Polarimetric Observations of

The Innermost Regions of Relativistic Jets

in X-ray Binaries

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The Innermost Regions of Relativistic Jets and Their Magnetic Fields

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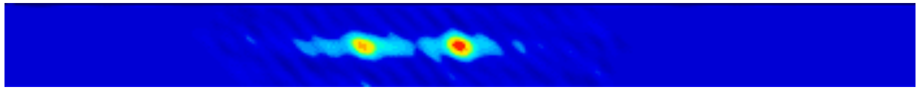
X-ray Binary Jets

Black hole XB: GRO J1655-40



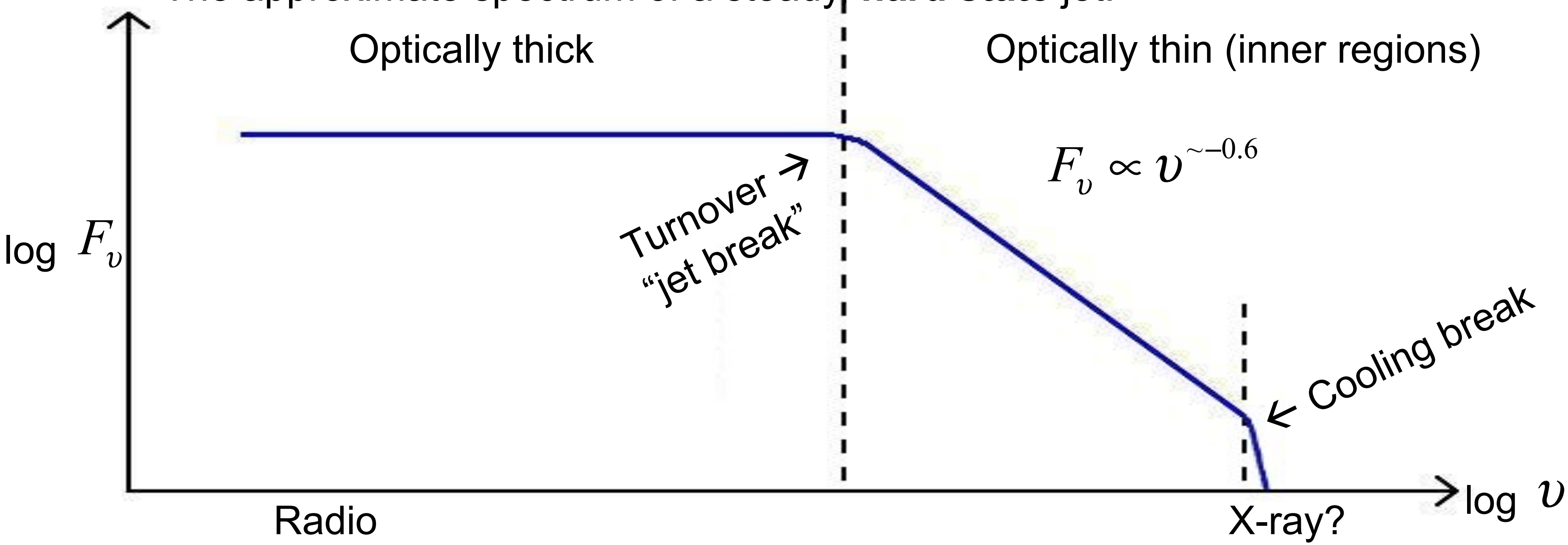
Tingay et al. 1995

Neutron star XB: Sco X-1

Fomalont et al. 2001

Radio emission: → is synchrotron in nature
→ unambiguously originates in collimated outflows (2 types of jet)

The approximate spectrum of a steady, **hard state** jet:

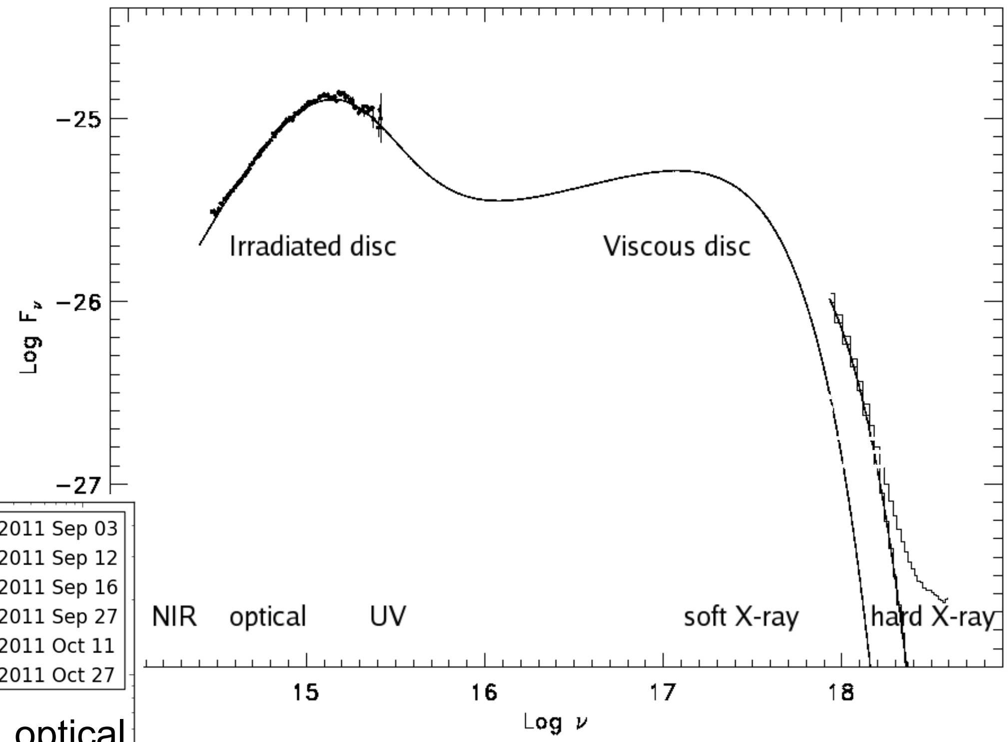


- The jet power and magnetic field strength are uncertain and highly dependent on the position of the spectral break(s)

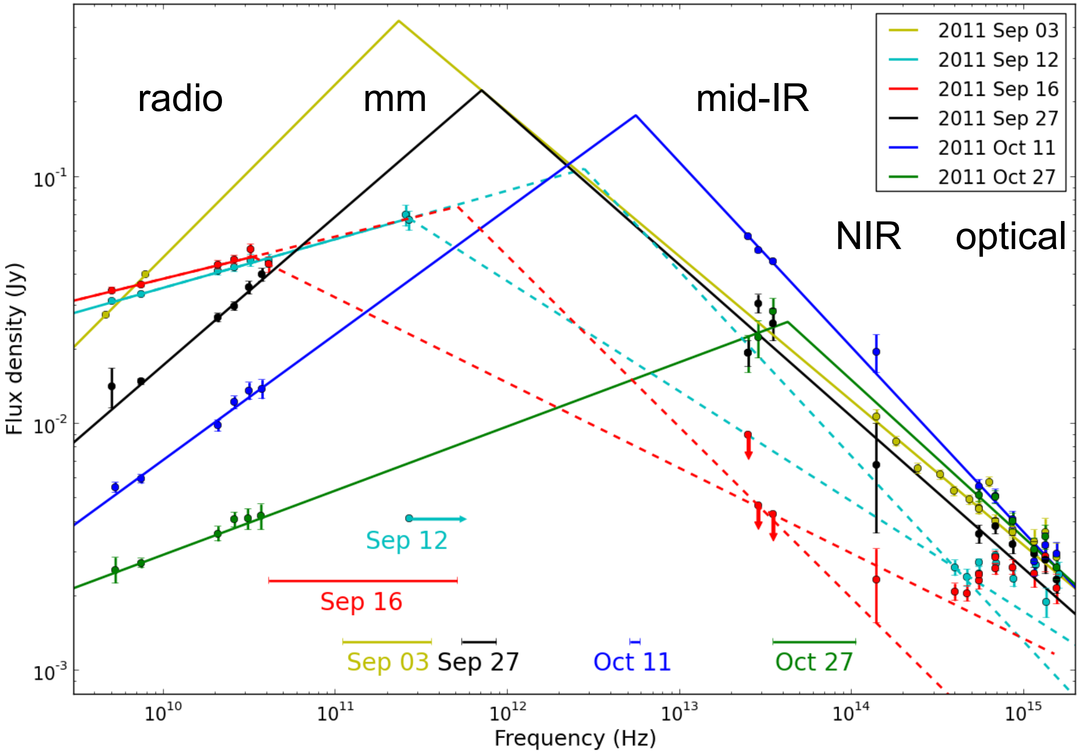
- How does the jet spectrum evolve during outbursts? → **Time evolution (impossible for AGN)**

