# The (obscene) Challenges of Next-Generation Pulsar Surveys


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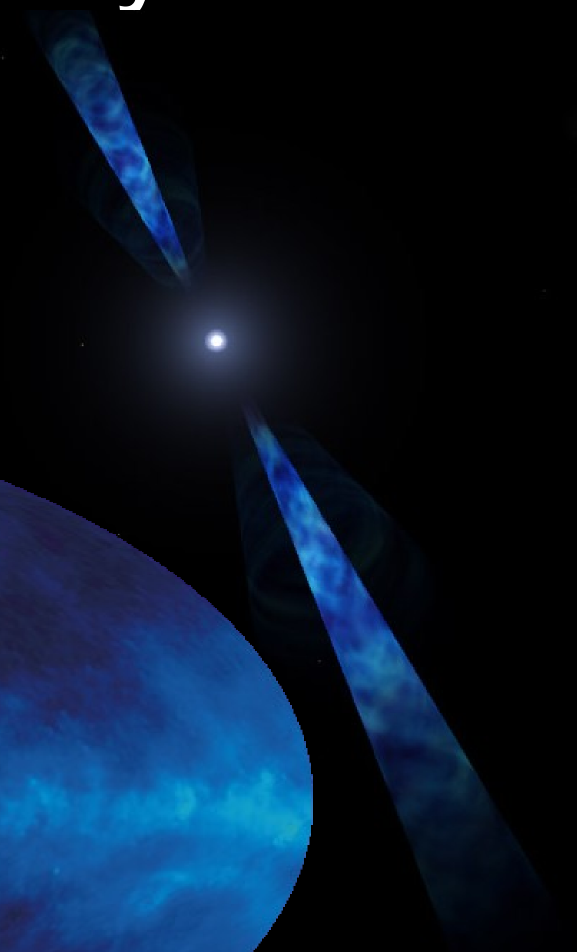
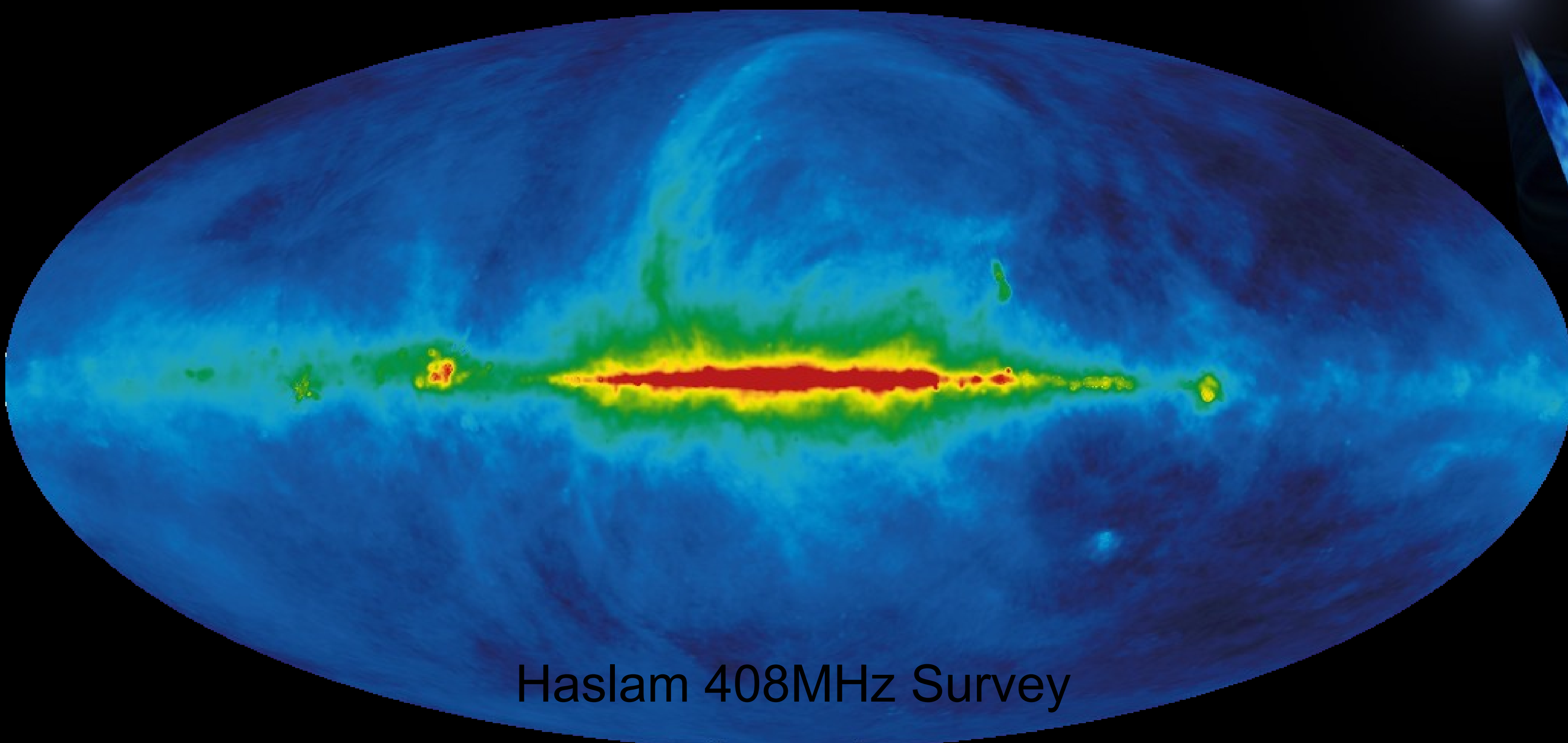




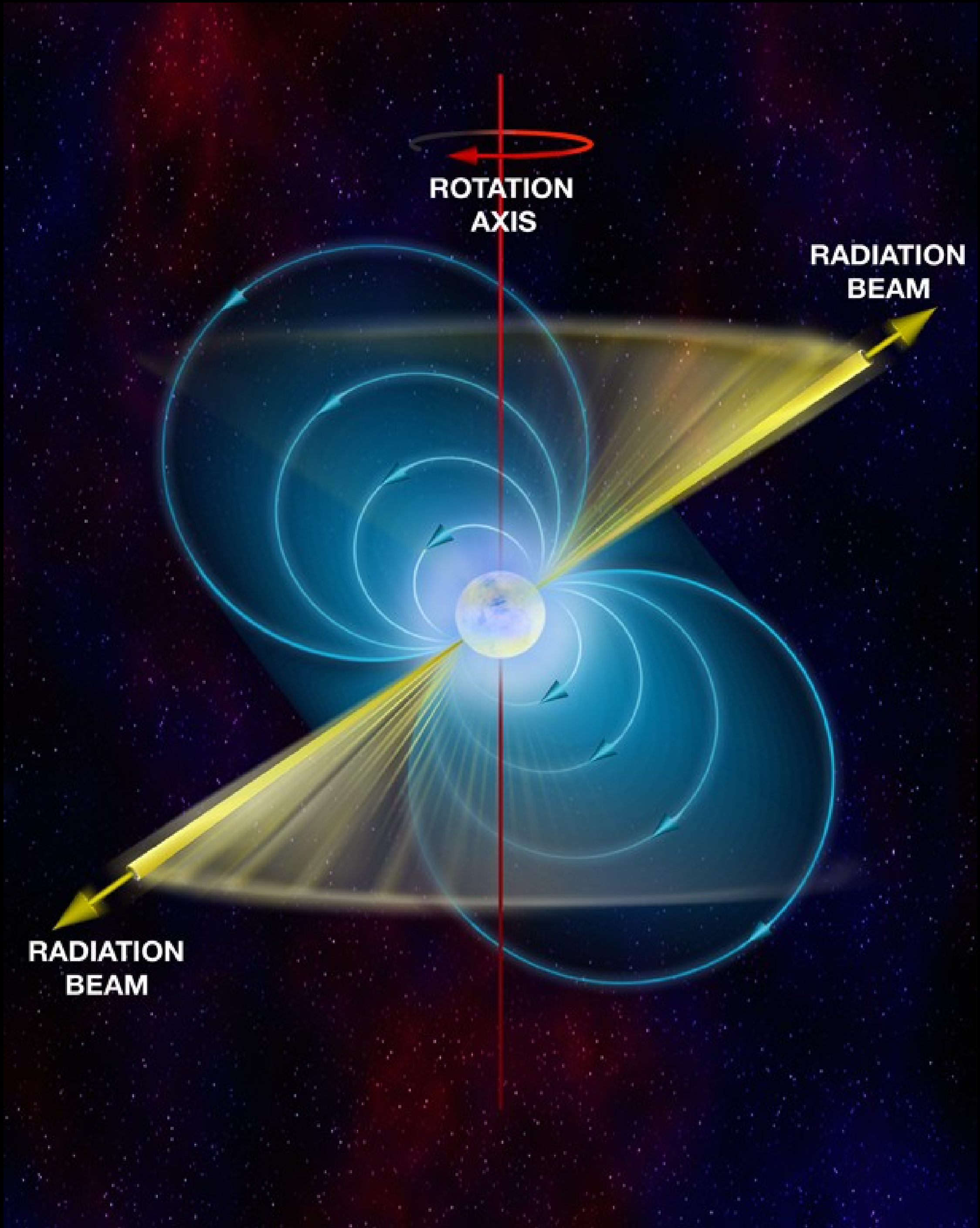
# Summary: The Pulsar Search Problem

- Pulsars are faint – we are sensitivity limited
- Only good way to get sensitivity is collecting area
- Large improvements in $A_{eff}$ mean arrays
- Coherent beam forming causes a data explosion

