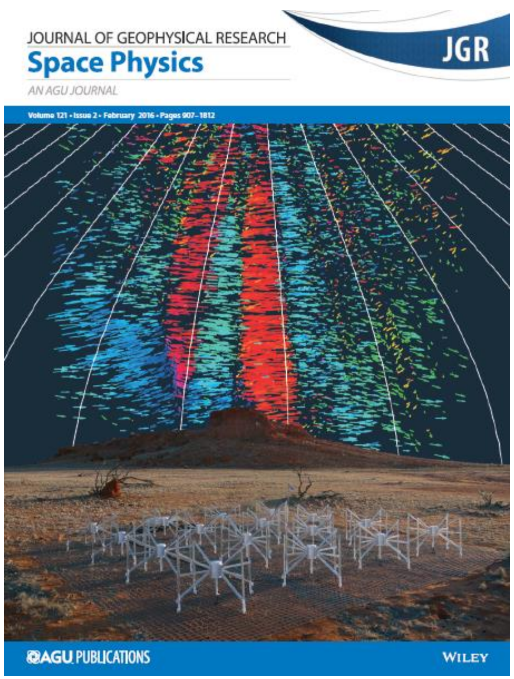
A celebration: Bruce Slee and 70 years of radio astronomy

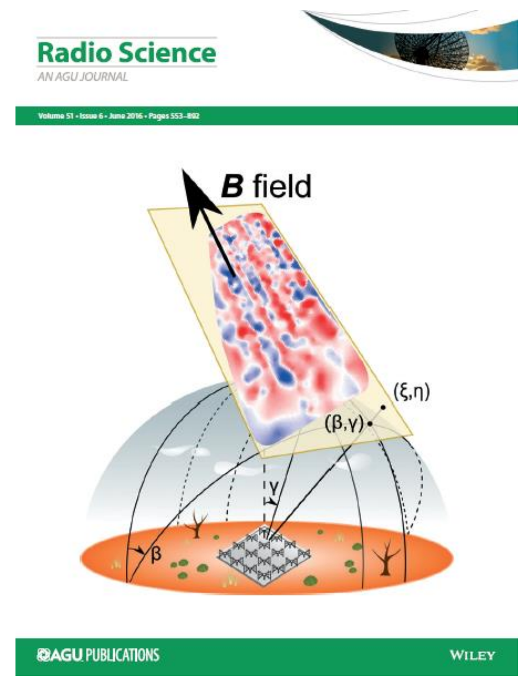
Ionospheric studies
with the
MWA



Cleo Loi

DAMTP, Centre for Mathematical Sciences
University of Cambridge

17th Aug 2016



UNIVERSITY OF CAMBRIDGE

THE UNIVERSITY OF SYDNEY

CAASTRO
ARC CENTRE OF EXCELLENCE FOR ALL-SKY ASTROPHYSICS

Earth's plasma environment

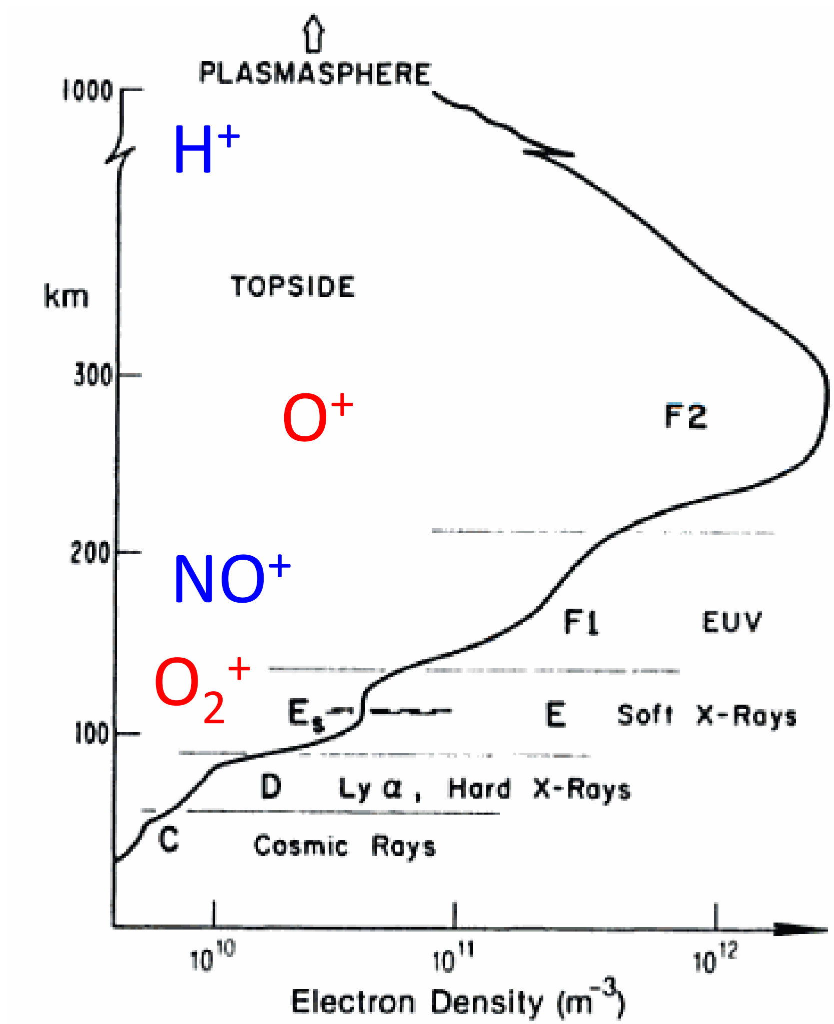


Image: Davies (1990)

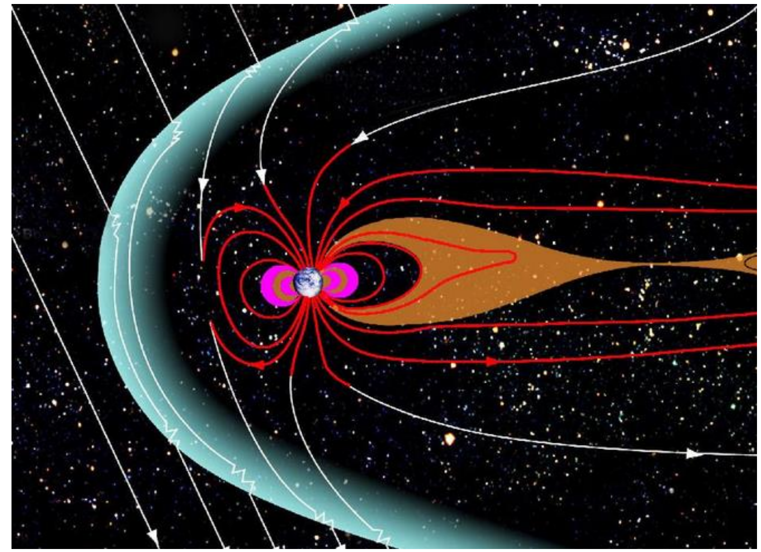


Image: http://www.nasa.gov/topics/solarsystem/sunearthsystem/magnetosphere2-unlabeled_prt.htm

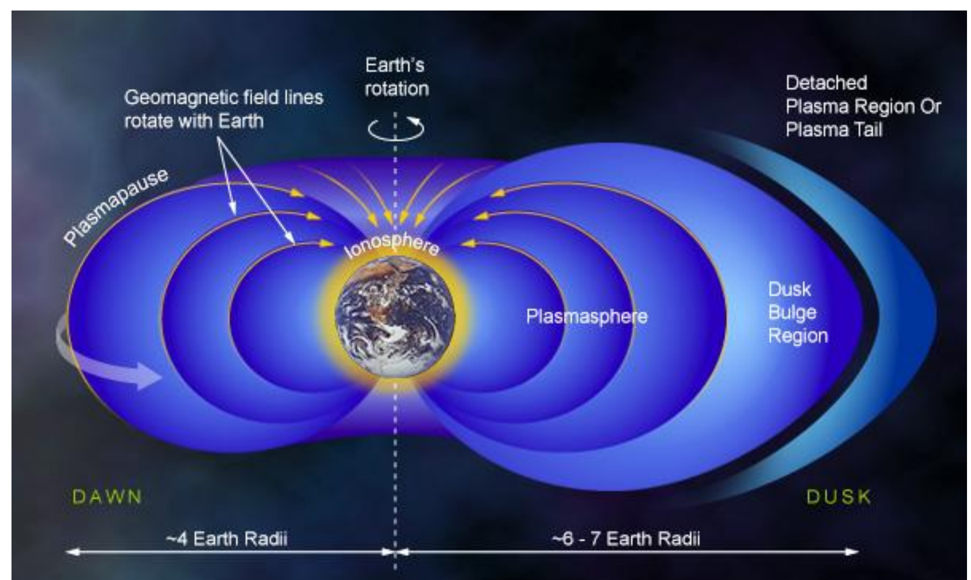


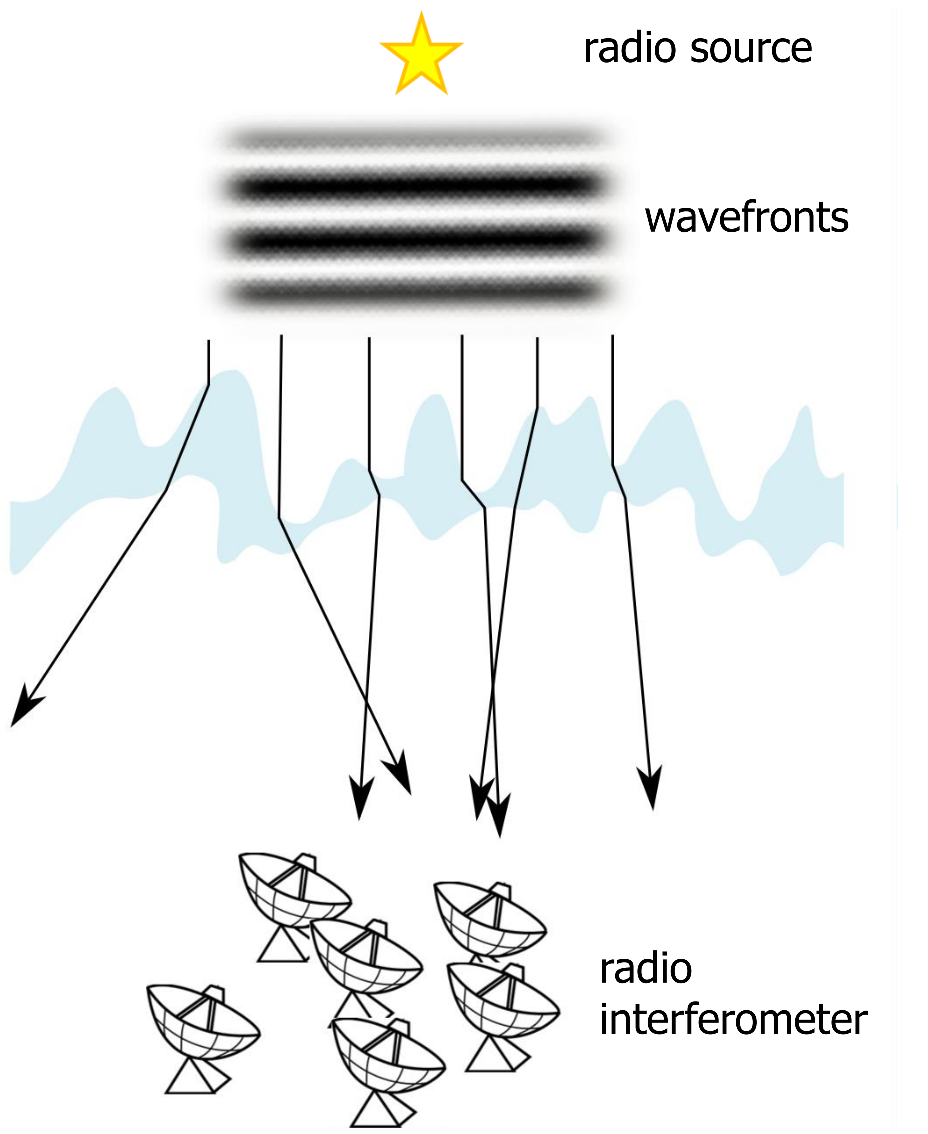
Image: http://www.windows2universe.org/glossary/plasmasphere.html