Jet emission in the optical/NIR

We typically see the X-ray heated disc (reprocessing) and the underlying viscous disc at optical to soft X-ray wavelengths



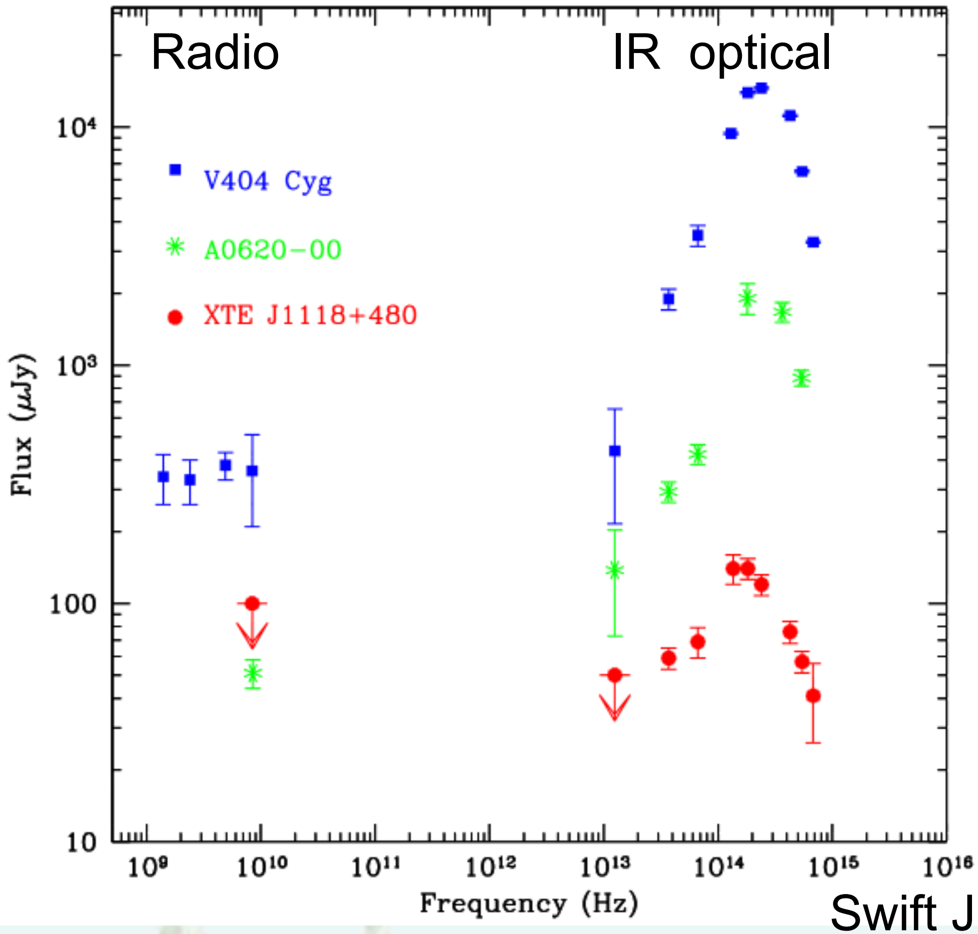
Hynes et al. 2002 (XTE J1859+226)

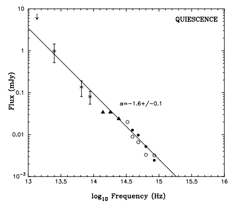


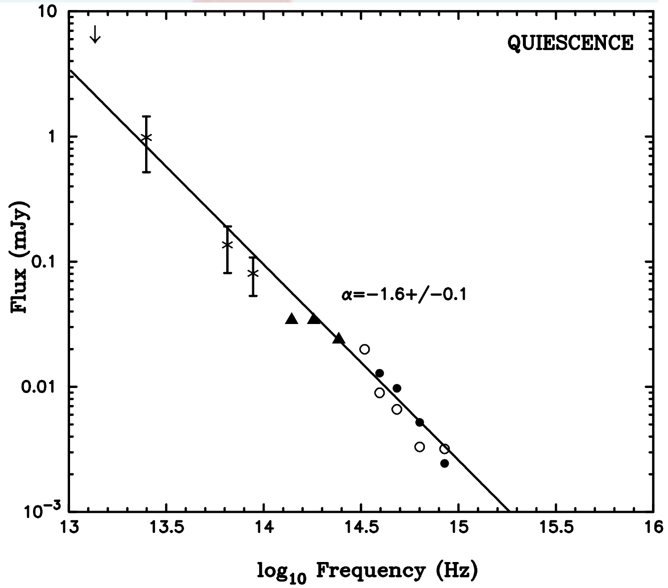
An extra red component is sometimes seen in the optical/NIR

MAXI J1836-194 (during/after transitions) Russell et al. 2013

Quiescent jets







V404 Cyg has flat spectrum radio

Gallo et al. 2005, 2007

Jets exist in quiescence

Swift J1357.2–0933 has a steep IR–optical spectrum

Optical, NIR, WISE mid-IR (3.4 to 22 mu)

power-law with index -1.6

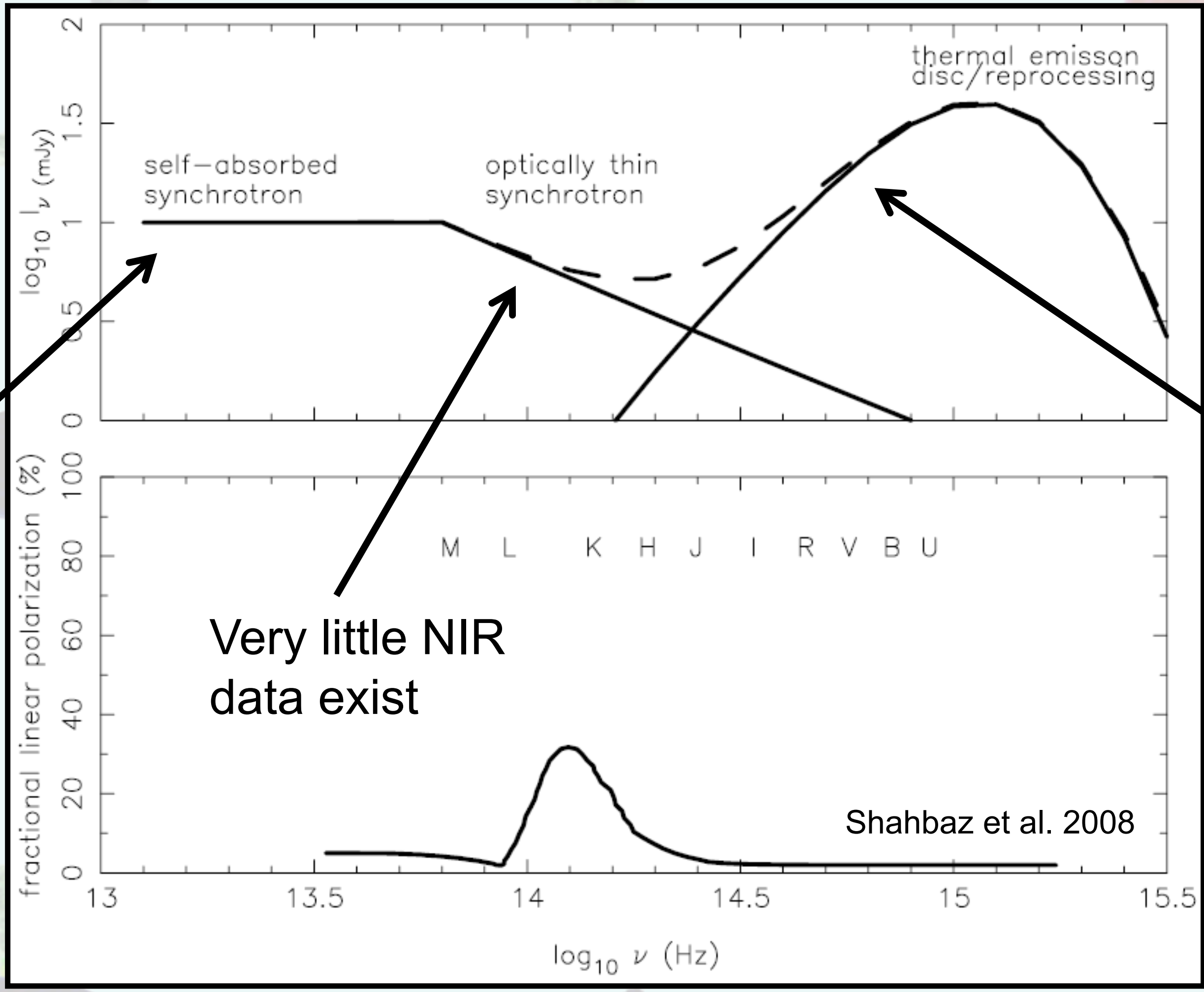
Shahbaz et al. 2013 (see poster)