  $N_{beams} \sim (D_{dish}/D_{core})^2 \sim$ **4000** (15m dishes in 1km core)
- To find MSPs, a single beam is ~50-200 MB/s
- Cannot record the data, must process in realtime
- This is a problem with *any* array (i.e. GMRT, JVLA, LOFAR, MeerKAT), not just SKA

# What are the radio properties of pulsars?

- Broadband continuum
- Steep spectra (0.1-3 GHz)
- Highly linearly polarized
- Point sources:
  - ISM effects (scintillation and scattering:  freq dependent)
  - Spatial resolution irrelevant
- No confusion or beam dilution
- Very weak average flux density (~mJy or less) – We are sensitivity starved



# Pulsar Population of the Galaxy

~2300 pulsars known, but the Galaxy has ~30000 (and ~10000 MSPs)

Only 2-3% of known pulsars are “interesting” for basic/astro physics individually

In Galaxy, we know:

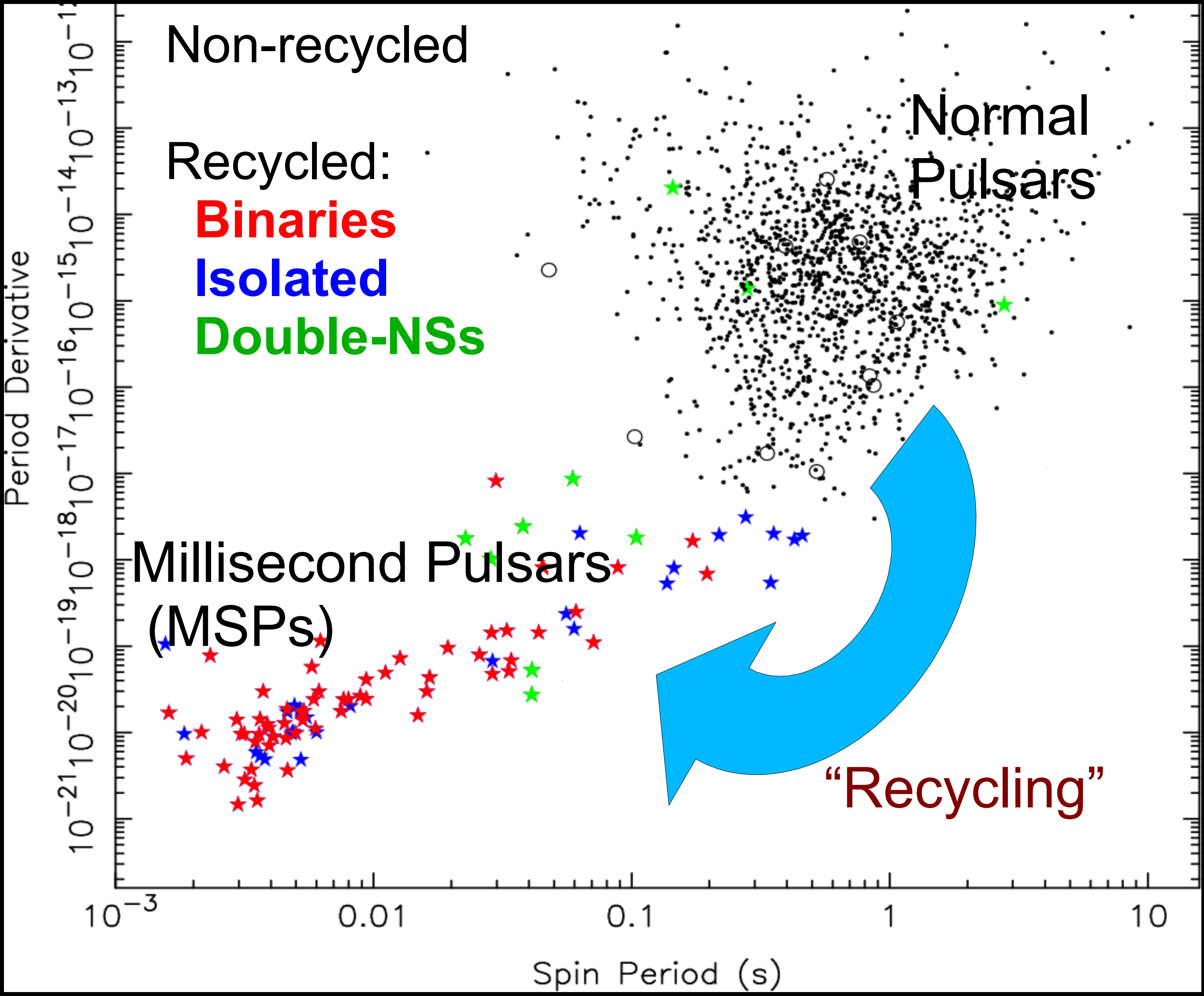
**~160 binary MSPs**
**~40 isolated MSPs**

**~40 binary part-recyc**
**~20 isolated part-recyc**

**Definitions:**

**Part-recycled:**
P > 20 ms, B < $3 \times 10^{10}$ G

**MSP**:
P < 20 ms, B < $10^9$ G



# Pulsars are an SKA KSP (and a Phase 1 “headline science”)

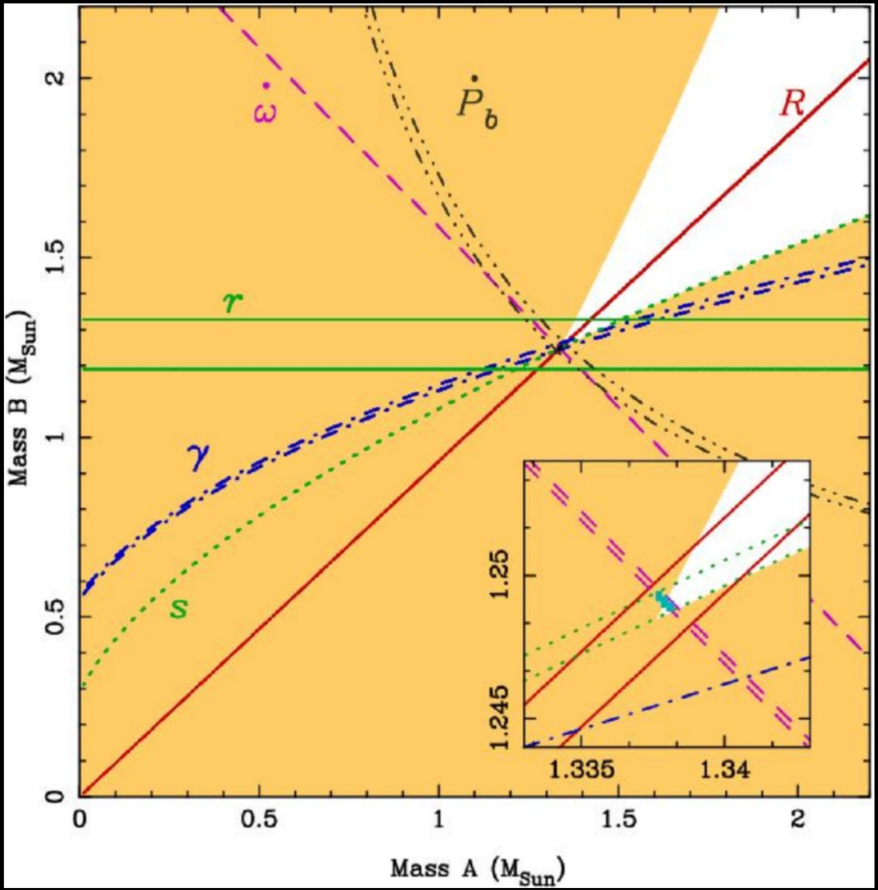
- Strong Field Tests of Gravity (PSR-NS, PSR-BH)
    - Was Einstein right?, Cosmic Censorship Conjecture (i.e. Naked singularities), No-hair theorem
- Detection of a Stochastic Gravitational Wave Background (MSP timing)
- Equation of State of Matter at Supra-Nuclear Density
- Lots of other astrophysics
    - NS masses, ISM structure, Galactic magnetic fields, plasma physics, binary evolution, SNR kicks...

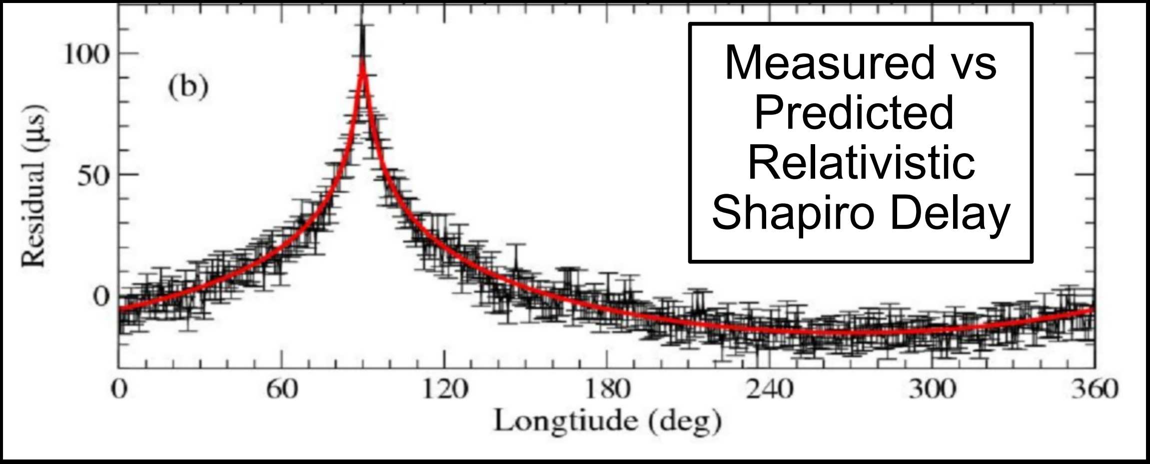
(See Kramer et al. In "Science with the Square Kilometer Array", eds. C. Carilli and S. Rawlings)

