From pulsar observations to tests of general relativity

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LUTH - 12 septembre 2019

European Research Council

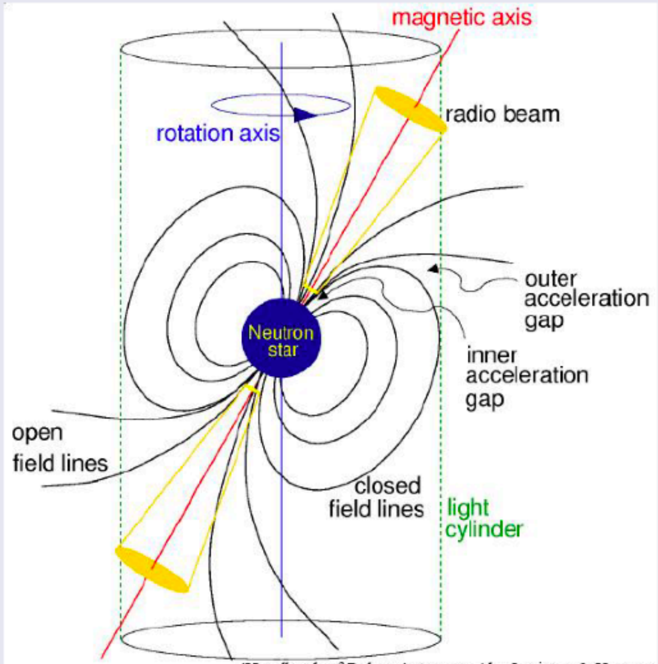
Established by the European Commission

Event Horizon Telescope

EPTA

Pulsar's characteristics

- Radius $\sim$ 10 km
- Mass : $1.2 - 2.1\,\mathrm{M}_{\odot}$
- Surface magnetic field : $10^{8} - 10^{15} G$
- Surface temperature : $10^{6} K$
- Luminosities up to $10^{4}\ L_{\odot}$
- Radio emission produced at the pulsar's magnetic poles



'Handbook of Pulsar Astronomy' by Lorimer & Kramer

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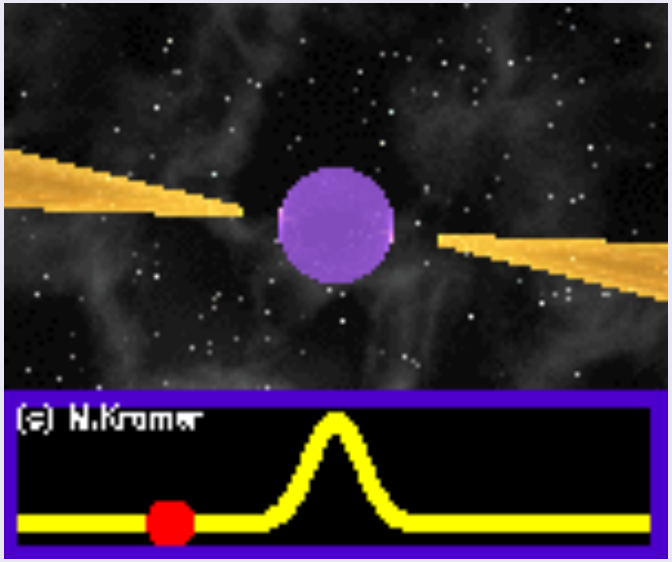


Part I: Finding new and exotic pulsars with the Nançay Radio Telescope

Motivations

3 main goals for the proposed survey:

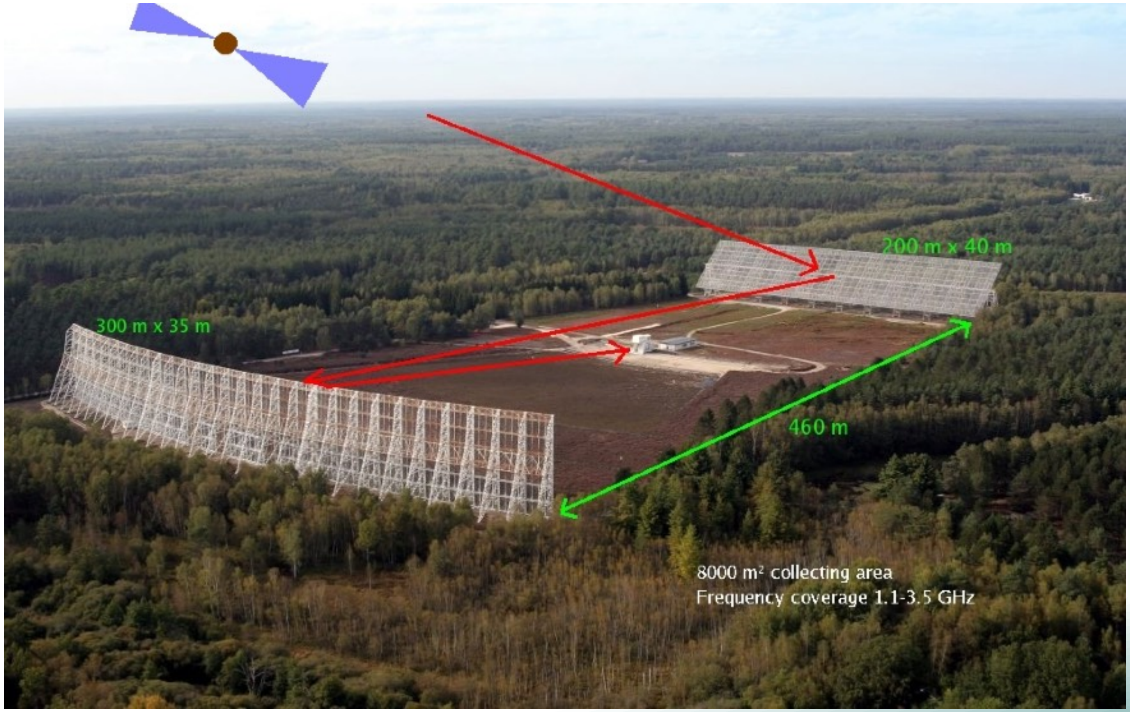
• Find compact binary pulsar (or even triple systems) to perform tests of GR:
PSR - PSR, PSR - NS, PSR - WD, PSR - BH

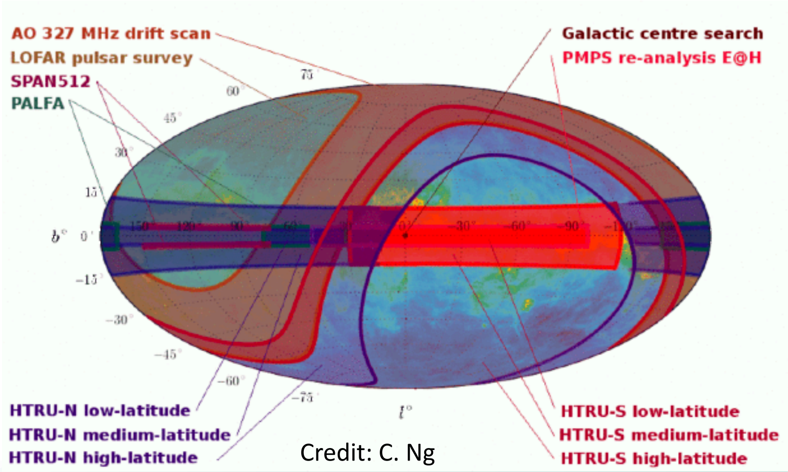
• Add millisecond pulsars to Pulsar Timing Arrays

• Find more Fast Radio Bursts

The Nançay Radio Telescope

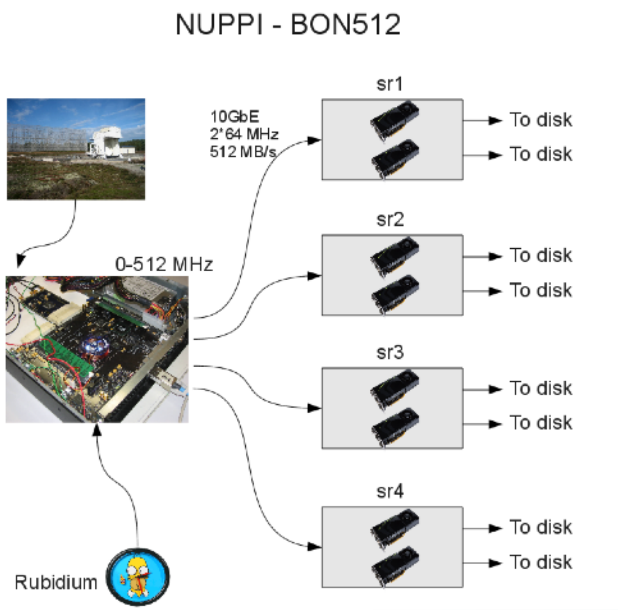
- Northern hemisphere not thoroughly searched at L-band
- Kraus-type radio telescope (94-m equivalent dish) located 1 hr south of Orleans.
- Observing frequency between 1.1 to 3.5 GHz

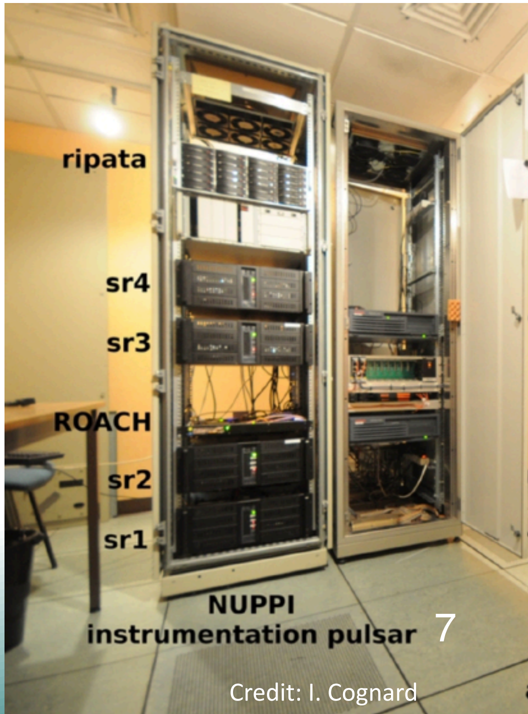




The pulsar instrumentation

- A large bandwidth and versatile pulsar backend commissioned in 2011
- Development of a FPGA firmware for ROACH2 hardware (2 GB/s) with UC Berkeley
- Adapt the Green Bank Telescope GPU software for this backend
- Pulsar timing mode, spectrometer mode, baseband recording.

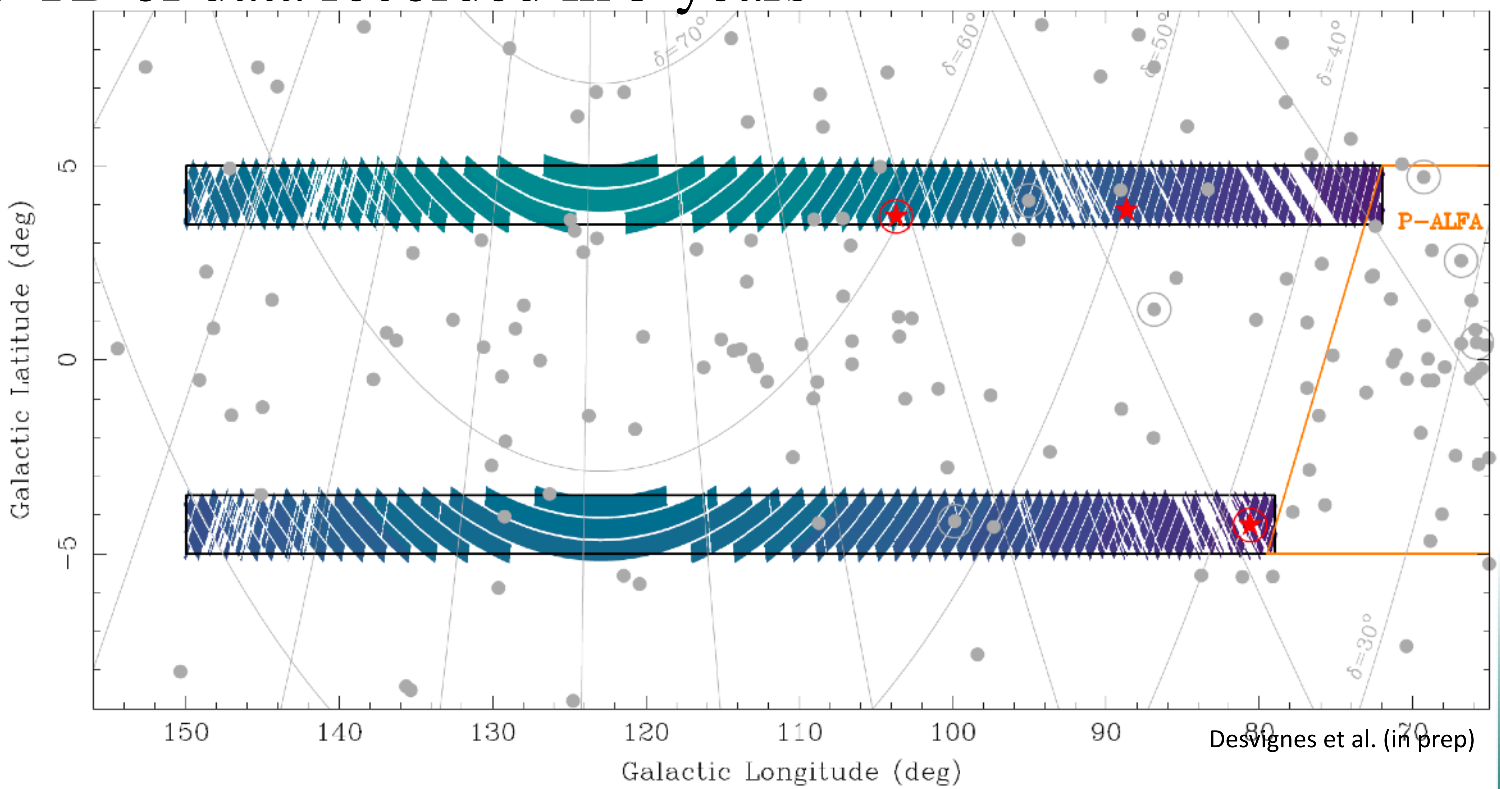




Credit: I. Cognard

The SPAN512 pulsar survey

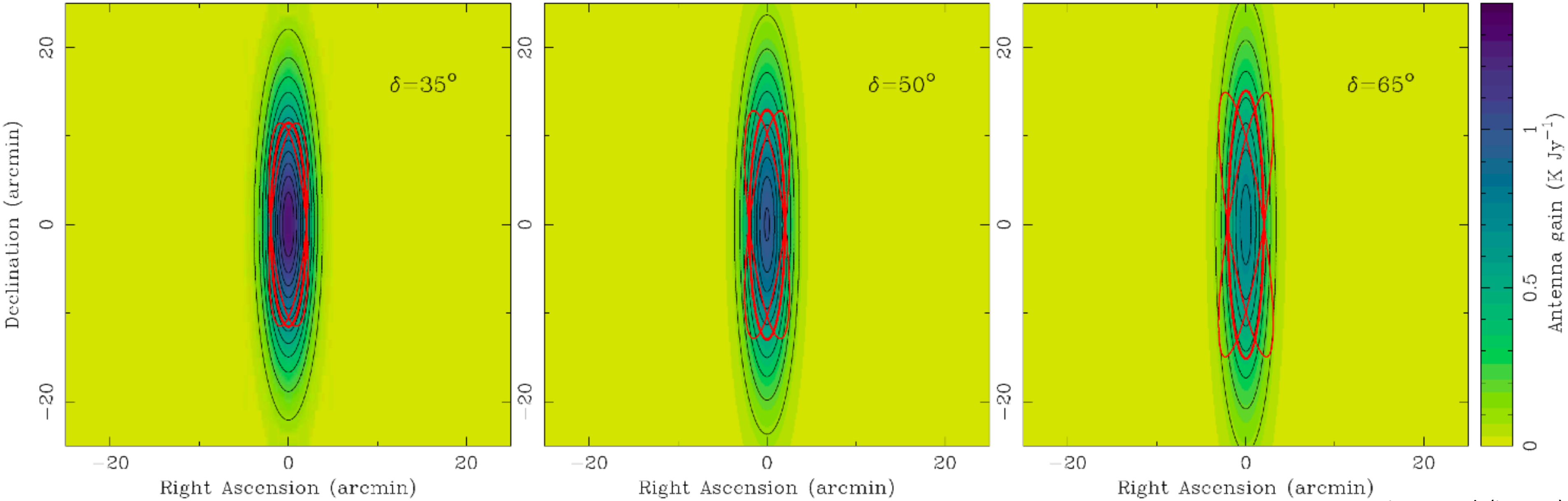
- We proposed in 2012 a ~ 2000 hr to survey the intermediate latitudes for millisecond pulsars and transients (PI Desvignes)
- 18 min scans, 64us, 4bits, 1024 frequency channels between 1.2 and 1.7 GHz
- ~ 65 TB of data recorded in 5 years