Radio propagation effects

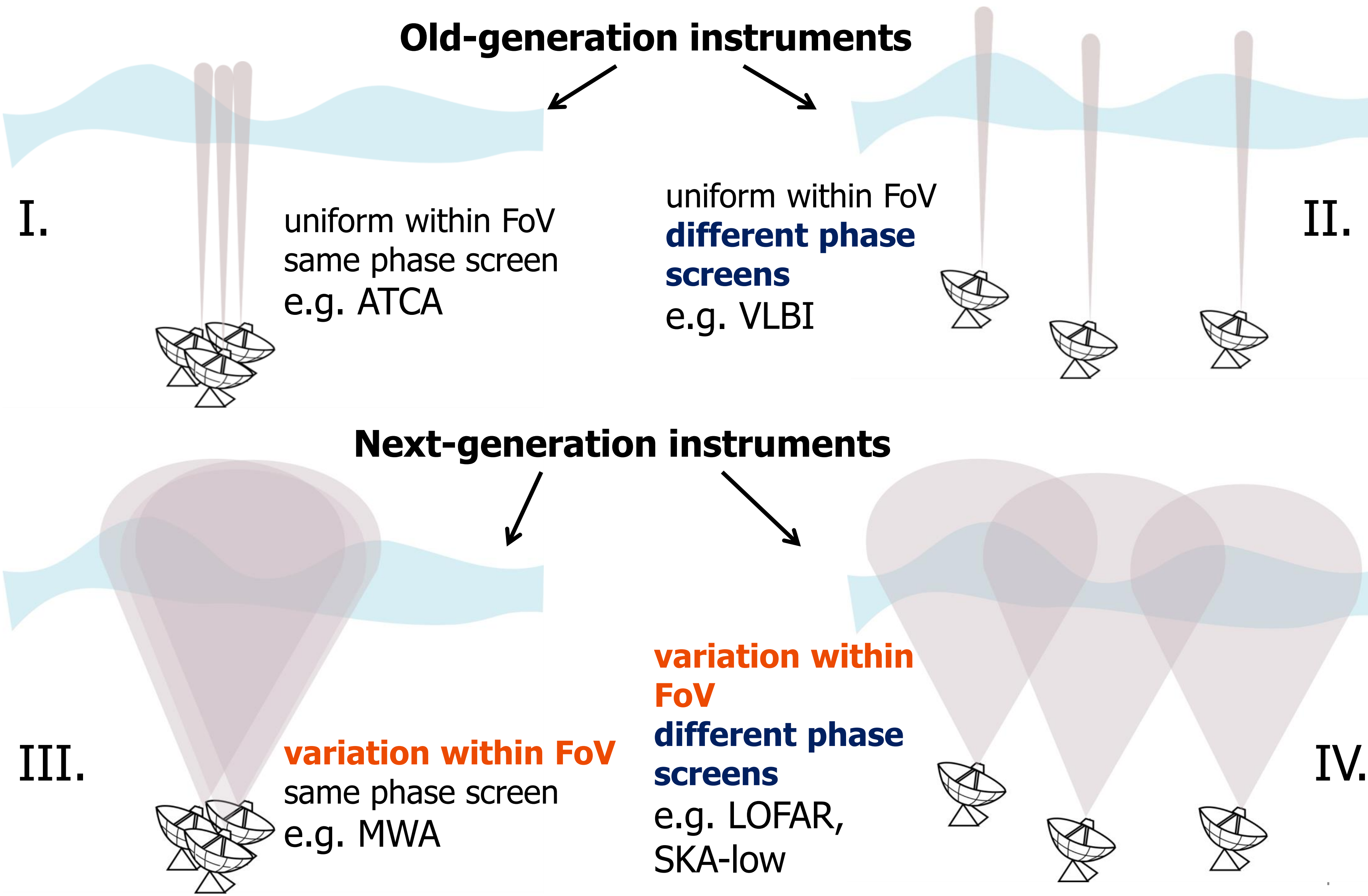
- Radio waves propagating through a plasma experience:
  - Refraction ~ λ^2
  - Dispersion ~ λ^2
  - Faraday rotation ~ λ^2
- Focus here on **refractive effects**

If the density distribution is...

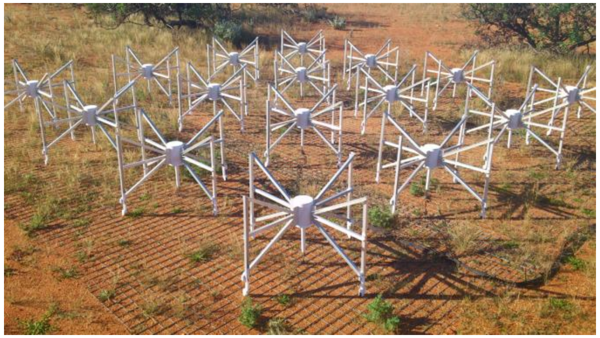
- Perfectly smooth: nothing happens
- Like a prism: get **deflection**
- Like a curved lens: get **shape distortion**
- Highly irregular: get **scintillation**



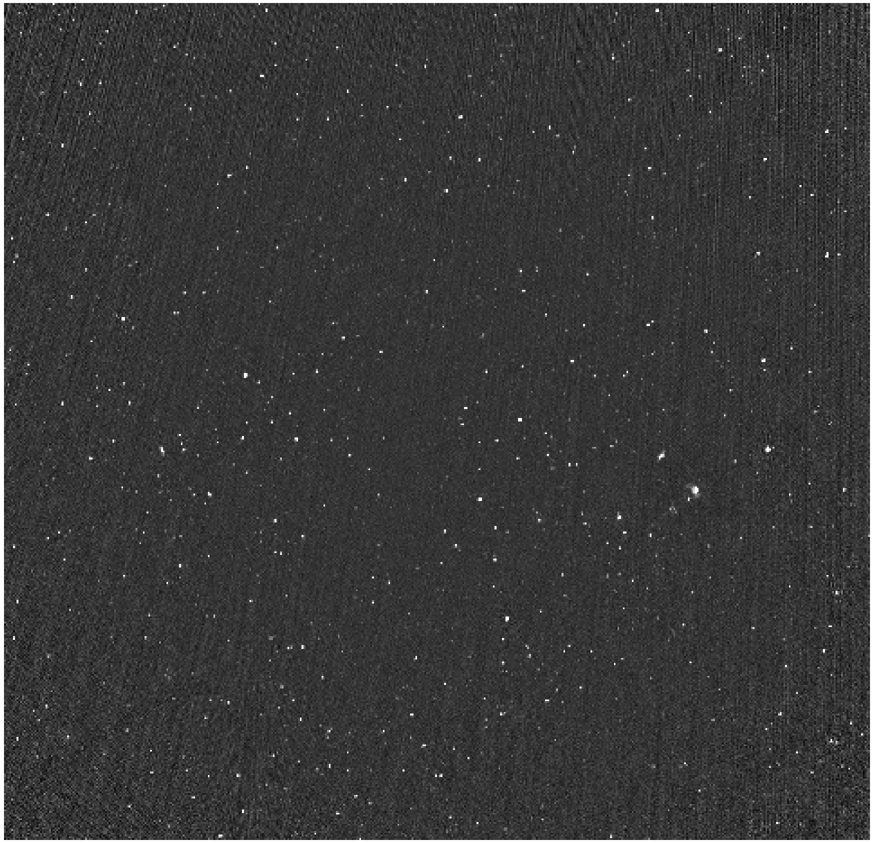
The four spatial regimes [C. J. Lonsdale, 2005, ASP Conf. Ser.]

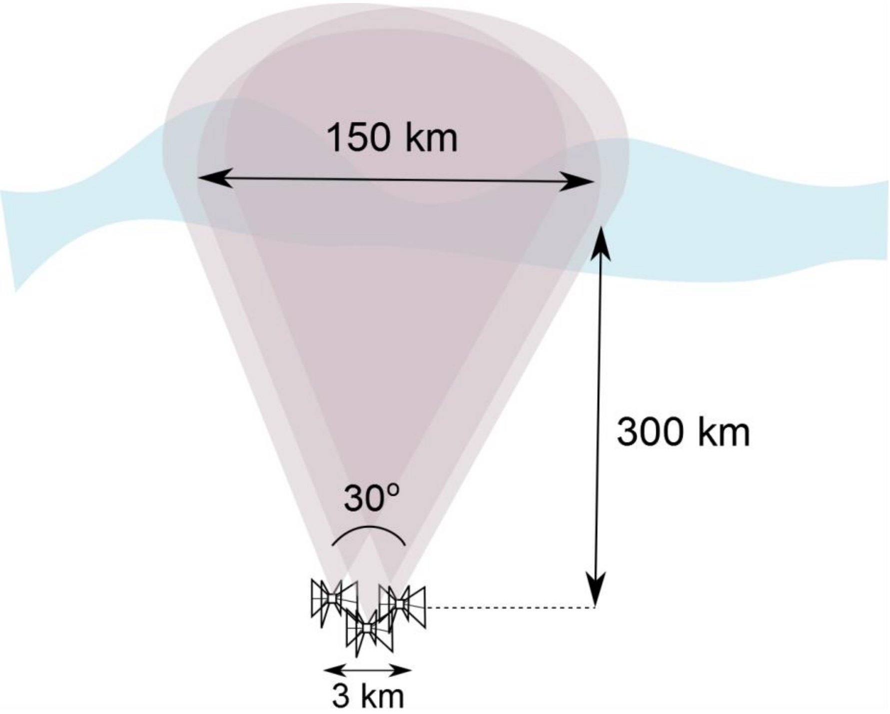


The Murchison Widefield Array



- Low frequency (80-300 MHz)
- Large-N (128 elements)
- Electronically beamformed
- Wide field of view (1000 deg^2)
- Spatially compact (3 km diameter)





Measuring density gradients

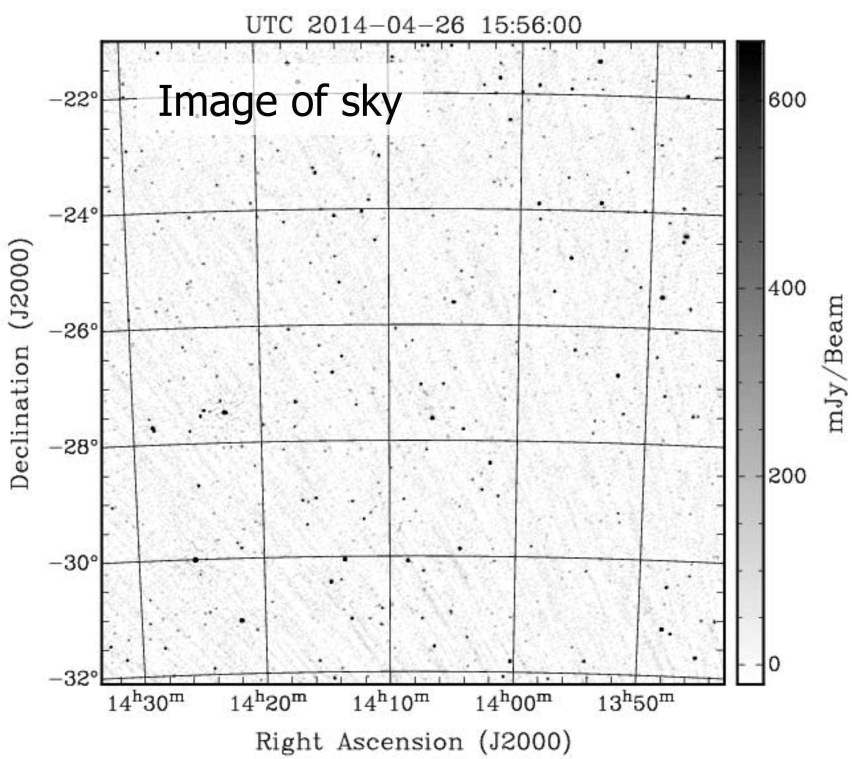
TEC = total electron content = $\int n_e \, dl$

