Pulsars in globular clusters with the SKA precursors and pathfinders

Alessandro Ridolfi

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Max-Planck-Institut für Radioastronomie Bonn

On behalf of *many* people in the MeerTIME and TRAPUM collaborations

The Third National Workshop on the SKA Project

The Italian Route to the SKAO Revolution

October 5, 2021

Pulsar populations

> 3100 pulsars currently known*, different populations

Ordinary Pulsars

$P \sim 1$ s

$\tau \sim 10^7$ yr

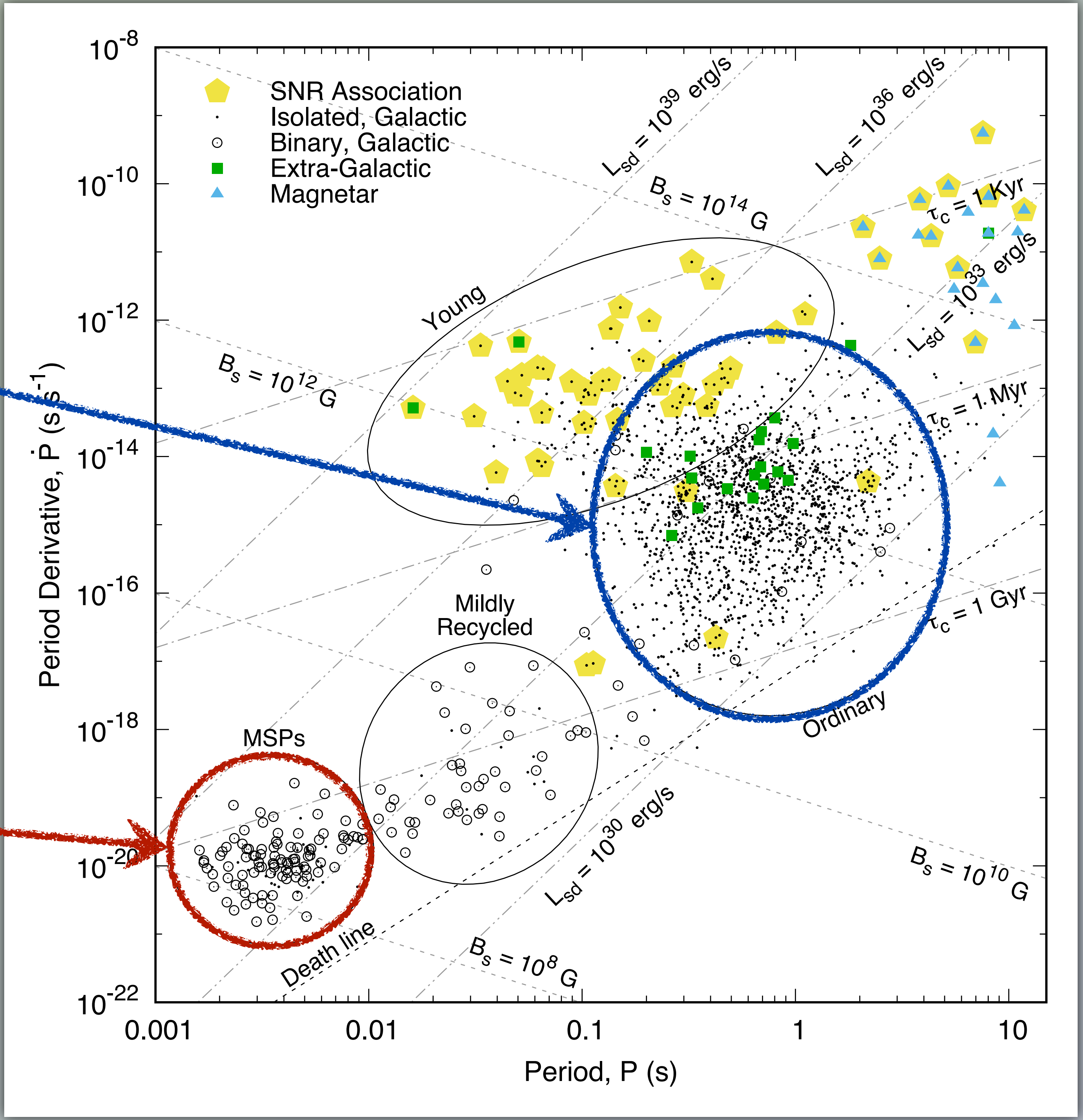
$B \sim 10^{12}$ G

Millisecond ("Recycled") Pulsars

$P \sim 1$ ms

$\tau \sim 10^9$ yr

$B \sim 10^8$ G



* ATNF catalog, v1.65 (Manchester et al. 2005) *http://www.atnf.csiro.au/people/pulsar/psrcat*

Pulsars in Globular Clusters

Globular Clusters (GCs) are spherical, gravitationally bound groups of 10^4 - 10^6 stars.

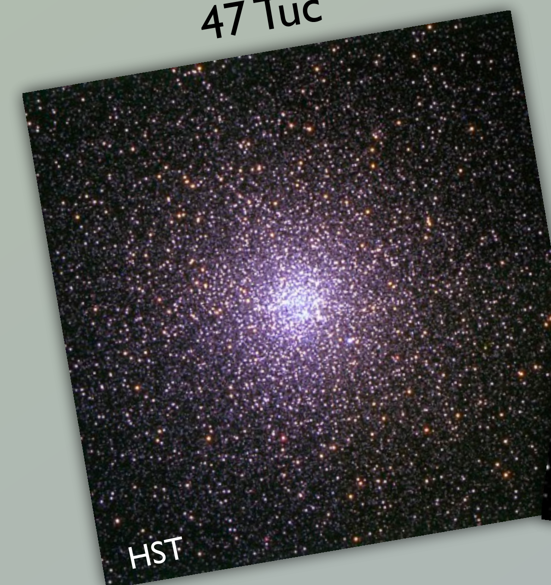
Currently ~150 known orbiting the Milky way.

https://www.physics.mcmaster.ca/~harris/mwgc.dat

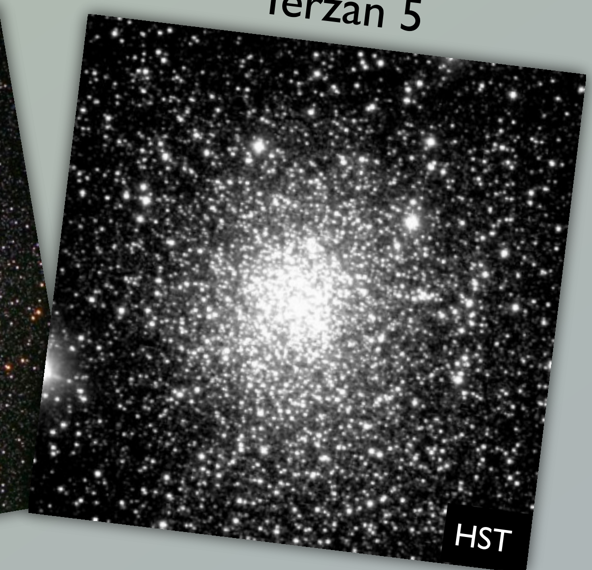
Star densities at the GC cores over 10^3 per cubic parsec.

Ideal environments for formation and disruption of binaries, for the spin-up of pulsars through accretion processes, and the formation of exotic systems through repeated exchange interactions.

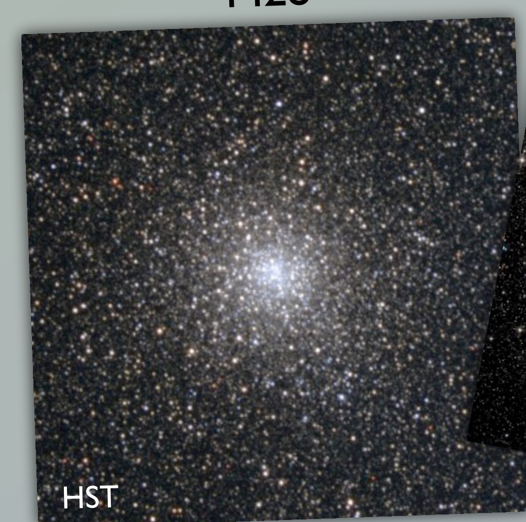
47 Tuc



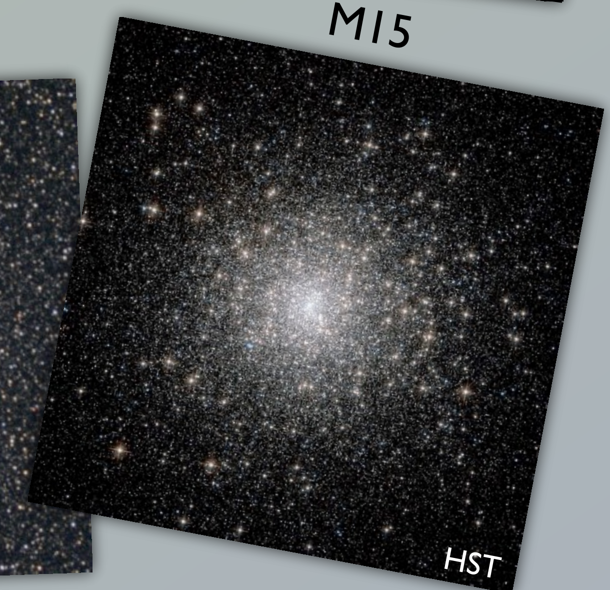
Terzan 5



M28

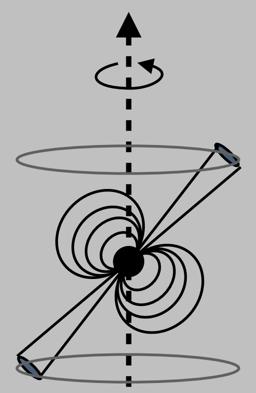


M15



Exciting pulsars can be found in Globular Clusters!

Extremely recycled pulsars



e.g.: Ter 5 ad (Hessels et al. 2006) ✔

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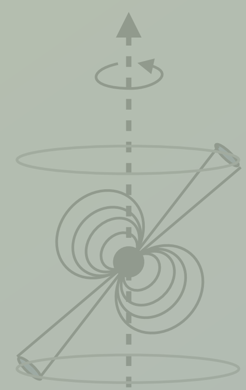

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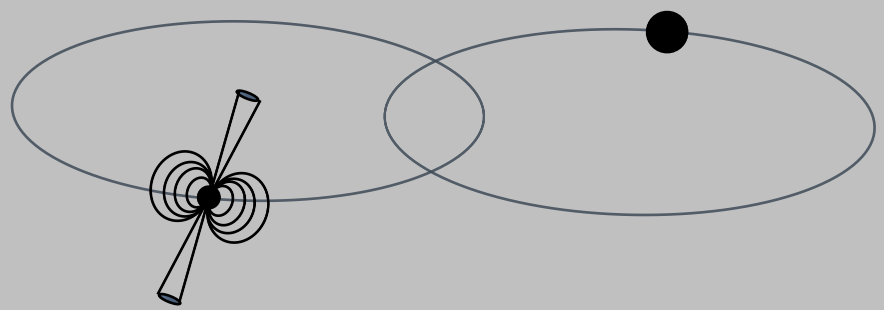
Extremely eccentric binaries



e.g.: NGC 6652 A (DeCesar et al. 2015) ✔

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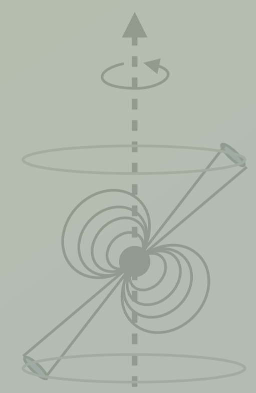
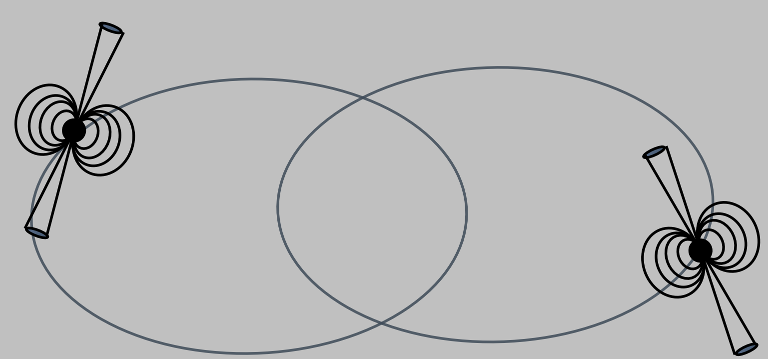


e.g.: Ter 5 ad (Hessels et al. 2006) ✔

Extremely eccentric binaries

e.g.: NGC 6652 A (DeCesar et al. 2015) ✔

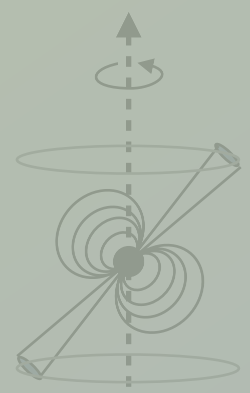
MSP - MSP



✘

Exciting pulsars can be found in Globular Clusters!

