U.S. NAVAL RESEARCH LABORATORY

The Serendipitous Tale of a Pulsar and an SNR

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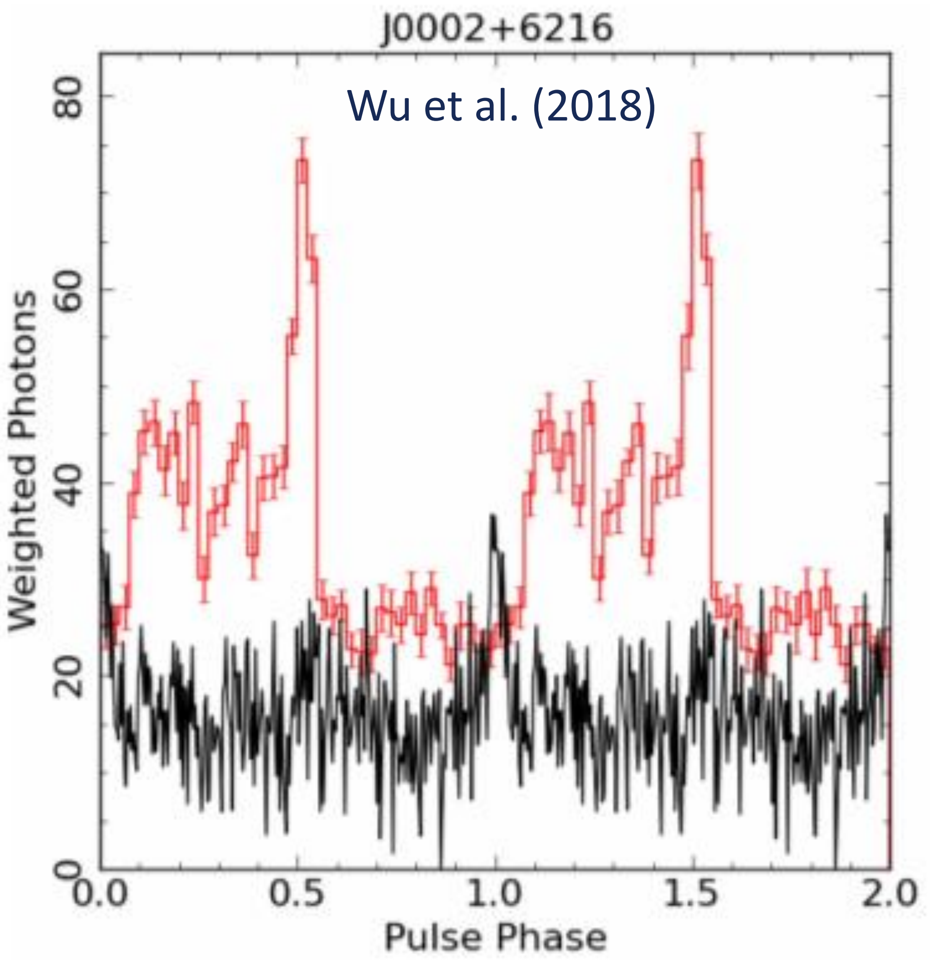
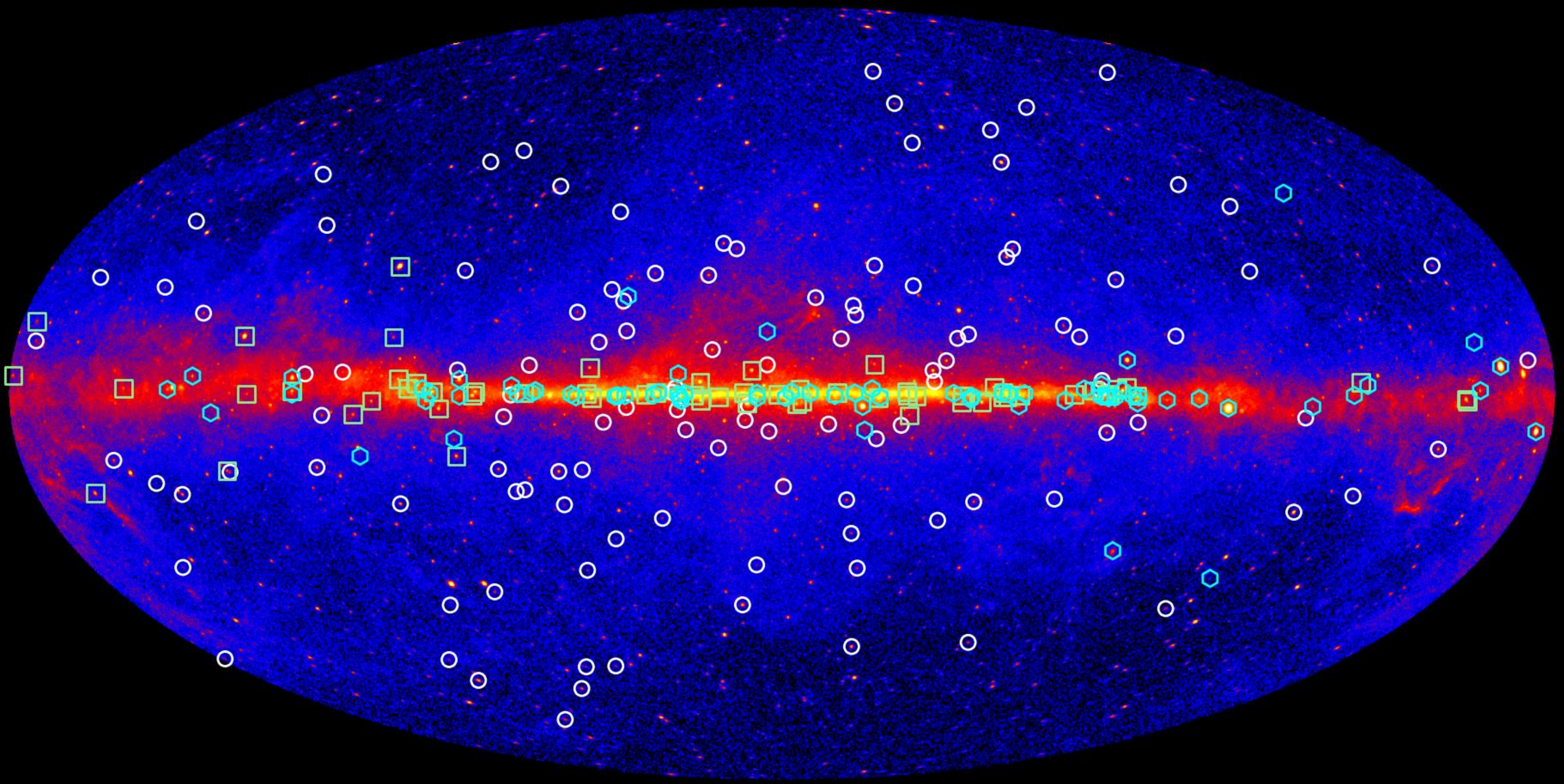
Image Credit: Scott Rosen

PSR J0002+6216

PSR J0002+6216

- Discovered in "blind" periodicity searches of Fermi data using the Einstein@Home volunteer computer (Clark et al. 2017)
- Relatively normal gamma-ray pulsar:
  - P=115 msec, B=0.8x10^{12} G, $\dot{E}$=1.5x10^{35} erg s^{-1}
  - Characteristic age τ_c = 306 kyr
- Weakly detected in radio (Wu et al. 2018)
  - Dispersion measure puts distance at 7 kpc





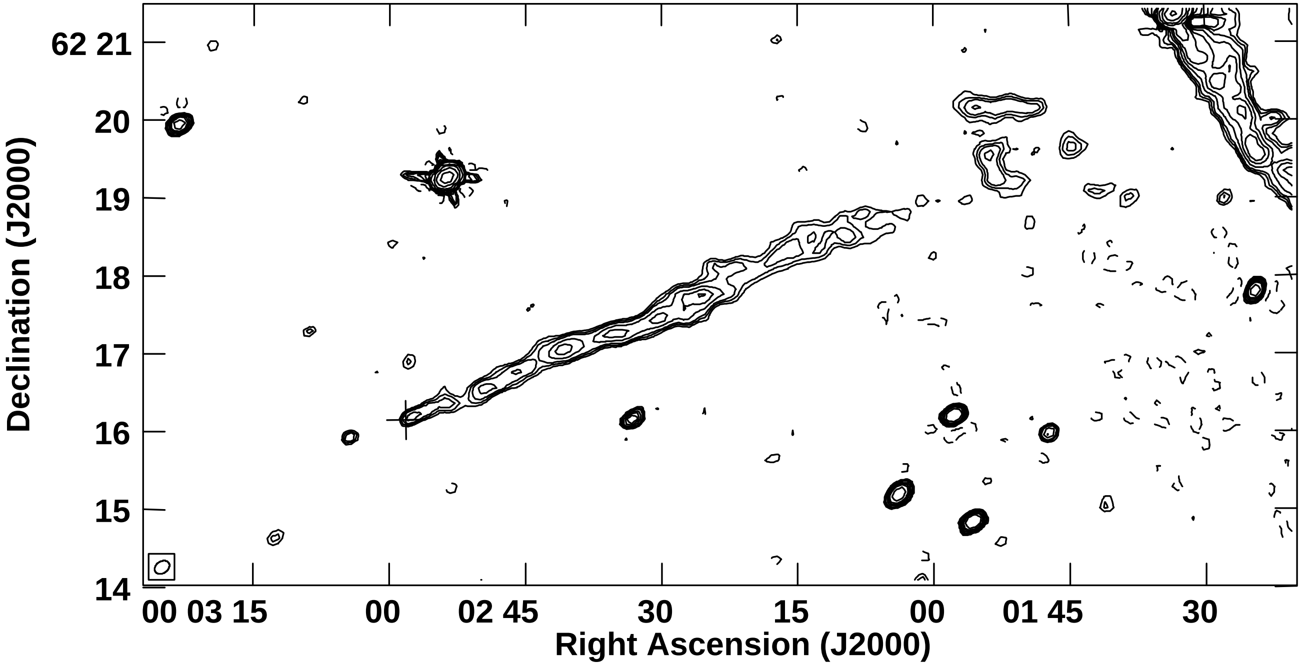
Serendipitous Discovery: a Hypersonic Pulsar-wind Nebula…

