X-ray polarimetry and other thoughts

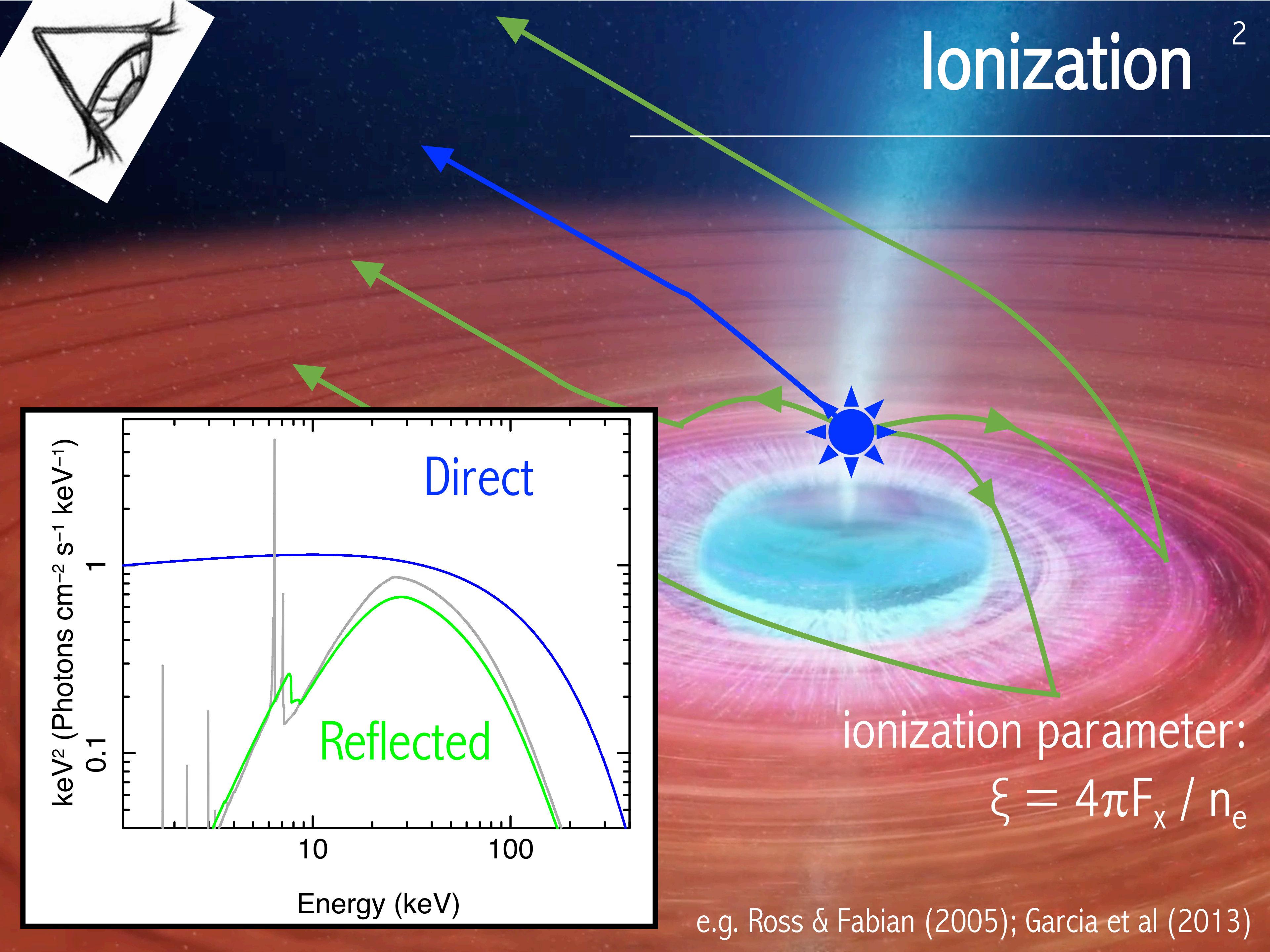
Adam Ingram – Royal Society URF

Soumya Shreeram, Tom Maccarone, Michiel van der Klis, Guglielmo Mastroserio & the IXPE team

THE ROYAL SOCIETY

UNIVERSITY OF OXFORD

Ionization

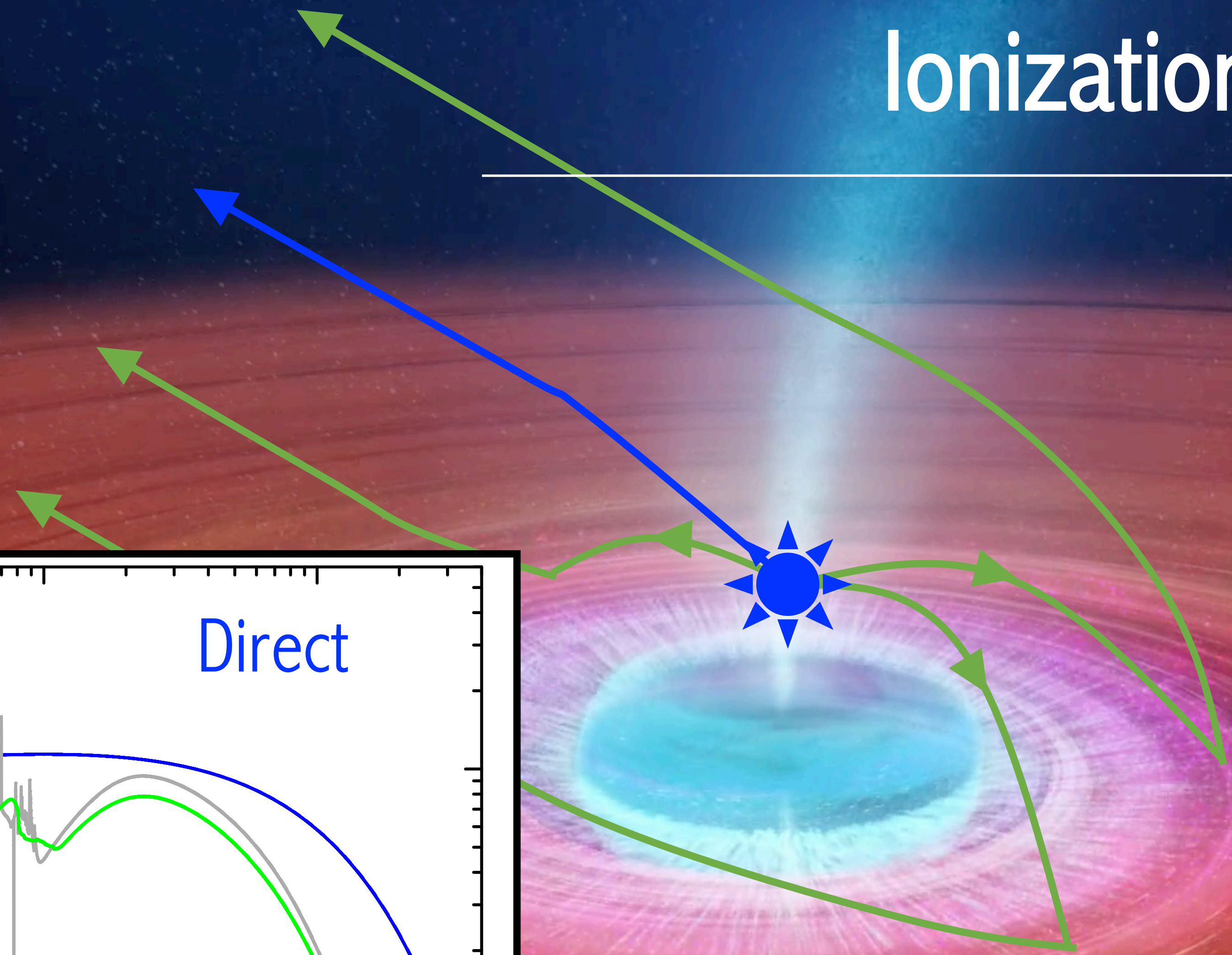


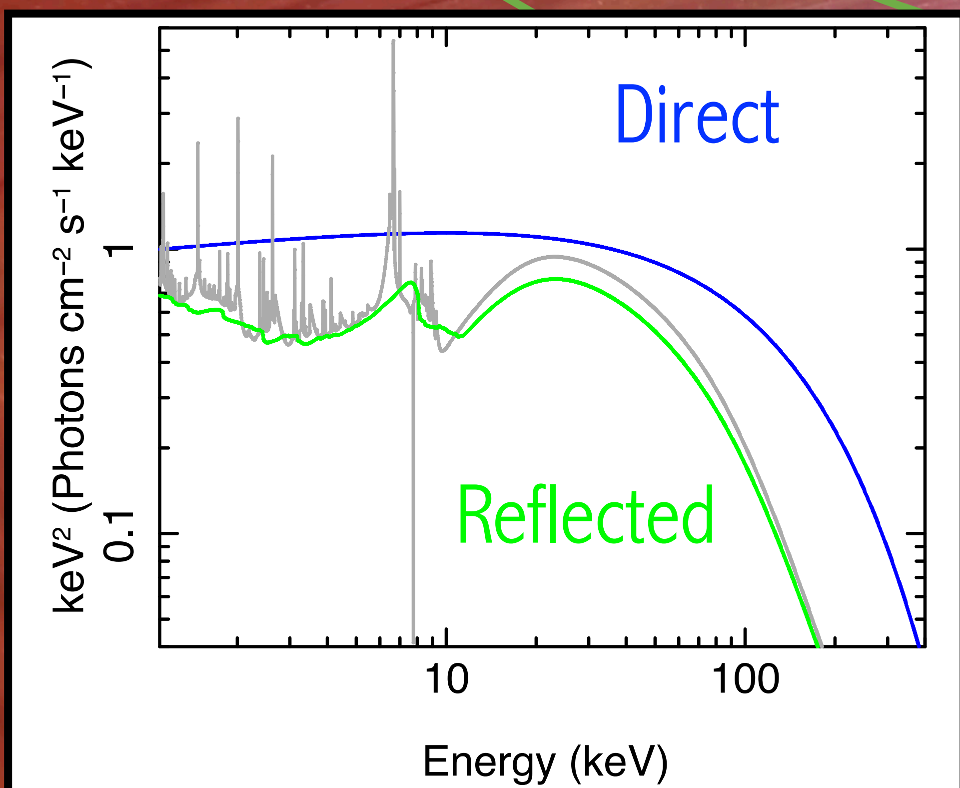
ionization parameter:

$$\xi = 4\pi F_x / n_e$$

e.g. Ross & Fabian (2005); Garcia et al (2013)

Ionization





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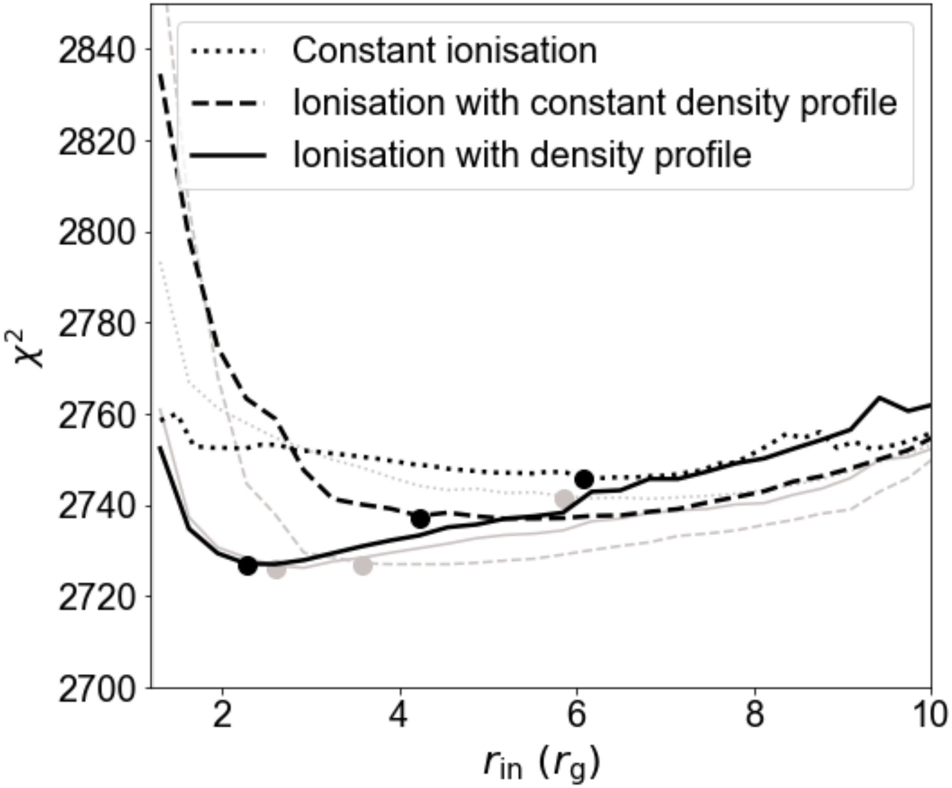
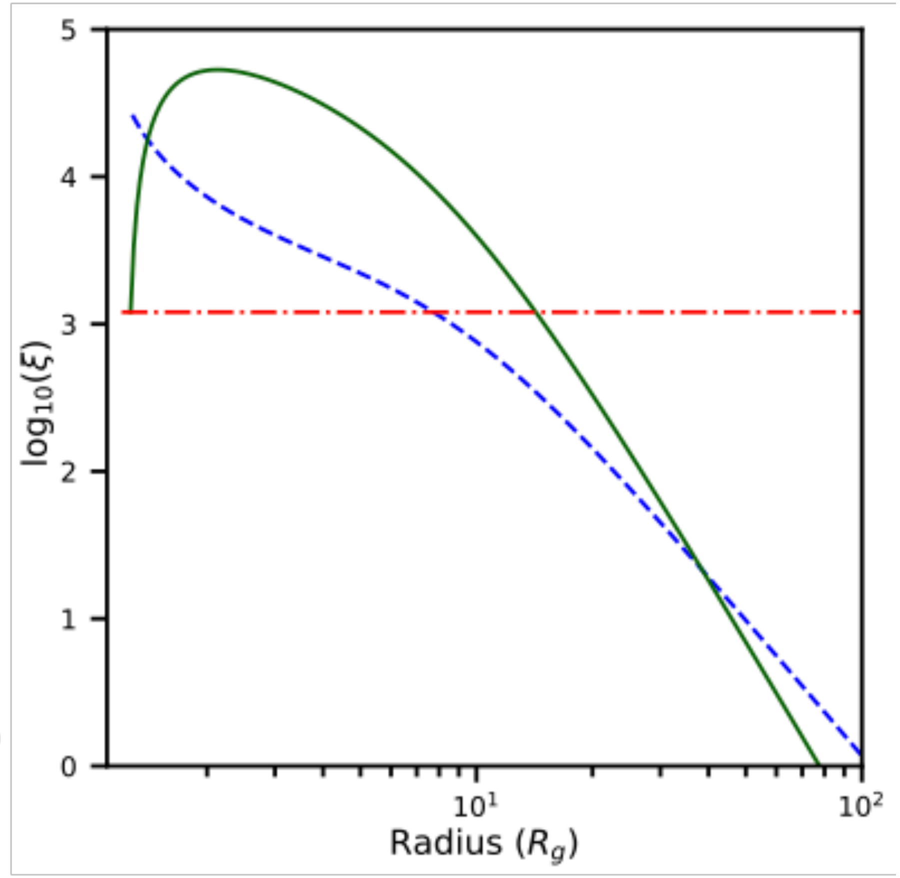
Ionization profile

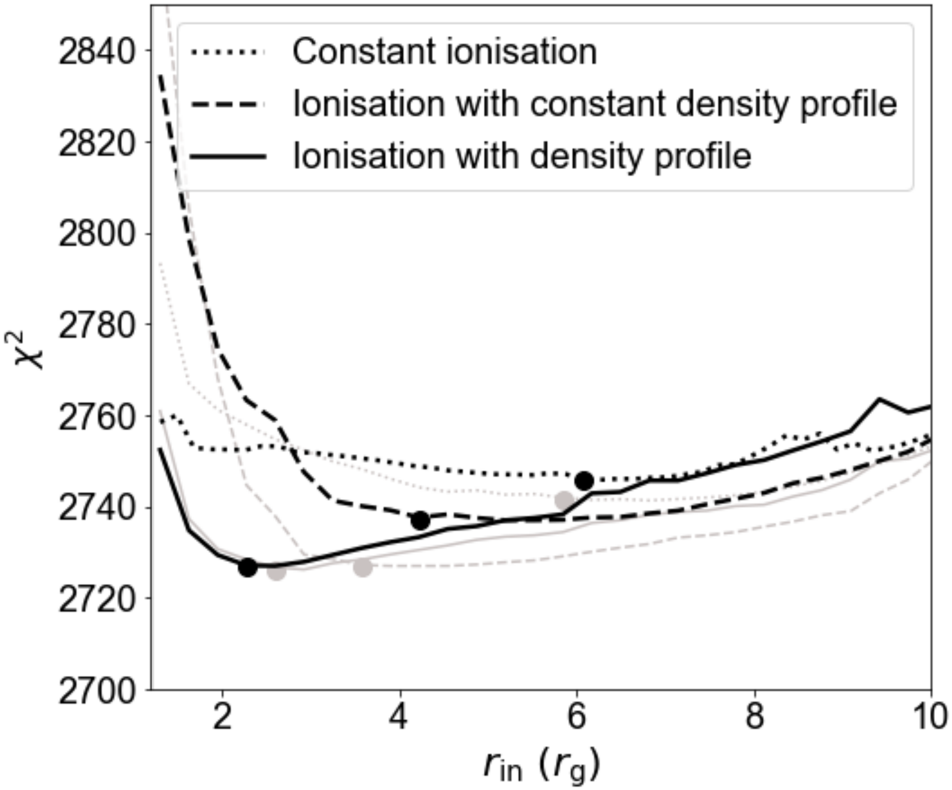


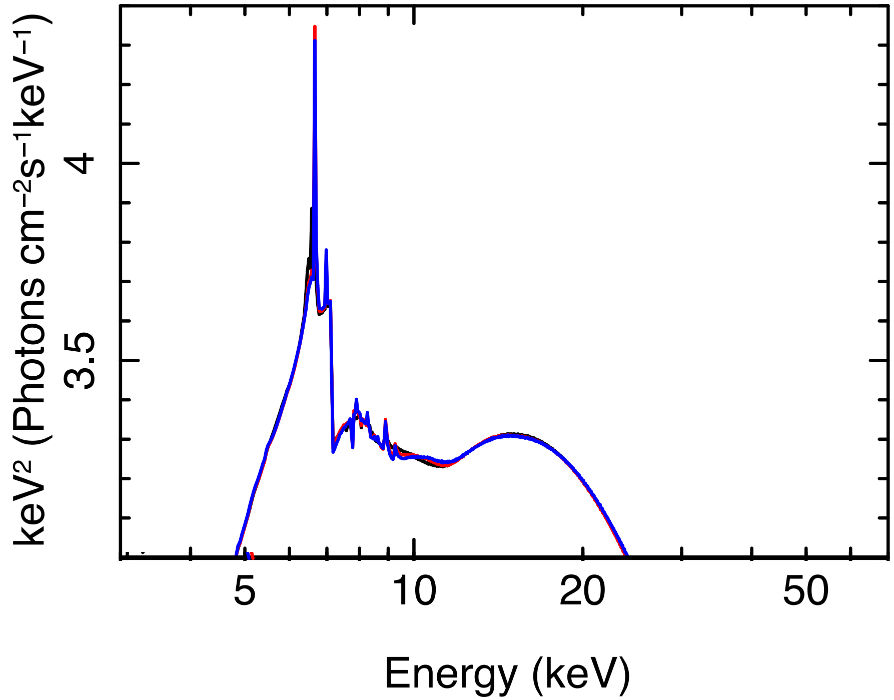


- NuSTAR observation of GRS 1915+105 in plateau state
- Radial ionization profile changes the best fitting disc inner radius (but not >ISCO)