Extremely recycled pulsars



e.g.: Ter 5 ad (Hessels et al. 2006) ✔

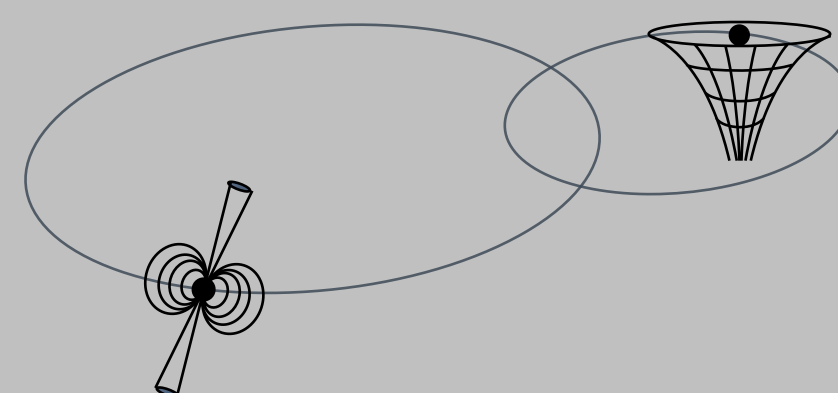
Extremely eccentric binaries

e.g.: NGC 6652 A (DeCesar et al. 2015) ✔

MSP - MSP

✘

Pulsar - BH



✘

Pulsars as probes of GC dynamics

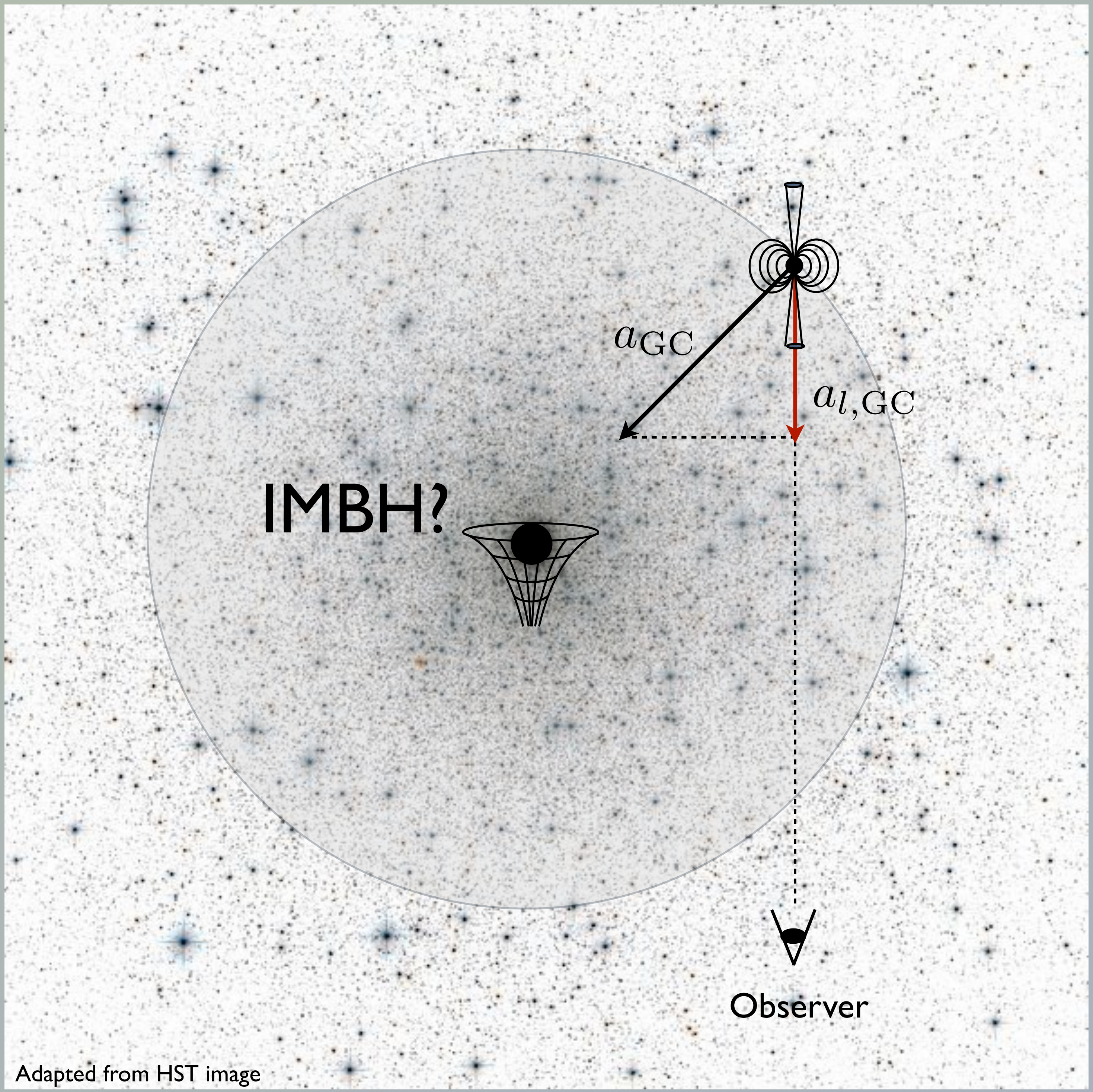
Pulsars in GCs can also be used to study the gravitational **potential of the host cluster** (e.g. Phinney 1993).

And possibly address questions such as:

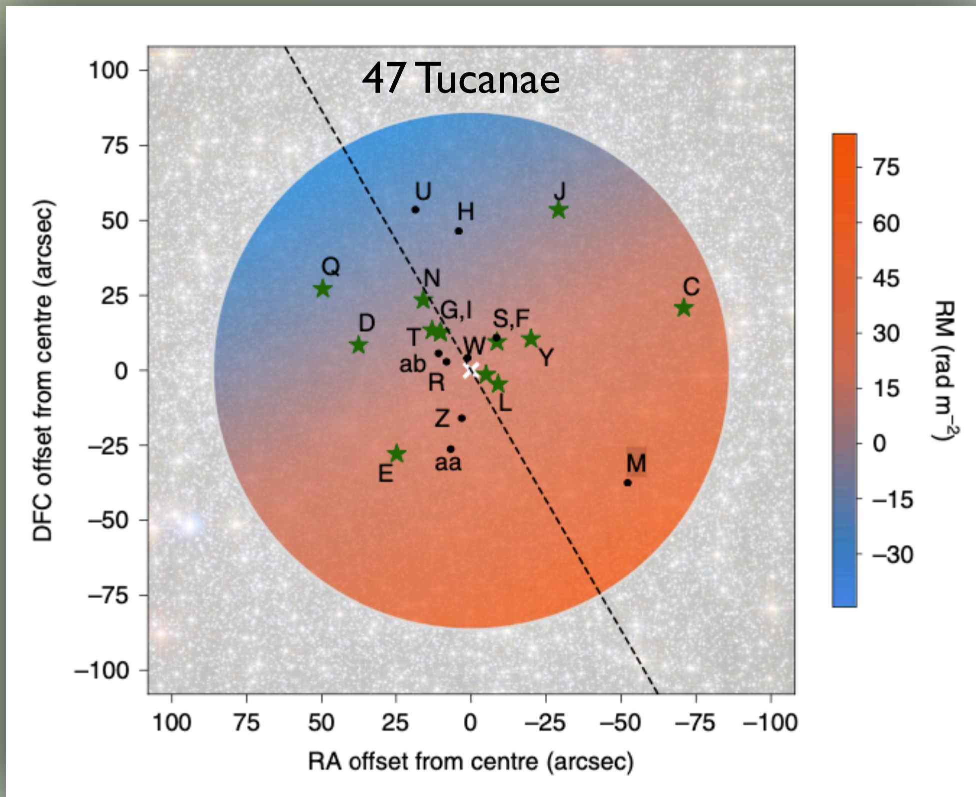
Is there an IMBH at the center of some clusters?

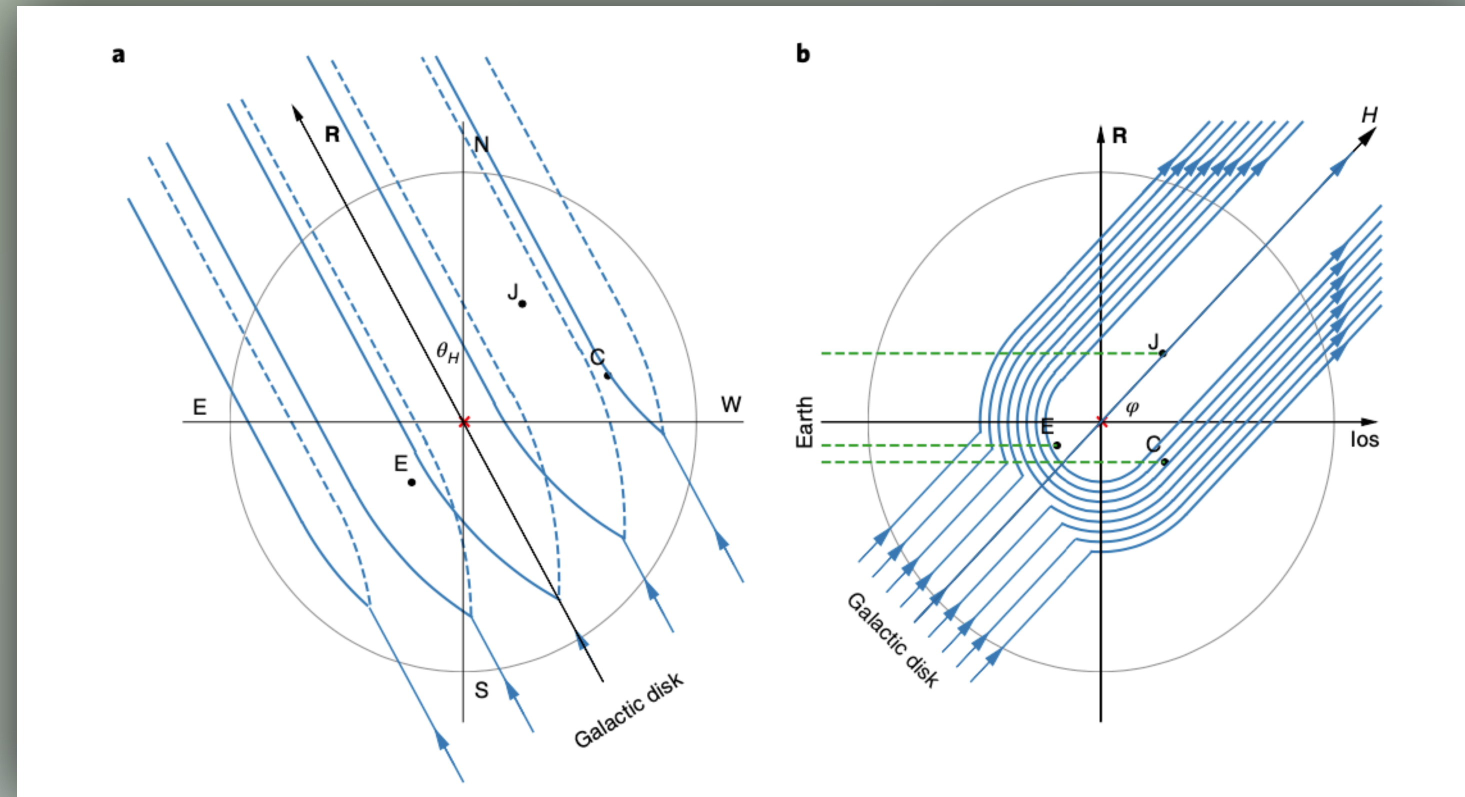
See e.g. some recent papers:

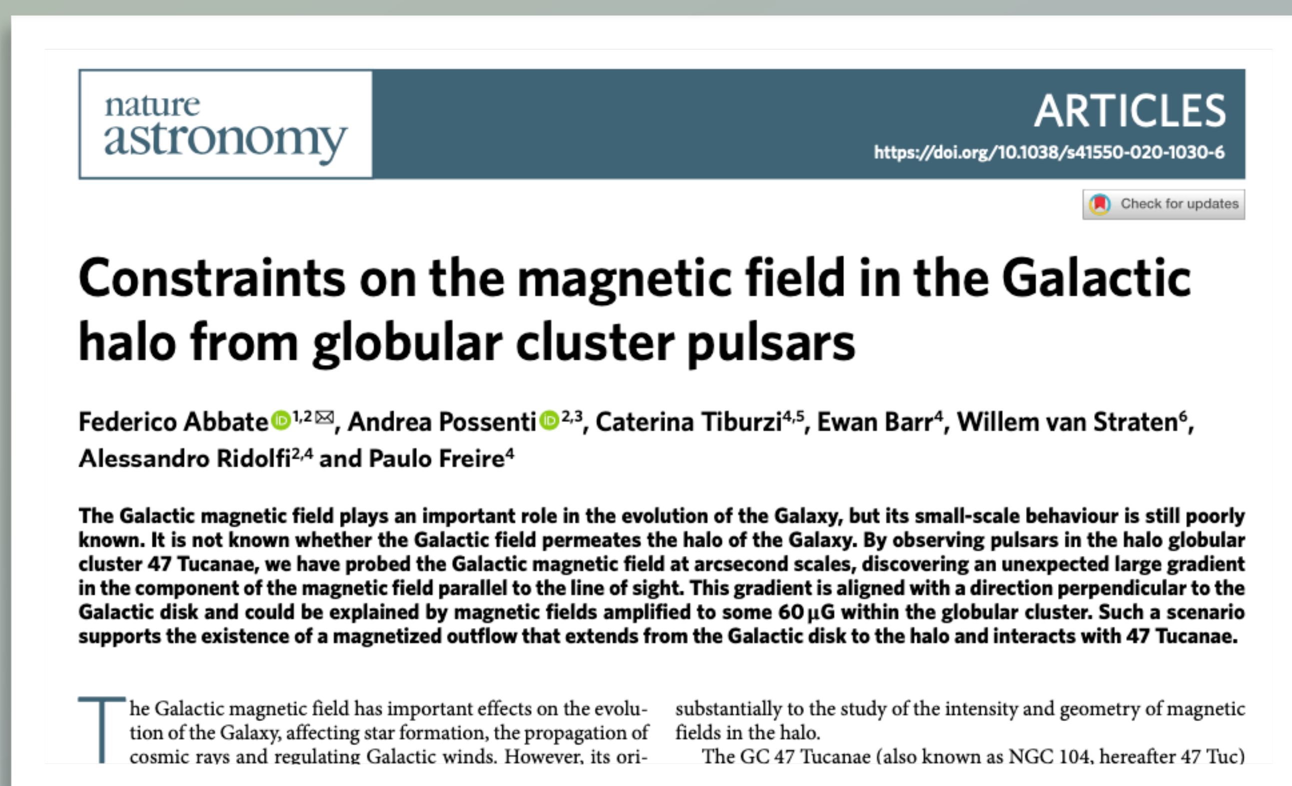
- Freire et al. (2017)
- Perera et al. (2017)
- Prager et al. (2017)
- Abbate et al. (2018, 2019a, 2019b)
- and others...



GC pulsars as probes of Galactic magnetization







nature astronomy

ARTICLES

https://doi.org/10.1038/s41550-020-1030-6

Check for updates

Constraints on the magnetic field in the Galactic halo from globular cluster pulsars

Federico Abbate[1,2], Andrea Possenti[2,3], Caterina Tiburzi[4,5], Ewan Barr[4], Willem van Straten[6], Alessandro Ridolfi[2,4] and Paulo Freire[4]

The Galactic magnetic field plays an important role in the evolution of the Galaxy, but its small-scale behaviour is still poorly known. It is not known whether the Galactic field permeates the halo of the Galaxy. By observing pulsars in the halo globular cluster 47 Tucanae, we have probed the Galactic magnetic field at arcsecond scales, discovering an unexpected large gradient in the component of the magnetic field parallel to the line of sight. This gradient is aligned with a direction perpendicular to the Galactic disk and could be explained by magnetic fields amplified to some 60 µG within the globular cluster. Such a scenario supports the existence of a magnetized outflow that extends from the Galactic disk to the halo and interacts with 47 Tucanae.

The Galactic magnetic field has important effects on the evolution of the Galaxy, affecting star formation, the propagation of cosmic rays and regulating Galactic winds. However, its ori- substantially to the study of the intensity and geometry of magnetic fields in the halo.

The GC 47 Tucanae (also known as NGC 104, hereafter 47 Tuc)

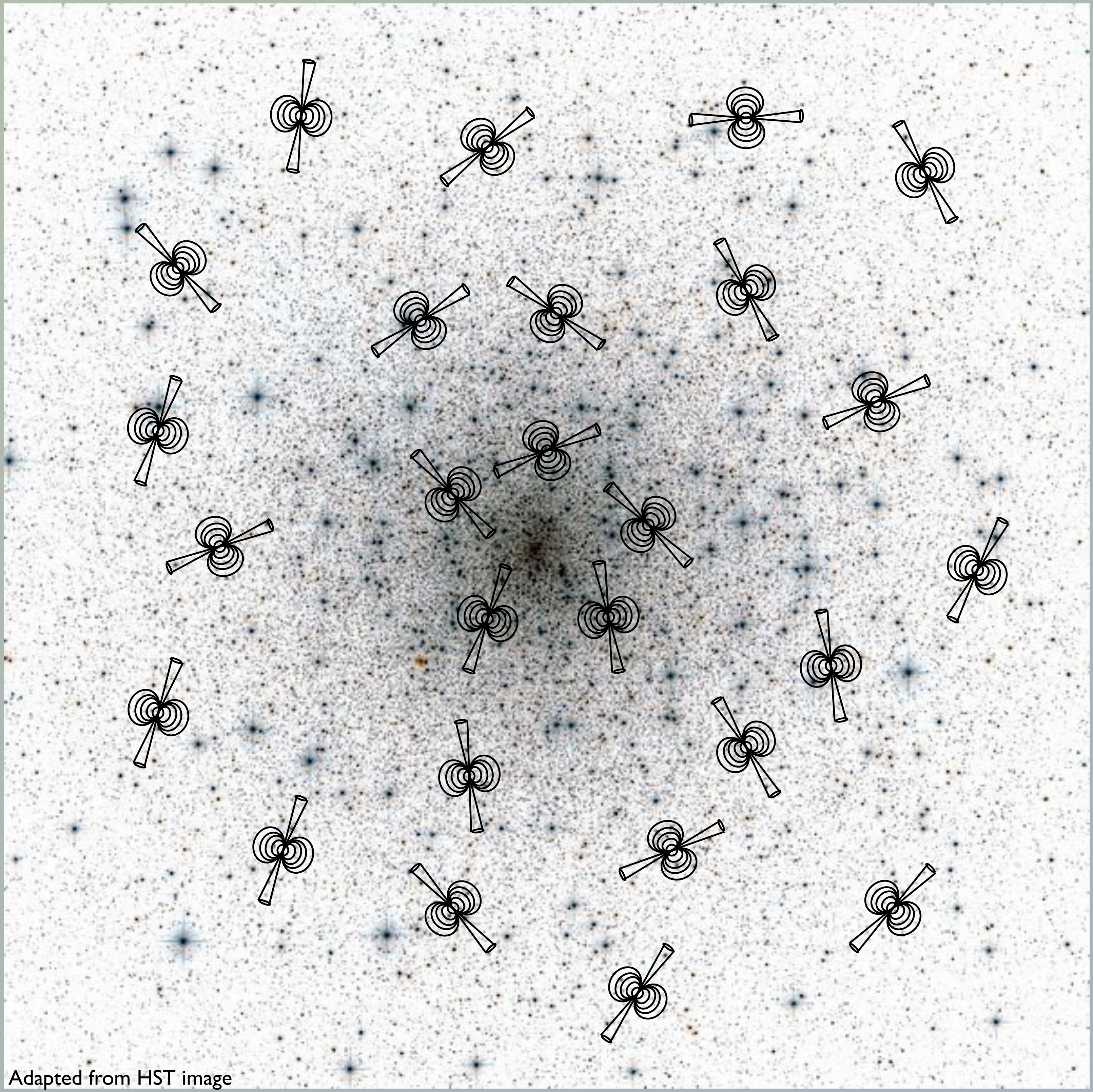
Abbate et al. (2020a)

The estimated GC pulsar population

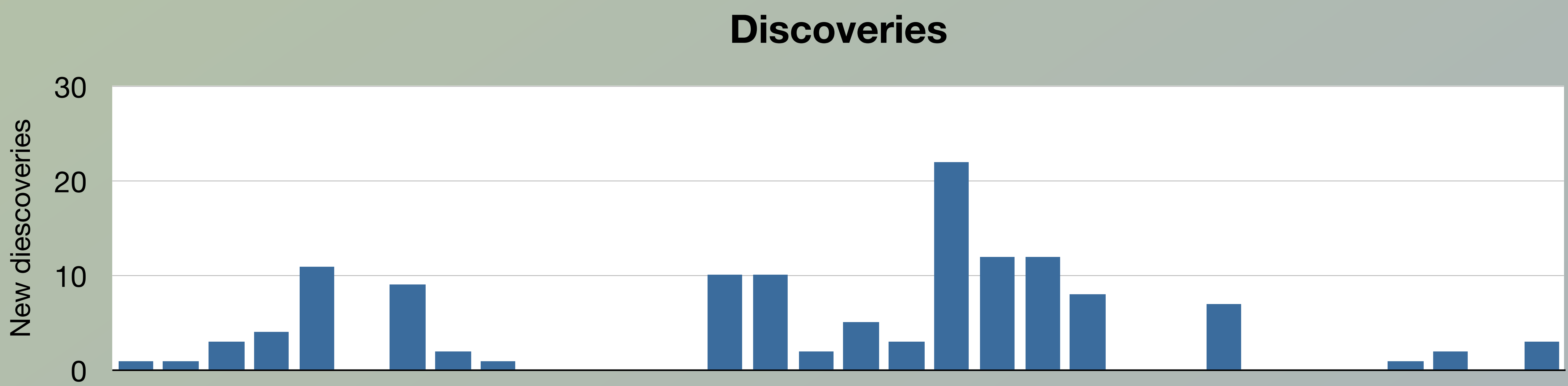
150 pulsars in 28 globular clusters

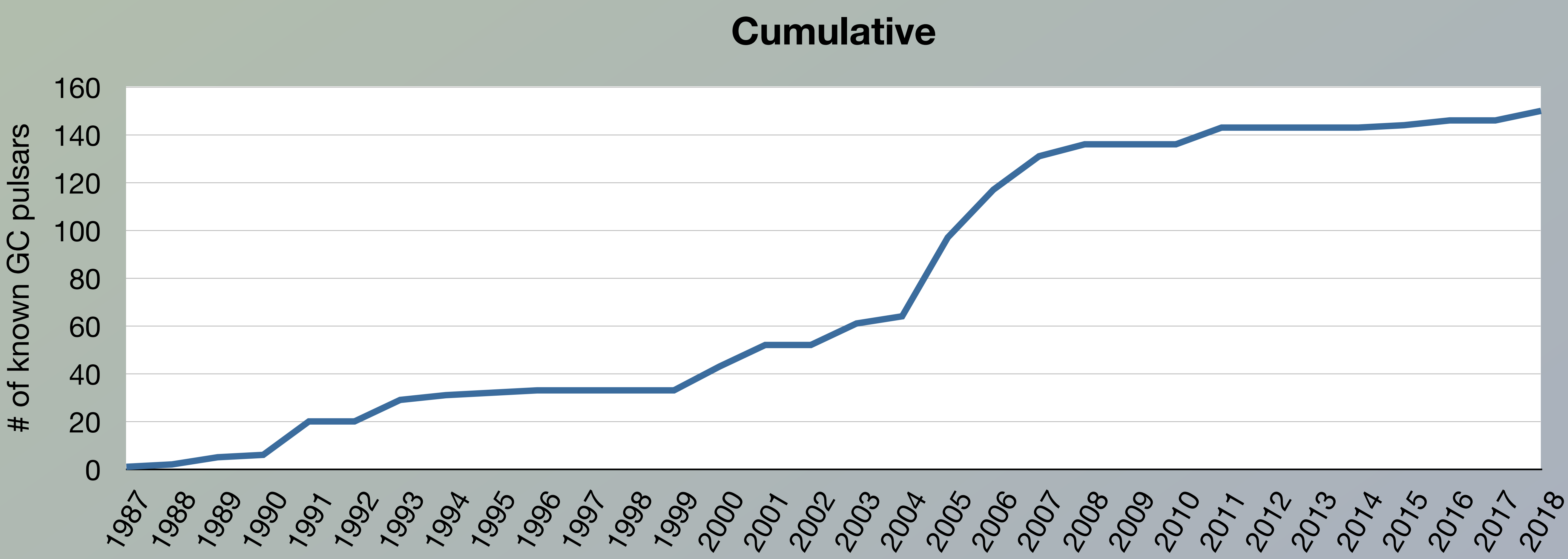
However, Turk & Lorimer (2013) estimated a population between **600-3000** potentially observable Galactic GC pulsars!

