NS Initial Spin, Kick and Magnetic Field

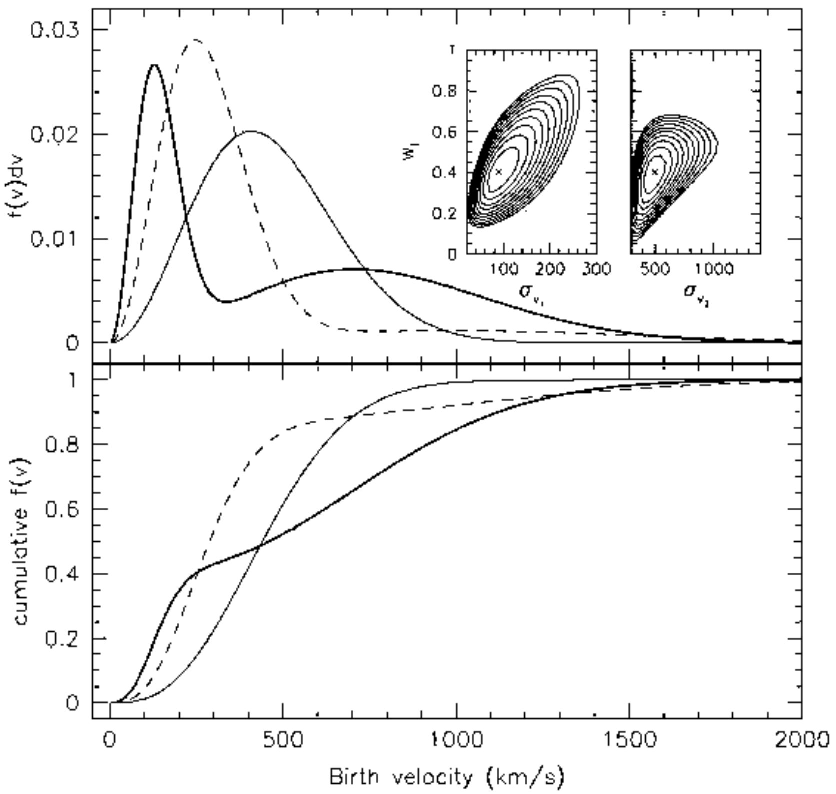
Dong Lai
Cornell University

Evidence for NS Kicks

Large NS Velocities (>> progenitors' velocities ~ 30 km/s):

- **Pulsar proper motion ⇒ V ~ 100-500 km/s, some with V>10^3 km/s**

  (Lyne & Lorimer 1994; Hansen & Phinney 1997; Lorimer et al. 1997; Cordes & Chernoff 1998; Arzoumanian et al. 2002)



3D σ_v=90 km/s (40%)
500 km/s (60%)

Arzoumanian et al. 2002

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- **Bow shock from fast moving pulsars in ISM**

  (e.g., PSR 2224+65 ⇒ V>800 km/s; Cordes et al.1993; Chatterjee & Cordes 2002)

- **NS-SNR association ⇒ large NS velocity up to ~ 10^3 km/s**

Characteristics of NS Binaries (Kicks are required, not just binary Breakup):

- **Pulsar-MS binaries: Orbital plane precession and orbital decay**

  PSR J0045-7319 binary (Kaspi et al. 1996; Lai et al. 1995; Lai 1996; Kumar & Quataert 1997)
  PSR J1740-3052 (Stairs et al. 2003)

- **Double NS Binaries: Geodetic precession, orbital eccentricities, systemic motion**

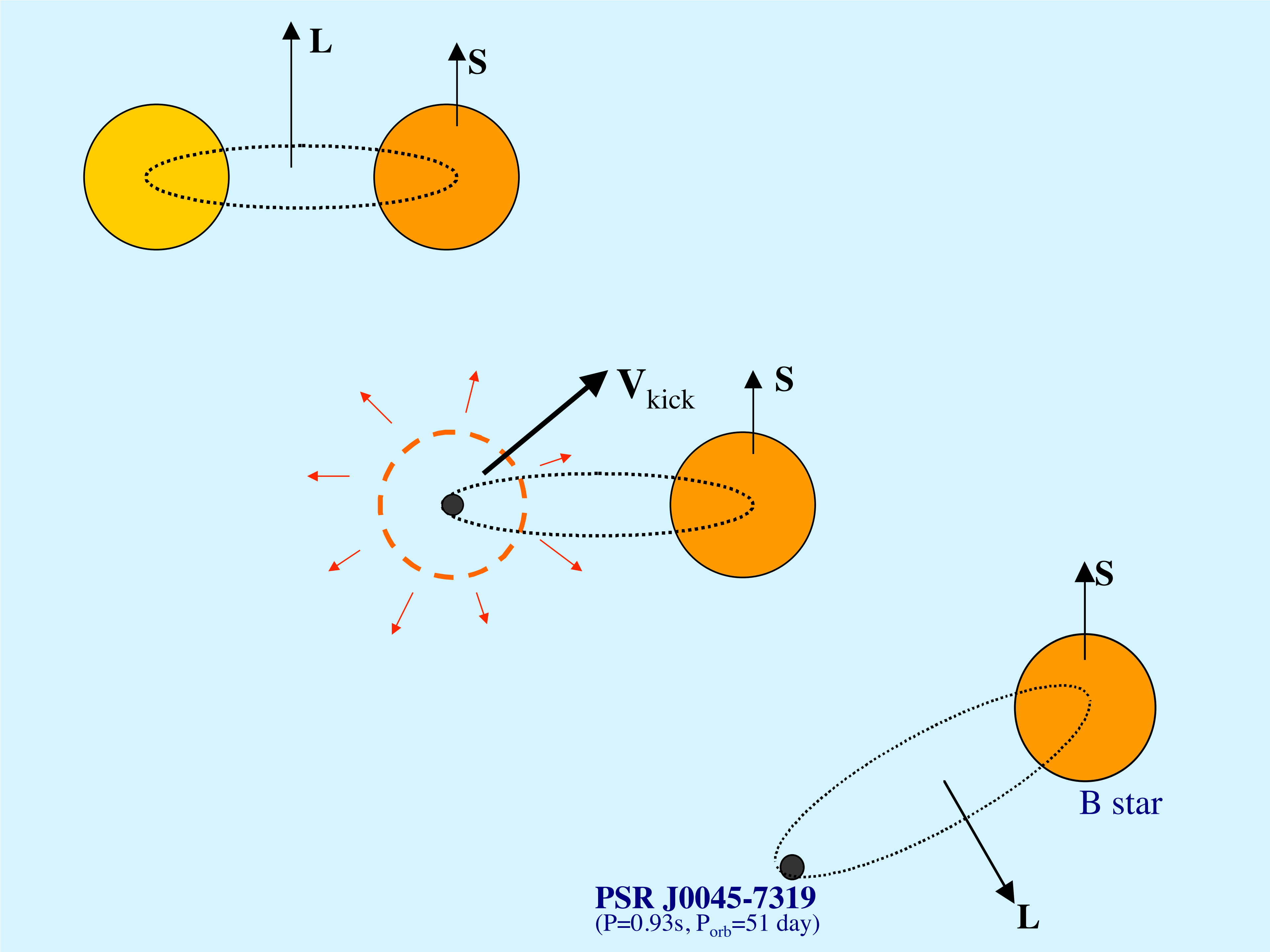
  PSR B1913+16 (Kramer 1998; Wex et al. 2000; Weisberg & Taylor 2002); PSR B1534+12
  PSR J0737-3039 (Dewi & van den Heuvel 2004; Willems et al 2004; Ransom et al. 2004)

