The first evidence for 3D spin-velocity alignment in PSR J0538+2817

Jumei Yao

Collaborator: Weiwei Zhu, Dick Manchester, Bill Coles, Di Li, Na Wang and et al. 2020

NAOC,ISM group

2020/08/29

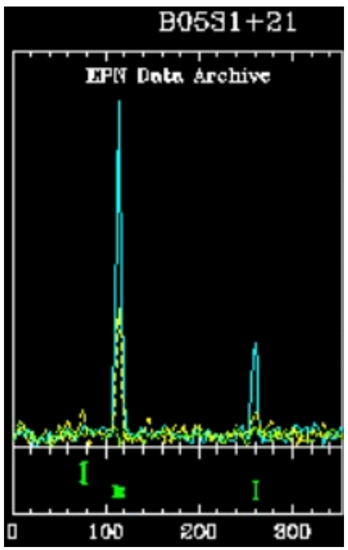
Outline

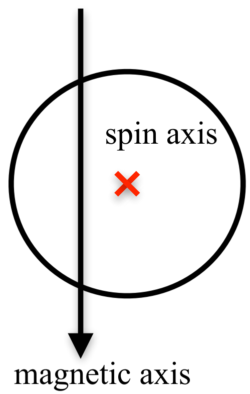
1. Two important vectors for pulsars
2. 2D spin-velocity alignment in pulsars
3. How to measure pulsar radial velocity
4. Interstellar scintillation of PSR J0538+2817
5. The first 3D spin-velocity alignment in J0538+2817
6. Current 3D supernova simulations
7. Summary

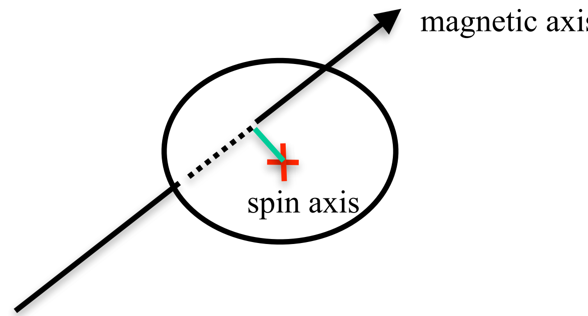
Two important vectors for pulsars

☆ Pulsars move and spin faster than their progenitor stars, but the origin of the initial spin and velocity remains largely a mystery. (Spin axis, and velocity vector)

PSR B531+21, PSR B0950+08, PSR 1055-51 have interpulses located asymmetrically at 140-150 deg from their main pulse:







electric-dipole and magnetic-quadrupole radiation fields. The asymmetric emission of low frequency electromagnetic radiation results in a net reaction force on the neutron star that is approximately

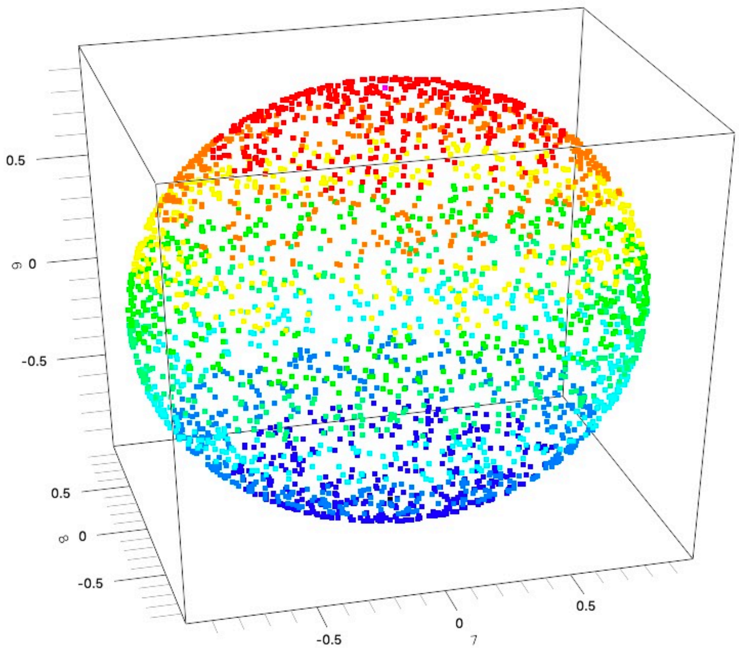
$$F = -2s\Omega^5\mu_z\mu_\varphi/15c^5 \qquad (2)$$

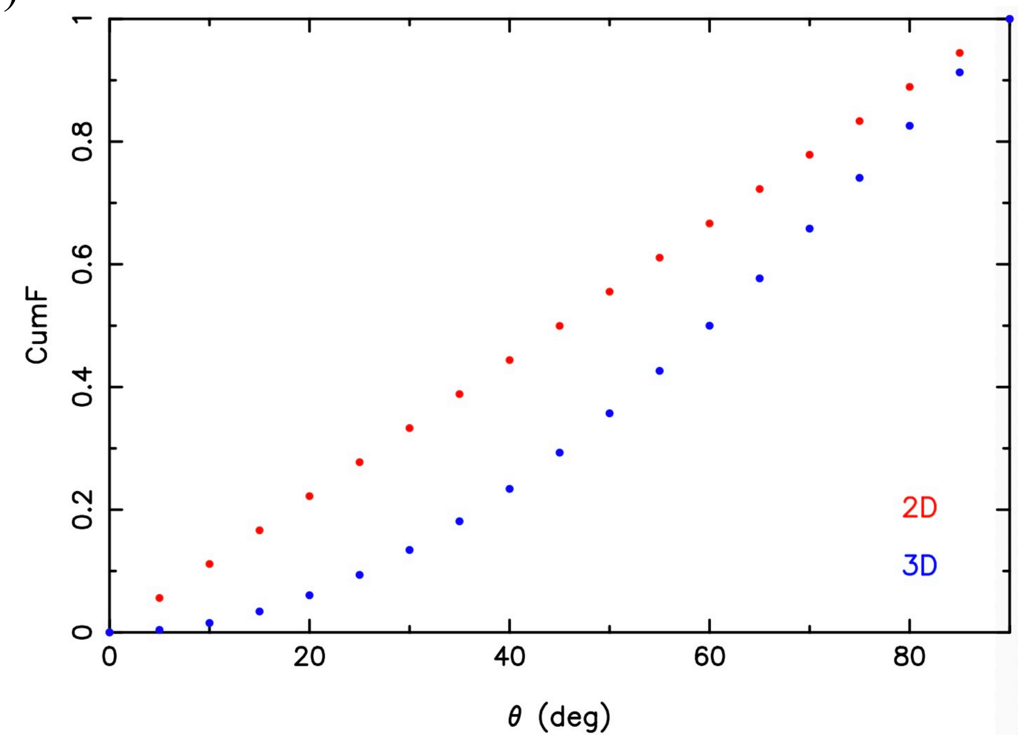
in the direction of Ω. On writing $F = \varepsilon L/c$, we have

Tademaru & Harrison (1975) (The rocket mechanism)

☆ The 2D and 3D angle between spin axis and velocity vector

Velocity, Spin, LOS (500000 data sets)





The probability for theta_2D<20 deg is about 22%, and for theta_3D deg is about 6%.
There is smaller probability for both small theta_2D and theta_3D.

2D spin-velocity alignment in pulsars

1. Observations before 2001:

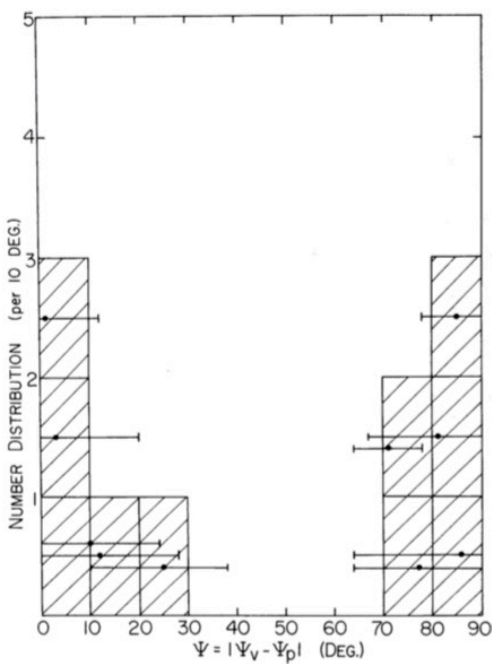
Table 1 Data for $\varphi_t - V$ for pulsars (See text for details)

Pulsar	SNR	V		ref.	φ_t	ref.	$\varphi_t - V$
0329+54	CTB13 ??	293±15	Sc	7	80±10	10	33±18
		126±8	PM	7			46±13*
0525+21	S147?	203±7	D		40±10	10	17±12
0531+21	Crab	294±8	PM	5	145±20	10	31±22
0611+22	IC443	274±10	D		150±70	16	56±71
0823+26		158±3	PM	7	73±6	17,16	85±7
0833−45	Vela X	234±15	D	†	47±10	18	7±18
0834+06		−19±10	PM	7	105±80	10	86±81
1133+16		0±15	PM	6	93±10	14,10	87±18
		−10±4	PM	7			77±11
1237+25		75±4	PM	7	0±15	10	75±15
1749−28	W28?	200±5	D		9±8	14,16	11±10
1929+10	CTB72?	22±8	D		64±6	14,10	42±10
2016+28		9±13	PM	7	100±50	10	89±51
2021+51	HB21?	287±5	D		50±7	15,16	57±9

Morris, Radhakrishnan & Shukre (1976) :

(13 pulsars)

Only pulsars (Crab and Vela) with SNR associations have relatively small angle between spin and velocity. For rest of pulsars, the angle between spin and velocity are close to 90 deg.