Where are all the others?



GC pulsar discoveries over the years





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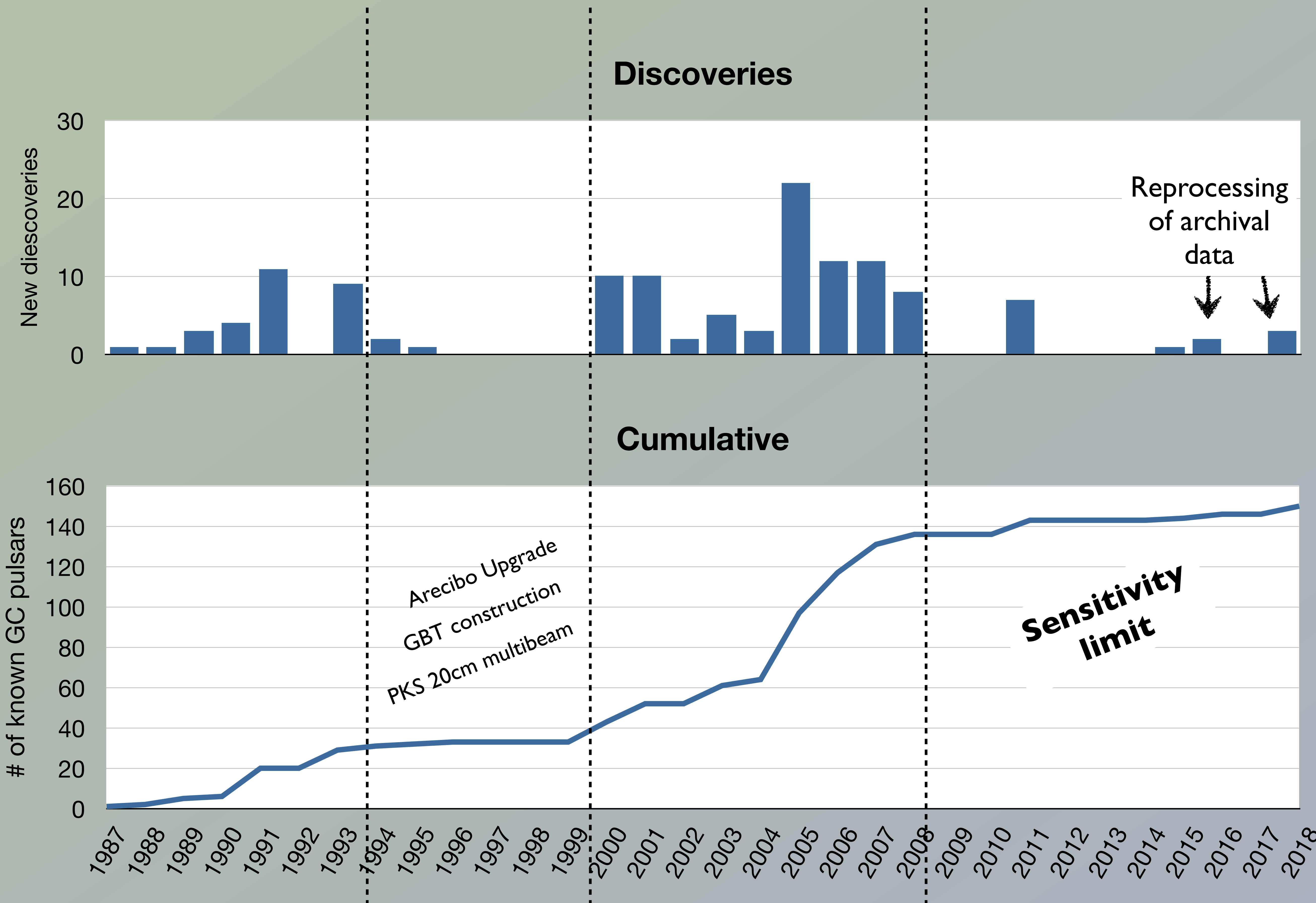
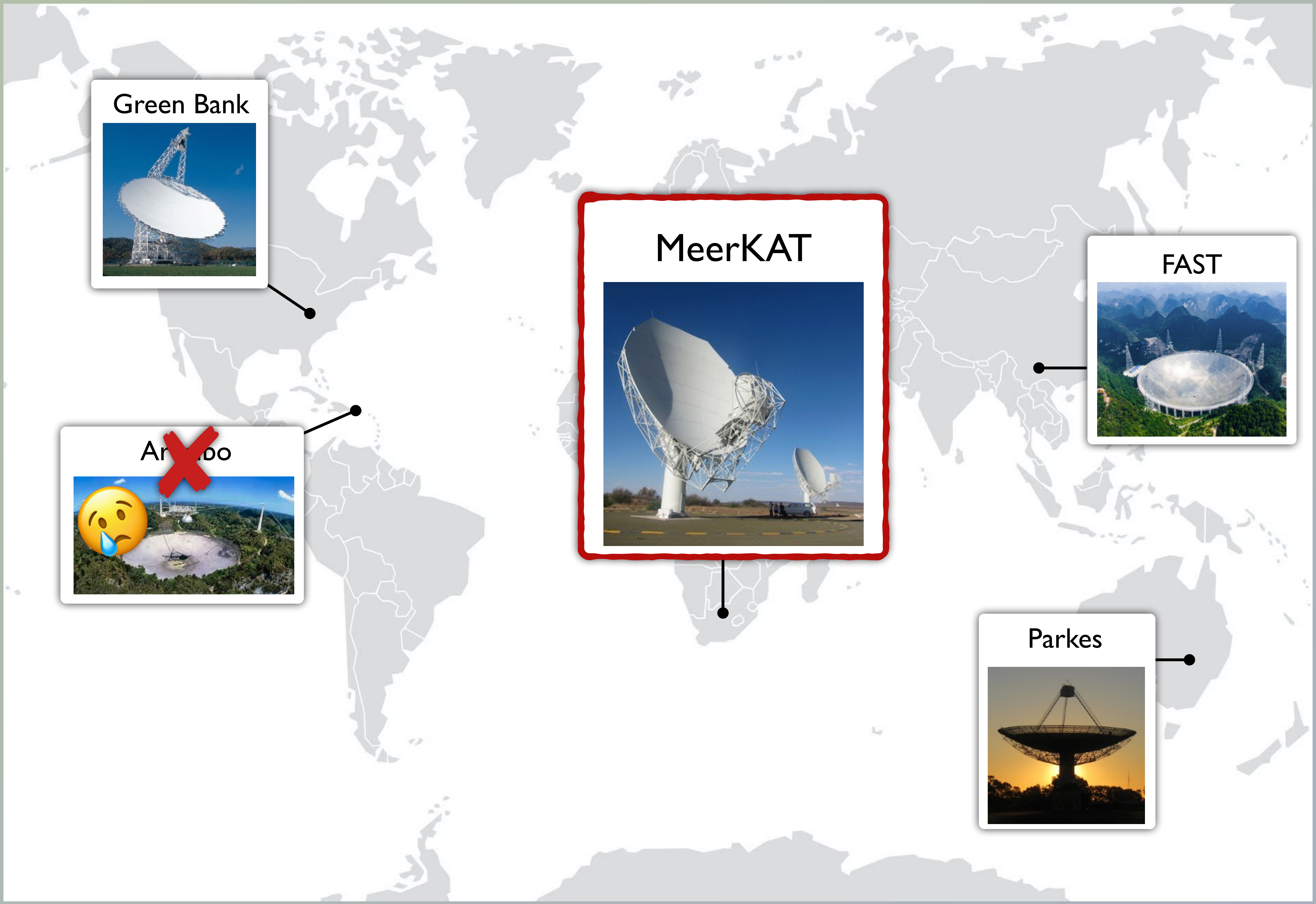


Major telescopes for GC pulsar science



The MeerKAT radio telescope



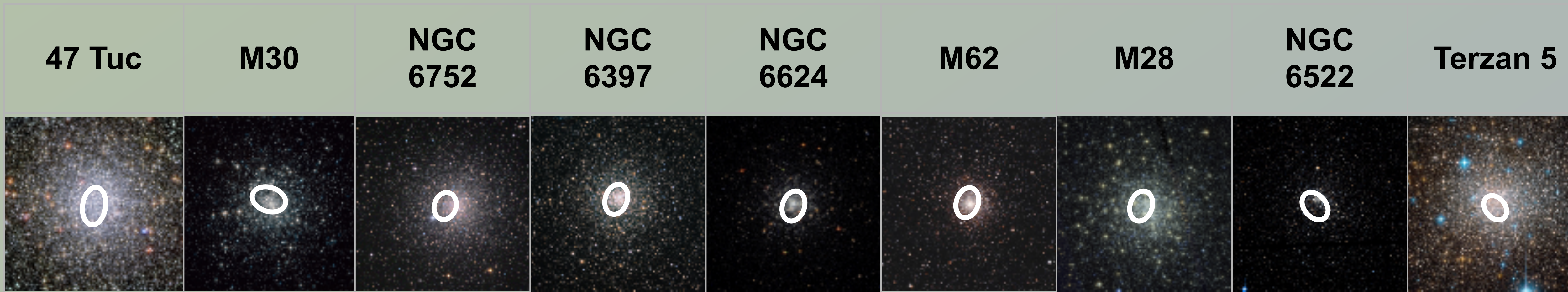
	MeerKAT	GBT	Parkes
Collecting Area:	~9000 m²	~8000 m²	~3200 m²
Telescope Gain:	2.8 K/Jy	2.0 K/Jy	0.7 K/Jy
Tsys:	~18 K	~20 K	~20 K
Bandwidth (L-band):	775 MHz	580 MHz	> 1 GHz

~ up to 2 x more sensitive than GBT

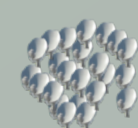
~4 - 8 x more sensitive than Parkes

A first GC census with MeerKAT

We observed the central regions 9 of different GCs from March 2019 to August 2020



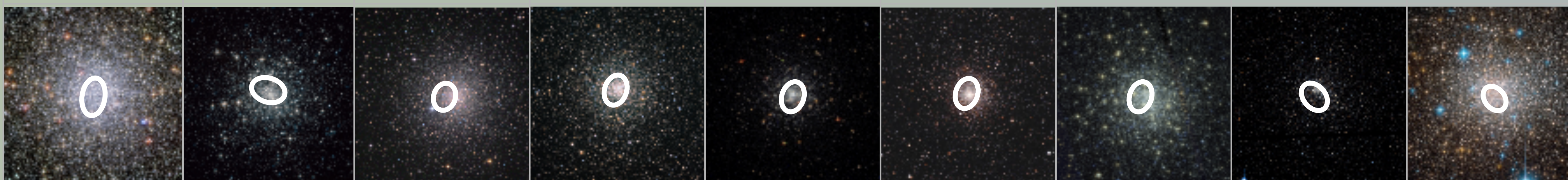
Observing setup

- 1-km core (44 antennas) 
- MeerTime backend <u>only</u>
- 1 Beam (radius: ~0.5')
- L-band receivers (900-1700 MHz)
- Integration time: 2.5 hours

A first GC census with MeerKAT

We observed the central regions 9 of different GCs from March 2019 to August 2020