Could be a thermal, possibly Maxwellian distribution of electrons in a weaker jet

Polarisation of optically thin synchrotron emission

Some radio data exist:

A few % polarised

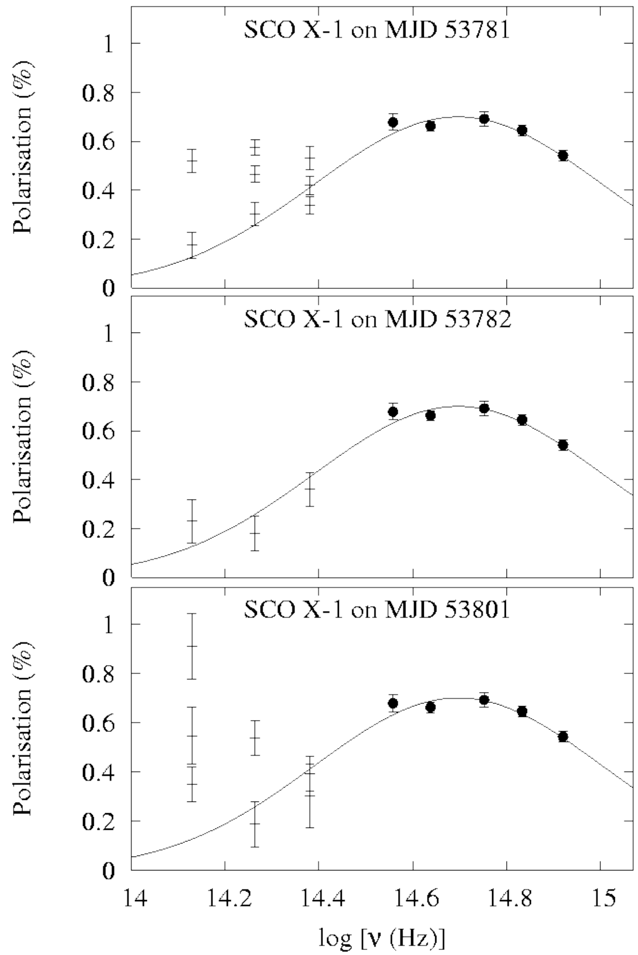


Some optical data exist:

A few % polarised due to scattering

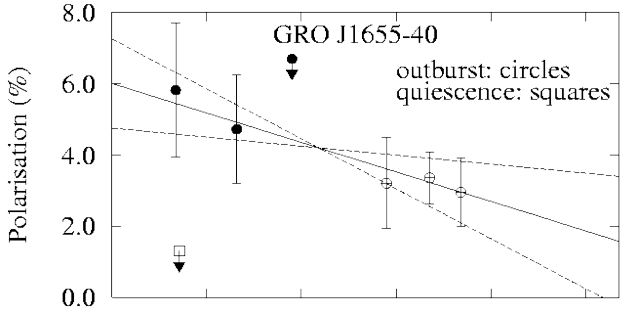
- In NIR, the observed emission of X-ray binaries can be highly polarised
- Depends on magnetic field configuration
- Ordered field → up to ~80% polarised
- Tangled field → ~ no net polarisation

Intrinsic infrared polarisation: the results so far



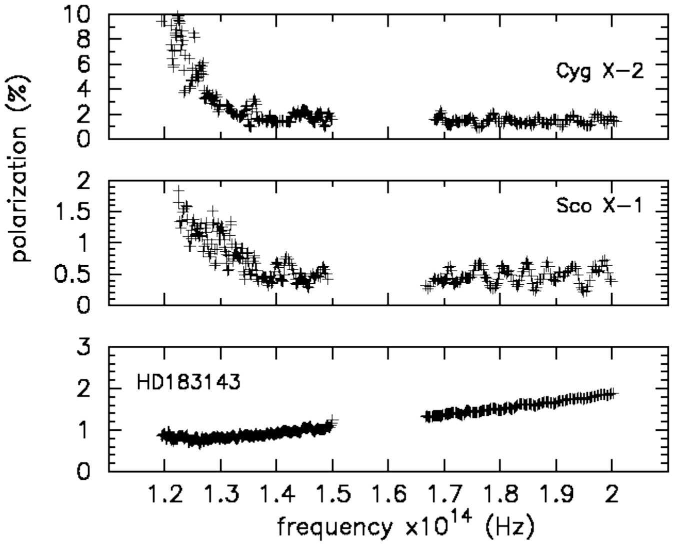
Sco X-1 (neutron star XRB)

NIR (Russell & Fender 2008) and optical (Schultz et al. 2004) polarization



GRO J1655-40 (black hole XRB)

NIR during hard state (Russell & Fender 2008) and optical (Gliozzi et al. 1998 during soft state) polarisation (NIR quiescence upper limit from Dubus & Chaty 2007)



Cyg X-2 and Sco X-1 (neutron star XRBs)

NIR spectropolarimetry (Shahbaz et al. 2008)

All detections are stronger at low frequencies

The results imply a predominantly tangled, likely variable magnetic field near the jet base

Gamma-ray polarisation detected in Cyg X-1

Polarised γ-ray emission from Cygnus X-1 might be from the jet (Laurent et al. 2011, Science)

Polarisation strength is very high: 67 +- 30 % !! (0.4-2 MeV)
Derived from 58 days of exposure time with INTEGRAL

