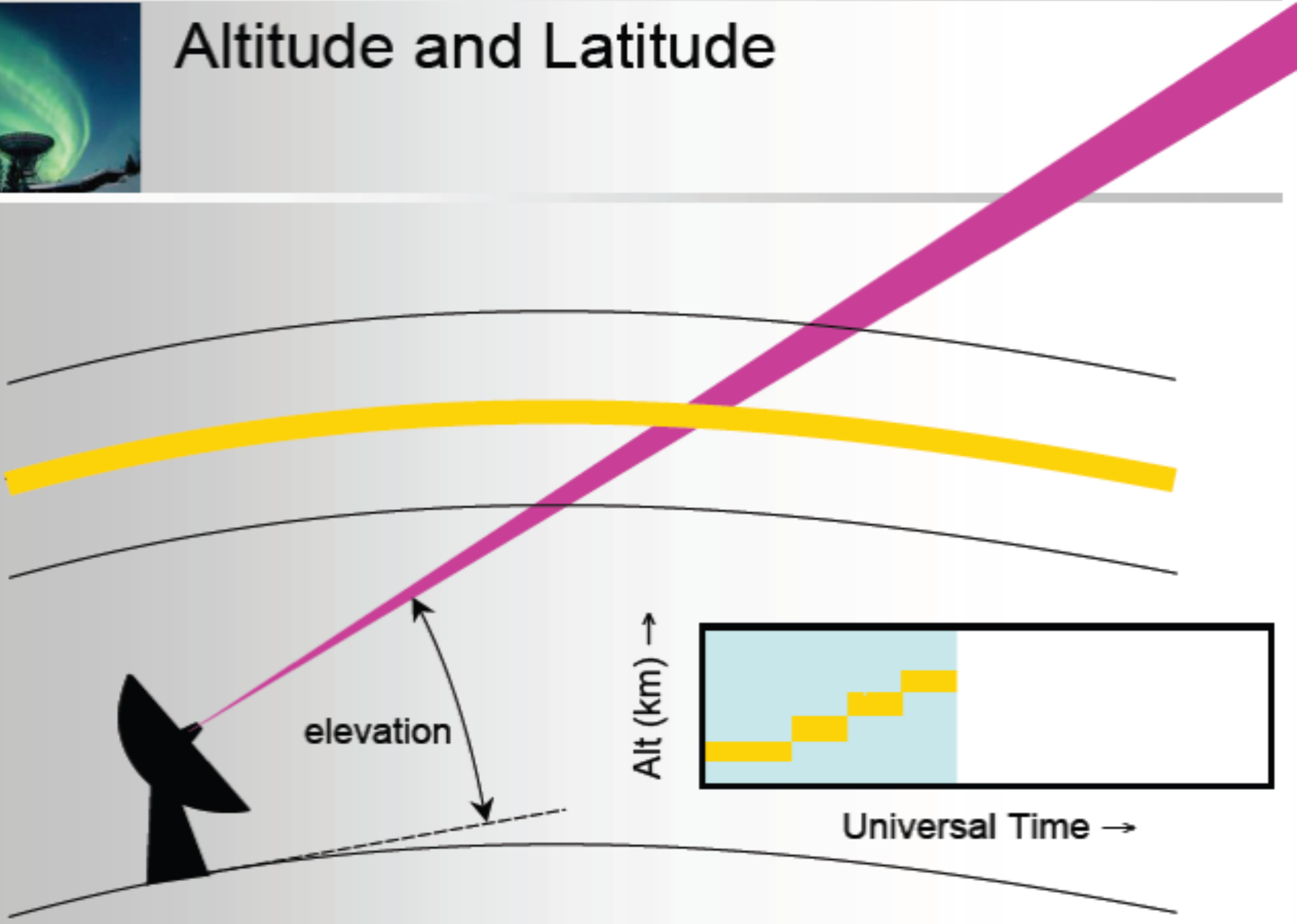

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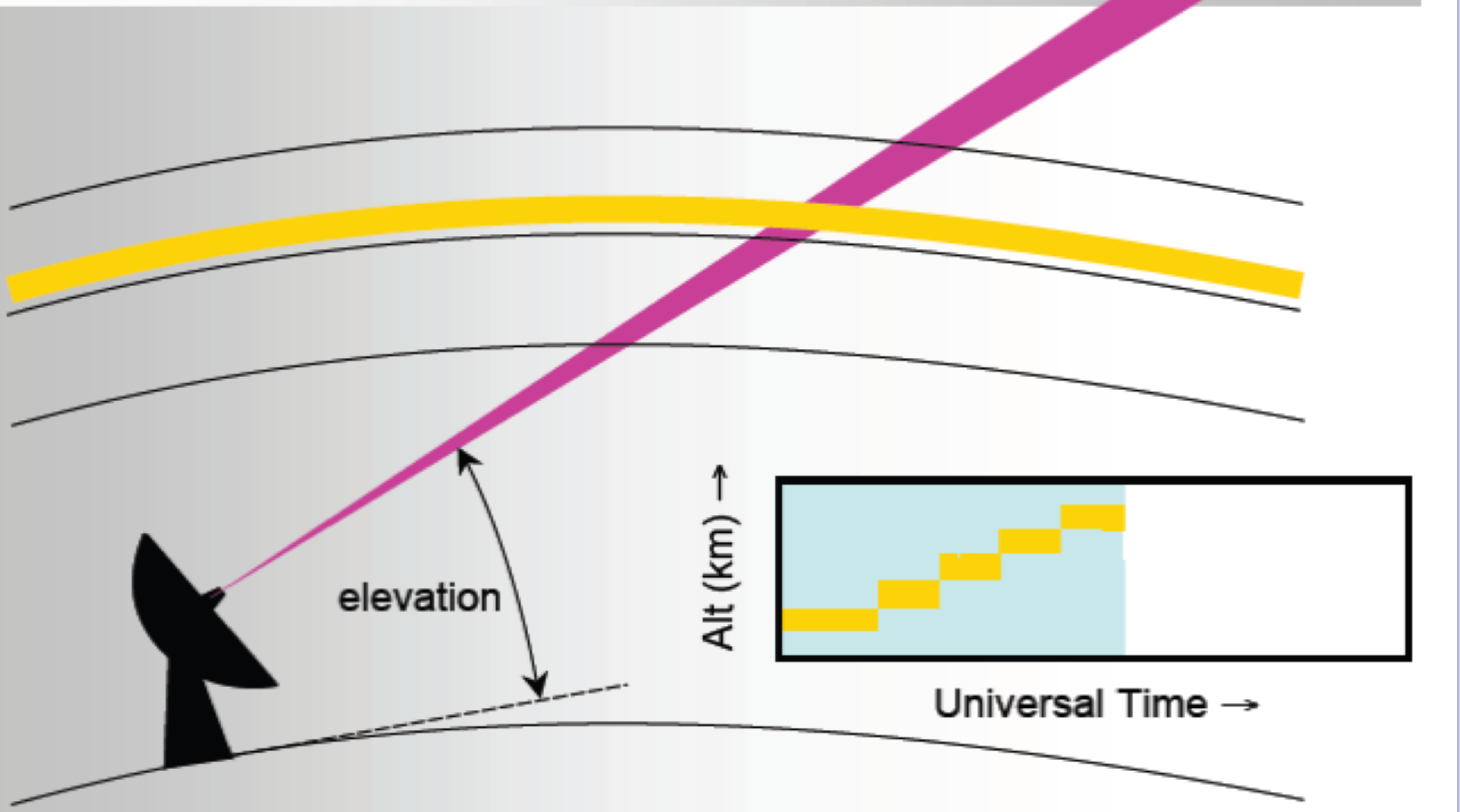

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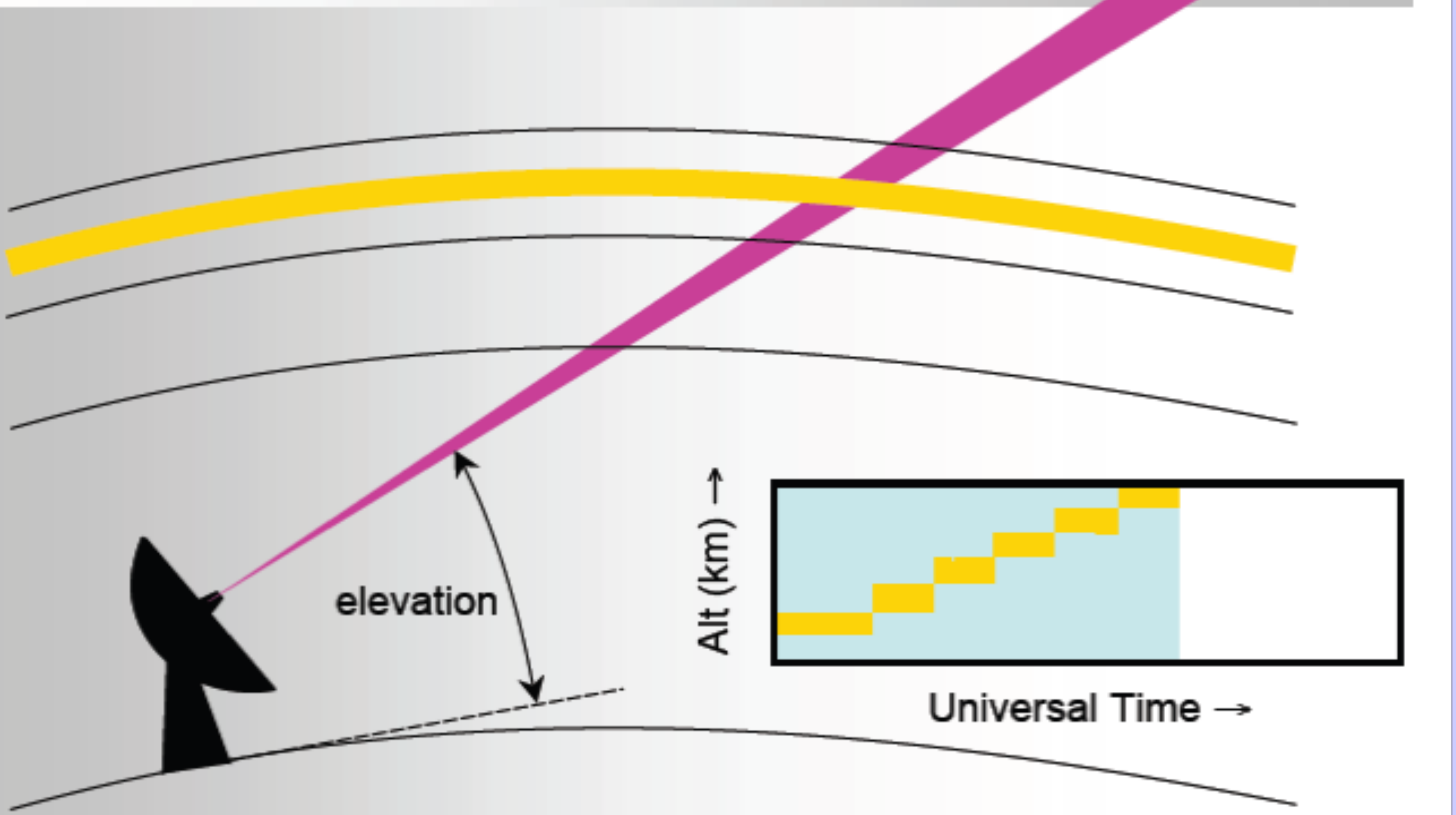

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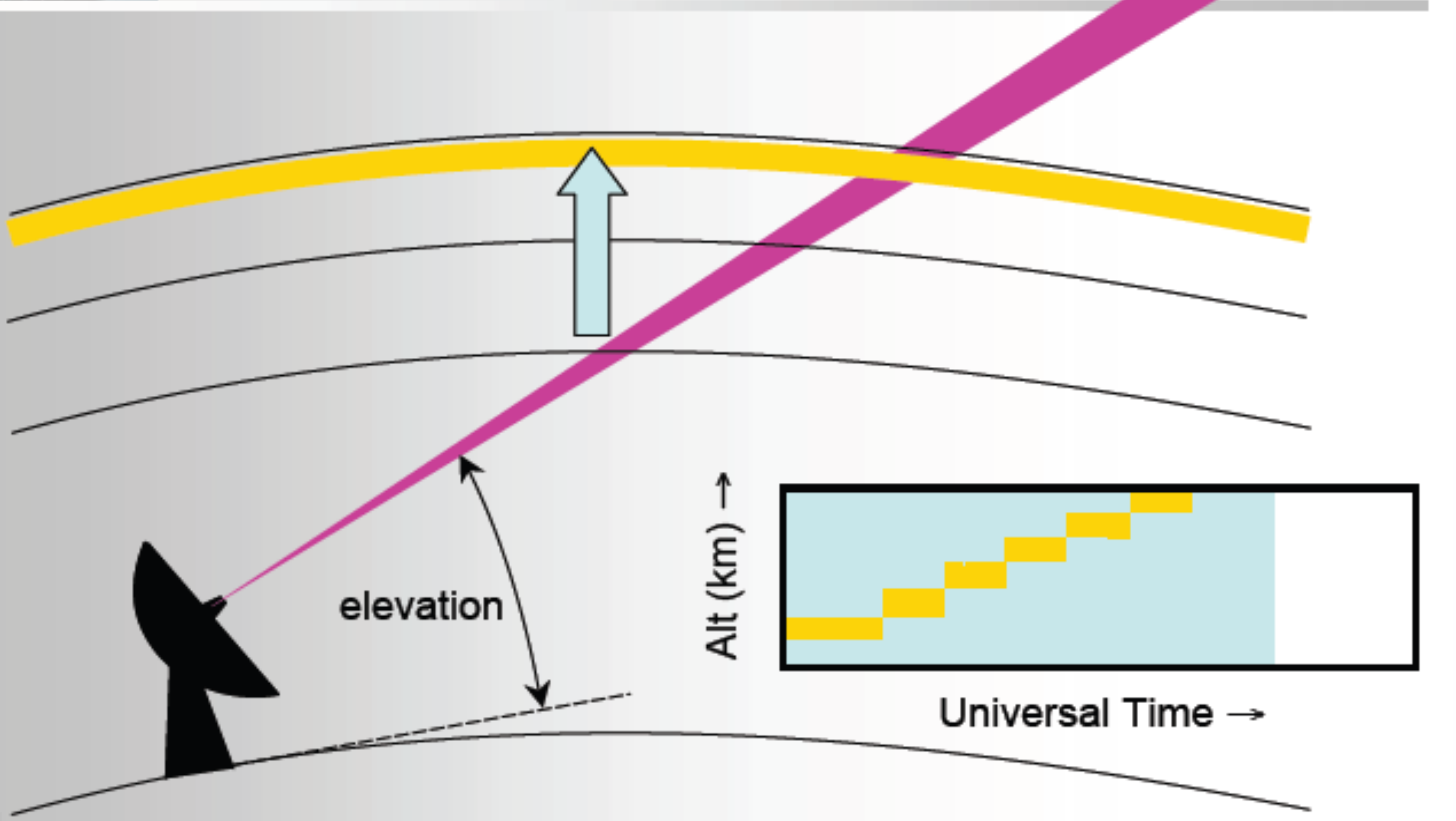

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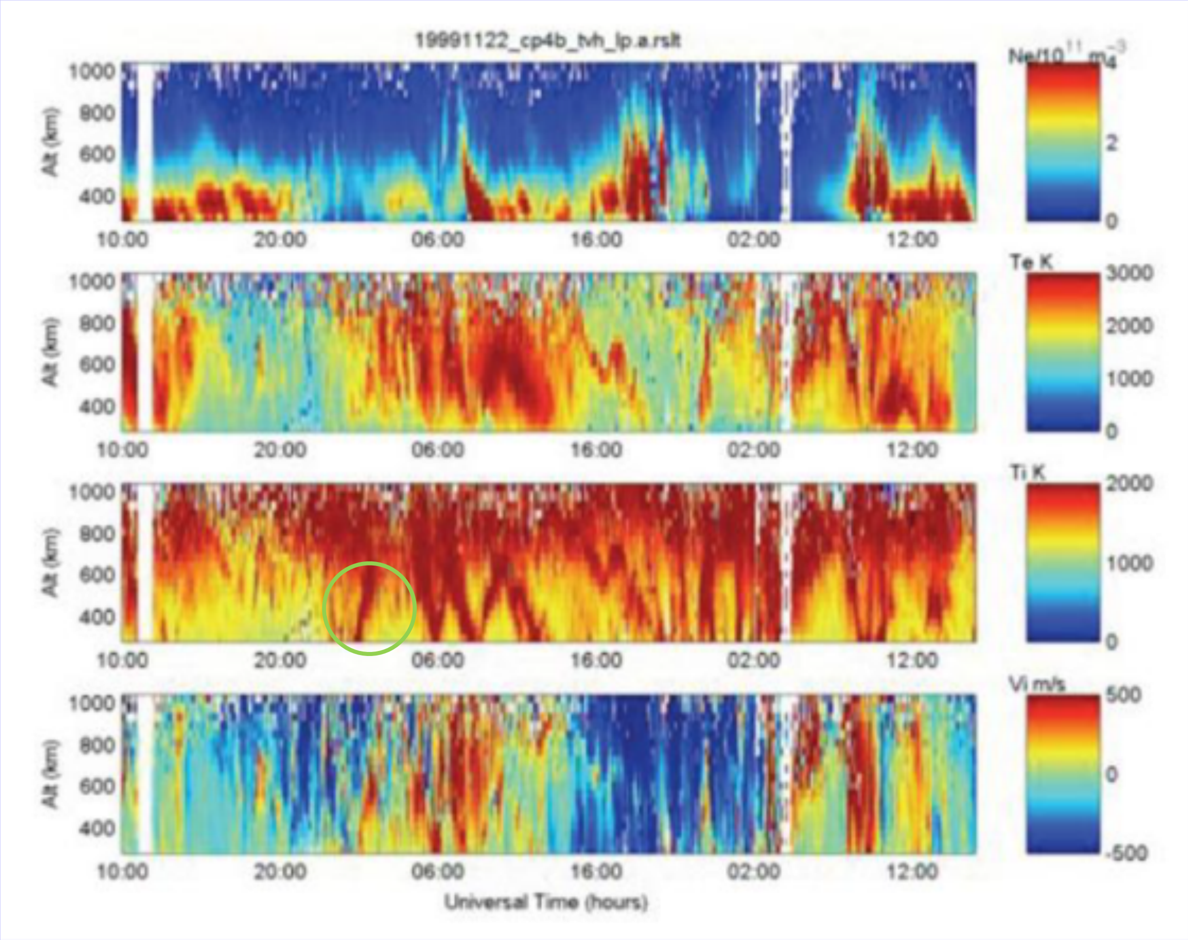

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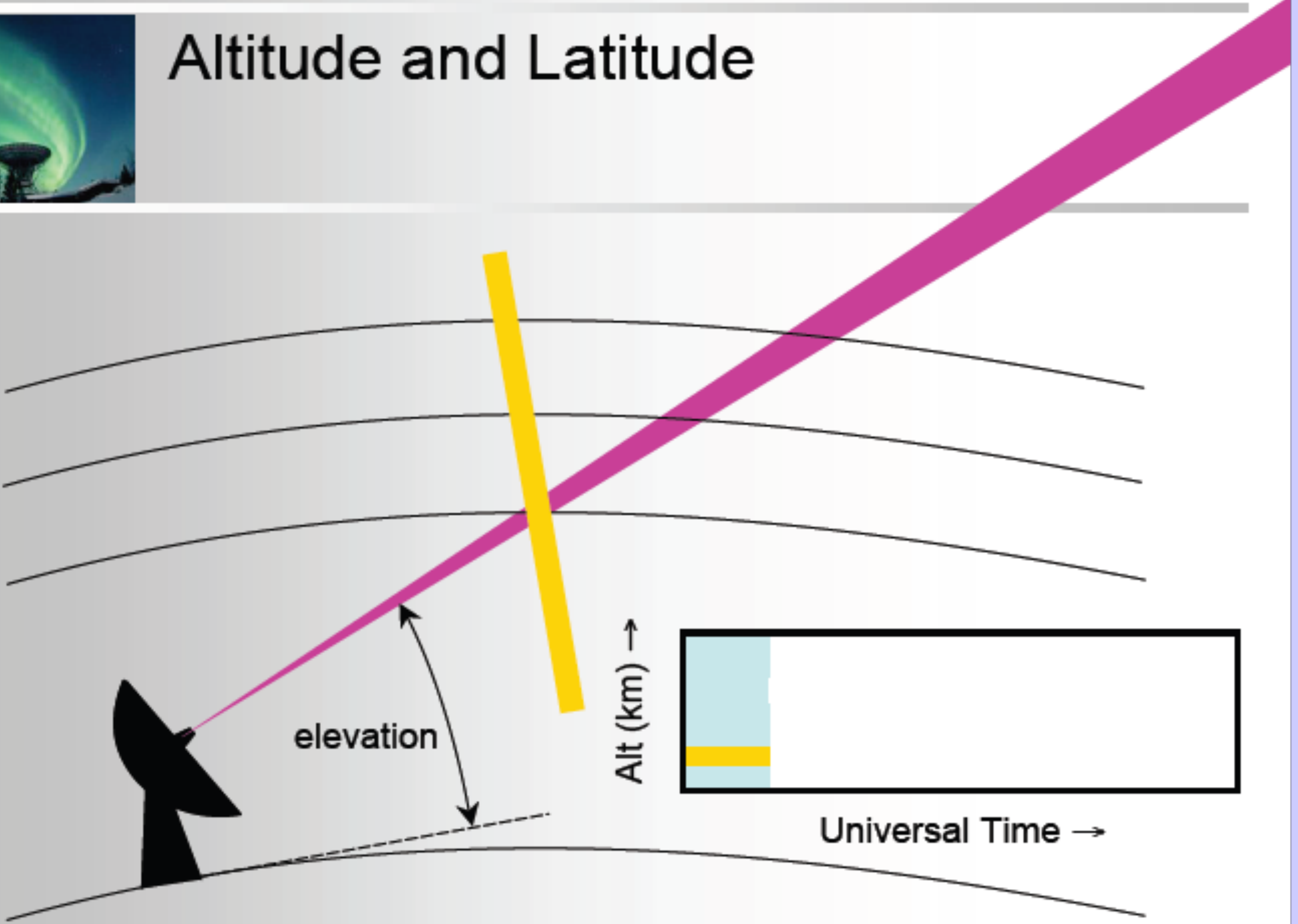

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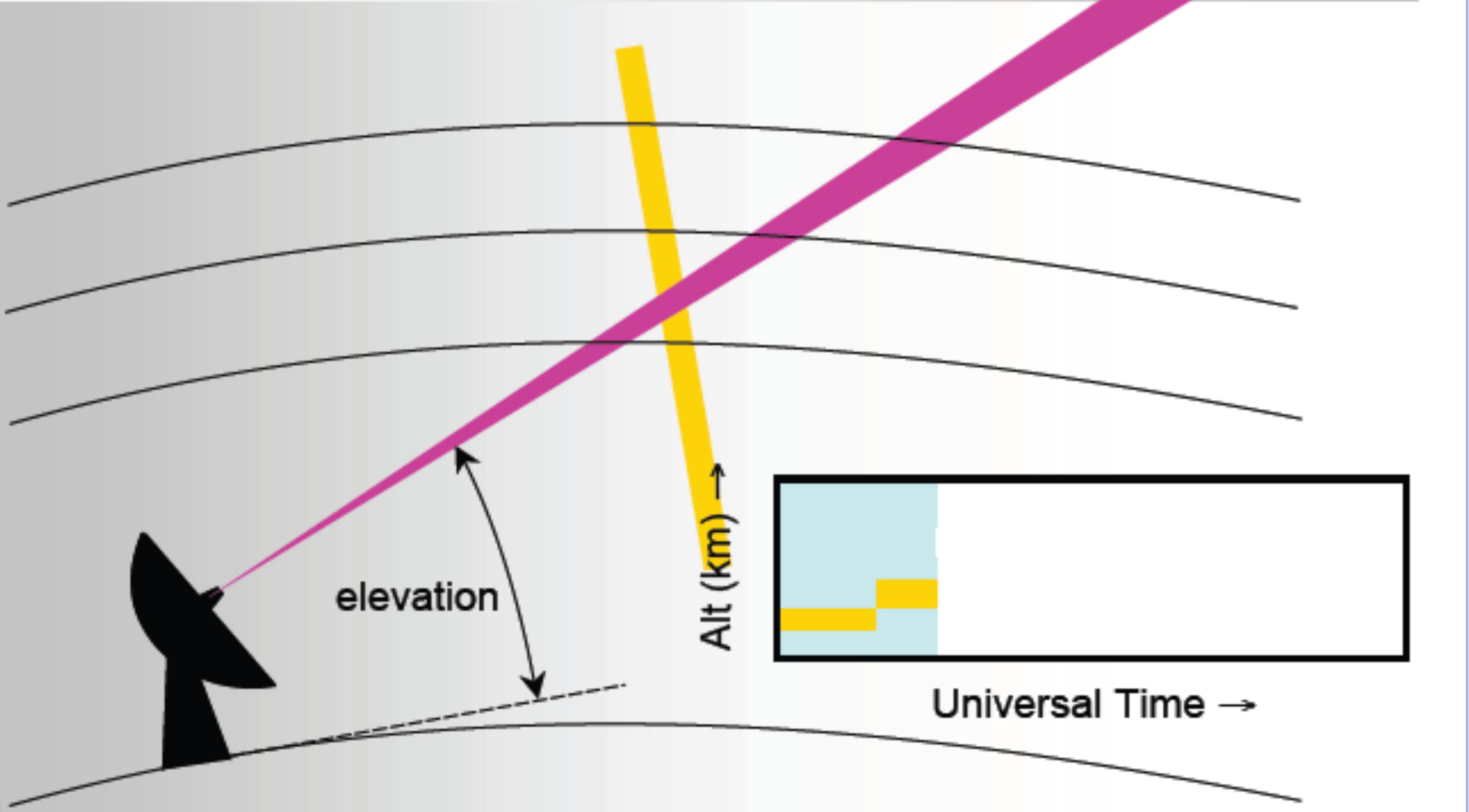

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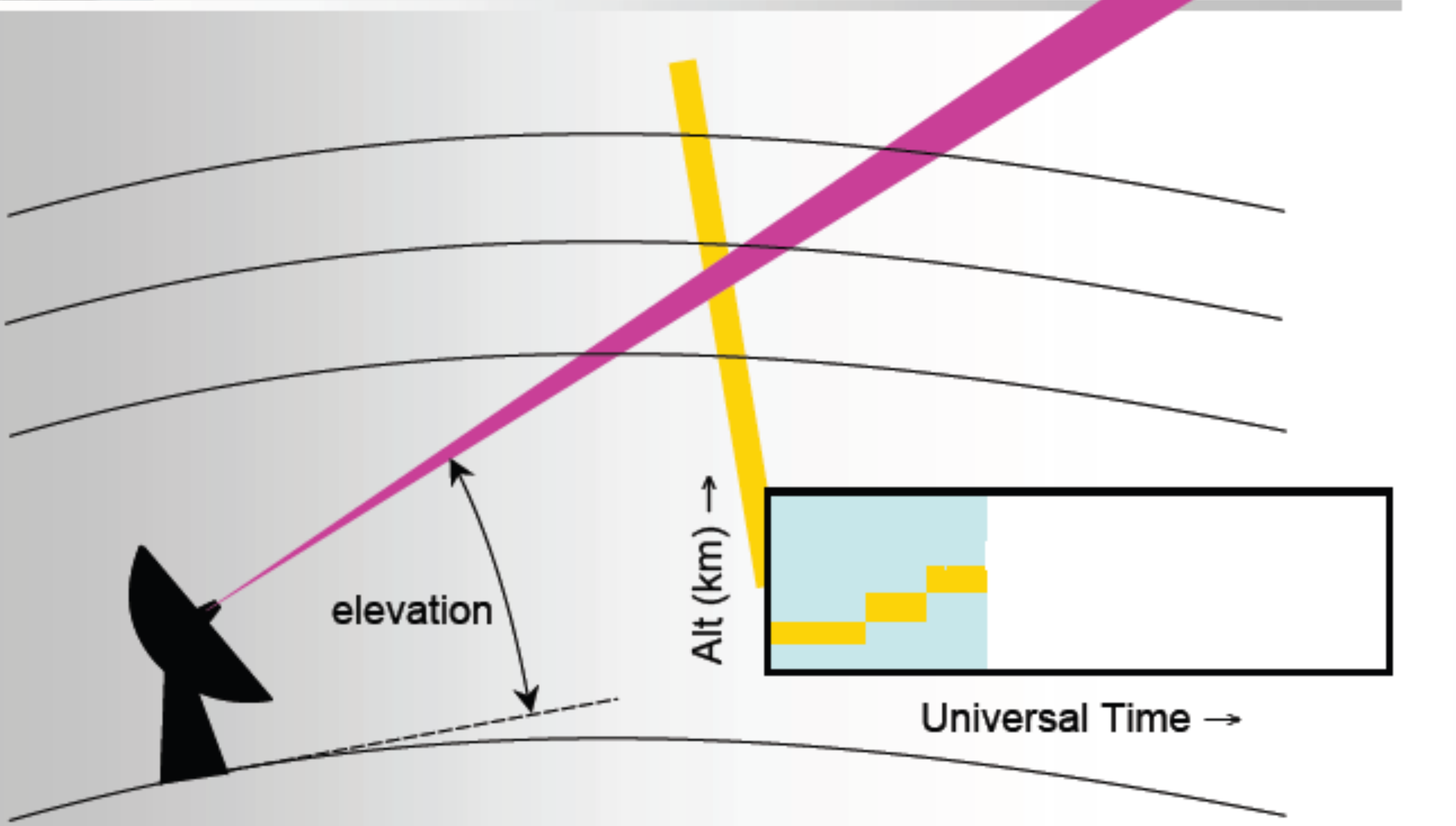

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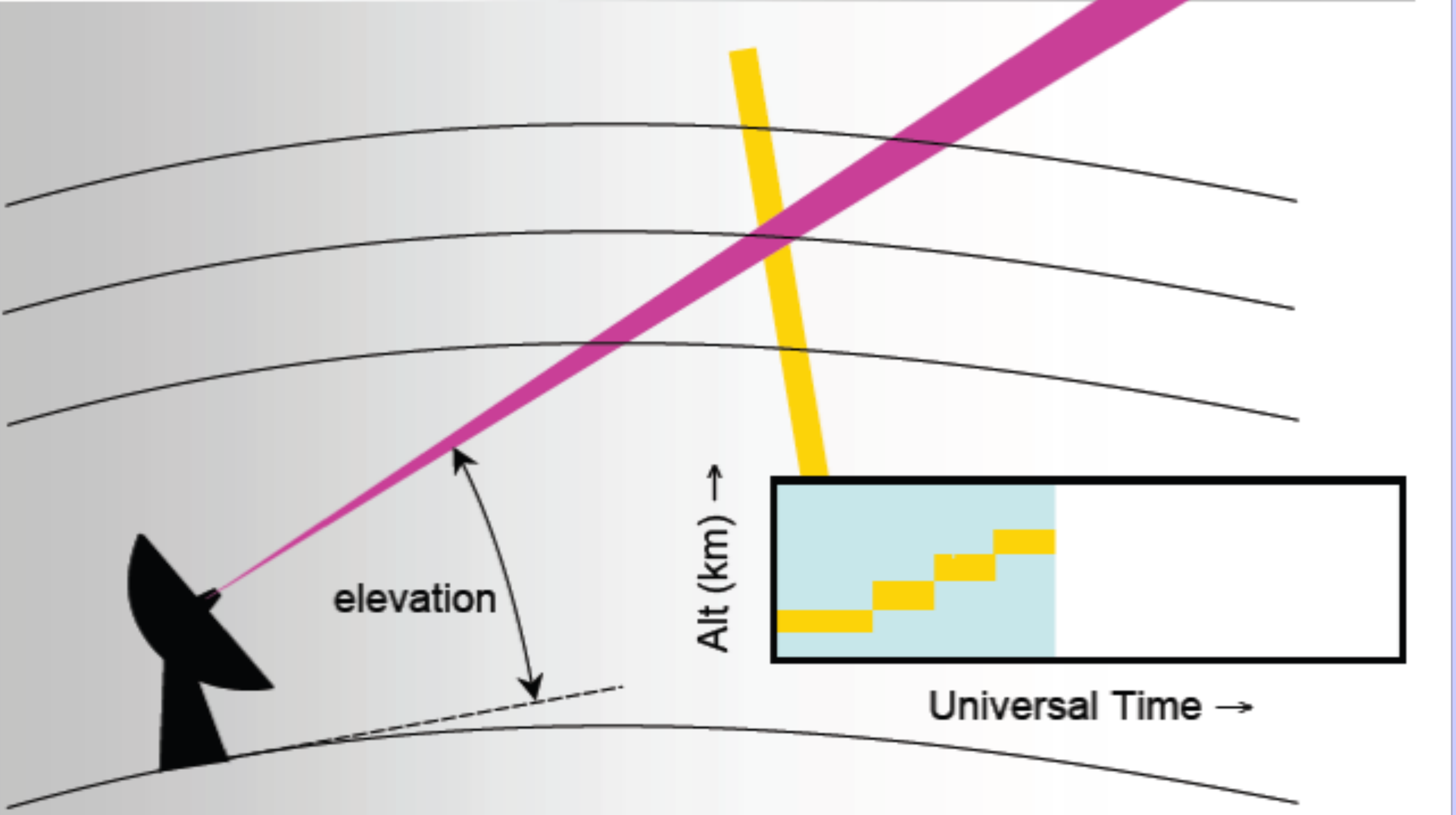

