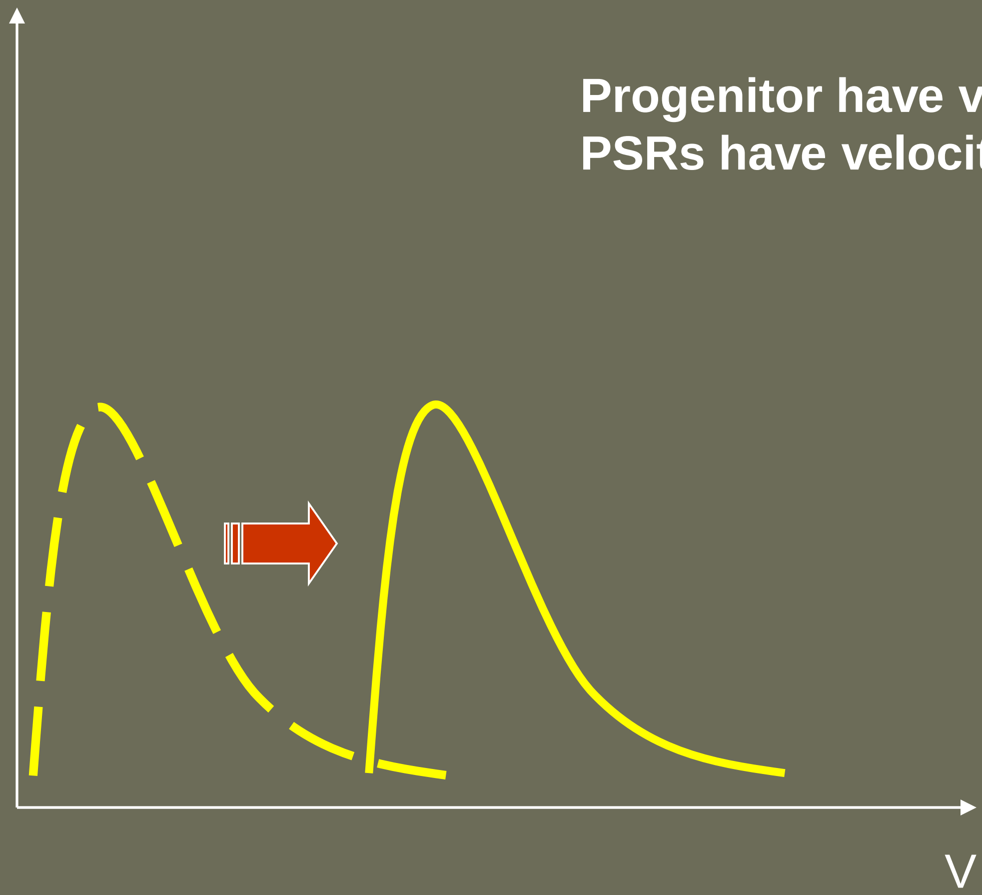
Kick velocity

Why do neutron stars move so rapidly?

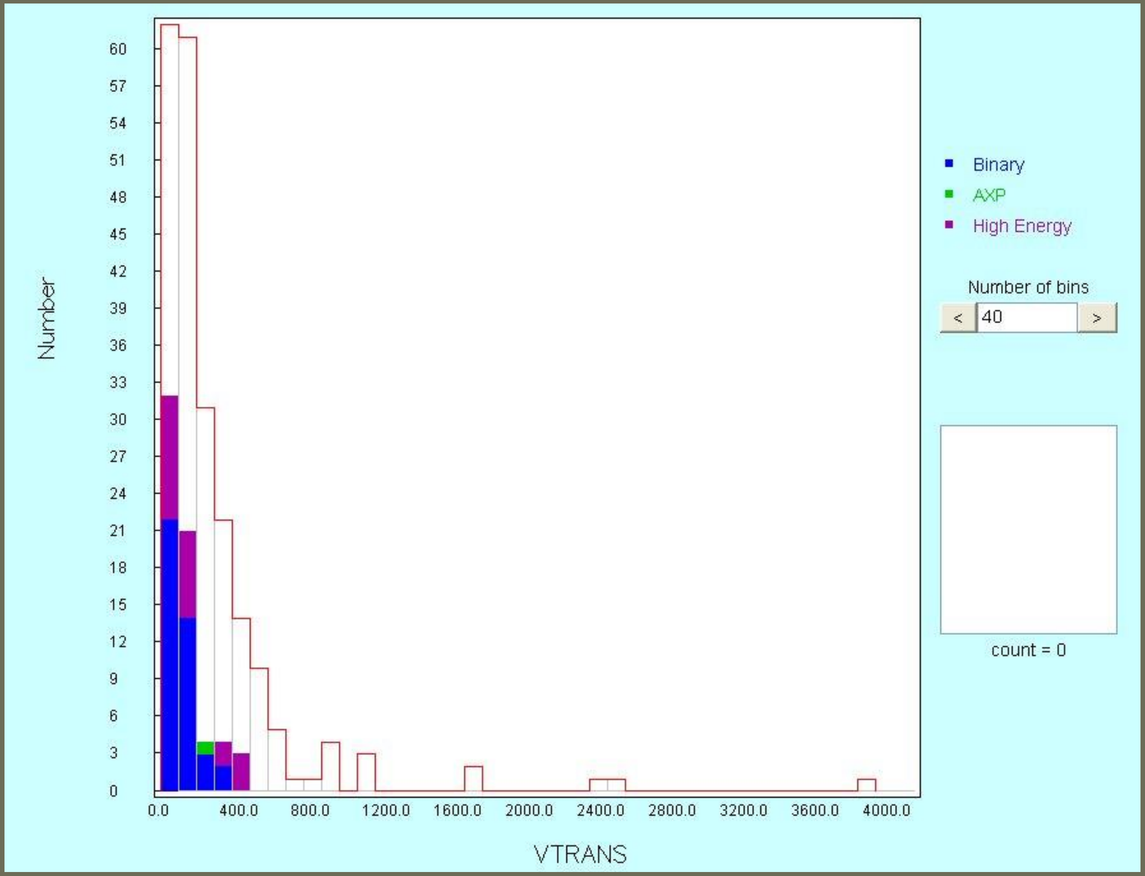
Stars vs. Neutron Stars

Progenitor have velocities about ~10-30 km/s
PSRs have velocities ~100-500 km/s



Pulsar velocity distribution

Normal stars have velocities ~10-30 km/s.

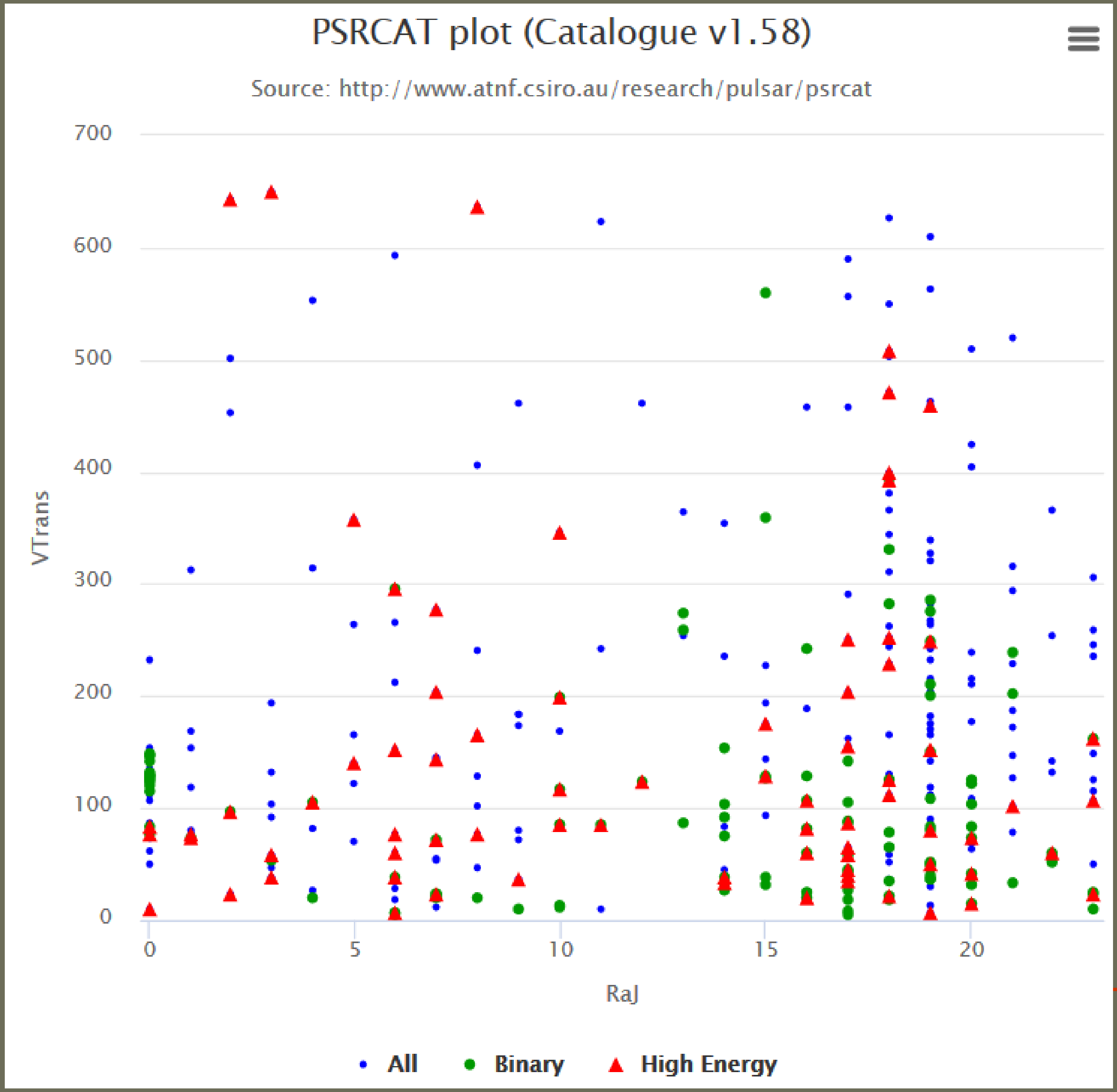


Already in 70s it became clear that PSRs have high spatial velocities (>>10 km/s).

A breakthrough happened in 1994 when Lyne and Lorimer in a seminal paper in Nature showed that velocities are even higher than it was thought before – hundreds km/s.

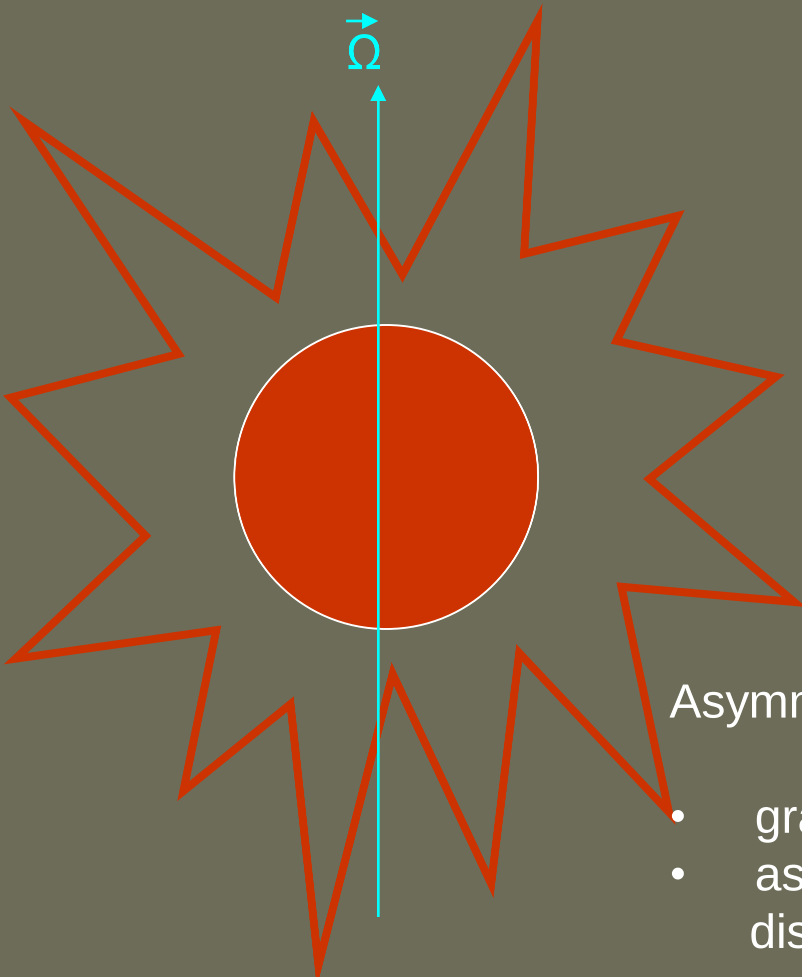
Note, that the observed distribution is much different from the initial one.
To derive the later it is necessary to calculate a model.

ATNF catalogue


PSRCAT plot (Catalogue v1.58)
Source: http://www.atnf.csiro.au/research/pulsar/psrcat
VTrans
700
600
500
400
300
200
100
0
0
5
10
15
20
RaJ
All
Binary
High Energy

ATNF

SN explosions should not be symmetric!



E_{total}~3 10^{53} erg
Most of energy is carried away by neutrinos.

~Few % asymmetry in energy release
can produce a strong kick up to 1000 km/s.

<u>Main kick mechanisms</u>

- Asymmetric mass ejection (Shklovsky 1970)
- Asymmetric neutrino emission (Chugai 1984)

Asymmetric mass ejection includes three mechanisms:

- gravitational pull due to asymmetric matter
- asymmetric neutrino emission due to matter distribution
- asymmetric matter jets (Khokhlov et al.1999)

Leonid Ozernoy in 1965 discussed asymmetry of SN explosions in the context of GW radiation.

SN and kick explosion mechanisms

Mechanism	Time scale	V_{max}, km s^{-1}	Alignment (spin and V)	Main recent refs.
Hydrodynamical	0.1 s	$\sim (100 - 200)$	random	Lai et al. (2001)
ν-driven	$\sim$ few s	$\sim 50\ B_{15}$	parallel	Lai et al. (2001)
Electromagnetic rocket	long	$1400\ R_{10}^2\ P_{ms}^{-2}$	parallel	Lai et al. (2001), Huang et al. (2003)
Binary disruption (without add. kick)	$<< P_{orb}$	~ 1000	perpendicular	Iben & Tutukov (1996)
NS instability	few ms	~ 1000	perpendicular	Colpi & Wasserman (2002), Imshennik & Ryazhskaya (2004)
Magnetorotational	0.2 s – minutes	~ 300 (up to 1000)	quasirandom	Moiseenko et al. (2003), Ardeljan et al. (2004)

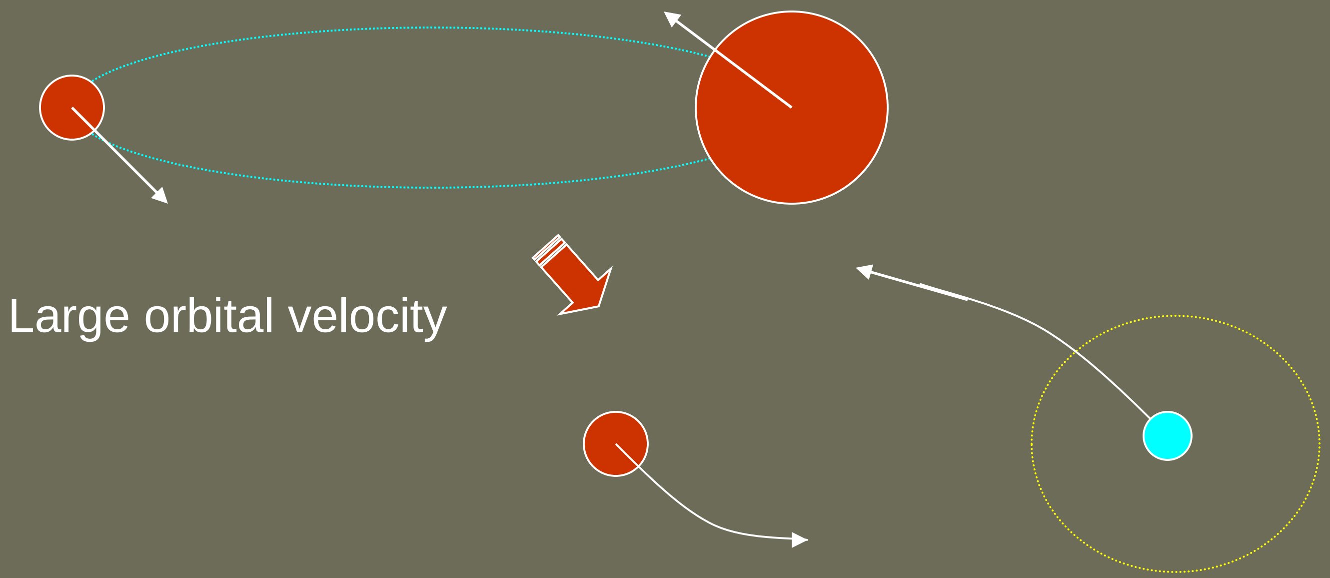
For neutrino emission: $V_{kick} = \varepsilon\ E_{tot}/Mc \sim 1000$ km/s $(\varepsilon/0.1)$ $(E_{tot}/10^{53}$ erg). Also it depends on the magnetic field.

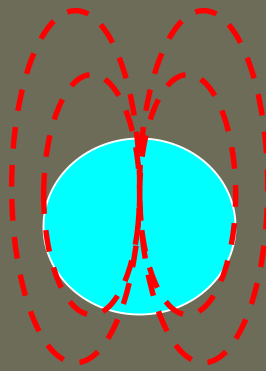
A review on SNae properties and explosion mechanisms: arXiv:1210.4921

To kick or not to kick?

Up to mid-90s it was not clear if kicks are absolutely necessary.

- Tademaru (rocket) mechanism
- Binary disruption (Blaaw mechanism)
- Core fragmentation (Berezinski et al., Imshennik)



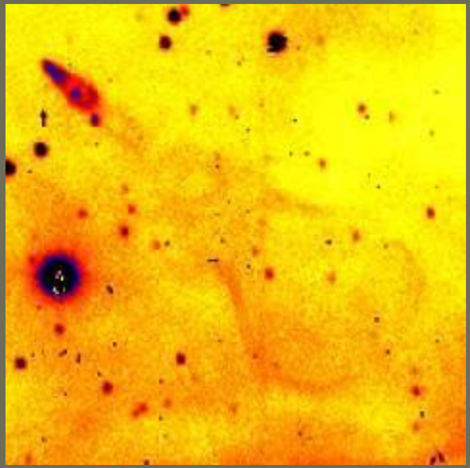


Asymmetric dipole

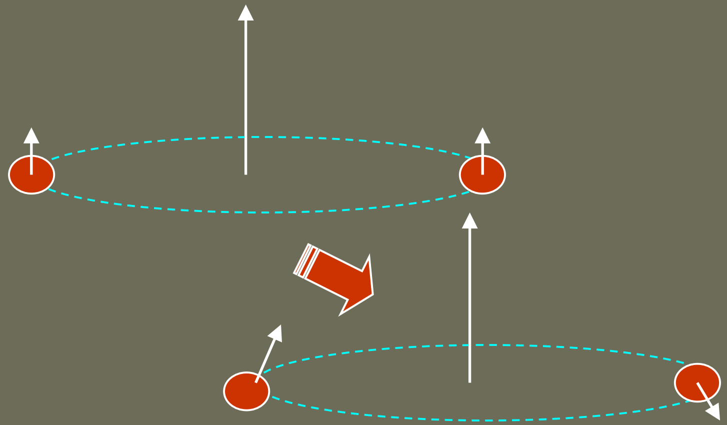
However, some discoveries directly point to necessity of natal kicks.

Direct evidence

1. High-velocity NSs and binaries
2. Spin inclination in binaries and geodetic precession



Guitar nebula, B2224+65



Orbit inclination relative to a normal star equator can be measure due to:

- orbital precession due to spin-orbit interaction (Kaspi et al. 1996)
- circumstellar disc inclination (Prokhorov, Postnov 1997)

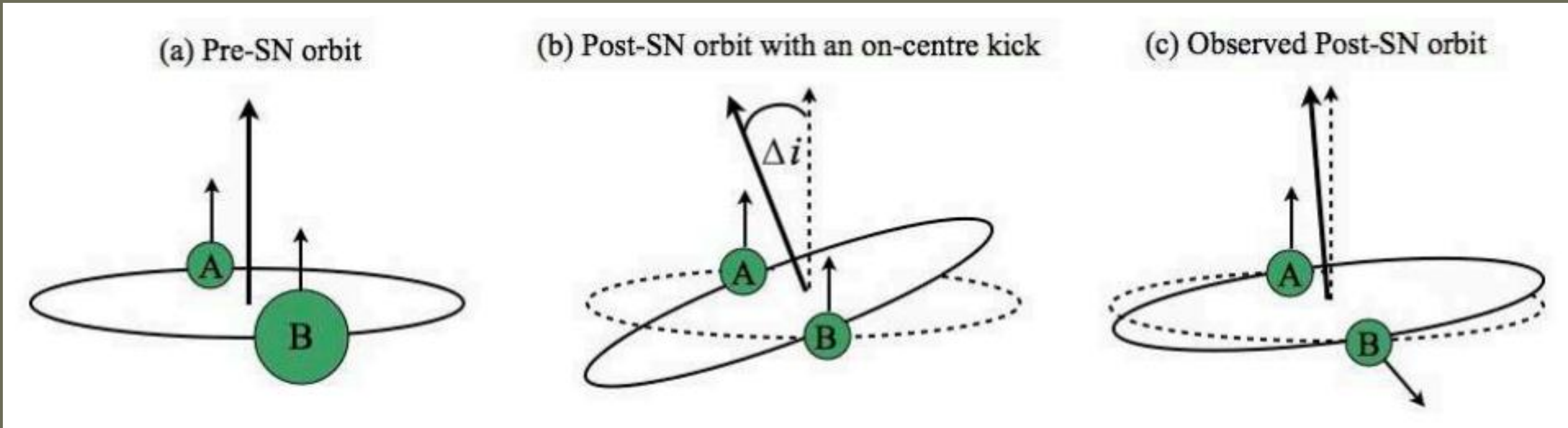
The most spectacular 3D velocity measurements for NSs are related to nebulae around these objects.

The transversal velocity can be measured by proper motion observations of radio pulsars and other neutron stars

For binaries large velocities are measured (Cir X-1: Johnston et al. 1999).

Double pulsar PSR J0737-3039

Pulsar A’s spin is tilted from the orbital angular momentum by no more than 14 degrees at 95% confidence;
pulsar B’s -- by 130 ± 1 degrees at 99.7% confidence.

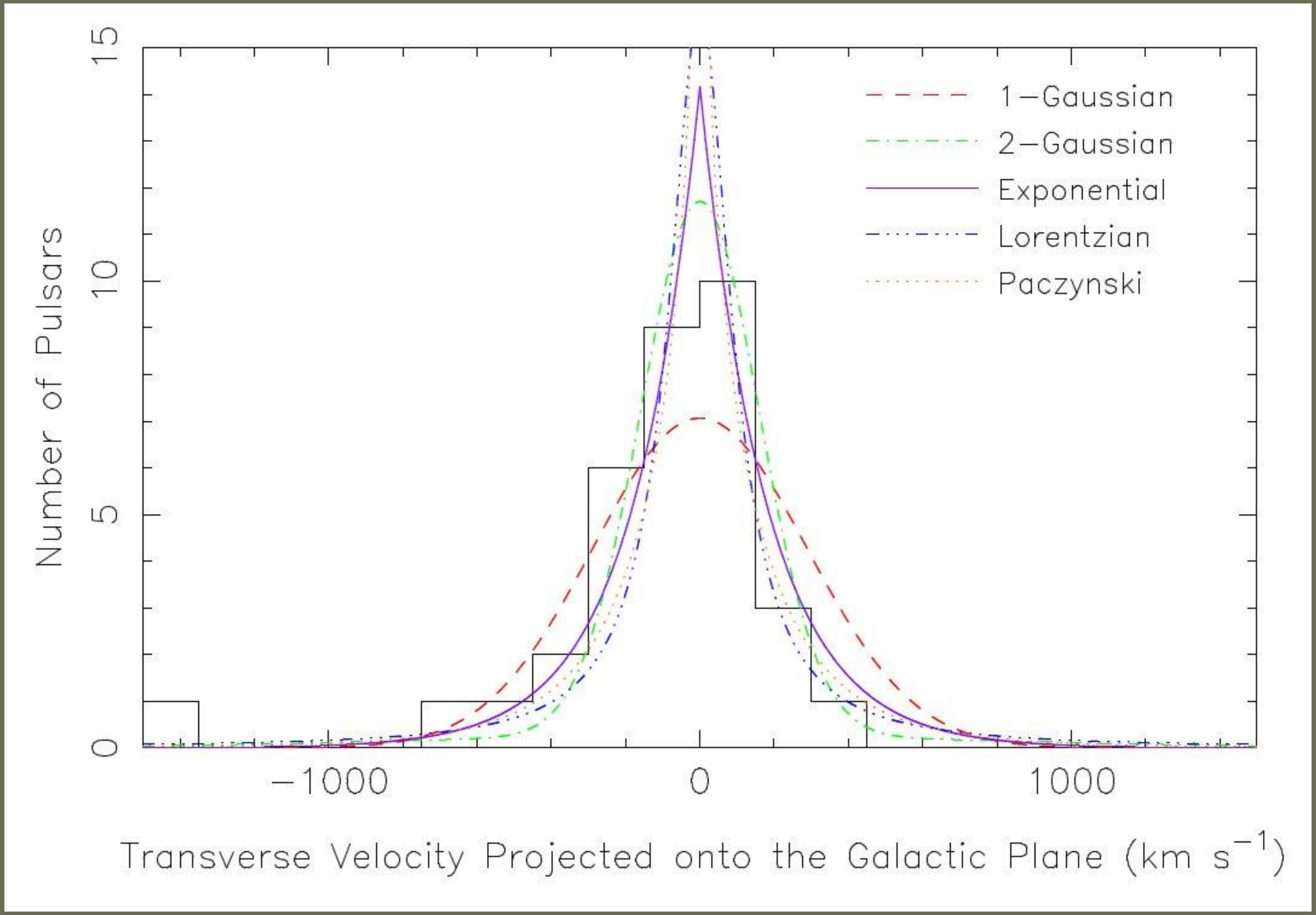


This spin-spin misalignment requires that the origin of most of B’s present-day spin is connected to the supernova that formed pulsar B.
The spin could be thought of as originating from the off-center nature of the kick.

