NSF Workshop Report: Strategic Vision for Incoherent Scatter Radar

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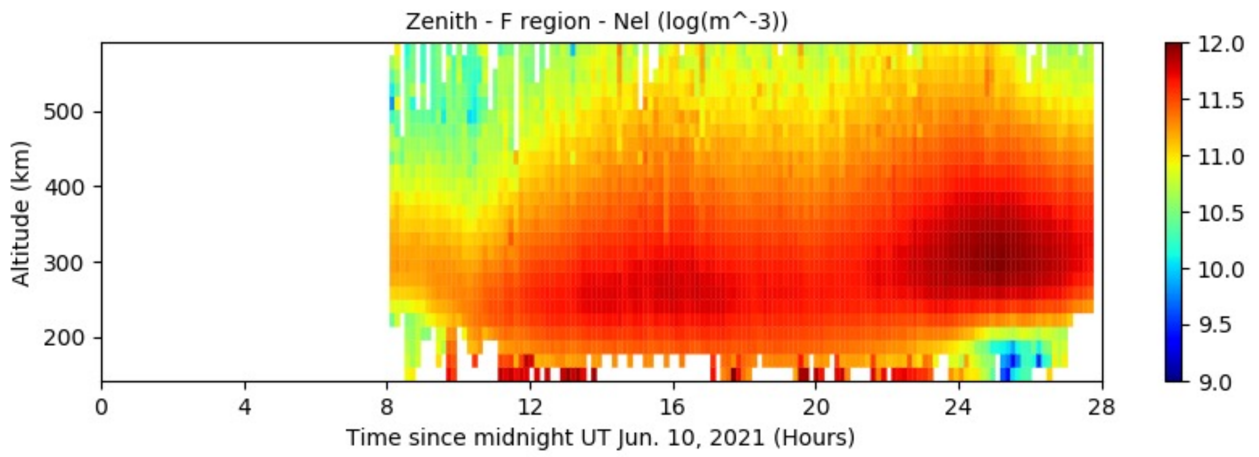
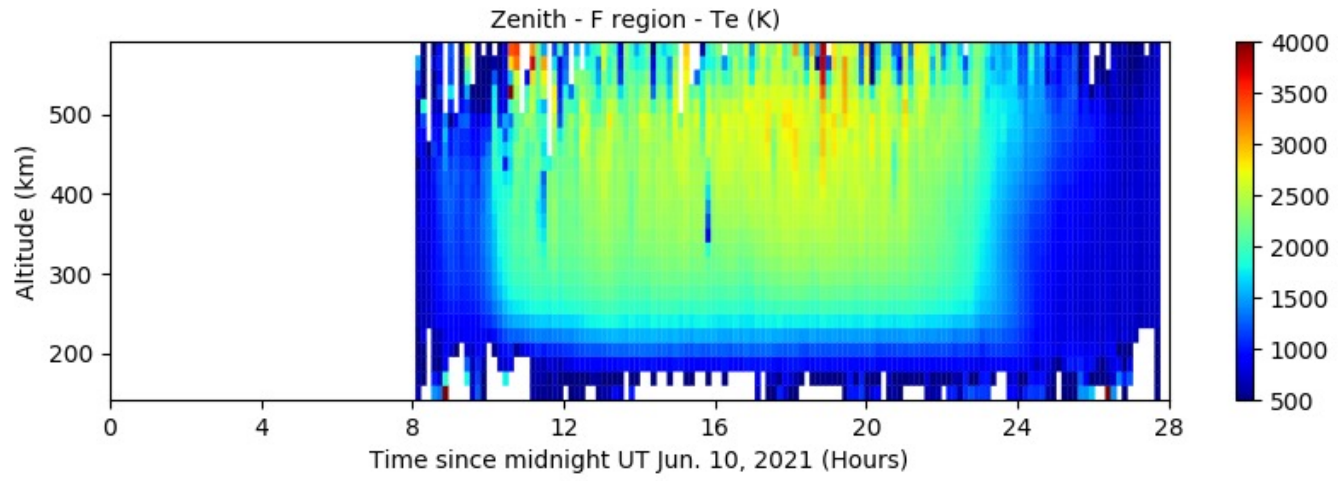
CEDAR 2021 Virtual Workshop 21 June 2021





Held virtually over Zoom on 26 - 28 April, 2021
100+ attendees
Requested by NSF Geospace Facilities 2018 program officer Carrie Black

Workshop charge:

- Identify and prioritize science questions that compel new investment in geospace facilities
- Emphasize science questions as a priority (new technologies inevitably also discussed)
- Avoid a focus on specific / existing facilities or locales

Workshop outputs:

- Report to NSF Geospace Section (drafted)
- NASEM Decadal Survey white paper (future)
- Future community proposals (NSF, others) for support to develop, actualize a facilities concept

Incoherent Scatter Radar

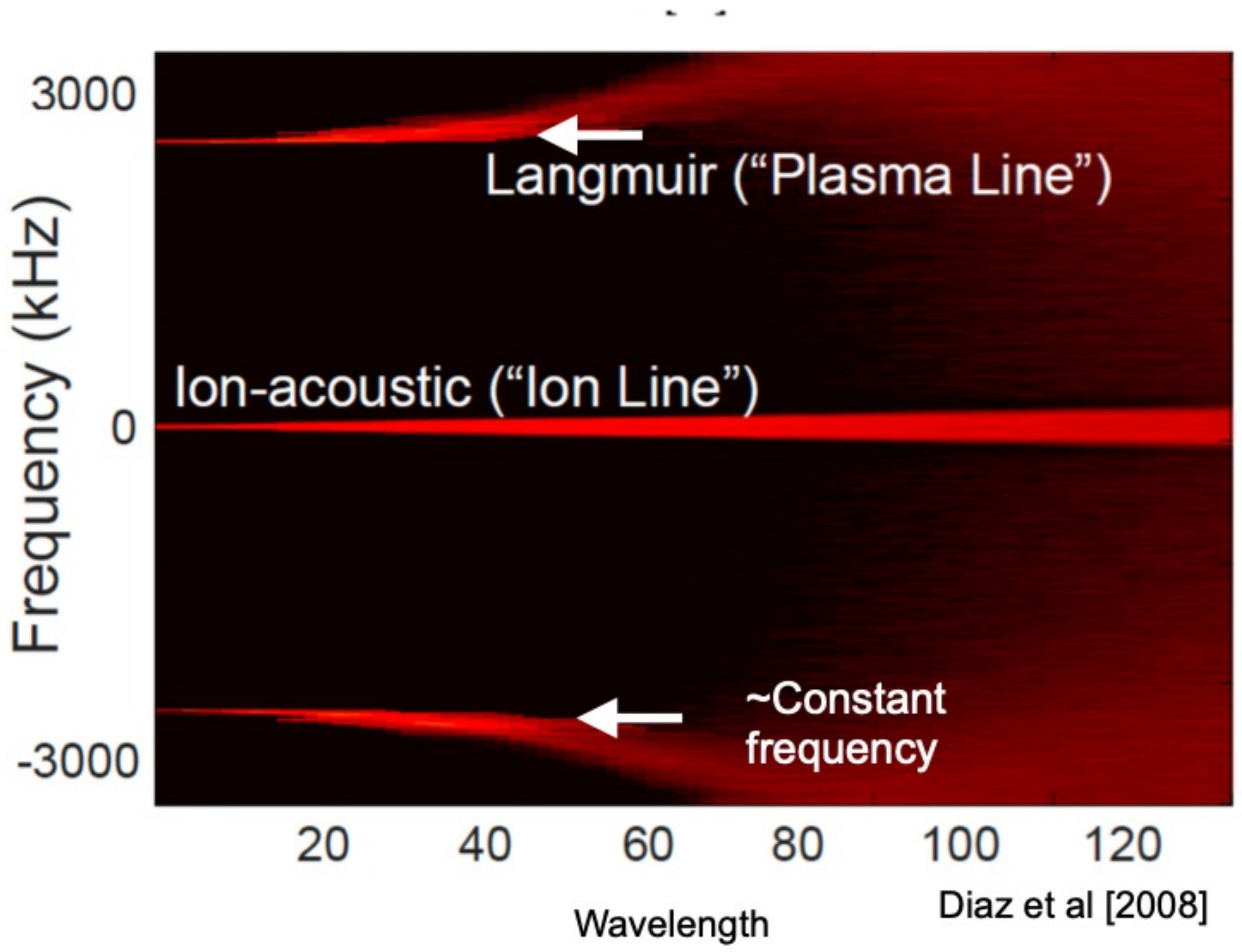
Thomson scatter from electrons: fundamental physical process

Even though one electron has a tiny cross section, scatter can still be detectable from a whole volume of electrons

Bragg scatter from those thermal waves matching the Bragg wavenumber for a particular TX frequency

Scattered spectral shape is a sensitive function of thermal plasma state: electron density, electron and ion temperature, velocity, ion composition, other parameters

Weak scattering means full altitude dependent profiles can be retrieved: scalars, gradients, vector quantities

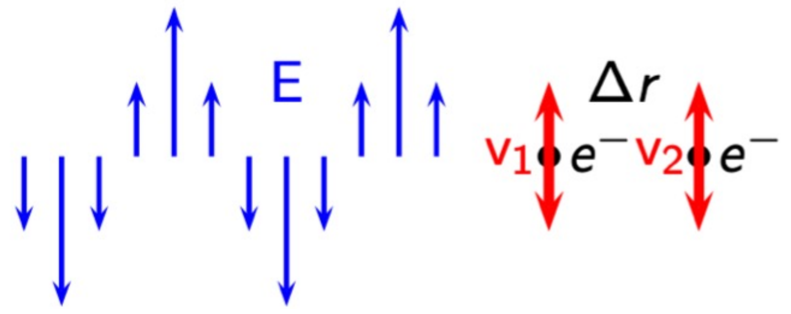


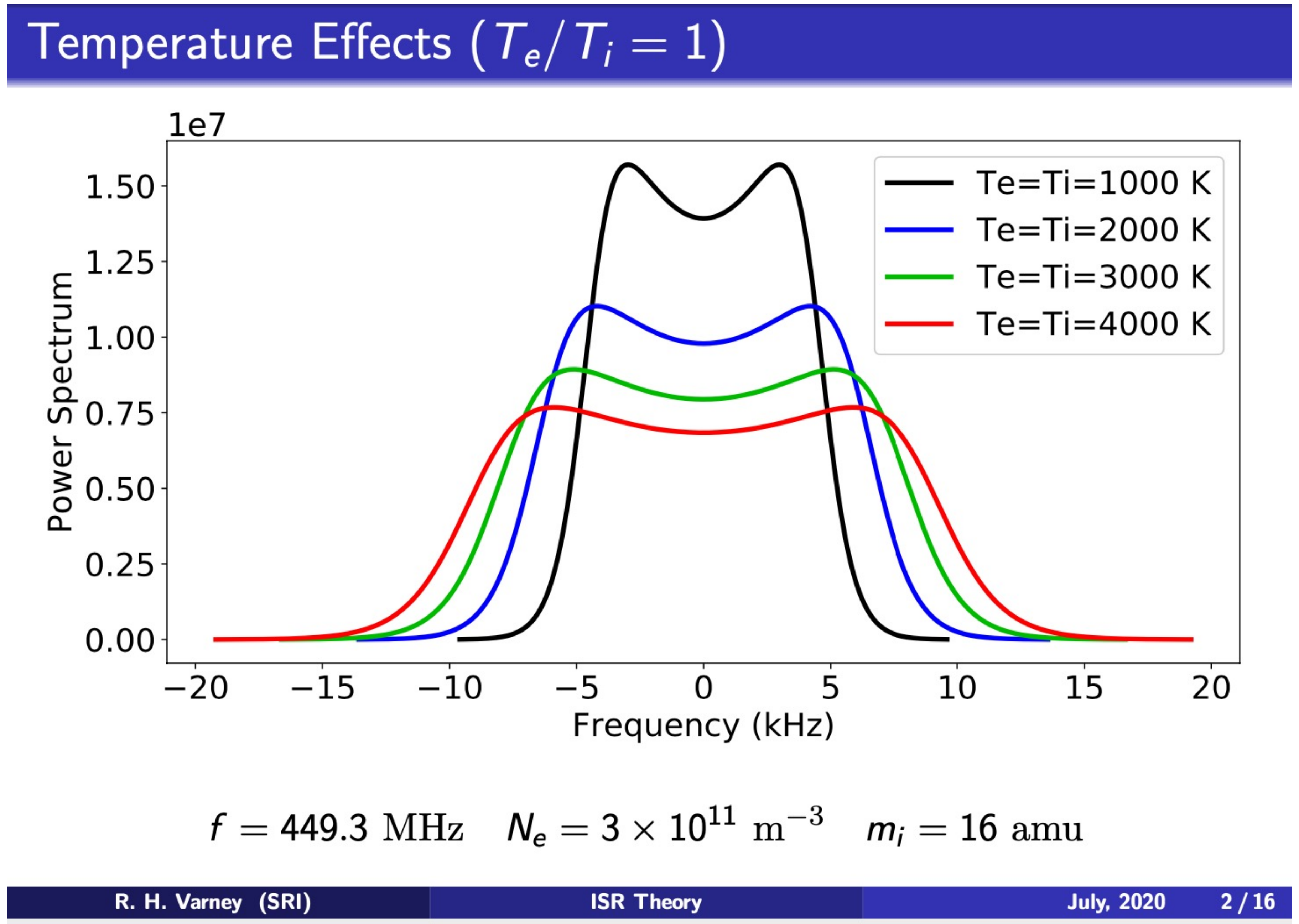
Diaz et al [2008]

