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Astronomy & Asrophysics

# Observing Accretion Disks II:

# Eclipse Mapping
# Disk Emission Lines
# Tomography

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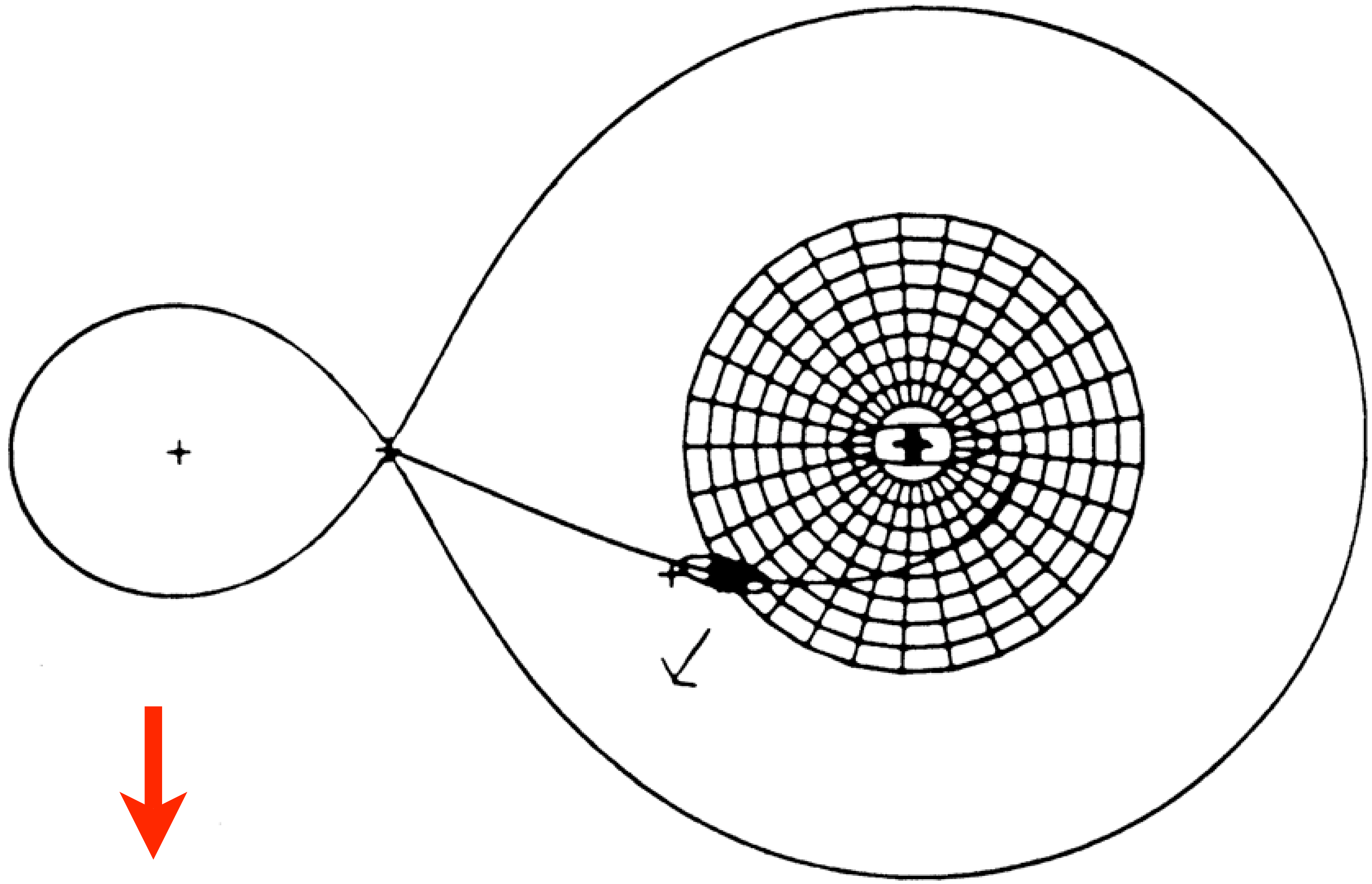
# Organization of Lecture II

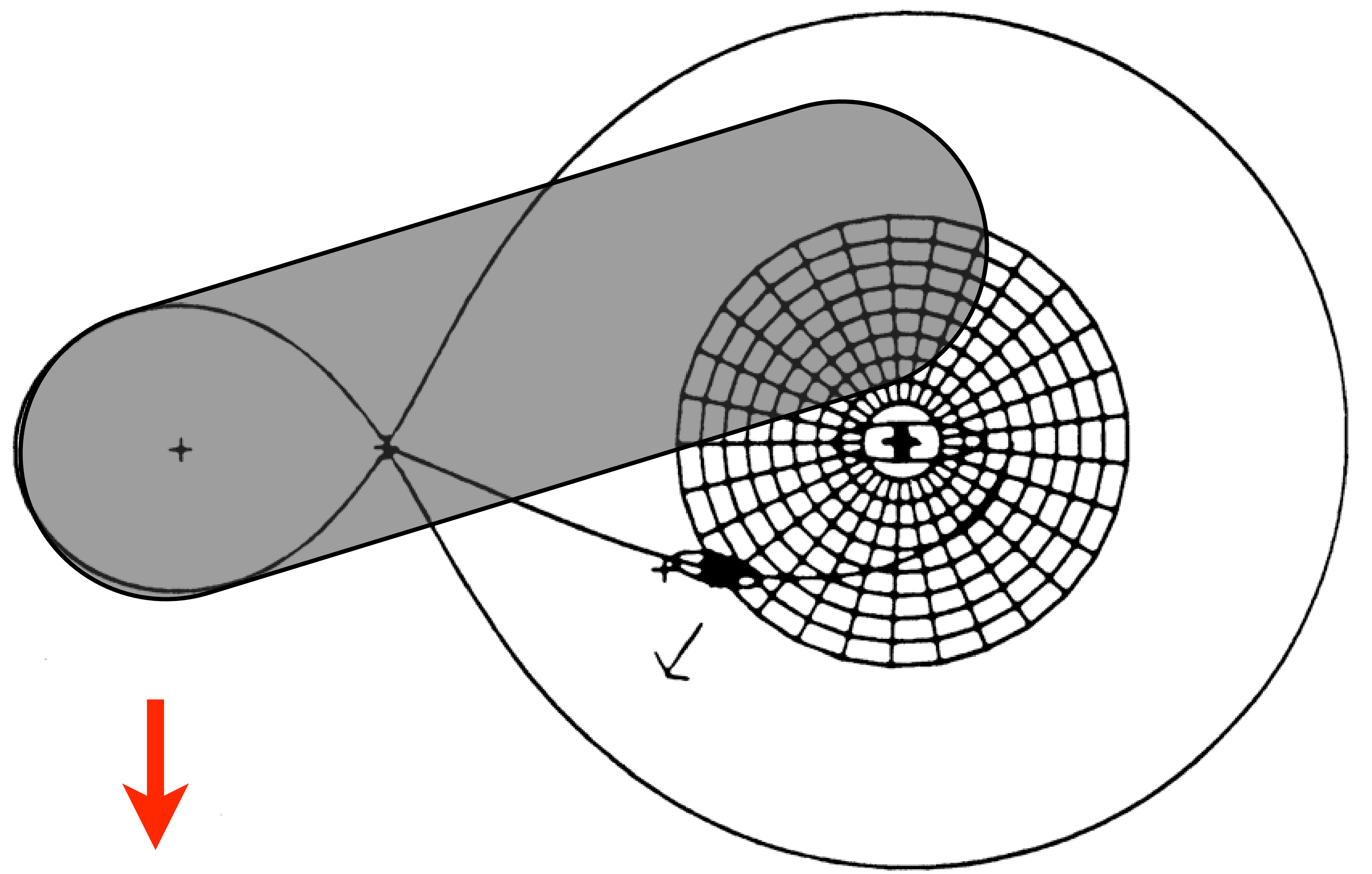
- **Indirect Imaging via Eclipse Mapping**
  - The method and its fundamental assumptions
  - Spatially resolved information
  - Application to the dwarf nova instability
- **Emission Lines from Disks and Tomography**
  - Signature of rotation
  - Tomographic imaging and results
- **Outflows and Their Emisson Lines**
  - Line profile models

# Eclipse Mapping

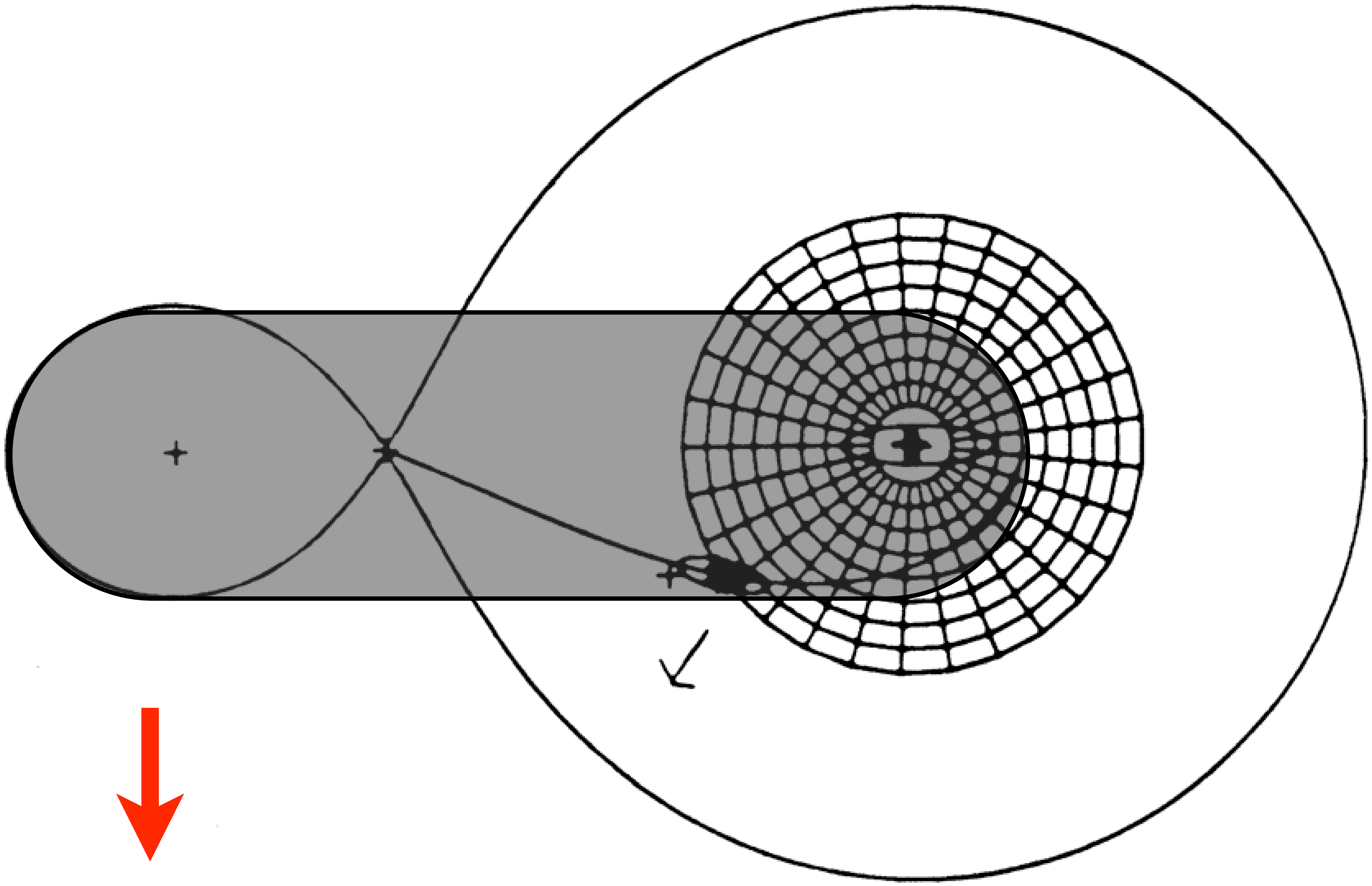
# The basic principle



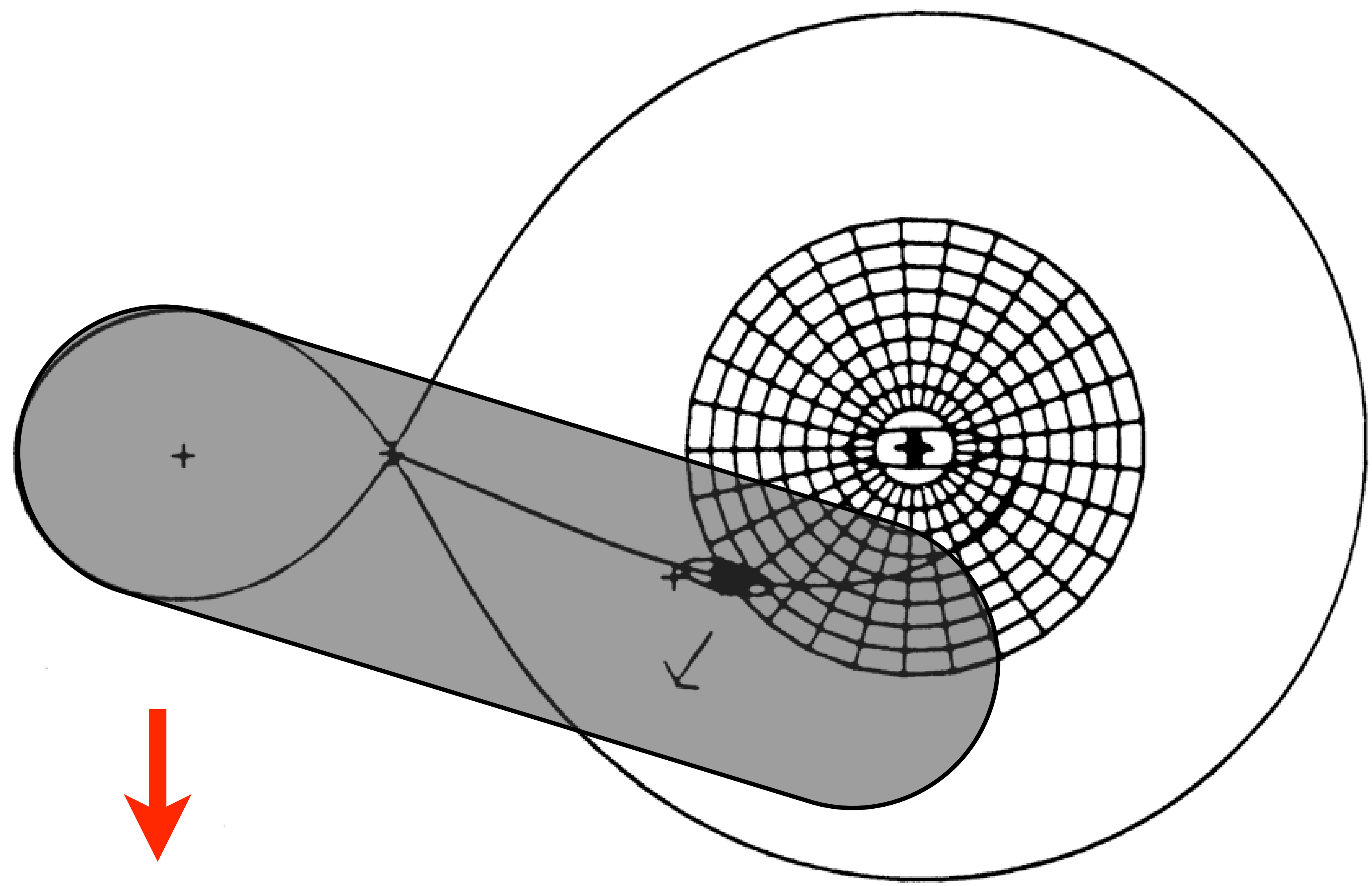
# The basic principle



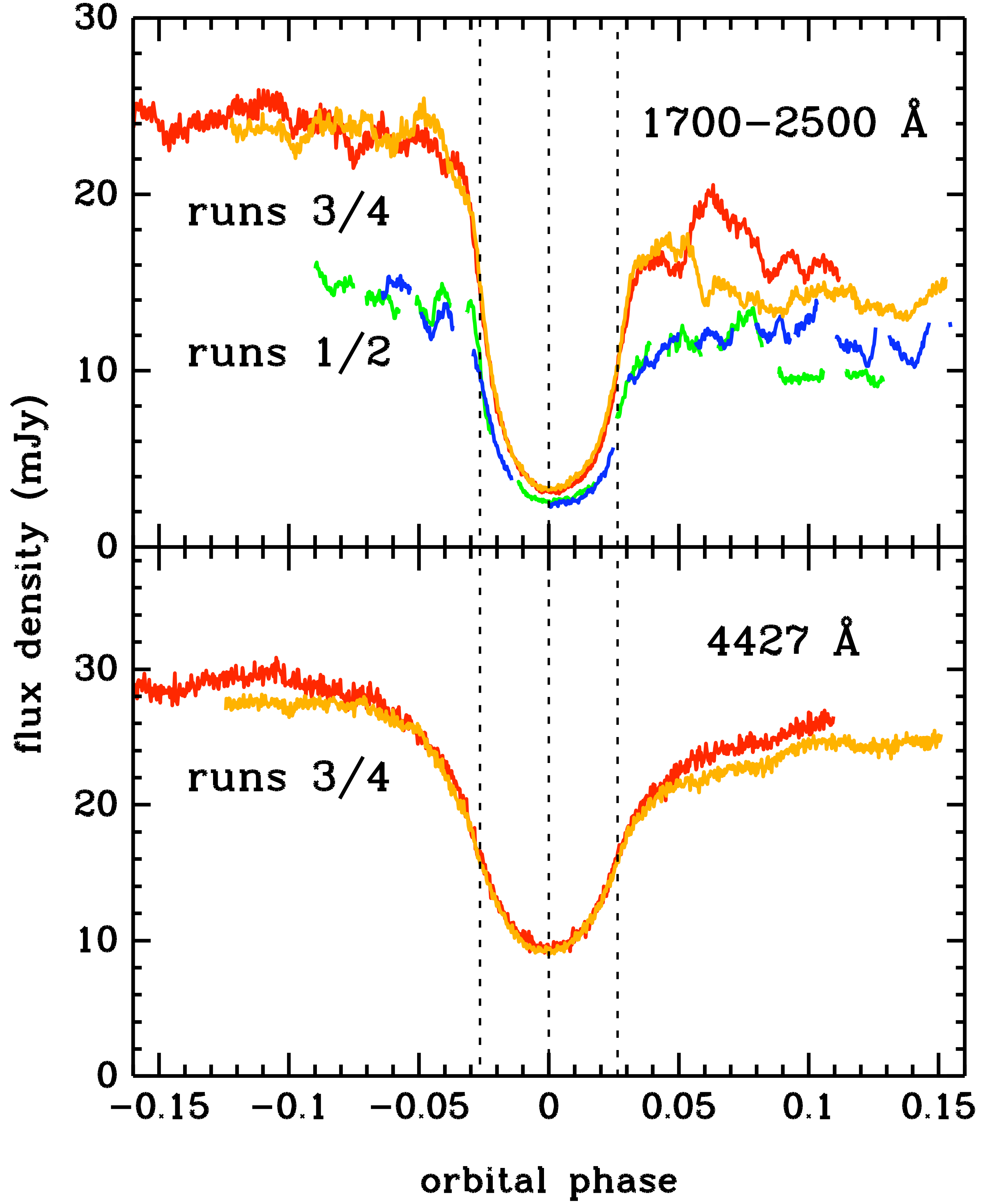
# The basic principle



# The basic principle

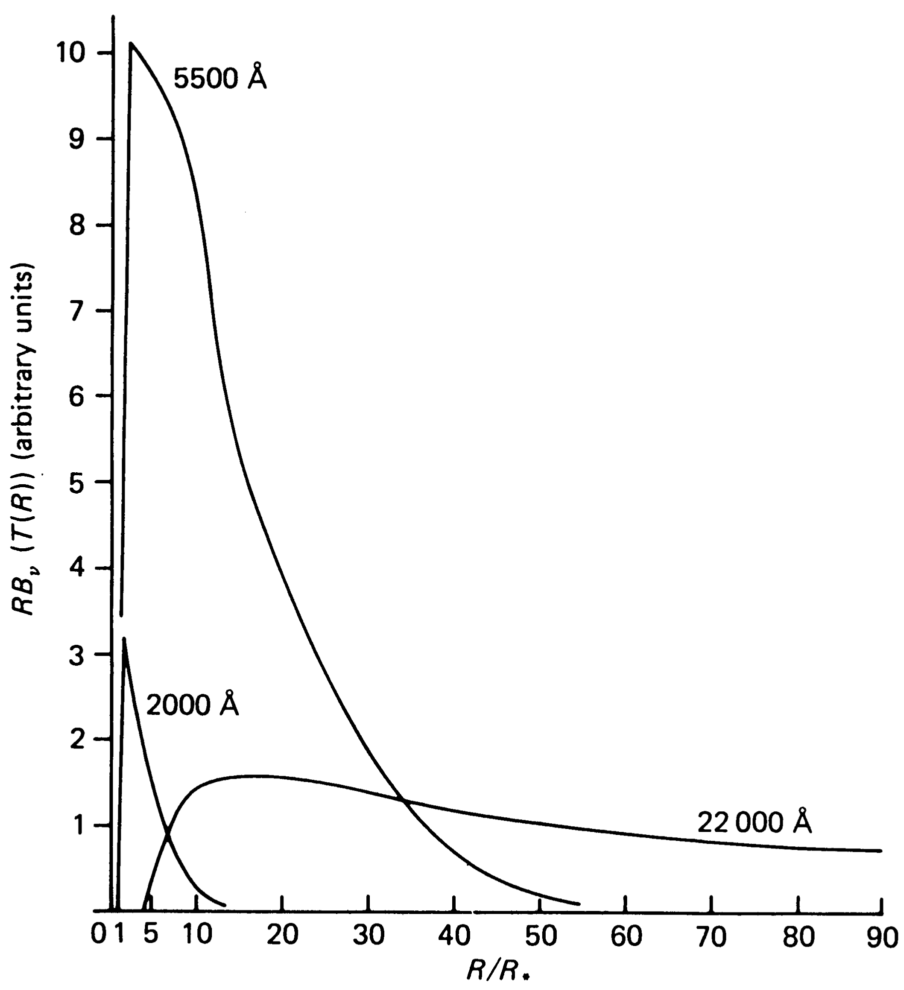


# Light curves vs wavelength

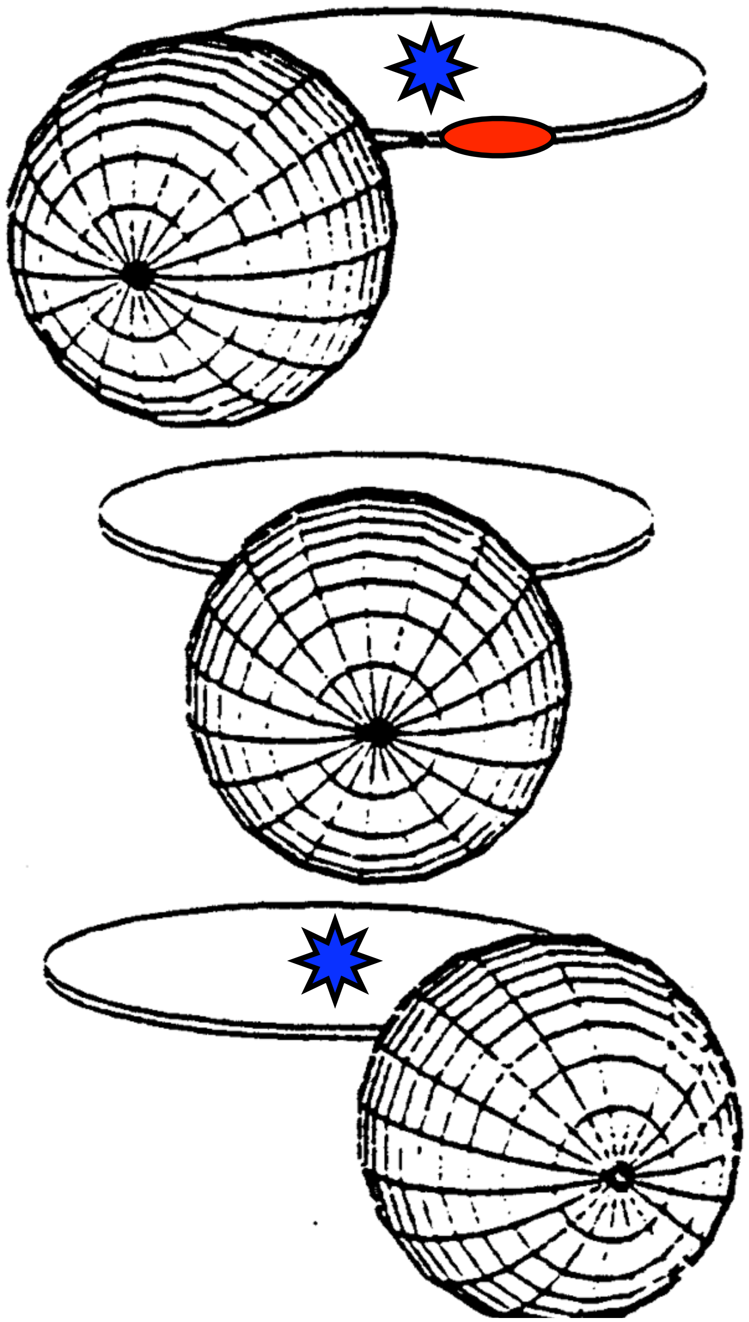



UX UMa
in UV and Optical

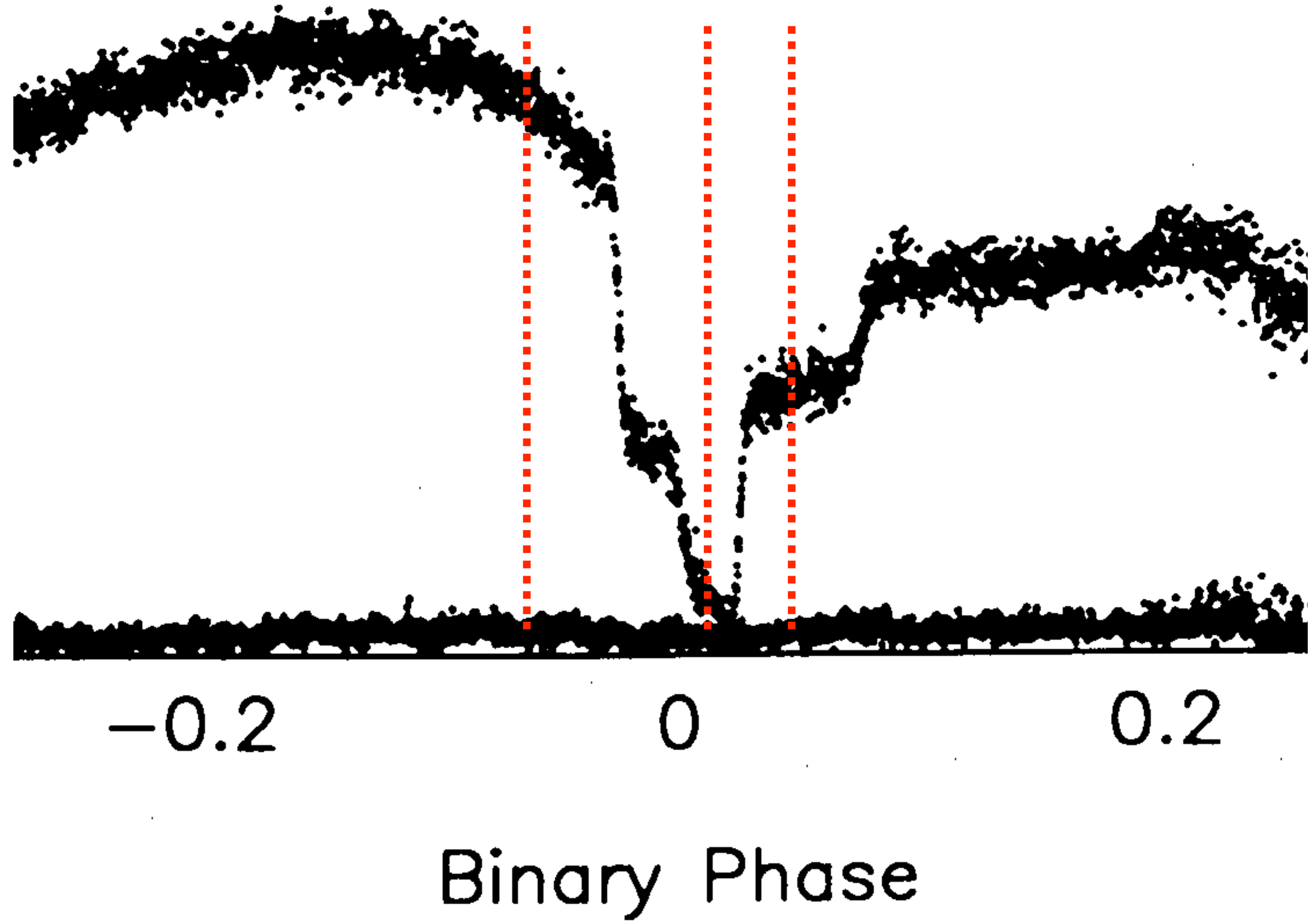
from Baptista et al. 1998
MNRAS, 298, 1079



