# WANTED

## ALIVE & SPINNING

## THE GALACTIC CENTRE PULSAR

FOR MEASUREMENT OF SPACETIME PERTURBATIONS NEAR A SUPERMASSIVE BLACK HOLE

**US$1,200,000 reward**


ICRAR
International Centre for Radio Astronomy Research

Jean-Pierre Macquart
Nissim Kanekar, Scott Ransom,
Paul Demorest, Anish Joshi & Dale Frail

Curtin University
The Government of Western Australia
The University of Western Australia

# Pulsars at the Galactic Centre

## Why?

## What have we tried?

- A long and distinguished history of failures

## Causes for optimism and for pessimism

- Fermi & X-ray backgrounds
- GC Magnetar

## The case for MSPs

## Where to from here?

# Why find a pulsar at the GC?

- Tests of General Relativity (Pfahl & Loeb 2004)
  - Spin of Sgr A*?
    - ***Measure the BH spin*** from frame dragging (Lens-Thirring precession)
  - Need something suitable for timing
    - Magnetar: 0.12pc away, if circular orbit, $P_{orb}$=2300 y
    - Ideally need an unassociated MSP

TABLE 1

PULSE ARRIVAL-TIME DELAYS

| Delay[a] | Amplitude | Width | References |
|---|---|---|---|
| Roemer[b] | $\sim(1\ \mathrm{day})M_{6.5}^{1/3}P_1^{2/3}\sin i$ | $\sim(1\ \mathrm{yr})P_1$ | 1 |
| Einstein[c] | $\sim(1\ \mathrm{hr})M_{6.5}^{2/3}P_1^{1/3}e$ | $\sim(1\ \mathrm{yr})P_1$ | 1 |
| First-order Shapiro[d] | $\sim(30\ \mathrm{s})M_{6.5}\lvert\ln[(1-e)(1-\sin i)]\rvert$ | $\sim(1\ \mathrm{yr})P_1(1-e)^{3/2}(\cos i)^{1/2}$ | 1 |
| Second-order Shapiro[e] | $\sim(0.1\ \mathrm{s})M_{6.5}^{5/3}P_1^{-2/3}(1-e)^{-1}/\cos i$ | $\sim(1\ \mathrm{yr})P_1(1-e)^{3/2}\cos i$ | 2, 3 |
| Frame dragging[f] | $\sim(0.1\ \mathrm{s})M_{6.5}^{5/3}P_1^{-2/3}(1-e)^{-1}\chi/\cos i$ | $\sim(1\ \mathrm{yr})P_1(1-e)^{3/2}\chi\cos i$ | 2, 3, 4, 5 |

[a] The dimensionless variables used are $M_{6.5}=M_{\mathrm{BH}}/10^{6.5}\ M_\odot$ and $P_1=P_{\mathrm{orb}}/1$ yr. For simplicity, we have adopted $\omega=90^\circ$ in estimating the amplitudes and widths.

[b] Light travel time across the orbit. The Keplerian orbit is evident in the Roemer delay.

[c] Combined effect of time dilation and the gravitational redshift.

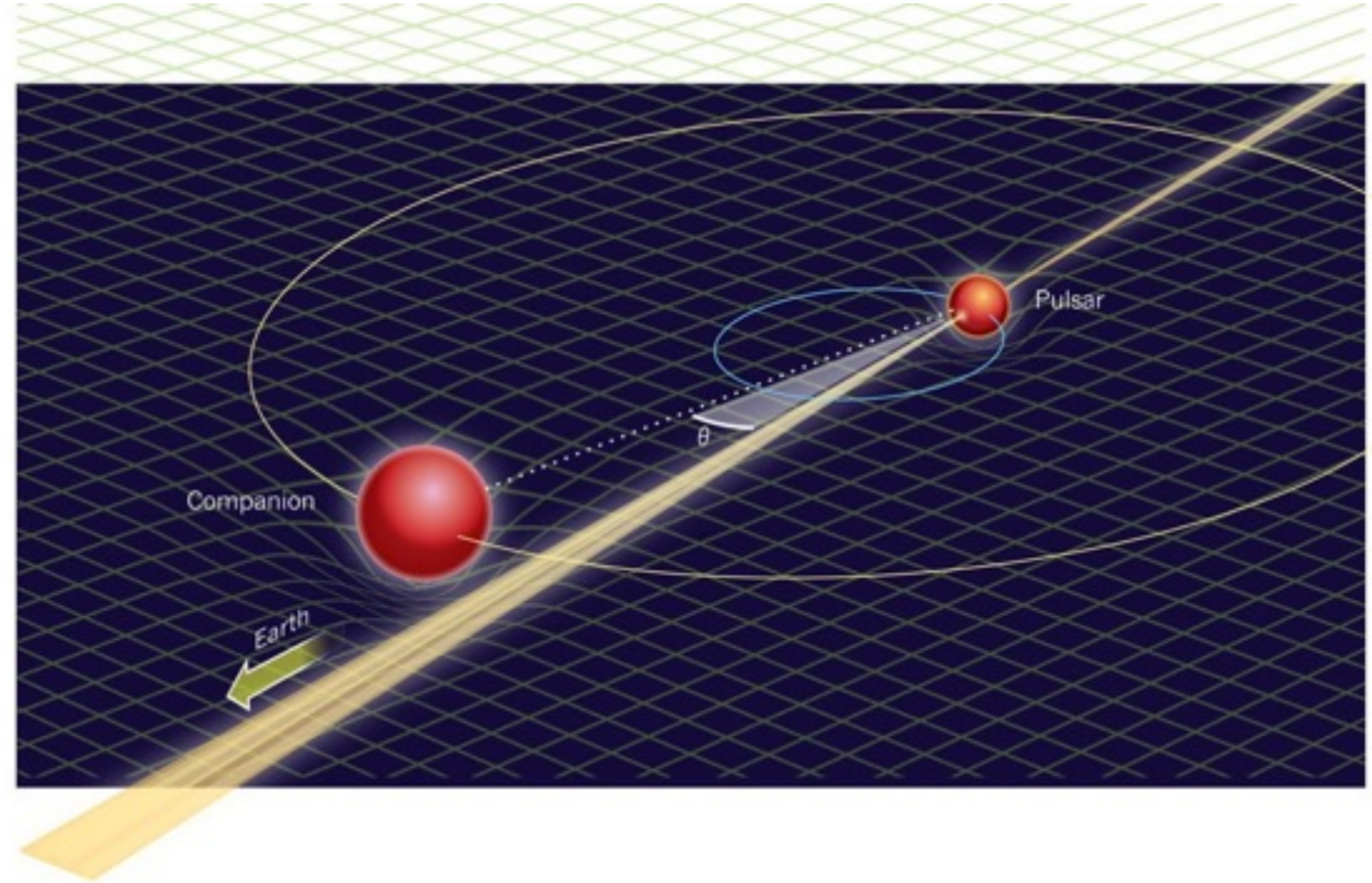
[d] Lowest order relativistic propagation delay in the gravitational field of a point mass.

[e] Next highest order contribution to the propagation delay that is independent of the BH spin.

[f] Contribution to the net propagation delay due to the BH spin, in the special case in which the spin direction is parallel to the orbital angular momentum of the pulsar. Here $0<\chi<1$ is the dimensionless spin parameter, where $\chi=1$ corresponds to an extreme Kerr BH.

# Pulsar timing effects

## Shapiro delay




$$\text{Shapiro: } 30\left(\frac{M}{10^{6.5}M_\odot}\right)\left|\ln\frac{1-e}{1-\sin i}\right|\,\mathrm{s}$$

$$\text{Second-order Shapiro: } 0.1\frac{1}{\cos i(1-e)}\left(\frac{M}{10^{6.5}M_\odot}\right)^{5/3}\left(\frac{P_{\mathrm{orb}}}{1\,\mathrm{yr}}\right)^{-2/3}\,\mathrm{s}$$

$$\text{Frame-dragging: } 0.1\frac{\chi}{\cos i(1-e)}\left(\frac{M}{10^{6.5}M_\odot}\right)^{5/3}\left(\frac{P_{\mathrm{orb}}}{1\,\mathrm{yr}}\right)^{-2/3}\,\mathrm{s}$$

# Reasons for optimism

**Pfahl & Loeb (2004) argue that**

~1000 pulsars orbit Sgr A* with periods <100 yr

- 1-10 of which are detectable
- Specifically, they argue that

$$f(>S_{\rm min}) \approx 16\% \left(\frac{S_{\rm min}}{10\,\mu{\rm Jy}}\right)^{-1} \left(\log\left[\frac{\nu}{400\,{\rm MHz}}\right]\right)^{-1}$$

based on the estimate that ~10% have shallow spectra.

