PROBING THE MAGNETIC FIELD, GEOMETRY AND ENVIRONMENT AROUND PULSARS:
AN OBSERVATIONAL STUDY IN THE X-RAY REGIME

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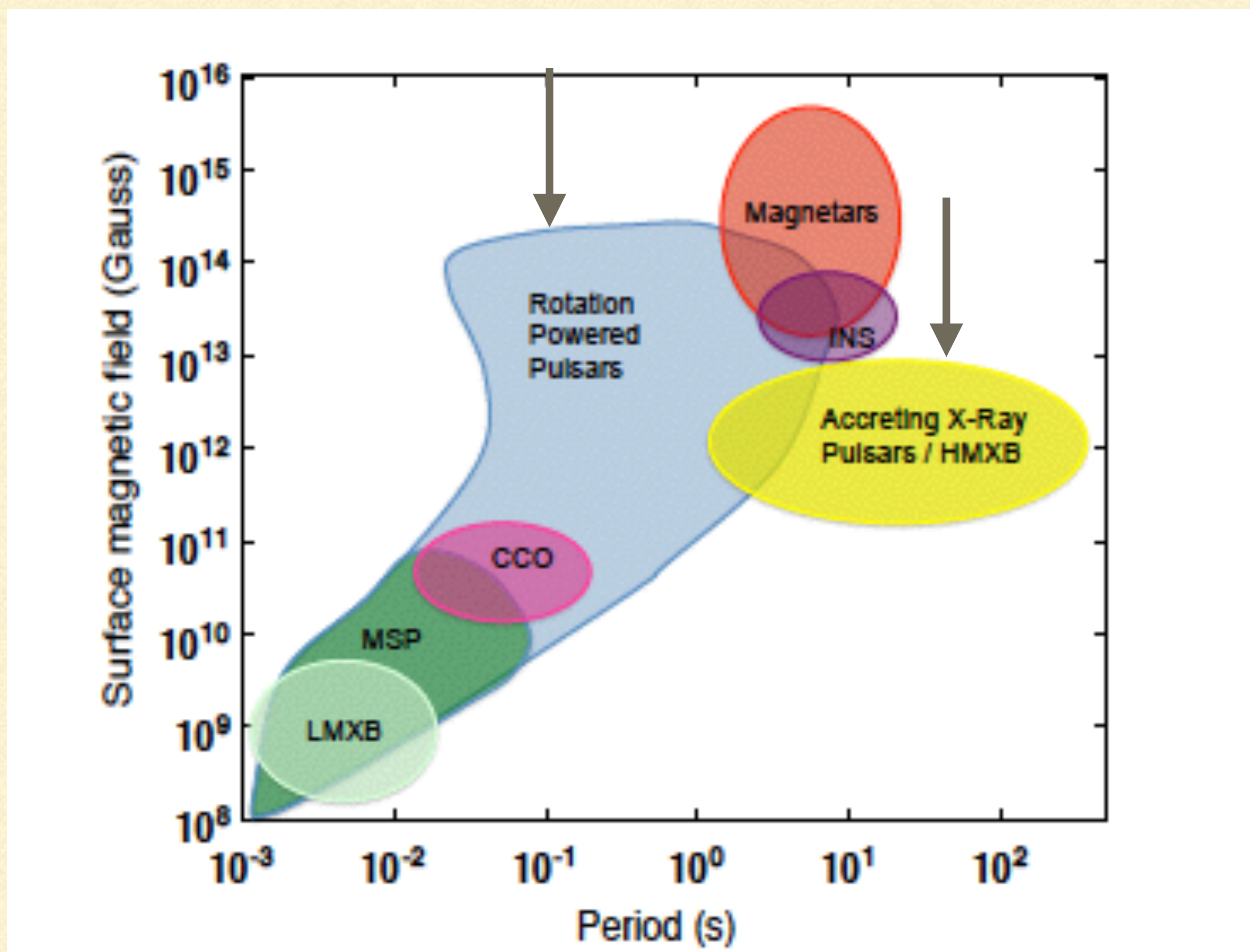
May 2014 onwards Postdoc Jean Ballet

PULSARS

Accretion powered pulsars

Rotation powered pulsars

Magnetars



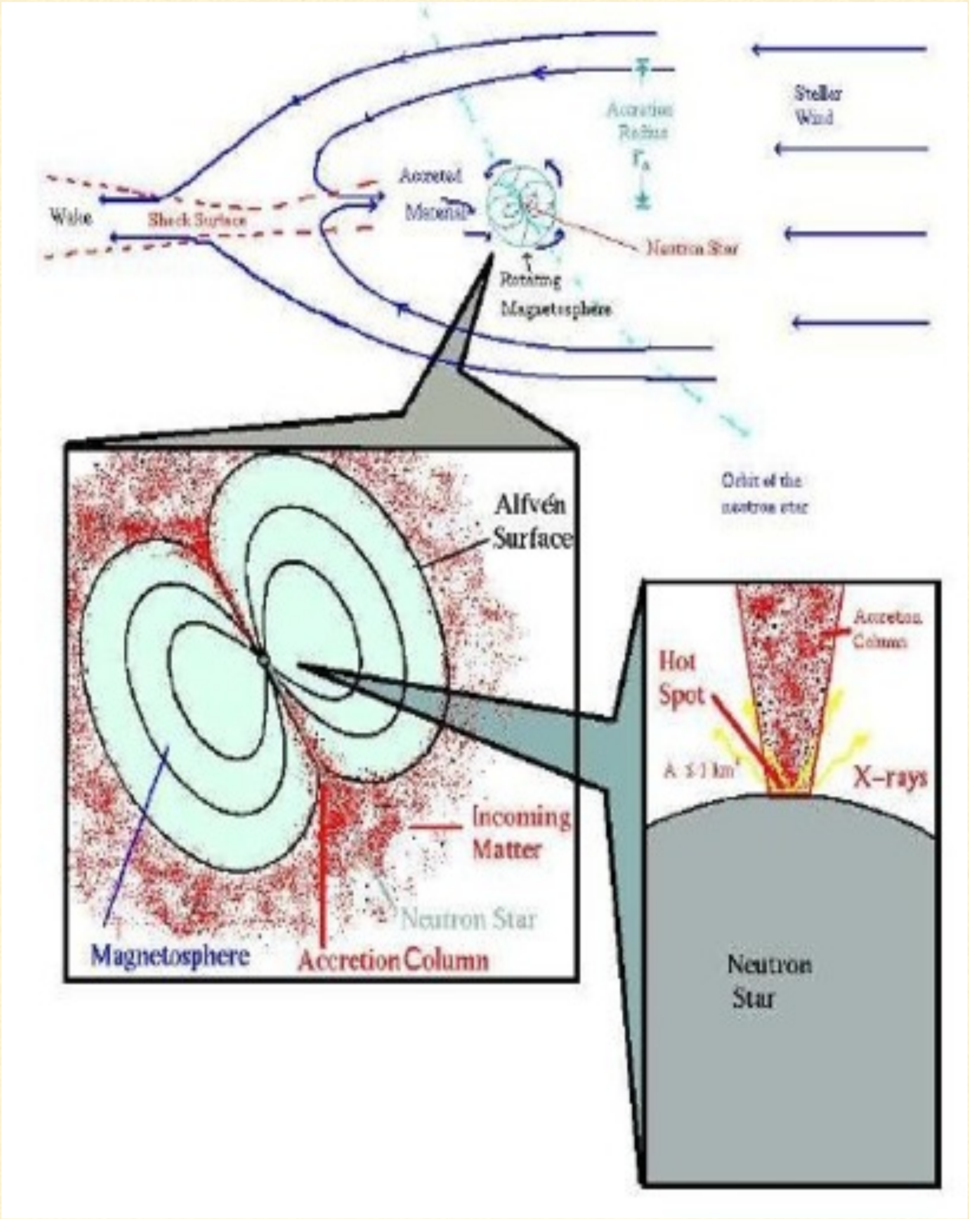
Alice .K. Harding

PhD thesis: High Magnetic Field neutron stars: Cyclotron lines & polarization

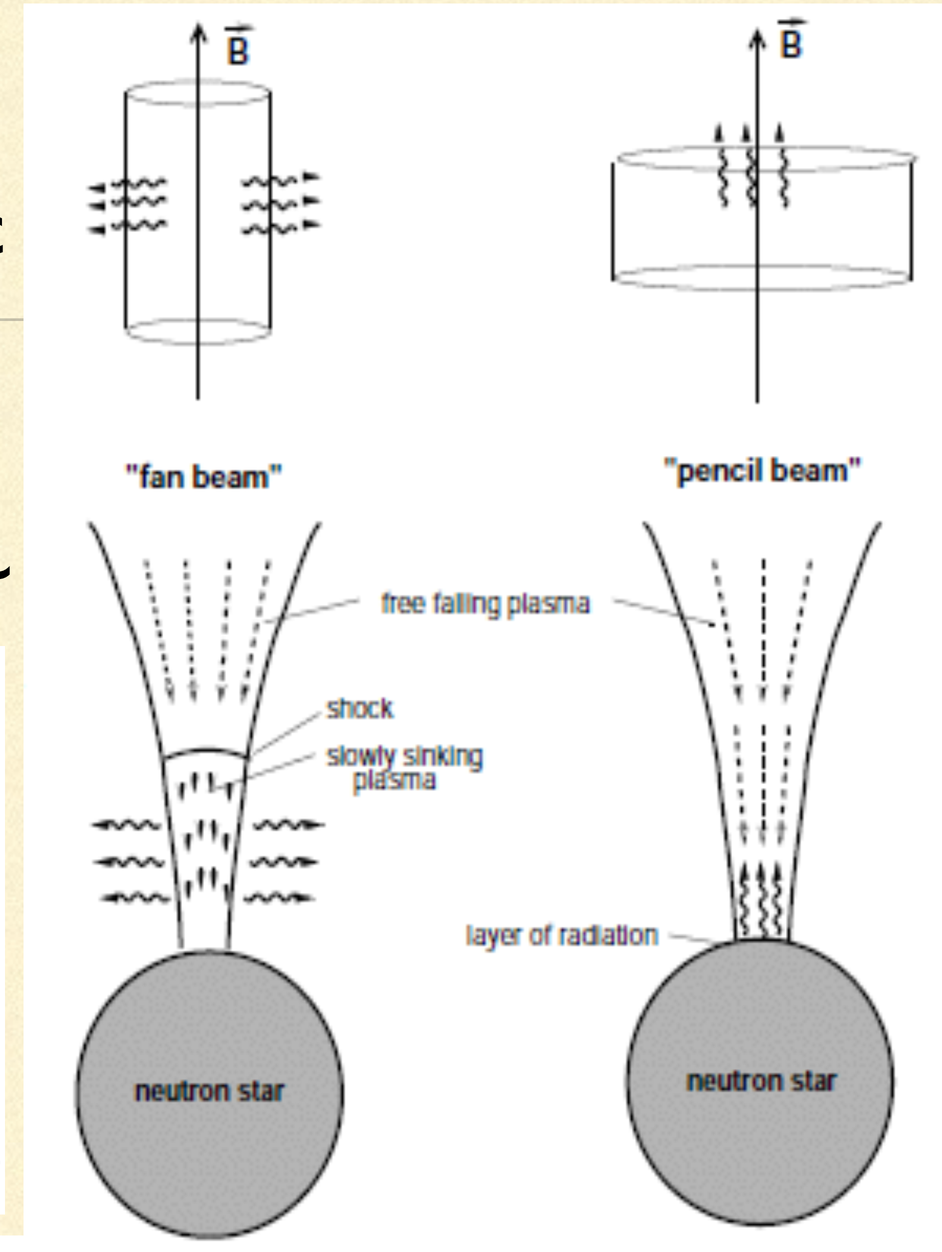
- Energy dependence of pulse profiles of X-ray pulsars to probe the local environment, especially the circumstellar matter
- **Probing the magnetic field and geometry of neutron stars through Cyclotron Resonance Scattering Features**
- Thomson X-ray polarimeter: prospect for compact objects