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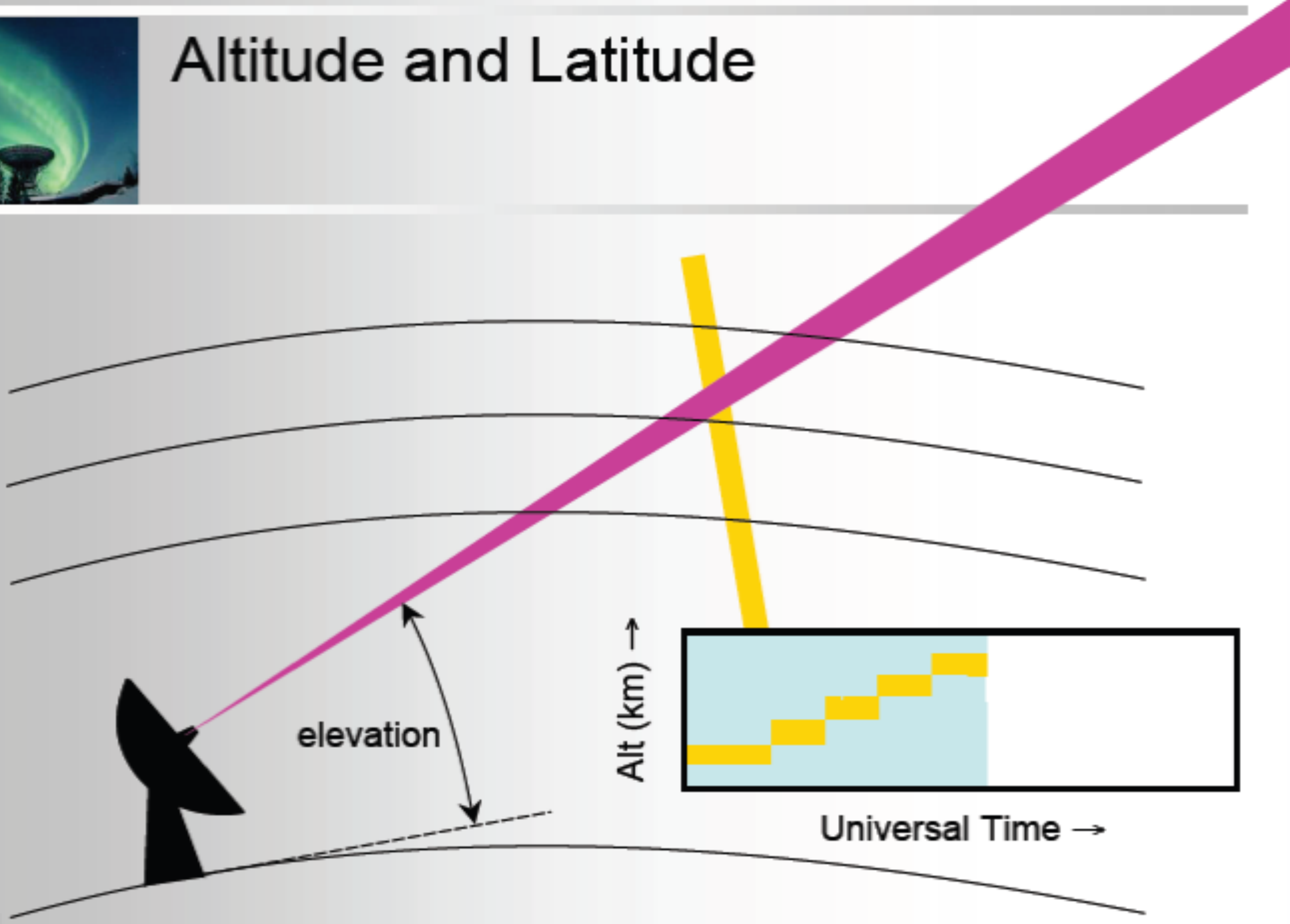

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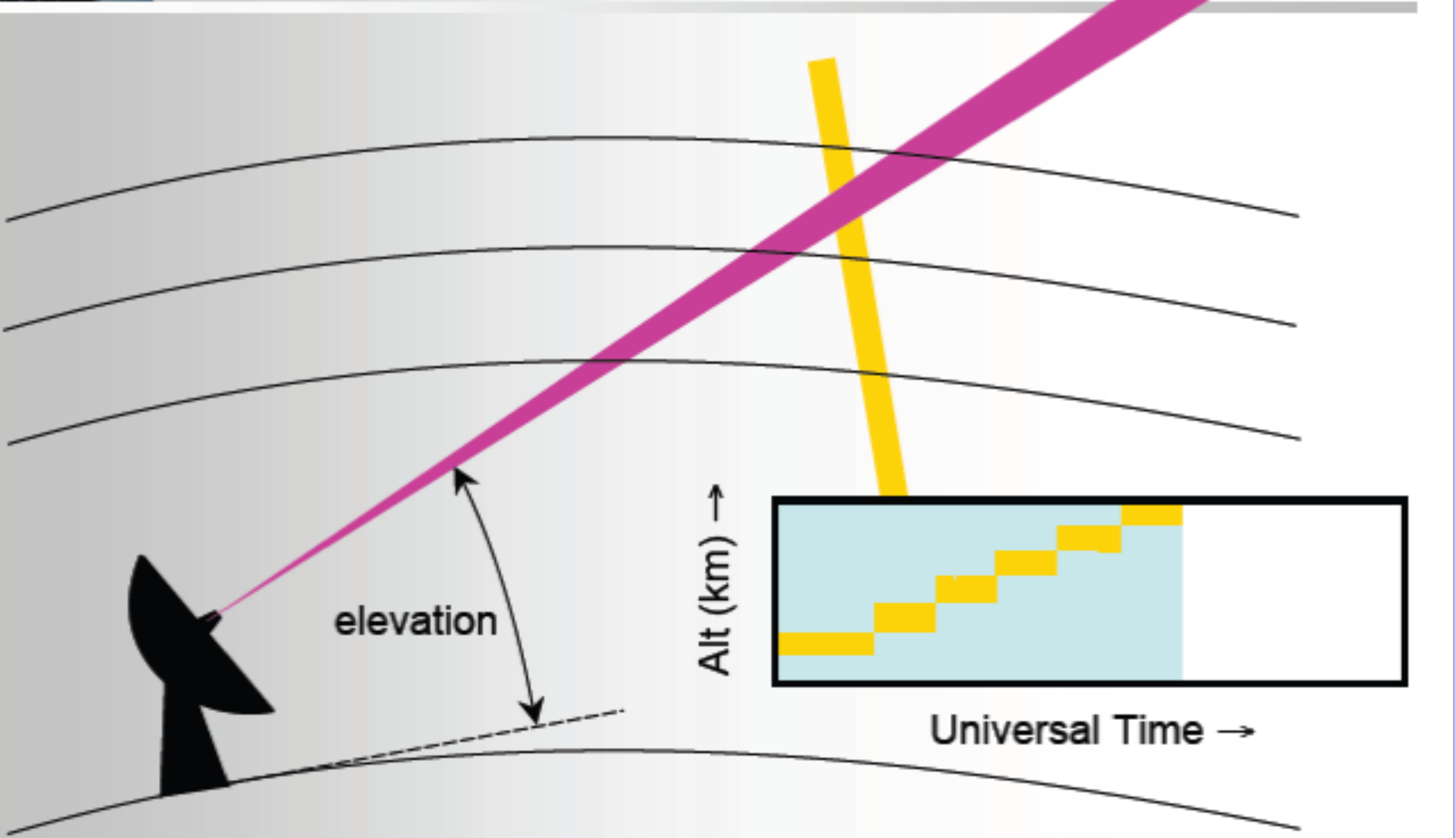

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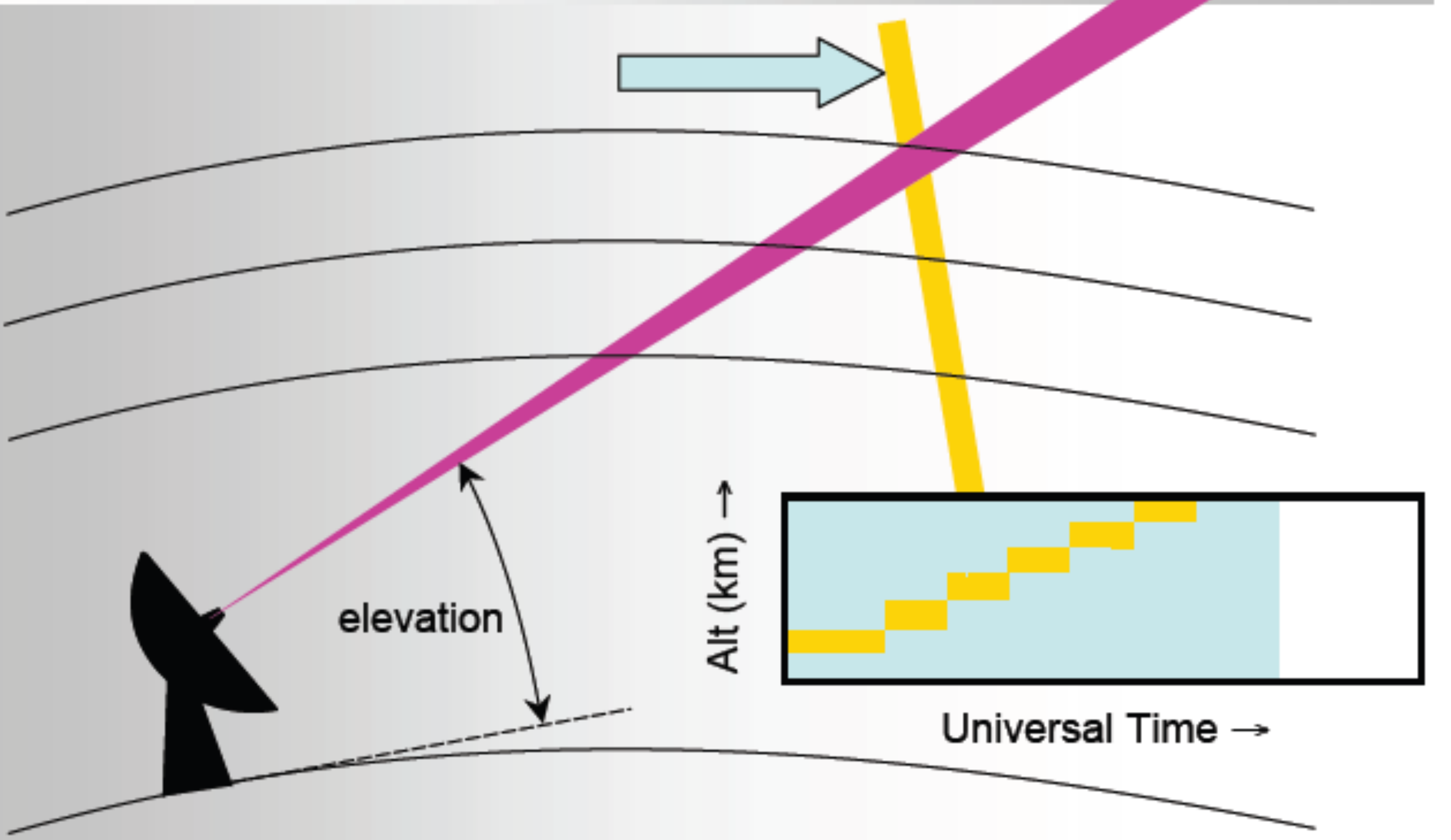
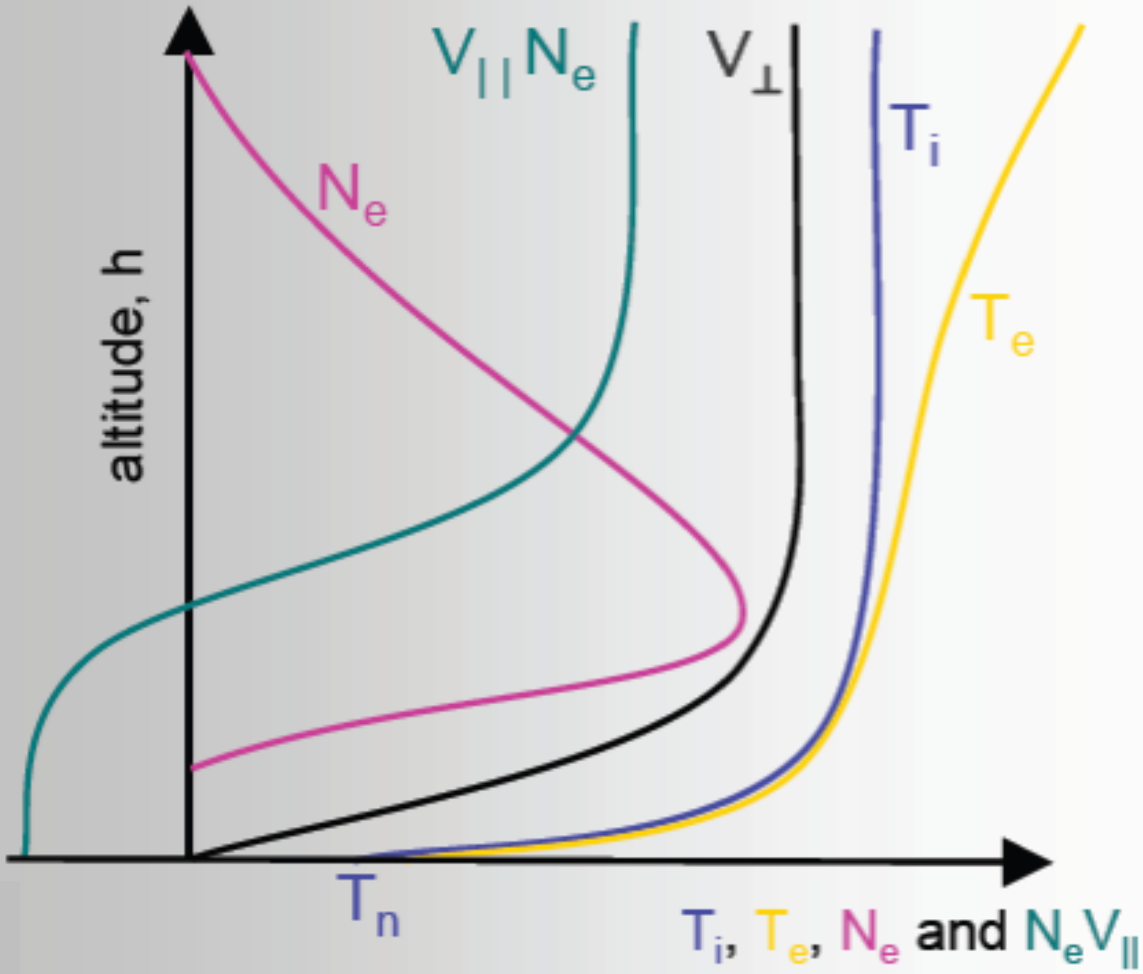


Is the feature moving in altitude or latitude?

- How can we tell whether we are observing an altitude-dependent process or a latitude-dependent process?
- Use our knowledge of physics to determine which kind of variation is more likely.
- Sometimes this can be easy because of the way that parameters change with height (or don't…)

Height Profiles



T_i , $V_\perp$ and $V_{||} N_e$ are approximately independent of h above about 200 km. Thus we can identify latitudinal structures and motions in these variables

T_i Profiles

Why is T_i independent of h?

Ion energy balance equation

Time derivative $d(N_i k_B T_i)/dt$ negligible on timescales $> (1/\nu_{in}) \sim 1$sec

Viscosity negligible on spatial scales > ~ 1km

Strictly, the divergence of heat flux $\nabla.q_i$ and the advection term $\underline{\mathbf{V}}.\nabla(N_i k_B T_i)$ are not always negligible but this is a good approximation at h < ~500km. Gives

$$Q_i - L_i = 0$$

Where the heat gained by the ion gas is the effect of collisions with the n neutral species which transfer some of their energy (of both thermal motions and bulk flow motions)

$$Q_i = \Sigma_n N_i m_i \nu_{in} \{3k_B(T_n - T_i)\, \psi_{in} + m_j\, (V_i - V_n)^2\, \phi_{in}\} /(m_i + m_n)$$

And the velocity dependent correction factors ϕ_{in} and ψ_{in} are close to unity.

T_i Profiles

Why is T_i independent of h?

Loss term L_i is heating of electron gas by collisions of ions with electrons (in fact it is a loss $L_i > 0$ if $T_e < T_i$, but another gain $L_i > 0$ if $T_e < T_i$). From same equation for electrons, for which $m_i/(m_e+m_i) \approx 1$

$$L_i = - N_e \nu_{ie} \{ 3k_B(T_e-T_i) + (V_i-V_e)^2 \}$$

$Q_i - L_i = 0$ gives

$$T_i = T_n + (m_n/3k_B)\,(\phi_{in}/\psi_{in})\,(V_i-V_n)^2 + (\nu_{ie}/\nu_{in})\,\{(m_i+m_n)/m_i\}\,(T_e-T_i)/\psi_{in}$$

For $\phi_{in} = \psi_{in} = 1$,

O^+ ions and O atoms (F-region ionosphere), $\{(m_i+m_n)/m_i\} = 2$

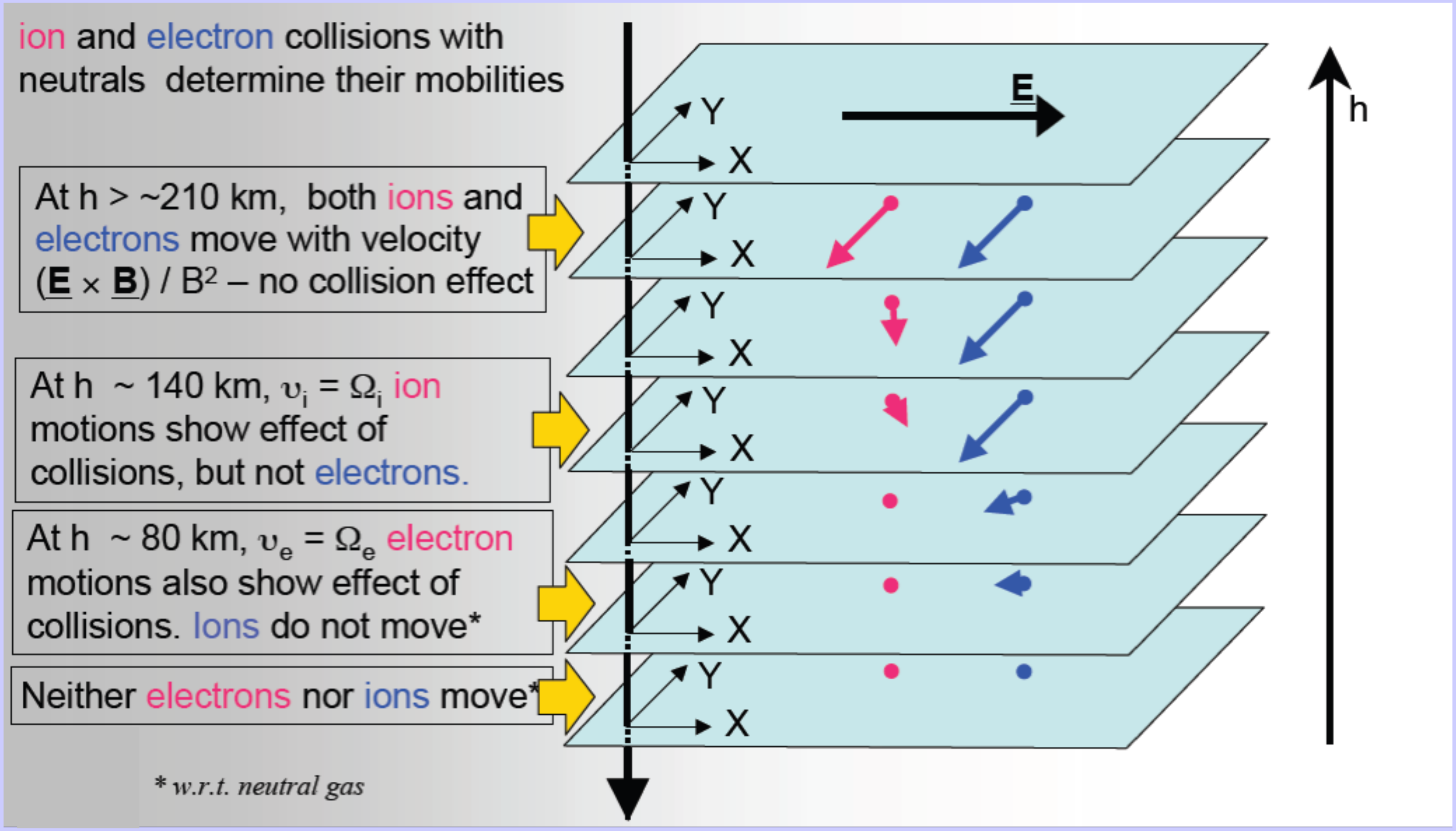
$(m_n/3k_B) = 6.46 \times 10^{-4}$ kg K J^{-1} (in SI units)

Because $T_e \sim T_i$, the second term on the RHS is usually negligible

$$T_i = T_n + 6.46 \times 10^{-4}\,(V_i-V_n)^2$$

T_n, V_i, and V_n are all roughly independent of h – so is T_i

Where is Vperp independent of height?



ion and electron collisions with neutrals determine their mobilities

At h > ~210 km, both ions and electrons move with velocity (**E** × **B**) / B^2 – no collision effect

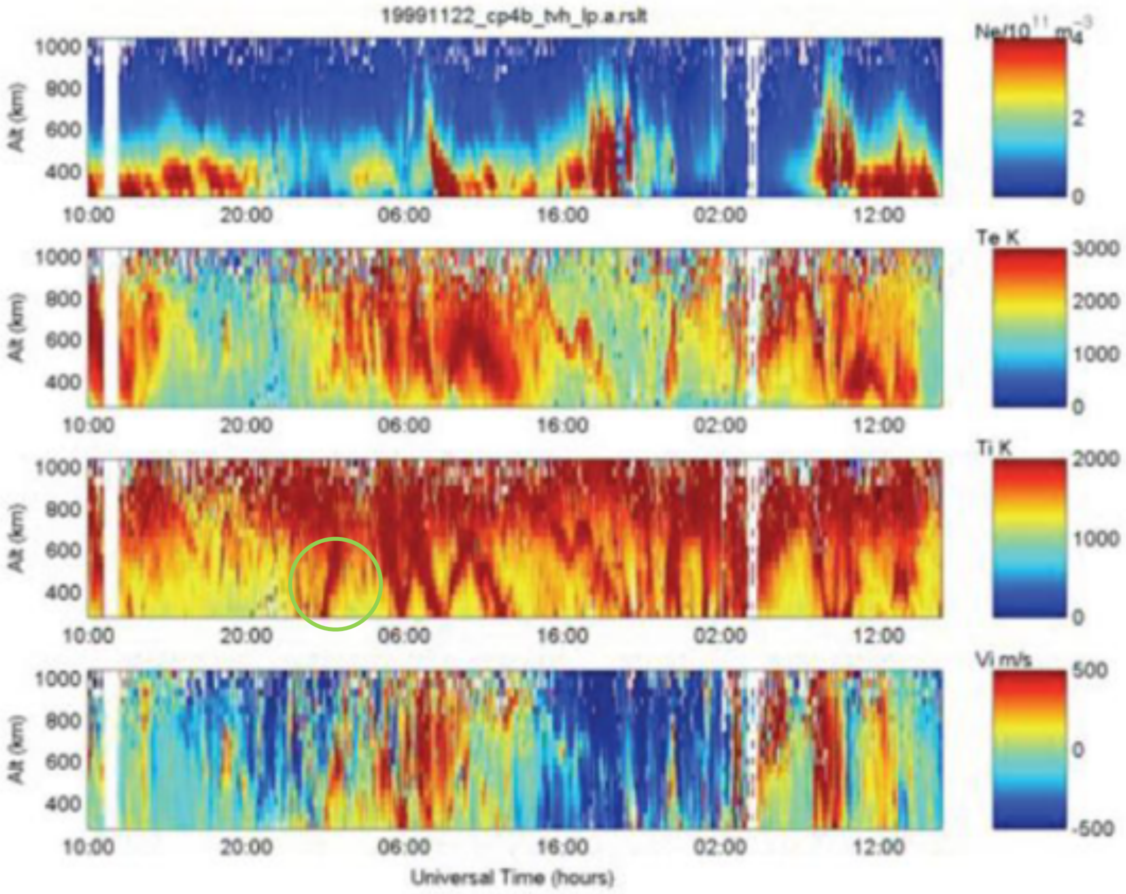
At h ~ 140 km, $\upsilon_i = \Omega_i$ ion motions show effect of collisions, but not electrons.

At h ~ 80 km, $\upsilon_e = \Omega_e$ electron motions also show effect of collisions. Ions do not move*

Neither electrons nor ions move*

*w.r.t. neutral gas

Moving in altitude or latitude?



Electron number density, N_e (m^{-3})

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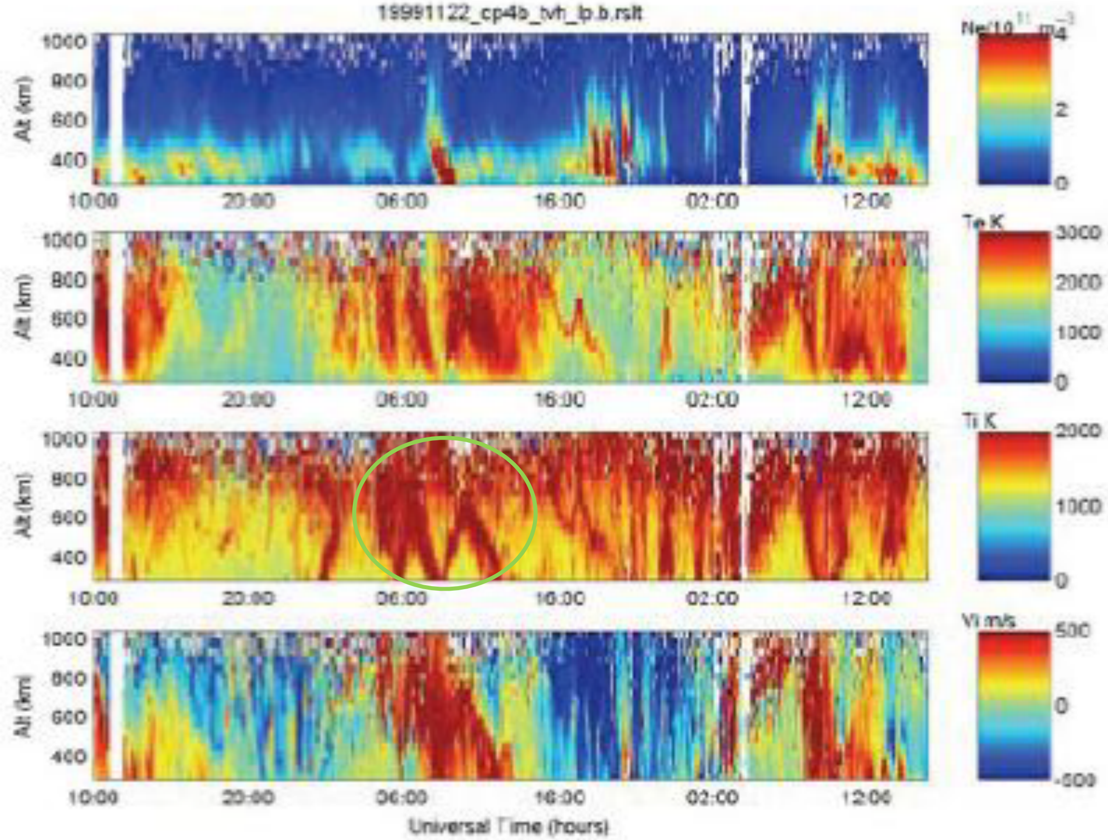
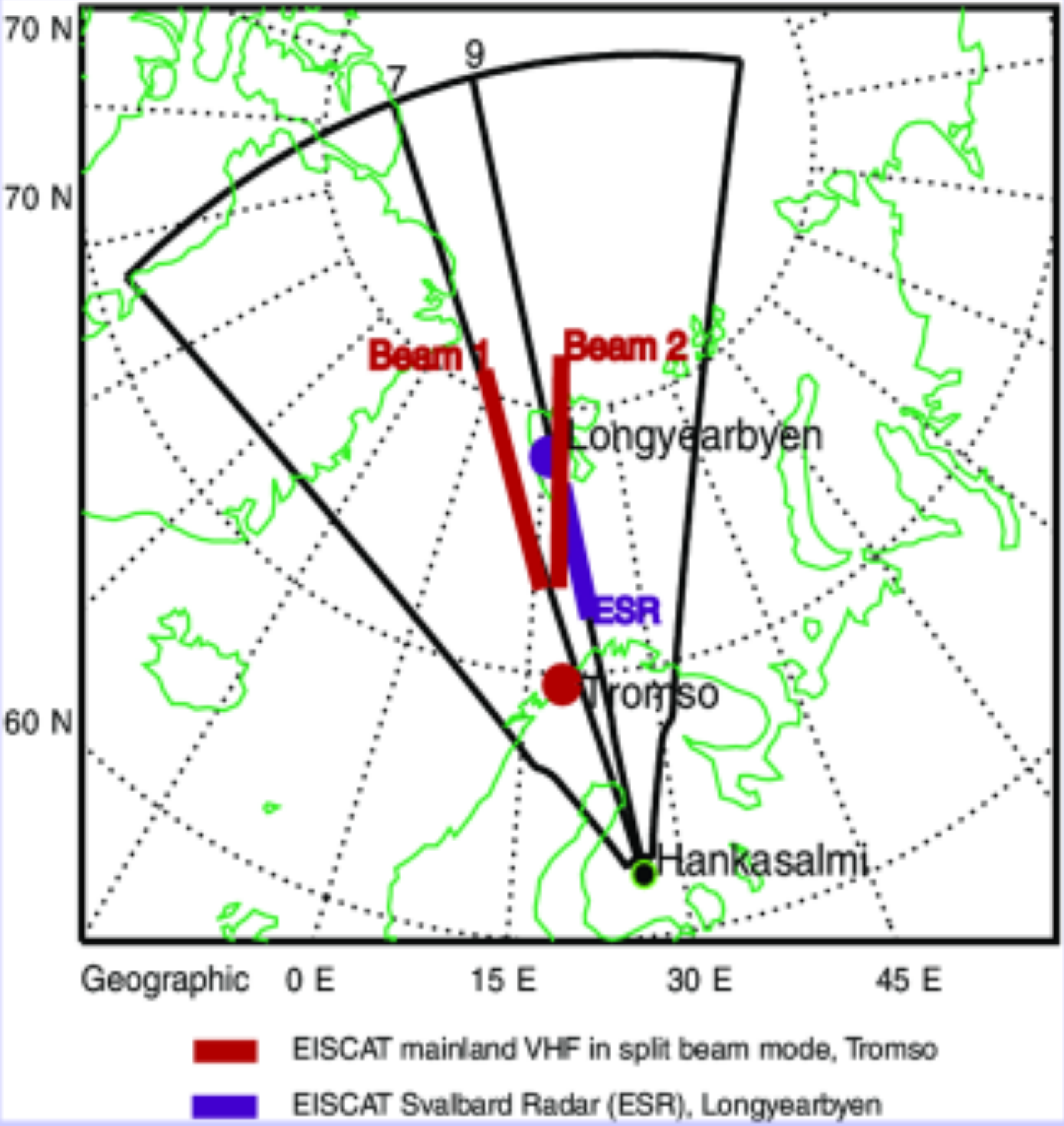
Substorm Cycles

