

***School on **G**ravitational **W**aves, neutrinos
and multiwavelength e.m. observations:
the new frontier of **A**stronomy***

16 April 2013 - INAF-Monteporzio

**Compact binaries as sources
of Gravitational Waves:
*exploiting pulsar Timing & Pulsar Timing Arrays***

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Astronomico
di Cagliari



Outline

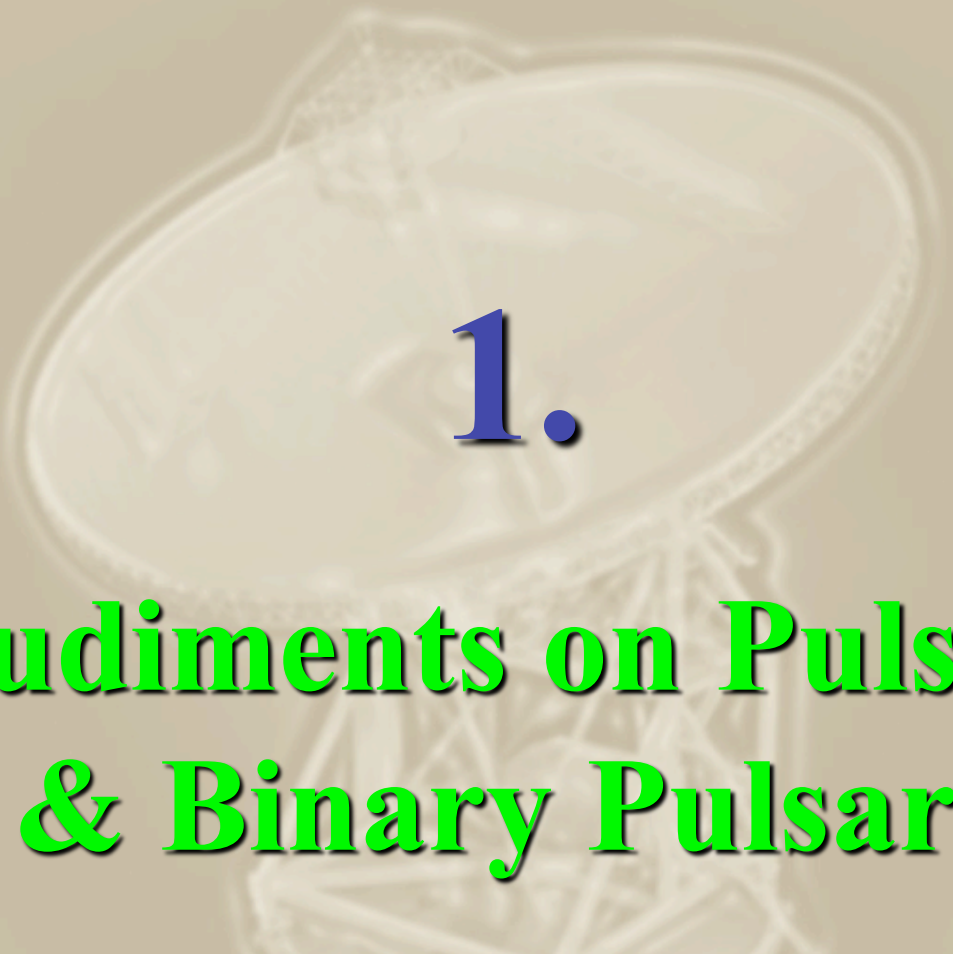
1. **Rudiments on Pulsars & Binary Pulsars**
2. **Pulsar Timing Concepts**
3. **Binary Pulsars as probes of GW emission**
4. **Merger rate and GW direct detection**
5. **Pulsar Timing Arrays as GW detectors**

Books

- Manchester & Taylor 1977 **“Pulsars”**
- Lyne & Smith 2005 **“Pulsar Astronomy”**
- Lorimer & Kramer 2005 **“Handbook of Pulsar Astronomy”**
- AA.VV. 2009 **“Physics of relativistic objects in compact binaries: from birth to coalescence”, Springer**

Review Articles

- Science, April 2004 – **Neutron Stars, Isolated Pulsars, Binary Pulsars**
- ARA&A, Jan 2008 – **The Double Pulsar**
- Living Reviews articles: (<http://relativity.livingreviews.org/Articles>)
 - Stairs 2003: **Testing General Relativity with pulsar timing**
 - Will, 2006: **The confrontation btw General Relativity and experiment**
 - Lorimer 2008: **Binary and millisecond pulsars**



1.

Rudiments on Pulsars & Binary Pulsars

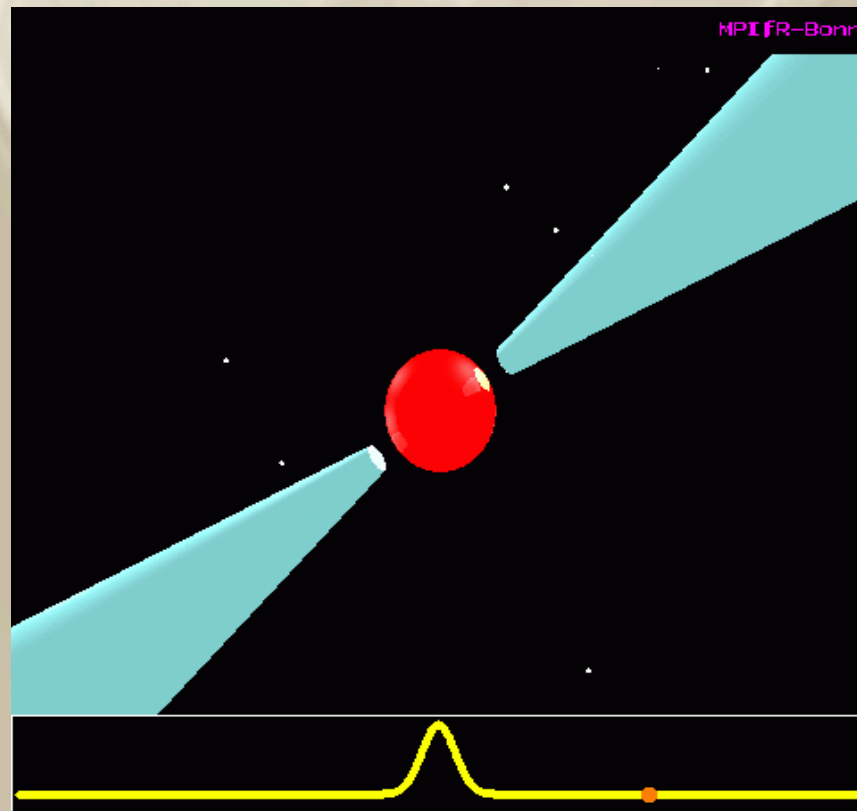


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What is a Radio Pulsar

A **PULSAR** is a rapidly **rotating** and highly **magnetized neutron star**, emitting a pulsed radio signal as a consequence of a **light-house effect**



@Kramer

The rotating magnetized NS in vacuum



$$\mu = \frac{1}{2} B_p R^3$$

is the magnetic
moment

R = NS radius

B_p = polar magn. field

Assuming that the rotational energy loss

$$L_{sd} = d/dt (E_{rot}) = d/dt (I\Omega^2/2) = I \Omega \dot{\Omega}$$

matches the emitted power (derived

from the basic electrodynamics formula):

$$L_{dipole} = [2/3c^3] |\ddot{\mu}|^2$$

one can infer...

Radio pulsar basic parameters

Radio pulsars are powered by **rotational energy**

The observation of the spin period **P** and of its derivative $\dot{P}$ allows one to give an estimate of various physical quantities:

Spin-down age: $\tau_c = 1.6 \cdot 10^7 P / \dot{P}_{-15} \text{ yr}$

Spin-down power: $L_{sd} = 3.9 \cdot 10^{31} P^{-3} \dot{P}_{-15} \text{ erg/s}$

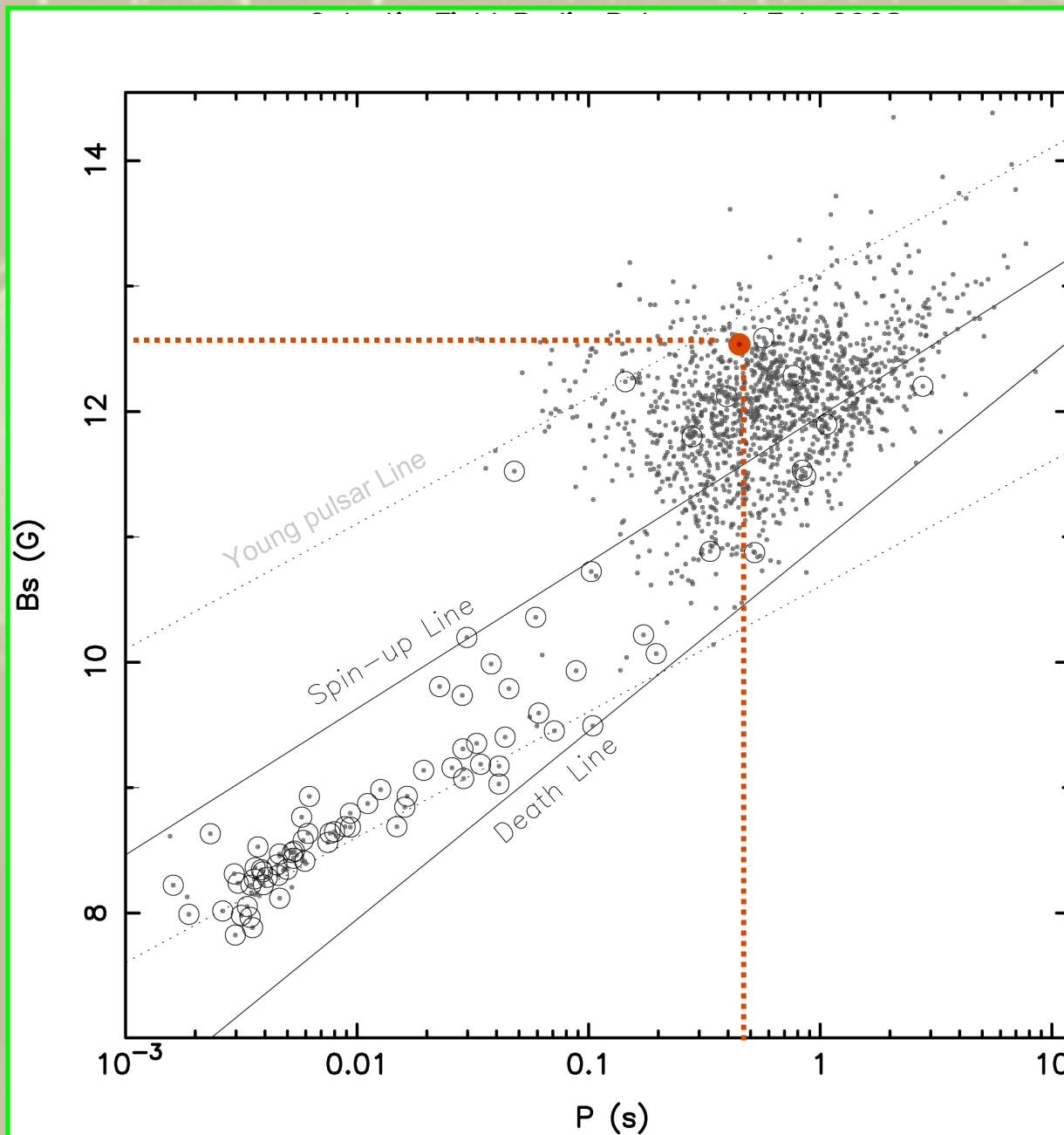
Surface magnetic field: $B_{surf} = 1.0 \cdot 10^{12} [P \dot{P}_{-15}]^{1/2} \text{ Gauss}$

...and allows one to place a pulsar on the basic **P vs $\dot{P}$**
[or **P vs B_{surf}**] diagram...

The B_s vs P diagram

A pulsar is put on it once both P and dP/dt are measured, from which

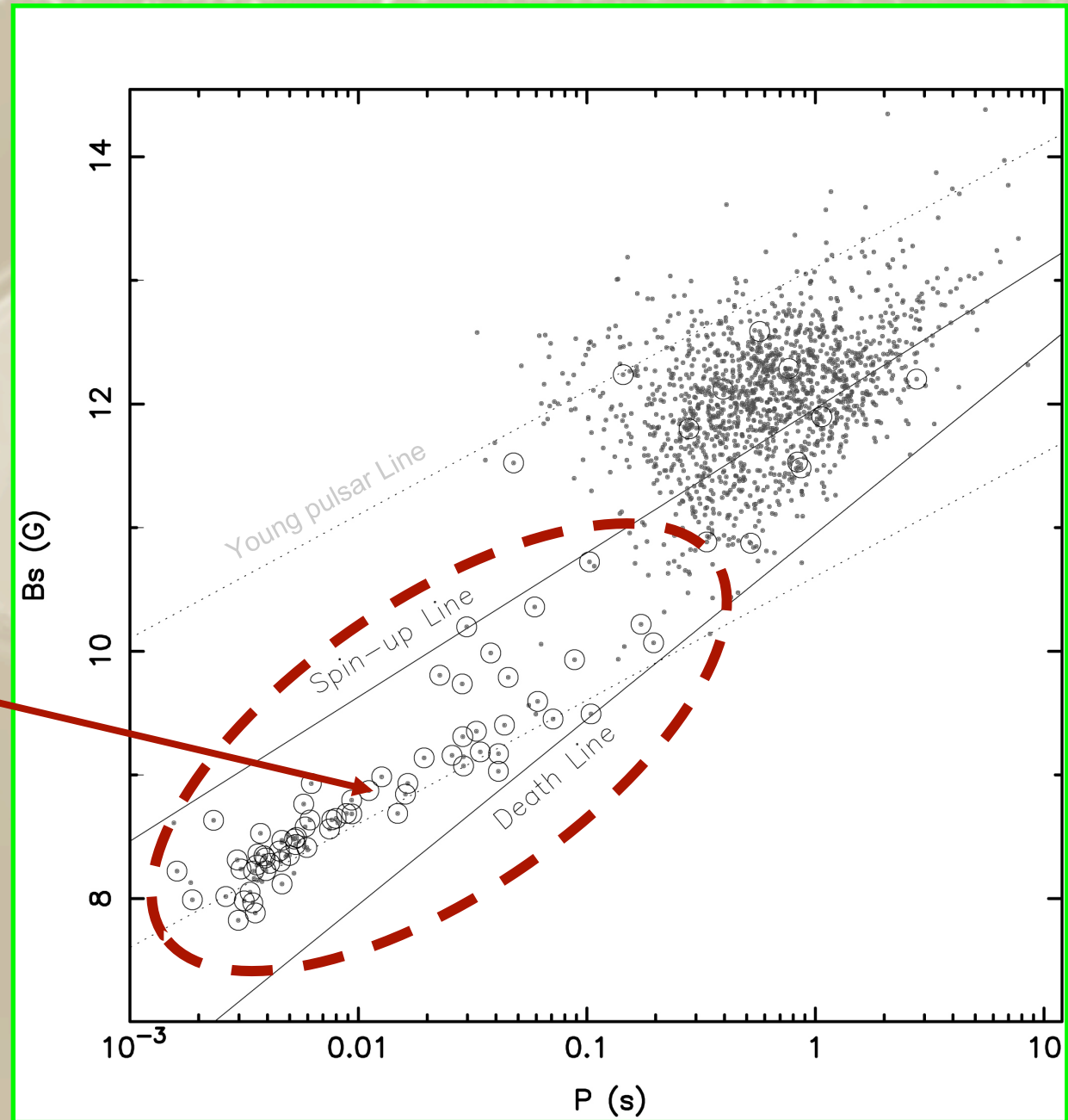
$$B_s = 3.2 \cdot 10^{19} [P \dot{P}]^{1/2} \text{ G}$$



