Galactic NS-NS Coalescence Rates

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NS-NS binary mergers

Prime targets to detect GWs with
km-scale laser interferometers in f_{gw} ~ 10-1000 Hz
(advanced LIGO-Virgo, GEO, KAGRA, ET)

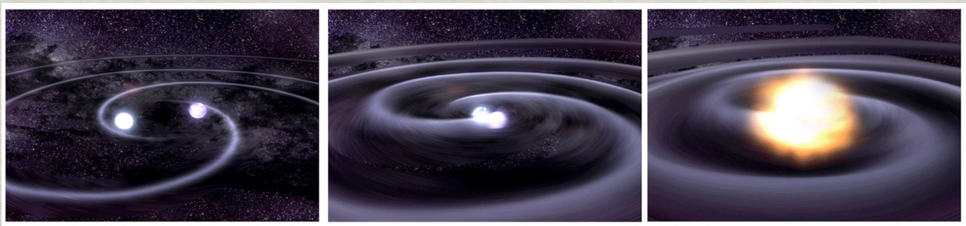
All known NS-NS binaries are pulsar-NS binaries

Empirical modeling is available

Galactic NS-NS merger rate → **GW detection rate for NS-NS inspirals**

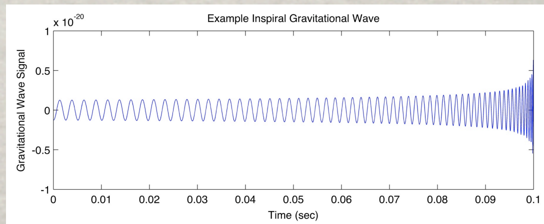
LIGO Livingston, LA, USA

Compact binary coalescences : inspiral + merge + ringdown



(Credit: NASA)

GW signal from NS-NS inspirals



(Credit: A. Stuver)

Galactic NS-NS merger rate estimates until 2010

Based on **recycled pulsars** in known PSR-NS binaries in the Galactic disk

The **beaming fraction** of the A pulsar **was assumed to be similar to** those measured from PSRs B1913+16 and B1534+12 (~ 17 %).

Kalogera, CK, et al. (2004)

MODEL[a]	$\mathcal{R}_{tot}$ (Myr^{-1})
1	$23.2^{+59.4}_{-[illegible]}$
6	$83.0^{+209.1}_{-66.1}$
9	$7.9^{+20.2}_{-6.3}$
10	$23.3^{+57.0}_{-18.4}$
12	$9.0^{+21.9}_{-7.1}$
14	$3.8^{+9.4}_{-2.8}$
15	$223.7^{+593.8}_{-180.6}$
17	$51.6^{+135.3}_{-41.5}$
19	$14.6^{+38.2}_{-11.7}$
20	$89.0^{+217.9}_{-70.8}$

Galactic NS-NS merger rate (empirical)

The LSC-Virgo "rates" paper (Abadie et al. 2010)

Table 5. Detection rates for compact binary coalescence sources.

IFO	Source[a]	$\dot{N}_{low}$ yr^{-1}	$\dot{N}_{re}$ yr^{-1}	$\dot{N}_{high}$ yr^{-1}	$\dot{N}_{max}$ yr^{-1}
	NS–NS	2×10^{-4}	0.02	0.2	0.6
	NS–BH	7×10^{-5}	0.004	0.1	
Initial	BH–BH	2×10^{-4}	0.007	0.5	
	IMRI into IMBH			<0.001[b]	0.01[c]
	IMBH-IMBH			10^{-4}[d]	10^{-3}[e]
	NS–NS	0.4	40	400	1000
	NS–BH	0.2	10	300	
Advanced	BH–BH	0.4	20	1000	
	IMRI into IMBH			10[b]	300[c]
	IMBH-IMBH			0.1[d]	1[e]

GW detection rate estimates extrapolated from Galactic NS-NS merger rate

Probability density function of the NS-NS merger rate estimates

$$\boxed{\begin{aligned}\mathcal{P}(\mathcal{R}) &= \left(\frac{\tau_{\rm life}}{N_{\rm pop}}\right)^2 \mathcal{R}\,\exp\left[-\frac{\tau_{\rm life}}{N_{\rm pop}}\mathcal{R}\right] \\ &\equiv C^2\mathcal{R}\,\exp[-C\mathcal{R}]\end{aligned}}$$

(e.g. CK, Kaglogera, & Lorimer 2003)

This is based on **one detection of a pulsar (say, psrX)** in a PSR-NS binary

Information on binary and pulsar properties is absorbed in the rate coefficient C.

