Searching for Pulsars in Future Radio Continuum Surveys

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How to find pulsars with arrays (e.g., SKA)?

How to find *extreme* pulsars?

- Why do we want to find more pulsars?
  - ✓ To understand the equation of state (EoS) of cold dense matter
  - ✓ To test gravity theories
  - ✓ To detect gravitational waves
- How to find a pulsar? The “old fashioned” way…
- Searching for pulsars in radio continuum surveys
  - ✓ Detecting pulsar with interstellar scintillation in variance images
- Multi-wavelength searching and observations

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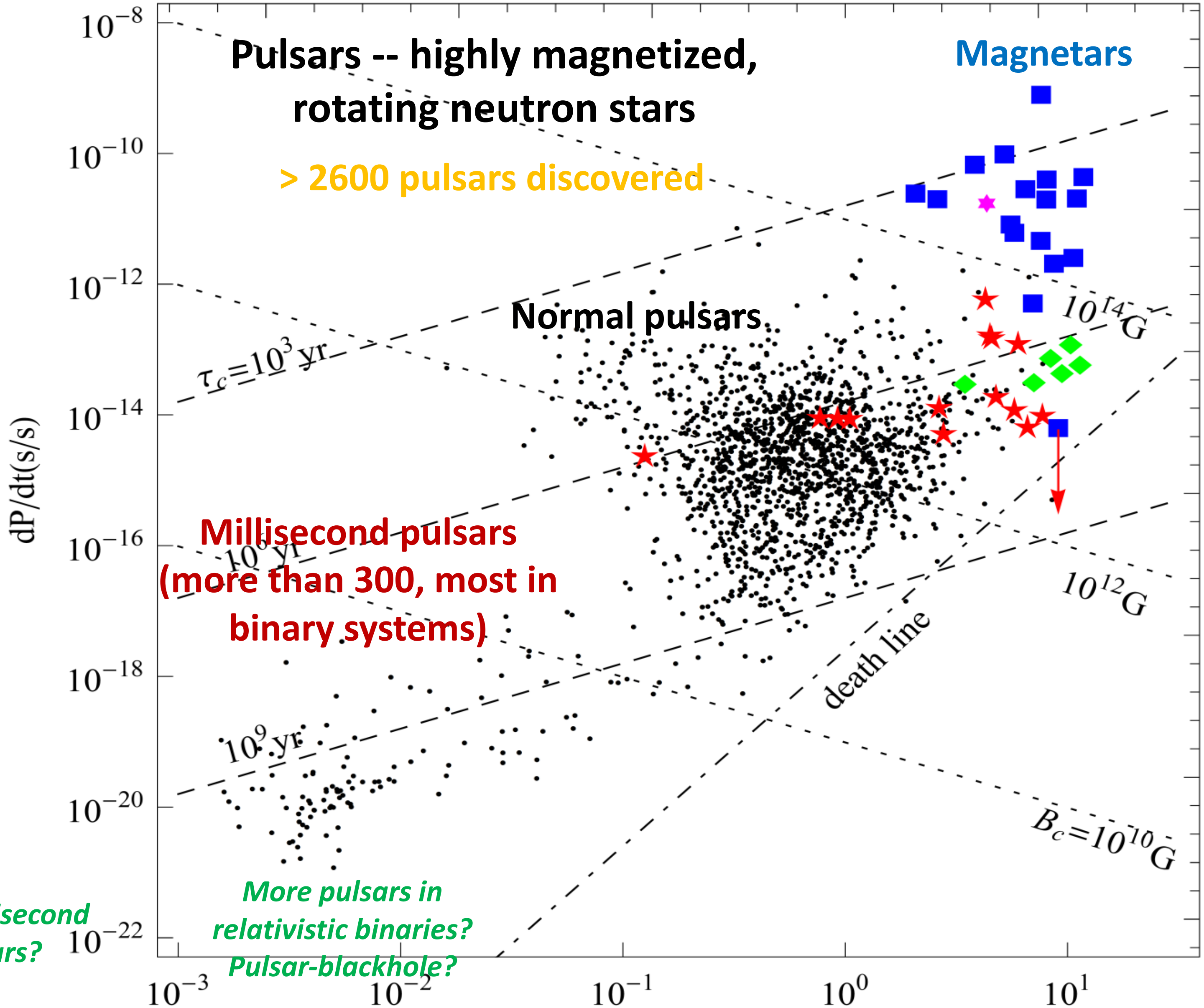
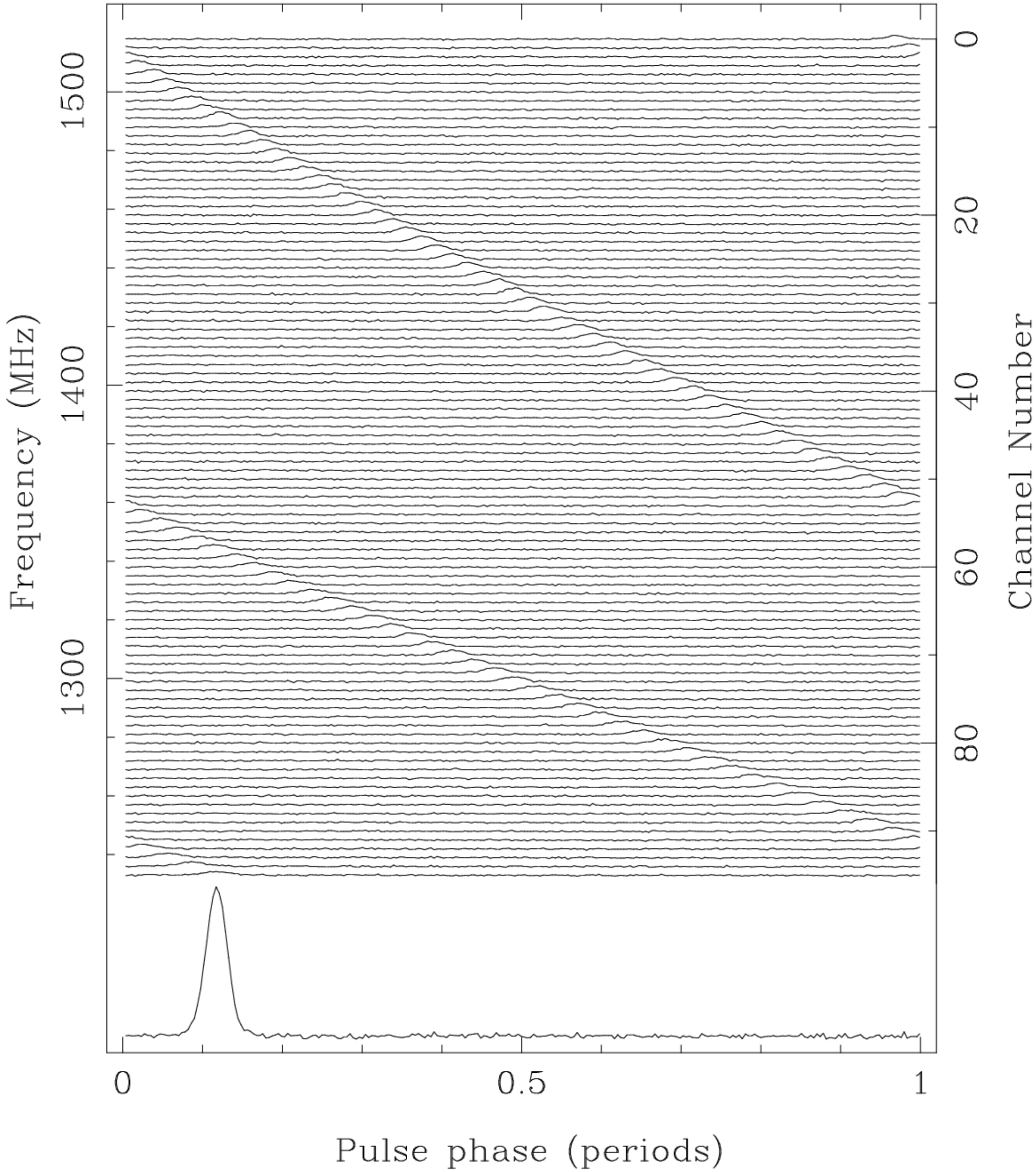


Sub-millisecond pulsars?

More pulsars in relativistic binaries? Pulsar-blackhole?

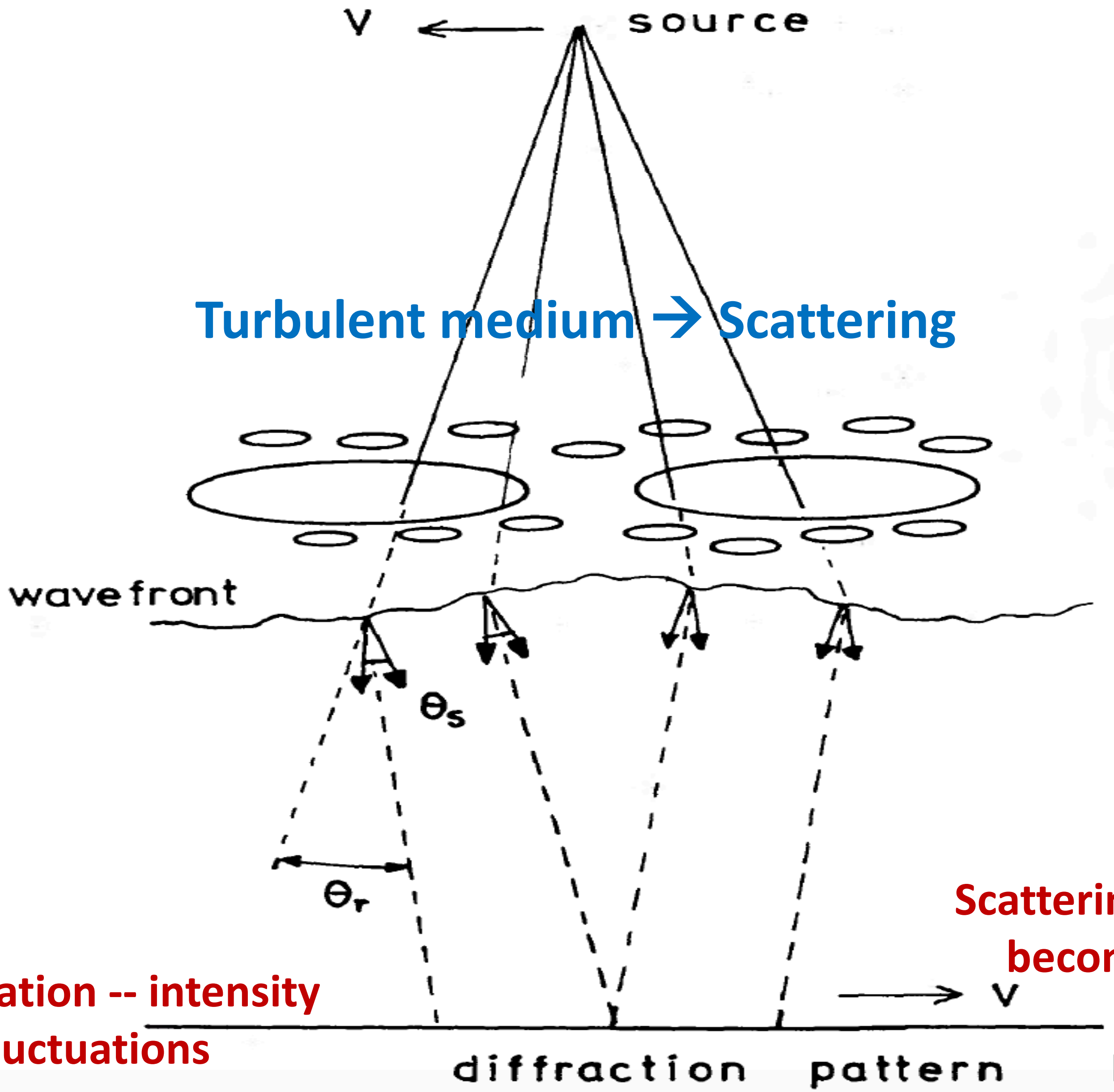
Tong & Xu (2011)



