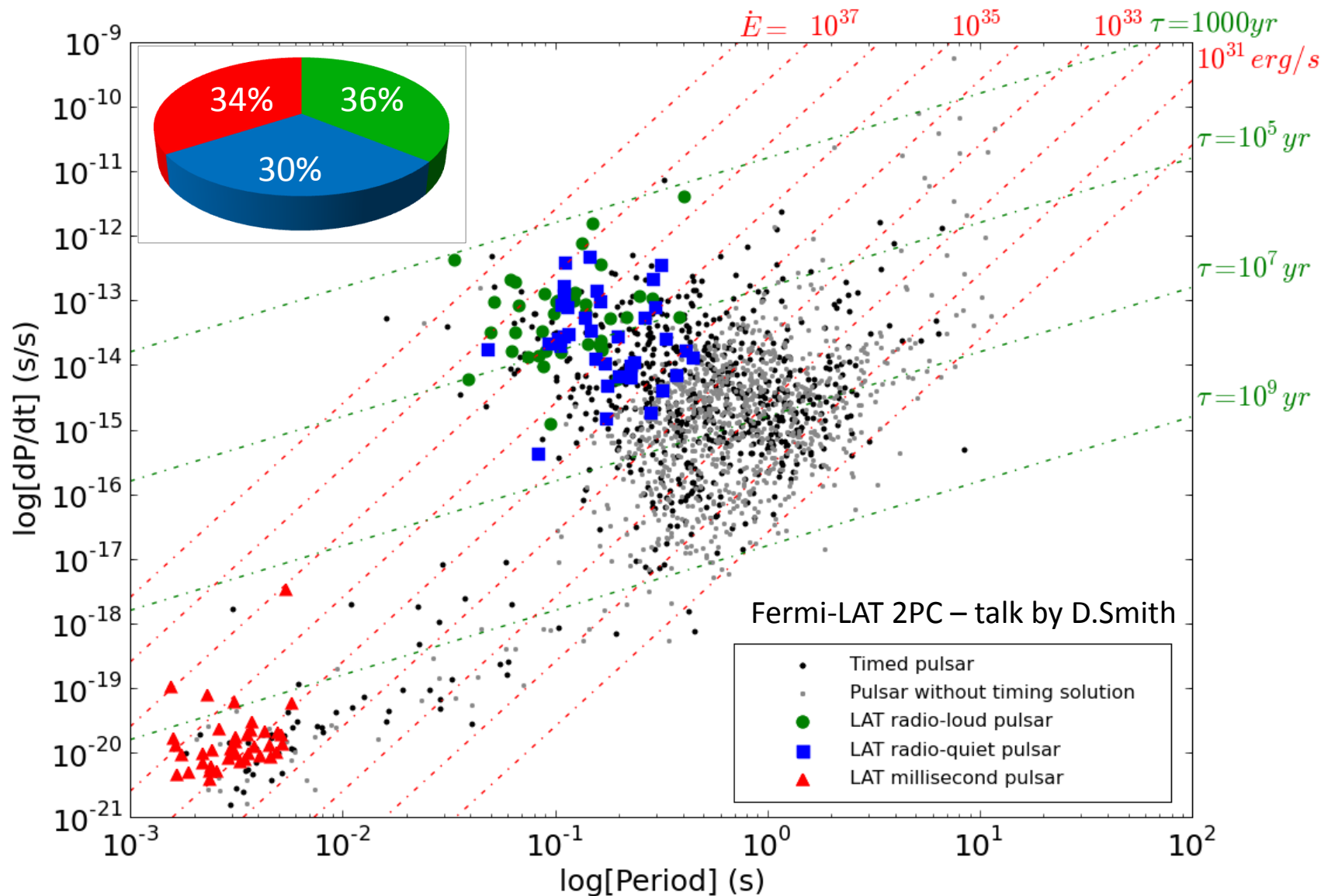


A nearby, fast-moving pulsar with a very unusual X-ray trail

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with P. Caraveo, M. Marelli, D. Salvetti, N. Sartore,
R. Mignani, A. Belfiore, P. Saz Parkinson

Fermi-LAT discovers pulsars



The soft X-ray side

Systematic follow-up campaign for RQ PSRs
(Chandra, XMM-Newton, Swift/XRT, Suzaku)

Goals: → are RQ PSRs and RL PSRs different ?
→ detailed study of interesting targets