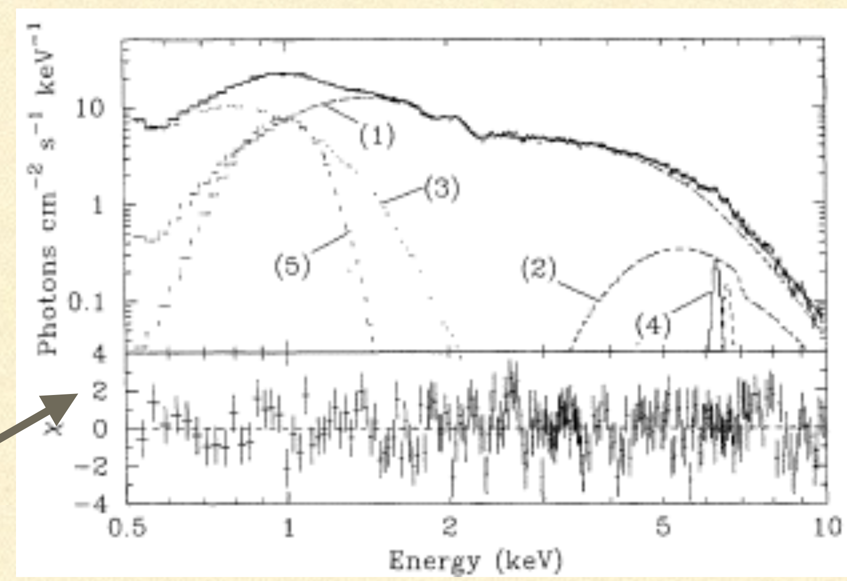
ACCRETING X-RAY PULSARS

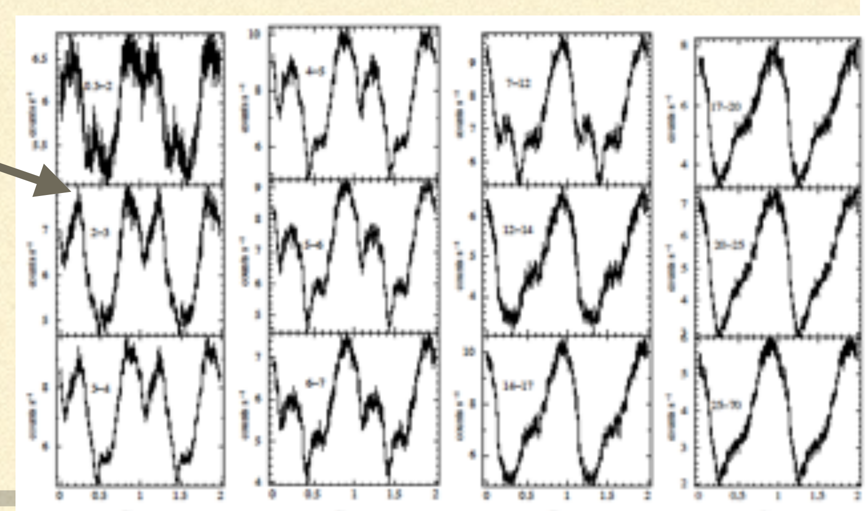
- Strong magnetic field ~ 10^{12} G
- Flow couples to the magnetic field at Alfven radius. : $B^2/8\pi = \rho v^2$
- $R_A = 2.7\times10^8\, \mu_{30}^{4/7} M_{\Theta}^{-1/7} M_{dot17}^{2/7}$ cm
- Channeling of matter along the magnetic field lines

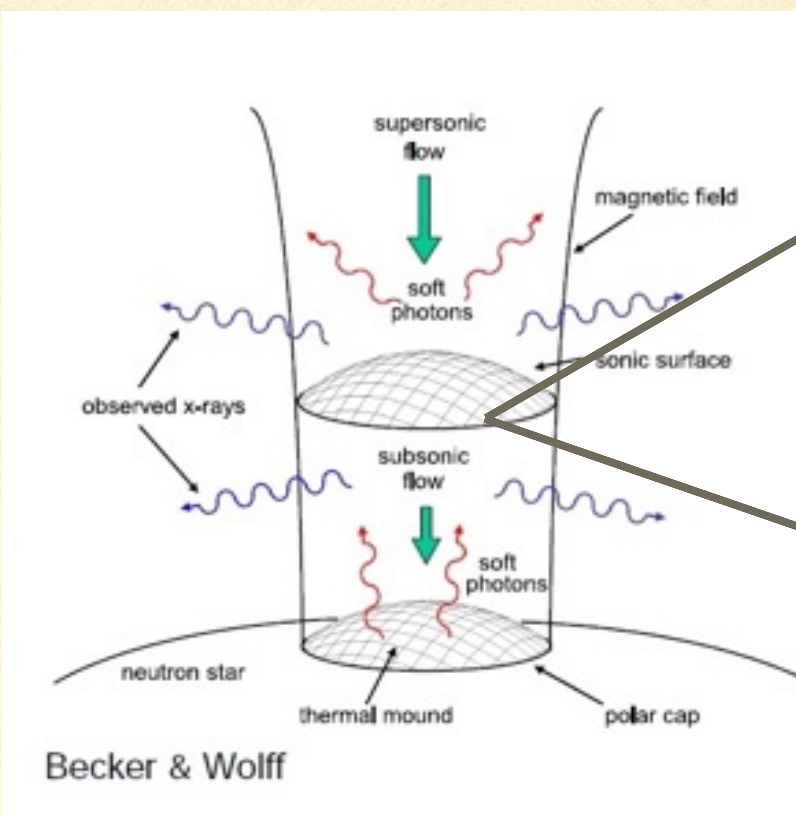


- Free fall along magnetic field lines with v ~0.65 c
- Accreting spot < 1 km^2
- Formation of accretion slab/column of plasma ~ few hundred metres









CYCLOTRON RESONANCE SCATTERING FEATURES

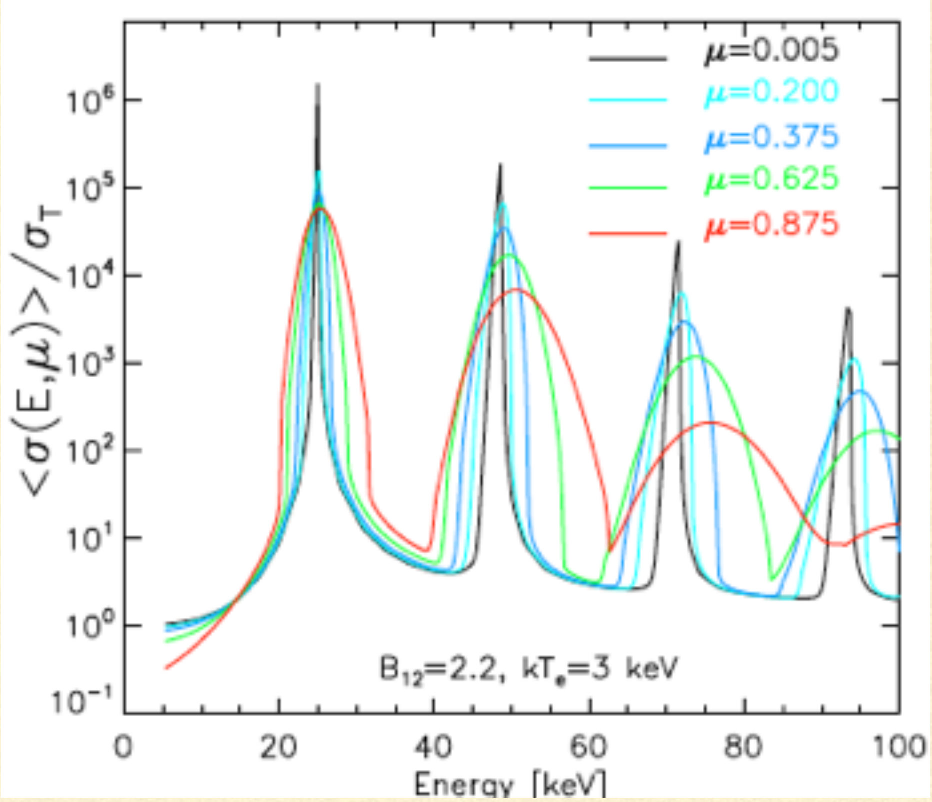
- Continuum X-ray photons resonantly scattered with the quantized plasma electrons forming CRSFs

$$r = \frac{m_e v_\perp}{eB} \qquad \omega = \frac{eB}{m_e}$$

- Quantization of electrons into Landau levels

$$E_n = m_e c^2 \sqrt{1 + \left(\frac{p}{m_e c}\right)^2 + 2n\frac{B}{B_{\rm crit}}}$$
$$\Delta E \approx 11.6\,\mathrm{keV}\,B_{12}$$