# The Double Pulsar J0737-3039

- 7(!) post-Keplerian orbital terms / effects
- 0.05% test of general relativity in "strong"-field
- Timing may eventually allow measurement of the neutron star moment of inertia


Kramer et al., 2006, *Science*, 314, 97

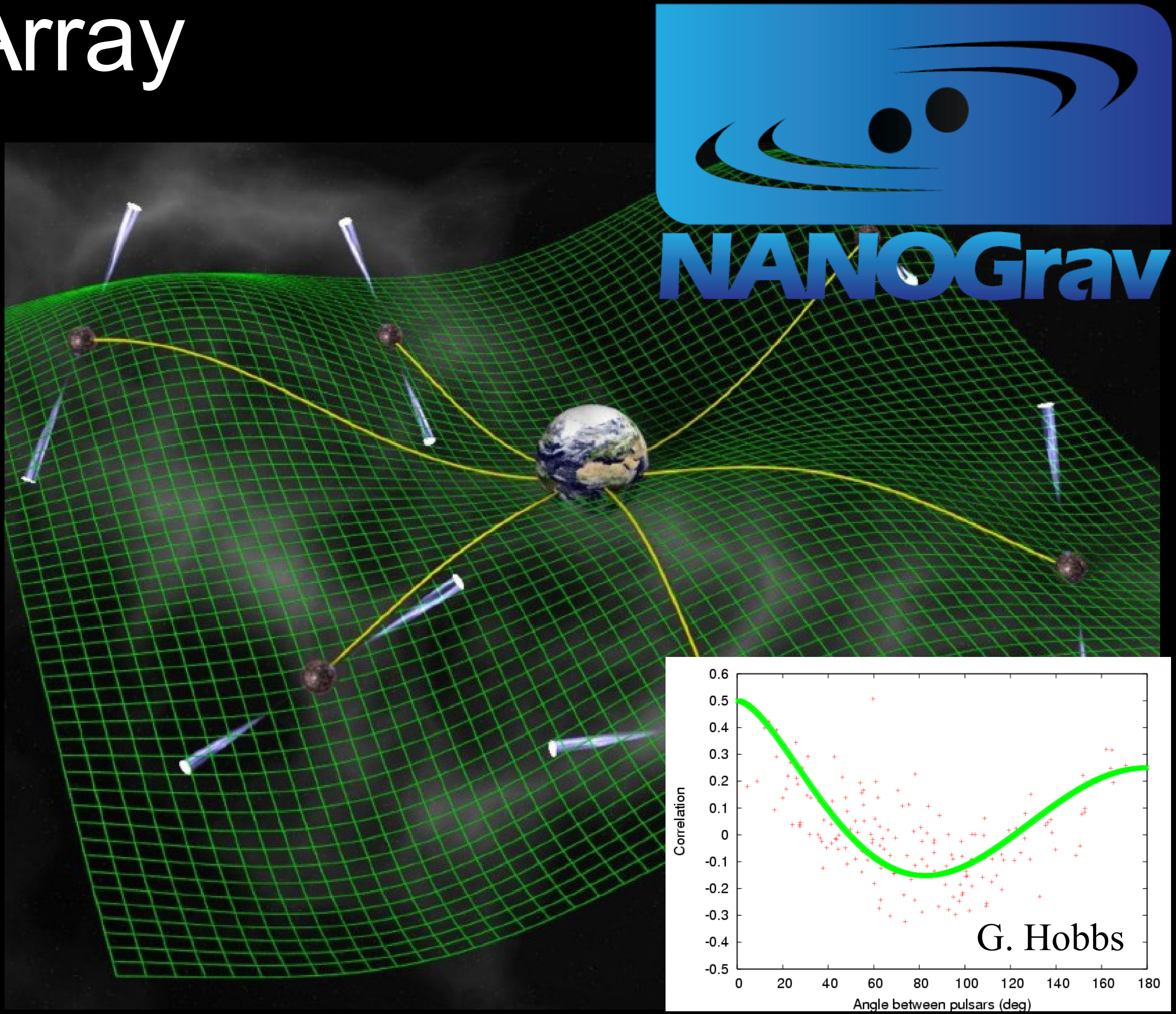



Measured vs Predicted Relativistic Shapiro Delay

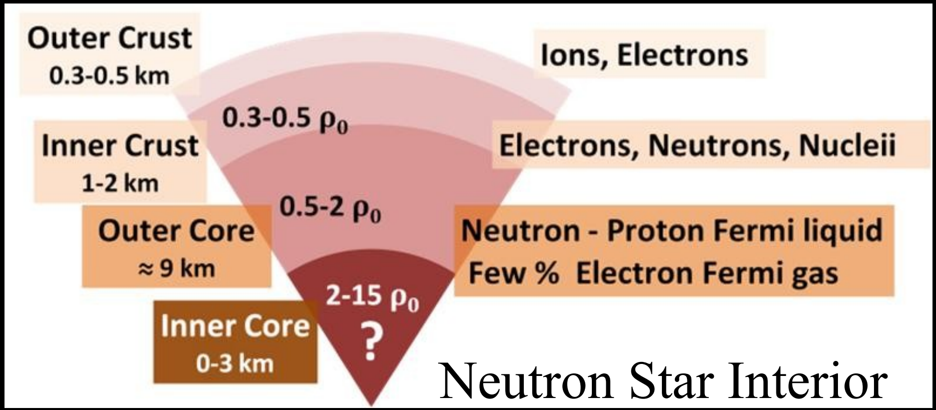
# Direct Gravitational Wave Detection with a Pulsar Timing Array

- Looking for nHz freq gravitational waves from super massive black hole binaries
- Need good MSPs:
  - Significance scales with the number of MSPs being timed
- Must time 20+ pulsars for 5-10 years at precision of ~100 nanosec!
- North American, European (EPTA), and Australian (PPTA) efforts

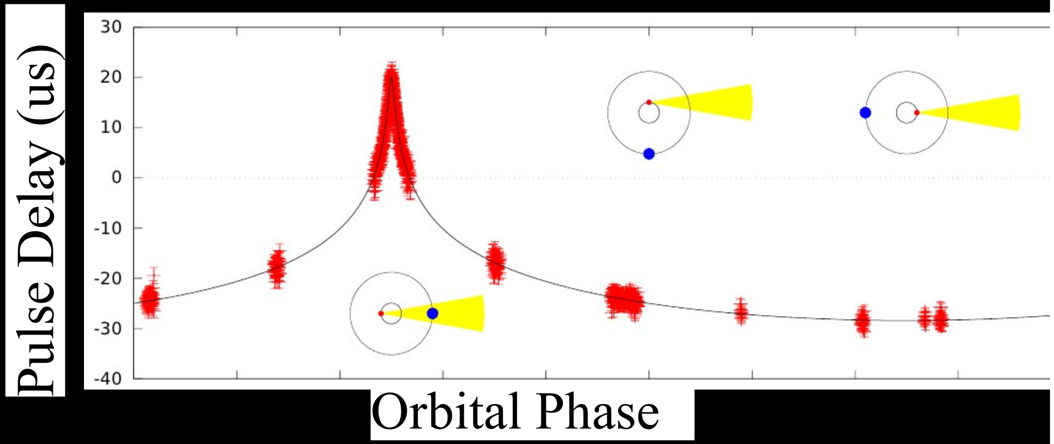


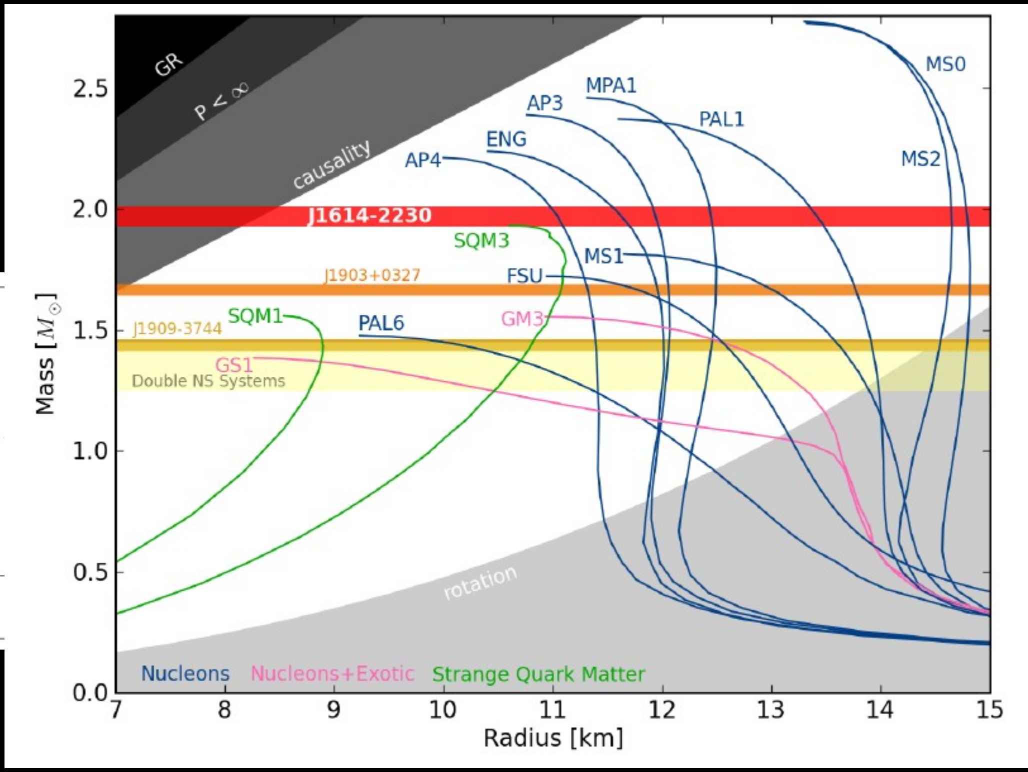

For more information, go to *nanograv.org*

# Physics at or beyond Nuclear Density




"Normal" Millisecond Pulsar J1614-2230




- 1.97(4) $M_\odot$ neutron star
- Orbit within 1 deg of edge-on
- Measured with Shapiro Delay
- Strongly constrains "soft" equations of state