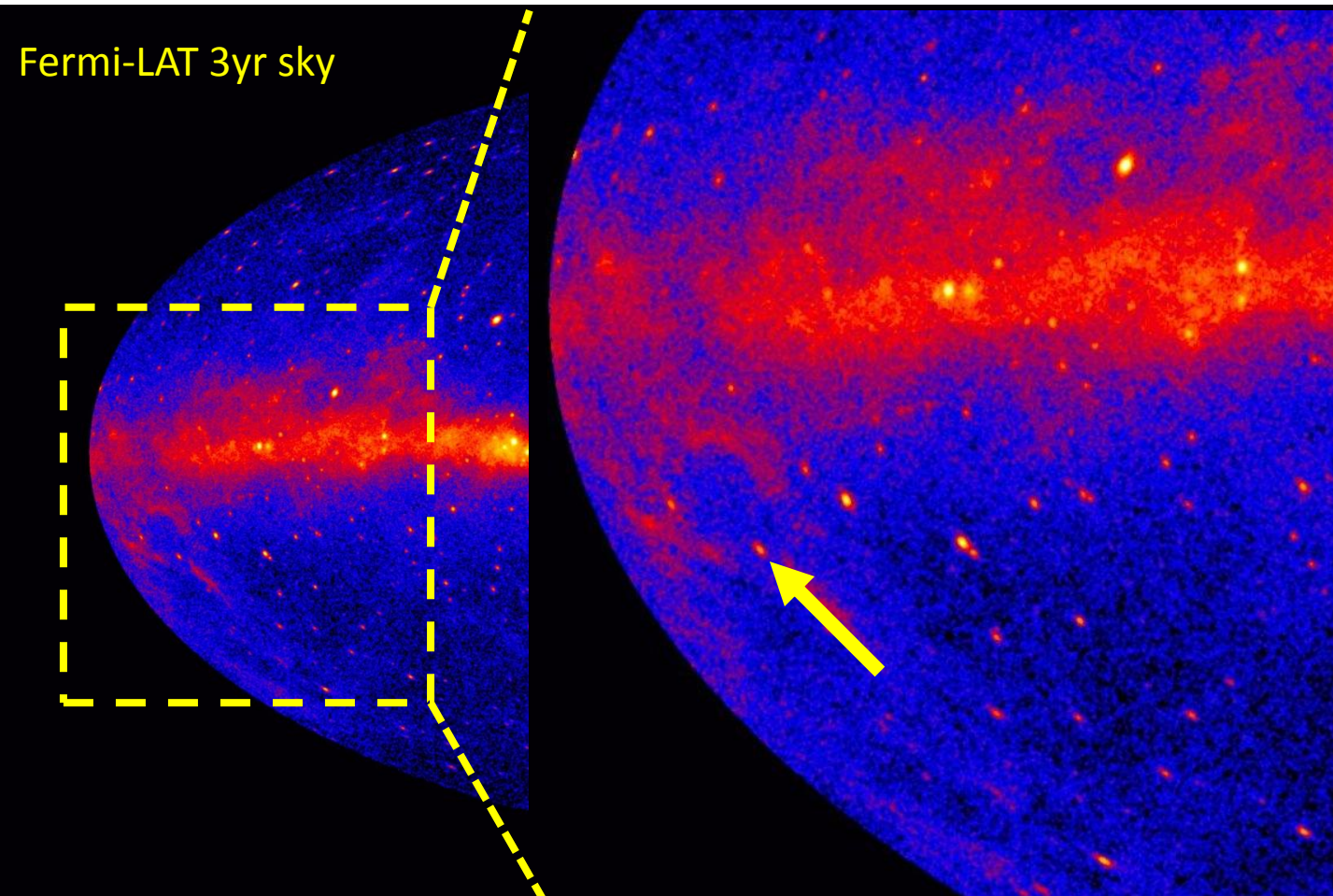
Status : → 76 Fermi PSRs with X-ray counterpart
→ 27 RL – 24 RQ – 25 MS

Chandra and Suzaku “mini-surveys” ongoing

→ deep obs of PSR J0007+7303, PSR J0357+3205,
PSR J2021+4026, PSR J1813-1246, PSR J2055+2539

(Caraveo et al. 2010; De Luca et al. 2011,2013; Marelli et al. 2012a,b,2013;
Weisskopf et al. 2011; Fermi-LAT 2PC; Sarazin et al. in prep; Marelli et al. in prep)

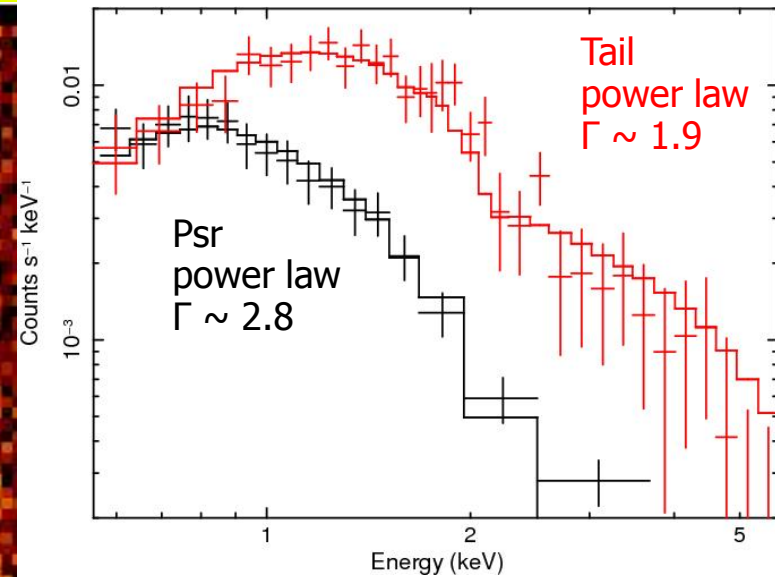
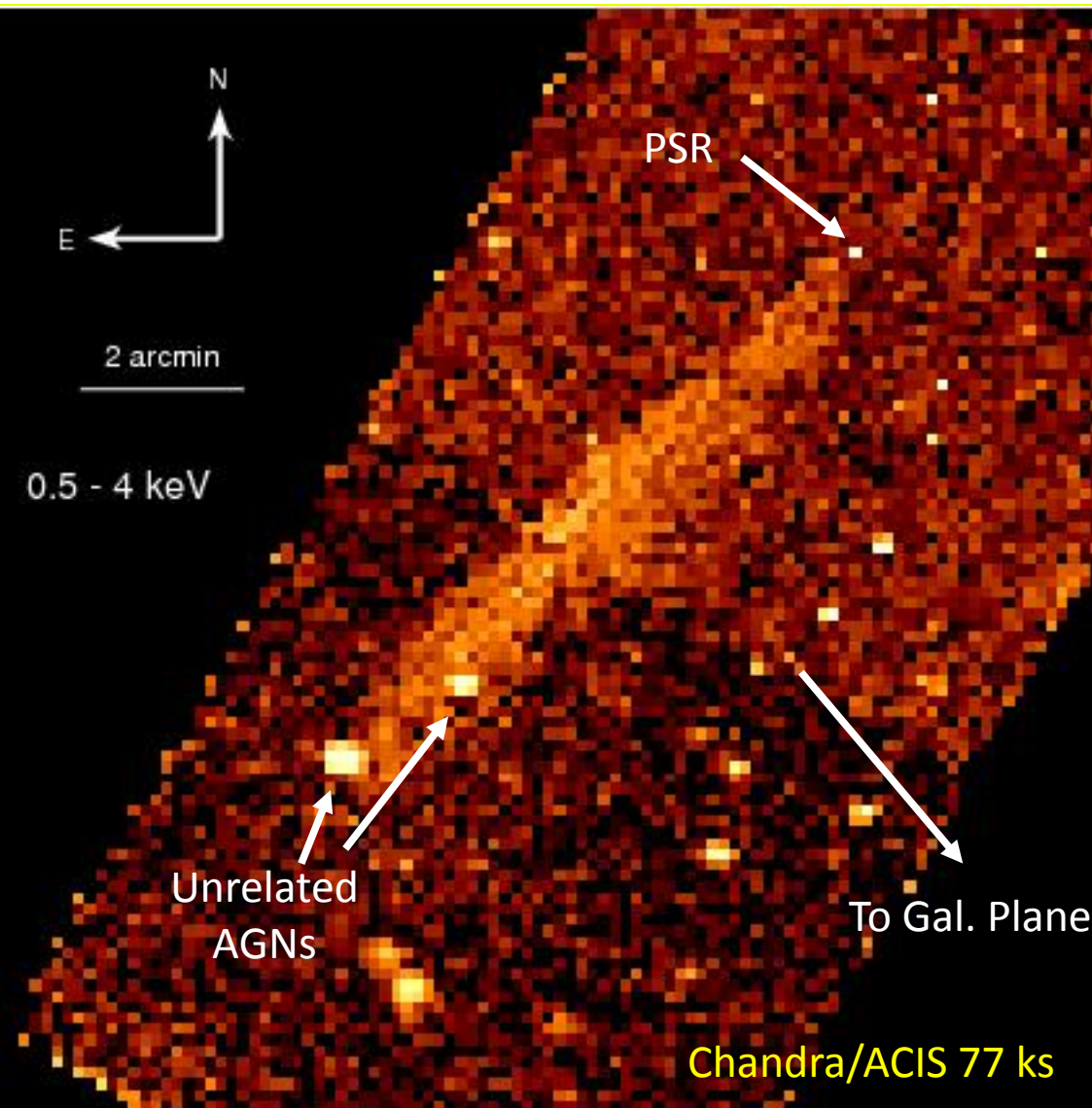
The radio quiet PSR J0357+3205



