New insights in astrophysics and space weather with widefield interplanetary scintillation

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Ron Ekers (CASS)
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International Centre for Radio Astronomy Research

Curtin University

The University of Western Australia

Scintillating Science
Hermanus, South Africa
16 July 2019

Overview

I. Why?

II. How?

III. What?

IV. Where?

Overview

I. **Why** use IPS for extragalactic studies?

II. **How** do we measure IPS with the MWA?

III. **What** interesting results have we found so far?

IV. **Where** to from here?

Overview

I. **Why** use IPS for extragalactic studies?

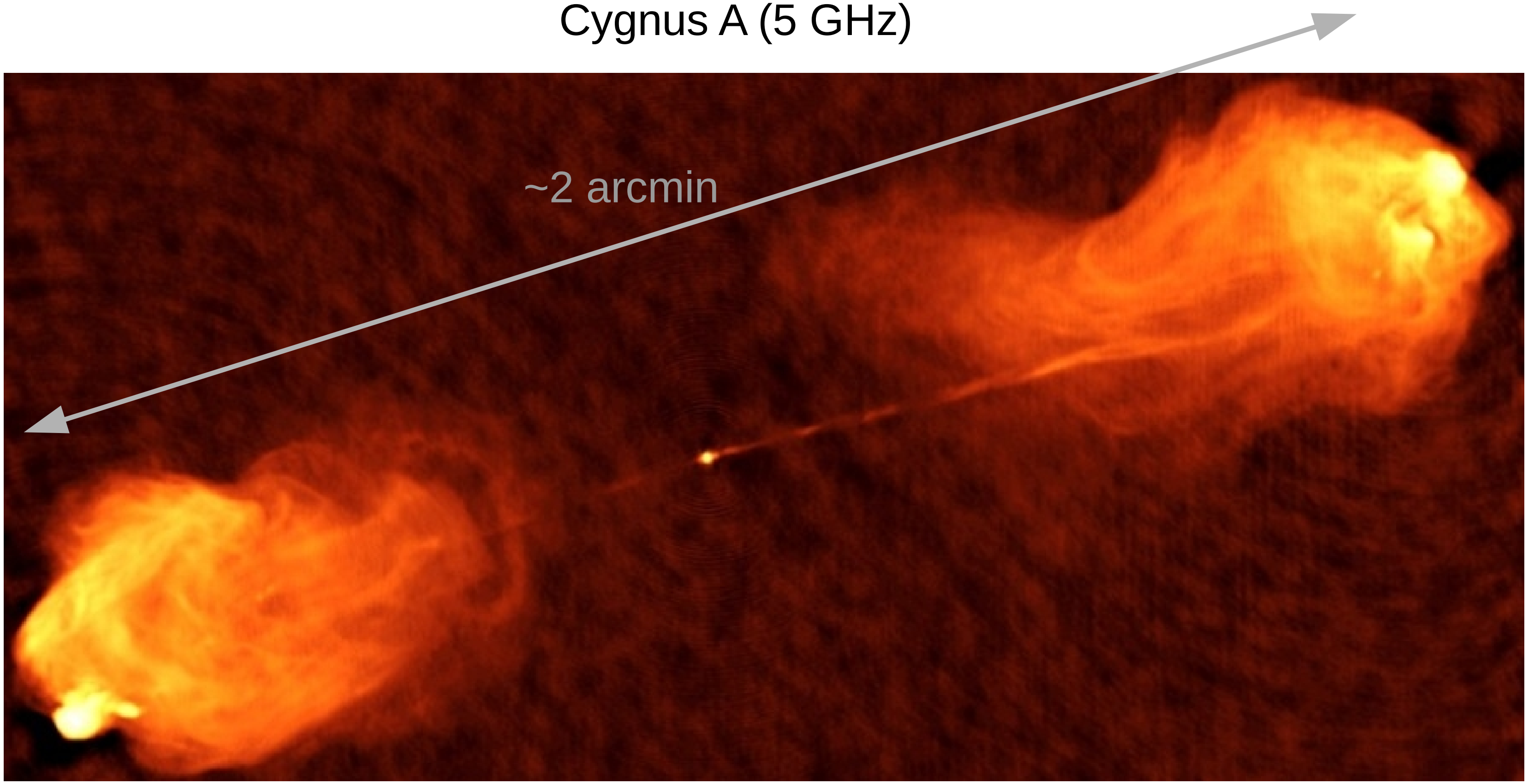
II. **How** do we measure IPS with the MWA?

III. **What** results did we get?

IV. **Where** to from here?

Background – Extragalactic Radio Sources

Cygnus A (5 GHz)



Credit: R. Perley, NRAO

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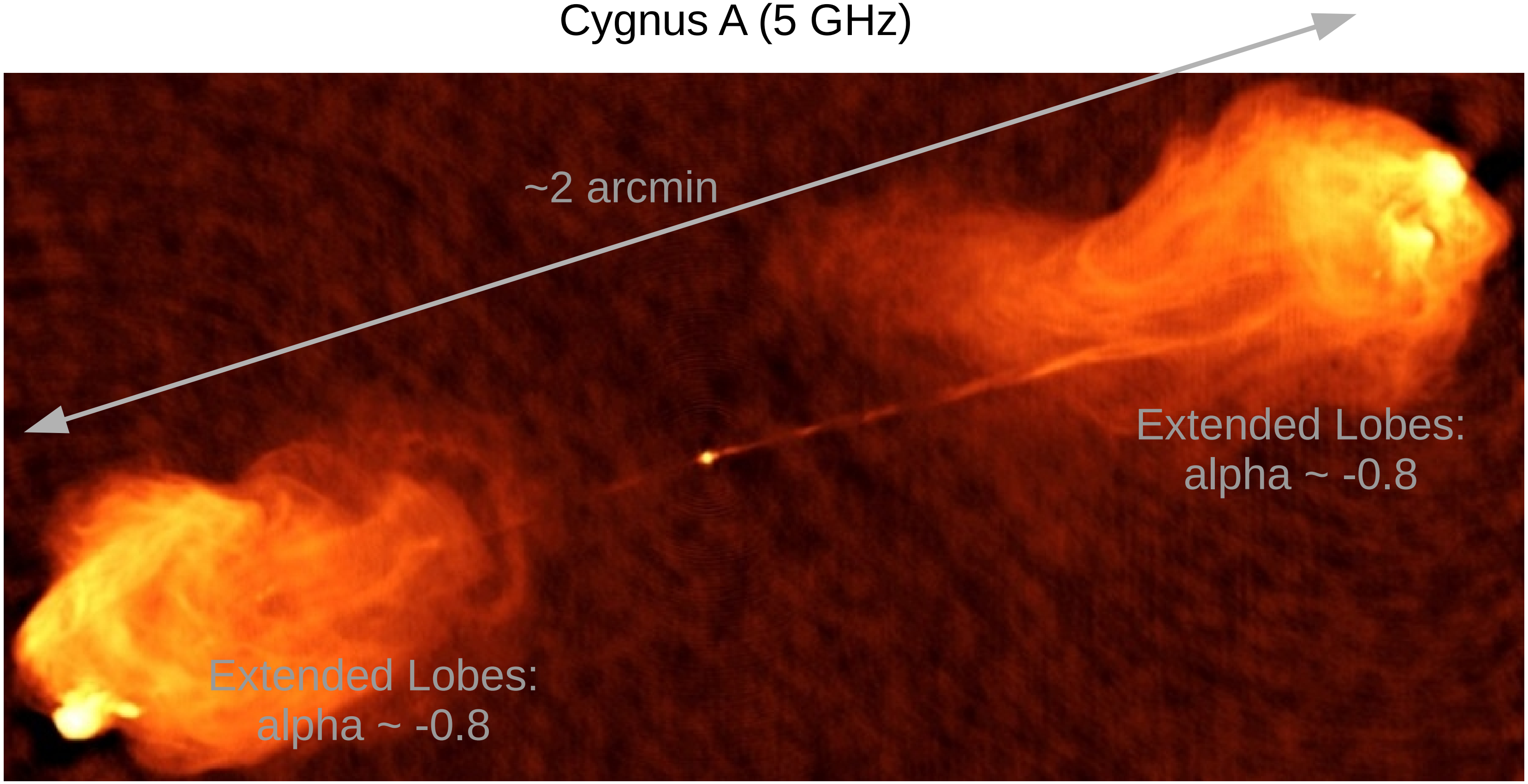

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$$S_\nu \propto \nu^\alpha$$

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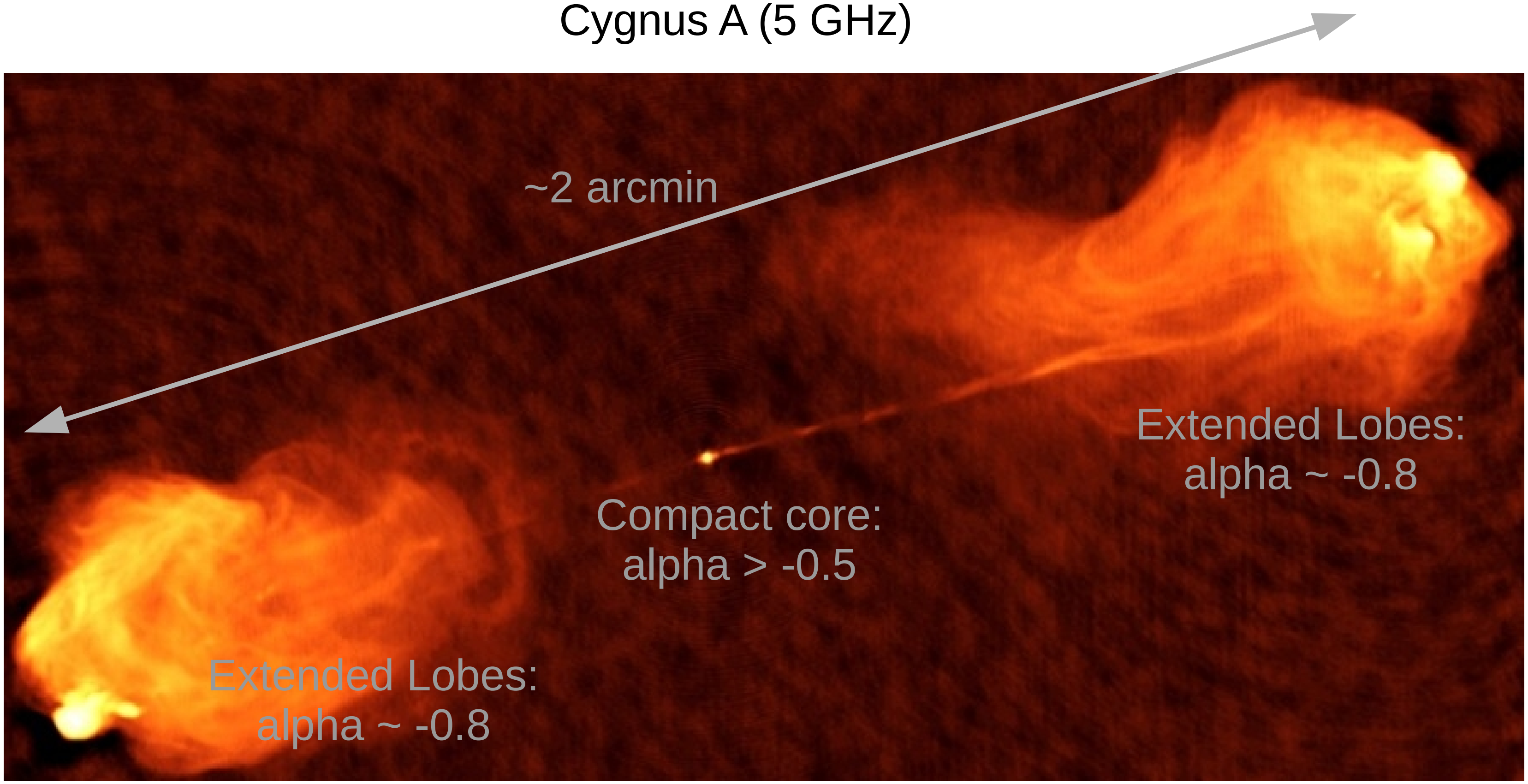

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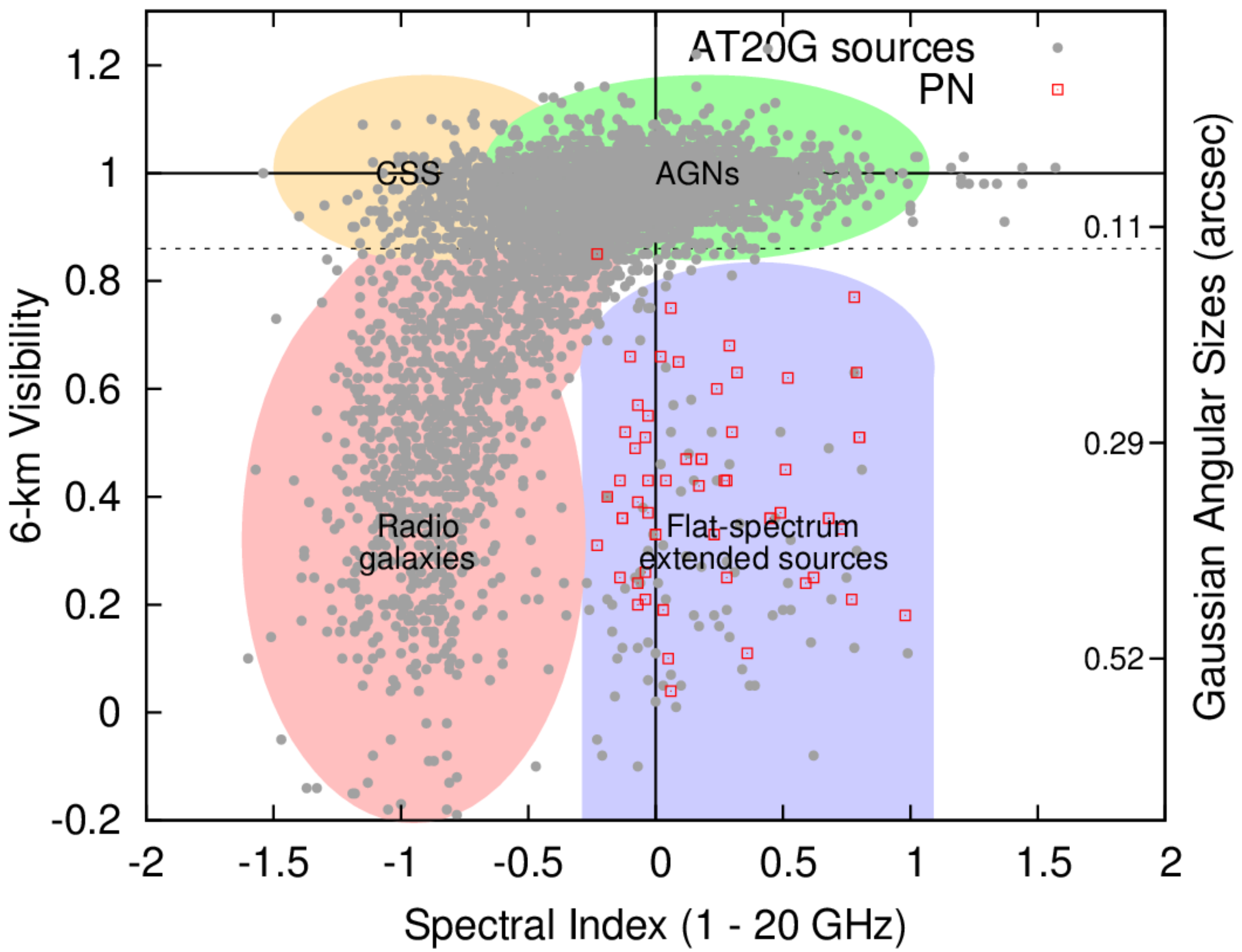
$$S_\nu \propto \nu^\alpha$$

The High Frequency (Extragalactic) Radio Sky



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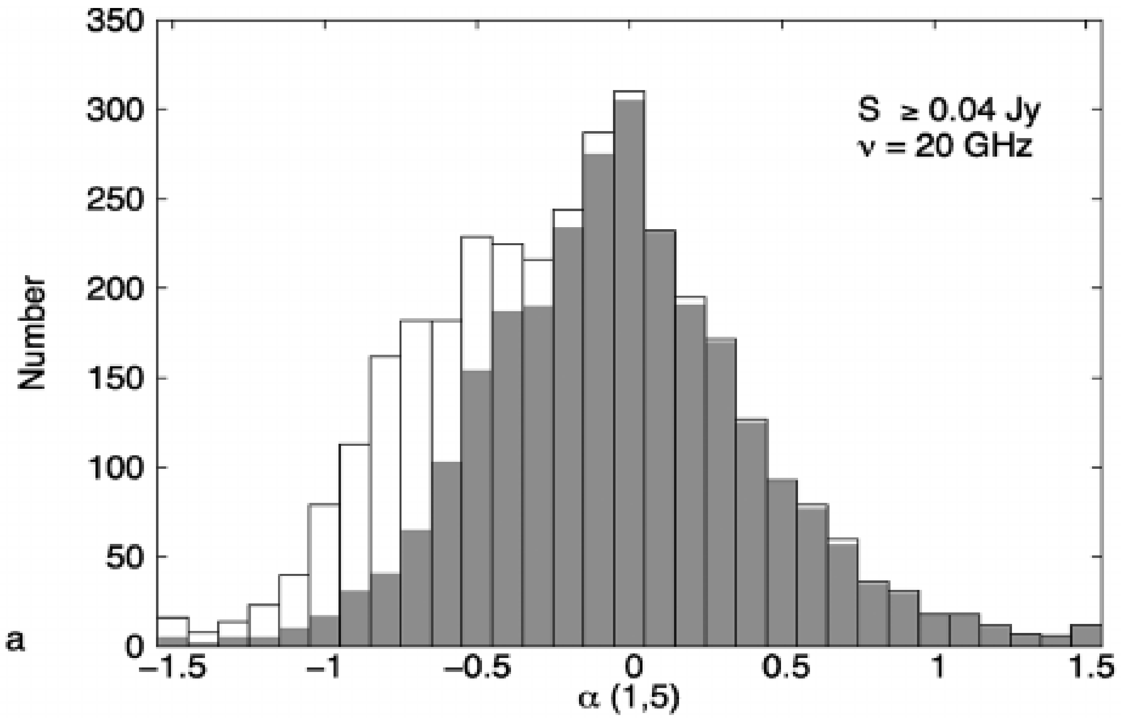
Change in Extragalactic Source Population with Frequency