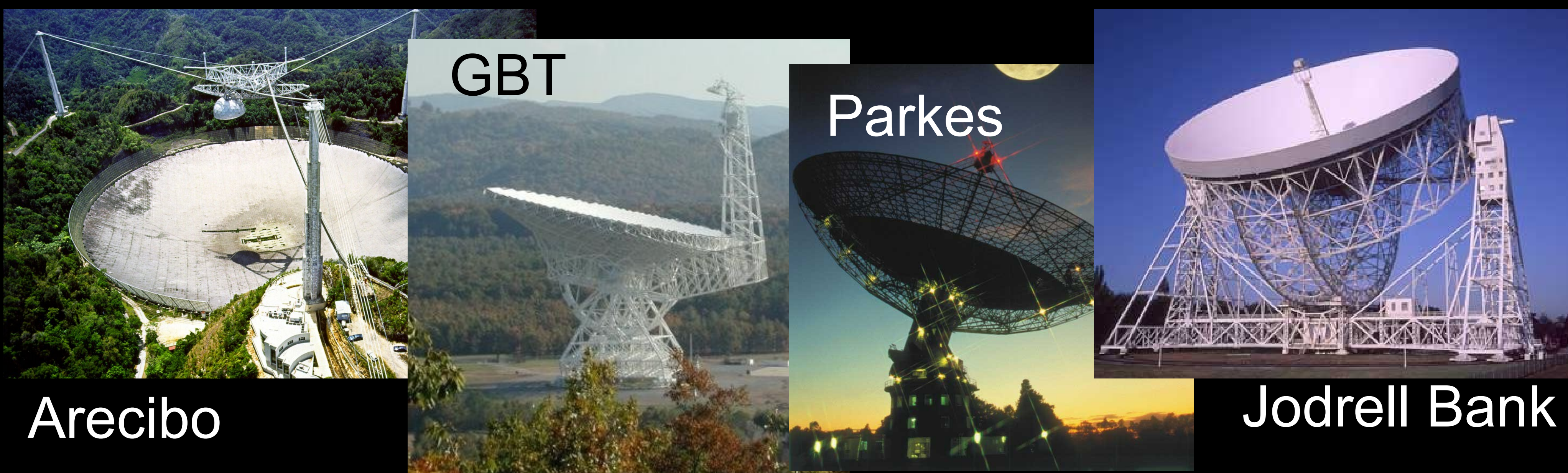
Demorest et al. 2010, *Nature*, 467, 1081D

# And (recent) exotic systems...

- Double pulsar J0737-3039 (Lyne et al., *Science*, 2004)
- Radio magnetar XTE J1810-197 (Camilo et al., *Nature*, 2006)
- P-dot changing PSR B1931+24 (Kramer et al., *Science*, 2006)
- Rotating Radio Transients (McLaughlin et al., *Nature*, 2006)
- Eccentric MSP J1903+0327 (Champion et al., *Science*, 2008)
- "Missing Link" MSP J1023+0038 (Archibald et al., *Science*, 2009)
- 2-Msun MSP J1614-2230 (Demorest et al., *Nature*, 2010)
- "Diamond Planet" J1719-1438 (Bailes et al., *Science*, 2012)
- Massive NS J0348+0432 (Antoniadis et al., *Science*, 2013)
- MSP-LMXB switching M28I (Papitto et al., *Nature*, 2013)
- MSP in triple system J0337+1715 (Ransom et al., *Nature*, 2014)
- *Future?*: MSP-MSP, PSR-BH, sub-MSP, ultra-massive, ….

# A PSR Renaissance from DSP & HPC

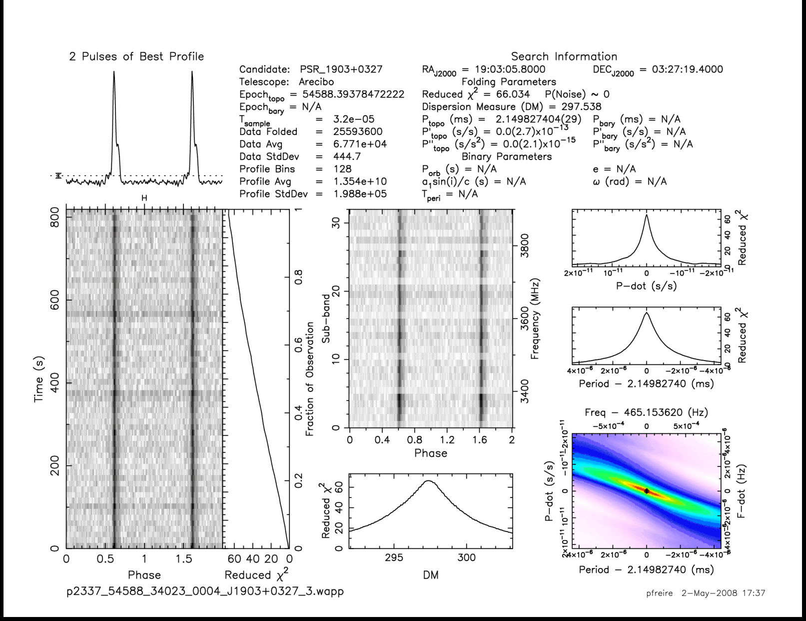
- ***Until very recently:*** pulsar observations were severely limited by our instrumentation, not by our telescopes
- ***Now:*** digital signal processing and computing are finally allowing us to fully use our telescopes



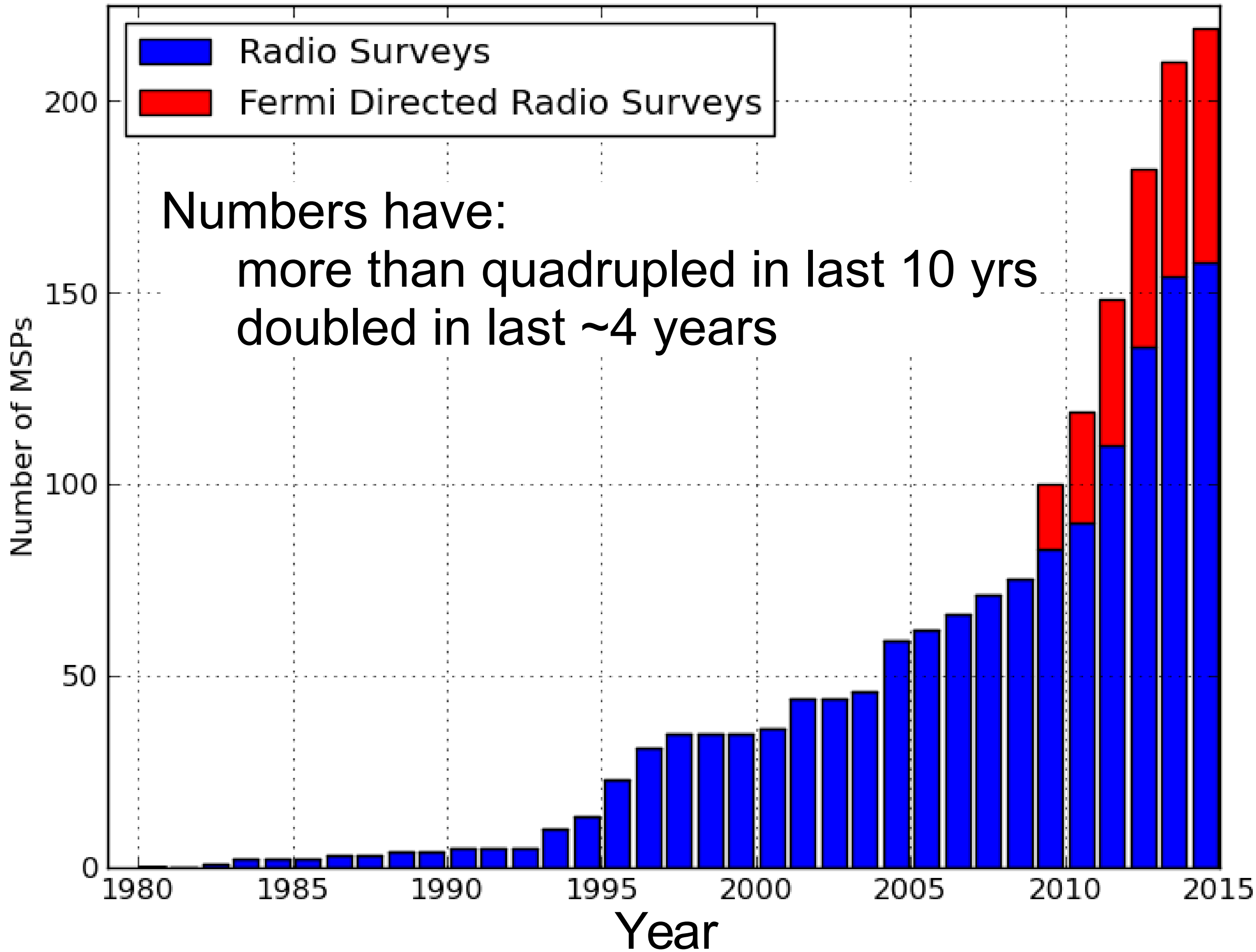

Plus: Nancay, Effelsberg, GMRT, Westerbork, Urumqi...