# Reading the eclipse light curve



OY Car in quiescence




from Wood et al. 1989, ApJ, 341, 974

# Clues from eclipse light curves

## Dwarf-novae in quiescence

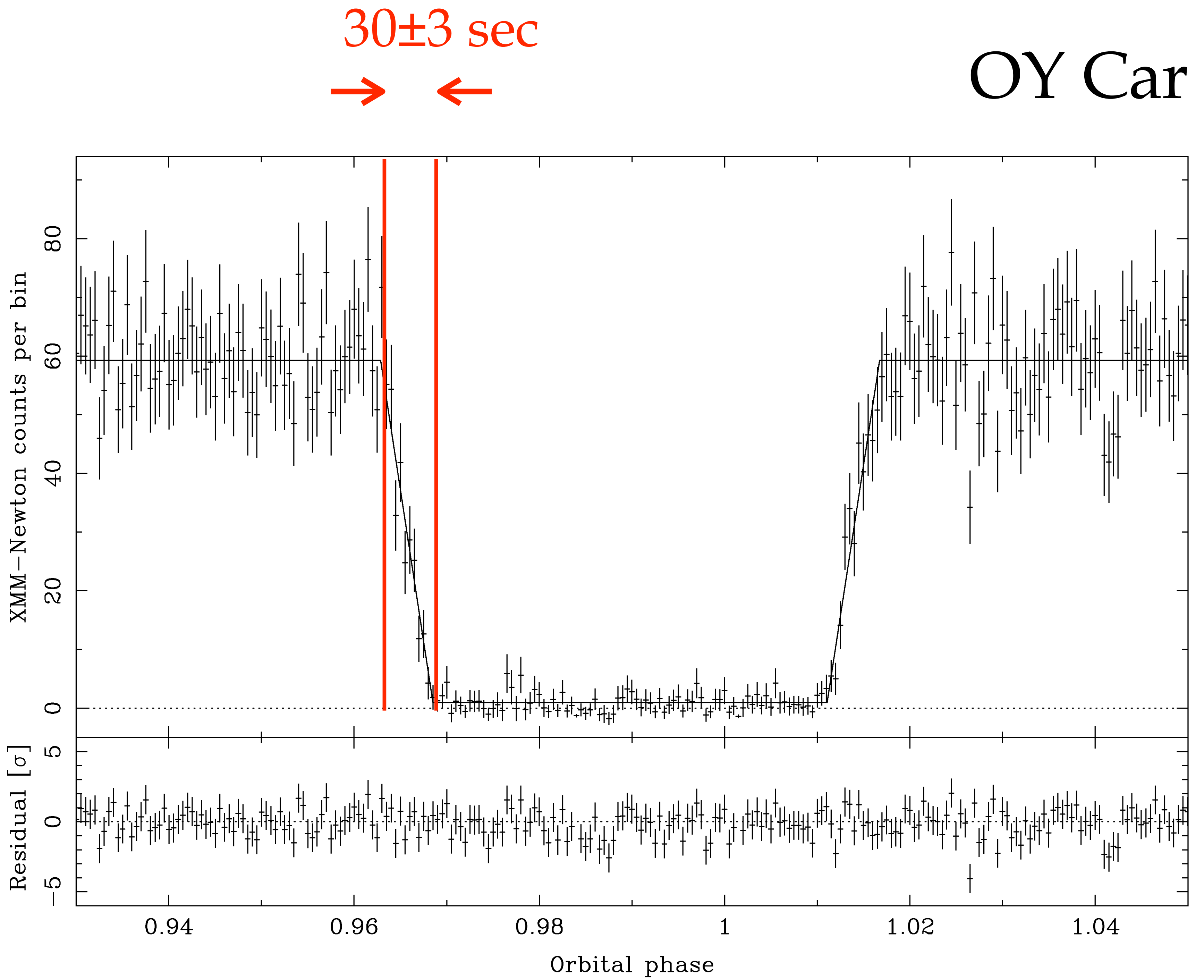
- Clear signature of bright spot and white dwarf
  - between them they contribute most of the light
- Very shallow disk eclipse
  - small contribution from disk to total light

## Dwarf-novae in outburst and nova-likes

- Disk is the primary source of light, white dwarf and bright spot not clearly seen
- Very broad and deep disk eclipse

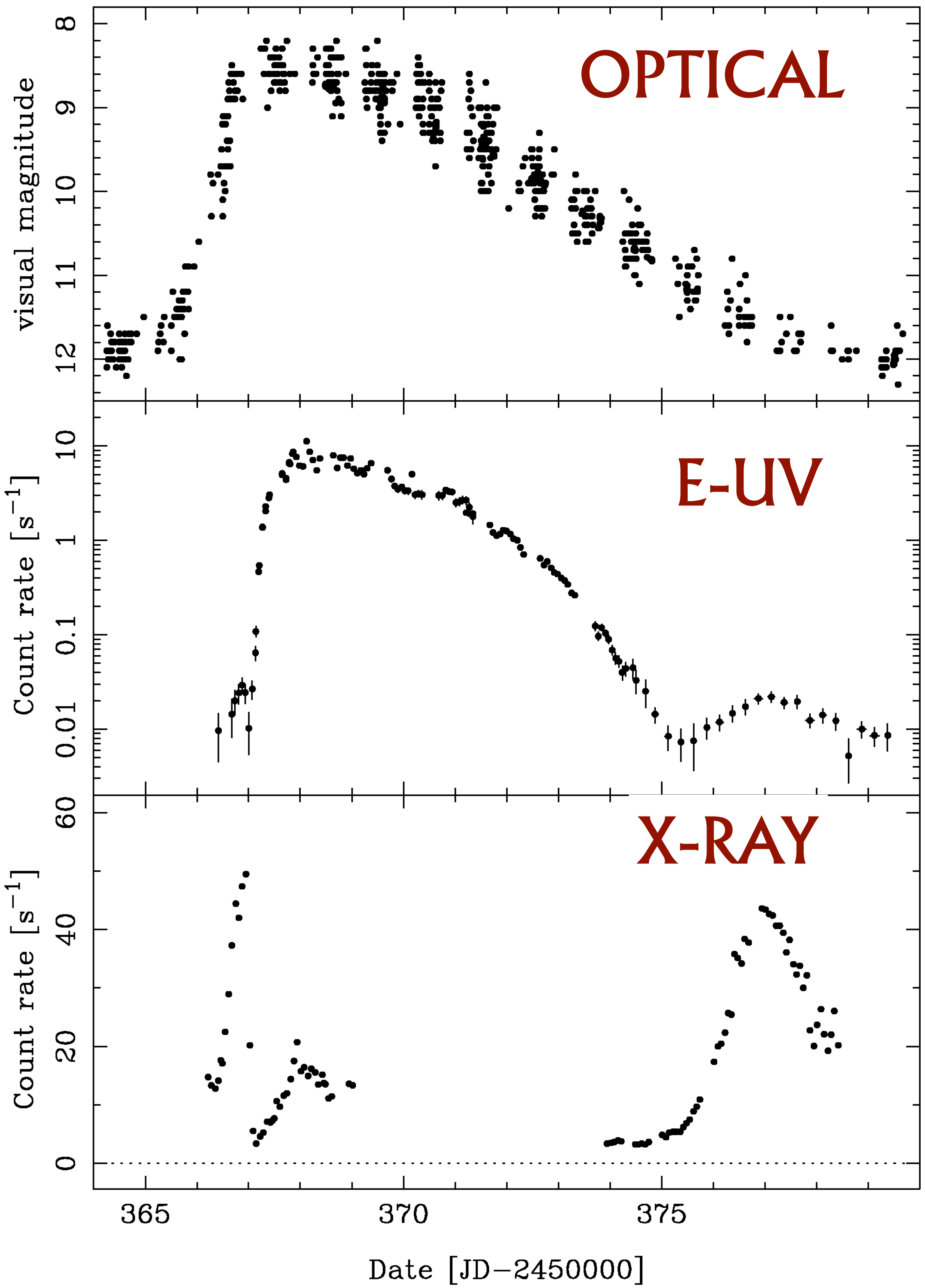
8

# X-Ray eclipse of the boundary layer




Wheatley & West 2003, MNRAS, 345, 1009

# A parenthesis on the boundary layer




- Observations of SS Cyg through a dwarf nova outburst
- Change in density of boundary layer opt. thin  opt. thick

Wheatley et al. 2003, MNRAS, 345, 49

# Eclipse mapping

- Recover 2-D surface brightness of the disk from the (1-D) eclipse light curve.
- Not enough constraints to solve the problem uniquely. Need help!
- Resort to maximum entropy method to incorporate expectations/prejudices, e.g.,
  - azimuthal symmetry
  - uniformity or smoothness

# How is this done in practice?

- **Synthesize eclipse light curve from assumed 2-D image of the disk. Iteratively adjust its surface brightness to satisfy two constraints:**
  - Good fit to the light curve (via $\chi^2$ test)

$$\chi^2 = \sum_{i=1}^{n} \left( \frac{F_i - M_i}{\sigma_k} \right)^2$$

  - Close resemblance to “default” image; maximum entropy constraint

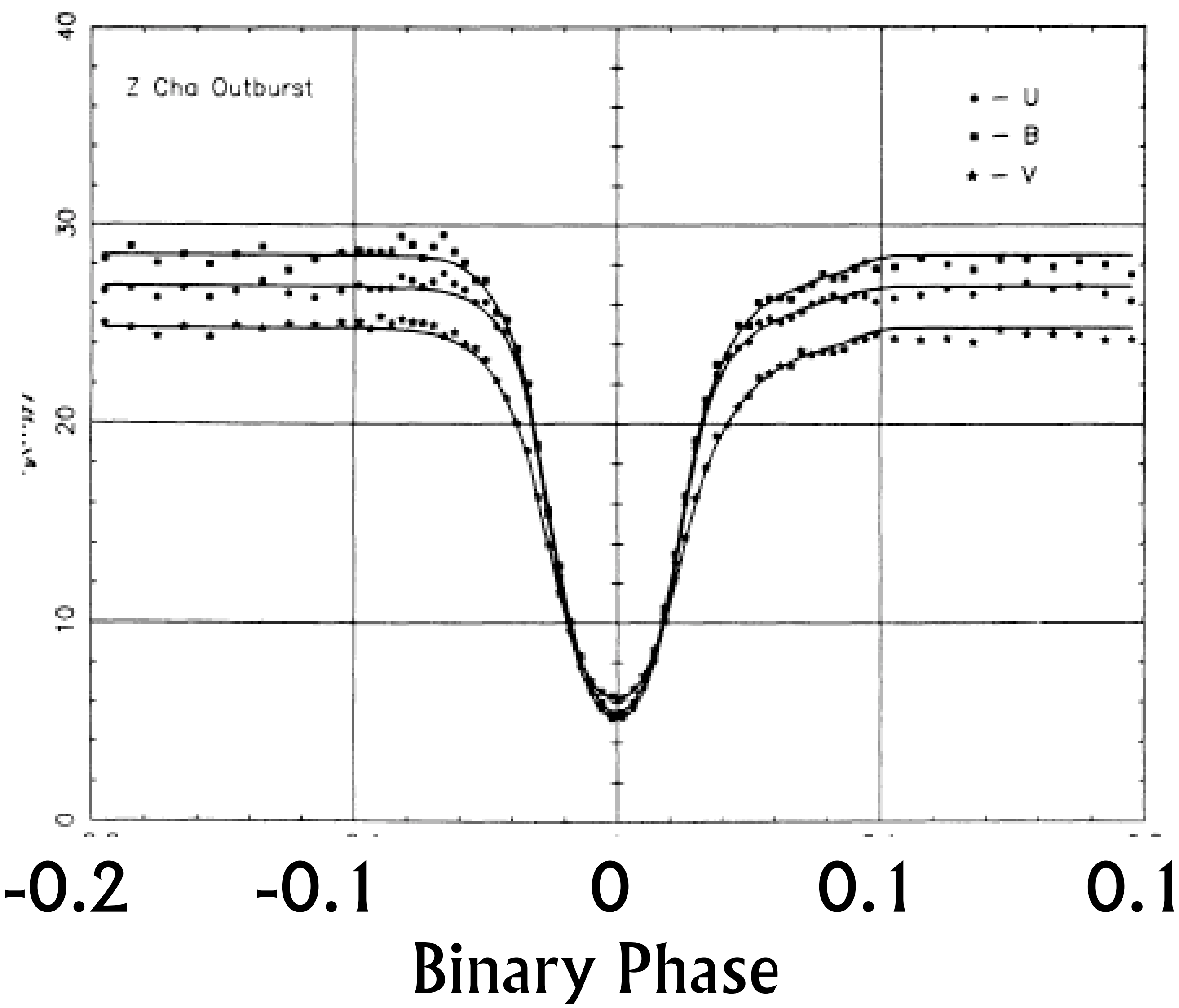
$$S = -\sum_{k=1}^{N^2} I_k \ln \left( \frac{I_k}{D_k} \right)$$

# Requirements and assumptions

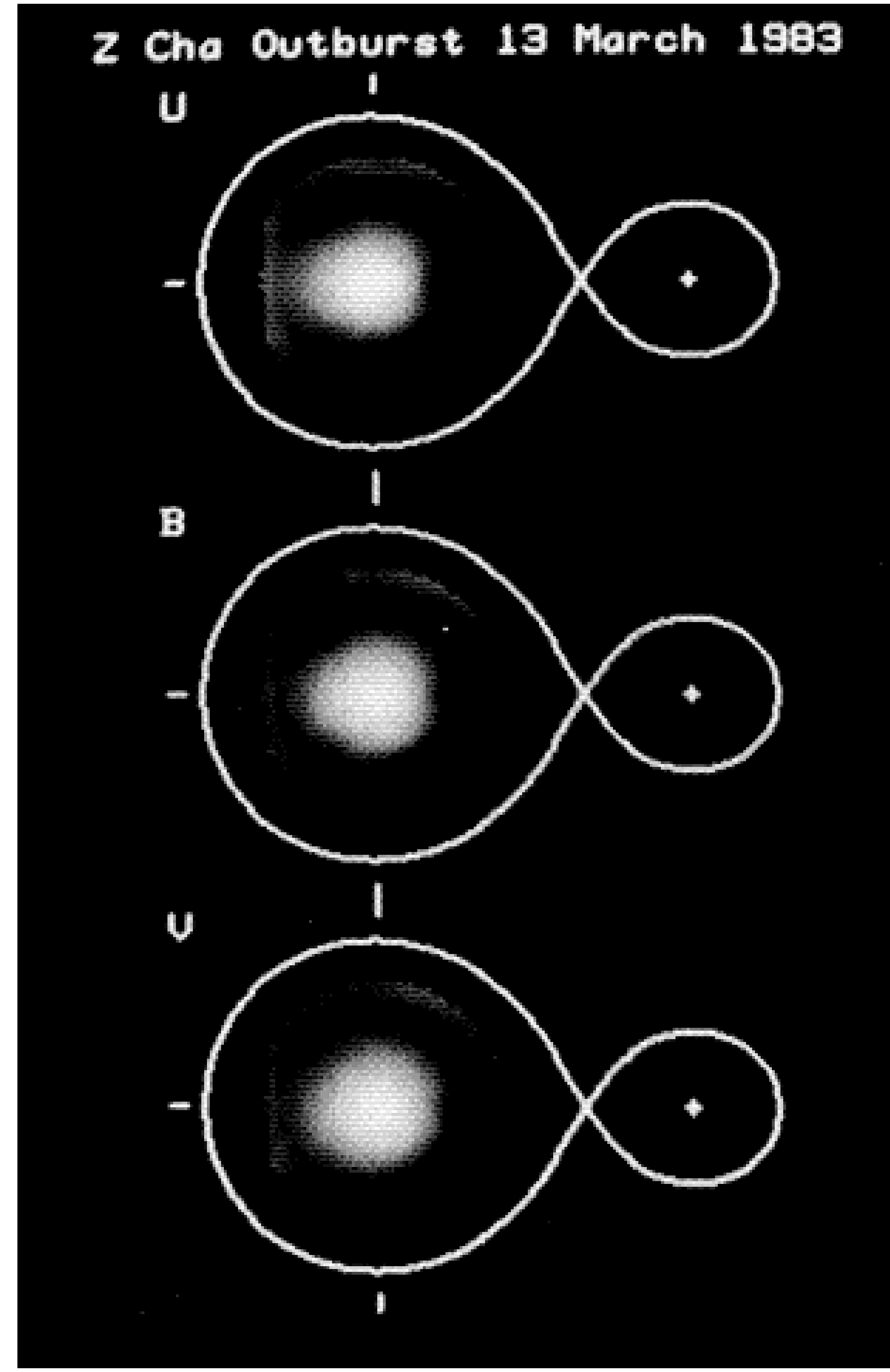
- Need to know the parameters of the binary in order to reconstruct the geometry correctly
- Must assume that disk is static.
- Initial implementation assumed flat disk. Current versions allow for 3-D structure.
- Default map may influence the results. Need to carry out tests to verify results.
- Reconstruction of physical parameters (e.g., temperature) is only as good as the adopted model.

# Early Applications of Eclipse Mapping

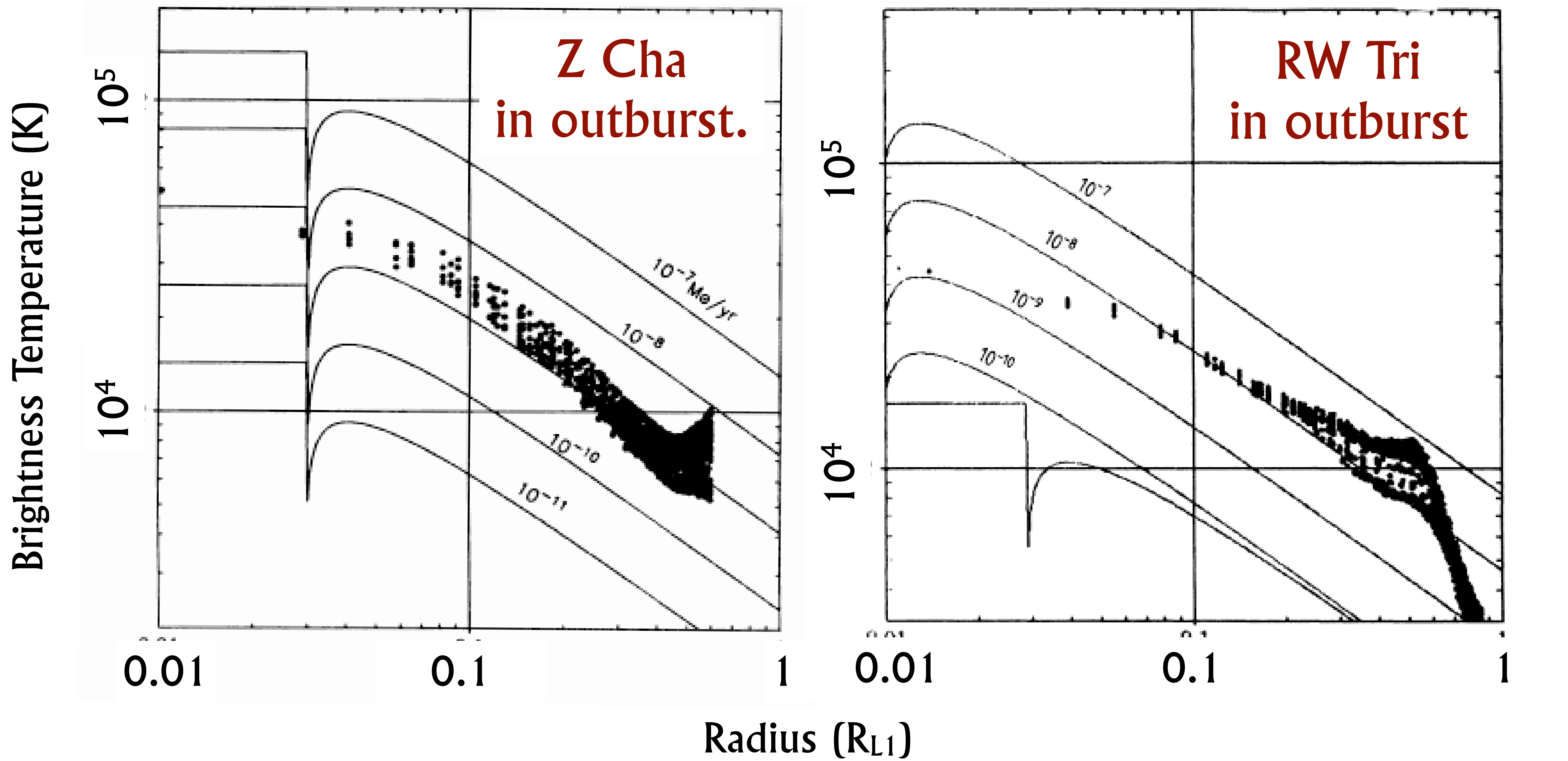
Eclipse maps of Z Cha in outburst.




Horne & Cook, 1985, MNRAS, 214, 307



# Radial brightness profile of the disk

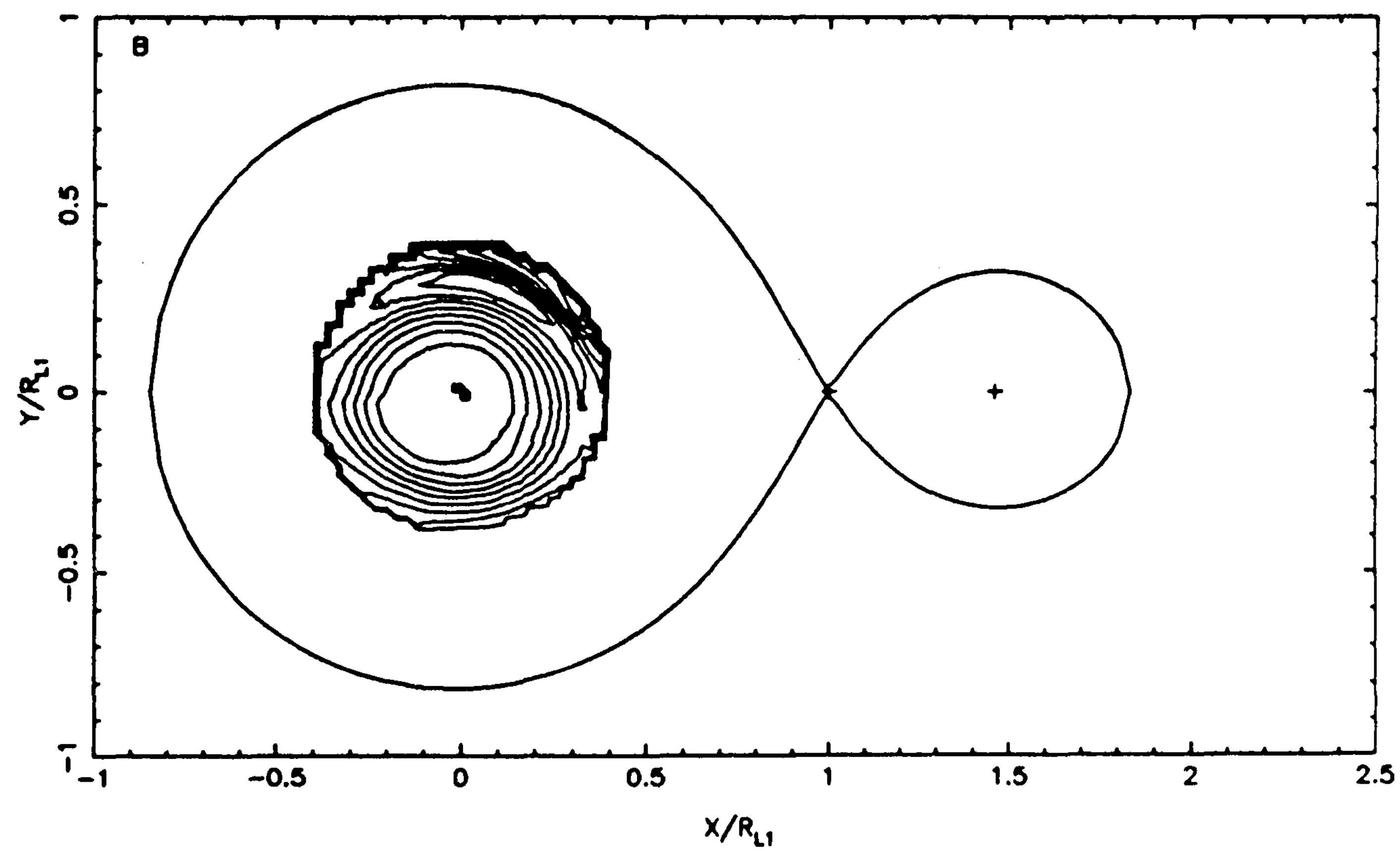


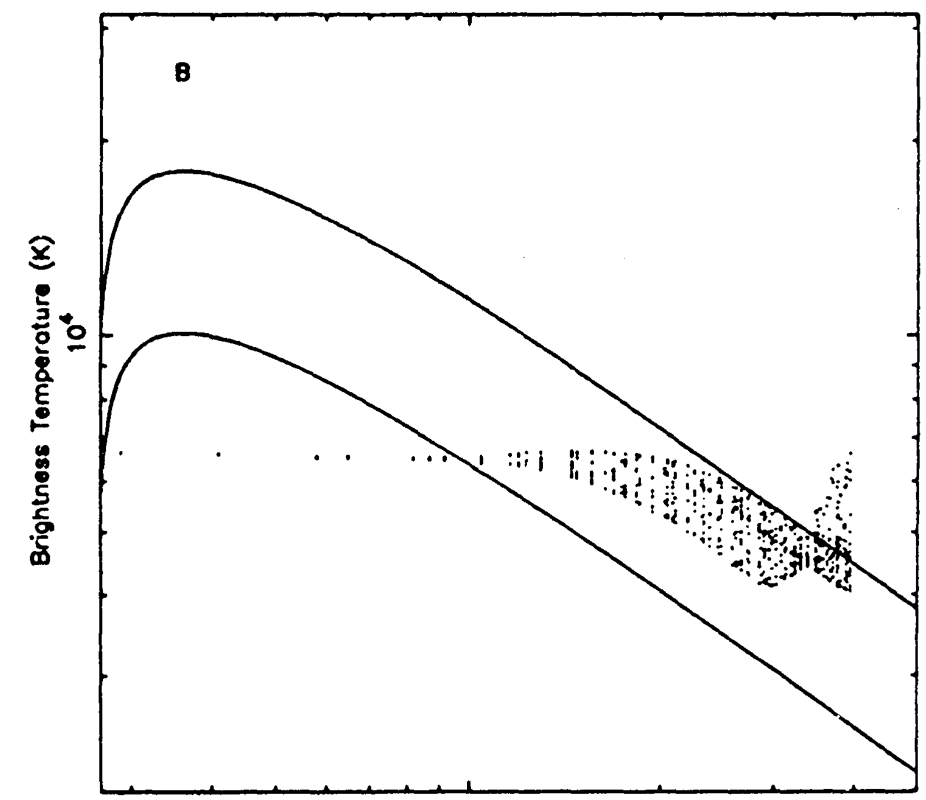

Horne & Cook, 1985, MNRAS, 214, 307

Horne & Stiening, 1985, MNRAS,216, 933

# Radial brightness profile of the disk

HT Cas in quiescence



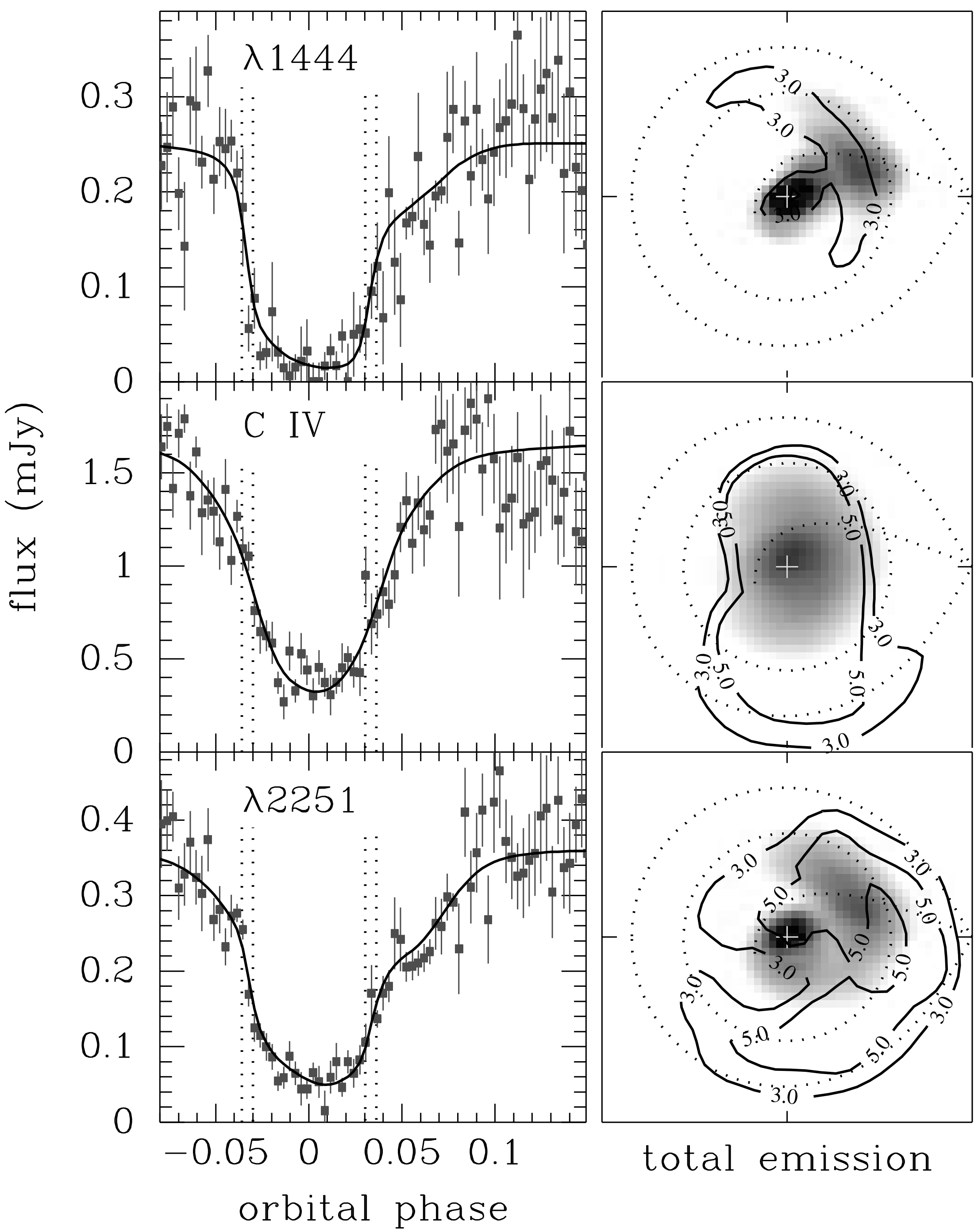

0.1

Radius (RL1)