47 Tuc	M30	NGC 6752	NGC 6397	NGC 6624	M62	M28	NGC 6522	Terzan 5



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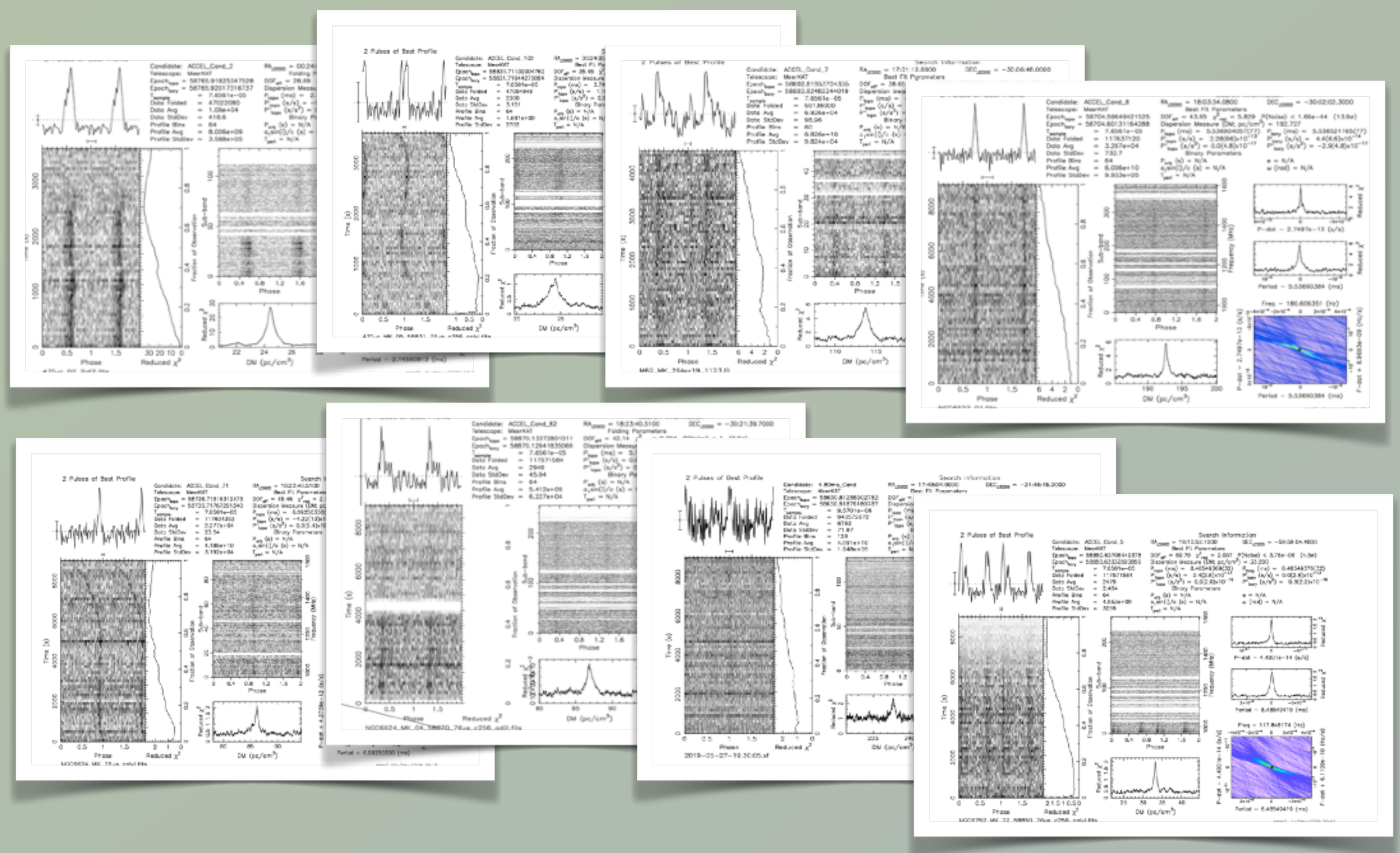
Science goals

- Verify telescope performance
- Test processing pipelines
- Search for new pulsars
- Study noteworthy pulsars
- Use results to plan the fully-fledged *TRAPUM* GC survey

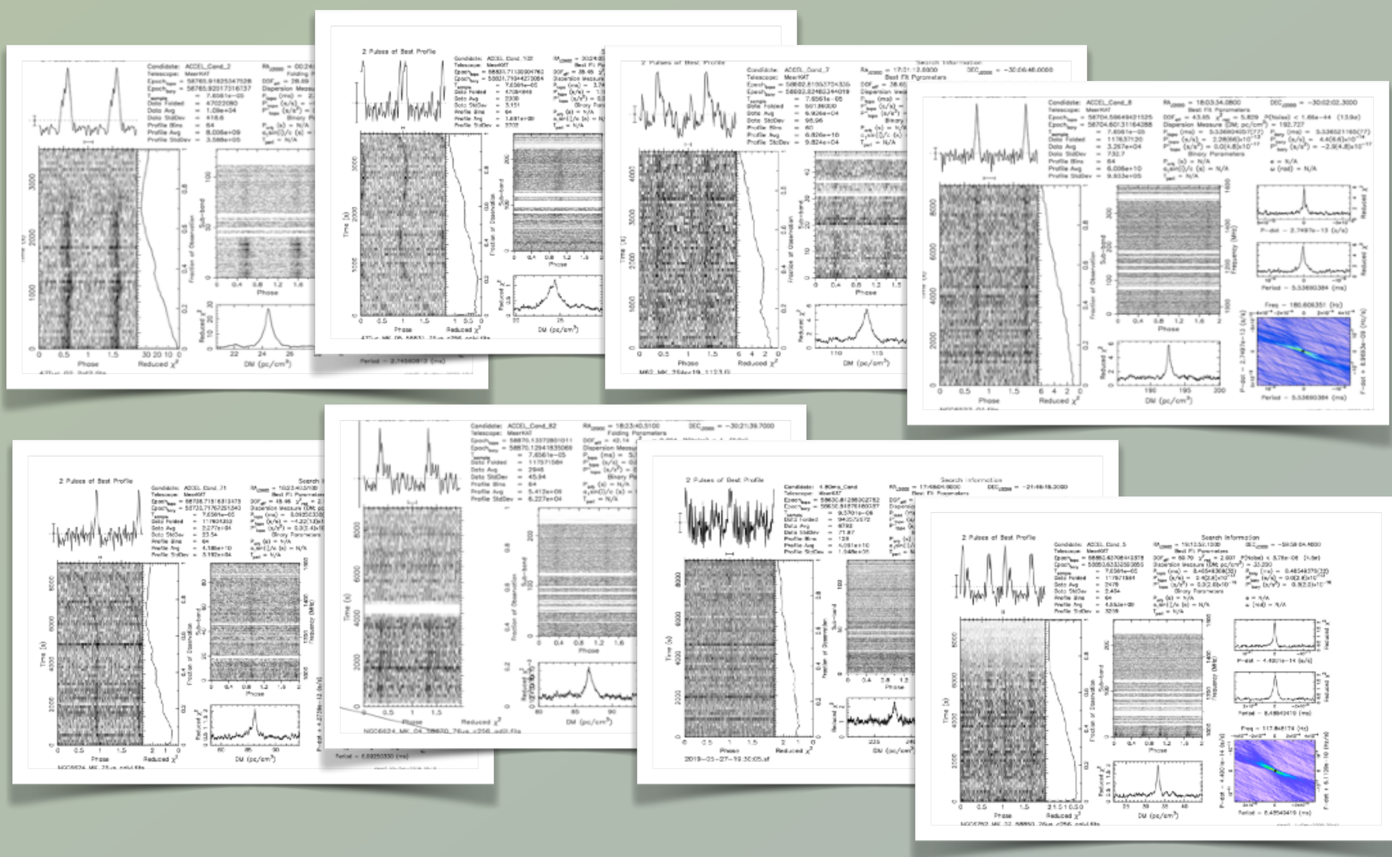
Discovery of 8 new pulsars



Name	P0 (ms)	Type
47 Tuc AC	2.74	Binary
47 Tuc AD	3.74	Binary
M62 G	4.61	Binary
Ter 5 AN	4.80	Binary
NGC 6522 D	5.53	Isolated
NGC 6624 G	6.09	Binary
NGC 6624 H	5.13	Isolated
NGC 6752 F	8.48	Isolated

- Found in 6 different clusters
- All of them MSPs (P < 10 ms)
- 5 binary, 3 isolated

Discovery of 8 new pulsars



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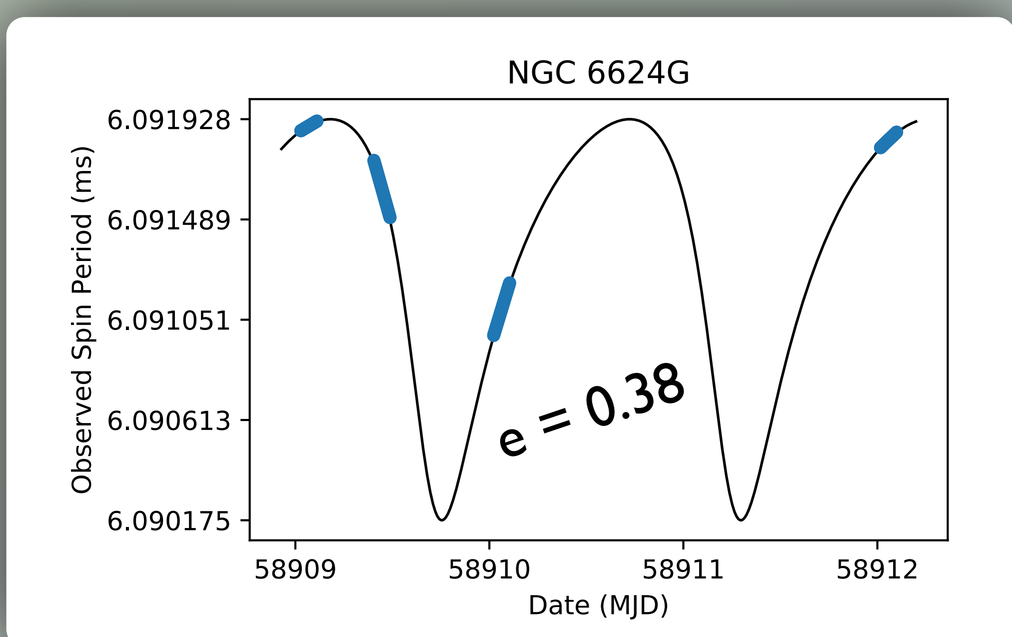

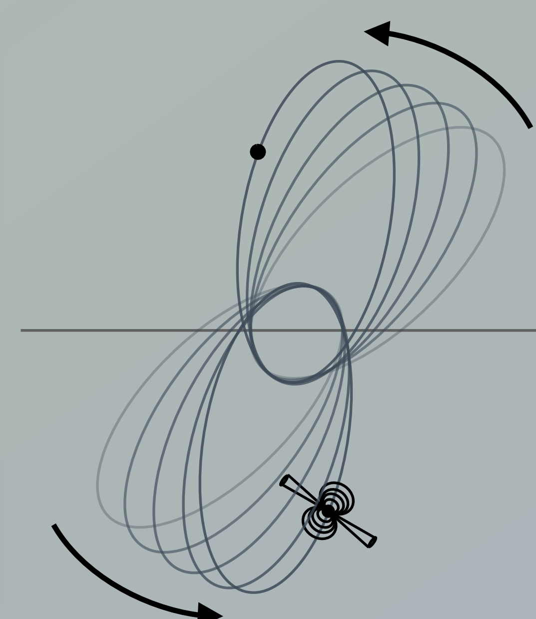

→ $M_{tot} = 2.65 \pm 0.07\ M_{sun}$

$M_p = 2.10^{+0.19}_{-1.23}\ M_{sun}$

$M_c = 0.53^{+1.30}_{-0.09}\ M_{sun}$

$p(M_p > 2\ M_{sun}) = 69\%$

Early discoveries from the MeerKAT GC census

Ridolfi et al. (2021)