Targeting unidentified (oops!) Fermi sources

1-hr integration at 20 cm (1-2 GHz) with 12-arcsec resolution

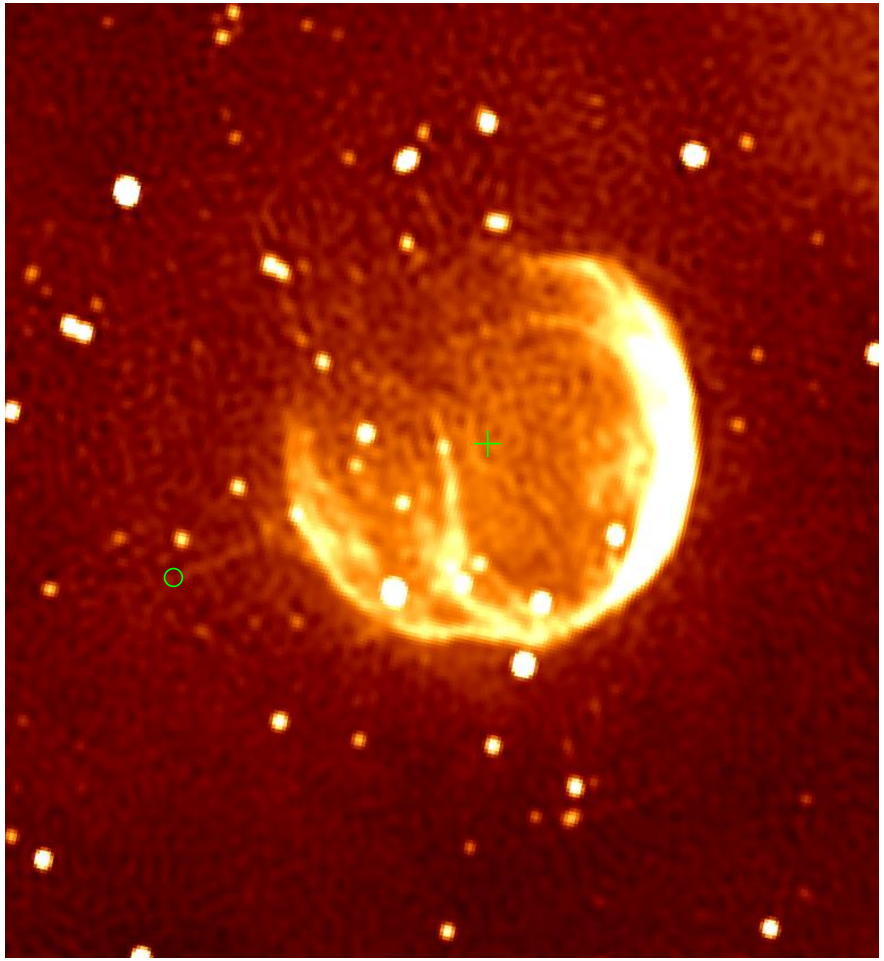
Used special experimental algorithms within CASA

- Wideband AW projection with conjugate beam models and
- Multi-term, multifrequency synthesis
- Multi-scale clean



… rather near to SNR CTB1…

- A middle-aged SNR (τ=10±0.2 kyrs)
- optical and radio. circular shell of radius 17.8 arcmin
- X-rays mixed morphology SNR with evidence for enhanced heavy element abundances
- located in Perseus arm with distance of d_k=2.0±0.4 kpc



… with a suggestive geometry!

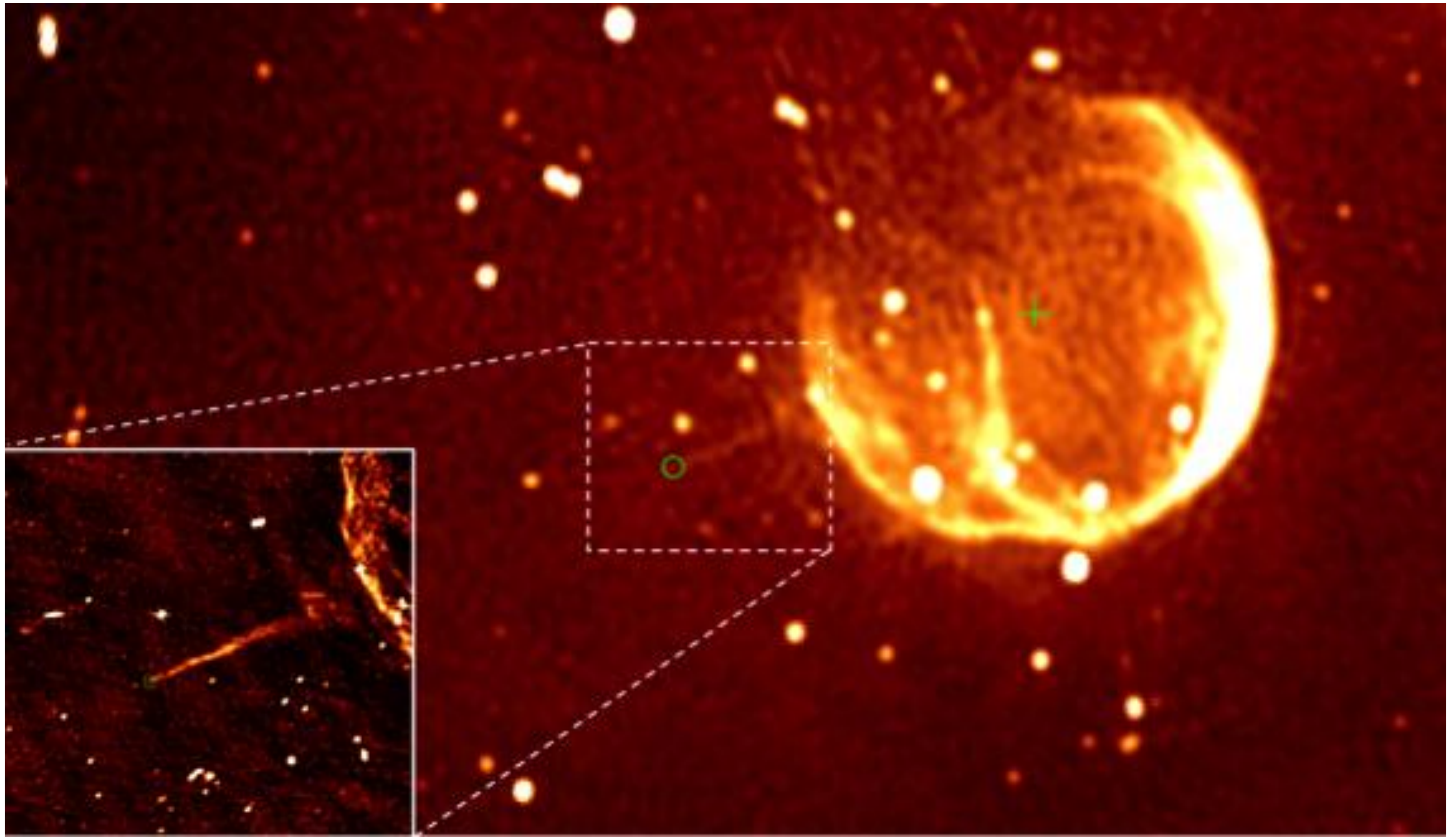
Extrapolation of least squares fit of 7-arcmin tail passes within 5-11 arcsec of the geometric center of SNR CTB1, 28±1 arcmin away.

Very small *a posteriori* probability of chance coincidence.

If PSR J0002+6216 is from the SN, predicts proper motion of

$\mu = \Delta\theta/\tau = 168 \pm 35$ mas/yr at a

PA of 113 degrees.