1104.5001

See also 1302.2914 about probably near-zero kick for the pulsar A.

Many kick velocity distributions are proposed



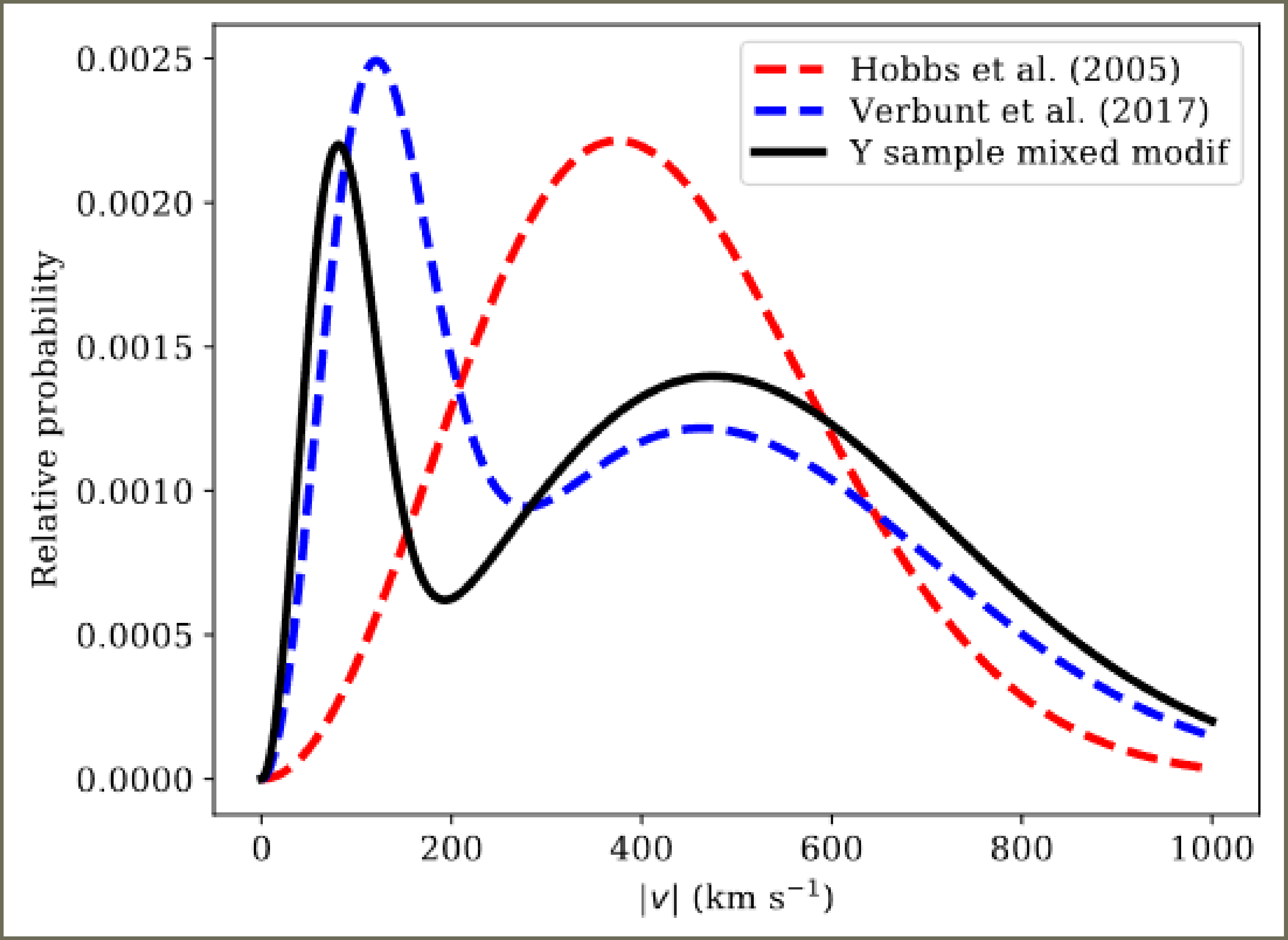
Three popular models:

- Arzoumanian, Chernoff, Cordes (2002)
- Hobbs et al. (2005)
- Faucher-Giguer and Kaspi (2006)

Note the difference:
We observe present day velocities with selection and evolutionary effects, but we are interested in the velocity at birth!

(Faucher-Giguer, Kaspi 2006)

Pulsar velocity distribution



For young pulsars (Y):

$w = 0.2$

$\sigma_1 = 56 \text{ km s}^{-1}$

$\sigma_2 = 336 \text{ km s}^{-1}$

For all ages:

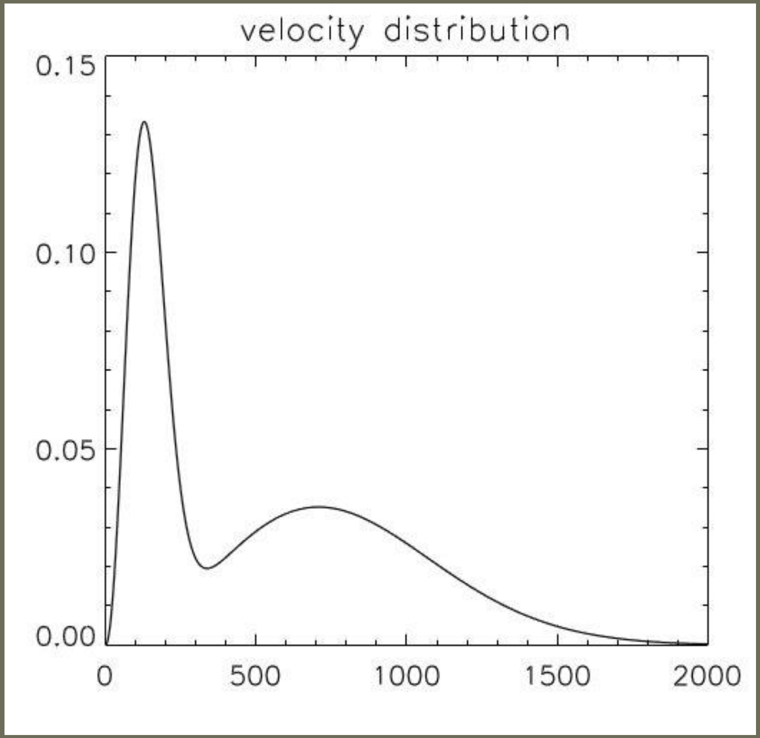
$w = 0.42$

$\sigma_1 = 128 \text{ km s}^{-1}$

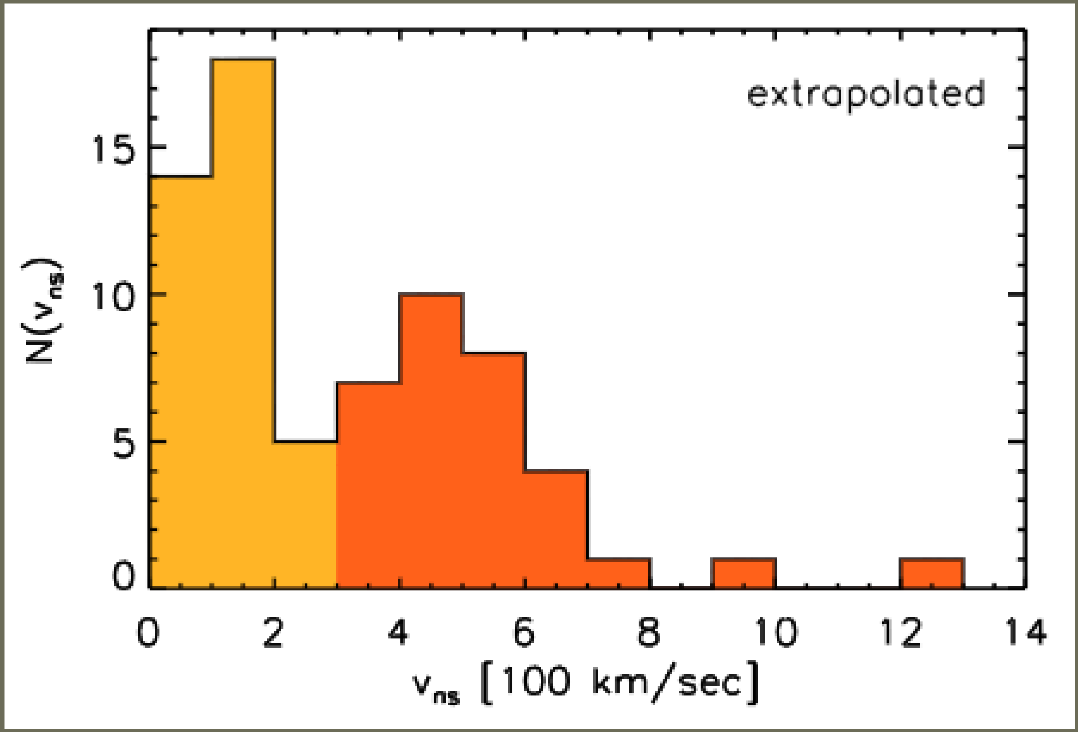
$\sigma_2 = 298 \text{ km s}^{-1}$

2002.01367

Bimodal distribution

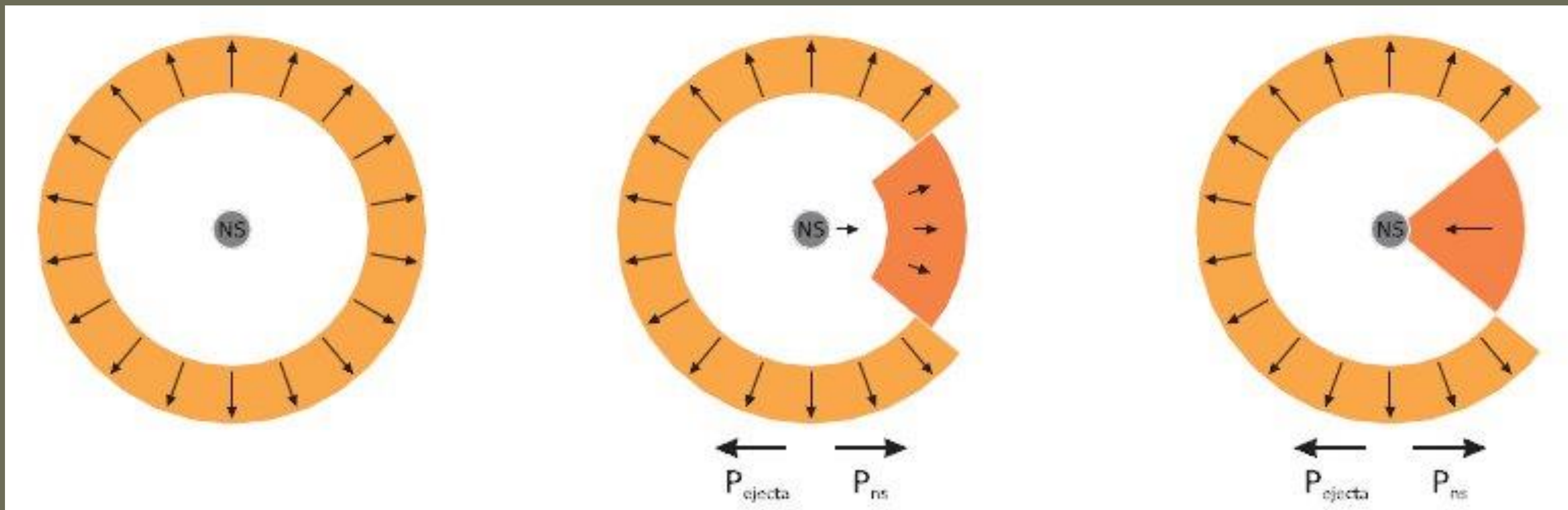


Arzoumanian et al. 2002



Scheck et al. 2006

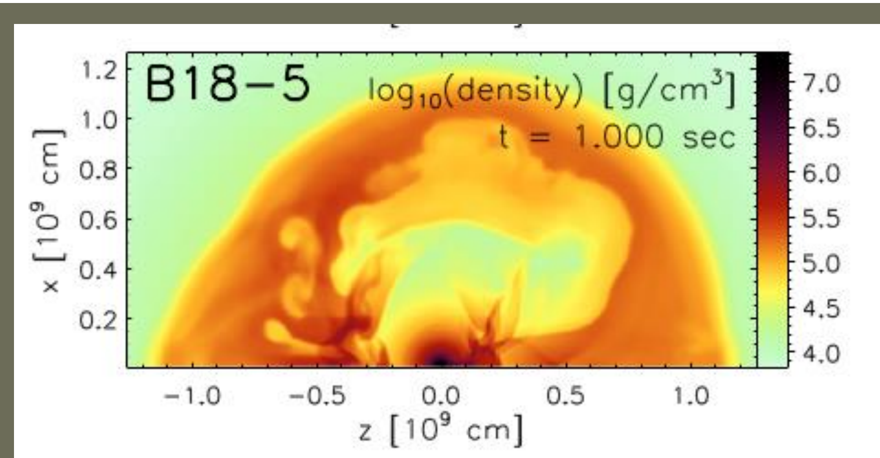
Hydrodynamical models



astro-ph/0601302

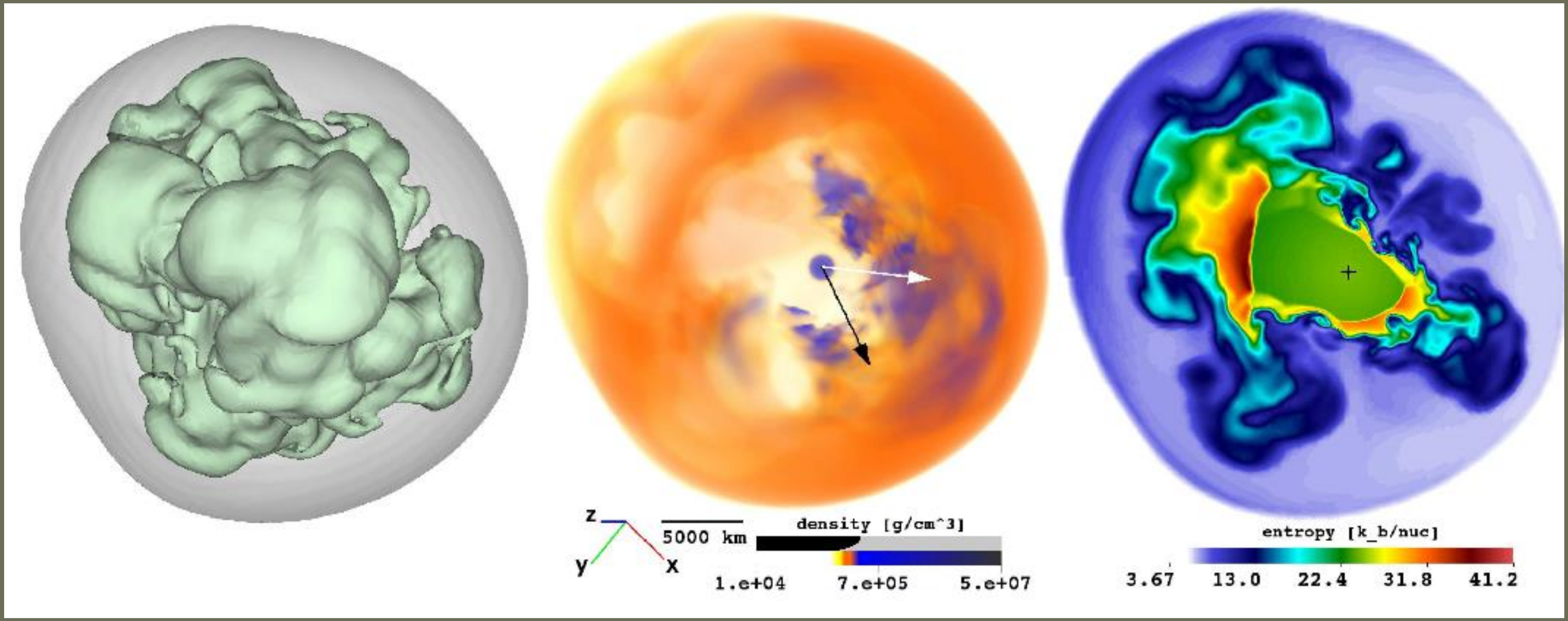
2D simulations

Acceleration of a NS is mainly due to gravitational pull of the anisotropic ejecta



Scheck et al. See 3D calculations in 1010.0167

3D hydrodynamics kicks



$$\mathbf{v}_{\rm ns}(t) = -\mathbf{P}_{\rm gas}(t)/M_{\rm ns}(t)$$

$$\mathbf{P}_{\rm gas} = \int_{R_{\rm ns}}^{R_{\rm ob}} {\rm d}V\,\rho\mathbf{v}.$$

$$v_{\rm ns} \approx 2G\Delta m/(r_{\rm i}v_{\rm s}) \approx 2700\,{\rm km\,s^{-1}}$$

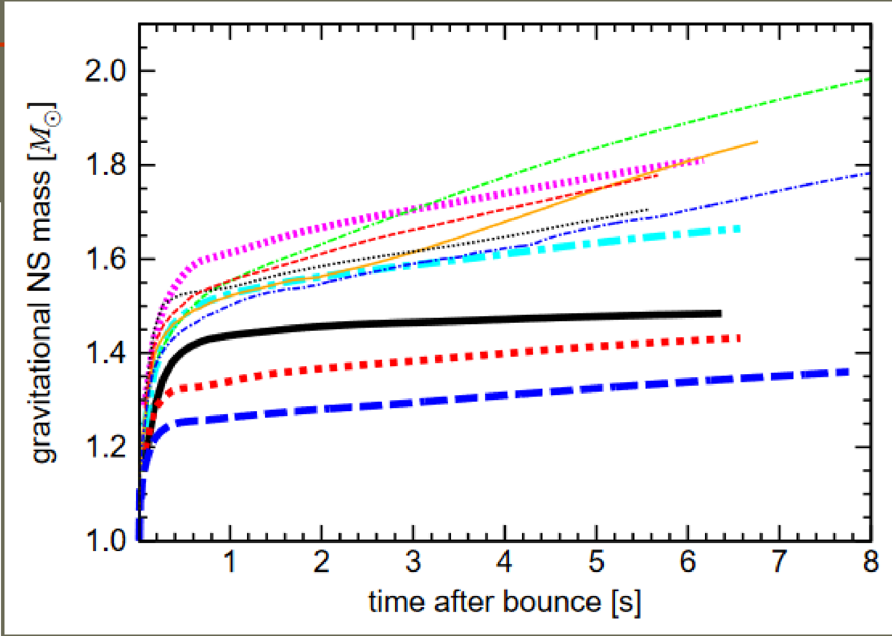
$$r_{\rm i} = 100\,{\rm km} \quad \Delta m = \pm 10^{-3}\,M_\odot$$

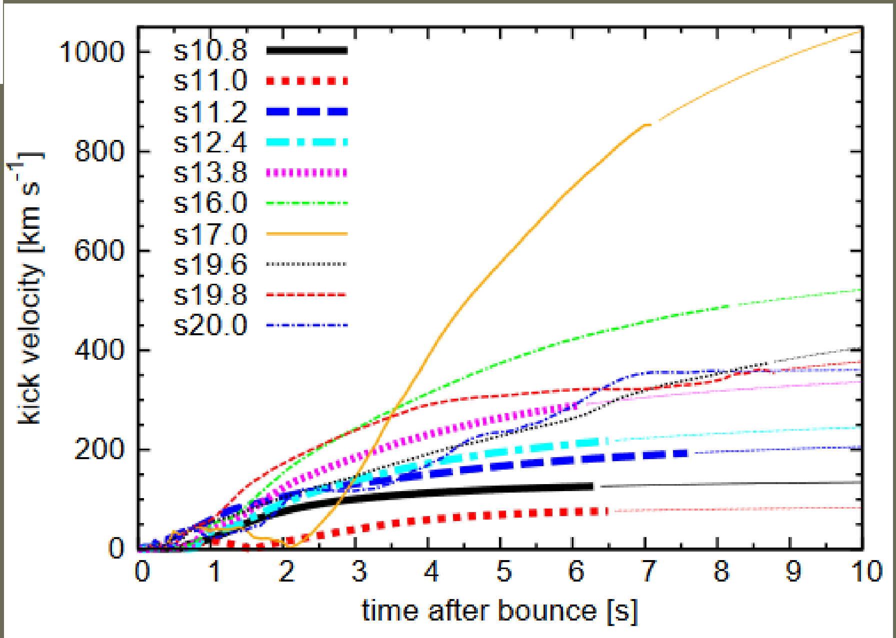
$$v_{\rm s} = 1000\,{\rm km\,s^{-1}}$$

1010.0167

2D models

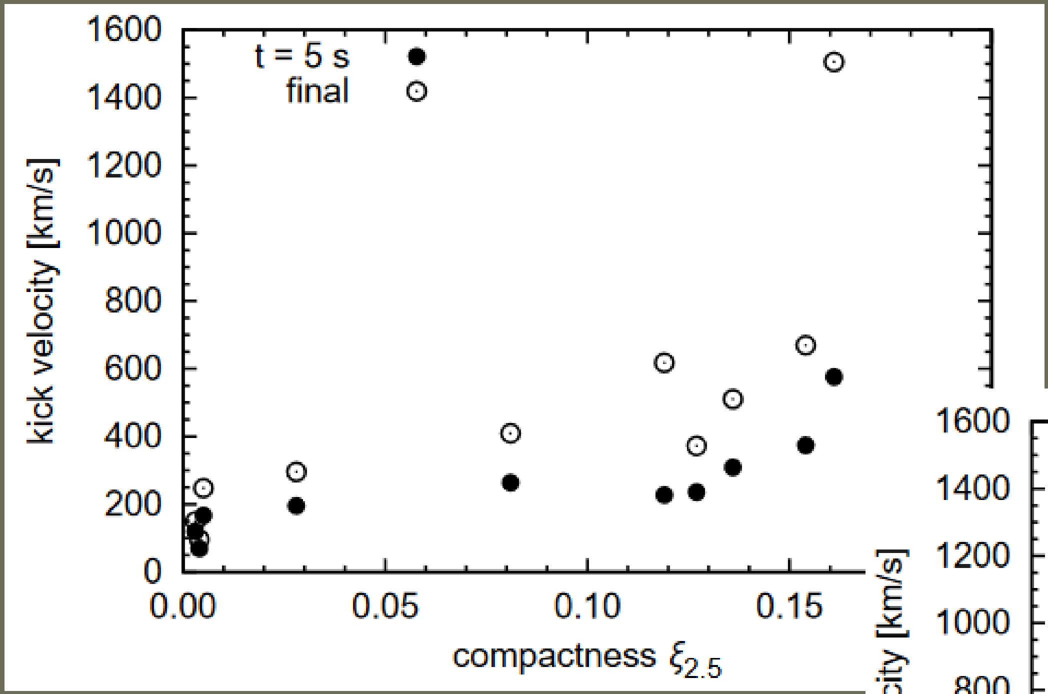
Progenitor	Mass ($M_\odot$)	Radius ($R_\odot$)	M_{Fe} ($M_\odot$)	R_{Fe} (km)	$R_{CO/HeC}$ (km)	M_{comp} ($M_\odot$)	$\xi_{2.5}$
s10.8	10.4	563	1.36	1560	17800	1.82	0.003
s11.0	10.6	587	1.37	1460	25400	1.87	0.004
s11.2	10.8	596	1.25	1000	33500	1.91	0.005
s12.4	11.0	680	1.45	1590	34500	2.55	0.028
s13.8	11.8	774	1.48	1590	40600	3.03	0.081
s16.0	13.2	913	1.44	1580	50900	3.69	0.154
s17.0	13.8	958	1.44	1500	54400	4.06	0.161
s19.6	13.4	1160	1.47	1570	88600	5.04	0.119
s19.8	14.5	1130	1.44	1500	80700	5.02	0.136
s20.0	14.7	1120	1.46	1690	84200	5.10	0.127

