NS kick induced by aspherical CCSN explosions

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NS proper motion

Young pulsars possess large proper motion velocities.

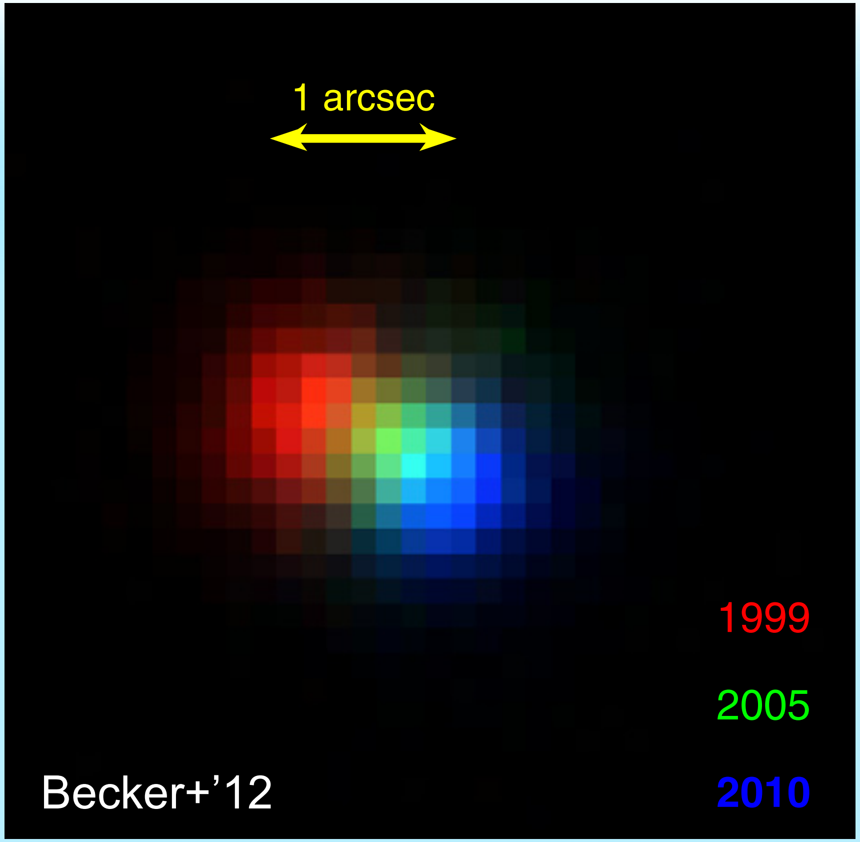
672±115 km/s (RX J0822-4300)

1083 $^{+103}_{-90}$ km/s (PSR B1508+55)

~ 200 – 500 km/s on average

<u>Implication for NS kick</u>

Some NS binary systems have
large inclination angle,
and large eccentricity.



RX J0822−4300 from three Chandra HRC-I epochs (after alignment to a common coordinate system) in different colors.

Two competing mechanism of NS kick

1) Neutrino kick mechanism

NS acceleration by aspherical neutrino radiation from SN core.

CCSN emits a huge amount of neutrino (~10^{53}erg).

A few % of anisotropy can accelerate NS to 1000km/s.

BUT it turned out to be very difficult.

2) Hydrodynamic kick mechanism

NS acceleration as a result of recoil of aspherical matter ejection.

Anisotropic mass ejection in CCSN would lead to a NS kick (recoil).

Aspherical structure of pre-collapse progenitor star.

Hydrodynamic instability (convection, SASI).

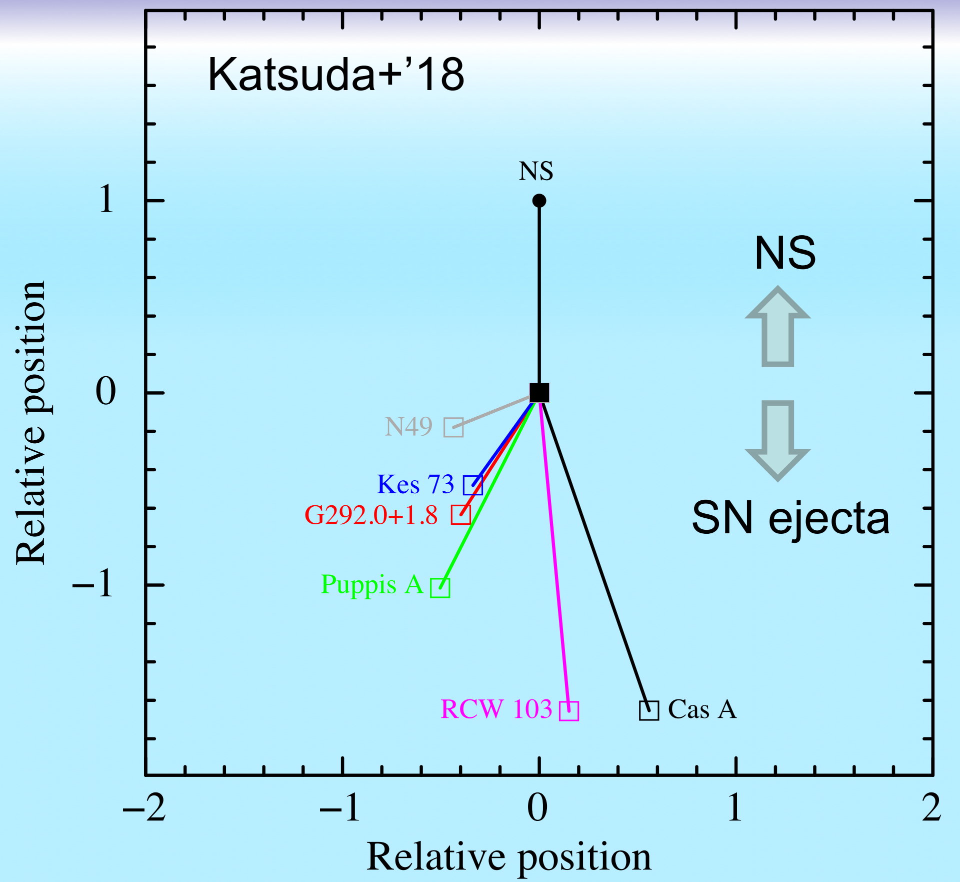
X-ray morphology of SNRs

Holland-Ashford+'17
analyze X-ray images of 18 SNR with Chandra & ROSAT.
*SN ejecta and CSM were not distinguished.