$P = 444 \text{ ms}$
 $\dot{E} = 6 \times 10^{33} \text{ erg/s}$
 $B = 2.3 \times 10^{12} \text{ G}$
 $\tau = 0.54 \text{ Myr}$

$b = -16^\circ$
 $d \sim 500 \text{ pc}$
 $S_{1400} < 4 \mu\text{Jy}$

A faint PSR with a parsec-long X-ray tail



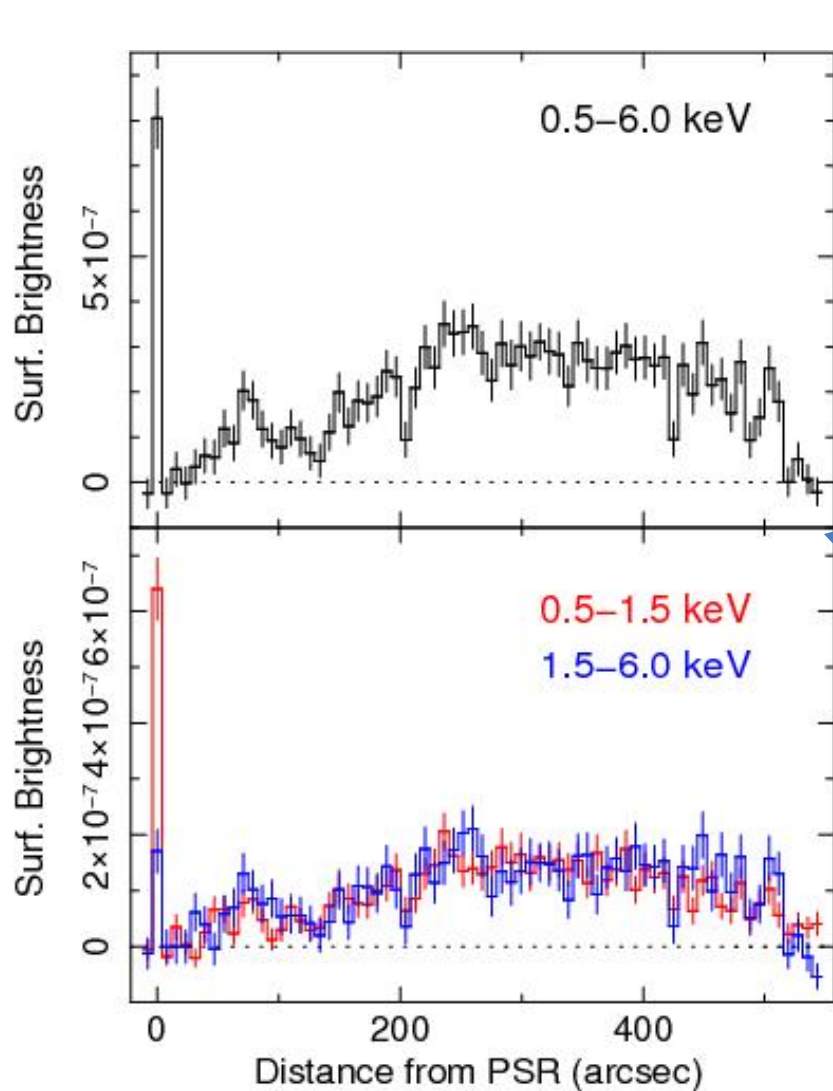
$$\text{Tail } L_x \sim 1.5 \cdot 10^{-3} E_{\text{rot}}$$