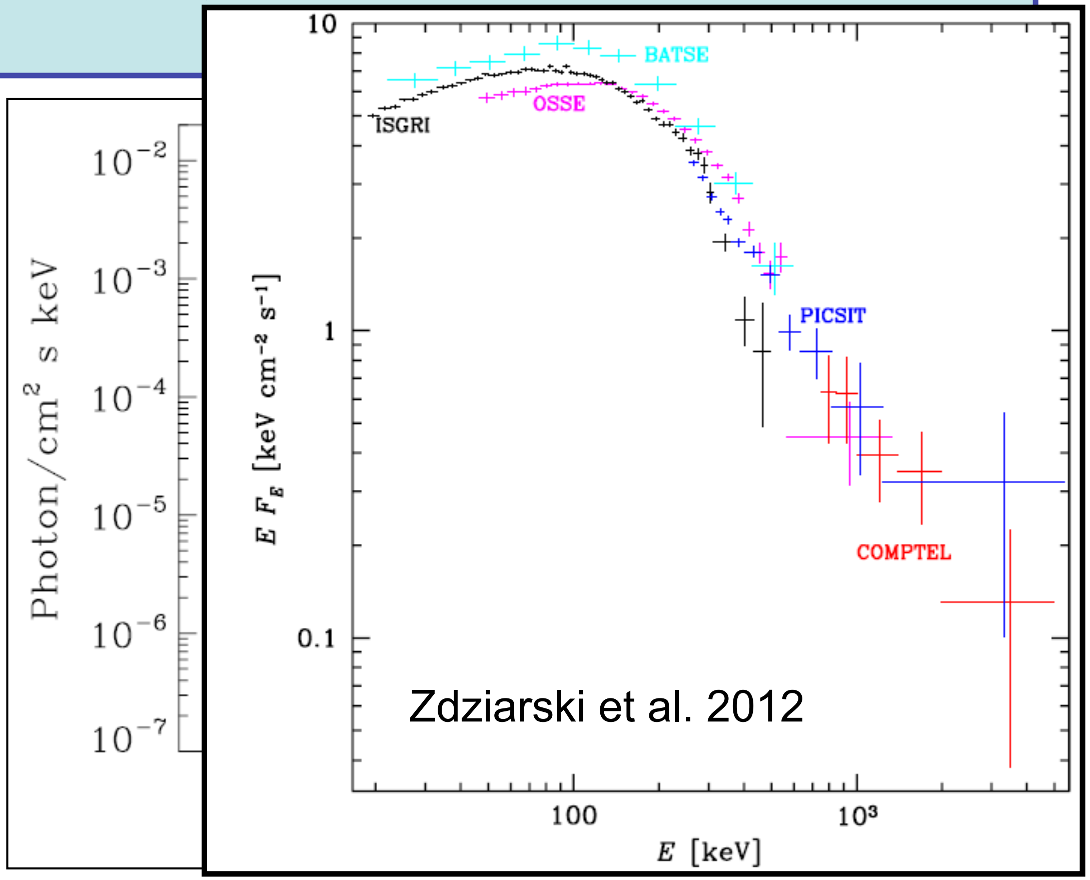
This would imply a very highly ordered, constant B field at the base of the jet of Cyg X-1

→ Jourdain et al. 2012 confirmed the result using a different instrument on INTEGRAL

→ 76 +- 15 % at 230-850 keV

→ <20% at 130-230 keV

→ (Jet) synchrotron is the only plausible origin



Broadband polarisation measurements of Cyg X-1

Our team observed Cyg X-1 in near-IR with William Herschel Telescope + LIRIS in June 2010 in polarimetry mode

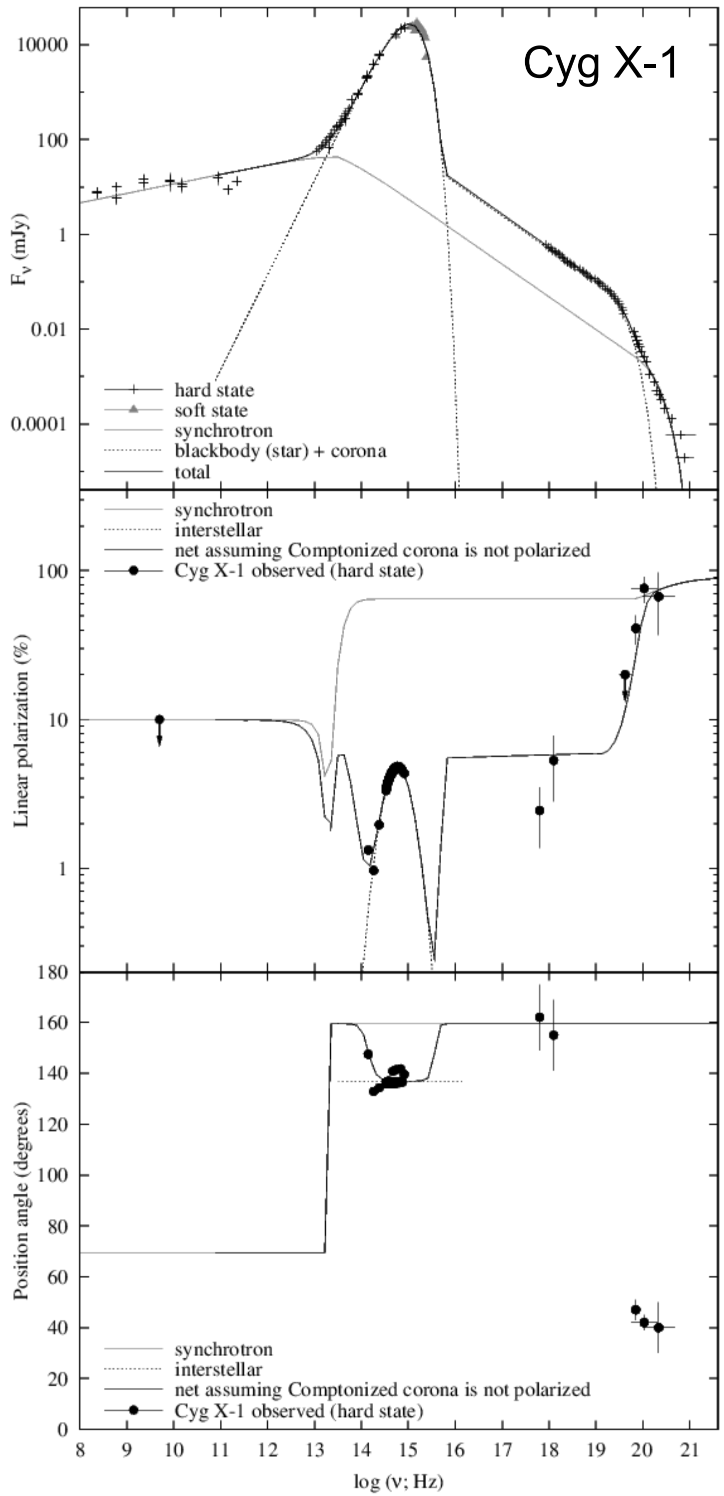
No previous near-IR polarisation measurements published

Its bright: achieved polarisation accuracy of 0.07 %

Multi-wavelength linear polarization values of Cyg X–1.

Waveband	log(*nu*; Hz)	FLP (%) Observed	PA (°) Observed	Reference
5 GHz	9.70	< 10	–	Stirling et al. (2001)
2.2 μm (K_S-band)	14.14	1.32 ± 0.07	147.5 ± 1.6	This paper
1.7 μm (H-band)	14.26	0.97 ± 0.06	132.9 ± 1.7	This paper
1.2 μm (J-band)	14.38	1.96 ± 0.07	134.3 ± 1.7	This paper
0.64 μm (R-band)	14.67	4.40 ± 0.08	140.8 ± 0.5	Dolan (1992)
0.55 μm (V-band)	14.74	4.77 ± 0.23	141.4 ± 1.4	Dolan (1992)
0.44 μm (B-band)	14.83	4.70 ± 0.30	141.8 ± 1.8	Dolan (1992)
0.37 μm (U-band)	14.91	4.35 ± 0.16	139.7 ± 1.0	Nolt et al. (1975)
0.40–0.90 μm[a]	14.52–14.87	3.3–4.8	135.9–137.1	Nagae et al. (2009)
2.6 keV	17.80	2.44 ± 1.07	162 ± 13	Long et al. (1980)
5.2 keV	18.10	5.3 ± 2.5	155 ± 14	Long et al. (1980)
130–230 keV	19.50–19.75	< 20	–	Jourdain et al. (2012)
230–370 keV	19.75–19.95	41 ± 9	47 ± 4	Jourdain et al. (2012)
230–850 keV	19.75–20.31	76 ± 15	42 ± 3	Jourdain et al. (2012)
400–2000 keV	19.99–20.68	67 ± 30	40 ± 10	Laurent et al. (2011)[b]

X-ray!