**Circumstantial evidence from:**

Pulsar Wind Nebulae

Supernova remnants

Fermi excess

NuStar excess

# Reasons for optimism

- GC *Fermi* GeV emission attributed to dark matter may actually be a signal of this as-yet undetected young pulsar population (O'Leary et al. 2015)

- Mirabel (2013) makes a similar argument

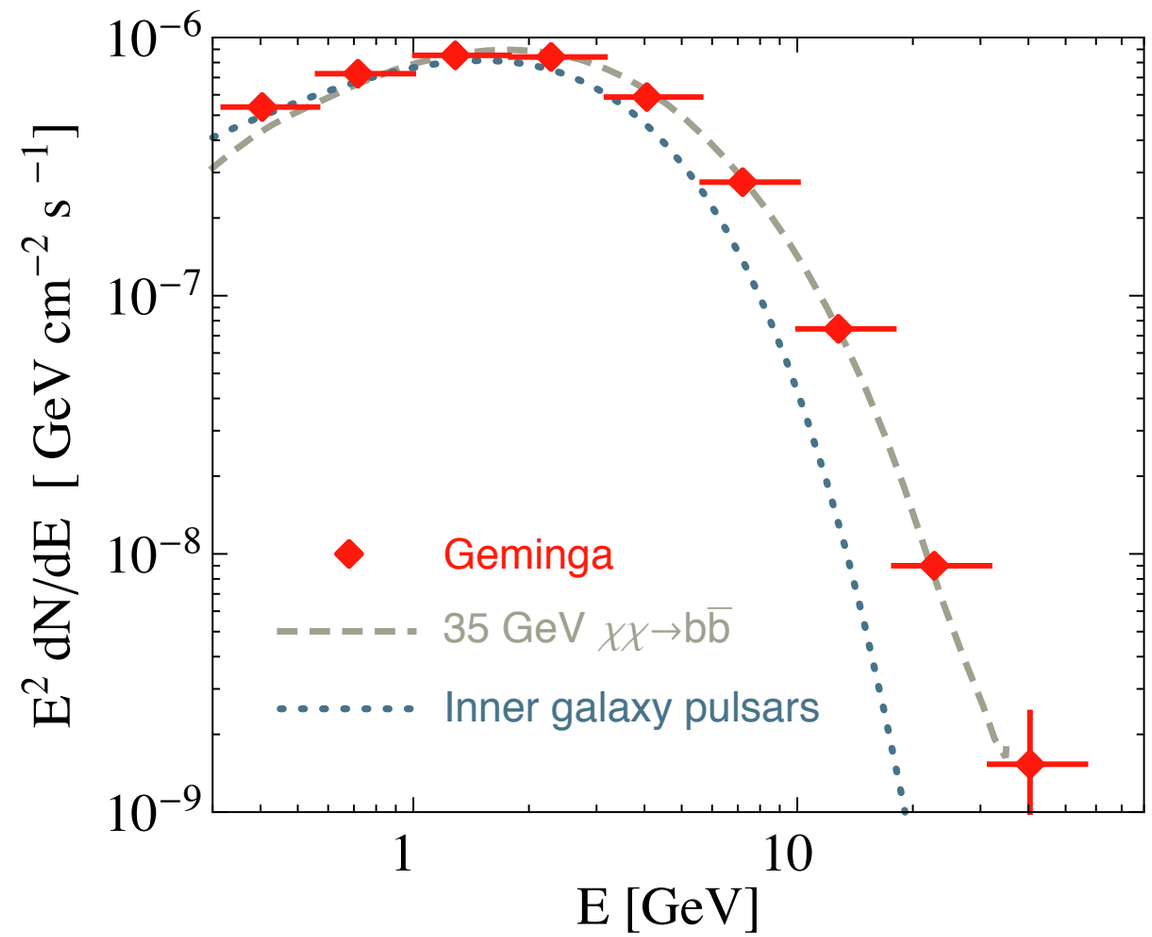



FIG. 1: A comparison of phase-averaged *Fermi* gamma-ray data of Geminga [52] to our spectral shape from pulsars within 5° of the GC and > 2° from the disk (see text), which resemble that from 35 GeV dark matter particles annihilating to $b\bar{b}$ as proposed to explain the GC Excess [25].

# Reasons for optimism

- Perez et al. (2015) find an excess of hard X-rays (20-40keV) at the GC that is either due to

- accreting white dwarfs
- large population of low-mass X-ray binaries
- large population of MSPs
- particle outflows interacting with radiation field, molecular material or magnetic field

- The X-ray MSP interpretation would strengthen the interpretation of the gamma-ray excess in terms of MSPs.

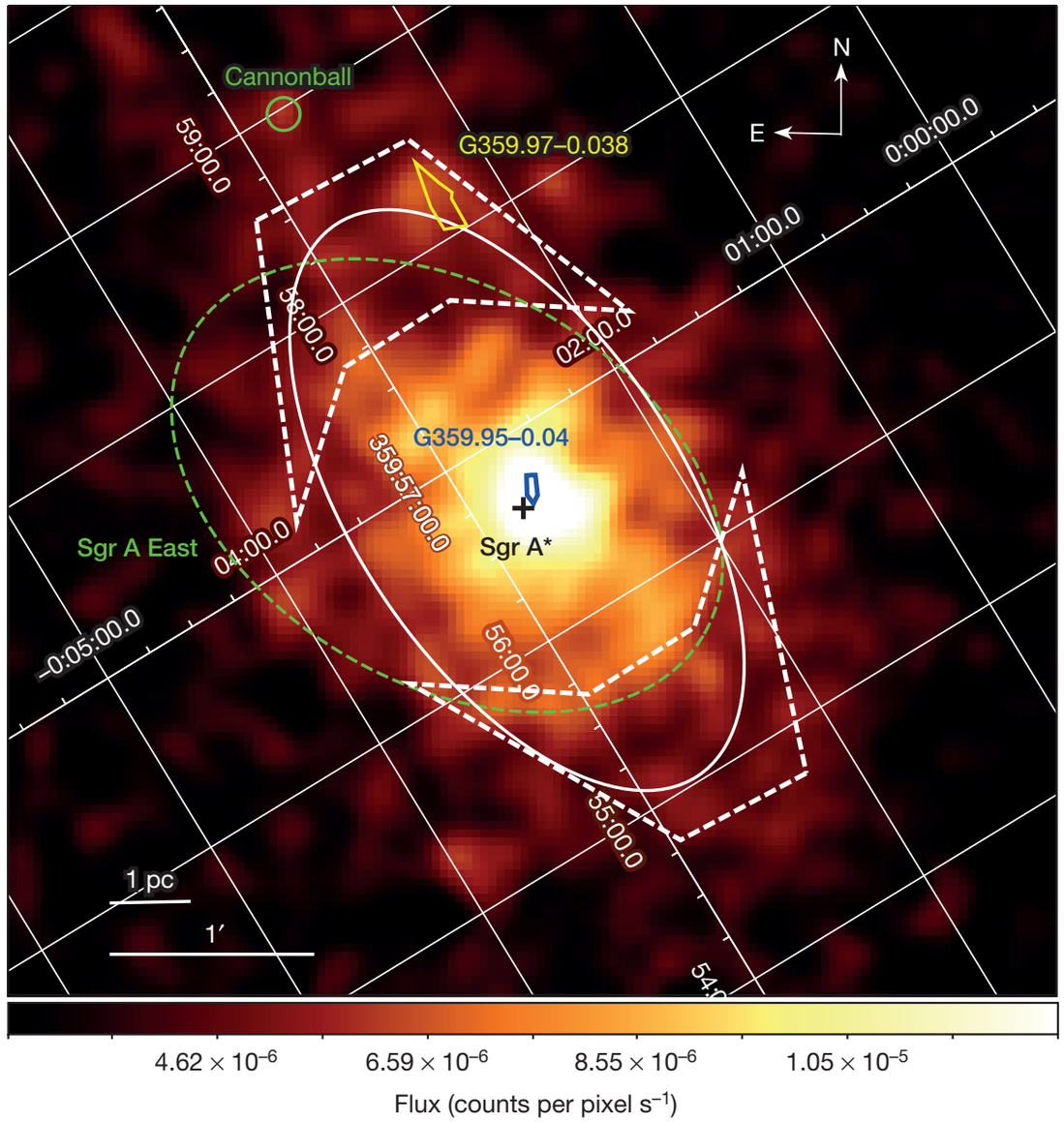


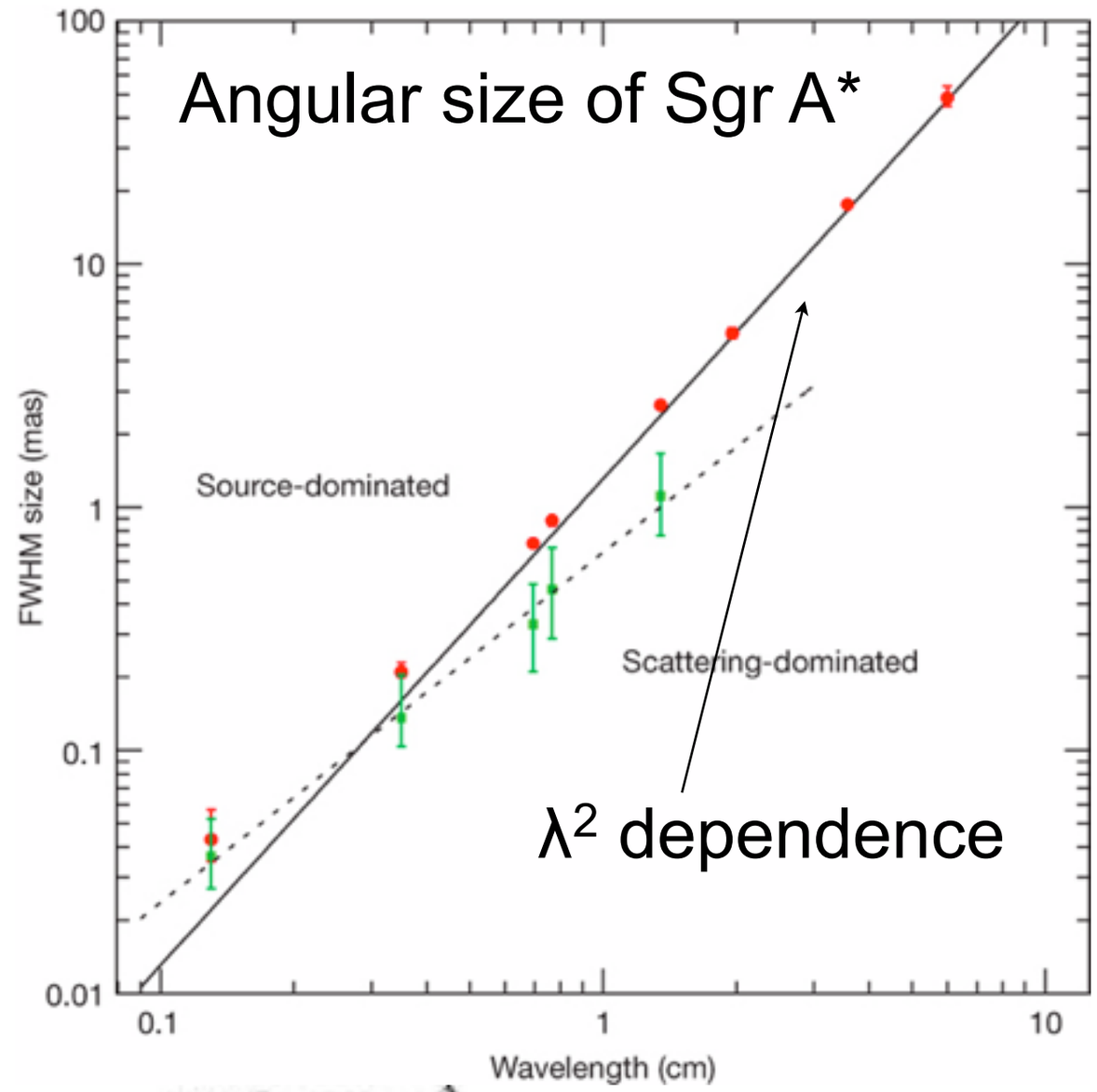

**Figure 1 | The 20–40 keV image of the inner 5′ × 5′ (12 pc × 12 pc) of the Galaxy.** The colour scale shows flux in units of counts per pixel $s^{-1}$. The image has been smoothed with a Gaussian kernel of width ~5″ (2 pixels). The solid ellipse (white) illustrates the FWHM of the fit to the unresolved emission.

