Neutron Star Magnetic Fields and Accretion Geometry

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in collaboration with

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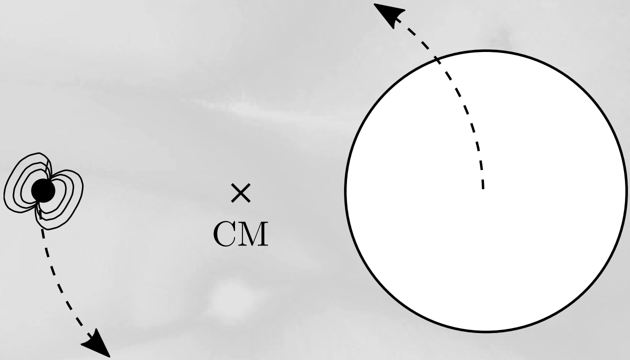
image: Walt Feimer, NASA/Goddard Space Flight Center

Outline: probing neutron star magnetic fields

- Accretion in X-ray binaries
  - Mass transfer
  - Accretion column
- Spin period evolution
  - Coupling at the magnetosphere
  - Angular momentum transfer
- Cyclotron resonant scattering features
  - Landau levels
  - Monte Carlo simulations
- Pulse profile formation
  - Light bending
  - B-field geometry

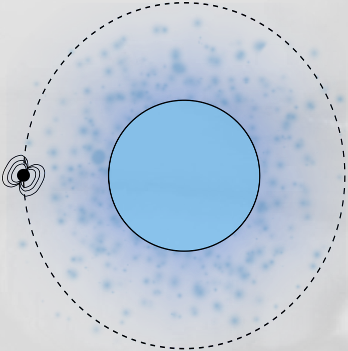
Accretion in X-ray binaries

Orbit and companion define type of accretion

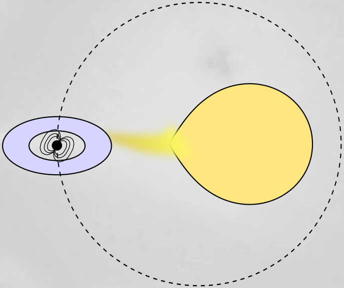


Orbit and companion define type of accretion

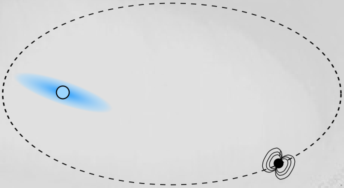
Wind accretion



Disk accretion

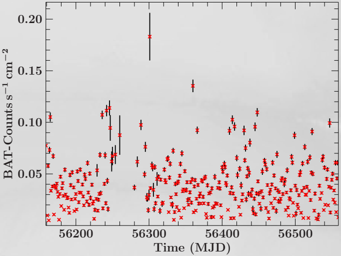


Transient XRBs

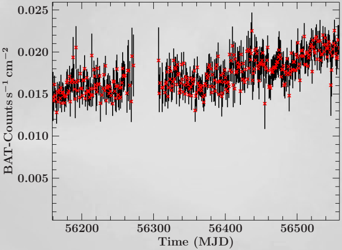


Huge range in variability and mass accretion rate

Wind accretion

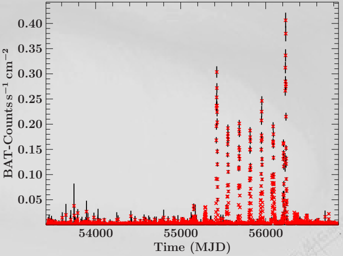


Disk accretion

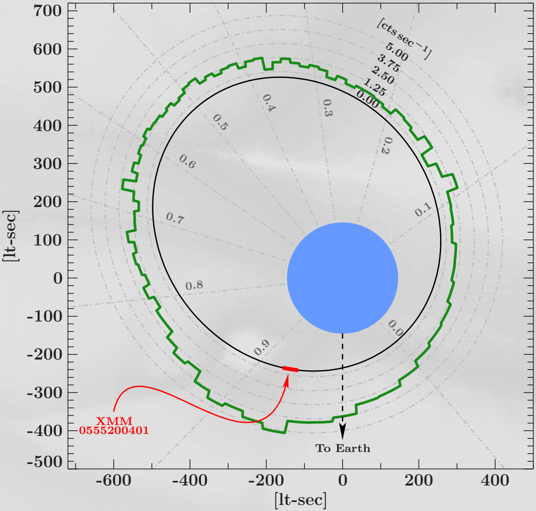


- mass accretion rate
  $\dot{M} \sim 10^{-12\ldots-8}\,\mathrm{M}_\odot\ \mathrm{yr}^{-1}$
- *B*-field interaction over several orders of magnitude