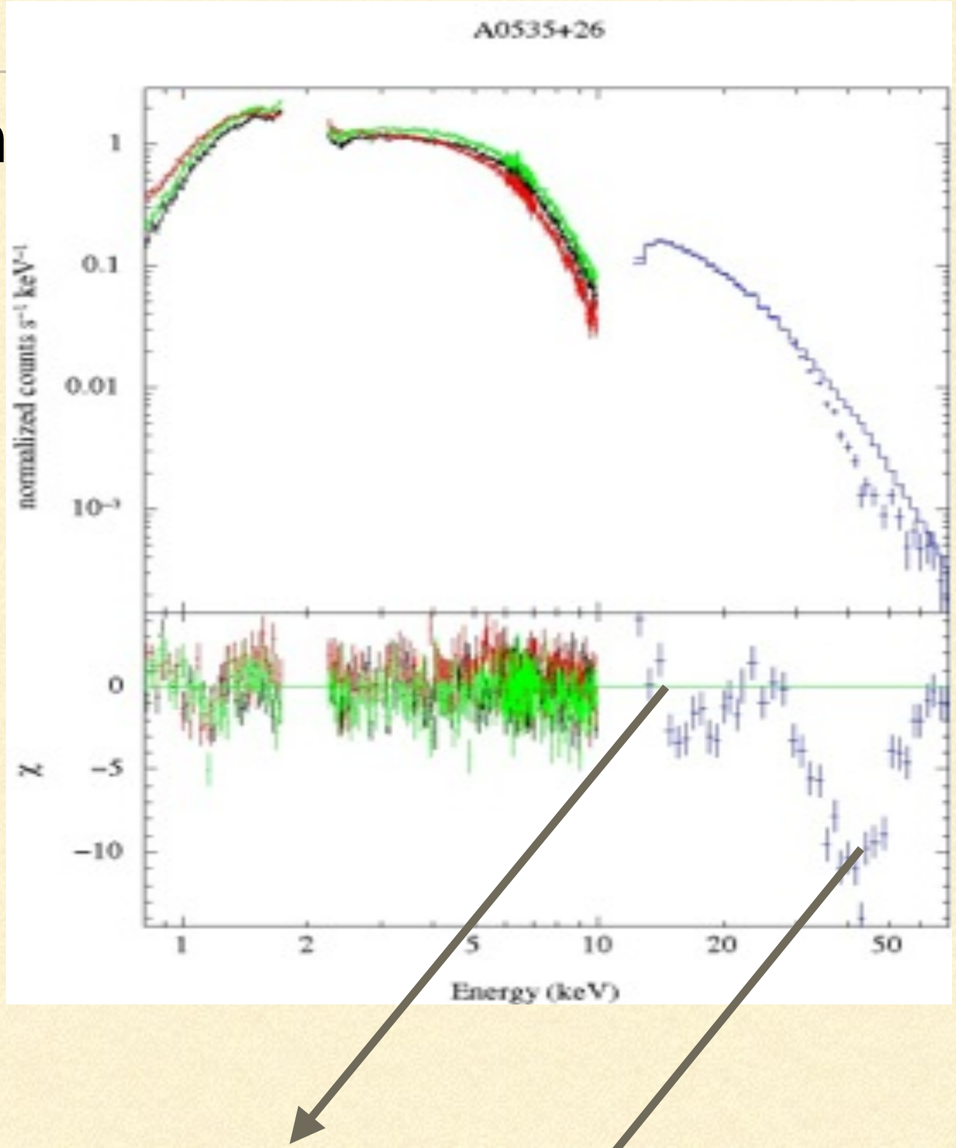
- CRSF cross section depends on KTe, τ of the plasma.
- Also on B, μ (angle between magnetic axis & L.O.S)



Schwarm 2014

CYCLOTRON RESONANCE SCATTERING FEATURE

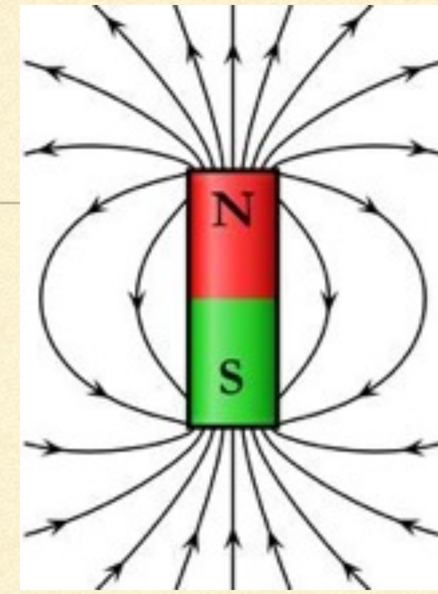
- Broad absorption feature against the continuum
- Continuum modeling is critical to correctly model the CRSF
- CRSF varies with rotation phase of pulsar

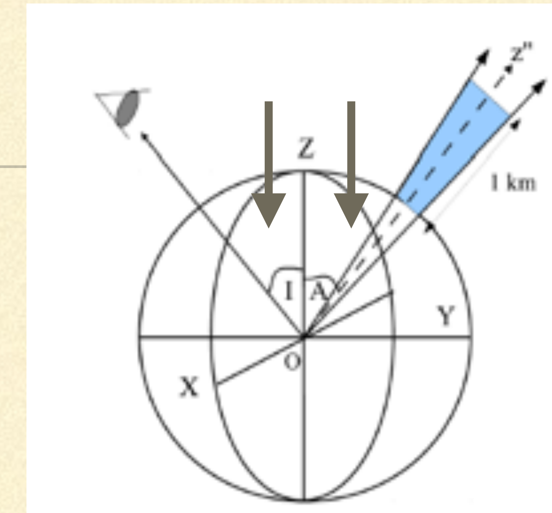


Vela X-1
Residuals left after continuum modeling showing the CRSF features

KEY UNKNOWNS OF THE SYSTEM

- Location of line forming region
- Nature of the continuum emission
- Magnetic field geometry
- Pulsar geometry



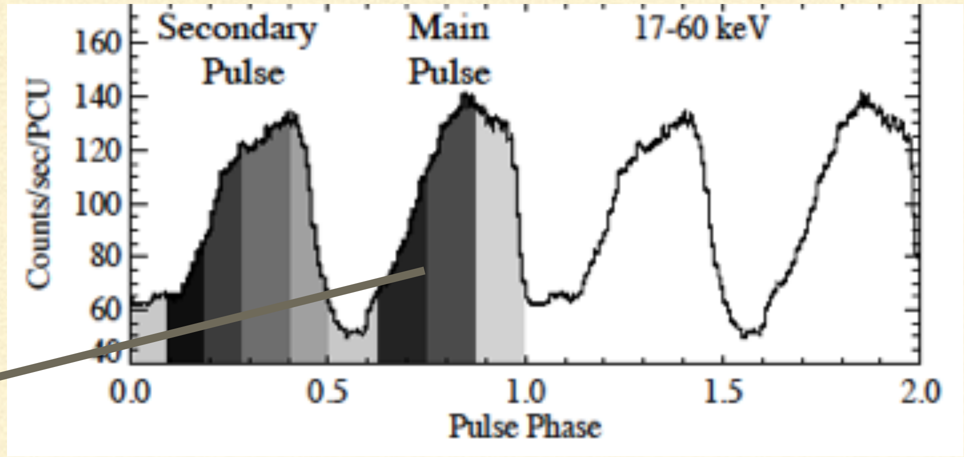


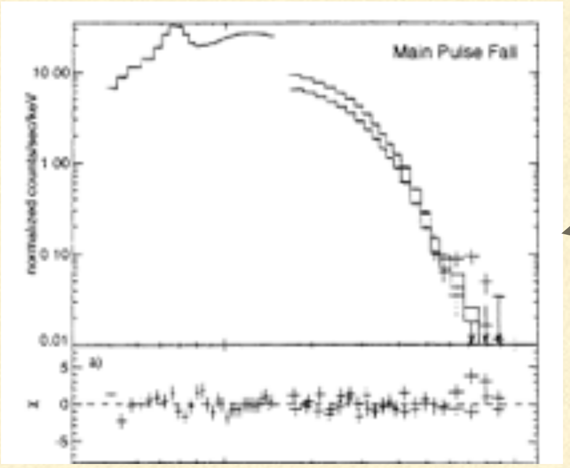
KEY OBSERVATIONAL INDICATORS

- Continuum spectrum and line shapes
- **<u>Pulse phase dependence of the CRSF parameters</u>**
- Harmonic ratio and their variations
- **<u>Beaming profile at different energies, specially around the CRSF</u>**

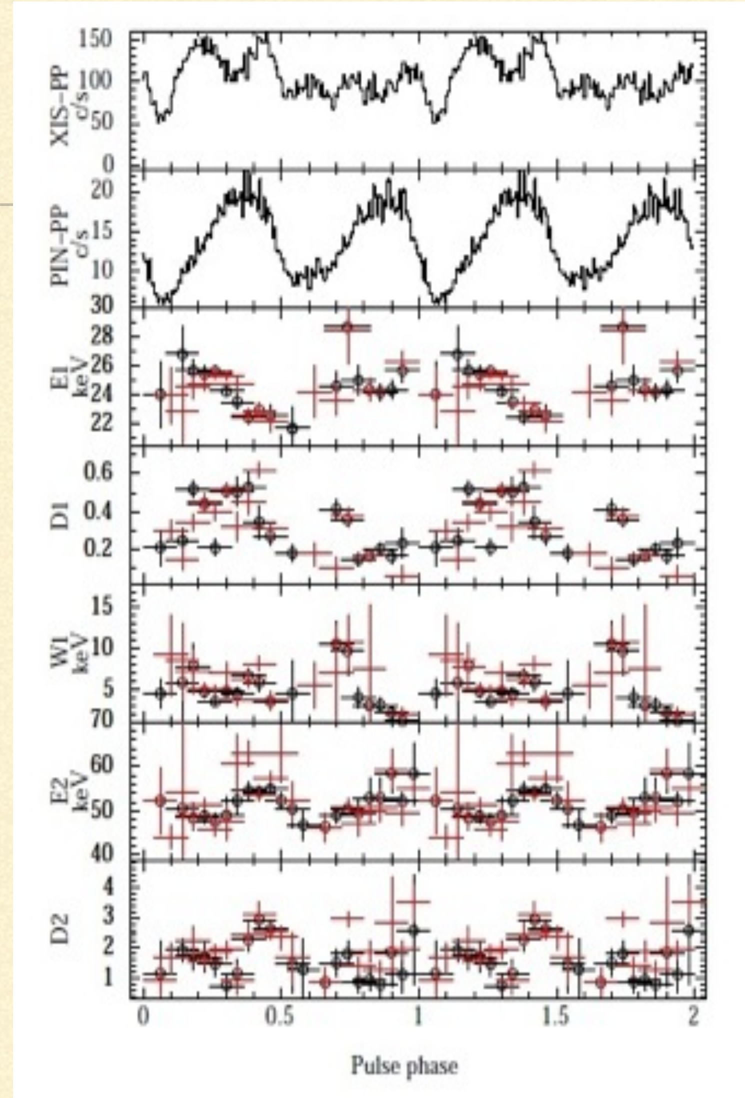
PULSE PHASE RESOLVED SPECTROSCOPY

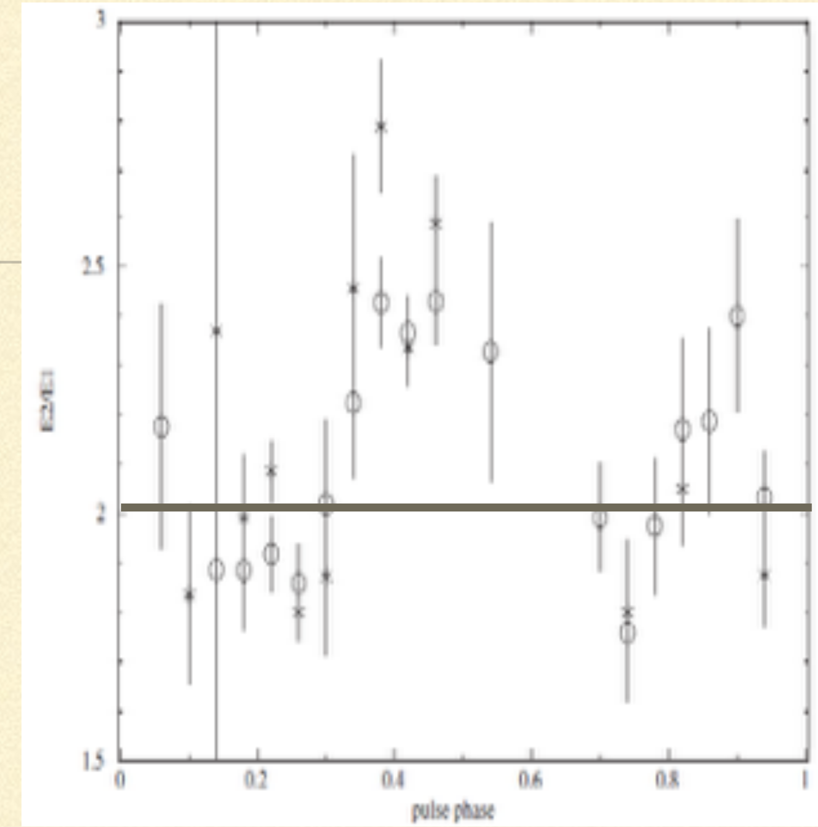
- Cross section viewing angle dependent, variations of few % expected
- Depends on physical parameters of emission region
- Projection of different parts at different angles
- Light bending near the neutron star can dilute the effects