# New All-Sky Pulsar Surveys

- All major radio telescopes are conducting all-sky pulsar surveys
- These generate lots of data:
  - 1000s of hrs, 1000s of channels, ~15 kHz sampling: gives more than a Petabyte
- Requires huge amounts of high performance computing
  - *Many* times real-time to process
  - Creates millions of candidates

# New Millisecond Pulsars



# What does the future hold?

- Single dishes (e.g. GBT, Arecibo, and FAST in China) with large numbers of simultaneous beams (40-100)
- Searches with arrays (e.g. LOFAR, MeerKAT, EVLA, SKA) *dramatically* increase the data rate

JVLA survey ~10 GB/s    SKA1 survey ~1 TB/s!

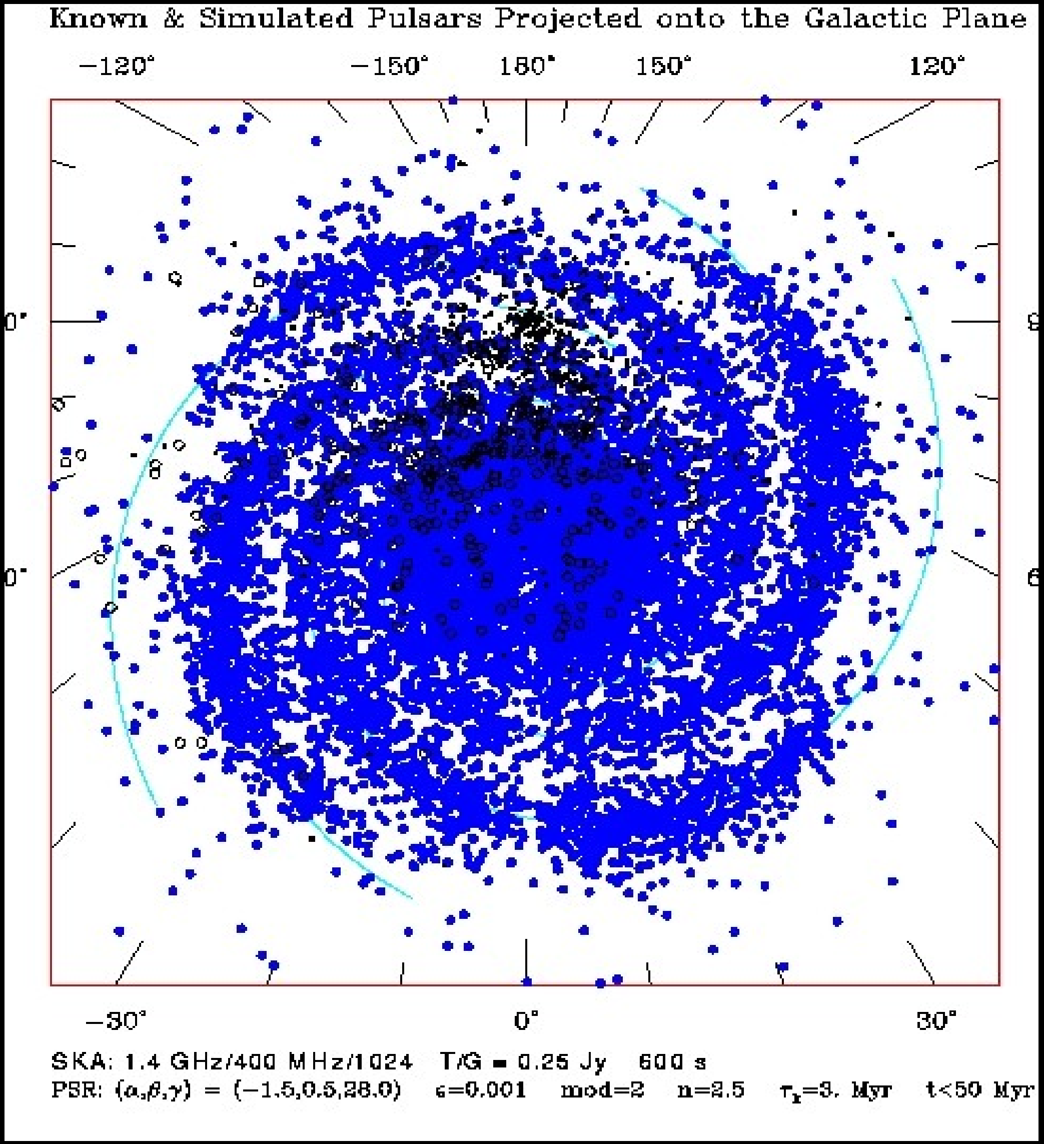
# SKA Sensitivity Summary

- SKA1-mid (~250 dishes x 15m): timing (search)
  - 1600 $m^2k^{-1}$ (~900 $m^2k^{-1}$ within 1 km diam)
- SKA2-mid (~2500(?) x 15m):
  - 16000(?) $m^2k^{-1}$ (~2000 $m^2k^{-1}$ within 1 km diam)

| | | |
|---|---|---|
| FAST: | 1800 $m^2k^{-1}$ | |
| | | > Factor of ~2 |
| Arecibo: | 1000 $m^2k^{-1}$ | |
| | | > Factor of ~4 |
| GBT / MeerKAT: | 250 $m^2k^{-1}$ | |
| | | > Factor of ~3 |
| Parkes: | 80 $m^2k^{-1}$ | |

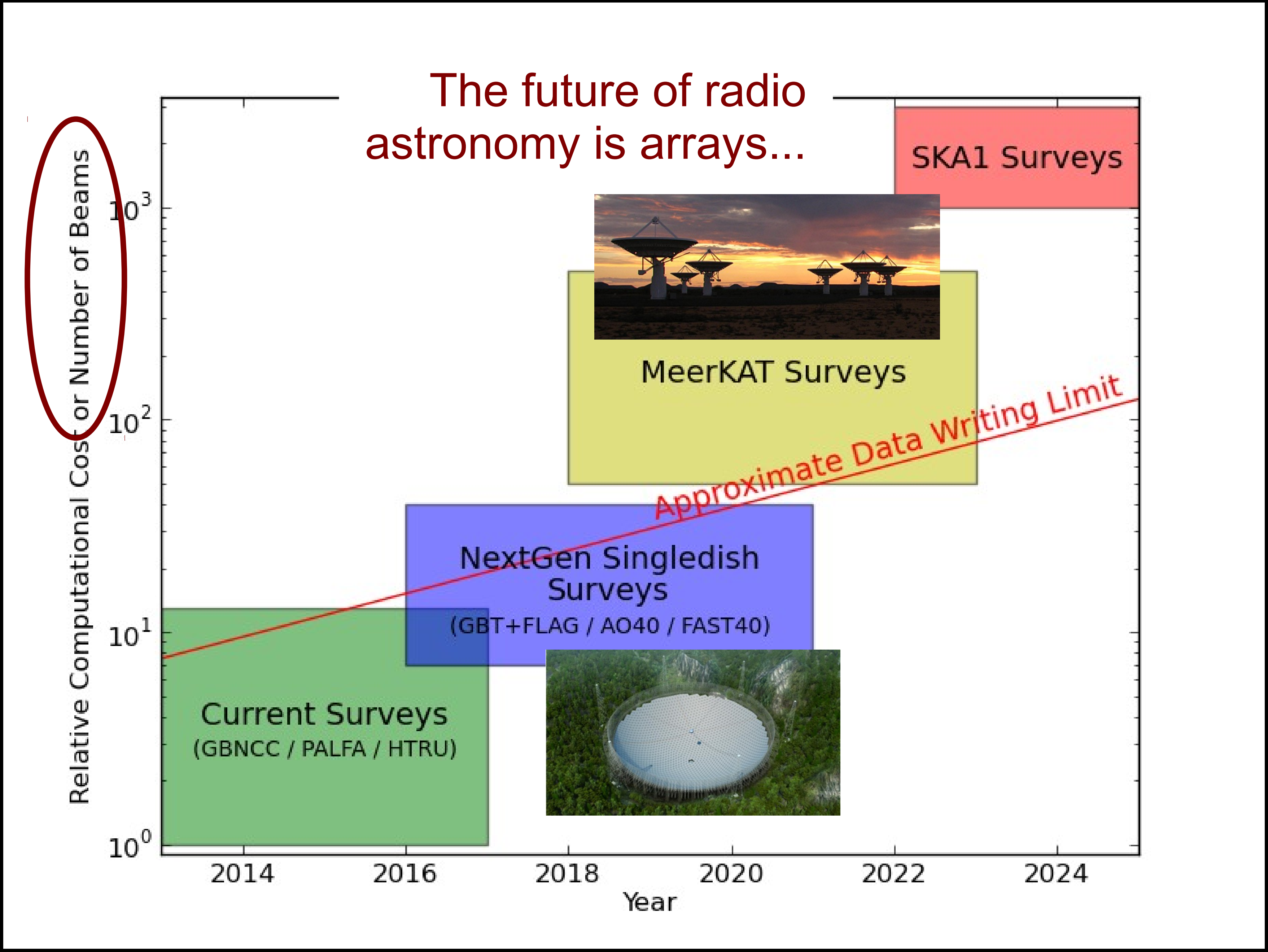
# SKA Phase 1 Pulsar Searching

- See Smits et al. 2009
- ~20,000 each of potentially visible normal pulsars, RRATs, and MSPs
- SKA1 has the potential to find a large fraction (~50%?) of these pulsars
- Survey speed for Phase 1 with 15m dishes and fully sampled primary beam is: 54x Parkes MB, 180x GBT, 70x Arecibo, 30x FAST