Transient XRBs

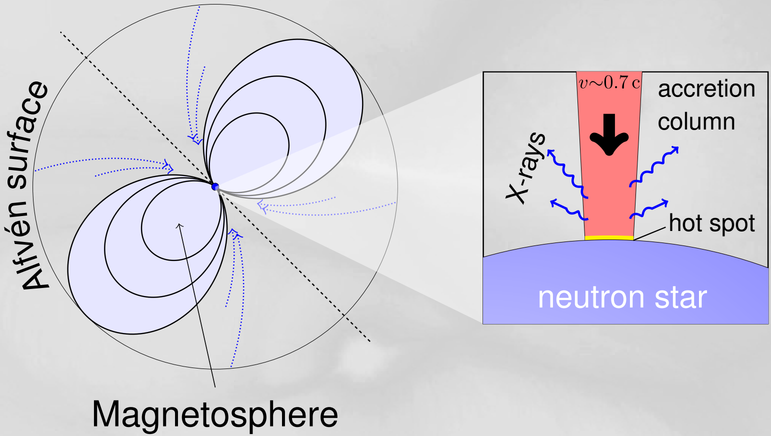


Eccentricity of orbit modulates mass accretion rate



GX 301−2
Fürst et al. (2011)

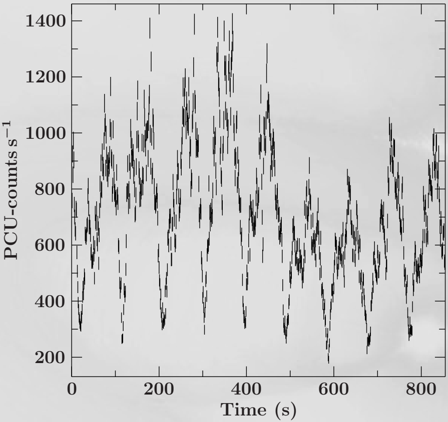
Material follows magnetic fields lines



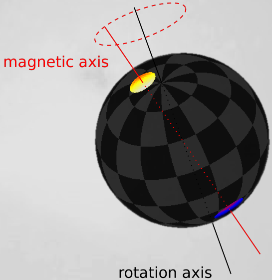
after Davidson & Ostriker (1973)

- Alfvén radius typically 1800 km
- $v \sim 0.7\,c$, hot spot with $T \sim 10^6$ K

Magnetic field axis and rotational axis are misaligned

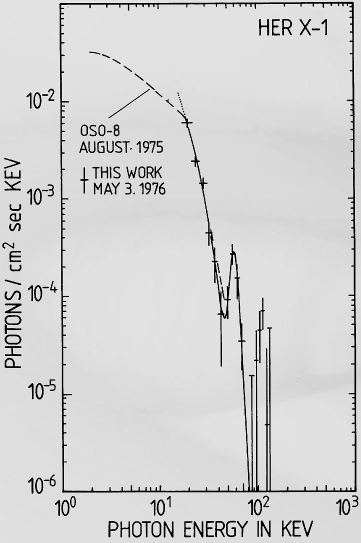


GRO 1008−57



- pulse period evolution
  → study magnetic coupling
- pulse profile shape
  → study *B*-field orientation

Cyclotron absorption in spectra allows us to measure B-field strength

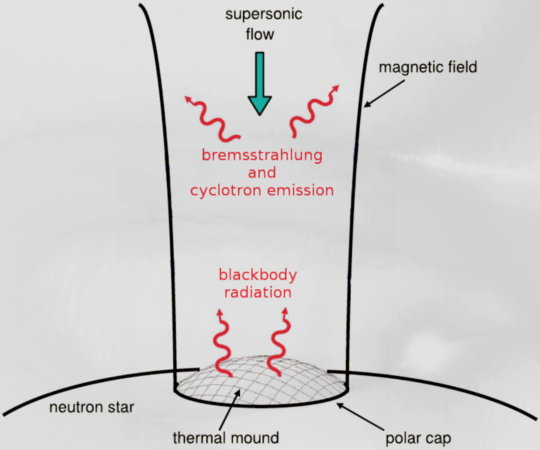


Hercules X-1, Trümper et al (1978)

X-ray spectral shape:

- power law continuum with exponential cutoff due to Compton scattering
  typically modeled with empirical continuum shape (Makishima et al., 1999; Tanaka, 1986)
- cyclotron line (in absorption!) due to strong B-field
  $\rightarrow$ study B-field strength

X-ray continuum emission due to bulk and thermal Comptonization



Becker & Wolff (2007)

- radiation pressure stopps material for $L_X > L_{crit} \sim 10^{37}\,\mathrm{erg\,s^{-1}}$ (Becker & Wolff, 2005a,b, 2007; Becker et al., 2012; Postnov et al., 2015b; Mushtukov 2015a)
- $L_X < L_{crit}$: gas or collisionless shock
- $L_X \ll L_{crit}$: ?