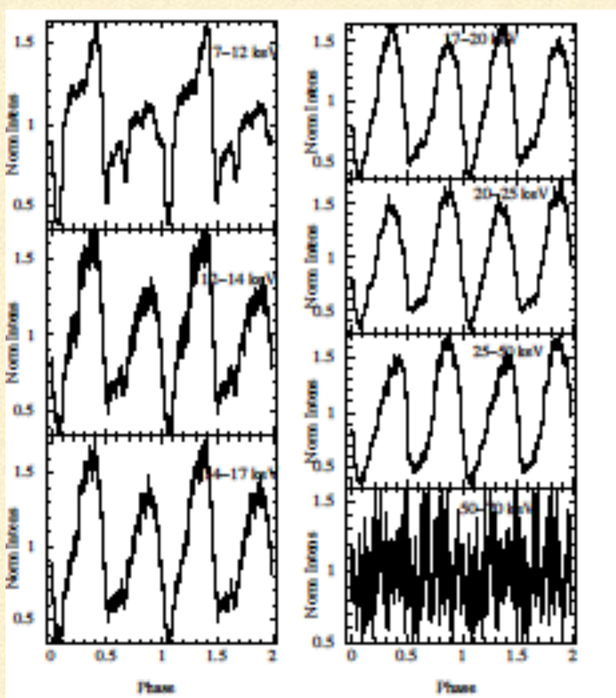


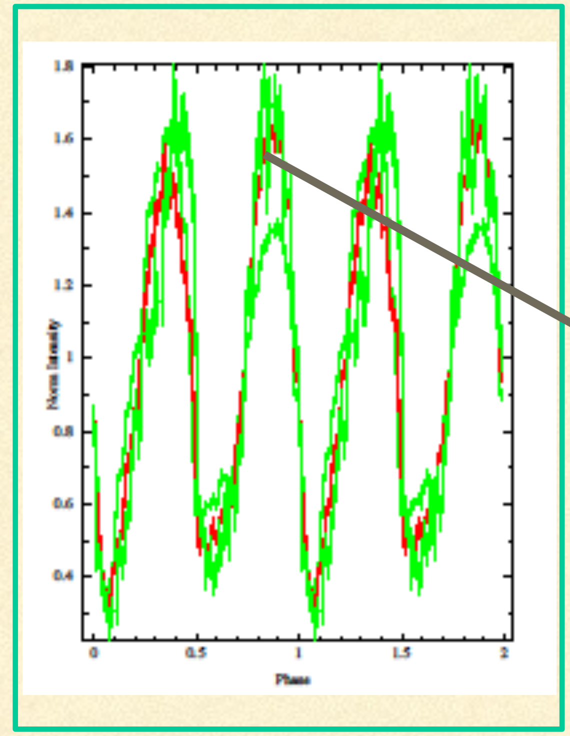


Vela X-1: An illustrative example





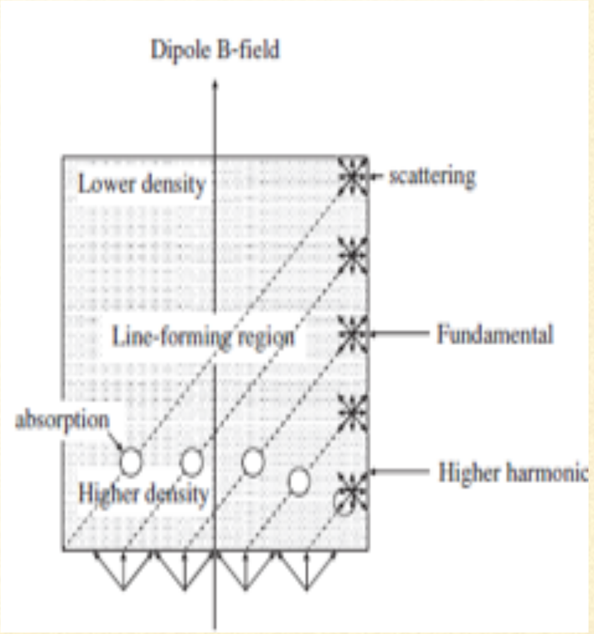


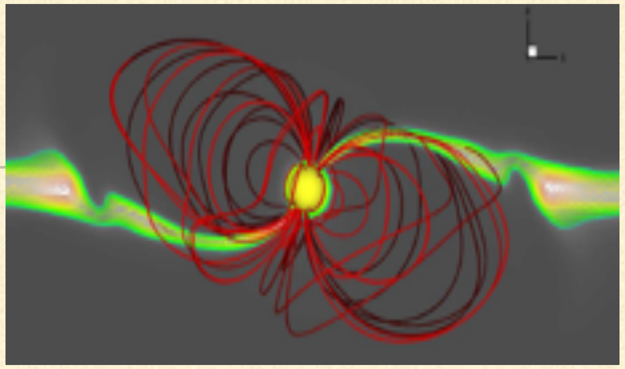


pulse profile at CRSF

RESULTS

- Large variations in CRSF cannot be explained by viewing angles alone
- Requires very large gradient of the parameter space
- Accretion columns several Kms



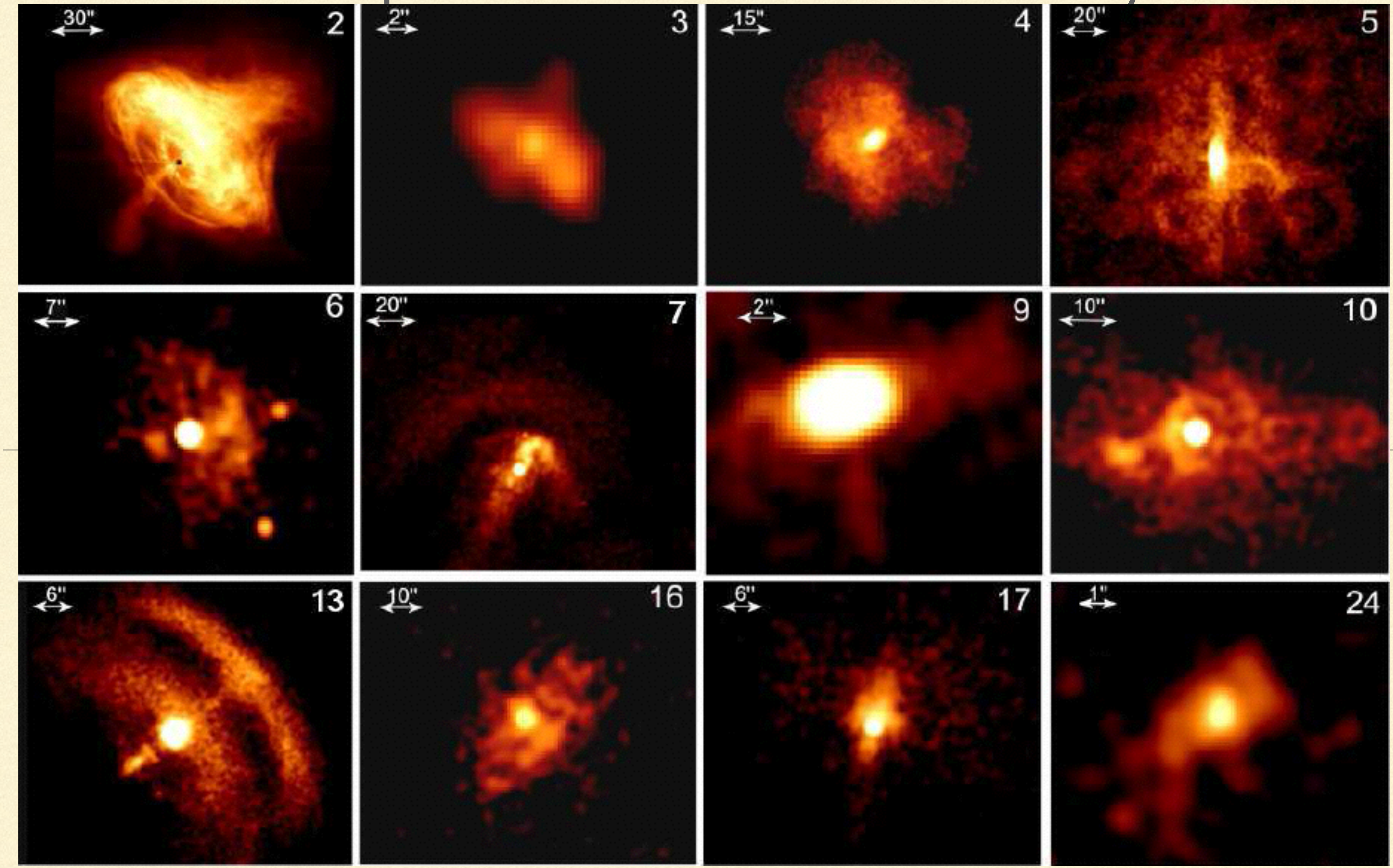


- Results indicates more complex system
- Non dipolar more complex variations from the sharp & large variations in the CRSF energy parameter
- The broad CRSF and its variation indicates superposition of CRSF from several regions
- Pulse phase dependence of the harmonics indicate different parameter space for the above with different components of the B field