Desvignes et al. (in prep)

Study of the beam pattern

- The beam pattern changes as function of declination and hour angle
- This is required to assess the survey sensitivity (thanks to E. Gerard @Paris obs)



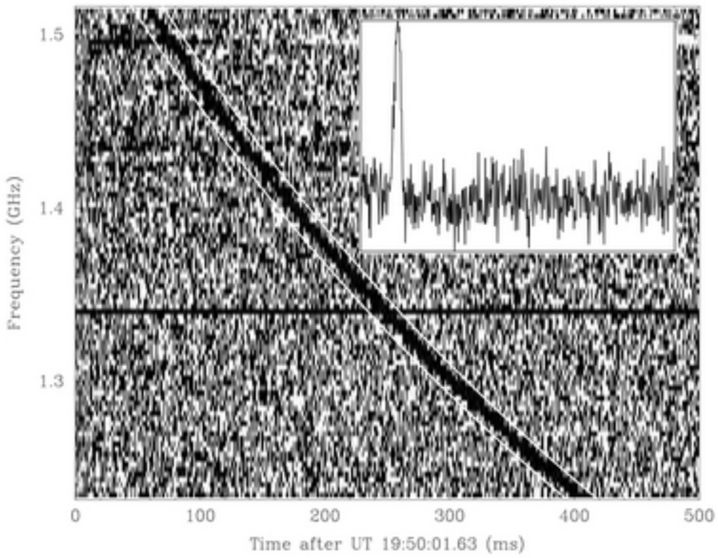
Desvignes et al. (in prep)

Analysis & results

- Unknown parameters: dispersion by the ISM, spin period, binary
-> Dispersion trials, FFT with acceleration searches
- Processing on the IN2P3 and Max-Planck clusters (1 pointing requires processing of ~24 hr on 24 cores)
- 3 new pulsars discovered so far: 2 millisecond pulsars (PSRs J2205+6012, J2055+3837 Guillemot et al. 2019) and one slow pulsar (PSR J2048+4951)

Analysis & results

- FRB are short duration (ms) radio pulses with extragalactic origin



Discovery in 2007 by Lorimer et al.

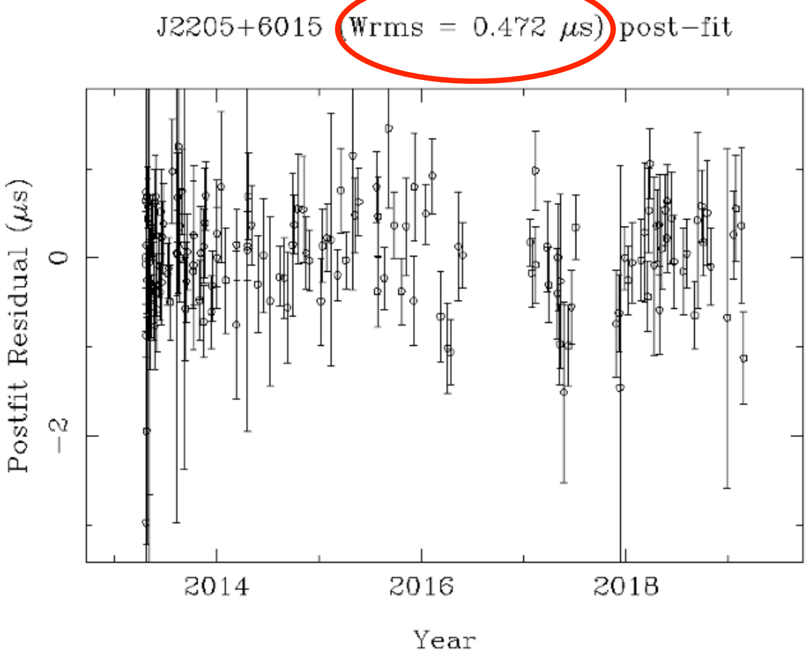
Can be used as probes for magnetised plasma in host galaxies and IGM

- Analysis for single pulse and Fast Radio Burst (FRB) still underway with matched filtering (PRESTO by Scott Ransom). FRB rate ~ $10^3 - 10^4$ sky^{-1} day^{-1} (Cordes & Chatterjee 2019) -> ~ 0 - 8 FRBs expected

Results: PSR J2205+6012

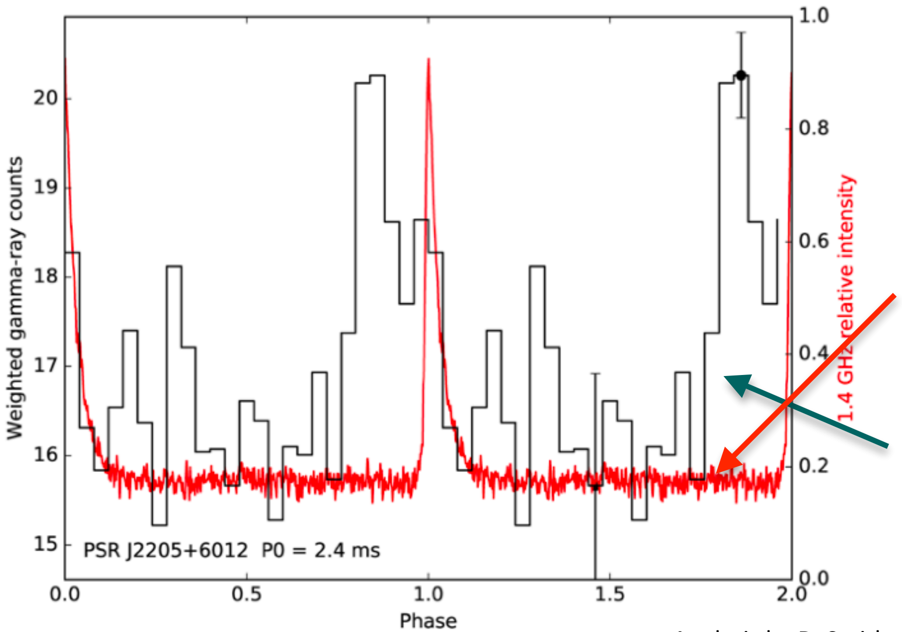
- Discovered in 2013 and timed with Nançay since then
- Parameters

Spin period: $2.41 \pm 8 \times 10^{-15}$ ms (MJD 56400)
Orbital period: ~1.0945513377576 day$\pm 1.1 \mu s$ around a WD
Eccentricity: $\sim 1 \times 10^{-6}$
Proper motion: 5.3266 ± 0.014576 mas/yr



- No Post-Keplerian parameters yet
- Good timing precision -> PTA
- We see γ-ray emission

Results: PSR J2205+6012



Analysis by D. Smith

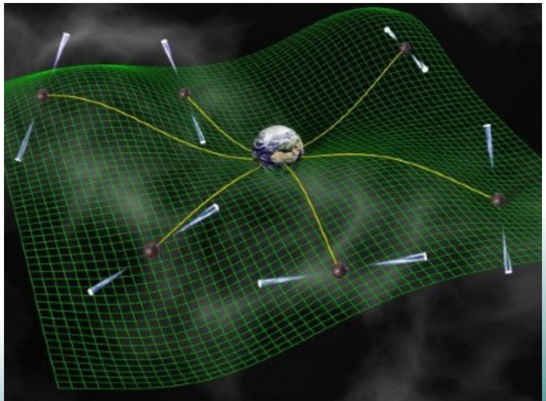
- 10-20% of MSPs with same $\dot{E} = 4\pi^2\dot{P}/P^3 = 6.4 \times 10^{34}\,\mathrm{erg\,s^{-1}}$ show gamma-ray pulsations (Smith et al. 2019).
- The gamma-ray peak precedes the radio peak, unusual for young pulsars but typical of the non-aligned MSP

Implications for the EPTA

- The European Pulsar Timing Array (EPTA) is a network consisting of the 5 largest radio telescopes in Europe
- Its aim is to detect the low-frequency GWB with an ensemble of pulsars
- Last data release (Desvignes et al. 2016) contained 42 MSPs used for:

- measuring new pulsars masses (Desvignes et al. 2016)
- limit on the isotropic stochastic GWB (Lentati et al. 2015)
- limit on the anisotropic stochastic GWB (Taylor et al. 2015)
- continuous GW from individual sources (Babak et al. 2016)

- Now working towards a new EPTA release with more pulsars and better data with new pulsar backends -> to be added to the International PTA



Credit: D. Champion

Part II: PSR J1906+0746
From relativistic spin-precession
to mapping a pulsar beam

PSR J1906+0746: background

- A DNS discovered in 2004 with Arecibo (Lorimer et al., 2006)
- Young pulsar with spin period of 144 ms that shows large timing noise

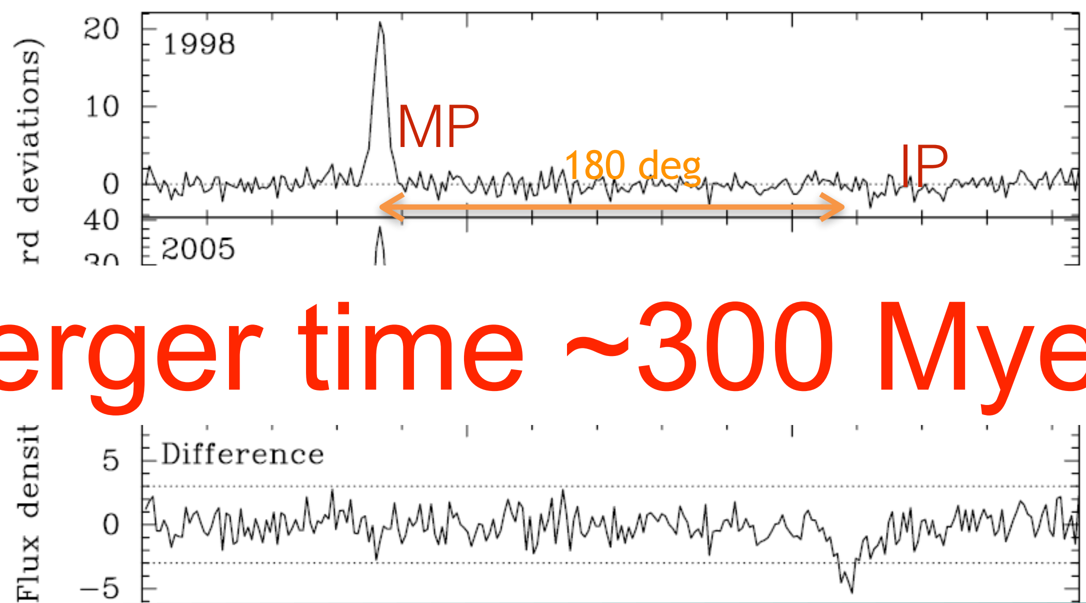
Orbital period ~ 4hr, 3 PK parameters measured

$$M_p = 1.29 \pm 0.01\,M_\odot,\ M_c = 1.32 \pm 0.01\,M_\odot$$

van Leeuwen et al. (2015)

$$\Omega_p \sim 2.23^\circ\,\mathrm{yr}^{-1},\ i \sim 43^\circ$$

- Hints of spin-precession effects showed in the discovery paper



PMPS
Archival data

Merger time ~300 Myears

Lorimer et al. (2006)

PSR J1906+0746: the observations

- The 2005-2009 campaign:

  Nançay - BON, Arecibo - ASP, GBT - GASP
- The 2012-2018 campaign:

  Monthly monitoring with Arecibo - PUPPI
- Calibrate the data (MTM calibration for Nancay)
- Measure and correct for Faraday effect (rotation of the plane of linear polarisation as a function of frequency)

$$\mathrm{RM} = 152 \pm 1\,\mathrm{rad\ m}^{-2}$$

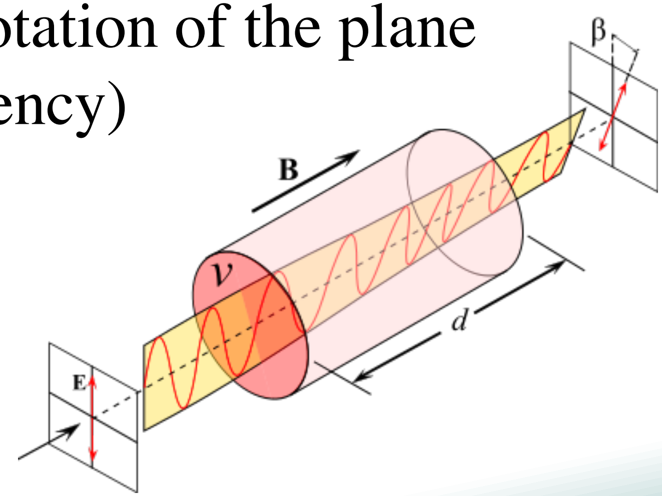
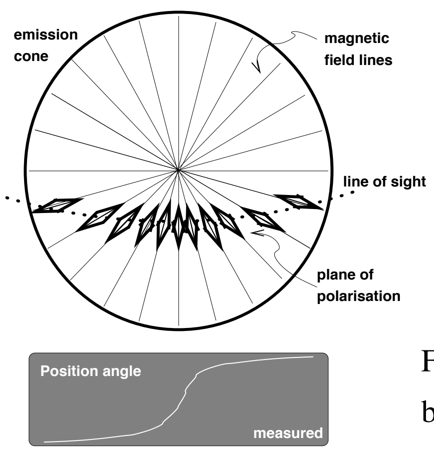


