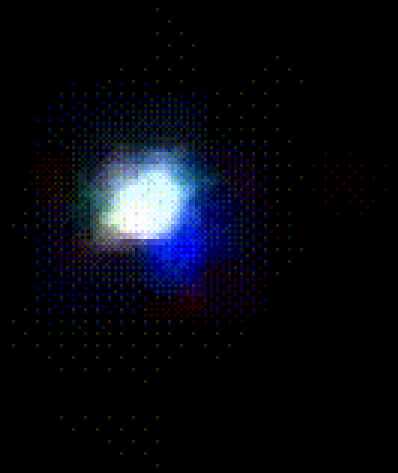
2,000 years of twinkling: lessons learned from a brief history of astronomical scintillation



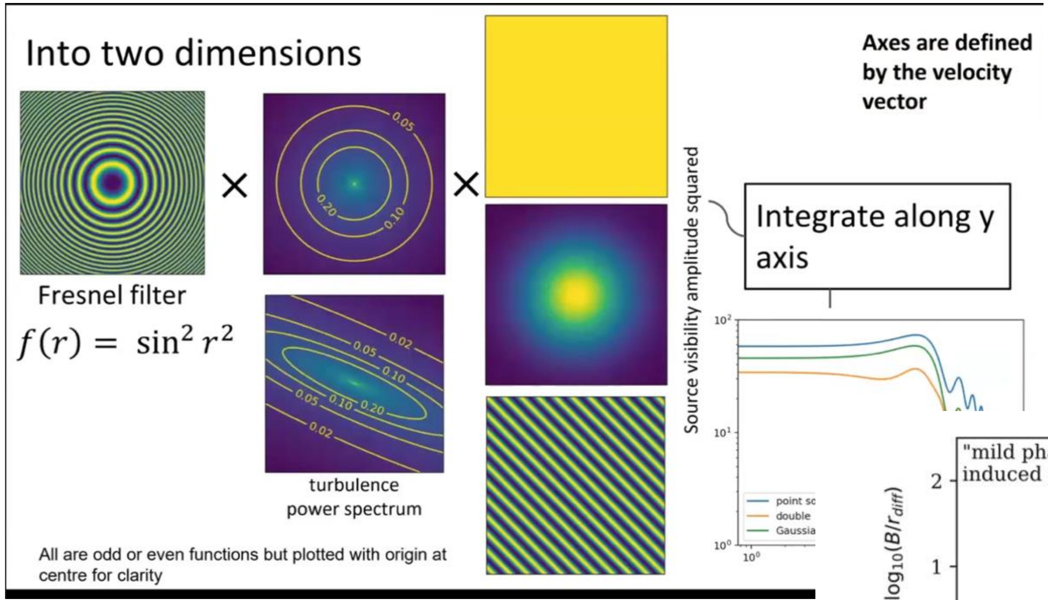
Emily Kerrison, Ron Ekers, Vanessa Moss, John Morgan and Rajan Chhetri

With thanks to: Don Melrose, Ray Norris, Bob Cowan, James Collins II

Image credit: Bautsch

A reminder

Turbulence (velocity) gives us a temporal power spectrum



A spatially varying 'lens' or phase screen between us and our point sources

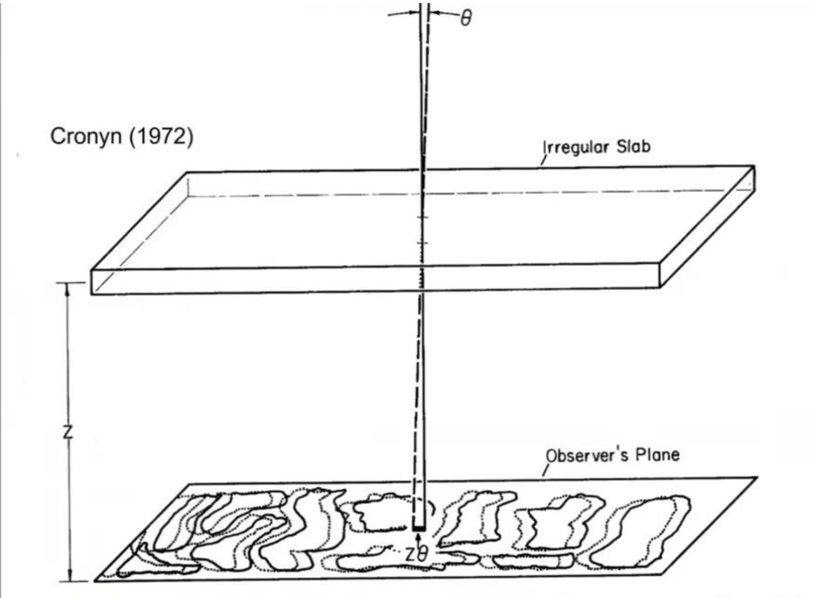
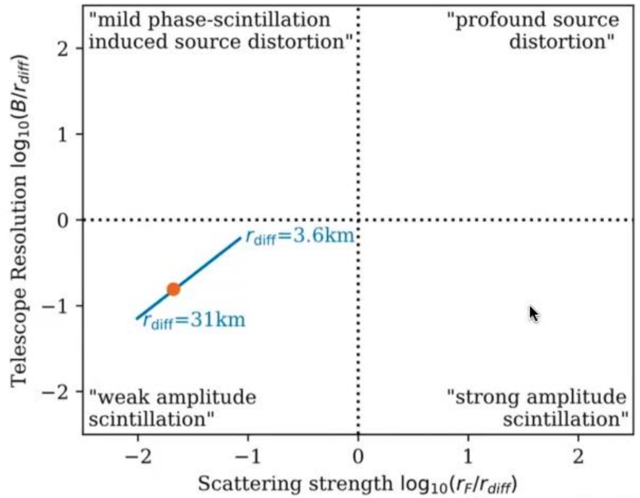


FIG. 3.—Pictorial idealization of diffraction patterns cast by two point sources separated by angle θ. Patterns are shifted with respect to each other by a distance $z\theta$, thereby smearing pattern structure finer than $z\theta$.

- Weak scintillation actually produces a diffraction pattern on the ground (characteristic size of patches is r_F)
- Velocity of the screen converts from spatial coordinates to a temporal power spectrum
- Finite source size (or large aperture for observing instrument) is a convolution
- Scattering is two dimensional!

Telescope resolution has a related effect!



Waszewski+ 2022

Figure 1. Scattering strength vs baseline length in terms of scattering scale, following Cornwell et al. (1989). Descriptions of asymptotic regimes are also from Cornwell et al. (though we adopt our definition of r_F; see Equation (7)). The blue line is for the range of r_{diff} observed by Mevius et al. (2016), but scaled to our observing frequency of 154 MHz. Baseline length B is assumed to be 2.2 km (MWA Phase I). The orange point is calculated from the scintillation index observed by Morgan & Ekers (2021) with the MWA at 162 MHz. Height of the ionosphere is assumed to be 300 km.