Dispersive delay – probe of the ionized interstellar medium (IISM)

$$\Delta\tau_D = \frac{e^2}{2\pi c m_e}\left[\frac{1}{\nu_1^2} - \frac{1}{\nu_2^2}\right]\int_0^L N(l)dl$$

Dispersion measure (DM) -- Column-density of the electrons in the intervening space between pulsar and observer



Turbulent medium → Scattering

Scintillation -- intensity fluctuations

Scattering – pulses become “fat”

Hewish (1980)

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  - ✓ **To understand the EoS of cold dense matter**
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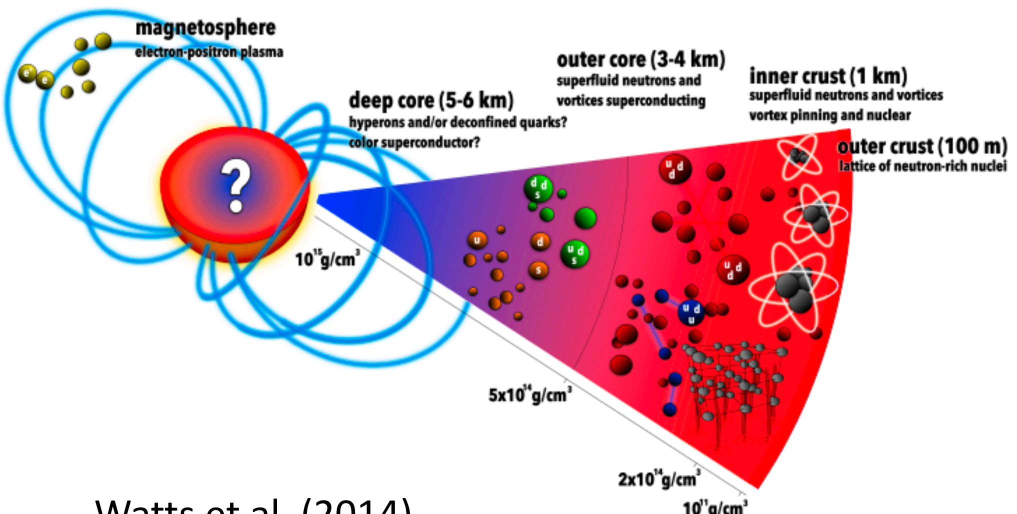


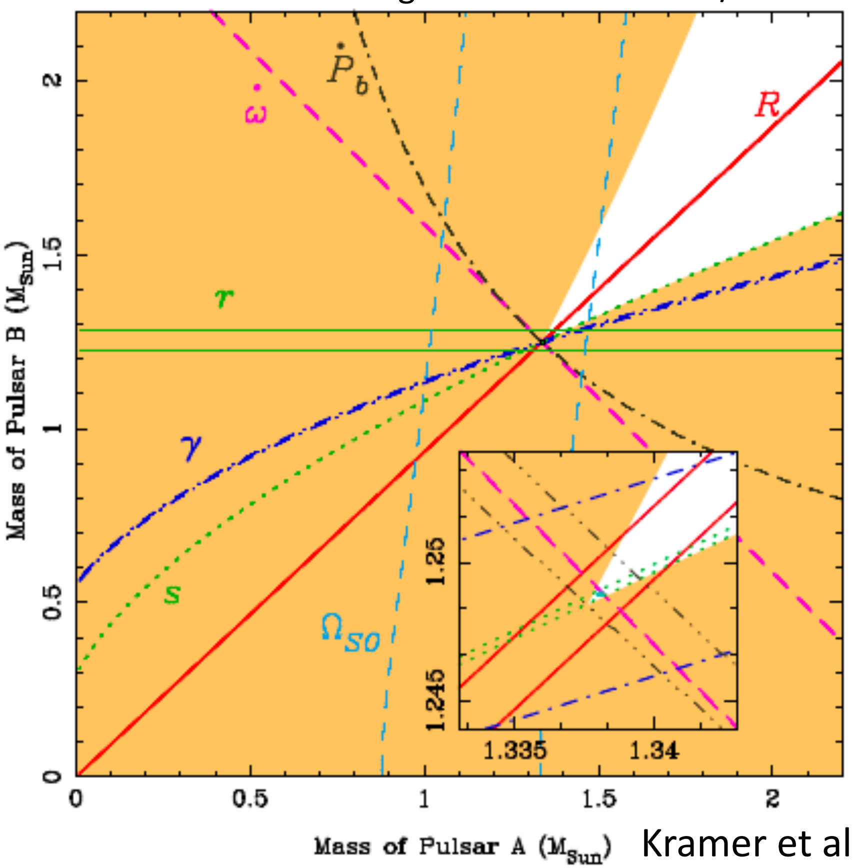
Watts et al. (2014)

Neutron stars (massive pulsars, sub-millisecond pulsars) provide a unique test ground for nuclear physics, quantum chromodynamics (QCD), and nuclear superfluidity!

- Why do we want to find more pulsars?
  - ✓ To understand the EoS of cold dense matter
  - ✓ **To test gravity theories**
  - ✓ To detect gravitational waves

Best high-precision experiments to probe strong-field deviations from GR **(relativistic binaries, pulsar-BH systems, pulsars in the Galactic center).**

Mass-mass diagram of J0737-3039A/B.

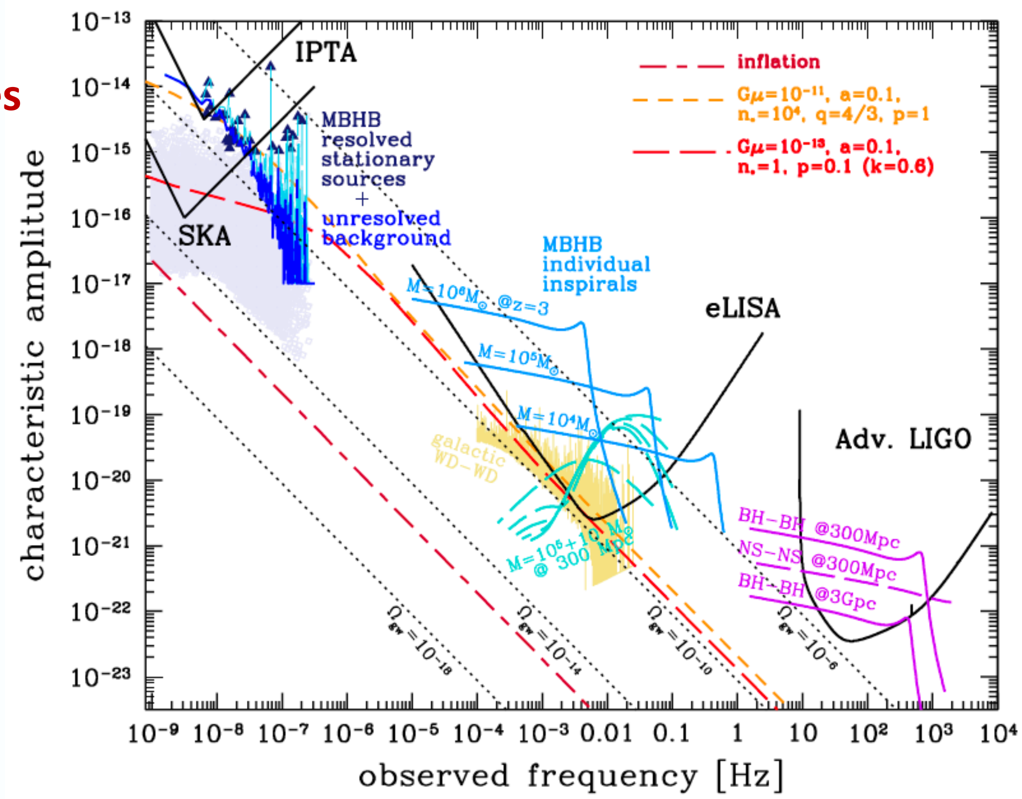


Kramer et al. 2006

- Why do we want to find more pulsars?
  - ✓ To understand the EoS of cold dense matter
  - ✓ To test gravity theories
  - ✓ **To detect gravitational waves**

Pulsar Timing Arrays

---- We need more millisecond pulsars!!!



