The CHARA, NPOI, and PTI view of eps Aur

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A preview of EXor observations at CHARA and the VLTI

Brian Kloppenborg

Part 1: The CHARA, NPOI, and PTI view of epsilon Aurigae

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In collaboration with:

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Michelle Creech-Eakman, various folks from PTI
Theo ten Brummelaar, Chris Farrington, PJ Sallave-Goldfinger,
Judit Sturmann, Laszlo Sturmann Ettore Pedretti, Nathalie Thureau,
Nils Turner, Sean M. Carroll

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Science objectives

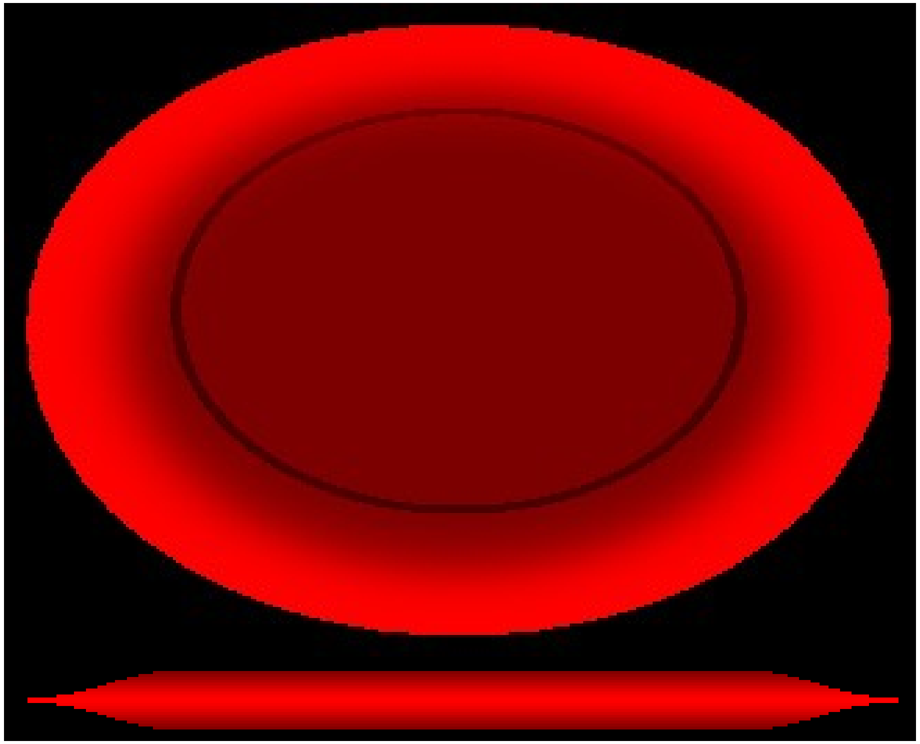
- Is there really a disk?
  - If so, what are its geometric properties?
    - Radius, height, opacity, inclination, flaring
  - Can we derive any optical properties?
- What is the evolutionary state of the system?
- What causes the photometric variations
  - Both in AND out of eclipse!

2012 status quo

- Last time, at CHARA-8
  - Model independent imaging
  - Poor astrometric orbit, needed something better
  - Using Bayesian evidence to do model selection
  - Beginning of multi-epoch interferometric model fitting
- Remaining problems
  - Modeling required 7-9 parameters, hard to search
    - Did we find the (global) minimum? If not, screws up 30 years of research.
  - Uncertainties
    - Unreasonably good results: <1% error with 15% calibrator uncertainty!
    - No way to include systematic errors
    - Are error distributions normal?
  - Modeling was interferometric only, no photometric constraints