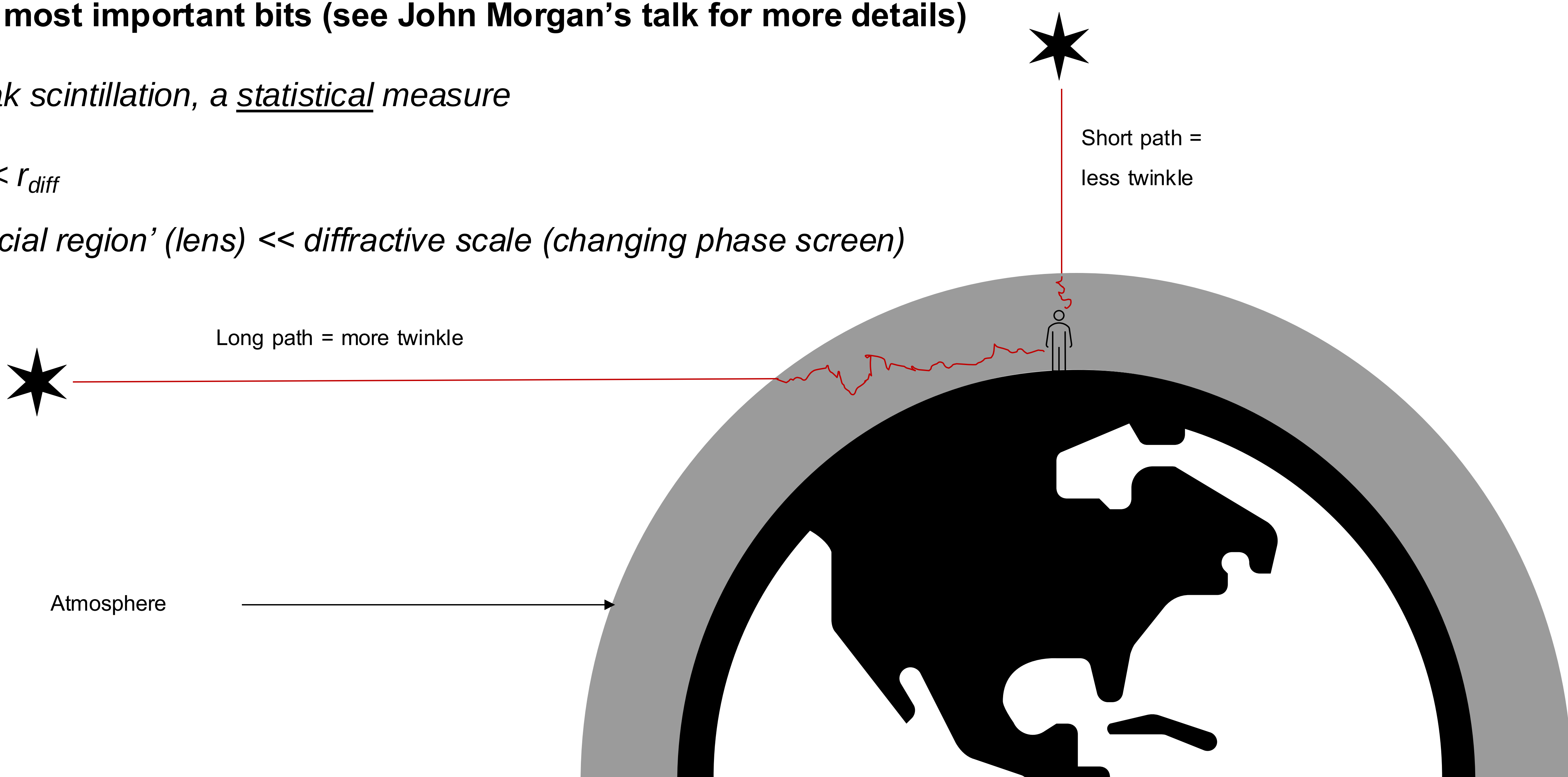
stellar scintillations

The most important bits (see John Morgan's talk for more details)

Weak scintillation, a statistical measure

$r_F << r_{diff}$

'special region' (lens) << diffractive scale (changing phase screen)



From stellar scintillations to space weather

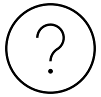
Overview:

- ✶ Early history (optical scintillation)
- ✶ Modern (re)discovery (optical → radio scintillation)
- ✶ Scintillation today (radio, applications)

Food for thought:

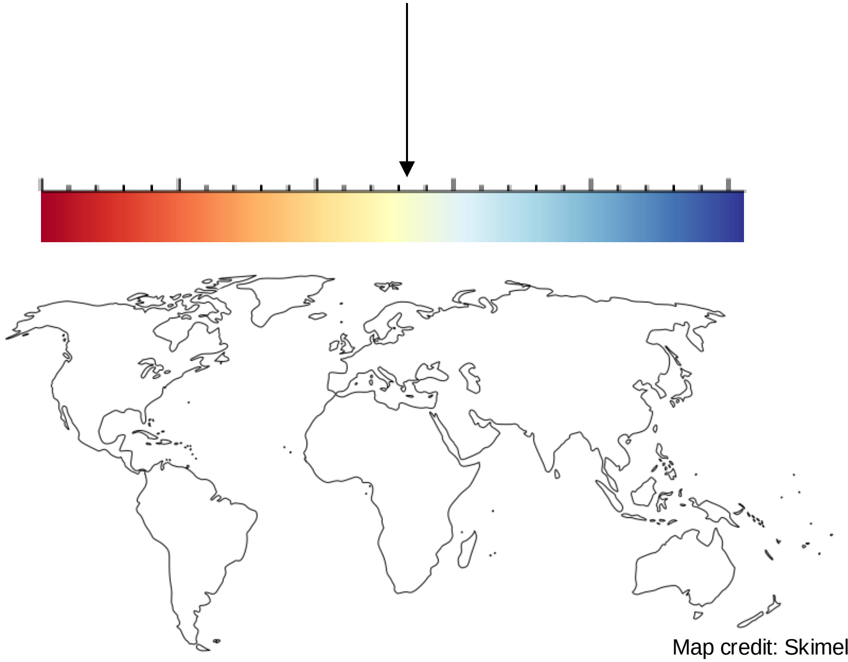

Angular dependence?


Understanding vs. application?


Assumptions challenged, assumptions held

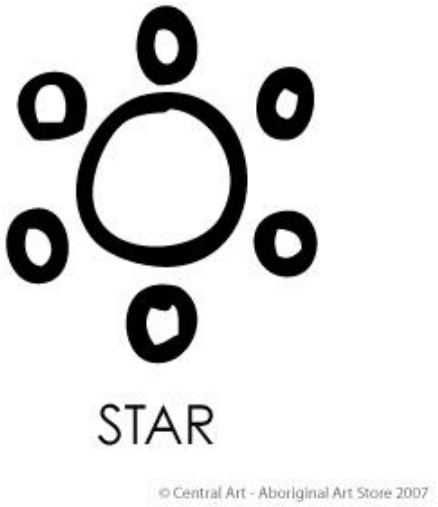
Keep track of where we are in space

and time!



Map credit: Skimel

Oral traditions in stellar scintillation (Hamacher+2019)



"If you lay on your back in the middle of the night you can see the stars all blinking.

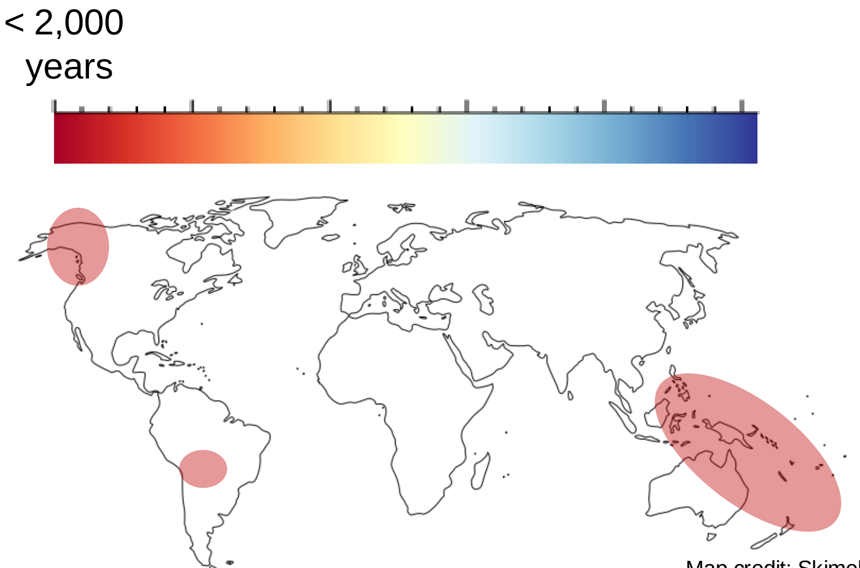
They're all talking."