(in CP-4-B data)



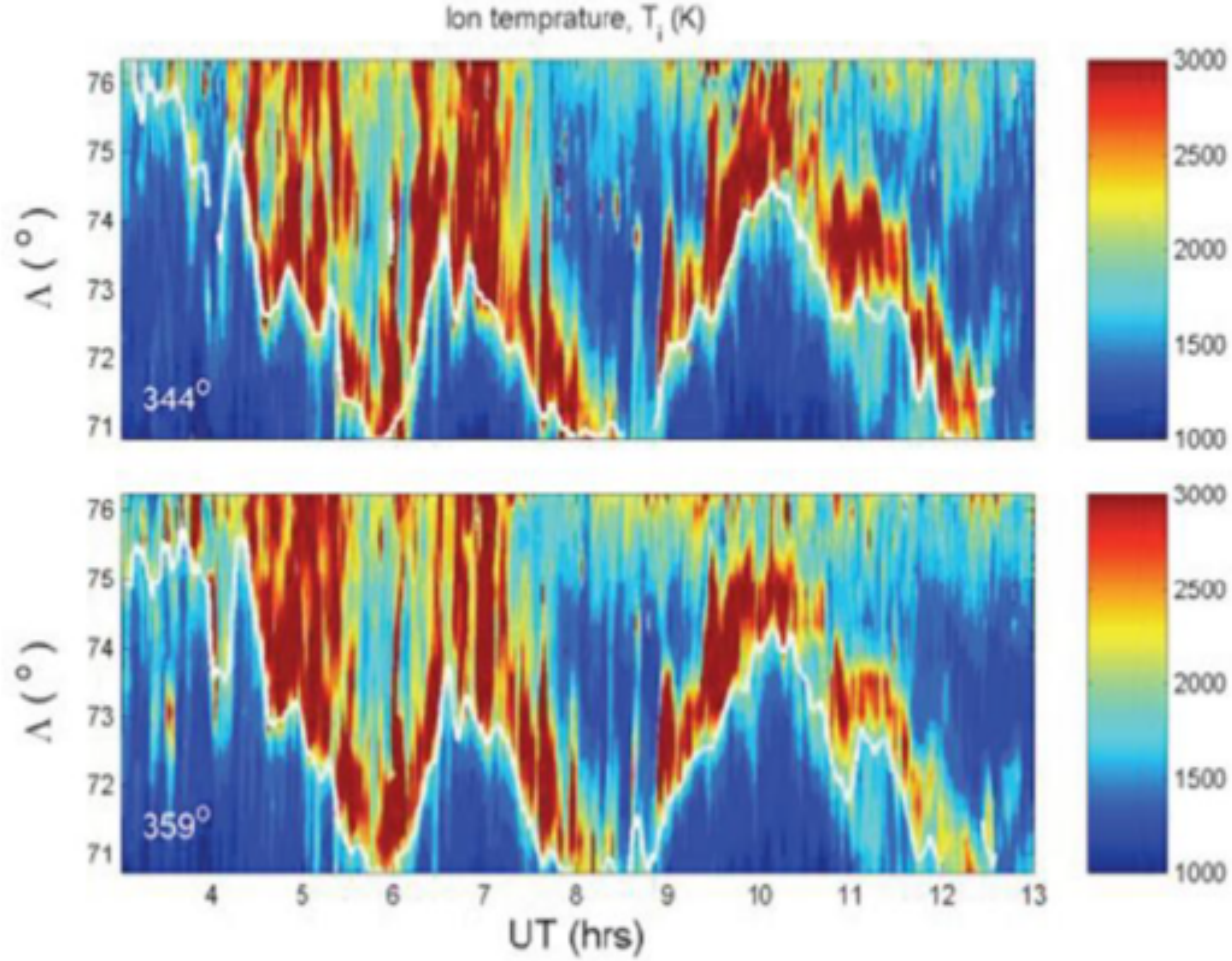
See expansions and contractions. This time MLT ≈ UT + 2.75hr

So 06-12 UT is 8:45-12:45 MLT


70 N
70 N
60 N
7
9
Beam 1
Beam 2
Longyearbyen
ESR
Tromso
Hankasalmi
Geographic
0 E
15 E
30 E
45 E
🟥 EISCAT mainland VHF in split beam mode, Tromso
🟦 EISCAT Svalbard Radar (ESR), Longyearbyen

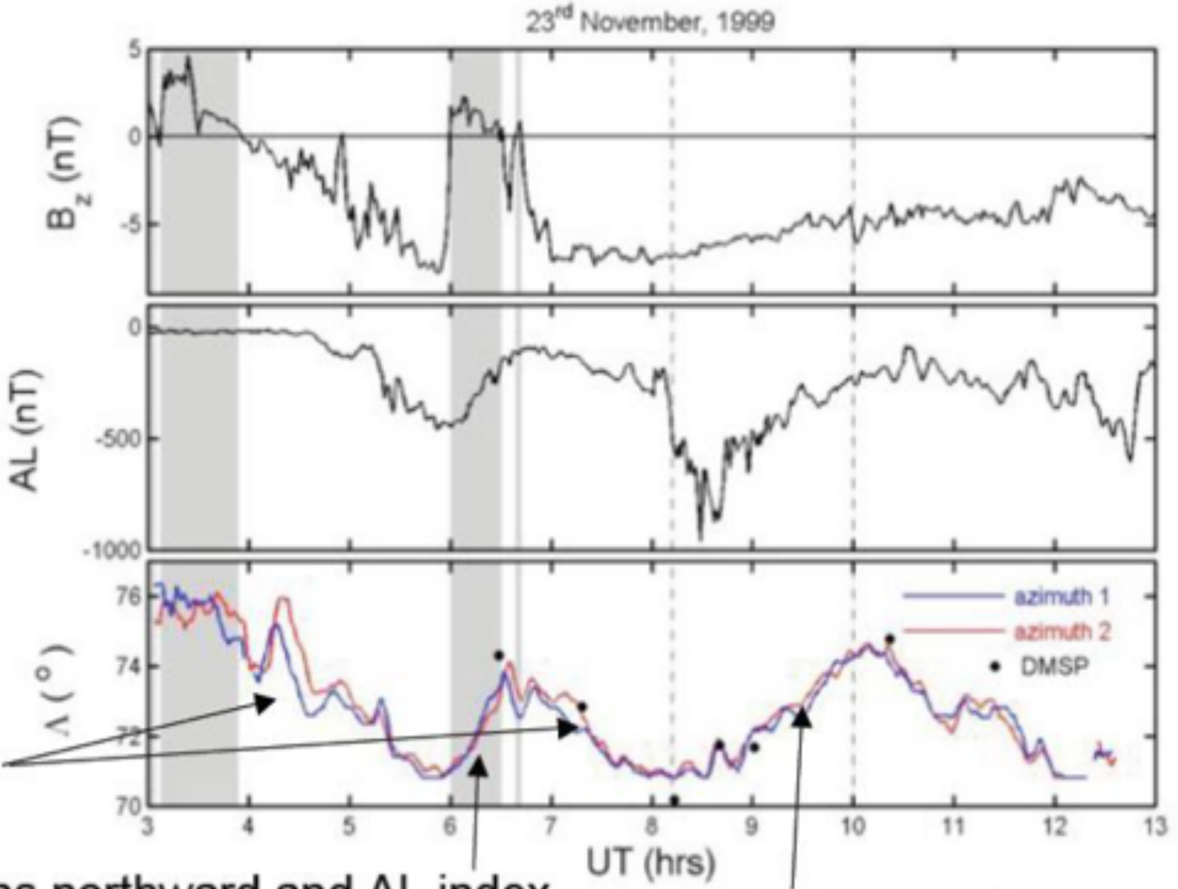
Substorm cycles

Note: changing the contour levels often helps you see an event



Substorm cycles

Use solar wind and magnetic indices to understand the radar data



IMF $B_z < 0$ gives polar cap expansion (growth phase)

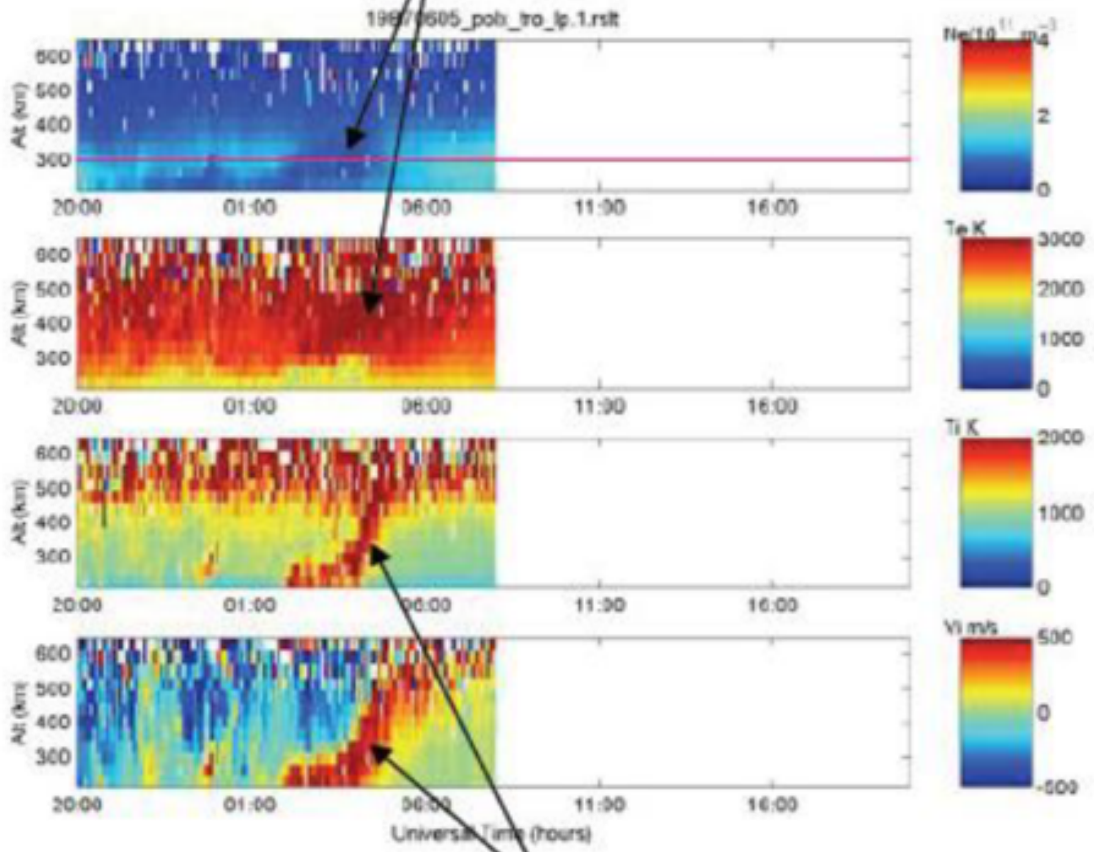
IMF turns northward and AL index shows a substorm expansion phase (polar cap contracts)

IMF stays southward and AL index shows a substorm expansion phase (polar cap contracts)

A Polar Cap Contraction

CP-4-A (UHF), azimuth 2 (points Magnetic north)

Elevation, $\xi = 21°$



Trough in N_e with enhanced T_e

Poleward moving event

N_e and T_e - latitude structure and height structure mixed for this low elevation beam

Look at one height at a time to see time variations

T_i and $V_{los} \approx V_{\perp N}$ approx. indep. of h and so this is a latitudinal structure and it migrates poleward

A word about recombination

- Of course, an O+ atom can directly recombine with a free electron:
    - $O^+ + e^- \rightarrow O + h\nu$ (with rate α_r)
    - But this turns out to be quite slow

- In fact, atomic ions turn into molecular ions more quickly than they recombine

- Hence a quicker process can be rearrangement, followed by dissociative recombination (e.g. with N_2 molecules):
    - $O^+ + N_2 \rightarrow NO^+ + N$ (with rate $k_1[O^+][N_2]$)
    - $NO^+ + e^- \rightarrow N + O$ (with rate $\alpha_1[NO+]Ne$)

- The same thing can be done with O_2 molecules
    - $O^+ + O_2 \rightarrow O_2^+ + O$ (with rate $k_2[O^+][O_2]$)
    - $O_2^+ + e^- \rightarrow O + O$ (with rate $\alpha_2\ [O_2^+]N_e$)

What do those rates depend on?

- $\alpha_r = 7.8 \times 10^{-14} (Te/300)^{-0.5}$

- $\alpha_1 = 2.1 \times 10^{-13} (Te/300)^{-0.85}$
- $\alpha_2 = 1.9 \times 10^{-13} (Te/300)^{-0.5}$

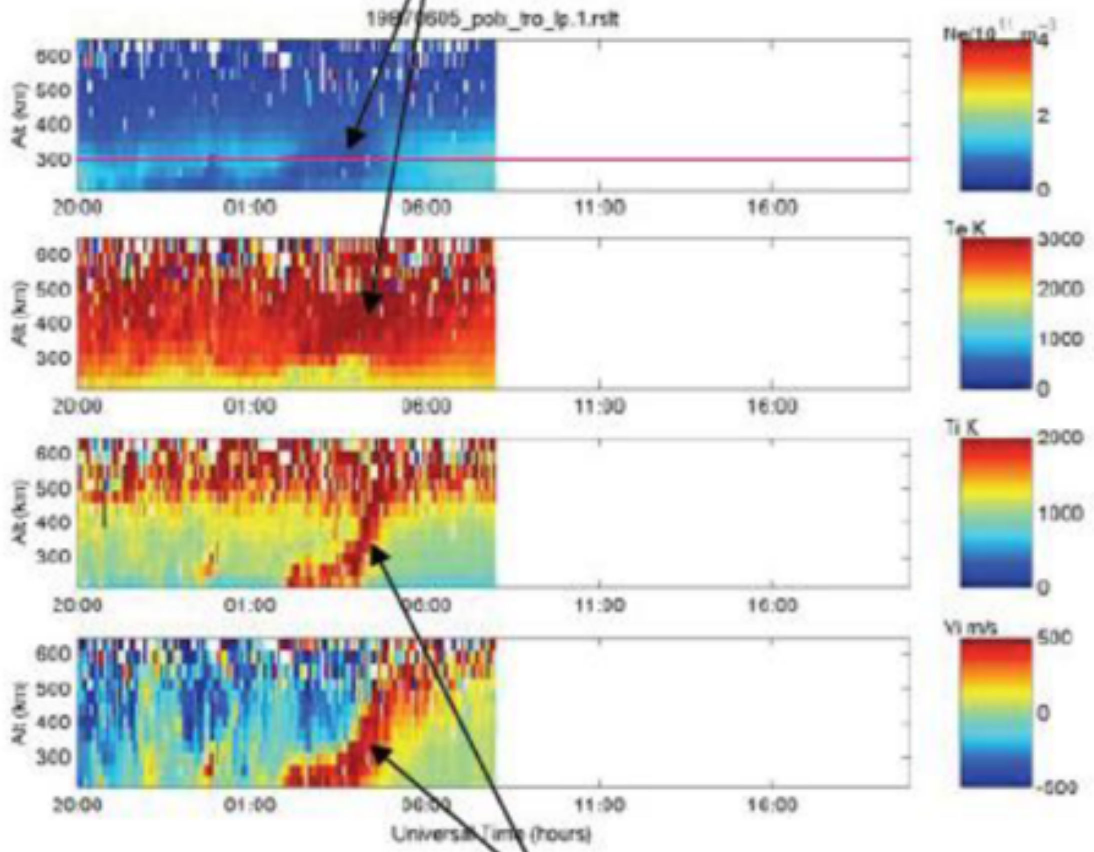
- $k_1 = 2.0 \times 10^{-18}$
- $k_2 = 2.0 \times 10^{-17} (Tr/300)^{-0.4}$
  - $Tr = (Ti+Te)/2$

So, the hotter the plasma, the quicker it recombines, and we often see F-region density depletions associated with high temperature

A Polar Cap Contraction

CP-4-A (UHF), azimuth 2 (points Magnetic north)

Elevation, $\xi = 21°$



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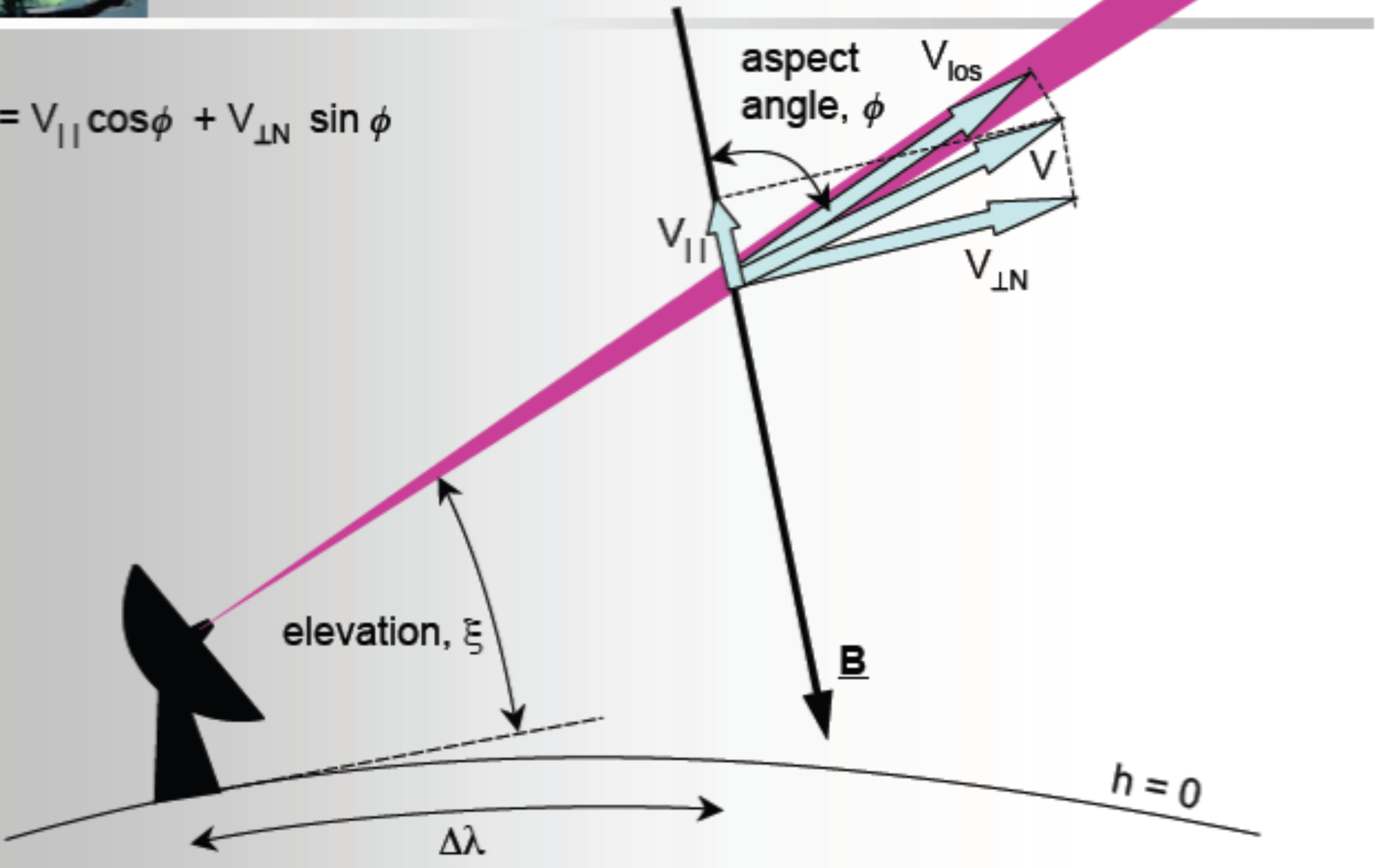
Line-of-sight velocity

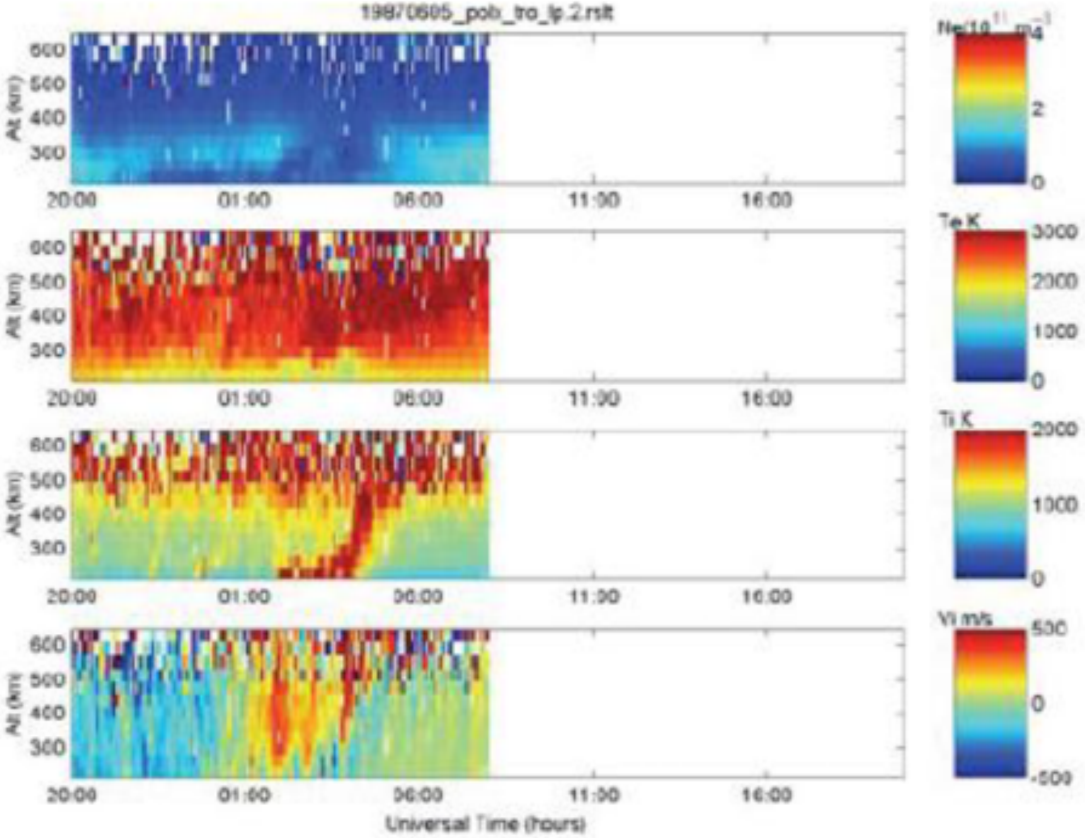
e.g. for a northward-pointing beam

$V_{los} = V_{||}\cos\phi + V_{\perp N}\sin\phi$



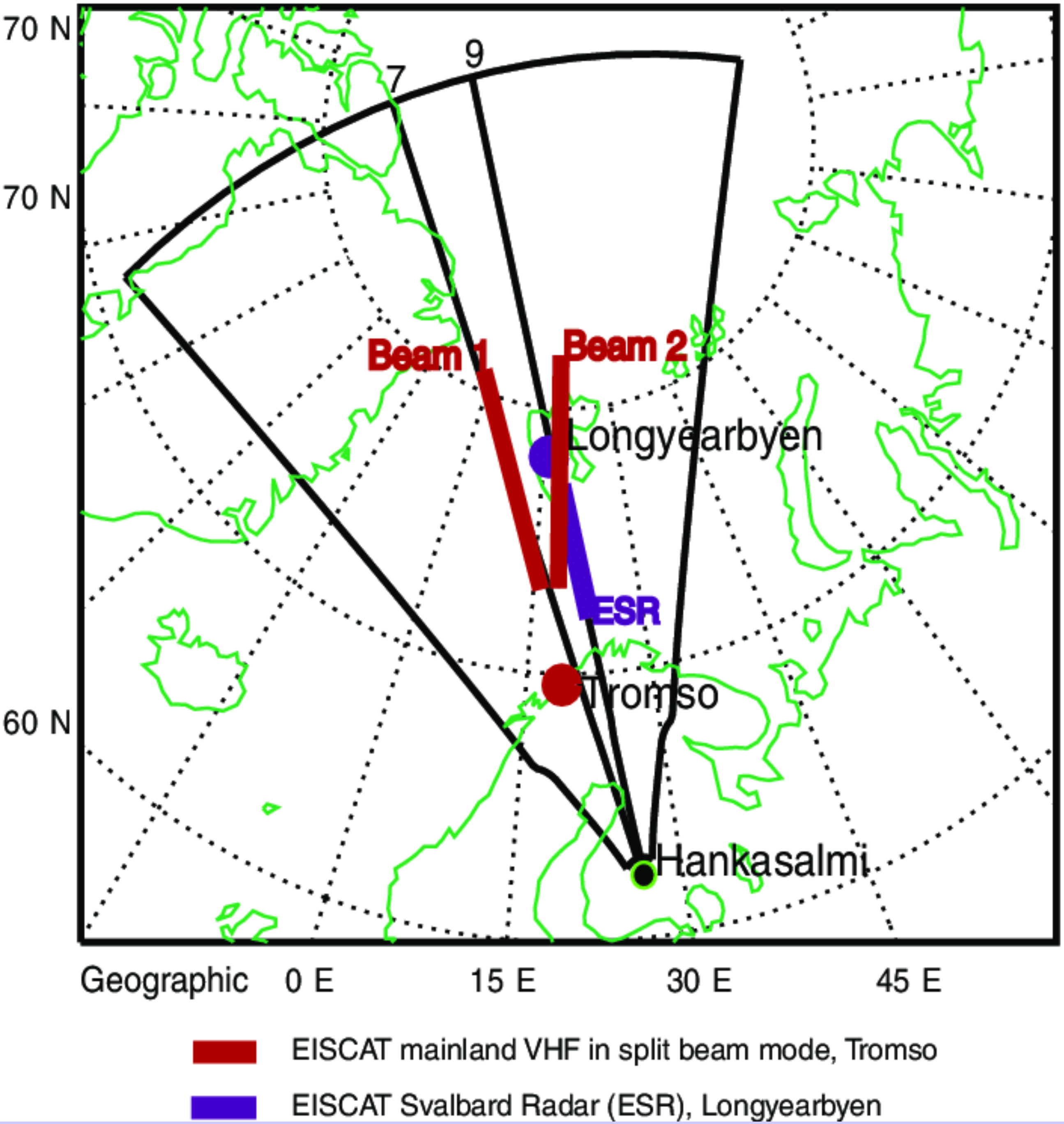
A Polar Cap Contraction

CP-4-A (UHF), azimuth 1 (points 12° east of magnetic north)



N_e, T_e and Ti show the same features as aximuth1 – gives us a orientation w.r.t. the L-shells and a minimum extent

V_{los} is quite different to that for azimuth 1 – shows either longitudinal structure or, more likely, along L-shell convection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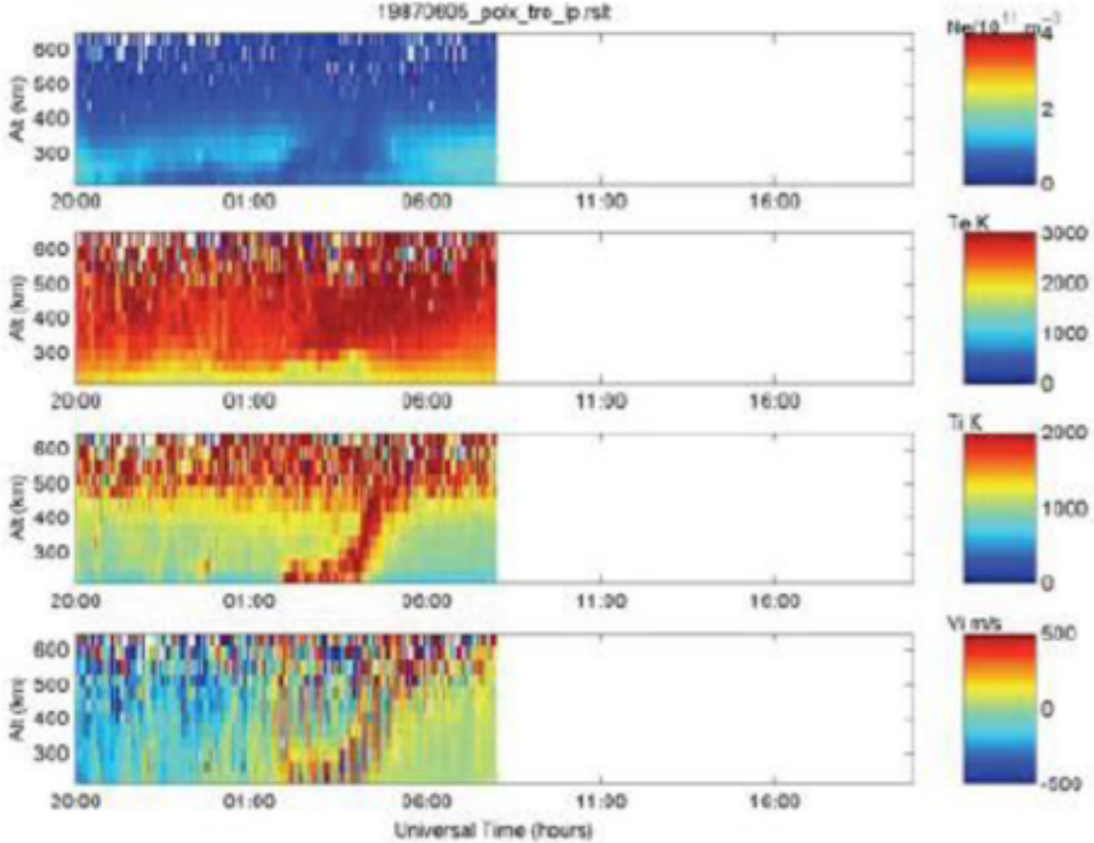
A Polar Cap Contraction

CP-4-A, both azimuths



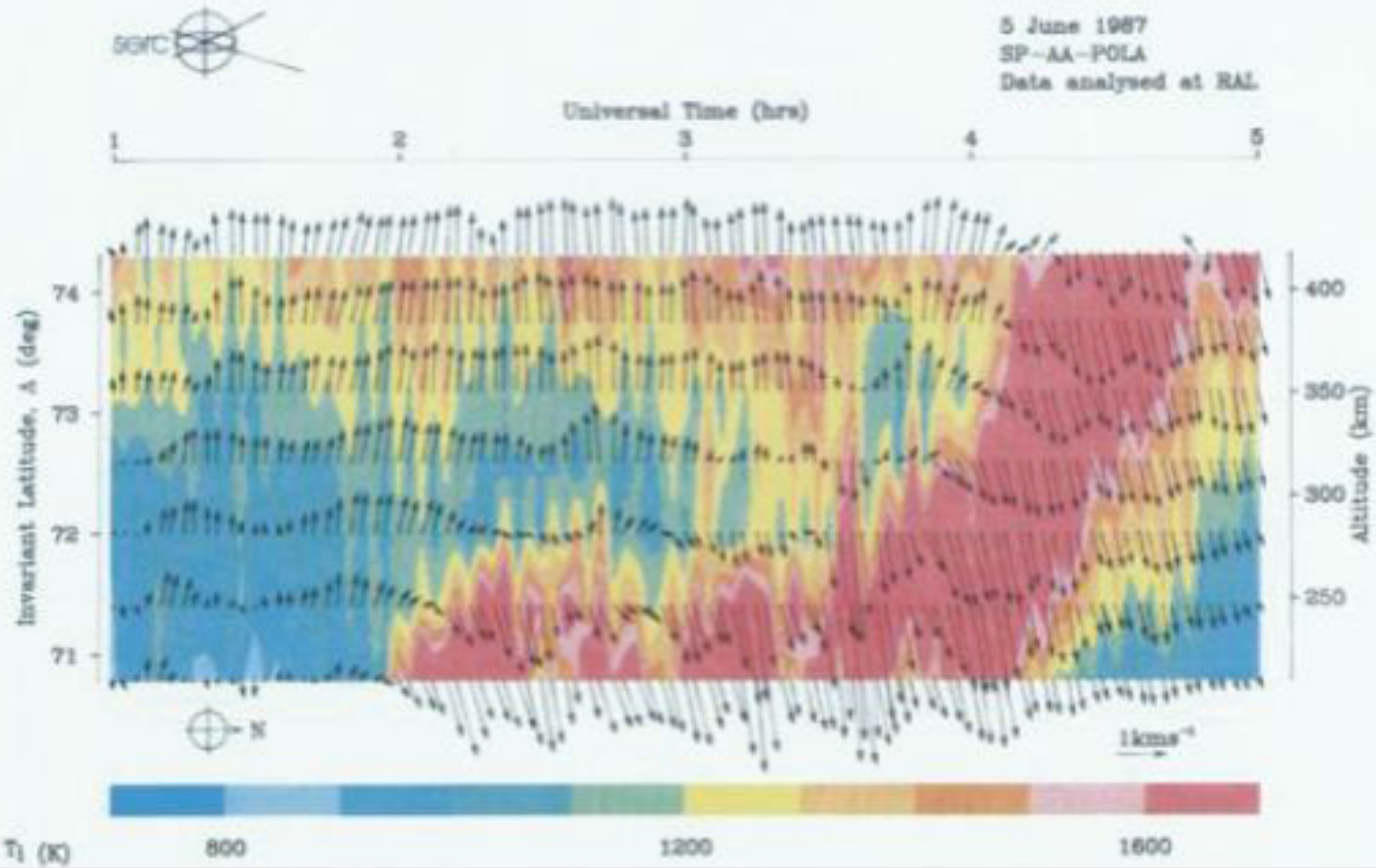
structure and differences show show best if both azimuths are interleaved on the same plot

