Pulsar searching and timing

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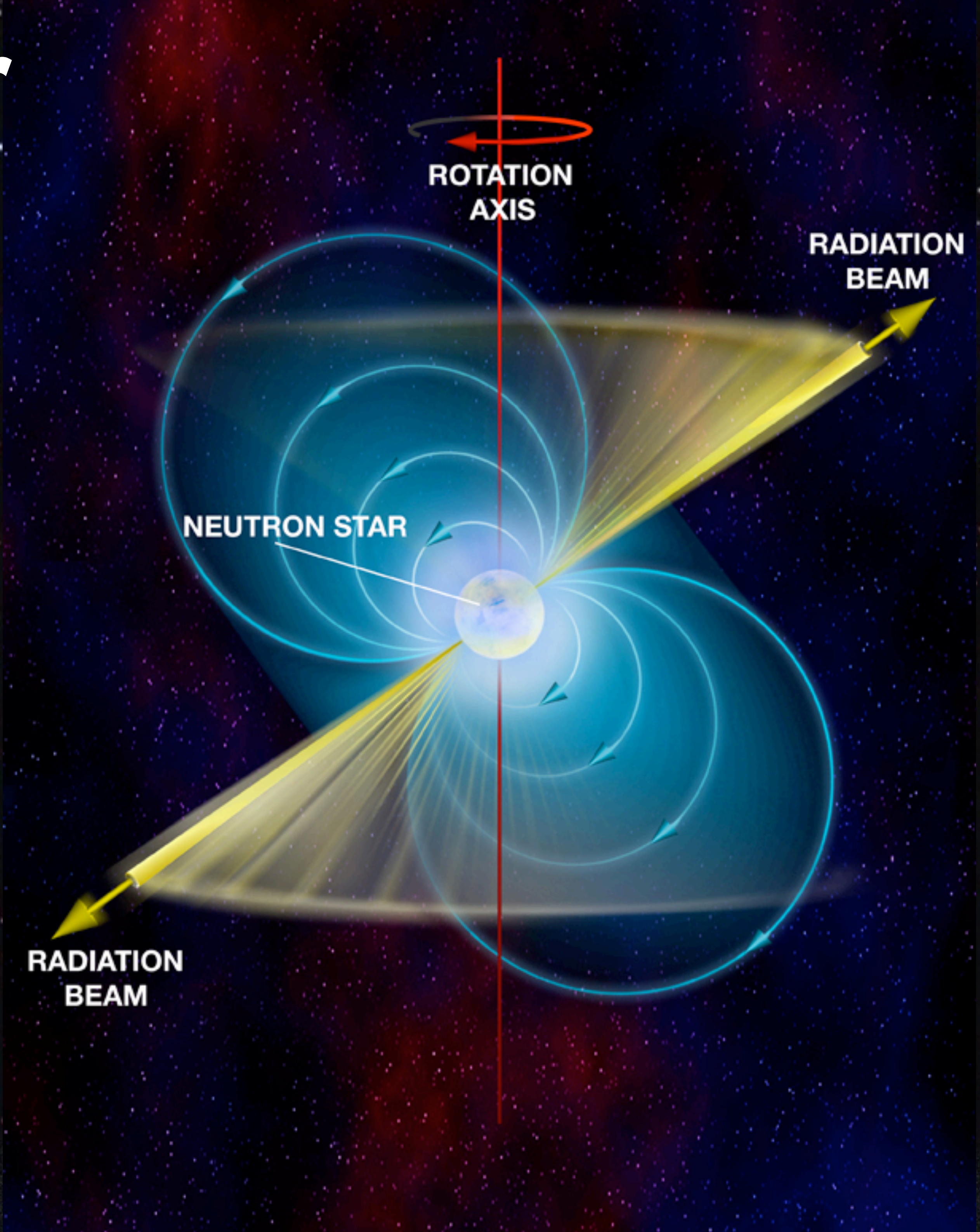
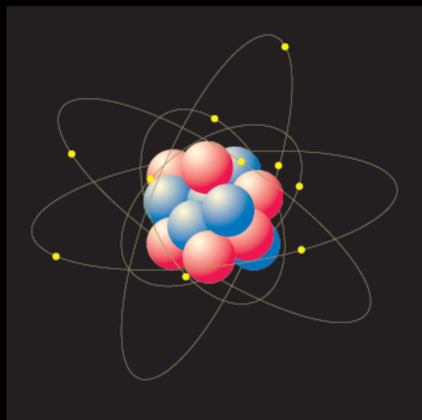
Pulsar