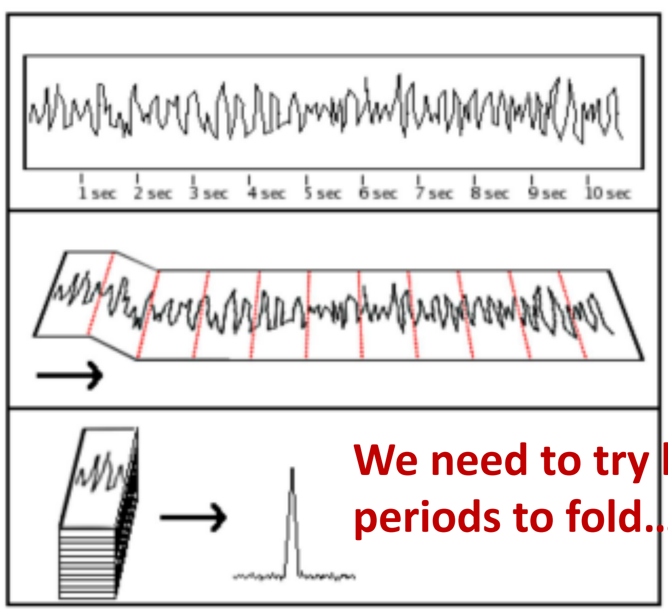
Janssen et al. (2014)

- Why do we want to find more pulsars?
  - ✓ To understand the EoS of cold dense matter **(massive, sub-millisecond pulsars)**
  - ✓ Testing gravity theories **(relativistic binaries, pulsar-BH, pulsars in the GC)**
  - ✓ Detecting gravitational waves
- **How to find a pulsar? Can the "old fashioned" way find extreme pulsars?**

How to find a pulsar? The “old fashioned” way…

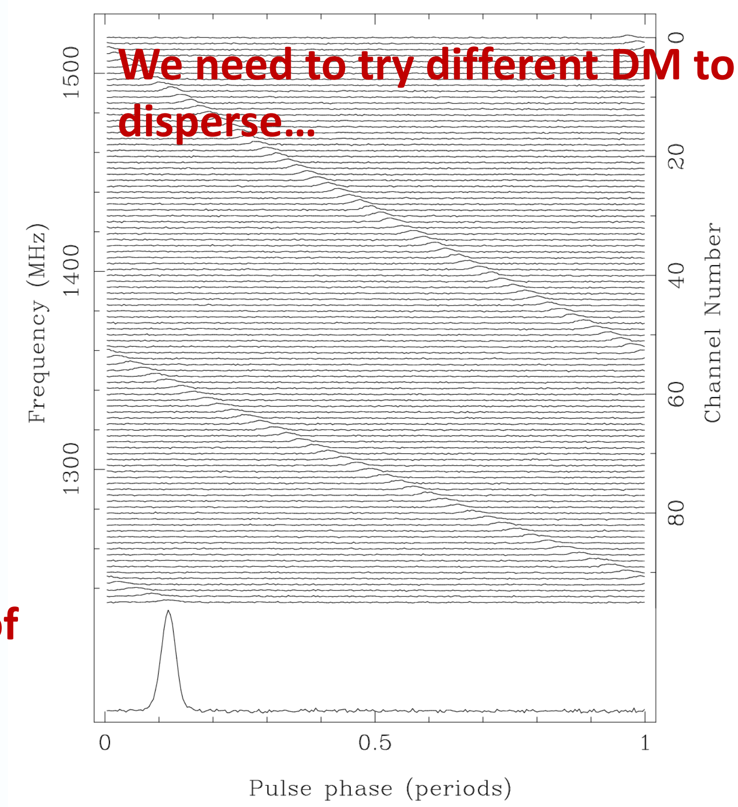
Search for ***periodic signals***? But pulsars are weak...

- De-disperse, and average in frequency
- FFT to search for periodicity
- Fold in time



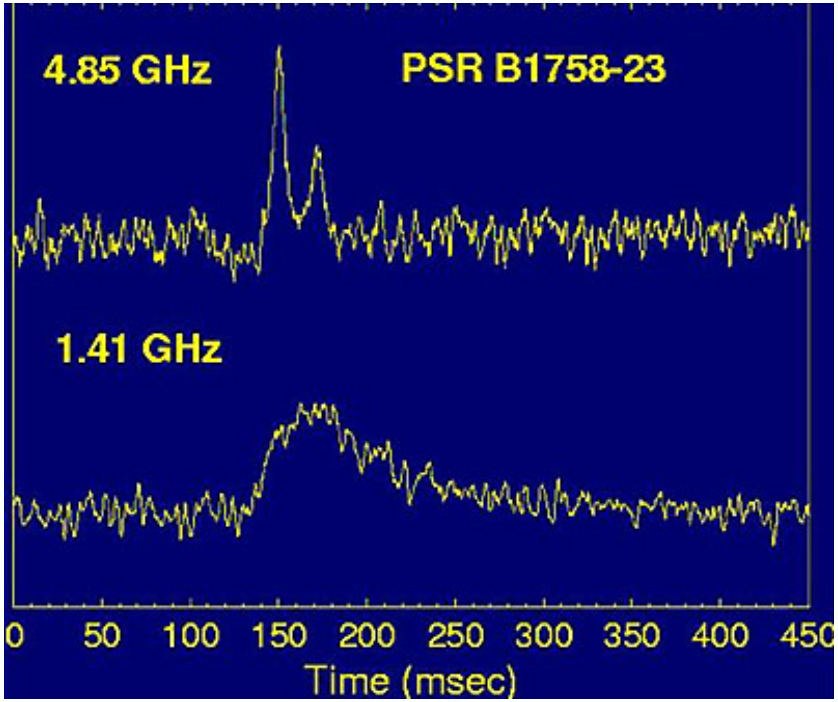
We need to try lots of periods to fold...

Credit: R. Lynch



We need to try different DM to de-disperse...

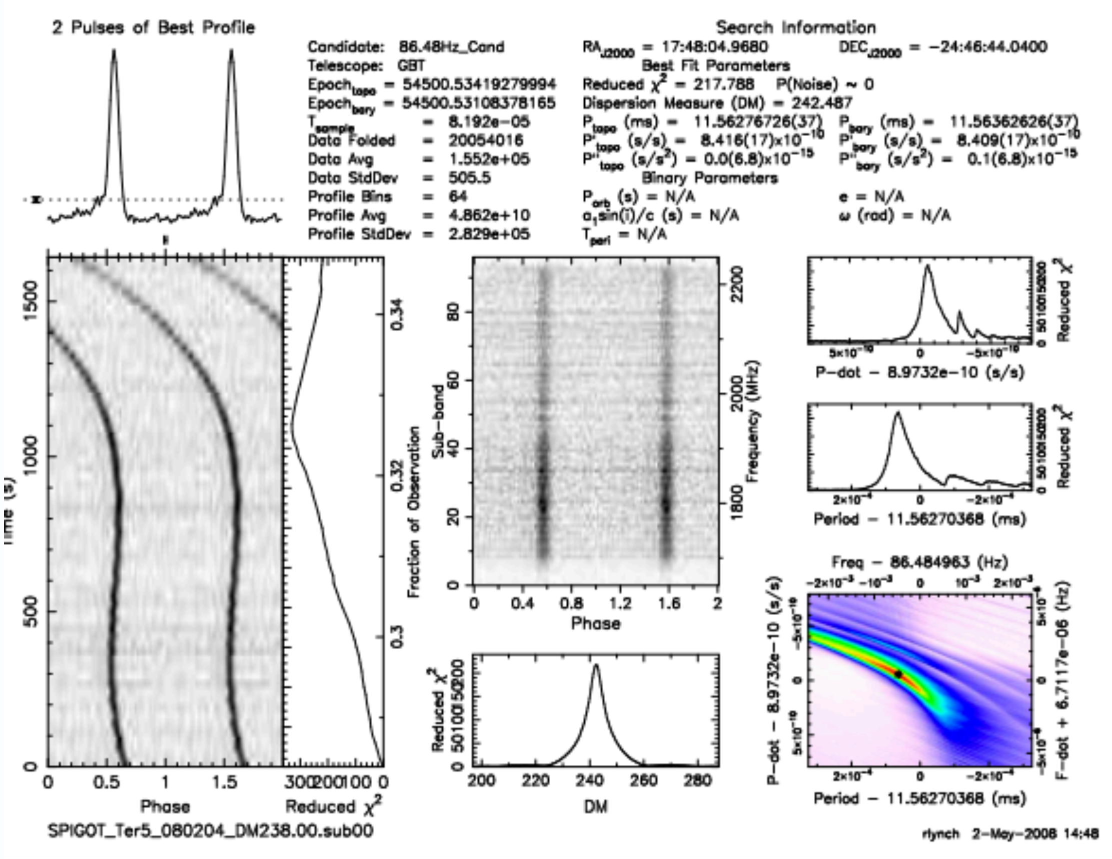
Conventional pulsar search is sensitive to narrow pulses, strictly periodic signals.



http://www.jb.man.ac.uk/distance/frontiers/pulsars

- DM smearing (DM/P) – smearing with frequency channels
- Scattering – exponential tails
- DM smearing and scattering are stronger at lower frequencies (e.g., SKA-Low)

Conventional pulsar search is sensitive to narrow pulses, strictly periodic signals.