# So, what's the problem?

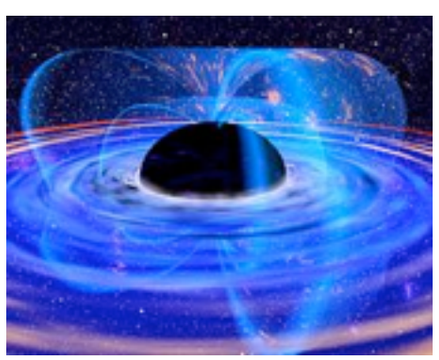
- Despite several deep searches, no regular pulsar has ever been found at the GC
- Thought that turbulent plasma associated with Sgr A* made this prohibitive
- Angular broadening constrains the scale of the scattering pattern, but the screen distance is need to determine the scattering time

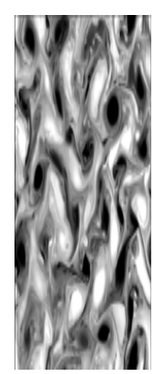
$$\tau = \frac{D}{c}\left(\frac{D}{\Delta} - 1\right)\theta_{\rm scat}^2$$

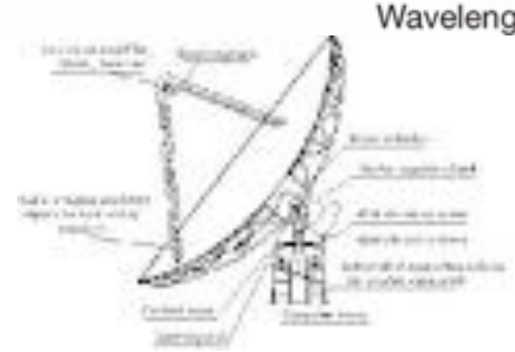
- D=130pc implies t~400s




*Doeleman et al. 2008*







D

Δ

# The GC scattering environment

- Lazio & Cordes (1998) estimated the scattering occurs within $133^{+200}_{-80}$ pc of Sgr A* based on
  - distribution of angular broadened sOH/IR stars in the GC
  - the paucity of AGN near the GC
  - Inconsistent with limits based on free-free absorption (van Langevelde et al. 1992)
  - If near to Sgr A*: to overcome lever-arm effect scattering has to be so strong that a high density and EM is implied
  - But absence of self-absorption at 1 GHz puts an upper limit on EM.