ROTATION POWERED PULSAR

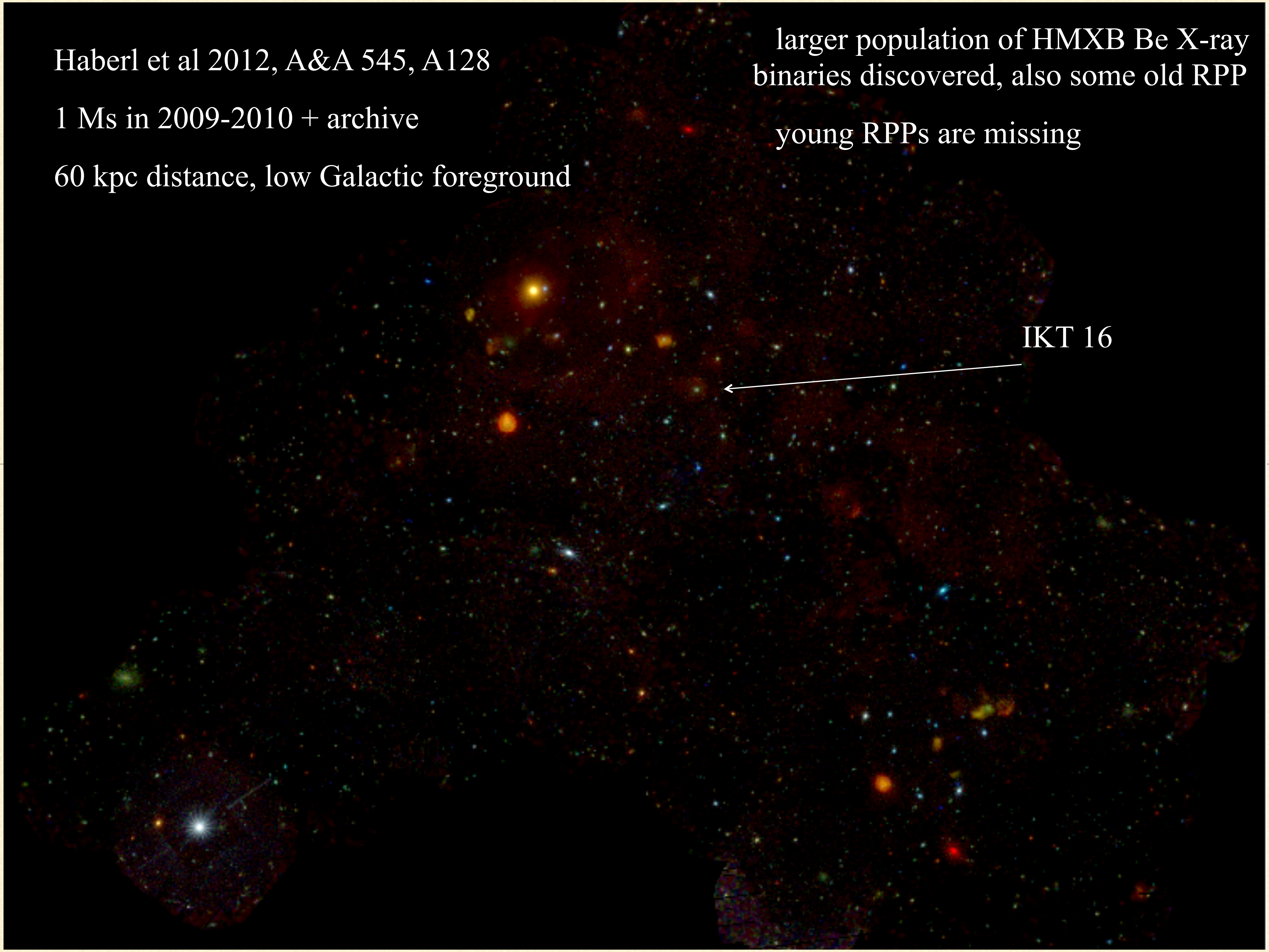
- Most of the spin-down power (~ 90 %) is released via relativistic wind
- Pulsar Wind Nebulae (PWNe) are powered by these relativistic winds of young neutron stars
- ~ 50 PWNe observed in Galaxy & LMC, majority associated with SNRs "**Composite SNRs (Kaspi et al. 2006)**"
- Seen from radio to Gamma rays mostly in radio and X-rays
- Properties of the PWNe provide information on geometry and particle distribution of pulsar wind and as well as the environment which which it interacts

High resolution images from the Chandra X-ray observations opened a new window in the study of PWNe



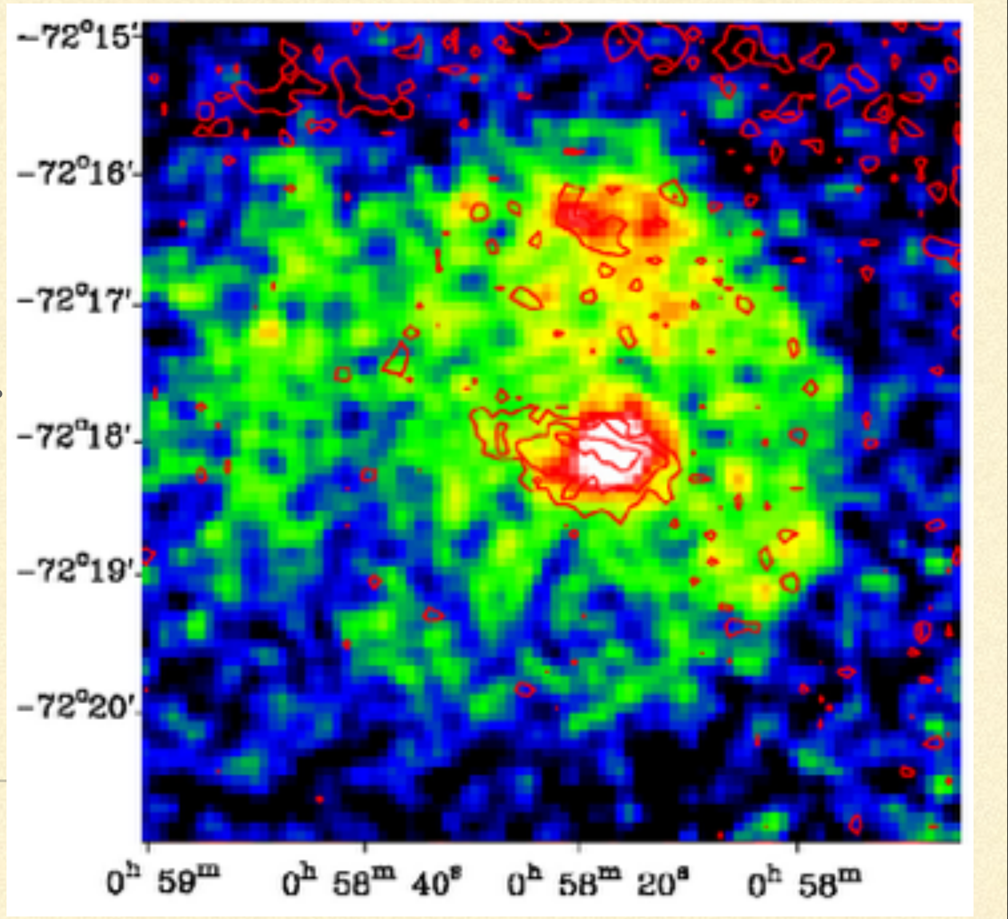
Pavlov & Kargalstev 08

Small Magellanic Cloud:
Confirmation of first PWN IKT 16



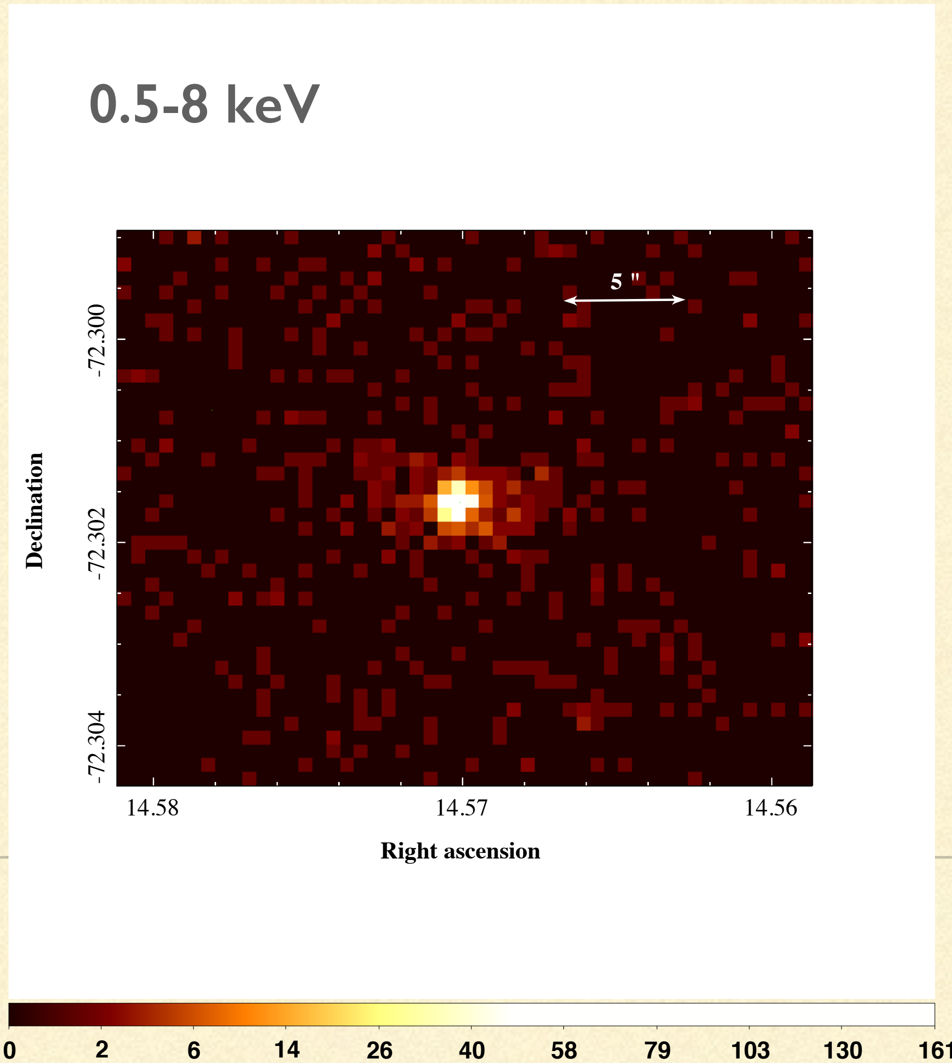
Composite SNR from XMM-Newton Observations