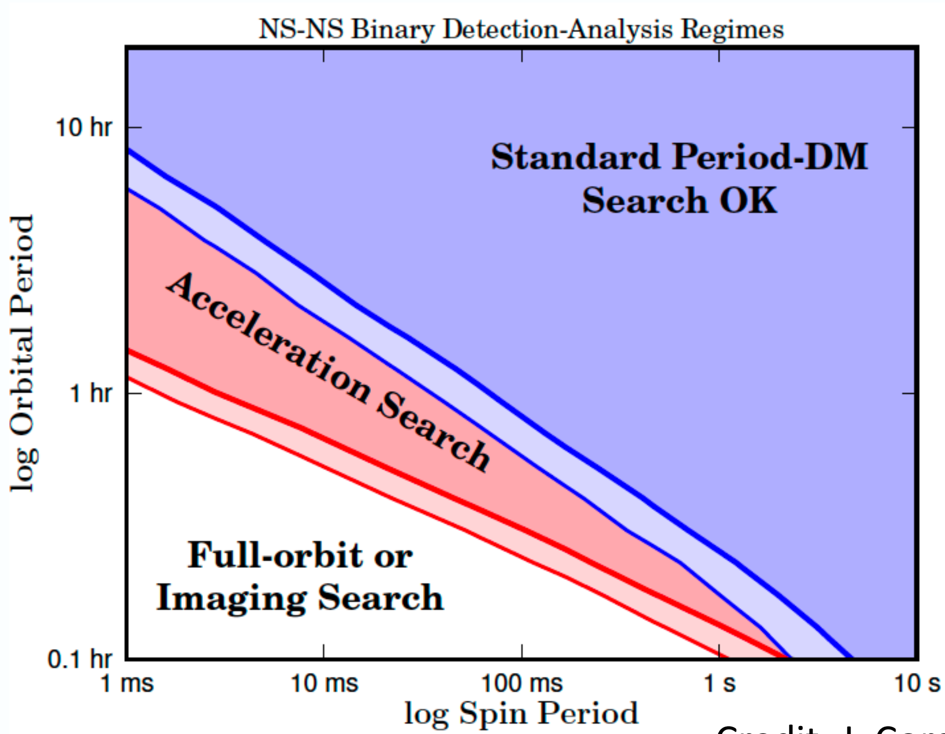


Credit: R. Lynch

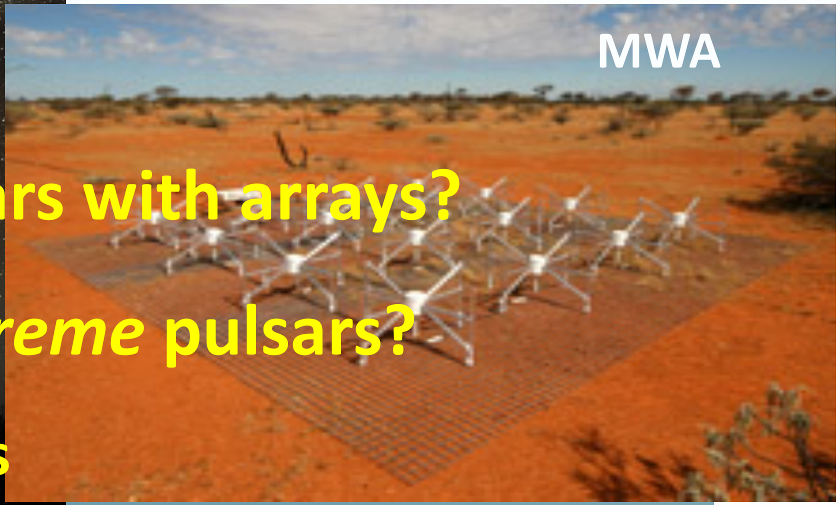
- Orbital period modulation and pulse smearing caused by orbital motion

Conventional pulsar search is sensitive to narrow pulses, strictly periodic signals.

- Sub-millisecond pulsars ---- DM smearing (DM/P)
- Pulsar-BH system ---- Period modulation and pulse smearing caused by orbital motion
- Pulsars in the Galactic center ---- Scattering



Credit: J. Cordes



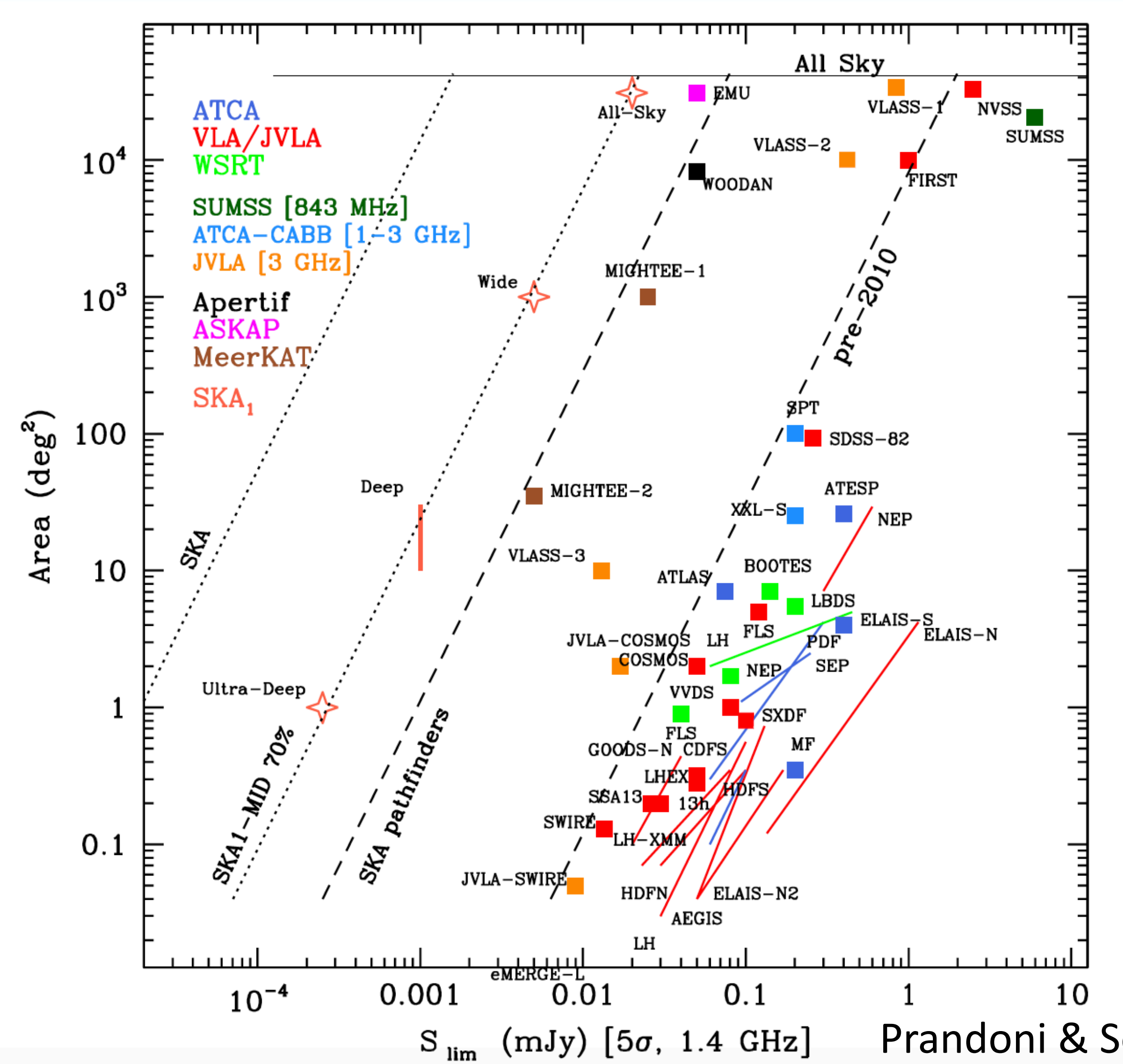
How to find pulsars with arrays?

How to find *extreme* pulsars?

- All-sky and deep surveys
- No scattering, no dispersion and no modulations

- Why do we want to find more pulsars?
  - ✓ To understand the EoS of cold dense matter
  - ✓ To test gravity theories
  - ✓ To detect gravitational waves
- How to find a pulsar? The “old fashioned” way can’t find extreme pulsars…
- **Searching for pulsars in radio continuum surveys**

All-sky and deep surveys

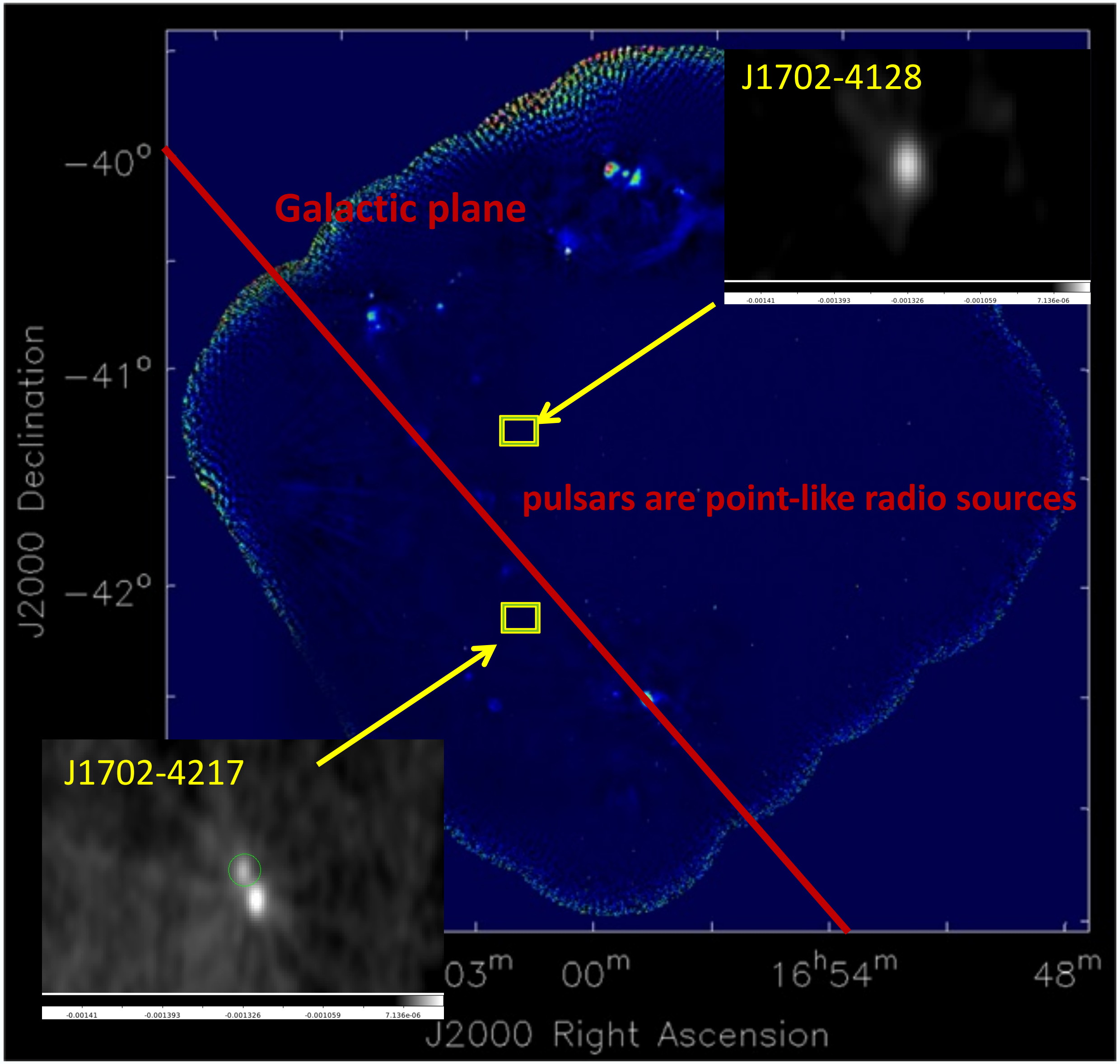


Prandoni & Seymour (2015)