- **High-Mass X-ray Binaries:**

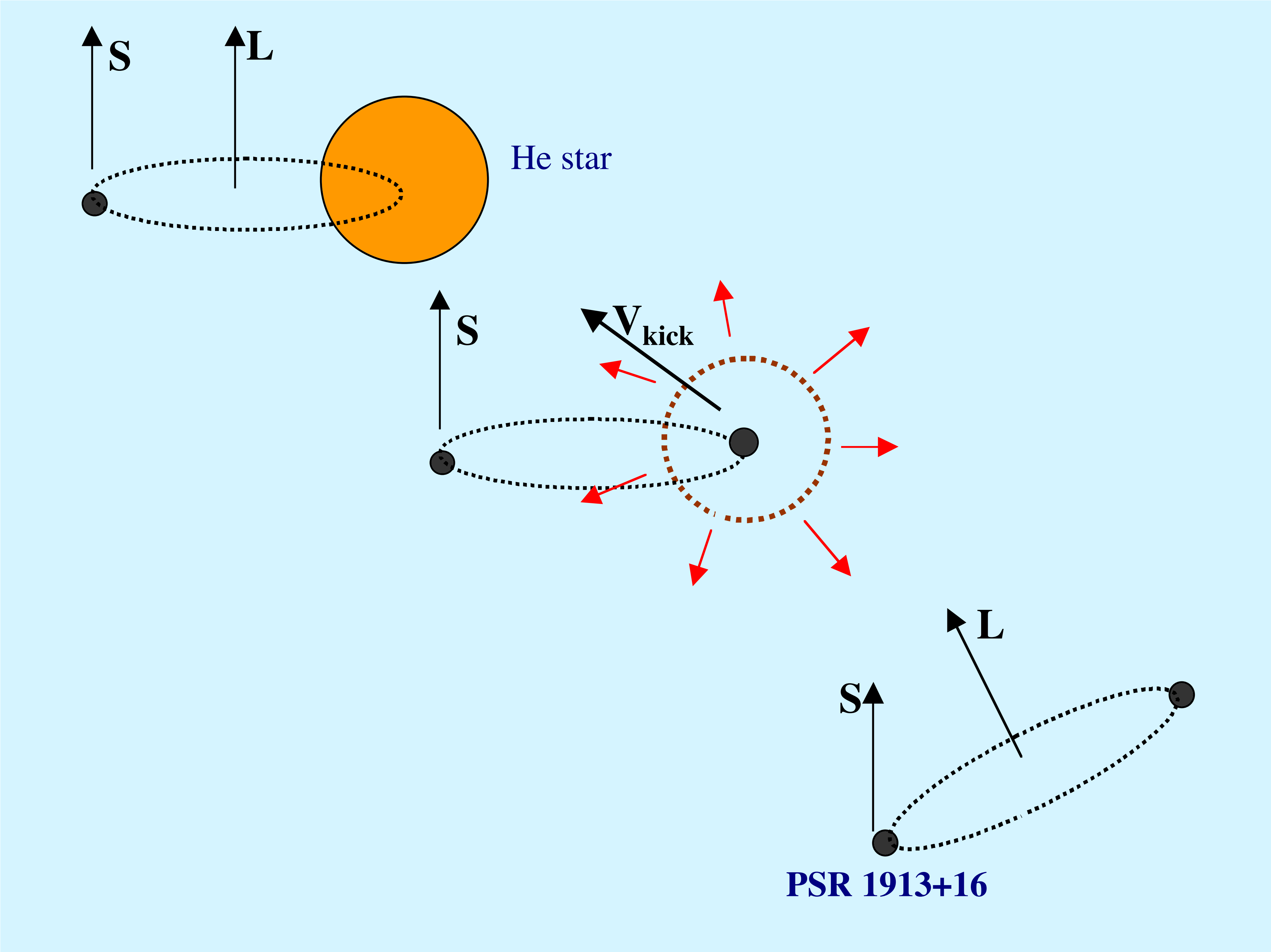
  High eccentricities of Be/X-ray binaries (Verbunt & van den Heuvel 1995; but Pfahl et al. 2002)
  High radial velocity (430 km/s) of Circinus X-1 (Tauris et al. 1999)

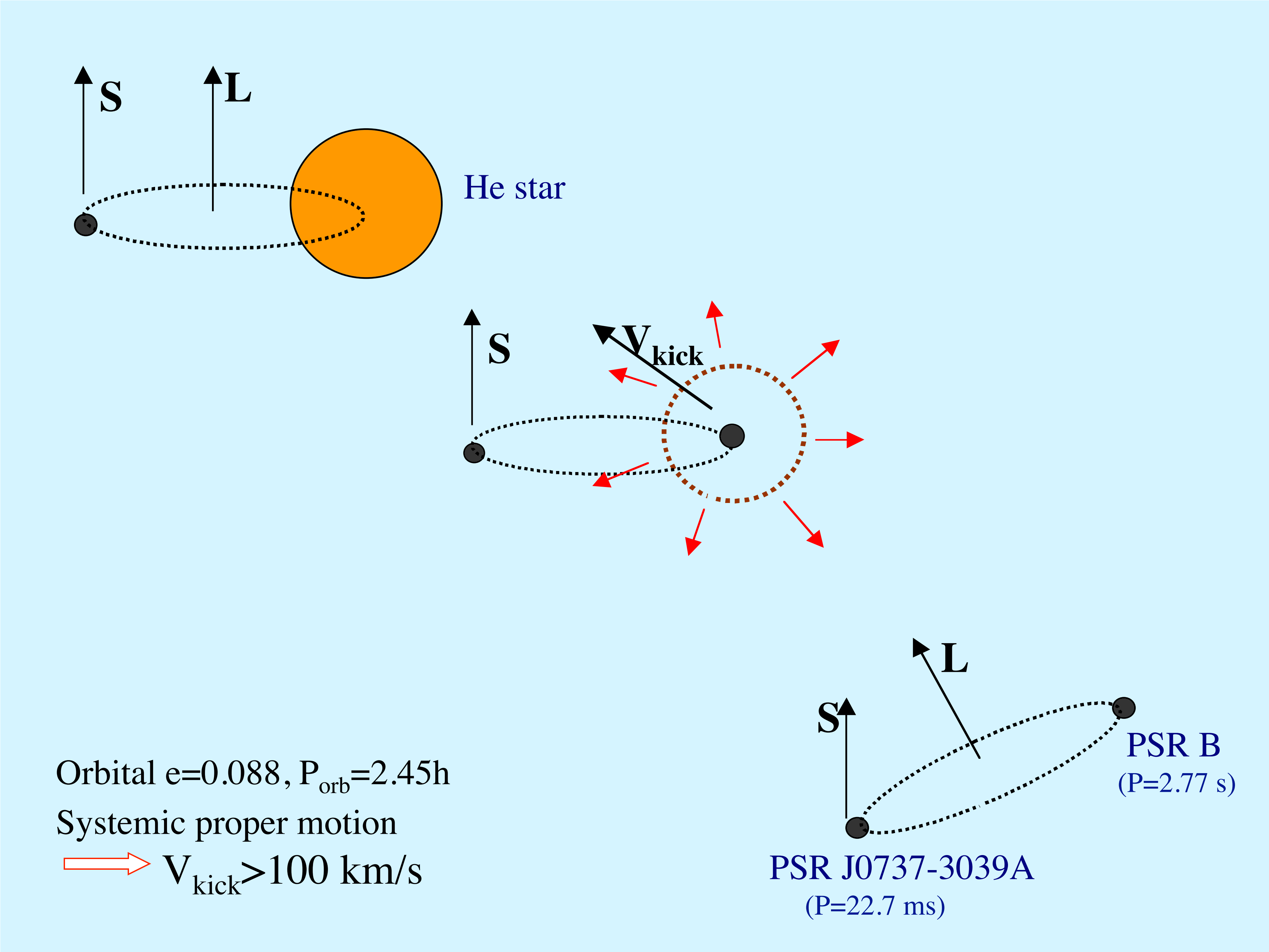
- **Evolutionary studies of NS population**

  (e.g., Deway & Cordes 1987; Fryer & Kalogera 1997; Fryer, Burrows & Benz 1998)



L
S
S
V kick
S
B star
PSR J0045-7319
(P=0.93s, P orb=51 day)
L


S
L
He star
S
V kick
L
S
PSR 1913+16


S
L
He star
S
V_{kick}
L
S
PSR B
(P=2.77 s)
PSR J0737-3039A
(P=22.7 ms)
Orbital e=0.088, P_{orb}=2.45h
Systemic proper motion
V_{kick}>100 km/s

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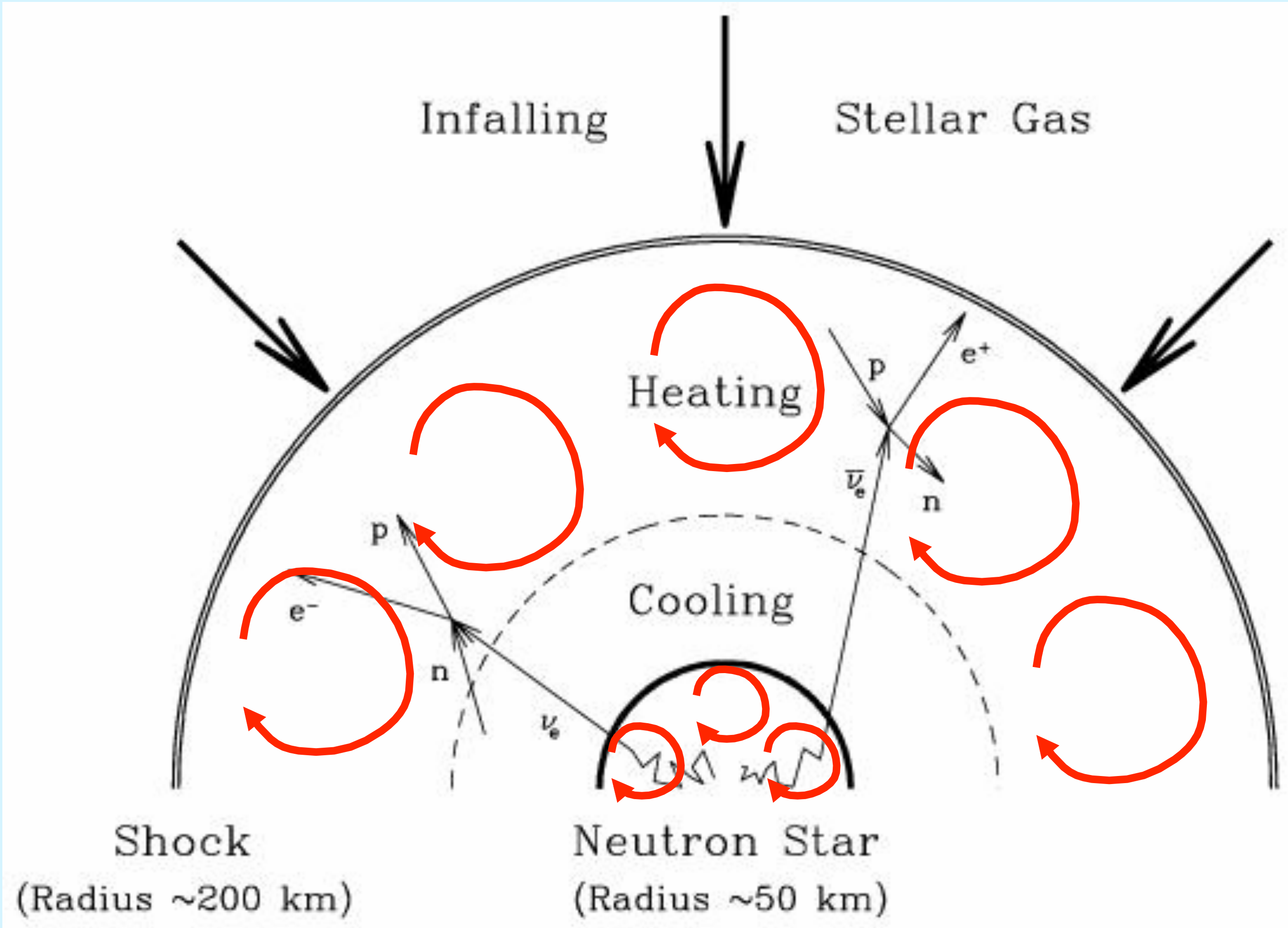
Kick Mechanisms