Vertical stripes in V_{los} highlight the differences between the two beams

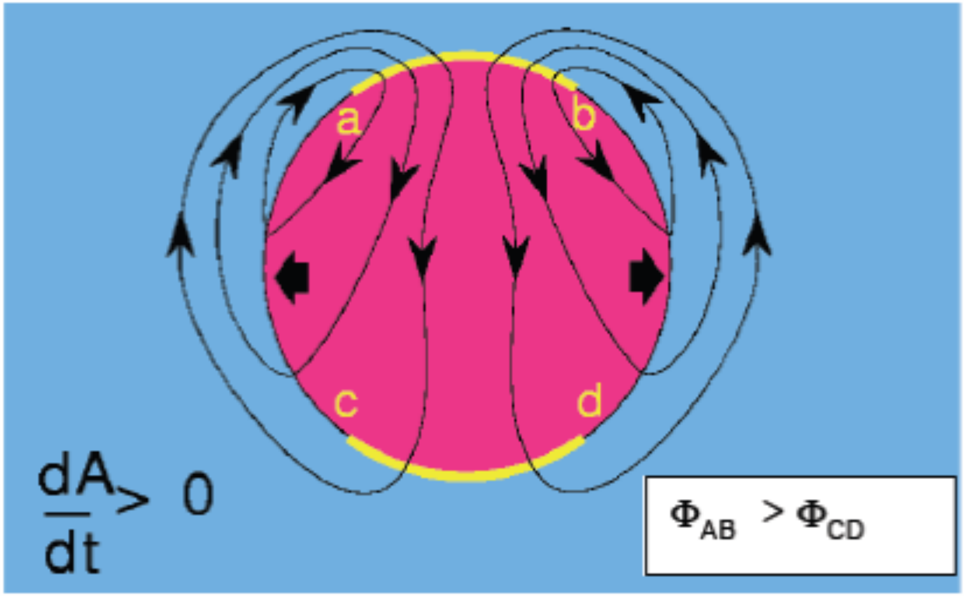
A Polar Cap Contraction

Beamswinging E vectors superposed on T_i plot

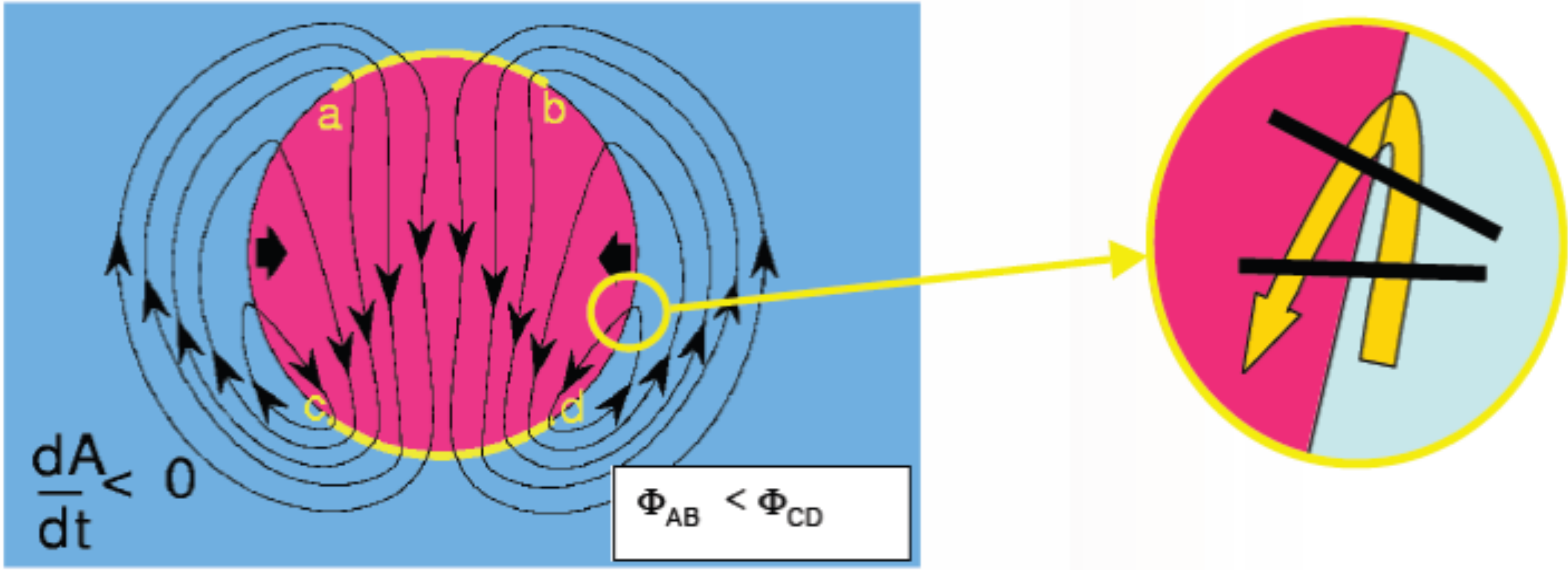
Note band of high T_i is only on trailing side of convection reversal boundary (OCB)



Westward velocity up, eastward velocity down growth phase



expansion and recovery phases

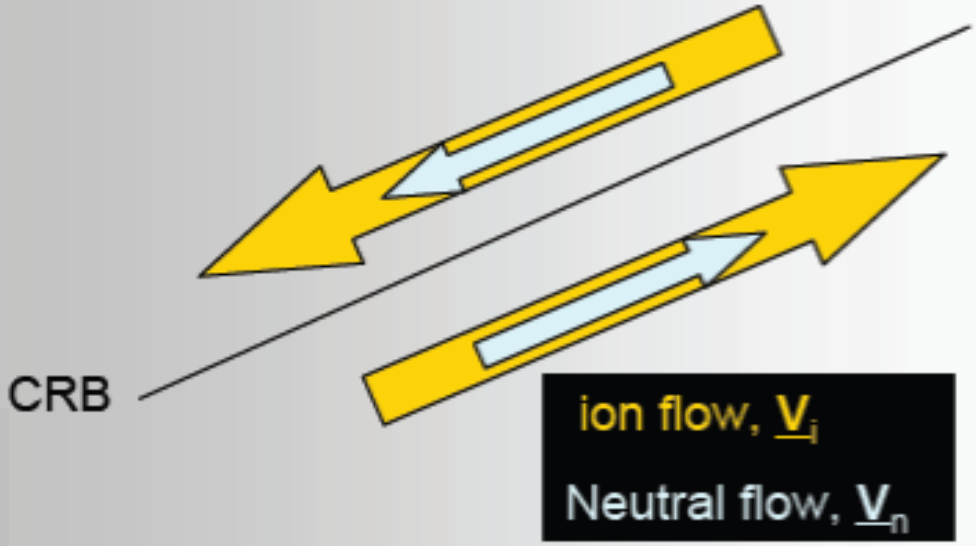


In substorm expansion phase, reconnection voltage in cross-tail current sheet (that destroys open flux) exceeds that at dayside magnetopause (which generates open flux) and so the open polar cap contracts

Ion-neutral frictional heating event

Caused by polar cap contraction

$T_i = T_n + (m_n/3k_B)\,|\underline{\mathbf{V}}_i-\underline{\mathbf{V}}_n|^2$



$N_n >> N_i$; means that responses in $\underline{\mathbf{V}}_n$ to changes of $\underline{\mathbf{V}}_i$ are small and slow

e.g. given enough time $\underline{\mathbf{V}}_n \sim \underline{\mathbf{V}}_i /3$. Would give:-

$|\underline{\mathbf{V}}_i-\underline{\mathbf{V}}_n|^2 = (2V_i/3)^2 = 4V_i^2/9$

typically $V_i = 1\ \mathrm{kms}^{-1}$

T_n estimate – use minima in observed T_i

→ $T_n \approx 800$ K

eqn. gives $T_i \approx 1090$ K

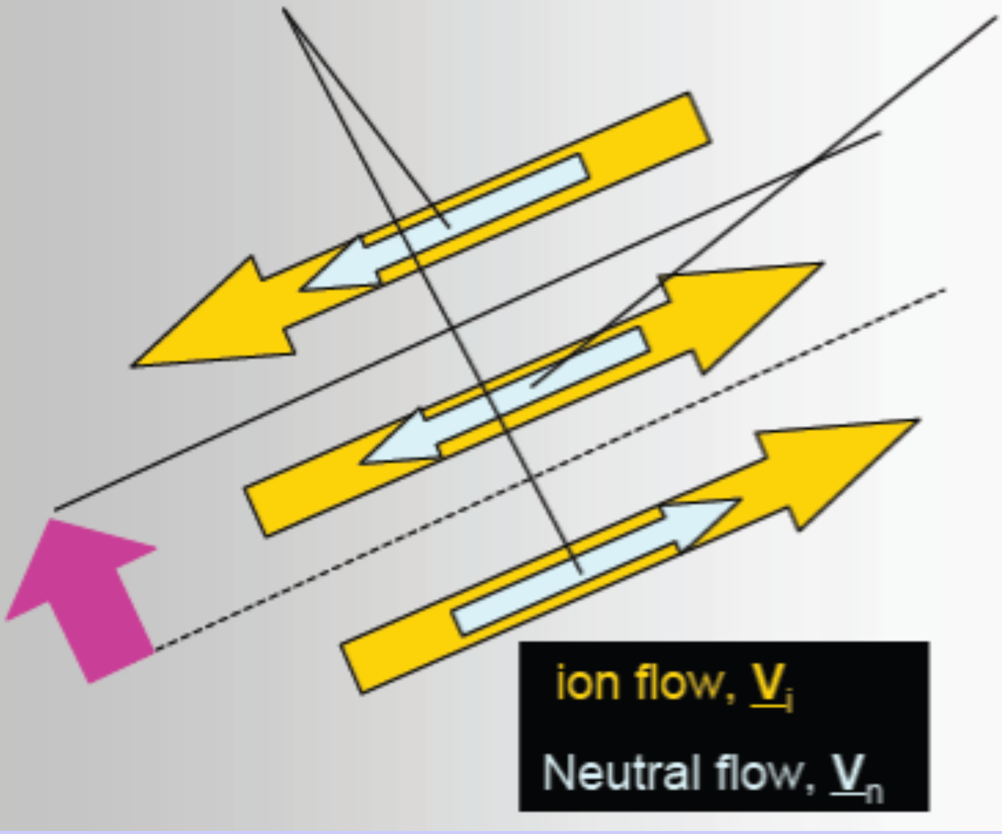
Ion-neutral frictional heating event

Caused by polar cap contraction

$T_i = T_n + (m_n/3k_B)\,|\underline{V}_i - \underline{V}_n|^2$

Boundary moves so ion flows reverse in band between old and new locations

As before $T_i \approx$ 1090 K here



Neutrals do not respond for a while. In the band $\underline{V}_n = -\underline{V}_i/3$

$(\underline{V}_i - \underline{V}_n)^2 = (4V_i/3)^2 = (16/9)V_i^2$

So this term is 4 times larger

For the typical $V_i = 1\ \mathrm{kms}^{-1}$

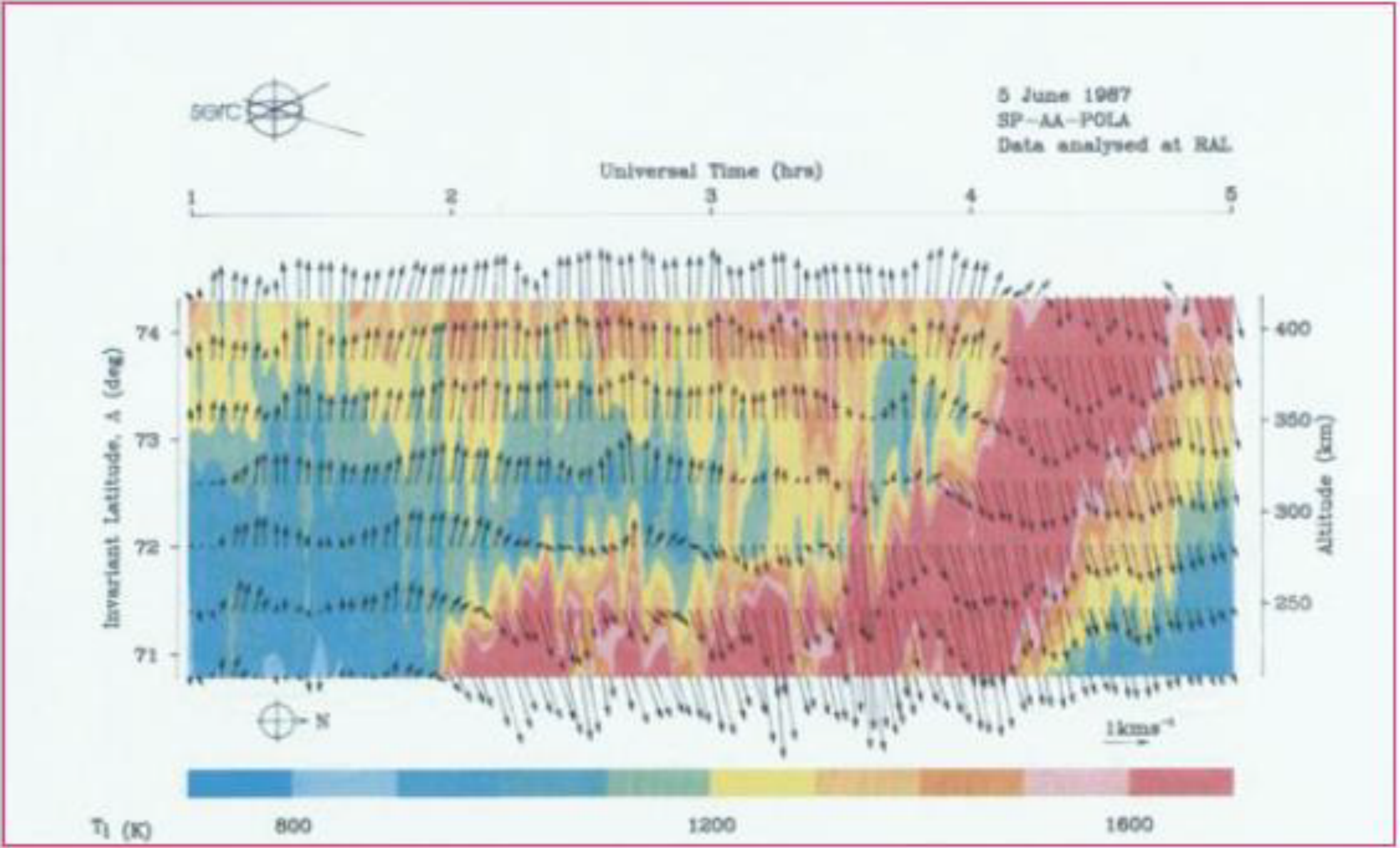
and $T_n \approx$ 800 K

eqn. gives $T_i \approx$ 1950 K

A Polar Cap Contraction

Beamswinging E vectors superposed on T_i plot

Note band of high T_i is only on trailing side of convection reversal boundary (OCB)

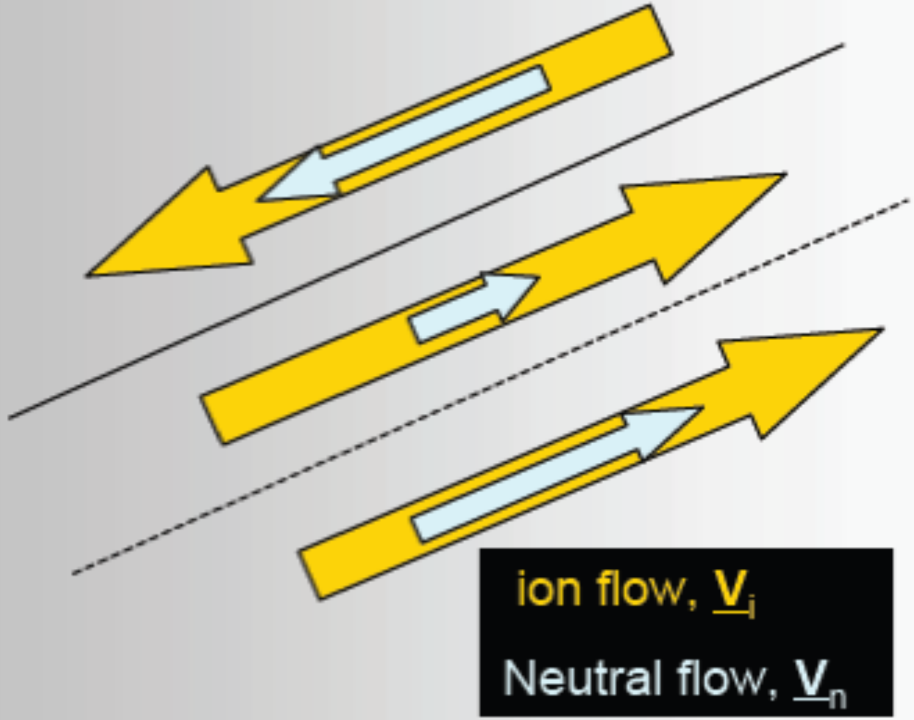


Ion-neutral frictional heating event

Caused by polar cap contraction

$T_i = T_n + (m_n/3k_B)\ |\underline{\mathbf{V}}_i - \underline{\mathbf{V}}_n|^2$

high Ti in this band slowly subsides as neutral begin to respond

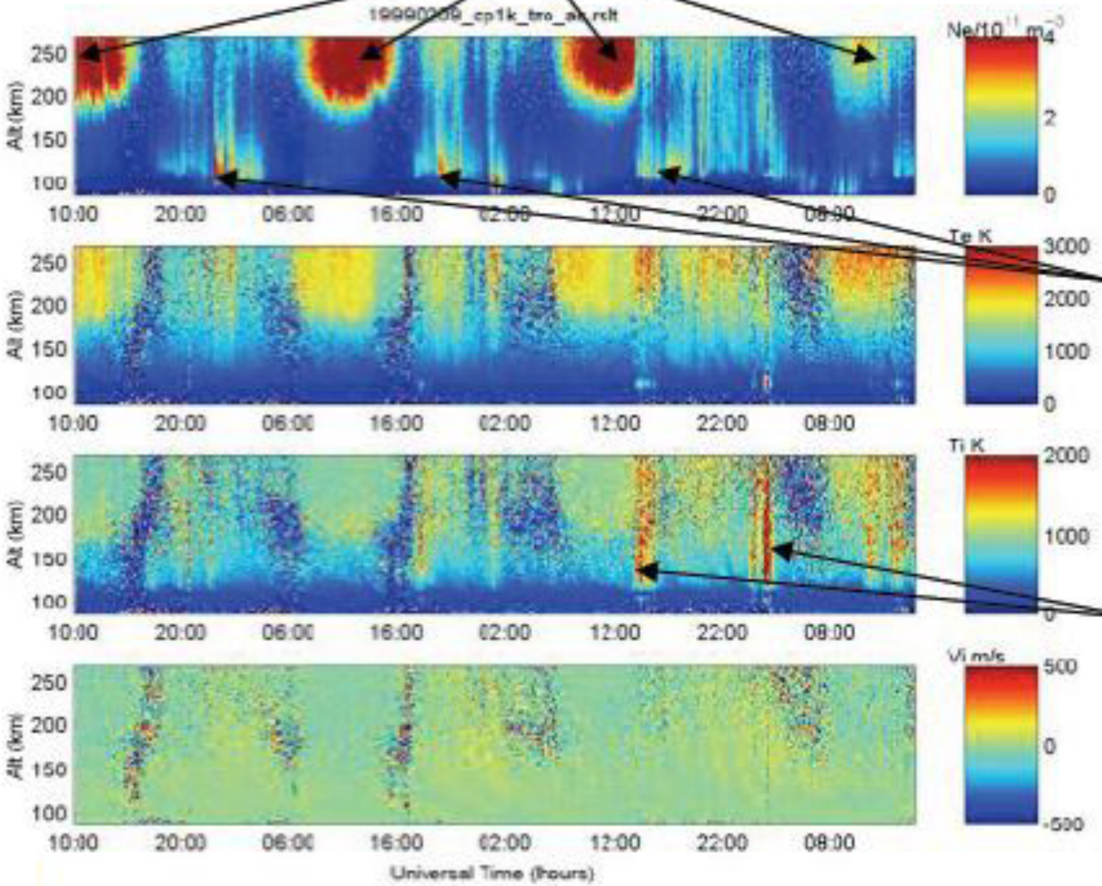


CP1 – Field-aligned

(a winter run lasting 3 days)

Dayside maxima in N_e (and T_e)