Pulsars are Extreme Objects



$R = 12$ km

$M = 1.4\ M_{Sun}$

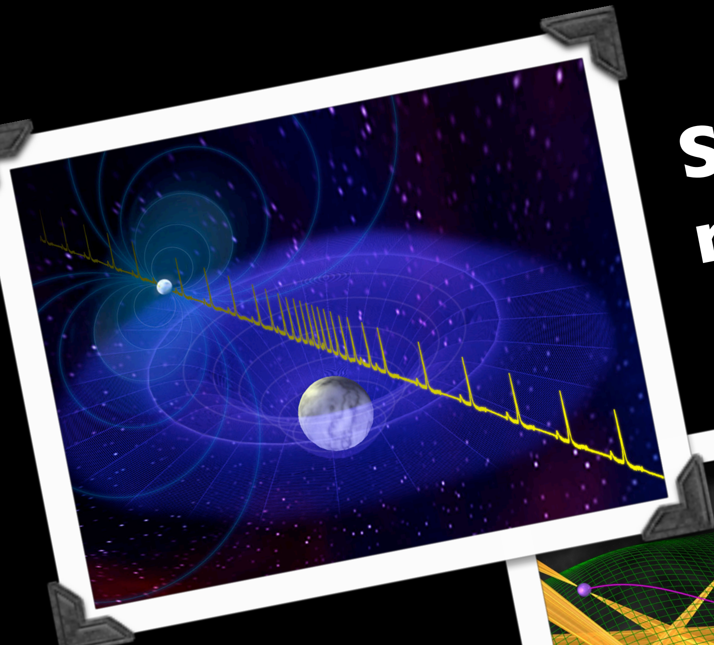
$B = 10^{12}\text{-}10^{15}$ G

$\nu_{spin} > 716$ Hz

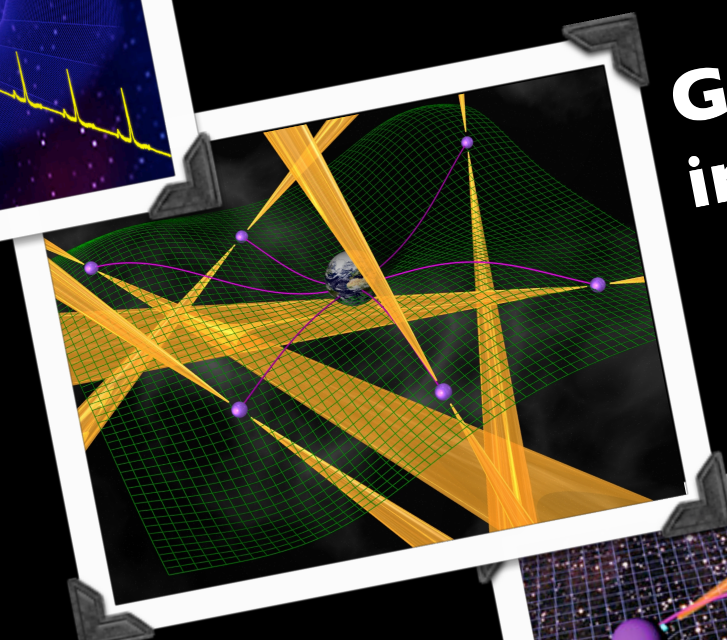
$v_t = 0.2\ c$

They are fascinating physical laboratories

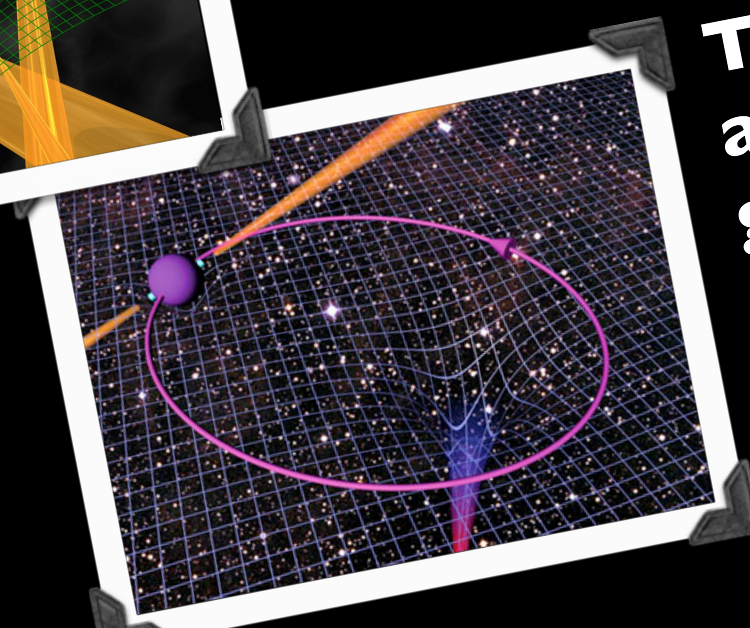
Pulsars as Precision Tools



Shapiro delay mass measurements

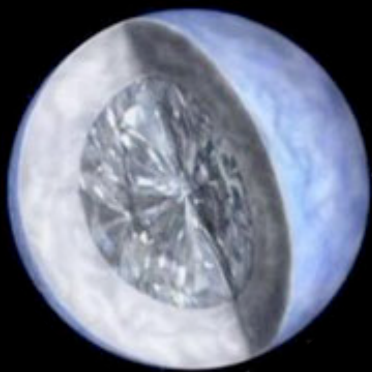


Gravitational wave interferometer



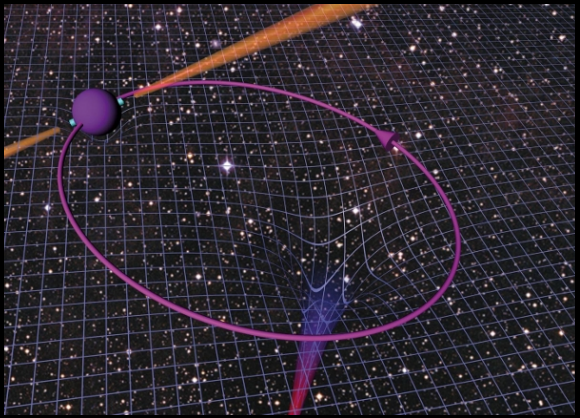
Tests of alternative gravity theories

Exotic Pulsar Systems



“Diamond Planet”

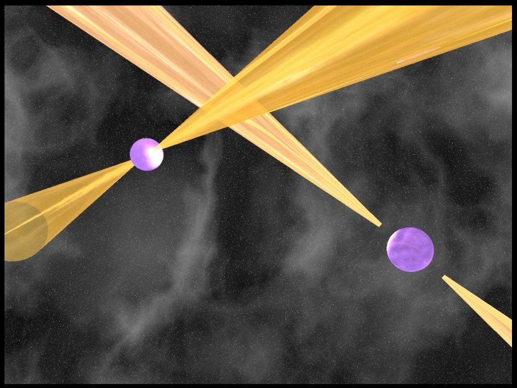
Bailes et al. 2012



PSR-BH

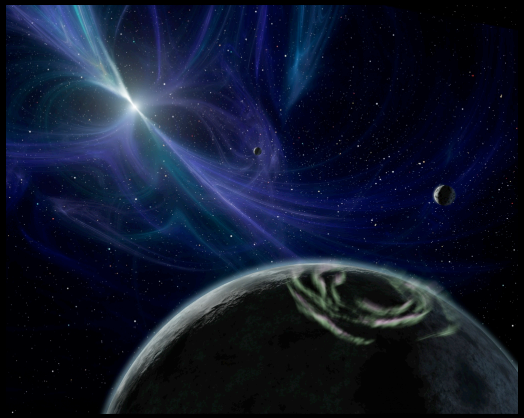
“The Holy Grail”

Someone et al. 20??



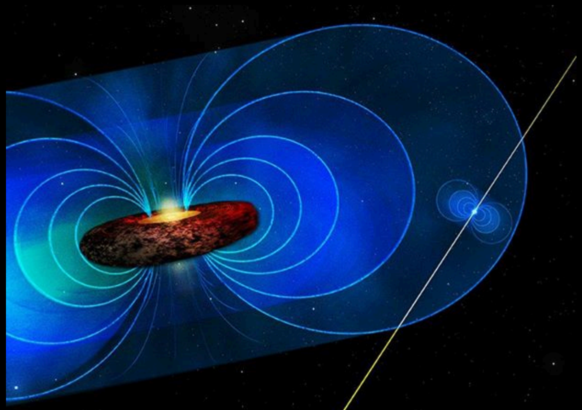
“Double Pulsar”