Shreeram & Ingram (2020)

Ionization profile

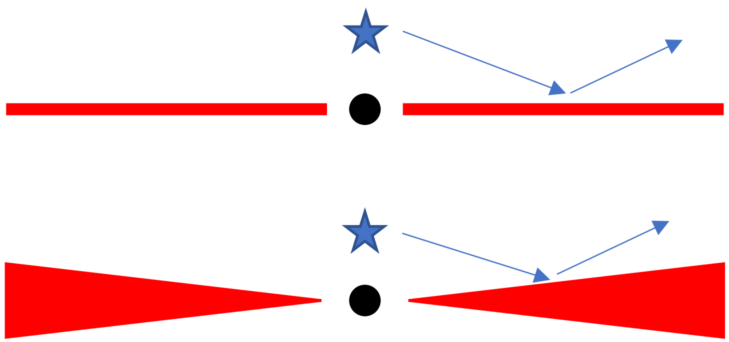




- Difference between models is very subtle
- Need high ionization parameter => low disc density ($n_e \lesssim 10^{19}\mathrm{cm}^{-3}$)

Shreeram & Ingram (2020)

Scaleheight & Distance

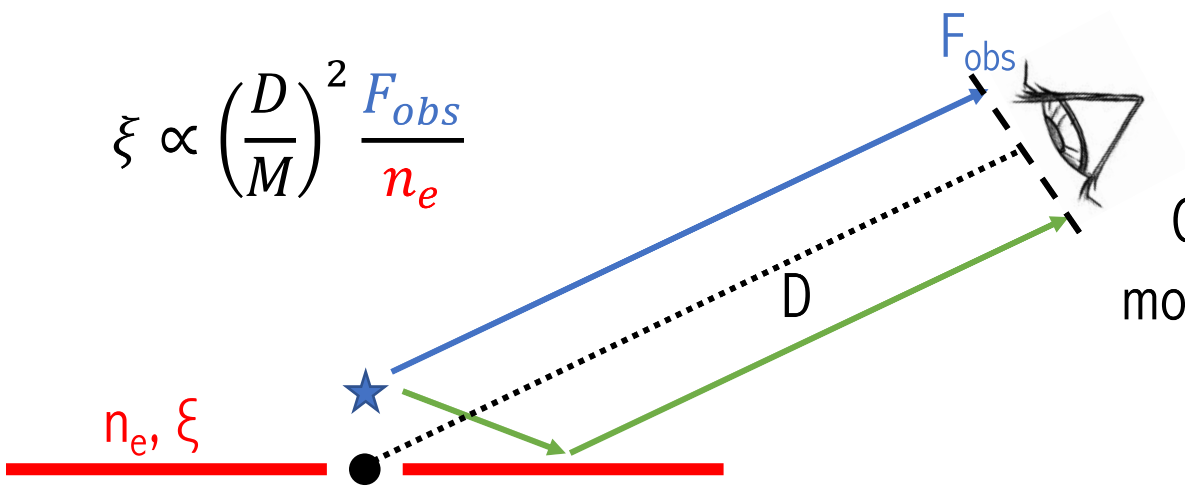


Disc scale height

- Currently assuming h/r=0
- For h/r finite, get more reflection from larger r

(Taylor & Reynolds 2018; 2019)

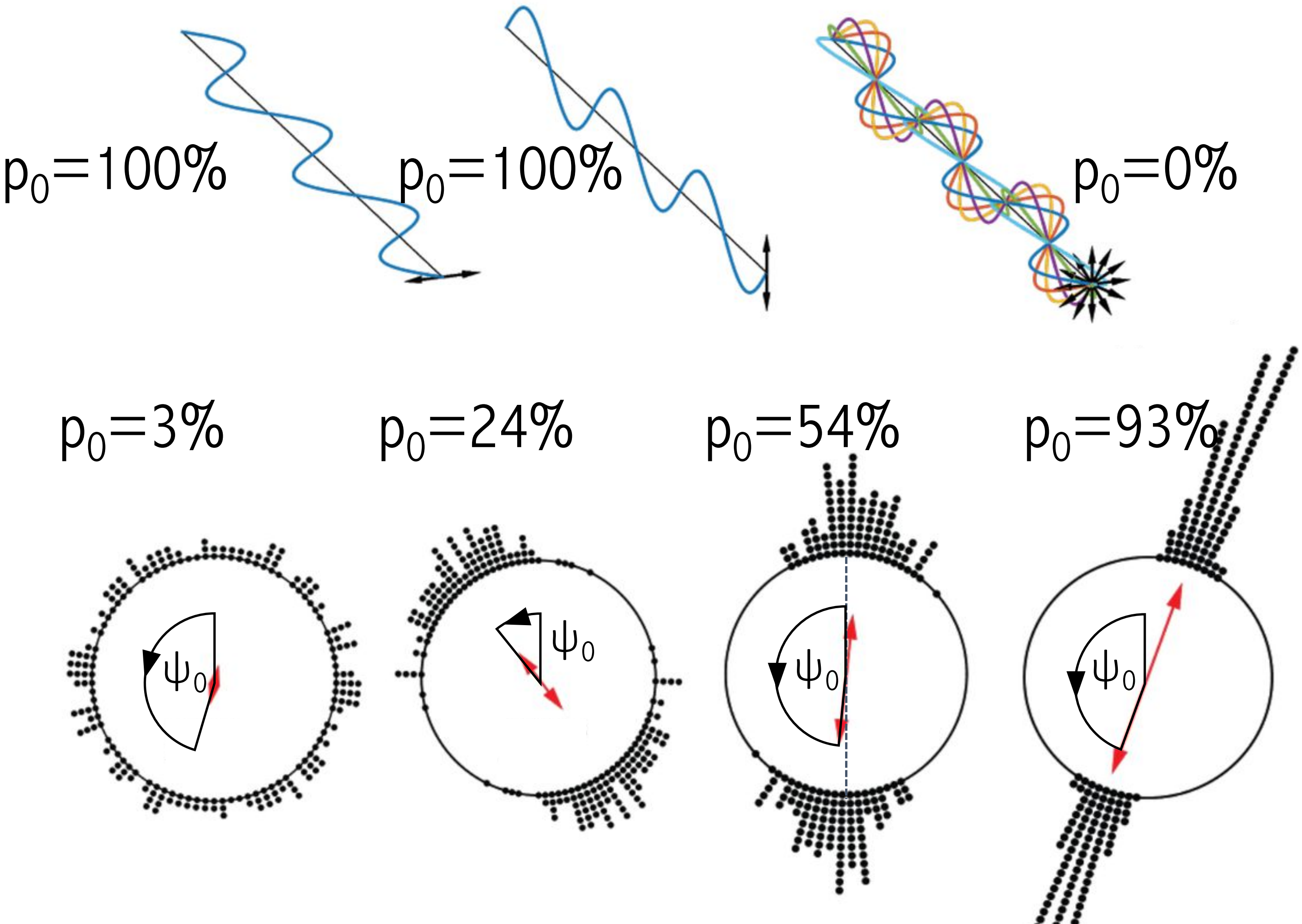
$$\xi \propto \left(\frac{D}{M}\right)^2 \frac{F_{obs}}{n_e}$$



Can now make distance D a model parameter instead of ξ

Ingram et al (in prep)

Linear polarization



Adapted from Foster et al (2017)

Basic expectations

Synchrotron

- $dn_e/dE \propto E^{-p}$, p~2.4

- Optically thin:

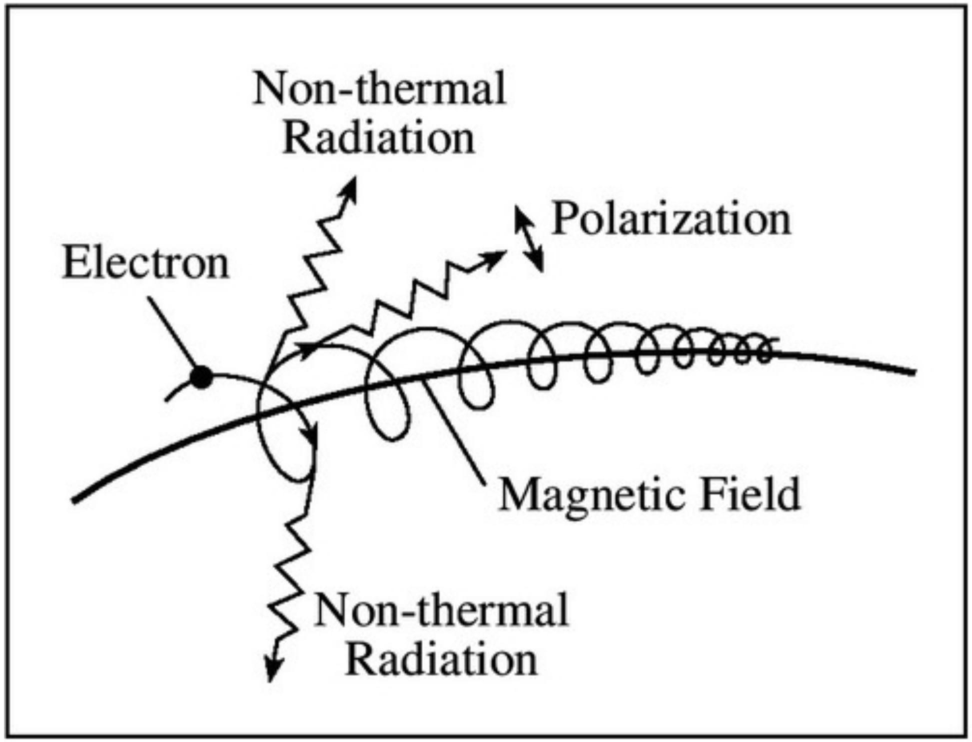
$$p_0 = f\,\frac{p+1}{p+7/3} \sim f\ 72\%$$

where f is order of B-field
ψ_0 perpendicular to B-field

- Optically thick (self-absorbed):

$$p_0 = f\,\frac{3}{6p+13} \sim f\ 11\%$$

ψ_0 parallel to B-field



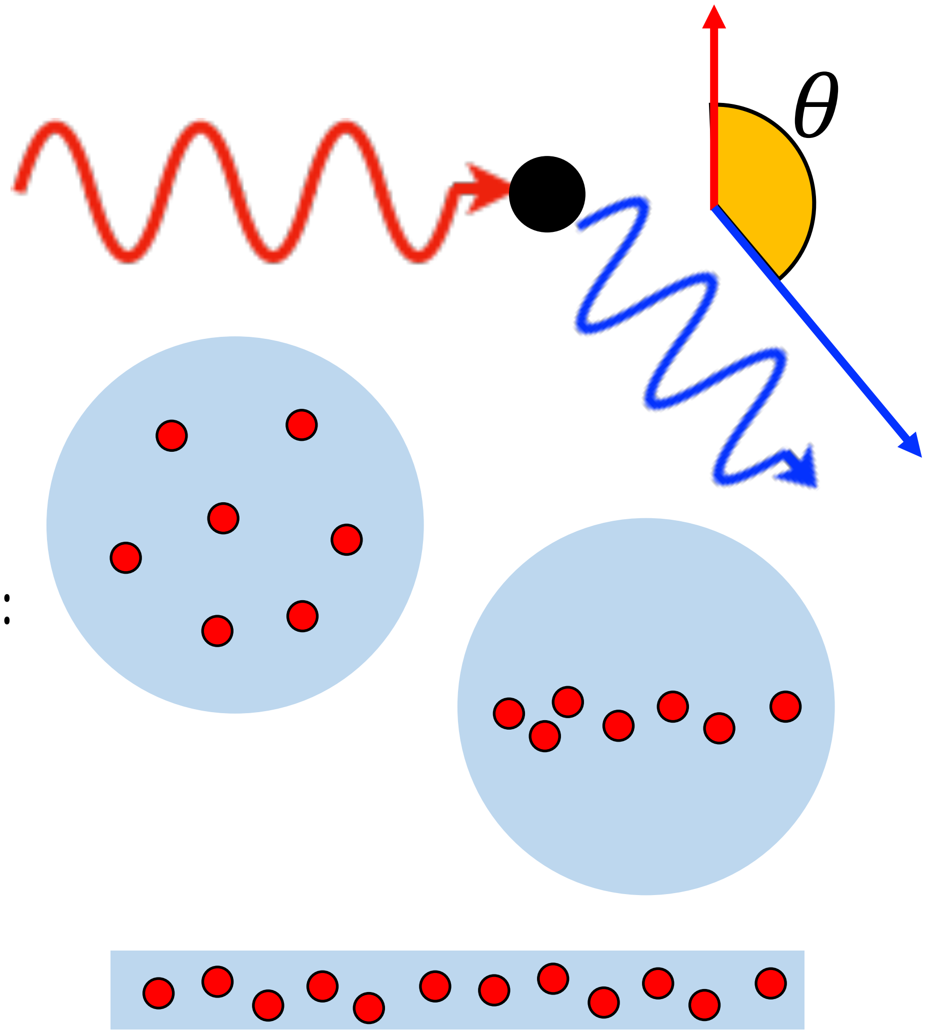
e.g. Rybicki & Lightman

Basic expectations

Compton scattering

- $d\sigma_e/d\Omega \propto \sin^2\theta$
- Sphere + symmetric seed photon dist: No polarization
- Sphere + asymmetric seed photon dist: $p_0 \sim 2 - 8\%$
- Slab: $p_0 \sim 2 - 15\%$

Higher scattering orders have higher p_0, emission angle dependent



e.g. Sunyaev & Titarchuk (1985)

Basic expectations

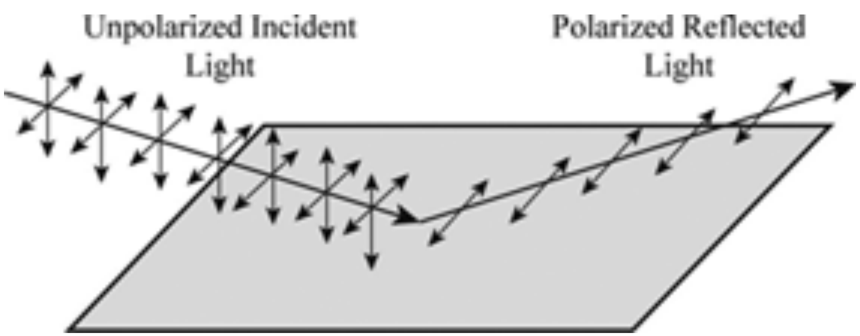
Disc

- Blackbody from mid-plane unpolarized, polarization from scattering in the atmosphere:
- $p_0 \sim 1-5\%$, angle dependent

Chandrasekhar (1960)

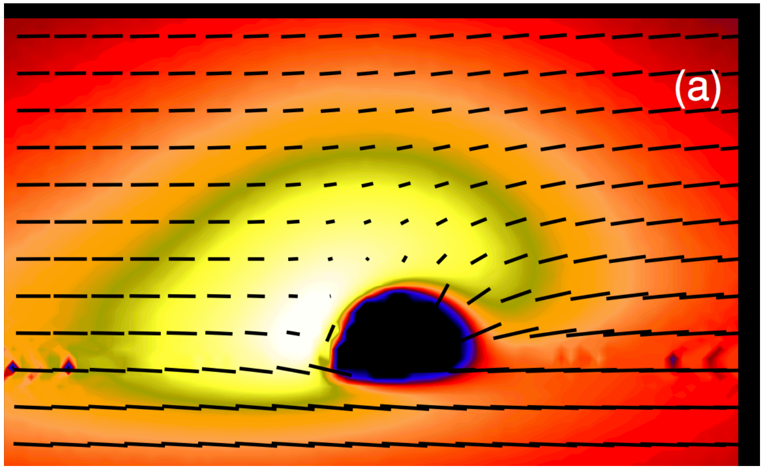
Reflection

- $p_0(\theta_e) \sim 0-100\%$, $\psi_0(\theta_e) \sim 0-180°$ depending on emission angle