Image from Wikipedia

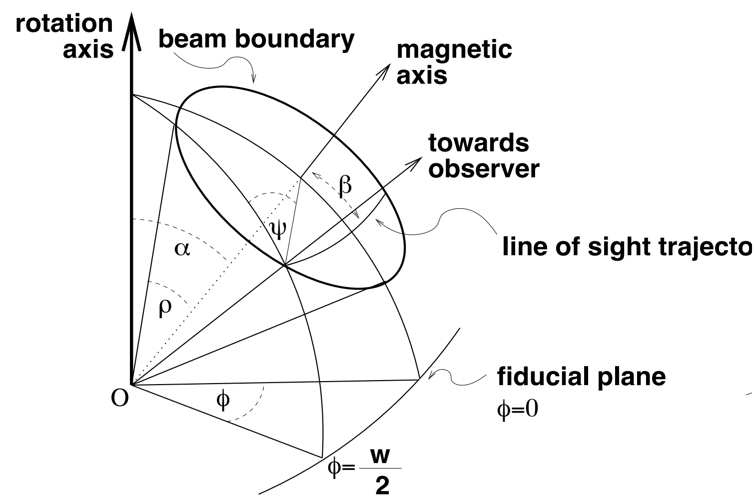

Arecibo/UCF

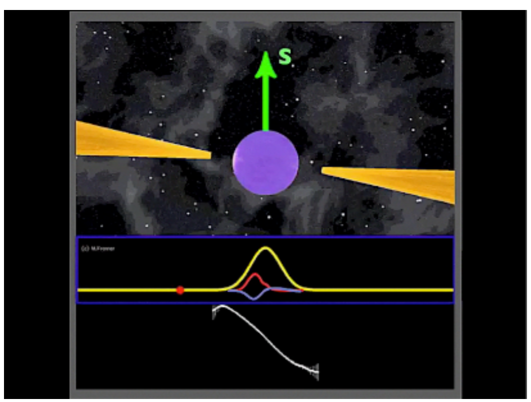
The rotating vector model (RVM)

The standard model to interpret the position angle of the linear polarisation is the RVM by Radhakrishnan & Cooke (1969). Hence the correction for Faraday rotation!



From Pulsar Handbook by Lorimer&Kramer





Adapted from Kramer by Noutsos

$$\tan(\psi - \psi_0) = \frac{\sin\alpha \sin(\phi - \phi_0)}{\sin(\alpha + \beta)\cos\alpha - \cos(\alpha + \beta)\sin\alpha\cos(\phi - \phi_0)}$$

4 parameters of interest

Fitting the RVM to the early data

MJD	α_{MP} (deg)	β_{MP} (deg)	$\phi 0_{MP}$ (deg)	$\psi 0_{MP}$ (deg)
53572.0	$99.37^{+0.62}_{-0.53}$	$-5.61^{+0.23}_{-0.24}$	$3.32^{+0.11}_{-0.11}$	$96.96^{+1.22}_{-1.19}$
53653.2	$99.38^{+0.77}_{-0.64}$	$-6.68^{+0.43}_{-0.47}$	$3.59^{+0.18}_{-0.17}$	$93.04^{+1.53}_{-1.47}$
53752.7	$98.50^{+1.22}_{-0.91}$	$-6.52^{+0.78}_{-0.91}$	$4.06^{+0.34}_{-0.30}$	$97.12^{+3.03}_{-2.88}$
53843.5	$99.05^{+1.47}_{-1.08}$	$-6.75^{+1.08}_{-1.40}$	$4.50^{+0.50}_{-0.41}$	$98.27^{+3.54}_{-3.42}$
53925.8	$100.56^{+2.12}_{-1.43}$	$-6.57^{+0.93}_{-1.16}$	$4.78^{+0.45}_{-0.37}$	$100.17^{+2.90}_{-2.85}$
54023.9	$100.42^{+2.03}_{-1.46}$	$-6.88^{+1.13}_{-1.43}$	$5.21^{+0.55}_{-0.45}$	$100.05^{+3.52}_{-3.54}$
54108.4	$99.97^{+1.22}_{-0.94}$	$-8.25^{+0.90}_{-1.05}$	$5.03^{+0.35}_{-0.30}$	$94.98^{+2.34}_{-2.23}$
54190.0	$100.34^{+1.26}_{-0.99}$	$-9.26^{+1.17}_{-1.40}$	$5.70^{+0.42}_{-0.37}$	$94.91^{+2.62}_{-2.52}$
54281.9	$98.84^{+2.01}_{-1.25}$	$-7.35^{+1.33}_{-1.64}$	$5.43^{+0.54}_{-0.45}$	$99.37^{+4.34}_{-3.96}$
54444.3	$99.65^{+4.28}_{-1.94}$	$-8.61^{+2.59}_{-3.64}$	$6.53^{+1.13}_{-0.82}$	$97.65^{+7.90}_{-7.10}$
54591.0	$101.09^{+6.58}_{-2.17}$	$-11.11^{+4.67}_{-4.94}$	$7.98^{+1.62}_{-1.19}$	$99.79^{+14.0}_{-9.27}$
54758.8	$99.85^{+0.86}_{-0.78}$	$-11.71^{+1.35}_{-1.57}$	$7.53^{+0.38}_{-0.36}$	$96.48^{+2.41}_{-2.33}$
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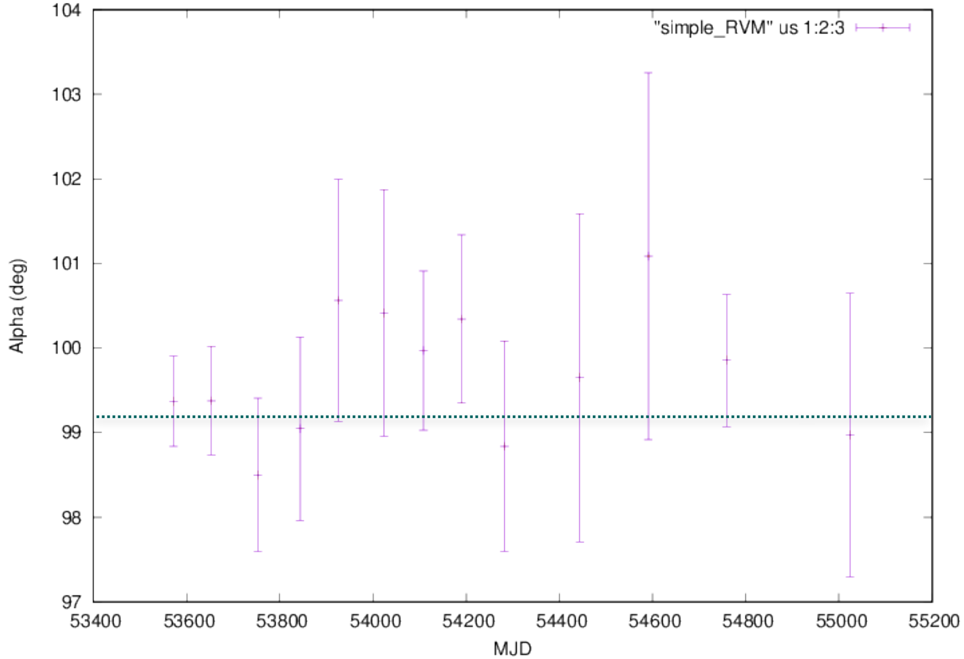

$\alpha \sim 99^\circ$ -> orthogonal rotator

Fitting the RVM to the early data, <2011

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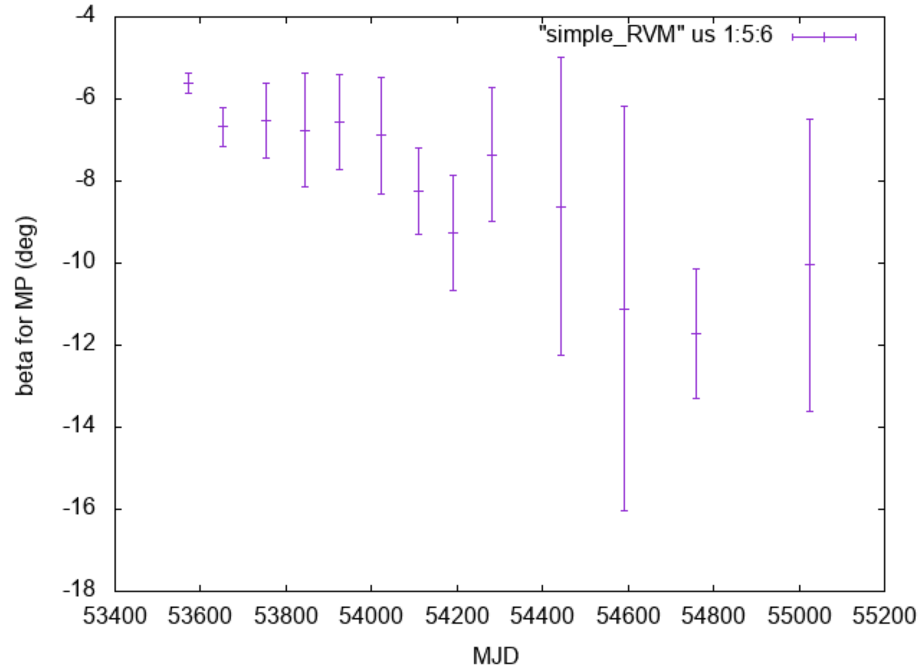

Our line of sight is moving away from the MP magnetic pole

Fitting the RVM to the early data, <2011

$$\beta_{\mathrm{IP}} = \alpha_{\mathrm{MP}} + \beta_{\mathrm{MP}} - \alpha_{\mathrm{IP}}$$

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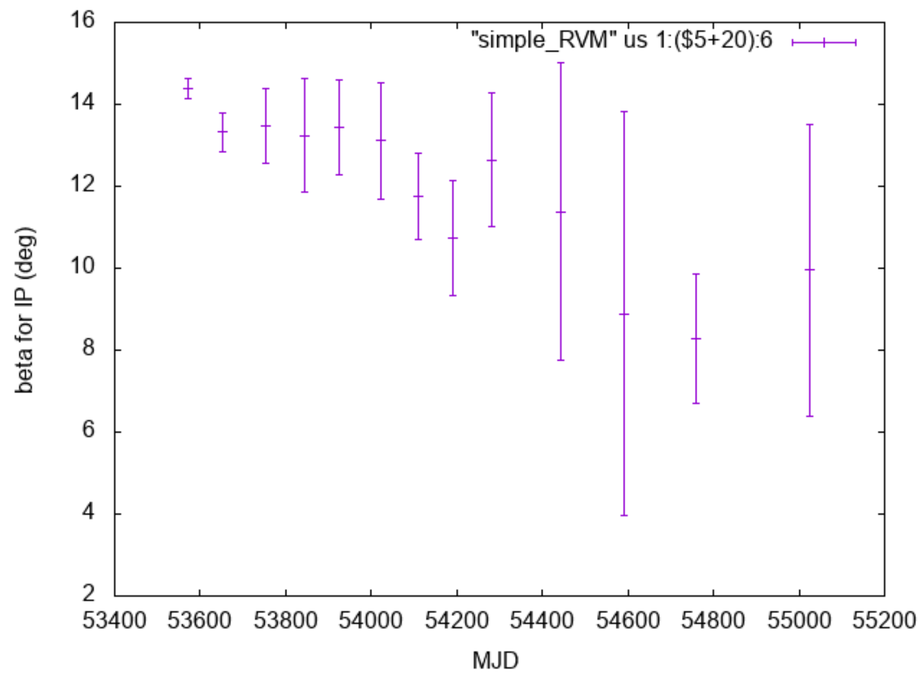


Our line of sight is getting closer to the IP magnetic pole

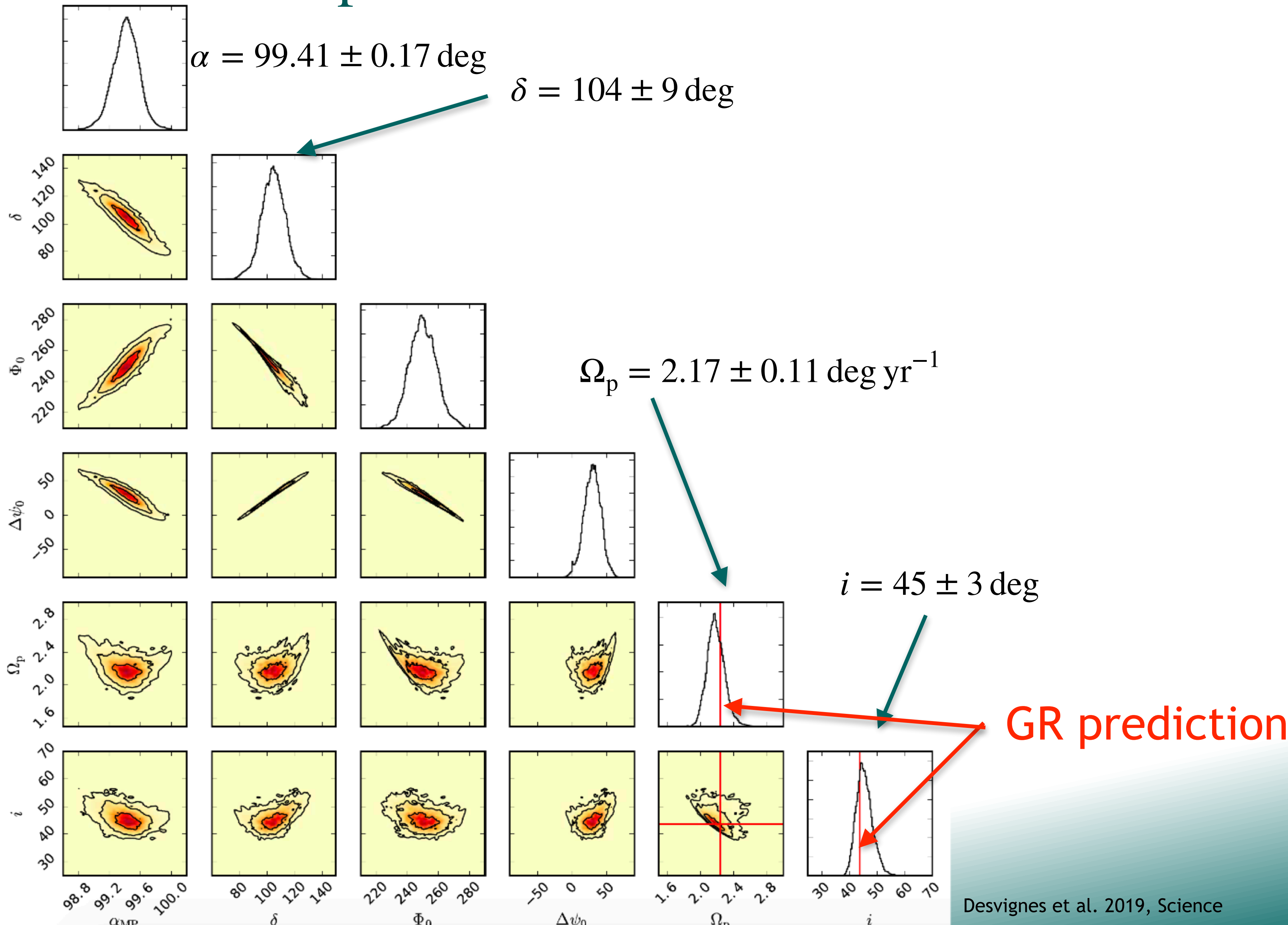
The "precessional" RVM model for polarisation

