Episodic Accretion in Young Stars

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Sources of Variability

- Intrinsic luminosity changes (this talk)
- Variable extinction (flared disks, periodic obscuration)
- Binarity; e.g. KH15-D (Mundt et al., 2010, ApJ, 708, 5); FU Ori (Reipurth & Aspin, 2004, ApJ, 608, 65)

On the Episodic Outbursts of Young Stars

-Does episodic accretion play an important role in star formation?

-Archetypal sources FU Orionis and EX Lupi

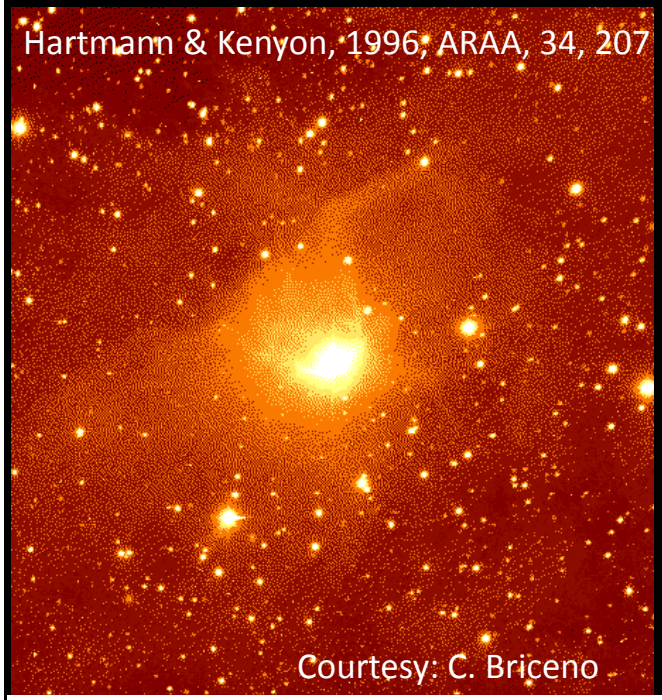
-How has our understanding of these objects changed since 1996, observationally?

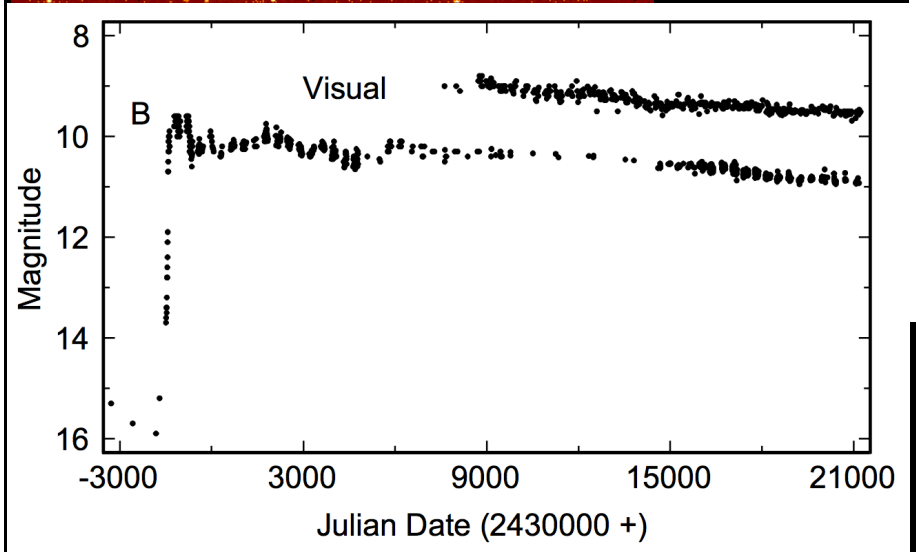
-How has our understanding changed theoretically?

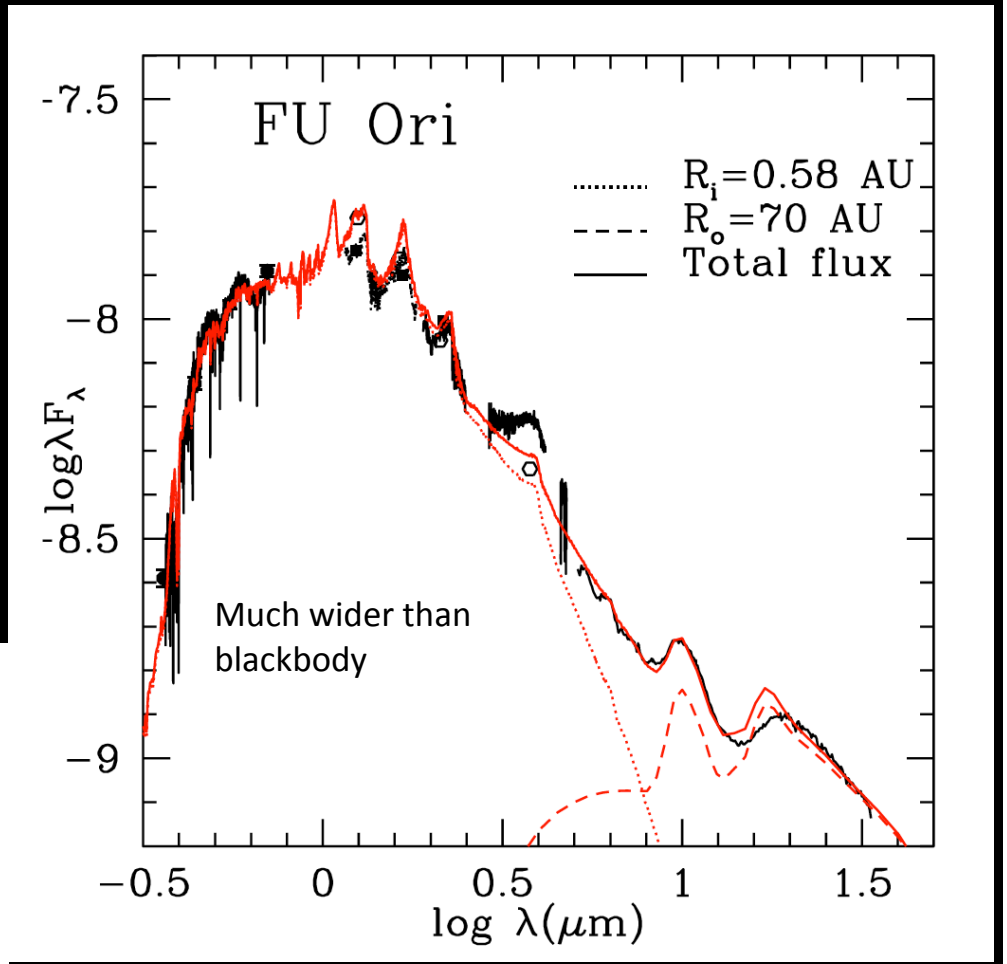
-Are FUors/EXors evidence of episodic accretion?

-Are FUors/EXors the same class of objects?

The FU Orionis Eruption: 1936





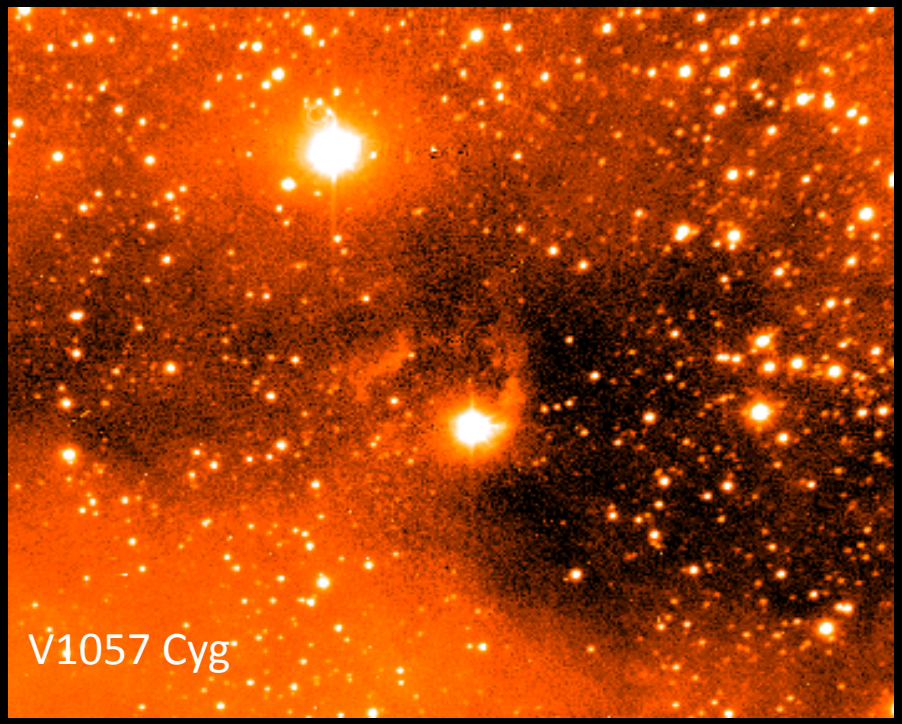


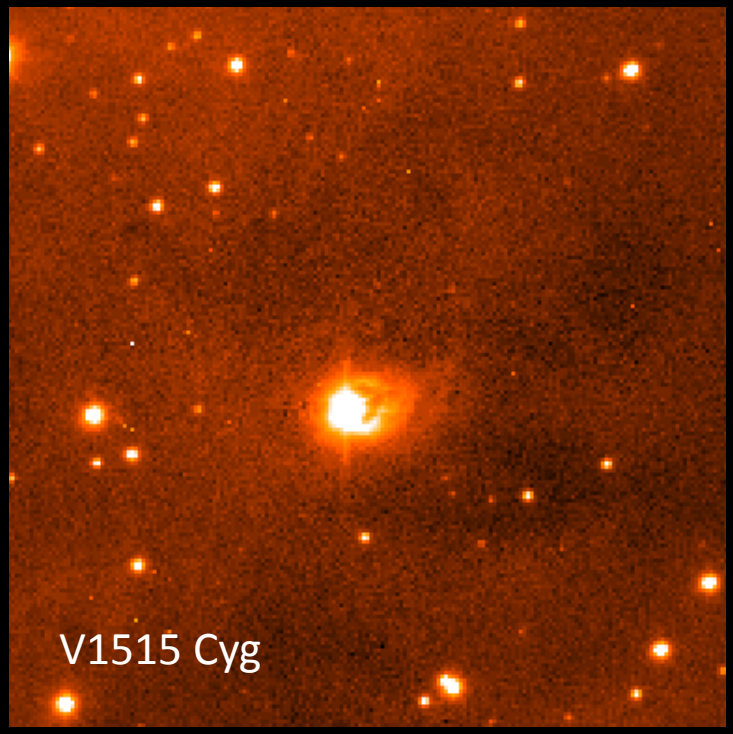
Zhu et al. 2008, ApJ 684, 1281

Kenyon et al. (2000, ApJ 531, 1028)