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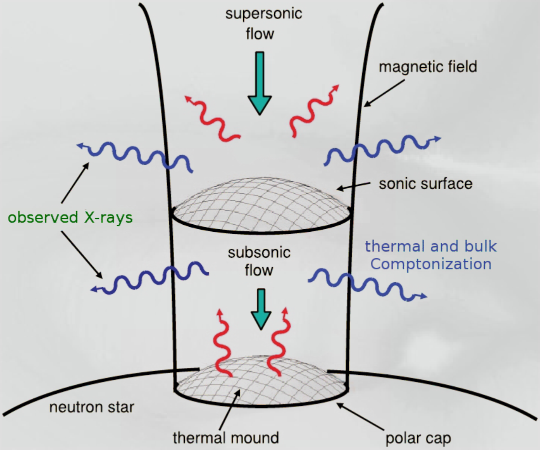

Becker & Wolff (2007)

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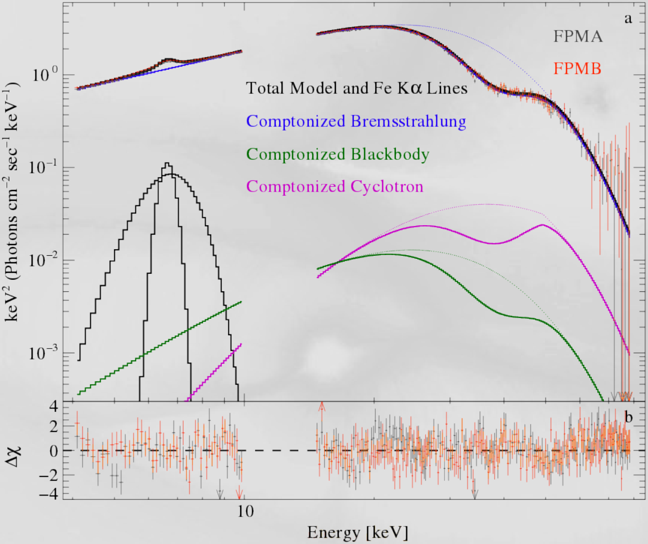
Theoretical models can now be fitted to data



Hercules X-1
Wolff et al. (2016)

Summarizing the B-field probes

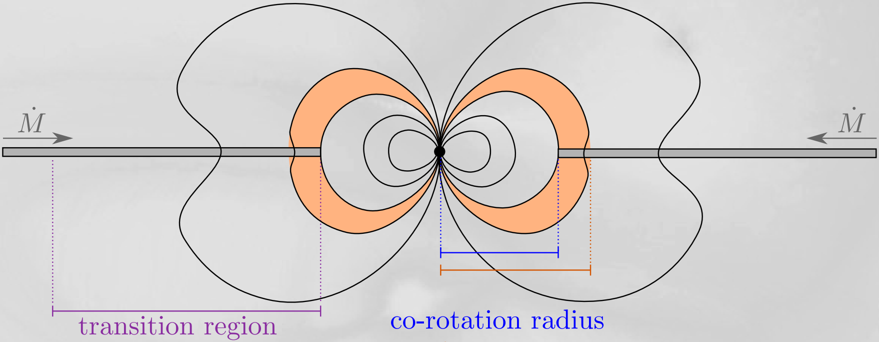
- spin period evolution
  → B-field strength
- cyclotron lines
  → B-field strength
- pulse profile shape
  → B-field orientation

caveat: each probe requires precise modelling of the underlying physics

Spin period evolution

Accreted matter couples to B-field at Alfvén radius

$$N = \int \frac{\mathrm{d}}{\mathrm{d}t\mathrm{d}S'}(-J_{\mathrm{acc}} + J_{\mathrm{mag}} + J_{\mathrm{heat}})$$