Lyne et al. 2004



First exoplanets

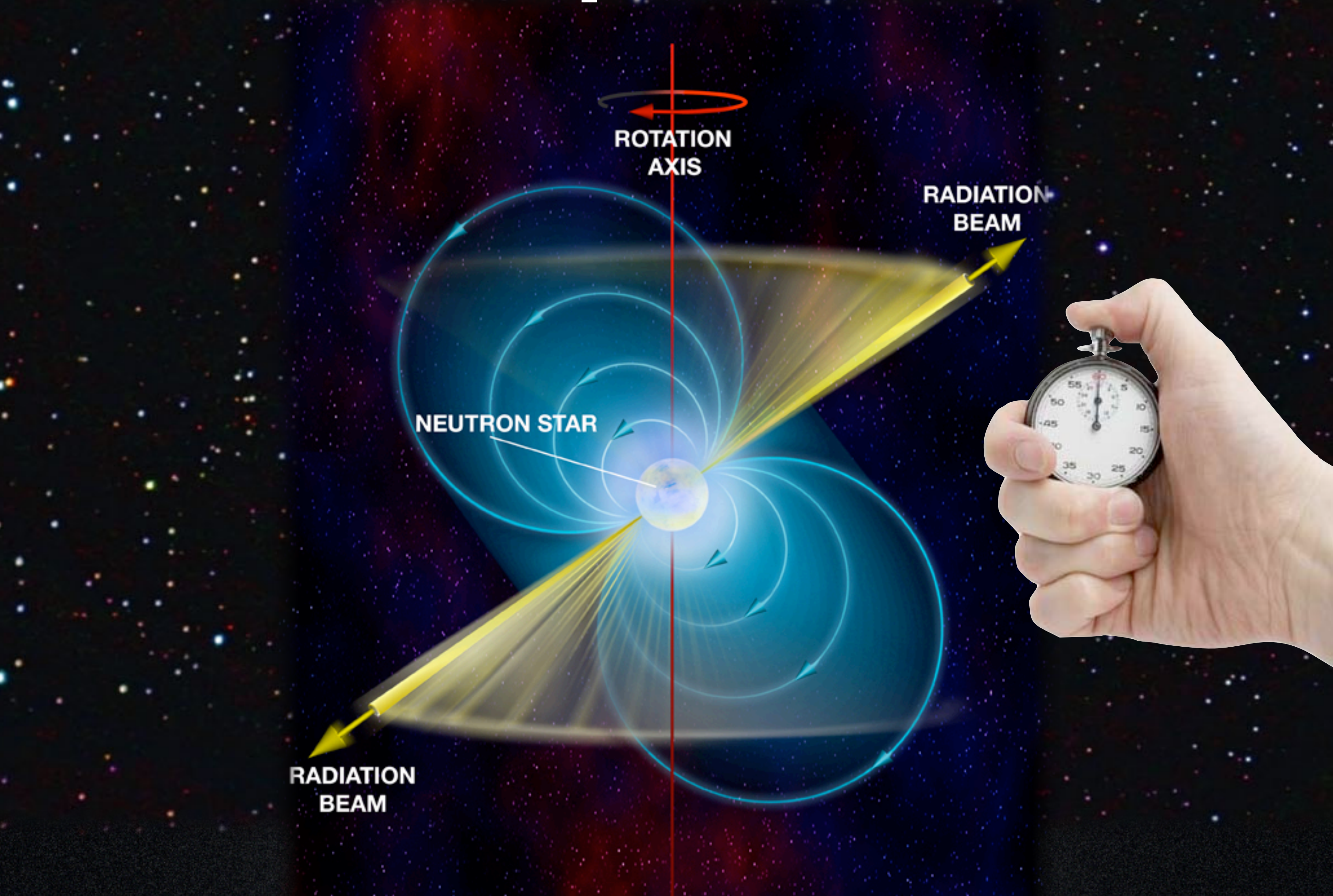
Wolszczan et al. 1992



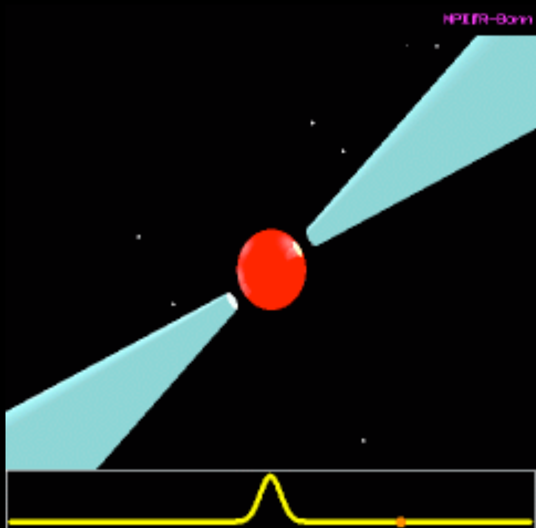
Galactic Center Magnetar

Eatough et al. 2013

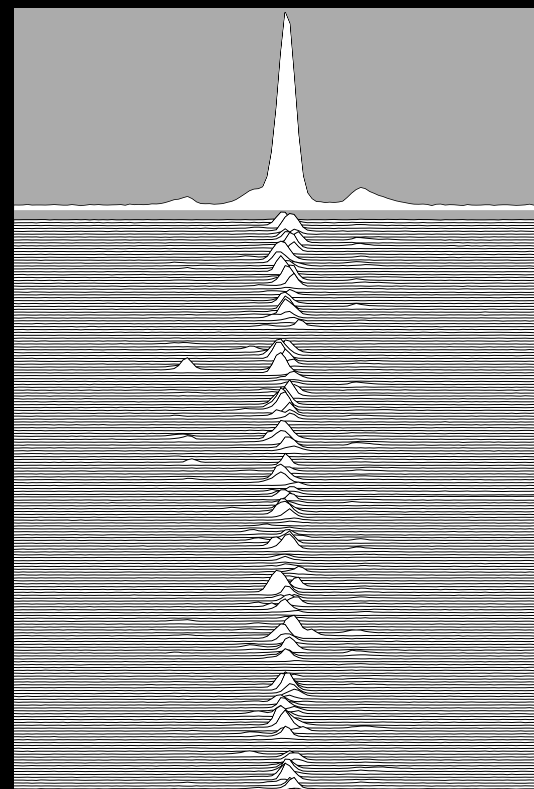
Pulsars are precision clocks



Pulsars timing process



Collect pulses

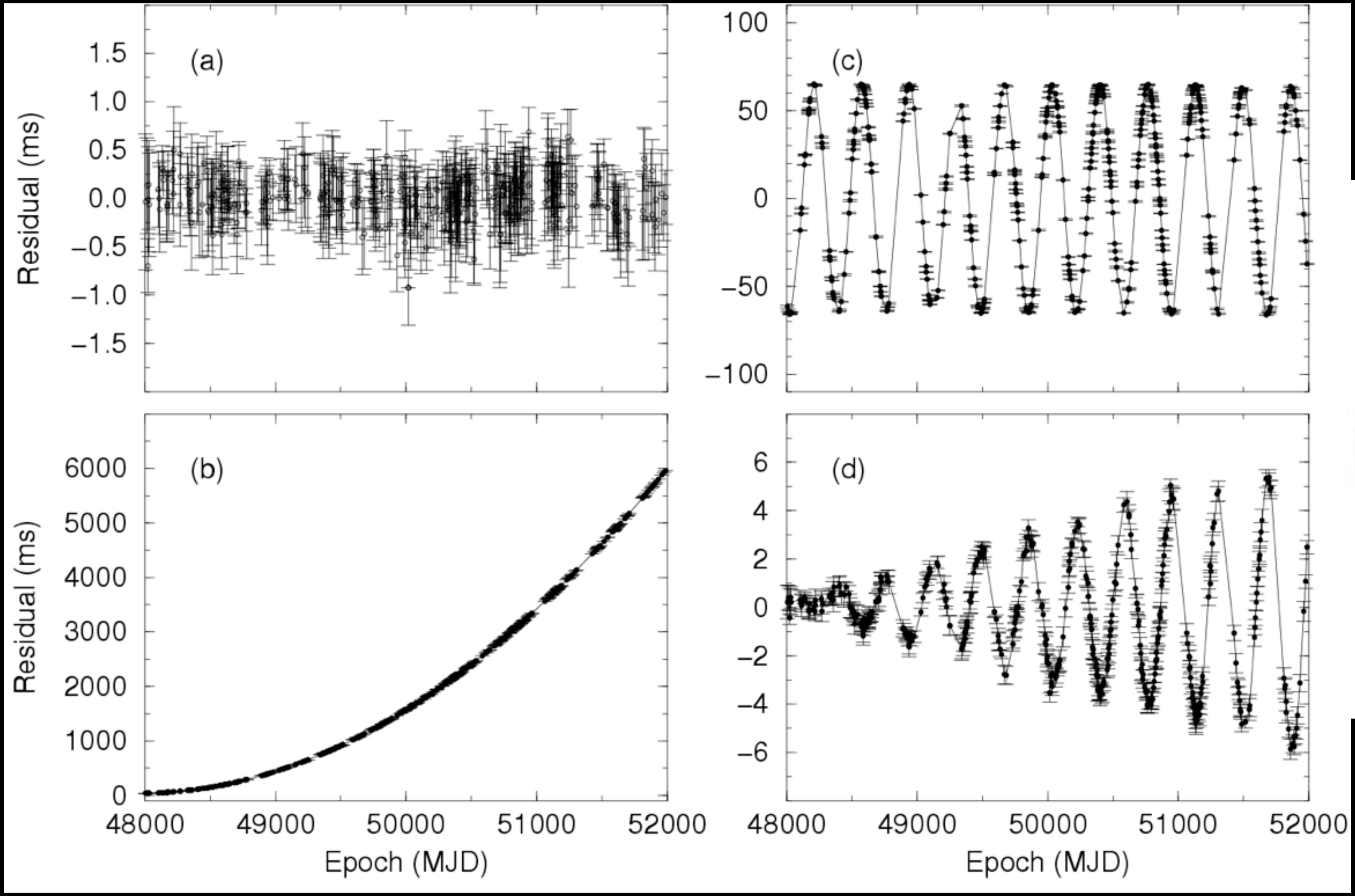


Dedisperse, fold and cross-correlate with template

54255.1231254524233
54255.2643443523453
54255.3123524545899
54255.3513745623467
54255.4418456543355
54255.5001234234688

Times of arrival (TOAs)

