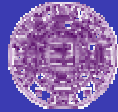


A New Relativistic Binary Pulsar: *Gravitational Wave Detection and Neutron Star Formation*

Vicky Kalogera

Physics & Astronomy Dept



NORTHWESTERN
UNIVERSITY

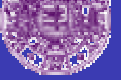
with

Chunglee Kim (NU)

Duncan Lorimer (Manchester)

Bart Willems (NU)

Mia Ihm (NU)



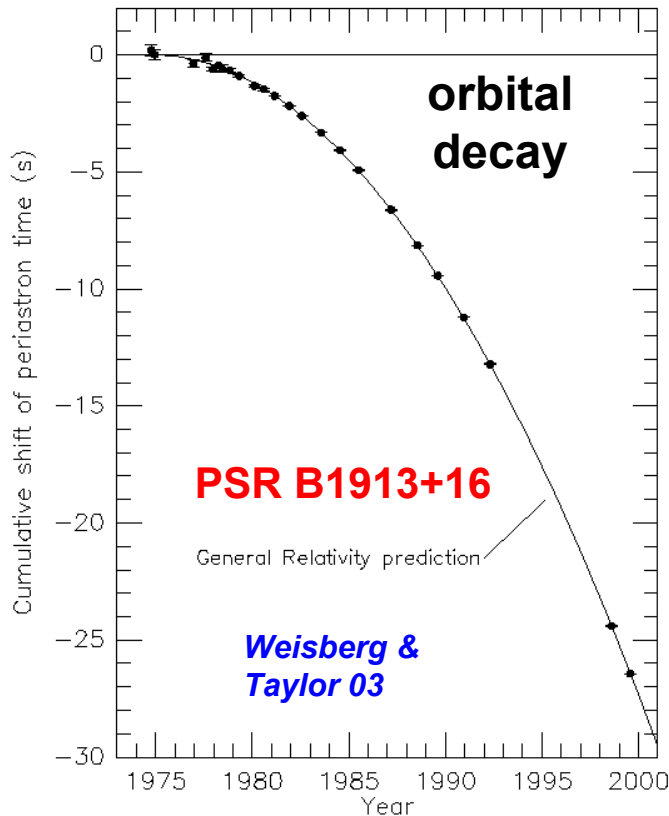
In this talk :

- Gravitational Waves and Double Neutron Stars
- Meet PSR J0737-3039:
the most relativistic binary and
the first double pulsar
- Inspiral Event Rates
for NS-NS, BH-NS, BH-BH
- Supernovae and NS-NS Formation

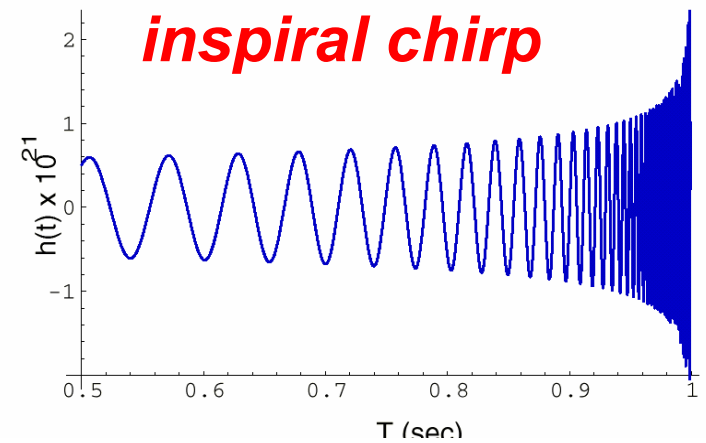
Binary Compact Object Inspiral

Do they exist ? **YES!**

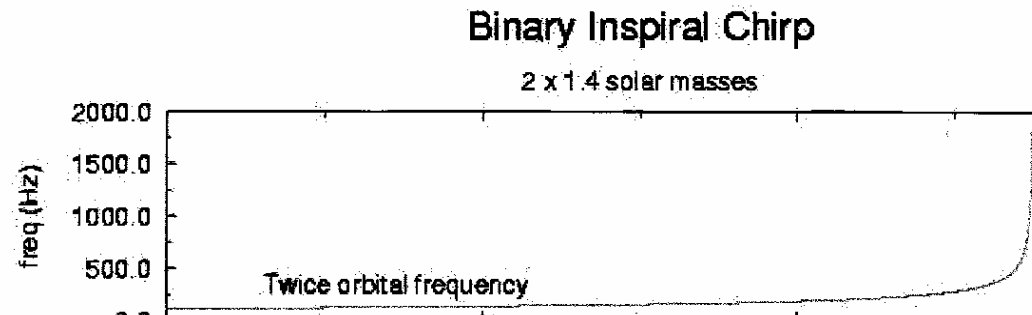
Prototype NS -NS: binary radio pulsar PSR B1913+16



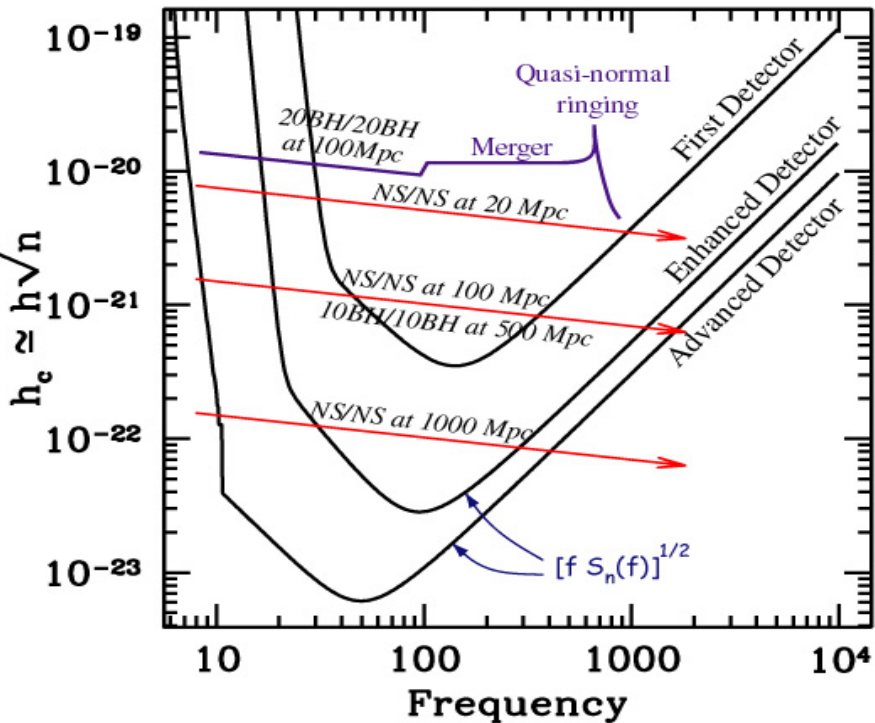
What kind of signal ?



GW emission causes orbital shrinkage leading to higher GW frequency and amplitude



Sensitivity to coalescing binaries



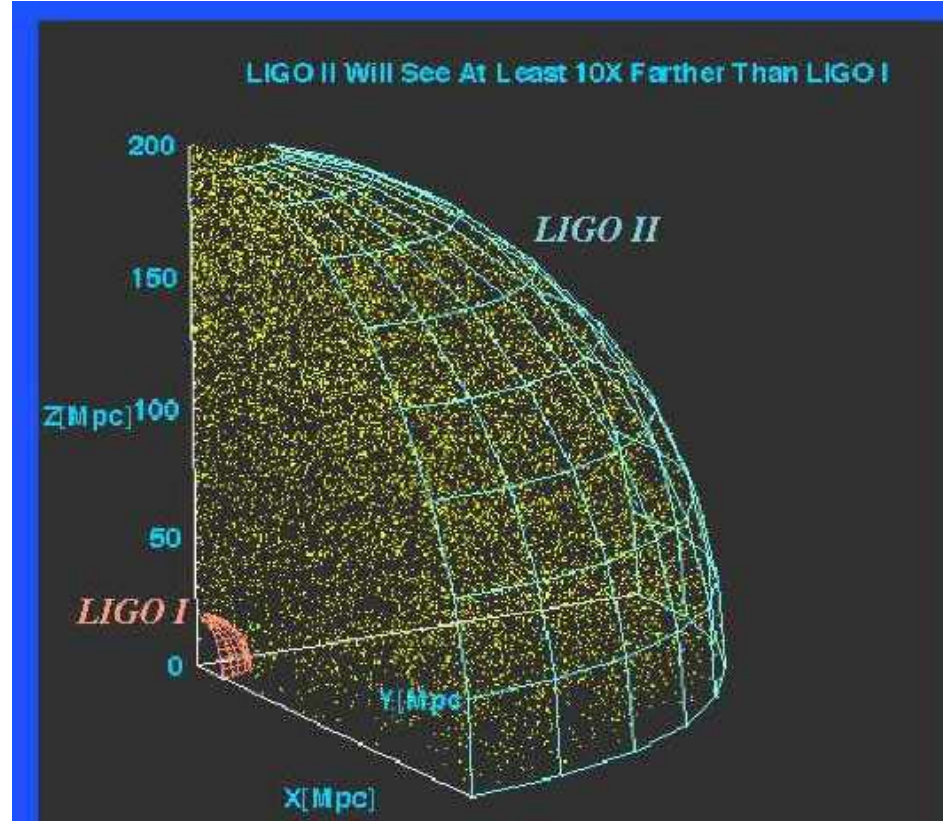
→ strength $\sim 1/r^2$

D_{max} for each signal sets limits on the possible detection rate

What is the expected detection rate out to

D_{max} ?

→ Scaling up from the Galactic rate



Inspiral Rates for the Milky Way

Theoretical Estimates

• *Based on models of binary evolution until binary compact objects form.*

for NS -NS, BH -NS, and BH -BH

Empirical Estimates

• *Based on radio pulsar properties and survey selection effects.*

for NS -NS only

Properties of known coalescing DNS pulsars

Galactic Disk pulsars

B1913+16

B1534+12

J0737-3039

Burgay et al. 2003

M15 (NGC 7078)

2127+11C

Properties of known coalescing DNS pulsars

P_s (ms) \dot{P}_s (ss⁻¹) L_{400}

Galactic Disk pulsars

B1913+16	59.03	8.6×10^{-18}	270
B1534+12	37.90	2.4×10^{-18}	9
J0737-3039	22.70	2.4×10^{-18}	28

Burgay et al. 2003

M15 (NGC 7078)

2127+11C	30.5	5.0×10^{-18}	67
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Properties of known coalescing DNS pulsars

P_s (ms) \dot{P}_s (ss⁻¹) L_{400} B_9 (G)

Galactic Disk pulsars

B1913+16	59.03	8.6×10^{-18}	270	22.8
B1534+12	37.90	2.4×10^{-18}	9	9.7
J0737-3039	22.70	2.4×10^{-18}	28	7.4

Burgay et al. 2003

M15 (NGC 7078)

2127+11C	30.5	5.0×10^{-18}	67	12.5
-----------------	------	-----------------------	----	------

Properties of known coalescing DNS pulsars

	P_s (ms)	\dot{P}_s (ss ⁻¹)	L_{400}	B_9 (G)	d(kpc)
--	------------	---------------------------------	-----------	-----------	--------

Galactic Disk pulsars

B1913+16	59.03	8.6×10^{-18}	270	22.8	7.3
B1534+12	37.90	2.4×10^{-18}	9	9.7	0.5
J0737-3039	22.70	2.4×10^{-18}	28	7.4	0.6

Burgay et al. 2003

M15 (NGC 7078)

2127+11C	30.5	5.0×10^{-18}	67	12.5	10.6
-----------------	------	-----------------------	----	------	------

Properties of known coalescing DNS pulsars

P_s (ms) \dot{P}_s (ss⁻¹) P_{orb} (hr)

Galactic Disk pulsars

B1913+16	59.03	8.6×10^{-18}	7.8
-----------------	-------	-----------------------	-----

B1534+12	37.90	2.4×10^{-18}	10.0
-----------------	-------	-----------------------	------

J0737-3039	22.70	2.4×10^{-18}	2.4
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Burgay et al. 2003

M15 (NGC 7078)

2127+11C	30.5	5.0×10^{-18}	8.0
-----------------	------	-----------------------	-----

Properties of known coalescing DNS pulsars

P_s (ms) \dot{P}_s (ss⁻¹) P_{orb} (hr) e

Galactic Disk pulsars

B1913+16	59.03	8.6×10^{-18}	7.8	0.61
-----------------	-------	-----------------------	-----	------

B1534+12	37.90	2.4×10^{-18}	10.0	0.27
-----------------	-------	-----------------------	------	------

J0737-3039	22.70	2.4×10^{-18}	2.5	0.09
-------------------	-------	-----------------------	-----	------

Burgay et al. 2003

M15 (NGC 7078)

2127+11C	30.5	5.0×10^{-18}	8.0	0.68
-----------------	------	-----------------------	-----	------

Properties of known coalescing DNS pulsars

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

Galactic Disk pulsars

B1913+16	59.03	8.6×10^{-18}	7.8	0.61	2.8 (1.39)
-----------------	-------	-----------------------	-----	------	------------

B1534+12	37.90	2.4×10^{-18}	10.0	0.27	2.7 (1.35)
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J0737-3039	22.70	2.4×10^{-18}	2.5	0.09	2.6 (1.24)
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Burgay et al. 2003

M15 (NGC 7078)

2127+11C	30.5	5.0×10^{-18}	8.0	0.68	2.7 (1.36)
-----------------	------	-----------------------	-----	------	------------

Properties of known coalescing DNS pulsars

τ_c (Myr) τ_{sd} (Myr) τ_{mrg} (Myr) $\dot{\omega}$ (yr⁻¹)

Galactic Disk pulsars

B1913+16	110	65	300	4°. ²³
-----------------	-----	----	-----	-------------------

B1534+12	250	190	2700	1°. ⁷⁵
-----------------	-----	-----	------	-------------------

J0737-3039	210	100	85	16°. ⁹
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Burgay et al. 2003

M15 (NGC 7078)

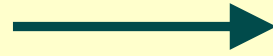
2127+11C	96	60	220	4°. ⁴⁶
-----------------	----	----	-----	-------------------

PSR J0737-3039 A and B in motion!