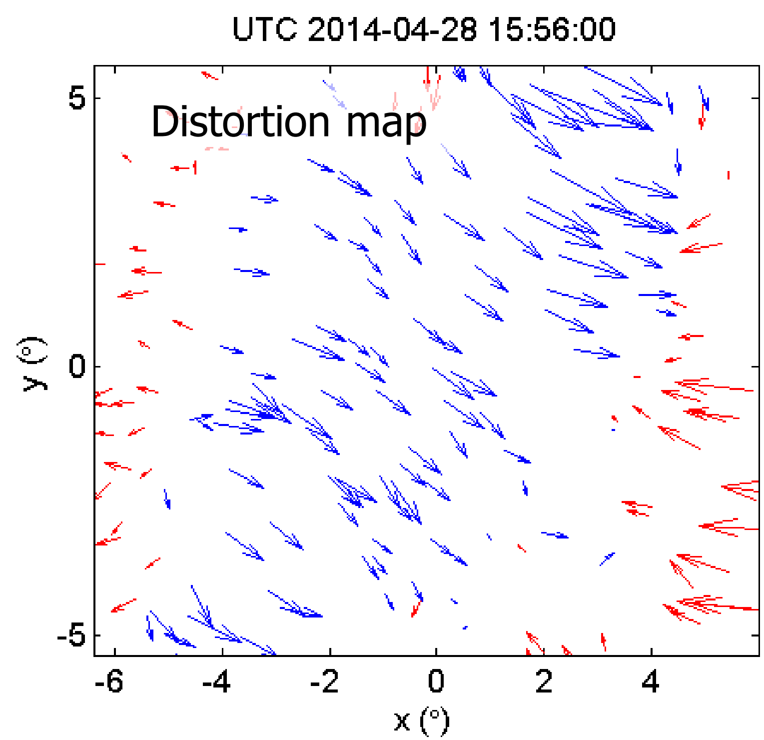
$$\Delta\theta = -\frac{40.3}{\nu^2}\nabla_\perp \mathrm{TEC}$$

refractive displacement (radians) → $\Delta\theta$

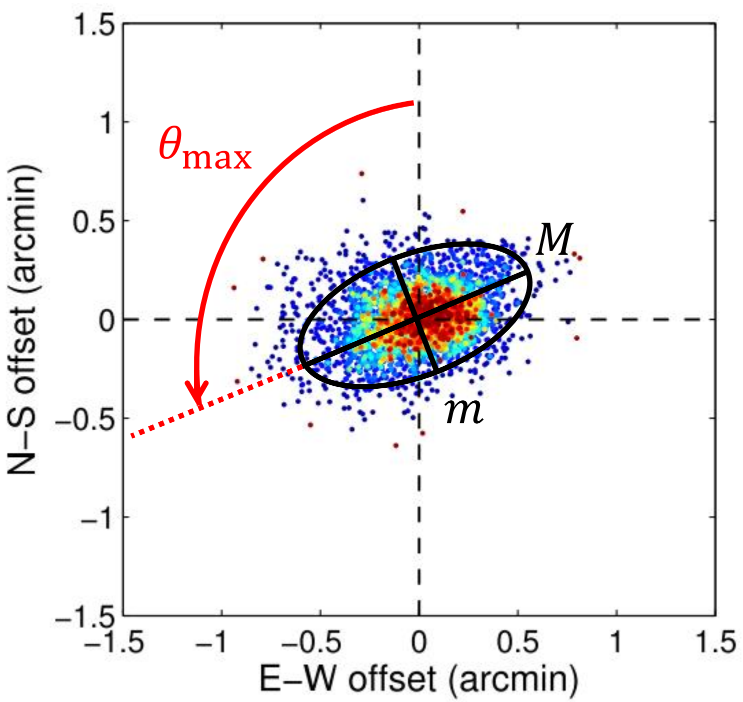
frequency (Hz) → ν

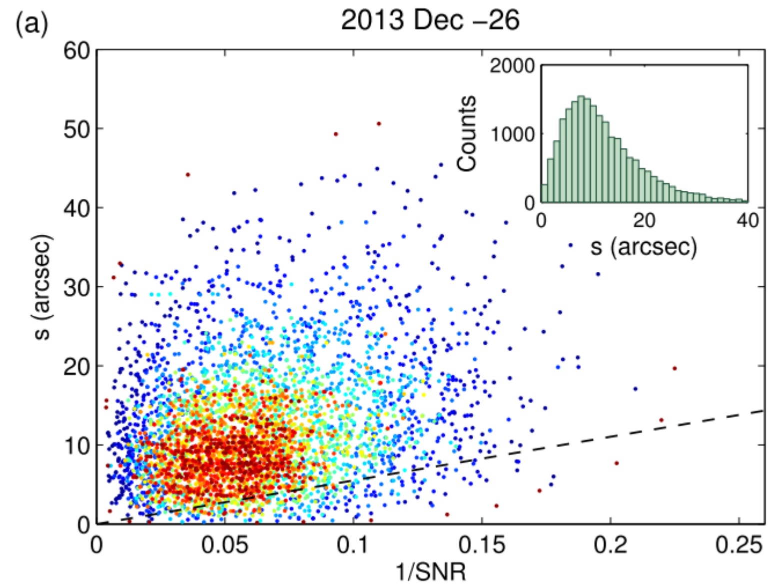
column density gradient (el m^{-3}) → $\nabla_\perp \mathrm{TEC}$





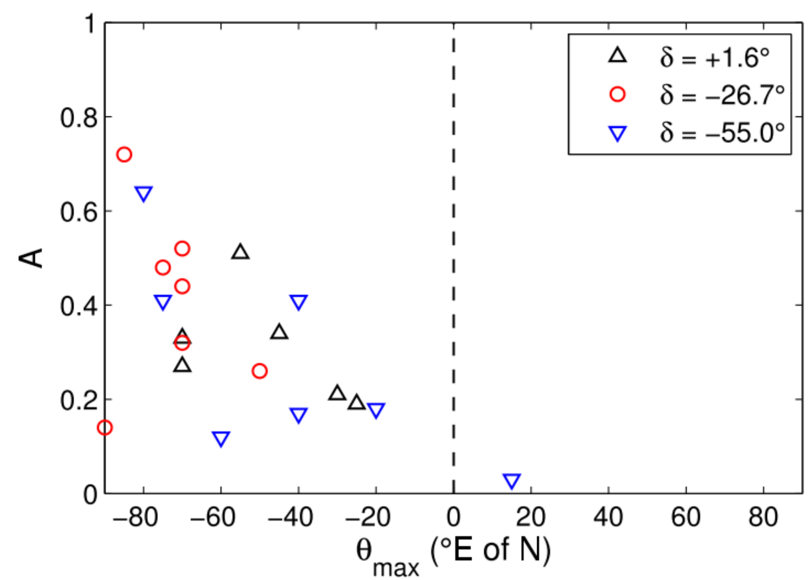
Basic diagnostics [S. T. Loi et al., 2015, MNRAS]





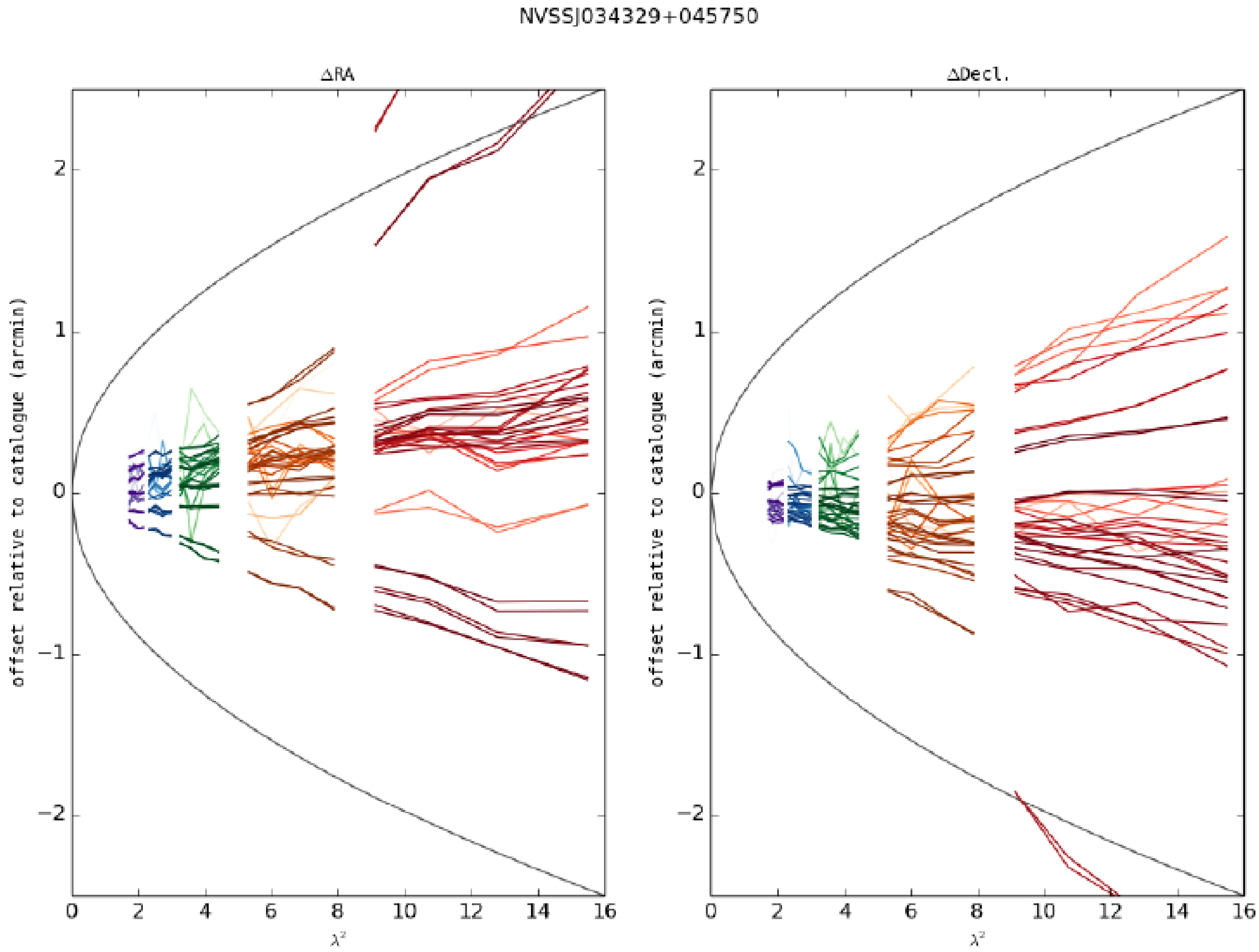
$A = \frac{M-m}{M+m}$ = degree of anisotropy

