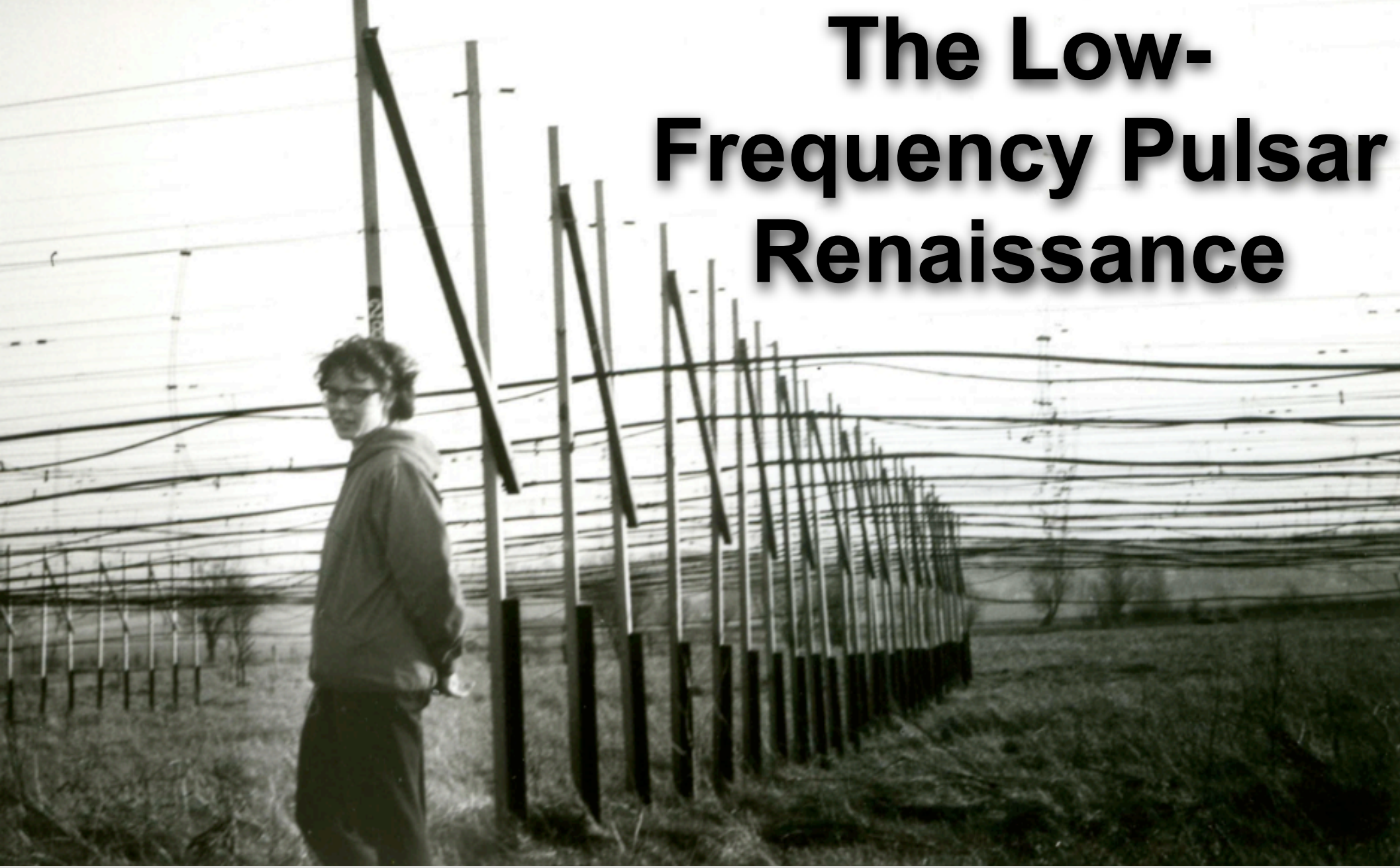
The Low-Frequency Pulsar Renaissance



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Jason Hessels

(ASTRON/U. of Amsterdam)

Nederlandse Organisatie voor Wetenschappelijk Onderzoek

University of Amsterdam

ASTRON

Bologna - 170619

LOFAR Pulsar Working Group

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Stefan Oslowski	Universität Bielefeld
Maura Pilia	Cagliari
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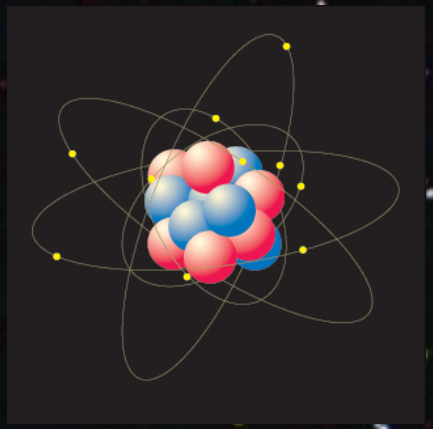
Joris Verbiest	Universität Bielefeld
Patrick Weltevrede	University of Manchester
Kimon Zagkouris	University of Oxford

Pulsars are extreme stars



$R = 12$ km

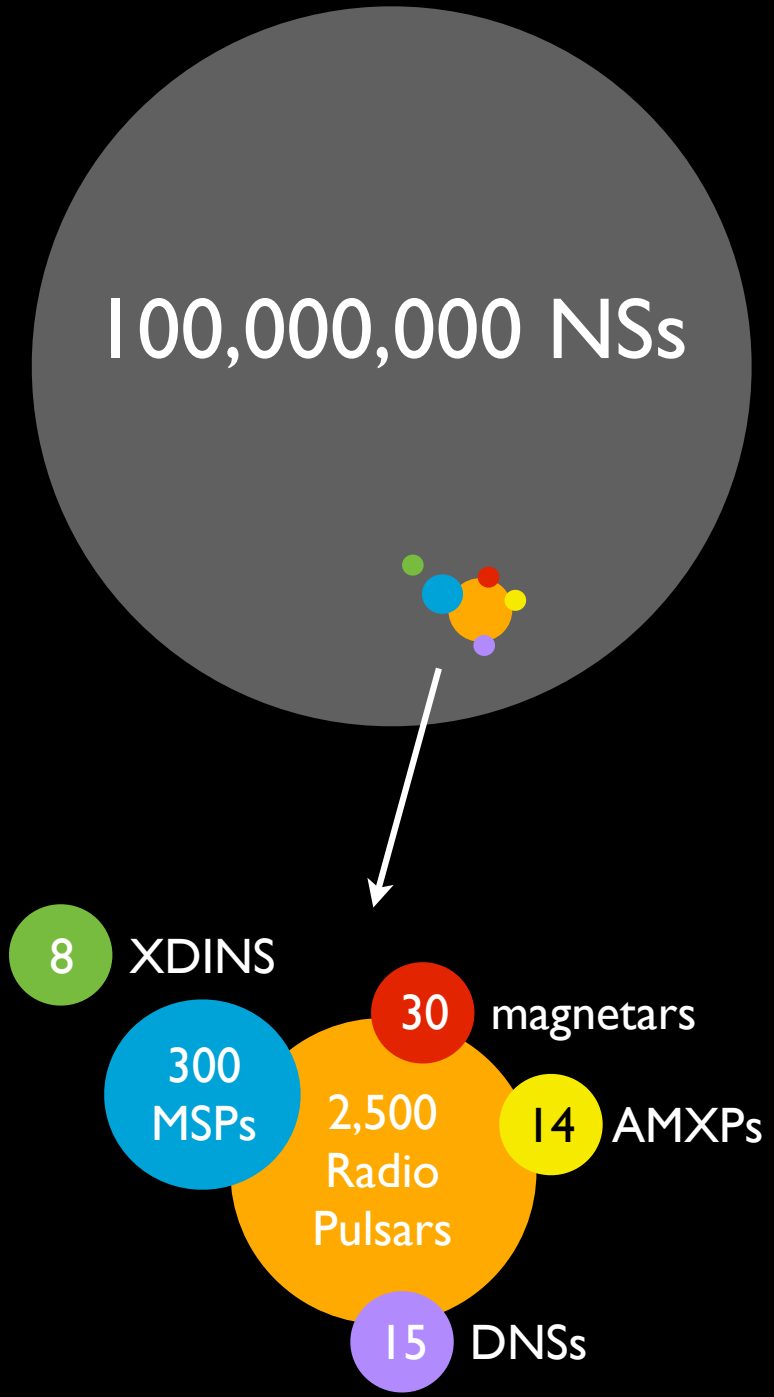
$M = 1.4\ M_{Sun}$

$B = 10^{12}\text{-}10^{15}$ G

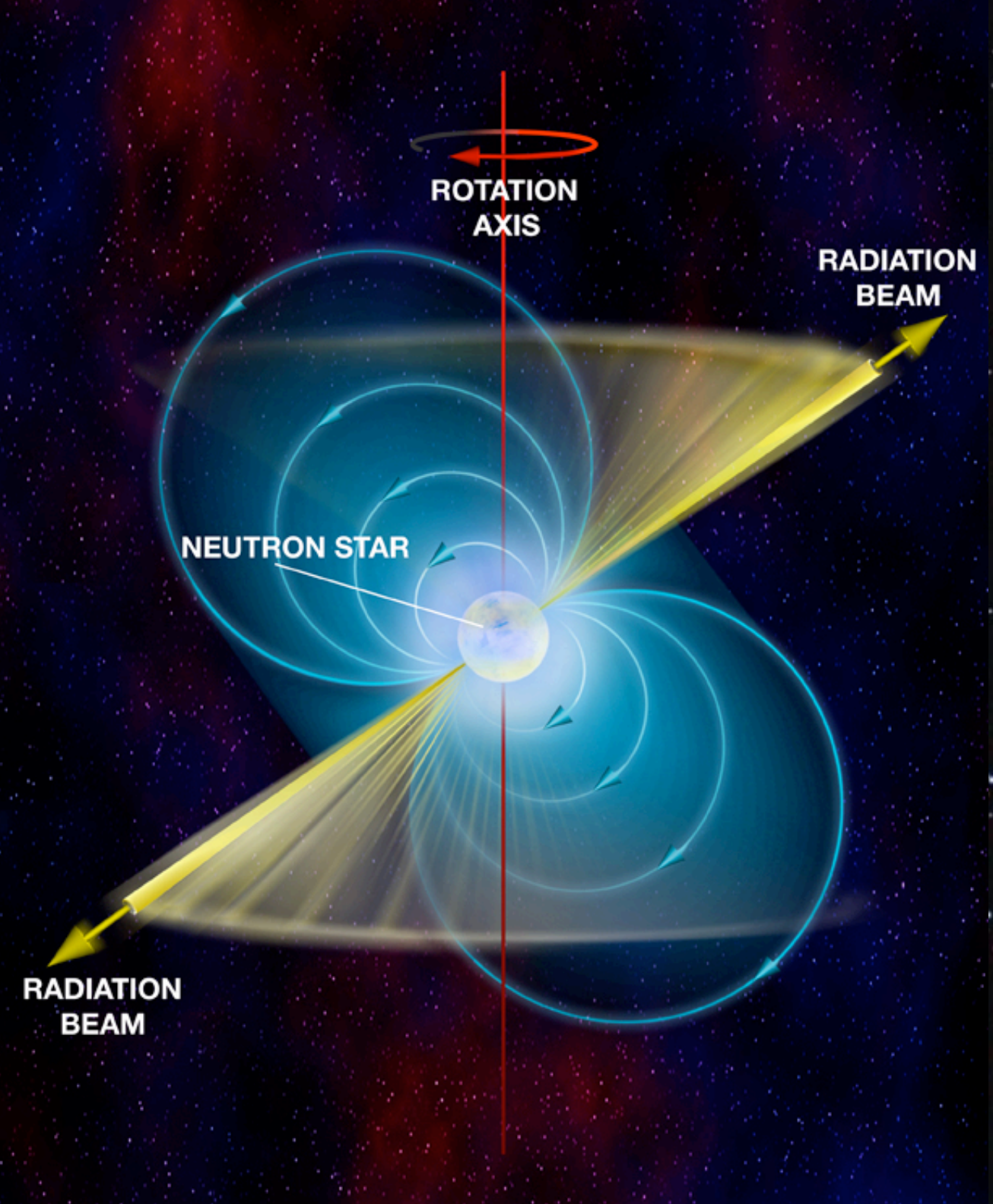
$\nu_{spin} > 716$ Hz

$v_t = 0.2\ c$

...and outstanding physics labs



Only 0.01% of Galactic neutron stars show detectable pulsations



Pulsars are cosmic lighthouses

Spin-down Luminosity

Energy budget

- ~ 100% pair-plasma wind
- ~ 0.1% g-rays
- ~ 0.01% X-rays
- ~ 0.000001% optical
- ~ 0.0000000001% radio

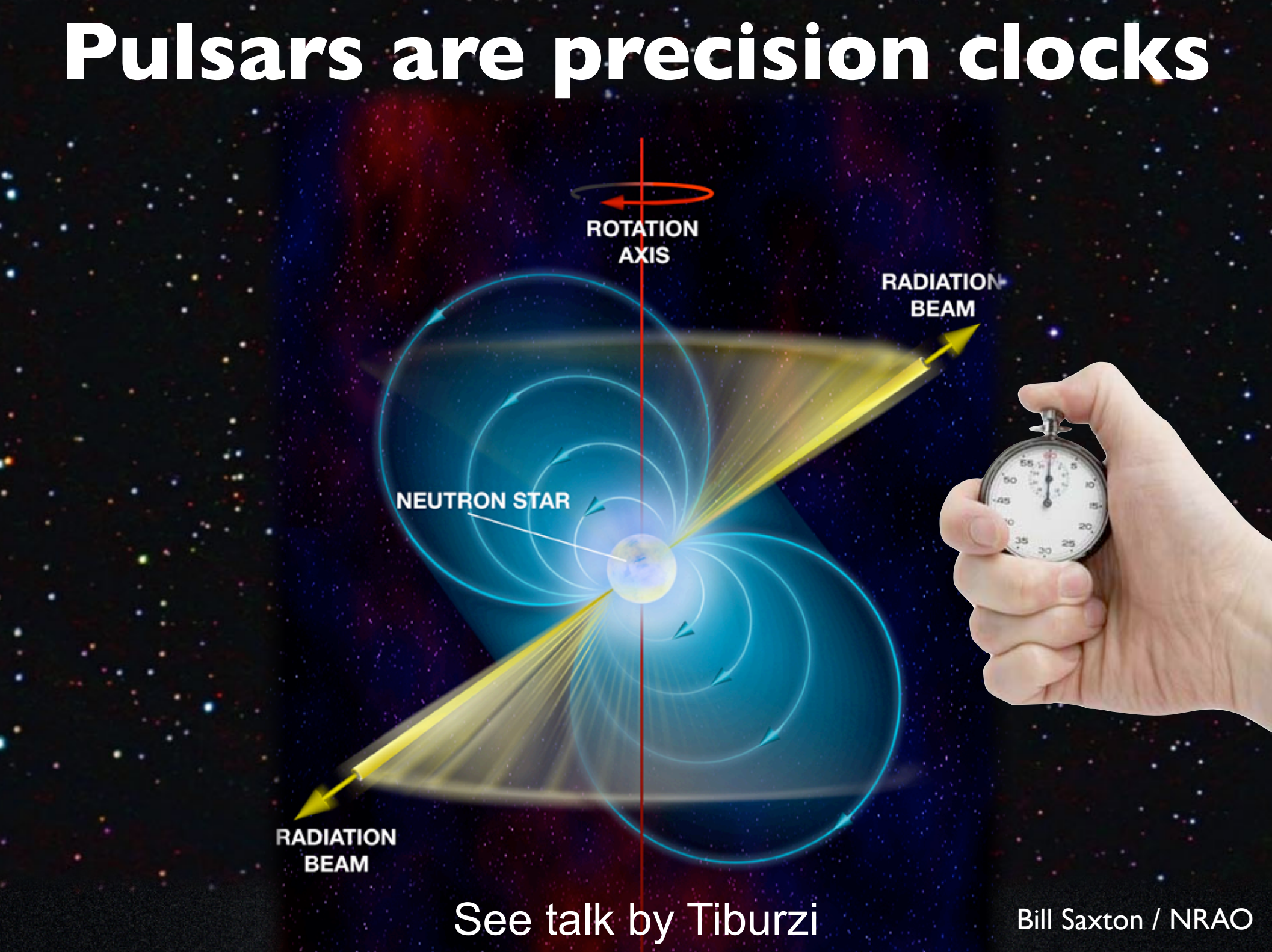
$$\dot{E} = 4\pi^2 I \dot{P} P^{-3}$$

$$= 3.95 \times 10^{31} \text{ erg s}^{-1} \left(\frac{\dot{P}}{10^{-15}}\right) \left(\frac{P}{s}\right)^{-3}$$

General assumptions:

$M = 1.4 M_\odot$
$R = 10$ km
$I = 10^{45}$ g cm^2
Pure dipole spin-down

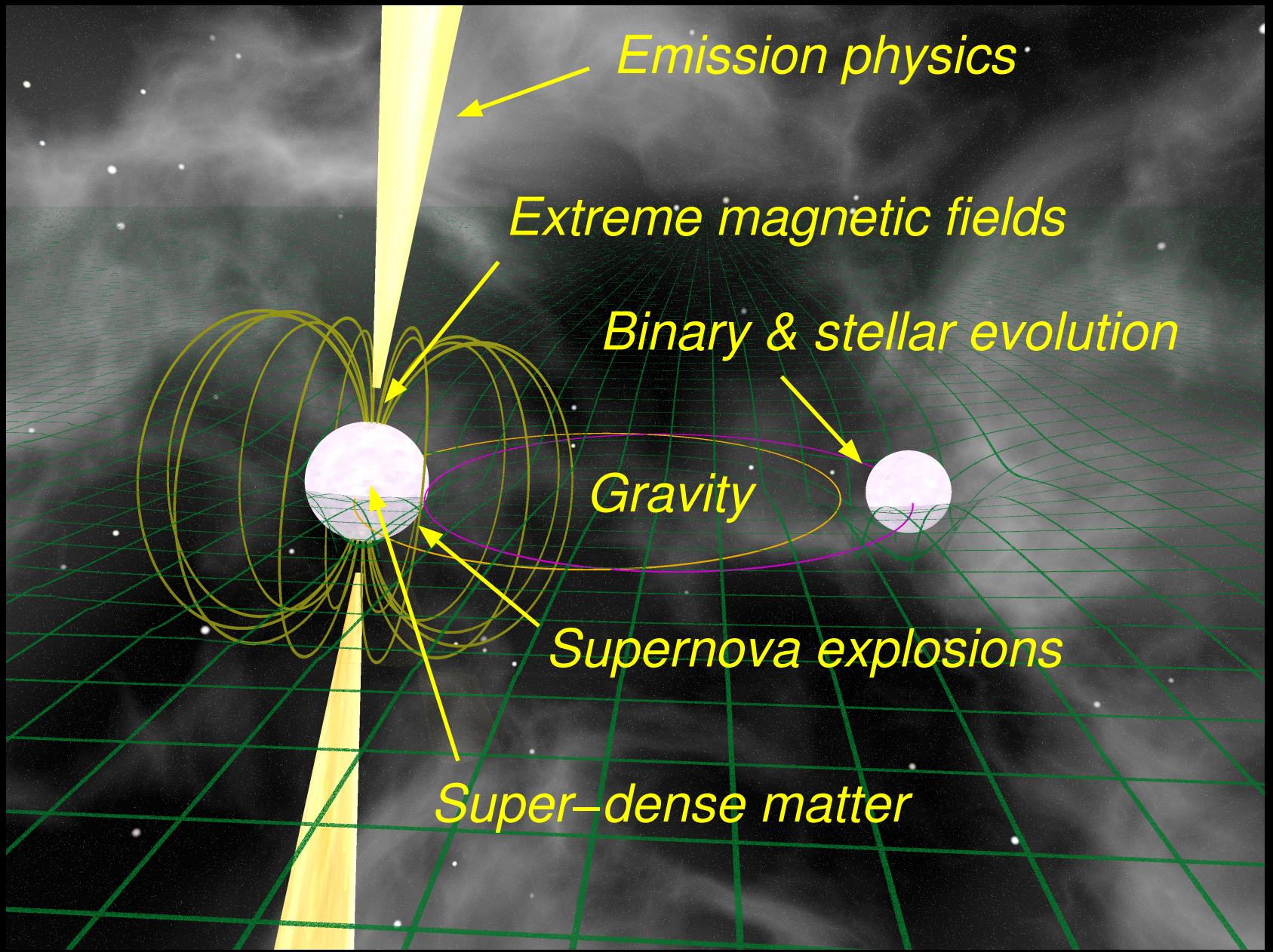
Pulsars are precision clocks



See talk by Tiburzi

Bill Saxton / NRAO

Pulsar Science



Kramer & Stappers 2015

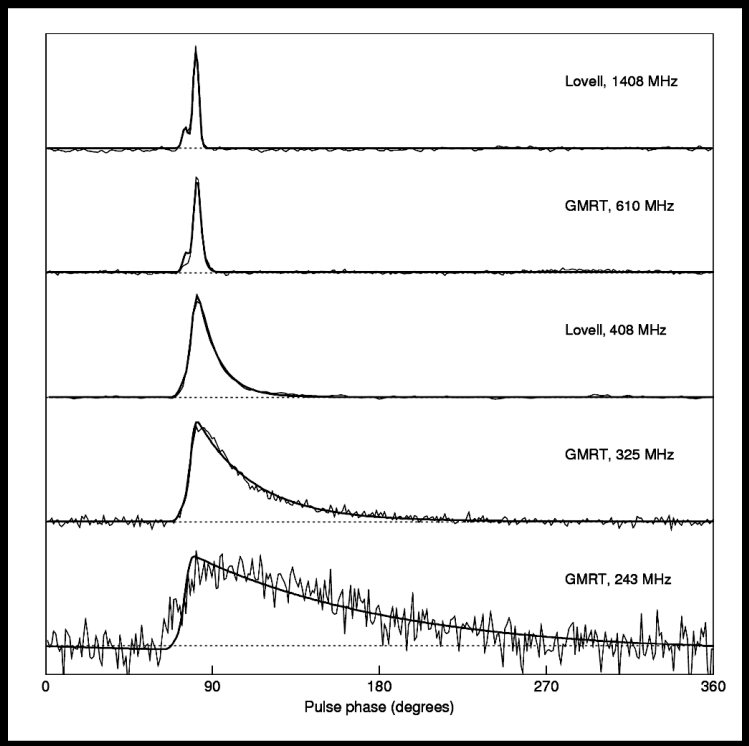
Propagation Effects

Observed signal →

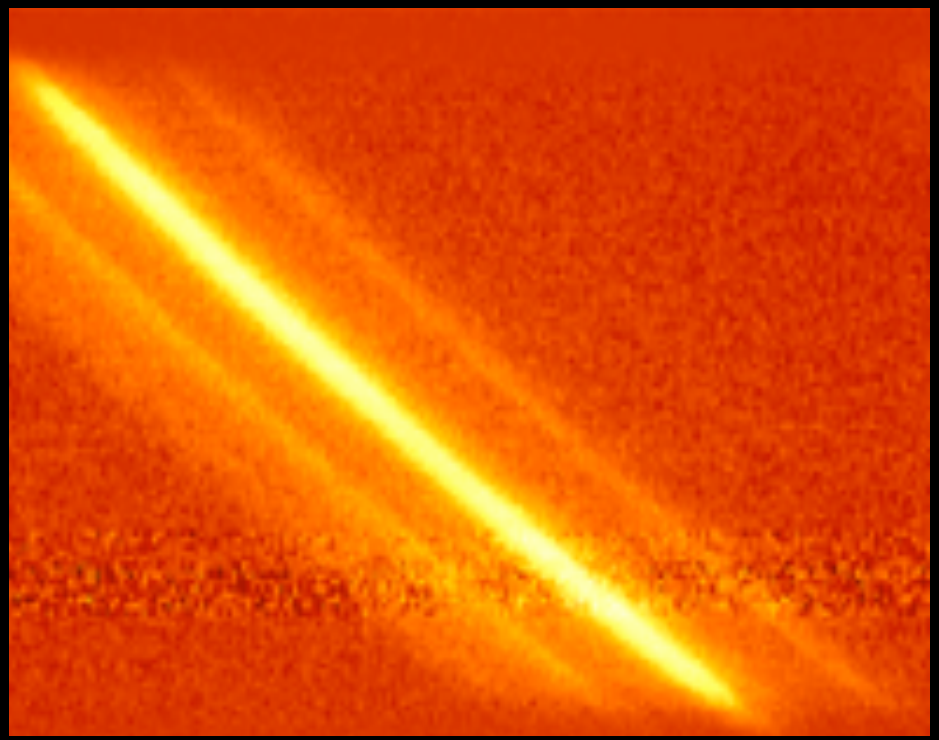
$$I(t) = g_r g_d S(t) * h_{\mathrm{DM}}(t) * h_d(t) * h_{\mathrm{Rx}}(t) + N(t)$$

Emitted signal

Scattering

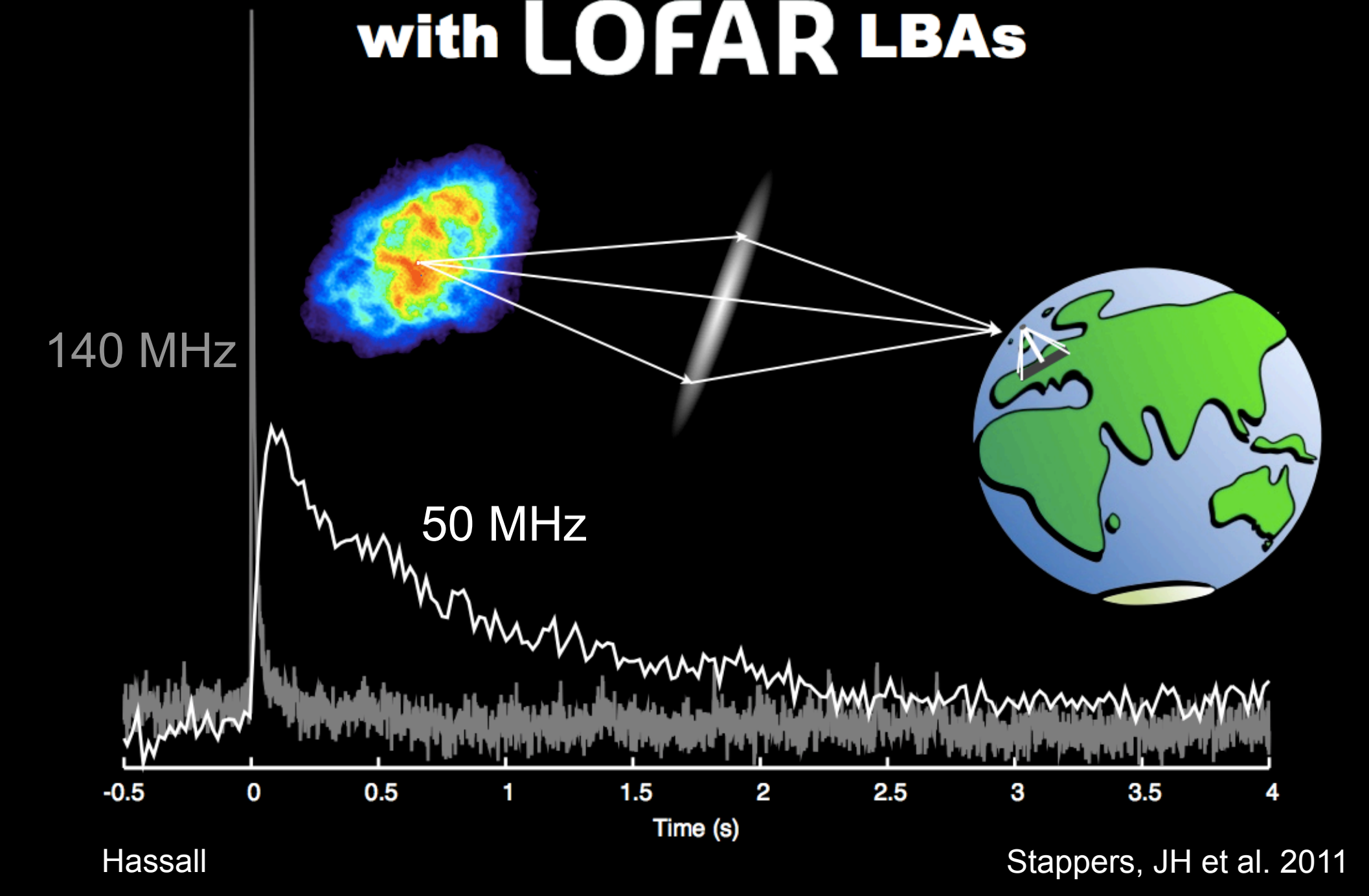


Dispersion



A hindrance but also a help

Detection of Crab Giant Pulses with LOFAR LBAs



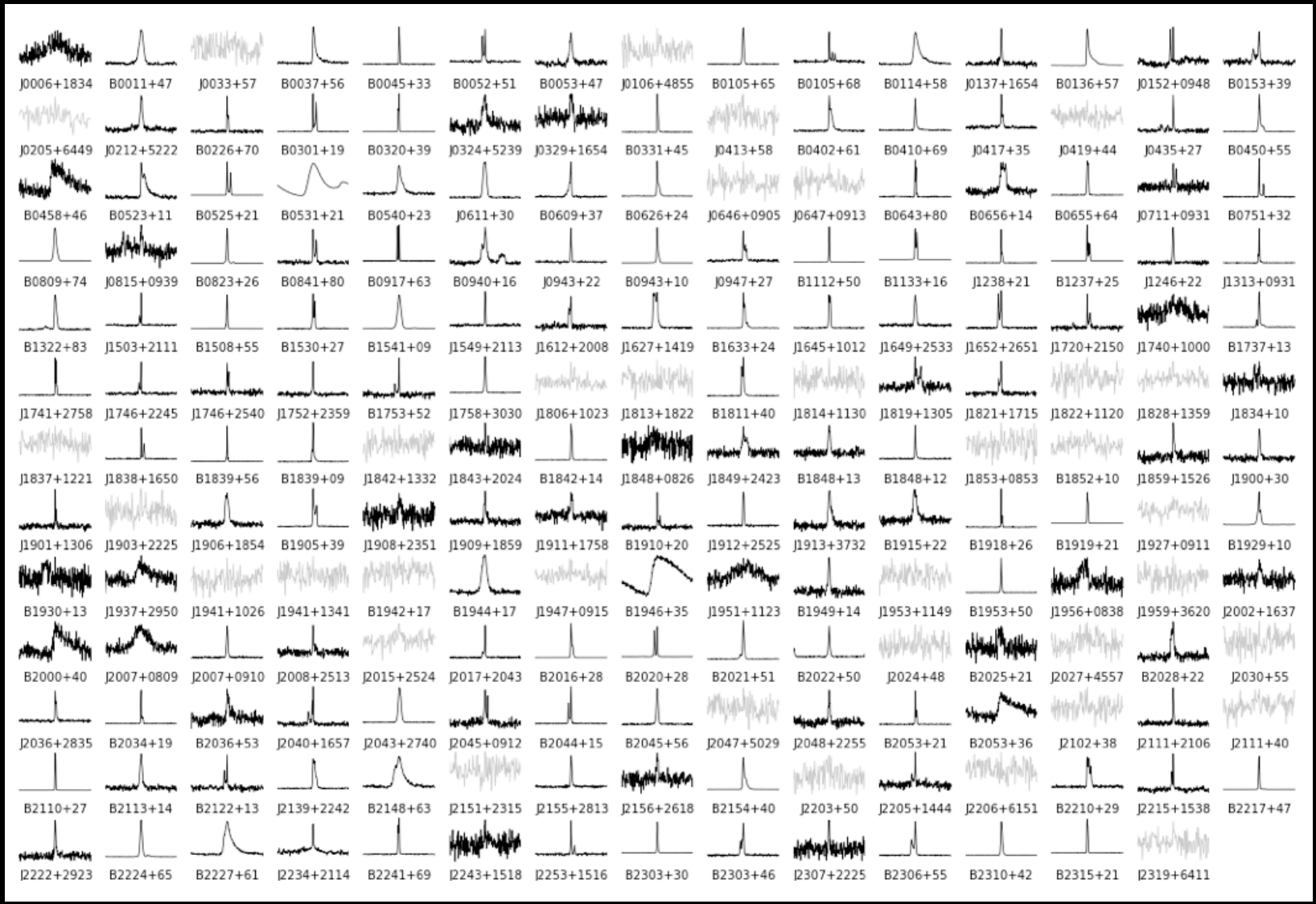
Hassall

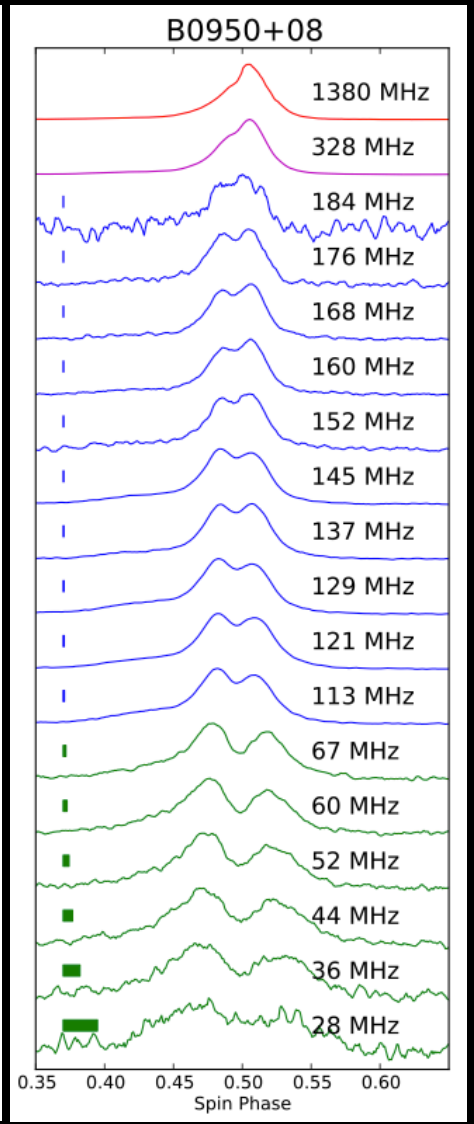
Stappers, JH et al. 2011


2017
Super-
computer

LOFAR Pulsar Census

LOFAR has detected >250 pulsars so far





Bilous et al. 2016

Pilia et al. 2016

Why Pulsars at < 300MHz

Emission mechanism

- Steep spectral indices
- Spectral turnover
- Profile evolution
- Moding

Interstellar medium

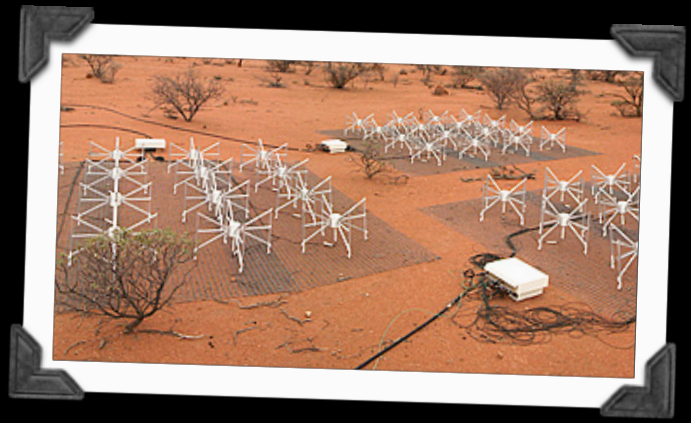
- Precision dispersion measure
- Scattering
- Precision rotation measures
- "Scintellometry"