$$\frac{\omega}{k} = \sqrt{\frac{k_B T_e + \gamma_i k_B T_i}{m_i}} = V_s$$

$$\omega^2 = \omega_p^2 + \frac{3}{2} k^2 v_{th}^2$$

$$v_{th}^2 = 2 k_B T_e / m_e$$



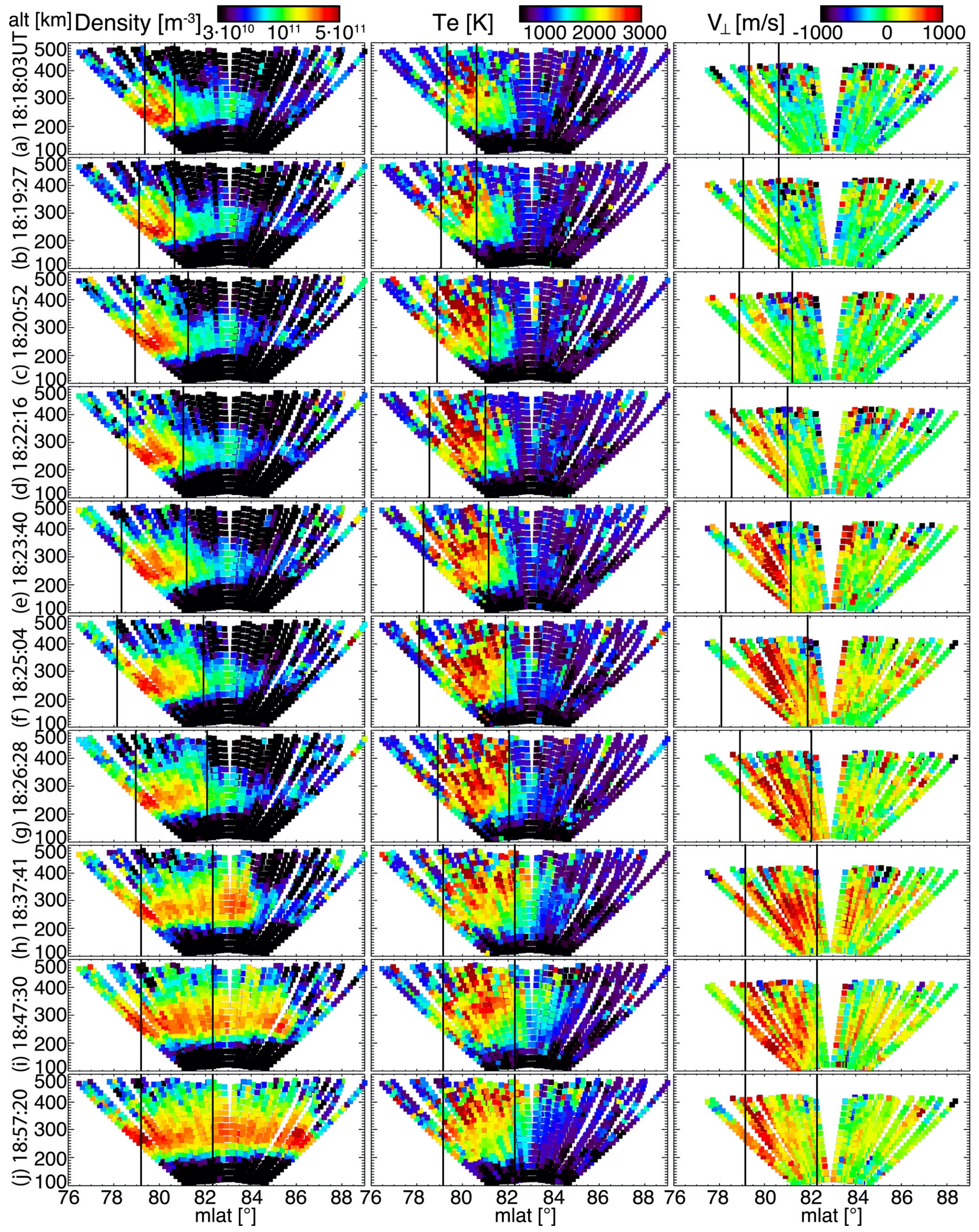


Temperature Effects ($T_e/T_i = 1$)

$f = 449.3$ MHz $\quad N_e = 3 \times 10^{11}$ m^{-3} $\quad m_i = 16$ amu

R. H. Varney (SRI) ISR Theory July, 2020 2 / 16

Science Priority: Cross-scale coupling



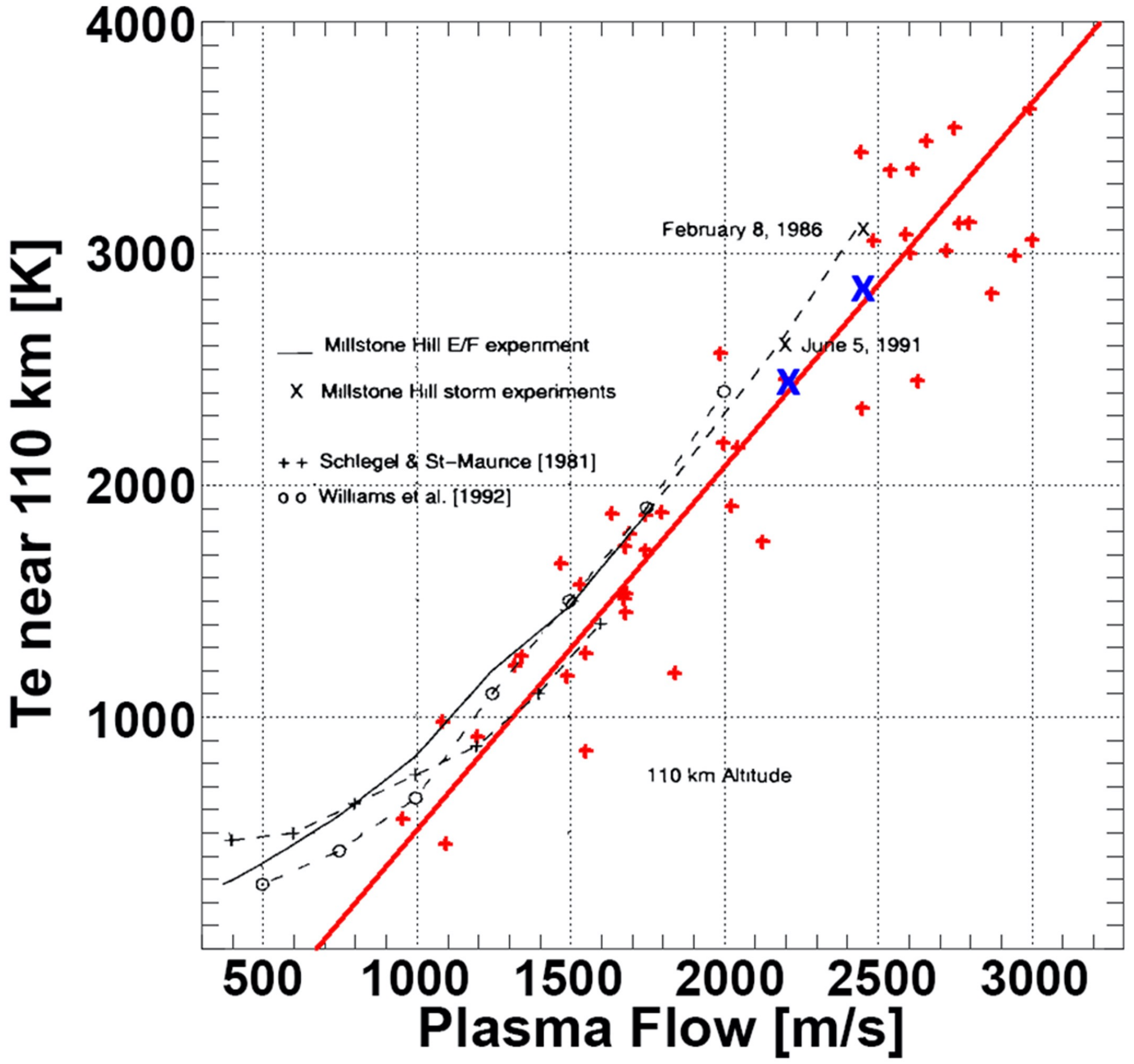
Nishimura et al 2021
Polar cap patch formation,
Cusp dynamics

Mesoscales (100 - 1,000 km)

- Auroral oval width ~1000 km
- Transformative: ISR imaging field as large as 1000x1000 km (All-sky imager field)
- Effectively track structure evolution in Lagrangian frame of reference

Instabilities (<1 - 100 km)

- Largest uncertainty: morphology and dynamics of gradients/shears at ~10 km scales
- Ion inertia cannot be neglected below 1 km scale: accessible with in-beam interferometry



St. Maurice and Goodwin 2021
E-region electron temperature
response to large amplitude
Farley-Buneman waves

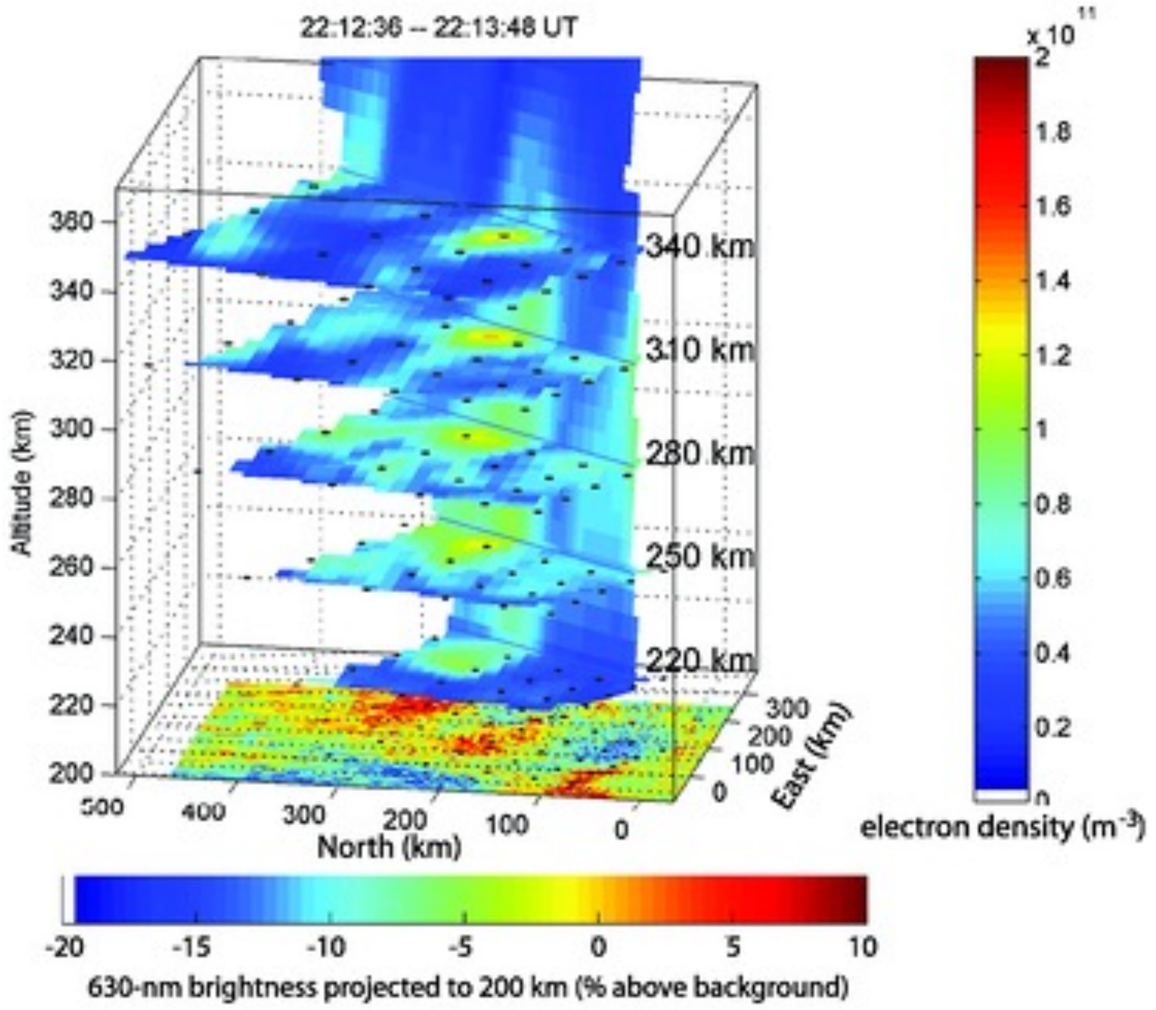
Fine scales (10 - 100 m) and microscales (10 cm - 10 m)