In order to calculate C, we need

observable lifetime of the binary $\tau_{\rm life}$
total # of psrs like psrX in the disk $N_{\rm pop}$

$$\mathcal{R} = \frac{N_{\rm pop}}{\tau_{\rm life}}$$

observable lifetime of a pulsar binary	=	spin-down age of the detected pulsar	+	radio emission or merging timescale

radio emission, magnetosphere, B-field and/or spin evolution

total # of psrs like psrX in the disk	=	# of observable pulsars by pulsar surveys	x	correction factors

psr survey simulation
(radiometer eq.)
geodetic precession, orbital acc.
Galactic psr population model
(x,y,z,L)

beam geometry

Galactic radio psr population model does not affect the results much unless spatial/luminosity distribution of psrs in NS-NS binaries is quite different from that of known pulsars (e.g. bulge population?)

Progresses made since 2010

- Attempting to estimate beaming correction factors for all known PSR-NS and merging PSR-WD motivated by an empirical spin-opening angle relation (e.g. Weltevrede & Joshston 2008)

O'Shaughnessy & CK (2010)

- Including the B pulsar in the rate calculation.

- Estimating beaming correction factors for A and B using the beam geometry obtained from latest pulse profile analyses

- Using 4 pulsars (in 3 PSR-NS binaries) with best observational constraints :
  PSRs B1913+16, B1534+12, J0737-3039A, J0737-3039B

- Simulating 22 large-scale pulsar surveys including PALFA precursur survey (Cordes et al. 2006)

(CK, Perera, McLaughlin, submitted to ApJ)

The Double-Pulsar (PSR J0737-3039)

A pulsar (Burgay et al. 2003): first-born, recycled, spin period=22.7 ms

B pulsar (Lyne et al. 2004): second-born, non-recycled, spin period=2.77s

step 1. Calculate C_A and C_B for A and B pulsars, respectively

The beaming correction factors for A and B:

Ferdman et al. 2013 for A
Perera et al. 2012 for B

Use an average equivalent width for B

$$C = \frac{\tau_{\rm life}}{N_{\rm pop}}$$

rate coefficient

step 2. Calculate P(R) for the Double Pulsar by combining individual PDFs

Assume, pulsar detection is an independent process

likelihood of detecting the Double Pulsar (both A and B) = likelihood of detecting A (with B as its companion) x likelihood of detecting B (with A as its companion)