- **Hydrodynamically Driven Kicks:** Asymmetric explosion
- **Neutrino-Magnetic Field Driven Kicks:** Asymmetric ν Emission
- **Electromagnetic Radiation Driven Kicks**

Hydrodynamically Driven Kicks

Asymmetric SN Explosion



Adapted from Janka et al

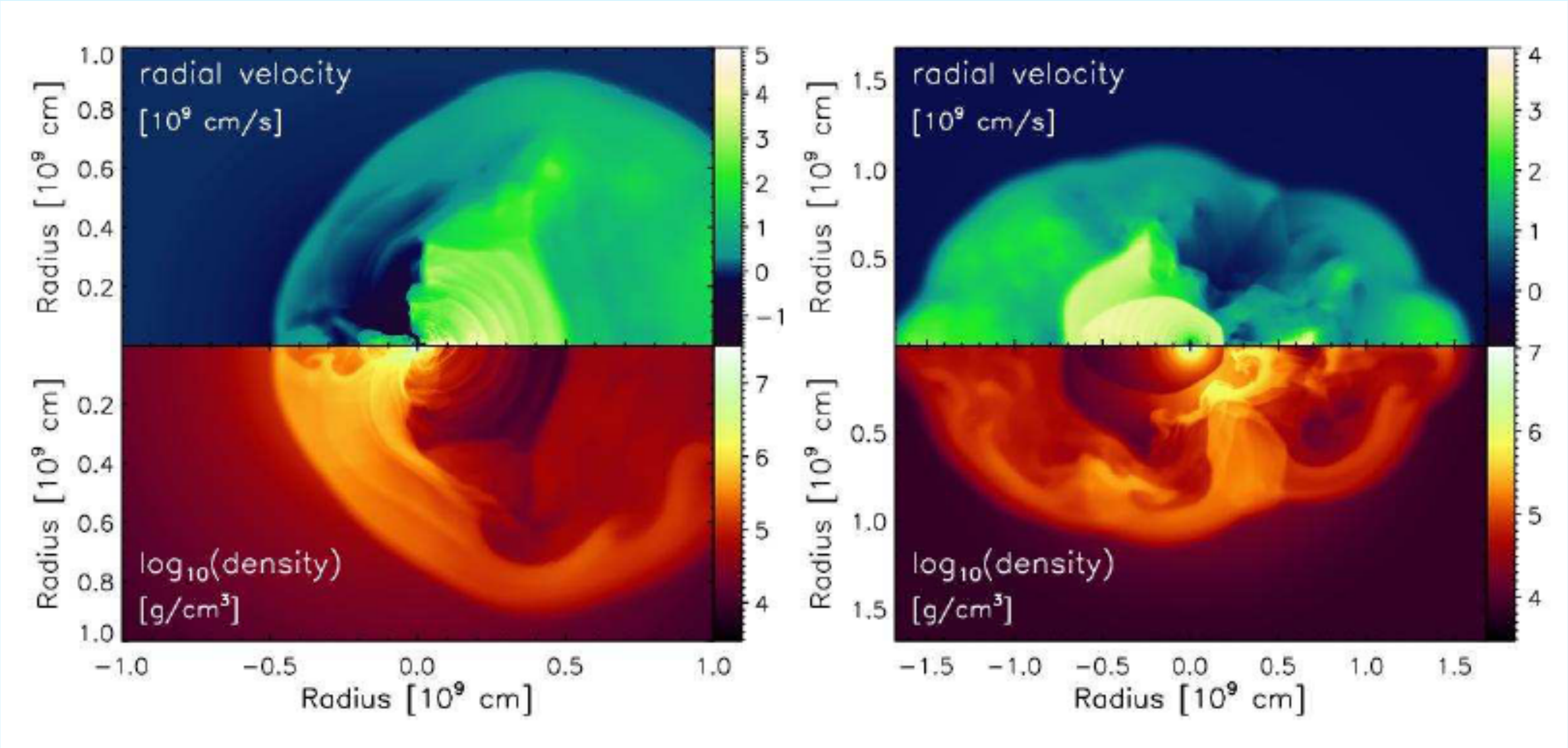
Convections in the the shocked mantle (and in proto-NS) can lead to asymmetric matter ejection and associated neutrino emission.

How much?

Numerical experiments of Scheck et al.(2004)

Adjust $L_\nu(t)$ from proto-NS so that explosion sets in slowly (100's ms--seconds)

Slow explosion leads to large kick (100's km/s)

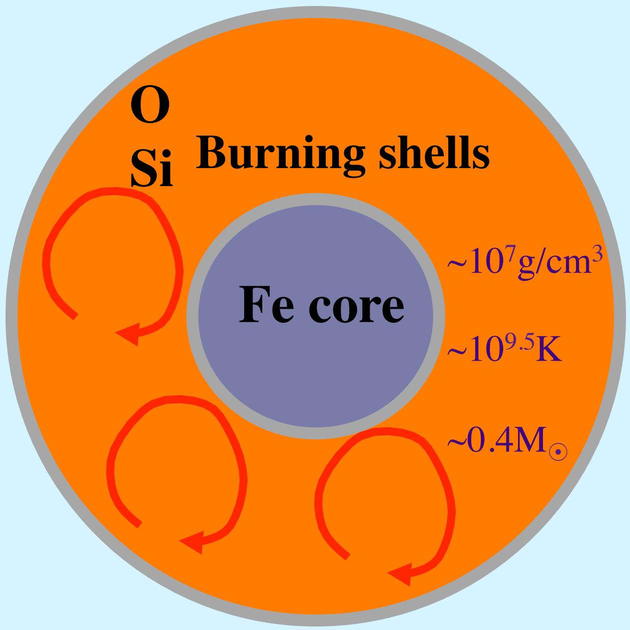


Pre-collapse Asymmetry

Arises from

- convective Si-O shell burning
- non-radial oscillations

(Goldreich et al.1996; Burrows & Hayes 1996;
Bazan & Arnett 1998,2000; Lai & Goldrecih 2002; Lai 2003;
Murphy et al. 2004)



Seed for global asymmetry

Neutrino - Magnetic Field Driven Kicks

References: Dorofeev et al. 1985; Bisnovatyi-Kogan 1993; Vilenkin 1995; Horowitz & Li 1998;
Janka & Raffelt 1998; Lai & Qian 1998-1999; Arras & Lai 1999; Fuller et al.2003

Magnetic field can modify the neutrino transport in the proto-neutron star

⟹ **Asymmetric neutrino emission ("Neutrino Rocket")**

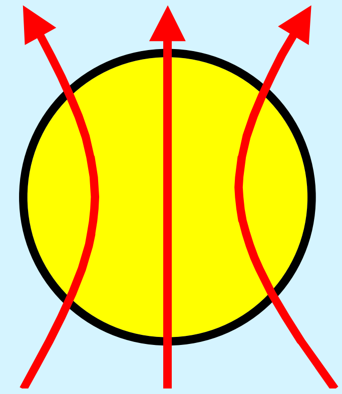
Require neutrino asymmetry of 3% for V=1000 km/s

Parity Violation

In strong B-field, neutrino opacities are asymmetric with respect to the magnetic field direction

