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Accretion Disk Tomography
― New Model with New Data ―

Contents

- Cataclysmic variables and tomography
- Disk height mapping
- Doppler tomography

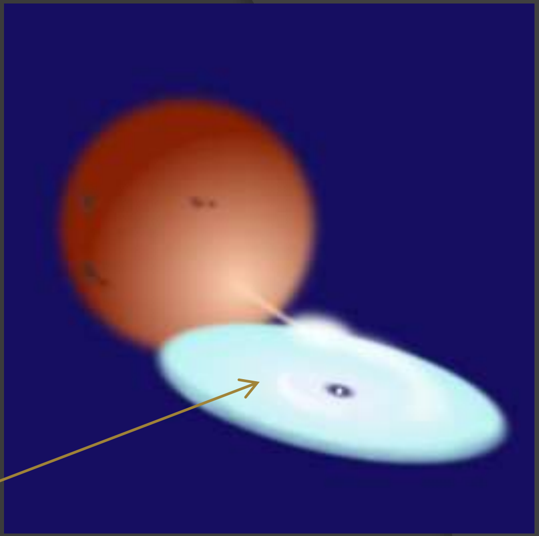
Cataclysmic Variables

- White dwarf + red dwarf
  - Orbital period:

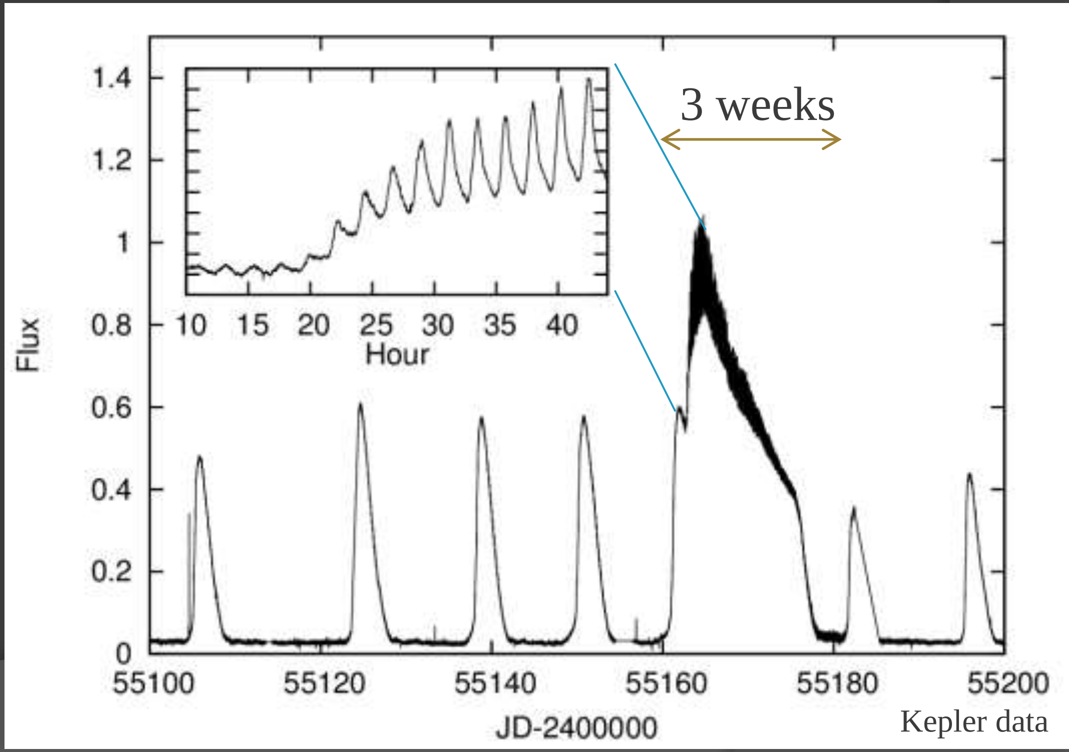
    80 min – a few hours

  (some systems have Porb>1 day)

- Nova, dwarf nova, novalike, magnetic CV



Accretion disk
(dominant source in outburst)



Tomography of accretion disks

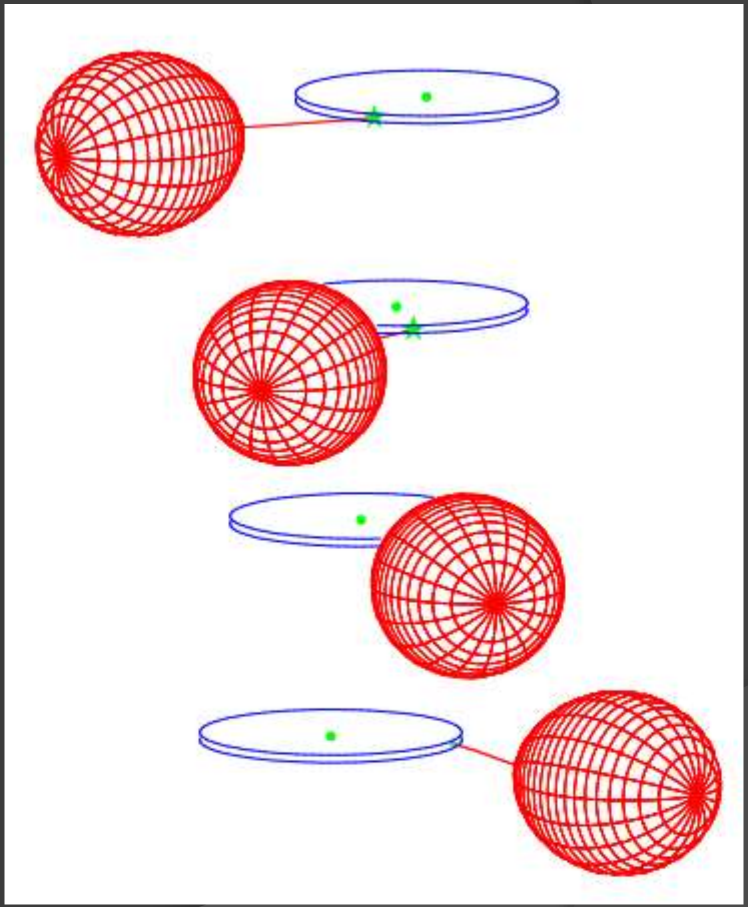
- We want to know the accretion disk structure and its evolution
  - Geometrical structure
  - Intensity distribution
  - Temperature distribution

- The disk structure cannot directly be resolved on images.
  - Too small angular size