θ_{max} = direction of greatest scatter



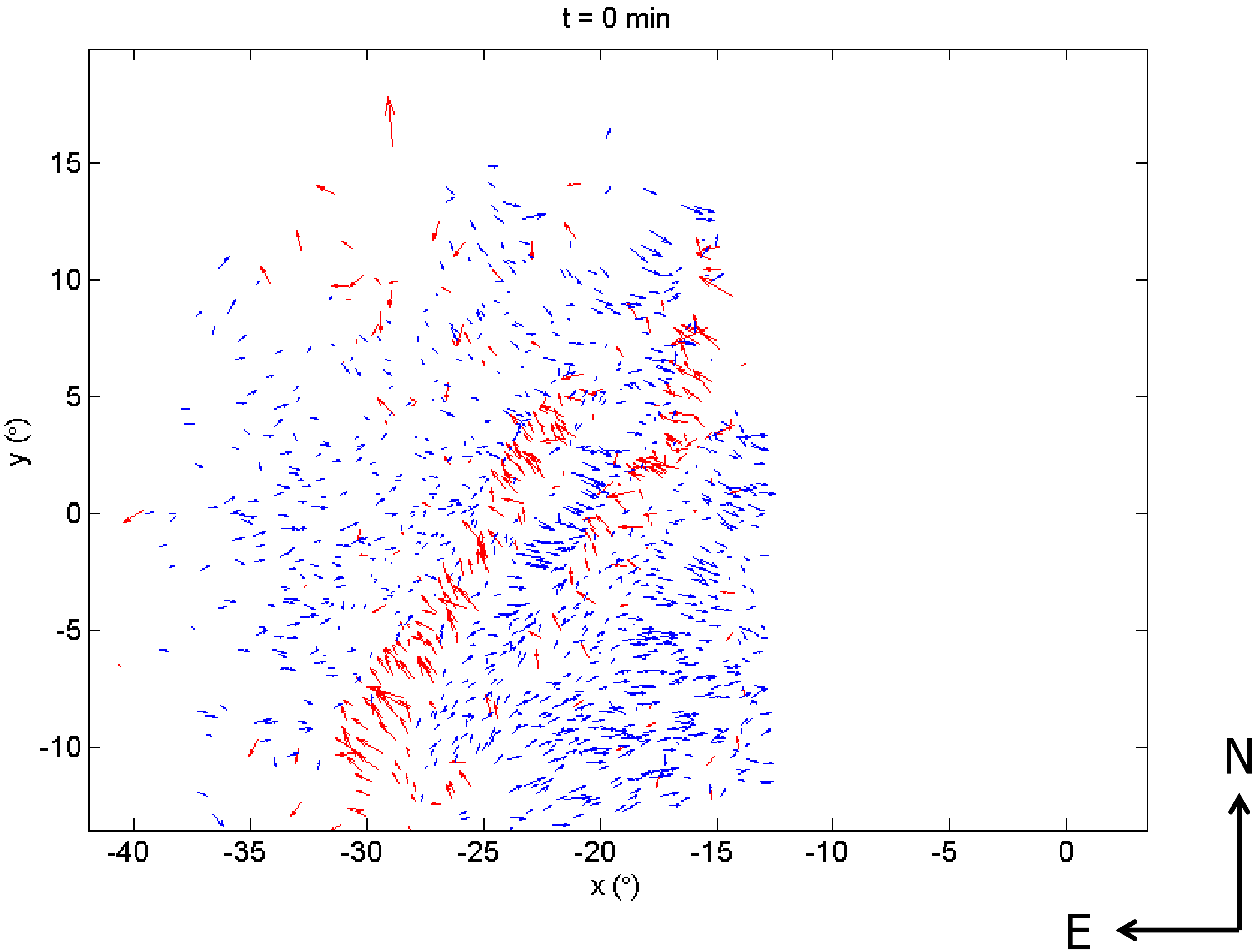
Signatures of refraction [J. Morgan, in prep.]

- Displacements exhibit λ^2 proportionality



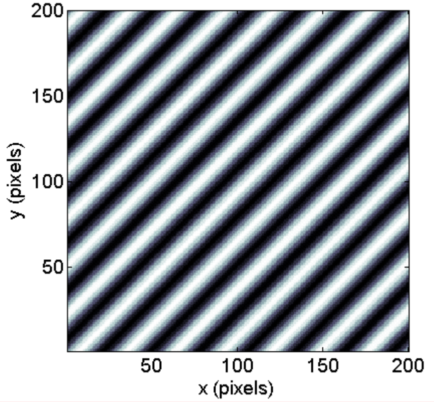
Waves in the sky [S. T. Loi et al., 2015, RaSc]

5th Feb 2014, 1514–1629 UTC



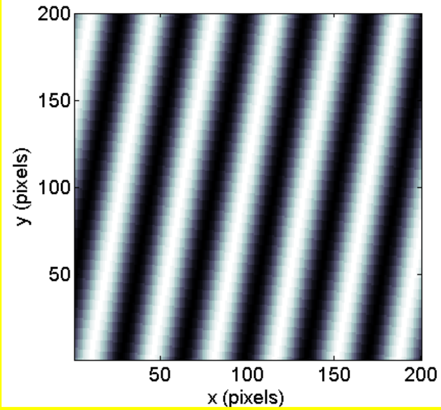
Everything is better in Fourier space

Plane wave 1
T = 4, L = 20



+

Plane wave 2
T = 10, L = 35



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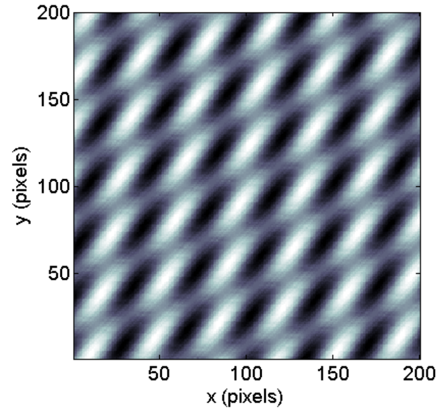
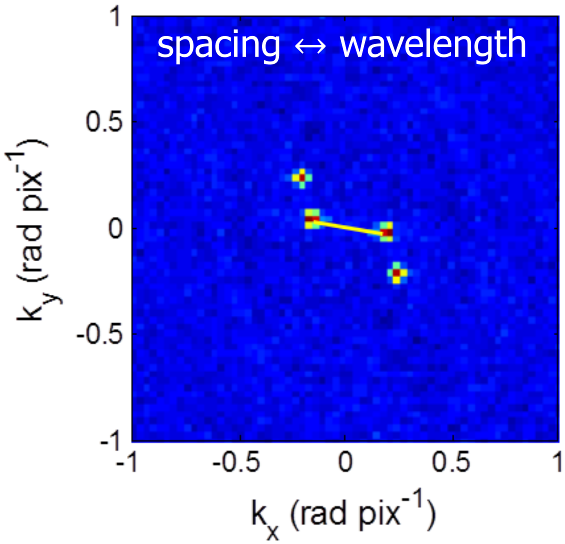
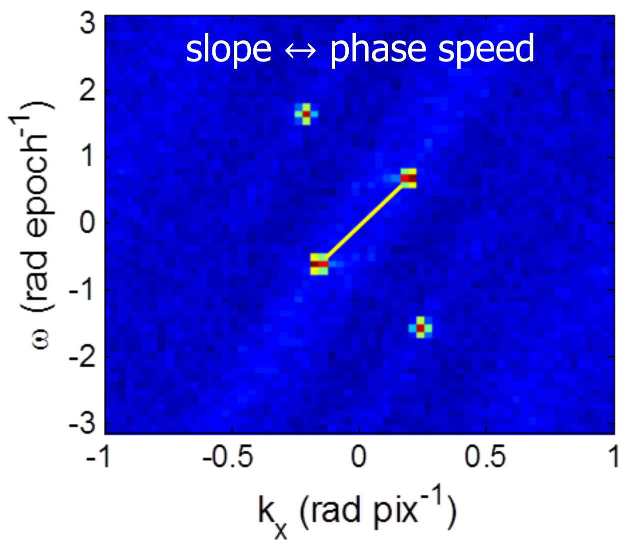
interference pattern



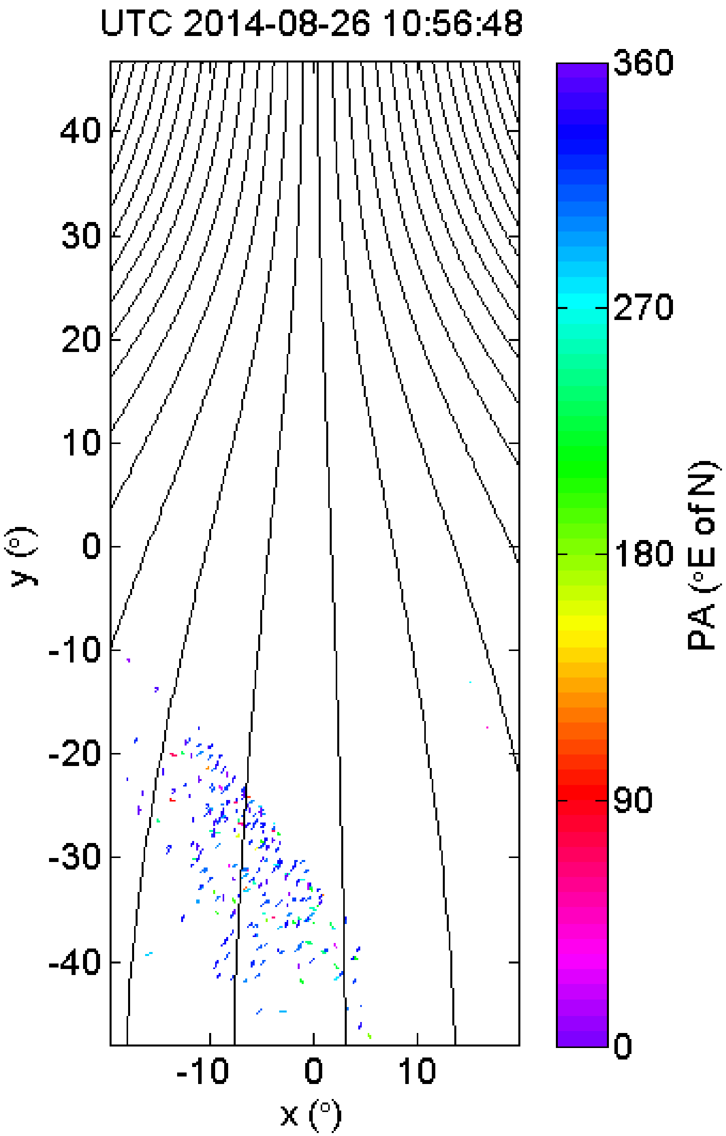
FT

↔

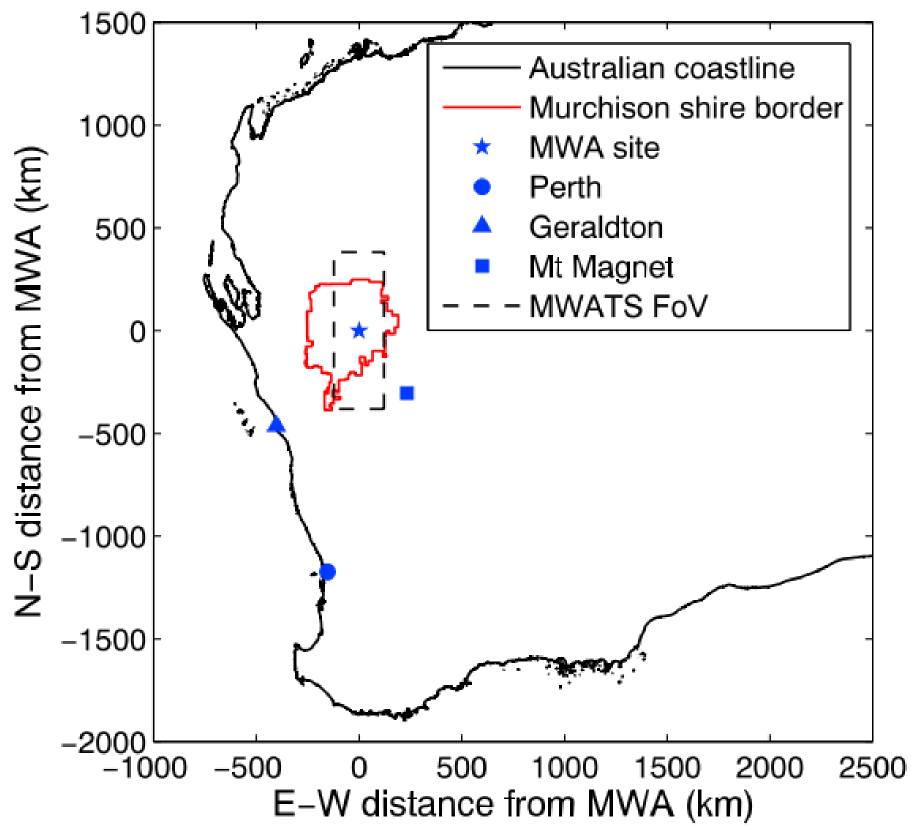




Caught in the act [S. T. Loi et al., 2016, JGR]