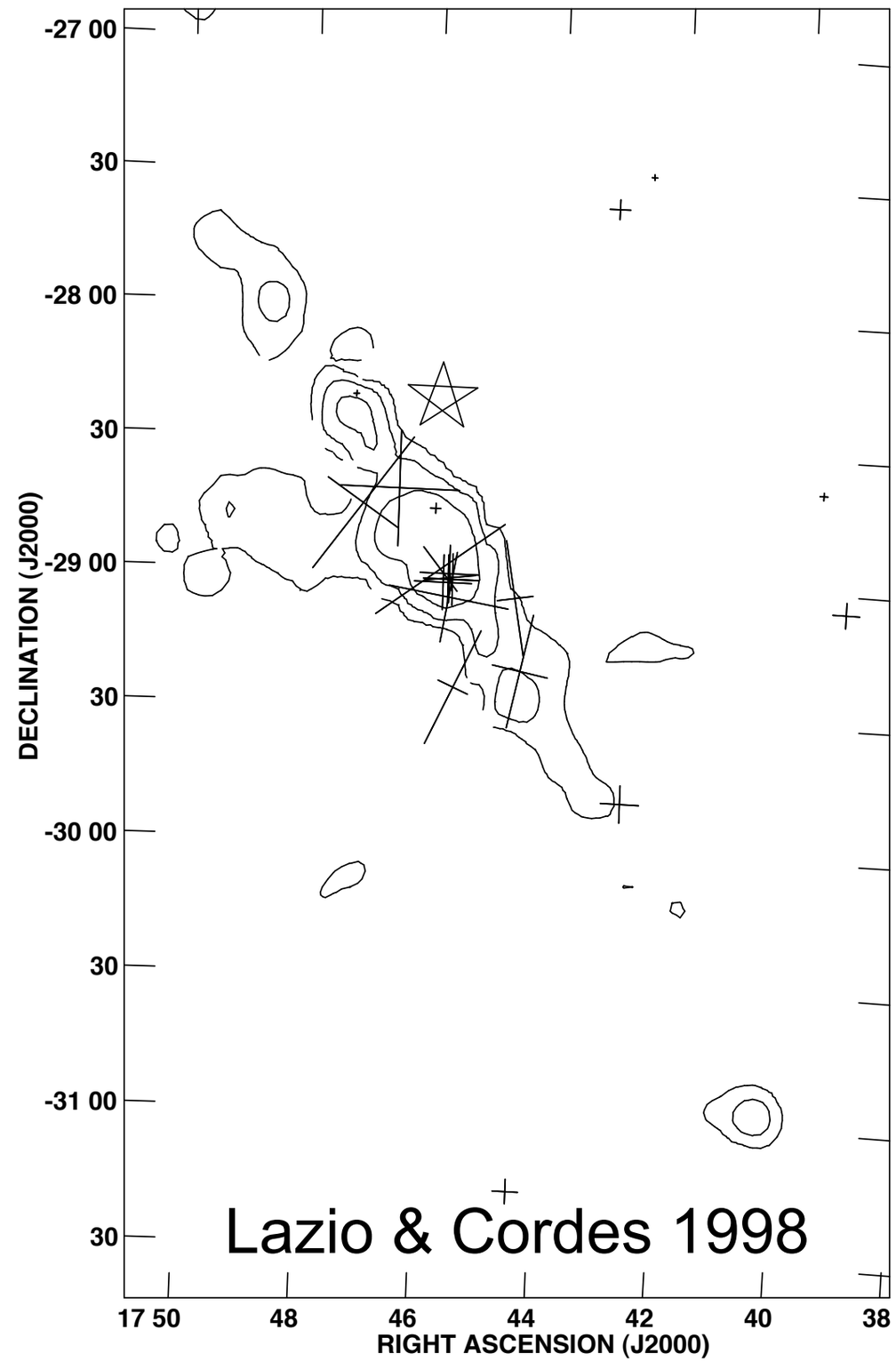


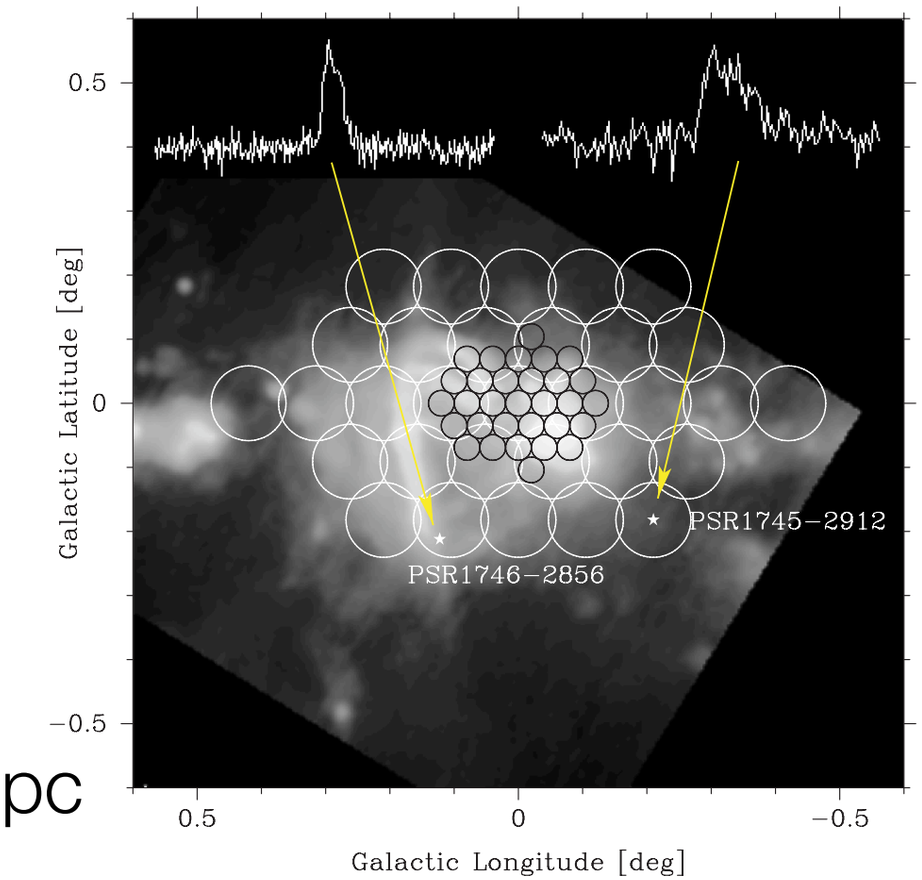

FIG. 3.—Angular broadening measurements toward the GC compiled

# Reasons for pessimism

**Not a single pulsar has been detected with 10' of Sgr A***

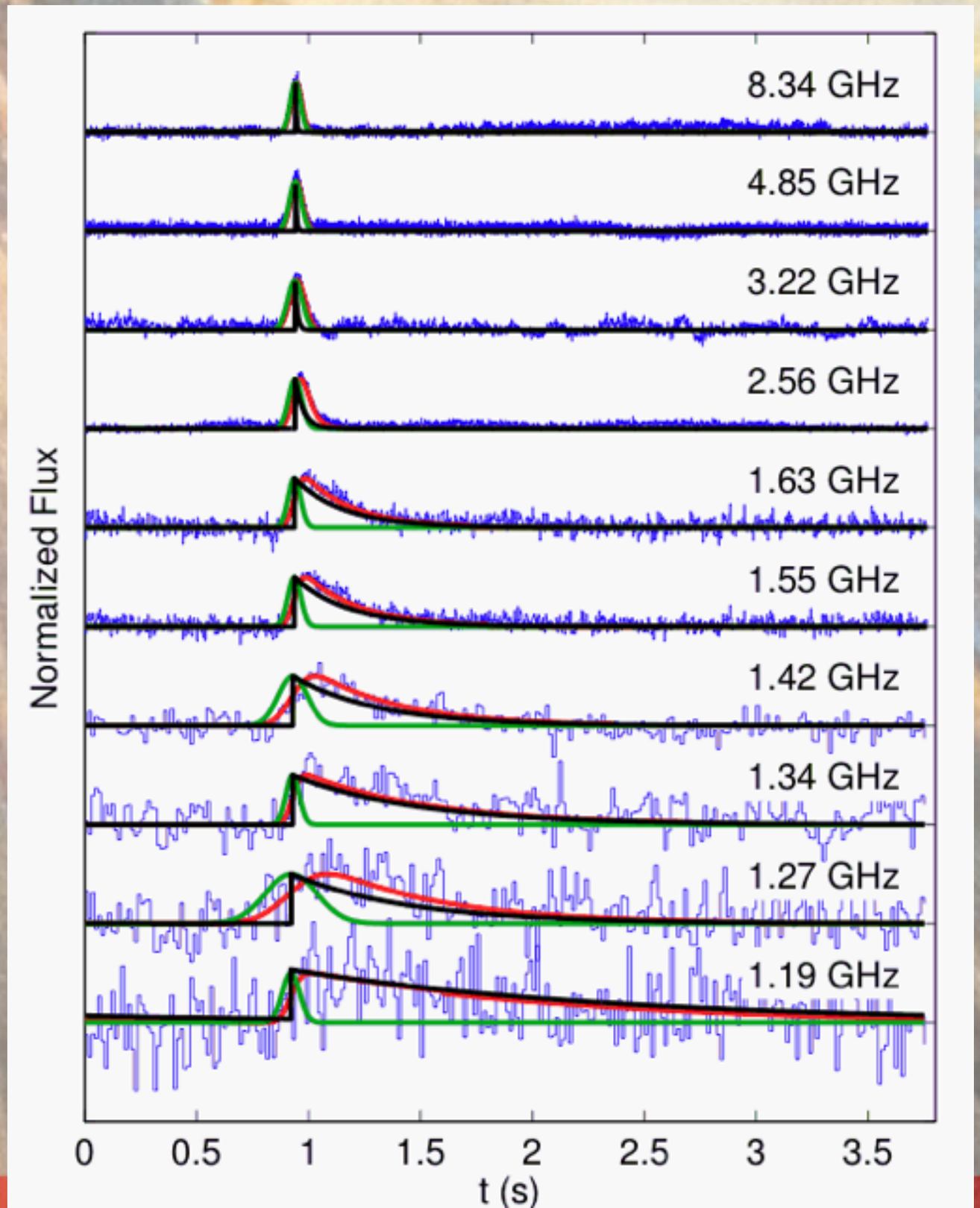
Previous searches by

- *Johnston* et al. 2006 (Parkes)
  - found 2 psrs at 3.1GHz within 0.3°
  - none found at 8.4 GHz
- *Deneva* et al. 2009
  - Searches at 2, 5 & 8 GHz with GBT
- *Macquart* et al. 2010
  - Searched to 10μJy at 15 GHz with GBT
  - Estimate <90 normal psrs within central pc
- *Siemion* et al. 2013: 12-18 GHz
- *Eatough* et al. 2013: 19 GHz




If the high-energy backgrounds are due to pulsars, where are the corresponding BH systems?

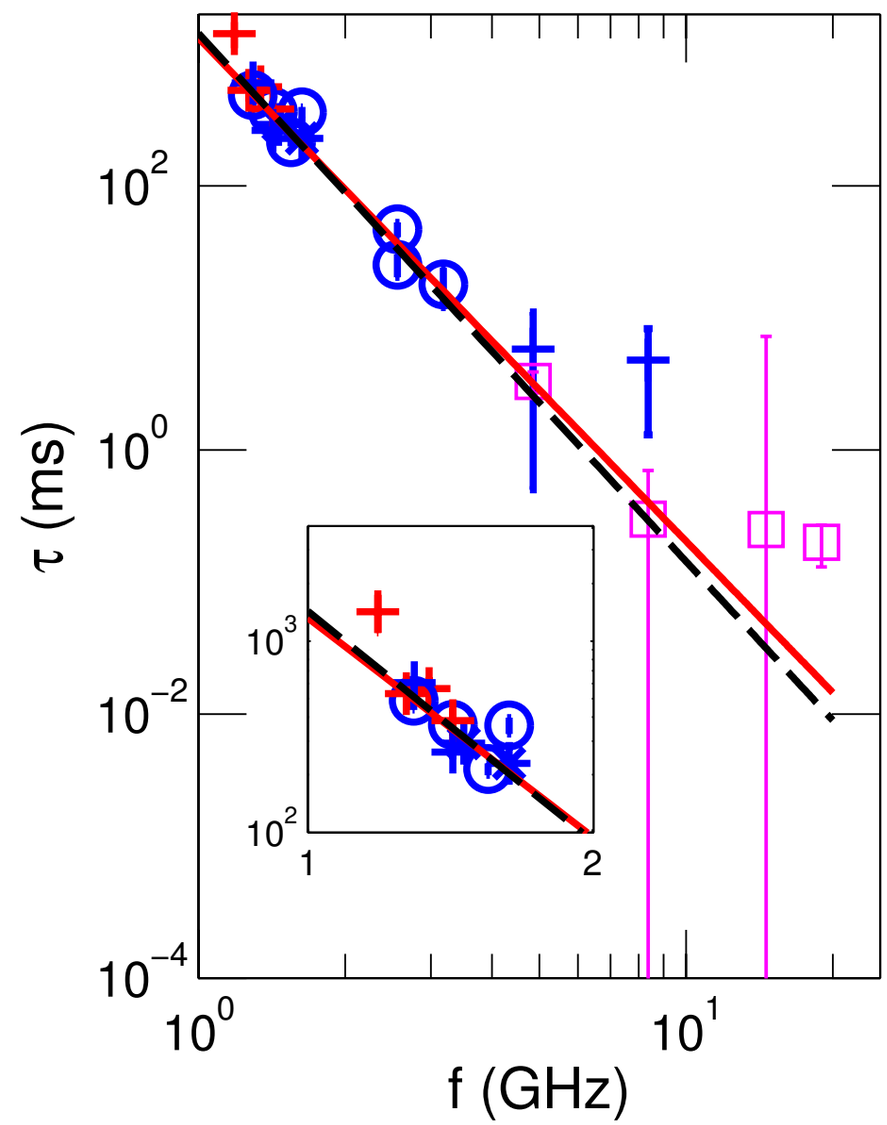
# The Abominable Magnetar



# Magnetar implications

- Magnetar scattering timescale is 1.3s at 1GHz
- Best screen distance is 5kpc from Sgr A* itself
- Since $\tau \propto \nu^{-4}$, finding regular pulsars should be easy at 5GHz
- We know pulsar should be there
  - many tens of XRBs are detected in the GC area (roughly half are inferred NS systems)
- Is the turbulent plasma highly patchy?
  - same angular broadening as Sgr A*
  - VLBI measurements (Wucknitz et al.) show illumination of scattering disk vs scattering time

$$\tau \propto \nu^{-3.8\pm0.2}$$




*Spitler et al. 2013*

# Magnetars?

Dexter & O'Leary (2014):

