EXors

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EXors: what are they?

Herbig 1989:

- Stars that mimic FUors in that they show sudden flare-ups from minimum light at irregular intervals
- At maximum light: T Tauri-like emission spectrum, stellar photosphere is masked/undetectable
- Less luminous than FUors
- Outbursts are short-lived, repetitive
- PV Cep, EX Lup (giving name to the whole group), NY Ori, V1118 Ori, V1143 Ori, UZ Tau E, VY Tau, DR Tau

PPVI list (Audard et al. 2014)

Name	Distance (pc)	A_V (mag)	L_{bol} ($M_\odot$)	$\dot{M}_{acc}$ ($M_\odot$/yr)	Companion
V1180 Cas ?	600	4.3	0.07 (L)	>1.6e-7 (L)	Y?
V512 Per	300	...	66 (L)	...	...
XZ Tau ?	140	1.4	0.5	1e-7	Y
UZ Tau E	140	1.5	1.7	1−3e-7	Y
VY Tau	140	0.85	0.75	...	Y
LDN 1415 IRS ?	170	...	>0.13 (L)	...	...
V1118 Ori	414	0−2	1.4 (L), 7−25 (H)	2.5e-7 (L), 1e-6 (H)	Y
NY Ori	414	0.3	...	...	N
V1143 Ori	500	...	...	...	...
V1647 Ori ?	400	8−19	3.5-5.6, 34−44	6e-7 (L), 4e-6−1e-5 (H)	...
V723 Car ?	...	...	...	...	...
GM Cha ?	160	≳13	>1.5	1e-7	Y
EX Lup	155	0	0.7, 2	4e-10 (L), 2e-7 (H)	Y?
PV Cep ?	325	12	41 (L), 100 (H)	2e-7−3e-6 (L), 5e-6 (H)	...
V2492 Cyg	600	6−12,10−20	14 (L), 43 (H)	2.5e-7 (H)	...

EXors: a heterogeneous group?

- Low-luminosity eruptive objects, but not considered EXors: HBC 722, V2775 Ori (L_{bol} = 10-50 $L_{\odot}$ in outburst)
- Objects with outburst/repetition timescale in-between FUors and EXors: OO Ser, V1647 Ori
- Objects where the brightening is partly due to decreasing extinction: V1647 Ori, V2492 Cyg, PV Cep
- Embedded/Class I objects: V723 Car, GM Cha, V2492 Cyg, V1647 Ori

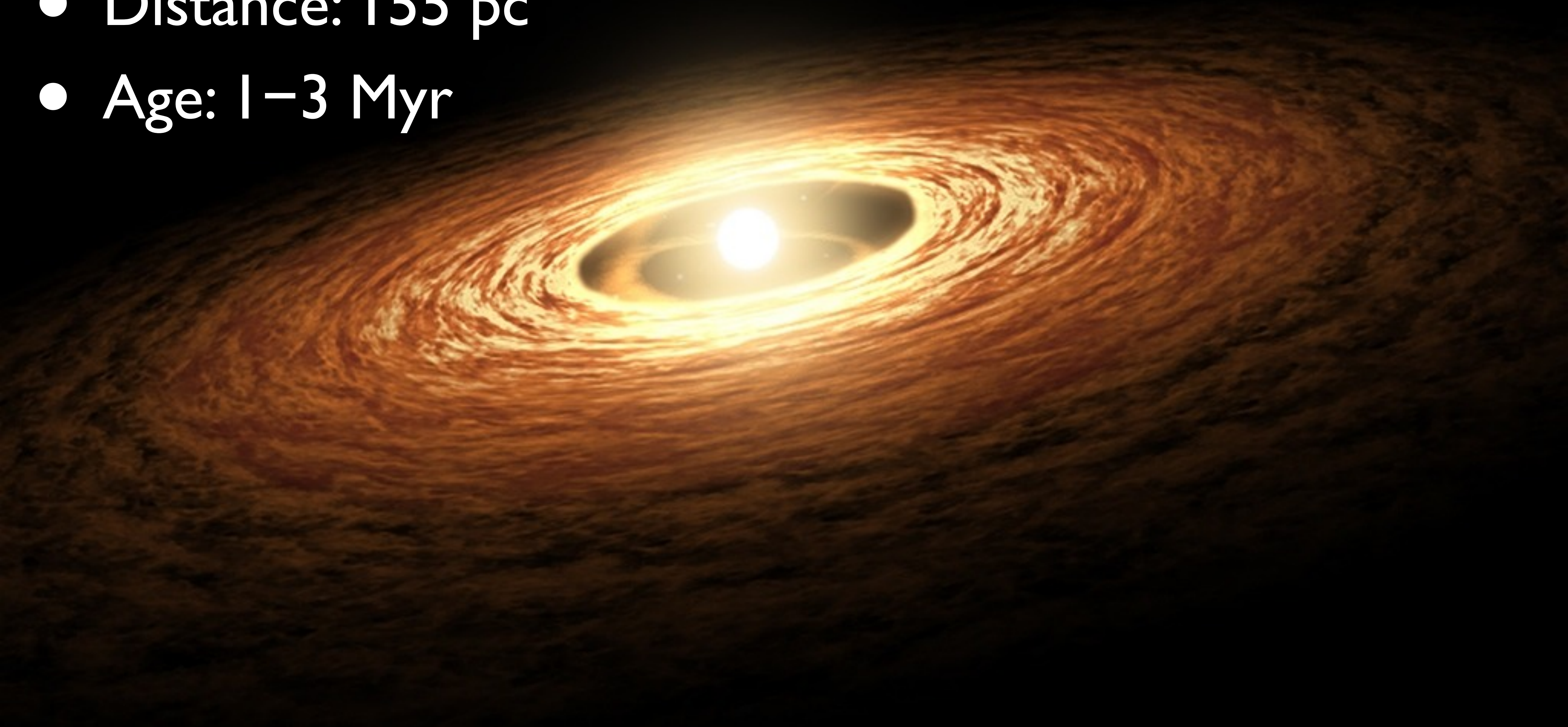
New class? Are FUors and EXors part of a continuum?

Observational advantages

- Short timescale: brightening and fading can conveniently be studied because they happen within a few months/few years
- If you miss an outburst, just wait for the next, it will happen again in a few years (except for VY Tau)
- Progenitor (i.e. quiescent state) can be well studied