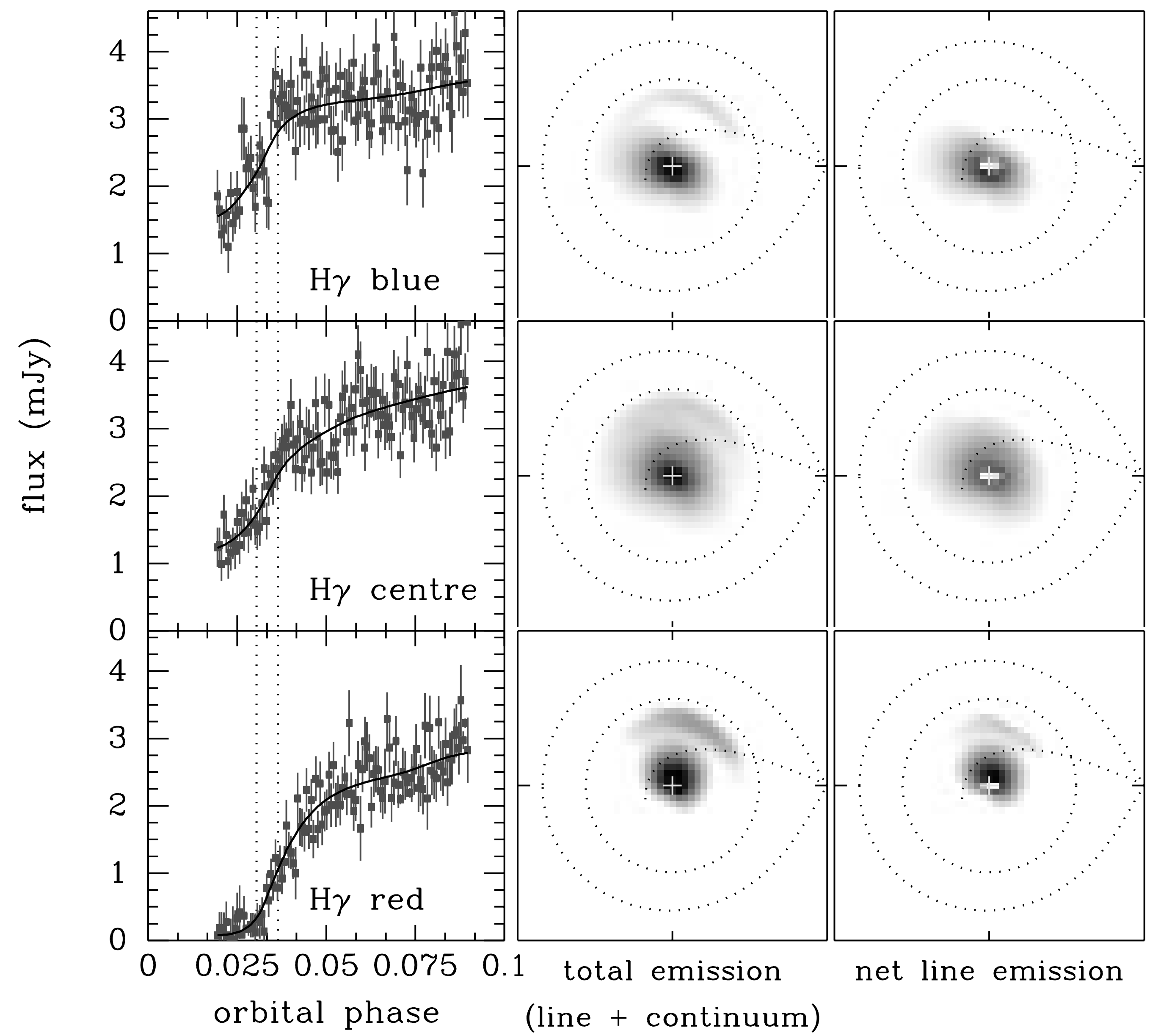
Wood et al. 1992, ApJ, 385, 294

# Spectral Mapping: V2051 Oph in quiescence

## C IV and UV continuum



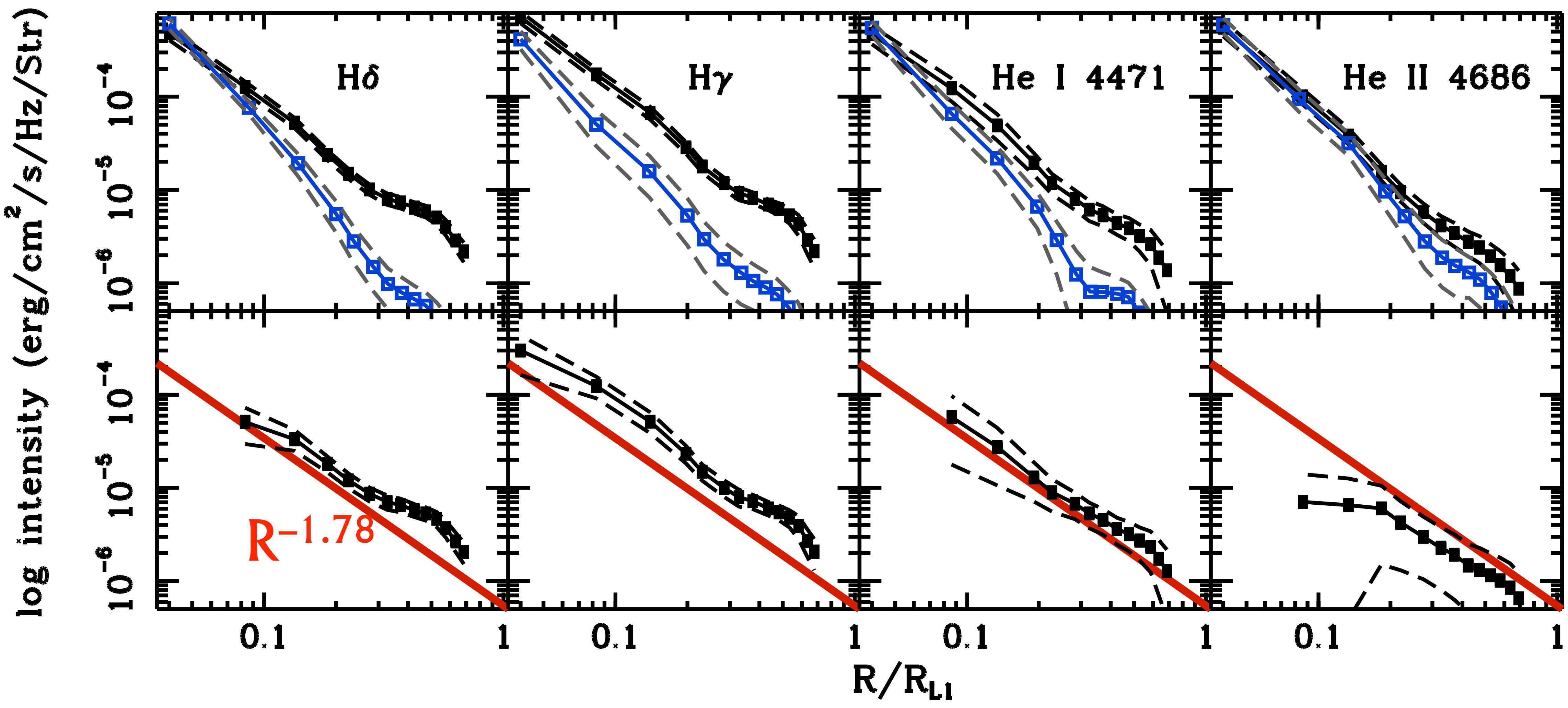

## sections of the Hγ line




from Saito & Baptista 2006, AJ, 131, 2185

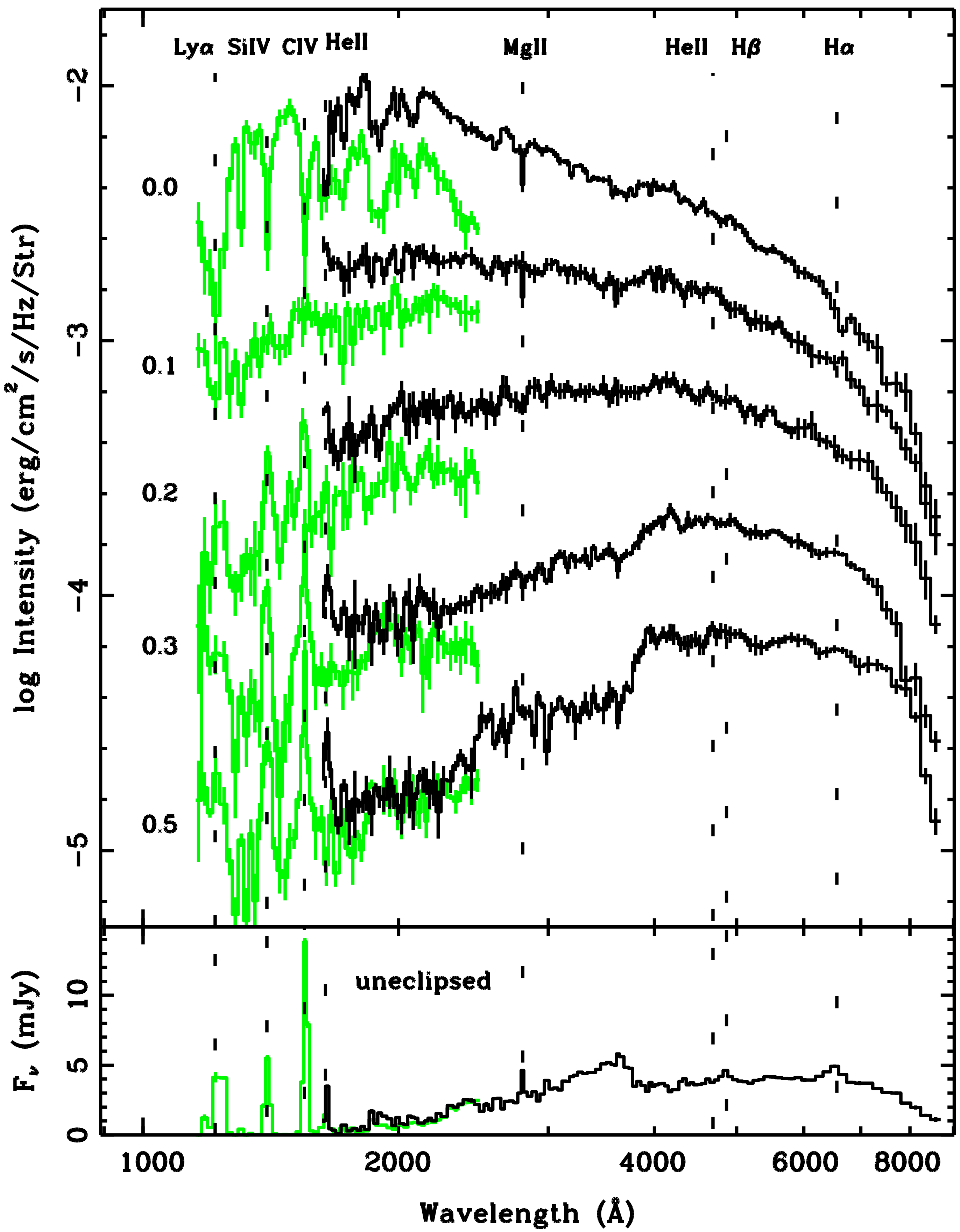
# Spectral Mapping: V2051 Oph in quiescence

Emissivity profiles of continuum and emission lines




from Saito & Baptista 2006, AJ, 131, 2185

# Spectral Mapping: UX UMa in high state




Radially resolved spectra of the disk (pioneered by Rutten et al 1993, Nature, 362, 518)

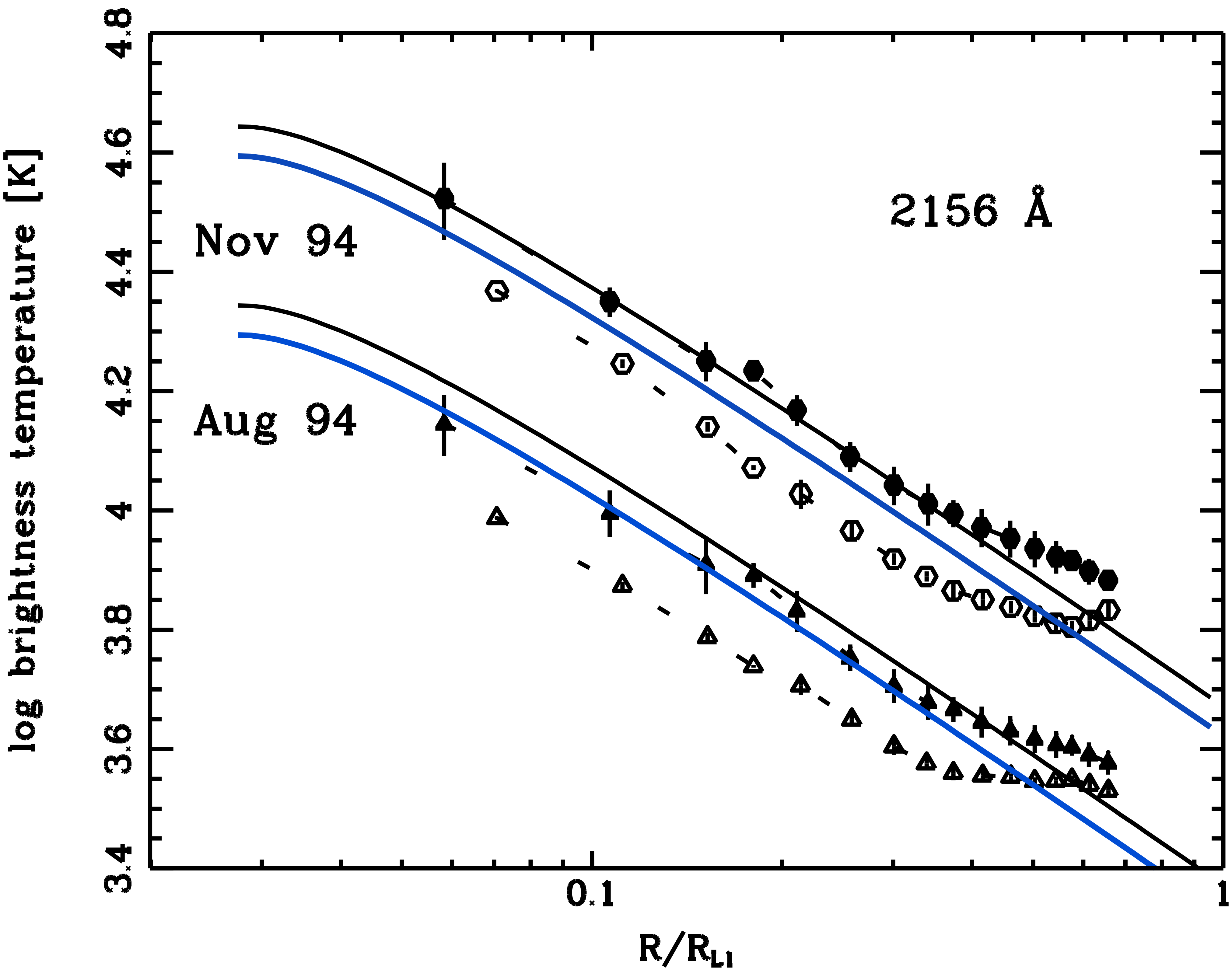
Eclipse mapping of UX UMa with HST/FOS spectra

Spectrum gets redder and lines go to emission in outer disk

from Baptista et al 1998, MNRAS, 298, 1079

# Spectral Mapping: UX UMa in high state

Brightness temperature profile of the disk




from Baptista et al 1998, MNRAS, 298, 1079

# Lessons from eclipse mapping

- **CVs in high state → α−disk models?**
- **Spatially-resolved disk spectra in qualitative agreement with theoretical expectations.**
- **Temperature profiles not in quantitative agreement with the predictions of disk models.**
  - Irradiated disk models may be able to do better. (Orosz & Wade 2003, ApJ, 593, 1032)
  - We see emission lines! Optically thin gas? Where is the source of the emission lines?

