Kicks and Spins of Neutron Stars in Supernova Remnants and PWNe

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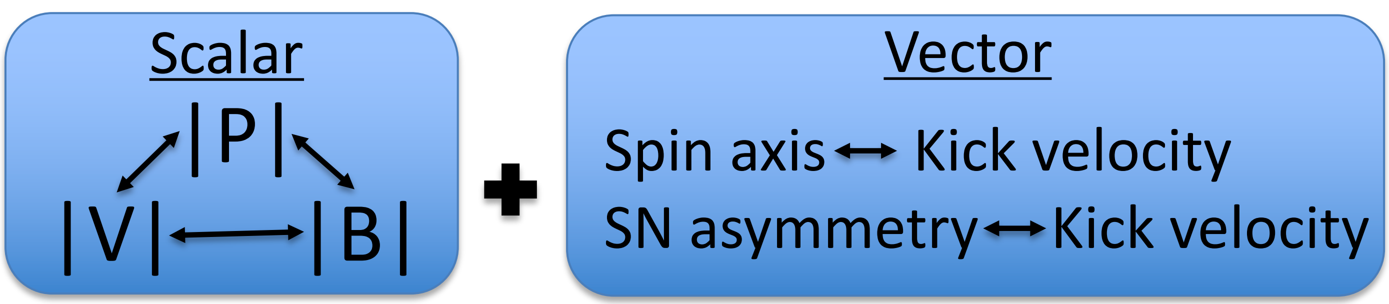
Neutron Star Properties → Core-Collapse Explosion Physics

- Neutron stars have extreme properties:
  - Rapid rotation (P ~ 10 – 500 ms)
  - Fast motion (V ~ 200 – 500 km/s)
  - Strong magnetic field (B ~ 10^{12} G)

  These should be reproduced by SN explosion models.

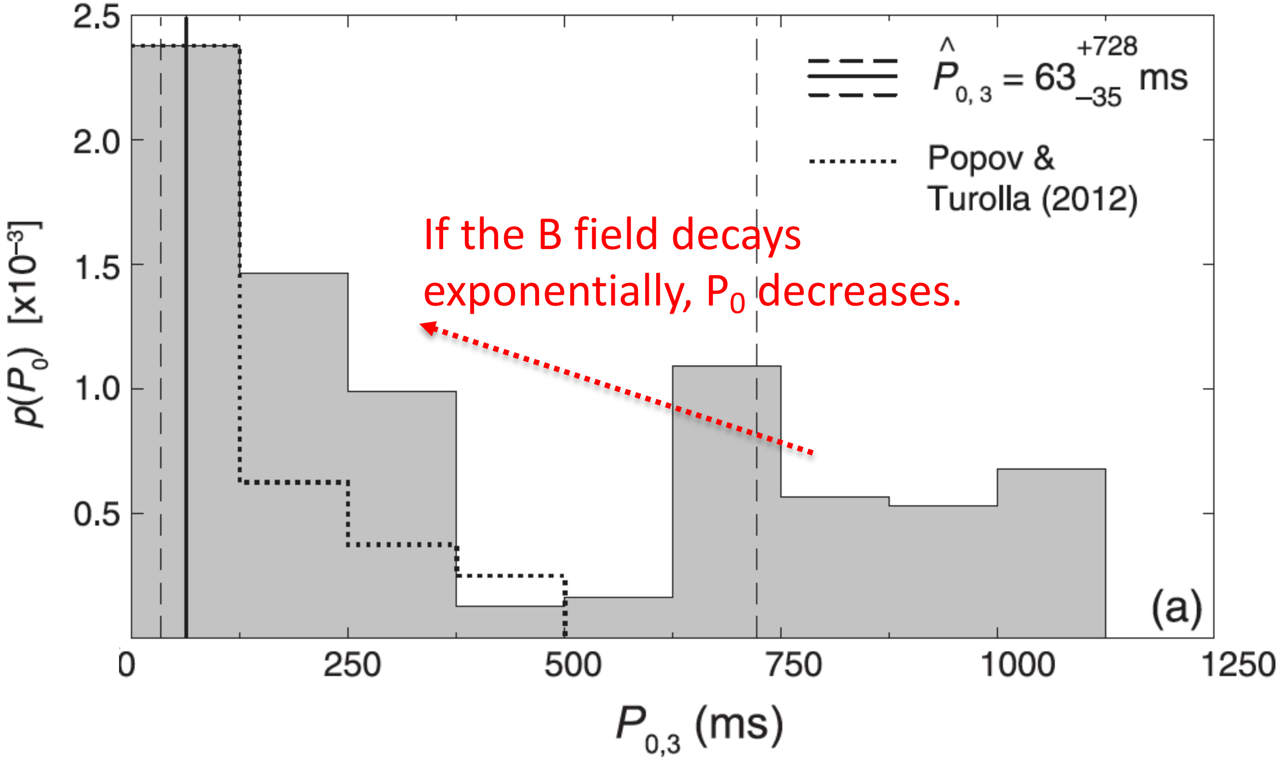
B. Mueller's talk

- Finding correlations among these parameters is important to constrain SN explosion models.



Distribution of Initial Spin Periods (P_0)

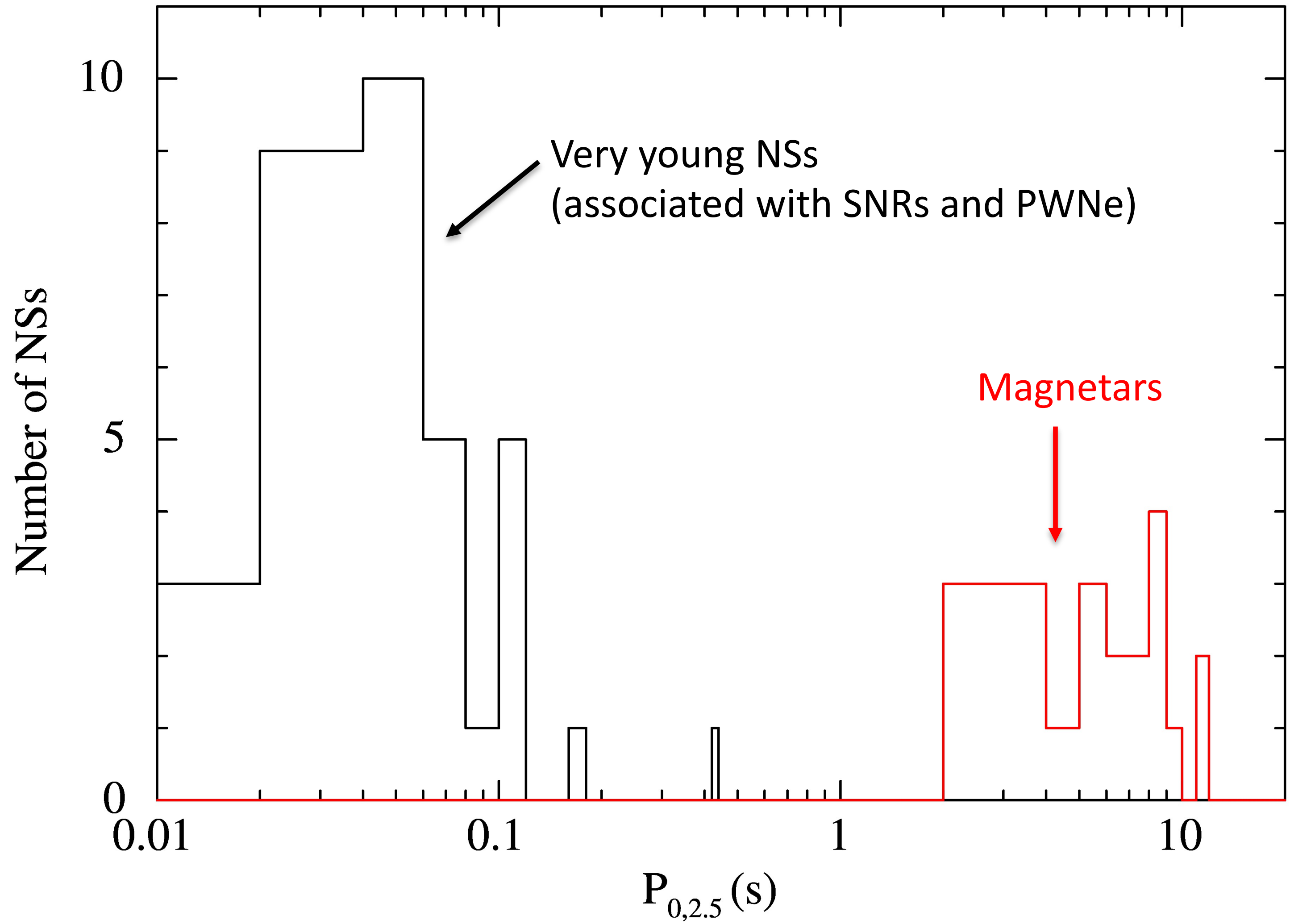
1) Noutsos et al. (2013) estimated P_0 for radio pulsars with relatively well-determined kinematic ages.
2) Popov & Turolla (2012) estimated P_0 for a much younger population of NSs associated with SNRs.



(1) and (2) do not coincide! → If we consider magnetic-field evolution, the two distinct P_0 distributions could converge (Igoshev & Popov 2013).

Magnetars: Another Population

How to explain magnetars? B-field evolution?

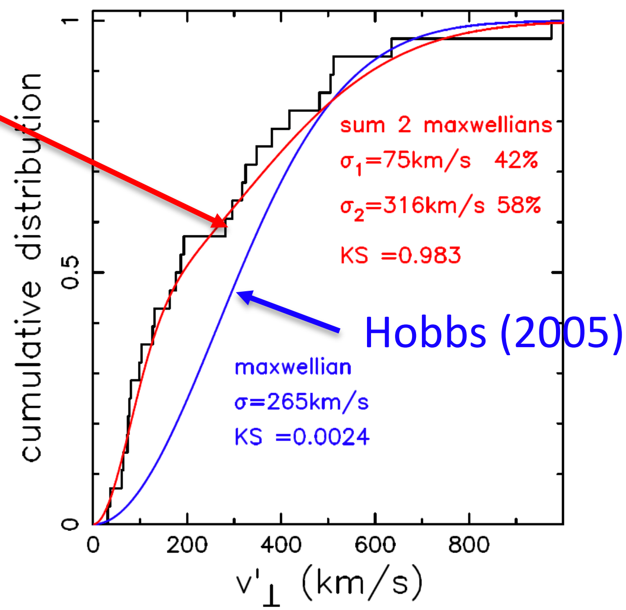


Distribution of Velocities

- Single peak or double peaks?

Reference	Single Maxwellian σ (km s^{-1})	range	Two Maxwellians σ_1 (km s^{-1})	range	σ_2 (km s^{-1})	range	w (%)	range
Arzoumanian et al. (2002)[a]	290	260–320	90	75–110	500	350–750	40	20–60
Brisken et al. (2003a)			99		294		20	
Hobbs et al. (2005)	265	239–291						
Faucher-Giguère & Kaspi (2006)	290	260–320	160	130–180	780	640–930	90	87–100
Verbunt et al. (2017)	239	219–267	75	60–95	316	276–368	42	30–52

NB: Average = σ * sqrt(8/π)



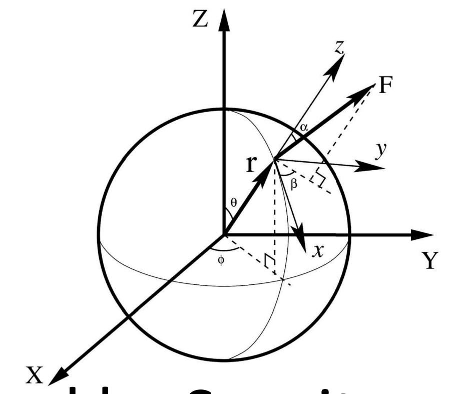
The most recent results favor a bimodal distribution.

Correlations among NS Parameters

	Correlation	References (mainly observations)
$P_0 - V_0$	No Yes ? ->	Spruit & Phinney 98 High V => slow rot. (e.g., Ng & Romani 07)
$V_0 - B_0$	No	Anderson & Lyne 83; Lorimer+95; Birkel & Toldra 97; Deshpande+99
$B_0 - P_0$	No Yes ? ->	Popov & Turolla 12; Igoshev & Popov 13 Mainly due to time evolution of B
Spin axis – kick velocity	Yes	Ng & Romani 04; Johnston+05; Noutsos+13; Rankin+15
V_{kick} – SN asymmetry	Yes	Holland-Ashford+17; SK+18

Here, we will focus on the observational status of
- Spin axis – kick velocity
- Kick velocity – SN asymmetry

Spin – Kick Alignment

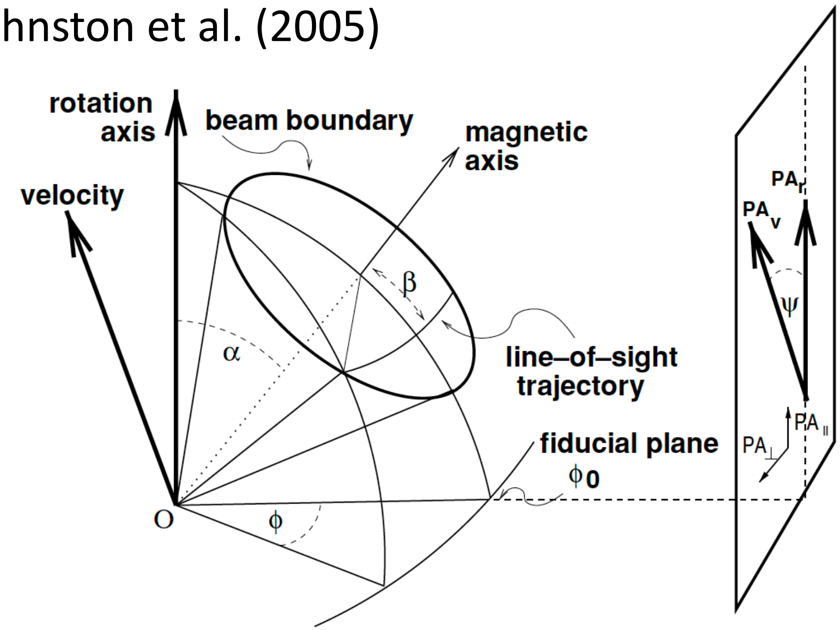


Theoretical expectation

- Off-centered (non-radial) thrusts during explosion give both angular and linear momenta to NS, which was proposed by Spruit & Phinney 1998; Cowsik 1998.
- If the number of thrust is unity, NSs always rotate about an axis perpendicular to the direction of motion.
- If the number of thrust exceeds 5 or so (which is likely realistic) and thrusts have long durations (τ ~> 10 P_0), spin-axis and kick-vector tend to be along the same direction. This is because the momentum perpendicular to the spin axis is rotationally averaged away (e.g., Wang et al. 2007).