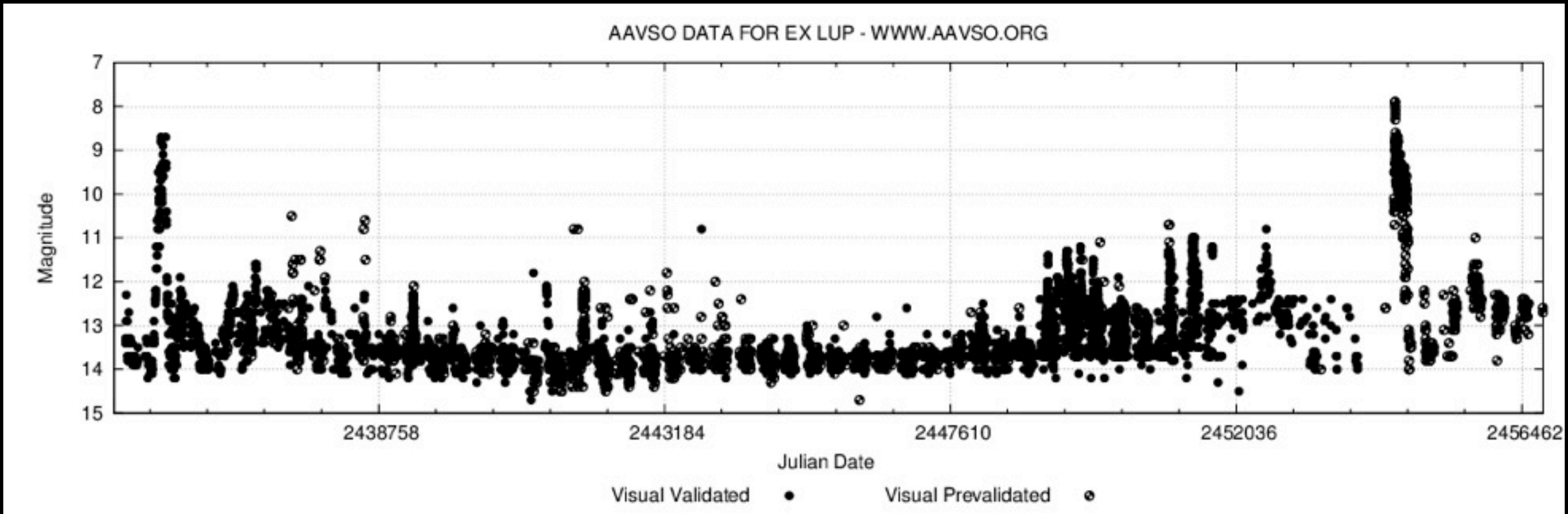
Prototype: EX Lup

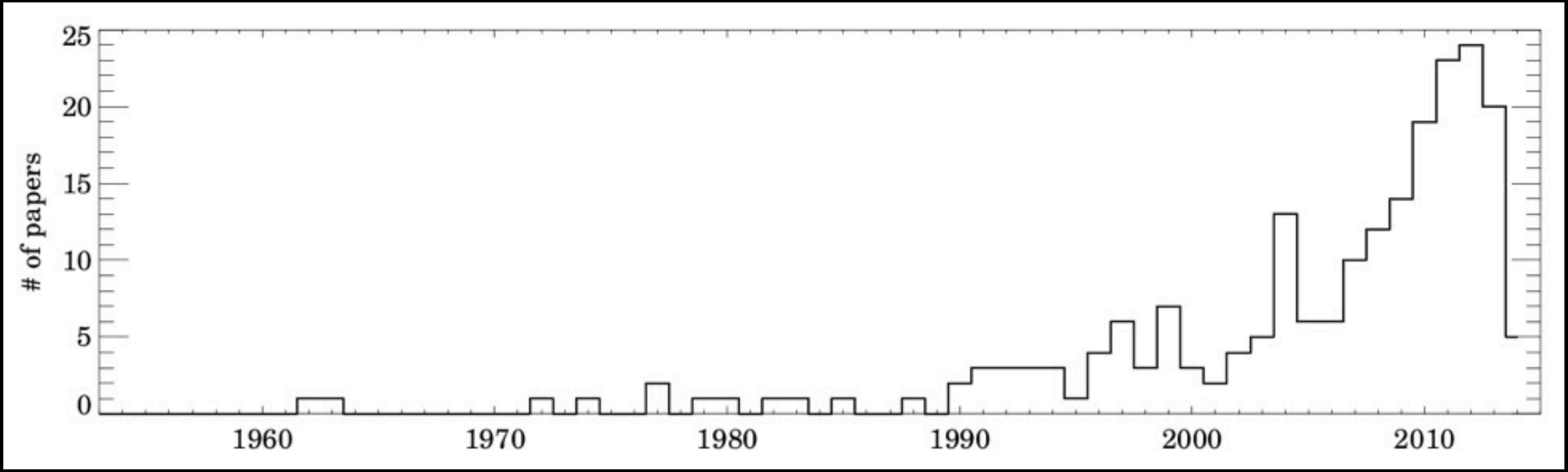
- Spectral type: M0
- Close to the Lupus 3 SFR
- Distance: 155 pc
- Age: 1−3 Myr



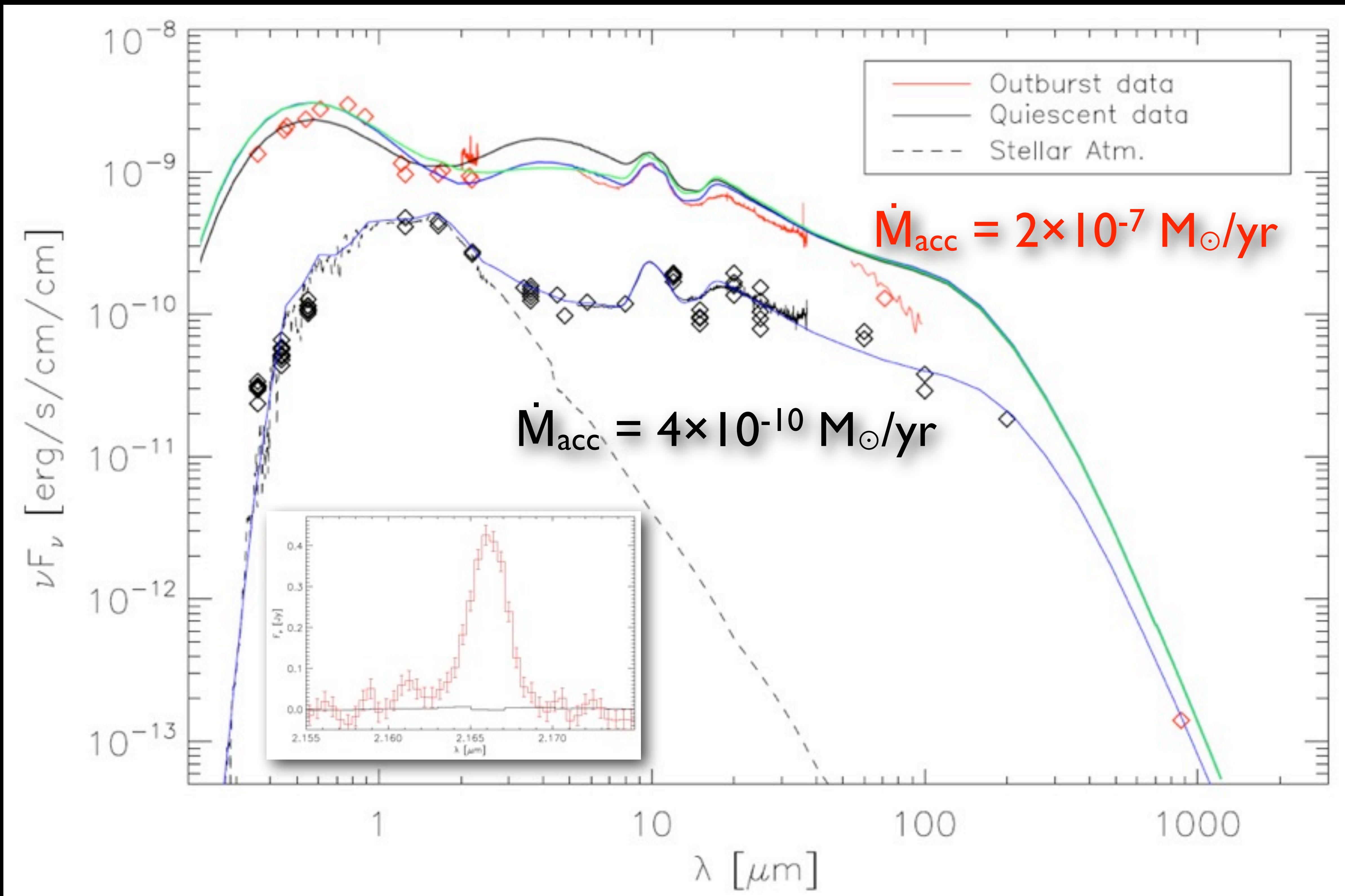
NASA/JPL-Caltech/T. Pyle

Prototype: EX Lup



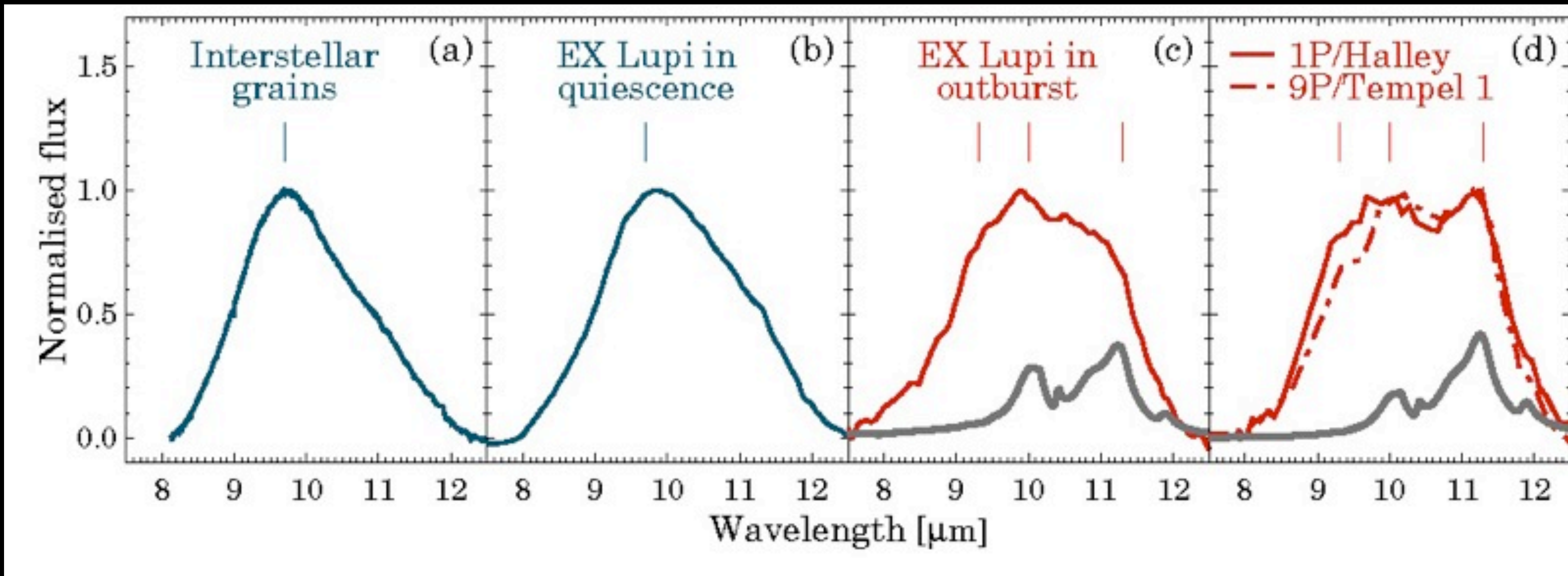


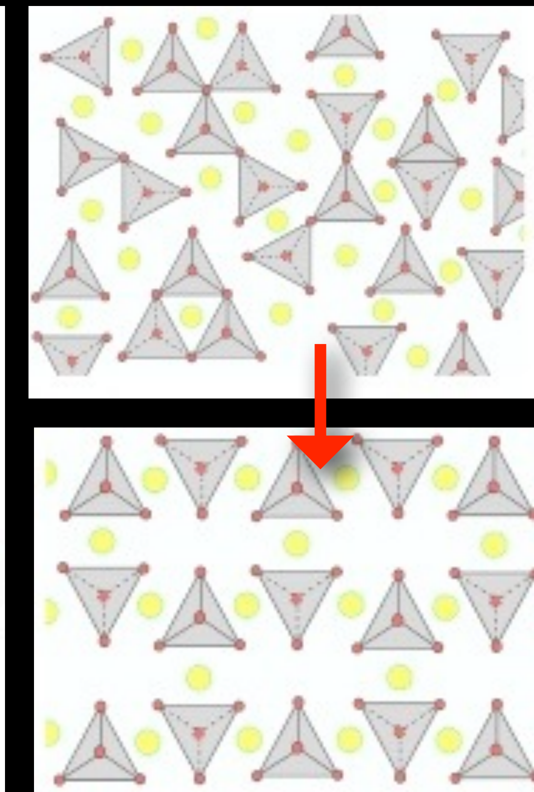
Evidence for episodic accretion?