- 'Precessional' RVM introduced by Kramer&Wex (2009)
- Fit the RVM as function of time to get the full geometry of the system
- 6 main parameters + 1 additional phase offset per epoch (47)

$$\alpha, \delta, \Phi_p, \Delta\psi, i, \Omega_p, \phi_{i=1..41}$$

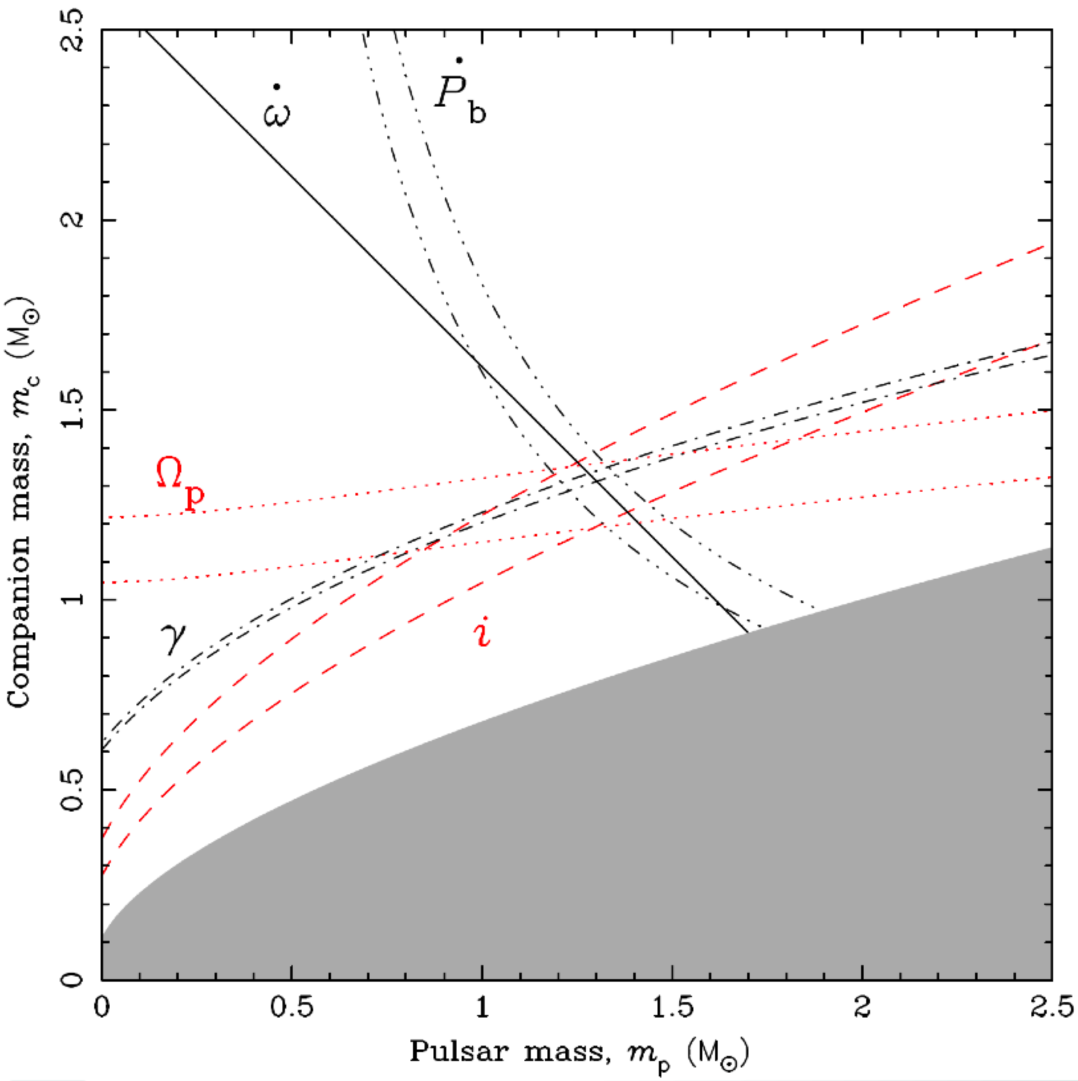
- Precession rate and inclination angle can be fixed to GR values (or set free)
- No ambiguity in inclination angle
- To map the 53-D problem, I developed modelRVM using nested sampling tools like MultiNest and PolyChord to explore the parameter space

The "precessional" RVM model: results



Desvignes et al. 2019, Science

The mass-mass diagram



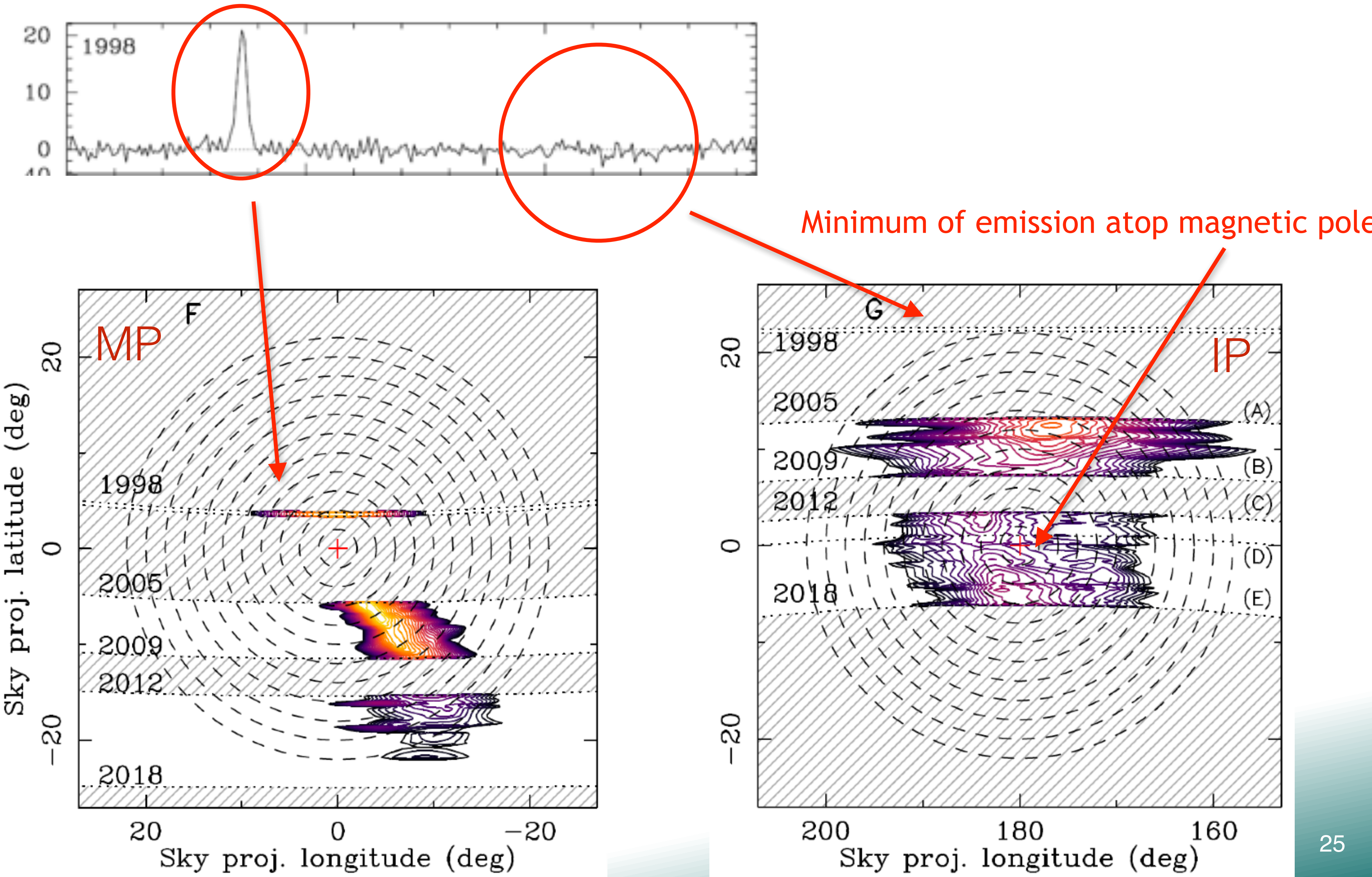
$$\dot{P}b, \dot{\omega}, \gamma$$

from Leeuwen et al. 2015

- 2 PK parameters gives the masses of the system
- Each additional parameter provides a test of GR
- $\Omega_p = 2.17 \pm 0.11$ deg yr^{-1} provides the best constraint on relativistic spin-precession

Desvignes et al. 2019, Science

Emission map



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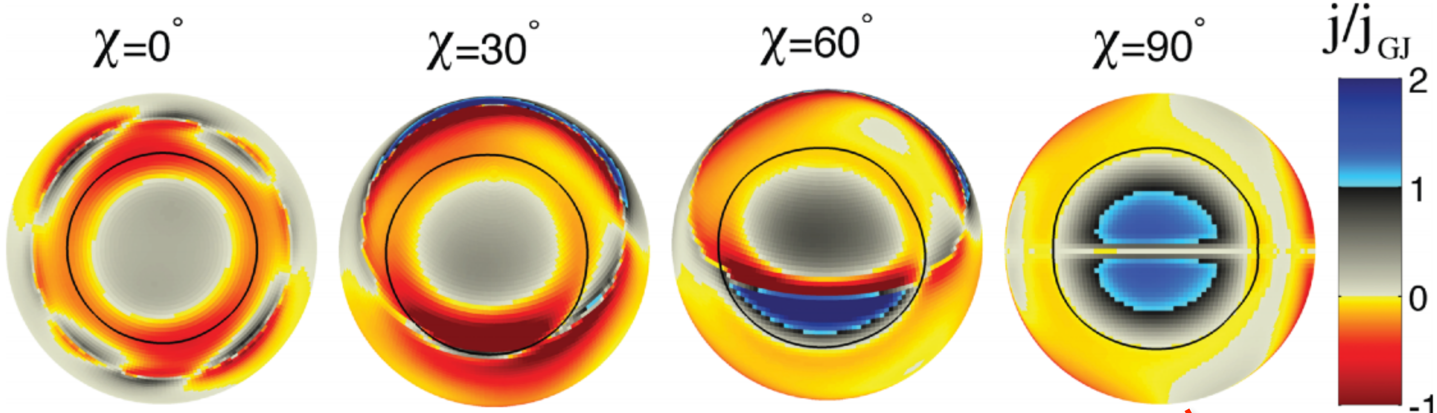
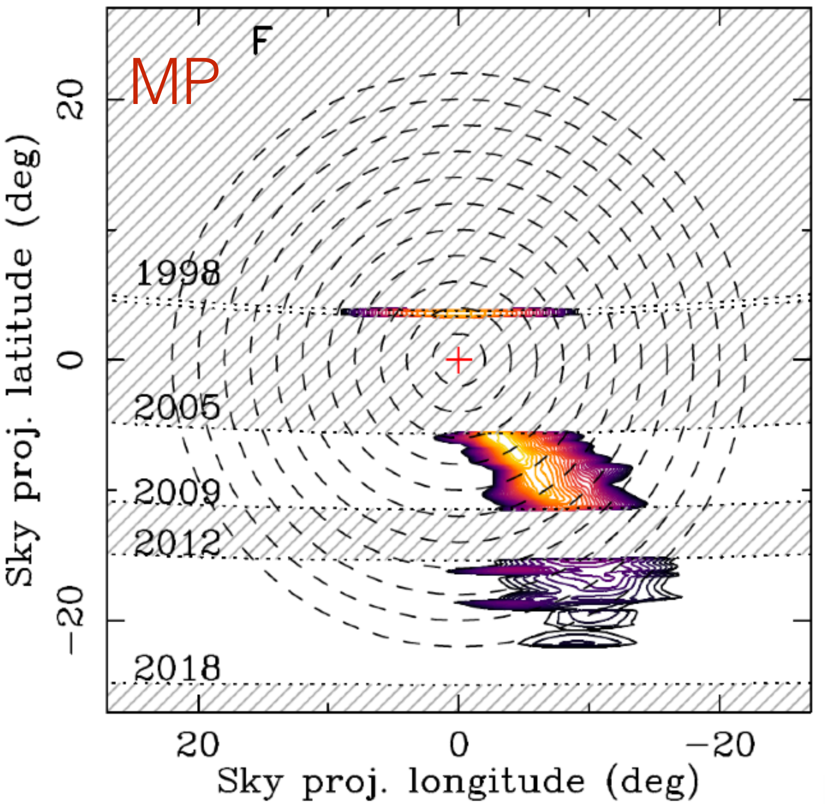
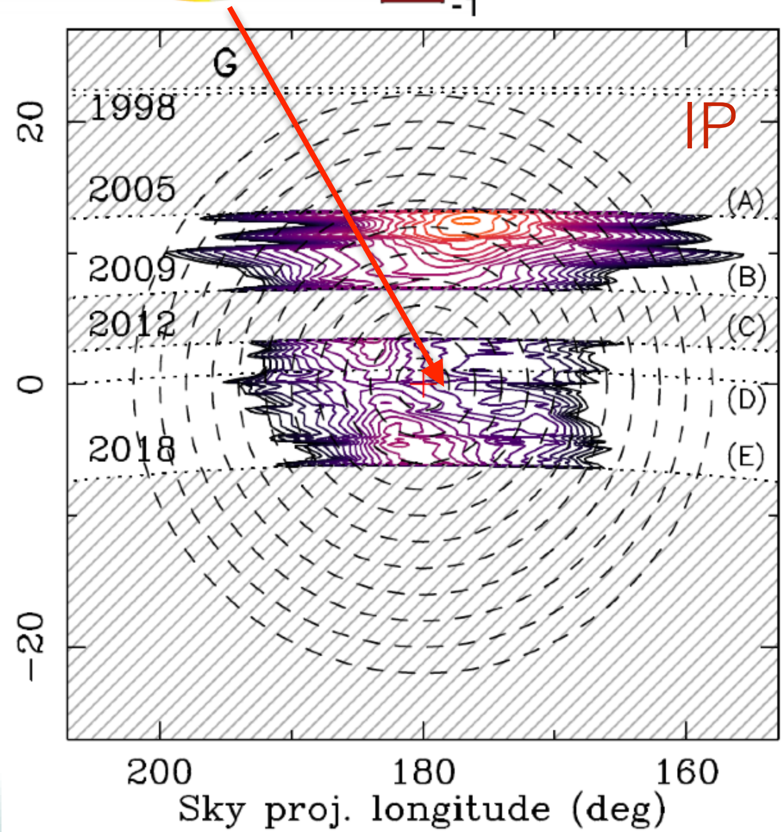
Emission map



