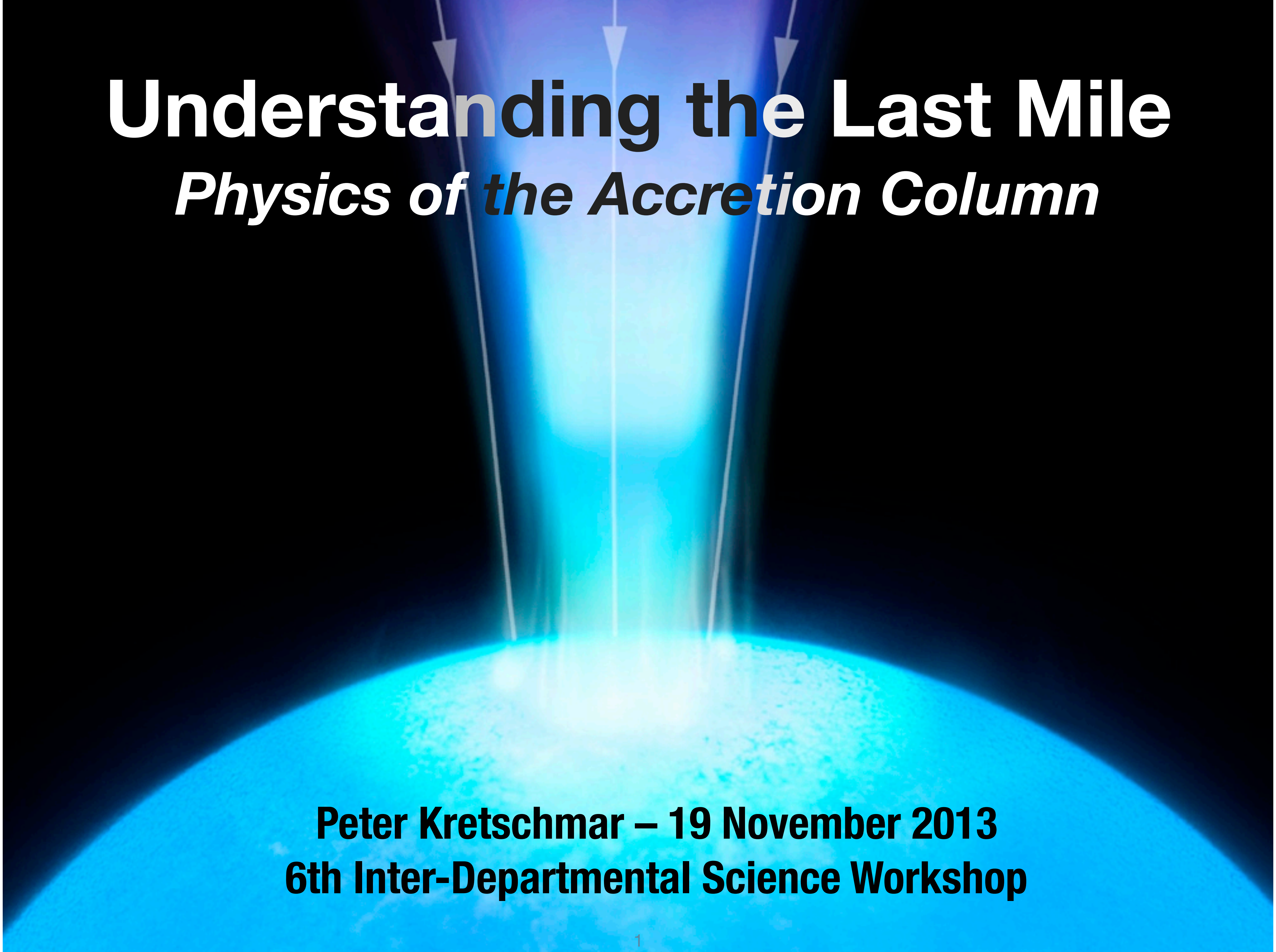
Understanding the Last Mile

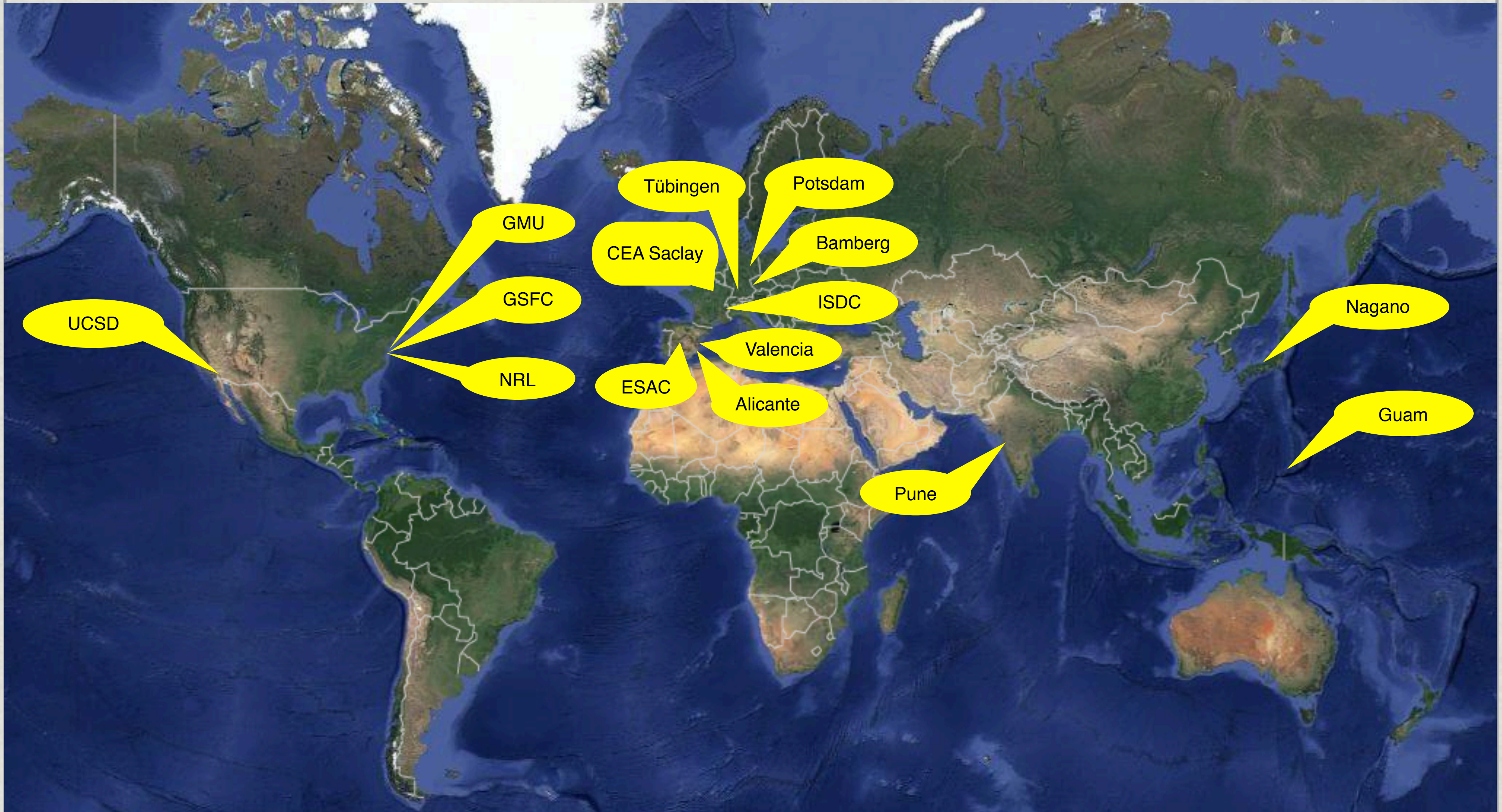
Physics of the Accretion Column



Peter Kretschmar – 19 November 2013

6th Inter-Departmental Science Workshop

On behalf of a large team ...



