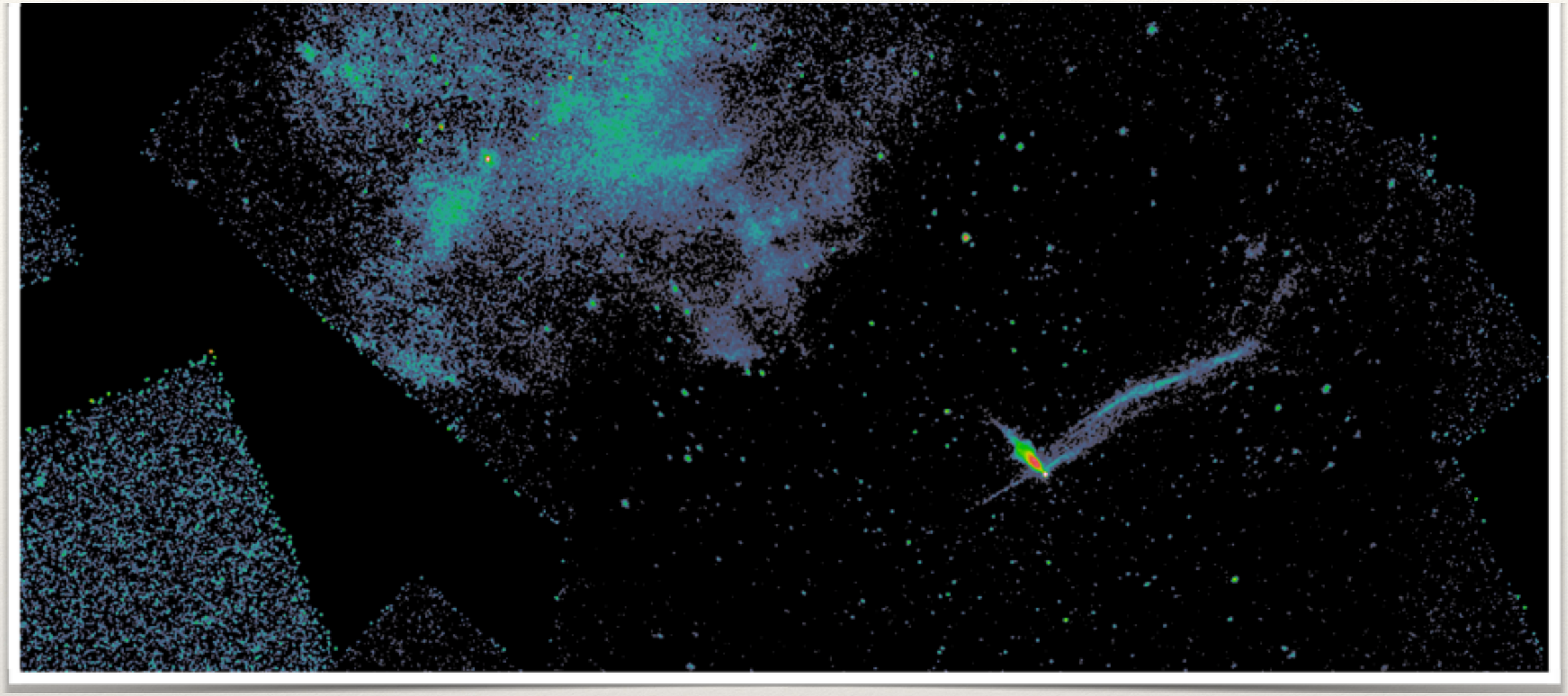


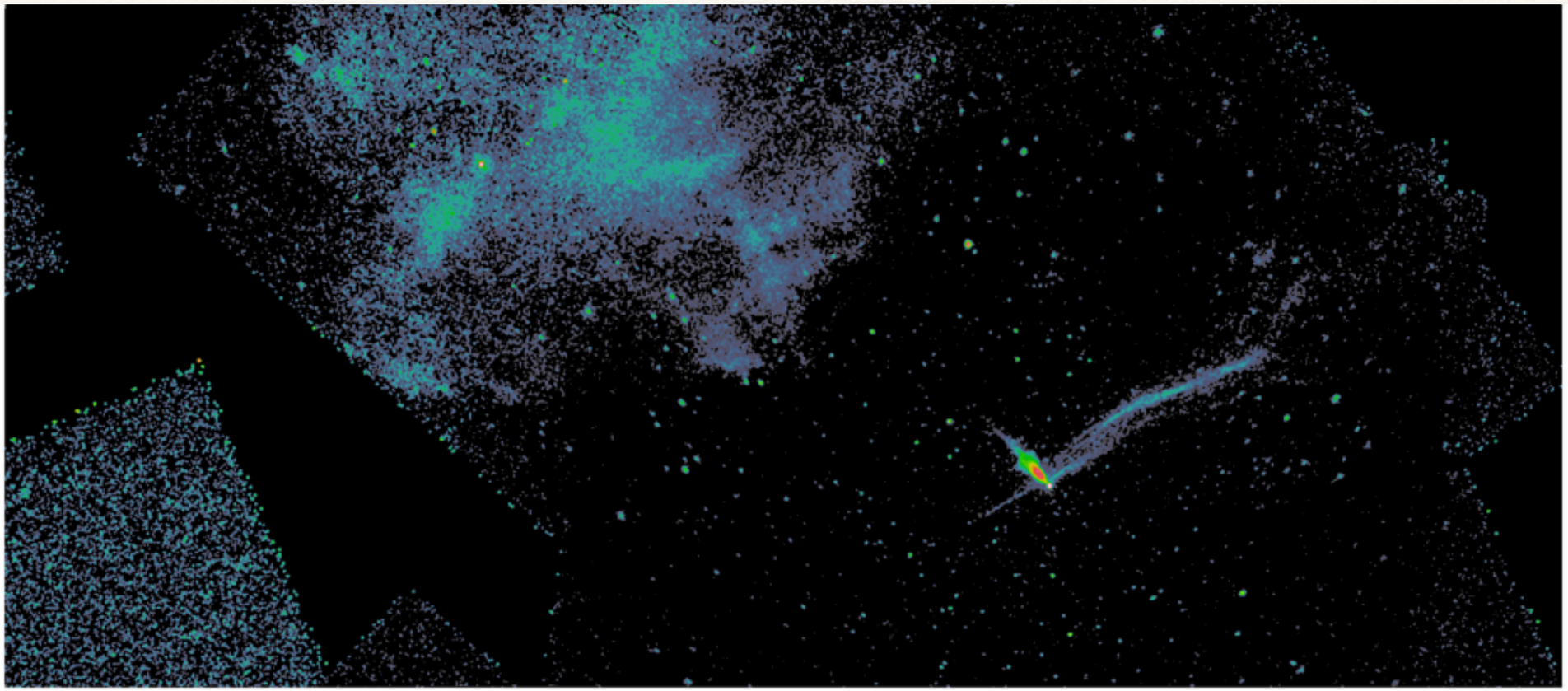
A new view on the Lighthouse Nebula, IGR J11014-6103

Lucia Pavan (ISDC Université de Genève)
Gerd Pühlhofer (IAAT Tübingen)
Pol Bordas (MPI-HD Heidelberg)
et al.

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

ISDC DATA CENTRE FOR ASTROPHYSICS

UNIVERSITÉ DE GENÈVE



Based on the following publications:

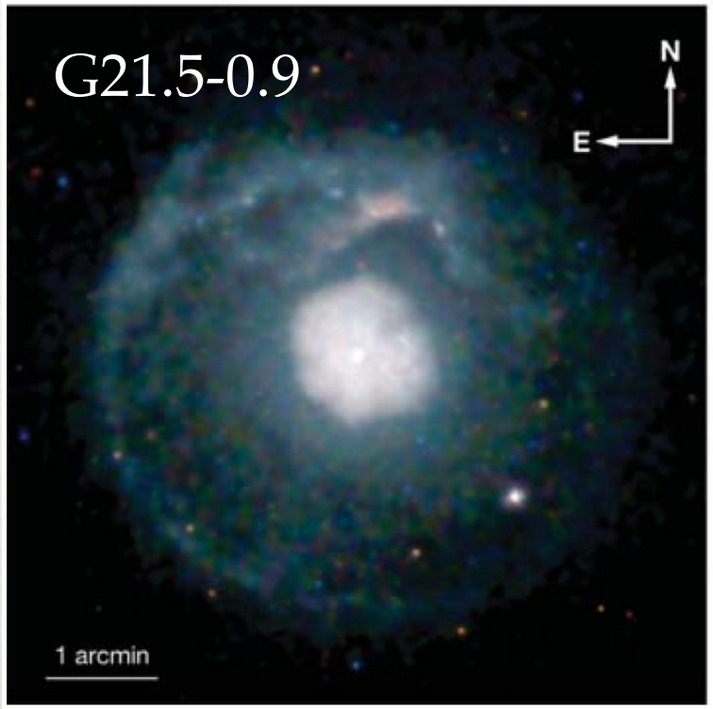
L. Pavan, G. Pühlhofer, P. Bordas, et al., A&A 2015: „Closer view of the IGR J11014-6103 outflows“

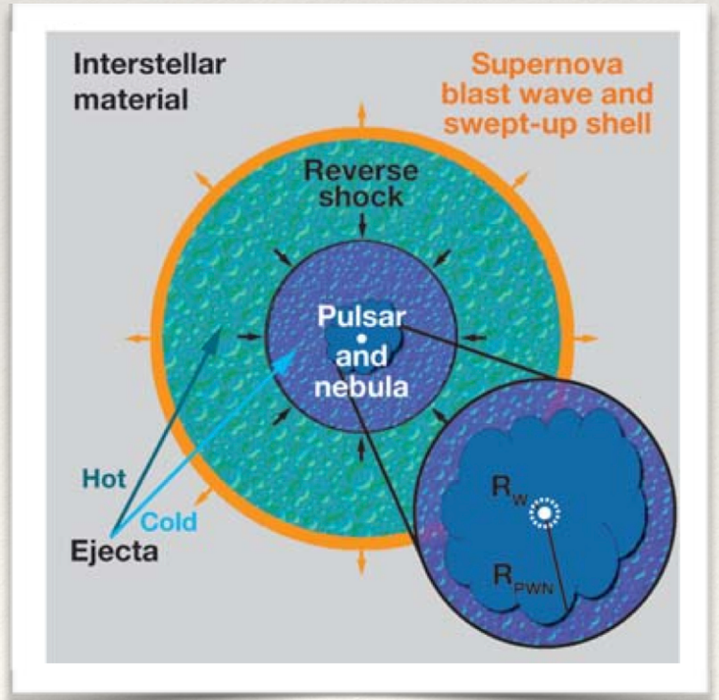
L. Pavan, P. Bordas, G. Pühlhofer, et al., A&A 2014: „The long helical jet of the Lighthouse nebula, IGR J11014-6103“

L. Pavan, E. Bozzo, G. Pühlhofer, et al., A&A 2011: „IGR J11014-6103: a newly discovered pulsar wind nebula?“

Pulsar wind nebulae (PWNe)

Gaensler & Slane 2006 ARA&A 44, 17
Matheson & Safi-Harb 2005 ASpR 35, 6





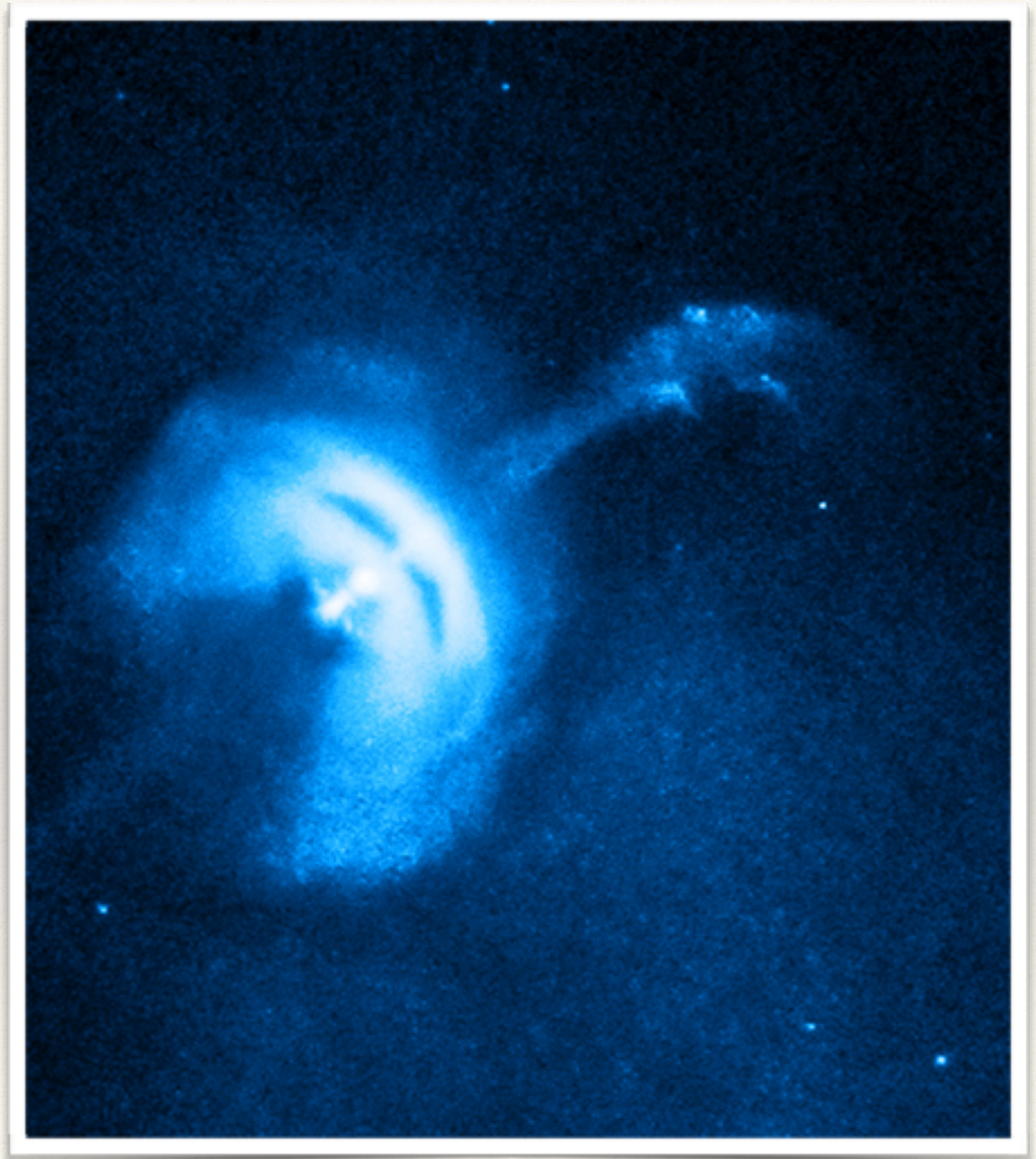
- **Rotational energy loss** from the PSR
- Relativistic magnetized wind (**e- e+, …?**)
- Synchrotron + Inverse Compton + optical Balmer lines
- Prominent PWNe from PSRs with $\dot{E} \gtrsim 4 \times 10^{36}$ erg/s

$$\dot{E} = 4\pi^2 I P_{dot}/P^3$$

$$10^{30} < \dot{E} < 5 \times 10^{38} \text{ erg/s}$$

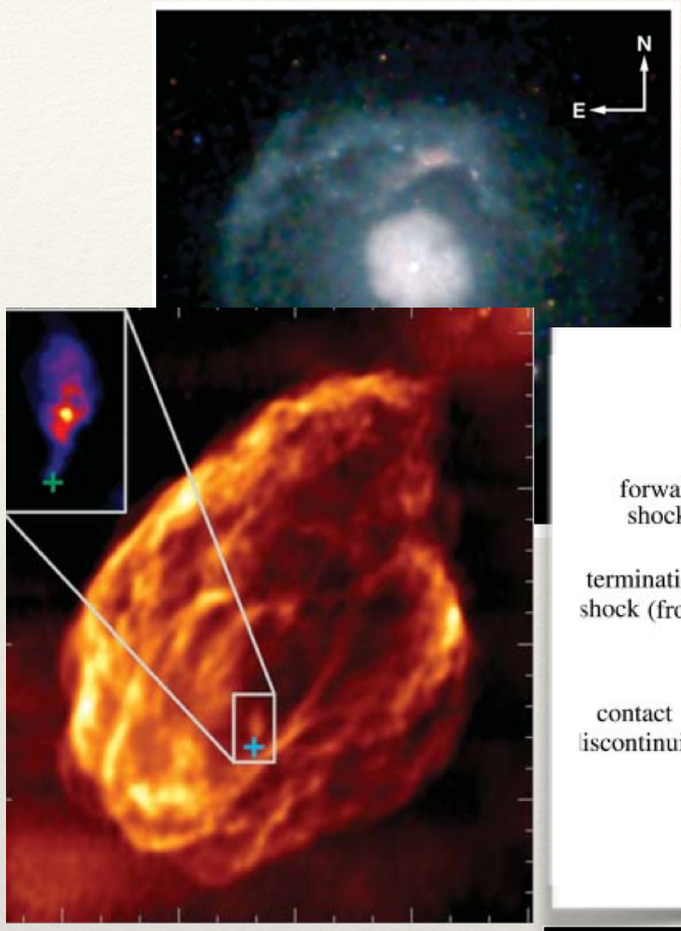
Example: Vela PWN

- Components:
  - PSR
  - PWN
  - Jet + Counter-jet
  - (SNR)

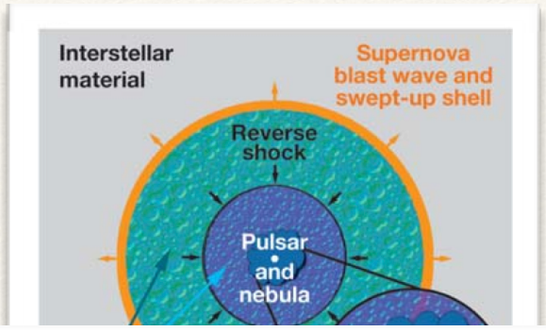


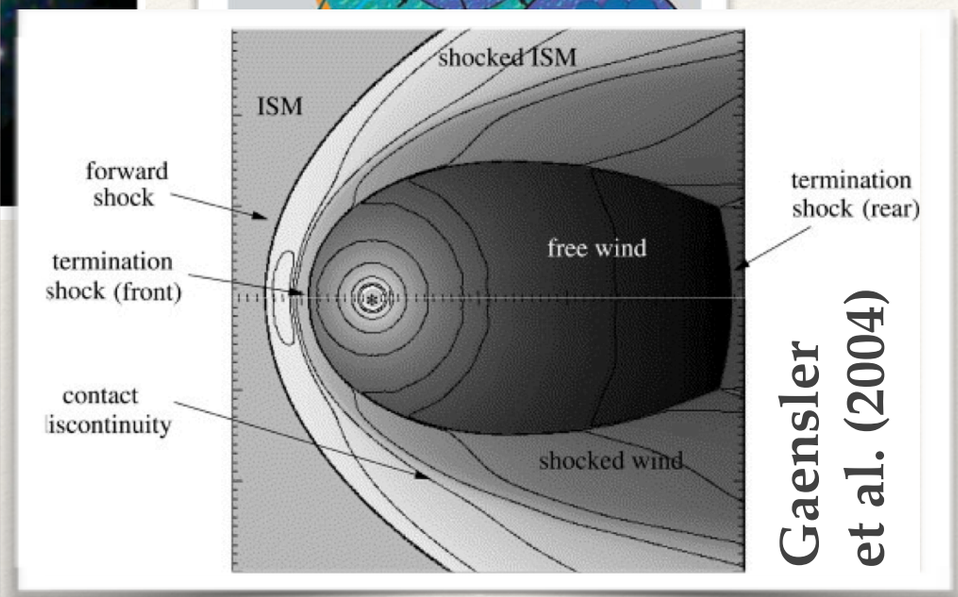
Durant et al. 2013 ApJ 763, 2

Adding velocity to the PSR…

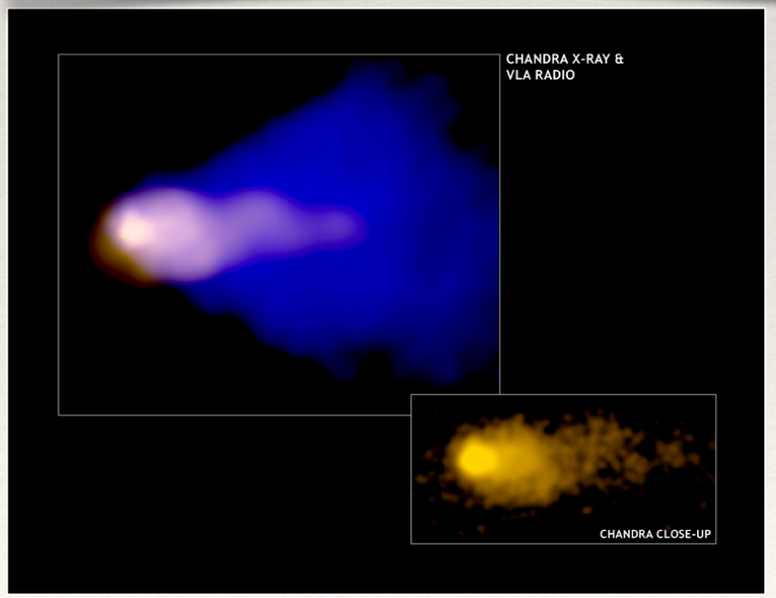


Gaensler & Slane ARA&A 2006, 44 17





Gaensler et al. (2004)



- If supersonic movement → Bow-shock morphology
- Hα due to collisional excitation and charge exchange at forward shock
- A pulsar will typically cross its SNR shell after ~40,000 years.
- If the SNR is still in the Sedov phase, the bow shock has a Mach number M ≈ 3.1 at this point (**van der Swaluw** et al., 2003).