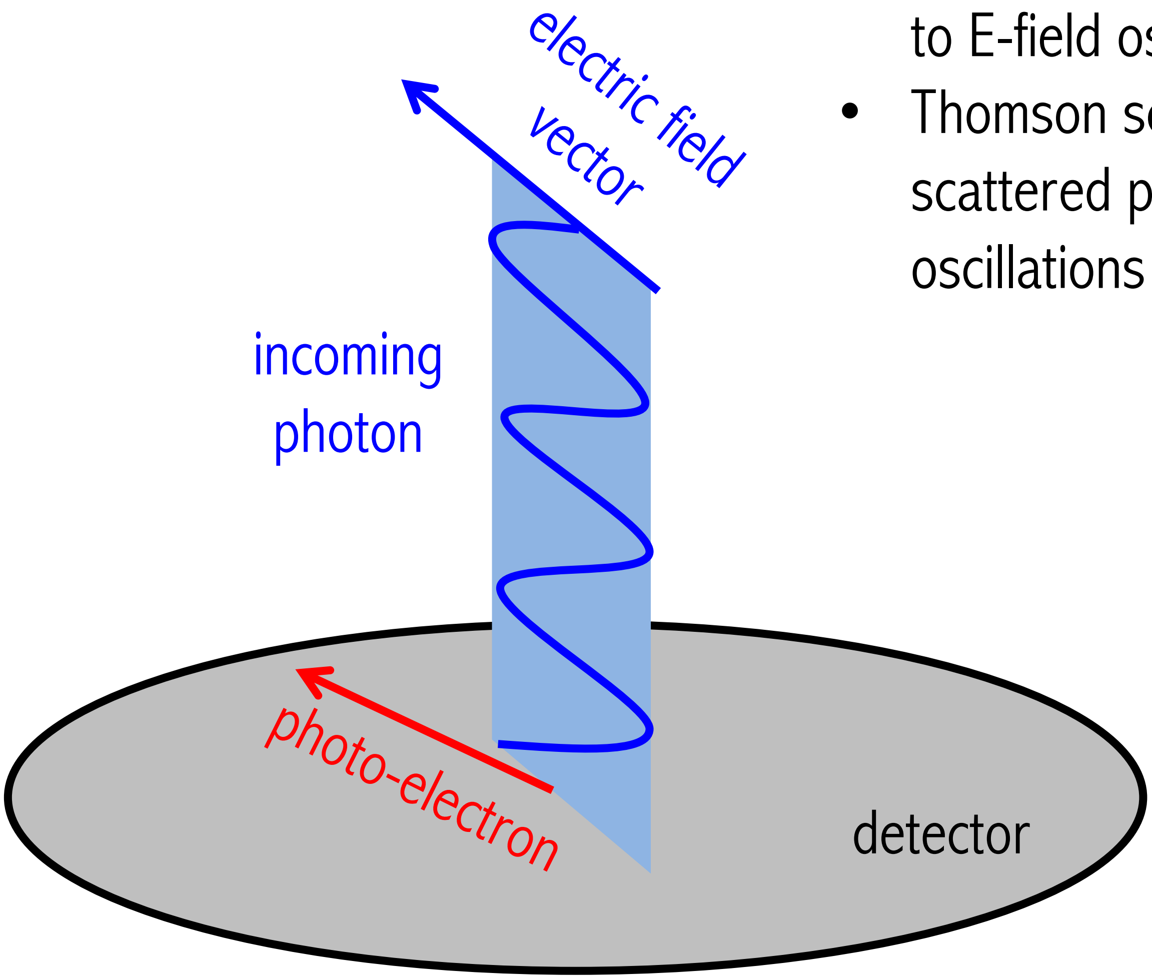
Relativistic effects

- Mixing of emission angles (like relxill)
- Parallel transport (gravitational Faraday rotation),
- Returning radiation



Schnittman et al (2010)

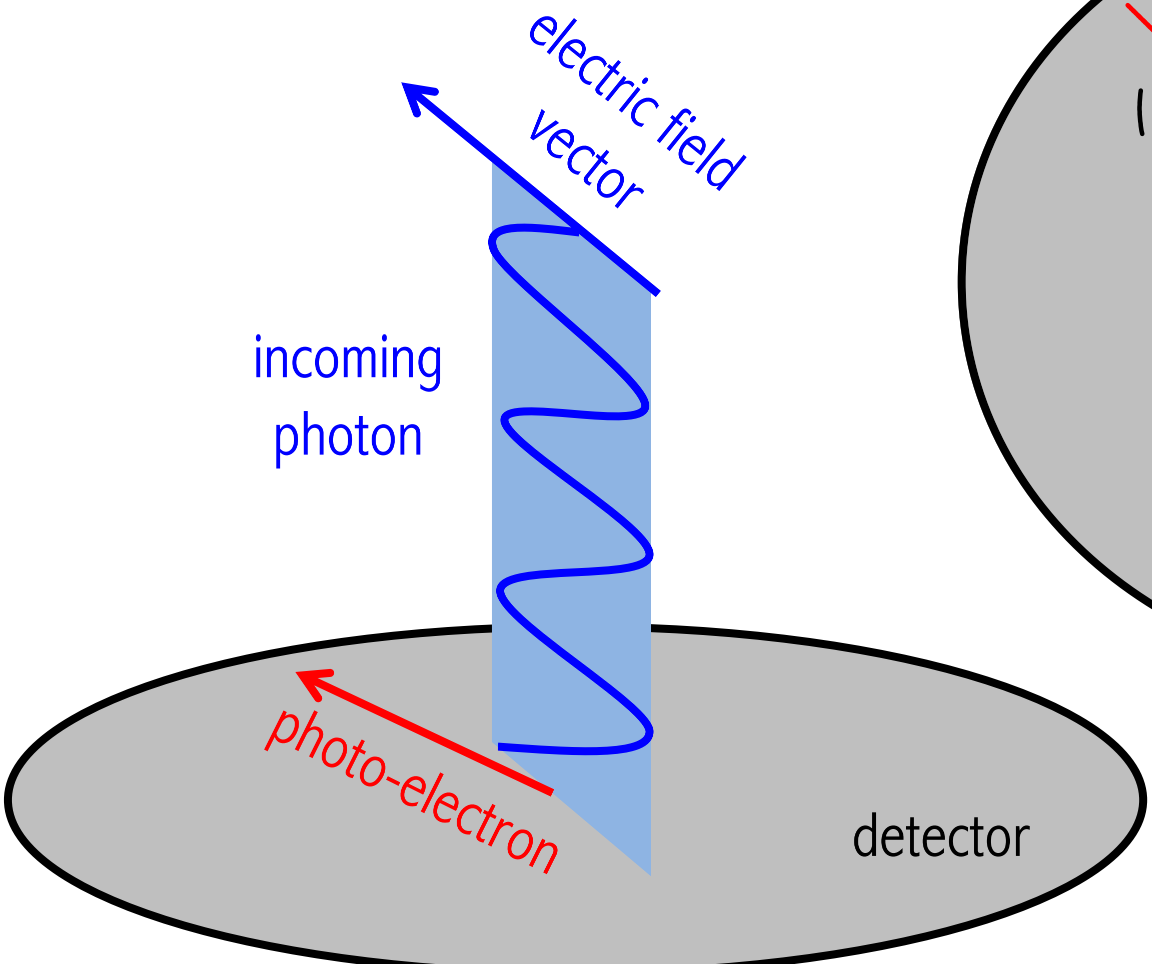
X-ray polarimetry

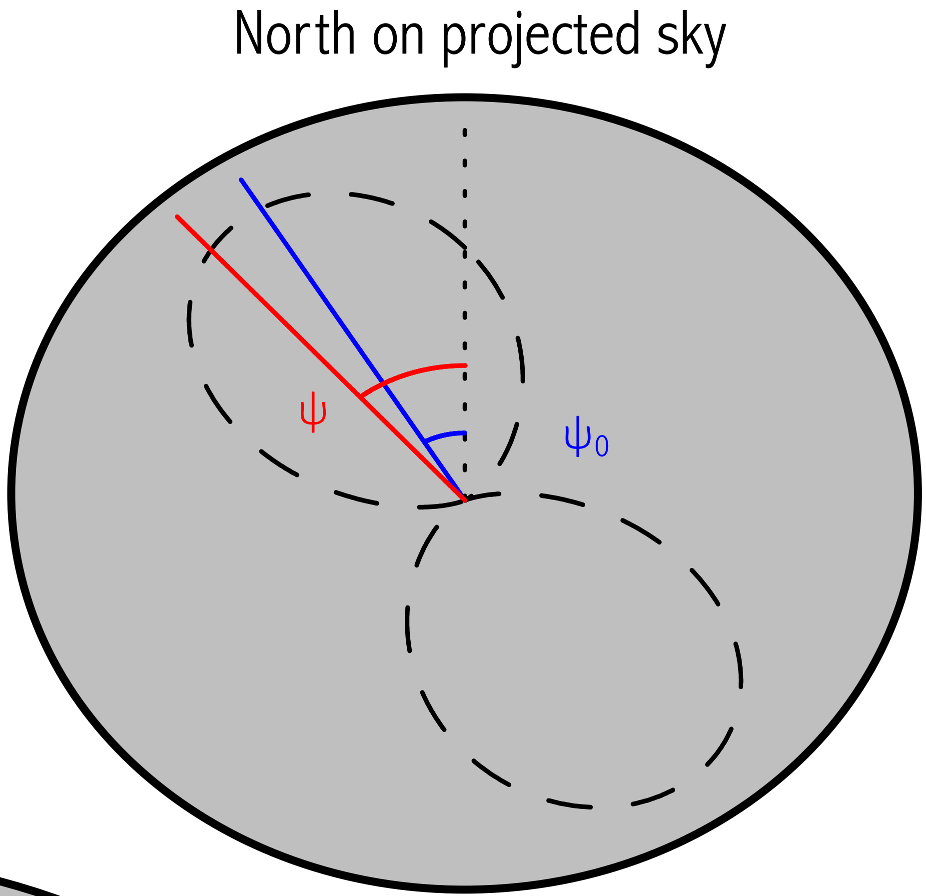


- Photo-electric effect: photo-electron preferentially travels parallel / anti-parallel to E-field oscillations
- Thomson scattering: photon preferentially scattered perpendicular to its E-field oscillations

X-ray polarimetry

ψ_0 = polarisation angle
ψ = modulation angle

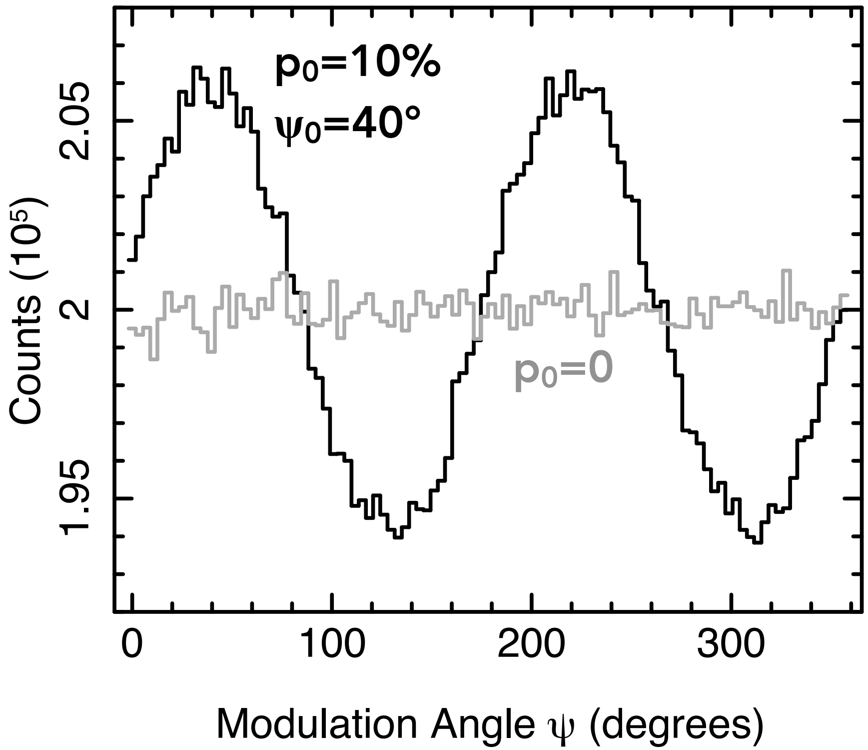


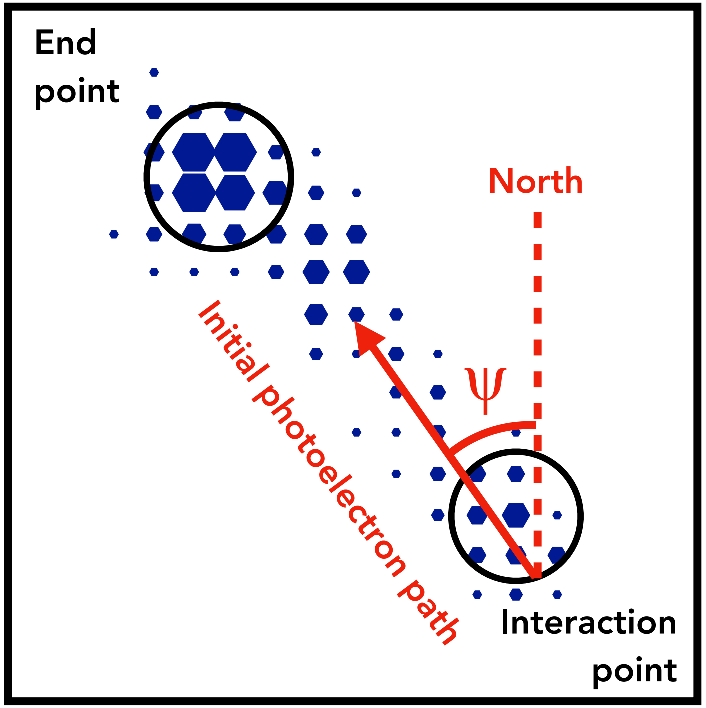


X-ray polarimetry

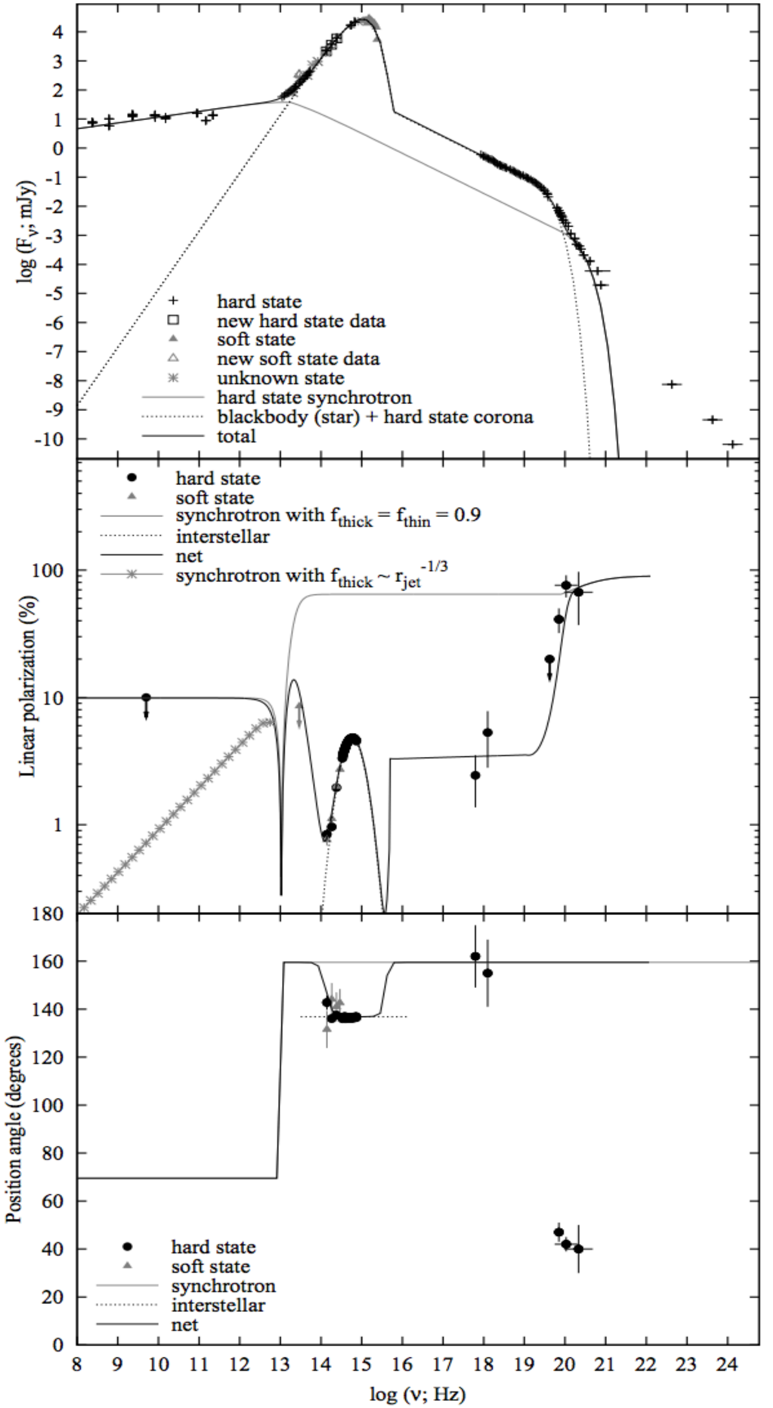
$$f(\psi) \propto 1 + \mu p_0 \cos[2(\psi_0 - \psi)]$$