- Energy dissipation at these small scales is poorly understood
- Nonlinear effects on E region conductivity / M-I coupling
- Radars can access:
  - Electron heating through e.g. Farley-Buneman instabilities
  - Unstable plasma waves through direct Bragg scattering (multiple k vectors!)
  - Langmuir cavitons, naturally enhanced ion-acoustic lines
  - Electron scale / ion scale coupling: photoelectrons, unstable waves, etc.

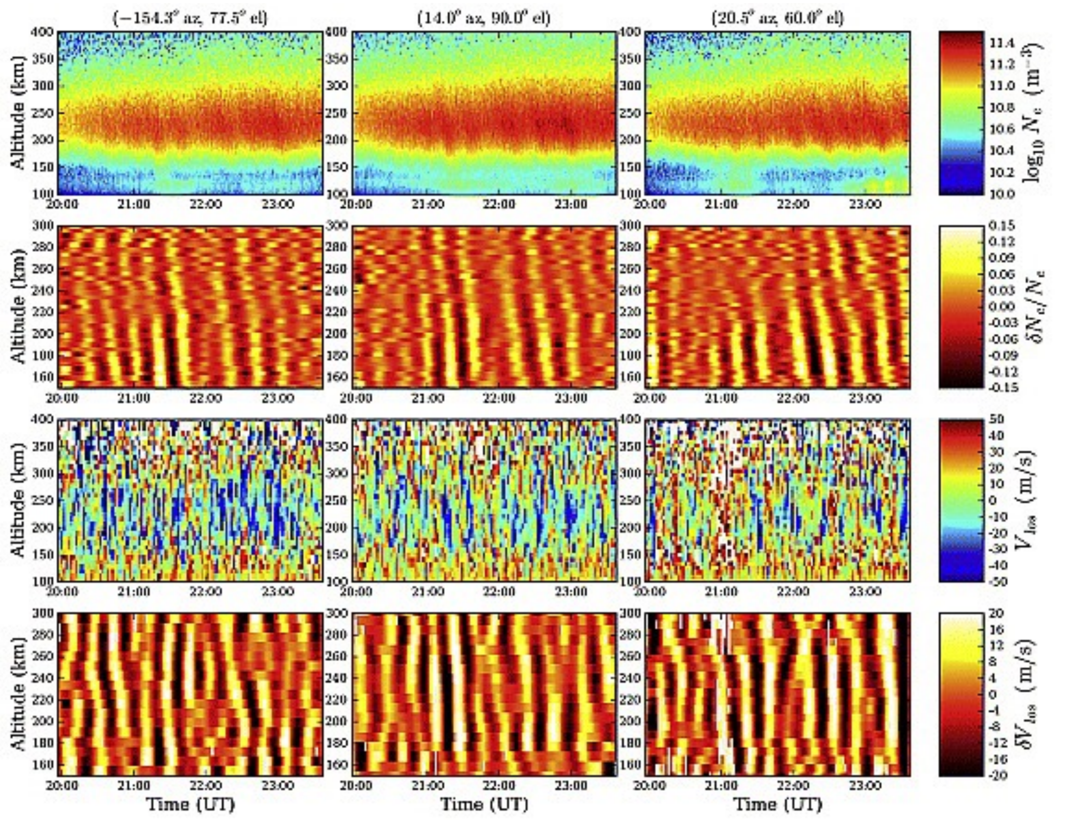
Science/Technique Priority: Data Assimilation

Data assimilation as key tool to advance frontier community models

- Instrument forward model readily available from robust IS radar theory
- First start with regional data assimilation, related to global boundaries (e.g. plasmapause)
- Transformative potential



Dahlgren et al 2012
Volumetric imaging of electron density structures fused with 630-nm airglow



Vadas and Nicolls 2008
Neutral winds through measurements + gravity wave dissipation theory

Key approaches and topics:

High latitude ionosphere and thermosphere response

- Fusion approaches: combine radars with as many other space/ground sets as possible
- Altitude-resolved observations essential for many topics: current closure, neutral wind dynamo/flywheel, Joule heating, conductivity
- Realistic boundary conditions for multi scale modeling

Whole atmosphere coupling

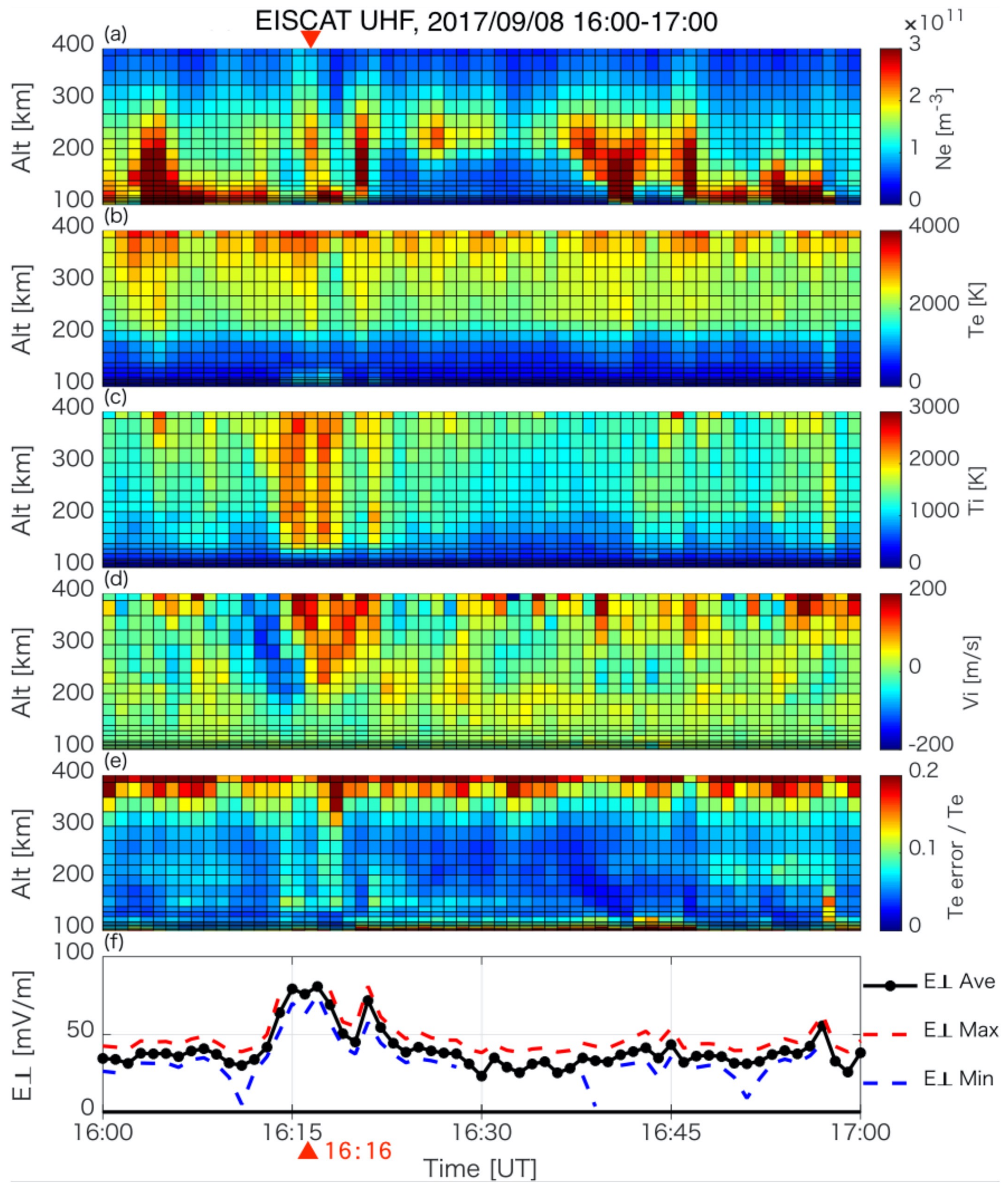
- Multi-scale gravity wave dissipation in the lower thermosphere
- Fundamental (not empirical) understanding of vertical eddy diffusion
- Neutral wind variations with altitude, and coupling to day-to-day electron density variability

Science Priority: System Scale Science

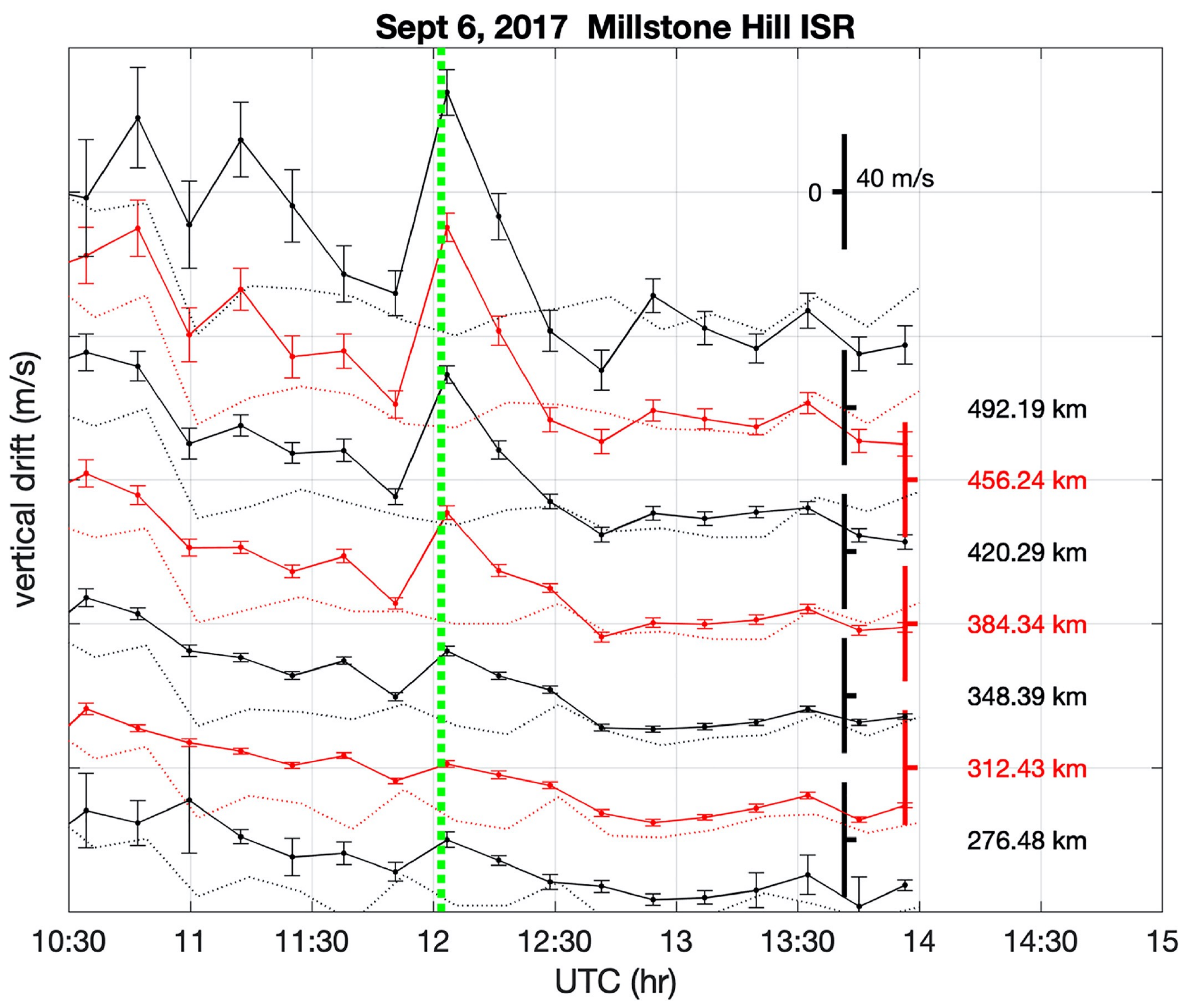
Subauroral zone
- SAPS, SAID, connections to STEVE
- Storm enhanced density: mass and energy flows
- Midlatitude generation and influence of MSTIDs and LSTIDs

