Pulsar Kicks and Proper Motions

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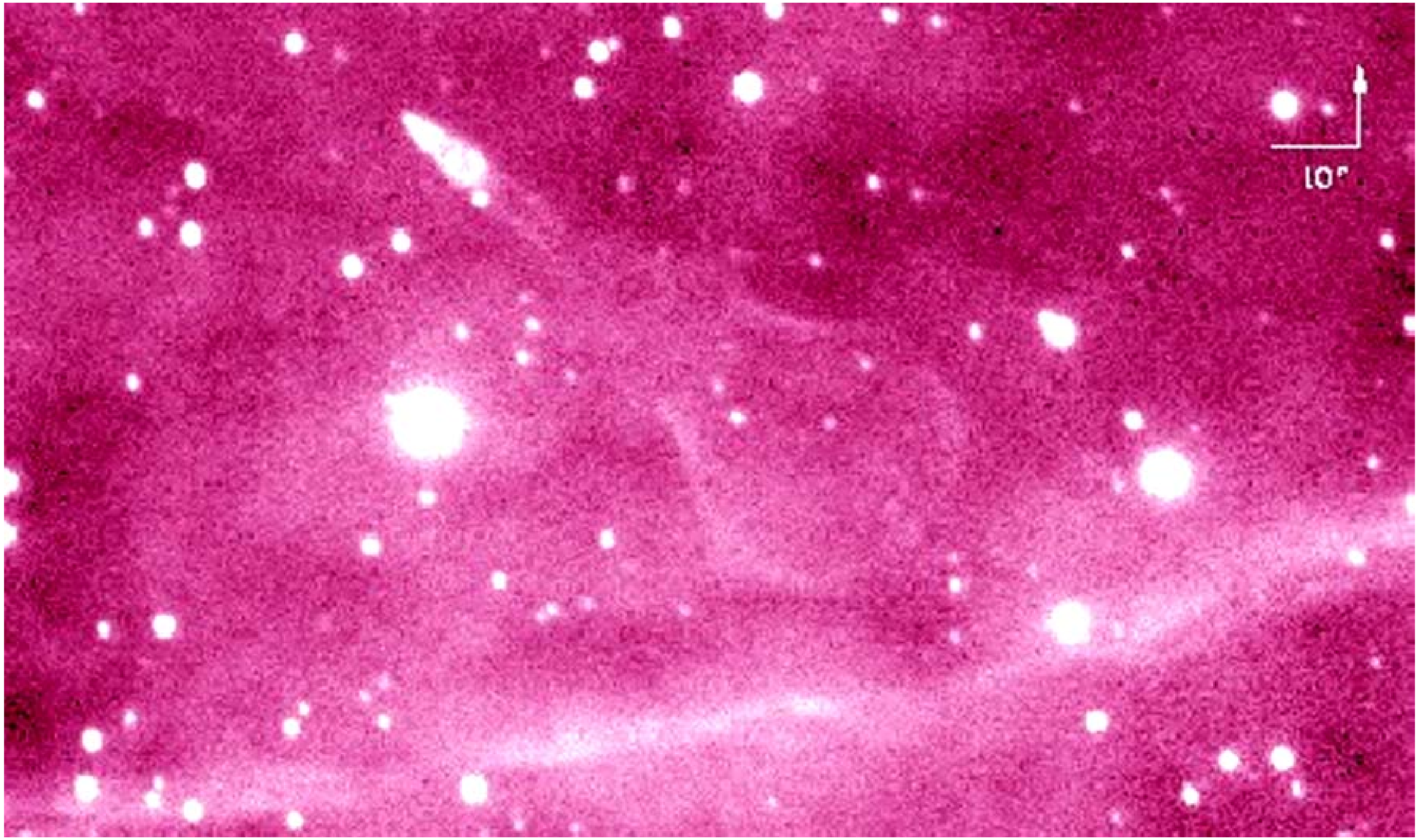
OUTLINE

- Evidences of pulsar kick.
- History of observational measurement of pulsar velocities.
- Theoretical model to explain pulsar kick

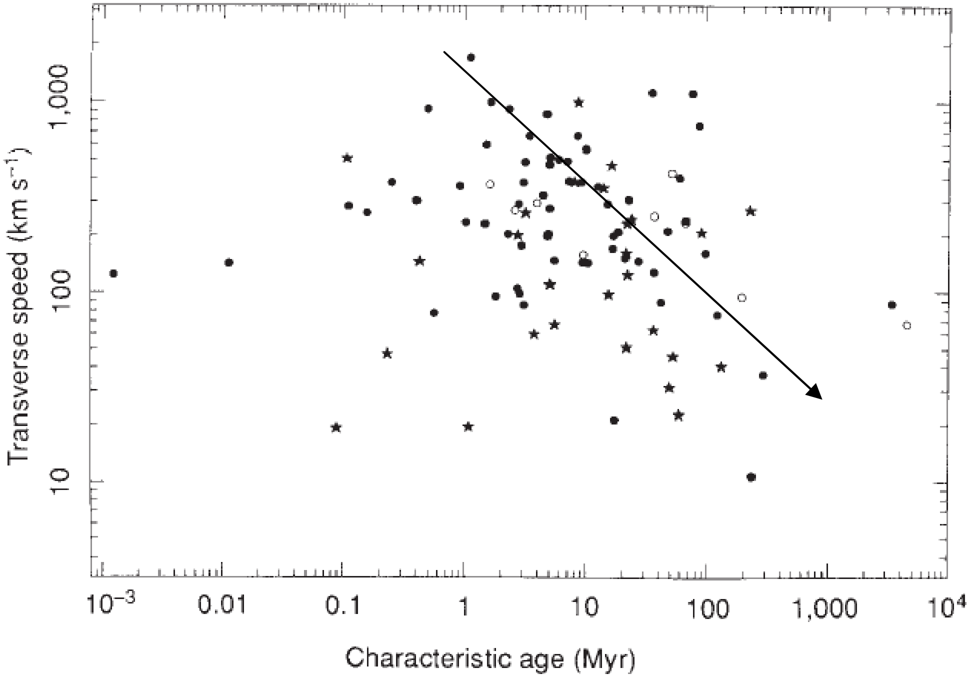
Evidences of Pulsar Kick



- Guitar nebula: Proper motion ~0.175 arcsec/yr, Distance ~2kpc
- Transverse speed: ~1600km/s

Evidences of Pulsar Kick (Lyne & Lorimer 1994)

- Proper motion measurements.
- Mean V_{tran}=300 km/s
- Monte Carlo simulation gives birth 3D space velocity ~450 km/s
- Major reasons for a higher V than previous results:

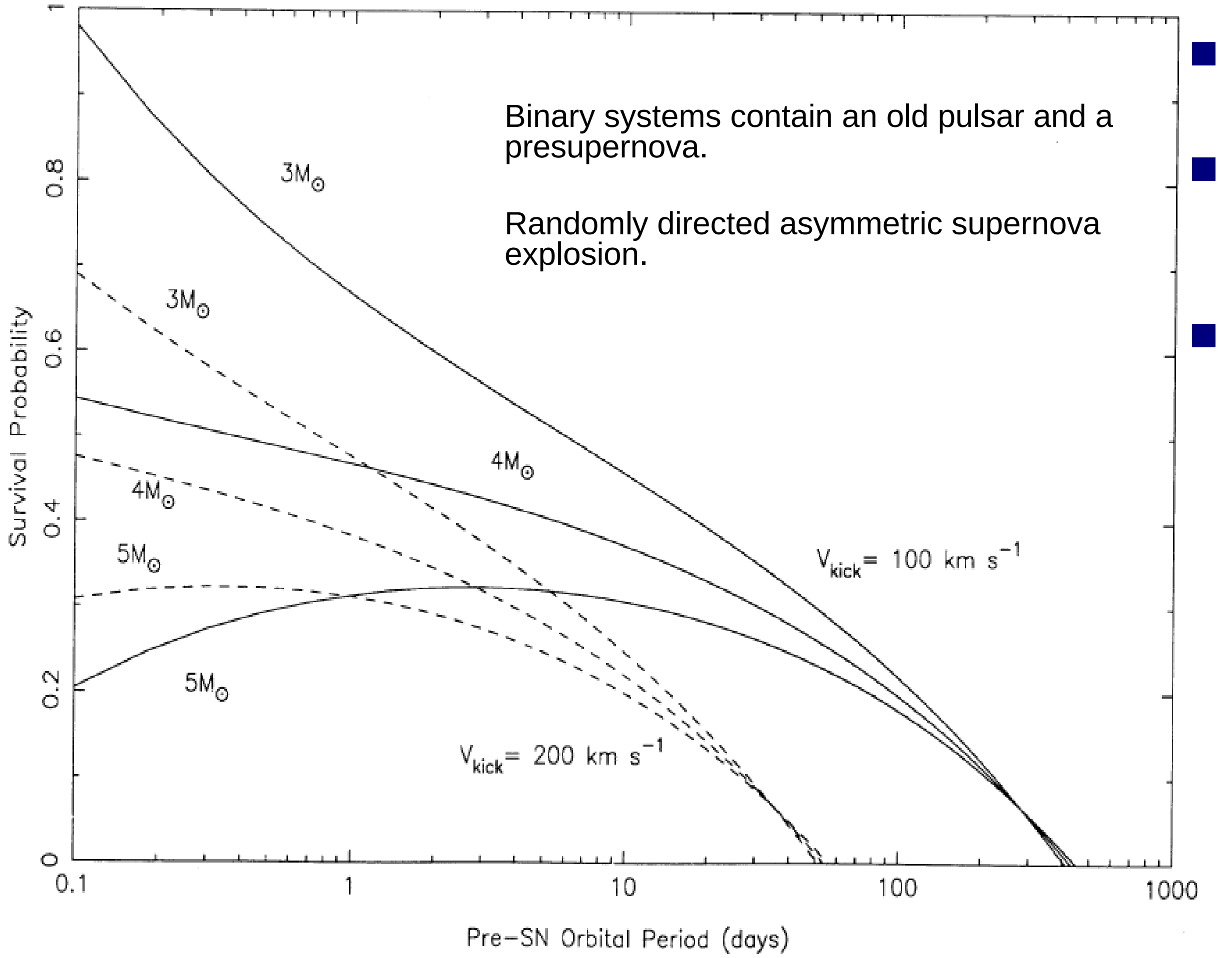


Selection effect

- 29 pulsars with age<3Myr: mean V_{tran}=345 km/s
- 10 oldest pulsars: mean V_{tran}=105 km/s

Evidences of Pulsar Kick

Bailes 1989, Dewey & Cordes 1987



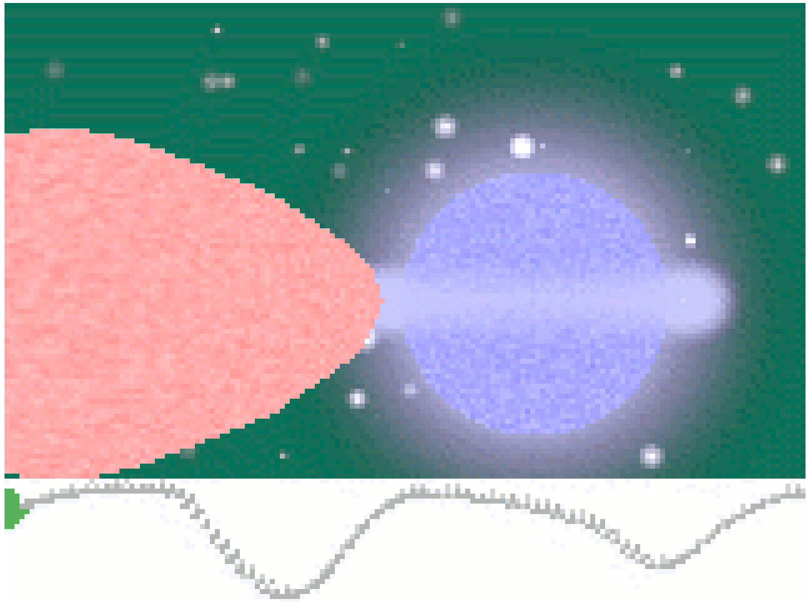
Binary systems contain an old pulsar and a presupernova.

Randomly directed asymmetric supernova explosion.

Generally, Kick V increases, survival probability decreases

- ~2% known pulsars are in binary system.
- ~50% (or higher) progenitors (OB) are in binary system.
- All population evolution models with symmetric supernovae produce birth rates some 1 or 2 orders of magnitude larger than observed value whereas simulations which include kicks of a few hundred km s~1 produce the correct birth rates (Spreeuw & Portegies Zwart 1995; Lipunov et al. 1996).

