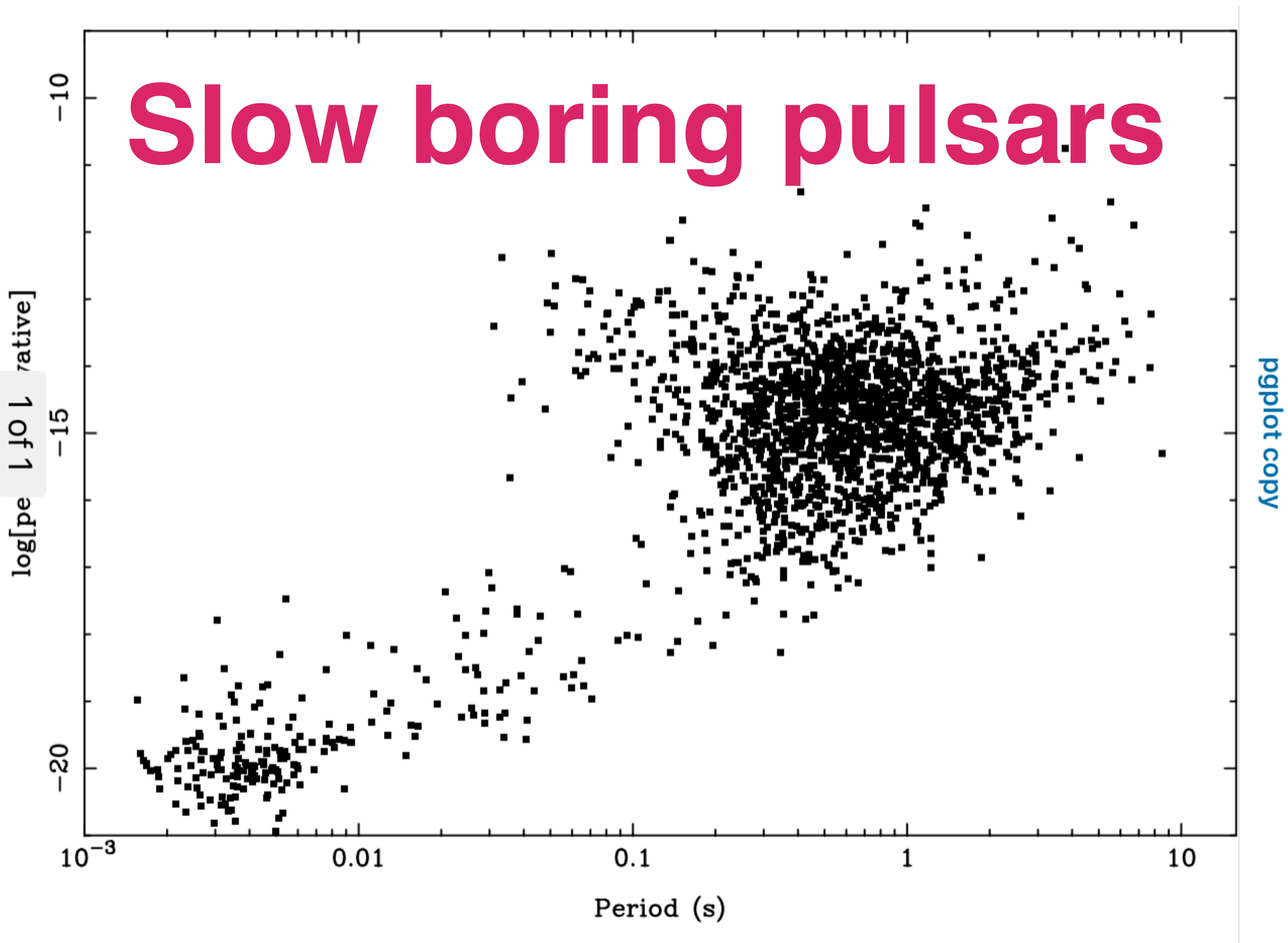
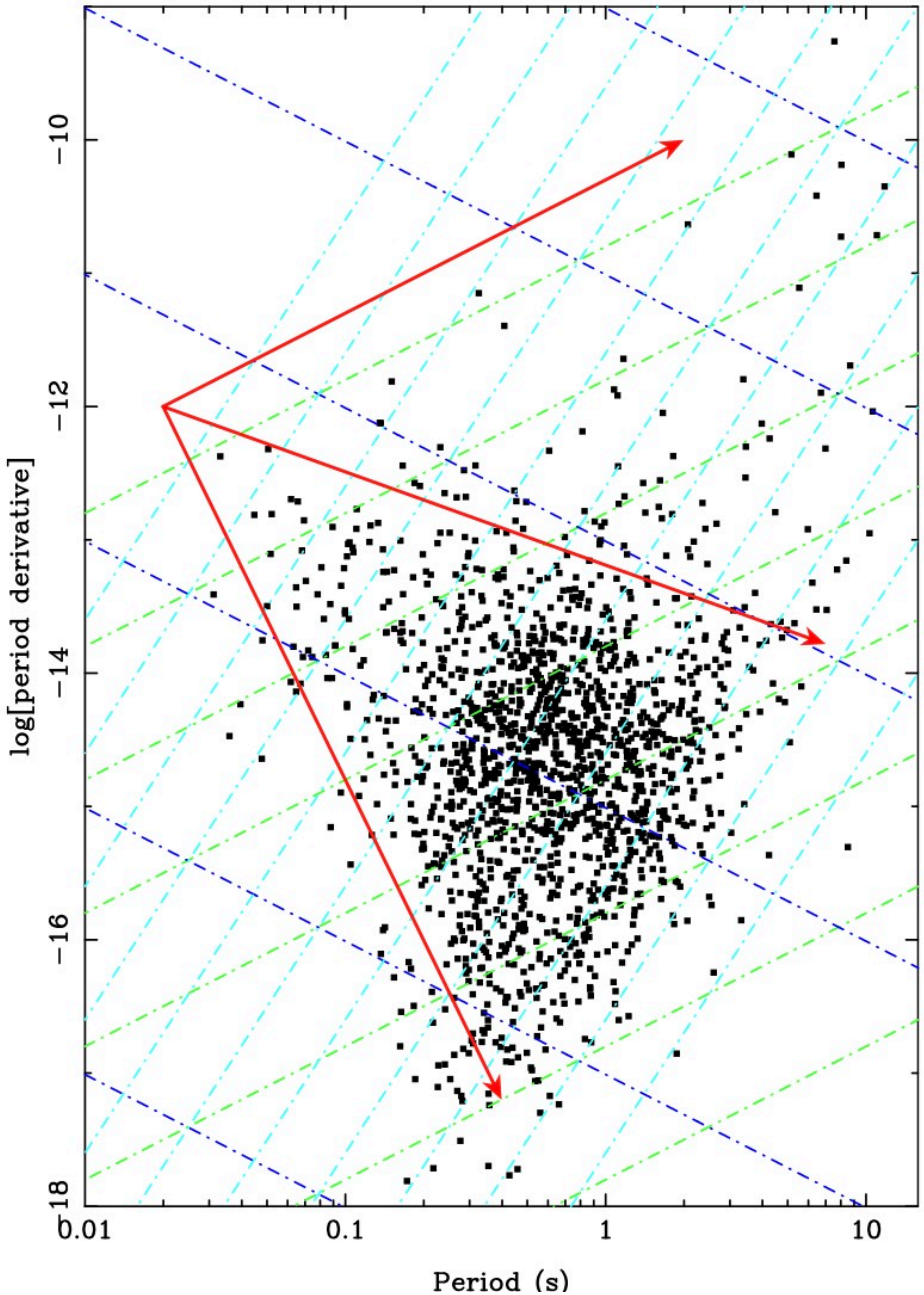
The pulsar population and PSR/FRB searches with MeerKAT