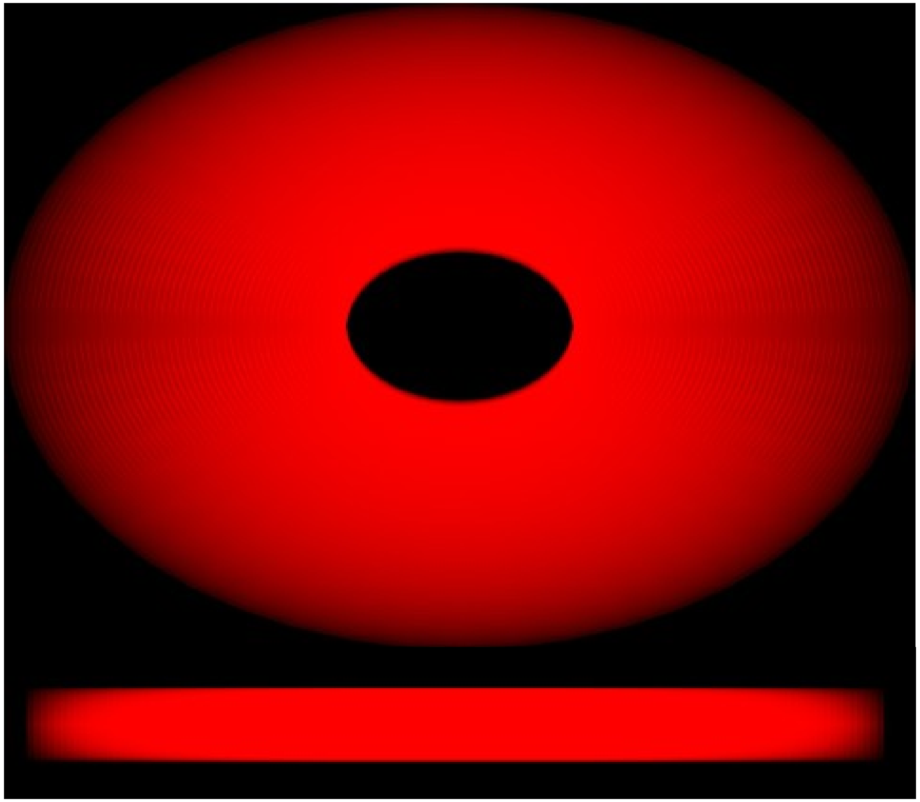
New disk model

- Old, “Disk B” model with power-law exterior and vertical transparency



Most results discussed herein use this model

- Concentric ring model with power-law radial and vertical transparency

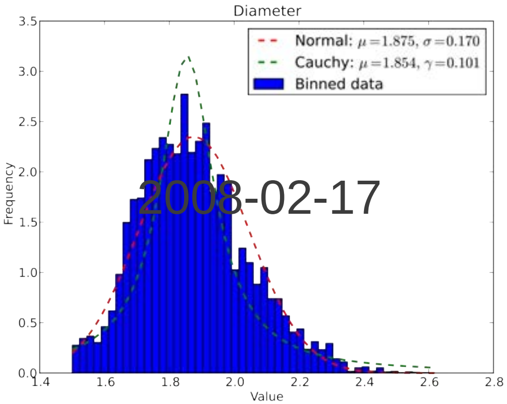


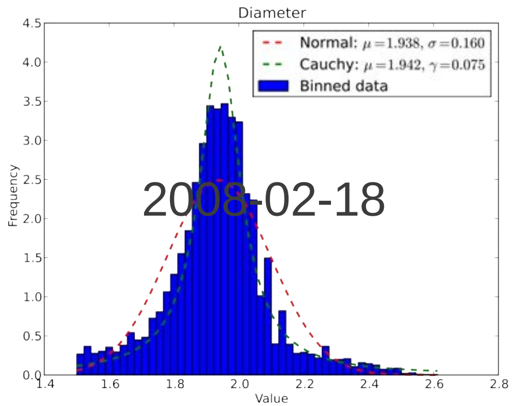
New software

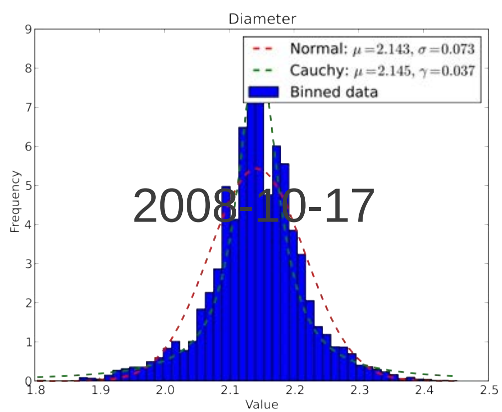
- OpenCL Interferometry Library (liboi)
  - Unit tests → computations are valid!
  - Profiling → 30% faster on ATI GPUs
  - 260 image → chi2r / sec on 530 UV point set
  - Images can be CPU, GPU, or OpenGL memory/buffers
- C++ OIFITS library (ccoifits)
  - A new C++ interface to OIFITS files
  - New “OIDataLists” permit sorting, filtering, pseudo-recalibration, merging, etc.
  - OIFITS to arrays with automatic UV point minimization via. KD-trees.
  - OIFITS to text files
  - Read only (at the moment)
- SImulation and Modeling Tool for Optical Interferometry (SIMTOI)
  - Plugin architecture for:
    - Data sources
    - Models
    - Minimizers
  - Support for OI and photometric data
  - Bootstrapping with dynamic pseudo-recalibration (via. ccoifits)
  - Time-dependent, 3D modeling
  - Wavelength-dependent framework built-in, not fully implemented.
  - New UI with interactive plots partially implemented
  - Command line execution for scripting!

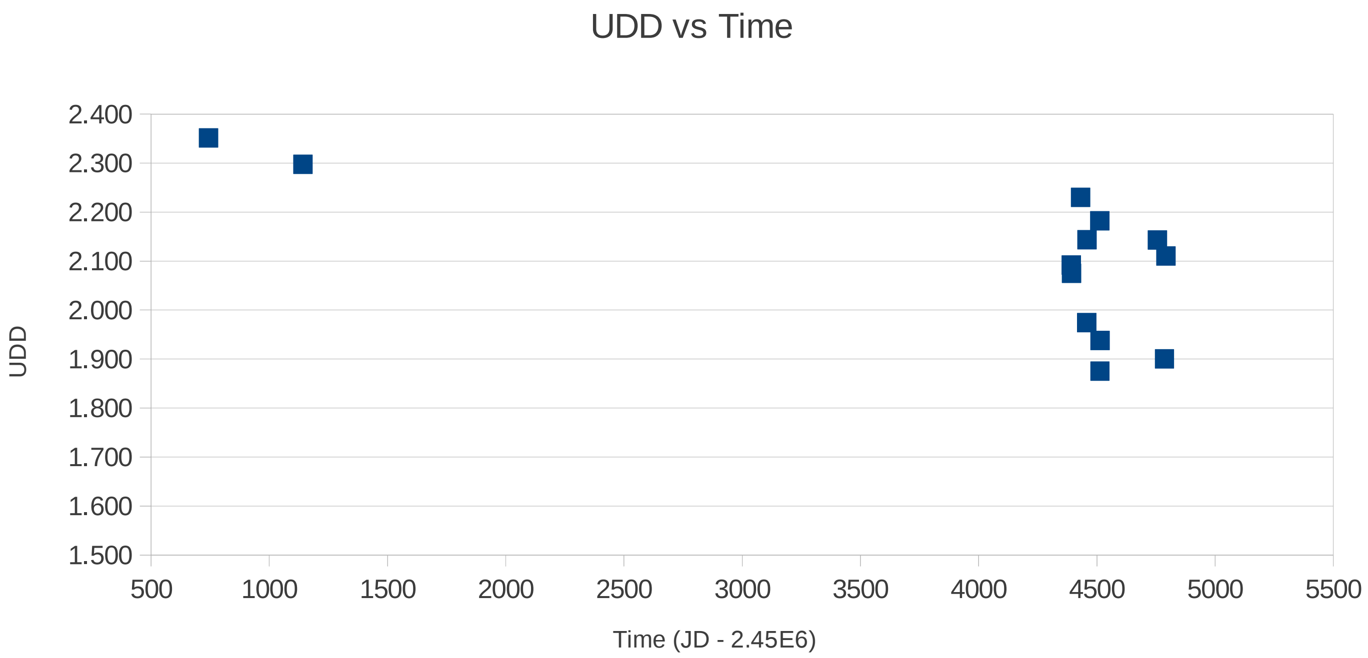
All Open source software! See http://github.com/bkloppenborg