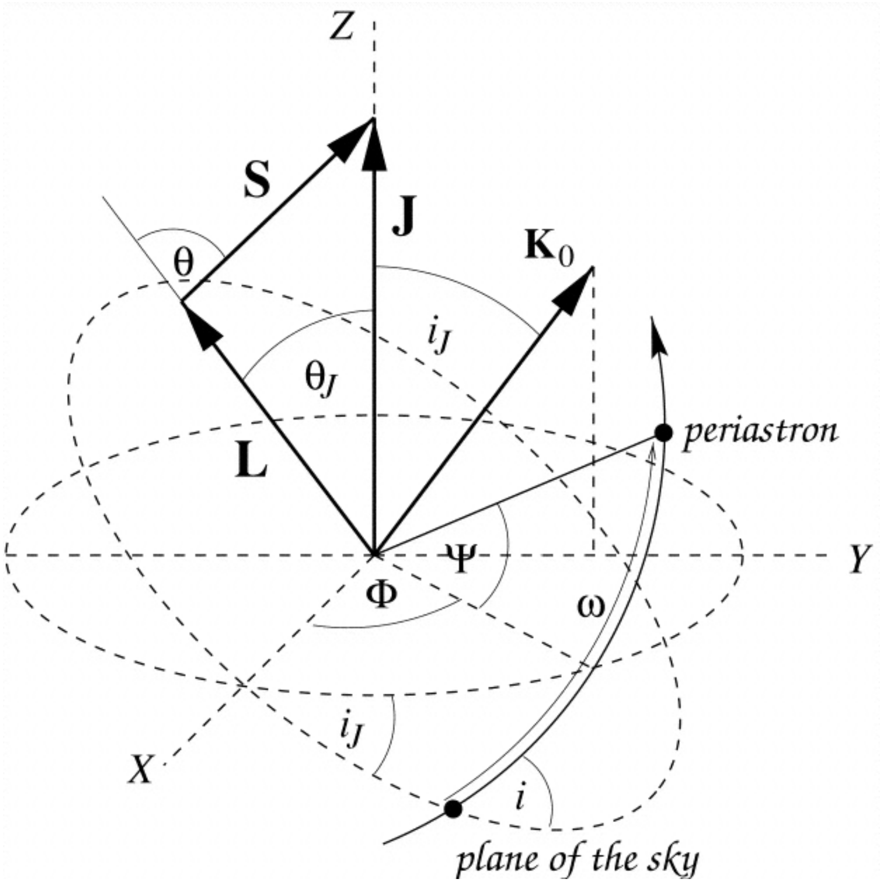
Evidences of Pulsar Kick



- Observed orbital e of X-Ray binaries with a NS and a normal companion is always high (0.3-0.9)
- Before SN: Large-scale mass accretion from the presupernova onto its companion have tidally circularized the orbits of the systems, e.g., initially e~0
- A symmetric SN explosion can only raise e to ~0.15. Asymmetric kick is required. (van den Heuvel 1994)
- Cir X-1: P: 16.6d; e: 0.94; radial velocity: 470 km/s (Johnston et al. 1999)
- A kick velocity of 740 km/s is needed to reproduce the system by simulations (Tauris et al. 1999).

Evidences of Pulsar Kick

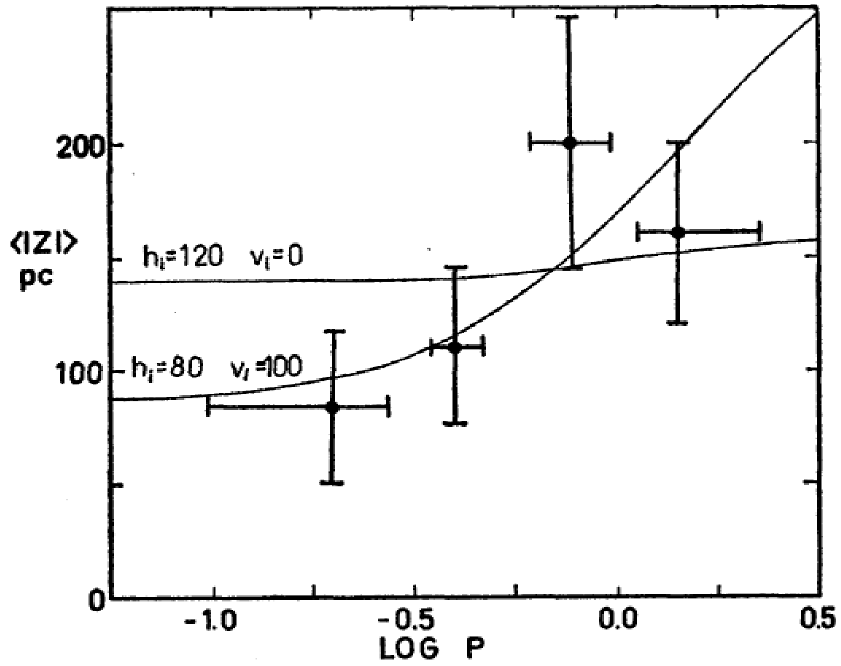
van den Heuvel & van Paradijs 1997



- Nonalignment of Spin and Orbit in PSR J0045 7319: a neutron star is in orbit around a B star.
- The large amount of mass accretion that the B star received from its companion before SN explosion must caused its rotation axis to have been aligned with the normal on the orbital plane.
- A kick at least 100 km/s is require to misalign the spin and the orbit

First Indication of Birth Velocity

Gunn & Ostriker 1970



The average pulsar may at birth acquire a rather large V. The young pulsars are close to the plane where they were born. When their age increases, their initial velocity carries them further and further from the plane.

- |Z|: the distance from the plane of the galaxy
- P: the period of the pulsars. (P increases with age)
- Four bins with approximately equal population

Measurement of Velocity

1. Angular proper motion measurements:

$$V_{pm} = 4.74 \frac{\mu}{mas/yr} \frac{D}{kpc} \quad km/s$$

   Accurate, but requires a long series of precise

   observations using a high-resolution radio interferometers.

2. Measure the pulsar velocity from the speed of the interstellar scintillation pattern as it moves across the Earth. (Lyne & Smith 1982)

$$V_{iss} = 4.8 \times 10^4 \sqrt{\frac{\Delta f}{MHz} \frac{D}{kpc}} (\frac{\tau}{s})^{-1} \quad km/s$$

   Single telescope, short time measurement, but based on assumptions of ISM

History of Pulsar Velocity Measurement

Lyne et al. 1982

- Observations of the proper motion of 26 pulsars, based on radio interferometry.
- rms transverse velocity $<v_t^2>^{1/2}$=170 km/s
- Mean transverse velocity $<v_t>$=134 km/s
- Assuming the velocity distribution is isotropic:

  $<v^2>^{1/2} = <1.5 v_t^2>^{1/2}$=208 km/s
- Consider the gravitational acceleration, the birth velocities will be typically 10-20% greater than the observed velocities now.

Notice: for Maxwellian distribution: $\frac{< v_t^2 >^{1/2}}{< v_t >} = \frac{2^{1/2}\sigma}{(\pi/2)^{1/2}\sigma} = 1.13$