ATNF Pulsar Catalogue

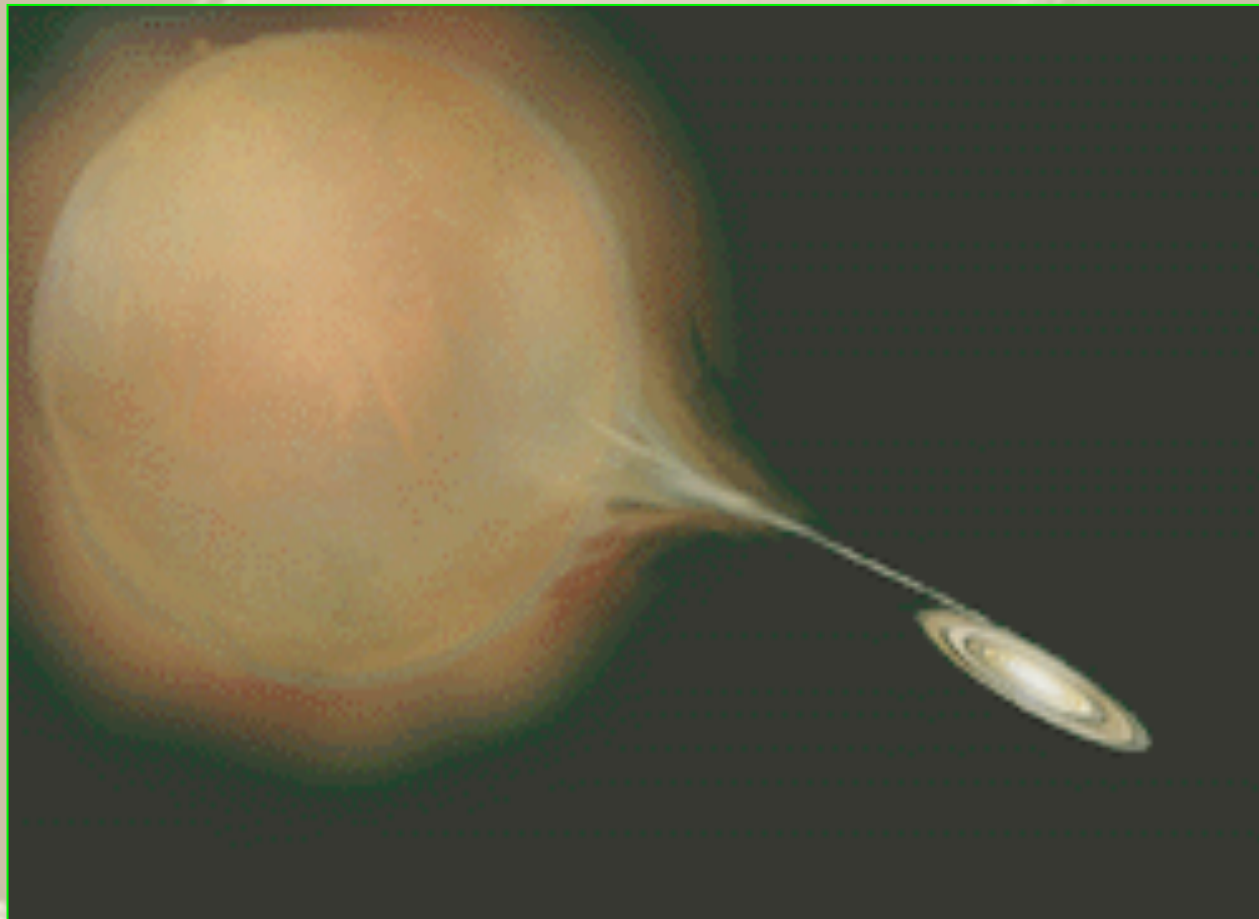
A dichotomy in the population

**How to explain
this group of
pulsars ?**



The MSP formation paradigm

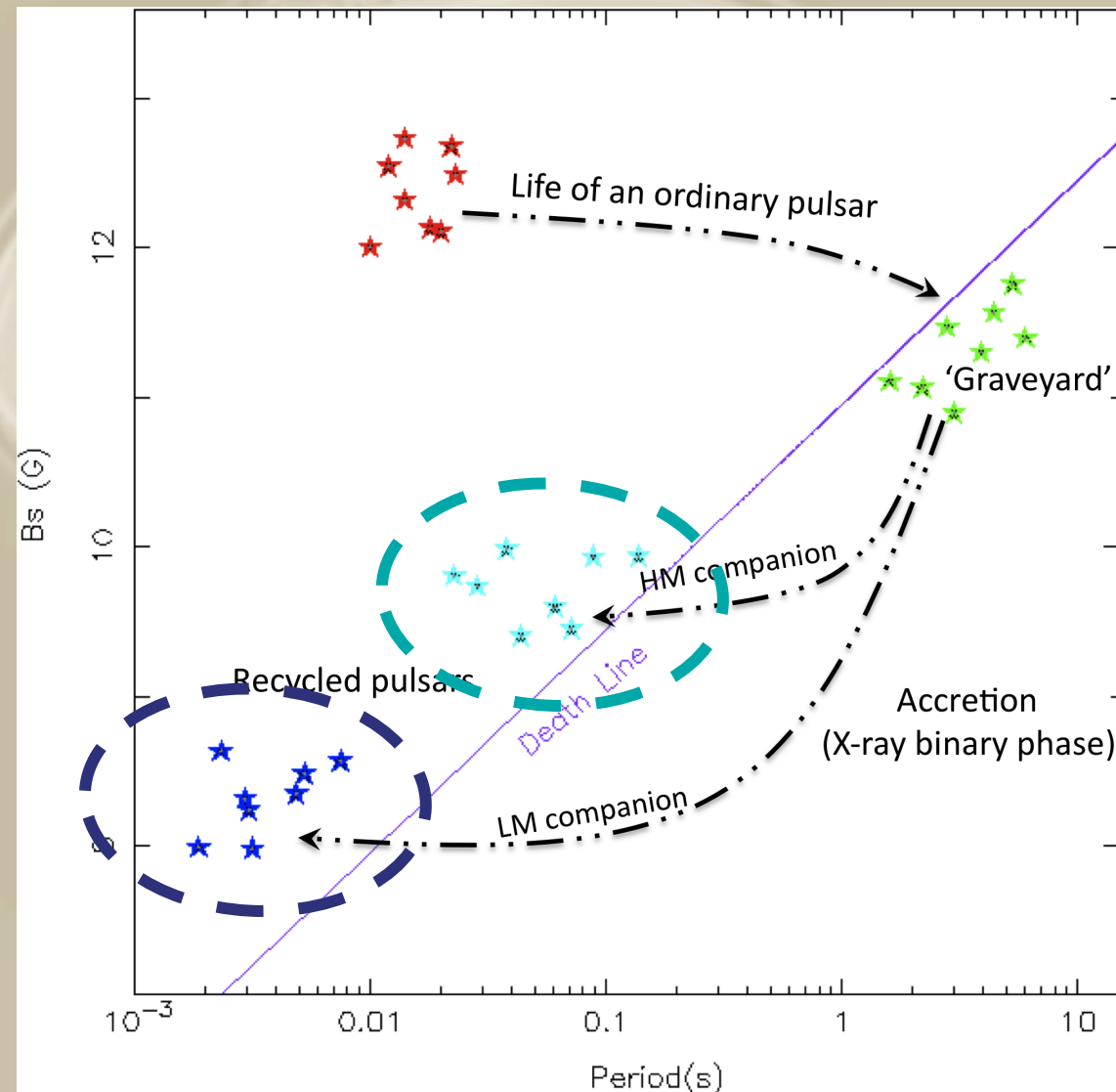
Recycling scenario: Millisecond pulsars are old neutron stars spun up by accretion of matter and angular momentum from a companion star in a multiple system [Bisnovati-Kogan & Kornberg 1974, Alpar et al. 1982]



Which evolution originates which?

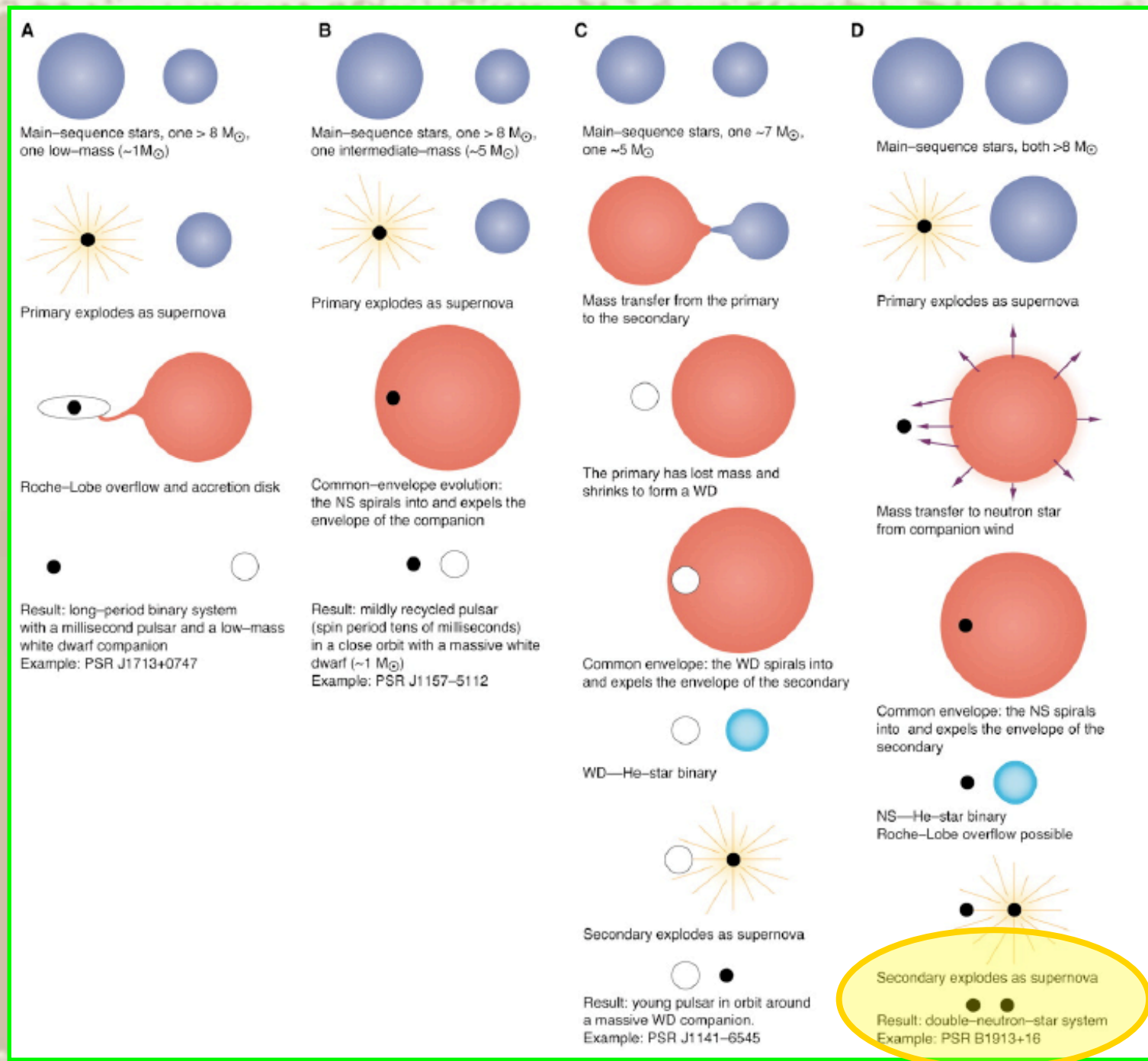
Mildly recycled: e.g.
double neutron
stars

Fully recycled: in
most cases
MSP+WD

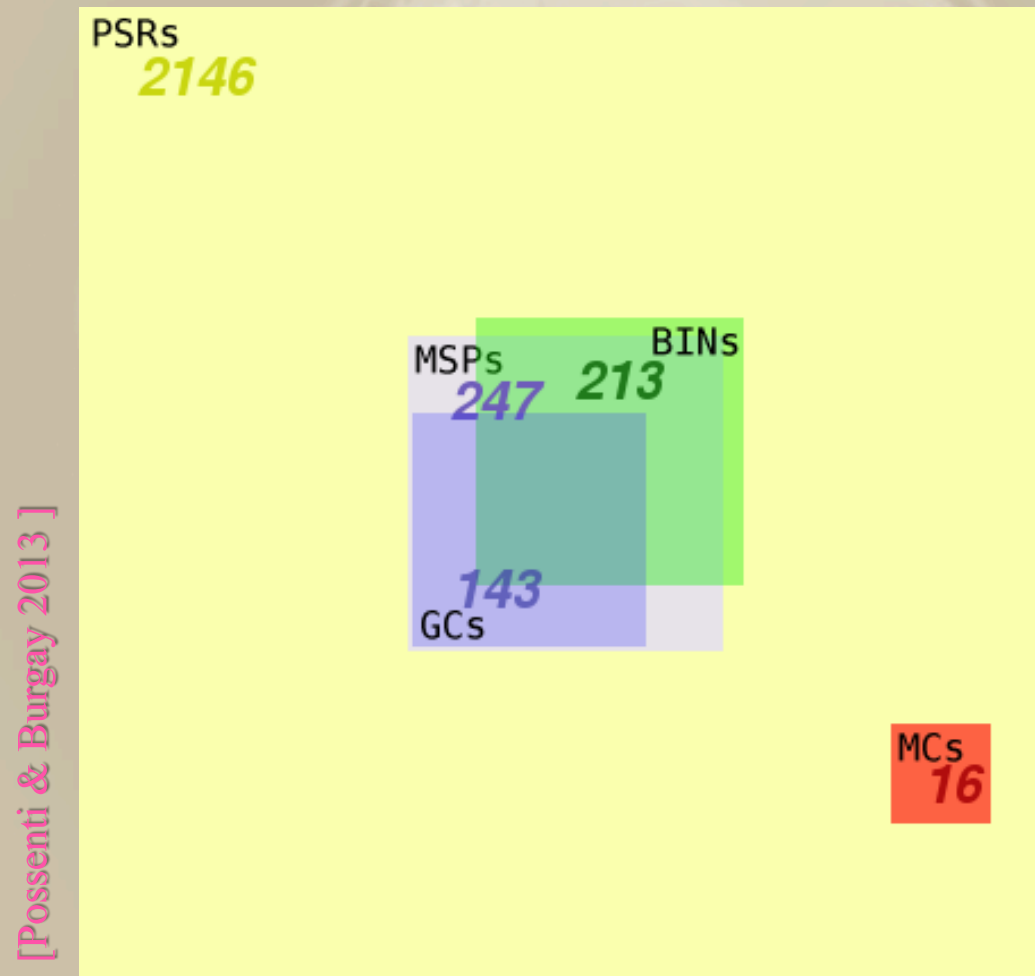


[@Burgay 2011]

Binary Evolution: at least 4 paths



The current pulsar demography



≈10 % of known pulsars are in binaries



2.

Pulsar Timing Concepts



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Timing idea: observations

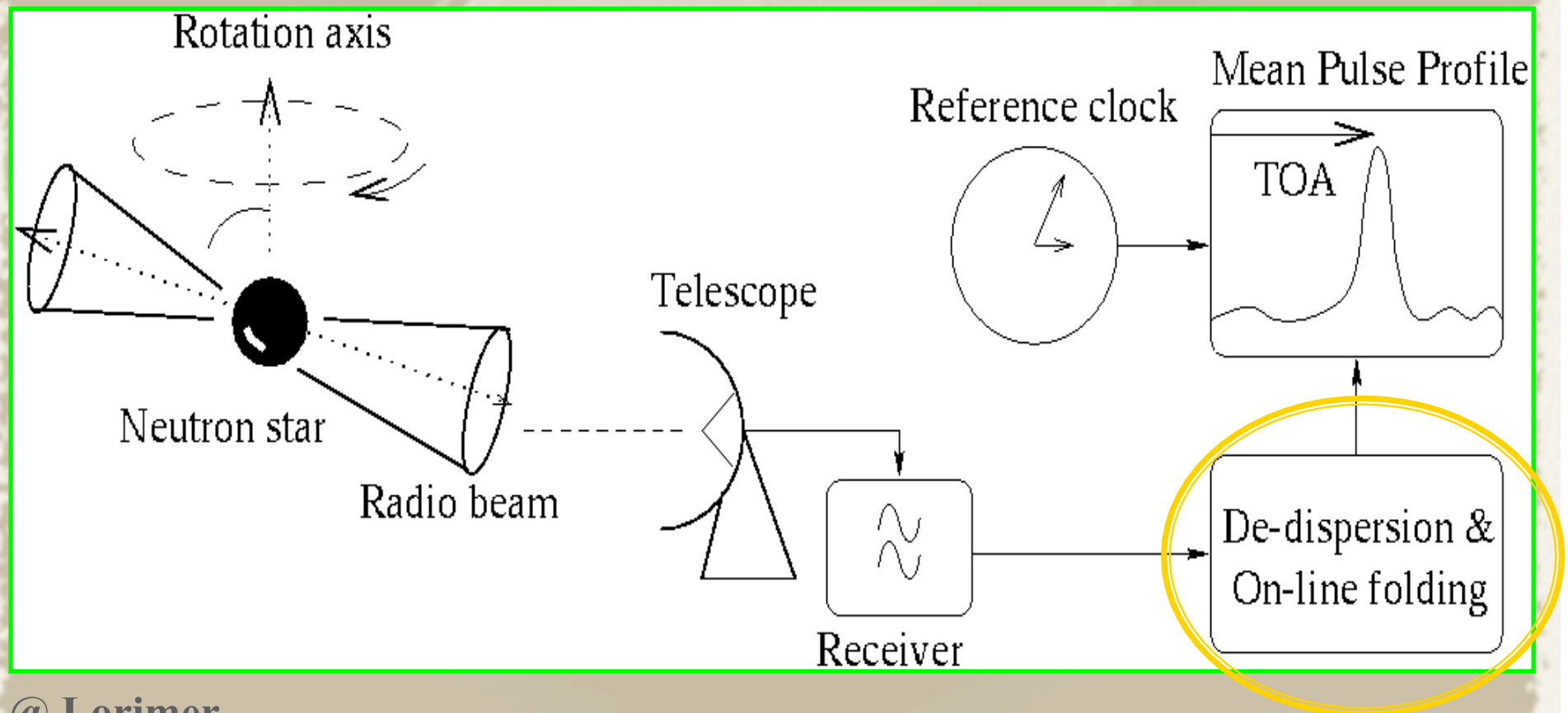
Performing **repeated observations of the Times of Arrival (ToAs)** at the telescope of the pulsations from a given pulsar