Surveys

- Huge field-of-view
- Ultra-steep-spectrum sources

Low-Freq Pulsar Telescopes

Arecibo
Puerto Rico



MWA
Australia

LWA
New Mexico

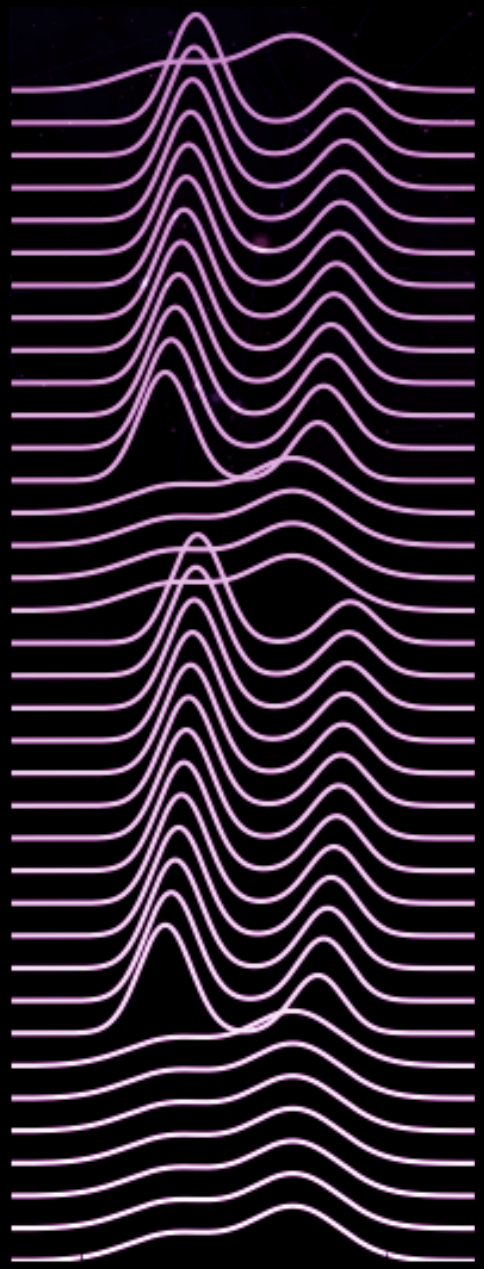
GMRT
India

GBT
West Virginia

LOFAR
Netherlands

Pulsar magnetospheres & moding

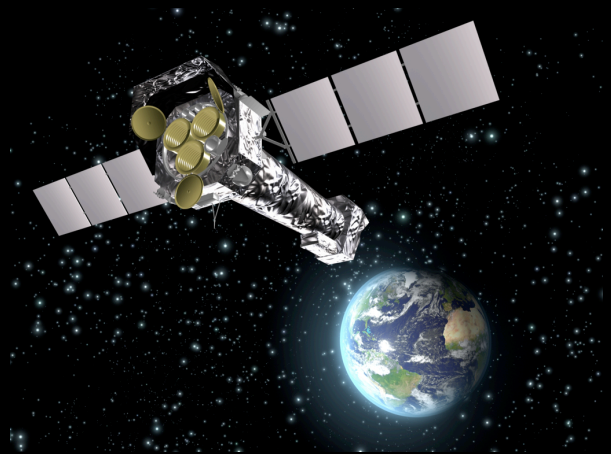
Moding Pulsars



LOFAR

GMRT

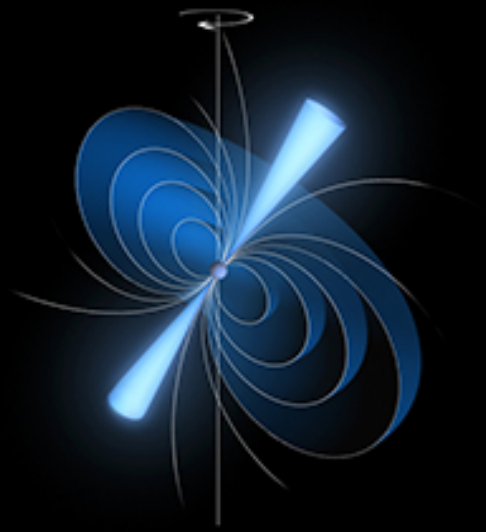
LWA

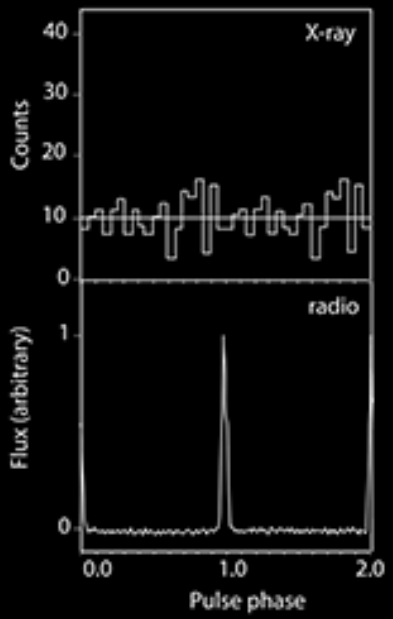


XMM-Newton

Radio/X-ray moding in B0943+10

"B-Mode"

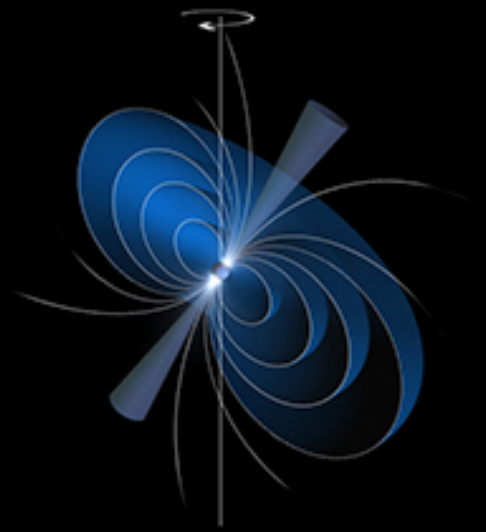


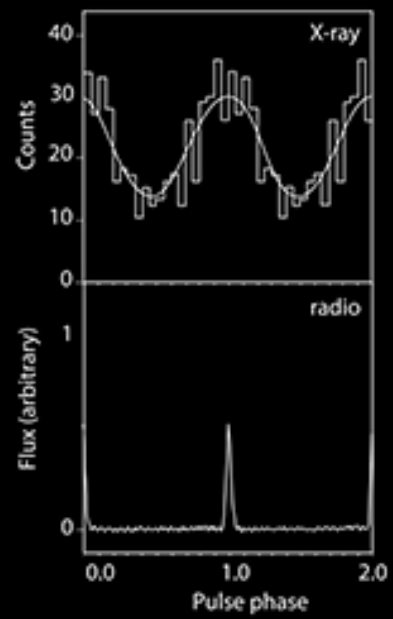


X-rays weak

Radio strong

"Q-Mode"



