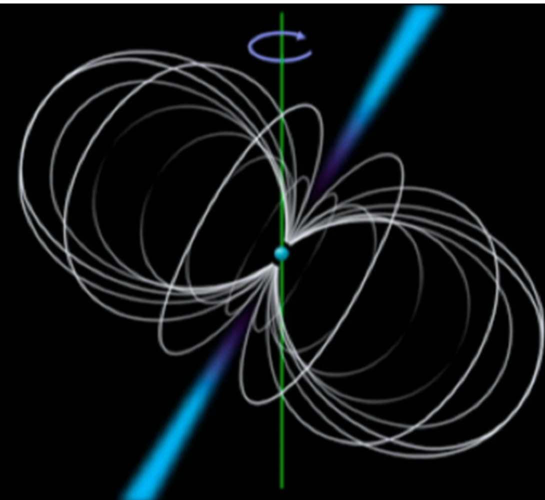
Title: The Hunt for Radio Pulsars and Fast Radio Bursts

Date: Feb 03, 2016 02:00 PM

URL: http://pirsa.org/16020100

Abstract: <p>Radio pulsars are Nature's most perfect clock and hence are useful for precision work on a wide variety of physical and astrophysical topics, ranging from sensitive tests of relativistic gravity to constraining the equation of state of ultradense matter. I will describe current ongoing surveys for radio pulsars using the two largest radio telescopes in the world, and how these surveys are also valuable for searching for Fast Radio Bursts, a newly recognized astrophysical phenomenon of unknown origin. </p>



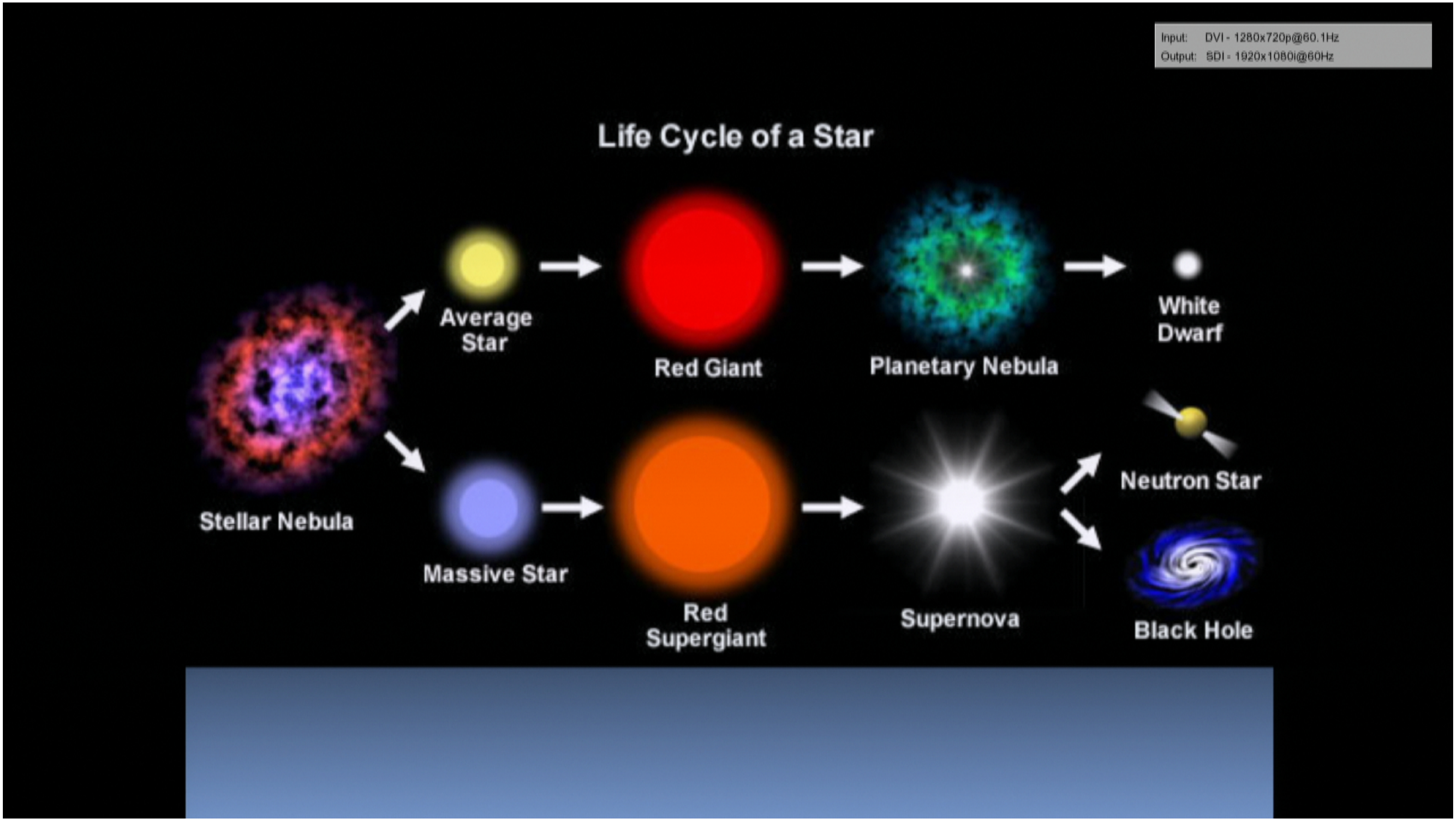
Pulsar and fast transient searches of the radio sky

Perimeter Institute Feb 3, 2016

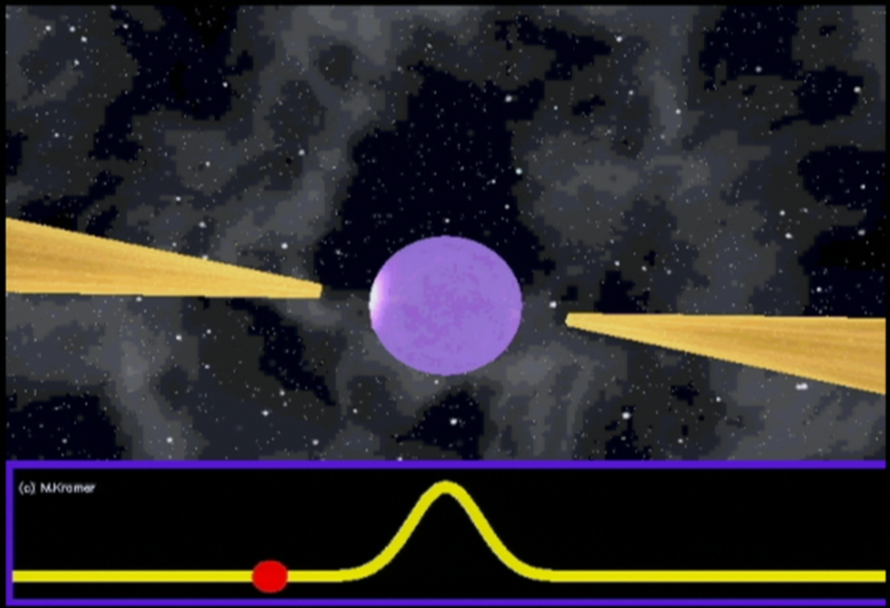
Vicky Kaspi, Dept of Physics & McGill Space Institute, McGill University

Overview of Talk

- Radio pulsar primer
- Why search for more pulsars?
- How to find pulsars
- Current pulsar surveys PALFA, GBNCC
- Discovery highlights:
  - PSR J1903+0327 (Champion et al. Science 2009; Freire et al. 2011)
  - PSR J1023+0038 (Archibald et al. Science 2009; Archibald et al. 2014)
  - PSR J0348+0432 (Antoniadis et al. Science 2013)
  - Fast Radio Burst +
- CHIME

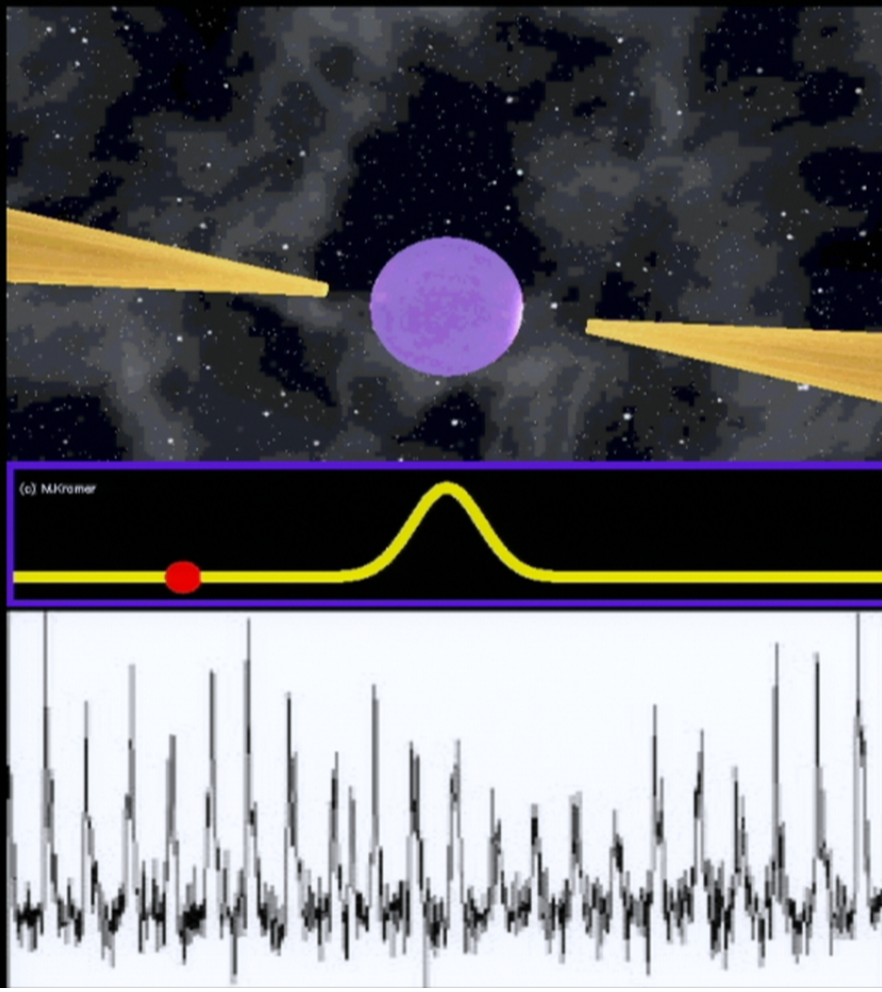

Input: DVI - 1280x720p@60.1Hz
Output: SDI - 1920x1080i@60Hz
Life Cycle of a Star
Stellar Nebula
Average Star
Red Giant
Planetary Nebula
White Dwarf
Massive Star
Red Supergiant
Supernova
Neutron Star
Black Hole

Radio Pulsars



- Rapidly rotating, highly magnetized neutron stars
- Over 2400 known today, nearly all in Milky Way
- Emit across full EM spectrum
- Generally most easily observed in radio band
- Some highly sporadic: "Rotating Radio Transients" or RRATs

Radio Pulsars



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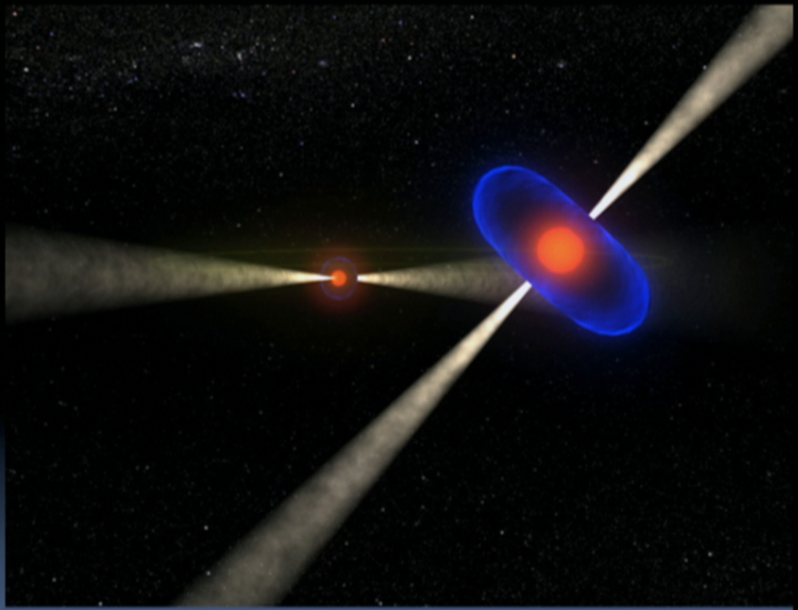
Basic Neutron Star Facts

- neutron star mass: **1.4 solar masses**
- typical neutron star radius: **10 km**
- Typical pulsar B field **$10^9 - 10^{13}$ G**
- Typical pulsar period **50 ms – 2 s**
- fastest known pulsar rotates **716 times per second!** **= millisecond pulsar**

Why So Interesting?

- Neutron stars embody **extremes:**
  - Gravity (z ~ 0.3)
  - Density (>10x nuclear)
  - Magnetic field
  - Dynamics
- ...yet **observable!**
- Physics dream come true!