Cusp region
- Solar wind magnetospheric shock compression effects
- Joule heating, 2-way magnetosphere/ionosphere feedback
- Ion upwelling/upflow understanding requires altitude profile information

Plasmasphere / ionospheric thermodynamics
- Altitude profiles required to gauge heat flux parallel and perpendicular to B
- Variability on O+ ionospheric outflow, populating the magnetosphere
- Ionospheric electron heating associated with ring current H+ precipitation

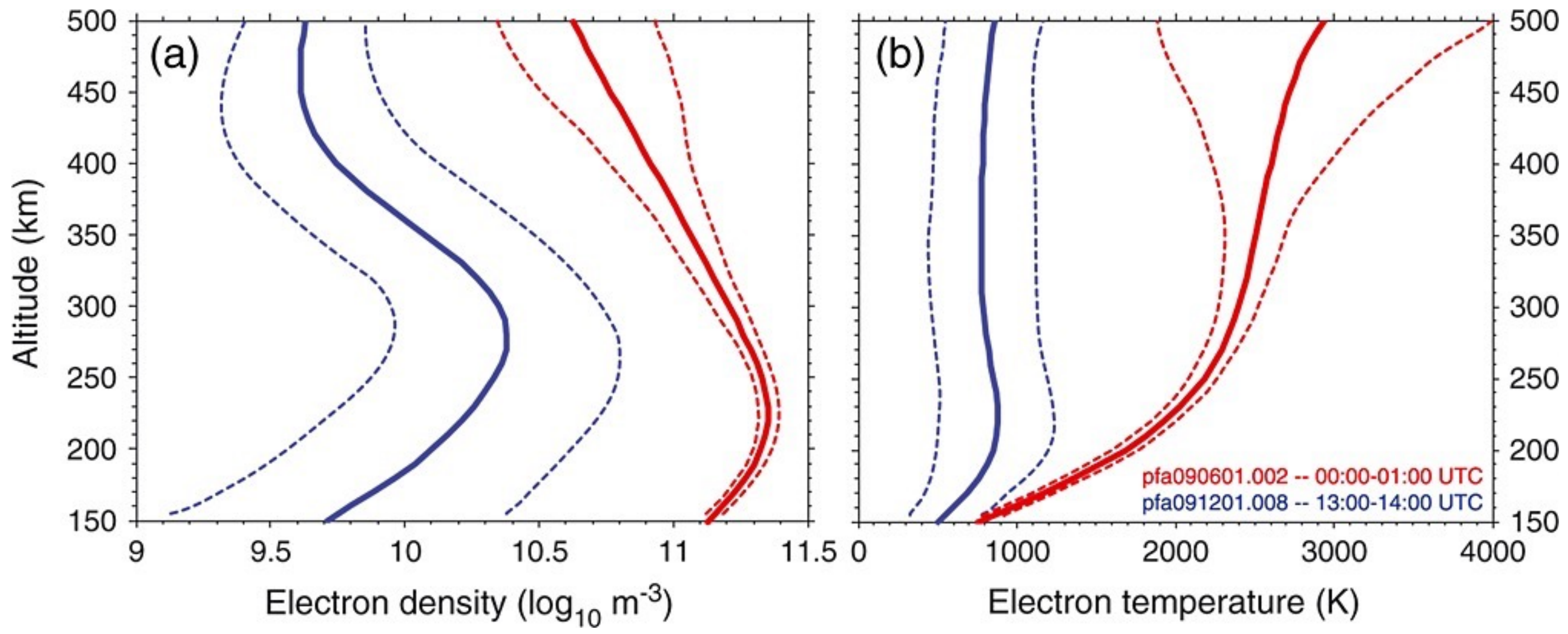


Takada et al 2021
Ion upflow in ring current footprint



Zhang et al 2019
Mid-latitude ionospheric upwelling and TID generation following large solar flare

Fallen and Watkins 2013
Topside electron heat flux seasonal variations



Science Priority: Neutral/Plasma Coupling

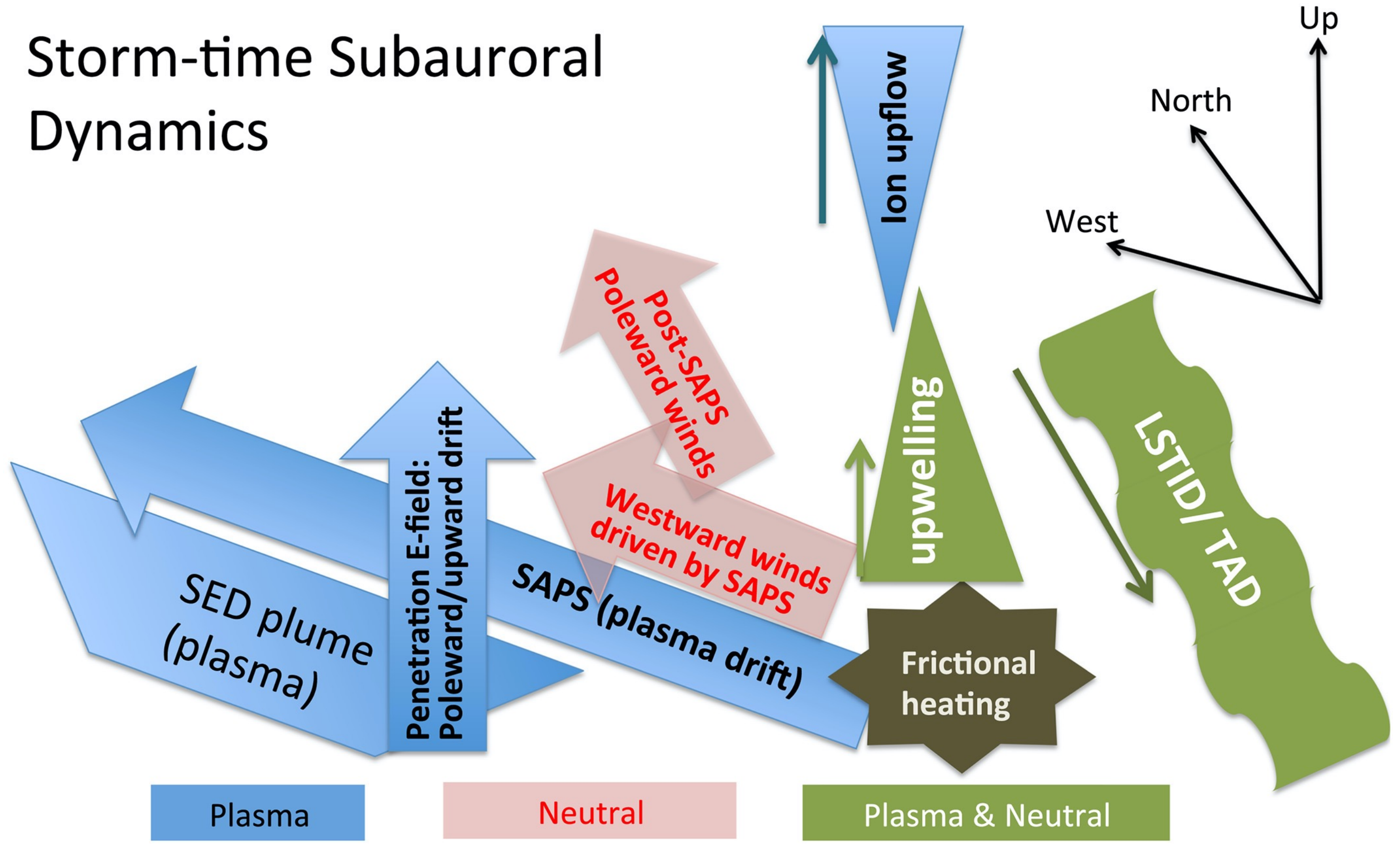
Ion-neutral coupling

- Especially strong in presence of magnetic fields
- Profoundly influences mass, momentum, energy transfer
- Dominant means of converting fast-ordered motion to heat
- Important during both storm and quiet times

Frontier questions

- Equatorial anomalies in neutral density, temperature, wind
- Storm-time neutral upwelling after thermosphere energy deposition
- Exchange of momentum, energy, charge state

Storm-time Subauroral Dynamics



Zhang et al 2017
Neutral-ion coupling effects on subauroral dynamics

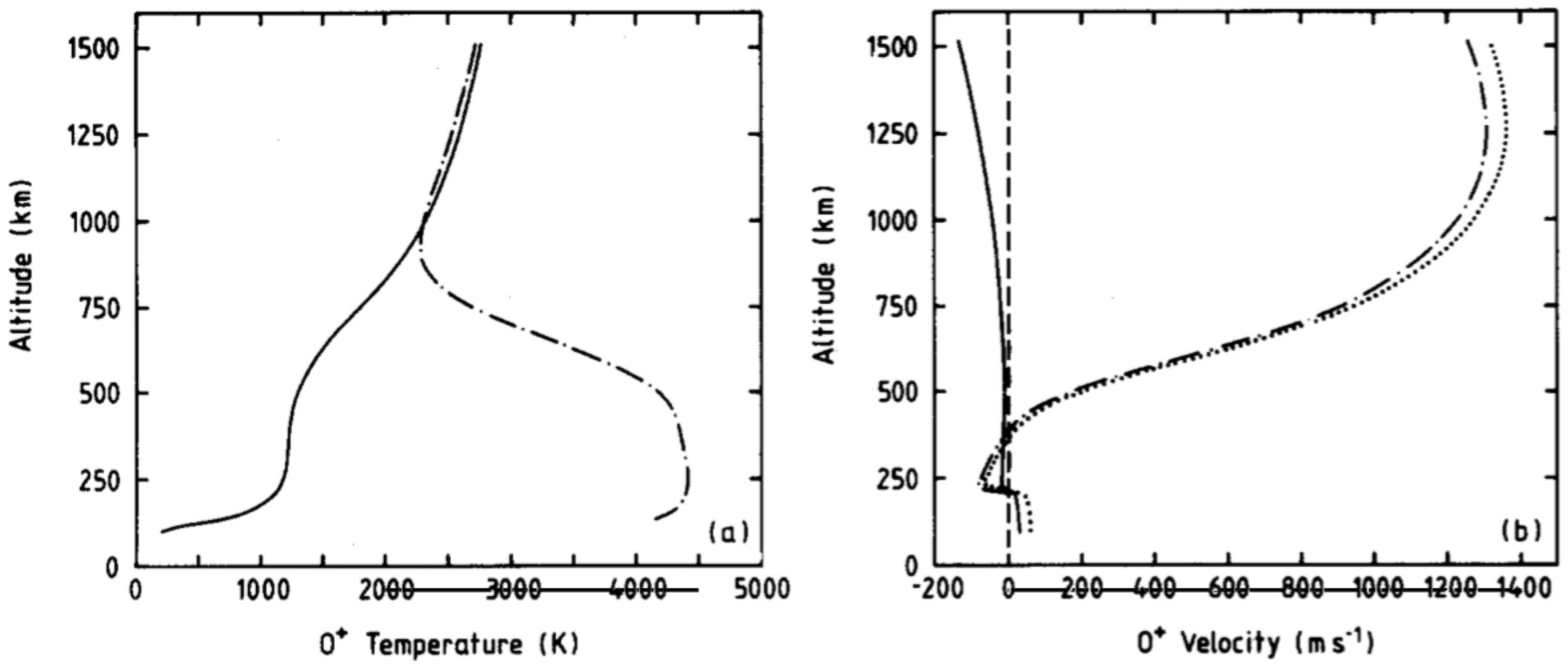


Fig. 2. (a) Calculated O^+ temperature profile (dot-dashed curve) after 10 minutes of elapsed time. The soild curve gives the O^+ temperature in the absence of the zonal drift. (b) Calculated O^+ field-aligned velocity profiles corresponding to the O^+ temperatures displayed in Figure 2a after 10 minutes of elapsed time. The dotted curve gives the O^+ field-aligned velocity in the presence of the zonal drift and of neutral air upwelling.