Evolutional Map of the Universe (EMU):

- 75% of the sky
- 40× deeper than NVSS (10 μJy)
- 5× better resolution than NVSS (10 arcseconds)
- 70 million sources

- **No scattering**
- **No dispersion**
- **No orbital modulations**



Credit: F. Cavallaro

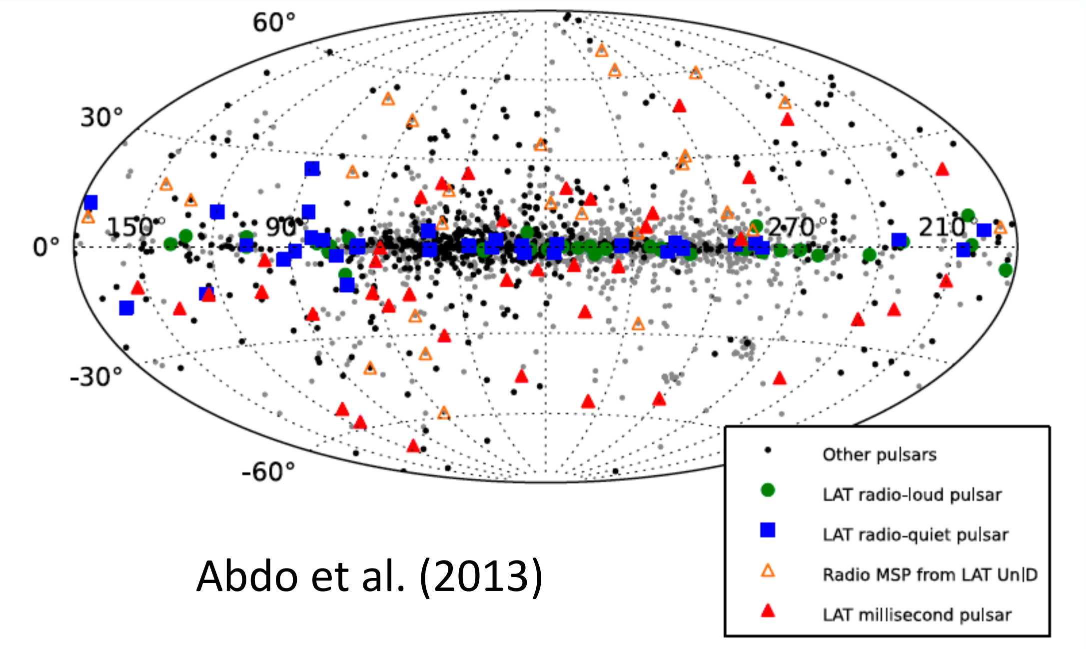
Umana et al. (2015)

Continuum images + Periodic search

Highly sensitive + targeted + "unbiased" survey

- Identify pulsar candidates in wide and deep continuum surveys
- Follow-up and search for periodic signals, with new technique to find extreme pulsars.

e.g., Fermi pulsar survey



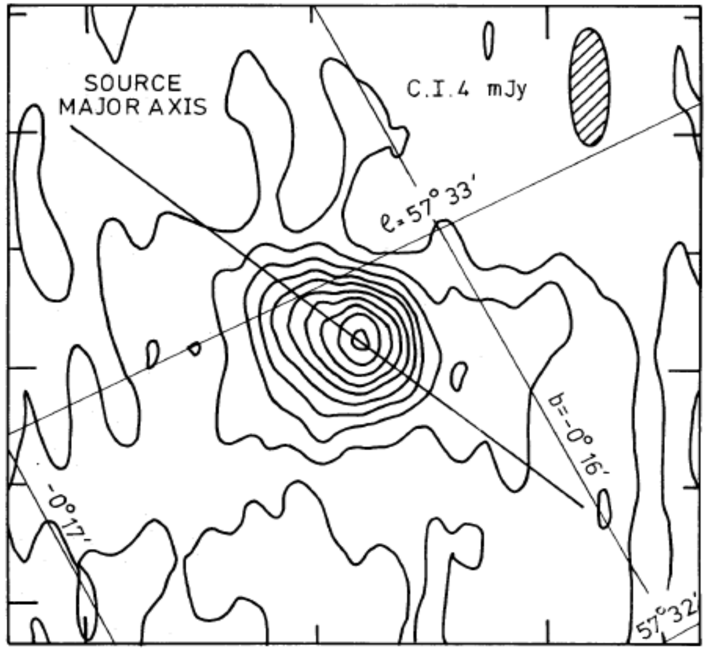
Abdo et al. (2013)

Continuum images + Periodic search

Highly sensitive + targeted + “unbiased” survey

First millisecond pulsar PSR B1937+21 was identified in radio continuum images

- Compact source
- Steep spectrum
- Highly polarized

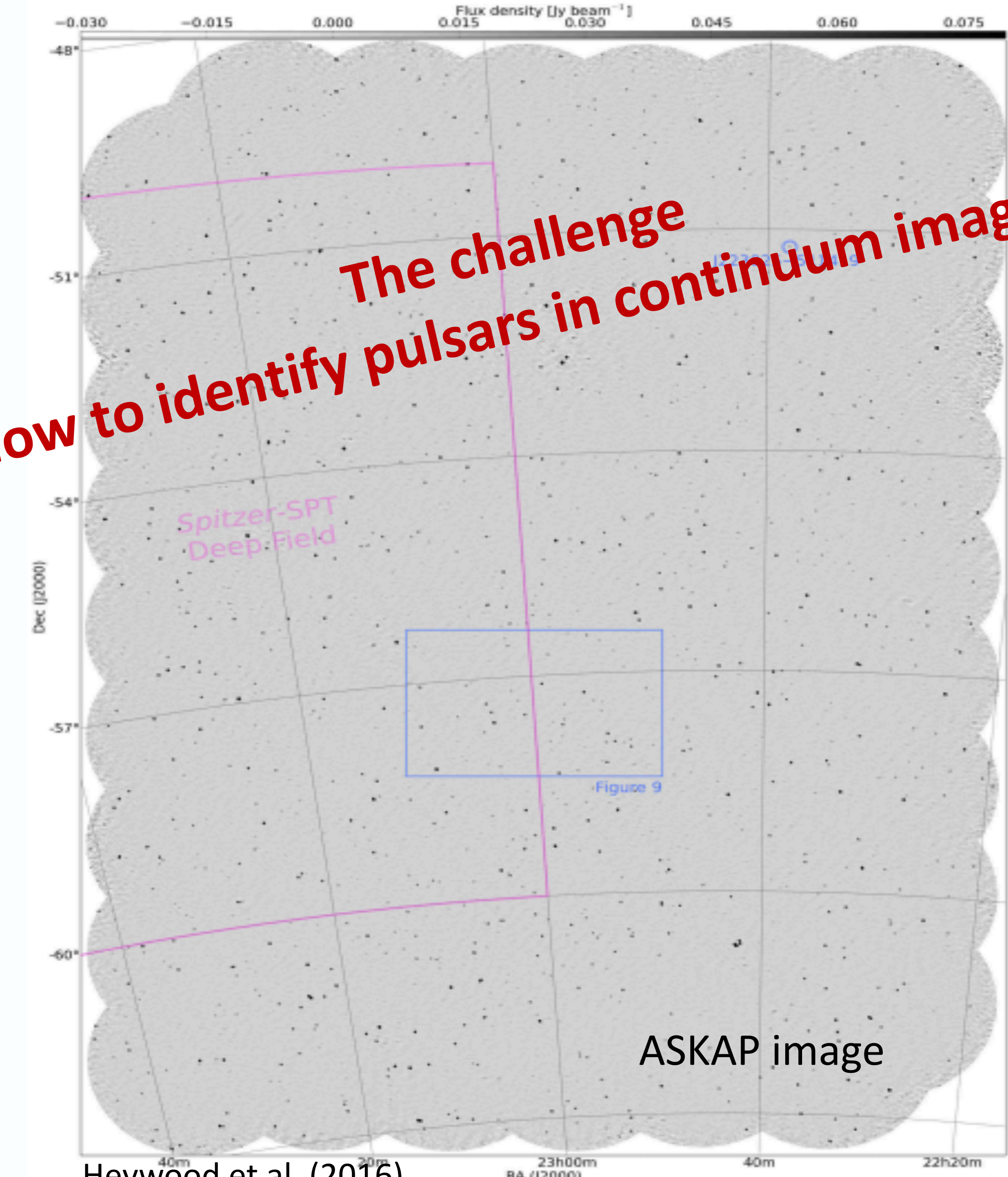


PSR B1937+21, Purvis (1983)

The challenge

How to identify pulsars in continuum images?

- Compactness
- Steep spectrum
- Highly polarized
- No optical counterpart



ASKAP image

Heywood et al. (2016)

How to identify pulsars in continuum images?