μ = modulation factor





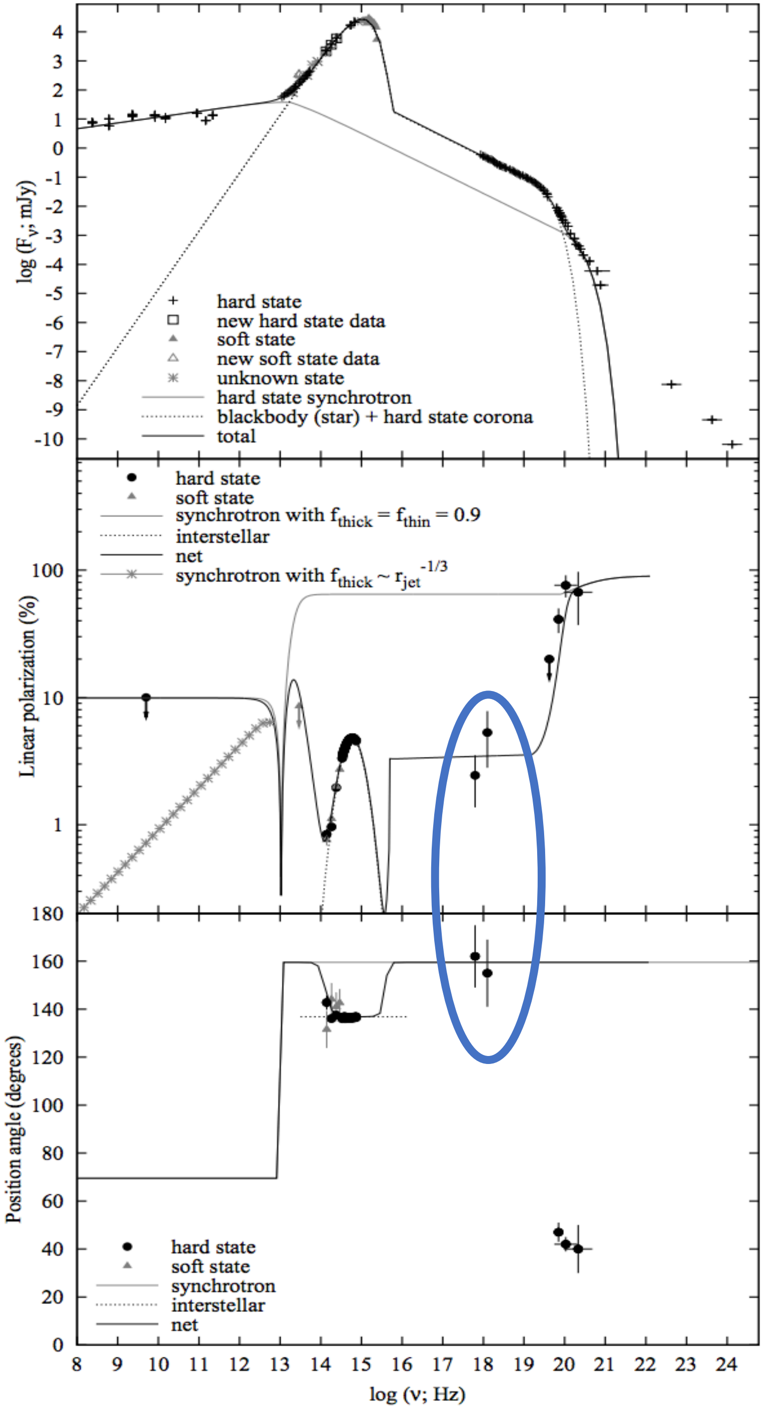
Cyg X-1 polarization

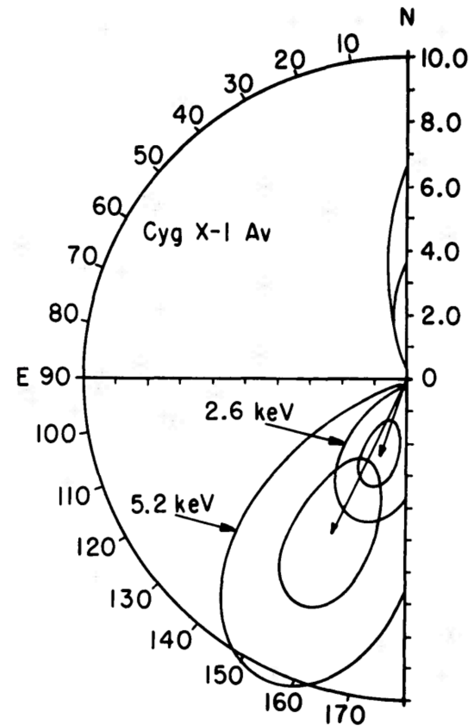


Russell & Shahbaz (2014)

Cyg X-1 polarization

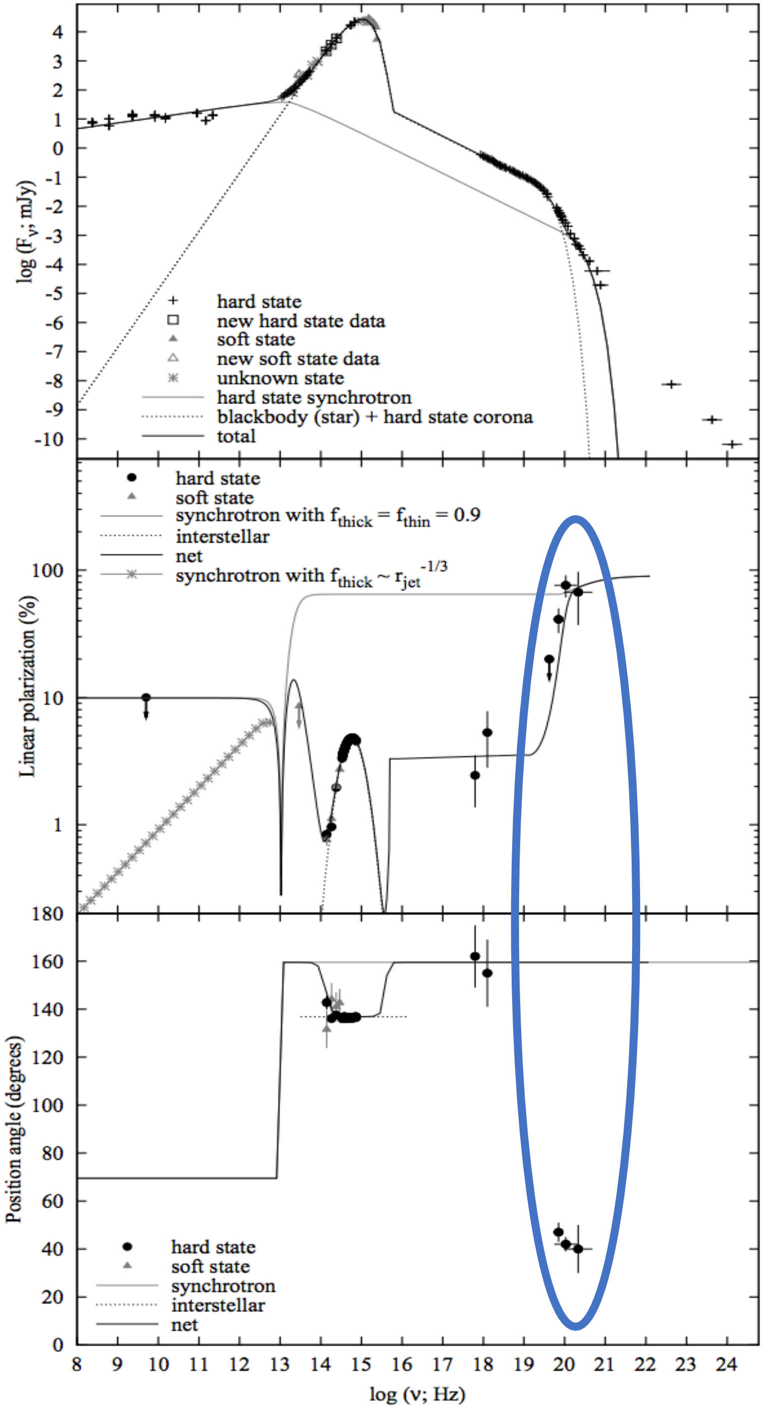
- Soft X-rays, OSO-8: ~5%, but less than 3σ significance
- Polarization angle aligned with jet



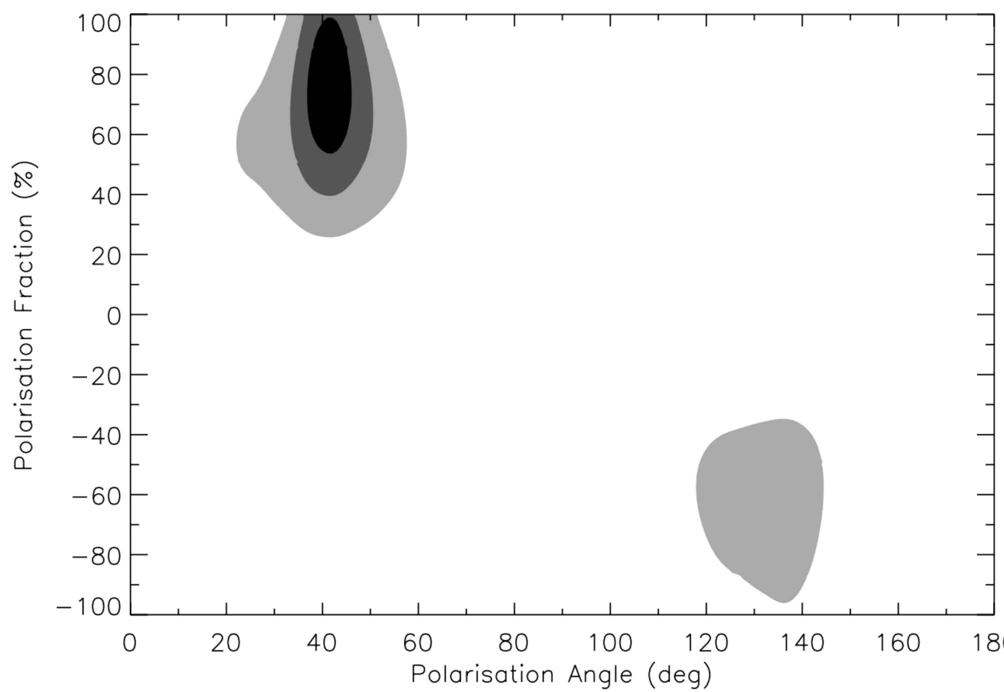


Long, Shanan & Novik (1980)

Cyg X-1 polarization

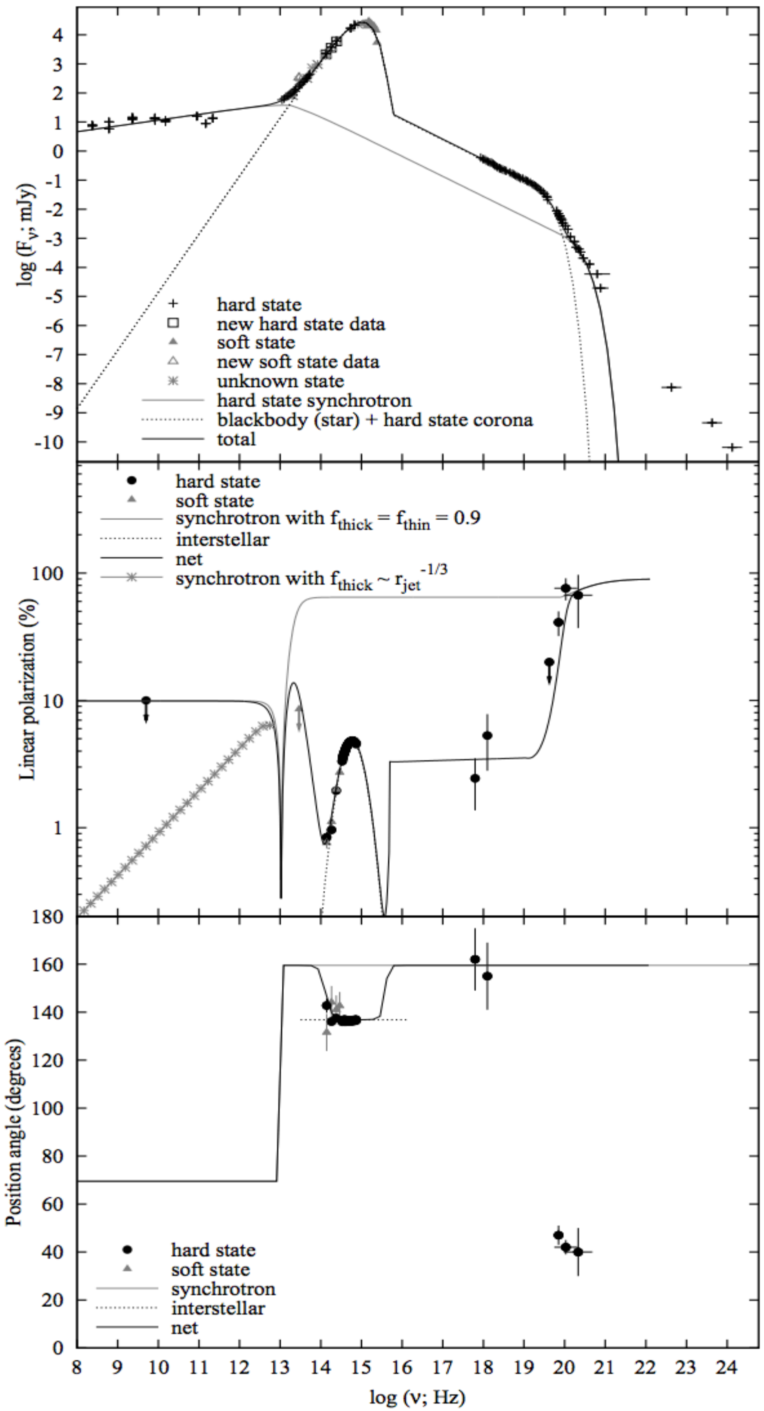


- γ-rays, INTEGRAL: ~70% polarization
- Polarization angle totally different to jet



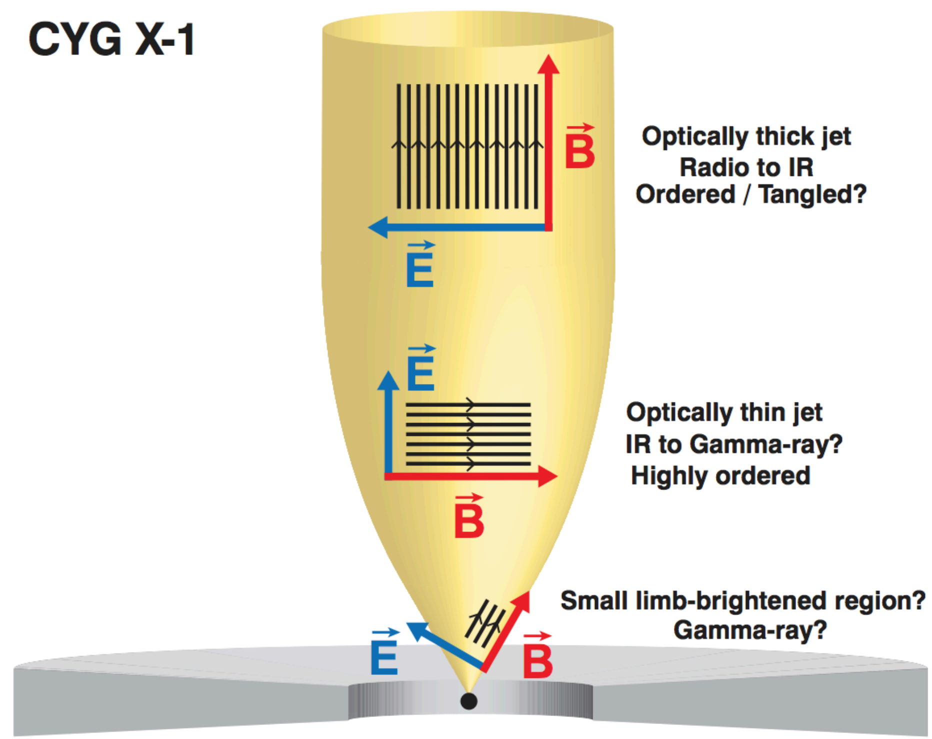
Laurent et al (2011); Jourdain et al (2012)

Cyg X-1 polarization



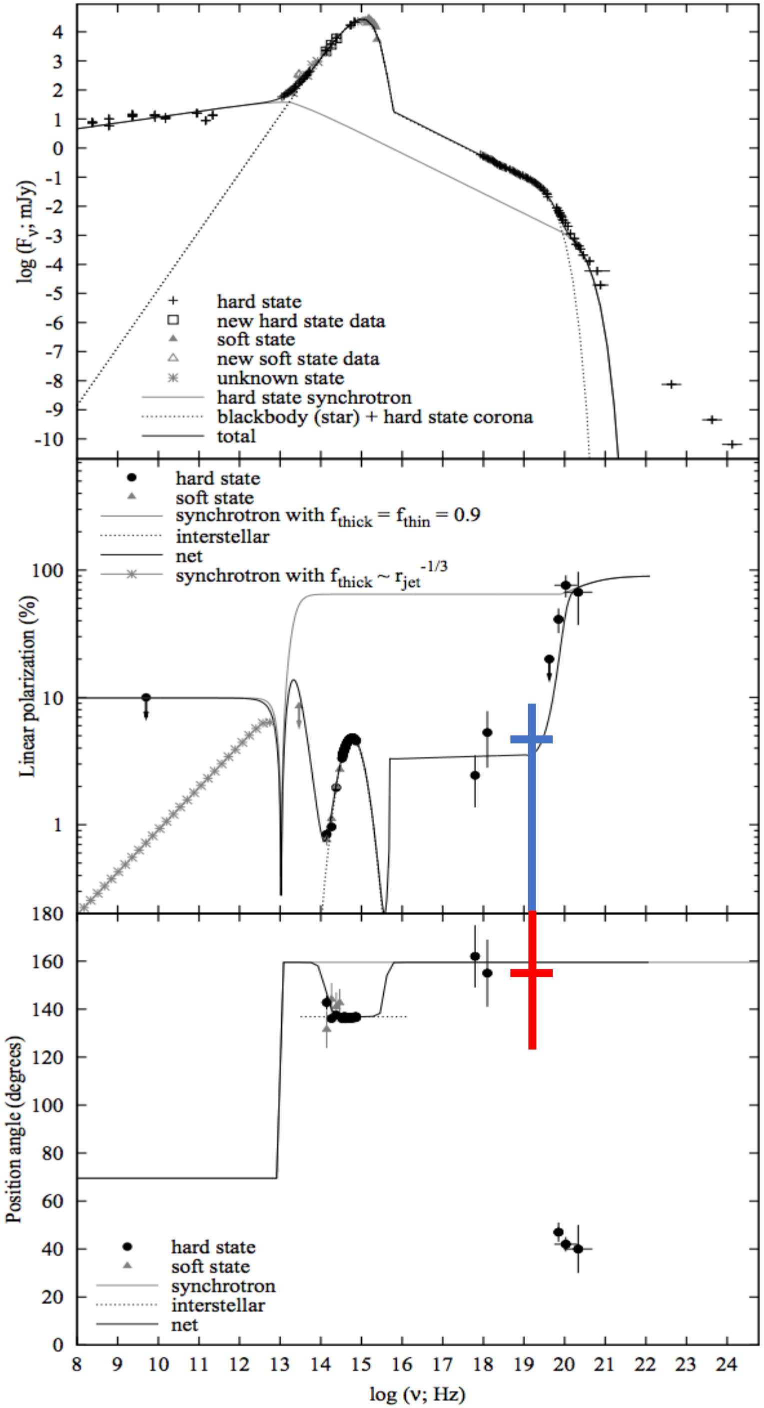
Toy model:

- Unpolarized corona
- 70% polarized optically thin synchrotron jet

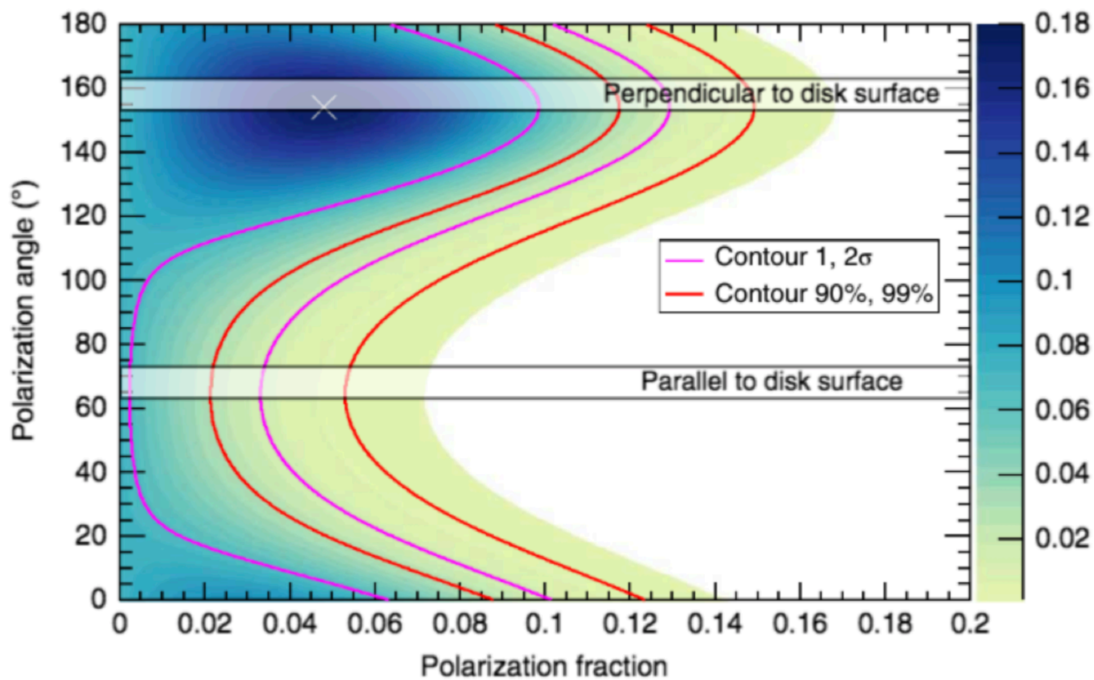


Russell & Shahbaz (2014)

Cyg X-1 polarization



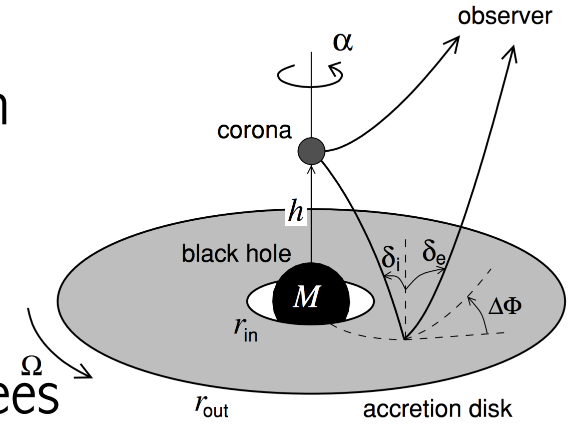
- Hard X-rays, POGO+ balloon flight: ~5%, but less than 1σ significance
- Polarization angle aligned with jet
- Fits Russell & Shabaz's toy model remarkable well!



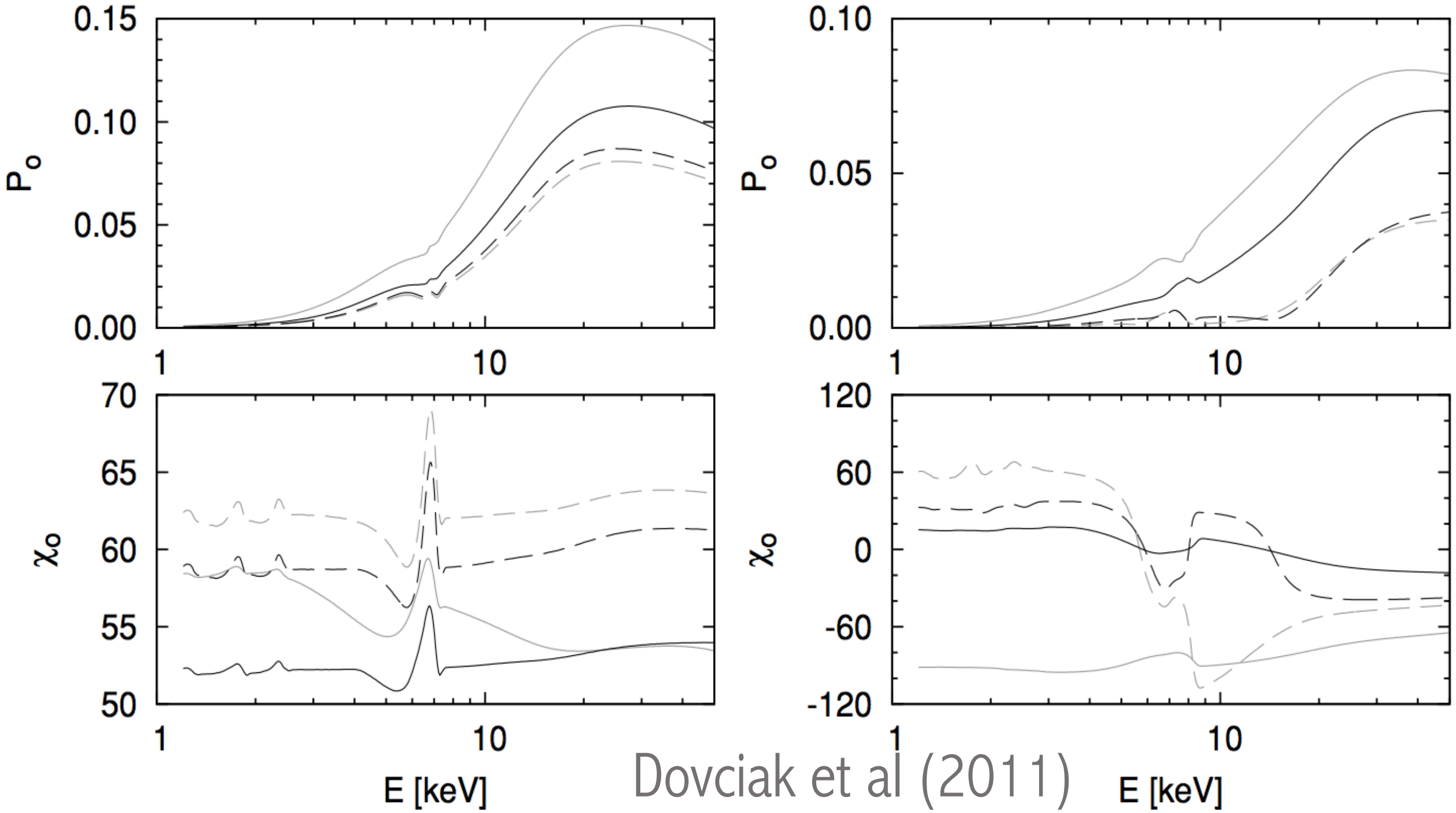
Chauvin et al (2018)

Lamppost model

- Corona unpolarized, all polarization comes from reflection
- Polarization angle = 0 means it aligns with disc normal



inc = 30 degrees | inc = 60 degrees



Dovciak et al (2011)

Black: spin = 0

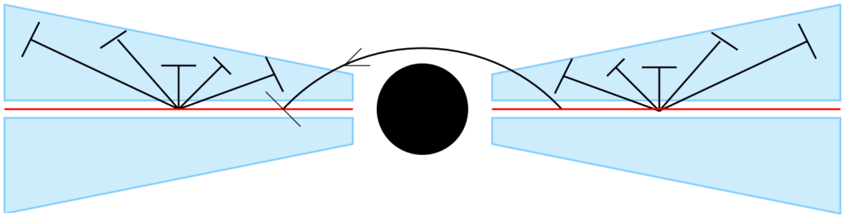
Grey: spin = 1

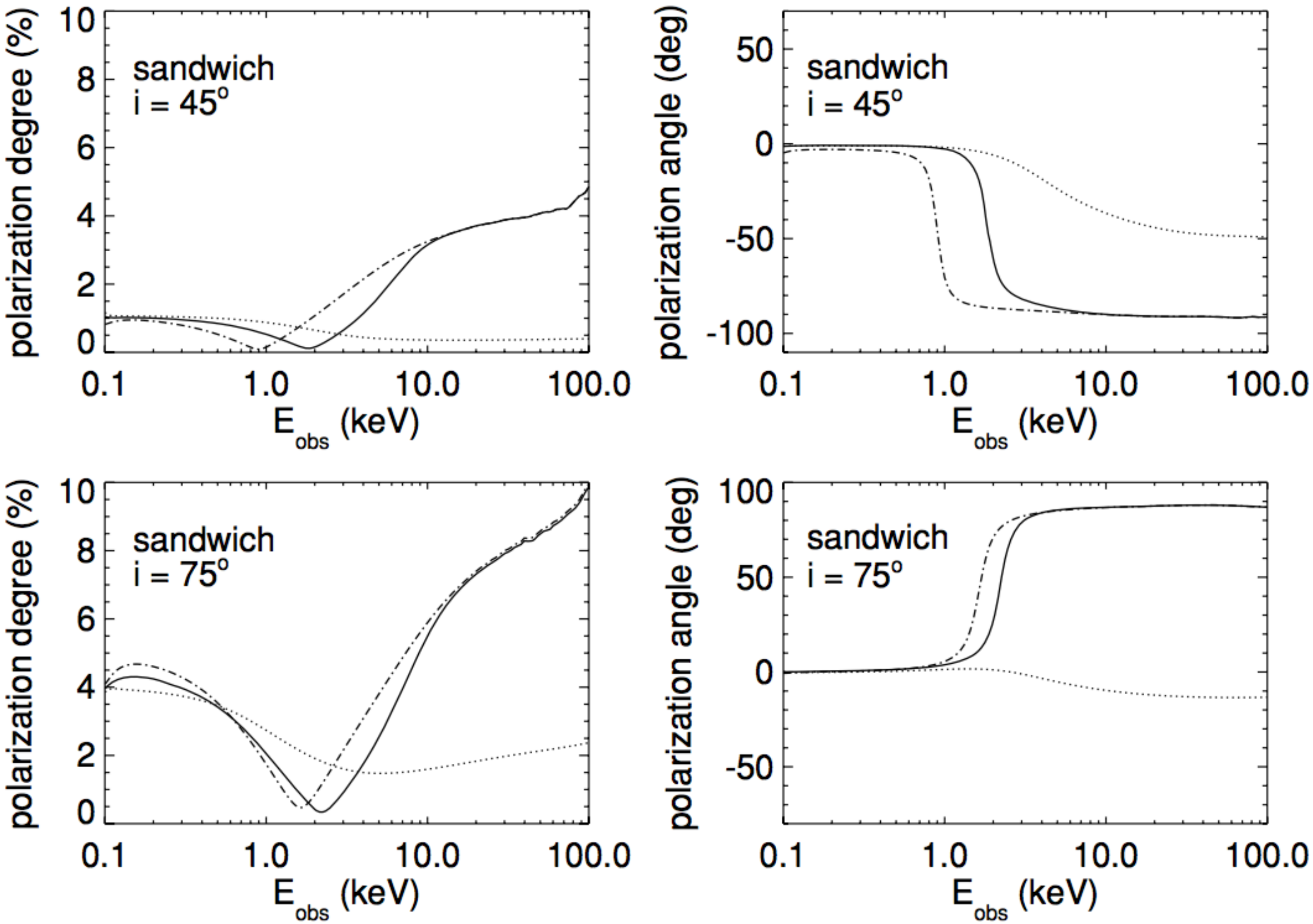
Solid: h = 3 Rg

Dashed: h = 15 Rg

Sandwich model

Schnittman et al (2010)



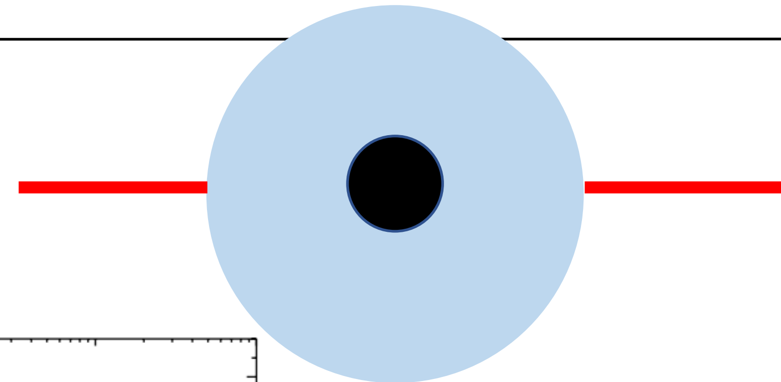


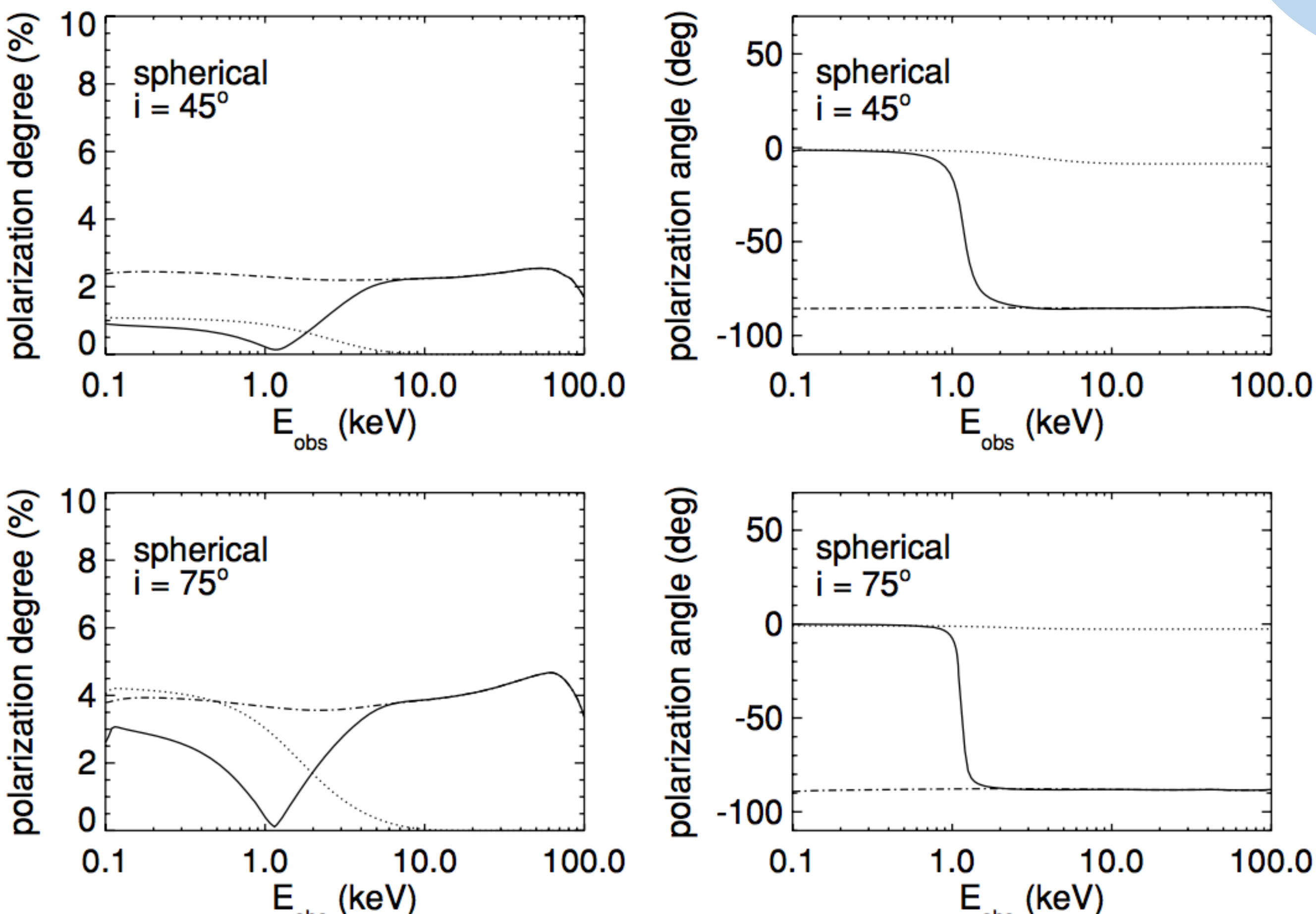
Dotted: only disc

Dashed: only corona

Truncated disc model

Schnittman et al (2010)

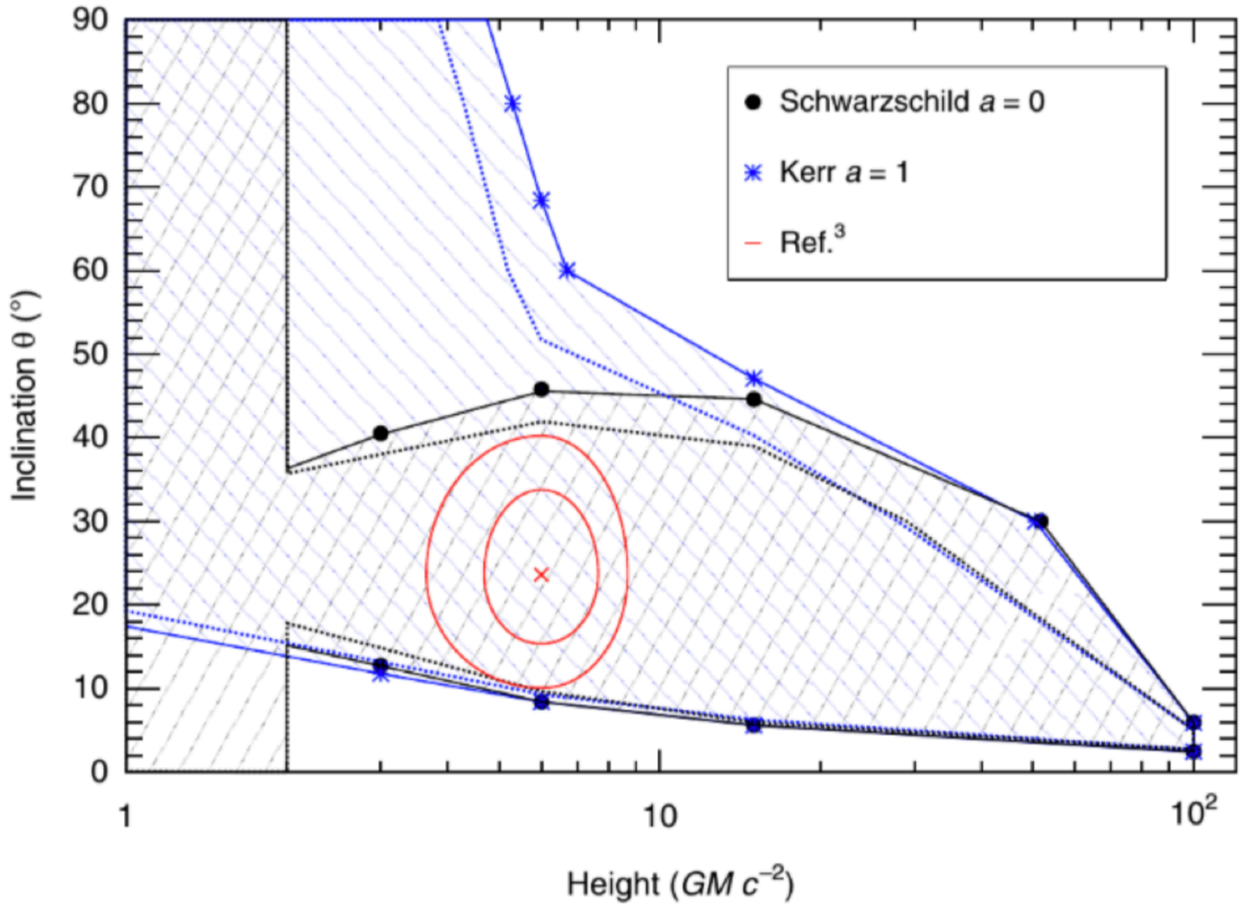




Dotted: only disc

Dashed: only corona

Lamppost model ruled out?