Simulation by J. Cordes

# Problem in a nutshell... data rates



# Pulsar searching basics:

- Normal pulsars come "free" if you can find MSPs
  - MSPs are in binaries and distributed isotropically
  - Slow, relativistic binaries (i.e. NS-NS, NS-BH) should be close to the Galactic Plane, where ISM effects are stronger
- Cannot trade sensitivity for integration time (need single, coherent integrations to find binaries)
- Searches have to be done *per sky pixel* (use fewer pixels!)
- Four main parts to the search process:

  *(Beam forming,)* De-dispersion, Acceleration searching, Folding

Arrays!

$$\text{Sensitivity} \propto \frac{\text{Collecting Area}}{\text{T}_{\text{sys}}\sqrt{\text{t}_{\text{int}}\ \text{Bandwidth}}}$$

$$\text{Computations} \propto f_{spin}^{3}\ t_{\text{int}}^{3}$$

# Coherent Beam Forming

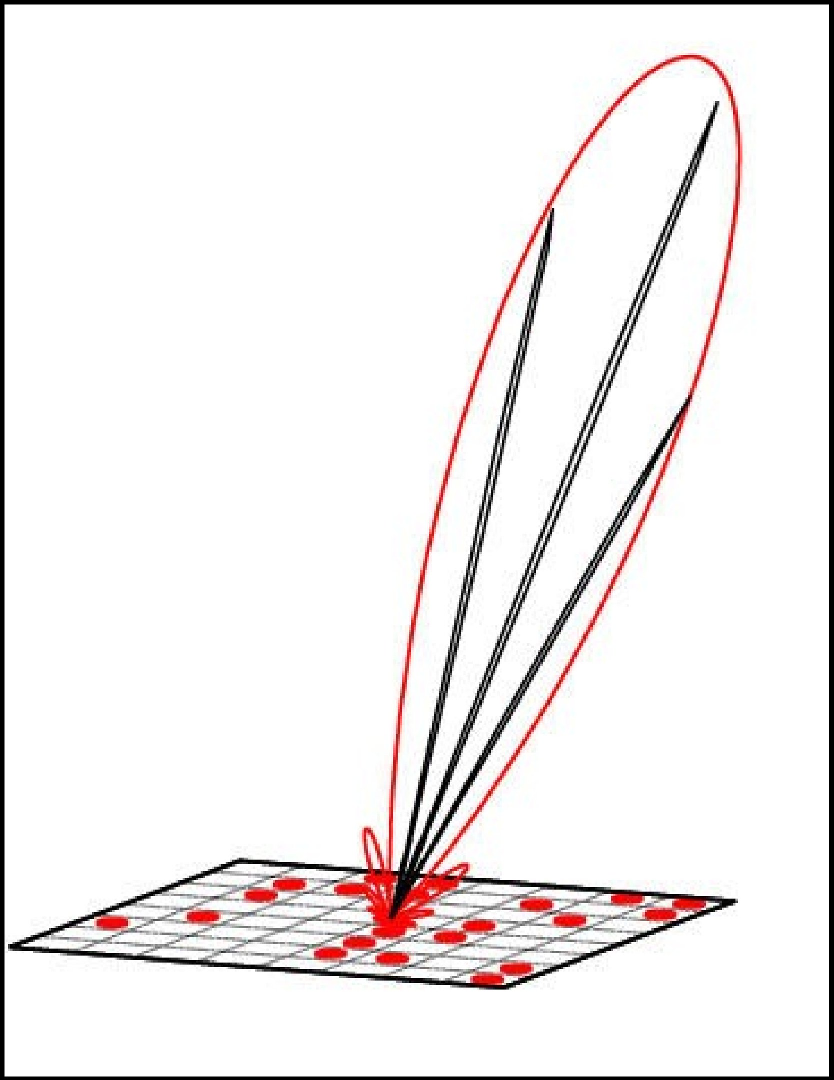
Spatial resolution is the main disadvantage to searching with arrays over a single dish: fill primary beam with synthesized or "tied array" beams

$N_{beams} \sim (D_{core}/D_{dish})^2 \sim$ **4000**
(MeerKAT / SKA using only ~1km diam core)

$N_{ops} \sim$ 1 Pops for all beams

Output ~ $N_{beams}$ x 300 MB/s
~ 10 Tbits/s

Every beam is independent with ~10-15K chans @ 20kHz



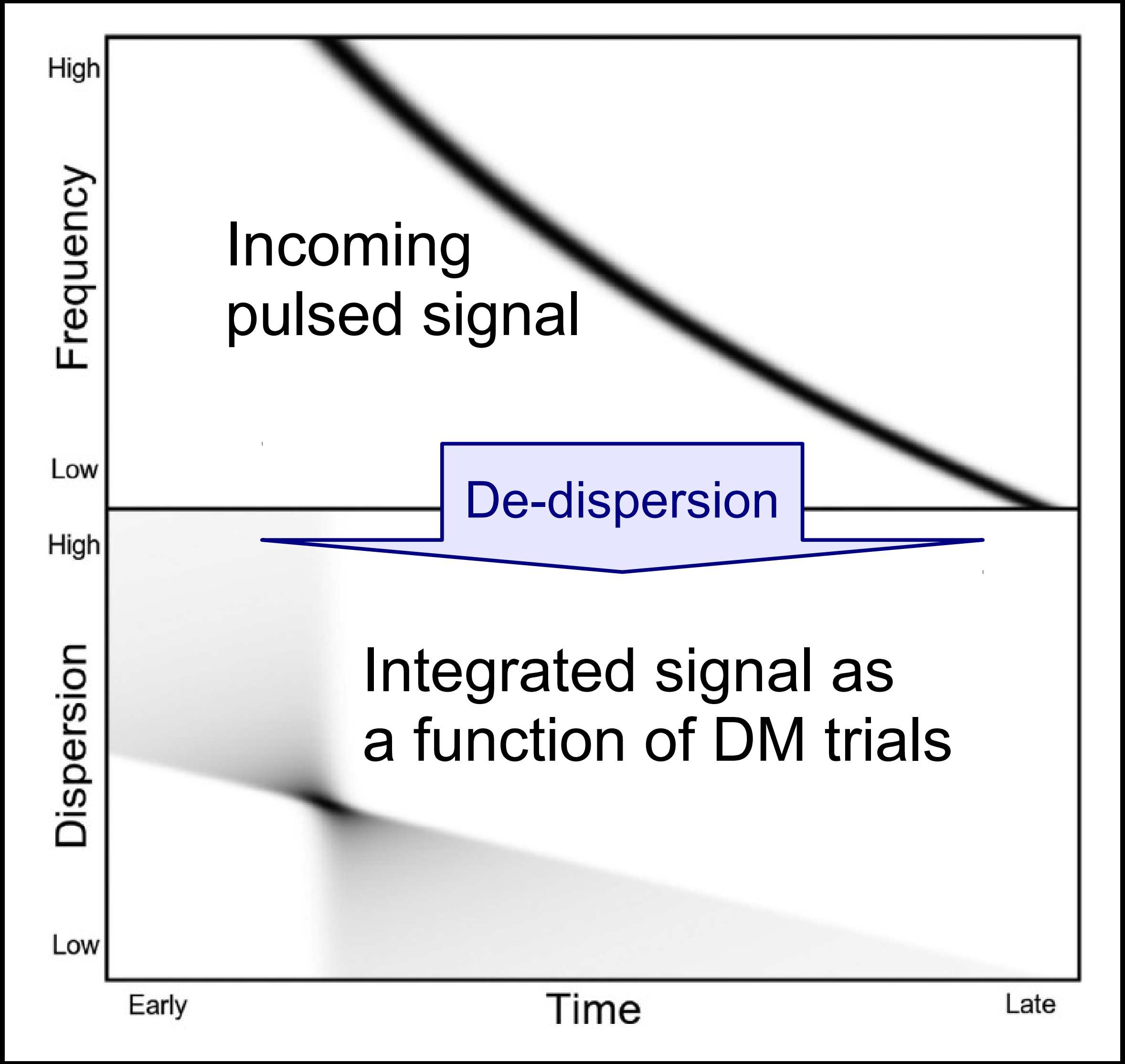
# Dispersion

Lower frequency radio waves are delayed with respect to higher frequency radio waves by the ionized interstellar medium

$\Delta t \propto DM\nu^{-2}$

(DM = Dispersion Measure)