- Observation at one phase

  = A section of the disk at one viewing angle

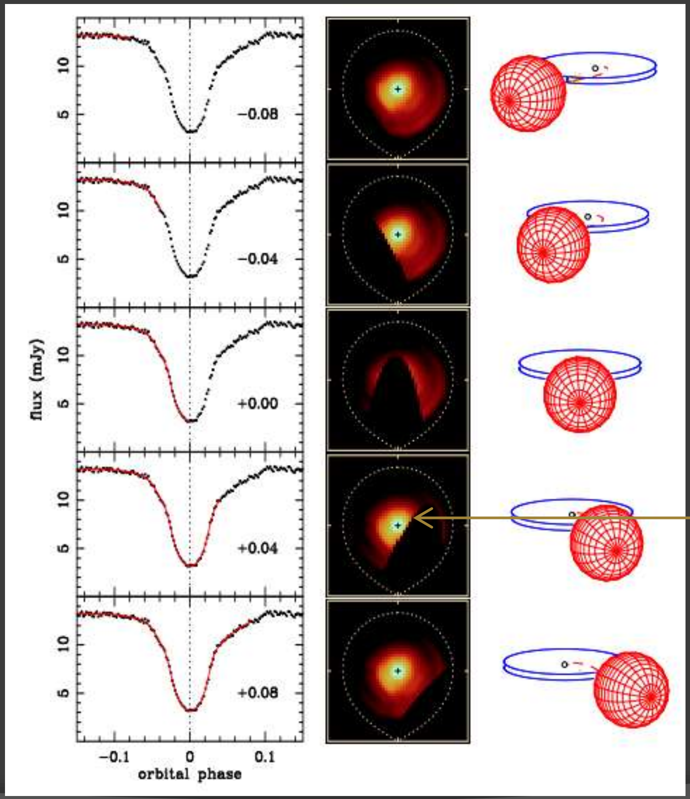
  → Tomography



Marsh+00

Accretion disk tomography: Examples

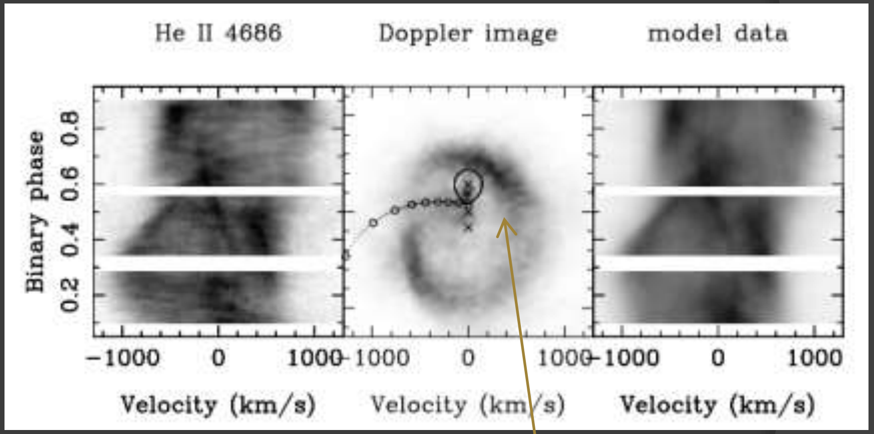
- Eclipse mapping
  (Horne 85; Baptista+93)
  - From the light curve
  - To the intensity map



Baptista+01

Flux $\propto r^{-3/4}$
(as theoretically expected)

- Doppler tomography
  (Marsh+88)
  - From the emission-line profile
  - To the intensity map in the velocity space



IP Peg (Harlaftis+99)

Spiral pattern

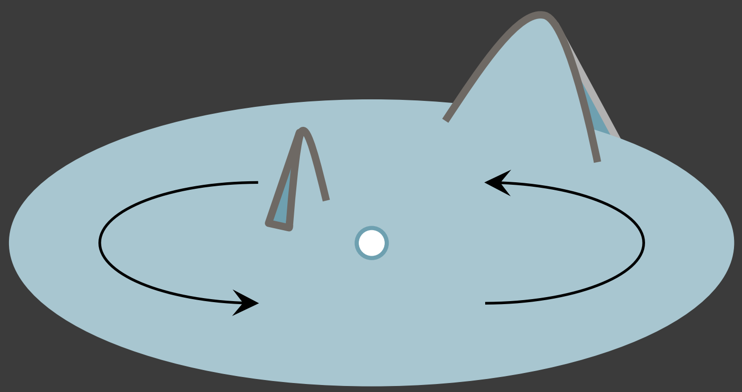
Disk height mapping

(Uemura+12, PASJ, 64, 92)

Early superhump

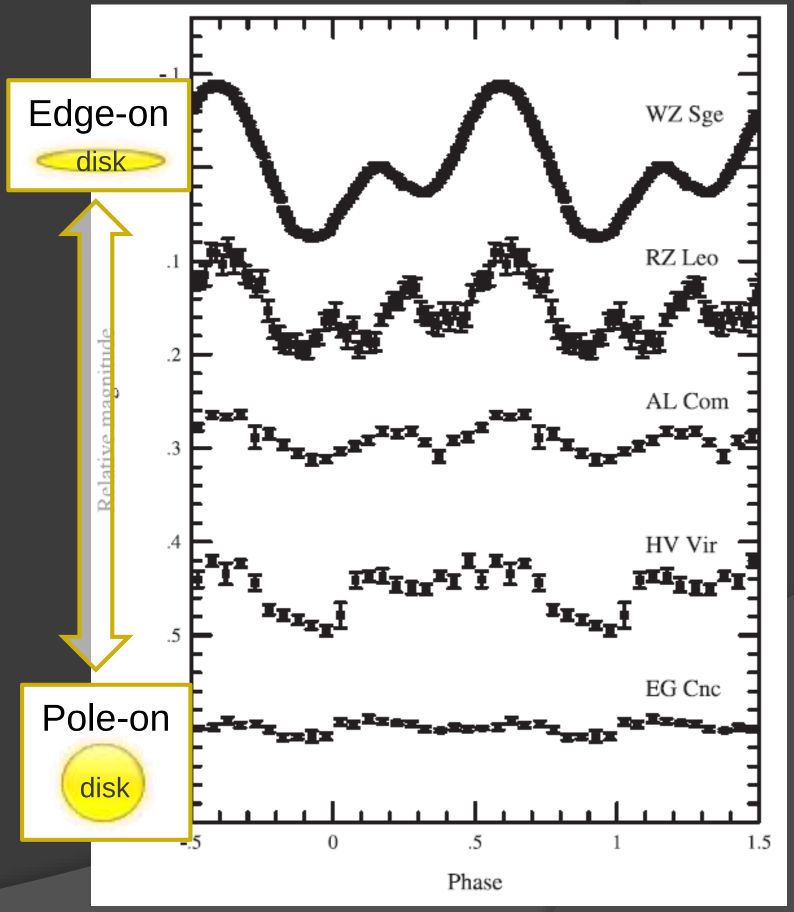
- Only observed in WZ Sge-type dwarf novae
  - Period = Porb
  - Doubly-peaked profile