area under
the pulse
profile
/
peak

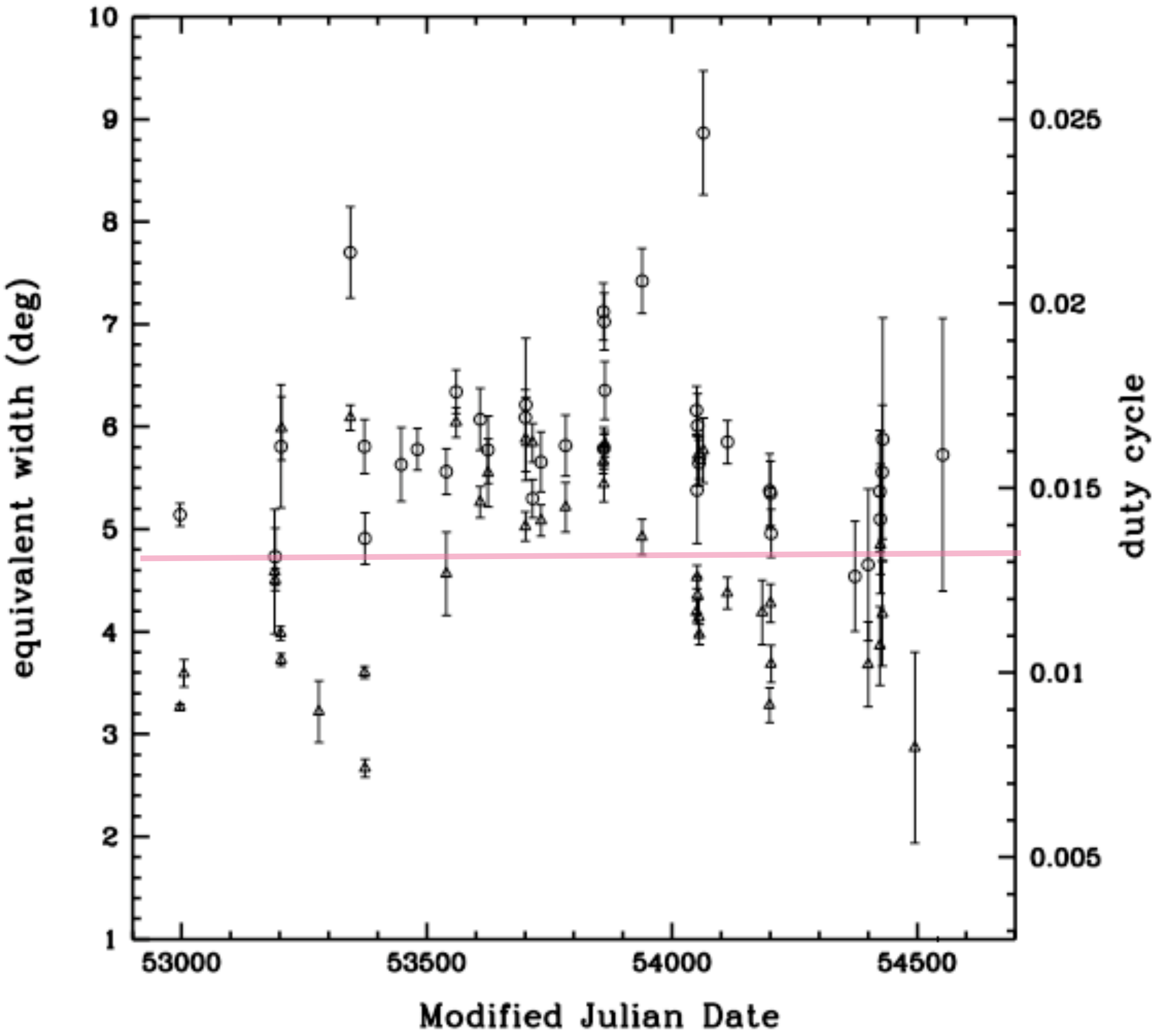
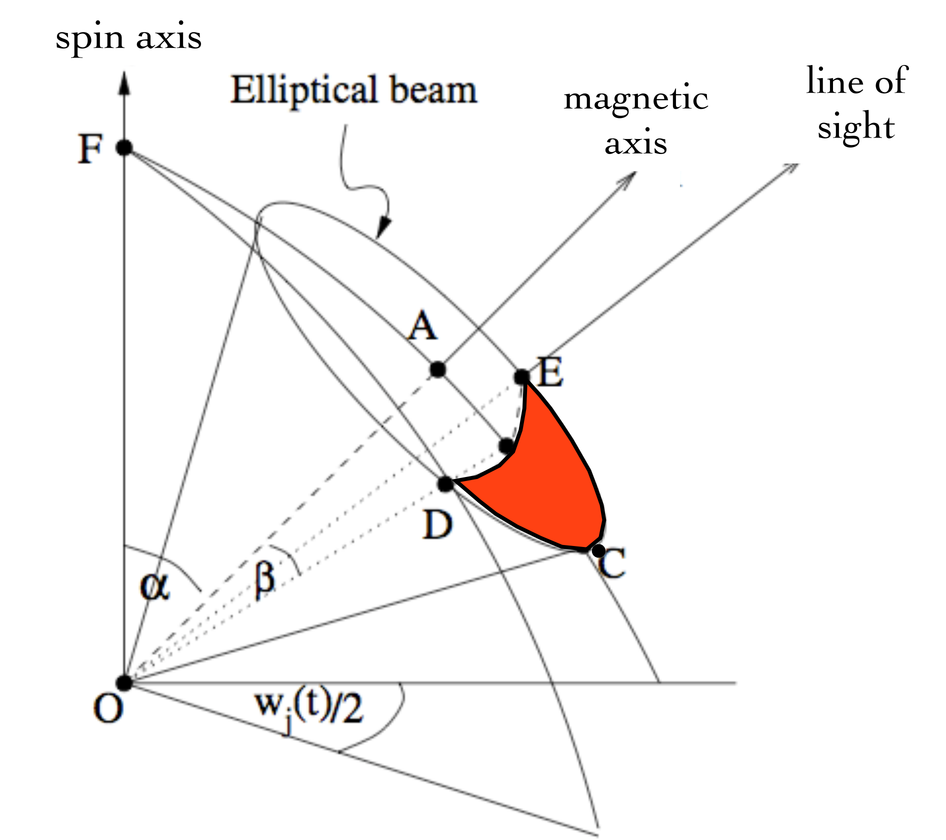
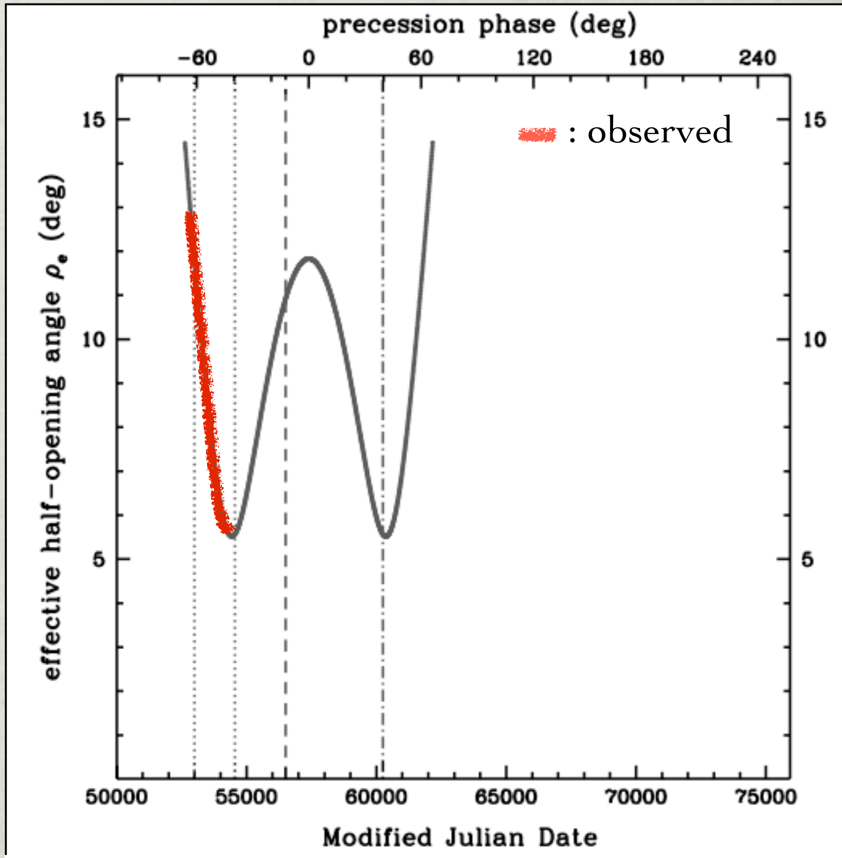