Juhász et al. (2012)

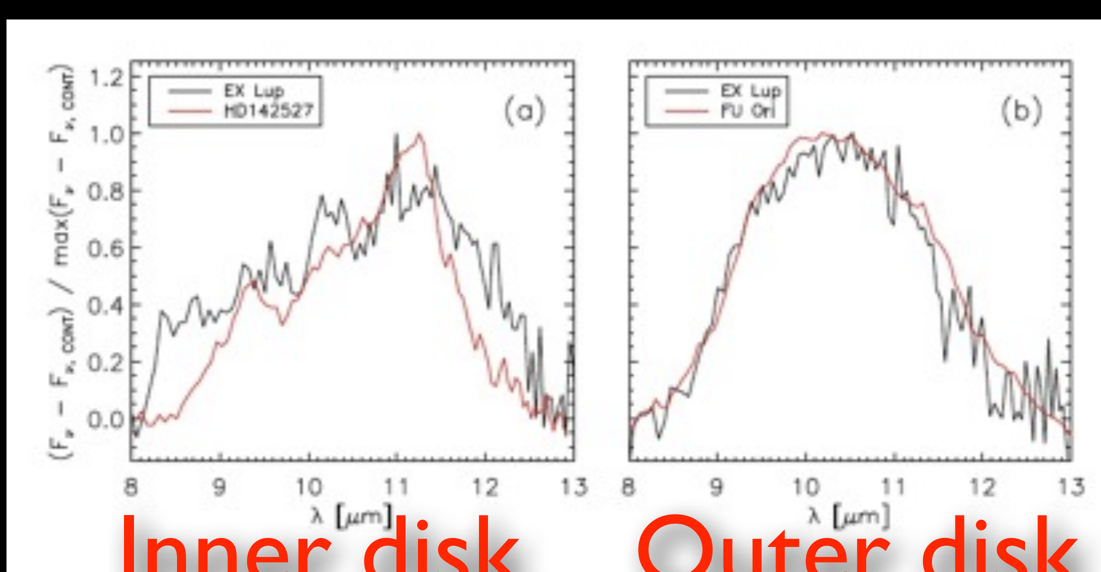
Episodic crystallization



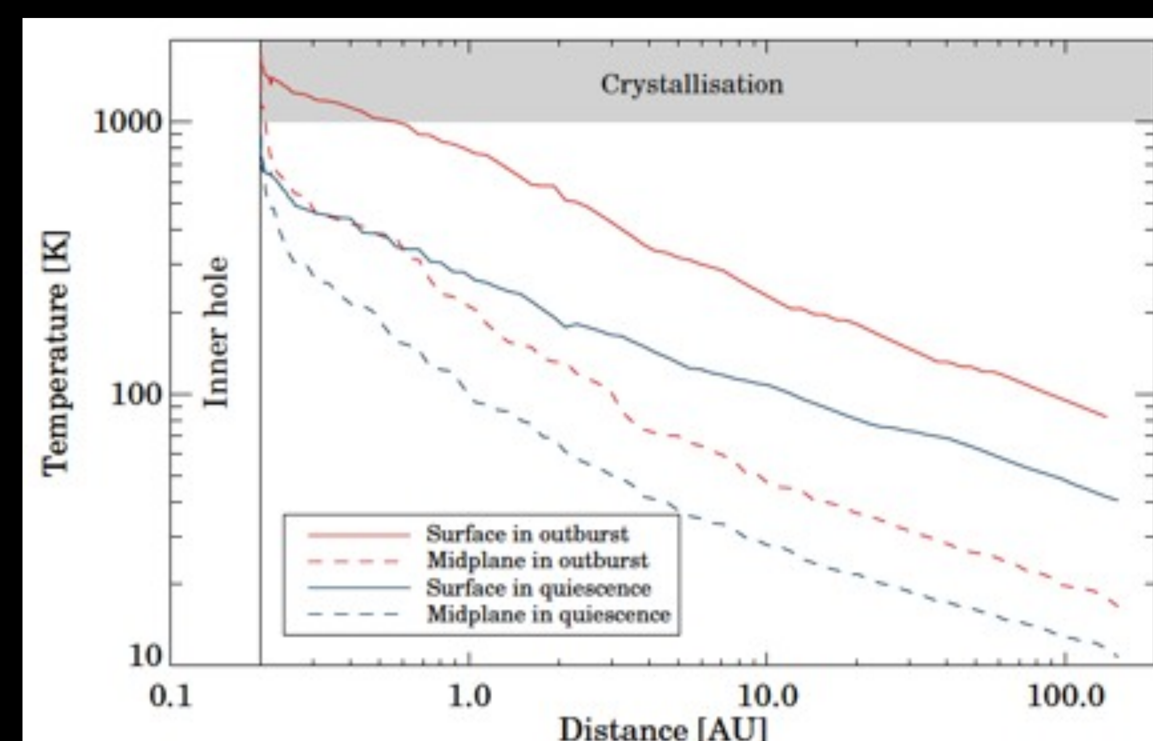


- Above 1000 K: thermal annealing
- Above 1500 K: evaporation

Ábrahám et al. (Nature, 2009)

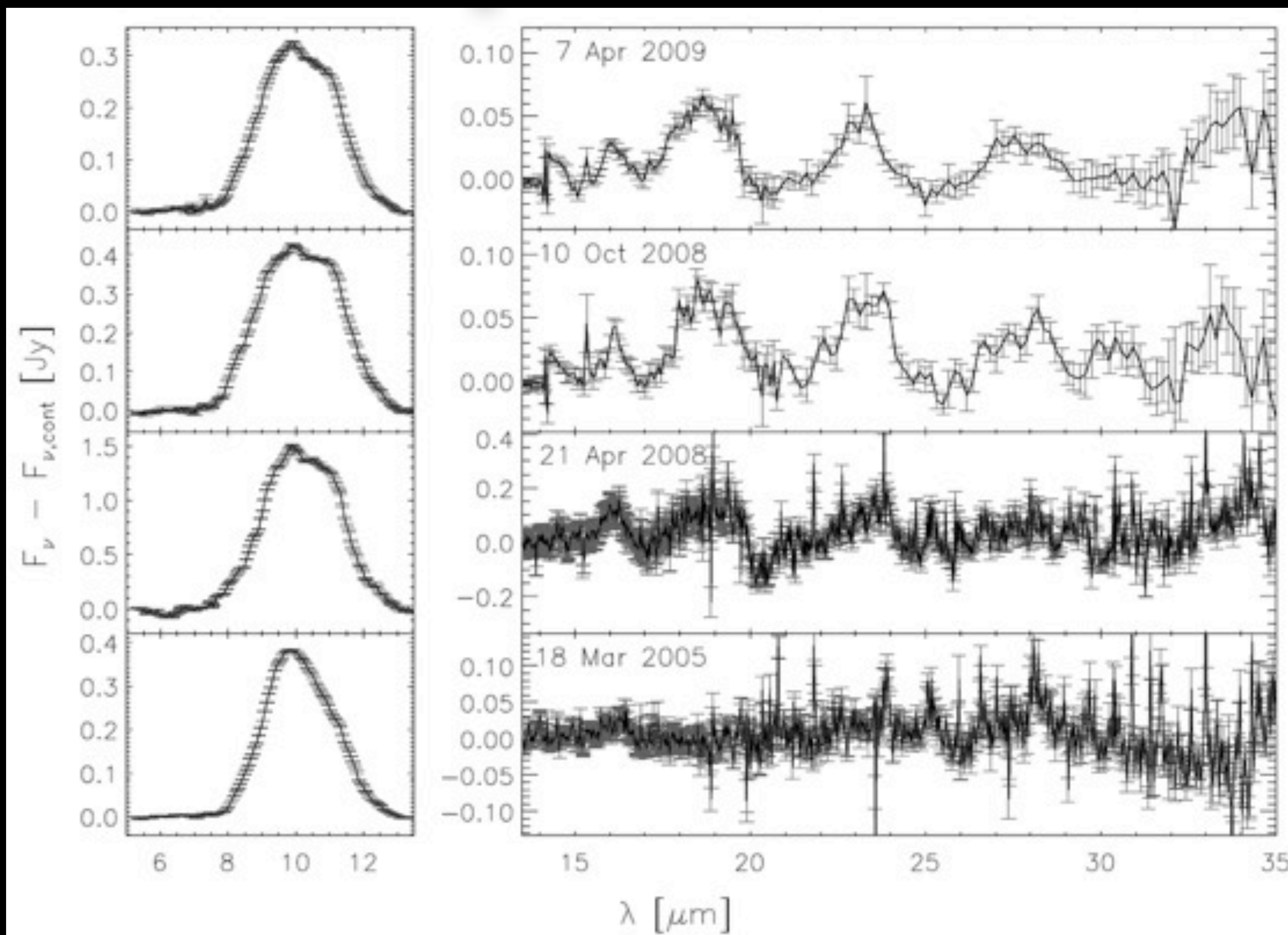


Juhász et al. (2012)