Introduction

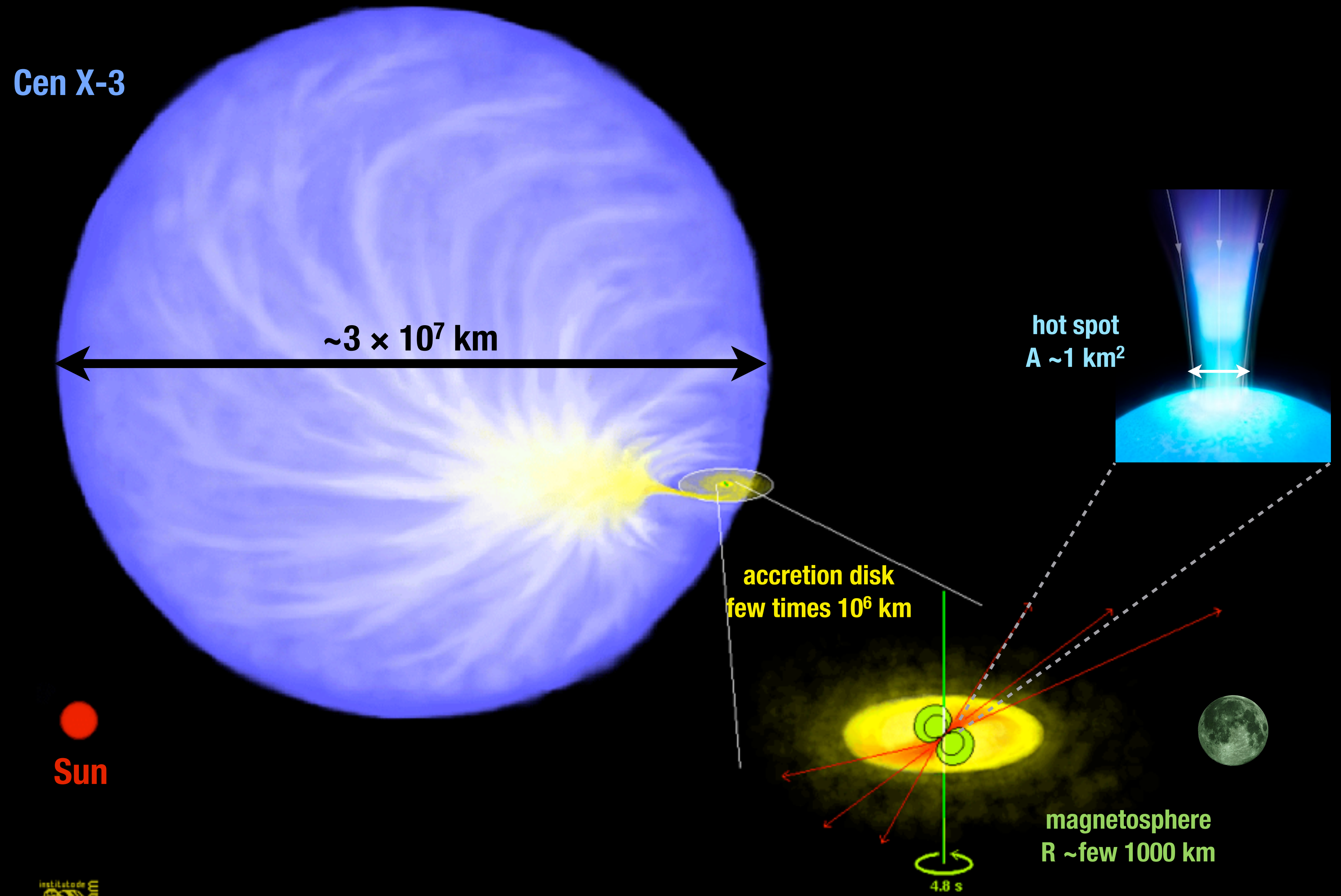
Accreting X-ray Pulsars

Accretion column properties

Observational features

Cyclotron resonant scattering

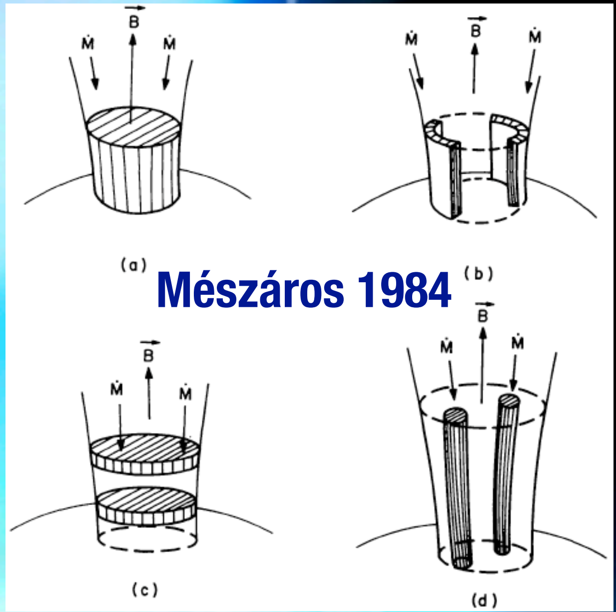
Accreting X-ray pulsar



Cen X-3 image by Dany Page

Accretion column properties

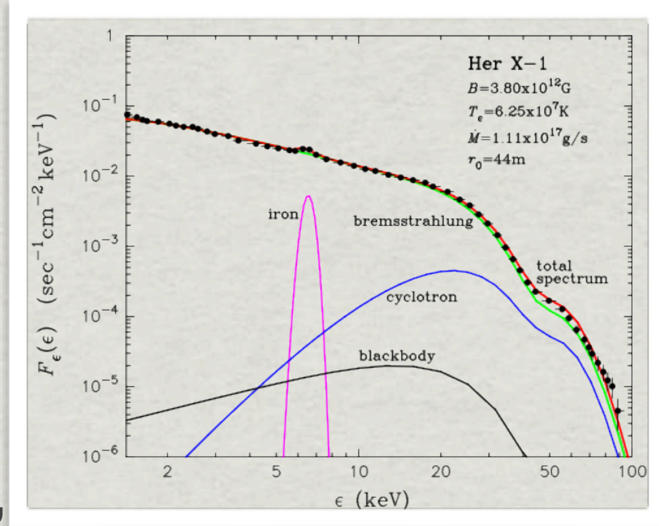
- Extreme energy density (10^{37} erg/s in ~1 km^3).
- Very strong magnetic fields (10^{12} – 10^{13} G)
  ➔ Exotic radiation processes possible.
  ➔ Very non-isotropic radiation transport.
- Many details uncertain, even geometrical structure!