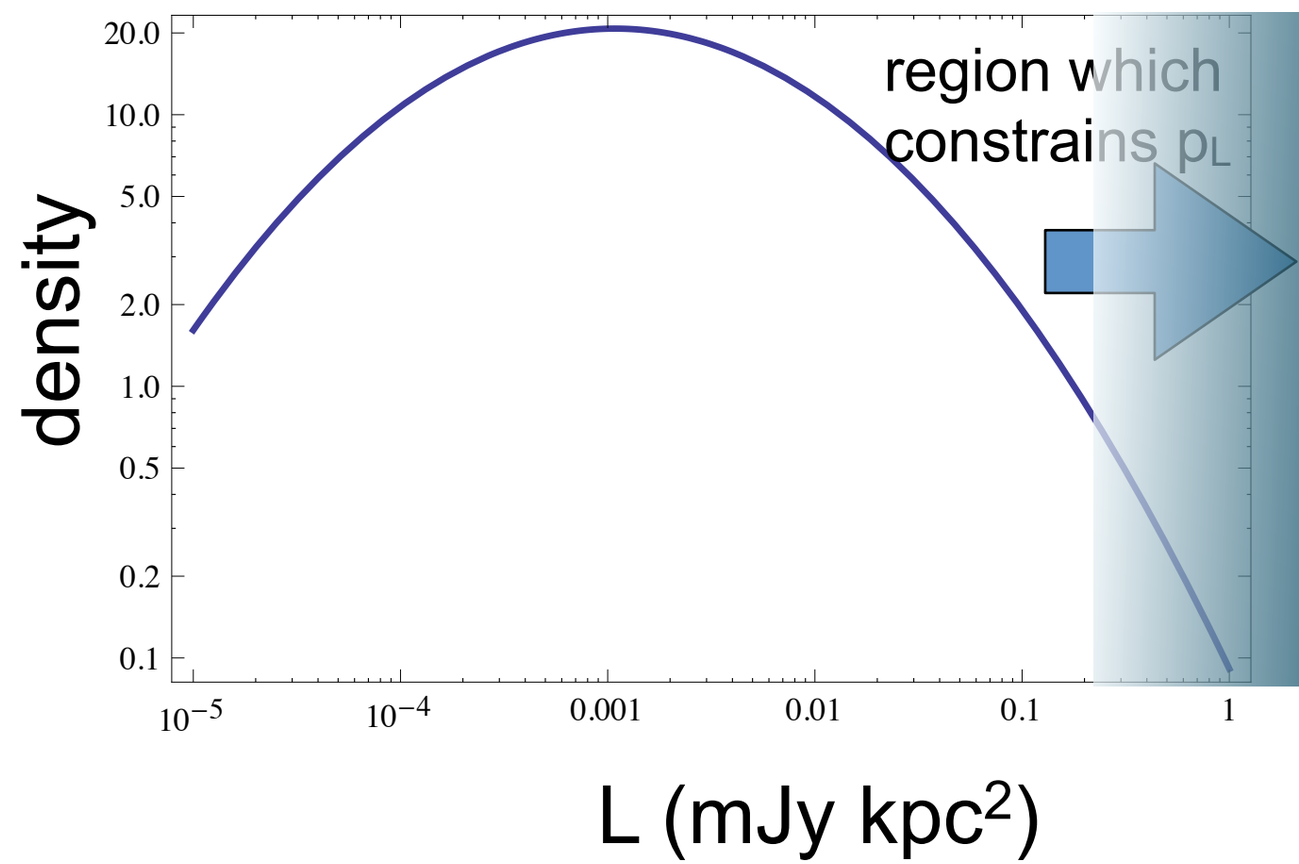
- Macquart et al. 15 GHz search was sensitive to 20% of the GC population if it resembles the characteristics of the known population

- Argue that GC population is very different from the rest of the Galaxy and dominated by magnetars

# Where are all the slow pulsars?

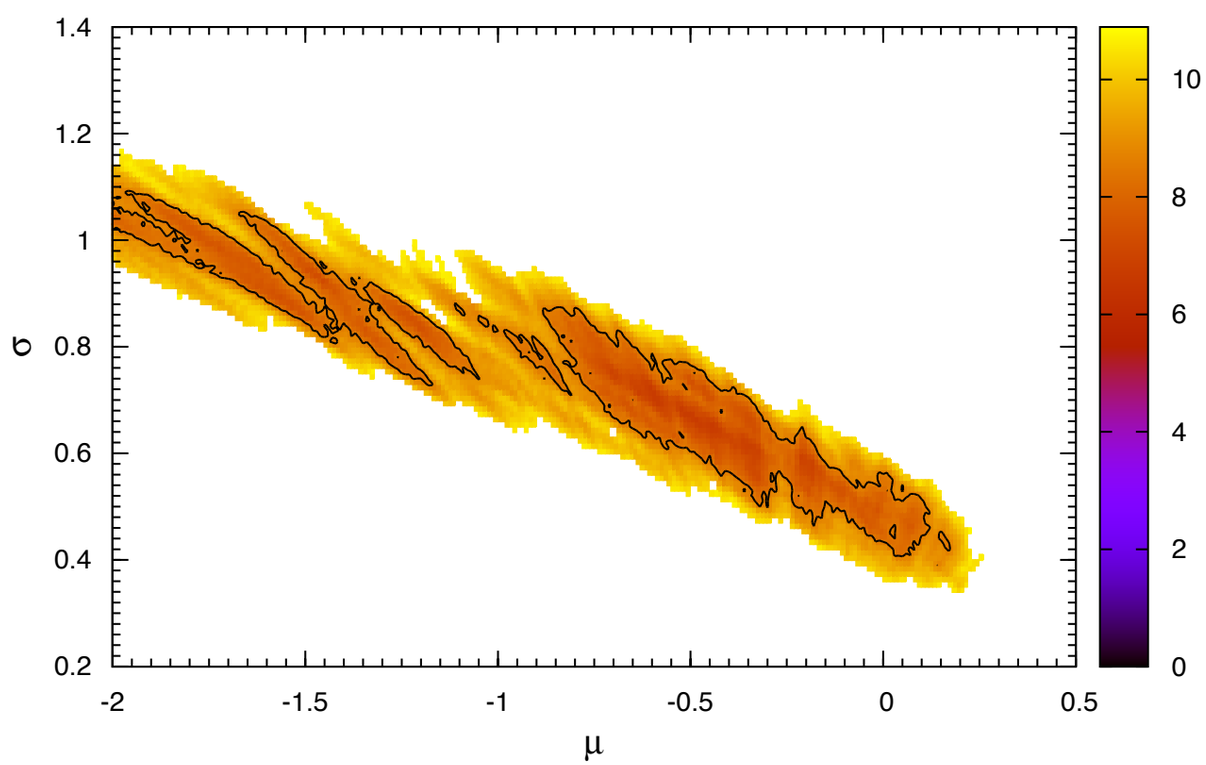
- If GC population resembles that detected elsewhere in the Galaxy we should have
  - detected a large number of slow pulsars
  - at most a few MSPs
- Are most of the pulsars at the GC are MSPs?
  - GC Stellar density is ~$10^3$ higher than in globular clusters. A high fraction should be spun up
- Contrary viewpoint (Chennamangalam & Lorimer 2014):
  - Macquart/Deneva surveys permit 3000/800 slow GC pulsars based on a Bayesian analysis that takes magnetar detection into account
  - Underpinned by an assumed specific log-normal pulsar luminosity function:

*Log-normal luminosity distribution of C&L14*



# The slow pulsar conundrum

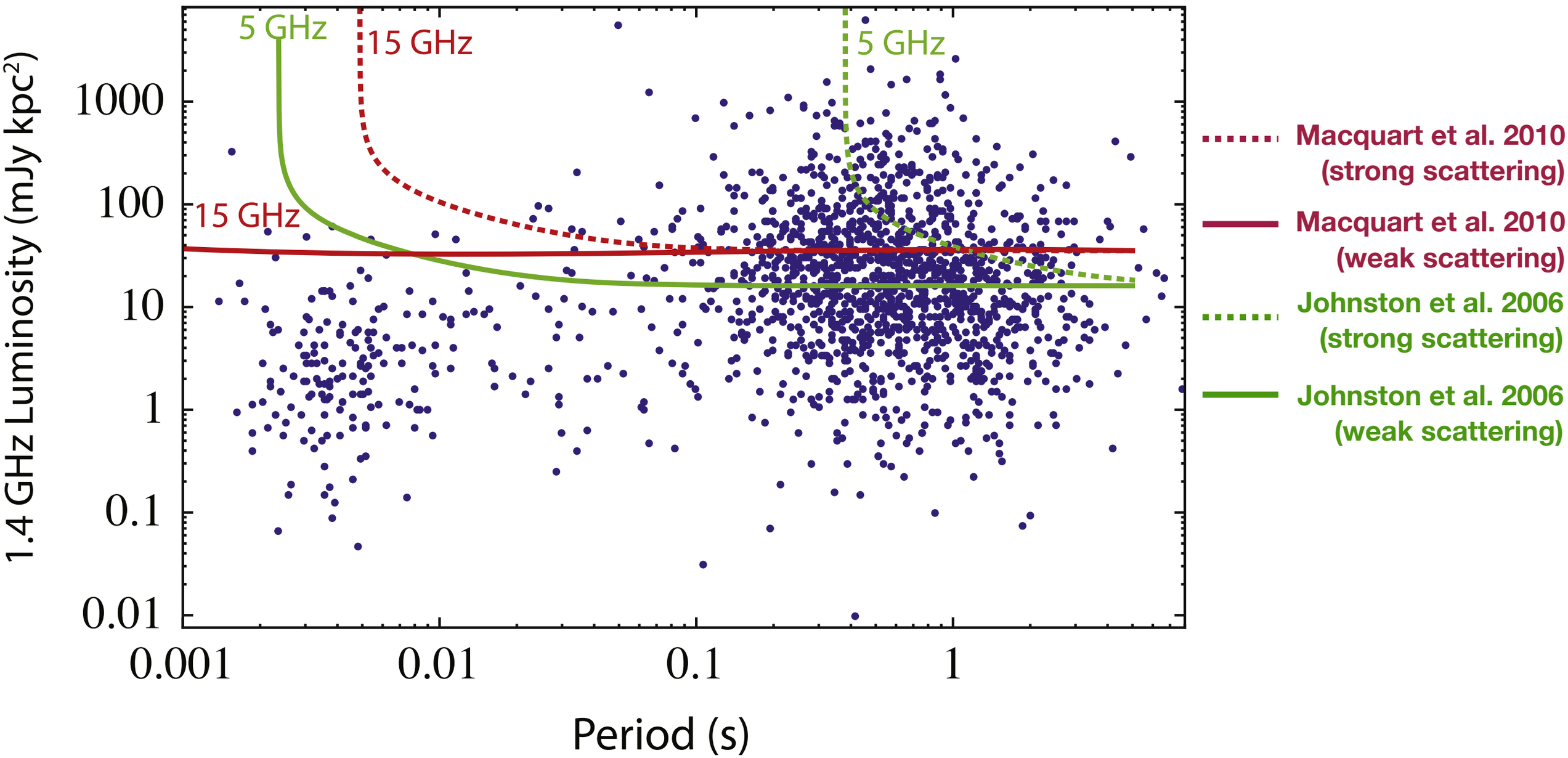
- Uncertainties in this distribution (constrained only by its tail) translate into ~100 uncertainty in the size of the missing population
  - Peak in the luminosity function predicted to occur at 1.1 mJy $kpc^2$
  - …but possibly as high as 400 mJy $kpc^2$ given the uncertainty in the distribution!
    - E.g. For fiducial parameters in $\mu$=-1.1 and $\sigma$=0.9 used by C&L14 the Deneva survey completeness is $5.2 \times 10^{-3}$, but for $\mu$=-0.9 and $\sigma$=1.1 the completeness is $3 \times 10^{-2}$.
  - For Galactic MSPs (Bagchi et al. 2012) $\mu$ varies between -2 and -0.3, and $\sigma$ between 0.25 and 1.0