Aris Karastergiou
with contributions from Simon Johnston, Ben Stappers
and the TRAPUM team



P and Pdot are the observables. Lines of constant surface magnetic field, characteristic age, and Edot can be drawn on the diagram, in the picture of a canonical pulsar.

How do pulsars move on this diagram?

$$B = \sqrt{\frac{3c^3 I}{8\pi^2 R^6 \sin^2\alpha} P \dot{P}}$$

$$\tau_c = \frac{P}{2\dot{P}}$$

$$\dot{E} = 4\pi^2 I \frac{\dot{P}}{P^3}$$

$$\dot{\nu} = -K \nu^n$$

$$n = \frac{\nu \ddot{\nu}}{\dot{\nu}^2}$$

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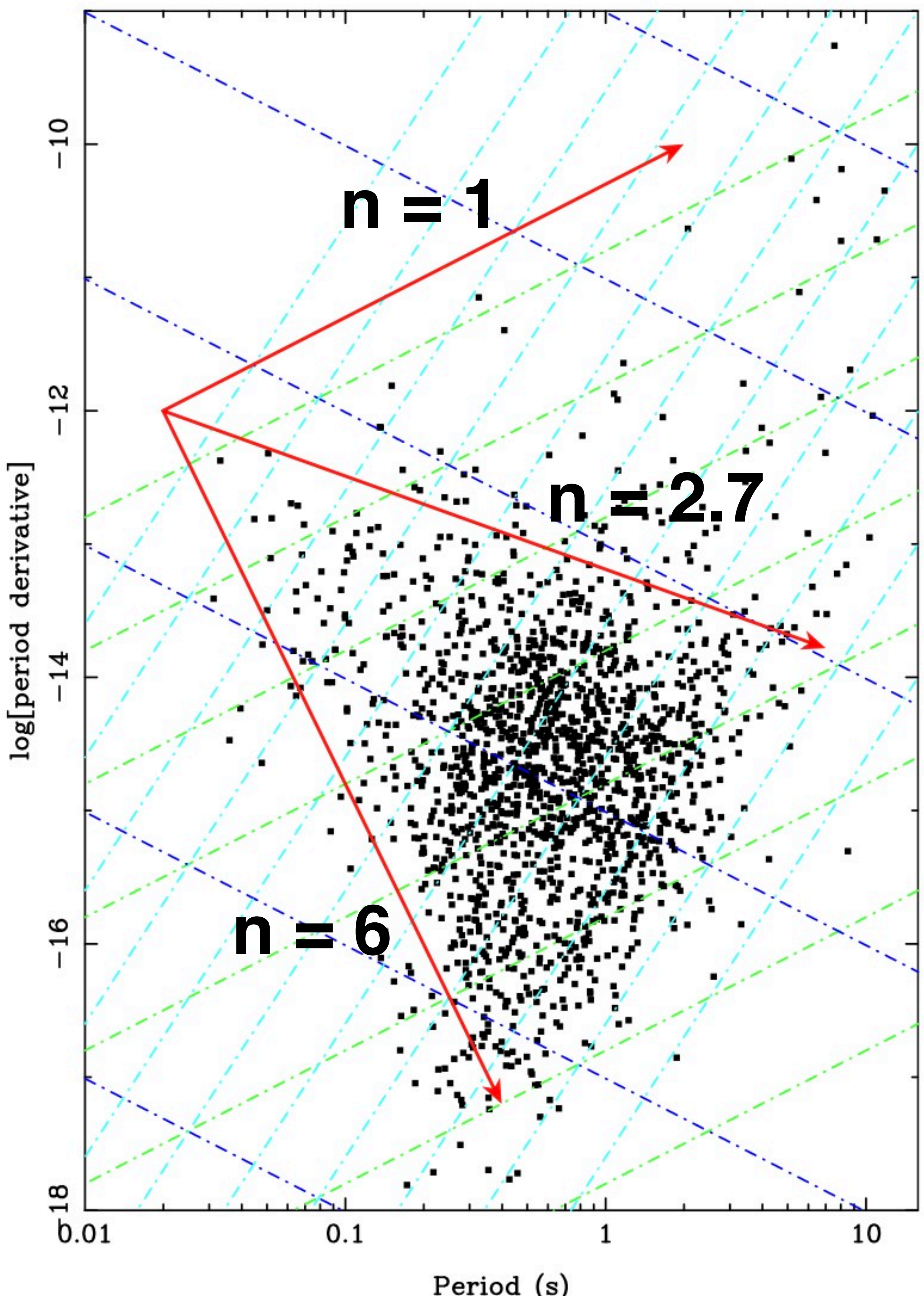