Results: PTI Pre-eclipse



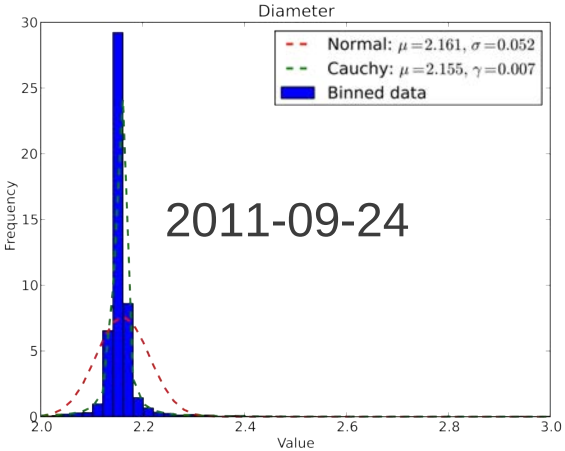


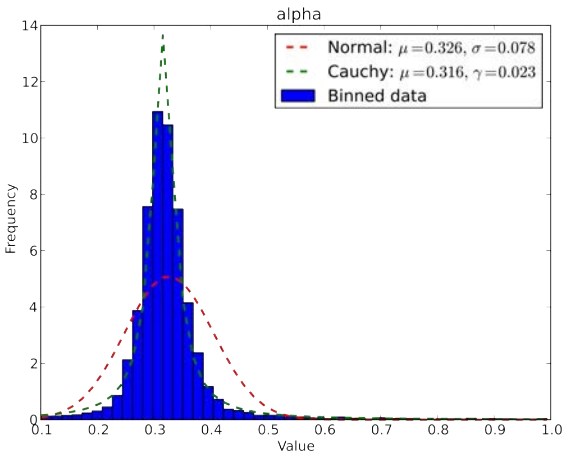


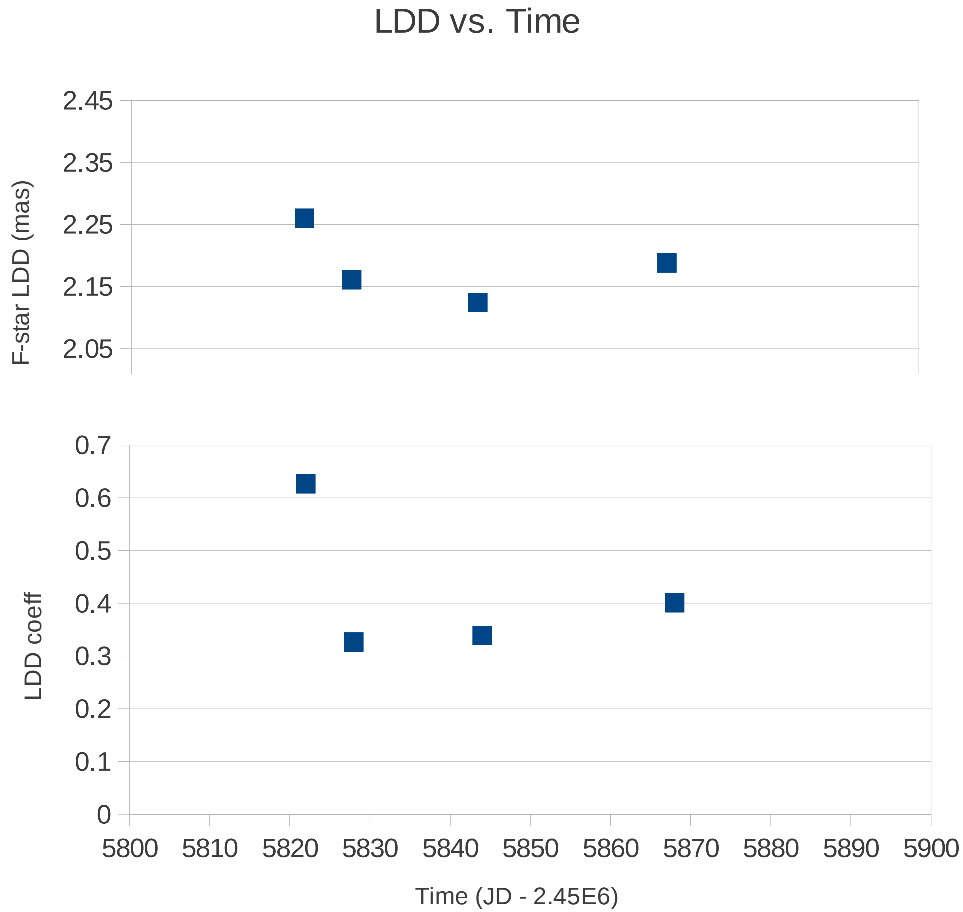


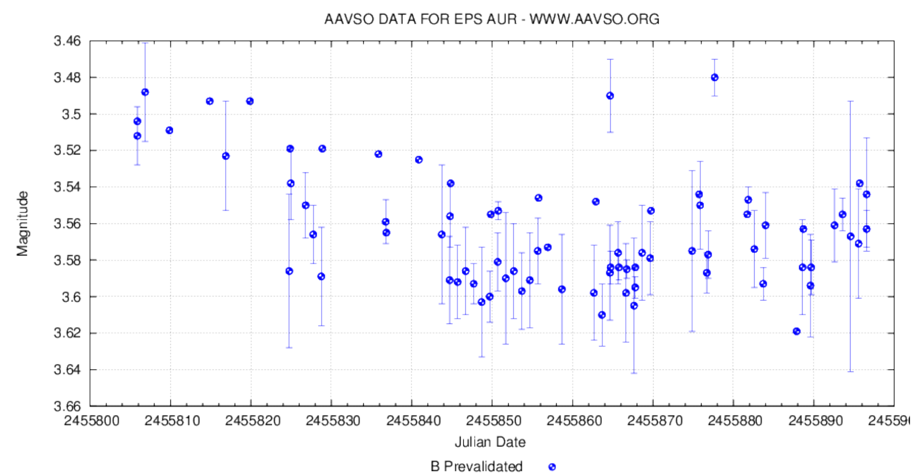
- Most distributions look good
- Most values consistent, within uncertainties
- K-band UDD 2.14 +/- 0.07 mas