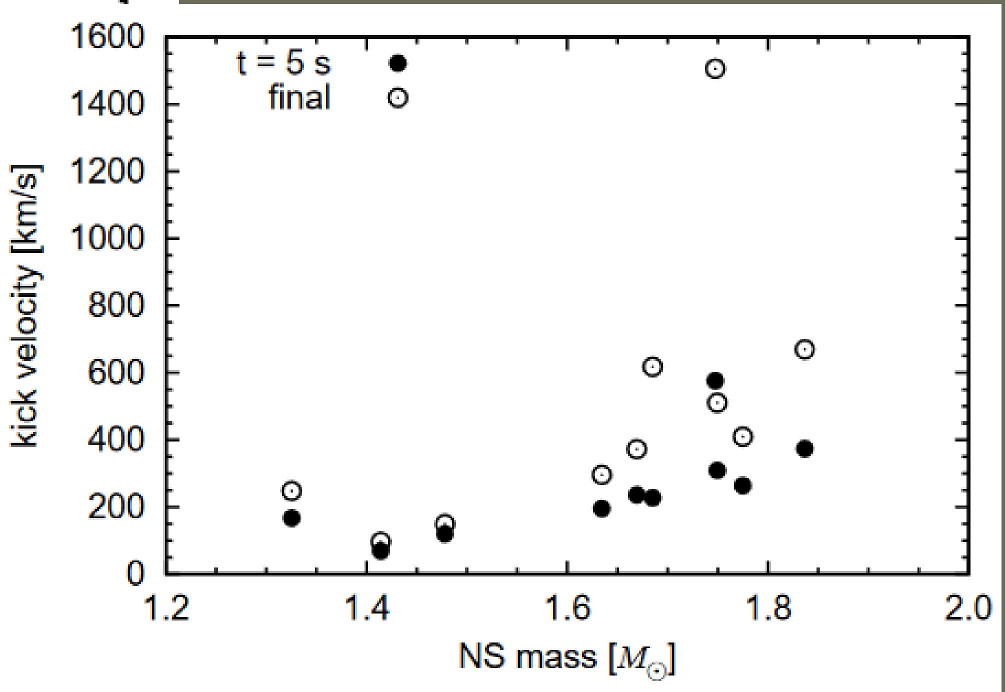




1904.08088

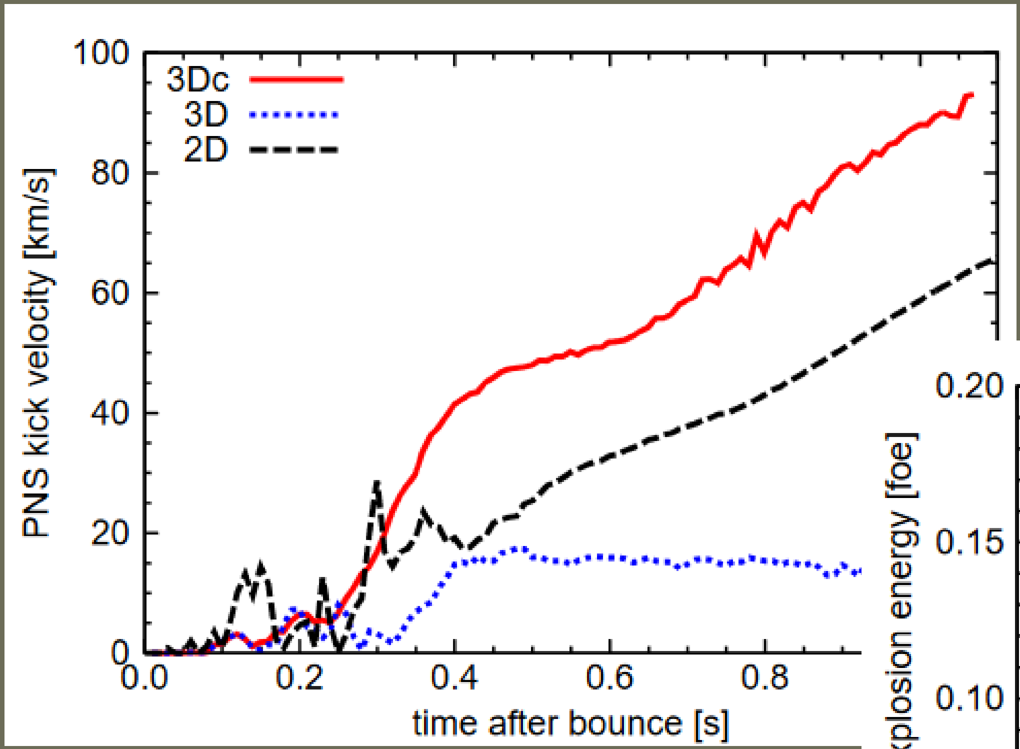
Correlations for 2D



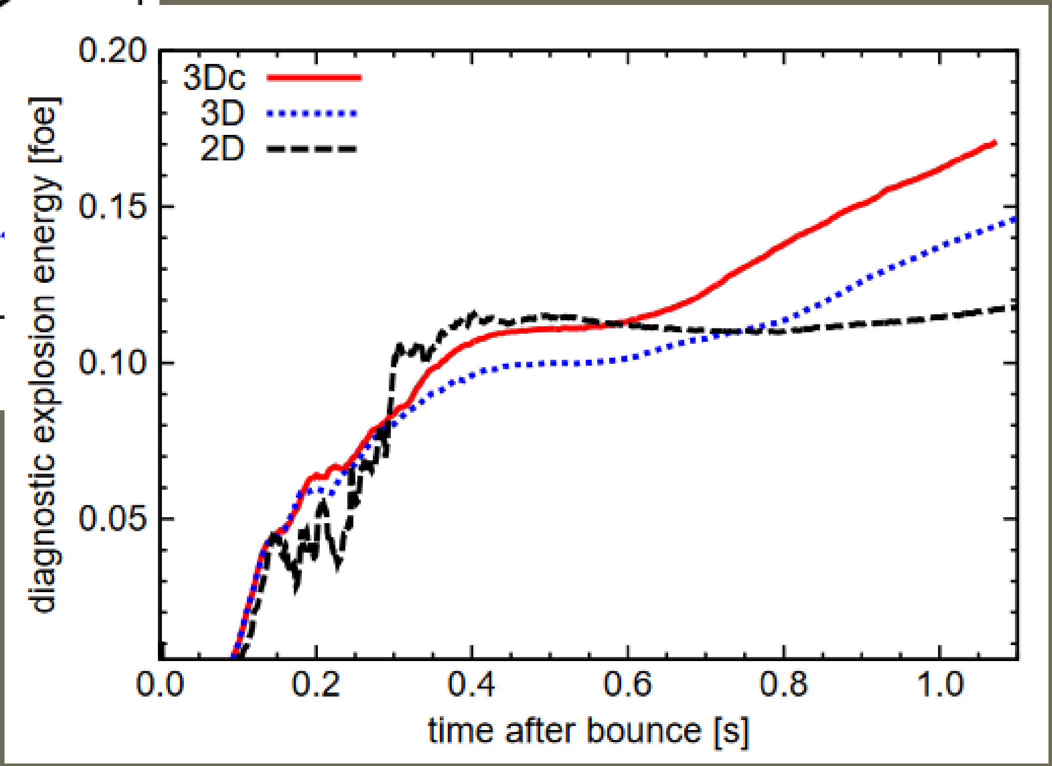


1904.08088

2D and 3D models comparison



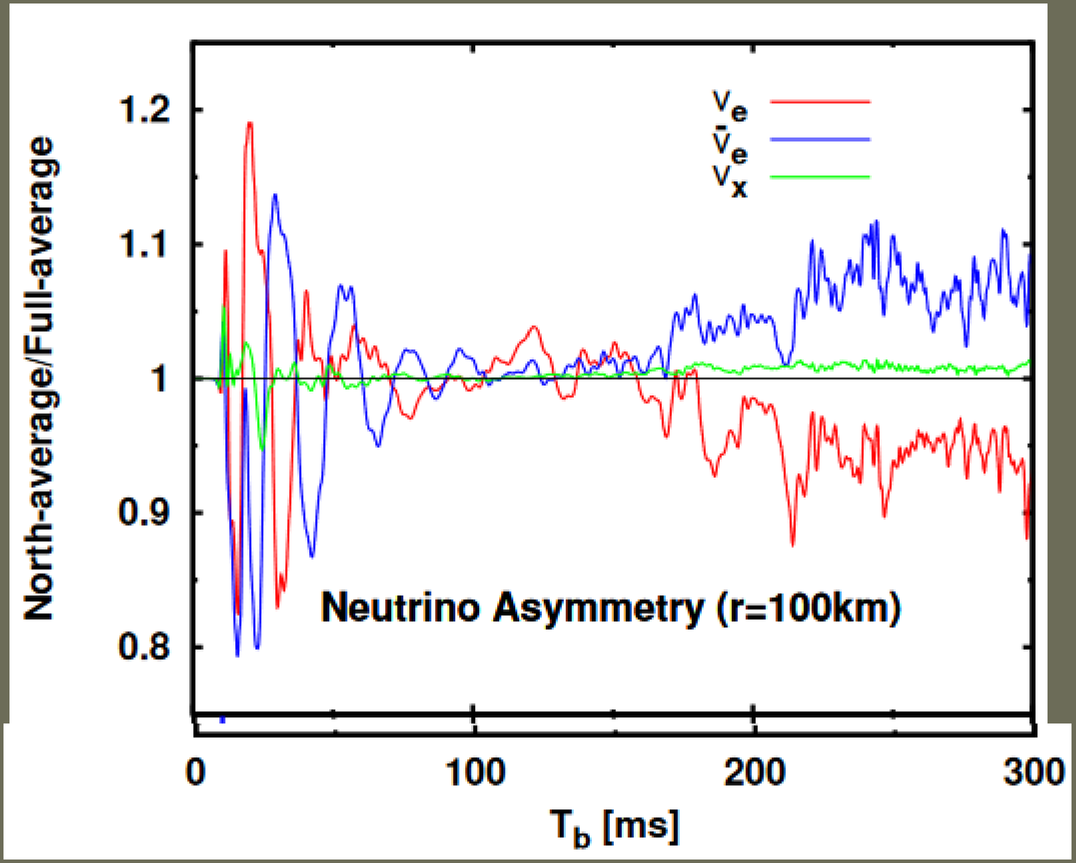
11.2 solar mass model

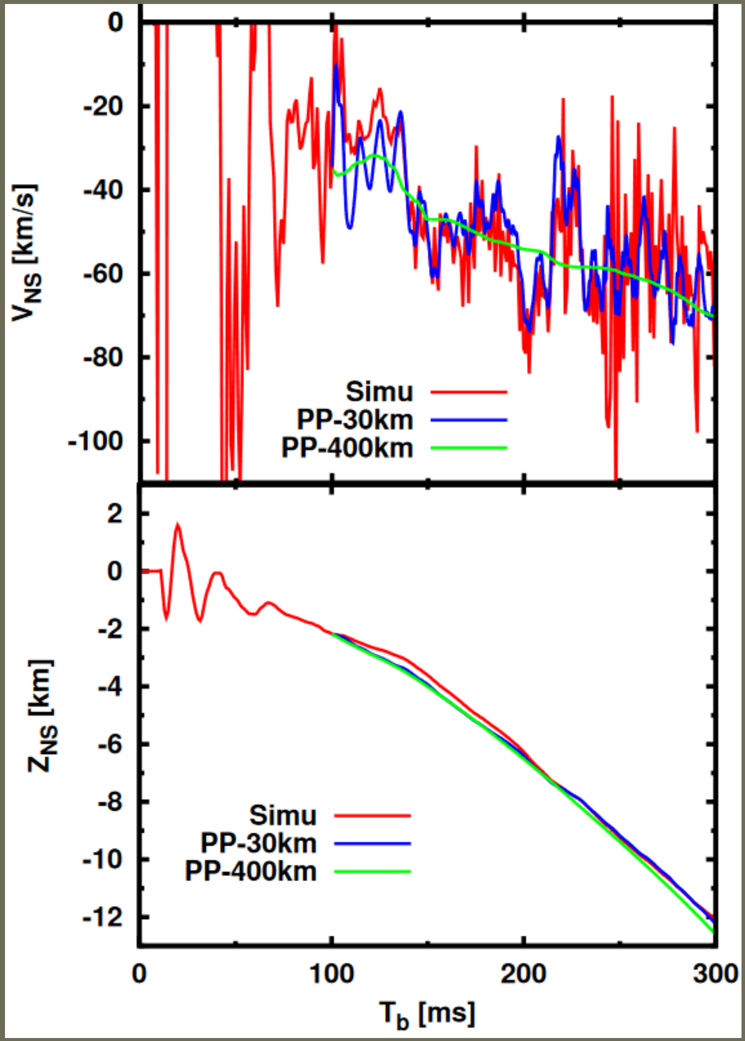


3Dc – with mesh coursing
3D - without

1904.08088

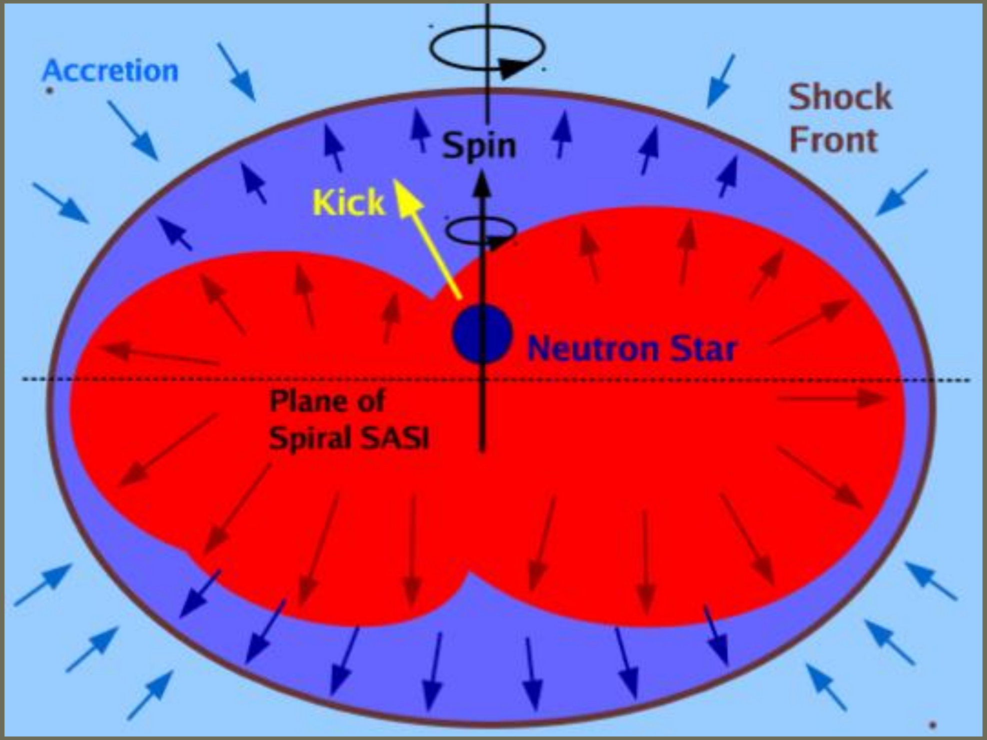
Neutrino emission asymmetry





1907.04863

NS kick models



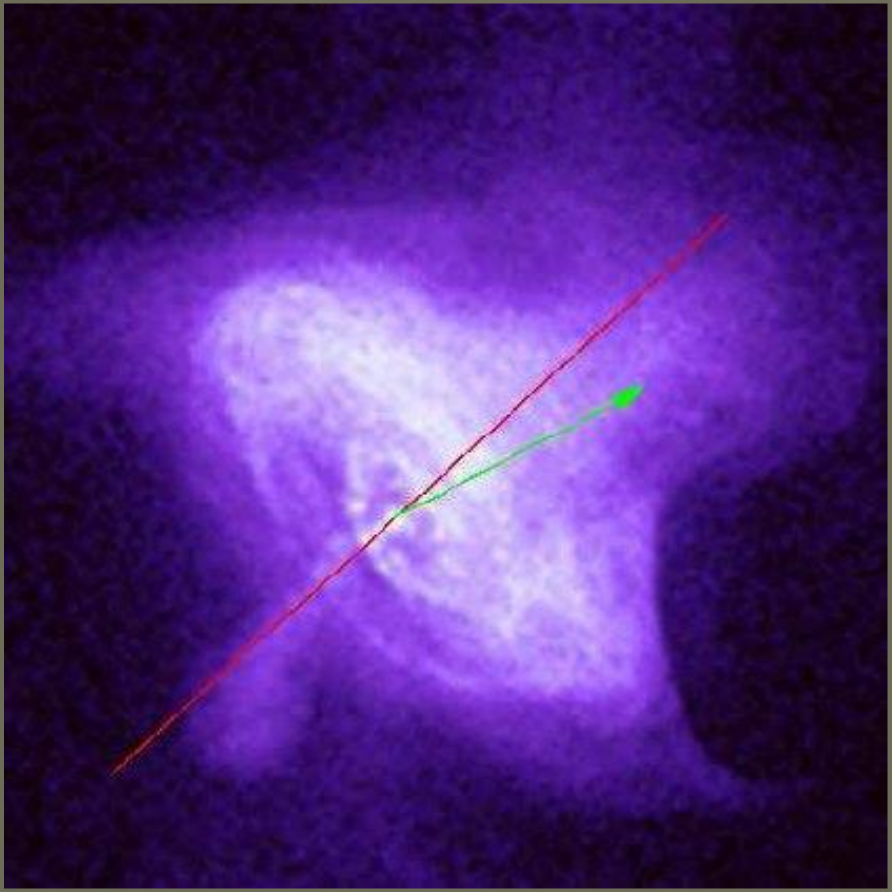
Spin-kick alignment resulting from a neutrino-driven explosion launched from a phase of strong spiral-SASI activity.

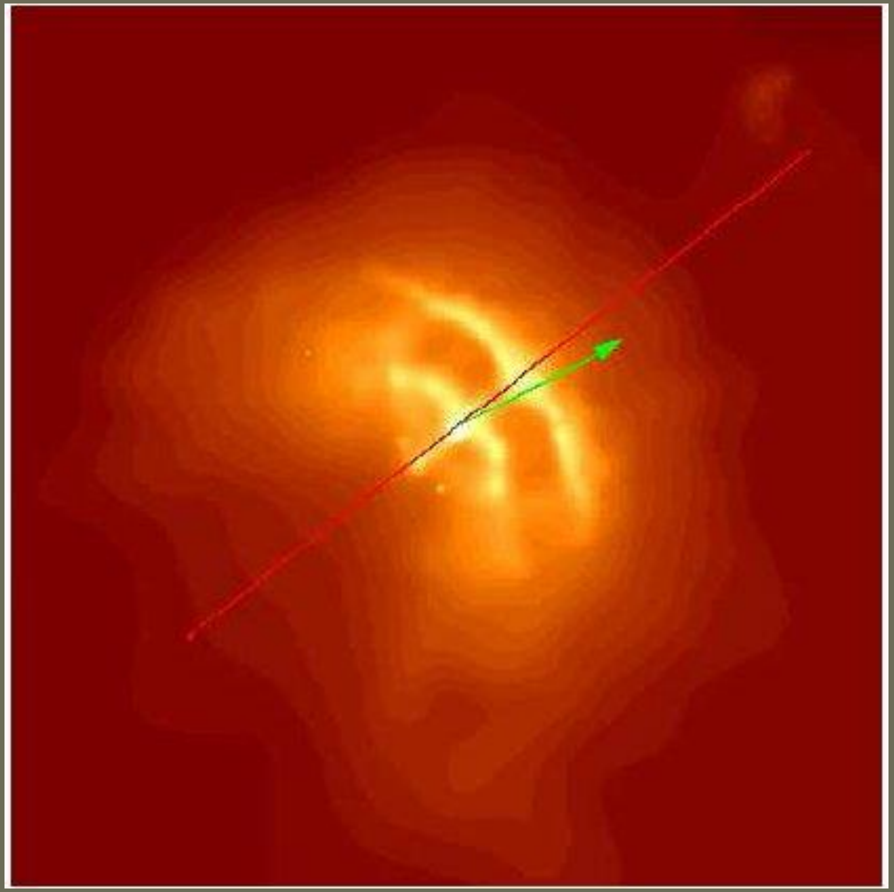
While the explosion starts by equatorial expansion, the final NS kick is determined by the slower mass ejection in the polar directions.

The NS is accelerated by the gravitational attraction of the mass in these more slowly expanding, dense regions.
In the cartoon the NS is pulled more strongly towards the northern direction and therefore opposite to the (southern) hemisphere where the explosion is more powerful.

1611.07562

Spin-velocity alignment

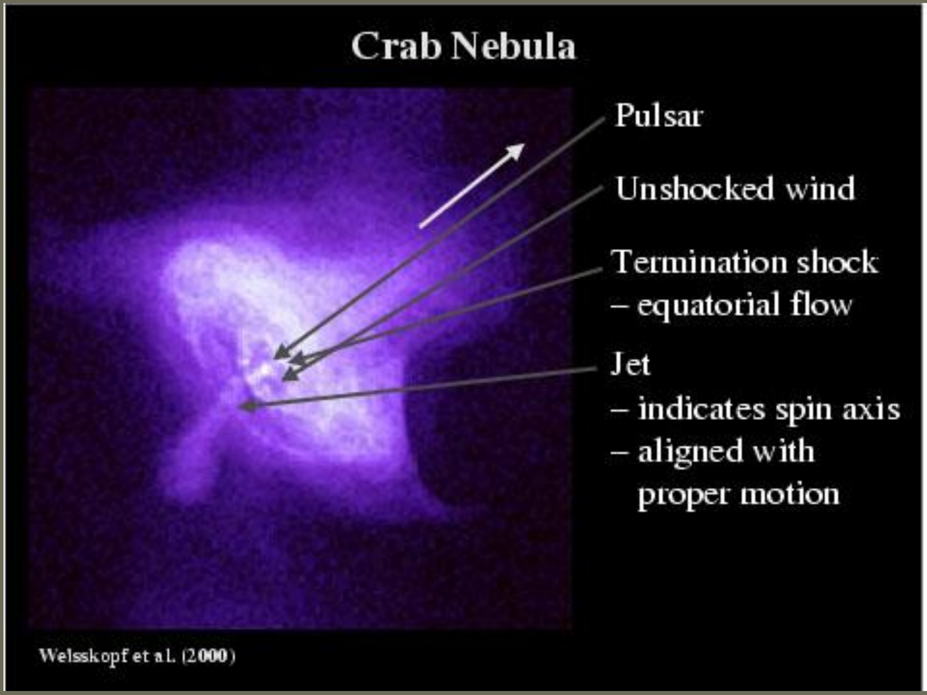


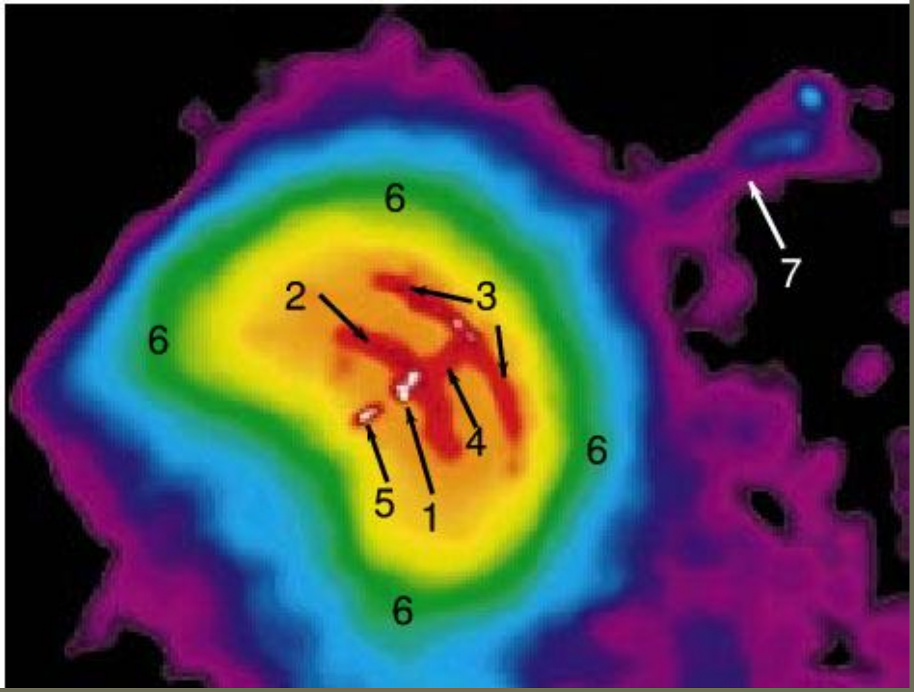


Spatial velocity and spin axis are nearly coincident.
Nearly is important: there is some misalignment.

[Ng & Romani]

The best studied cases: Crab and Vela





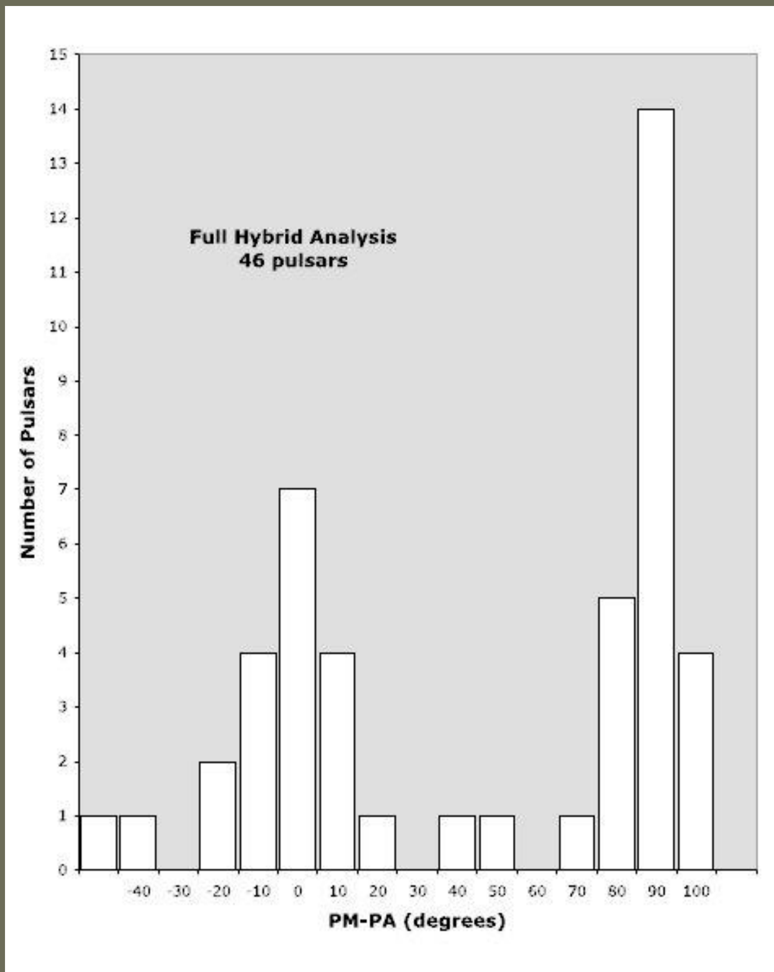
Crab and Vela are not the only cases, but are the best studied ones.
Spin-velocity correlation (in direction) is reported for many radio pulsar.
For some of them pulsar wind nebula observations are used,
for some only direction of proper motion and polarization properties can be used.