Sellek et al 1992
Rapid zonal flow effects on field-aligned ion flow: modulated by neutral air upwelling

Science Priority: Meteor Science

Meteor applications for geospace science

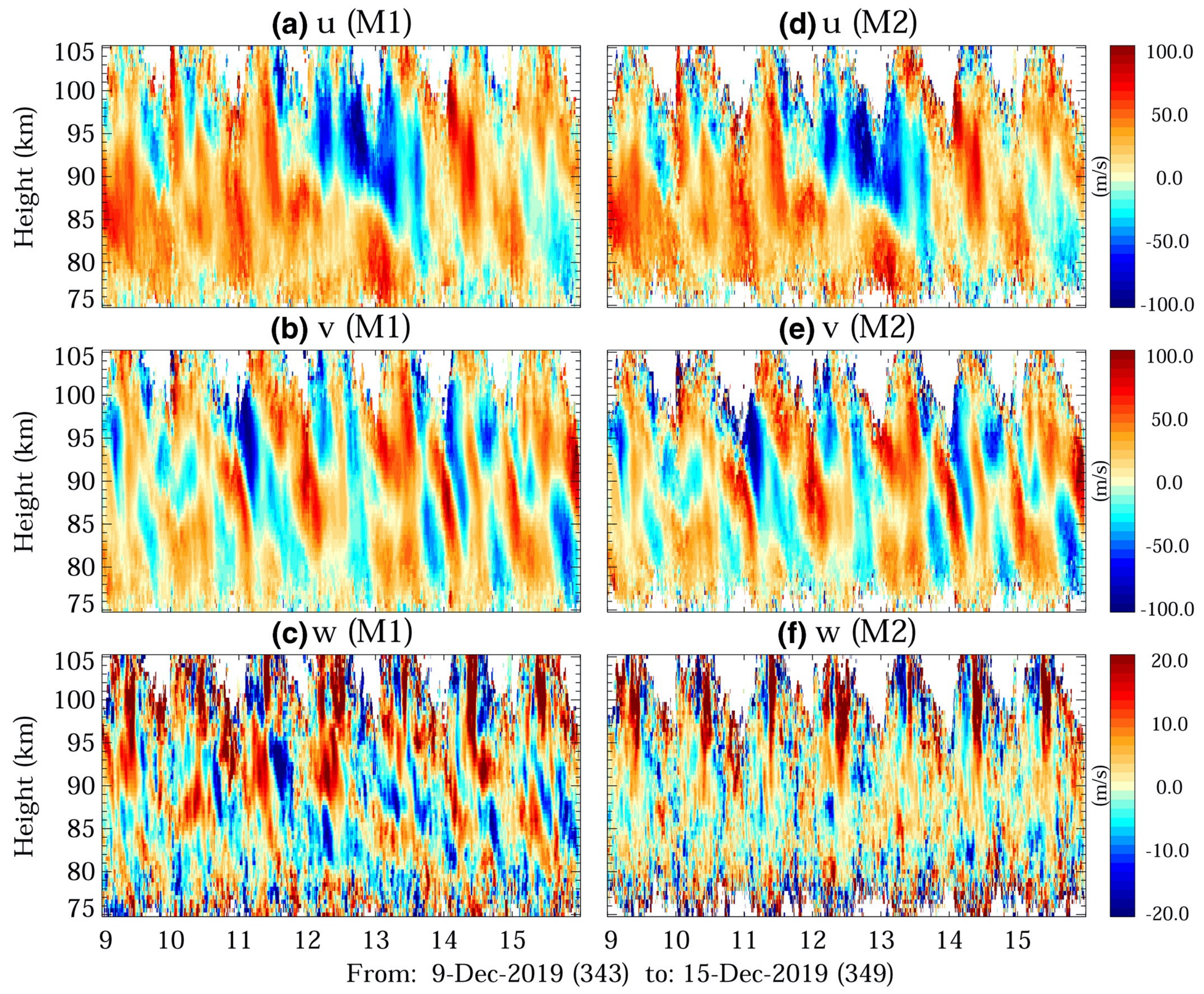
- Fundamental for study of MLT dynamics
- Interplay of gravity waves, stratified turbulence
- Mesospheric ice particles: tracers for km-scale instabilities (Kelvin-Helmholtz, mesospheric bores)
- High-resolution 3D MLT wind profiles from non-specular meteor reflections

High-power large aperture meteoroid studies

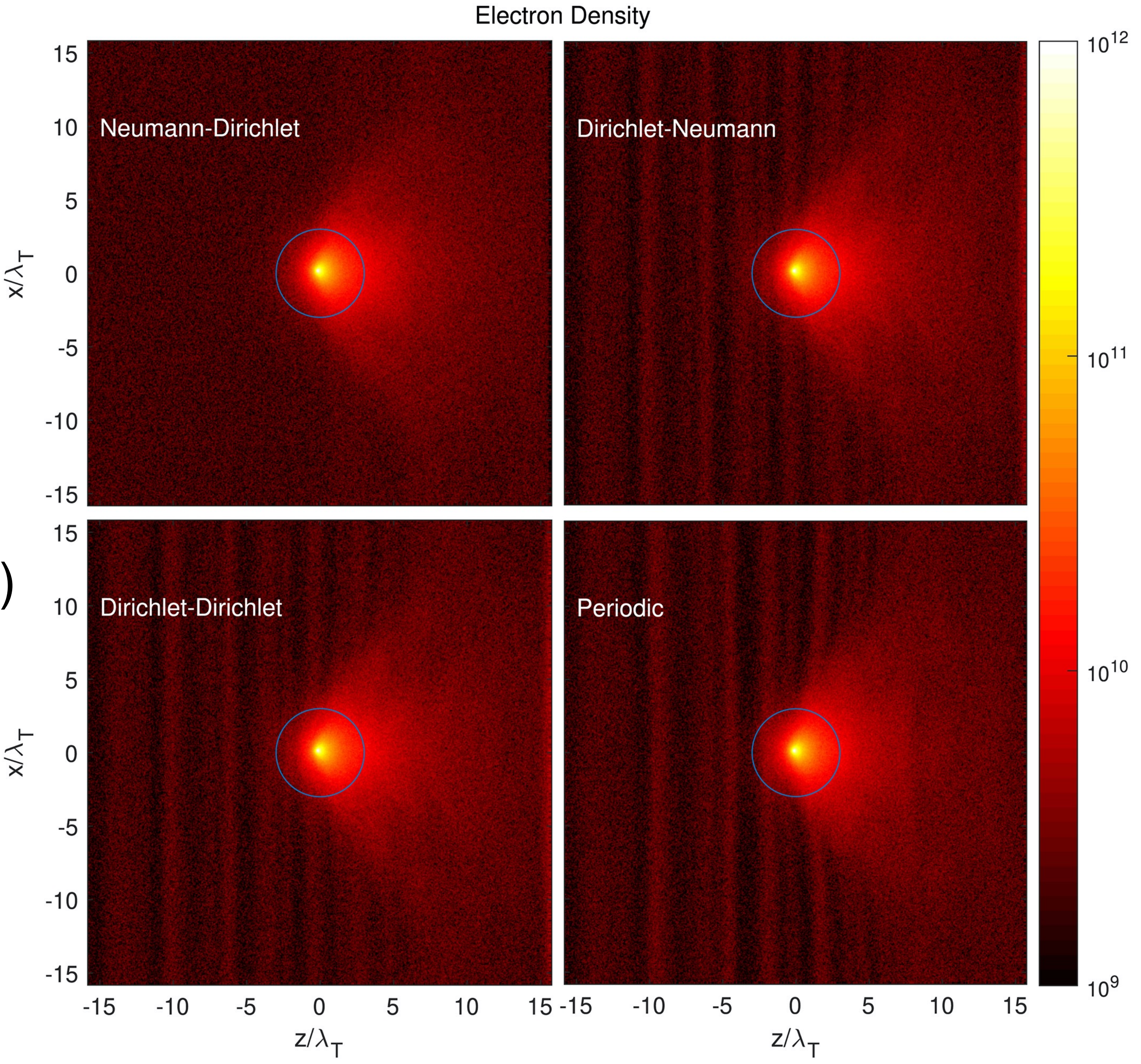
- Meteoroid orbits, interstellar origins
- Meteoroid mass flux
- Atmospheric chemistry, fragmentation

Observational technique improvements:

- Multi-static time of flight
- Multi-wavelength: compare echo models with observations
- Full-trajectory observations: e.g. MIMO



Chau et al 2020
Mean 3D winds
derived from MIMO meteor
radar observations



Sugar et al 2019
Meteoroid electron density under
different boundary conditions
(Affects meteoroid mass calculations)

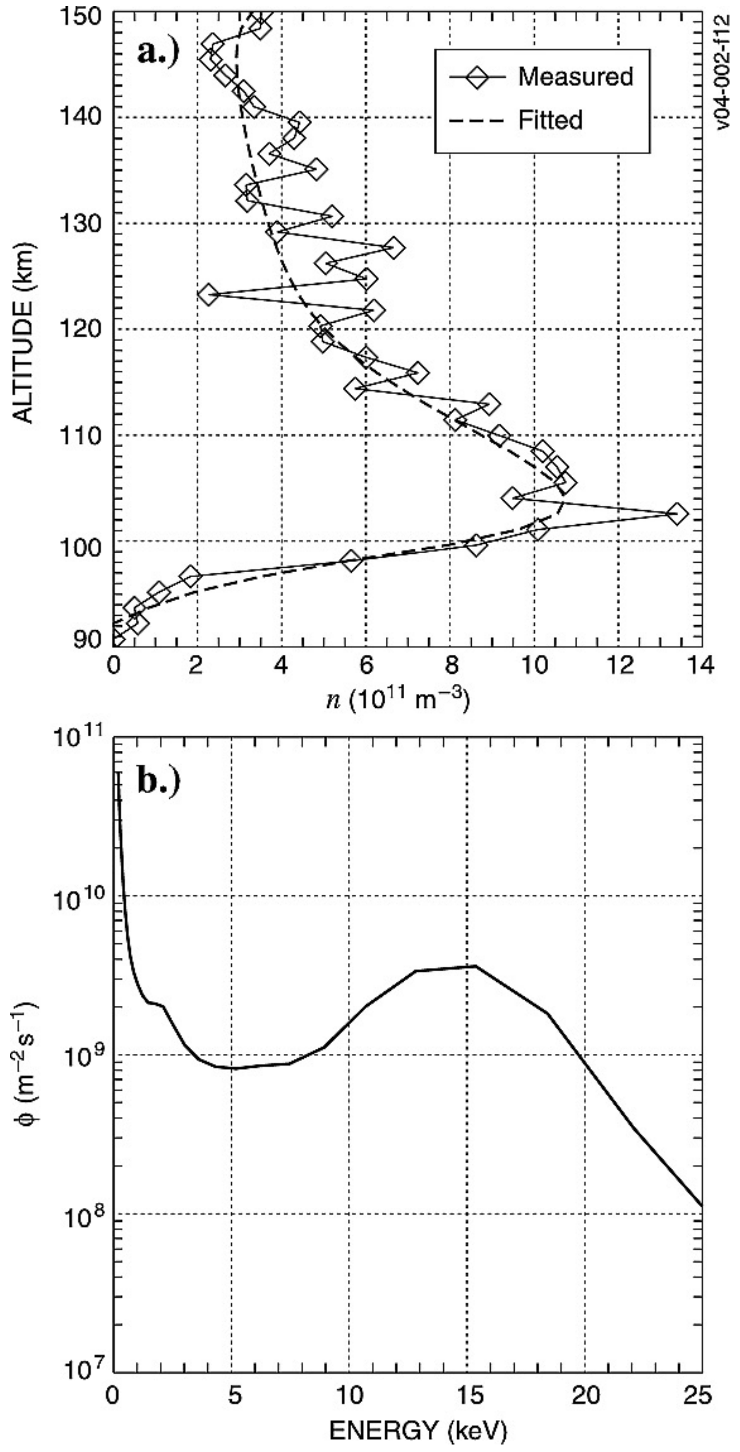
Science Priority: Energetics, Dynamics, Transport