and

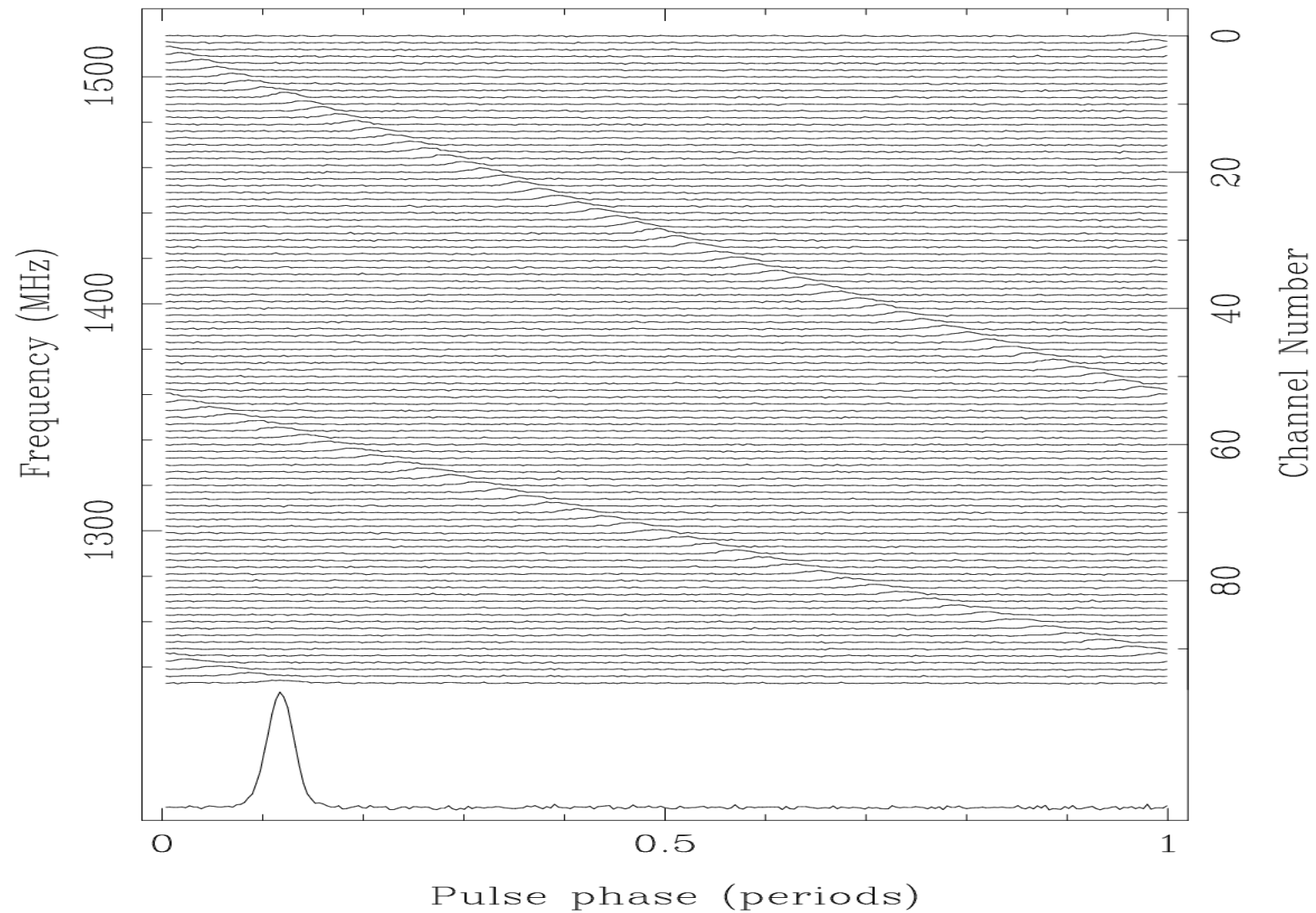
searching the ToAs for systematic trends on many different timescales, from minutes to decades



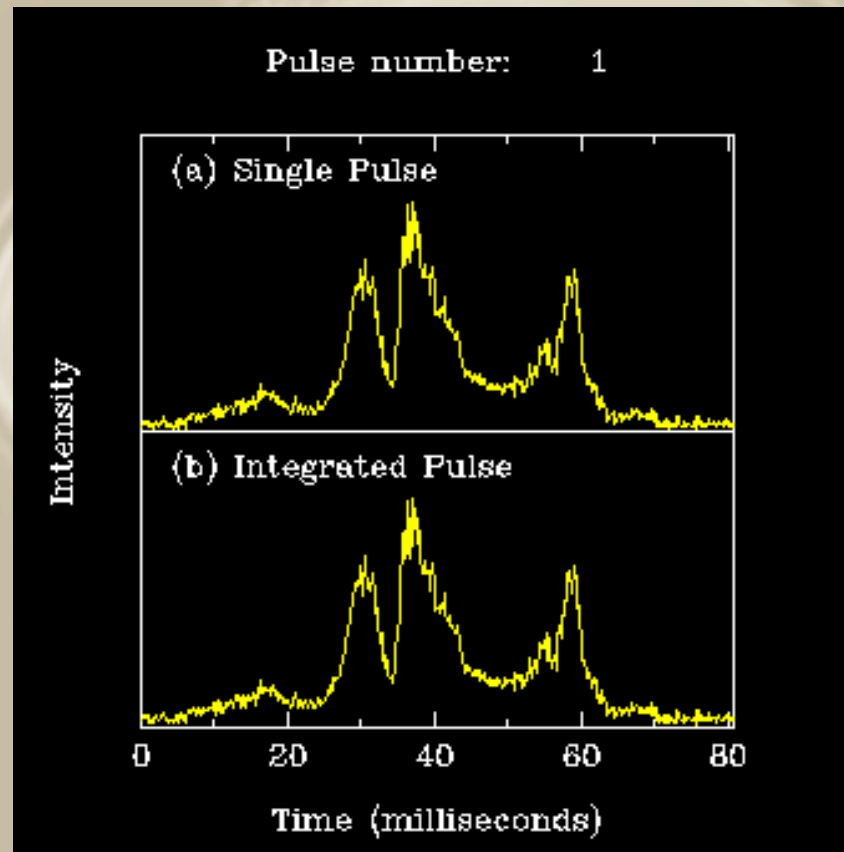
Timing of a radio pulsar: operations for getting a ToA



The dedispersion

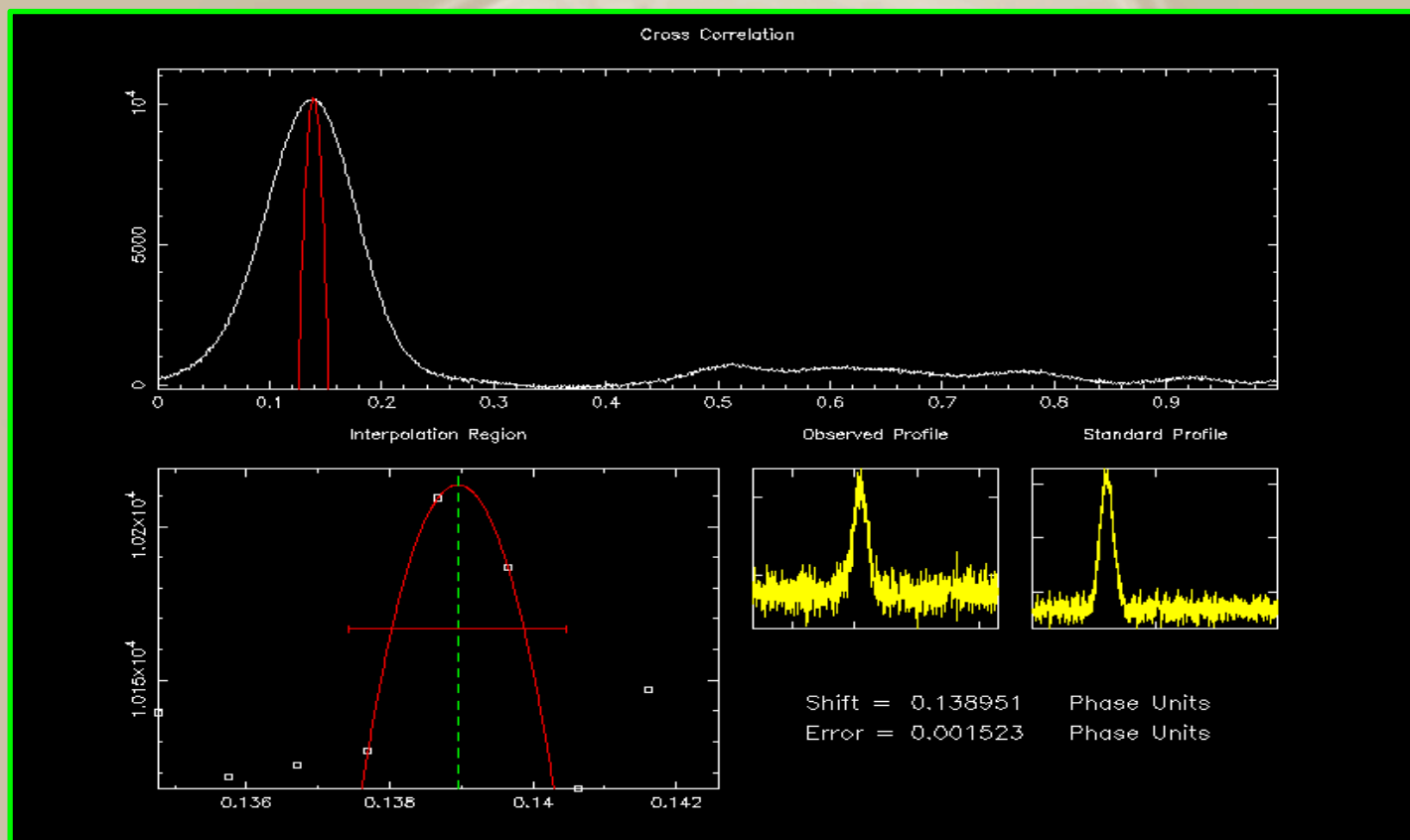


Folding



*Single pulse profile vs
integrated profile*

Determination of the TOPOCENTRIC Times of Arrival (ToAs)



ToA uncertainty (w = width of the pulse, P =pulsar period):

$$\sigma_{TOA} \approx w/(S/N) \approx \frac{S_{sys}}{S_{psr} (t_{obs} \Delta\nu)^{1/2}} P \delta^{3/2}, \quad \delta = w/P$$

Timing idea: modeling

if a physical model **adequately describes** the systematic trends in the ToAs, it is applied with the smallest number of parameters
otherwise

if a physical model **is not adequate**, it is extended (adding parameters) or rejected in favour of another model



when a model finally describes accurately the observed ToAs, the values of the **model's parameters shed light onto the physical properties** of the pulsar and/or of its environment

Timing key quantity: the residuals

Given the full set of parameters ($a_1, a_2, \dots, a_n$) of a model, the i -th **residual r_i is the difference in rotational phase Φ** (with $-0.5 < r_i < +0.5$) between the observed phase of arrival of the i -th pulse and the phase of arrival of that pulse as predicted by the model

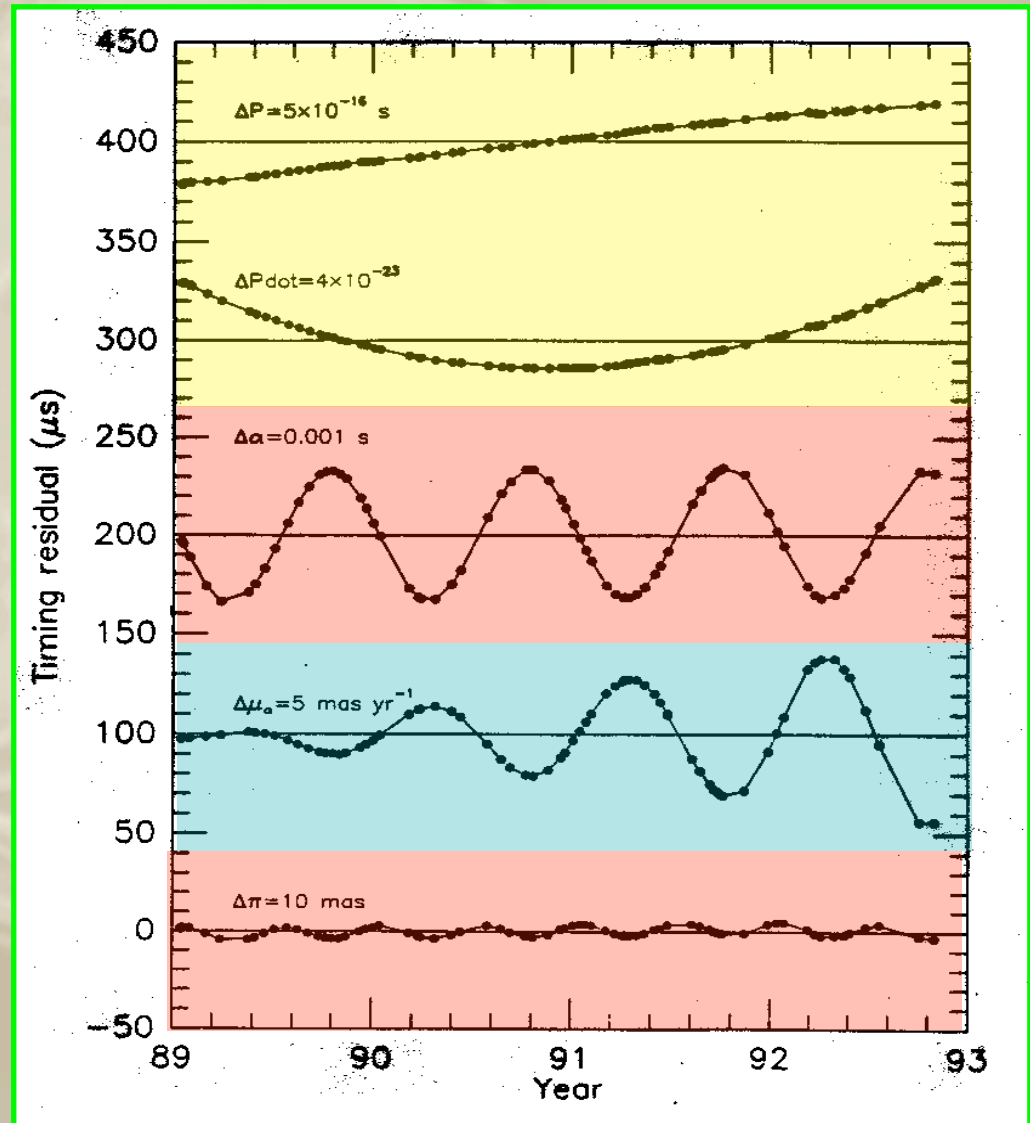
$$r_i = \Phi_{\text{observed}}(\text{i-th pulse}) - \Phi_{\text{model}(a_1, a_2, \dots, a_n)}(\text{i-th pulse})$$



In an iterative procedure, **one least-square fits** on suitable subsets of the possible parameters ($a_1, a_2, \dots, a_n$) of the model, **in the aim** to remove apparent trends and thus eventually **to approach $r_i \ll 1$**

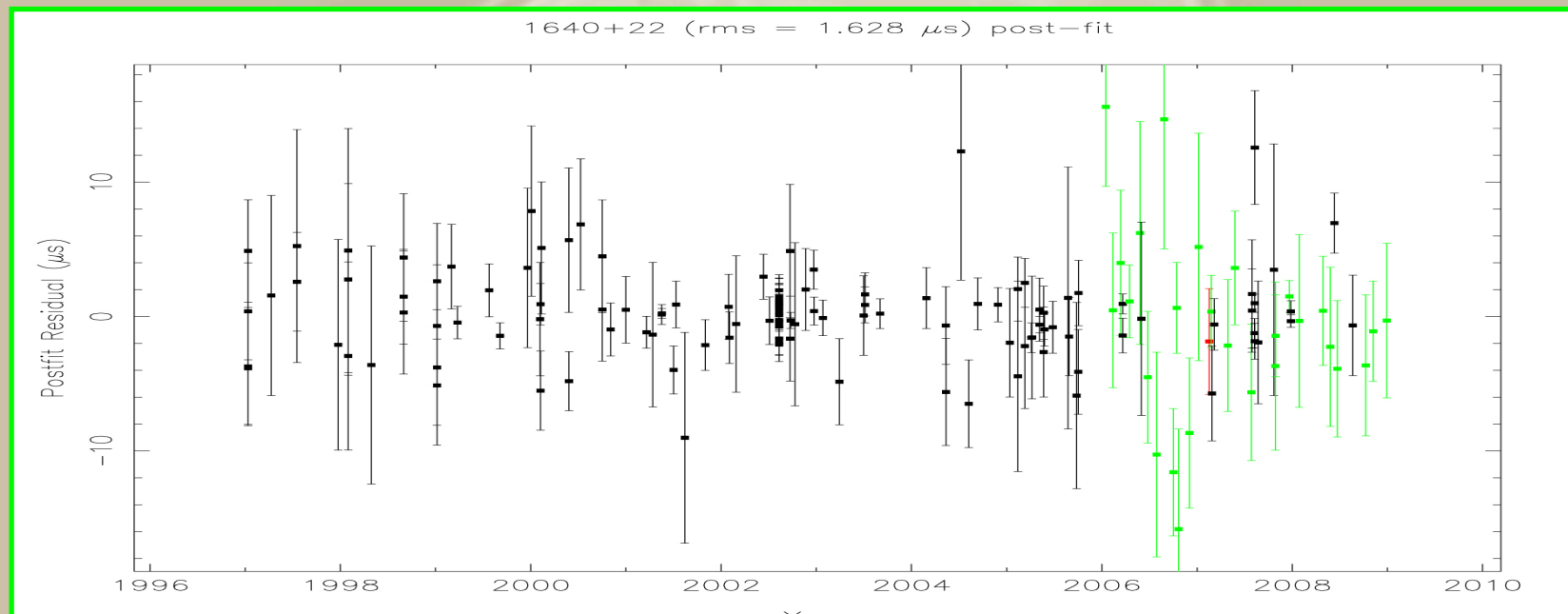
Timing analysis: removing trends

Thanks to the least-square fit procedure, one can iteratively solve for **rotational**, **positional** and **kinematic** parameters, as well as for **keplerian** (when applicable) and **post-keplerian** parameters