P and Pdot are the observables. Lines of constant surface magnetic field, characteristic age, and Edot can be drawn on the diagram, in the picture of a canonical pulsar.

How do pulsars move on this diagram?

Braking by particle wind: n=1
Braking by magnetic dipole: n=3
Braking by quadrupole magnet: n=5

$$n(t) = 3.0 - \frac{3c^3 I \dot{B}(t)}{R^6 B^3(t) \sin^2\alpha(t) \Omega^2(t)} - \frac{3c^3 I \cos\alpha(t) \dot{\alpha}(t)}{R^6 B^2(t) \sin^3\alpha(t) \Omega^2(t)}$$

Tauris & Konar 2001

$$n(t) = 3.0 - \frac{3c^3 I \dot{B}(t)}{R^6 B^3(t) \sin^2\alpha(t) \Omega^2(t)} - \frac{3c^3 I \cos\alpha(t) \dot{\alpha}(t)}{R^6 B^2(t) \sin^3\alpha(t) \Omega^2(t)}$$

Magnetic field decay:

Young pulsars appear to have stronger magnetic fields than older pulsars

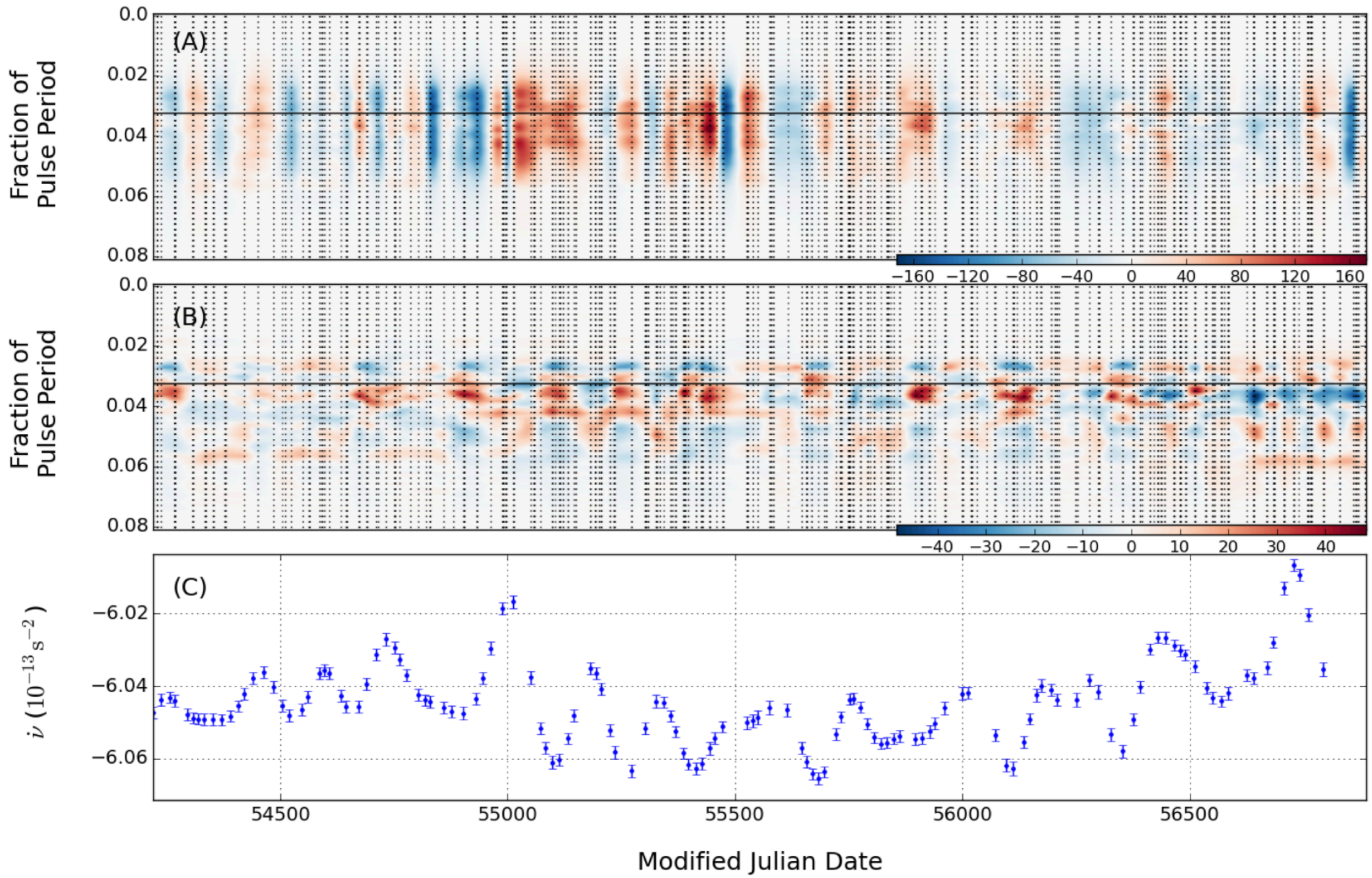
Gunn & Ostriker 1970
Gonthier et al. 2004 **PRO**
Lorimer et al. 1997 **AGAINST**