The observational value: $\frac{< v_t^2 >^{1/2}}{< v_t >} = 1.27$

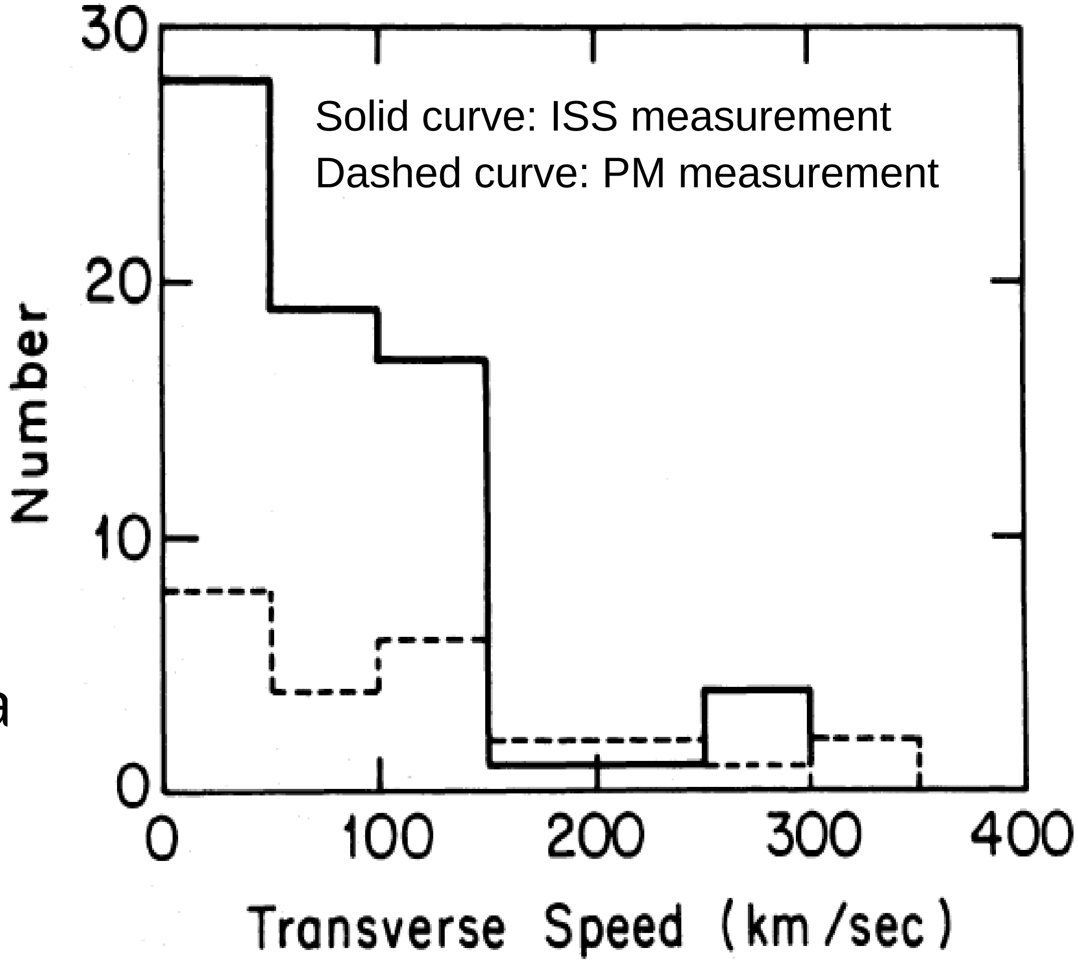
Not Maxwellian (confirmed by later observations)

History of Pulsar Velocity Measurement

Cordes 1986

- 71 pulsars
- Based on interstellar scintillations.
- Average V_{tran}: ~100 km/s
- 3D space V: ~160 km/s

- The observations overestimate the number of low-V objects since high-V ones spend only a small fraction of their radio lifetime at a detectable distance



- Later found to be systematically low by a factor of ~2 (Harrison & Lyne 1993), due to a concentration of scattering material close to the galactic place.

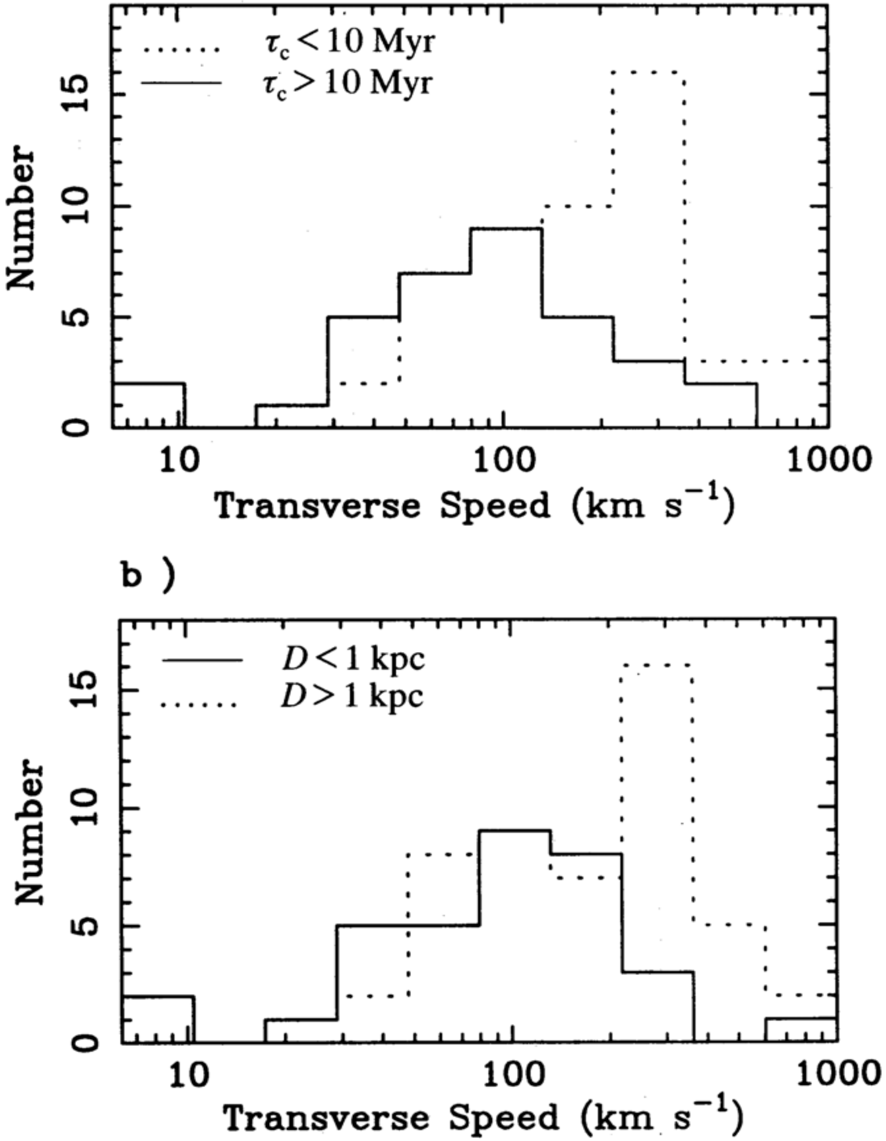
History of Pulsar Velocity Measurement

Harrison & Lyne 1993

- Proper motion measurement. (similar to Lyne et al, 1982.)
- 3D space velocity: mean ~ 220 km/s rms ~ 300 km/s
- Correlation: the younger and the more distant ones have the greater velocities.