Maps of current density at the polar cap

Timokhin&Arons (2012)

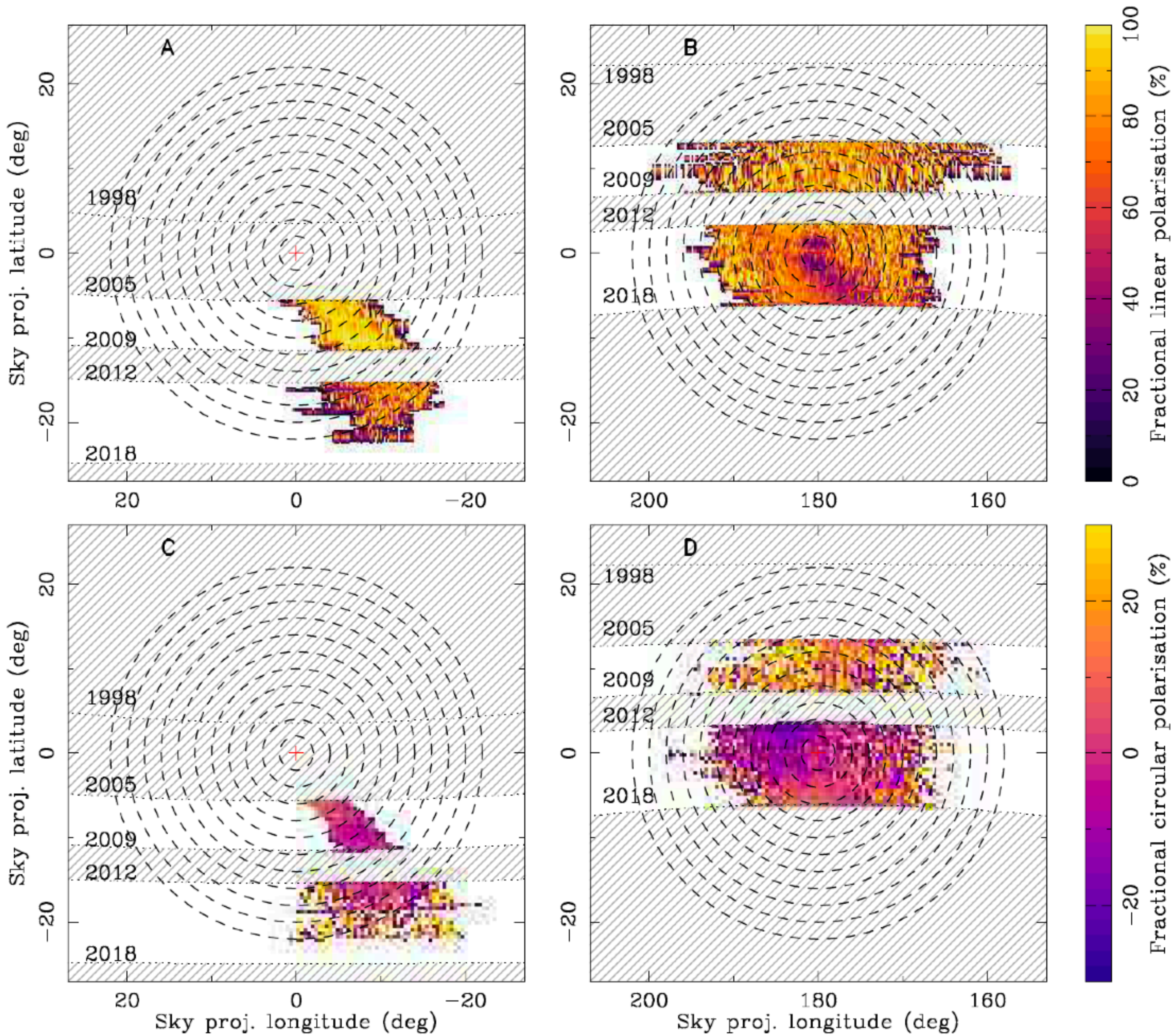




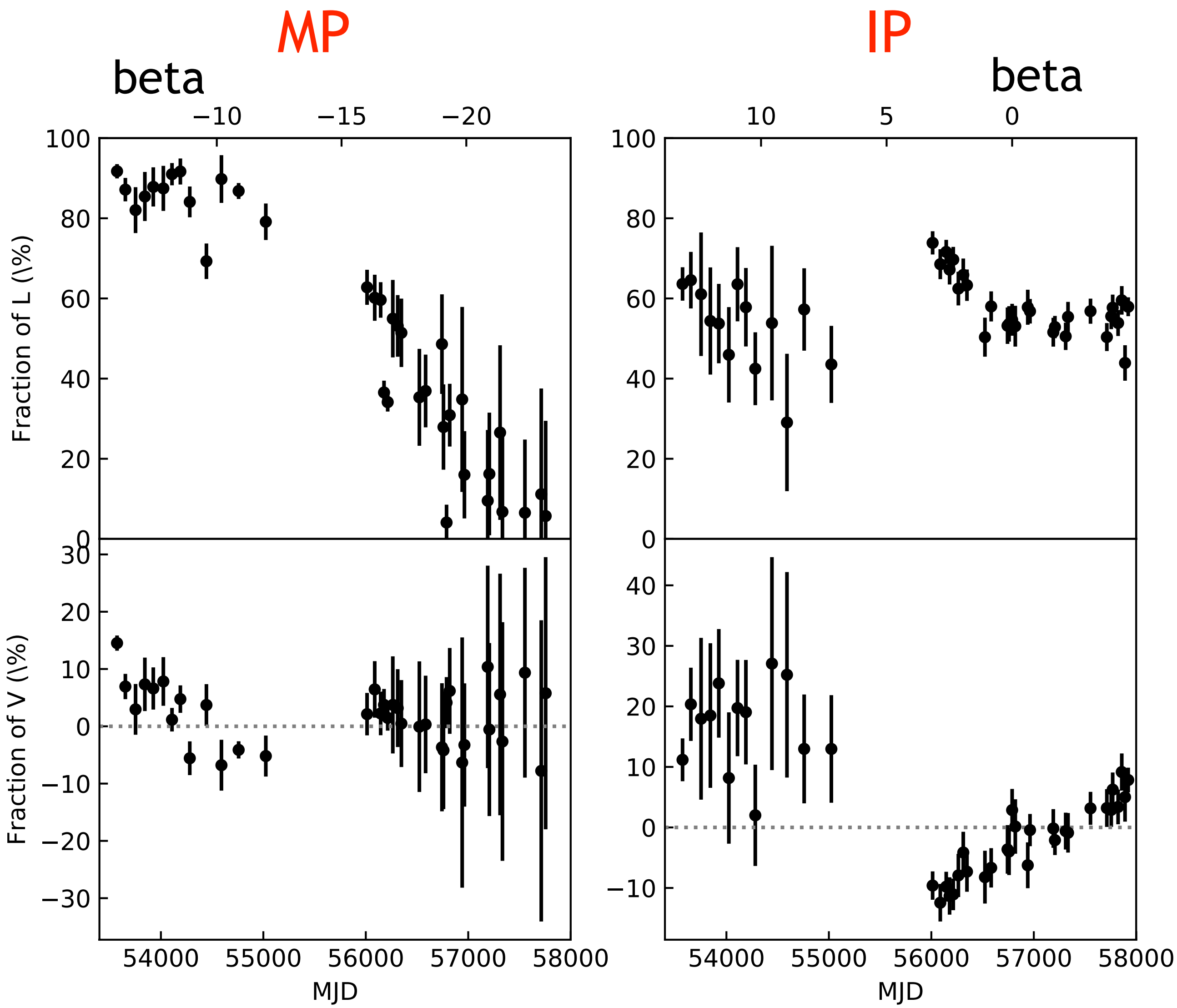
Emission map: polarisation

Linear polarisation

Circular polarisation

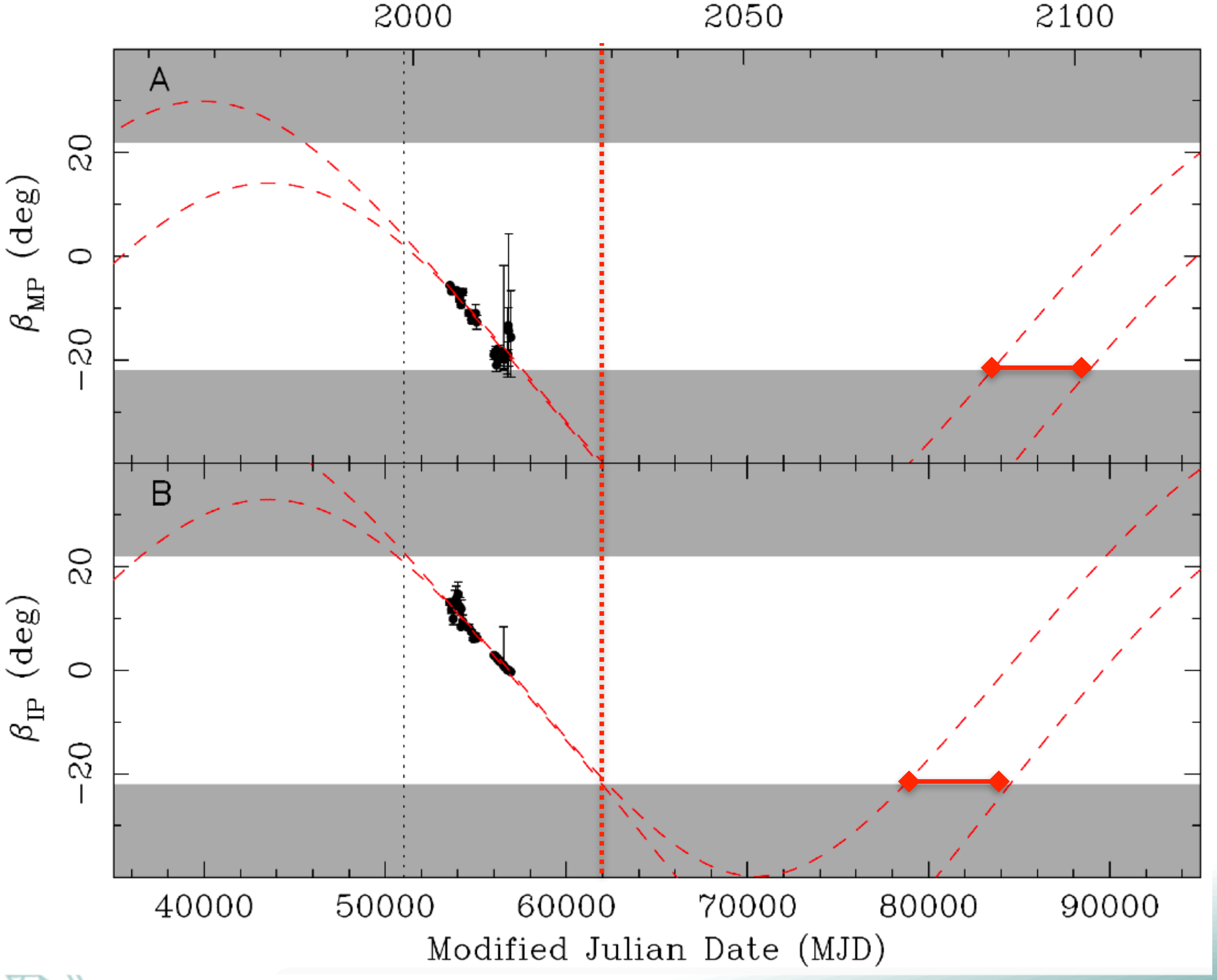


Emission map: average polarisation



Desvignes et al. 2019, Science

Predictions for the pulses' s visibility



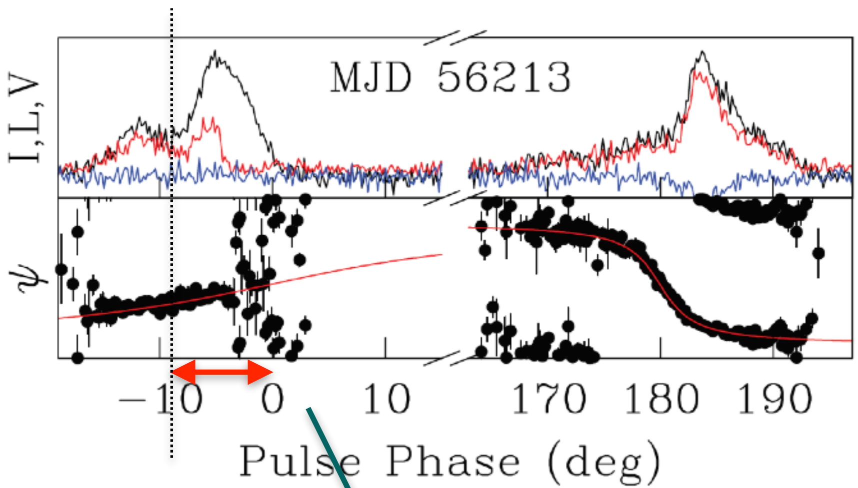
IP will disappear around 2028.