The Lighthouse nebula

- Object discovered serendipitously with INTEGRAL
- Analysis of all archival observations (XMM-Newton, optical, radio MOST)
  → bow-shock PWN from MSH 11-61A
  Pavan et al. 2011 A&A, 533A, 74
  Tomsick et al. 2012 ApJ 750, 39
- 50 ks Chandra observation → helical jet
  Pavan et al. 2014 A&A, 562A, 122
- P and Pdot determination with XMM-Newton
  Halpern et al. 2014 ApJ 795, 27
- 2014: 250 ks Chandra observation
  Pavan et al. 2015 A&A arXiv 1511.01944

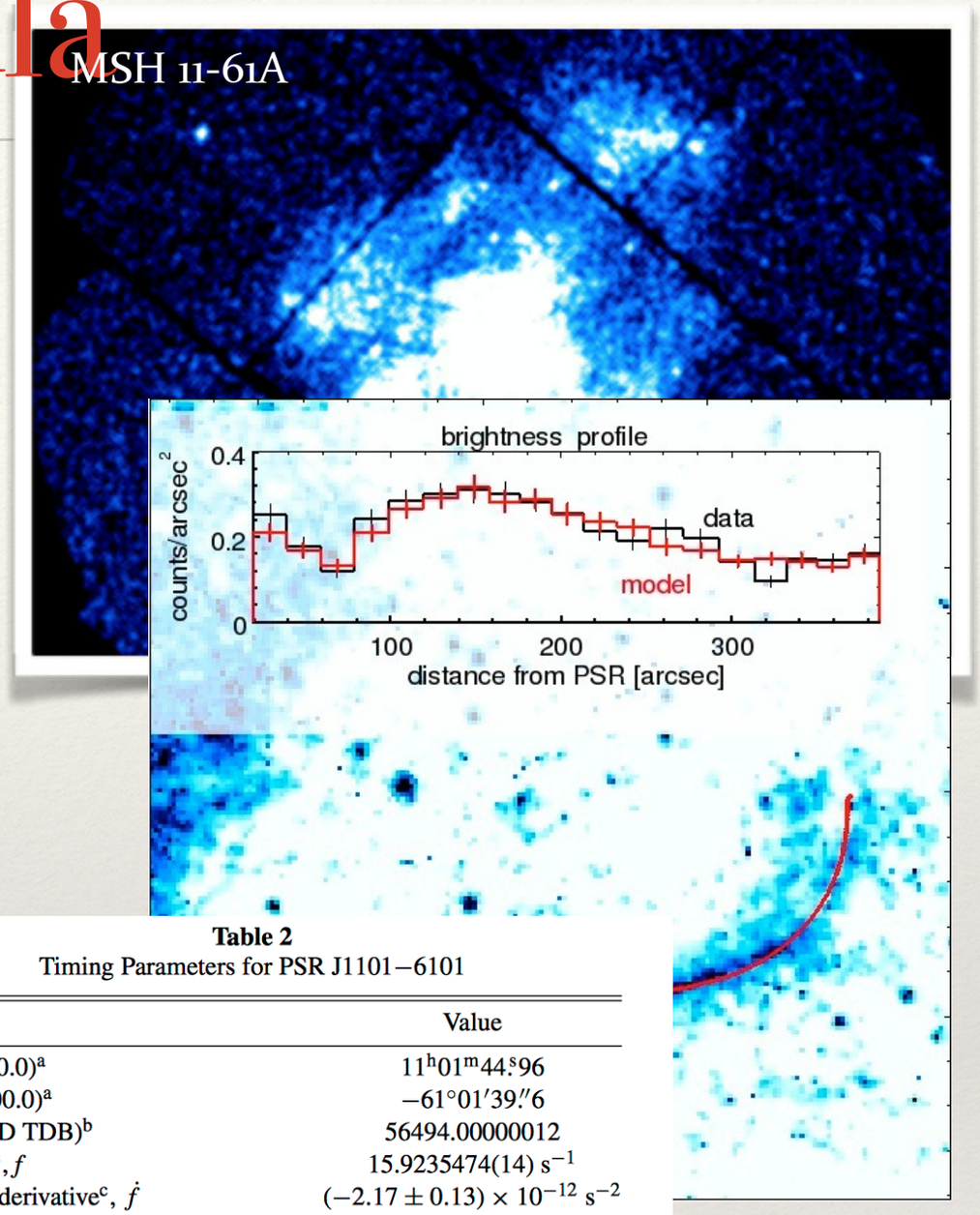
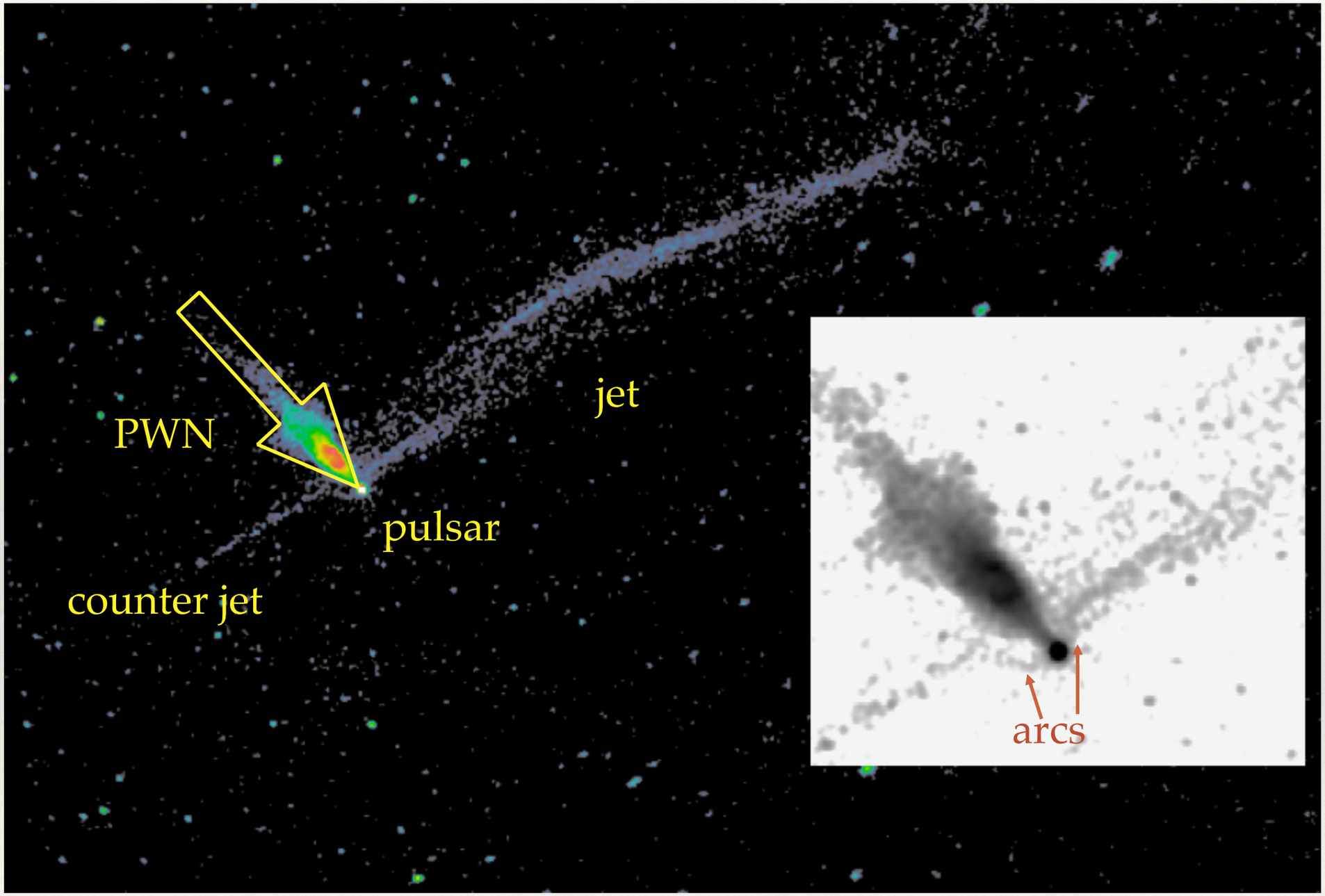


Table 2
Timing Parameters for PSR J1101−6101

Parameter	Value
R.A. (J2000.0)[a]	$11^h01^m44.^s96$
Decl. (J2000.0)[a]	$-61°01'39.''6$
Epoch (MJD TDB)[b]	56494.00000012
Frequency[c], f	15.9235474(14) s^{-1}
Frequency derivative[c], $\dot{f}$	$(-2.17 \pm 0.13) \times 10^{-12}$ s^{-2}
Period[c], P	0.062800077(6) s
Period derivative[c], $\dot{P}$	$(8.56 \pm 0.51) \times 10^{-15}$
Range of dates (MJD)	56494–56817
Spin-down luminosity, $\dot{E}$	1.36×10^{36} erg s^{-1}
Characteristic age, τ_c	116 kyr
Surface dipole magnetic field, B_s	7.4×10^{11} G

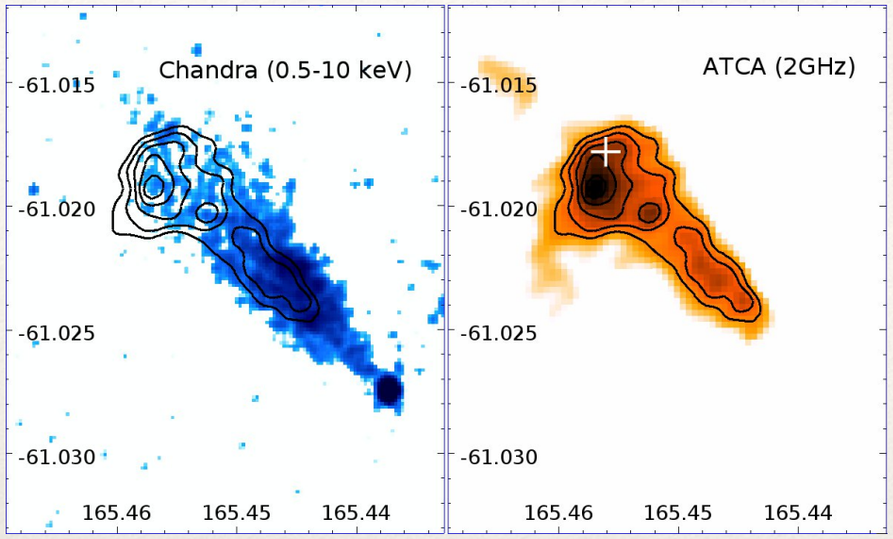
Notes.
[a] *Chandra* position from Tomsick et al. (2012).
[b] Epoch of phase zero in Figure 3.
[c] 1σ uncertainty in parentheses.

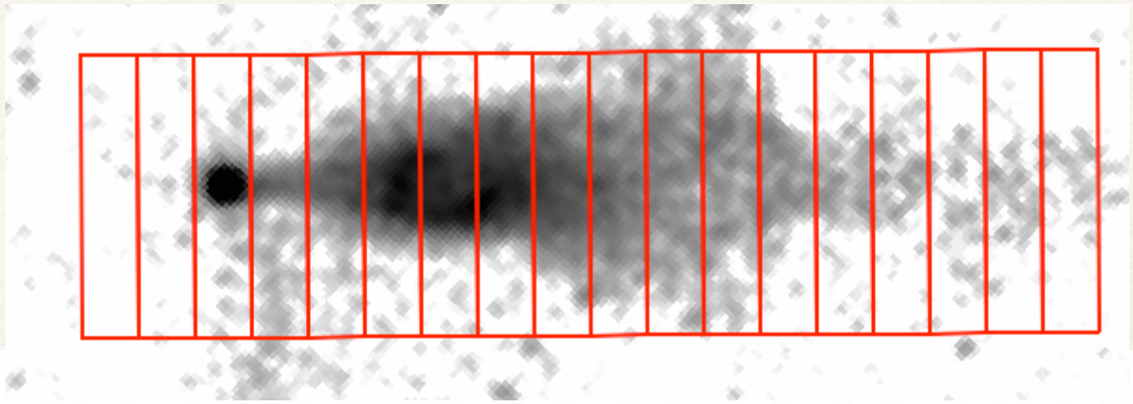
Lighthouse nebula: 300 ks mosaic ACIS-I

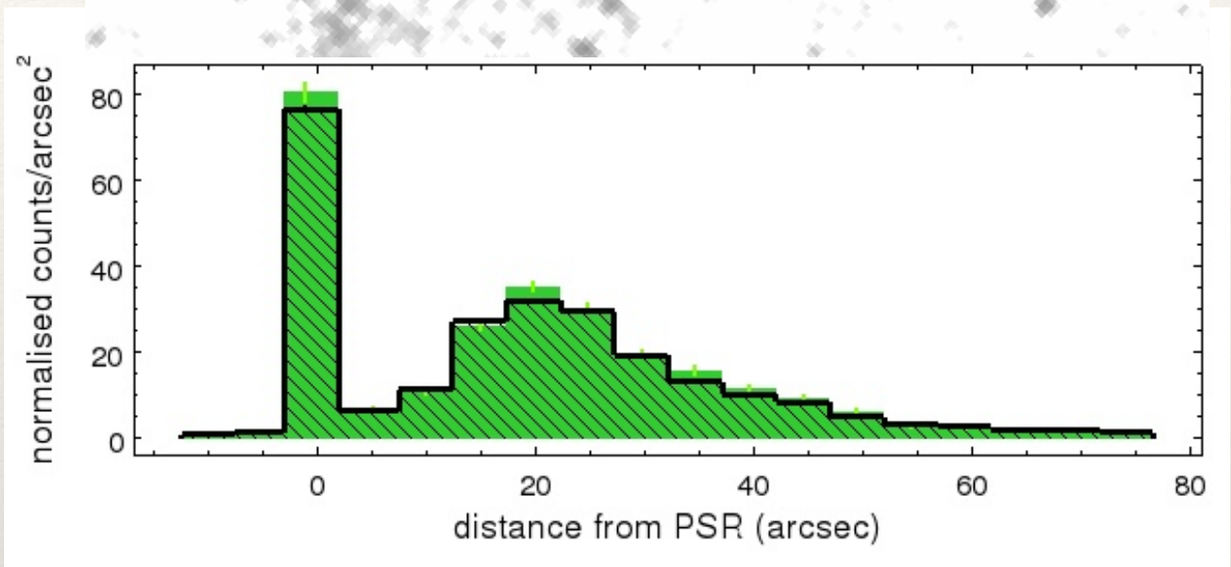


LP et al., A&A in press (2015)

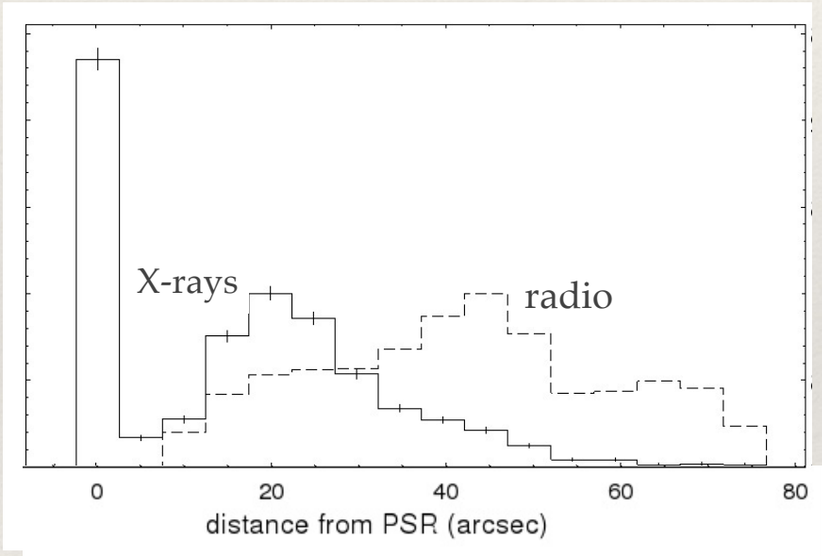
The PWN



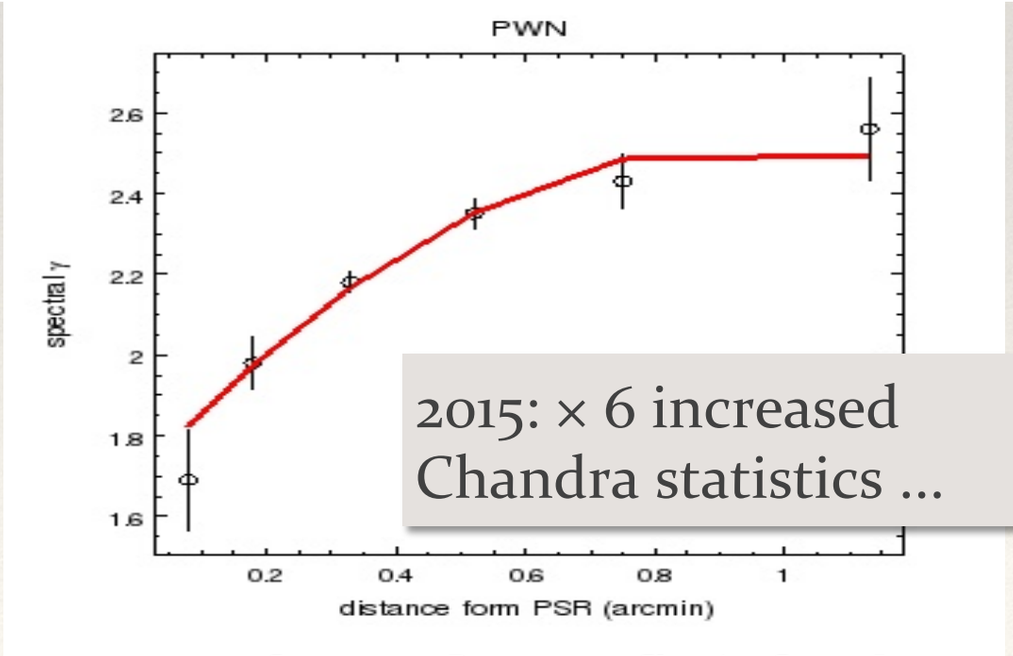




LP et al. 2015



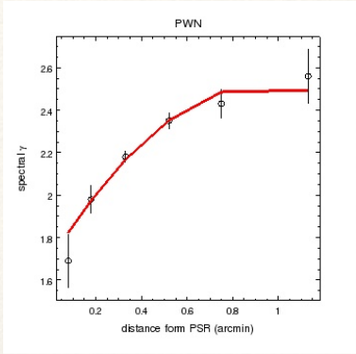
LP et al. 2014

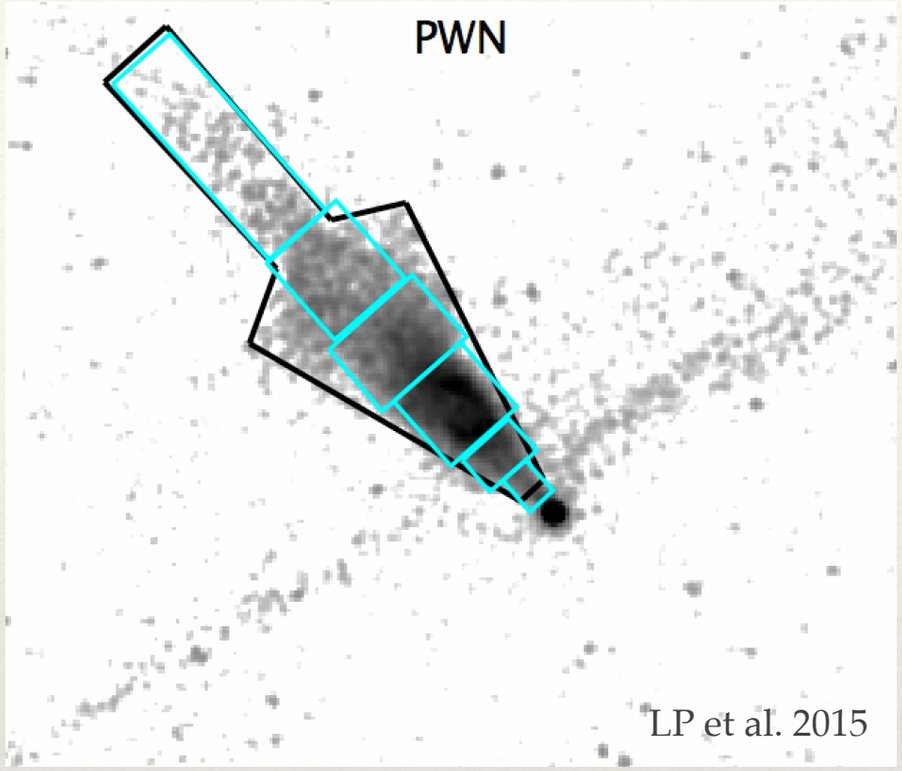


2014: Proof of PWN nature, synchrotron cooling times, velocity estimate (confirmation through detection of pulsations only afterwards)