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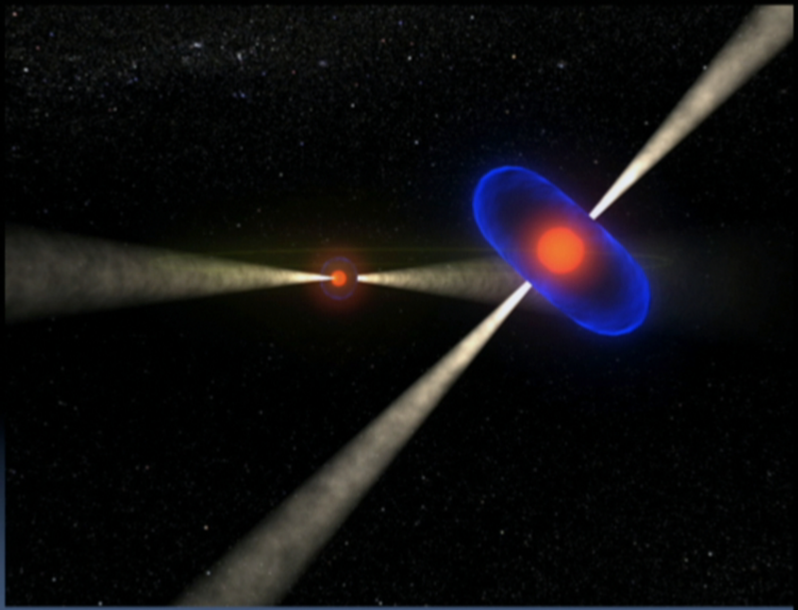

Pulsars: Extremes of Precision

PSR B1937+21 on MJD 47899.5:

P=0.001557806472448817(3)

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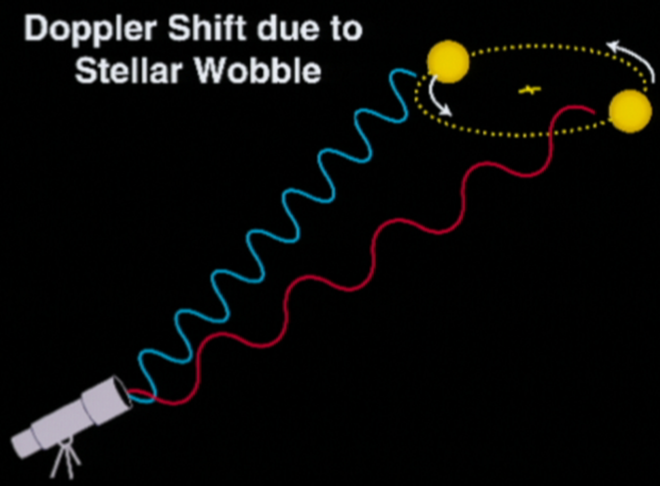
P=0.001557806472448817(3)

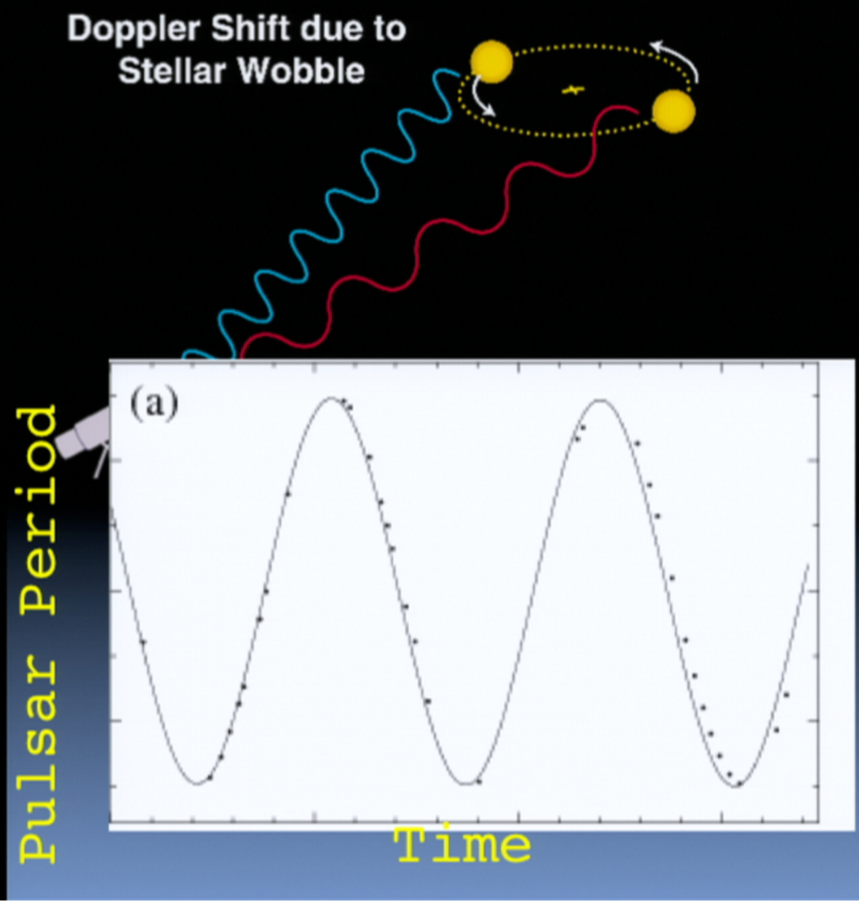
Pulsars as clocks can be comparable to the world's best atomic clocks!

Doppler Shift in Binary Stars



- Pulse period in binary system changes!
- Can study binary motion with *exquisite* precision
- Nobel-celebrated experiments in relativistic gravity

Doppler Shift in Binary Stars



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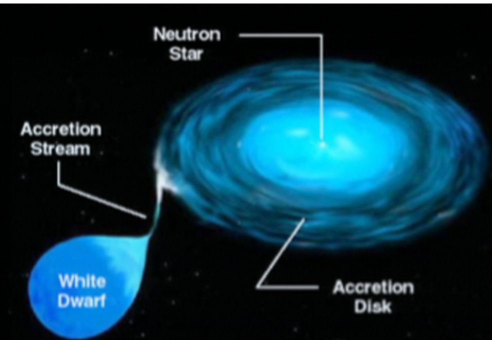
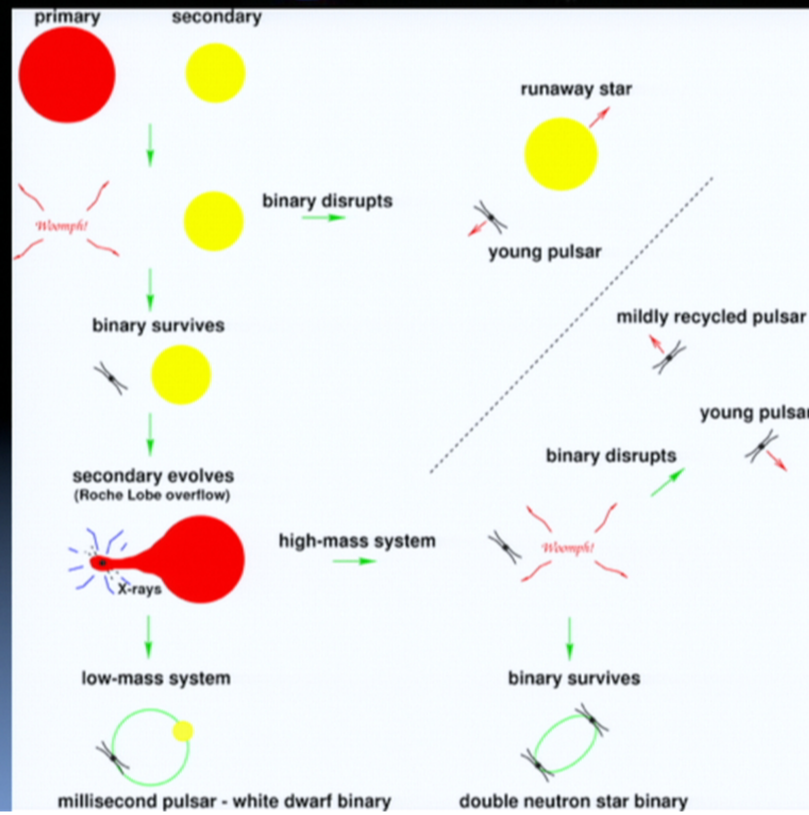
What makes an MSP?

- Regular pulsar “recycled” by mass transfer from a binary companion
- Old objects; once recycled, live forever
- Distributed ~isotropically on the sky, in circular binaries with degenerate companions
- Predicted evolutionary relationship between LMXBs and MSPs



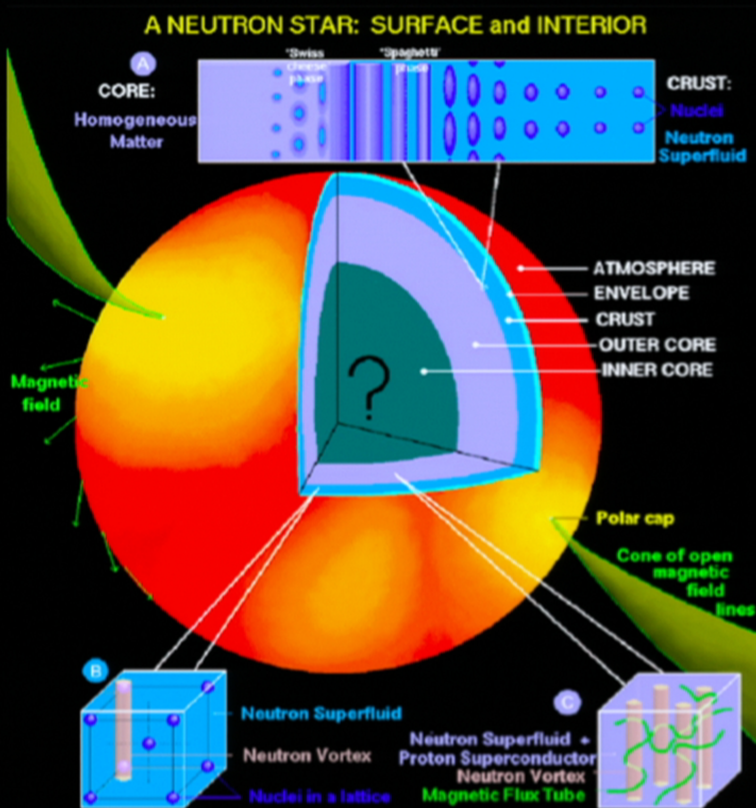


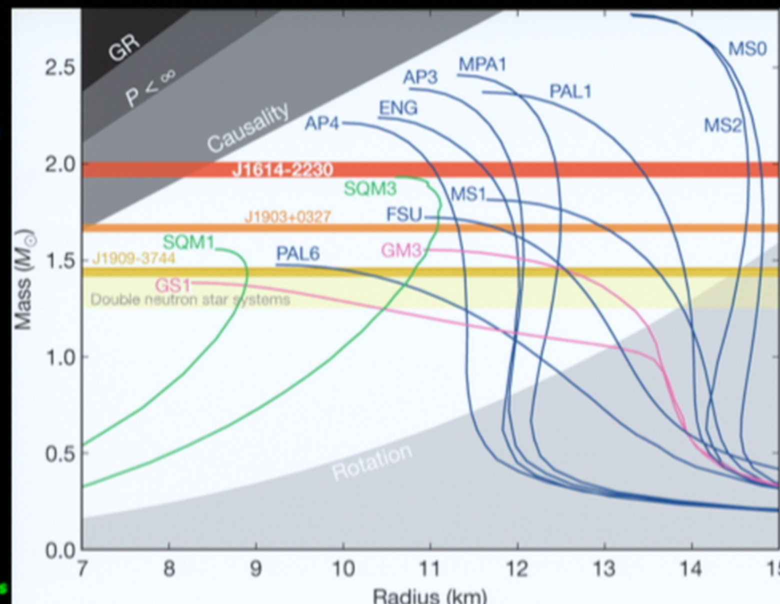
Lorimer 2005

Pulsars as Laboratories

- Equation-of-State of ultradense matter:
  - Maximum mass
  - Maximum rotation speed
- Tests of Relativistic Gravity Theories:
  - Famed dynamical tests via PK parameters
    - General Relativity, SEP, alternative theories e.g. TS
- Binary evolution:
  - Relation to HMXBs, LMXBs, qLMXBs
  - Branching ratios, stellar winds, eclipse mechanisms
- Connections between topics:
  - E.g. want pulsar/black hole binary for superb GR tests

Neutron Star Equation of State





Demorest et al. 2010

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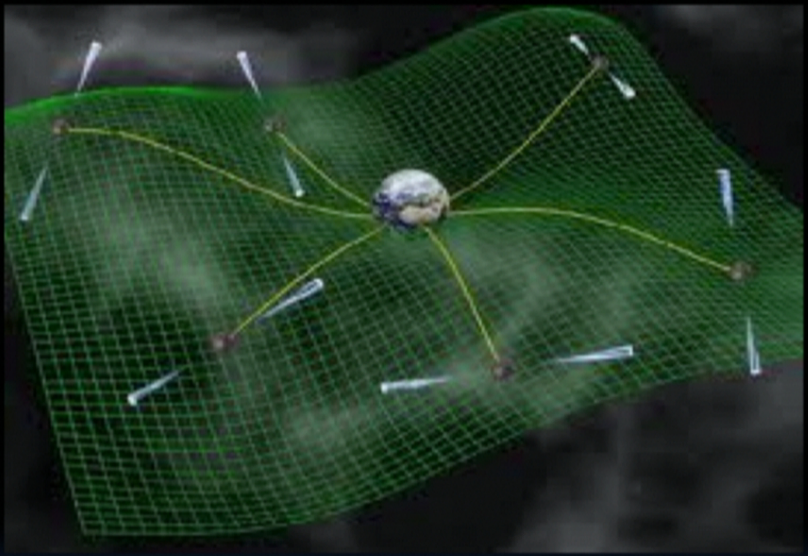
Pulsars as Laboratories II: GWs

- `Pulsar Timing Array' (PTA): detect gravitational waves with nanohertz frequencies using millisecond pulsars
- Need many MSPs distributed ~isotropically on the sky, timed with very high precision simultaneously over many years



Gravity Wave Sources for IPTA

- Merging supermassive black holes (SMBH), natural prediction of galaxy evolution
- Stochastic background with amplitude dependent on SMBH merger rate

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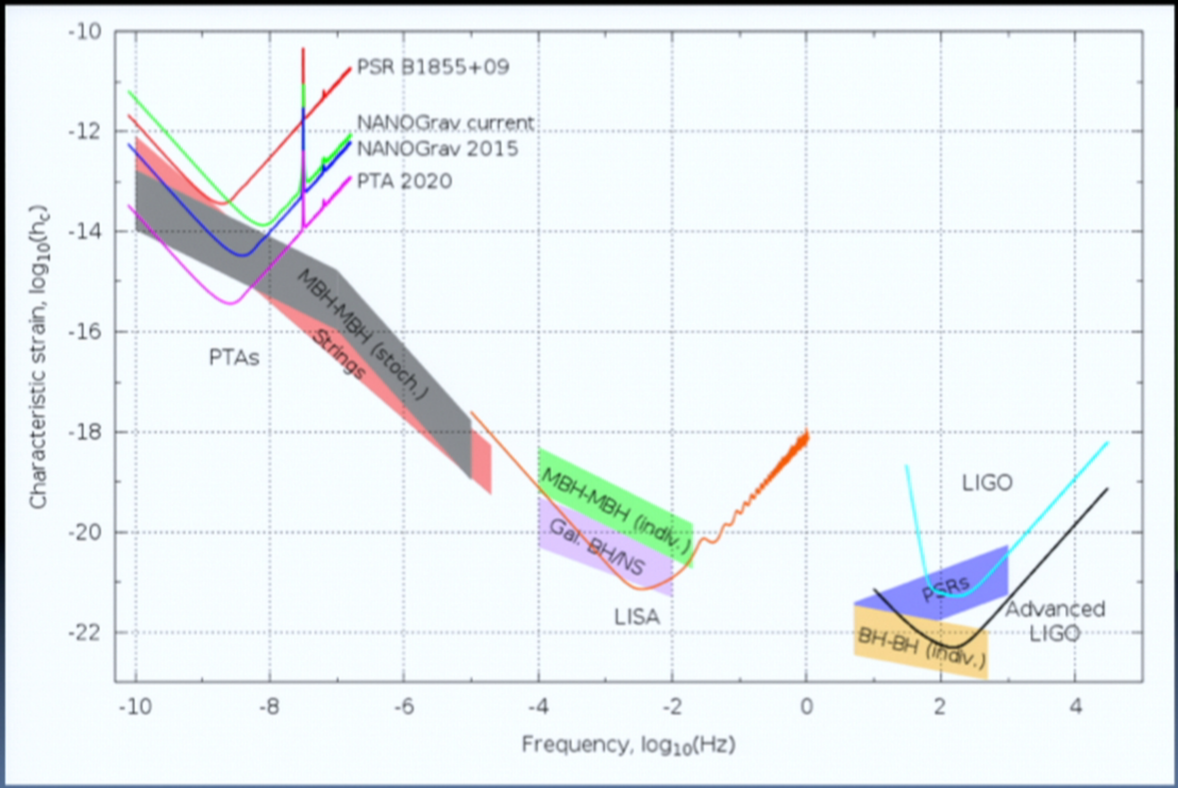
Complementarity of IPTA, aLIGO, LISA



Current upper limit:

$h < 7 \times 10^{-15}$ at 1 yr^{-1} 95% c.l.