- Rotation effect of the disk having non-axisymmetric structure



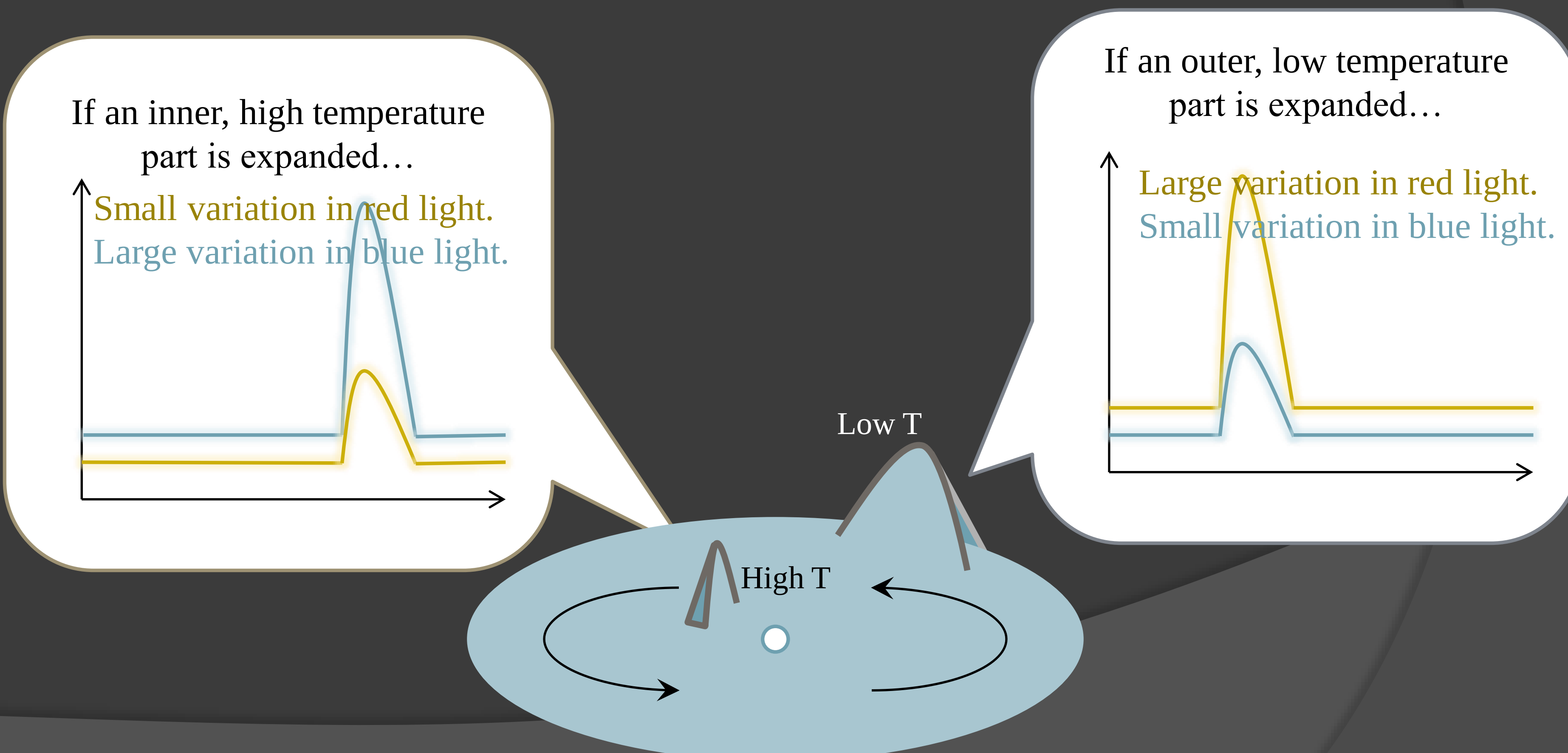
Zoo of early superhumps (Kato , et al. 2002).

Larger amplitude in edge-on systems.



Reconstruction of the geometrical structure from early superhumps

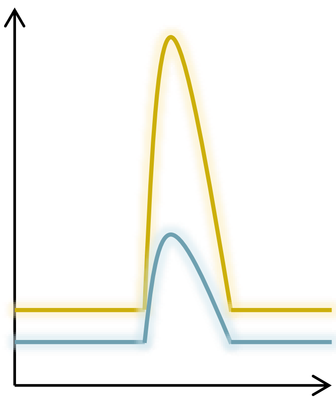
- Data = Time-series multi-band photometric data
  - Phase information → azimuthal structure of disks
  - Color information → radial structure of disks



Model

Input

Multiband light curves



Model

Bayesian estimation of the height, h(i,j)

$$P(h) \propto L[f_{\nu,obs}(\phi), f_{\nu,model}(\phi)]\pi(h)$$

Posterior likelihood prior

＊Likelihood function

$$L \propto \prod_{i,j} \exp - \frac{[f_{\nu_i,obs}(\phi_j) - f_{\nu_i,model}(\phi_j)]^2}{2\sigma^2}$$

＊Prior distribution

（locally smooth）

$$\pi_{\rm smooth}(h) \propto \prod_{l,m} [\exp - \frac{(h_{l,m} - 2h_{l-1,m} + h_{l-2,m})^2}{2w^2} \exp - \frac{(h_{l,m} - 2h_{l,m-1} + h_{l,m-2})^2}{2w^2}],$$

$$\pi_{\rm disk} \propto \begin{cases} \prod_{l,m} \exp - \frac{(h_{l,m} - h_{{\rm disk},l,m})^2}{2h^2_{{\rm disk},l,m}} & (h_{l,m} \geq 0) \\ 0 & (h_{l,m} < 0) \end{cases}$$

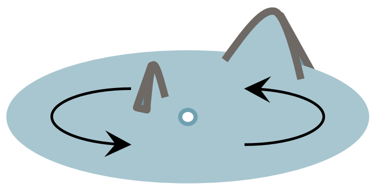
＊Estimation of “h” is done with MCMC

＊The temperature distribution is like an standard disk model:

$$T = T_{\rm in}(\frac{r}{r_{\rm in}})^{-3/4}$$

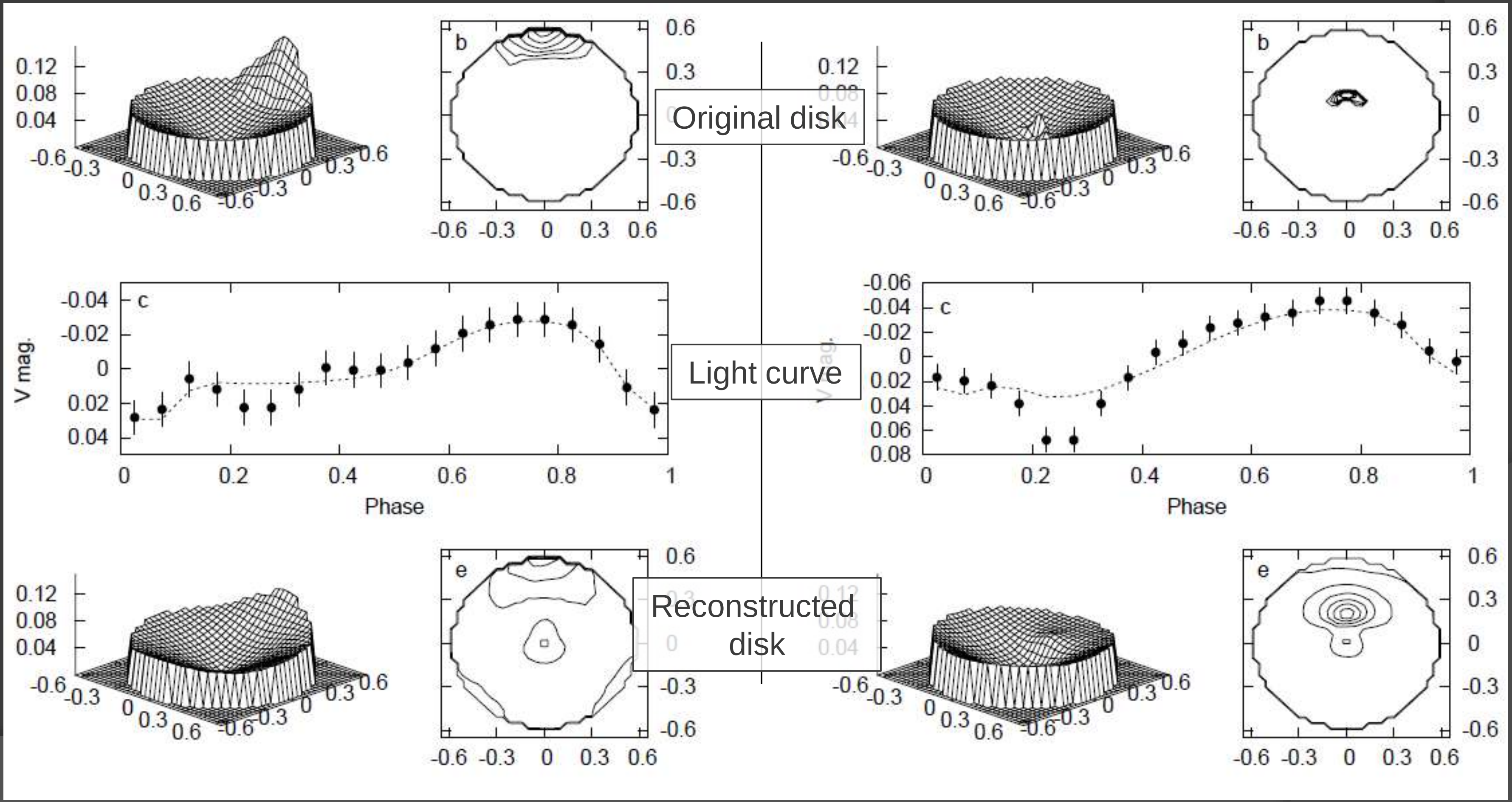
Output

Height map of disk



Demonstration with artificial data sets

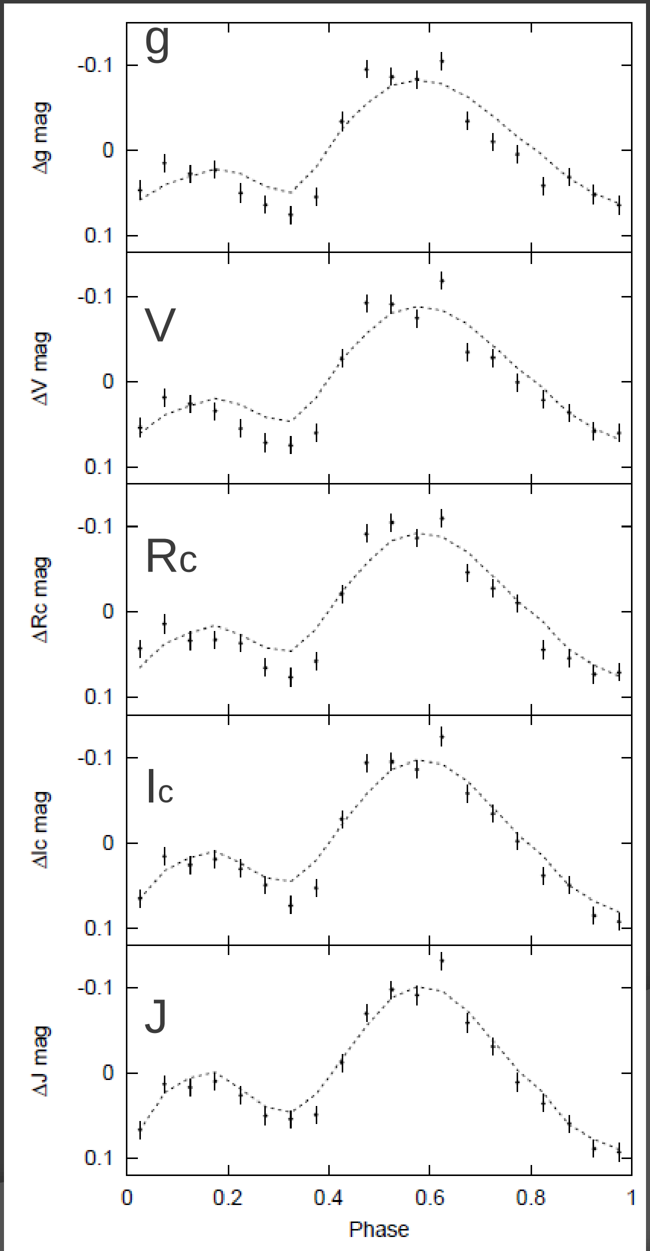
- Working as expected
  - Outer structures are reconstructed to be outer, and vice versa
  - Smoother structures than assumed, due to the prior distribution.

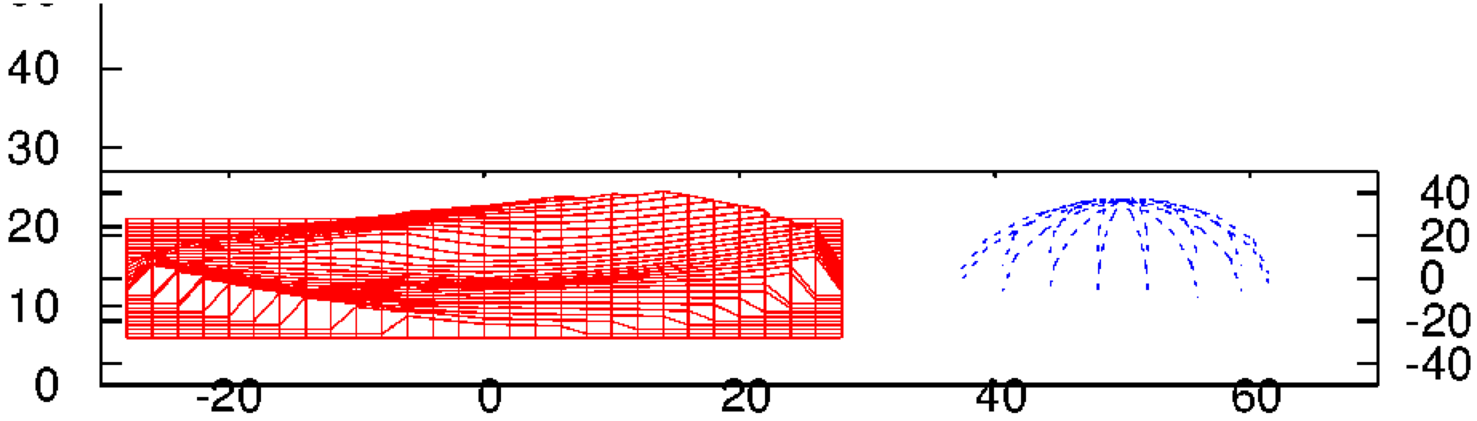


Data

- Dwarf nova V455 And
- 8 Sep. 2007
  - The 5th day of outburst
- Telescope
  - 1.5m Kanata (V, J, Ks)
  - 50cm MITSuME (g, Rc, Ic)