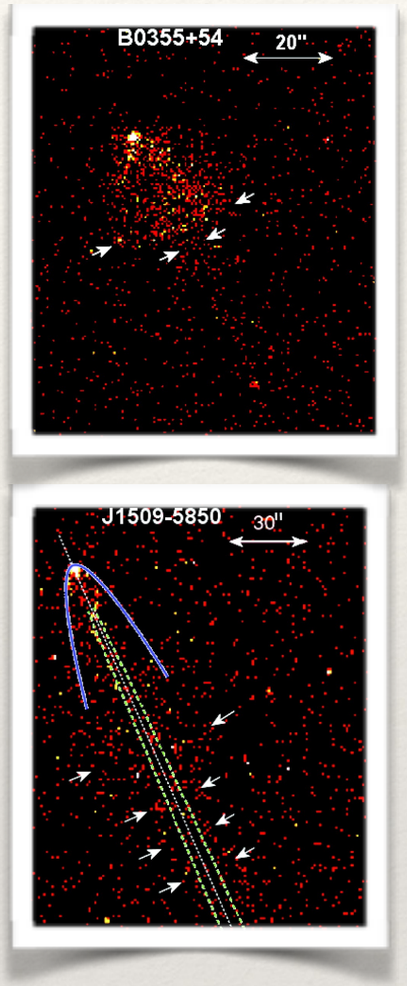
2015: × 6 increased Chandra statistics …

possible PWN explanations…

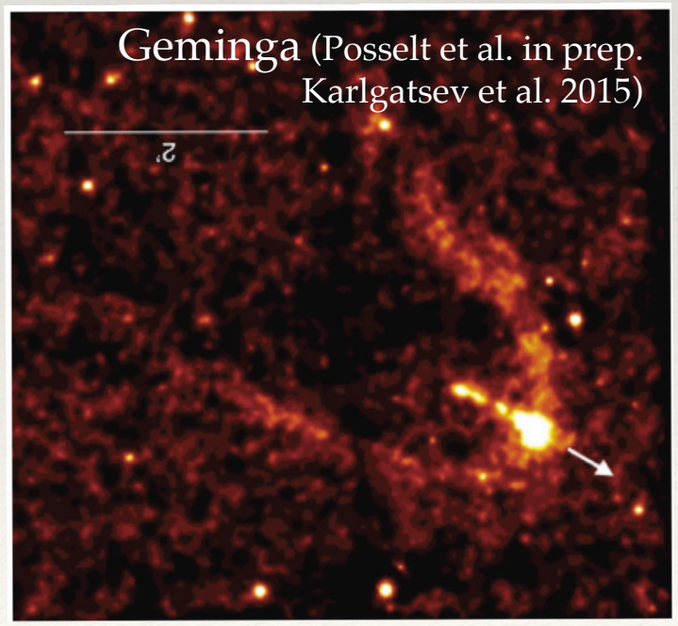




LP et al. 2015



- collimated PWN: cooling of particles
- a shaft? → similar appearance to Mushroom (PSR B0355+54) or PSR J1509-5850 nebulae
  - first hypothesis for those objects: a rear **jet** on top of the PWN → seems difficult here
  - different degree of (magnetic) collimation?
- arcs: similar to Geminga?



Two (main) possibilities for the jet „feature“

1. True ballistic jet

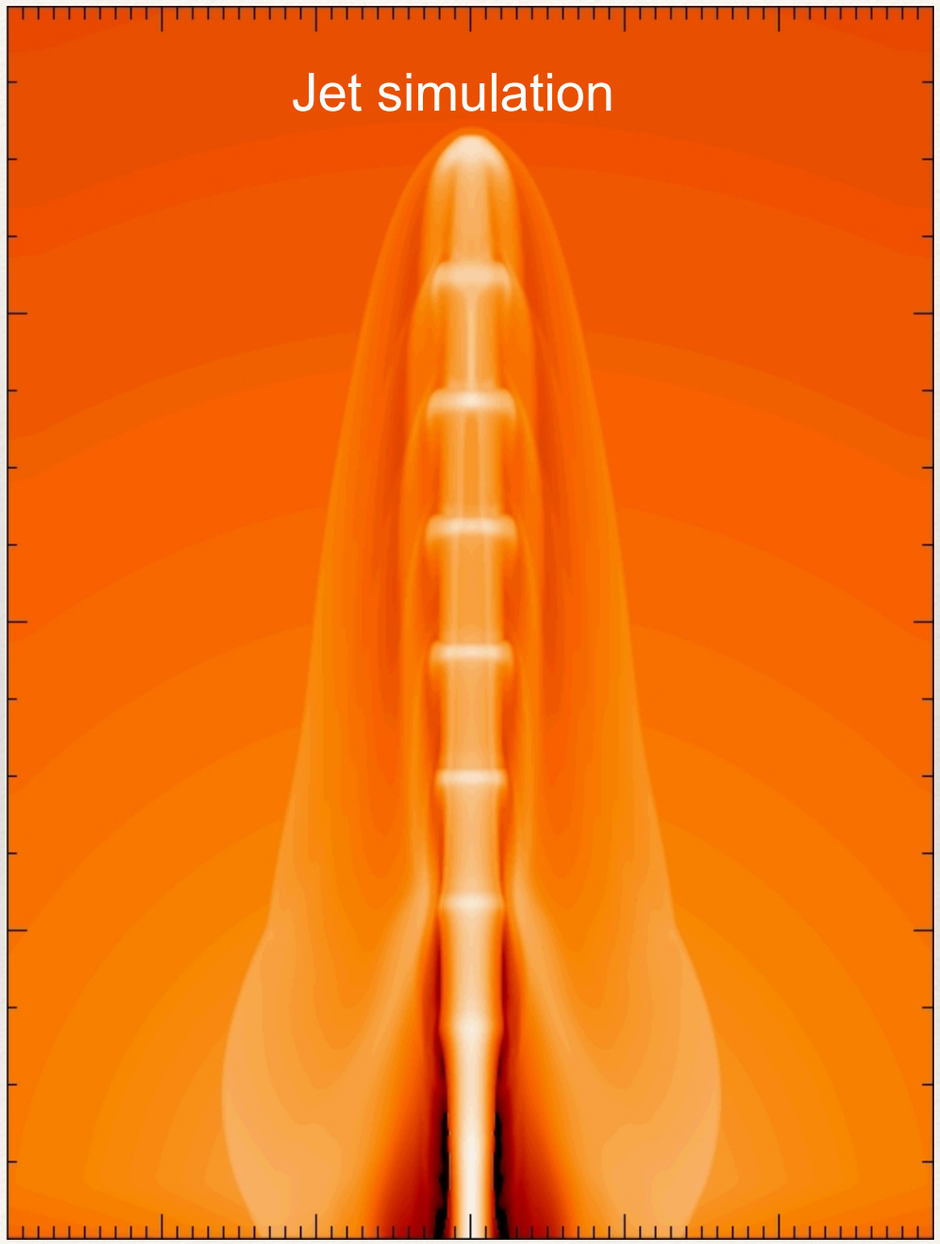
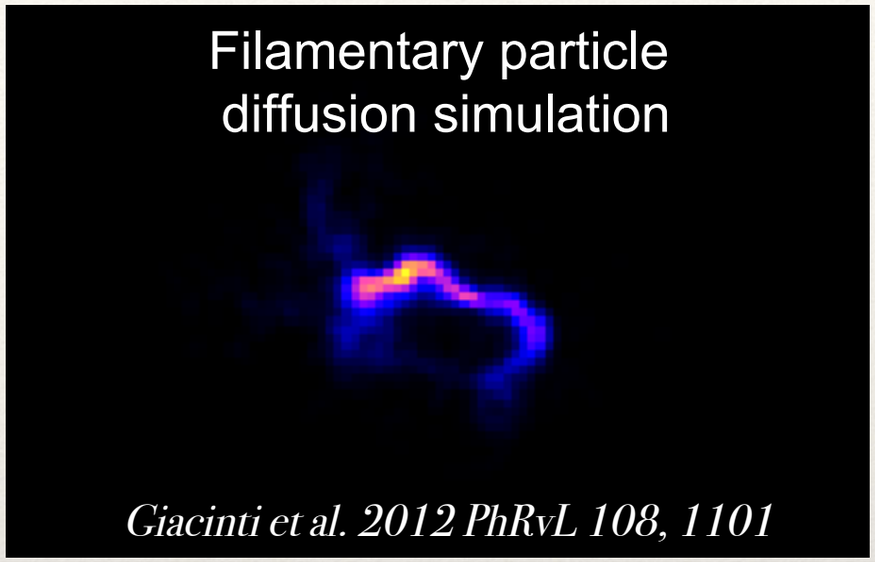
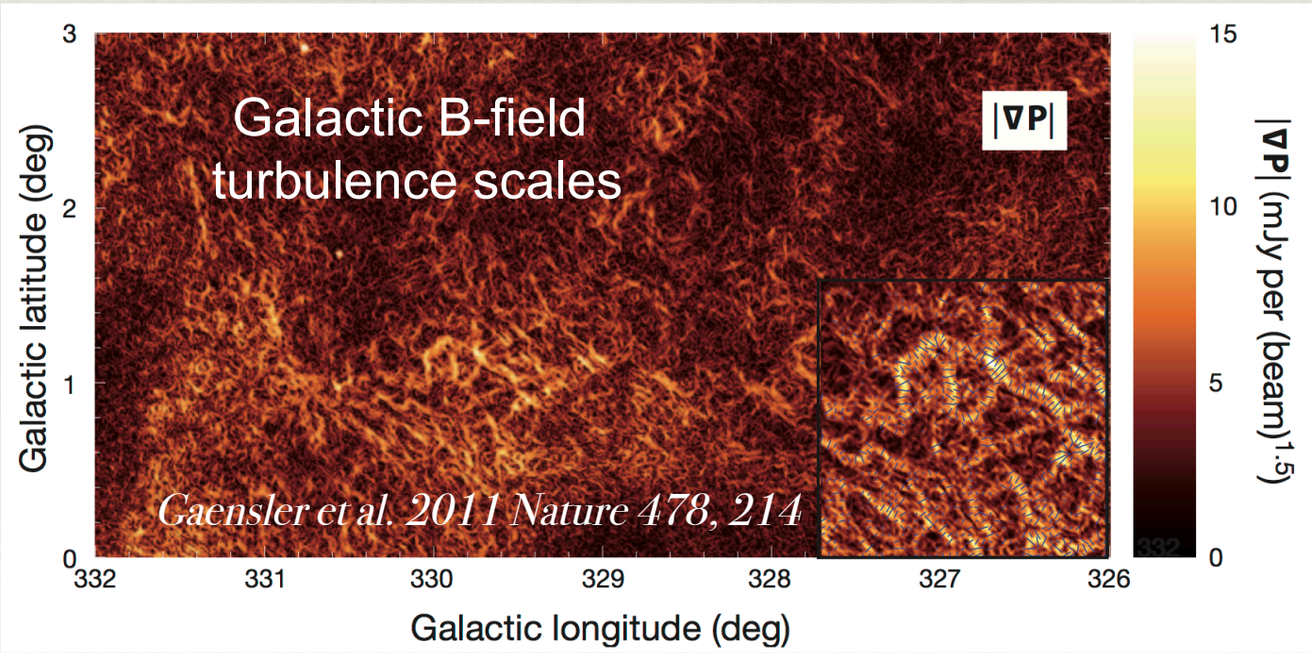


Image credit: Stute, 2012

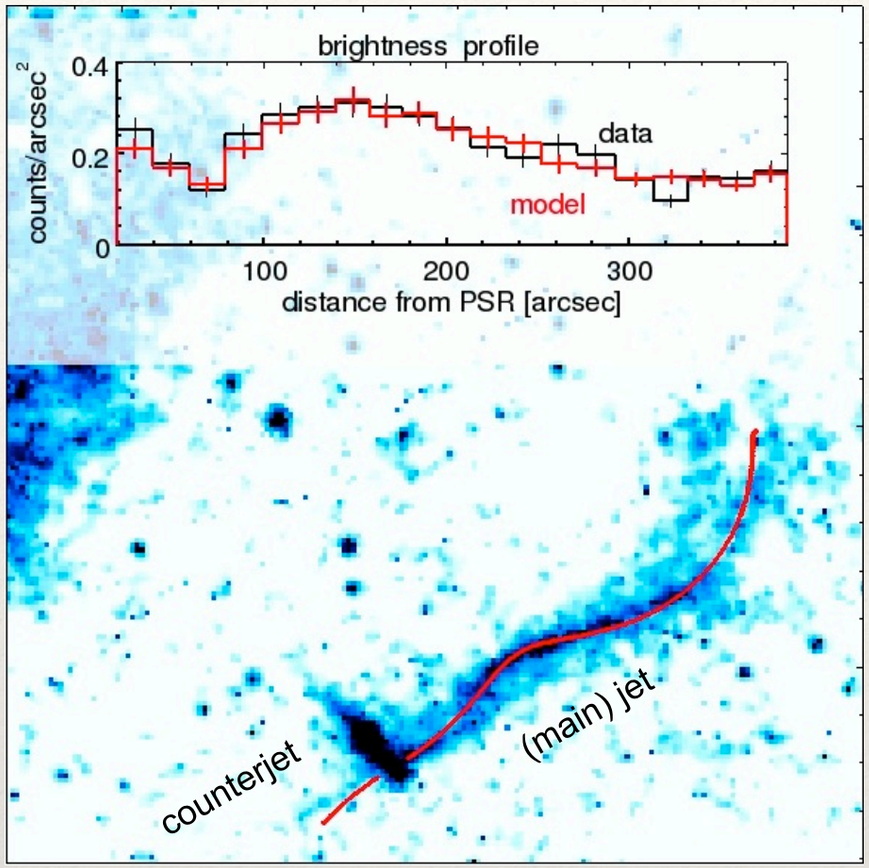
2. Particle diffusion along preexisting B-field structures





Application to PWN jet: Bandiera (2008)

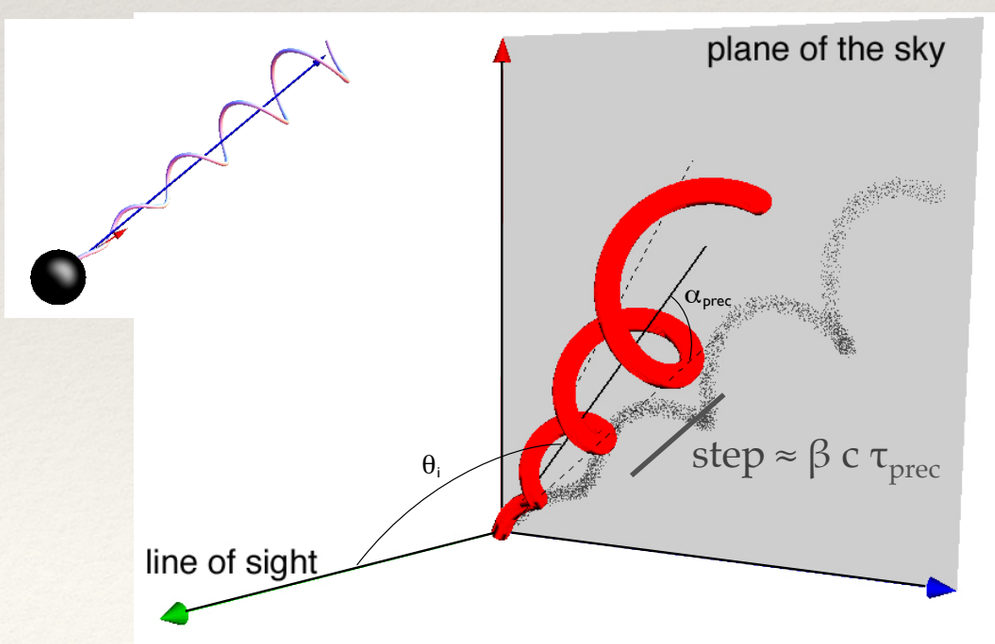
A precession model for a seemingly helical structure