Some set of PSRs with known spin-velocity orientation

		2D Pulsars	
B0628−28	318	+61/−64	5 ± 4
B0740−28	259	+190/−149	7 ± 5
B0823+26	189	+55/−34	21 ± 7
B0835−41	170	±30	13 ± 11
B0919+06	506	±80	32 ± 17
B1133+16	639	+38/−35	22 ± 2
B1325−43	597	±254	31 ± 22
B1426−66	150	+40/−24	5 ± 9
B1449−64	219	+55/−18	1 ± 3
B1508+55	1082	+103/−90	23 ± 7
B1642−03	160	+34/−32	26 ± 5
B1800−21	347	+48/−57	7 ± 8
B1842+14	512	+51/−50	5 ± 15
B1929+10	173	+4/−5	16 ± 2
B2045−16	304	+39/−38	3 ± 6
IC 443	250	±50	45 ± 10
		3D Pulsars	
J0205+6449	838	±251	21 ± 10
B0531+21	140	±8	26 ± 3
J0537−6910	634	±50	3 ± 5
J0538+2817	407	+116/−74	12 ± 4
B0540−69	1300	±612	34 ± 33
B0833−45	61	±2	10 ± 2
B1706−44	645	±194	35 ± 10
J1833−1034	125	±30	16 ± 15
B1951+32	273	±11	18 ± 5

[Ng & Romani 2007]

Recent data on radio pulsars



Rankin (2007)

J name	B name	log[age] (yr)	V_T km s^{-1}	PA_v (○)	PA_0 (○)	Ψ (○)
J0452−1759	B0450−18	6.2	185	72(23)	47(3)	25(23)
J0659+1414	B0656+14	5.0	65	93.1(4)	−86(2)	−1(5)
J0738−4042	B0736−40	6.6	180	313(5)	−21(2)	−26(5)
J0837+0610	B0834+06	6.5	170	2(5)	18(5)	−16(7)
J0837−4135	B0835−41	6.5	360	187(6)	−84(5)	−89(8)
J1604−4909	B1600−49	6.7	510	268(6)	−17(3)	−75(7)
J1735−0724	B1732−07	6.7	570	355(3)	55(5)	−60(6)
J1801−2451	B1757−24	4.2	300	270	−55(5)	−35(5)
J1820−0427	B1818−04	6.2	190	338(17)	42(3)	−64(17)
J1850+1335	B1848+13	6.6	300	237(16)	−45(3)	−78(16)
J1915+1009	B1913+10	5.6	280	174(15)	85(3)	89(15)
J1937+2544	B1935+25	6.7	210	220(9)	−9(5)	49(10)
J2048−1616	B2045−16	6.5	330	92(2)	−13(5)	−75(6)
J2330−2005	B2327−20	6.7	180	86(2)	21(10)	65(10)

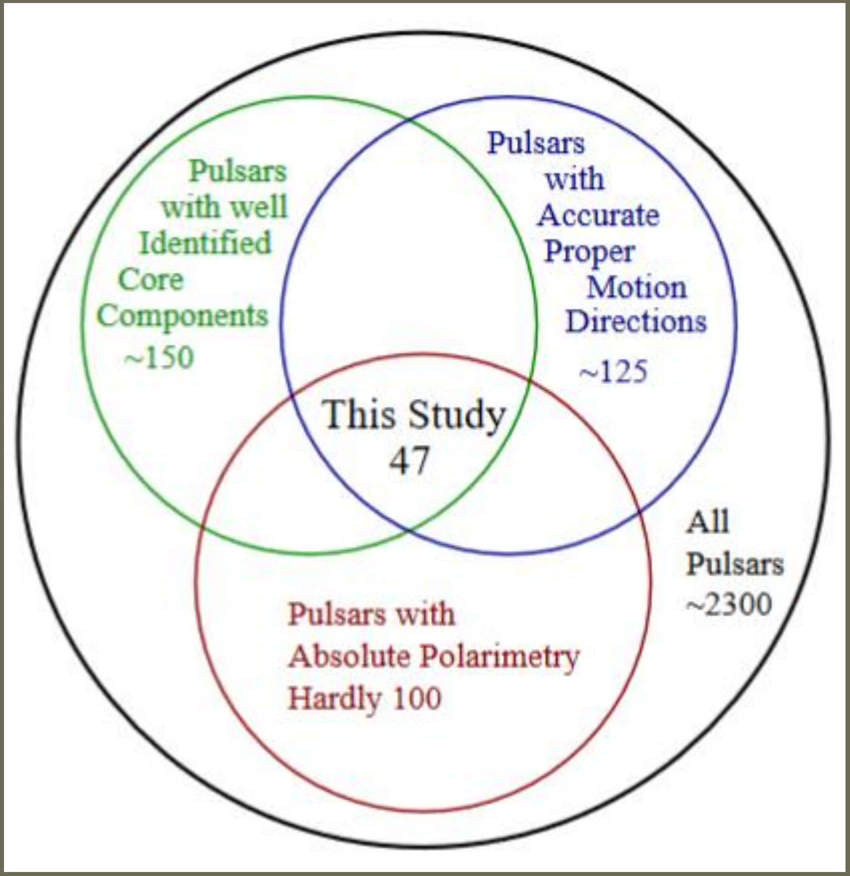
Johnston et al. (2007)

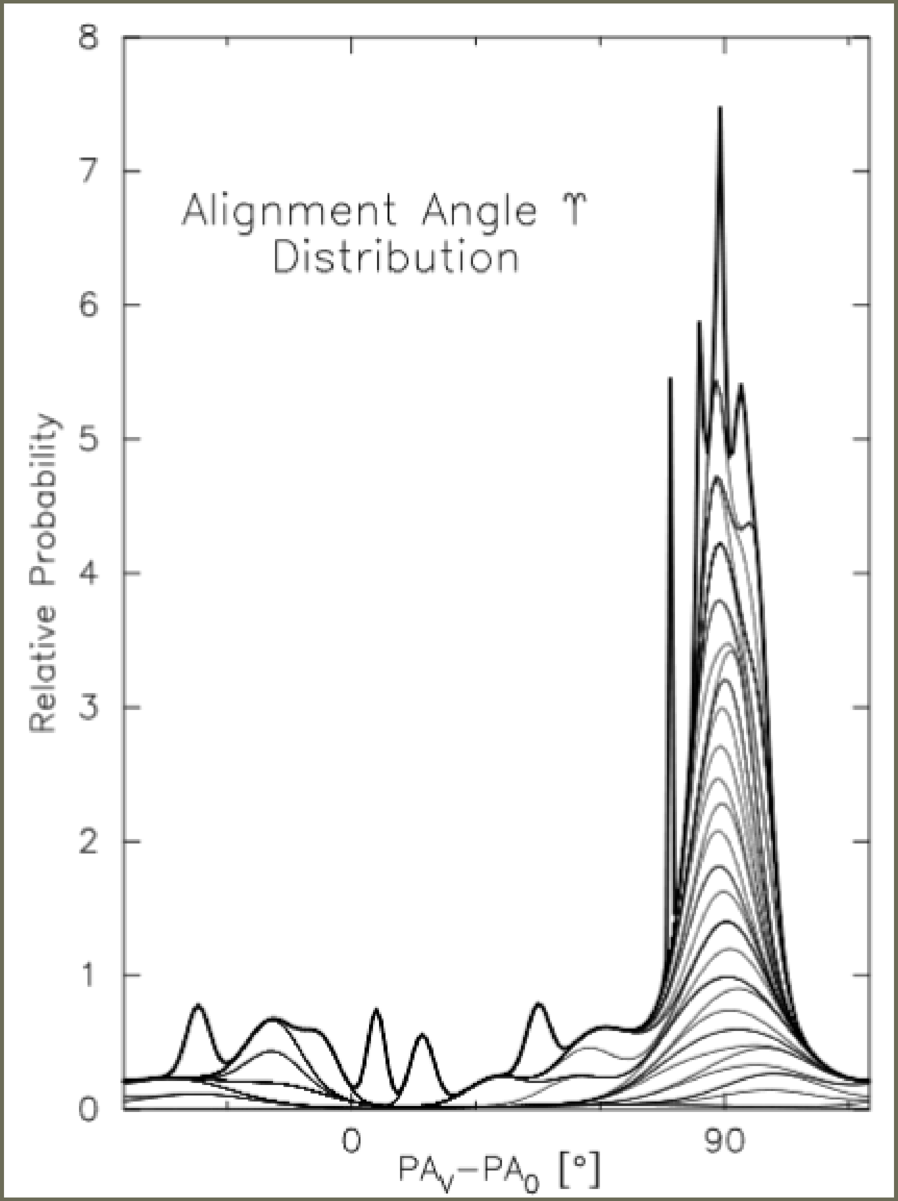
The tendency is clear, but it is only a tendency.

New data and discussion in 1502.05270

Alignment

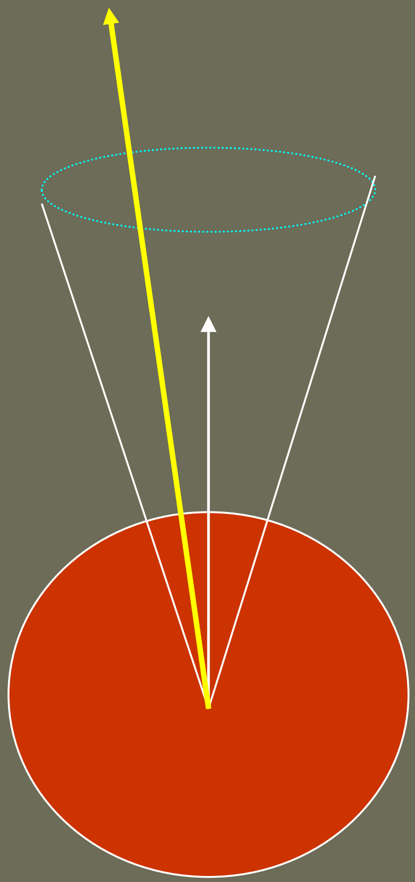
47 pulsars with well-determined parameters.



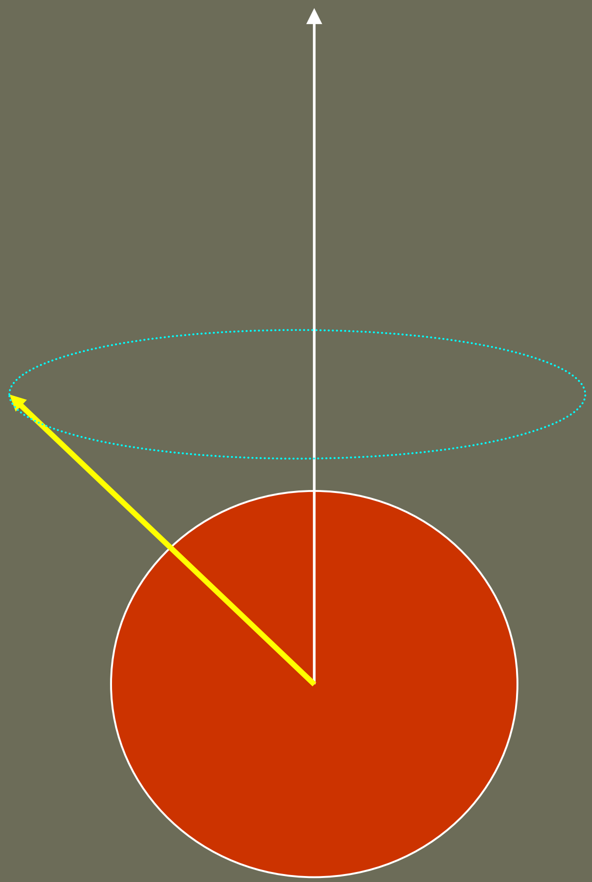


1502.05270

Why?

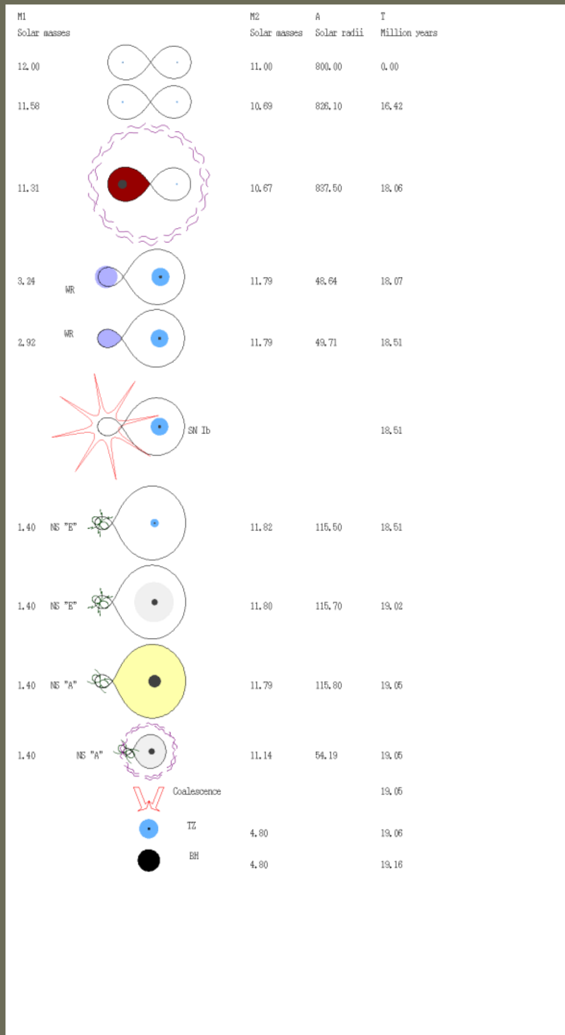


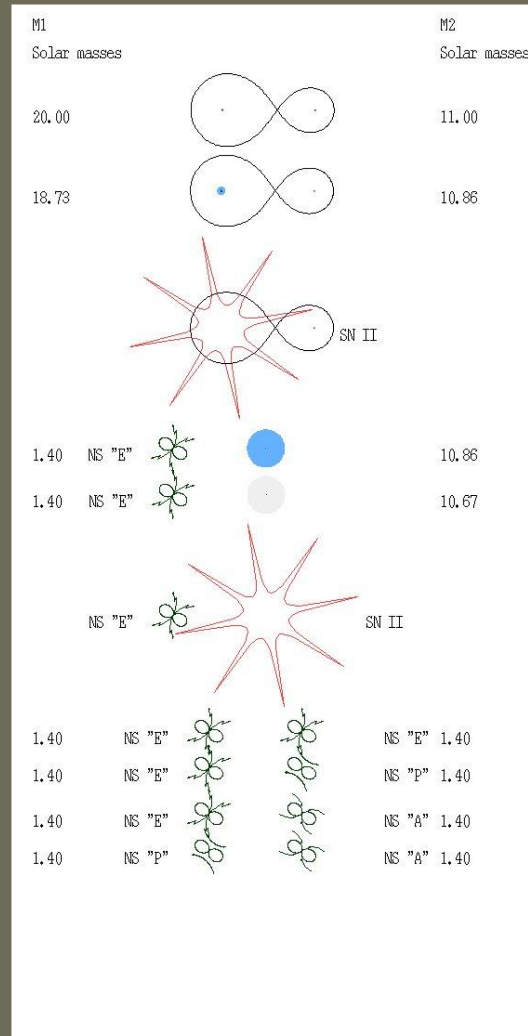
Kick can be confined in some angle around the spin axis. Typical cones must be <~10^{o} (see, for example, Kuranov et al. 2009).

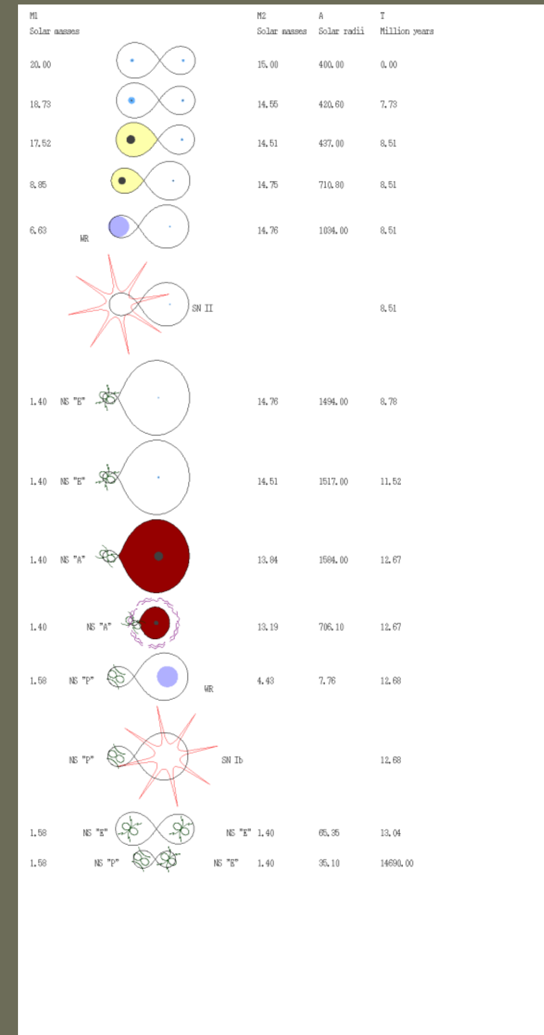


Kick mechanism can be operative for a long time (many spin periods), so that its influence is average. Typical duration must be 1-10 sec.

Kicks in binary evolution

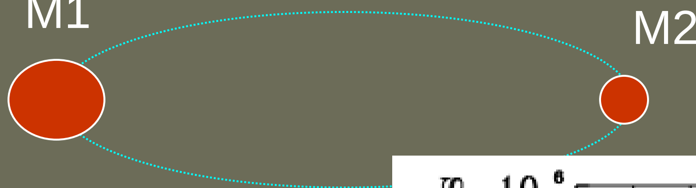


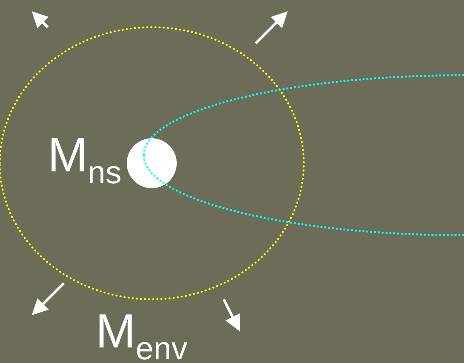


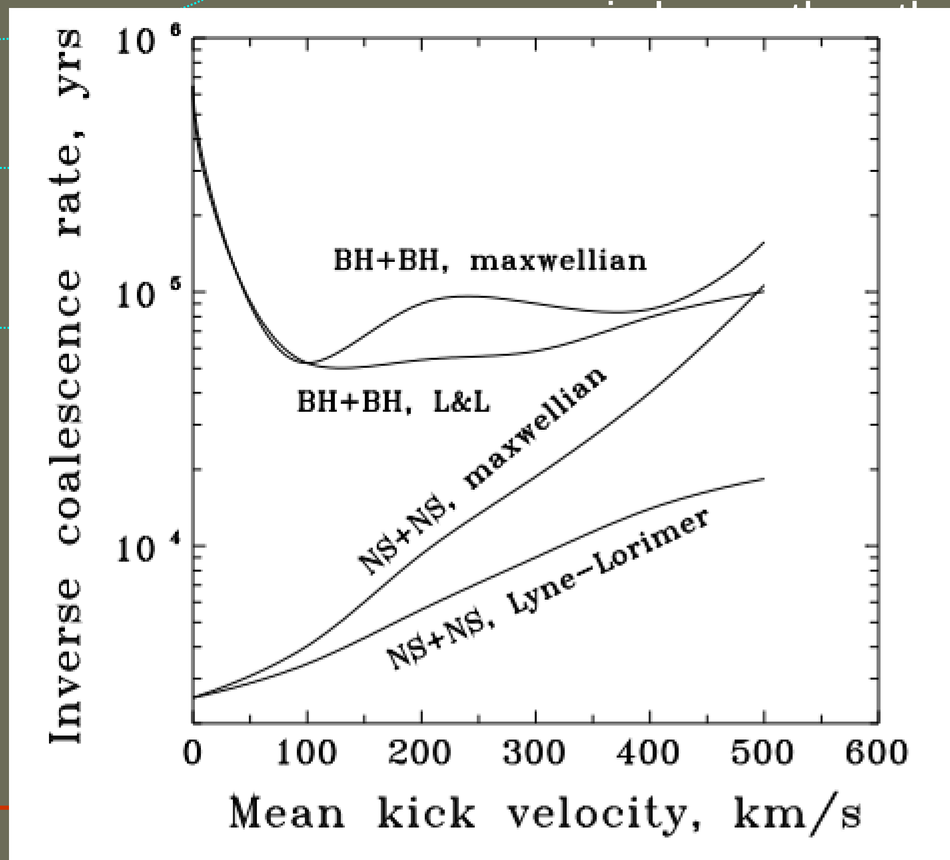


Influence of kicks on binaries

Kicks can both – destroy and **save** – binaries!







If a more massive star is about
to explode, and the lost mass
sum of the
nd the secondary mass,
should be destroyed.
k can save it.

+BH, BH+BH binaries.
l the more massive star
ns to produce GW.

astro-ph/9702060

Parameters of binaries after kicks

Kicks significantly influence binary parameters (for example, eccentricity distribution). This is specially important for systems which survived the second explosion (NS+NS).

There are examples, when a NS rotates “in a wrong direction”, i.e. its orbital motion is in the direction opposite to the spin of the second companion.

For detailed description see Postnov, Yungelson (astro-ph/0701059) pp. 18-22.

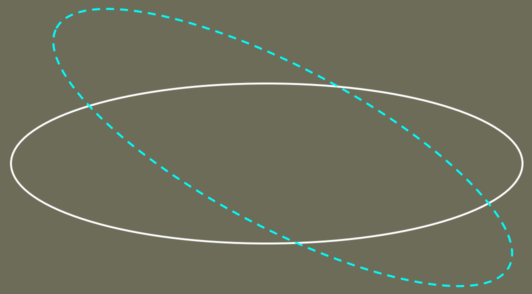
$$\frac{a_\mathrm{f}}{a_\mathrm{i}} = \left[2 - \chi\left(\frac{w_x^2 + w_z^2 + (V_\mathrm{i} + w_y)^2}{V_\mathrm{i}^2}\right)\right]^{-1}$$

$$1 - e^2 = \chi\frac{a_\mathrm{i}}{a_\mathrm{f}}\left(\frac{w_z^2 + (V_\mathrm{i} + w_y)^2}{V_\mathrm{i}^2}\right)$$

$$\chi \equiv (M_1 + M_2)/(M_\mathrm{c} + M_2) \ge 1.$$

$$\cos\theta = \frac{\vec{J}_\mathrm{f}\cdot\vec{J}_\mathrm{i}}{|\vec{J}_\mathrm{f}|\,|\vec{J}_\mathrm{i}|},$$

$$\cos\theta = \frac{V_\mathrm{i} + w_y}{\sqrt{w_z^2 + (V_\mathrm{i} + w_y)^2}}.$$



$$\frac{V_\mathrm{f}}{V_\mathrm{i}} \ge \sqrt{\frac{2}{\chi}}.$$

Disruption condition

e^--supernovae with low kicks

In 80s it was proposed by Nomoto, Miyaji et al. that in some cases a SN explosion can happen due to electron capture by ^{24}Mg and ^{20}Ne (no iron core is formed).

It was noticed (Pfahl et al. 2002, Podsiadlowski et al. 2004; van den Heuvel 2004, 2007) that among Be/X-ray binaries there is a group of systems with small eccentricities.
But they suffered one SN explosion and there was no Roche-lobe overflow.
This means that kicks in these systems were low.
The same is true for some of NS+NS binaries.