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

animation credit
John Rowe

Radio Pulsars in NS-NS binaries



NS-NS Merger Rate Estimates

Use of *observed sample* and models for PSR survey *selection effects* estimates of *total* NS- NS *number* combined with *lifetime estimates*

(Narayan et al. '91; Phinney '91)

Dominant sources of rate estimate uncertainties identified:

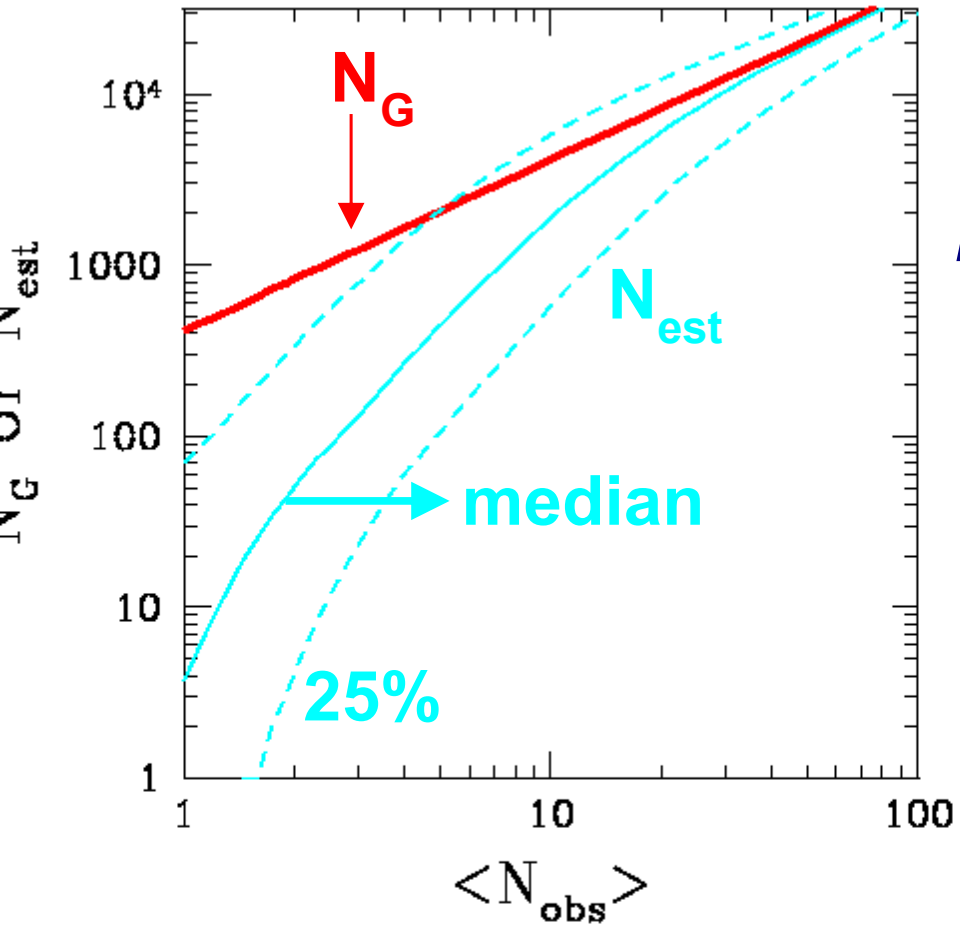
(VK, Narayan, Spergel, Taylor '01)

➡ small - number observed sample (~~3~~ NS - NS in Galactic field)

➡ PSR population dominated by faint objects

➡ Robust lower limit for the MW (10^{-6} per yr)

➡ Upward correction factor
for faint PSRs: $\sim 1 - 500$



pulsar luminosity function:

$$\sim L^{-2}$$

i.e., dominated by faint, hard-to-detect pulsars

small-N sample is:

- > assumed to be **representative** of the Galactic population
- > dominated by **bright** pulsars, detectable to large distances

→ **total pulsar number is underestimated**

Radio Pulsars
in
NS-NS binaries



NS-NS
Merger
Rate Estimates

(Kim, VK, Lorimer 2002)

*It is possible to assign statistical significance
to NS-NS rate estimates
with Monte Carlo simulations*

Bayesian analysis developed to derive the
probability density of NS-NS inspiral rate

Small number bias and selection effects for faint
pulsars are implicitly included in our method.

Statistical Method

1. Identify sub-populations of PSRs with pulse and orbital properties similar to each of the observed DNS

Model each sub-population in the Galaxy

with Monte-Carlo generations

- Luminosity distribution

power-law: $f(L) \propto L^{-p}$, $L_{\min} < L$ (L_{\min} : cut-off luminosity)

- Spatial distribution

2. Pulsar-survey simulation

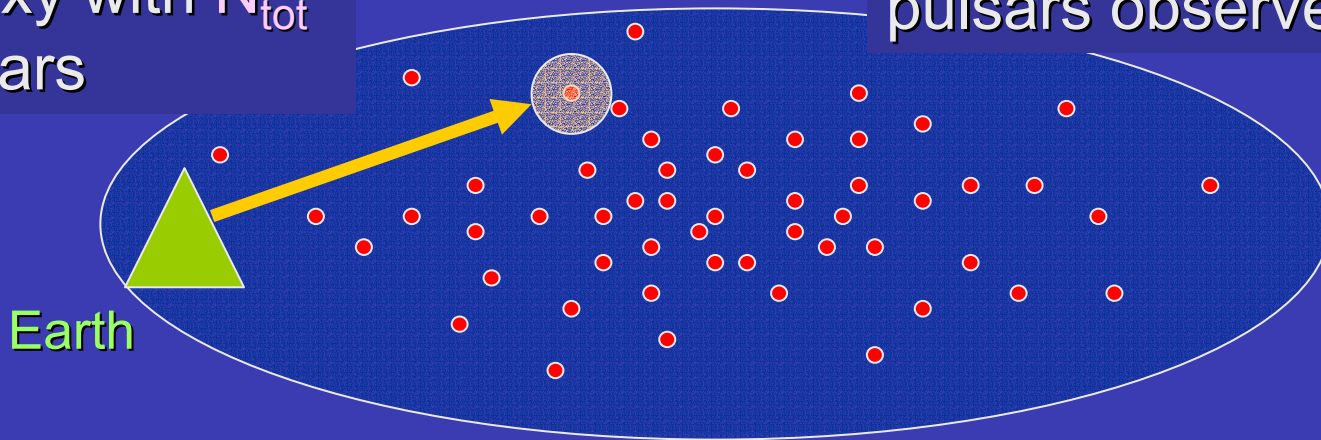
- consider selection effects of all pulsar surveys

- generate ``observed'' samples

Statistical Method

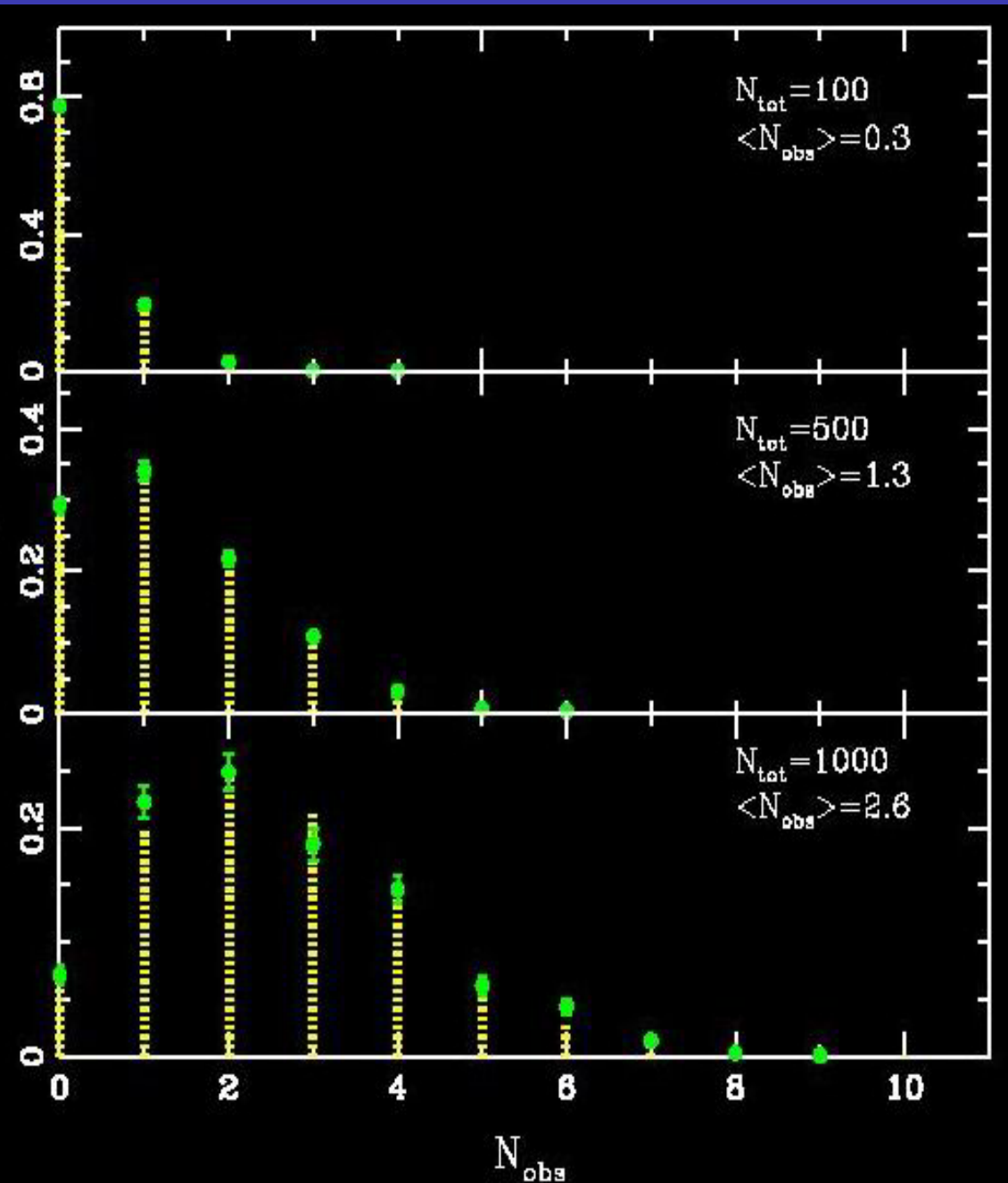
fill a model galaxy with N_{tot} pulsars

count the number of pulsars observed (N_{obs})



3. Derive rate estimate probability distribution $P(R)$

Statistical Analysis

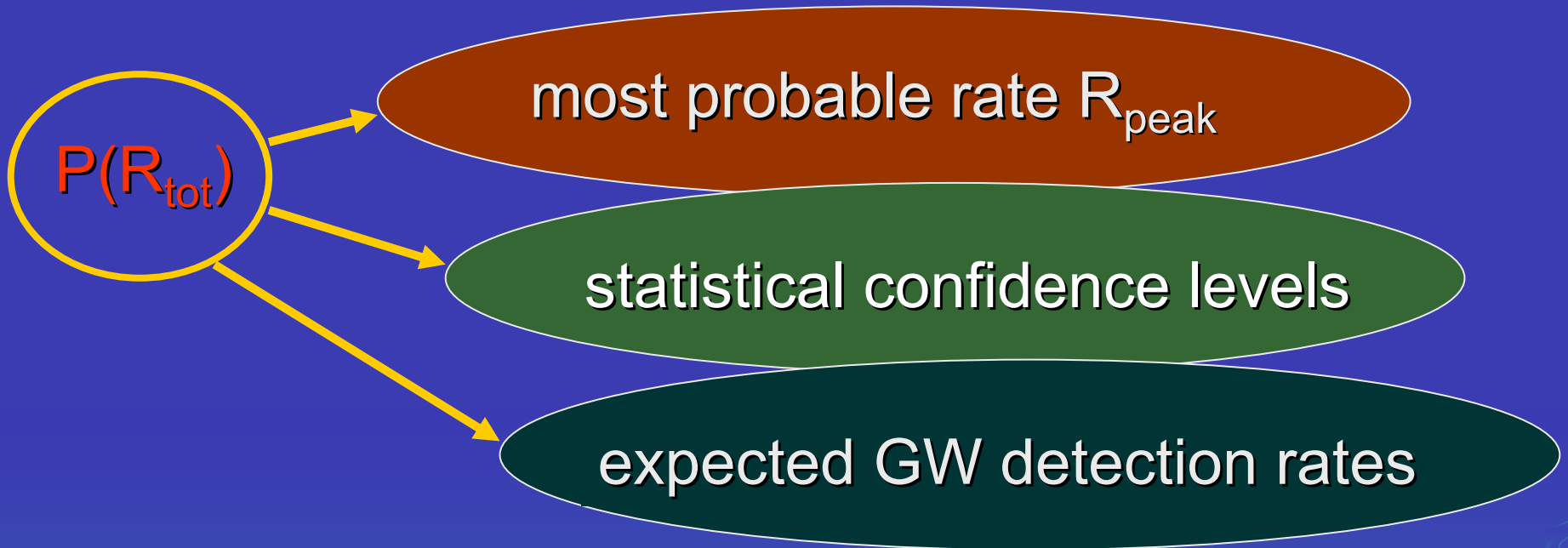


For a given total number of pulsars, N_{obs} follows a Poisson distribution.