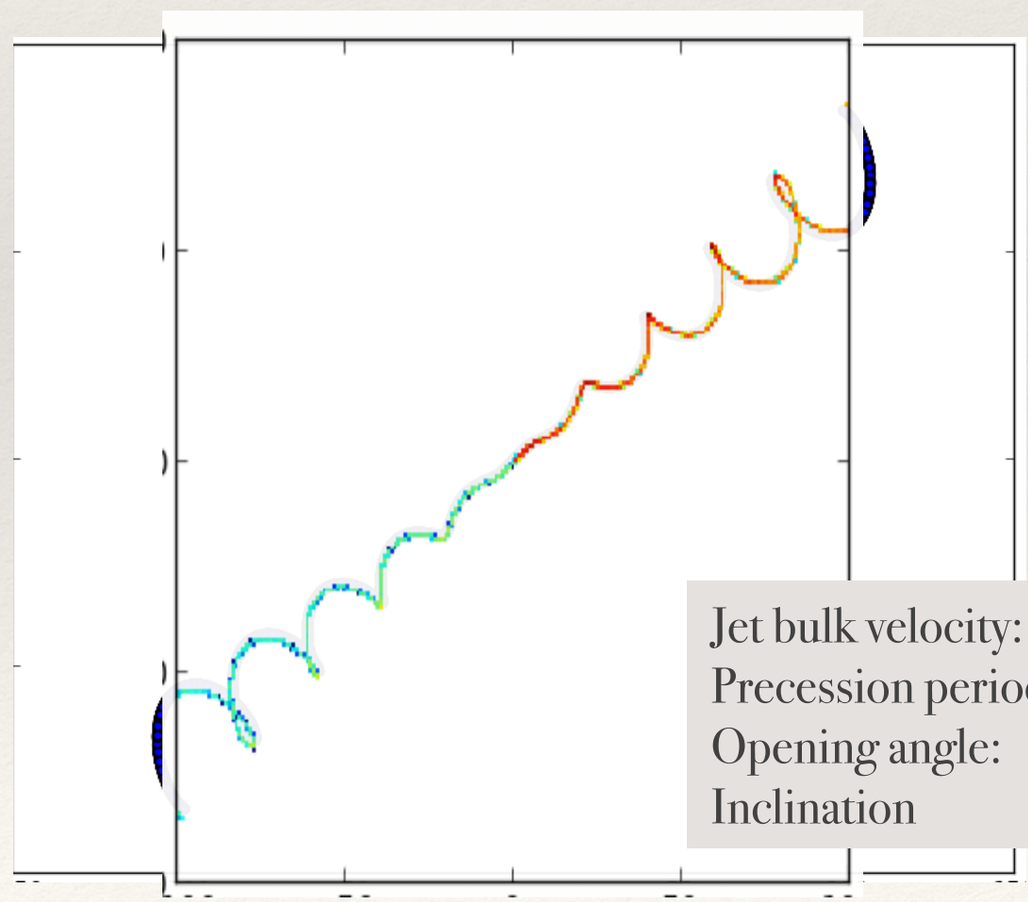


2014:

- Precession model predicts measured jet brightness profile very well (was not tuned to fit!)
- Doppler boost explains counterjet suppression

LP et al. 2014

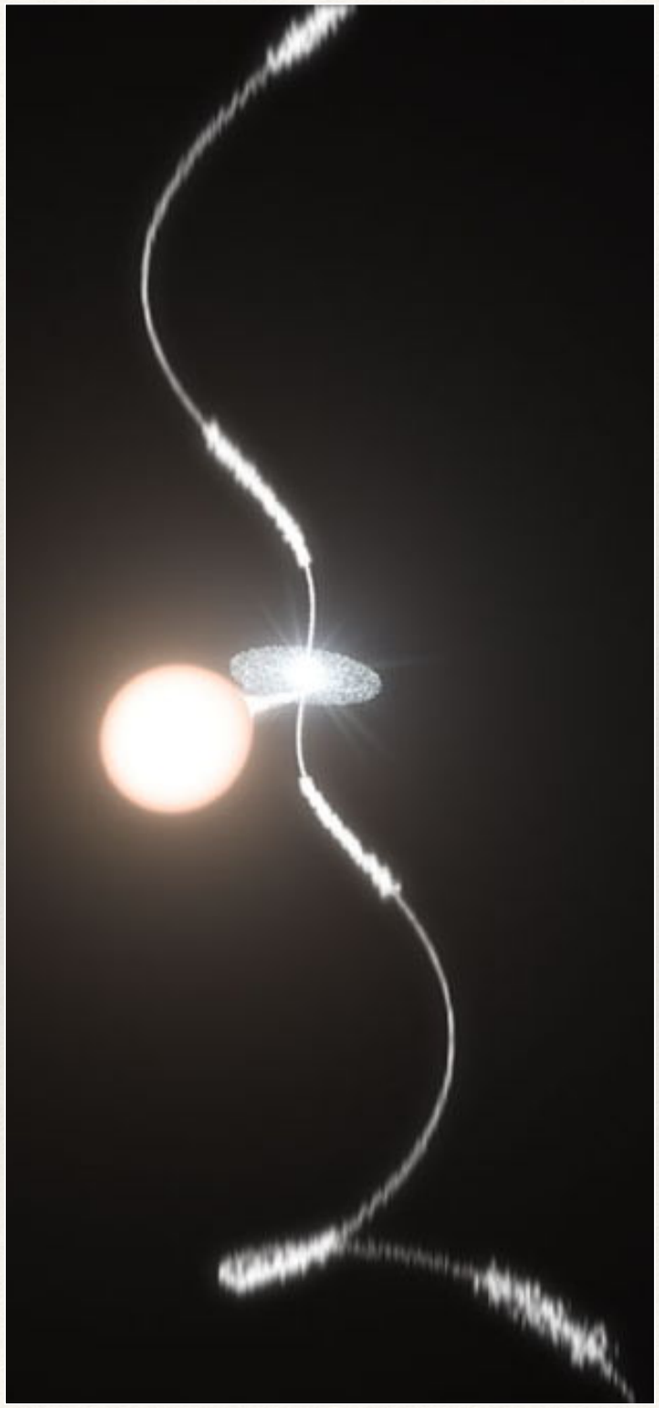




Jet bulk velocity:	$\beta = v/c = 0.8$!!
Precession period:	$\tau_{prec} = 66$ yrs
Opening angle:	$\alpha_{prec} = 4.5^o$
Inclination	$= 50^o$

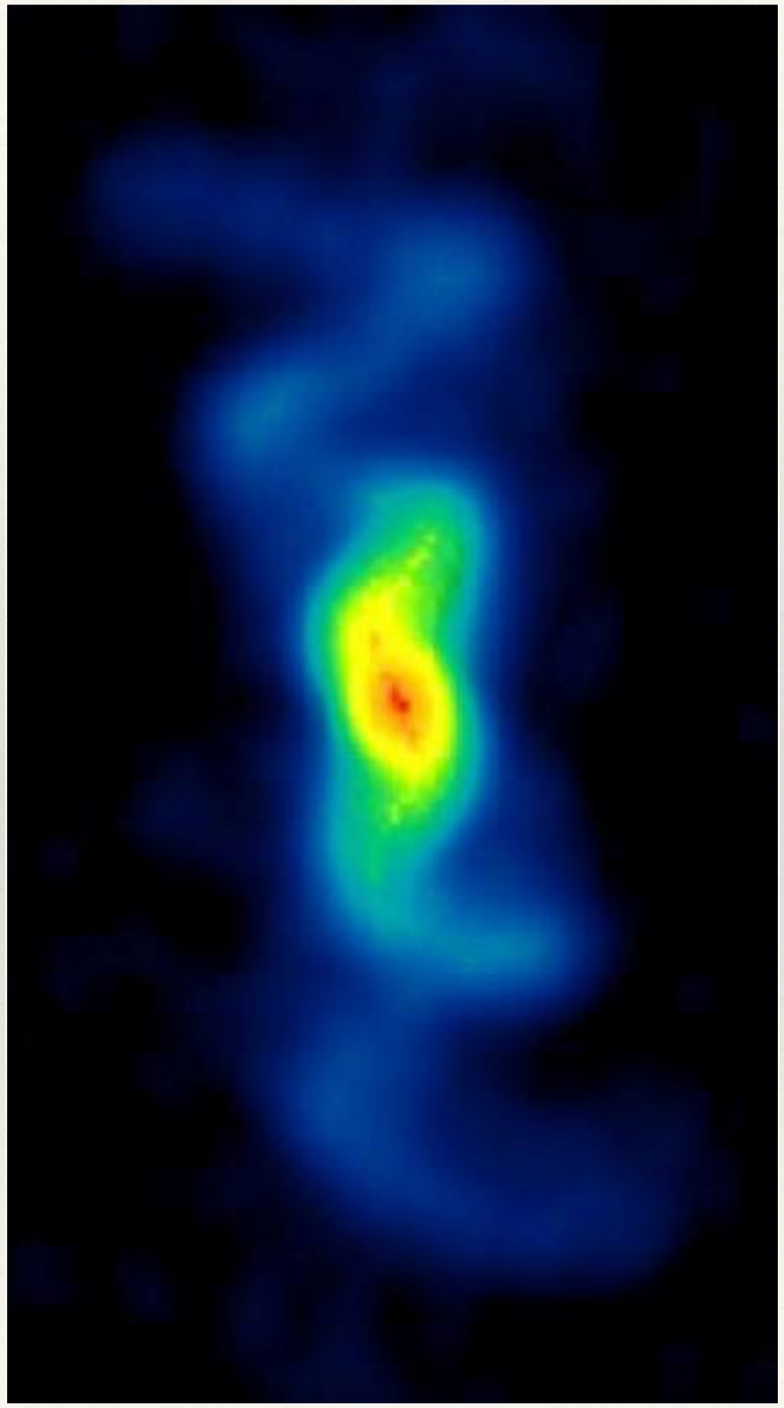
Jet precession in binaries

Fleming 1 (planetary nebula)



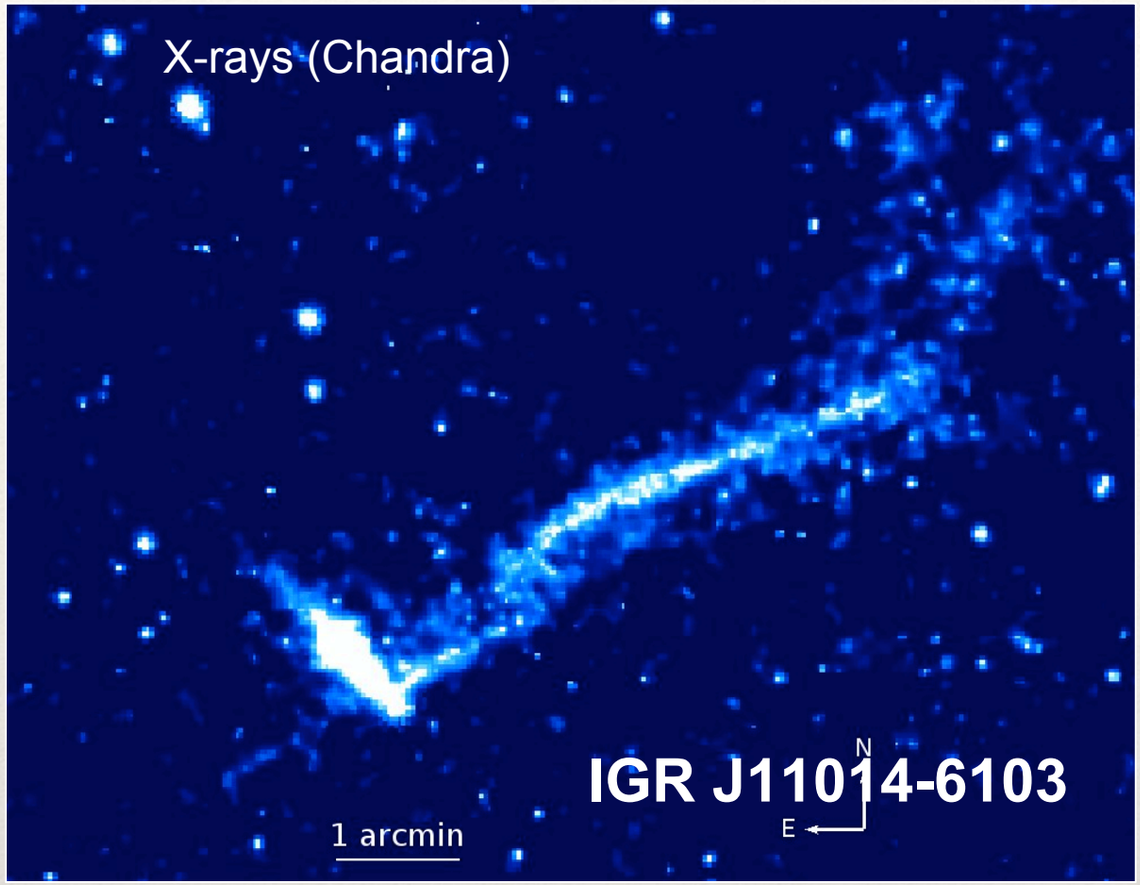
L. Pavan, G. Pühlhofer , P. Bordas, et al.

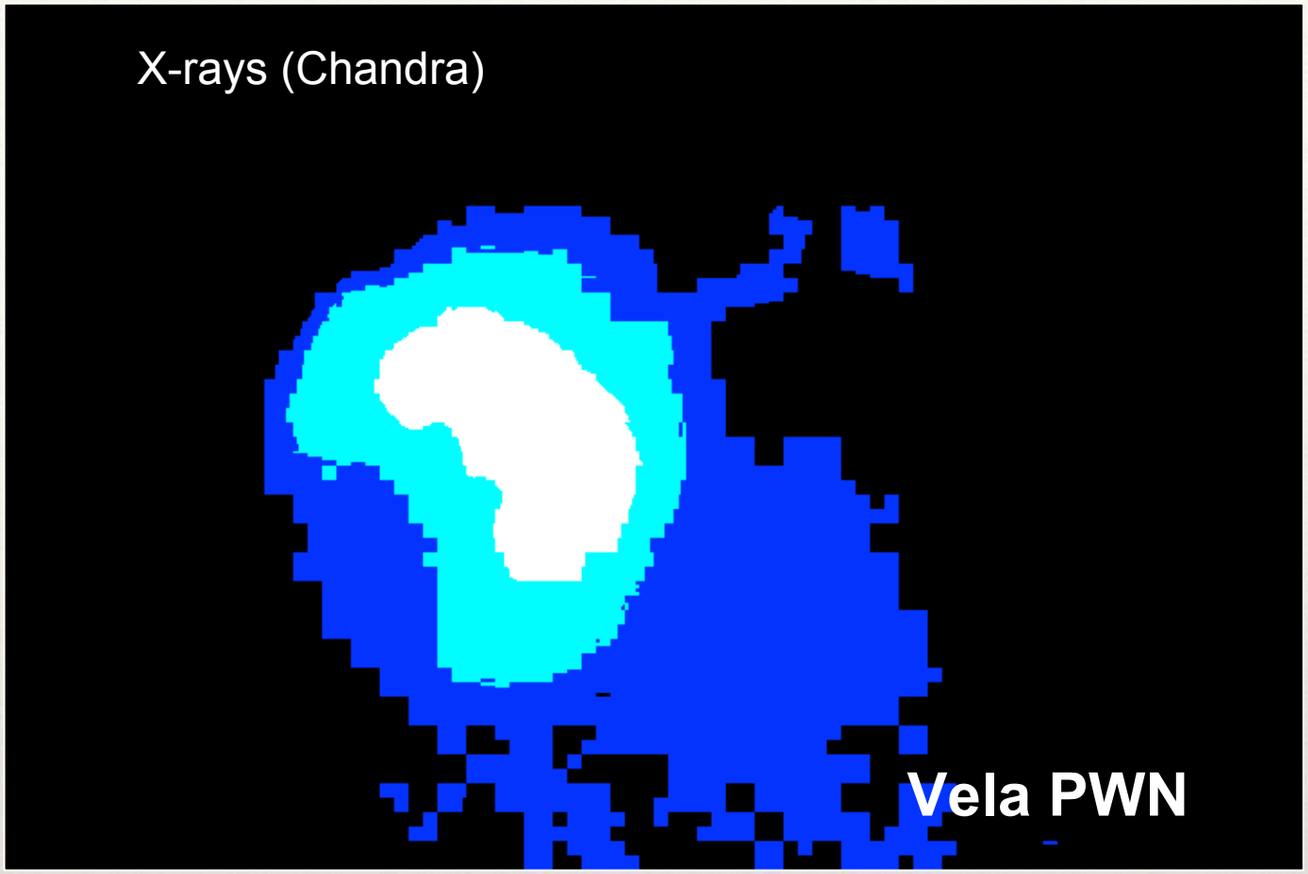
SS 433 (black hole binary)



Supernova Remnants, Chania, Crete, June 7, 2016

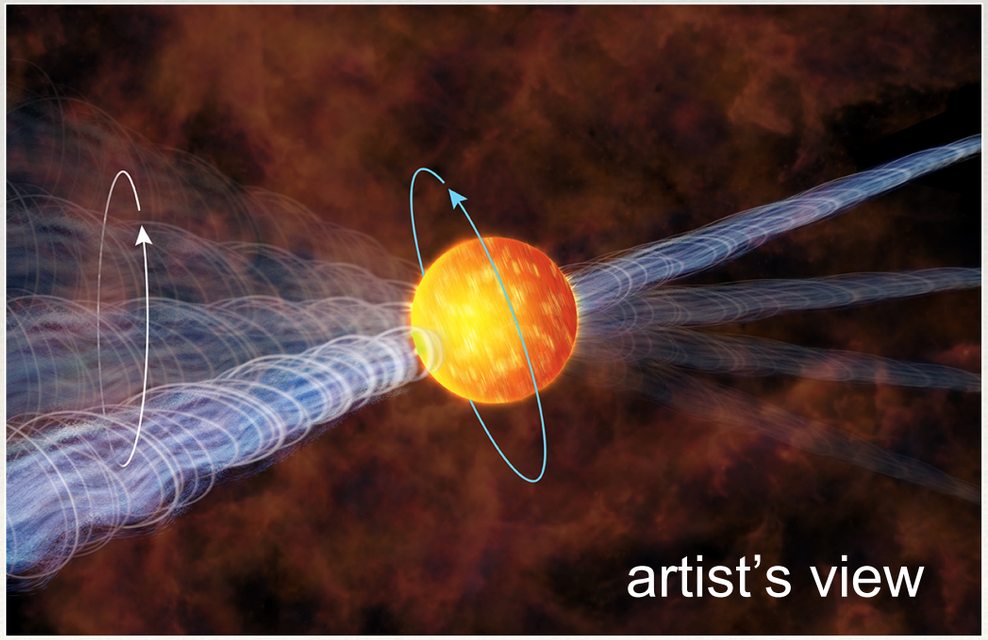
Jet precession in freely precessing systems