MP will reappear in ~2085-2105

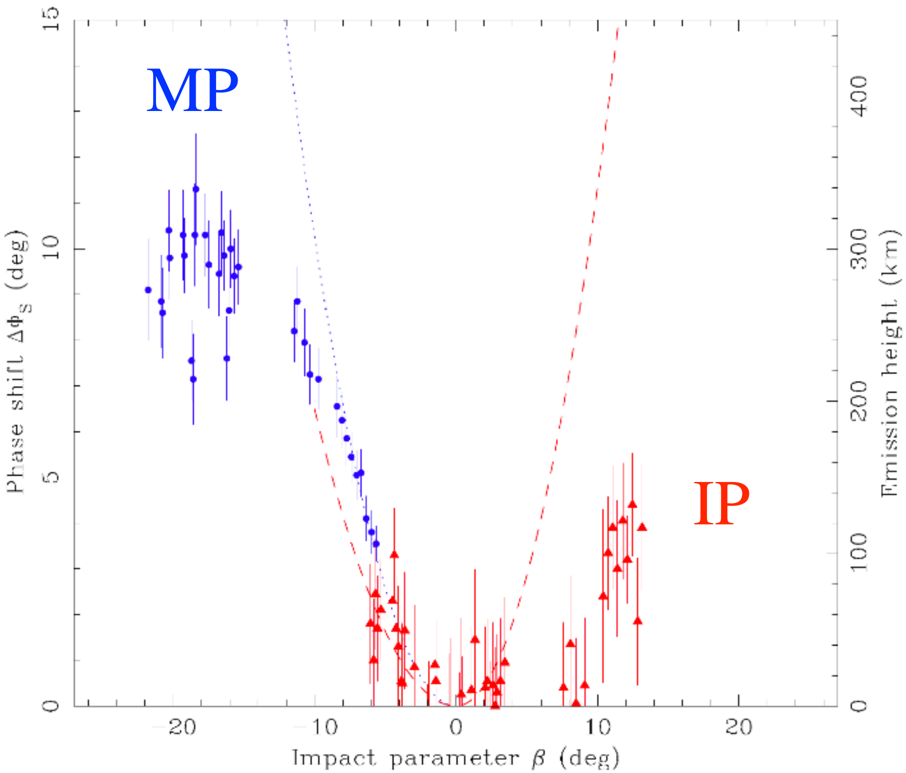
Desvignes et al. 2019, Science

Emission heights

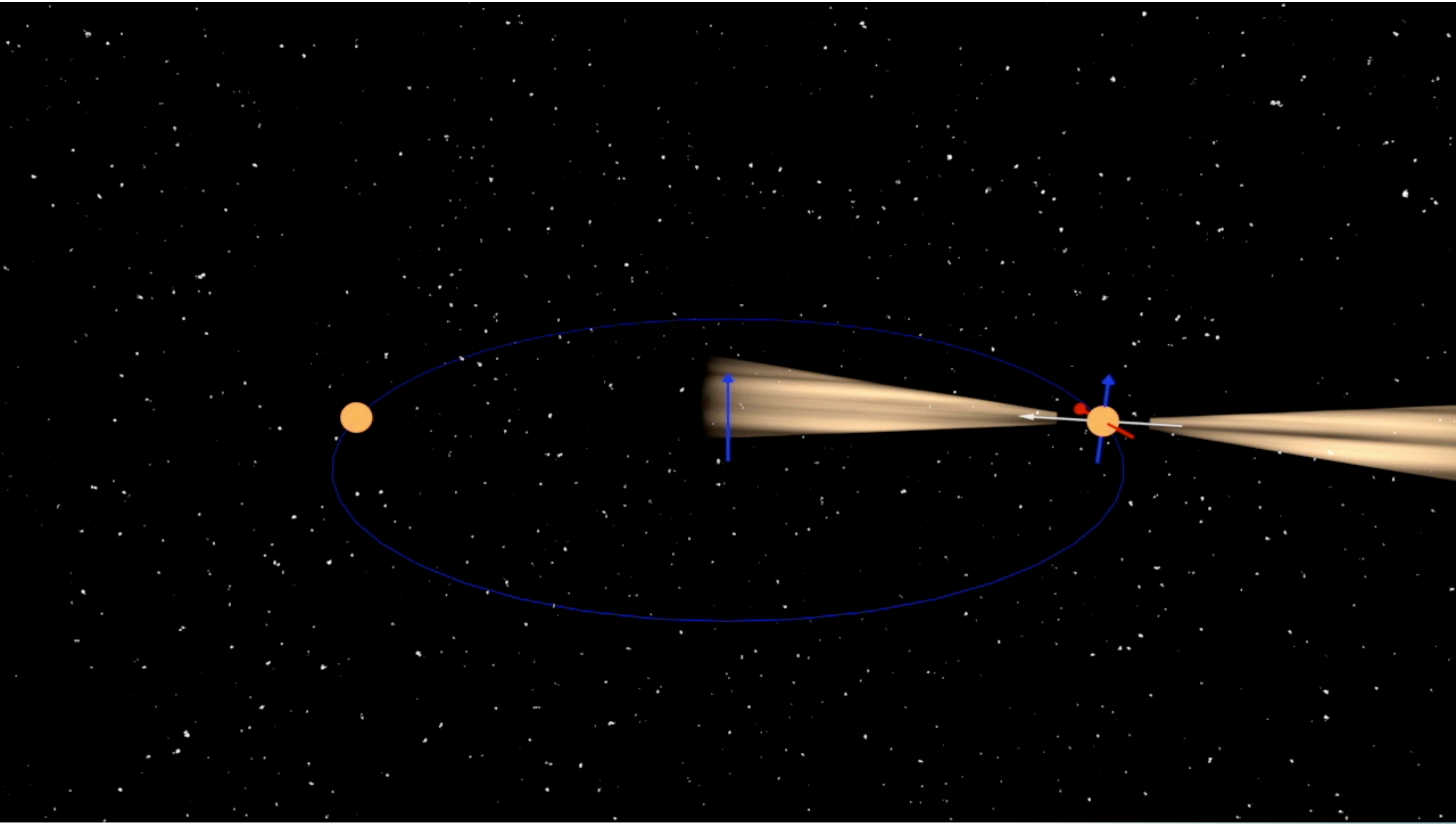
Blaskiewicz et al. (1991) interpreted the longitude delay $\Delta\Phi_S$ as caused by (to the first order) special relativistic effects such as aberration and retardation assuming the emission originates from an altitude h.



$$h_{em} = \Delta\Phi_S \times \frac{Pc}{4}$$



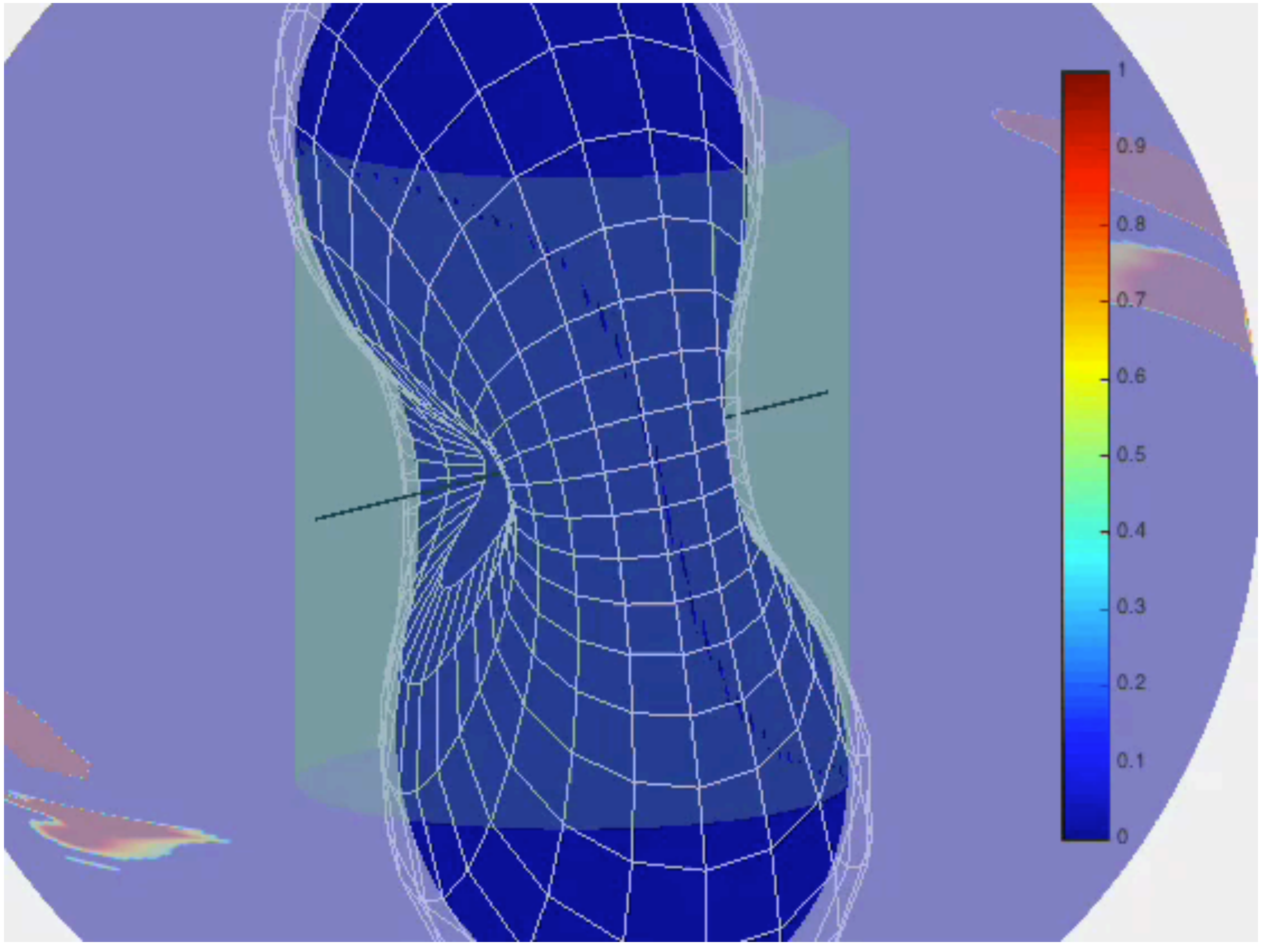
Desvignes et al. 2019, Science



Results

- Large relativistic spin-precession effects -> Our l.o.s crossed the IP magnetic pole
- Beam is more elongated than previously thought
- Drop of intensity and linear polarisation atop the magnetic pole
- Two additional tests of GR: precession rate and inclination angle Best constraint (5%) on spin-precession rate.
- Ambiguity in inclination angle is removed
- IP should disappear around 2028. MP will reappear in 2062-2090.
- Can constrain the relativistic treatment of pulsar polarisation
- Beam shape and beaming fraction will help on refining the pulsar population and DNS merger rate

Future work: going back to the polar cap



$R_{\mathrm{LC}} \sim 6875\,\mathrm{km}$

MATLAB script by KJ Lee

Part III: Exploring the Galactic Centre with radio pulsars

Motivations

Based on high star formation rate and density of massive stars, the GC is expected to harbour many pulsars (Wharton et al. 2012).

Observing/Timing a pulsar in close orbit around Sgr A* has the potential to:

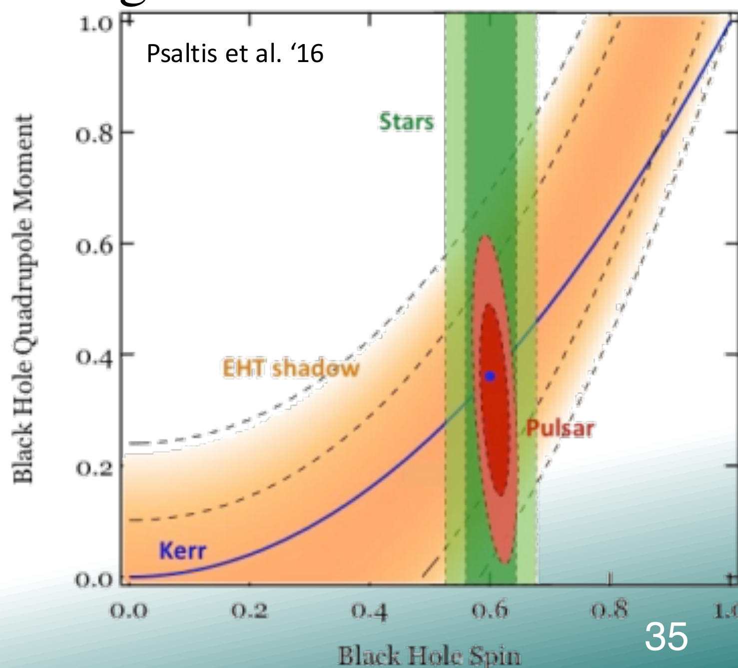
- Allow the study of the GC environment.

- Perform precise strong-field gravity tests as large relativistic effects are expected on the orbital motion and signal propagation.

Ranging capability of pulsar timing

$$\delta t = 1\,\mathrm{ms} \longrightarrow \delta r = 300\,\mathrm{km} \longrightarrow 0.00025\,\mu\mathrm{as}$$

- Measure the Black Hole properties with high precision: mass, spin, quadrupole moment.
  - Combine near- and far-field tests.
  - Provide input parameters to interpret an EHT image on Sgr A*.



Pulsars in the GC

- Before 2013, only 5 pulsars were known within 0.5 deg of Sgr A*.
- April 2013: Detection of a radio magnetar 3’’ from Sgr A* (Eatough et al. 2013), following detections of X-ray pulsations with NuStar.