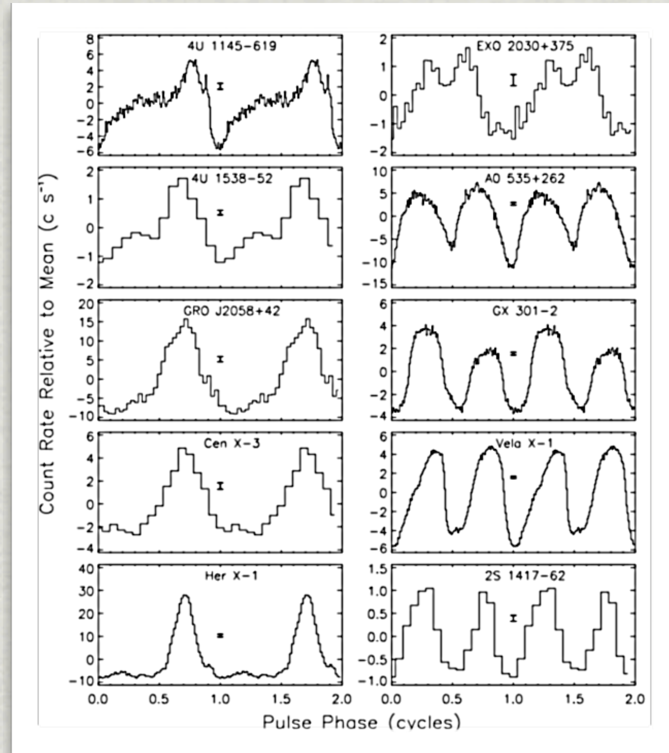
Mészáros 1984

Becker & Wolff, 2007, ApJ, 654, 435

Observational features

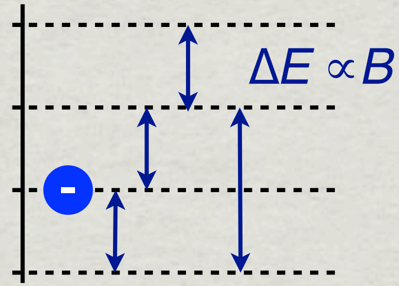


- Relatively simple spectra, with similar shape across sources and mostly stable in shape. Explained by cyclotron, bremsstrahlung and blackbody radiation, scattered by high speed electrons.
- Some sources (<20) show cyclotron line features as broad lines. Line position varies with luminosity for few sources.
- Pulse profiles quite different between sources. Sometimes stable for decades ("fingerprint"), sometimes very variable. No clear explanation for differences.



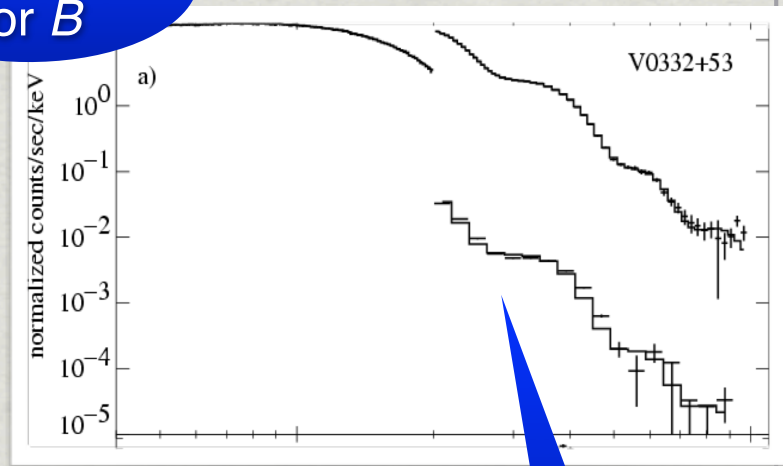
Cyclotron line formation

- Scattering of X-ray photons with quantized electrons in a strong magnetic field.
- Electron perpendicular momentum/energy restricted to Landau levels.
- Photons induce e transitions: “12-B-12 rule”: $\Delta E \approx 11.6\, B_{12}$



$$E_n = m_e c^2 \sqrt{1 + \left(\frac{p}{m_e c}\right)^2 + 2n \frac{B}{B_{\mathrm{crit}}}}$$
$$B_{\mathrm{crit}} = (m^2 c^3)/(\hbar e) = 44.14 \times 10^{12}\ \mathrm{G}$$