Additional FUors 1950-1978

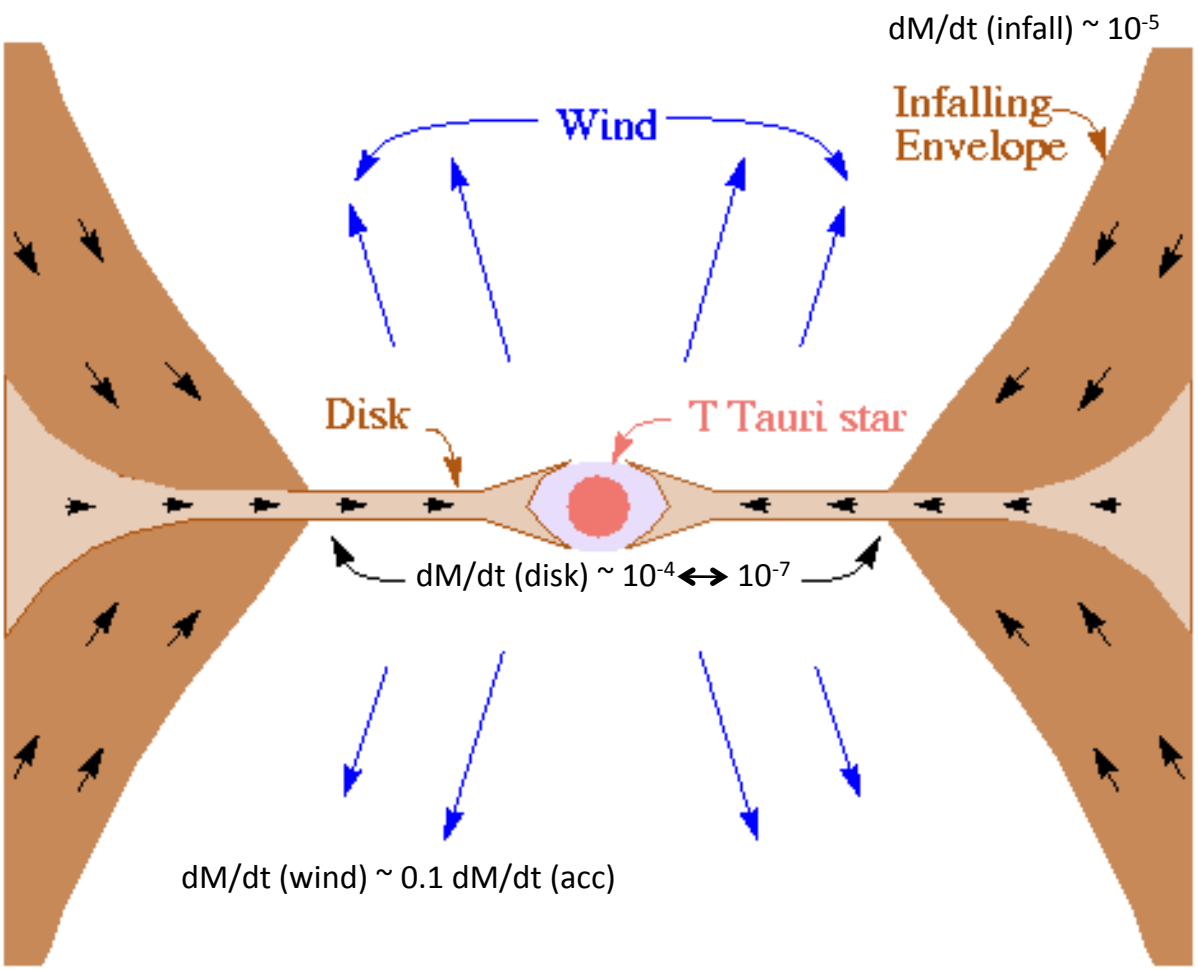
Hartmann & Kenyon, 1996, ARAA, 34, 207





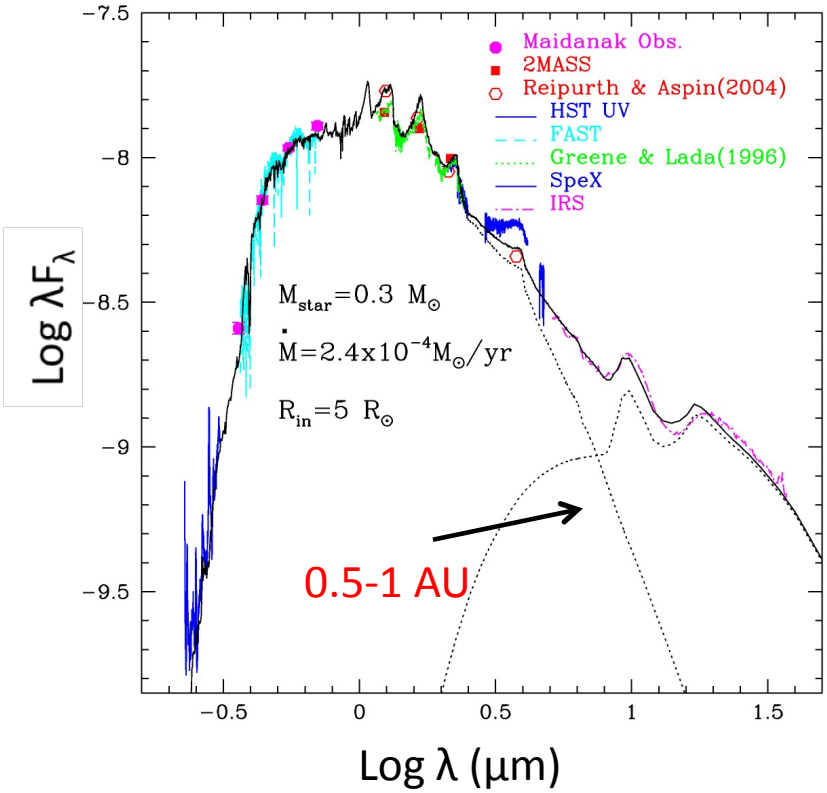
A few other stars with similar properties to FU Orionis were discovered, forming the "classical" FUor group (Herbig, 1977, ApJ, 217, 693; Elias, 1978, ApJ, 223, 859)

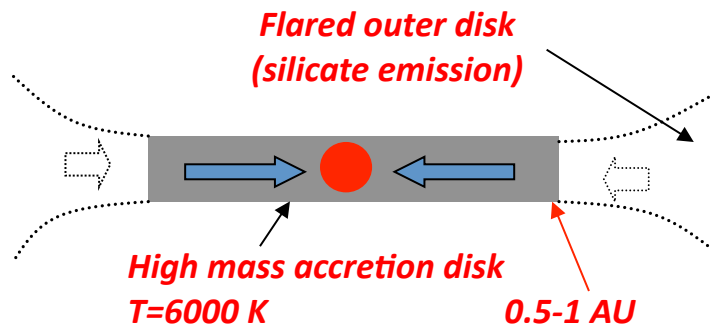
Protostar to Protoplanetary Disk: the Nature of Accretion



Modified from Hartmann & Kenyon, 1996, ARAA, 34, 207

FU Ori: Accretion Disk Radiative Transfer Modeling





Zhu et al 2007, ApJ, 669, 483
Zhu et al. 2008, ApJ, 684, 1281

- Steady accretion model + hot inner disk extending from 5 $R_\odot$ to 0.5-1 AU
- Constrained by Keck (Eisner & Hillenbrand, 2011, ApJ, 738, 9) and MOST (Siwak et al. 2013, MNRAS, 432, 194)
- Decay timescale: $t_{visc} \sim R^2/\nu \Rightarrow \alpha \sim 0.01\text{-}0.1$

How significant are the bursts?

(Updated from Hartmann & Kenyon, 1996, ARAA, 34, 207)

FUors are **rarely** seen…
but they are common events!

Within 1 kpc of the Sun:

10^4 – 10^5 T Tauri stars x avg. accretion rate 10^{-8} $M_\odot$ yr^{-1} = 10^{-3} $M_\odot$ yr^{-1}
8 FUors, combined accretion rate ~ few x 10^{-4} $M_\odot$ yr^{-1}

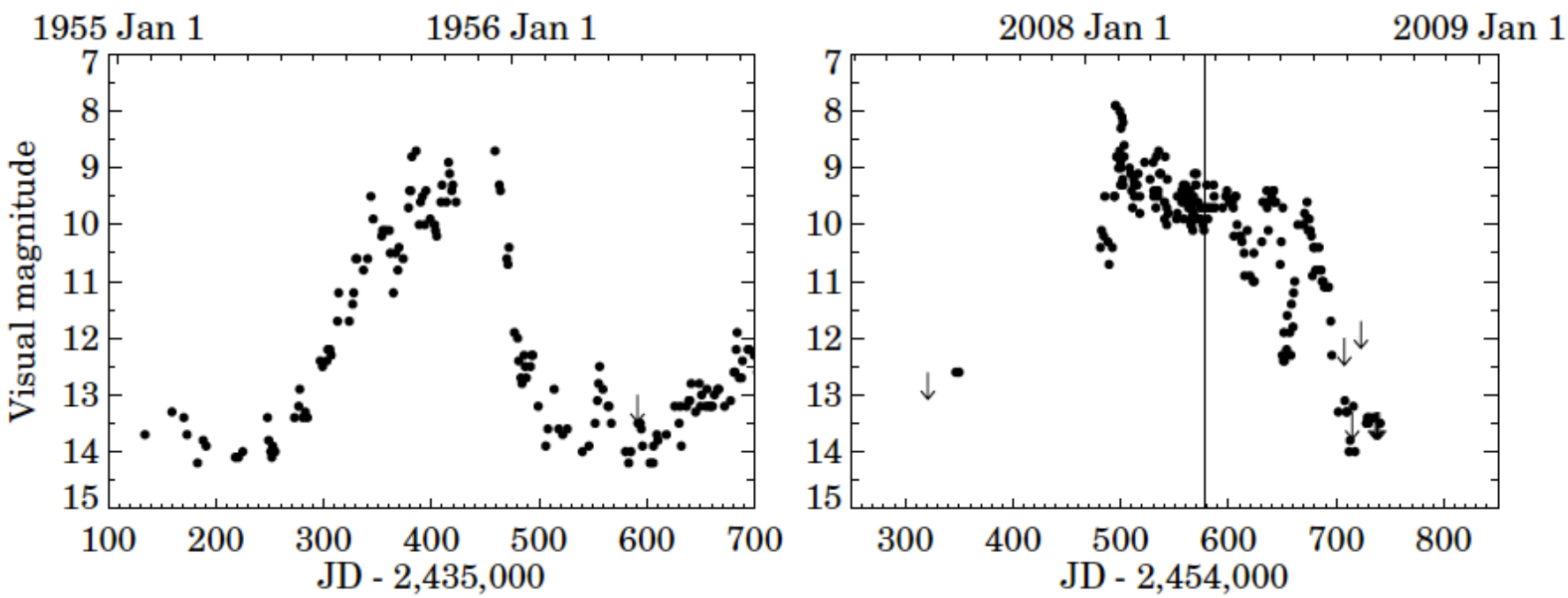
-FUors are responsible for ~ 10% of the current nearby accretion

About 8 FUors since 1936; average star formation rate 1 / 50 yr
(FUor list updated from Reipurth & Aspin 2010, Evolution of Cosmic Objects through their Physical Activity, 19; star formation rate from Miller & Scalo 1979, ApJS, 41, 513; see also Offner & McKee 2011, ApJ, 736, 53)

-FUors occur at several times the rate of star formation; averaging multiple bursts per star

EX Lup: Multiple Bursts

1955: EX Lupi was seen to outburst to a somewhat lesser degree, and much shorter timescale, and was referred to as an "EXor" (Herbig, 1989, ESO Workshop, 233)

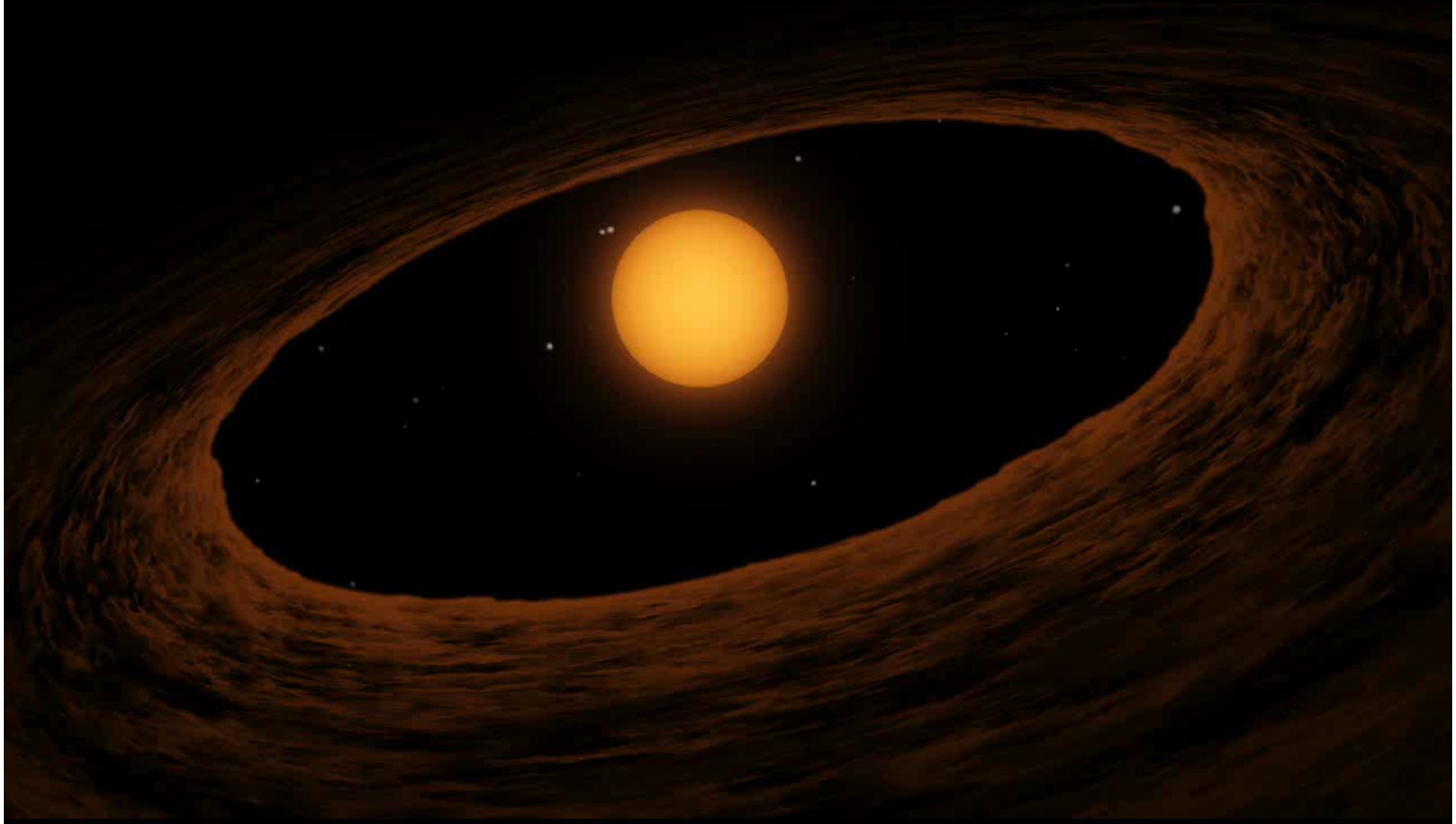


And again in 2008: Ábrahám et al., 2009, Nature, 459, 224

Why study these sources?