We calculate the best-fit value of $\langle N_{\text{obs}} \rangle$ as a function of N_{tot} and the probability $P(1; N_{\text{tot}})$

We use Bayes' theorem to calculate $P(N_{\text{tot}})$ and finally $P(R)$

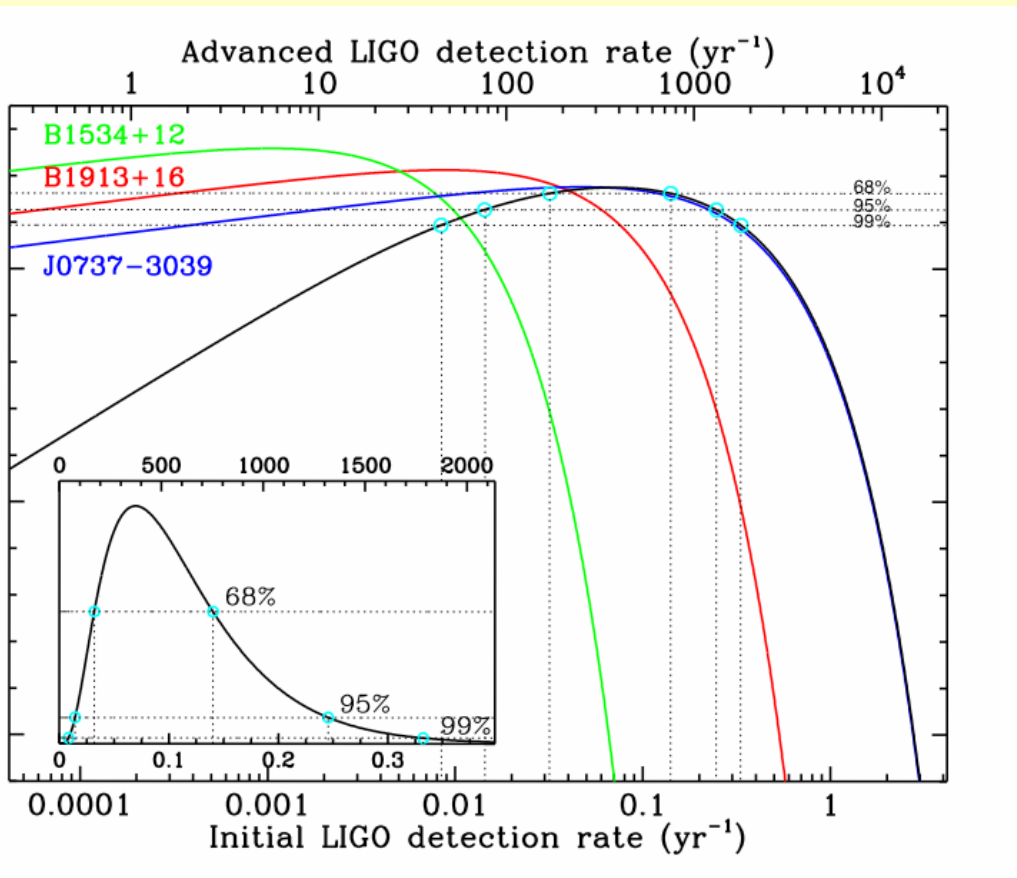
Results:



Current Rate Predictions

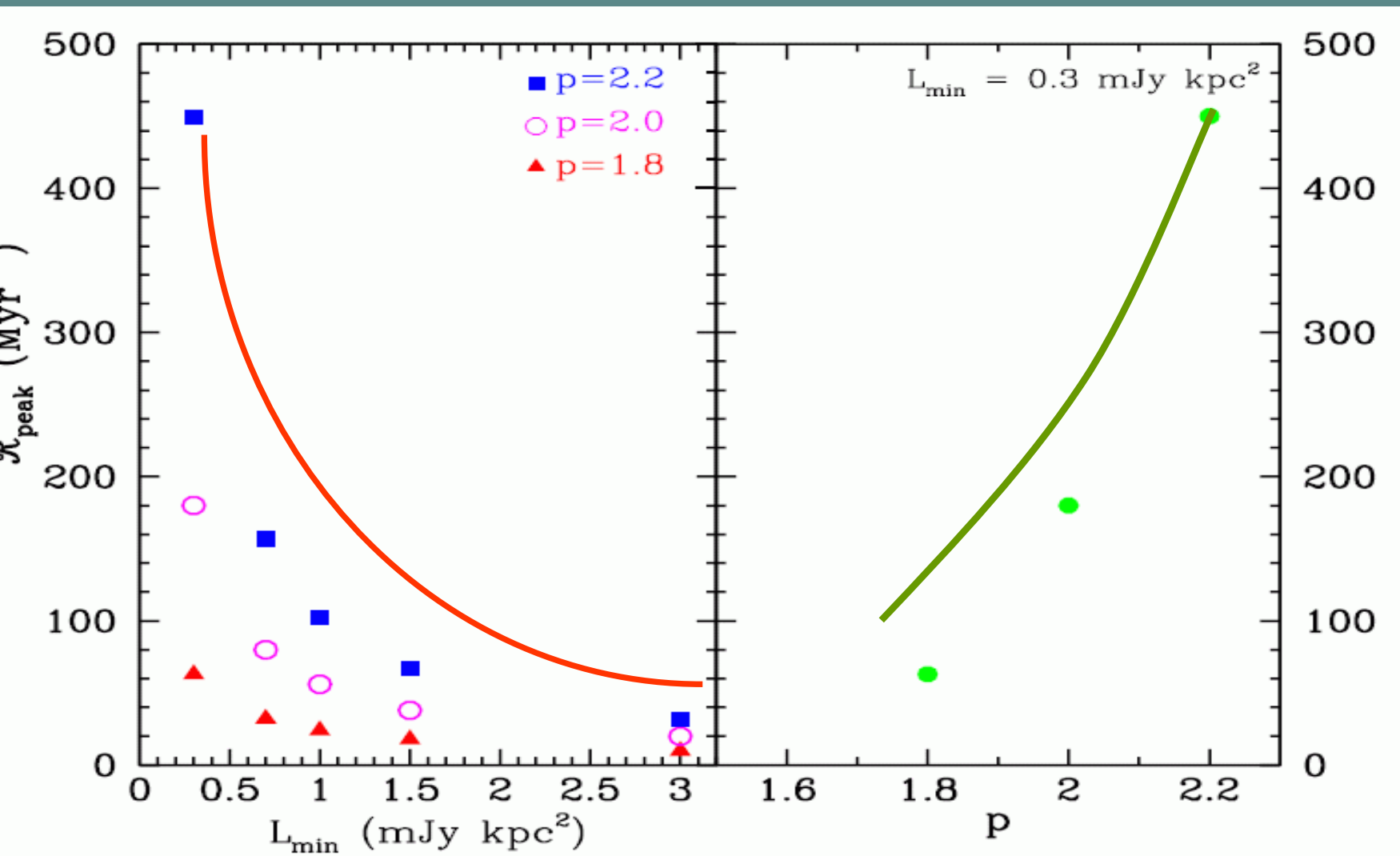
Burgay et al. 2003, Nature, 426, 531
 VK et al. 2004, ApJ Letters, in press

NS-NS : a factor of 6-7 rate increase



	Initial LIGO per 1000 yr	Adv. LIGO per yr
ref model:		
peak	75	400
95%	15 - 275	80 - 150
opt model:		
peak	200	1000
95%	35 - 700	200 - 370

Results: R_{peak} vs model parameters



Current expectations for **LIGO II** (**LIGO I**) detection rates of inspiral events

	NS -NS	BH -NS	BH -BH
D_{max} (Mpc)	350 (20)	700 (40)	1500 (100)
R_{det} (/yr)	5 - 3700 (6×10^{-3} - 0.7)	1.5 - 1500 (3×10^{-4} - 0.3)	15 - 10,000 (4×10^{-3} - 3)

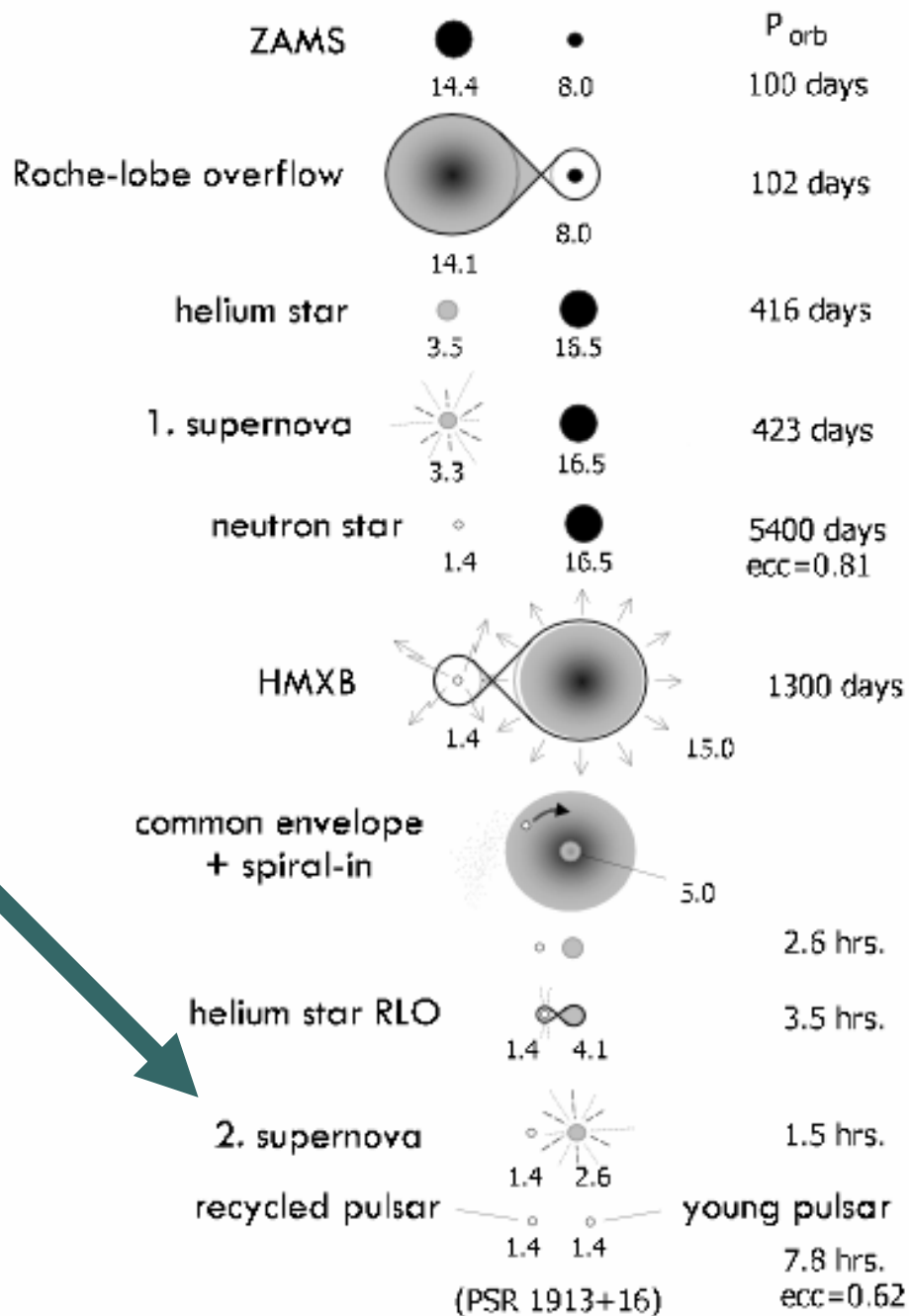
from population synthesis

Use empirical NS-NS rates: constrain

pop syn models > BH inspiral rates

How was PSR
0737-3039
formed ?