A simple model can reproduce the broadband fractional linear polarization (FLP) given the input SED (Russell & Shahbaz, in prep.)

$$\alpha_{\rm thin} = 0.5(1-p).$$

Components:

- Self-absorbed synchrotron (radio to IR):

$$FLP_{\rm thick} = f\frac{3}{6p+13}$$ (e.g. Blandford et al. 2002)

0 < *f* < 1

Max FLP = 11%

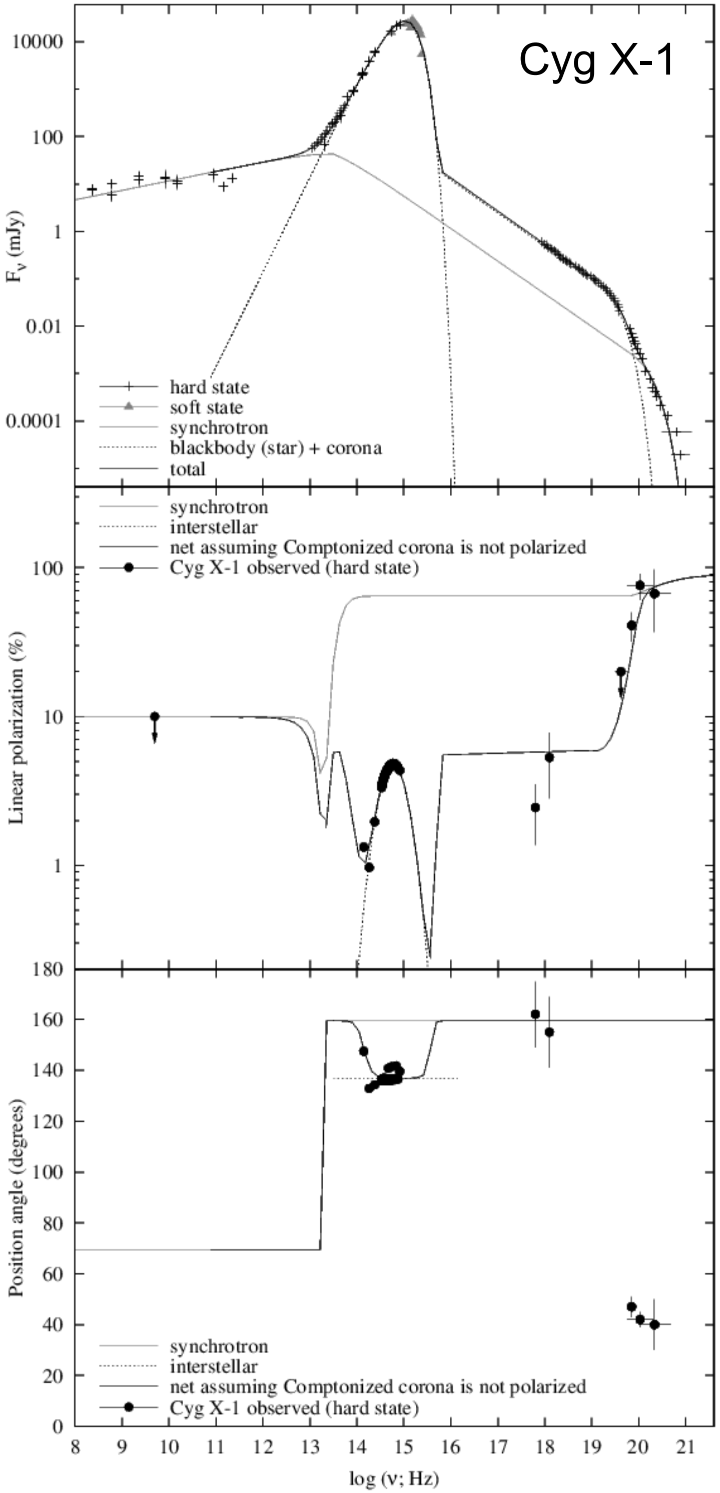
- Optically thin synchrotron (IR to X-ray) with cut-off in X-ray

$$FLP_{\rm thin} = f\frac{p+1}{p+7/3} = f\frac{1-\alpha_{\rm thin}}{5/3-\alpha_{\rm thin}}$$

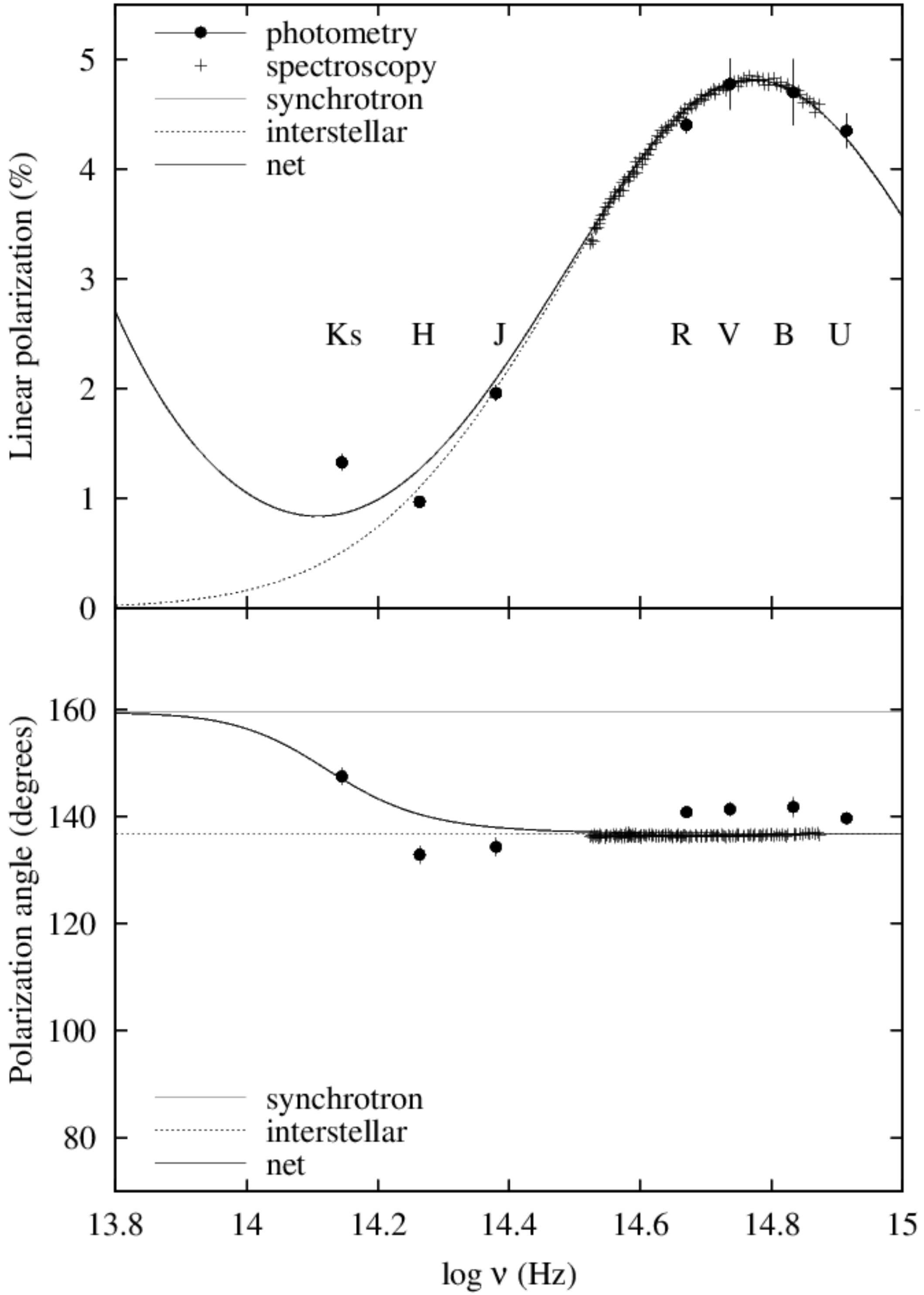
(Bjornsson & Blumenthal 1982)