Timing analysis quality: rms

Good timing solution $\rightarrow$ no evident trend and $r_i \ll 1$ for all observed pulses



The quality of the timing solution is usually given in term
of the root mean square **rms** of the residuals:
the smaller rms is, the smaller physical effects can
be measured

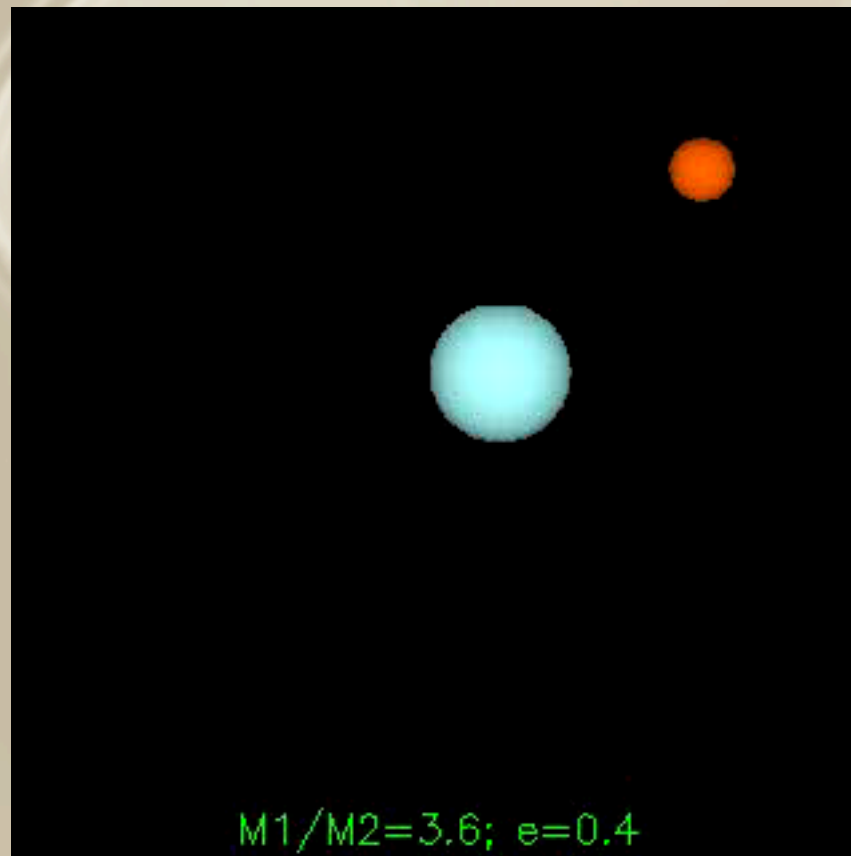
Timing model: isolated pulsars

From timing of an isolated pulsar over a long enough time span, one can in principle get

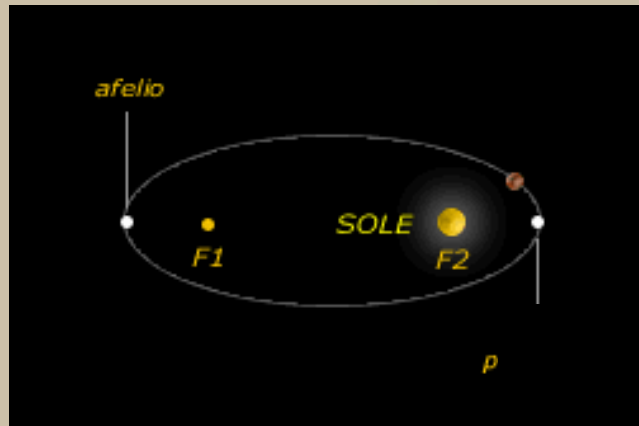


- **RA & DEC**: Celestial coordinates
- **PMRA & PMDEC**: Proper Motion
- **π** : Trigonometric Parallax (i.e. Distance)
- **DM** : Accurate Dispersion Measure
- **DM1** : Time Derivative of Dispersion Measure
- **P0**: Rotational Period
- **P1**: Time derivative of P0
- **P2**: Second time derivative of P0
- **P3**: Third time derivative of P0
- ...

*Since 1974 pulsars in binary
systems are known*

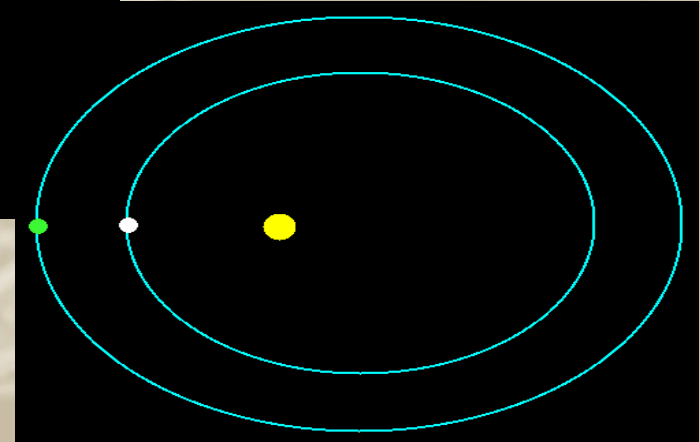
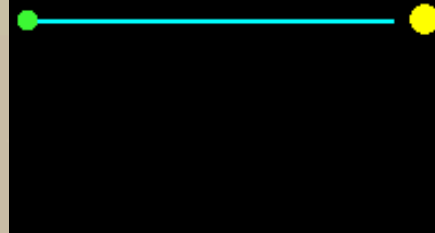


Binary systems: the classic laws



1] Elliptical and planar orbit

2] Constant areolar velocity

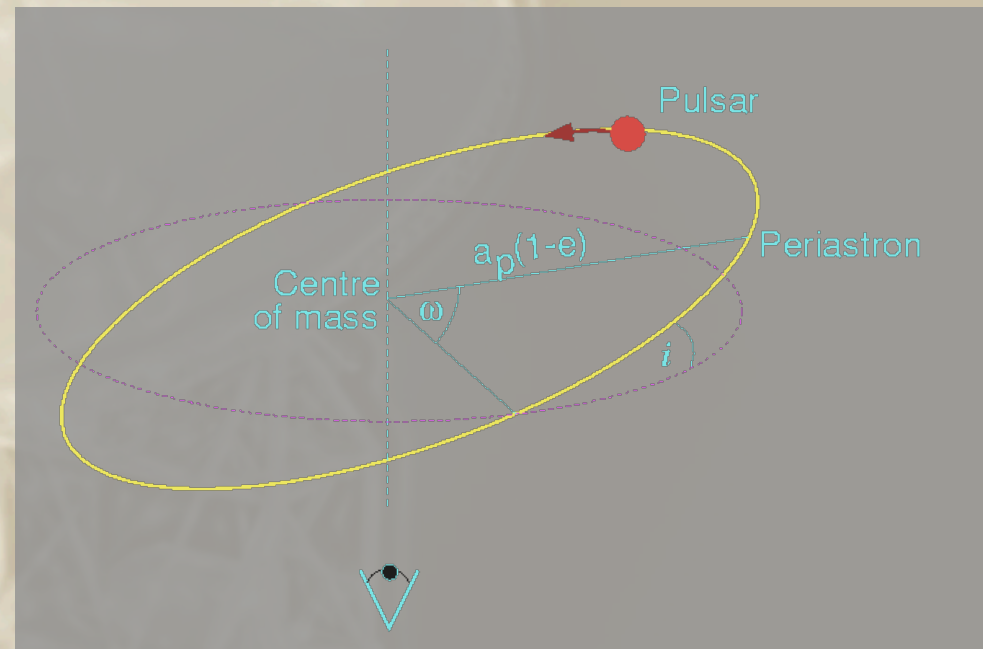


$$3] a^3 = (G/4\pi^2) M_{\text{tot}} P^2$$

Keplero (1609, 1609, 1619)

For most binaries, 5 keplerian parameters are measured and they are (well) enough to satisfactorily describe all the data

- P_b : Orbital period
- $x = a_p \sin i$: Projected semi-major axis
- ω : Longitude of periastron
- e : Eccentricity of orbit
- T_0 : Time of periastron



- Whence the pulsar mass function:

$$f(m_p, m_c) = \frac{4\pi^2}{G} \frac{(a_p \sin i)^3}{P_{orb}^2} = \frac{(m_c \sin i)^3}{(m_p + m_c)^2}$$

for $i = 90^\circ$ Minimum companion mass

for $i = 60^\circ$ Median companion mass

High precision pulsar timing: which targets?

Ordinary pulsars:

~ **1900** known objects;

$NS_{\text{age}} < \text{few } 10^7 \text{ yr}$

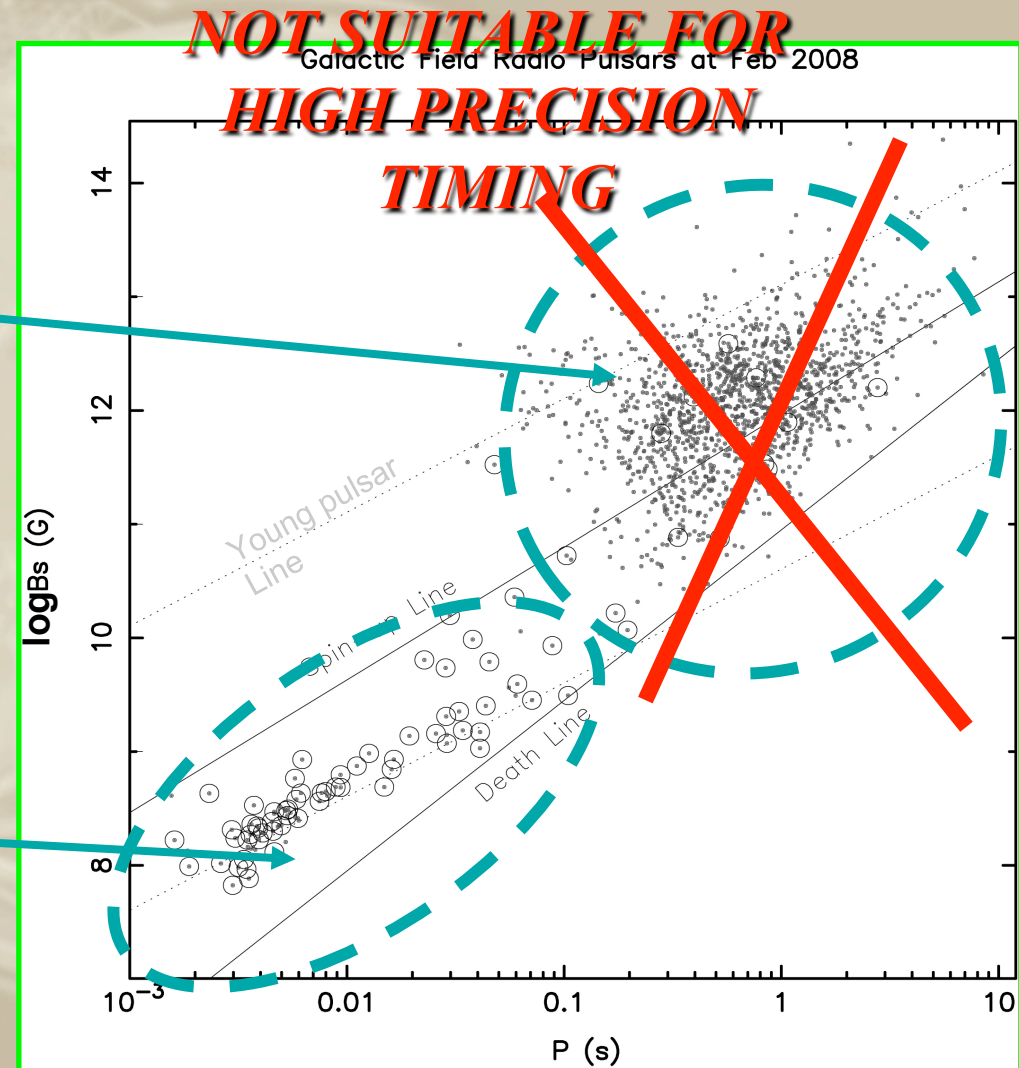
relatively long pulses &
rotational irregularities

Recycled pulsars:

~ **250** known objects;

$NS_{\text{age}} > 10^8\text{-}10^9 \text{ yr}$

The most rapidly rotating
are known as **millisecond
pulsars**



ATNF Pulsar Catalogue

Millisecond pulsars (MSPs) *as clocks*

Pulsar periods can sometimes be measured with unrivalled precision

e.g. on Jan 16, 1999 at UT=00:00

PSR J0437-4715 (a MSP+WD) had a period of

5.757451831072007 $\pm$ 0.00000000000000008 ms



16 significant digits!

3.

Binary pulsars as probes of gravitational waves emission



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...for some binary pulsars, the accuracy of the ToA data is so high that - by using only the keplerian description - one cannot obtain an acceptable timing solution !

Additional physics is needed!

...but... which physics?

Going beyond Kepler...

Tests of Gravity theories in the strong-field limit

Strong in which sense?

In term of the compactness parameter ϵ the source should satisfy

$$\epsilon_{source} = \left| \frac{E_{grav}}{E_{rest}} \right| = \frac{GM_{source}}{R_{source}c^2} \approx 0.1 - 1$$

Where to find a laboratory for testing GR in extreme conditions?

Not on Earth or on Solar System...
but in the Cosmo...very interesting targets are
“relativistic objects in compact binaries”

NSs and BHs are
“relativistic” objects

“compact” binaries

$$\epsilon_{NS} = \left| \frac{E_{grav}}{E_{rest}} \right| = \frac{GM_{NS}}{R_{NS}c^2} \approx 0.2 \quad \epsilon_{BH} = \left| \frac{E_{grav}}{E_{rest}} \right| = \frac{GM_{BH}}{R_{BH}c^2} \approx 0.5$$

Gravitational radiation inspiral affects binary evolution within an Hubble time

Going beyond Kepler...

Tests of Gravity theories in the strong-field limit

Astrophysical contexts:

- during late stages of coalescence of a binary hosting relativistic objects, the orbital velocity approaches c and the orbital separation approaches the size of the star(s), whence physical processes occur in strong-field conditions: **according to the BH mass, they are wonderful targets for LIGO, VIRGO, for the Pulsar Timing Arrays (PTAs) and, in future, LISA**
- emission processes occurring in relativistic objects close to the event horizon: e.g. spectral and timing features in the electromagnetic emission (often X-ray) from the neighborhood of the last stable orbit of accretion disks surrounding NS or BH hosted in a binary system: **some hints from XMM-Newton and Rossi-XTE but targets for future high energy (most X-ray) observatories: LOFT,...**
- compact relativistic binary pulsars: **targets for current TIMING observations in the RADIO band**

Going beyond Kepler...

Tests of Gravity theories in the strong-field limit

Wait a minute! Orbits of known binary pulsars are never entering the strong-field limit...

$$\varepsilon_{bin-psr} = \left| \frac{E_{grav}}{E_{rest}} \right| = \frac{GM_{bin-psr}}{a_{bin-psr}c^2} \approx 10^{-5} - 10^{-3}$$

$$\frac{V_{bin-psr}}{c} \approx 10^{-5} - 10^{-3}$$

But in most alternative theories of gravity (e.g. in the tensor-scalar ones) the orbital motion and the gravitational radiation damping depend on the gravitational binding energy (i.e. self gravity, e.g. $\varepsilon_{NS} \approx 0.2$, $\varepsilon_{BH} \approx 0.5$) of the involved bodies

[e.g. Esposito-Farese 2005, Will 2006]

If enough accuracy in the measurements is provided, significant effects are expected to be detectable even in the weak-field limit for the orbits

Going beyond Kepler...