Silicate crystals in motion

Radial transport

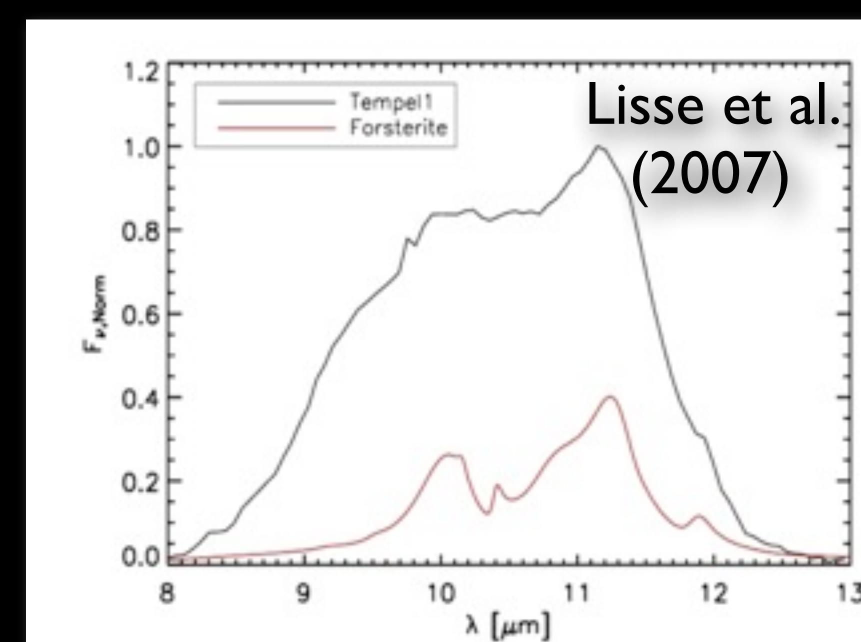


Time

Juhász et al. (2012)

Comet Tempel/1

Crystalline fraction:
> 80%



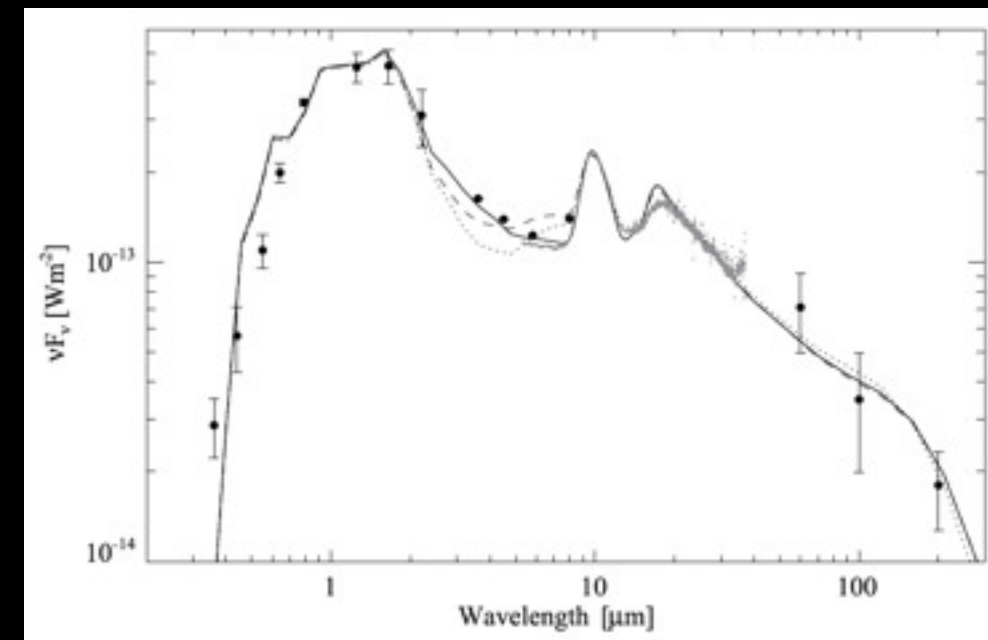
Could the crystalline material of Solar System comets have been "cooked" in EXor-type outbursts around the young Sun?

Why do EXors erupt?

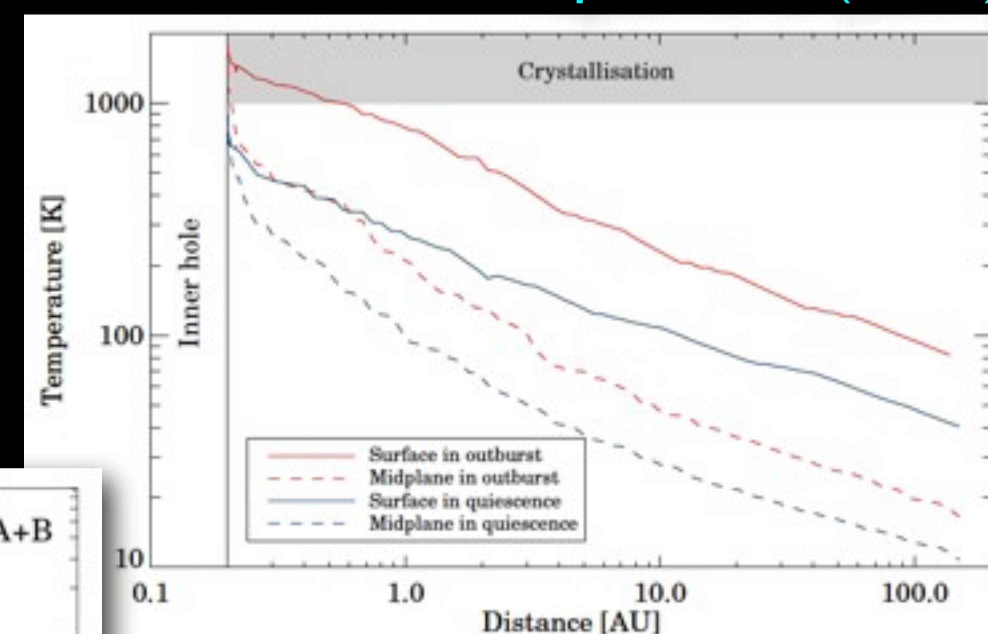
- Do all T Tauri stars produce outbursts?
- Are EXors special in some way?
- EX Lup's specialties:
  - inner hole
  - companion

The role of inner holes?

- Inner hole in the quiescent EX Lup system:
  r_{in} = 0.2 au ↔ r_{subl} = 0.05 au
- Inner holes in other EXors?
- Where does the accumulated material pile up?



Sipos et al. (2009)



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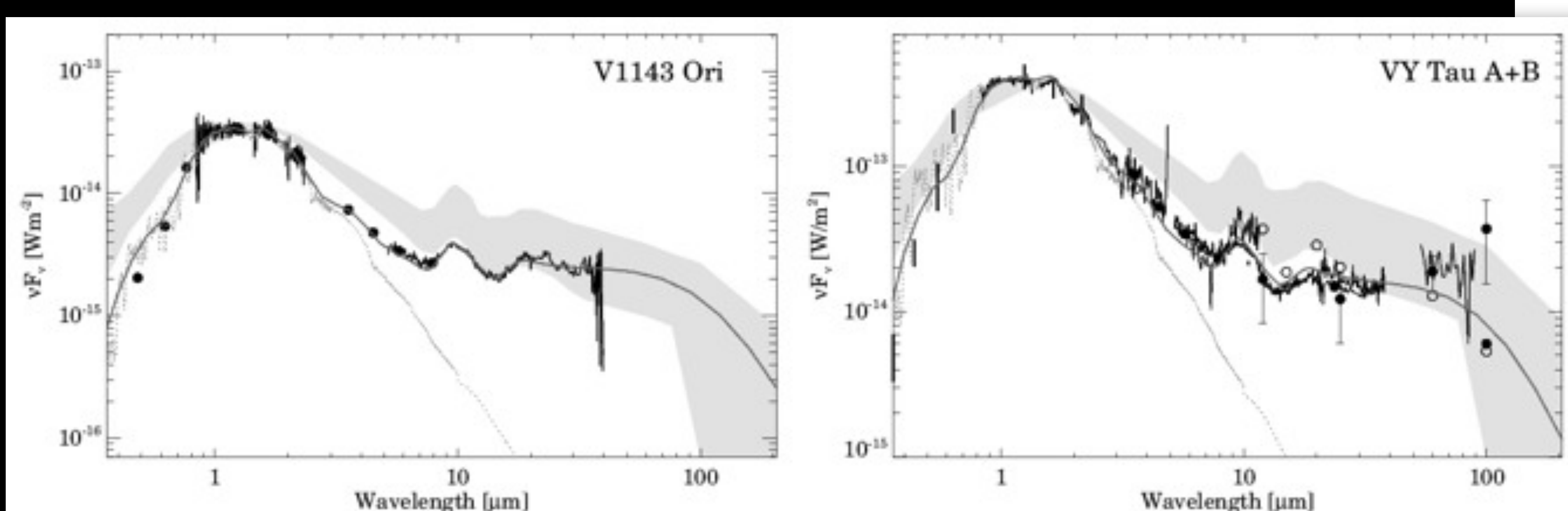
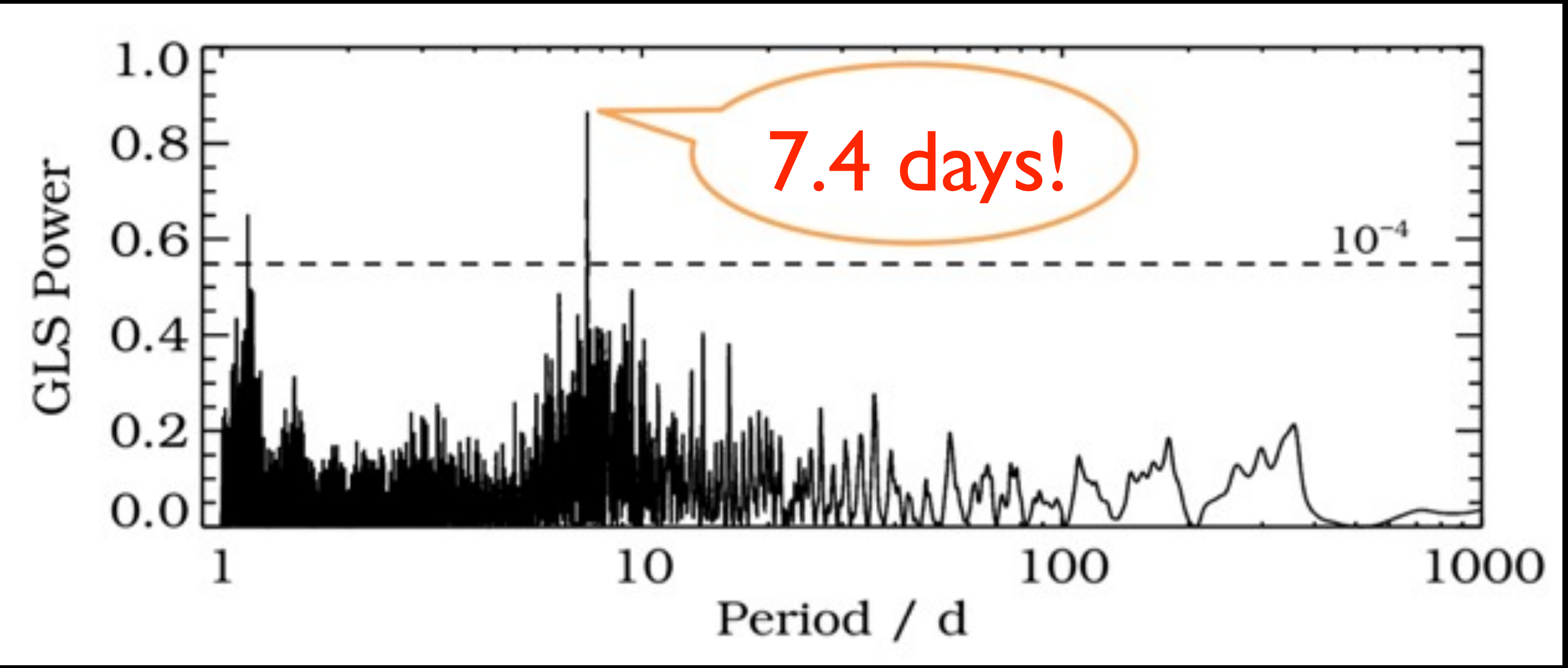