FIG. 1.— The measured equivalent pulse width W_{eq} and duty cycle δ obtained from B's pulse profiles in two bright phases, BP1 (triangles) and BP2 (open circles), respectively. We use the average value of $W_{eq} \simeq 4\overset{\circ}{.}68$ ($\delta \simeq 0.013$) as our reference.

Elliptical beam model for B (Perera et al. 2012)



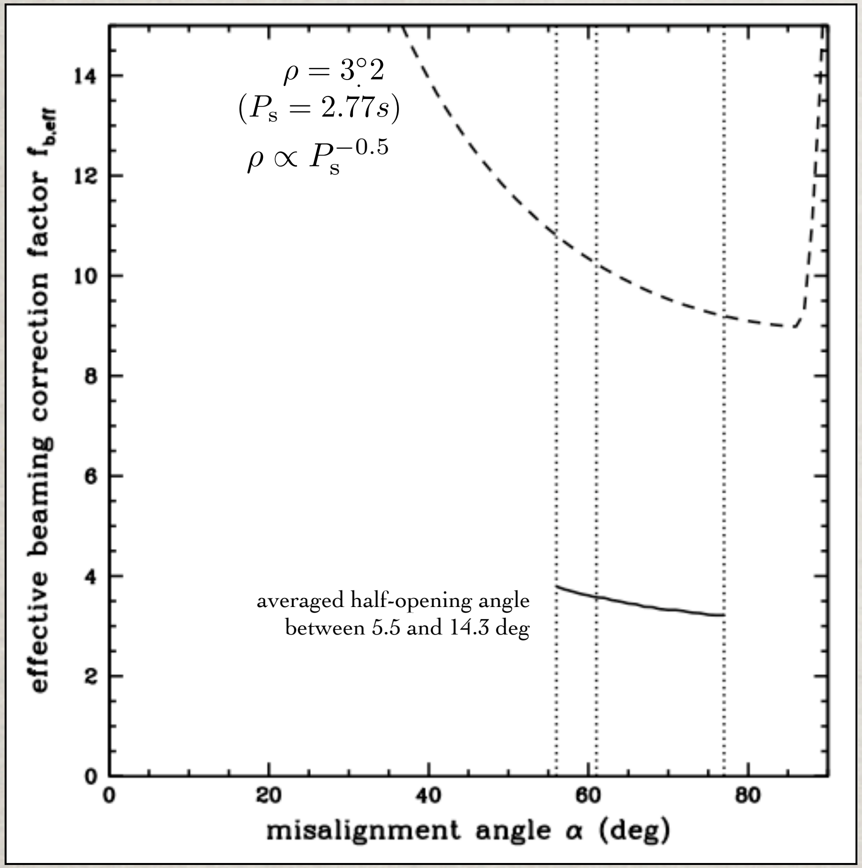
< AOC is the half-opening angle of the elliptical beam (~14 deg)