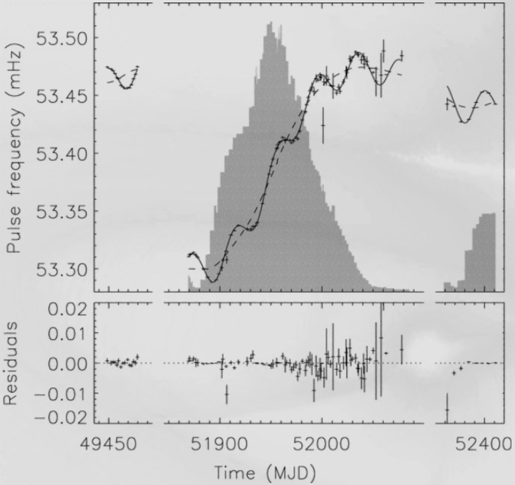


$$v_{\mathrm{mag}}(r_{\mathrm{co}}) = v_{\mathrm{disk}}(r_{\mathrm{co}})$$
$$2\pi r_{\mathrm{co}}/P_{\mathrm{spin}} = \sqrt{GM/r_{\mathrm{co}}}$$

$$P_{\mathrm{mag}}(r_{\mathrm{A}}) = P_{\mathrm{ram}}(r_{\mathrm{A}})$$
$$B^2R^6/r_{\mathrm{mag}}^6 = v(r_{\mathrm{mag}})\dot{M}/4\pi r_{\mathrm{mag}}^2$$

Ghosh et al. (1977), Ghosh & Lamb (1978a,b)

Spin period evolution depends on $\dot{M}$

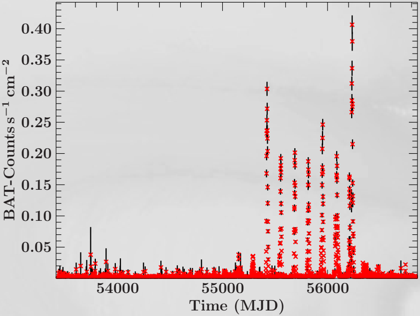


KS 1947+300
Galloway, Morgan, & Levine (2004)

- $\dot{P}_{\mathrm{spin}}(t) \propto P_{\mathrm{spin}}(t)^2 \dot{M}(t)^\alpha$
  $\rightarrow$ driven by luminosity
  $\rightarrow$ distance important!
- $\alpha \sim 1$ depends on accretion geometry (disk vs. wind accretion)
- further parameters: B-field strength, mass, radius

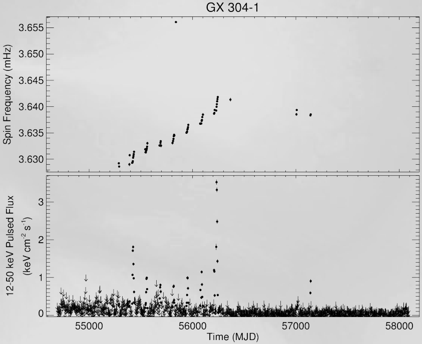
Simultaneous flux and period data needed over several weeks

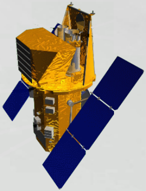
All sky monitors, e.g., *Swift-BAT*

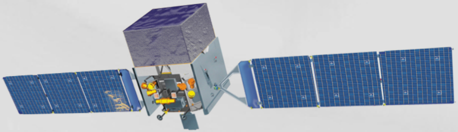


Fermi-GBM pulsar project

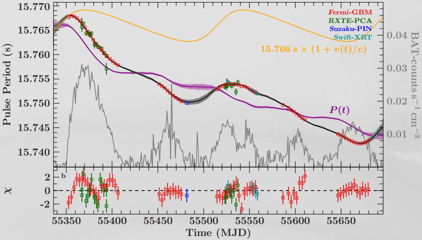
https://gammaray.nsstc.nasa.gov/gbm/science/pulsars.html



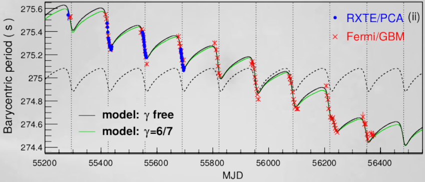




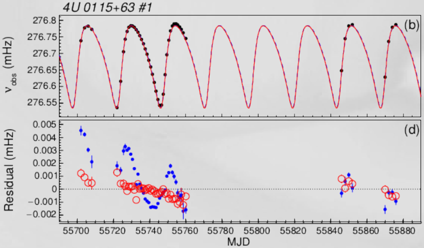
Various applications in recent literature



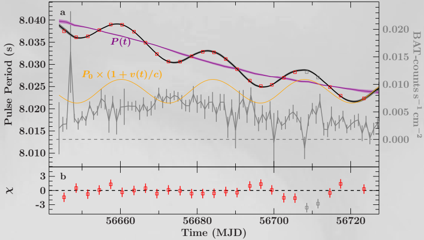
Marcu-Cheatham et al. (2015)



Sugizaki et al. (2015)