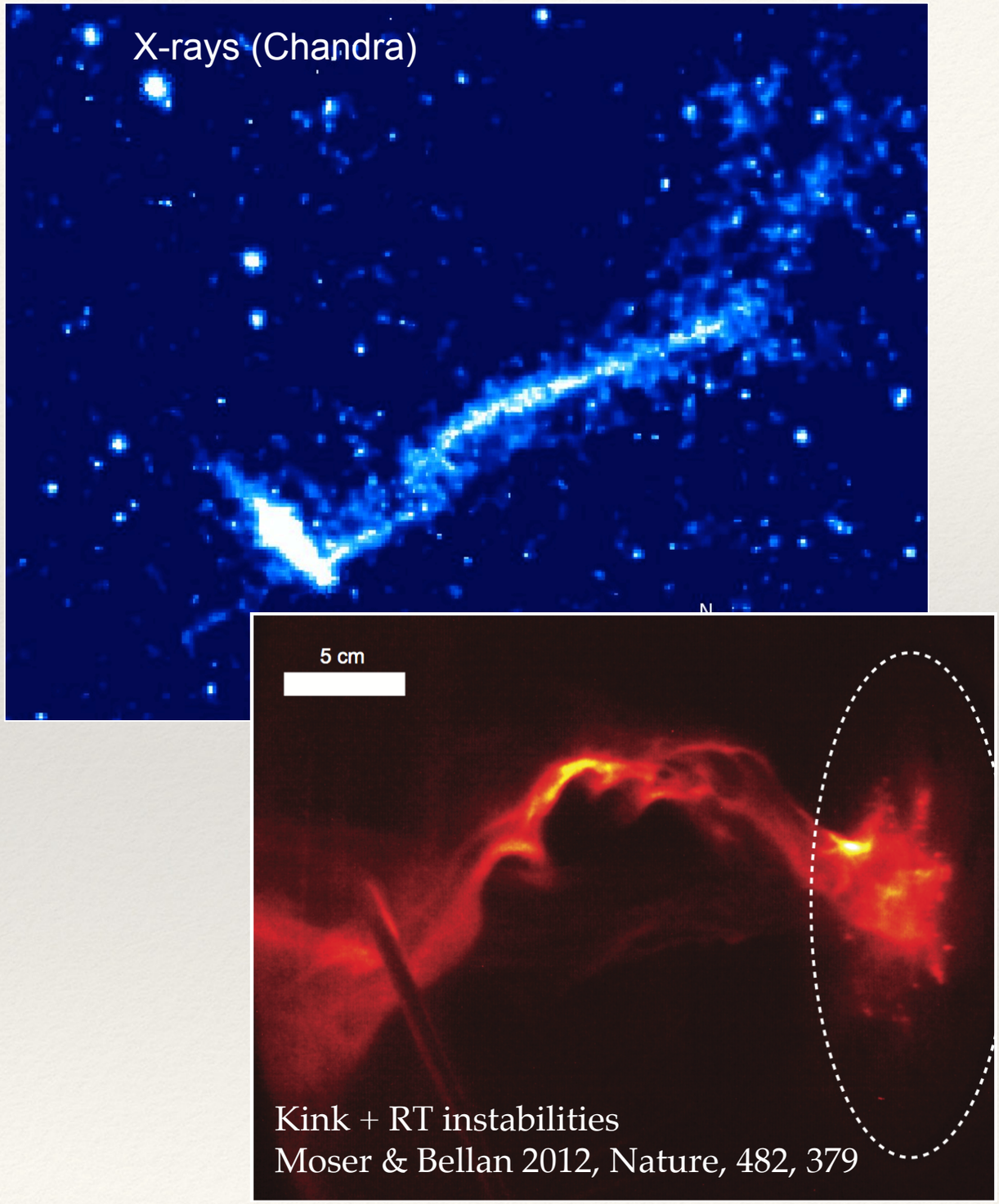


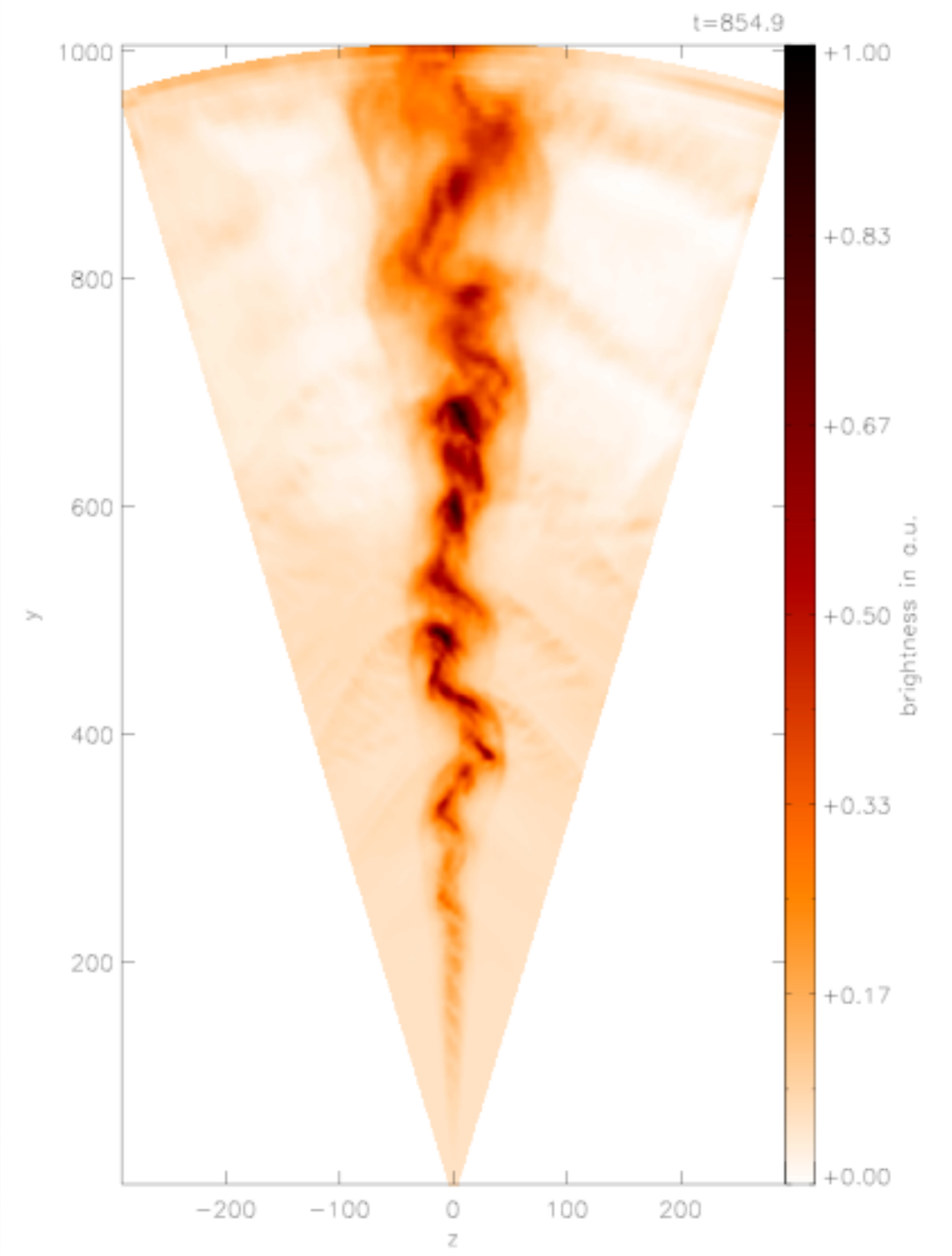
IGR J11014-6103:

- 66 years variability period has not been observed before at other pulsars, but usual methods insensitive to such long time scales
- Free precession due to neutron star oblateness o.k.



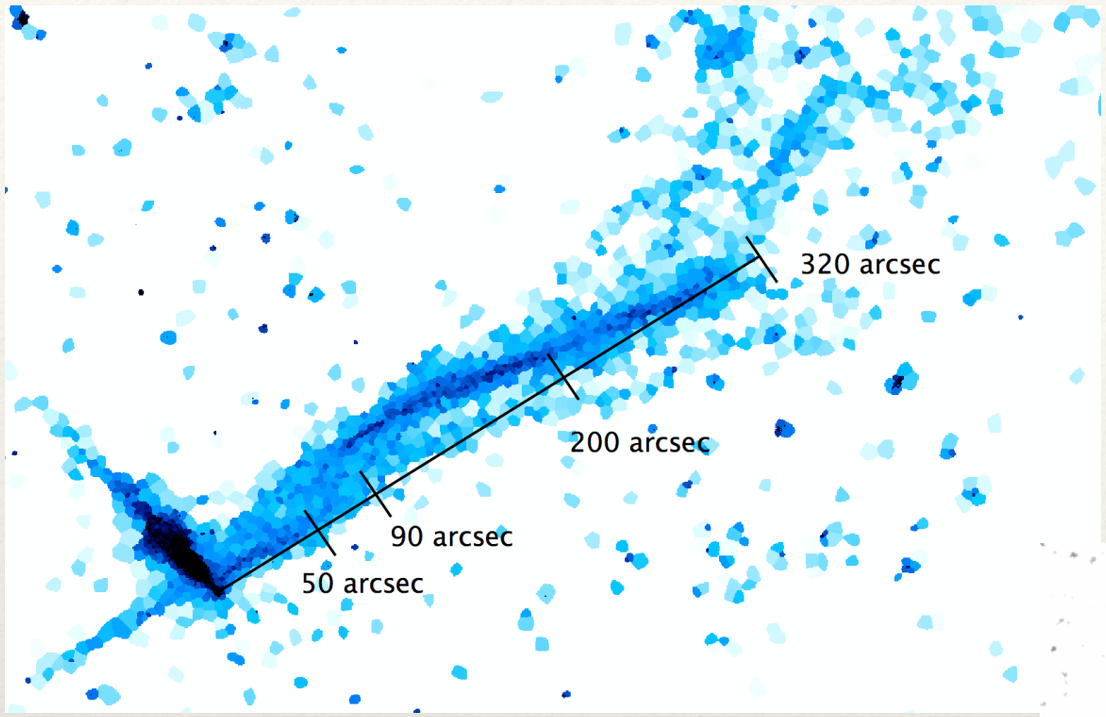
Alternative: Kink instabilities



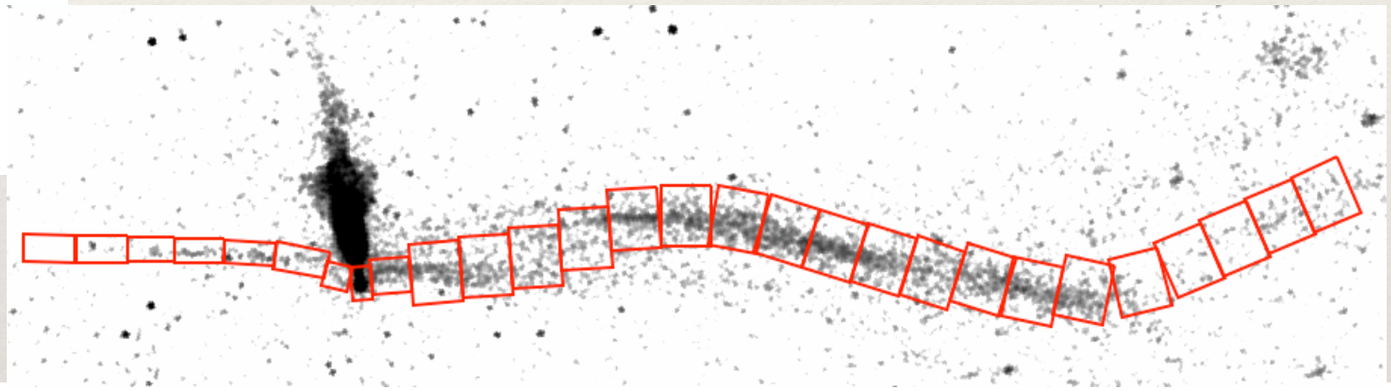


R. Moll 2010 PhD thesis

The helical structure after 300 ksec Chandra

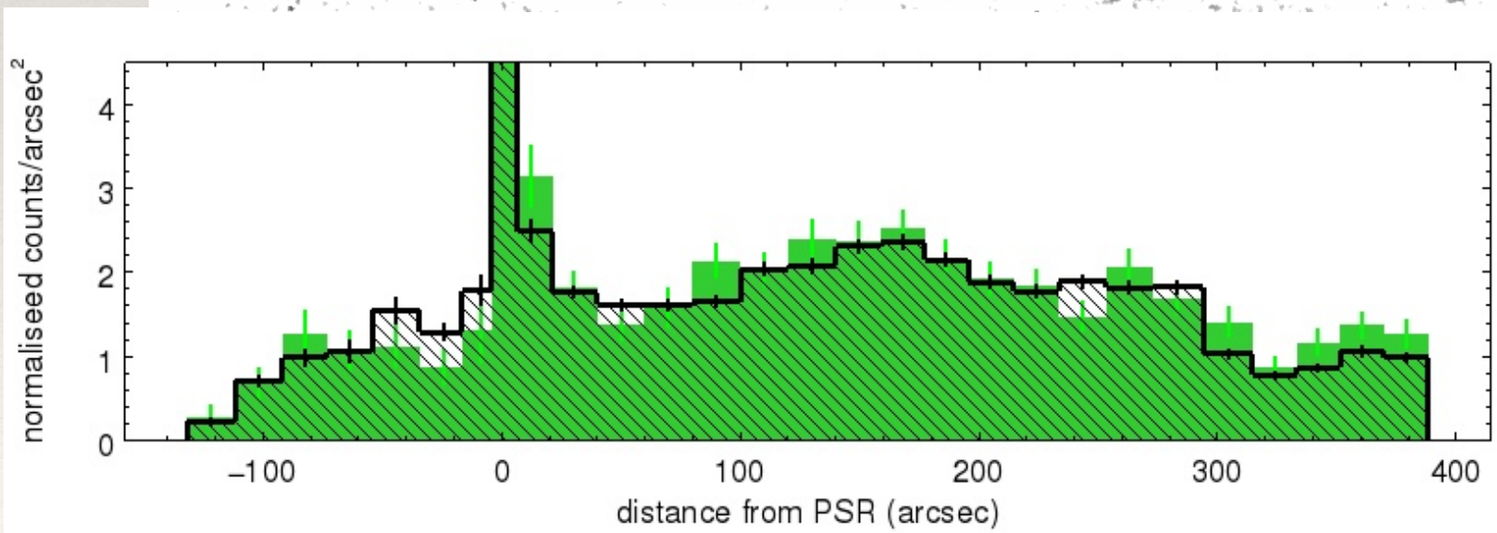


LP et al. 2015

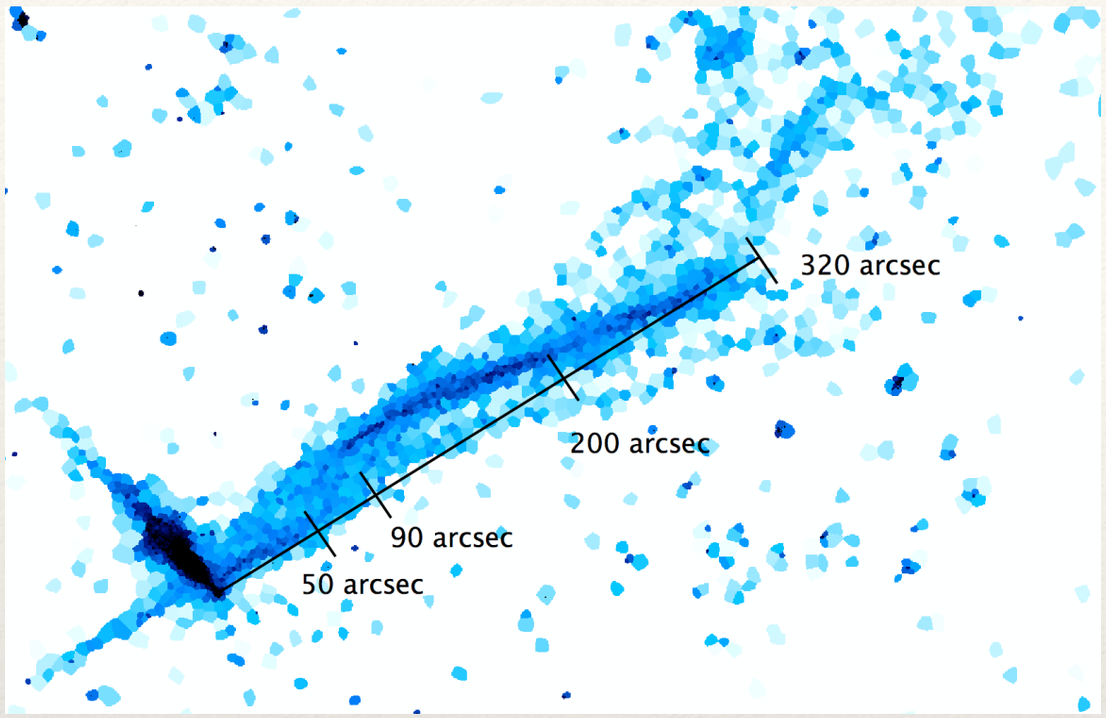


2015:

- Globally, the brightness profile still seems to fit the picture
- But …

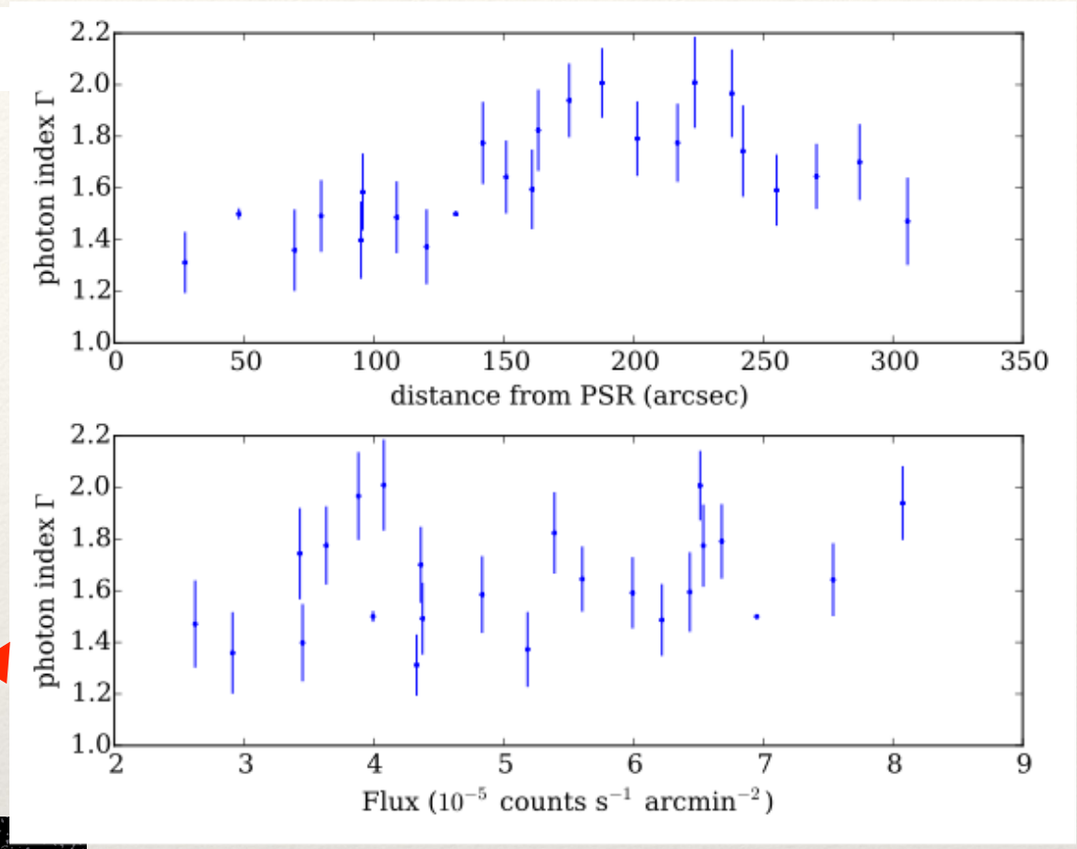


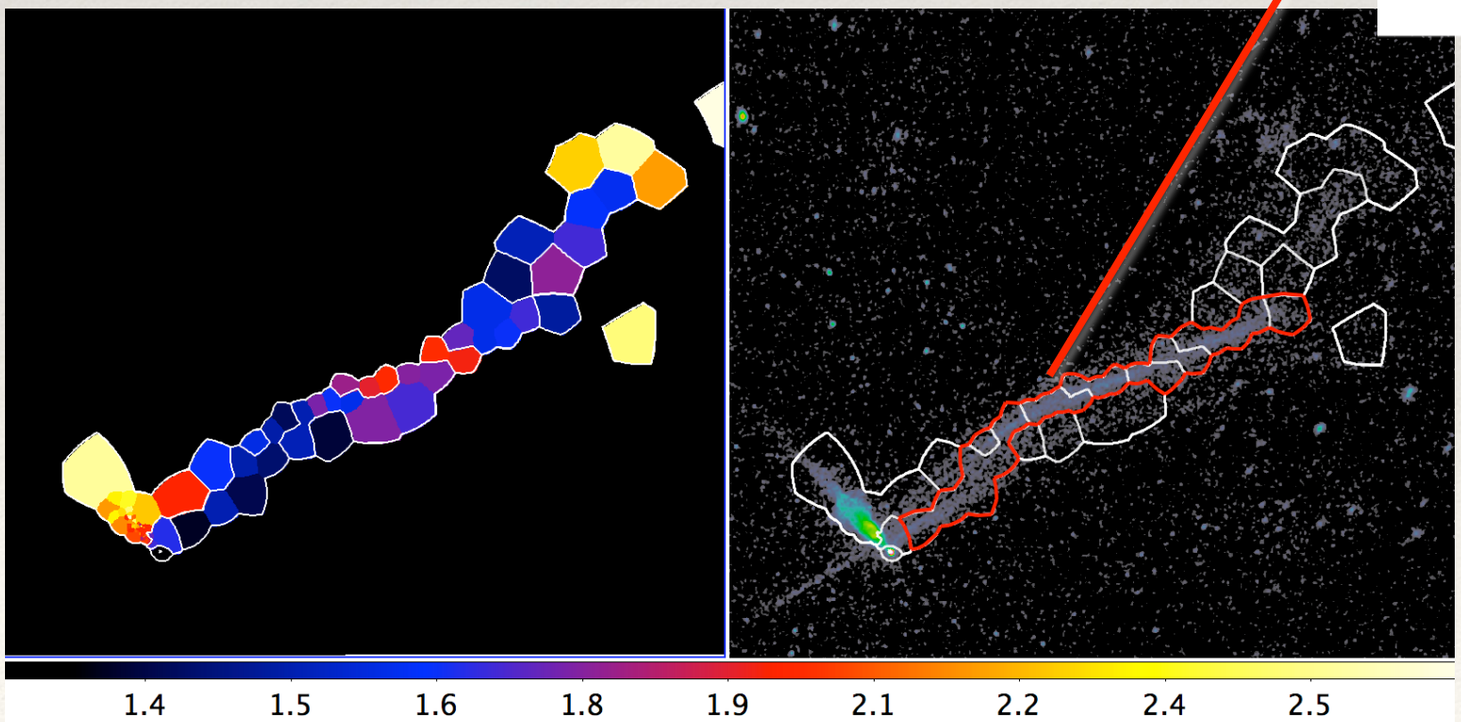
Photon index map



LP et al. 2015

main jet

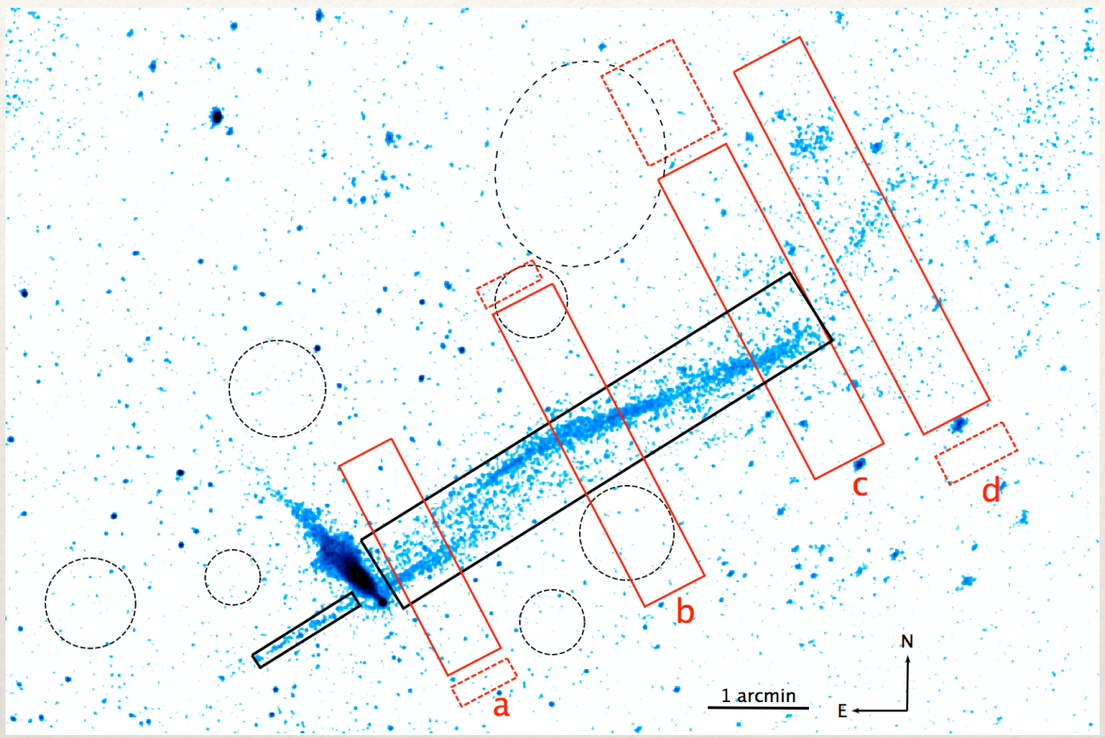


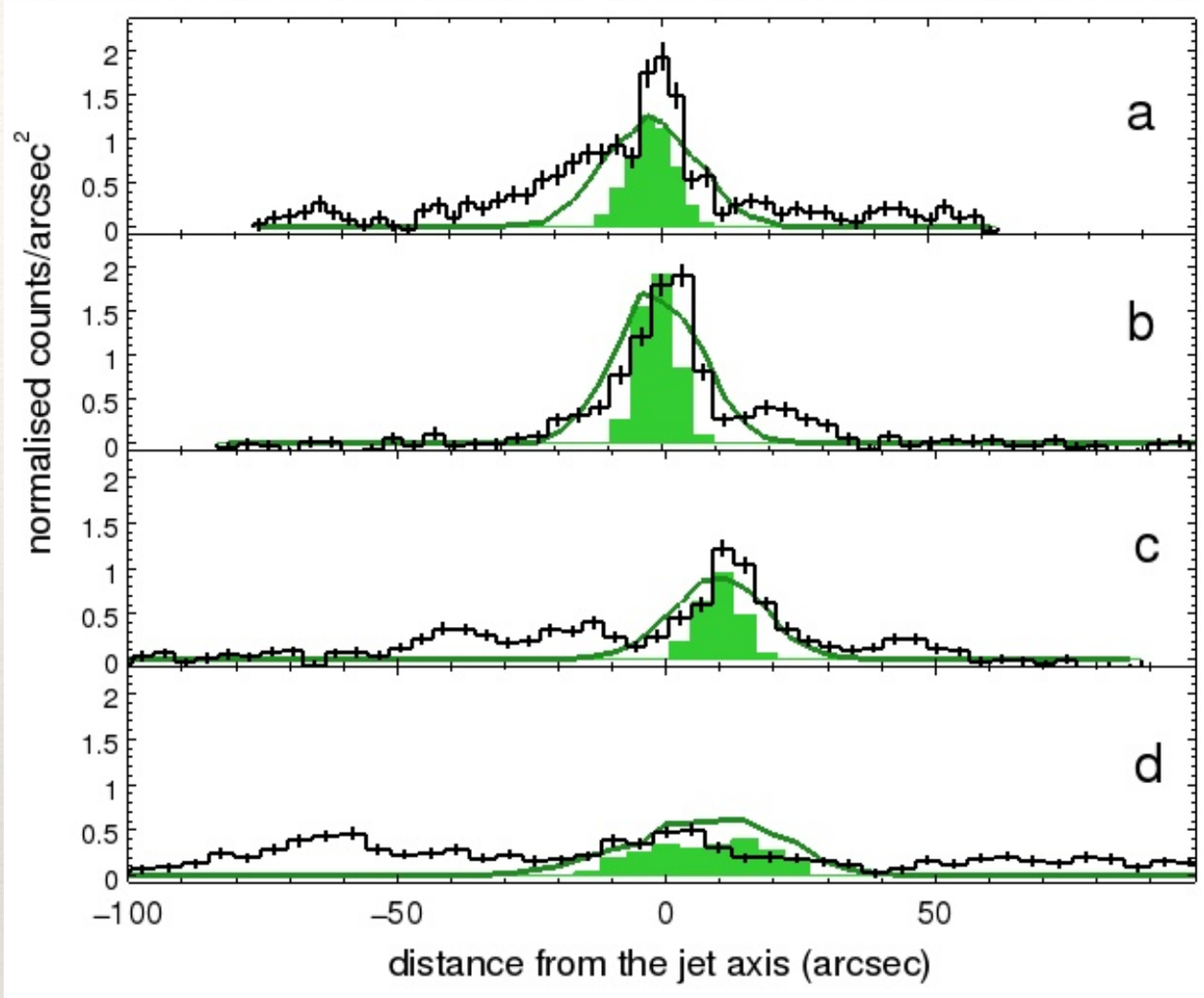


2015:

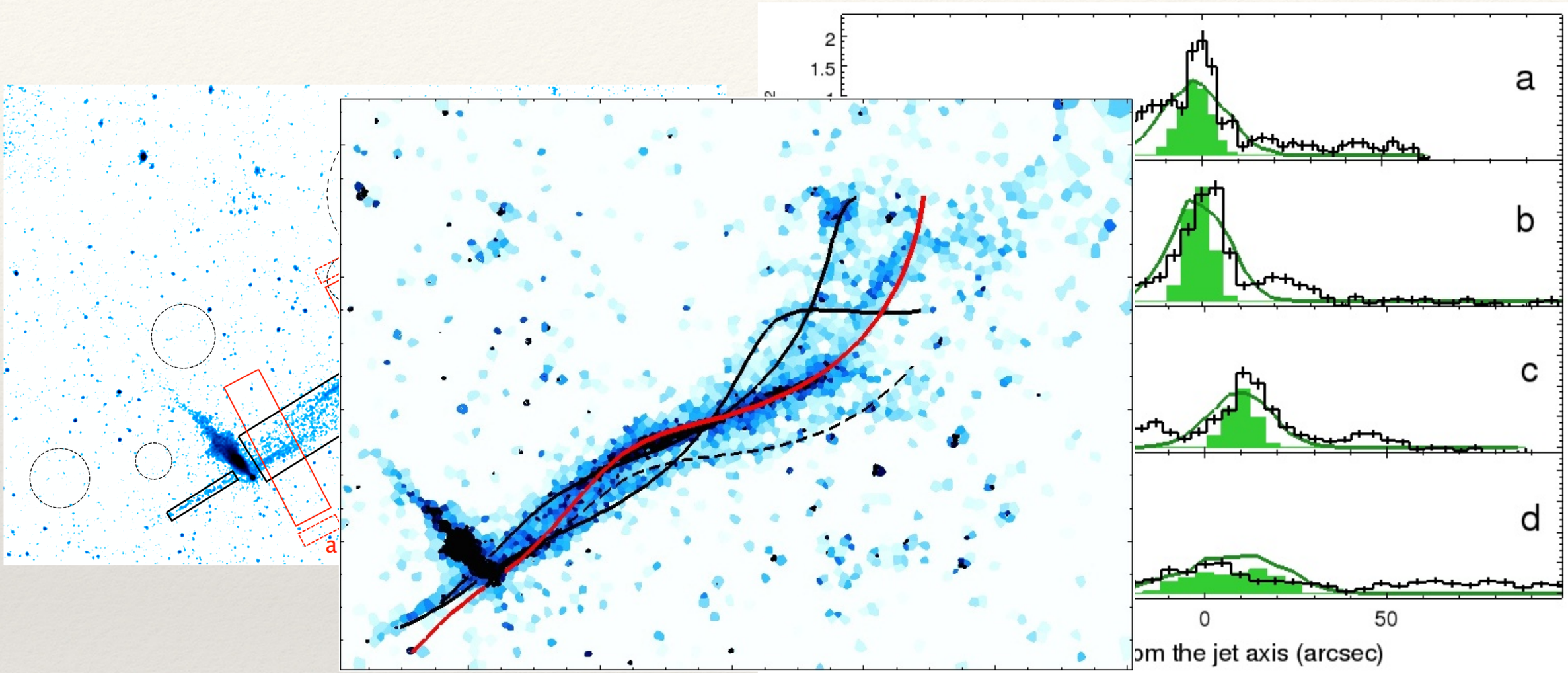
- Photon index map in conflict with simple Doppler boosting
- A signature for reacceleration?

Not understood: Structures around the jet





Not understood: Structures around the jet

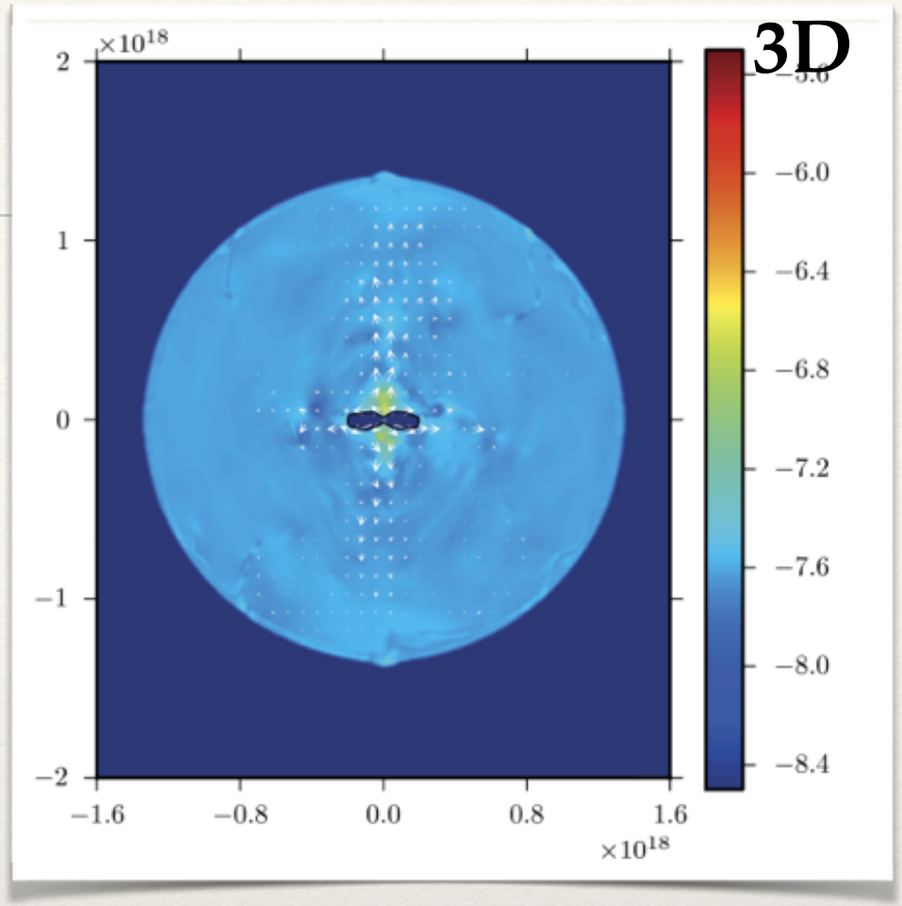


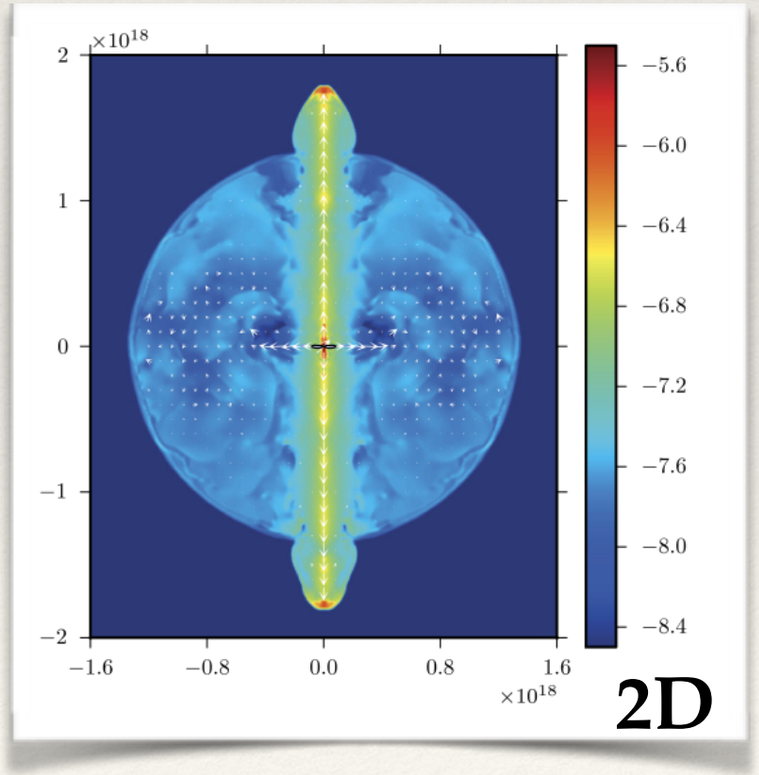
- Multiple active (simultaneously emitting) jet launching points ?
- Perhaps easier to accomodate with a diffusion process with magnetic confinement (rather than a ballistic jet), but how to explain the morphology ?
- (cf. also jet in Guitar nebula: possible hardening with time incompatible with confinement) (Johnson & Wang MNRAS 2010, Hui & Wang ApJ 2012)

Pulsar wind jets

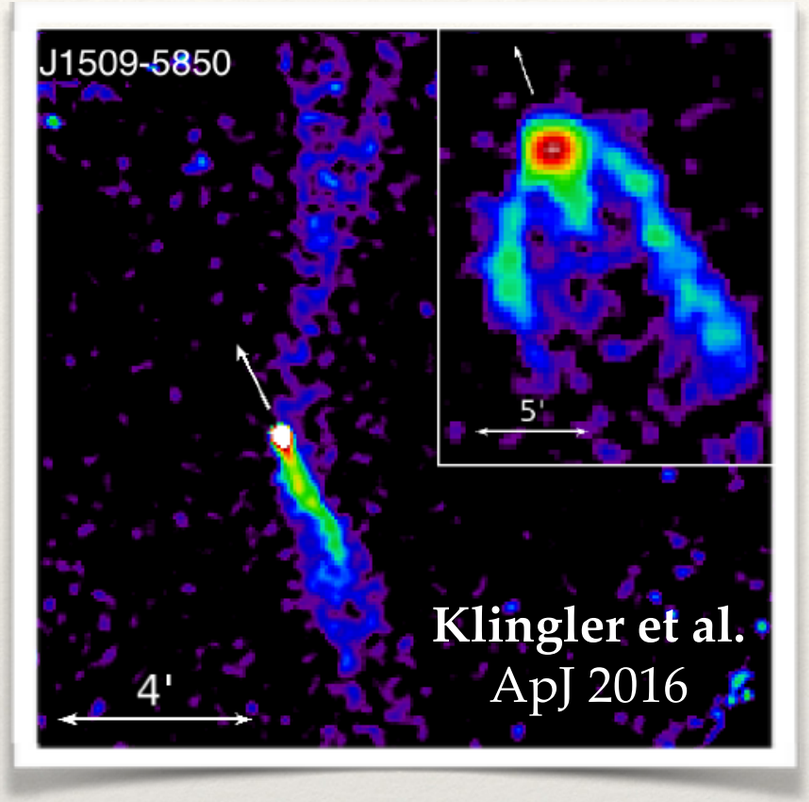
- Jets not launched directly from the PSR, but rather from the wind (after termination shock) (Lyubarsky 2002, Bogovalov & Khangoulyan (2002), Komissarov & Lyubarsky (2003), ...)
- Magnetic hoop stresses in the highly magnetised wind, very close to the PSR polar axis: $E_B \rightarrow E_{plasma}$
- "Jet" launching mechanism is quite inefficient
- Still several unknowns!
- High speed PSRs
  → Maybe the PWN geometry change is responsible for the jet strength (?)
  indications from other systems exist, e.g. Kargaltsev et al. (2008)