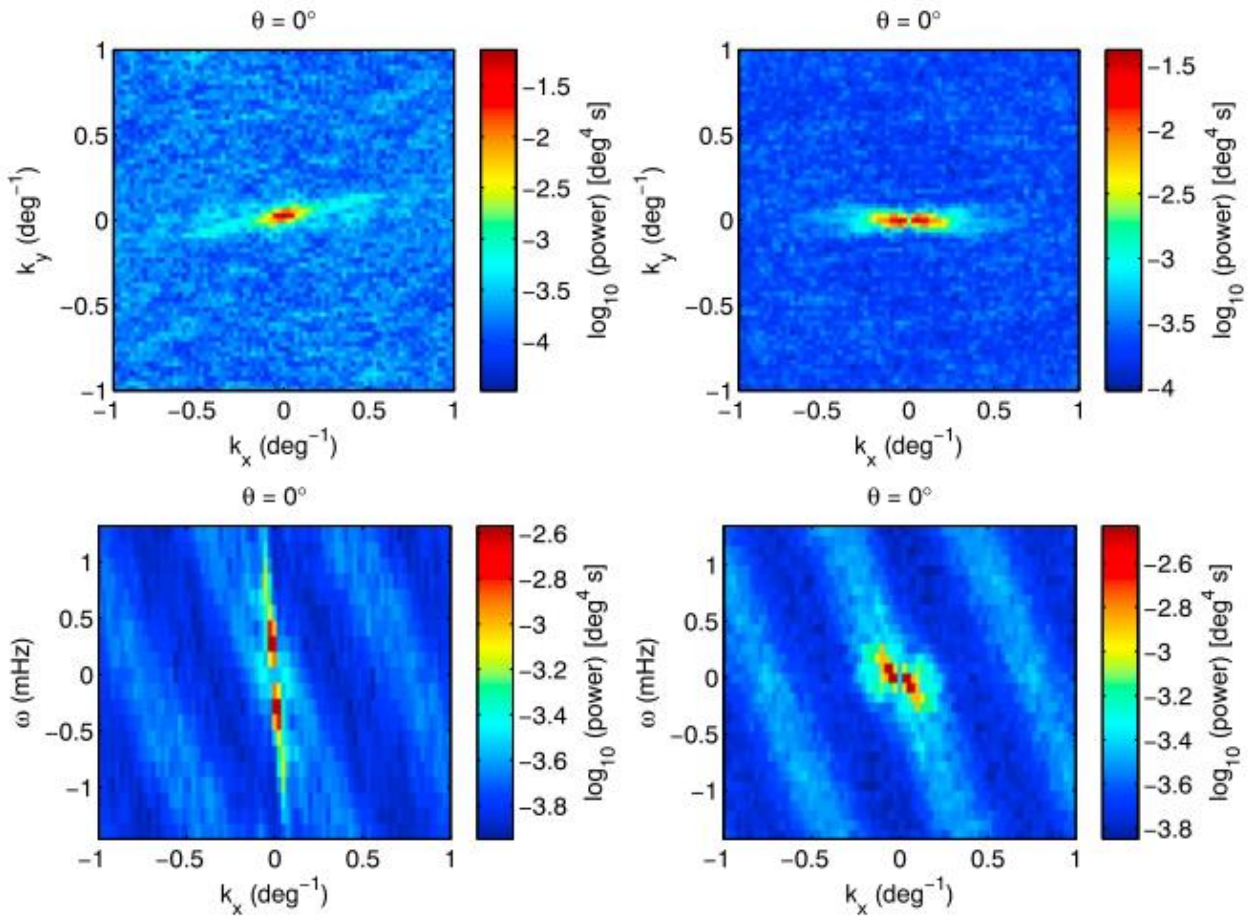


- TID triggers formation of ducts
- Observed over 3 x FoV using raster scan strategy

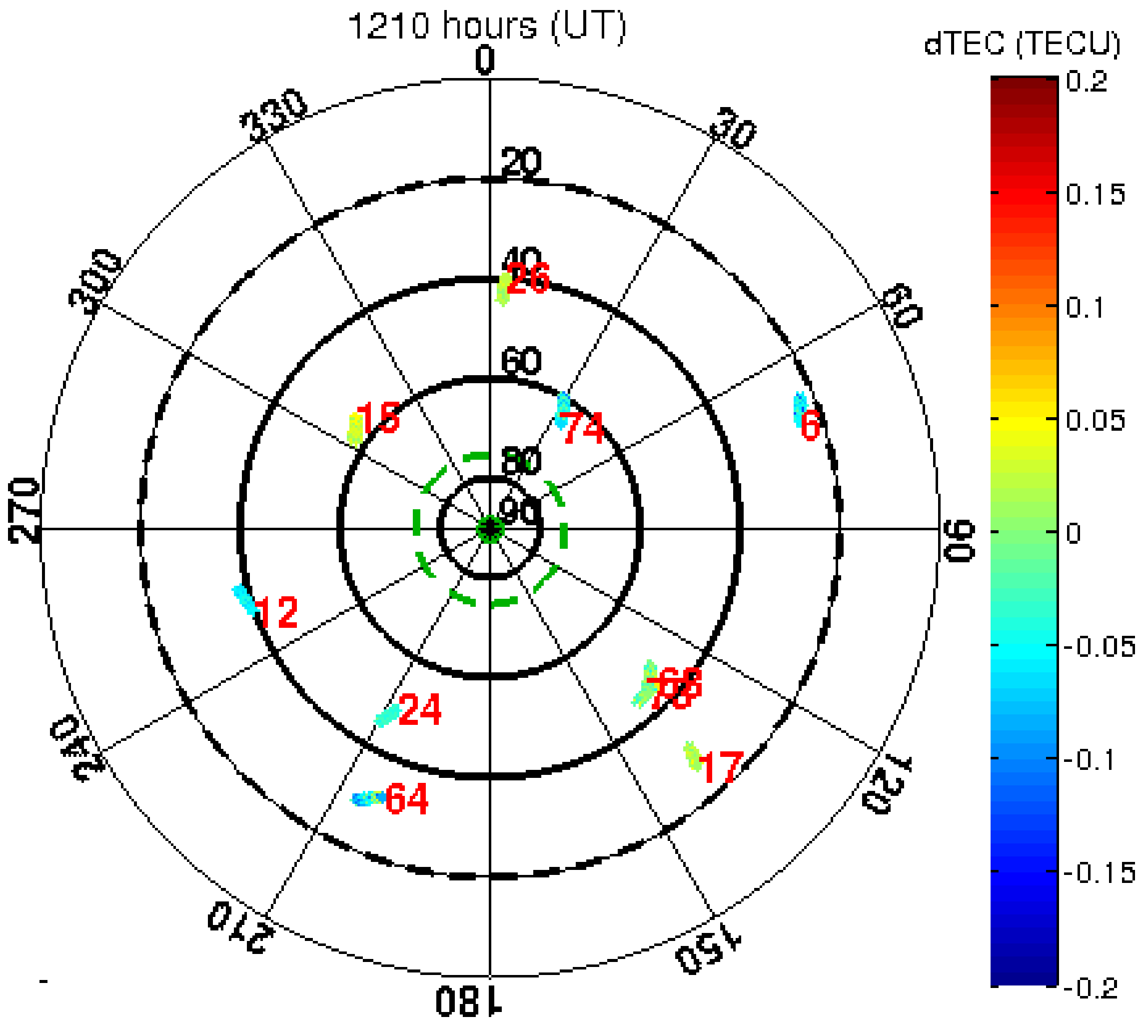


Quantifying spatiotemporal properties

Property	TID	Ducts
Azimuth	N80°W	W
Speed (m/s)	~100	<10
Spatial scale (km)	~200	~60



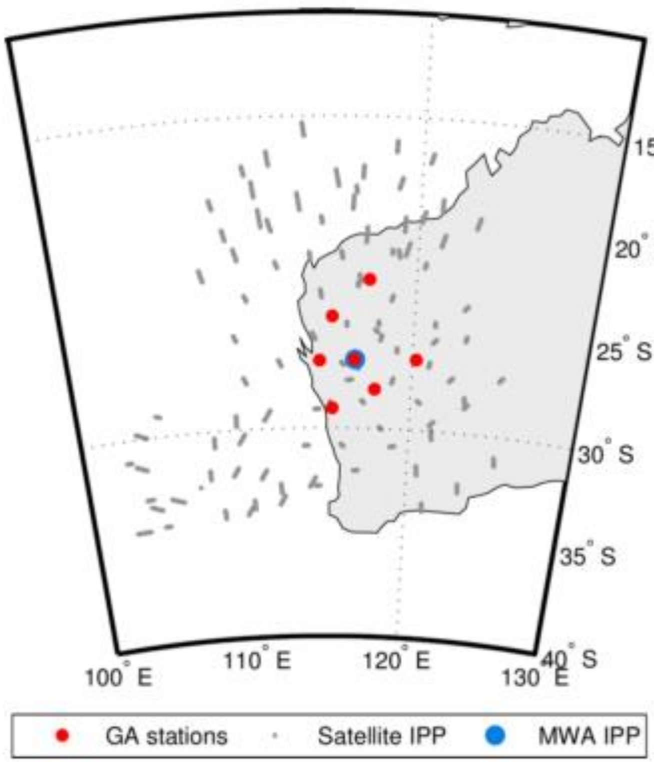
GPS satellites see them too

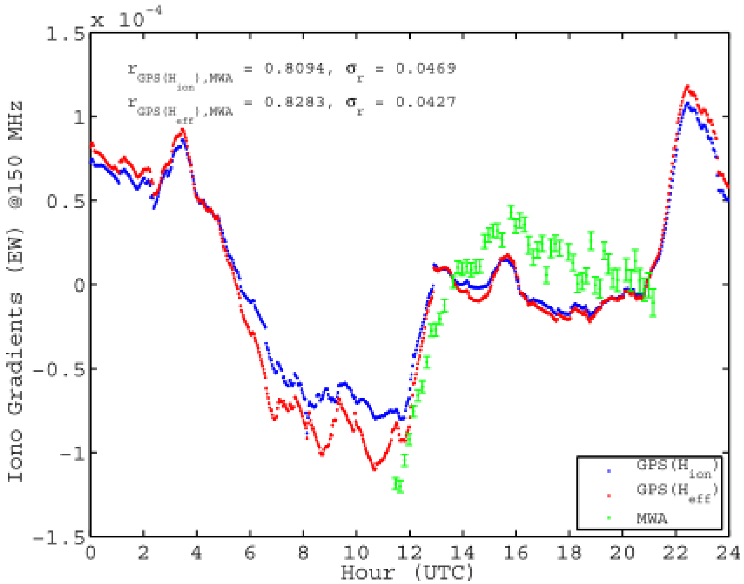


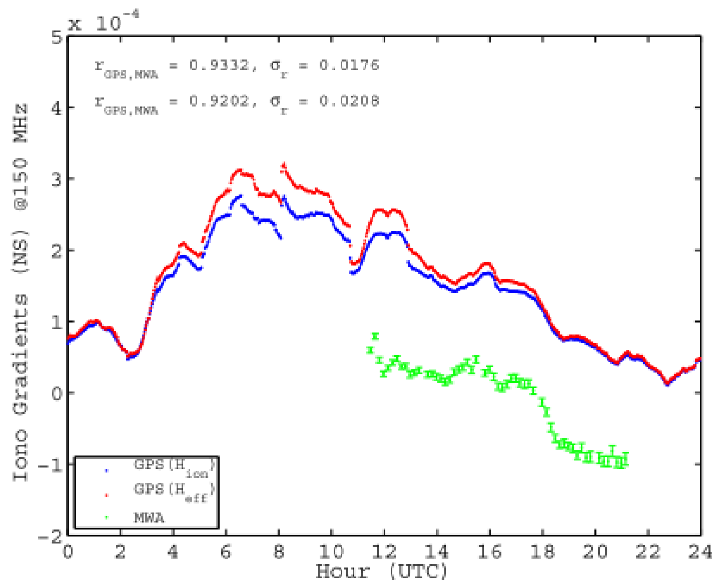
Movie: B. S. Arora

Combining MWA and GNSS [B. S. Arora et al., 2015, 2016, PASA]