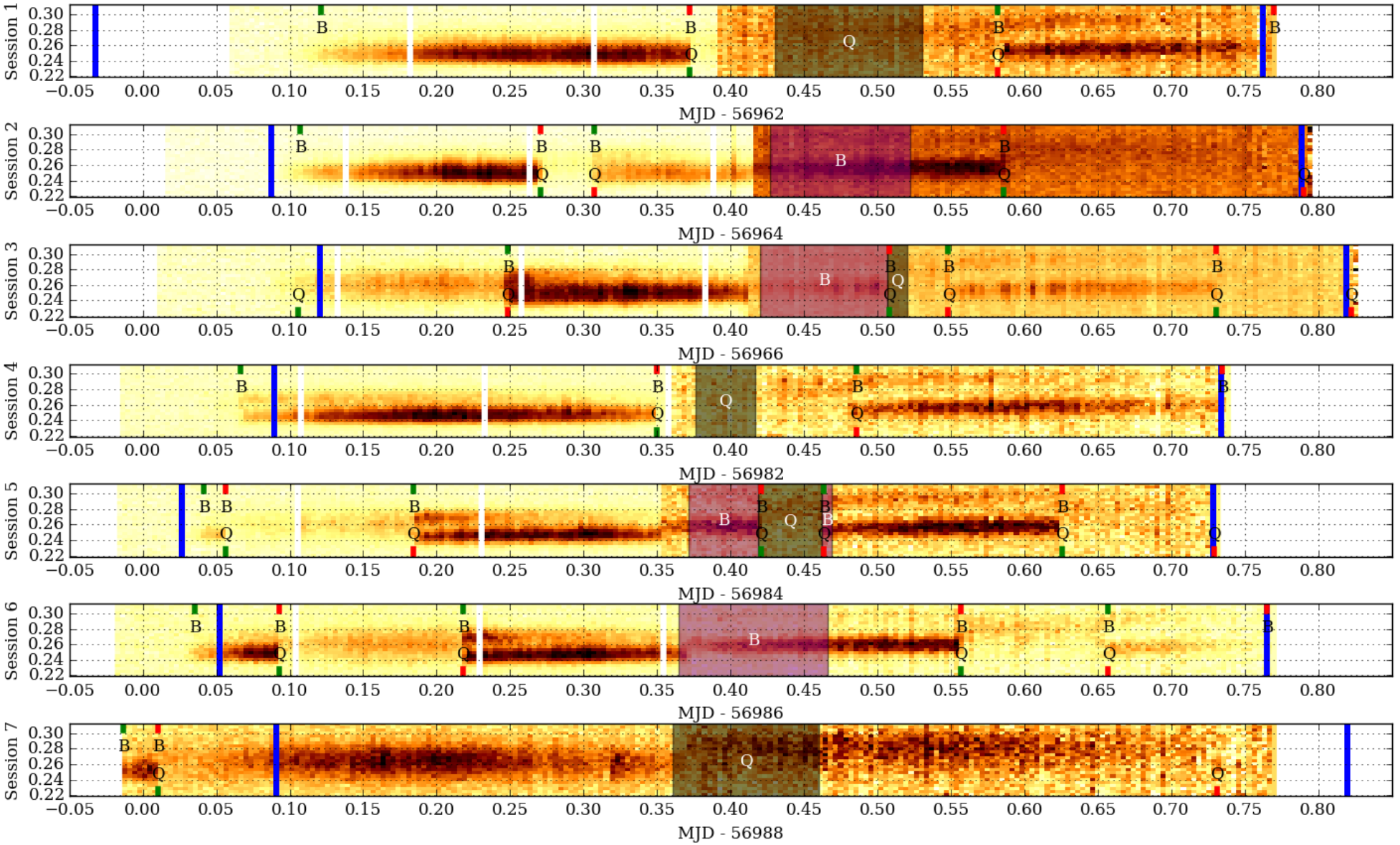


X-rays strong

Radio weak

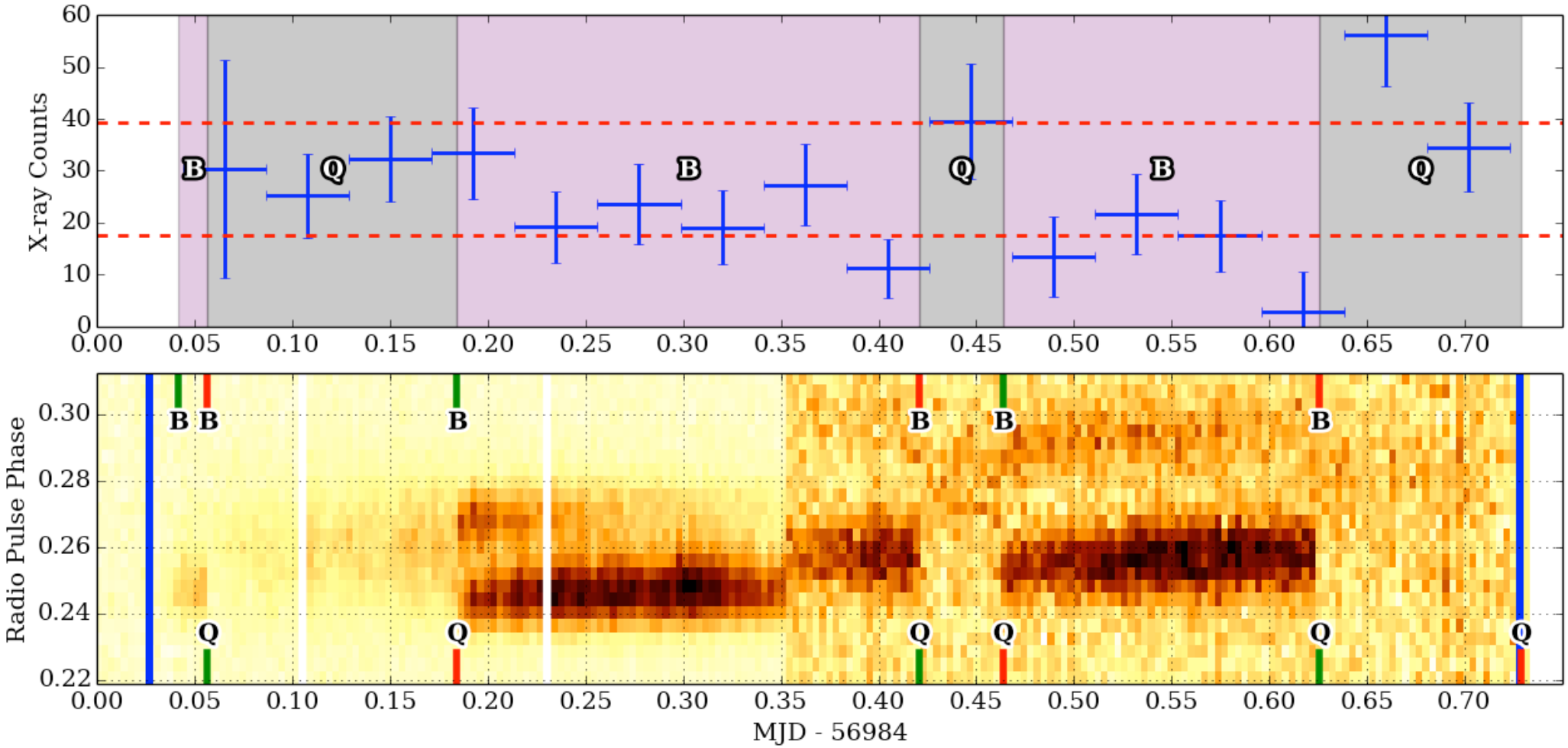
Hermsen et al. 2013

Radio/X-ray moding in B0943+10



Probed this more deeply using a 4x longer campaign

Evolving modes in B0943+10



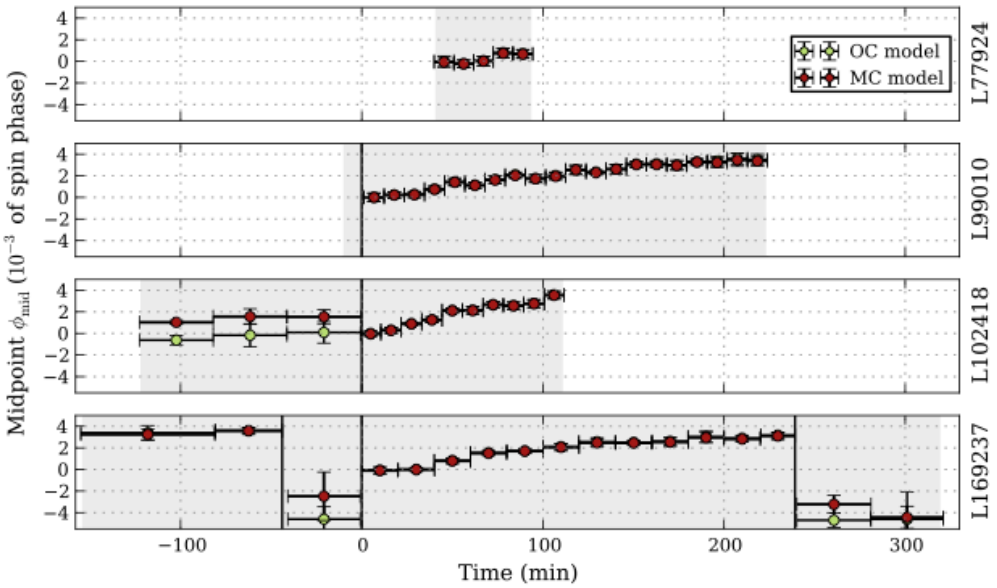
LOFAR data

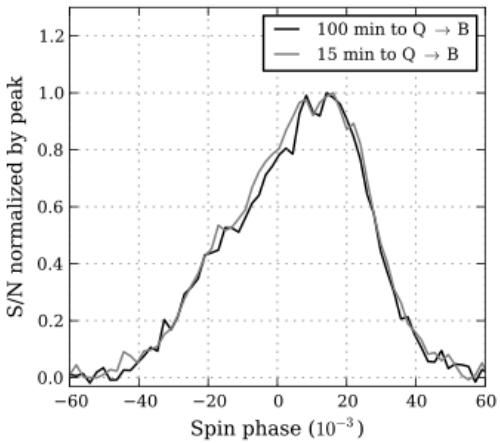
LWA data

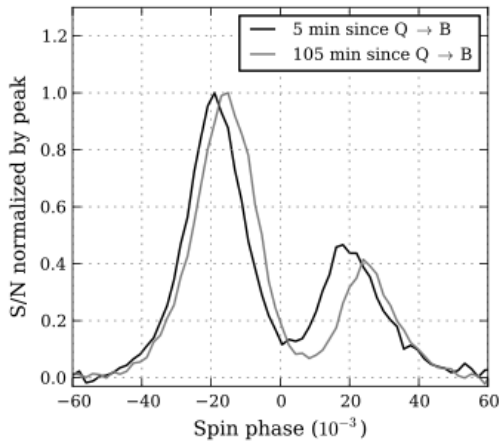
Mereghetti et al. 2016

Evolving modes in B0943+10

Systematic profile drift during B-mode





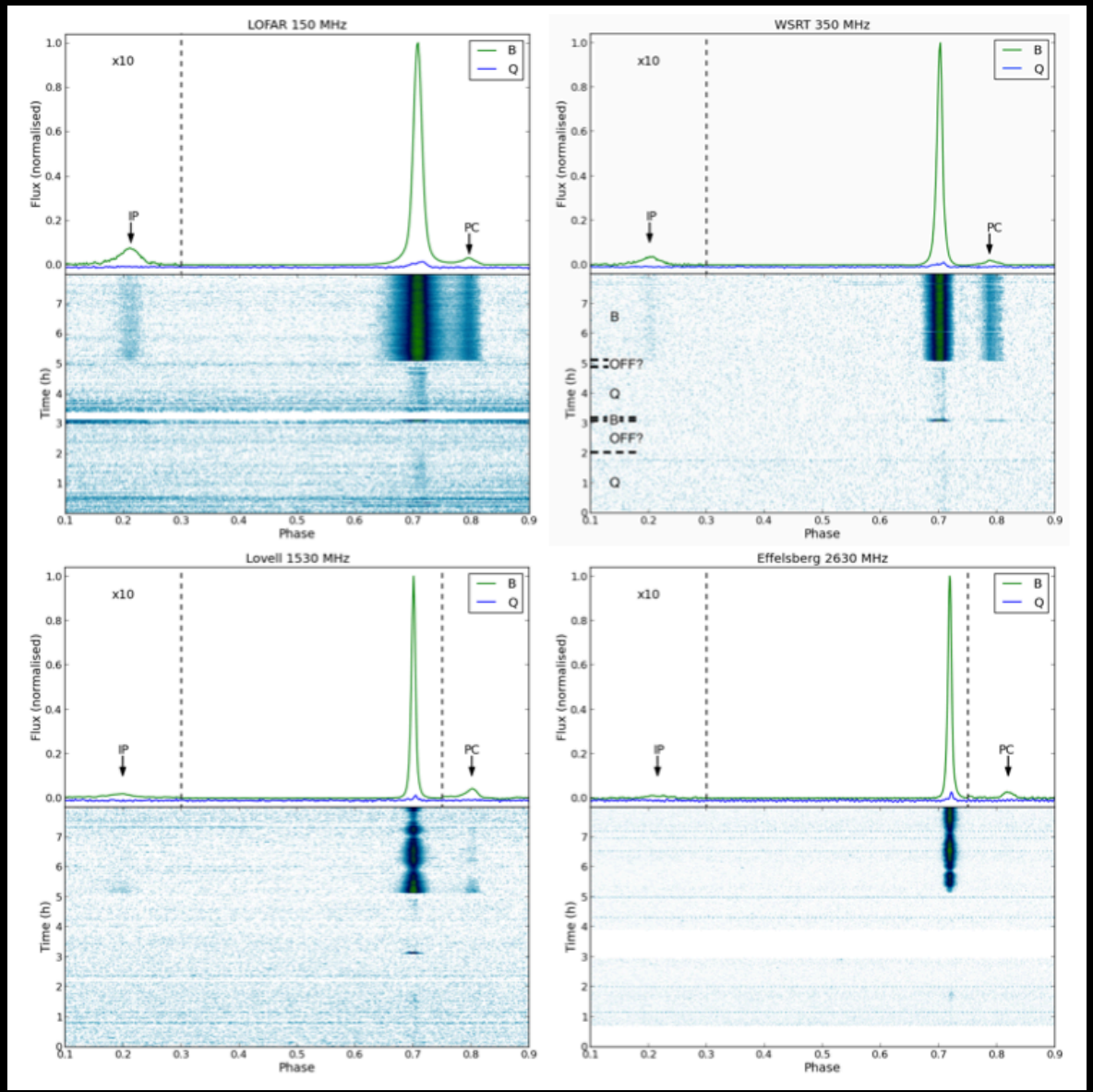


Increase in X-ray pulse fraction during B-mode?

Bilous et al. 2014

Mereghetti et al. 2016

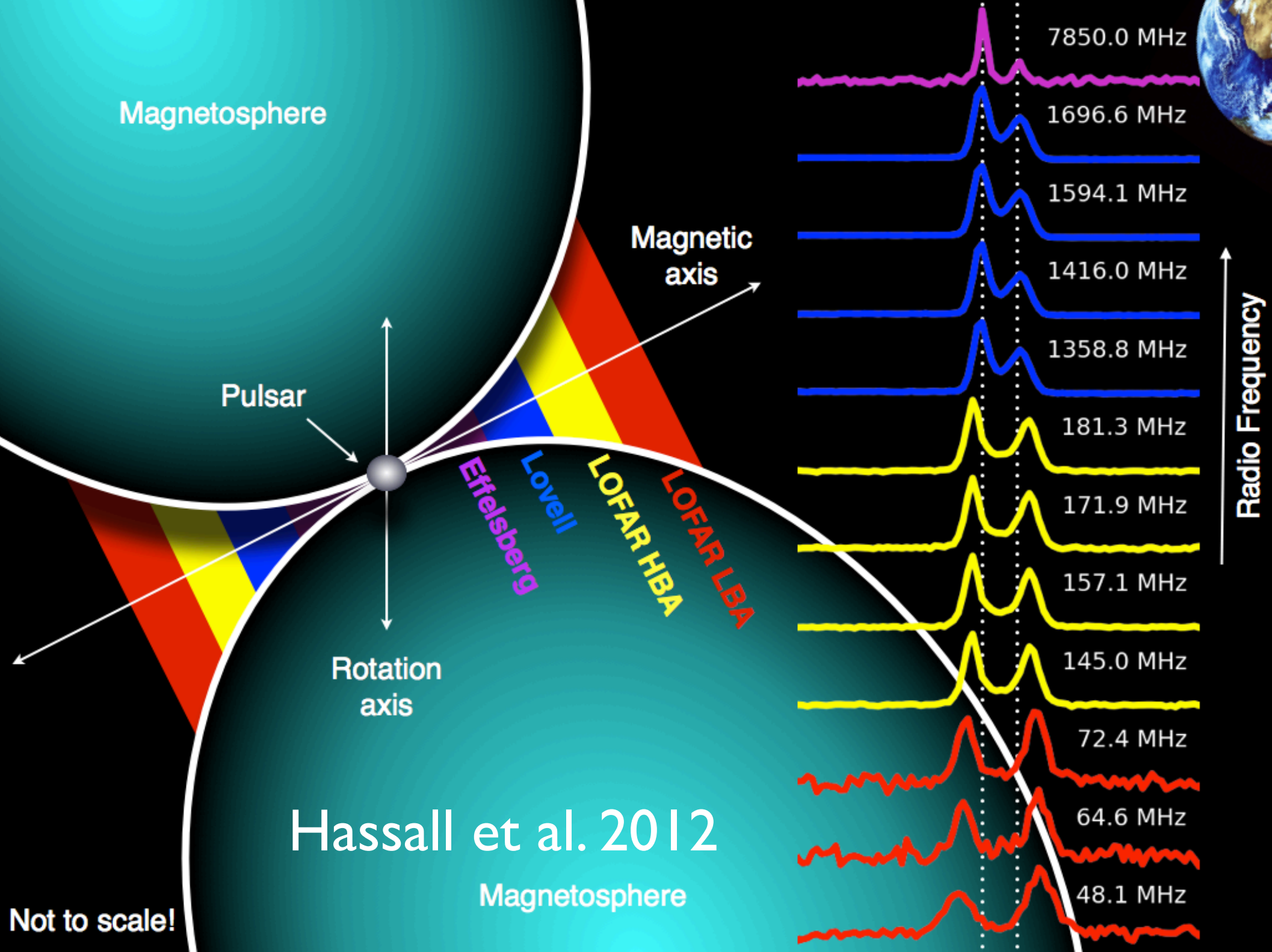
Mode-switching in PSR B0823+26



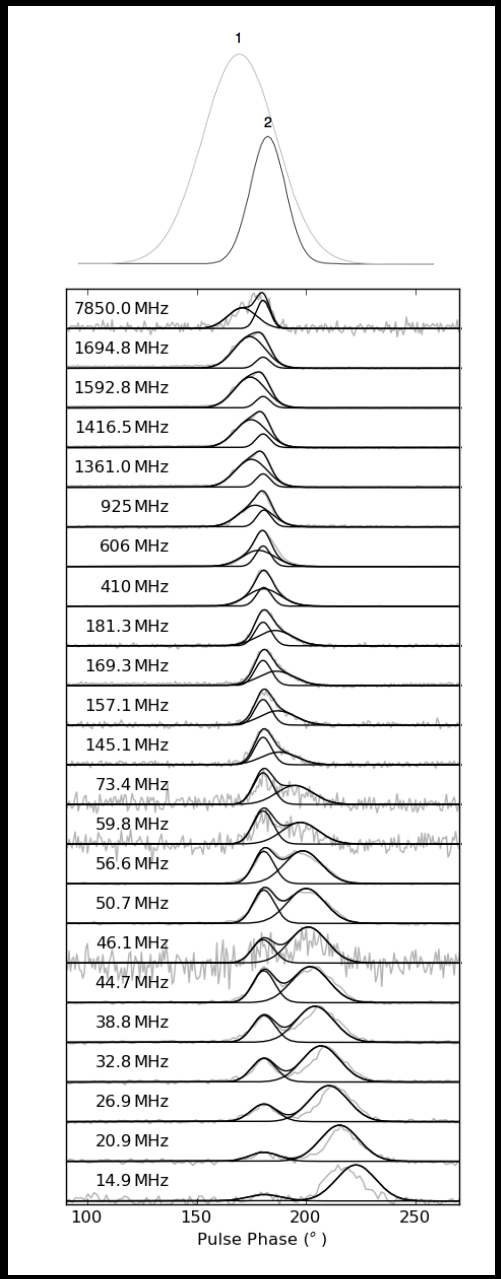
Discovery of a 170x fainter Quiet-mode

Successful radio/X-ray campaign in Spring 2017

Sobey et al. 2015

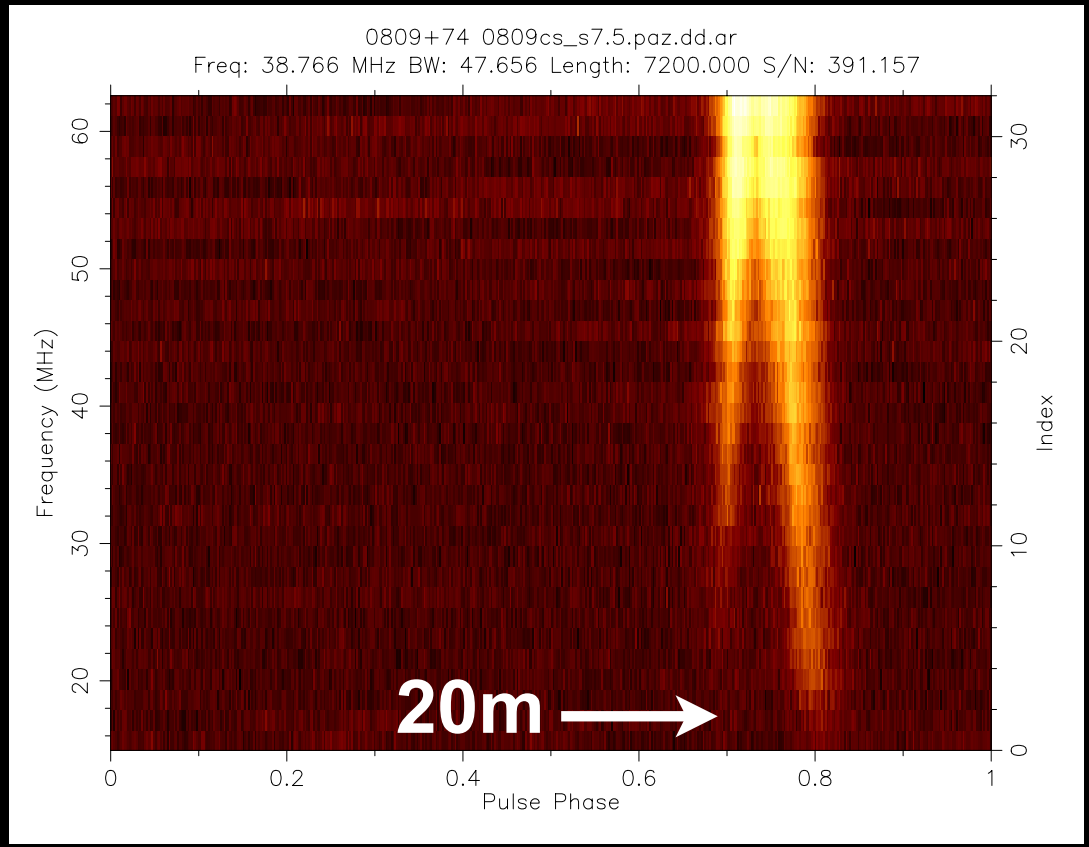

Magnetosphere
Magnetic axis
Pulsar
Rotation axis
Effelsberg
Lovell
LOFAR HBA
LOFAR LBA
Hassall et al. 2012
Magnetosphere
Not to scale!
7850.0 MHz
1696.6 MHz
1594.1 MHz
1416.0 MHz
1358.8 MHz
181.3 MHz
171.9 MHz
157.1 MHz
145.0 MHz
72.4 MHz
64.6 MHz
48.1 MHz
Radio Frequency

Pulsar magnetospheres



Hassall et al. (2012)

15 - 63 MHz Observing Frequency



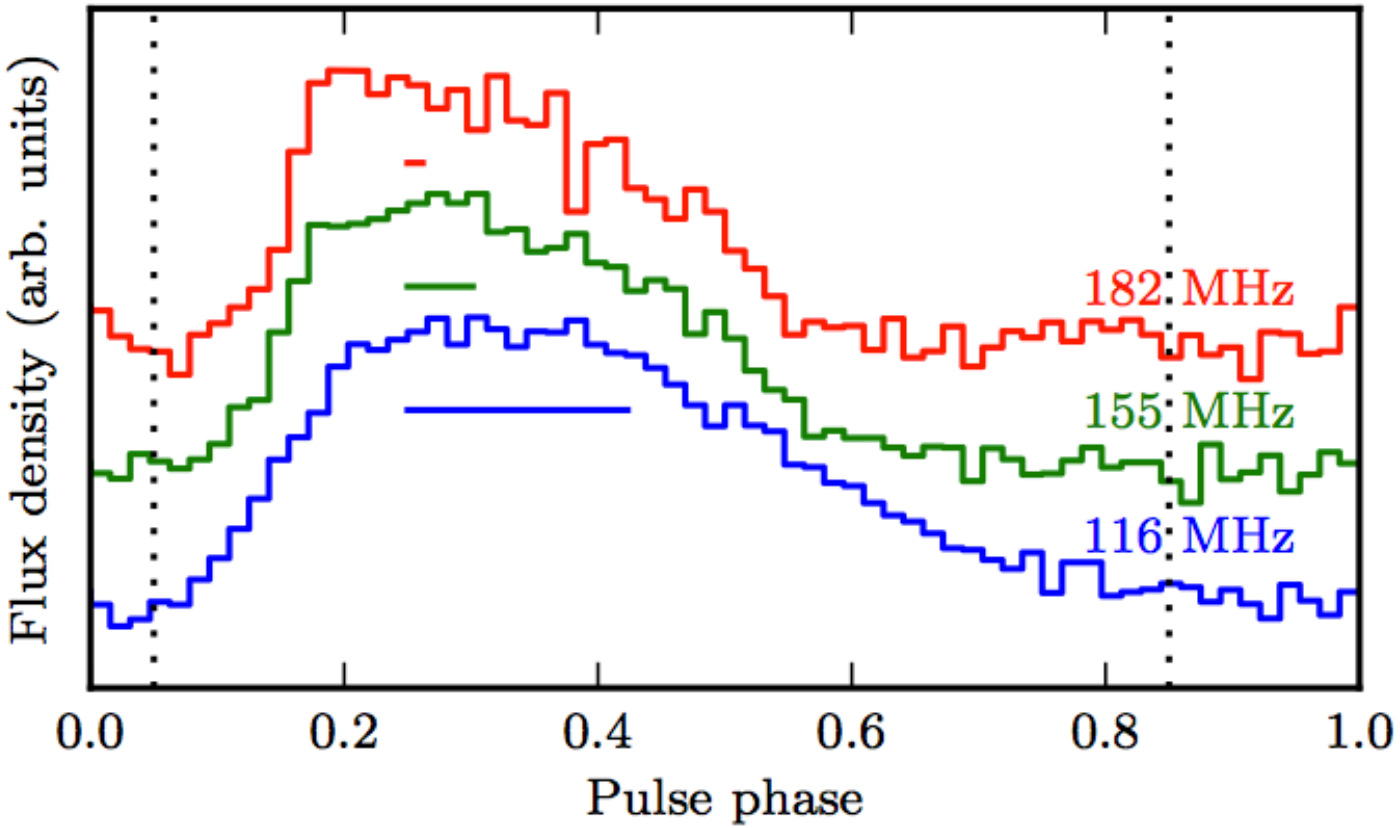
van Haarlem et al. (2013)