(NANOGrav; Demorest et al. 2013)

Demorest 2009

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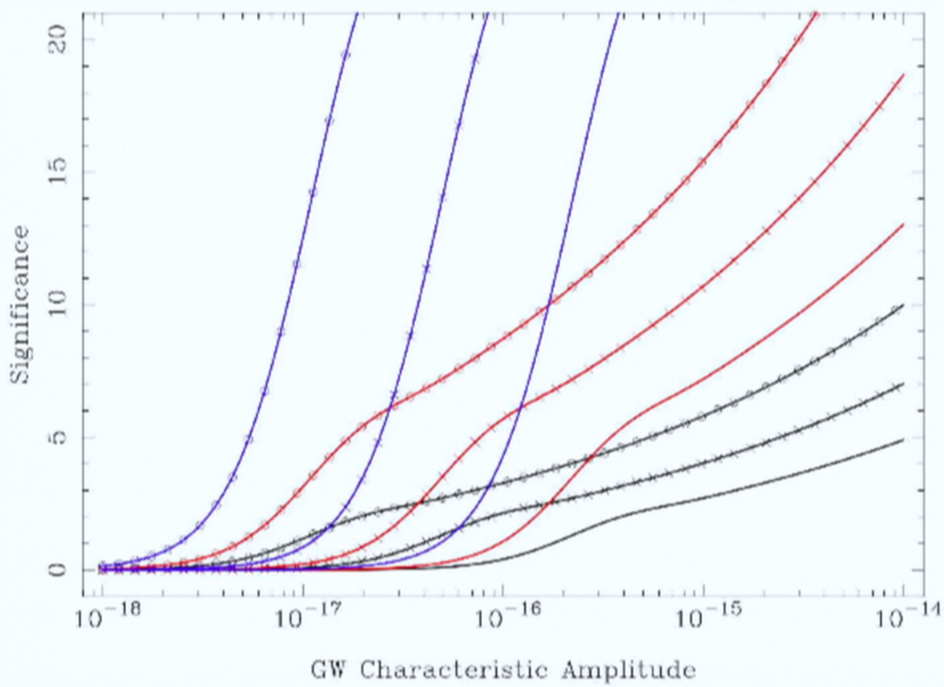
Why we want more MSPs!



Manchester et al. 2012

Figure 12: Sensitivity of a PTA to a stochastic background of GWs as a function of total data span $T_{\rm obs}$, number of pulsars N in the PTA and assumming 100 ns rms timing residuals. Black lines are for $N_{\rm psr} = 20$ and, $T_{\rm obs}$ of 5 yr (unmarked), 10 yr ($\times$) and 20 yr ($\circ$), respectively, red lines are similar for $N_{\rm psr} = 50$ and blue lines for $N_{\rm psr} = 200$.

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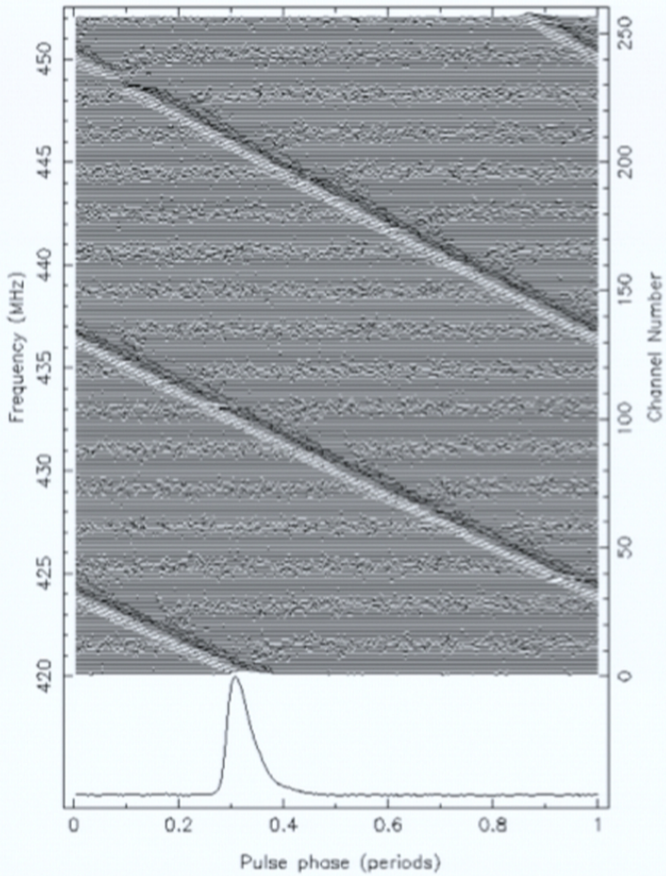
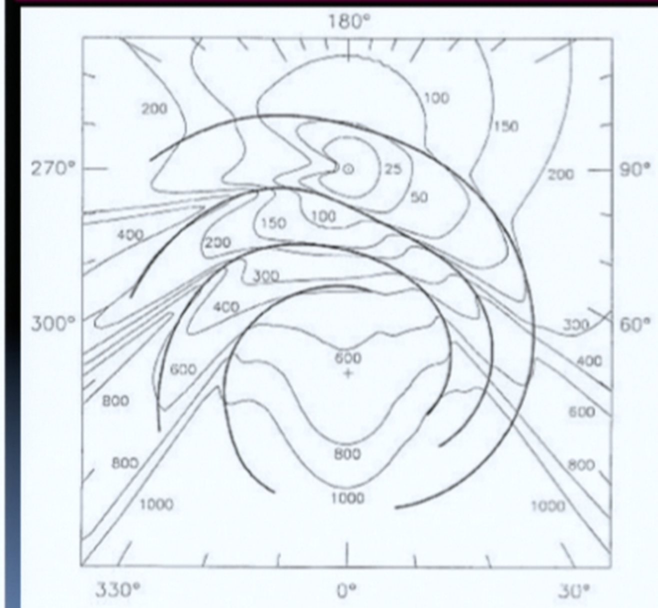
How Do We Find Pulsars?

- Define survey area
- Systematic pointings with big radio telescope
- For each pointing, record fast-sampled, frequency-channelized data for fixed integration time
- RFI removal
- Dedisperse at many trial dispersion measures
- For each trial DM:
  - FFT, acceleration search, harmonic summing, folding
  - Single pulse search

Dispersion of Radio Pulses



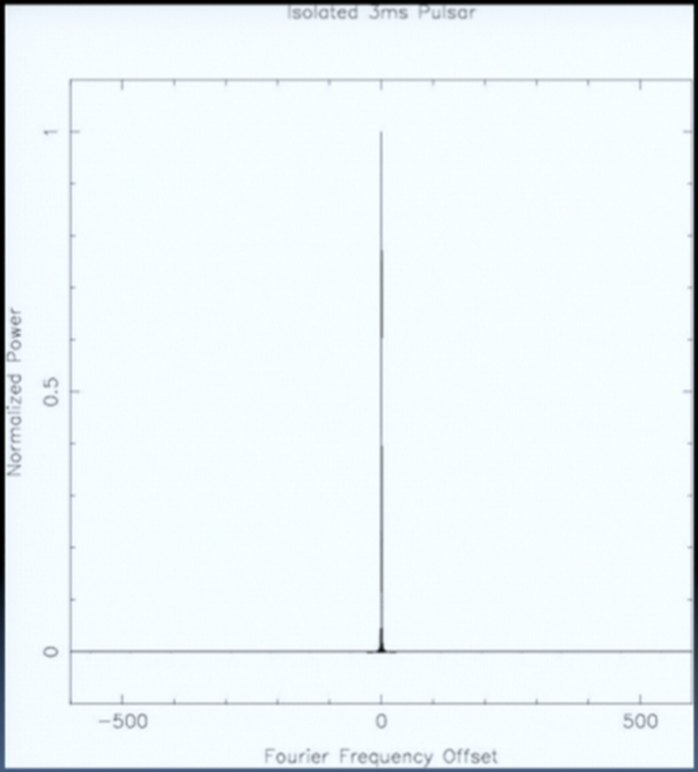
$$DM \propto \int n_e dl$$



Cordes & Lazio 2002

Binary Pulsar Search Techniques

- Isolated Pulsars
- Fourier analysis



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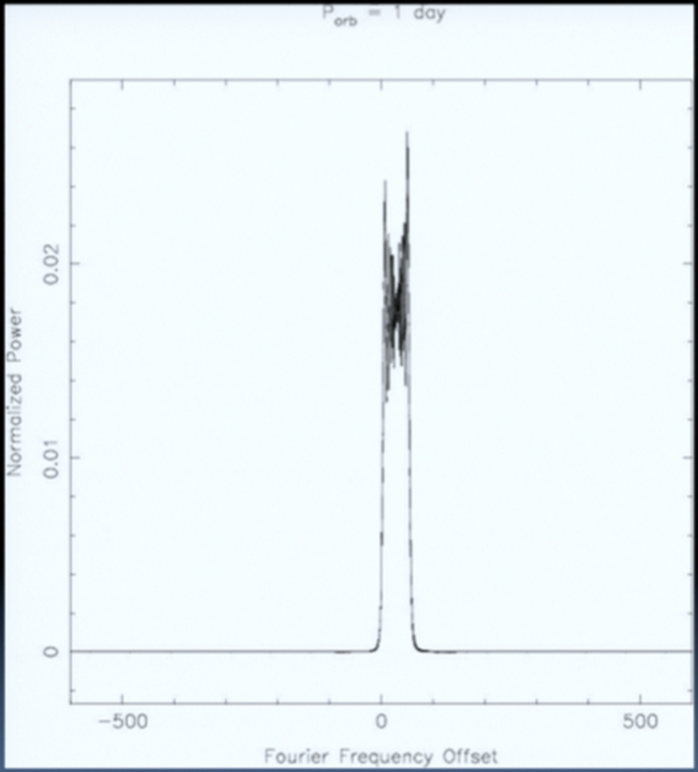
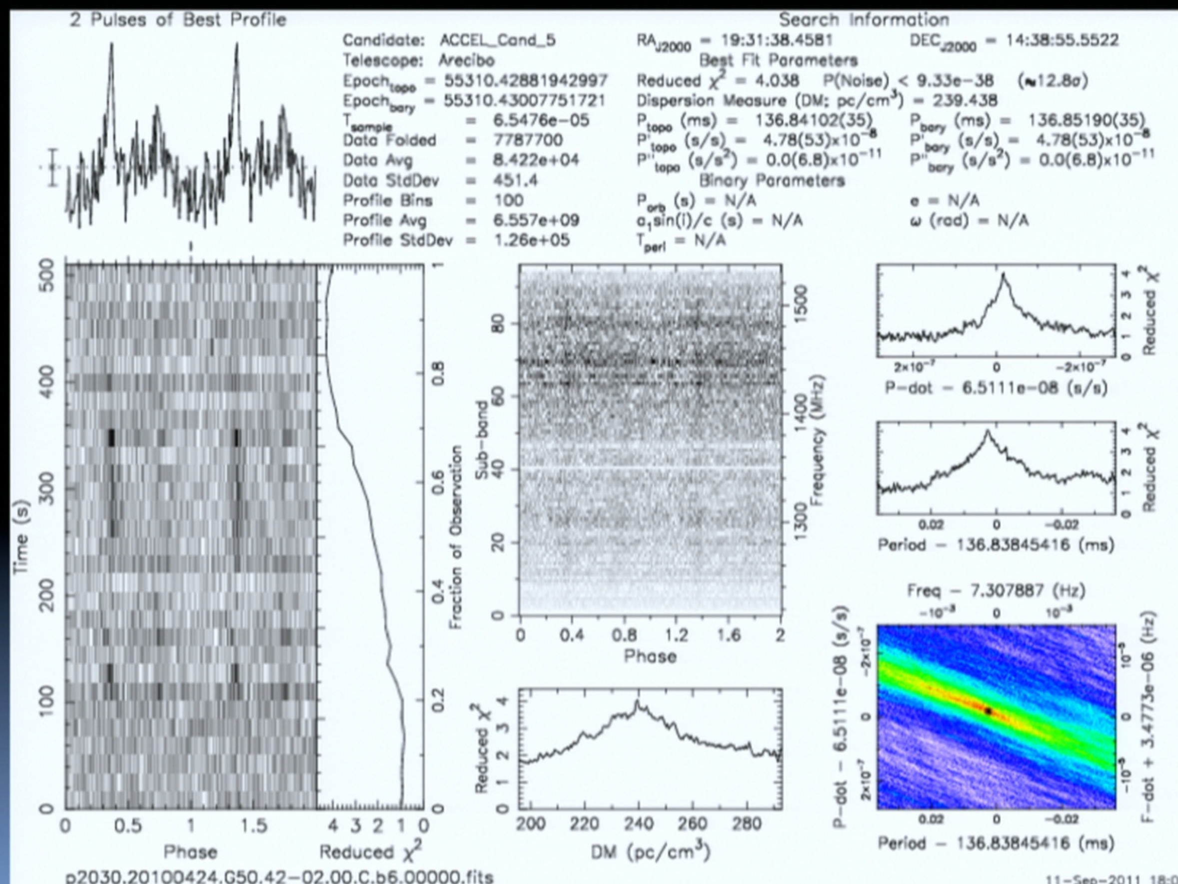
HPC