Credit: Chhetri+2013

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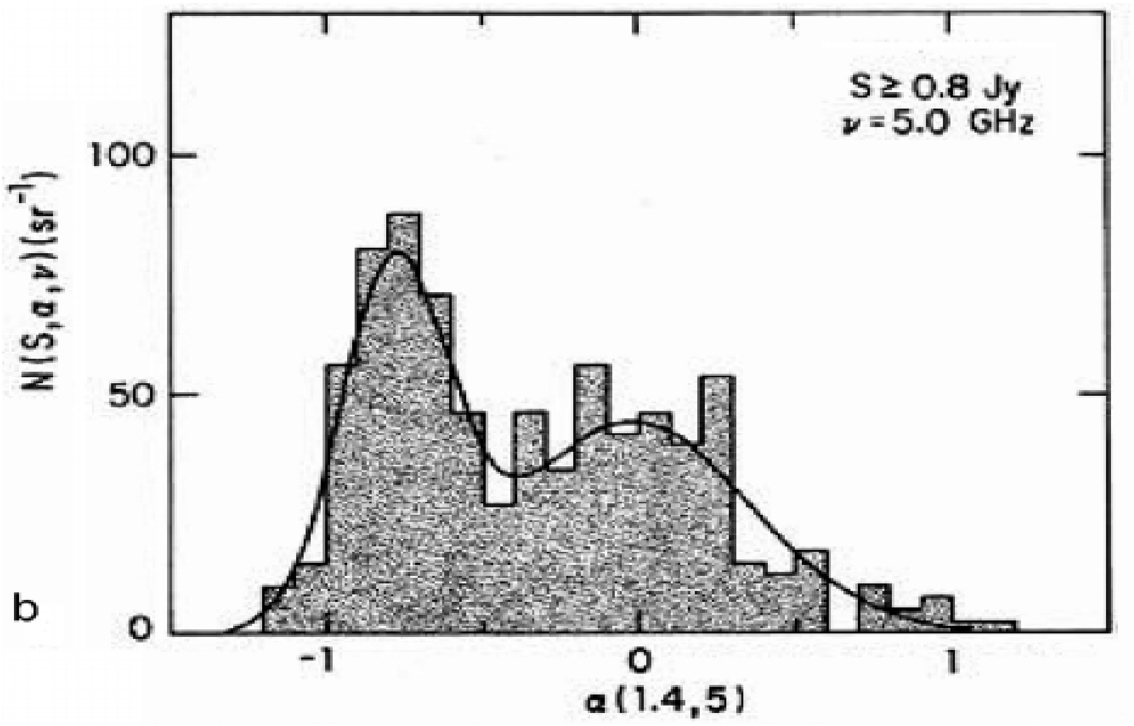

Credit: Verschuur & Kellermann 1988, Chhetri+2013

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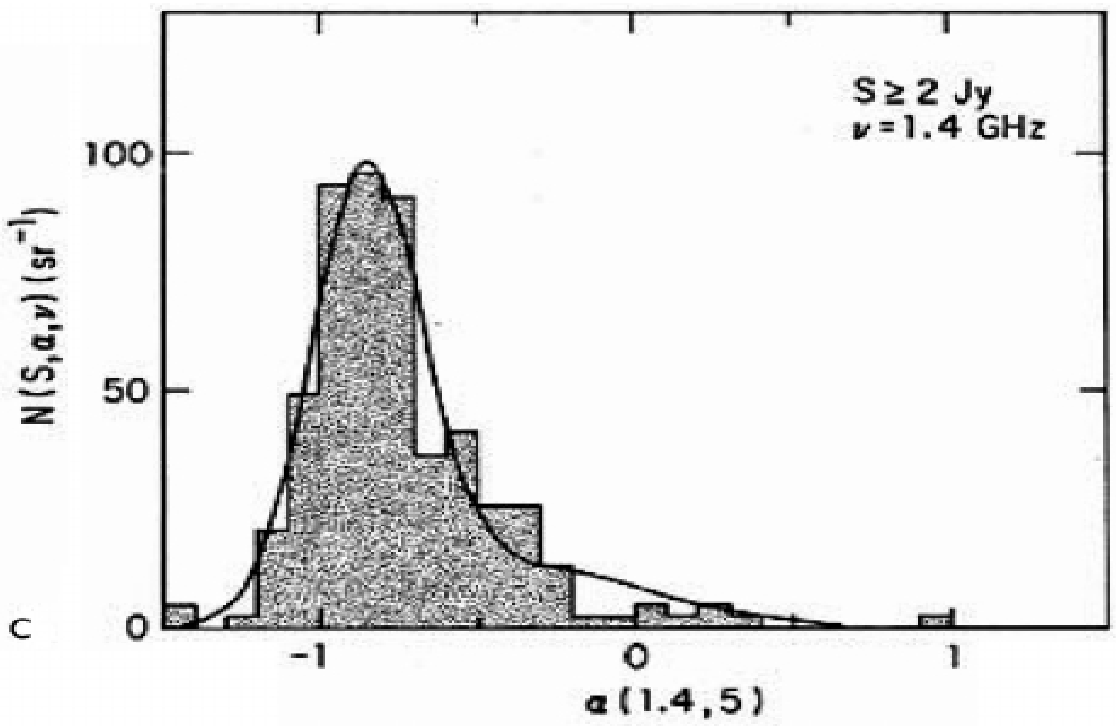

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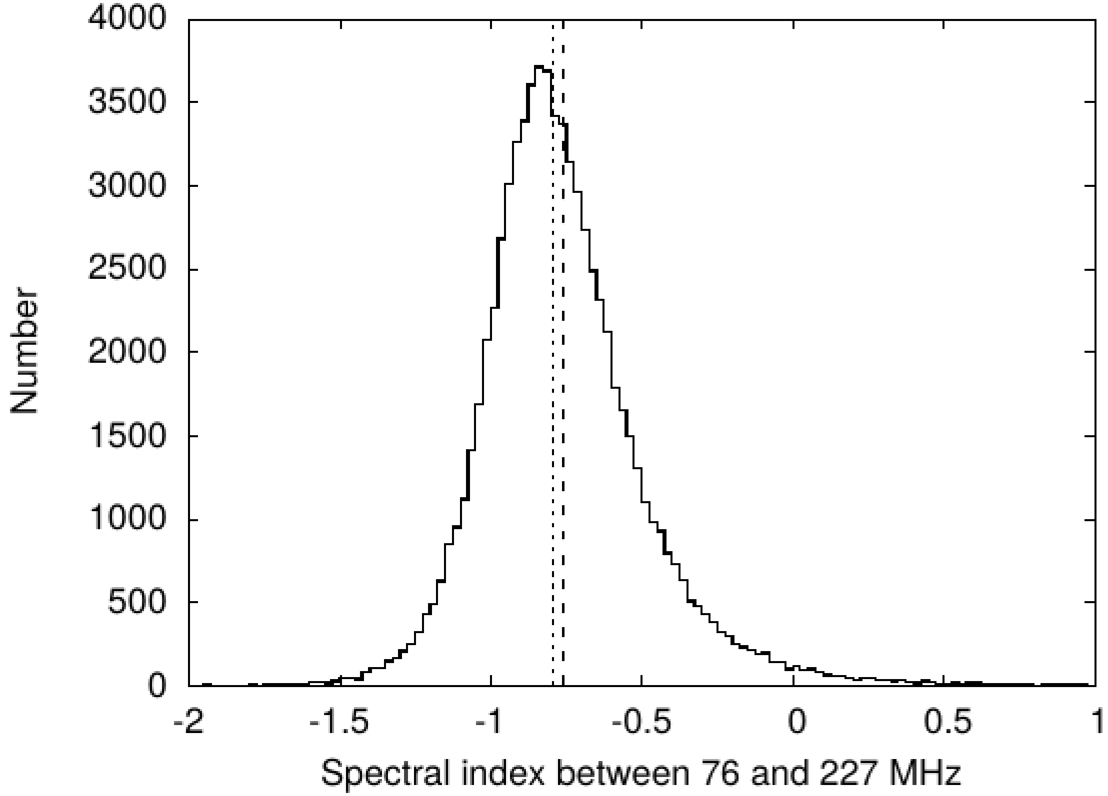
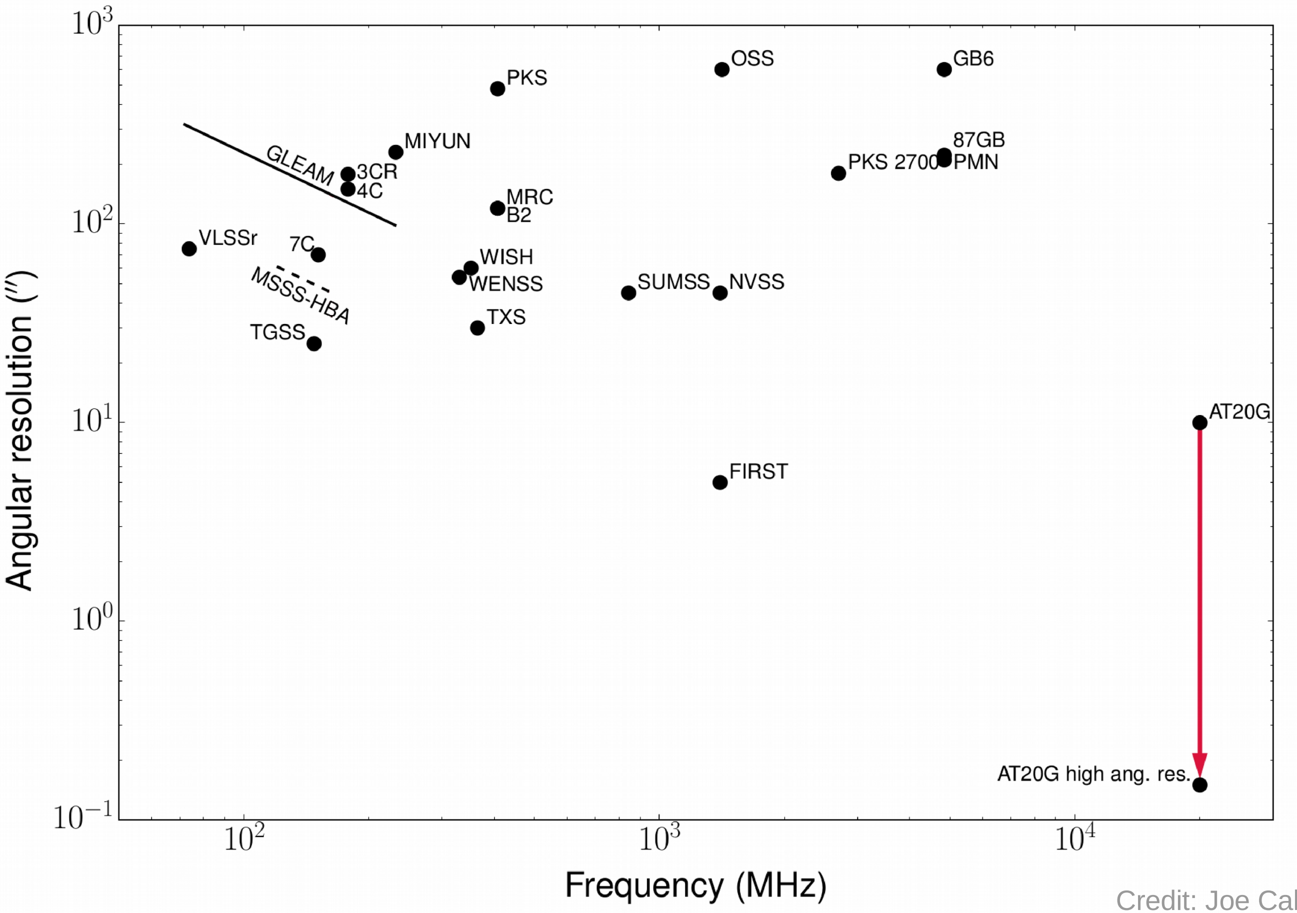
Change in Extragalactic Source Population with Frequency

GLEAM Survey



Credit: Franzen+2018

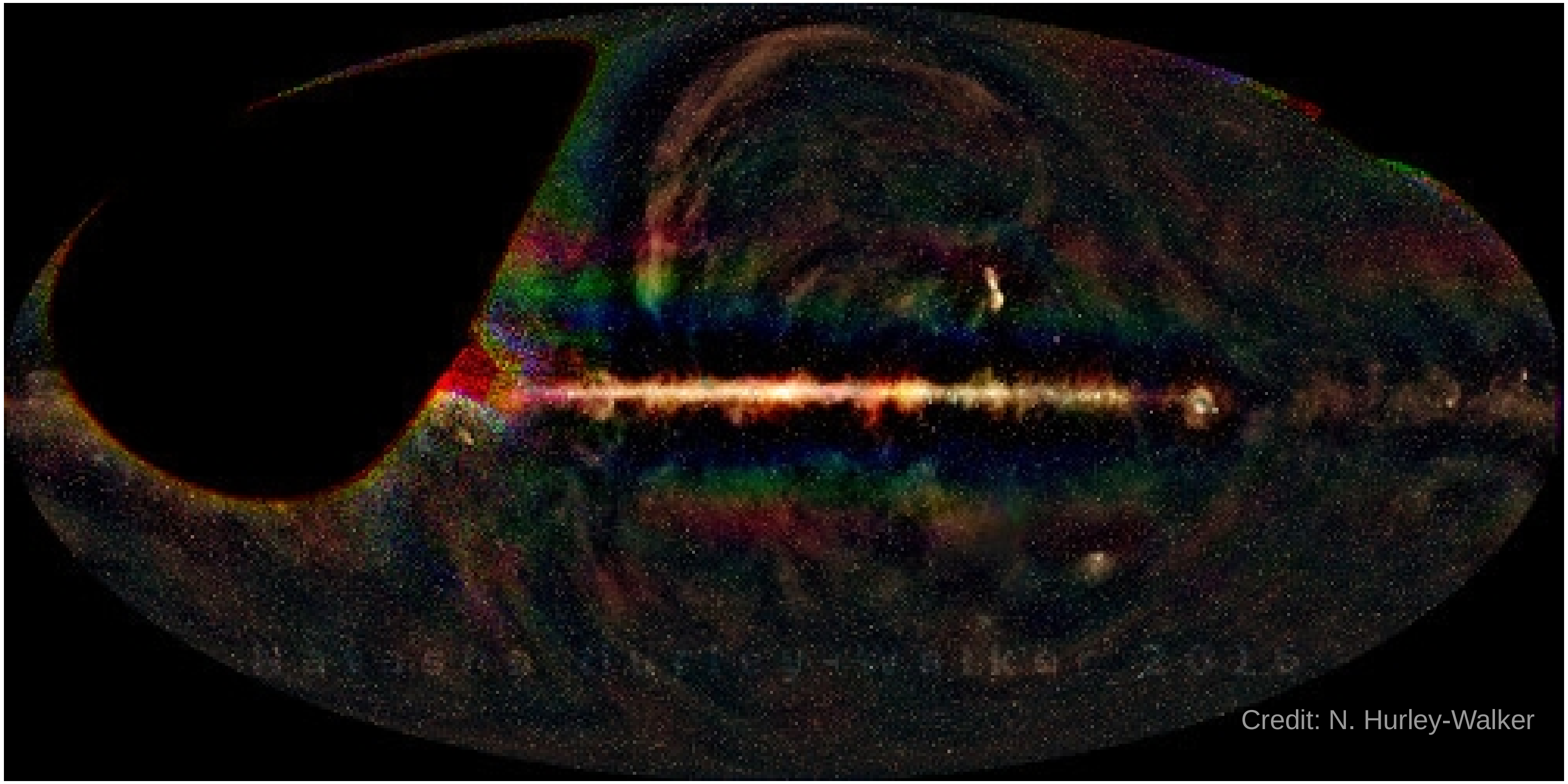
Large Area Radio Surveys and their Angular Resolutions



Credit: Joe Callingham

Example: The GLEAM Survey

> 300 000 sources in the field
~ 50 mJy flux density limit



The instrument

The **Murchison Widefield Array** (MWA) in Western Australia
128 tiles with 2 x 16 dipoles each
Operating frequencies: 80 – 300 MHz
Bandwidth: 30.72 MHz
Angular resolution (3-km array) at 150 MHz > 2 arcmin!

Credit: N. Hurley-Walker

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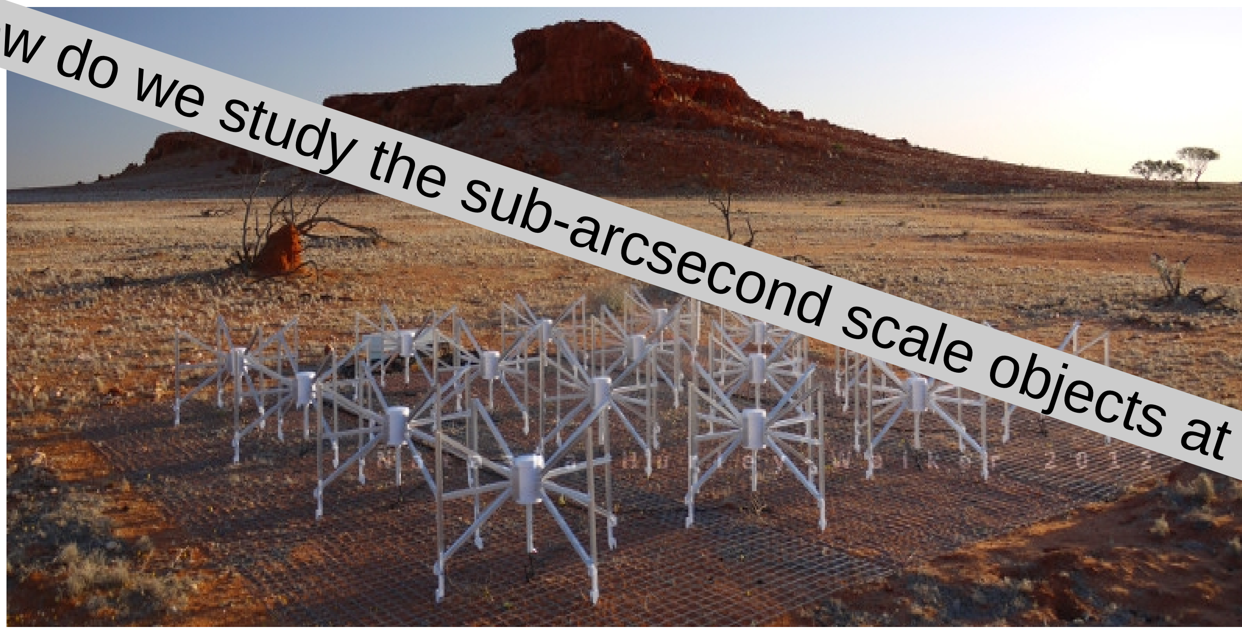
How do we study the sub-arcsecond scale objects at low frequencies?