Katsuda+'18
reanalyze 6 SNR using more sophisticated way.

Result：NSs are really moving to the opposite direction to SN ejecta !

→ **Hydrodynamic-kick mechanism**.



Center-of-mass positions of SNRs relative to their NSs. All opening angles are large, which means that NSs are moving to opposite directions to SN ejecta.

Previous theoretical works

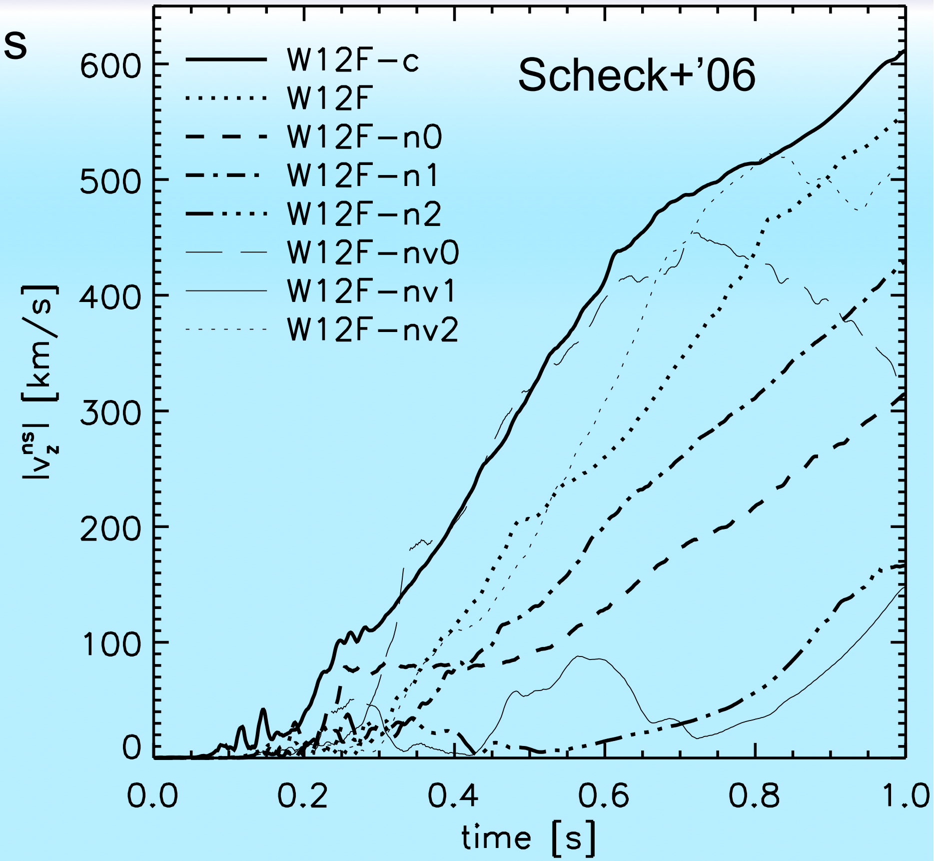
NS kick estimation from numerical simulations based on the hydrodynamic-kick scenario.

Burrows & Hayes'96
2D, ~300ms.
assuming a large anisotropy in a progenitor model.

Scheck+'04,'06
2D, ~1 s.

Wongwathanarat+'13
3D, >3 s.

Problems:
- excising the central (NS) region,
- explosion by hand,
- and a small number of progenitor models.



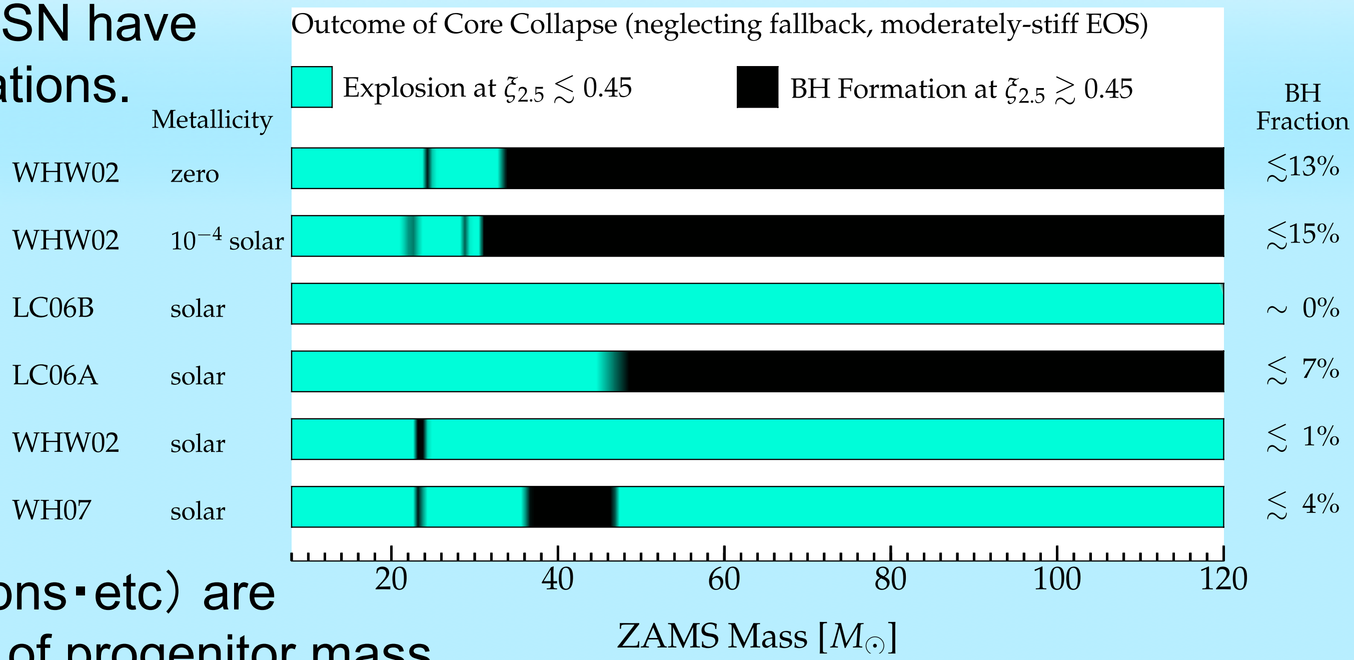
NS recoil velocity for one progenitor model with different parameter sets.