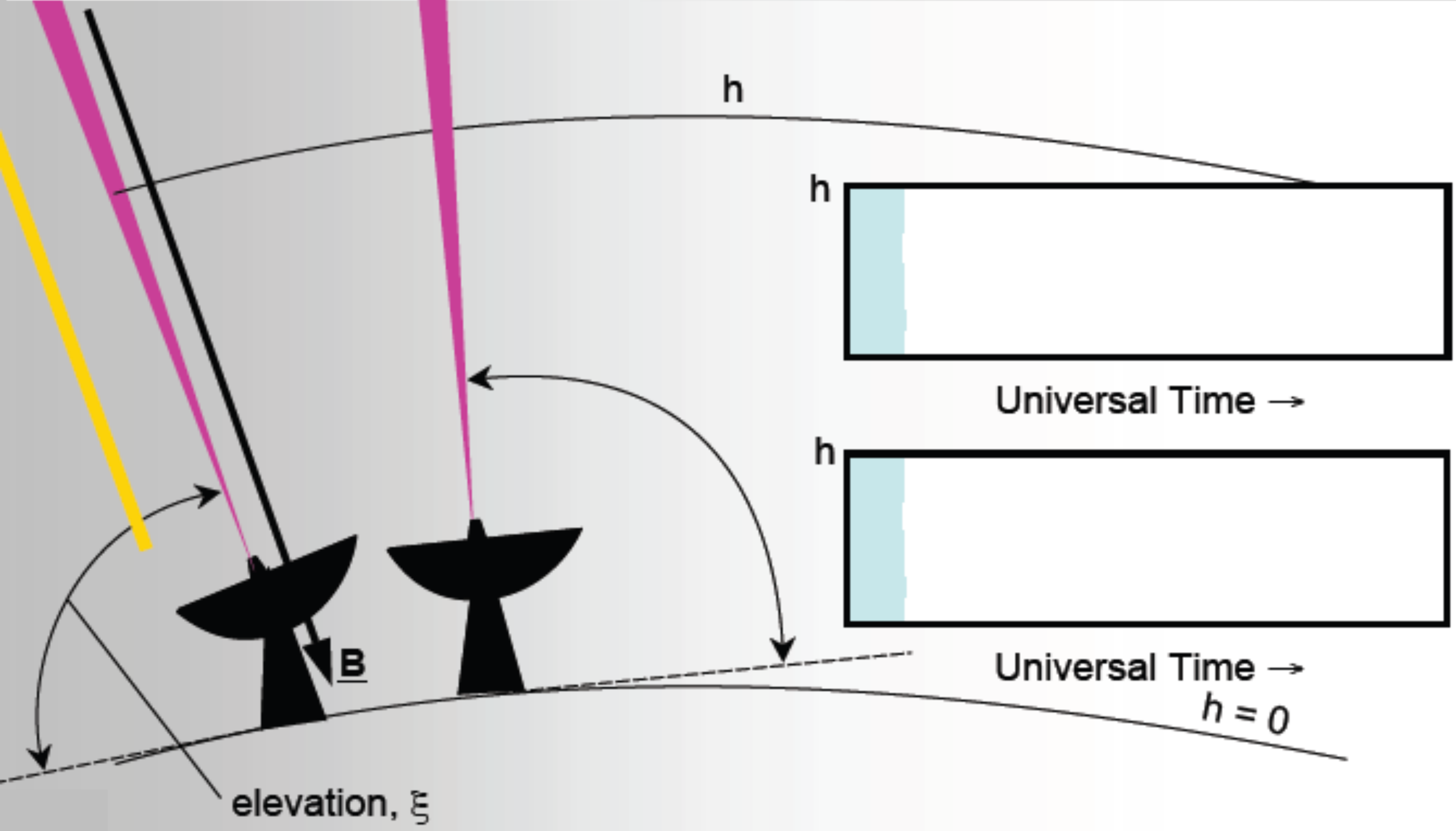
Note day-to-day variability in N_e



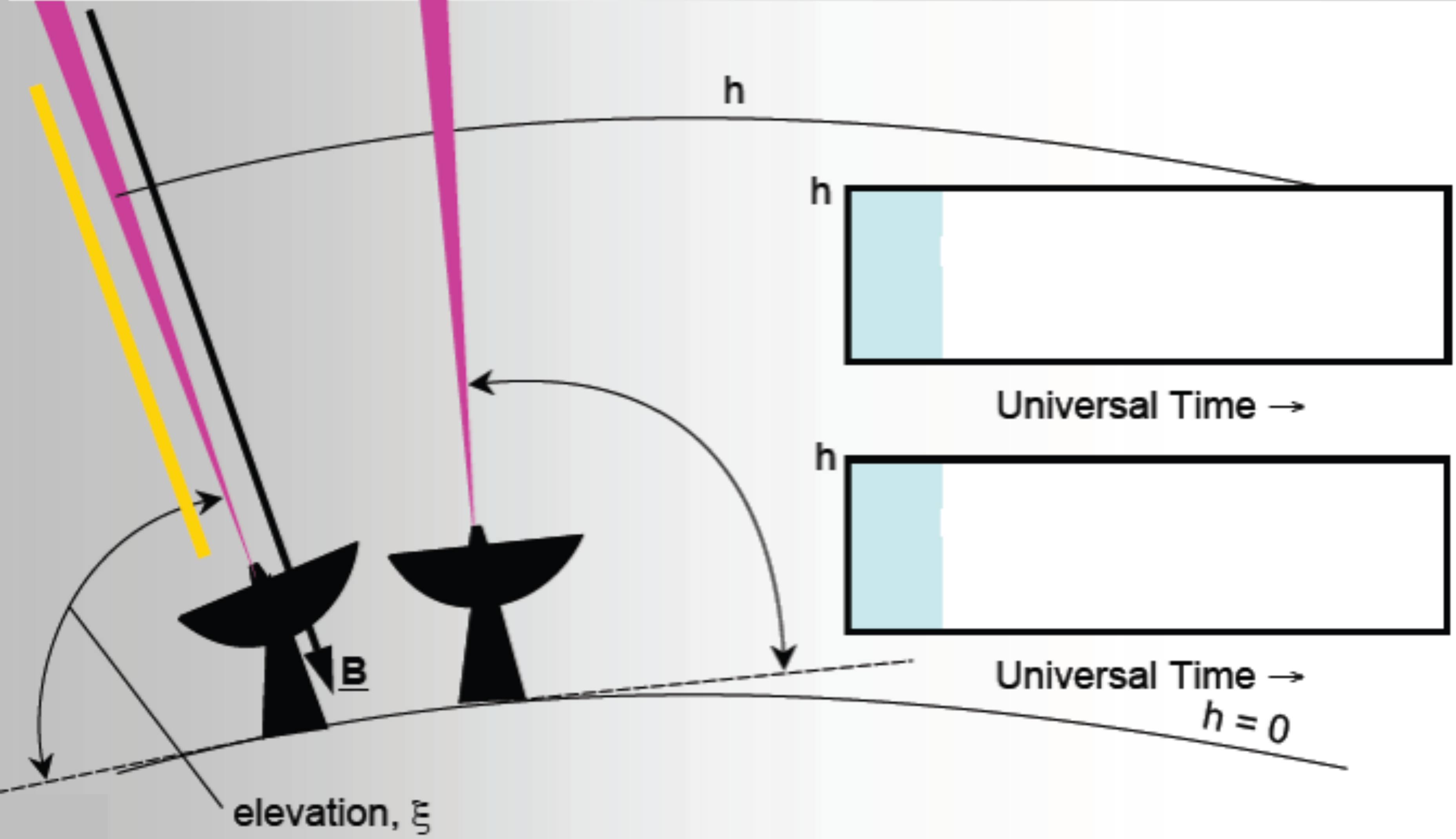
Precipitation effects

Ion heating events (Note T_i is almost independent of h at h > 130 km in events

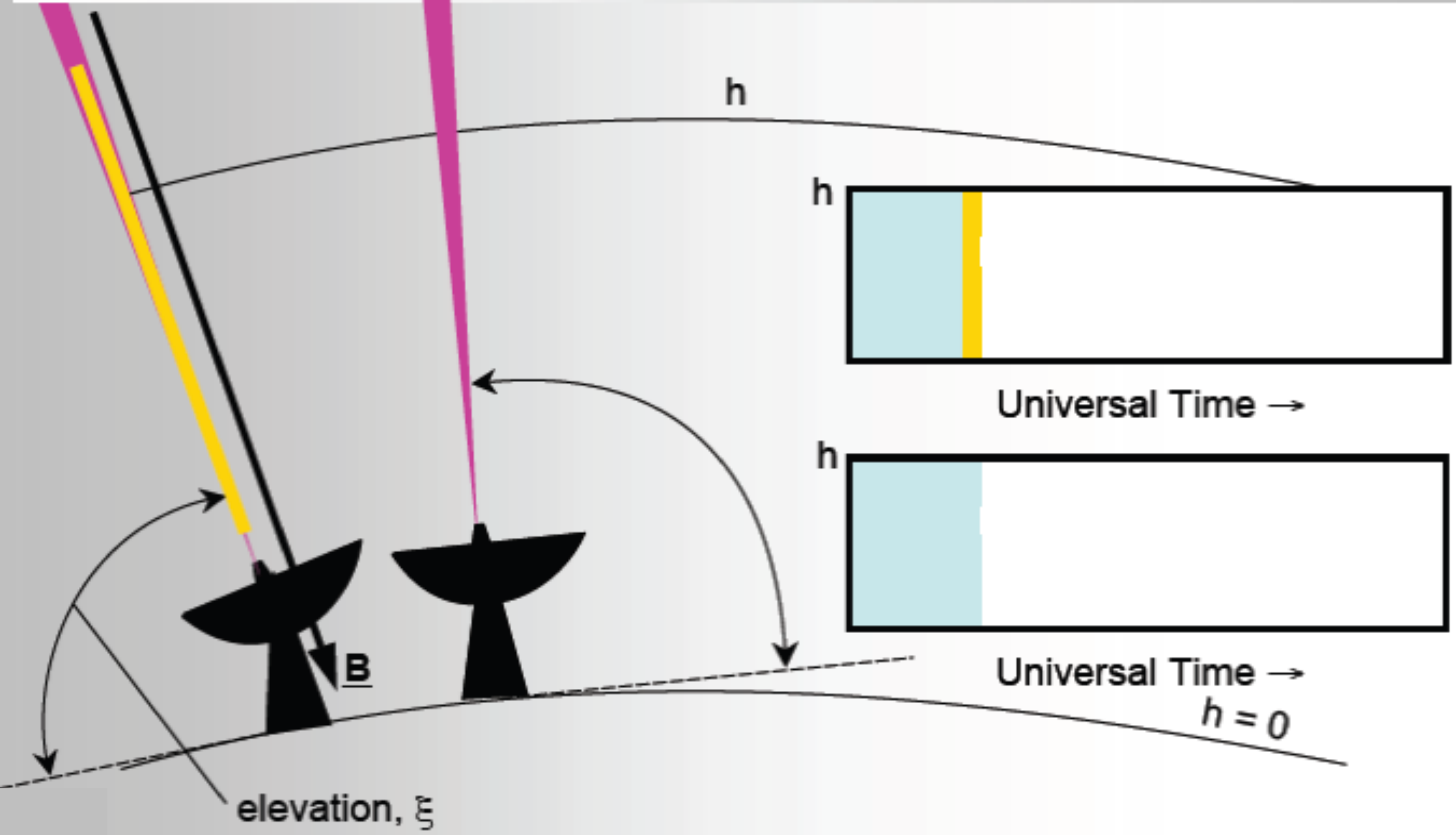
Arcs, field-aligned and vertical beams



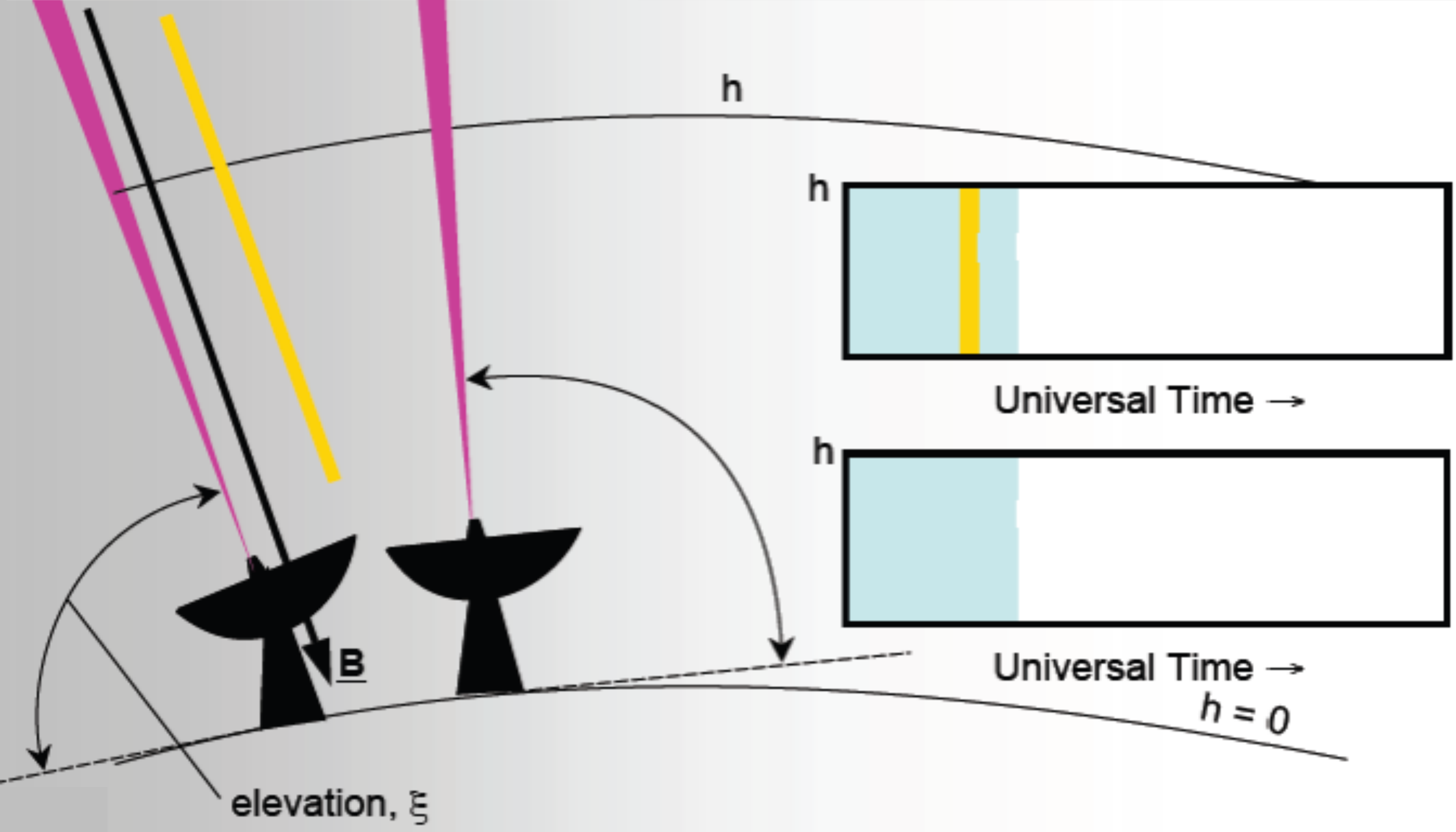
Arcs, field-aligned and vertical beams



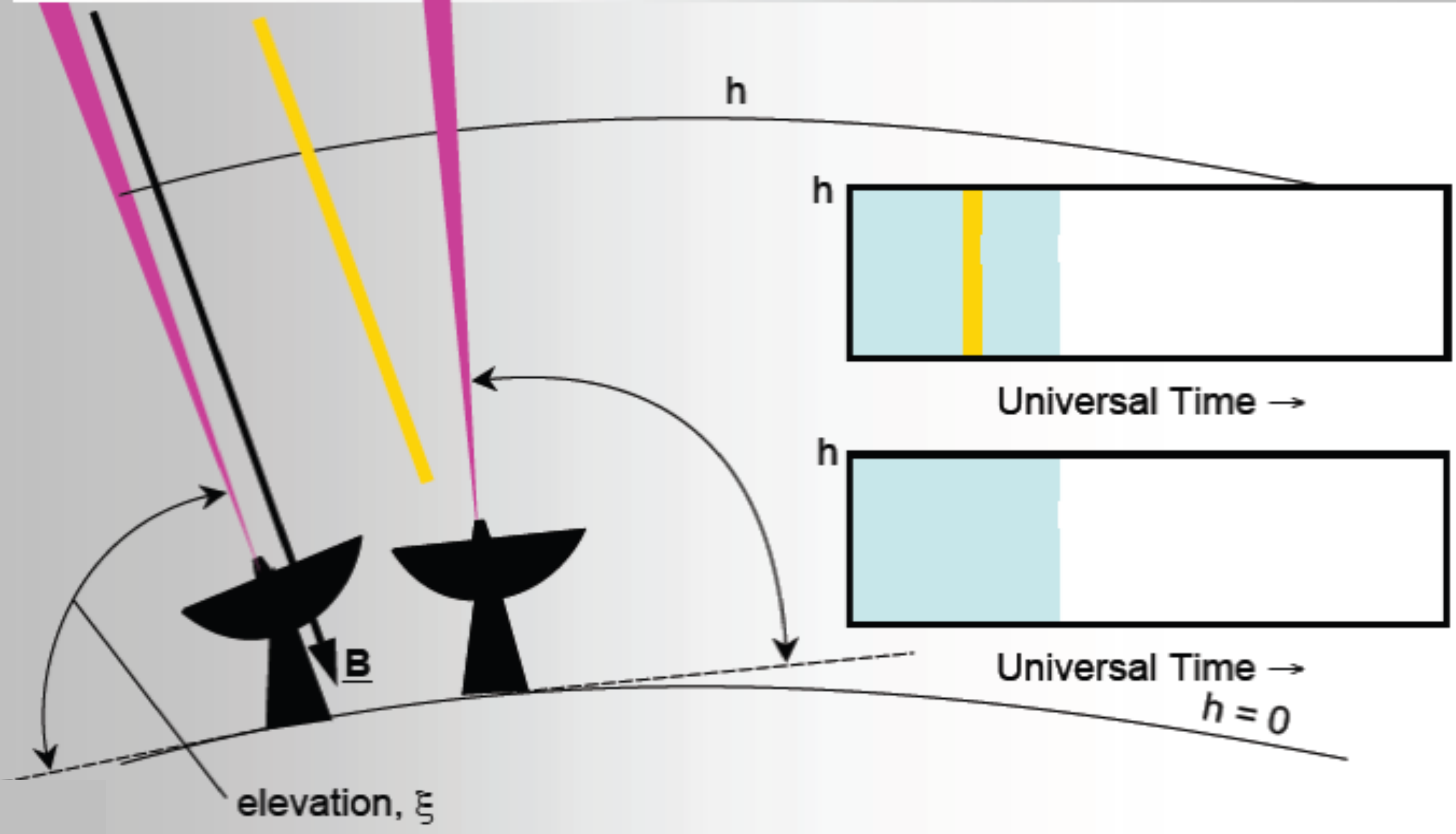
Arcs, field-aligned and vertical beams



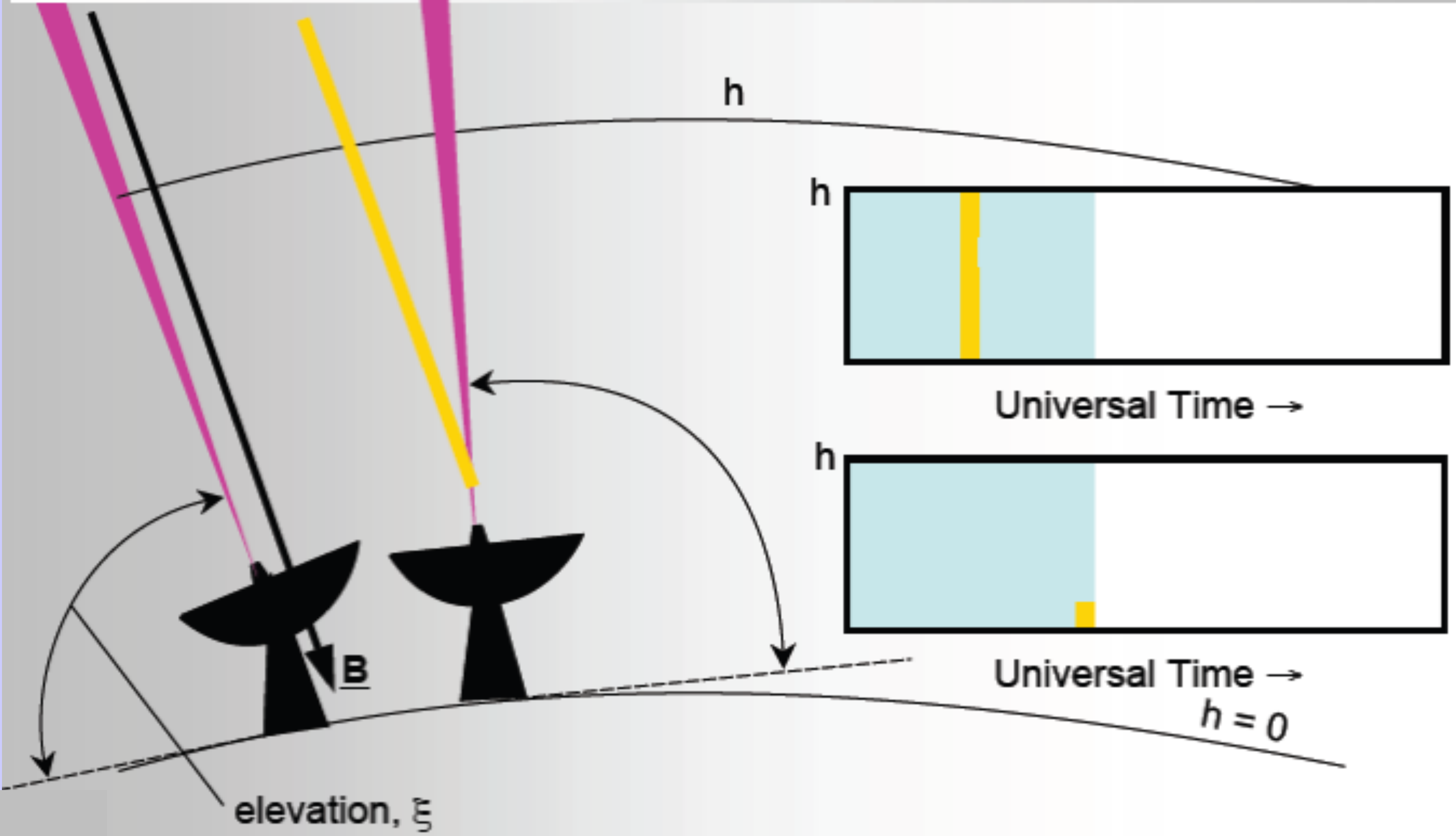
Arcs, field-aligned and vertical beams



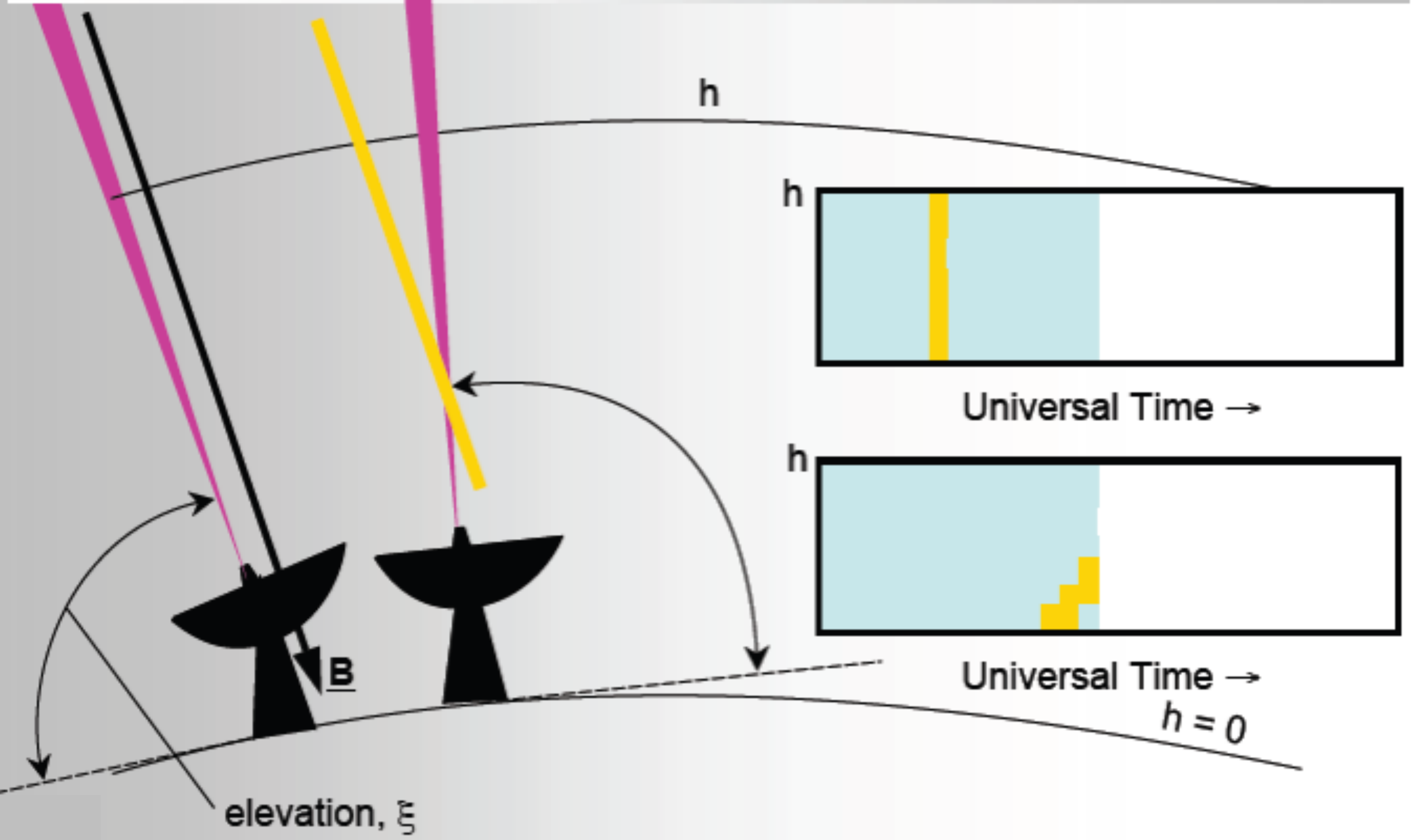
Arcs, field-aligned and vertical beams



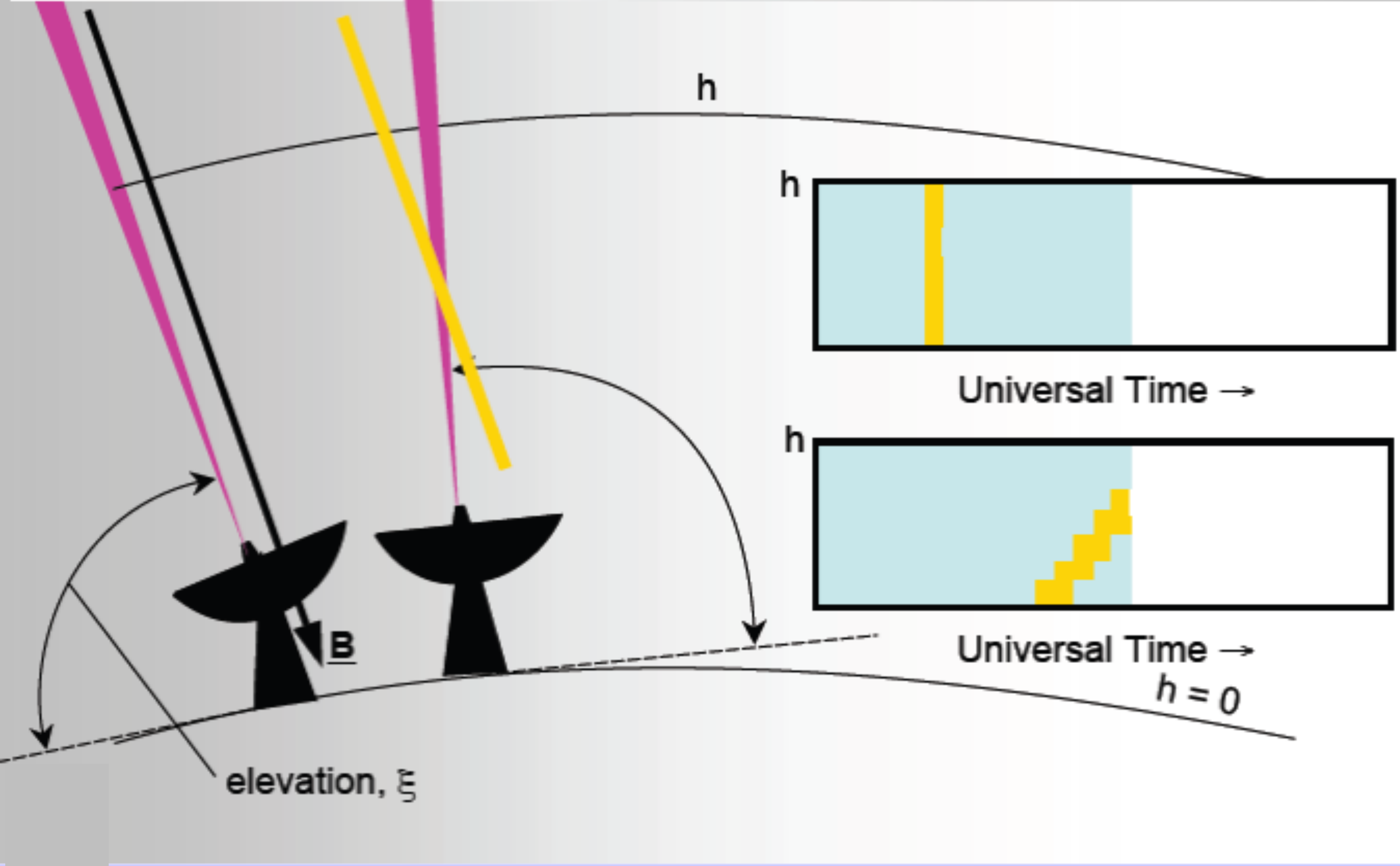
Arcs, field-aligned and vertical beams



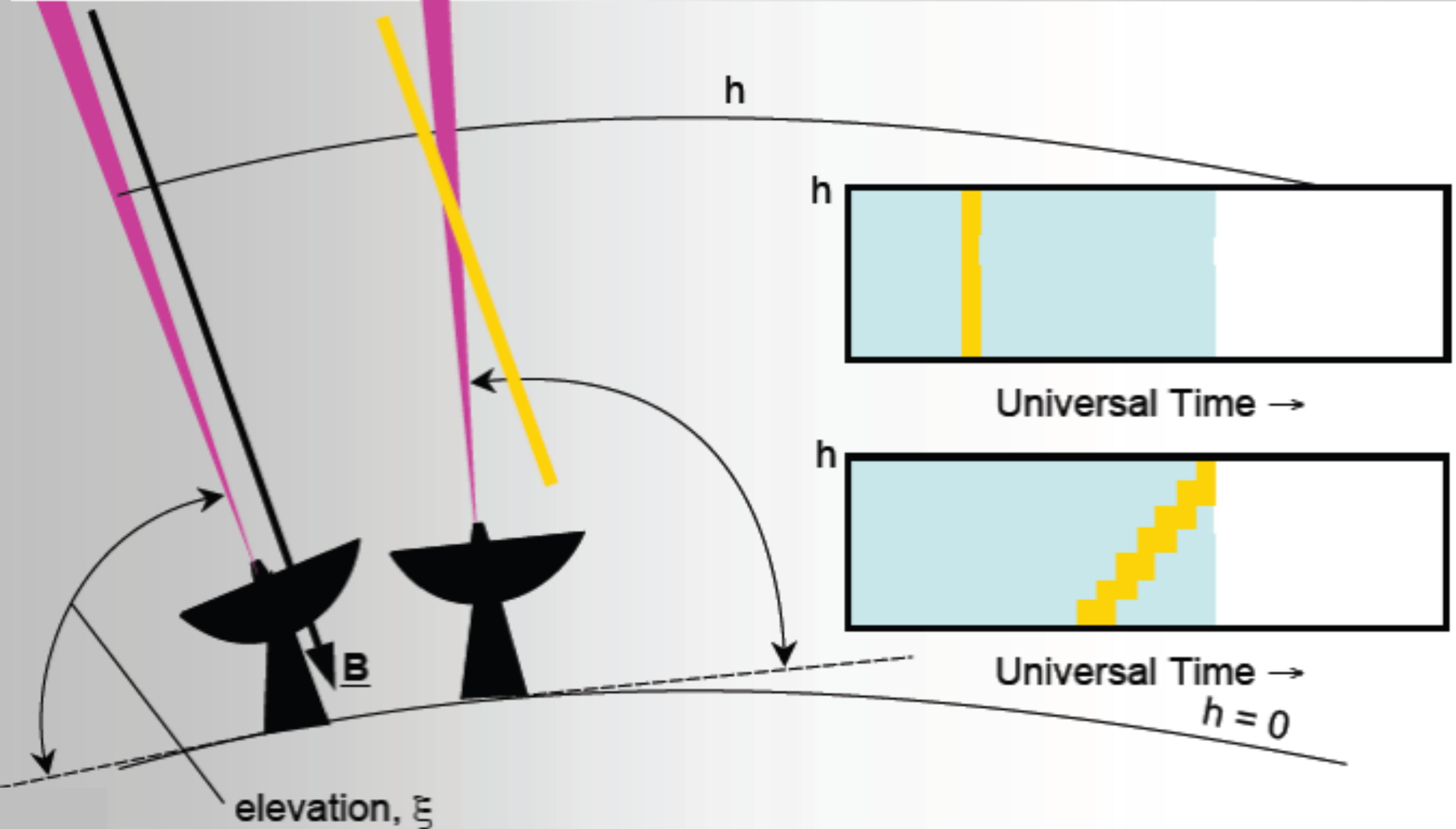
Arcs, field-aligned and vertical beams



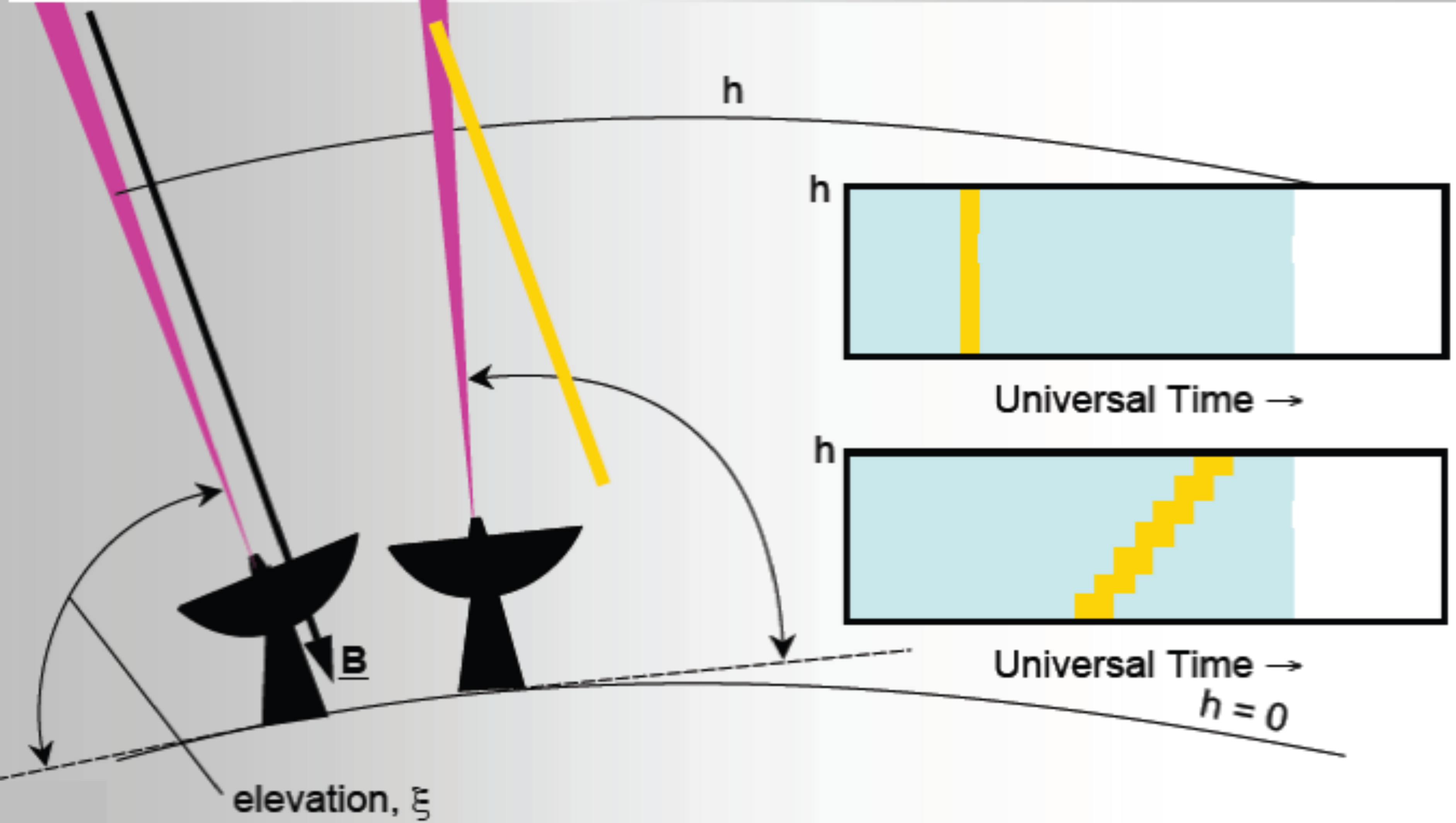
Arcs, field-aligned and vertical beams



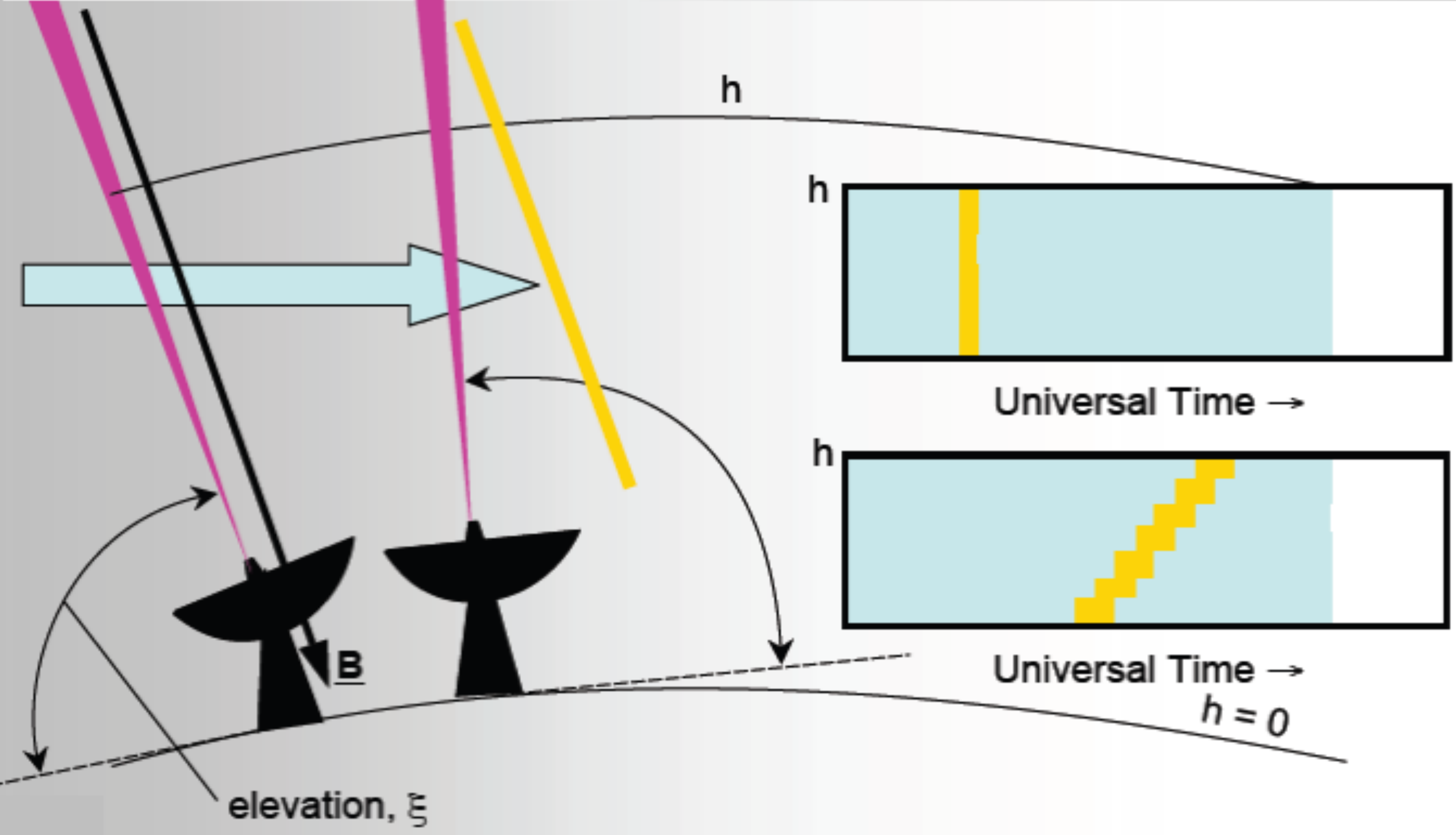
Arcs, field-aligned and vertical beams



Arcs, field-aligned and vertical beams



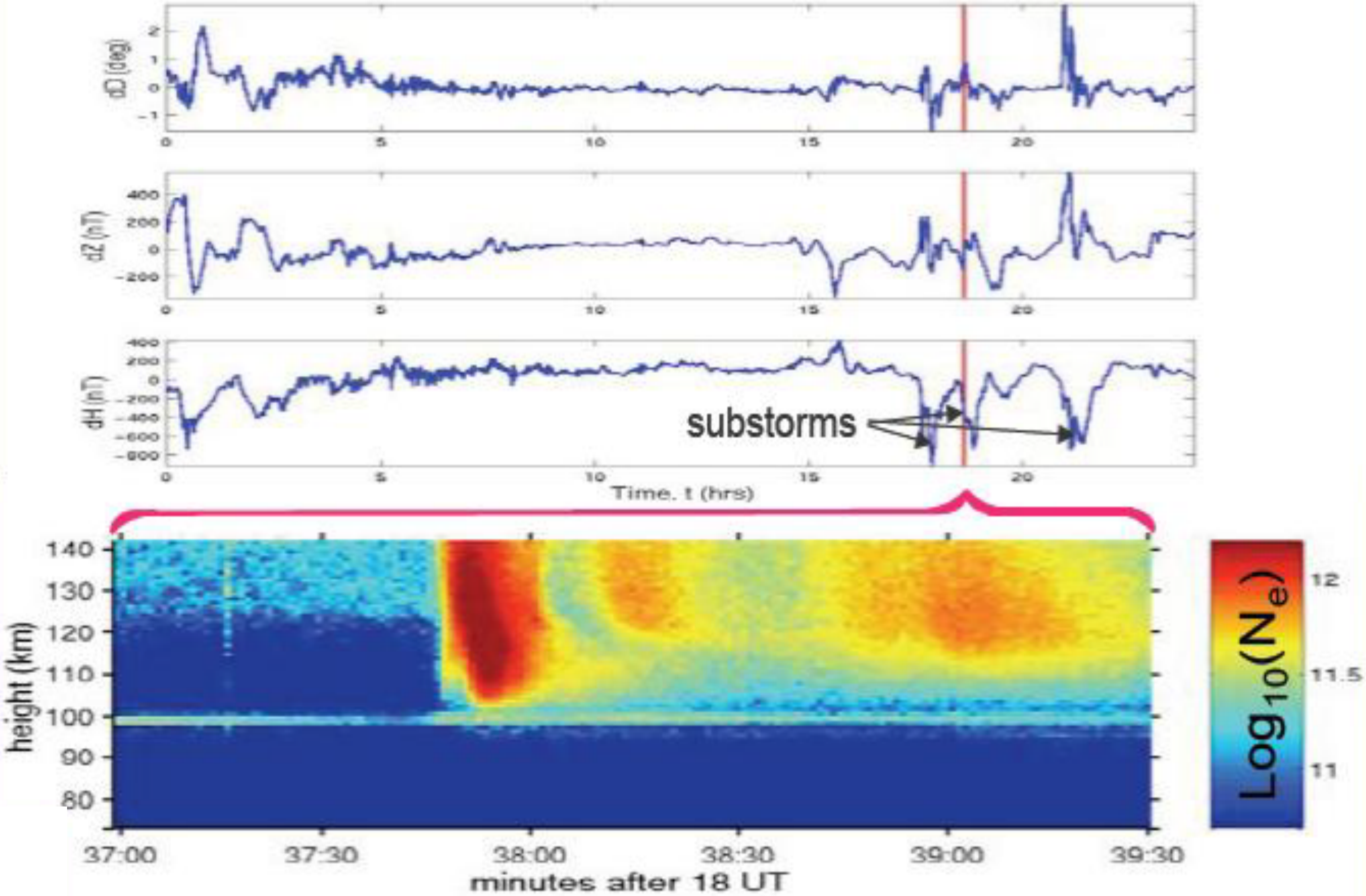
Arcs, field-aligned and vertical beams



A note on field-aligned features

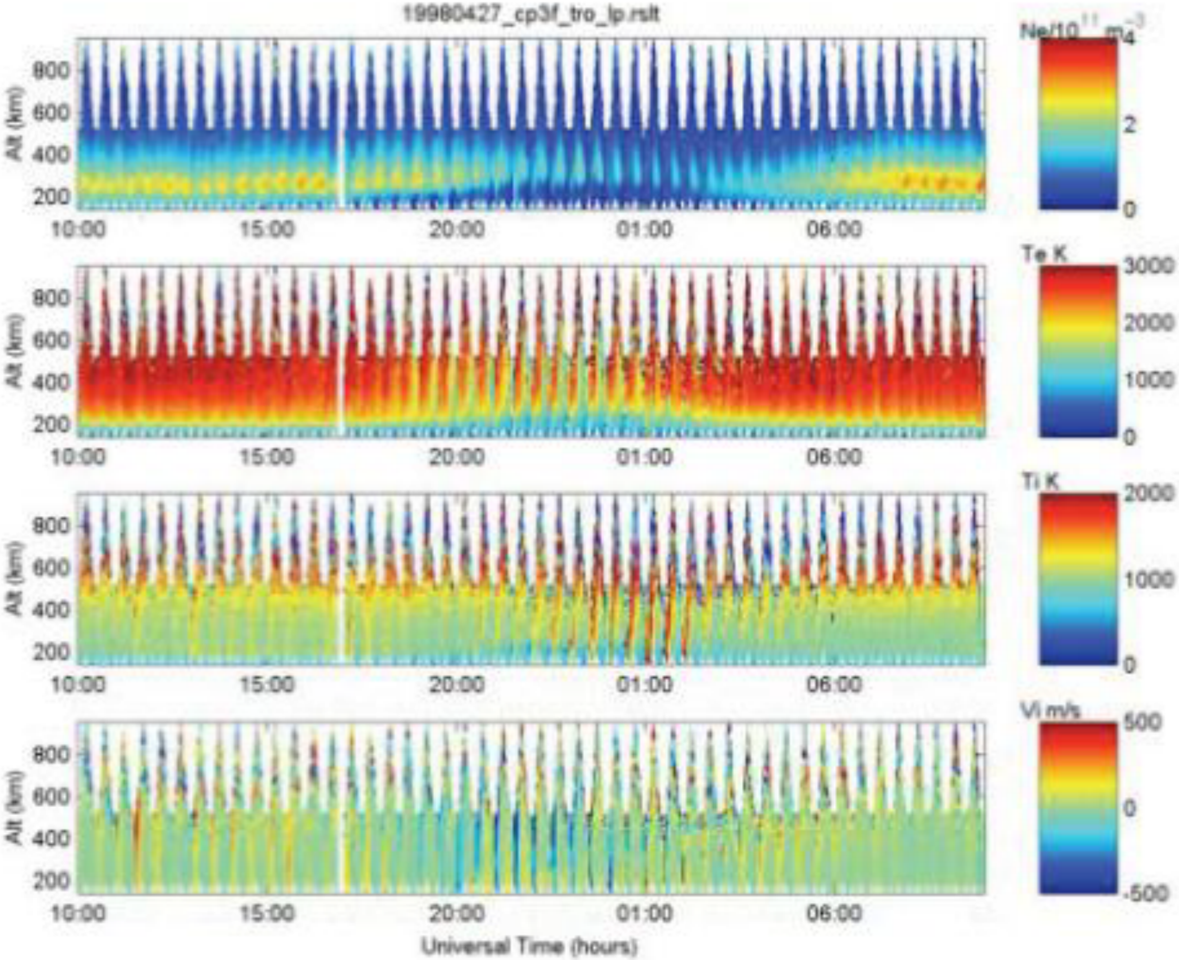
- The above slides give the impression that a field-aligned feature is seen as a single time-point by a field-aligned dish.
- In reality that is not true, because:
  - Auroral precipitation can be spatially extended
  - Its motion can be very complicated