- GPS + GLONASS satellite data
- Obtain large-scale (~100 km) information about ionospheric conditions

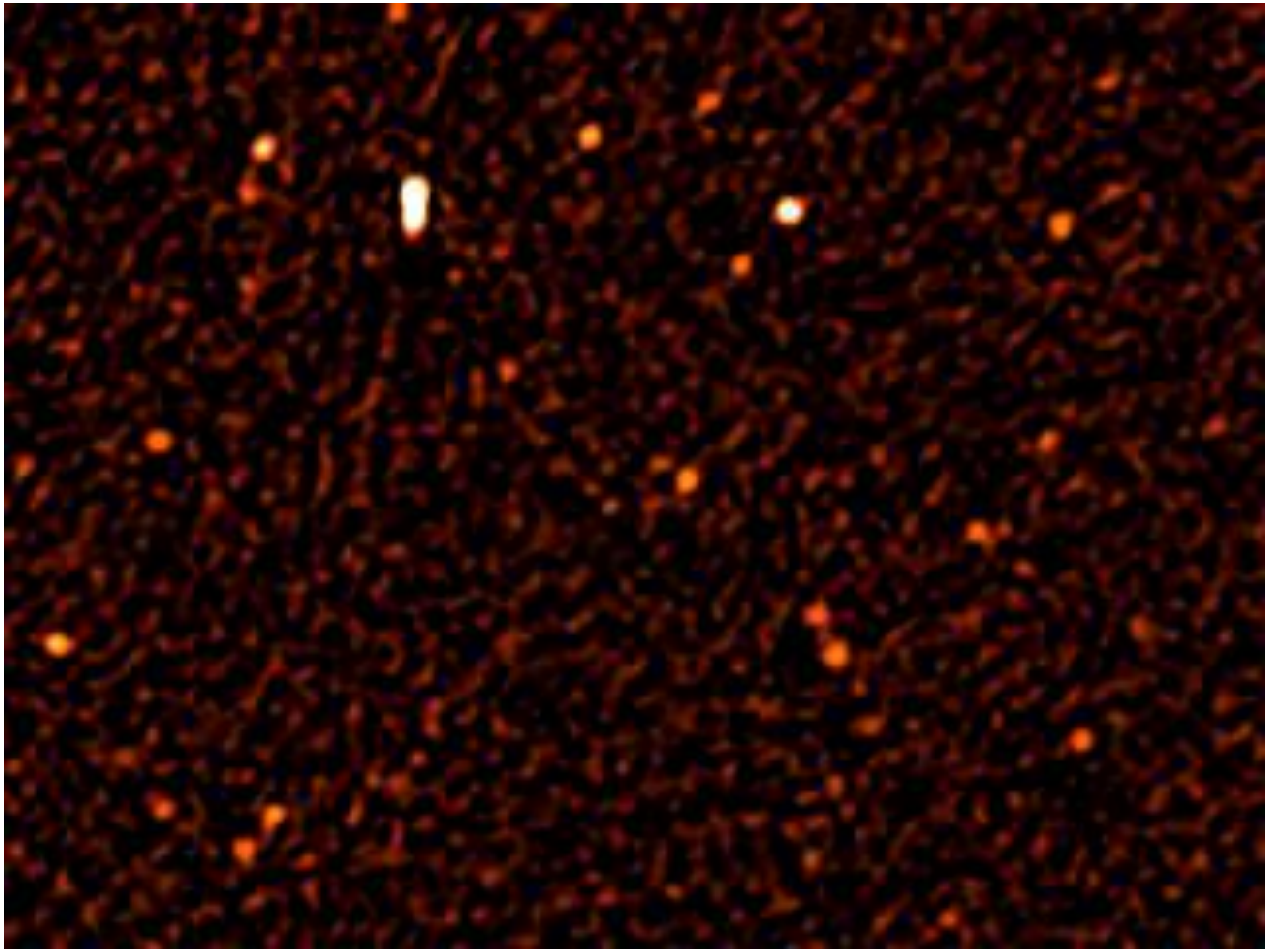






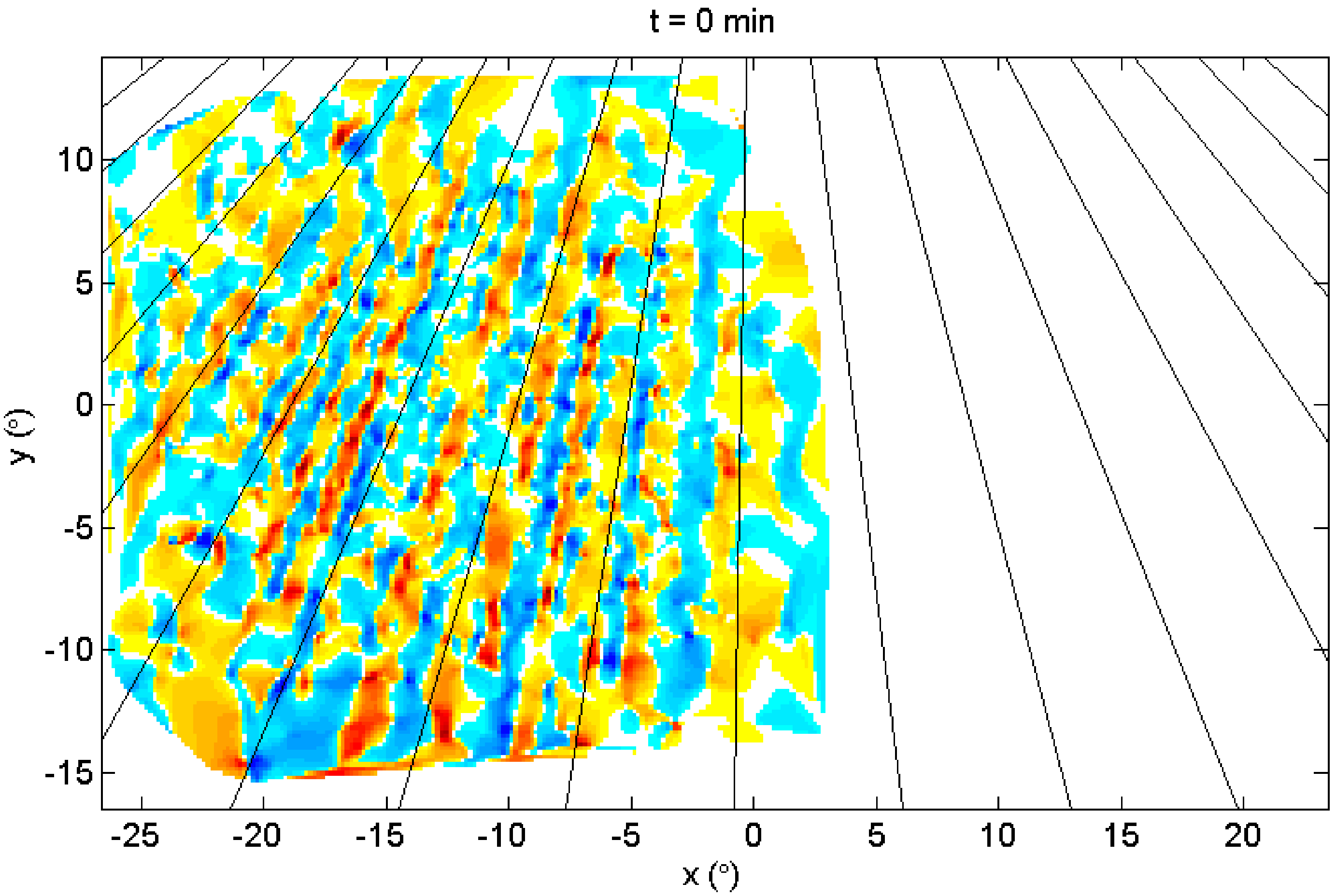
The radio astronomer’s nightmare

15th Oct 2013, 1346–1517 UTC

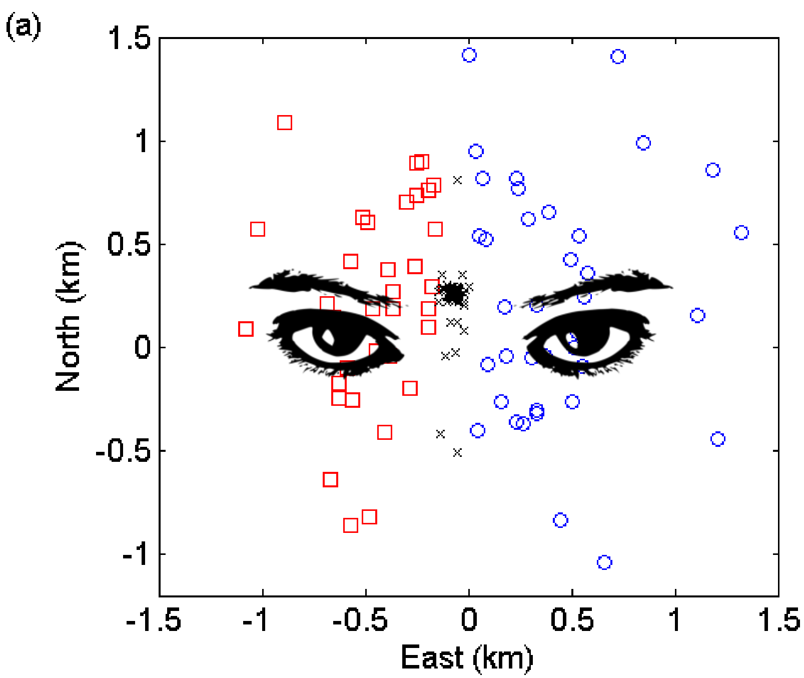


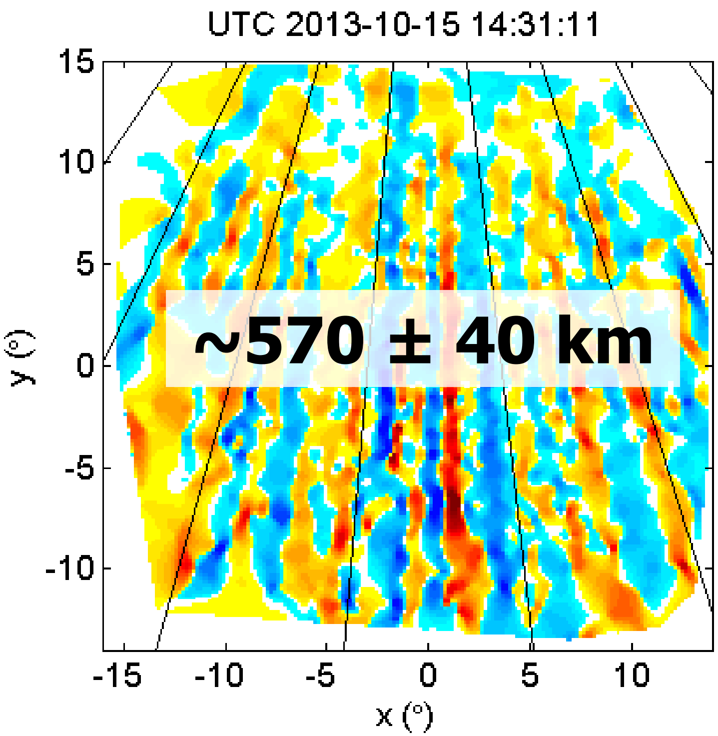
Movie: N. Hurley-Walker

Blame the plasma tubes



Seeing the third dimension