Credit: N. Hurley-Walker

Possibilities

Very Long Baseline Interferometry (VLBI)

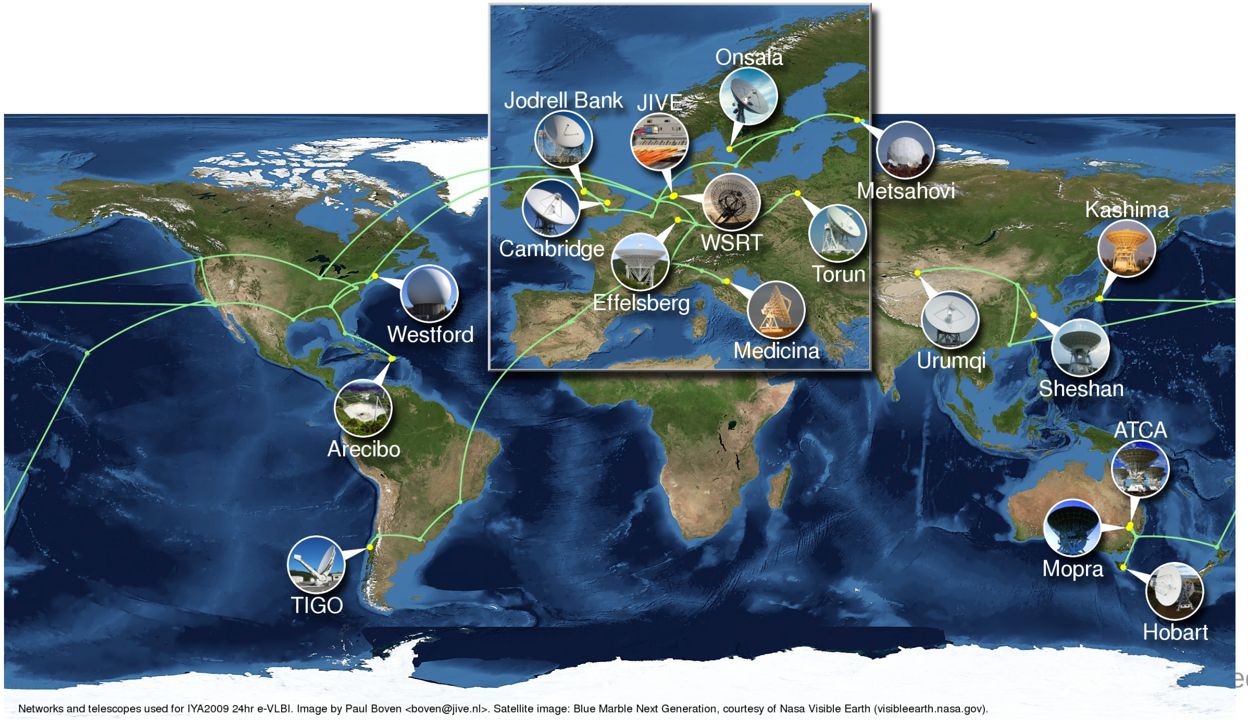
Networks and telescopes used for IYA2009 24hr e-VLBI. Image by Paul Boven <boven@jive.nl>. Satellite image: Blue Marble Next Generation, courtesy of Nasa Visible Earth (visibleearth.nasa.gov).

edit: EXPRes

Possibilities

Very Long Baseline Interferometry (VLBI)

Time/source x Very large number of sources = Challenging



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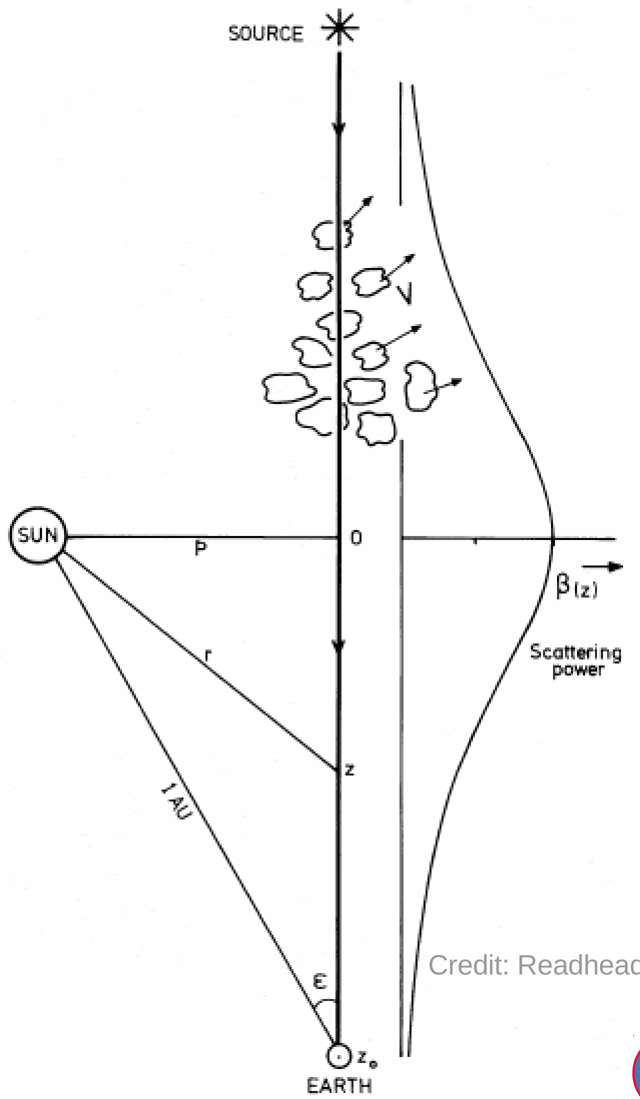
Possibilities

Interplanetary Scintillation (IPS)

Compact radio sources (< 1 arcsec)
+
Turbulence in interplanetary plasma

=

Scintillation effects
(random fluctuations in flux density)



Credit: Readhead+1978

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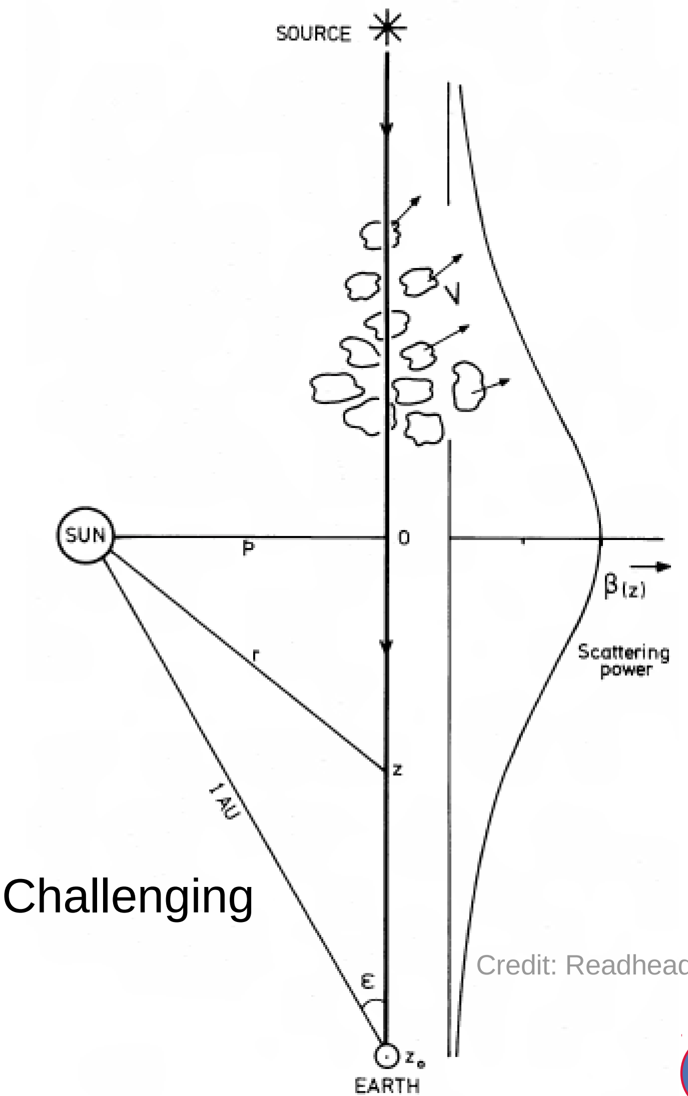

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Bandwidth: 30.72 MHz
~~Angular resolution (3-km array) at 150 MHz > 2 arcmin!~~

Field of View: 15 – 50 degrees (200 – 2500 sq degrees)
Temporal resolution: 0.5 sec
Excellent instantaneous UV coverage

Credit: N. Hurley-Walker

The Opportunity

15 – 50 degrees (200 – 2500 sq degrees) Field of View

+

Interplanetary scintillation

=

Widefield IPS

History of IPS with the MWA

Kaplan et al. 2015 detected a night time IPS.

Pilot study on wide-field IPS by J. Morgan, Curtin University

Regular daytime observations (late December 2015 – July 2016)

Observations at two bands 80 MHz & 162 MHz

Over 4000 observations made of different parts of sky

Overview

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II. **How** do we measure IPS with the MWA?

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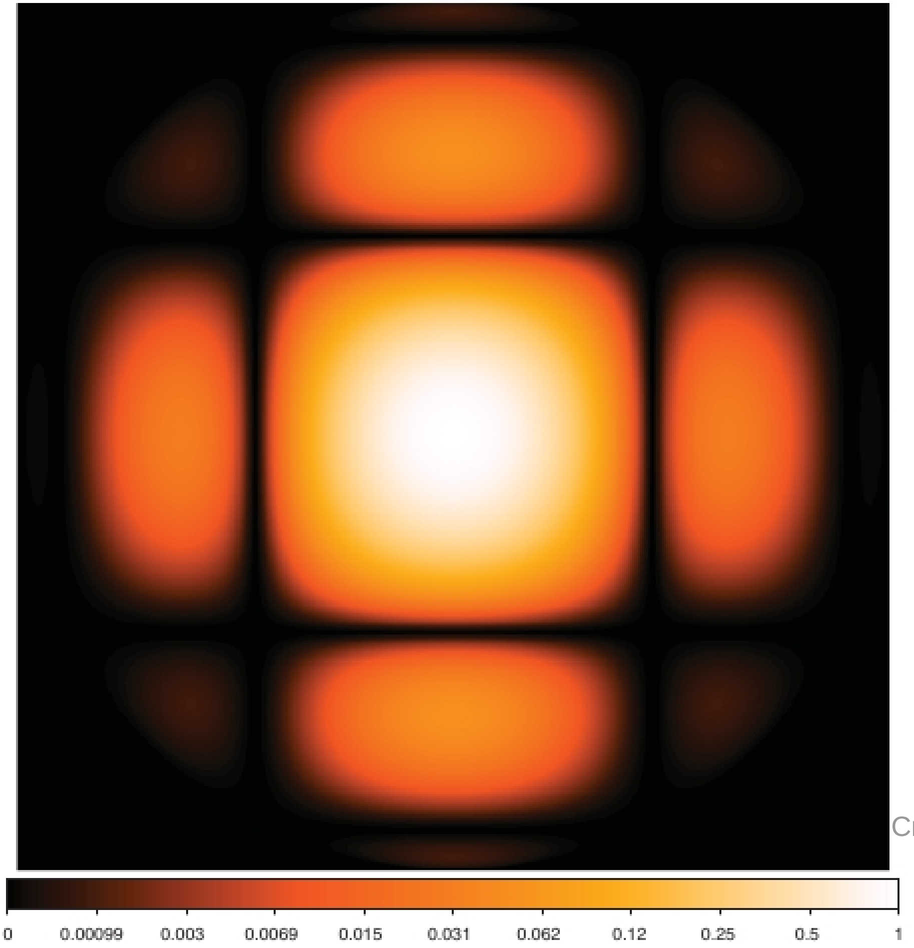
Important Properties of the MWA

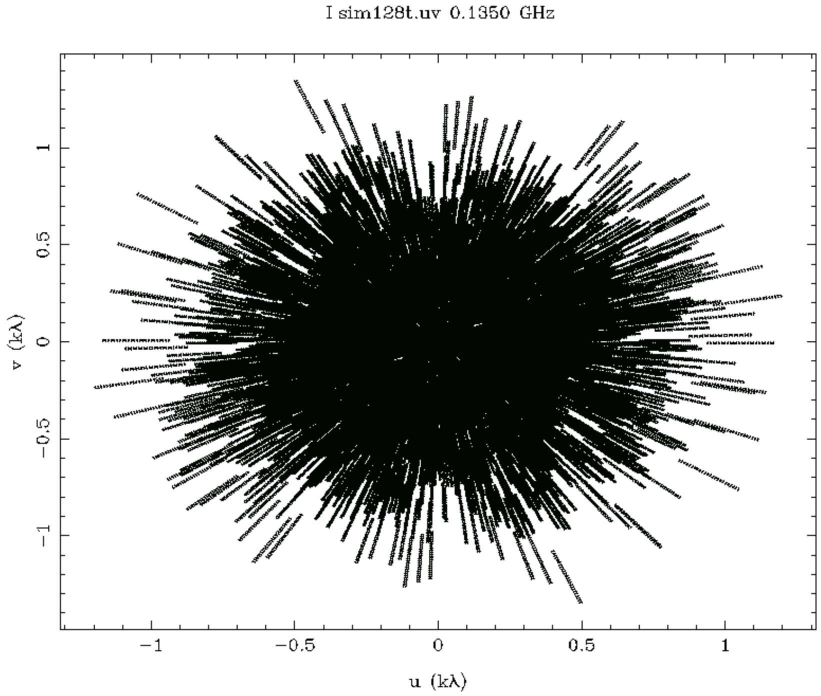
Large field-of-view
(~900 sq. deg at 162 MHz)



Credit: Tingay+ 2012

Important Properties of the MWA

Excellent instantaneous UV coverage

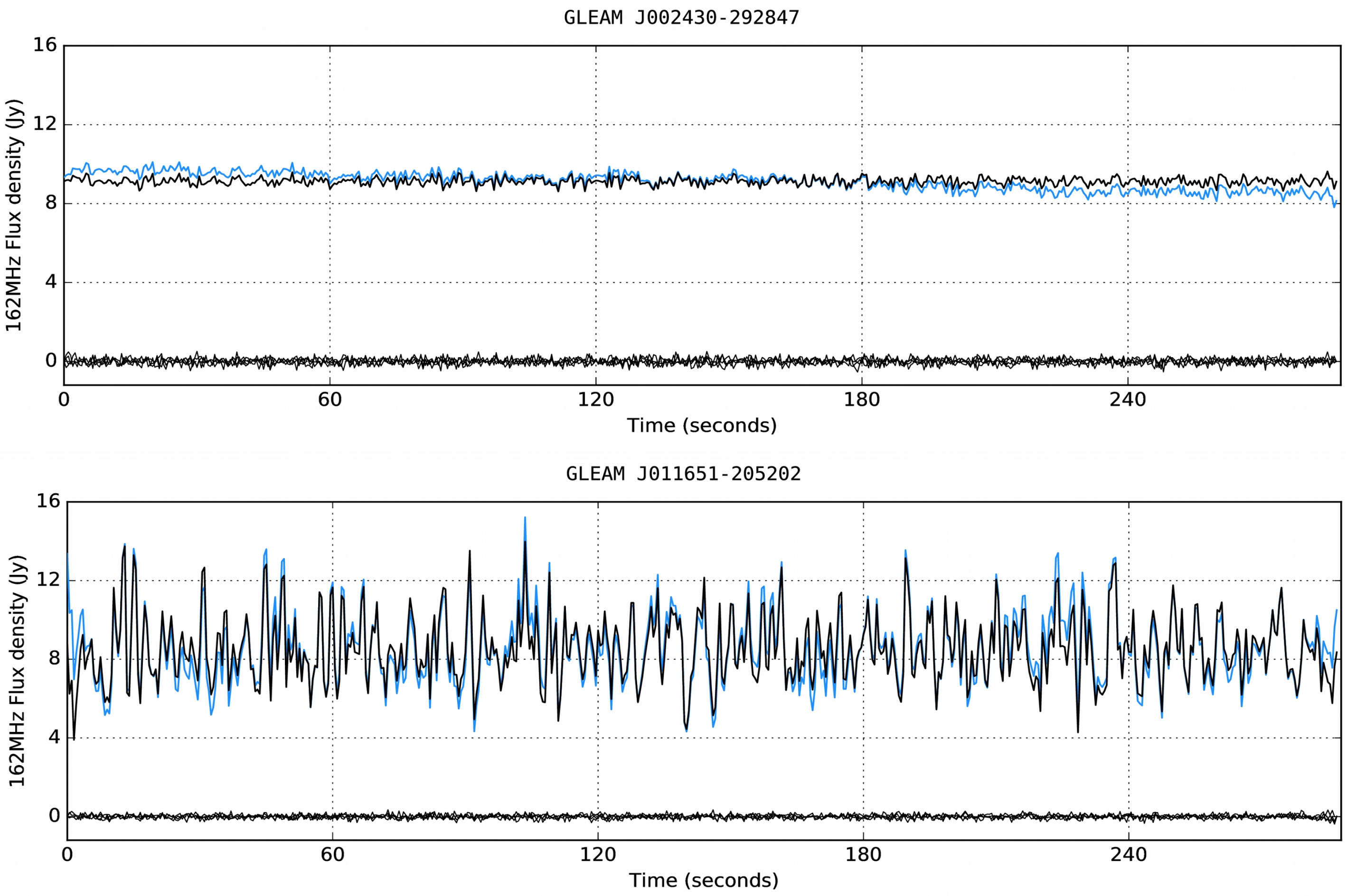


Credit: J. Morgan

IPS with the MWA

- ~5 minutes of observations with 0.5 second integration time
    - 80 and 162 MHz
- Make a continuum image from the total observation.
- Make separate images at 0.5 second intervals.
    - Measure intensity fluctuation at each pixel of the images along time axis

Time series


GLEAM J002430-292847
162MHz Flux density (Jy)
16
12
8
4
0
0
60
120
180
240
Time (seconds)
GLEAM J011651-205202
162MHz Flux density (Jy)
16
12
8
4
0
0
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240
Time (seconds)

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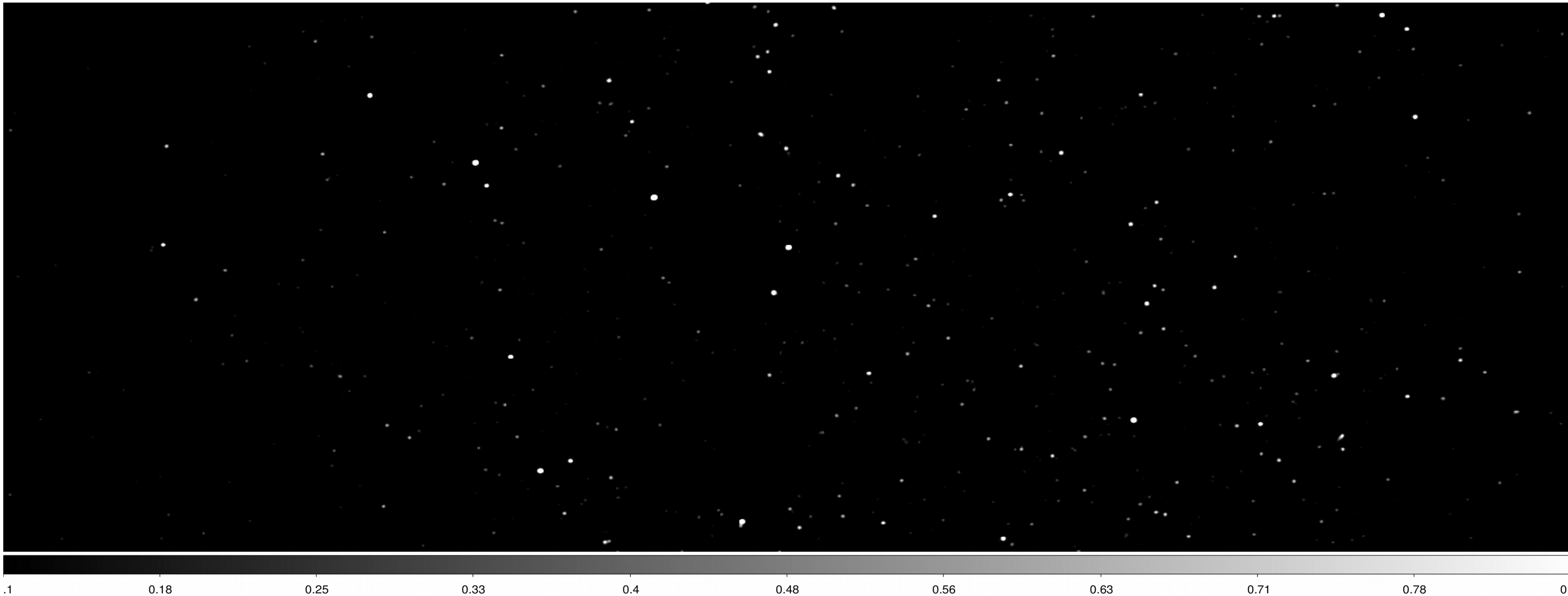
- Make a continuum image from the total observation.