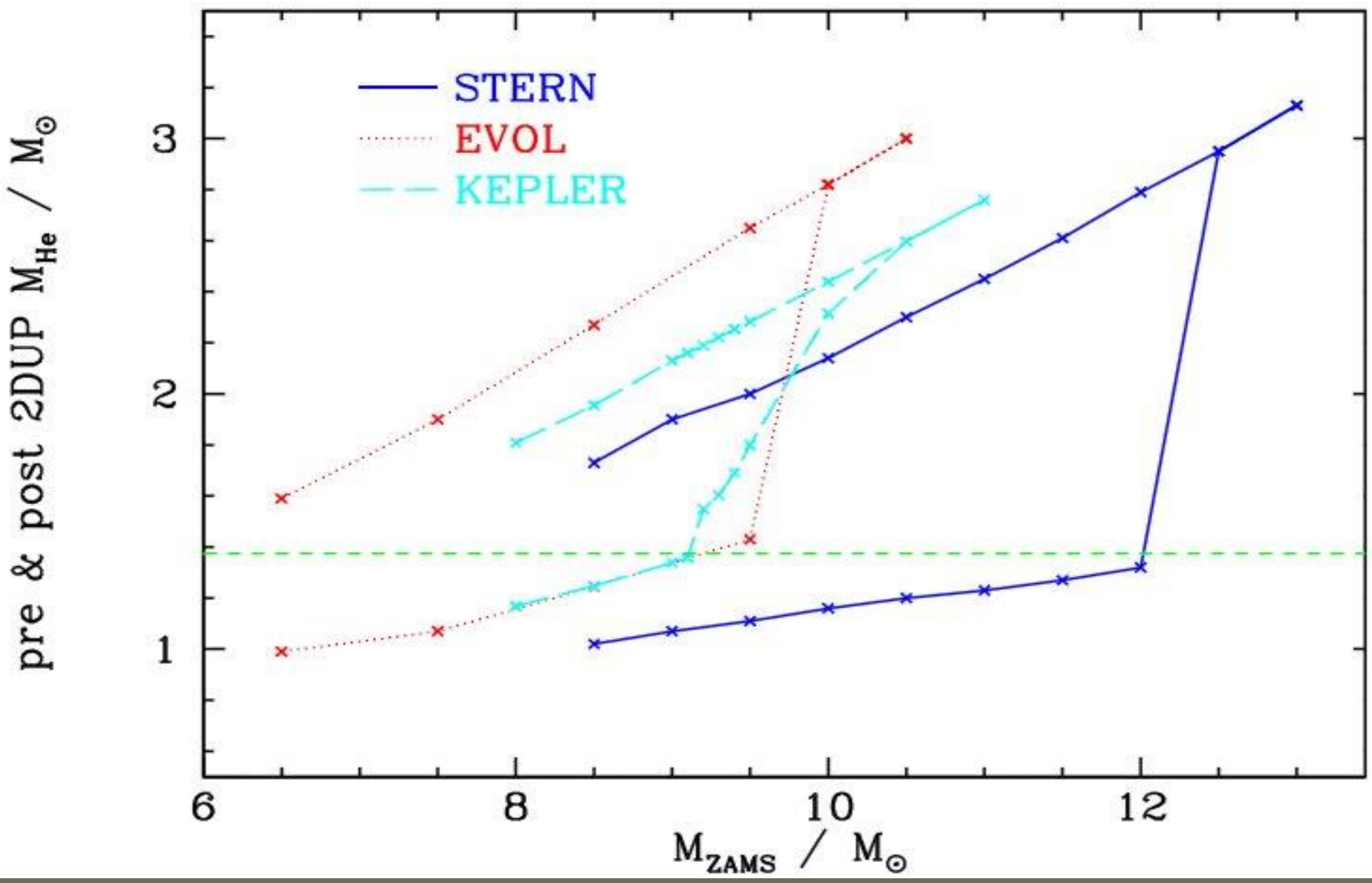
The proposed mechanism is related to e^- -capture SN.

Such explosions can appear not only in binary systems, but in binaries they can be more frequent.
Among isolated stars about 4% (up to ~20%!) of SN can be of this type (Poelarends et al. 2008). [It is not clear if they appear among normal PSRs.]

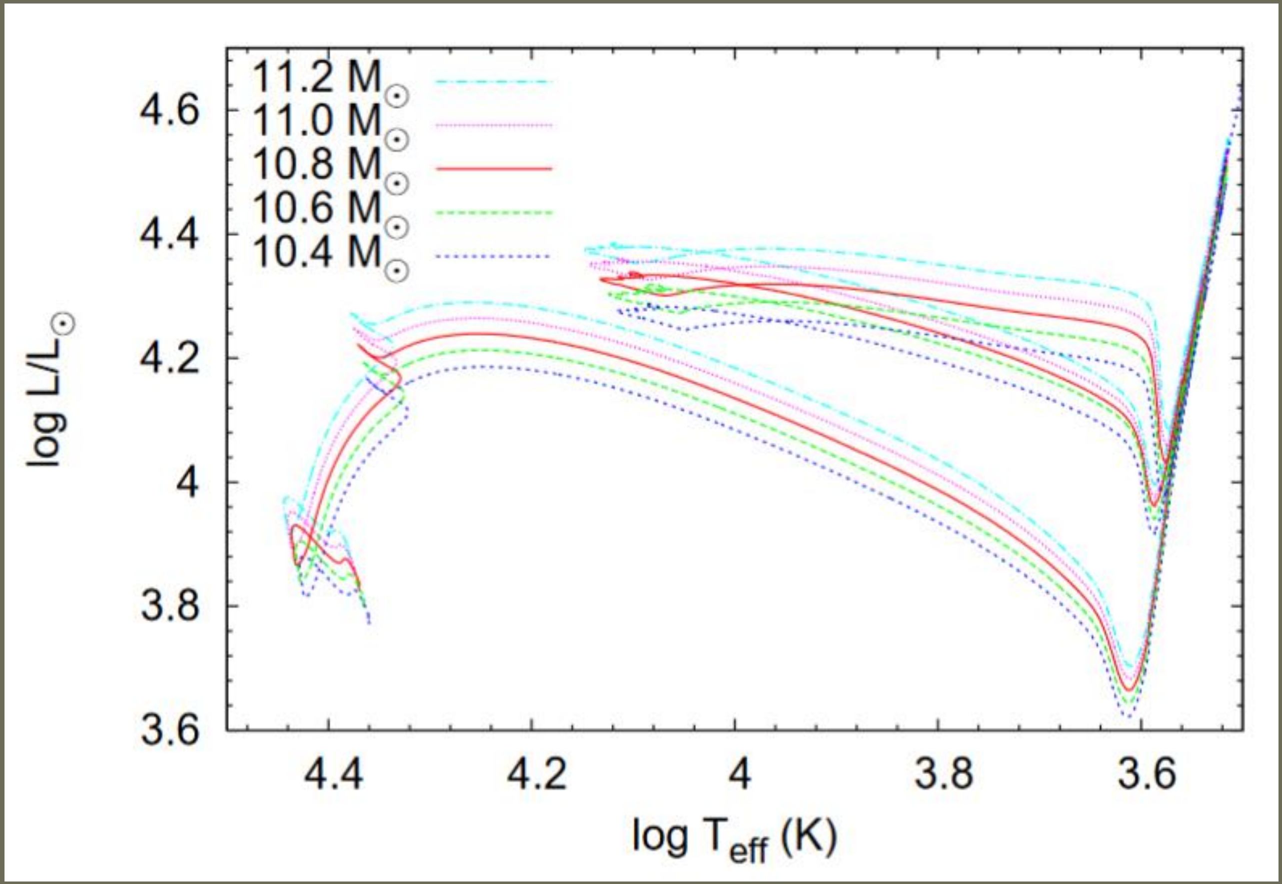
Why kick is low? Uncertain. Low core mass, rapid explosion, low mass ejection…

e^- -capture SN in binaries

Poelarends et al. 2008. 0705.4643



Evolution of e⁻-capture SN progenitors

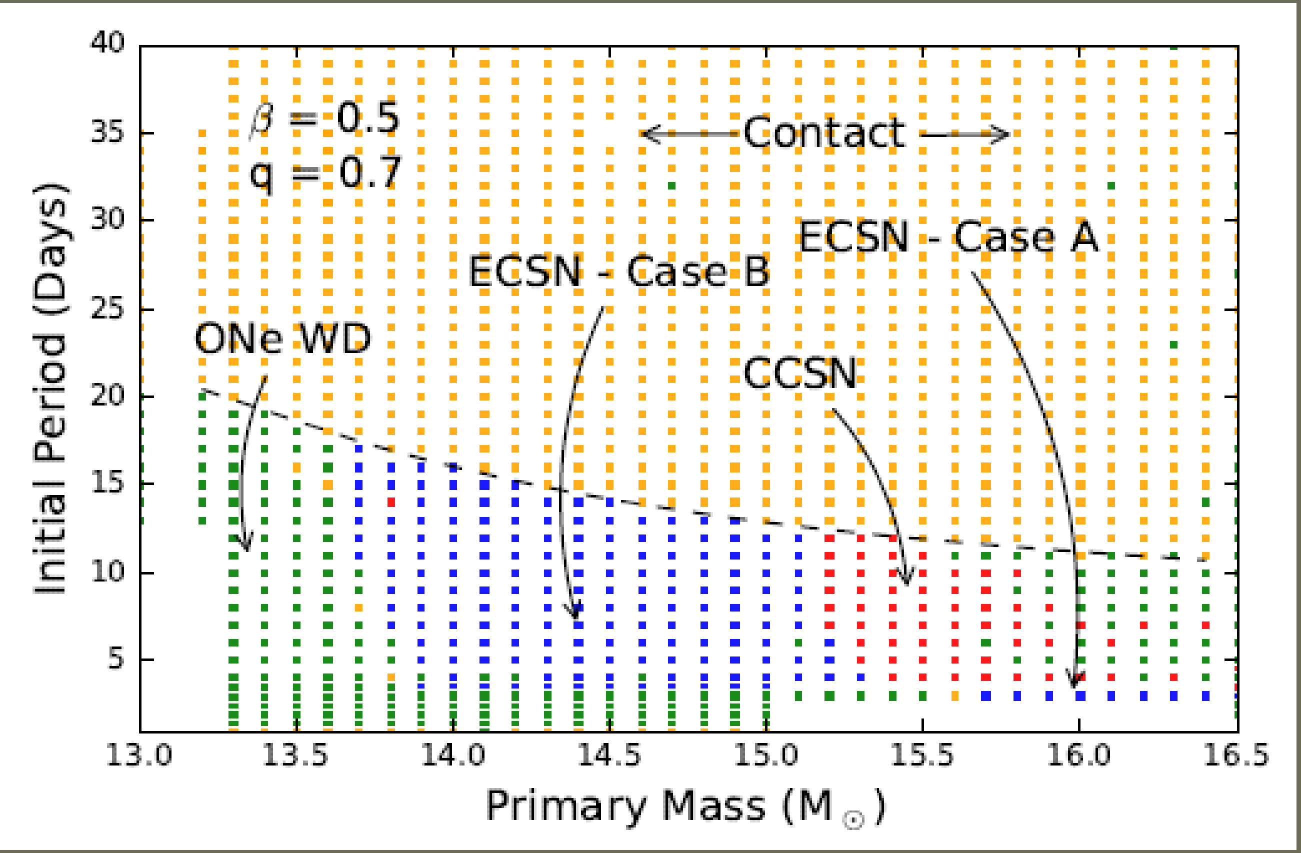


Critical core mass 1.367 solar masses.

For initial stellar masses >11 solar neon is ignited, and later on a Fe-core is formed.

1302.6402

e⁻-capture SN in close binaries

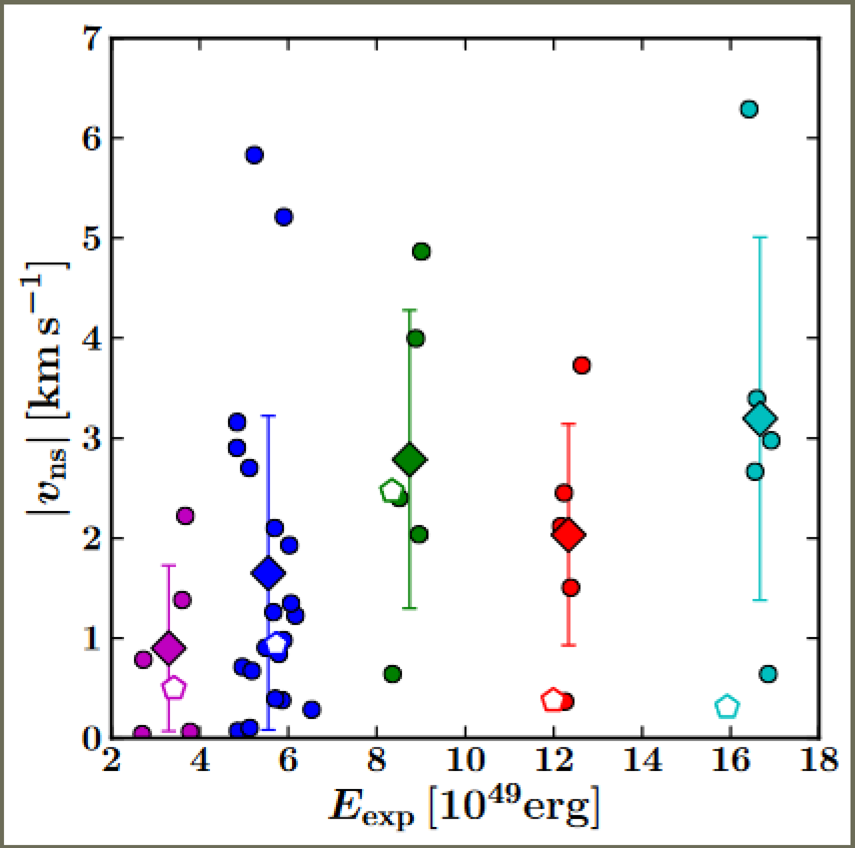


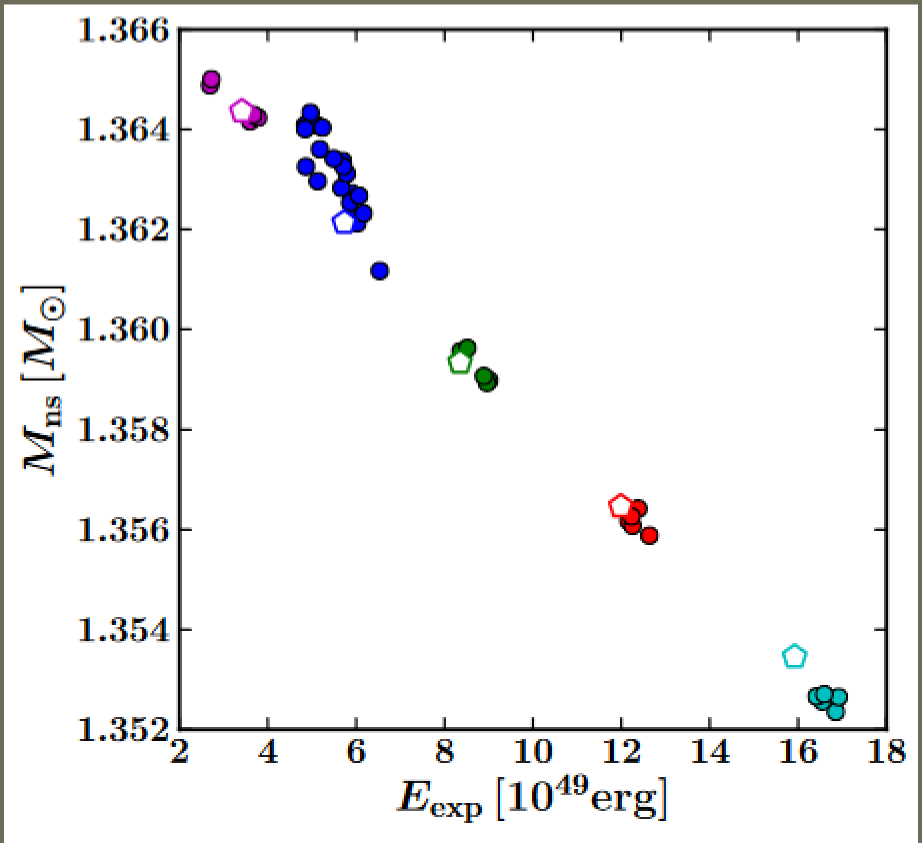
The initial primary mass and the mass transfer evolution
are important factors in the final fate of stars in this mass range

1710.11143

e^--capture SN and Crab

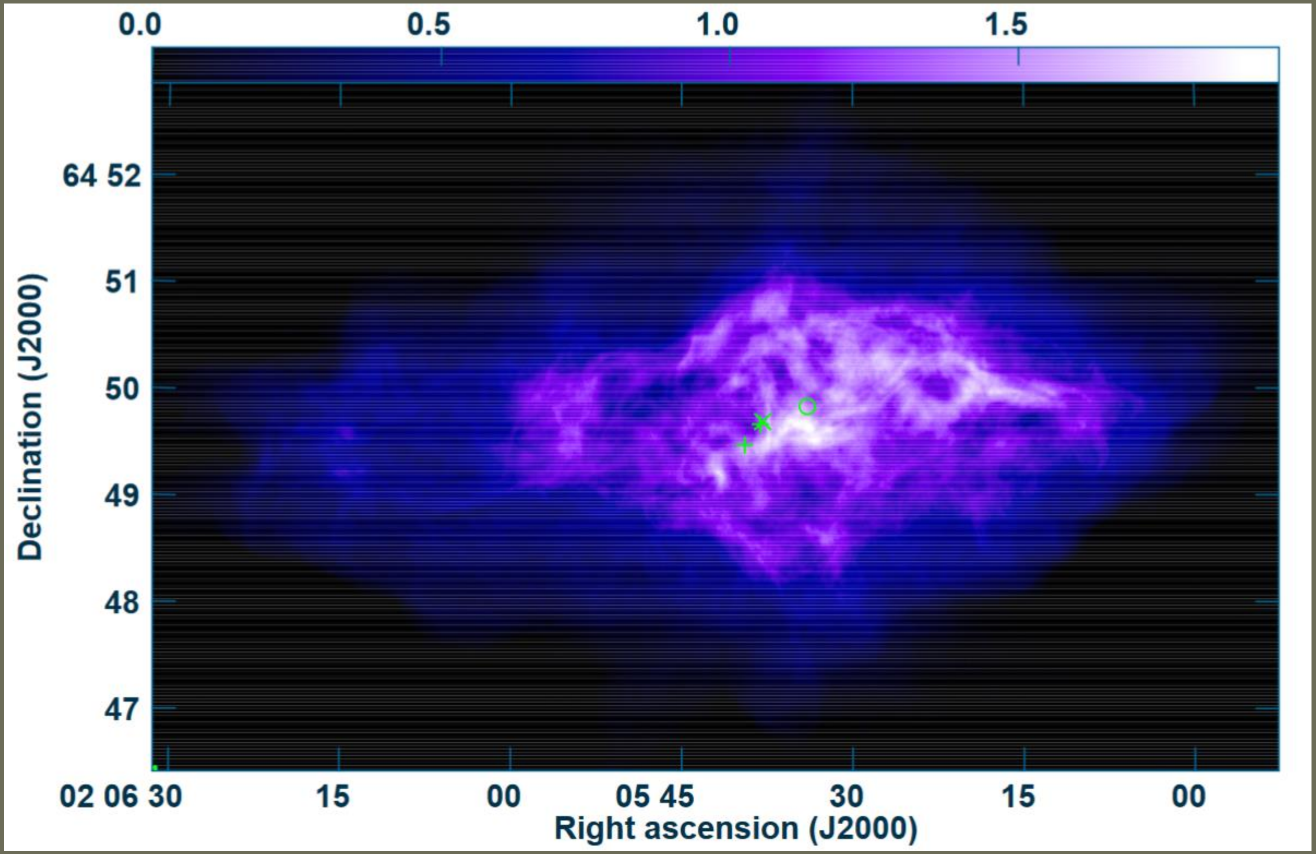
Calculations confirm that in e- -capture SN kicks are low (tag-boat, i.e. gravitational pull mechanism, is not effective). Thus, Crab pulsar was not born in an e- -capture explosion.





1802.05274

Pulsars with low velocities



Some NSs demonstrate low spatial velocities. Obviously, this is due to low kicks.

3C58.
Low kick velocity.
Projected velocity 30-40 km/s

1302.5625

Kicks as fingerprints

Think about young highly magnetized NSs of different types:

- SGR
- AXP
- RRATs
- Magnificent Seven

Are they relatives?

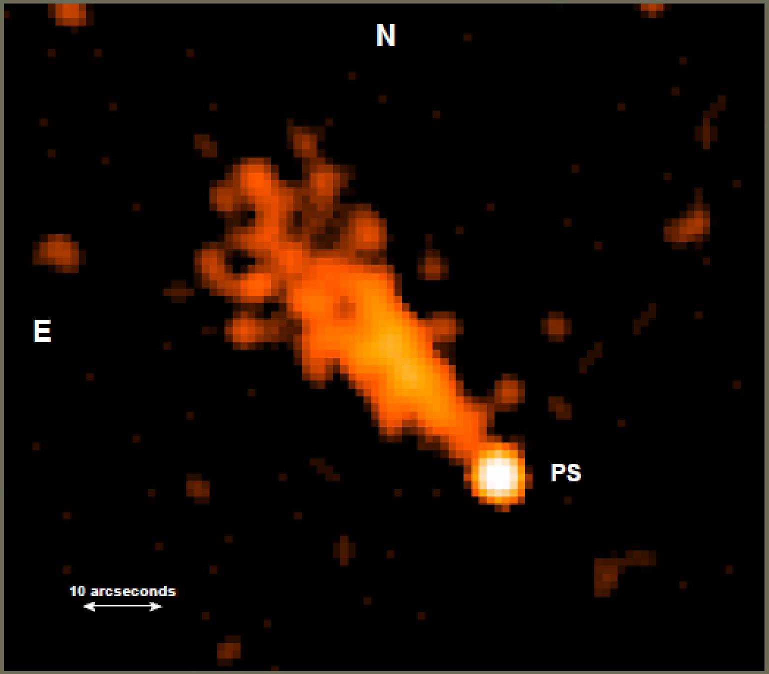
It is a difficult question, but velocity measurements can give you a hint.
Even if fields are decayed, rotation is slowed down, thermal energy is emitted …
if they are relatives – velocity distributions must be identical.
Unfortunately, now we do not know the answer.

Magnetar velocity measurements

SGR 1806-20 350 +/- 100 km/s arXiv:1210.8151
SGR 1900+14 130 +/- 30 km/s arXiv:1210.8151
PSR J1550-5418 280 +/- 130 km/s arXiv:1201.4684
XTE J1810-197 200 km/s Helfand et al. (2007)

Record velocities

1. PSR J1357-6429   1600-2000 km/s arXiv: 1206.5149   - shown to be wrong
2. IGR J11014-6103 2400-2900 km/s arXiv: 1204.2836 (Lighthouse nebulae)
3. PSR J0357+3205 1900-2000 km/s arXiv: 1212.6664 (Morla nebula)

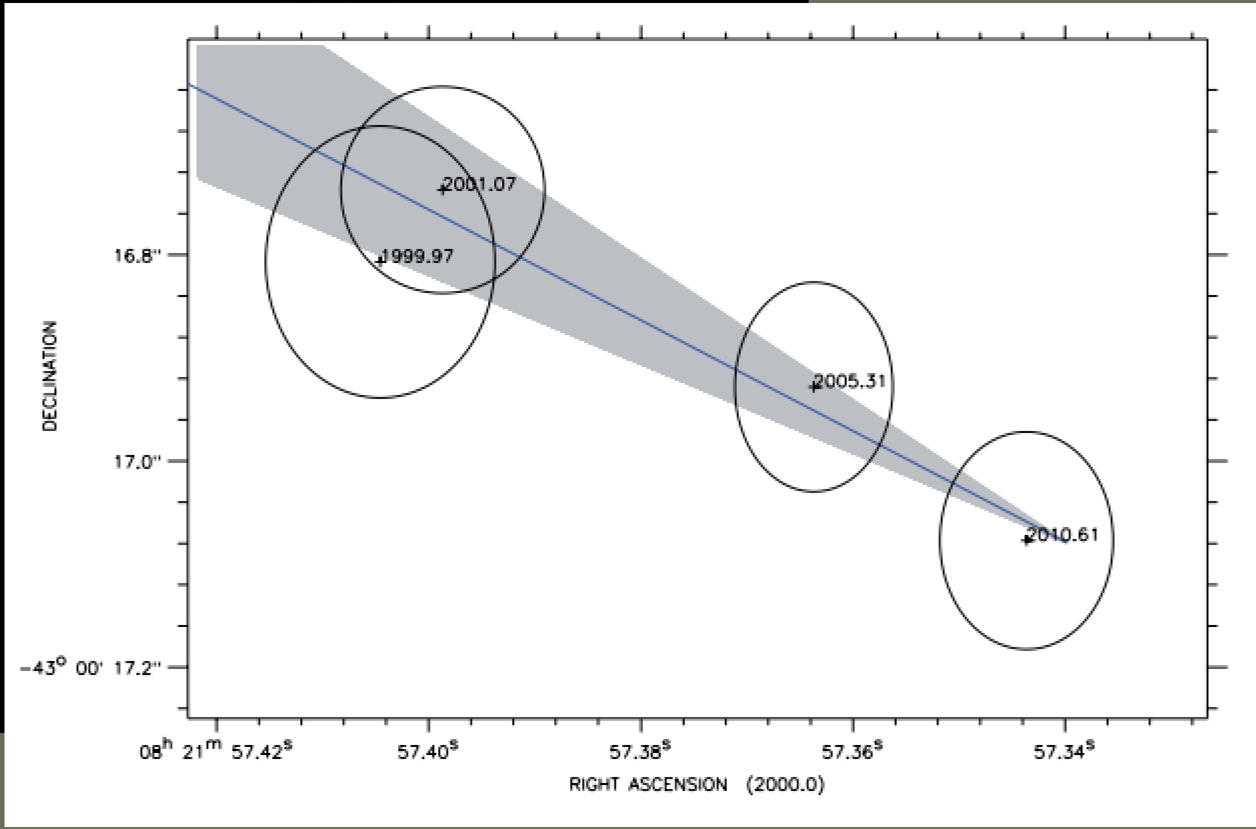


High velocity neutron stars allow to probe properties of the ISM.

See 1708.00456, 2002.12111.