CHARA-MIRC 6T post-Eclipse



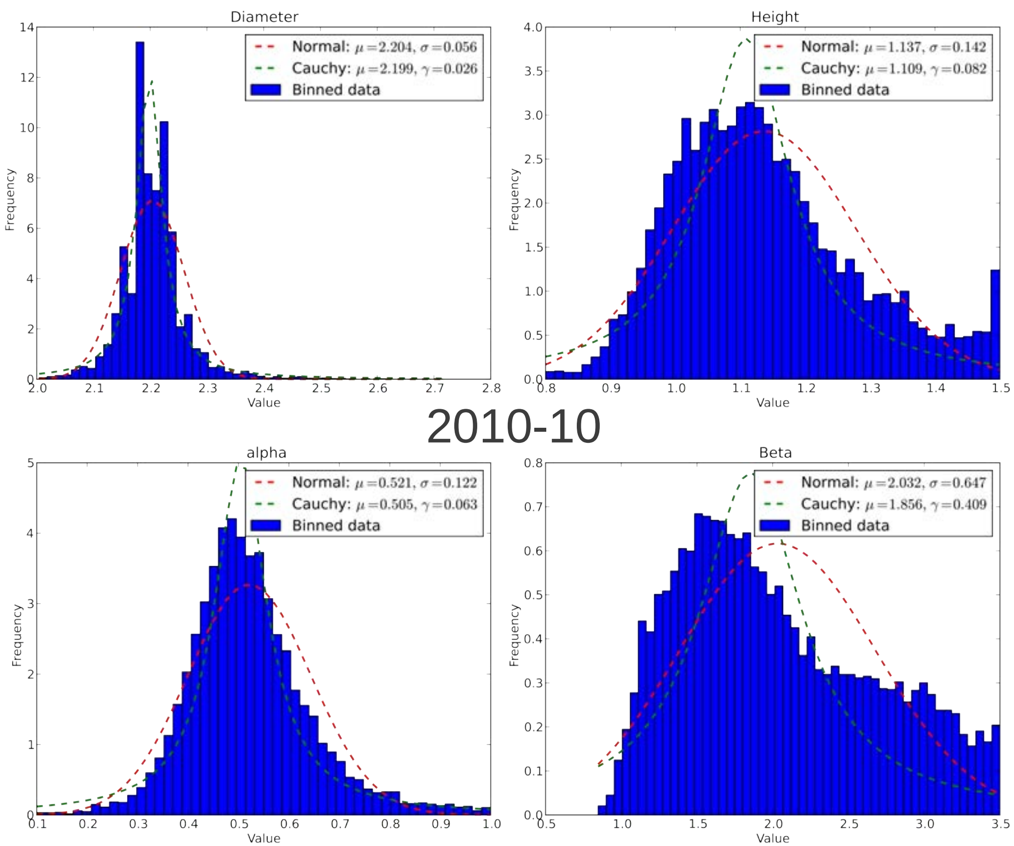




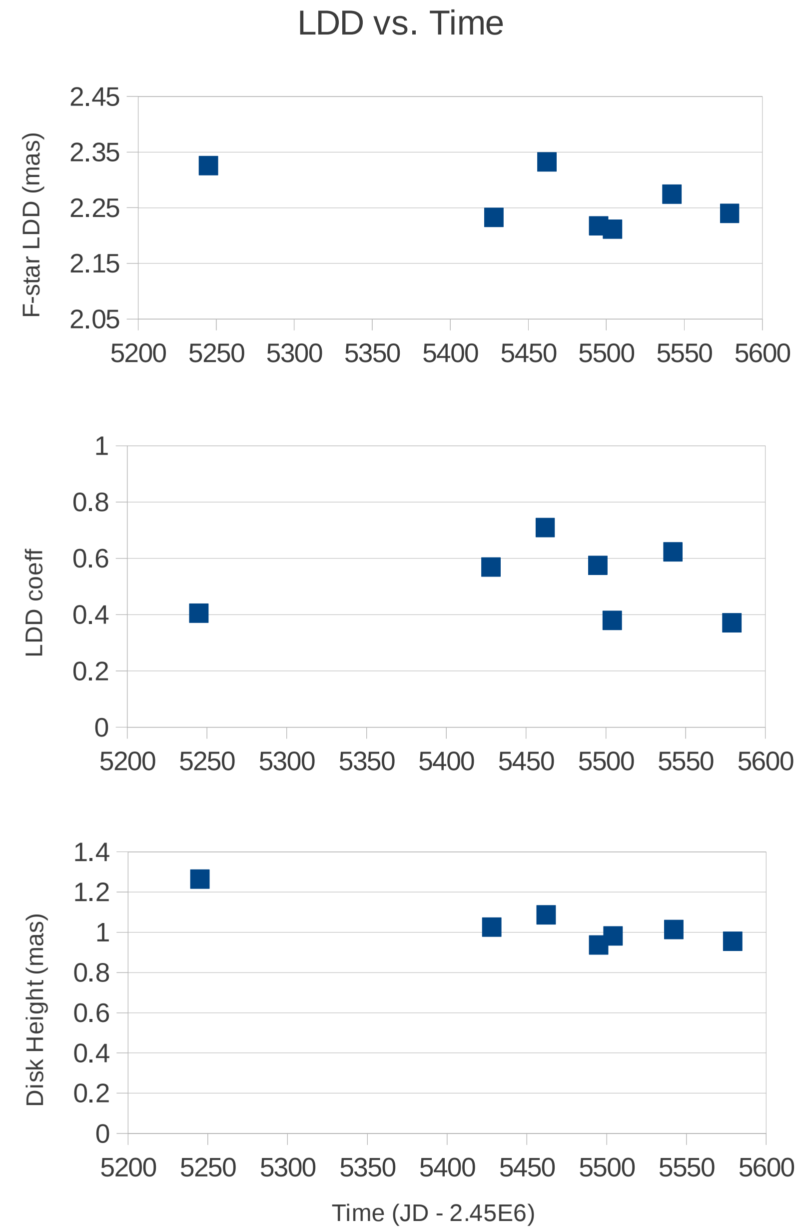


- Errors appear to follow Cauchy (Lorentzian) distribution
- Possible radial changes, could also be spots, but difficult to tell.