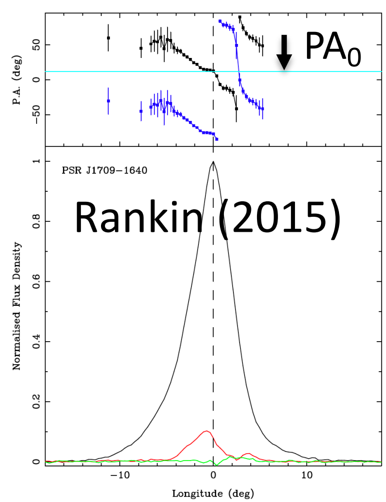
Radio Polarization → Spin Axis

Johnston et al. (2005)



The rotating vector model (Radhakrishnan & Cooke 1969) gives the position angle of the polarization:

$$\mathrm{PA} = \mathrm{PA}_0 + \arctan\left[\frac{\sin\alpha\,\sin(\phi-\phi_0)}{\sin\zeta\,\cos\alpha - \cos\zeta\,\sin\alpha\,\cos(\phi-\phi_0)}\right]$$



The spin axis (PA_r) is generally difficult to measure…

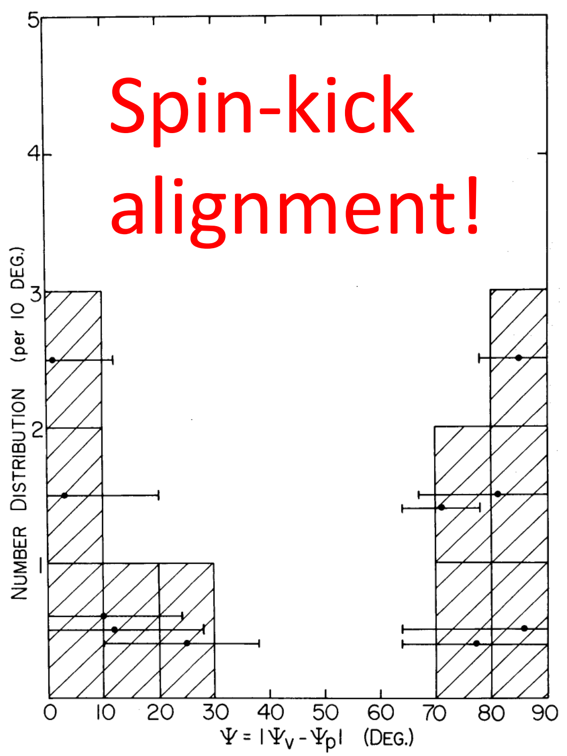
<u>But, there is a way.</u>

Determine PA ($\phi = \phi_0$) = PA_0, the position angle of polarization at the point of closest approach of the observer's line of sight. Then, PA_r is equated to PA_0 (or $PA_0 + 90^o$ if the pulsar emission is in the orthogonal mode), after correcting for the rotation measure.

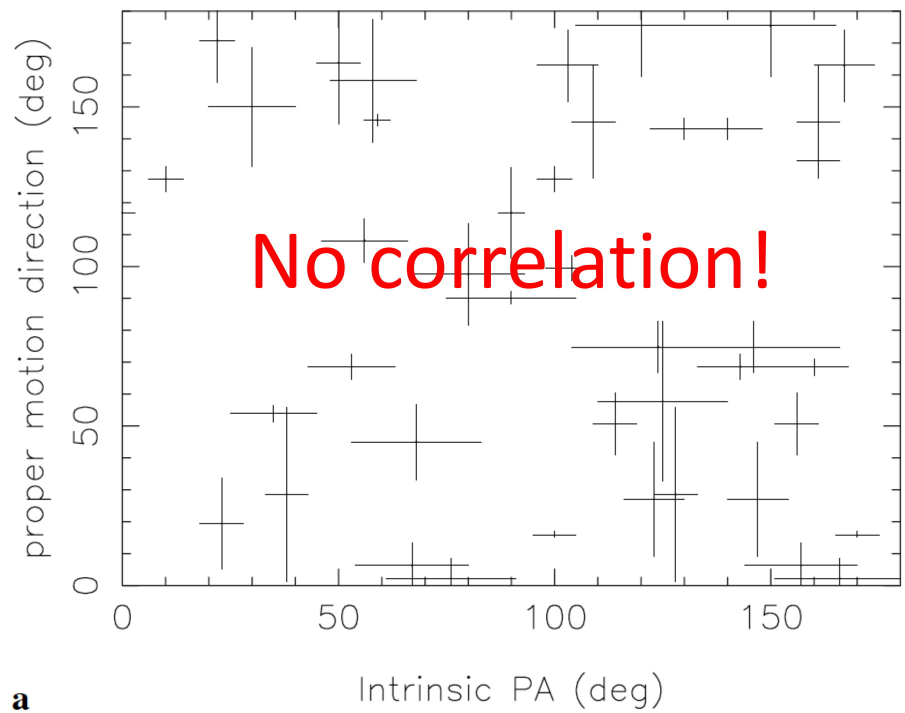
Early Results

- Early studies were ambiguous.

Tademaru (1977)



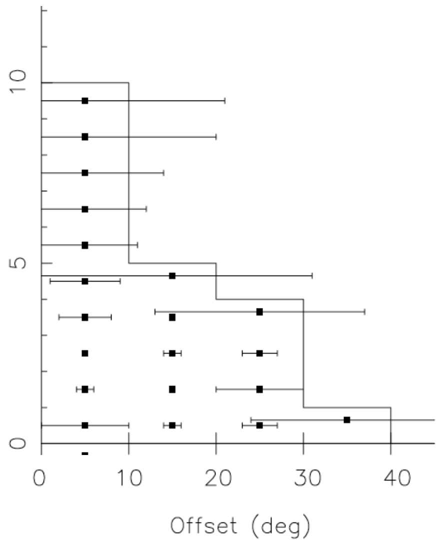
Deshpande et al. (1999)



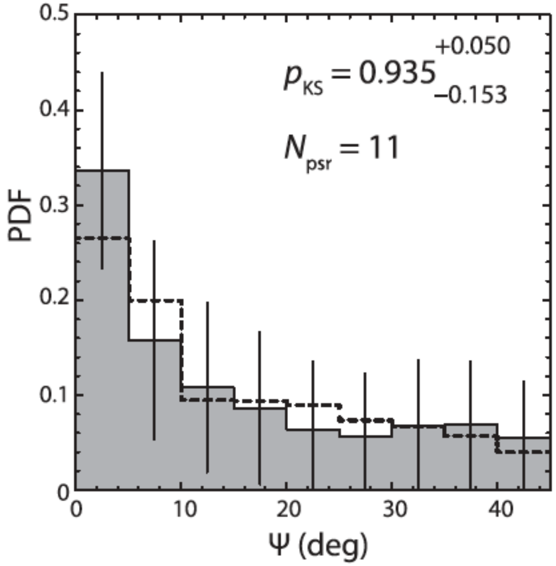
Later Results

- Refined polarization measurements provided evidence for spin-kick alignments (Johnston et al. 2005).
- The alignment became even stronger for young pulsars with ages < 10 Myr (Noutsos et al. 2013).

Johnston et al. 2005



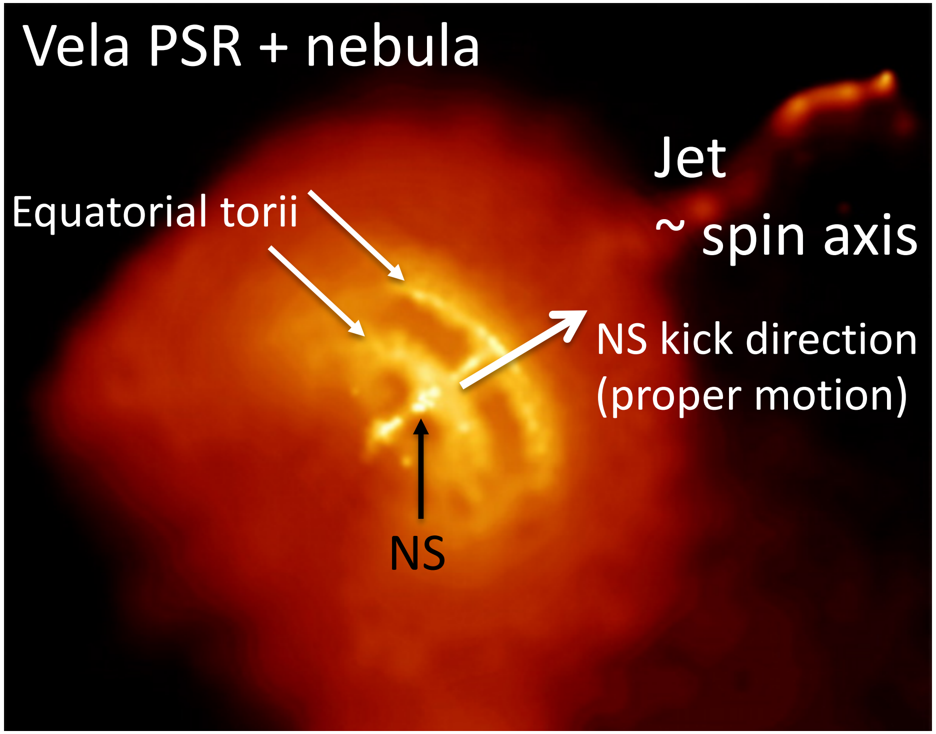
Noutsos et al. 2013



Pulsar Wind Nebulae → Spin Axes

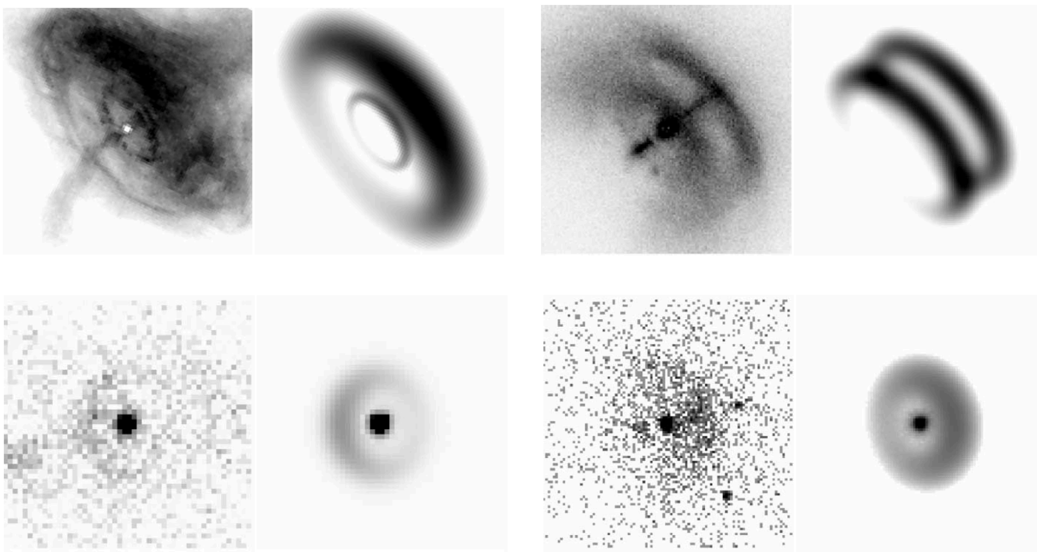
- Fine structures of pulsar wind nebulae with CXO

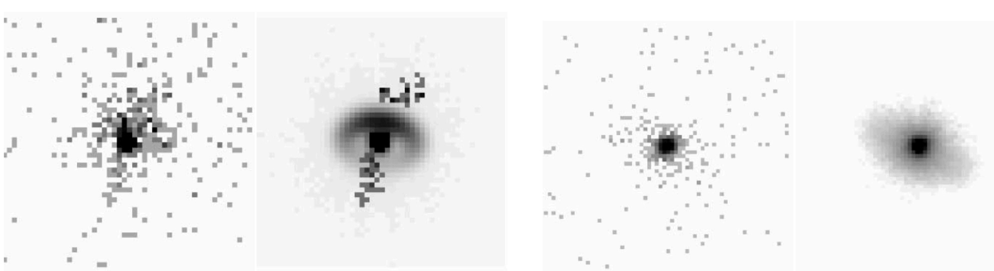
Helfand et al. (2001) showed high-resolution X-ray images of the Vela PWN, finding two prominent arcs. Their symmetry axis is 310°, which is within 10° of the proper motion vector of 301° for the pulsar.