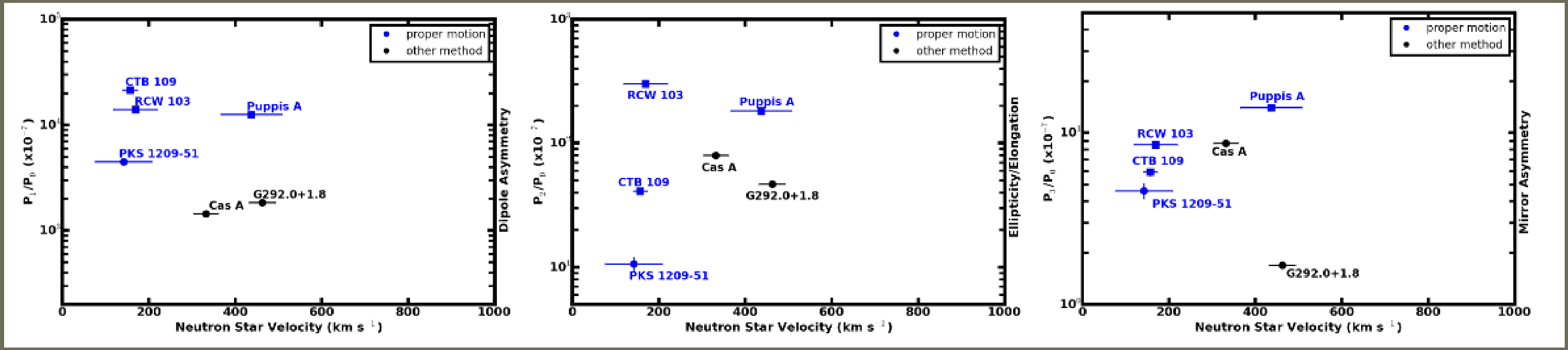
CCO velocities

RX J0822-4300 in the Supernova Remnant Puppis A
672 +/- 115 km/s
arXiv: 1204.3510

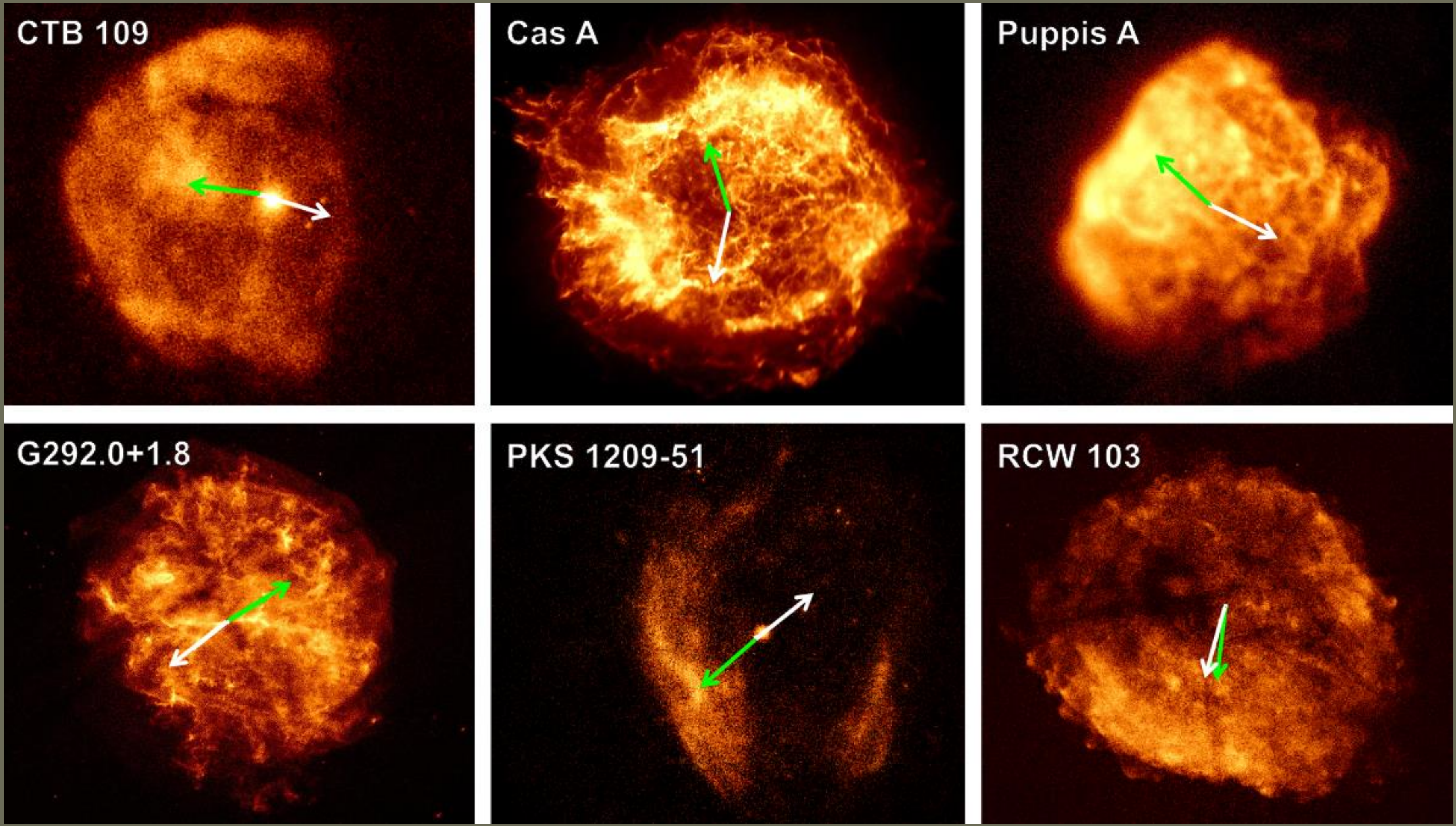


Kick velocity and SNR morphology

18 young (<20 kyr) SNR with NSs (with velocity) fully imaged by Chandra or ROSAT.
Thermal X-ray emission distribution is stidued.



Dipole anisotropy and velocity

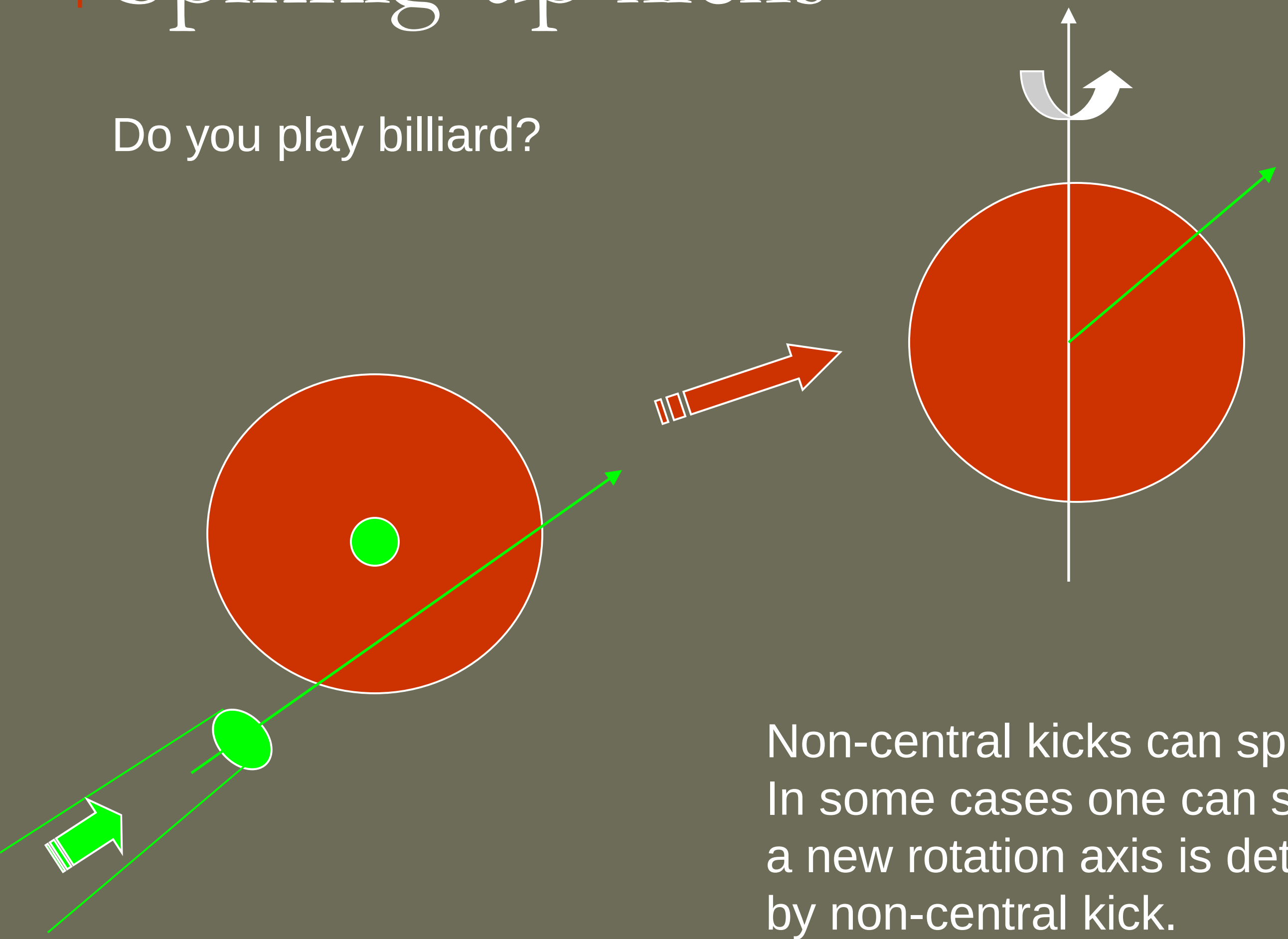


Green – dipole anisotropy of X-ray thermal emission distribution

1705.08454

Spinnig-up kicks

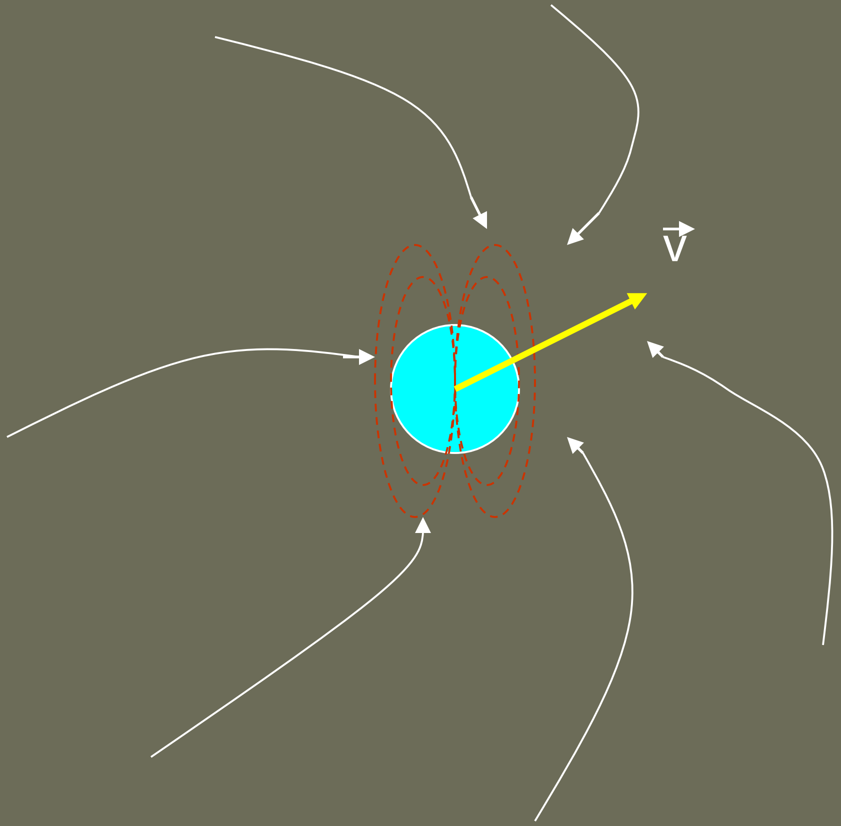
Do you play billiard?



Non-central kicks can spin-up a NS.
In some cases one can speculate that
a new rotation axis is determined mainly
by non-central kick.
But then velocity - spin period correlation is expected.

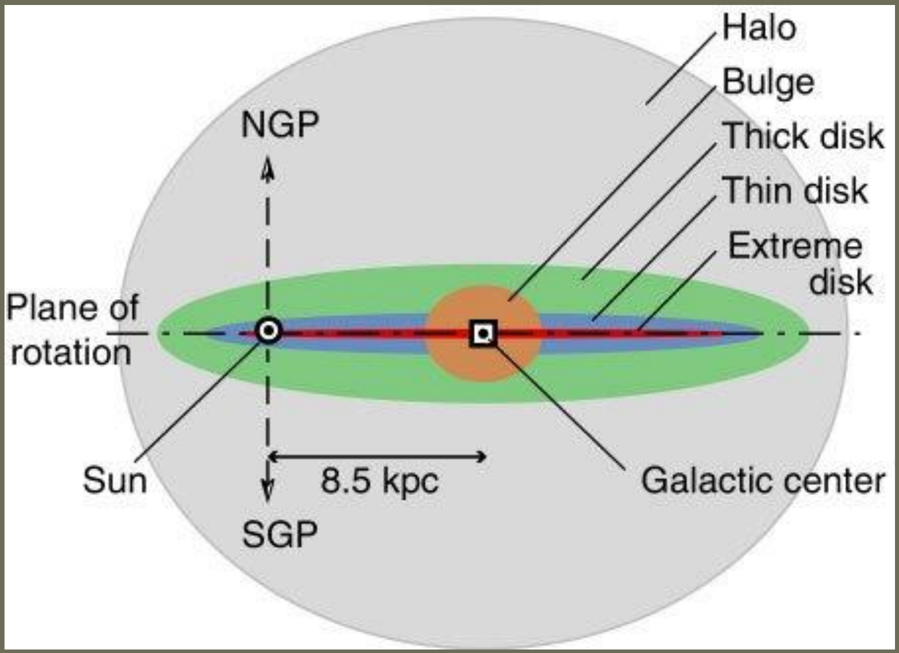
Evolution of isolated NSs and kicks

Evolution of an isolated NS depends on the intensity of its interaction with the ISM.
This intensity depends on the relative velocity of a NS and the ISM.



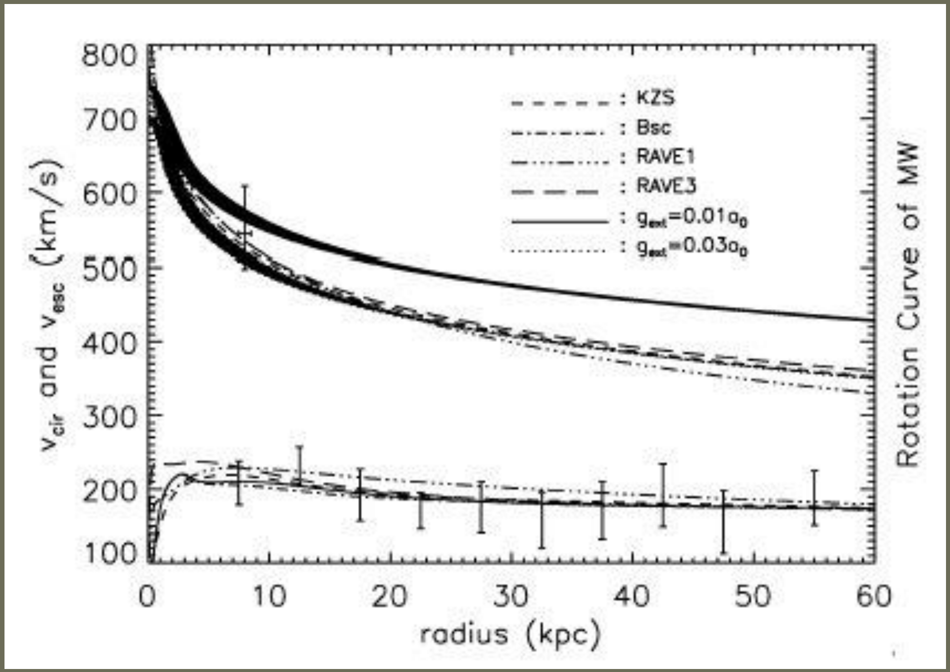
Will a NS start to accrete from the ISM,
or will it stay as Ejector, or Propeller,
or will in enter another regime
strongly depends on the relative velocity
of a NS and the ISM.

Galactic potential



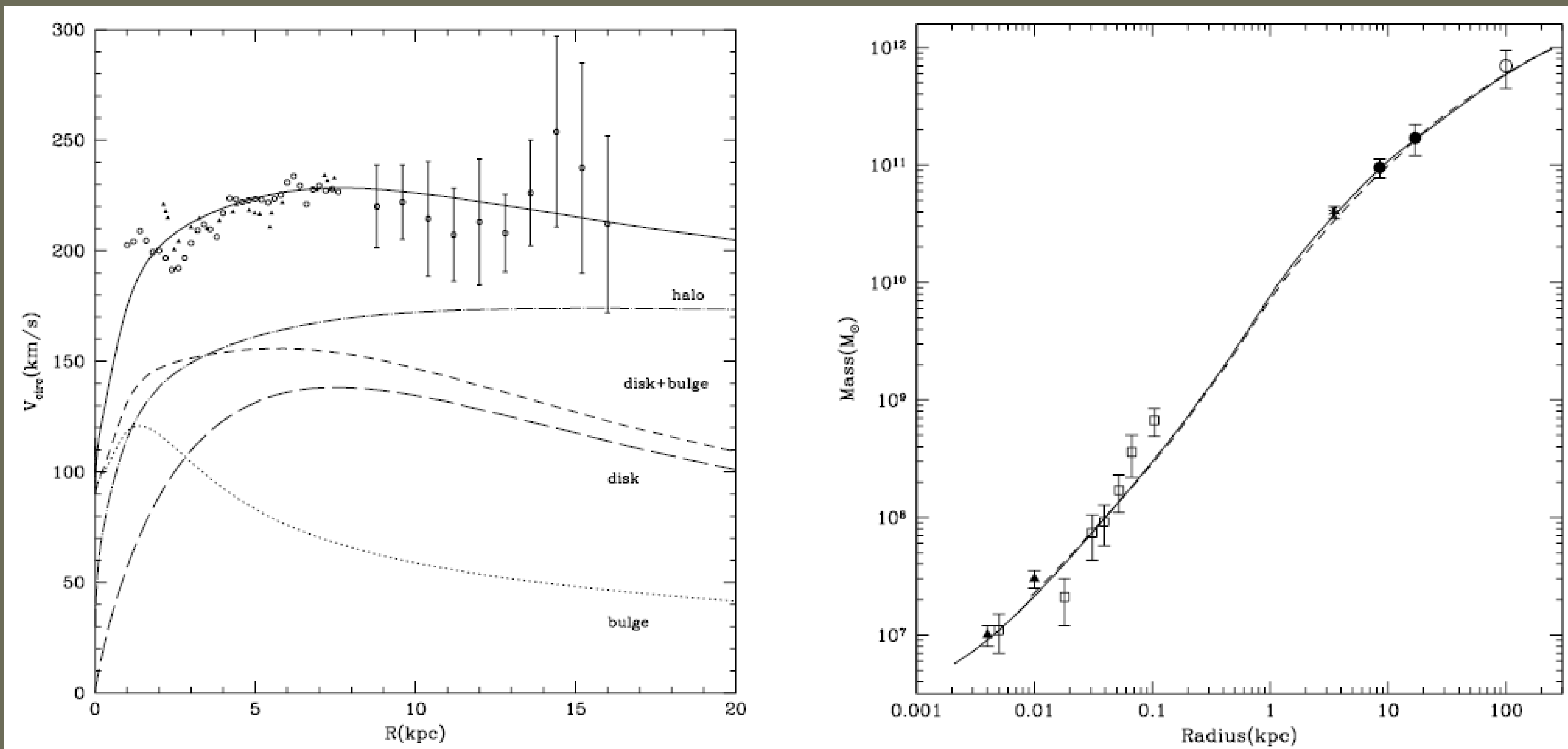
Clearly, some NSs are rapid enough to leave the Galaxy.

Z-distribution of PSRs is much wider than the progenitors' one.



Wu et al. 2008

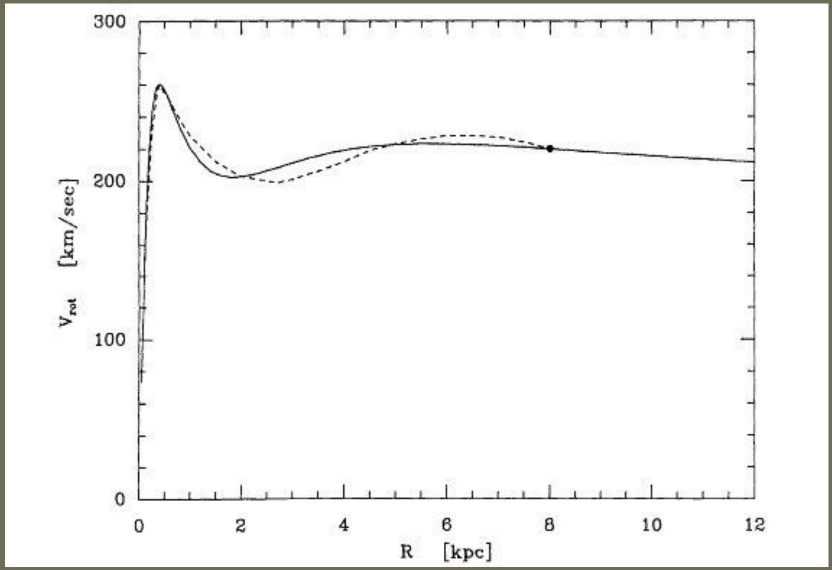
Mass distribution in the Galaxy



Klypin et al. (2002)

"Paczynski" model

Disc+Buldge+Halo
Actually, it is Miyamoto, Nagai (1975) model.
It is simple and popular in NS motion calculations.



$$\Phi_i(R, z) = \frac{GM_i}{\{R^2 + [a_i + (z^2 + b_i^2)^{1/2}]^2\}^{1/2}}, \quad R^2 = x^2 + y^2$$

$$\Phi_h = -\frac{GM_c}{r_c}\left[\frac{1}{2}\ln\left(1 + \frac{r^2}{r_c^2}\right) + \frac{r_c}{r}\,\mathrm{atan}\left(\frac{r}{r_c}\right)\right],$$

$$M_c \equiv 4\pi\rho_c r_c^3$$

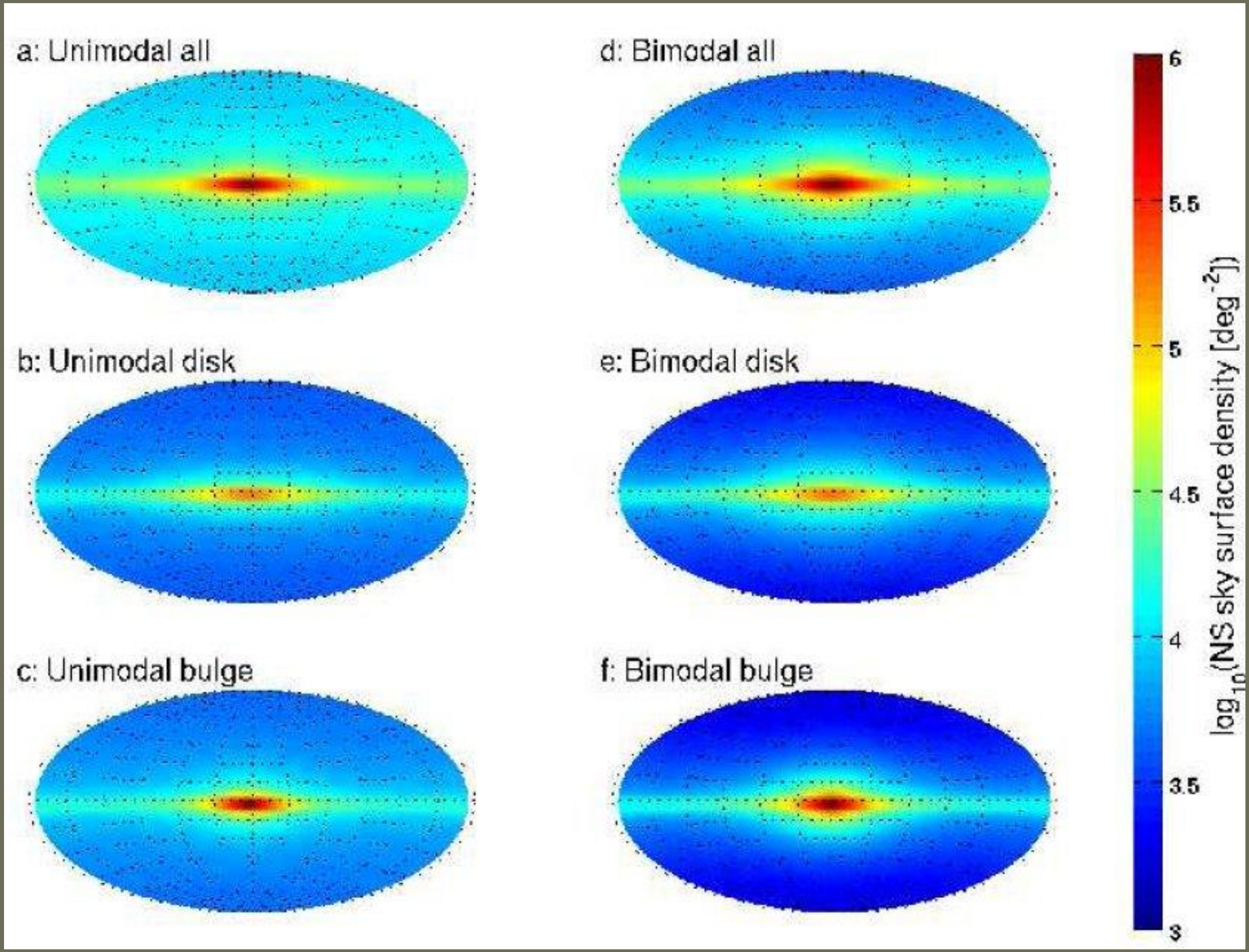
$$a_1 = 0, \quad b_1 = 0.277\ \mathrm{kpc}, \quad M_1 = 1.12 \times 10^{10}\ M_\odot,$$

$$a_2 = 3.7\ \mathrm{kpc}, \quad b_2 = 0.20\ \mathrm{kpc}, \quad M_2 = 8.07 \times 10^{10}\ M_\odot,$$

$$r_c = 6.0\ \mathrm{kpc}, \quad M_c = 5.0 \times 10^{10}\ M_\odot,$$

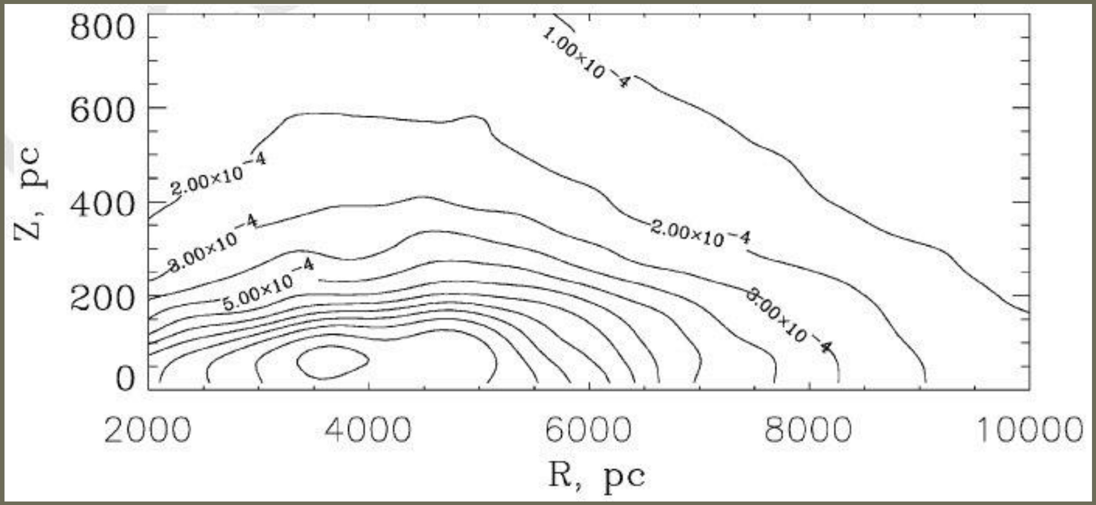
At the very center one has to add the central BH potential