Decay of α:

Moving towards alignment
Tauris & Manchester 1998
Weltevrede & Johnston 2008

Counter example:
Crab pulsar over the last few decades shows α increasing

$$n(t) = 3.0 - \frac{3c^3 I \dot{B}(t)}{R^6 B^3(t) \sin^2\alpha(t) \Omega^2(t)} - \frac{3c^3 I \cos\alpha(t) \dot{\alpha}(t)}{R^6 B^2(t) \sin^3\alpha(t) \Omega^2(t)} + TN(t)$$



State changing pulsars, see Brook et al. 2016

Also: intermittents, timing noise, glitches -> variable **n**

Faucher-Giguère & Kaspi 2006

1. Magnetic field decay is not significant
2. Pulsar luminosity probably scales with $Edot^{1/2}$
3. The spin period at birth is 300 ms on average, with a broad distribution

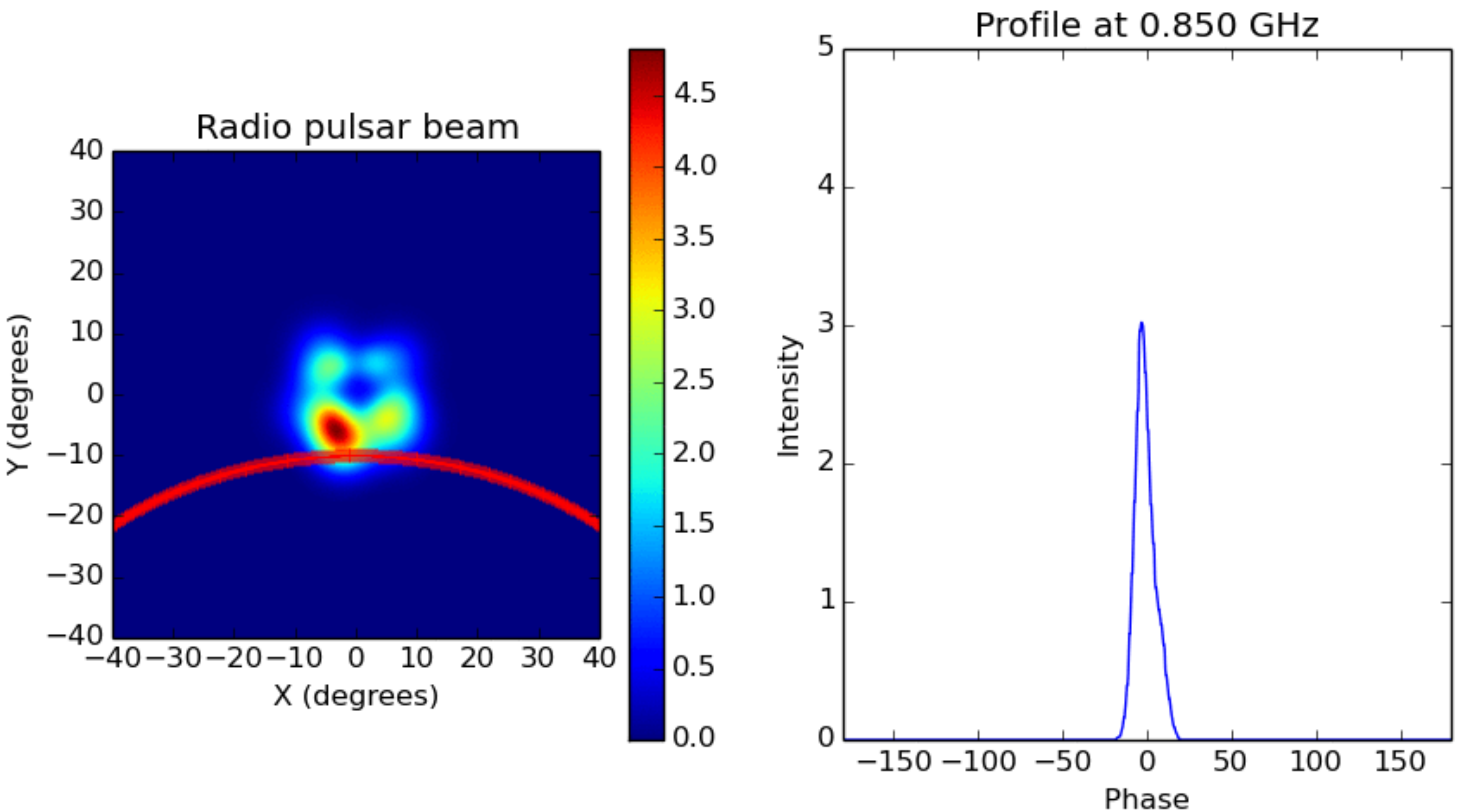
Ridley & Lorimer 2010

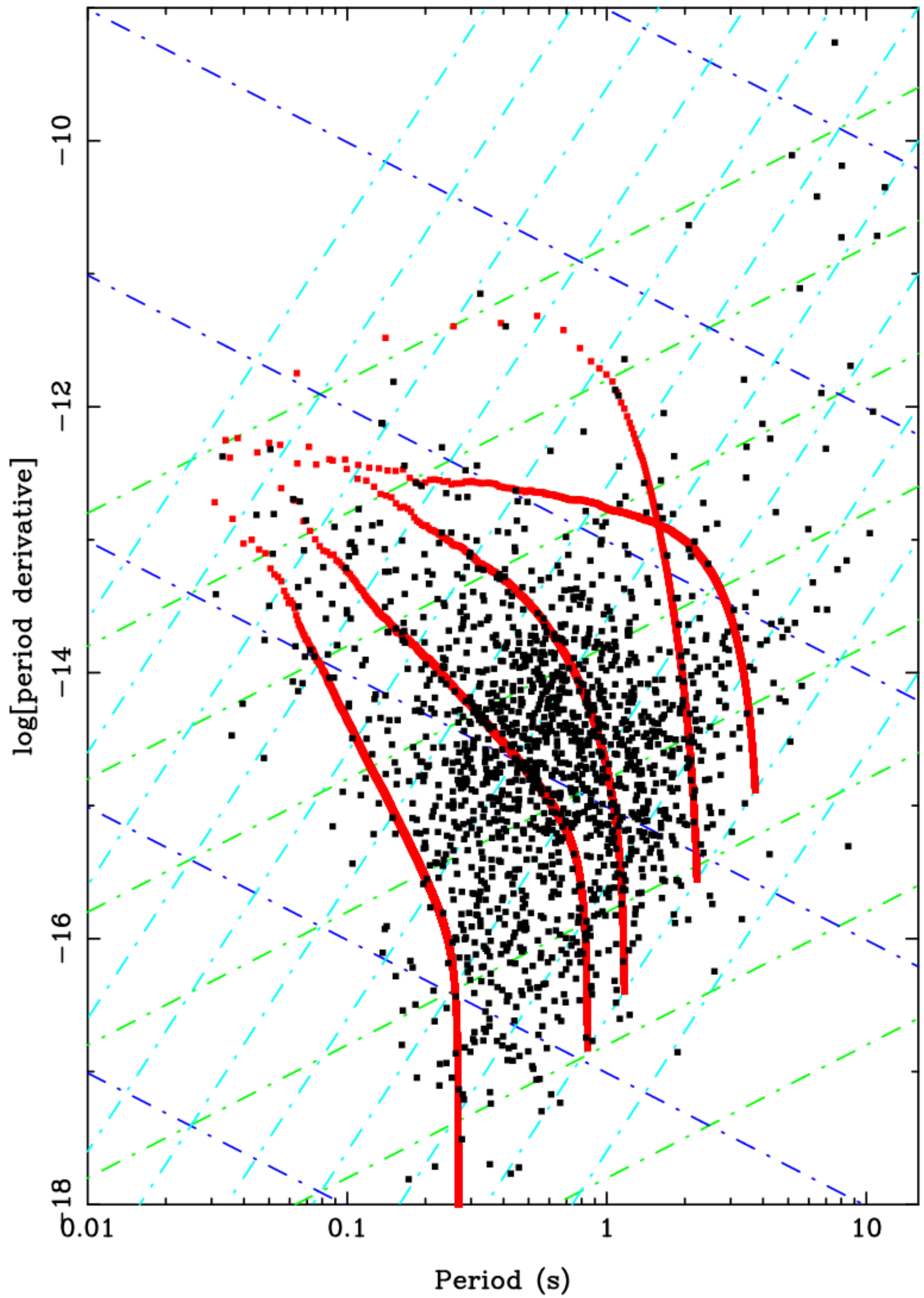
Variable **n** at birth, but like FGK, no time variability in **n**

Can we use a time variable component of **n** to generate the P-Pdot diagram, assuming all pulsars are born with the P and Pdot of the Crab?

A simulation

1. All pulsars born with Crab-like properties (P = 20 ms, Pdot = 10^{-12}).
2. Pulsars are born with a random geometry.
3. Pulsars are born at random distances from Earth, based on the Galactic stellar density distribution.
4. One pulsar is born every X years, with X ranging between 30-100 (Keane & Kramer 2008)
5. The noise term **TN(t)** is given a new value every Y years.
6. Pulsar luminosity is a function of P and Pdot.
7. Pulsars are only added to the diagram, if they are detectable, i.e. they are beaming towards us, and they are sufficiently bright.
8. Some law for Bdot and αdot can be assumed.
9. Pulsars with an intrinsic log(Edot) less than 30 do not produce detectable radio emission.
10. Exponential decay of α on timescale of 10^7 yr.