Statistical Study of PWNe

Following X-ray observations showed similar equatorial torii and polar jets from a number of PWNe. Ng & Romani (2004) found good spin-kick alignments for six PWNe.

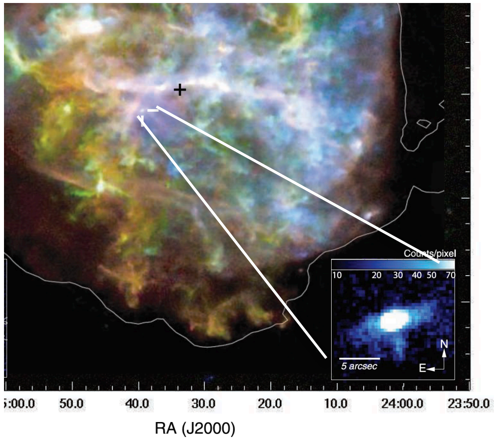




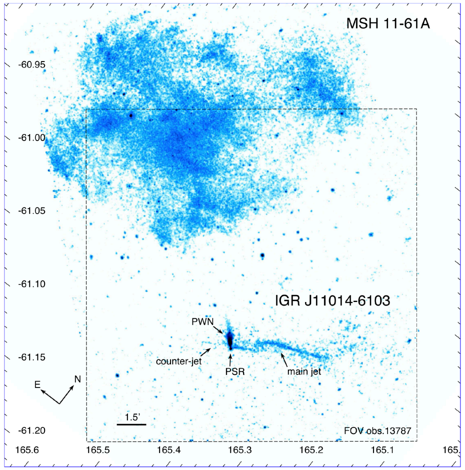
Pulsar	Ψ (deg)	Ψ_{PM}[a] (deg)	$\lvert \Delta\Psi_{\Omega \cdot v} \rvert$ (deg)
B0525+21...............	124.0 ± 0.1	292 ± 10	12 ± 10
B0656+14...............	...	93.1 ± 0.4	...
J0538+2817............	155 ± 8	328 ± ~4	7 ± 9
B0833−45...............	130.6 ± 0.1	302 ± 4	8.6 ± 4
B1706−44...............	175 ± 4	160 ± ~10	15 ± ~11
B1951+32...............	85 ± ~5	252 ± 7	13 ± ~9

Exceptions

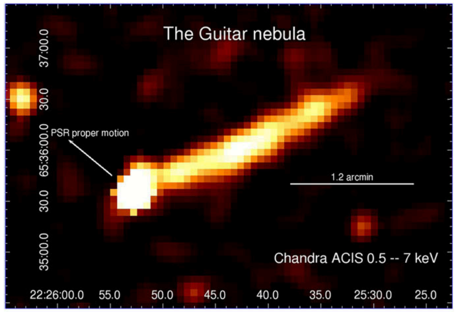
However, exceptions have been emerging.



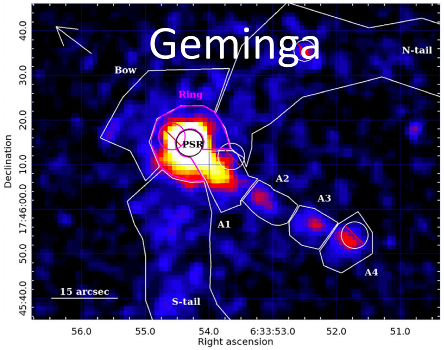
Park et al. (2007)



Pavan et al. (2014)



Bykov et al. (2017)



Posselt et al. (2017)

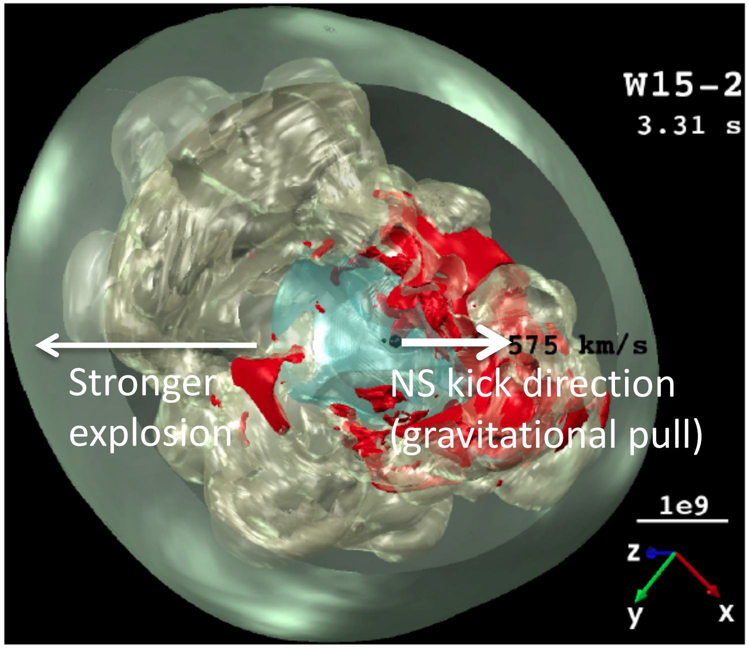
→ The PWN-based spin-kick alignment is still controversial.

Kick – SN Asymmetry

Theoretical expectation

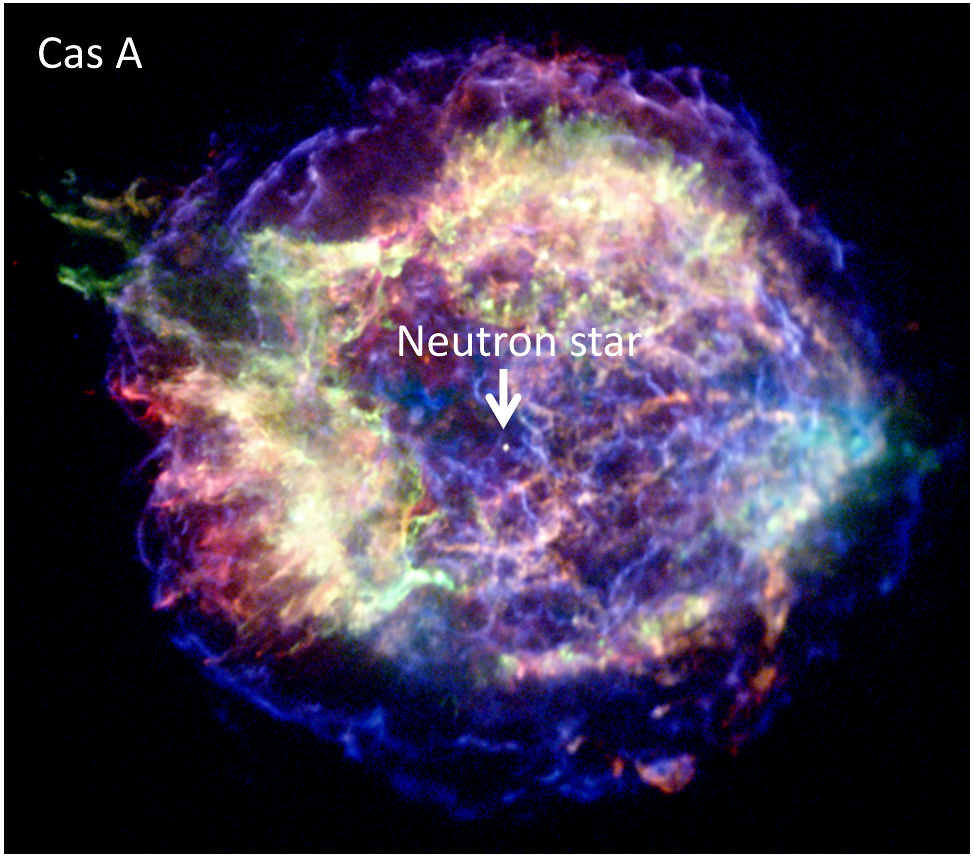
- Janka & Muller (1994) argued that anisotropic ejection of mass due to hydrodynamic instabilities can produce the high velocities of NSs.
- Recently, Bray & Eldridge (2016; 2018) showed that the NS velocity distribution can be described by a simple formula:
  $V_{kick} = \alpha\ (M_{ej}/M_{NS}) + \beta$,
  with α = 100 km/s and β = -170 km/s.

3D simulation by Wongwathanarat et al. (2013)



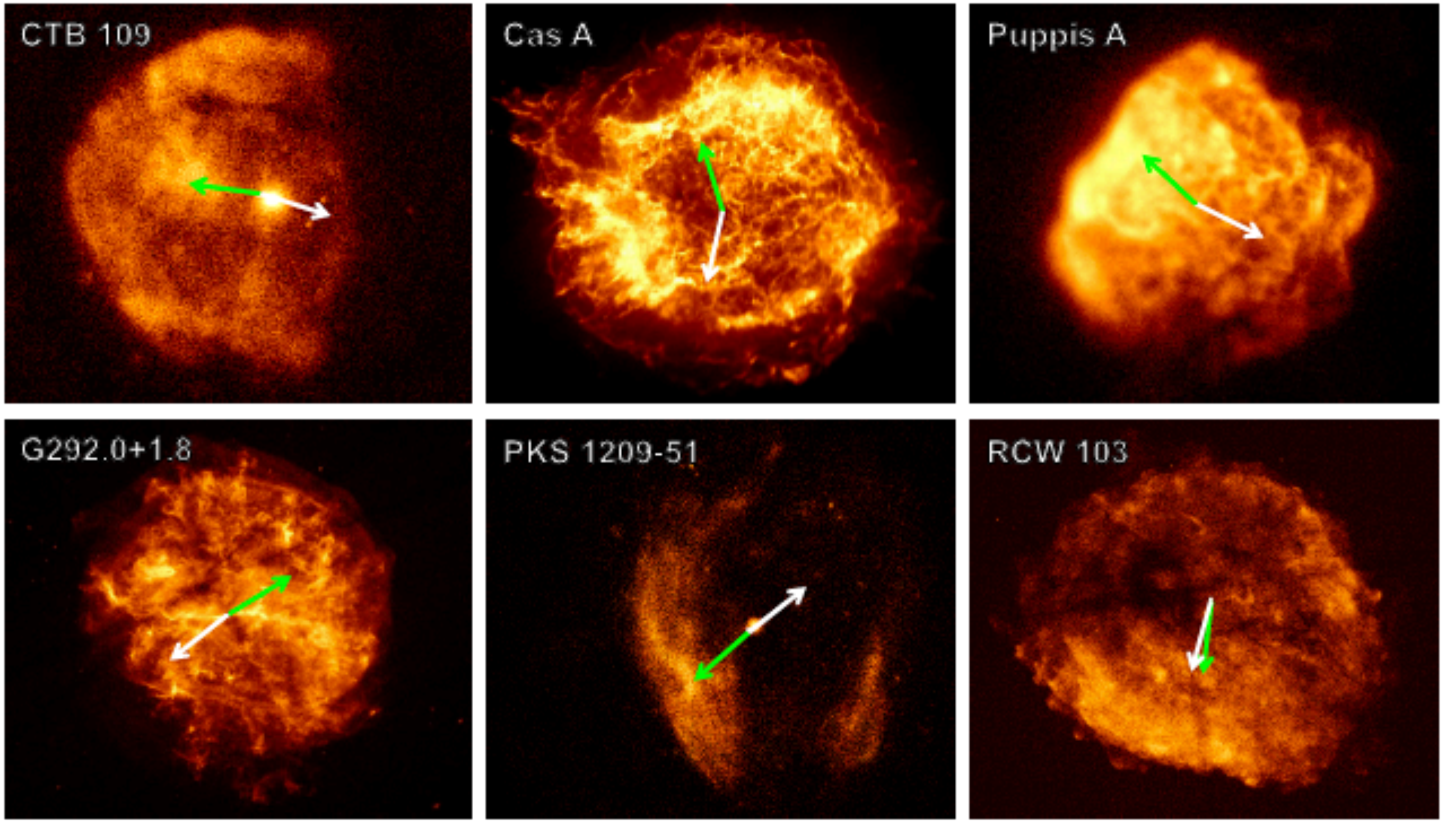
Supernova Remnants

Supernova remnants allow us to reveal detailed explosion morphologies and locations of neutron stars, offering a unique site to directly test the kick scenario.



Observational Results by Holland-Ashford+

Holland-Ashford et al. (2017)



Anti-correlation between center-of-mass of X-ray emission and NS kick direction was found, which supports the hydrodynamic kick mechanism. But, several caveats remain.

(1) The CSM and ejecta components are not resolved.

(2) The energy range used is 0.5-2.1 keV, dominated by light elements like O, Ne, and Mg.

(3) Explosion sites are not so accurate, given that systematic errors on PMs are ignored.