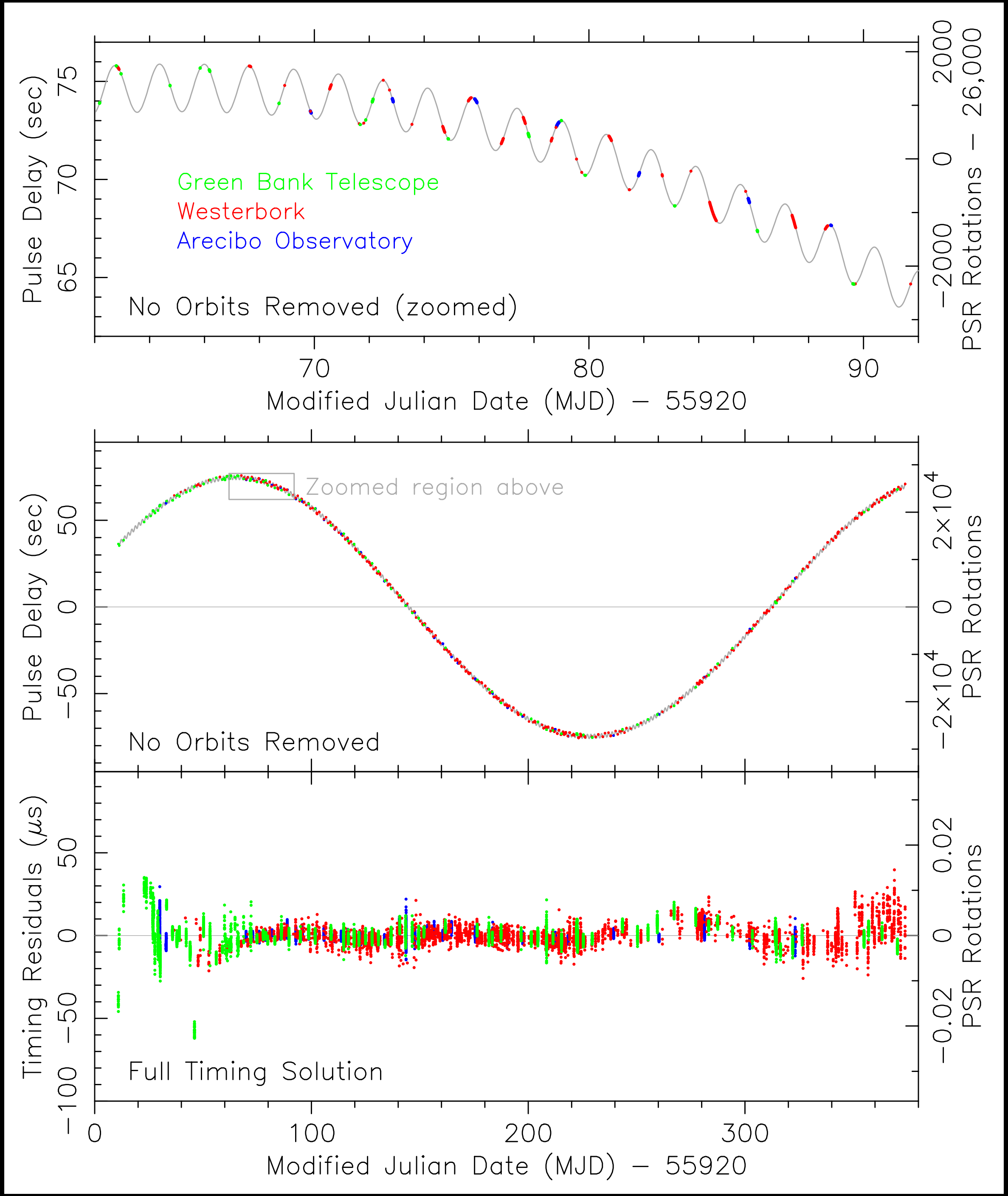
Pulsar Timing Model



Lorimer & Kramer

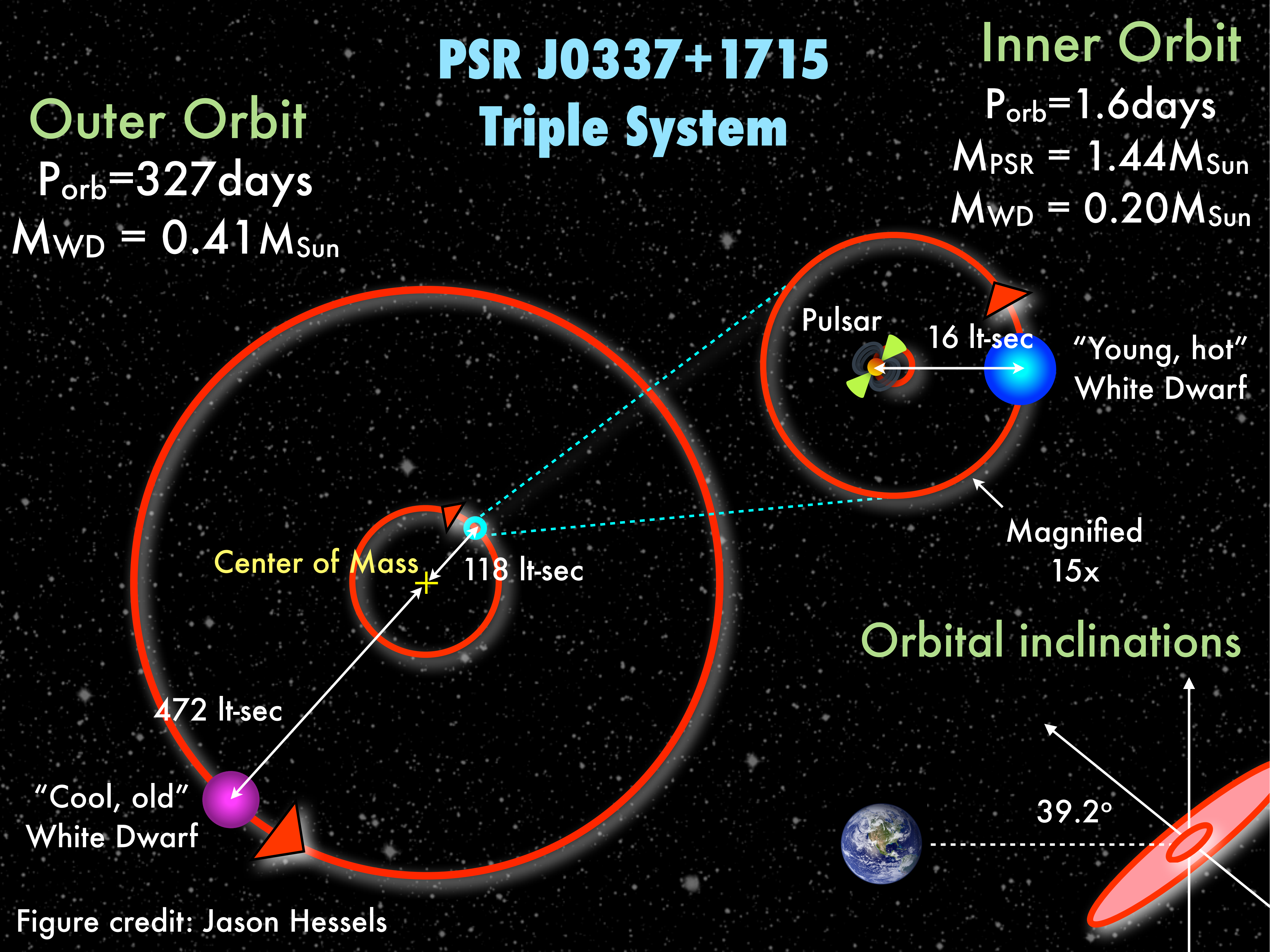
Coherent timing: use TOAs to unambiguously count every single rotation of pulsar over timescales of years.

J0337+1715 - Timing Observations



- Full outer orbit now observed.
- ~1000hrs of observations.
- Near-daily Westerbork observations.
- 25,000 times-of-arrival.

Ransom et al. 2014, *Nature*



PSR J0337+1715
Triple System
Outer Orbit
P_{orb}=327days
M_{WD} = 0.41M_{Sun}
Inner Orbit
P_{orb}=1.6days
M_{PSR} = 1.44M_{Sun}
M_{WD} = 0.20M_{Sun}
Pulsar
16 lt-sec
"Young, hot" White Dwarf
Magnified 15x
Center of Mass
118 lt-sec
472 lt-sec
"Cool, old" White Dwarf
Orbital inclinations
39.2°
Figure credit: Jason Hessels

J0337+1715 - Timing Observations

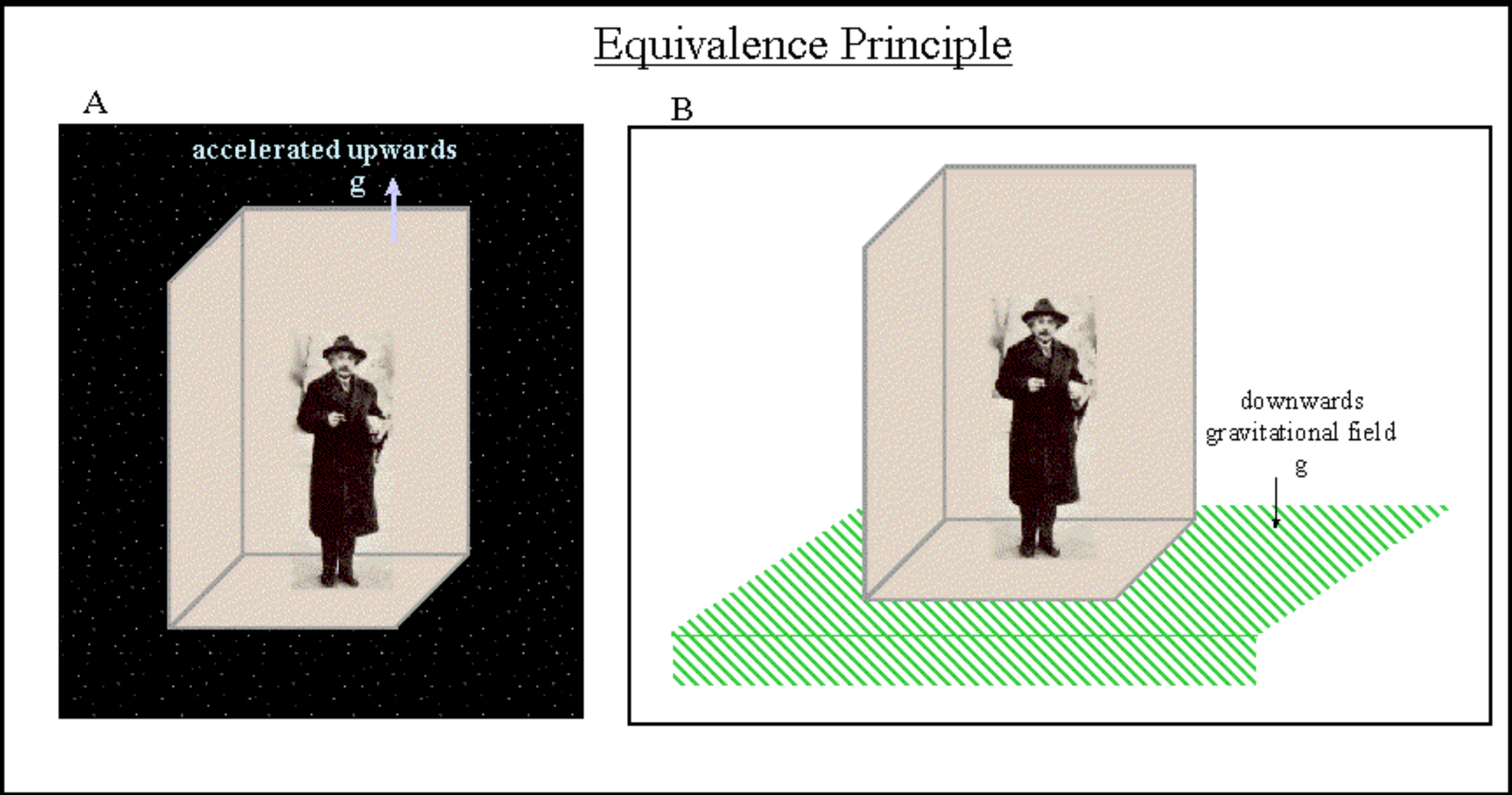
Parameter	Symbol	Value
Fixed values		
Right ascension	RA	$03^h37^m43^s.82589(13)$
Declination	Dec	$17°15'14''.828(2)$
Dispersion measure	DM	$21.3162(3)$ pc cm^{-3}
Solar system ephemeris		DE405
Reference epoch		MJD 55920.0
Observation span		MJD $55930.9 - 56436.5$
Number of TOAs		26280
Weighted root-mean-squared residual		$1.34\,\mu$s
Fitted parameters		
Spin-down parameters		
Pulsar spin frequency	f	$365.953363096(11)$ Hz
Spin frequency derivative	$\dot{f}$	$-2.3658(12) \times 10^{-15}$ Hz s^{-1}
Inner Keplerian parameters for pulsar orbit		
Semimajor axis projected along line of sight	$(a \sin i)_I$	$1.21752844(4)$ lt-s
Orbital period	$P_{b,I}$	$1.629401788(5)$ d
Eccentricity parameter ($e \sin \Omega$)	$\epsilon_{1,I}$	$6.8567(2) \times 10^{-4}$
Eccentricity parameter ($e \cos \Omega$)	$\epsilon_{2,I}$	$-9.171(2) \times 10^{-5}$
Time of ascending node	$t_{\mathrm{asc},I}$	MJD $55920.407717436(17)$
Outer Keplerian parameters for centre of mass of inner binary		
Semimajor axis projected along line of sight	$(a \sin i)_O$	$74.6727101(8)$ lt-s
Orbital period	$P_{b,O}$	$327.257541(7)$ d
Eccentricity parameter ($e \sin \Omega$)	$\epsilon_{1,O}$	$3.5186279(3) \times 10^{-2}$
Eccentricity parameter ($e \cos \Omega$)	$\epsilon_{2,O}$	$-3.462131(11) \times 10^{-3}$
Time of ascending node	$t_{\mathrm{asc},O}$	MJD $56233.935815(7)$
Interaction parameters		
Semimajor axis projected in plane of sky	$(a \cos i)_I$	$1.4900(5)$ lt-s
Semimajor axis projected in plane of sky	$(a \cos i)_O$	$91.42(4)$ lt-s
Inner companion mass over pulsar mass	$q_I = m_{cI}/m_p$	$0.13737(4)$
Difference in longs. of asc. nodes	δ_Ω	$2.7(6) \times 10^{-3}$ °
Inferred or derived values		
Pulsar properties		
Pulsar period	P	$2.73258863244(9)$ ms
Pulsar period derivative	$\dot{P}$	$1.7666(9) \times 10^{-20}$
Inferred surface dipole magnetic field	B	2.2×10^8 G
Spin-down power	$\dot{E}$	3.4×10^{34} erg s^{-1}
Characteristic age	τ	2.5×10^9 y
Orbital geometry		
Pulsar semimajor axis (inner)	a_I	$1.9242(4)$ lt-s
Eccentricity (inner)	e_I	$6.9178(2) \times 10^{-4}$
Longitude of periastron (inner)	ω_I	$97.6182(19)$ °
Pulsar semimajor axis (outer)	a_O	$118.04(3)$ lt-s
Eccentricity (outer)	e_O	$3.53561955(17) \times 10^{-2}$
Longitude of periastron (outer)	ω_O	$95.619493(19)$ °
Inclination of invariant plane	i	$39.243(11)$ °
Inclination of inner orbit	i_I	$39.254(10)$ °
Angle between orbital planes	δ_i	$1.20(17) \times 10^{-2}$ °
Angle between eccentricity vectors	$\delta_\omega \sim \omega_O - \omega_I$	$-1.9987(19)$ °
Masses		
Pulsar mass	m_p	$1.4378(13)\, M_\odot$
Inner companion mass	m_{cI}	$0.19751(15)\, M_\odot$
Outer companion mass	m_{cO}	$0.4101(3)\, M_\odot$