⇨ Asymmetric neutrino transport

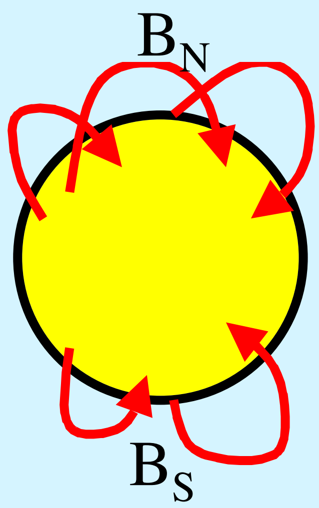
Require ordered field: $V_{kick} \sim 50\ B_{15}$ km/s



Asymmetric Field Topology

The neutrino absorption opacities depend on **|B|**

Require $|B_N - B_S| \geq 10^{16}$ **G to get $V_{kick} \sim 300$ km/s**



Nonstandard Neutrino Physics

e.g. sterile neutrinos (Fuller et al.2003)

All require $B>10^{15}$G

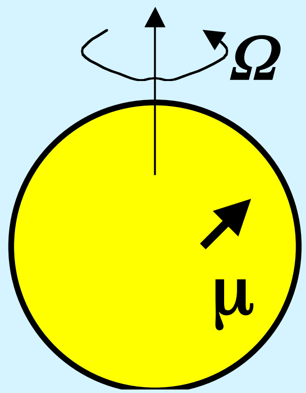
Dynamical Effects of Magnetic Fields

- **"Dark spots" on proto-neutron stars:** A strong local B field ($>10^{15}$G) may suppress neutrino-driven convection, and reduce neutrino flux (Duncan & Thompson)

- **MHD (+Rotation) driven explosion:** Asymmetric jets (e.g., Khokhlov et al. 1999 …)

Electromagnetic Radiation Driven Kick (Boost)

Radiation from off-centered dipole carry away linear momentum, and imparts a "kick" to the pulsar along its spin axis (Harrison & Tademaru 1975)



formula wrong by a factor of 4 (Lai et al. 2001)

$$V_{kick} = 1400\left(\frac{\alpha}{0.63}\right)\left(\frac{\nu_{init}}{1kHz}\right)^2 \text{ km/s}$$

where α is the asymmetry parameter (maximum 0.63)

The kick is attained on the initial spindown time $\sim 10^7 B_{13}^{-2}(\nu_{init}/1 \text{ kHz})^{-2}$ s

Neutron Star Kick Mechanisms

- **Hydrodynamically driven kicks ("Mass Rocket")**
  calculations uncertain

- **Neutrino-magnetic field driven kicks ("Neutrino Rocket")**
  B-field affects neutrino opacities; dark spots
  Require $B_{init} > 10^{15}$G

- **Electromagnetic radiation driven kicks ("EM Radiation Boost")**
  Require fast initial rotation (msec)

NS kick is connected to initial spin and B-field

Initial Spin of Neutron Stars (Observations)

P, Pdot, n=2-3, + Age ⟹ Initial period P_i

Pulsars associated with historical SNe (see Camilo et al. 2004 for references)

PSR B0531+21 (SN1054, Crab): P=33ms ==> P_i ~ 19 ms

\- PSR J1811 1925 (SN386, G11.2-0.3): P=64ms ==> P_i ~ 62 ms

PSR J0205+6449 (SN1181, 3C58): P=65ms ==> P_i ~ 60 ms

Pulsars in SNRs (many…)

e.g., PSR J0537-6910 (LMC SNR N157B): P=16ms ==> P_i ~ 10ms (Marshall et al.1998)

Pulsars in Binaries:

e.g. PSR J0045-7319 (with B star): P=0.93s, age from orbital decay (~1Myr)
==> P_i ~ 0.7s (Lai 1996)

Energy Content of plerions

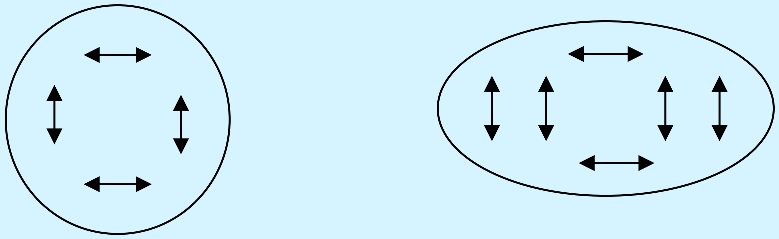
e.g., Crab pulsar P_i >10 ms

Pulsars are not born rotating fast (P_i = 10-10^3ms>>1ms)

Some SN cores have very rapid rotation

Spectropolarimetry probe of SN geometry

(see Leonard, Fillipenko et al; Wang, Wheeler et al)



P_{net}=0% $P_{net} > 0\%$

Net polarization up to a few%
==> The cores of SNe are aspherical, at ~50% level

==> (Maybe) Bipolar explosion
Need rapid rotation (the resulting NS would have P_i~1 ms)

GRBs: To make GRBs in SNe requires very rapid rotating cores

Initial Spin of Neutron Stars (Theory)

- Massive MS stars rotate rapidly (~10% breakup)
- As star evolves, envelope slows down due to expansion and mass loss
- Core slows down by coupling to envelope via **hydrodynamic/magnetic stress**

Model results:

- No magnetic field: $P_i < 1$ ms (e.g. Heger et al. 2000)
- With B-field (rigid rotation up to central C burning): $P_i \sim 100$s (Spruit & Phinney 1998)
- Current magnetic model result: $P_i \sim 5$ ms (Heger et al. 2003)

Early Spindown of Neutron Star

Can ms NS spin down to 10's ms in an "invisible" way (with rotational energy not going to pulsar wind)?

- **Gravitational radiation:**

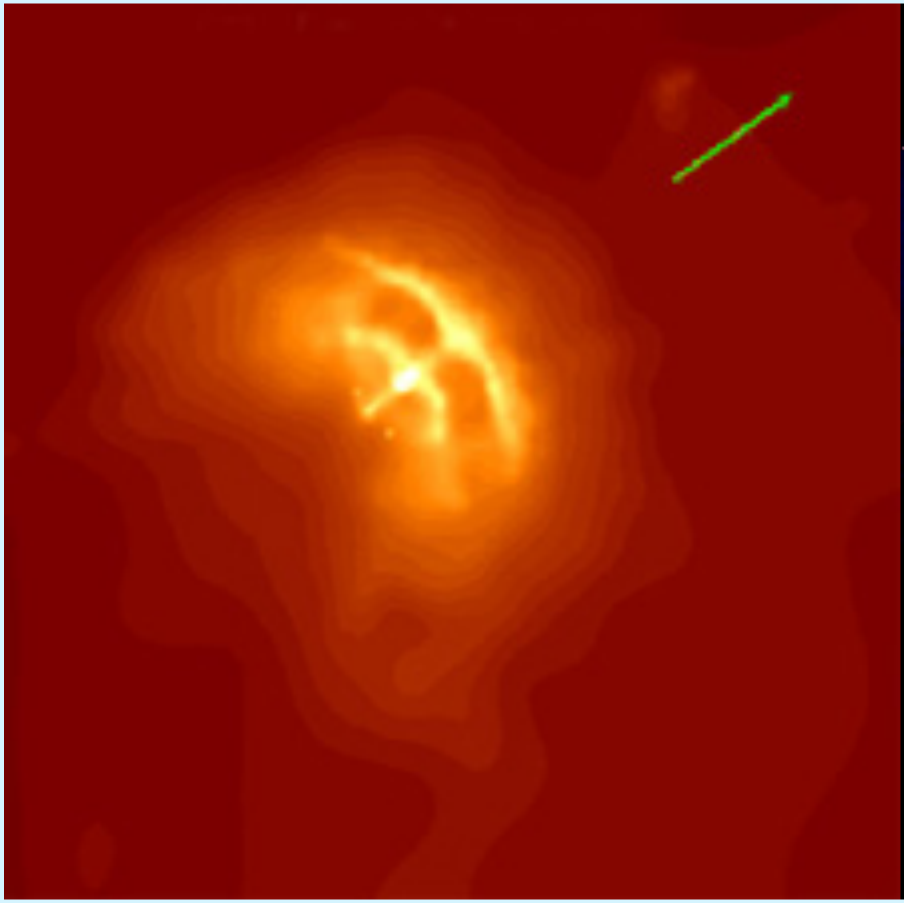
  R-mode unlikely to be efficient (Arras et al. 2003)