- Make separate images at 0.5 second intervals.

    - Measure intensity fluctuation at each pixel of the images along time axis
    - Calculate standard deviation of each pixel using all (~600) time steps.
    - Produce a *variability image*.

A Typical MWA field

Continuum image
23 x 8 sq deg



A Typical MWA field

Variability image
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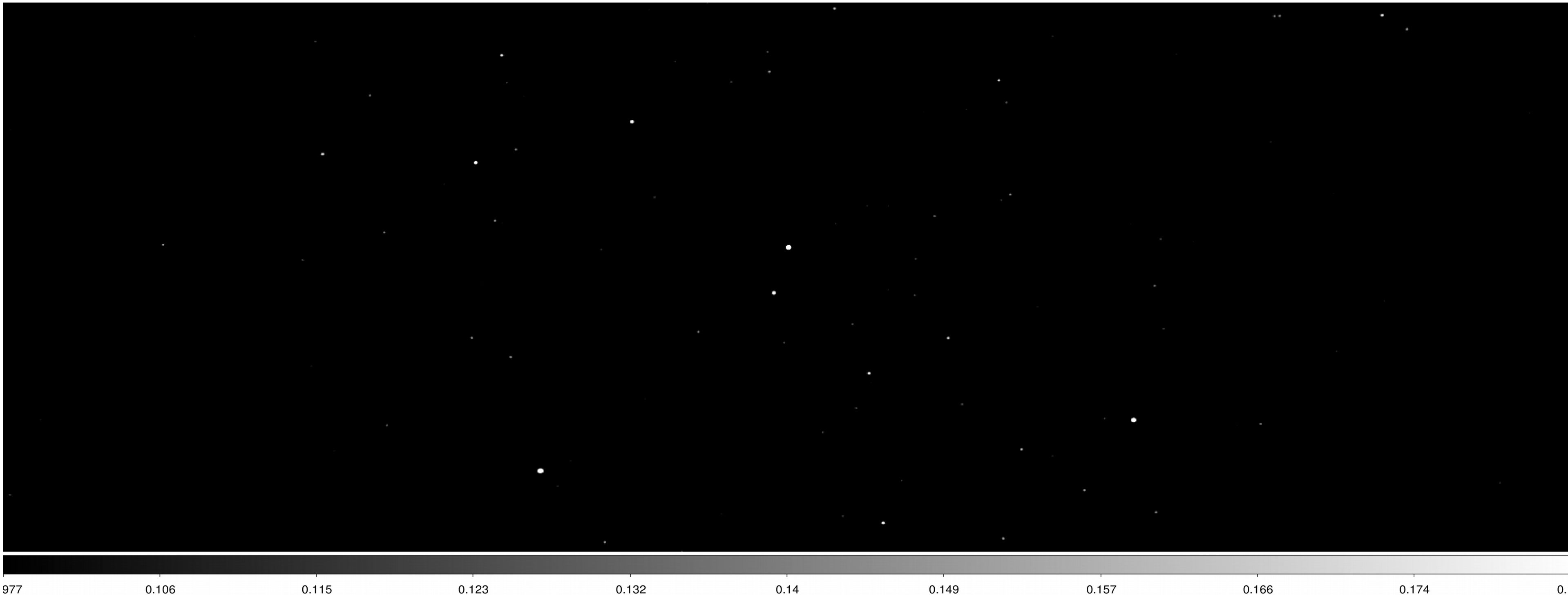

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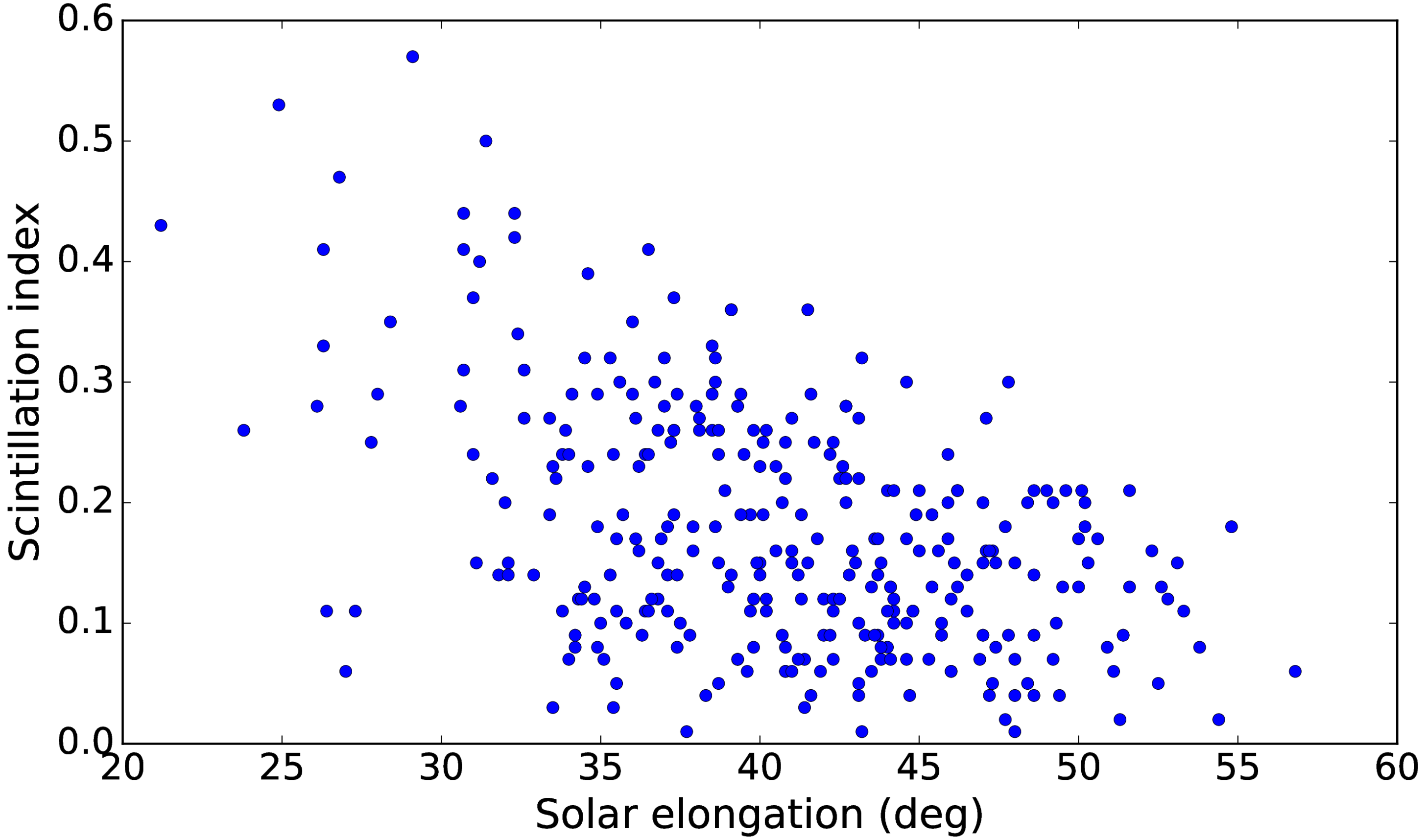
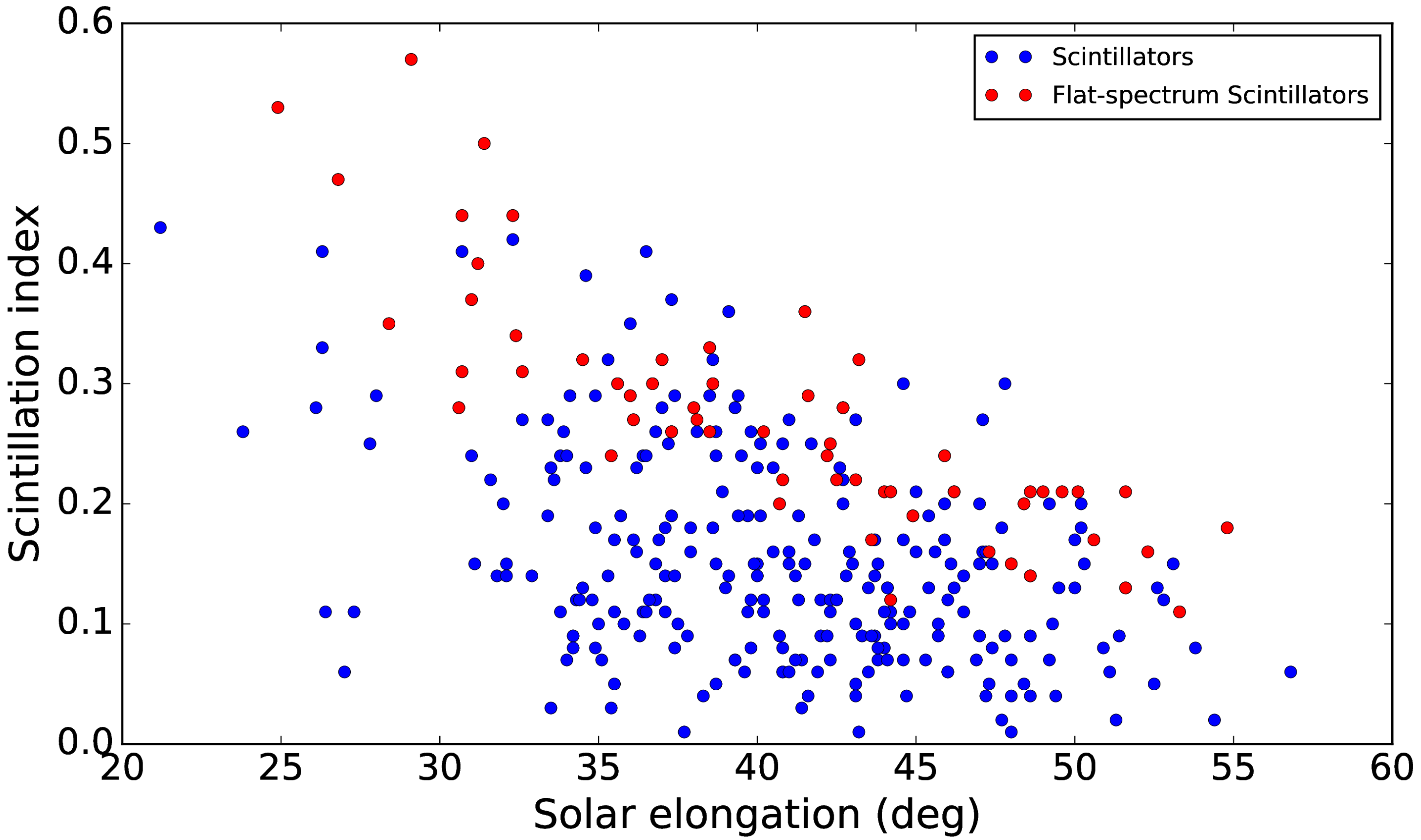
- Make separate images at 0.5 second intervals.
  - Measure intensity fluctuation at each pixel of the images along time axis
  - Calculate standard deviation of each pixel using all (~600) time steps.
  - Produce a *variability image*.
- Calculate scintillation index using values in variability image & continuum image for each source.

Observable



Detect scintillation on 302 out of 2550 objects (12%)

Observable



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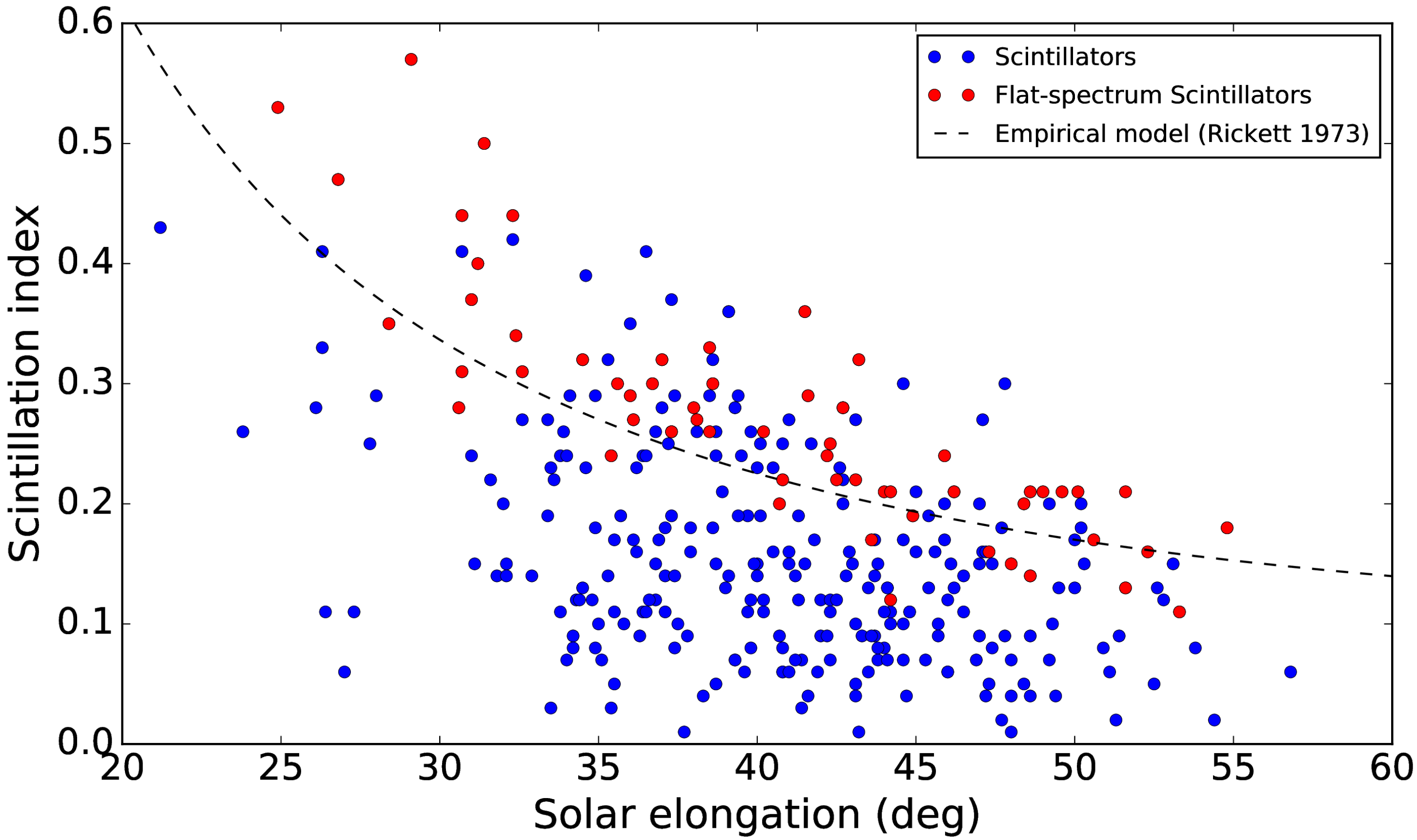