Potential Issues and Implications

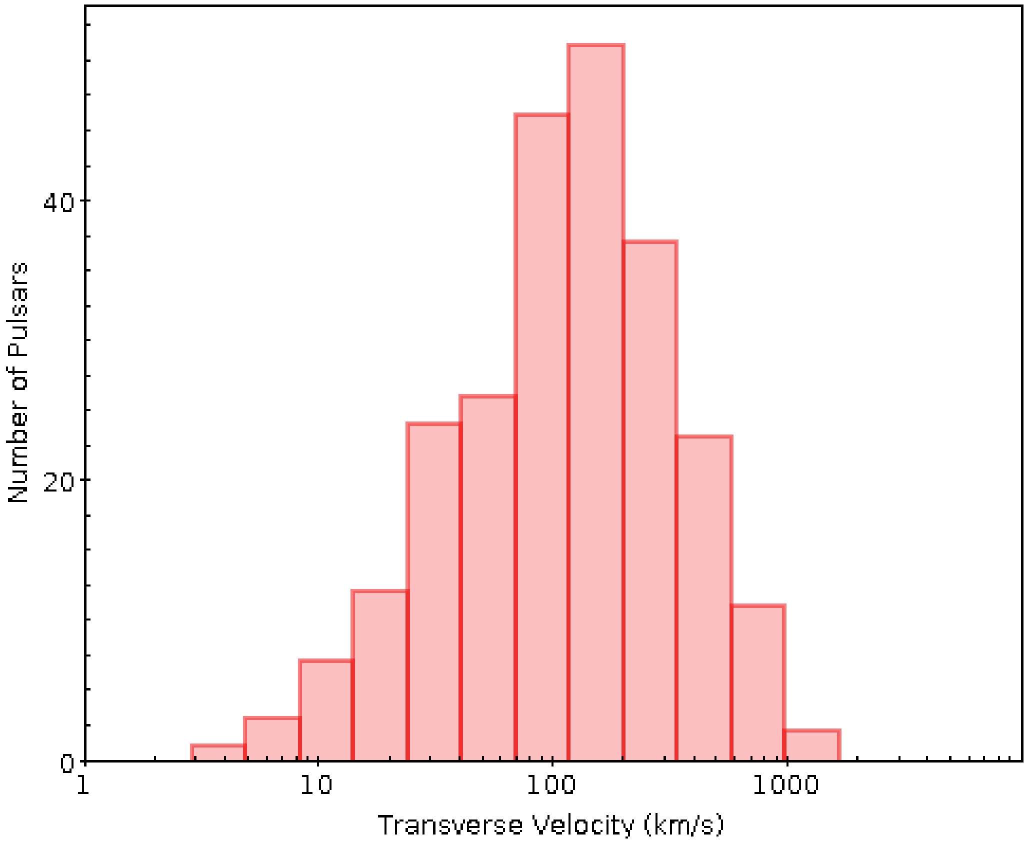
If the association is true, then

- The pulsar is **much** younger than its characteristic age (born spinning slowly)
- The pulsar is moving at ~810 d_{kpc} km/s.

  Recall d_{DM}=7kpc and d_{SNR}=2kpc.

Really desire an independent measure of the pulsarproper motion!

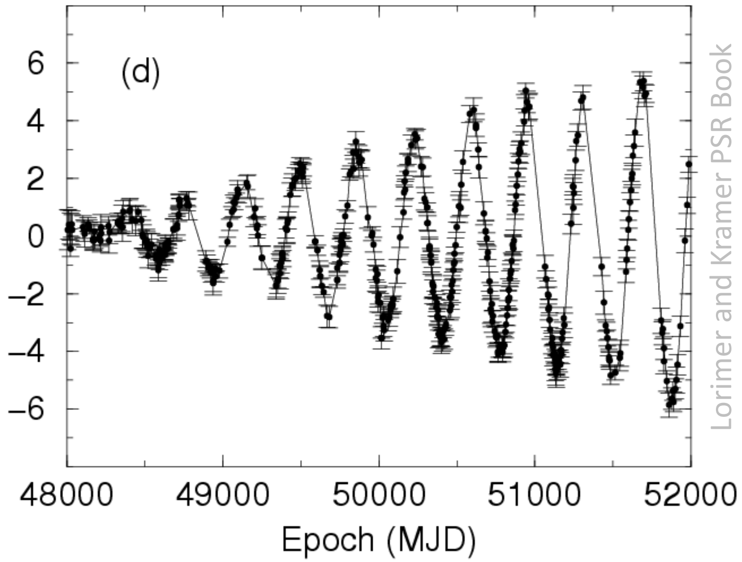
CSIRO PSRCAT



Fermi Pulsar Timing

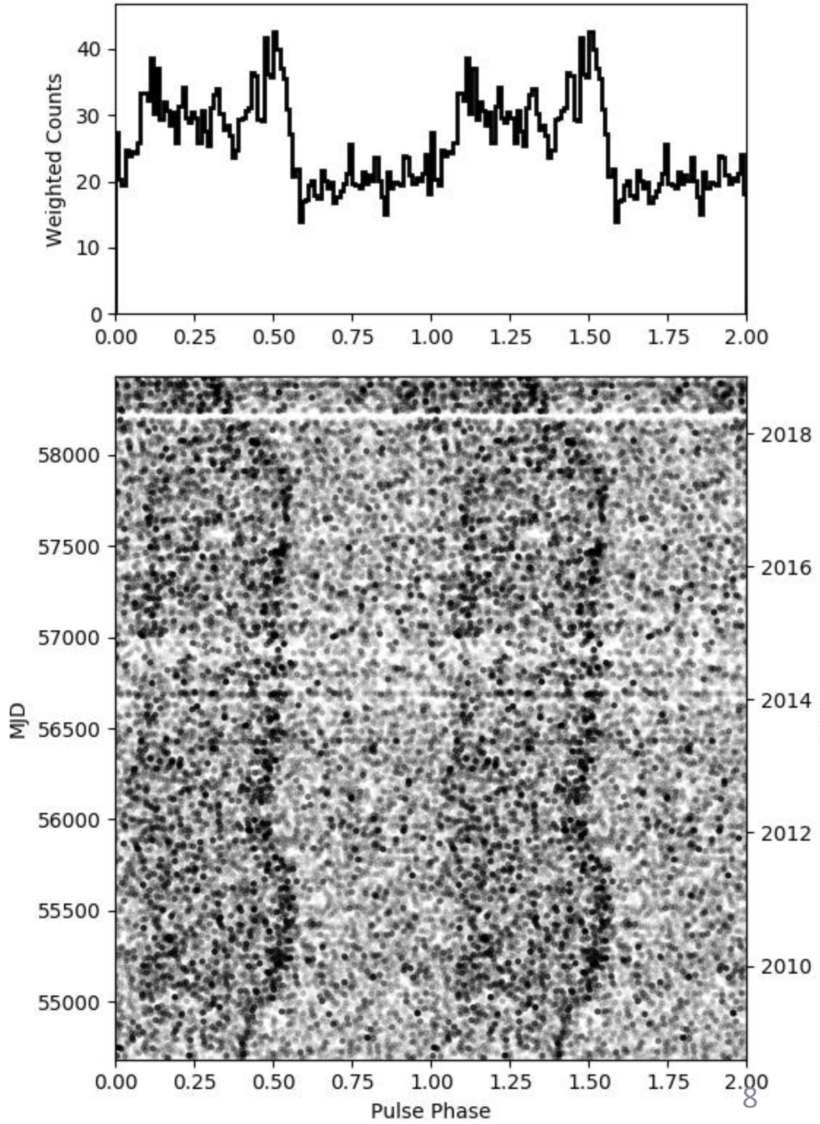
Fermi “instantly” gives us >10 years of data with which to perform pulsar timing.

An error in the position of a pulsar produces an annual sinusoid in the pulse arrival time. So an error in the proper motion produces a linearly-growing sinusoidal error (chirp).



Unfortunately, young pulsars are far from ideal! Plot at right shows the pulsar with only its simple spindown and position modeled. The residual is timing noise.

With Fermi, we have reliably measured proper motions really only for millisecond pulsars (low timing noise) .