- Bill Yidumduma Harney, Indigenous Australian Elder

Encoded in song/story, using the **language of human interaction**

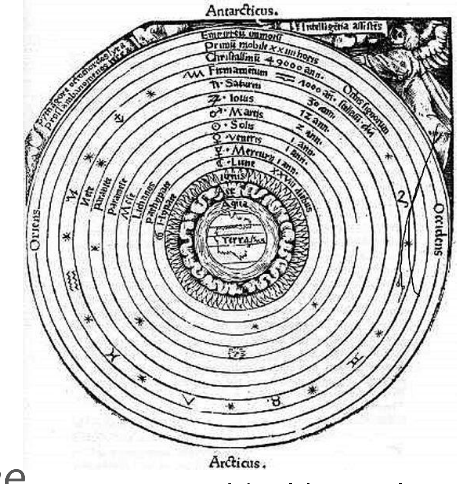
- ✶ talking – Wardaman, Australia
- ✶ laughing – Kamilaroi and others, Australia
- ✶ dancing – Mocovi, South America ; Yup'ik, Alaska

Known to be caused by wind, and therefore used as a **predictor of bad weather**



Map credit: Skimel

Written traditions in stellar scintillation



Aristotle’s cosmology

Aristotle *De Caelo* 290a (~350 BCE)

the apparent twinkling (τοὺς ἀστέρας … στίλβειν) of the fixed stars and the absence of twinkling in the planets (πλάνητας μὴ στίλβειν).

Aratus *Phaenomena* (~270 BCE)

*933ff: Often **before the coming rains** some star has a **darkening disk (ἅλωα μελαινομένην)***

*1013ff: When the bright light of the stars is dimmed, and yet no oppressive clouds press upon it … but they suddenly **become wavering (ἀμενηνὰ)** … **expect a storm***

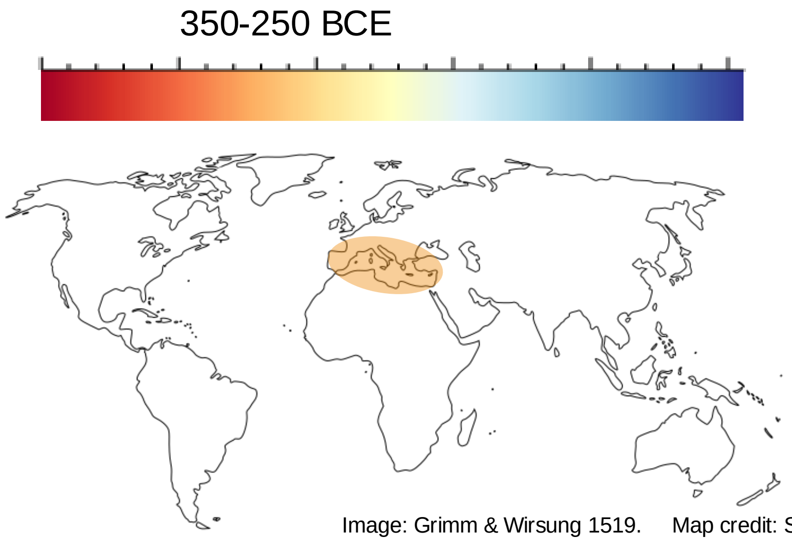


Image: Grimm & Wirsung 1519. Map credit: Skimel

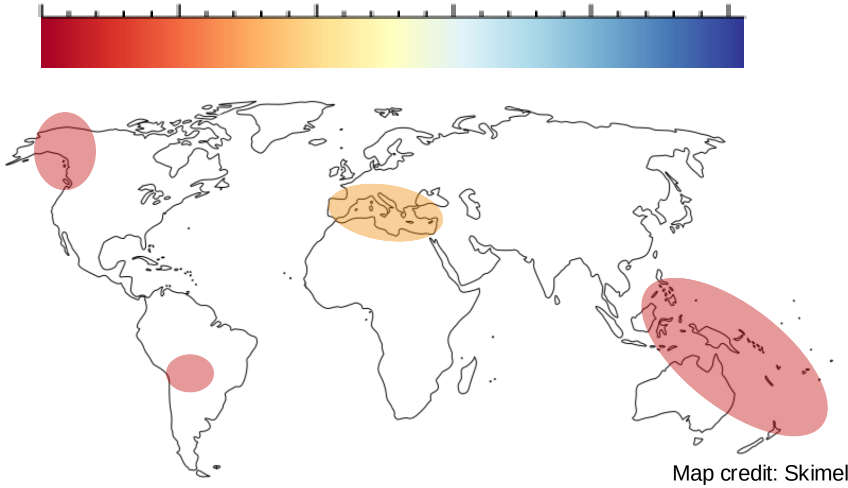
Early observations of scintillation

Explanations largely divorced from observations (no angular dependence!)

A *tool* for weather prediction → observations driven by practical applications

Noticed independently by several cultural groups across several centuries

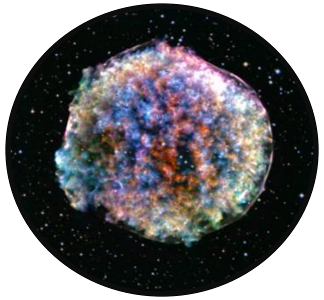
(Do you know of any more?)



Map credit: Skimel

What about scintillation in modern science?

Renaissance & Modern scintillation (Sofieva+2013)



Tycho's SN remnant composite image

da Vinci's moon glow

SN1604 remnant composite image

Leonardo da Vinci (circa 1505): an *optical illusion* in the eye (Veltman 1984)

Tycho Brahe (circa 1570): *intrinsic variability* (Monaco 1990)

Johannes Kepler *De Stella Nova in pede serpentari* (1605): *intrinsic variability* (SN1604)

Sir Isaac Newton *Opticks* (1704): *PROP. VIII. Prob. II: the air … is in a perpetual tremor; as may be seen … by the twinkling of the fix'd Stars. But these stars do not twinkle when viewed through telescopes which have large apertures*

Ellison & Seddon*, MNRAS 112:1* (1952): detailed discussion of observations, experiments and *angular dependence of the source*

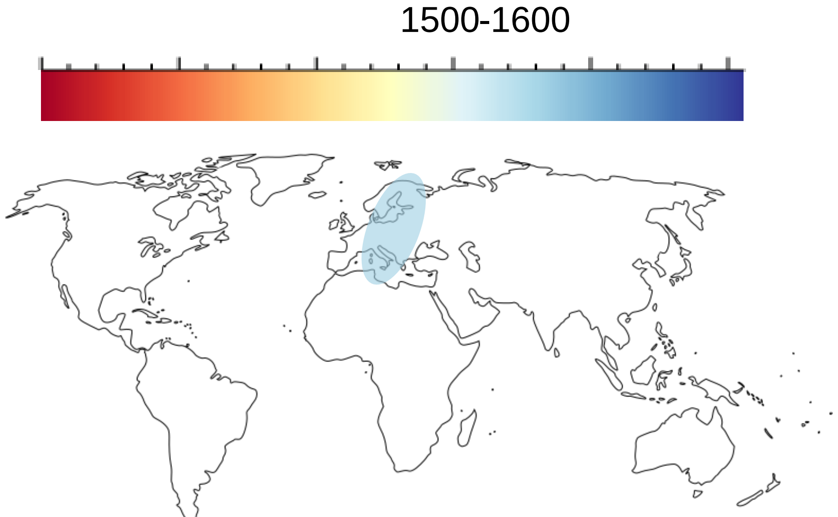
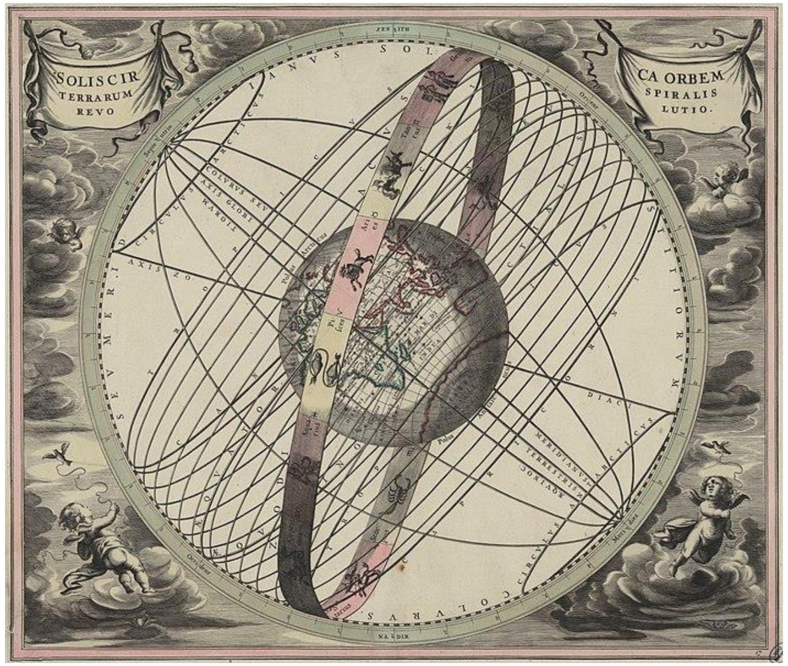