Systematic CCSN studies – 1D

Systematic features of CCSN have been studied by 1D simulations.

O'Connor & Ott'11,'13

Ugliano+'12



Results：
CCSN properties（Lnu・Mpns・etc）are
- not a monotonic function of progenitor mass,
- monotonically increasing with **compactness**.

Compactness parameter
（*O'Connor & Ott 2011*）

$$\xi_M \equiv \frac{M/M_\odot}{R(M)/1000\mathrm{km}}$$

Problems of 1D simulations：
- explosion by hand,
- and no NS kick.

*All progenitors are from *Woosley, Heger & Weaver (2002)*

Solar-metallicity (Z=Zo) models

s10.8 - 40.0 （#100）

Metal-poor (Z=$10^{-4}$$Z$o) models

u11.0 - 22.8 / u23.0 - 46.8 / u47.0 - 58.8

（#240）

Zero-metallicity (Z=0) models

z11.0 - 40.0 （#30）

Systematic CCSN studies – 2D

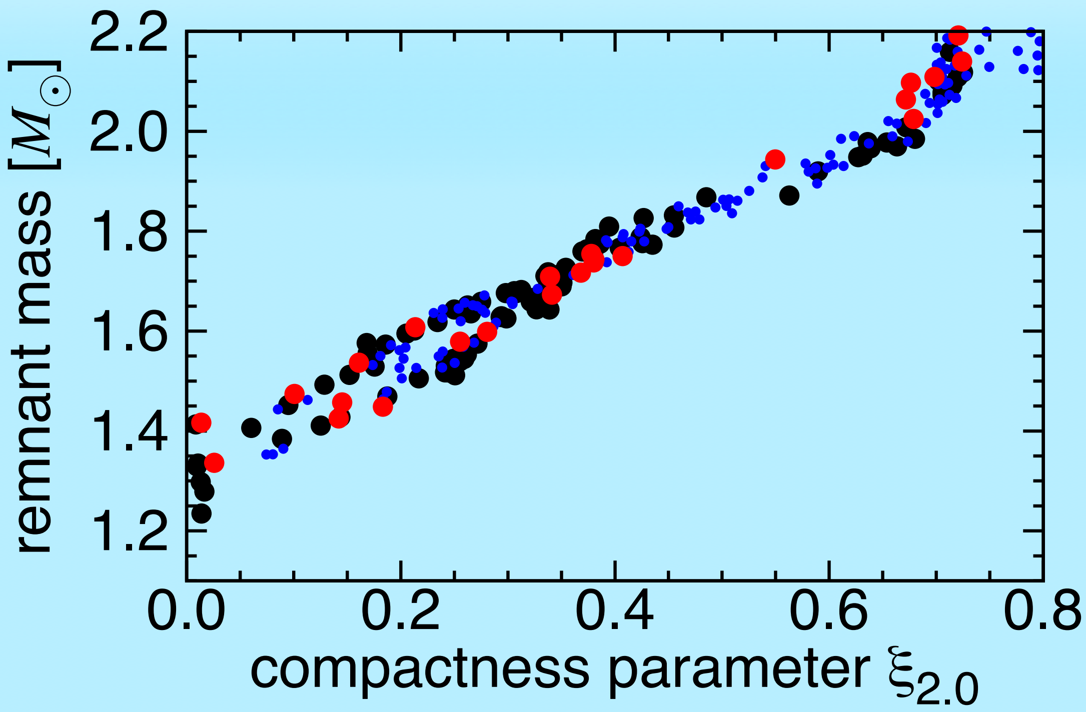
Nakamura+'15

~400 progenitor models covering a wide range of mass（10.8-75Mo）and metallicity (0-1 Zo), 2D, ~1 s.

Self-consistent simulation including neutrino transport and PNS evolution.

Result：
confirm the compactness dependence of CCSN properties.

Problem：
too short to estimate NS acceleration.



NS mass of exploding models with different ZAMS mass and metallicity. Different color shows different metallicity. Here the compactness is defined at M = 2.0 Mo.