Tademaru (1977) (left):

(10 pulsars with improved V and PA measures)

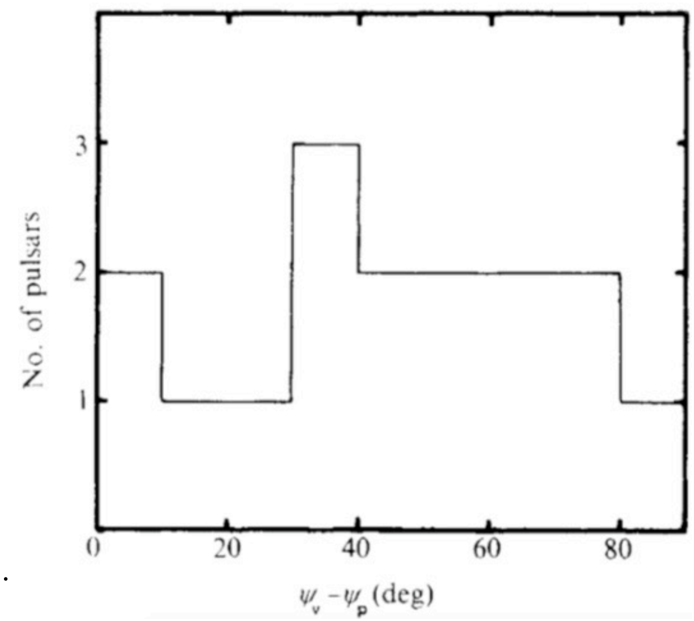
Bimodal distribution peaked at 0 deg and 90 deg

Considering orthogonal polarization of pulsars, spin-velocity are well aligned (PA0+0 deg, PA0+90 deg).

Anderson & Lyne (1983) (right):

(16 pulsars)

No bimodal distribution peaked at 0 deg and 90 deg.



2. Multiple kicks model - (Spruit and Phinney 1998)

momentum impulses $\mathbf{\Delta P}_i$

$$v = M^{-1}\Sigma_i \mathbf{\Delta P}_i$$

$$\mathbf{\Omega}_{\rm NS} = \Delta J / I_{\rm NS} = I_{\rm NS}^{-1}\Sigma_i \mathbf{R}_i \times \mathbf{\Delta P}_i$$

I. Single kick: velocity || momentum impulse, angle velocity (spin)⊥momentum impulse, **velocity ⊥ spin**

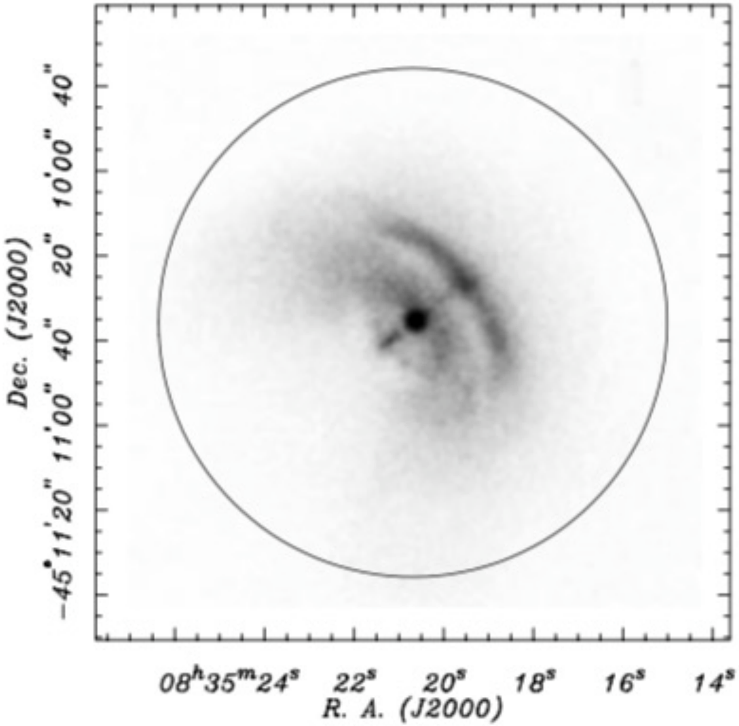
II. Multiple kicks:

1> Random position and random direction about the local radial direction
- no correlation between spin and velocity (direction and magnitude).

2> If there are asymmetric kicks and the location of the kicks rotate with the NS, the **rotational averaging effect** will **reduce the contribution to the kick velocity perpendicular to the rotation axis, not the contribution to the angular velocity.**
—— **spin-velocity alignment**

3. Observations after 2001 - X-ray observation of pulsar tori and more pulsars

Helfand et al. 2001 (x-ray, vela, toroidal PWN)



Spin axis:
1> the direction of the jet
2> the symmetry axis of toroidal.
PA of the spin axis: 130 deg from North

VLBI-PM: (Dodson et al. 2003)
PA of velocity is: 301+/-1.8 deg

Spin is aligned to within 9 deg with velocity.

Johnston et al. 2005 (new polarizations, Timing PM)

J name	B name	PA_v (deg)	PA_0 (deg)	$\vert\Psi\vert$ (deg)
Pulsars with $\vert\Psi\vert < 10°$ or $\vert\Psi\vert > 80°$				
J0630−2834	B0628−28	294(3)	26(2)	88(4)
J0742−2822	B0740−28	278(5)	−81.7(1)	0(5)
J0820−1350	B0818−13	159(6)	65(2)	86(6)
J0835−4510	B0833−45	301.0(1)	36.8(1)	84.2(2)
J1239+2453	B1237+25	295.0(1)	−66(1)	1(1)
J1430−6623	B1426−66	236(9)	−28.5(7)	85(9)
J1453−6413	B1449−64	217(3)	−56.9(4)	86(3)
J1709−1640	B1706−16	192(16)	15(2)	3(16)
J1740+1311	B1737+13	227(6)	−46(4)	87(7)
J1844+1454	B1842+14	36(15)	−52(2)	88(15)
Pulsars with $10° < \vert\Psi\vert < 80°$				
J0525+1115	B0523+11	132(16)	−65(4)	17(16)
J0953+0755	B0950+08	355.9(2)	14.9(1)	19.0(2)
J1136+1551	B1133+16	348.6(1)	−78(2)	67(2)
J1456−6843	B1451−68	252.7(6)	−31.6(6)	76(1)
J1645−0317	B1642−03	353(3)	56(4)	63(5)
J1900−2600	B1857−26	202.8(7)	−43(2)	66(2)
J1913−0440	B1911−04	166(11)	−68(2)	54(11)
J1921+2153	B1919+21	34(12)	−35(2)	69(12)
J1932+1059	B1929+10	65.2(2)	−11.3(1)	76.5(2)
J1935+1616	B1933+16	176(1)	10.1(7)	14(1)
Pulsars for which PA_0 and hence Ψ cannot be determined				
J0601−0527	B0559−05	194(16)		
J0908−1739	B0906−17	167(2)		
J0922+0638	B0919+06	12.0(1)		
J1709−4429	B1706−44	160(10)		
J1941−2602	B1937−26	130(17)		

10 out of 25 have PA_diff>80 deg and <10 deg, and 5 the them have age smaller than 3 Myr. —unlikely by random chance.

Recent observations :Noutsos et al. 2013 (33 out of 52 pulsars with reliable kinematic age)

Kinematic age: It is therefore a reasonable assumption that pulsars are born at Galactic heights of $|z_{\rm birth}| \ll R_{\rm MW}$. Based on this assumption, pulsar ages can be estimated using a kinematic analysis, by calculating the length of time required for a pulsar to travel between its location at birth and that at present, through the gravitational potential of the Galaxy.

33 pulsars in total

N	PSR	$\log \tau_c$ (yr)	$\log t^{d}_{\rm kin}$ (yr)	$\log t^{d/2}_{\rm kin}$ (yr)	$\log t^{2d}_{\rm kin}$ (yr)
1	J0139+5814	5.6	$6.3^{+0.1}_{-0.1}$	$6.2^{+0.3}_{-0.3}$	$6.3^{+0.1}_{-0.1}$
5	J0358+5413	5.8	$5.7^{+0.3}_{-0.5}$	$6.0^{+0.3}_{-0.6}$	$5.5^{+0.3}_{-0.4}$
6	J0452−1759	6.2	7.3	$6.8^{+0.3}_{-0.1}$	–
7	J0454+5543	6.4	$5.9^{+0.2}_{-0.2}$	$5.8^{+0.5}_{-0.4}$	$5.9^{+0.1}_{-0.1}$
8	J0538+2817	5.8	$5.8^{+0.1}_{-0.6}$	$6.1^{+0.2}_{-0.7}$	$5.0_{-0.5}$
9	J0630−2834	6.4	$6.2^{+0.2}_{-0.1}$	$6.1^{+0.4}_{-0.1}$	$6.3^{+0.1}_{-0.1}$
10	J0659+1414	5.0	$5.7^{+0.3}_{-0.4}$	$5.8^{+0.2}_{-0.5}$	$5.9^{+0.4}_{-0.3}$
11	J0738−4042	6.6	$6.7^{+0.1}$	$6.6^{+0.2}$	–
12	J0742−2822	5.2	$5.6^{+0.2}_{-0.3}$	$5.7^{+0.3}_{-0.4}$	$5.6^{+0.1}_{-0.1}$

Main results: Pulsars with ages greater than ~10^7 yr, whose 3D velocities have almost certainly been significantly altered by the gravitational pull of the Galaxy, yielded no correlation. Spin and velocity axes in young pulsars are correlated.