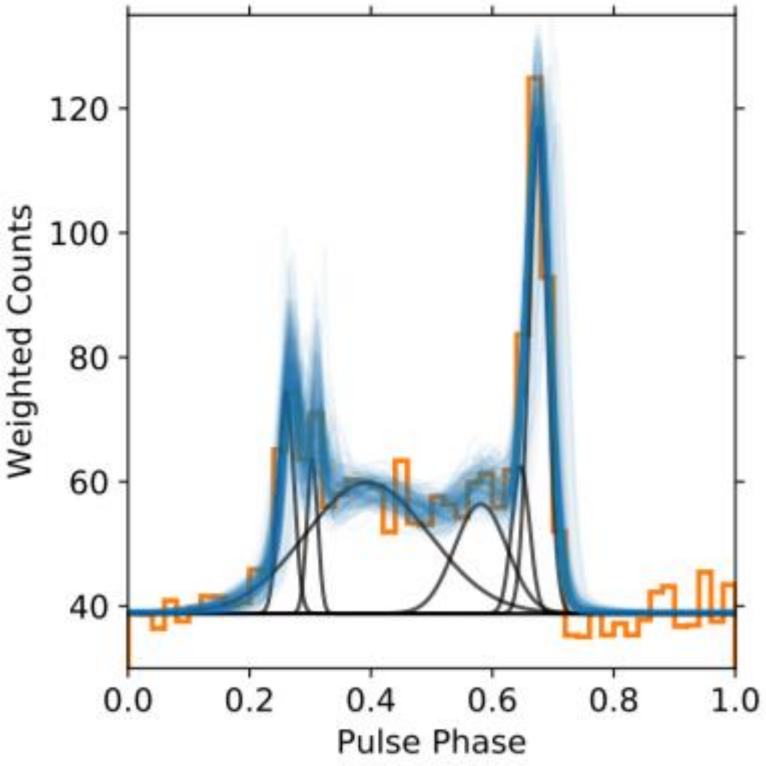


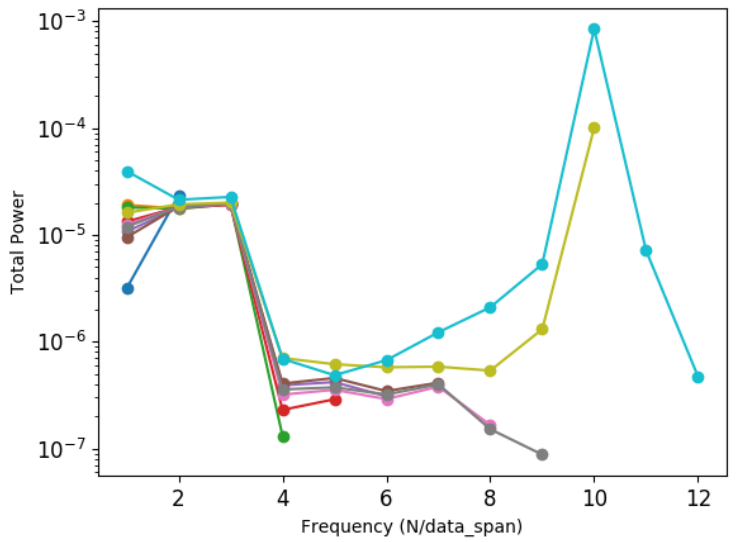
Fermi Pulsar Timing

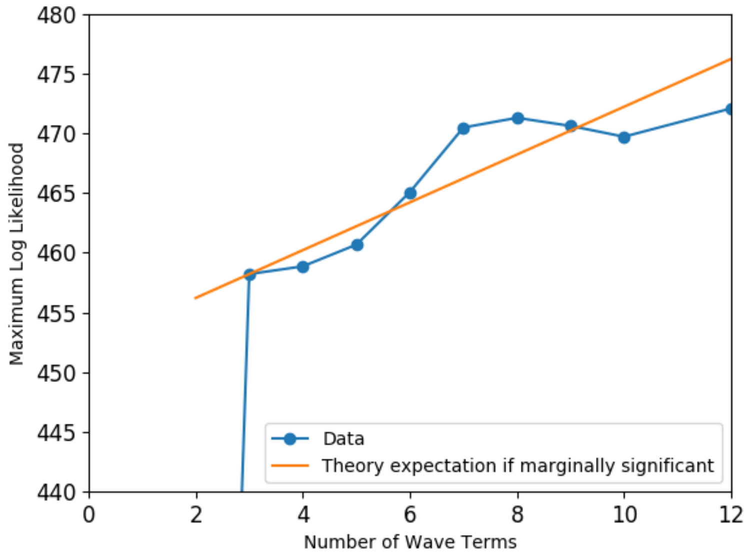
Unfortunately, we also don't know what the true pulse profile looks like… We need the profile to get the timing solution, and we need the timing solution to the profile!

So, we tried a range of models of timing noise while jointly fitting a model for the template.

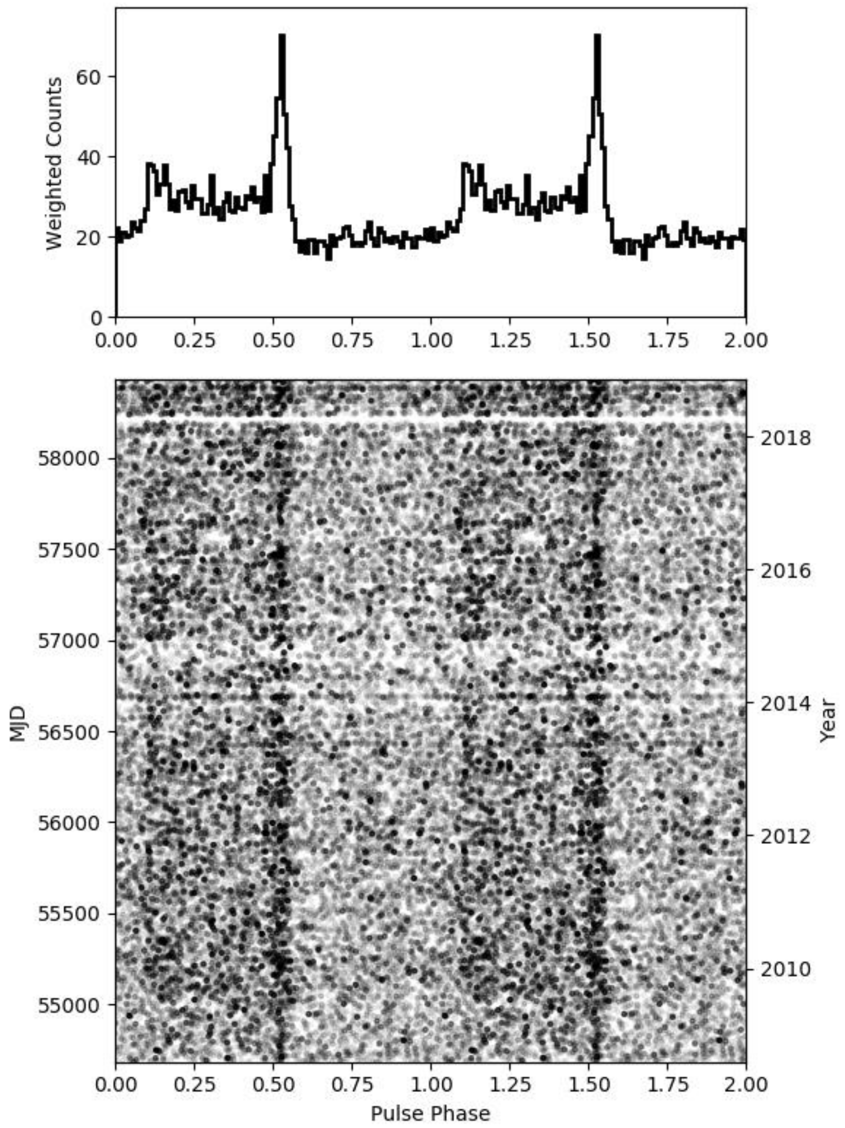
A model with three sinusoidal components fully fit the data, an unusually red timing noise signal.

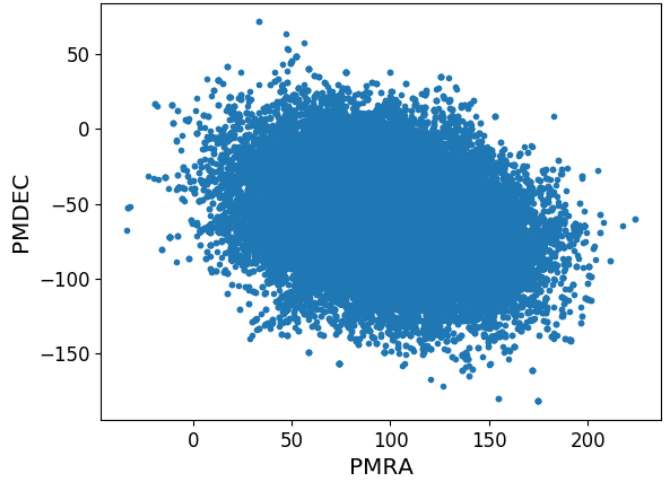


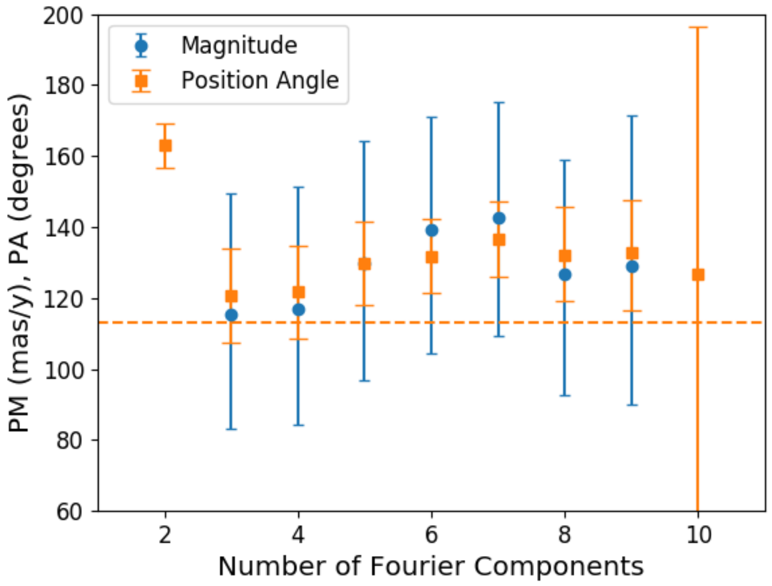




Fermi Pulsar Timing







Best-fit timing noise and pulsar timing model prefer proper motions that agree in <u>magnitude</u> and <u>direction</u> with the values required by the PWN-SNR direction and the PWN-SNR offset/SNR age!

(This is one of the only gamma-ray pulsars with a measured proper motion – a real testament to the quality of Fermi data.)