Binary Pulsar Search Techniques

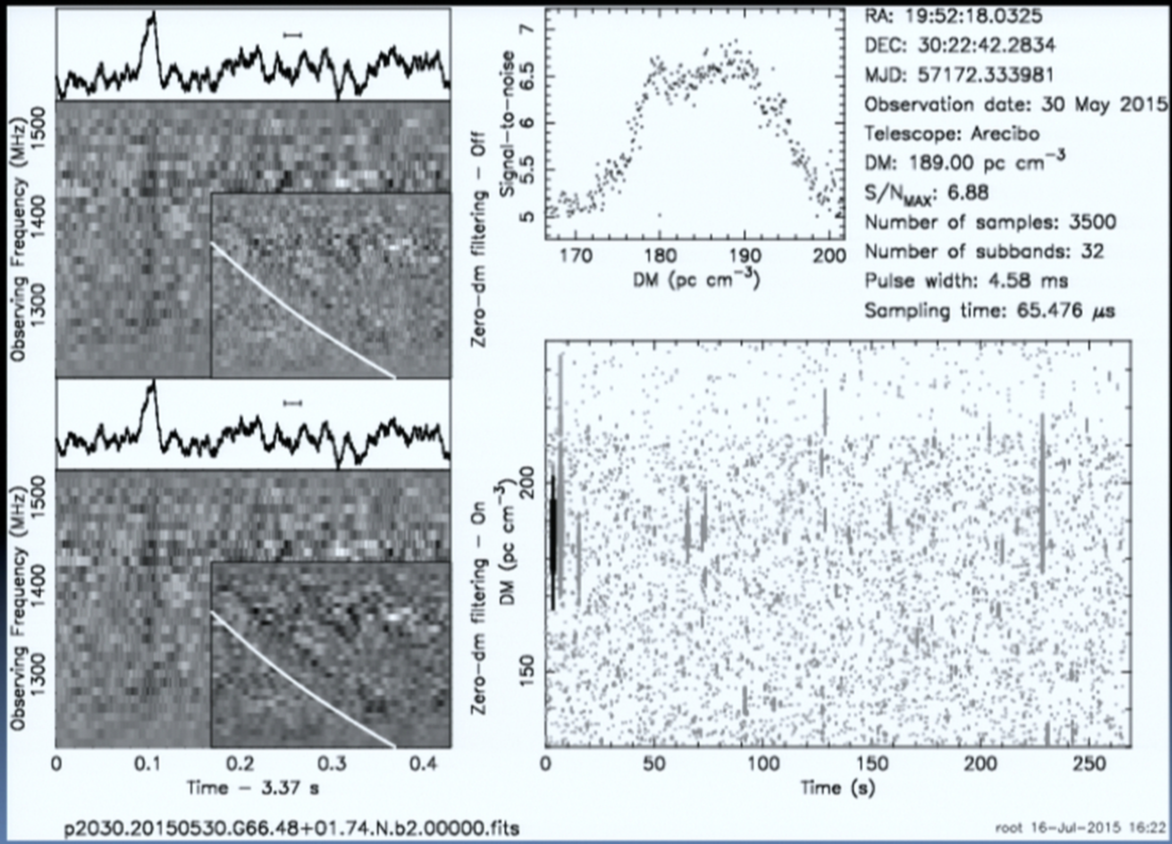
- Isolated Pulsars
- Fourier analysis
- Binary $P_{orb} > 10T_{obs}$
- "Acceleration" Searches



Pulsar Candidate: PRESTO



PALFA SP Pipeline



Courtesy Chitrang Patel

Searching for MSPs: PALFA & GBNCC

Pulsar Arecibo L-Band Feed Array (PALFA)

- Survey of Galactic Plane with 7-beam PALFA receiver
- Center freq 1.4 GHz, BW 300 MHz,
- Plan to survey $|b|<5$ deg in $35<l<75$ deg
- ~1 Petabyte

Green Bank North Celestial Cap Survey (GBNCC)

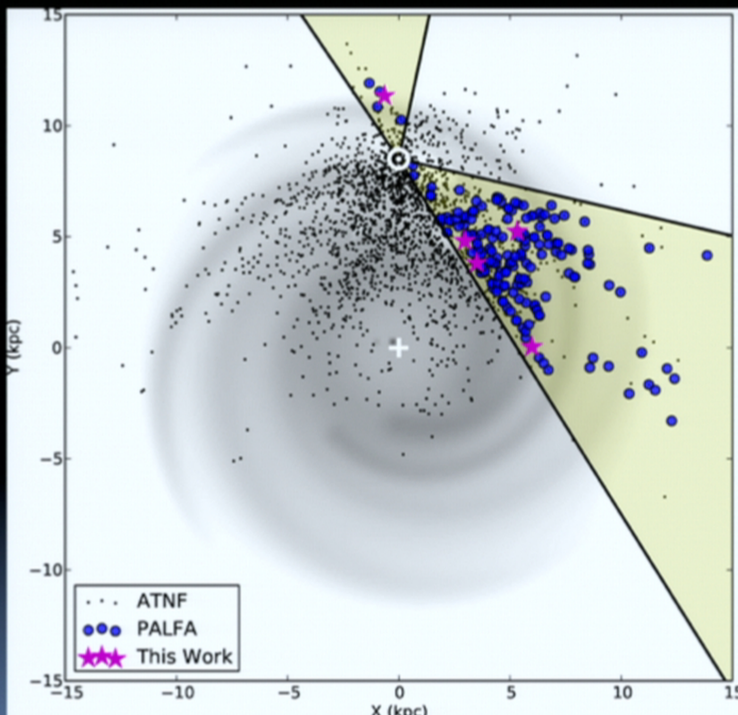
- Survey of full GBT-visible sky
- Centre freq 350 MHz, BW 100 MHz,
- ~0.4 Petabytes

PALFA+GBNCC Processing

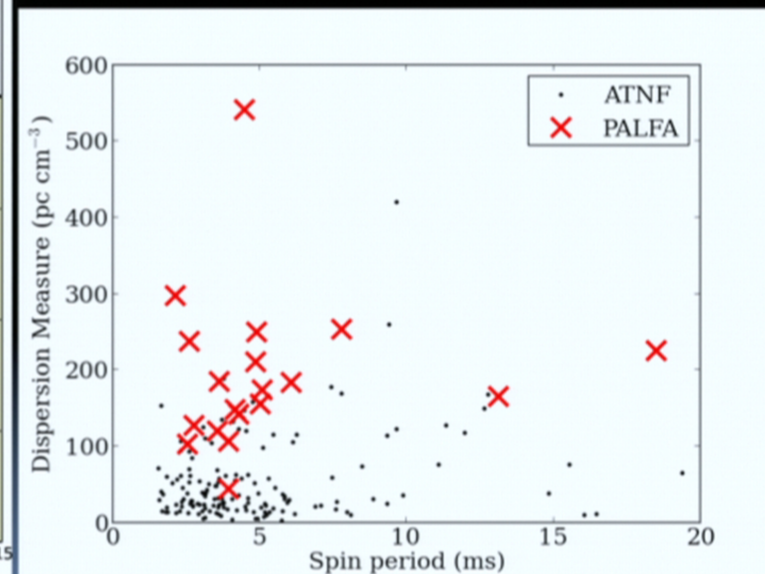
Guillimin @ McGill

Calcul Quebec/
Compute Canada

PALFA Discoveries



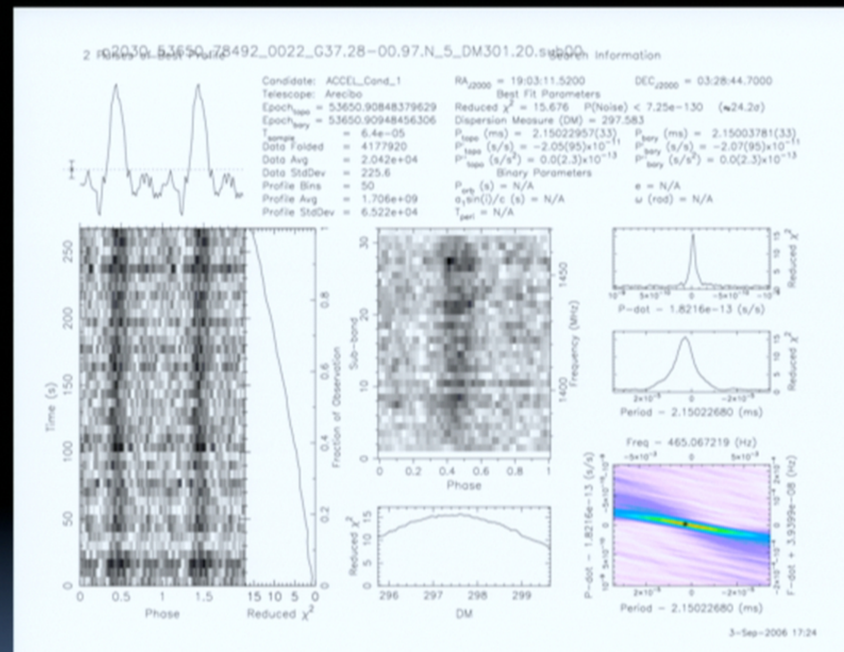
The most distant MSPs known



Plots courtesy P. Scholz

PALFA Highlight 1:
PSR J1903+0327: An Eccentric MSP

- 2 ms pulsar in 95-day e=0.44 orbit with 1-sm non-degenerate companion (Champion et al. 2009; Science)
- Freire et al. (2011):
  - Vr of companion
  - 3D velocity of system
- Present & past motion mainly in the Plane
- Suggests formation in a triple system, with recycler gone



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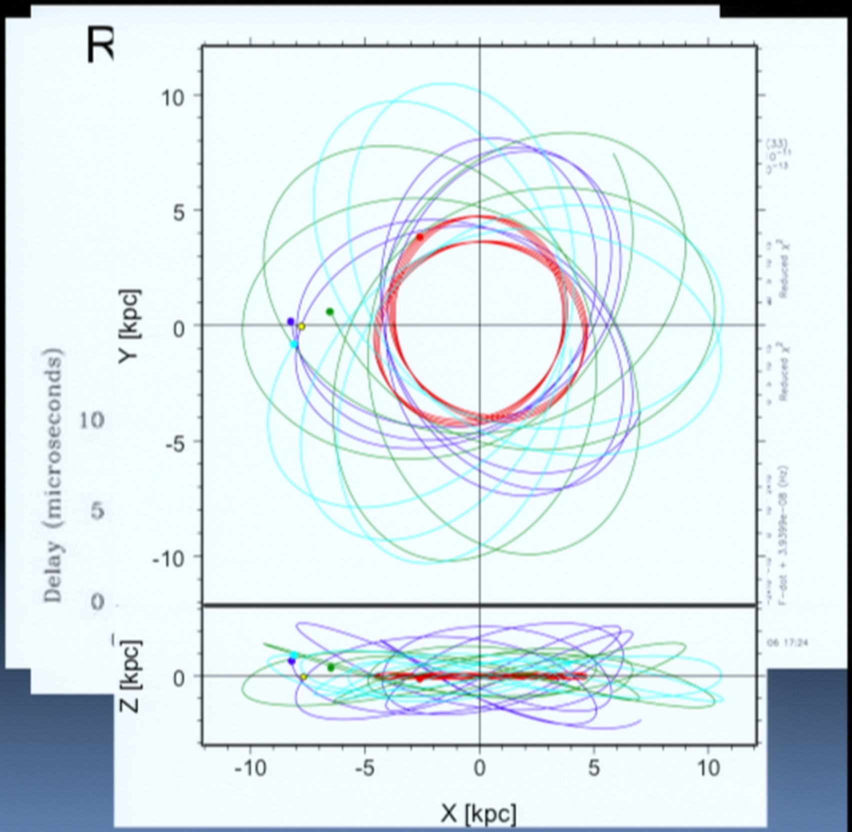

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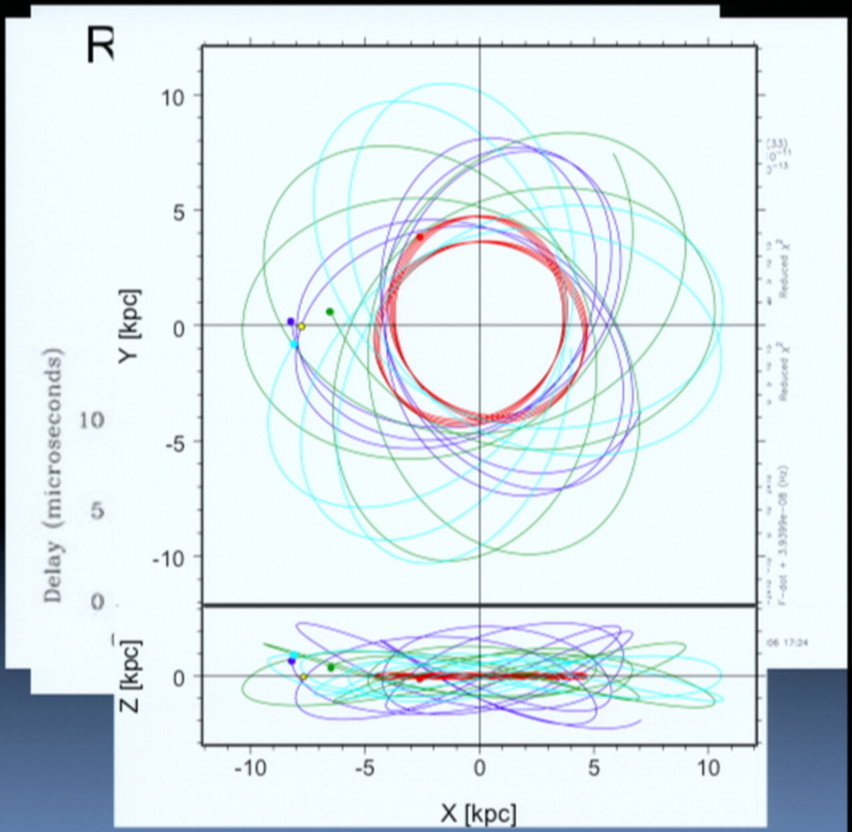

PALFA Highlights: More MSPs

- Deneva et al. 2012:
  - 2 PALFA MSPs: J1949+3106, J1955+2527
  - Both also stuck in Plane
  - New Plane population?
    Or selection effect?
- Crawford et al. 2012: 4 more MSPs
- NEW 1: 2nd eccentric MSP found! (Knispel et al., in prep.)
- NEW 2: 5 more MSPs, 1 highest DM ever (Scholz et al. 2015); 5 more MSPs (Stovall et al. in prep.)

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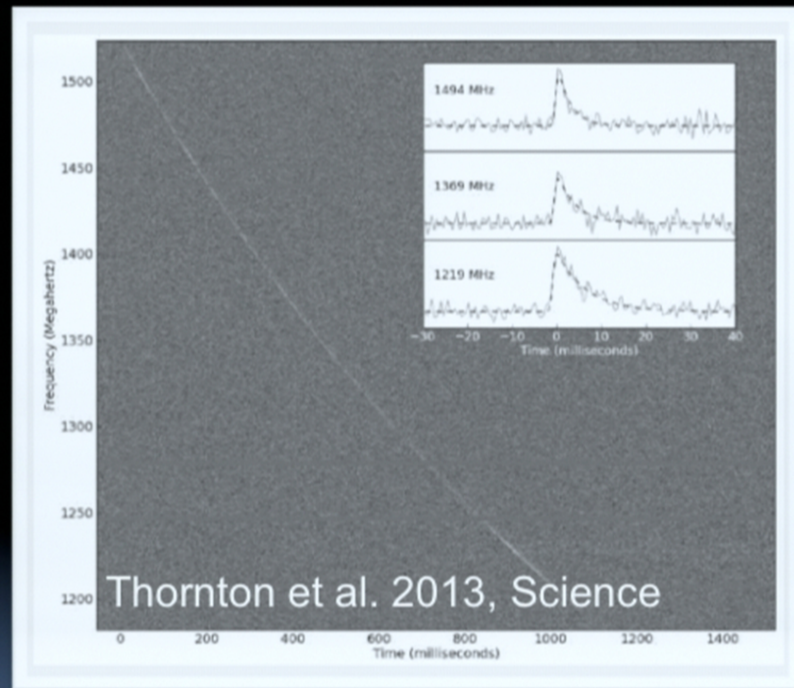
PALFA Highlight 2: Fast Radio Burst

- Single few-ms radio burst detected with DM > DMGalaxy
- Handful of FRBs previously detected (Lorimer et al. 2007; Thornton et al. 2013) all at Parkes telescope
- Spitler et al. 2014: 1st non-Parkes FRB
- Estimated rate: 3,000 /sky/day
- ORIGIN UNKNOWN!