MNRAS, Volume 504, Issue 1, June 2021, Pages 1407-1426

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **504**, 1407–1426 (2021)
Advance Access publication 2021 March 18

doi:10.1093/mnras/stab790

Eight new millisecond pulsars from the first MeerKAT globular cluster census

A. Ridolfi,[1,2★] T. Gautam,[2★] P. C. C. Freire,[2] S. M. Ransom,[3] S. J. Buchner,[4] A. Possenti,[1,5] V. Venkatraman Krishnan,[2] M. Bailes,[6,7] M. Kramer,[2,8] B. W. Stappers,[8] F. Abbate,[2] E. D. Barr,[2] M. Burgay,[1] F. Camilo,[4] A. Corongiu,[1] A. Jameson,[6,7] P. V. Padmanabh,[2] L. Vleeschower,[8] D. J. Champion,[2] W. Chen,[2] M. Geyer,[4] A. Karastergiou,[9,10] R. Karuppusamy,[2] A. Parthasarathy,[2] D. J. Reardon,[6,7] M. Serylak,[4] R. M. Shannon[6,7] and R. Spiewak[8,6]

[1] *INAF – Osservatorio Astronomico di Cagliari, Via della Scienza 5, I-09047 Selargius (CA), Italy*
[2] *Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany*
[3] *National Radio Astronomy Observatory, 520 Edgemont Rd., Charlottesville, VA 22903, USA*
[4] *South African Radio Astronomy Observatory (SARAO), 2 Fir Street, Black River Park, Observatory, Cape Town 7925, South Africa*
[5] *Dipartimento di Fisica, Università di Cagliari, S.P. Monserrato-Sestu Km 0,700, I-09042 Monserrato (CA), Italy*
[6] *Centre for Astrophysics and Supercomputing, Swinburne University of Technology, P.O. Box 218, Hawthorn, VIC 3122, Australia*
[7] *OzGrav: The ARC Centre of Excellence for Gravitational-wave Discovery, PO Box 218, Hawthorn, VIC 3122, Australia*
[8] *Jodrell Bank Centre for Astrophysics, Department of Physics and Astronomy, The University of Manchester, Manchester M13 9PL, UK*
[9] *Department of Astrophysics, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, UK*
[10] *Department of Physics and Electronics, Rhodes University, PO Box 94, Grahamstown 6140, South Africa*

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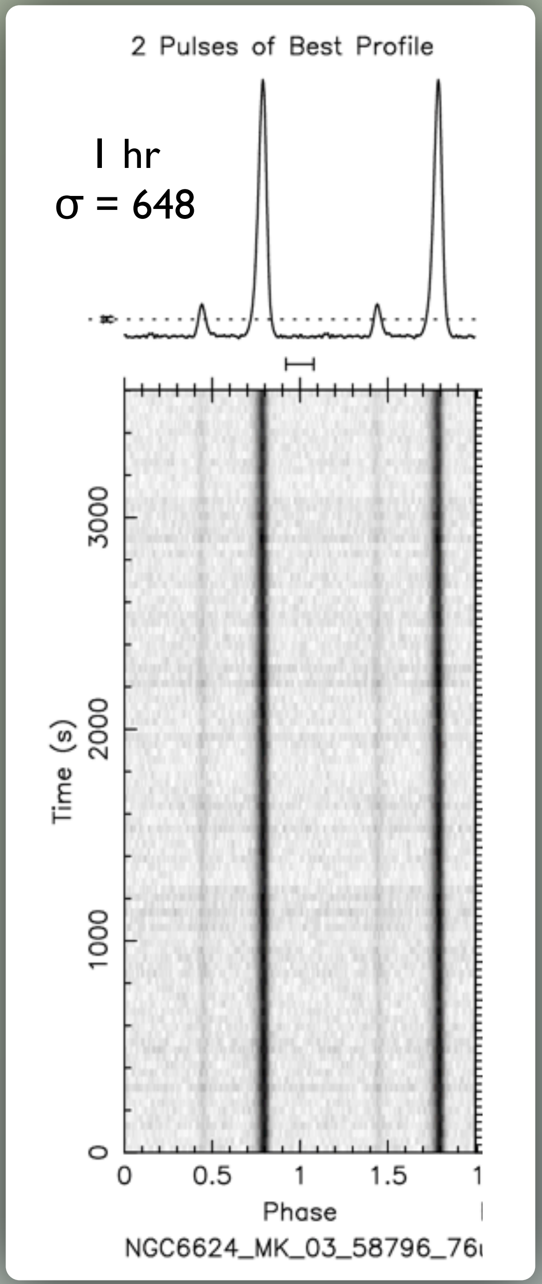
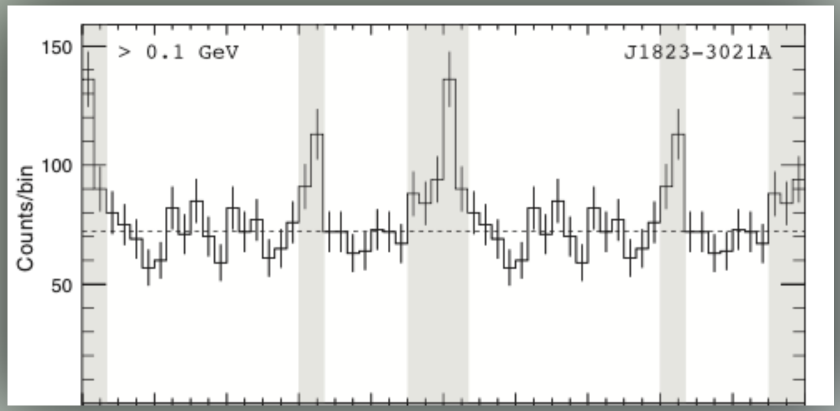
Giant pulses (GPs) from NGC 6624A

40 antennas
@L-band



Strong gamma-ray emitter
(Freire et al. 2011)

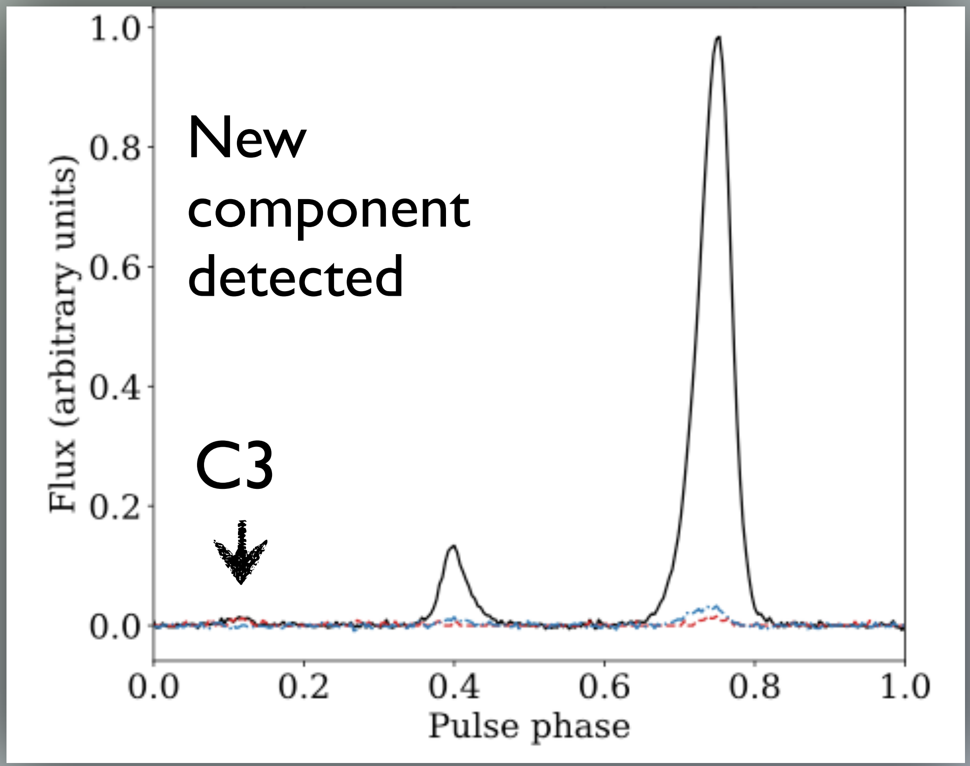


5 h of MeeKAT obs ➔
14350 GPs (~0.8 GP/s)

➔

Most active known GP
emitter amongst MSPs

4% of total flux emitted in the form of GPs



Giant pulses (GPs) from NGC 6624A

Abbate et al. (2020b)

MNRAS, Volume 498, Issue 1, pages 875-882

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **498,** 875–882 (2020)
Advance Access publication 2020 August 19

doi:10.1093/mnras/staa2510

Giant pulses from J1823−3021A observed with the MeerKAT telescope

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[1]*Max Planck Institut fur Radioastronomie, Auf dem Hugel 69, Bonn D-53121, Germany*
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[6]*Universitá di Cagliari, Dipartimento di Fisica, S.P. Monserrato-Sestu Km 0,700, I-09042 Monserrato (CA), Italy*
[7]*Department of Physics and Astronomy, University of the Western Cape, Bellville, Cape Town 7535, South Africa*
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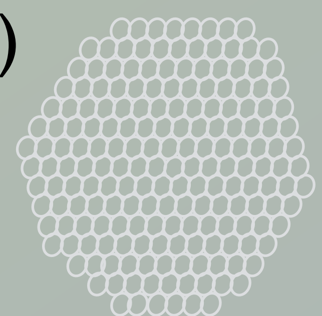
The TRAPUM GC survey

Targeting 28 different GCs

NGC 104 (47 Tuc)	NGC 5139 (w Cen)	NGC 6342	Terzan 5	NGC 6522	Mercer 5	NGC 6656 (M22)
NGC 362	NGC 5946	Liller 1	NGC 6440	NGC 6544	NGC 6624	NGC 6717
NGC 1851	NGC 6093 (M80)	NGC 6388	NGC 6441	NGC 6541	NGC 6626 (M28)	NGC 6752
NGC 2808	NGC 6266 (M62)	NGC 6397	NGC 6517	2MS-GC01	NGC 6652	NGC 7099 (M30)

Observing setup

- 64 antennas (whole array)
- 288 beams (2-4 ')



- UHF-band, L-band, S-band receivers
- Integration time: 4 hours

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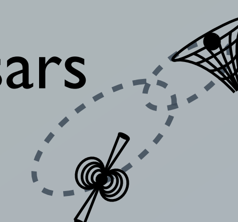
- Increase the # of GCs known to host pulsars
- Find the most extreme pulsars (e.g. pulsar-BH, MSP-MSP)



and more...

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and more...

✔ **24** discoveries (in < 5% of data) as of today

http://www.trapum.org/discoveries.html

The TRAPUM GC survey - early results

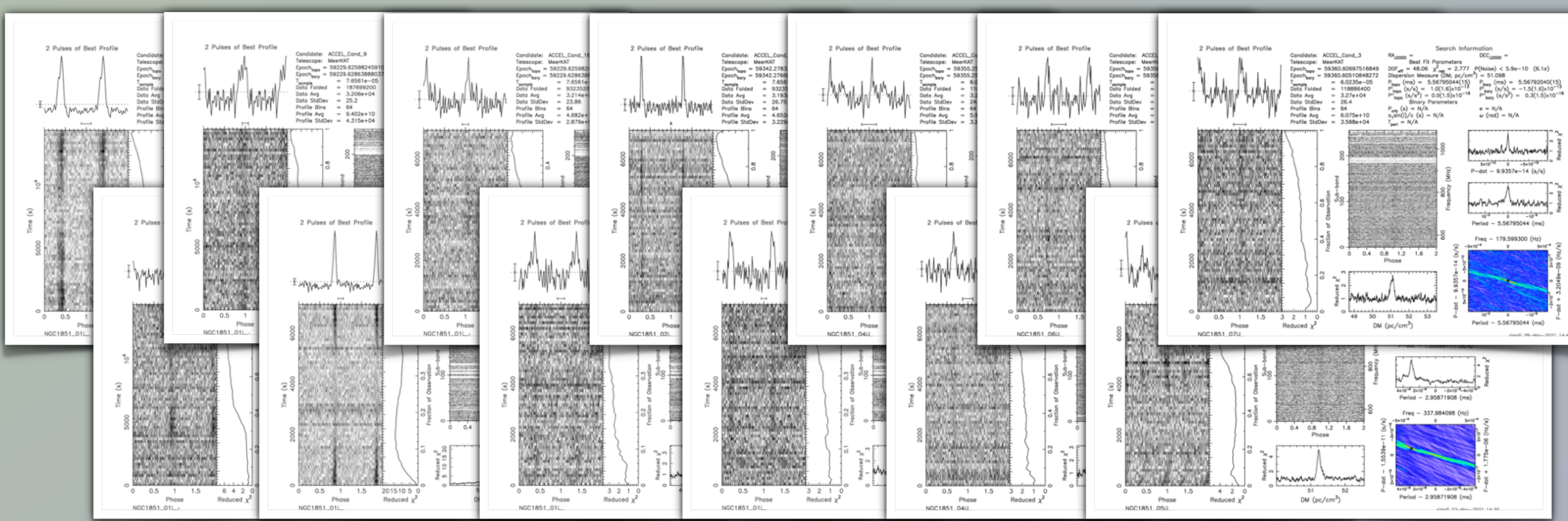
NGC 1851

Credits: NASA

1 pulsar known - discovered by GMRT by Freire et al. (2004)