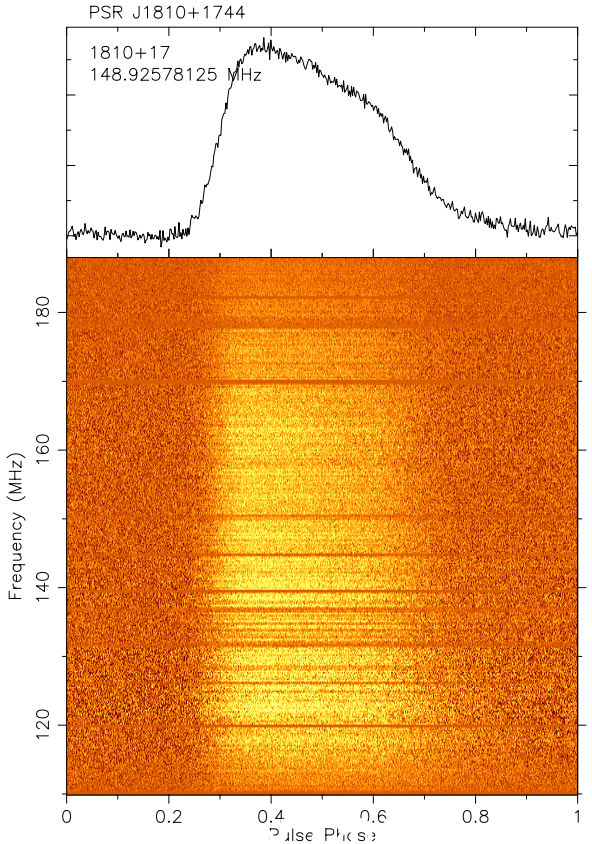
DM law works to 1/100,000

Probing the ISM

See also talks by Tan & Bassa

Cyclic Spectroscopy

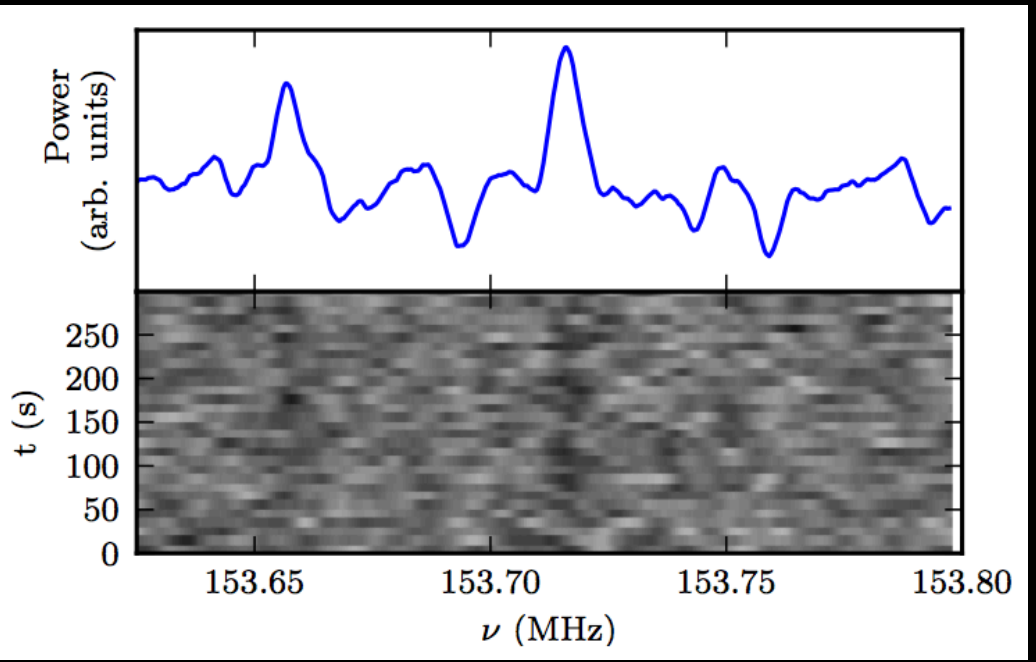




Horizontal bars indicate scattering time, τ, as inferred from the diffractive bandwidth, $\Delta\nu_{\rm d}$

Archibald et al. 2014

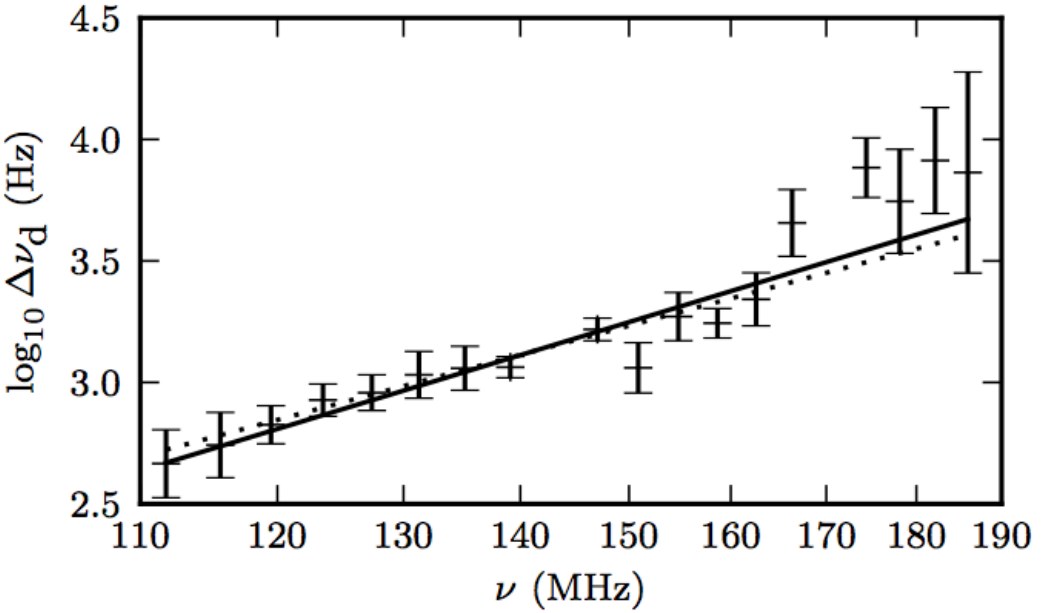
Cyclic Spectroscopy



200kHz

Example dynamic spectrum

Smoothed to ~2kHz resolution



Diffractive bandwidth vs. frequency

$$\Delta\nu_{\rm d} = \frac{1}{2\pi\tau}$$

Solid line: best-fit power-law

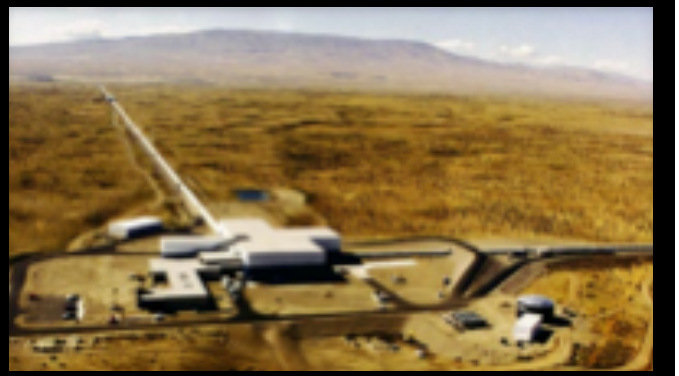
Dotted line: power-law of -4

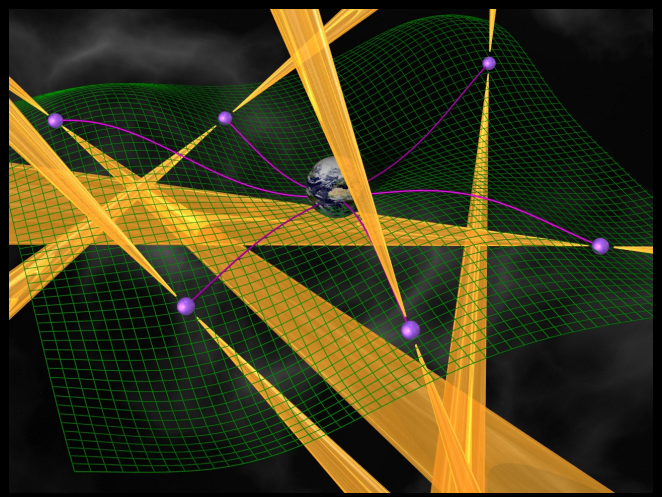
Probes scattering in a previously unreachable regime

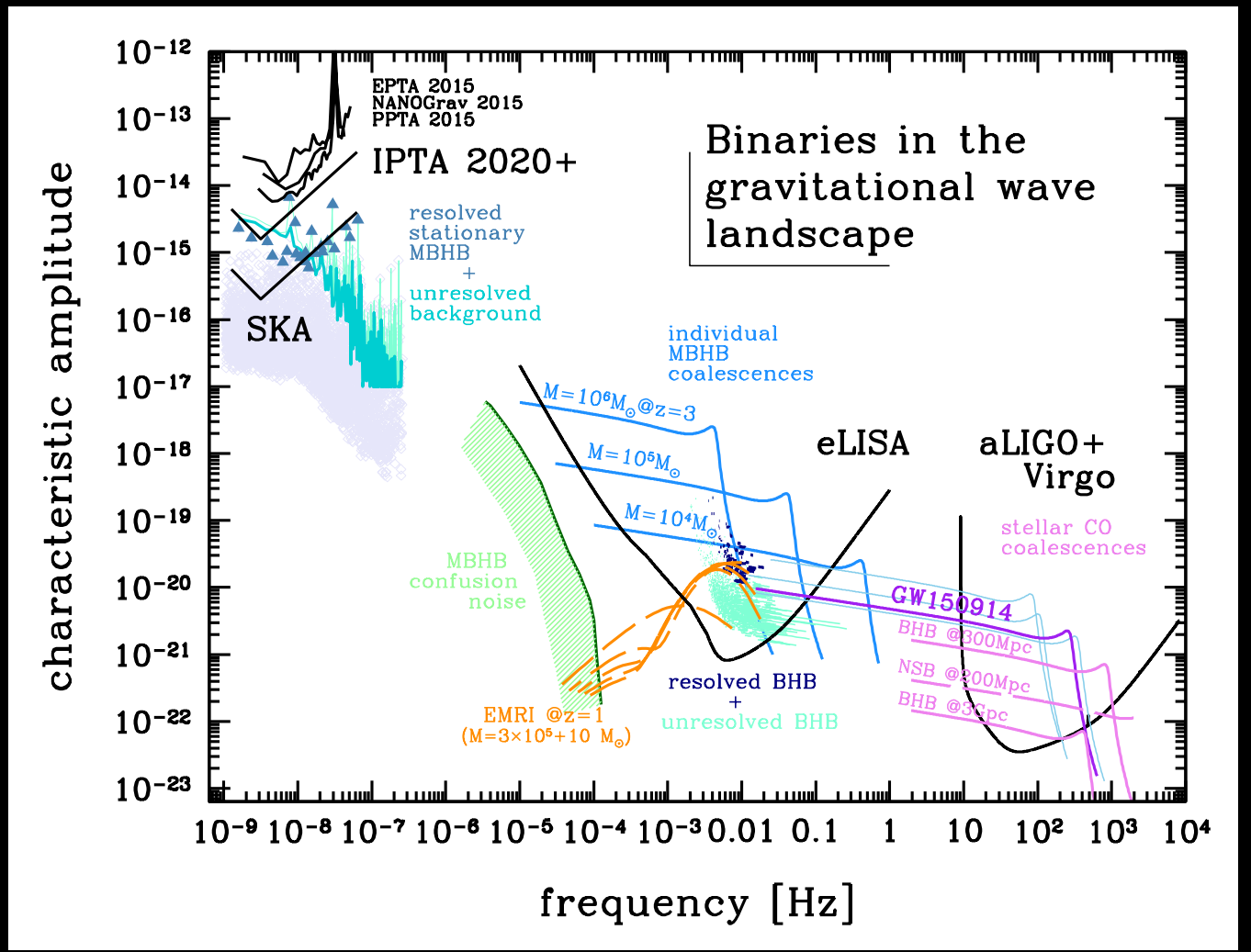
Archibald et al. 2014

Pulsar Timing Array

nanoHZ gravitational waves

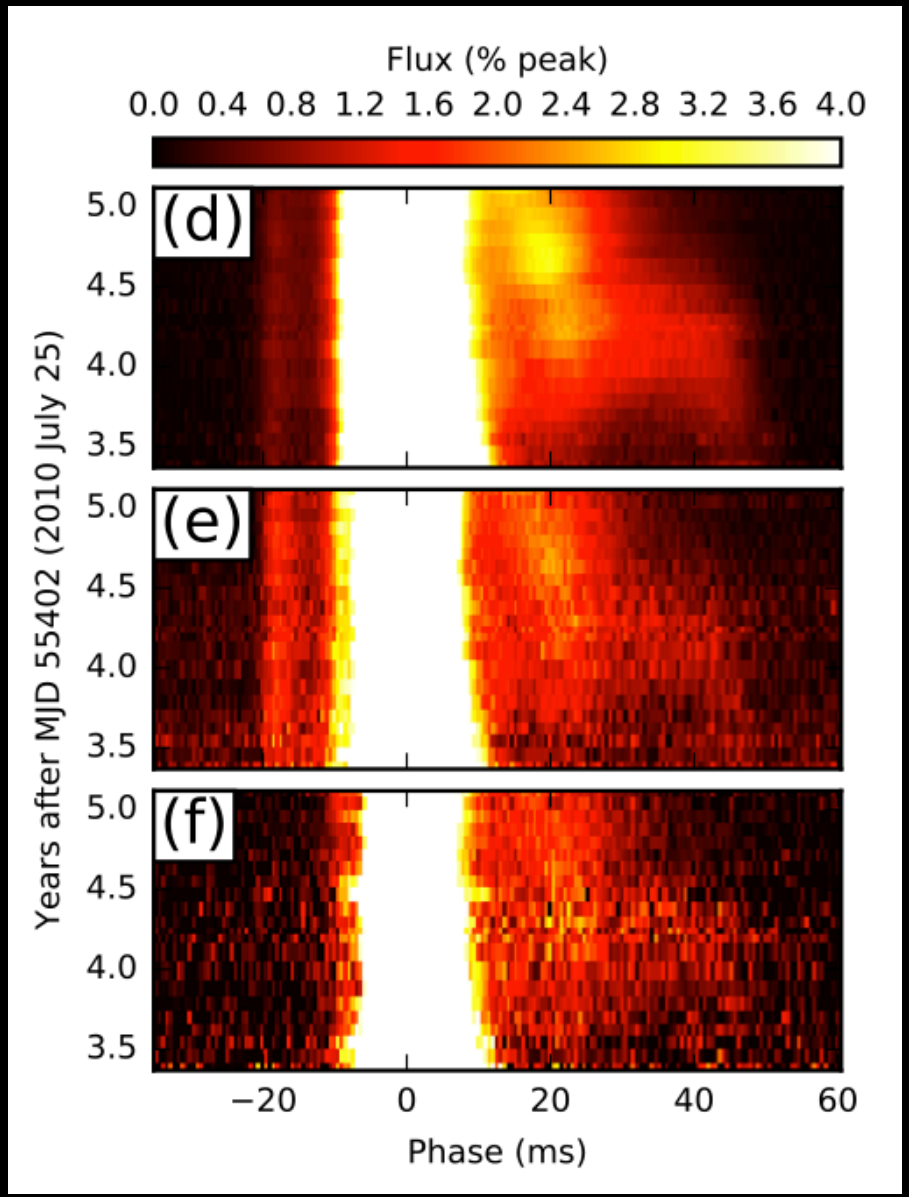






Sesana

Pulse echoes from the ISM



Michilli et al., in prep.

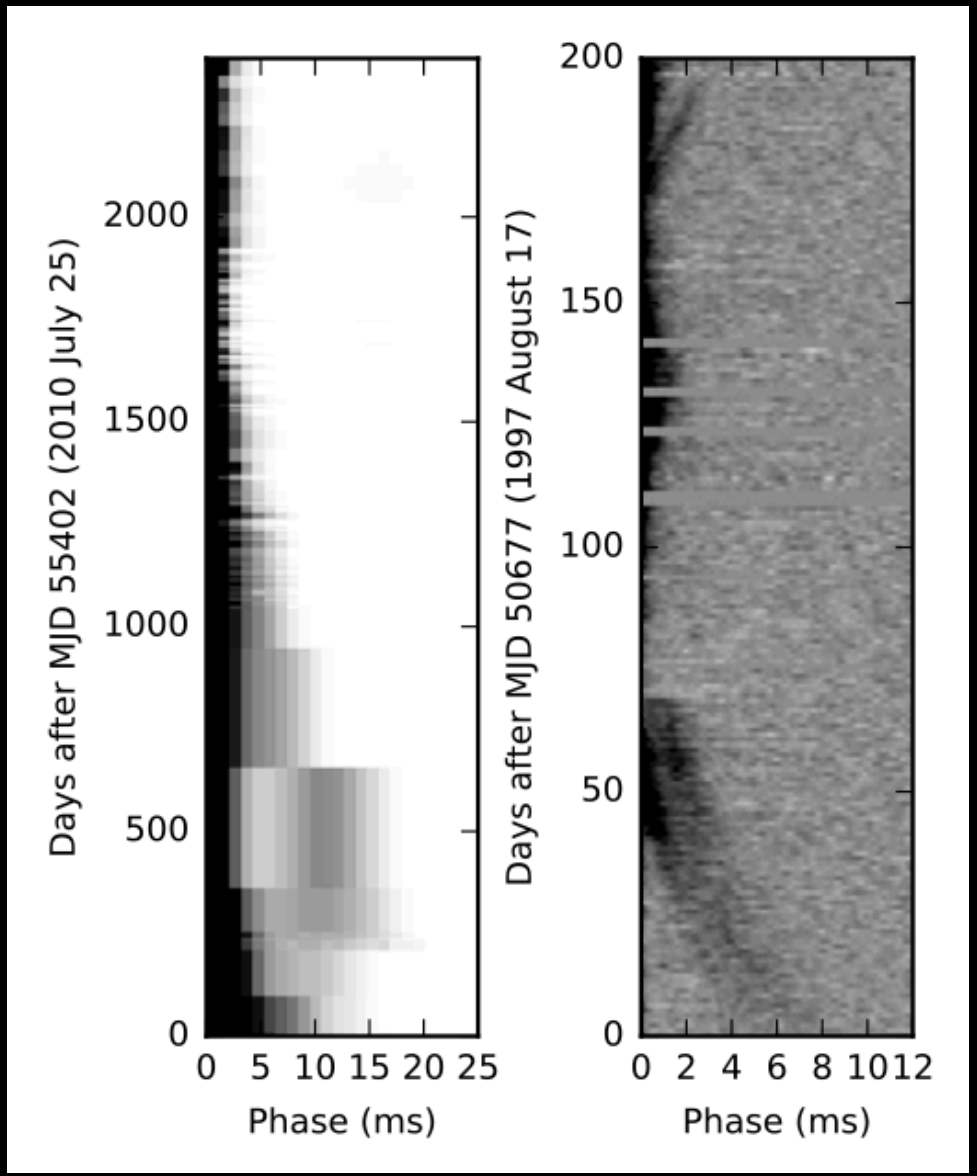
PSR B2217+27

Echoes are from refraction by structures in the ISM.