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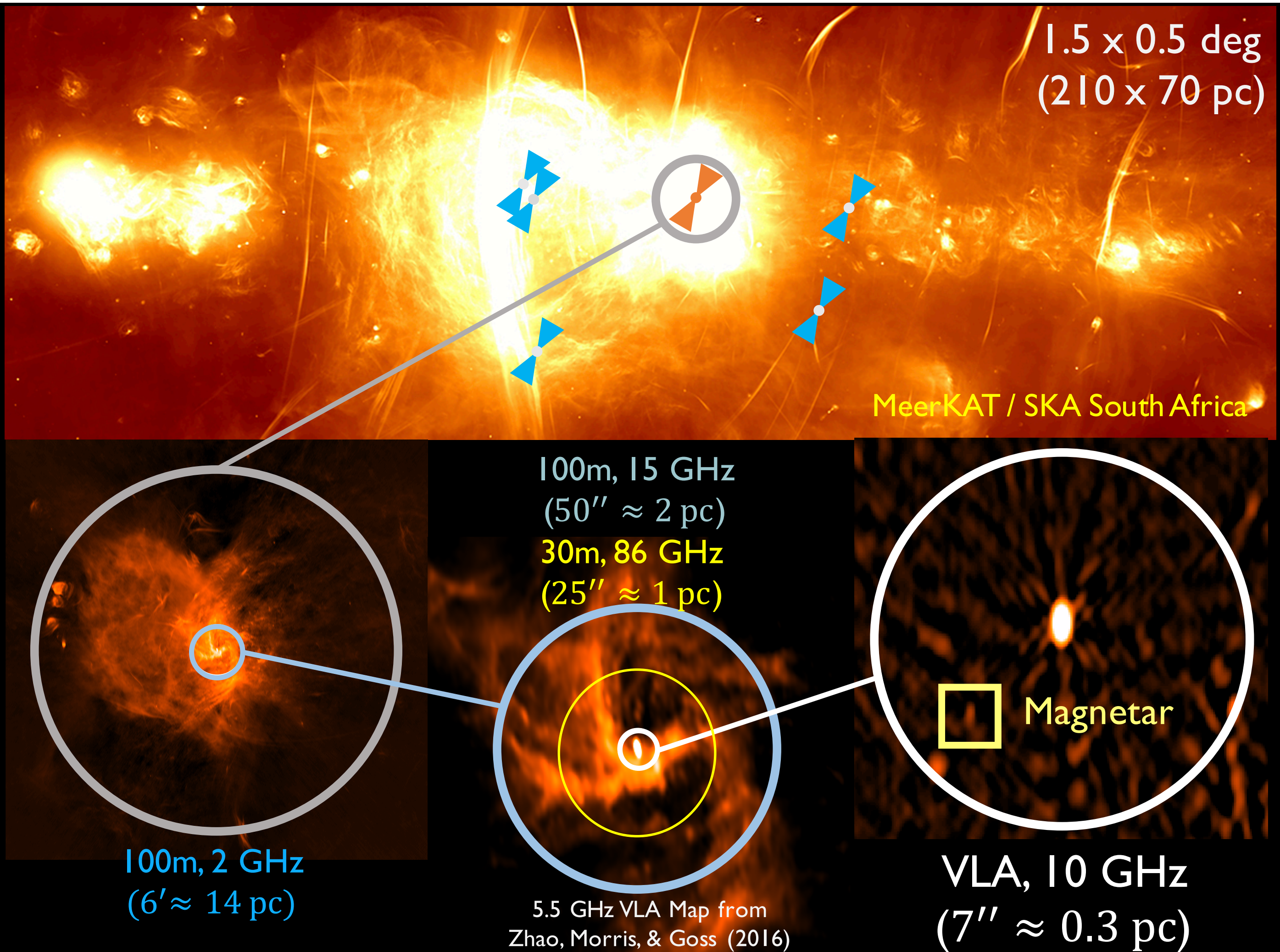
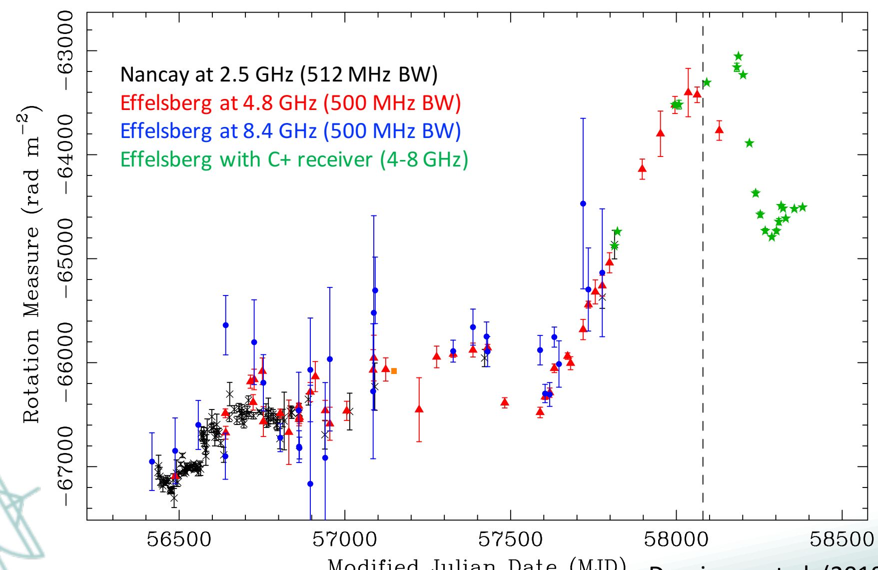


Plot by R. Wharton

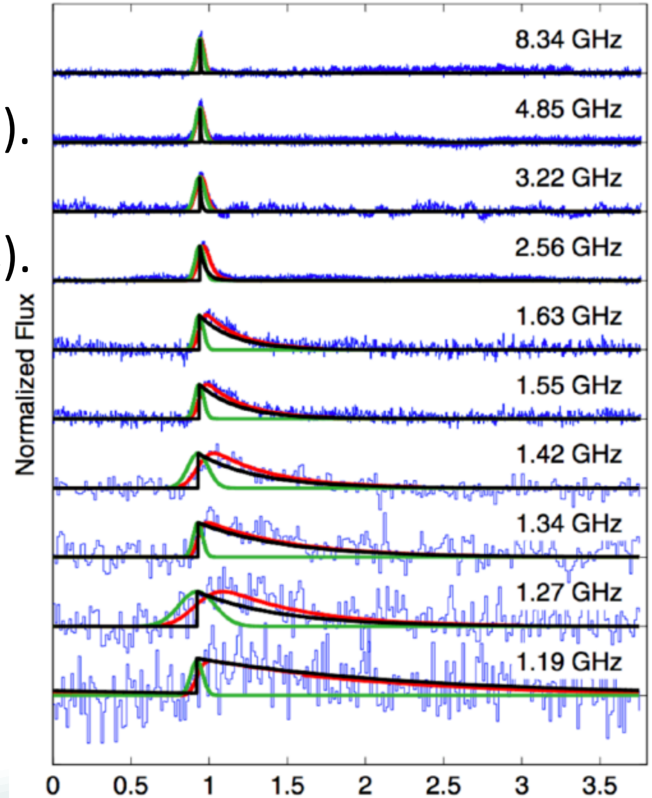
The GC magnetar

- With the GC magnetar we can:
  - Constrain the B-field in the Bondi-Hoyle accretion region (Eatough et al. 2013).
  - Scatter-broadening of pulsars much less than expected (Spitler et al. 2014).
  - Precisely measure its position and proper motion (Bower et al. 2016) w. VLBA
  - Time variations of the interstellar medium properties (Desvignes et al. 2018).
  - Study the single pulse emission (Wharton et al. 2019).

- 2019: Follow-up of the other 5 GC pulsars (PI Noutsos).



Desvignes et al. (2018)



Spitler et al. (2014)

Further complimentary GC searches

- The GC magnetar is not close enough to Sgr A* for constraining the BH properties.
- Further deep searches are warranted to find this elusive system.

Conflicting observational effects

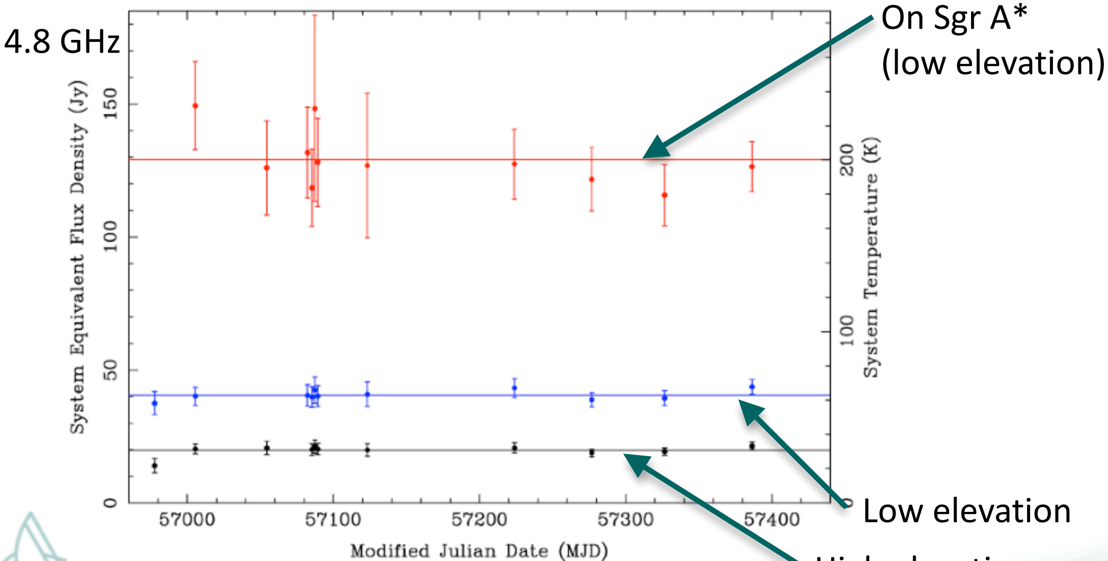
Observing frequency	Low	High
Pulse dispersion smearing ($\propto f^{-2}$)	✗	✓
Pulse scatter broadening ($\propto f^{-4}$)	✗	✓
Pulsar spectra ($\sim f^{-1.7}$)	✓	✗
Intense GC background	✗	✓
Integration time	**Short**	**Long**
Signal/Noise	✗	✓
Possible binary motion	✓	✗

These effects impose on using different observatories/frequencies and search strategies.

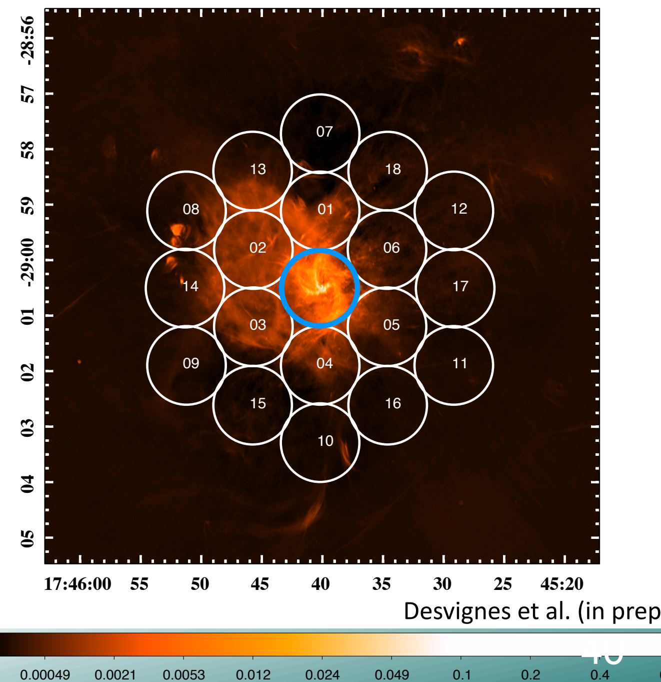
Searching with Effelsberg

- Effelsberg monitoring campaign on Sgr A* since 2012 at 4.85, 8.35, 14 GHz. (PIs G. Desvignes, R. Eatough)
- No good pulsar candidates but we provide new measurements of the GC background -> Previous surveys vastly underestimated the background and led to overoptimistic constraints on pulsar population (Eatough et al., in prep).

- New C-X band receiver and pulsar backend (PSRIX2 4-8 GHz) commissioned in 2018. Started a new survey of GC region (Desvignes et al, in prep).



Eatough et al. (in prep)

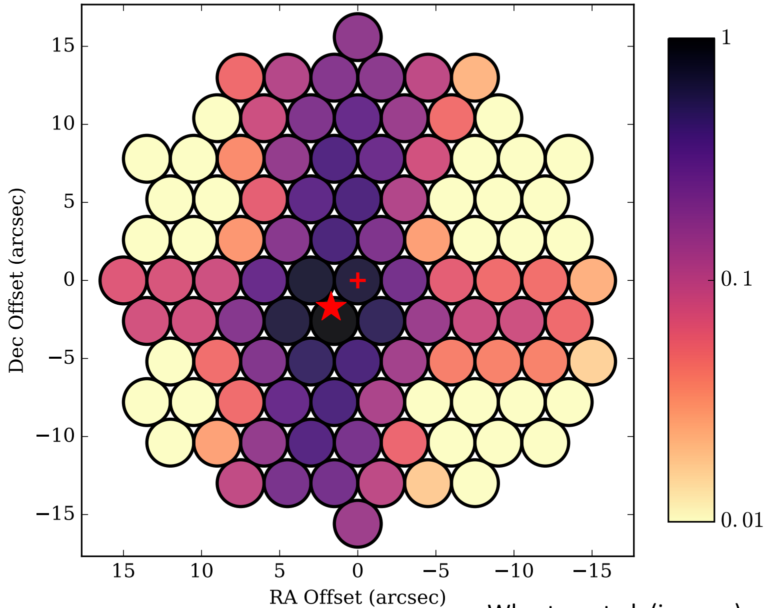


Desvignes et al. (in prep)

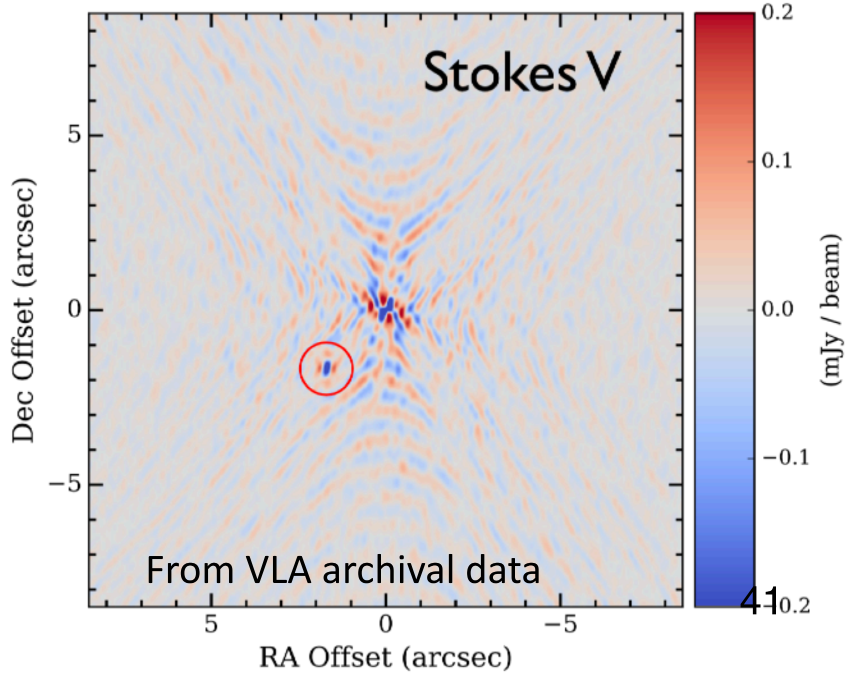
Searching with Karl G. Jansky VLA

Three different GC search projects (PI Wharton):

- Phased array search (D~100 m), 8-12 GHz, 2*6.5 hr: on-going processing.
- Fast imaging, 2-4 GHz: on-going processing (~13 000 beams to reconstruct).
- Imaging in Stokes V, 2-4 GHz: on-going observations



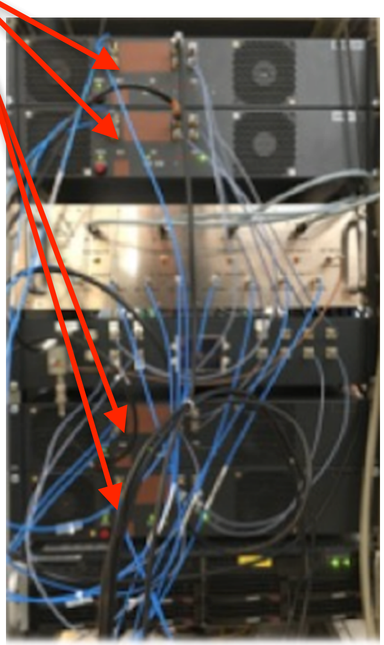
Wharton et al. (in prep)