Variation in $\chi^2$ as a function of $\sigma$ and $\mu$ in the Galactic Globular Cluster MSP population

# A missed population

*Best GC survey limits against objects in the ATNF pulsar catalogue*
*10σ limits*



# Solution to the conundrum

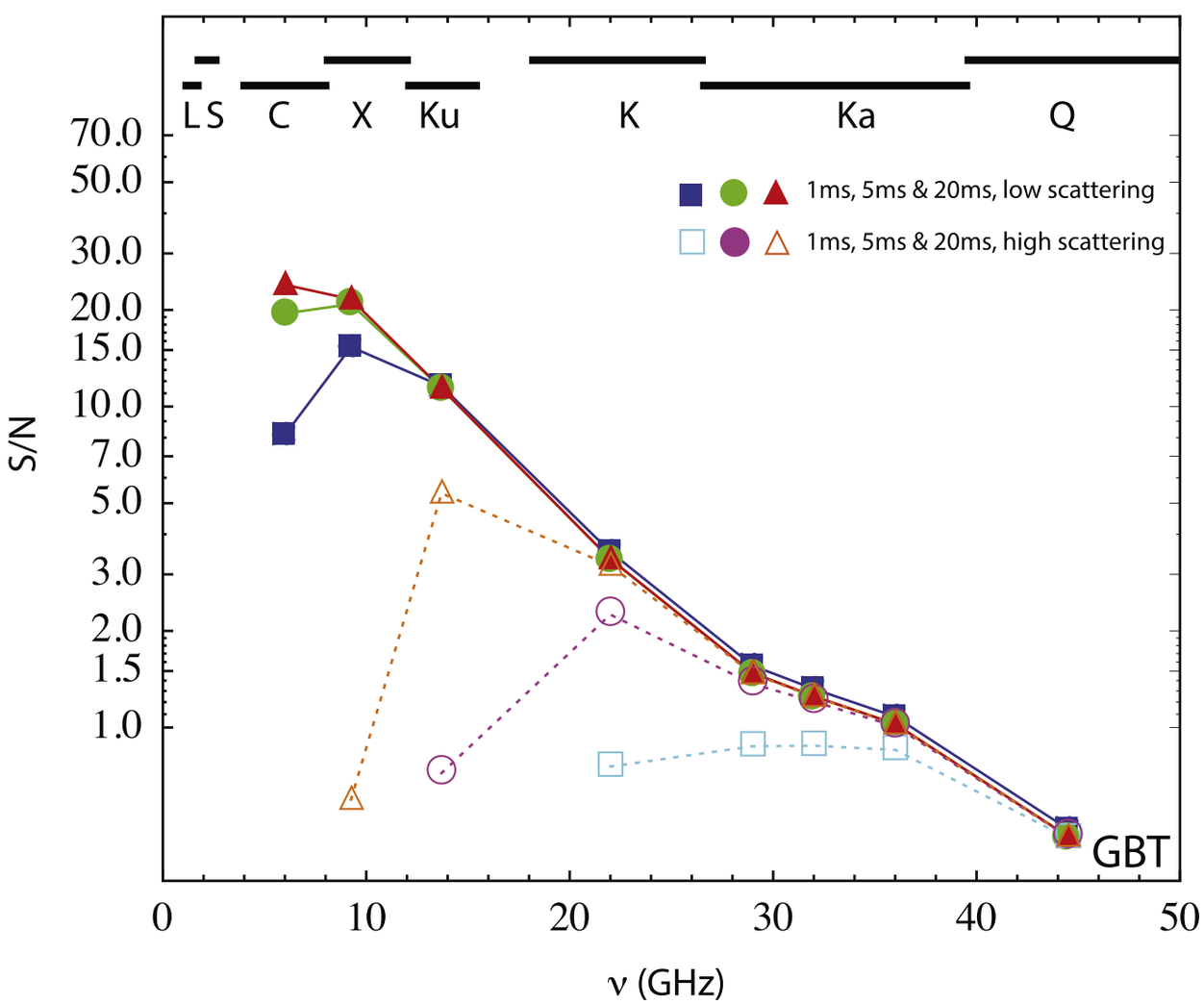
- Given the previous non-detections, where is the next best place to look?

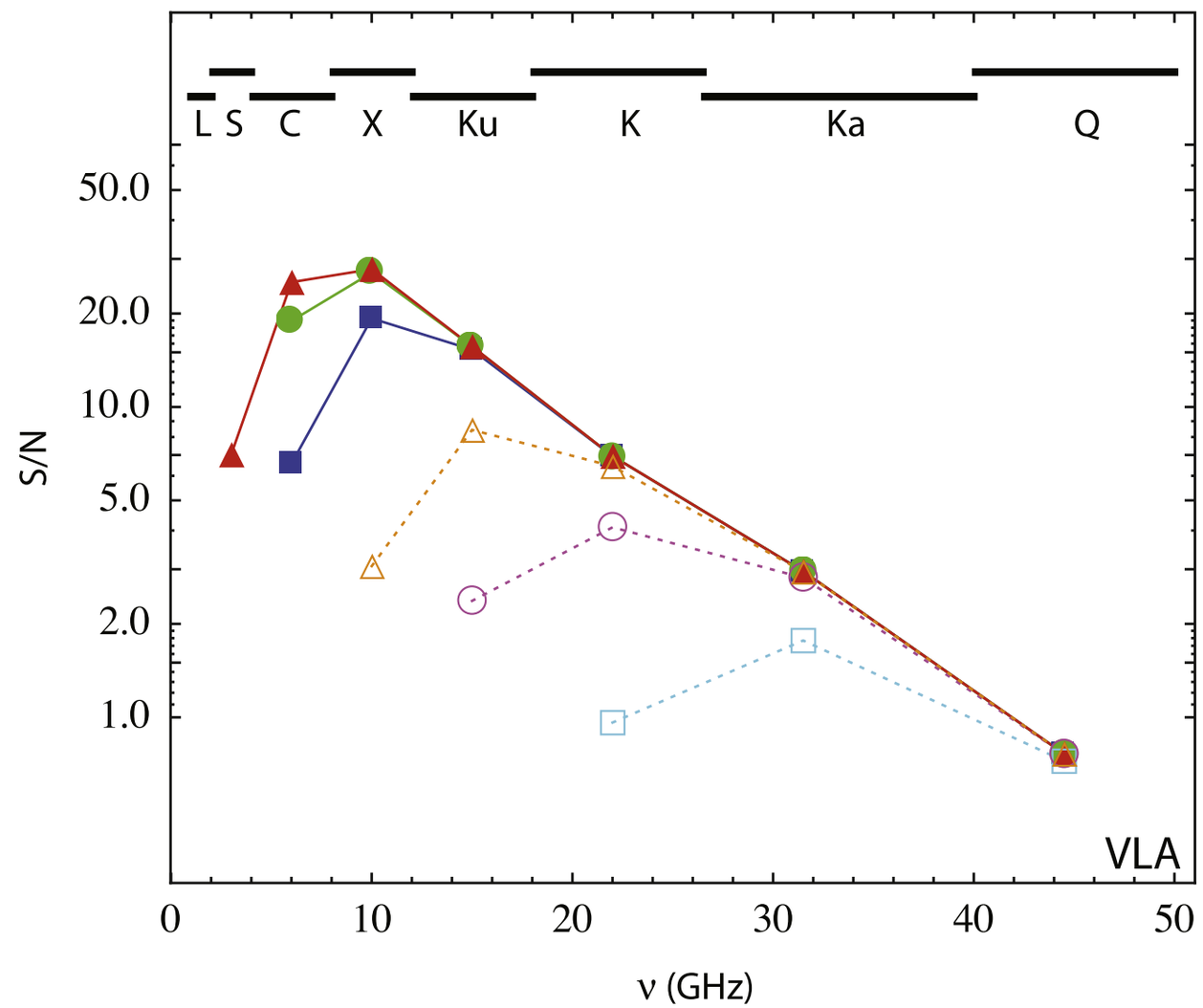
- Rigorous S/N calculations that take into account all possible instrumental characteristics (especially large bandwidth)
  - GC contribution to the sky temperature (beam size dependent)
  - Revised scattering model
  - New telescope bandwidths, receivers & upgrades
    - GBT
    - JVLA
    - SKA1
  - Pulsar spectral index across band