Tests of Gravity theories in the strong-field limit

A suitable and successful framework for testing and constraining a very large class of gravity theories is that of the **Post-Keplerian (PK) formalism** [Damour & Deruelle 1986]

1st → PK parameters are operationally defined:

i.e. they are phenomenological quantities, which there is a prescription to measure for

2nd → In ANY specific gravity theory (picked in a large range of metric theories), and for negligible spin contributions, the PK parameters can be written only as a function of the masses of the two stars and of the keplerian parameters of the binary system

[Damour & Deruelle 1986]

Timing model:post-keplerian params

The easiest to observe post-keplerian parameters



- $\dot{\omega}$: Periastron precession
- γ : Time dilation and gravitational redshift
- r : Shapiro delay “range”
- s : Shapiro delay “shape”
- $\dot{P}_b$: Orbit decay due to Gravitational Wave emission

Pulsar Timing: relativistic pulsars

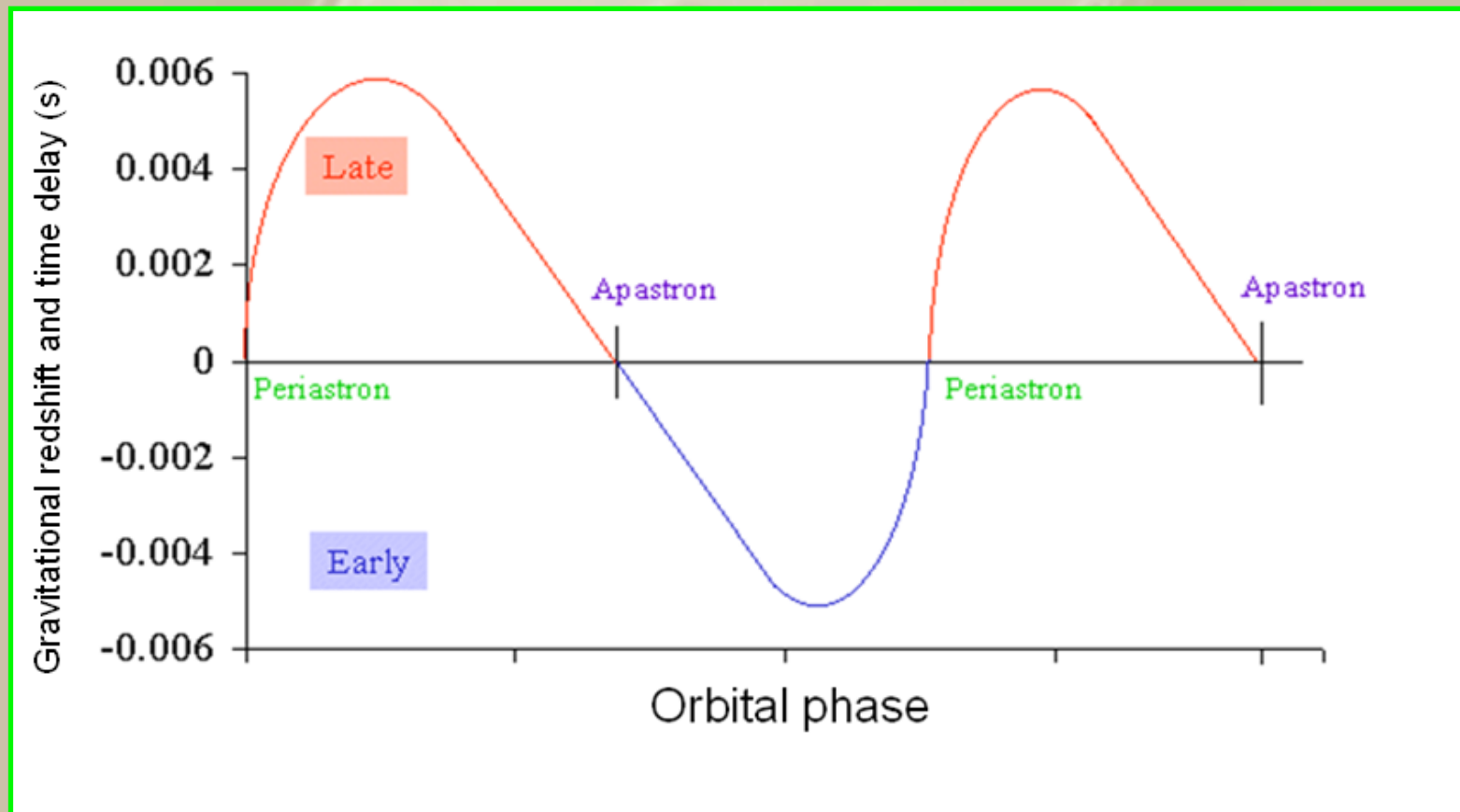
periastron precession

© Weisberg – Carlton College



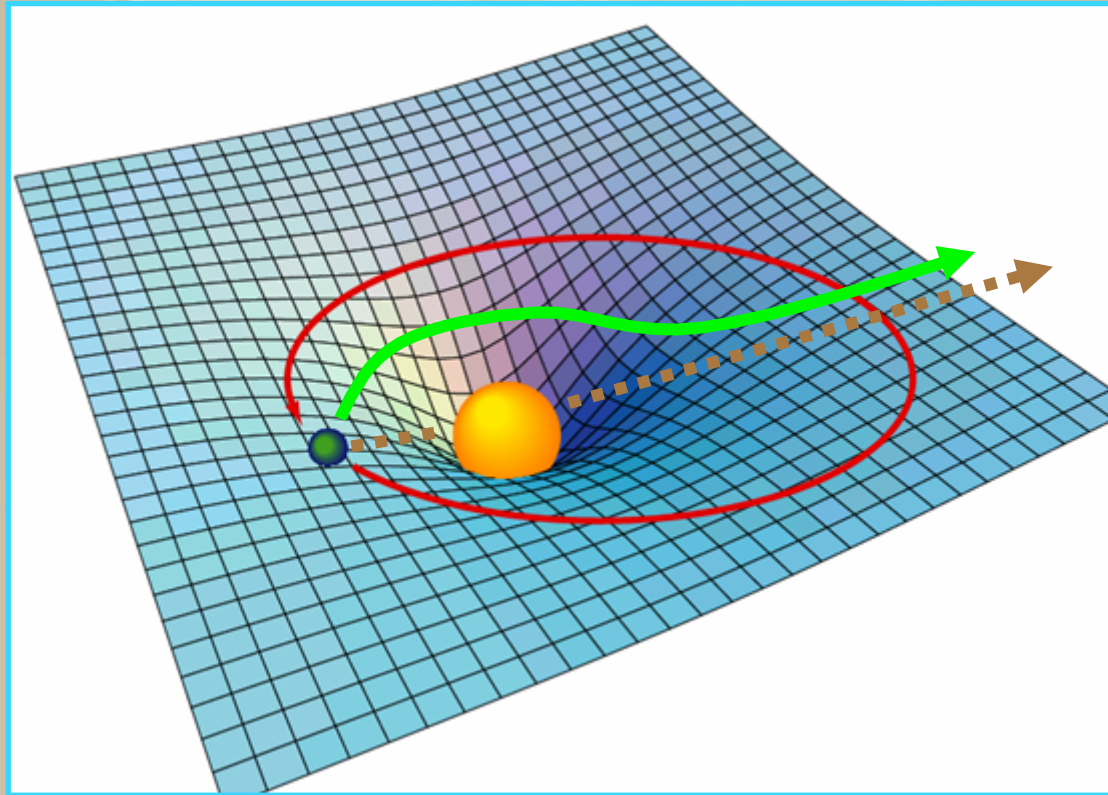
Pulsar Timing: relativistic pulsars

gravitational redshift and time dilation



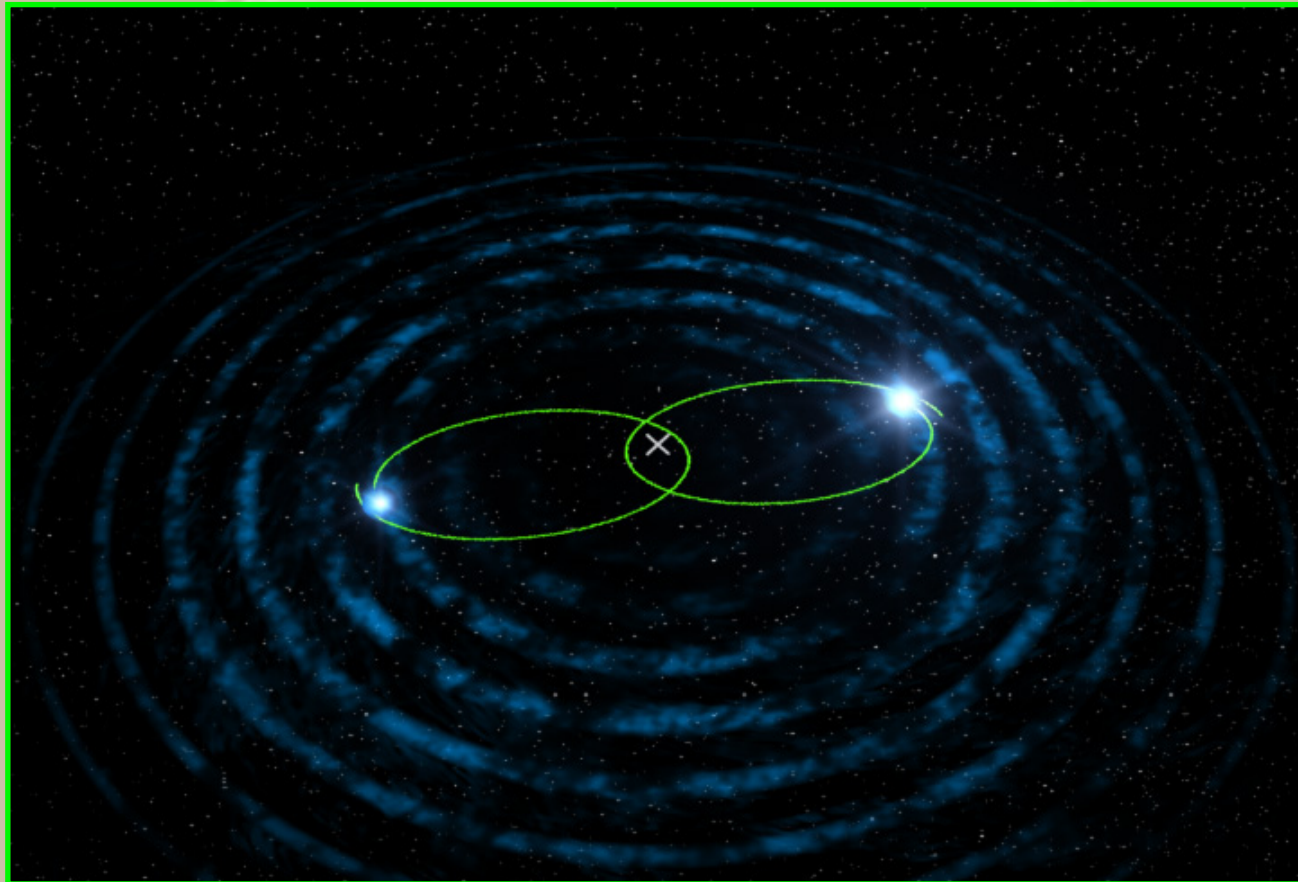
Pulsar Timing: relativistic pulsars

Shapiro delay



Pulsar Timing: relativistic pulsars

orbital decay



What do we learn when observing also the Post-keplerian parameters ?

$$\begin{aligned} \dot{\omega} &= 3 \left(\frac{P_b}{2\pi} \right)^{-5/3} (T_\odot M)^{2/3} (1 - e^2)^{-1}, & \text{Periastron precession} \\ \gamma &= e \left(\frac{P_b}{2\pi} \right)^{1/3} T_\odot^{2/3} M^{-4/3} m_c (m_p + 2m_c), & \text{Time dilation \& gravitational redshift} \\ \dot{P}_b &= -\frac{192\pi}{5} \left(\frac{P_b}{2\pi} \right)^{-5/3} \left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4 \right) (1 - e^2)^{-7/2} T_\odot^{5/3} m_p m_c M^{-1/3}, & \text{Orbital period decay} \\ r &= T_\odot m_c, & \text{Shapiro delay (amplitude)} \\ s &= x \left(\frac{P_b}{2\pi} \right)^{-2/3} T_\odot^{-1/3} M^{2/3} m_c^{-1}. & \text{Shapiro delay (shape)} \end{aligned}$$

...where...

- e orbital eccentricity
- P_b orbital period
- x projected semimajor axis
- m_p pulsar mass
- m_c companion star mass
- $M = m_p + m_c$ total system lagrangian mass

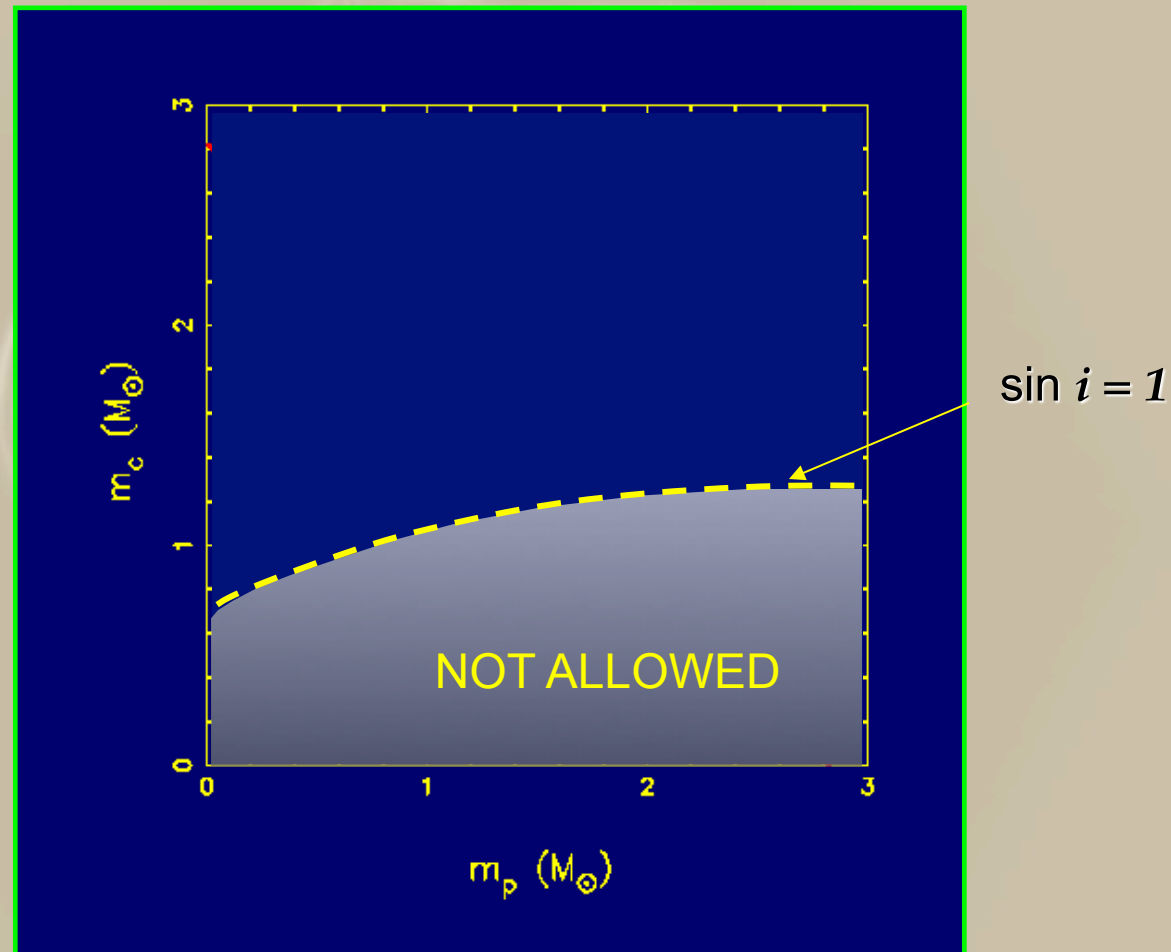
Once more than 2 relativistic PK parameters are known, one derives the masses of the 2 bodies and hence predicts the further PK par on the basis of a given Gravity Theory



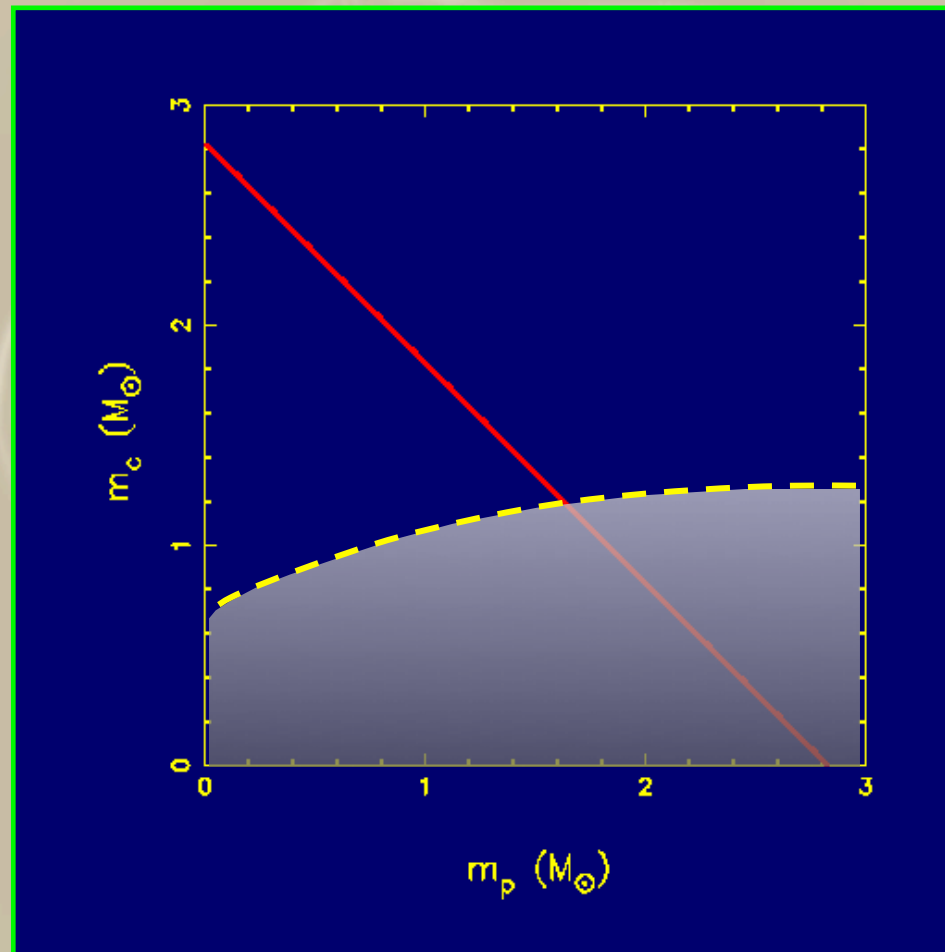
A test for Gravity Theories

$$f(m_p, m_c) = \frac{4\pi^2}{G} \frac{(a_p \sin i)^3}{P_{orb}^2} = \frac{(m_c \sin i)^3}{(m_p + m_c)^3}$$