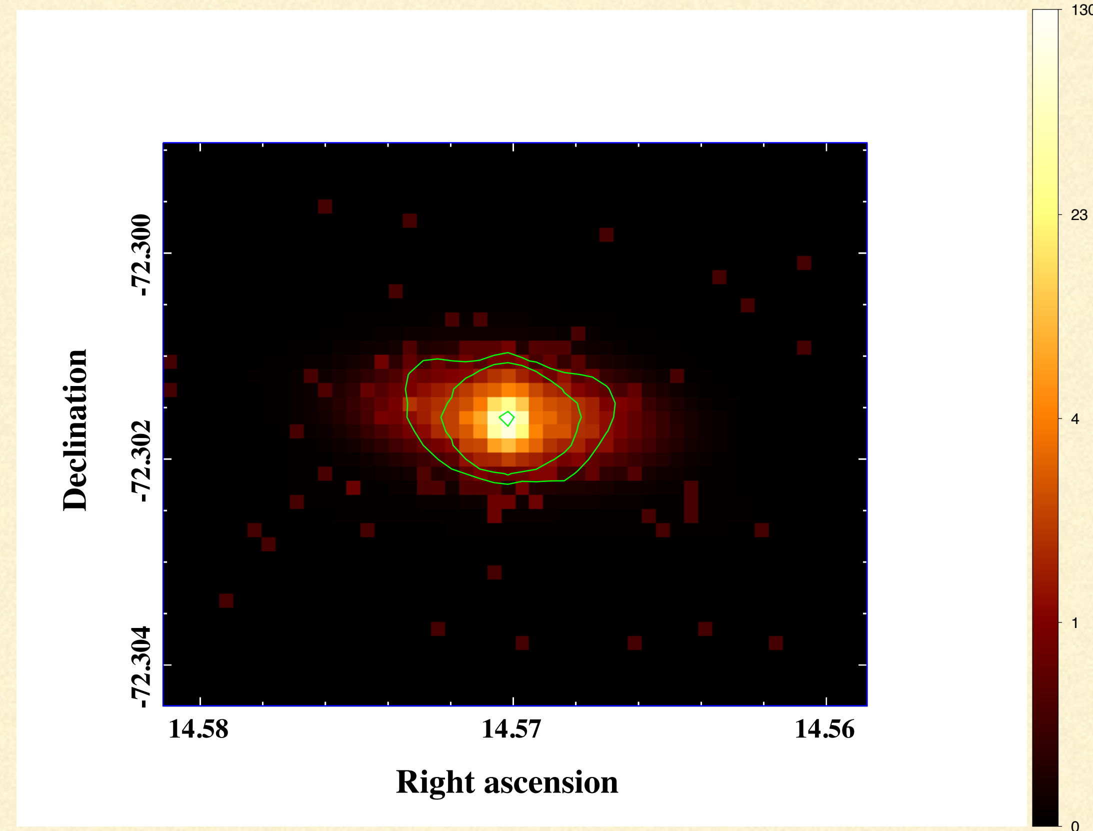
Owen et al. 2011, A&A, 530, A132



- IKT 16 known optical SNR; previously known hard X-ray emission from the centre (Van der Heyden 2004).
- Owen 2011 : Multi-wavelength study of spatial and spectral properties & central source
- No obvious optical counterpart
- Radio images from ATCA and MOST surveys : faint radio structure overlayed on remnant dominated by extended radio emission (40 “”) corresponding to central source , but no known radio pulsar. Radio feature directed towards the SNR
- Offset from the centre by 30 "
- If associated with SNR (t ~ 15 kyr), $V_{psr} \geq 580 \pm 100$ km/s
- **Picture consistent with a pulsar moving inside the SNR in Sedov phase:**
- **Evidence for first PWN in SMC: IKT 16 an composite SNR**

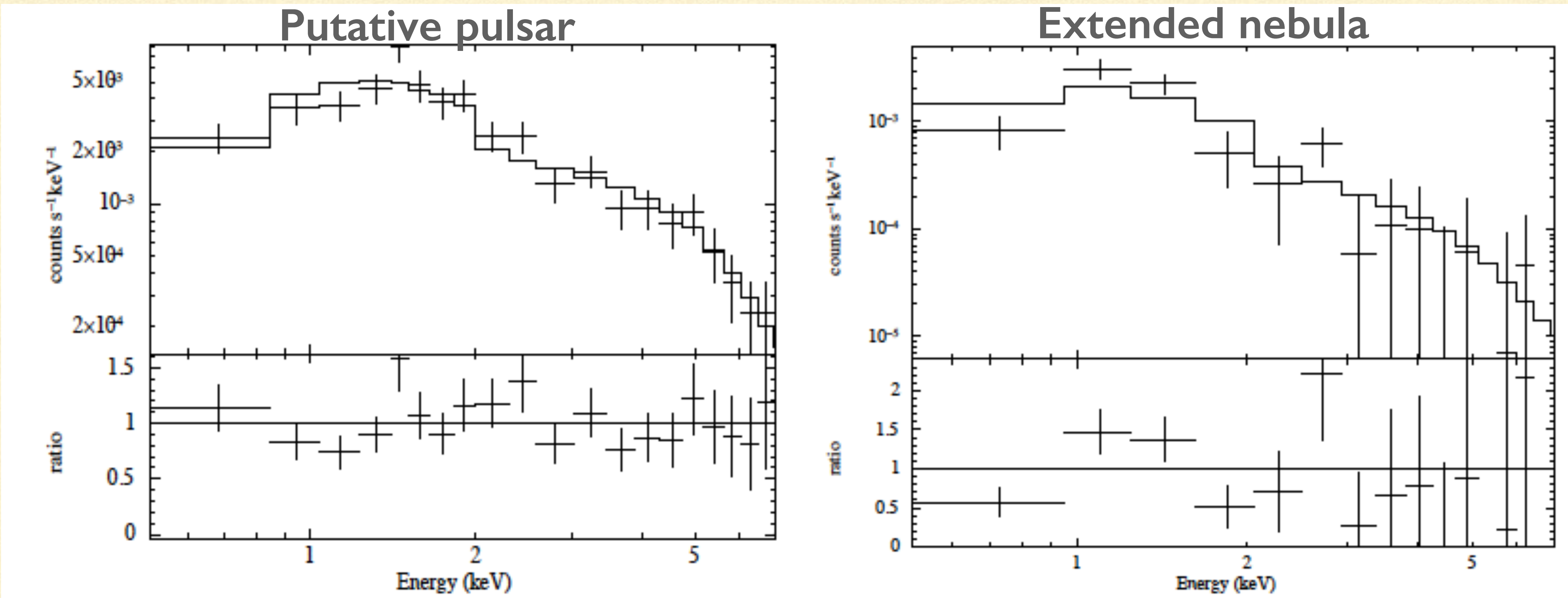
On-axis Chandra observation 38.5 ks



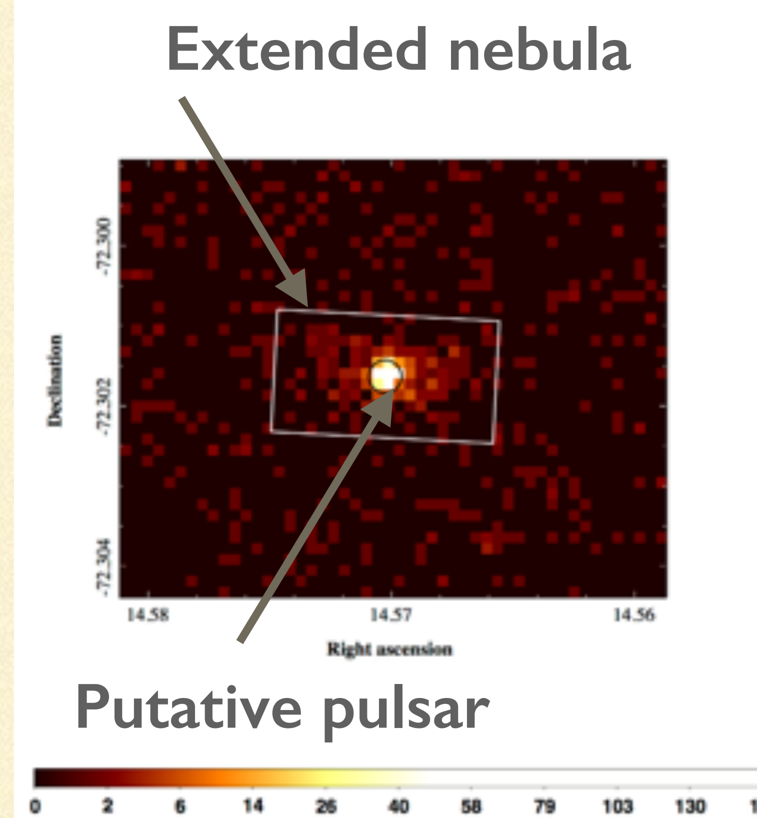


- Image shows elongated feature centered on point source
- Point source 3 times brighter, no offset between the point source & extended emission
- Modelling with point source (simulated PSF) + 2D Gaussian
- FWHM = 5.2 ± 1 " , e = 0.6 ± 0.1 for the morphology, source extent 1.5 pc at SMC distance
- Aligned with the radio feature