Light curve of early superhumps in V455 And (Matsui+09)

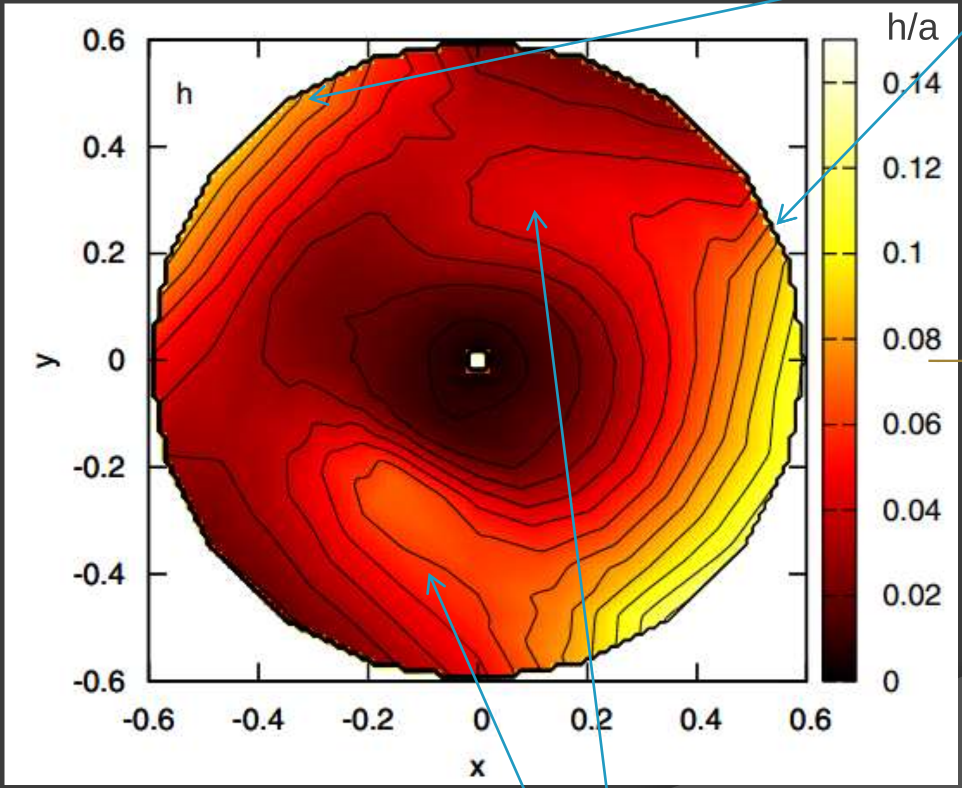



40
30
20
10
0
-20
0
20
40
60
40
20
0
-20
-40

Reconstruction of the disk using the data of V455 And

- Flaring outermost parts making primary and secondary maxima of the light curve
- Arm-like structures
- Useful for the comparison with numerical simulations.
  - SPH
  - hydro-dynamic

Height map (contour & color)



Flaring regions

Companion star

Arm- (spiral?) like structure

Doppler tomography
with total variation minimization

(Uemura, et al. in prep.)

Doppler tomography

(Horne 85; Baptista+93)

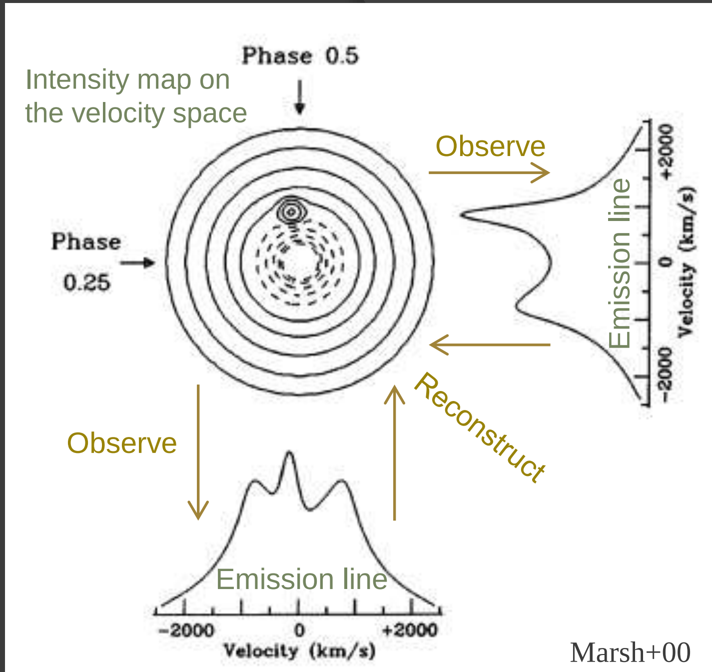
- Data (Input)
  - Time variation in emission-line profiles
- Estimates (Output)
  - Intensity map in the velocity space

$$\hat{\boldsymbol{x}} = argmin \left\| \begin{pmatrix} y_1 \\ \vdots \\ y_m \end{pmatrix} - \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{m1} & \cdots & a_{mn} \end{pmatrix} \begin{pmatrix} x_1 \\ \vdots \\ \vdots \\ x_n \end{pmatrix} \right\|_2^2 + \lambda f(\boldsymbol{x})$$

Data　　Observation Matrix　　image

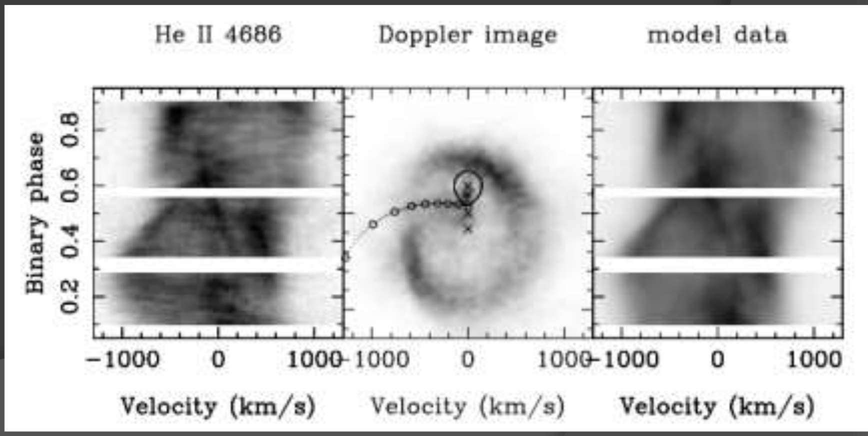
2nd order norm
= least-square term

Regularization term
Ex. MEM, TVM



Marsh+00

IP Peg (Harlaftis+99)