How to measure pulsar radial velocity

1. Why can we only have 2D alignment evidence for two vectors?

3D Spin axis: Polarization and Tori (3D, PA and the inclination angle)

2D Velocity (projected onto the Galactic plane): VLBI, Association with SNR, Timing (2D PA)

2. The key is to measure pulsar radial velocity. Is there any methods?

Method I: timing method, radial velocity could contribute to spin frequency second derivatives

Method II: BS, systemic radial velocity, the companion has suitable spectral lines)

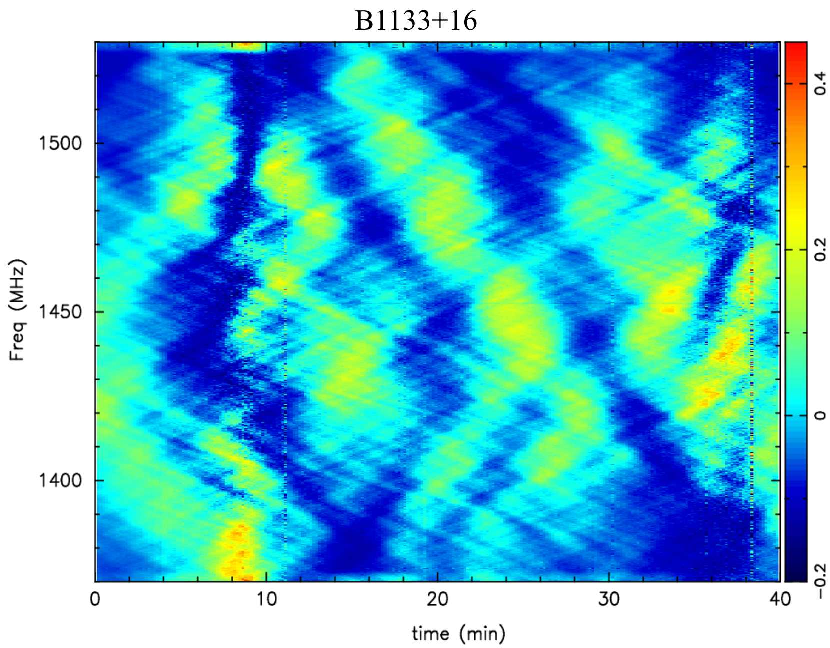
Liu et al. 2018

PSR	f (Hz)	$v_{\parallel}$ (km s^{-1})	μ (mas yr^{-1})	$\ddot{f}_{\parallel}$ (10^{-30} s^{-3})
J1012+5307	190	44 ± 8[1]	25.6[7]	1.3 ± 0.2
J1024−0719	194	185 ± 4[2]	59.7[7]	30.2 ± 0.7
J1738+0333	171	−42 ± 16[3]	8.65[7]	−0.13 ± 0.05
J1903+0327	465	42.1 ± 2.5[4, 5]	7.04[8]	0.23 ± 0.07
J1909−3744	339	−73 ± 30[6]	37.0[7]	−8 ± 3

But these **two methods are not suitable for young single pulsar**. Whether we can obtained radial velocity based on ISS of pulsar located within SNR.

Interstellar scintillation of J0538+2817

1. Dynamic spectrum, ACF, SF, and secondary spectrum



ACF:

$$A(\Delta\nu, \Delta t) = \sum_{\nu}\sum_{t} \Delta F(\nu, t)\Delta F(\nu + \Delta\nu, t + \Delta t)$$

$$\rho(\Delta\nu, \Delta t) = C_0 \exp[-(C_1\Delta\nu^2 + C_2\Delta\nu\Delta t + C_3\Delta t^2)],$$

ISS timescale, bandwidth and velocity:

$$\Delta\nu_d = \sqrt{\frac{\ln 2}{C_1}} \qquad \Delta t_d = \sqrt{\frac{1}{C_3}}$$

$$V_{iss} = 3.85 \times 10^4 \left(\frac{\sqrt{x D_{kpc} \Delta\nu_{d,MHz}}}{\nu_{GHz}\Delta t_{d,s}}\right)$$

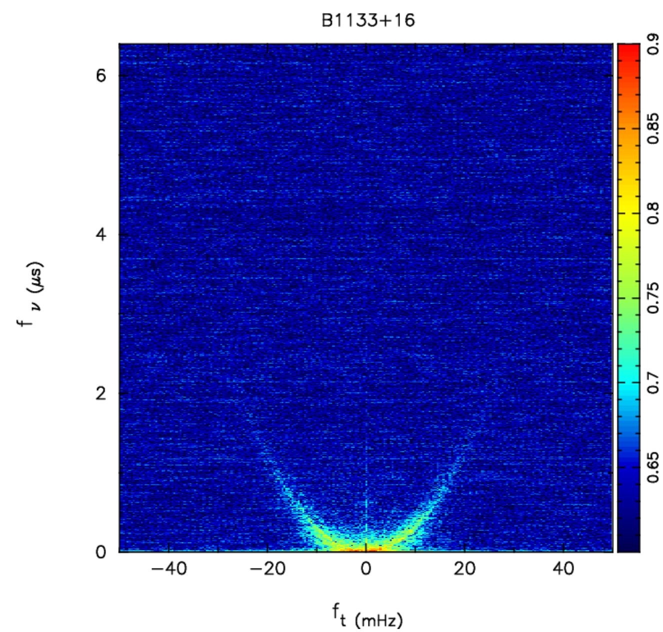
SS:

$$S(\nu, t) \longrightarrow S^{\dagger}(f_\nu, f_t),$$

$$S_2(f_\nu, f_t) = \left|S^{\dagger}(f_\nu, f_t)\right|^2.$$

$$\eta = 4625 \frac{D_{\rm kpc}}{\nu_{\rm GHz}^2 V_\perp^2}\left(\frac{s}{1-s}\right)$$

The location of the screen: $D_{\rm ps} = sD$

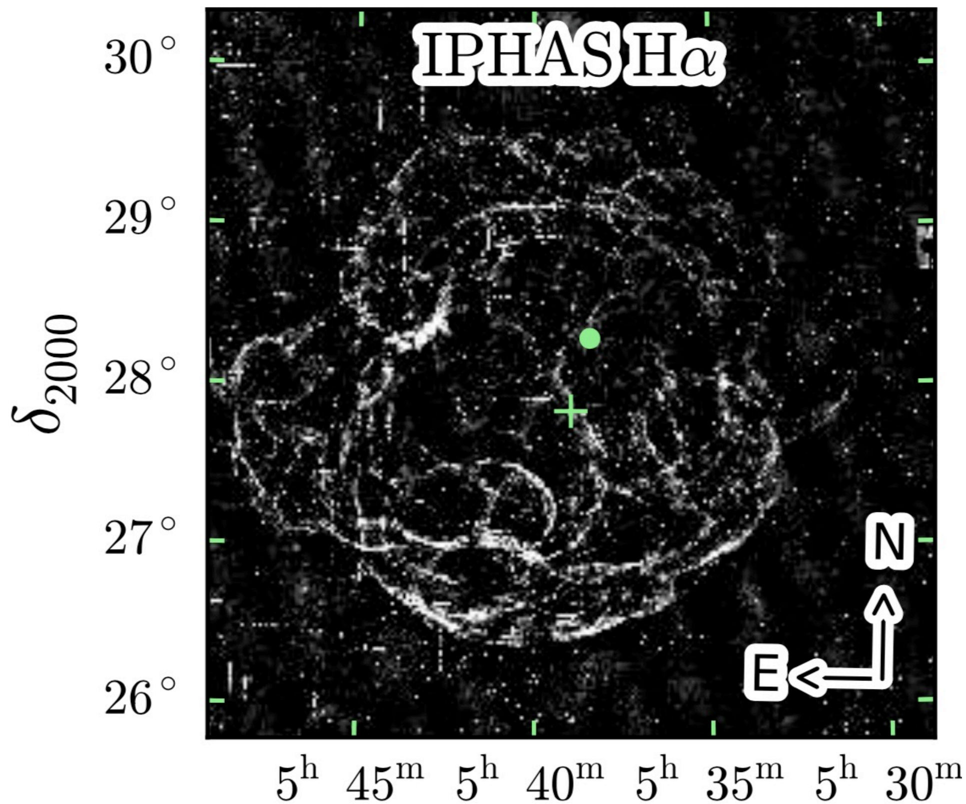


2. PSR J0538+2817 and SNR S147

What kind of ionized structures could dominate pulsar scattering?
(Local bubble shell, the HII regions or old SNR shell)

What information can we get from the location of the scattering screen?
(The radial location and radial velocity of pulsar)

83 arcmin, 36 arcmin, Drew et al. 2005



Criterion for judging the association:

I. Consistent independent distance estimates;

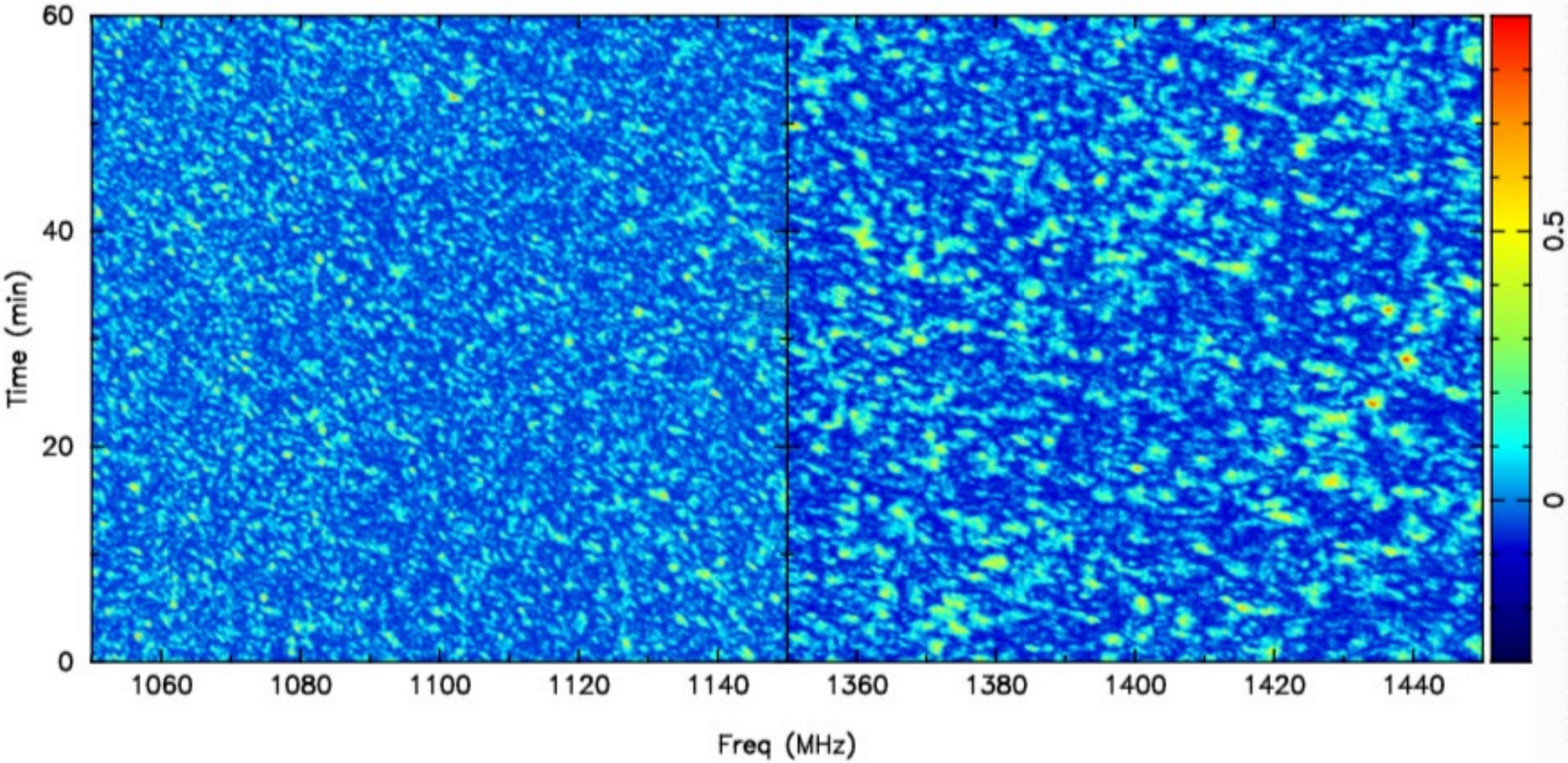
II. Consistent age estimates;

III. Reasonable proper motion;

IV. Interaction between NS and SNR - PWN;

Inconsistent: characteristic age of 600 kyr, the kinematic age of 30 kyr.

3. Dynamic spectrum at 1100 and 1400 MHz

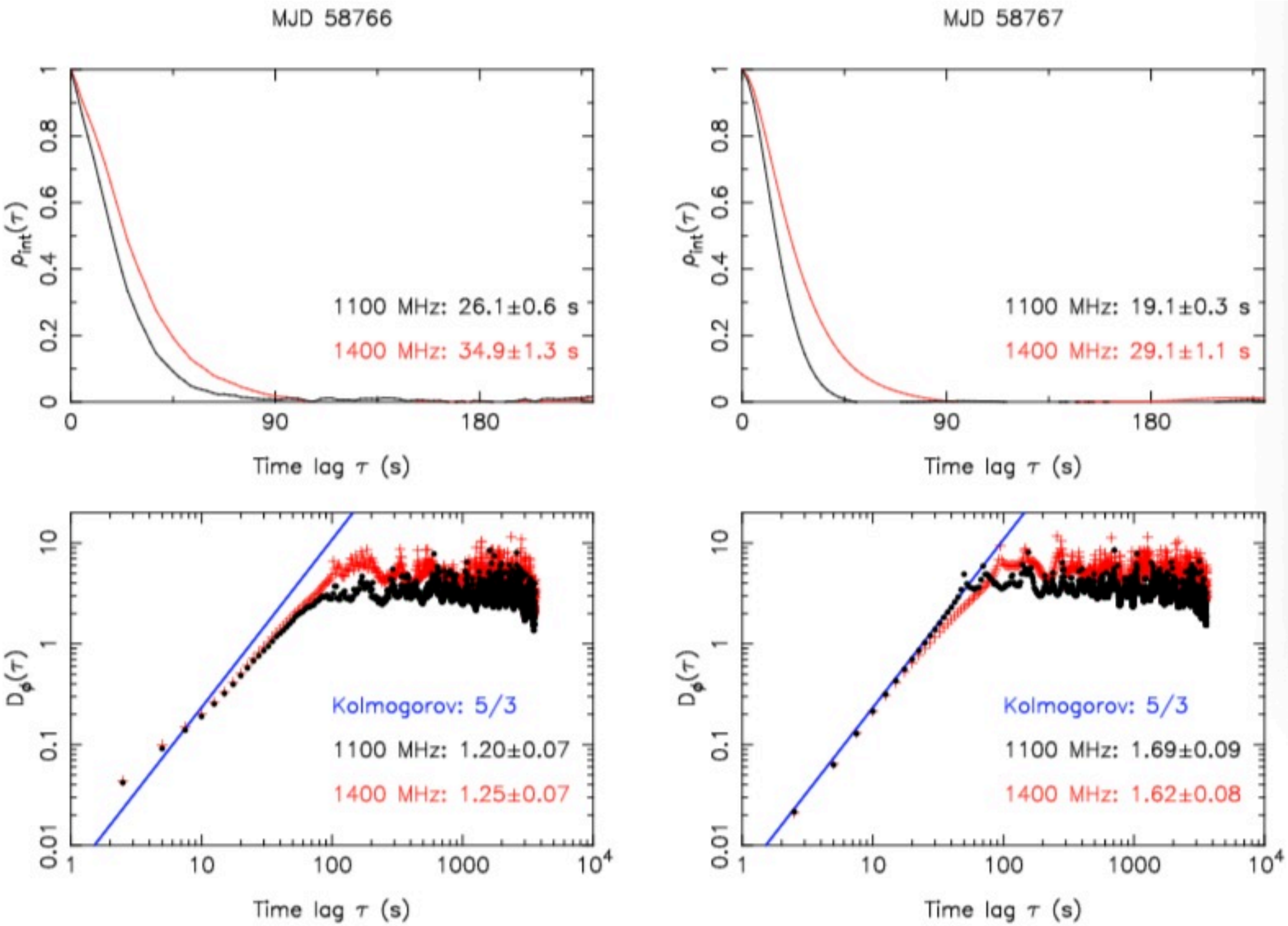


I. Strong frequency dependence of scintillation in both time and frequency;

II. Small scale scintillation scintles indicating that ISS is very strong ISS;

III. Small scintillation timescale indicating very close scattering screen to PSR.

4. Reveal turbulent property of the ionized SNR shell (ACF, and SF)



$$P_{ne}(q) = C_{ne}^2 q^{-\beta}$$

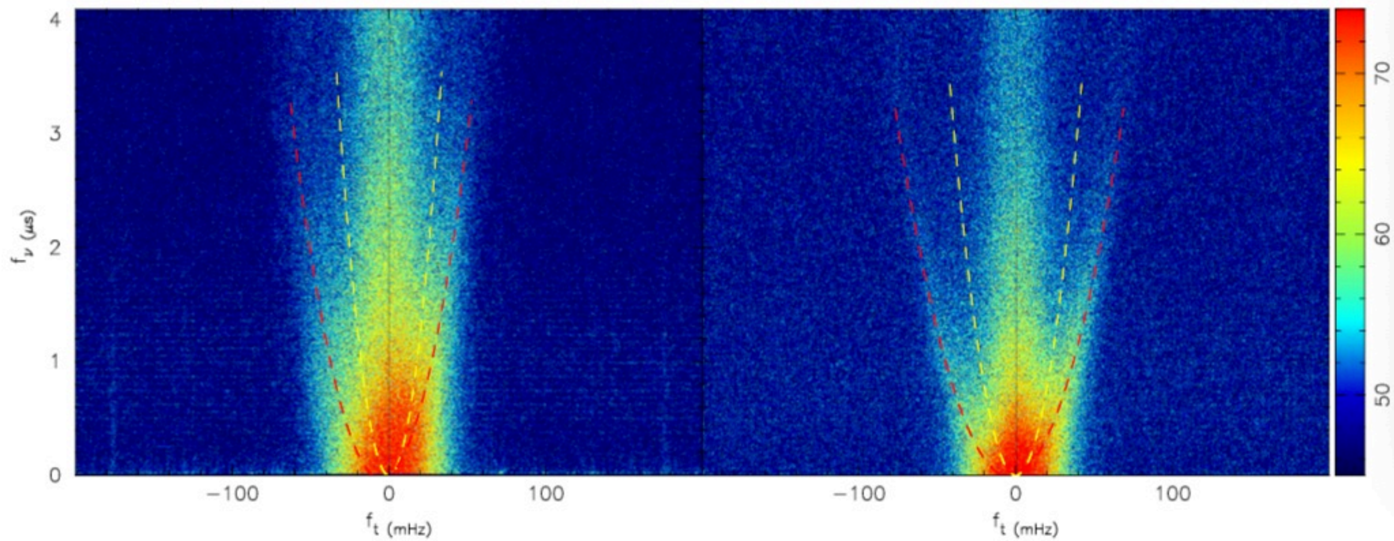
$$\Delta\tau_r = u^2 \Delta\tau_d \quad 14.3 \text{ h}$$

$D_\phi(\tau) \approx m^2 \tau^\alpha$ $\quad D_\phi(\tau) = -log_e[\rho_{\rm int}(\tau)]$

For $\beta < 4,\ \alpha = \beta - 2$ For $\beta > 4,\ \alpha = 2$

The slope of is flatter than 5/3 predicted by the Kolmogorov spectrum.