Image credits: NASA, X-ray: NASA/CXC/RIKEN & GSFC/T. Sato et al; Optical: DSS, Harvard CfA, Map credit: Skimel

Stellar scintillation: modern and ancient



Illustrated star chart, 17th century

In ancient times scintillation was **used for weather prediction.** Observations were **forward looking**, an understanding of the underlying physics was not necessary. **Theoretical discussions were separate.**

Post-renaissance there was a growing interest in the **physics behind scintillation** combined with greater records of observations, but **preconceived theories hampered progress.**

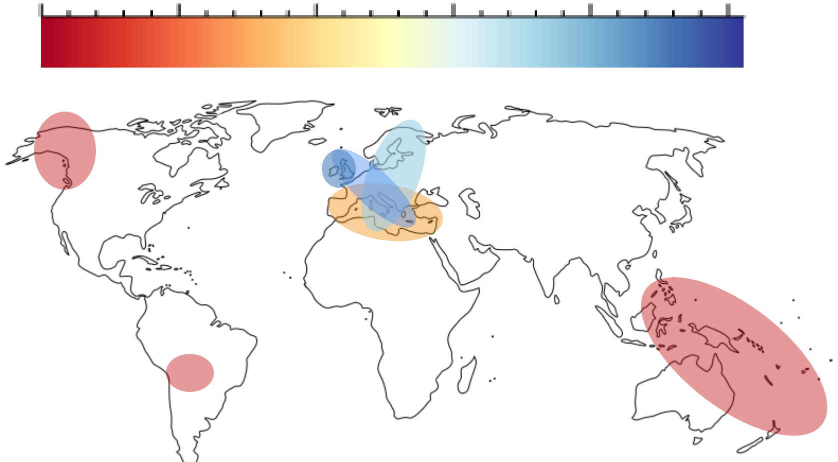
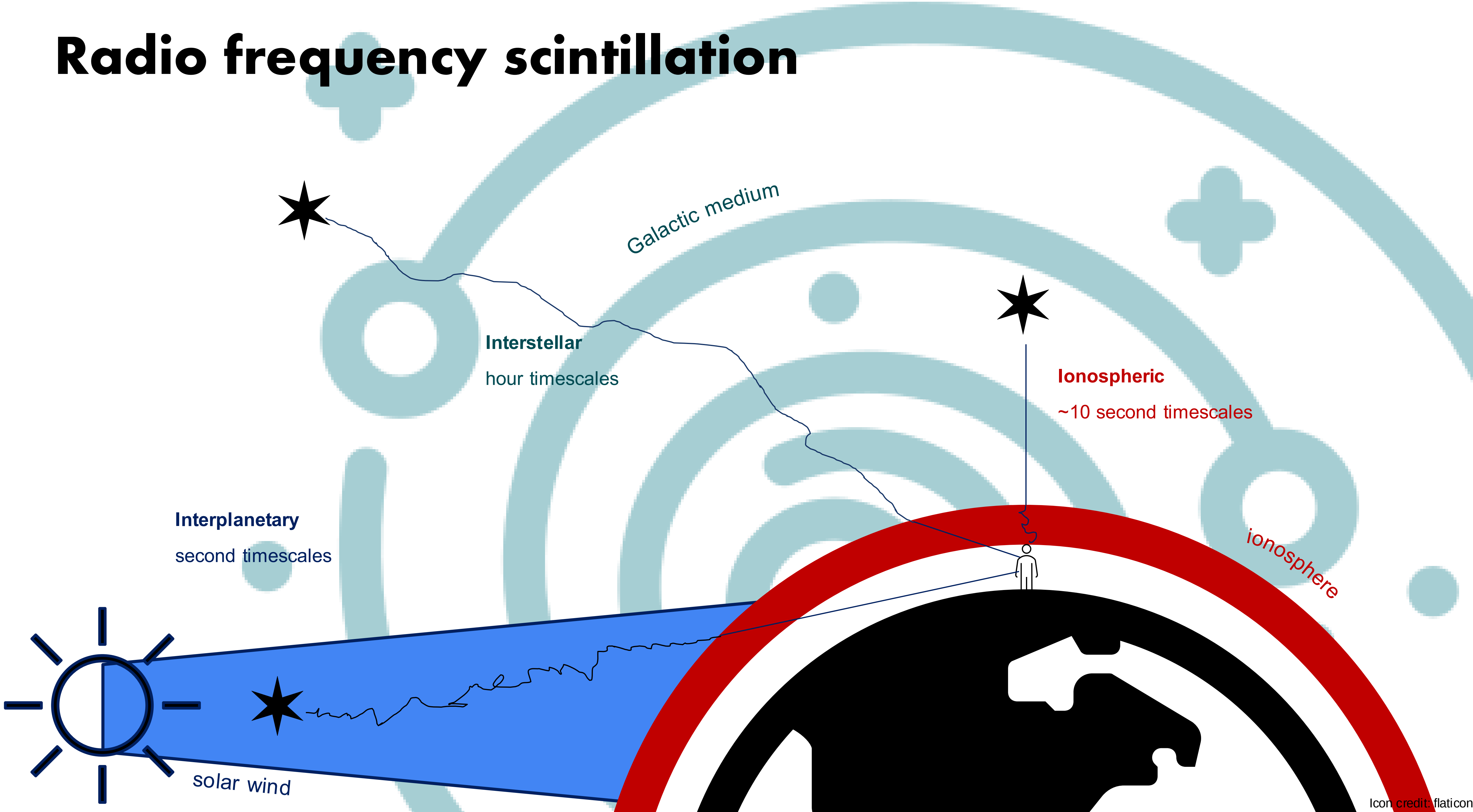