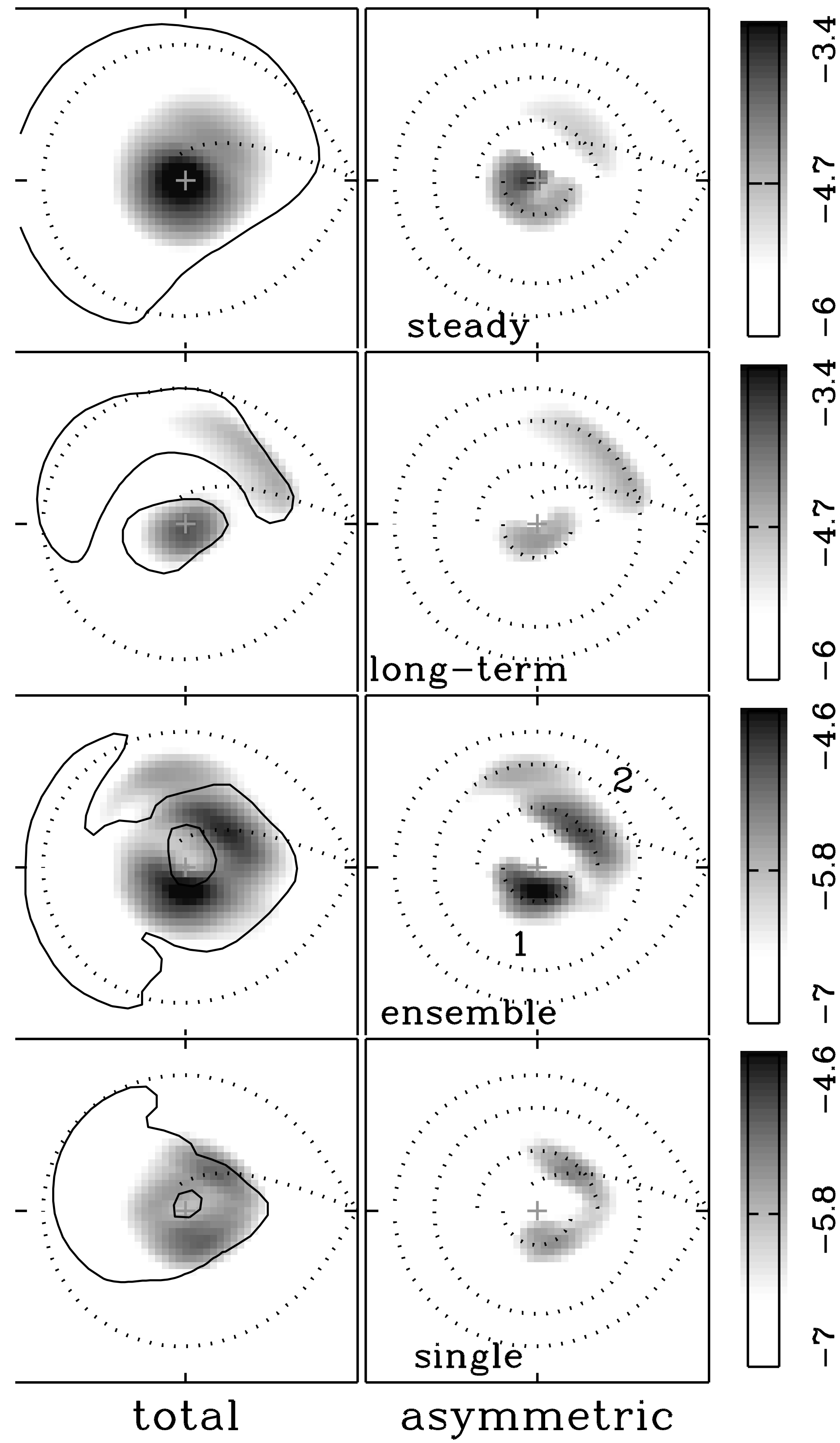
# Maps of flickering

Maps of flickering in UU Aqr

Baptista & Bortoletto 2008, ApJ, 676, 1240

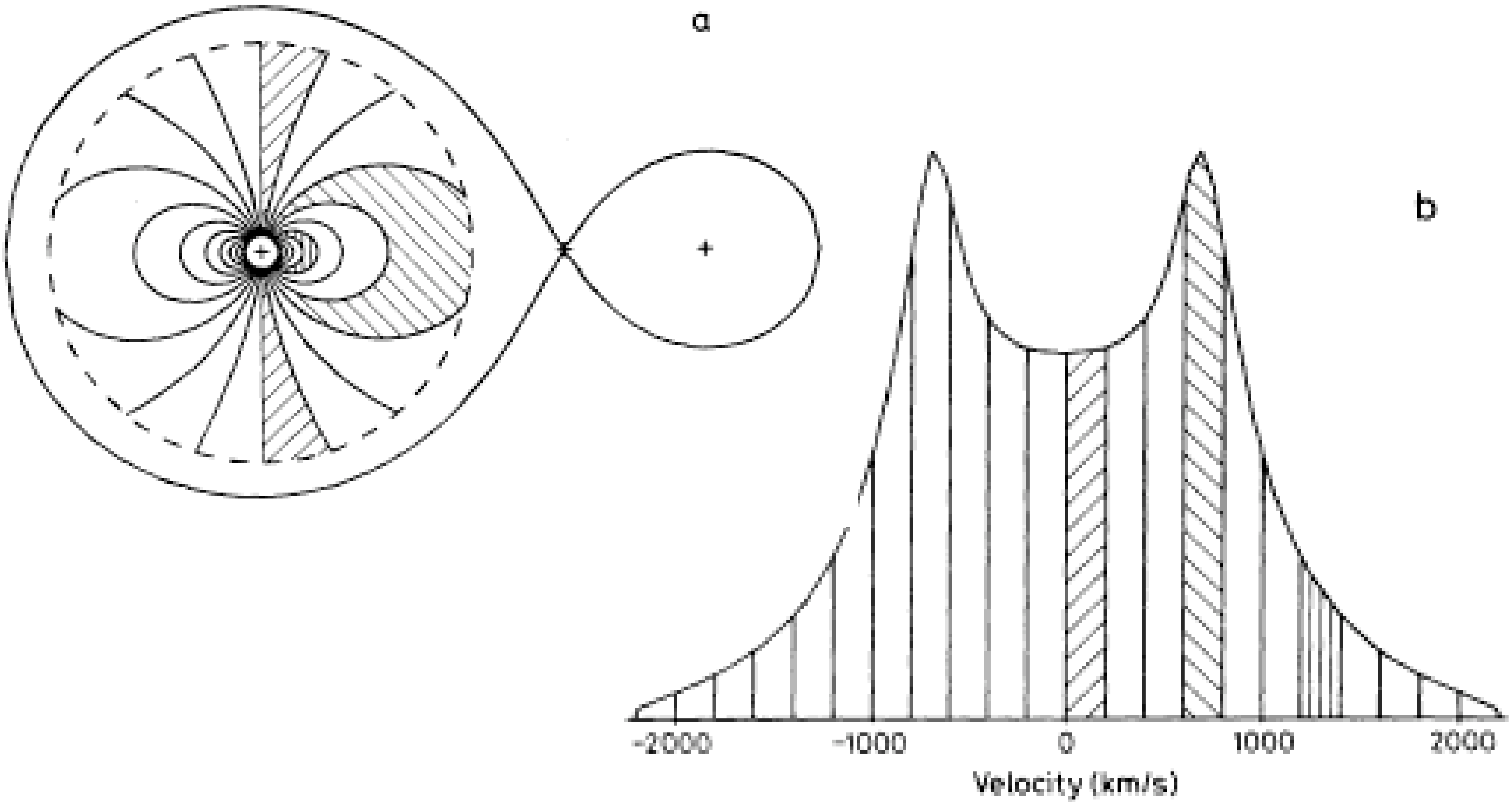
$f$ = 0.1–100 mHz

$f$ > 2 mHz



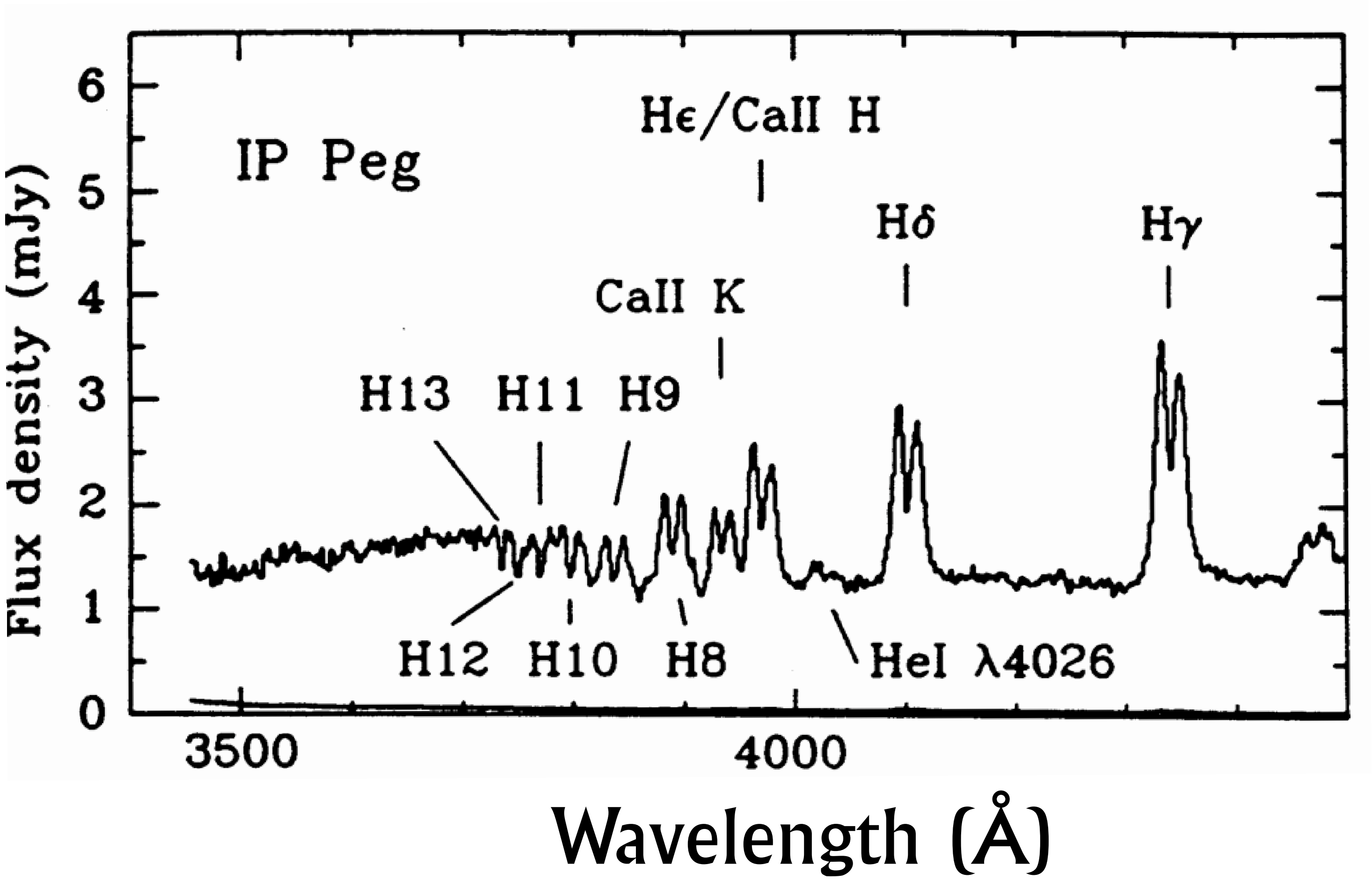
# Emission Lines from Disks

# Line Profiles from Rotation

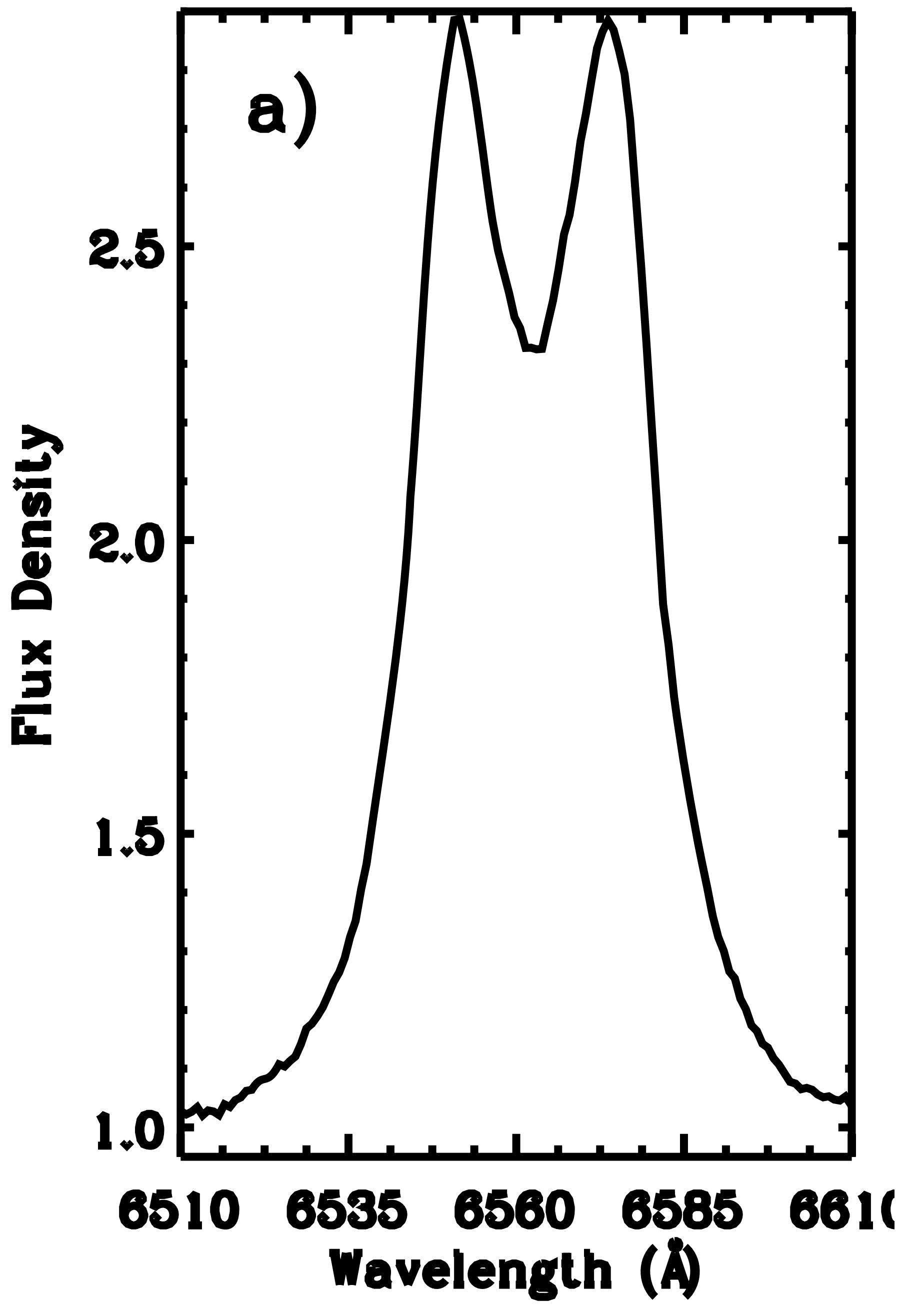



figures from Horne & Marsh 1986, MNRAS, 218, 761

# Examples of observed line profiles: I

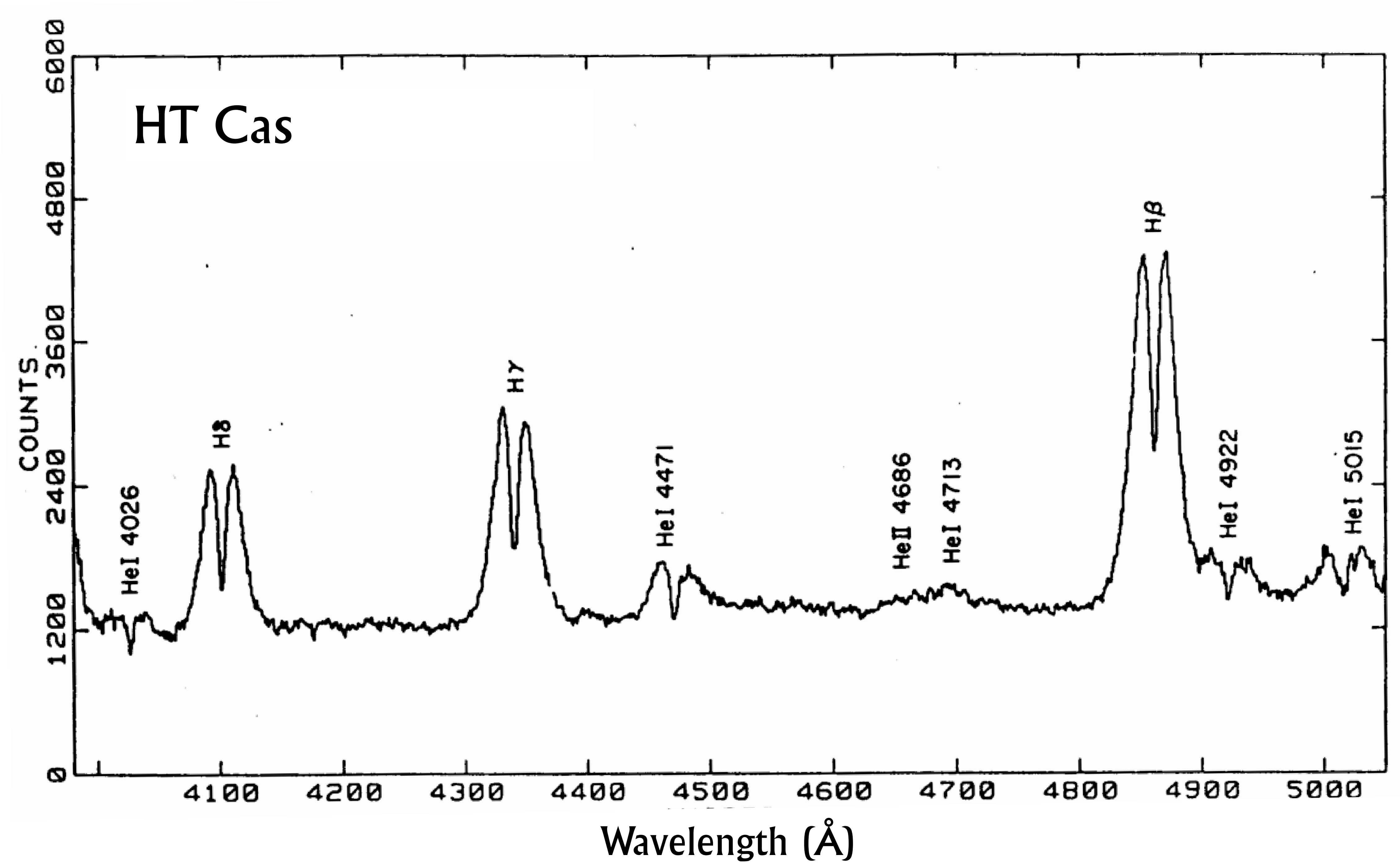



IP Peg in low state
from Marsh 1988, MNRAS, 231, 1117



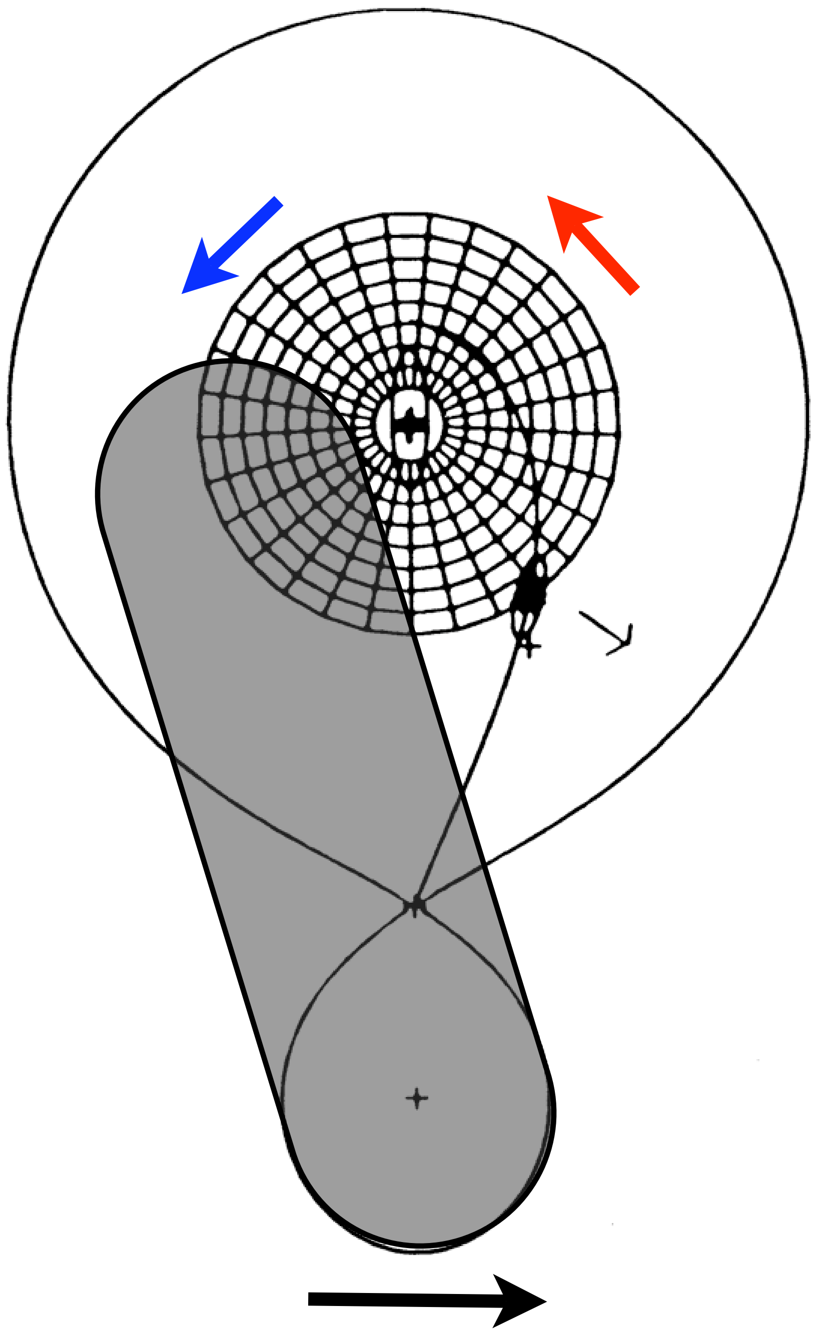

A 0620-00
Nielsen et al. 2008, MNRAS, 384, 849

# Examples of observed line profiles: II

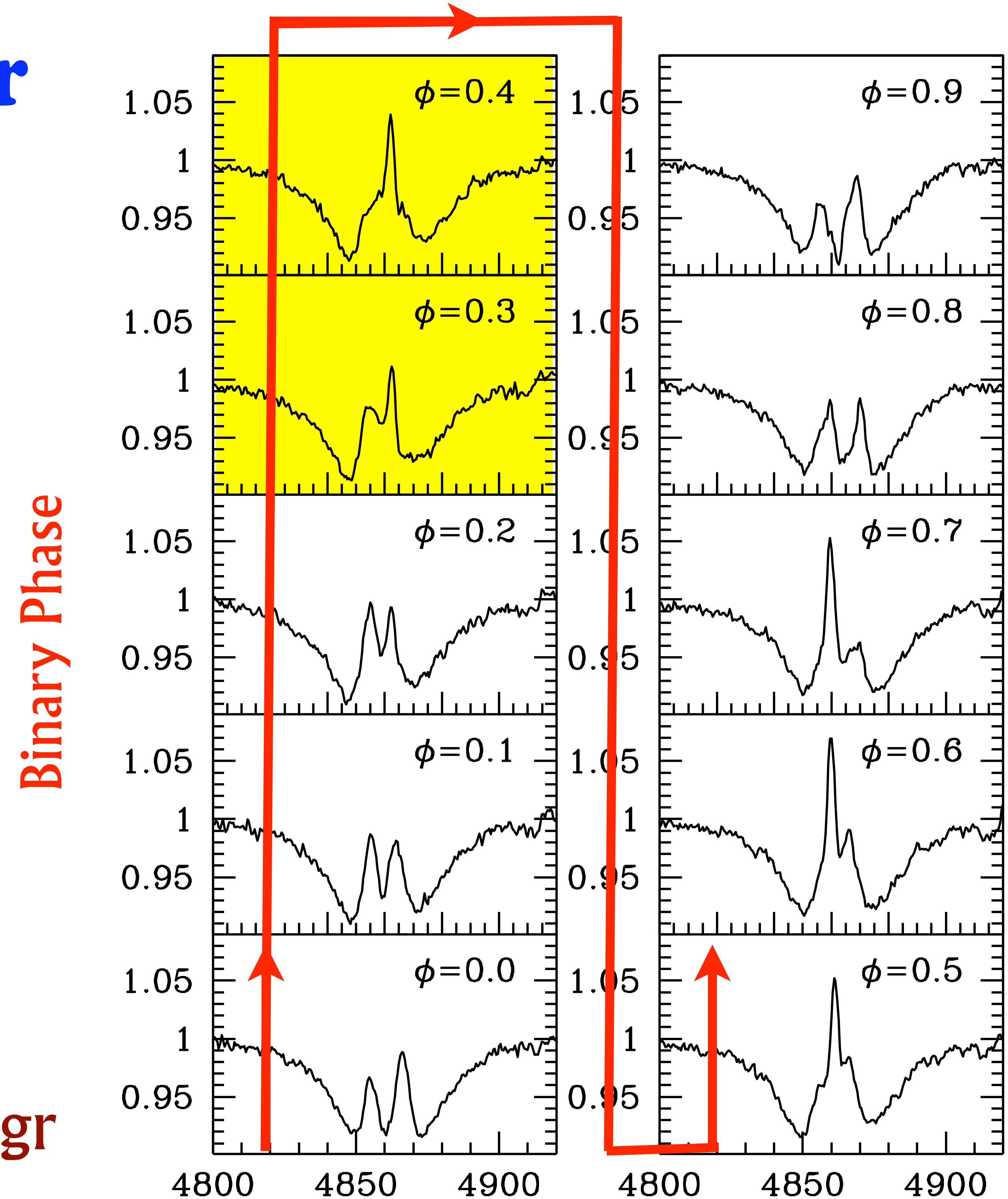



from Young & Schneider 1980, ApJ, 238, 955

# Eclipse behavior

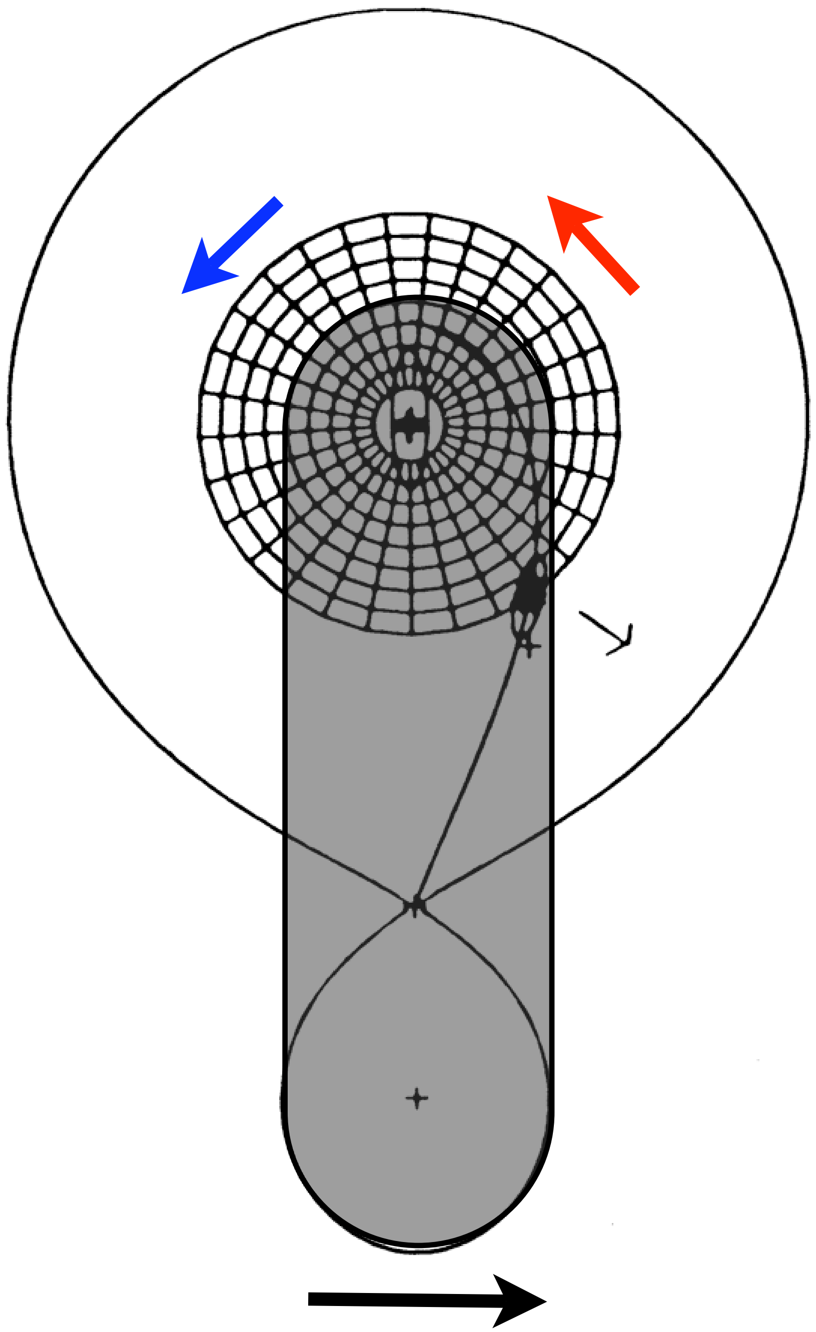


V3885 Sgr

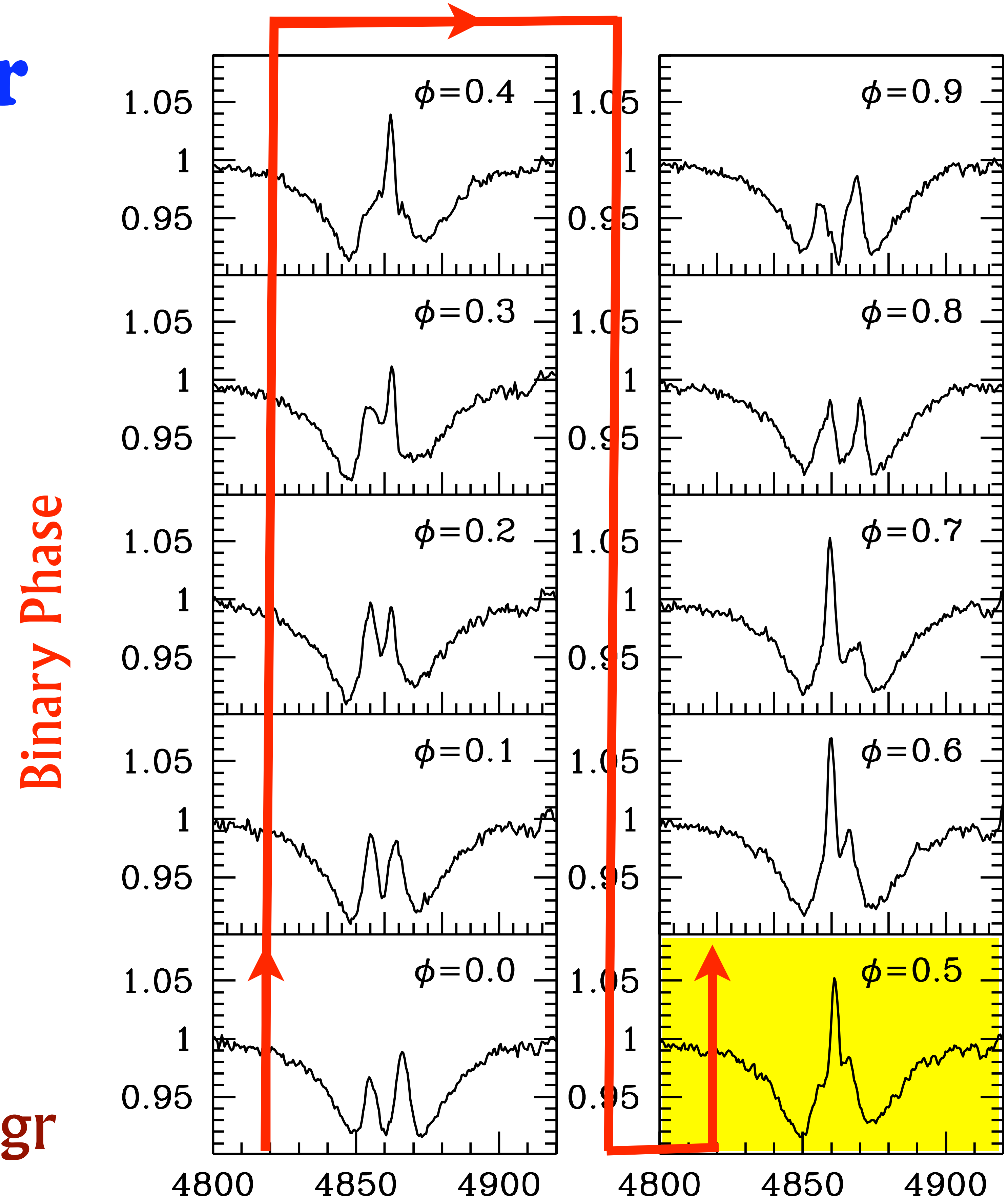



Hartley et al. 2005, MNRAS, 363, 286)

# Eclipse behavior



V3885 Sgr




Hartley et al. 2005, MNRAS, 363, 286)

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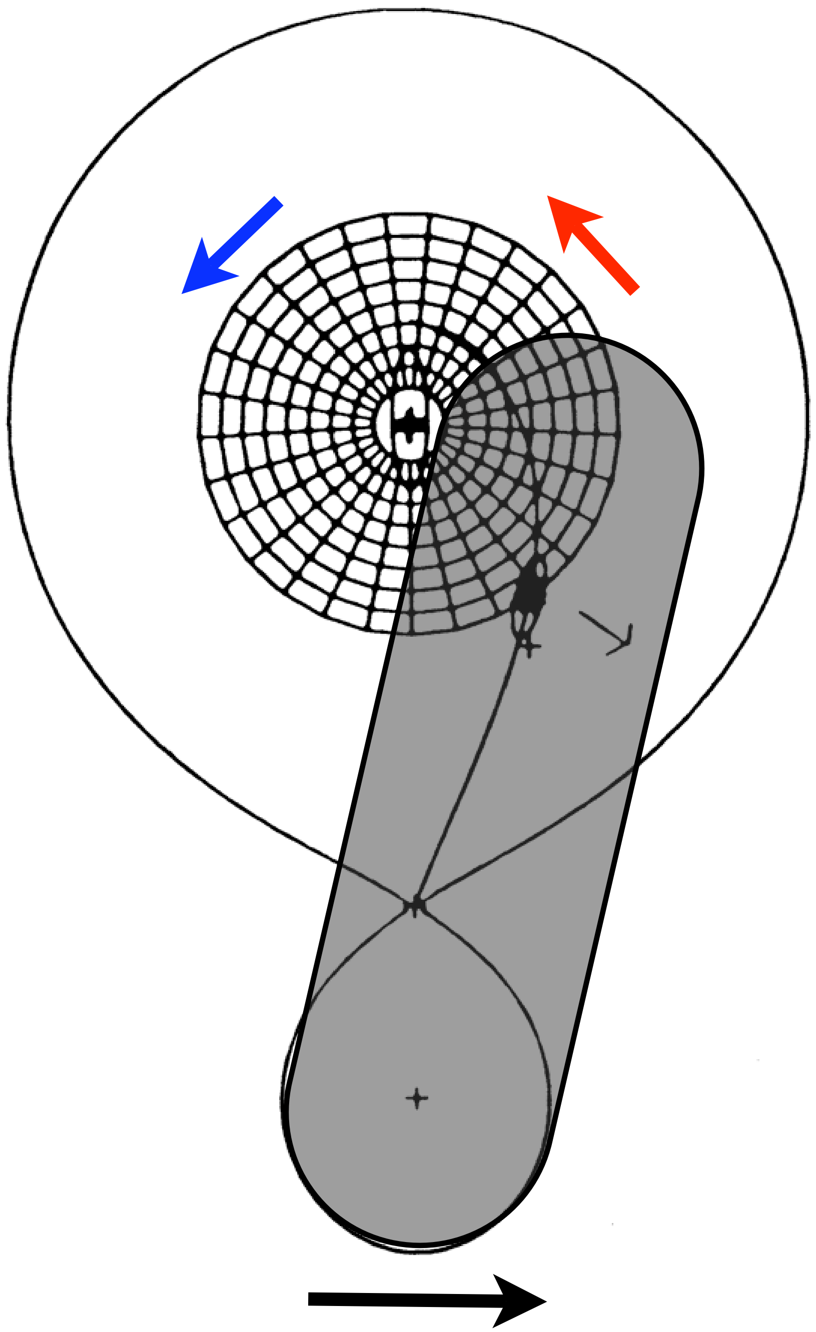
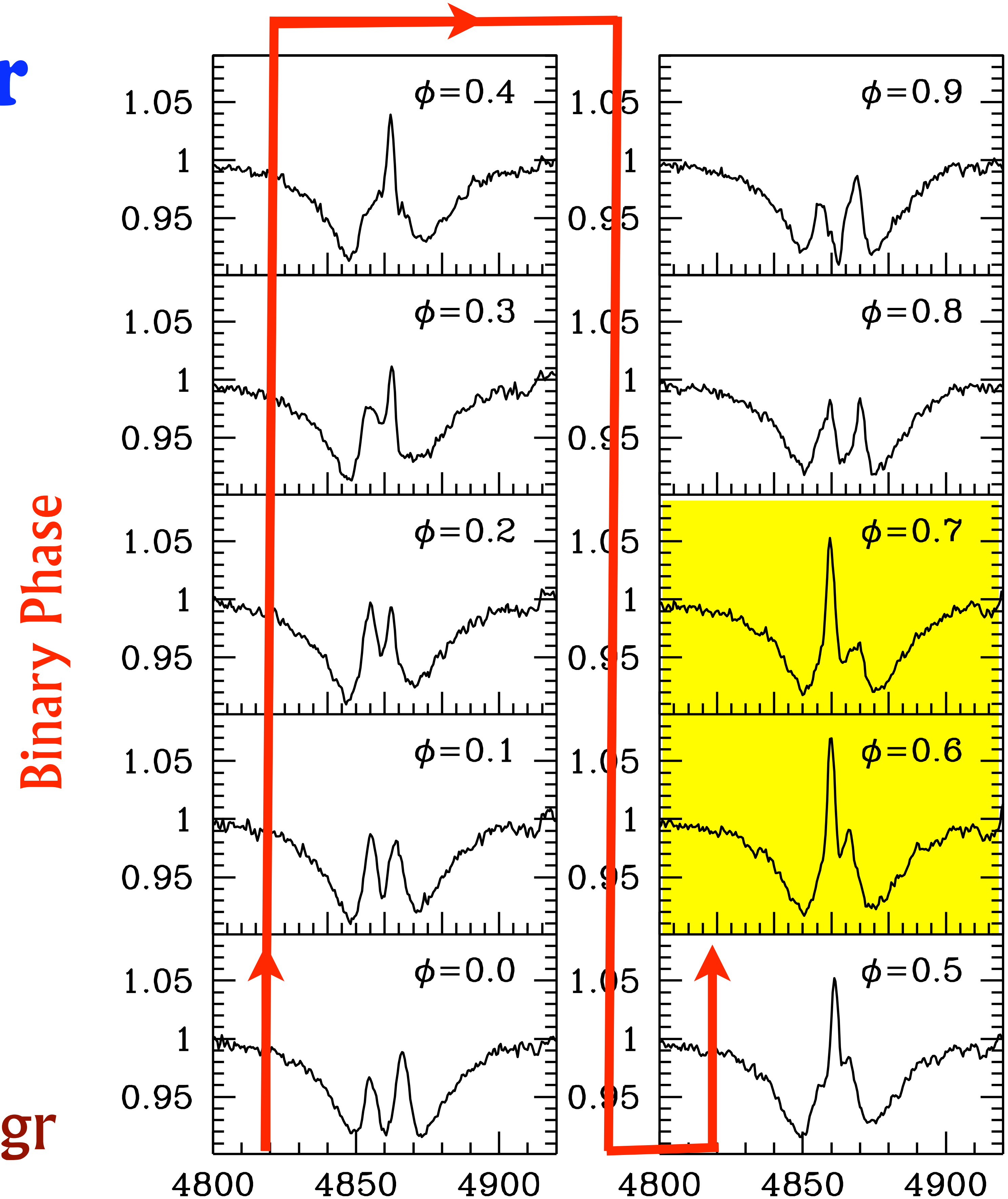
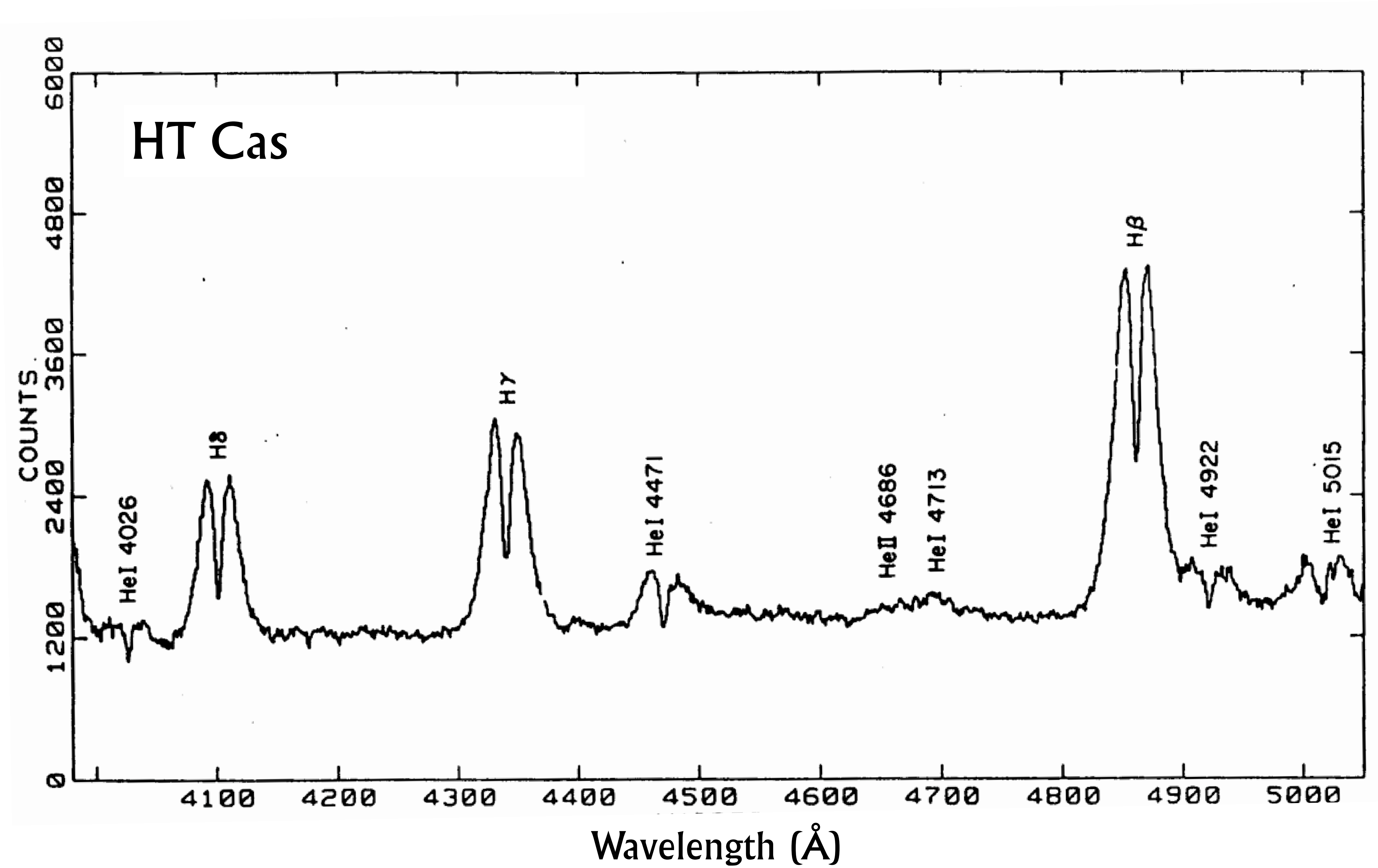