Timing modeling by:
Anne Archibald

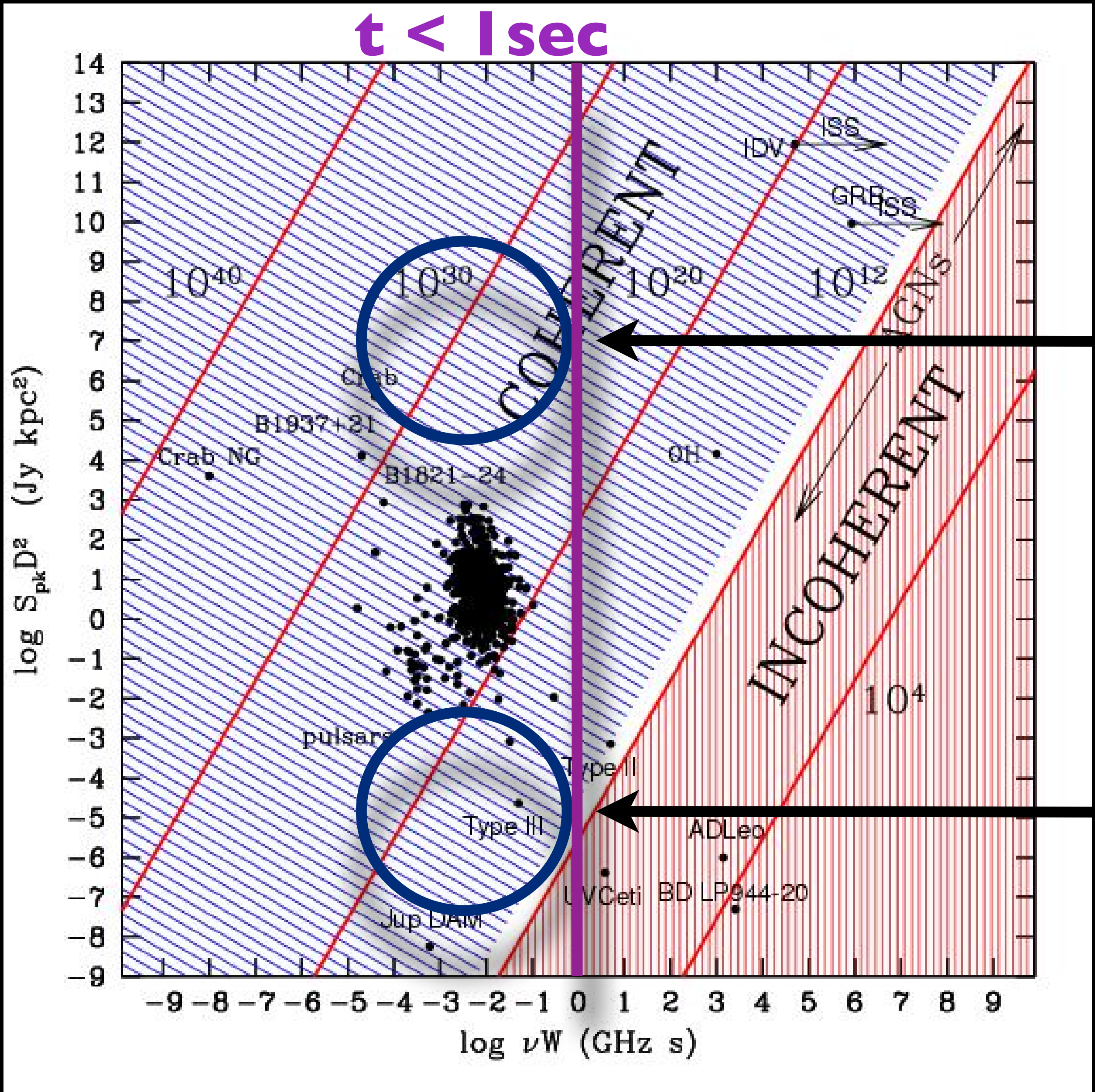
Pulsar mass: 1.4378(13) Msun
Inner WD mass: 0.19751(15) Msun
Outer WD mass: 0.4101(3) Msun

You are impressed by all the high-precision numbers...

Also test the Strong Equivalence Principle?