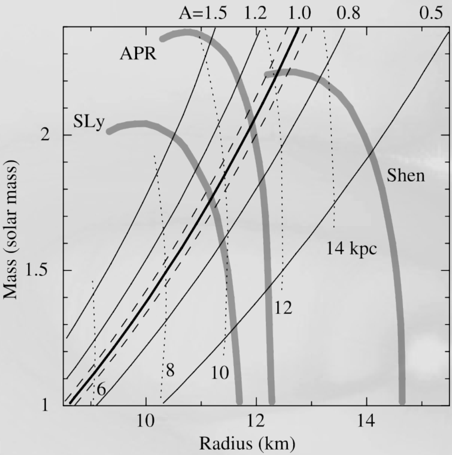


Sugizaki et al. (2017)



Kühnel et al. (2014)

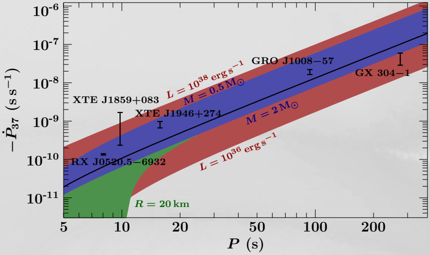
B-field strength still difficult to derive



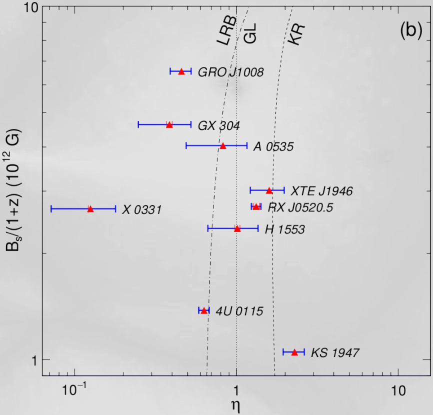
Takagi et al. (2014)

- degeneracy of parameters
  distance, radius, mass,
  B-field strength

Need to study larger sample and combine probes!



Kühnel et al. (in prep.)



Sugizaki et al. (2017)

- different accretion torque theories
- constrain remaining parameters
  → CRSF, distances from GAIA, mass/radius from NICER

Cyclotron Resonant Scattering Features

a.k.a. “cyclotron lines”

Quantization of electron energies (Landau levels)

$$E_{n'} = E_n + m_e c^2 \frac{B}{B_{crit}} \quad \rightarrow \quad E_0 = 11.6\,\mathrm{keV}\, B_{12} \quad \text{(12-B-12 rule)}$$

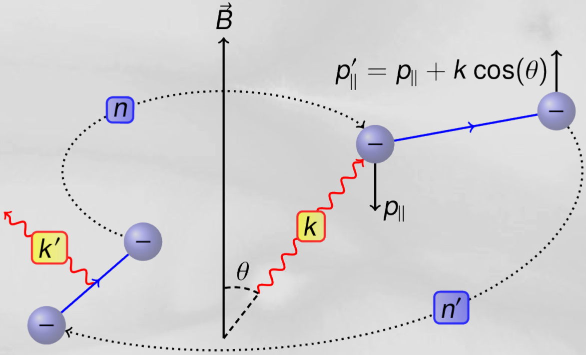
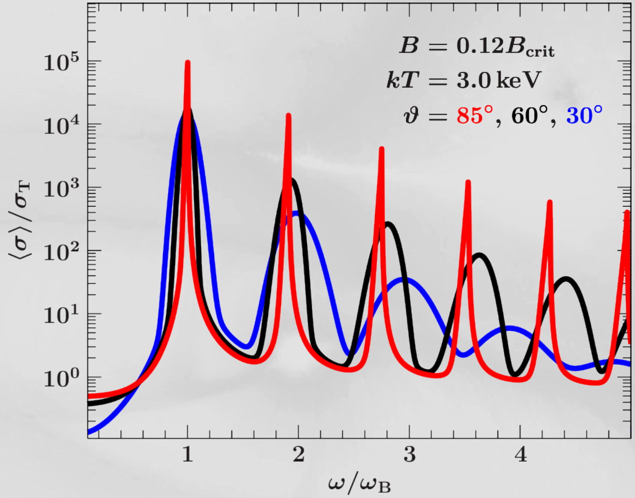