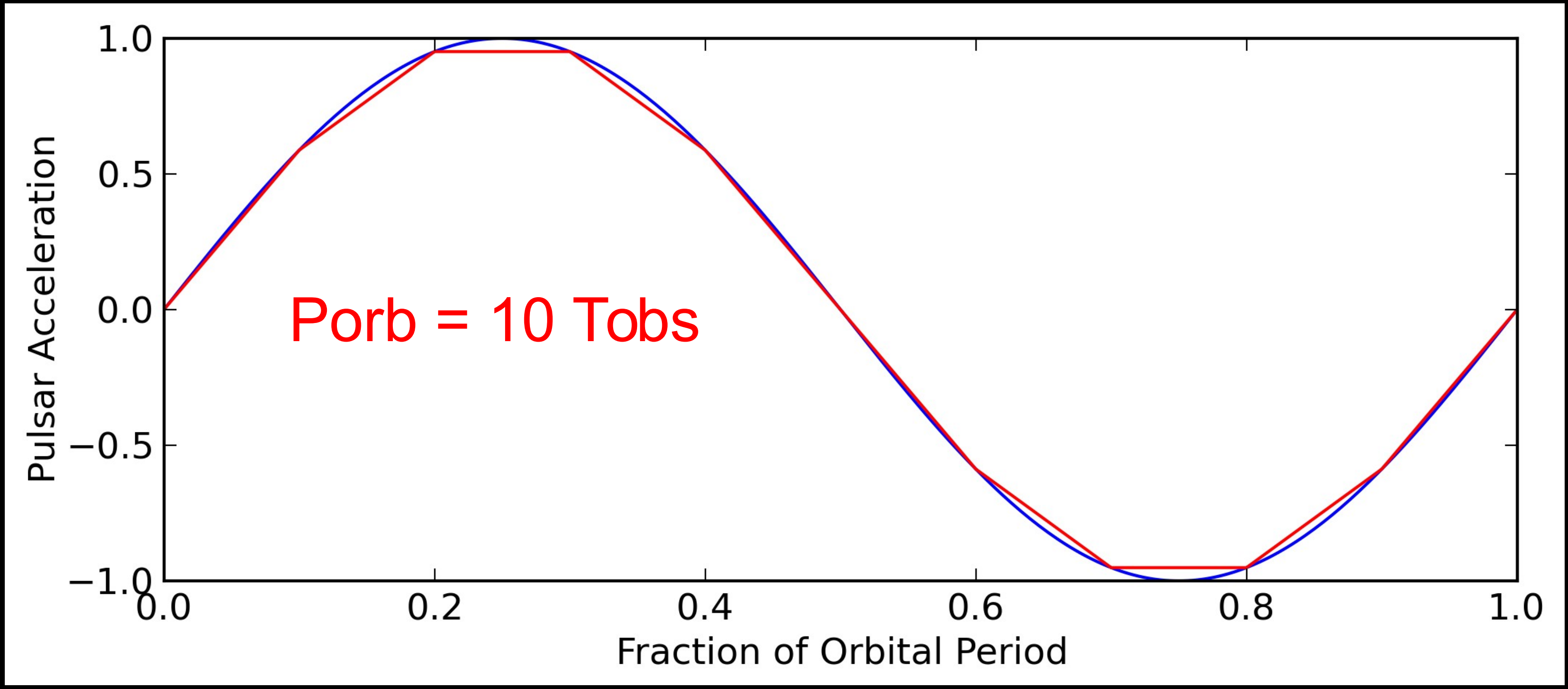
- Need ~$10^4$ frequency channels
- DM for undiscovered pulsar is unknown
- Must search over ~few x $10^4$ trial DMs!
- This multiplies data rate by factor of few
- ~0.1 Pops for SKA1
- De-dispersion is very I/O intensive




Barsdell et al 2012

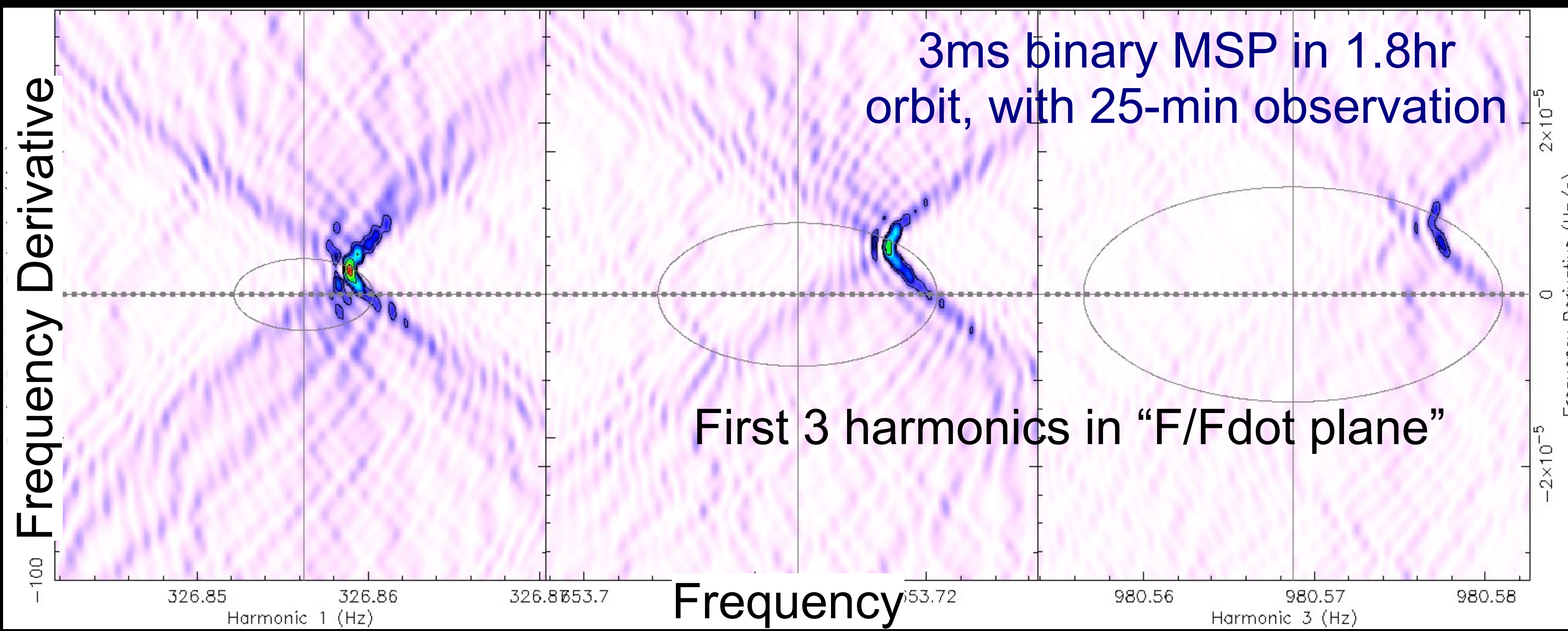
# “Acceleration Searches”

- Most interesting PSRs are in binaries: Doppler effect
- If the orbital period >> observation time, then the acceleration is approx constant during the observation
- A “chirp” with small Δf/f (phase changes quadratically)
- Correction done in time or freq domain



# Acceleration Search Logistics

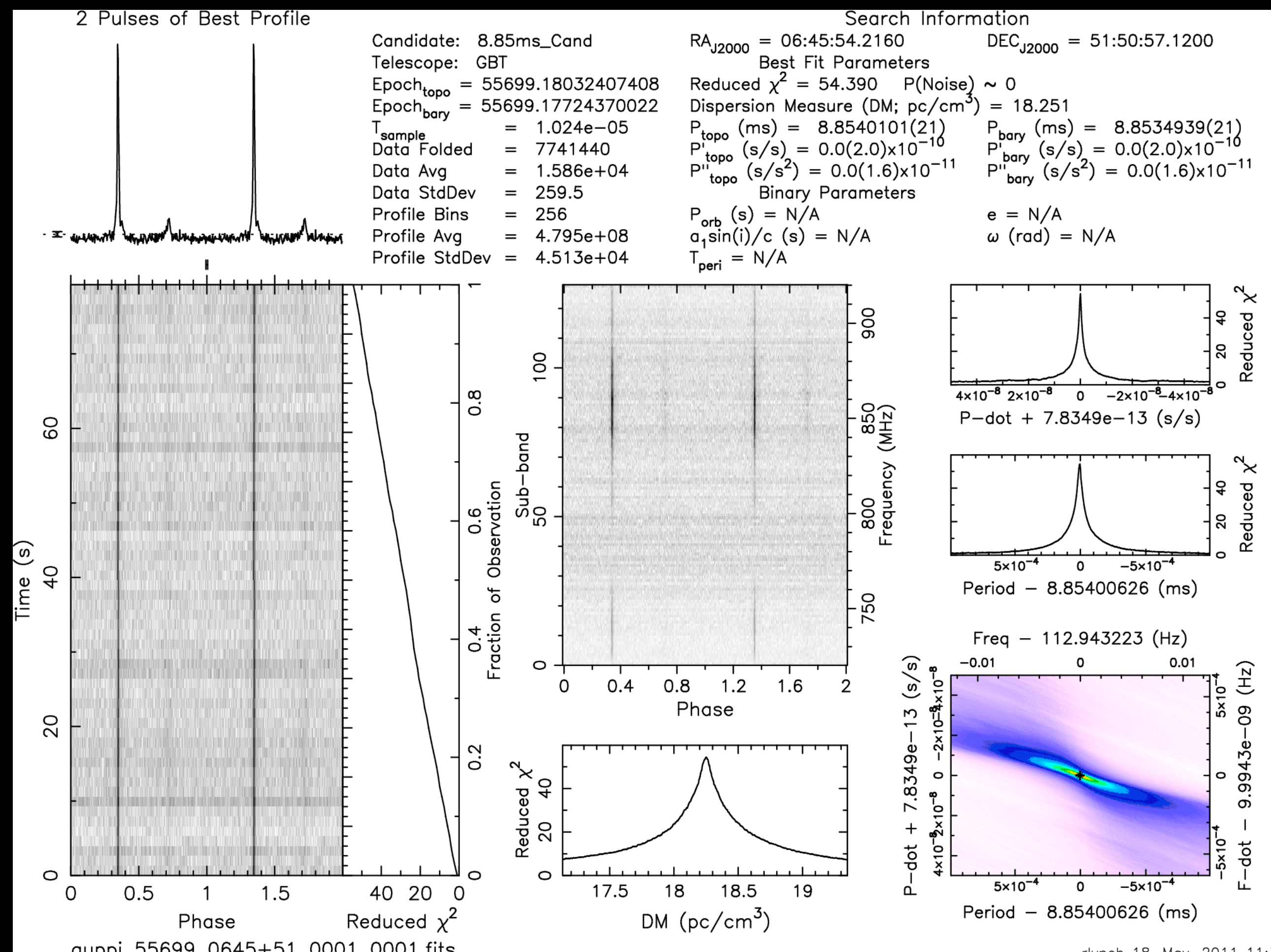
- Fourier-based searches use harmonic summing (increases sensitivity by 2-5x over continuum imaging)
- CPU + memory intensive, but embarrassingly parallel
- Datarate multiplied ~100x: Need real-time searches!
- Dominates processing: ~10 PFLOPS for SKA1