2D long-term CCSN simulations

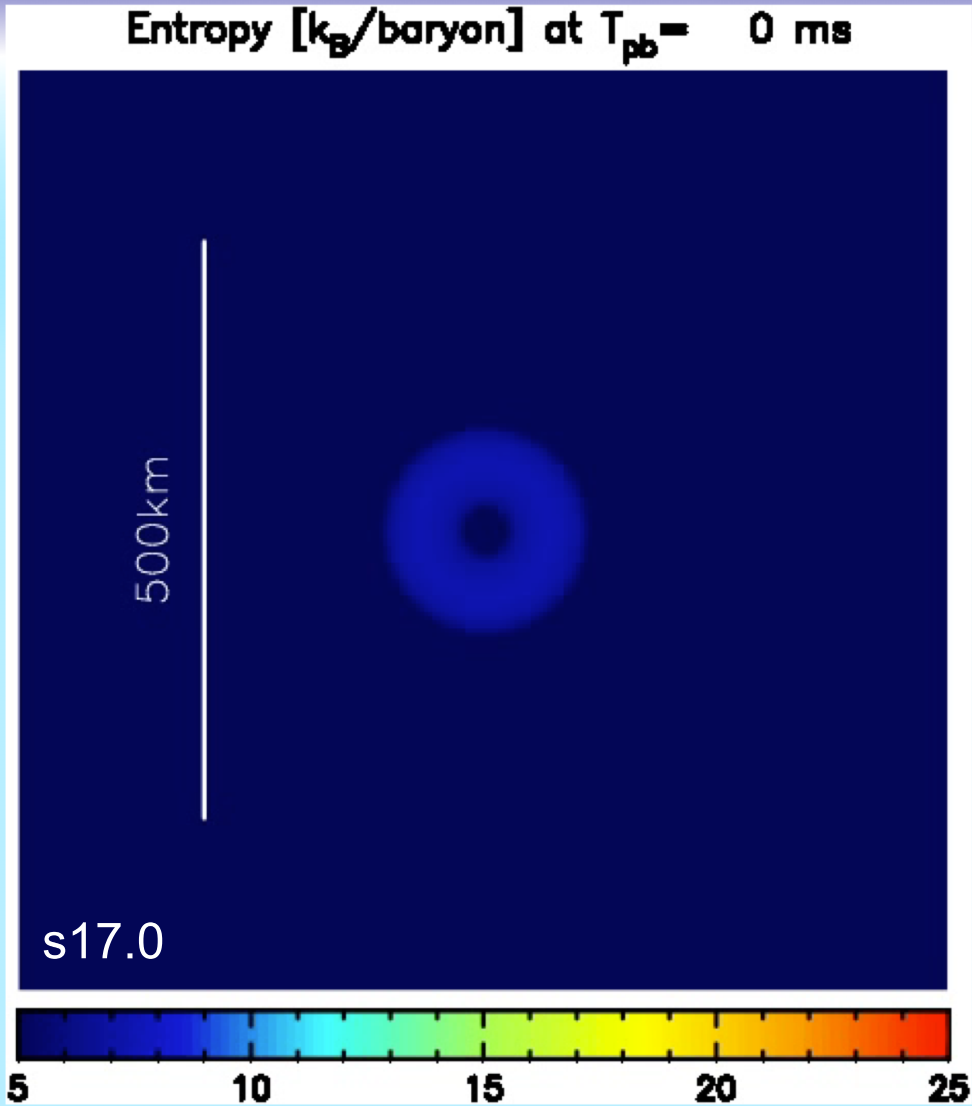
Computation range：
r=0-5000 km → **100,000km**, θ=0-π,
n(r)*n(θ) = 1008*128.

neutrino transport: IDSA (νe,$\overline{\nu}e$)+ Leakage (νx).

EOS: LS220 + Si gas.

Progenitor models:
exploding 10 models selected from
Nakamura+'15 (M=11-20 Mo, Z=Zo).

13-alpha nuclear network.



NS kick – how to estimate

Anisotropy of SN ejecta

$$\alpha_{\rm gas} \equiv |P_{z,\rm gas}|/P_{\rm gas}$$
$$\equiv |\int {\rm d}m\, v_z|/\int {\rm d}m\, |\vec{v}|.$$

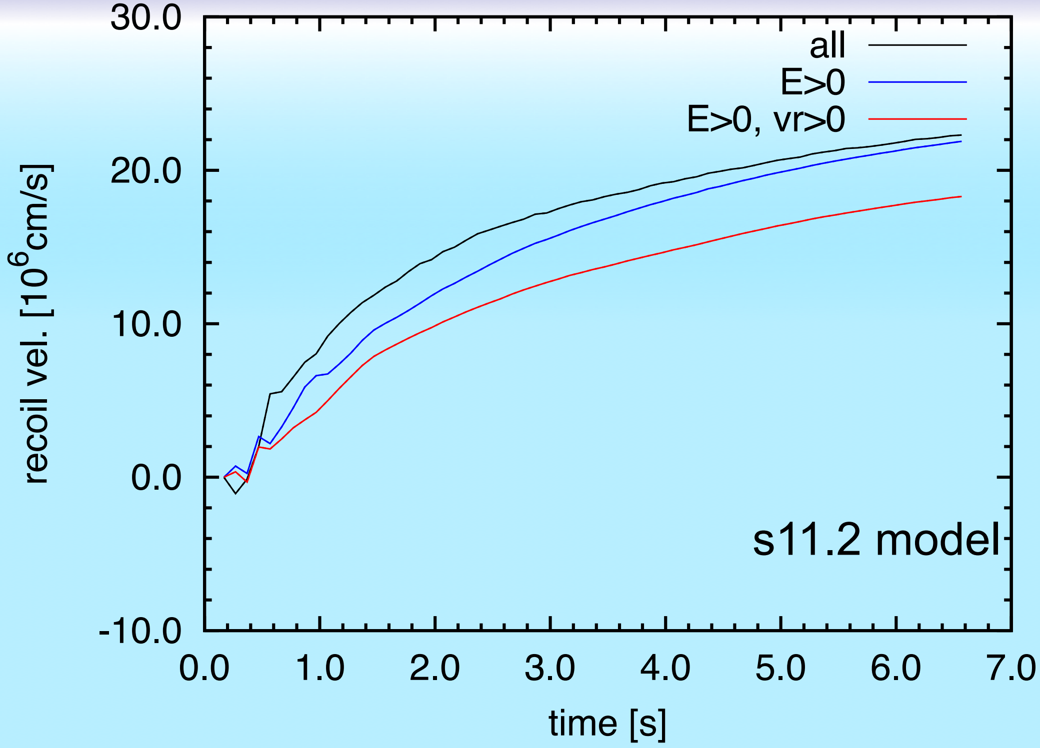
NS kick velocity (recoil velocity)

$$v_{\rm NS} = \alpha_{\rm gas} P_{\rm gas}/M_{\rm NS}.$$

Dependence on integration range (definition of "ejecta"):