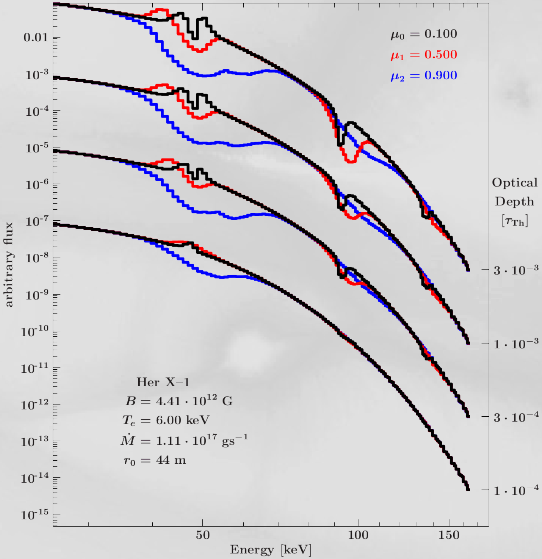
image courtesy F. Schwarm

Cross sections depend on photon energy and angle



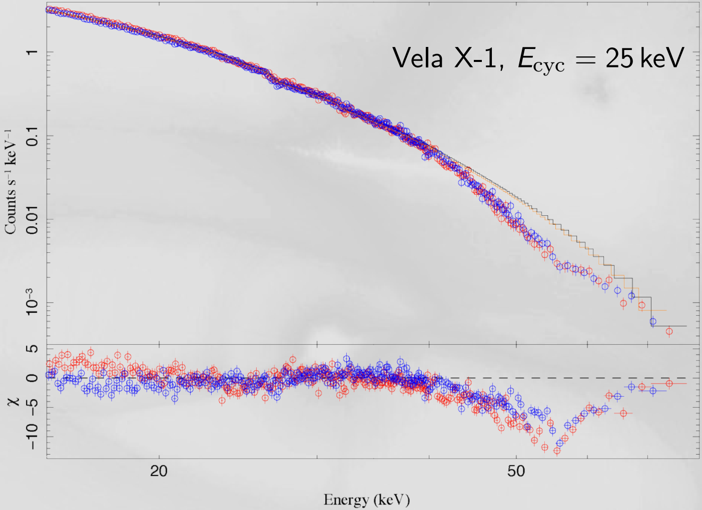
Schwarm et al. (2017a)

Simulation: photon spawning and thermal broadening



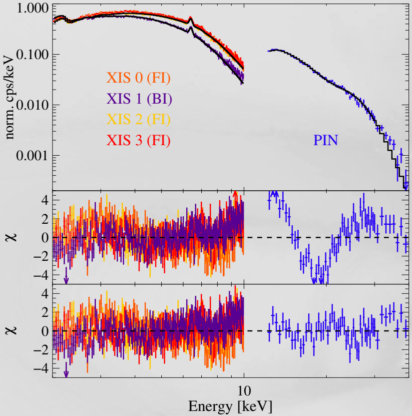
Schwarm et al. (2017b)