- Represent stages wherein most of the YSO mass *may* be accumulated
- Accretion mechanism may differ from the classical magnetospheric TTS accretion model: "new" accretion physics
- Diagnostic for outburst triggering mechanisms, an important problem
- Offer "unveiled" examples of YSOs with accretion rates comparable to embedded sources

EXors and FUors are a Natural Laboratory for Accretion Physics



Ábrahám et al., 2009, Nature, 459, 224

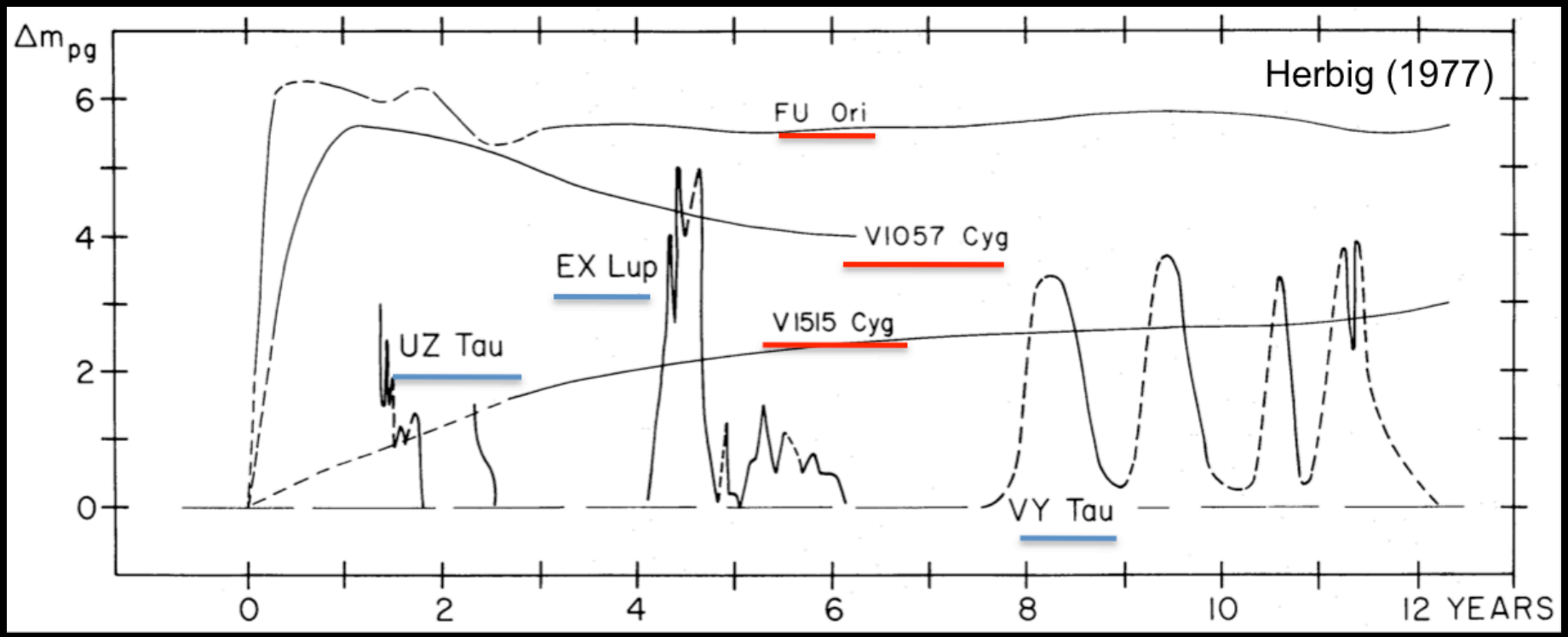
Courtesy: R. Hurt, SSC

FUors vs. EXors, observationally

- Commonalities:
  - low mass pre-main sequence stars
  - Show strong optical outbursts
  - IR excess indicating circumstellar disk material (gas and dust)
  - Variability is primarily* accretion-driven

*Both types generally exhibit small scale variability due to rotational and inclination effects; e.g. Kenyon et al., 2000, ApJ, 531, 1028; Clarke et al, 2005, MNRAS, *361, 942;* Bastien et al., 2011, AJ, 142, 141; Green et al., 2013, ApJ, 764, 22

EXor Timescales Allow Characterization of the Complete Burst

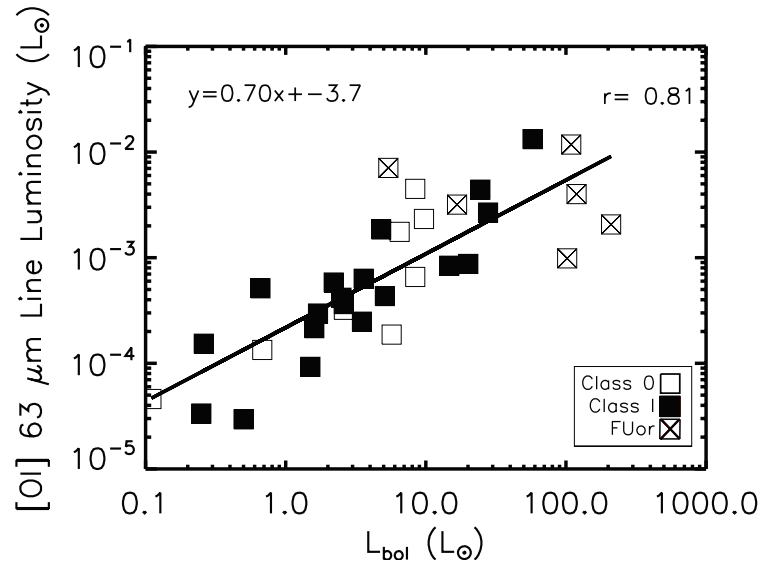


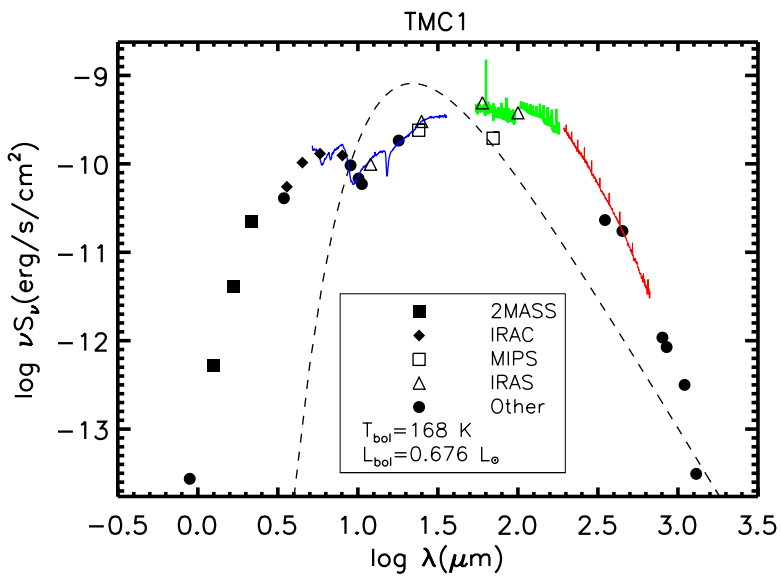
Herbig G. H., 1977, AJ., 217, 693

FUors vs. Protostars

Previously noted similarities at submillimeter wavelengths (e.g. Sandell & Weintraub, 2001, ApJS, 134, 155);
--And from ISO: Lorenzetti et al., 2000, A&A, 357, 1035

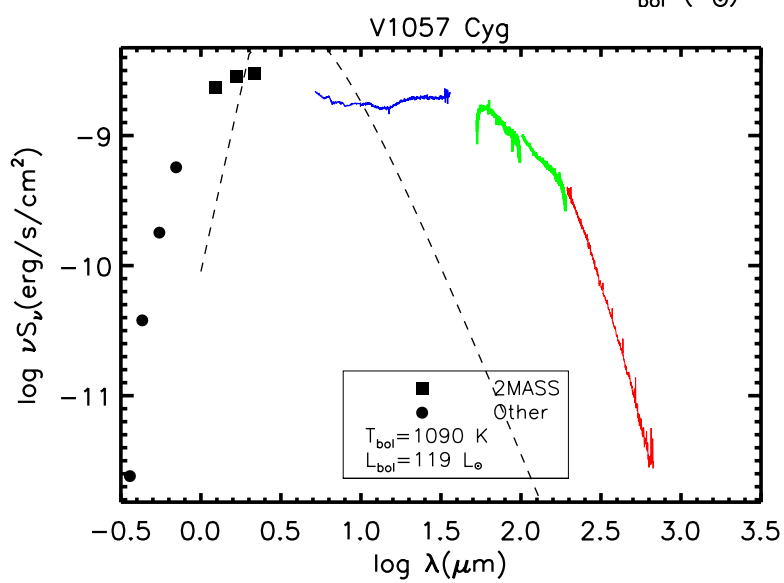
Consistent with the Spitzer/Herschel perspective





Class I Protostar

Green et al., in prep.

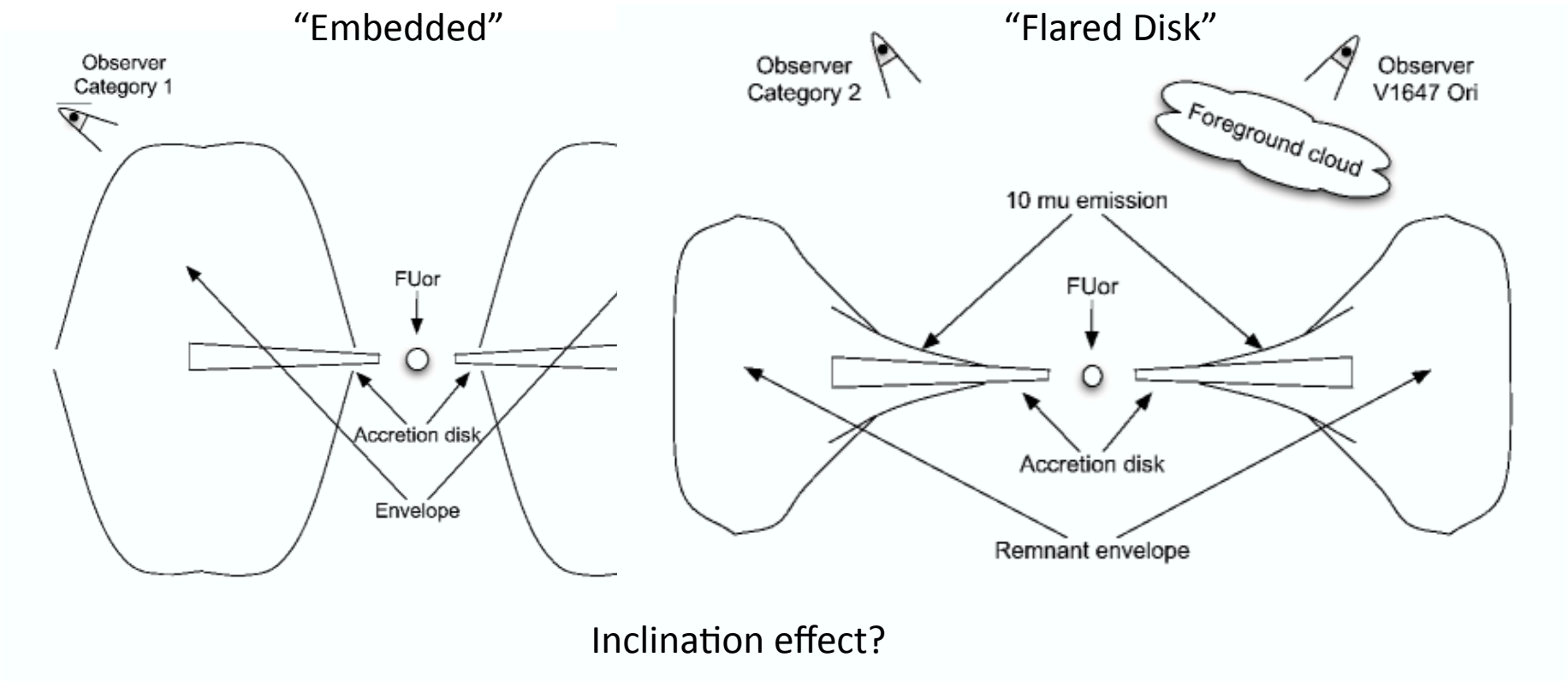


Classical FUor

Green et al., 2013, ApJ, 772, 117

Characteristic Properties, Classically	FUor (all remain in outburst)	EXor (during outburst)
Optical burst strength	4-6 mag; 20-500 $L_\odot$	3-5 mag; 0.5-20 $L_\odot$
Optical line profiles	Fe I, Li I, and Ca I double-peaked/broadened profiles	Infall and outflow signatures in Na I $D_{1,2}$ – like CTTS (P Cygni profiles)
Repeated burst?	Not in human timescale	Yes ~ 1/few yrs
IR line profiles	first-overtone CO absorption at 2.2 µm; double-peaked profiles	CO bandhead emission and absorption, variable
Inferred accretion rates	> 10^{-6} –10^{-4} $M_\odot$ yr^{-1}	10^{-7} –10^{-5} $M_\odot$ yr^{-1}
Extended reflection nebula?	Yes	Sometimes
Spectral type	F-M, wavelength dependent	K-M
Pre-Main Sequence Stage; envelope?	I/II	II ?
Crystalline silicates	No	During outburst
Burst rise time	0.3-10 yr	~ 0.1-0.3 yr
Burst decay time (e-folding)	> 20-100 yr	0.5-2 yr