Hartley et al. 2005, MNRAS, 363, 286)

# Examples of observed line profiles: II




from Young & Schneider 1980, ApJ, 238, 955

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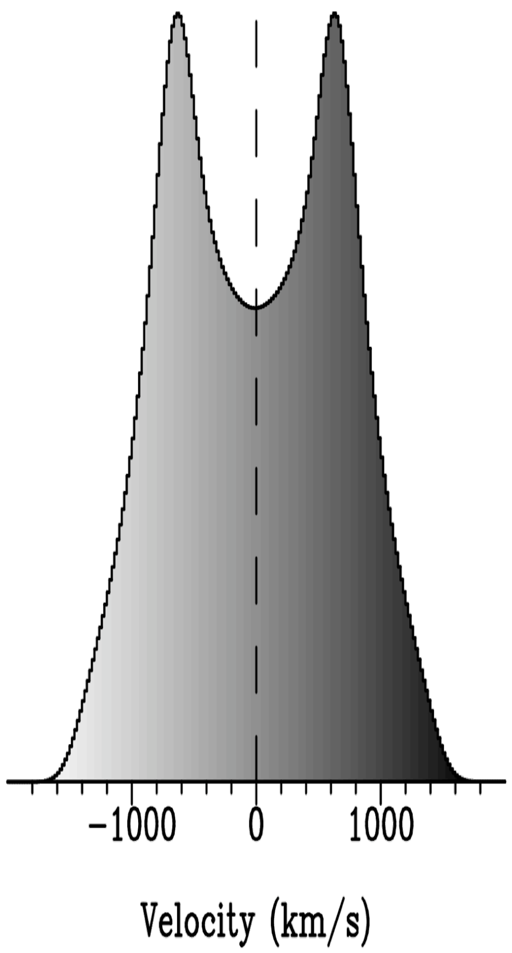
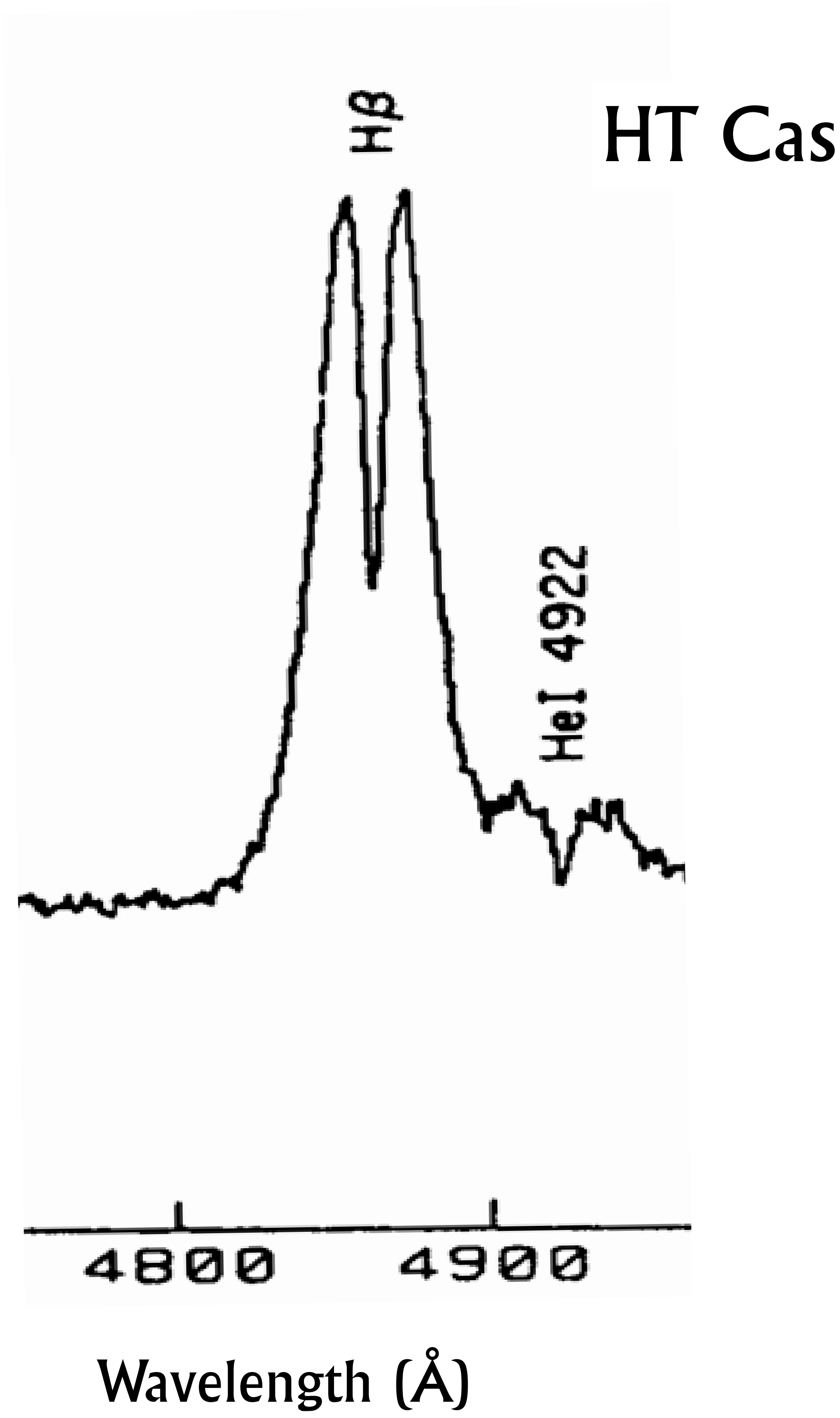
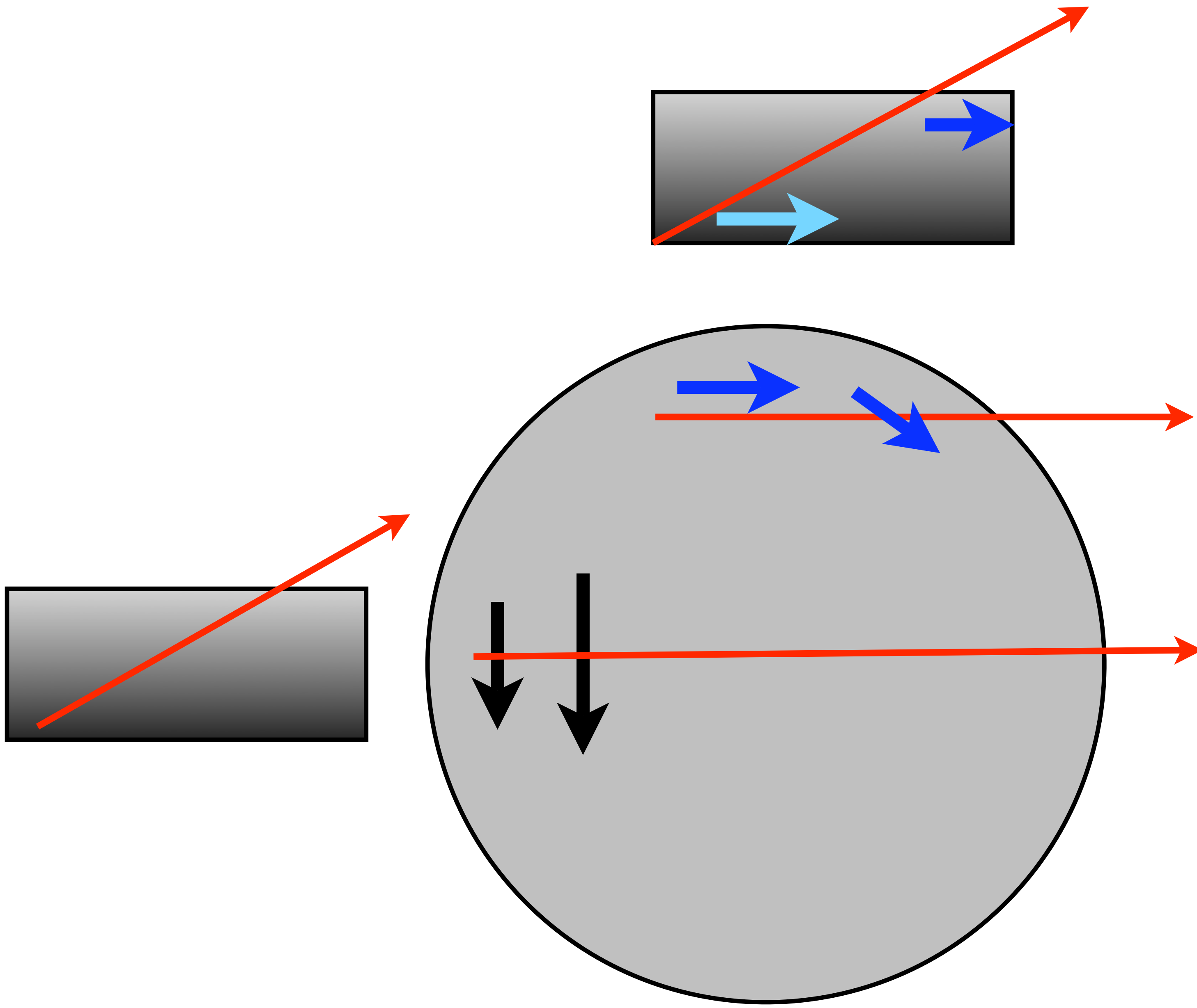
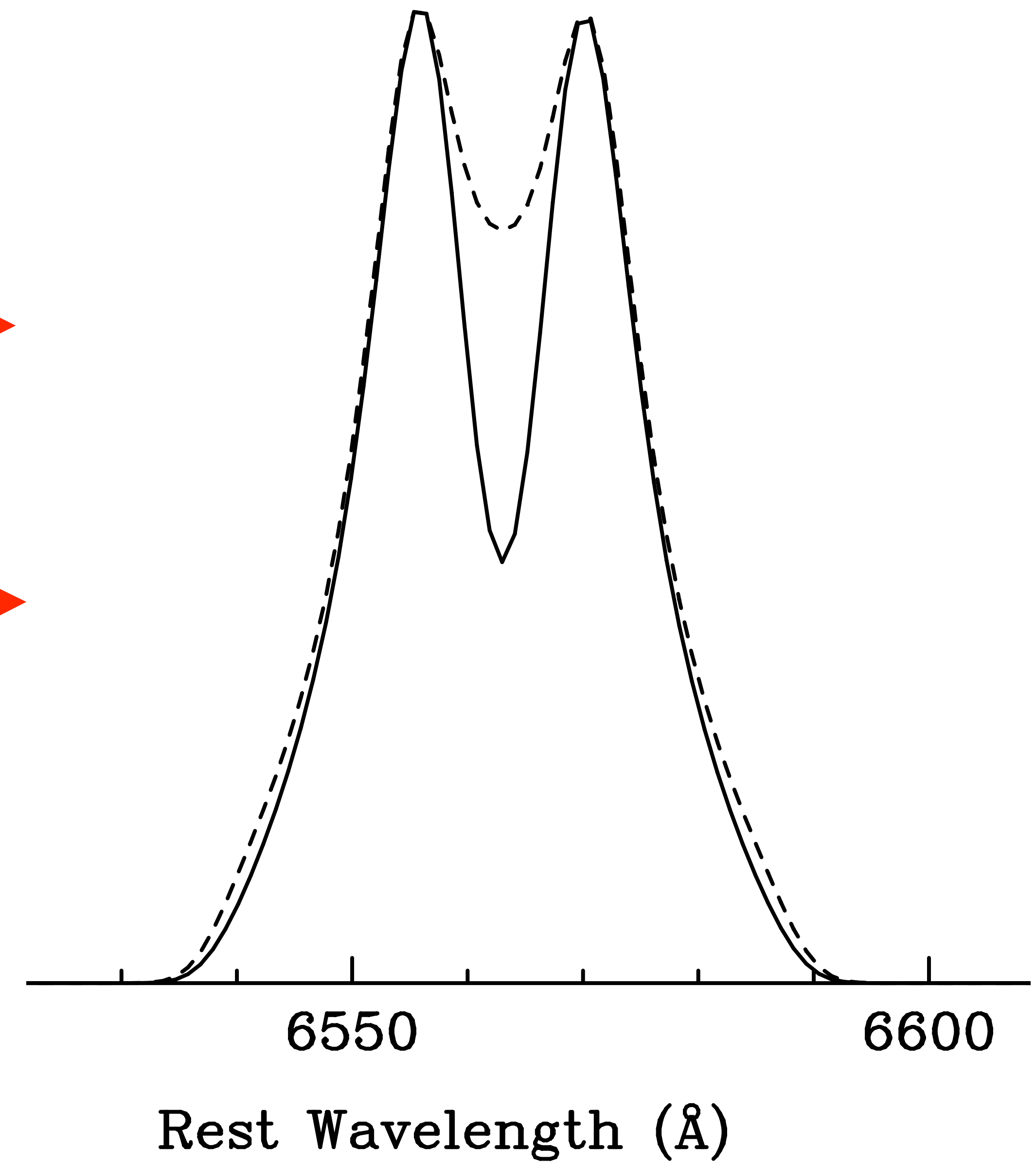



from Young & Schneider 1980, ApJ, 238, 955

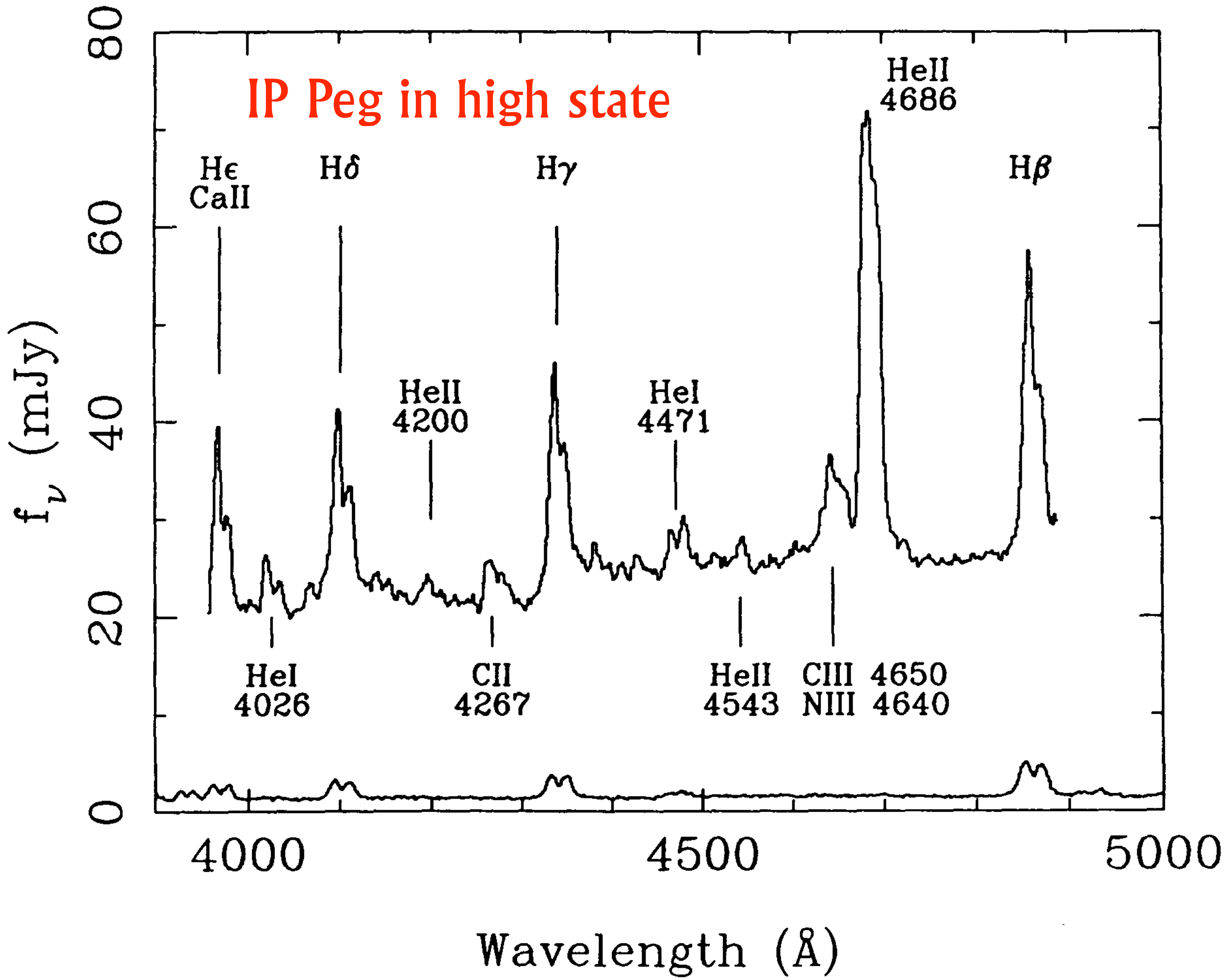
# Radiative transfer effects






Horne & Marsh 1986,
MNRAS, 218, 761

# Something changes in outburst!




from Horne & Marsh 1990, ApJ, 349, 593

# Source of power for the lines

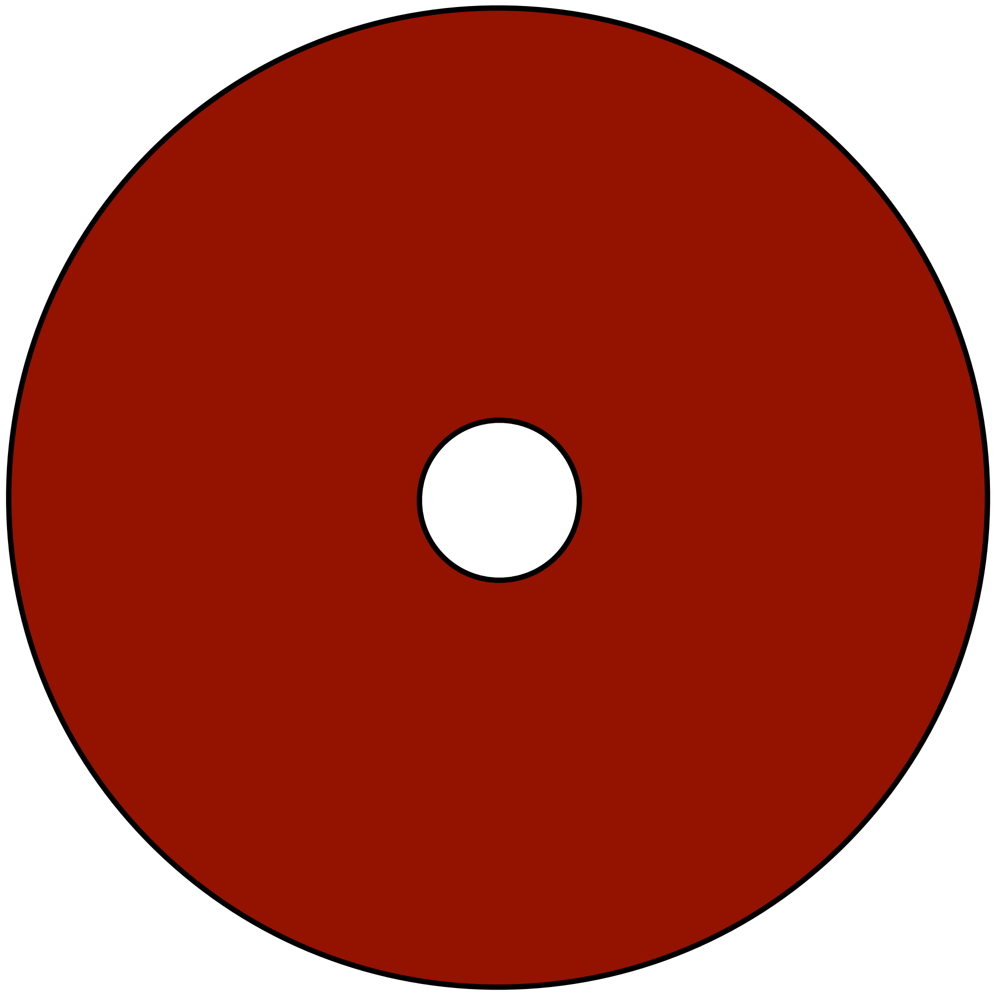
- **Local Energy Dissipation**
  - Emission from optically thin disk in LTE probably the case in low state
    Williams 1980, ApJ, 235, 939
  - Coronal loops over the disk, analogous to solar magnetic loops
    Horne & Saar 1991, ApJ, 374, L55
- **Photoionization**
  - CVs in high state:
    Horne & Marsh 1990, ApJ, 349, 593

# Relativity matters in the hottest disks

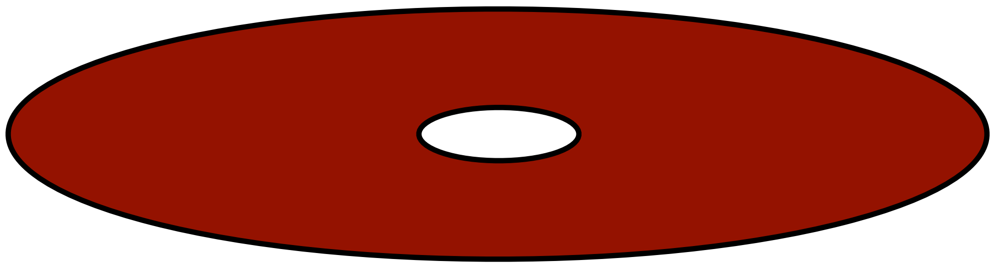
- **Lines originate at $\xi$ < 1000**
  - if $\xi$ < 100 need fully relativistic calculation
  - $\xi$ > 100 weak-field approximation
- **Special and General Relativistic effects:**
  - Light bending
  - Doppler boosting
  - Transverse & gravitational redshift

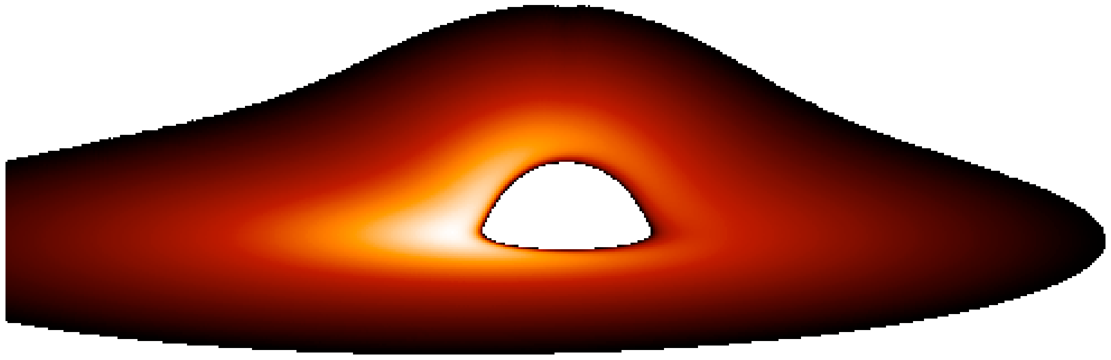
# Illustration of Relativistic Effects

Face-On Disk



Inclined Disk





Inclined Disk With Light Bending and Doppler Boosting

# Simple, approximate approach

## 2-step transformation:

(Mathews 1982, ApJ, 258, 425; but see critique in Chen & Halpern 1989, ApJ, 339, 742)

- disk frame → stationary observer above disk → stationary observer at infinity
- step 1: Lorentz transformation

$$I_\nu = I'_{\nu'}\,\gamma^2\,(1+\beta\cos i')^2$$

$$\gamma = (1-2/\xi)^{1/2}(1-3/\xi)^{-1/2}$$

- step 2: Gravitational redshift

$$I''_{\nu''} = I_\nu$$

$$\nu'' = \nu(1-2/\xi)^{-1/2}$$

# Need a more general approach

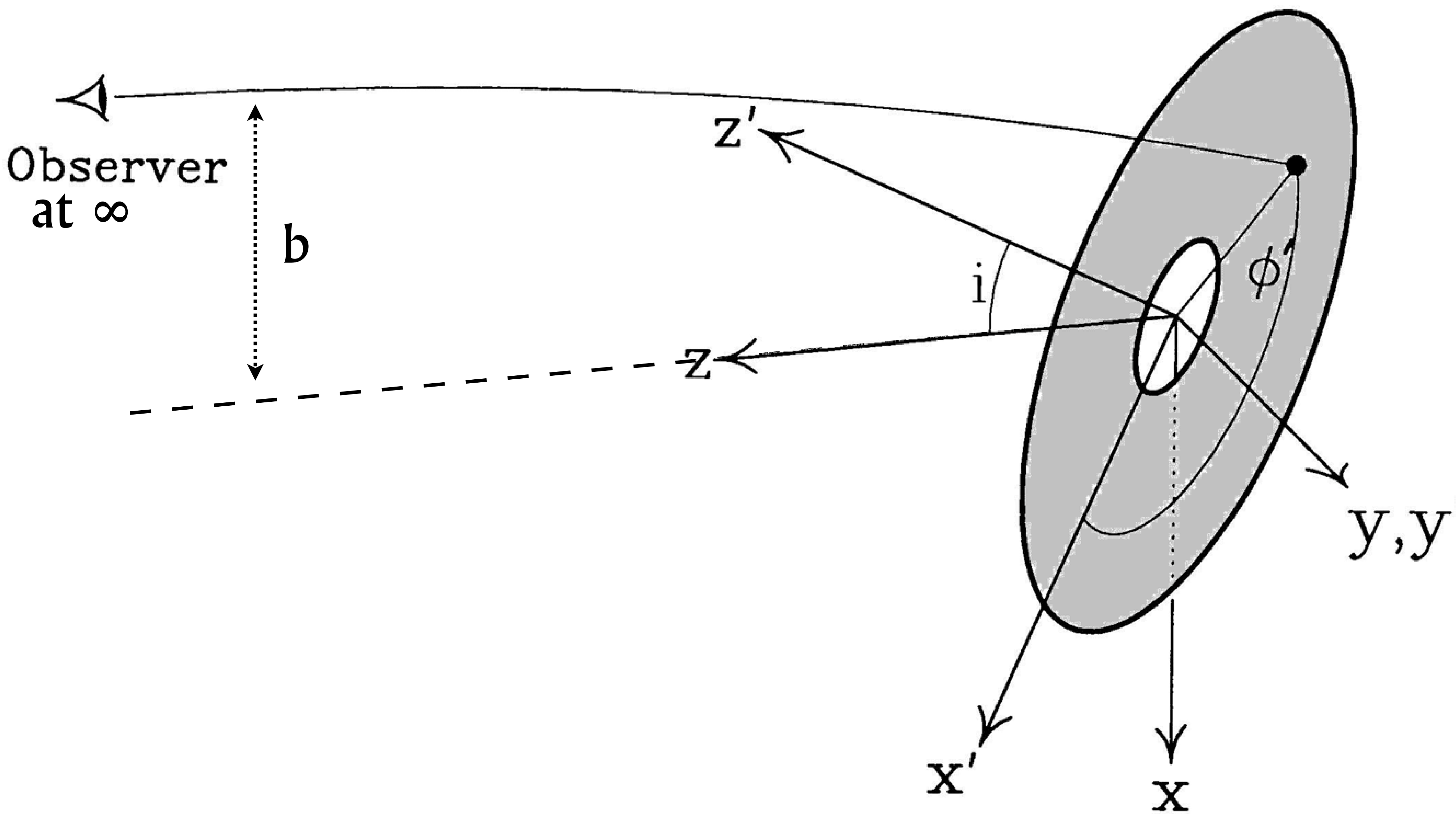



figure from Chen & Eardley 1991, ApJ, 382, 125

# Formalism

- Chen et al. 1989, Chen & Halpern 1989, Chen & Eardley 1990

  - Emission line profile in the frame of the observer (i.e., the image at ∞ in the plane of the sky):

$$F_\nu = \int\int d\Omega \;\; I_\nu(b, \varphi, \nu) \; ,$$

    Where $d\Omega = b\, db\, d\varphi / d^2$ is the solid angle in the plane of the sky.

  - We need to connect the coordinates frame of the image to the coordinate frame in the frame of the disk, i.e.

$$(b, \varphi, \nu) \quad \longrightarrow \quad (r, \varphi', \nu_{\rm e}) \; .$$

# Tricks

Chen et al. 1989, Chen & Halpern 1989, Chen & Eardley 1990

- Trace photon trajectories to connect image in disk frame to image at $\infty$

$$\frac{d\theta}{dr} = \frac{b/r^2}{\sqrt{1-(b/r)(1-2M/r)}} \quad \longrightarrow \quad b = f(r, \varphi')$$

- Exploit invariance of $I_\nu/\nu^3$ to transform specific intensity to observer's frame

$$I_\nu = I'_{\nu_e}\left(\frac{\nu}{\nu_\mathrm{e}}\right)^3 = I'_{\nu_e}\, D^3; \qquad \text{compute } D \text{ from } p^\alpha u_\alpha$$

# The Bottom Line

$$F_\nu = \int_0^{2\pi} d\varphi' \int_{\xi_1}^{\xi_2} \xi d\xi \;\; I'_{\nu_e}(\xi, \varphi', \nu_{\rm e}) \; D^3(\xi, \varphi', \nu_{\rm e}) \; \Psi(\xi, \varphi')$$

disk emission properties (local)

potential and phase space distribution of emitting particles (velocity field + metric + geometry)

photon trajectories (metric + geometry)

$$I'_{\nu_e} \propto \xi^{-q} \;\; \exp\left[ -\frac{(\nu_e - \nu_o)^2}{2\sigma^2} \right]$$

Radial emissivity profile from central illumination. Broadening due to random motions, finite integration cells, and instrumental resolution.