@ 500 pc

not detected in NVSS

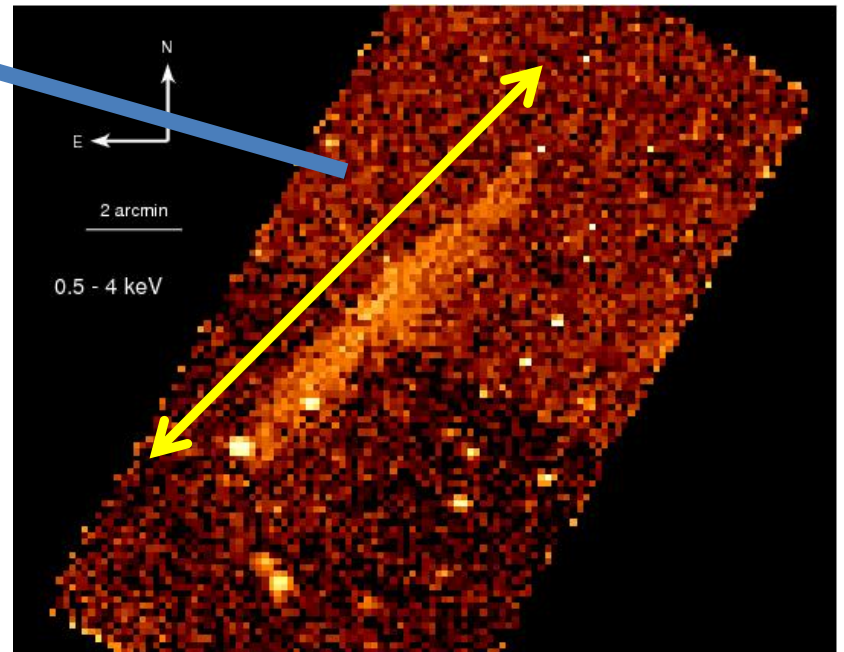
$$9 \text{ arcmin} \rightarrow 1.3 \text{ pc @ 500 pc}$$