Thornton et al. 2013, Science

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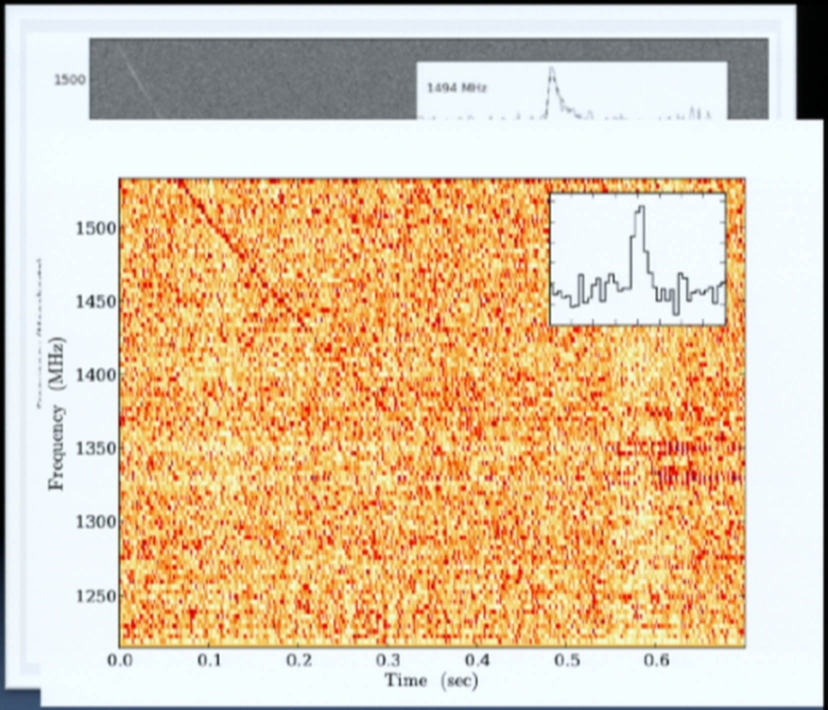
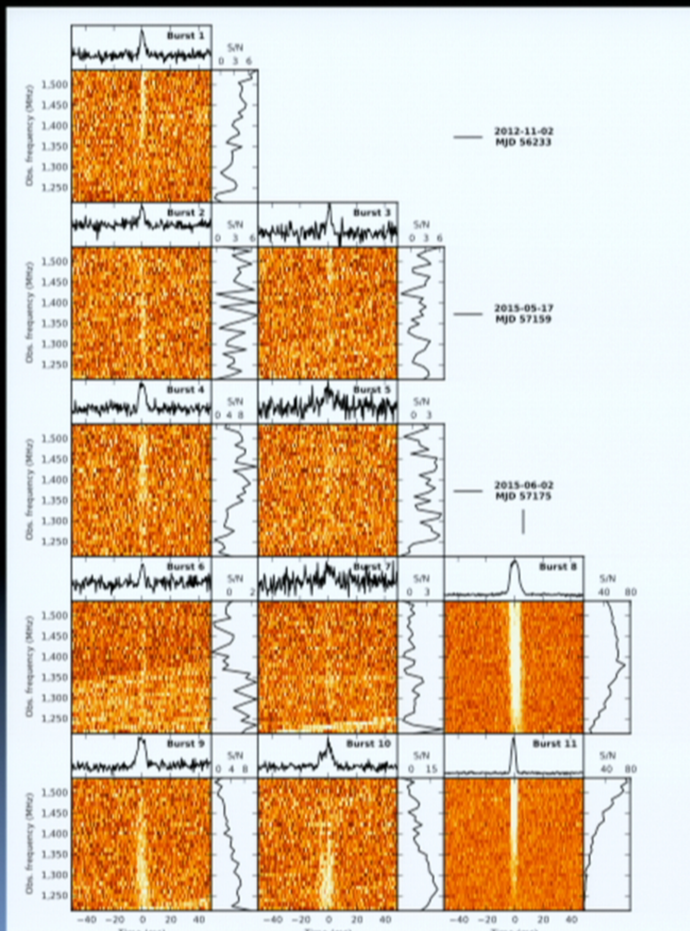


Arecibo FRB Repeats!



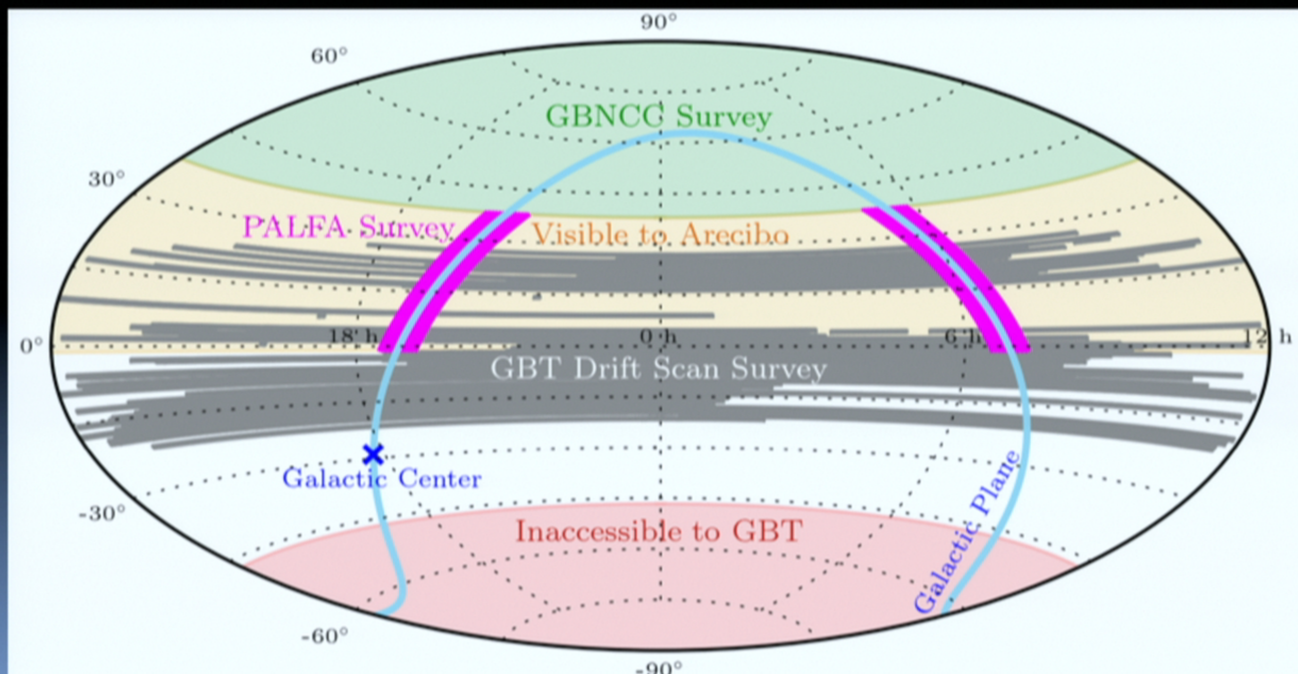
- >10 more bursts detected
- Spitler et al. 2015 Nature, in press
- Hugely varying spectra
- Bursts come in clusters

Plot courtesy P. Scholz

GBNCC 350 MHz Survey

Green Bank
North Celestial Cap Survey

GBT Driftscan Precursor Survey



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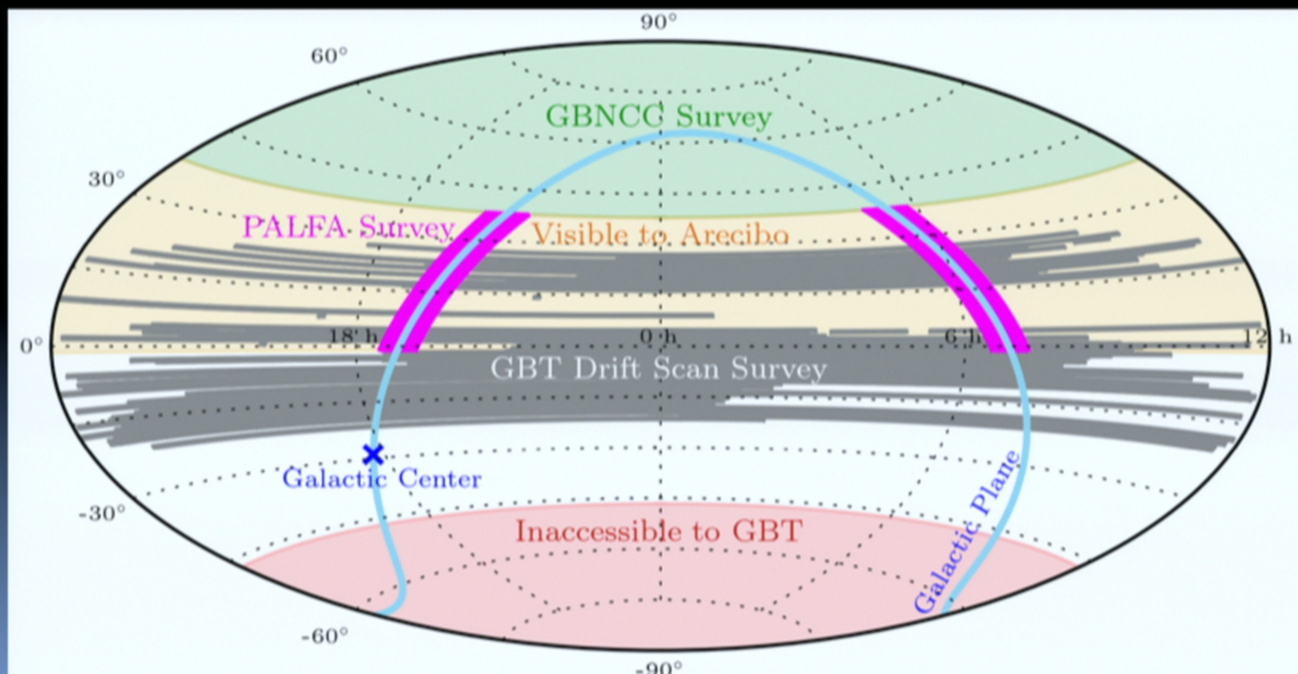

GBT Highlight 1: PSR J1023+0038 MSP/LMXB Transition Object

- Bright 1.7 ms MSP at position of catalogued CV/LMXB with accretion disk, with same 0.2-day orbit! (Archibald et al., Science, 2009)
- Evidence for recent accretion disk: `missing link' between LMXBs and MSPs!
- Not accreting today…maybe tomorrow?!
- Interesting eclipsing phenomenology
  - See Archibald et al. (2014)

NEW! J1023+0038 Disappears!

- In ~June 2013 radio pulsar vanished from the sky! (Stappers et al. 2014)
- At same time, coincident *Fermi* gamma-ray source got factor of ~5 brighter!
- X-ray flux increased by 20x!!
  - Spectrum softened
  - X-ray phenomenology radically different
    - Flares, dips…(Tendulkar et al. 2014; Archibald et al. 2014)
- **Will it return??**

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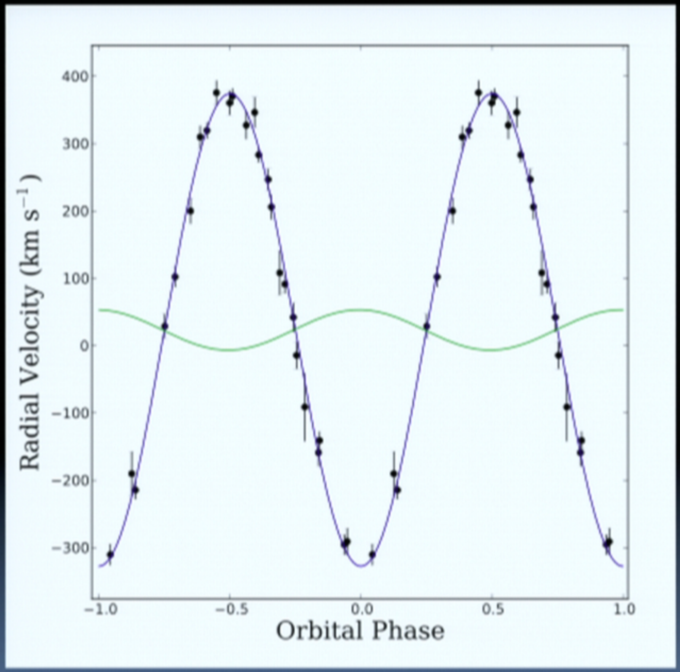
GBT Highlight II: J0348+0432

- Pulsar P=39 ms, P_{orb}=2.4 hr
- Highly relativistic! (Antoniadis et al. Science, 2013)
- WD companion, mass well determined from spectrum, models: 0.175+/-0.020 solar mass
- WD absorption lines show orbital Doppler shifts: q = 11.70 +/- 0.013



Testing Dipolar Radiation Damping: Tensor-Scalar theories

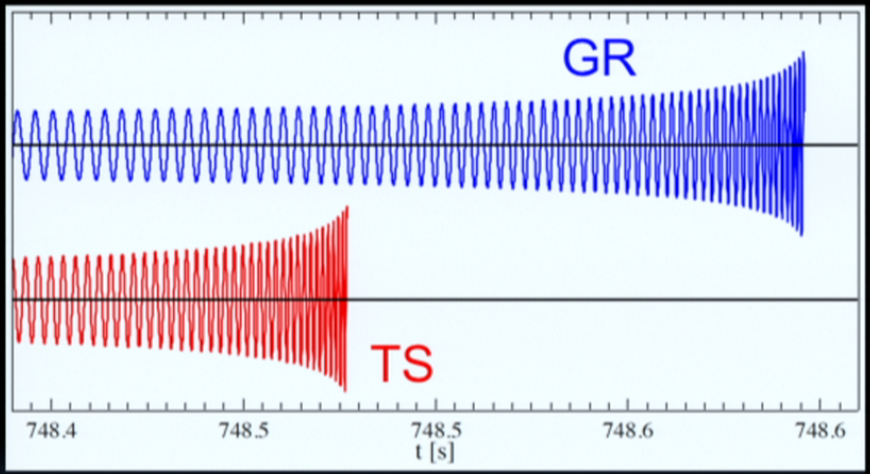
- Radio timing of pulsar at GBT, Arecibo determines relativistic PK parameter
  Pbdot = (-0.273+/-0.045)x10^{-12}

$$\dot{P}_b^D = -2\pi n_b \frac{G_* m_c}{c^3} \frac{q}{q+1} (\alpha_p - \alpha_c)^2$$

- PSR J0348+0432: $(\alpha_p - \alpha_c)^2 < 0.005$

J0348 and aLIGO/Virgo

- To detect merging NS-binaries, need template
- More realistic template = greater sensitivity
- Major effort to calculate post-Newtonian (PN) approximation to GR
- But alternative tensor-scalar (TS) theories could pose problem with this strategy