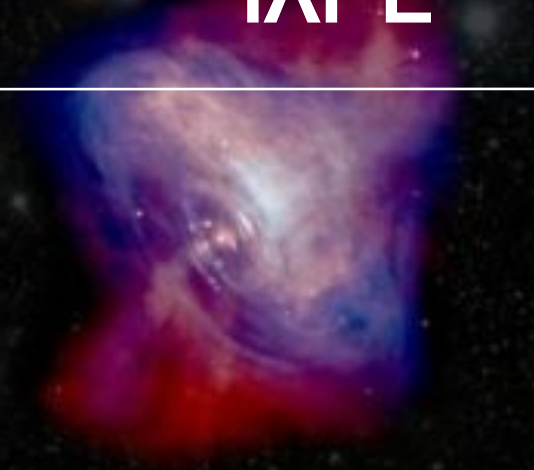


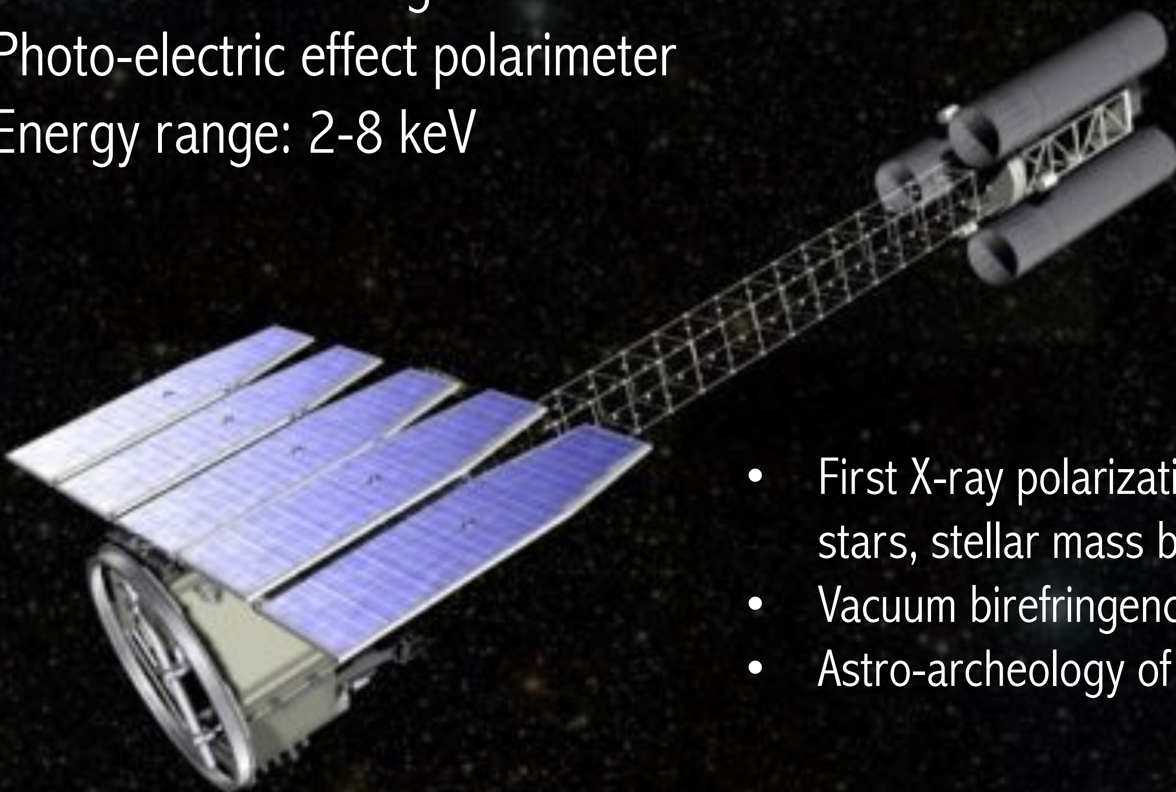
- Chauvin et al (2018) argue their POGO+ result rules out parameter space of lamppost model
- The Dovciak (2011) model has many simplifications though

IXPE

The Imaging X-ray Polarimetry Explorer

- NASA Small Explorer mission
- Launch: May 2021
- Passed Critical Design Review
- Photo-electric effect polarimeter
- Energy range: 2-8 keV





Some Science

- First X-ray polarization measurements of neutron stars, stellar mass black holes and AGN
- Vacuum birefringence from high B-field NSs (QED)
- Astro-archeology of Galaxy center

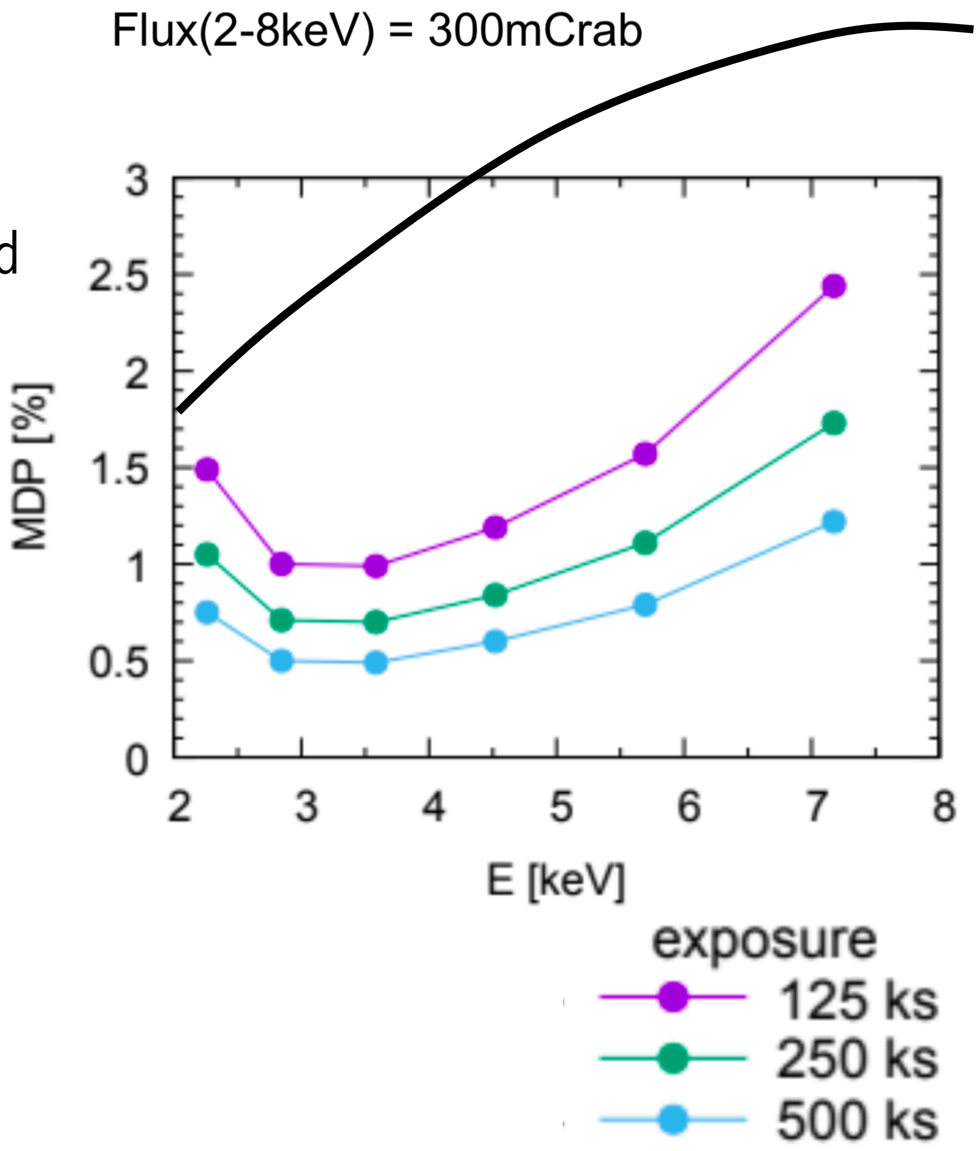
IXPE

Y1 Observing plan

BH XRB transients:
3 ~300 ks ToOs, each one includes a hard state and soft state pointing

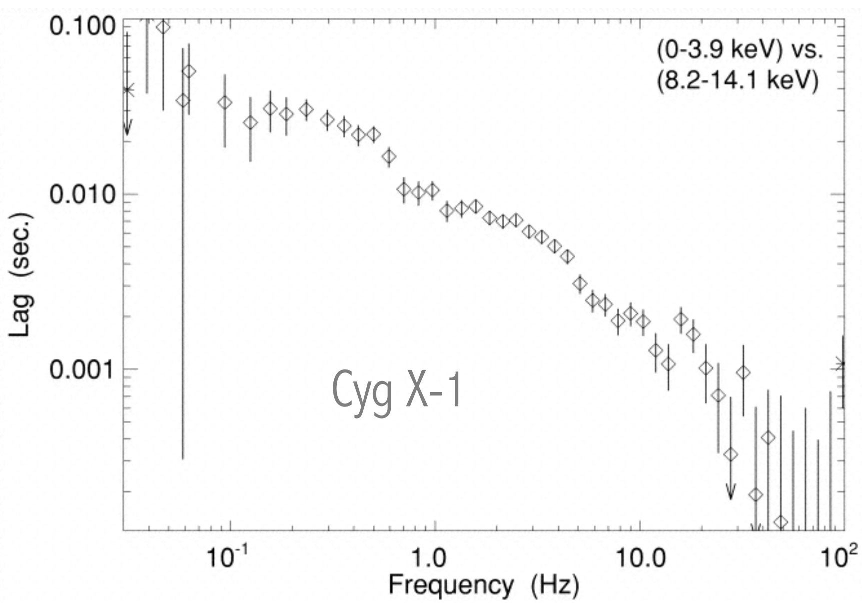
BH XRB persistent sources:
4 targets are GRS1915+105, Cyg X-1, 1E1740.7-2942 & GRS1758-258 (300 ks each)

AGN:
Circinus galaxy ~ 800ks
MCG-5-23-16 ~ 500ks
IC 4329A ~ 500ks

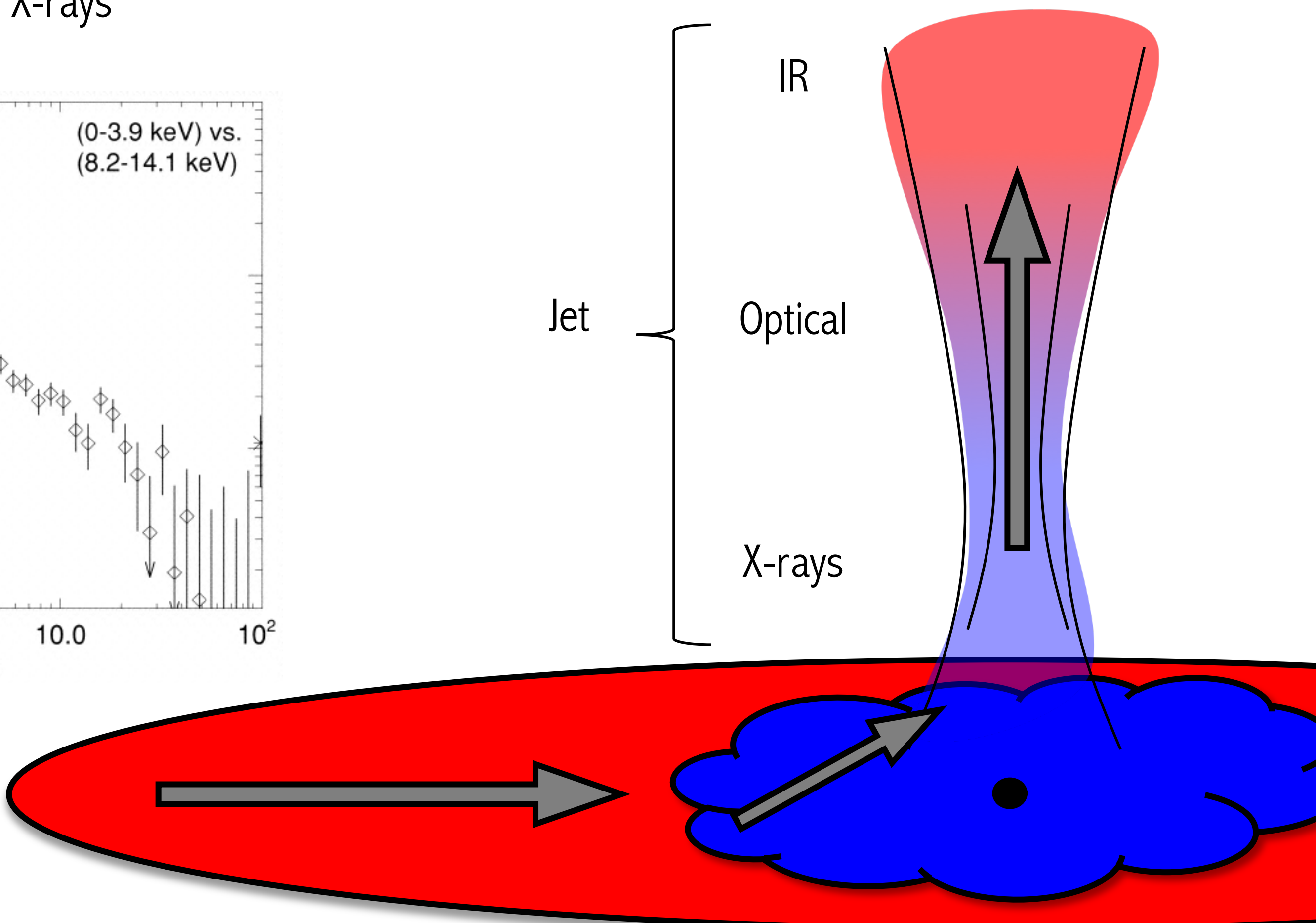


Propagating fluctuations

Hard X-rays lag soft X-rays

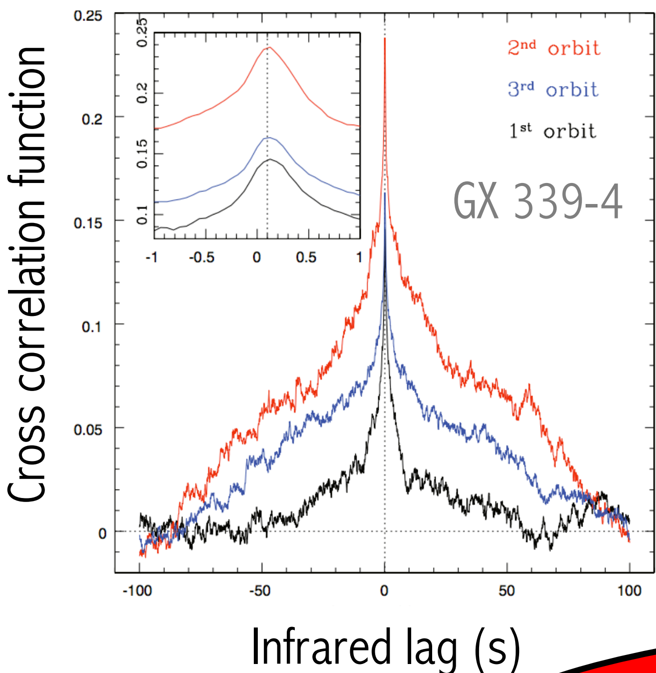


Nowak et al (1999)