Max FLP = 82%

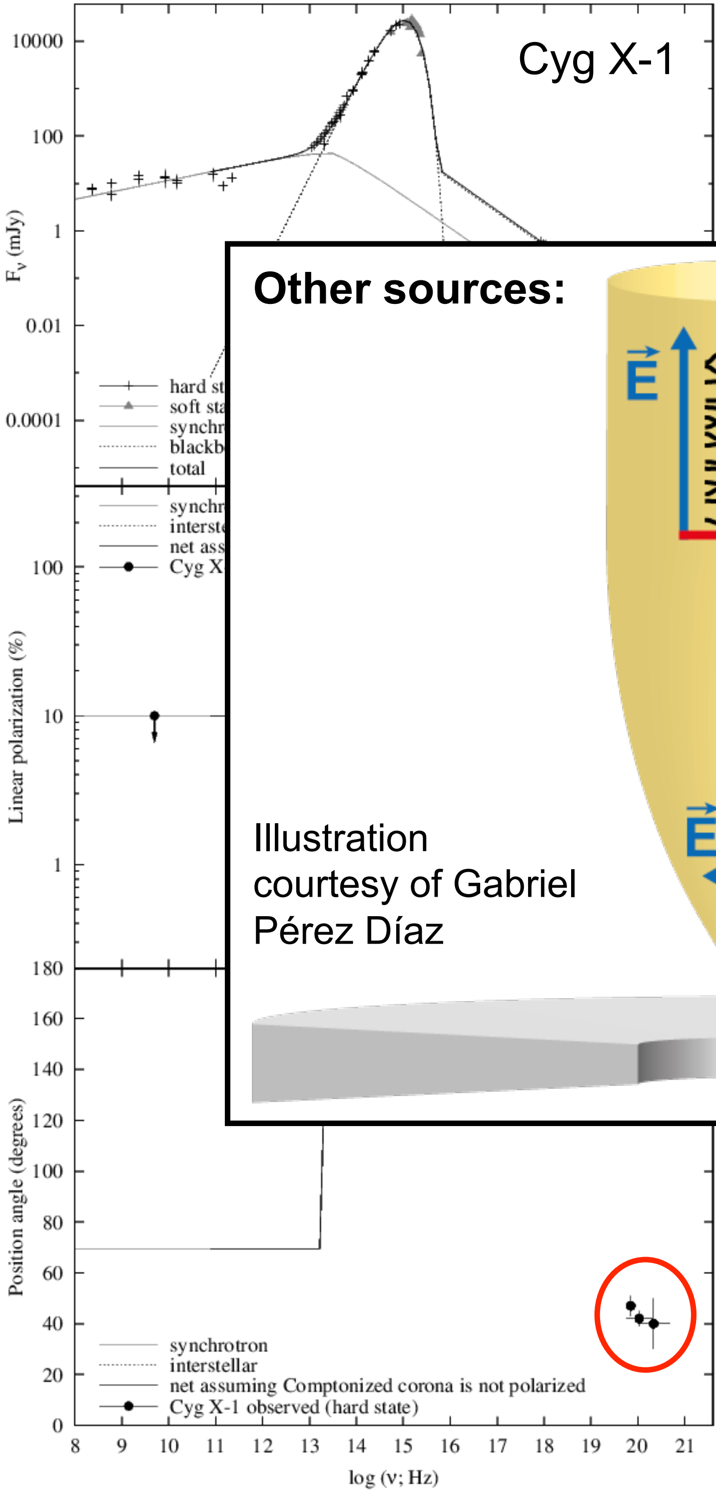
- Comptonized corona, assumed here to be unpolarized (chaotic corona geometry, no net aligned field?)



Cyg X-1
hard state
soft state
synchrotron
blackbody (star) + corona
total
F_ν (mJy)
synchrotron
interstellar
net assuming Comptonized corona is not polarized
Cyg X-1 observed (hard state)
Linear polarization (%)
synchrotron
interstellar
net assuming Comptonized corona is not polarized
Cyg X-1 observed (hard state)
Position angle (degrees)
log (ν; Hz)



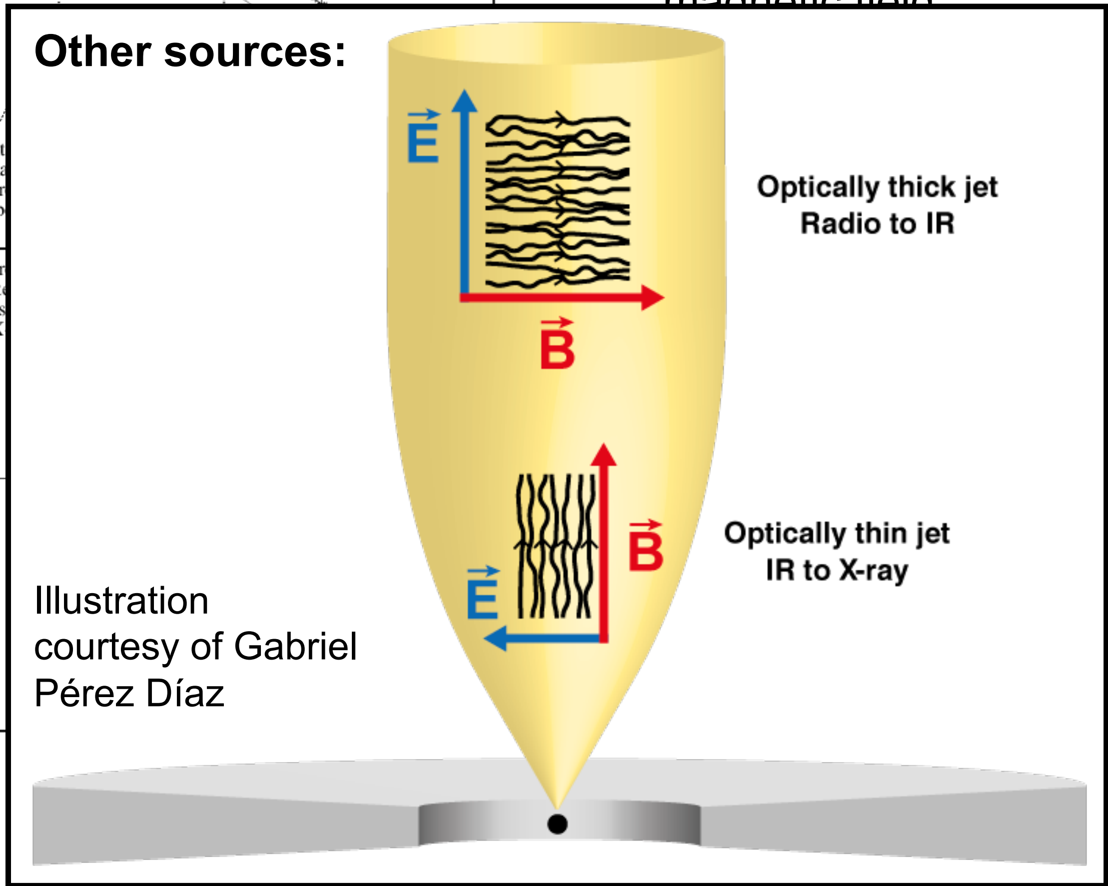
photometry
spectroscopy
synchrotron
interstellar
net
Linear polarization (%)
Ks
H
J
R
V
B
U
Polarization angle (degrees)
synchrotron
interstellar
net
log ν (Hz)