MEM & TVM

- Maximum Entropy Method (MEM)
  - Standard method to date
  - Regularization:

$$S = -\sum_{i=1}^{M} p_i \ln \frac{p_i}{q_i}.$$

$$q_i = \frac{D_i}{\sum_{j=1}^{M} D_j},$$

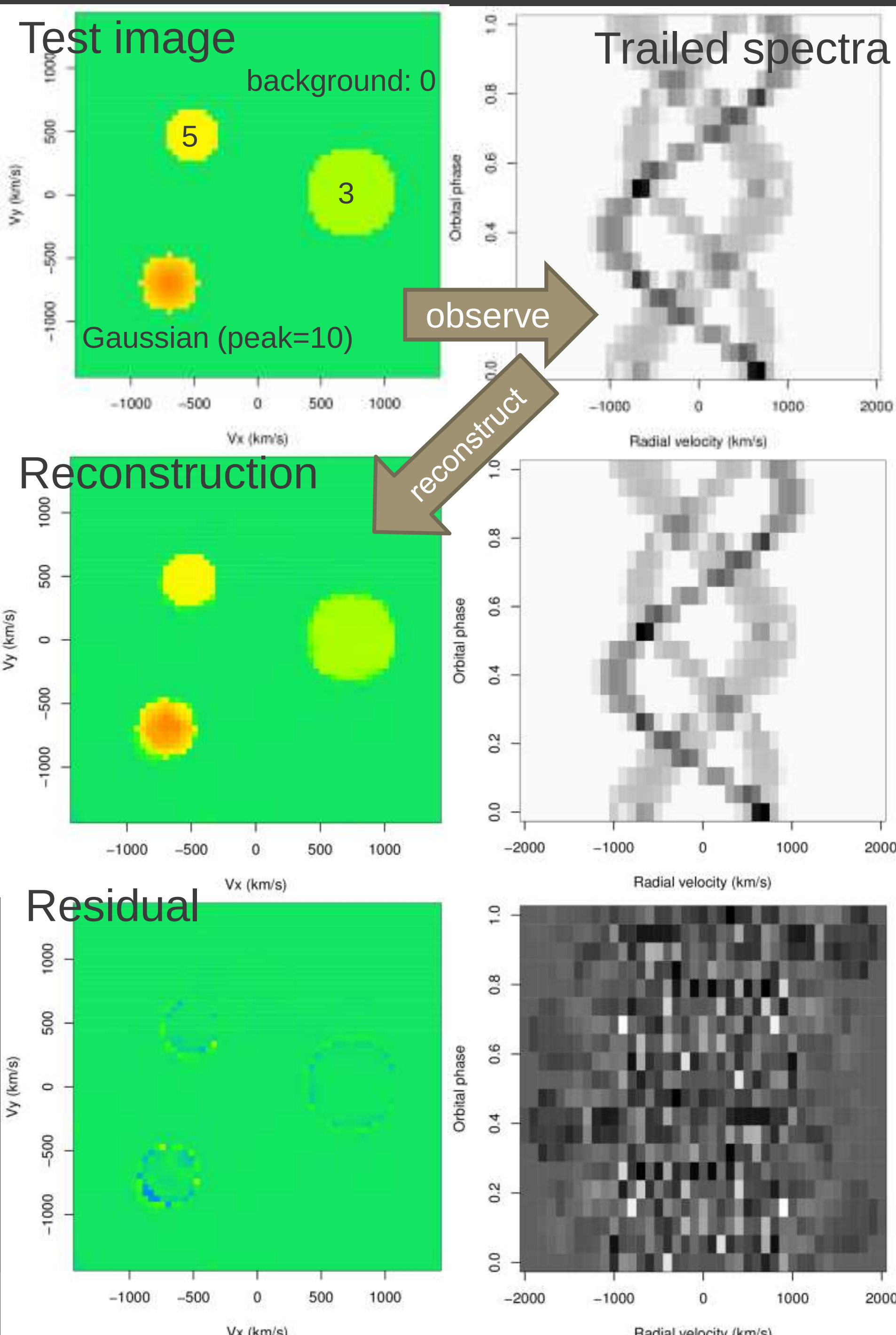
  - MEM is statistically best, but physically best?
    - Hot spot and/or shock region may have sharp edges, making entropy low

- Total Variation Minimization (TVM)
  - Simple prior
  - Regularization:

$$TV(\boldsymbol{x}) = \sum \sqrt{(\Delta^h \boldsymbol{x})^2 + (\Delta^v \boldsymbol{x})^2}$$