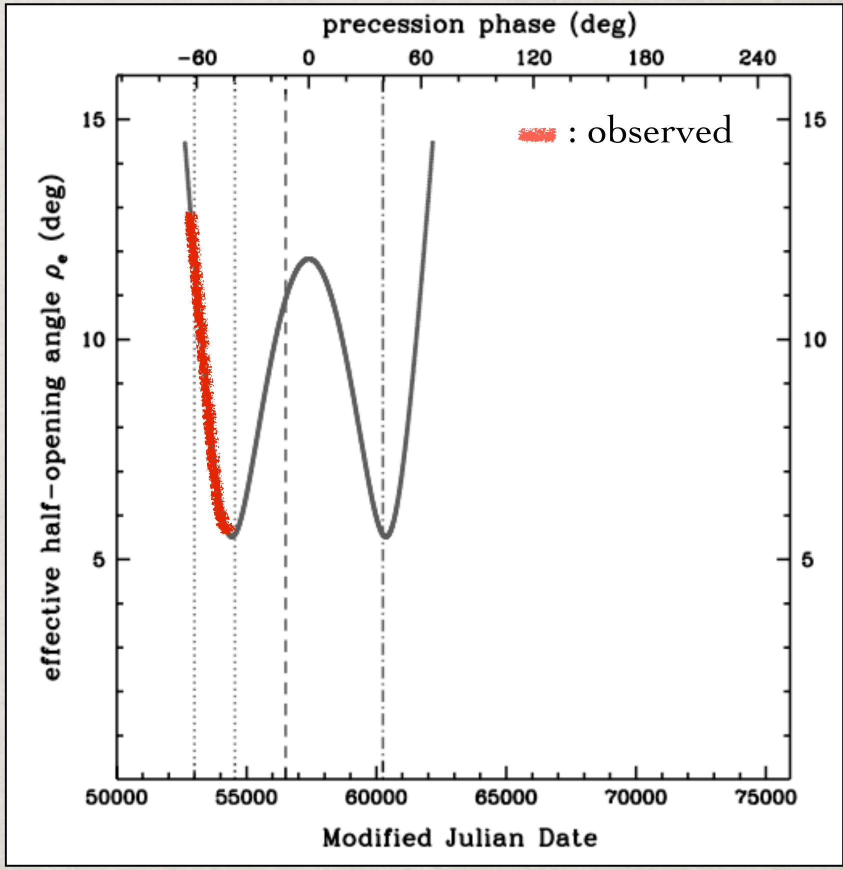


< AOD is the effective half-opening angle =[5.5, 14.3] deg

misalignement angle = 61 deg (fixed)

Effective beaming correction factor for B





beaming correction factor f_b = 1/(beaming fraction)

empirical spin-opening angle relation doesn't work for B !

A pulsar

polarization measurements
(Demorest et al. 2004)

pulse profile analysis
(Ferdman et al. 2008, 2013)

$$\langle f_{\rm b,eff,A} \rangle \sim 2$$

$$\alpha \sim 90^{\circ}{}^{+5}_{-10}$$

$$\rho \sim 11^{\circ} - 18^{\circ} \text{ or } \sim 30^{\circ}$$

B pulsar

pulse profile analysis
(Perera et al. 2010, 2012)

polarization measurments are difficult, due to strong modulations in the pulse profile induced by geodetic precession

$$\langle f_{\rm b,eff,B} \rangle \sim 3 - 4$$

$$\alpha = 61^{\circ} \text{ (best} - \text{fit)}$$

$$\rho = [5\overset{\circ}{.}5, 14\overset{\circ}{.}3]$$

The observed pulse profiles imply wide beams for both pulsars (i.e. beaming correction factor for A is much smaller than what was used in Kalogera et al. 2004)

The B pulsar is more difficult to detect than the A pulsar

• If we correct selection biases perfectly,

total estimated number of psrs like A
~ # of psrs like B
~ # of systems like the Double Pulsar
~ 1600 (most likely from the combined PDF)