Radio pulsar beam
Y (degrees)
X (degrees)
40
30
20
10
0
−10
−20
−30
−40
−40 −30 −20 −10 0 10 20 30 40
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Profile at 0.850 GHz
Intensity
Phase
5
4
3
2
1
0
−150 −100 −50 0 50 100 150



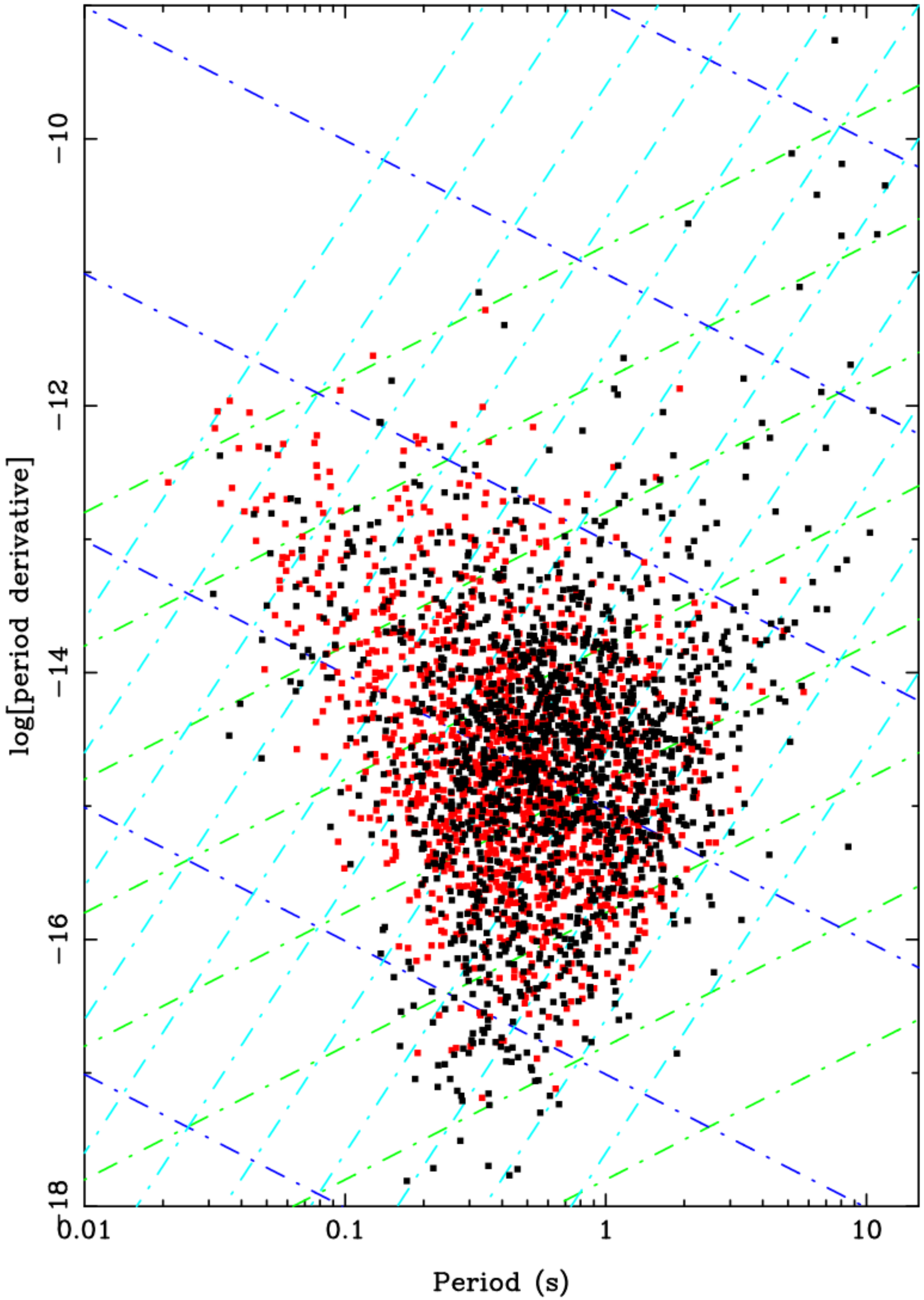
log[period derivative]
−10
−12
−14
−16
−18
0.01
0.1
1
10
Period (s)