We observed NGC 1851 with MeerKAT multiple times at L-band and UHF-band

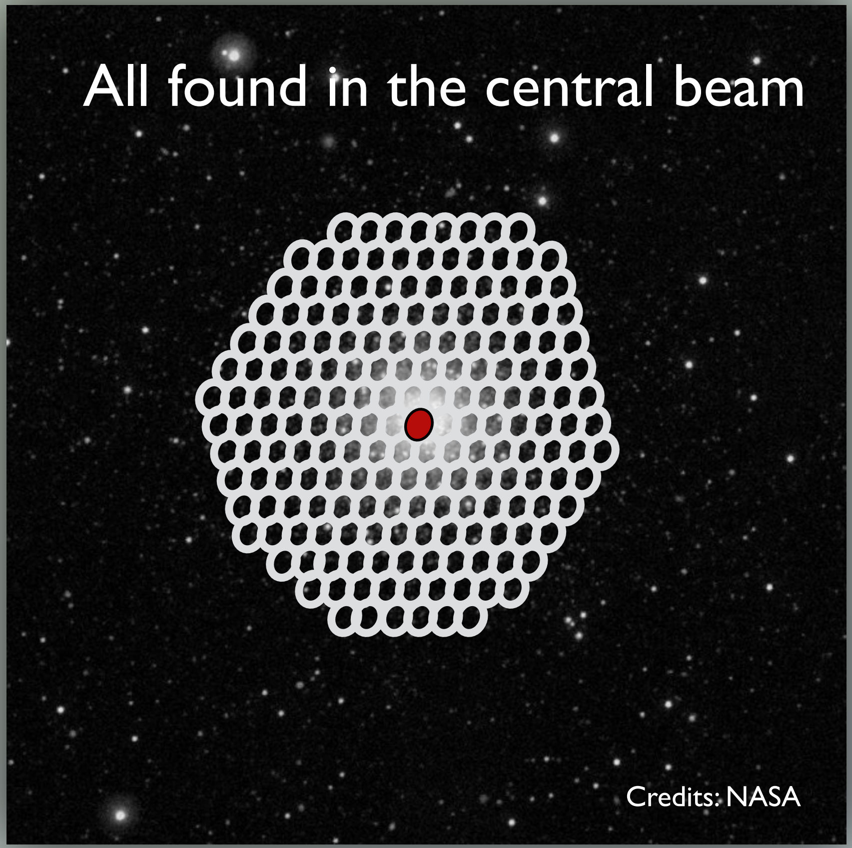
13 new pulsars discovered in NGC 1851!



New pulsars in NGC 1851

13 new pulsars

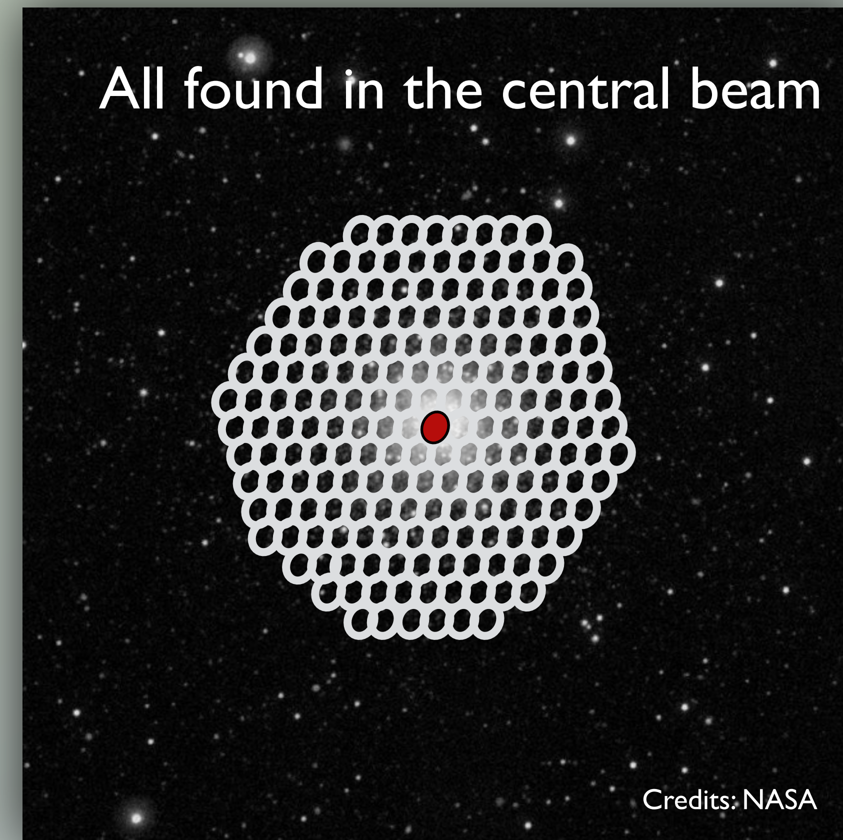
Name	P (ms)	DM (pc cm-3)	Type
NGC 1851B	2.8162	52.07	Isolated
NGC 1851C	5.5648	52.05	Isolated
NGC 1851D	4.5543	52.17	Isolated
NGC 1851E	5.5952	51.95	Binary
NGC 1851F	4.3294	51.63	Binary
NGC 1851G	3.8028	51.01	Binary
NGC 1851H	5.5061	52.26	Binary
NGC 1851I	32.6538	52.42	Binary
NGC 1851J	6.6329	52.06	Isolated
NGC 1851K	4.6920	51.93	Isolated
NGC 1851L	2.9586	51.23	Binary
NGC 1851M	4.7977	51.66	Isolated
NGC 1851N	5.5679	51.11	Isolated



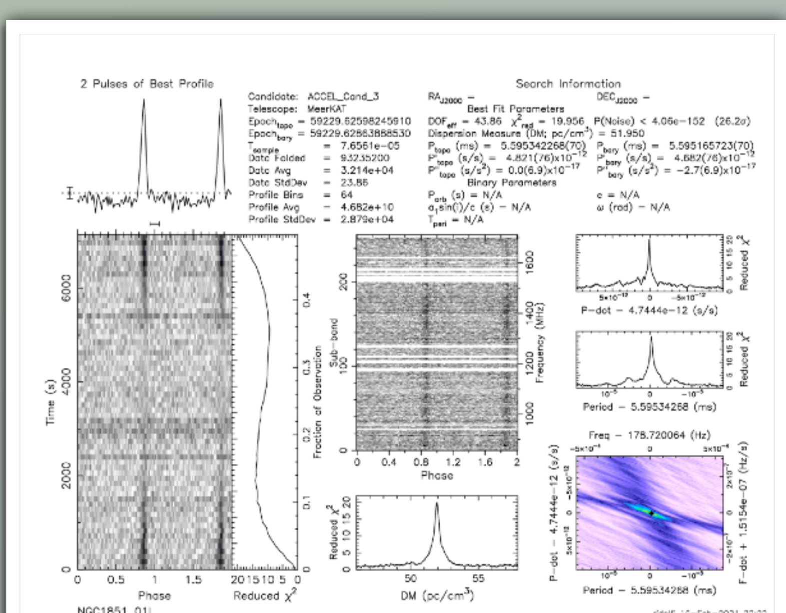
New pulsars in NGC 1851

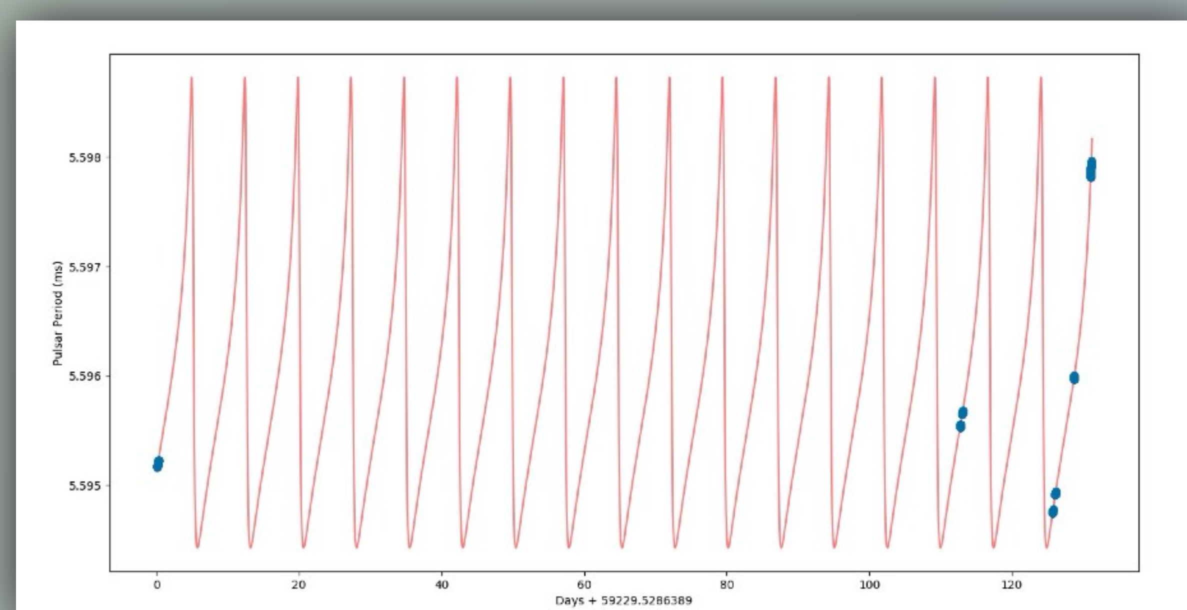
13 new pulsars

Name	P (ms)	DM (pc cm-3)	Type
NGC 1851B	2.8162	52.07	Isolated
NGC 1851C	5.5648	52.05	Isolated
NGC 1851D	4.5543	52.17	Isolated
NGC 1851E	5.5952	51.95	Binary
NGC 1851F	4.3294	51.63	Binary
NGC 1851G	3.8028	51.01	Binary
NGC 1851H	5.5061	52.26	Binary
NGC 1851I	32.6538	52.42	Binary
NGC 1851J	6.6329	52.06	Isolated
NGC 1851K	4.6920	51.93	Isolated
NGC 1851L	2.9586	51.23	Binary
NGC 1851M	4.7977	51.66	Isolated
NGC 1851N	5.5679	51.11	Isolated