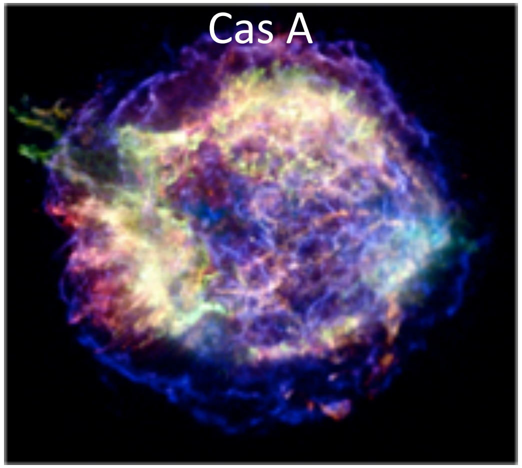
Our Target Selection

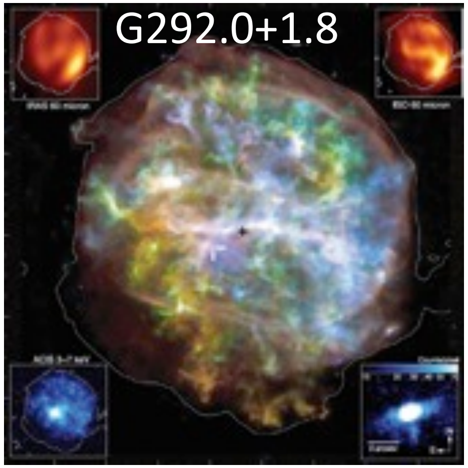
We selected six supernova remnants that pass the following three criteria:

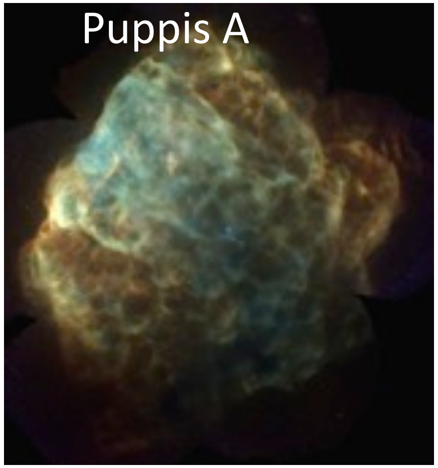
(1) Relatively young (< a few 10^3 yr)

(2) Intermediate elements (Si, S, Ar, Ca) are detected in X-rays

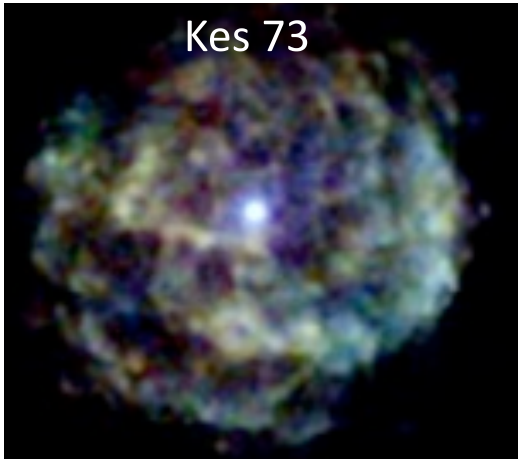
(3) Host neutron stars

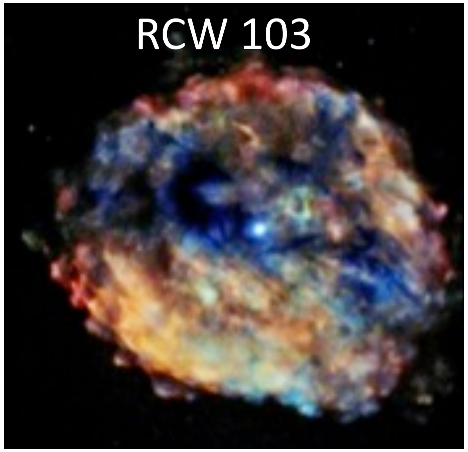


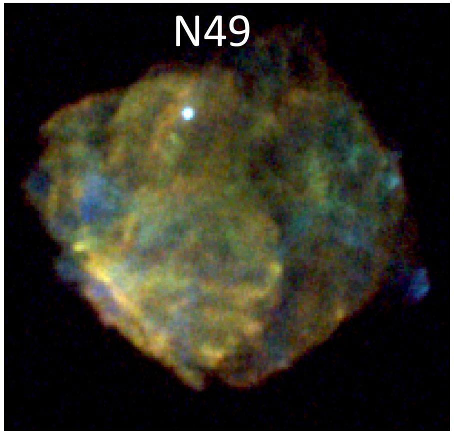




O-rich SNRs



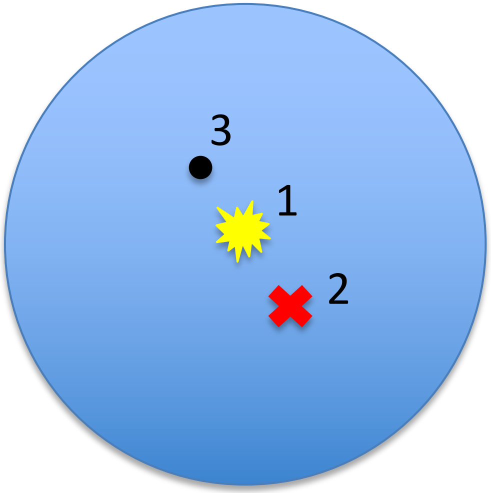




Host magnetars

What Should We Measure?

1) Explosion sites (CoE and/or CoX)
(We already know them for O-rich SNRs.)

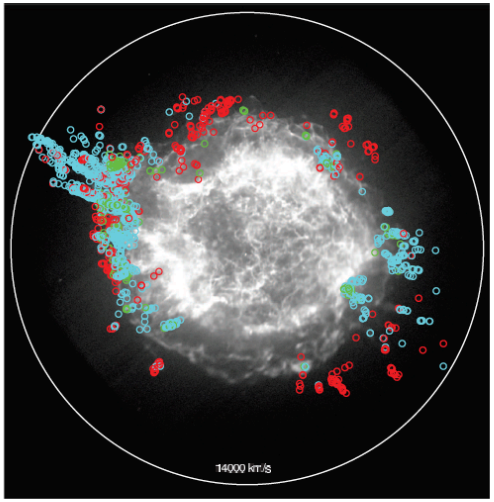


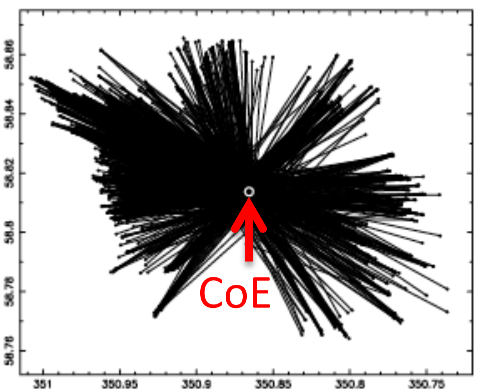
2) Center of mass of ejecta (CoM)

3) NS positions and their proper motions if available (We already know NS positions for all SNRs.)

Inferring Explosion Sites 1: O-rich SNRs

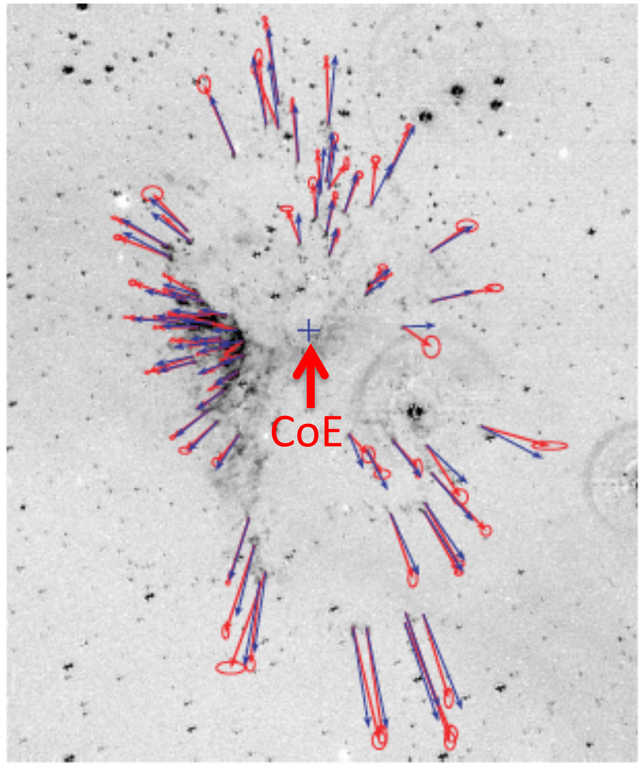
Cas A





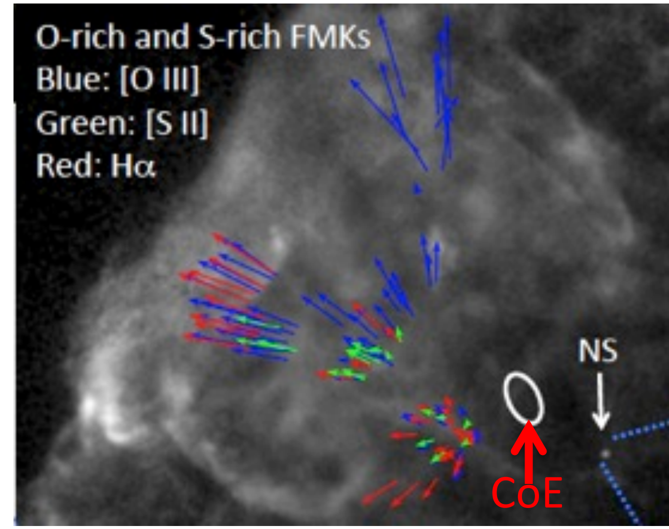
Fesen et al. (2006)

G292.0+1.8



Winkler et al. (2009)

Puppis A



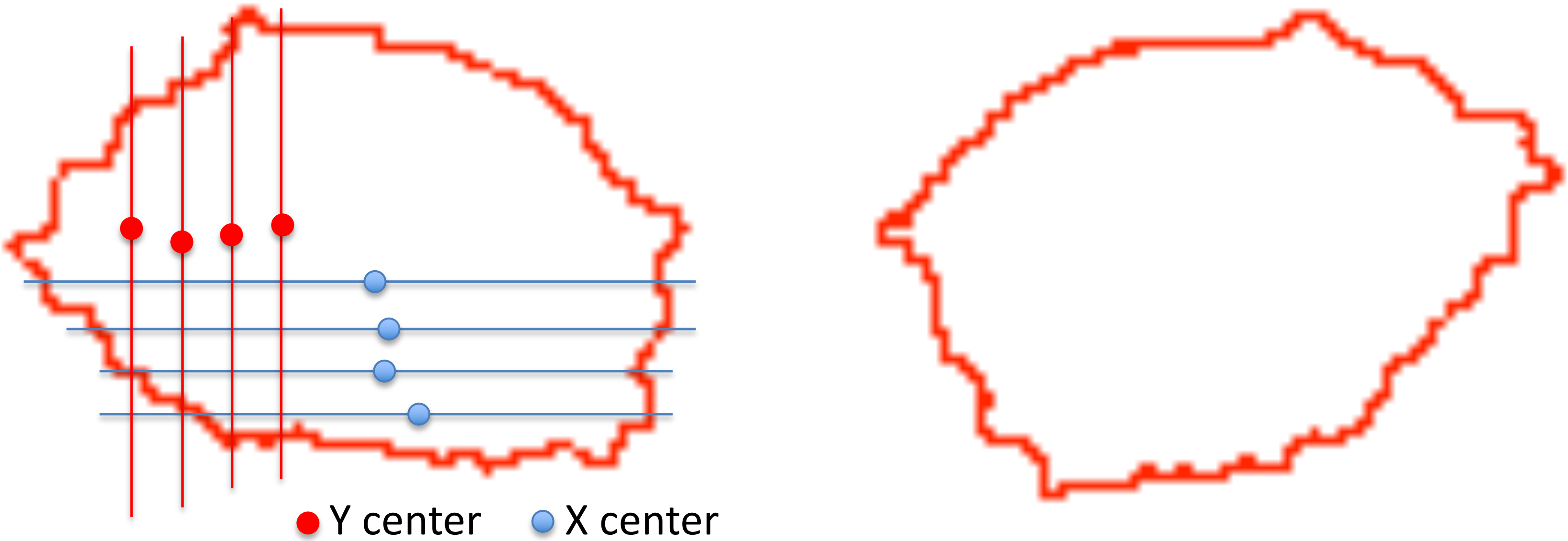
Winkler et al. (1988); Garber et al. (2010)

Tracing back the optical fast-moving knots' proper motions.
→ Center of expansion (CoE)

Inferring Explosion Sites 2: Other SNRs

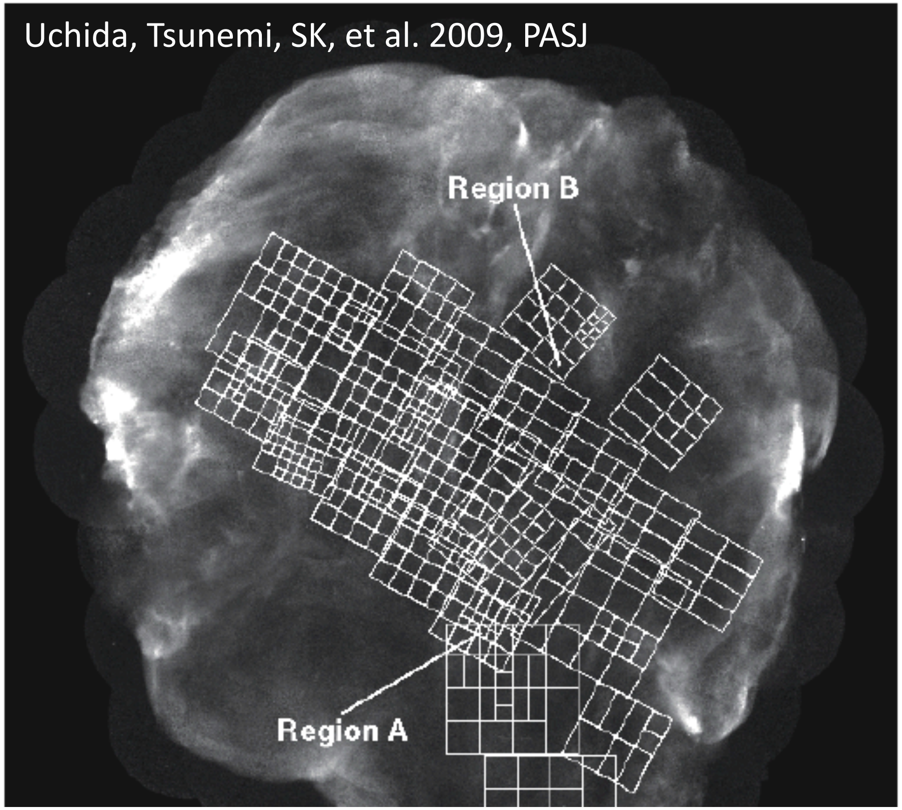
For other SNRs, we inferred the explosion sites based on the X-ray boundaries.