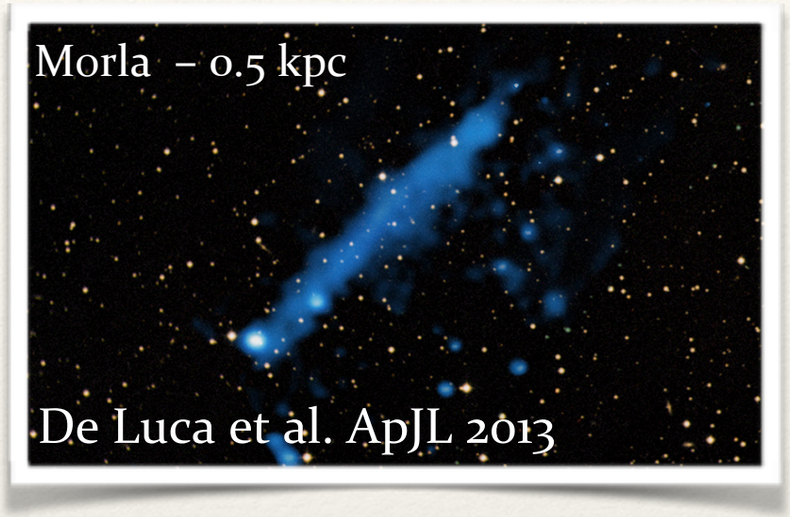
Porth et al. 2014 MNRAS 438, 278

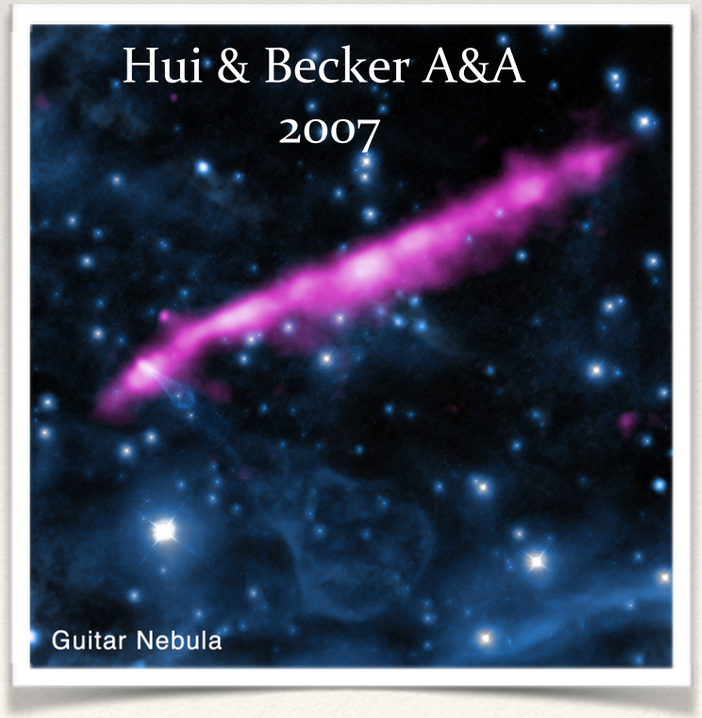


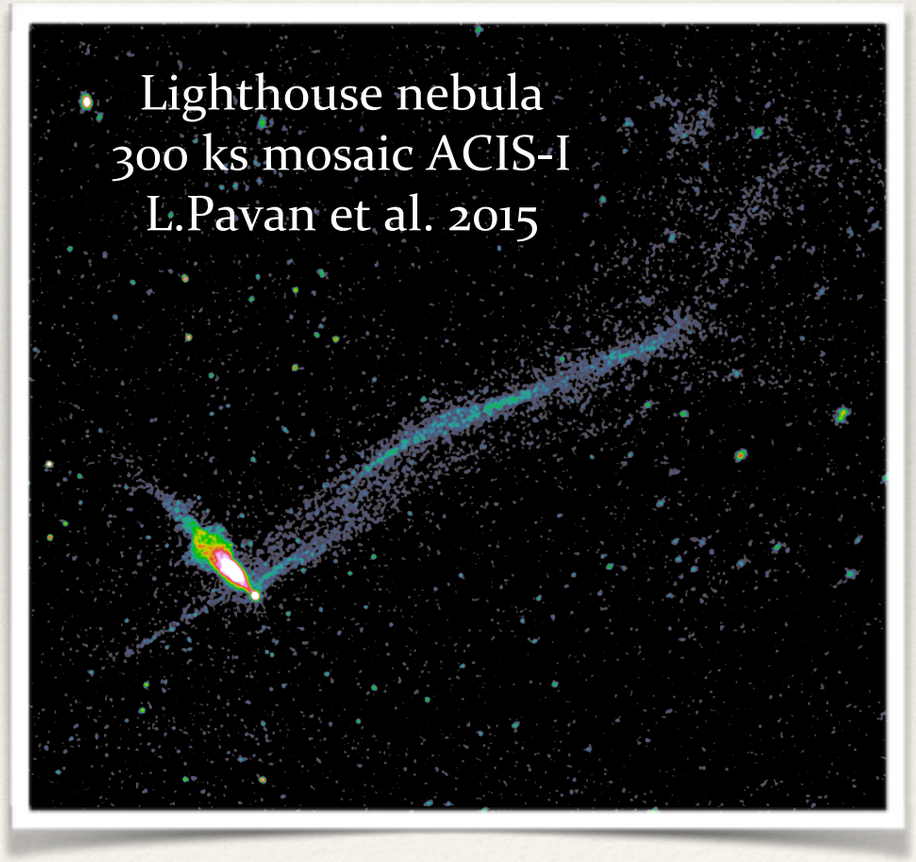


Adding velocity to the pulsar…

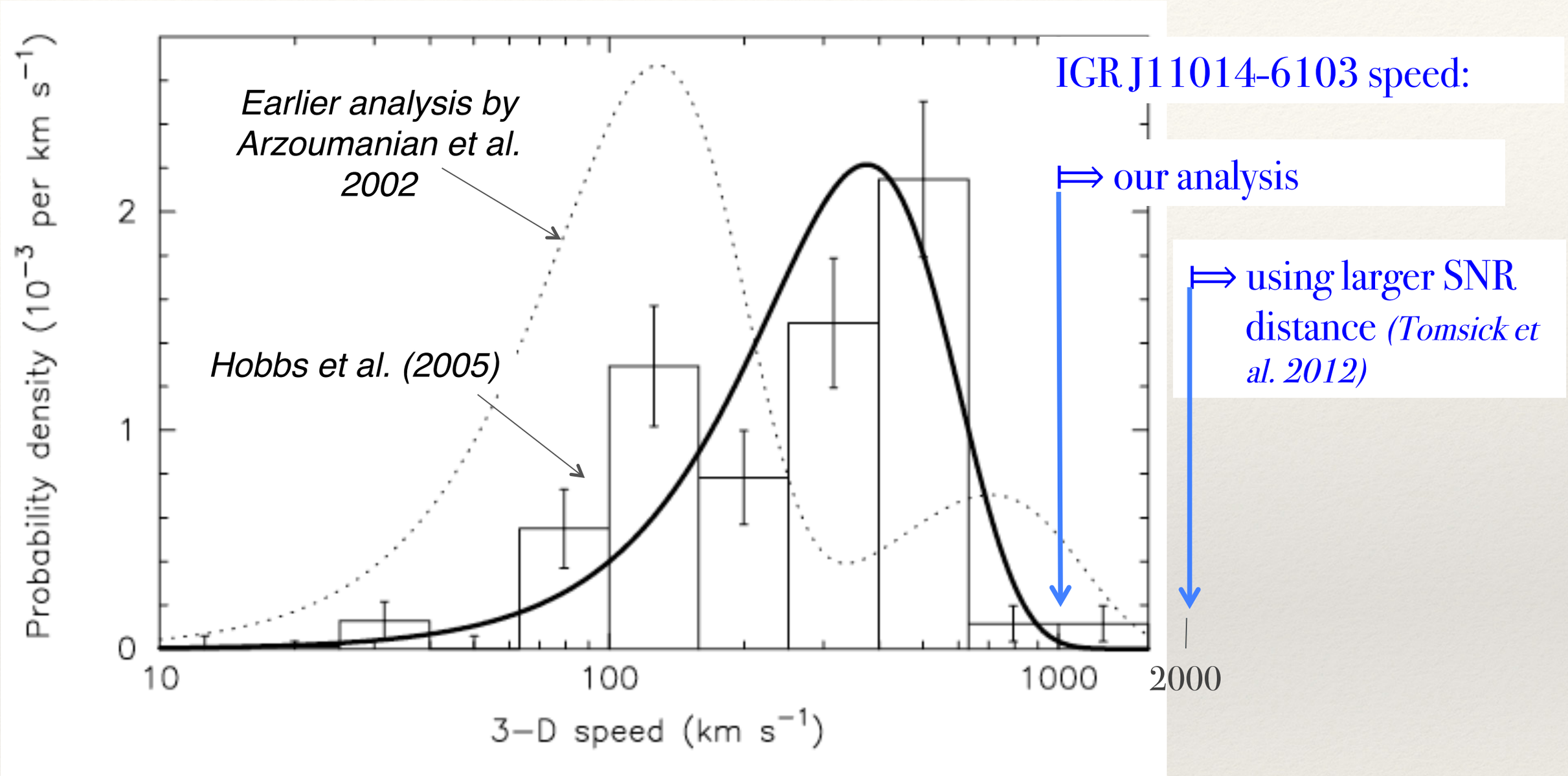








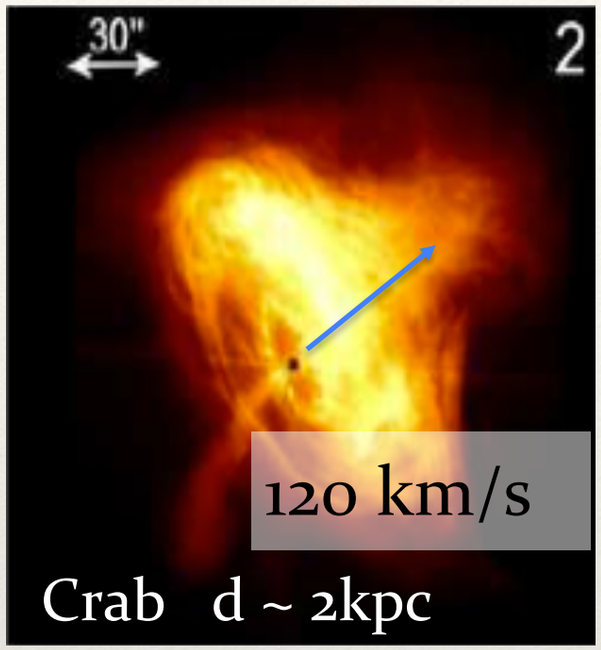
Pulsar speeds

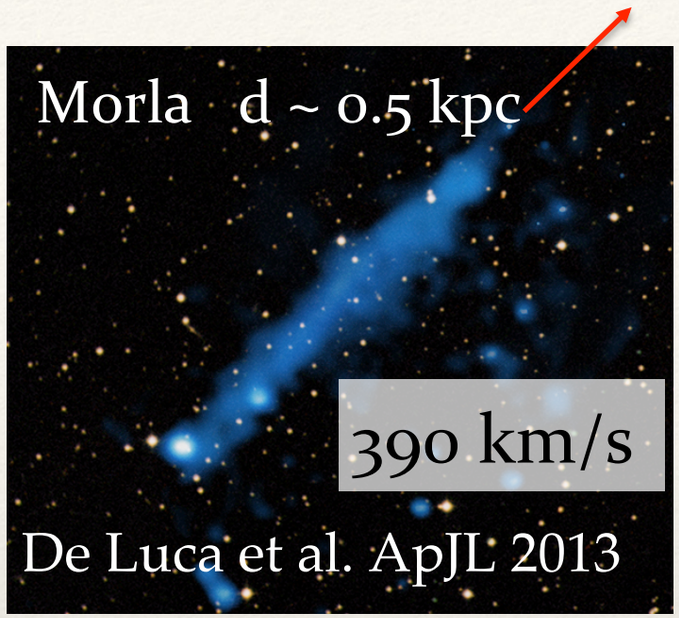


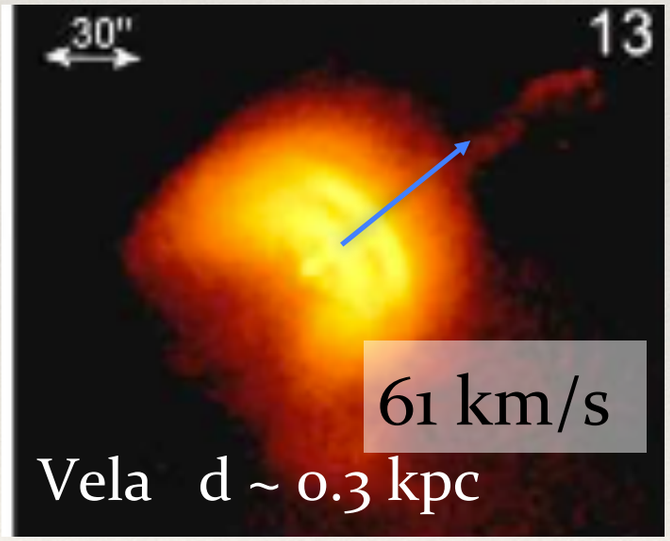
- PSR B1508+55—> parallax: v_{PSR} = 1083±100 km/s (Chatterjee et al. 2005 ApJ, 630, L61)
- Guitar nebula: proper motion v~800 km/s (Harrison, Lyne & Anderson 1993 MNRAS, 261, 113)
- Frying pan radio PSR : v~1000 km/s (Ng et al. 2012)

Kick velocity - pulsar spin alignment

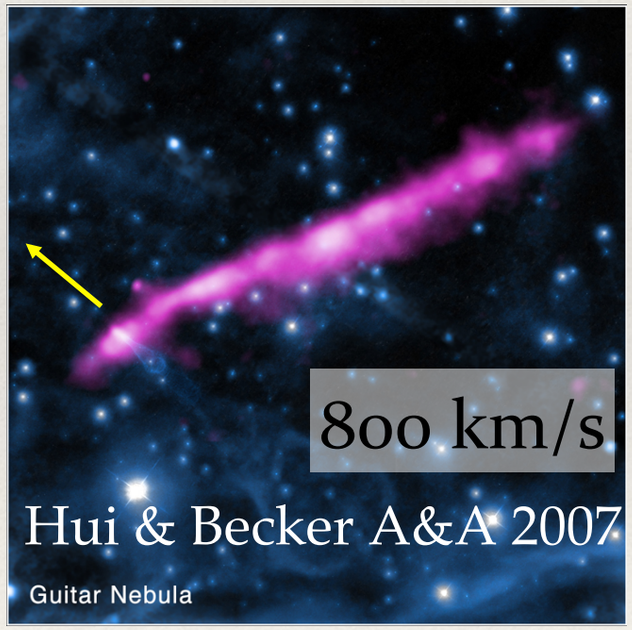
Kaplan et al., 2008







Ng & Romani, 2007

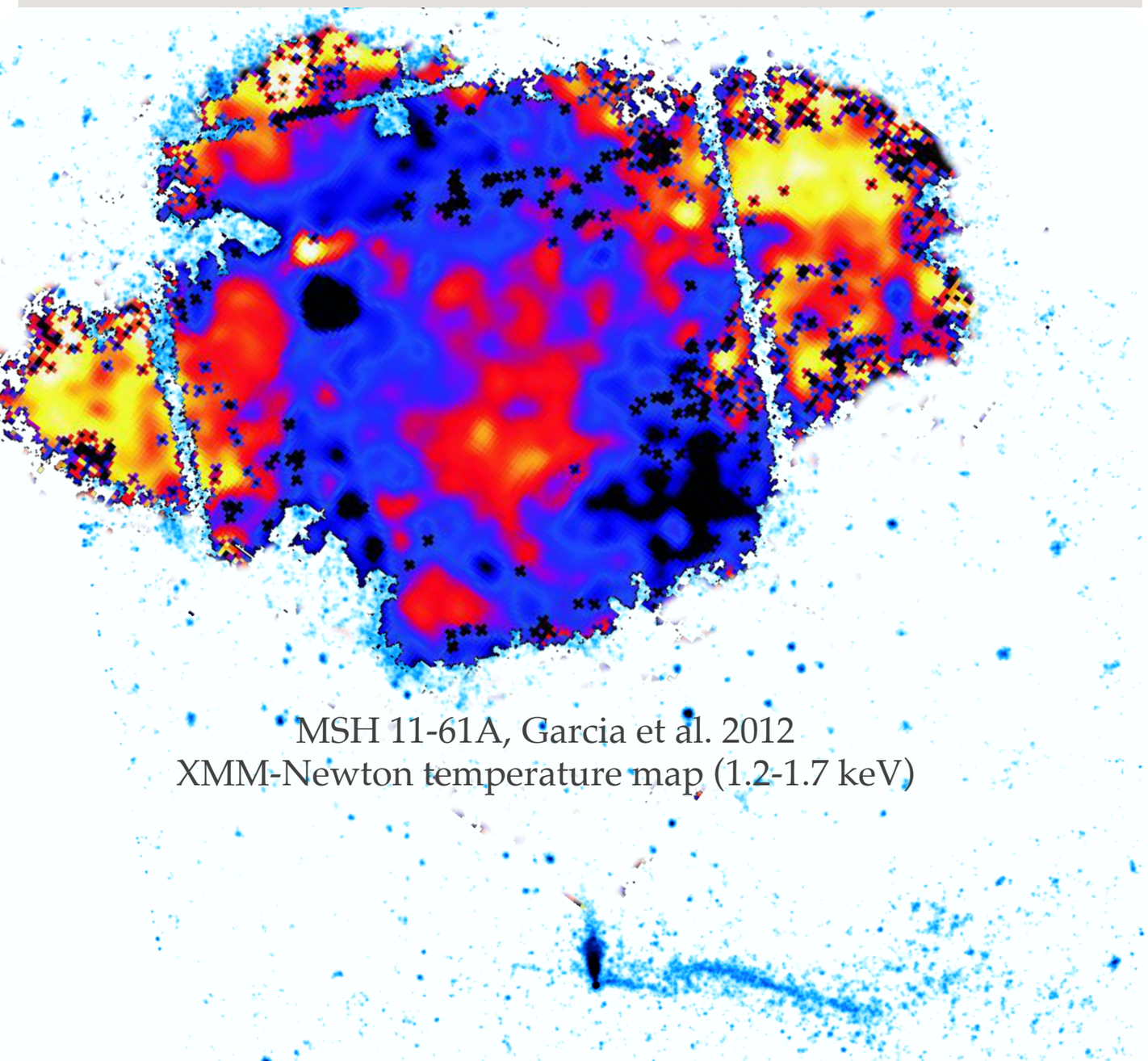


Spruit & Phinney 1998 Nature 393, 139
Lai et al. , 2001 ApJ 549, 1111
Johnston et al. 2007 MNRAS 381, 1625
Noutsos et al. 2013 MNRAS 430, 2281

- Kicks due to asymmetric core-collapse SNe (Janka, 2012 ARNPS 62, 407; Wongwathanarat et al. 2013 A&A 552, A126) (explosion also spins up the pulsar)
- Most models show <u>correlation</u> between velocity direction and spin axis
  - hydrodynamical kicks
  - asymmetric neutrino emission
  - electromagnetic rocket (postnatal kick)
- Jets are on the spin axis (no equatorial jet)
- Polarization data for 25 pulsars → P.A. of the linear polar. → P.A. of spin axis
- Orthogonal pol. modes in the PSR radio emission: either // or ⊥ (Johnston et al. 2005, 2007)