- NGC 1851E - an extremely eccentric and massive binary MSP



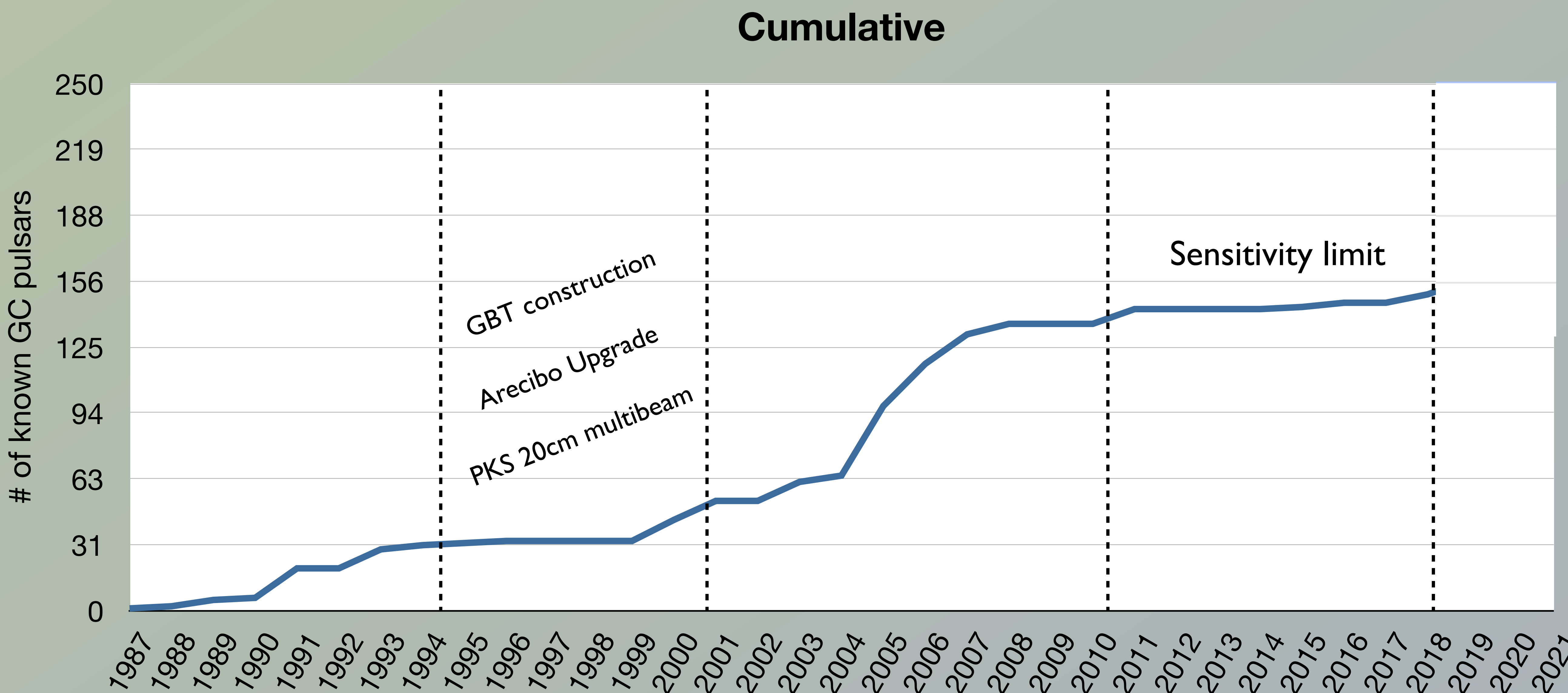


P_b = 7.44 d
e = 0.71
ω_p = 65.4°
x_p = 27.8 s

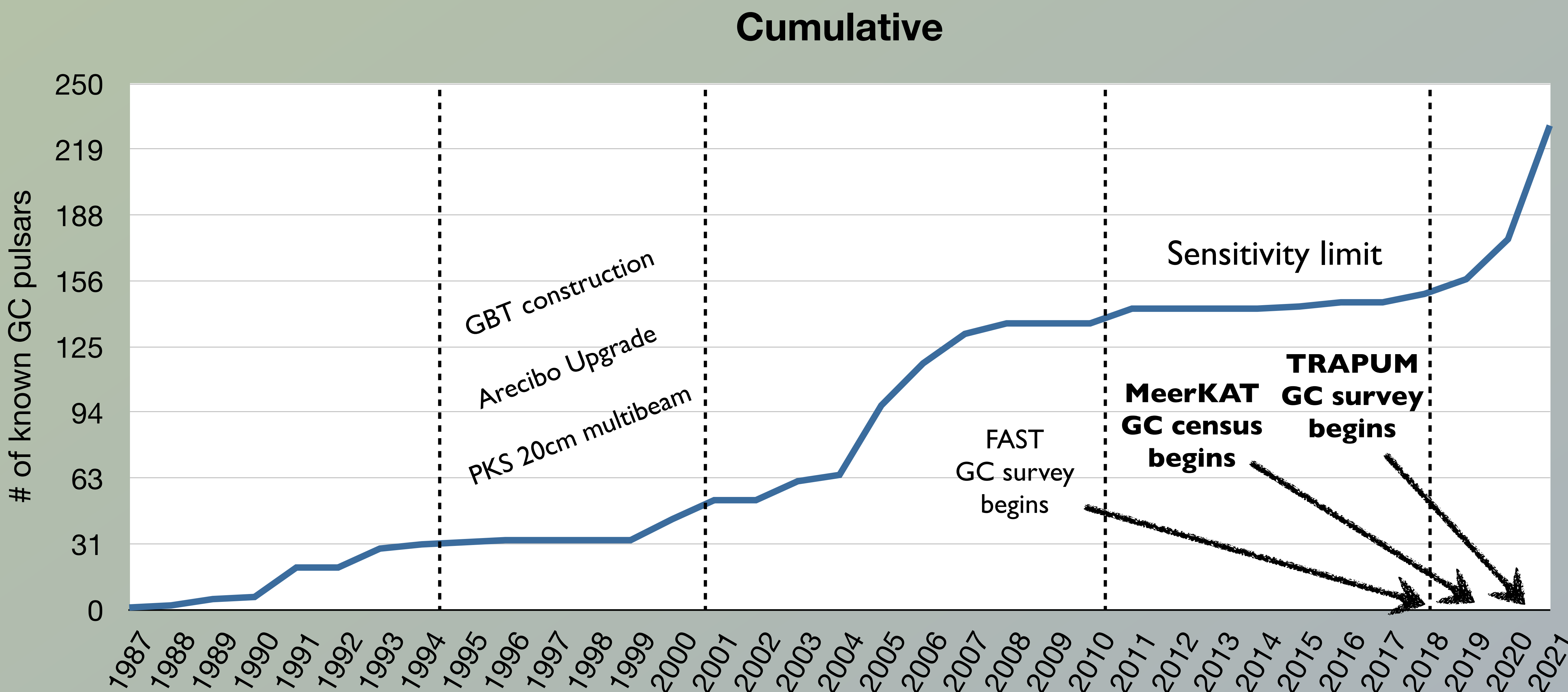
$M_c > 1.5\ M_{sun}$

(for $M_p = 1.4\ M_{sun}$)

Where are we now?



Where are we now?



MeerKAT	FAST	GBT	Parkes	GMRT
+36	+32	+7	+6	+1
Ridolfi et al. (2021) Vleschoveer et al. (in prep.) Douglas et al. (in prep.) Ridolfi et al. (in prep.) Abbate et al. (in prep.)	Pan et al. (2020) Wang et al. (2020) Pan et al. (2021)	De Cesar et al. (in prep)	Dai et al. (2020)	Gautam et al. (in prep)

A new SKA pathfinder: NenuFAR

Nenufar

Green Bank

FAST

Summary of NenuFAR characteristics

https://nenufar.obs-nancay.fr/en/astronomer/

- **Number of antennas :** 1938 = 96 (core) + 6 remote Mini-Arrays of 19 antennas each
- **Frequency range : <u>10-85 MHz</u>** (λ = 3.5 – 30 m)
- **Time-Frequency resolutions :** δf = 195.3125 kHz x δt = 5.12 μs
  Channelization down to 3.05 kHz x time integration down to 1 ms
  Waveform at 5 ns time resolution - **Full polarization** (4 Stokes)
- **Pointing :** from declination δ = -23° to δ = +90°
- **Field of View (FWHM) :** ~46° at 15 MHz to ~8° at 85 MHz)
- **Sensitivity** (thermal noise) :
  from ~130 mJy at 15 MHz to ~9 mJy at 85 MHz with Δf=10 MHz x Δt=1 h
  (similar values for the core & core+remote MA)

Challenges of low-frequency GC observations

Extremely low frequencies

- ! Severe Scattering
- ! Huge intrachannel dispersion delays
- ! Computationally demanding

GC pulsars

- ! Almost all MSPs
- ! Almost all faint
- ! Many have large DMs

However...

- ✔ Quite a few GCs far from the Galactic plane
- ✔ Pulsars (and in particular MSPs) have steep spectra
- ✔ Several GC pulsars easily seen down to 300 MHz (with GBT, GMRT, SRT)
- ✔ Computers are pretty powerful nowadays!

GC pulsar programme with NenuFAR

People involved

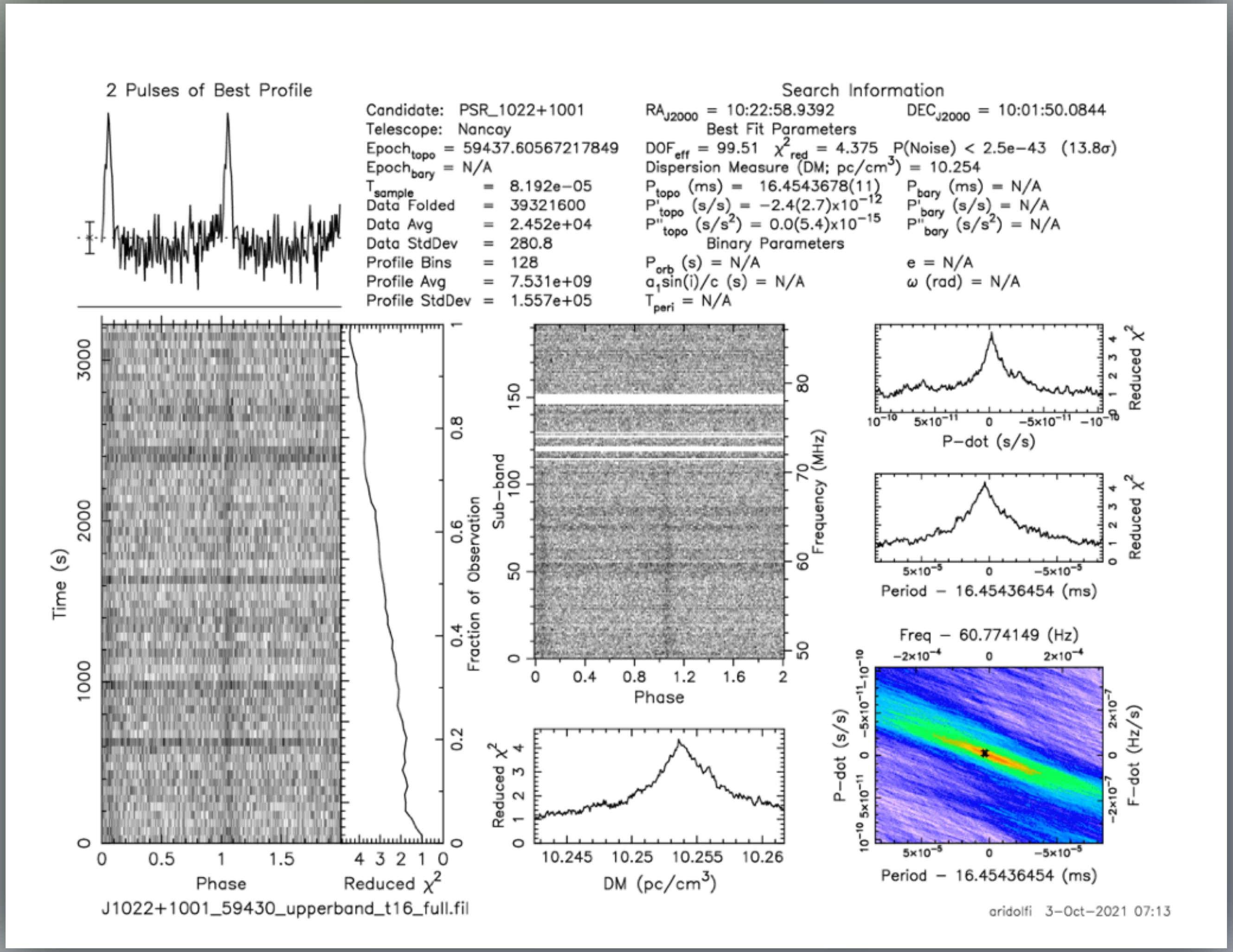
LPC2E - Université d'Orléans / CNRS: J.-M. Griessmeier, L. Bondonneau, M. Brionne

INAF - OACa: A. Possenti, A. Ridolfi

Activity

- Development and optimization of data reduction pipeline
- Application to bright, possibly fast-spinning, test pulsars (ongoing)
- Application to actual GC data

M5	NGC 6517
M13	NGC 6749
M15	NGC 6760
M71	(more coming...)



Summary

- MeerKAT is a game changer for GC pulsar astrophysics
  - Enables observations of southern GCs with unprecedented sensitivity
  - Up to 2x more sensitive than GBT, 8x more sensitivity than Parkes
  - Paves the way for **SKA1-mid**

- Exciting early results from the first 1.5 years of data
  - 36 new GC pulsars discovered
  - At least two very eccentric and massive binary MSPs
  - 13 new pulsars in NGC 1851
  - Most detailed study of giant pulses from an MSP to date

- NenuFAR as a testbed for **SKA-low**
  - GC data reduction pipeline ready
  - Test observations being processed

THANK YOU!