FUor Subgroups

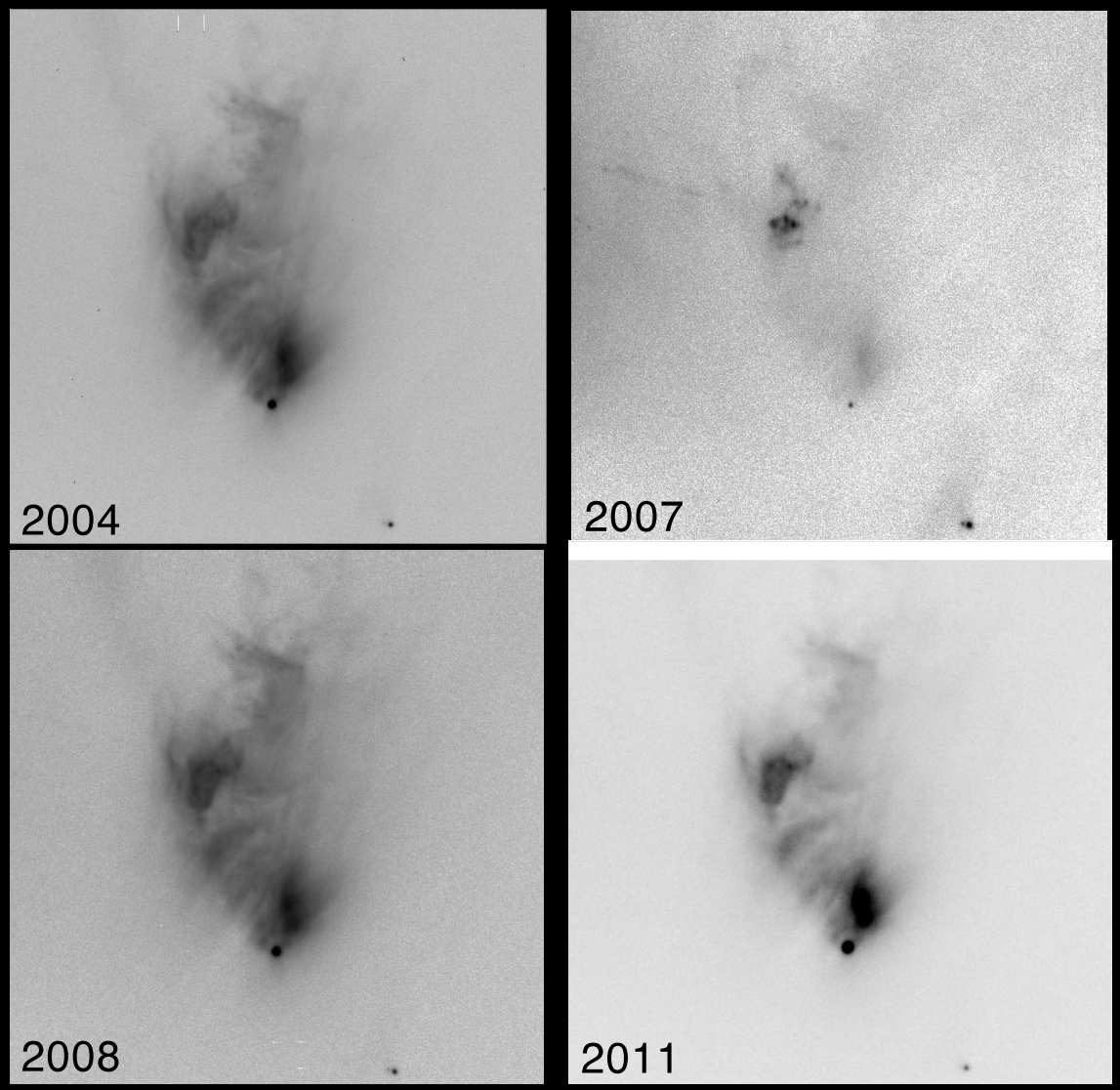


Inclination effect?

Figure from Quanz et al., 2007, ApJ, 668, 359;
see also Green et al., 2006, ApJ, 648, 1099

New Outbursts

The Case of V1647 Ori



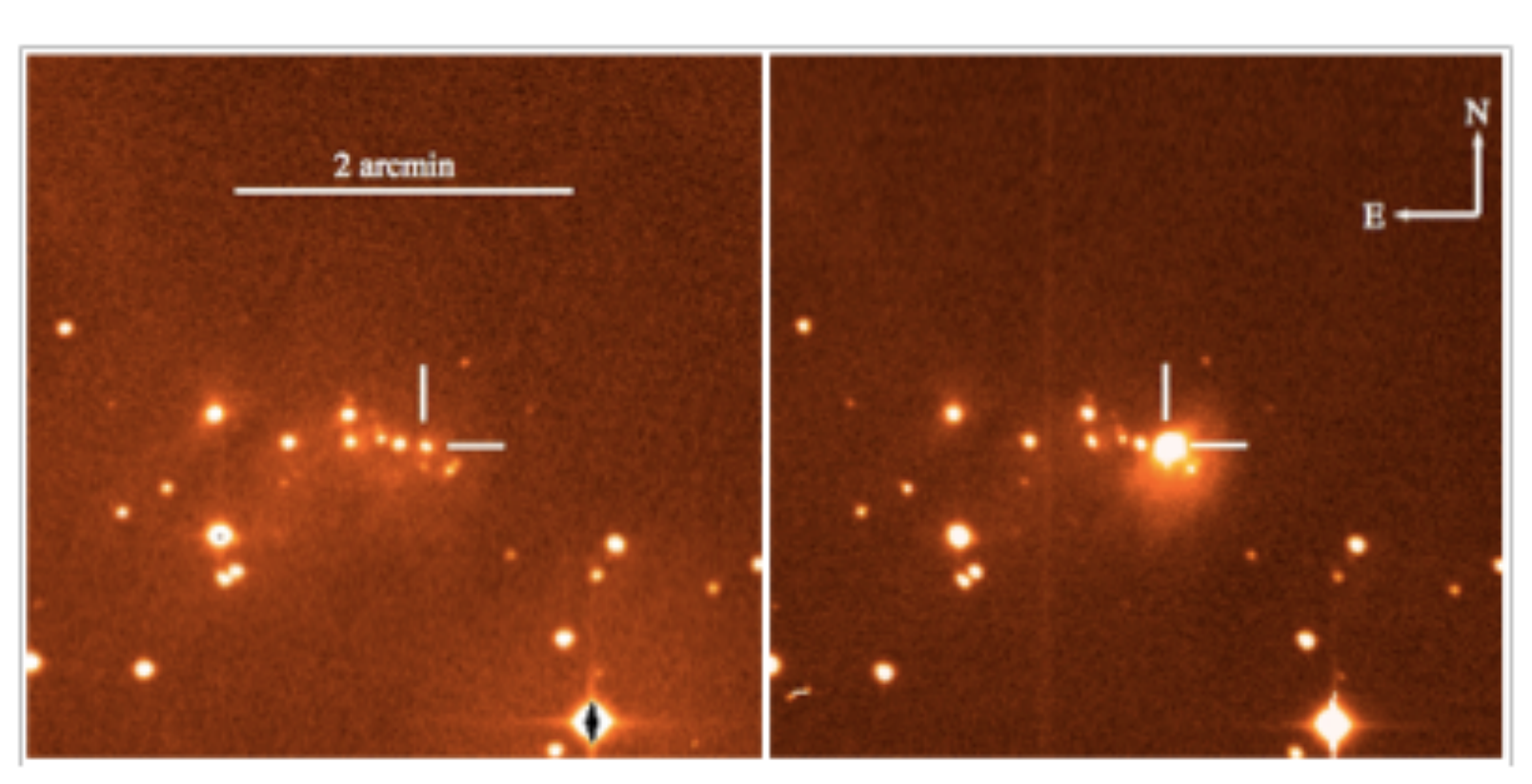
One year after return to quiescence

Aspin, C., 2011b, AJ, 142, 135

V1647 Ori/ McNeil's Nebula

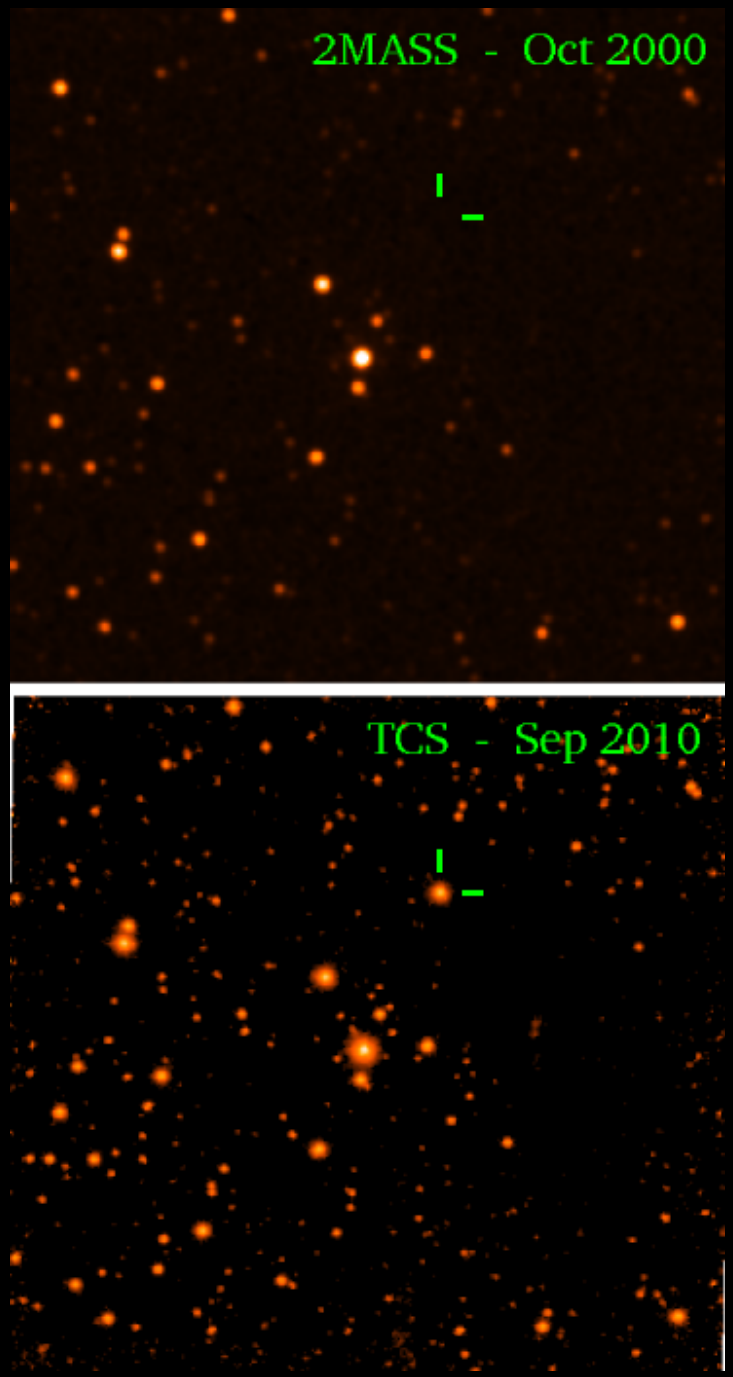
Meanwhile, in Cygnus…

August 17, 2010: Semkov & Peneva (2010), ATel , 2801, announces outburst
September 24: HBC 722/V2493 Cyg reaches maximum light and begins decaying