- inside the shock ("all")
- and unbound matter ("E>0")
- with positive v_r ("E>0, vr>0")

Here we adopt "all".



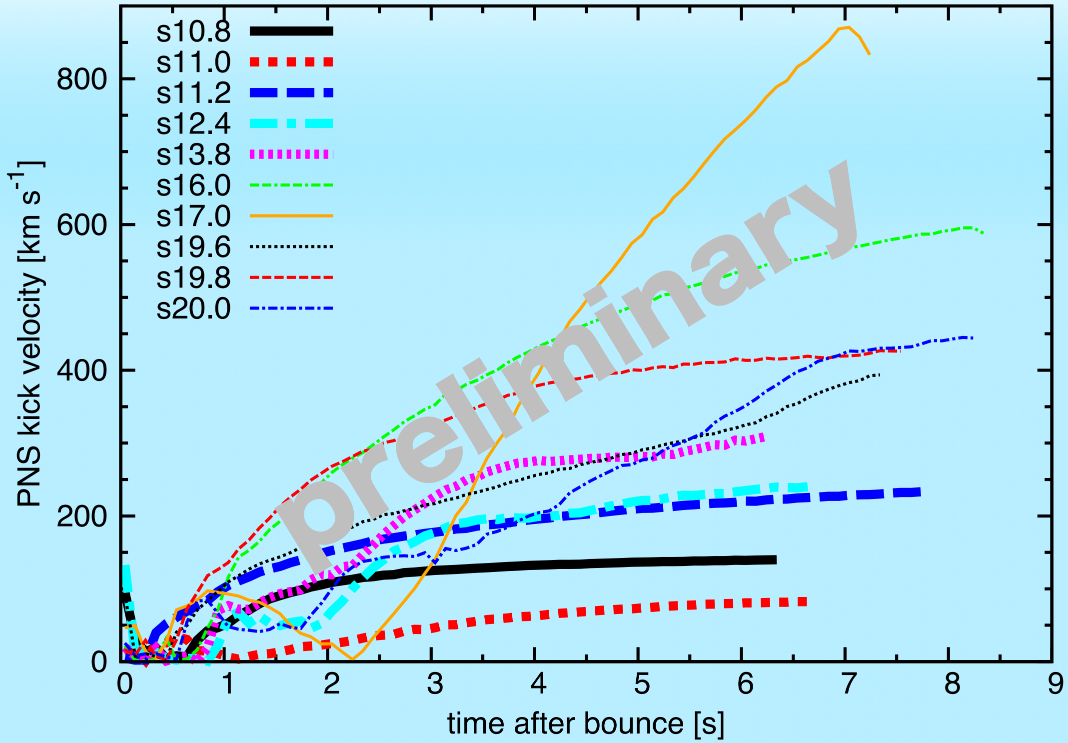
NS kick velocity estimated from recoil formula. "Ejecta" is defined as all the shocked region except NS (black), the region with positive local energy (blue), and with positive local energy and radial velocity (red).

NS kick – result (1)

NS kick velocities range between ~100 km/s (s10.8) and ~850 km/s (s17.0).

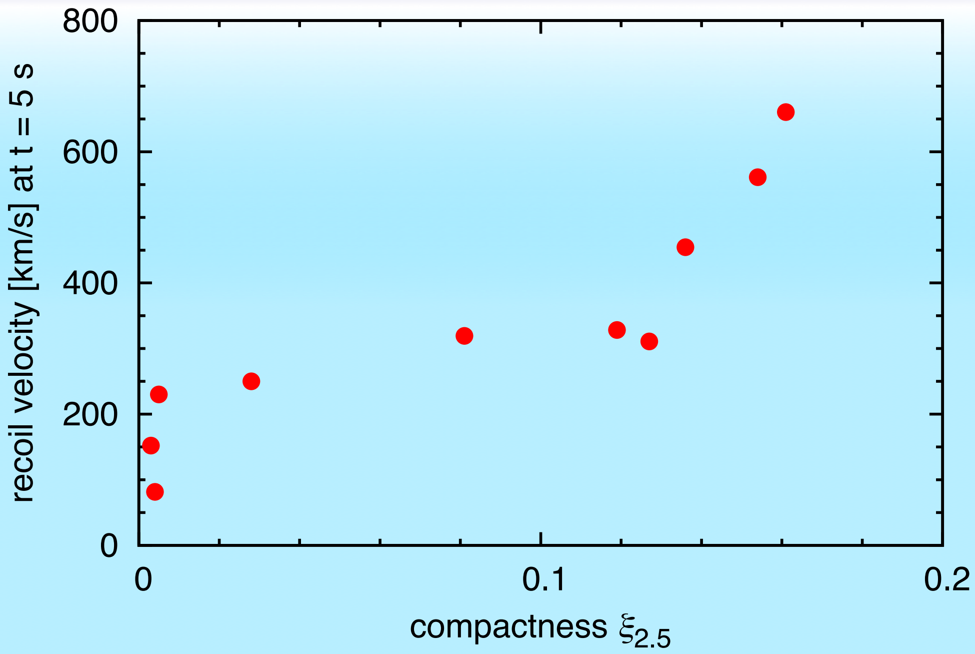
Some models with small kick velocity show convergence within the simulation time.