Putting it all together

Rule out μ<63 mas/yr with 95% confidence

Measured:

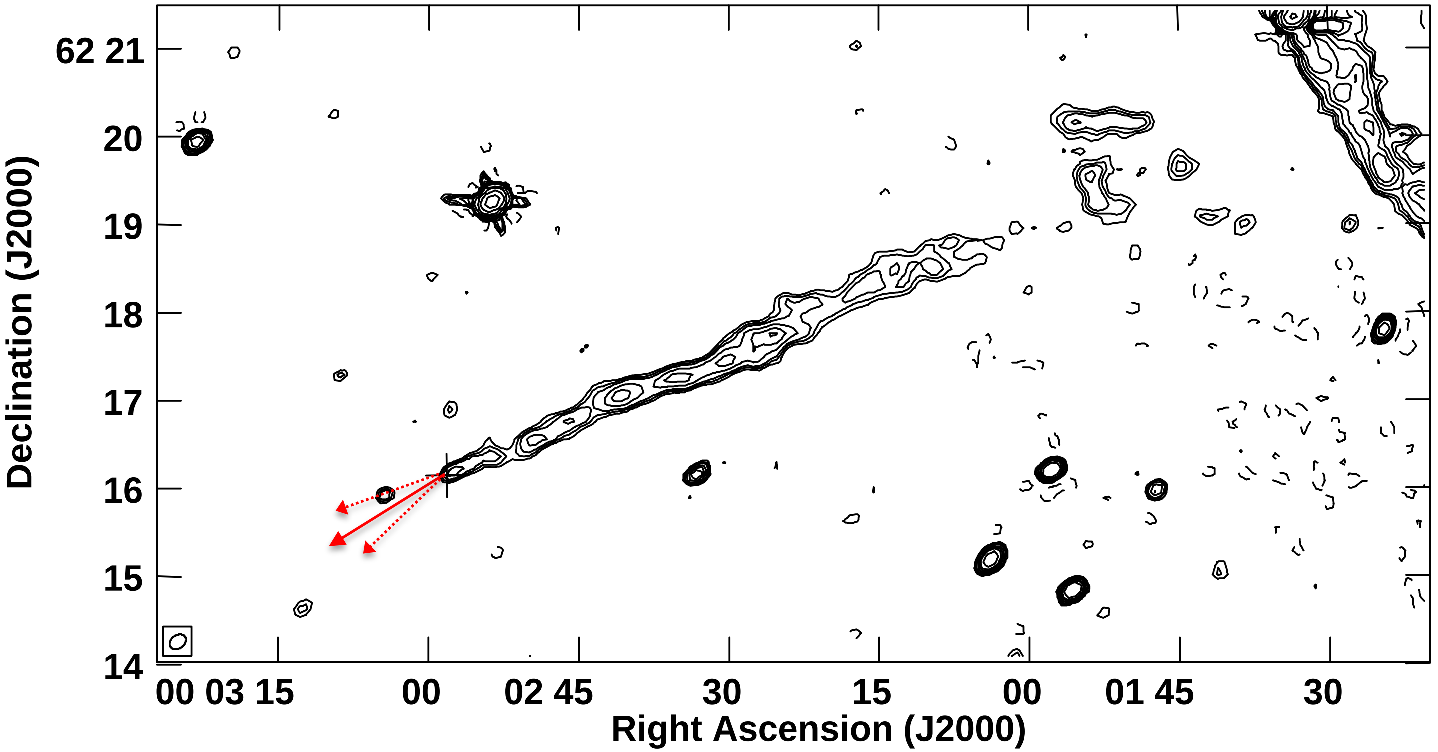
μ=115±33 mas/yr (3.5σ)

θ_μ=121±13^o

Inferred:

μ=Δθ/τ=168±35 mas/yr

θ_μ=113±2^o



What can we learn from the association?

How pulsars get their kicks (and spins)

Highest V_{PSR} provide severe constraints on models

x binary disruption

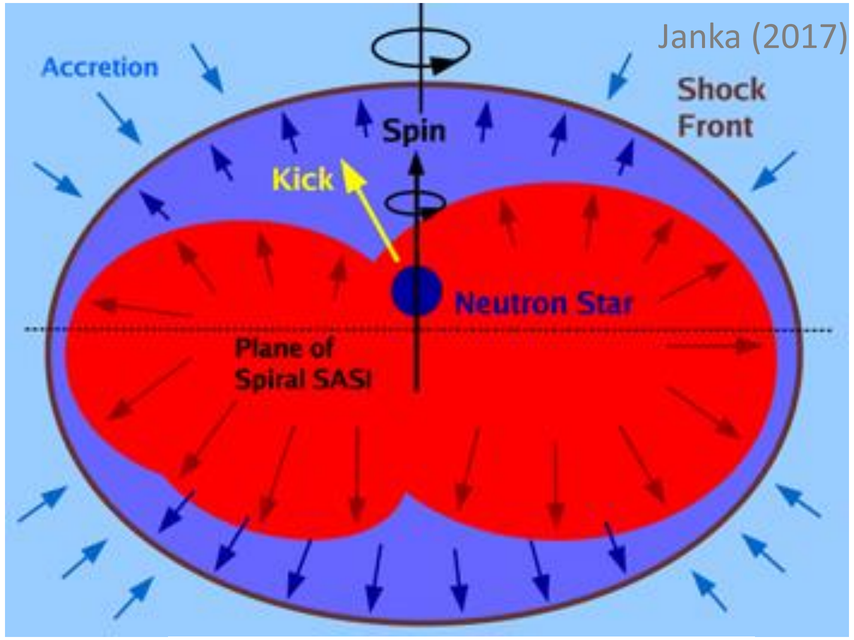
x electromagnetic ("Rocket effect")

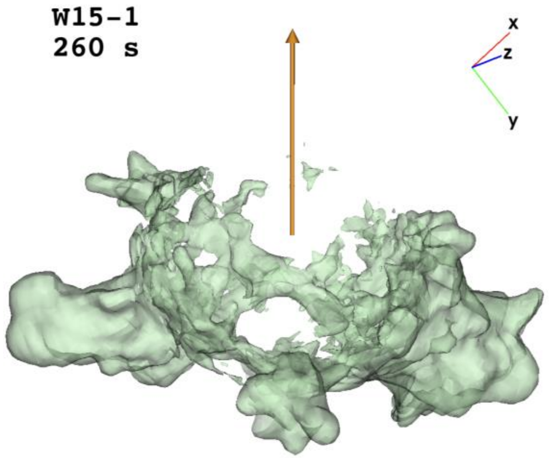
✓neutrino-driven (E_o=10^{53} erg)

- V_{PSR} aligned with Ω

✓ejecta-driven (hydro recoil; E_k=10^{51} erg)

- V_{PSR} anti-aligned with V_{ejecta}





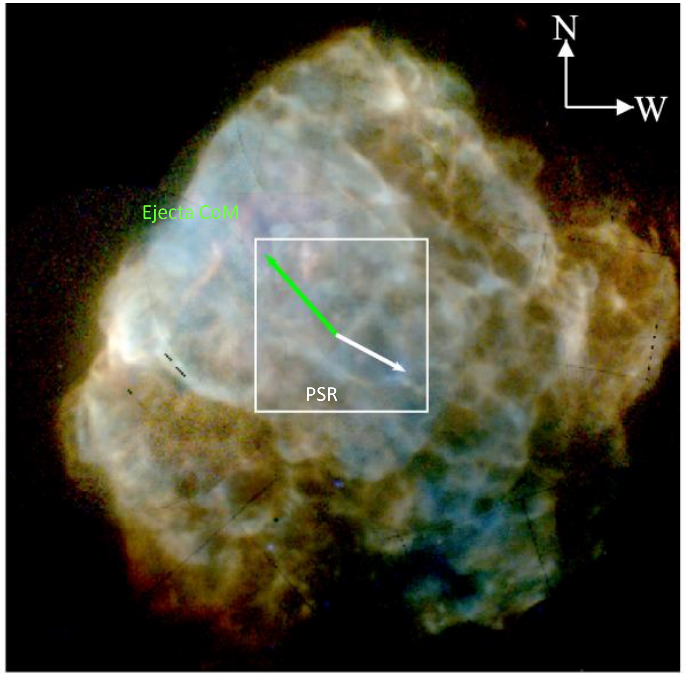
Wongwathanarat, Janka and E. Müller (2013)