Tail: weird brightness profile

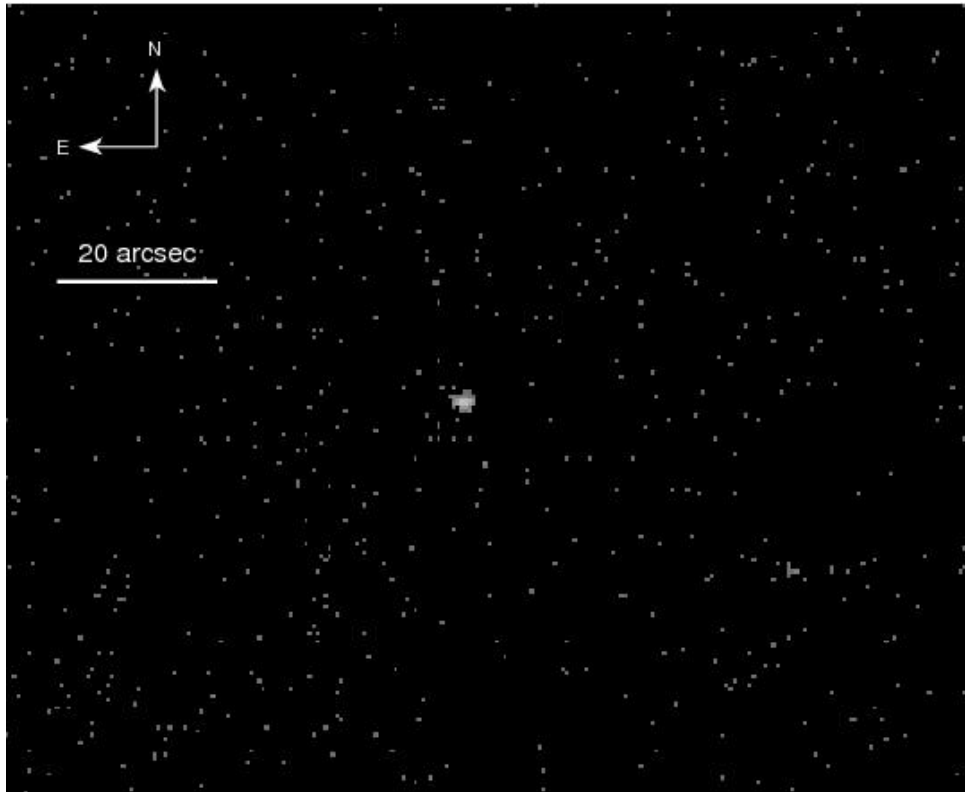


Peak
5 arcmin away
from PSR

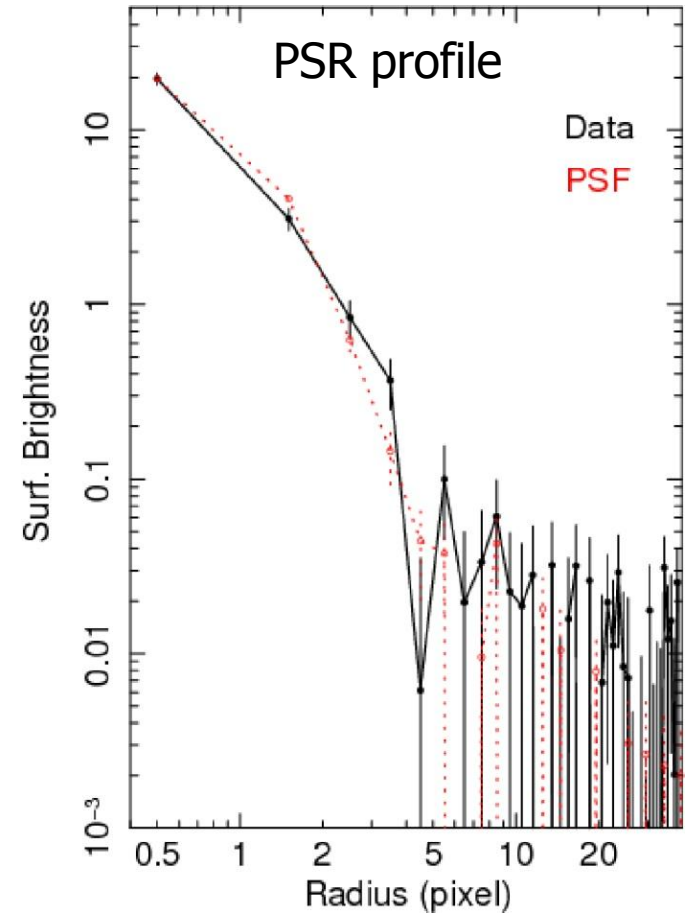
No apparent
spatial/spectral
evolution



Weird brightness profile – 2



No hints for diffuse emission surrounding the PSR



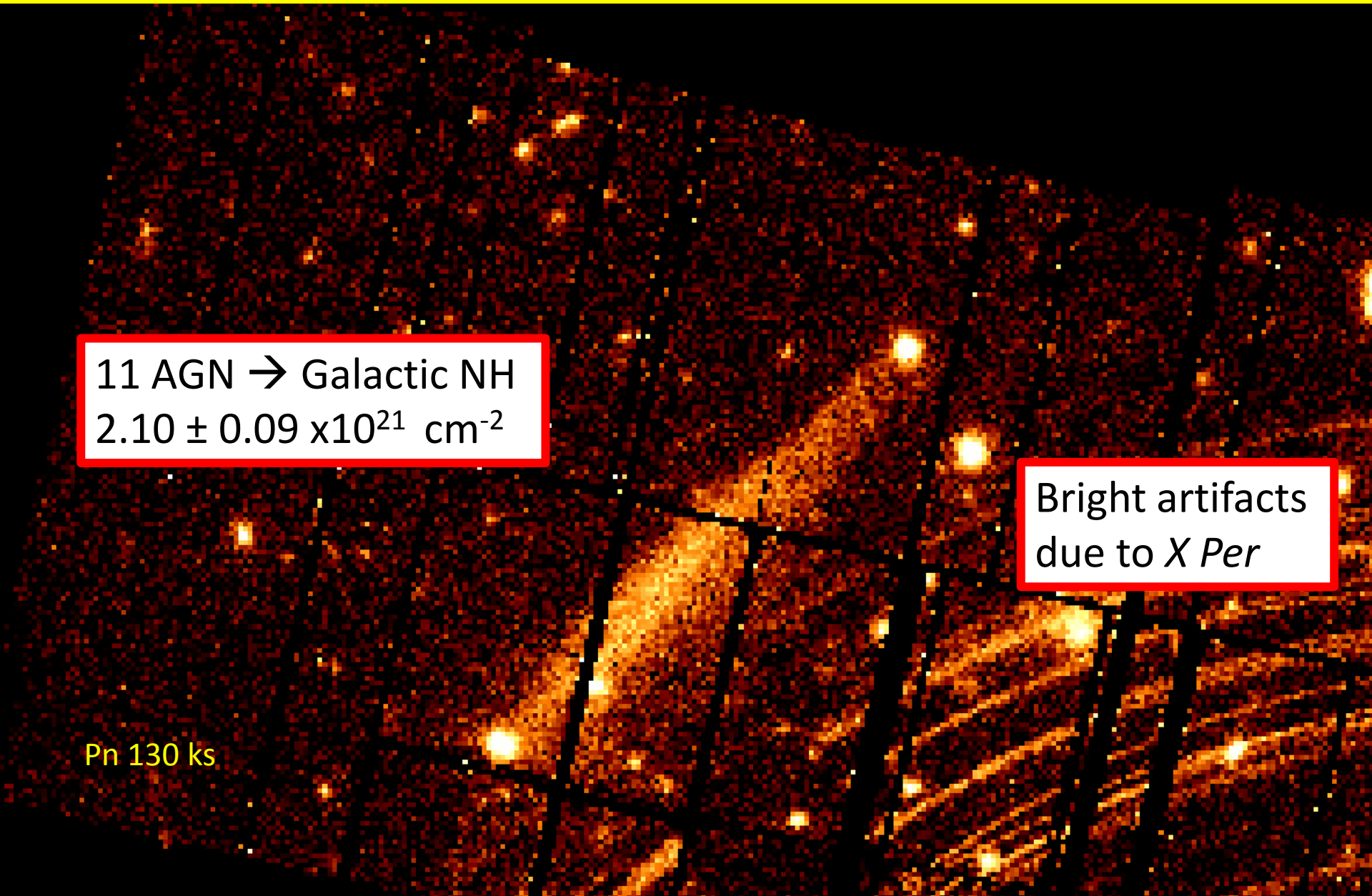
De Luca et al. 2011
ApJ 733, 104

A very deep observation with XMM

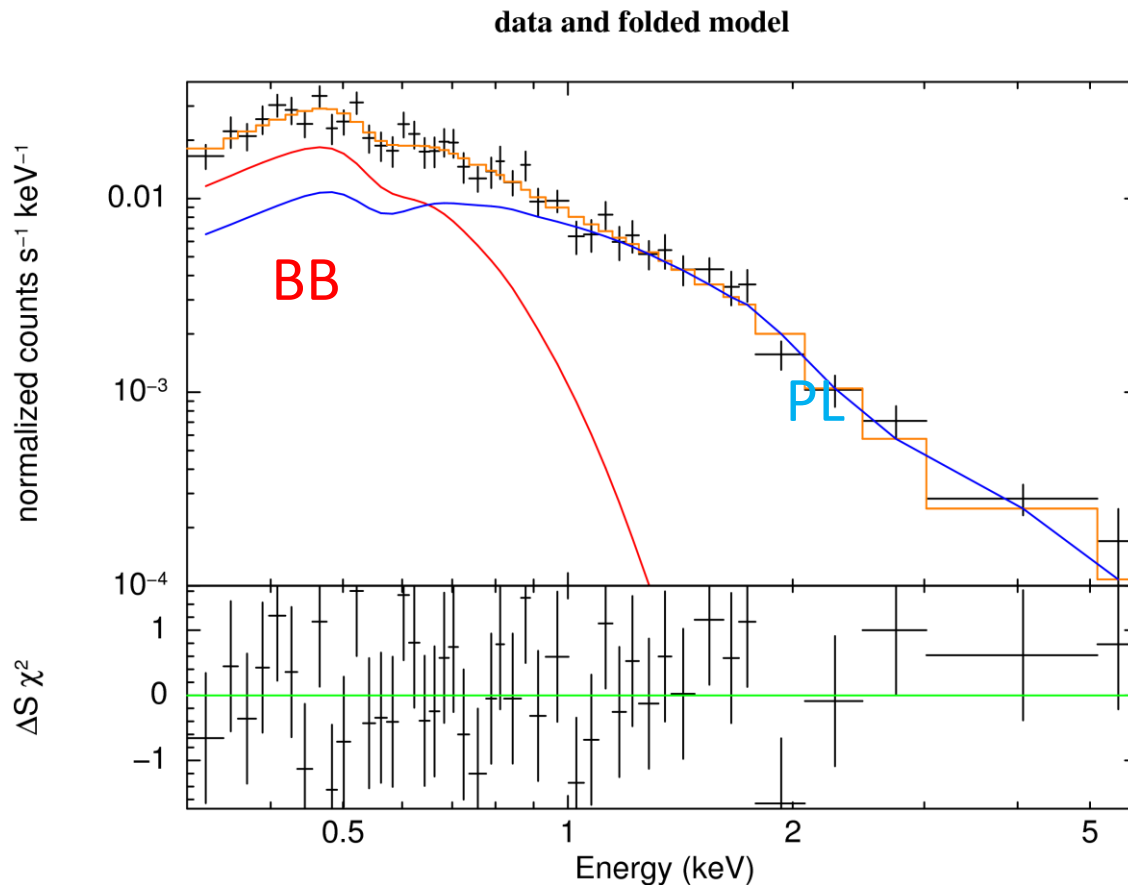
11 AGN \rightarrow Galactic NH
 $2.10 \pm 0.09 \times 10^{21} \text{ cm}^{-2}$