$$\log L = \log(L_0 \quad P^{\epsilon_1} \quad \dot{P}^{\epsilon_2})$$

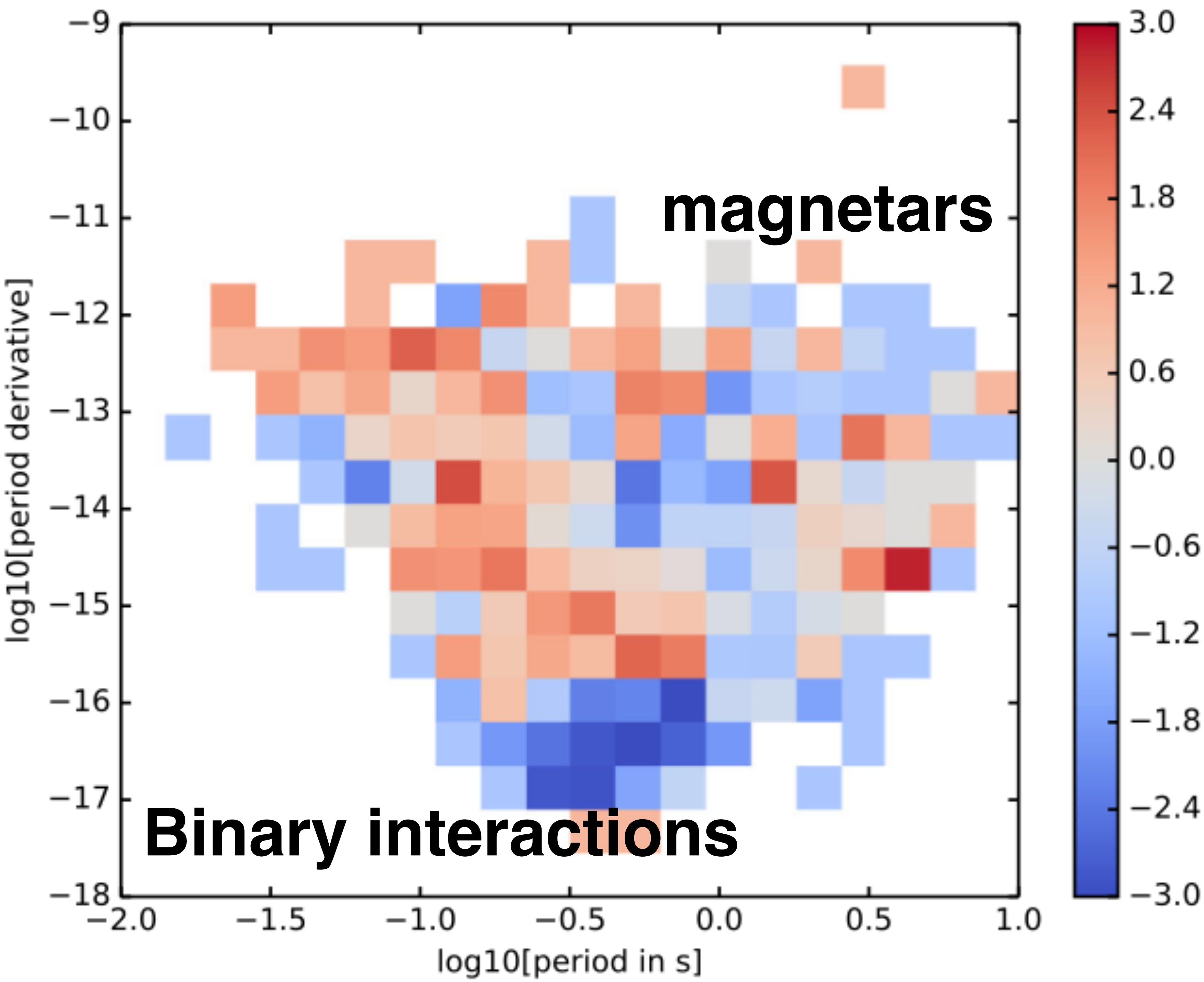
Set ε1 = ε2 = 0
Too many old pulsars

Set ε1 = -1.5, ε2 = 0.5 as per F-G & Kaspi (2006)
Too many young, short period pulsars

Set ε1 = -0.75, ε2 = 0.25, and one pulsar born every 100 yr



Simulated
Observed



$$R = \frac{N_{\rm sim} - N_{\rm obs}}{\sqrt{N_{\rm sim} + N_{\rm obs}}}$$

Implications

- Old pulsars may be moving vertically on the P-Pdot diagram.
- In general, smaller α means larger **n**
- It is possible for all pulsars to be born with short, ~20 ms periods, in contrast to previous works that require large fractions of the population to be born with periods > 150 ms
- The true ages of our pulsars are significantly less than the characteristic ages τ_c. There is only 7% of the simulated population that are over 10^7 years.
- The decay in α suggests the total radio loud population could be 5x smaller than previous estimates. 20000 pulsars in the Galaxy?