  - Δx: differential operator $= x_{i+1} - x_i$
  - Sparse gradient

Test

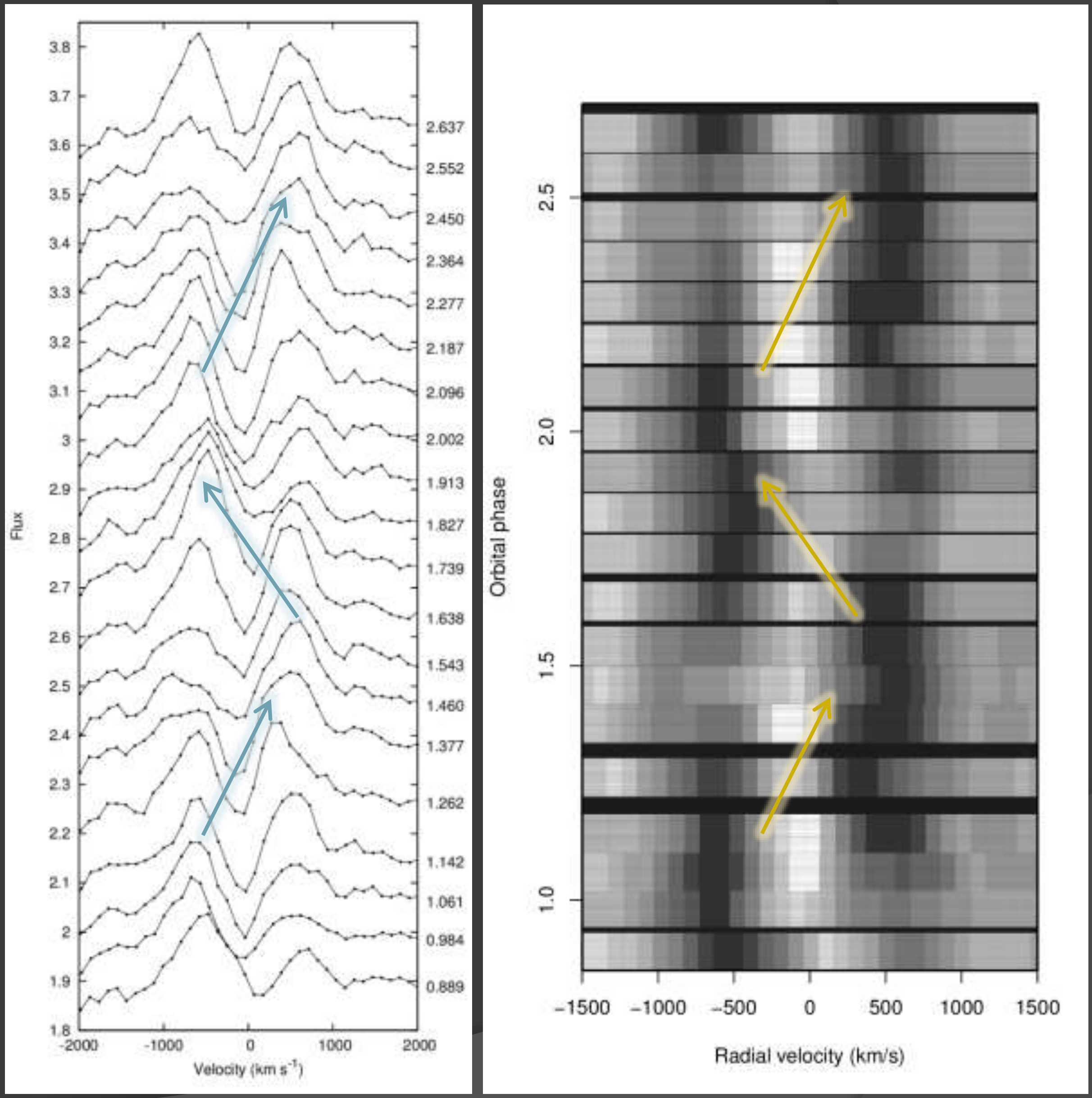


- Well reconstructed
  - Size
  - Position
  - Intensity
  - Structure (flat top & gaussian)
- The Residual of observations = 0.8%

Data

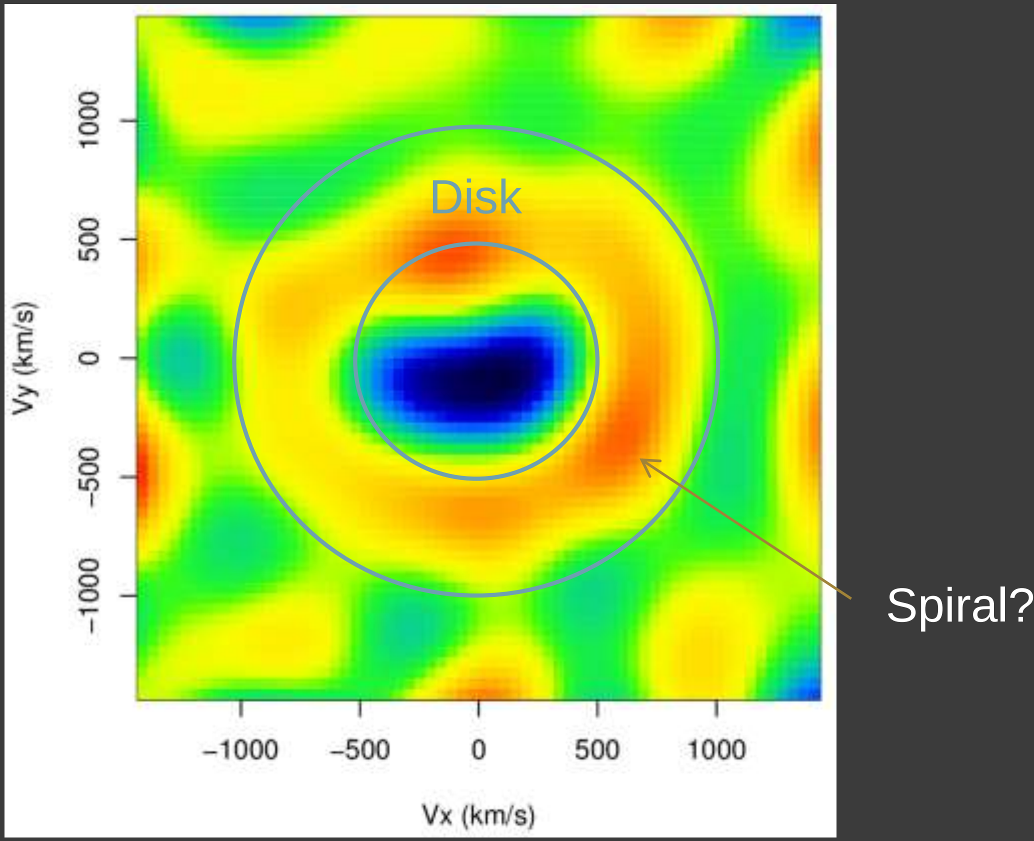
- Dwarf nova WZ Sge
- 1 Aug 2001
  - (the 10th day of the outburst)
- Telescope
  - 122-cm Asiago
  - Resolution ~6 Å

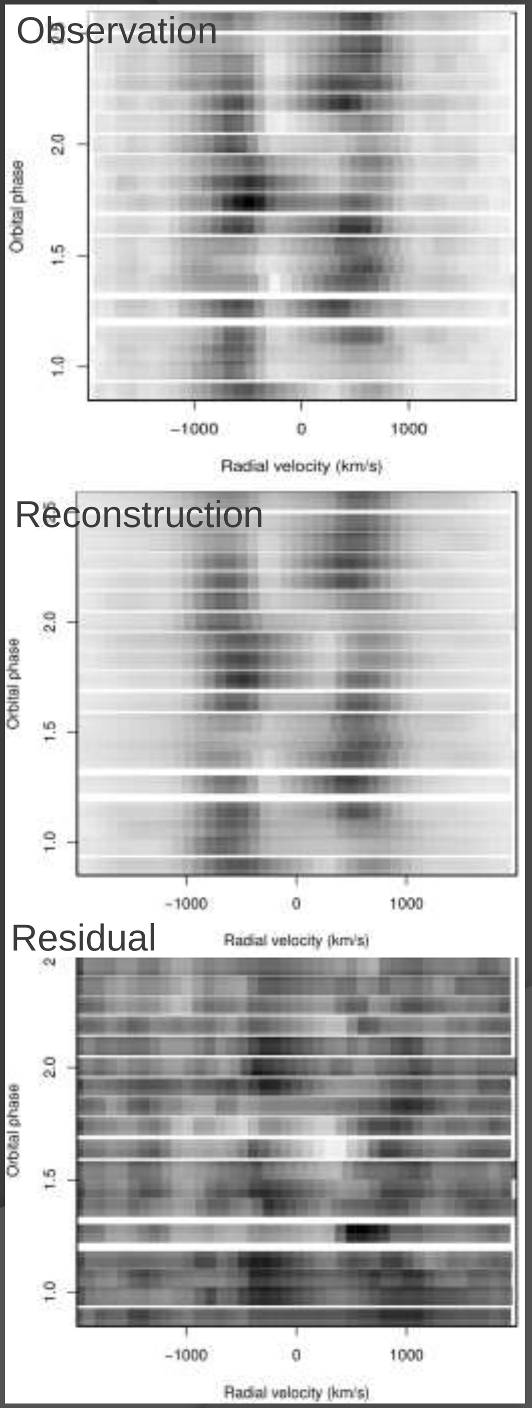
Variation of the Hα line (Nogami+04)



Result with the data (WZ Sge)