- **Nonrelativistic outflows:**

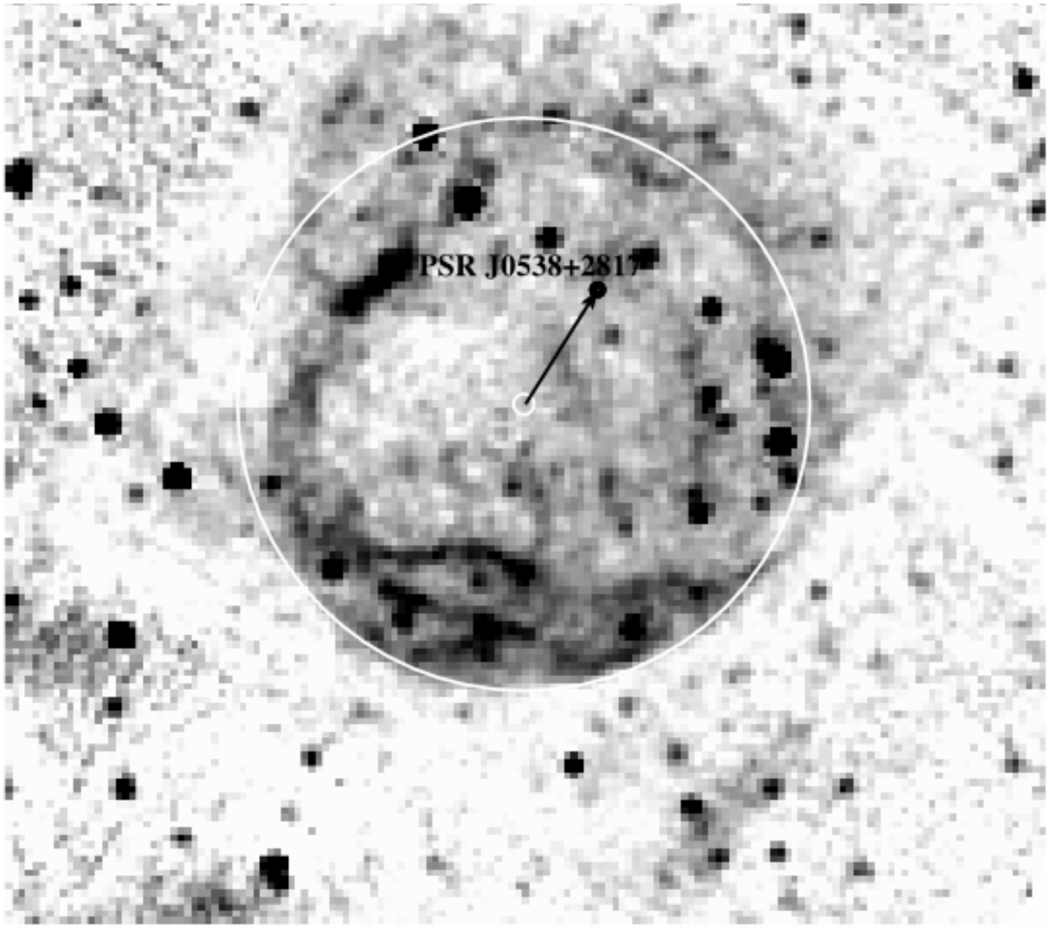
  Neutrino-driven magnetic wind: NS spins down in the first 10's.
  provided $B>10^{15}$G (e.g. Woosley 2003; Thompson et al. 2004)
  Propeller effect of fall back disks

Spin-Kick Connection

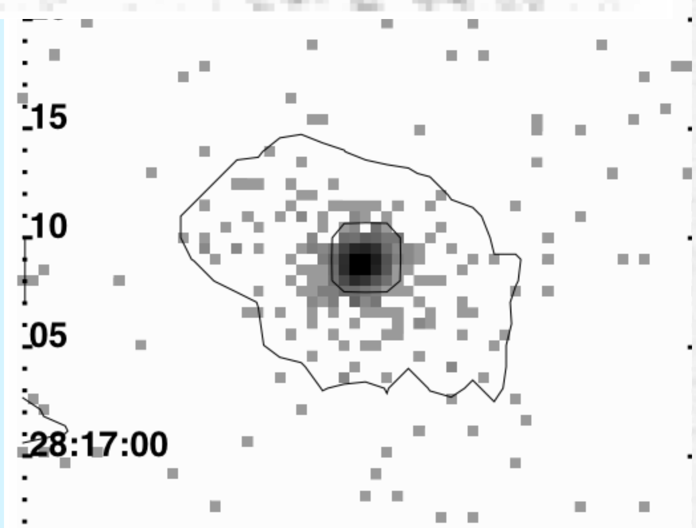
Spin-velocity alignment in Vela and Crab

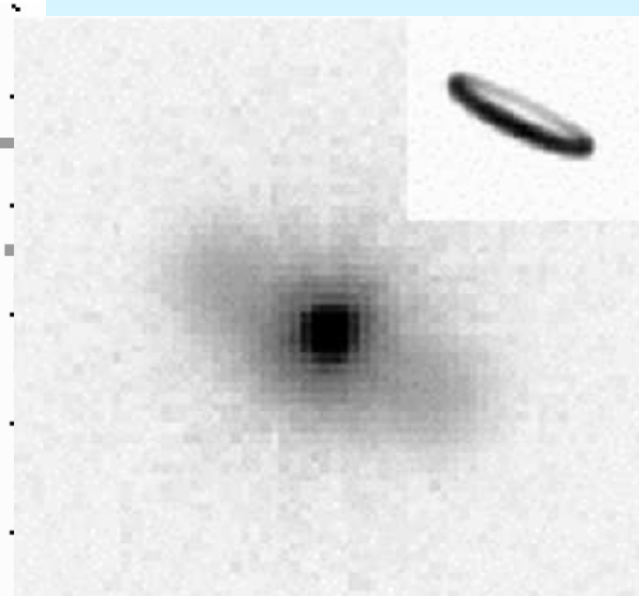


PWN Torus of PSR J0538+2817 in SNR S147



Ng & Romani 2004





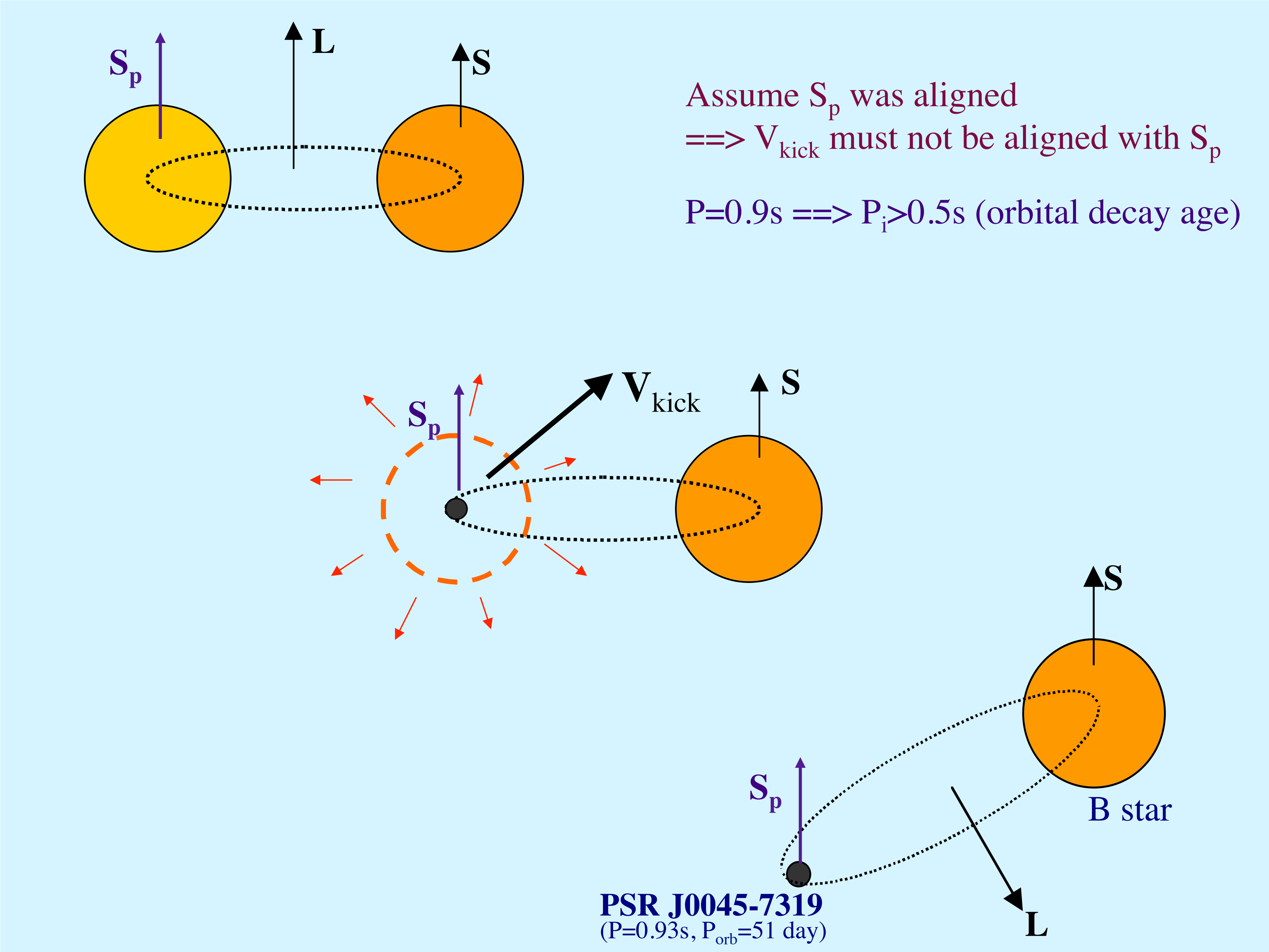
Conditions for spin-kick alignment:

- **Electromagnetic radiation driven kick:** **OK** (but need $P_{init} <$ a few ms)

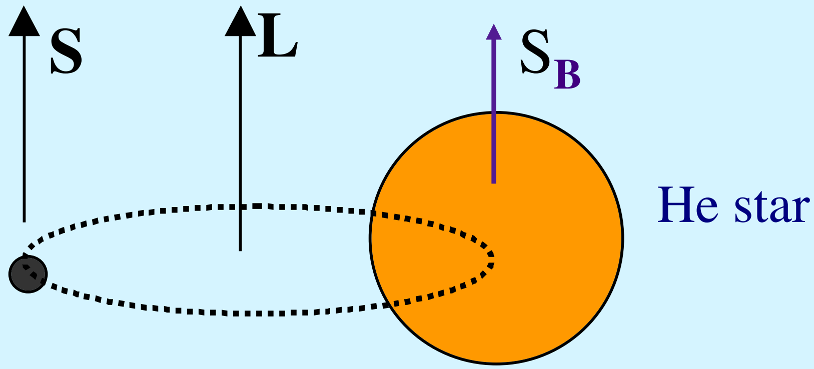
- **Neutrino-magnetic field driven kicks:**
  require $P_{init} < \tau_{kick} \sim 1$ s **OK** (but need $B > 10^{15}$G)

- **Hydrodynamically driven kicks:**
  require $P\ (r \sim 100\ \text{km}) < \tau_{kick} \sim 100$ ms $\Rightarrow P_{init} <$ a few ms

Spin-kick alignment/misalignment provides strong constraints on the kick mechanisms and other properties of nascent NSs.



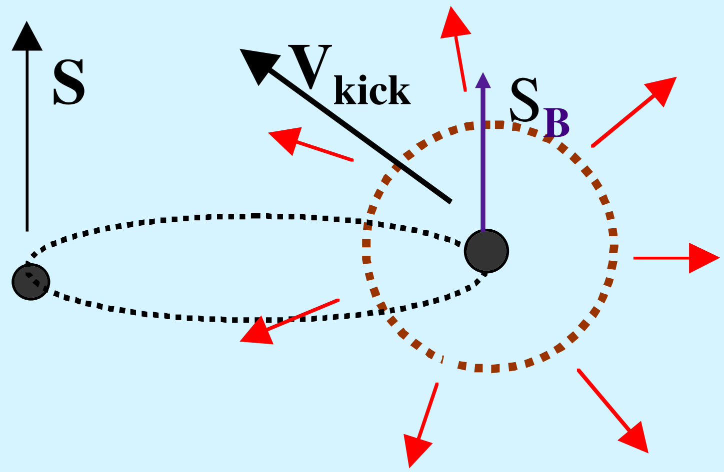
S_p
L
S
Assume S_p was aligned
==> V_kick must not be aligned with S_p
P=0.9s ==> P_i>0.5s (orbital decay age)
S_p
V_kick
S
S
S_p
B star
PSR J0045-7319
(P=0.93s, P_orb=51 day)
L

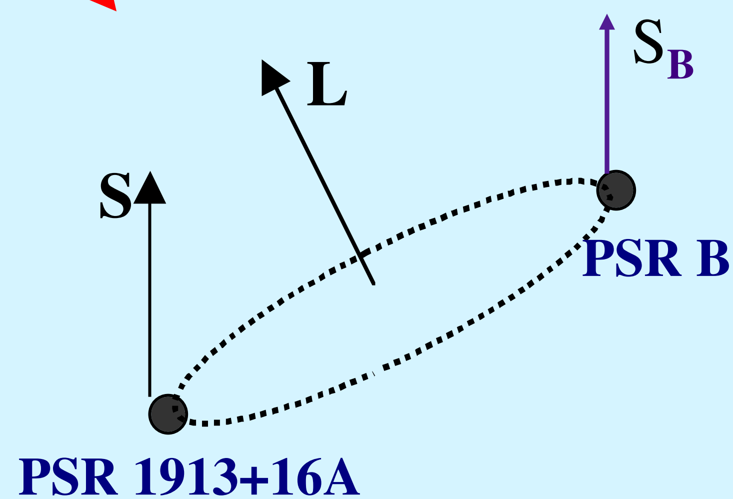


Assume S_B was aligned

==> V_{kick} must not be aligned with S_{B}.

PSR B spin period? ~ 1s





Similarly for double Pulsars J0737A-B

Hint/Tentative Conclusion:

- Kick timescale ~ 1 s (as in neutrino-magnetic kicks)

- If $P_i << 1$ s, spin-kick aligned (mostly)
  If $P_i \gtrsim 1$ s , spin-kick misaligned in general

Summary

- **Kick, initial spin, initial B are linked**
- **Promising kick mechanisms**

  (consistent with observations but not well constrained):

  Hydrodynamical: uncertain; part of the SN problem

  Neutrinos: Require extreme (but allowed) initial B fields
- **Initial spin period of pulsar >> 1 ms**

  But some SN cores have rapid spin; GRB central engine

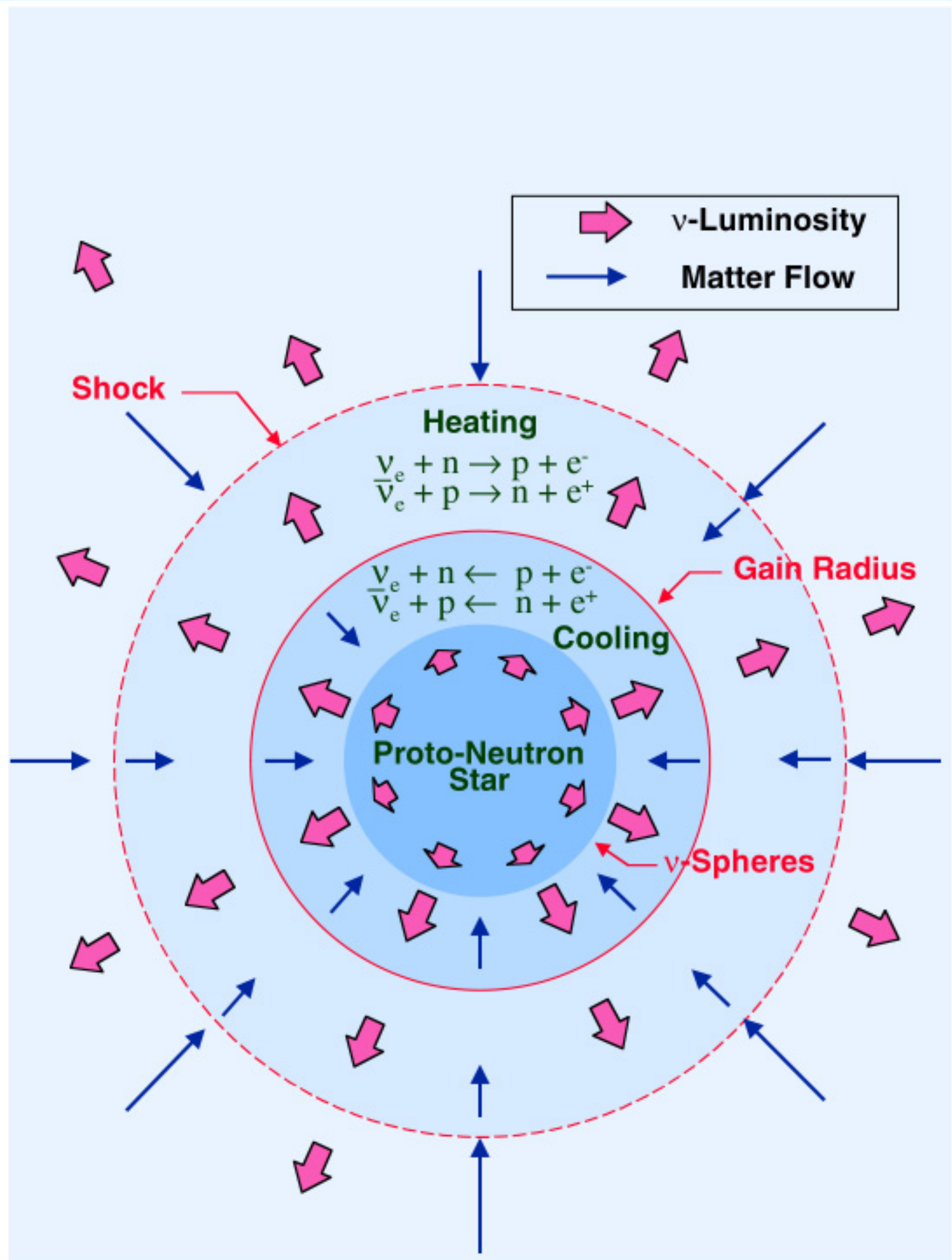
  Possible earlier spin-down before pulsar phase?
- **Initial B (in the first 10's seconds) completely unknown**
- **Spin-kick alignment/misalignment: young pulsars/binaries**

  Kick time ~ 1 s? ==> neutrino-magnetic field; explosion with long delay?
- Gravitational wave (LIGO) probes NS initial conditions

Black Hole Kicks

- Most galactic BH binaries have small velocity (<40 km/s).

