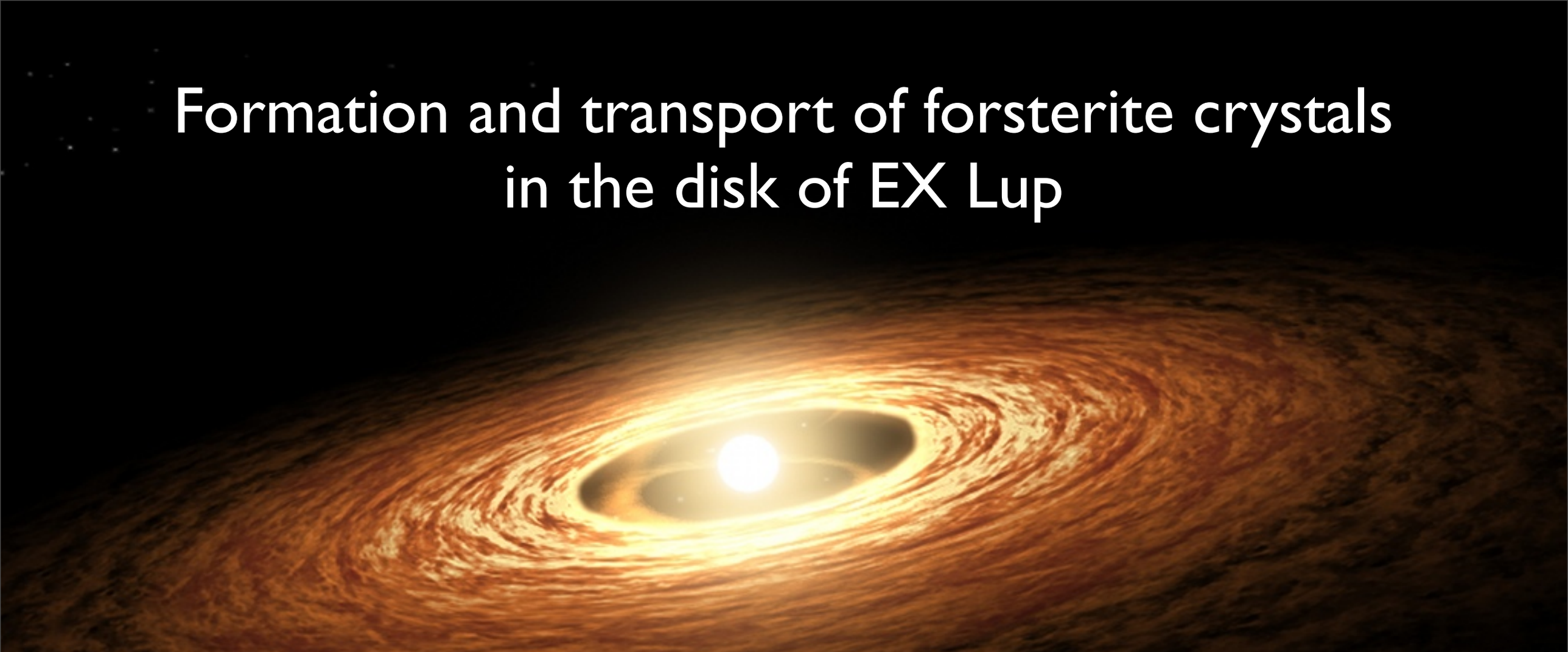
Formation and transport of forsterite crystals in the disk of EX Lup



Attila Juhász[1], Jeroen Bouwman[2], Cornelis Dullemond[2], Roy van Boekel[2], Péter Ábrahám[3], Thomas Henning[2], Albert Jones, Aurora Sicilia-Aguilar[2], Ágnes Kóspál[1], Attila Moór[3], José Acosta-Pulido[4], László Mosoni[3], Zsolt Regály,[3] Gyula Szokoly[5], Nikoletta Sipos[3]

[1]*Leiden Observatory, Leiden University, Leiden*
[2]*Max-Planck-Institute for Astronomy, Heidelberg*
[3]*Konkoly Observatory, Budapest*
[4]*Instituto de Astrofisica de Canarias, La Laguna*
[5]*Eötvös Loránd University, Budapest*

Vienna Observatory, 10 Jan 2011

Forsterite crystals (Mg_2SiO_4)