# Examples of other calculations

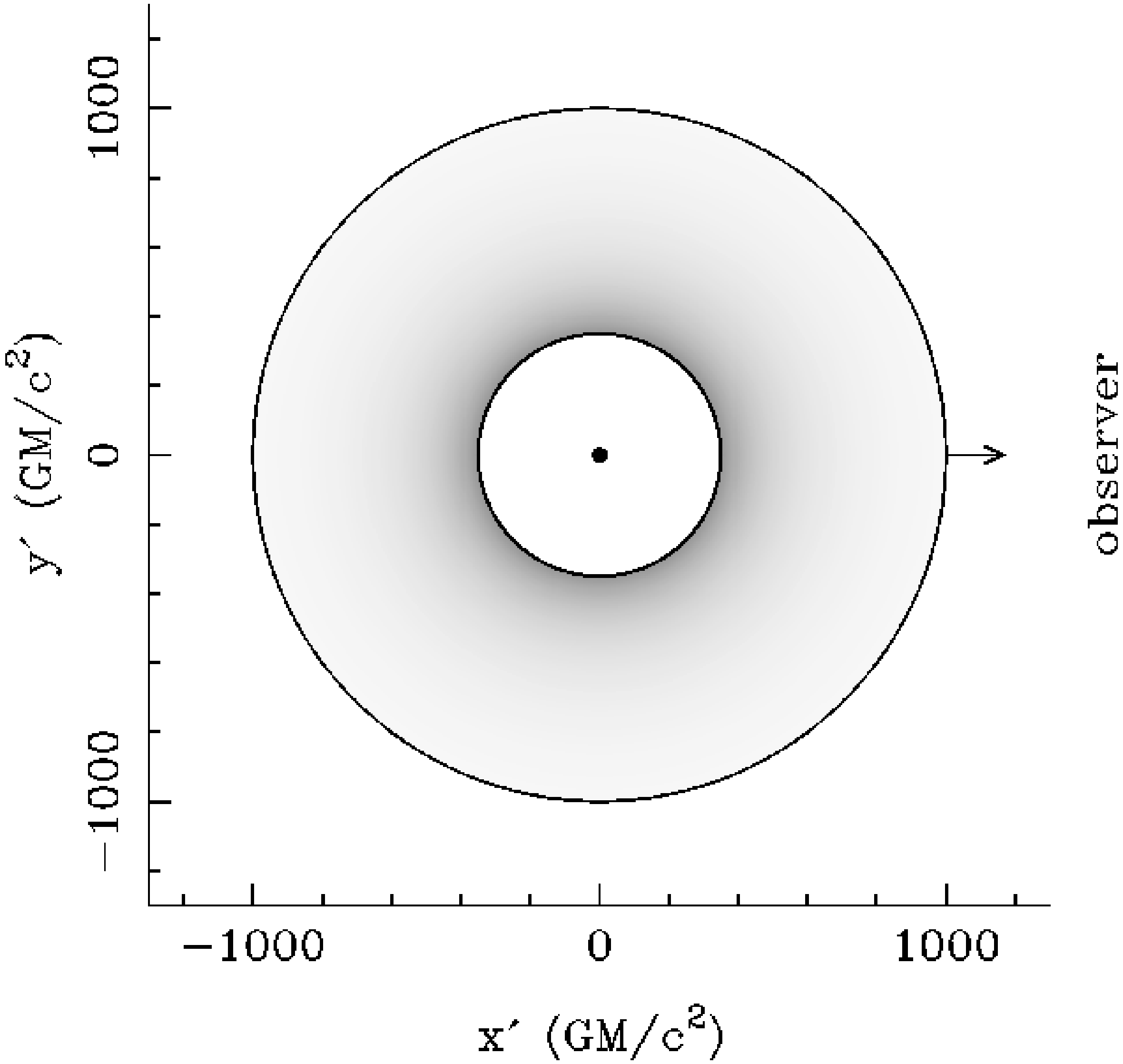
- **General treatment of photon propagation from a disk around a black hole of arbitrary spin**
  Cunningham 1975, ApJ, 202, 788
  Cunningham 1976, ApJ, 208, 534

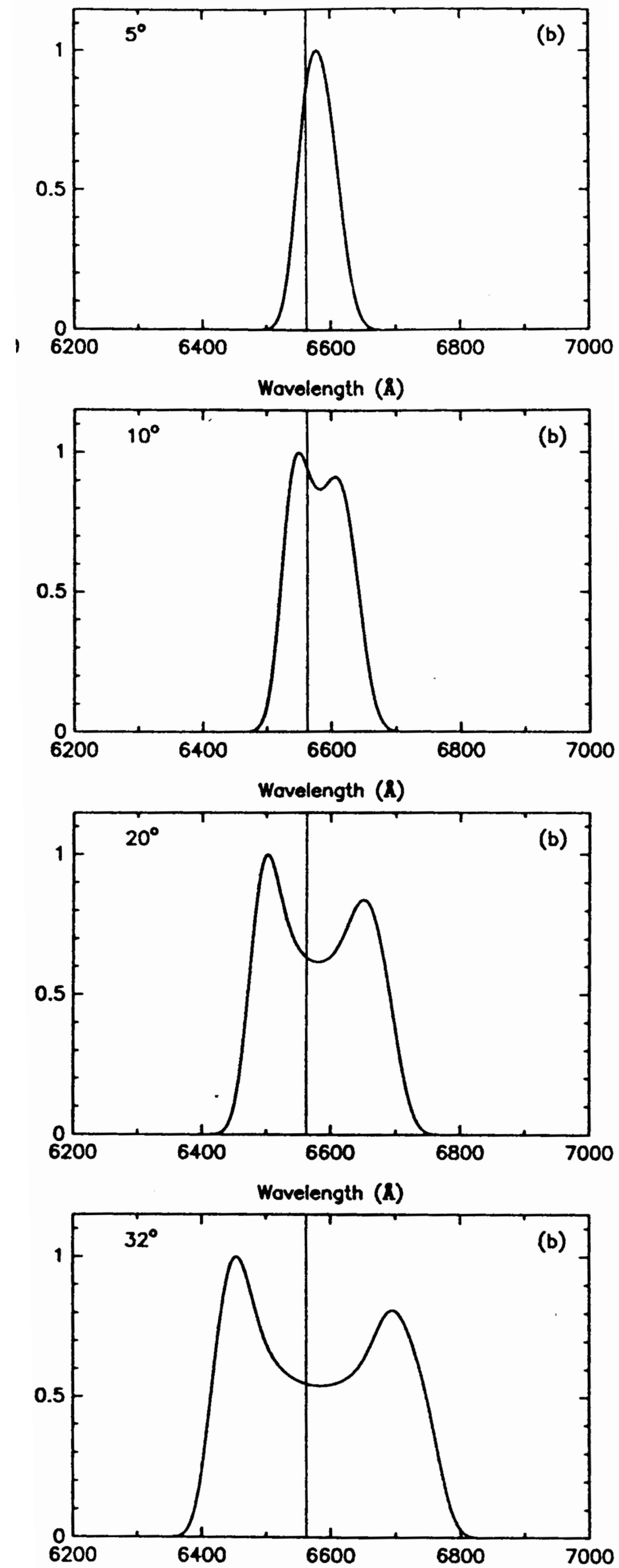
- **Line profiles from the inner accretion disk around a non-rotating black hole**
  Fabian et al 1989, MNRAS, 238, 729

- **Line profiles from the inner disk in a rotating black hole**
  Laor 1991, ApJ, 376, 90

# Optical Balmer line

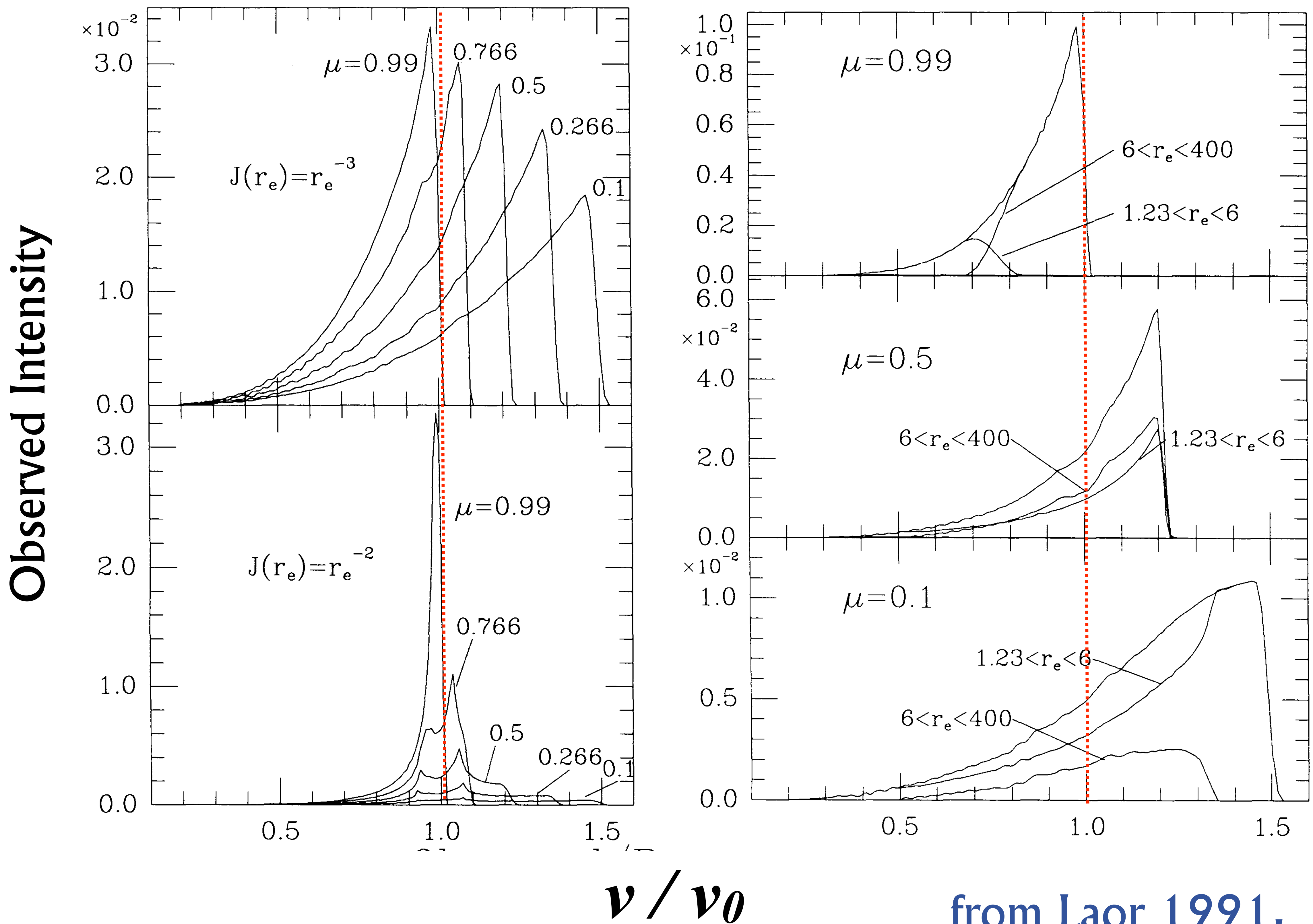
- Origin in outer disk at $\xi \sim 10^2$–$10^3$
- Approximate treatment of relativistic effects




from Chen & Halpern 1989, ApJ, 344, 115

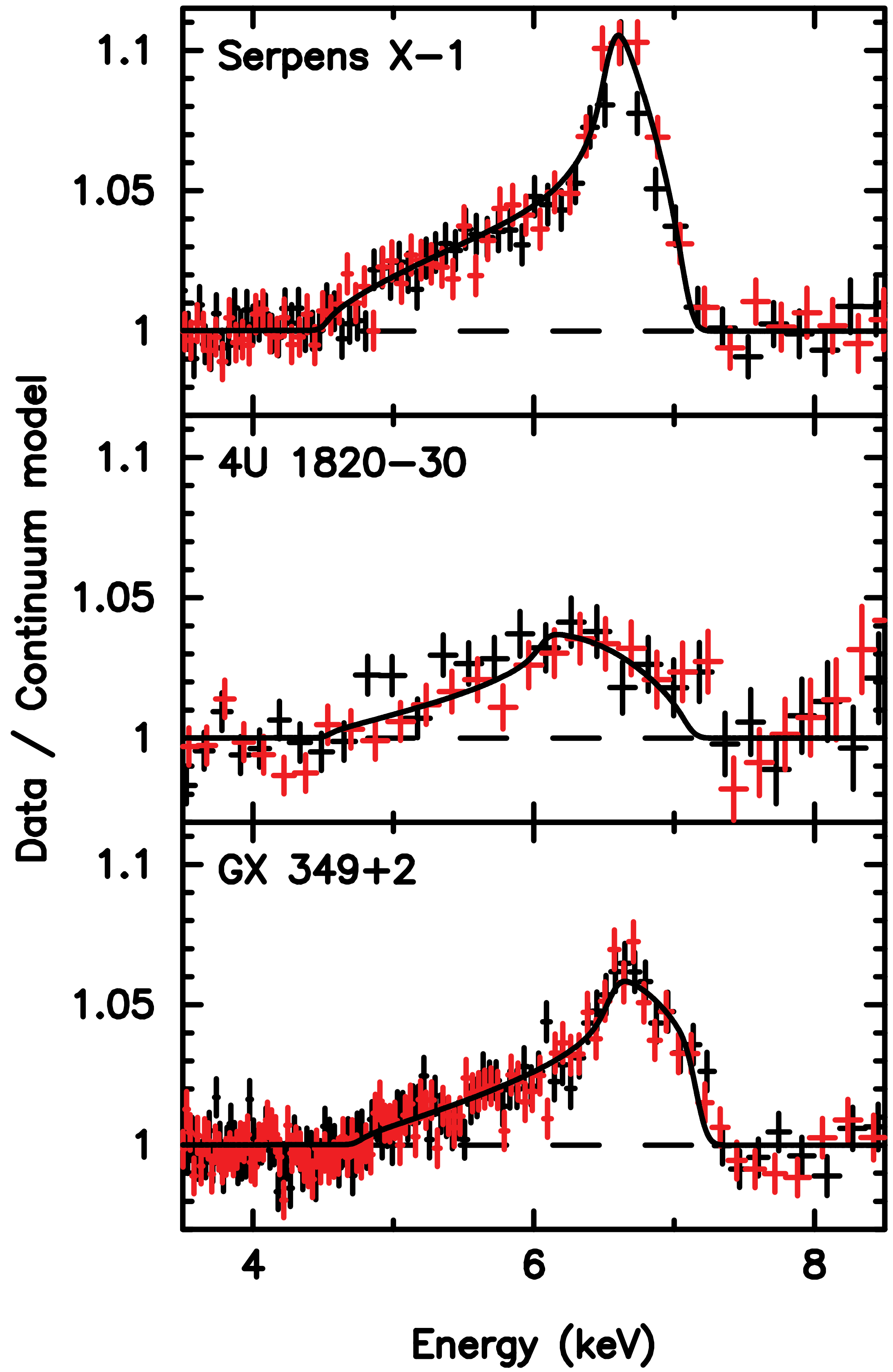
# Fe Kα X-Ray Lines from Inner Disk




from Laor 1991, ApJ, 376, 90

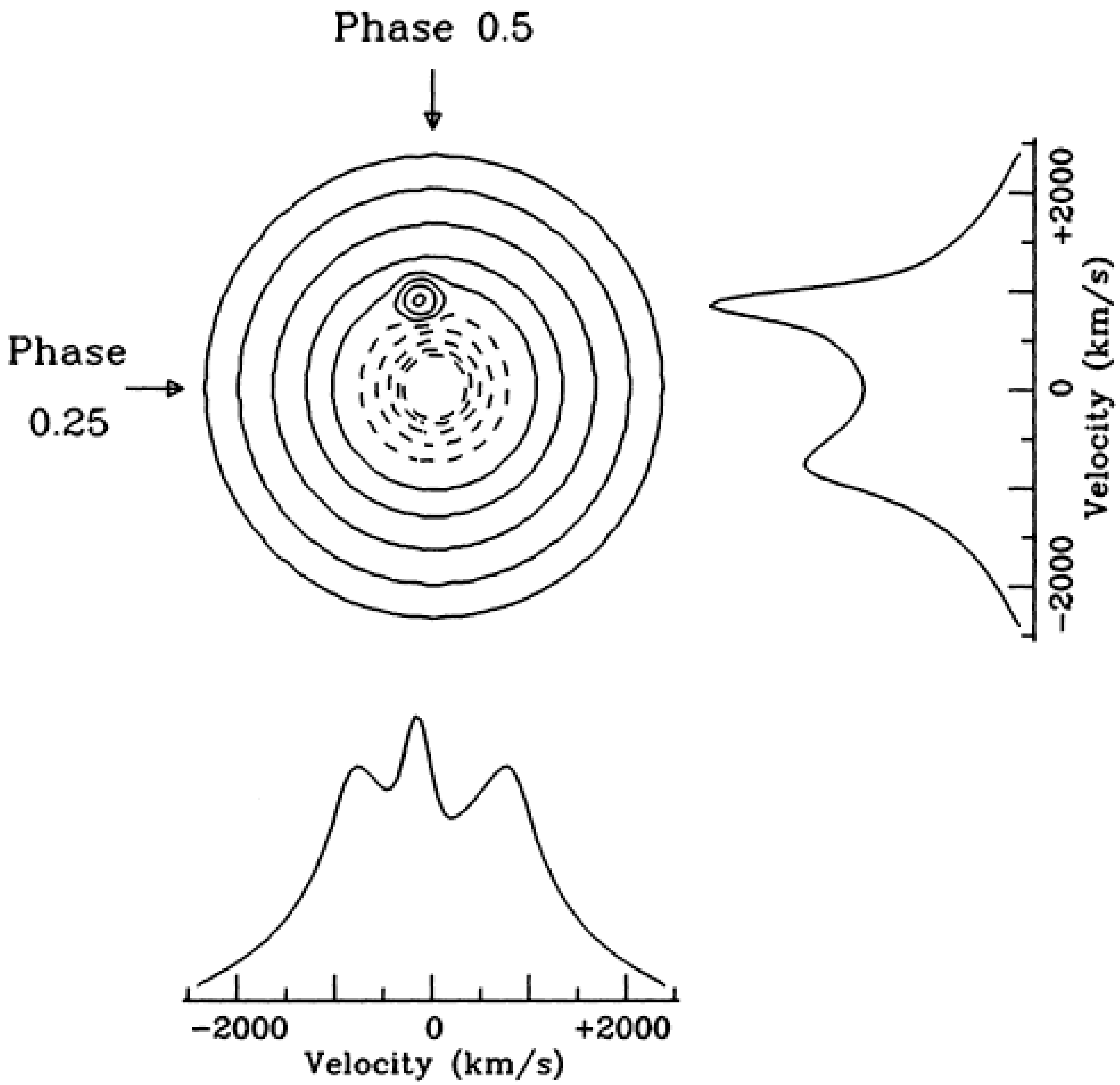
# Observed Fe Kα Lines in XRBs

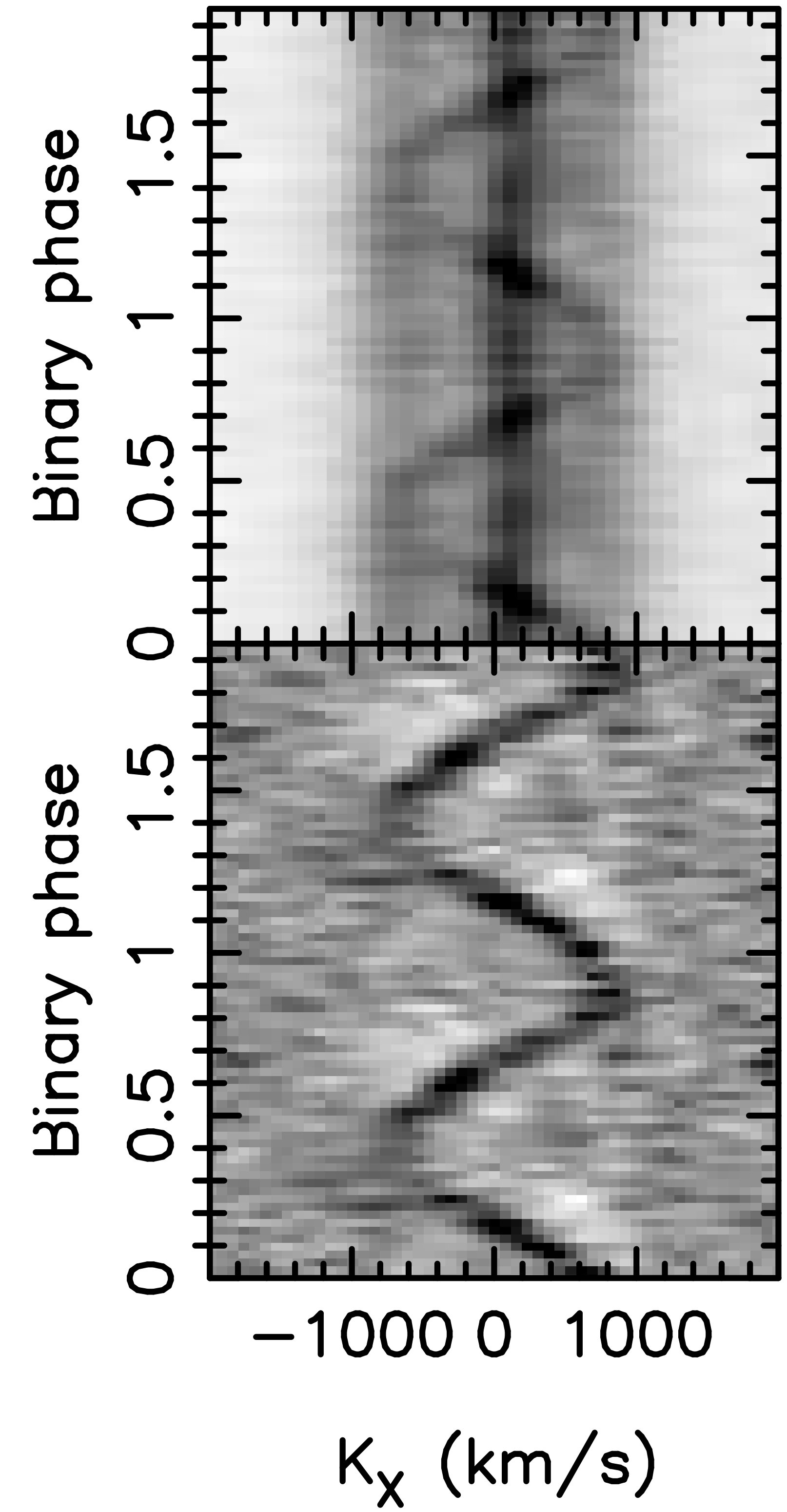
- Examples from NS XRBs
  - from Cackett et al. 2008, ApJ, 674, 415
- Can use such line profiles to infer BH spin or constrain NS radius
- Caveats
  - disk emission properties
  - wind
  - variability



# Doppler Tomography

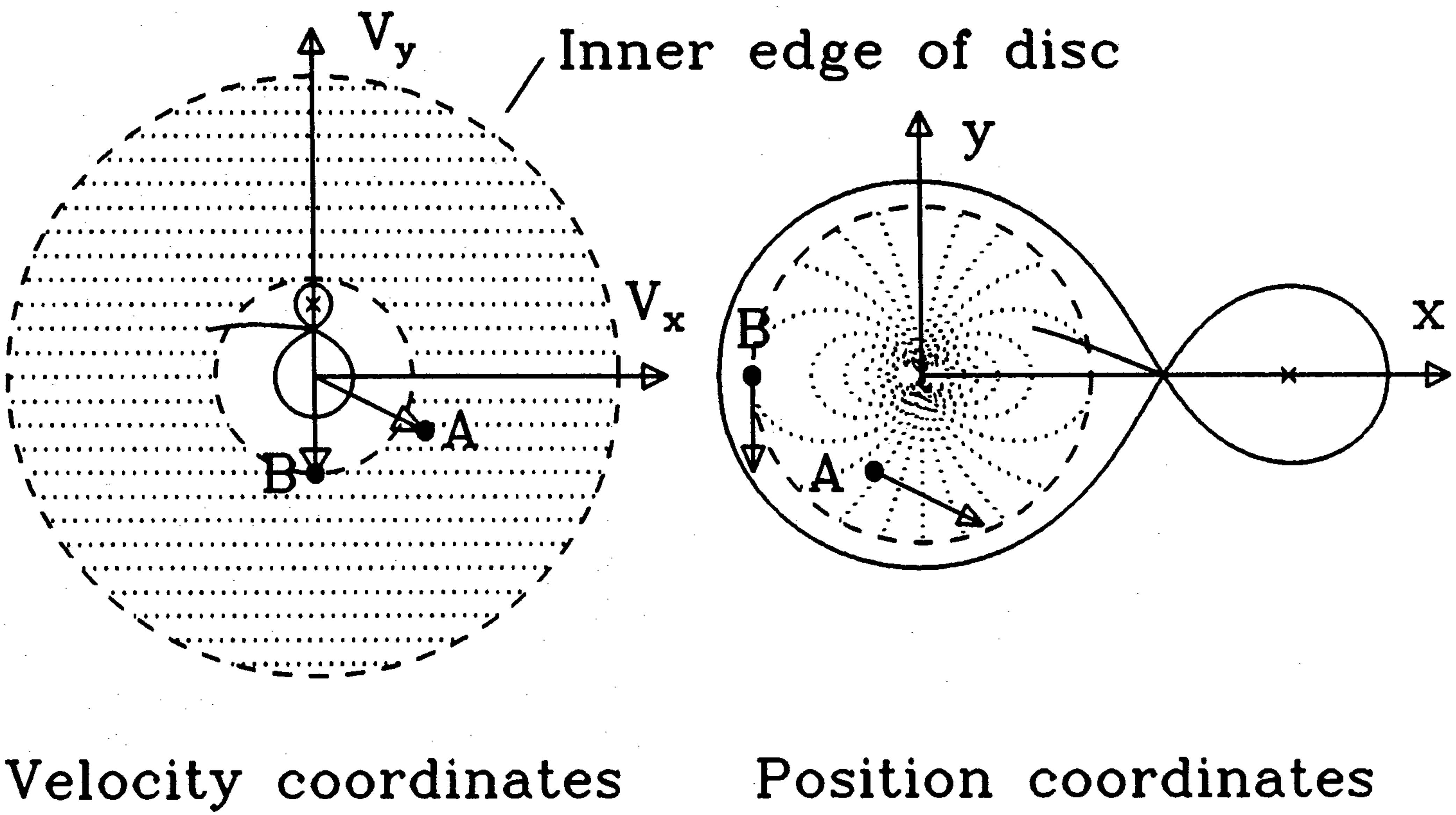
# Principle of Doppler tomography




from Marsh & Horne 1988, MNRAS, 235, 269

# Principle of Doppler tomography




from Marsh & Horne 1988, MNRAS, 235, 269

# Computing Doppler maps

- Observed line profile at binary phase $\phi$ in terms of parameters in binary frame

$$f(V,\,\phi)=\int\!\!\int\!\!\int I(V_x,\,V_y,\,V_z)\,g(V-\gamma+V_x\cos\phi-V_y\sin\phi+V_z)\,dV_x\,dV_y\,dV_z,$$

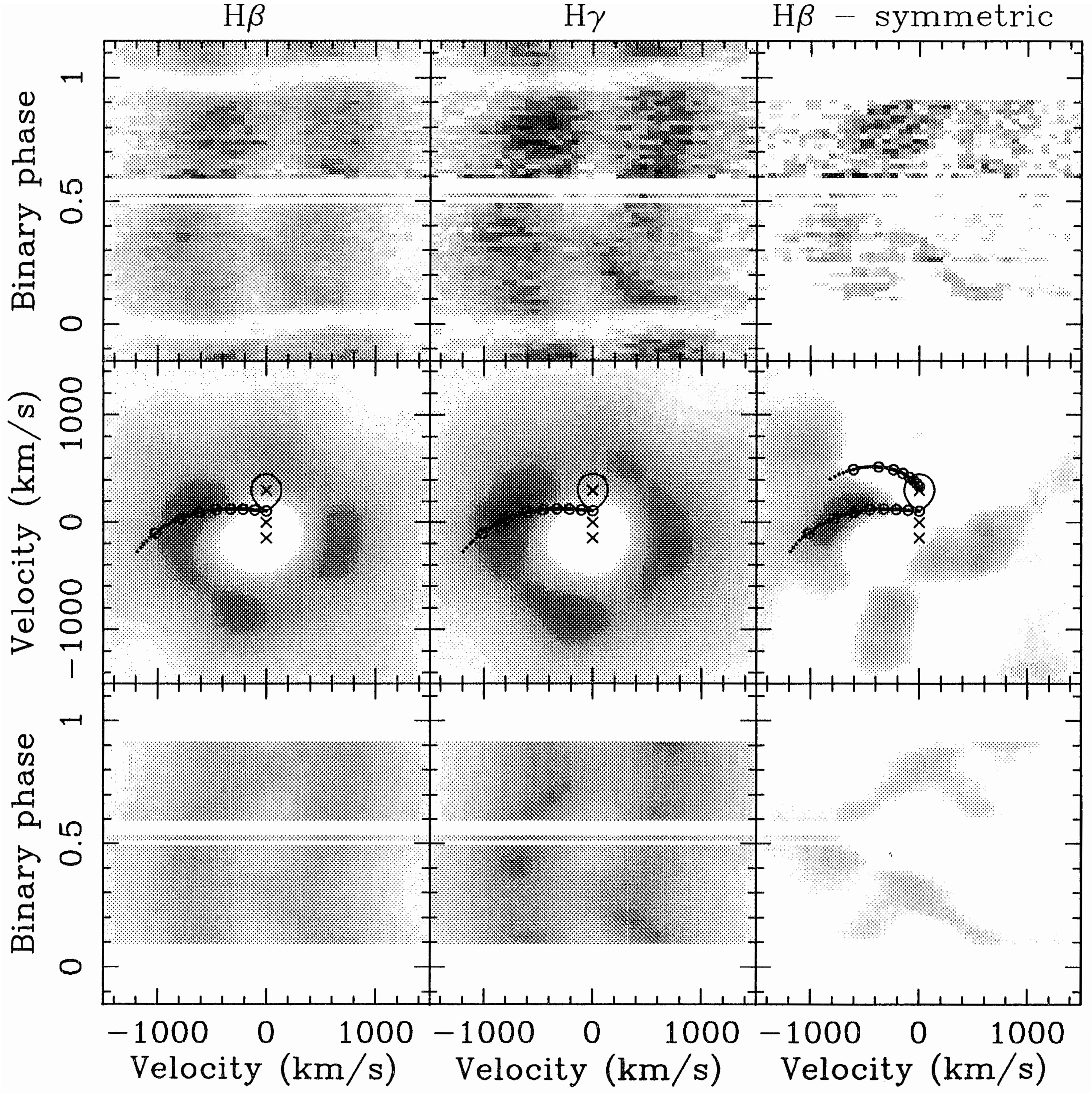
line intensity in disk frame — local line profile — projected velocities