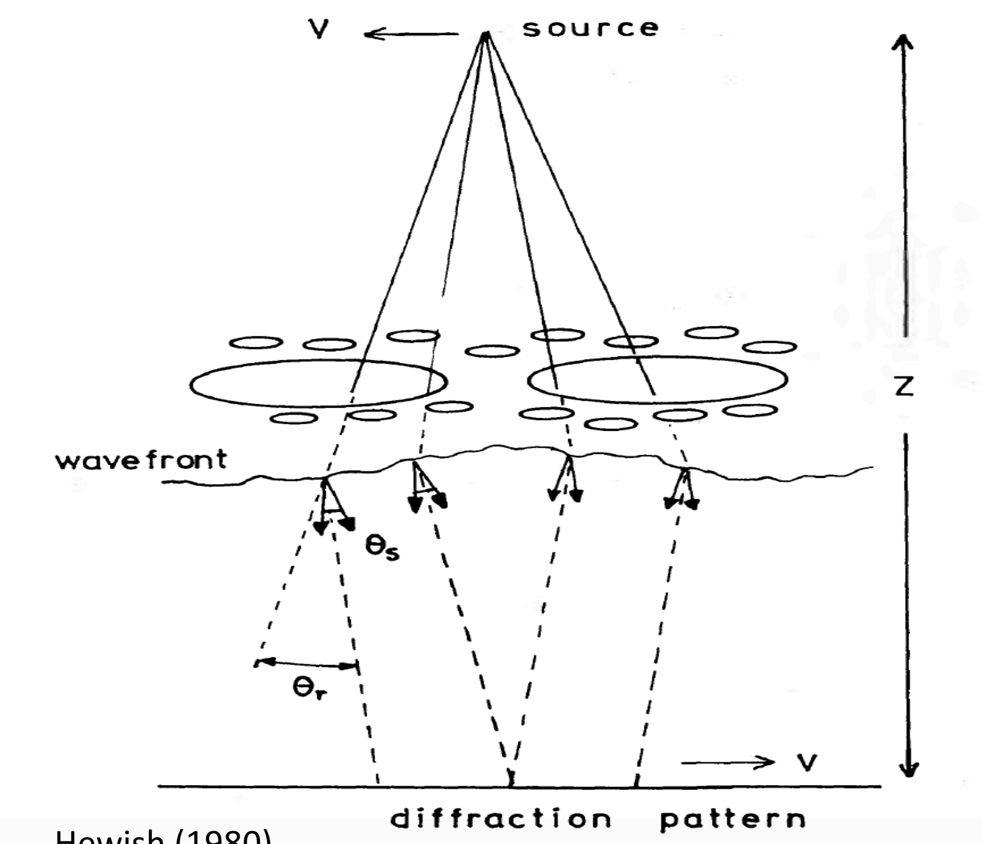
- Compactness ---- Too many compact sources
- Steep spectrum ---- Galaxies can have steep spectrum
- Highly polarized ---- Polarization averaged out in continuum images
- No optical counterpart ---- Limited by optical surveys

We are working on using current continuum surveys to identify pulsar candidates (see Hiroki's talk)! And recent papers show some exciting results (Frail et al. 2017)

We need more powerful tools!

Detecting pulsar with interstellar scintillation

- Interstellar scintillation of pulsars



Hewish (1980)

Scintillation -- intensity fluctuations in both time and frequency

In the strong scattering:

- Refractive scintillation
- Diffractive scintillation (angular size < micro-arcsecond)

Detecting pulsars with interstellar scintillation

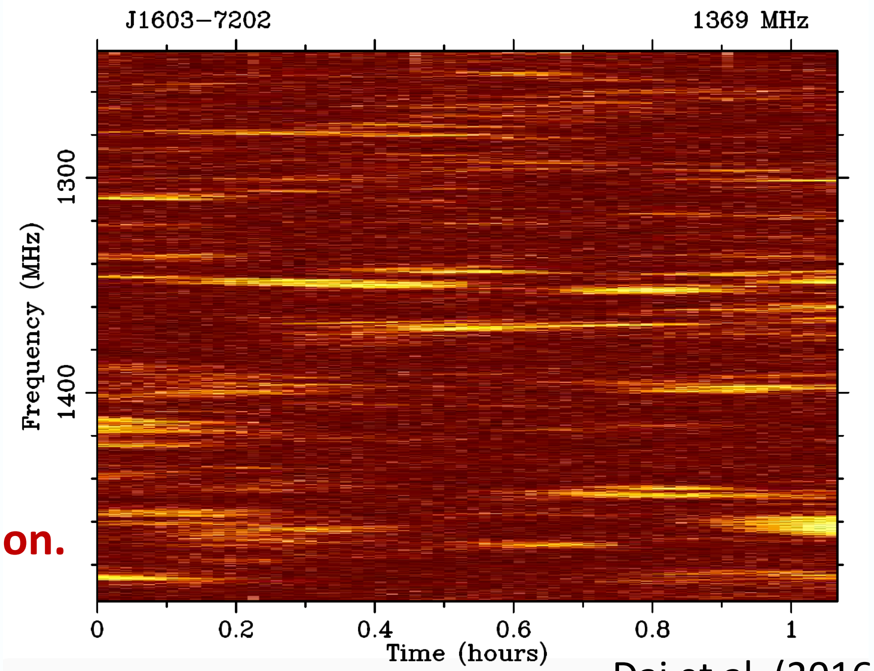
- Diffractive scintillation

Pulsars are the only source compact enough to show diffractive scintillation

$$\tau_{\mathrm{DISS}} \propto \nu^{6/5} D^{-3/5} V_{\mathrm{eff}}^{-1}$$

$$\delta\nu_{\mathrm{DISS}} \propto \nu^{22/5} D^{-11/5}$$

τ_{DISS} and $\delta\nu_{DISS}$ are determined by the observing frequency, DM, distance and so on.



Dai et al. (2016)

Detecting pulsar with interstellar scintillation

- Diffractive scintillation of pulsars

  Pulsars are the only source compact enough to show diffractive scintillation

$$\tau_{\mathrm{DISS}} \propto \nu^{6/5} D^{-3/5} V_{\mathrm{eff}}^{-1}$$

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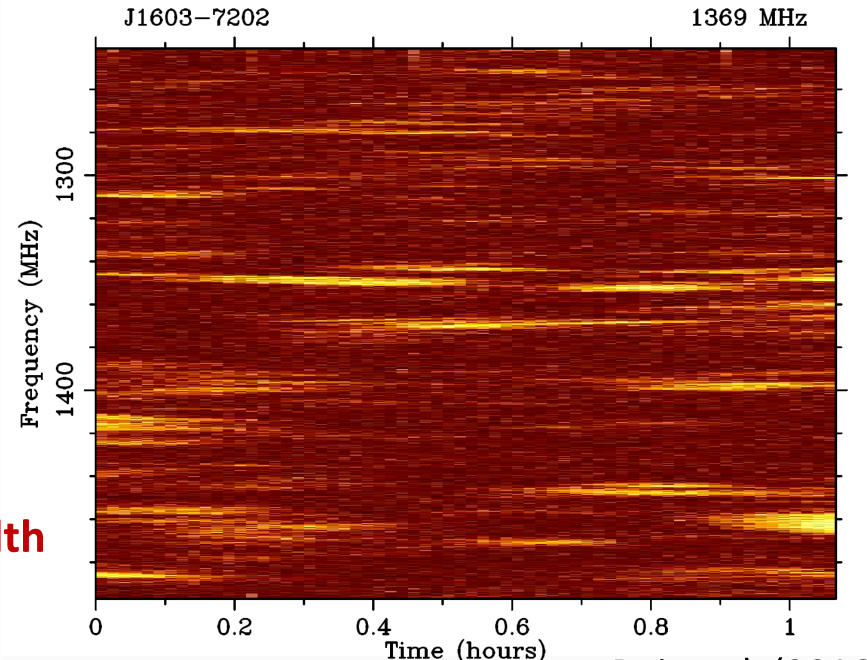
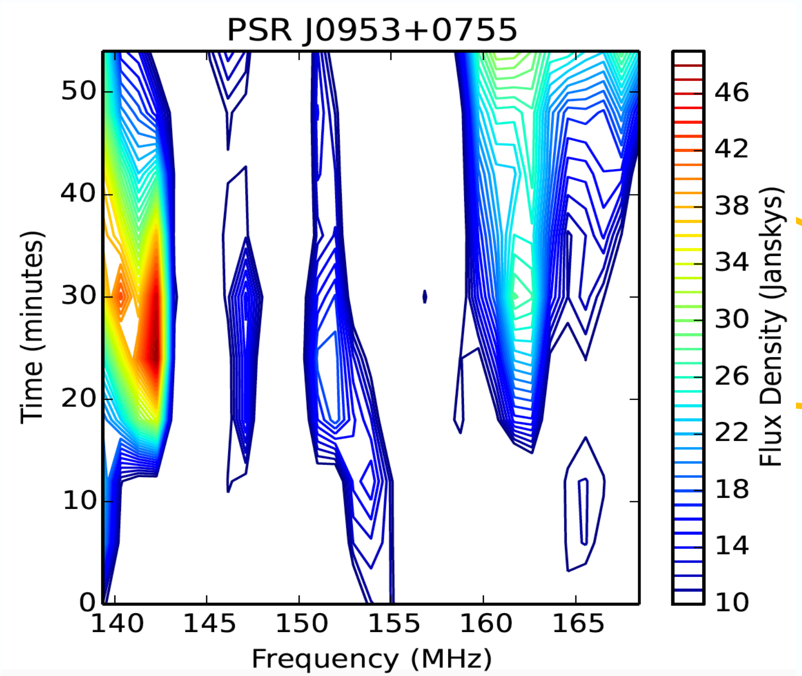
100% modulation of the intensity, with a typical time-scale of minutes and bandwidth of MHz (at 1.4GHz).