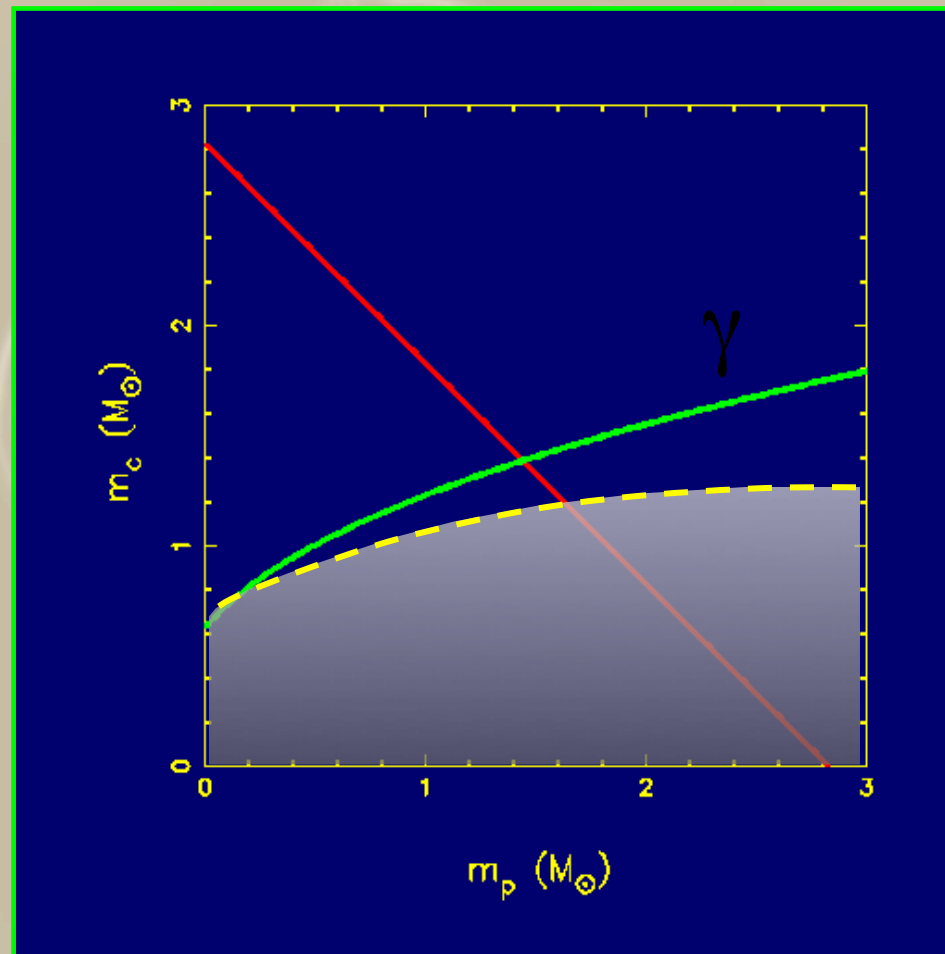
**Mass Function
constraint**



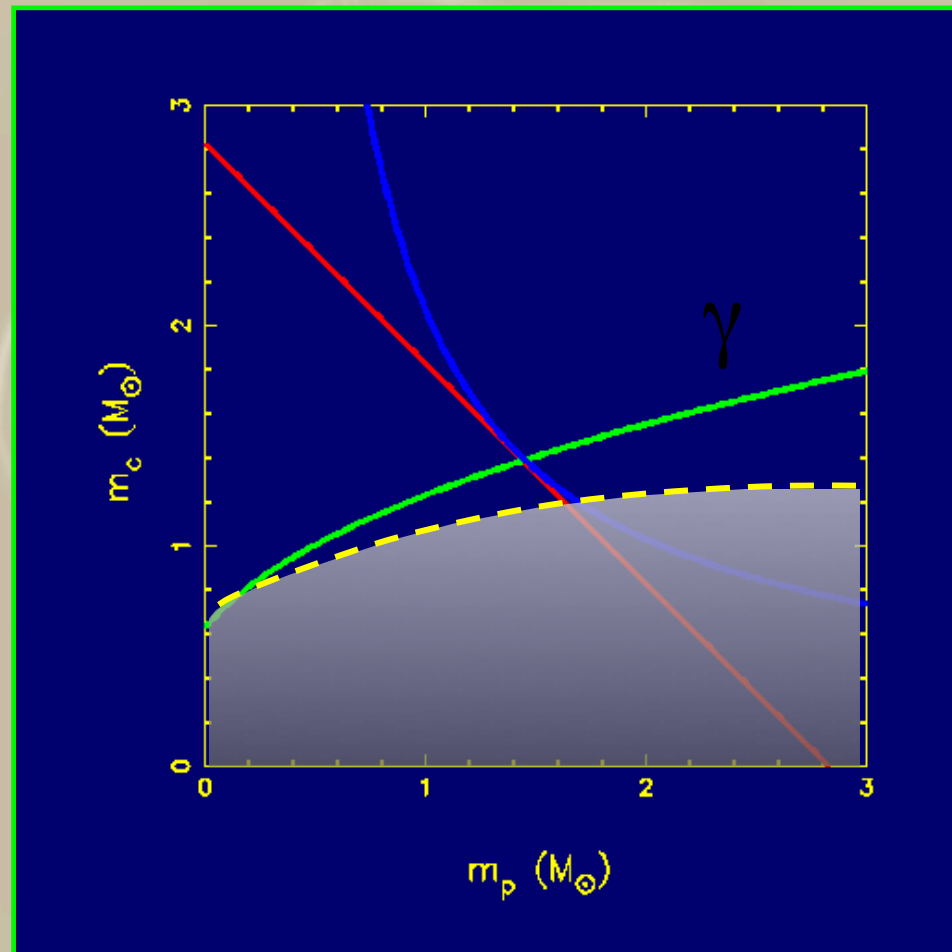
The pulsar and companion star masses are unconstrained



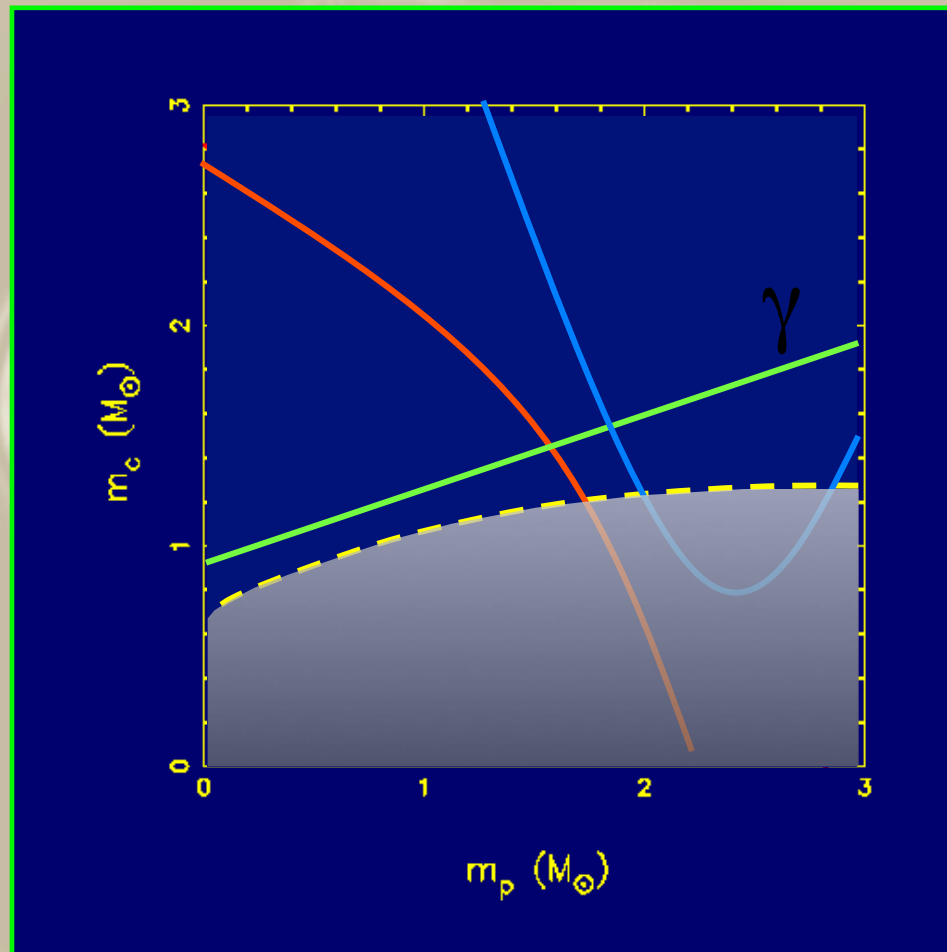
One PK-parameter: constraining mass



Two PK parameters: mass determined **within** a theory



Three PK parameters: in **correct theory lines meet !**



But **not in a wrong** theory !!!

Now the catalog contains 9-10 *Double Neutron Star Binaries*

PULSAR	Pspin [ms]	DM [cm-3 pc]	Porb [day]	ap sin(i) [lt-s]	Mc+Mp [Msun]	ecc	TimeSpDwn [10 ⁸ yr]	TimeMerg [10 ⁸ yr]
J0737-3039	22.70	48.91	0.10	1.42	1.34+1.25	0.09	210	0.85
J1518+4904	40.93	11.62	8.63	20.04	2.72	0.25	200	>T Hubble
B1534+12	37.90	11.62	0.42	3.72	1.33+1.33	0.27	2.5	27.0
J1756-2251	28.45	121.60	0.32	2.75	2.57	0.18	tbd	11.0
J1811-1736	104.18	477.00	18.78	34.78	2.57	0.82	970	>T Hubble
J1829+2456	41.00	13.90	1.18	7.24	>1.22 <1.38	0.14	tbd	>T Hubble
B1913+16	59.03	168.77	0.32	2.34	1.387+1.441	0.62	1.1	3.0
J1906+0746	144.10	217.78	0.17	1.42	1.25+1.37	0.08	0.001	3.0 NS+WD?
B2127+11C	30.53	67.13	0.34	2.52	1.36+1.34	0.68	1.0	2.2

The most interesting for GR tests are:

PULSAR	Pspin [ms]	DM [cm-3 pc]	Porb [day]	ap sin(i) [lt-s]	Mc+Mp [Msun]	ecc	TimeSpDwn [10 ⁸ yr]	TimeMerg [10 ⁸ yr]
J0737-3039	22.70	48.91	0.10	1.42	1.34+1.25	0.09	210	0.85
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PSR B1913+16

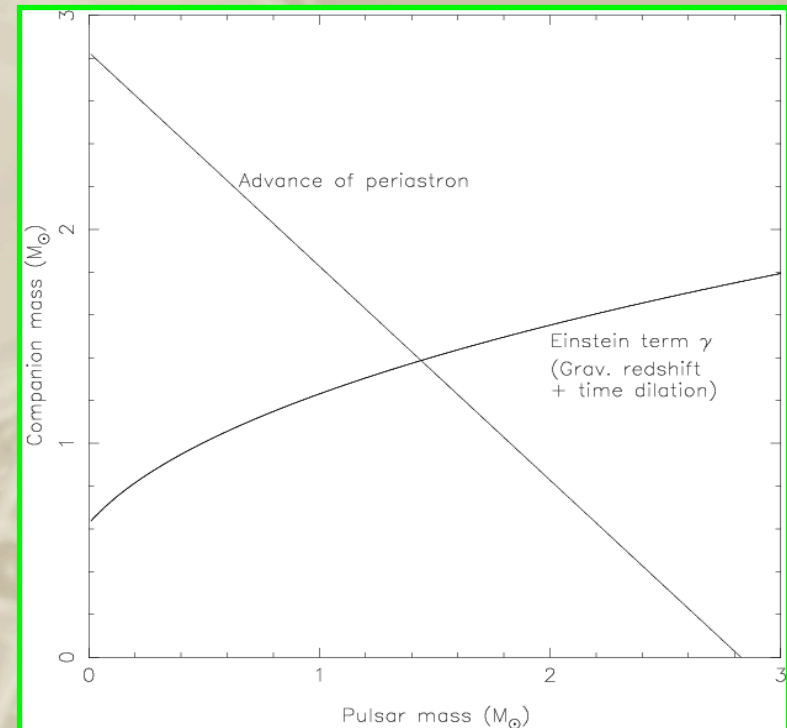
Discovered on 1974 [Hulse & Taylor 75]

Pulsar + Neutron Star

Spin period = 59 ms

Orbital period = 7.8 hrs

Eccentricity = 0.61



Measured 3 PK pars: $\dot{\omega}$ γ $\dot{P}_b$

Most precise NS mass determination to date:

$1.4414(2) M_{\text{sun}} + 1.3867(2) M_{\text{sun}}$ [Weisberg & Taylor 2004]

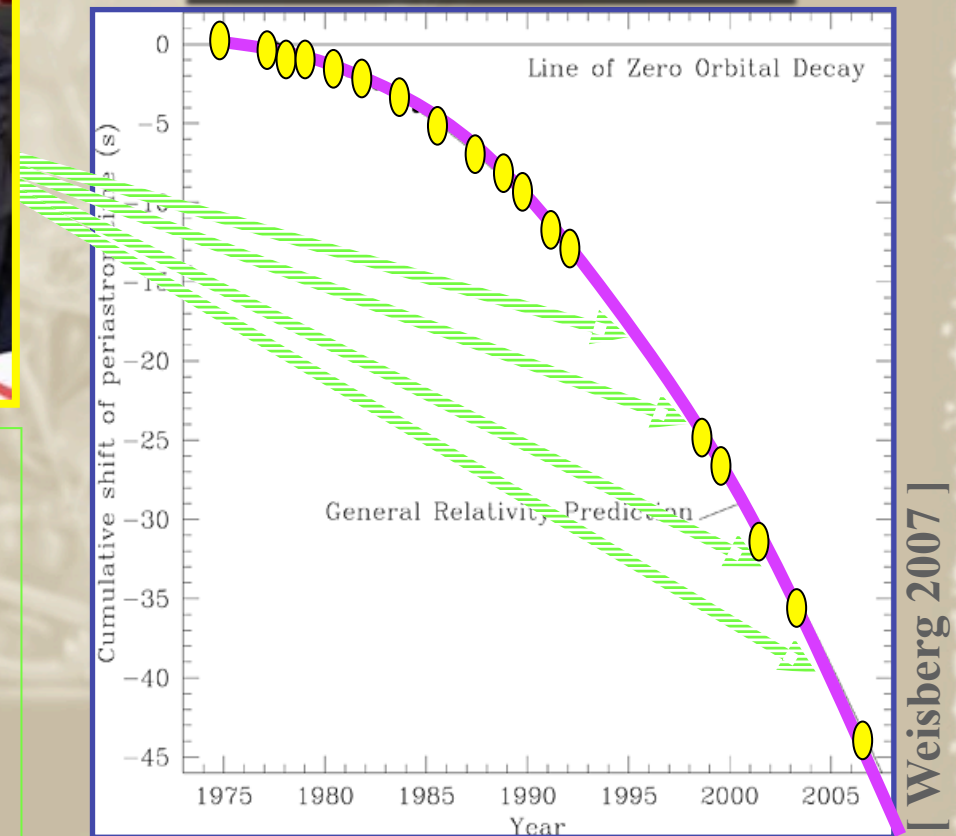
The measurements of Russell Hulse
 and of Joe Taylor...
 Einstein's equations...