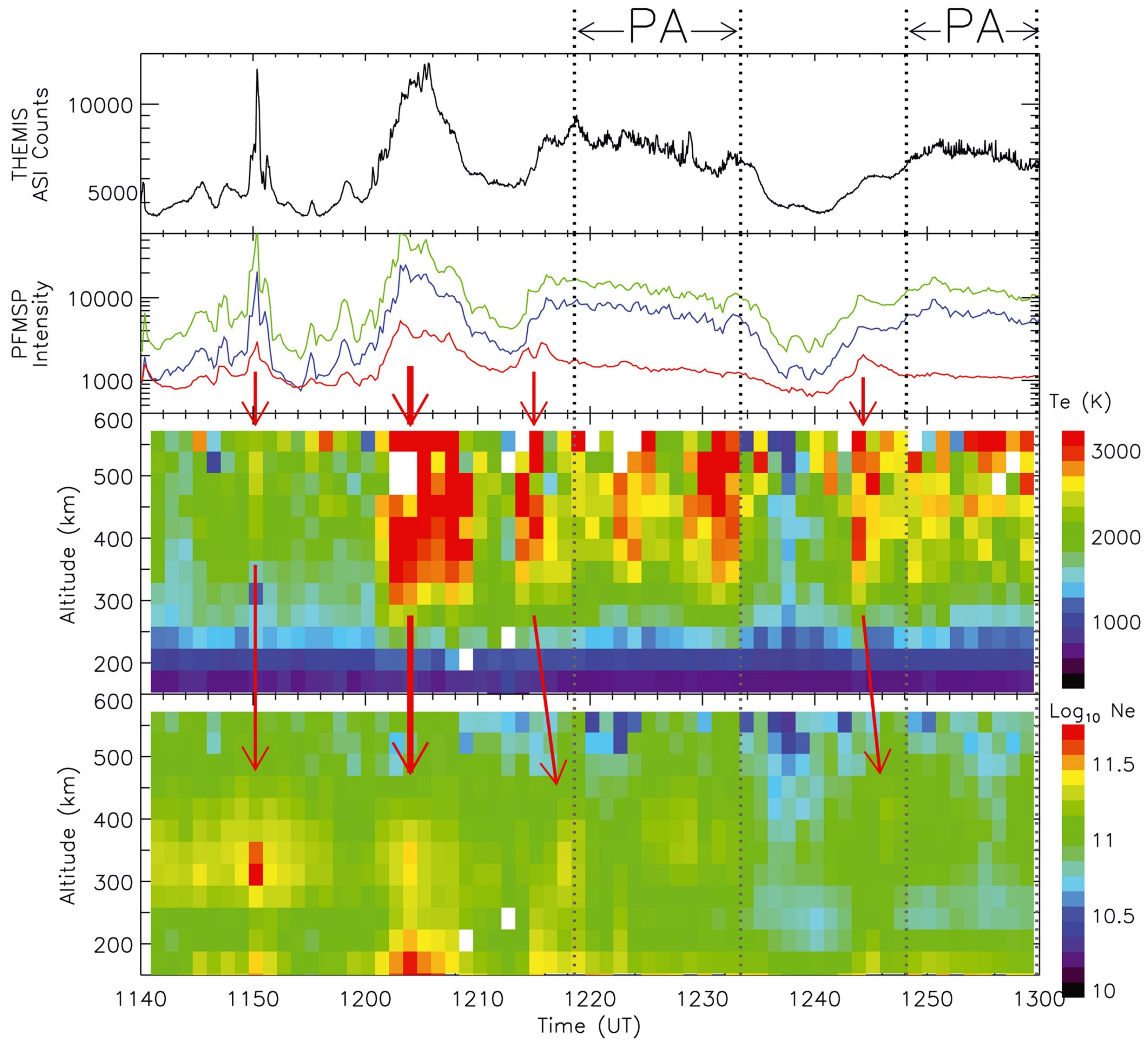
IS radars have multiple applications:
- Direct measurements of cold ion, electron temperatures
- Ion velocity distribution functions
- Magnetosphere-ionosphere heat flow (e.g. pulsating auroras)

Derivatives of temperature, density
- Field-aligned: heat flux
- Pressure gradients
- Ambipolar electric fields

E-region density profiles
- Precipitating particle energy spectra
- Ionospheric conductivity
- Middle atmospheric chemistry

Semeter and Kamalabadi 2005
Precipitating energy spectra from
electron density altitude profiles





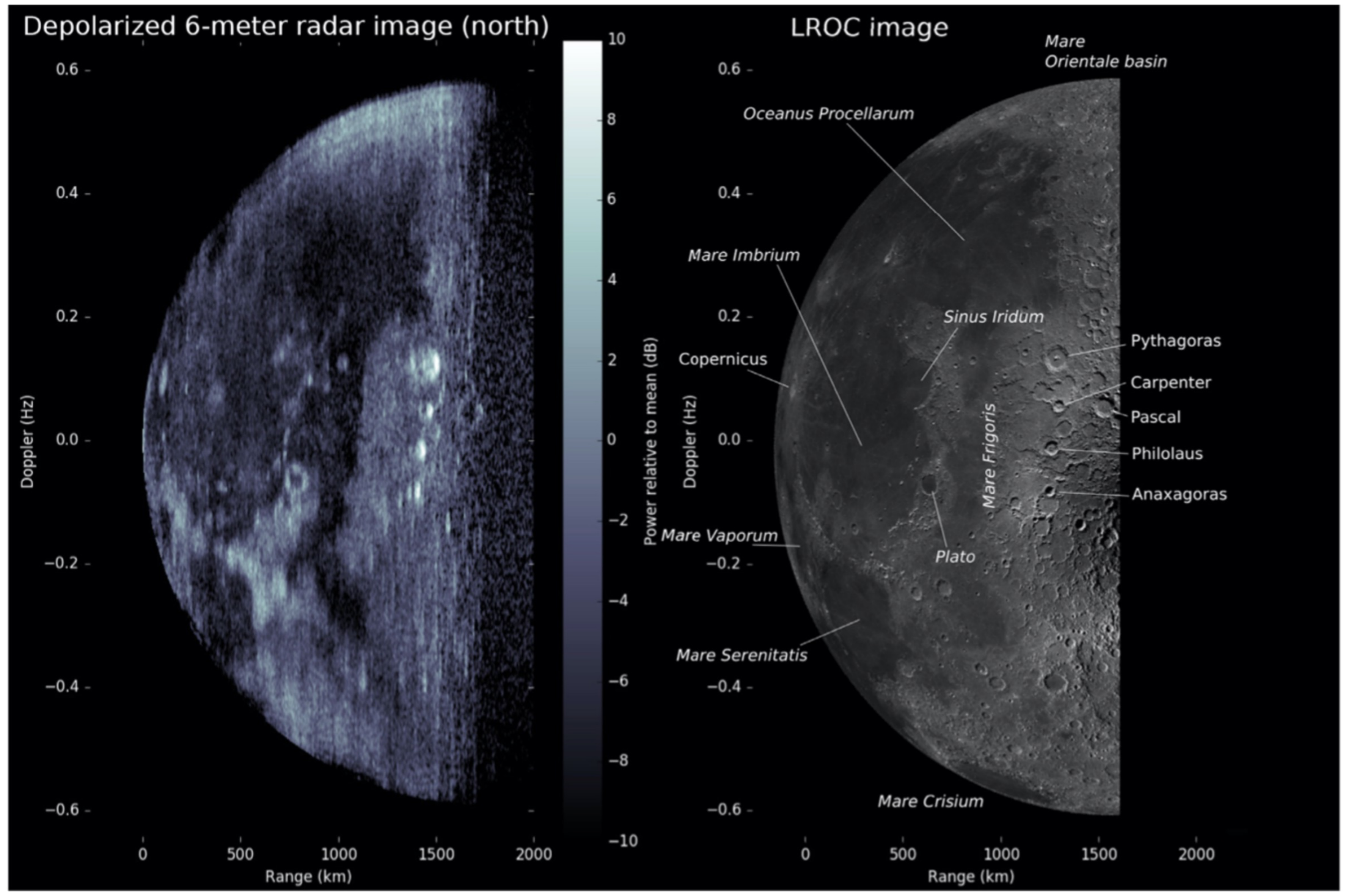
Liang et al 2018
Pulsating aurora
ionosphere signatures

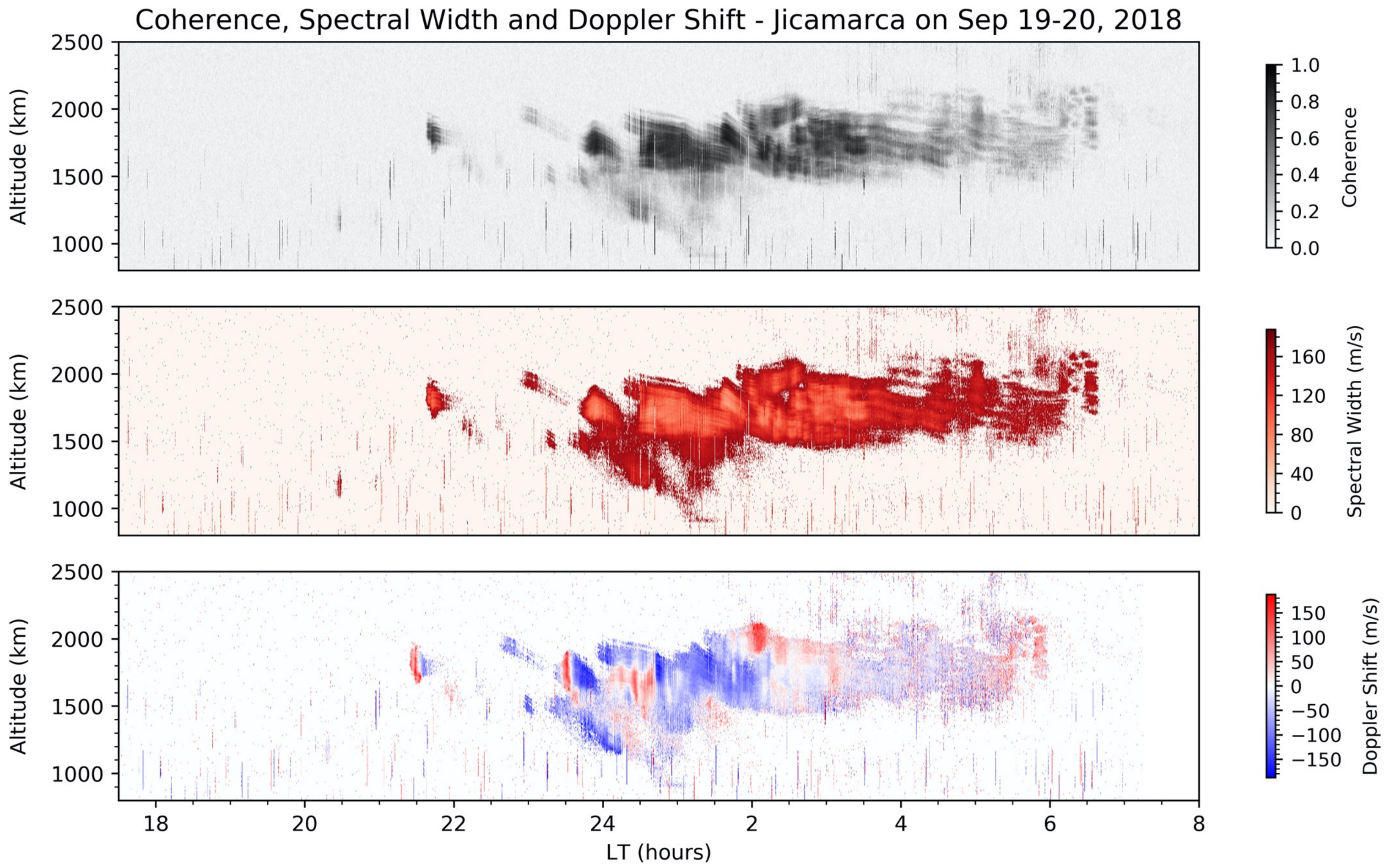
Science / Technique Priority: Beyond The Ionosphere