Courtesy Norbert Wex

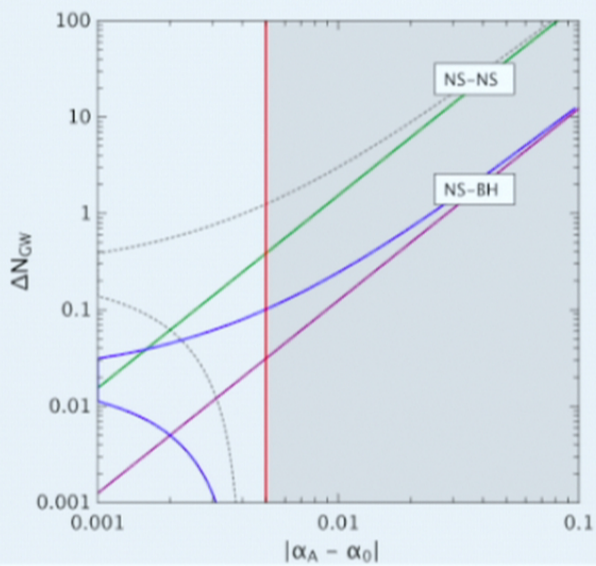
J0348: Good News for GWs

- Binary pulsars are useful for testing TS gravity
  - Was true for low-mass NSs (Damour & Esposito-Farese 1998)
  - Now true for high-mass NSs
- Good news for calculating templates: Limit from J0348 suggests PN formalism should work for massive NSs as well

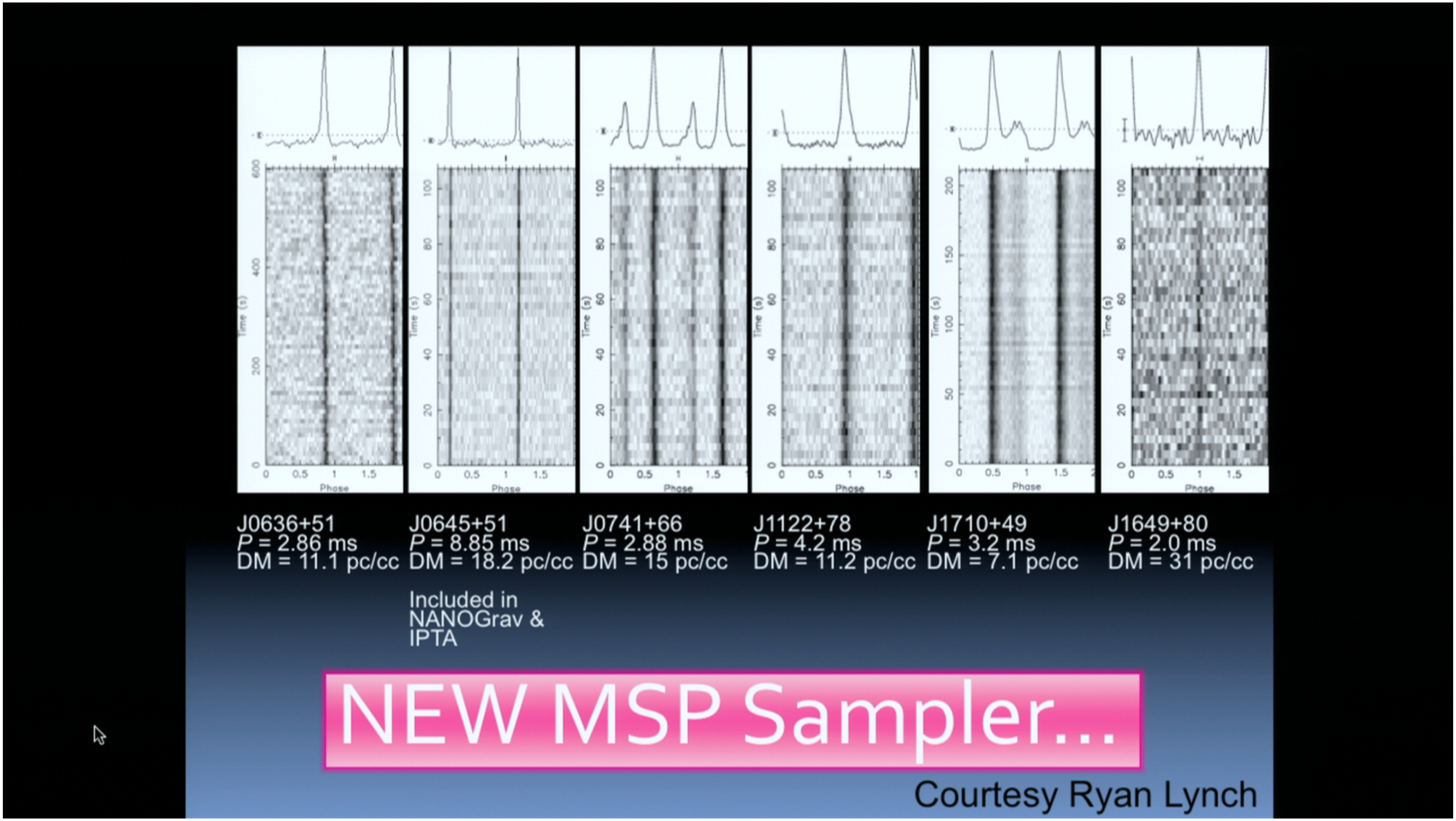
Figure 5.

Constraints on the Phase Offset in Gravitational Wave Cycles in the LIGO/VIRGO bands

Maximum offset in GW cycles in the LIGO/VIRGO band (20 Hz to a few kHz) between the GR template and the true phase evolution of the in-spiral in the presence of dipolar radiation, as a function of the effective coupling of the massive NS for two different system configurations: a $2\,M_\odot$ NS with a $1.25\,M_\odot$ NS (NS-NS), and a merger of a $2\,M_\odot$ NS with a $10\,M_\odot$ BH (NS-BH). In the NS-NS case, the green line is for $\alpha_B = \alpha_0$, and the gray dotted line represents the most conservative, rather unphysical, assumption $\alpha_0 = 0.004$ and $\alpha_B = 0$ (8). In the NS-BH case, α_B is set to zero (from the assumption that the no-hair theorem holds). The blue line is for $\alpha_0 = 0.004$ (Solar System limit for scalar-tensor theories), and the purple line represents $\alpha_0 = 0$. The gray area to the right of the red line is excluded by PSR J0348+0432. In this plot there is no assumption concerning the EOS.



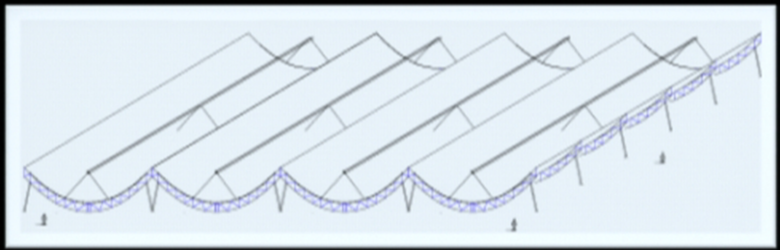
Antoniadis et al. Science, 2013

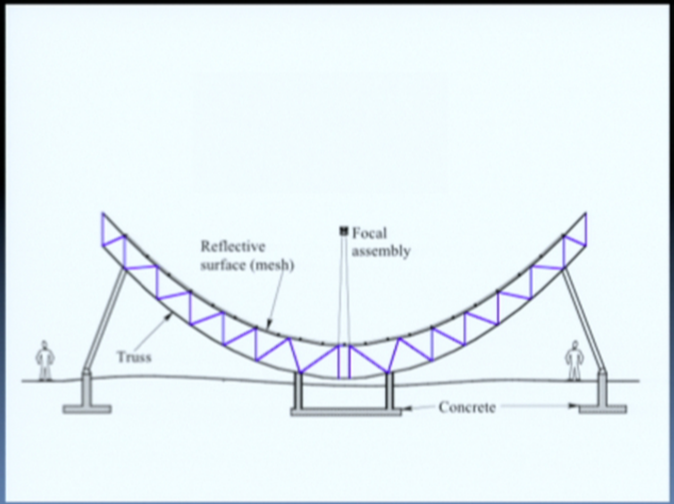


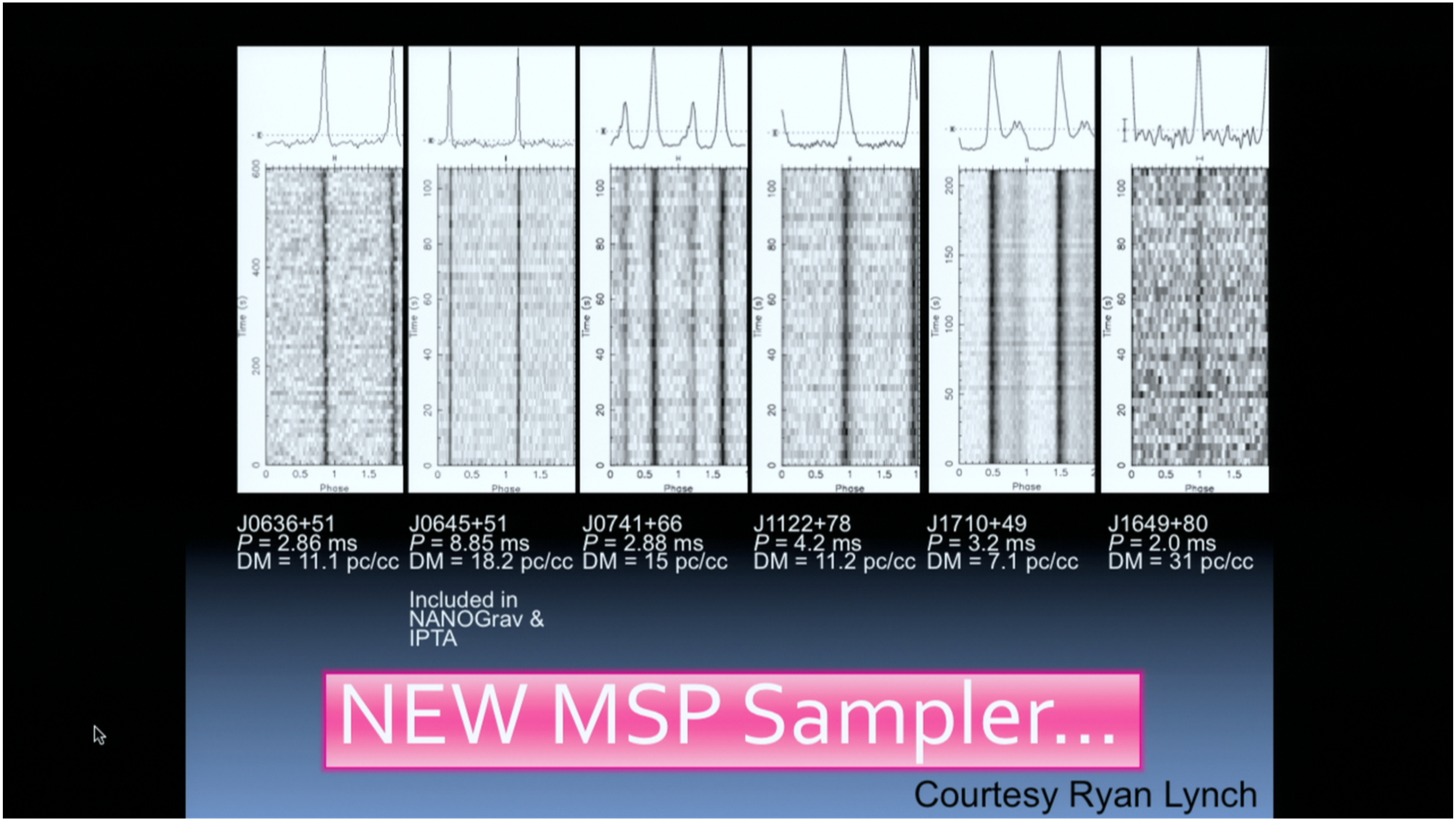
J0636+51
P = 2.86 ms
DM = 11.1 pc/cc
J0645+51
P = 8.85 ms
DM = 18.2 pc/cc
Included in NANOGrav & IPTA
J0741+66
P = 2.88 ms
DM = 15 pc/cc
J1122+78
P = 4.2 ms
DM = 11.2 pc/cc
J1710+49
P = 3.2 ms
DM = 7.1 pc/cc
J1649+80
P = 2.0 ms
DM = 31 pc/cc
NEW MSP Sampler...
Courtesy Ryan Lynch

CHIME: Canadian Hydrogen Intensity Mapping Experiment

- Penticton, BC at DRAO
- 4 20 m x 100 m cylinders
- Transit telescope
- 256 dual-pol feeds per axis, 2048 input signals
- 400-800 MHz
- FOV: E-W 2.5°-1.3°,
  N-S ~120°
- Beam size 0.5°-0.3°
- <u>CFI-funded $12M CDN</u>