# Where should we search?

*Macquart & Kanekar 2015*

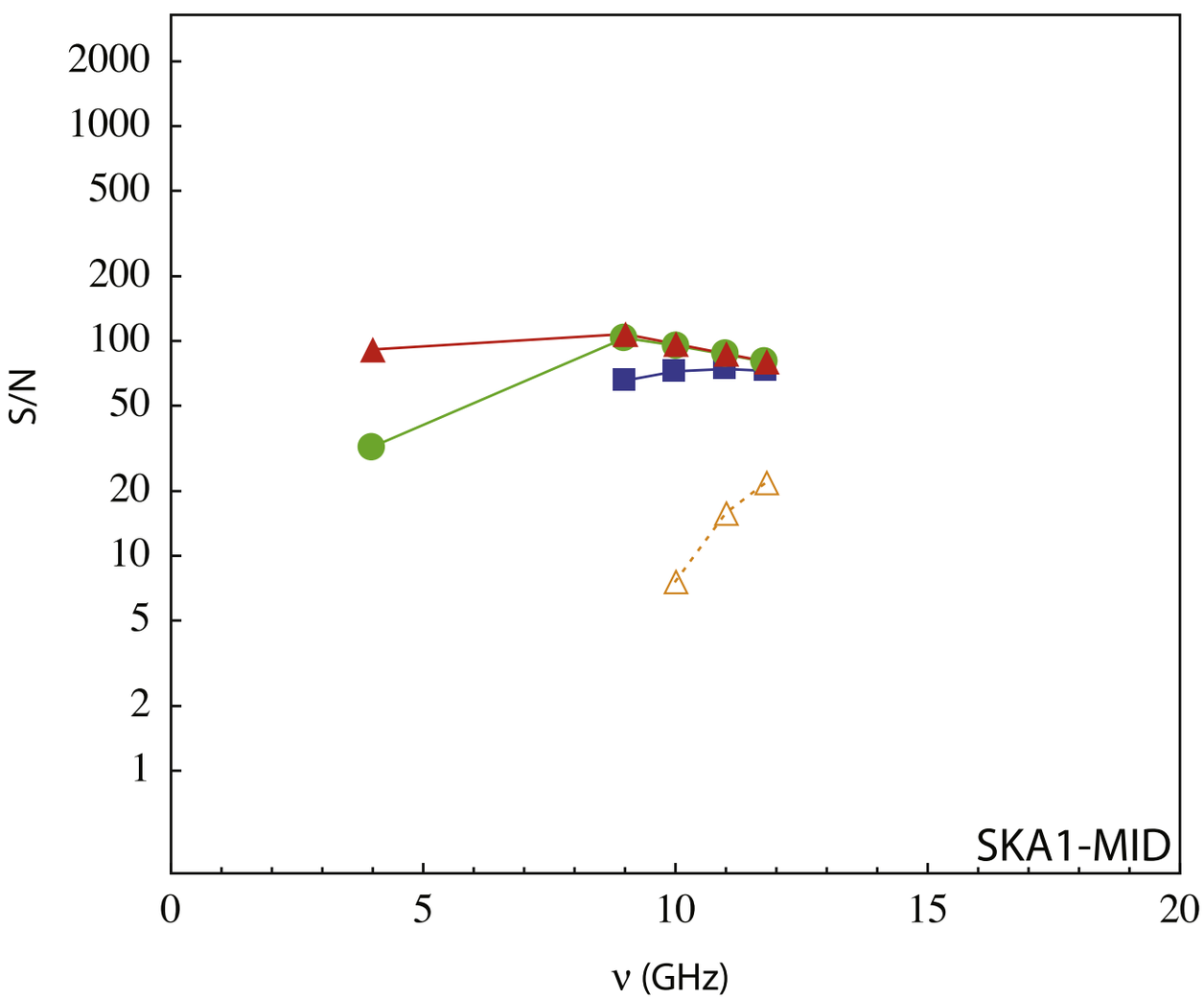
**GBT and JVLA S/N for a 30h integration on a $L_{1.4}$=10 mJy kpc$^2$ pulsar with α=-1.7 & 10% duty cycle**

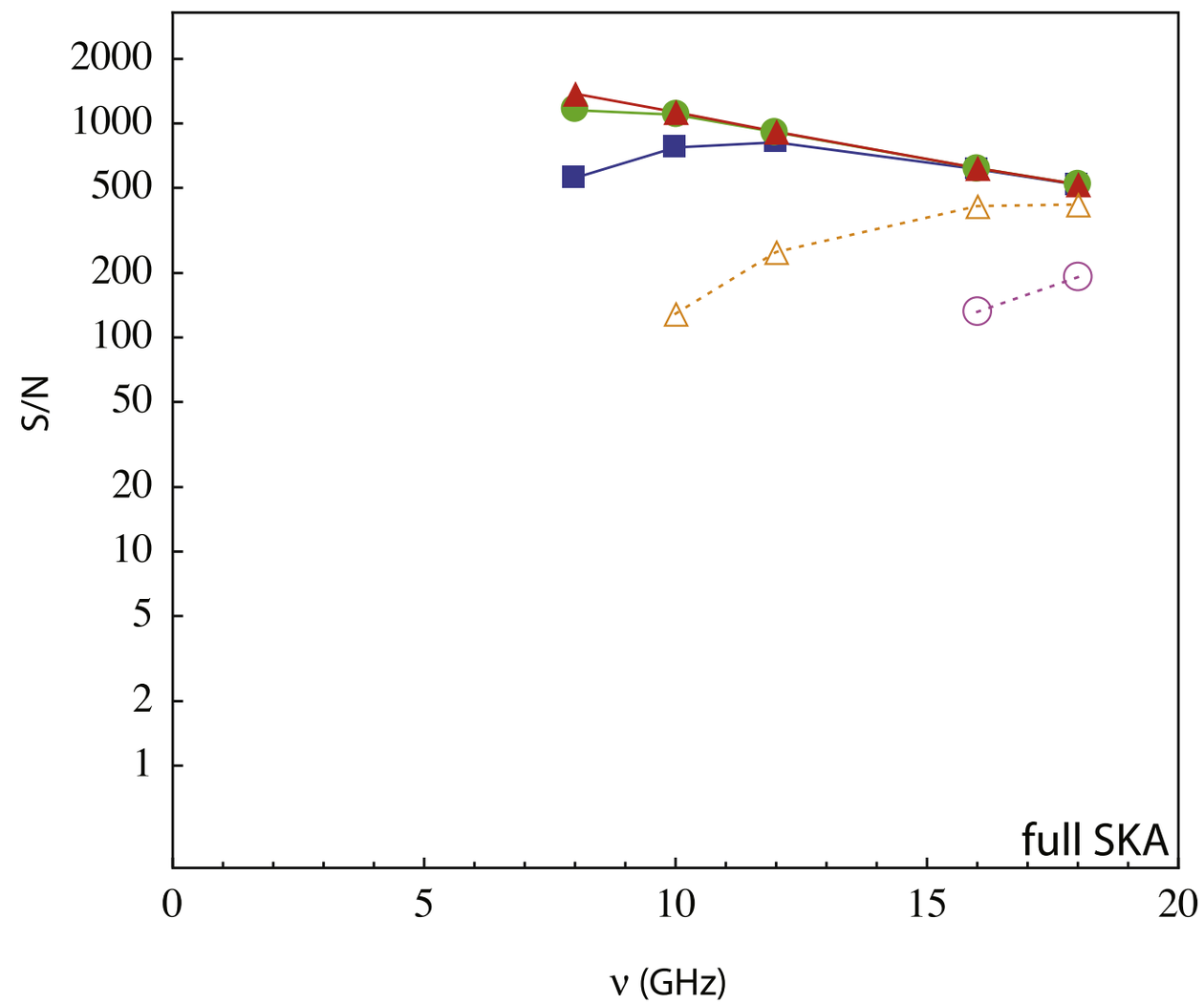


# Where should we search?

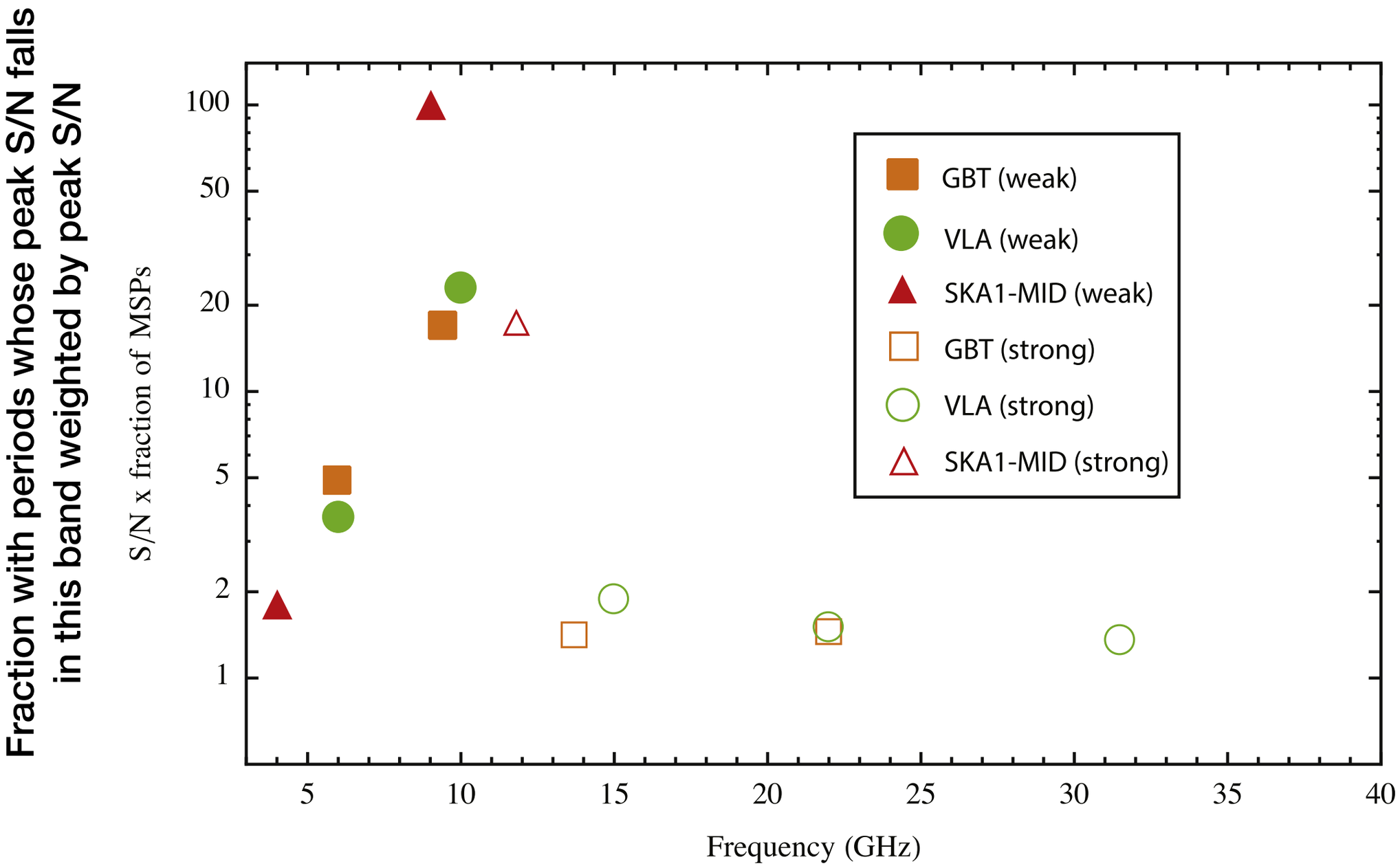
**SKA1-MID and SKA2 S/N for a 30h integration on a $L_{1.4}$=10 mJy kpc$^2$ pulsar with α=-1.7 & 10% duty cycle**