Transient Parameter Space



Cordes et al. 2004

Large FoV for rare, bright events

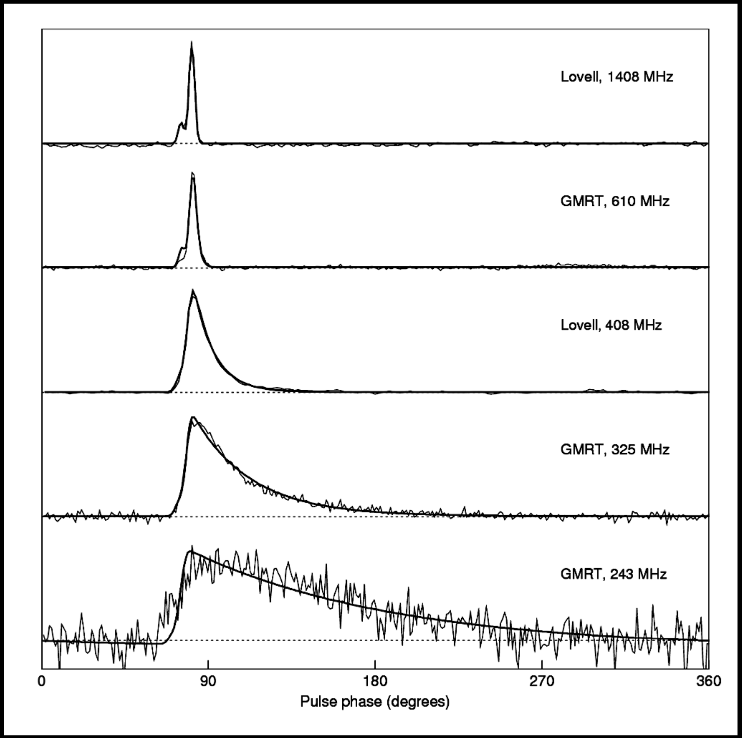
Large instantaneous sensitivity for weak source classes