Sipos & Kóspál (in prep.)

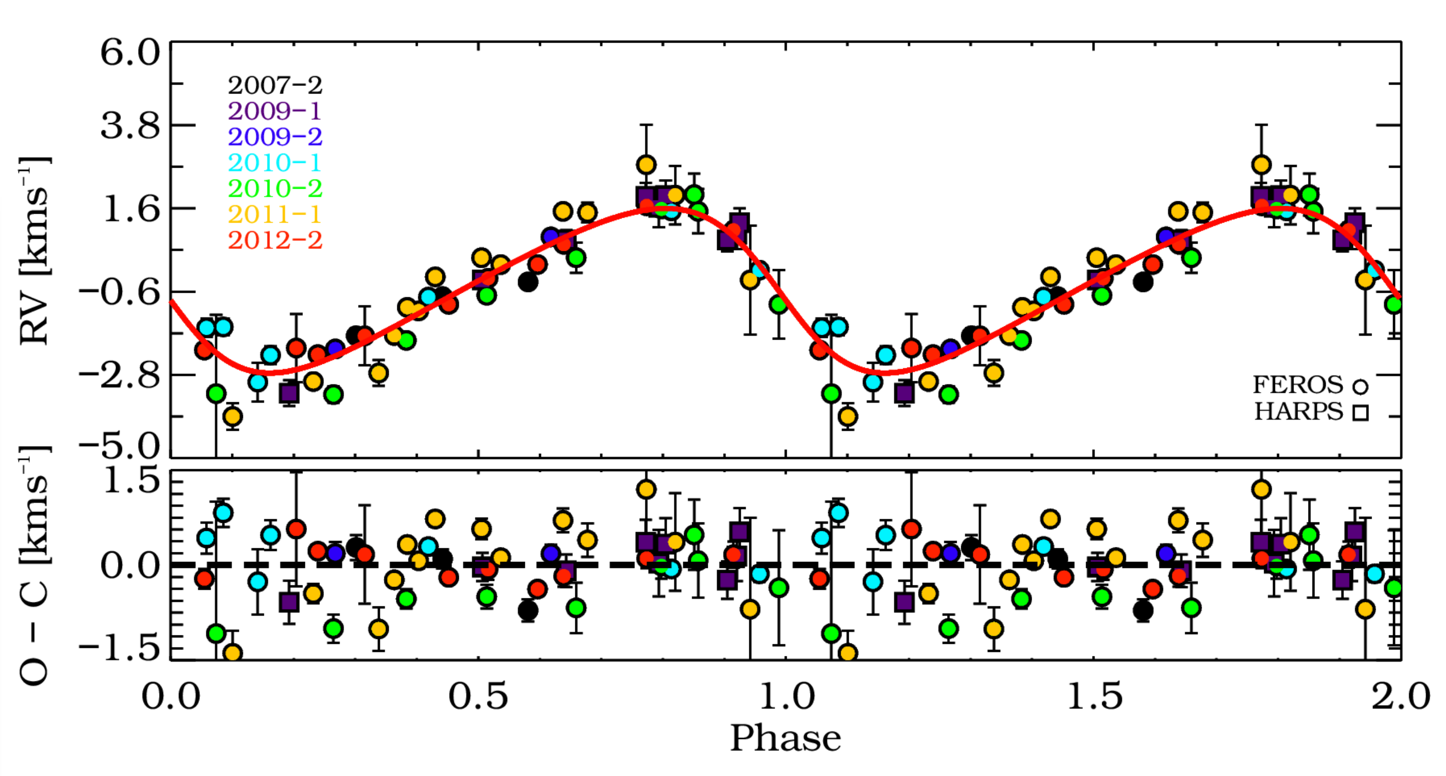
The role of companions?



EX Lup:

Possible brown dwarf companion orbiting within the dust-free inner hole

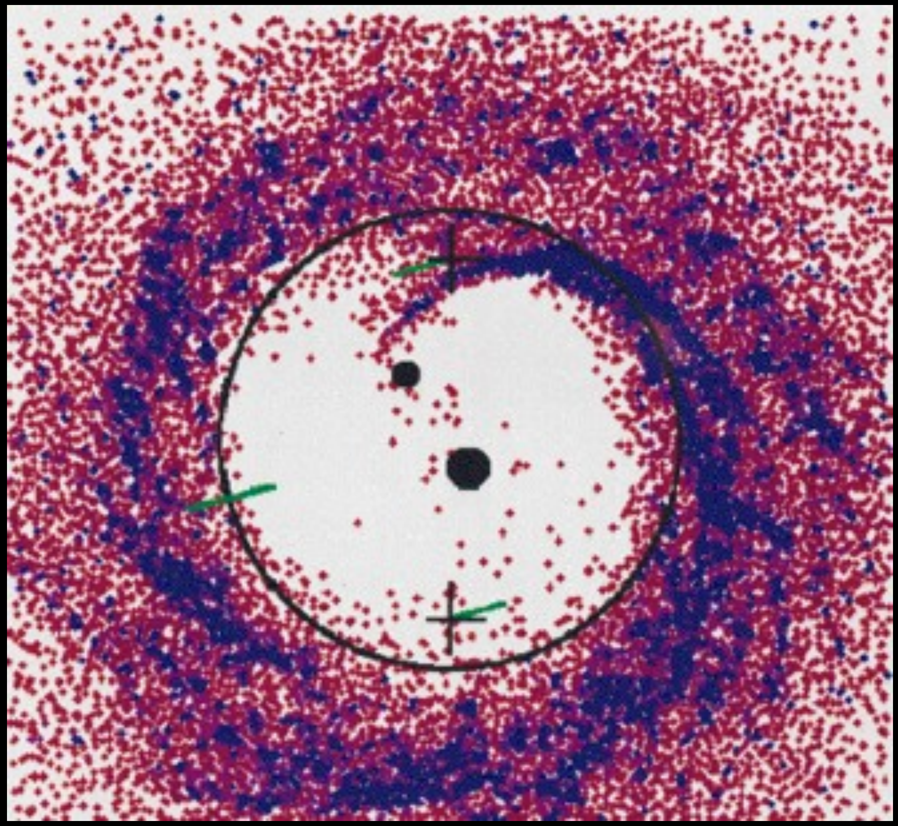
Parameter	Fitted value	Unit
Period	7.417 ± 0.001	day
RV semi-amplitude	2.18 ± 0.10	km s^{-1}
Eccentricity	0.23 ± 0.05	
m sin i	14.7 ± 0.7	$M_{Jupiter}$
Semi-major axis	0.063 ± 0.005	au