5. The secondary spectra and the location of the scattering screen

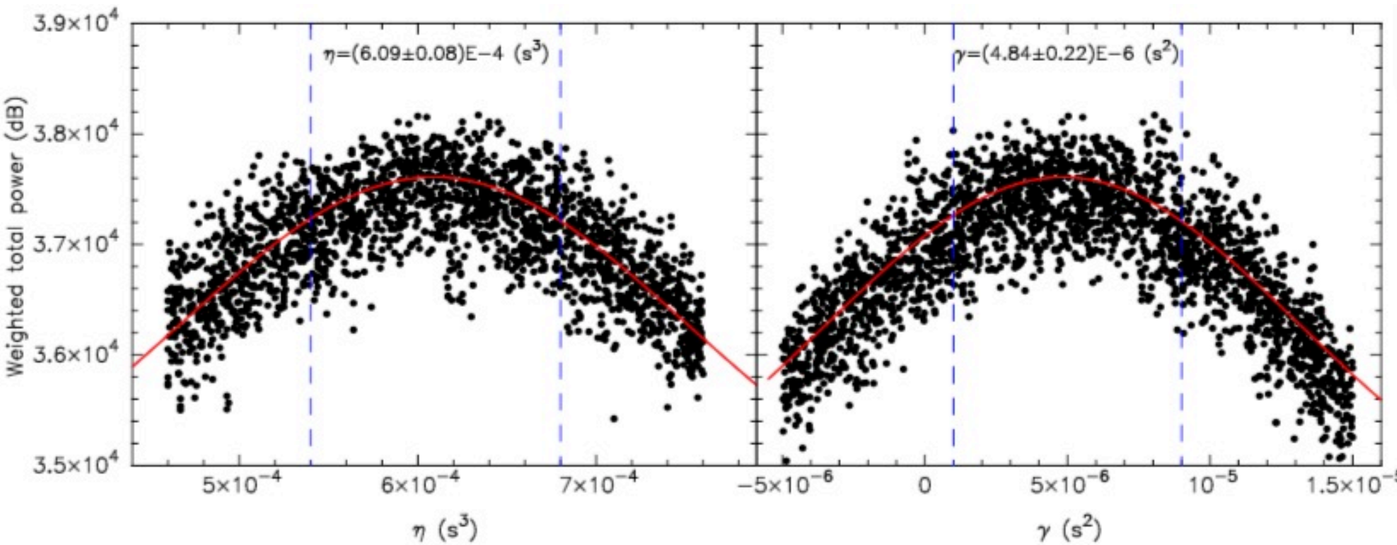


The arc:

$$f_\nu = \eta f_t^2 + \gamma f_t$$

$$\eta = 4625 \frac{D_{\rm kpc}}{\nu_{\rm GHz}^2 V_{\perp,{\rm km/s}}^2} \left(\frac{s}{1-s}\right)$$

$$\gamma = 0.1496 \frac{D_{\rm kpc}\theta_{\rm g,mas}}{\nu_{\rm GHz} V_{\perp,{\rm km/s}}} \quad {\rm s}^2$$



Results:

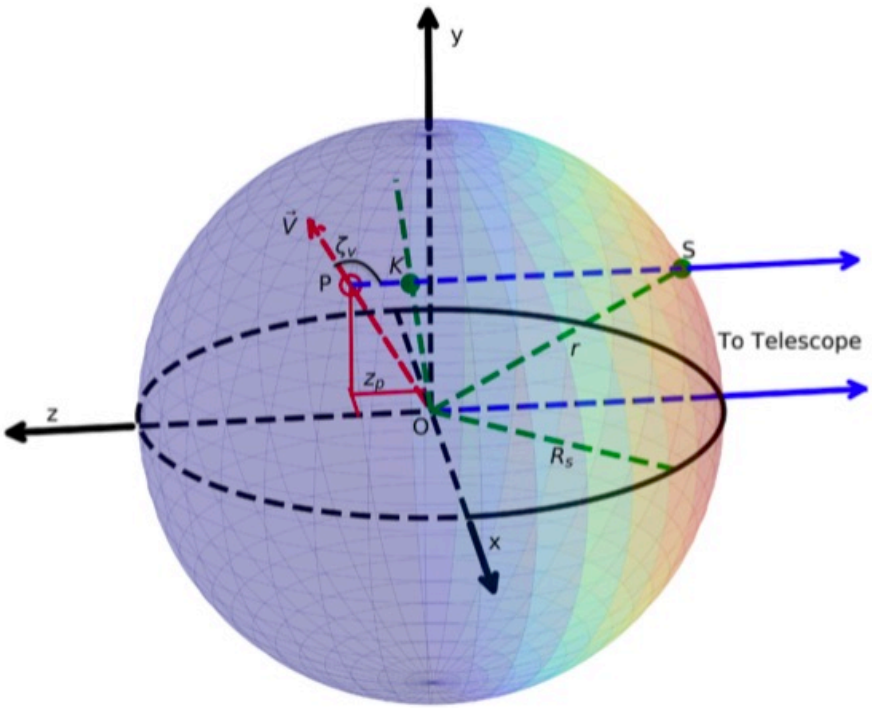
$$\theta_g = 0.0124 \pm 0.0006 \text{ mas}$$

$$D_{\rm ps} = sD = 33.5 \pm 9.5 \text{ pc}$$

Radius of SNR S147:

$$R_s = D\,\theta_s = 32.1 \pm 4.8 \text{ pc}$$

6. 3D velocity from interstellar scintillation



6.1 PM and distance (Chatterjee et al. 2009)

$$D = 1330 \pm 190 \ \text{pc}$$
$$V_\perp = 365 \pm 52 \ \text{km/s}$$

6.2 The radial velocity, 3D velocity direction

$$z_p = D_{\text{ps}} - \sqrt{R_s^2 - x_p^2 - y_p^2}$$
$$z_p = 4.4 \pm 4.8 \ \text{pc}$$

$$V_z = \frac{z_p}{\tau}$$
$$V_z = 114 \pm 125 \ \text{km s}^{-1}$$

$$\zeta_v = 109^\circ \pm 18^\circ$$

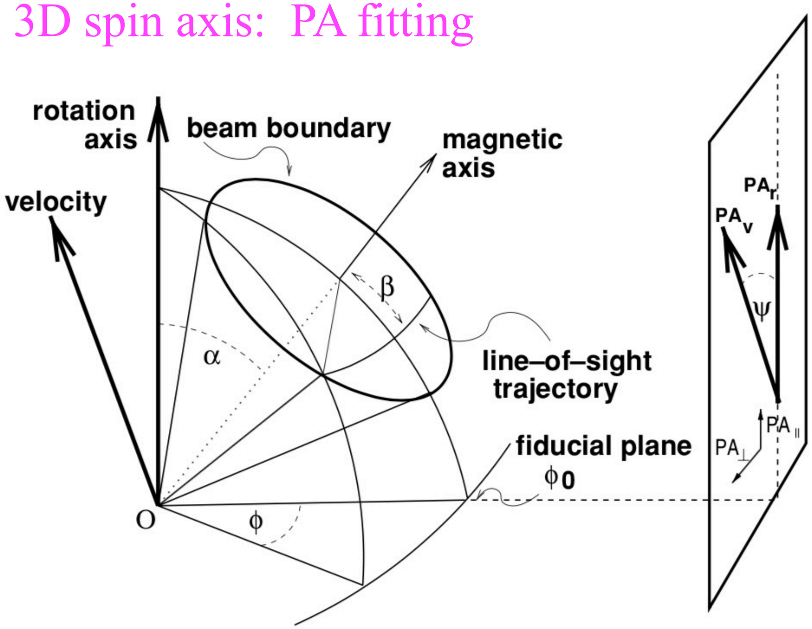
PA (V) - proper motion (VLBI): -24+/- 0.1 deg (Chatterjee et al .2009)

Inclination angle (V) - ISS observation: 109+/-18 deg (This paper)

The first 3D spin-velocity alignment in J0538+2817

1. 3D spin axis obtained from PA fitting, toroidal PWN (X-ray)

3D spin axis: PA fitting



Johnston et al. 2005

rotating vector model (RVM)

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

3D spin axis: toroidal PWN (X-ray)