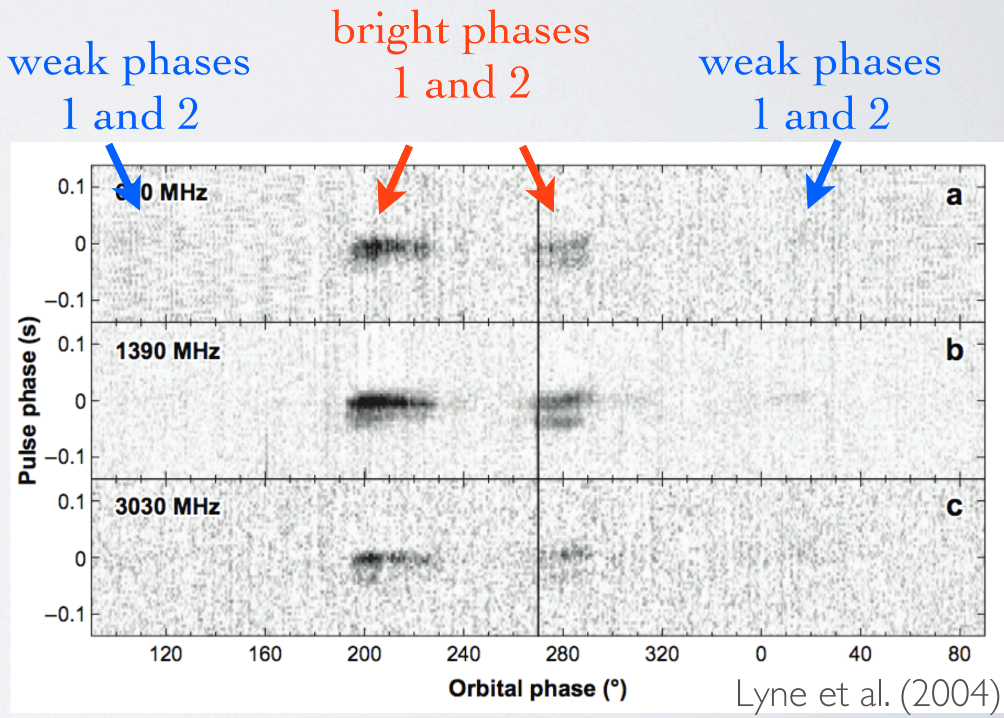
B is observable only
~50% of orbital phase