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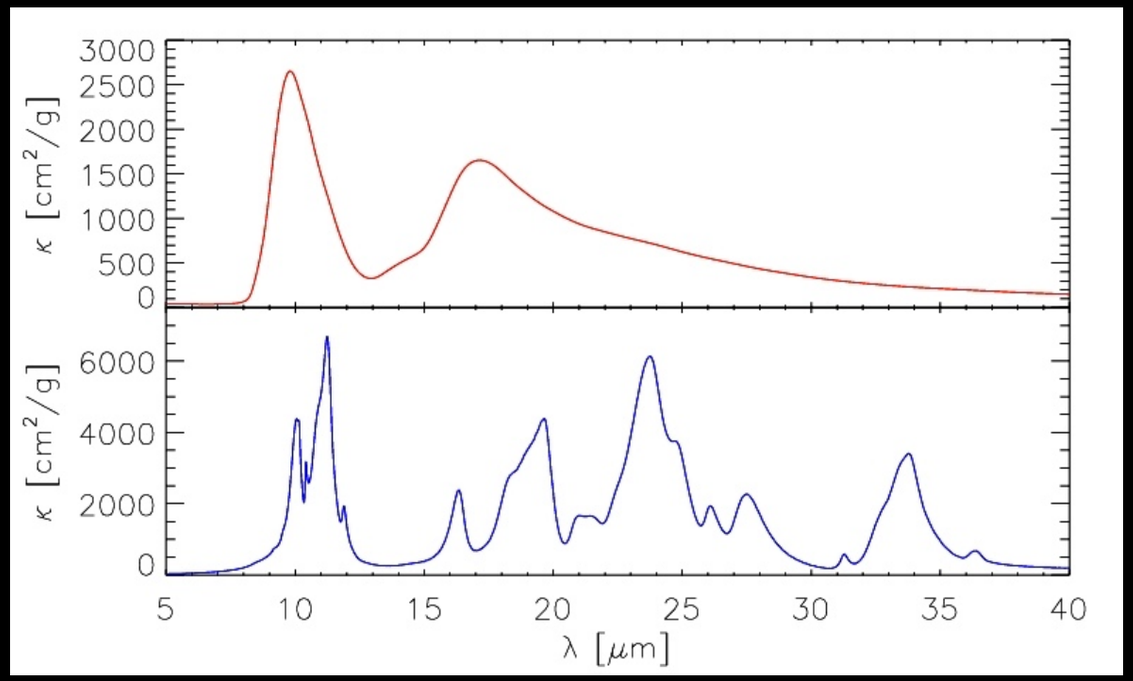

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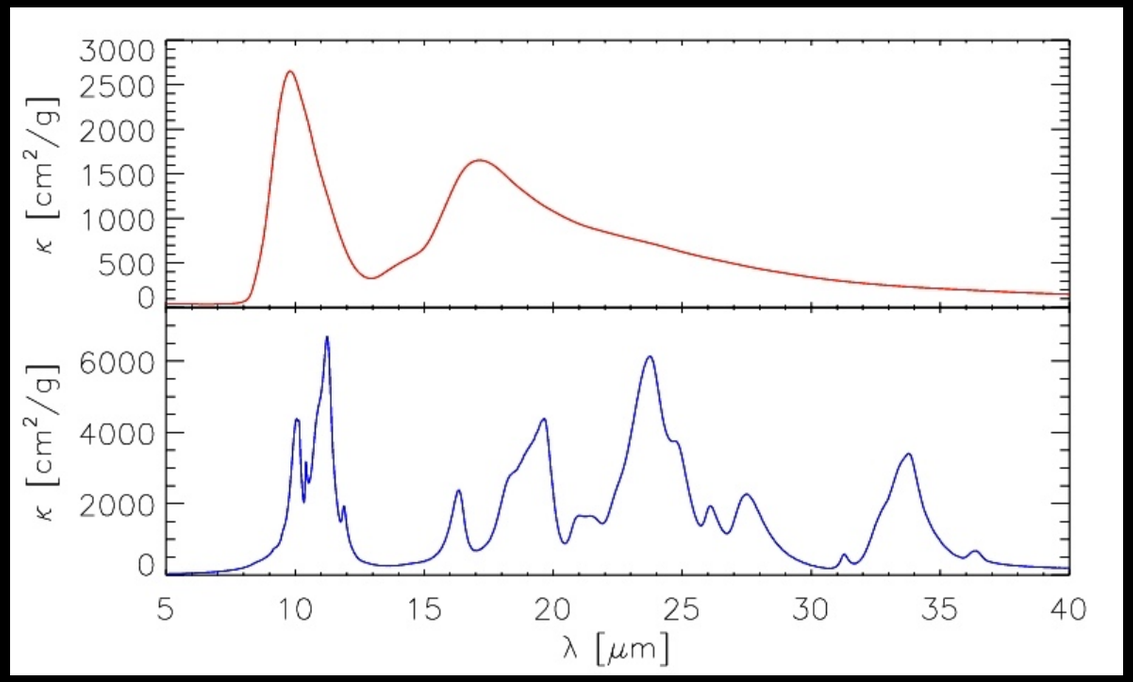