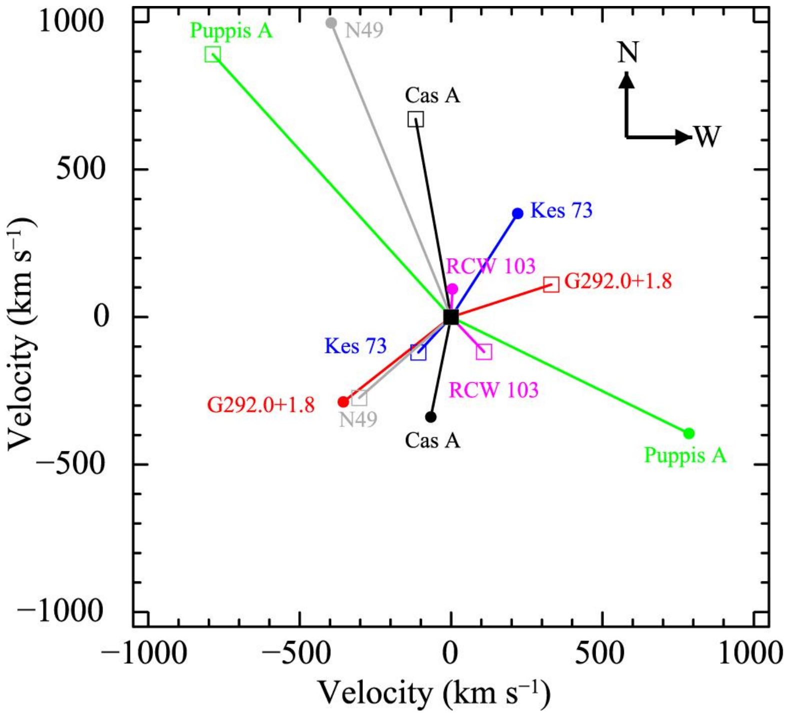
Hydrodynamic or Ejecta-driving Kicks

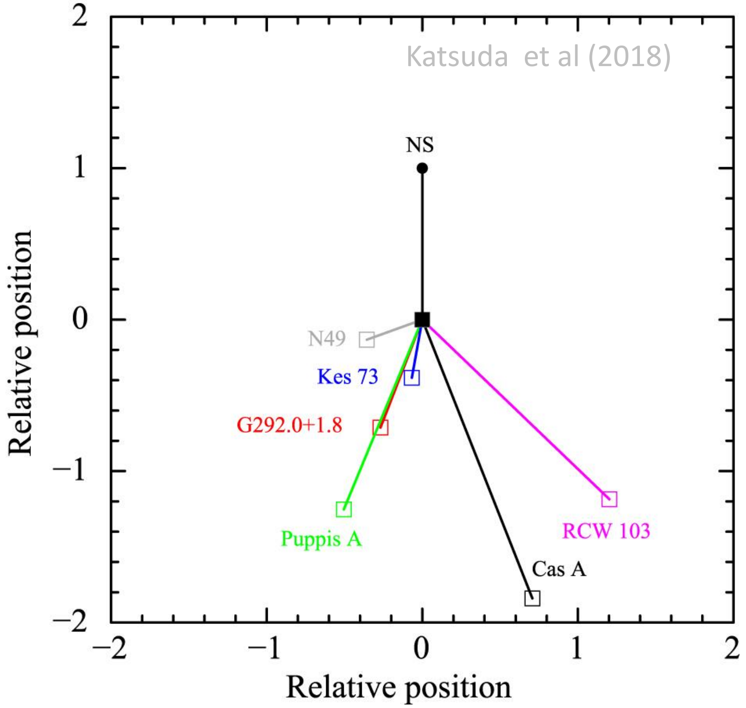
Originate in large-scale asymmetries seen in CC SNe explosion modeling

Signature in the SNR morphologies and (heavy element) ejecta distribution

What does the SNR CTB1 tells us?



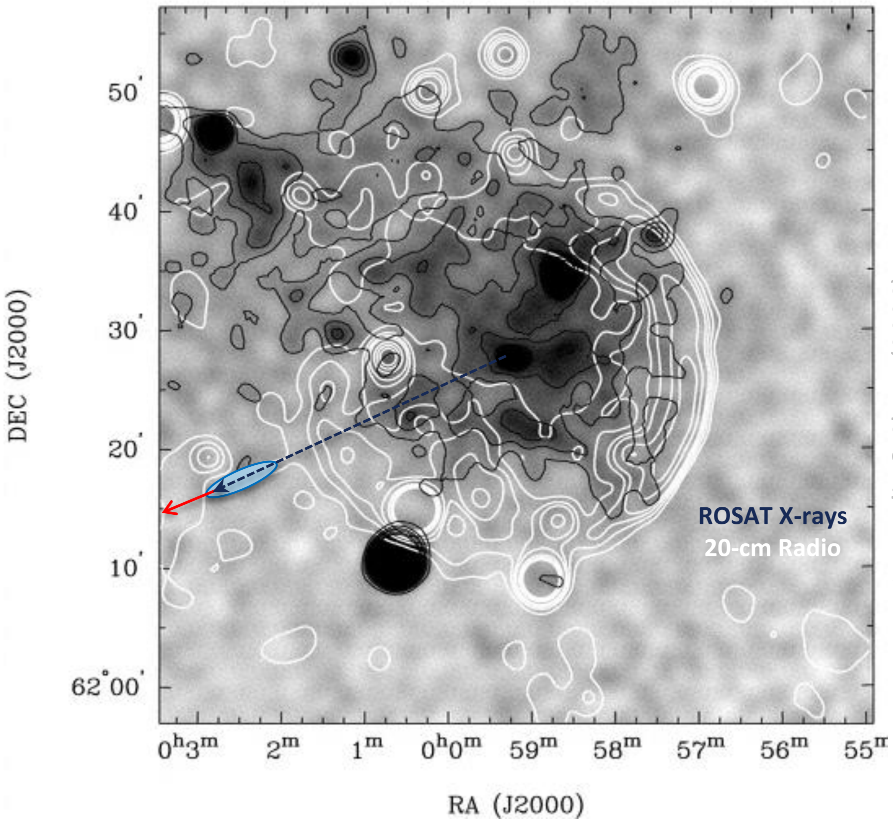




Evidence for asymmetry in CTB 1

X-rays are offset to NW but mixed morphology so SNR is likely dominated by ISM

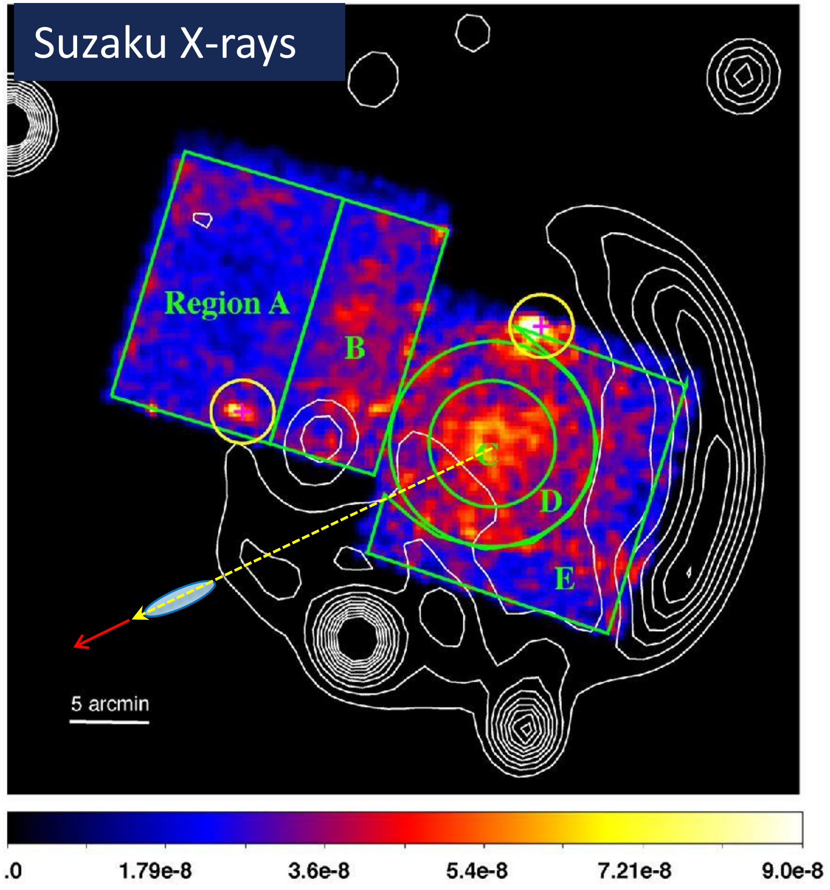
X-ray spectra have enhanced heavy element abundances



Lazendic & Slane (2006)