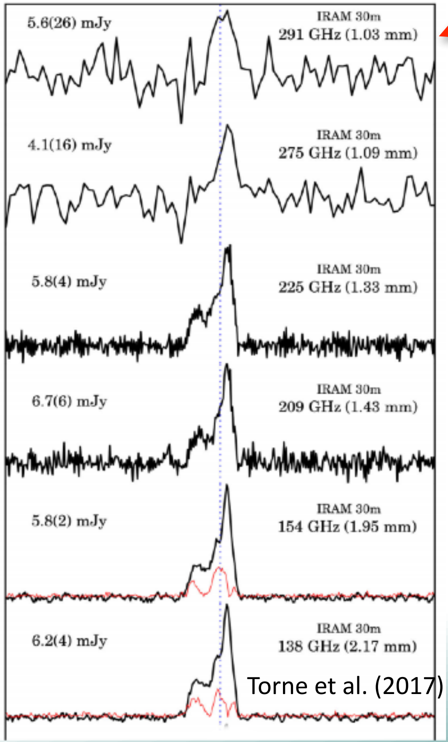


Searching with IRAM 30-m telescope

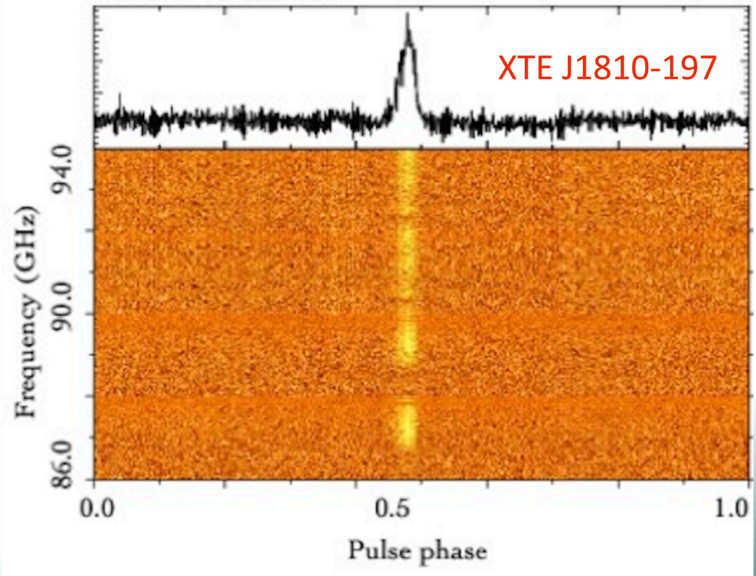
- To further mitigate ISM effects, push to even higher observing frequencies.
  -> IRAM 30m telescope (PI P. Torne)
- Required installation of a dedicated pulsar backend (4 ROACH2 boards).
- Pulsed detection of the GC magnetar up to 291 GHz (Torne et al. 2017).
- Study of normal pulsars and other radio magnetars.

4*ROACH2 boards
8 GHz band



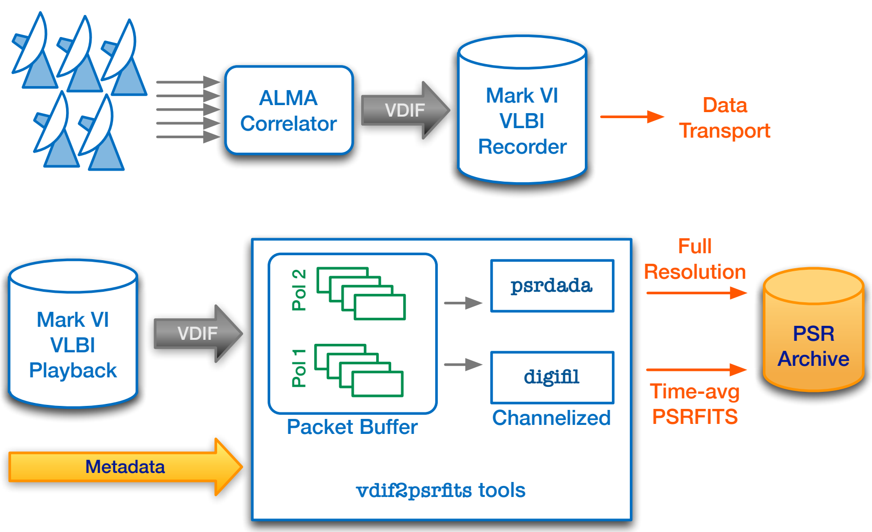


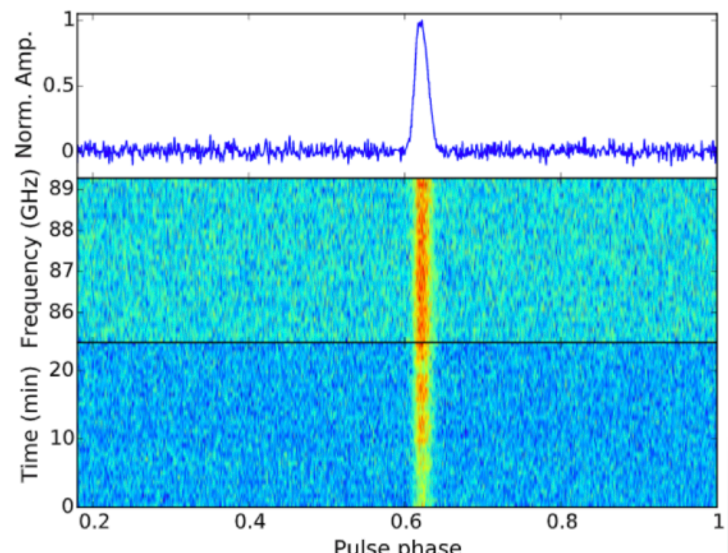
Highest frequency (291 GHz)
of a pulsar detection



Searching with EHT - ALMA

- Under the umbrella of the EHT we search the data for pulsars
- Dedicated software developed as part of NSF-funded ALMA DS to allow for pulsar, magnetar, transient observing mode (PI Jim Cordes, Cornell)
- The ALMA 37*12m antennas are phased up thanks to the APP and the data are recorded with the Mark6 data recorder developed for EHT
- Successful tests on the Vela pulsar in January 2017 at 86 GHz (40 min).
- No ALMA official pulsar capability yet.





First pulsed detection with ALMA

Liu et al. (submitted)

Searching with EHT data

- EHT 2017:
  8 telescopes: phased-ALMA, LMT (32m), PV APEX, JCMT, SMA, SMT, SPT
  32 Gb/s, 3.5 PB raw data
  5 nights with excellent weather

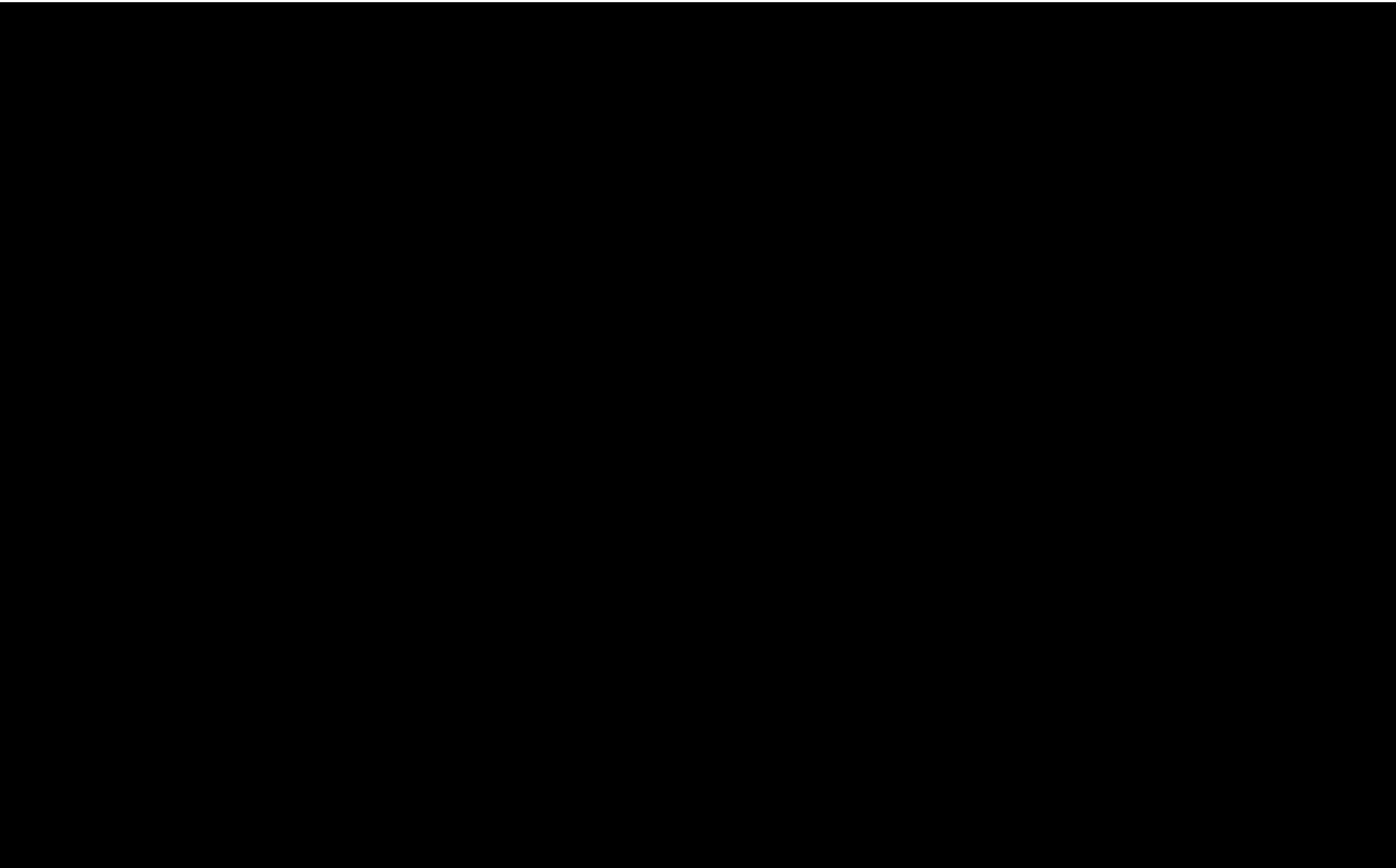
- EHT 2018:
  8 same telescopes + GLT
  64 Gb/s, 5.5 PB raw data
  4 nights with OK weather

- No observations in 2019 due to various telescopes issues

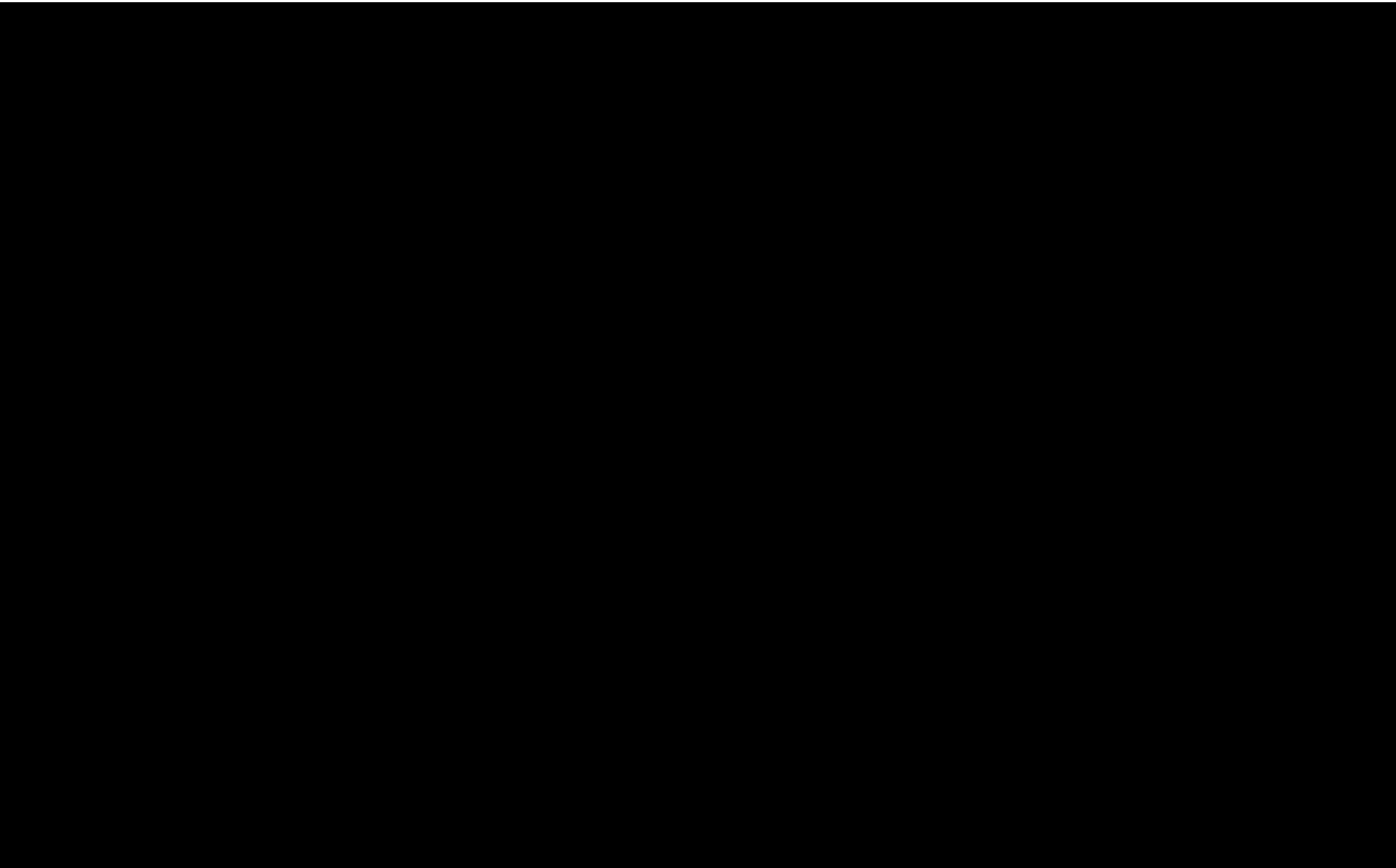
- NOEMA and KP should join for the 2020 campaign, adding 345 GHz observations

Current focus on EHT2017 data

Searching with EHT - ALMA



Searching with EHT & GMVA data



Conclusion & Future Prospects

- No discovery yet of a close pulsar-Sgr A* binary. But the prospects of finding this object warrant the need for continuous pulsar searches with several ongoing projects & more search techniques to be applied.

- Set constraints (if no discovery) on the GC pulsar population and stellar evolution by the end of the BHC project from current surveys.

- The magnetar continues to provides interesting constraints on the GC environment.

- Looking at phasing-up EHT and GMVA data from the most sensitive stations (ALMA, LMT, PV) for increased sensitivity.

- Interests for the next-generation facilities:
  - ALMA Band 1.
  - The MPIfR S-Band system for MeerKAT. See Vivek's presentation.
  - The ngVLA (next-generation VLA; see Astro2020 white paper)