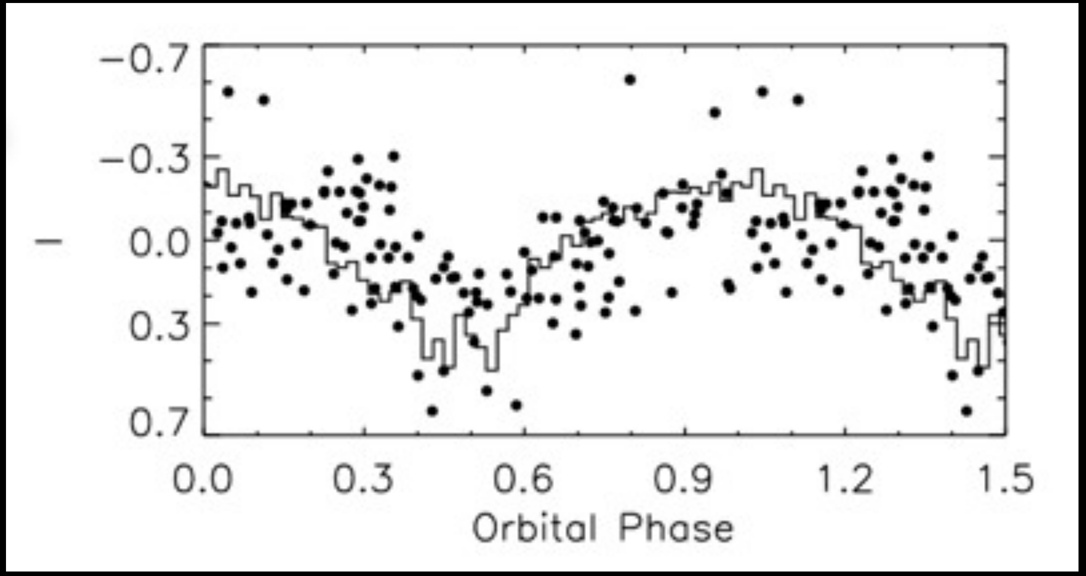
Kóspál et al. (2014)

The role of companions?

- Several EXors are known binaries (7/15, i.e. 47% of the sample)
- How does the companion affect the accretion process?
- Does the companion cause pulsed accretion?
  In UZ Tau E – yes
  In EX Lup – maybe
- Speculation: does the companion prevent steady accretion and induce outbursts?



Artymowicz & Lubow (1996)



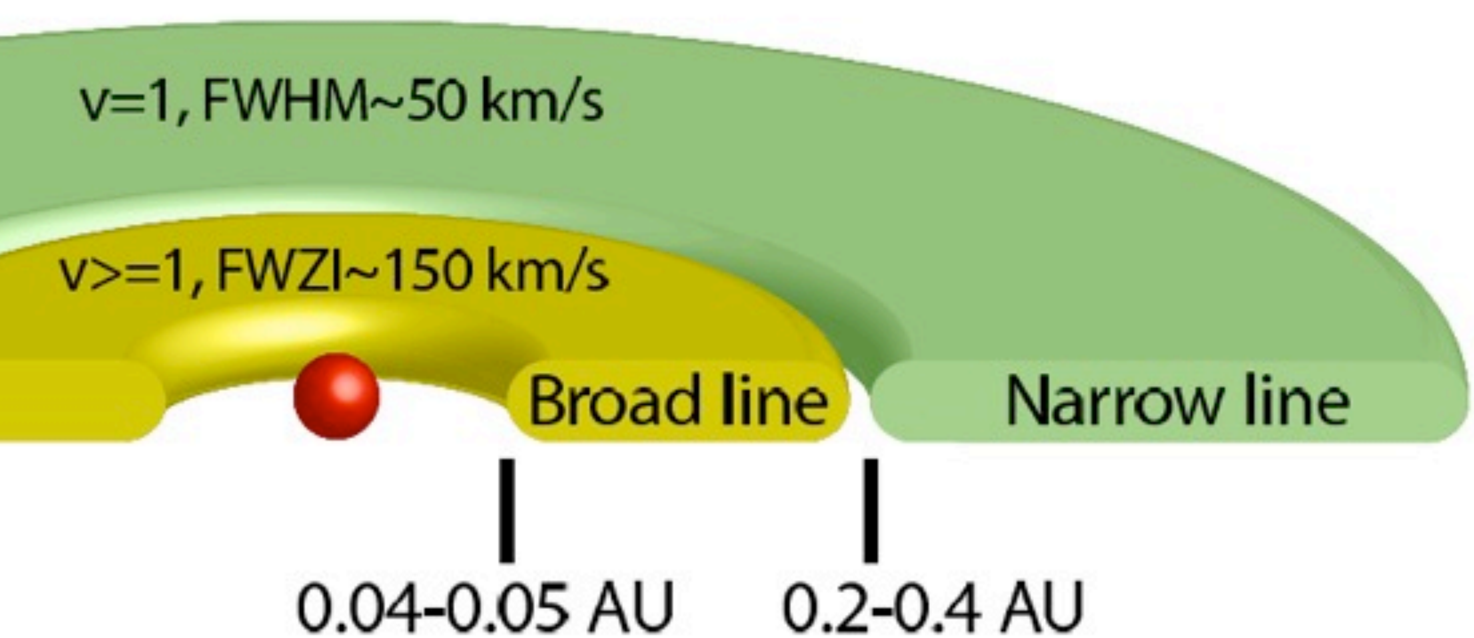
Jensen et al. (2007)

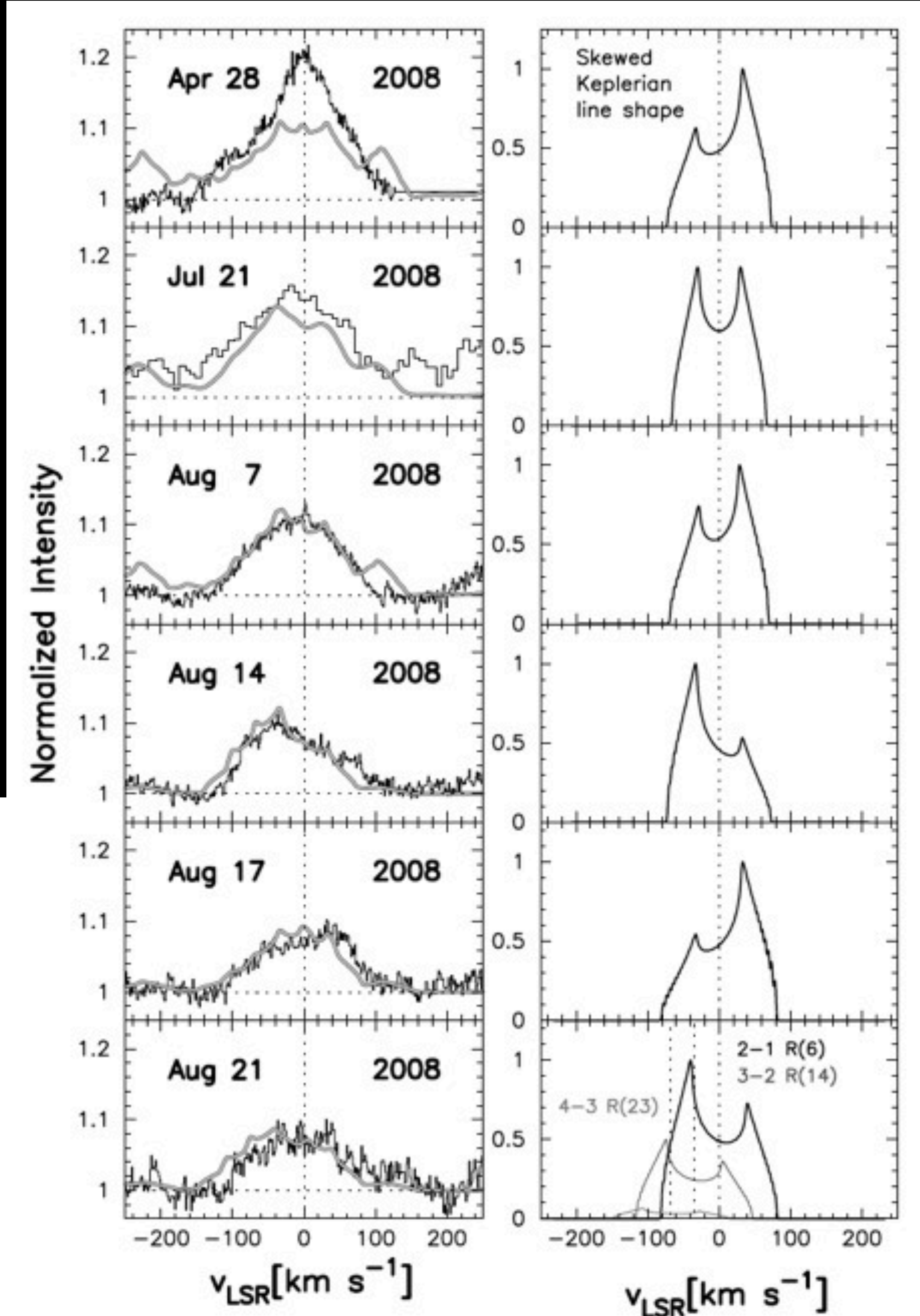
Active disk regions?