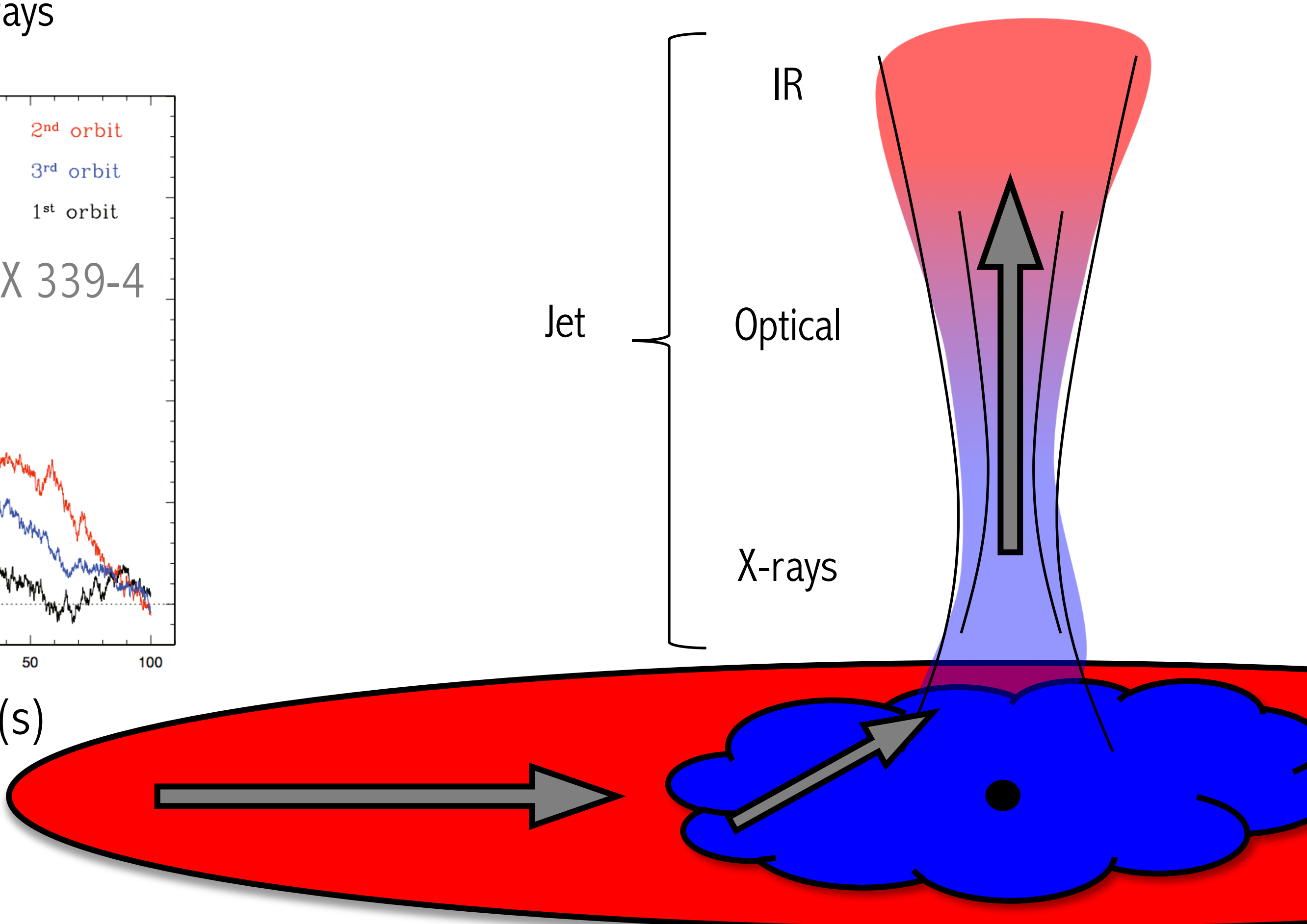


Propagating fluctuations

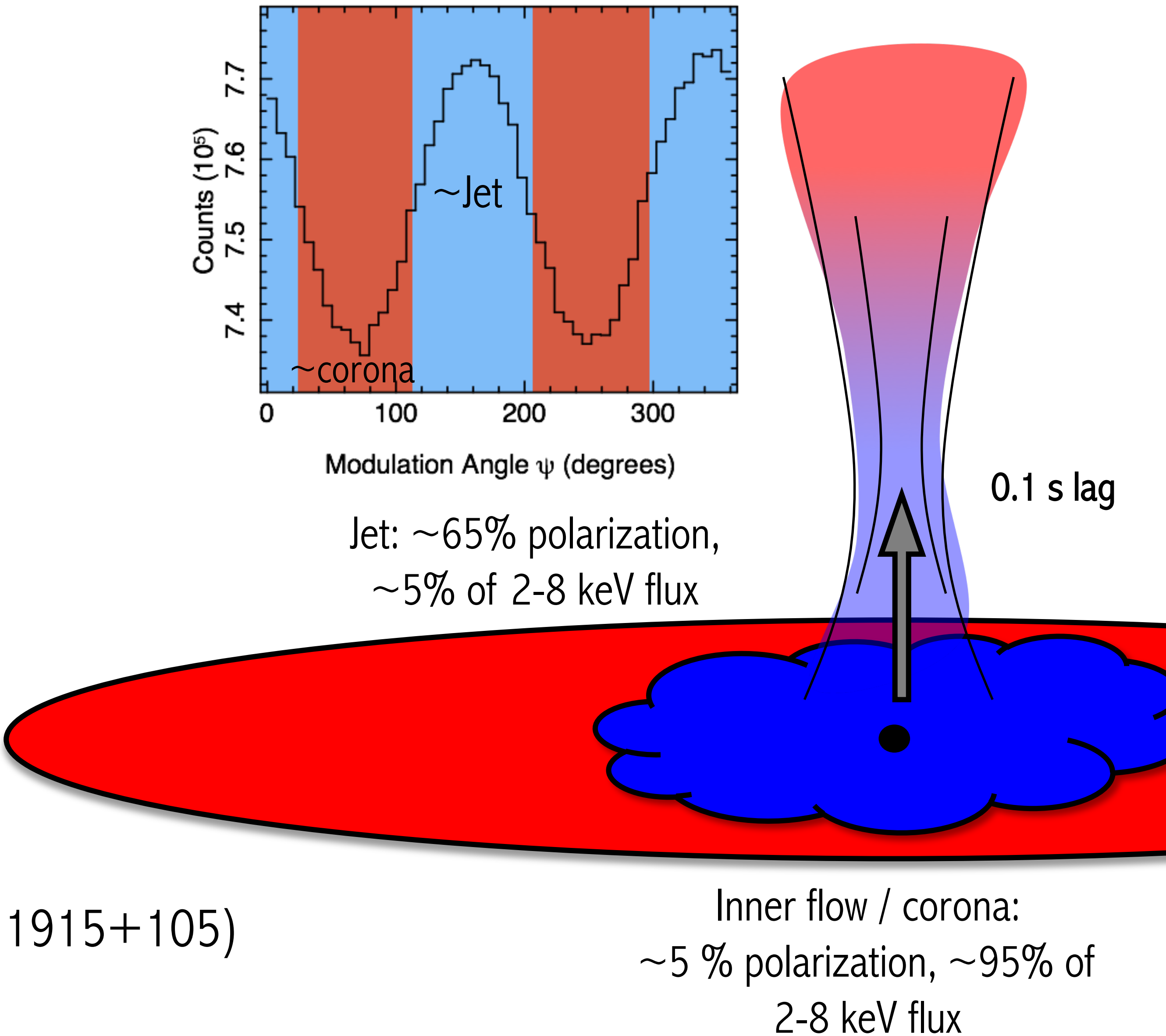
Infrared lags X-rays



Casella et al (2010)

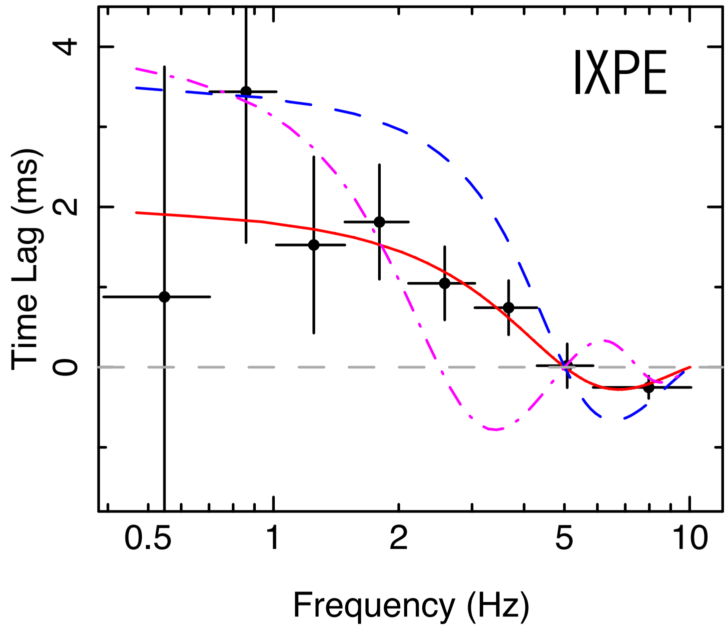


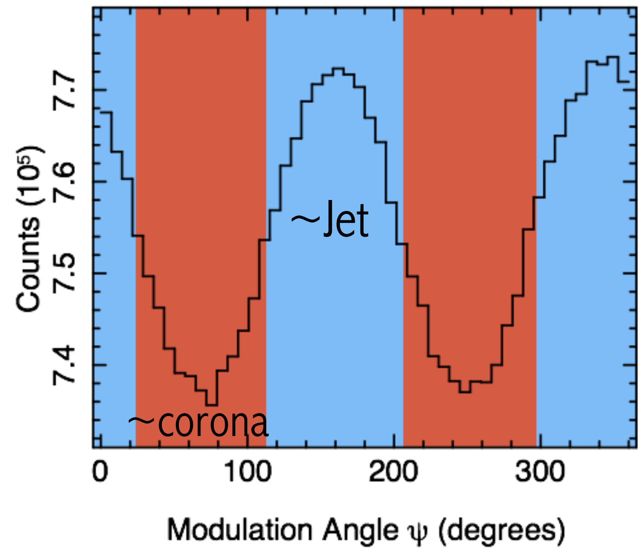
Propagating fluctuations



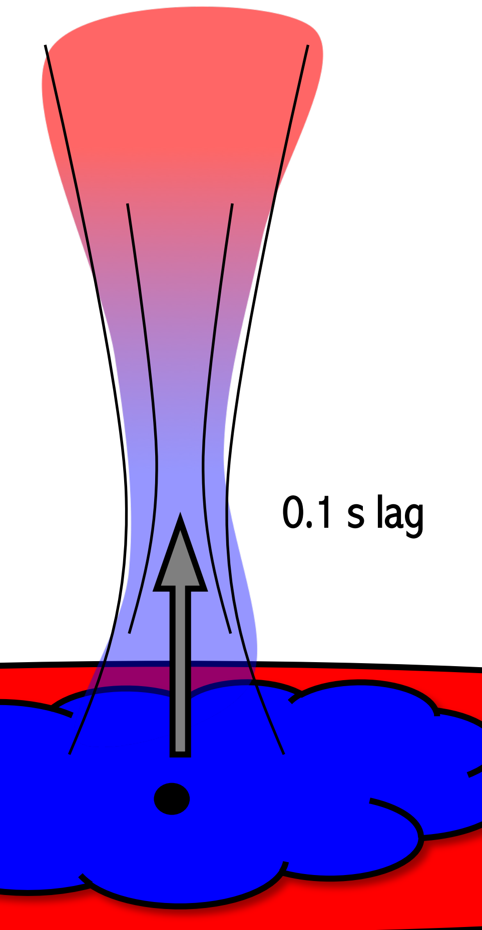
- 200 ks exposure
- Bright source (~GRS 1915+105)

Propagating fluctuations





Jet: ~65% polarization, ~5% (10%) of 2-8 keV flux

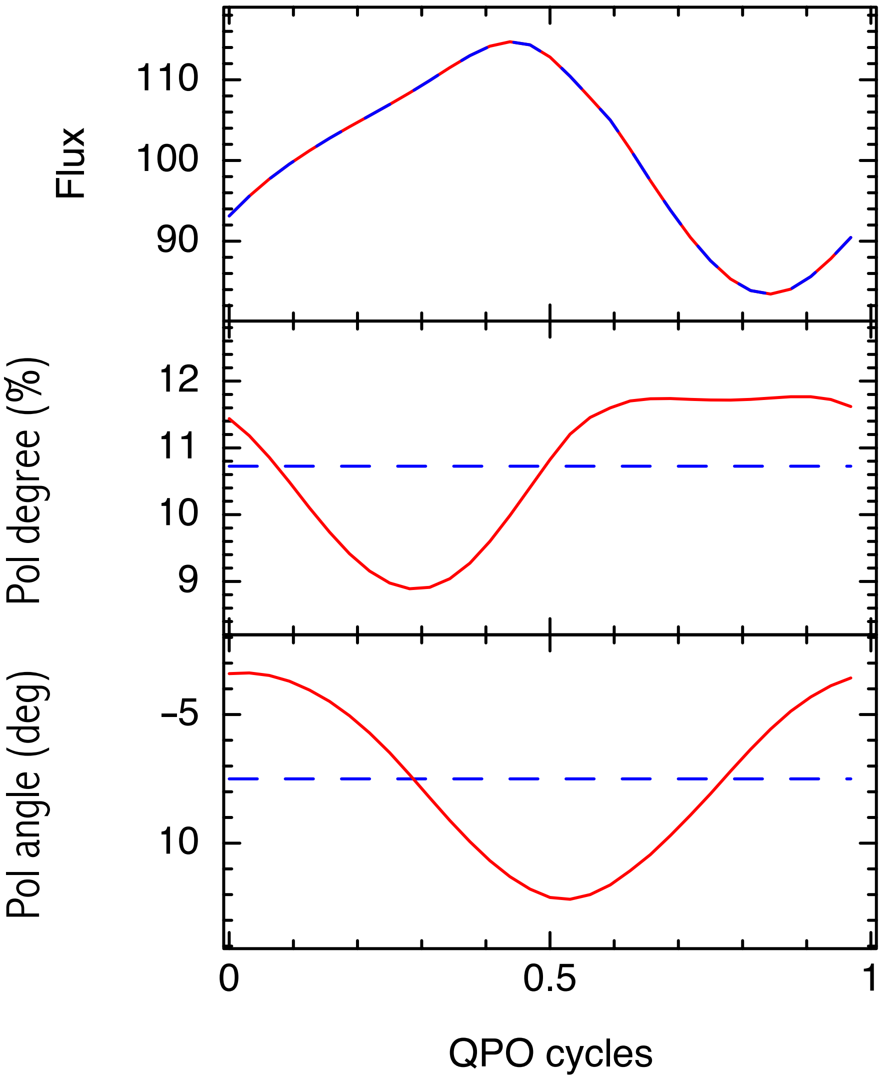


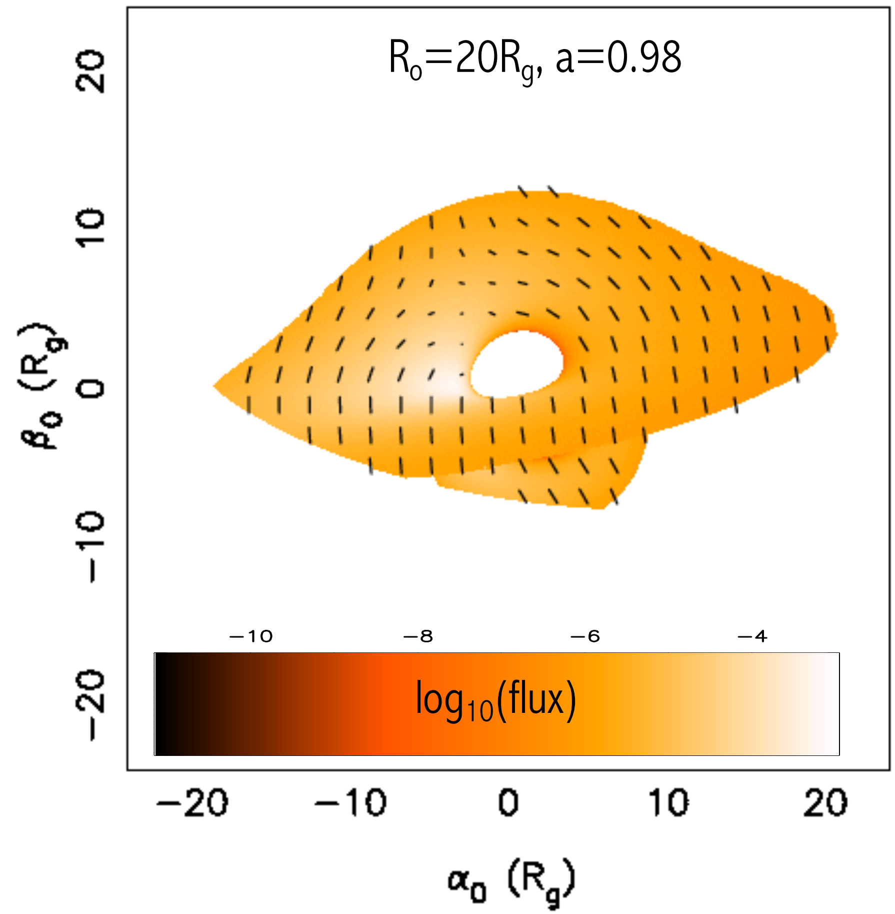
Inner flow / corona:
~5 % (10%) polarization,
~95% (90%) of 2-8 keV flux

- 200 ks exposure
- Bright source (~GRS 1915+105)

Polarization modulation

i = 70 degrees

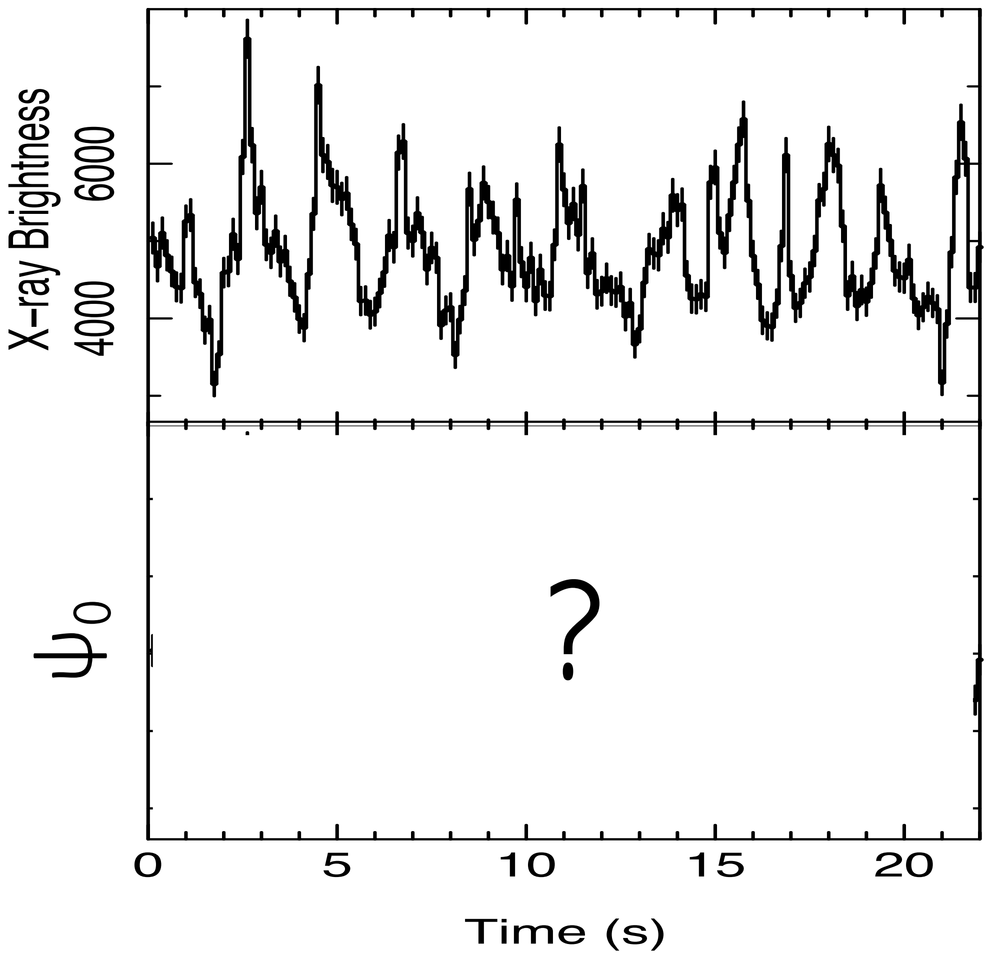




Ingram et al (2015)

www.youtube.com/watch?v=ieZYYfCapJg&feature=youtu.be

Detection



Can we make a time series?