Region in between the North America & Pelican Nebulae, distance 520 pc

Semkov et al., 2012, A&A, 542, 43

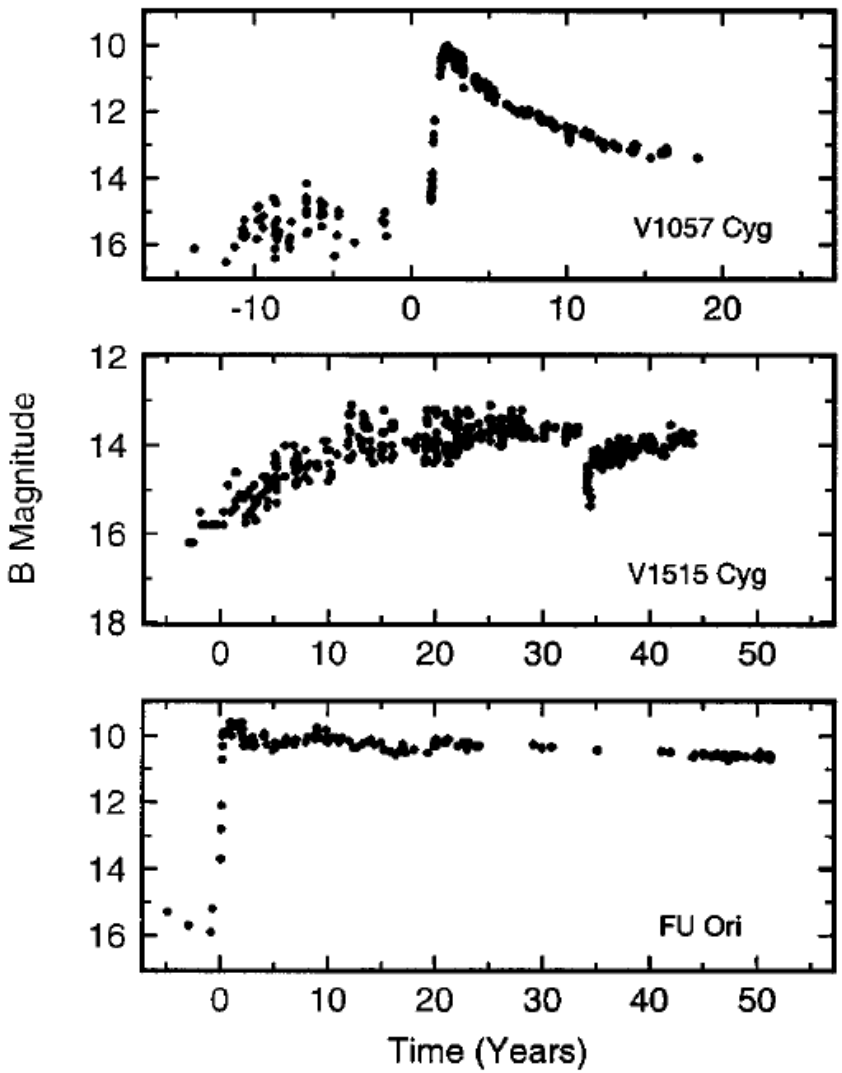


Nearly Simultaneously, an EXor with a slow rise time but fast decay time

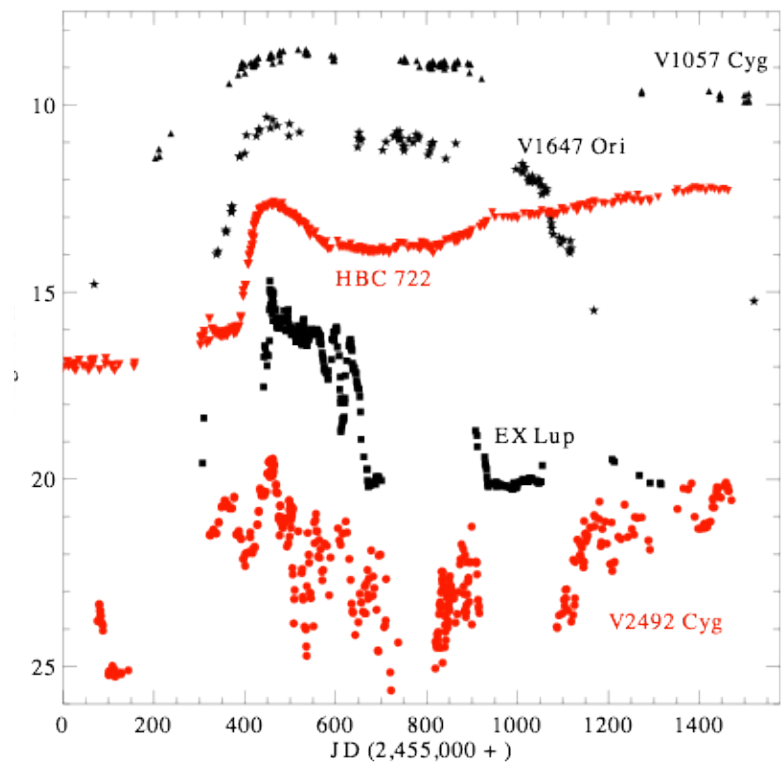
V2492 Cyg

Kóspál et al., 2011, A&A 527, 133

The Distinction via Lightcurve is Becoming Less Straightforward



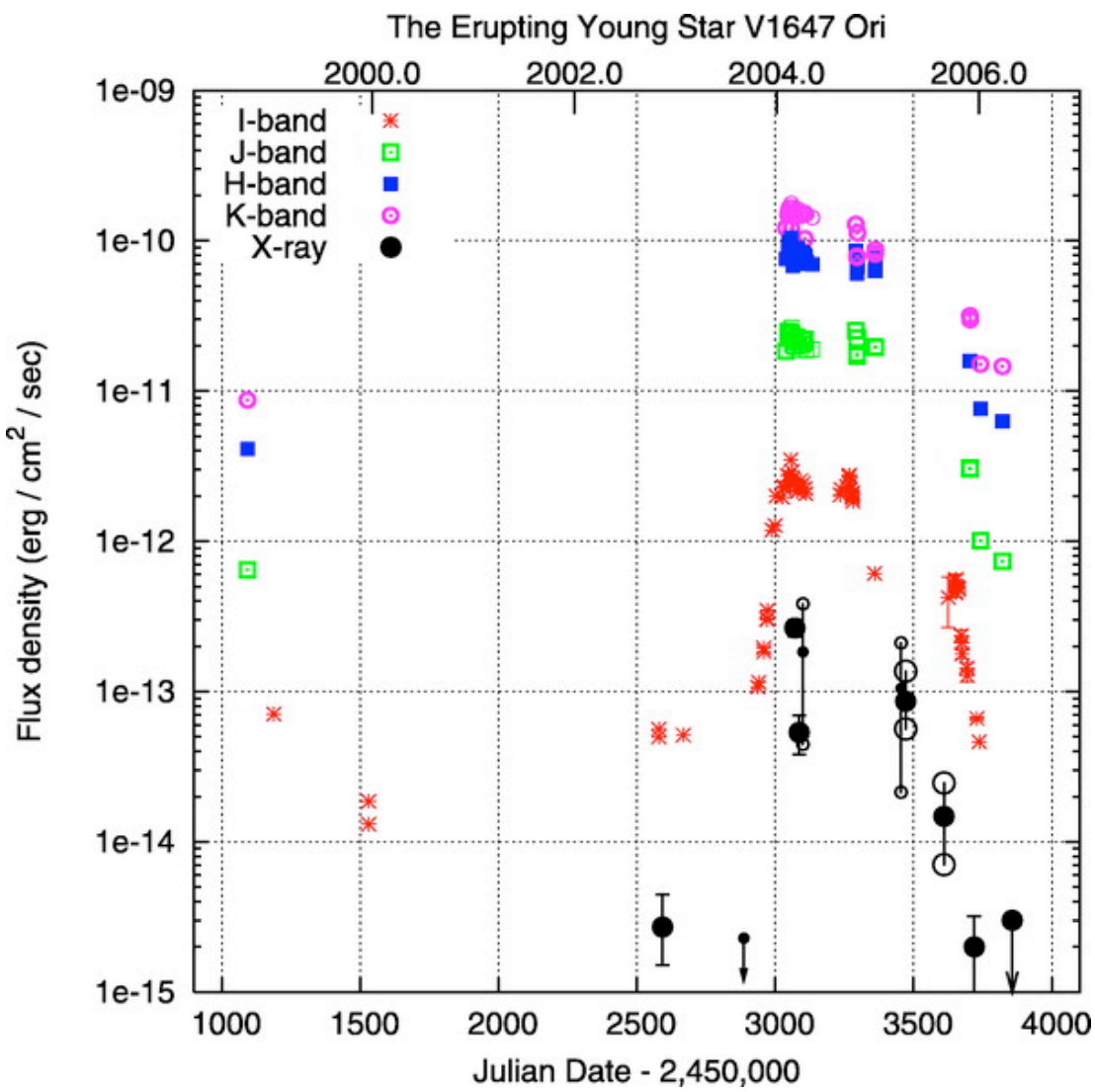
Hartmann & Kenyon, 1996 , ARAA, 34, 207



Based on data from Kóspál et al., 2011, A&A, 527, 133 and from AAVSO

Difficult to classify outburst type from early behavior!

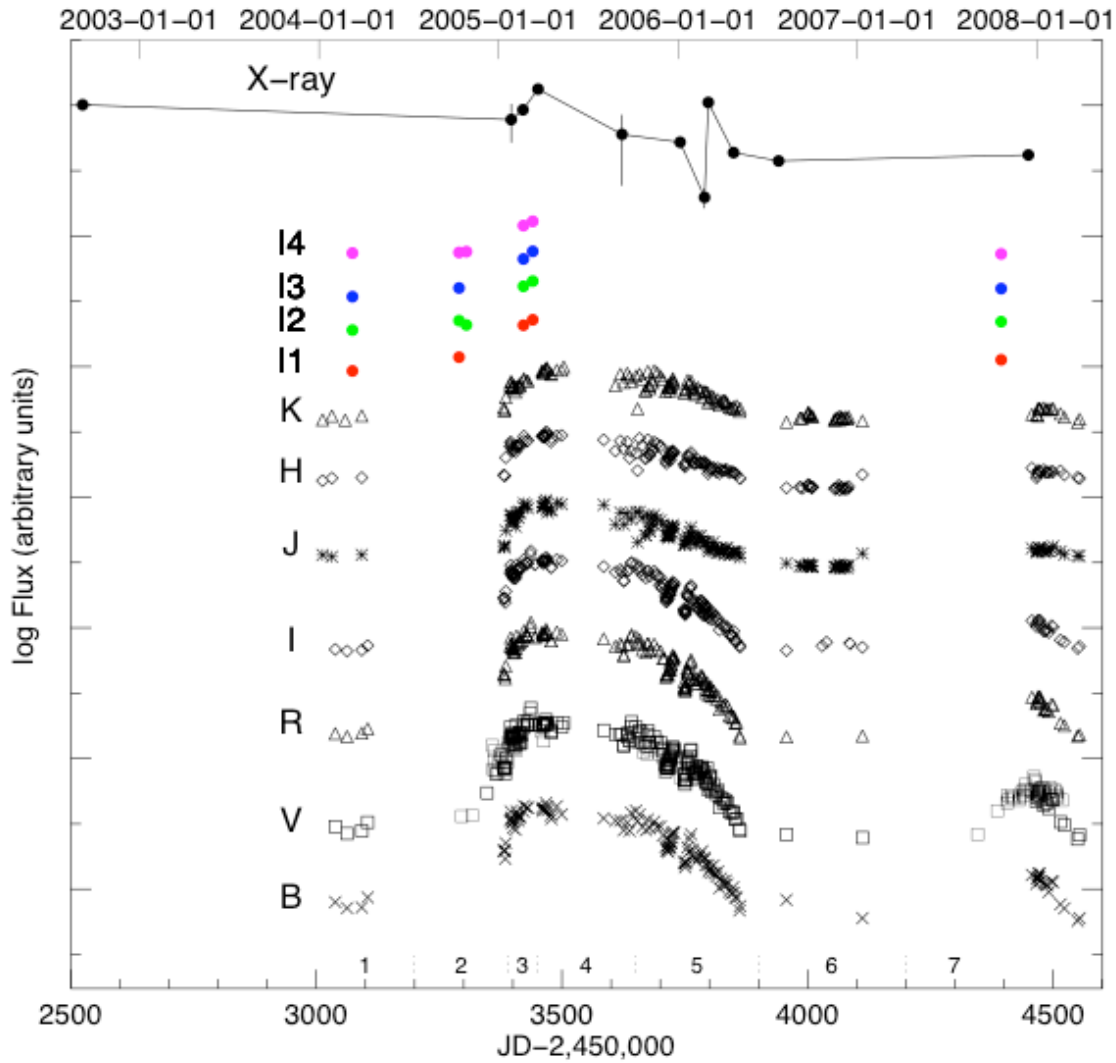
Can X-rays Distinguish Between EXors and FUors? Do X-rays follow accretion processes?