- Assume no vertical motions, replace local profile, g(V), by its Fourier transform, G(s), and invert

$$I(V_x,\,V_y)=\int_0^{2\pi}\int_0^{\infty}\frac{s}{G(s)}\int f(V,\,\phi)\exp\left[-i2\pi s(V-\gamma+V_x\cos\phi-V_y\sin\phi)\right]dV\,ds\,d\phi.$$

- Alternative: maximum entropy inversion

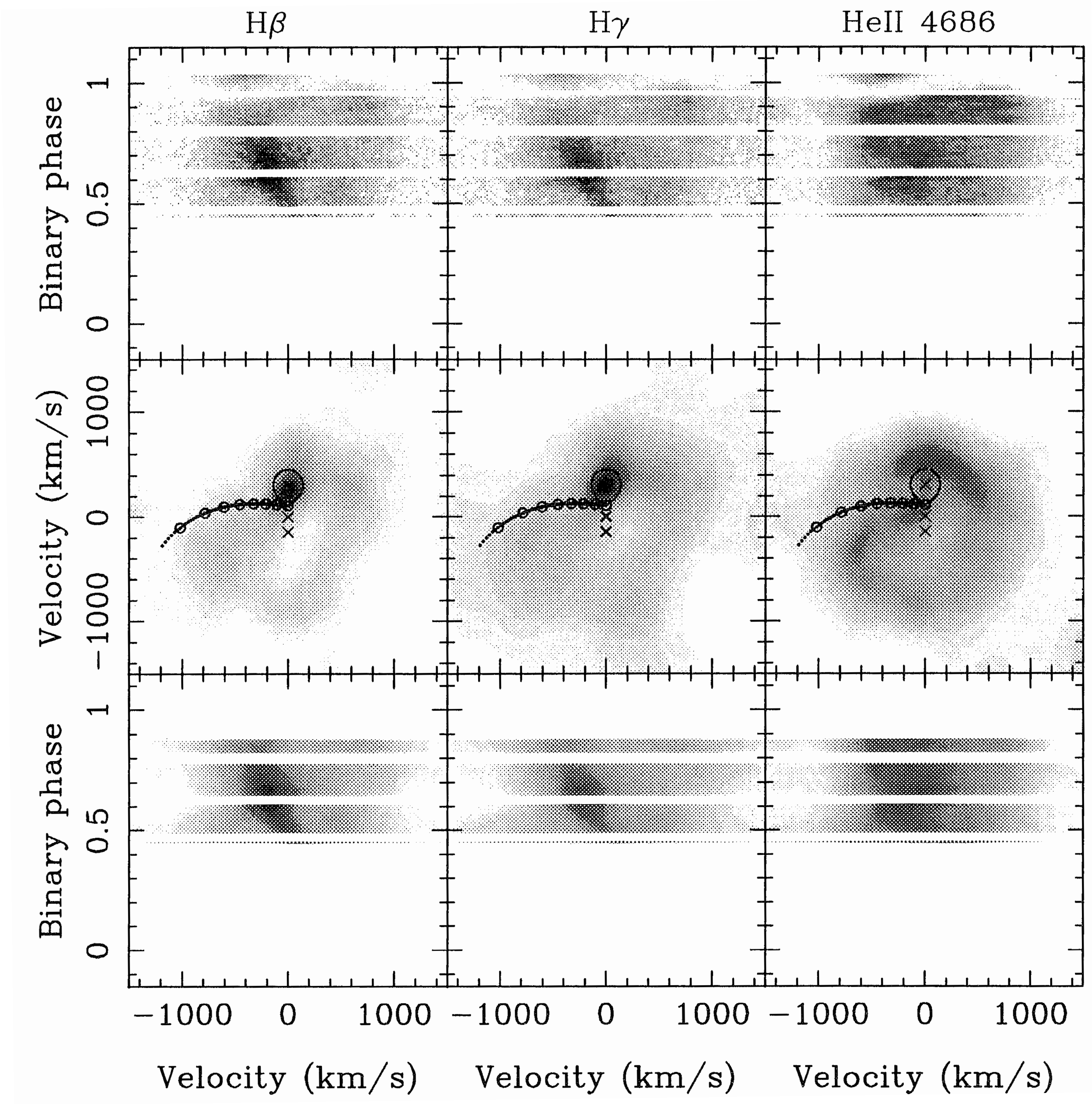
# Early applications CV disks: IP Peg




Low State

Horne & Marsh 1990, ApJ, 349, 593

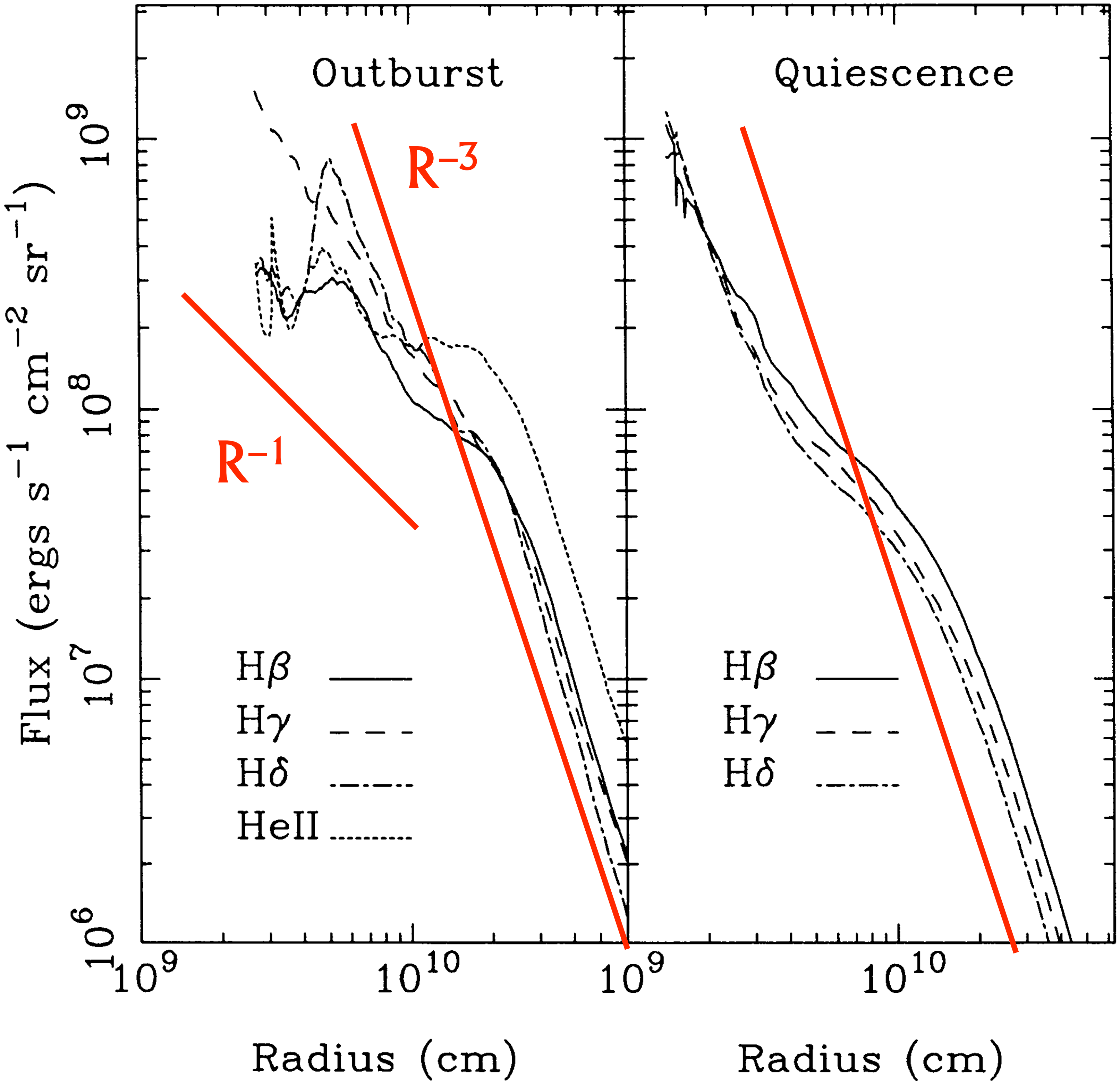
# Early applications CV disks: IP Peg




High State

Horne & Marsh 1990, ApJ, 349, 593

# Early applications CV disks: IP Peg

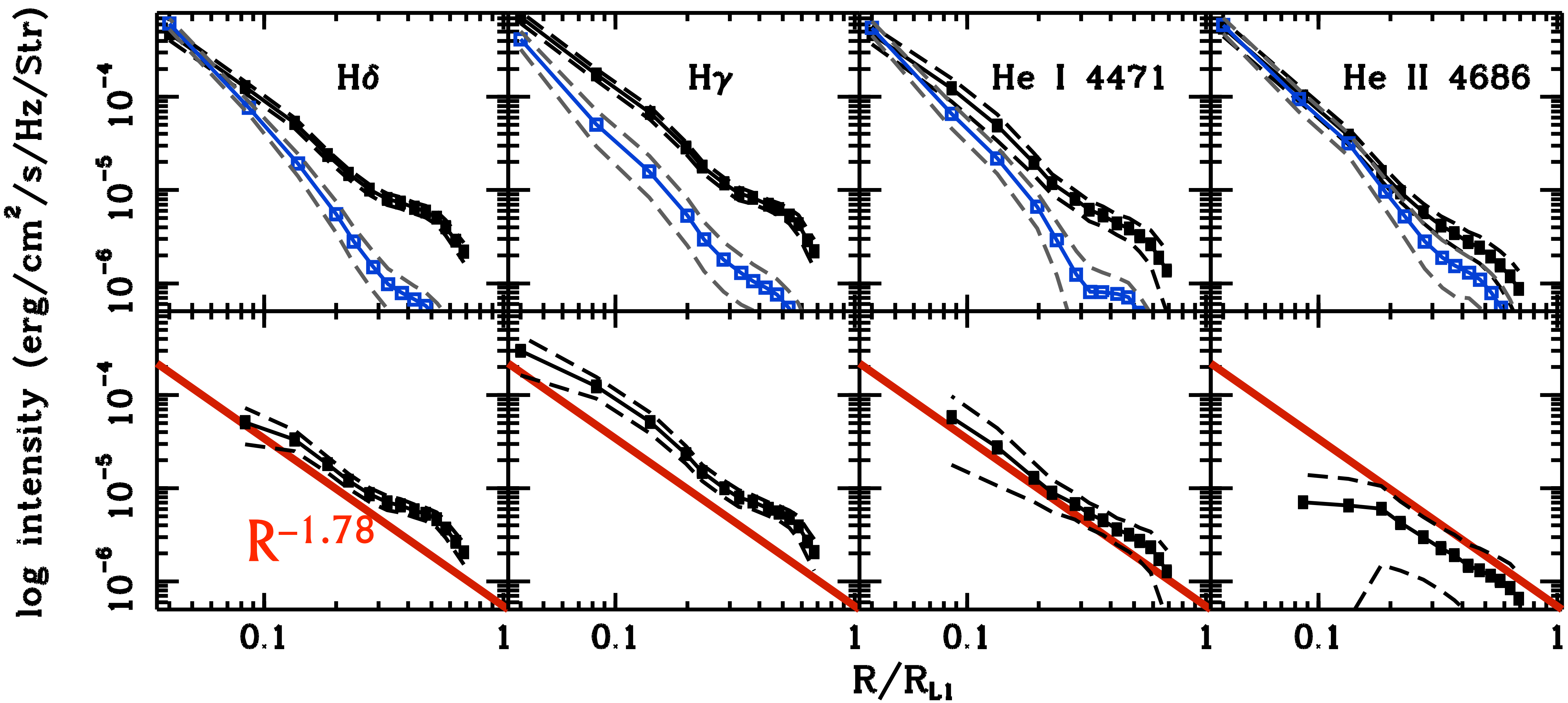



Line Emissivity in outburst and quiescence,.

Horne & Marsh 1990, ApJ, 349, 593

# Recall spectral eclipse mapping

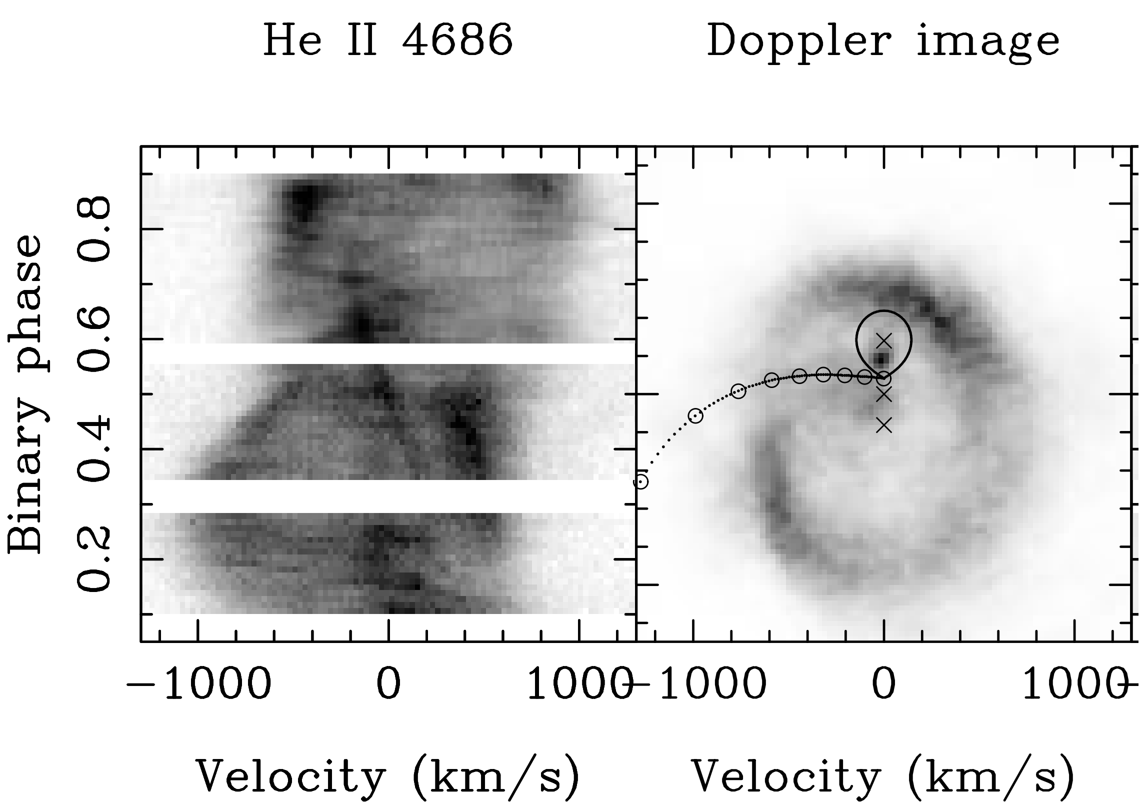
V2051 Oph in quiescence

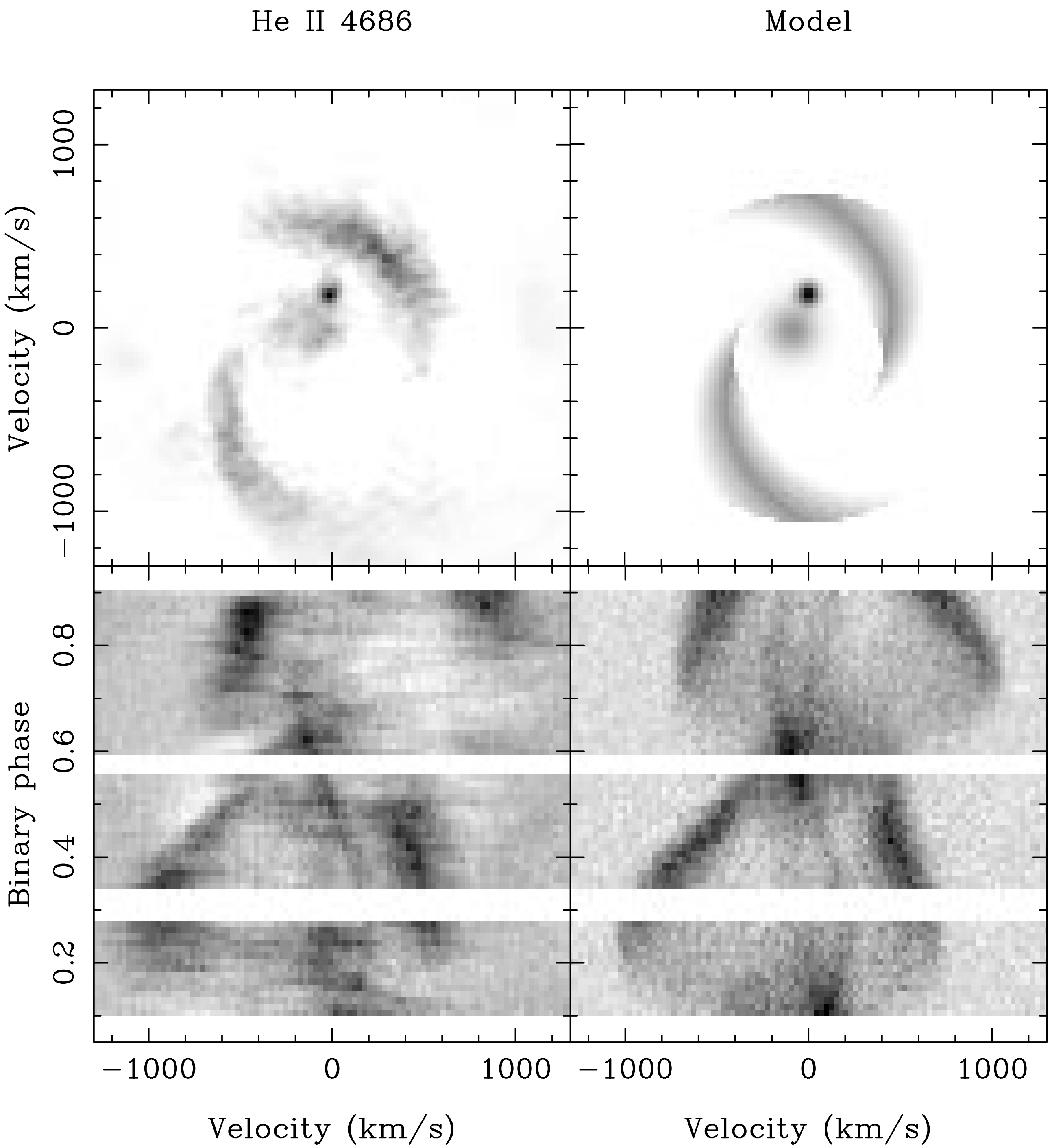



from Saito & Baptista 2006, AJ, 131, 2185

# Recent applications: spiral arms

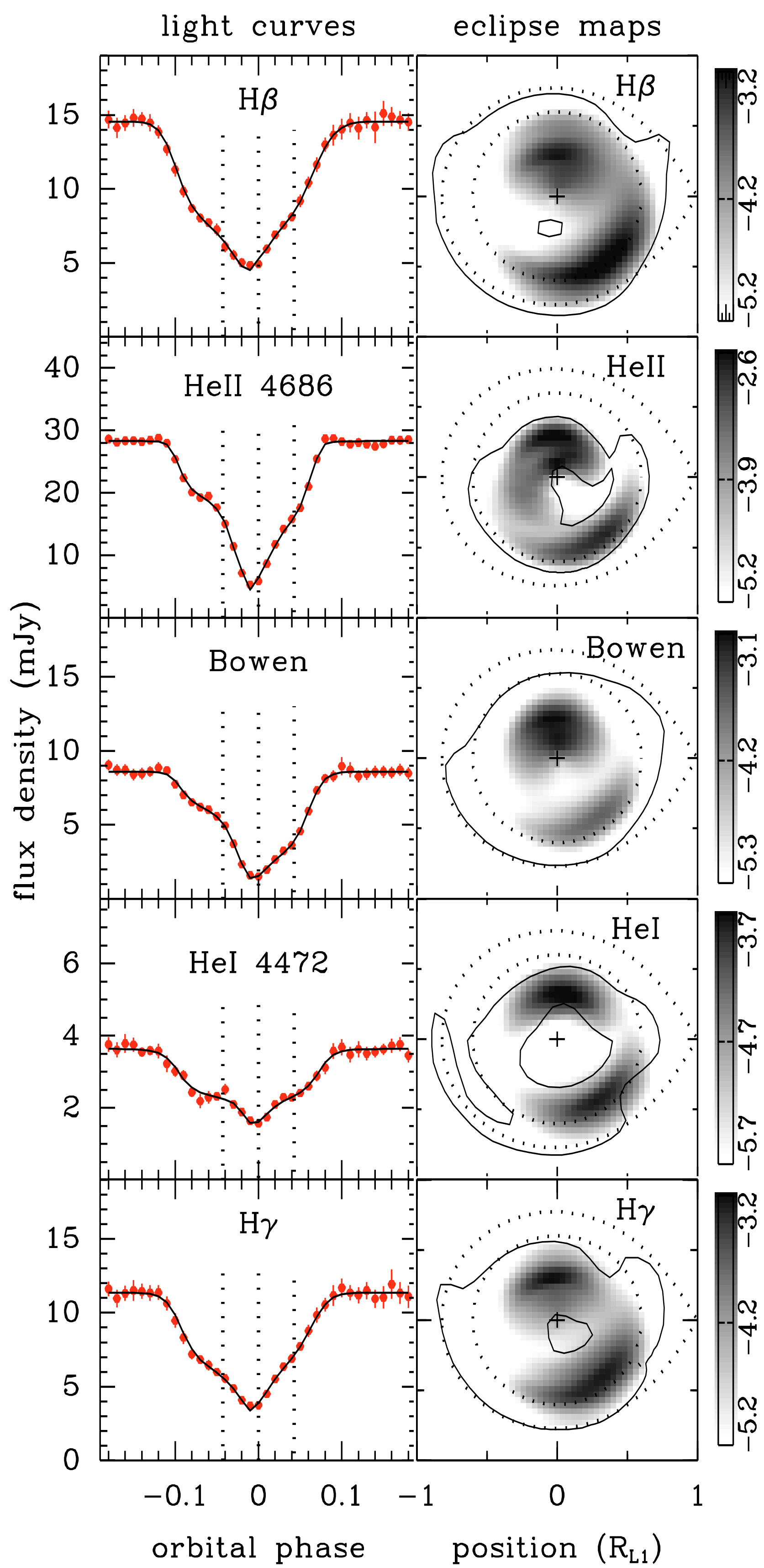
## IP Peg in outburst




from Harlaftis et al. 1999, MNRAS, 306, 348

# Confirmation from eclipse mapping




Eclipse maps in selected emission lines of IP Peg in outburst

Detection of spiral structure

from Baptista et al. 2005, A&A, 444, 201

# What's the big deal with spiral arms?

- **Predicted by theory**
  (Sawada et al. 1986; Savonije et al. 1994)

- **Angular momentum transport mechanism.**

- **Observed around peak of outburst: Puzzling…**

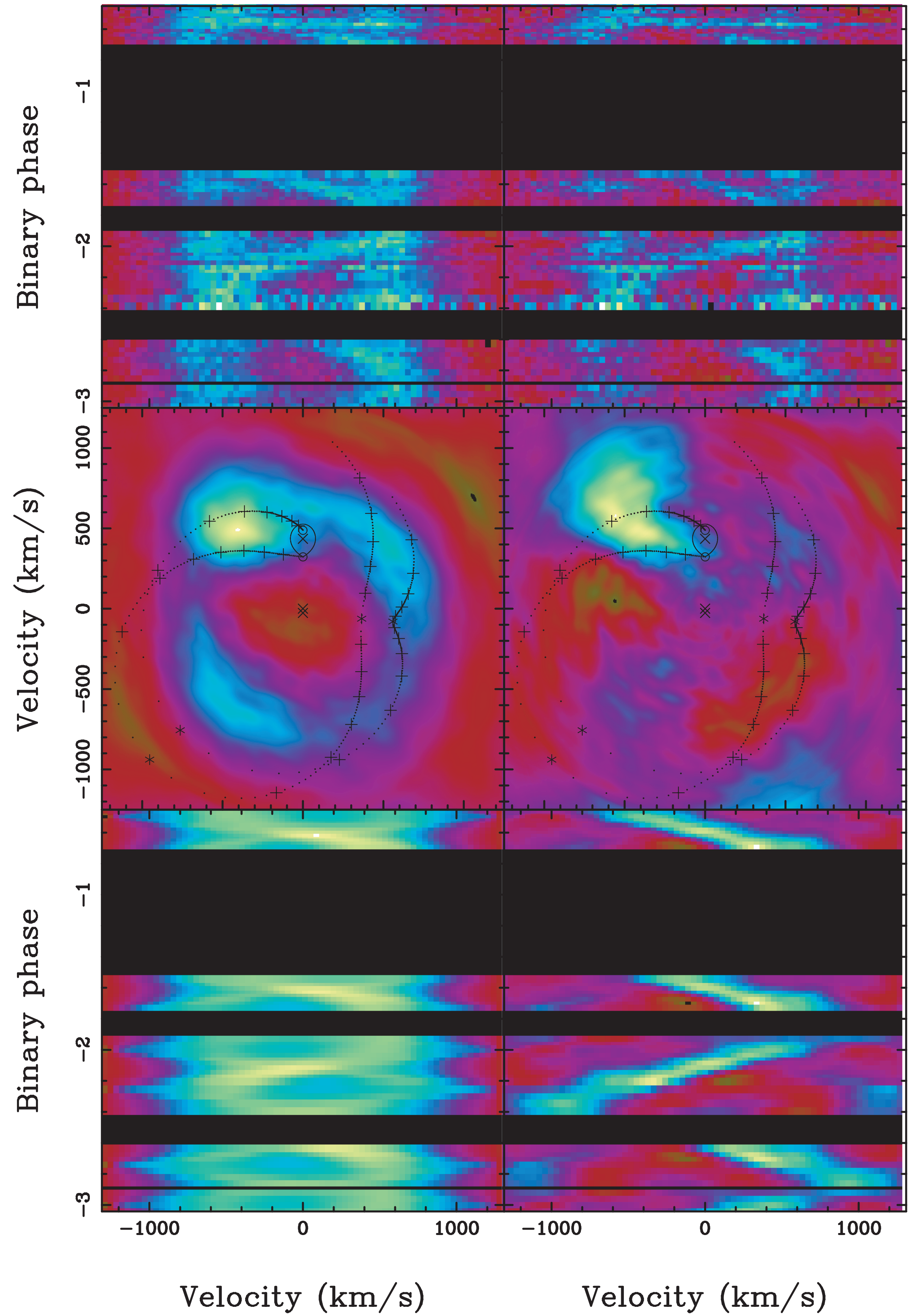
  - IP Peg (DN) — Harlaftis et al. 1999
    WZ Sge (DN) — Kuulkers et al. 2002
    SS Cyg (DN) — Steeghs et al. 2001
    U Gem (DN) — Groot et al. 2001

    V 3885 Sgr (NL) — found by Hartley et al. 2005
    but not found by Ribeiro & Diaz 2007.

# Disk eccentricity

- Tidal perturbation of the disk by the secondary star at $q < 0.25$
- Proposed to explain "superhumps" in CVs
  Whitehurst 1988
  Lubow 1991

figure from
Nielsen et al. 2008, MNRAS, 384, 849



# Single Peaked Lines?

- Why do the lines change from double-peaked to single-peaked during outburst?
- Do single-peaked lines still come from the disk?
- Close connection with the emission lines of AGNs and far-reaching implications.