Spectrum

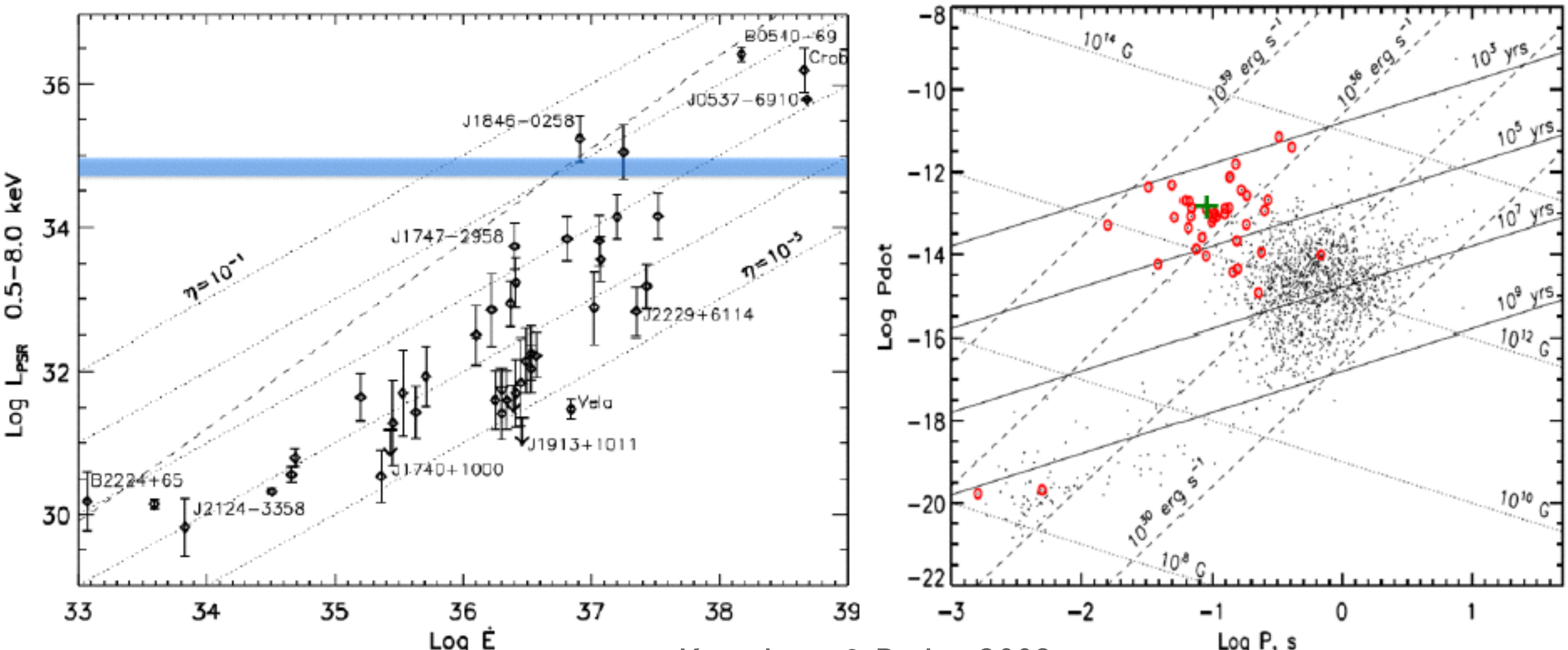


IKT 16	SMC N_H $10^{21} cm^{-2}$	Index	Flux ergs cm^{-2} s^{-1}	Unabs. L_x ergs s^{-1}
Extended nebula	3.4 (fixed)	$2.21^{+0.38}_{-0.37}$	2.1×10^{-14}	1.19×10^{34}
central point source	$5.28^{+0.39}_{-0.35}$	$1.10^{+0.23}_{-0.22}$	1.58×10^{-13}	7.20×10^{34}



- Point source much **harder** than the extended nebula
- To look for radial steepening of the spectral index, compared the spectrum of the inner and outer part of the extended nebula.
  No spectral steepening detected
- **No east-west asymmetry** detected in the nebular emission.

Inferred properties of the putative pulsar



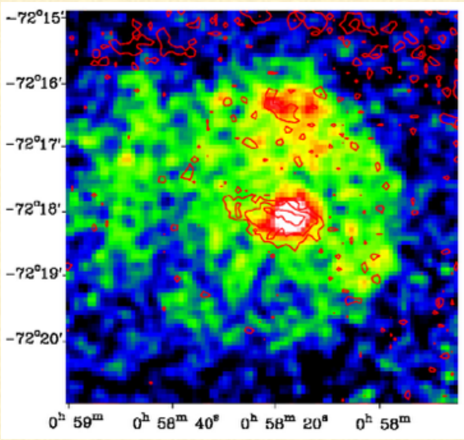
Kargaltsev & Pavlov 2009

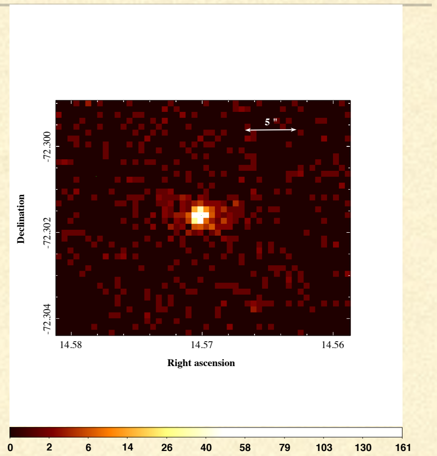
X-ray luminosity of pulsars vs spin-down power, L_x pulsar : blue band

P-Ṗ diagram from the ATNF catalog, assuming SNR age, pulsar shown in green cross

- IKT 16 inferred to host a energetic pulsar with $\dot{E} \sim 10^{37}$ erg s^{-1} (Left)
- pulsar expected to spin < 100 ms with $\dot{P} \sim 10^{-13}$ s s^{-1} (Right)
- Expected to host the youngest and energetic pulsar ever detected in SMC.

SUMMARY





- the central hard emission from IKT 16 can be resolved into a symmetrical elongated feature centering the point source 1.5 pc in extent & aligned with the radio feature

- Morphology of IKT 16 consistent with pulsar moving subsonically inside SNR, and the feature in radio is the "Relic PWN" which has been moved aside by reverse shock (Swarluv 2003, Gelfand et al. 2009)

- The putative pulsar is brighter than total nebular emission (not very common) and very hard spectrum.

- Point source with non-thermal dominated spectrum? alternately, presence of a compact nebula unresolved at the distance of SMC cannot be ruled out

ACTIVITIES AS PART OF THE XMM-SSC

XMM-NEWTON

ESA mission launched in 1999

Six science instruments on-board operated simultaneously

- European Photo imaging camera (EPIC): 3 CCD cameras; 2 different kinds
- 2 MOS CCD cameras and one PN (wide F.O.V 30 ‘, 0.5-15 keV, angular PSF 6 " FWHM)
- 2 Reflection grating spectrometers: high resolution X-ray spectroscopy
- Optical monitor : UV/optical imaging & grism spectroscopy

LOW ENERGY NOISE ON MOD CCDS

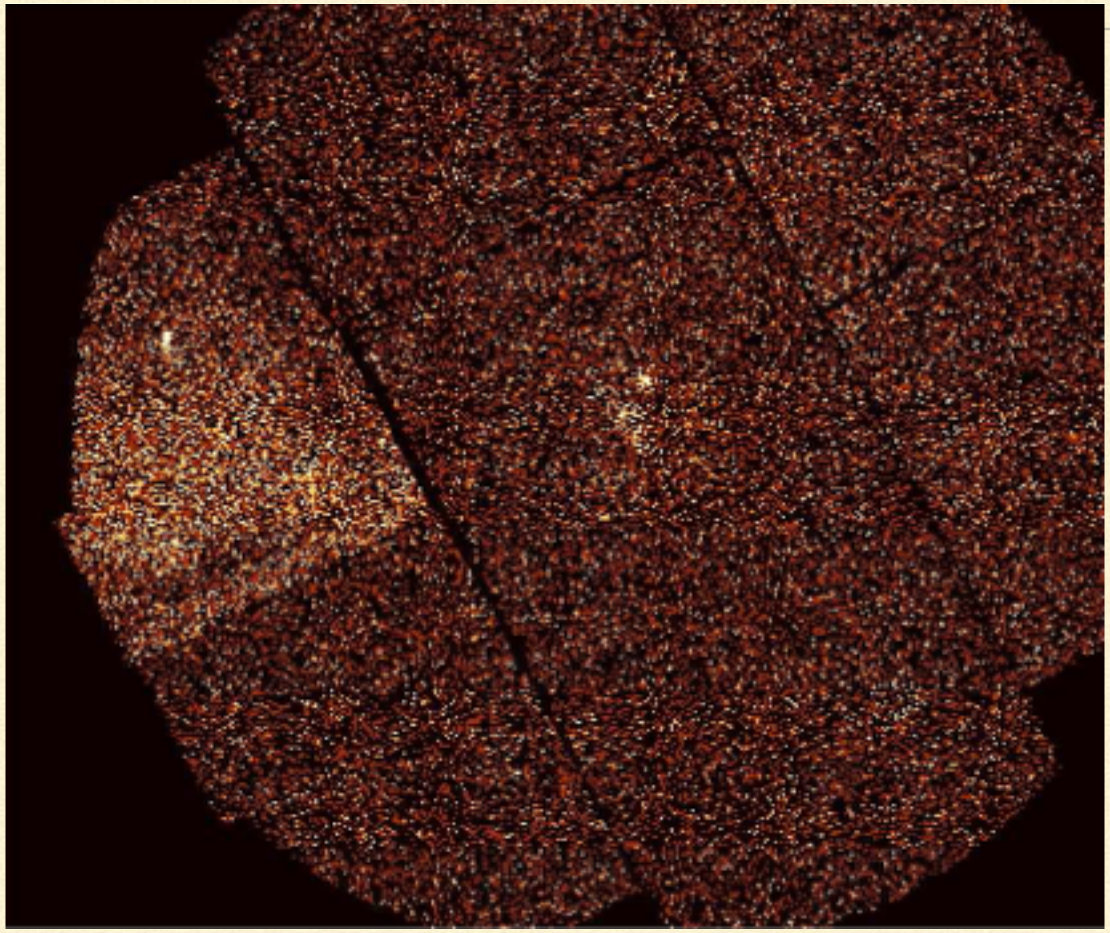
a.k.a anomalous state in CCDs (Kuntz & Snowden 2008)

Time variable component in the EPIC-MOS non-cosmic particle background

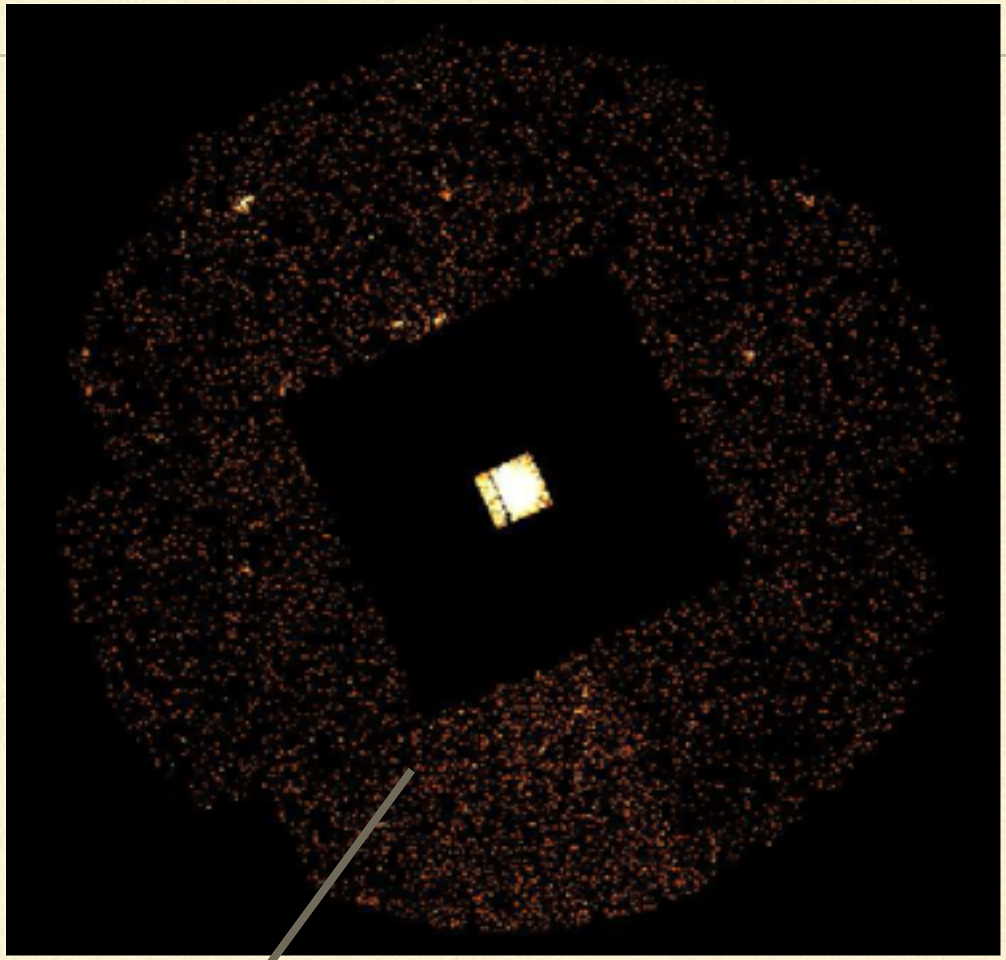
Enhanced total count rate and **low hardness ratio.**

Most affected **MOS 2 CCD 5** and **MOS 1 CCD 4** but found in other CCDs as well.