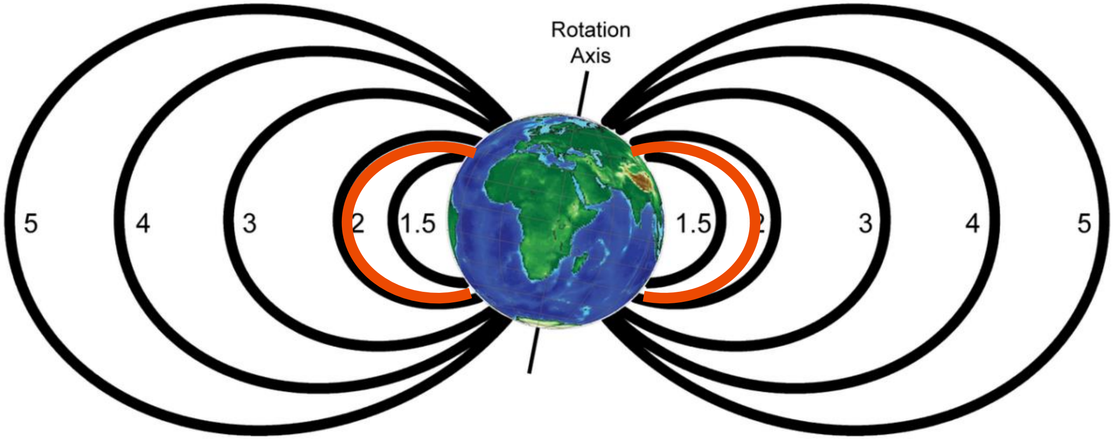
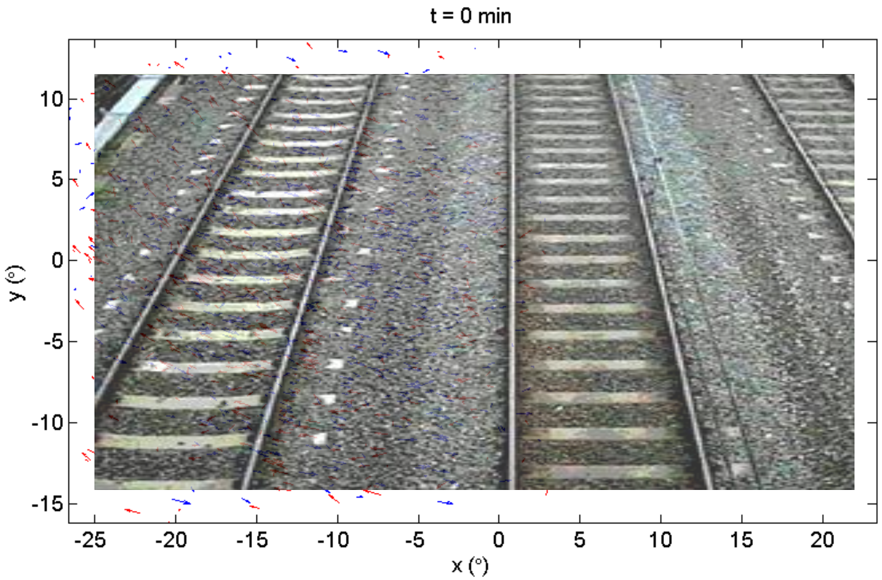
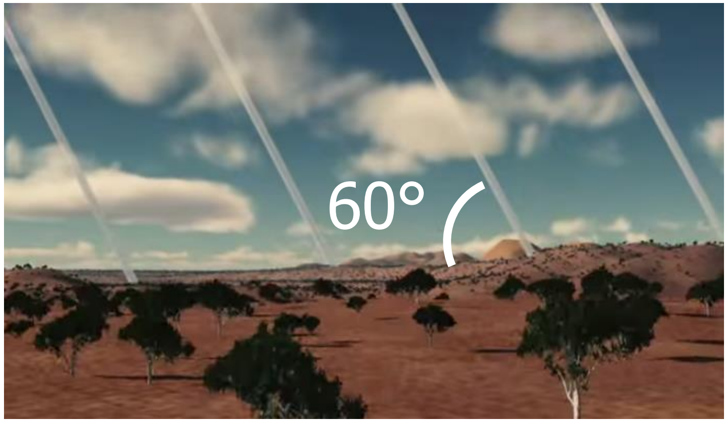
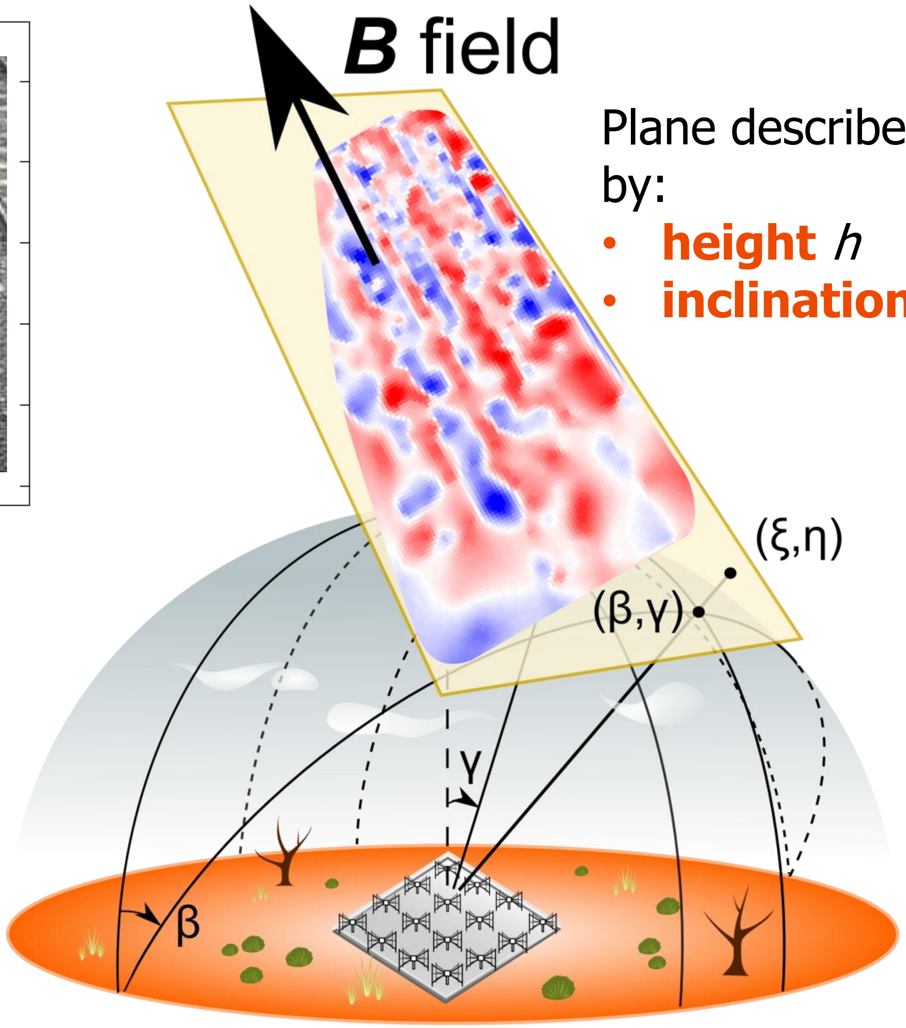


Image: Wikipedia

The inclined plane model [S. T. Loi et al., 2016, RaSc]



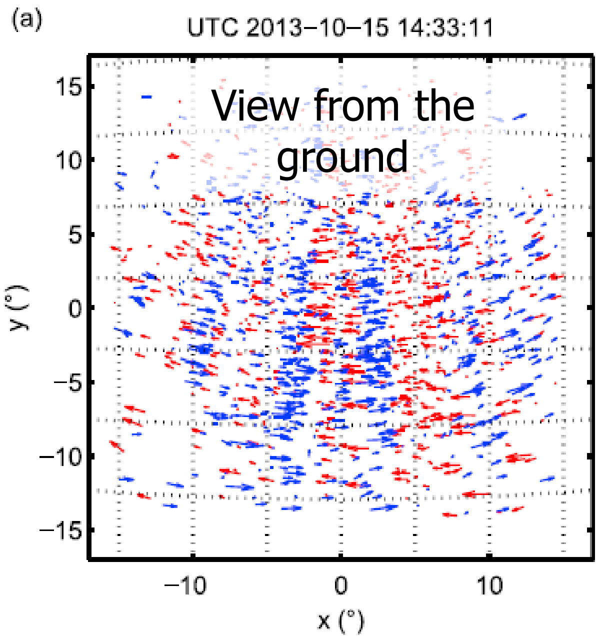




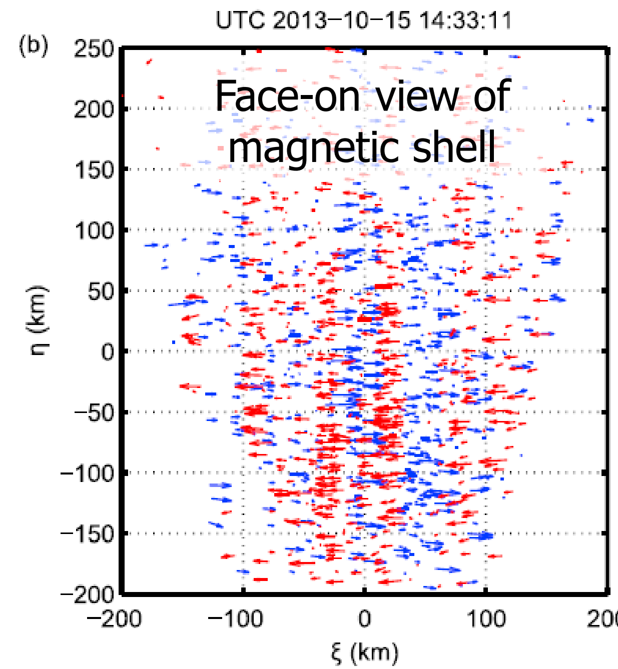
Plane described by:

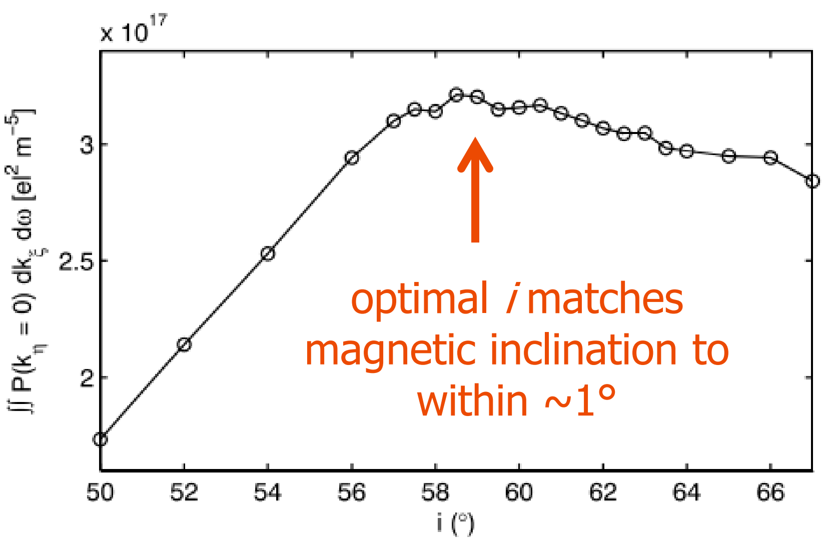
- **height** ***h***
- **inclination** ***i***