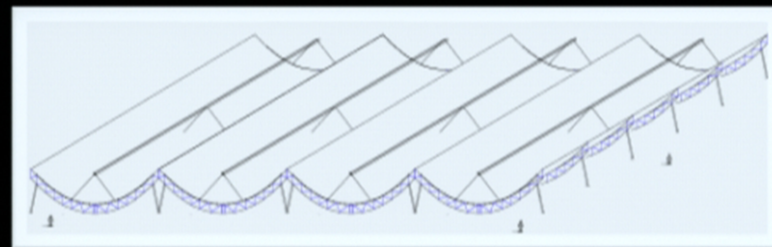


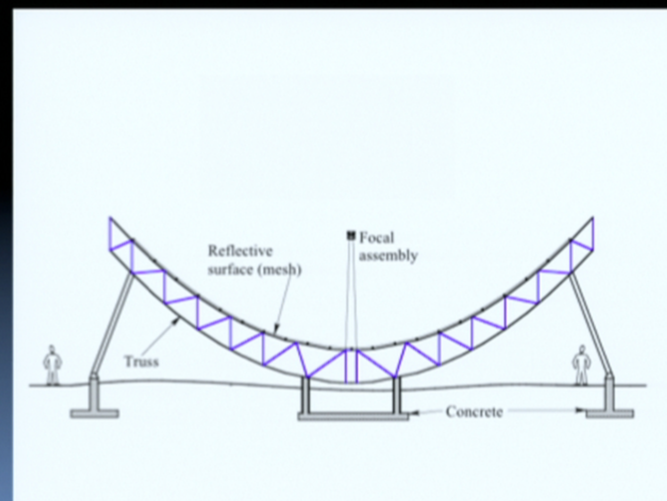


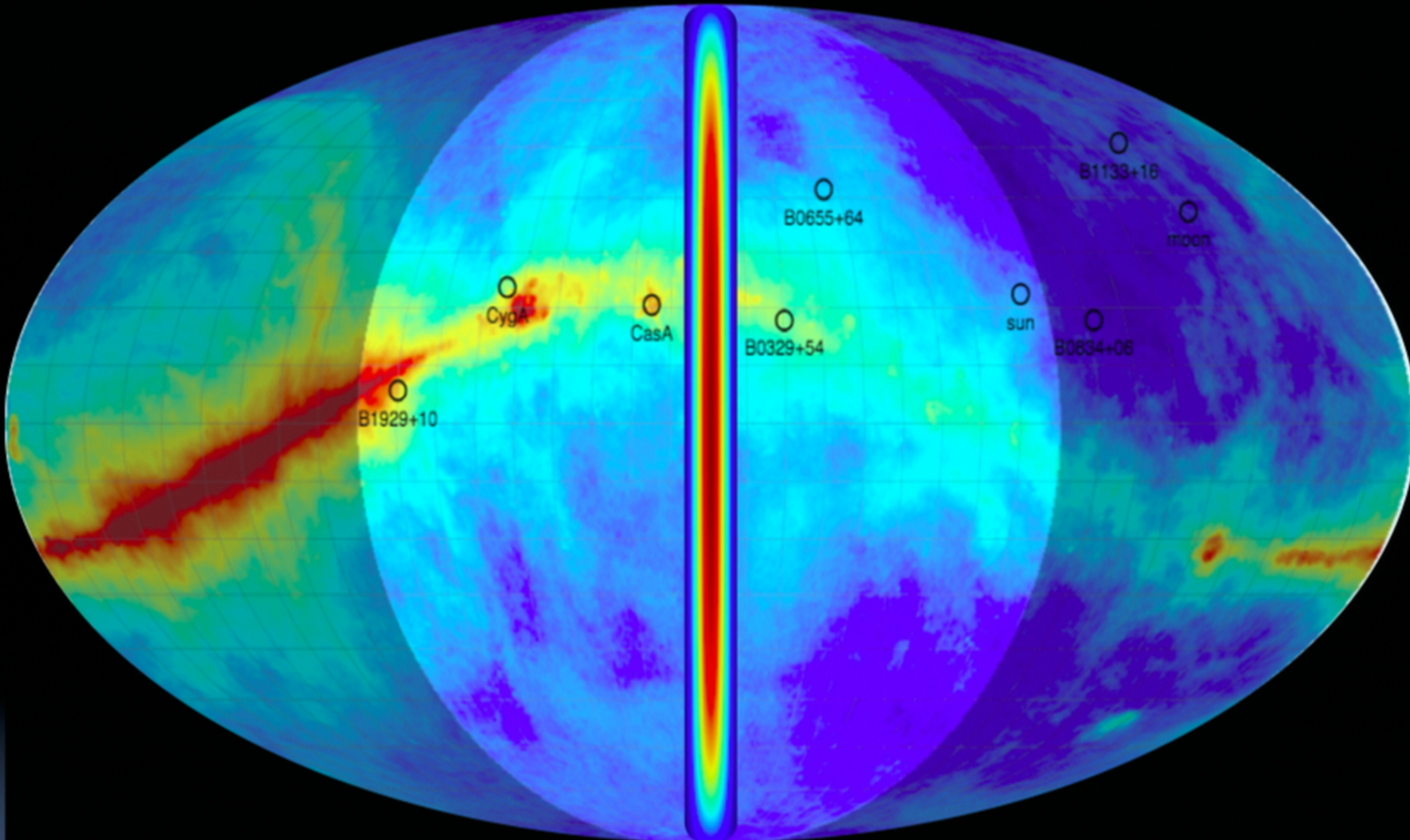

J0636+51
P = 2.86 ms
DM = 11.1 pc/cc
J0645+51
P = 8.85 ms
DM = 18.2 pc/cc
Included in NANOGrav & IPTA
J0741+66
P = 2.88 ms
DM = 15 pc/cc
J1122+78
P = 4.2 ms
DM = 11.2 pc/cc
J1710+49
P = 3.2 ms
DM = 7.1 pc/cc
J1649+80
P = 2.0 ms
DM = 31 pc/cc
NEW MSP Sampler...
Courtesy Ryan Lynch

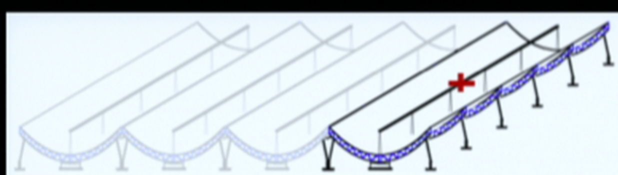
CHIME: Canadian Hydrogen Intensity Mapping Experiment

- Penticton, BC at DRAO
- 4 20 m x 100 m cylinders
- Transit telescope
- 256 dual-pol feeds per axis, 2048 input signals
- 400-800 MHz
- FOV: E-W 2.5°-1.3°,
  N-S $\sim 120^{\circ}$
- Beam size 0.5°-0.3°
- CFI-funded $12M CDN

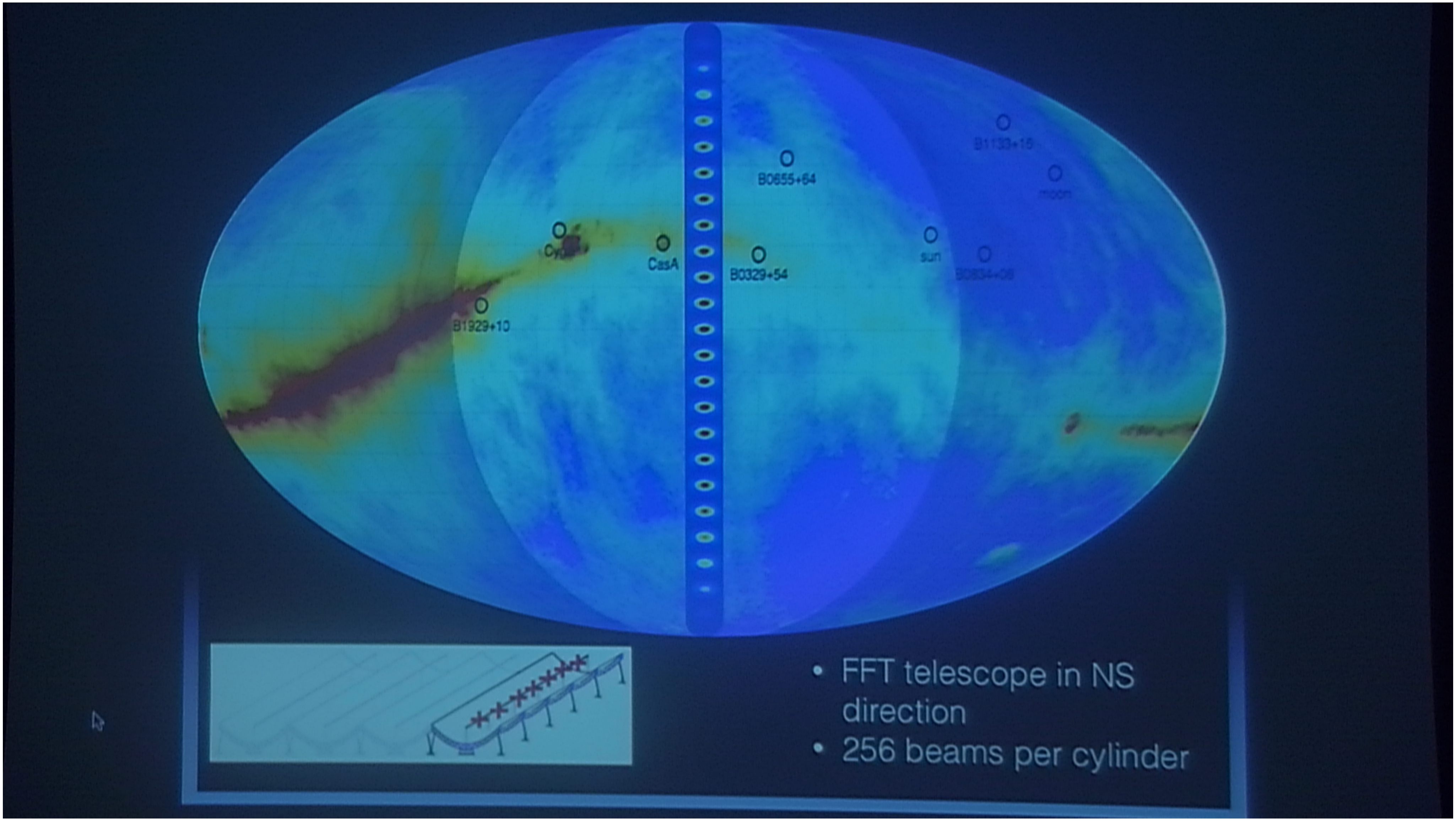


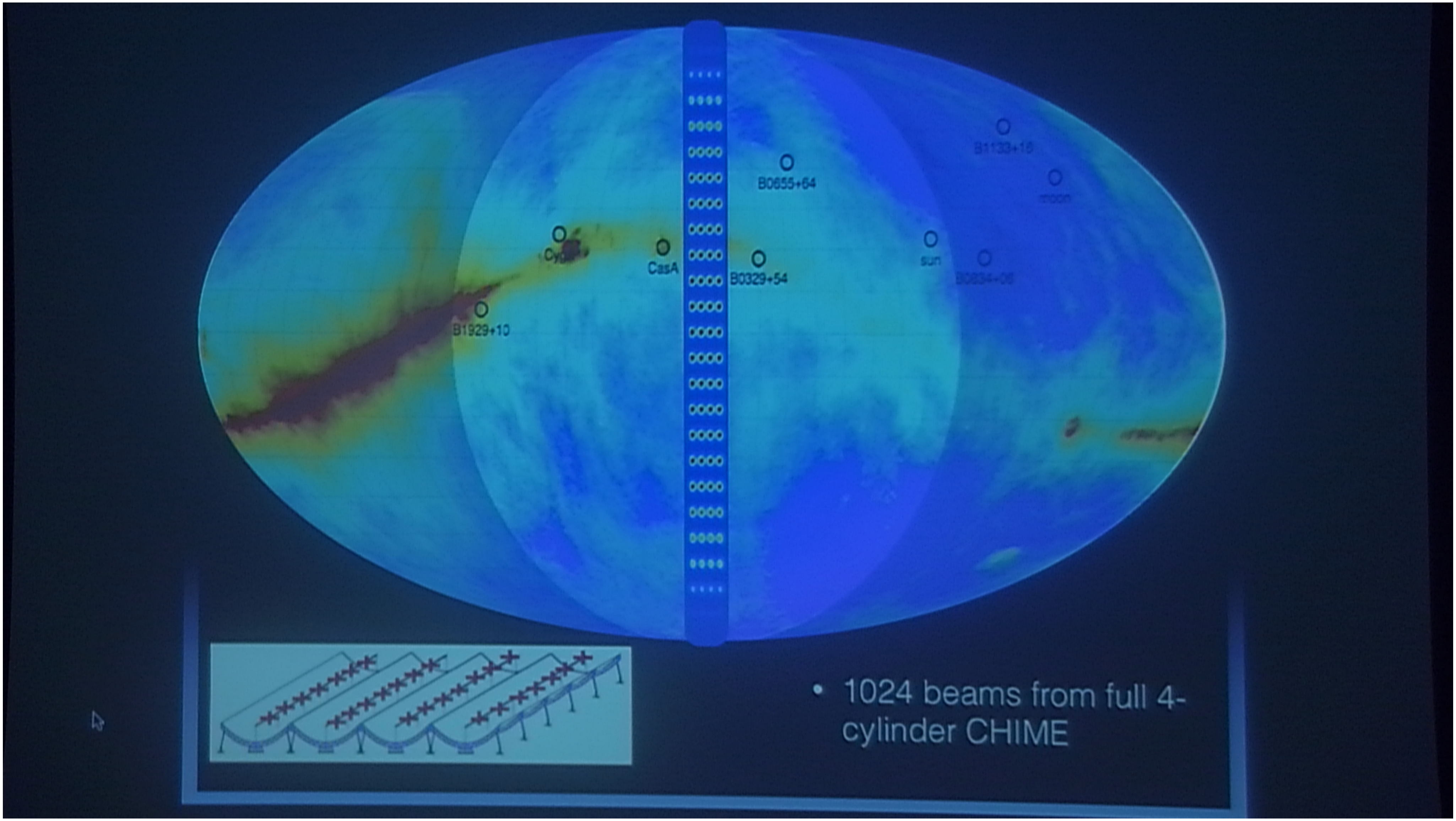






- Cylinder focuses light only in EW direction
- Gives us large FOV


B1133+16
B0655+64
moon
CasA
B0329+54
sun
B0834+06
B1929+10
• FFT telescope in NS direction
• 256 beams per cylinder


B0655+64
CasA
B0329+54
B1929+10
sun
1024 beams from full 4-cylinder CHIME

CHIME Cosmology Science Goal

- Measure Baryon Acoustic Oscillations (e.g. Chang et al. Nature, 2010)
- Map redshifted HI to look for periodic fluctuations in matter power spectrum
- 400-800 MHz → z=0.8-2.5
- Cosmic standard ruler: see size evolve with z
- Superb constraints on Dark Energy

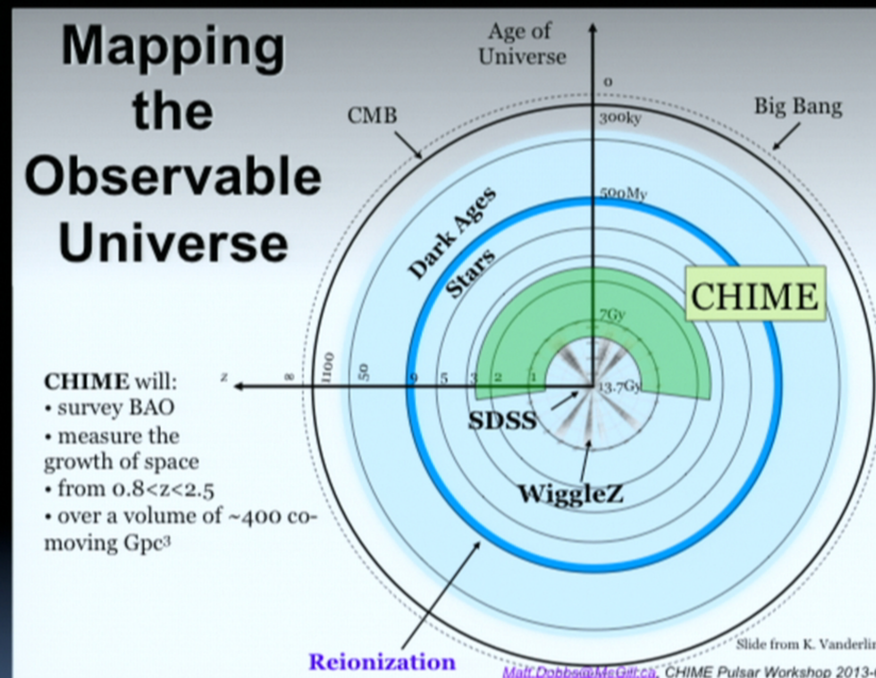


Figure from M. Dobbs

Cosmology Collaboration

UBC

Mandana Amiri
Meiling Deng
Mateus Fandino
Ken Gibbs
Mark Halpern
Adam Hincks
Gary Hinshaw
Kiyo Masui
Richard Shaw
Kris Sigurdson
Mike Sitwell
Carolin Hofer

McGill

Kevin Bandura
Jean-Francois Cliche
Matt Dobbs
Adam Gilbert
David Hanna
Gilbert Hsyu
Juan Mena Parra
Tristan Pinsonneault-Marotte
Amy Tang
Graeme Smecher

UofT

Dick Bond
Liam Connor
Nolan Denman
Peter Klages
Laura Newburgh
Ivan Padilla
Ue-Li Pen
Andre Recnik
Keith Vanderlinde
Kendrick Smith
Jeff Peterson (CMU)

DRAO

Tom Landecker

CHIME structure as of July 23

CHIME structure as of July 23

NEWS IN FOCUS

(NOAA), 5% less than the current level and about $800 million short of Obama's request. The Senate bill would reduce NOAA spending by just 1%.