Nature of structure is still debated.

Also seen in PSR B1508+55.

Pulse echoes from the ISM

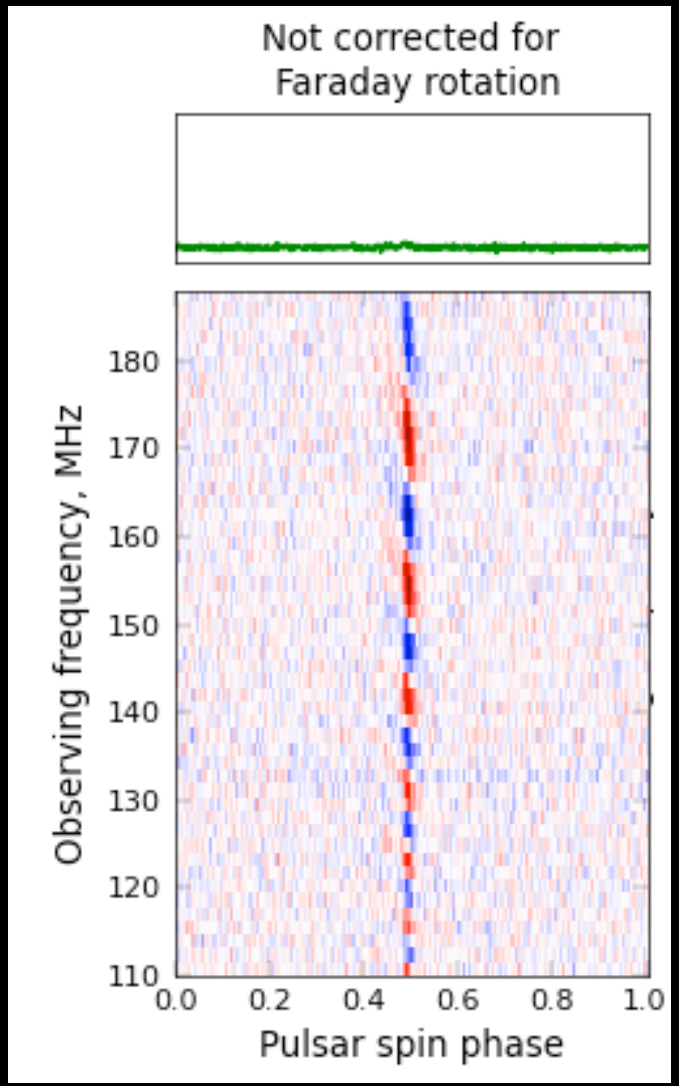


Michilli et al., in prep.

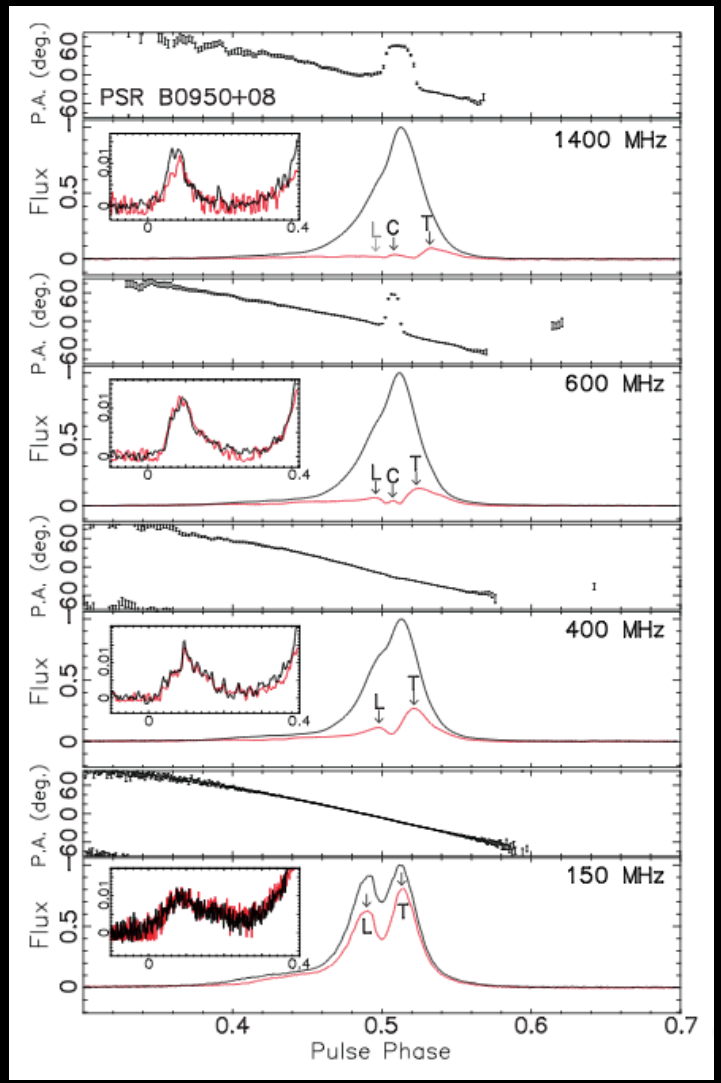
Similar phenomenon previously seen in the Crab Pulsar.

Origin: narrow filaments in the Crab Nebula.

Pulsar Polarimetry



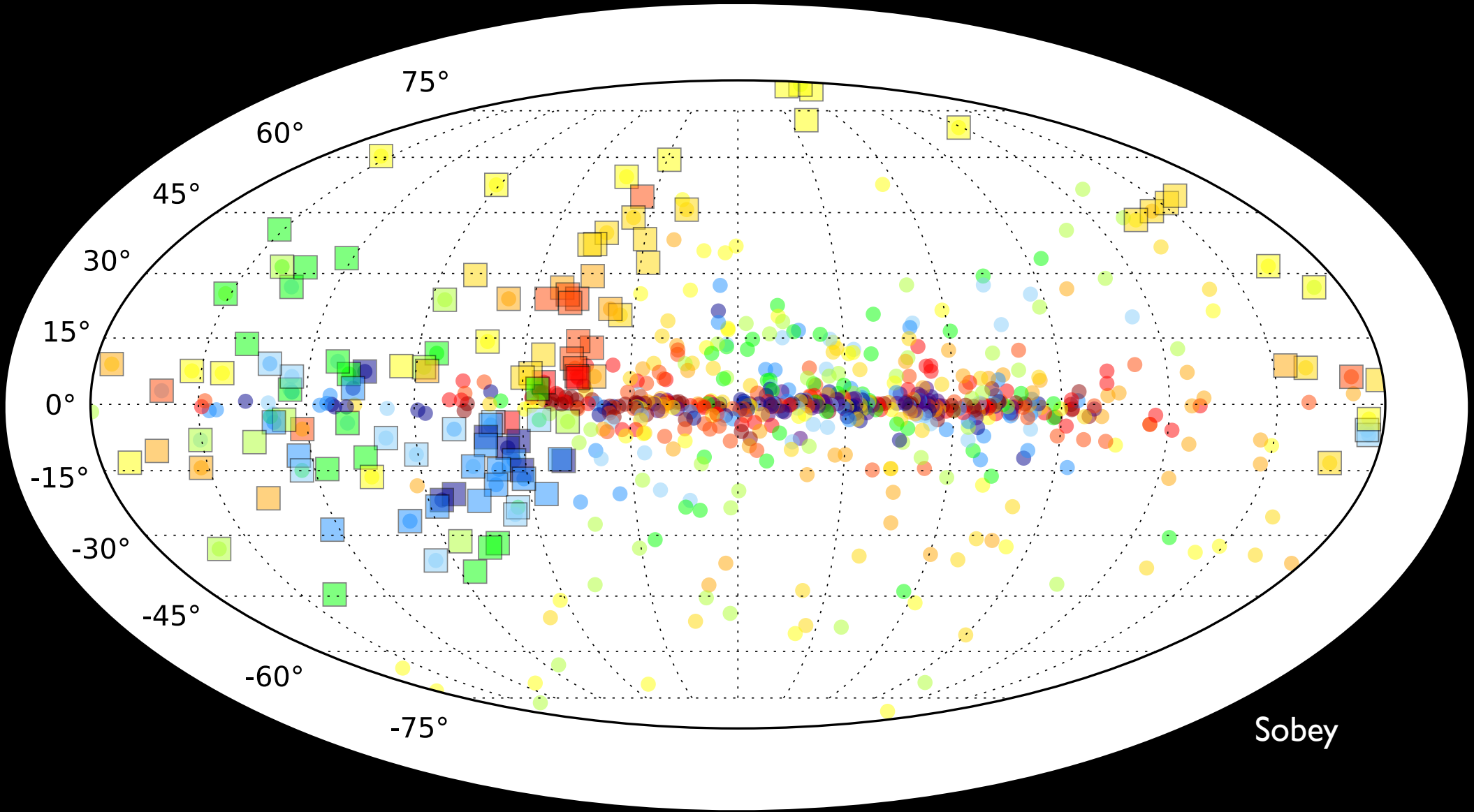
Bilous



Noutsos et al. 2015

LOFAR data

Pulsar RM Catalog



LOFAR RMs

ATNF catalog RMs

57 new RMs and 71 significantly more precise

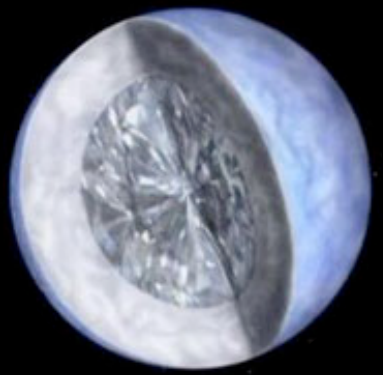
Pulsar Searches

See also talks by Tan & Bassa

Observing/Processing

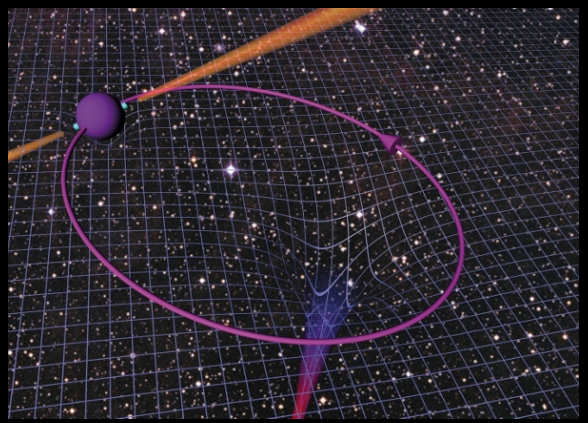
- Processing on Cartesius: 3hrs/pointing/24-core node.
- ~2PB of data collected and archived.
- Also started coherent dedispersion searches on DRAGNET GPU cluster.

Exotic Pulsar Systems



"Diamond Planet"

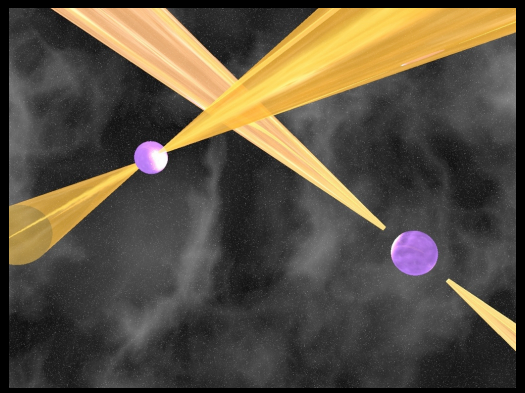
Bailes et al. 2012



PSR-BH

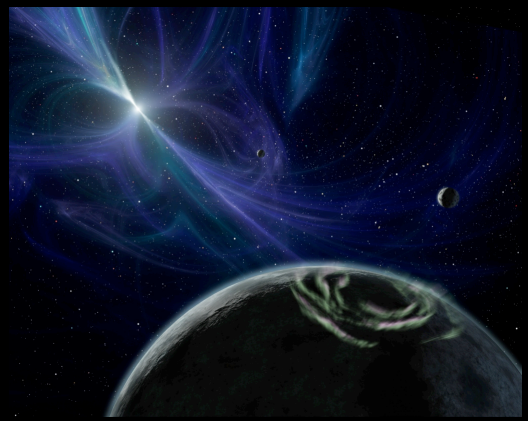
"The Holy Grail"

Someone et al. 20??



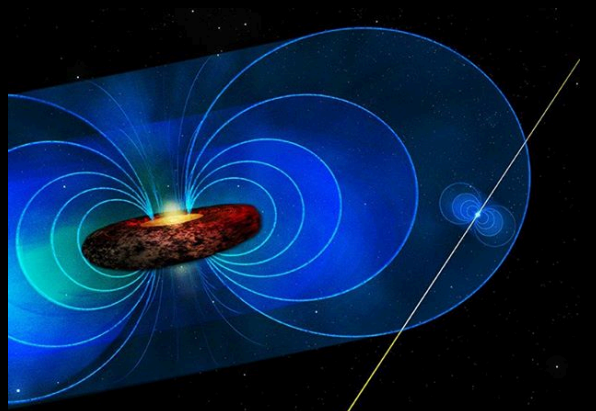
"Double Pulsar"