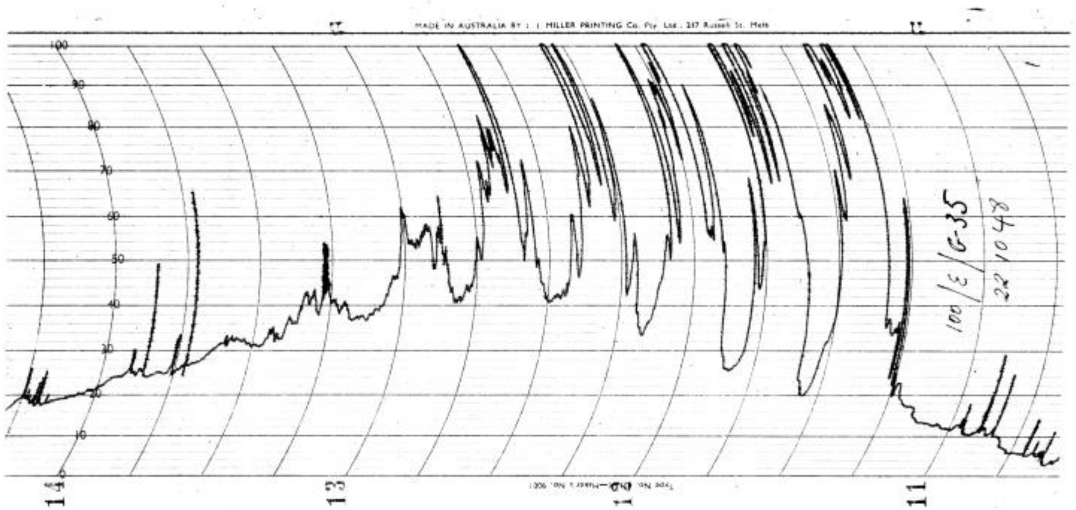
Image credits: Peter Schenk l'Ancien, Gerhard Valk, Map credit: Skimel

What about at other wavelengths?

Radio frequency scintillation



Radio frequency scintillation: ionospheric



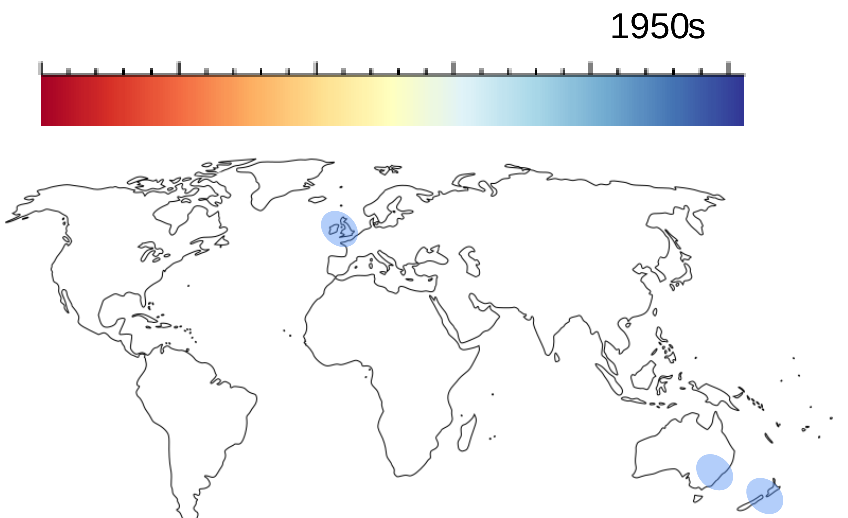
Ionospheric variation modulating interference fringes towards Cygnus A

Discovered as **minute-scale variations** towards Cygnus A in 1946 (Hey, Parsons & Phillips 1946), and further localised to a **theorised point source** in 1948 (Bolton & Stanley, 1948)

Rapid succession of papers between competing Cambridge & Australian groups to try and explain phenomenon (years, not centuries!)

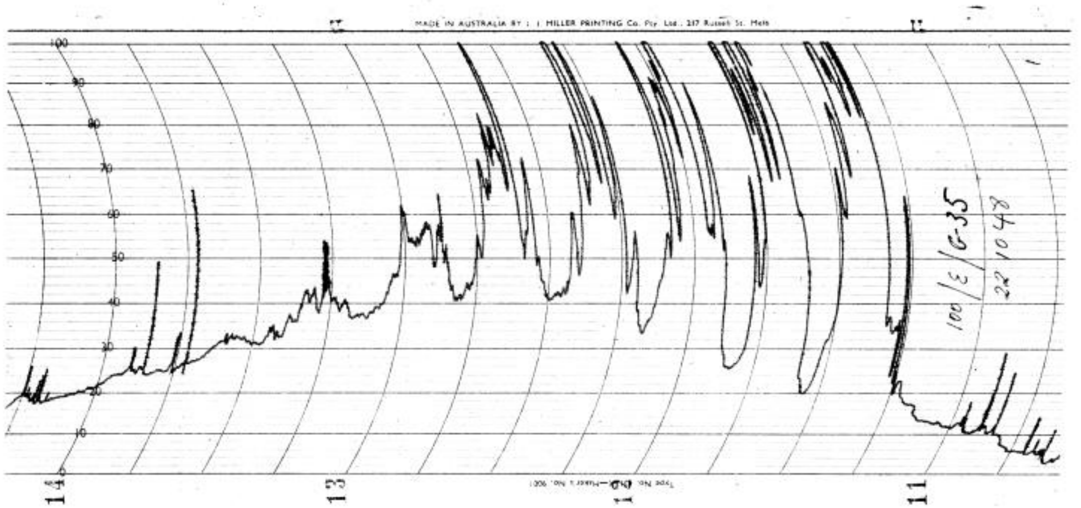
Proposed explanations alternated between an **intrinsic, sunspot analogue** and a *local, ionospheric effect*:

- ✶ **1946**: **intrinsic**, UK Ministry of Supply (Hey, Parsons & Phillips, 1946)
- ✶ *1947*: *local*, Jan Oort (Goss, Hooker & Ekers, 2023)
- ✶ *~1949: local*, Bolton & Slee spaced receiver (Sullivan, 2009)
- ✶ **1950: intrinsic**, Cambridge group (Smith, 1950)
- ✶ *1950: local*, Cambridge & Manchester Smith (1950) and Little and Lovell (1950)
- ✶ *1951:* theory behind ionospheric scintillation laid out incl. angular dependence (Hewish, 1951)



Map credit: Skimel

Radio frequency scintillation: ionospheric



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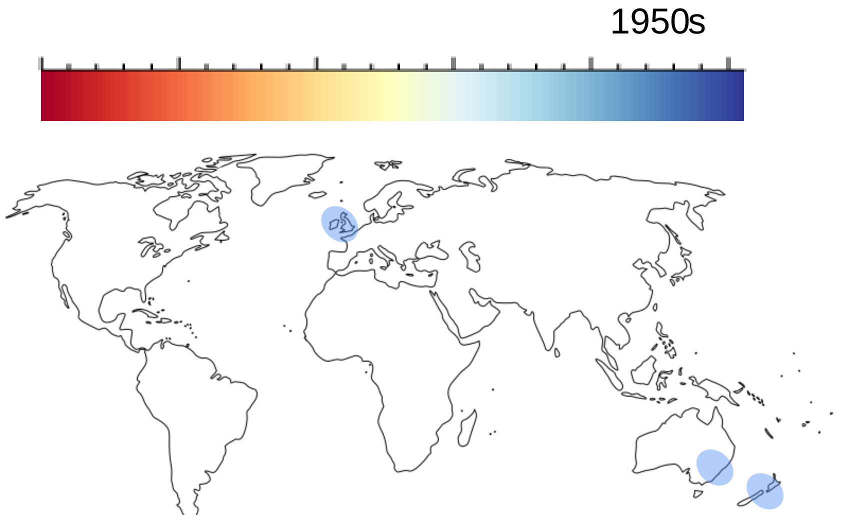
Intrinsic, sunspot analogue (Cambridge) vs. a *local, ionospheric effect* (Australia)

1946-1950 (1951 – introduction of theory)