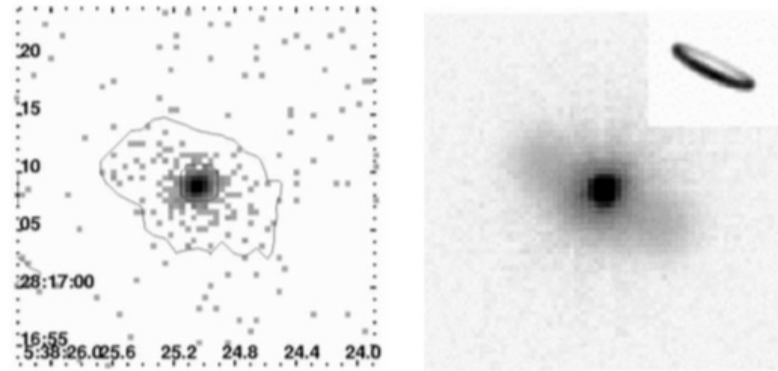


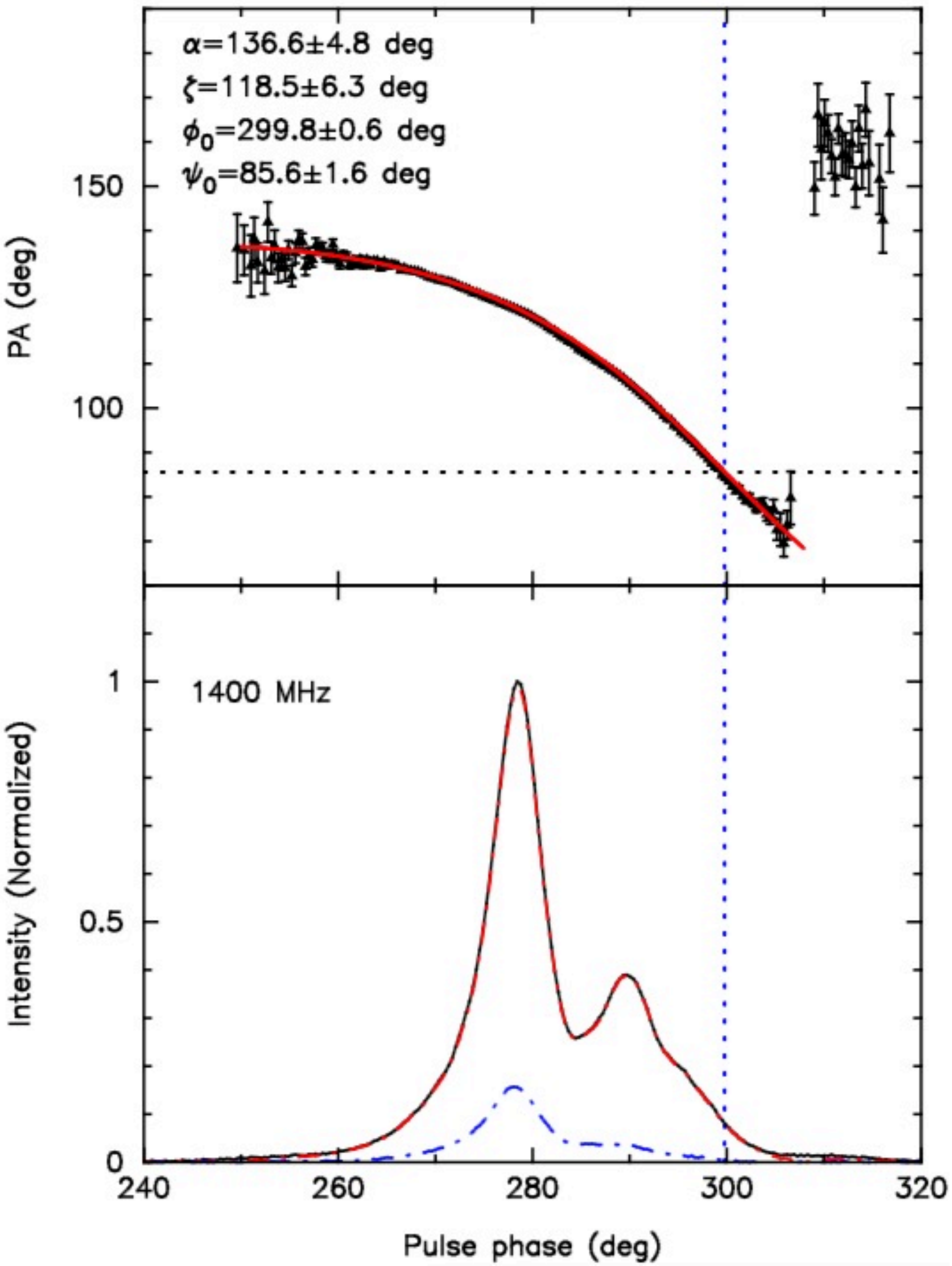
FIG. 2.—*Left:* ACIS 0.5–5 keV image with smoothed low-level contours. *Right:* Best-fit point-source+torus model. *Inset:* Best-fit torus model at half-scale, with δ reduced to 0".5 to show geometry.

Romani et al. 2003, PSR J0538+2817

toroidal PWN

Spin: the direction of the jet,
or the symmetry axis of toroidal.

2. FAST polarization analysis of J0538+2817



2.1. Revise the RM measures

$$RM = +39.56 \pm 0.14 \ \text{rad m}^{-2}$$

$$RM = -7 \pm 12 \ \text{rad m}^{-2}$$ Mitra et al.2003

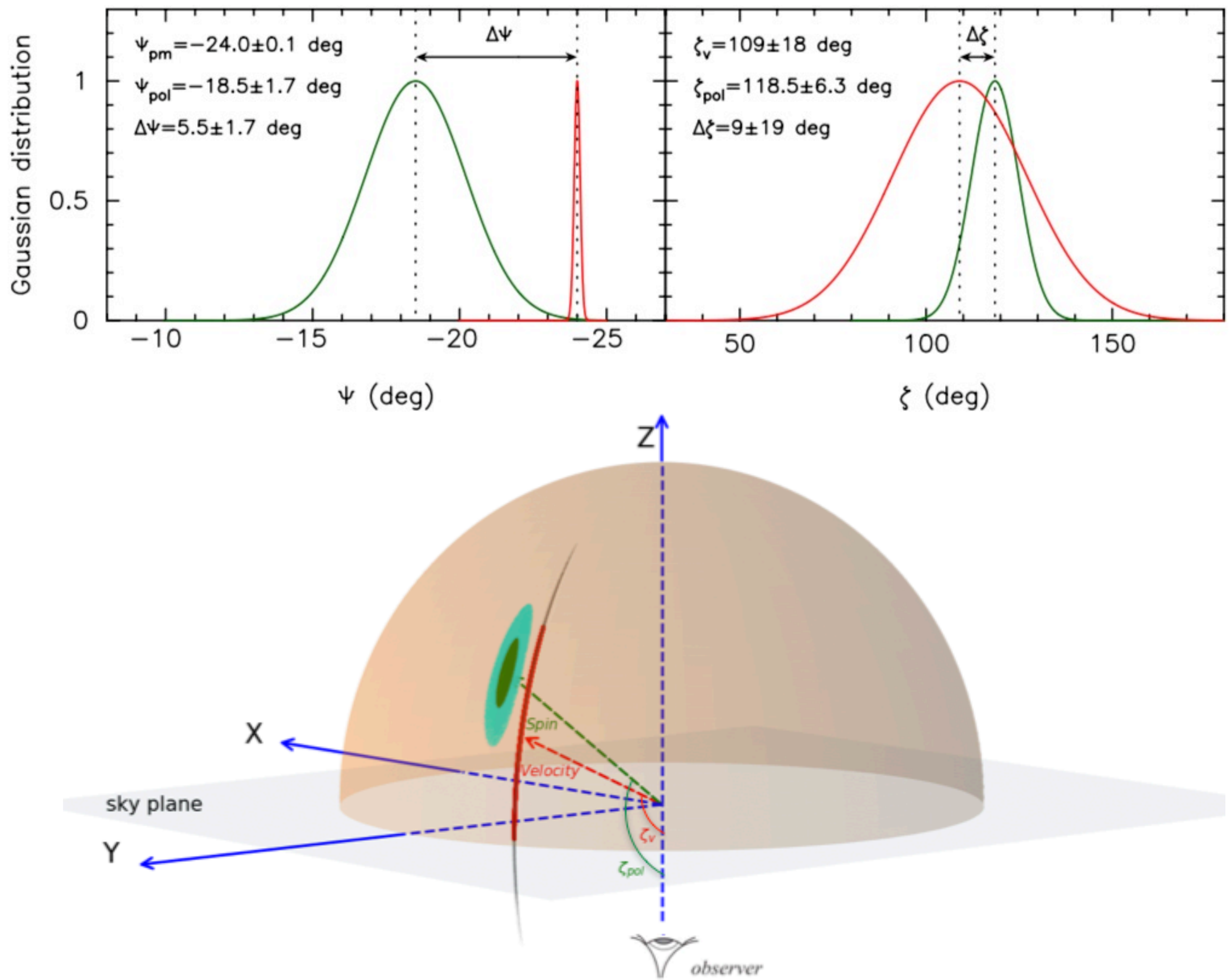
2.2 The inclination angle and PA0 (after RM correction)