Diagnostic for B

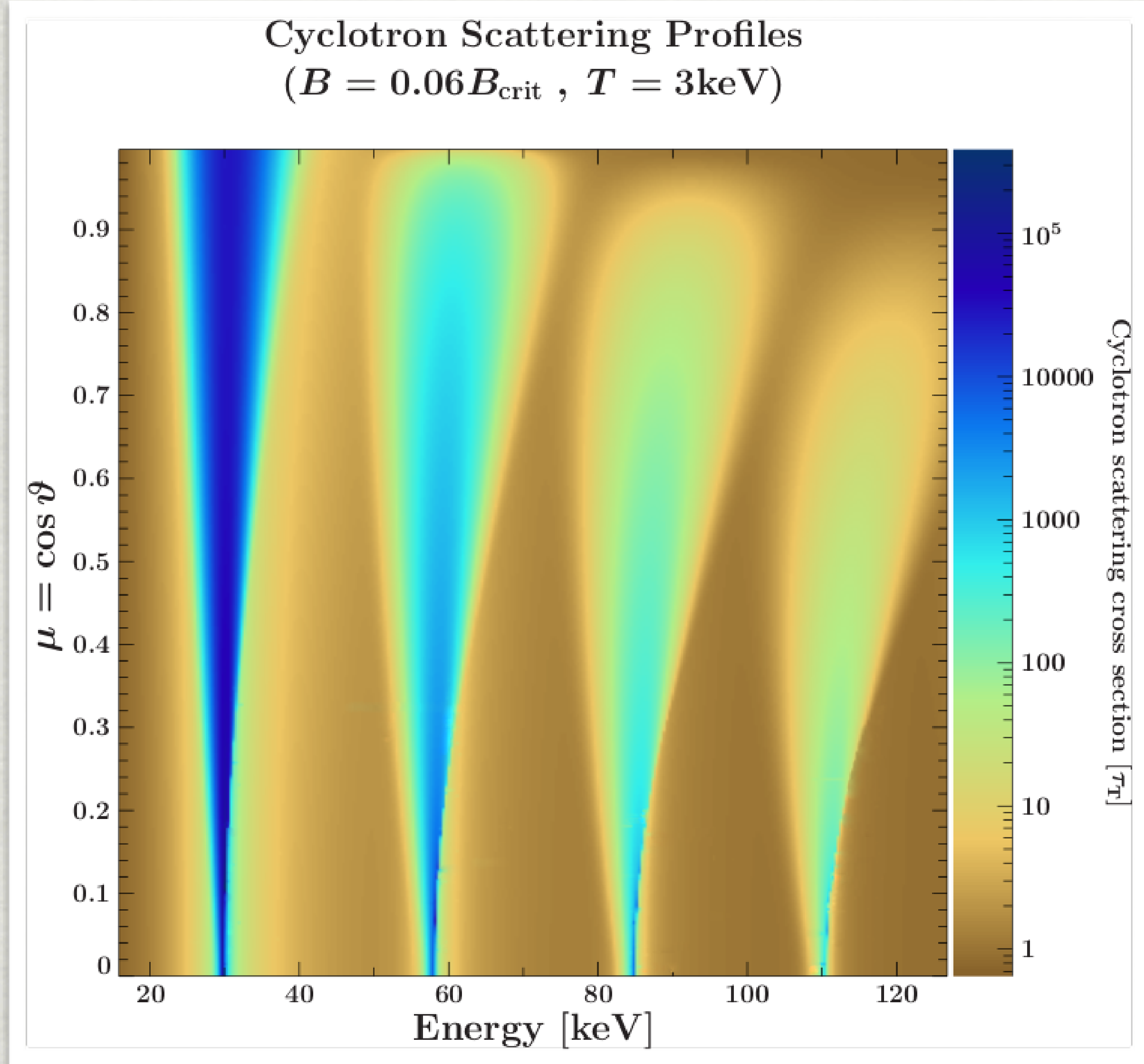


Quasi-harmonic features

- Resonant cross sections
  - ➡ Photons at nΔE can hardly escape line forming region
  - ➡ Lines form in absorption

Cyclotron scattering cross-sections

- Difficult radiative transfer calculation because of strong dependence of cross section on energy and angle.
- Possible to redis-tribute photons from higher harmonics to fundamental line (“photon splitting”).



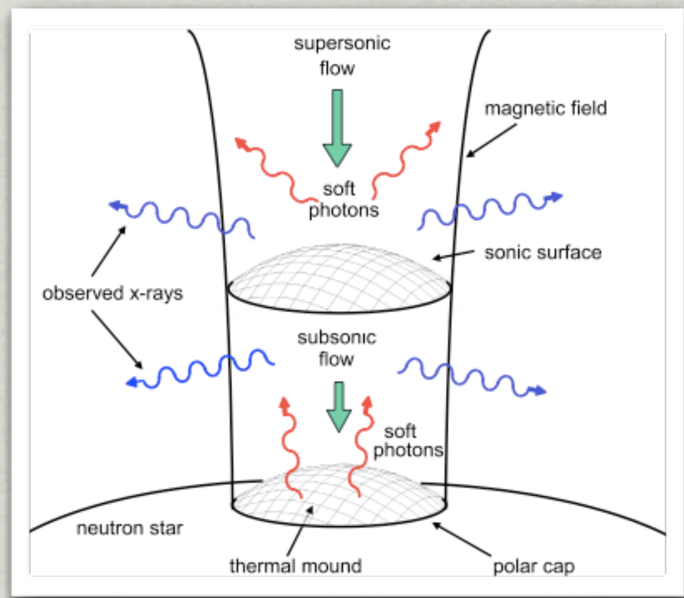
Schwarm et al., 2012, INTEGRAL Workshop 2012

Recent Results

Luminosity regimes and cyclotron line variations

Pulse profile decomposition

Luminosity regimes



- ISSI Team Meeting between theorists and observers ➟ identification of luminosity regimes in accretion columns.

- Lowest luminosities: plasma hits surface or gets stopped in gas shock very close to pole.

accretion mode & Thomson optical depth

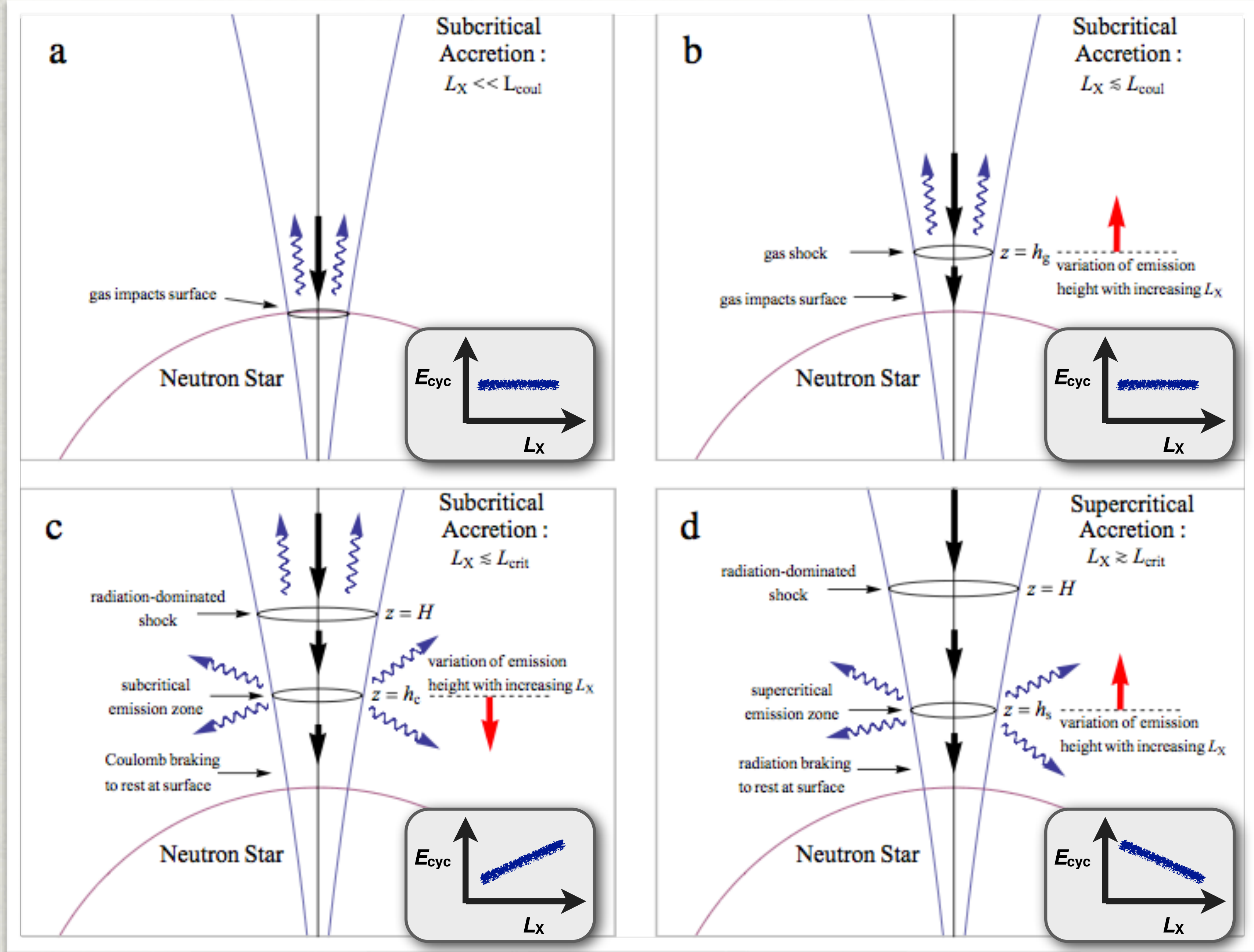
- Above $L_{\mathrm{coul}} \approx [4\text{-}6] \times 10^{37}$ erg/s $\times B_{12}^{-1/3}$ (for $M_{NS} = 1.4\ M_\odot$ and $R_{NS} = 10$ km) plasma decelerated by Coulomb interactions.