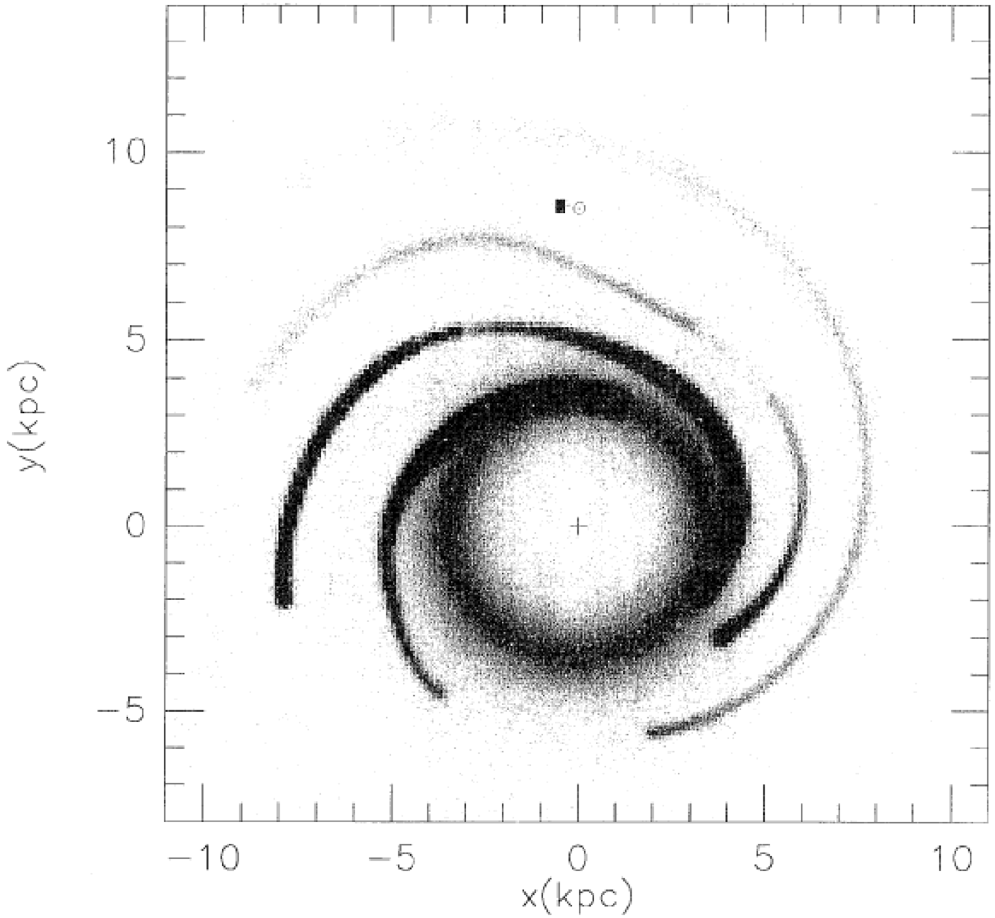
The reasons that these previous results are systematic lower than the later results:

1. Younger sample
3. Selection effect
2. New pulsar distance model (Taylor & Cordes 1993)



History of Pulsar Velocity Measurement

- A new model for the distribution of free electrons in the Galaxy (Taylor & Cordes 1993), largely improves the distances estimation.
- Abandon the previous assumption of an axsymmetric Galaxy model. Instead, take into account the structure of arms and other structures.
- Previous models underestimate the pulsar distance by a factor of 1.5-2. ➔ The same for the pulsar velocity.

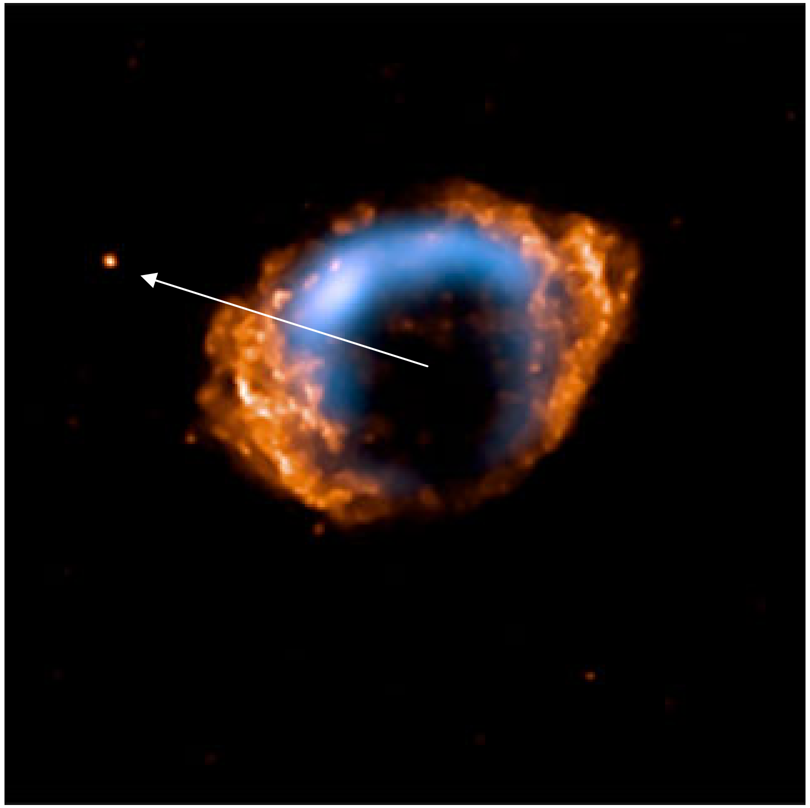


Free electron density in the galactic plane

History of Pulsar Velocity Measurement

Caraveo 1993

- A sample of 11 pulsar-SNR associations (based on age, distance, and spatial coincidence), 10 of them are the 10 youngest pulsars!).
- Pulsar velocity. ($v=D/t_{age}$)
- 4 V ~> 1000 km/s, the highest one > 1700 km/s
- The reliability of the result depends on the correct association between pulsars and SNR.