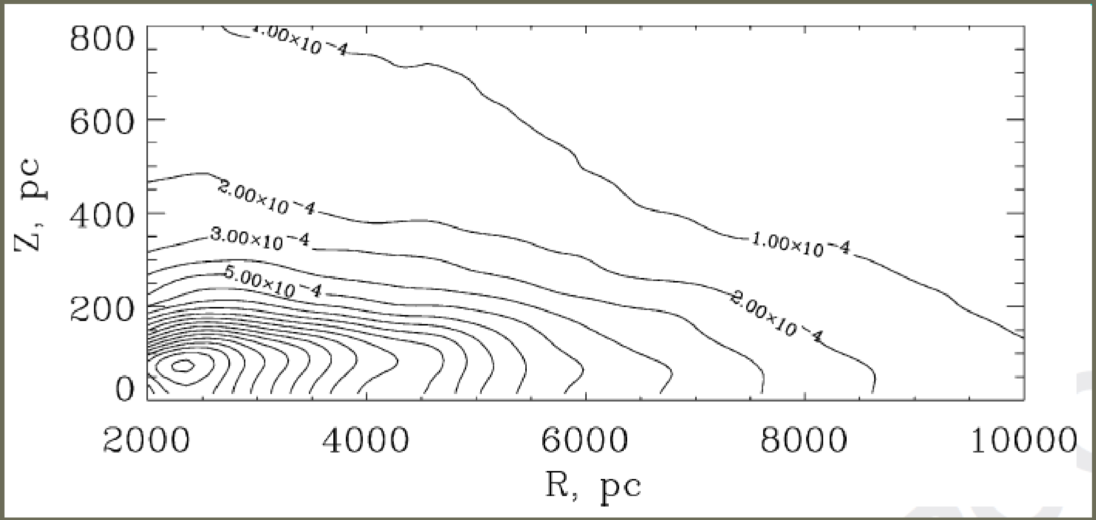
Examples of old NS distribution



0910.3684

Spatial density of NSs





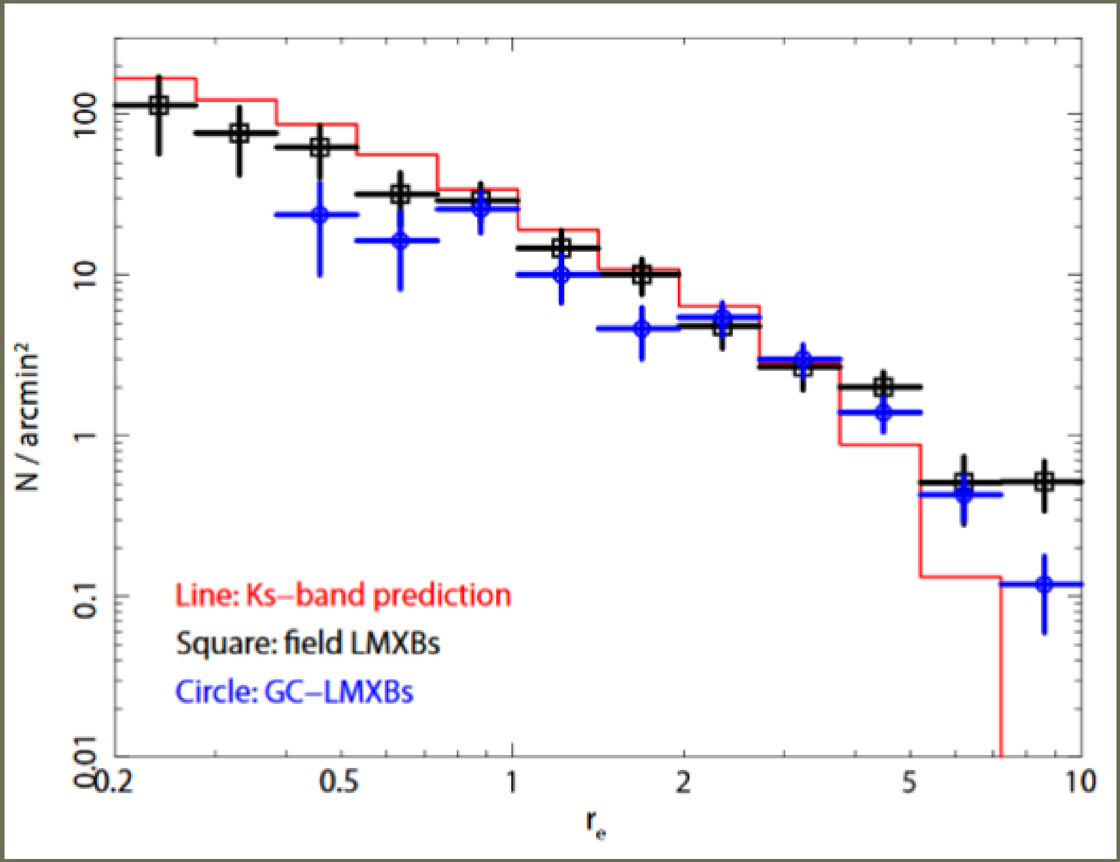
In both models $N=5\ 10^8$.
Kick: ACC02.
Potential: Paczynski 1990

NS formation rate is assumed to be proportional to the square of the ISM density at the birthplace.

Formation rate is proportional to $[\exp(-z/75\ \mathrm{pc})\ \exp(-R/4\ \mathrm{kpc})]$.

astro-ph/0305599

X-ray sources in other galaxies



X-ray sources are shifted from the stellar light distribution.
This might be due to kicks, especially in the case of NS binaries.

The effect cannot be explained by sources in globular clusters.

1211.0399

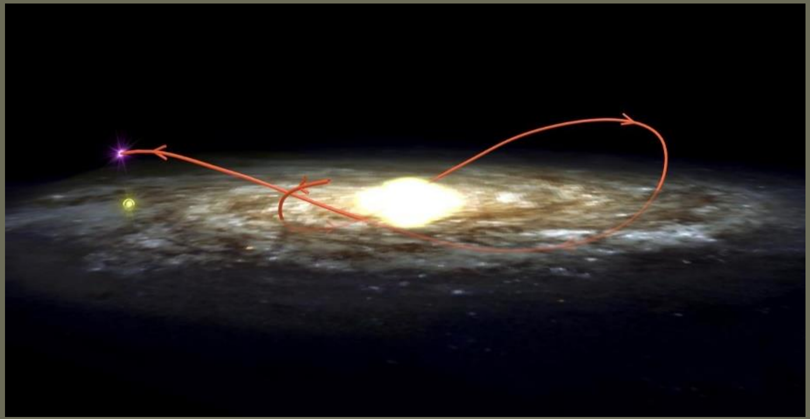
Black hole kicks

Do BHs obtain kicks?

- they are more massive
- horizon is formed
- SN mechanism can be different

If before the horizon formation a "protoNS-like" object is formed, then there should be a kick, but smaller (in km/s) due to larger mass.

We do not know isolated BHs, but we know binaries.
It is possible to measure velocity.



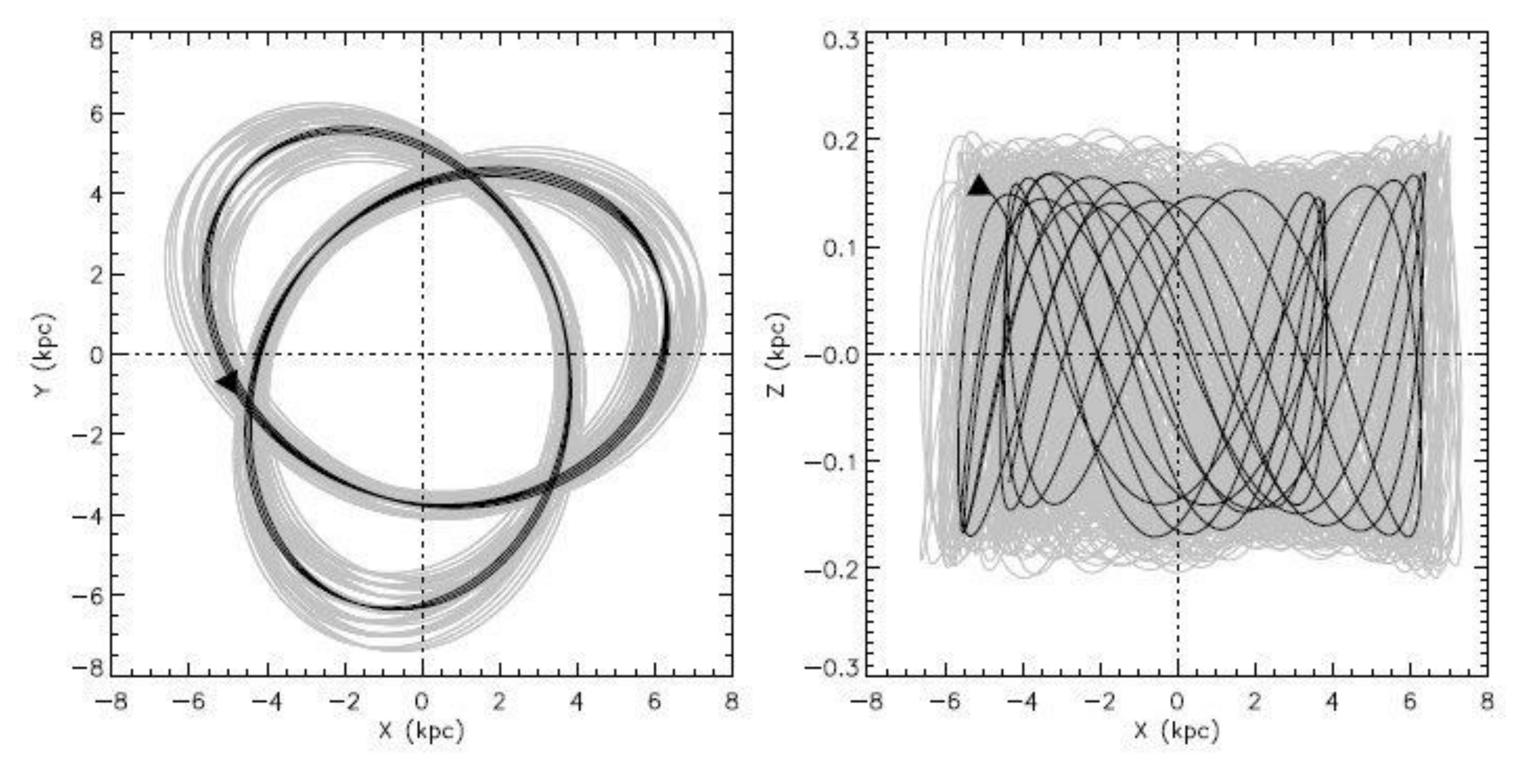
XTE J1118+480

Knowing just a velocity it is difficult to distinguish kick from dynamical interaction or initially large velocity (for example, a system can be from a globular cluster).

On the mechanism of BH kick see 1306.0007

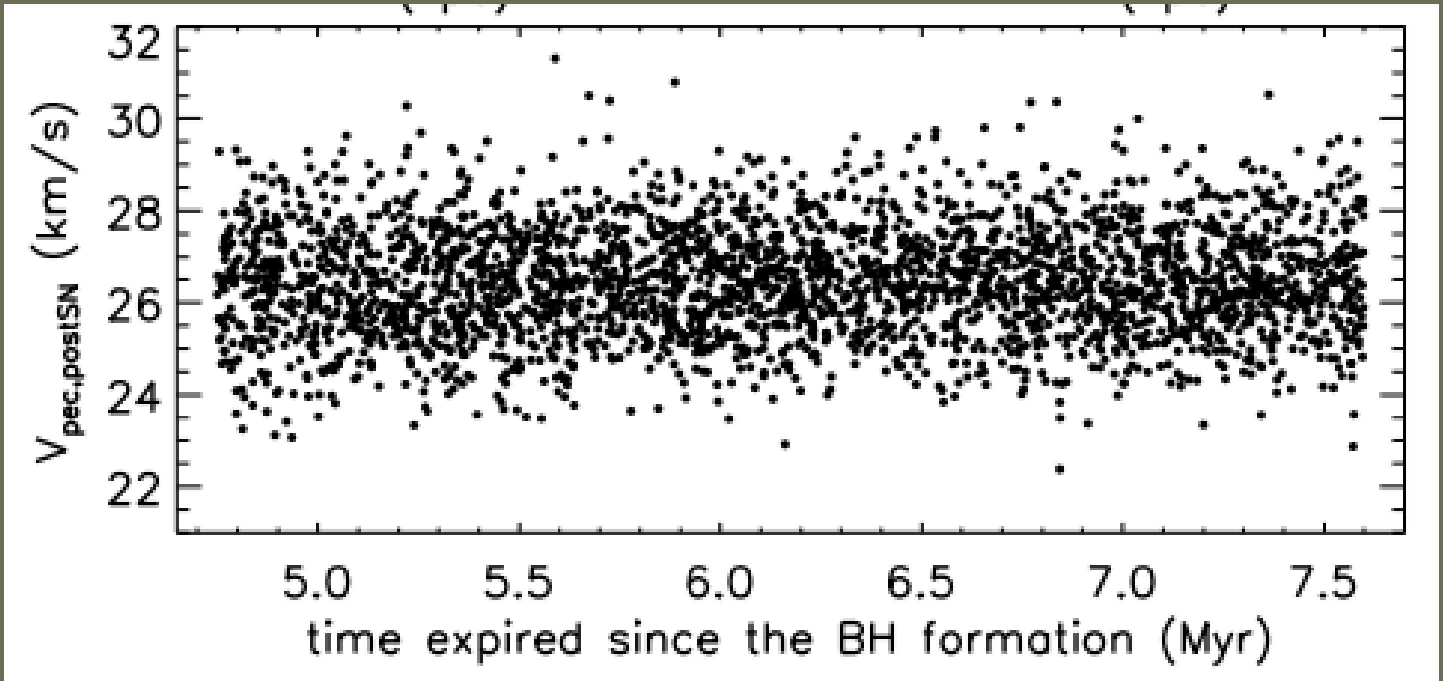
GROJ1655-40

Kick 45-115 km/s



Willems et al. (2005)

Cyg X-1

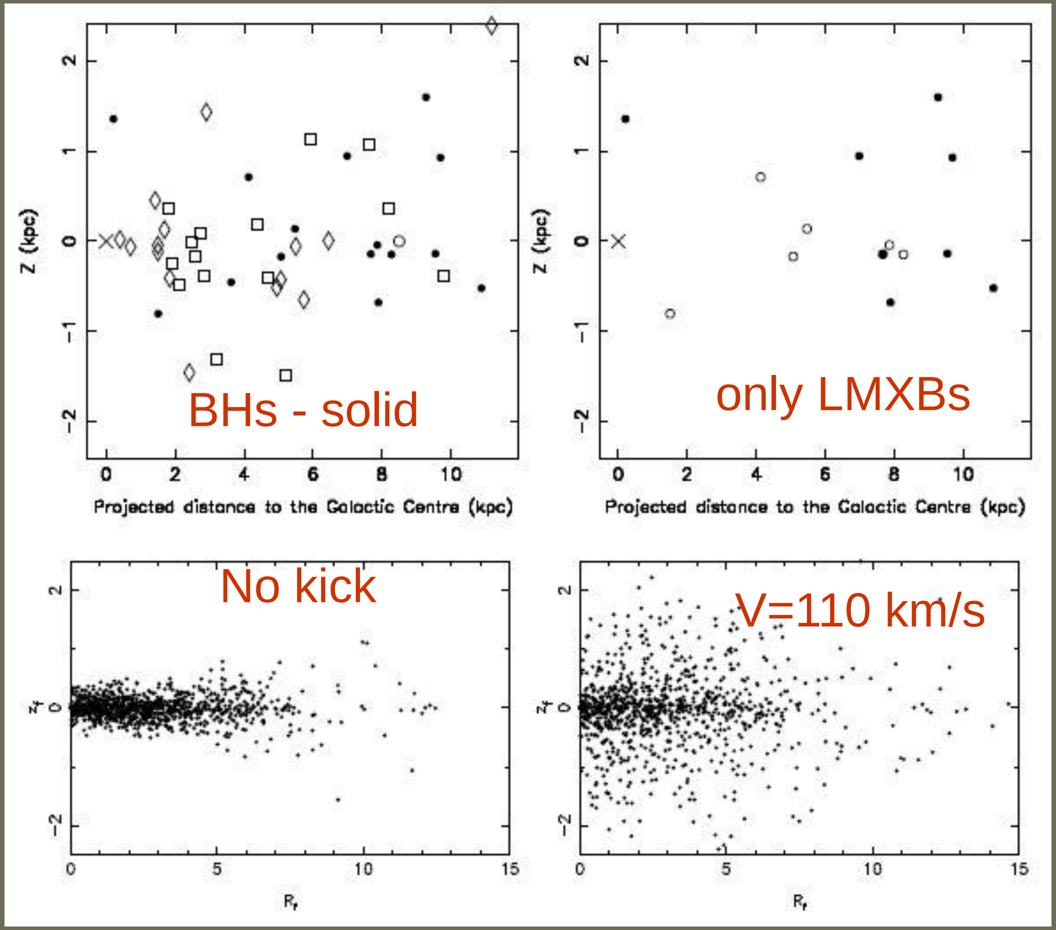


For this system the distance is known very precisely.
This allows to trace the trajectory back
and derive the value of post-SN peculiar velocity.

It is equal to 22-32 km/s.
Probably, the BH obtained a moderate kick <77 km/s.

1107.5585

BH binaries in the Galaxy



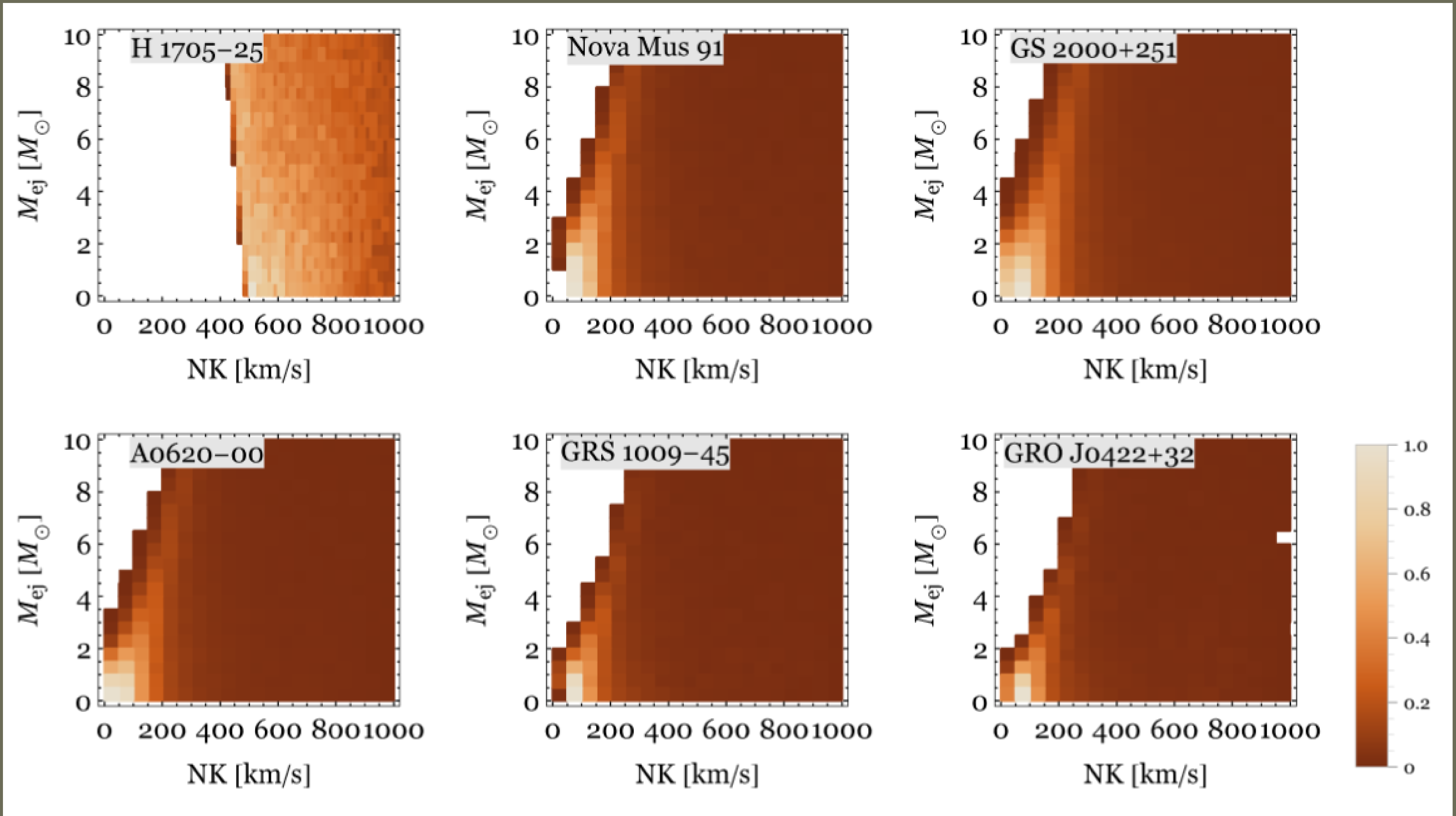
The situation is not clear when we look at the whole population:

- Distribution for BHs is similar to the one for NS (for kick)
- Modeled distribution for zero kick can explain, roughly, the spatial distribution (against large kick)

Also line-of-site velocities are not high

Nelemans (2004)

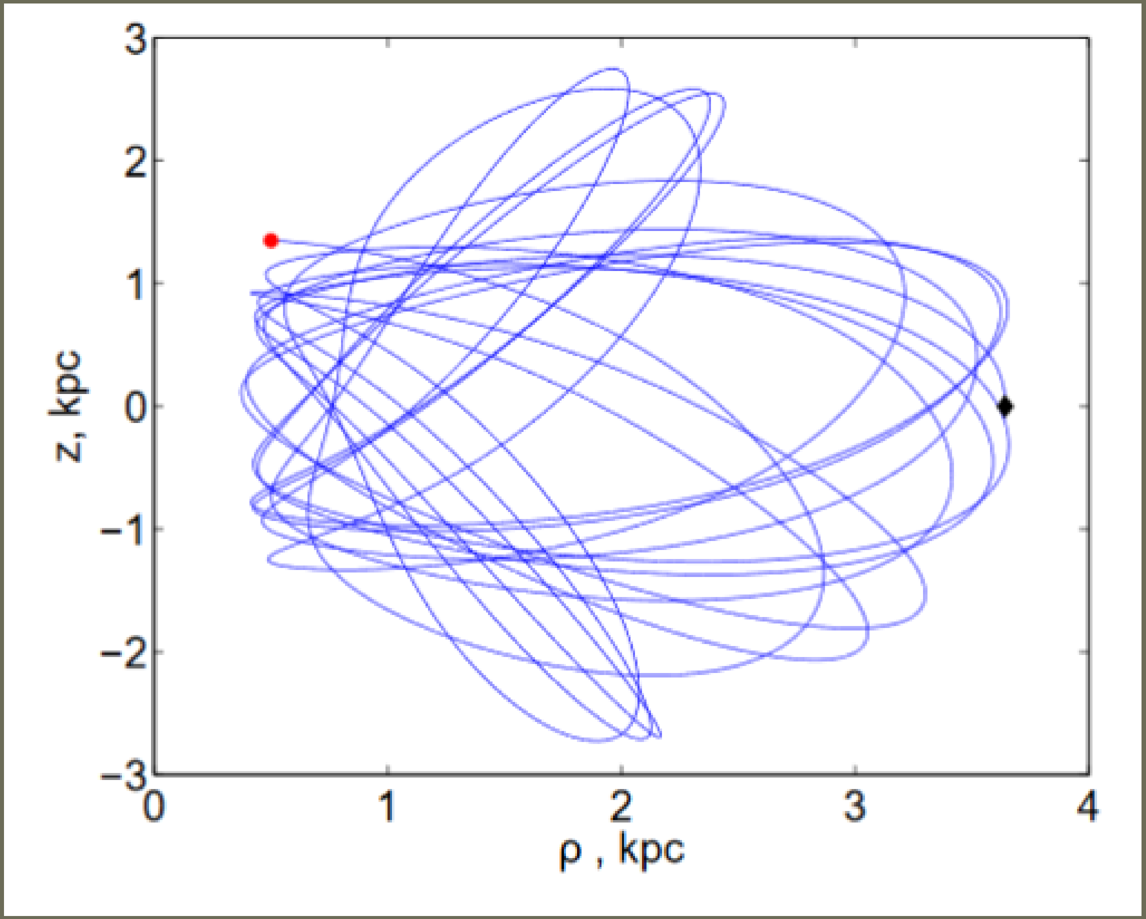
Black hole kick velocities



Some BHs receive large kicks at birth. Difficult to explain by scaling from NSs.