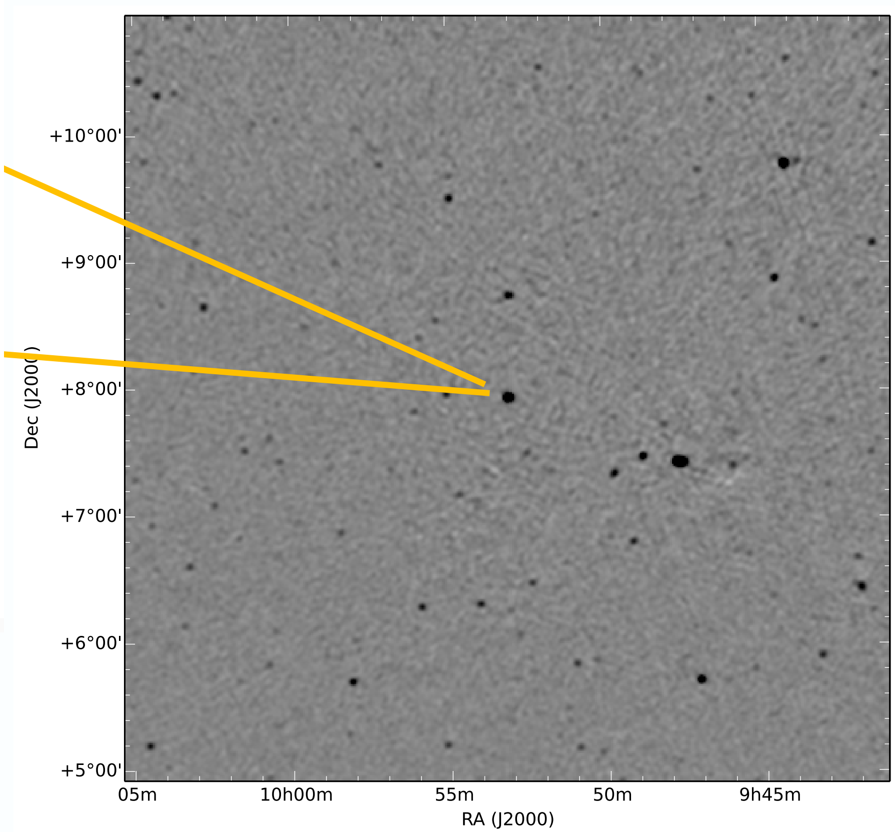
Dai et al. (2016)

Variance image: images of the variance of pulsar intensities (in both time and frequency)



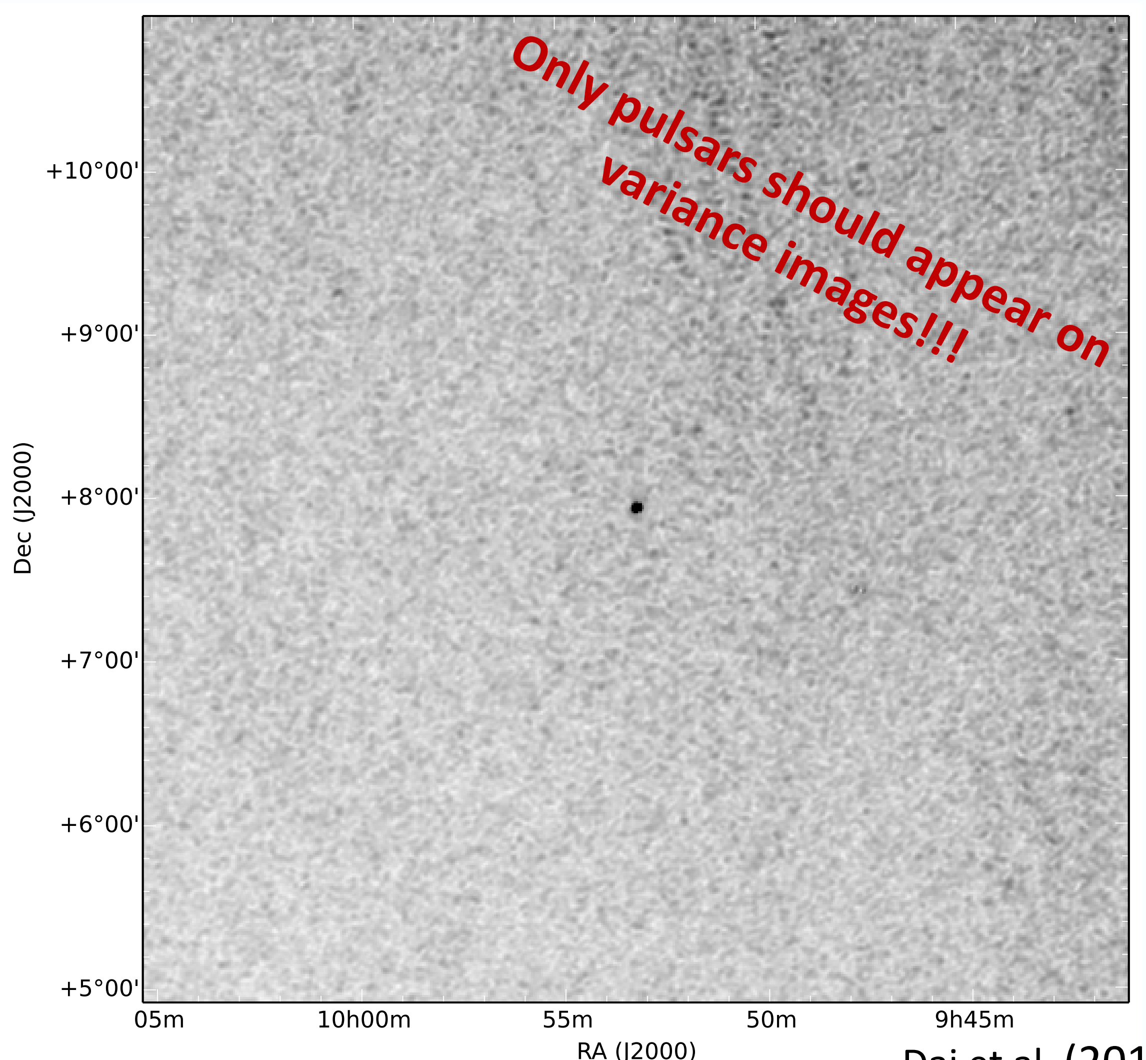
Bell at al. (2016)

PSR J0953+0755 in the continuum image



Dai et al. (2016)

PSR J0953+0755 in the variance image

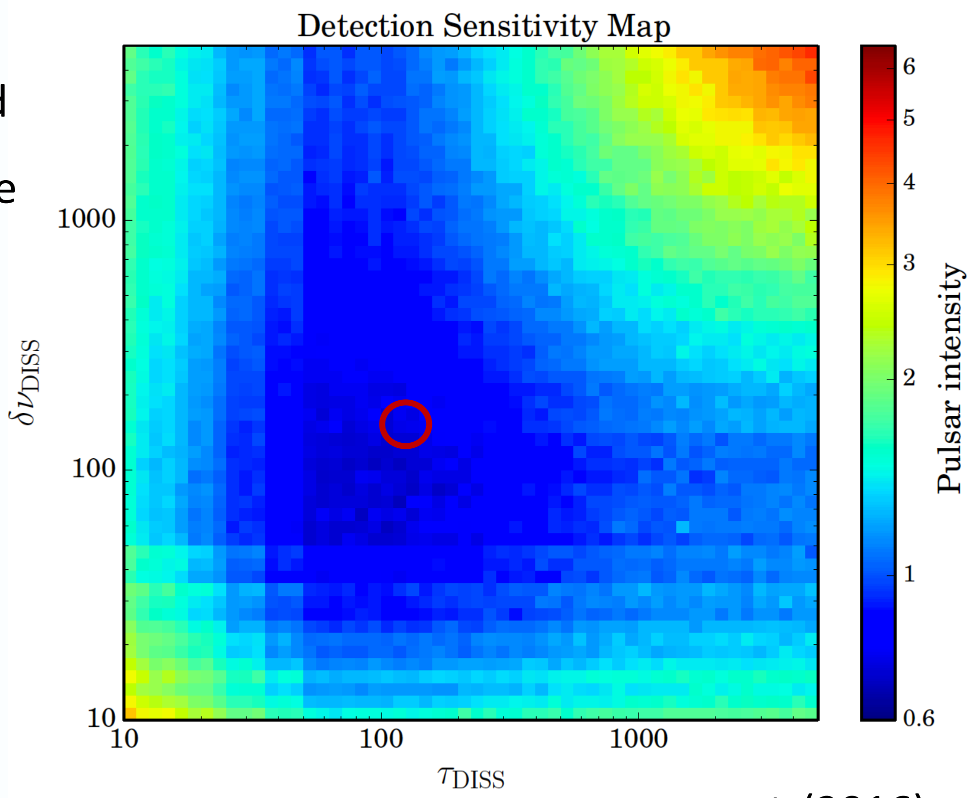


Dai et al. (2016)

What pulsars are variance images sensitive to?

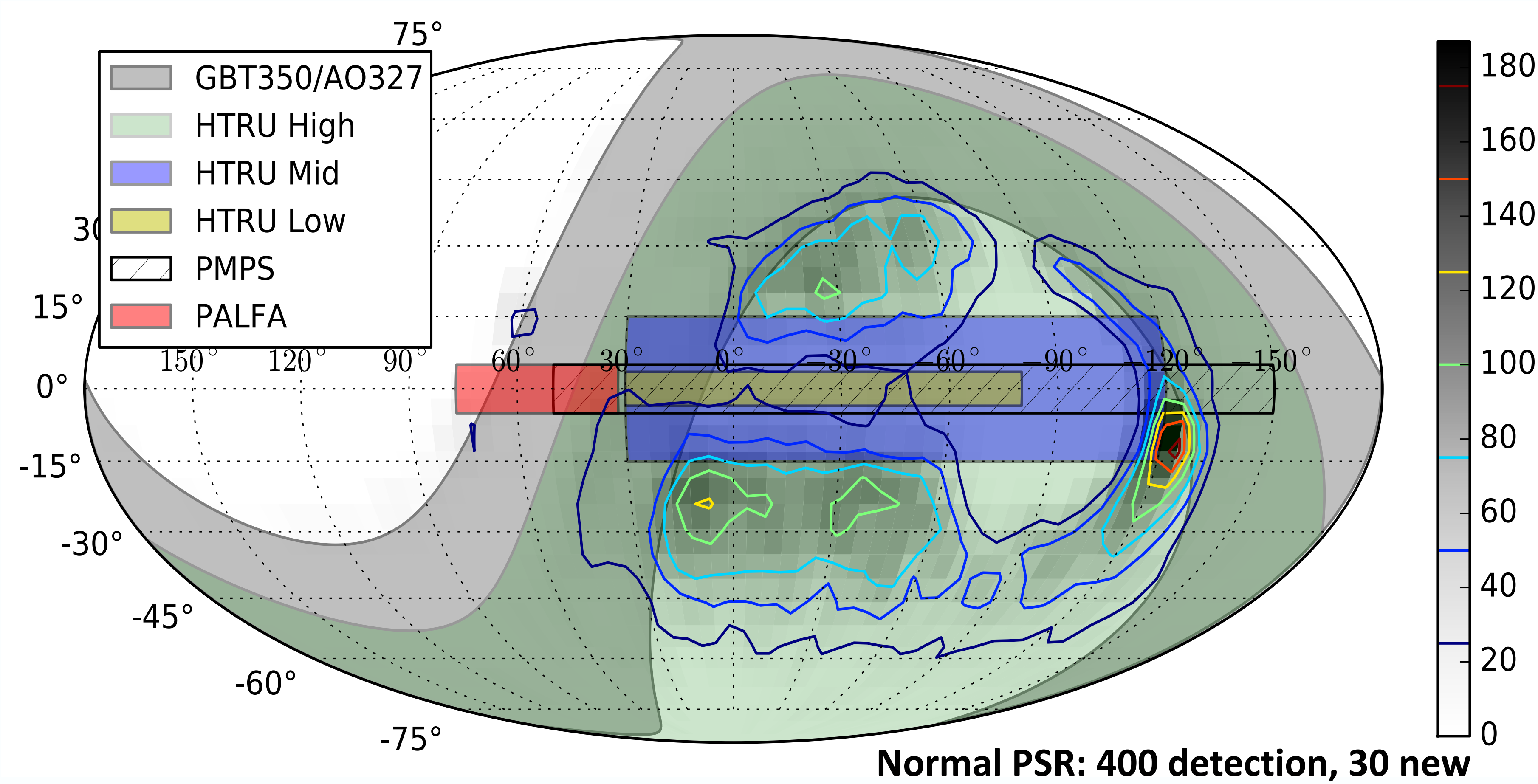
- For a given survey, depending on the central frequency, sensitivity and time and frequency resolution, we are only sensitive to pulsars within a certain distance range.
- Variance images provide information of DMs and distance of pulsars.