Current properties
constrain NS #2
formation process:
NS kick
NS progenitor



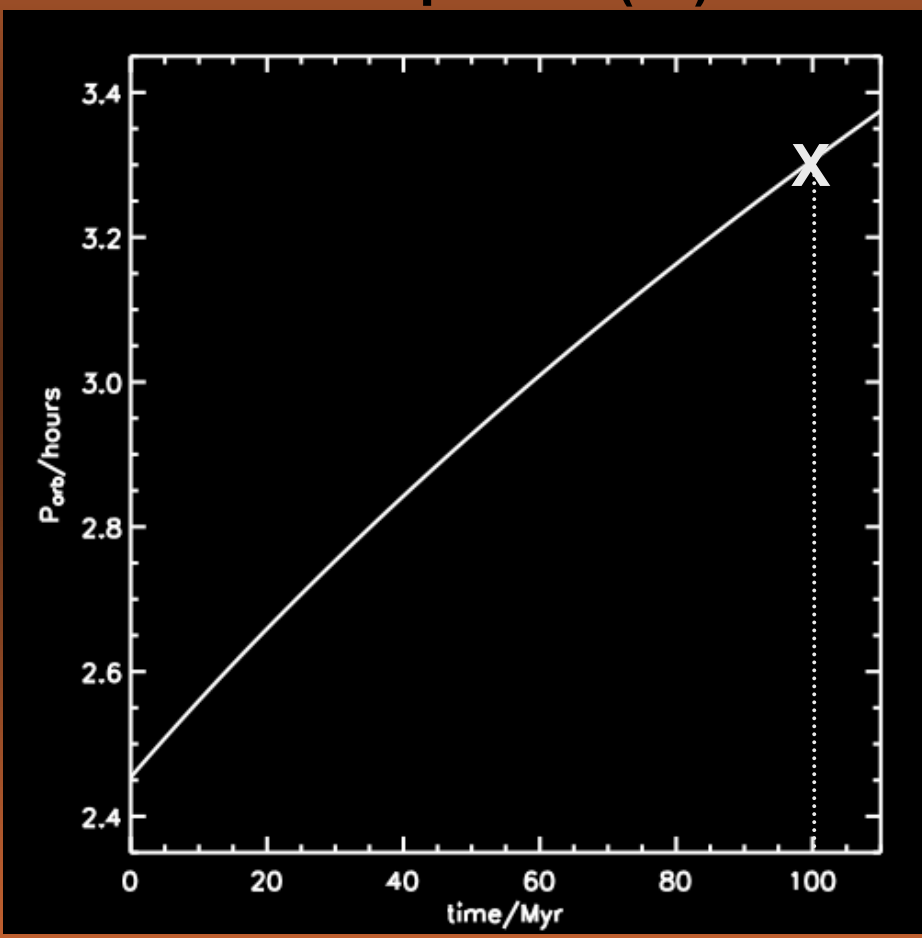
NS-NS Formation Channel

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

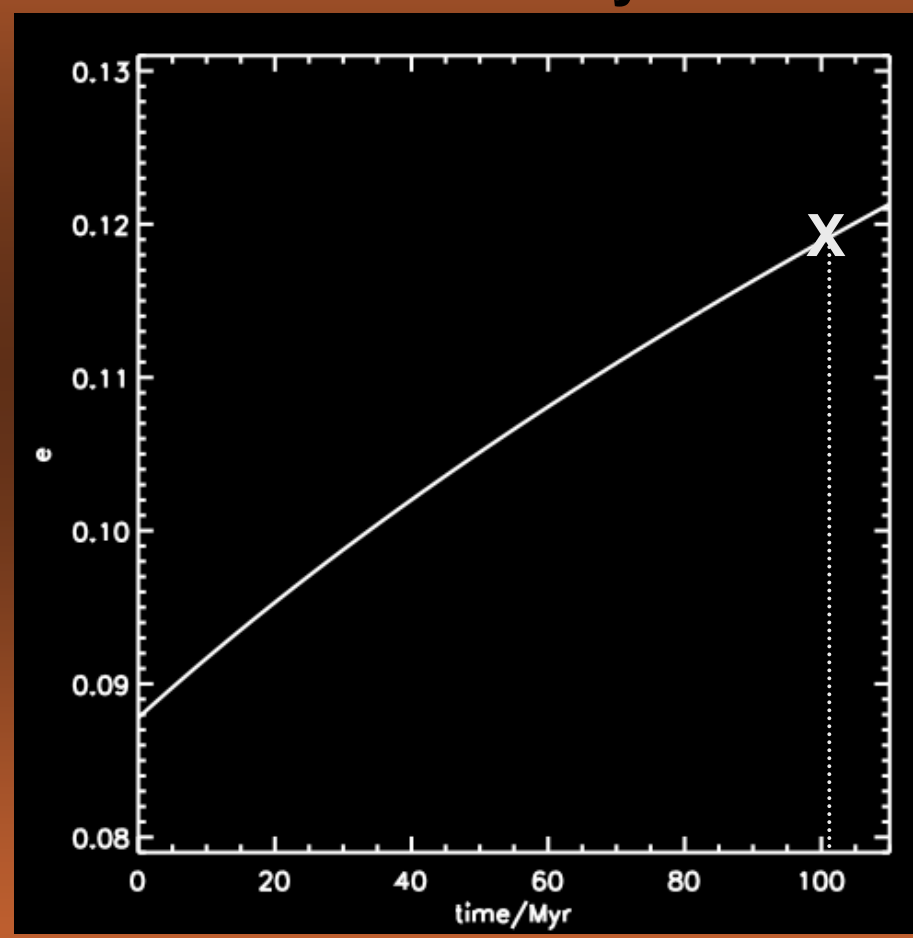
animation credit
John Rowe

➤ GR evolution back to post-SN #2 properties:

orbital period (hr)



eccentricity

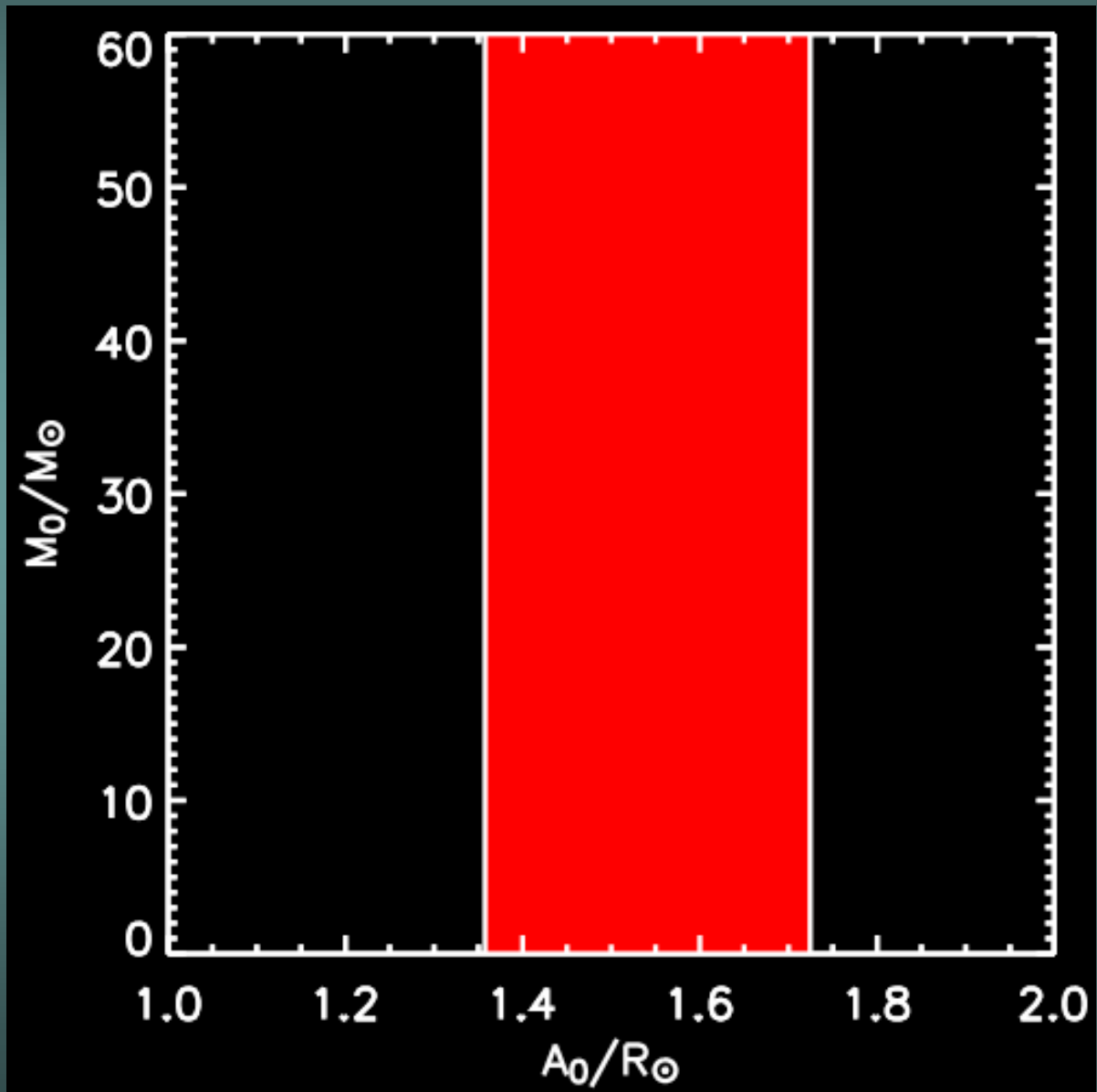


N.B. time since SN #2 can be set equal to

> the spin-down age from maximum spin-up: $\sim 100\text{Myr}$ (Arzoumanian et al. 2001)

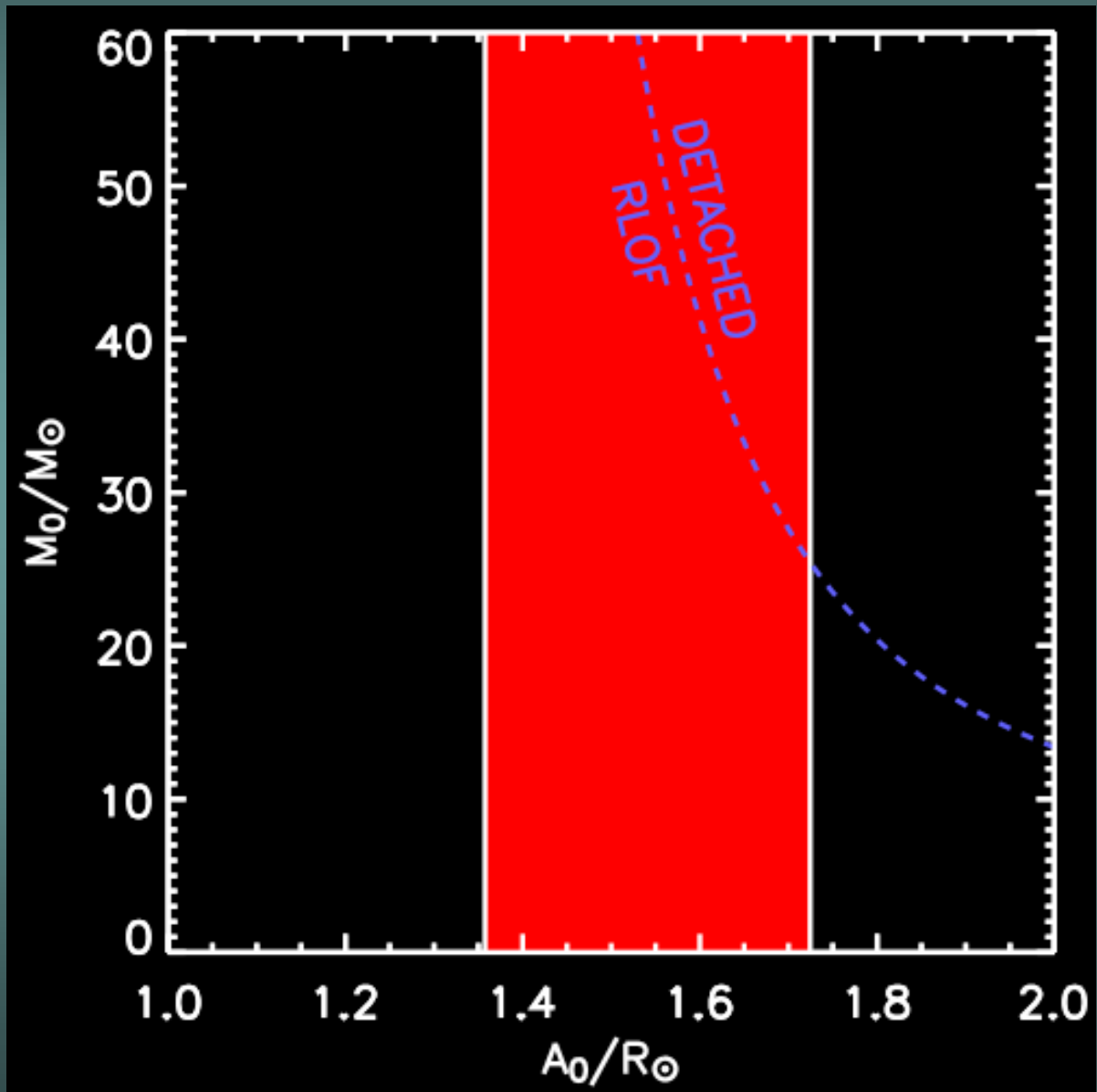
➤ Constraints on pre-SN #2 properties:

Willems & VK 20



post-SN orbit must contain pre-SN position (in circular orbit):
 $A (1-e) < A_0 < A (1+e)$

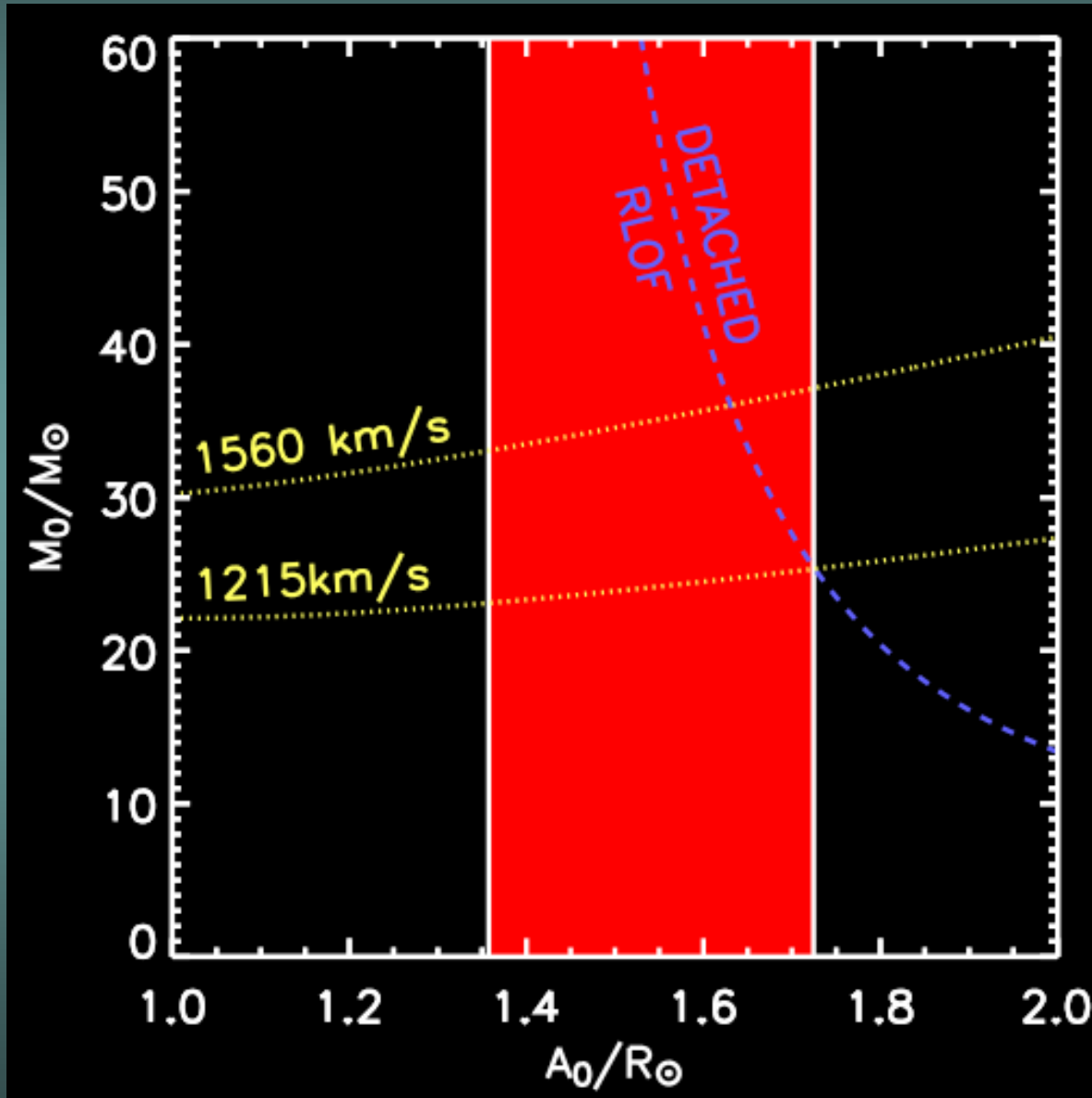
➤ Constraints on pre-SN #2 properties:



post-SN orbit must contain pre-SN position (in circular orbit):
 $A(1-e) < A_0 < A(1+e)$

NS #2 progenitor: helium star to avoid mass transfer
 $A_0 > A_{\min} = R_{\text{HE}}^{\max} / r_L$

➤ Constraints on pre-SN #2 properties:



post-SN orbit must contain pre-SN position (in circular orbit):

$$A(1-e) < A_0 < A(1+e)$$

NS #2 progenitor: helium star

to avoid mass transfer

$$A_0 > A_{\min} = R_{\text{HE}}^{\max} / r_L$$

to satisfy post-SN

masses, a, e:

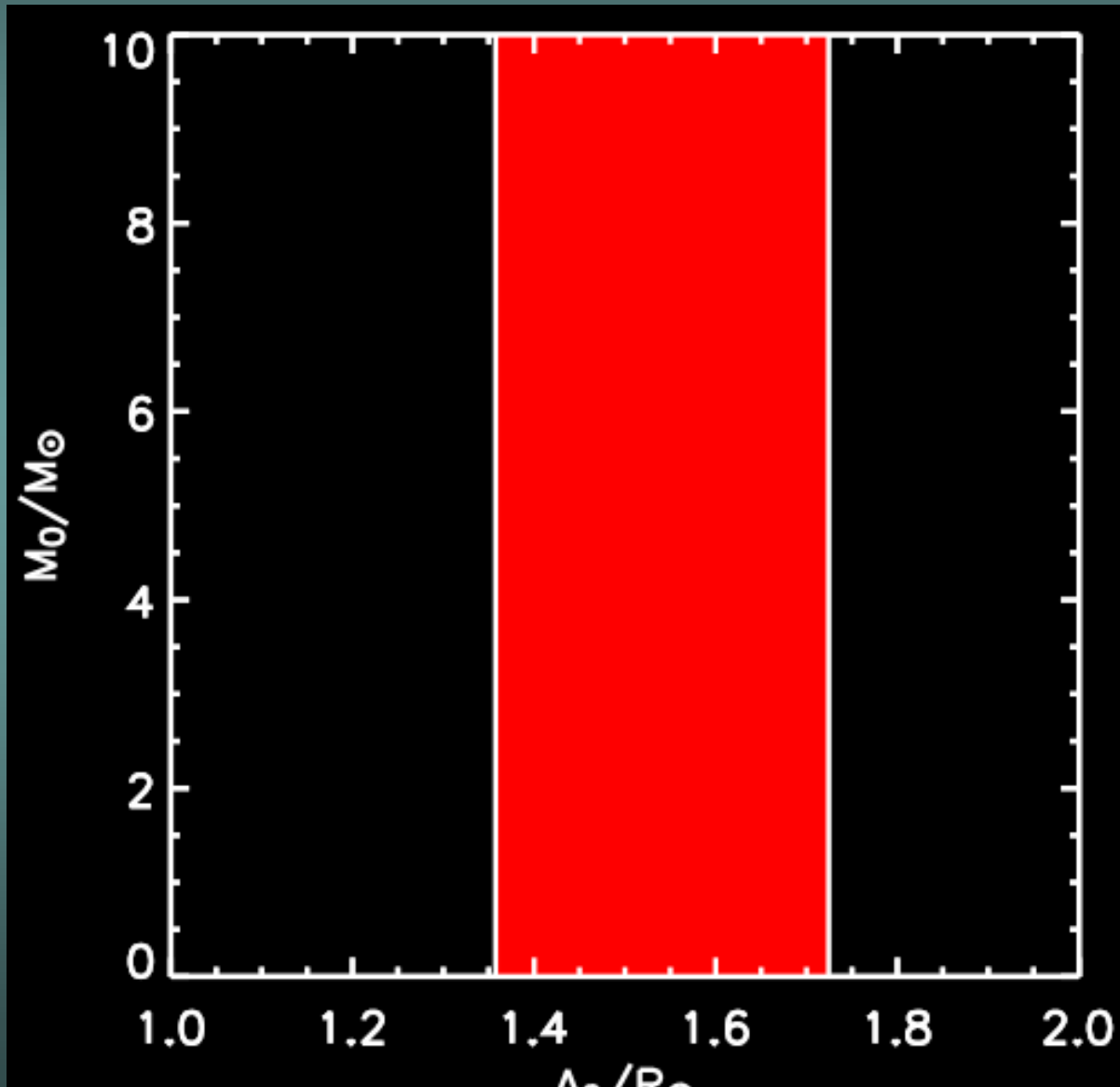
$$M_0 < M_{\max} = f(V_k)$$

$$M_0 > 20 M_{\text{solar}} \text{ and}$$

$$V_k > 1215 \text{ km/s}$$

Evolve the system backwards in time...

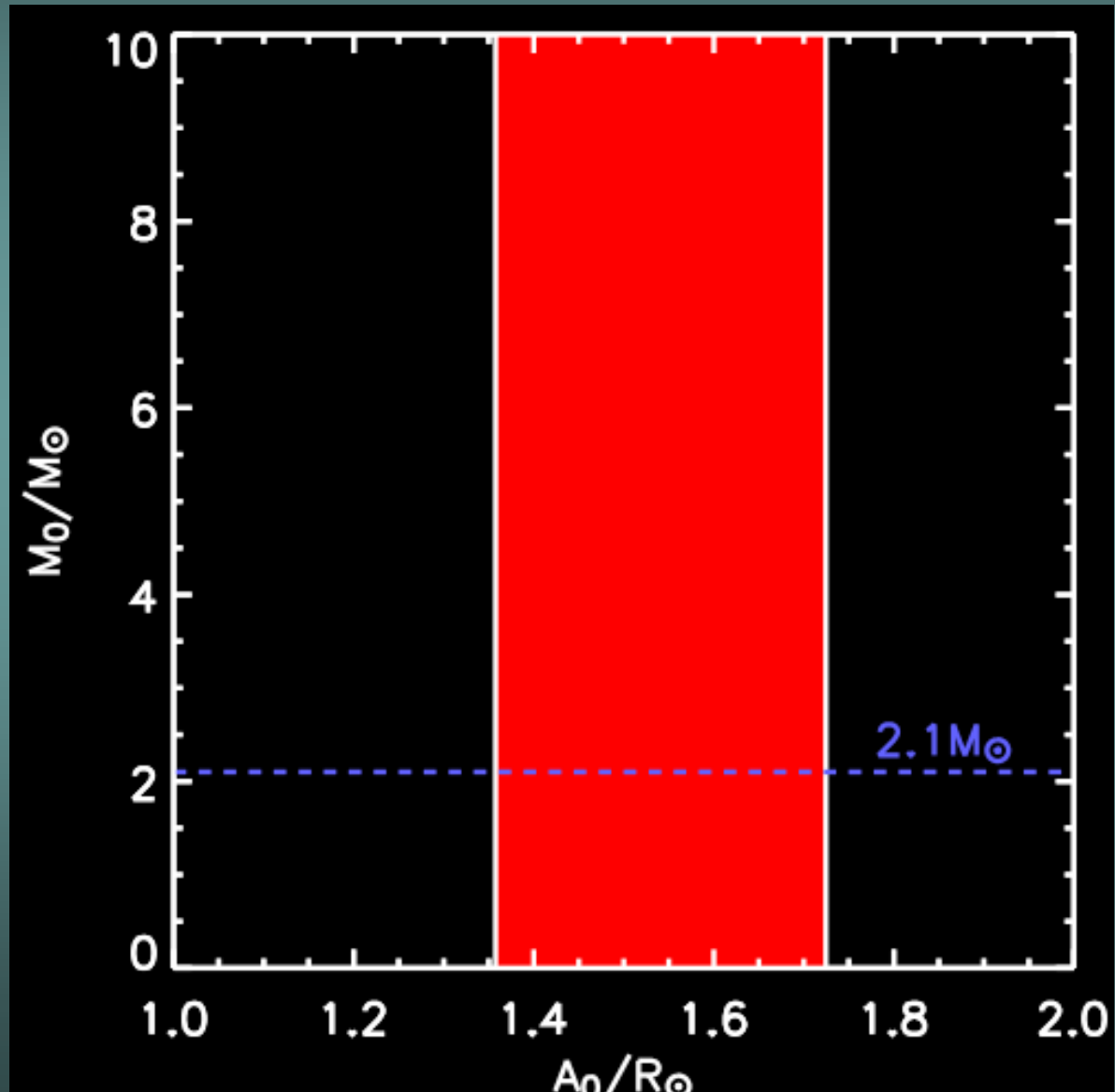
- Constraints on pre-SN #2 properties -
- allow for mass transfer from the He star:



post-SN orbit must contain pre-SN position (in circular orbit):
 $A(1-e) < A_0 < A(1+e)$

Evolve the system backwards in time...