# Single Peaked Lines?

- Why do the lines change from double-peaked to single-peaked during outburst?
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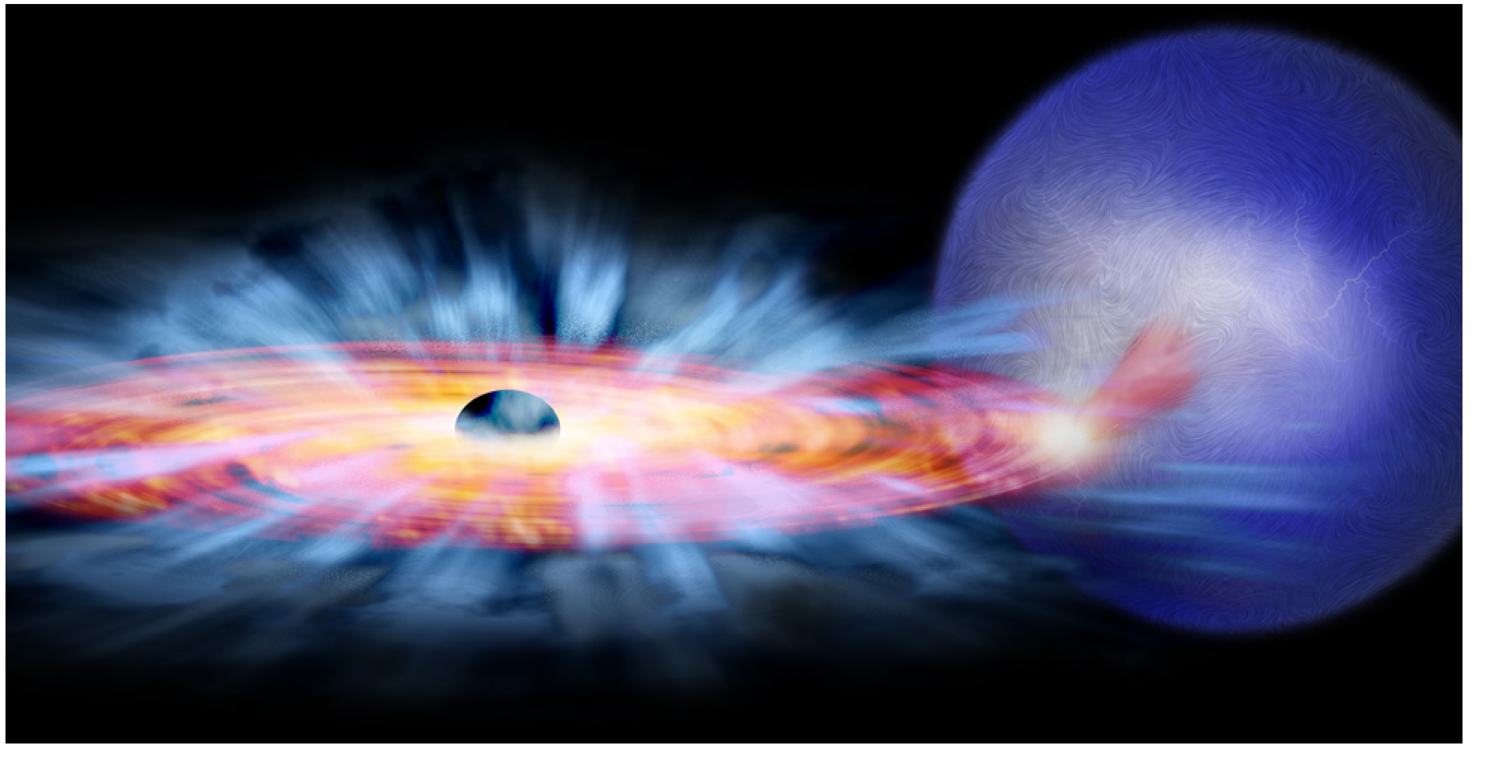
"The answer is blowin' in the wind"

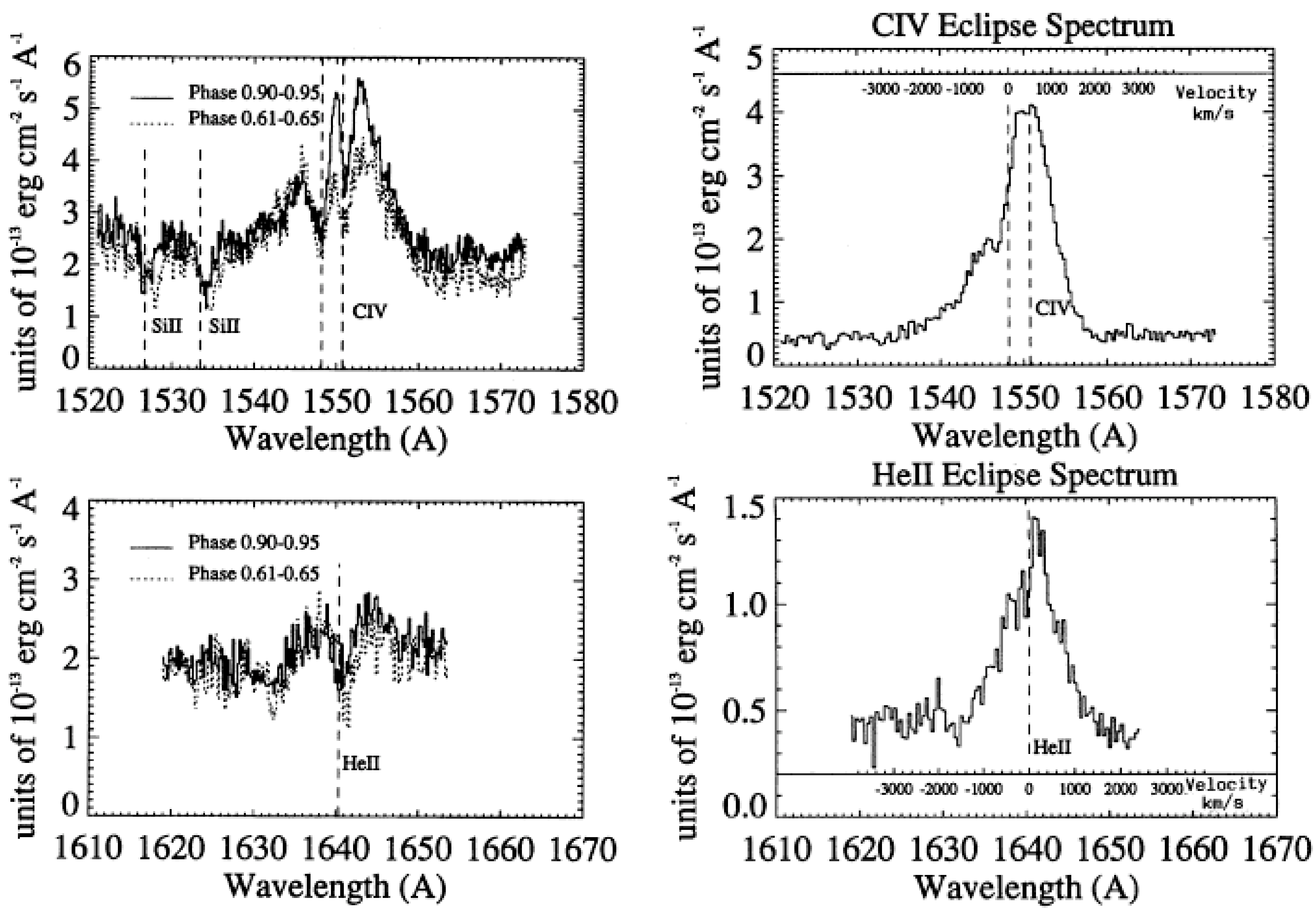
— Dylan, B.1962, Special Rider Music

# How do we know there are outflows?

- Blueshifted absorption lines in
  - the UV spectra of CVs and AGNs (P-Cygni profiles)
  - the X-ray spectra of XRBs and AGNs
- Residual flux during eclipse (vertically extended gas)
  - X-Ray continuum
  - UV emission lines

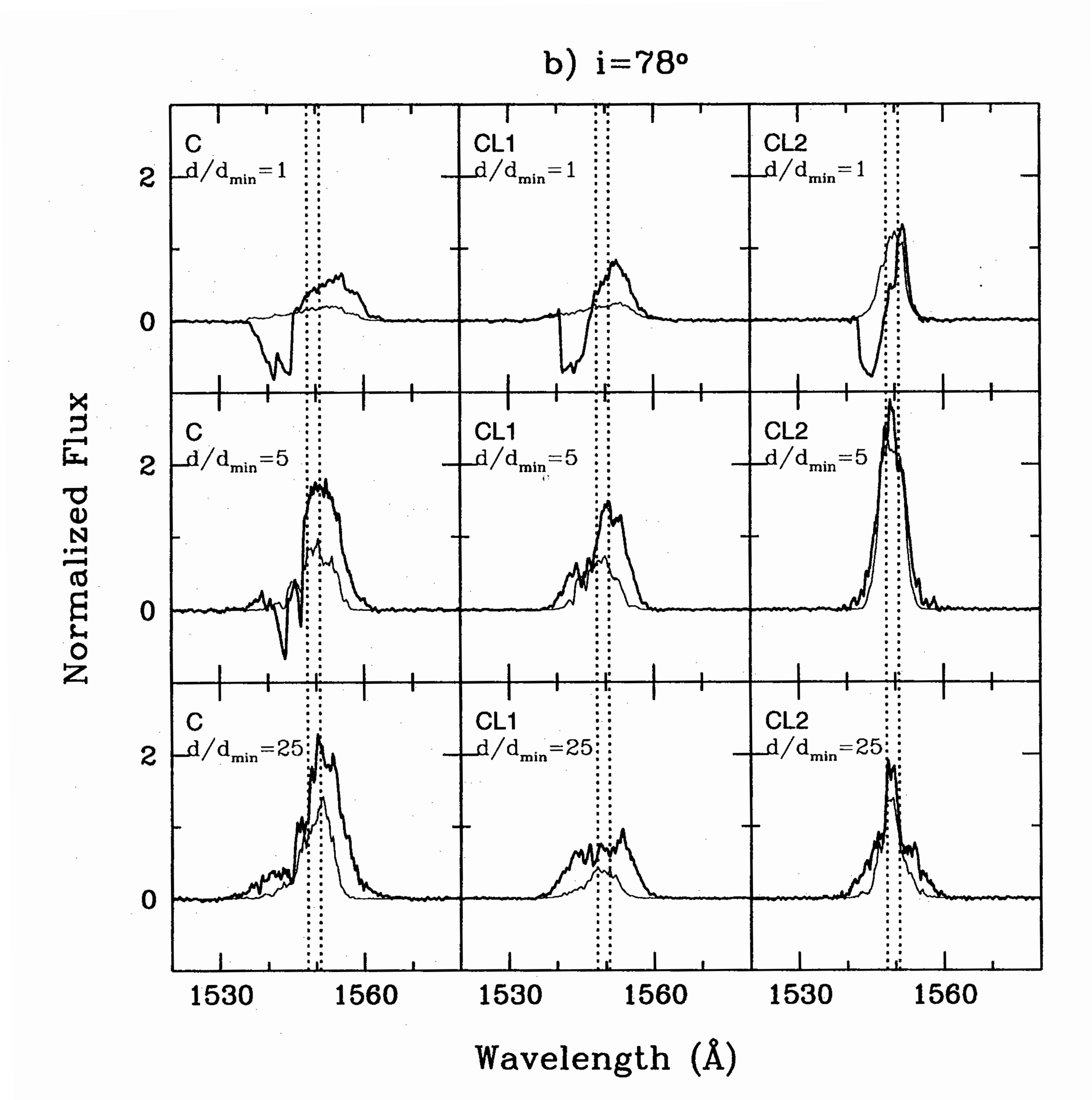


# The Wind of UX UMa




figures from Mason et al. 1995, MNRAS, 274, 271

# Resonance scattering in wind




Simulated C IV line profiles for different outer radii at a fixed inclination.

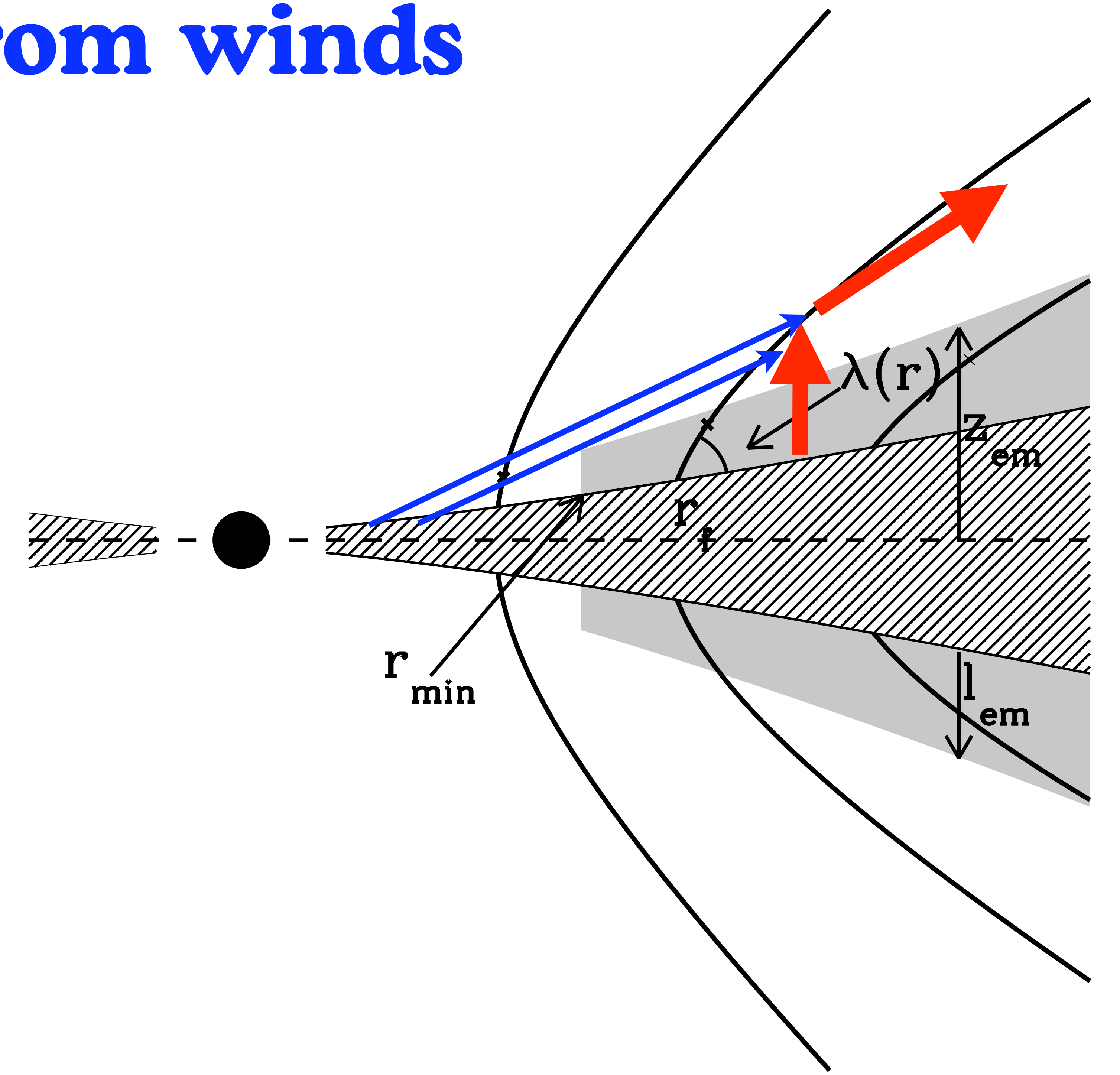
Knigge & Drew 1996, MNRAS, 281, 1352

# Emission lines from winds

- Dense layer at the base emits the lines.
- Powered by photoionization
- $v_r \ll v_\varphi$

  but

  $dv_r/dr \gg dv_\varphi/dr$




from Murray et al. 1995, ApJ, 451, 498

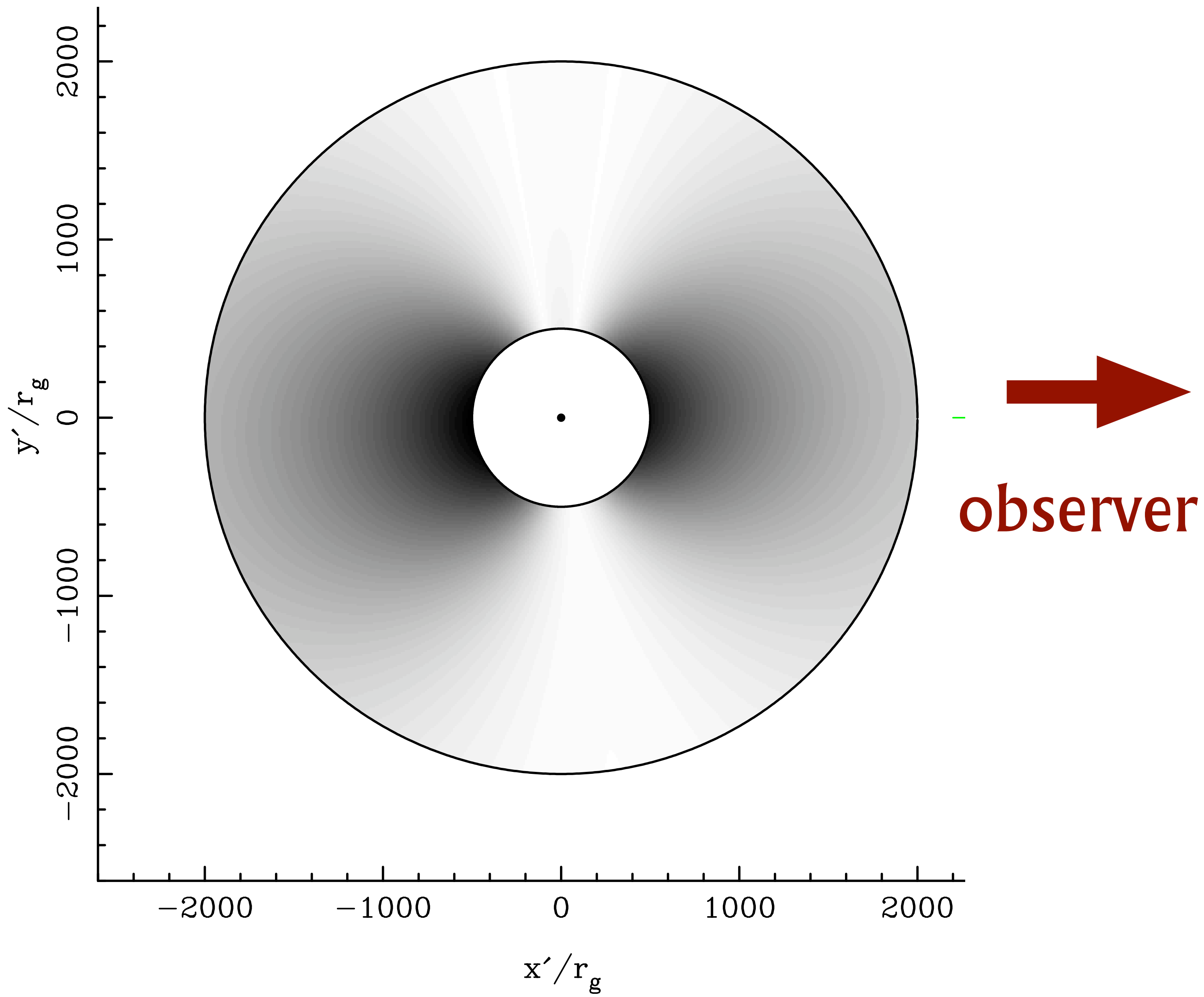
# Non-axisymmetric emissivity pattern

- Directional escape probability:

$$\beta = \frac{1 - e^{-\tau}}{\tau}$$

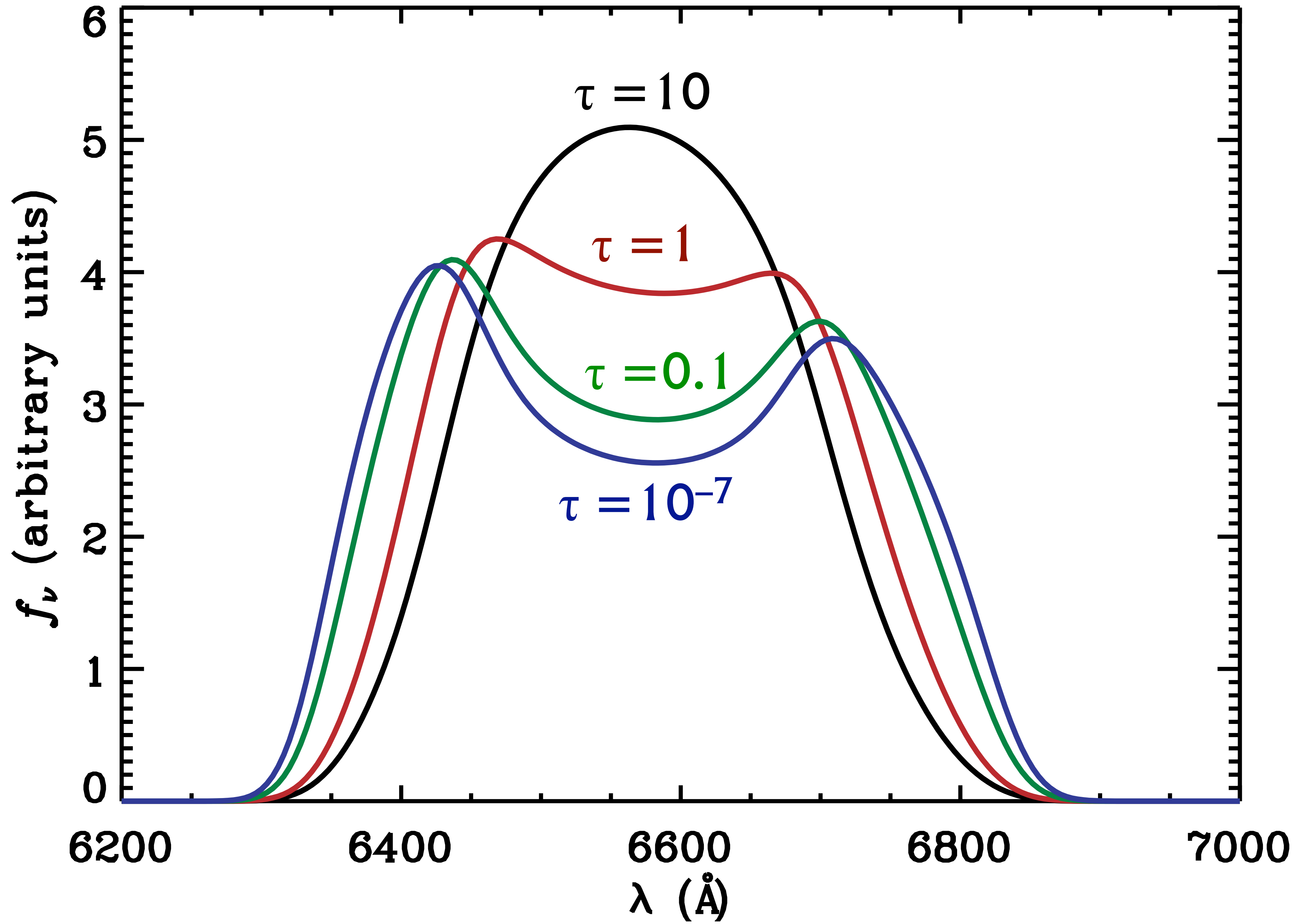
- where

$$\tau = \frac{\rho\,\kappa\,\sigma_v}{|\mathbf{n}\cdot\boldsymbol{\Lambda}\cdot\mathbf{n}|}$$




formalism by Rybicki & Hummer 1978, ApJ, 219, 654
see also Shlosman et al. 1985, ApJ, 294, 96
and Hamann et al. 1993, ApJ, 415 541

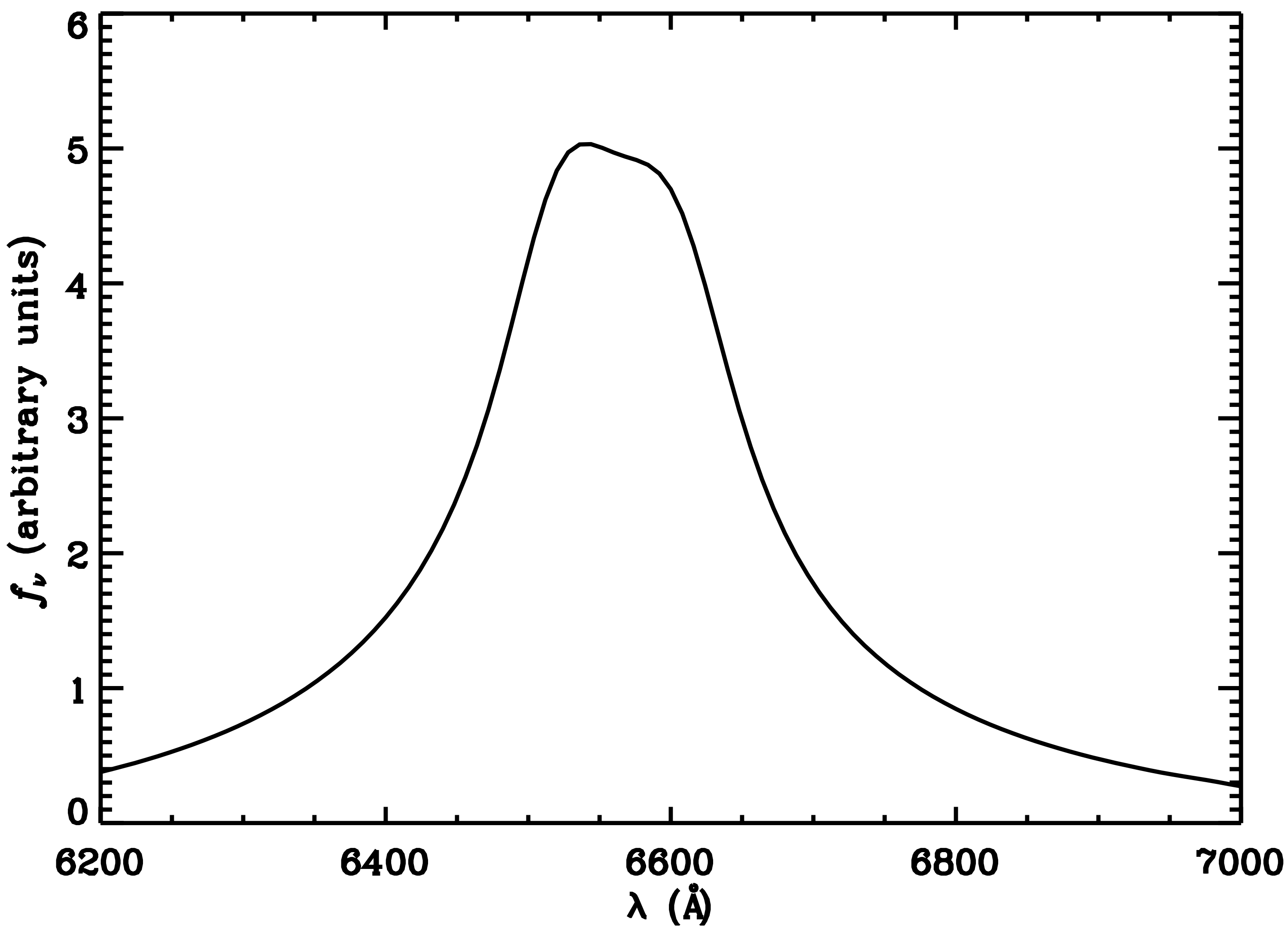
# Effect of optical depth at base of wind



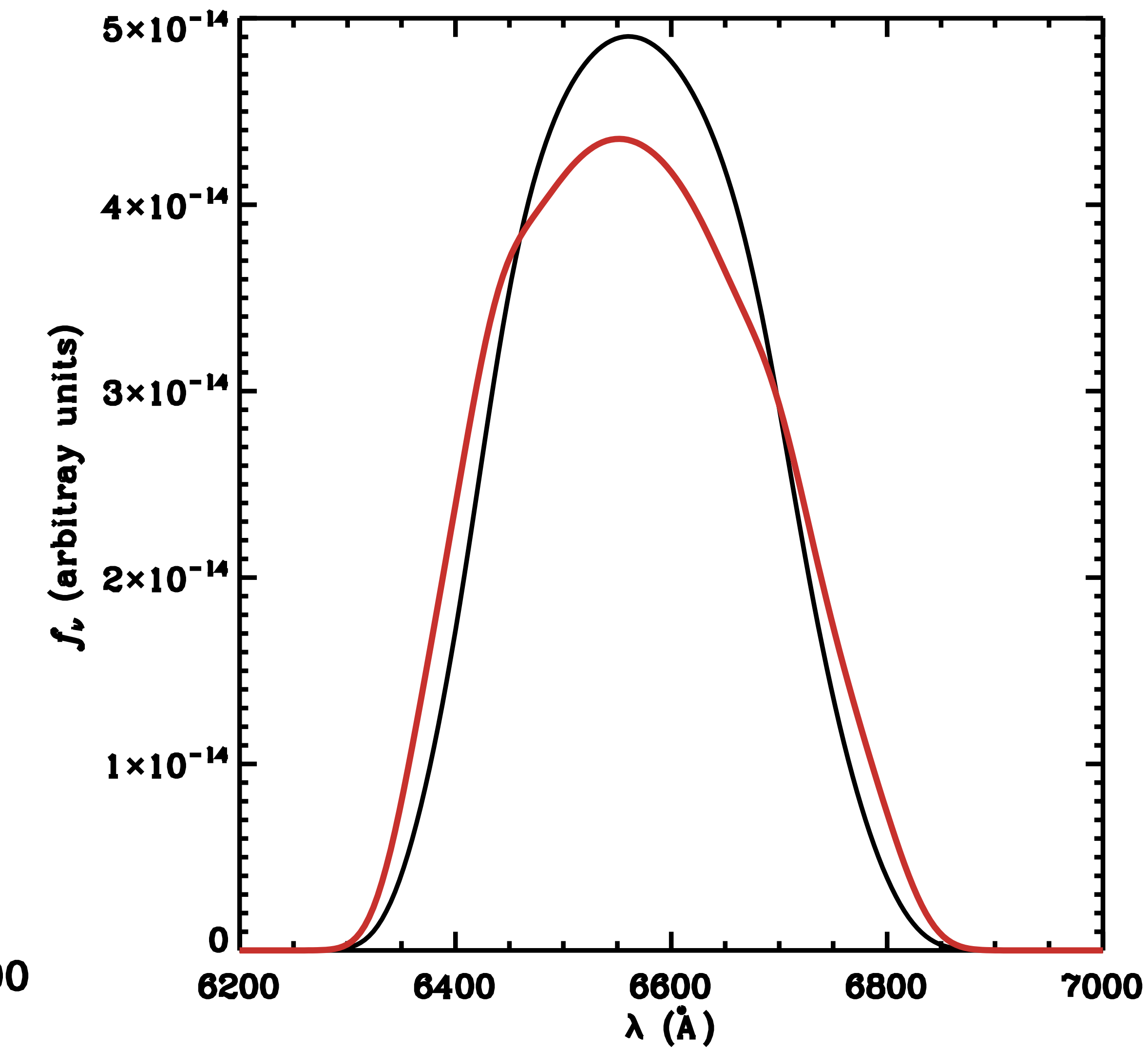

originally by Murray & Chiang 1997, ApJ, 474, 91
figure from Flohic, 2008, PhD Thesis, Penn State

# More examples of line profiles

Trying to emulate quasar line profiles




Variations on the velocity law




figures from Flohic, 2008, PhD Thesis, Penn State University

# End of Lecture II