Bright artifacts
due to *X Per*

Pn 130 ks



The XMM view of the PSR counterpart



Pulsation search hampered by time jumps

Composite
BB+PL spectrum

$kT=94\pm 8$ eV
 $R=0.5\pm 0.1$ km

$\Gamma=2.28\pm 0.15$

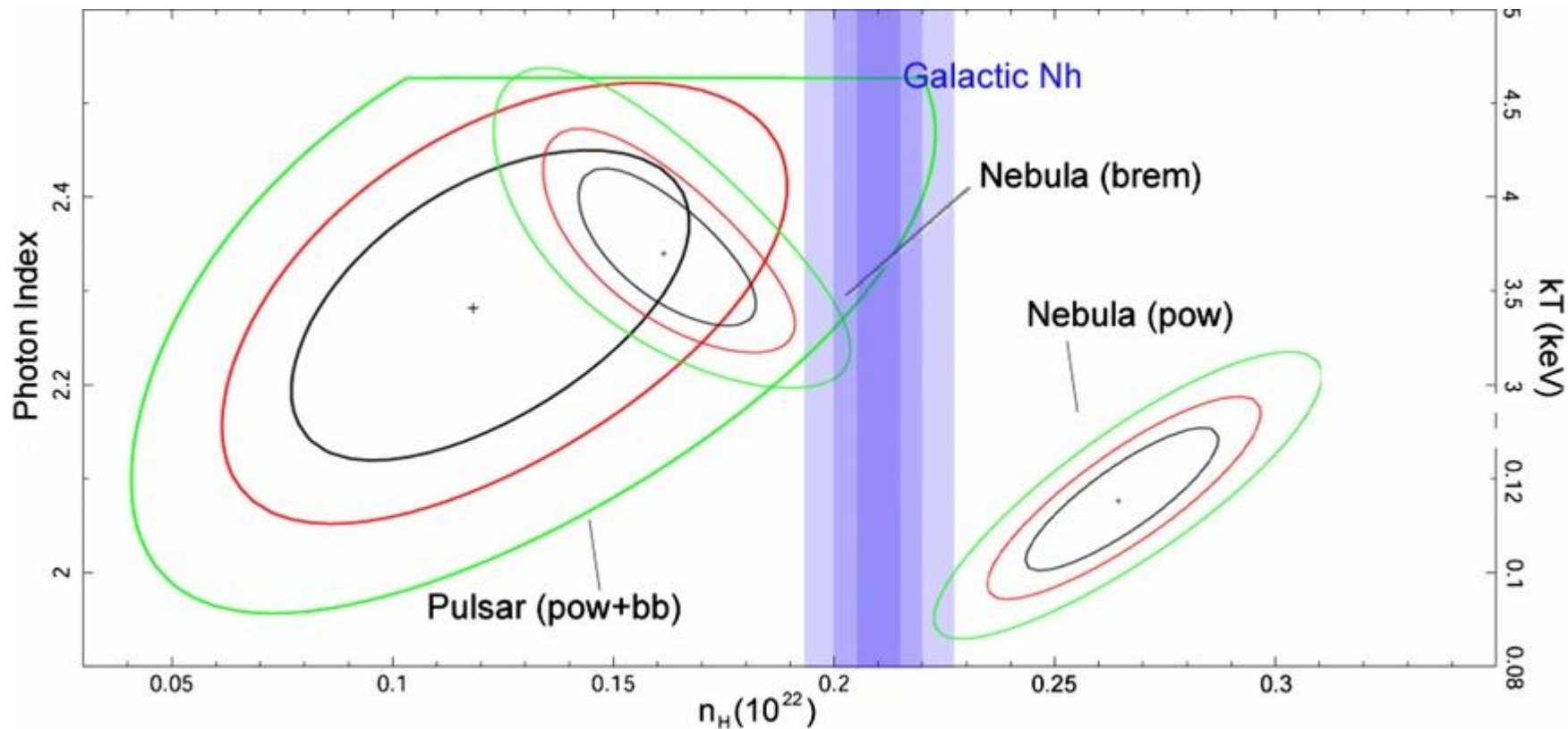
$NH=(1.2\pm 0.4)\times 10^{21}$ cm $^{-2}$

XMM view of the Tail

No hints of spectral
evolution

$\Delta\Gamma < 0.2$ at 3σ c.l.
along both axes

Any issue with the NH?



Non-thermal model for the PWN yields large NH .