Planetary radar applied to the moon
- Subsurface structure and composition (long wavelengths)
- Water ice within polar regions
- SAR multi-wavelength radar map

Plasmaspheric radar
- Electron densities out to ~2 Re: plasmasphere drainage, refilling
- Inner magnetospheric waves, instabilities

Solar coronal echoes
- Huge potential impacts
- Diagnostic method for space weather forecasting
- Challenging radar scattering problem (observational discrepancies)





Derghazarian et al 2020
Equatorial irregularity
scatter from potential
lower-hybrid waves at
2000+ km

Vierinen et al 2017 (above)
6 m lunar radar images

Hagfors 1970 (right)
Wavelength dependence
of lunar echoes

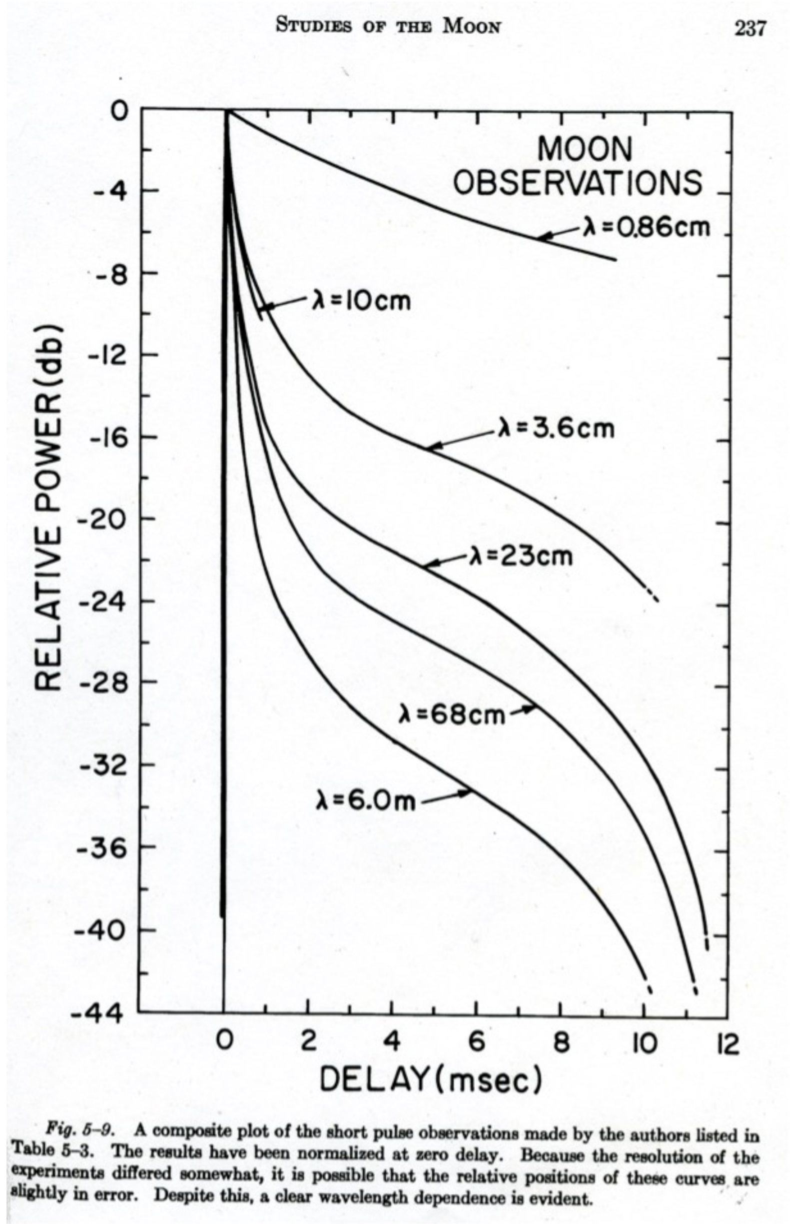

Studies of the Moon 237

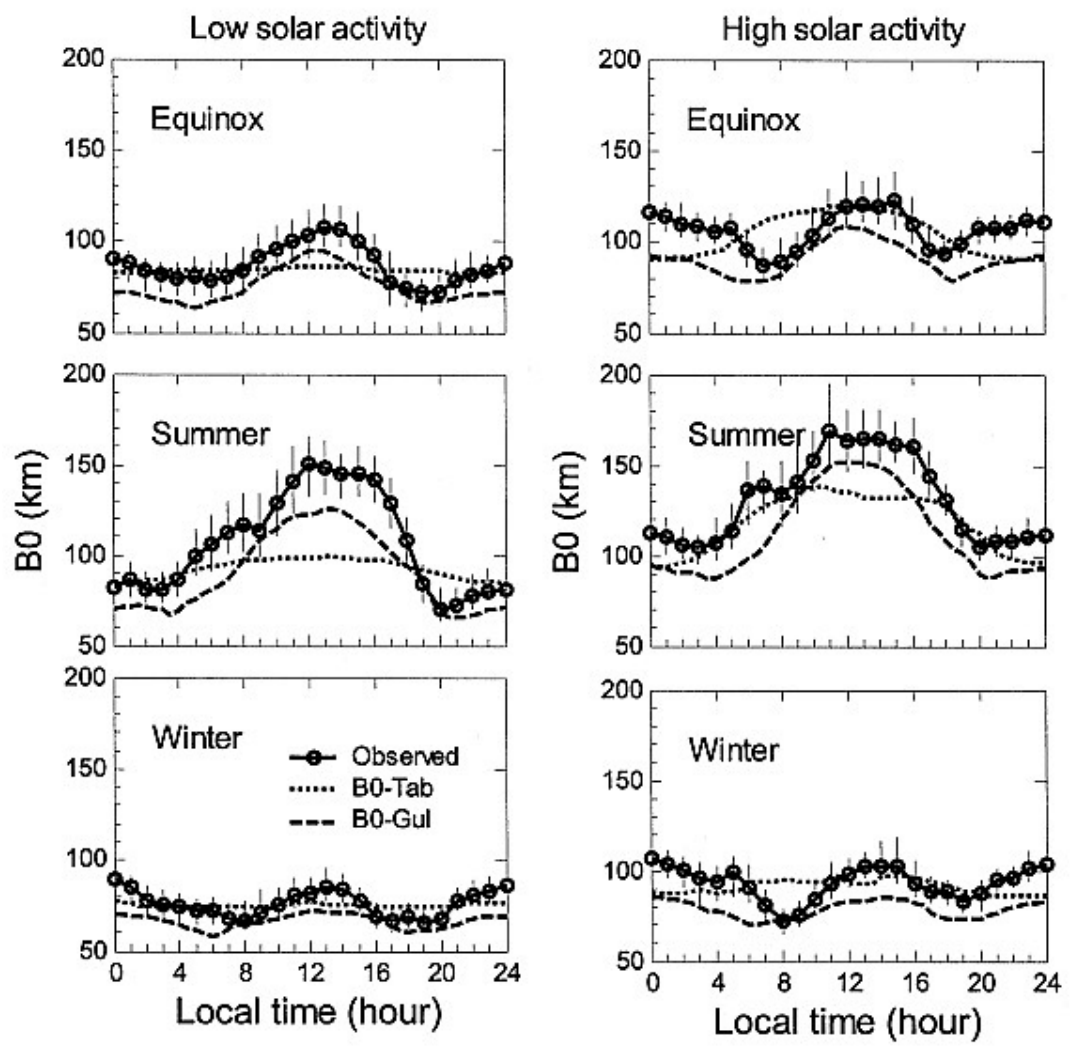
Fig. 5–9. A composite plot of the short pulse observations made by the authors listed in Table 5–3. The results have been normalized at zero delay. Because the resolution of the experiments differed somewhat, it is possible that the relative positions of these curves are slightly in error. Despite this, a clear wavelength dependence is evident.

Science / Operational Priority: Space Weather

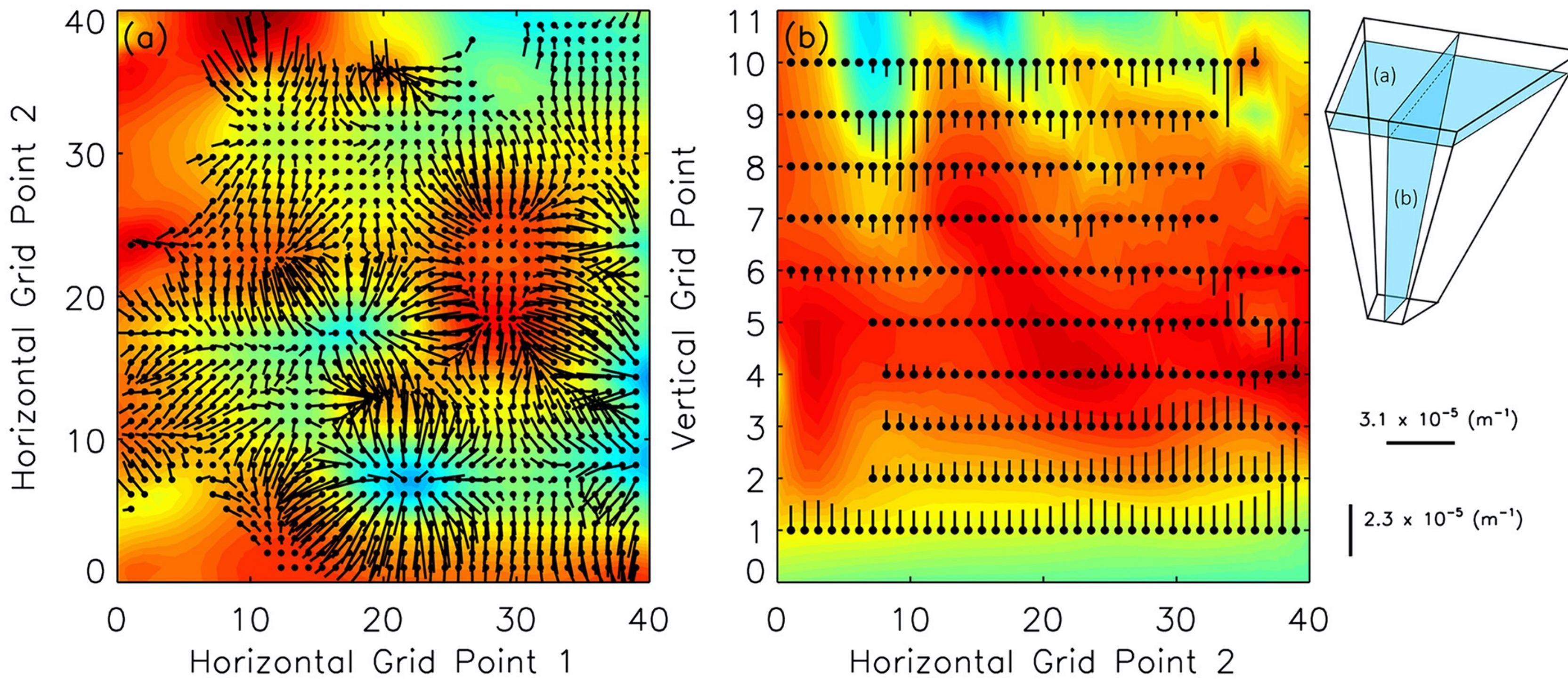
Ionospheric refraction
- Myriad impacts on Positioning, Navigation, Timing (PNT)
- D region absorption not well characterized - but it is accessible to IS radars
- Bottomside ionospheric altitude variability essential for HF propagation prediction

Electron density gradients
- Irregular precipitation of energetic e- leads to scintillation, loss of signal lock
- Density depletions/enhancements, 20-200 km irregularities: positioning errors
- Mid-latitude SED features
- Equatorial features (EIA, electrojet, pre-reversal enhancement, etc.)