Lyne et al. 2004



First exoplanets

Wolszczan et al. 1992



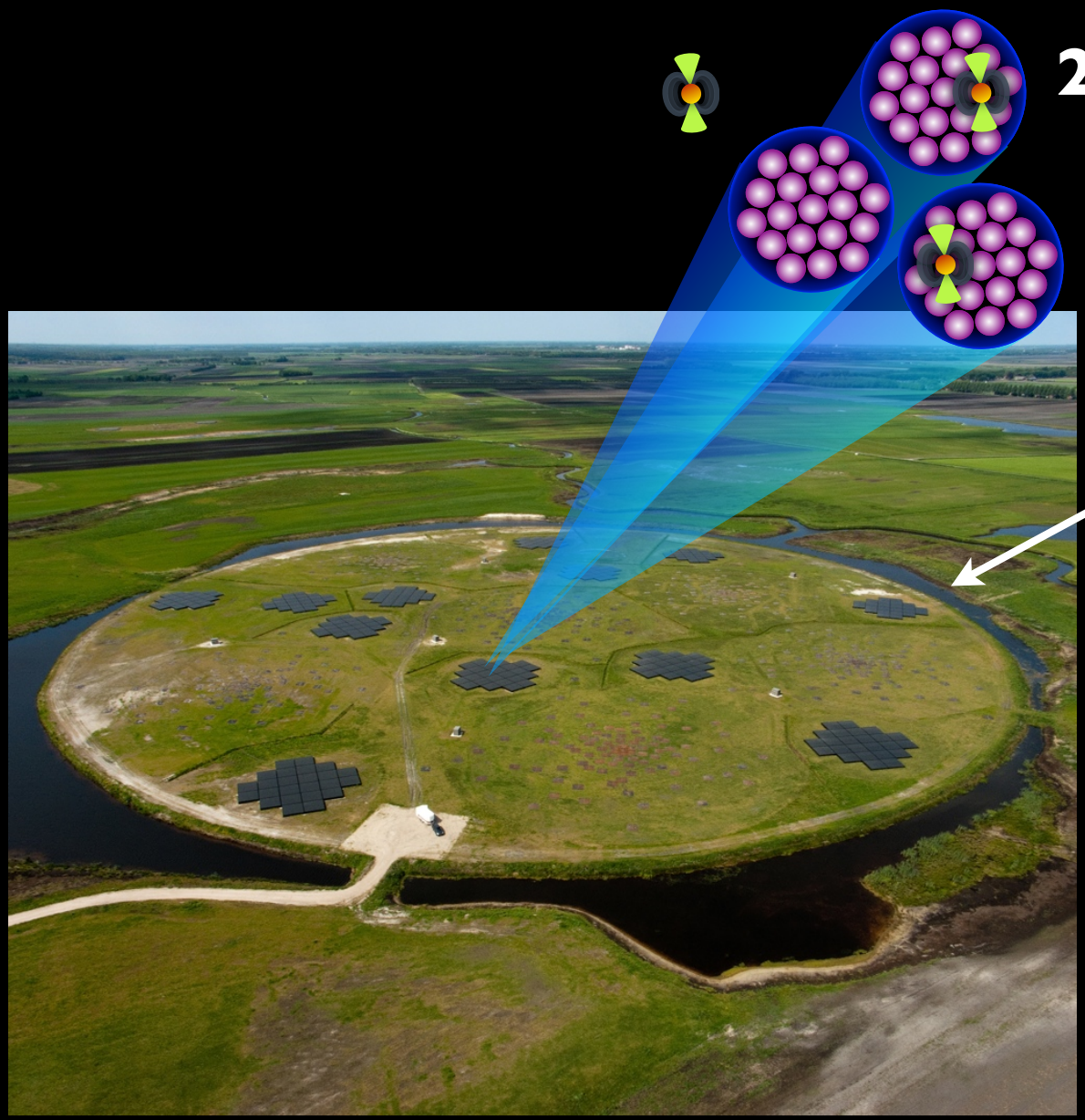
Galactic Center Magnetar

Eatough et al. 2013

LOTAAS

LOFAR Tied-Array All-Sky Survey

http://www.astron.nl/lotaas



219 coh. beams

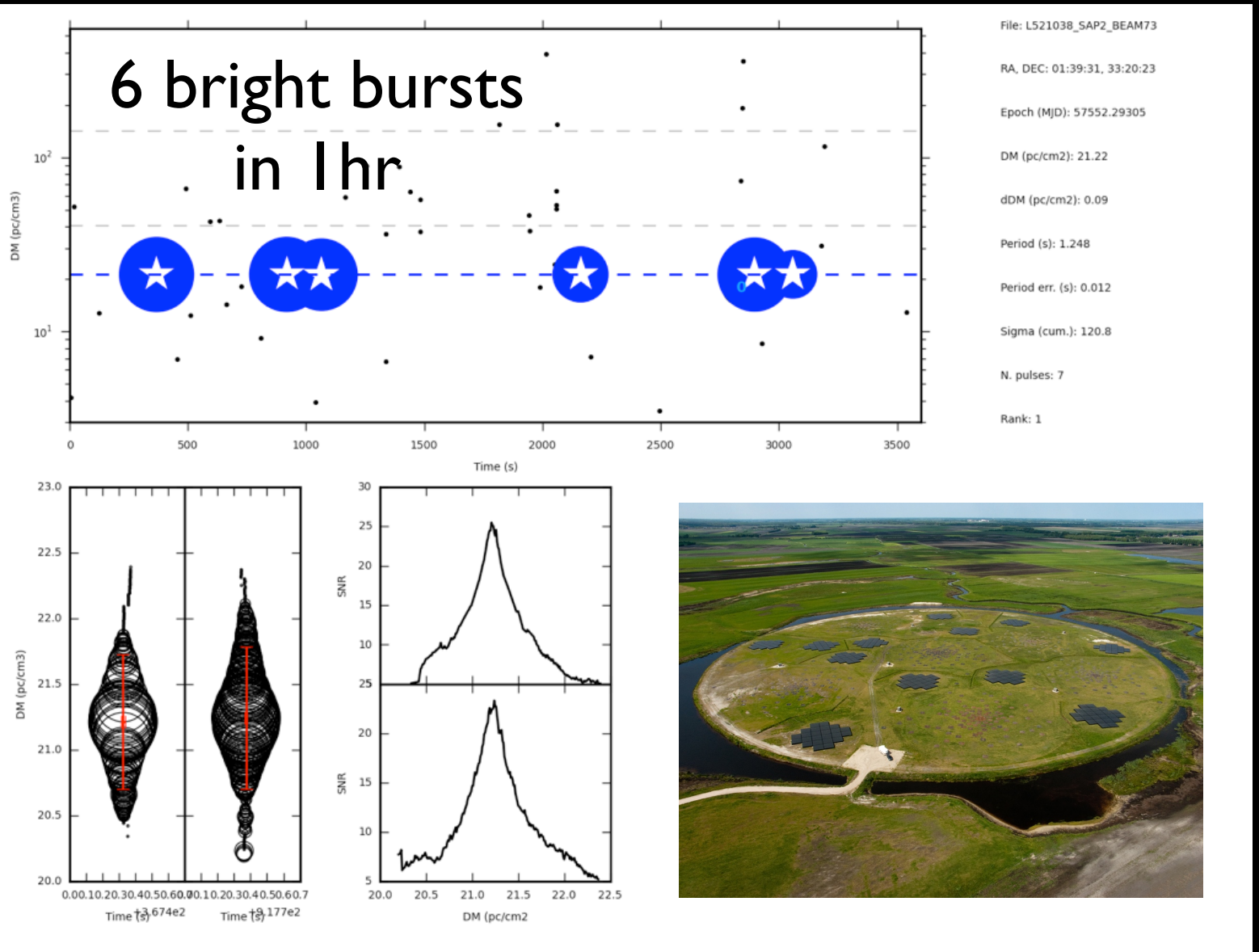
3 incoh. beams

LOFAR "Superterp" (innermost 12 HBA sub-stations)

LOTAAS Collaboration

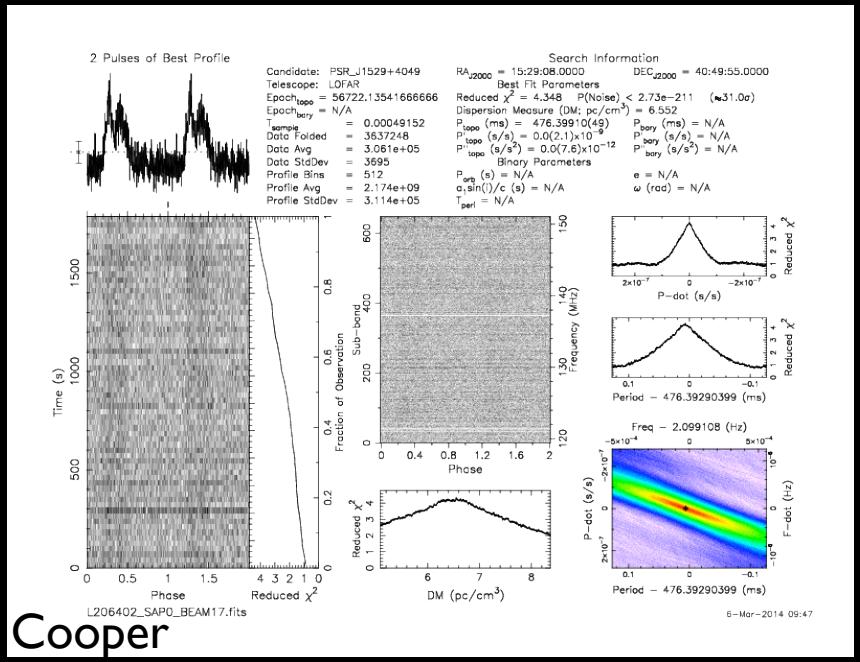
Jason Hessels, Sotiris Sanidas, Vlad Kondratiev, Sally Cooper, Daniele Michilli, Chia Min Tan, Cees Bassa, Ziggy Pleunis, Joeri van Leeuwen + LOFAR PWG