- Constraints on pre-SN #2 properties -
- allow for mass transfer from the He star:

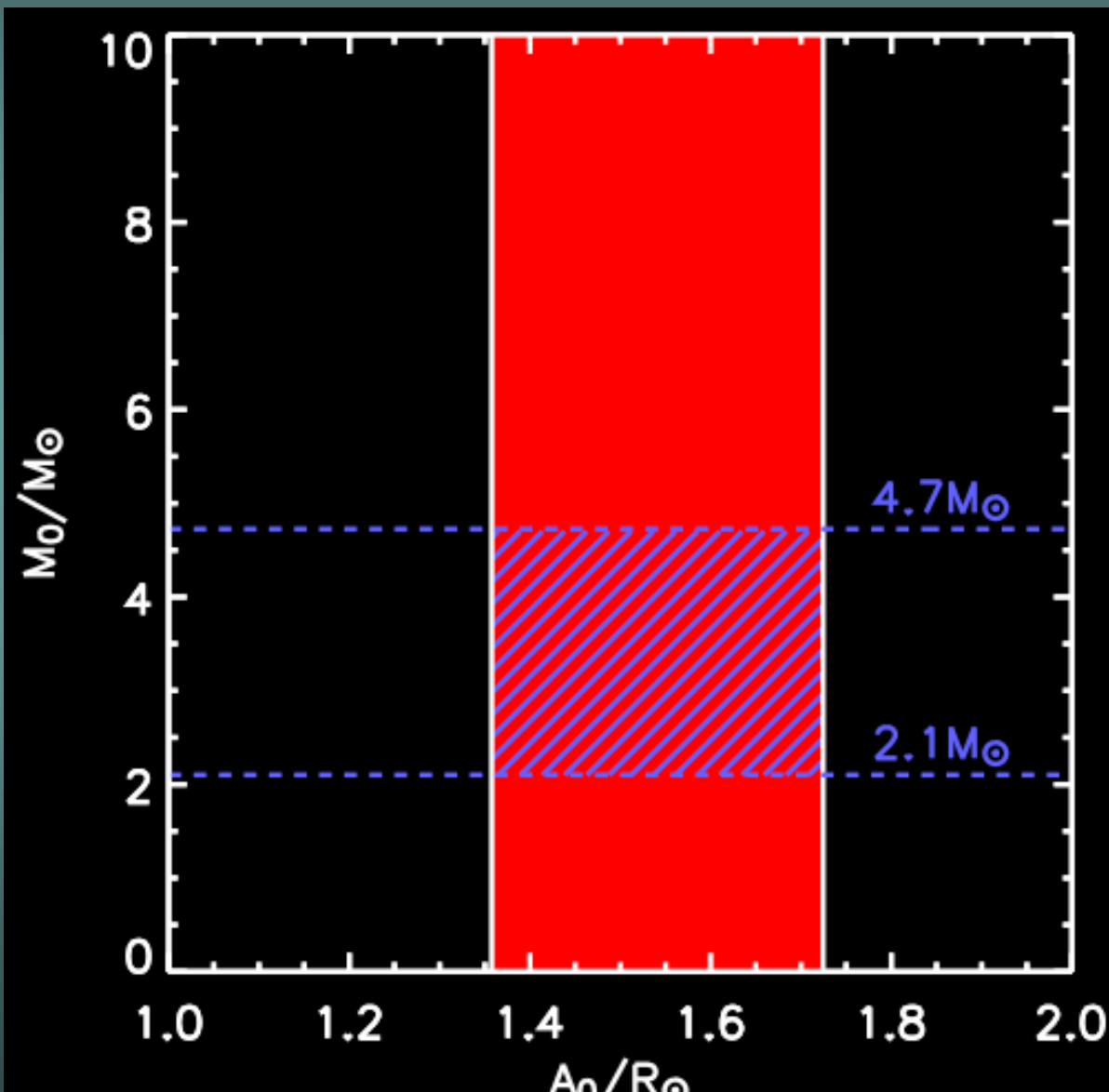


post-SN orbit must contain pre-SN position (in circular orbit):
 $A(1-e) < A_0 < A(1+e)$

to form a NS:
 $M_0 > 2.1 M_{\text{solar}}$ Habets 1

Evolve the system backwards in time...

- Constraints on pre-SN #2 properties -
- allow for mass transfer from the He star:



post-SN orbit must contain pre-SN position (in circular orbit):
 $A(1-e) < A_0 < A(1+e)$

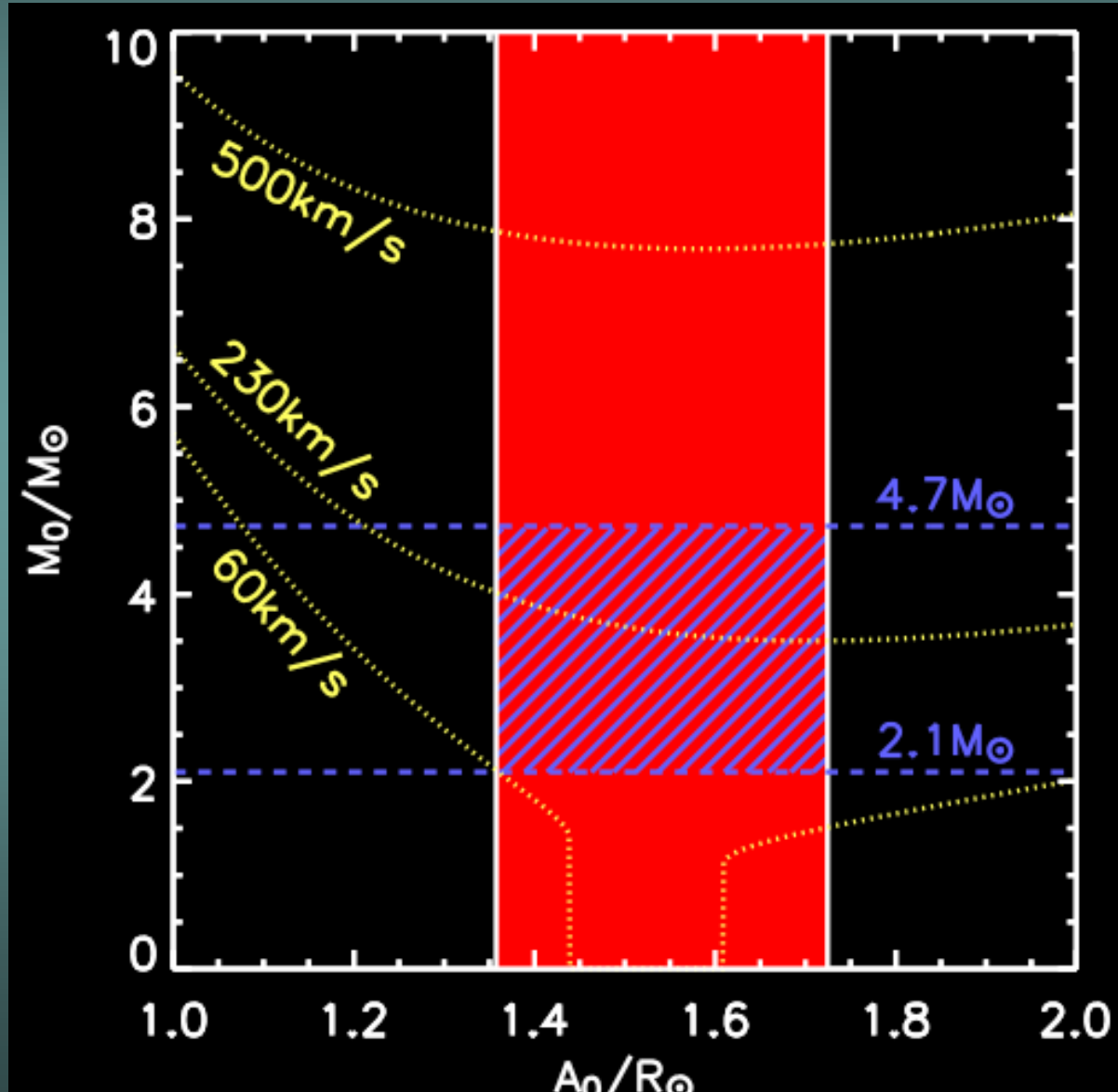
to form a NS:
 $M_0 > 2.1 M_{\text{solar}}$ Habets 1

to avoid a merger:
 $M_0 < 3.5 M_{\text{PSR}} = 4.7 M_{\text{solar}}$ Ivanova et al. 2

Evolve the system backwards in time...

- Constraints on pre-SN #2 properties -
- allow for mass transfer from the He star:

Willems & VK 20



post-SN orbit must contain pre-SN position (in circular orbit):
 $A(1-e) < A_o < A(1+e)$

to form a NS:
 $M_o > 2.1 M_{\text{solar}}$ Habets 1

to avoid a merger:
 $M_o < 3.5 M_{\text{PSR}} = 4.7 M_{\text{solar}}$ Ivanova et al. 2

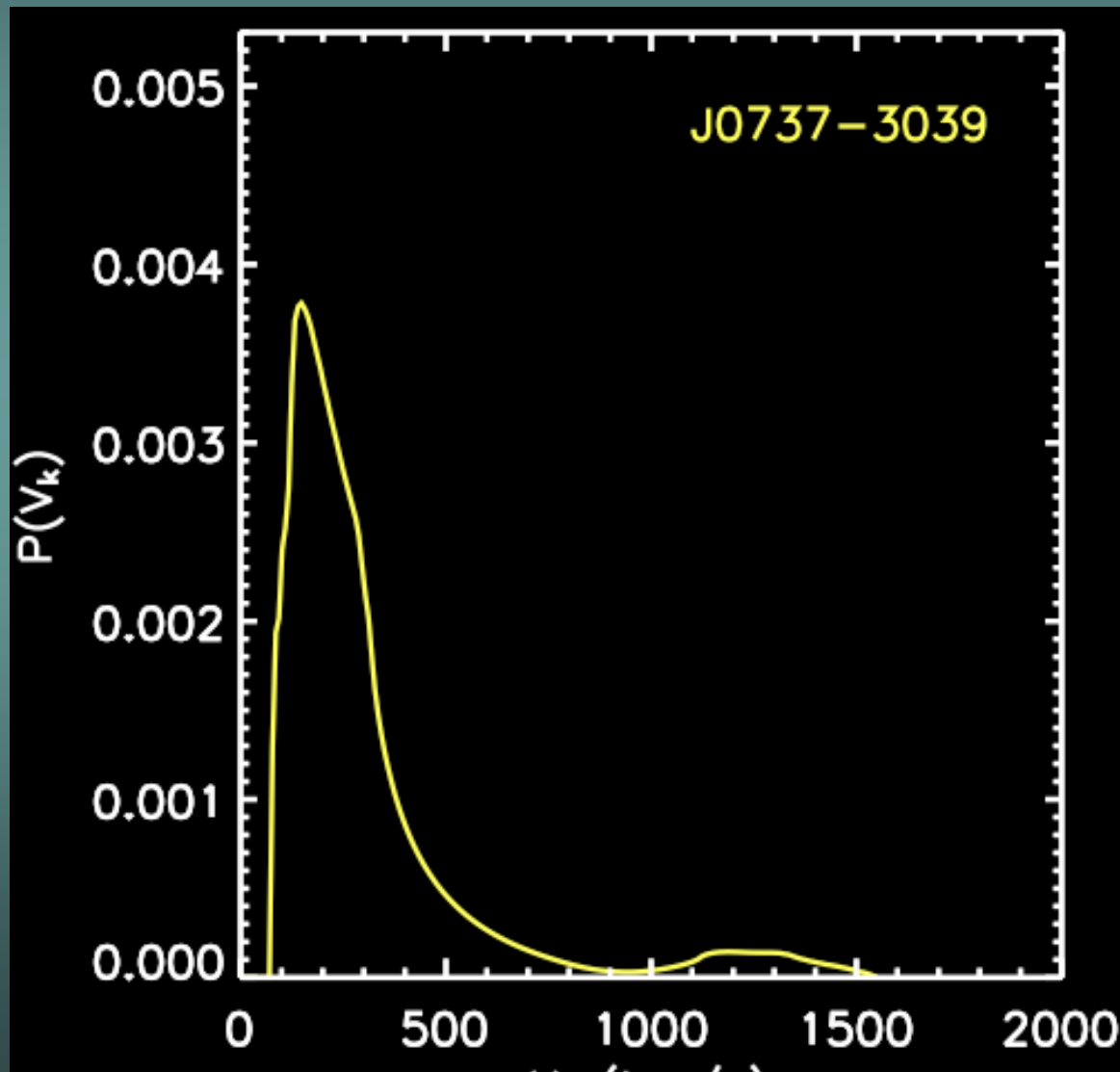
to satisfy post-SN masses, a, e:

$$M_o < M_{\text{max}} = f(V_k)$$

$$2.1 < M_o < 4.7 M_{\text{solar}}$$
$$V_k > 60 \text{ km/s}$$

What is the probability distribution
of the natal kick imparted to NS #2 ?