CHARA-MIRC in-eclipse

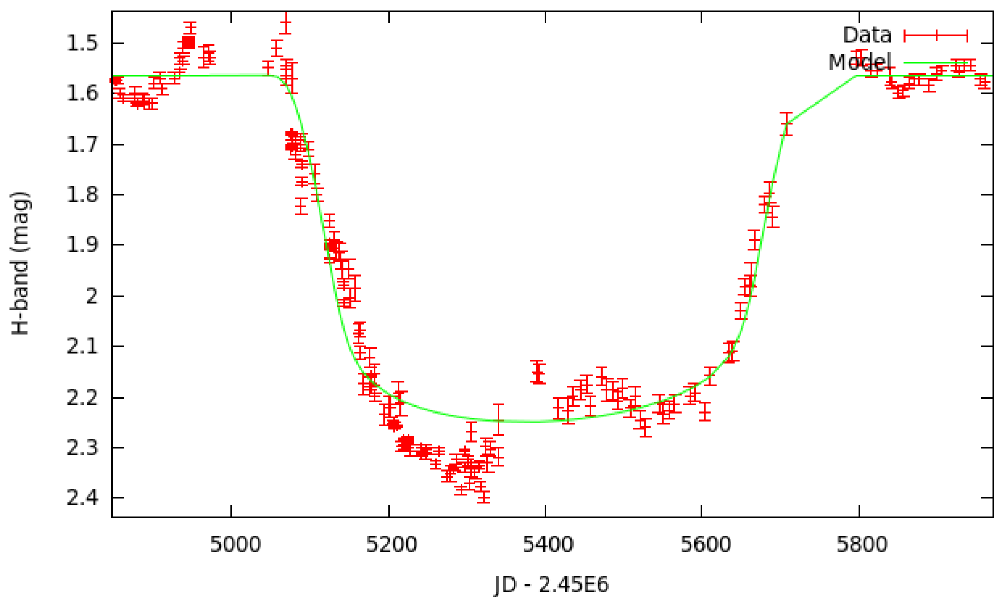


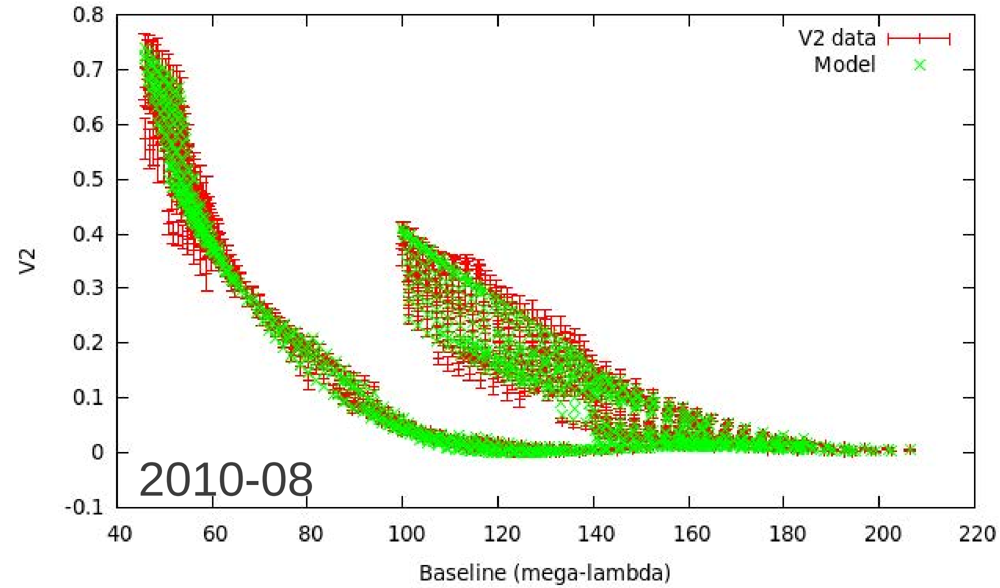
2010-10

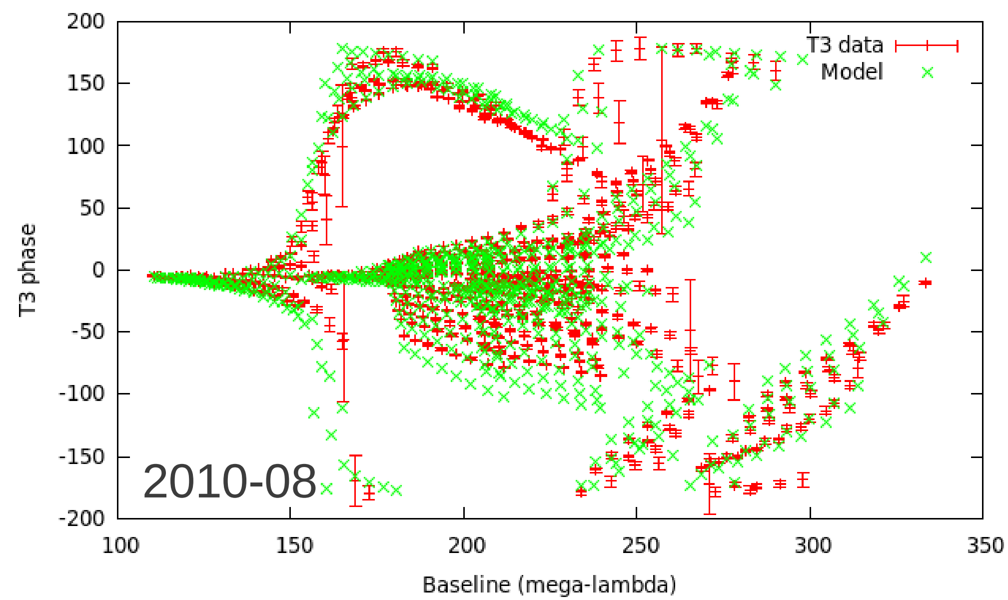


- F-star has fairly regular size
- Limb darkening stable during eclipse
- Disk thickness (amazingly) stable
    - Slightly thicker in 2010 Feb (~5250)
- Disk parameters follow log-normal distribution

New multi-epoch fit w/photometric constraints w/new disk model

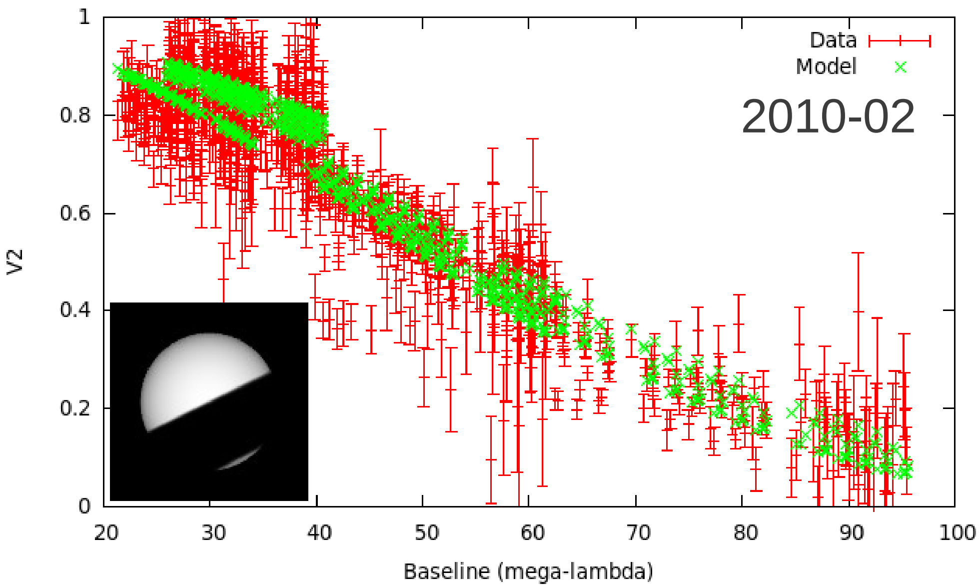


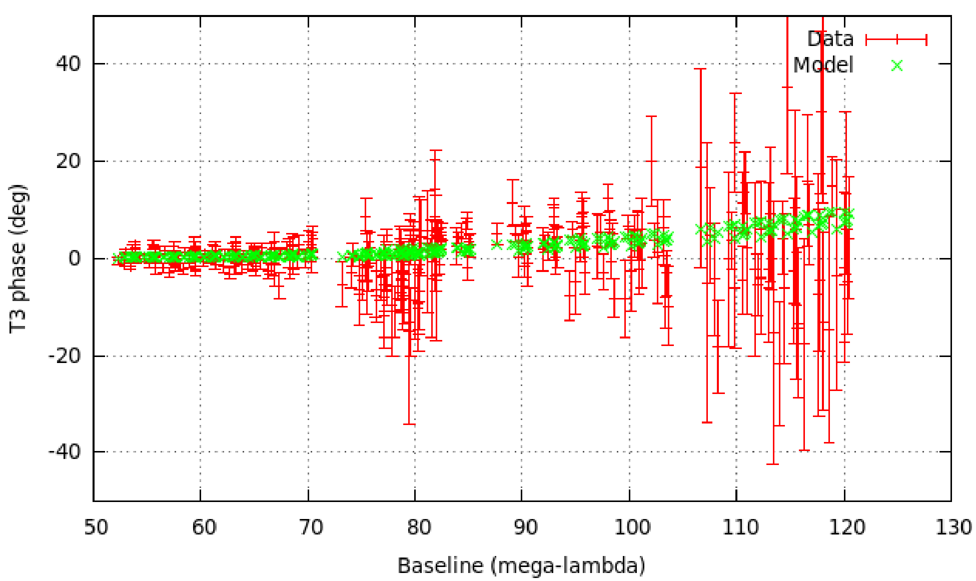




- Photometric data is a good fit
  - Symmetric disk model → disk is asymmetric (supporting evidence exists)
- Interferometric modeling looks *good*
- 2009-11/12 + 2010-08/10 + photometry chi2r ~ 2.0
- Re-running individual epoch fits now!

NPOI





- Out of eclipse
  - Star is 0.1 – 0.3 mas larger
  - ~ linear limb darkening
- In eclipse
  - Signature of eclipse at short baselines
  - Consistent with CHARA result
  - 2010-02: Not clear if southern cap is covered.
- Issues:
  - Consistent diameter for calibrator (eta Aur)?