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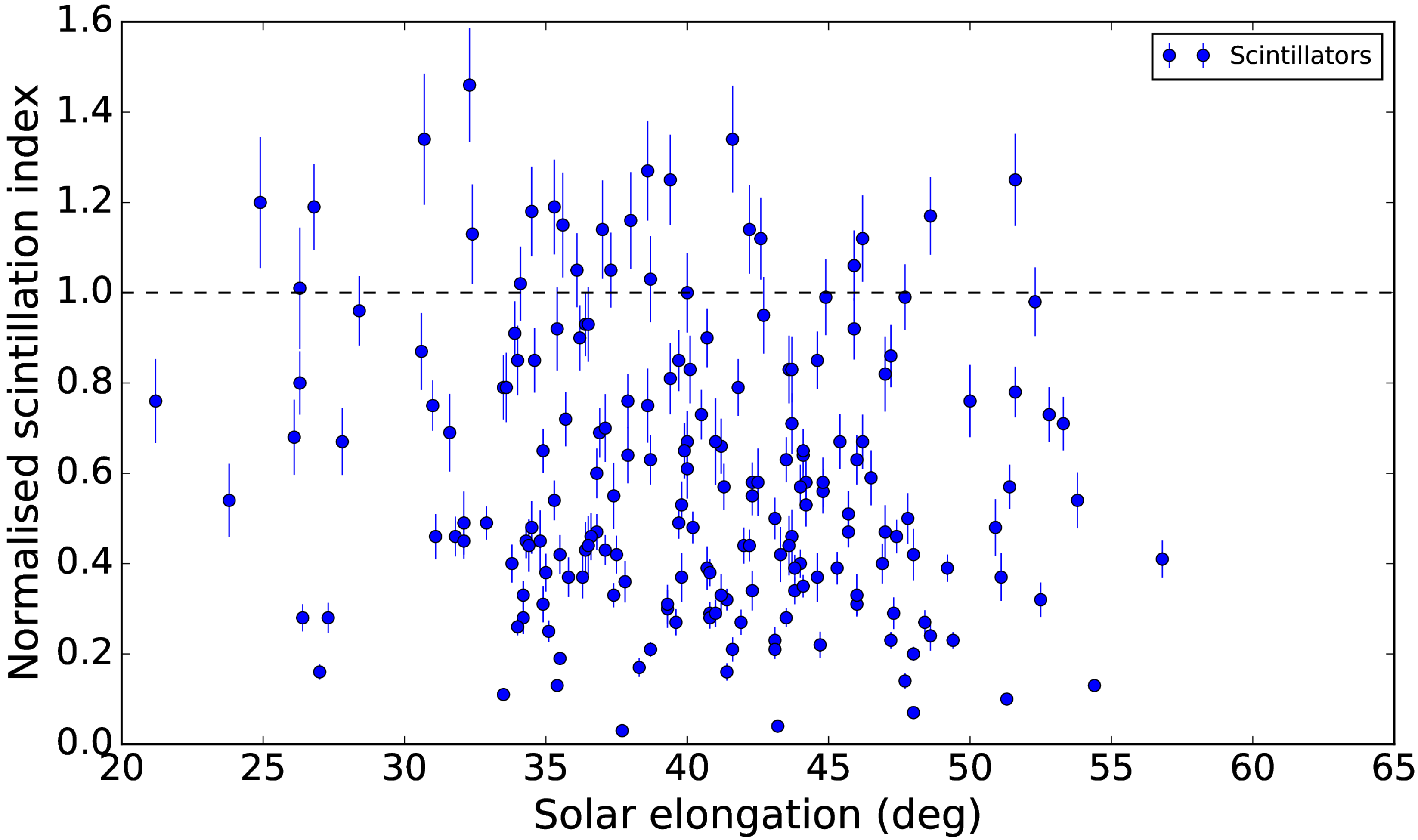

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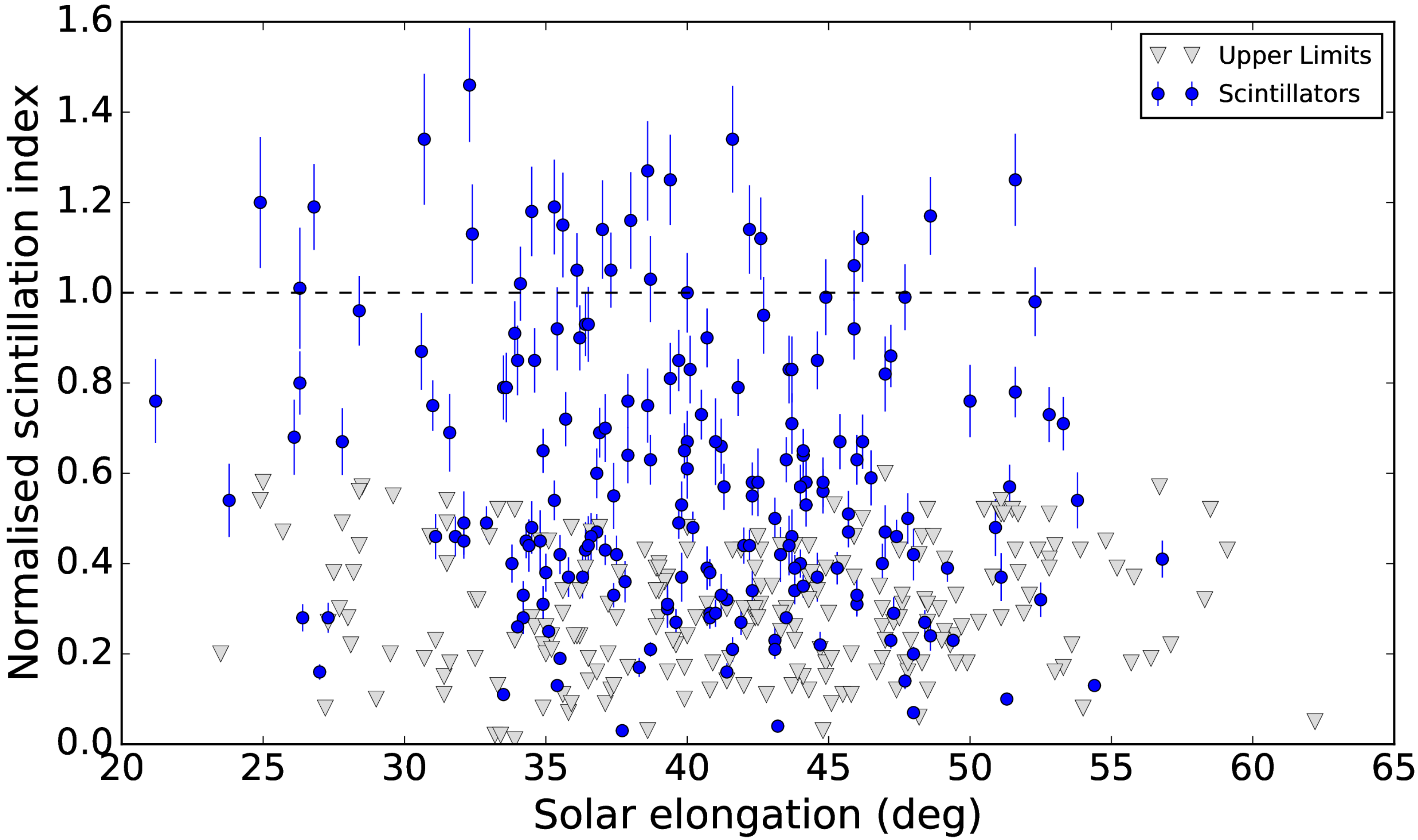

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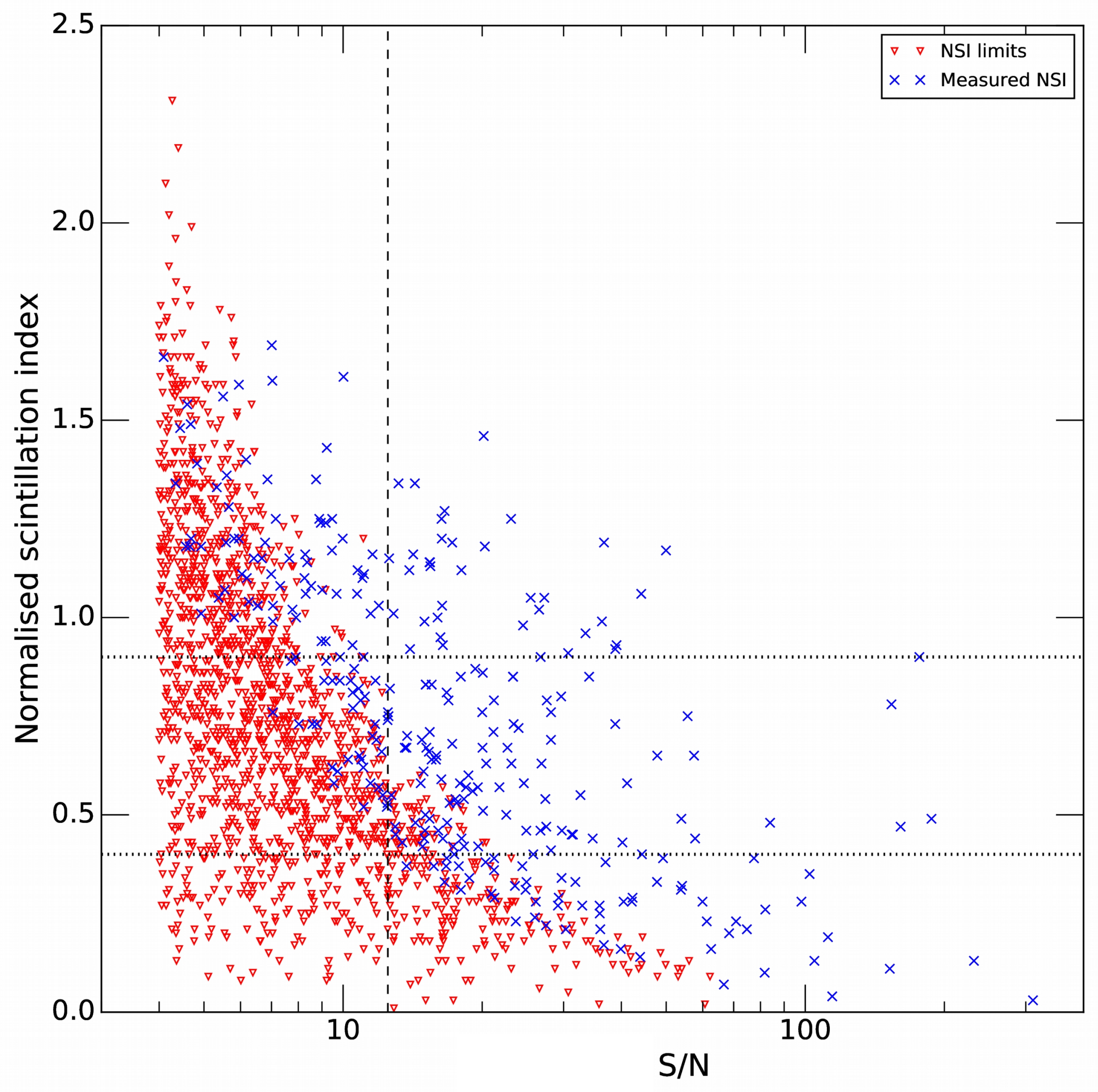
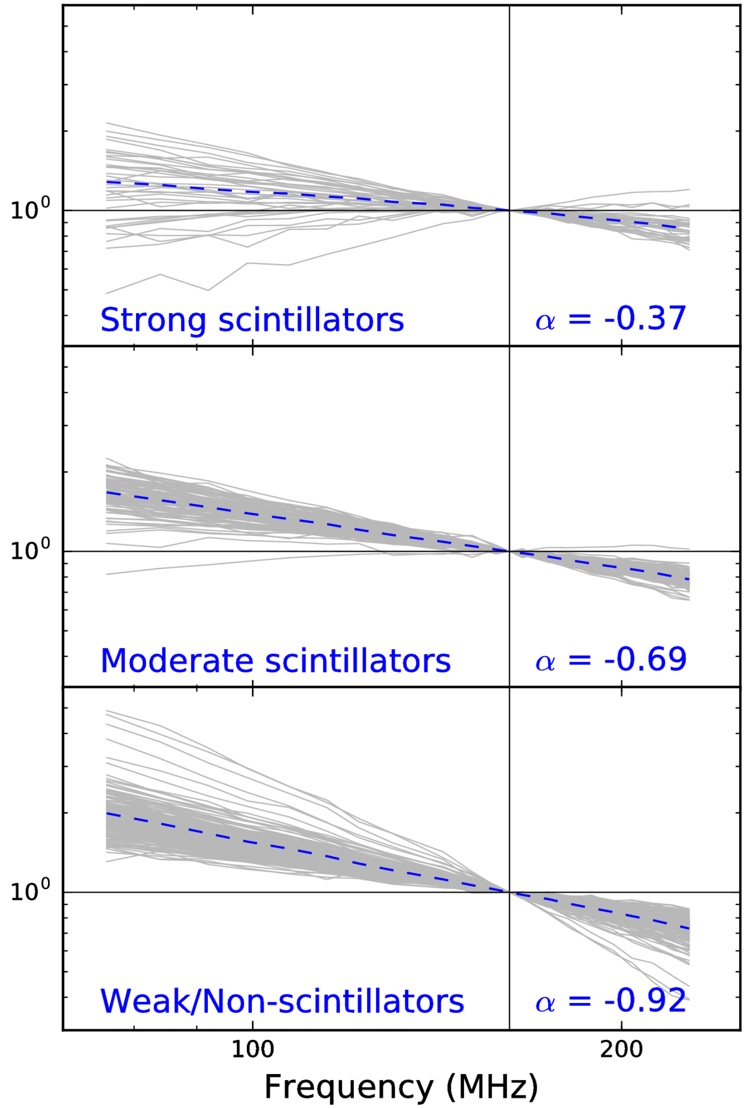
Detection Statistics



High S/N: 414 objects

- **Strong Scintillators**
  (NSI ≥ 0.9)
  9%
- **Moderate Scintillators**
  (0.4 ≤ NSI < 0.9)
  23%
- **Weak/non Scintillators**
  (NSI < 0.4)
  54%
- Unrestrictive NSI limits
  All have NSI < 0.6
  14%

Source properties



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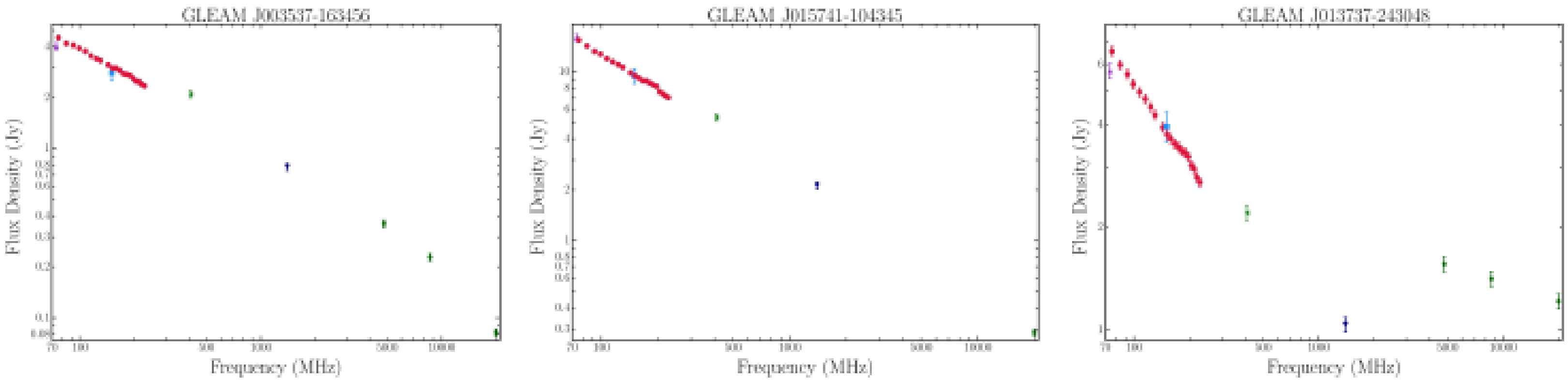
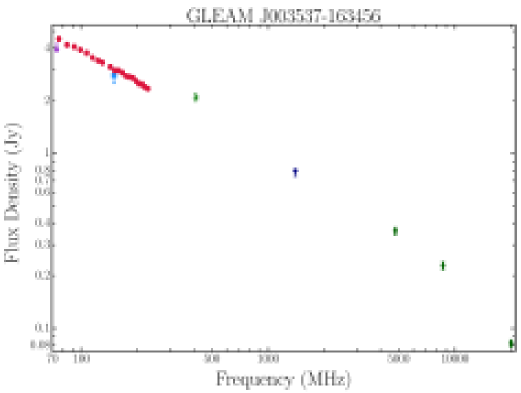
Source properties