Evidence for asymmetry in CTB 1

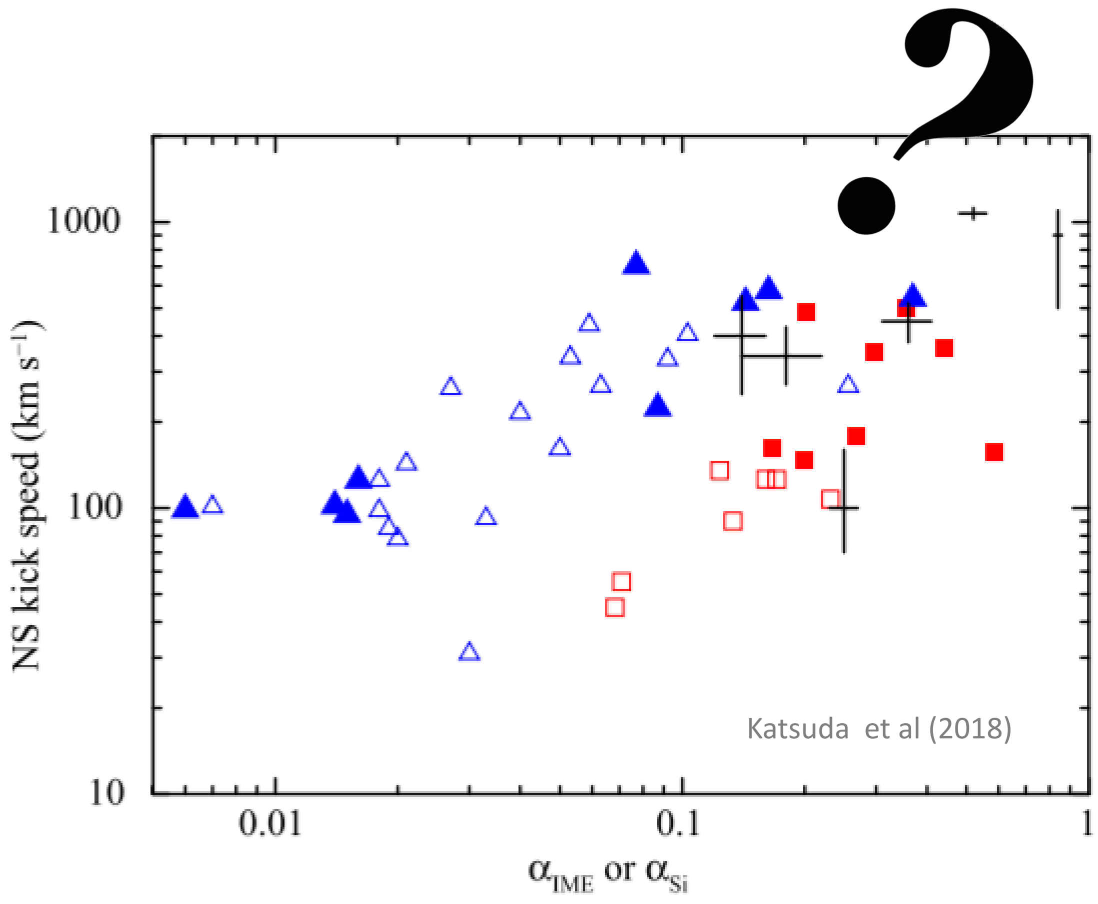
- X-rays are offset to NW but mixed morphology so SNR is likely dominated by ISM
- X-ray spectra have enhanced heavy element abundances
- Spatial distribution of iron is consistent with asymmetric SNe explosion
  - regions not optimized wrt PSR proper motion direction



Katsuragawa et al. (2019)

Evidence for asymmetry in CTB 1

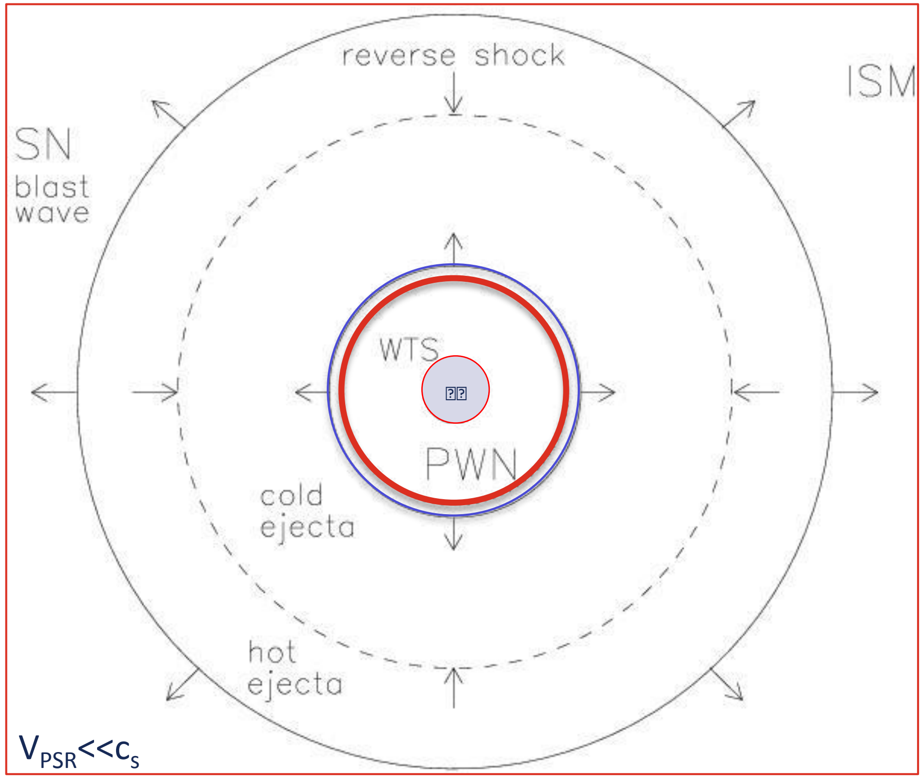
- X-rays are offset to NW but mixed morphology so SNR is likely dominated by ISM
- X-ray spectra have enhanced heavy element abundances
- Spatial distribution of iron is consistent with asymmetric SNe explosion
  - regions not optimized wrt PSR proper motion direction
- High PSR velocity requires very asymmetric explosion
  - i.e. $MV^2_{PSR} = 20\% \ E_k$



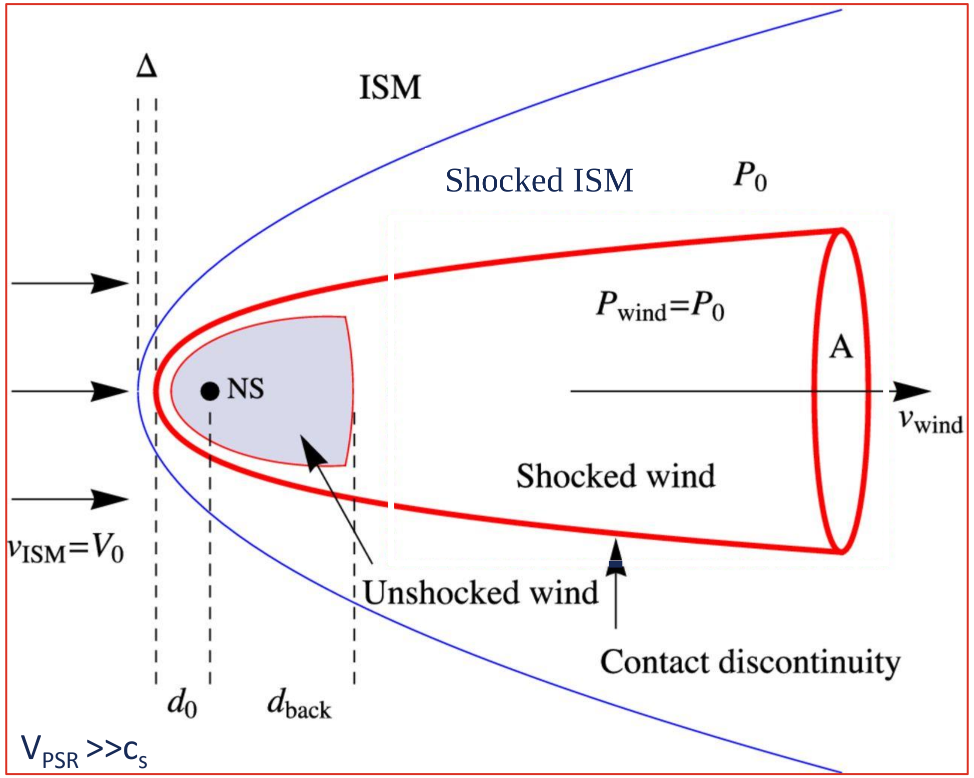
Asymmetry Parameter

Quick notes on the PWN

Zajczk et al. (2011)