accretion mode & spectral shape

- Above **critical luminosity** $L_{\mathrm{crit}} \approx [4\text{-}70] \times 10^{37}$ erg/s $\times B_{12}^{16/15}$ plasma decelerated by radiation pressure.

- Different reaction of columns and emission regions to luminosity changes, depending on regime, which depends on magnetic field.

Luminosity regimes & E_{cyc} variations



Becker et al., 2012, A&A 544, A123

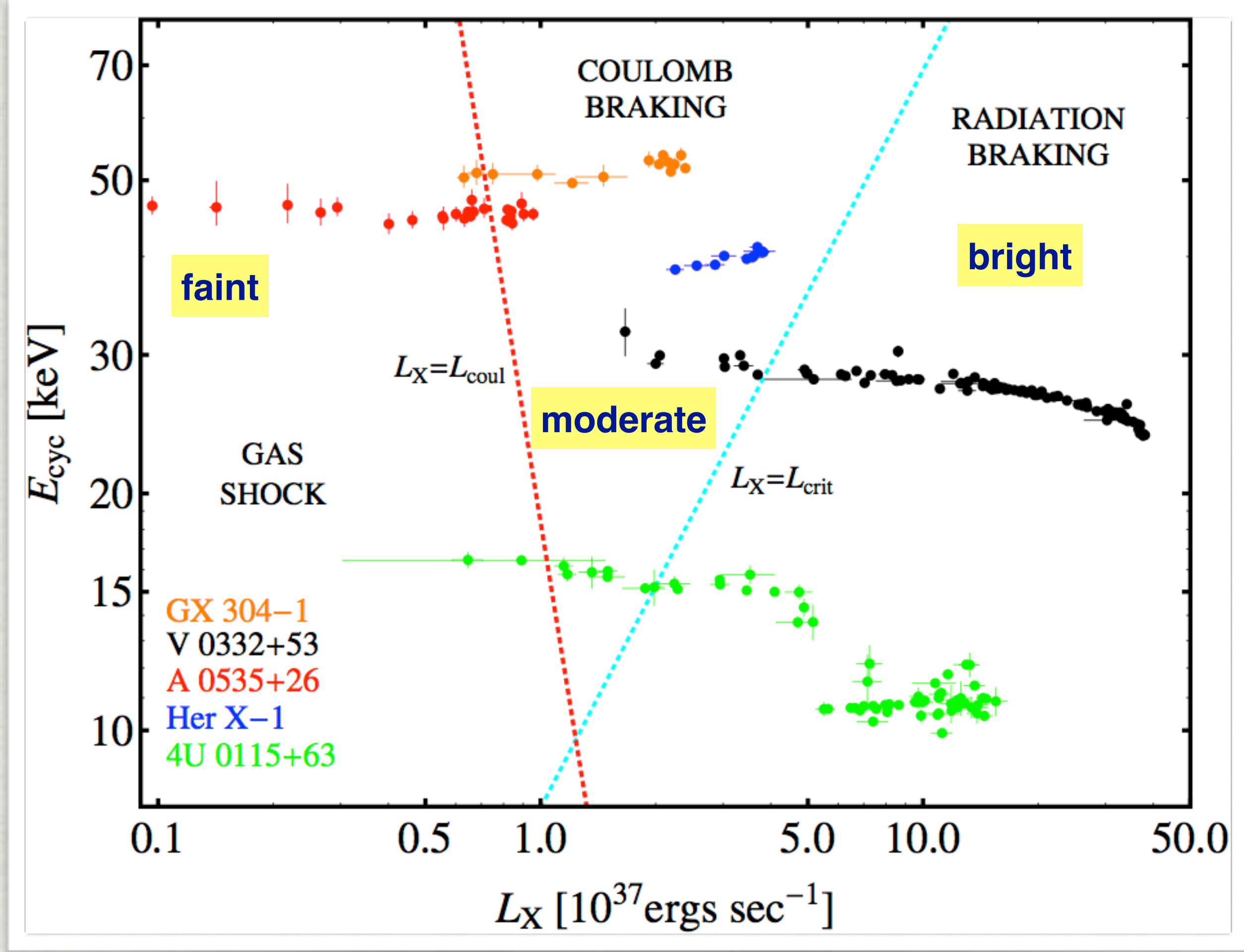
Comparison with observations

- Model explains different variations of E_{cyc} in several transient sources by dominant braking process in column, driven by luminosity regimes.

Becker et al., 2012, A&A 544, A123

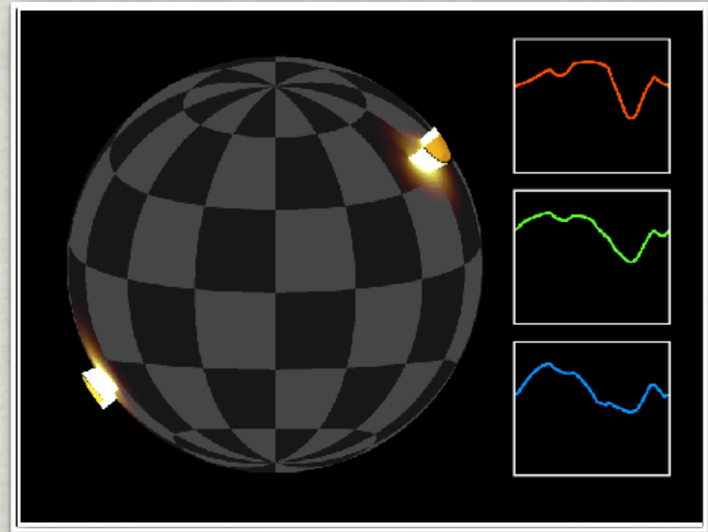
- Caveat 1: Luminosities often quite uncertain (distance!)