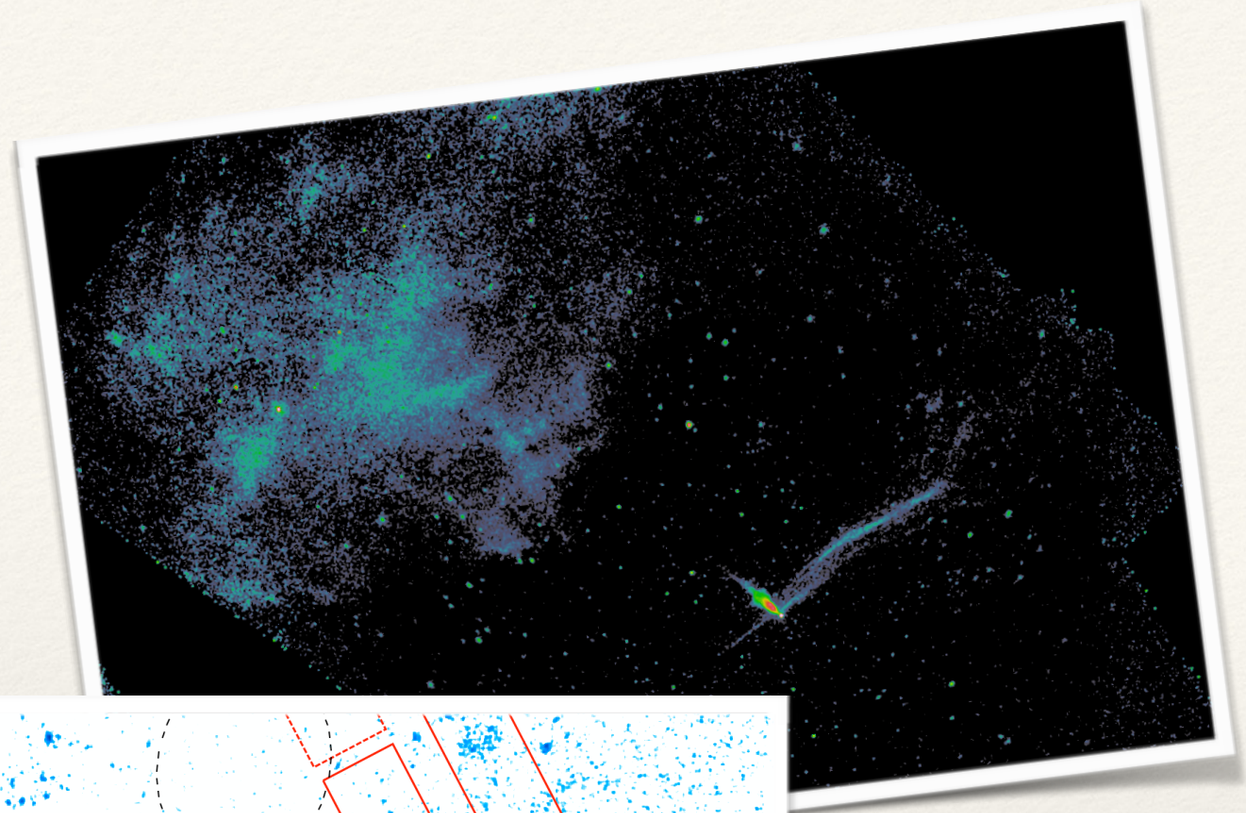
Association with the supernova remnant MSH 11-61A

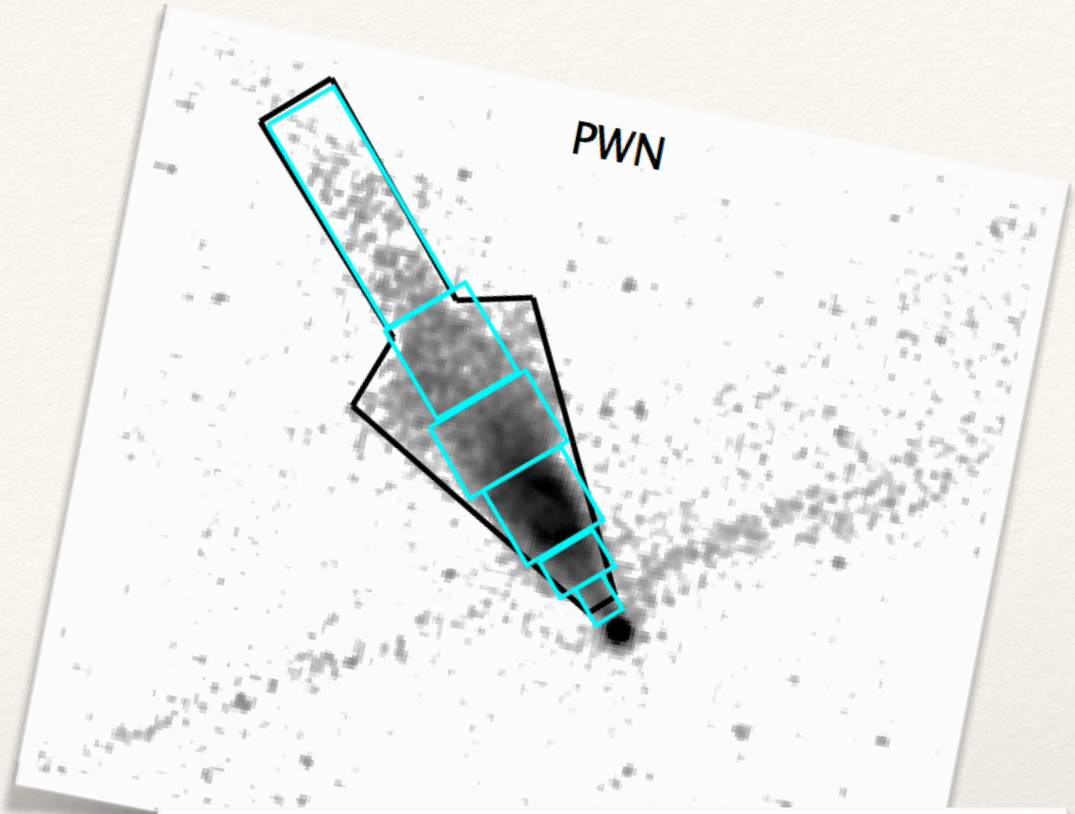
Garcia et al. 2012, Slane et al. 2002, Reynoso et al. 2006:
→ Age: ~10 .. 20 thousand years
→ Distance 7 kpc (earlier estimates were a bit larger)
→ Core collapse supernova
→ Missing neutron star remainder

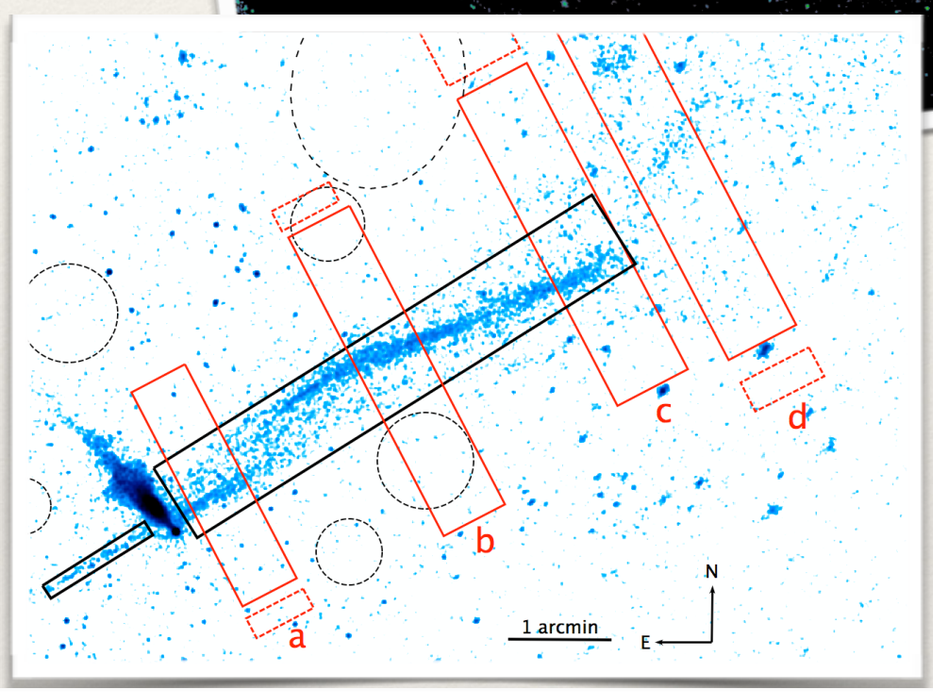


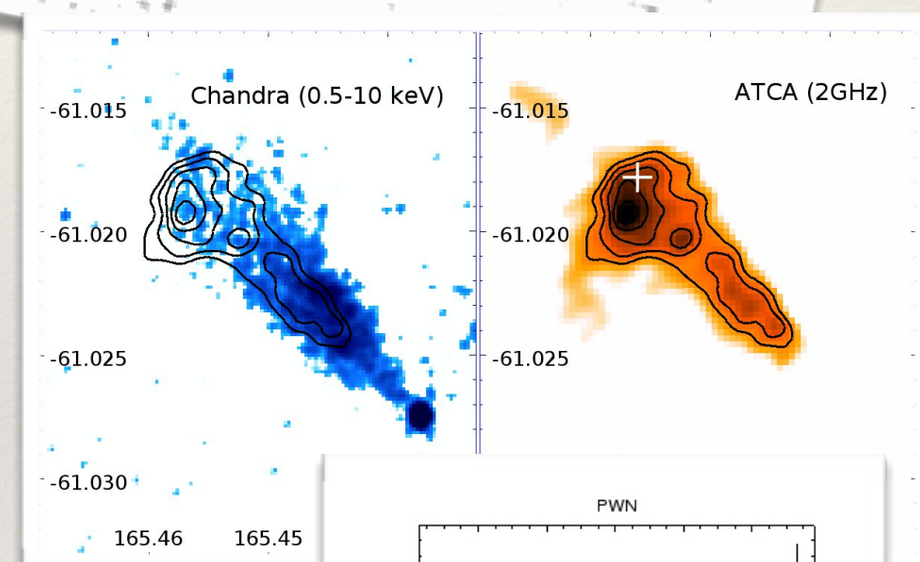
MSH 11-61A, Garcia et al. 2012
XMM-Newton temperature map (1.2-1.7 keV)

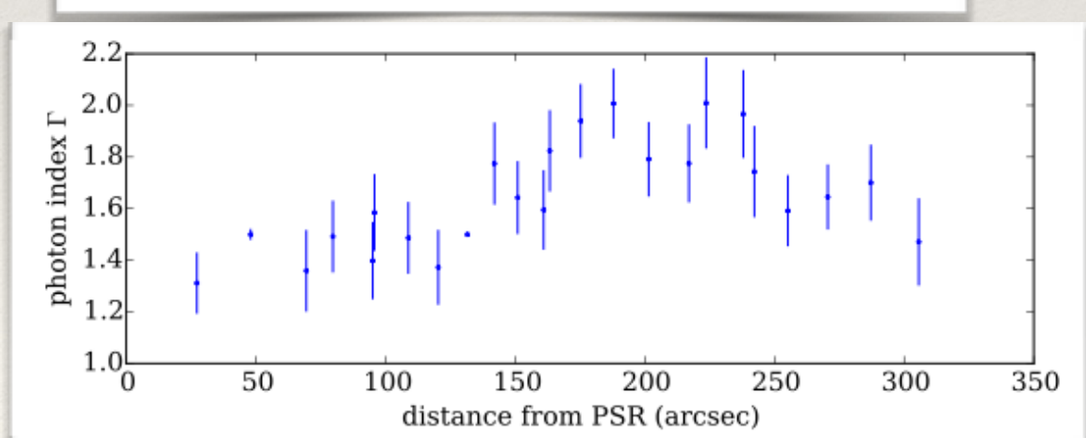
- Asymmetric SN / ejection should be accompanied by asymmetric distribution of heavy elements (Wongwathanerat et al. 2013)
- Somewhat confirmed with XMM-Newton data from Garcia et al. 2012
- Bar-instable core collapse model also predicts large recoil of NS (Colpi&Wasserman 2002)
- Would explain misaligned NS spin axis (if jet feature is really a true ballistic jet)



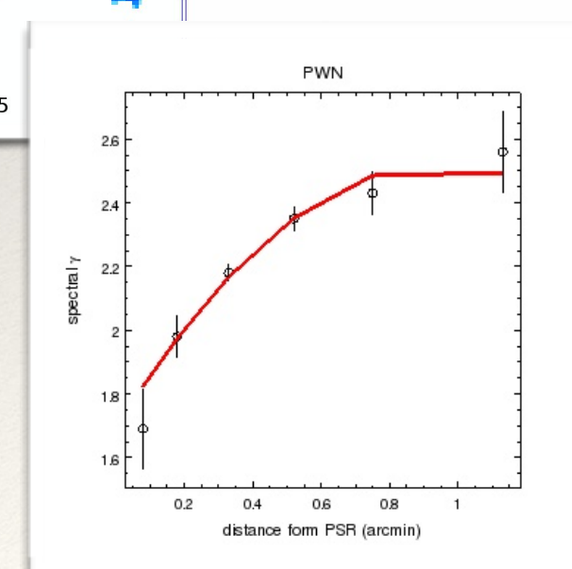

PWN


a
b
c
d
1 arcmin
N
E

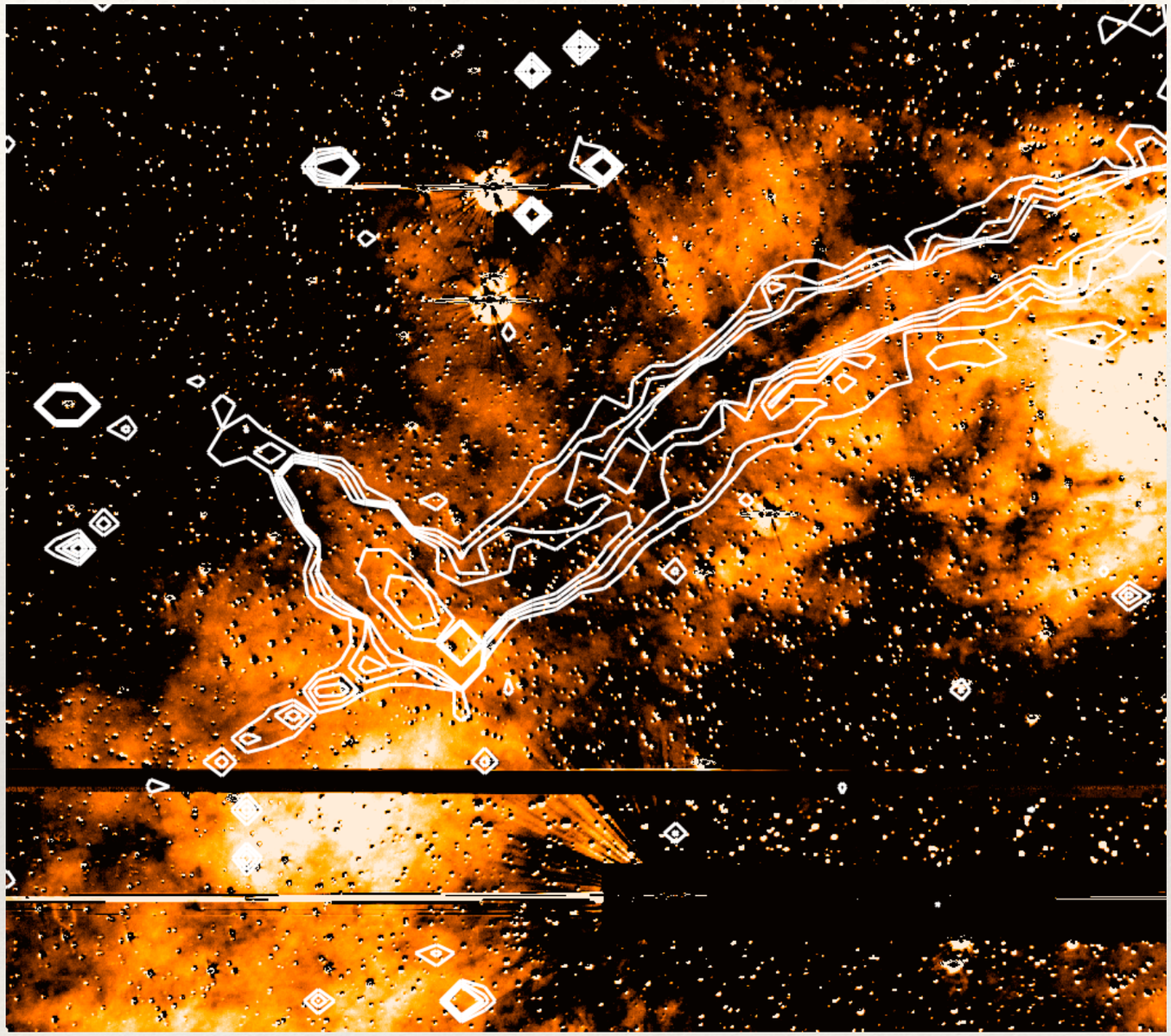

Chandra (0.5-10 keV)
ATCA (2GHz)
-61.015
-61.020
-61.025
-61.030
165.46
165.45


photon index Γ
distance from PSR (arcsec)
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0
50
100
150
200
250
300
350

Thanks!

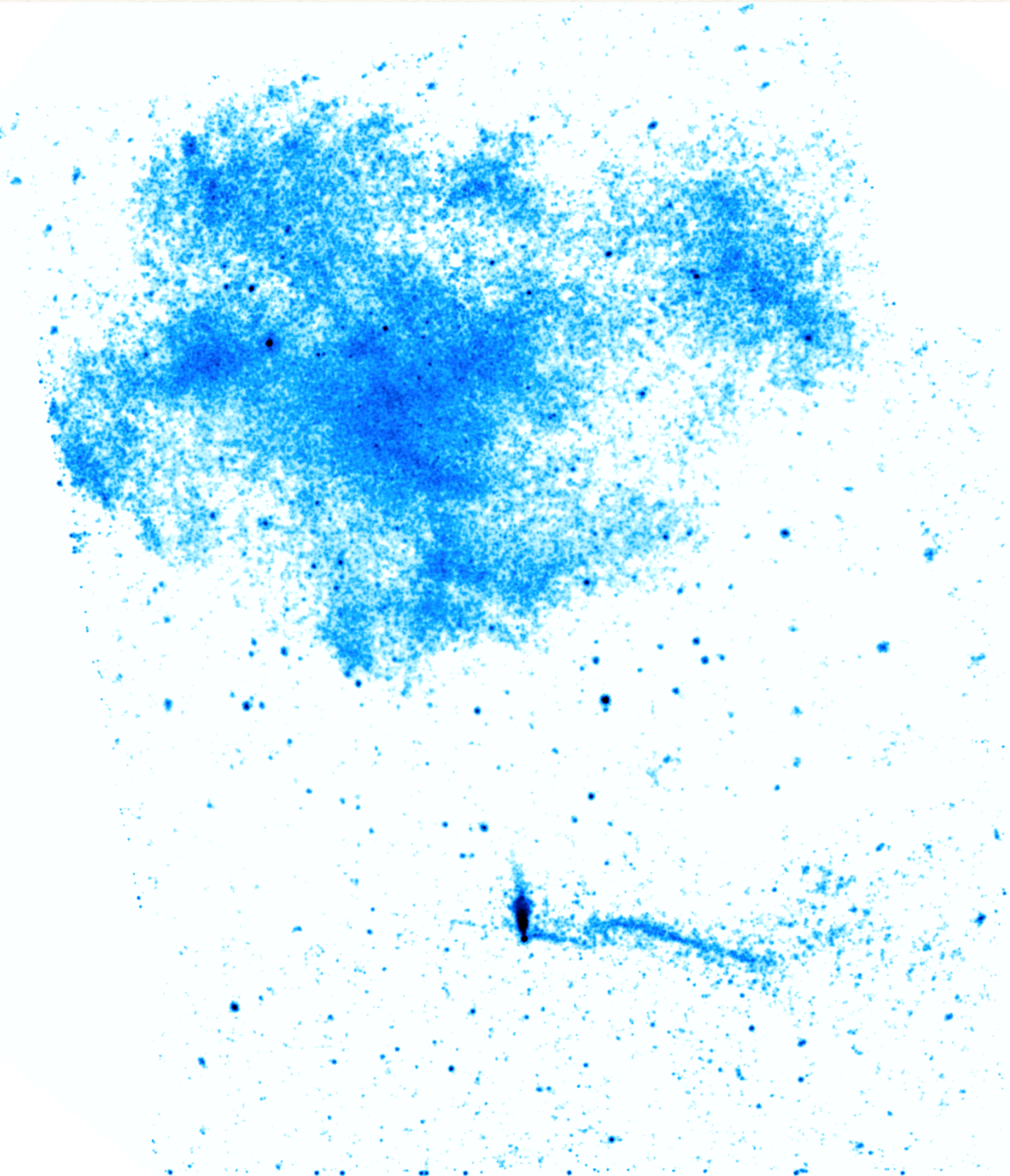

PWN
spectral Γ
distance form PSR (arcmin)

Search for Hα emission



- Search with VLT/FORS2
- No detection, but masked by larger emission region

… so, what is this jet „feature“?



- Is this a true, ballistic jet? If yes, then
  - The properties of this jet would be very outstanding (length, non-bending, X-ray luminosity, precession ...)
  - But also the determined spin axis alignment of the NS would be very interesting
- Alternatively, particles follow pre-existing magnetic field lines
  - If yes, probing ISM structures would be very interesting