  - Sources can be dispersive as a function of time

Tromsø, 30 January 1995



Large Scans (e.g. CP3)

(summary plot dominated by the beam scan pattern)



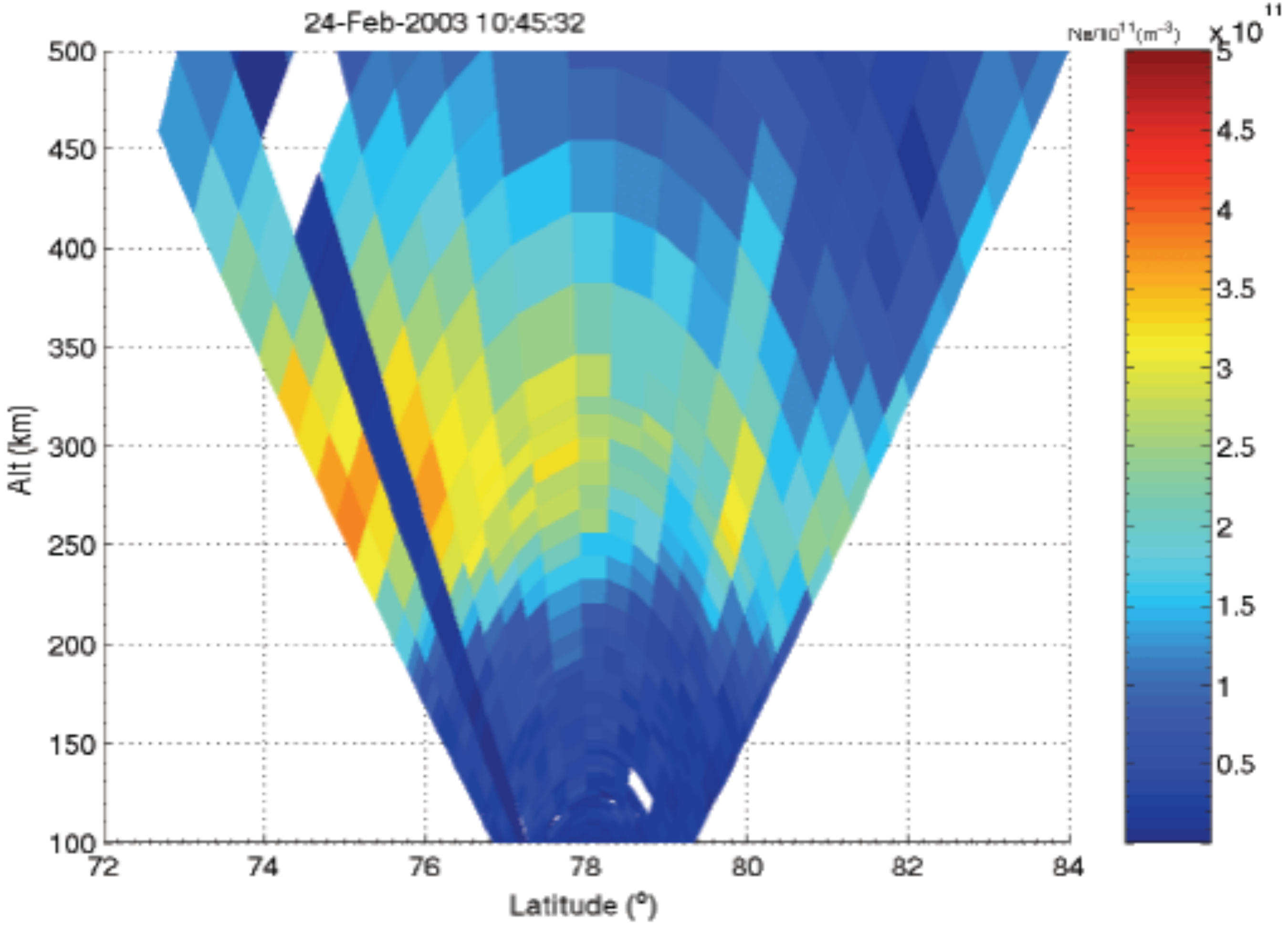
Summary plot hard to interpret because of scan pattern.

But can make out basic N_e and T_e variation as seen for CP1

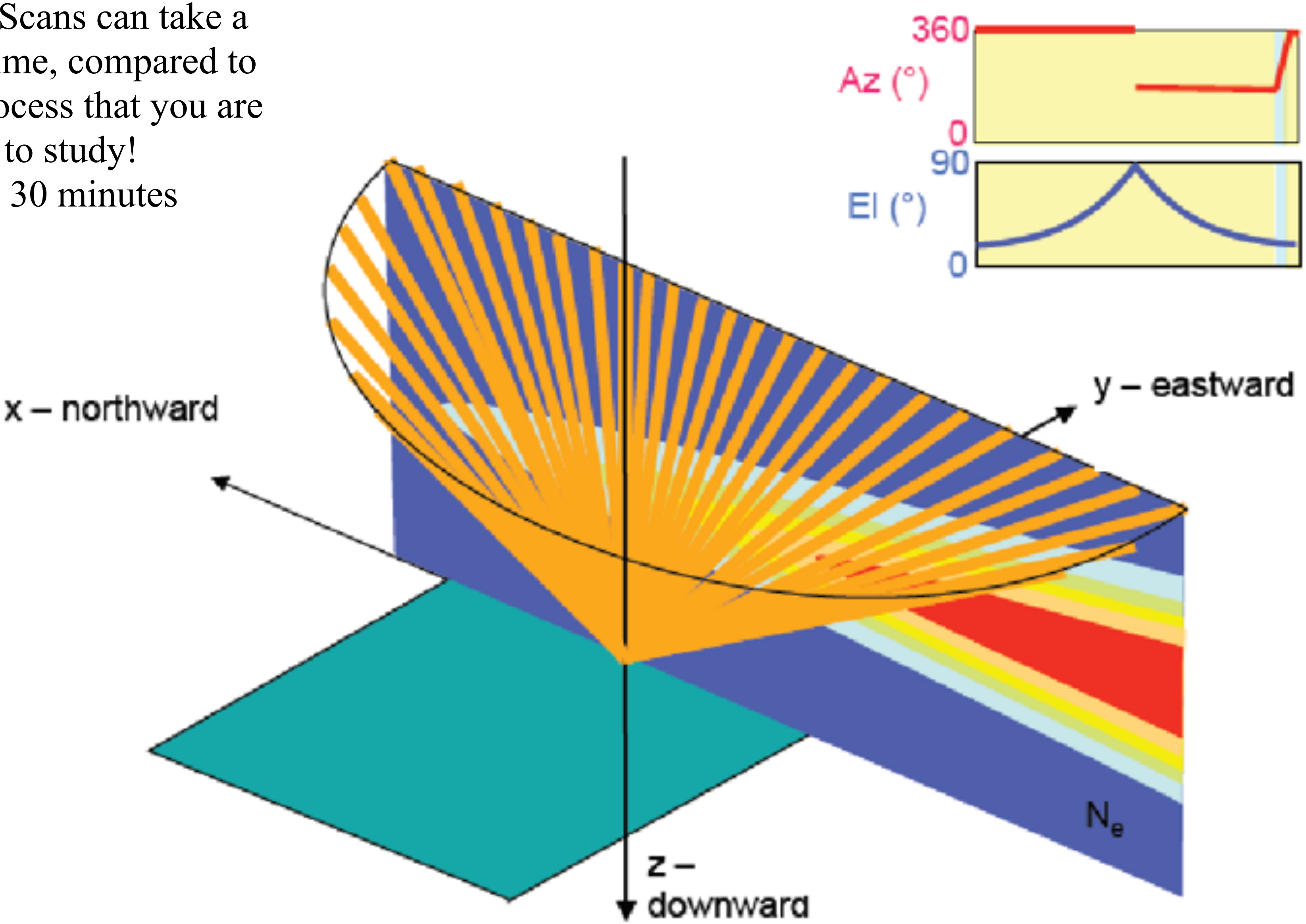
Stripes with scan period (30 min) reveal latitudinal structure

Large Scans (e.g. CP3)

(summary plot dominated by the beam scan pattern)



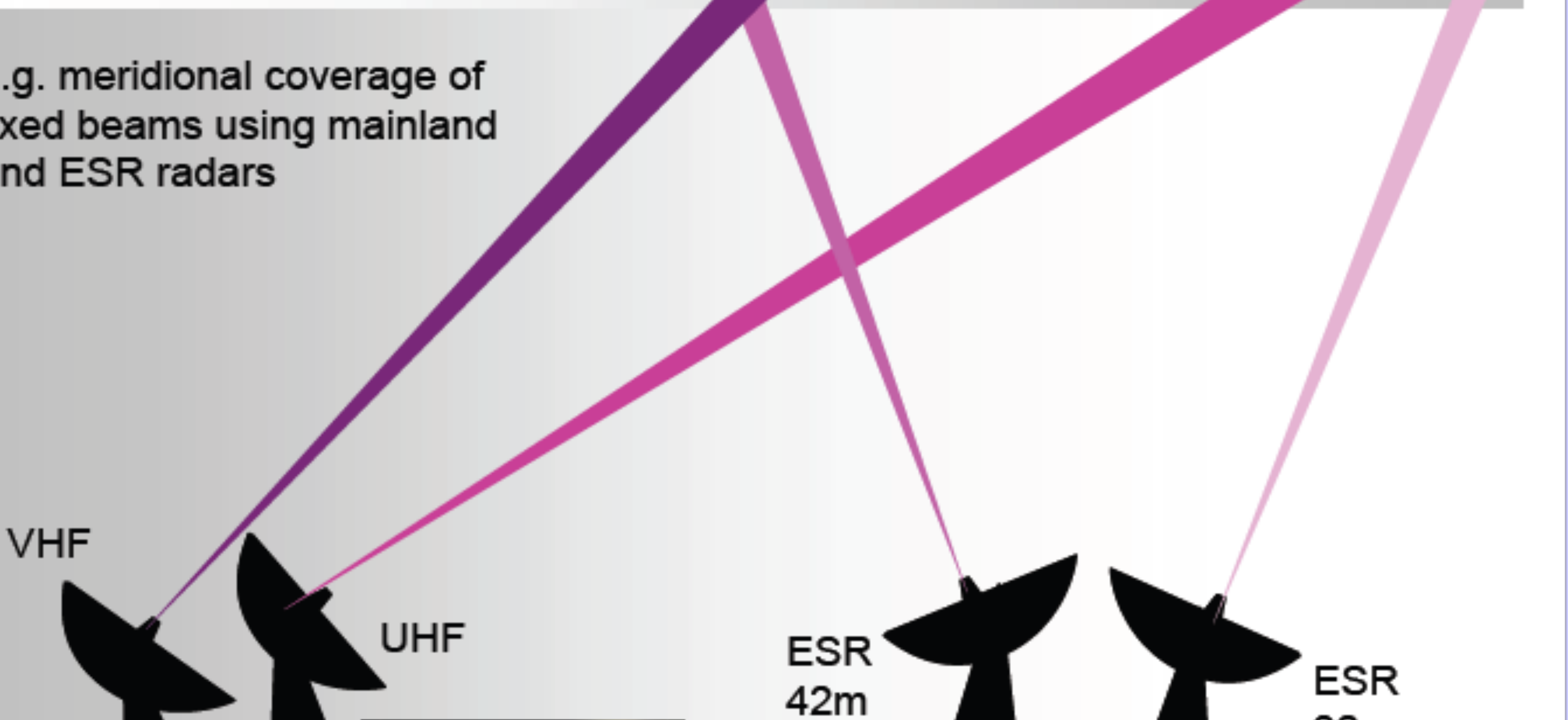
Note: Scans can take a long time, compared to the process that you are trying to study!
CP3 = 30 minutes

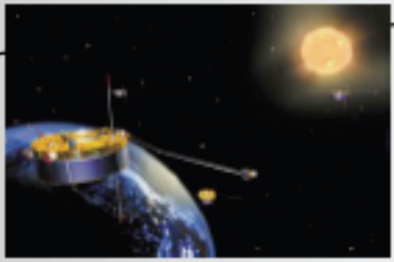


The scan can often be limited by the properties of the radar!
Scan up – spin – and scan down

Multiple Radar use

e.g. meridional coverage of fixed beams using mainland and ESR radars

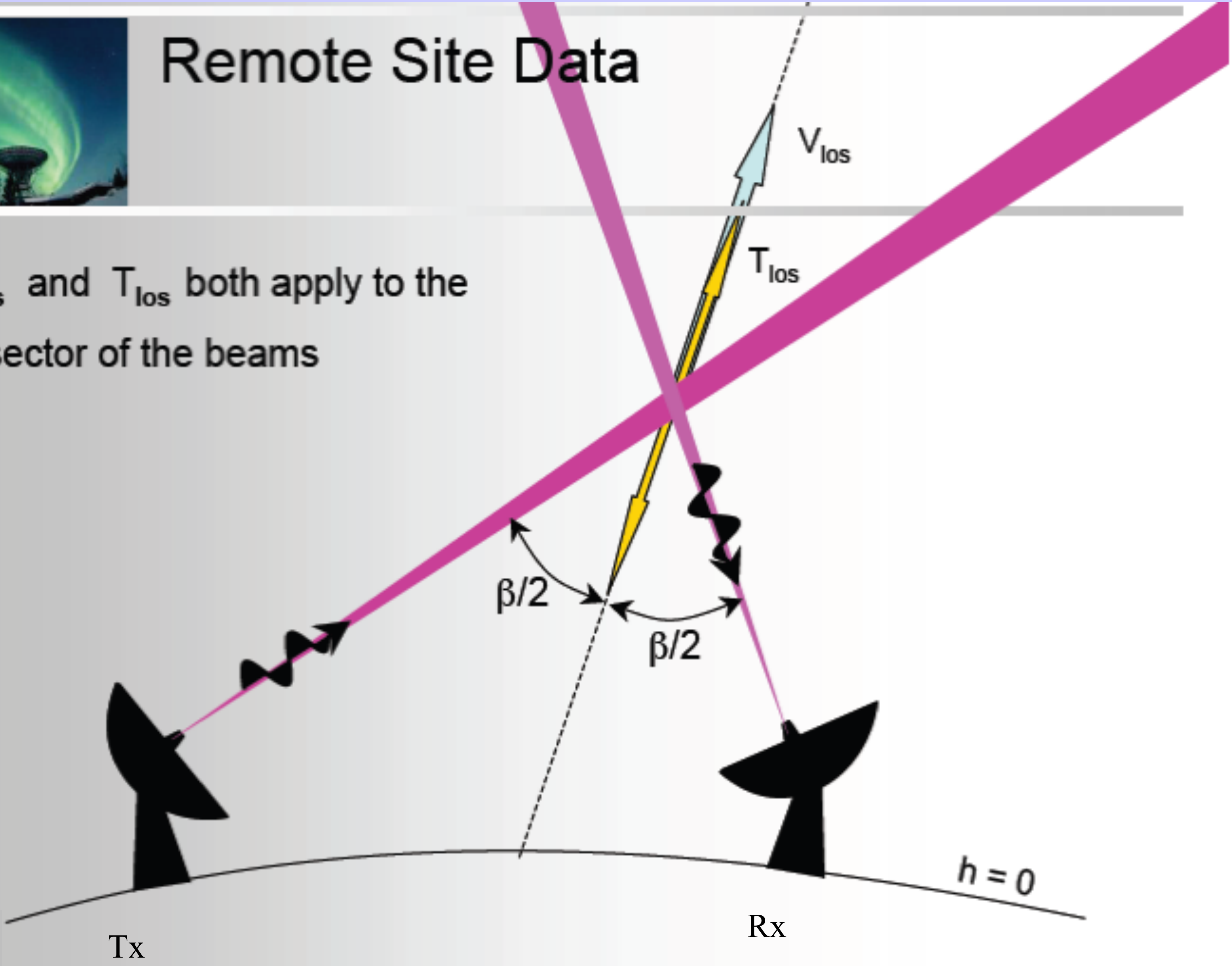




Remember that EISCAT is not the only Instrument in the world! You have other ISRs, SuperDARN, spacecraft, optics etc. etc.

Remote Site Data

V_{los} and T_{los} both apply to the bisector of the beams



Multiple Radar use

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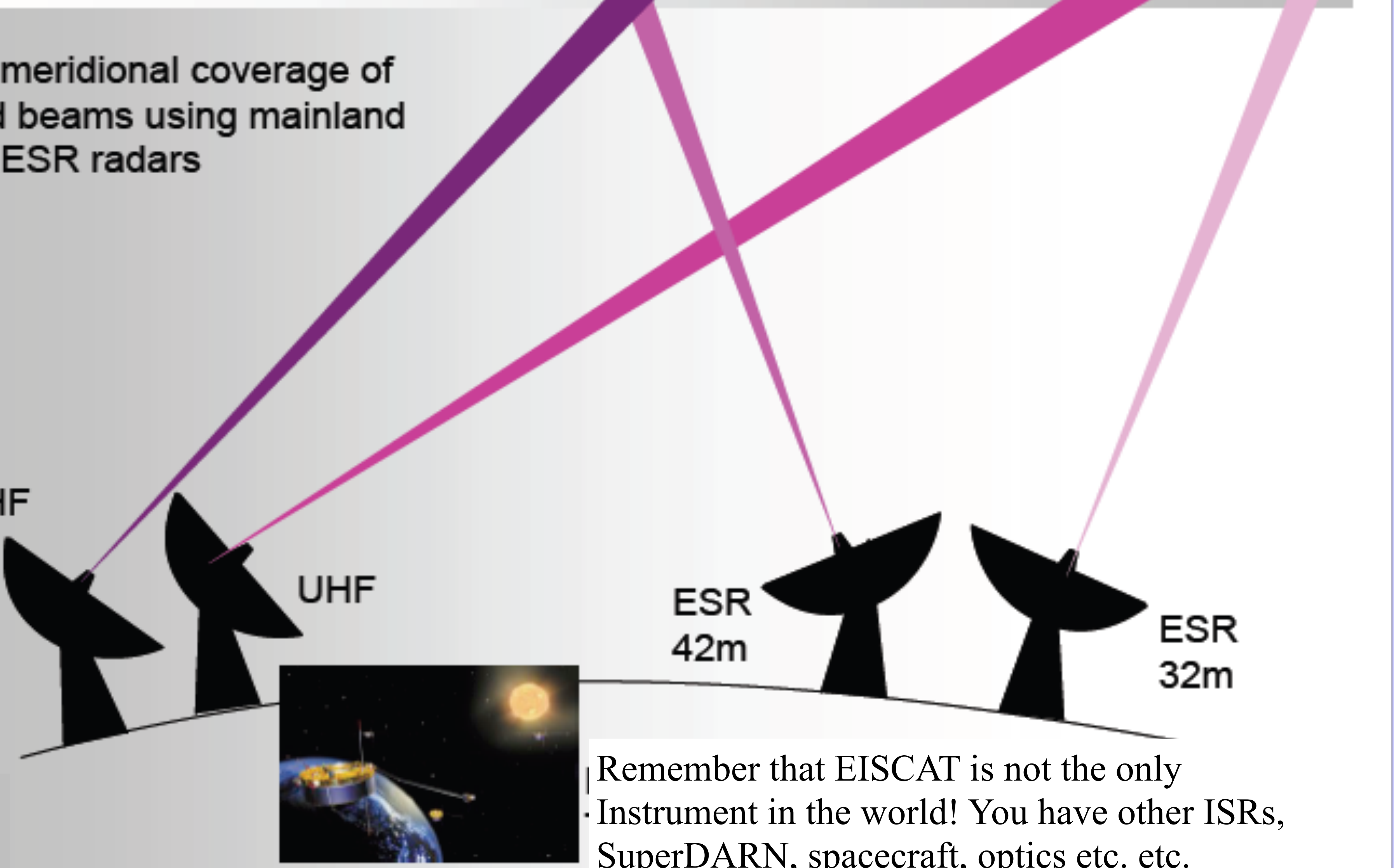

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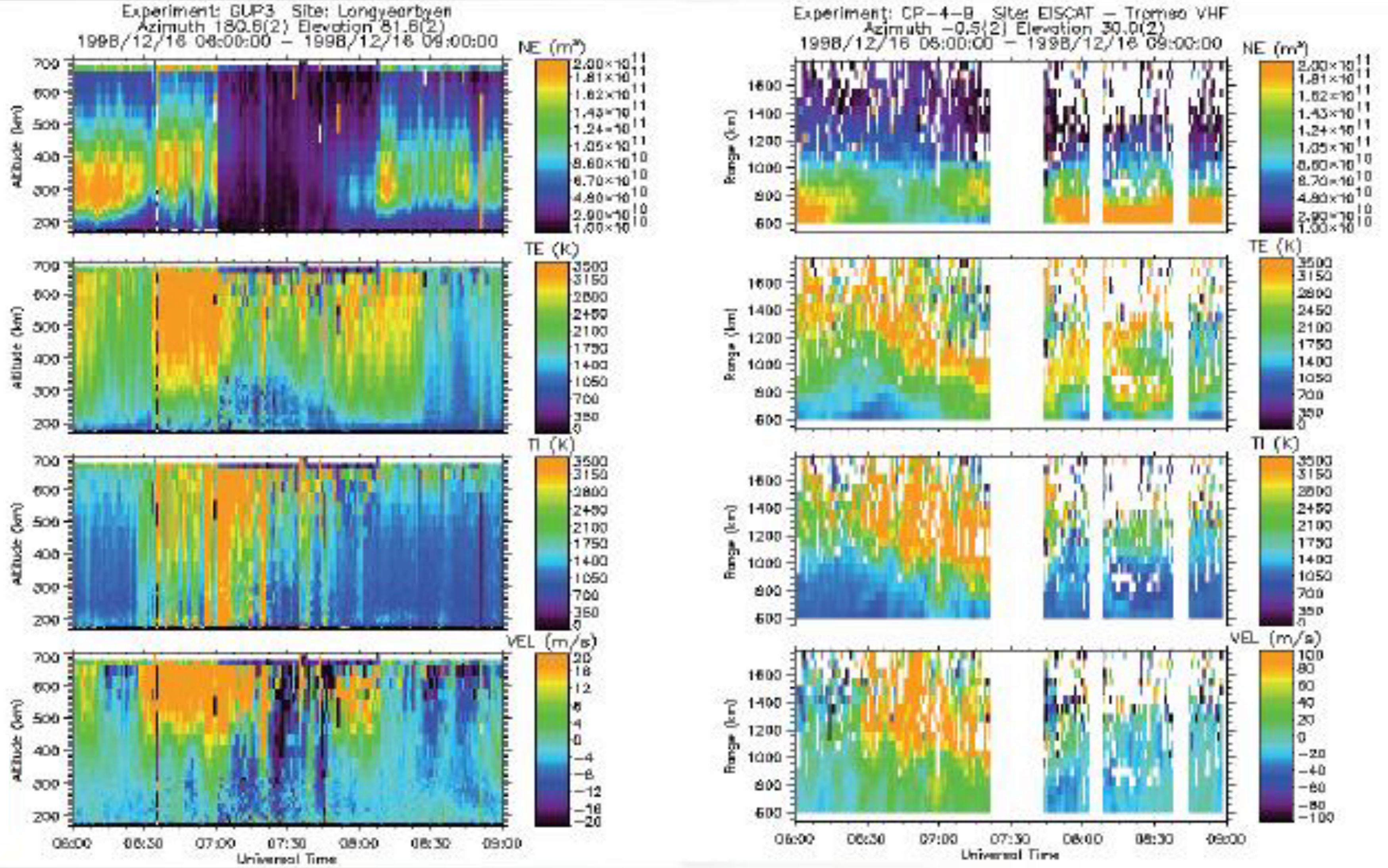
Identifying the cusp (ESR and CP4)

McCrea et al., Annales Geophys., 18, 1009-1026, 2000.