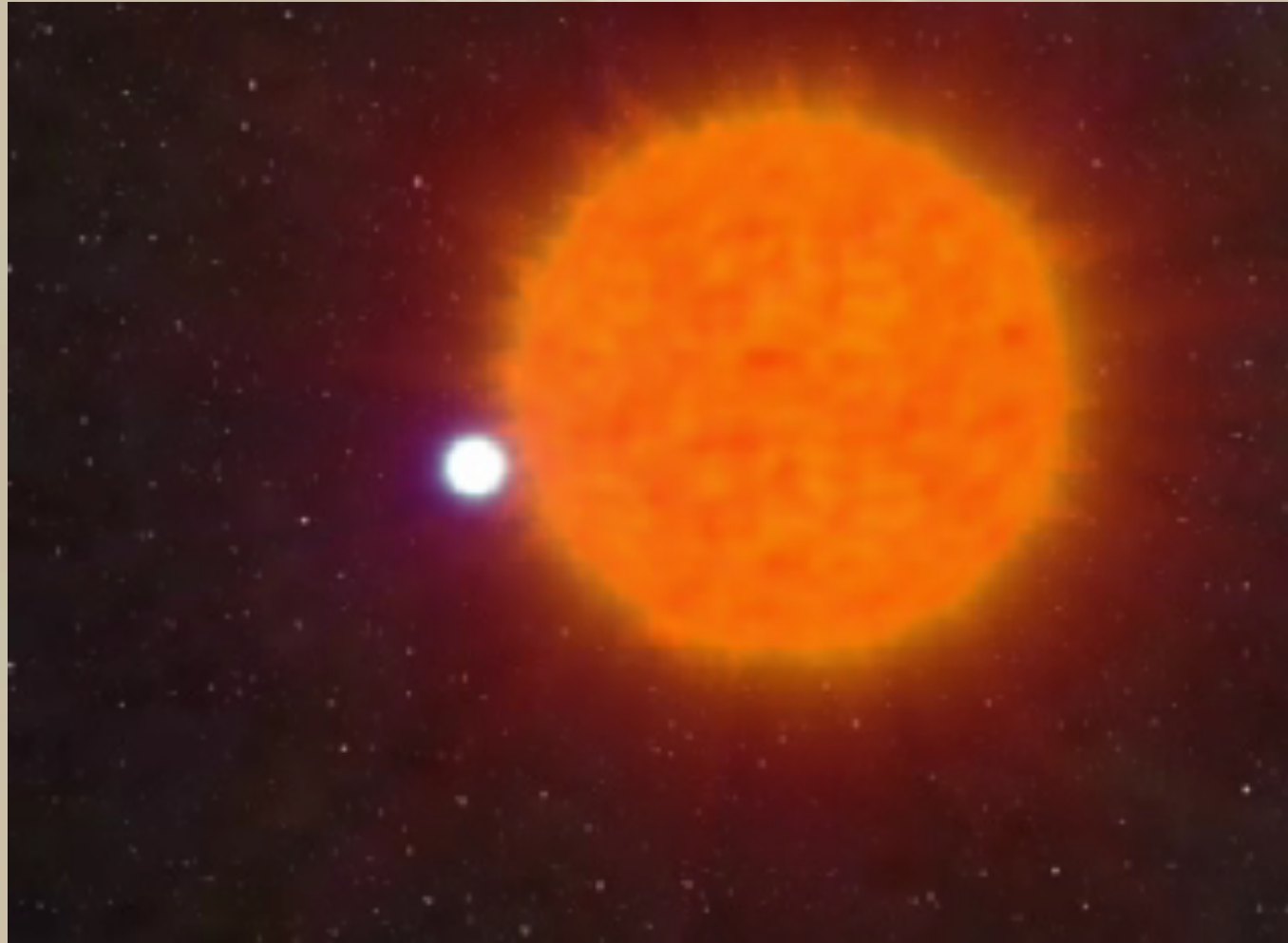
GR provides an accurate
 description of
 orbital motion
 i.e. as
 S:
 t

NOBEL PRIZE
 1993
 Taylor & Hulse

The (in?)direct proof of
GW existence:
PSR B1913+16



The double pulsar PSR J0737-3039A/B



© Howe - ATNF

The origin of the double pulsar

Summary of the tests of GR with the Double Pulsar

[Kramer et al 2006]

Based on:

$$R = 1.0714 \pm 0.0011 \text{ \& } \dot{\omega} = 16.89947 \pm 0.00068 \text{ deg/yr}$$

Expected in GR:	Observed:	Ratio:
$\gamma = 0.38418(22) \text{ ms}$	$0.3856(26) \text{ ms}$	$1.0036(68)$
$dP_b/dt = -1.24787(17) 10^{-12}$	$-1.252(17) 10^{-12}$	$1.003(14)$
$r = 6.153(26) \mu\text{s}$	$6.21(33) \mu\text{s}$	$1.009(55)$
$s = 0.99987(-48.+13)$	$0.99974(-39,+16)$	$0.99987(50)$

$$\frac{S^{\text{exp}}}{S^{\text{obs}}} = 1.0000 \pm 0.0005$$

- Precision of 5×10^{-4} : best in strong-field
- Expect to supersede solar system tests

Why bother with more deeply testing the predictions of GR on GW emission rates ?

Is GR still the best **available theory for describing Nature also under** extreme physical conditions?

This is NOT an ACADEMIC question:

e.g. **extreme conditions** are certainly those at which any long sought **unified model** for interactions applies [e.g. Antoniadis 2005]

Moreover, is enough to test alternative theories only **in the weak-field limit?**

There exist alternative metric gravity theories (e.g. a subclass among the tensor-scalar theories) which would pass ALL Solar System (weak-field limit) tests, but would be violated as soon as extreme conditions (strong-field limit) are reached

[Damour & Esposito-Farese 1996]

4.

Merger rates and Gravitational Wave direct detection



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Metodologies for coalescence rate calculations

1) **Empirical approach: starting from the properties of the OBSERVED sample of binaries + accounting for the observational bias**

2) **Running extended simulations of the most likely evolutionary scenario starting from a population of primordial binaries**

Coalescence rate calculation

Empirical approach

1) Empirical approach: starting from the properties of the **OBSERVED** sample of binaries + accounting for the observational bias

$$R = \frac{\text{Number of sources}}{\text{Lifetime of a system}} \times \text{correction factor}$$

[Kalogera et al. 2004]

[Kim et al. 2004, 2006, 2010]

[Lorimer et al 2008]

[Bulik, Belczynski, Prestwich 2010]

Coalescence rate R for $NS+NS$

$$R = \frac{\text{Number of sources}}{\text{Lifetime of a system}} \times \text{correction factor}$$

- ✓ Correction factor : correction for pulsar beaming

[O'Shaughnessy & Kim 2009]

- ✓ Lifetime of a system = current age of a pulsar + merging time of a system

Properties of pulsars in DNSs

P_s (ms)	$\dot{P}_s$ (ss ⁻¹)	P_{orb} (hr)	ecc	M_{tot} ($M_\odot$)
------------	---------------------------------	-----------------------	-----	--------------------------------

Galactic disk pulsars merging in less than an Hubble time

B1534+12	37.90	2.4×10^{-18}	10.0	0.274	2.7 (1.35)
-----------------	-------	-----------------------	------	-------	------------

J1756-2251	28.45	1.0×10^{-18}	7.7	0.181	2.6 (...)
-------------------	-------	-----------------------	-----	-------	-----------

J1906+0746	144.10	2.0×10^{-14}	4.1	0.085	2.6 (1.37)
-------------------	--------	-----------------------	-----	-------	------------

B1913+16	59.03	8.6×10^{-18}	7.8	0.617	2.8 (1.39)
-----------------	-------	-----------------------	-----	-------	------------

J0737-3039	22.70	2.4×10^{-18}	2.4	0.087	2.6 (1.24)
-------------------	-------	-----------------------	-----	-------	------------

Properties of pulsars in DNSs (cont)

τ_c (Myr) τ_{merg} (Myr) $d\omega/dt$ (deg/yr)

Galactic disk pulsars merging in less than an Hubble time

B1534+12	250	2500	1°.75
-----------------	------------	-------------	--------------

J1756-2251	400	15900	2°.59
-------------------	------------	--------------	--------------

J1906+0746	0.11	320	7°.57
-------------------	-------------	------------	--------------

B1913+16	110	320	4°.23
-----------------	------------	------------	--------------

J0737-3039	200	86	16°.90
-------------------	------------	-----------	---------------

Coalescence rate R (empirical approach)

$$R = \frac{\text{Number of sources}}{\text{Lifetime of a system}} \times \text{correction factor}$$

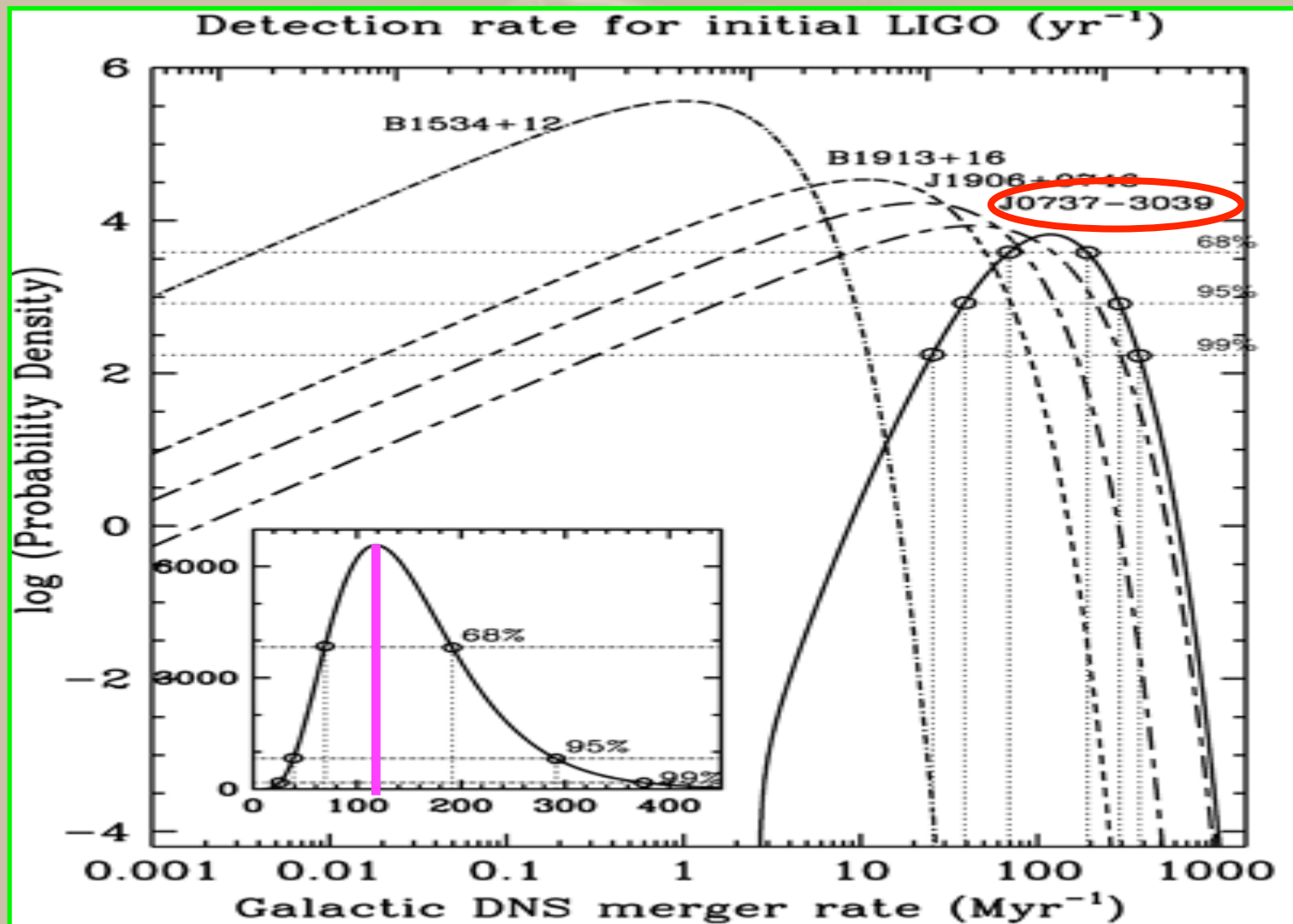
- ✓ **Correction factor : correction for pulsar beaming**

- ✓ **Lifetime of a system = current age of a pulsar + merging time of a system**

- ✓ **Number of sources : number of pulsars in coalescing DNSs in the galaxy of a given type**

How many pulsars “similar” to each of the known NS+NS exist in our Galaxy? It needs estimating the SCALE factor

Results for NS + NS binaries



[Chunglee Kim 2008]

The Galactic coalescence rate R for NS + NS binaries

For the reference model (at 95% CL):

Coalescence
rate

R (current) (Myr^{-1})

R (previous) (Myr^{-1})

118^{+174}_{-79}

27^{+80}_{-23}

B1913+B1534+J0737+J1906

B1913+B1534

[Lorimer 2008]

Increase rate factor

$$\frac{R_{\text{peak}} (\text{current})}{R_{\text{peak}} (\text{previous})} \sim 5-6$$

Detection rate of NS + NS inspirals

The most probable inspiral detection rates for LIGO/VIRGO

[Lorimer 2008]

R_{det} (initial) = ~ 1 event per 8 yr (95% CL, most optimistic)

R_{det} (advanced) = ~ 650 events per yr (95% CL, most optimistic)

Many uncertainties in the model

Rates may be significantly higher if a substantial population of highly eccentric binary systems exists. It could escape detection due the short lifetime before GW inspiral

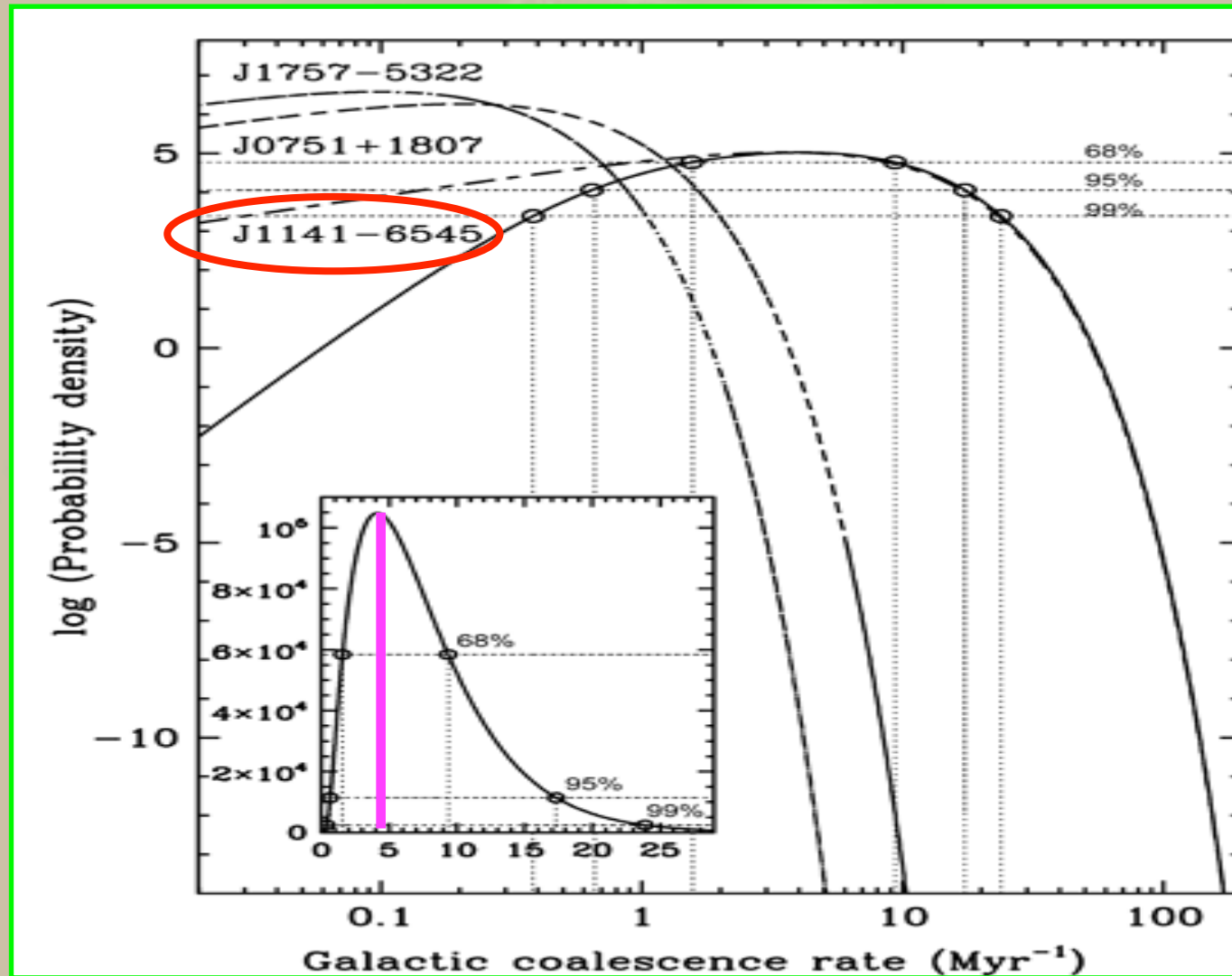
[Chaurasia & Bailes 2005]

One year of observation with LISA of the Double Pulsar would detect the continuous emission at freq=0.2 mHz with a S/N $\approx$ 2

[Kalogera 2004]

Results for NS + WD binaries

[Chunglee Kim 2008]



Only 3 known coalescing systems known to date

The Galactic coalescence rate R for NS + WD Binaries

For the reference model (at 68% CL), not corrected for beaming:

Coalescence
rate

$R \text{ (Myr}^{-1}\text{)}$

4^{+5}_{-3}

J0751+J1757+J1141

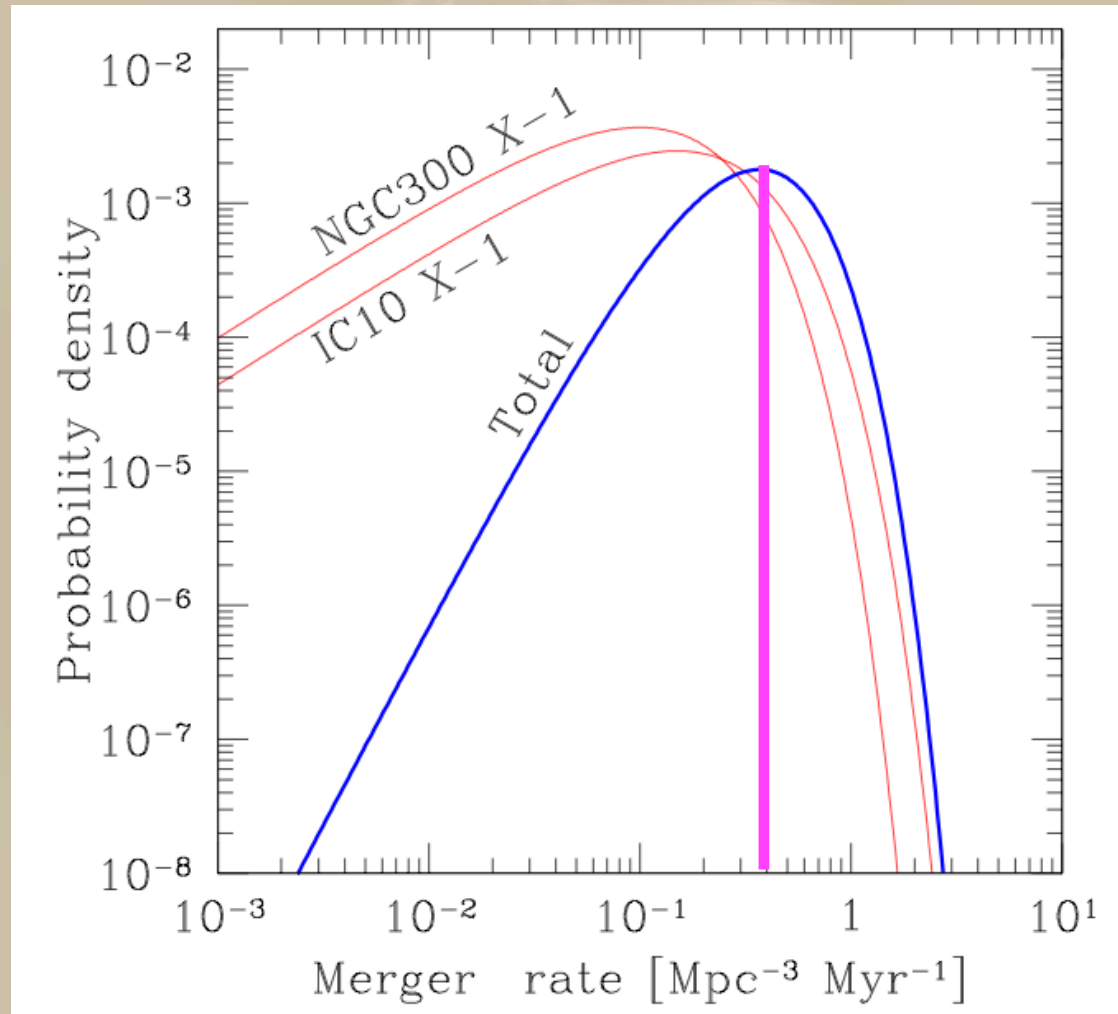
[Chunglee Kim et al 2010]