• Based on our reference pulsar model,

# of observable psrs like A ~ 800
# of observable psrs like B ~ 200

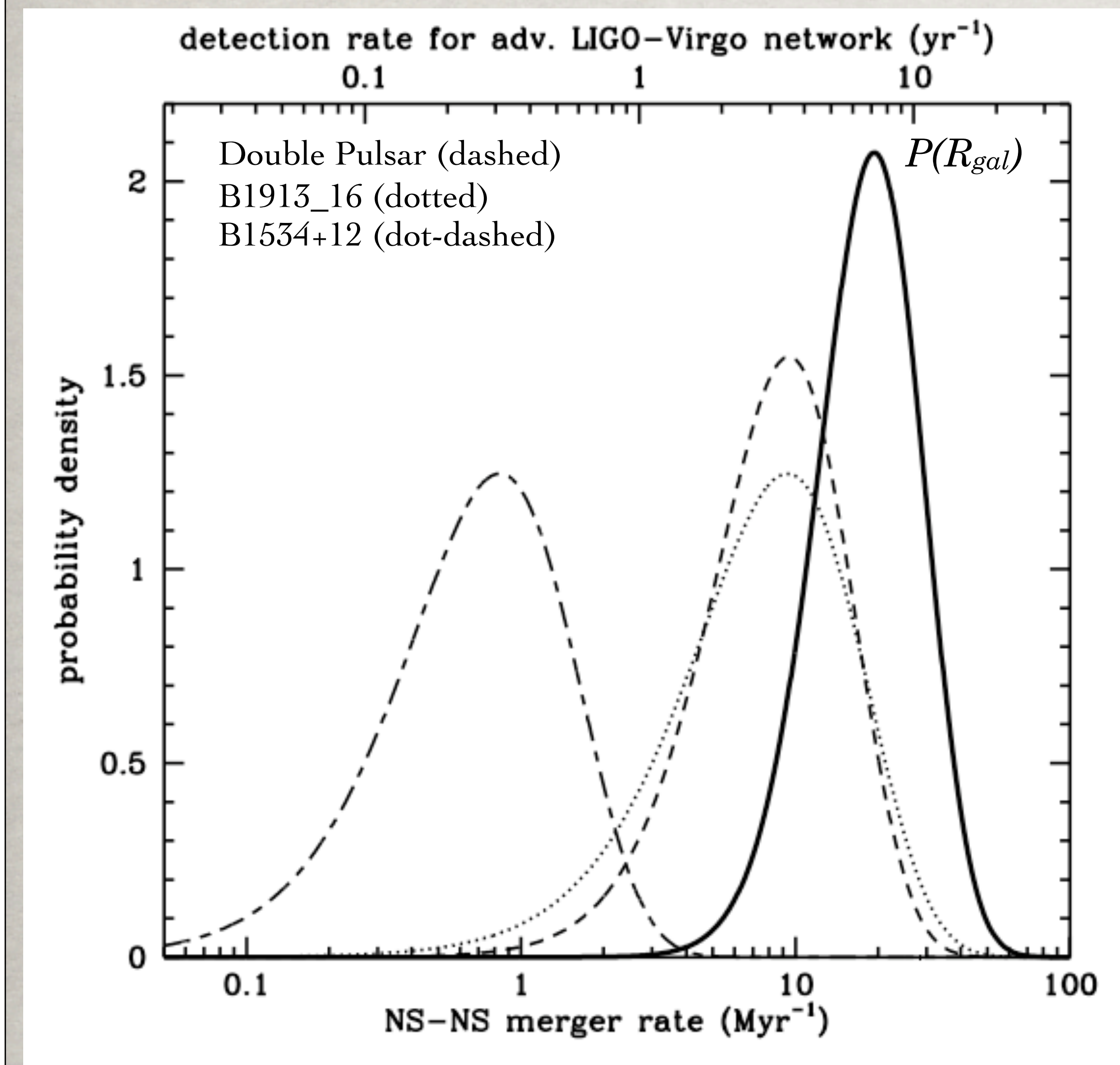
among those beaming toward us

• We expect there are total 500 - 6000 Double Pusar-like binaries in the disk (95%)



Lyne et al. (2004)

Results



R ~ 20 Myr^{-1} [peak]

Galactic NS-NS merger rate is NOT dominated by the single system.

We need more samples!

100+ PSR-NS binaries are needed to really beat systematic uncertainties (Kalogera et al. 2001)

There are most likely to be total ~5000 PSR-NS binaries in the disk

$$\mathcal{R}_{\rm det} = 8^{+10}_{-5}\ {\rm yr}^{-1}$$

GW event rates for NS-NS binaries with an advanced LIGO-Virgo network (horizon distance = 445 Mpc)

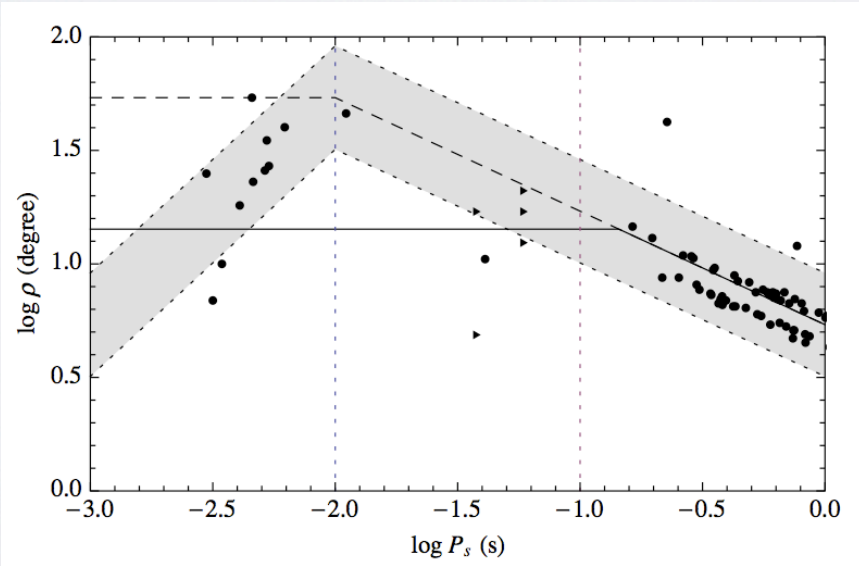
•PSR J1906+0746

A cousin of the Double Pulsar (where only B is beaming toward us) or another example of J1141 or B2303-like system (an older WD + non-recyced PSR)?

	P_s (ms)	P_{orb} (days)	e	pulsar mass (M_{sun})	companion mass (M_{sun})	companion type
J1141-6545[2]	393.9	0.198	0.17188	$1.27^{+0.01}_{-0.01}$	$1.02^{+0.01}_{0.01}$	WD
J1906+0746[3]	144.1	0.166	0.08530	$1.323^{+0.011}_{-0.011}$	$1.290^{+0.011}_{-0.011}$	WD or NS

Kasian (2012) Ph.D. thesis

If the opening angle of J1906 (also J1141, B2303) can be measured, this will provide another test of the spin-opening angle relation



effective half-opening angle of B = [5.5, 14.8] deg preferred by observed pulse profiles