Thermal Bremsstrahlung model yields better results

Measuring the proper motion

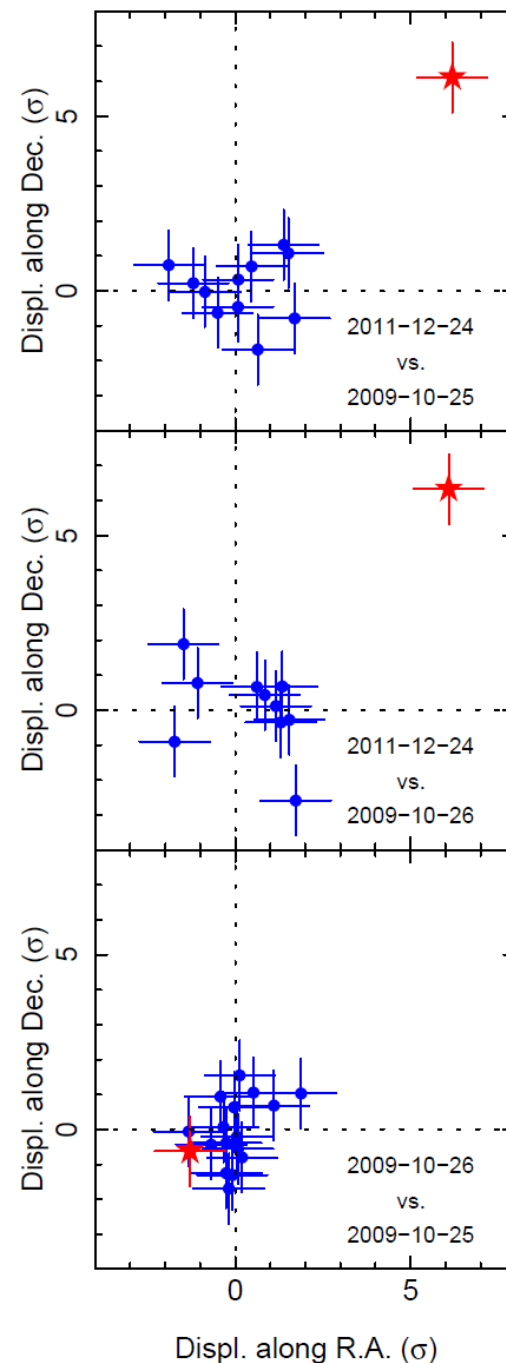
Chandra multi-cycle program

Relative astrometry on field sources
within 4 arcmin from aimpoint

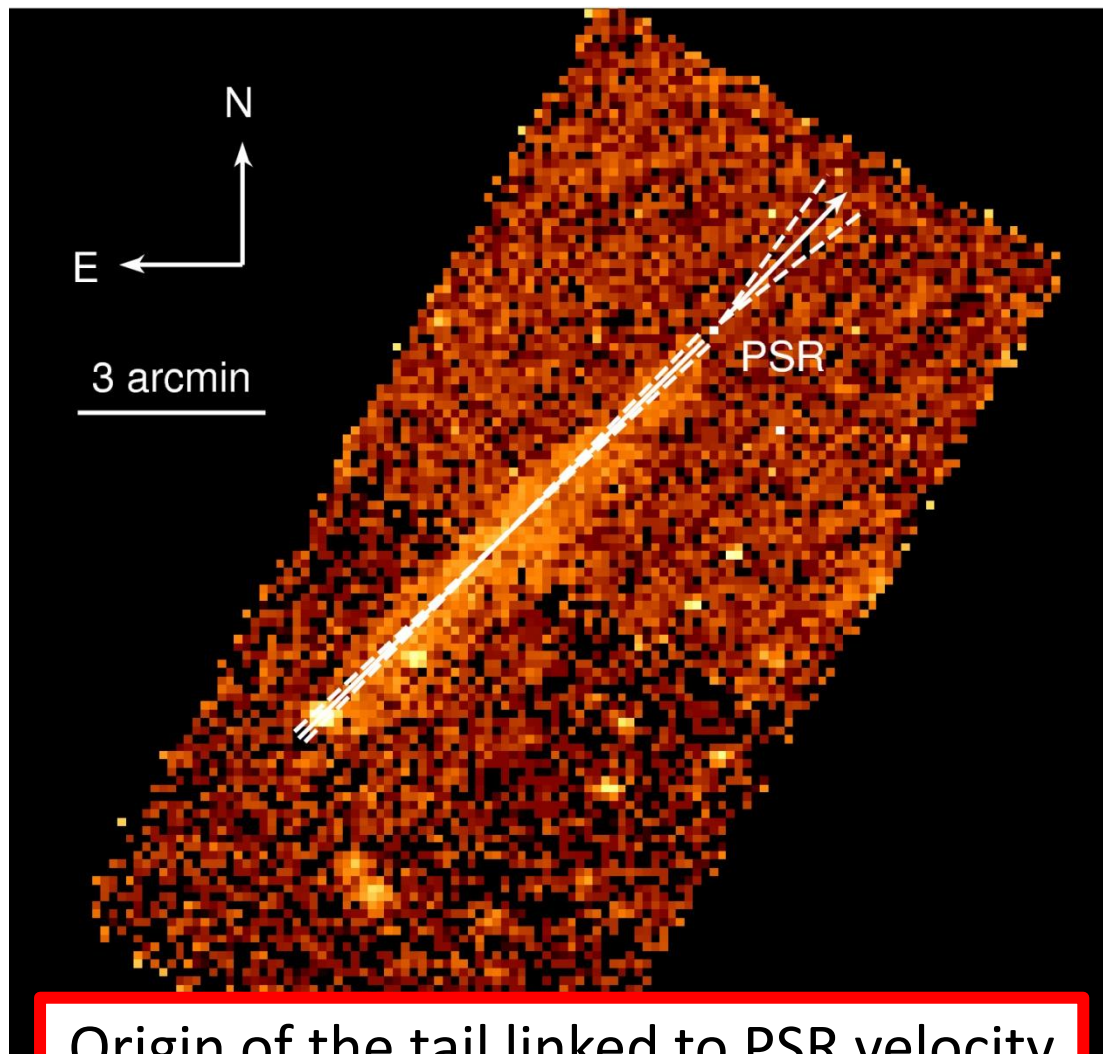
	2011 vs. 2009a	2011 vs. 2009b	2009a vs. 2009b
Time baseline	2.16 yr	2.16 yr	1 day
Number of ref.srscs	11 ^a	10	16
uncertainty on X_{shift} (pixels)	0.09	0.08	0.06
χ^2 (dof)	13.6 (10)	15.6 (9)	7.8 (15)
uncertainty on Y_{shift} (pixels)	0.08	0.07	0.06
$\frac{\lambda}{l}$			13.8 (15)
PSR Y displacement (pixels)	0.54 ± 0.11	0.50 ± 0.10	0.10 ± 0.10
			0.04 ± 0.10