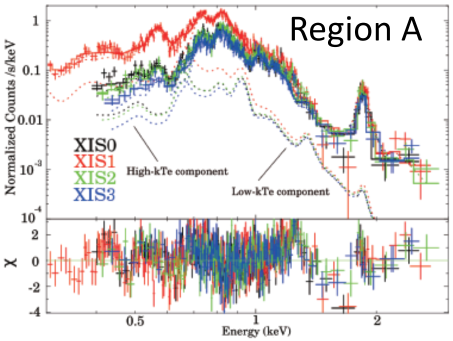
RCW 103 @ rotation angle = 0 deg   @ rotation angle = 35 deg

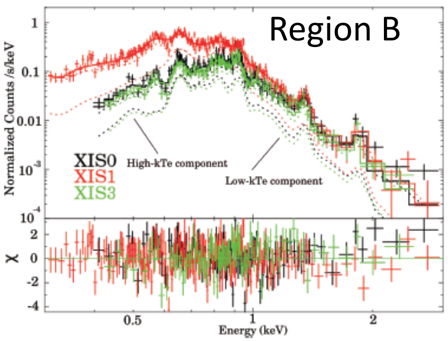


0) Draw X-ray boundaries
1) Slice the boundaries in X, Y directions, and calculate a number of (X, Y) centers.
2) Take the average of the lots of (X, Y) centers.
3) Rotate the remnant, and repeat the same procedures 1) and 2), deriving lots of averaged (X,Y) centers. The average and standard deviation of these centers are taken as our best-estimated CoX and its uncertainty, respectively.

Center of Mass: Conventional Method







<u>Conventional method</u>:
Spatially-resolved spectral analyses

<u>Problem with the conventional method:</u>
Takes too much time.
→ Need for more efficient analysis technique.

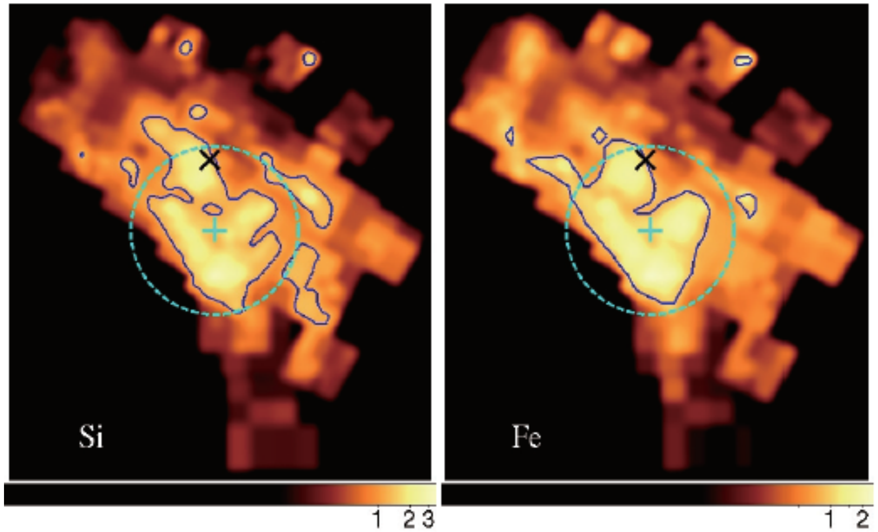
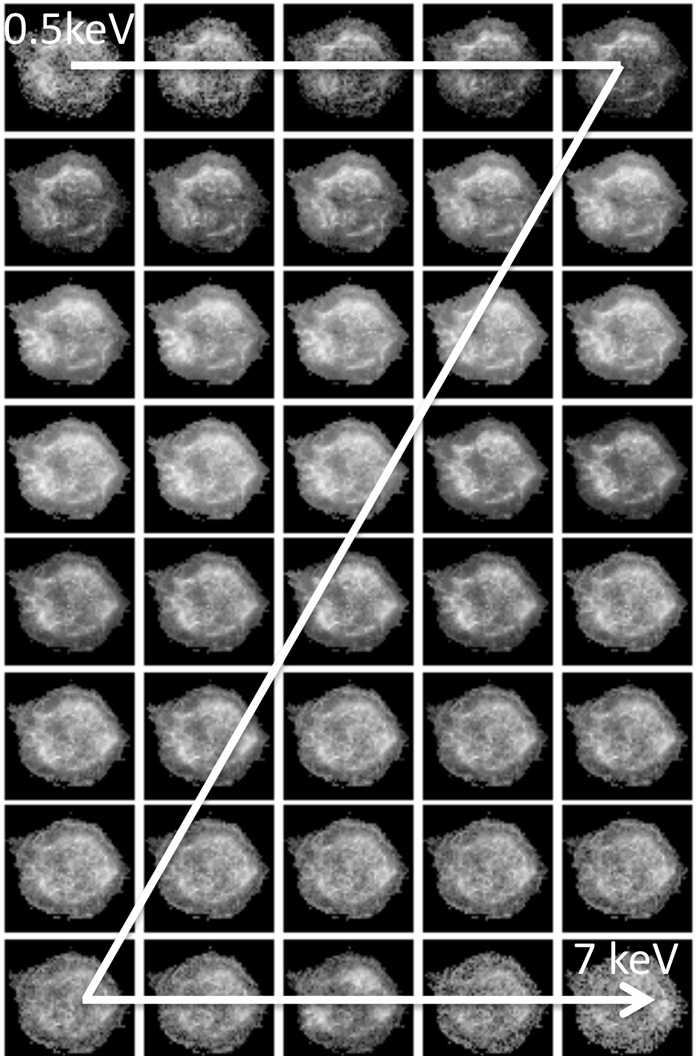
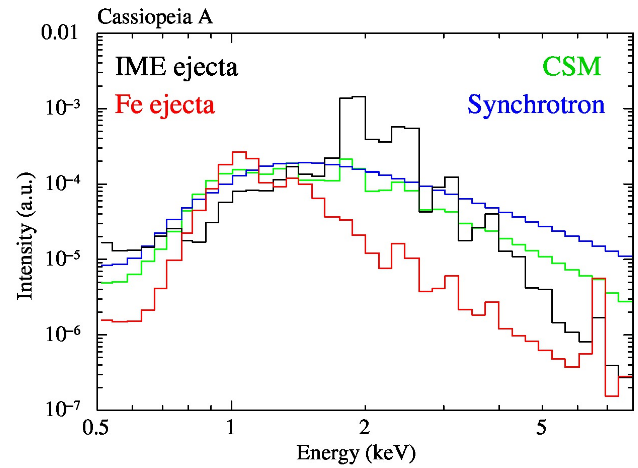


Image Decomposition

1. Narrow band images



2. Templates of individual spectral components (e.g., IME-rich ejecta, CSM)



Input 1

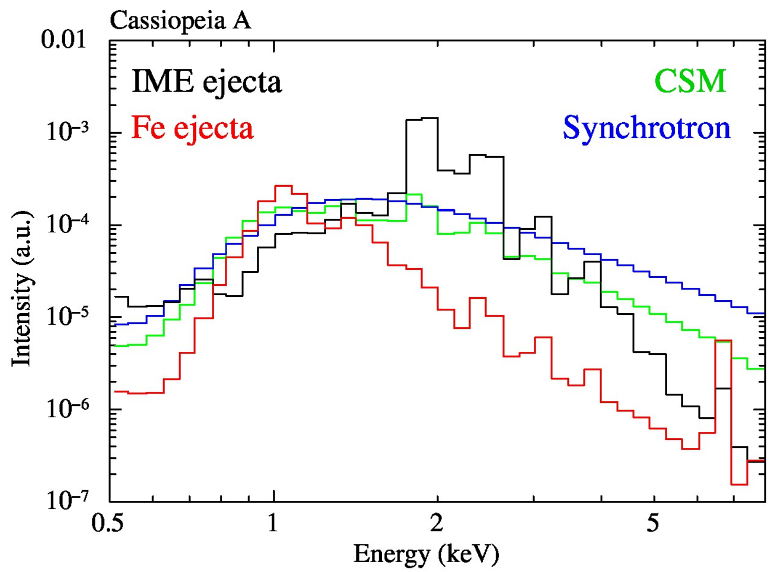
Input 2

Spectrum from each pixel

We estimate contributions of the individual components in each pixel.

When fitting, we utilize the Quadratic Programing (not XSPEC) to reduce the computational time.

Image Decomposition for Cas A



IME distribution

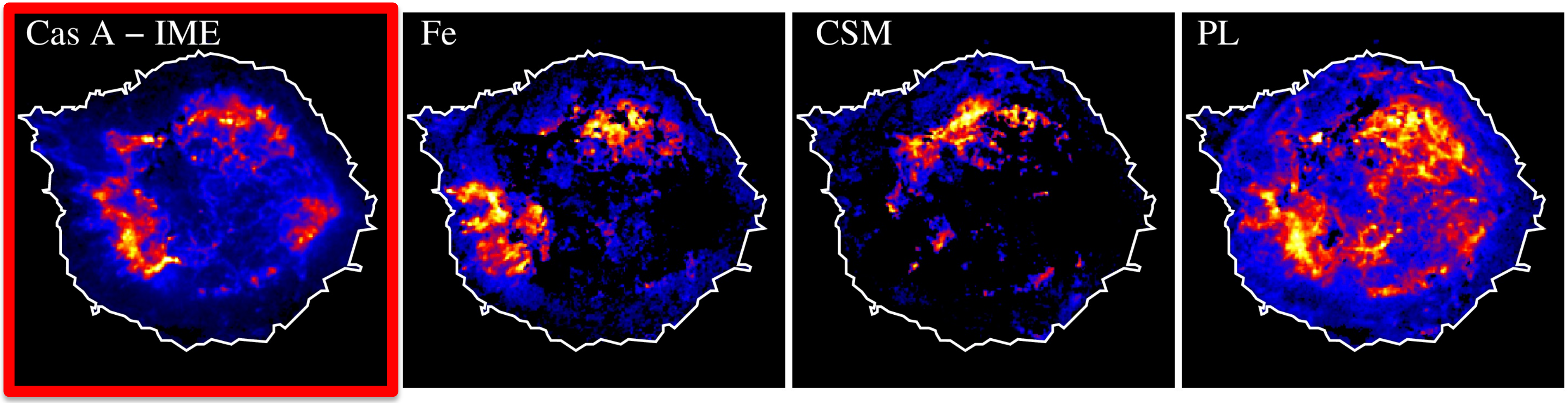
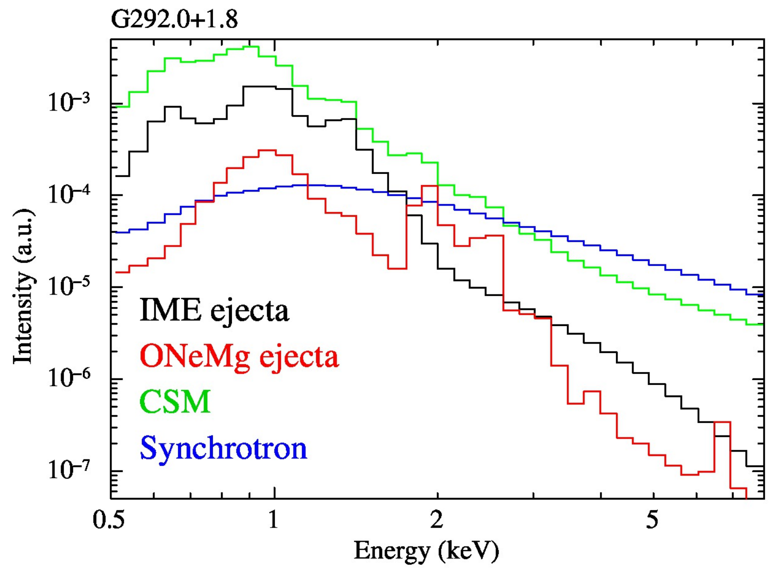