Plasma tubes from a new angle



"de-projection" transformation



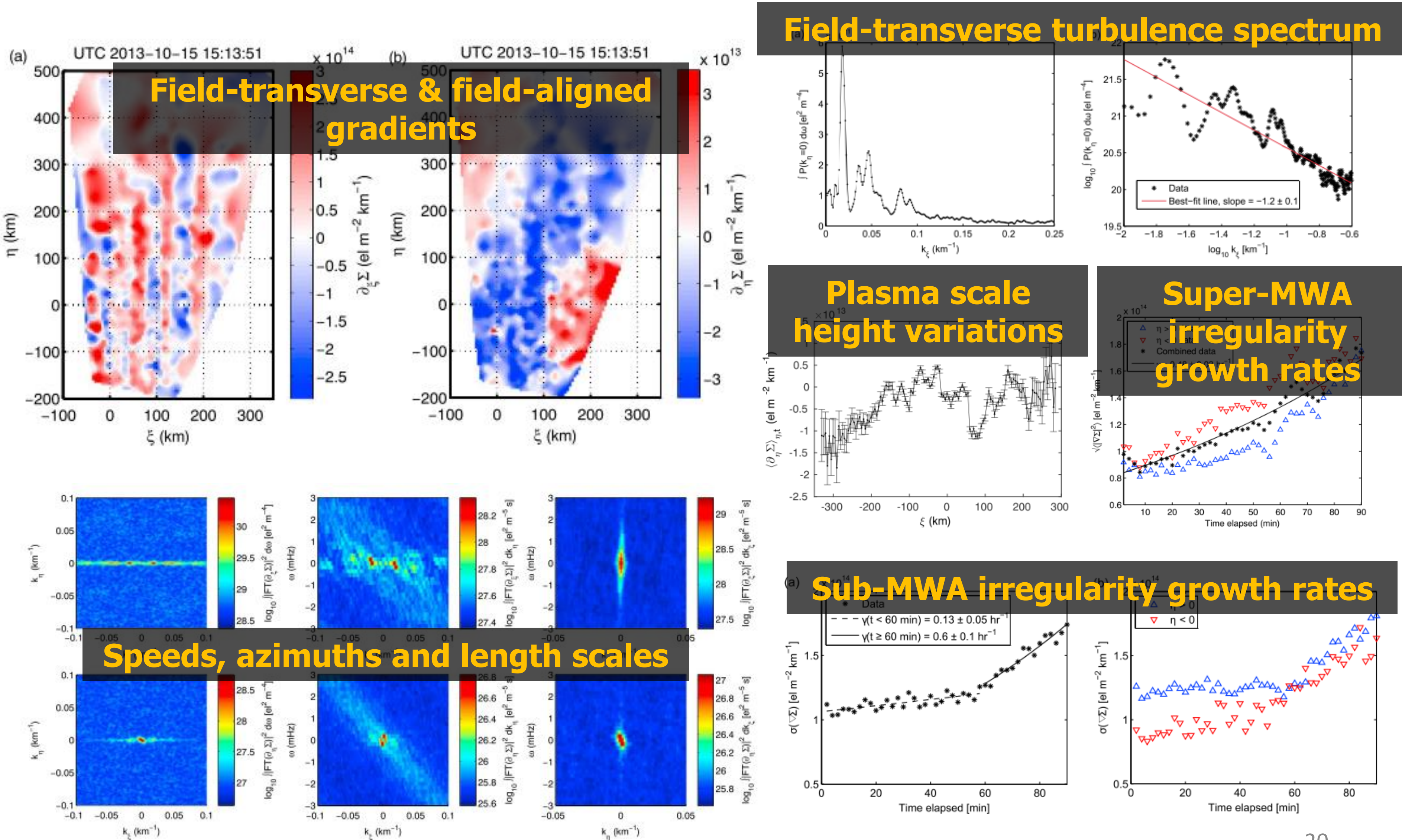


$$\partial_\xi \Sigma = \sin\gamma\cos\gamma\sin(\beta+i)\cos(\beta+i) \times [\cos i\cos\gamma\cos(\beta+i)+\sin i-1]\partial_\beta \mathrm{TEC} + \{\sin^2\gamma\cos\gamma\cos^2(\beta+i)[\cos i\cos(\beta+i)+\sin i] + \cos\gamma\sin^2(\beta+i)\}\,\partial_\gamma \mathrm{TEC} \quad \text{(A3)}$$

$$\partial_\eta \Sigma = \cos(\beta+i)\,\{\sin^2(\beta+i)\cos^2\gamma \times [\cos(\beta+i)\cos\gamma\cos i+\sin i] + \sin^2\gamma\}\,\partial_\beta \mathrm{TEC} + \sin(\beta+i)\sin\gamma\,\{\cos^2(\beta+i)\cos^2\gamma \times [\cos(\beta+i)\cos i\cos\gamma+\sin i]-1\}\,\partial_\gamma \mathrm{TEC}\,. \quad \text{(A4)}$$

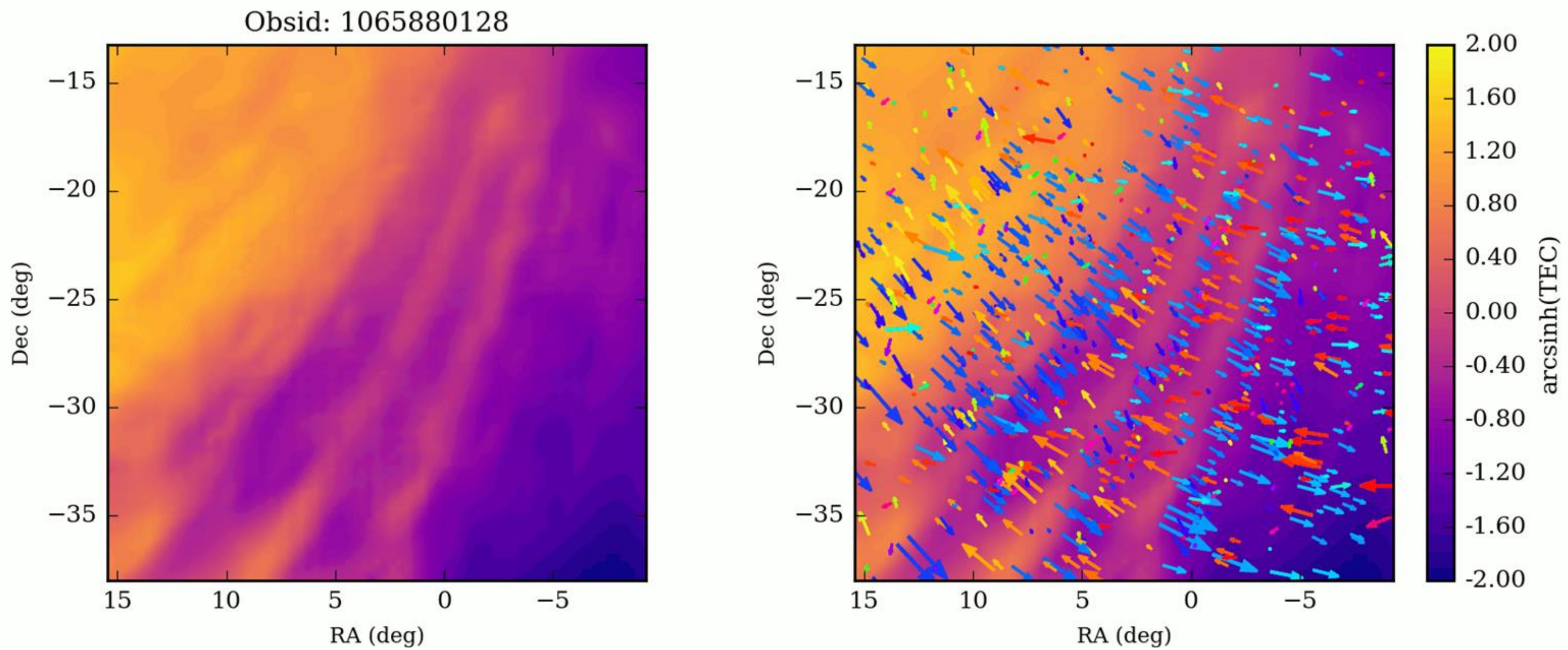
(if you care)

Unlocking a wealth of physics



From $\nabla_\perp$TEC to TEC and beyond [C. Jordan, C. M. Trott et al., in prep.]

- Interferometers measure $\nabla_\perp$TEC (2-comp't vector)
- In fact there is only **one degree of freedom** – scalar TEC
- Grid interpolation + surface reconstruction to get TEC from $\nabla_\perp$TEC

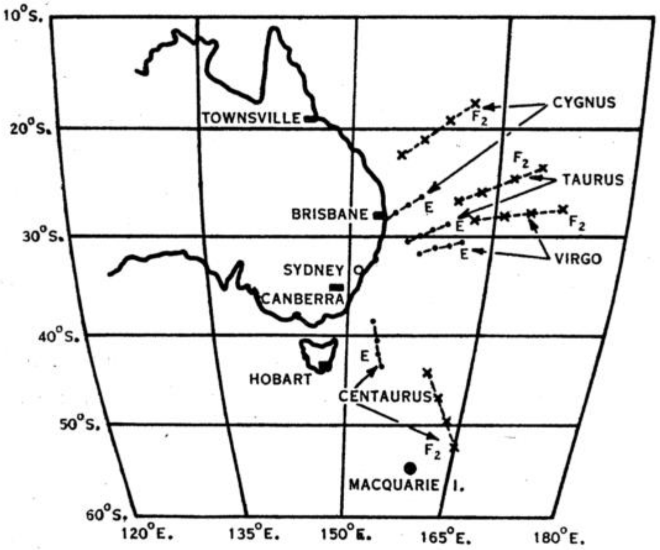


Snippets from an old paper

“A strong correlation is established between the occurrence of the scintillations and sporadic E. The difference in the scintillation rates for different sources can be explained in terms of variations in the size of irregularities and the effects of the winds in the E_s layer.”

RAY TRACKS OF SOURCES AND SCINTILLATION RATES

Source	Velocity of Ray Track		Scintillation Rate (min⁻¹)	Velocity (km) Rate (*Apparent* Size of Irregularities)
	Speed (km/min)	Direction of Travel of Ray Track		
Cygnus	4·1	30° S. of W.	1·14	3·6
Taurus	7·2	20° S. of W.	1·24	5·8
Virgo	8·0	10° S. of W.	1·18	6·8
Centaurus	6·1	75° N. of W.	1·80	3·3



Q: Was this written by radio astronomers or ionospheric physicists?

A: Radio astronomers!

→ **Bolton**, **Slee** & **Stanley**, “Galactic radiation at radio frequencies. VI. Low altitude scintillations of the discrete sources”, 1953, Aus. J. Phys.

Summary and outlook

- **Low-frequency, large-N** radio telescopes probe Earth's plasma environment in unprecedented **breadth** and **detail** and on **previously inaccessible scales**
- Gaining foothold in ionospheric/geospace physics arena: **>50%** of above results published in **geophysics-dominated journals** (JGR, GRL, RaSc)
  – Even though all data were originally obtained for astronomical purposes!