Kastner et al 2006, ApJ 648, L43

For V1647 Ori, yes

…. But not for V1118 Ori



Weak correlation between X-ray and IR (also for EX Lup)

Audard M. et al. (2005) AJ, 635, L81
Audard M. et al. (2010) A&A, 511, A63

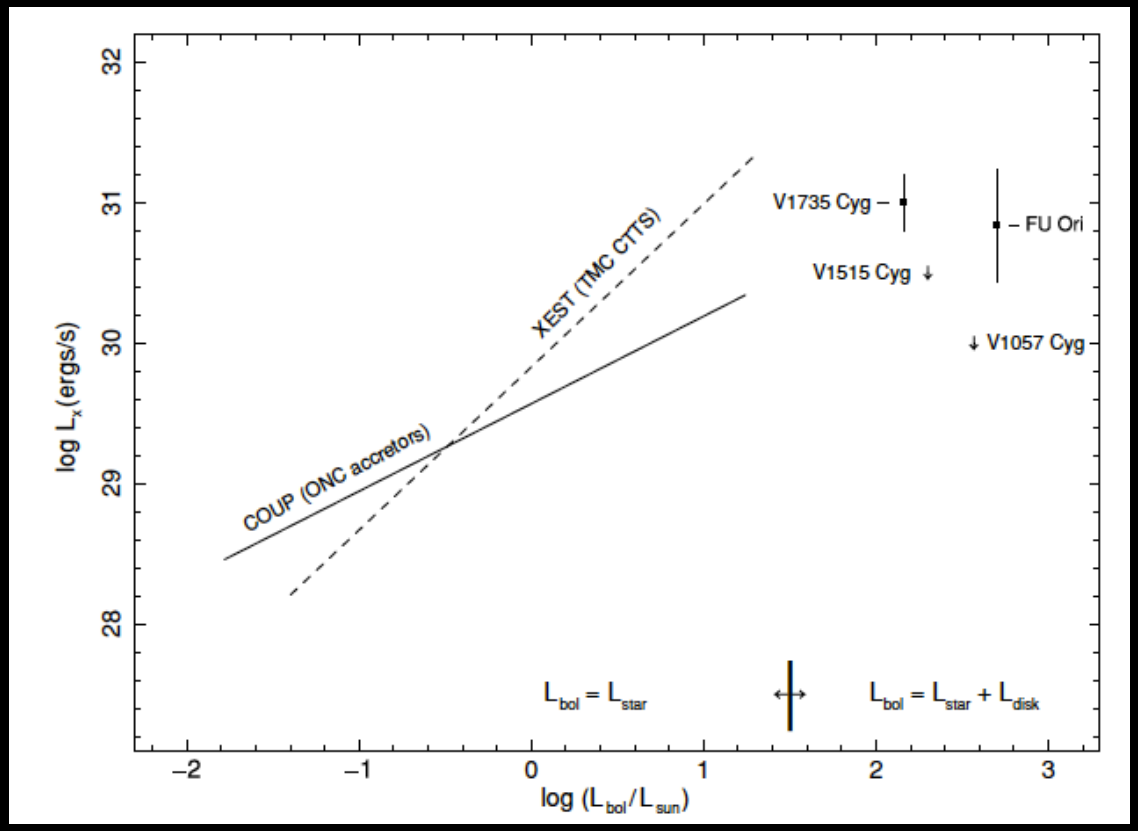
At least *some* (soft) X-rays in EXors arise in accretion shocks
Grosso et al. 2010, A&A 522, A56

X-Rays from FUors

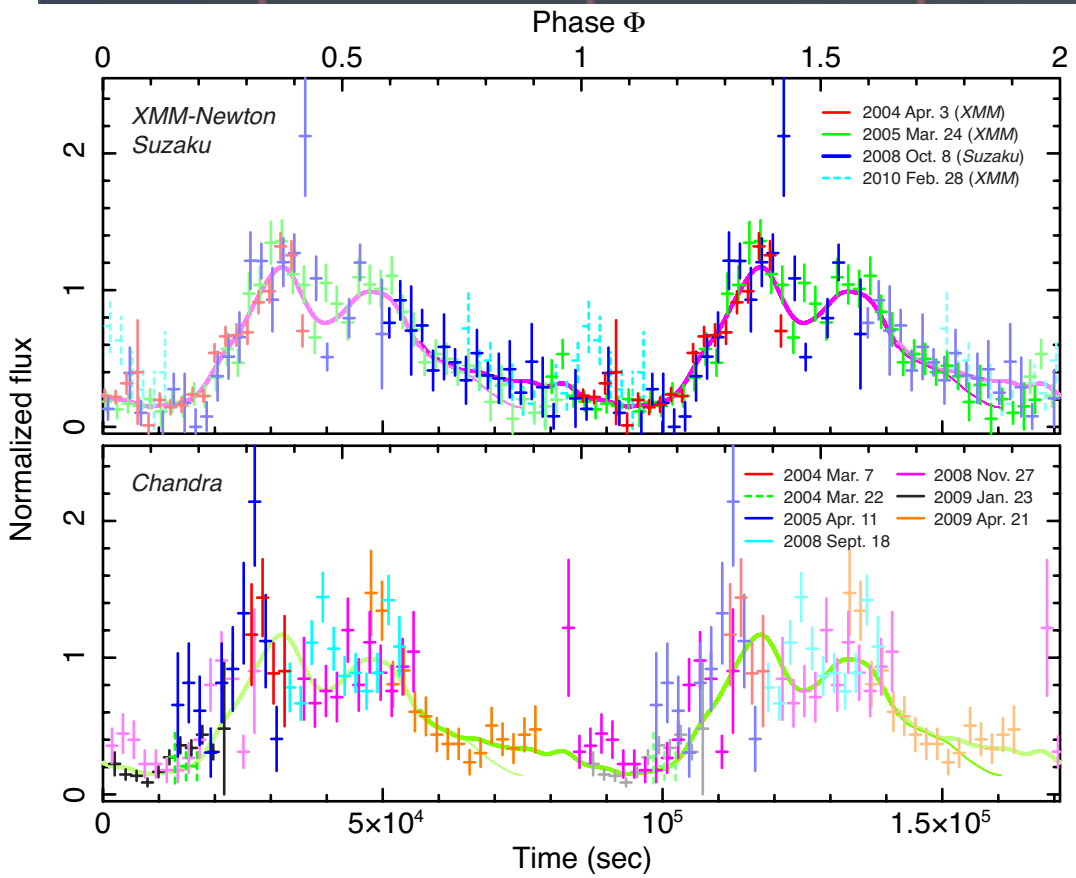
- FUors are X-ray bright, compared to X-ray active T Tauri stars, but not relative to the total system output
- Multiple (hard and soft) X-ray components sometimes seen but can be attributed to binaries?

Hard X-rays = magnetically-driven
Soft X-rays = accretion processes

e.g. Grosso et al. 2010, A&A 522, A56



Skinner et al., AJ, 2006, 643, 995; Skinner et al. 2009, ApJ, 696, 766



Hamaguchi et al. 2012, ApJ, 754, 32

- 1-day periodicity stable over five yr
- (caveat: flux amplitude is relative)
- Star/disk magnetospheric geometry is highly stable

Detailed model of the disc–star interaction and the formation of a conical wind. The wind/outflow base originates very close to the stellar photosphere.

-Infalling matter compresses the magnetosphere of the star
-Field lines enhanced via differential rotation between disk and star
-Conical winds & outflows twist from the inner disk

Romanova et al., 2009, MNRAS, 399, 1802
Kurosawa and Romanova, 2012, MNRAS, 426, 2901

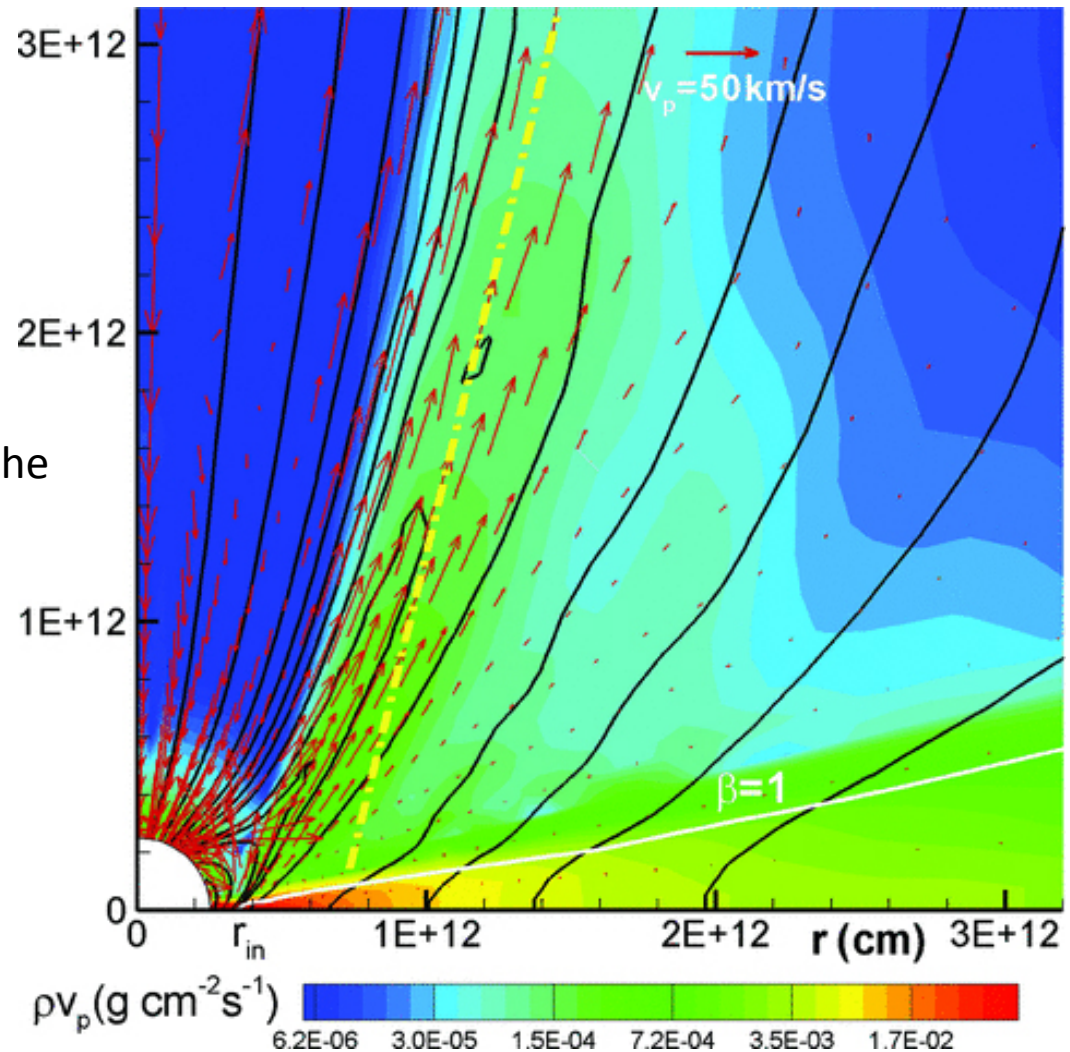
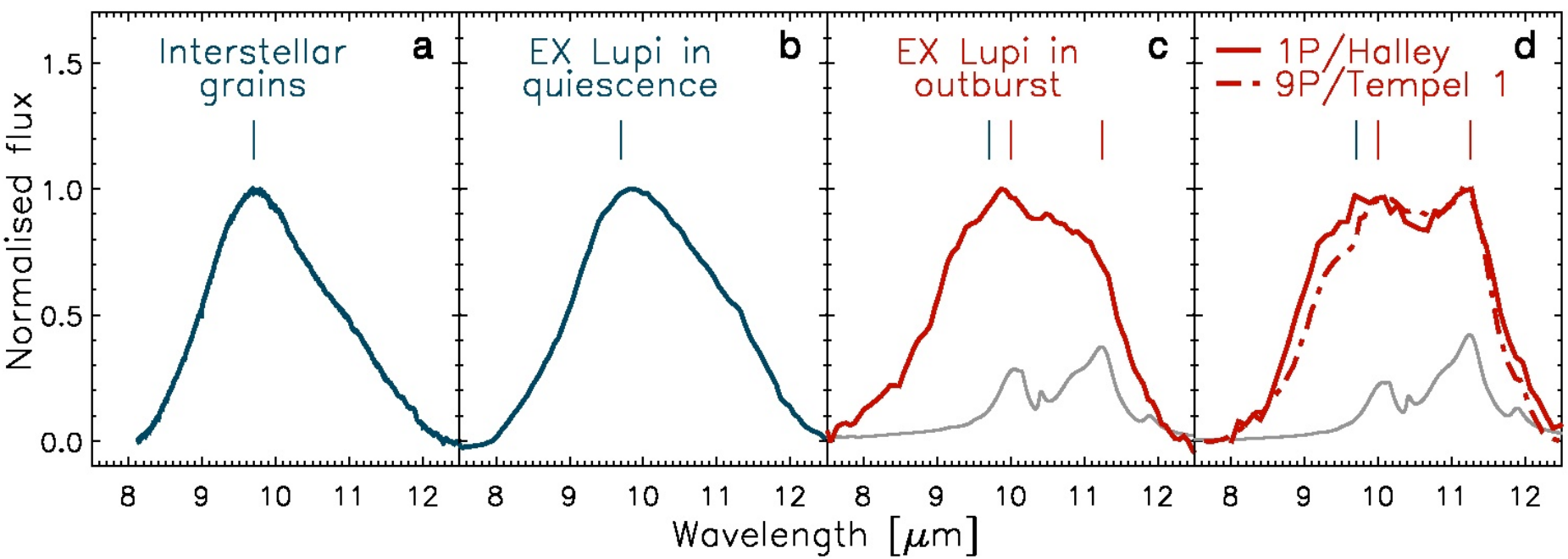