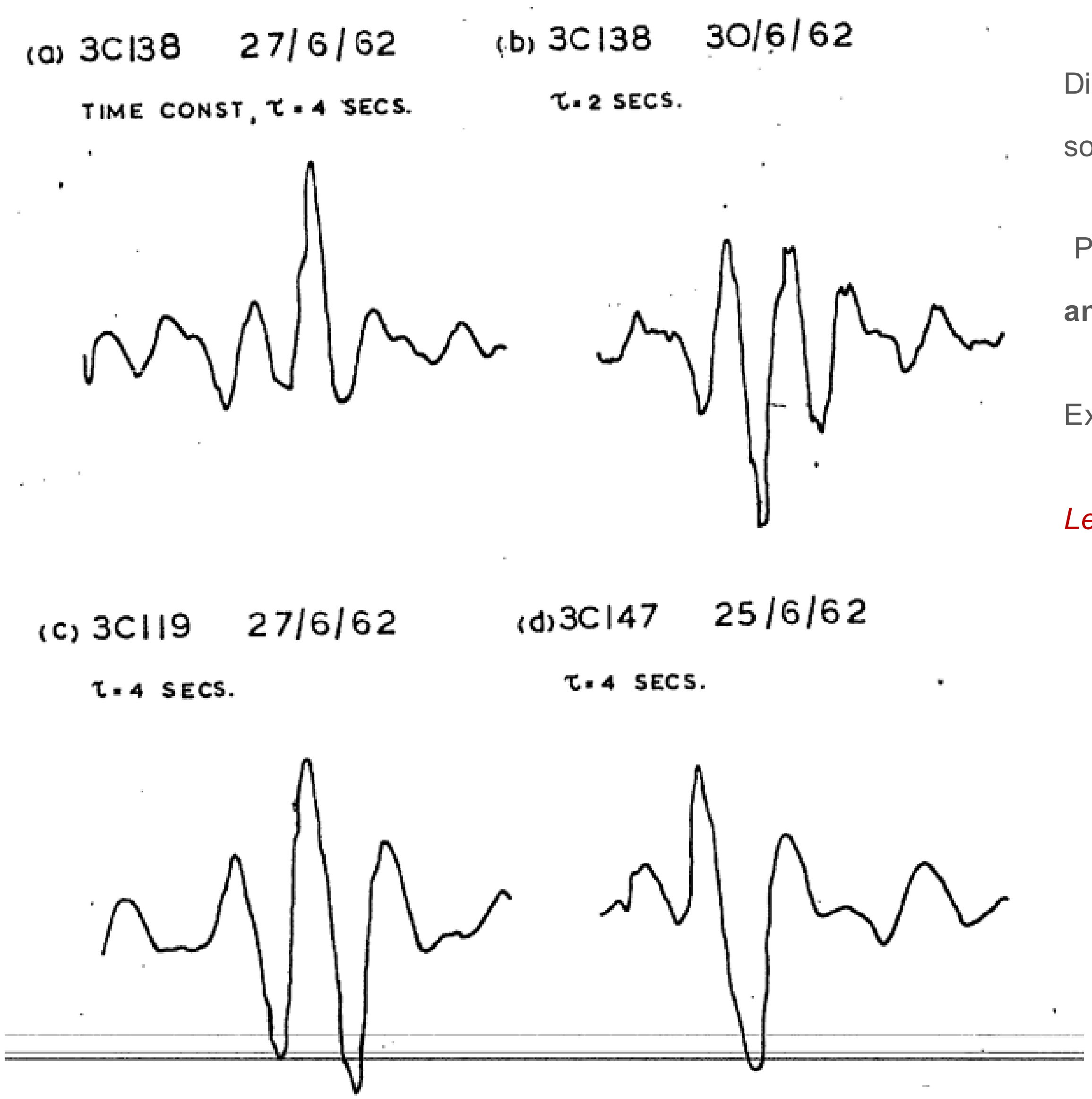
Competing Cambridge, Australian groups drove **fast progress in the field.**

Cambridge was initially led astray by the similarity with sunspots, and the hypothesis that the discrete sources of emission were radio stars. **Slowed by preconceived ideas.** (c.f. Brahe & Kepler!)



Map credit: Skimel

Radio frequency scintillation: interplanetary



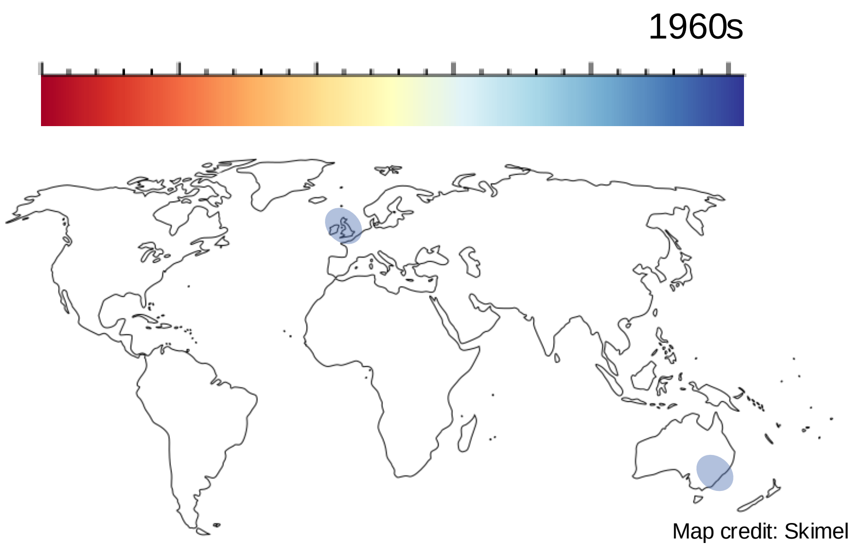
The very first IPS measurements! Using the Cambridge interferometer: Clarke 1964

Discovered serendipitously as **second-long variations** towards a number of compact sources.

Published as an appendix to Margaret Clarke's thesis with **correct identification of angular dependence AND of solar corona as scattering screen!** (Clarke 1964)

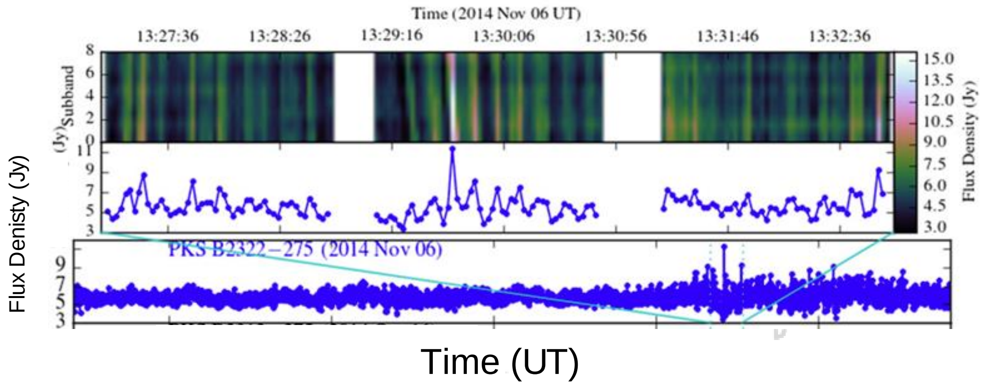
Explanation not immediately accepted but soon published in *Nature* (Hewish, 1964)

Less than a year from discovery to correct theory!



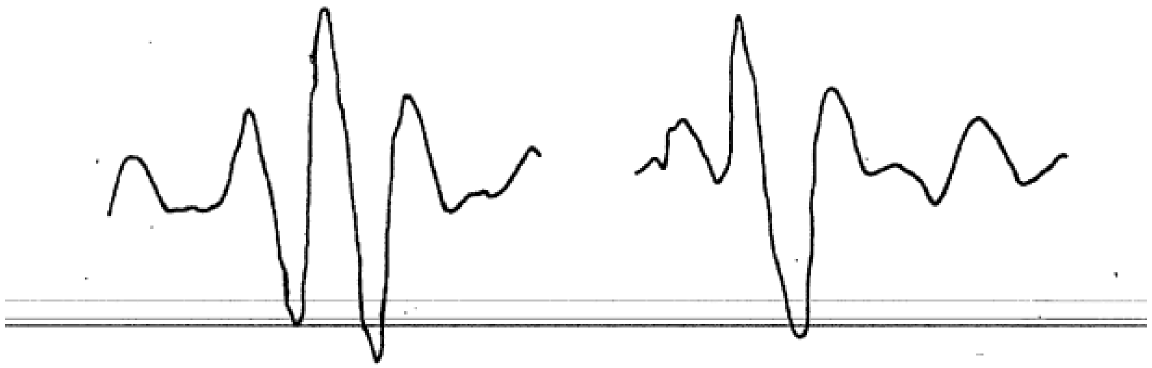
Map credit: Skimel

Radio frequency scintillation: interplanetary



The first IPS measurement observed at night, data taken with the MWA (Kaplan+2015)

But there are still new surprises!