CRIRES monitoring:

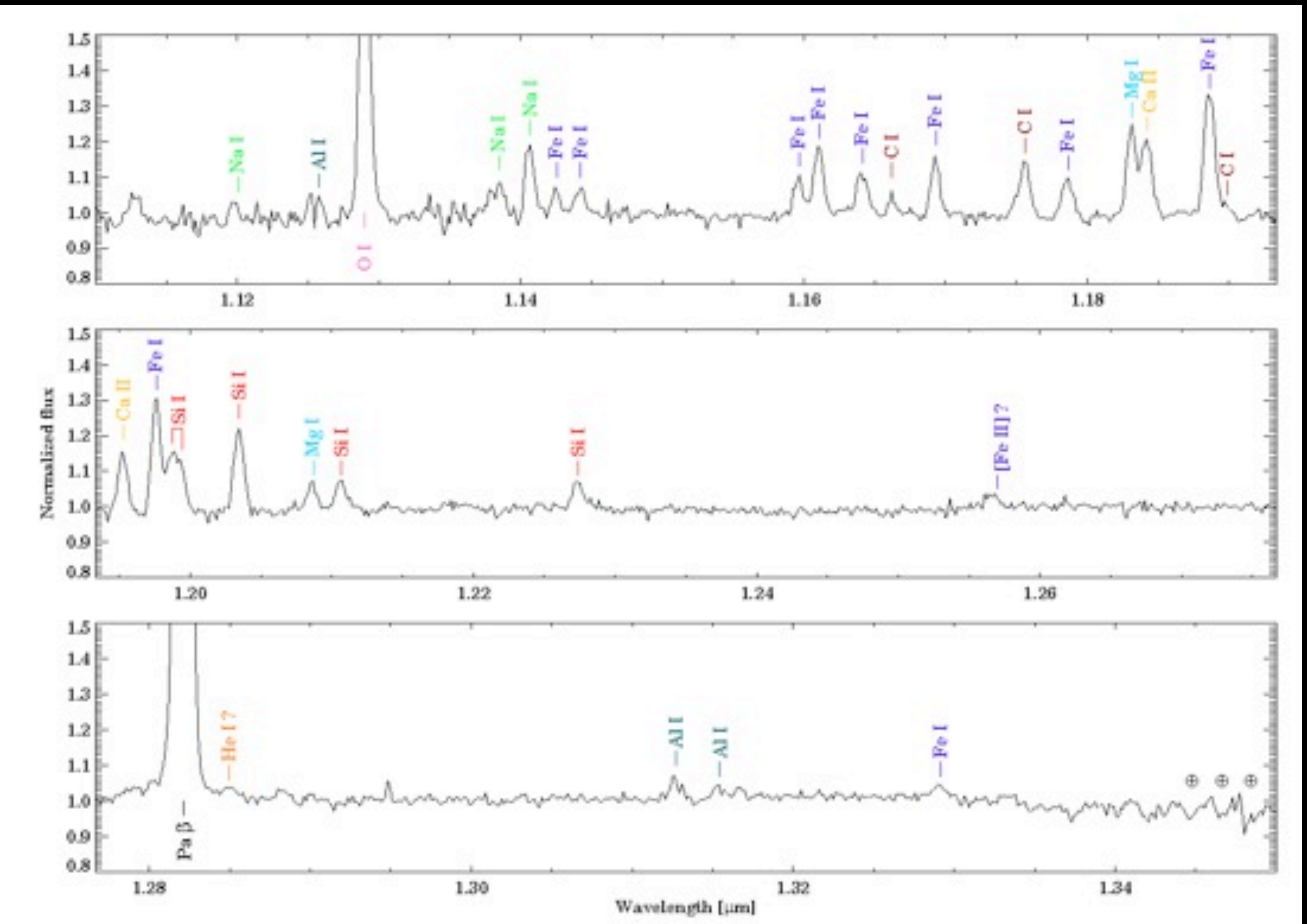
- Narrow line region: constant in time
- Broad line region: decays with the outburst
- Dust-free inner hole is filled up with gas

Goto et al. (2011)





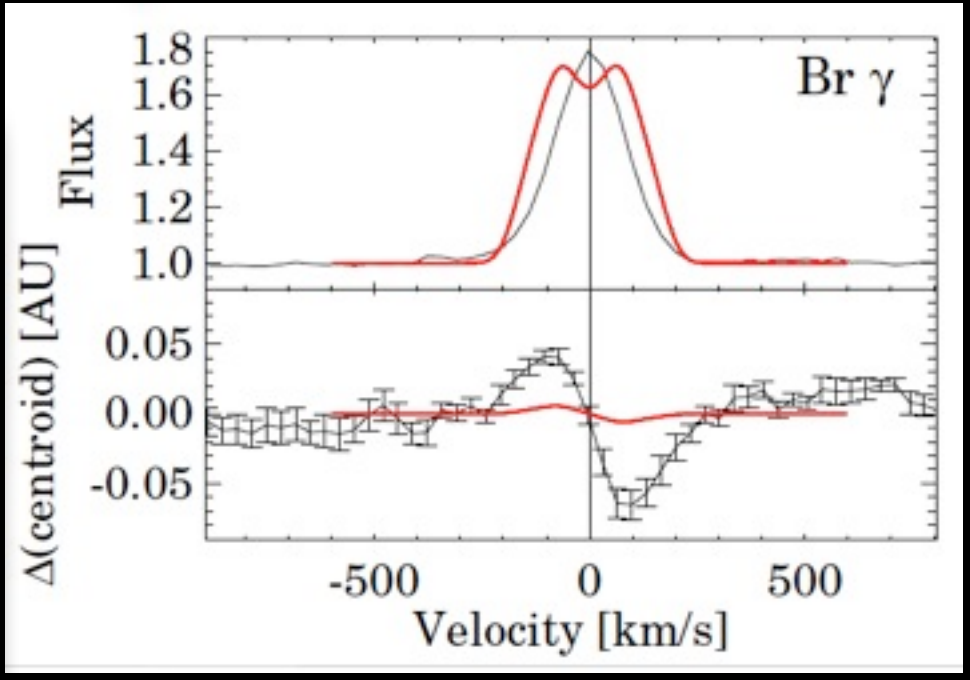
Boundary layer/accretion column?



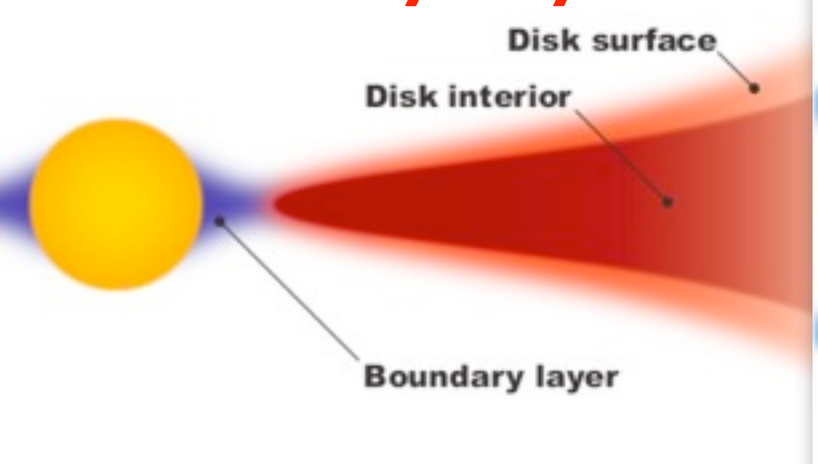
Kóspál et al. (2012)

SINFONI spectra:

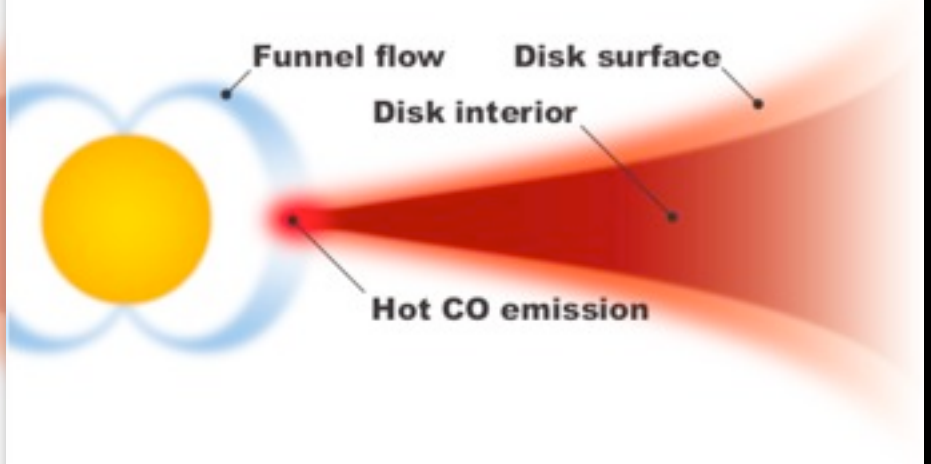
- Spectro-astrometry for the Br gamma line
- High-velocity gas is present much farther from the star than what is expected for a Keplerian disk