1507.08105

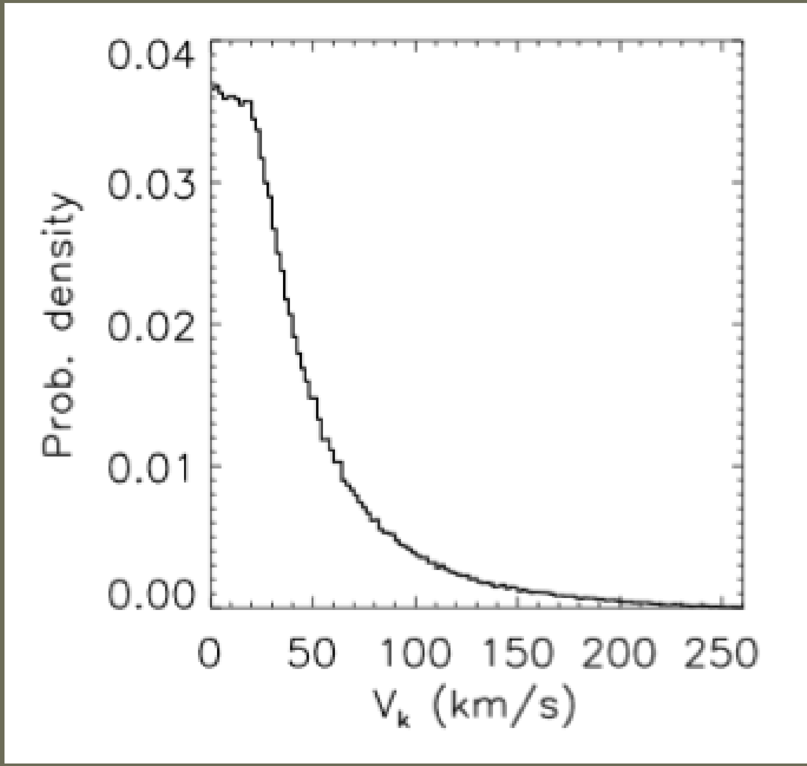
H 1705-250



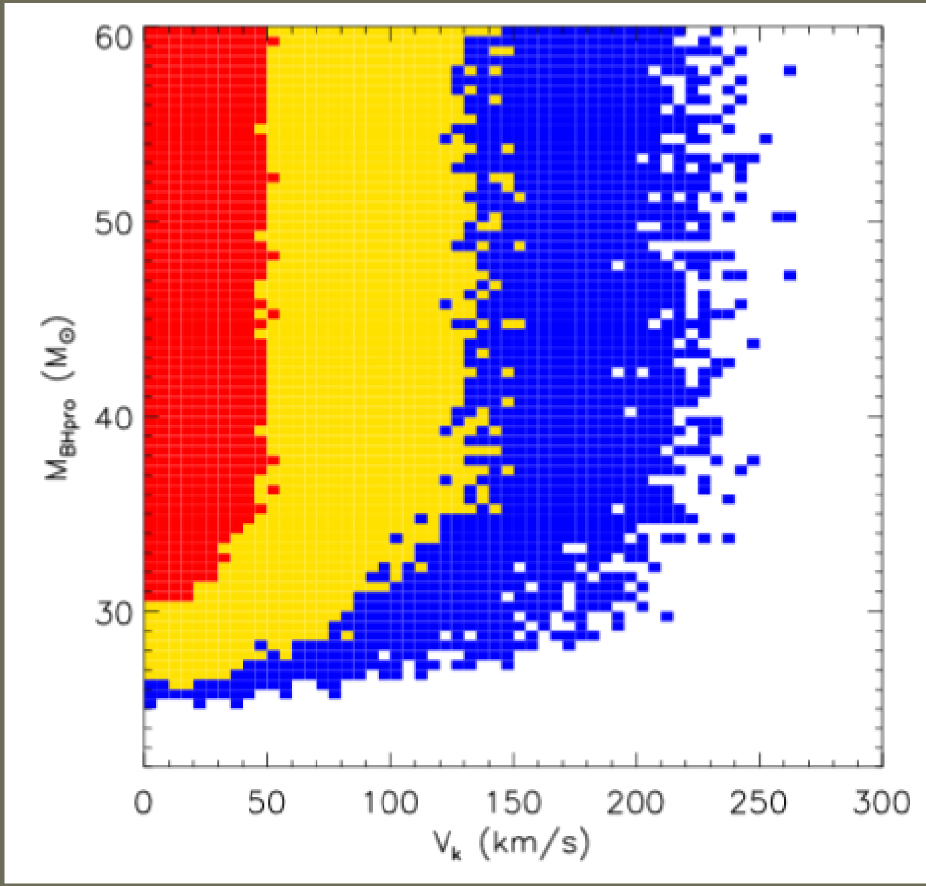
Large kick is not necessary.
~100 km/s is enough.

1510.03871

IC 10 X-1

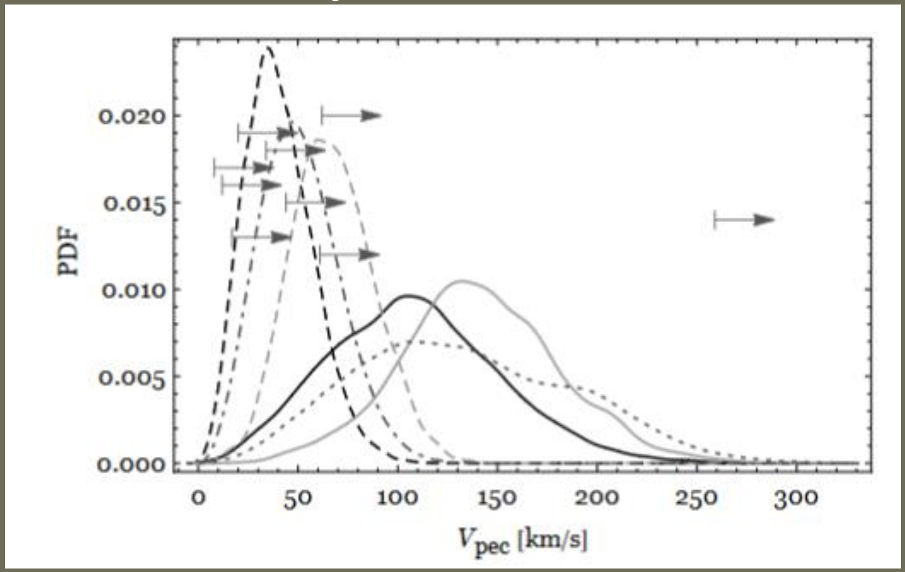


Low kick <130 km/s.



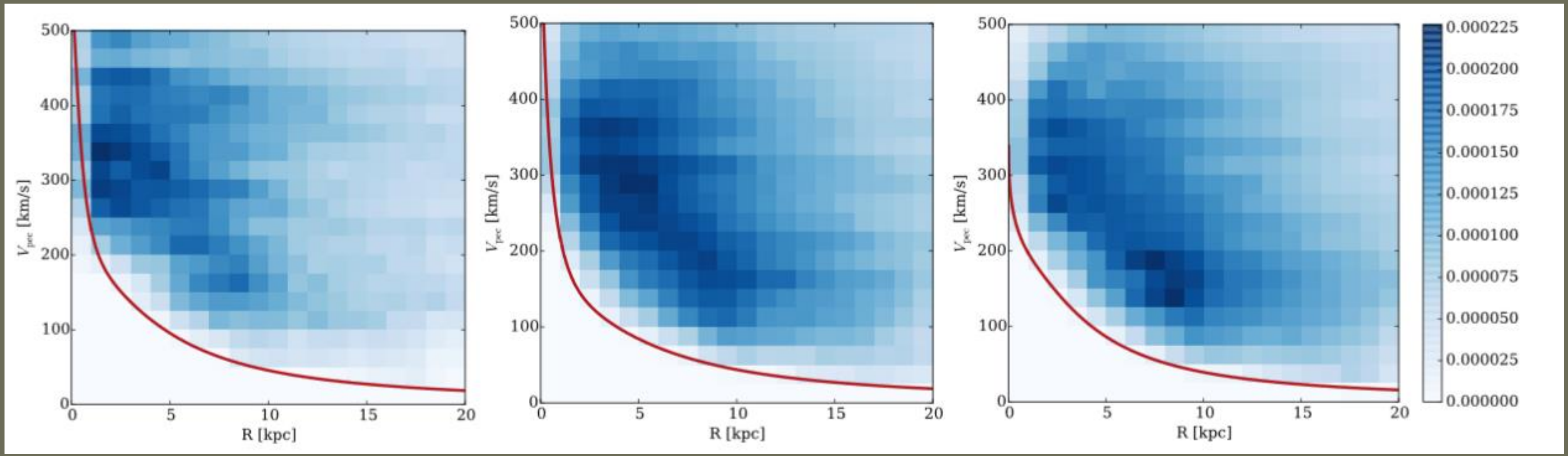
$M_{BH\ Pro}$ – progenitor mass before BH formation

Velocity of BH and NS X-ray binaries



Some BHs might obtain significant kick.

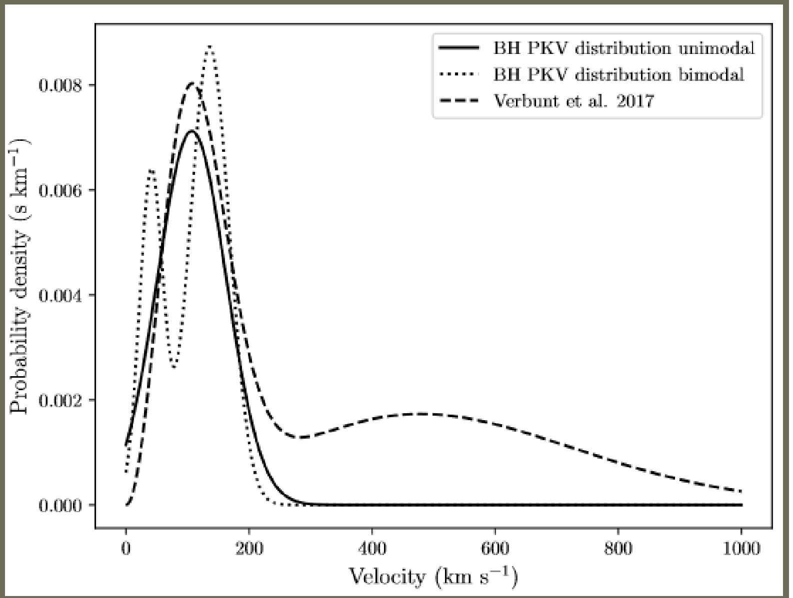
NS binaries kick distribution
is compatible with the one
derived from PSRs.

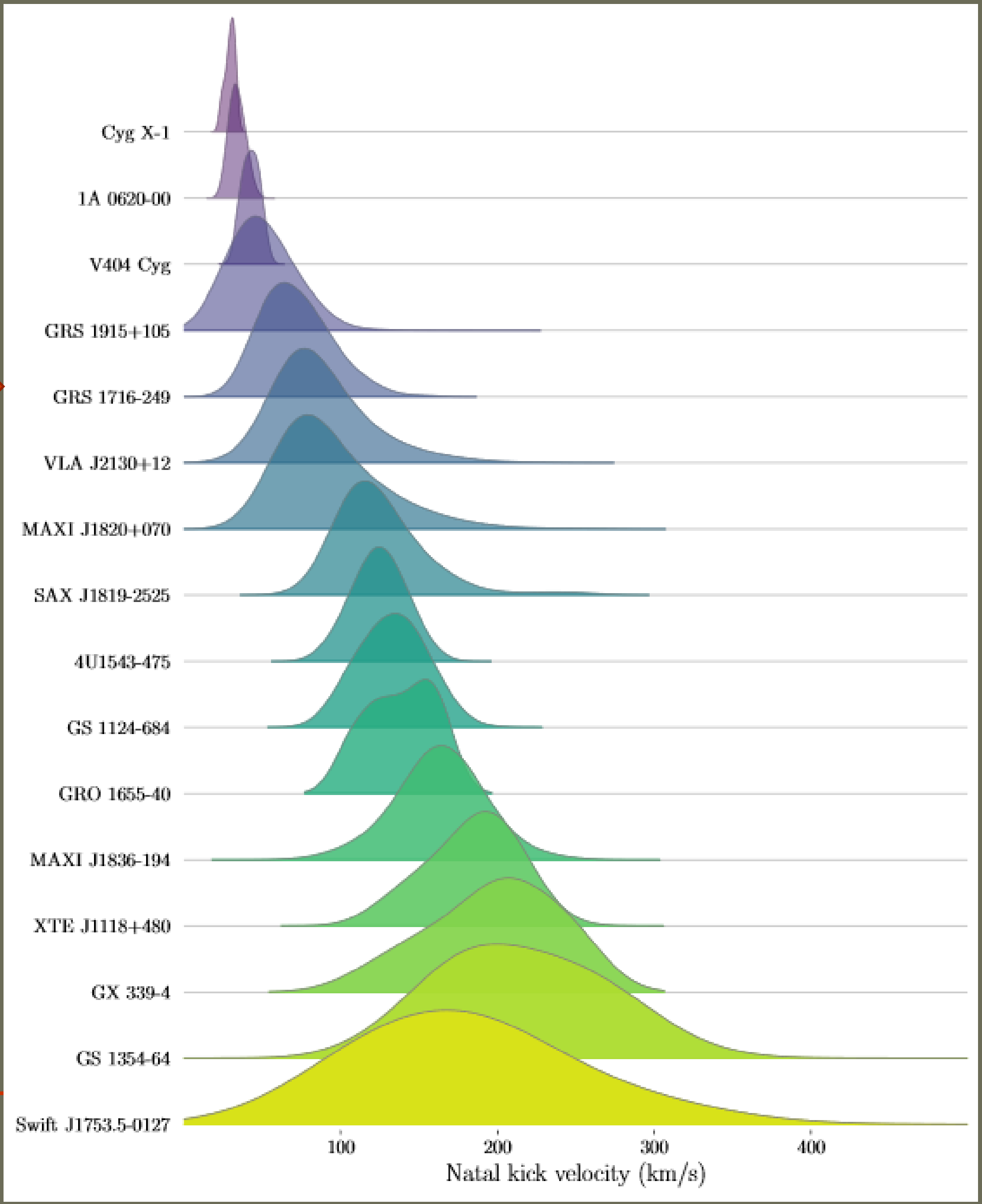


$$V_{\rm pec,min} = \sqrt{2[\Phi(R_0, z) - \Phi(R_0, 0)]},$$

1701.01347

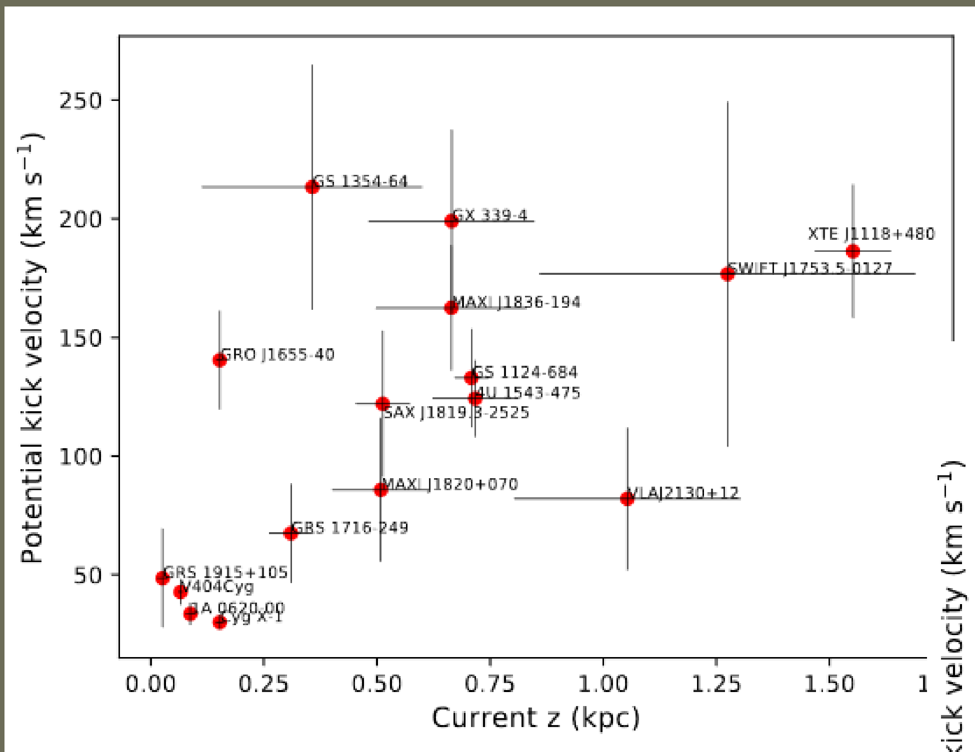
Three BHXB: VLBI+Gaia

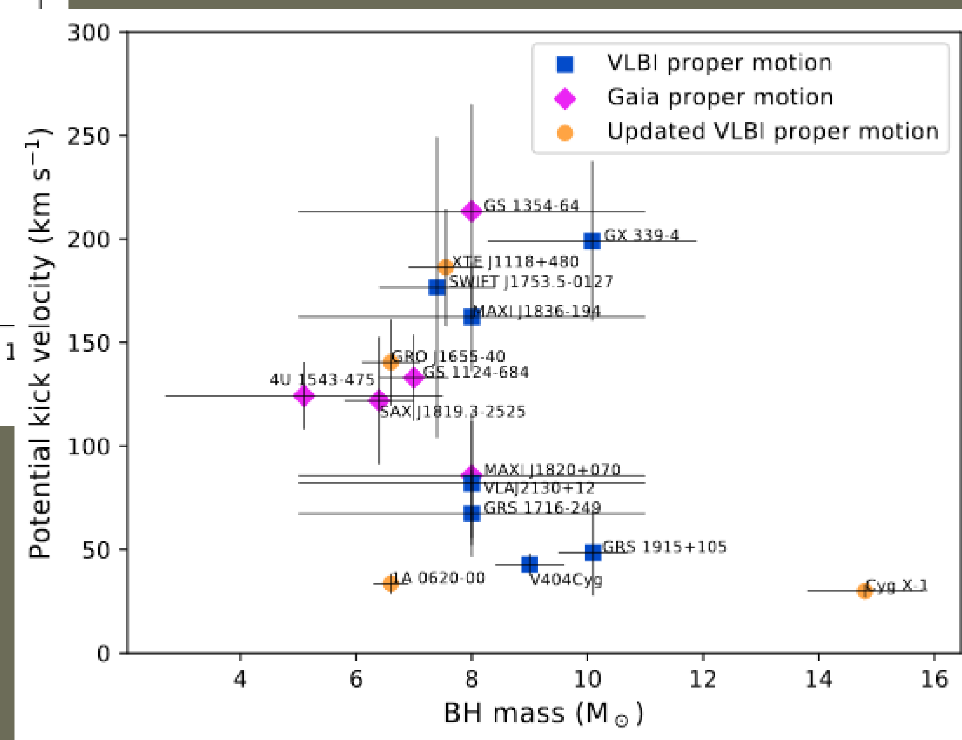




1908.07199

Mass vs. velocity

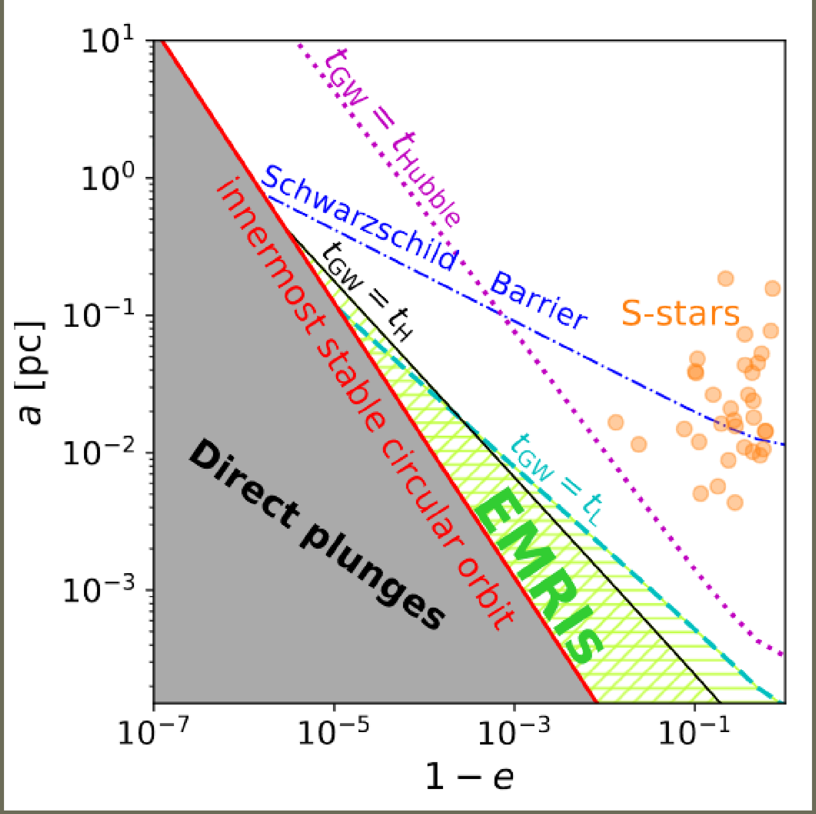




1908.07199

EMRI and compact objects kicks

Kicks received by NSs and BHs in the nuclear cluster around a SMBH can result in extreme mass ratio inspirals (EMRI).
The rate is >~10^{-8} per year per galaxy.
eLISA can detect up to tens of event per year of observations.



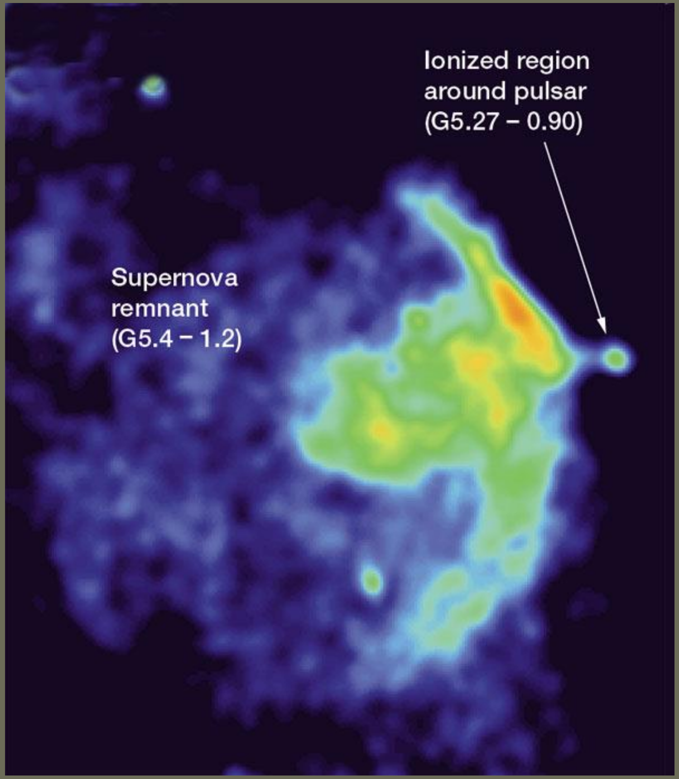
Populations with higher kick produce more SN-EMRI.

SN-EMRI contribute ~10% of all EMRI (in the case of the Milky Way).

1902.04581

Conclusions

- NSs and (most probably) BHs obtain natal kicks
- For NSs kick velocity can be as large as >1000 km/s
- The direction of the kick and rotation are correlated
- Kicks depend on the SN mechanism
- Kicks influence parameters of binaries
- Kicks influence evolution of isolated NSs



Important papers

- Lai astro-ph/0212140– different kick mechanisms
- ATNF catalogue – database including PSR transversal velocities
- Ng & Romani, ApJ 660, 1357 (2007) – spin-velocity alignment in PSRs with nebulae
- Johnston et al. MNRAS 381, 1625 (2007) and Rankin ApJ 664, 443 (2007) – spin-velocity alignment in dozens of radio pulsars (polarization)
- Postnov, Yungelson astro-ph/0701059 – kicks in binaries (pp.18-23)
- Ofek et al. NS spatial distribution. arXiv: 0910.3684

Kick modeling

Recently, new results on the origin of NS and BH kicks have been obtained:

- Neutrino-triggered asymmetric magnetorotational mechanism arXiv:1110.1041
- Hydrodynamic Origin of Neutron Star Kicks arXiv: 1112.3342
- Three-dimensional neutrino-driven supernovae arXiv:1210.8148
- BH kicks arXiv:1203.3077

A review on SNae properties and explosion mechanisms: arXiv:1210.4921