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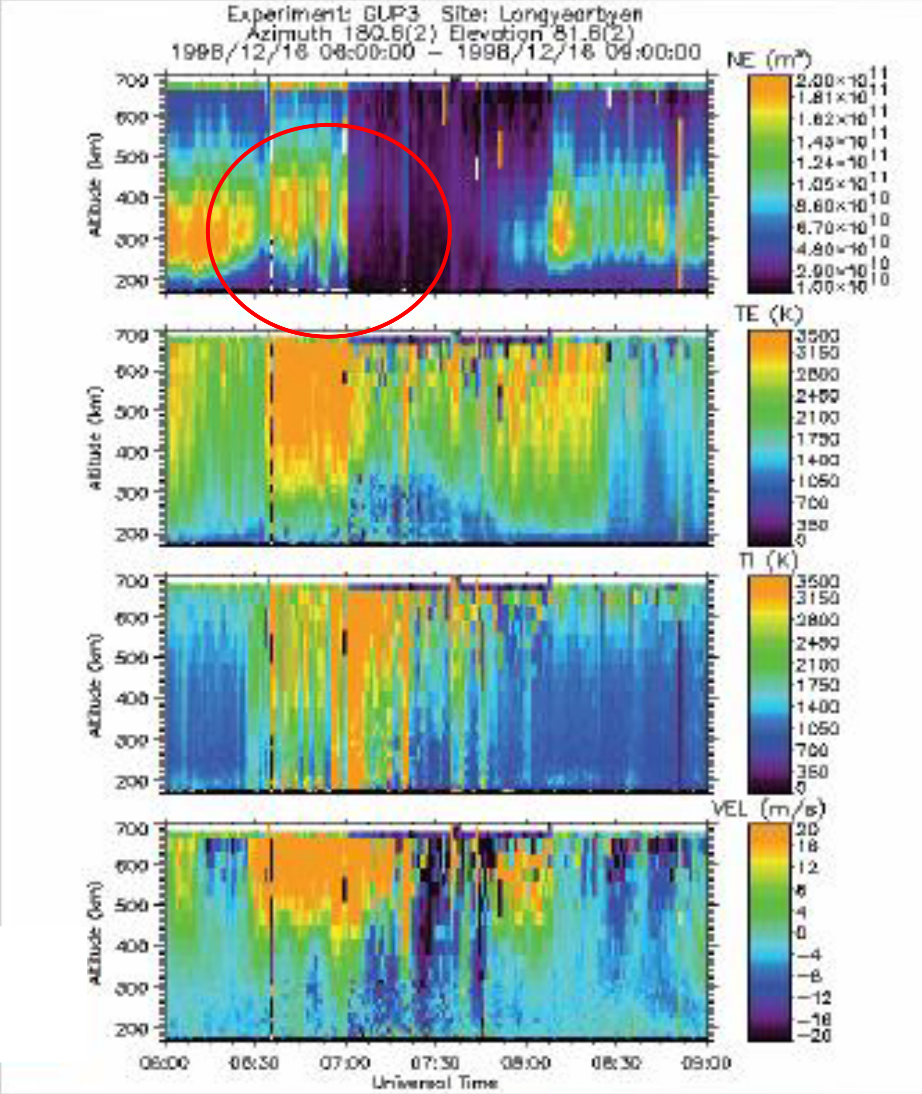
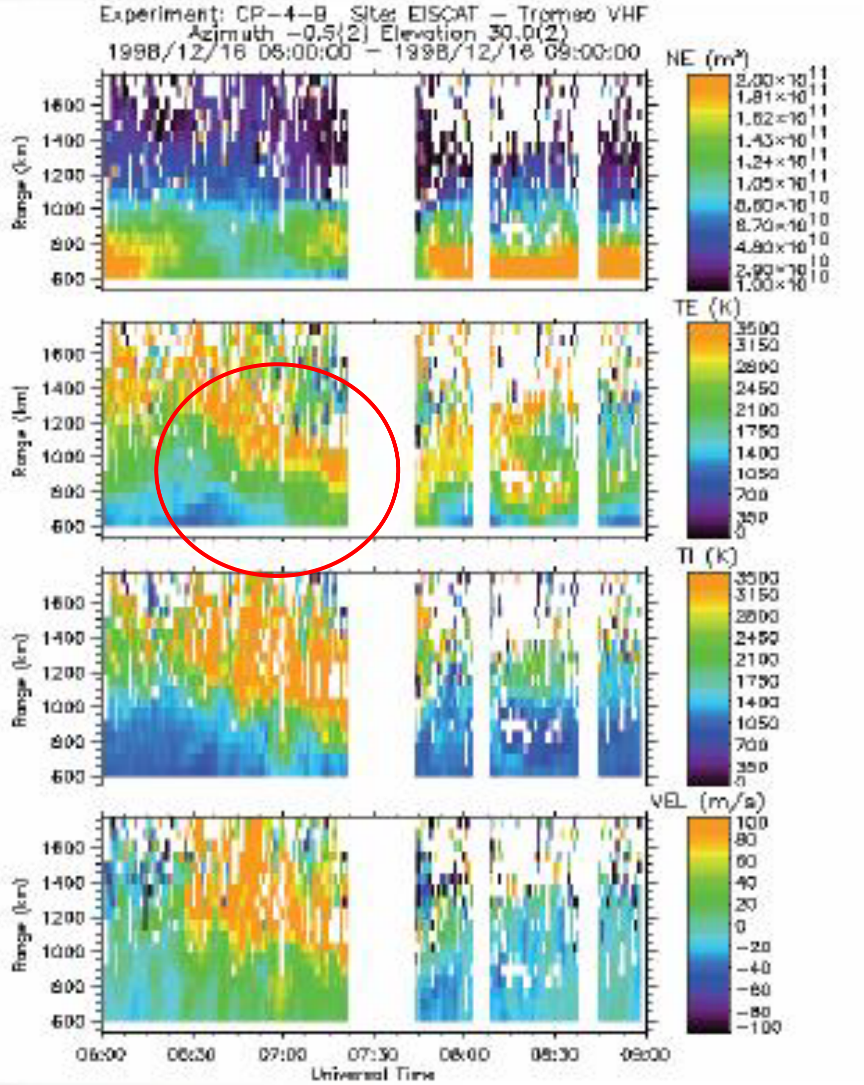
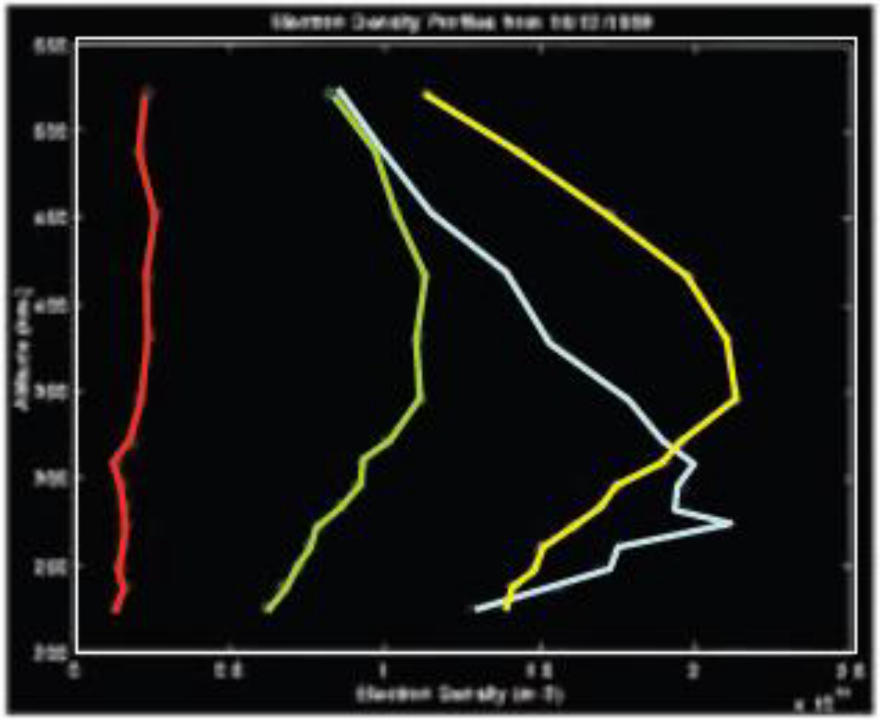


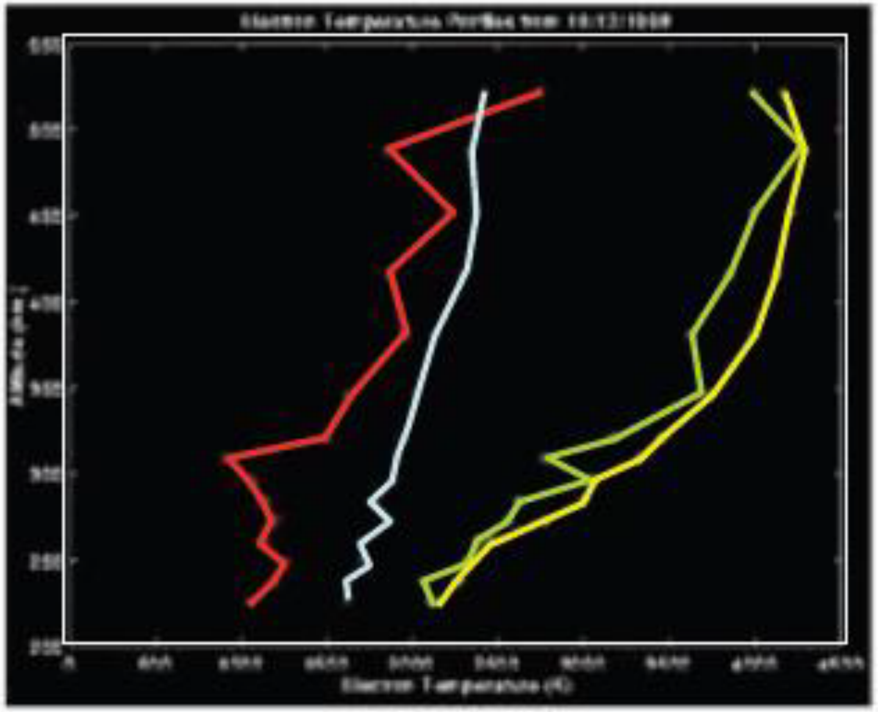


Identifying the cusp (ESR)

Plasma density profile



Electron temperature profile



Polar Cap

Sub-auroral

Cusp – outside 630nm transient

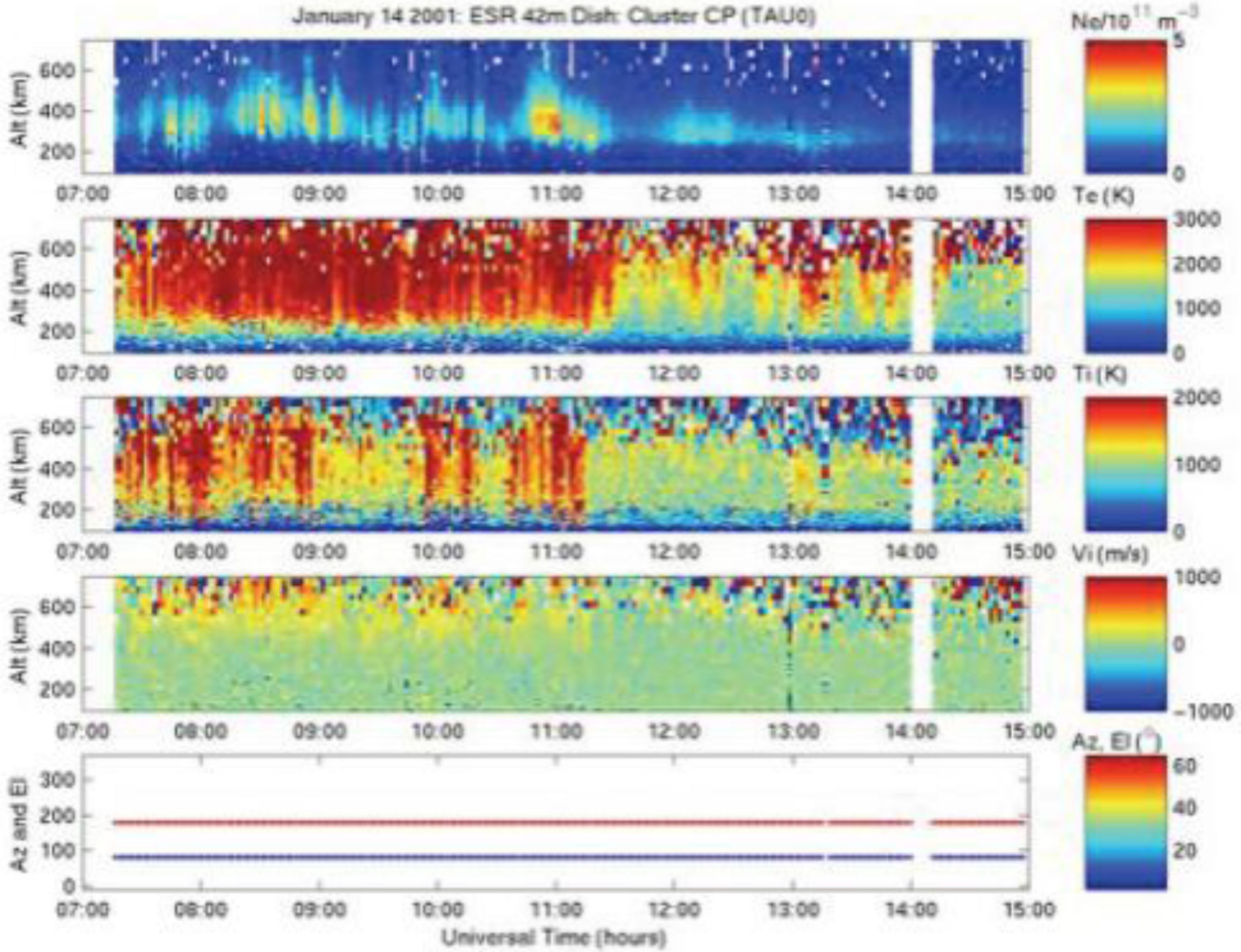
Cusp – inside 630nm transient

Identifying the cusp region

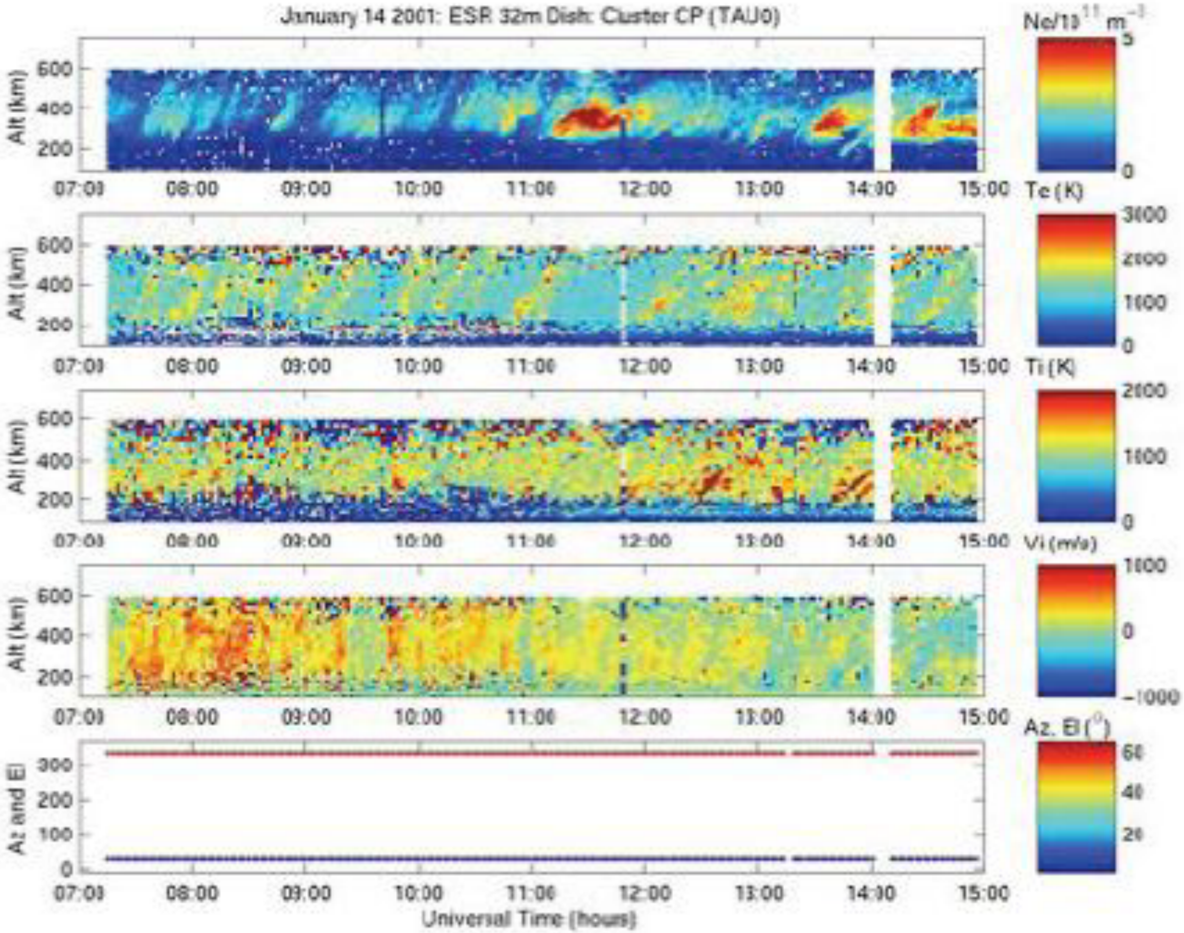
(especially relevant to EISCAT Svalbard Radar)

- High-latitude midday sector
- Characterised by low-energy precipitation
- Solar wind driven dynamics
- Reconnection transients etc.
- Features move north at noon MLT when Bz south (and vice versa)
- Cusp precipitation gives high Ne, elevated Te
- Polar cap patch might give high Ne, low Te

Identifying the cusp (ESR 42m – field aligned)



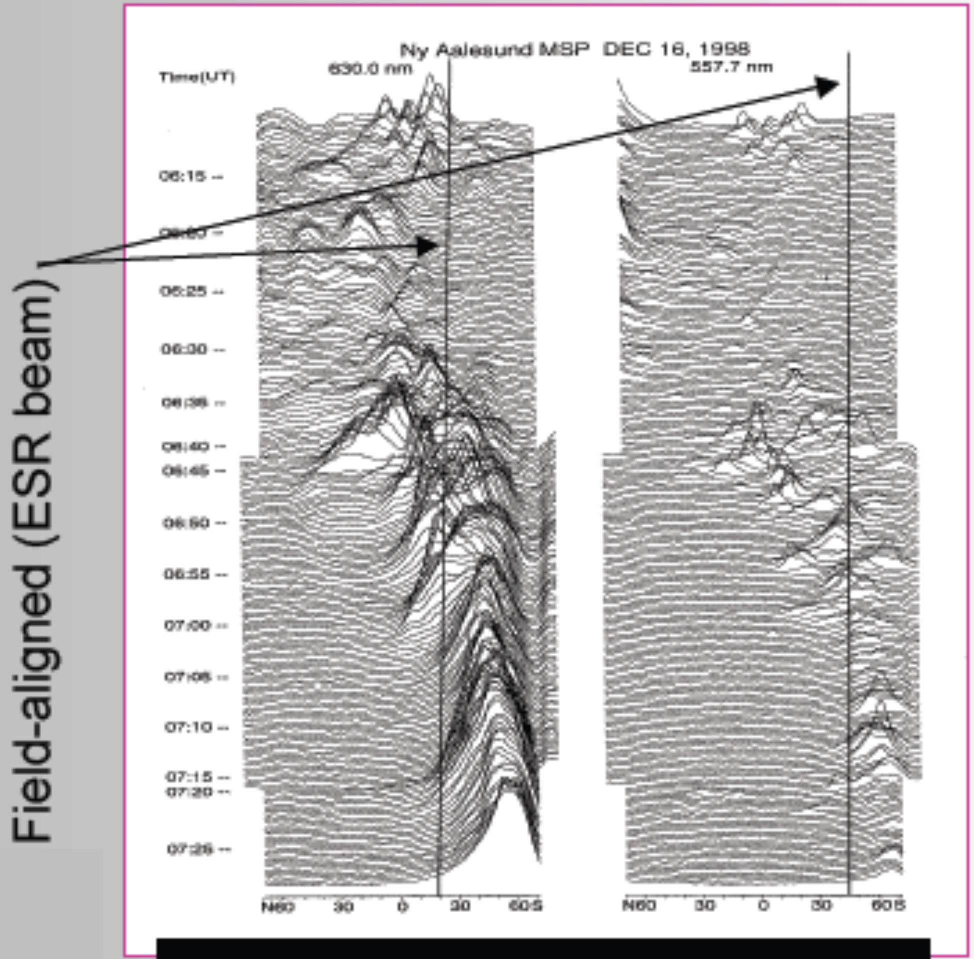
Identifying the cusp (ESR 32m – looking north)



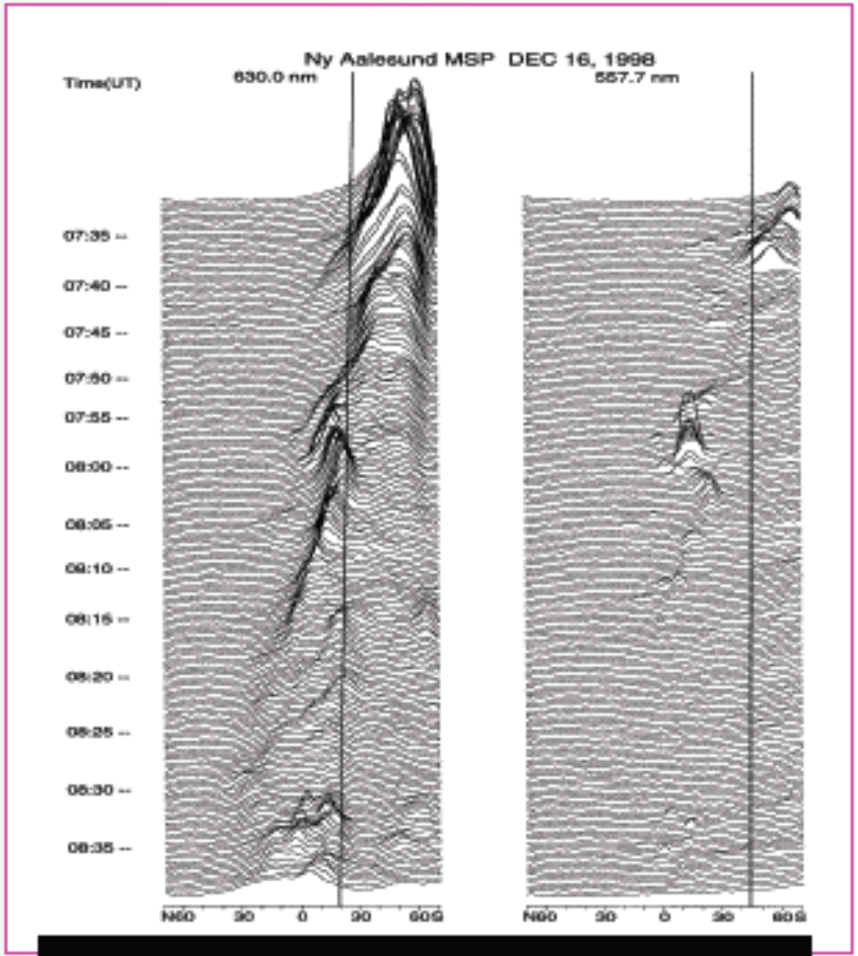
Identifying the cusp (Photometer)

McCrea et al., Annales Geophys., 18, 1009-1026, 2000.

In cusp red line dominant, but there is always some green



Red (630nm) Green (557.7nm)

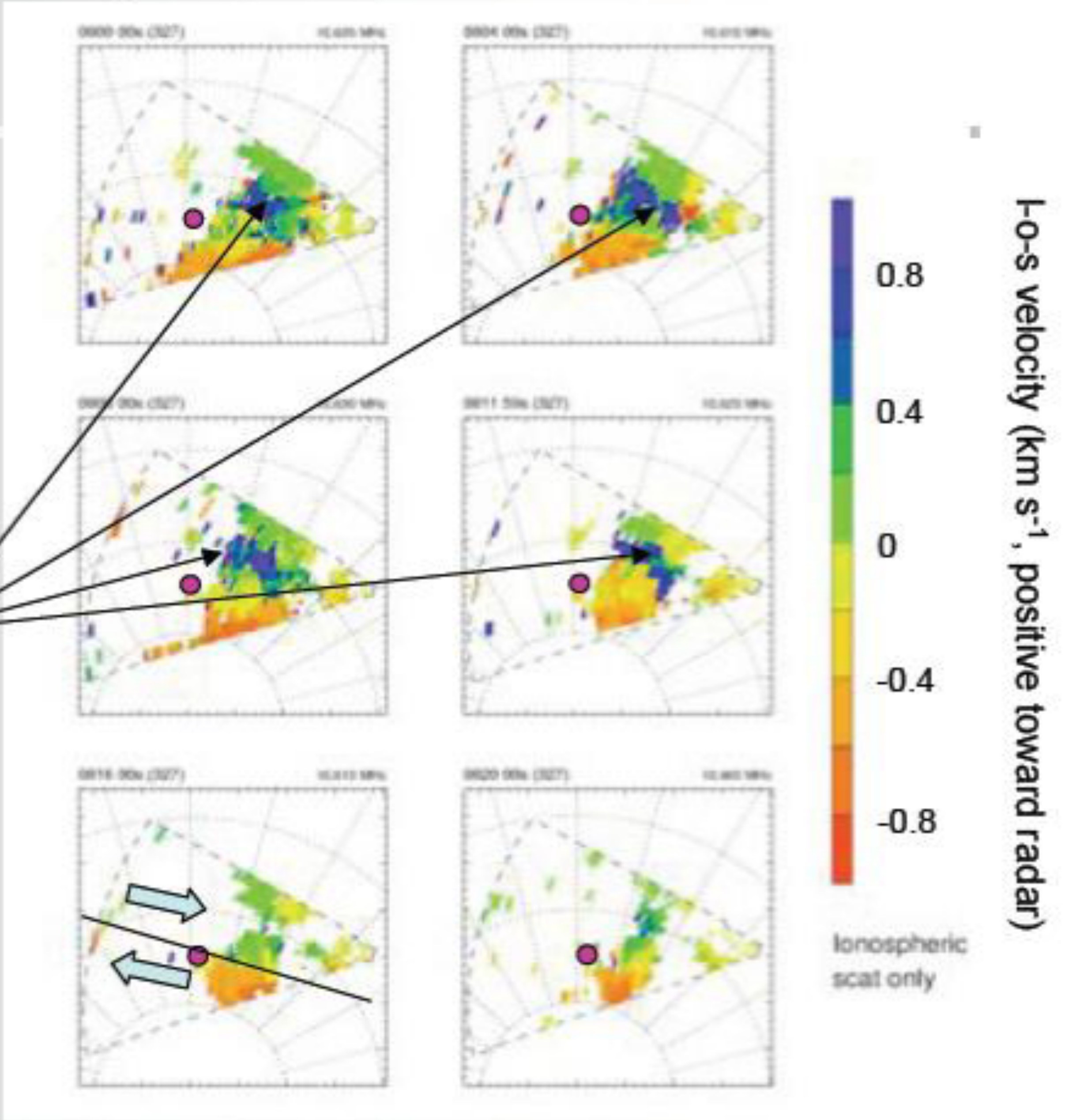


Red (630nm) Green (557.7nm)

Working out where the radars were

e.g. Using Iceland CUTLASS SuperDARN HF radar

(can use IMAGE magnetometer chain & Imagers also)



Transient westward flow burst

Here ESR is just poleward of CRB (Convection Reversal Boundary)

Conclusions

- When trying to interpret ISR data, remember:
  - The data can contain random and systematic errors
  - Beware of time/space ambiguities
  - Treat unusual events with suspicion (check raw data if possible)
  - Data can be ambiguous (e.g. ion temperature/ion mass)
  - Use your knowledge of physics and ask yourself what is reasonable
  - Make as certain as possible that your "event" is real!

- For EISCAT data in particular, remember
  - The high-latitude region is highly structured in latitude and longitude
  - The ionosphere responds dynamically to the solar wind
  - There is a danger of convolving altitude variations with latitude/longitude variations (unless you look field-aligned)
  - Looking in any one direction, you miss what is happening in others.
  - Scanning modes can take a long time, compared to physical processes.

Conclusions

- Good experiment design is critical
  - Think about times, scale sizes and measurements needed
  - Make sure your experiment and analysis are appropriate to the conditions
  - Being too ambitious (e.g. with multi-point scans) can destroy your experiment!!

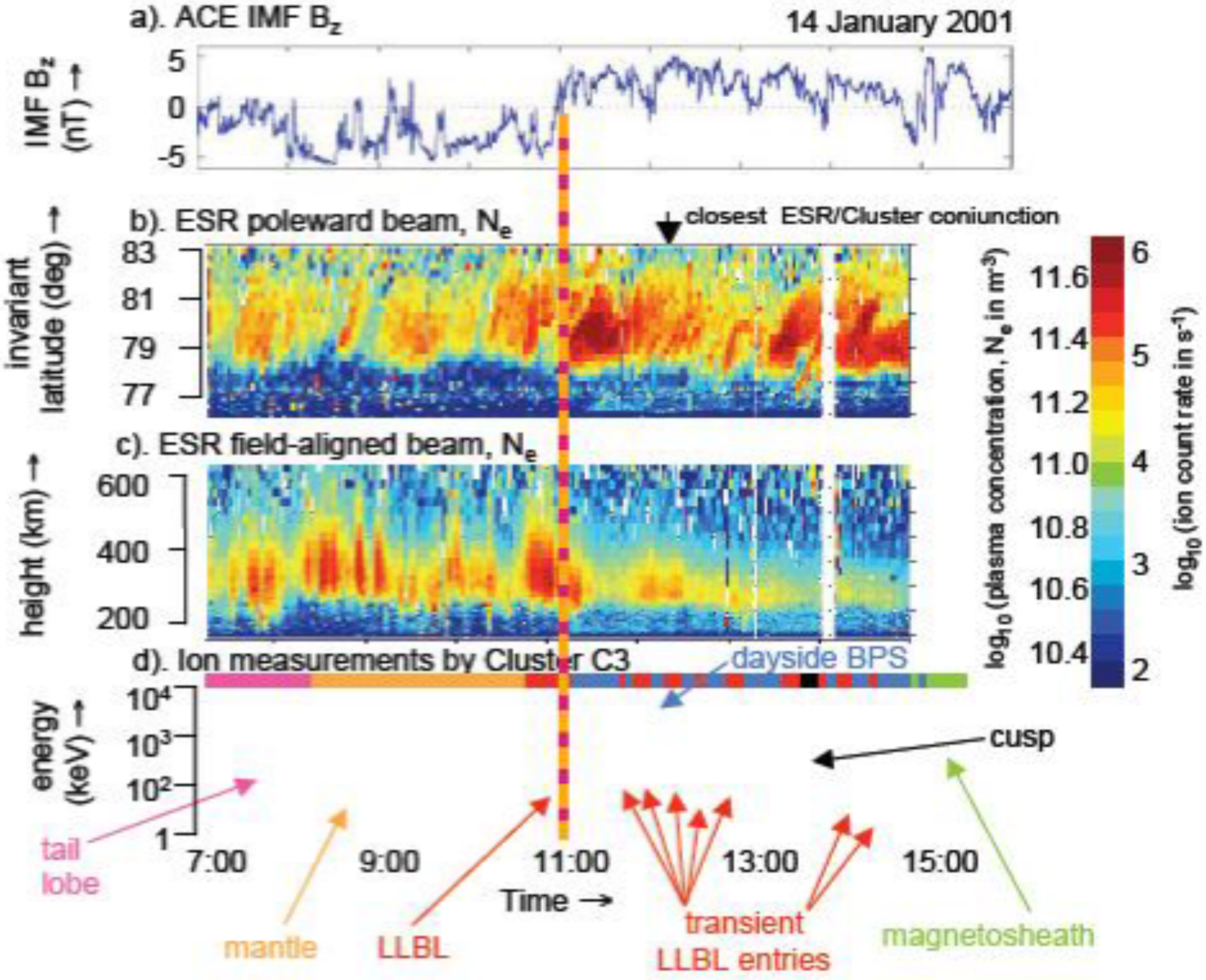
- Even ISR data do not tell you everything!
  - Use supporting data from other instruments to provide context
  - Optical/magnetometer/SuperDARN are all good ground-based data sources
  - Satellite data can also be very valuable (e.g. DMSP, Cluster)

- Keep an open mind!
  - "If you torture the data enough it will confess to anything!"
  - Don't try too hard to make the data fit your story
  - Avoid over-interpretation of poor data

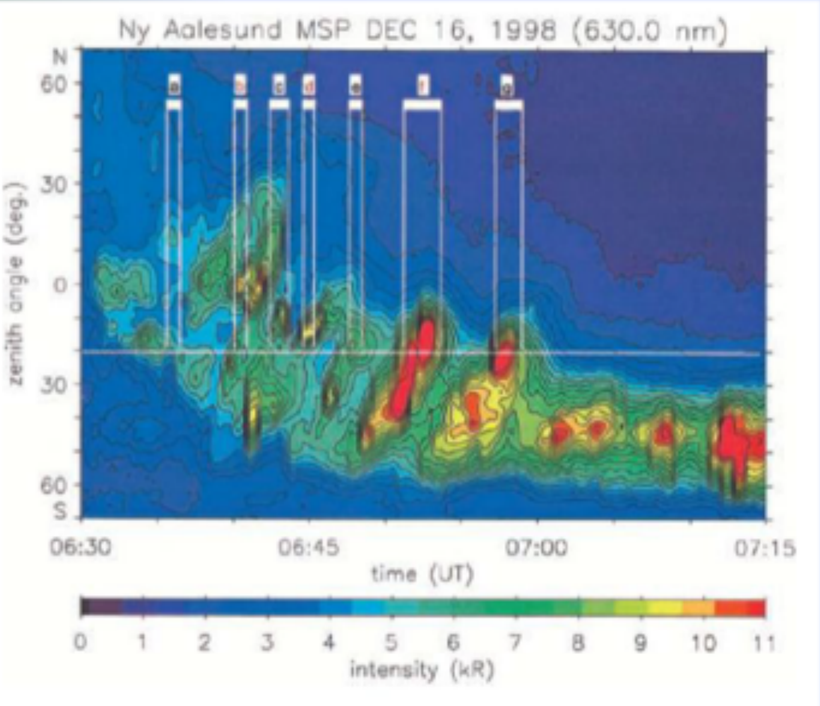
Putting the field-aligned data in context