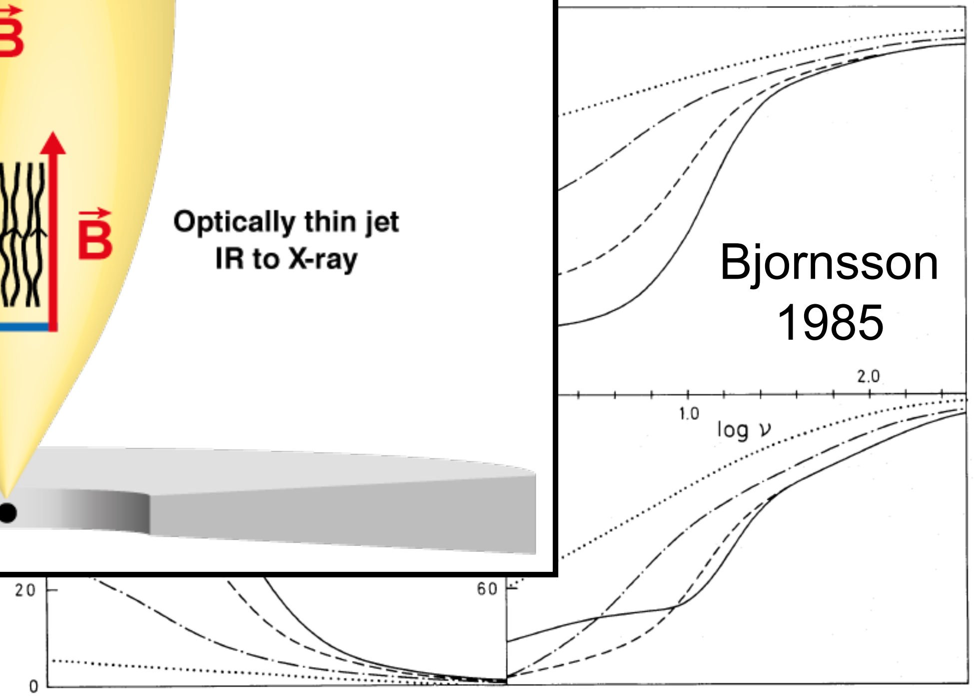


- We find $f \sim 0.85$
- This implies a stable, highly ordered magnetic field

…endicular to the jet
… the jet

…ic data needed to test
… further out





Angle in gamma-ray is off by 60 degrees – why?

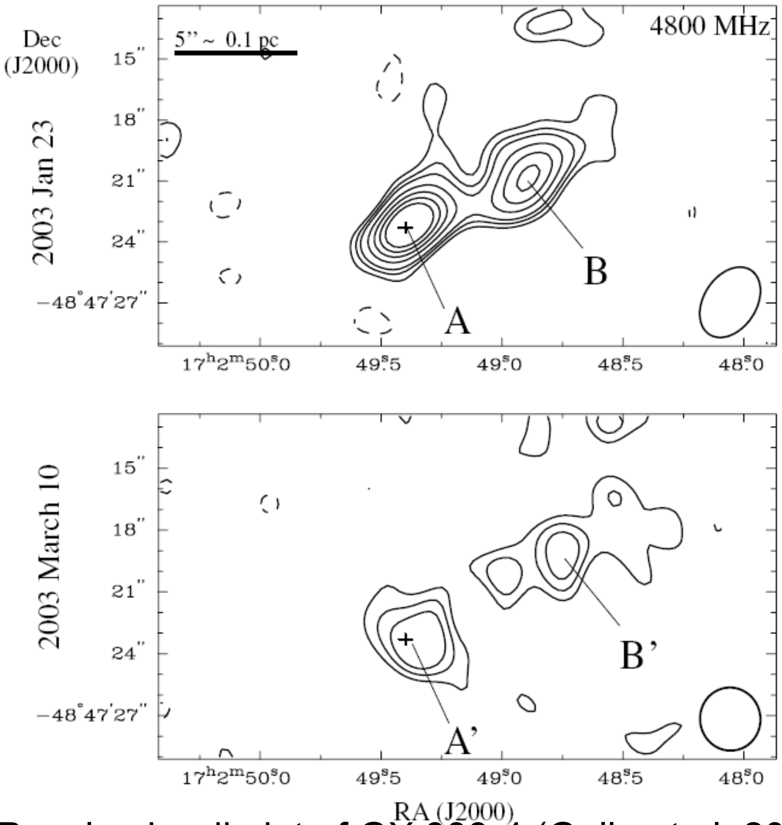
Conclusions

- **NIR synchrotron emission from jets in X-ray binaries is polarized**
- **The results so far suggest:**
- **Near the jet base the magnetic field is probably:**
  - **→ generally turbulent (only partially ordered) and rapidly changing**
  - **→ parallel to the jet axis**
  - **→ except in Cyg X-1, where it is highly ordered & perpendicular to jet axis**
- **More data and more models are needed to explain the observations**
- **Future spaceborne X-ray polarimeters should be able to detect variable X-ray polarization from synchrotron emission from XRB jets**

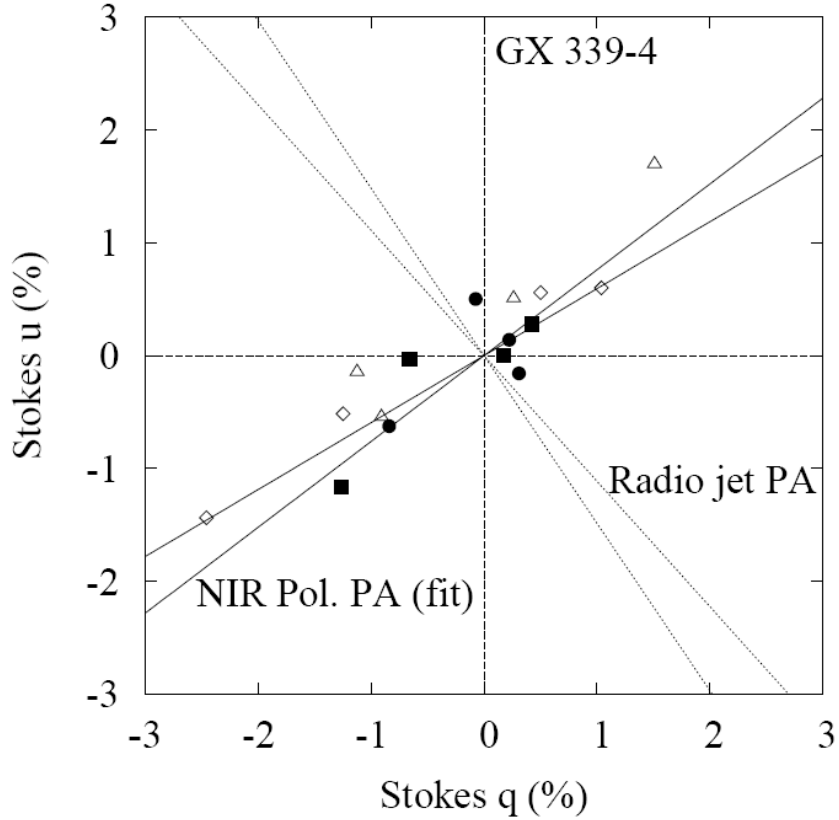
Thanks for listening

VLT observations of GX 339-4 in 2008

→ We observed GX 339-4 in September 2008 during a hard state with VLT+ISAAC
→ We detect significant, variable linear polarisation in the near-infrared (when the jet dominated)



Resolved radio jet of GX 339-4 (Gallo et al. 2004)