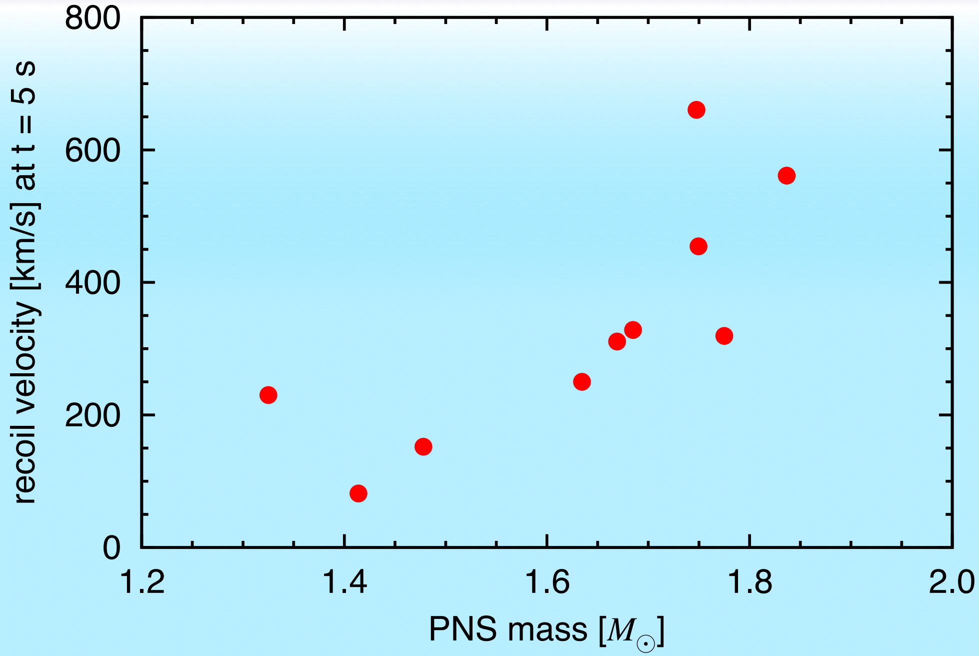
A similar trend to PNS mass and explosion energy.



NS kick velocity estimated from recoil formula. Some models exceeds v_kick > 500 km/s and s17.0 has a final velocity of ~850 km/s.

NS kick – result (2)





High compactness progenitors have high kick velocity.

- development of hydrodynamic instability → large asphericity.
- large explosion energy (Pz).

Massive NSs have high kick velocity.

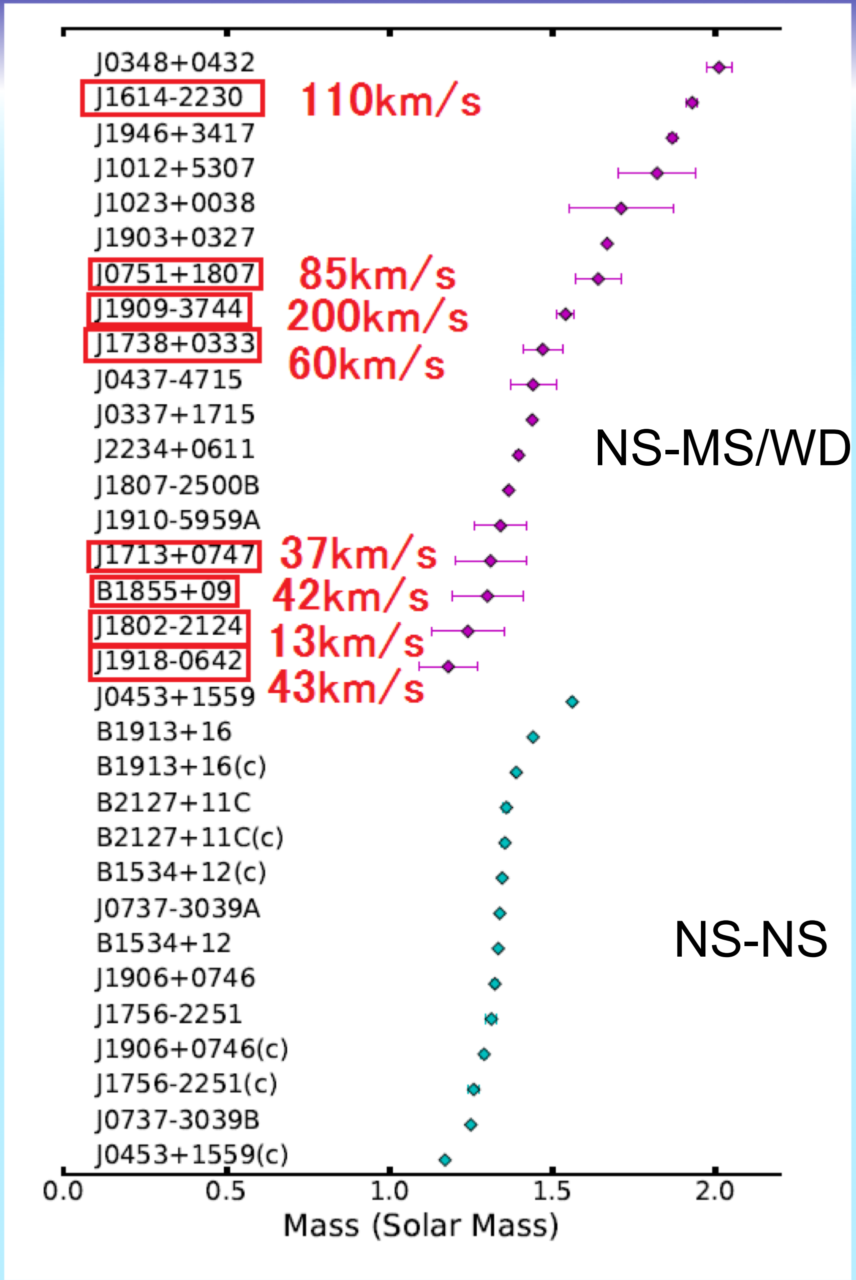
- a monotonic correlation between compactness and NS mass（KN+'15）.
- high compactness → high accretion rate → massive NS.