Low frequency surveys are sensitive to nearby pulsars while high frequency surveys are sensitive to distant pulsars.



Dai et al. (2016)

How many new pulsars can we find with **EMU**?

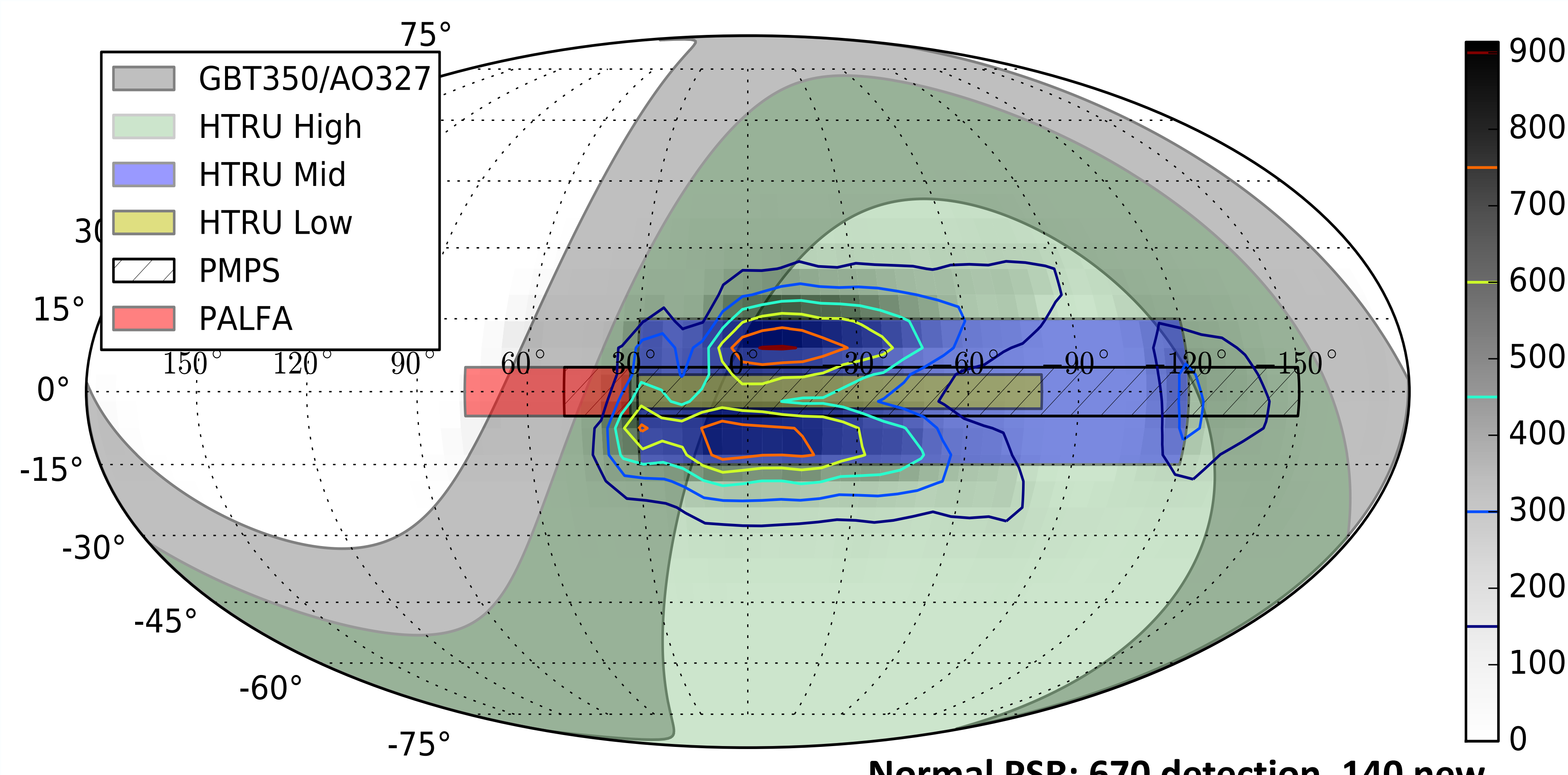


Normal PSR: 400 detection, 30 new

MSP: 170 detection, 40 new

Dai et al. 2017

How many new pulsars can we find with SKA?

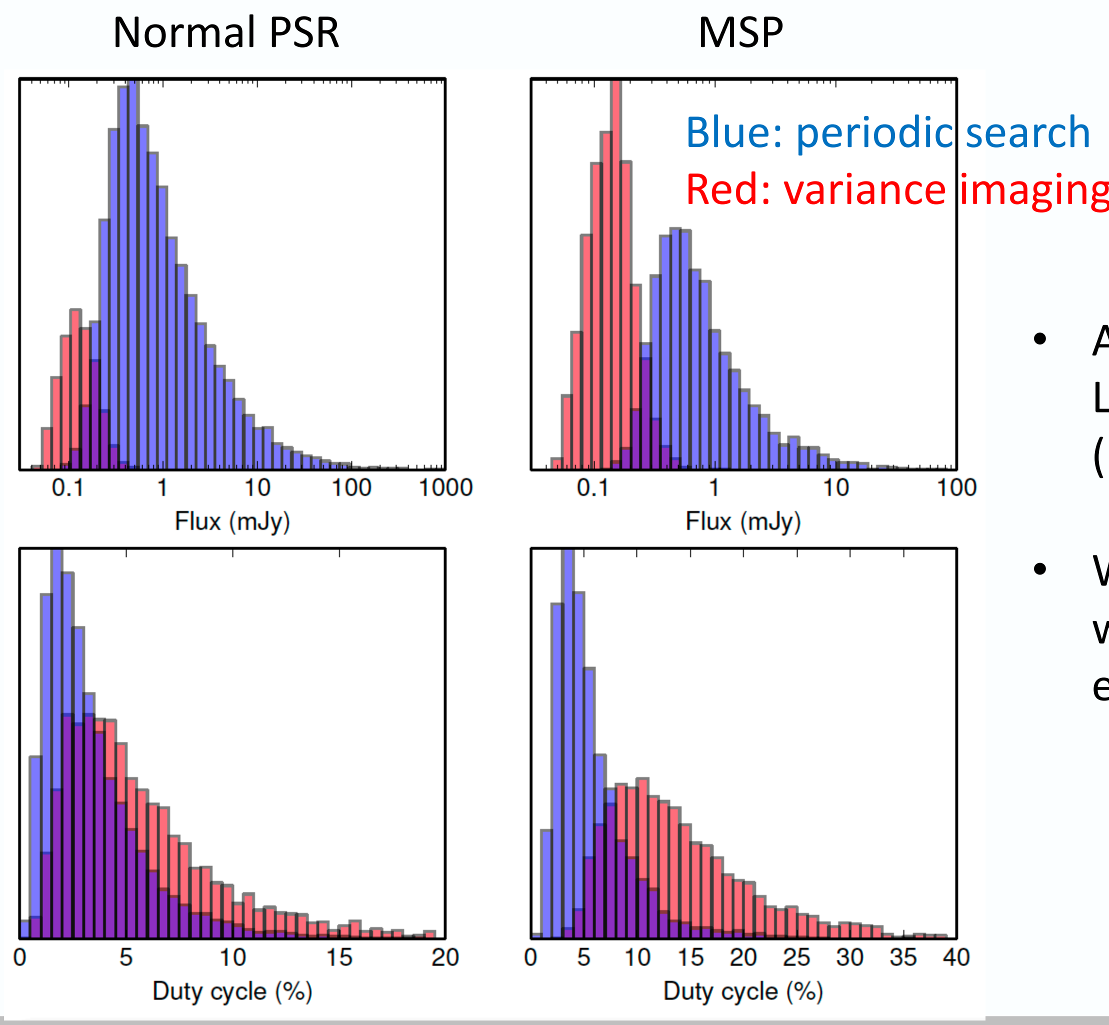


Normal PSR: 670 detection, 140 new

MSP: 210 detection, 110 new

Dai et al. 2017

We can find *extreme* pulsars



- All-sky pulsar survey with SKA-LOW can detect ~900 MSPs (before the re-baselining!)
- We can detect ~210 MSPs, and will be more sensitive to extreme pulsars!

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Multi-wavelength searching and observations

- Targeted search of unidentified Fermi sources is by far the most efficient pulsar survey
  - ✓ By cross-match Fermi catalogue with GMRT continuum source catalogue, Frail et al. (2017) found ***six millisecond pulsars and one normal pulsar out of 16 candidates***
  - ✓ Targeted search of WDs to find millisecond pulsars
- Optical follow-up of new millisecond pulsars (e.g., Subaru)
  - ✓ Measure the mass of both the WD and pulsar
  - ✓ Crucial for testing gravity theories
  - ✓ FAST and Subaru collaborations?

Summary

- Pulsar is one of the key science of SKA
- Future pulsar surveys, with SKA and interferometers:

  continuum image + periodic search
- Interstellar scintillation is useful! Variance imaging?
- Multi-wavelength searching and observations are the future