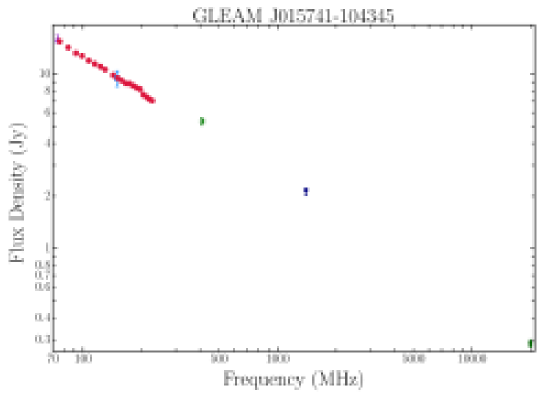
Weak Scintillators

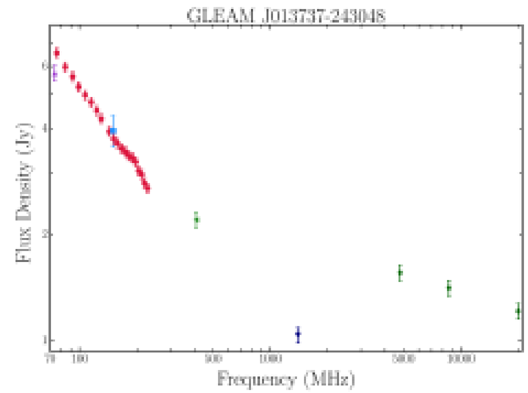


Source properties

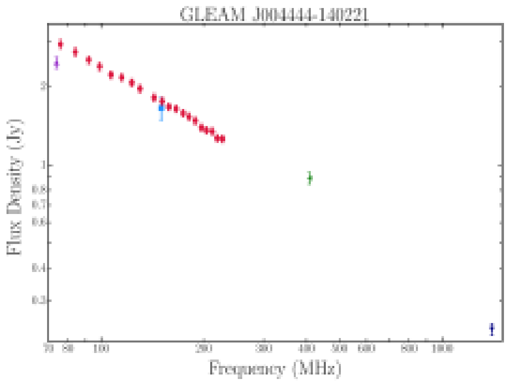
Weak Scintillators

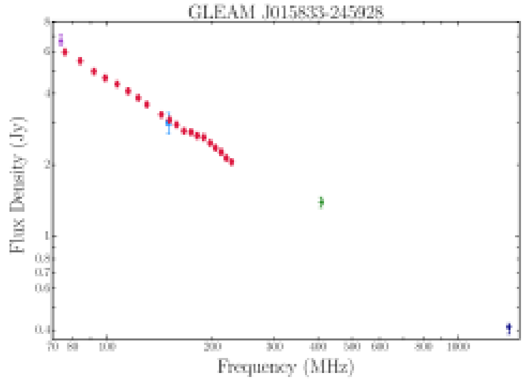


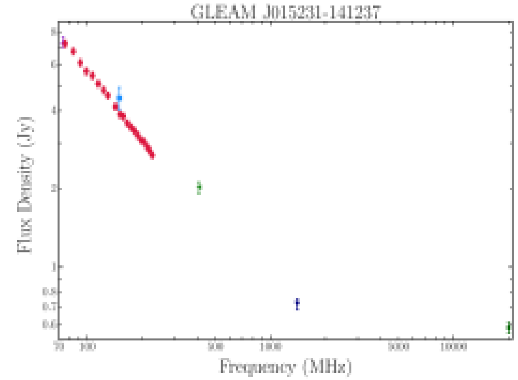




Moderate Scintillators



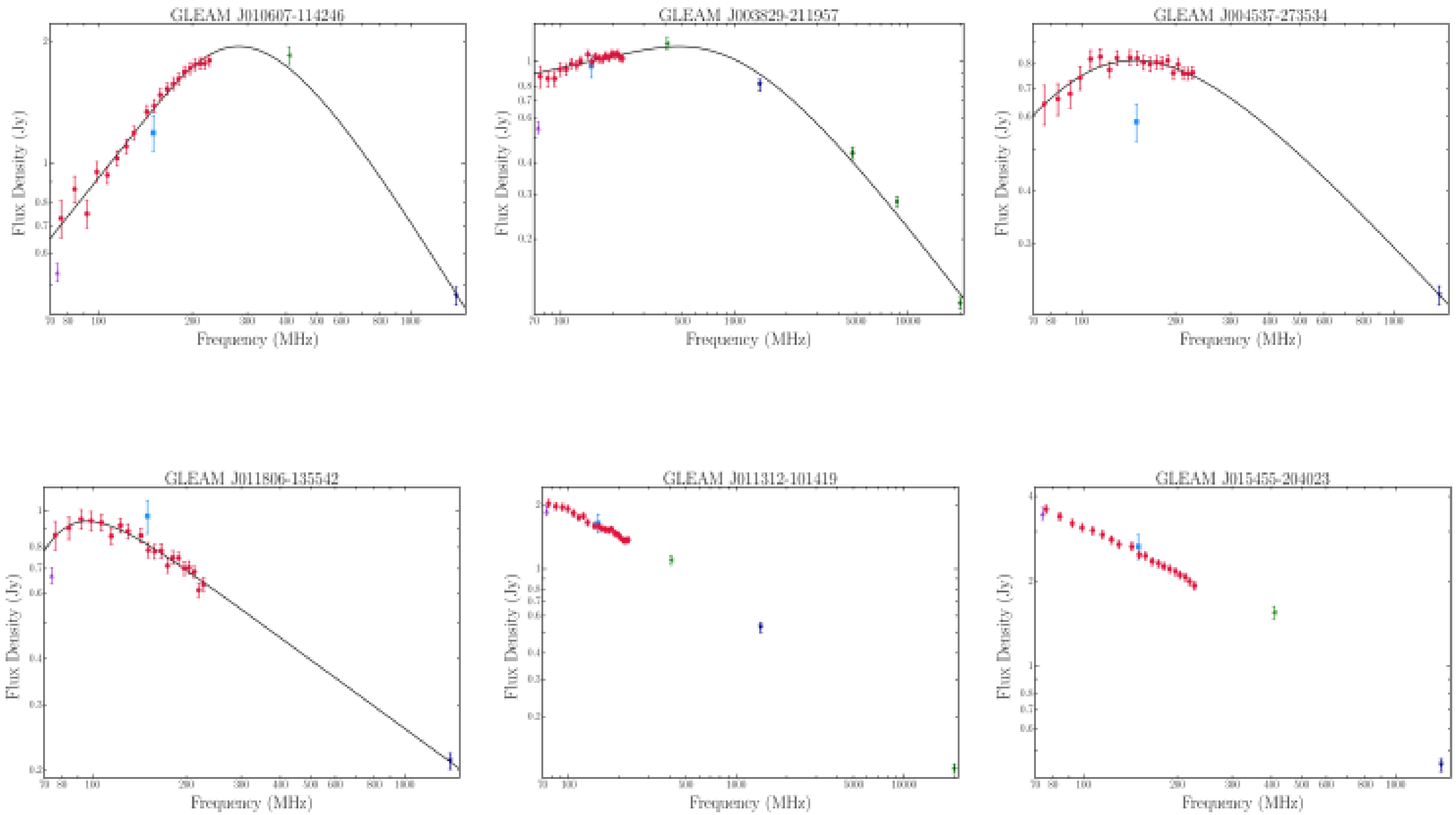




SEDs: Joe Callingham

Source properties

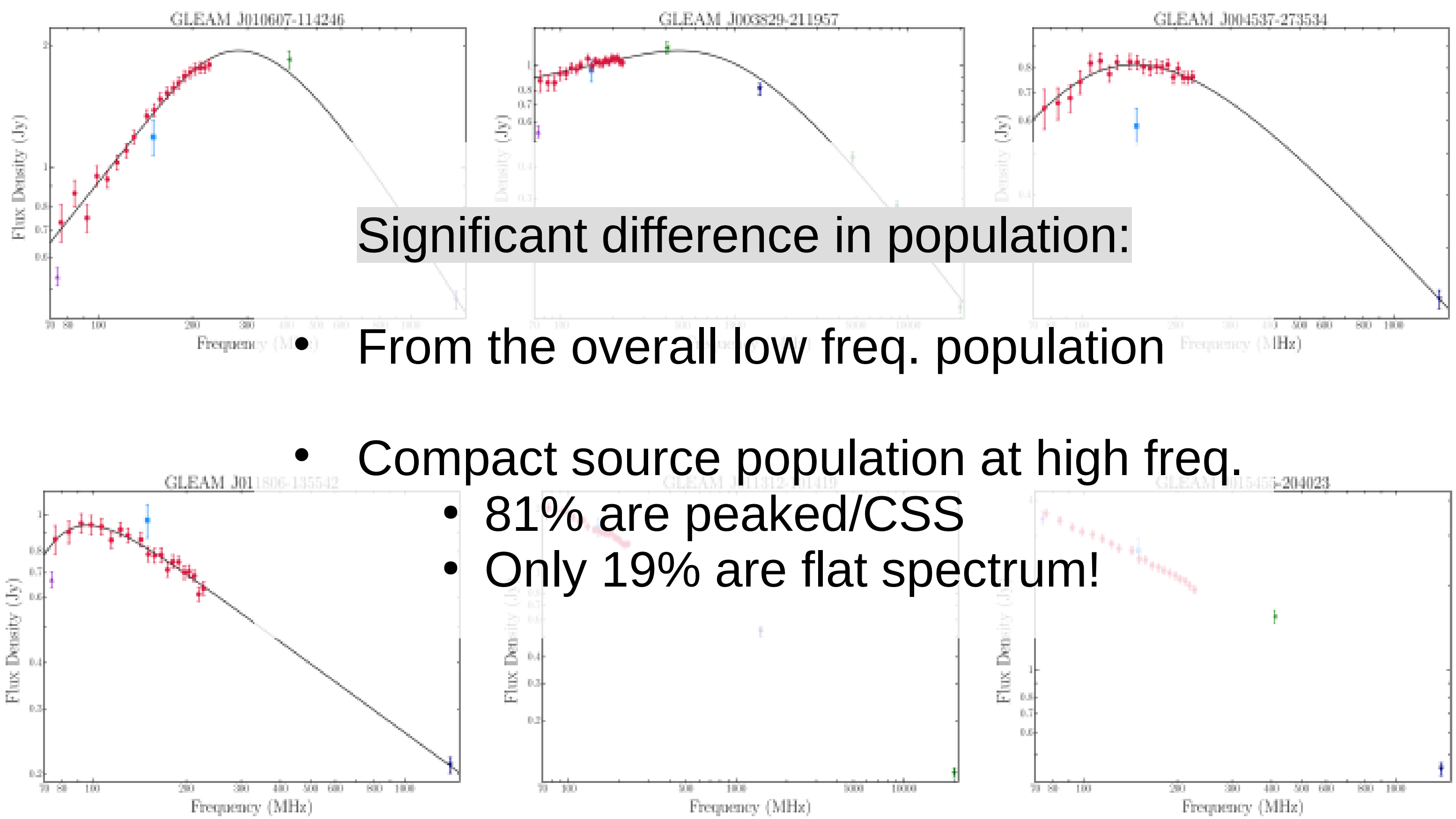
Strong Scintillators



SEDs: Joe Callingham

Result - population

Strong Scintillators

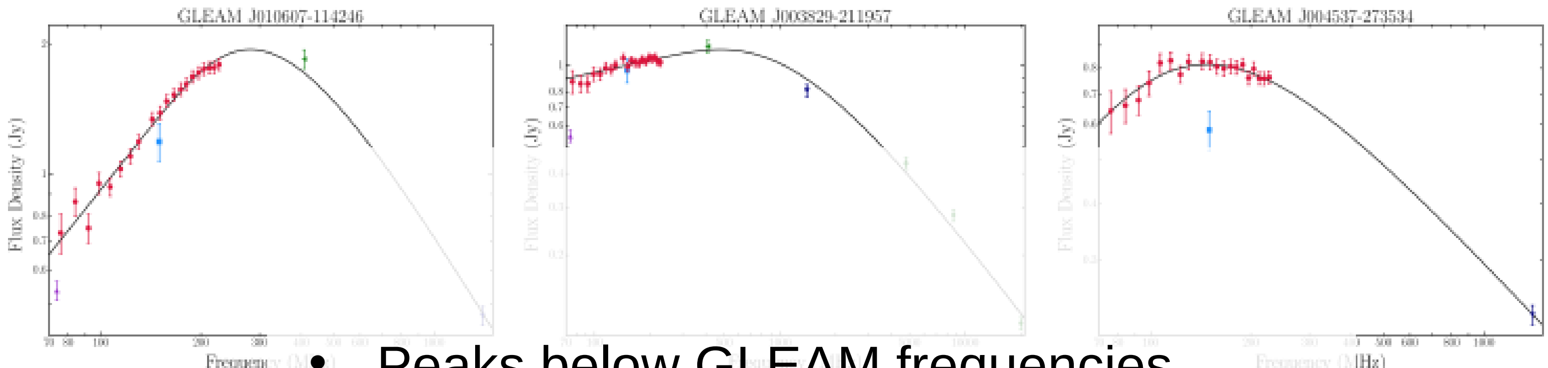


Significant difference in population:

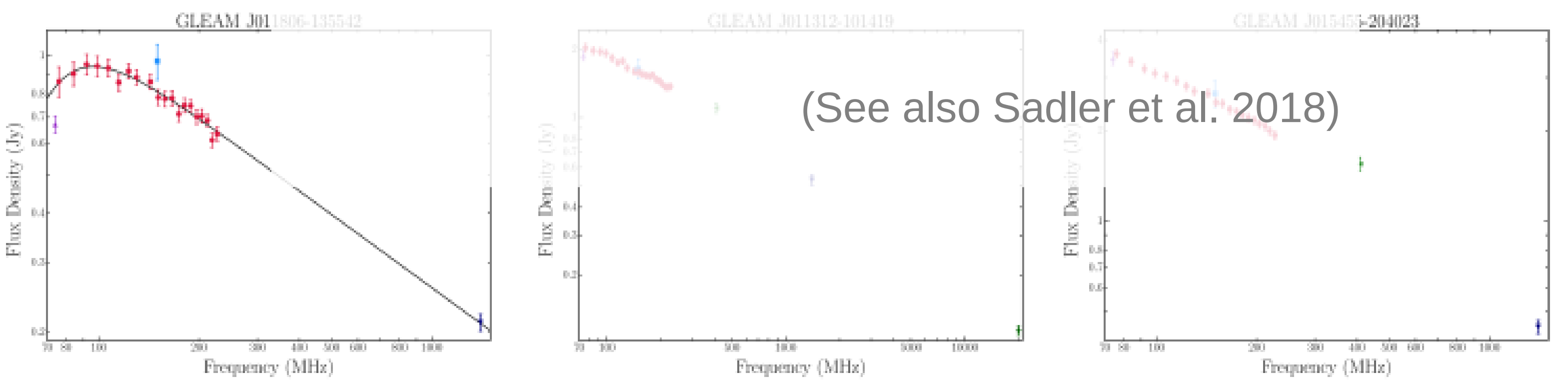
- From the overall low freq. population
- Compact source population at high freq.
  - 81% are peaked/CSS
  - Only 19% are flat spectrum!

Result – high redshift candidates

Strong Scintillators



- Peaks below GLEAM frequencies, possible high redshift objects (z>2).



(See also Sadler et al. 2018)

SEDs: Joe Callingham

Result – pulsars

PSR J0034-0721

Detected with S/N of 4.6 in I image
5.6 in variability image

Normalised scintillation index 1.92+/-0.49
(Highest in the field)

Result – pulsar candidates

PSR J0034-0721

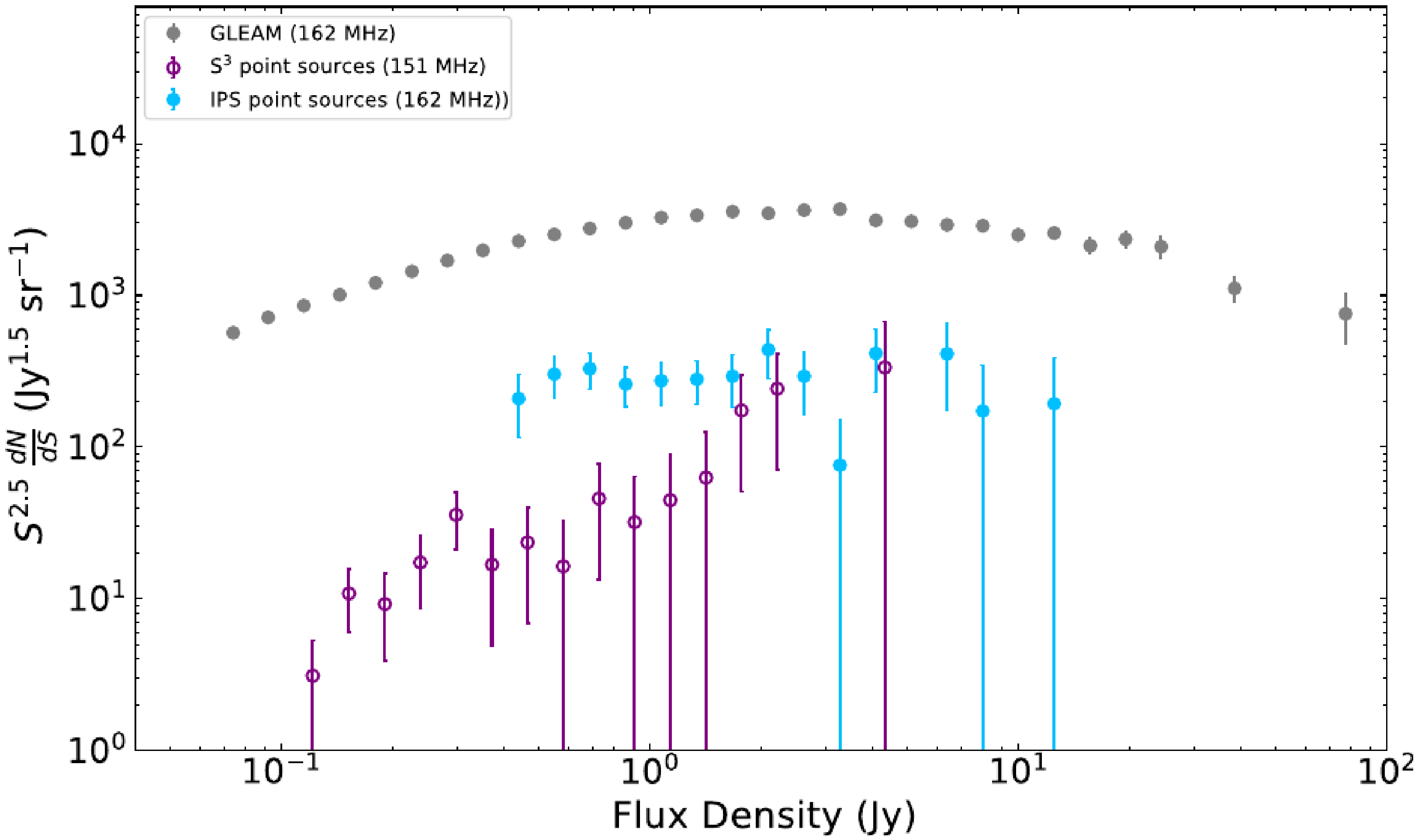
Detected with S/N of 4.6 in I image
5.6 in variability image

Normalised scintillation index 1.92+/-0.49
(Highest in the field)