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

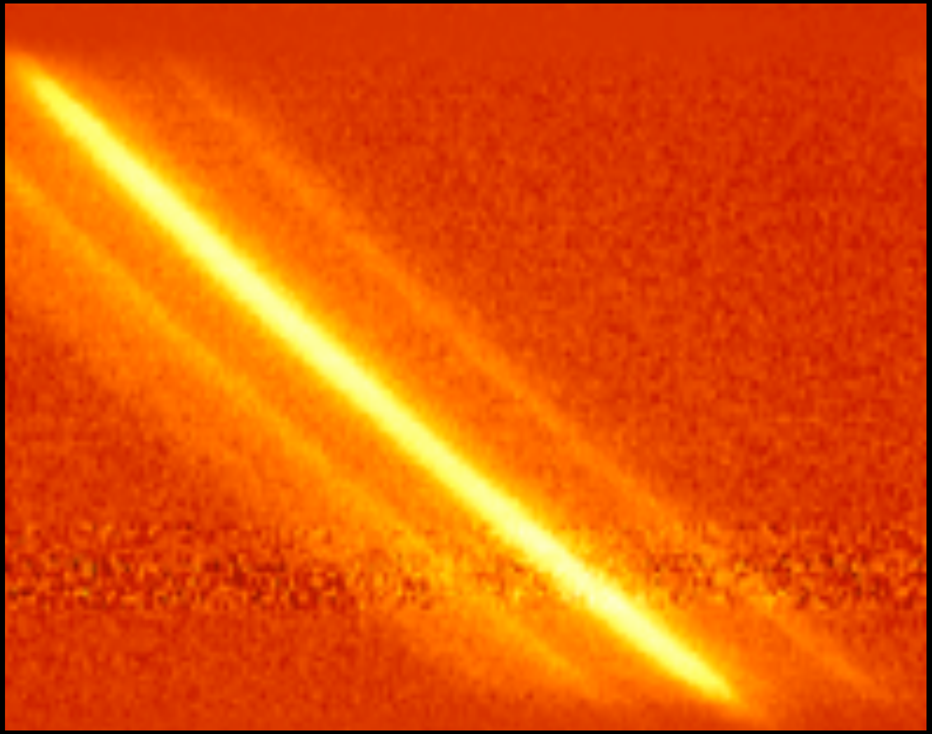
Scattering



Frequency ↑

Time →

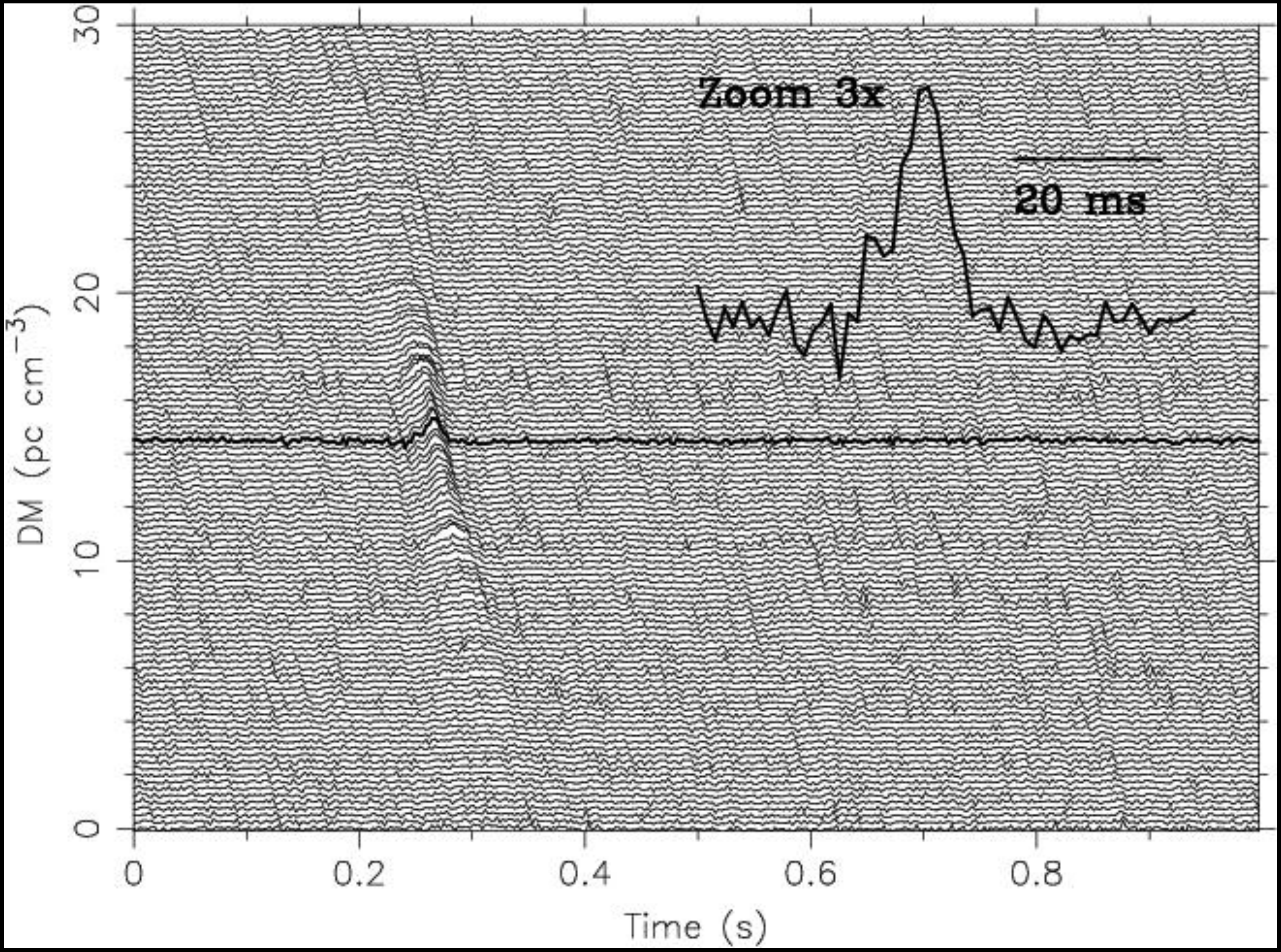
Dispersion



Frequency ↑

Time →

Pulsar Searching



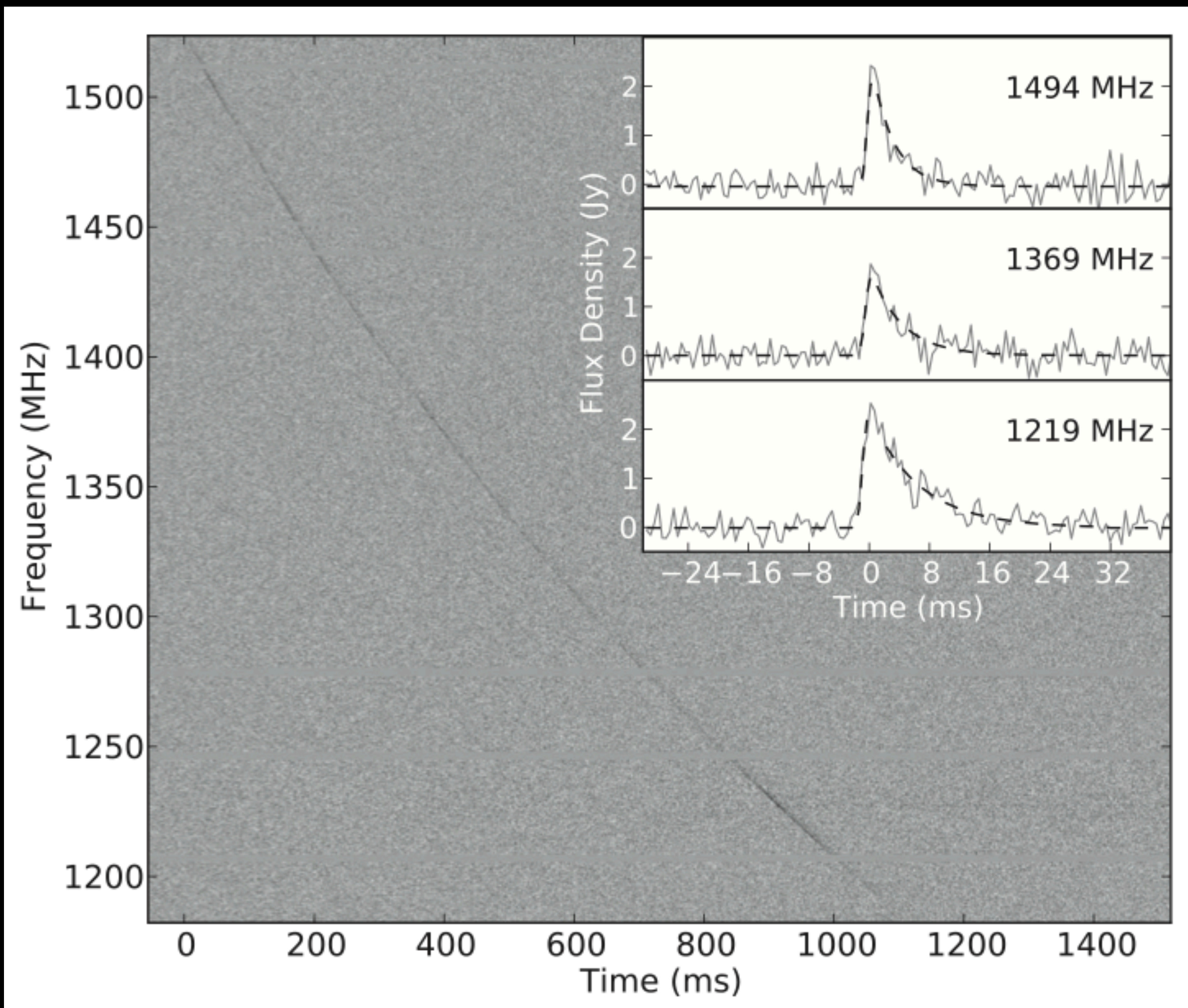
Dispersion measure trial →

Time →

The Thornton Bursts

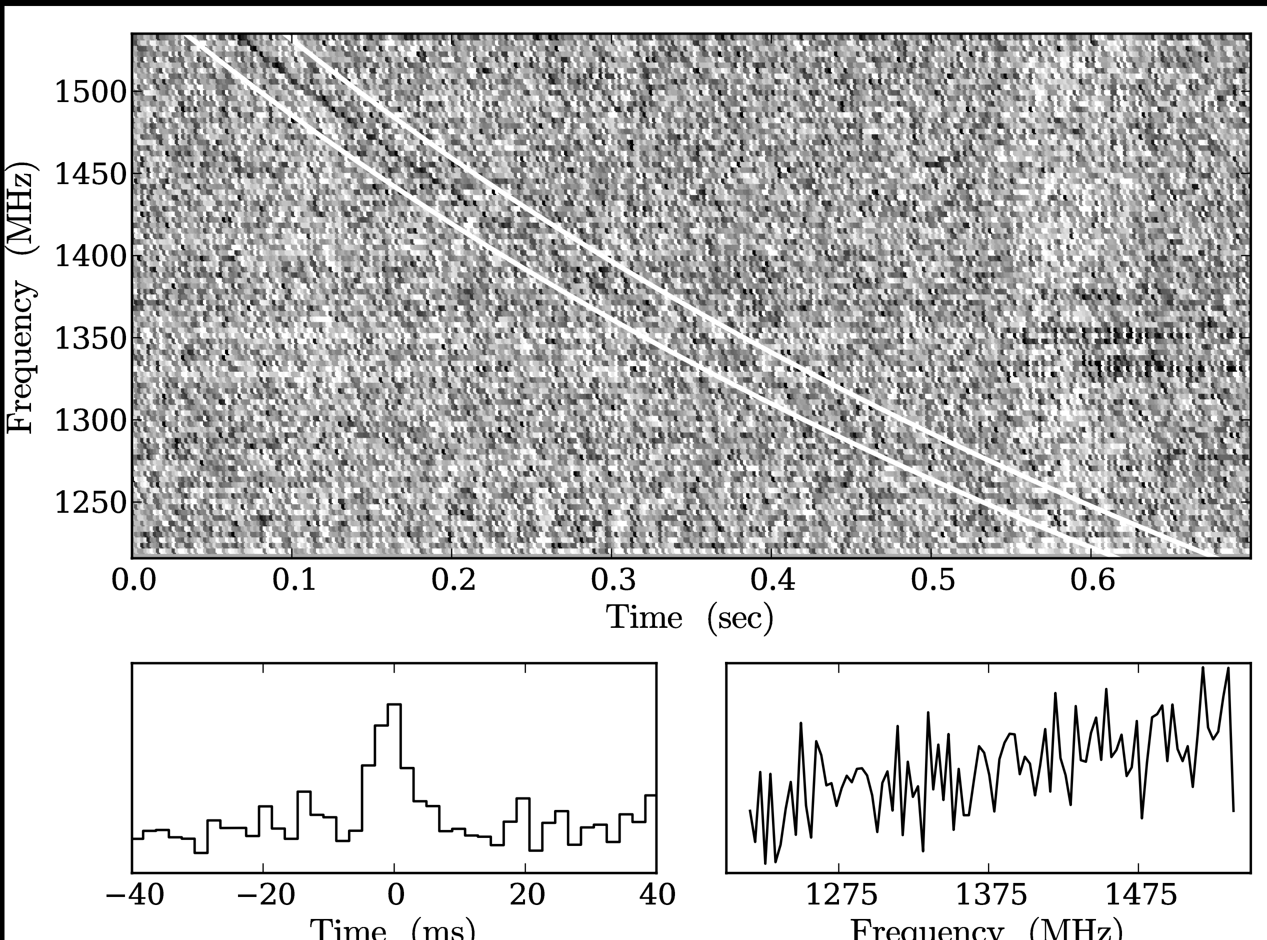
a.k.a. *Fast Radio Bursts* (FRBs)

Thornton et al. 2013, *Science*

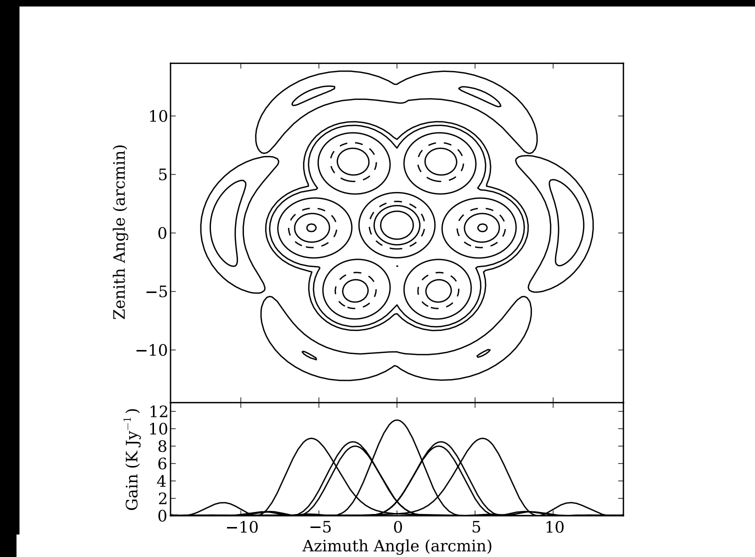


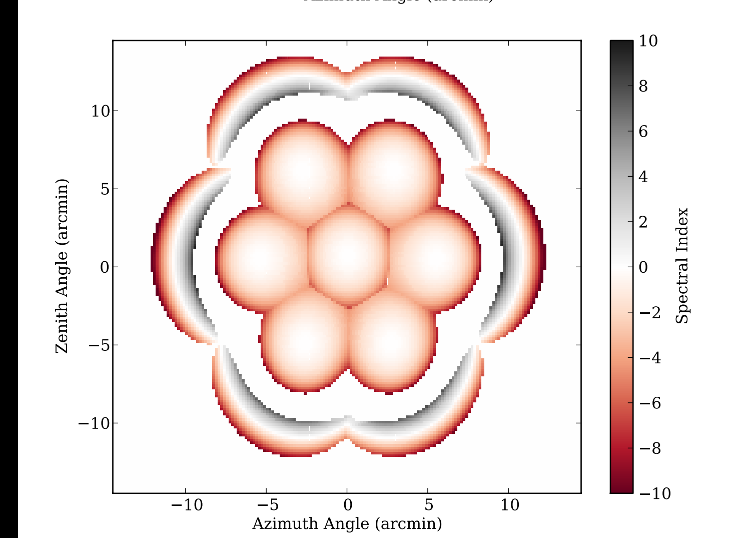
- FRB 110220.
- DM = 944 pc/cc
- z ~ 0.8?
- Shows expected dispersive delay *and* scatter-broadening.
- 10,000 /sky/day?!