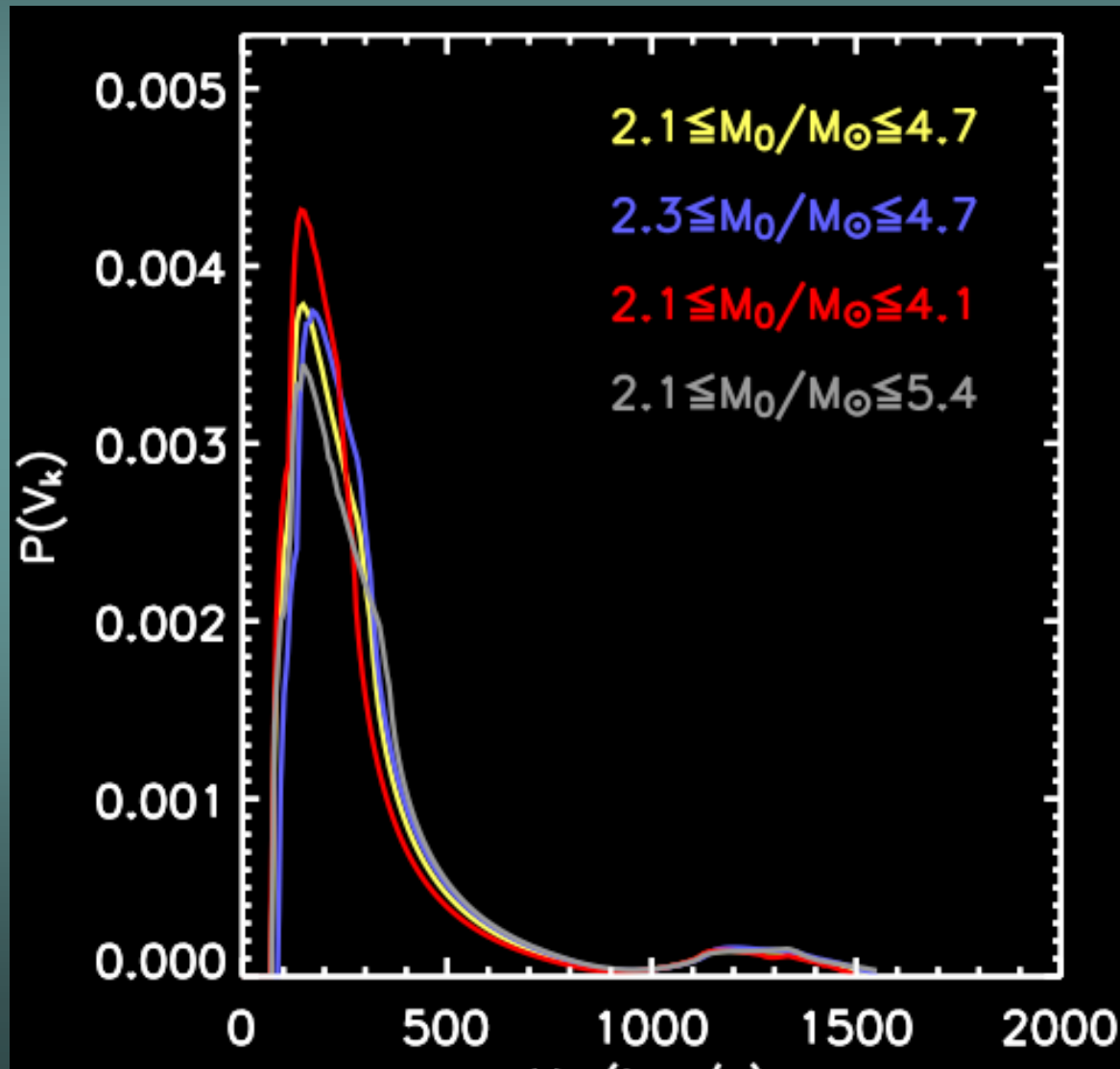
Willems & VK 20



Assumption:
isotropic natal kick

What is the probability distribution
of the natal kick imparted to NS #2 ?

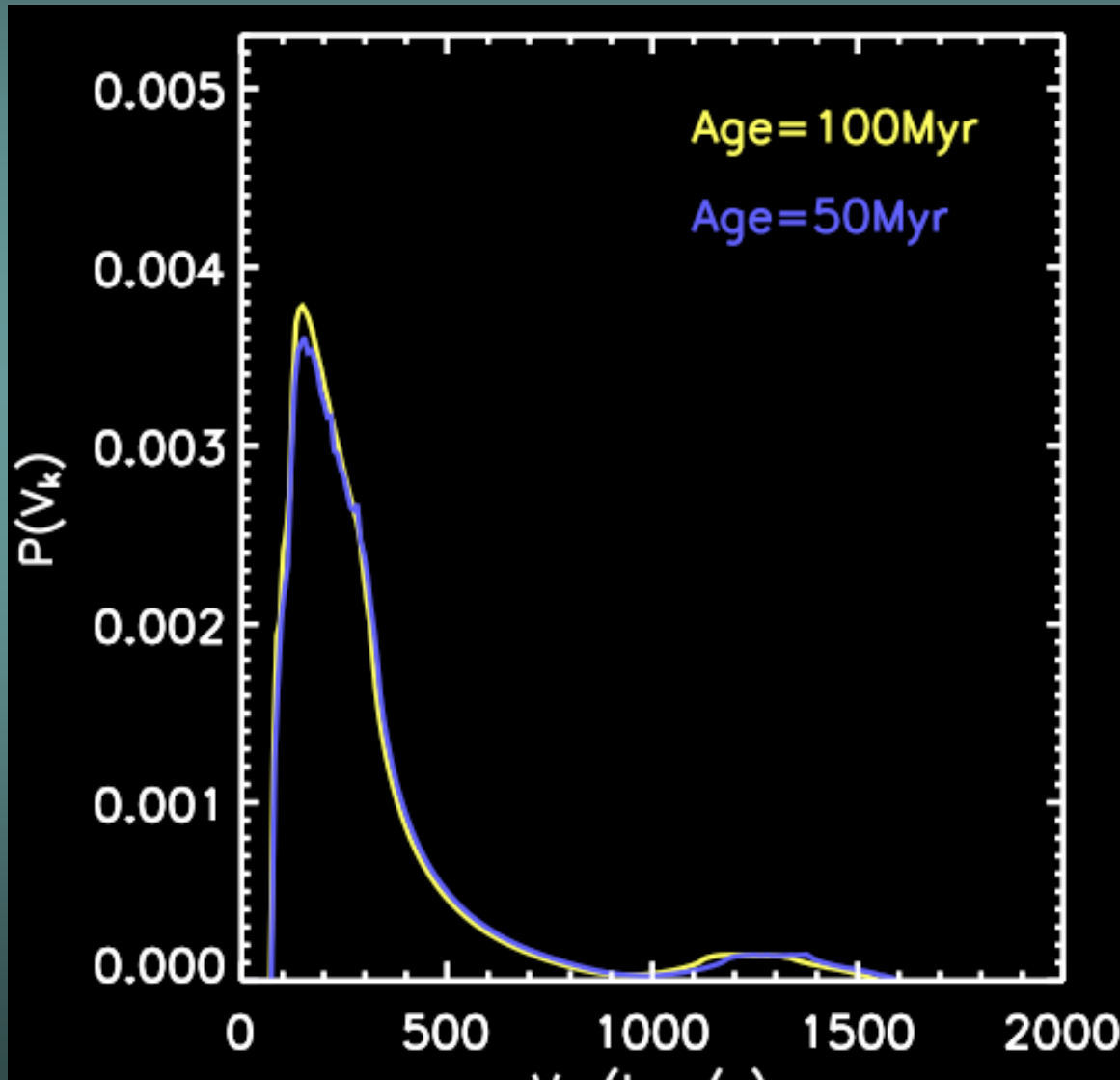
Willems & VK 20



insensitive to
progenitor mass
uncertainties

What is the probability distribution
of the natal kick imparted to NS #2 ?

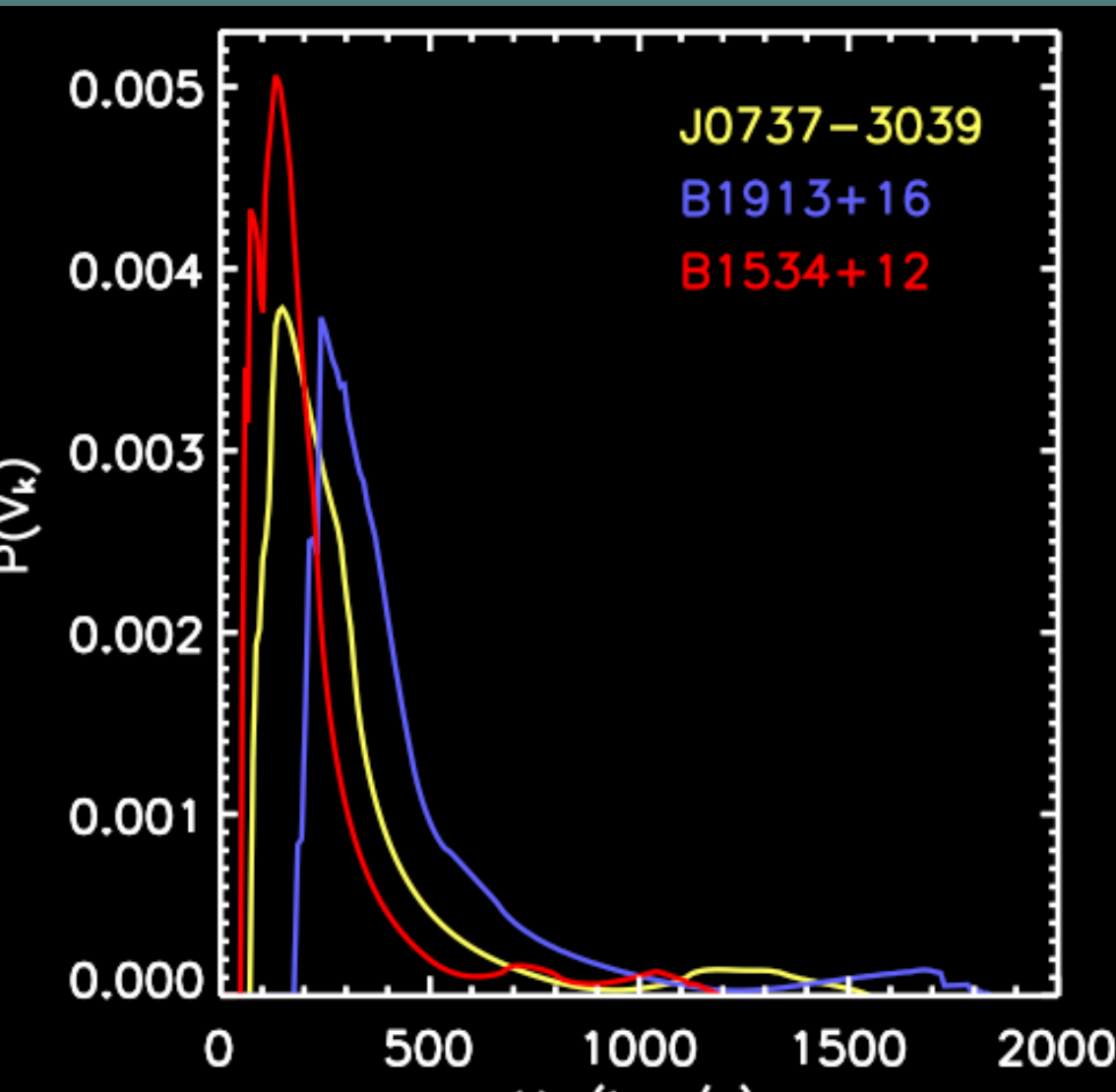
Willems & VK 20



insensitive to
NS age
uncertainties

What is the probability distribution of the natal kick imparted to NS #2 ?