Using IPS (NSI>0.9)
= candidate pulsars ~ 9%

+ spectra (< -0.7)
= Reduction in contamination by AGNs ~ 45 x

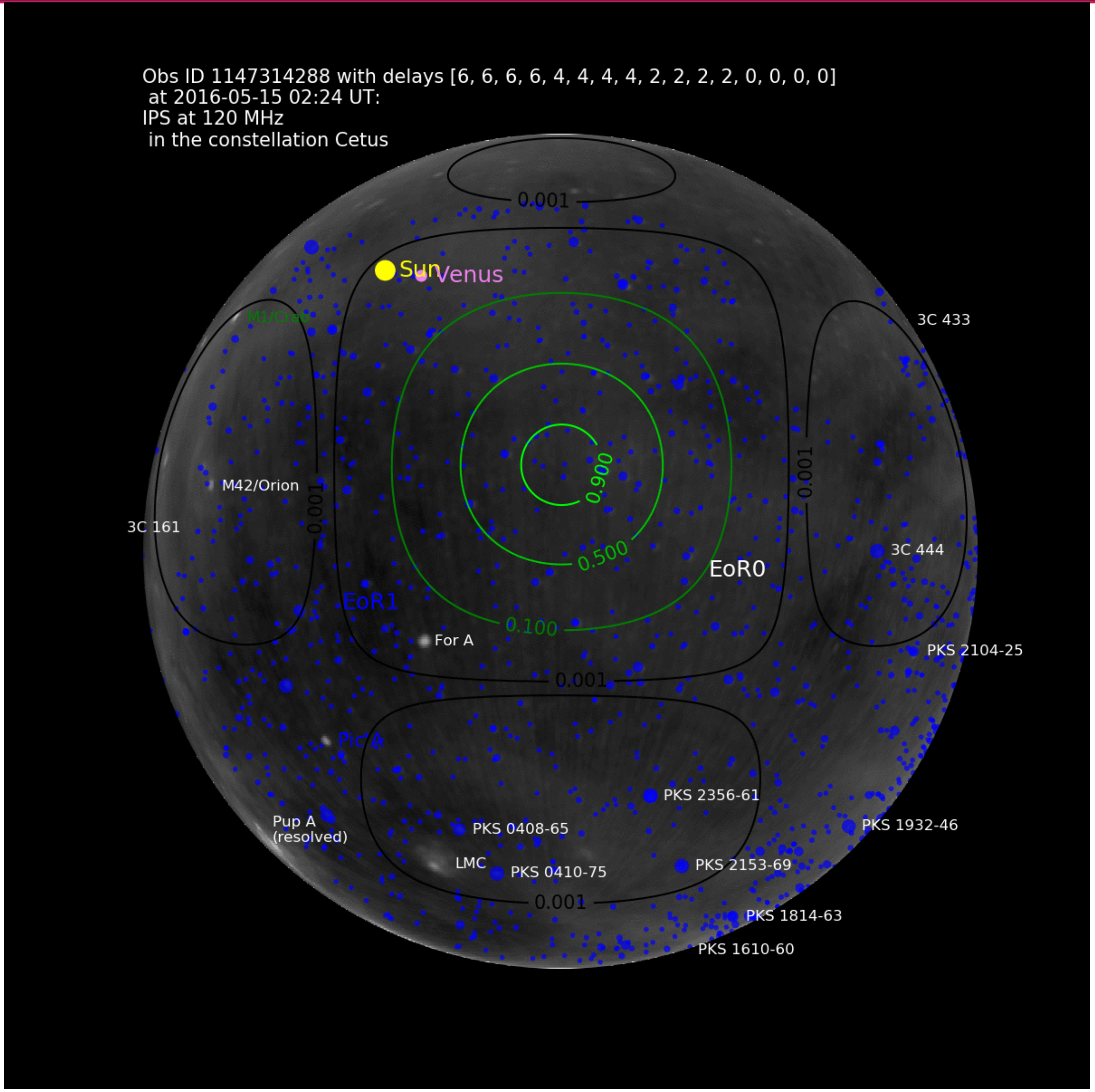
Result – source counts



Space weather

Unprecedented number of pierce points in FoV

Space weather



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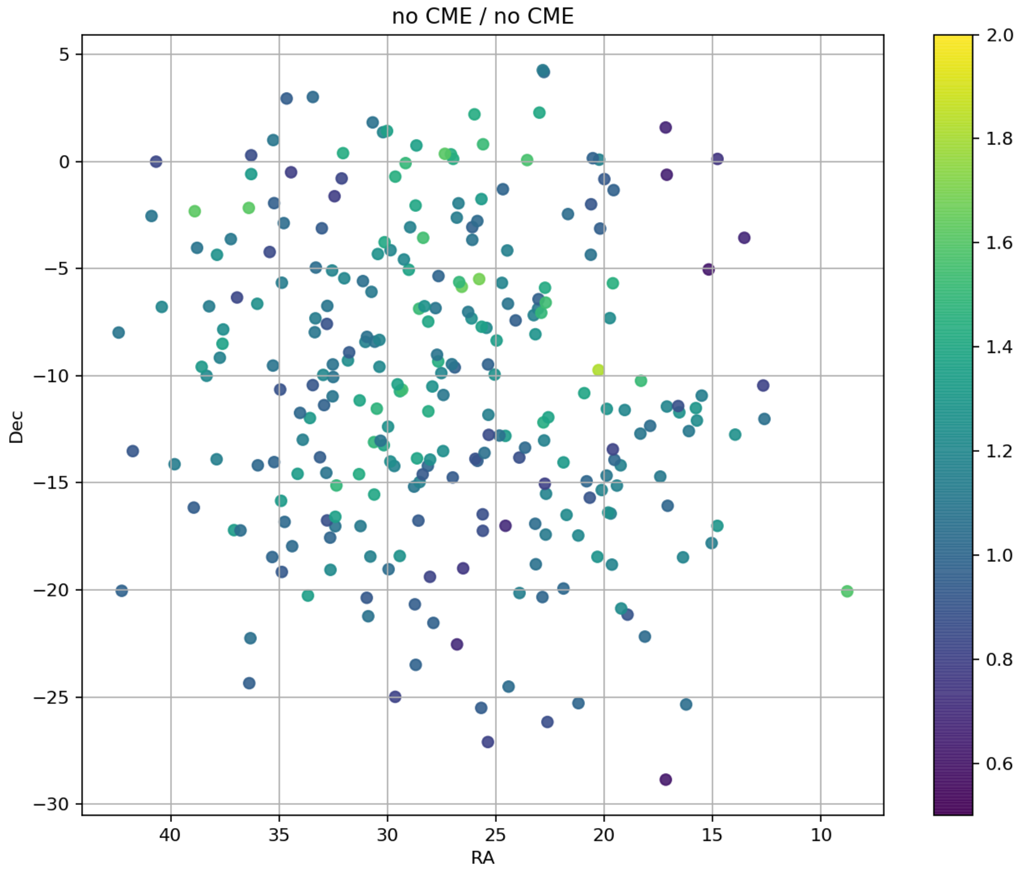
Space weather
Scintillation index ratio



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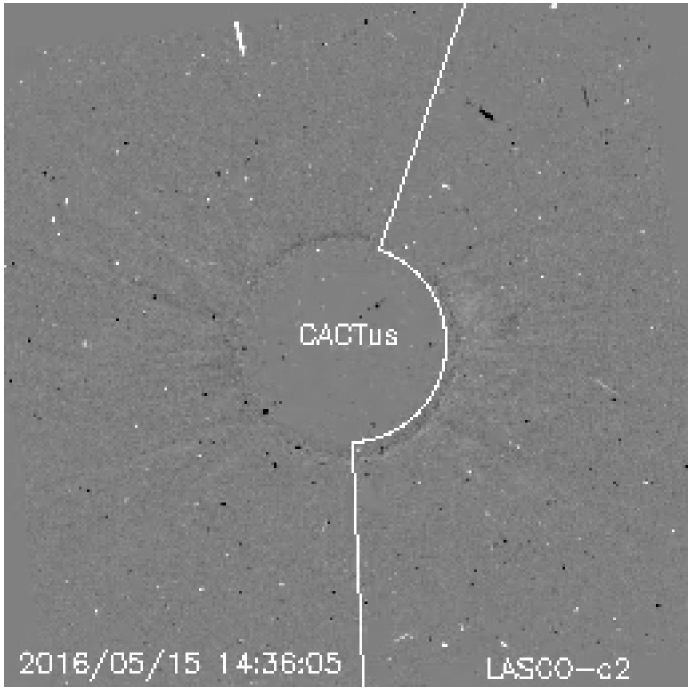
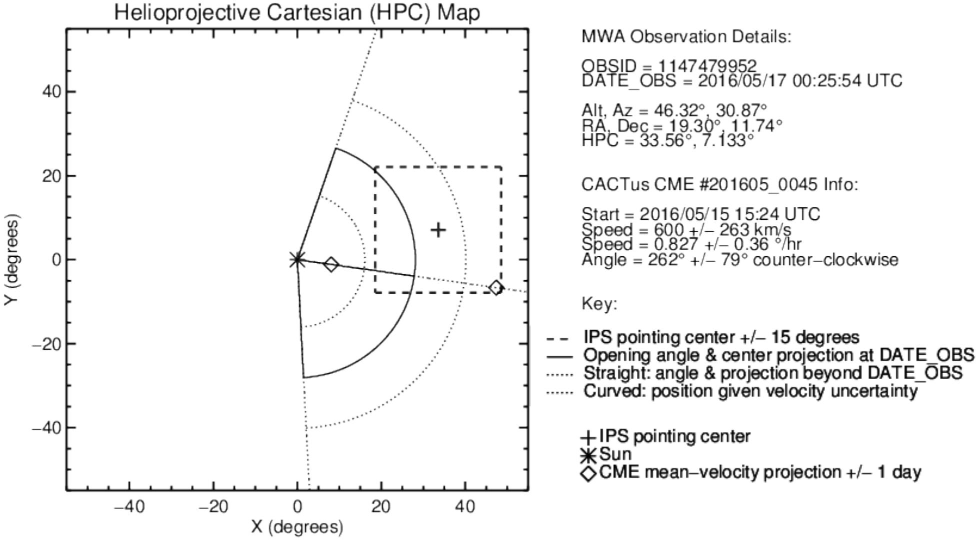
Space weather – first steps towards heliosphere measurement

- Choose observations which we believe are likely to contain a CME
- Analyse these along with a control sample



CME Projection for IPS OBSID 1147479952 and CACTus CME 201605_0045
http://sidc.oma.be/cactus/catalog/LASCO/2_5_0/qkl/2016/05/CME0045/CME.html



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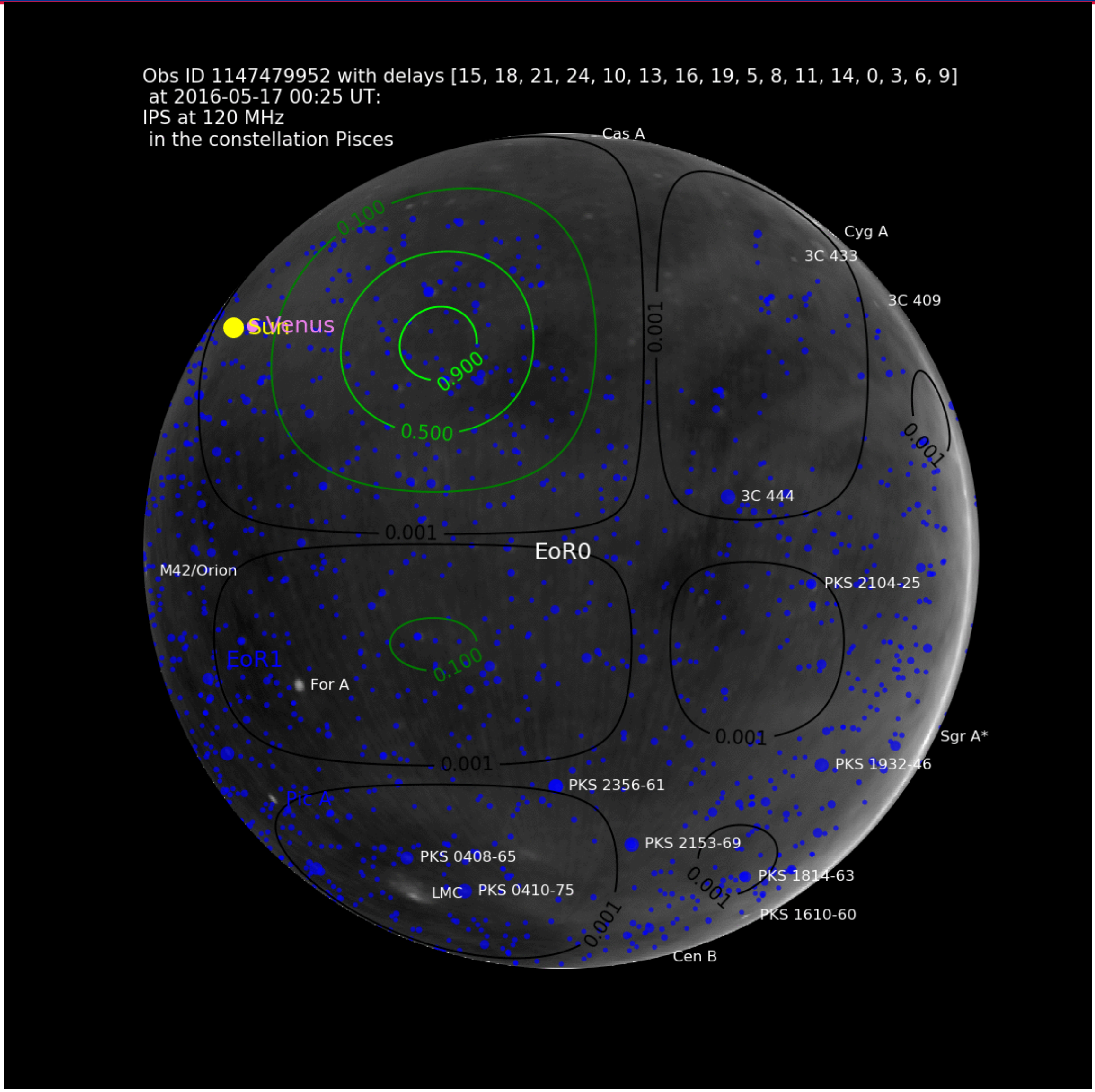

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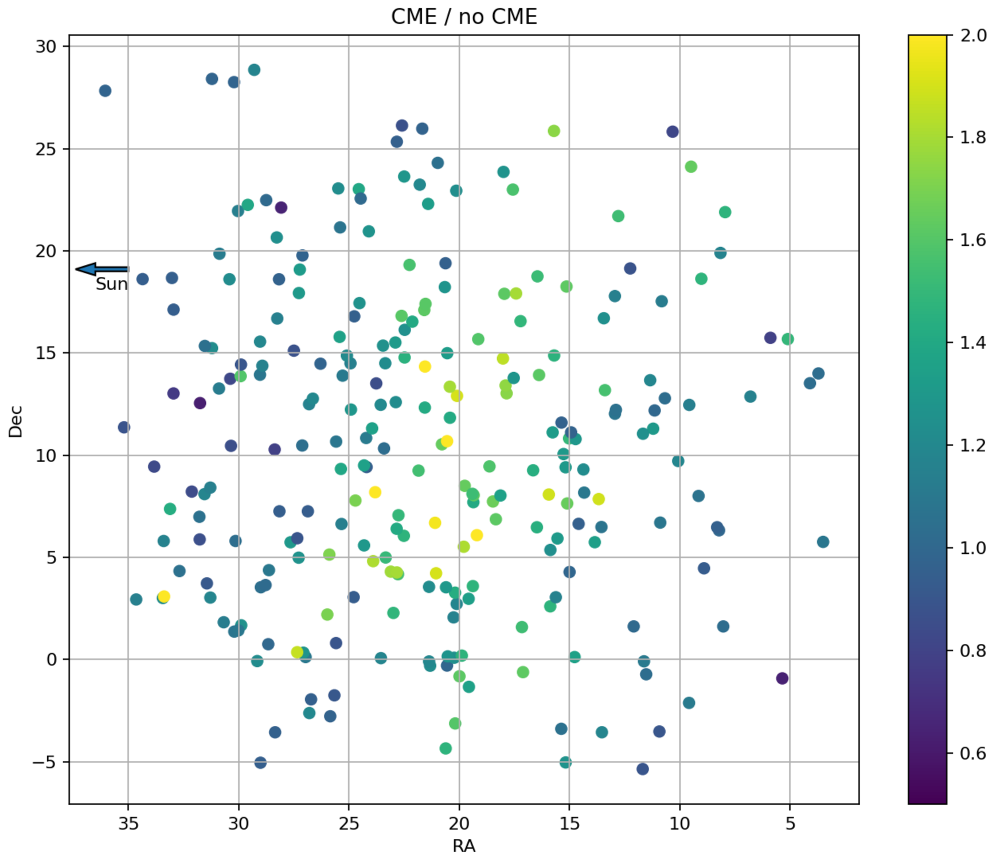

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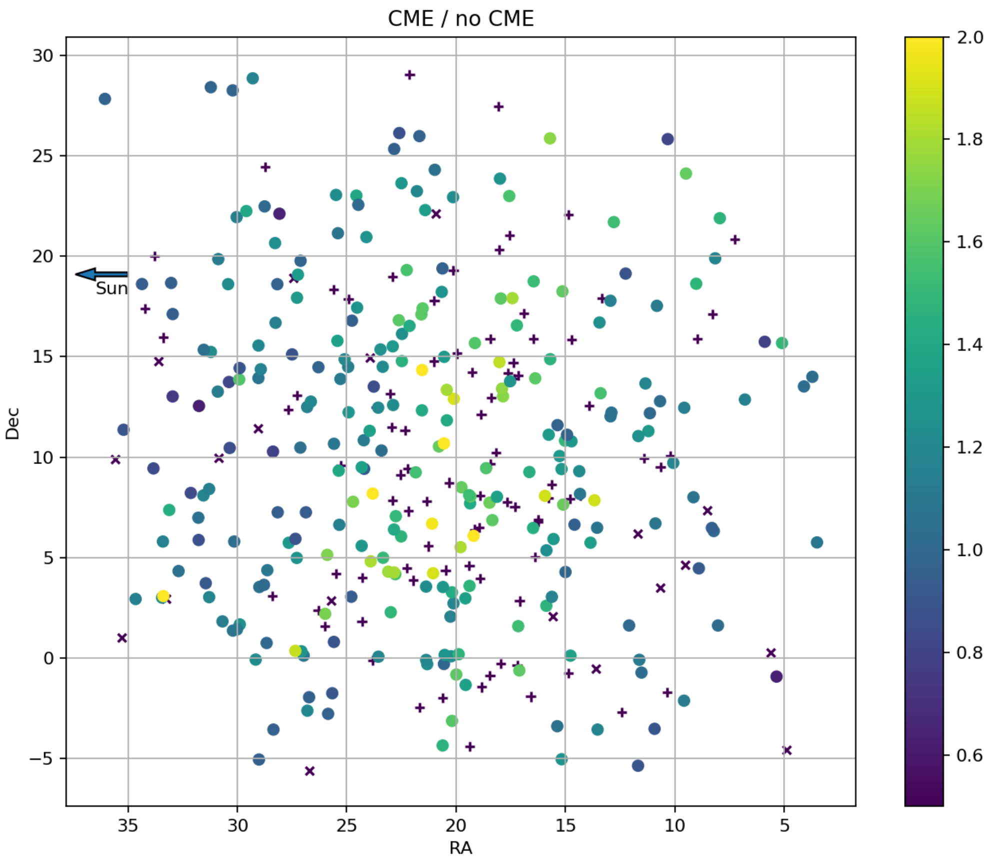

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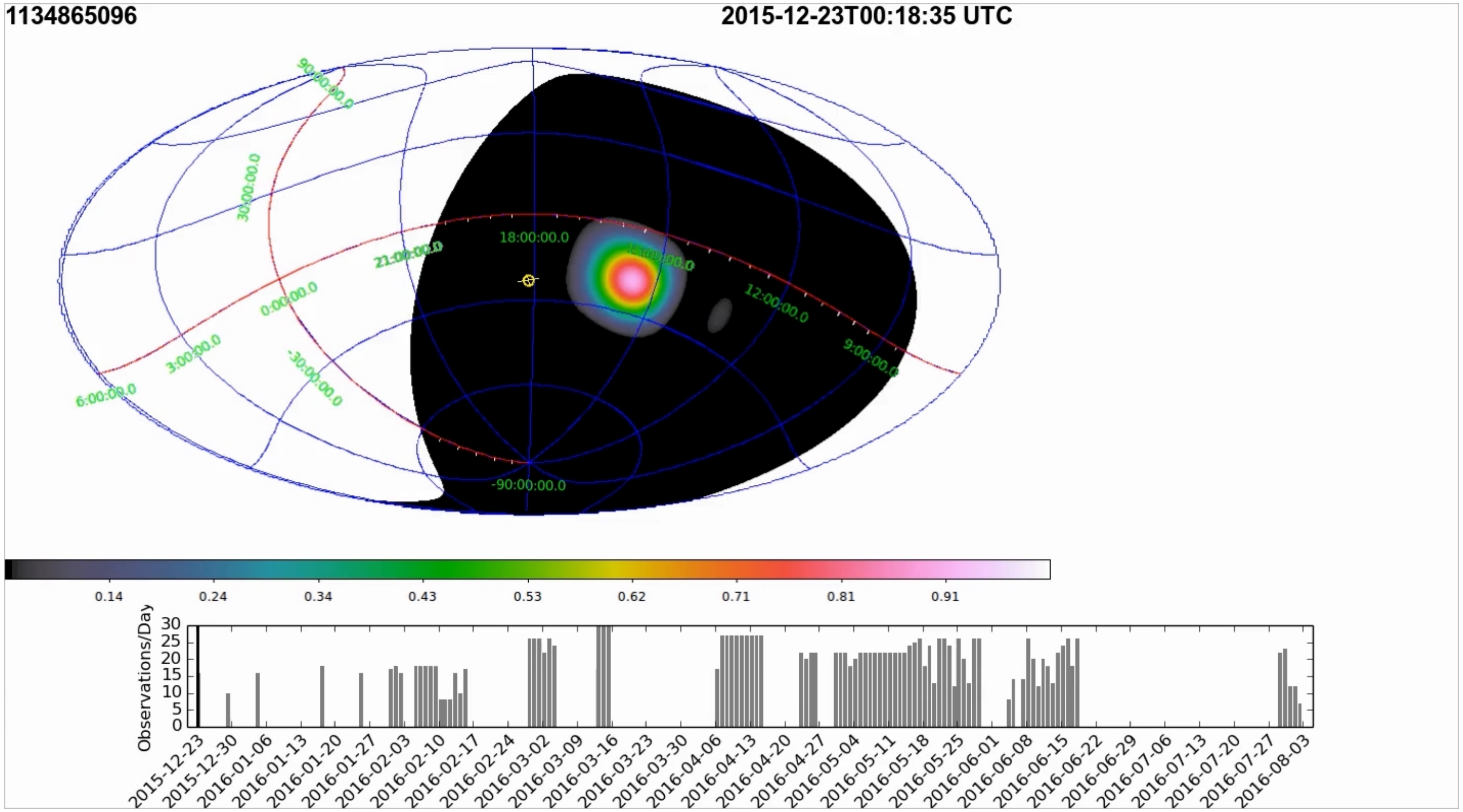
Future

- Improvements in sensitivity (factor of ~1.5) using "natural" weighting schemes
- New observations being made since June 2019 with expanded MWA.