Observations – NS mass vs. v

NS mass ranges
from ~1.2 Mo to ~2 Mo.

Massive NSs tend to have high velocities.

Caution !
The velocity shown here is of binary system (not the kick velocity itself).

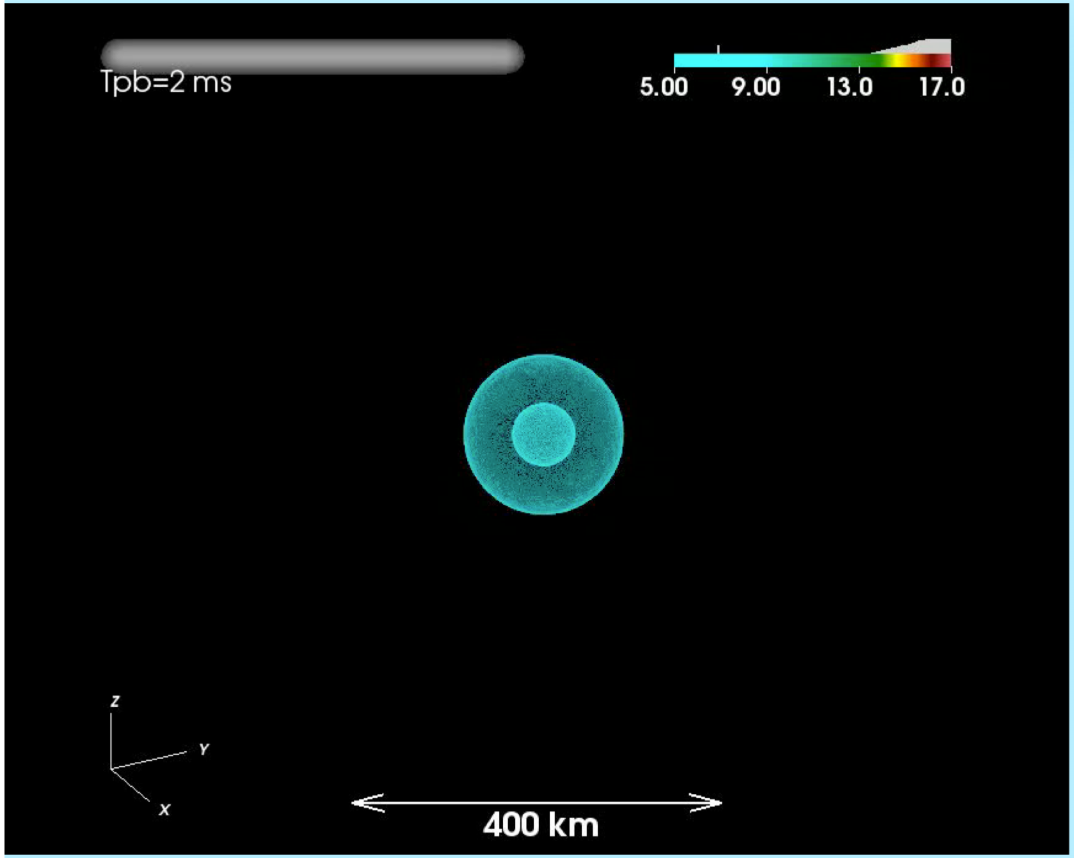


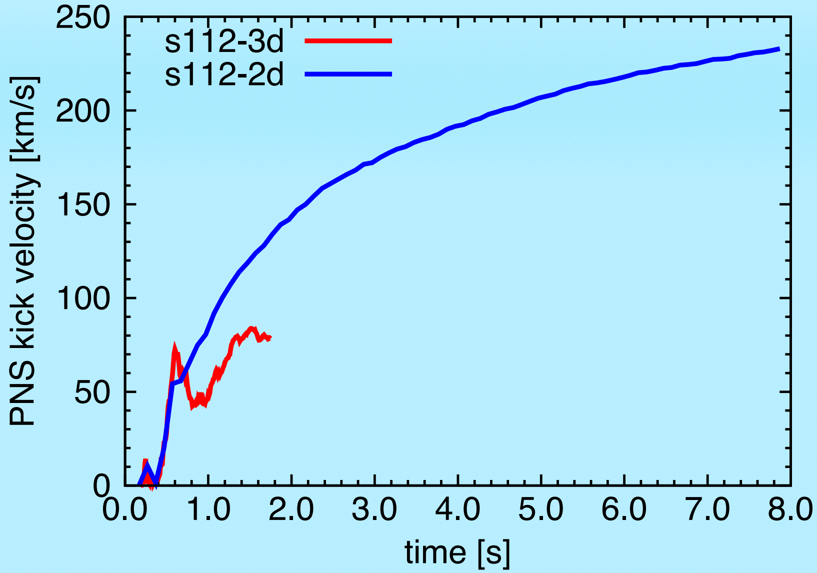
Summary & discussions

- ✓ NS kick velocities estimated from 2D self-consistent long-term CCSN simulations.
- ✓ 10 models have kick velocity between ~100 km/s (s10.8) and ~850 km/s (s17.0).
- ✓ Massive NSs tend to have high kick velocity ← supported by observation.