Figure from Königl A et al. MNRAS 2011;416:757-766

The Mid-IR: Long-Term Outburst Effects

Does dust processing from flash heating (or vertical transport and stirring of dust grains) occur on few month timescales?

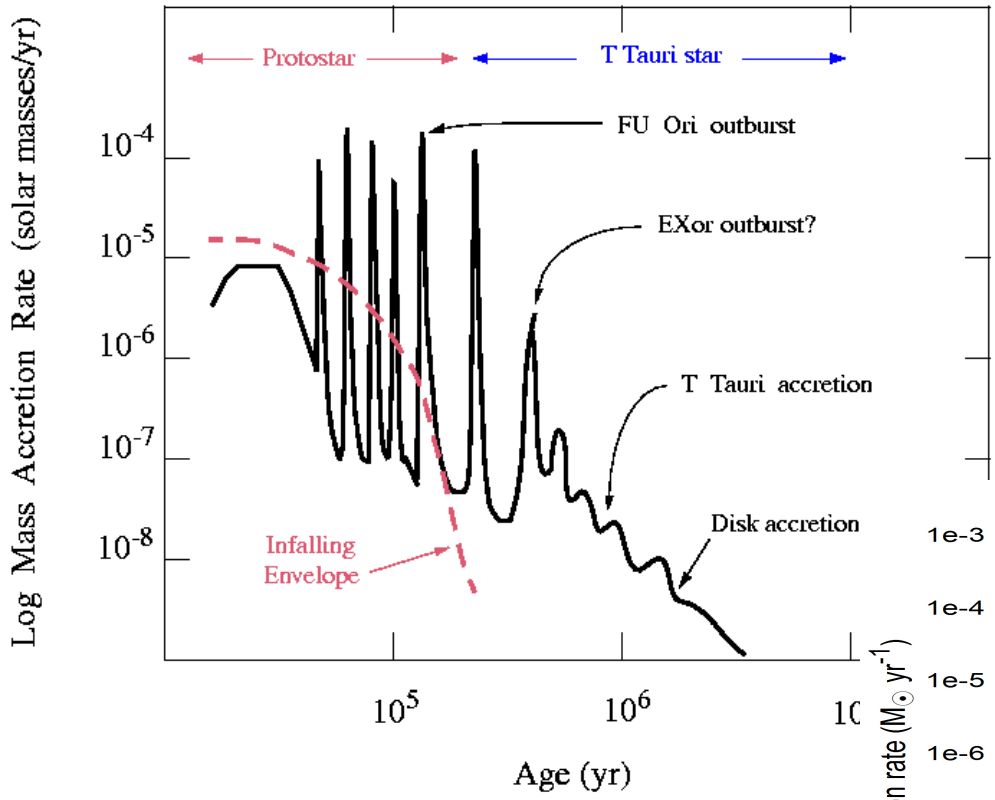
Ábraham et al., 2009, Nature, 459, 224



What sets the conditions in the protoplanetary disk?

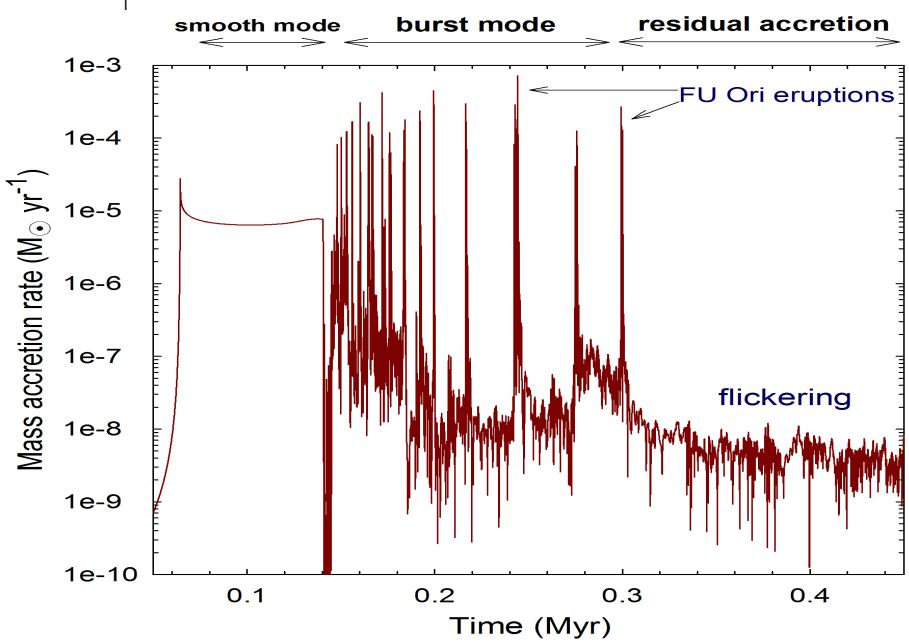
- In the usual paradigm, the Class I protostar lifetime is ~ 0.5 Myr, during which the envelope thins and eventually vanishes
- The accretion rate from disk to star diminishes and planets form, perhaps early on by gravitational instability, and then later by core accretion, and other processes
- But does accretion decrease steadily from 10^{-5} in Class I to 10^{-8} in T Tauri stars, to 10^{-10} or less in Class III sources?

Empirical Prediction → New Accretion Paradigm

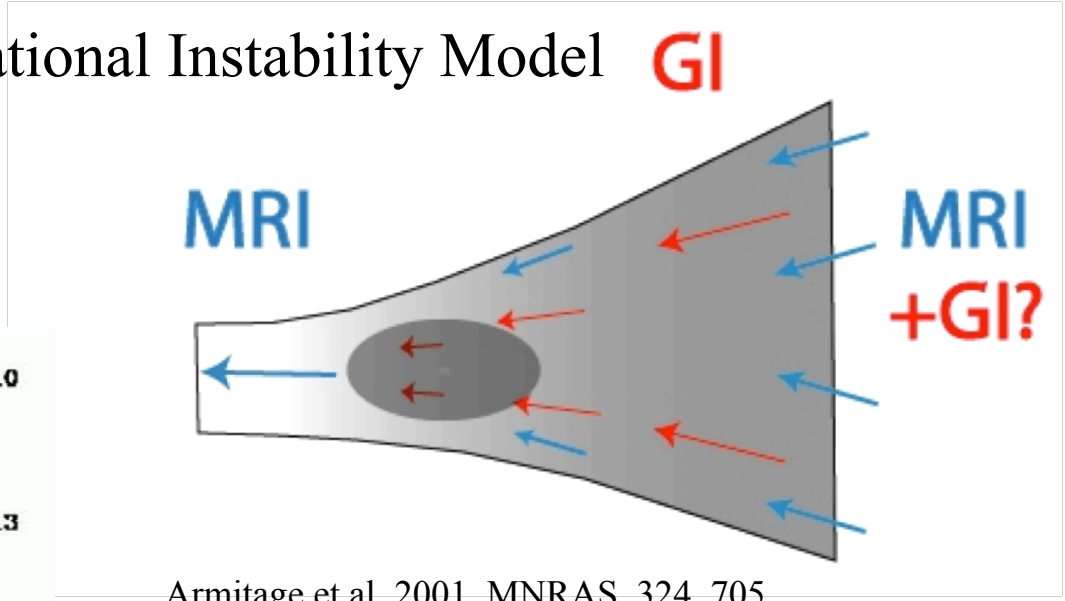


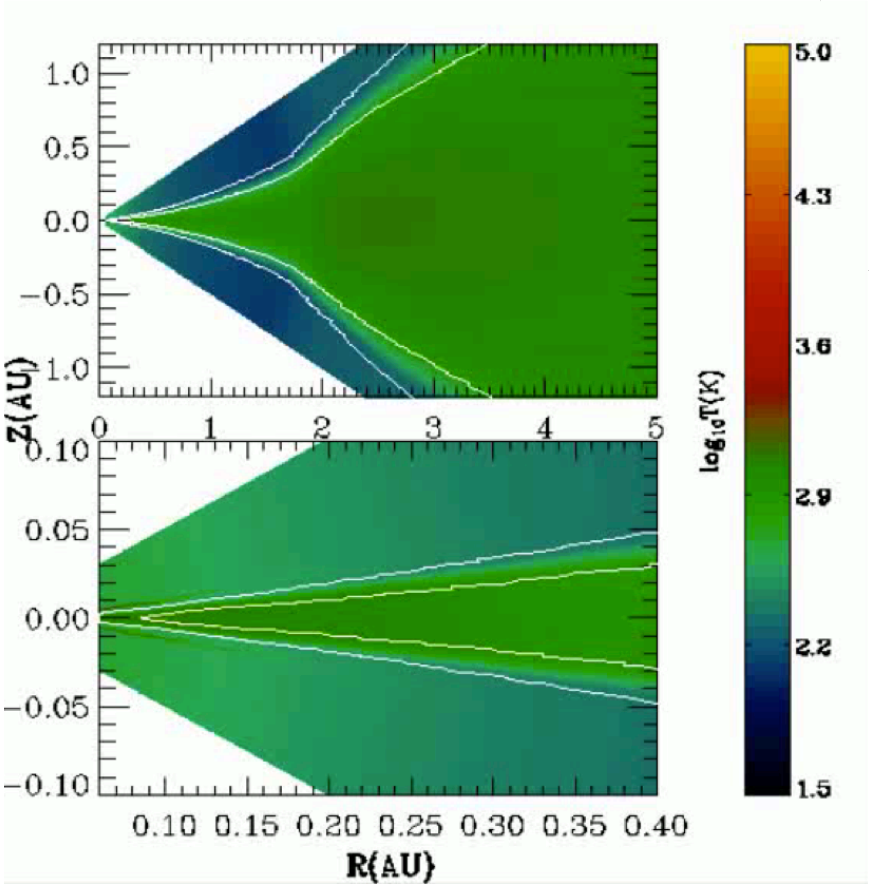
Hartmann 1998, Camb. Astrophys. Ser., Vol. 32

From disk fragmentation model of Vorobyov & Basu 2010, ApJ, 719, 1896



Magnetorotational + Gravitational Instability Model (MRI+GI)





Armitage et al. 2001, MNRAS, 324, 705
Zhu et al. 2009, ApJ, 694, 1045
Zhu et al. 2010, ApJ, 714, 1143
Martin & Lubow 2011, AJ, 740, 6
Martin et al. 2012, MNRAS, 423, 2718
Bae et al. 2013, ApJ, 764, 141