Future

- Processing of large number of observations from 2016 under way.



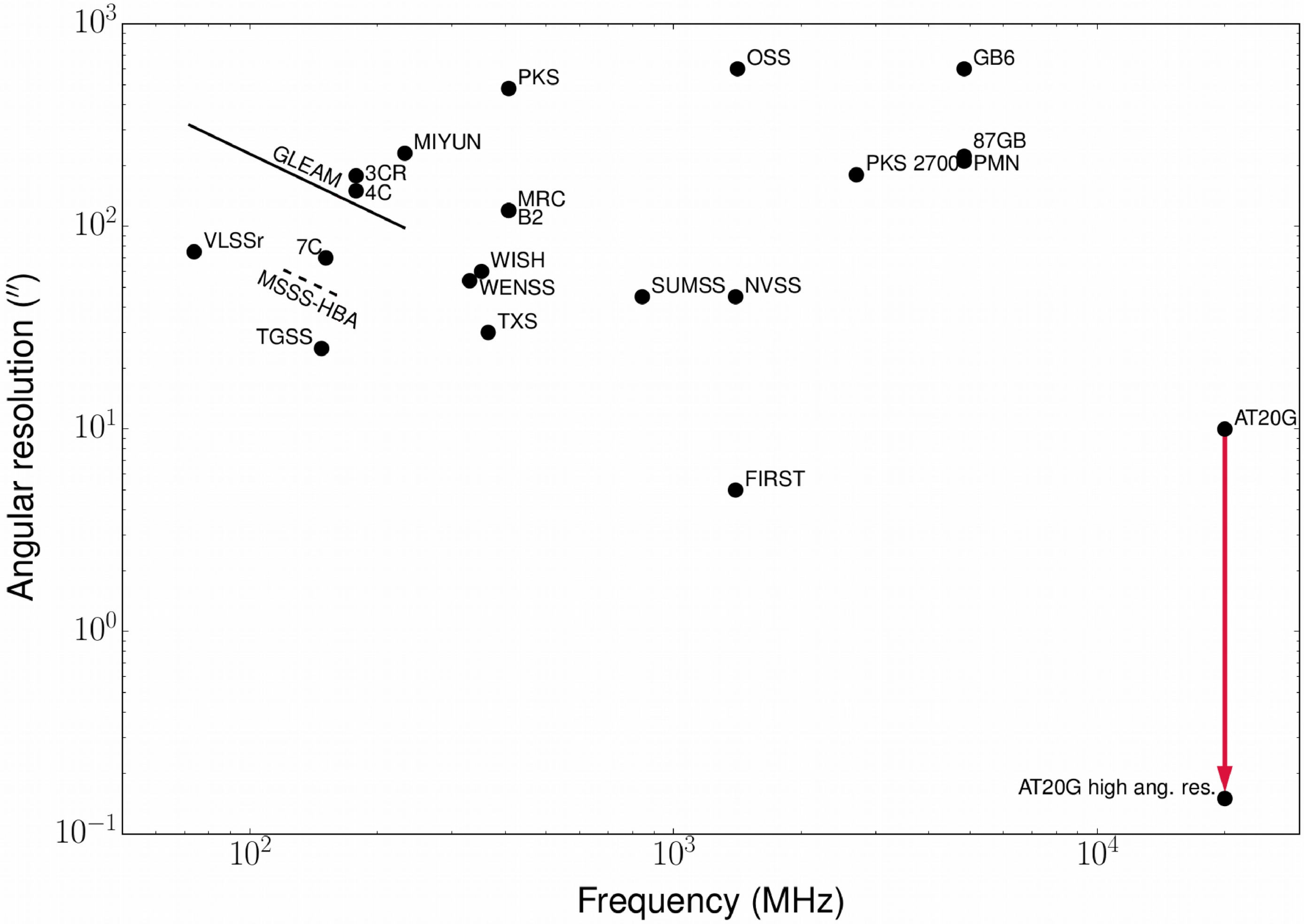
Summary

- Widefield IPS with the MWA extremely efficient to study large parts of the sky for:
  - Pulsars
  - Subarcsecond scale extragalactic radio sources (e.g. AGNs)
  - Rare very high redshift sources.
  - space weather studies by mapping CME (enabled by large number of pierce points)

- Low frequency compact radio source population:
  - Significantly different from overall low frequency population
  - Composition very different from that at high frequencies
    - Dominated by peaked-spectrum/steep-spectrum sources (~80%)

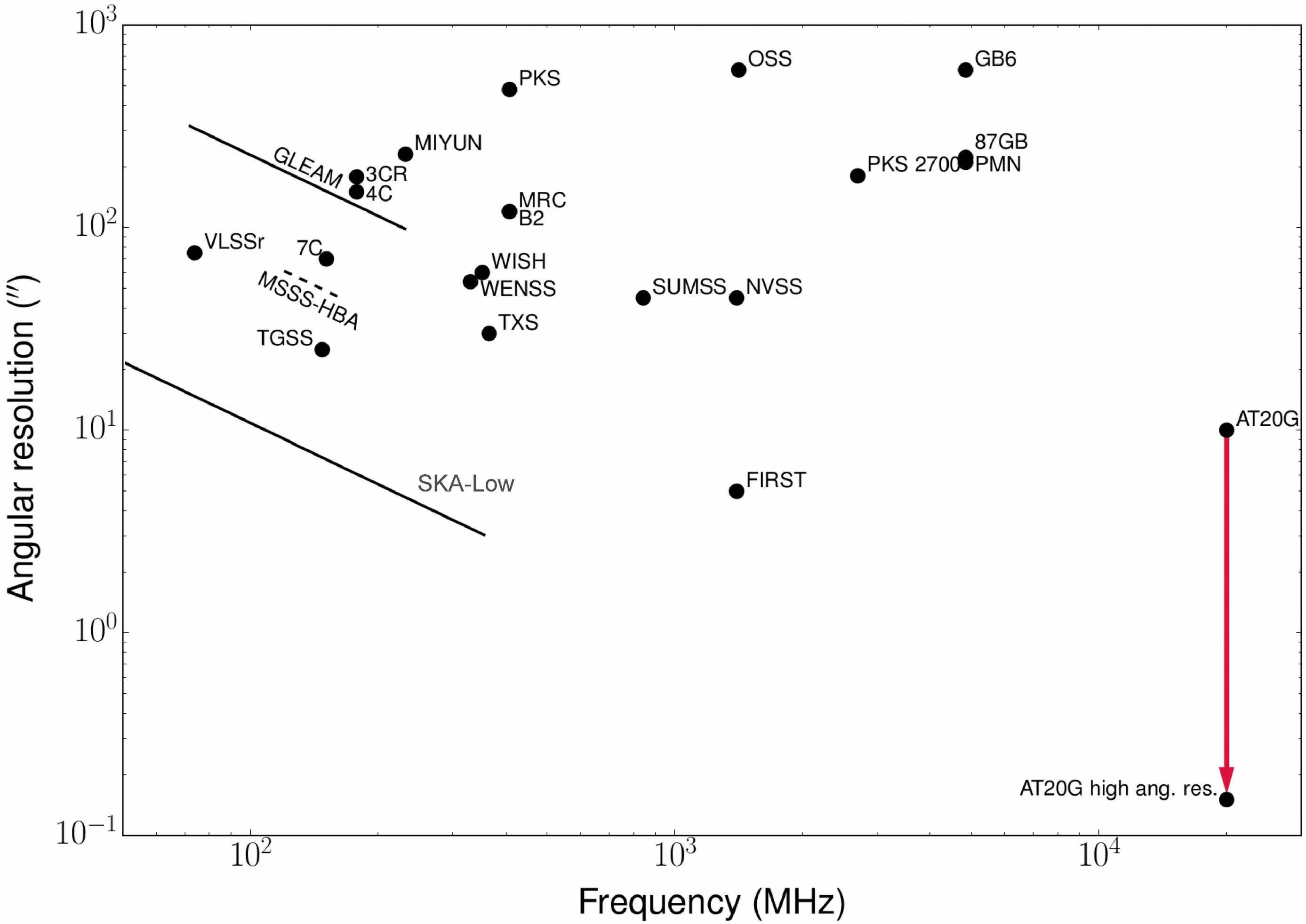
www.icrar.org/ips for our list of publications

Summary



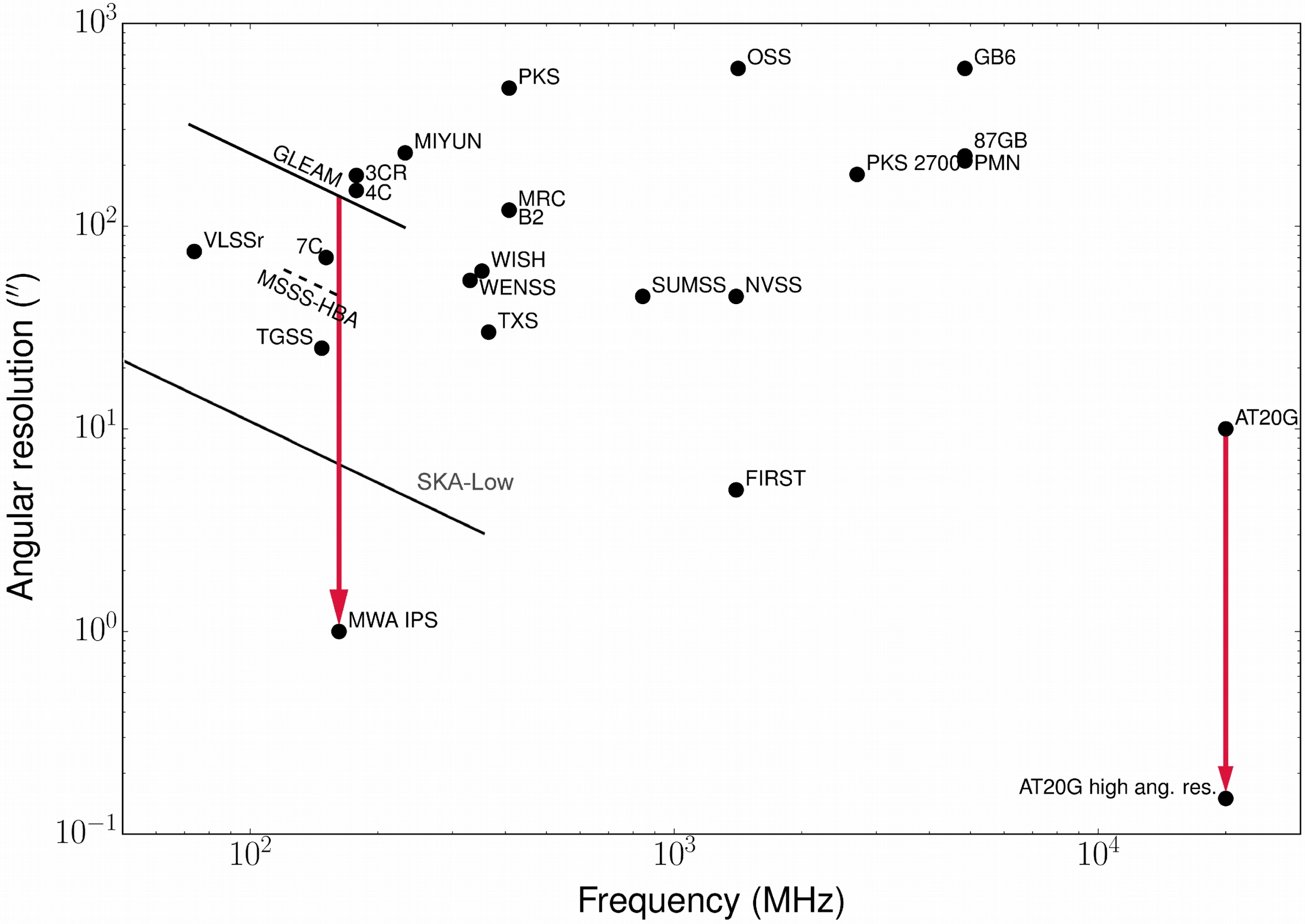
Angular resolution (″)
Frequency (MHz)
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{2}
10^{3}
10^{4}
PKS
OSS
GB6
MIYUN
GLEAM
3CR
4C
87GB
PKS 2700
PMN
MRC
B2
VLSSr
7C
MSSS-HBA
WISH
WENSS
SUMSS
NVSS
TXS
TGSS
AT20G
FIRST
AT20G high ang. res.

Summary



Angular resolution (″)
Frequency (MHz)
10^3
10^2
10^1
10^0
10^{-1}
10^2
10^3
10^4
PKS
OSS
GB6
MIYUN
GLEAM
3CR
4C
87GB
PKS 2700
PMN
MRC
B2
VLSSr
7C
MSSS-HBA
WISH
WENSS
SUMSS
NVSS
TXS
TGSS
AT20G
SKA-Low
FIRST
AT20G high ang. res.

Summary



Angular resolution (″)
Frequency (MHz)
10^3
10^2
10^1
10^0
10^{-1}
10^2
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PKS
OSS
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MRC
B2
VLSSr
7C
WISH
WENSS
SUMSS
NVSS
MSSS-HBA
TXS
TGSS
AT20G
SKA-Low
FIRST
MWA IPS
AT20G high ang. res.

Summary

- Widefield IPS with the MWA extremely efficient to study large parts of the sky for:
  - Pulsars
  - Subarcsecond scale extragalactic radio sources (e.g. AGNs)
  - Rare very high redshift sources.
  - space weather studies by mapping CME (enabled by large number of pierce points)

- Low frequency compact radio source population:
  - Significantly different from overall low frequency population
  - Composition very different from that at high frequencies
    - Dominated by peaked-spectrum/steep-spectrum sources (~80%)

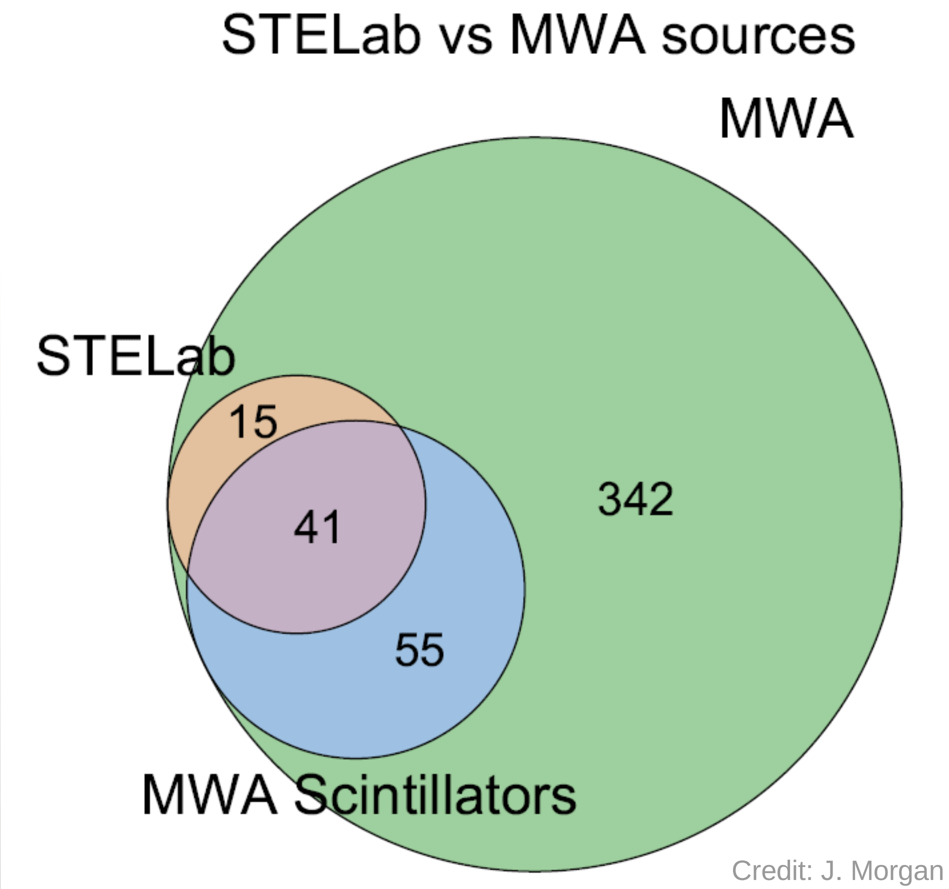
- Technique can be implemented on SKA-Low for angular resolution improvement.

www.icrar.org/ips for our list of publications

Thank you

Additional Slides

MWA sources vs known scintillators



MWA scintillators v known scintillators