PALFA FRB



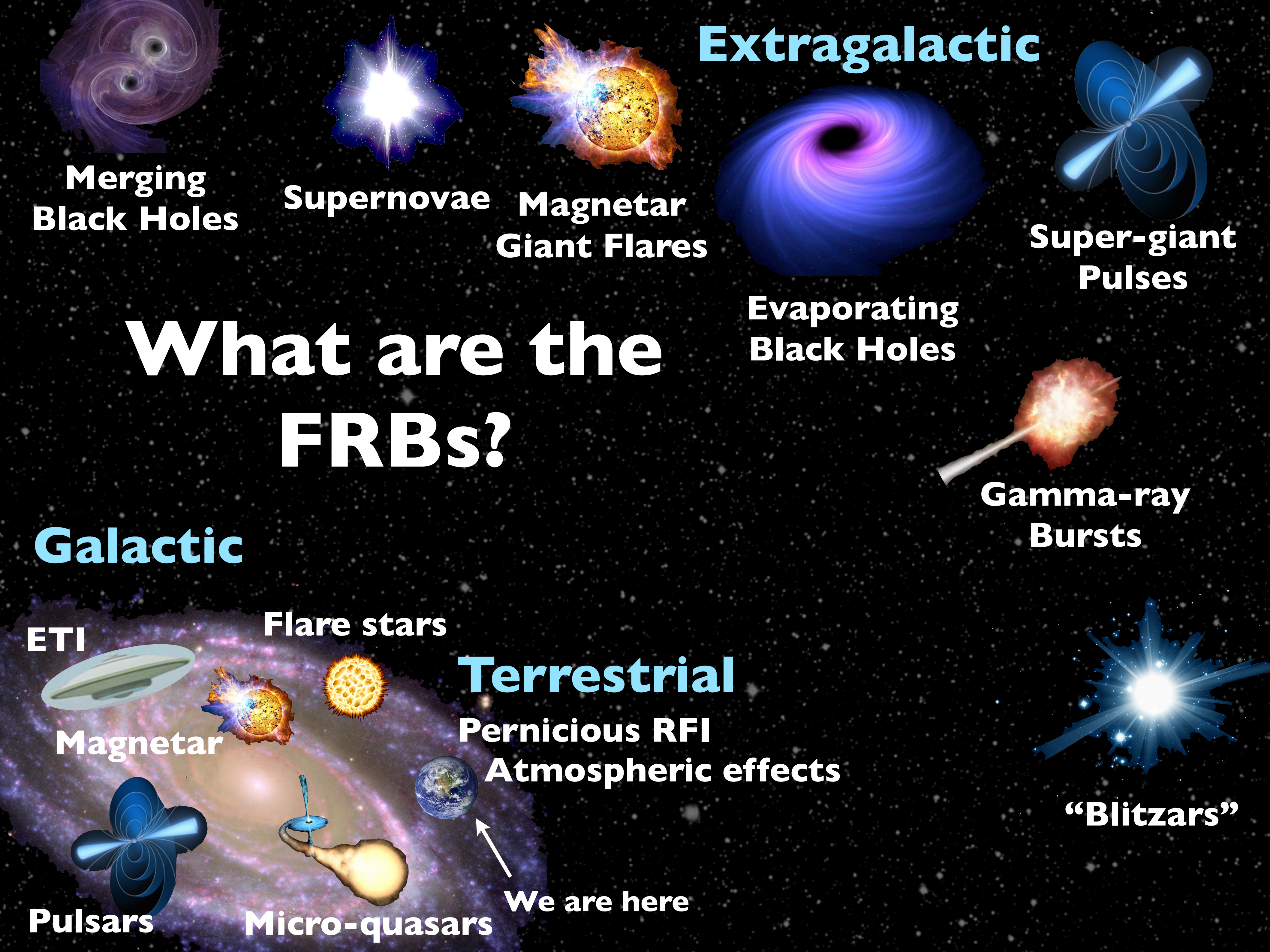
Spitler





Cordes & Chatterjee

Spitler, Cordes, Hessels, Lorimer, McLaughlin, Chatterjee,...



Extragalactic
Merging Black Holes
Supernovae
Magnetar Giant Flares
Super-giant Pulses
Evaporating Black Holes
What are the FRBs?
Gamma-ray Bursts
Galactic
ETI
Flare stars
Terrestrial
Pernicious RFI
Atmospheric effects
Magnetar
"Blitzars"
Pulsars
Micro-quasars
We are here

Why Interesting

If at least some FRBs are extragalactic:

- Origin in a cataclysmic event (study extreme physics).
- Complement to grav. wave events?
- Probe intergalactic medium. Missing baryon problem (McQuinn 2013; Deng & Zhang 2014). Also map intergalactic magnetic fields.
- Use as cosmic rulers. Measure dark energy equation-of-state parameter "*w*" at z>2 (Zhou et al. 2014).

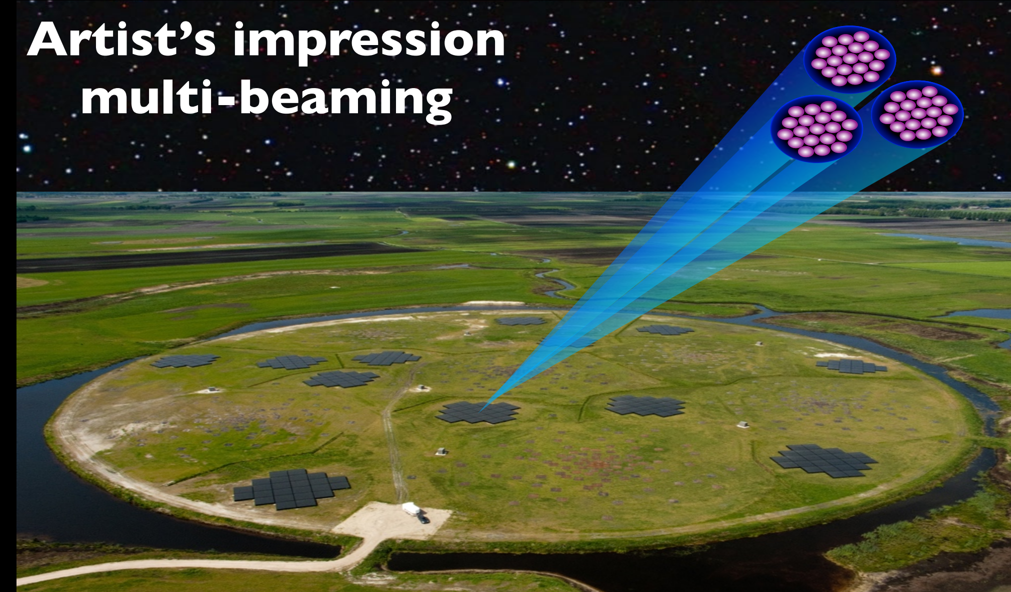
Need an "FRB factory" capable of detecting and localizing 1000s of these.

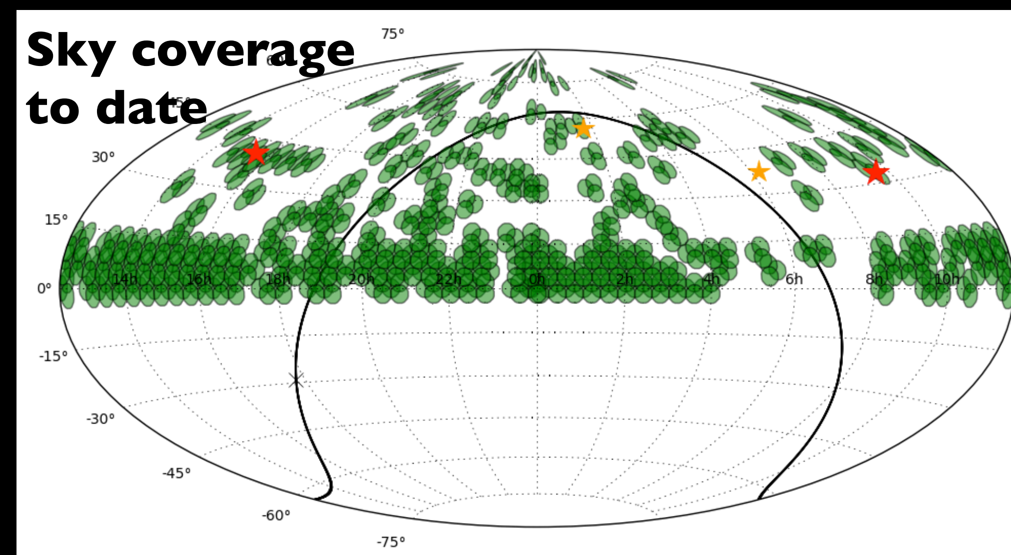
LOFAR Pulsar and Fast Transient Survey

• All-sky coverage enabled by LOFAR software multi-beaming.
• Scientific *and* technical pathfinder for SKA-Low/-Mid.

• Data rate = 36Gb/s!
• 1 petabyte of data collected.
• 10 million CPU core hrs needed for analysis.
• First SKA-like pulsar survey.

• 4 nearby pulsars discovered already.
• Expect ~200 discoveries over the whole sky.





LOFAR Pulsar discoveries