Image Decomposition for G292.0+1.8



IME distribution

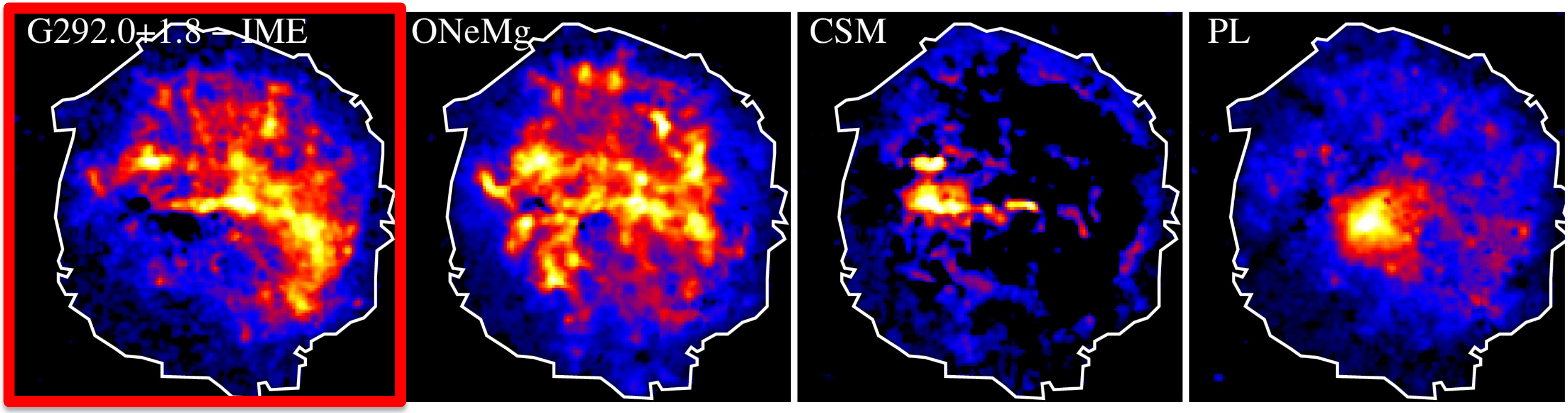
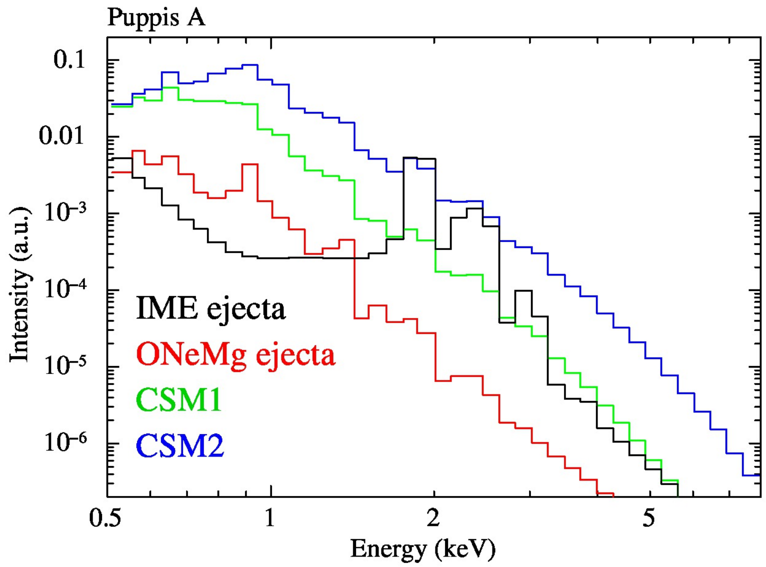


Image Decomposition for Puppis A



IME distribution

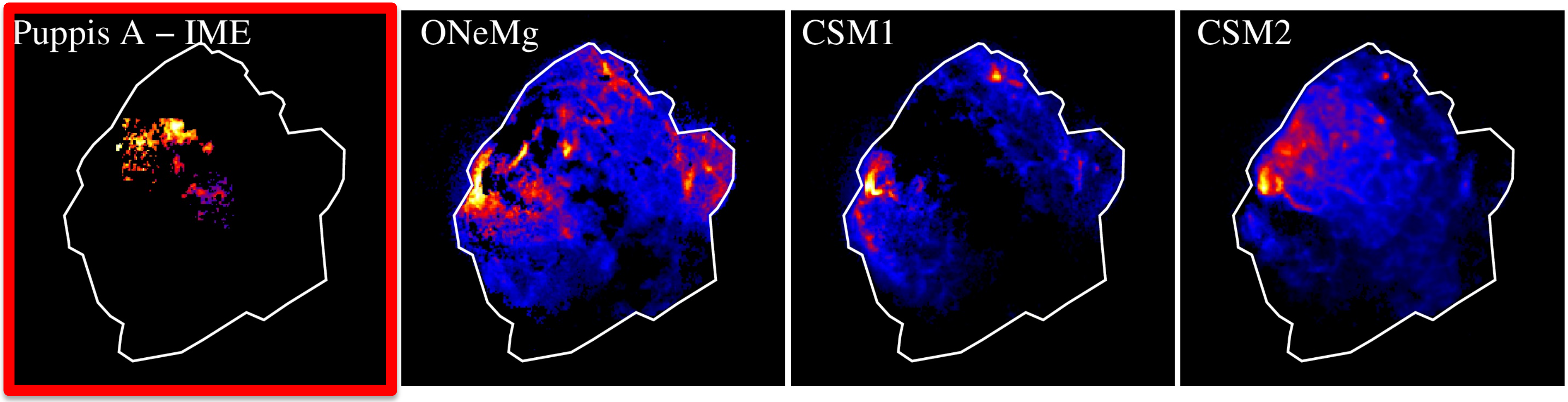
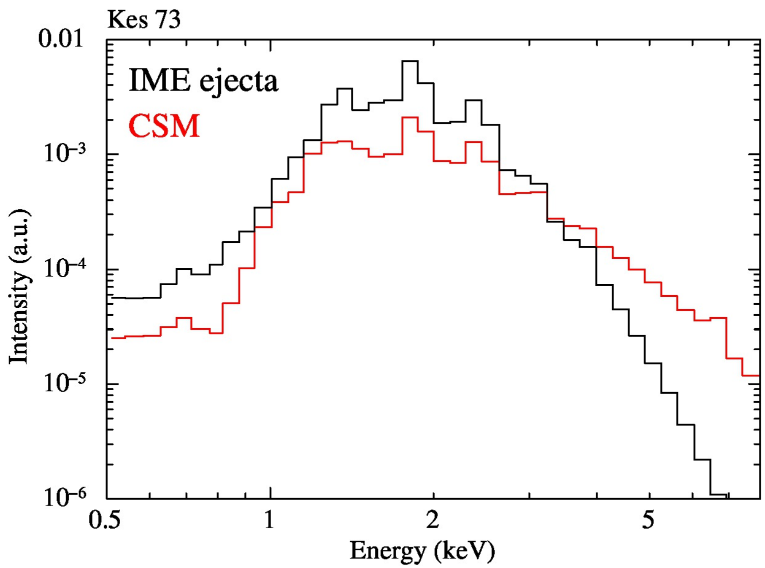


Image Decomposition for Kes 73



IME distribution

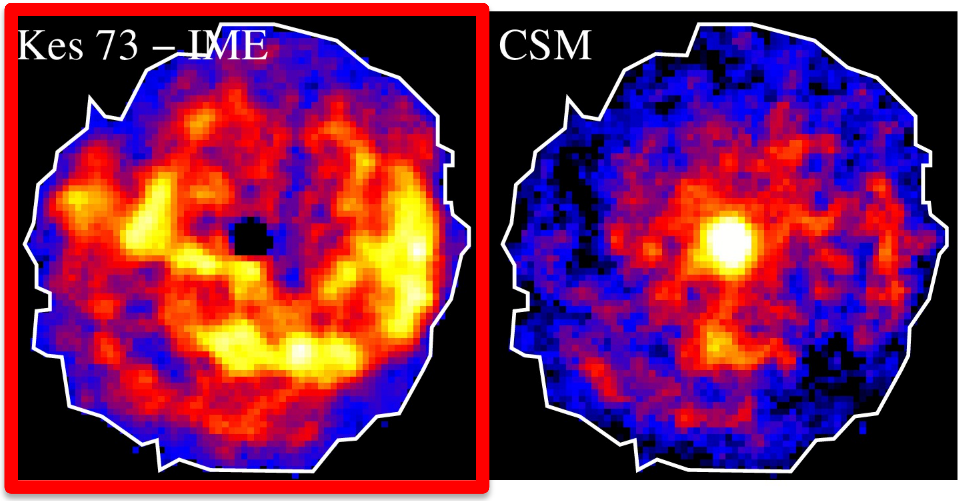
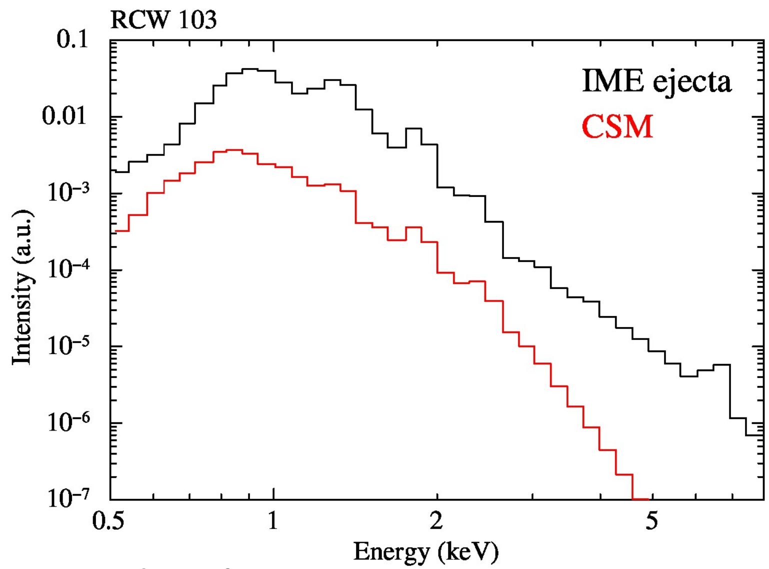


Image Decomposition for RCW 103



IME distribution

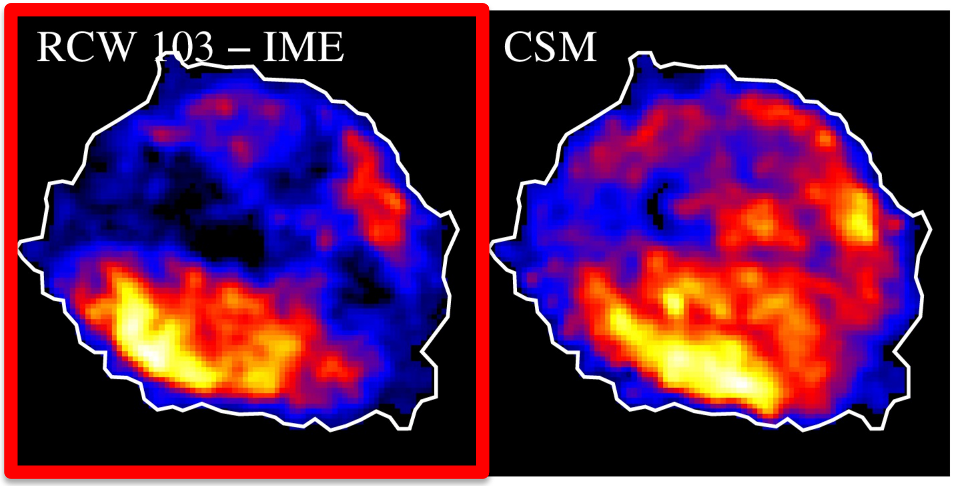
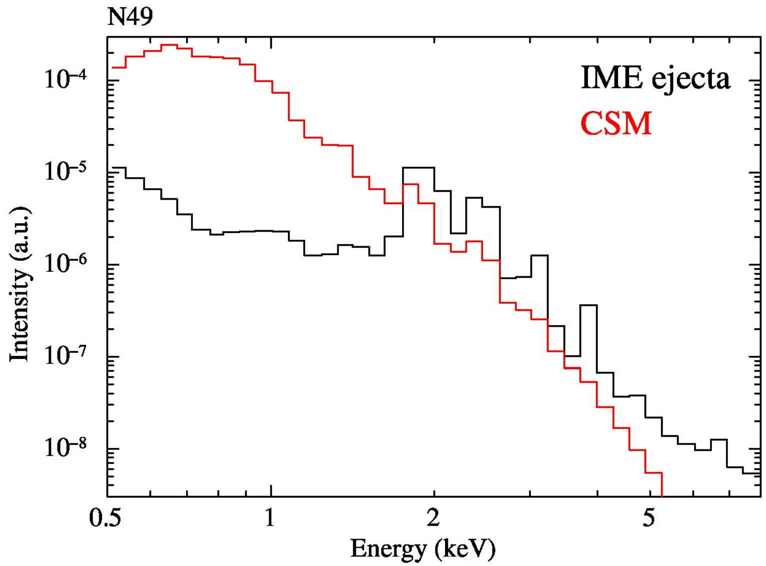
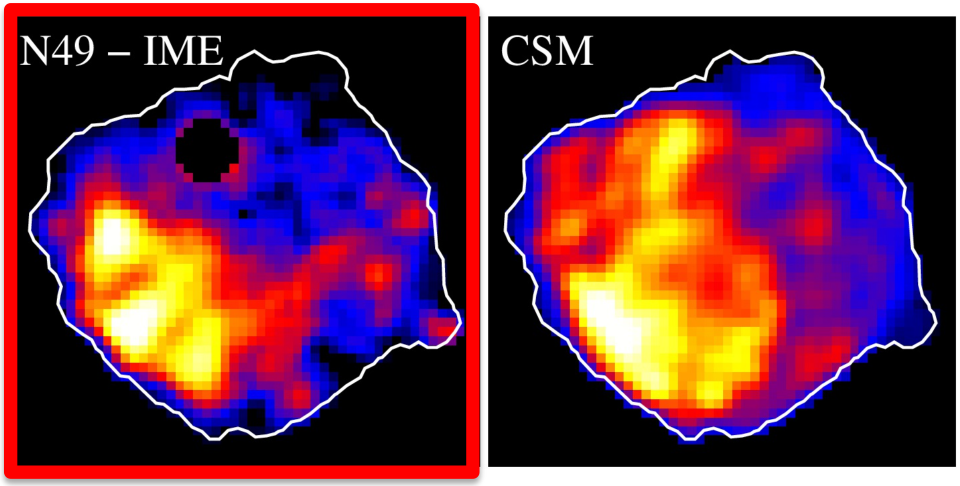