CRSFs detected with high signal-to-noise by *NuSTAR*



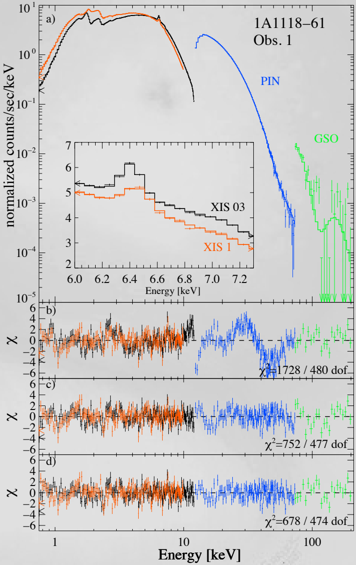
Fürst et al., 2014

Often detailed analysis required for reliable detections



4U 1907+09, $E_{\mathrm{cyc}} = 19\,keV$

Rivers et al., 2010

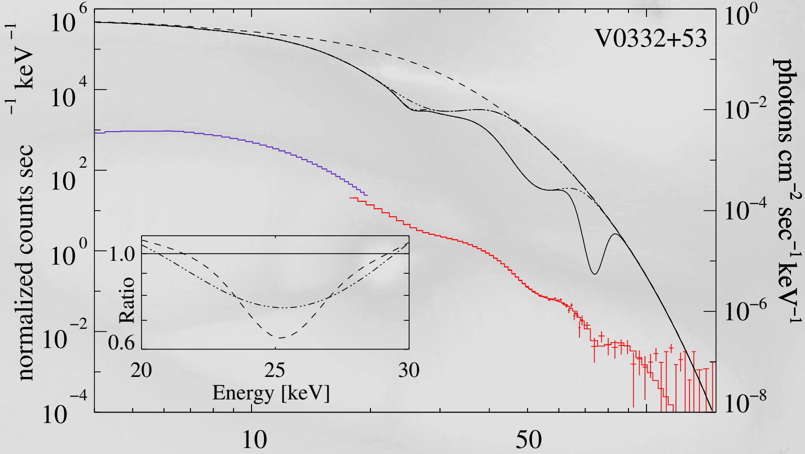


1A 1118−61, $E_{\mathrm{cyc}} = 58\,\mathrm{keV}$

Suchy et al., 2012

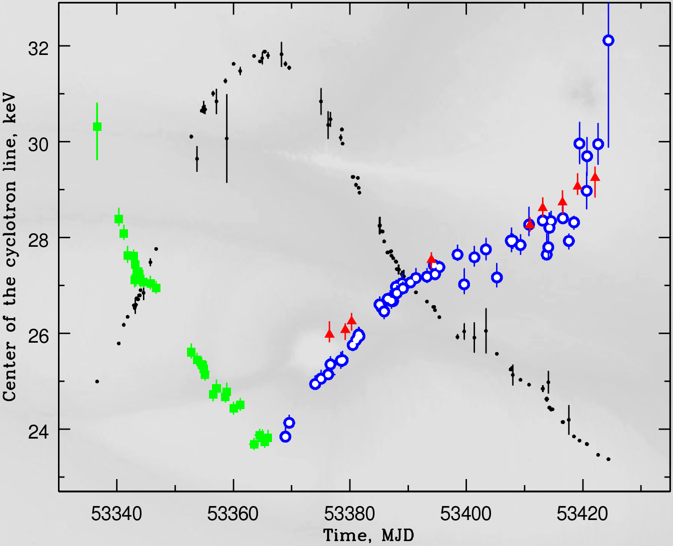
Higher harmonics are found for a few sources

- V0332+53: cyclotron lines at 27, 51, and 74 keV and complex fundamental
- line ratios ≠ 2, agrees with QED prediction



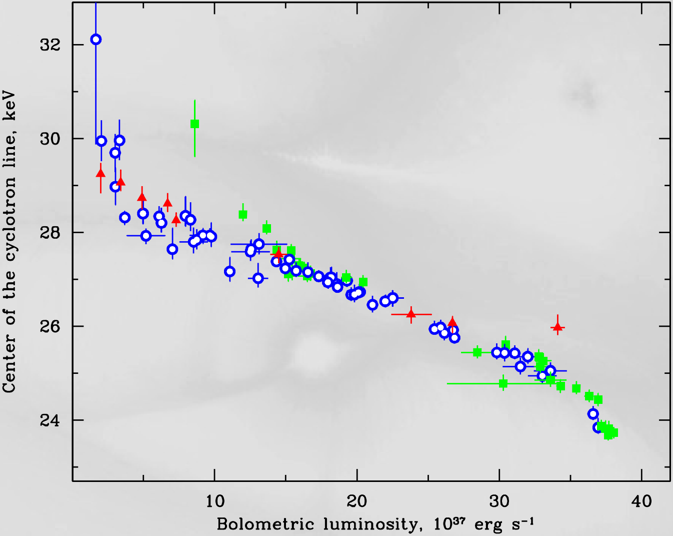
Pottschmidt et al. (2005)

V0332+53: cyclotron line energy is time dependent



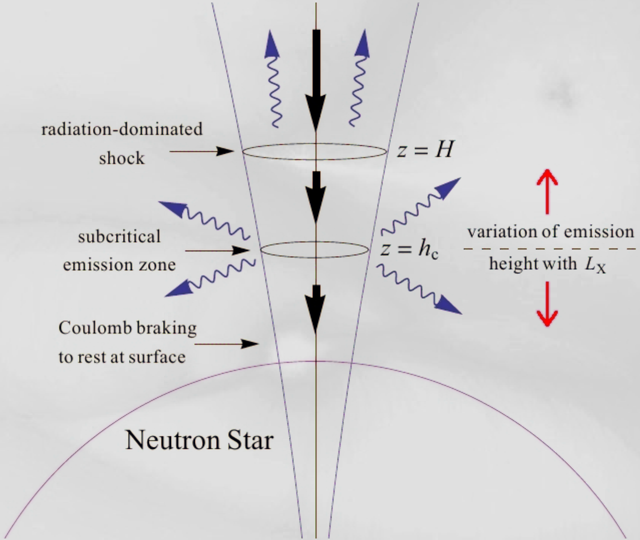
Tsygankov et al. (2010)

V0332+53: cyclotron line depends on luminosity



Tsykankov et al. (2010)