Intensity map of the line photons
in the velocity space

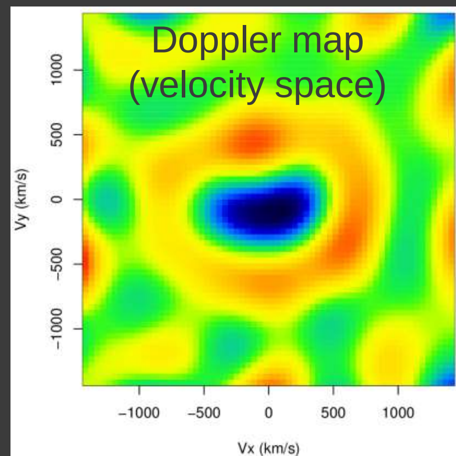




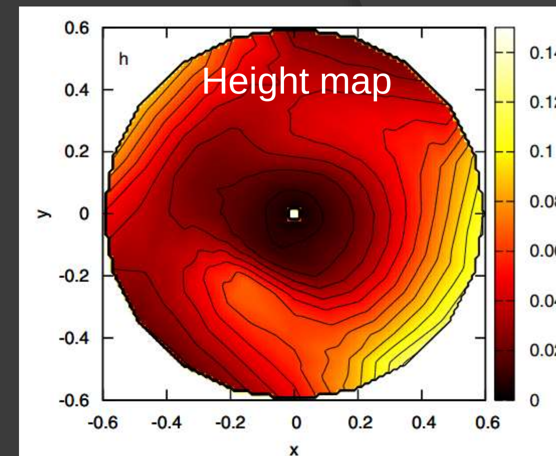
- Disk + spiral ? + companion star ?

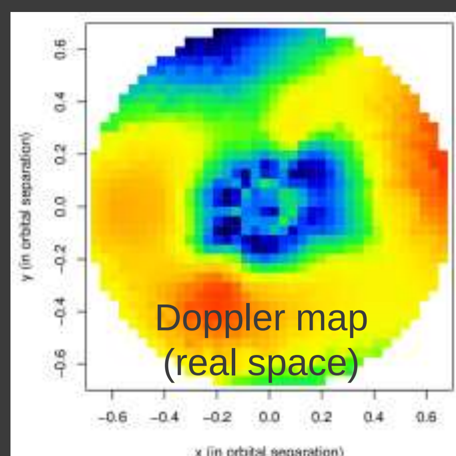
Disk height & Line forming region

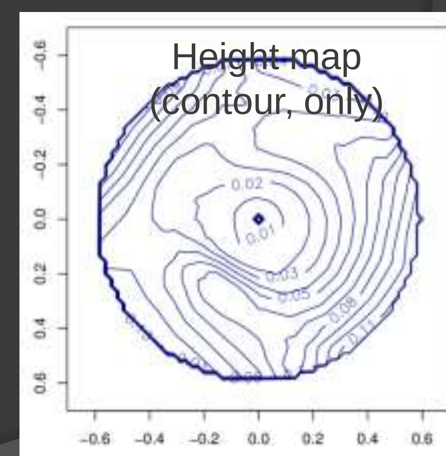
- Disk height mapping
  - Data: V455 And
  (the 5th day of outburst)
- Doppler tomography
  - Data: WZ Sge
  (the 10th day of outburst)
- Similar type of object
- Similar state of the accretion disk



Kepler rotation

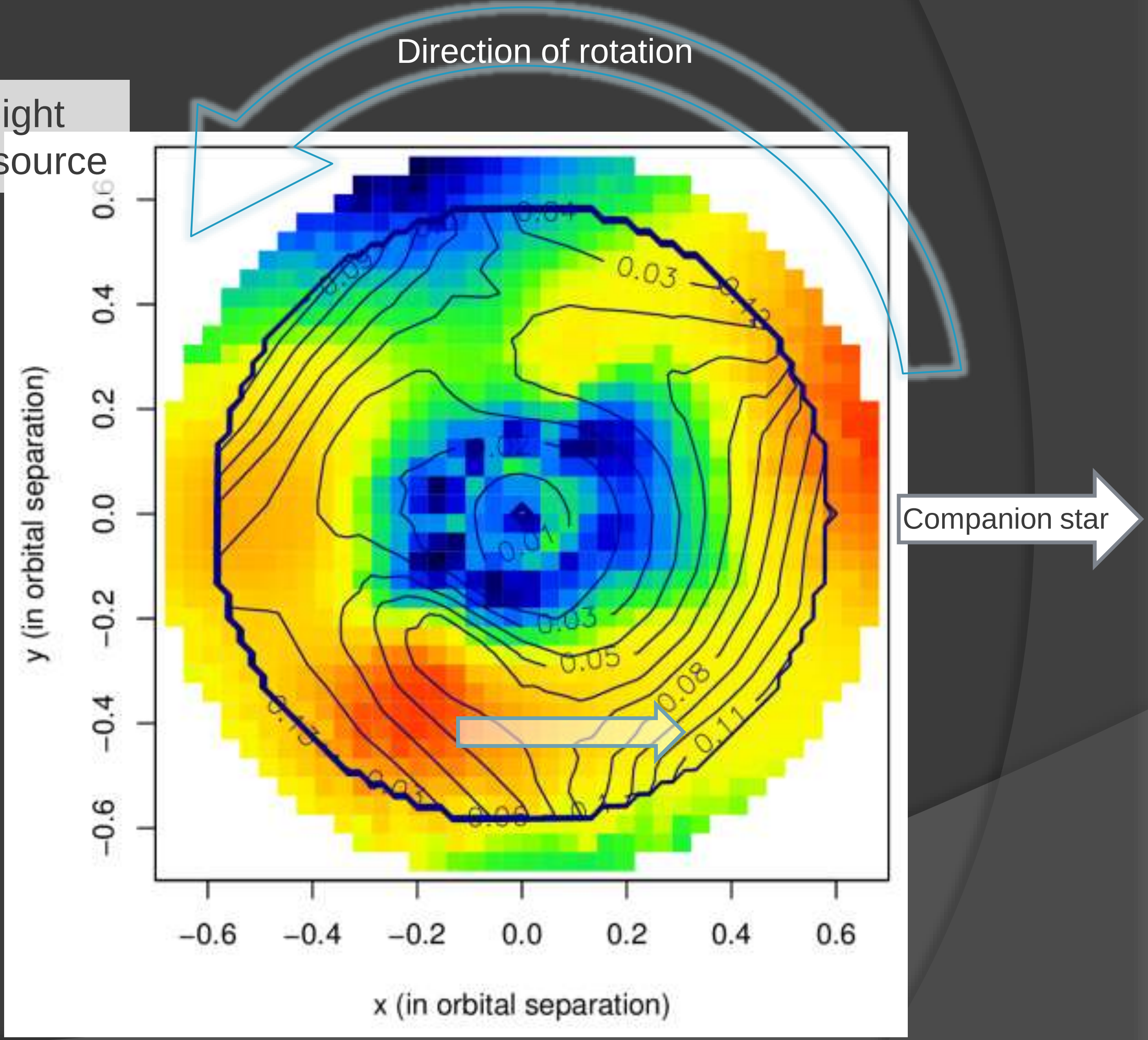






Disk height & Line forming region

Contour: disk height
Color map: line source



- Large Height region ≠ strong line-forming region
  - Irradiation from the central region may not play an important role
- The strong line-forming region precedes the large height region
  - Compressed, then flared?

Summary

- Tomography is a powerful tool to study accretion disks.

- New data need new methods
  - Disk height mapping using light curves of early superhumps
  - Doppler tomography with total variation minimization

- It is important to keep up with new methods.