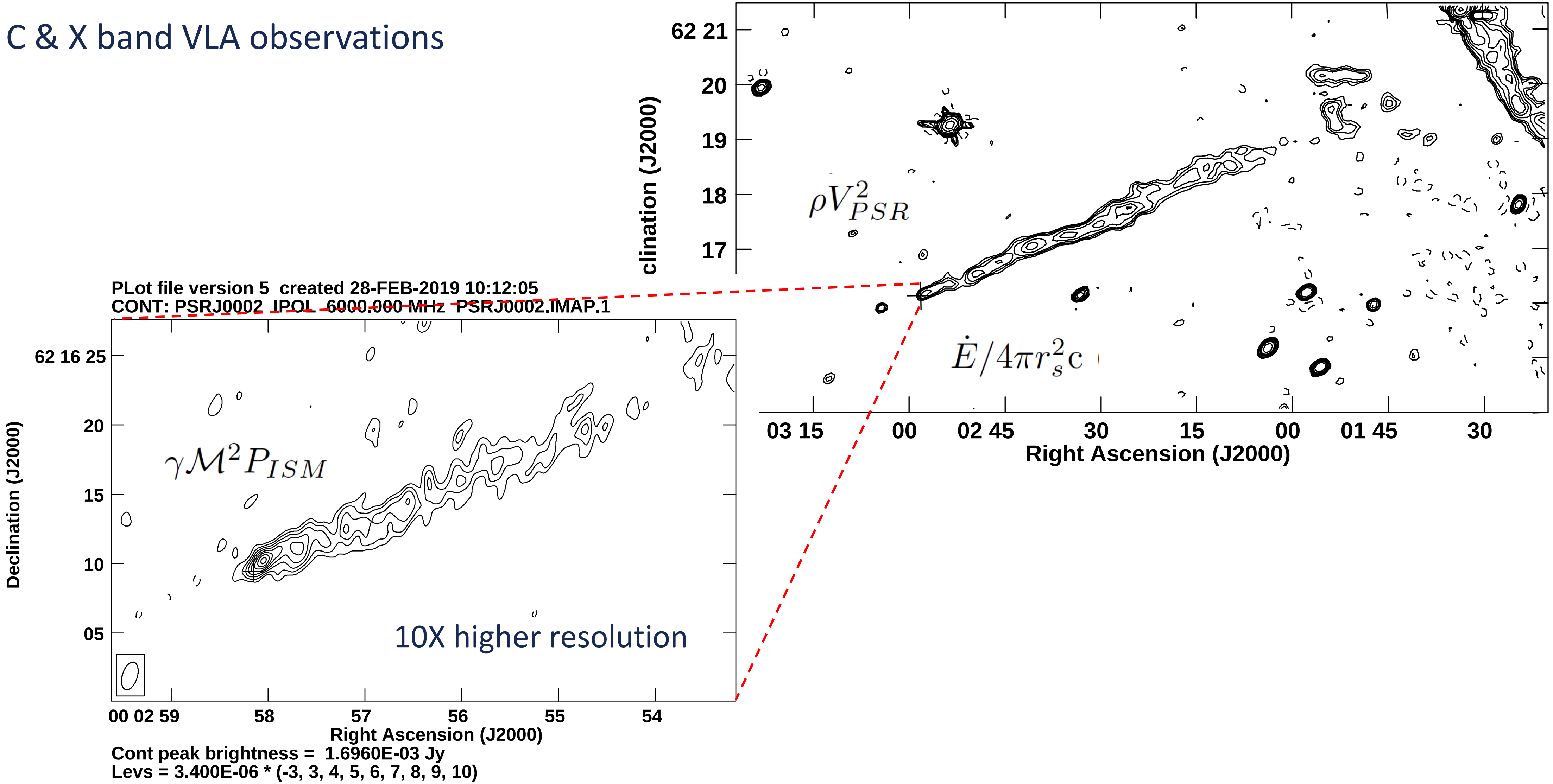
Morlino, Lyutikov & Vorster (2015)



In general, bow shock nebulae provide a “clean” probe of the pulsar wind. Resolving the bow shock is a direct probe of the ISM density/pressure. Radio and X-ray spectra characterize the injected particles and their evolution downstream.

New observations

C & X band VLA observations



Summary and Future Work

A new, very high-velocity (>1000 km/s) pulsar associated with a middle-aged supernova remnant provides insight into, and hopefully some constraints on, core collapse and pulsar kicks.

- PSR was not born spinning rapidly ($P_o \approx 113$ ms)
- highly asymmetry SN was required to give PSR its natal “kick”

A new bow shock nebulae, potentially one of the closest with such a high Mach number, provides a new way to probe pulsar winds and the ISM.

- Physical properties are similar to a subset of bow-shock PWN that includes The Duck, The Mouse and the Frying Pan

Hoping for Chandra imaging of the PWN head to detect the youngest injected electrons and measure flow properties.

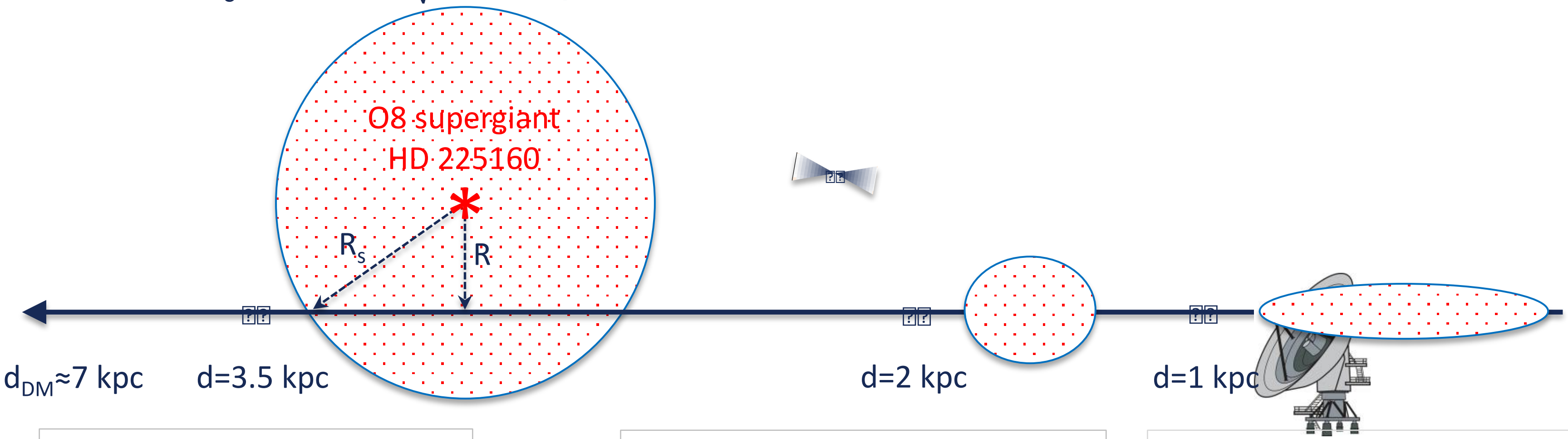
VLBA+VLA+Effelsberg VLBI observations will determine parallax and more accurate proper motion (in two years).

Future high-frequency VLA observations can resolve the head to measure standoff distance and Mach disk; polarimetry to study magnetic field in downstream flow.

Backup Slides

The Distance to PSR J0002+6216

$$DM_e = 2neRs\sqrt{1-(R/Rs)^2}$$



d=3.5 kpc	d=2 kpc	d=1 kpc
DM_e=50 pc cm^{-3}	DM_e=130 pc cm^{-3}	DM_e=200 pc cm^{-3}
EM_e=2500/L_{pc} pc cm^{-6}	EM_e=1.7x10^4/L_{pc} pc cm^{-6}	EM_e=4x10^4/L_{pc} pc cm^{-6}
A_v=2.1 mag	A_v=1.3 mag	A_v=0.9 mag

Bottom line:

d=2 kpc is the closest distance that satisfies all constraints

Agrees with empirical relation between Lɣ and Ė

Pulsar Birth Periods: Evidence for Injection

If the association is real why is $\tau_{SNR} << \tau_c$?

τ_c assumes $P_o << P$

n=3 (dipole) $P_o = P\sqrt{1 - \frac{\tau_{SNR}}{\tau_c}}$

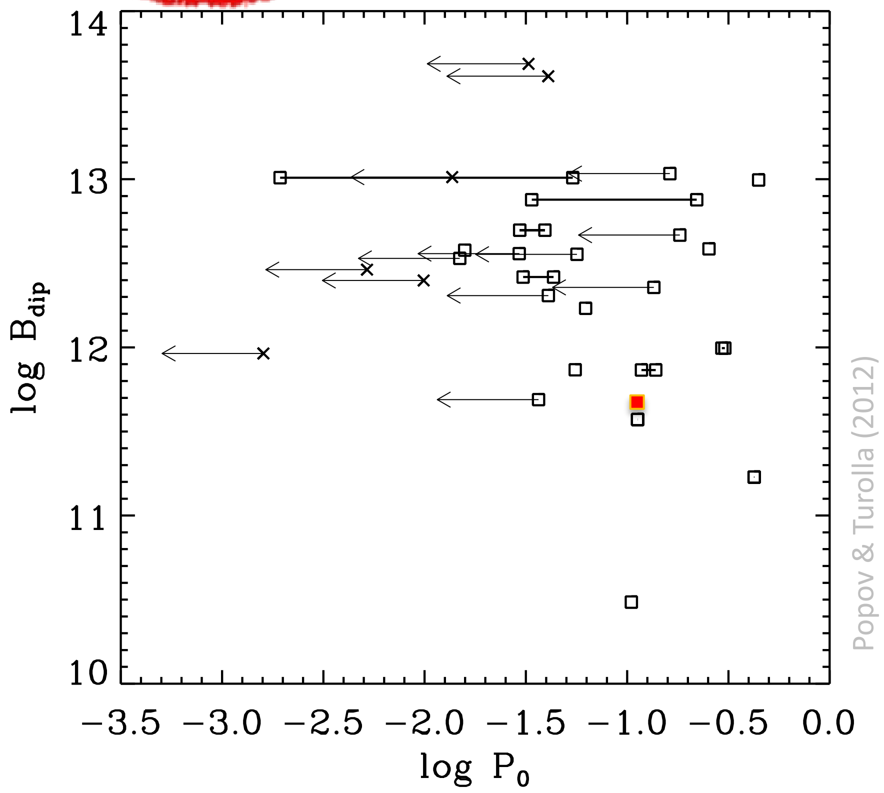
PSR J0002+6216 was born with a period P_o~113 ms

Consistent with there being a wide distribution of pulsar birth periods (10-300 ms)

Agrees with results of CC models of massive stars

τ_c

$$t_{\rm true} = \frac{P}{(n-1)\dot{P}}\left[1 - \left(\frac{P_0}{P}\right)^{n-1}\right], \quad \text{if } n \neq 1.$$



Popov & Turolla (2012)