$$\psi_{\rm pol}(\text{intrinsic}) = -18^\circ.5 \pm 1^\circ.7$$

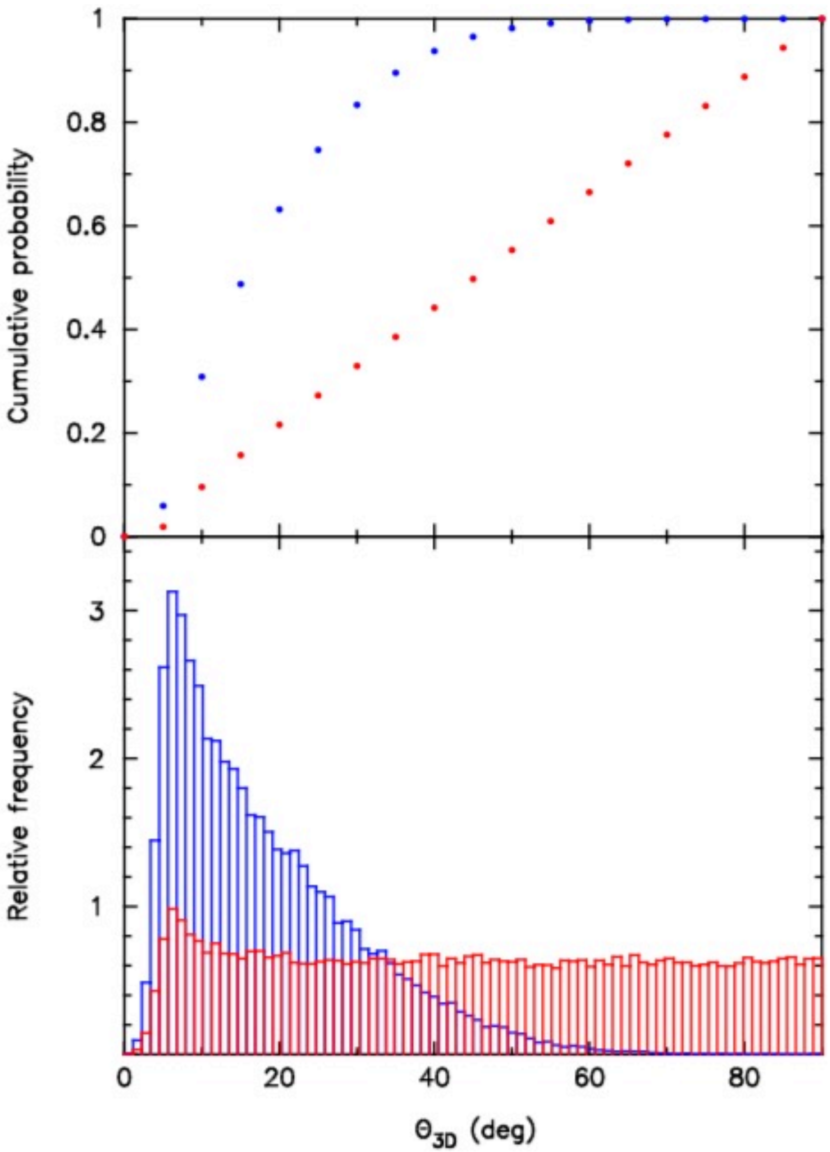
$$\zeta_{\rm pol} = 118^\circ \pm 6^\circ$$

3. The first evidence of 3D spin-velocity alignment from J0538+2817

PA (V) - proper motion (VLBI): -24 deg (Chatterjee et al .2009) PA (spin) - X-ray observation: -26 deg (Romani et al. 2003) PA (spin) - FAST polarization: -19 deg	Inclination angle (V) - ISS observation: 109+/-18 deg Inclination angle (spin) - X-ray observation: 100 deg Inclination angle (spin) - FAST polarization: 118+/-2 deg



4. Compare 3D with 2D spin-velocity alignment for J0538+2817



Red: \theta_3D without inclination angle

Blue: \theta_3D with inclination angle

For new result, there is a clear peak around 6 deg, and a 68% probability that \theta_3D<22 deg.

Rocket model can not explain the 3D spin-velocity for PSR J0538+2817 because of the long initial period of this pulsars (400 km/s, require <0.25 ms, 140 ms), nor the current 3D SN simulations.

Current 3D supernova simulations

Janka et al. 2017

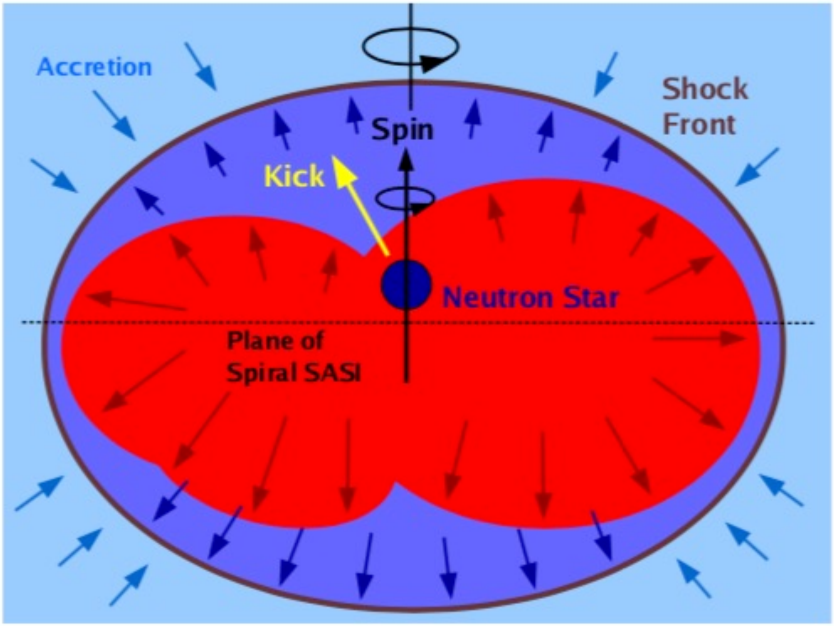
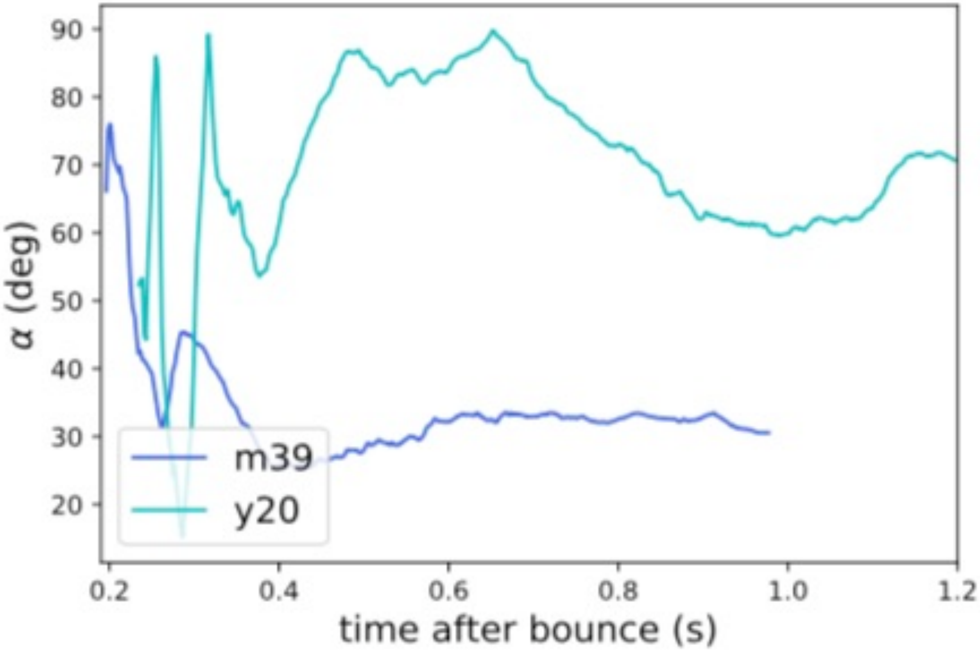


Figure 1. Spin-kick alignment resulting from a neutrino-driven explosion launched from a phase of strong spiral-SASI activity. While the explosion starts by equatorial expansion, the final NS kick is determined by the slower mass ejection in the polar directions. The red region symbolizes low-density, SASI deformed bubbles of high-entropy, neutrino-heated matter, whereas the two inward pointing "noses" in dark blue near the north pole and south pole indicate the relics of long-lasting polar downflows of shock-accreted low-angular-momentum matter. 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

Powell et al. 2020



m39: the mass of progenitors, 39 M_Sun, rapid rotating.

y20: the mass of the progenitors, 20 M_Sun, non-rotating.