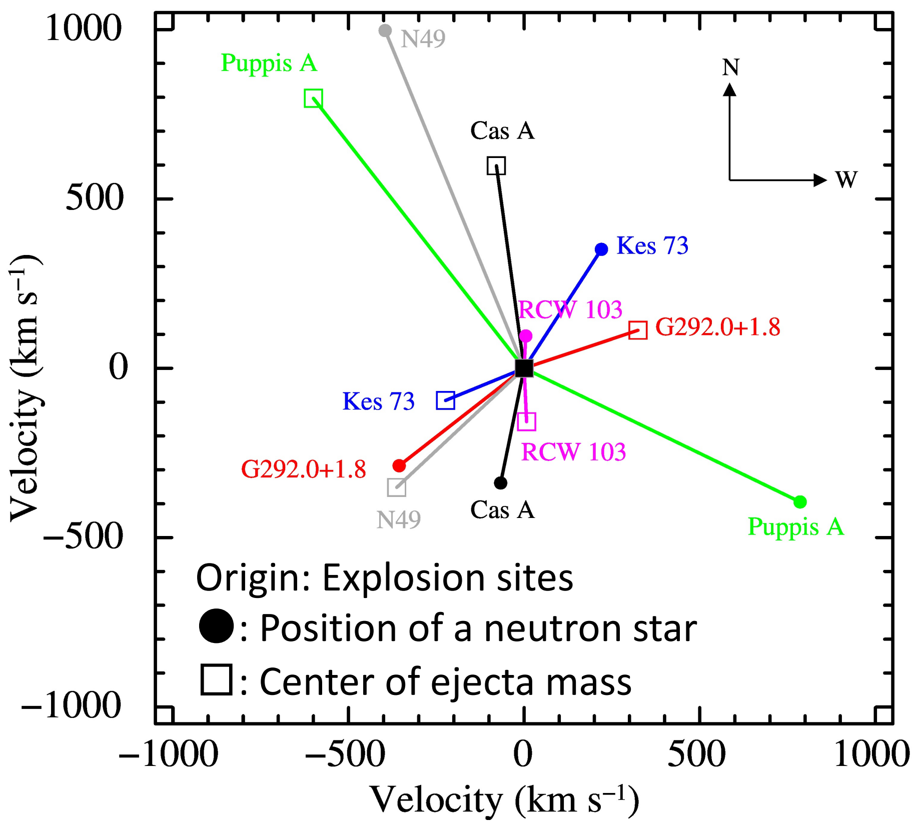
Image Decomposition for N49

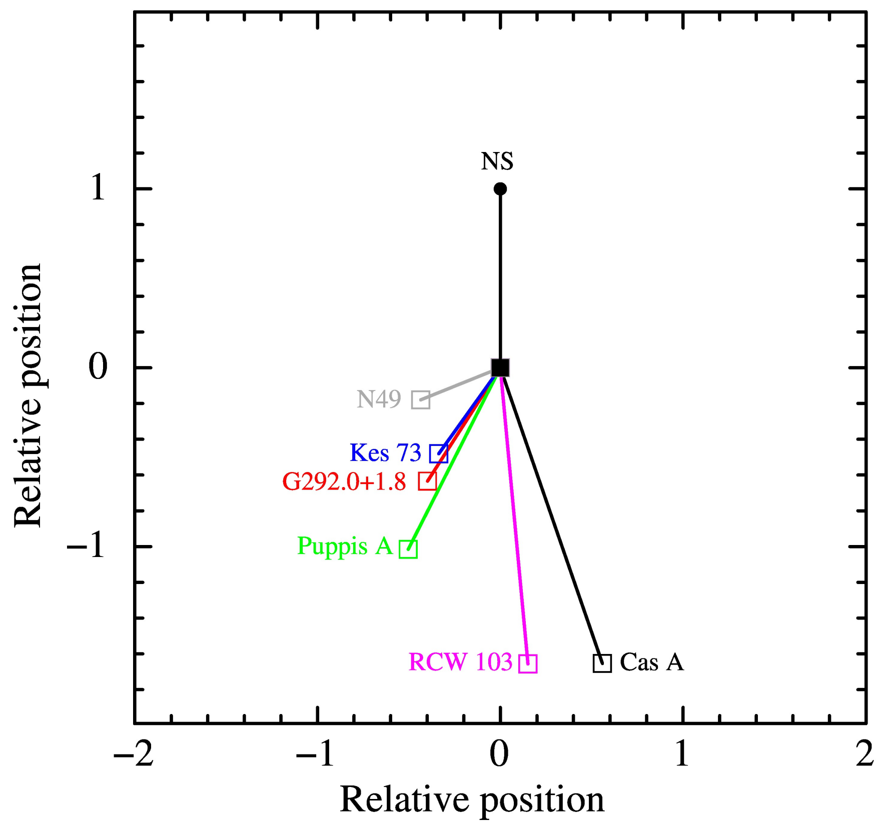


IME distribution



Summary of CoM, CoX/E, NS





Consistent with the hydrodynamic-kick scenario!

NS Speed ∝ Degree of Asymmetry (α)

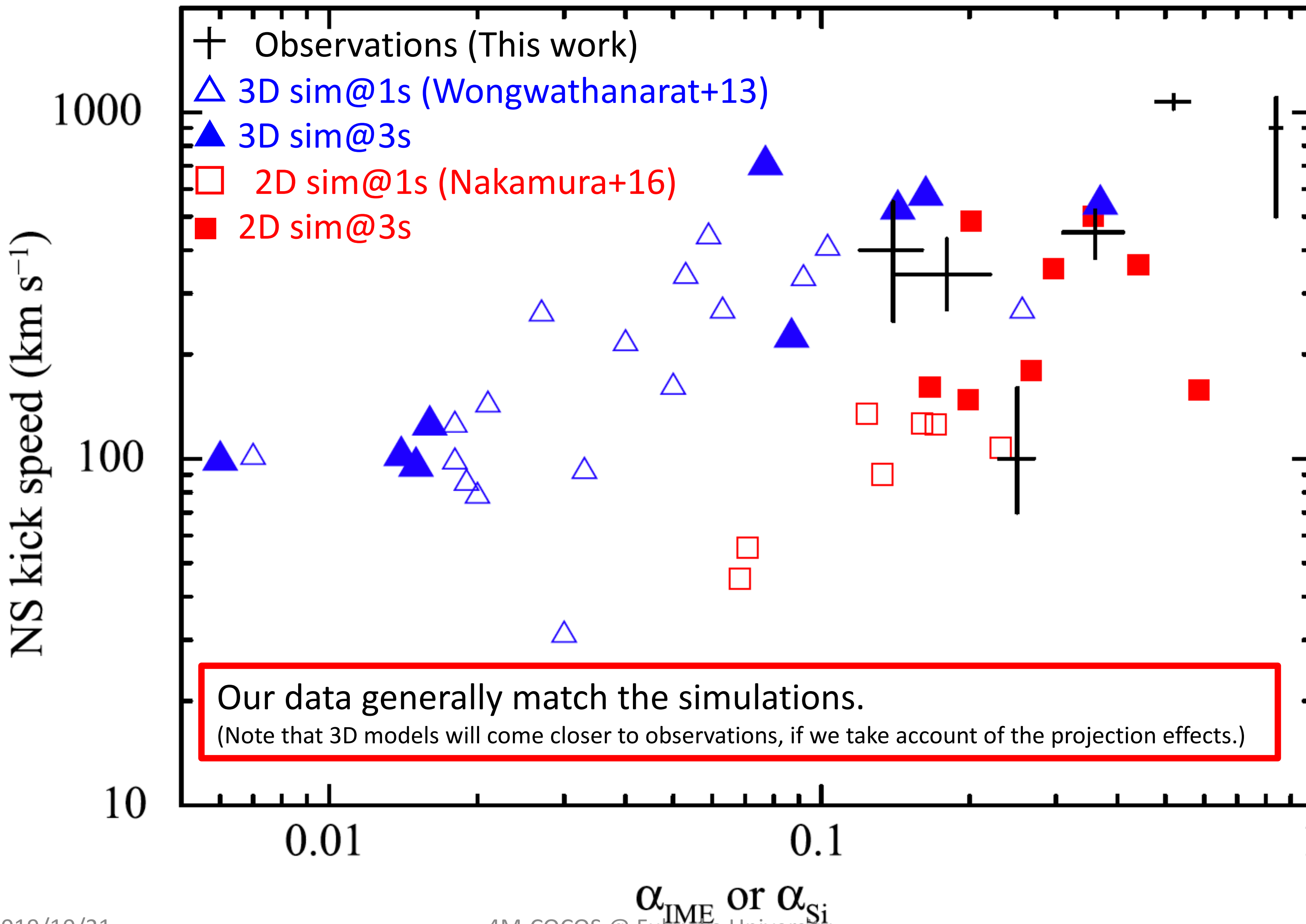
In the hydrodynamic kick scenario (Janka 2017), NS kick velocity is expressed by:

$$V_{NS} = 211\,km\,s^{-1}\left(\frac{f}{\varepsilon_5 \beta_\nu}\right)^{0.5}\left(\frac{\alpha_{ej}}{0.1}\right)\left(\frac{E_{\exp}}{10^{51}\,erg}\right)\left(\frac{M_{NS}}{1.5M_{sun}}\right)^{-1}$$

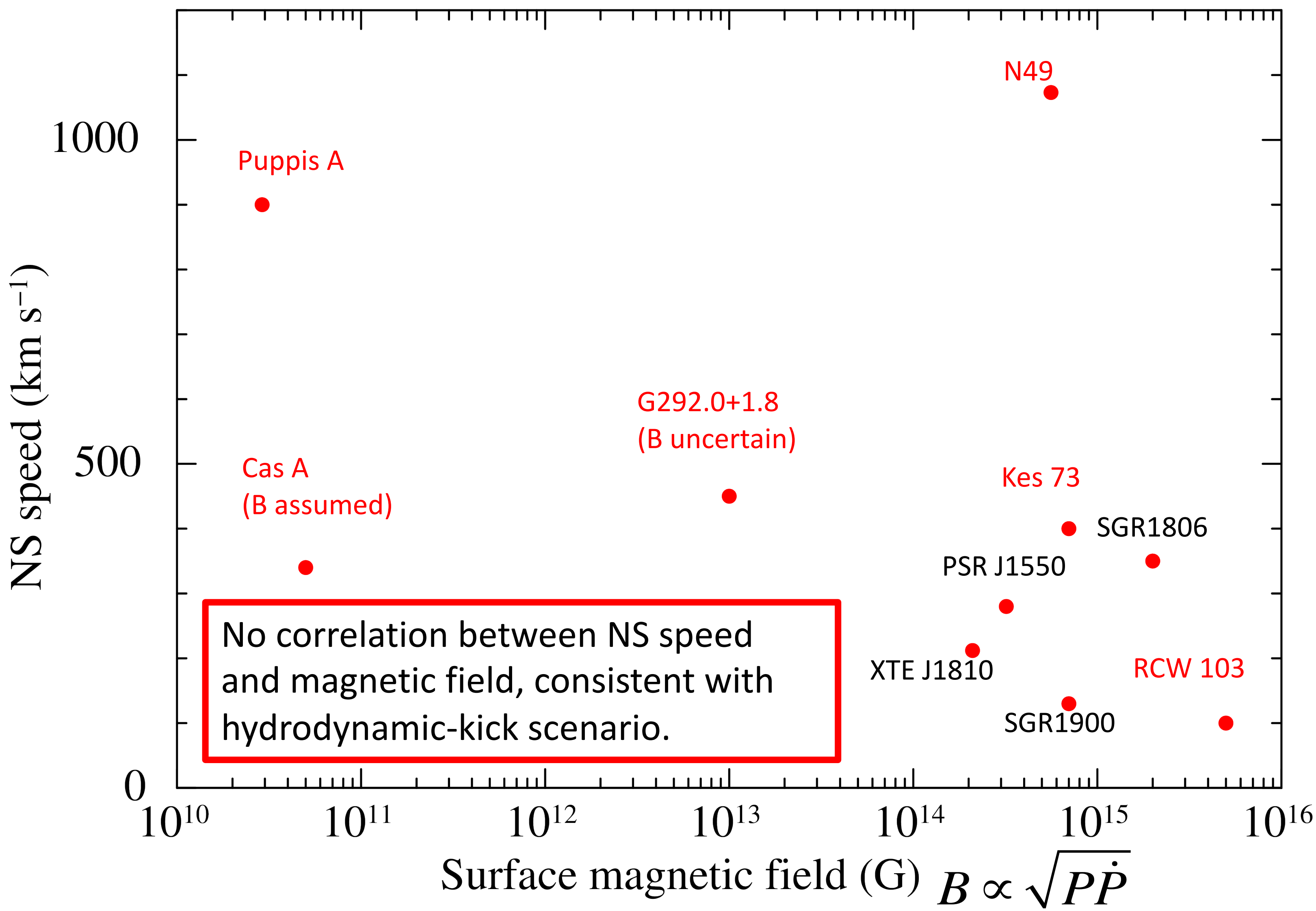
α_{ej}: momentum-asymmetry parameter, defined as $\alpha_{ej} = \int dV \rho_{ej}\, v \,/ \int dV \rho_{ej}\, |v|$.
In other words, $\alpha_{ej} = (m_+V_+ - m_-V_-)/(m_+V_+ + m_-V_-)$.