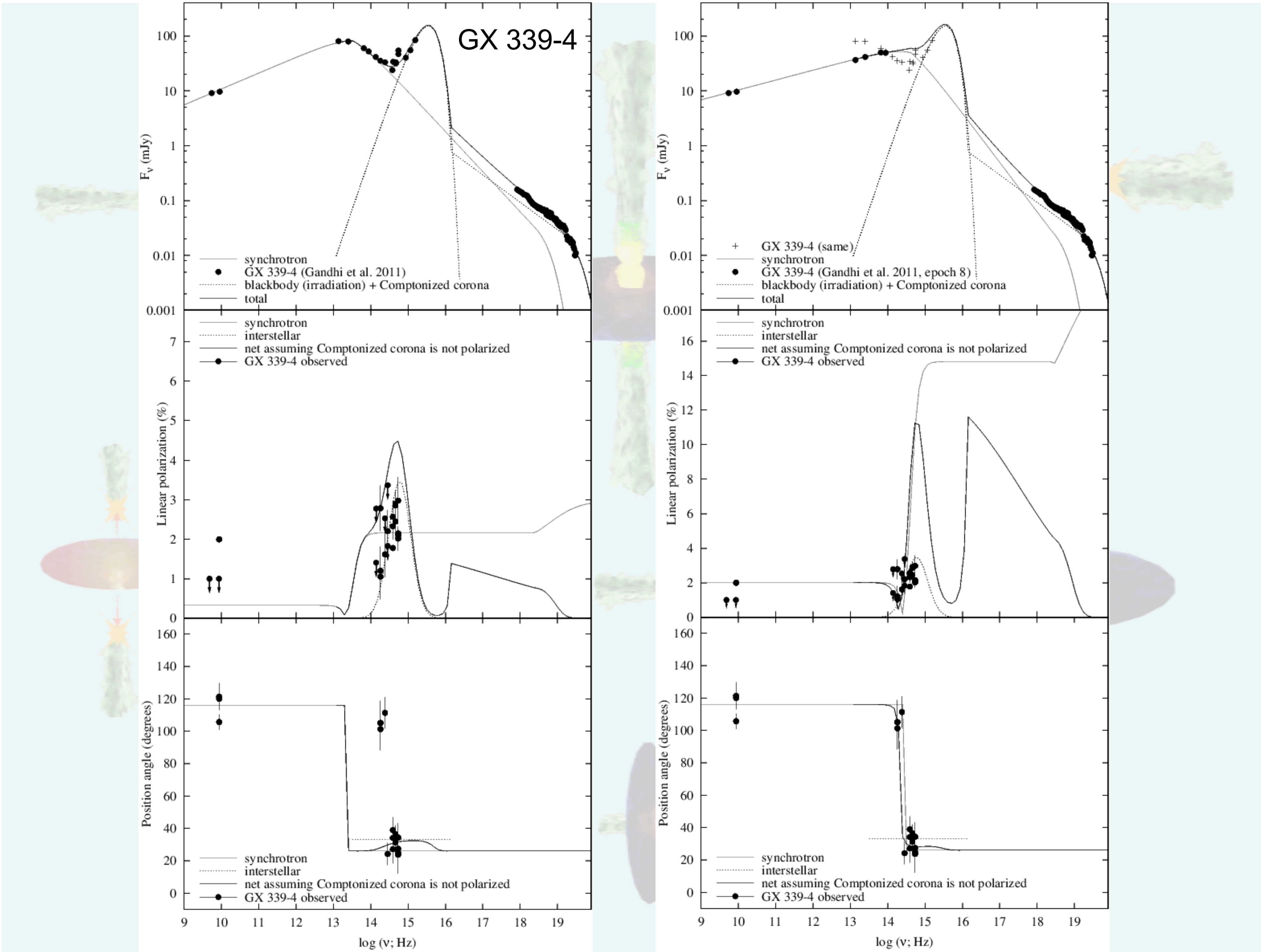
$$FLP = \sqrt{q^2 + u^2} \text{ and } PA = 0.5tan^{-1}(u/q)$$

We infer a predominantly tangled, variable magnetic field near the jet base

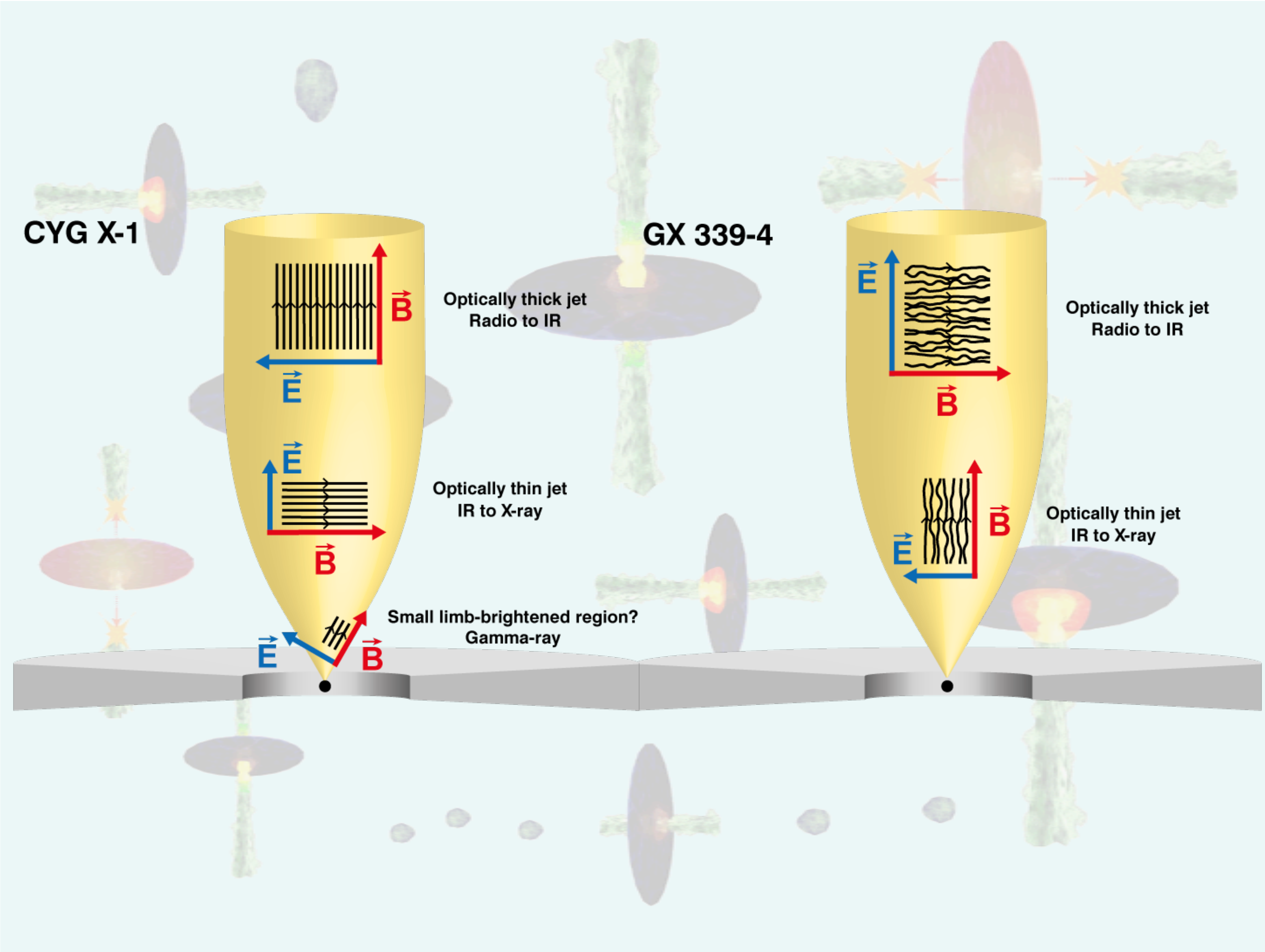
→ The PA of polarisation is ~ perpendicular to the PA of the resolved radio jet

→ The magnetic field is approximately parallel to the jet axis

Russell et al. 2011



GX 339-4
F_ν (mJy)
synchrotron
GX 339-4 (Gandhi et al. 2011)
blackbody (irradiation) + Comptonized corona
total
synchrotron
interstellar
net assuming Comptonized corona is not polarized
GX 339-4 observed
Linear polarization (%)
synchrotron
interstellar
net assuming Comptonized corona is not polarized
GX 339-4 observed
Position angle (degrees)
log (ν; Hz)
GX 339-4 (same)
synchrotron
GX 339-4 (Gandhi et al. 2011, epoch 8)
blackbody (irradiation) + Comptonized corona
total
synchrotron
interstellar
net assuming Comptonized corona is not polarized
GX 339-4 observed
Linear polarization (%)
synchrotron
interstellar
net assuming Comptonized corona is not polarized
GX 339-4 observed
Position angle (degrees)
log (ν; Hz)



CYG X-1
GX 339-4
B
E
Optically thick jet
Radio to IR
E
B
Optically thin jet
IR to X-ray
E
B
Small limb-brightened region?
Gamma-ray
E
B
Optically thick jet
Radio to IR
B
E
Optically thin jet
IR to X-ray