B psr (~ 3 deg) if $\rho \propto P_s^{-0.5}$

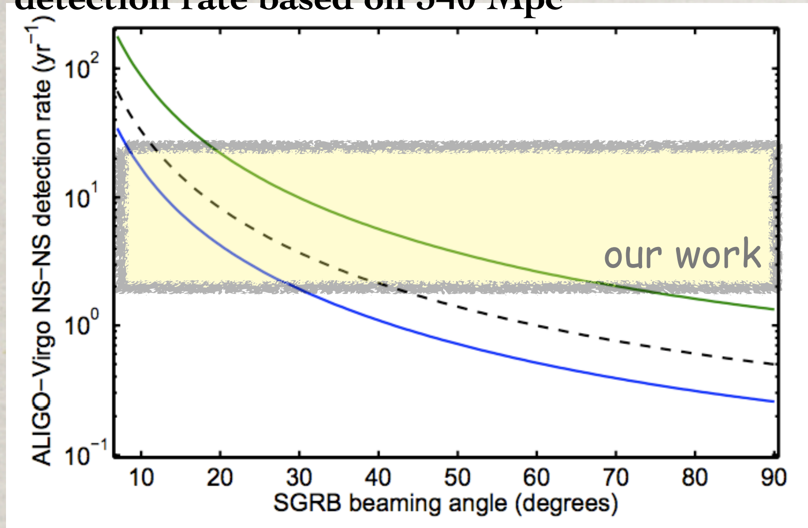
Ps=2.77s

O'Shaughnessy & CK (2010)

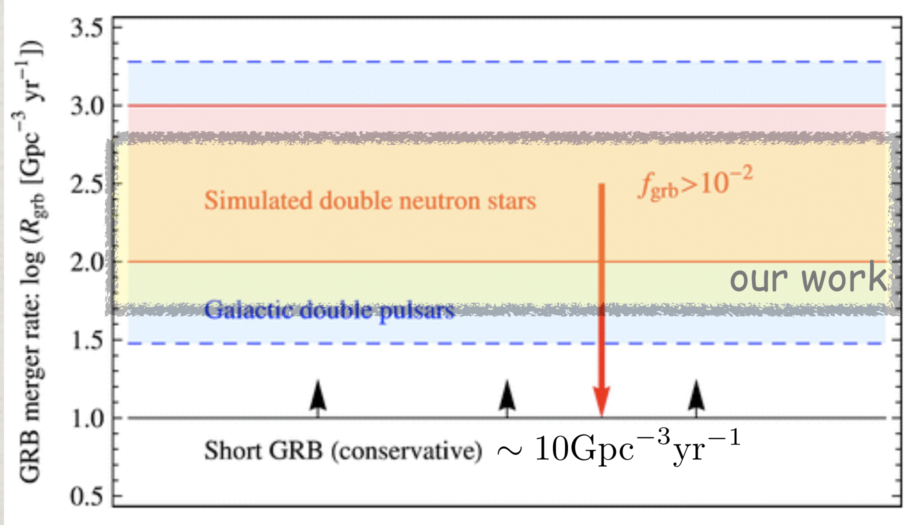
Our results are consistent with sGRB rate and theoretical expectations but we can do better with GW detections

coward et al. (2012)

detection rate based on 340 Mpc



Belczynski et al. (2008)



based on 8 Swift sGRBs with z measurements

(popsyn) NS-NS merger rate : ~ 1 - 100 Myr^{-1}

(empirical) NS-NS merger rate : ~ 3 - 20 Myr^{-1}

150-2000 Gpc^{-3} yr^{-1} [Gehrels]
(if all sGRBs are formed from NS-NS mergers, beaming angle ~ 5-20 deg)

At 99% C.L., the NS-NS merger rate per volumn from our work is

$$\mathcal{R}_{\mathrm{gal,NS-NS}} \sim 50 - 700\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$

Summary

- We estimate Galactic NS-NS merger rate based on known PSR-NS systems: PSRs B1913+16, B1534+12, J0737-3039A, an J0737-3039B

- Using long-term observations with GBT, it is possible to constrain beam geometry of A and B pulsars in the Double Pulsar and to calculate P(R) of this binary.

- **P(R) of A and B are consistent based on our reference model**

- **The estimated beaming correction factor of A is ~2** (or 50% of beaming fraction). **This is supported by independent constraints from B.**

- **Realistic models for psr beam geometry, radio emission, and spin evolution will be useful to further constrain P(R)**

- The Galactic NS-NS merger rate ~10-50 Myr^{-1} (based on a perfect dipole + standard PSR population model). GW detection rate for advanced LIGO-Virgo ~ $\mathcal{O}(1\text{-}10)\ \mathrm{yr}^{-1}$