- ◆ NS mass, explosion energy, and NS kick velocity of models with high compactness are still increasing at ~ 10 s.
- ◆ continuous accretion from the equatorial plane.

3D simulation (preliminary)



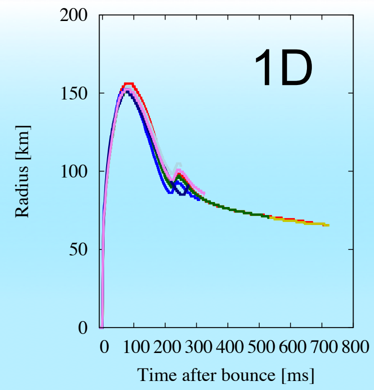


s11.2 (WHW02)
LS220 + Si gas
2-flavor IDSA + leakage
Newtonian

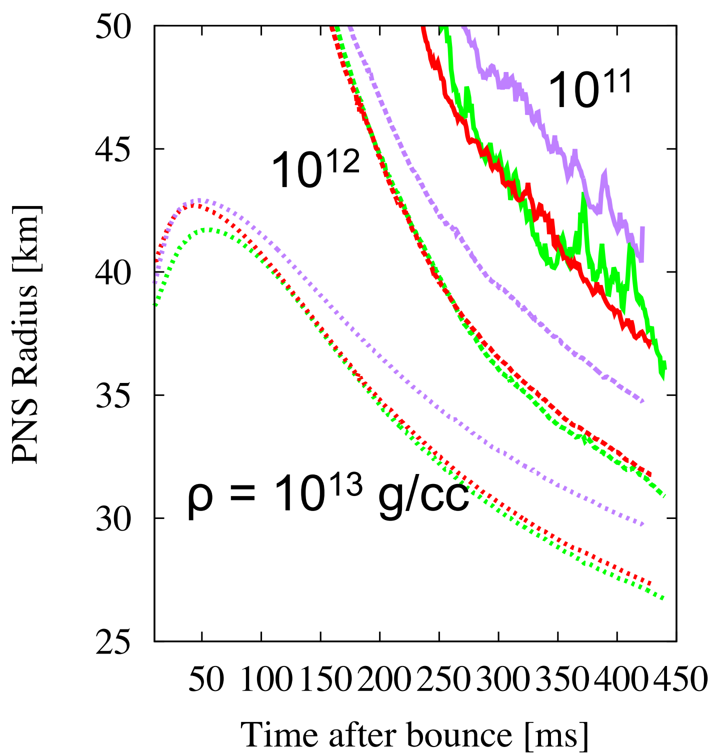
EOS dependence (preliminary)

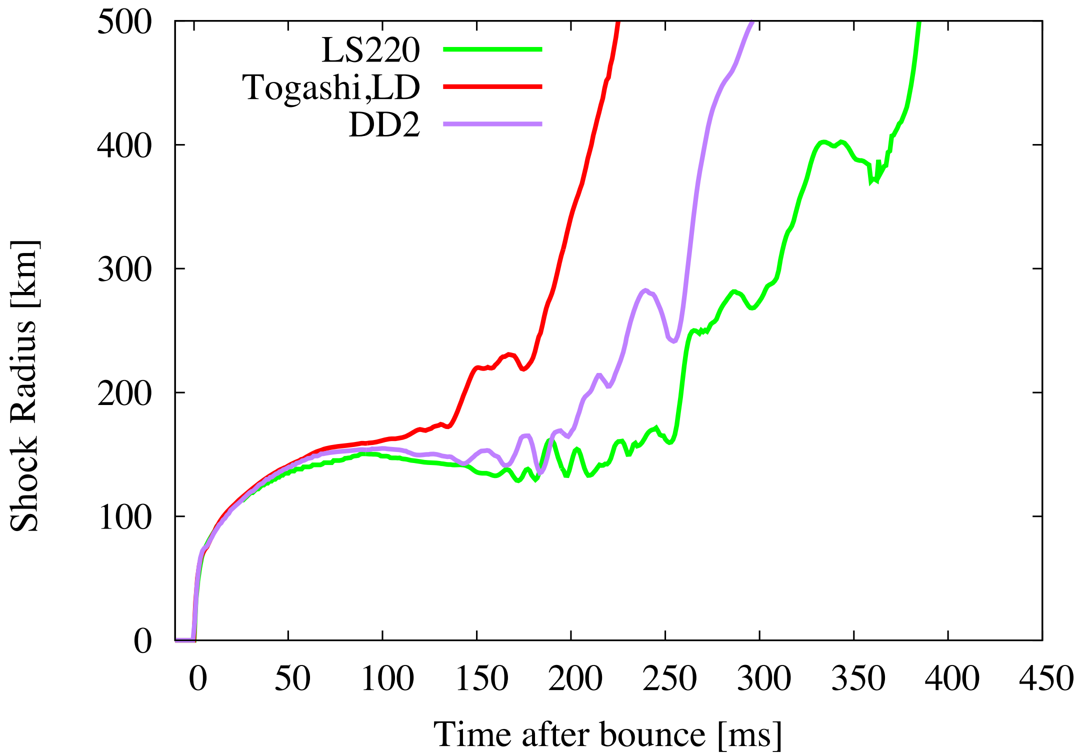
1D models are almost identical.

2D models show different evolution of shock waves.



2D (512x64), s27.0





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- ◆ NS mass, explosion energy, and NS kick velocity of models with high compactness are still increasing at ~ 10 s.
- ◆ continuous accretion from the equatorial plane.

◆ 3D long-term simulation are required,
for multiple progenitors
with sophisticated (*the true*) EOS !