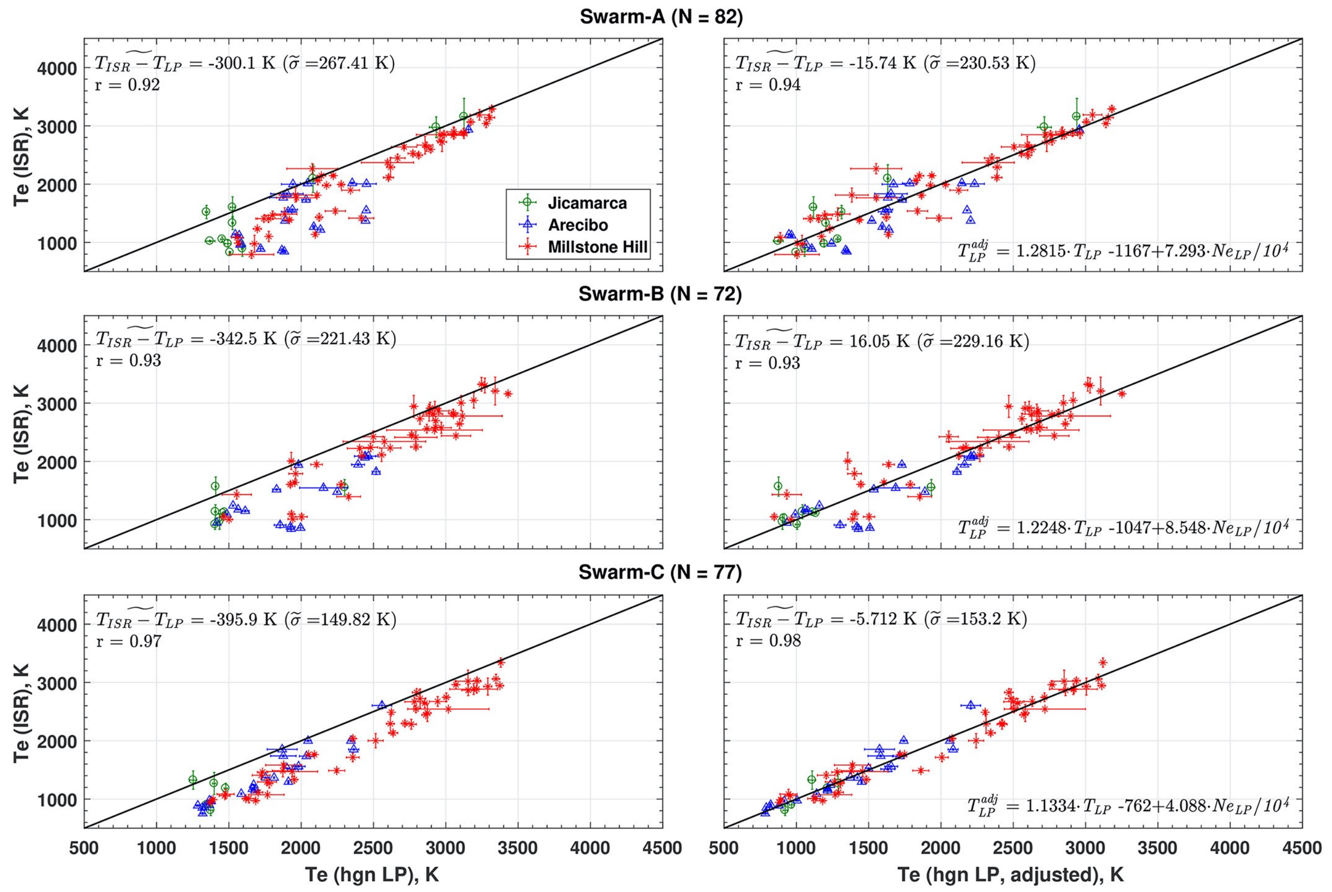
Better ionospheric specification including irregularities is needed
- Altitude profiling
- Multi-scale studies: IS radar + in-situ (e.g. Swarm) + GNSS signal phase analysis
- Drivers of diffraction effects
- Operational benchmarks/thresholds



Lei et al 2015
Bottomside electron density shape parameters and variability



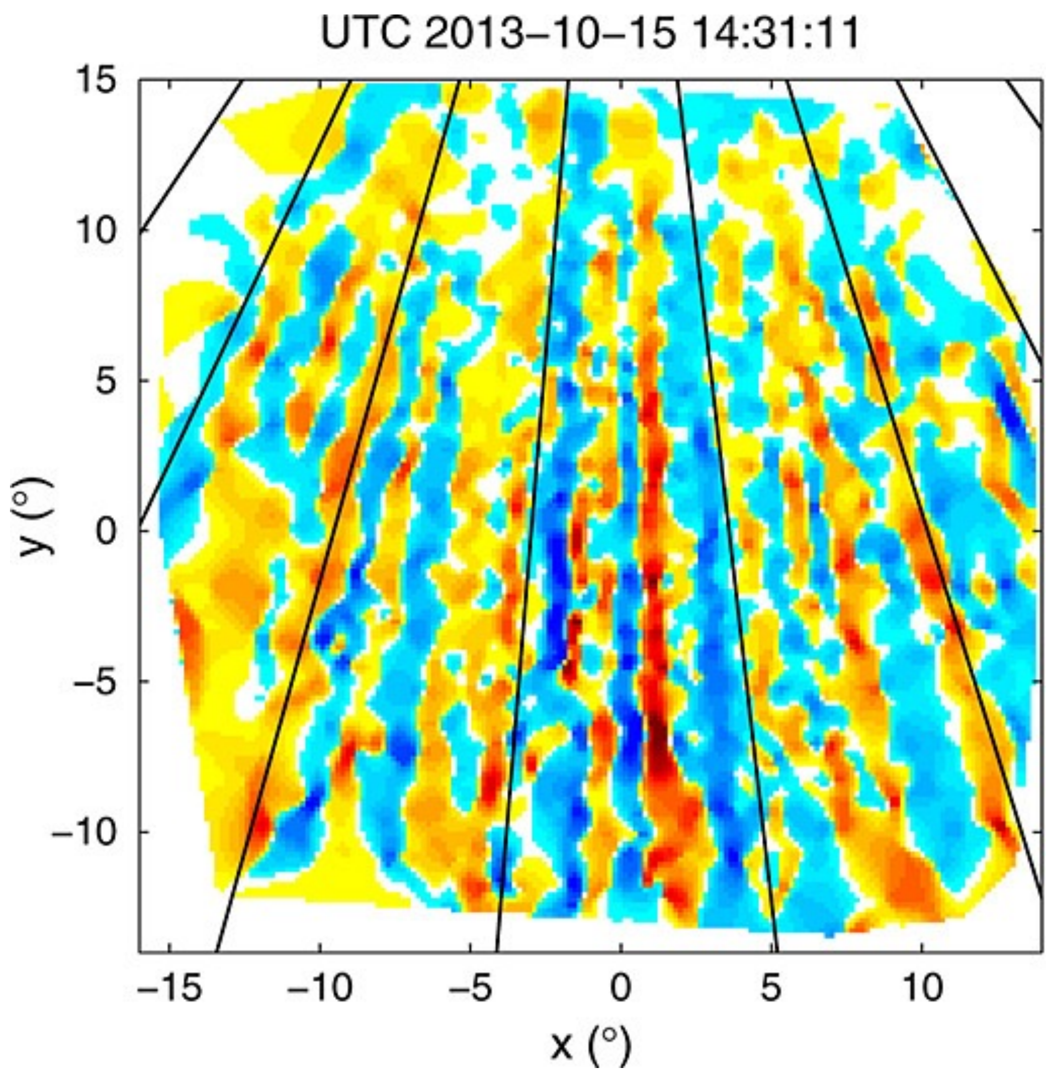
Forsythe and Makarevich 2018
Horizontal and vertical F region electron density gradient vectors in the polar ionosphere



Lomidze et al 2018
SWARM satellite Te, Ne comparison to ISRs

Cross-cutting Workshop Themes

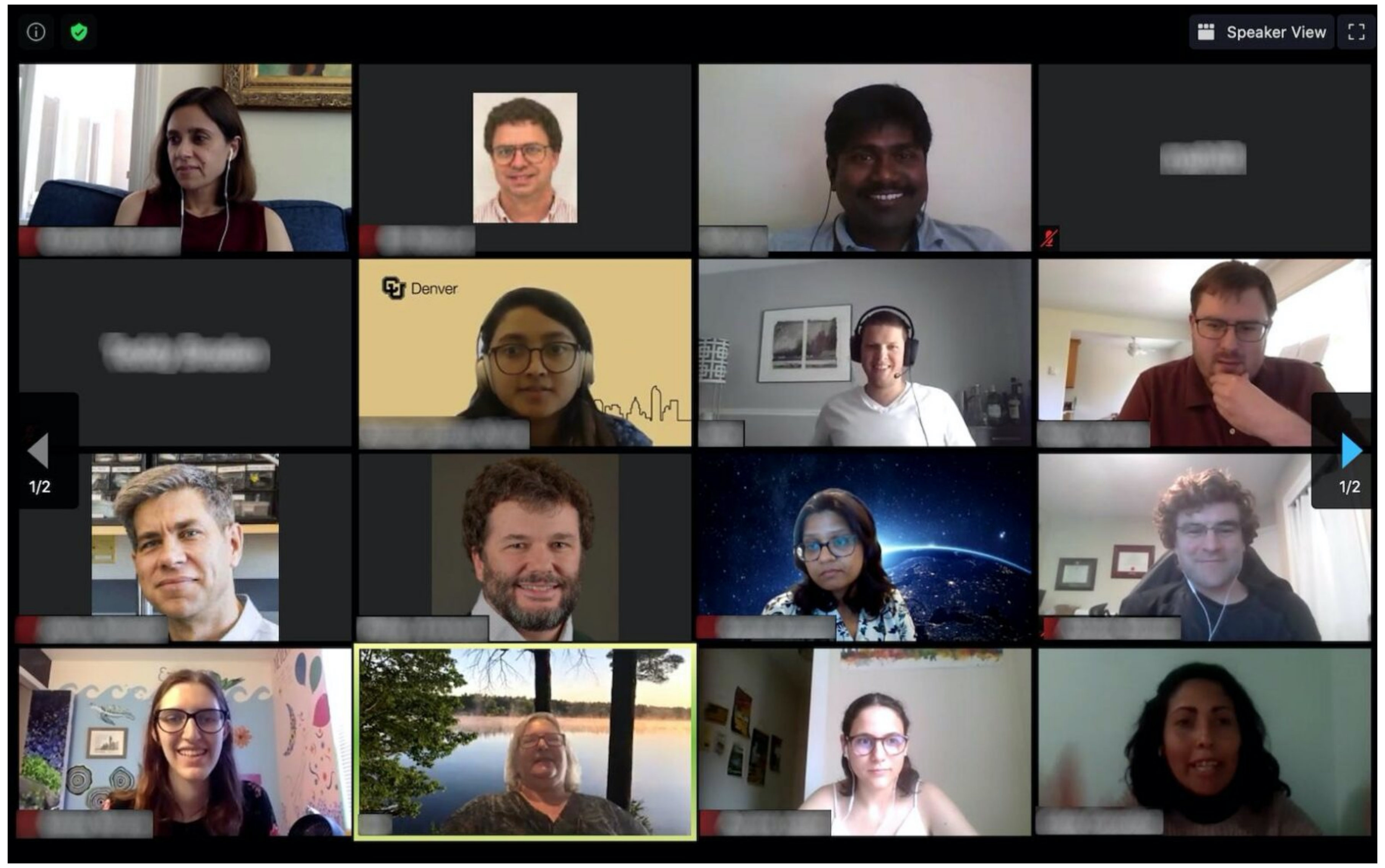
Theme 1: Leverage emerging technology for maximum benefit
- Astronomy, aeronomy, space weather have large breadth of technique synergy
- Use knowledge and resources from other communities (e.g. low frequency radio astronomy)
- International collaboration: early and sustained (e.g. meridian chains)



Loi et al 2015
Plasmaspheric density ducts
from MWA low frequency
radio astronomy

Theme 2: Flexibility
- Pair already existing technical capability of wide band radio telescopes with a frequency-agile transmit array
- Develop a new geospace radar that follows in the footsteps of modern developments in radio astronomy arrays, phased array radar techniques

Theme 3: Workforce Development
- Crucial for sustaining and expanding geospace research impact
- Train next generations of scientists and engineers in both theory/technique and use
- Strong collaborations with international education programs (e.g. UNIS program in Svalbard)
- Partner with US university engineering and physics departments
  - 3-week classes including in-person on-site facility work
  - IS radar topic ‘nuggets’ embedded in popular courses



NSF IS Radar Summer School 2020
Held virtually