# Where is the best chance?

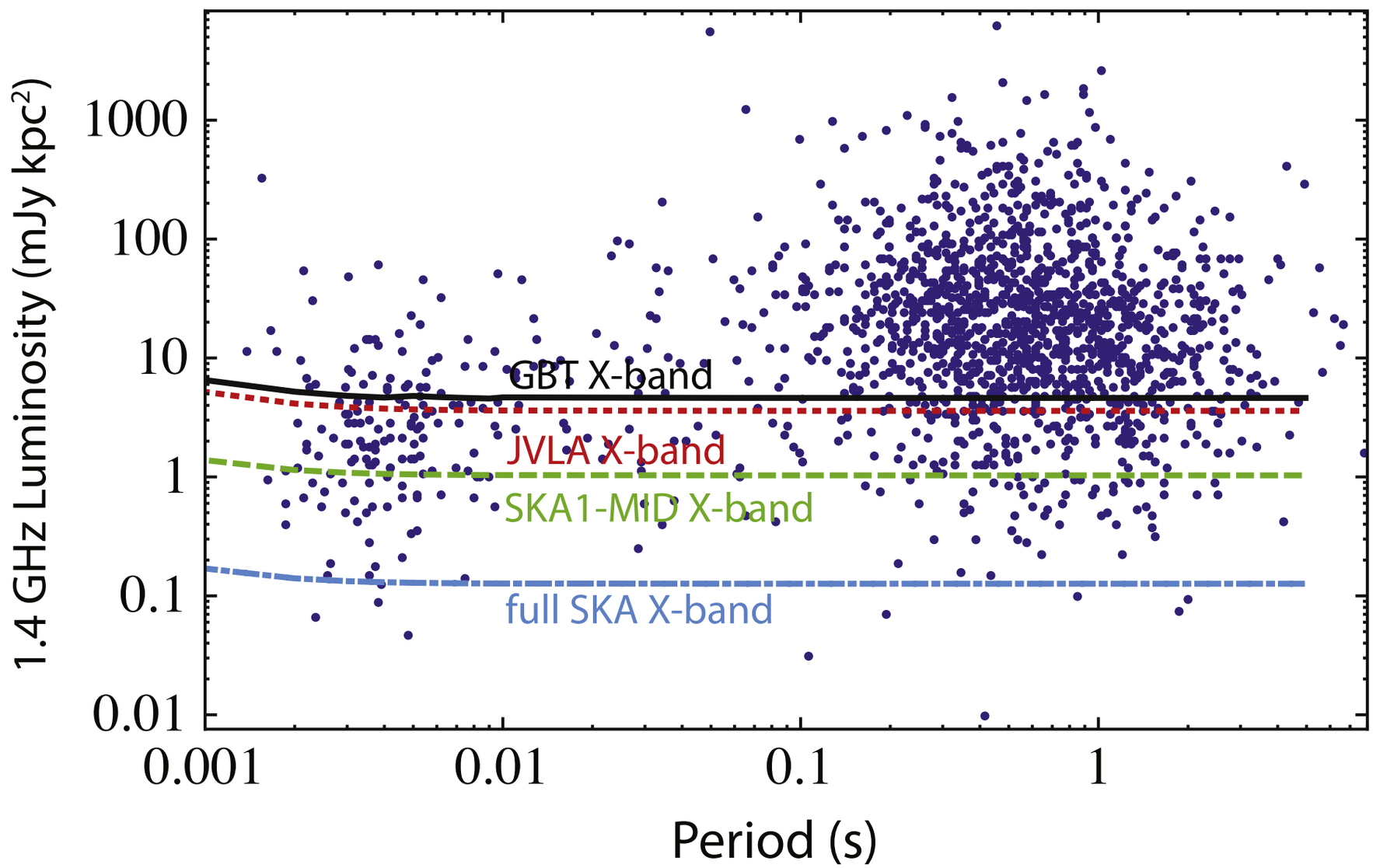
**Optimal detection frequency for P<50ms MSPs assuming a period distribution the same as the known MSP population**



# MSP Detectability

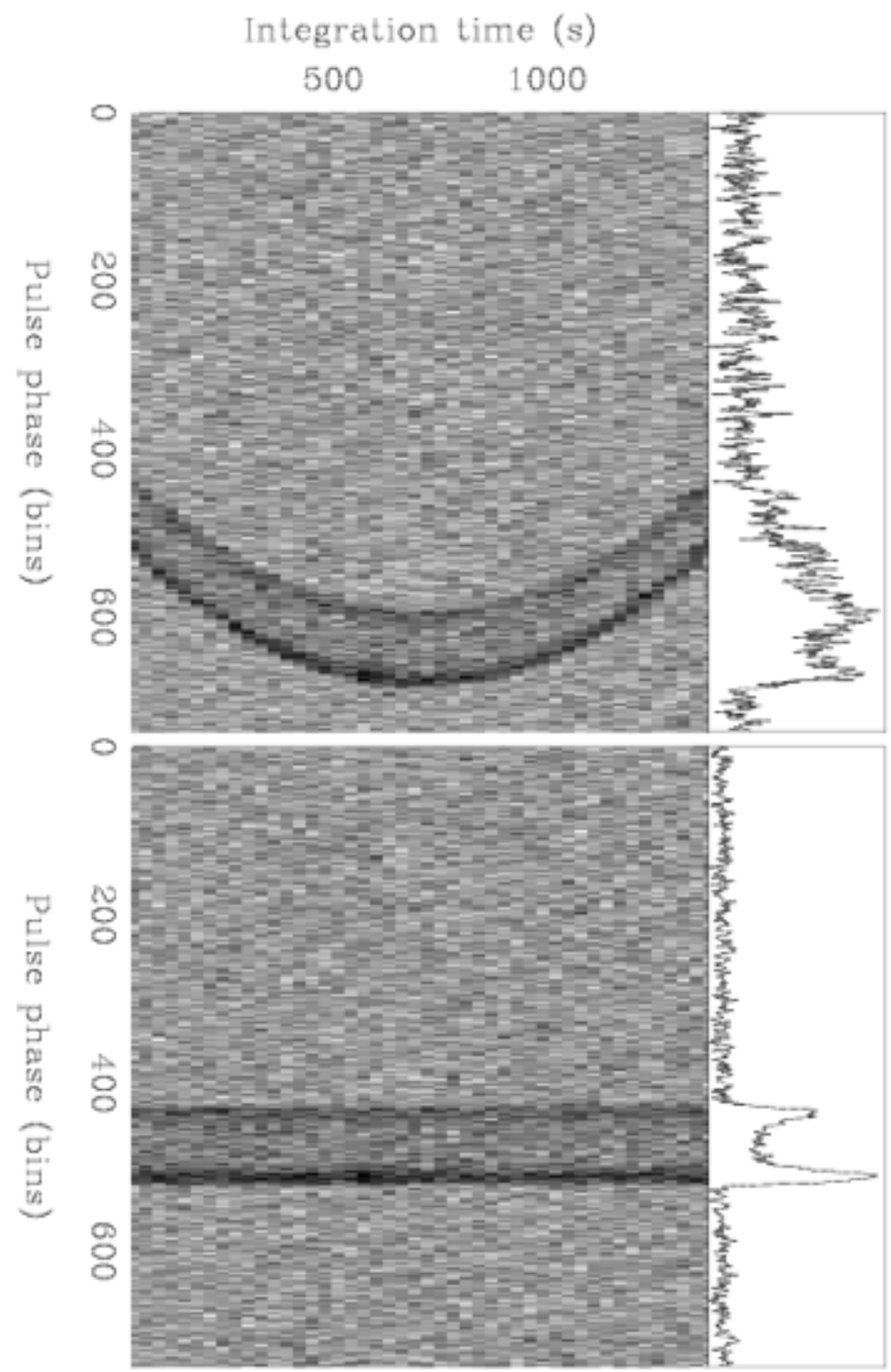
- Peak S/N as a function of frequency occurs where scattering timescale matches pulse width:
  - ~10GHz for MSPs!

*10σ limits for a 30h integration*



# Highly accelerated systems?

- >50% of known MSPs arise in binaries, periods 1.6h— 191d
- Pulse phase drift a consideration: can only observe the GC for 5h at GBT/VLA
  - 30h of time requires several days
  - orbital acceleration likely large over 6 days
- Nature of search depends on ratio $T_{obs}/T_{orb}$:
  - <0.1: standard acceleration searches
  - >1.5 phase modulation searches (e.g. Ransom et al. 2003)
  - $0.1<T_{obs}/T_{orb}<1.5$: full search over six orbital Keplerian parameters
    - e.g. Einstein@Home/Supercomputing centre to do a full orbital search (Knispel et al. 2013)



# Conclusions

Existing radio limits are **not** constraining on the Galactic Centre MSP population yet

Searches for MSPs are hard because they must combine multiple observations to reach constraining sensitivities

Coming soon:
JVLA 12-18 GHz 35h to search MSPs (Kanekar et al.)

Failure to detect pulsars in this survey would mean the GC population must be very different from populations elsewhere in the Galaxy