# Candidate “Folding”

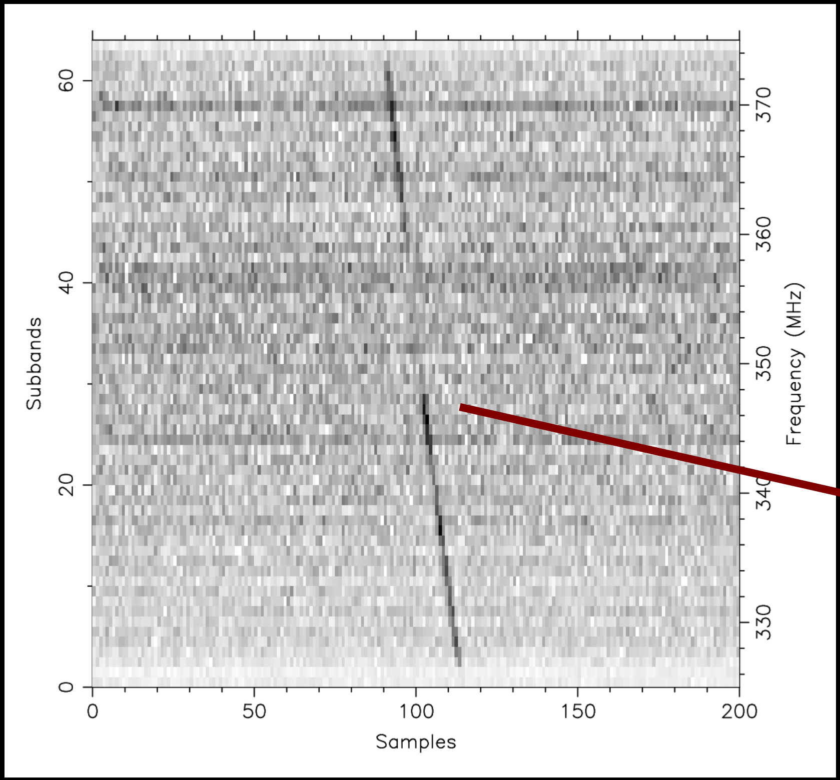
- Surveys generate millions of candidate pulsar signals with associated metadata. Candidate “sifting” is a big problem...
- For best candidates, “fold” raw data modulo candidate spin period at the detected DM. Extremely I/O intensive

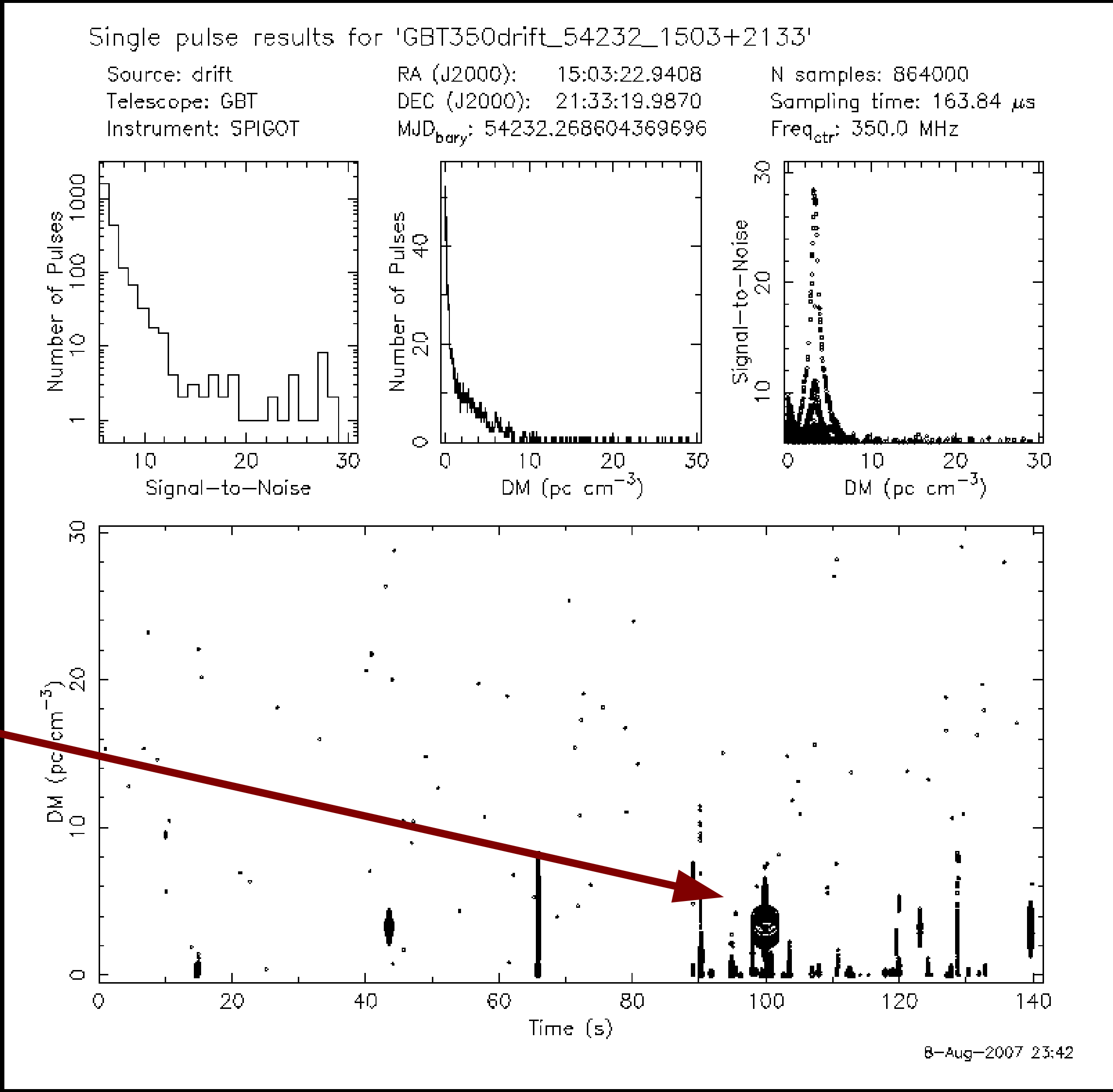
Data cube of pulse phase vs time vs observing frequency



# Single Pulse Searches

- Many PSRs (or RRATs) have highly variable pulse amplitudes
- Look for dispersed individual pulses (e.g. McLaughlin & Cordes, 2003, ApJ, 596, 982)
- Possible new transients...
  - "Lorimer Bursts", FRBs



# Possible SKA1 Searches

- Very Early Science: Targeted Searches
  - SNRs, gamma-ray sources, PWNe (0.5-3 GHz)
  - Globular Clusters (0.5-3 GHz)
- Early Science: Limited Surveys
  - Local Galaxies (LMC, SMC; 1.5-3 GHz)
  - Gal Ctr Region (1.5-3 GHz)
  - Low Latitude Galactic Plane (<|1deg|, ~1.5-3 GHz)
- Full Science: Large Area Surveys
  - Galactic Plane (<|5deg|, 0.8-1.6 GHz, ~10-30 min)
  - All-sky survey (0.45-0.9 GHz, ~10 min)
  - <u>These are real-time: need to buffer ~0.5 PB!</u>

# After discovery, they all need timed!

- Timing tells us if the pulsars are interesting
- Follow up timing will take more telescope time than the surveys (although spread over more time)
- Timing can use *all* of SKA instead of the core, *or*, the SKA can be sub-arrayed (this is extremely inefficient, though)…
- Large FoV will allow simultaneous timing of multiple PSRs (large number of PSRs will *require* it)
    - Not the case for high-precision MSPs – too sparse
- Imaging capabilities should provide excellent starting positions for the pulsars (requiring fewer timing obs for “boring” pulsars)
- Triage of pulsars will be crucial

# So what's happening now?

- GPU-ized de-dispersion (i.e. Barsdell, Magro...)
- GPU-ized acceleration searches
  - PRESTO's *accelsearch* by Jintao Luo
  - Ewan Barr's PEASOUP
- Experiments with de-dispersion and acceleration searching (with harmonic summing) on FPGAs
- Real-time RFI detection and removal
- Many efforts in machine learning for candidate ID
- Need high-speed, parallel folding algorithms for multiple candidates (one-pass through raw data)
- Completely new search algorithms?

# Summary

PSR searching with arrays is hard, primarily because of synthesized beams (want most compact core $D_{core}$)

Expand capabilities over time as computing improves by using more of the primary beam and/or increasing $D_{core}$

Only need more sensitivity than Parkes in the South to start with targeted surveys

- Core dishes of MeerKAT will give ~GBT sens
- FAST will see some of the South with 2xArecibo sens

SKA -1 will find ~5000-10000 PSRs. All will need to be timed. Some will be timed long term (and with full sensitivity) with SKA-2

No ability to re-do analysis: Re-do = Re-observe

All-sky SKA1 surveys will be real-time and very difficult

# JVLA Pulsar Survey?

Would use fast-dump correlation mode. At L-band, resulting VLA survey speed is ~10x single-pixel GBT. Sounds good, except for...

Problem #1:

$$\text{Data Rate (B/s)} = N_{\text{pol}} \times N_{\text{chan}} \times \frac{N_{\text{dish}}(N_{\text{dish}}-1)}{2} \times \frac{\text{Bytes}}{\text{vis}} \times \frac{1}{dt}$$

= 2 x 1000 x 351 x 1 x 10000

= 7 GB/s! (compare to ~10MB/s for 1 beam of the GBT)

and Problem #2:

$$\text{Computation Rate} \propto T_{\text{int}}^3 \log_2(T_{\text{int}}) \times D_{\text{array}}^2$$

D-configuration needs ~100x more computation than a similar single-dish survey. E-config necessary to make this reasonable!