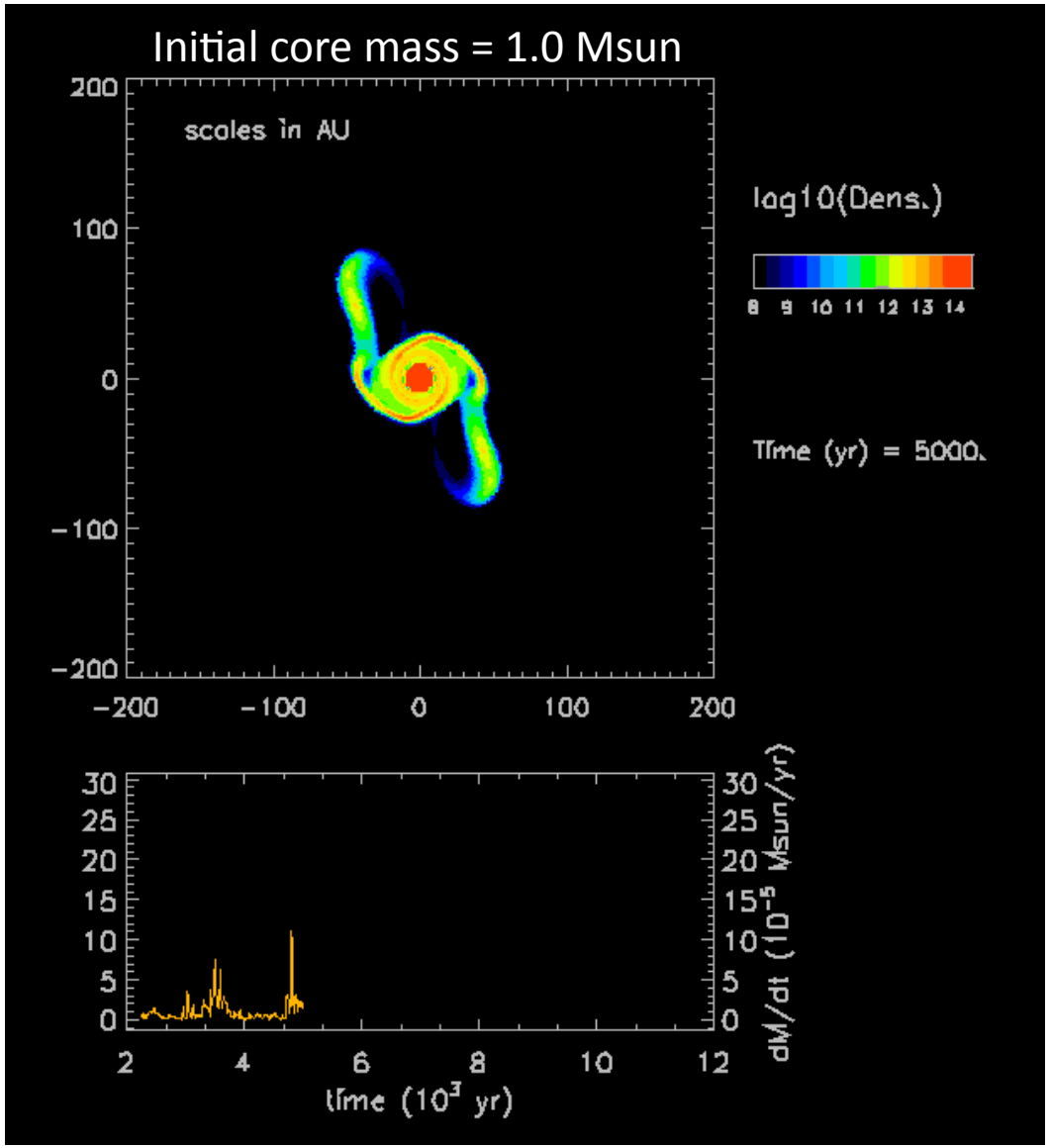
GI: Outer Disk: Q~1
MRI: Inner Disk (hot/ionized)

Transition region: (1-10 AU) GI-MRI junction not smooth => episodic accretion

Predicts correct outburst strength and timescale
But the details of MRI triggering are uncertain

Accretion bursts due to disk fragmentation in the embedded phase

If Toomre parameter $Q \leq 1.0$ and disk cooling is fast ($\Omega * t_c <$ a few), disk fragmentation can occur (e.g. Gammie 2001, ApJ, 553, 174)



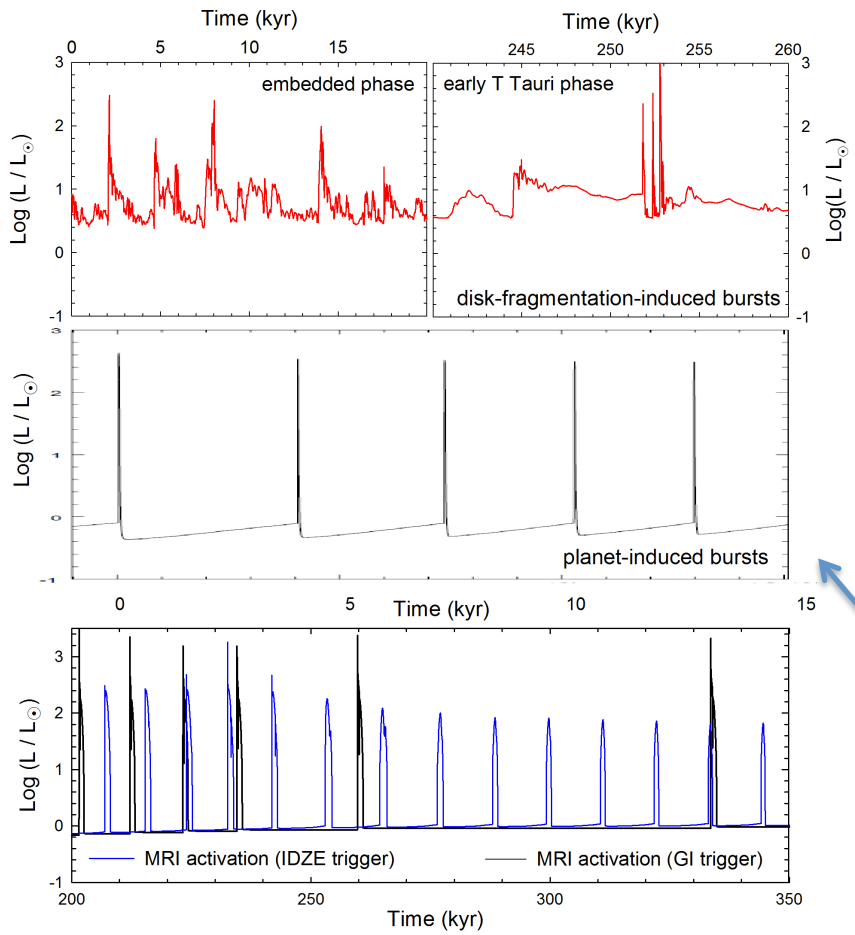
Face-on view on the inner 400x400 AU, The total computational box is 10 times larger.

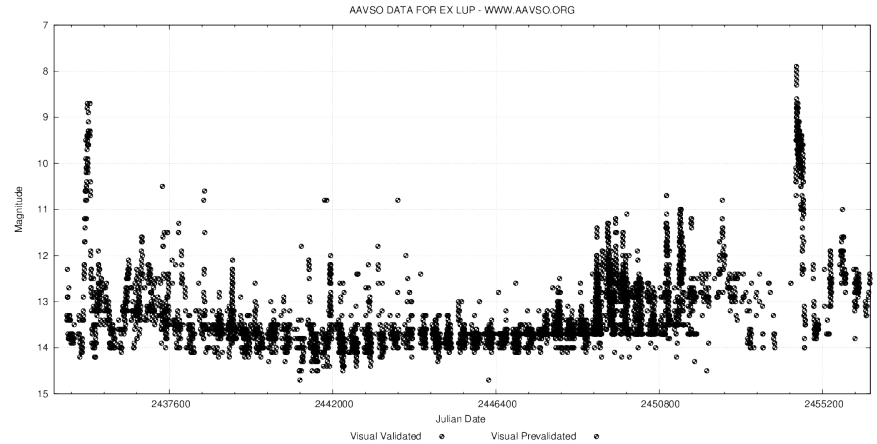
Black regions are not empty but filled with infalling envelope (off the scale)

protostellar accretion rate 10^{-5} $M_\odot$ / year

Vorobyov & Basu 2006, ApJ, 650, 956
Vorobyov & Basu 2010, ApJ, 719, 1896
(see also Machida + 2011, ApJ, 729, 42)

Modeled Outburst Frequency via Disk Instability





EX Lup (AAVSO; 1955-2010)

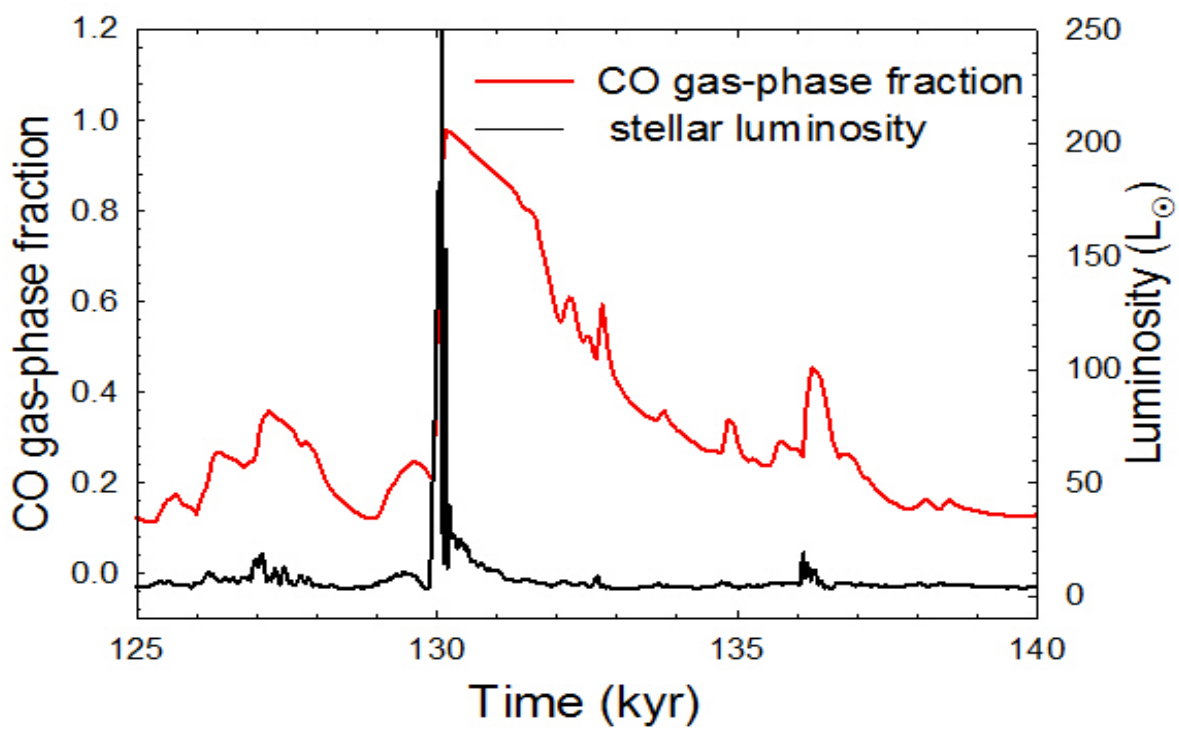
Or binary companion?

Lodato & Clarke, 2004, MNRAS, 353, 841

Vorobyov & Basu 2010, ApJ, 719, 1896

Outbursts affect chemistry

CO-gas phase fraction in the envelope steeply rises during the burst and gradually declines after the burst. The relaxation time to the pre-burst stage is notably longer than the burst duration



Vorobyov et al. 2013, A&A, in press; Kim et al. 2012, ApJ, 758, 38

Looking forward: what are the contributions of the FUor/EXor observational group to our understanding of young stars?

Looking forward (1)

- Are FUors and EXors regularly occurring events, or are they special cases of young stars?
  - Evidence for episodic accretion comes from both observation and theory
    - Observed burst frequencies, accretion rates, lifetime estimates from decay times all match the idea that 5-10% of total YSO accretion occurs in FUor bursts
    - Preponderance of low luminosity sources "balances" the distribution (Dunham et al. 2010, ApJ, 710, 470)
    - Offer a partial solution to the transport of newly crystallized small dust grains in disks
    - Theory of duty cycles from episodic accretion models agrees with observed timescales
    - Chemical evolution models (increased CO gas abundance, CO_2 ice processing in currently low luminosity stars)
    - Outflow morphology (bullets, multiple epochs)

Looking forward (2)

- Are FUors and EXors different classes?
  - Clear distinction has blurred through intermediate cases like V1647 Ori, V2492 Cyg, and HBC 722
  - Primary remaining distinction is the timescale

The Future of Episodic Accretion Studies

- ALMA continuum/line imaging -> envelope vs. disk masses -> evolution stage
- Comprehensive large-field monitoring facilities (PTF, LSST) to detect new eruptive stars early in outburst
- WISE will help detect new sources, more deeply embedded eruptive stars

The Next Step

- Move away from FUor vs. EXor classification
- Modeling to better understand accretion burst mechanisms
- Identify key parameters controlling bursts
- **These objects are no longer oddities, but fundamental to the analysis of the evolution of young stars!**