De Luca et al. 2013
ApJ 765 L19

2013 - XMM-Newton Science Workshop



The proper motion of PSR J0357+3205



Origin of the tail linked to PSR velocity

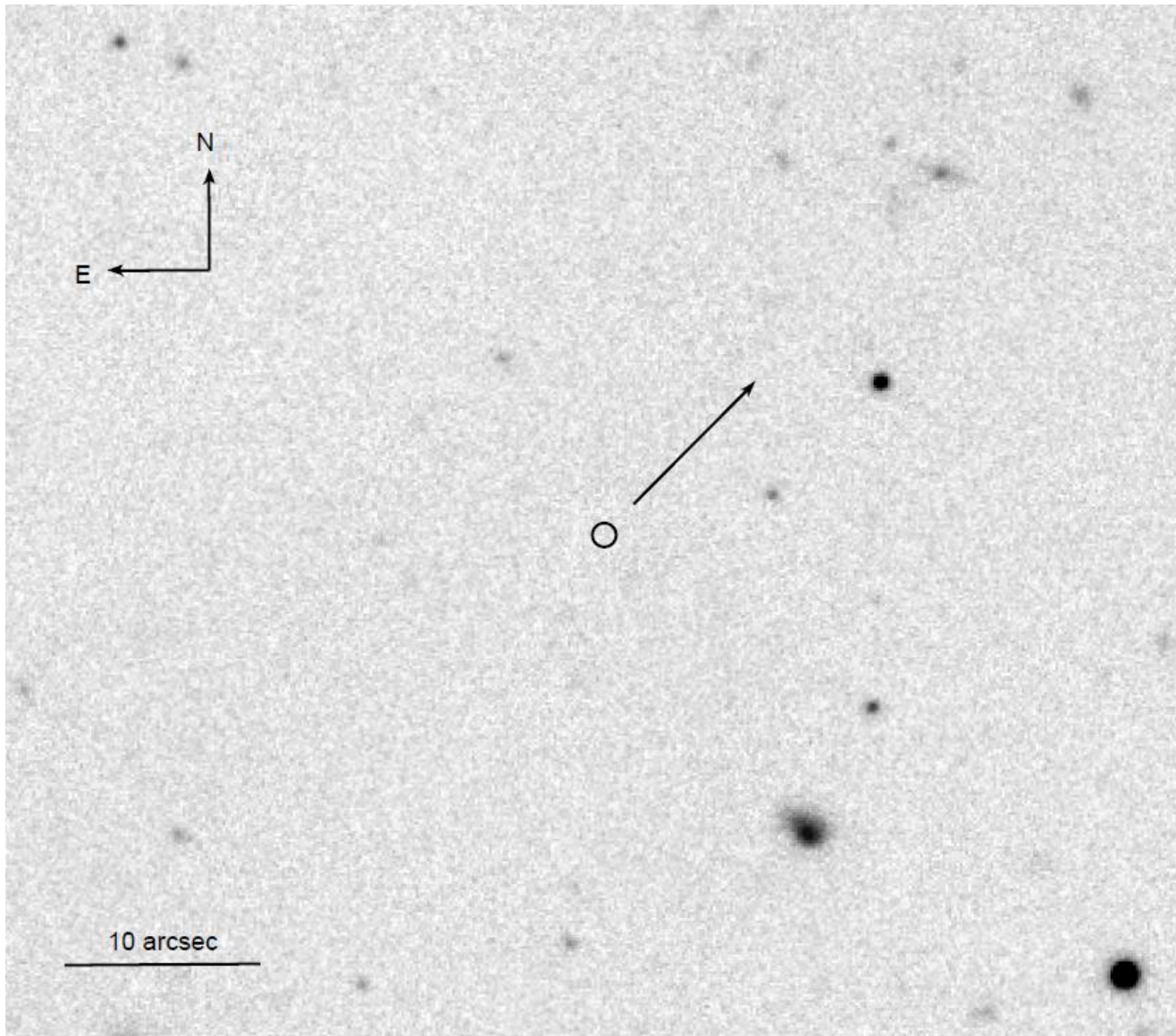
Proper motion
 165 ± 30 mas/yr

Position Angle
 $314^\circ \pm 8^\circ$

PA of tail's axis
 $315.5^\circ \pm 1.5^\circ$

(projected) PSR velocity
390 km/s at 500 pc

No Balmer-dominated bow-shock



Deep observation
with Gemini
telescope in $H\alpha$

Upper limit to
bow-shock
 $5 \times 10^{-18} \text{ erg cm}^{-2} \text{ s}^{-1}$

Neutral fraction
 $X_{\text{ISM}} < 0.01$

De Luca et al. 2013
ApJ 765 L19

Is the trail a ram pressure-confined PWN ?

seems most “natural” explanation for an elongated tail aligned with PSR proper motion

Cons:

- where is the pulsar wind termination shock ?
- how to explain brightness profile?
- ... as well as lack of spatial/spectral evolution?
- any problem with PSR energetics?
- $NH \approx$ inconsistent with PSR

Is the trail a thermally emitting nebula?

- free-free emission from ISM, shock-heated by the fast moving PSR. The first seen example?
- Order of mag estimates: $v_{\text{psr}} \sim 1900 \text{ km/s}$, $d=300\text{-}900 \text{ pc}$, $i=68^\circ\text{-}83^\circ$, $\rho_{0,\text{ISM}} = 0.15\text{-}0.3 \text{ cm}^{-3}$, $T_{0,\text{ISM}} = 1\text{-}9 \times 10^5 \text{ K}$

- ***could explain*** alignment with proper motion
peak away from PSR position (long t_{heat})
lack of spectral evolution (long t_{cool})
NH (vs. PSR and Galactic)

- Cons ?***
- very low metallicity from the fit
 - medium denser than typical hot phase of ISM
 - Morphology of the tail ?

Conclusions

Nature of PSR J0357+3205 trail is puzzling. Possibly thermal?

Population of energetic, nearby PSRs unveiled by Fermi will teach us a lot about pulsar winds and their interaction with the ISM

A new peculiar case from Fermi:

a low- \dot{E} RQ PSR with an 11 arcmin-long tail

Coming soon!