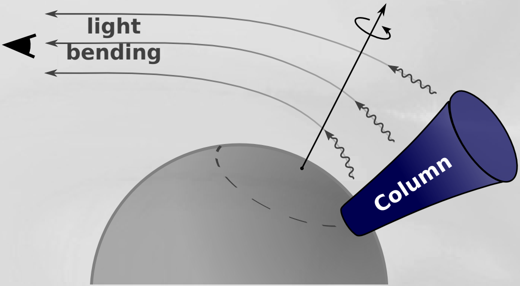
We measure B-field strength at different heights

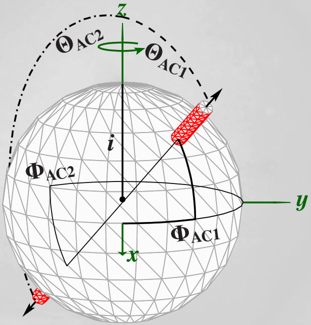


Becker et al. (2012)

Pulse profile shape

Emission pattern is light bended towards observer

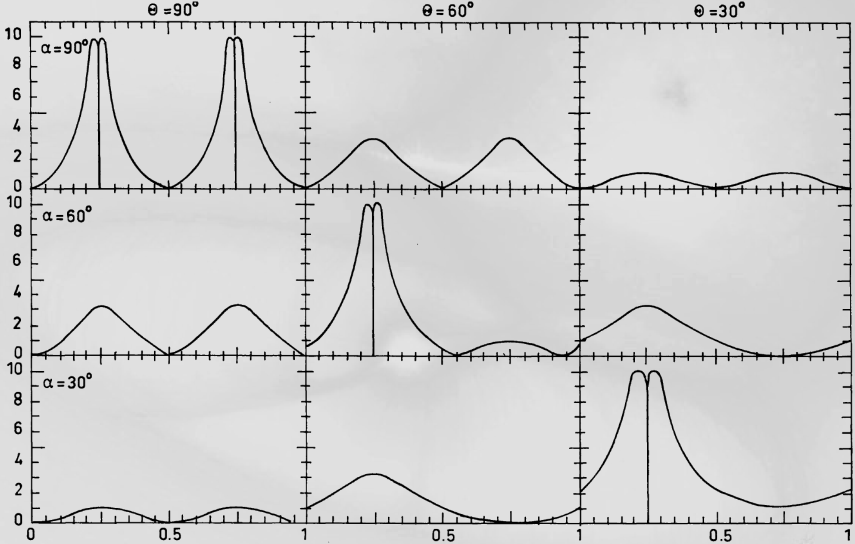




- assume (or model) a beam pattern
  depends on energy, height, ...
- calculate photon trajectories towards observer

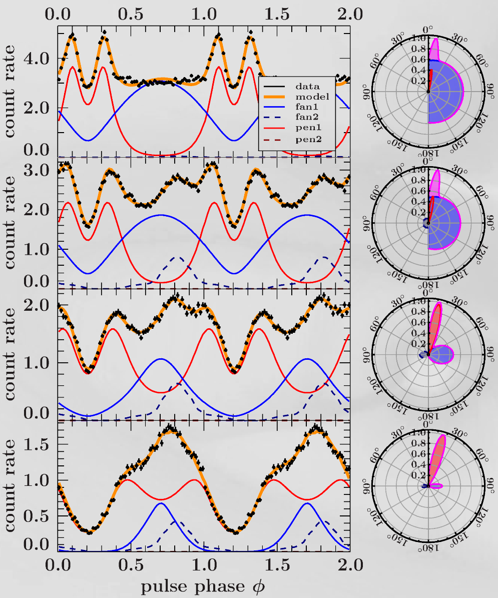
Falkner et al. (in prep.)

In principle derive *B*-field orientation from pulse profiles



Basko & Sunyaev (1975)

We find complex, asymmetric field geometries



4U 1626−67
Iwakiri et al. (subm.)

- top- and side-wall emission (pencil- and fan-beam)
- relative contribution changes with energy
- off-center magnetic axis azimuthal offset ∼10°
- inclined magnetic axis ∼16–21° to rotational axis

Take home messages

Three tools for magnetic field investigationsx:

- spin period evolution
  - magnetic coupling of accreted material
    $\rightarrow$ angular momentum transfer $\rightarrow$ spin-up
  - parameter degeneracy $\rightarrow$ difficult to measure B-fields
- cyclotron lines
  - absorption on quantized electron levels in strong B-field
    $\rightarrow$ direct measurement of B-field strength
  - line energy correlates with luminosity
    $\rightarrow$ line formation at certain height above surface
- pulse profile shape
  - model emission pattern using 3D light bending
    $\rightarrow$ investigate B-field orientation
  - asymmetric and inclined magnetic fields