Part 2: A preview of EXor observations at CHARA and VLTI

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Star formation

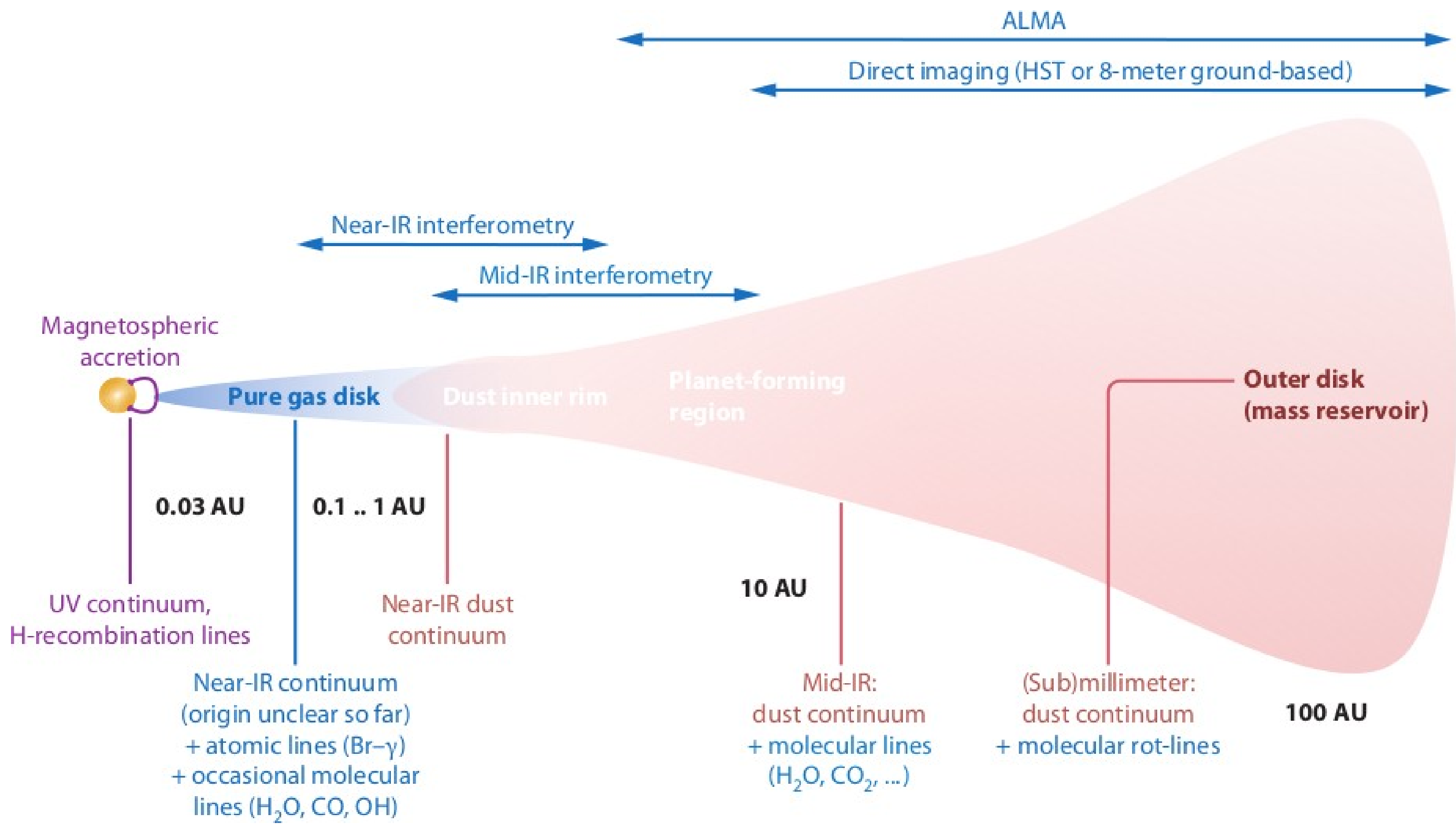
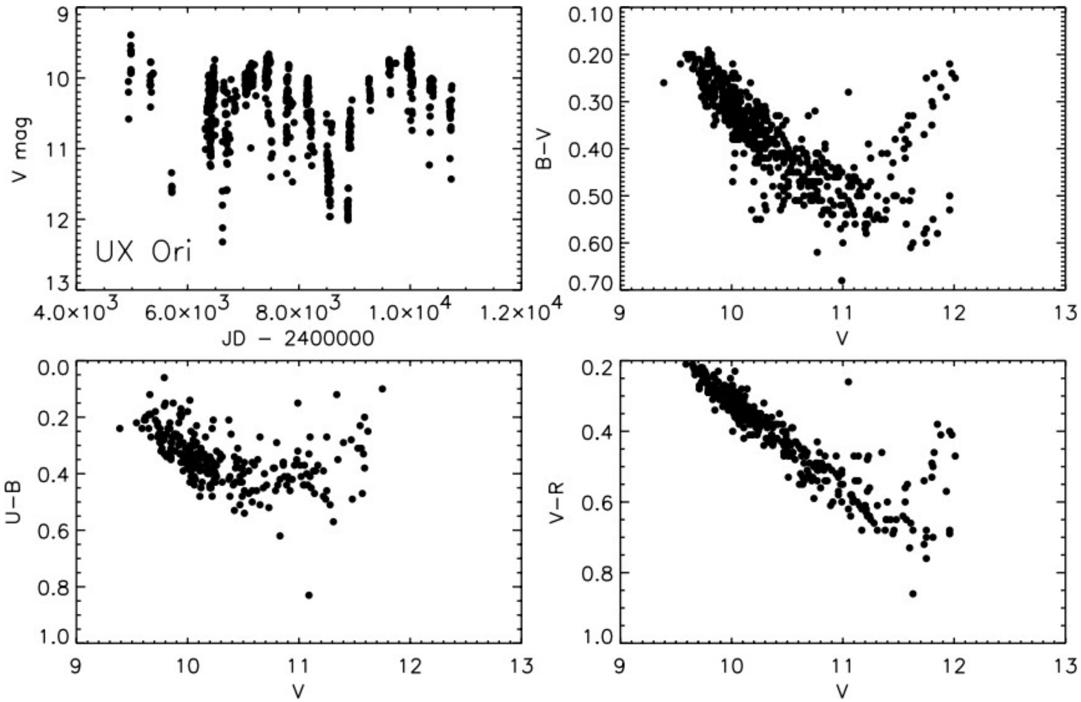


Figure from Dullemond & Monnier 2010

(Probably) not accretion: UXors

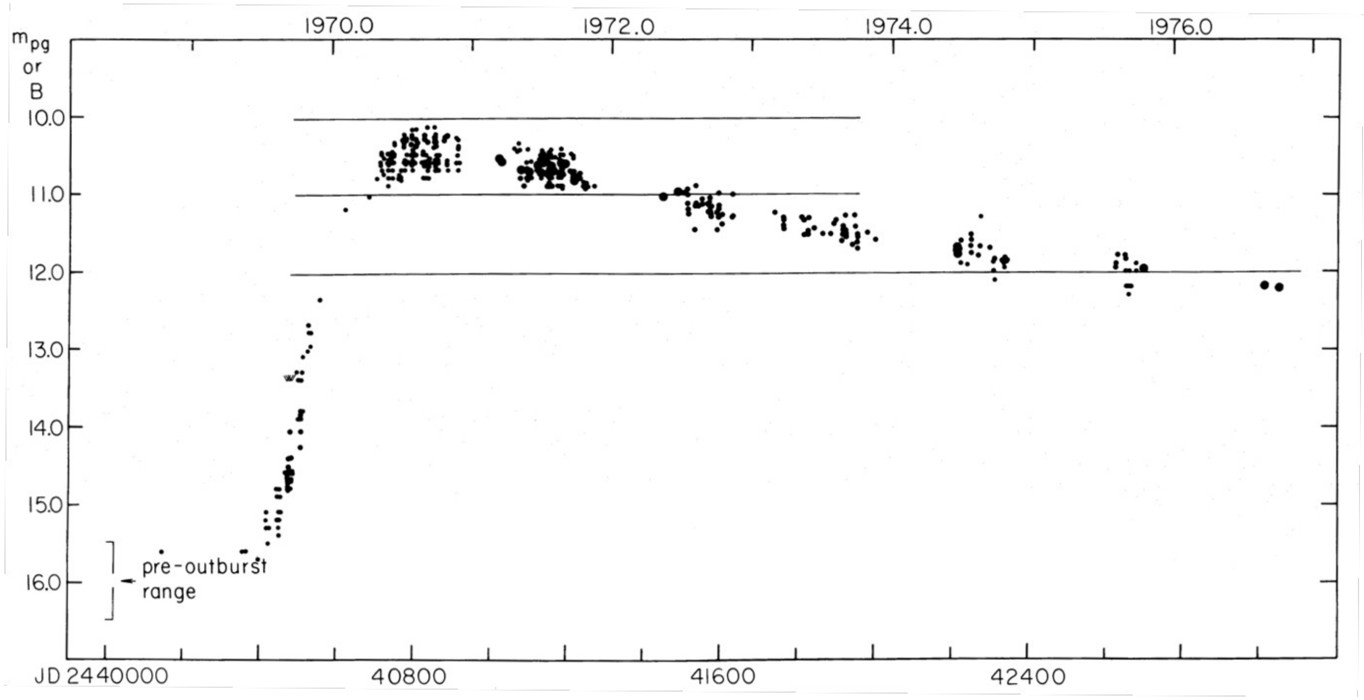
- UXor (Zaitseva 1983; Grinn 1998) Prototype: UX Ori
  - Feature rapid (few hour/day), irregular fading with superimposed repeating patterns
  - Color reversal called “bluing” at minimum light
  - Probably Herbig Ae/Be stars seen at high inclination