- Caveat 2: small sample and serious doubts about results for 4U 0115+63! (Müller et al., 2013, A&A 551, A6)

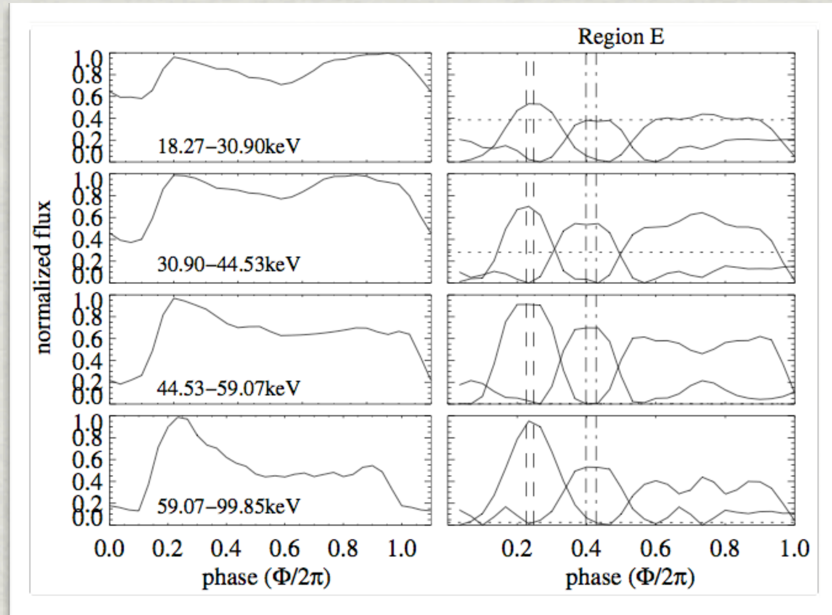


Pulse profile modeling

Caballero et al., 2011, A&A, 526, A131
Sasaki et al., 2012, A&A, 540, A35



- Decomposed pulse profiles of A0535+26 (Caballero et al. 2011) as well as 4U 0115+63 and V 0332+53 (Sasaki et al. 2012) using methods of Kraus et al. (1999, 2003), accounting for light bending.
- Assume axisymmetric emission from each pole and same beam pattern from both poles, but **poles offset from antipodal position**.
- Combination of accretion column, halo around hotspot, and scattering of photons in upper accretion stream.
- Non-unique decomposition
  ➔ human judgement needed.



Current Developments

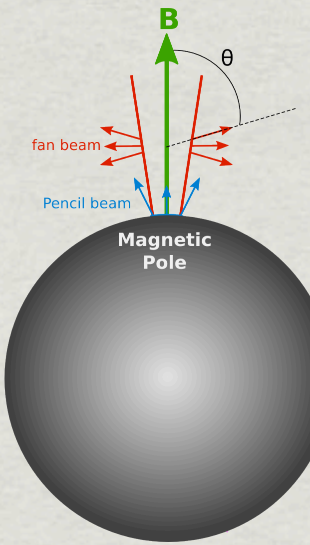
Tackling the bigger picture

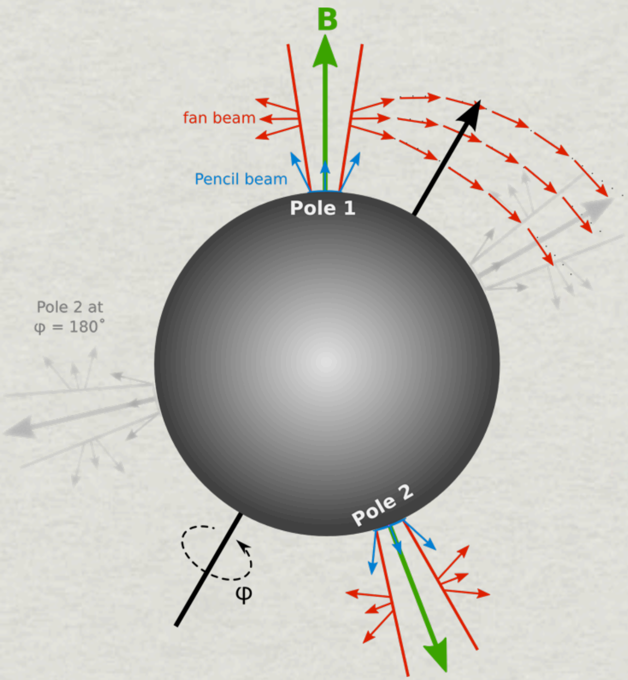
Flexible cyclotron scattering models

Realistic relativistic light bending

Application: pulse peak phase shifts

Challenge: tackling the bigger picture





X-ray production
➔ continuum F_{cont} (E,Θ)

+

Photon/electron scattering
➔ cyclotron lines
$F_{cont+lines}$ (E,Θ)

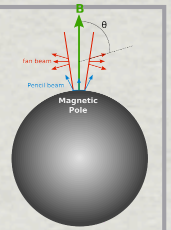
+

GR Light bending & NS rotation
➔ observed spectrum as function of phase
$F^{GR}_{cont+lines}$ (E,Θ,φ)

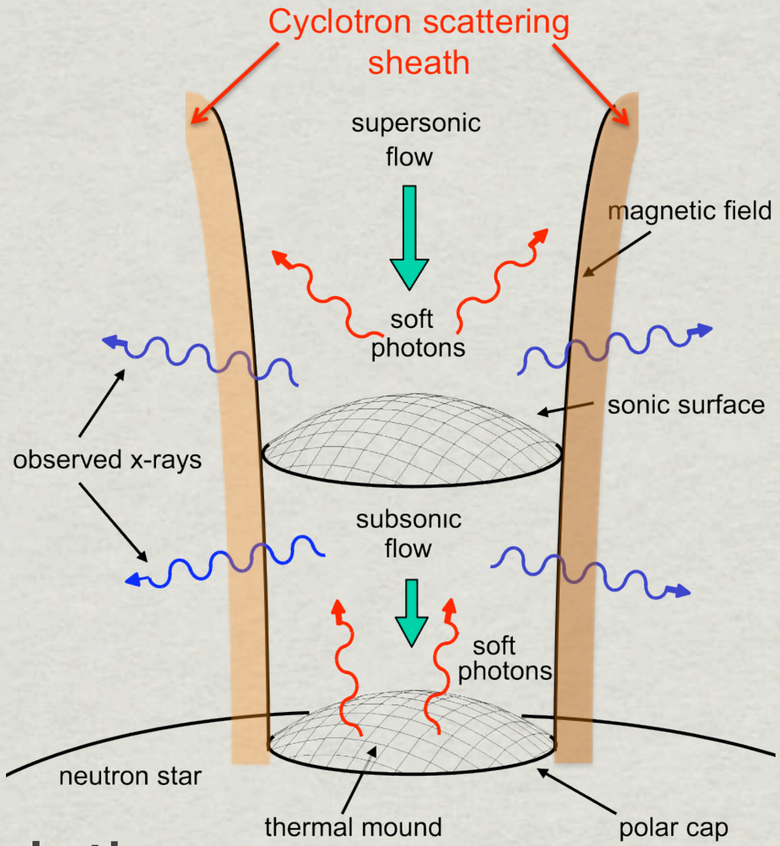
One Pole Geometry

Two Pole Solution

‘Hybrid’ column model

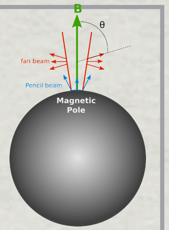


- Merging strengths of cyclotron MC model with column model.
- Column dimensions from Becker et al. (2012)
- Cyclotron layer sheath for small τ_{Thom}, assuming dipole.
- Density and bulk velocity gradients from continuum calculations.