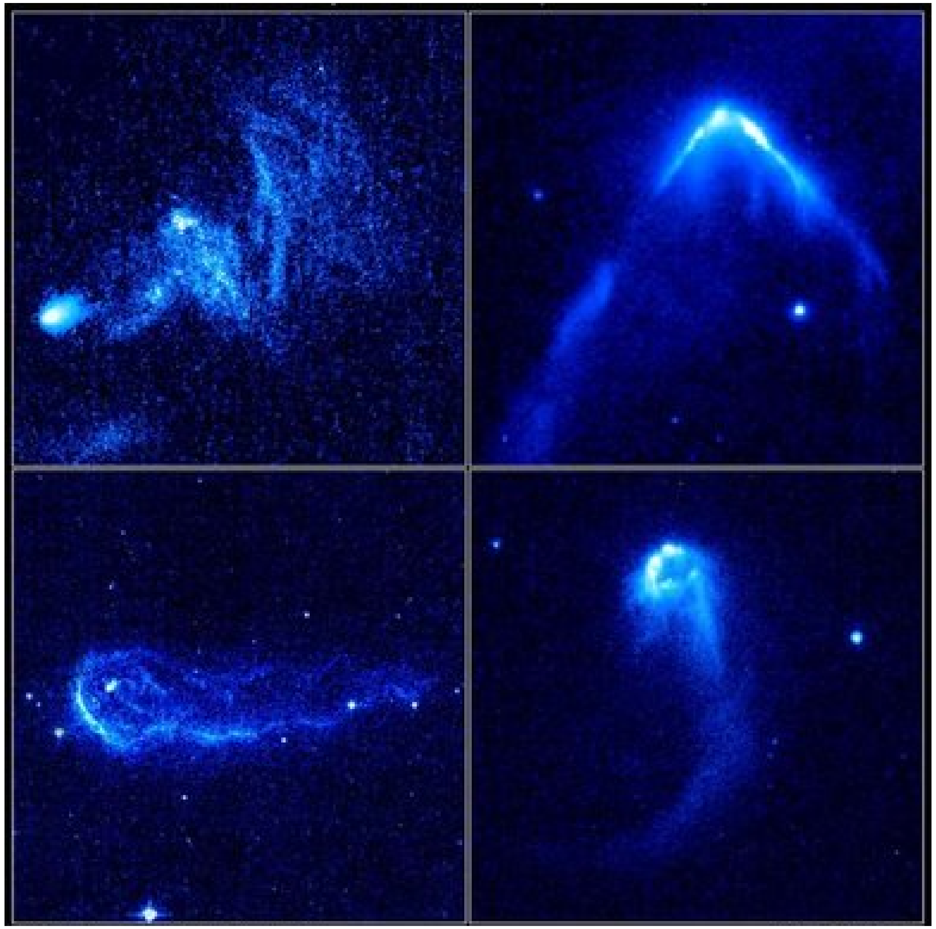
Summary of Observation History

- ~100 km/s: interpretation of vertical distribution of pulsars with different ages. (Gunn & Ostriker 1970)
- ~210 km/s: rms space velocities extracted from measurement of proper motion. (Lyne et al. 1982)
- ~160 km/s: rms space velocities from interstellar scintillations. (Cordes 1986) (systematically low by a factor of 2: Harrison & Lyne 1993)
- ~300 km/s: rms space velocities extracted from measurement of proper motion. (Harrison et al. 1993, larger V due to more young pulsars.)
- ~450 km/s: mean pulsar birth V. (Lyne & Lorimer 1994)
- ~690 km/s: Pulsar-SNR association. 4 out of 11 gives V >~1000 km/s (Caraveo 1993)

Mechanisms to Explain the Observed High Velocity

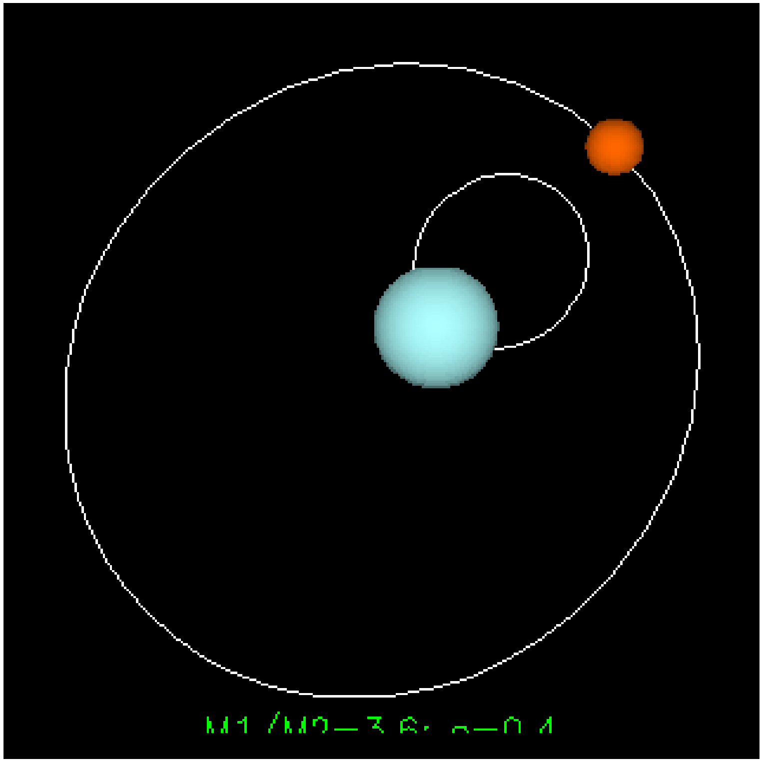
High Velocity Progenitors

- For progenitors with intrinsic high velocities (runaway progenitors), a symmetric explosion will leave the new-born NS a high velocity (inherit from its progenitors).
- Only 20% O and 2% B (the progenitors of the pulsars) are runaway stars (with V>40 km/s), and vary rare to have V>200 km/s.
- Failed to explain the observed faction of high velocity and the highest velocities.



Mechanisms to Explain the Observed High Velocity

Disruption of Binary Systems



- Sufficient and impulsive mass loss (supernova) of one component of a binary pair➔ Disruption of the system ➔ Components (nascent NSs) leave with nearly orbital velocity. (Gott et al. 1970)

- Failed to explain the observed velocity distribution with the requisite mean and dispersion (Iben & Tutukov 1996).

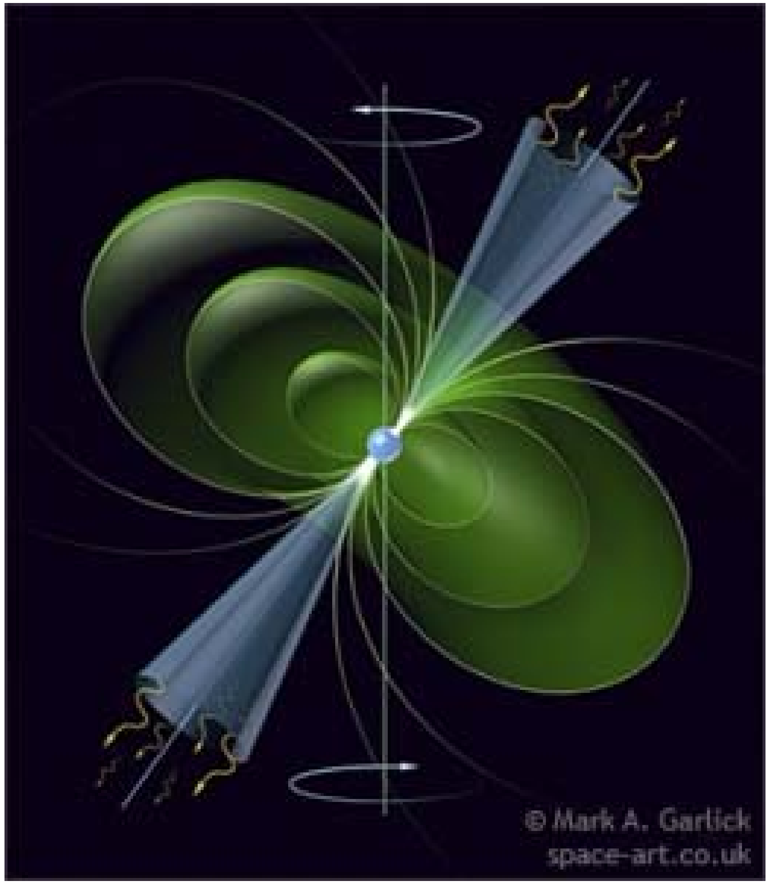
Mechanisms to Explain the Observed High Velocity

Radiative Acceleration

- Pulsars are accelerated to their present velocities after they are born, due to asymmetric radiation field. (Harrison & Tademaru 1975)

- The force due to asymmetric radiation field can be initially extremely large, and diminishes rapidly.