UX Ori photometry from Herbst 1999

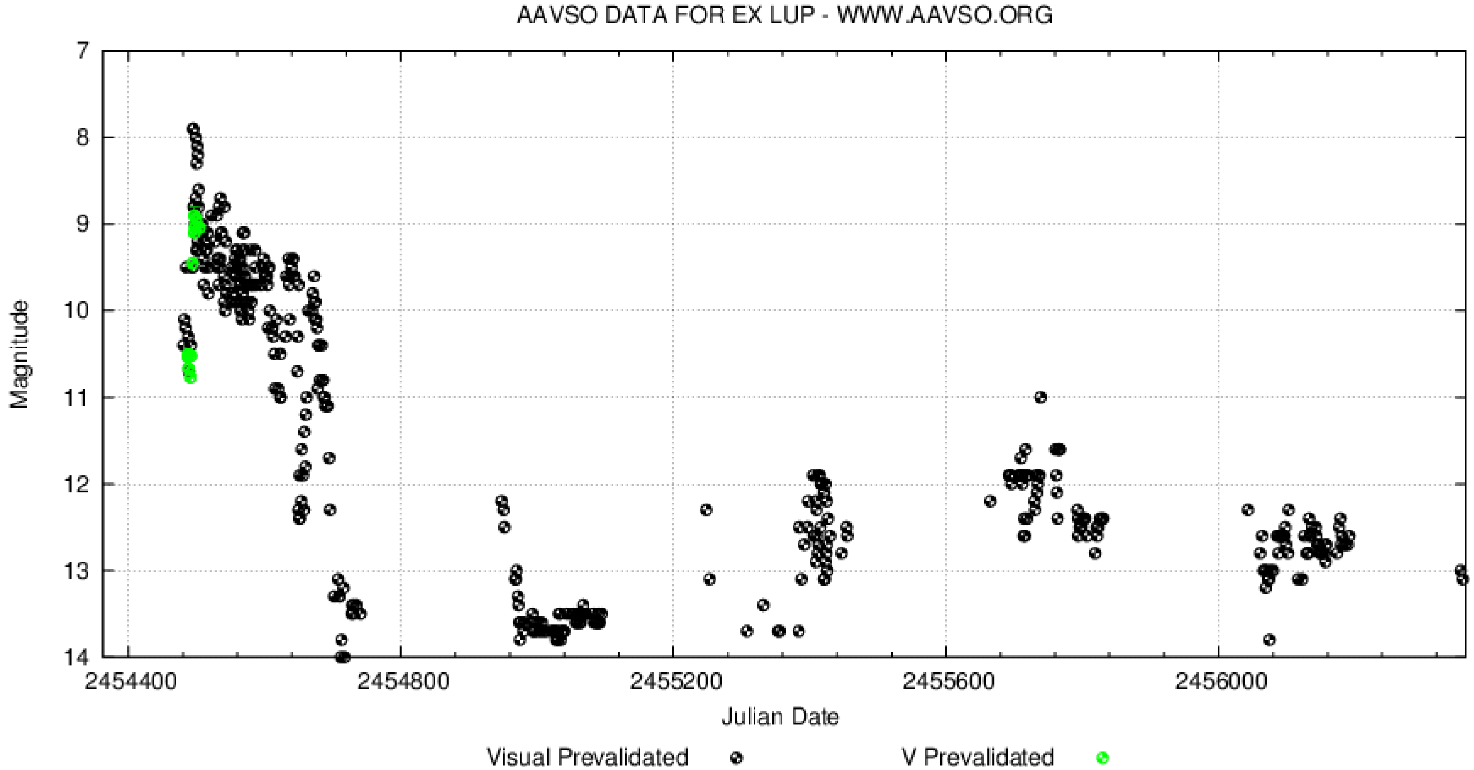
FUor

- FUor (Hartman & Kenyon 1985) Prototype: FU Ori
  - Long outbursts of 10s of years
  - Accretion rates $10^{-4} – 10^{-5}$ MSolar/yr
  - When in eruption, spectra dominated by absorption lines
  - Progenitors thought to be Classical TTauri Stars (CTTS)



FU Ori eruption. Figure from Herbig 1977

EXors



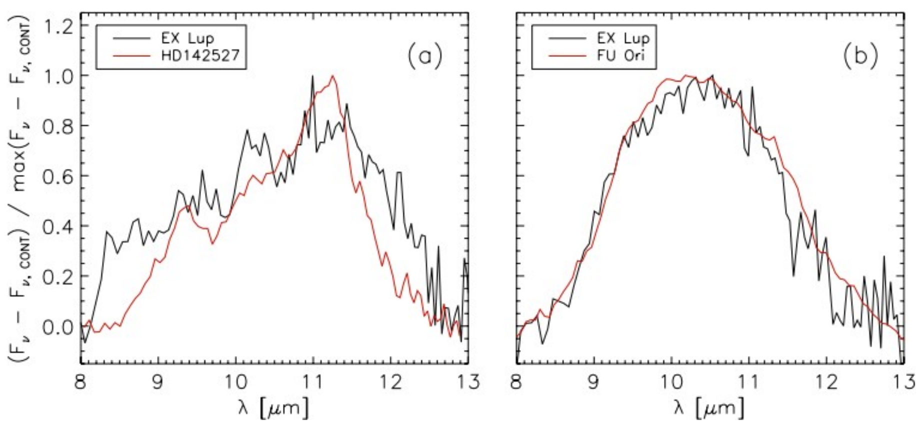
– EXor (Herbig 1989) Prototype: EX Lup

- Short outbursts (weeks-months) with similar recurrence times
- Accretion rates of $10^{-6} – 10^{-7}$ MSolar/yr
- Resemble CTTS when in quiescence; characterized by numerous emission lines when erupting.
- 23 Known objects with 8.5 < V < 20+; 6.2 < K < 13.2; 0.2 < N < 10