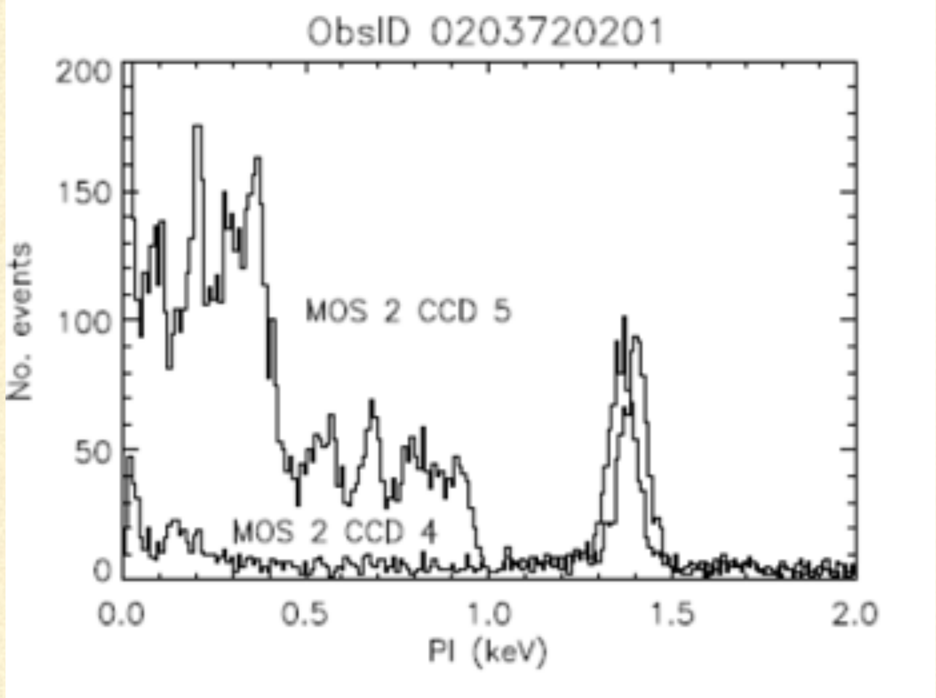
No correlation with radiation monitor or HK parameters found exact cause unknown.



MOS1 CCD 2



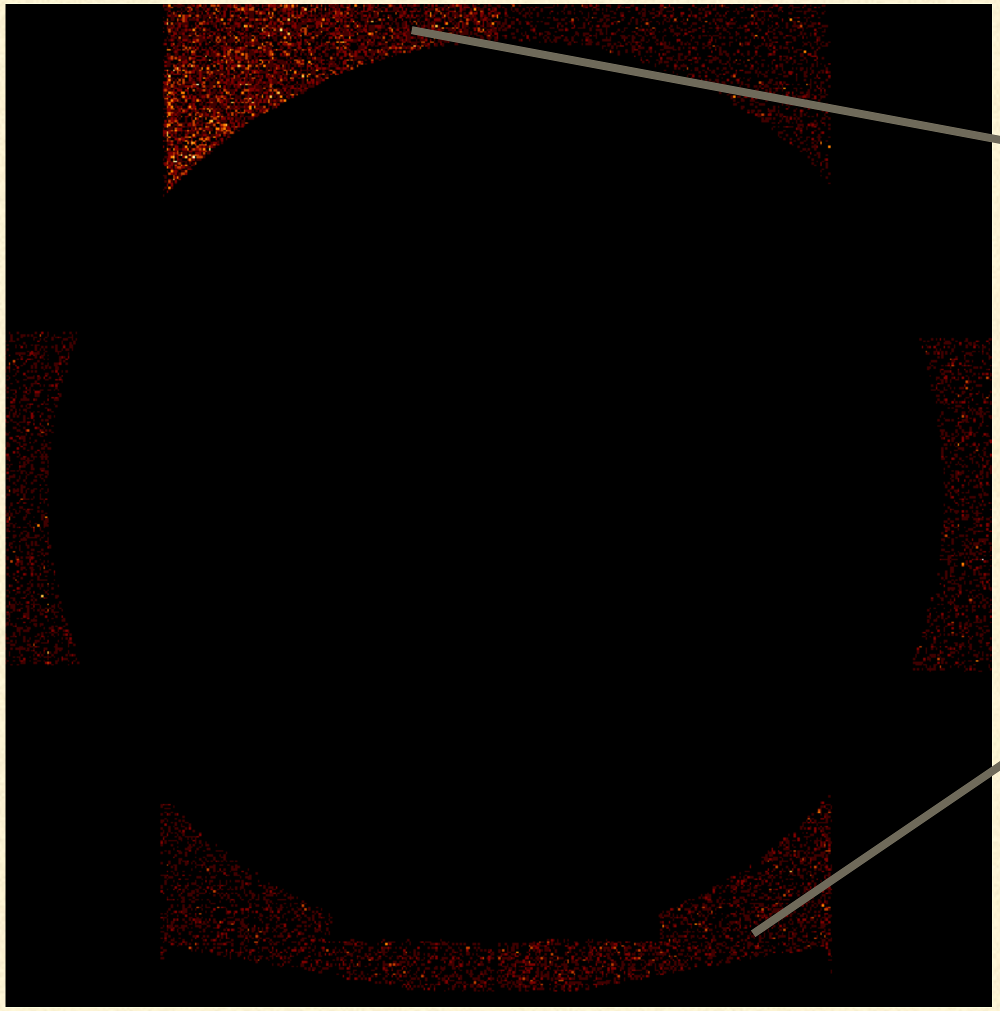
MOS 2 CCD 5

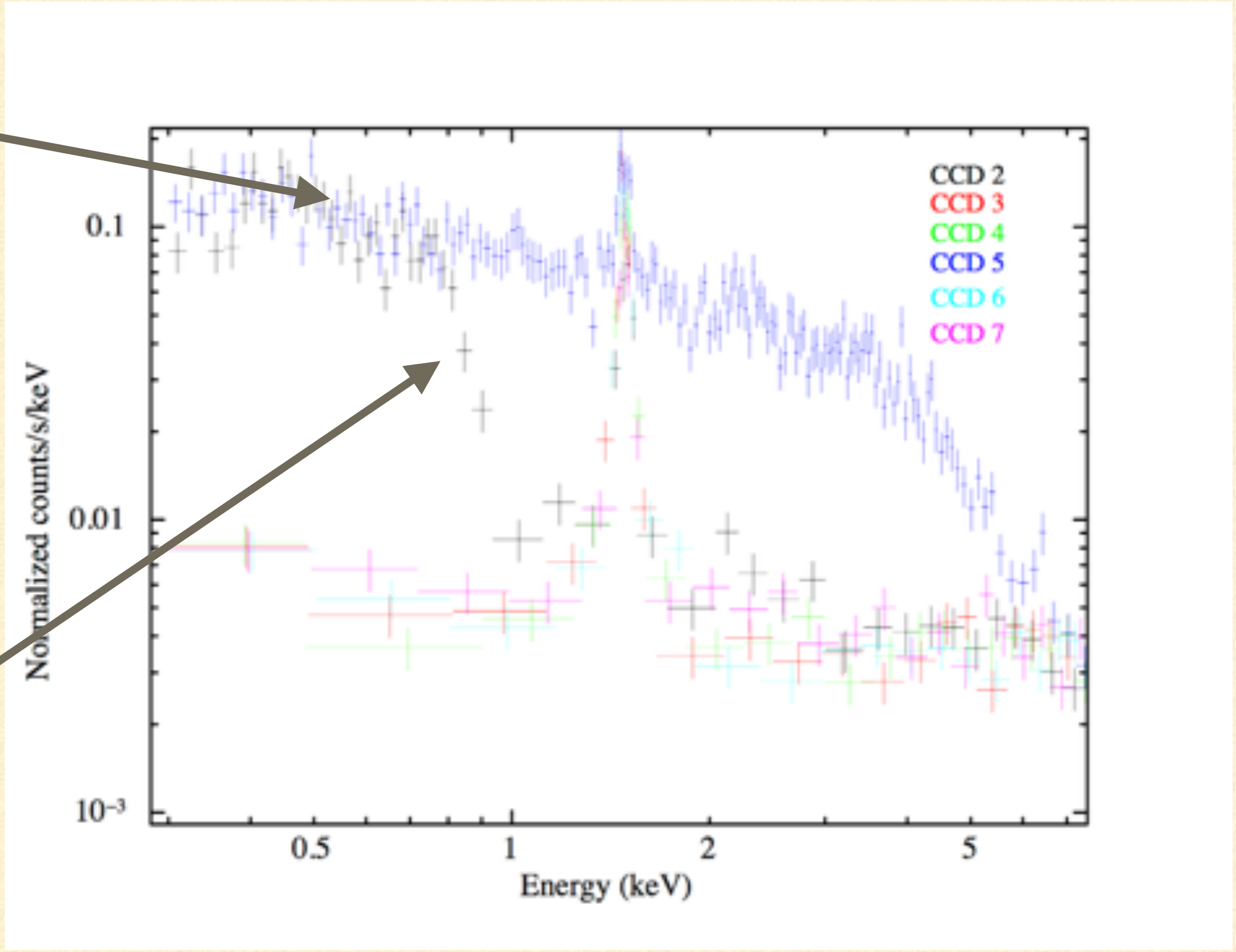


- The CCDs in "anomalous state" quasi uniformly brighter than its neighbours
- Spatial distribution is fairly homogenous within & outside the F.O.V
- Analysis of extended sources difficult when the noise is present
- Interferes with the source detection in PPS and spurious sources detected

Chen & Ballet

- Noticed recently that the electronic noise extends over the full energy range for some CCDs in an observation
- Observations where "both" categories of the noisy MOS CCDs present
- Develop an algorithm based on inter-CCD comparison within an observation which can detect noise independent of its extent of the spectral energy range.
- Choose out of F.O.V regions which should be free of source photons





MOS 2 CCD 5

work in progress

- Compare the normalized count rates in each CCD with the median count rate of all CCDs in the ObsId
- Tag the noisy CCDs along with its characteristics : noise fraction, break E etc..
- Test this over a large sample of observations
- Incorporate in SAS as an updated “emtaglenoise”

Thank you