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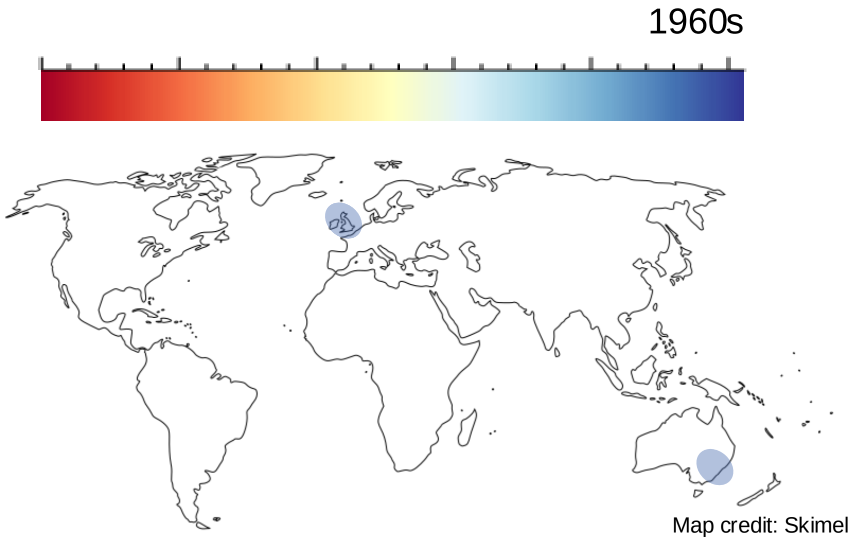
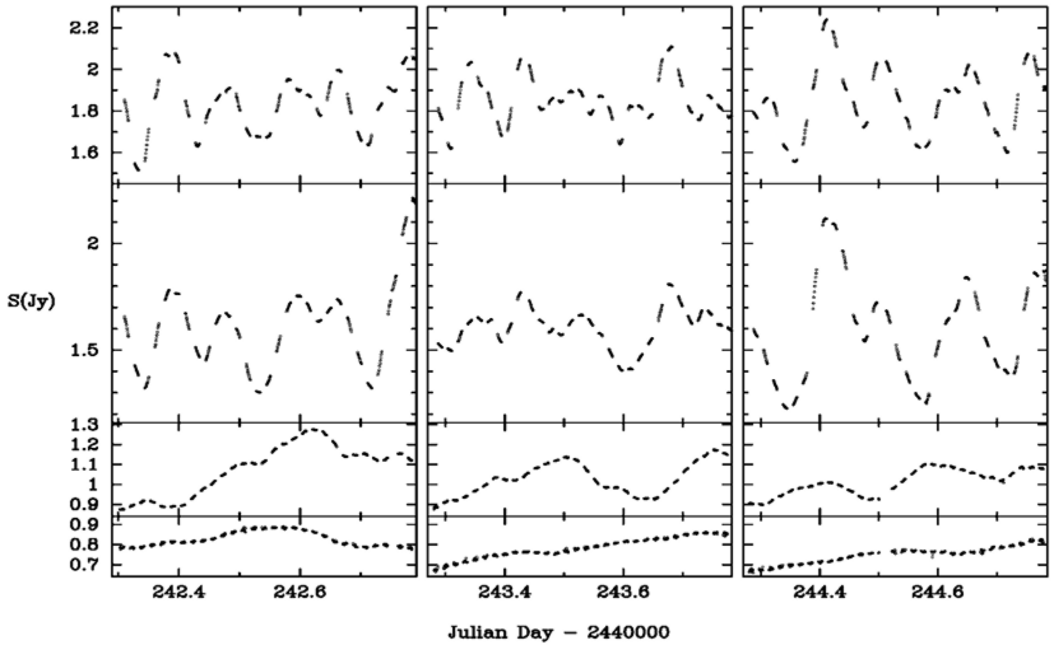


Map credit: Skimel

Radio frequency scintillation: interstellar



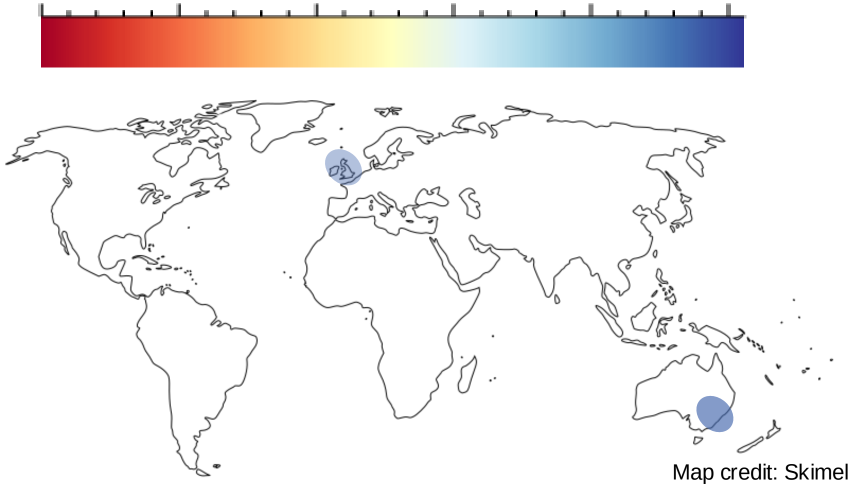
Multifrequency ISS / IDV measurements of PKS 0405-385 (Kedziora-Chudczer+1997)

Initially observed towards **pulsars** and compact **AGN** as variation over hours (Rickett 1977)

The extragalactic groups were excited by the idea of intrinsic variability which would suggest **new physics** (called it IDV).

A correlation between scintillation and the DM of pulsars **ruled out intrinsic variability** – but the groups took a while to talk to each other! (IAU Colloquium #160, 1996 vs. Bignall+2006)

Extragalactic astronomers still refer to IDV in AGN (e.g. Liu+2013, Bignall+2022)



Map credit: Skimel

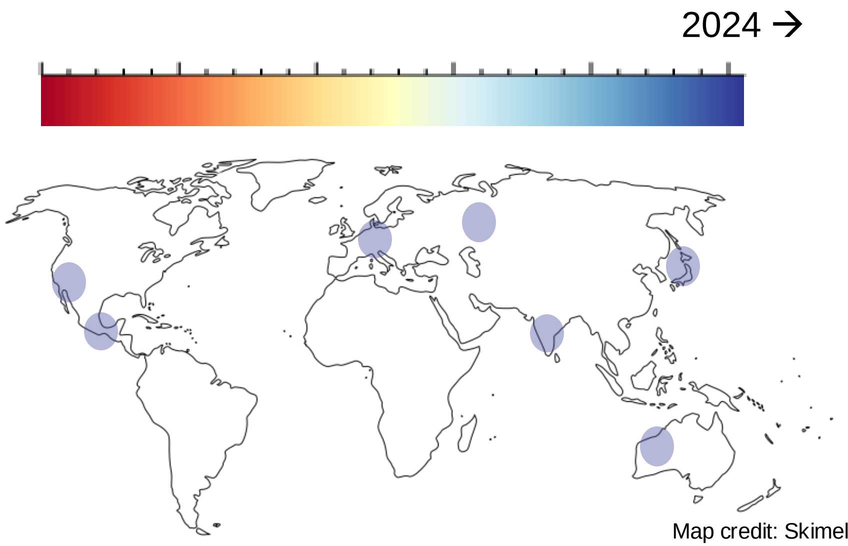
IPS: a modern tool for (space) weather prediction