Willems & VK 20

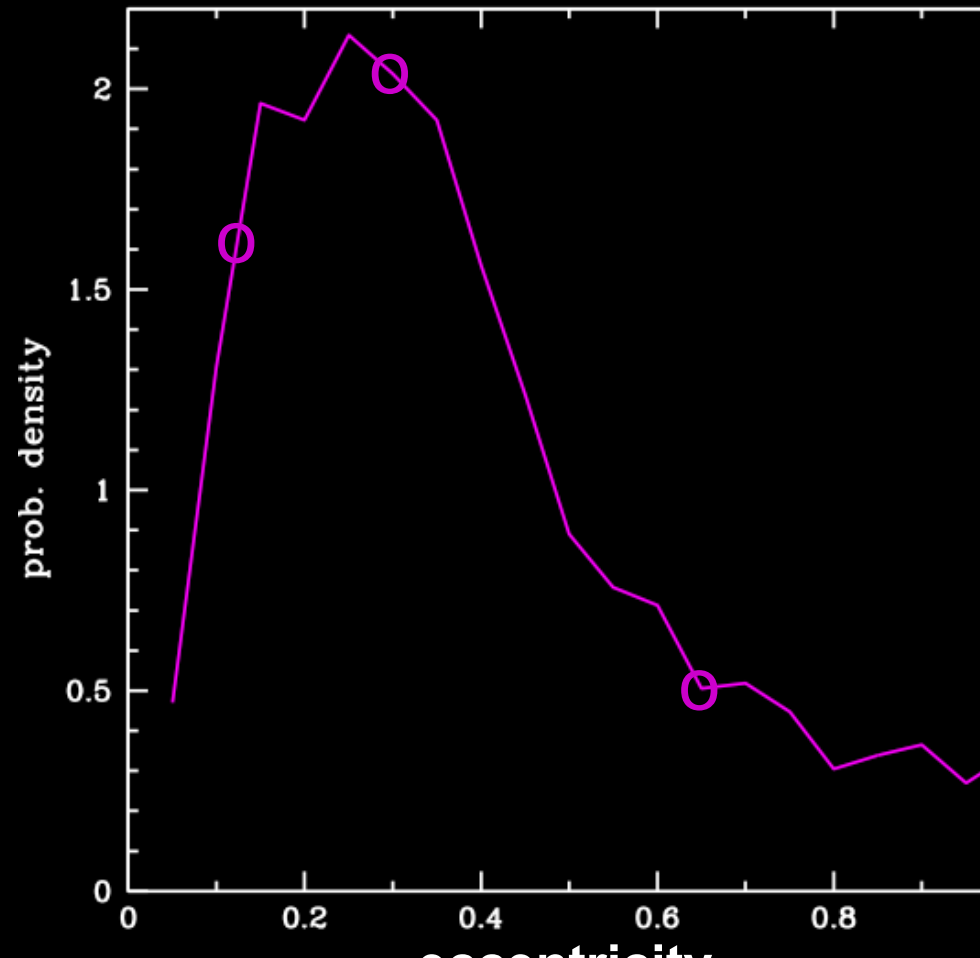
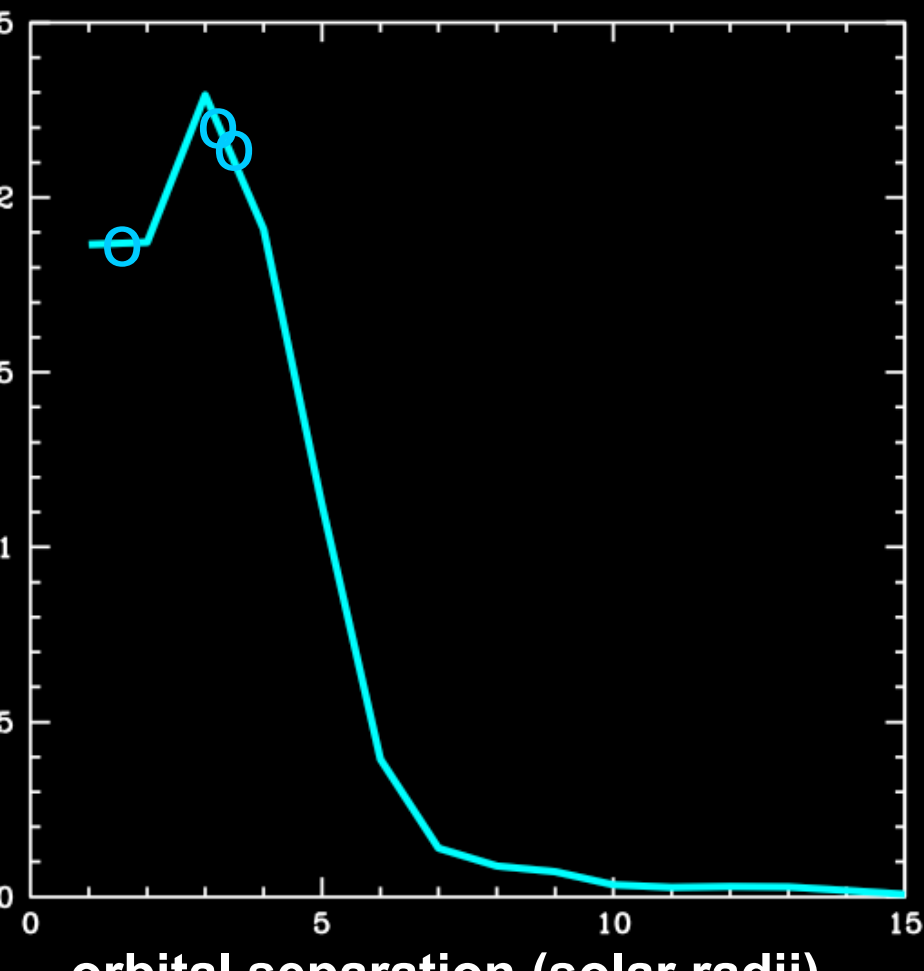


additional constraint
from center-of-mass
velocity measurement
(Willems, VK, Henninger,
in prep.)

Probability distribution of post-SN orbital characteristics

(Ihm, VK & Belczynski, in prep)

Are tight binaries with low eccentricity surprising ?



What have we learned already from PSR J0737-3039 (A and B) ?

Burgay et al. 2003

Lyne et al. 2004

Inspiral detection rates as high as 1 per 1.5 yr (at 95% C.L.) are possible for initial LIGO

Detection rates in the range 20 - 1000 per yr are most probable for advanced LIGO (VK, Kim, Lorimer, et al. 2004)

PSR-B progenitor is constrained to be less massive than $\sim 5 M_{\text{solar}}$

PSR-B kick is constrained to be in the range 60 - 1560 km/s

the most probable isotropic magnitude is 150 km/s (Willems & VK 2004)

PSR-A eclipses: magnetosphere physics

PSR-B is torqued by PSR-A (Kaspi et al. 2004)

PSR-A and B polarimetry: A's beam is a very wide hollow cone

A's spin and magnetic axes nearly aligned (Lyne et al. 2004)

What will we learn in the near future ?

center-of-mass velocity measurements
--> tighter constraints on NS formation

(Ransom et al.)

(Willems, VK, & Henning)

complete understanding of double PSR geometry
--> PSR-A precession predictions

(Jenet & Ransom)

constraints of NS-NS population characteristics
and binary evolution

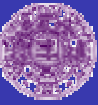
(Ihm, VK & Belczynski)

better confirmation of GR

new relativistic effects/tests

better understanding of PSR magnetospheres

Parikes MultiBeam survey and acceleration searches

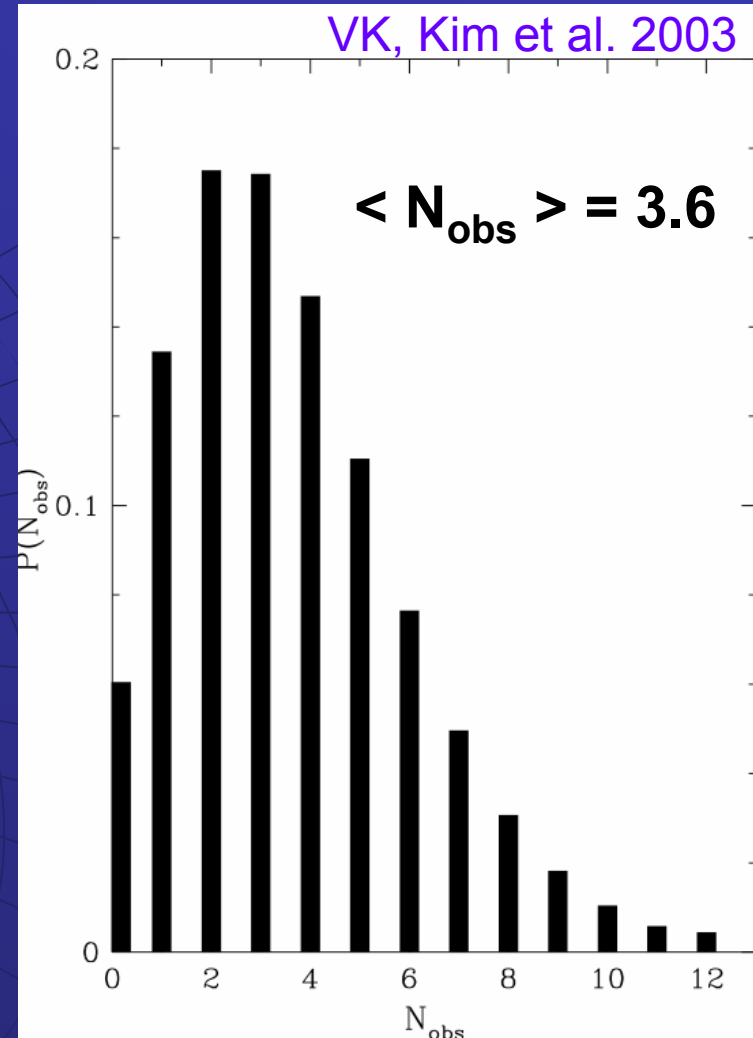


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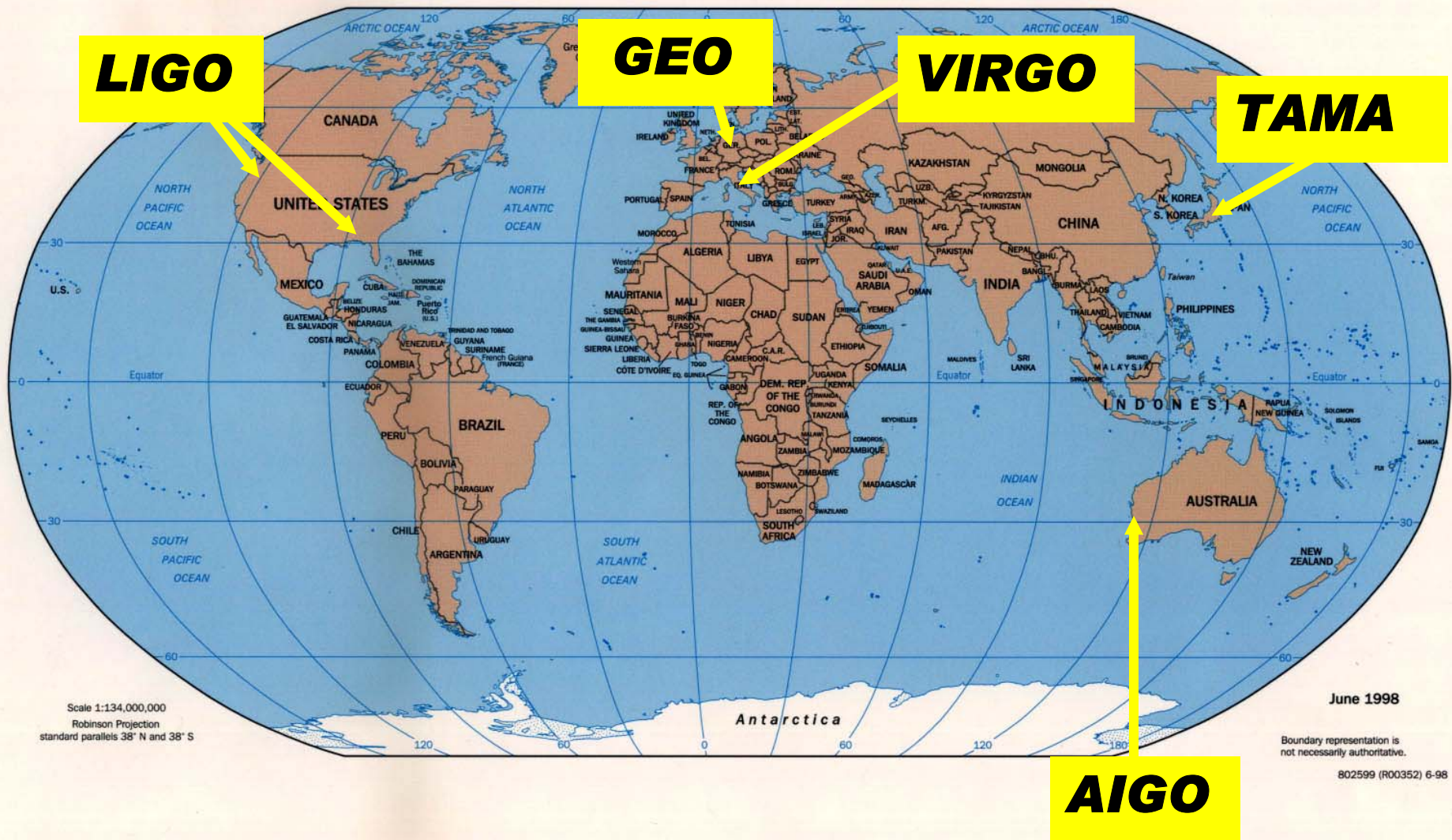
Assuming that acceleration searches
are perfectly correct for any pulse
Doppler smearing due to orbital motion...

How many coalescing DNS pulsars
could we expect the PMB survey to
detect?

A.B. Not every new coalescing DNS pulsar
will significantly increase the DNS rates ...



Global network of GW detectors



LIGO

GEO

VIRGO

TAMA

AIGO

Scale 1:134,000,000
Robinson Projection
standard parallels 38° N and 38° S

June 1998

Boundary representation is not necessarily authoritative.

802599 (R00352) 6-98