TRAPUM

TRansients and PUlsars with Meerkat

PIs Michael Kramer & Ben Stappers

Kerastari 2007

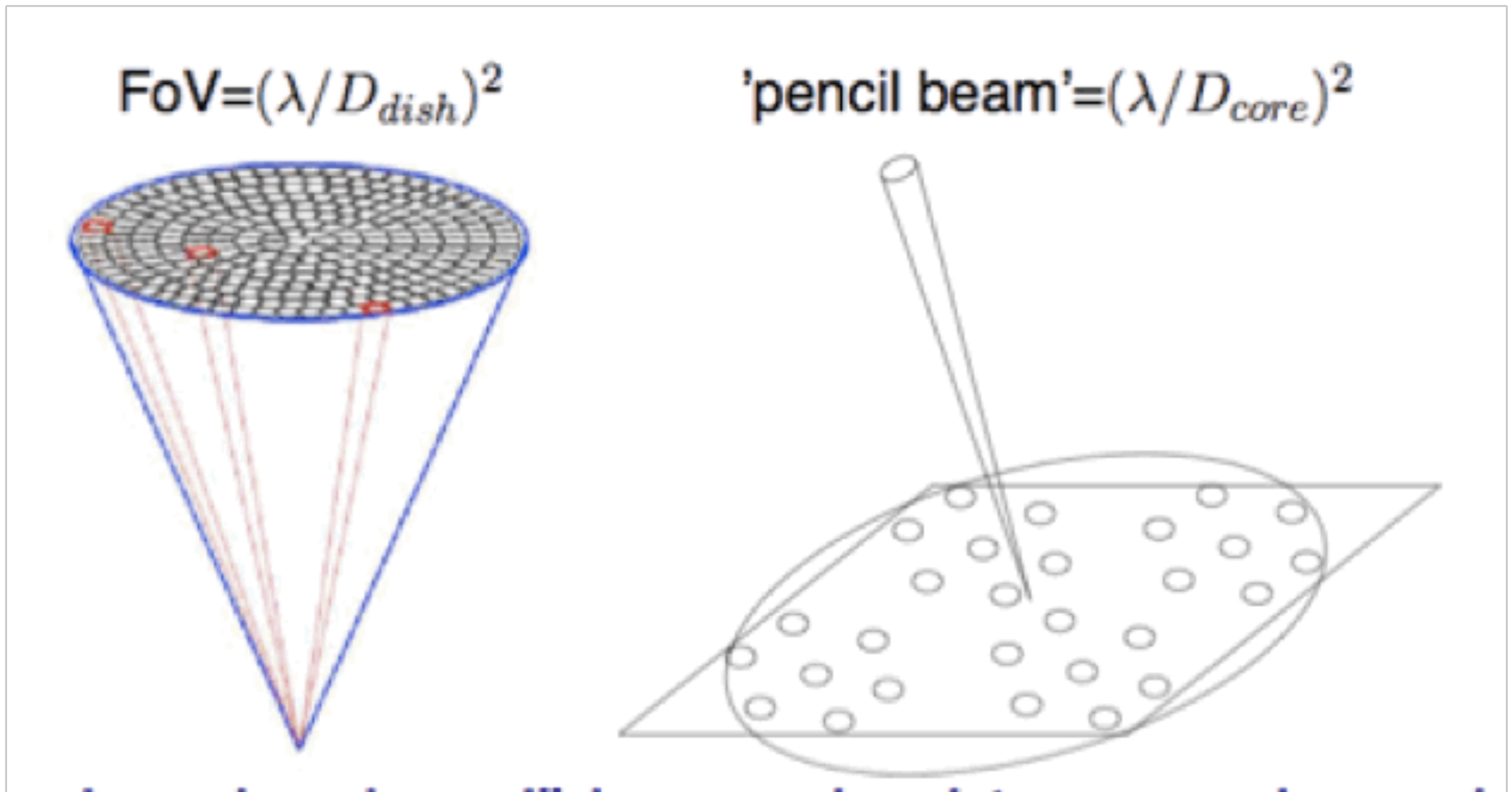
Kerastari 2007

Science Themes

The science case for TRAPUM covers a broad range of neutron-star, galactic and extra-galactic astrophysics as well as gravitational and high-energy physics. The primary science objectives are:

- **Increasing the sample size of all types of radio pulsars**, constraining the birth rates and distribution of neutron stars in the Galaxy.
- **Exploring the properties and evolution of globular clusters** by discovering and timing many new puilsars and transients associated with them.
- **Investigate the dependence of the pulsar and fast transient populations on host galaxy properties**, by searching for them in external galaxies.
- **Probe the Galactic centre**, by discovering pulsars interacting with Sgr A*, dark matter, interstellar plasma and stellar populations in the central region of the Galaxy.
- **Improve our understanding of gravity**, by discovering relativistic binaries and millisecond pulsars suitable for gravitational wave experiments.
- **Expand the searchable parameter space for fast transient radio sources**, enabling study of the most energy-dense events in the Universe, and potentially identify electromagnetic counterparts to gravitational radiation events.
- **Search for high red-shift radio bursts** and use them to refine cosmology.

- Exceptional sensitivity --- greatly increased since 2010.
  - Large collecting area.
  - Wide bandwidths
  - Required for finding relativistic binaries.
- Wide field of view
  - Allows for fast surveys.
  - Access through combination of incoherent and coherent beams
- Resolution
  - Useful for searching in regions of diffuse high brightness temperature regions – e.g. SNRs & Galactic centre
  - Essential for accurate localisation of transients
- Wide range of frequencies
  - Optimise for searching in / through different parts of the Galaxy
  - S-band for deep in the Galactic Centre
  - L-band for intermediate Galactic latitudes
  - UHF band for wide area searches
- Location
- Flexibility & commensality



And a “pulsar backend” is required to search each one.

- Initial TRAPUM proposal allocated time for targetted searches – few beams.
- But requested time to do Galactic plane could be made available if funding for more beams found.
- MPIfR – funding for 200 beams and offline processing
- MeerTRAP – funding for 200 beams – real time proc.

Current Solution

- 400 beams formed in real time
- Incoherent beam as well
- Generally use the core (40 dishes)
- ~ 800 MHz BW at L-band / S-band
- Likely GPU based
- Observations stored for acceleration processing
- Real time search for pulsars and transients
- Transient buffers for storage / imaging

- Targeted searches of SNRs, PWNe, high energy sources - understand PSR-SNR association, birthrate, find new pulsars associated with high energy emission.

- Globular clusters

- Globular clusters

146 known Globular Cluster pulsars Could be several 1000s. Understanding evolution of pulsar binary systems.

Potential homes to extreme binaries, including PSR-BH system.

- Targeted searches of SNRs, PWNe, high energy sources - understand PSR-SNR association, birthrate, find new pulsars associated with high energy emission.
- Globular clusters
- Extragalactic pulsars - LMC, SMC, beyond the local group with giant pulses, overlap with FRB science
- Galactic Centre - start with L, but continue with S, C, and X-band (if/when available)
- Galactic plane search; majority of PSRs in plane: 900 s integrations $-30 < l < 60$, $|b| < 3$, expect ~600 new pulsars

- Commensal observations for FRBs using 400 tied-array beams and incoherent beam

- Mix of targets, on and off the plane: GRBs, SNe, magnetars, RRATS, intermittent pulsars, transitional MSPs, flare stars, and potential counterparts to GW sources.

- Targeted observations of FRB repeaters, with localization possibilities using transient buffer boards to record raw data for offline imaging.

- Fly's eye mode

- Can detect Lorimer-burst brightness (30 Jy and >400-sigma) FRBs with a MeerKAT Fly's Eye experiment
- In Fly's Eye mode, MeerKAT will instantaneously cover 0.8 * 64 = 51.2 deg2, or 0.00128 of the sky.
- Conservative assumptions on sensitivity and detection significance result in about 9 bursts of this brightness.
- Assuming logN-logS = -1.5 results in a total of about 30 FRBs in 720 h.
- Crucial information on the luminosity distribution and potentially very useful probes of the local IGM and the host galaxy.
- Localization will be poorer, but can use beamforming tricks – Obrocka et al.