- Should have the spin axis aligned with the velocity vector (Morris et al. 1976), but not confirmed by observations (Anderson & Lyne 1983).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Mechanisms to Explain the Observed High Velocity

Asymmetric Explosion: Approximate Scale Relations (Burrows et al. 2007)

Recoil force= $(\sin\alpha)v\frac{dM_e}{dt}$

$\sin\alpha$ average “anisotropy parameter” (would be 0 for isotropic explosion).

V: the characteristic wind velocity.

dM_e/dt is the wind mass-loss rate.

Recoil (kick) velocity v_k is $v_k = \frac{2E\sin\alpha}{M_{ns}v}$

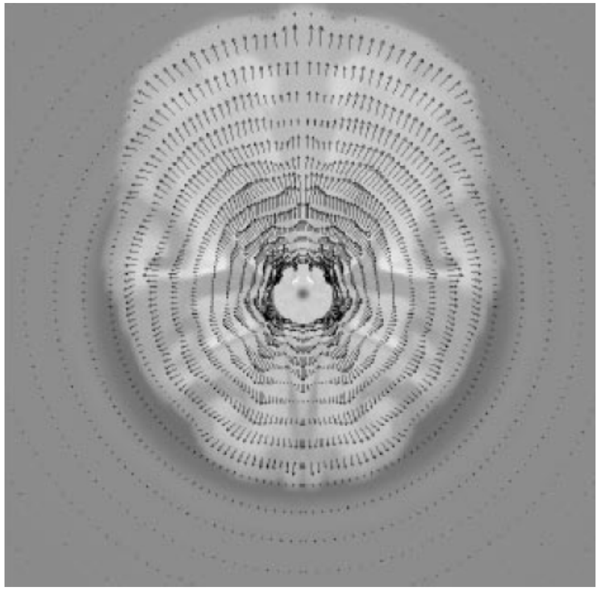
M_{pn}: residue mass. E: explosion energy

Assume the scale of v is set by a sound speed (~30,000-100,000 km/s)

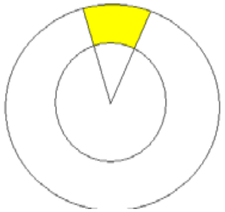
$$v_k = 1000\frac{E}{10^{51}ergs}\sin\alpha \quad km/s$$

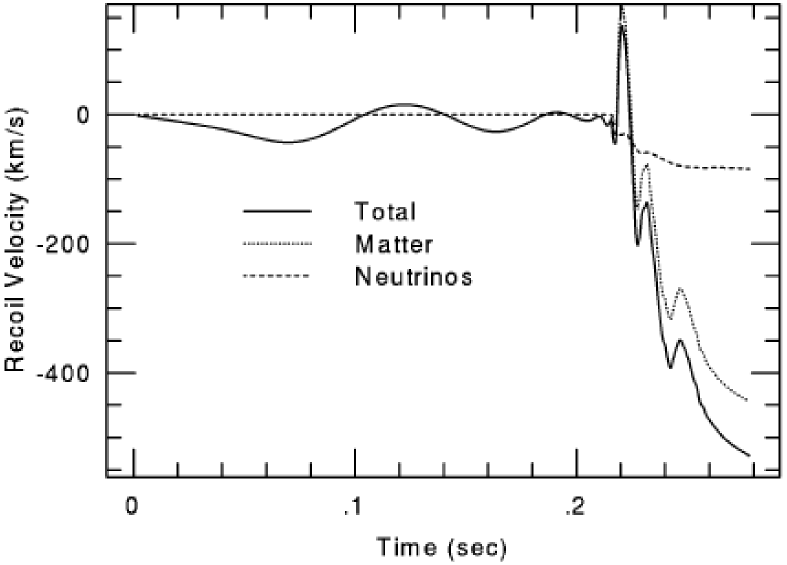
Simulations of Asymmetric Explosion

Burrows & Hayes 1996



Initial conditions: artificially introduces a density dipole anisotropy < 0.1%





- Entropy distribution at ~50 ms into the explosion
- The explosion erupted preferentially in the direction of the wedge -- the least resistance direction. The initial asymmetry ➔ Asymmetric explosion

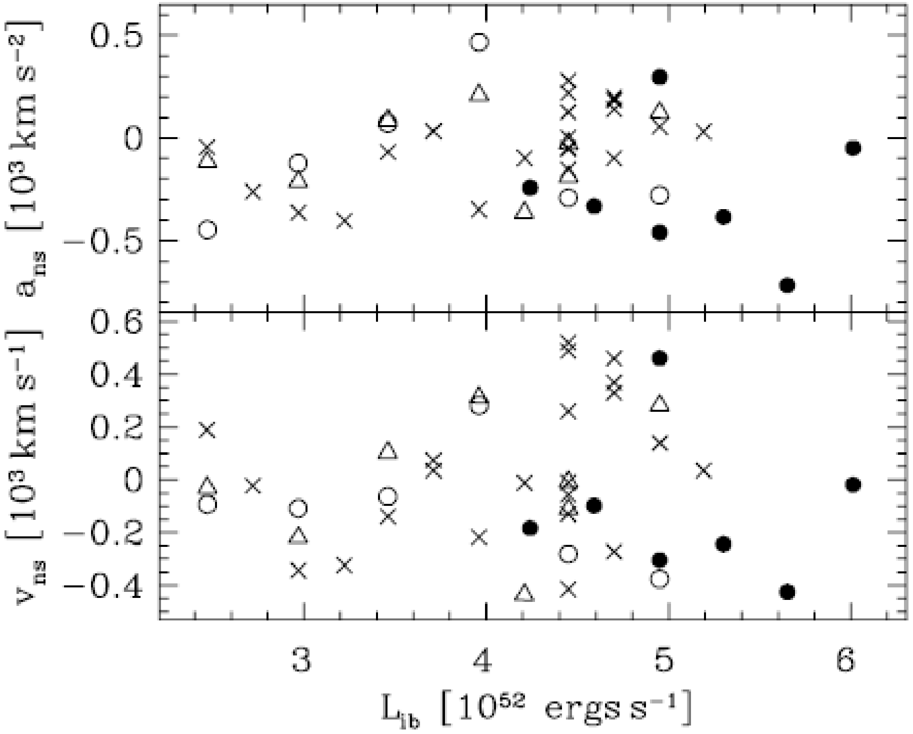
- Recoil speed (km/s) vs time
- Minus in sign indicates the opposite direction of the wedge