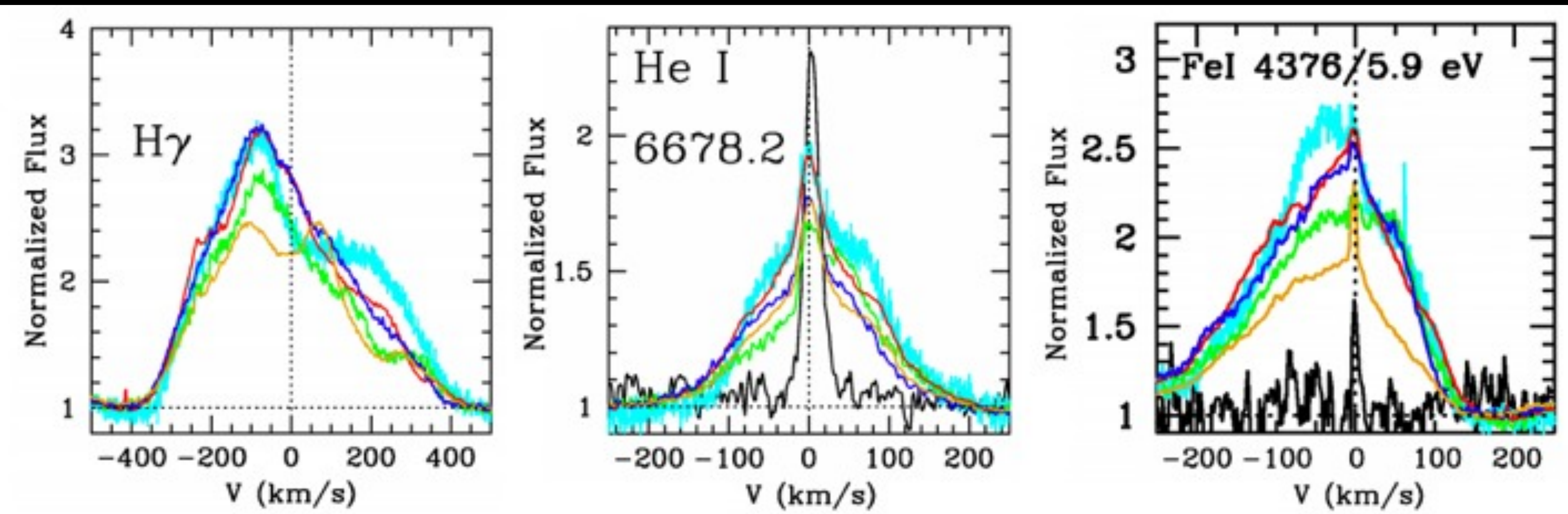
Boundary layer



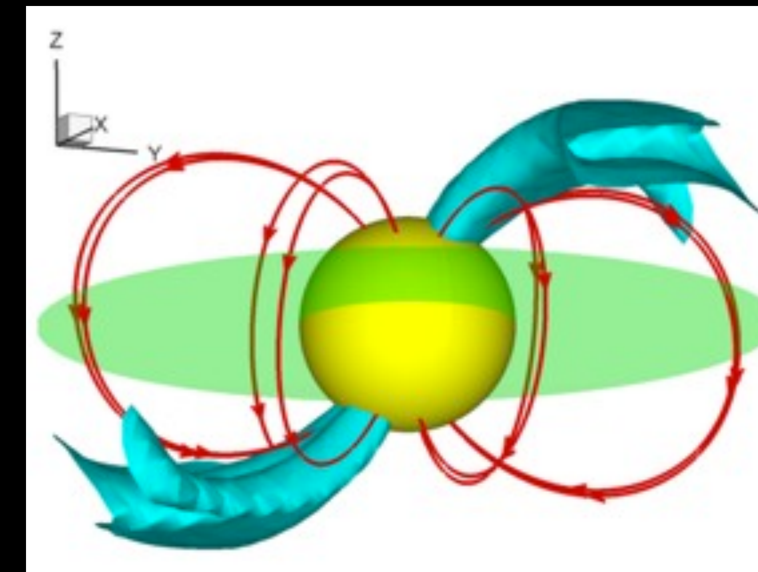
Accretion columns



The star's immediate vicinity



Sicilia-Aguilar et al. (2012)



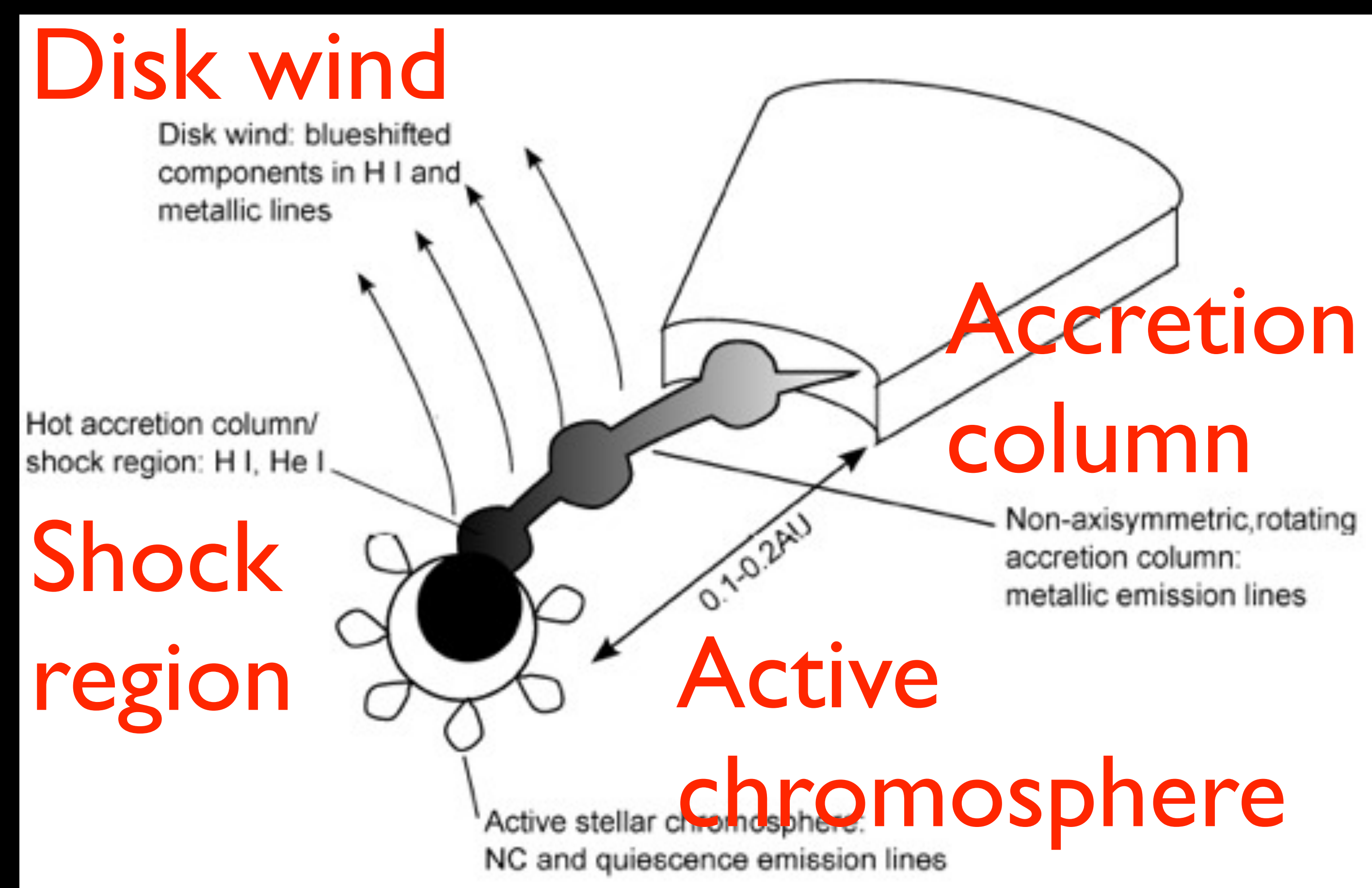
Kulkarni & Romanova (2008)

FEROS and HARPS monitoring:

- Accretion goes through the same channels both in outburst and in quiescence

Missing pieces:

- mol. outflow? HH object?
- magnetic field?



Outburst mechanism for EXors?

Are EXors the down-scaled versions of FUors? Do they occur at a later evolutionary phase than FUor bursts?

Disk instability:

- self-regulated thermal instability (Bell & Lin 1994)
- thermal instability induced by a planet (Lodato & Clarke et al. 2004)
- gravitational + magnetorotational instability (Zhu et al. 2009)
- disk fragmentation (Vorobyov & Basu 2010)

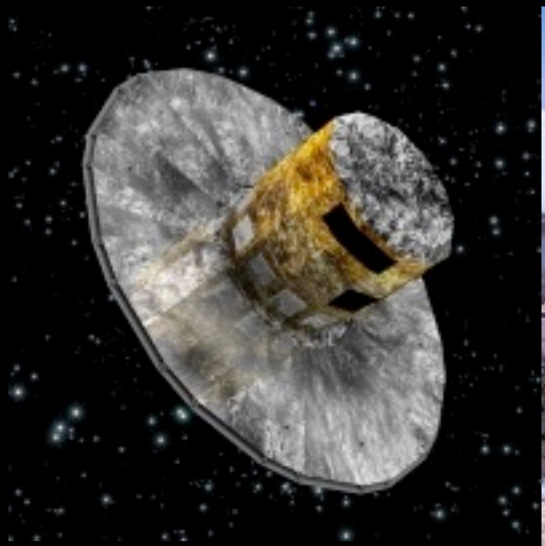
Perturbation by external body:

- close encounter with nearby star (Pfalzner et al. 2008)

Outburst mechanism for EX Lup?

- Gravitational instability?
  No – disk is not too massive (M_{disk} = 0.025 $M_\odot$)
- Self-regulated thermal instability?
  No – brightening is too fast
- Mass transfer occurs on the viscous timescale.
  Duration of the outburst: 10 months → radius from where material could be accreted onto the star: 0.12 au
- Mass reservoir should have been in the dust-free inner hole, where only optically thin gas could be present
- Critical mass accretion rate in the Bell & Lin model: 5×10^{-7} $M_\odot$/yr, much higher than in the quiescent EX Lup system

Future prospects: large surveys



- GAIA
- Pan-STARRS
- LSST
- Discover many more outbursting objects
- Trigger follow-ups

Future prospects: high spatial res.

- ALMA, NOEMA: kinematics of the circumstellar material (non-Keplerian?), chemistry (changes?)
- MATISSE: inner part of the dust disk (re-arrangement of material? evaporation?)
- LBT: gaseous material in the innermost regions (where is the material that piles up before the outburst?)
- JWST, SPICA: push the study of young eruptive stars to earlier evolutionary phases and to farther-off star-forming regions