- GRO J1655-40 (Nova Sco) has V~120 km/s (radial velocity and proper motion; Mirabel et al 2002)
  The companion has enhanced α elements ===> SN (Isrealian et al. 1999)
- XTE J1118+480: V ~ 180 km/s



ν-Luminosity
Matter Flow
Shock
Heating
$\nu_e + n \rightarrow p + e^-$
$\bar{\nu}_e + p \rightarrow n + e^+$
Gain Radius
$\nu_e + n \leftarrow p + e^-$
$\bar{\nu}_e + p \leftarrow n + e^+$
Cooling
Proto-Neutron Star
ν-Spheres

How to get the kick?

Asymmetric shock propagation ⟹ “Mass Rocket”

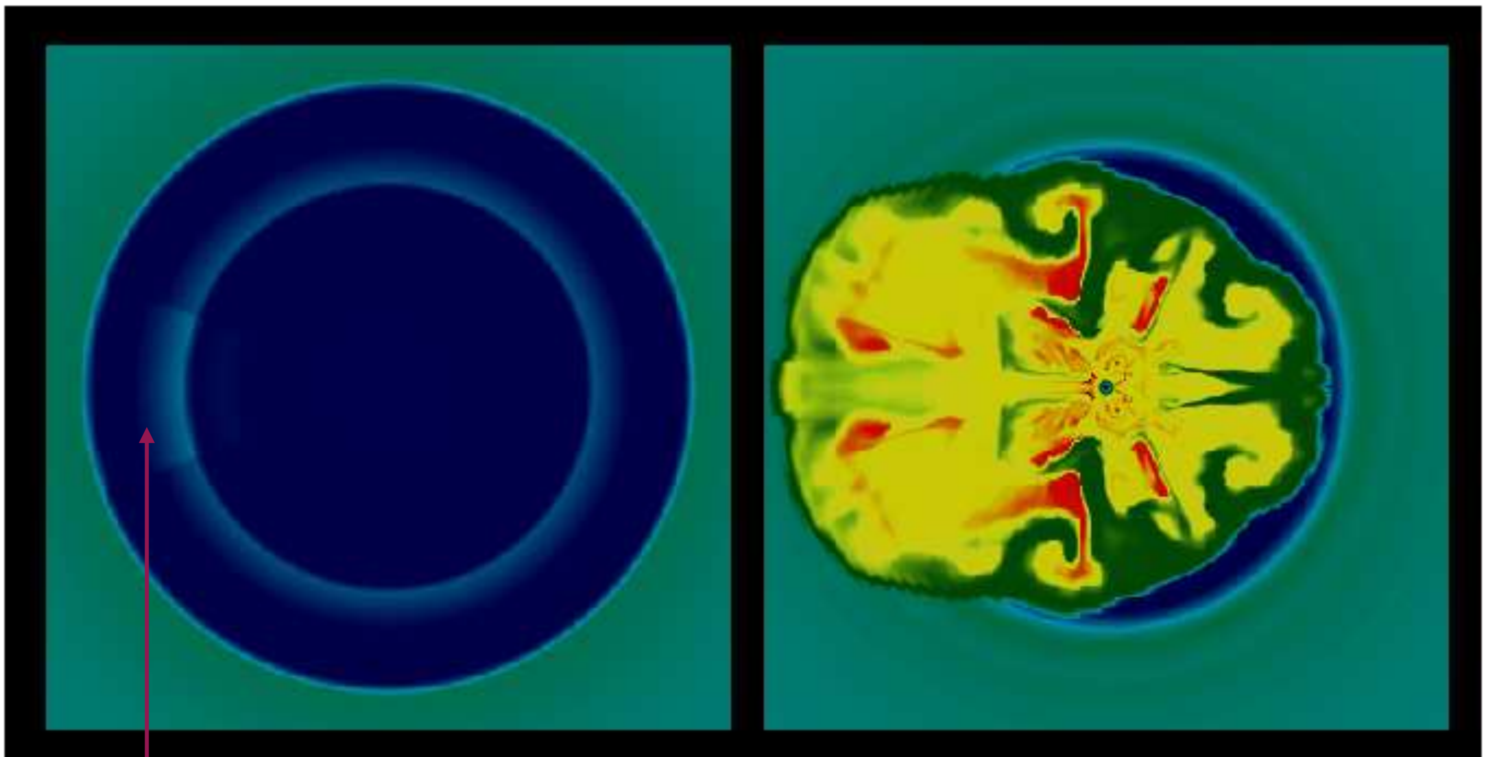
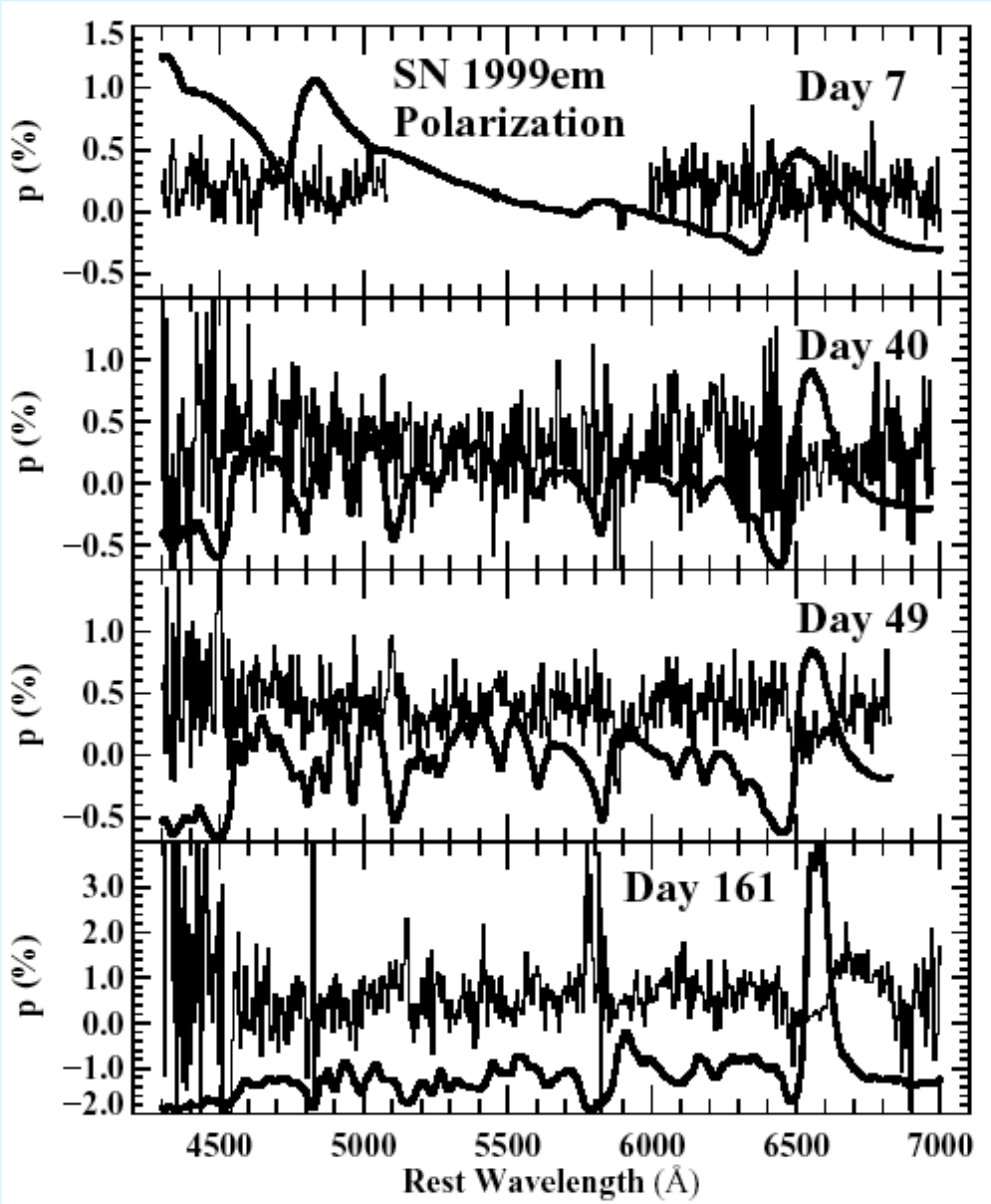


Fig. 3.—Kick Sequence: Initial and Final States

Less dense

A. Burrows



Leonard et al. 2001

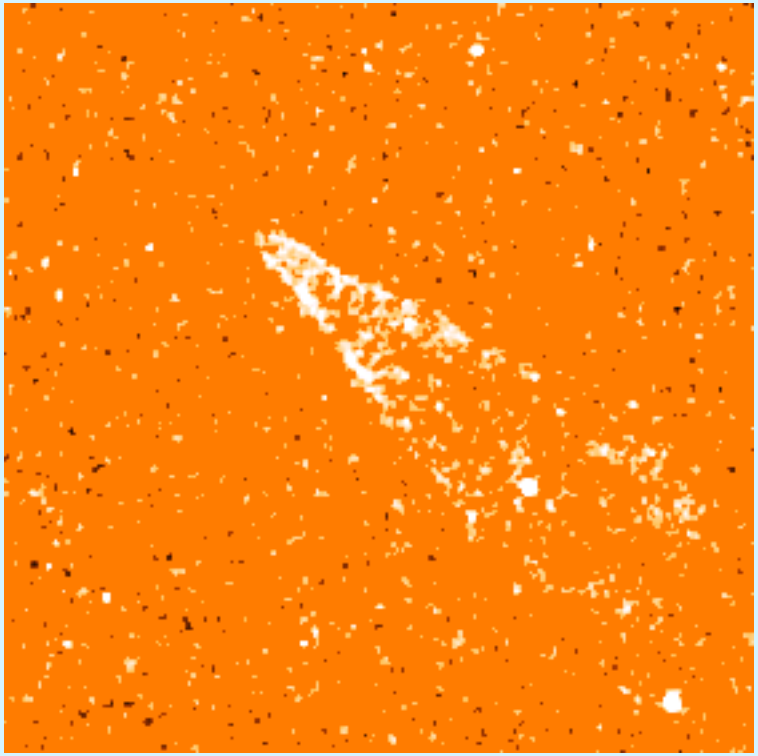
P% increases with time, as we look deeper into ejecta!