But it is the National Science Foundation (NSF) that has most polarized lawmakers. The House's NSF spending bill would require the agency to award 70% of its $6-billion research fund to biology, computer science, engineering, mathematics and the physical sciences. The unusual provision would effectively impose a 16% cut to geoscience and social-sciences programmes, according to an analysis by the American Institute of Physics. By contrast, the Senate's bill does not set funding levels for particular disciplines.

BASIC FOCUS

Powerful House Republicans, most notably science-committee chair Lamar Smith of Texas, have argued that the NSF should concentrate on basic research. Smith has also tried to highlight what he sees as questionable grants by the science agency, such as funding for a study of mental health in Nepal. But Gloria Waters, vice-president and associate provost for research at Boston University in Massachusetts, says that legislators often misunderstand the role of basic science. "People have this idea that science funding should go to something that should have an immediate and direct impact on society, but that's not how science works," she says.

Deciding which projects to fund is made more difficult by a lack of money, says Hannah Carey, a physiologist at the University of Wisconsin–Madison. "I've experienced it — you put in a grant to continue your work that gets a very, very good score and would have been funded in a better climate," says Carey, who spent a year working as a programme director in the NSF's biosciences division. "It's disheartening."

A short-term spending deal would avert a government shutdown of the sort that ground most research to a halt in October 2013. But a stopgap arrangement could still make life difficult for researchers

The CHIME telescope array will search for a particular kind of hydrogen emission from ancient galaxies.

MARK HALPERN/CHIME COLLABORATION

COSMOLOGY

Half-pipe array to map teen Universe

Canadian telescope aims to chart cosmic expansion rate between 10 billion and 8 billion years ago.

BY DAVIDE CASTELVECCHI

It sounds almost too apt to be true. An observatory shaped like the half-pipes used by snowboarders, and dependent on technology originally designed for gaming and mobile phones, will soon be tasked with plugging a crucial gap in the cosmological record: what the Universe did when it was a teenager.

The information will allow cosmologists to

expansion rate between 10 billion and 8 billion years ago, a period in which the cosmos went "from being a kid to an adult", says Mark Halpern, the leader of CHIME and an experimental cosmologist at the University of British Columbia in Vancouver. Straight after the Big Bang 13.8 billion years ago, the rate of the Universe's expansion slowed. But somewhere during the 'adolescent' period, dark energy — which eventually turned the Universe's slowing

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But that's not all!

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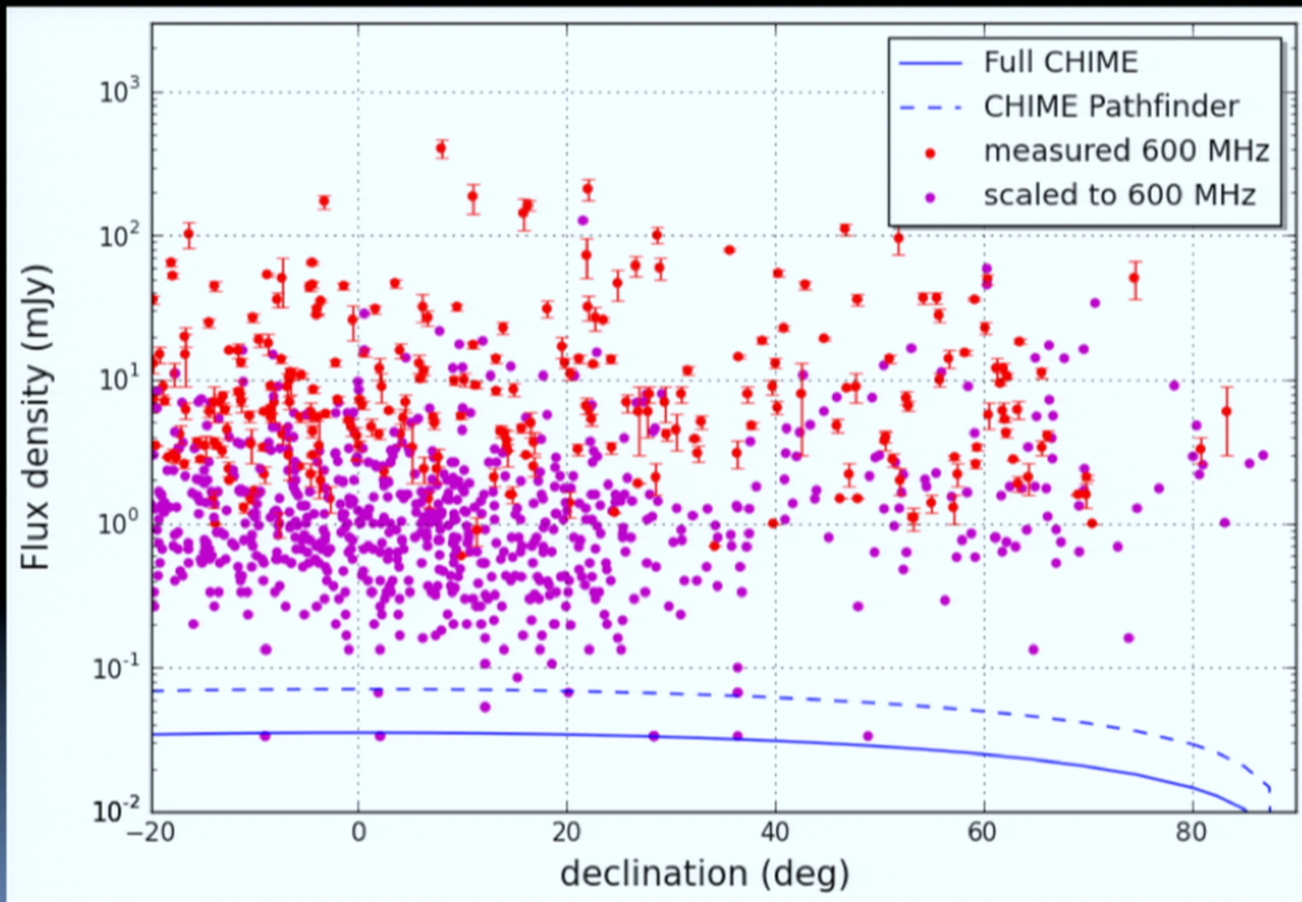
expansion rate between 10 billion and 8 billion

Big Bang 13.8 billion years ago, the rate of the Universe's expansion slowed. But somewhere during the 'adolescent' period, dark energy — which eventually turned the Universe's slowing

CHIME Sensitivity to Pulsars

- Large area, wide bw → CHIME can detect nearly all pulsars above horizon
- NSERC funding for pulsar backend:
  - 10 simultaneous steerable beams 24/7
  - Coherently dedispersed, dual polarization
  - Online folding for monitoring known pulsars
    - Binaries (GR tests, eclipse studies, LMXB transitions, ...)
    - ISM monitoring (NANOGrav/IPTA, DM variations, scattering, scintillation, RMs, ESEs...)
    - Nullers, mode changers, magnetospheric phenomena
    - Glitches, timing noise
    - Radio magnetar outbursts

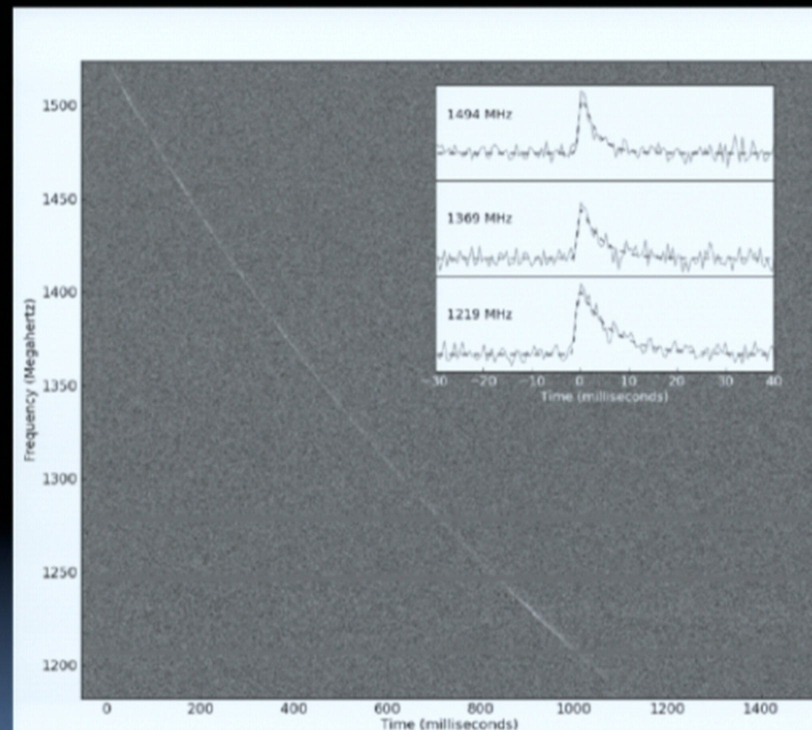
CHIME Sensitivity to Pulsars



Courtesy Cherry Ng

Mystery of Fast Radio Bursts

- Few-ms radio bursts
- DM >> DM_{MW}
- Some scattered
- ~3 x 10^4 /sky/day
- Origin unknown
- Likely cosmological
  - Other models too
  - Not microwave ovens



CHIME can be an excellent FRB detector!

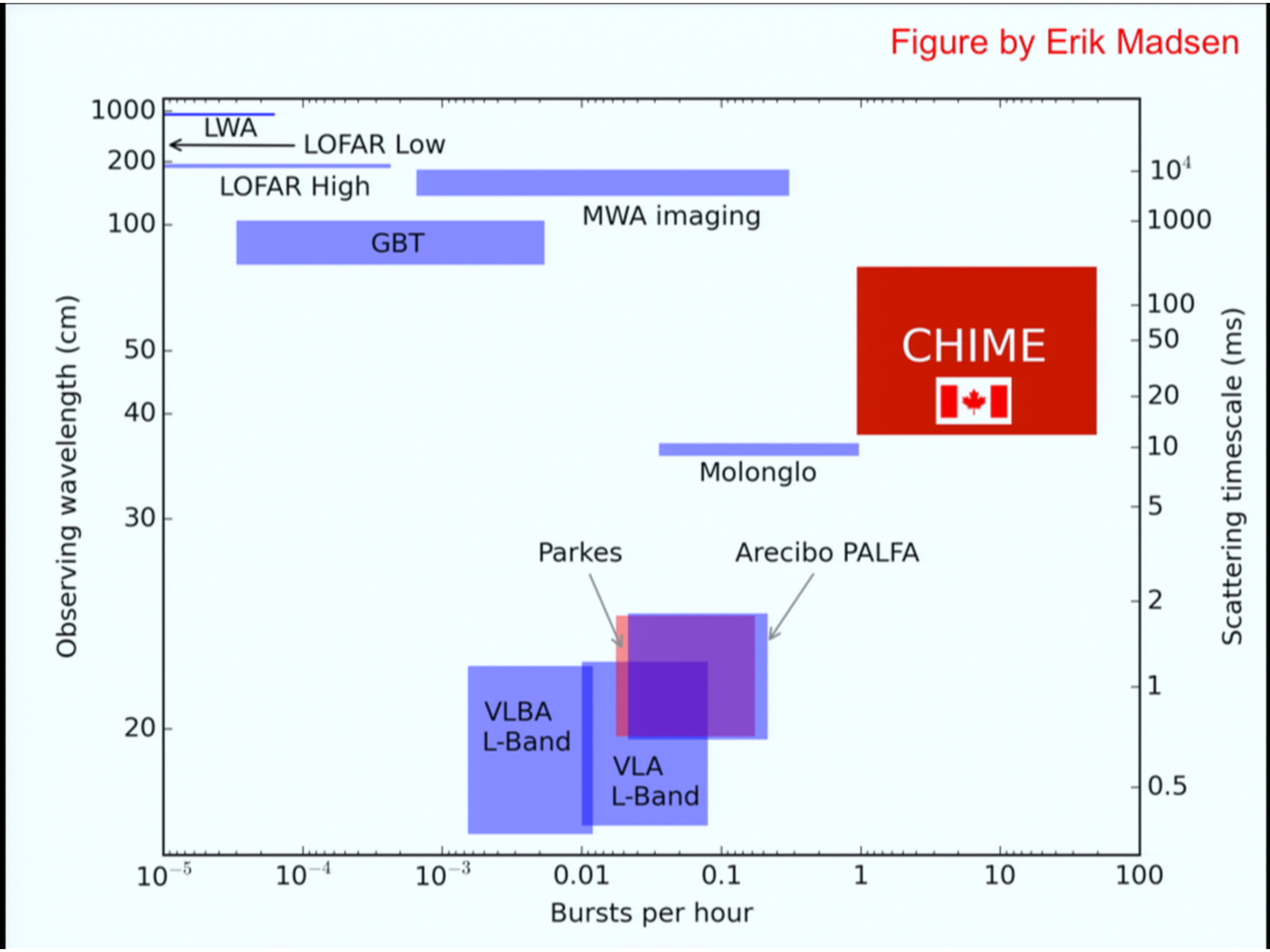


Figure by Erik Madsen
LWA
LOFAR Low
LOFAR High
MWA imaging
GBT
CHIME
Molonglo
Parkes
Arecibo PALFA
VLBA
L-Band
VLA
L-Band
Observing wavelength (cm)
Scattering timescale (ms)
Bursts per hour
1000
200
100
50
40
30
20
10^4
1000
100
50
20
10
5
2
1
0.5
10^{-5}
10^{-4}
10^{-3}
0.01
0.1
1
10
100

CHIME/FRB Collaboration

- Vicky Kaspi (PI, McGill U.)
  - Alex Josephy, Erik Madsen, Shriharsh Tendulkar
- Ingrid Stairs (UBC)
  - Cherry Ng
- Scott Ransom (NRAO)
- Paul Demorest (NRAO)
- Bryan Gaensler (U. Toronto)
- Plus CHIME Cosmology team

CHIME/FRB Project

- CFI-funded $5.6M for onsite GPU-based back-end
- Significant changes to CHIME GPU-based correlator
- <u>Current status</u>: FRB back-end under design
- Predicted event rate depends on design:
  - Minimize GPU power consumption (~140 kW max) but maximize sky coverage (no. beams searched)

FRBs and CHIME

What we want	Can CHIME deliver?
Thousands of events for event rate, flux distribution, angular distribution, DM distribution, scattering vs DM, ...	Yes
Detect or rule out repetition	Yes
Real-time triggers	Yes
Arcsecond localization	Maybe, if optical/X-ray counterparts exist, are long-lived & bright
Sensitivity to linear polarization vs freq, vs time	Yes

Conclusions

- Pulsar surveys important for many reasons!
- PALFA, GBT surveys very fruitful
  - New MSPs for Pulsar Timing Arrays
  - Interesting binary pulsars:
    - Eccentric MSPs
    - Missing Links
    - Tests of Relativistic Gravity
- Lots more to come!
  - Sub-ms pulsars?? Pulsar/BH binary??
  - CHIME & FRBs

Thanks to...

Institut Spatial de McGill
McGill Space Institute

NSERC CRSNG

Fonds de recherche Nature et technologies Québec

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Lorne Trottier Chair in Astrophysics & Cosmology