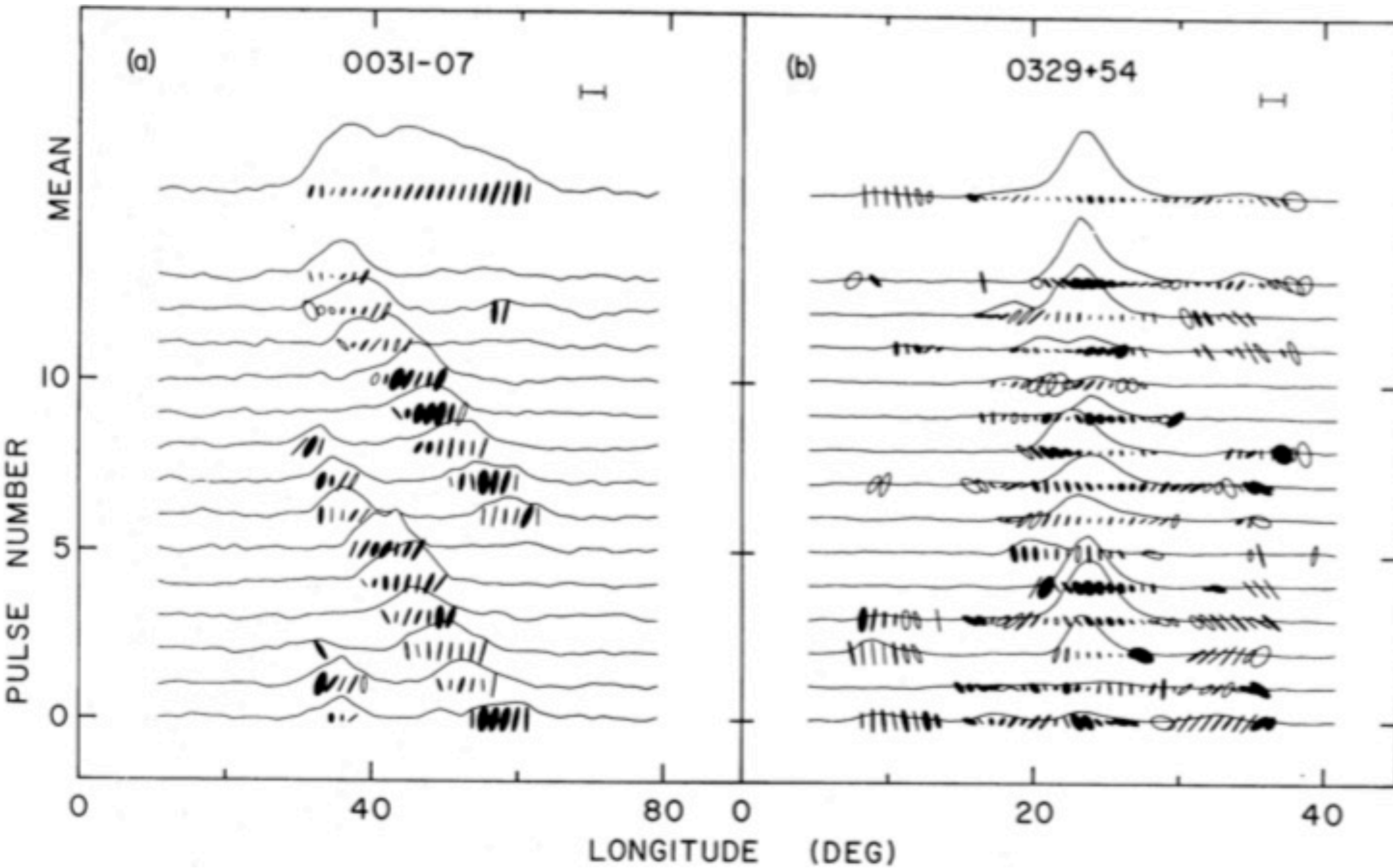
The rapid rotating have some effect on the angle between spin-velocity, but it is still larger than 30 deg.

Summary

- ☆ The SNR shell dominate the scattering of PSR J0538+2817.
- ☆ Using ISS, we confirmed the association between PSR J0538+2817/S147.
- ☆ Using ISS, we obtained the radial velocity and its inclination angle.
- ☆ Combined with polarization analysis, we find the first evidence for 3D alignment.
- ☆ It’s difficult to explain this by rocket model or 3D SN simulations, thus deepening the mystery of pulsar birth.

Thanks

I. Explanation of orthogonal polarization in pulsars:



Manchester et al. 1975

II. Explanation of magnitude of velocity:

Thus, the velocity of the pulsar, as a result of asymmetric emission of radiation, is

$$\Delta V \sim \varepsilon_0 I \Omega_0^2 / 2Mc \qquad (5)$$

For a neutron star of radius 10 km this gives $\Delta V \sim 10^{-4} \varepsilon_0 \Omega_0^2$ km s^{-1}, and for initial values $\varepsilon_0 \sim 0.1$, $\Omega_0 \sim 10^4$, the final velocity is $\sim 10^3$ km s^{-1}. It is evident that with reasonable

Tademaru & Harrison (1975) （The rocket mechanism)

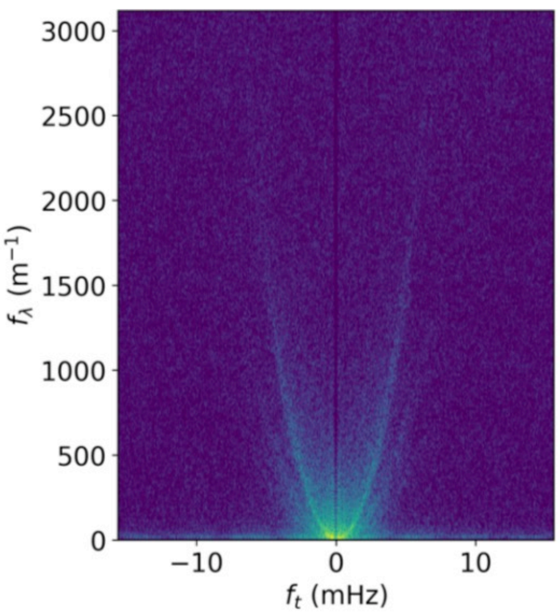
I. V~1000 km/s, the initial period should smaller than 0.1 ms

II. V~400 km/s, the initial period should smaller than 0.25 ms

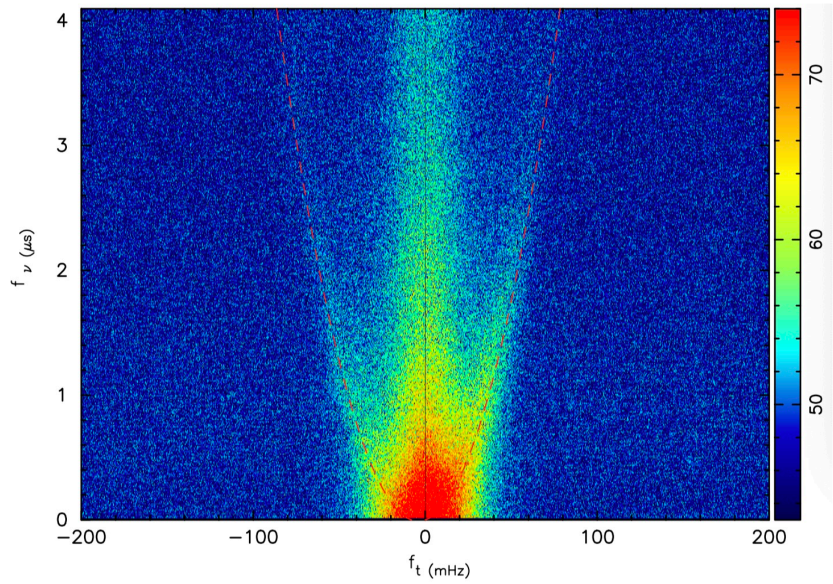
But for PSR J0538+2817, the initial period is about 140 ms.

III. The arc shape of J0538+2817 is special

J0437+4715 (Reardon et al. 2020)



J0538+2817 (shape edge+diffuse power+center bright widge)



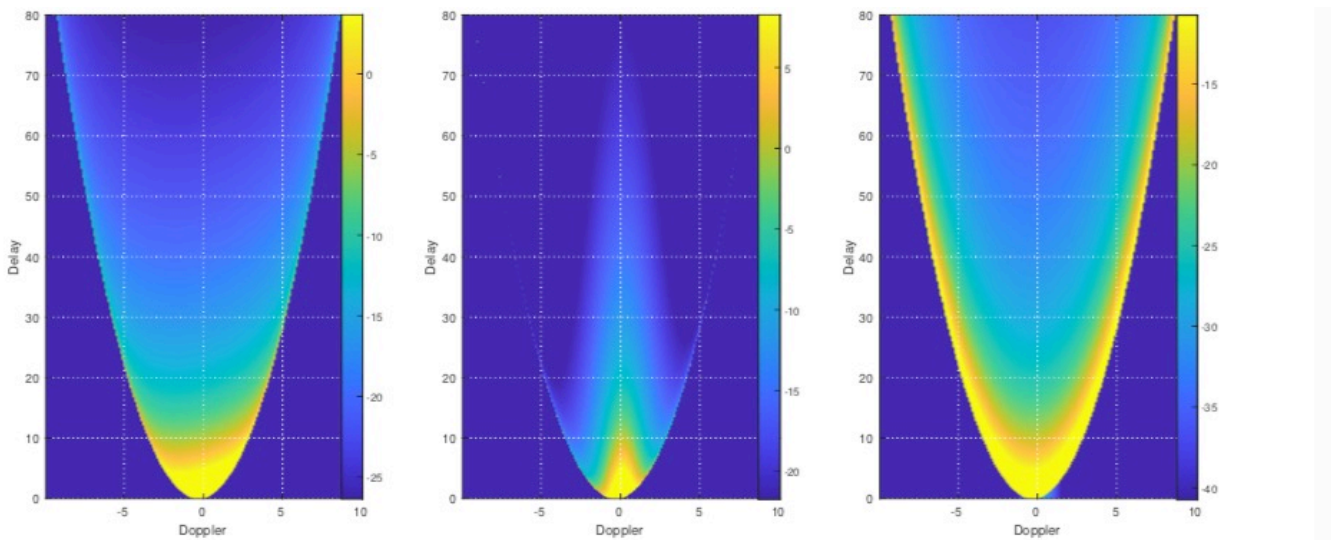


Figure 7. Modeled secondary spectra: isotropic (left); anisotropic aligned with V (center); anisotropic perpendicular to V (right) with a logarithmic (dB) colour scale. The axial ratio of the anisotropic cases is 3. Each has the same phase gradient.