Net polarization ~1%
==>
The core of core-collapse Sne are aspherical at 10-50% level

Also trend:
P% increases from
II --> Iib -->Ib --> Ic
(Wang, Wheeler et al)

Guitar Nebula (observed by HST)

(PSR 2224+65 moving with V>800 km/s)



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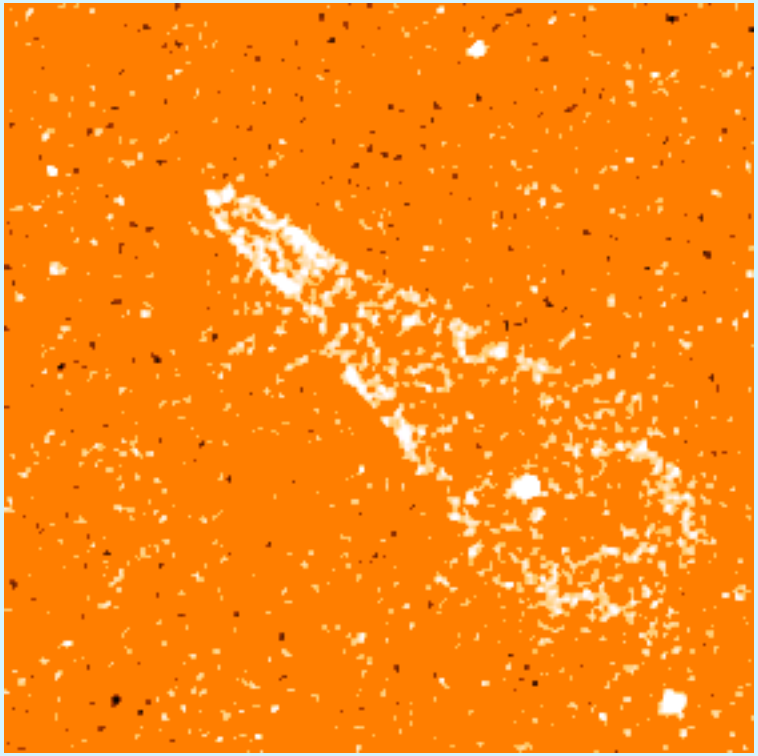

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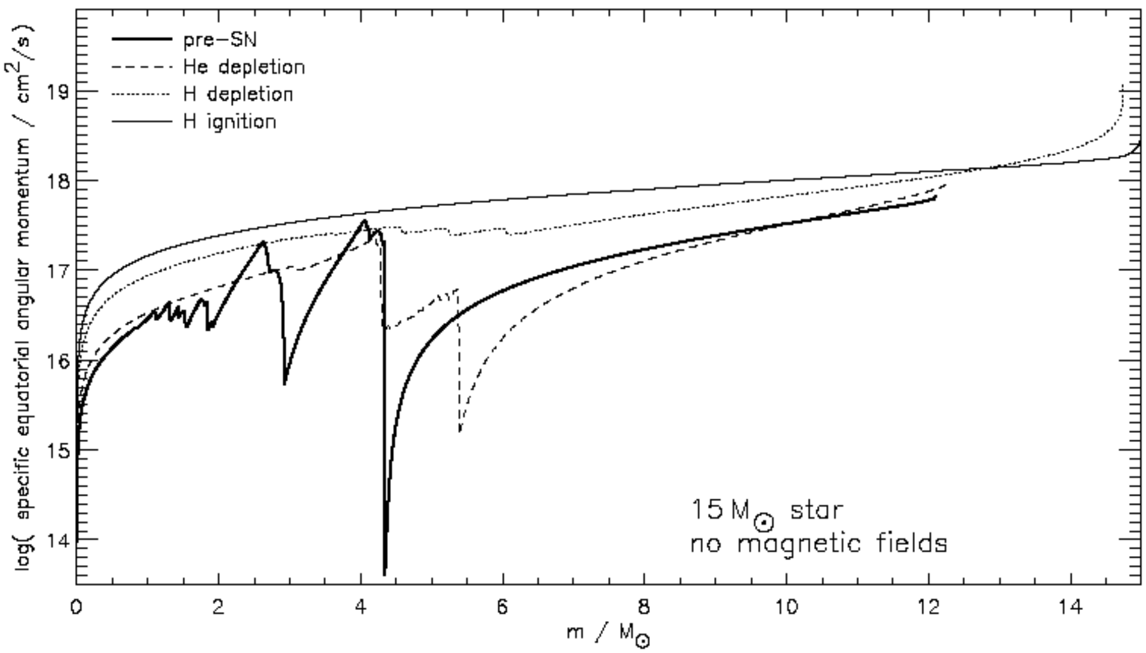
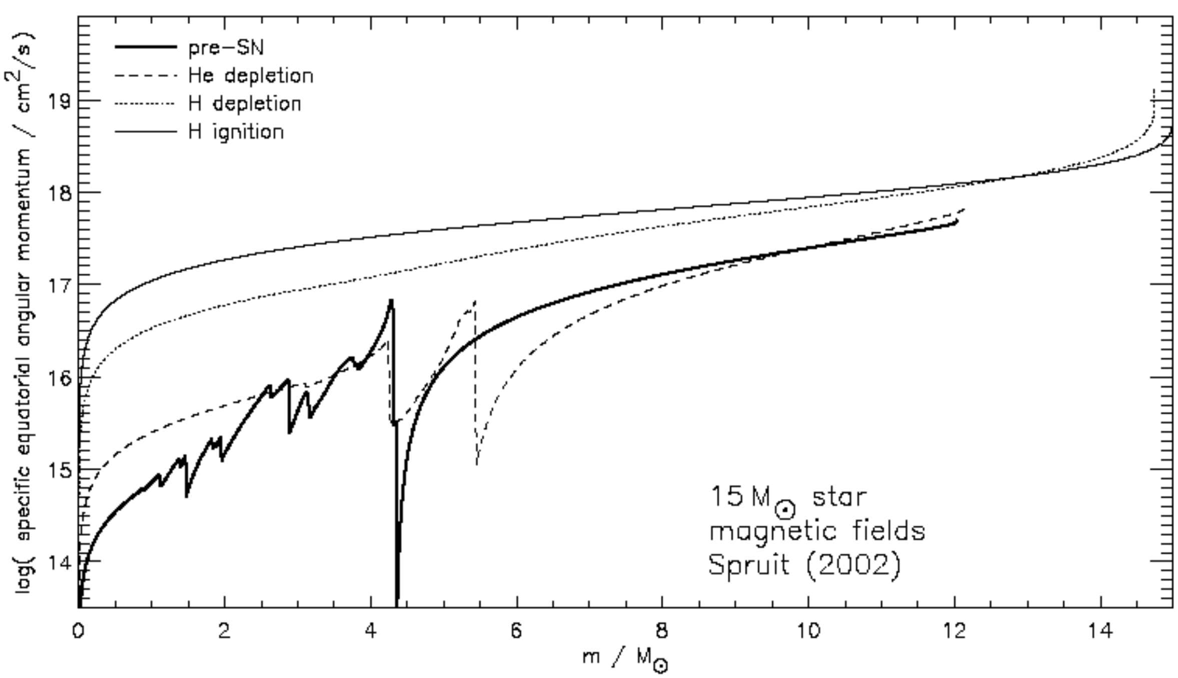
S. Chatterjee & J. Cordes





Heger, Woosley, Langer, Spruit 2003

Pre-collapse Asymmetry

- In pre-SN core, asymmetric perturbations may arises from

  convective Si-O burning

  nonradial oscillations

  (Goldreich et al.1996; Bazan & Arnett 1998,2000; Lai 2002; Murphy et al.2004)

- During collapse, perturbation is amplified.

  (Lai & Goldreich 2000)

- After core bounce: asymmetric shock propagation (“mass rocket”)

  (Burrows & Hayes 1996; Fryer 2004)