Space weather prediction is now a **global effort,** with multiple **ground-based** observatories recording **IPS measurements to track the heliosphere and identify CMEs**:

- ✶ ISEE (Japan)
- ✶ ASKAP (Australia)
- ✶ MWA (Australia)
- ✶ LOFAR (Netherlands+)
- ✶ BSA3 (Russia)
- ✶ MEXART (Mexico)
- ✶ ORT (India)

Outcomes

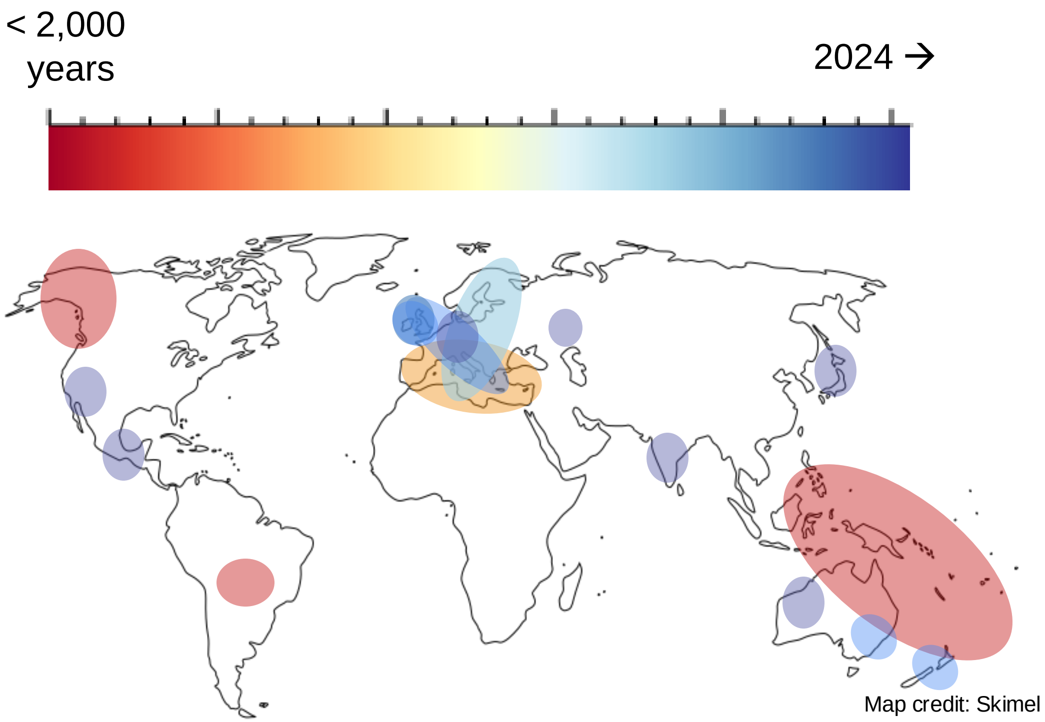
- ✷ Input into **heliospheric models** (B.V. Jackson, many papers)
- ✷ Measurement of **solar wind speeds** (Mejia-Ambriz+2015)
- ✷ Detection (Morgan+2023) and modelling (Iwai+2023) of **CMEs**
- ✷ Detection of **SIRs** (Breen et al., 1998; Bisi et al., 2010; Waszewski+2023)



Map credit: Skimel

2,000+ years, lessons learned

- ✶ Deep historical roots of observation, theorization and prediction
- ✶ Similar (mis)conceptions repeated across fields (intrinsic/local, aperture/source size)
- ✶ Interaction + competition driving rapid progress



Global science

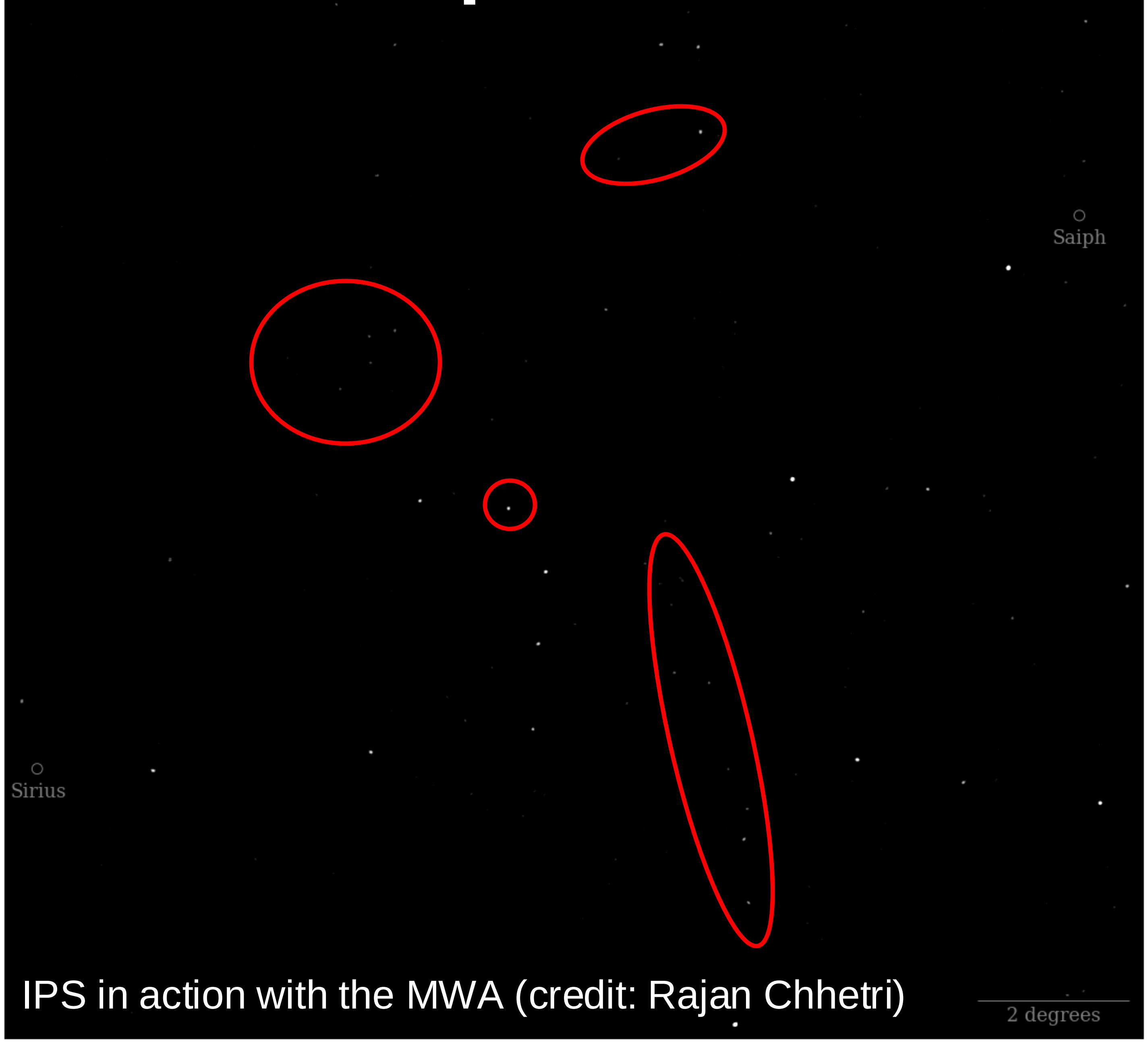
at its best!

IPS: a modern tool for (space) weather prediction and more

From weather prediction

to

space weather prediction!



IPS in action with the MWA (credit: Rajan Chhetri)