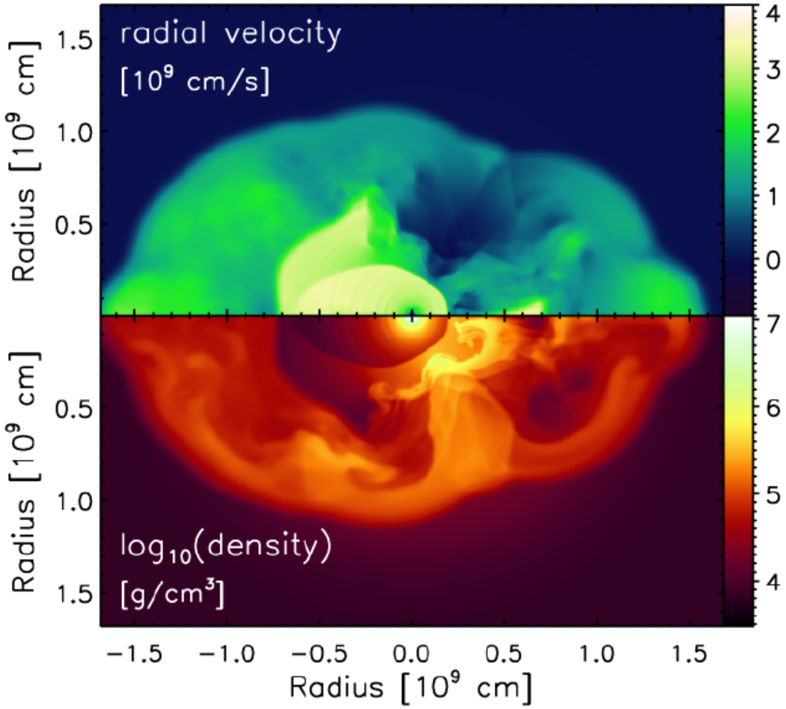
Conclusion: a small initial asymmetry translates into an appreciable intrinsic neutron star recoil. Final neutron star (1.2 Mo) velocity ~ 530 km/s

Simulations of Asymmetric Explosion

Sheck et al. 2004

- Asymmetric explosion due to Anisotropic neutrino emission from the PNS.
- Reasons for anisotropy of neutrino emission
  - ☐ Hydrodynamical instability due to convection
  - ☐ Inhomogeneous neutrino opacity
  - ☐ Dependence of neutrino transportation on magnetic field direction.

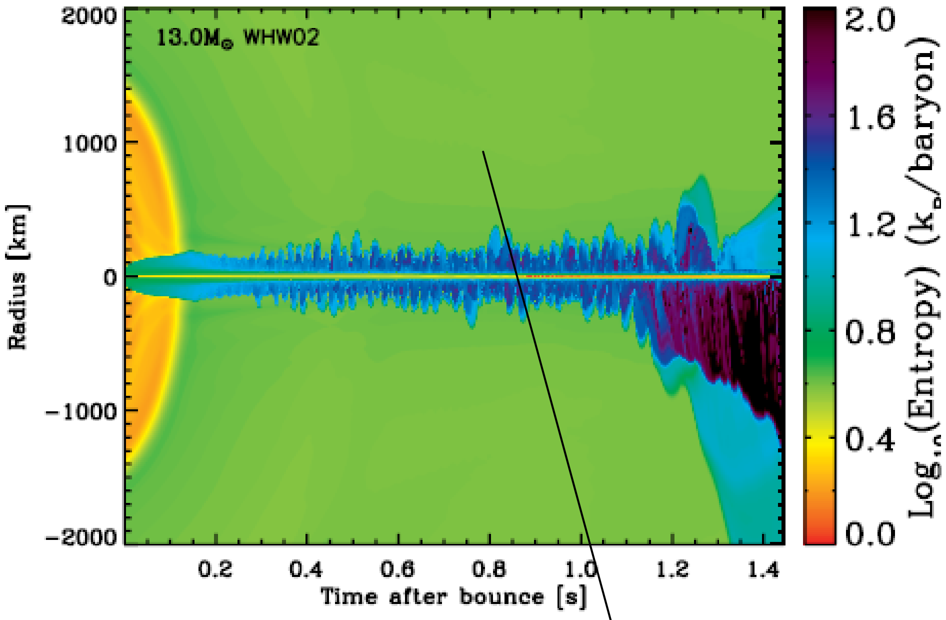




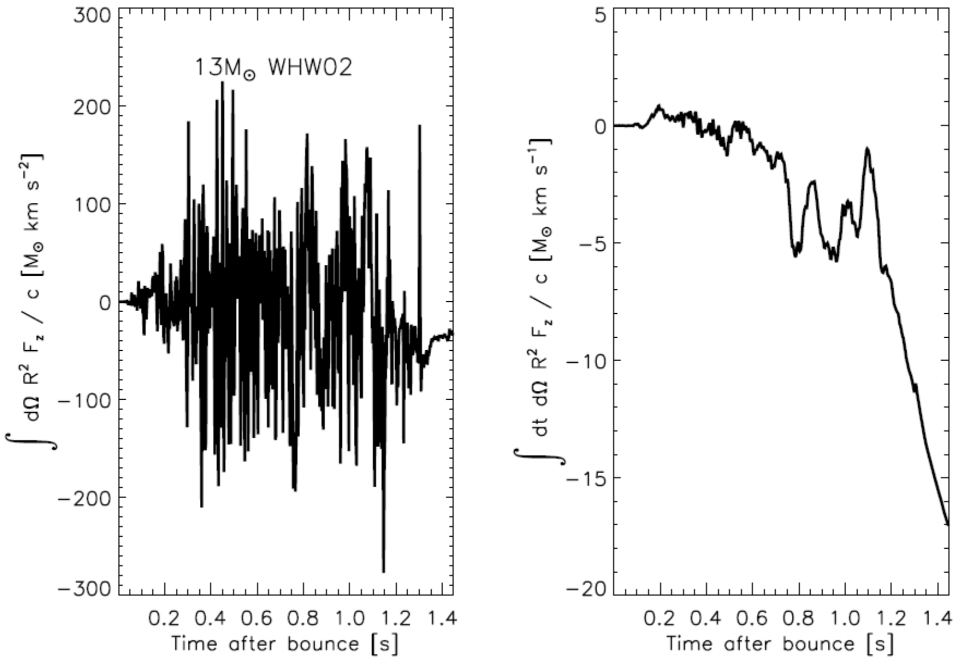
Neutrino luminosity L_{ib}=4.45x10^{52}ergs/s, explosion energy=1.2x10^{51}ergs, and kick velocity of the NS=520 km/s

Simulations of Asymmetric Explosion

Burrows et al. 2007



Entropy profile. Shock position



Net force (left) and The accumulated impulse (right) due to neutrinos.

Negative sign indicates the neutrinos are emerging preferentially in the direction of the exploding matter.

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