→ α_{ej} ranges from 0 (spherical) to 1 (extremely anisotropic)
The kick velocity should strongly depend on this parameter.
※ E_{exp} in a range of several 10^{50} - 2×10^{51} erg; M_{NS} in a range of 1 - 2 $M_\odot$

Kick Velocity vs. α_{ej}



Kick Velocity – Magnetic Field



No correlation between NS speed and magnetic field, consistent with hydrodynamic-kick scenario.

Possibilities for Spin-Kick Alignments

In the context of hydrodynamic-kick models, Janka (2017) raised three possibilities to explain the spin-kick alignment.

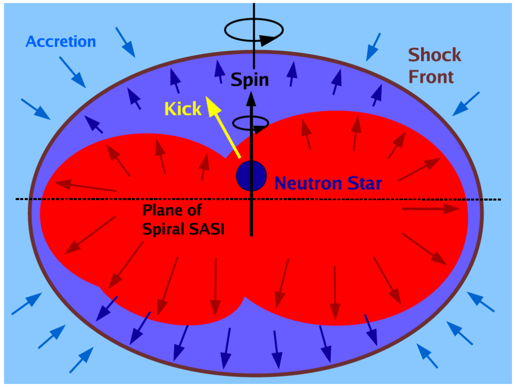
A) The explosion first pushes outward around equatorial plane, leaving long lasting polar downflows. If this downflow has a significant north-south asymmetry, then the NS will get kicked toward one of the poles.

B) Large-scale perturbations in the O and Si burning shells (e.g., Arnett & Meakin 2011).

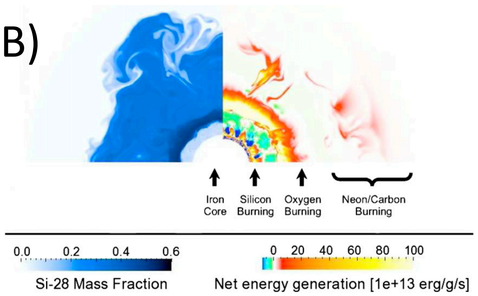
T. Yoshida's talk

C) Dipolar neutrino-emission asymmetry associated with LESA (Tamborra et al. 2014). But, the velocities thus obtained are likely less than 100 km/s.

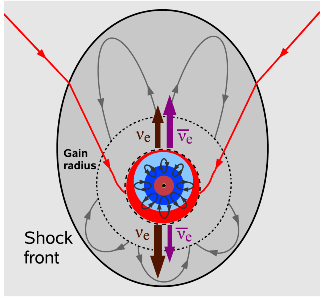
A)



B)



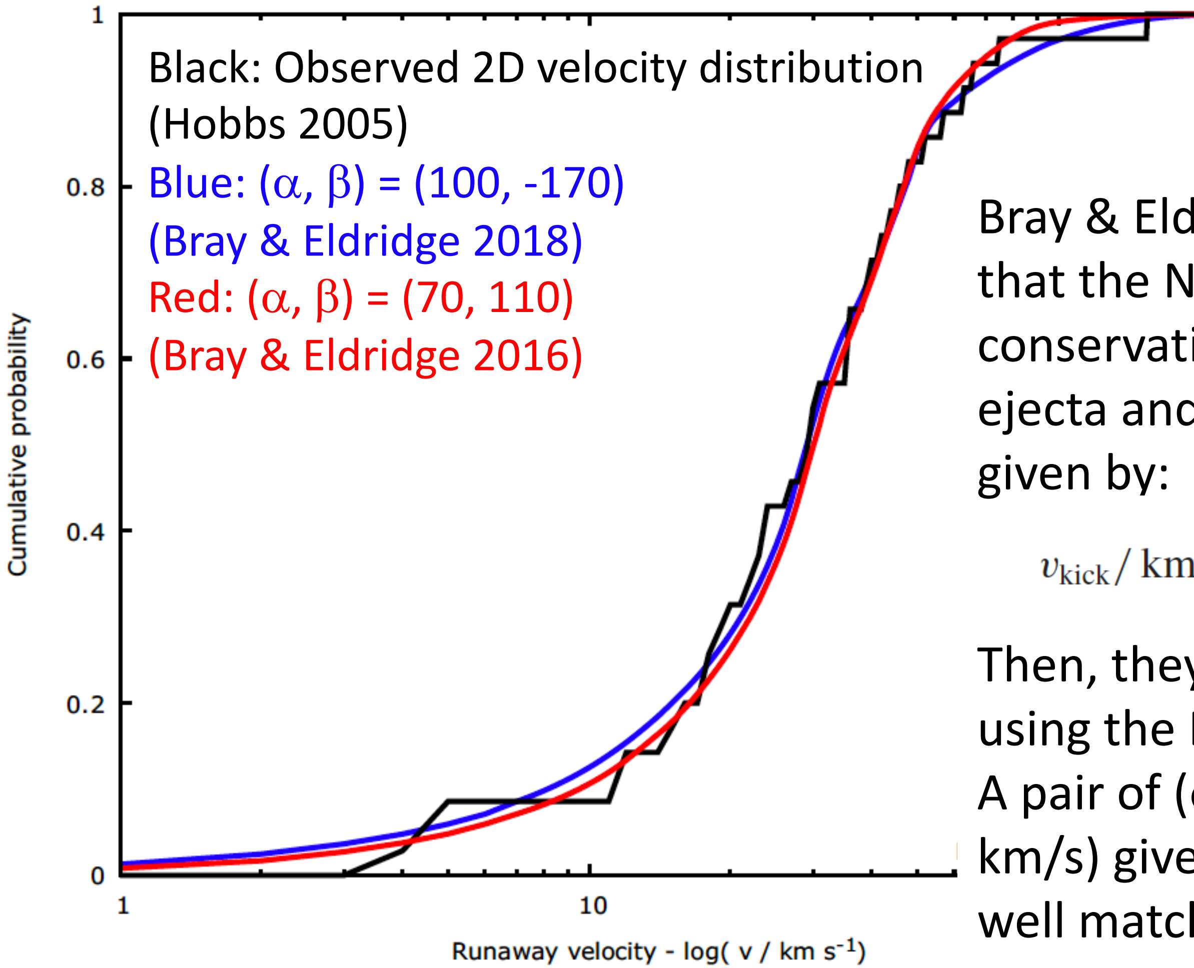
C)



Summary

- Distributions of P_0 and V_0
  - P_0 distribution peaks around <~ 0.1 s with an exception of the magnetar population.
  - Velocity distribution is likely to be bimodal with peaks of ~120 km/s and ~500 km/s.
- Parameter correlations
  - There seem no correlations among P_0, V_0, and B_0 in magnitudes.
  - Spin-kick orientation alignments are suggested by both polarization measurements and morphologies of pulsar wind nebulae.
  - Anti-correlation between SN asymmetries (in IME-rich ejecta) and neutron stars kick velocities has been seen in young SNRs.
    → Both of the spin-kick alignments and the anti-correlation between kick velocities and SN asymmetries are a natural consequence of the neutrino-driven explosion mechanism.

Distribution of Velocities



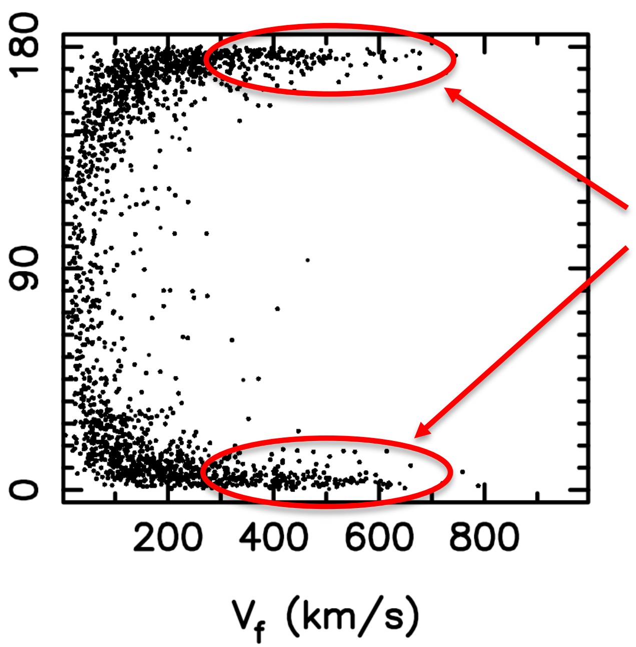
Bray & Eldridge (2016; 2018) assumed that the NS kick is due to momentum conservation between asymmetric ejecta and NS. The kick velocity is given by:

$$v_{\mathrm{kick}} / \mathrm{km\,s^{-1}} = \alpha \left(\frac{\mathrm{M_{ejecta}}}{\mathrm{M_{remnant}}} \right) + \beta$$

Then, they estimated NS velocities, using the BPASS/REAPER codes.
A pair of (α, β) = (100 km/s, -170 km/s) gives a velocity distribution that well matches Hobbs (2005) data.

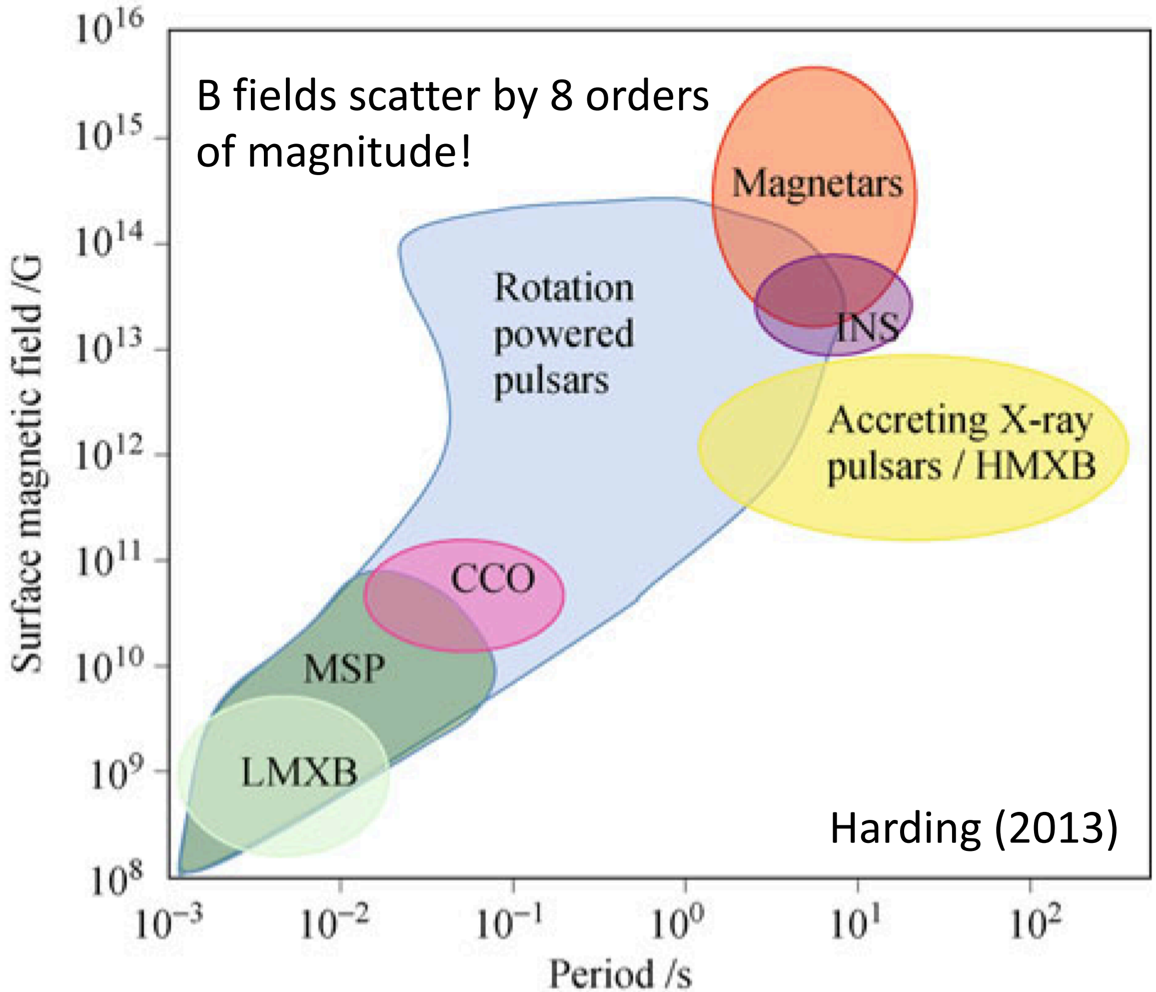
Better Alignments for High Speed Pulsars?

- Wang et al. (2007) claimed that high velocity pulsars have a strong tendency for spin-kick alignment, based on their simulations in the context of the Spruit & Phinney (1998) model.



Fast motion => spin-kick aligned
→ No observational evidence yet.

Magnetic Field vs. Period



The B – P correlation would be mainly due to time evolution of B field, but could be partly explained by initial condition related to SN explosion.