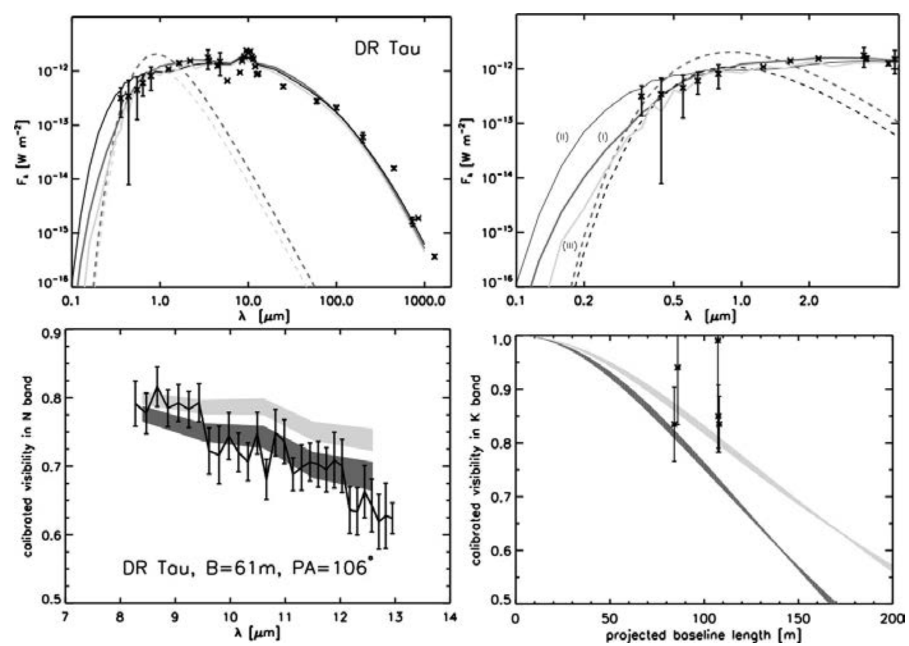
EXors: Present knowledge

- EX Lup
  - Crystalline interior
  - Large-grain silicate exterior

- DR Tau
  - Accretion vs. stellar luminosity difficult to disentangle
    - PTI Akeson et al. (2005)
    - MIDI Schegerer et al. (2009)

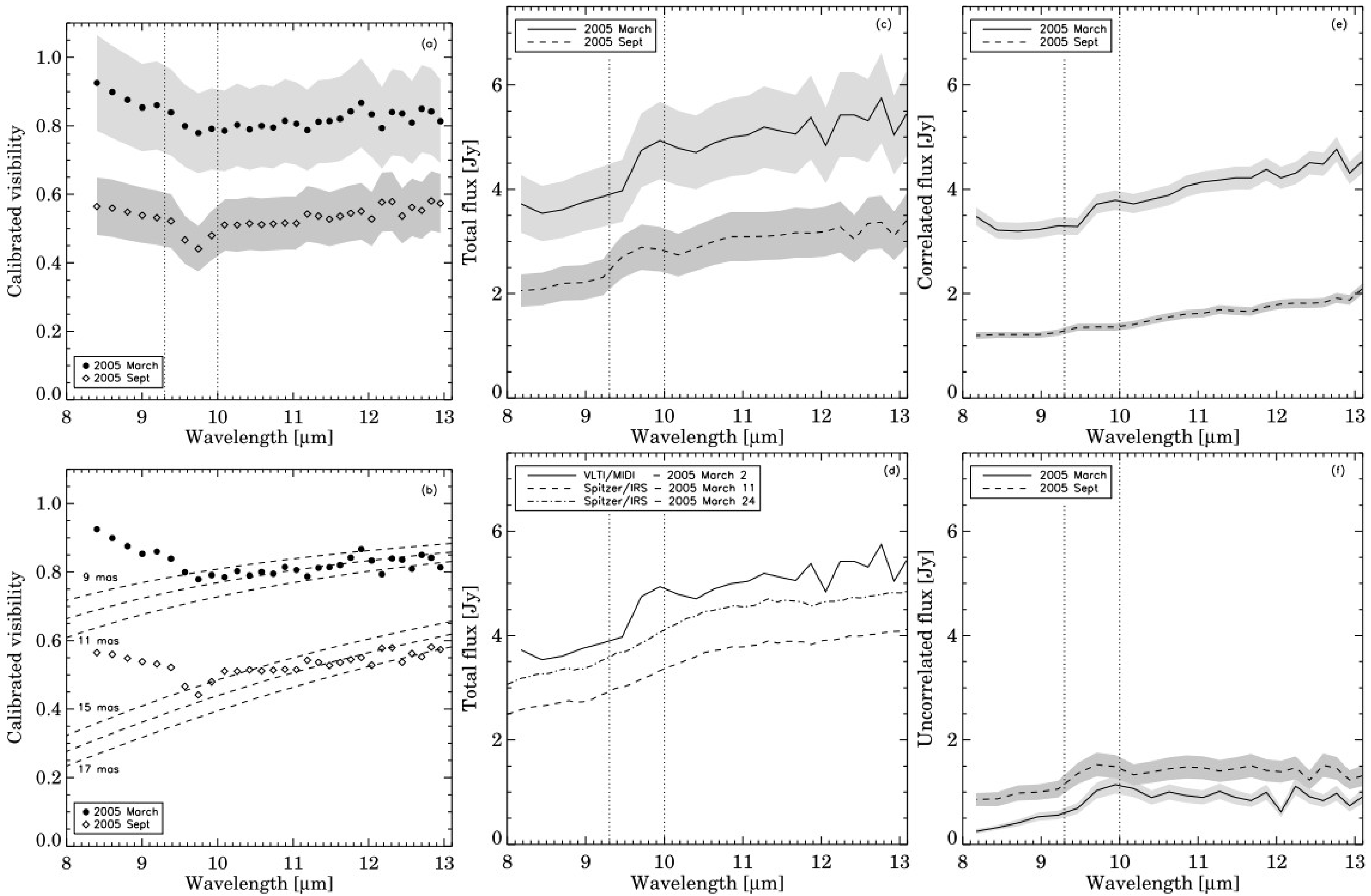


EX Lup in outburst. Juház et al. 2012



DR Tau on MIDI. Schegerer 2009

V1647 Ori



MIDI observations of V1647 Ori during the 2003-2006 outburst (Monsoni et al. 2013)

Program objectives

- 23 known and several suspected EXor stars
  - Monitor all of them photometrically (EXORCISM – EXORs optiCal-Infrared Systematic Monitoring via. REM at La Silla).
  - 7 observable interferometrically at VLTI/CHARA
  - DDT proposals when they go in outburst.
- Derive global morphology via. interferometric + SED model fitting
- Investigate geometry of line emission (Br alpha, CO) regions (AMBER-MR)
- Study properties of inner gas disk via. NIR visibilities and excess emission (CHARA-CLIMB, AMBER-LR)
- Test EXor to CTTS evolutionary scenario by comparing published data, scaled to some standard distance.
- Compare outburst and quiescent states of systems with MIDI observations.