Find sporadic sources



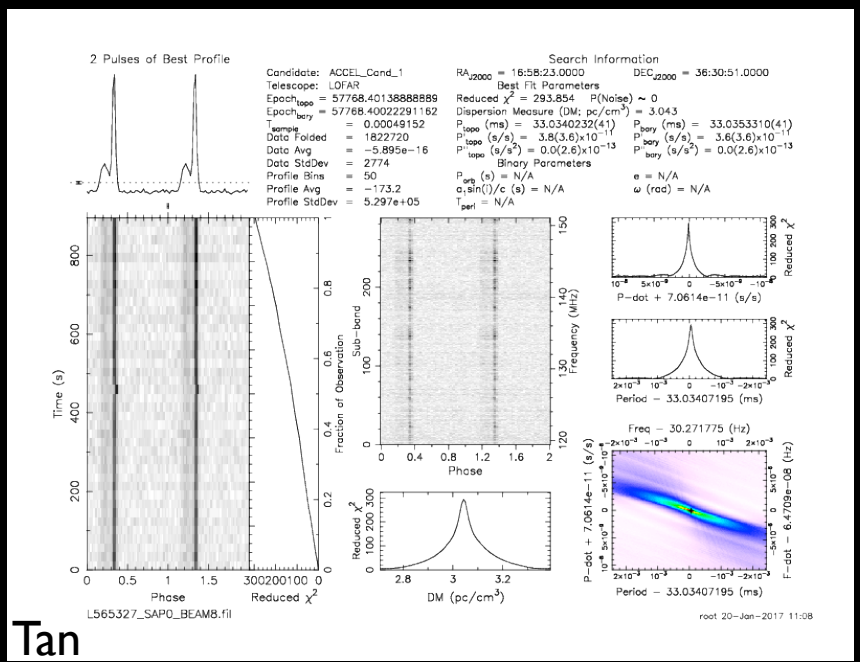
See poster by Michilli

Find low-lum nearby sources



Cooper

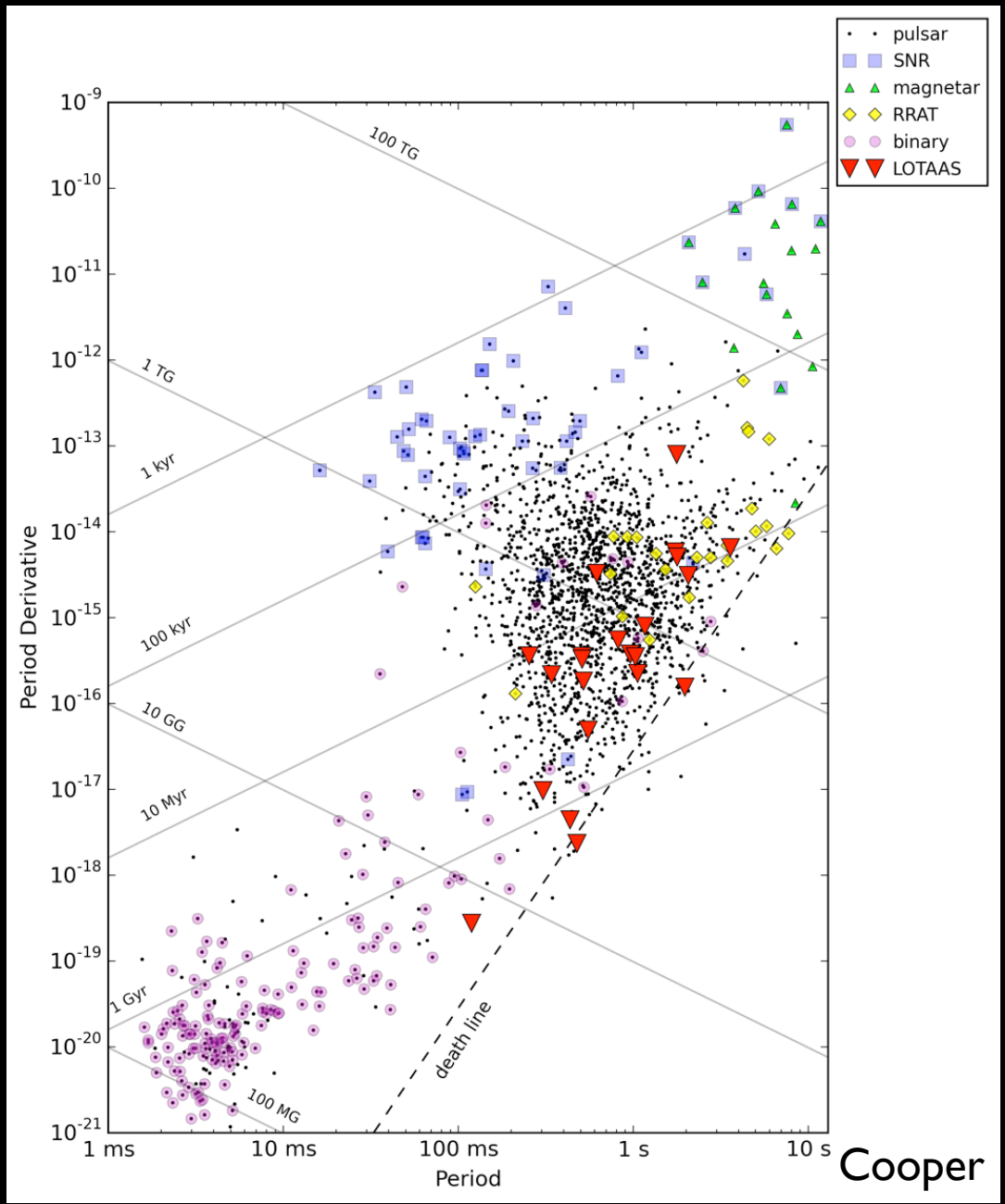
P = 476ms
DM = 6.5pc/cc
d ~ 0.5kpc



Tan

P = 33ms
DM = 3.0pc/cc
d ~ 0.1kpc

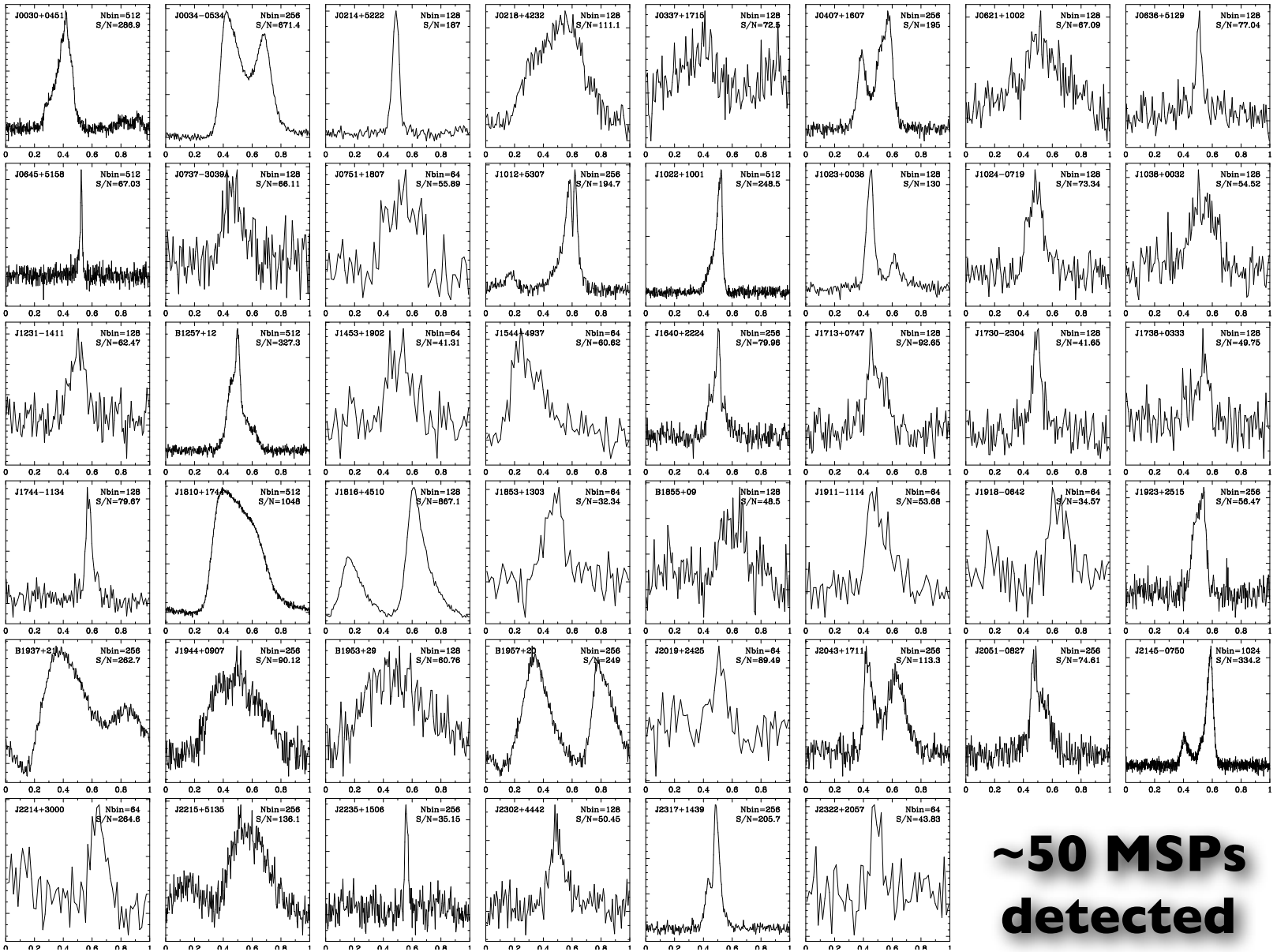
A complementary population



Millisecond pulsars

See also talks by Polzin & Bassa

Millisecond Pulsars



~50 MSPs detected

The premier low-frequency sample

Kondratiev et al. 2016

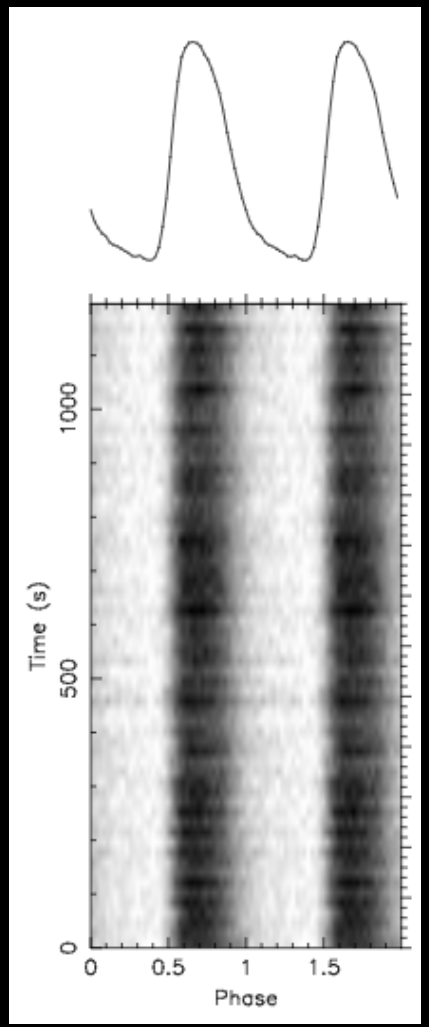
Find millisecond pulsars

Many of the fastest-spinning MSPs have ultra-steep spectra

J1810+1744 - 1.66ms

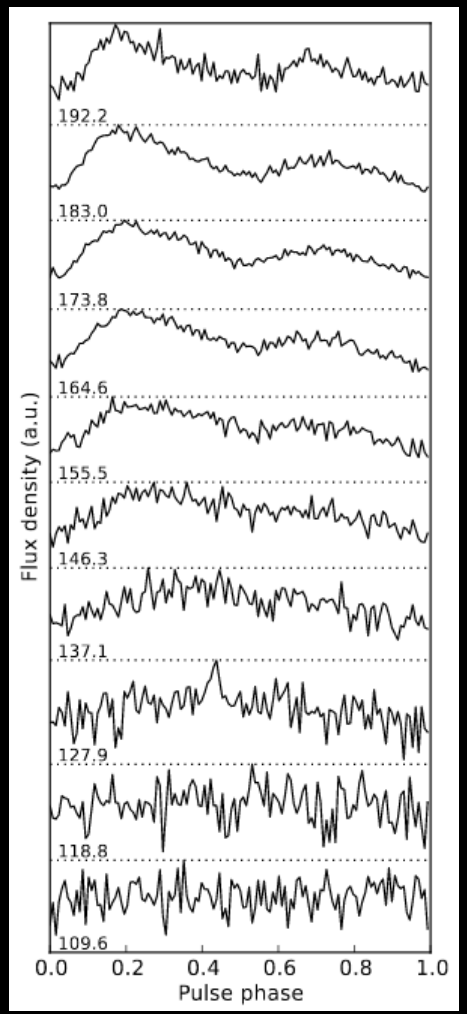
B1937+21 - 1.56ms

0.5Jy at 135MHz!
α ~ -2.6



Bassa et al. 2016

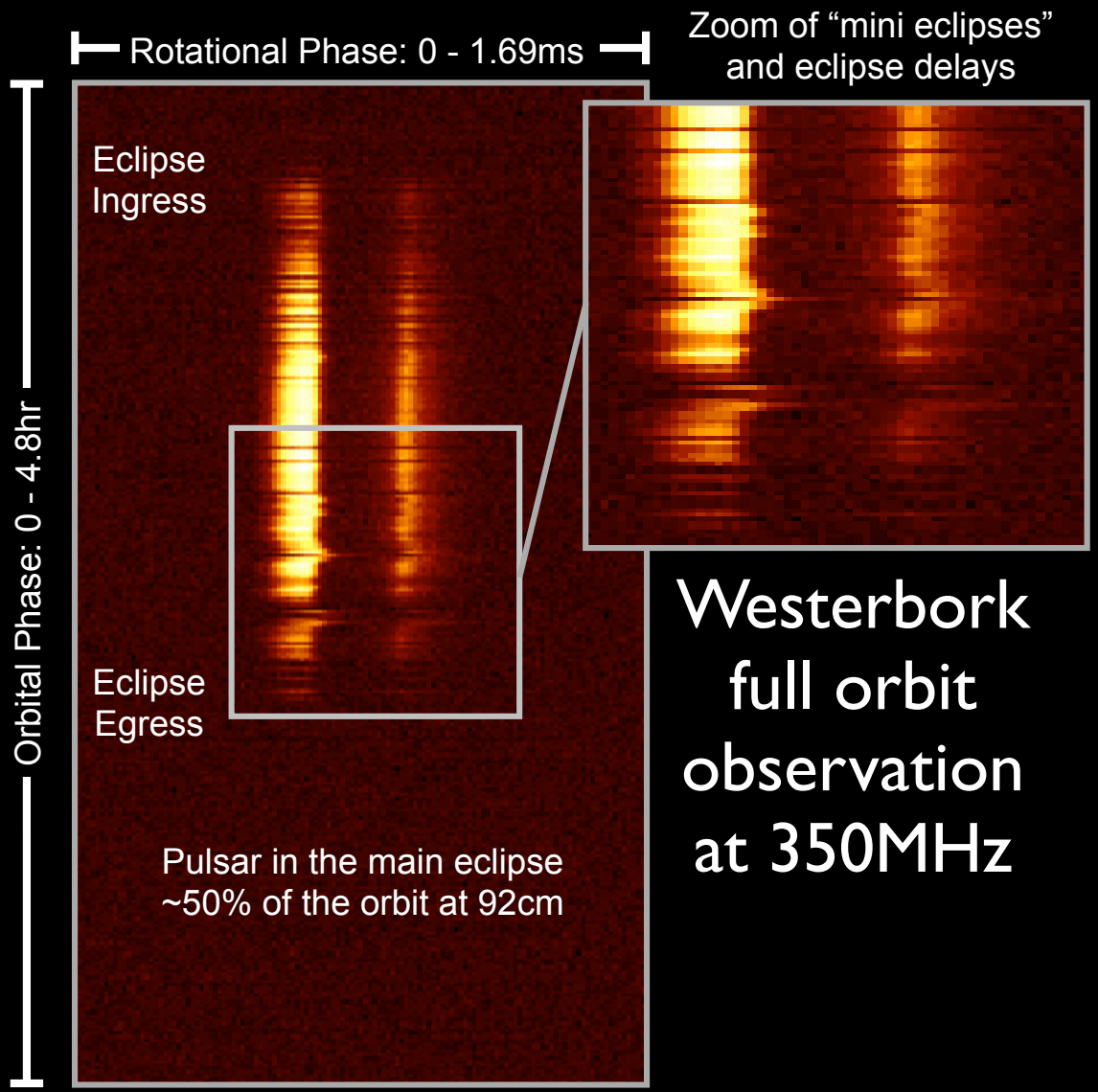
Frequency



Kondratiev et al. 2016

Scattered out for LOFAR
α ~ -2.6

Eclipsing pulsars



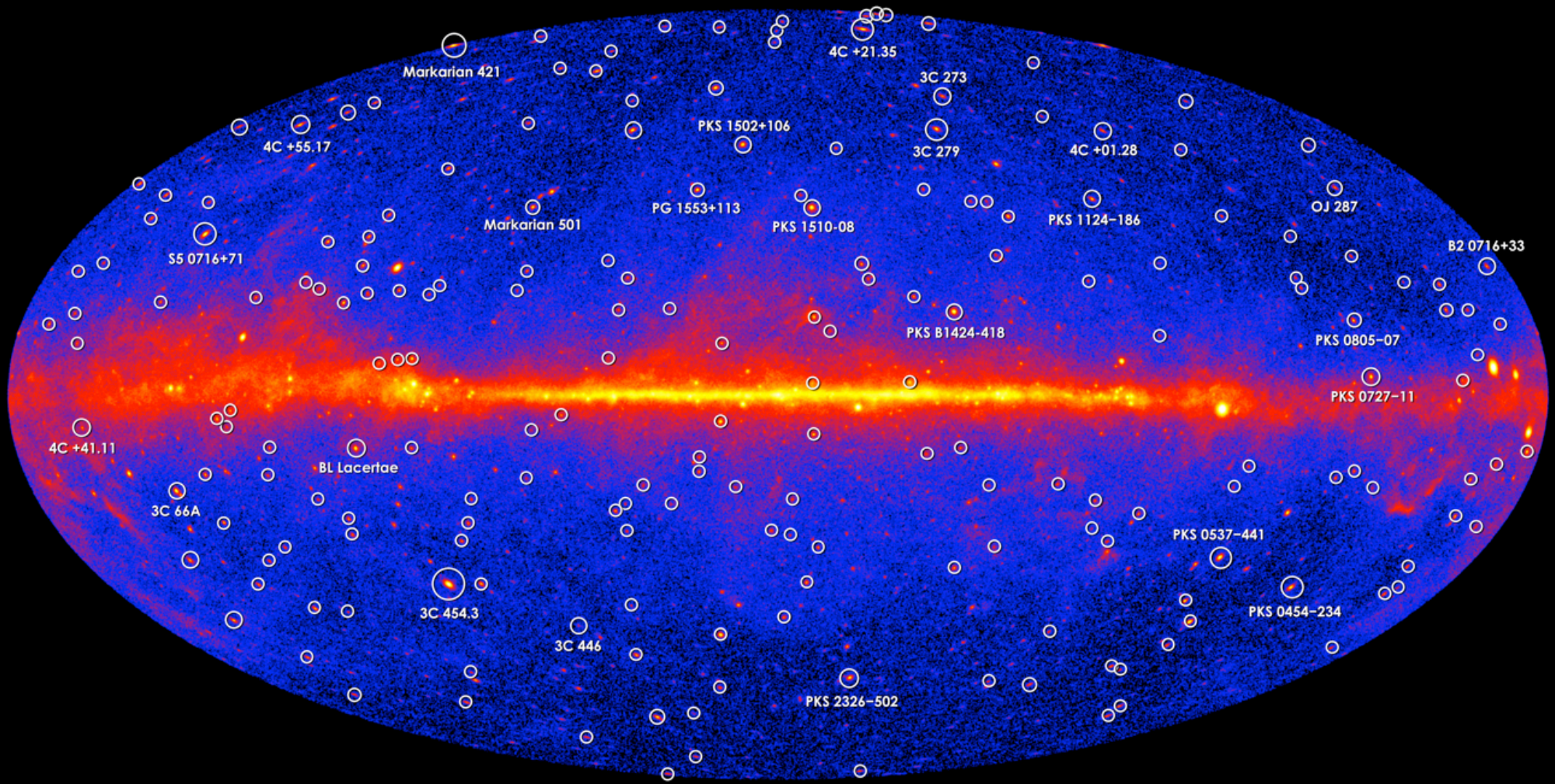
Westerbork full orbit observation at 350MHz

Hessels; Archibald et al. 2013

See also talk by Polzin

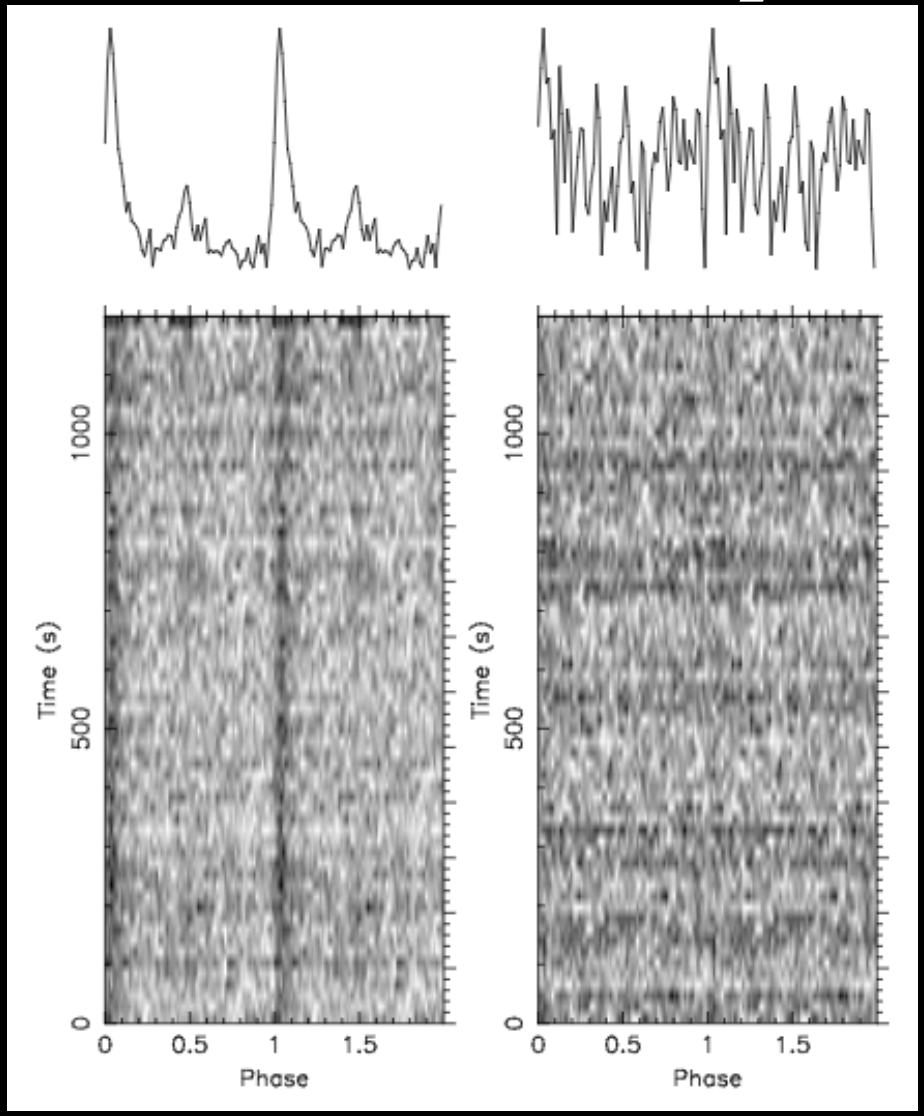
Fermi

Gamma-Ray Space Telescope



First LOFAR Millisecond Pulsar Discovery

~2mJy at 135MHz
$\alpha \sim< -2.6$



With coherent dedispersion

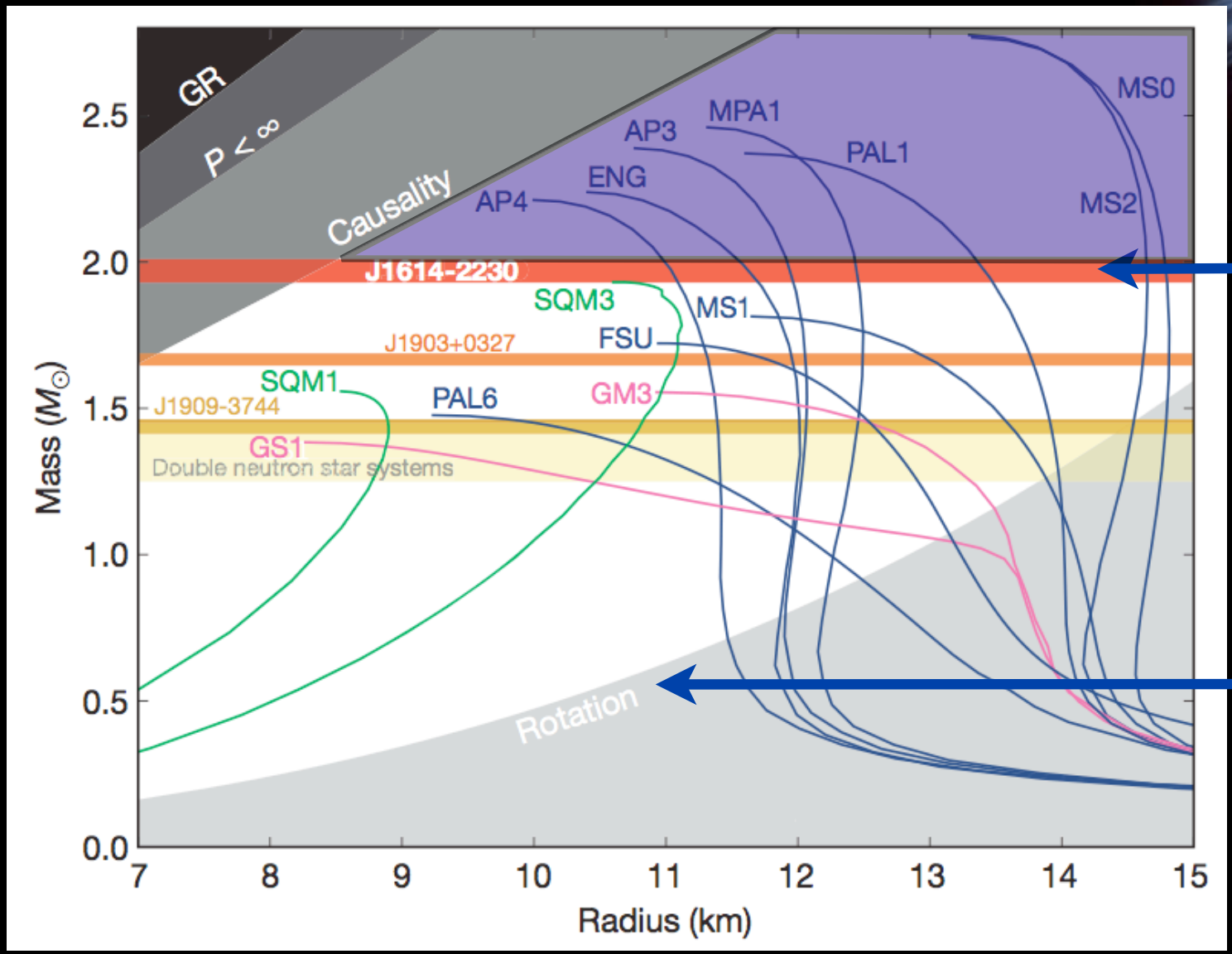
Without coherent dedispersion

First pulsar found < 200MHz

Pleunis et al., submitted

Ultra-dense matter

Neutron star equation-of-state



2MSun Pulsar

Demorest et al. 2010

716Hz Pulsar

Hessels et al. 2006

Summary

Low-frequency radio pulsar observations:

- Probe pulsar magnetospheres.
- Probe the interstellar medium.
- Find pulsars, especially millisecond pulsars, missed at higher frequencies.