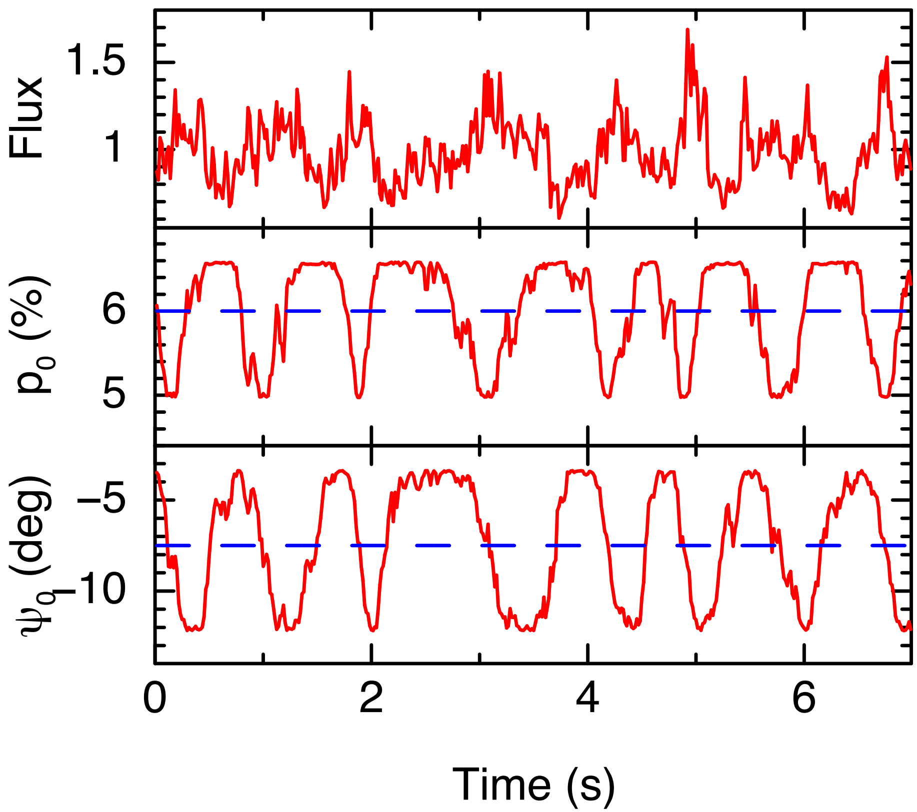
- IXPE count rate ~ 100 c/s
- p_0 of source < ~10%
- Integration time:

T ~ 4 minutes!

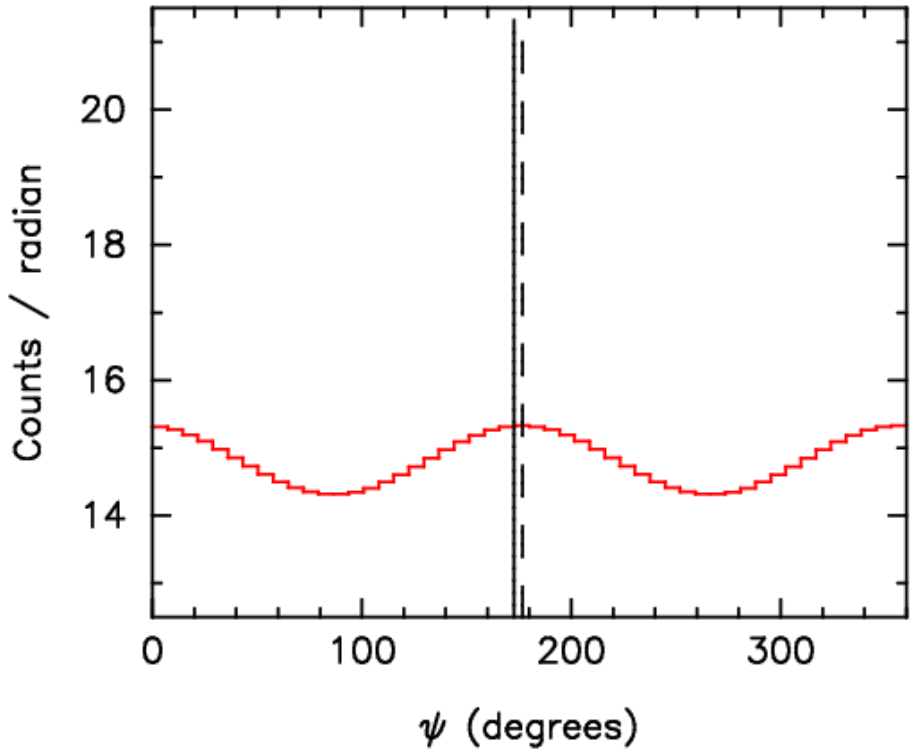
So can't probe variability on timescales of seconds ☹

Detection

Model



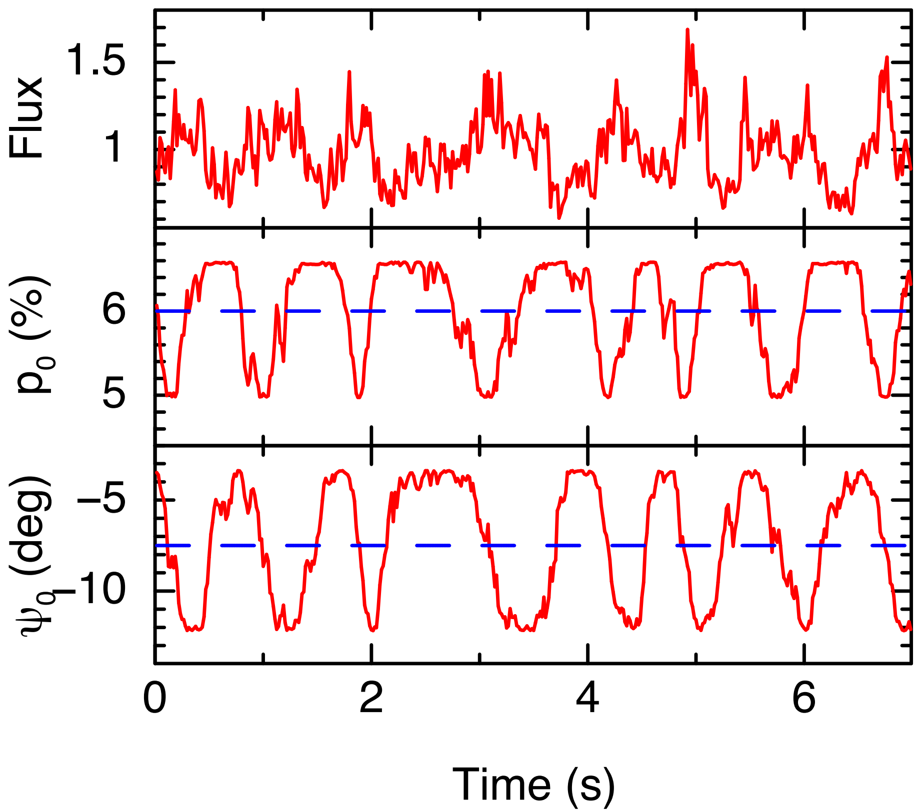
Modulation function



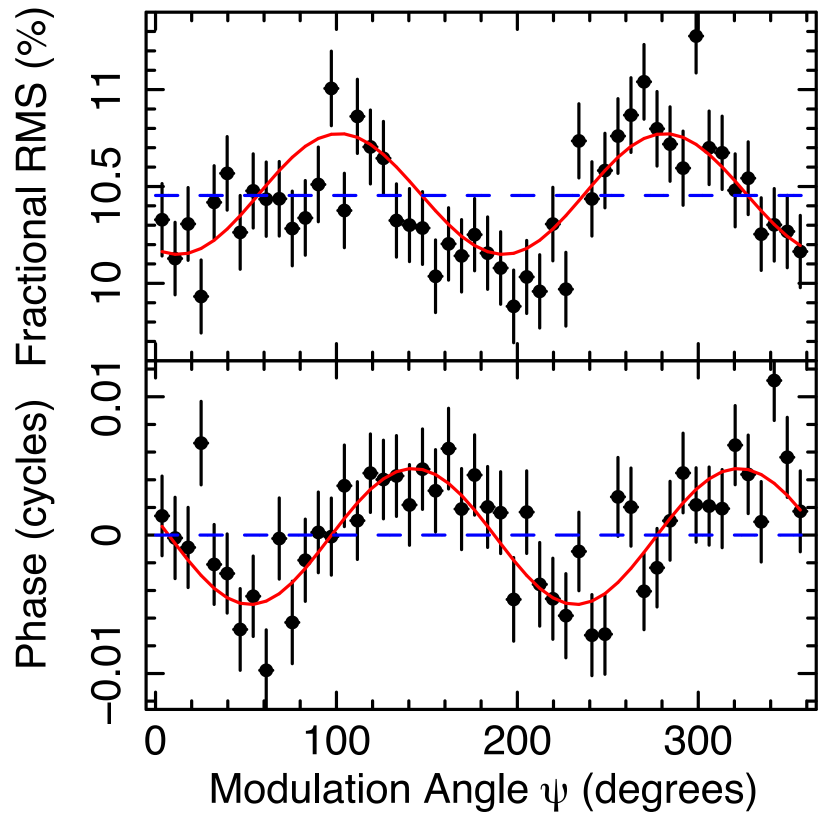
Ingram & Maccarone (2017)

Detection

Model



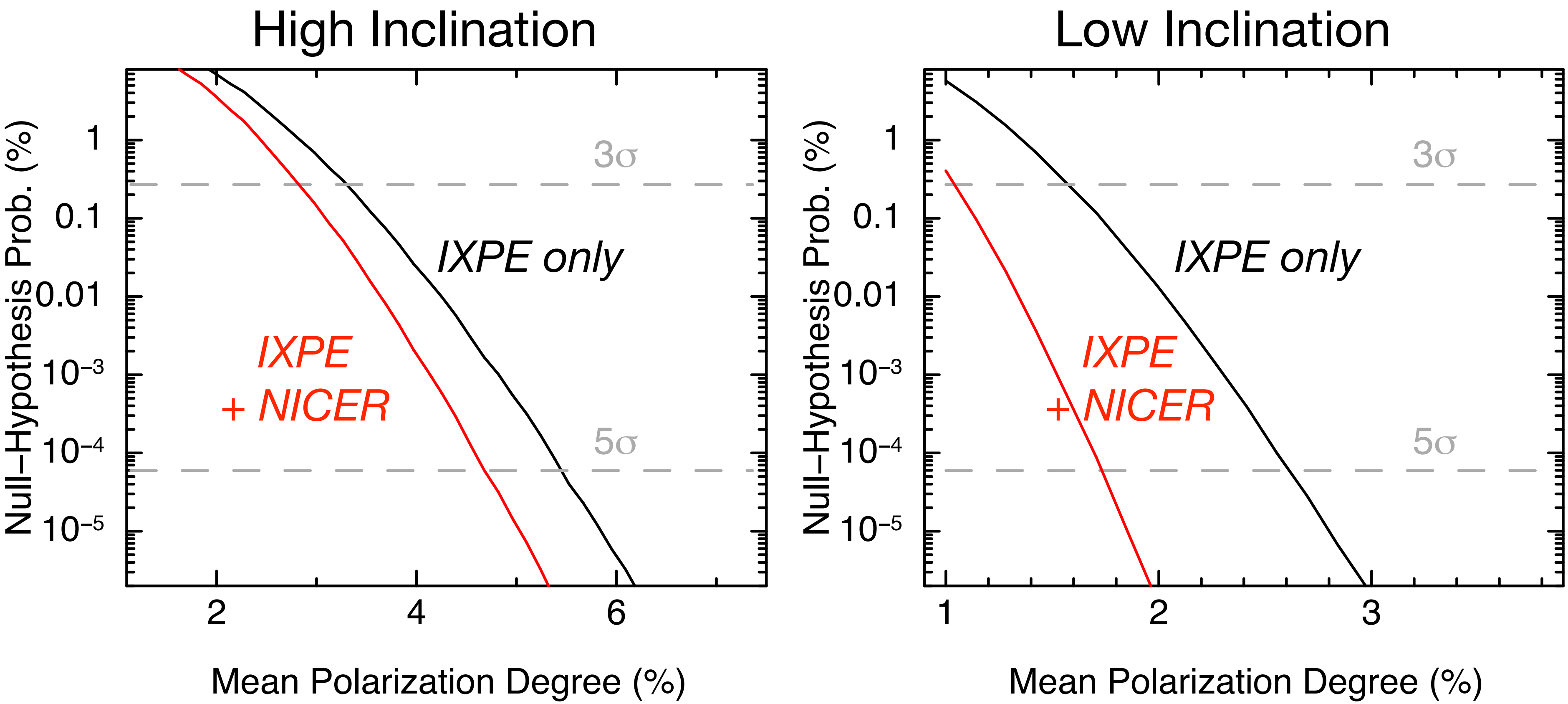
Modulation function



- Make light curves selected on modulation angle
- Calculate QPO amplitude for each light curve
- Calculate phase lag between the different light curves

Ingram & Maccarone (2017)

Sensitivity

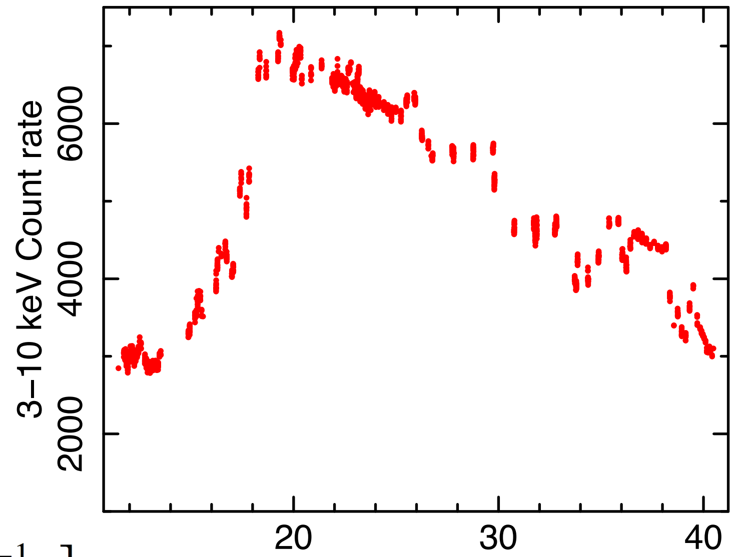


- Mean pol degree most uncertain thing in modelling (everything else just geometry + GR)
- High inclination = low amplitude pol variability; Low inclination = high amplitude pol variability
- But high inclination sources expected to have higher mean pol degree
- Cross-correlation with a bigger detector boosts signal

Ingram & Maccarone (2017)

Dealing with gaps

- NICER light curve has gaps (Earth occultations, ISS structures etc).
- IXPE light curve has gaps at different times.
- Therefore not much strictly simultaneous time ☹



Solution

- Maximum likelihood method: Miller et al (2010); Zoghbi et al (2013)
- Likelihood =

$$\mathcal{L}(\boldsymbol{a_p}) = (2\pi)^{-N/2} |\mathsf{C}_x|^{-1/2} \exp\left[-\tfrac{1}{2}\boldsymbol{x}^T \mathsf{C}_x^{-1} \boldsymbol{x}\right]$$

Parameters (power in each frequency bin)

Matrix calculated from power spectral model

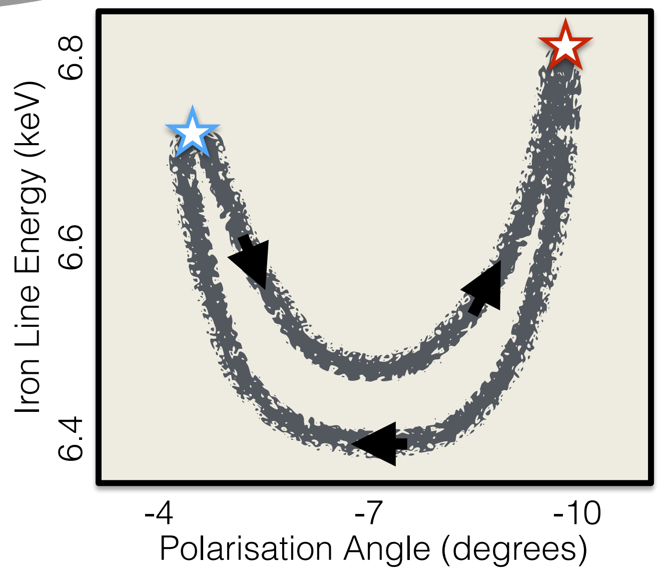
Observed light curve

- Maximize likelihood to get e.g. cross-spectrum between IXPE and NICER
- Already works on e.g. NuSTAR data (Zoghbi et al 2013)

Ingram et al (in prep)

Reconstruction of spin axis

Smile/frown diagram



- Detect polarization QPO with method of Ingram & Maccarone (2017)
- Tomography (NuSTAR, NICER): gives disk illumination pattern
- Polarization: gives orientation of corona
- = reconstruction of black hole spin axis + shape of corona!

The End