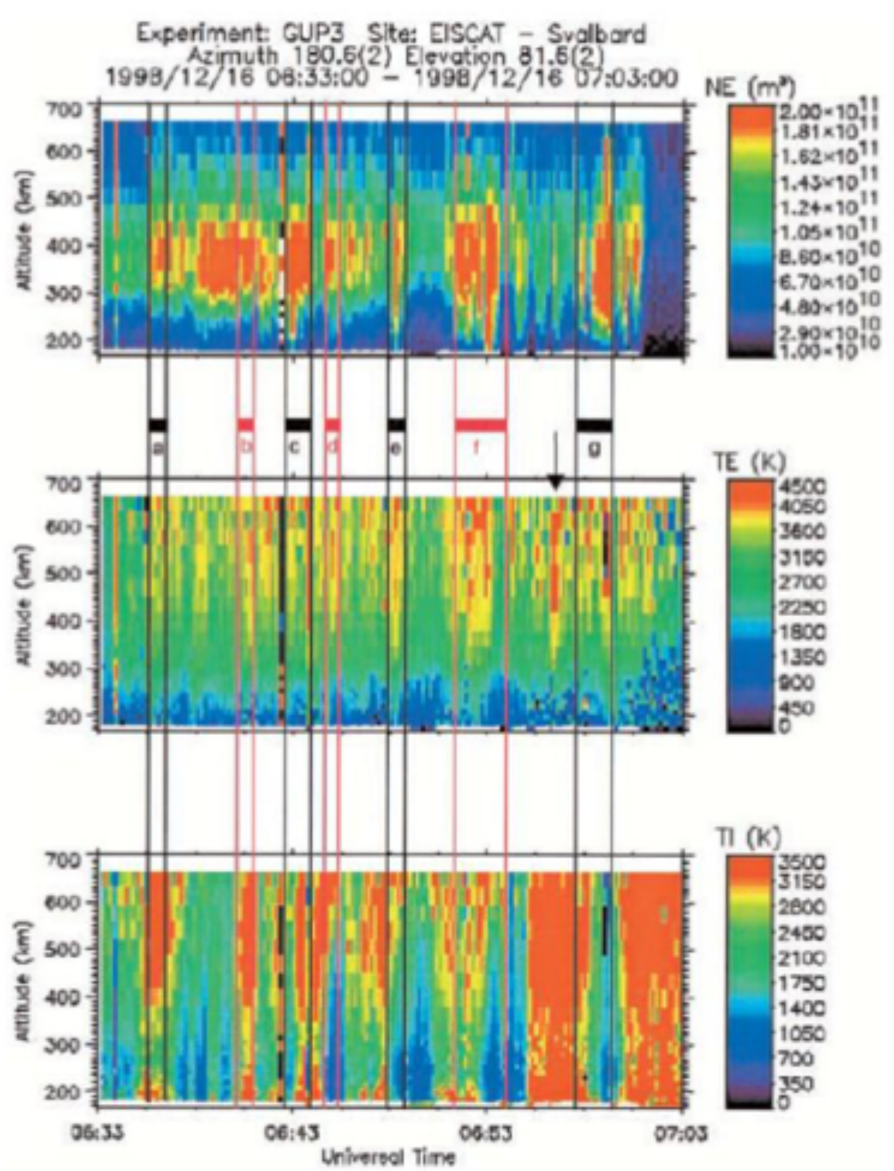
using 2 ESR beams

- effect of northward turning
- motions over radar matched to those over Cluster
- poleward-moving events shown to be caused by low-energy electron flux changes
- transient LLBL and cusp entries shown to be FTEs



Identifying the cusp (ESR)





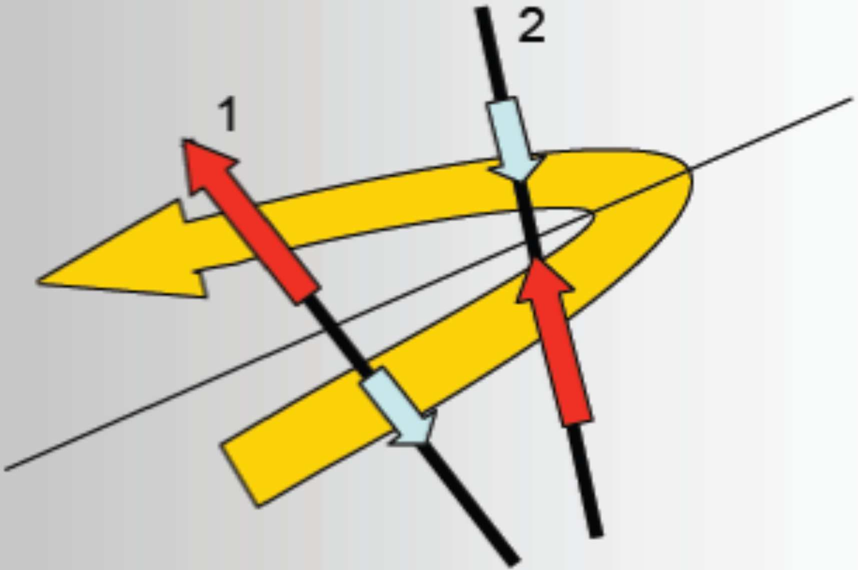
Lockwood et al, Ann. Geophys., 18, 1027-1042, 2000

A Polar Cap Contraction

Where are we?

In fact there is an asymmetry in observed V_{los}, flow – as shown below

It reveals that there is flow across the convection reversal boundary

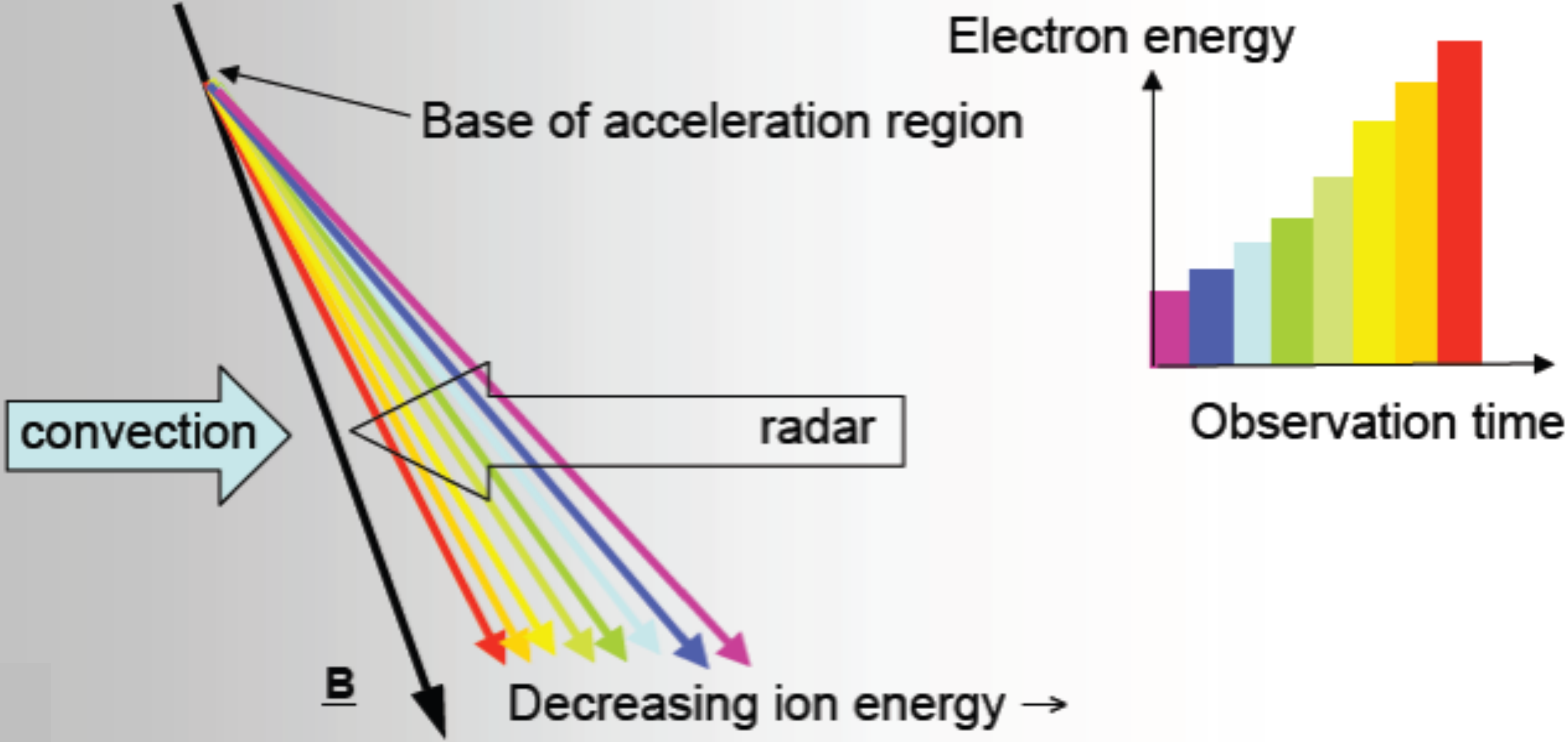


A precipitation event

(dispersion structure)

In the rest frame of the arc

(in the radar rest frame, the arc moves over radar in same direction as convection, but is moving more slowly then convection)



Base of acceleration region

convection

radar

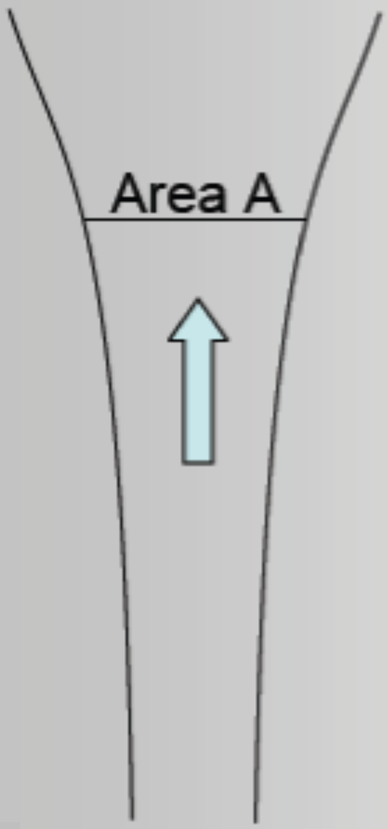
B

Decreasing ion energy →

Flux Profiles

Why is $N_eV_{||}$ independent of h?

Continuity equation on a flux tube



$d(N_iAV_{||})/dh = q - L$

Above h of about 200 km production q and loss L are negligible

(note we consider total ion flux so charge exchange is not a factor)

$(1/F)\ dF/dh = (1/A)\ dA/dh$

In the ionosphere A(h) is approximately constant (and is known from magnetic field model) so F is approximately constant)

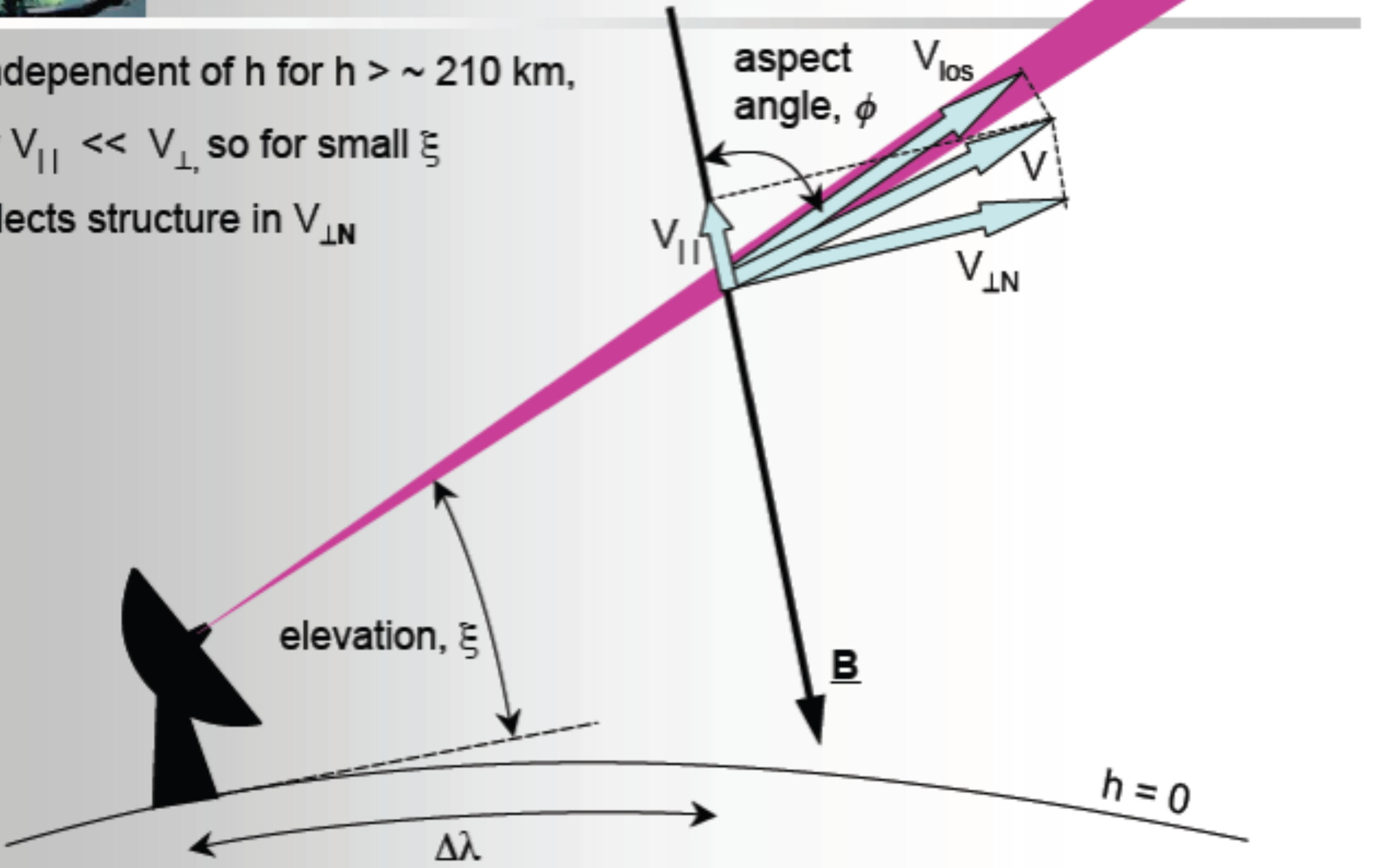
Line-of-sight velocity

e.g. for a northward-pointing beam

$V_\perp$ is independent of h for h > ~ 210 km,

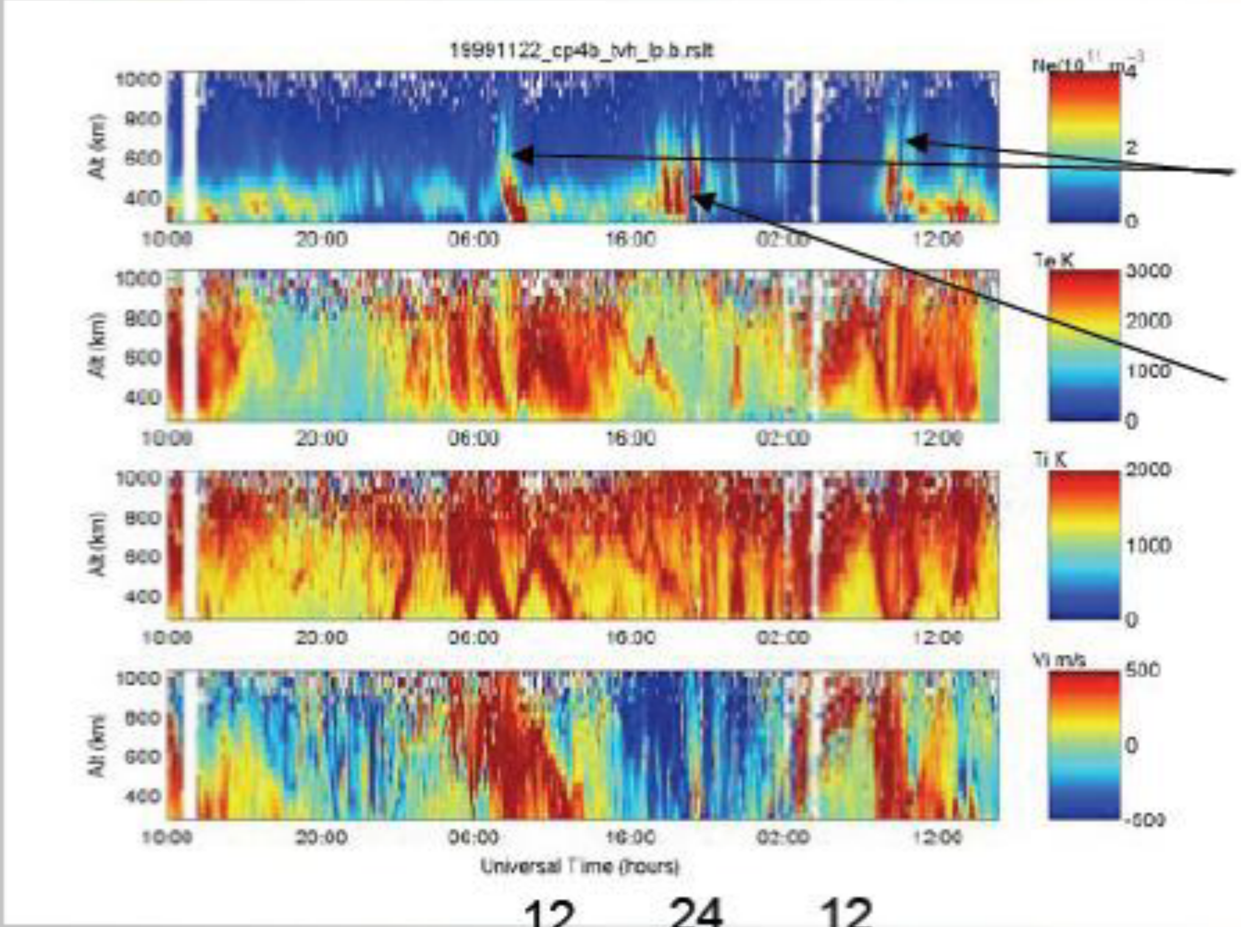
usually $V_{||}$ << $V_{\perp}$, so for small ξ

V_{los} reflects structure in $V_{\perp N}$



Polar Cap Patches

(in same CP-4-B data)



Poleward-moving events

Equatorward-moving events

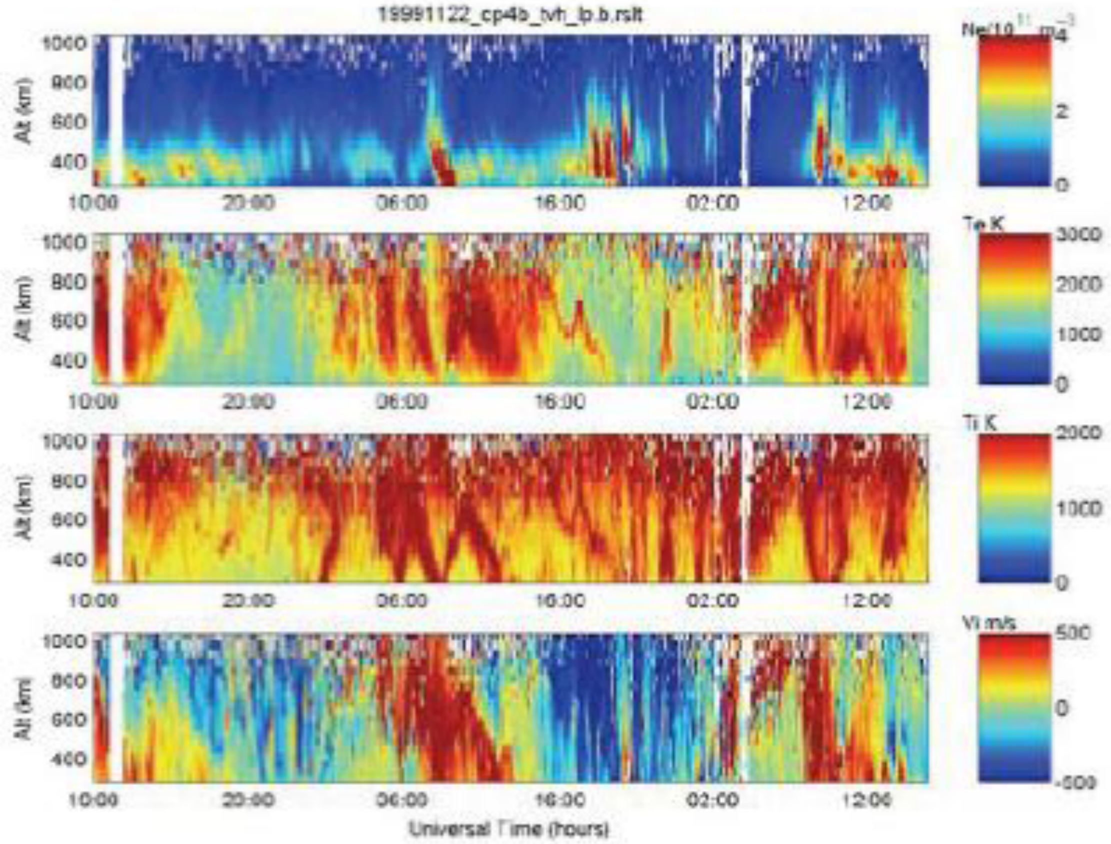
12 MLT

24 MLT

12 MLT

Substorm Cycles

(in CP-4-B data)



See expansions and contractions. This time MLT ≈ UT + 2.75hr

So 06-12 UT is 8:45-12:45 MLT

A Polar Cap Contraction

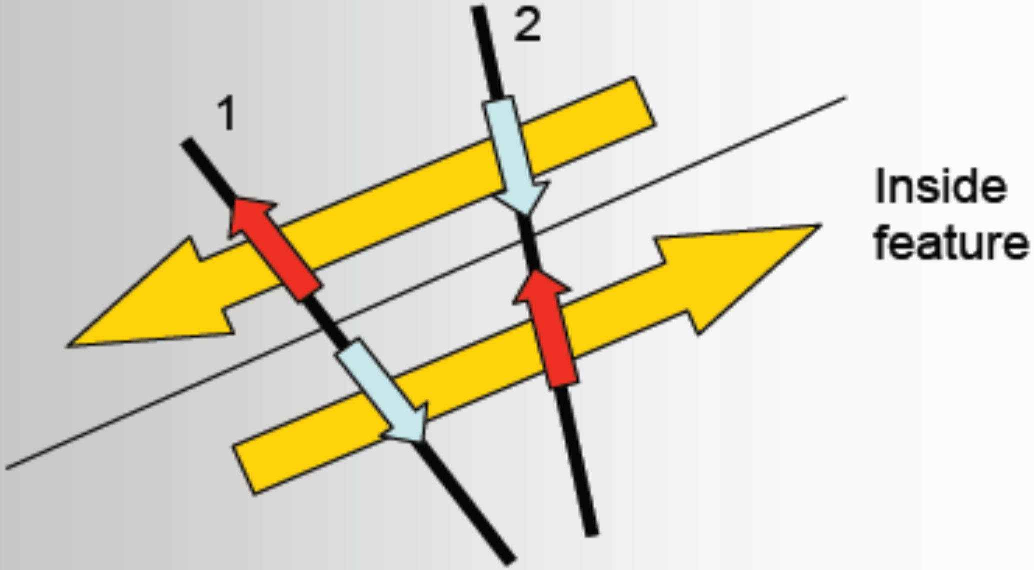
Where are we?

F-o-v is north of Tromsø (latitudes λ = 70.5 - 74.5°)

For this f-o-v MLT ≈ UT + 1.75 hrs

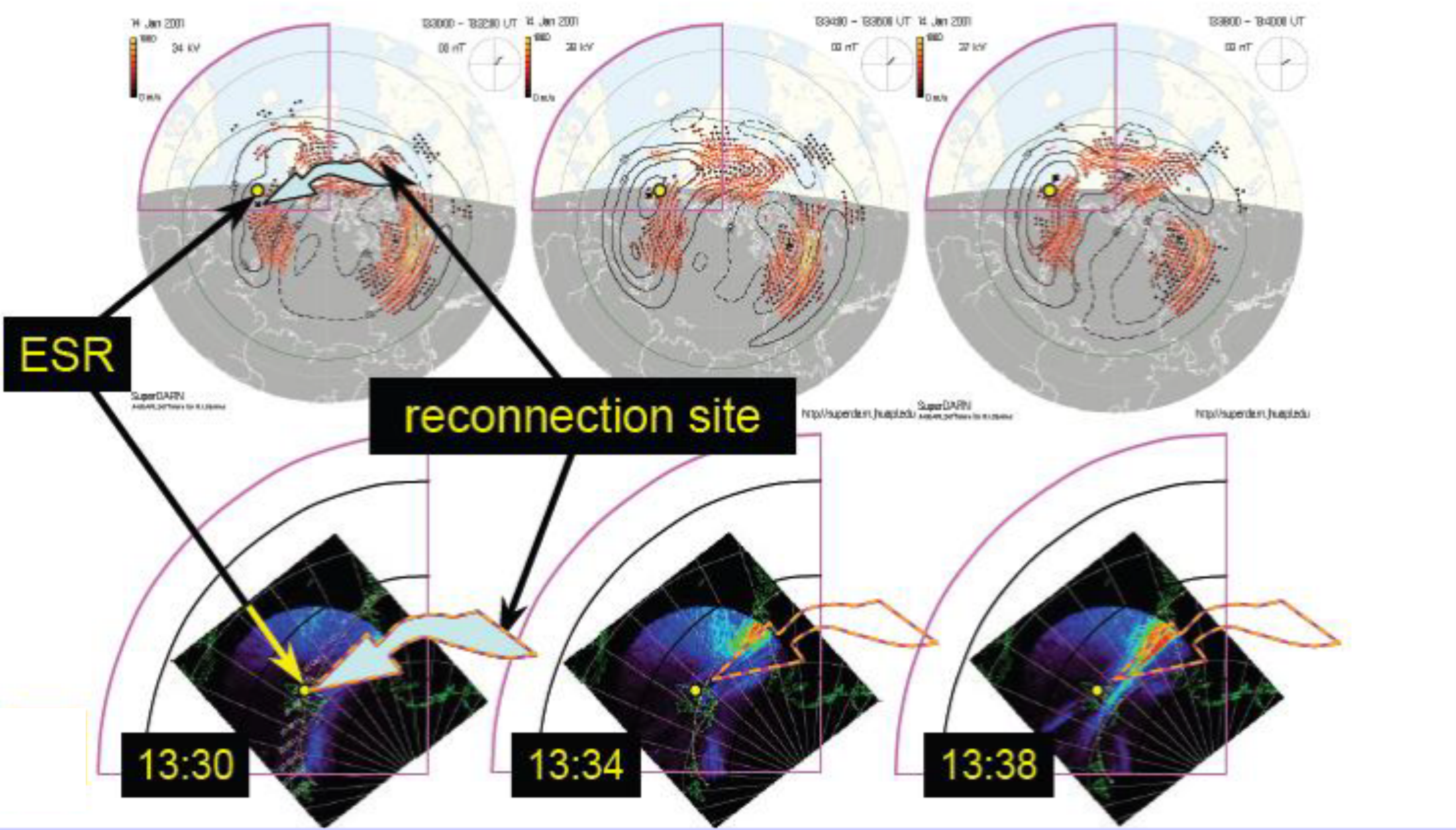
(use, e.g. http://lewes.gsfc.nasa.gov/space/cgm/cgm.html)

Poleward-moving event is at about 4:00UT, ≈ 5:45 MLT, i.e. near dawn



Putting ESR and Cluster data into context

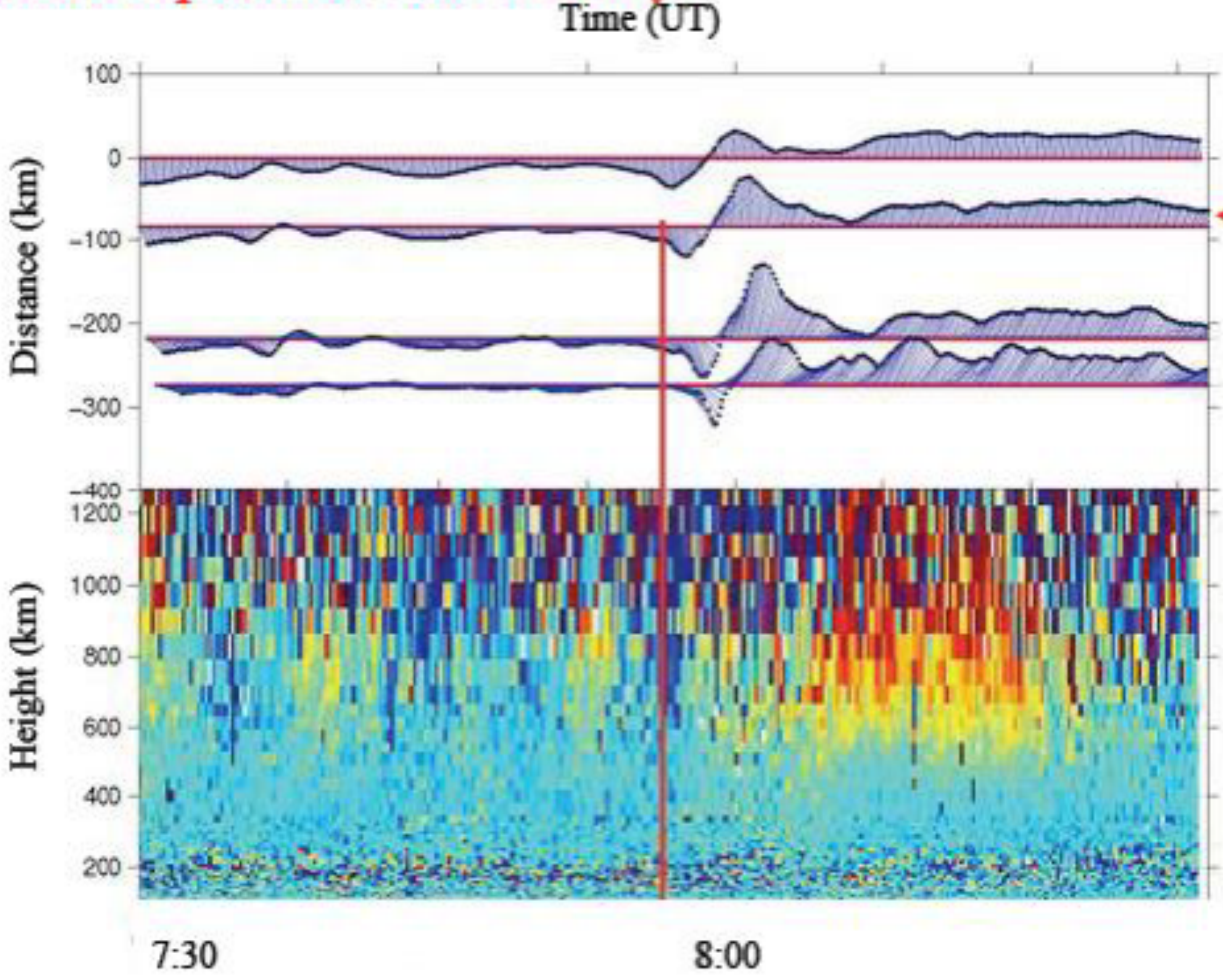
Using SuperDARN radar convection maps and imagers



Field-aligned flows

(put into context of a TCV using IMAGE magnetometers)

SW pressure pulse arrival time ↓



← LYR

Identifying the cusp (ESR)

- High F-region electron density N_e (but can be confused with EUV-enhanced polar cap patches convecting poleward)
- High Electron Temperature (patches of sub-aurorally EUV-produced plasma would not show enhanced T_e)
- Electron density highly variable in cusp – gives poleward-moving 630nm transient aurorae