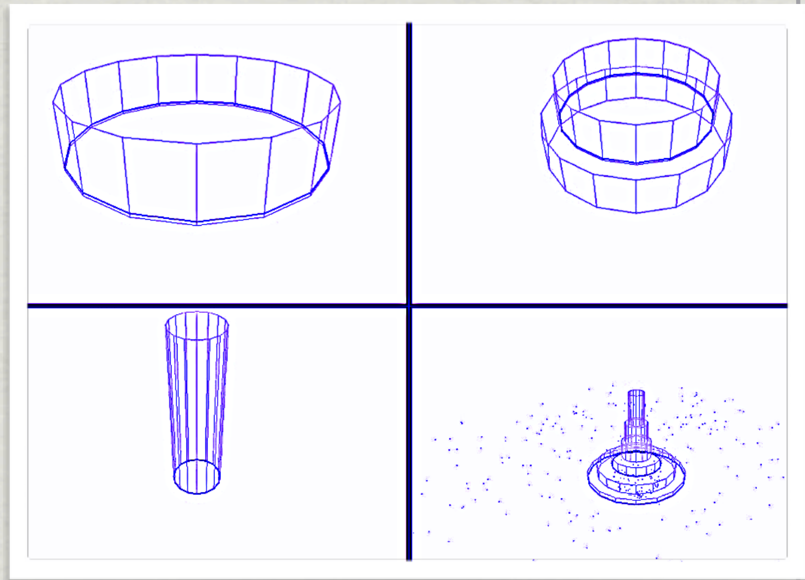


- Seed photons from continuum; angular redistribution by scattering.

Flexible cyclotron scattering model

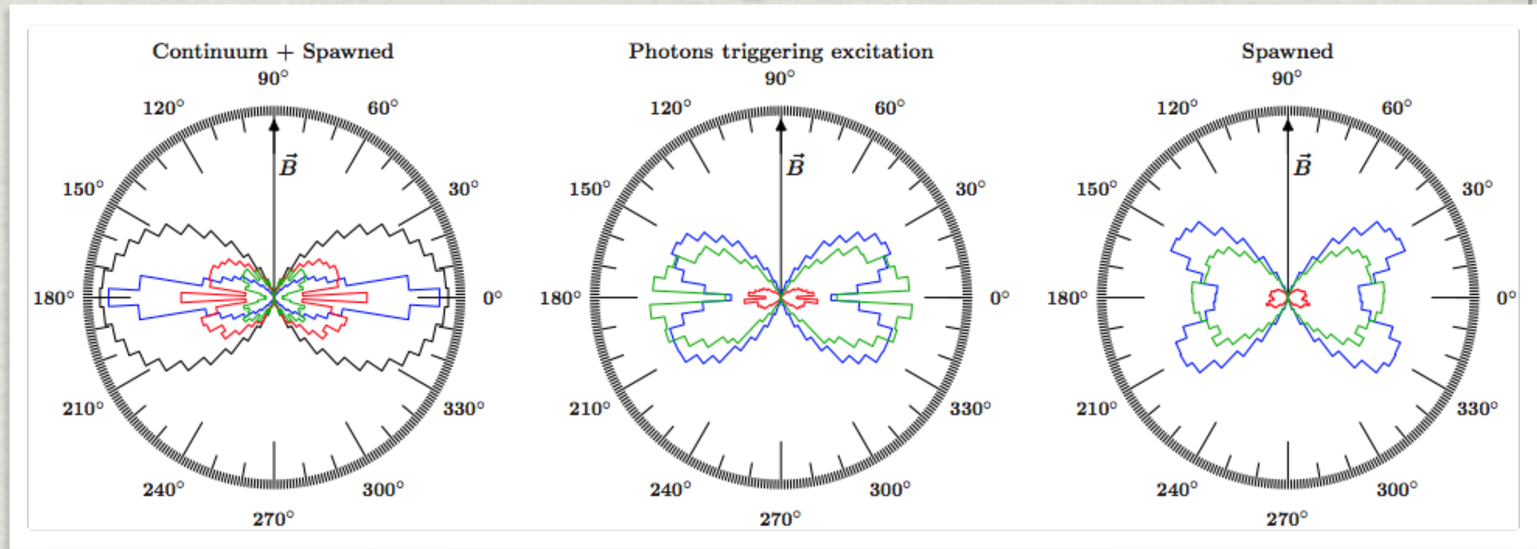


- Schwarm et al.: Green's function approach for cyclotron line scattering ➔ apply to any continuum.

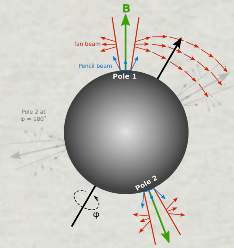


- Simulation of complex geometries ➔ adapt to light-bending models.