**Coalescing frequencies are in the LISA band:
but expected event rate not very encouraging**

[Lorimer 2008]

Results for BH + BH binaries

[Bulik, Belczynski, Prestwich 2010]



To date, only known 2 compact BH+WR binaries, which will likely evolve in 2 coalescing BH + BH binaries

Rates of coalescing BH + BH

Formation/
Coalescence
rate

$R \text{ (Mpc}^{-3} \text{ Myr}^{-1} \text{)}$

$0.36^{+0.50}_{-0.26}$

NGC300+IC10

[Bulik et al 2010]

The most probable inspiral detection rates for LIGO/VIRGO

$R_{\text{det}} \text{ (initial)} = \sim 0.08\text{-}2 \text{ events per yr (99\% CL, range 100 Mpc)}$

Few uncertainties in the model

At the maximum of the probability ($R \approx 0.8$ events per yr), S6 run of LIGO should have detected one such event... Maybe BH+BH formation rate is largely reduced by the effects of the **common envelope** in binary evolution, even in low metallicity environments [Bulik et al. 2010]

Coalescence rate calculations: *Full population synthesis approach*

The alternate option is to run extended simulations of the most likely evolutionary scenario starting from a population of primordial binaries

[Dewey & Cordes 1987]
[Lipunov et al 1996]
[Belczynski, Kalogera, Bulik 2002]
[Belczynski et al 2008]
[O'Shaughnessy et al 2008]
[Bulik, Belczynski, Prestwich 2010]
[O'Shaughnessy et al 2010]
[Osłowski et al. 2011]
[O'Shaughnessy et al 2012]
[Dominik et al 2012 . I]

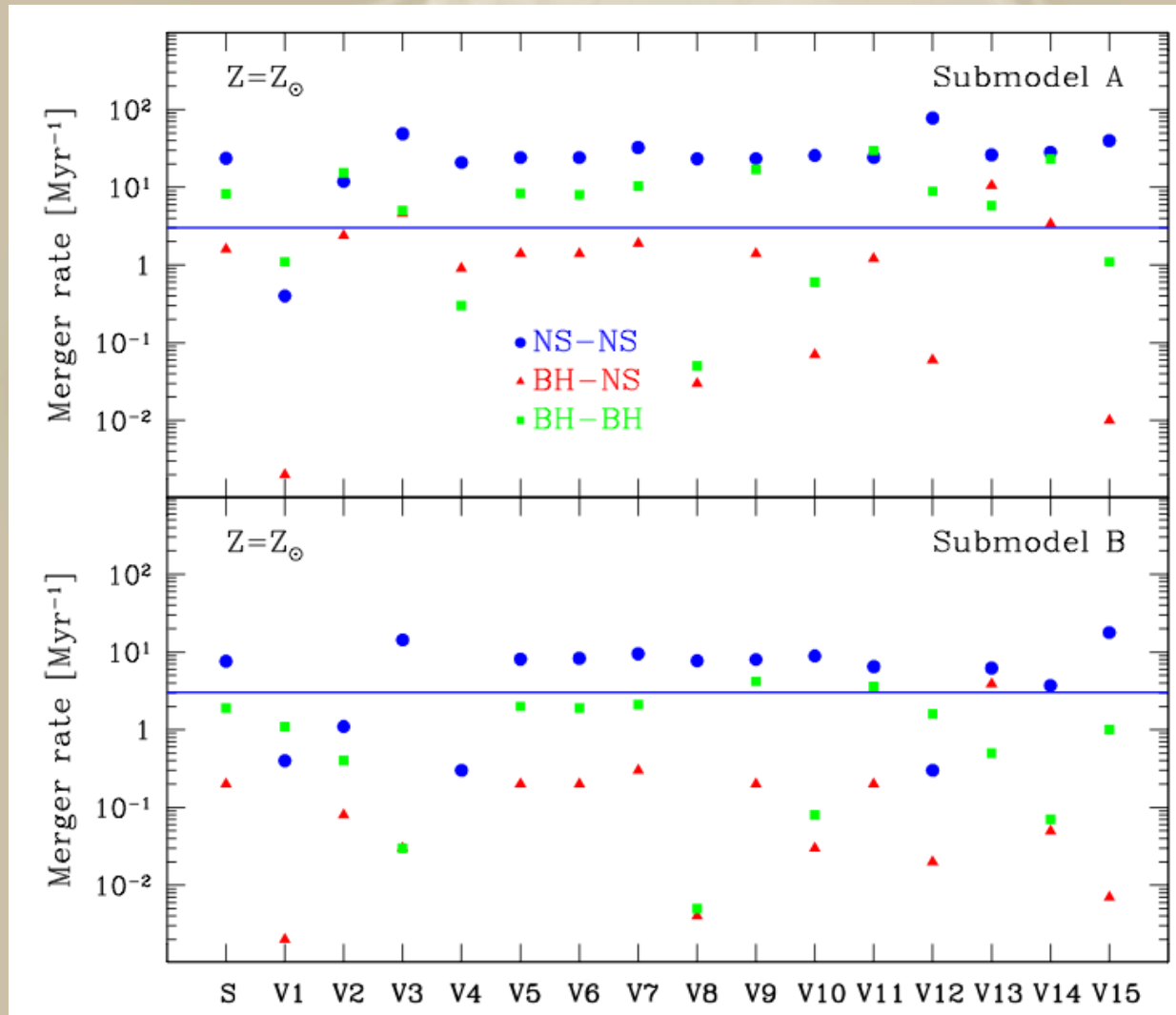
Coalescence rate calculations: The most recent large effort

GALACTIC MERGER RATES, $Z_{\odot}$ [Myr^{-1}] ^a

Model	NS-NS	BH-NS	BH-BH
S	23.5 (7.6)	1.6 (0.2)	8.2 (1.9)
V1	0.4 (0.4)	0.002 (0.002)	1.1 (1.1)
V2	11.8 (1.1)	2.4 (0.08)	15.3 (0.4)
V3	48.8 (14.3)	4.6 (0.03)	5.0 (0.03)
V4	20.8 (0.3)	0.9 (0.0)	0.3 (0.0)
V5	24.1 (8.1)	1.4 (0.2)	8.3 (2.0)
V6	24.1 (8.3)	1.4 (0.2)	8.0 (1.9)
V7	32.4 (9.5)	1.9 (0.3)	10.4 (2.1)
V8	23.3 (7.7)	0.03 (0.004)	0.05 (0.005)
V9	23.4 (8.0)	1.4 (0.2)	16.9 (4.2)
V10	25.6 (8.9)	0.07 (0.03)	0.6 (0.08)
V11	24.2 (6.5)	1.2 (0.2)	29.7 (3.6)
V12	77.4 (0.3)	0.06 (0.02)	8.9 (1.6)
V13	26.1 (6.2)	10.6 (3.9)	5.8 (0.5)
V14	28.2 (3.7)	3.4 (0.05)	23.0 (0.07)
V15	39.8 (17.8)	0.01 (0.007)	1.1 (1.0)
Range	0.4–77.4 (0.3–17.8)	0.002–10.6 (0.0–3.9)	0.05–29.7 (0.0–4.2)

^a Rates are calculated for a synthetic galaxy similar to the Milky Way (solar metallicity, and 10 Gyr of continuous star formation at the level of $3.5 \text{ M}_{\odot} \text{ yr}^{-1}$). Rates are presented for submodel A (CE HG donor allowed), with the rates for submodel B listed in parentheses (CE HG donor forbidden); see Section 2.3.1 for details. The range presents the minimum and maximum value for each DCO type.

Coalescence rate calculations: The most recent large effort



[Dominik et al 2012 paper 1]

Methodologies for coalescence rate calculations

1) Empirical approach: starting from the properties of the OBSERVED sample of binaries + accounting for the observational bias

Many uncertainties in modeling the observational bias + limited statistics in the observed sample

“Tuned” on an observed population of objects

2) Running extended simulations of the most likely evolutionary scenario starting from a population of primordial binaries

The uncertainties in the assumption for the initial state of the binaries make the range of the predicted merging rates larger than with the empirical approach

Combination of various observational constraints resulting from binary population synthesis code are very promising

5.

Pulsar Timing Arrays as Gravitational Wave detectors



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Pulsars as GW detectors

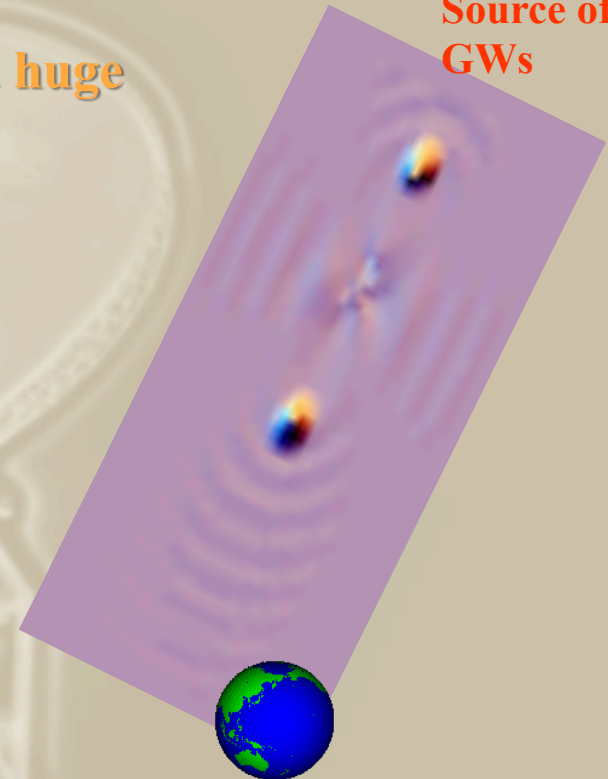
The Pulsar-Earth path can be used as the arm of a huge cosmic gravitational wave detector

Perturbation in space-time can be detected in timing residuals over a suitable long observation time span

Radio
Pulsar



Source of
GWs



Earth

Sensitivity (rule of thumb):

$$h_c(f) \sim \frac{\sigma_{TOA}}{T}$$

where

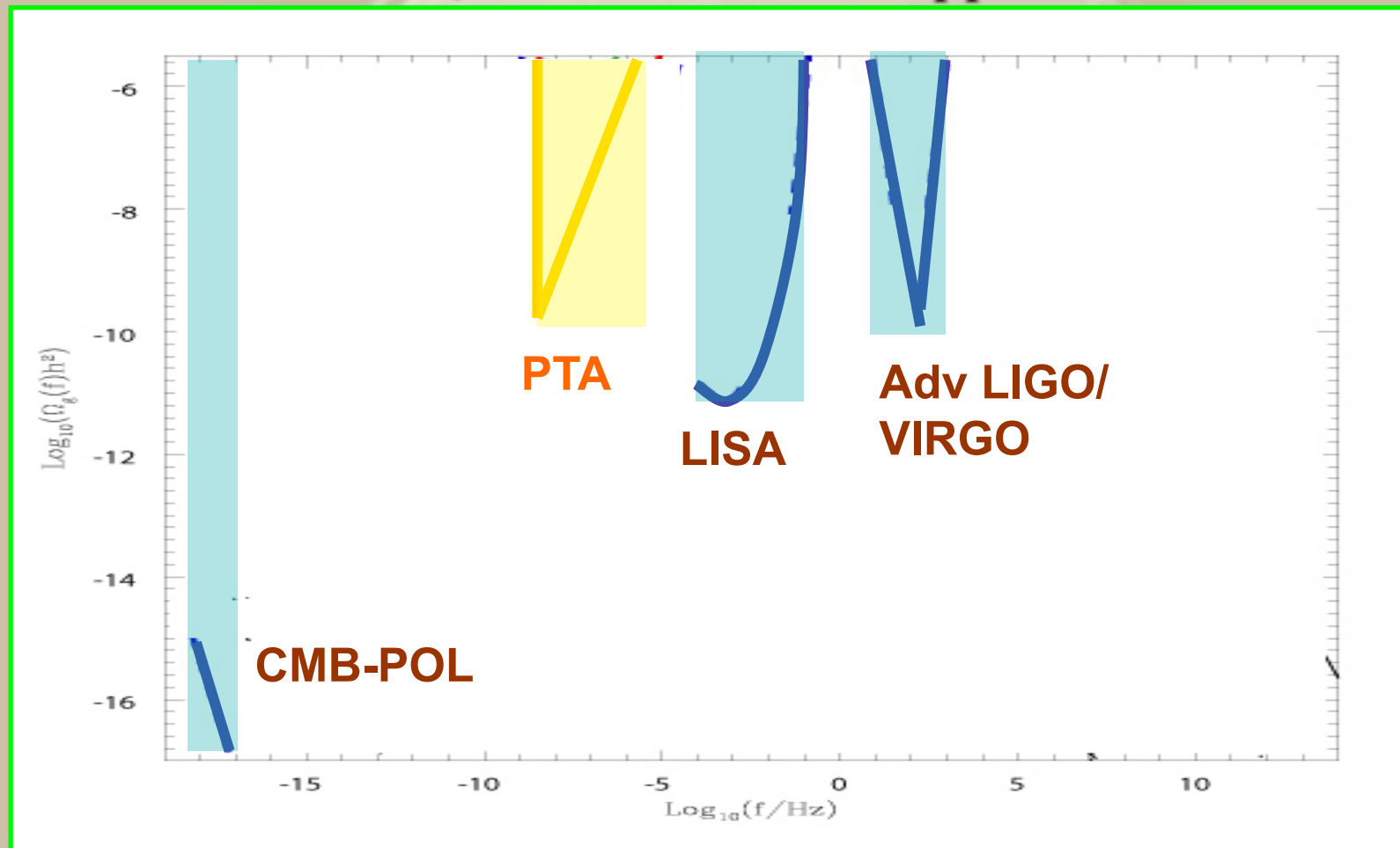
$h_c(f)$ is the dimensionless strain at freq f

σ_{TOA} is the rms uncertainty in Time of Arrival

T is the duration of the dataspan

Pulsar Timing array(s): the frequency space

Note the **complementarity in explored frequencies** with respect to the current and the future GW observatories, like LIGO, advLIGO, advVIRGO and supposed LISA



Current best limits on GW background from SMBH binaries (with a GW spectral index $-2/3$)



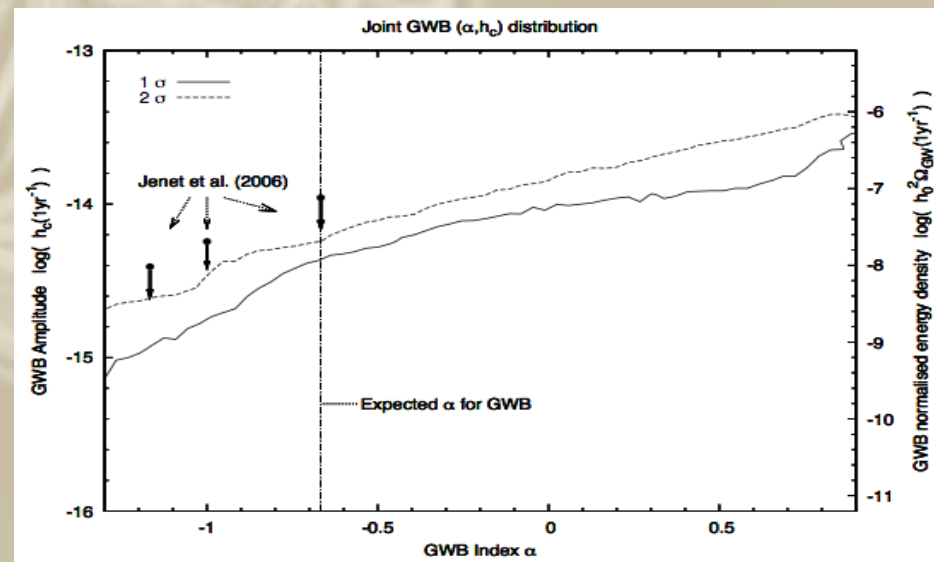
Jenet et al., 2006: $A < 11 \times 10^{-15}$



Demorest et al., 2012: $A < 7 \times 10^{-15}$



van Haasteren et al., 2011: $A < 6 \times 10^{-15}$



[van Haasteren et al. 2011]

Happy hunting for GWS!

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