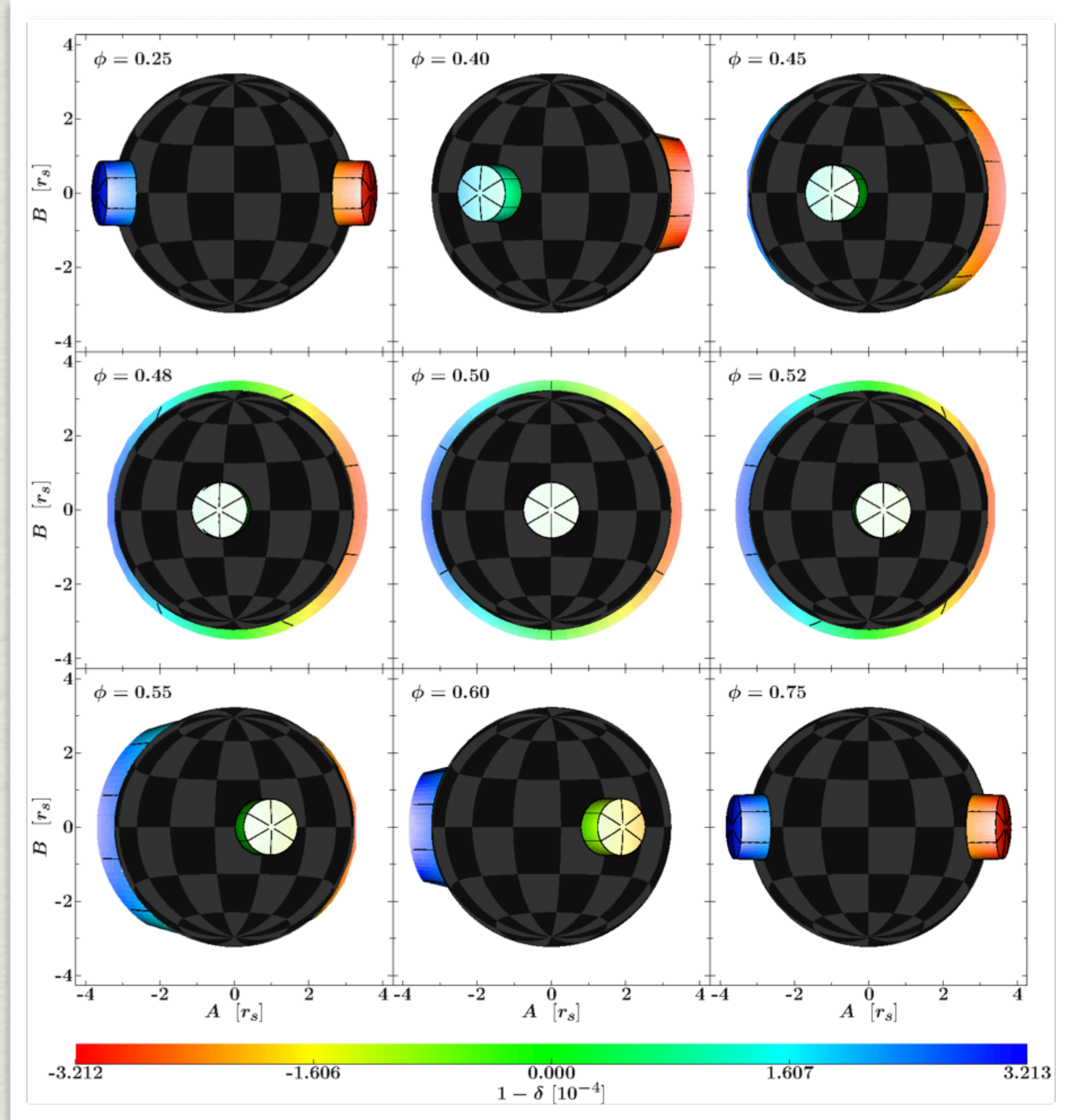
- Photon tracing, treat micro-physics



Realistic relativistic light bending

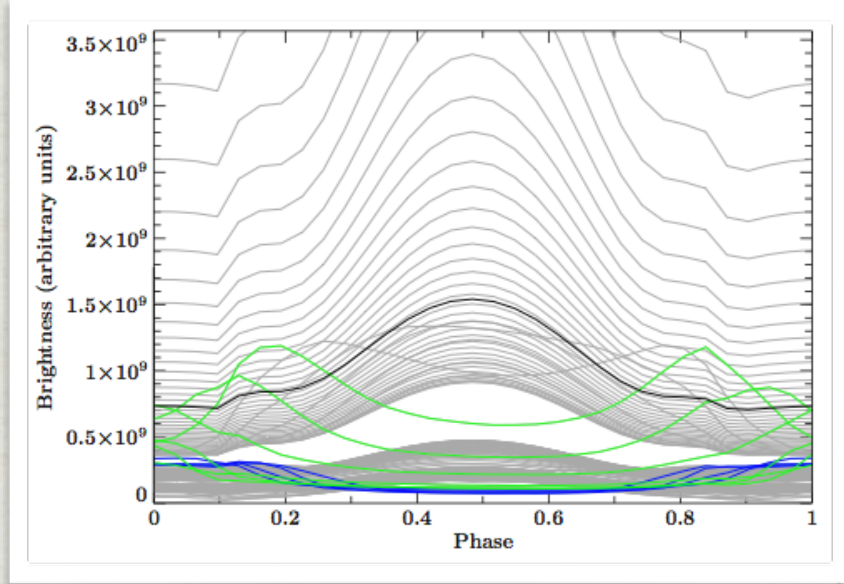


- Falkner 2013 (PhD thesis): Software to describe observed flux from neutron star for **arbitrary emission profile**, accounting for special and general relativistic effects.

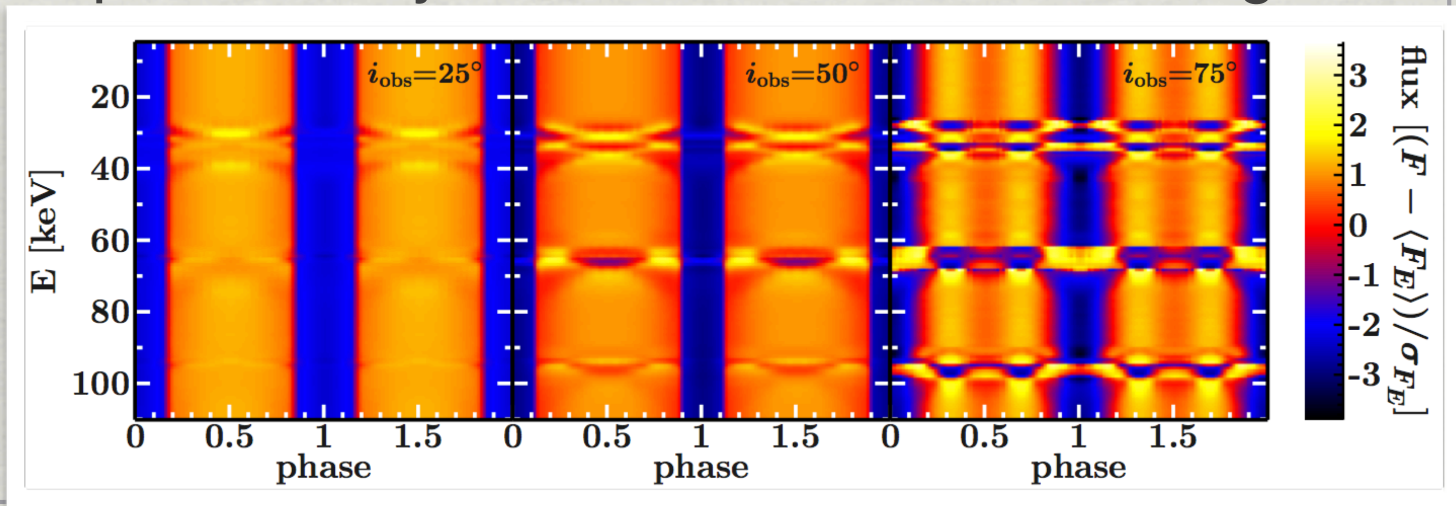


Application: pulse peak phase shifts

- Column + light-bending can be used to calculate flux as F(E,ϕ)
  = phase-resolved spectra
  = energy-resolved pulse profiles
  for any set-up.



- Schönherr *et al.* (submitted): observed shifts in pulse profile peaks around cyclotron line energies can results as direct consequence of cyclotron resonance scattering plus relativistic bulk motion of plasma.



Conclusions

- Exciting times for study of accretion column in X-ray pulsars.
- Increased computing resources and improved methods yield new tools for modeling of observations.
- Encouraging results, but also much increased complexity of factors to be taken into account!
- Need to identify best observables to test model results.