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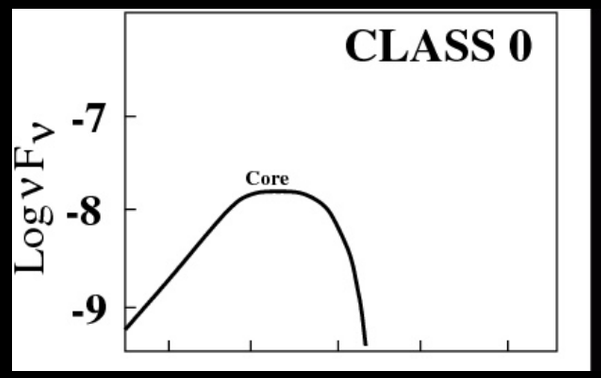
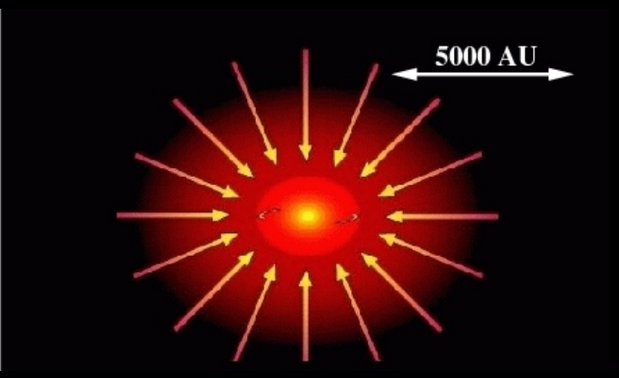
Where are they observed?

On Earth, meteorites, comets, AGB, post-AGB stars, young stars

Star formation in a nutshell





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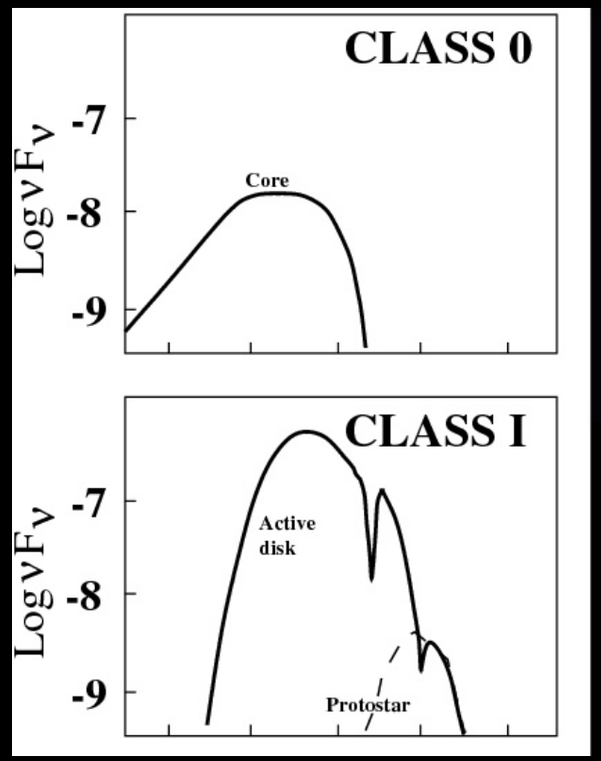

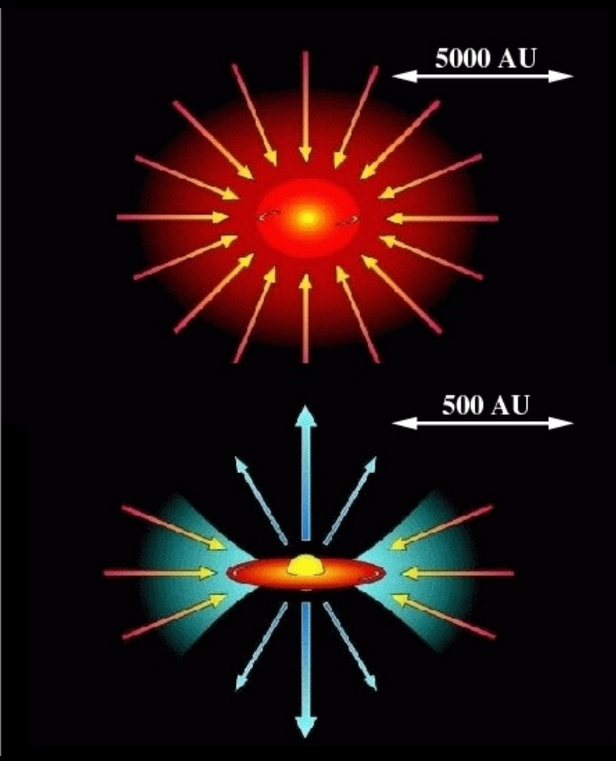

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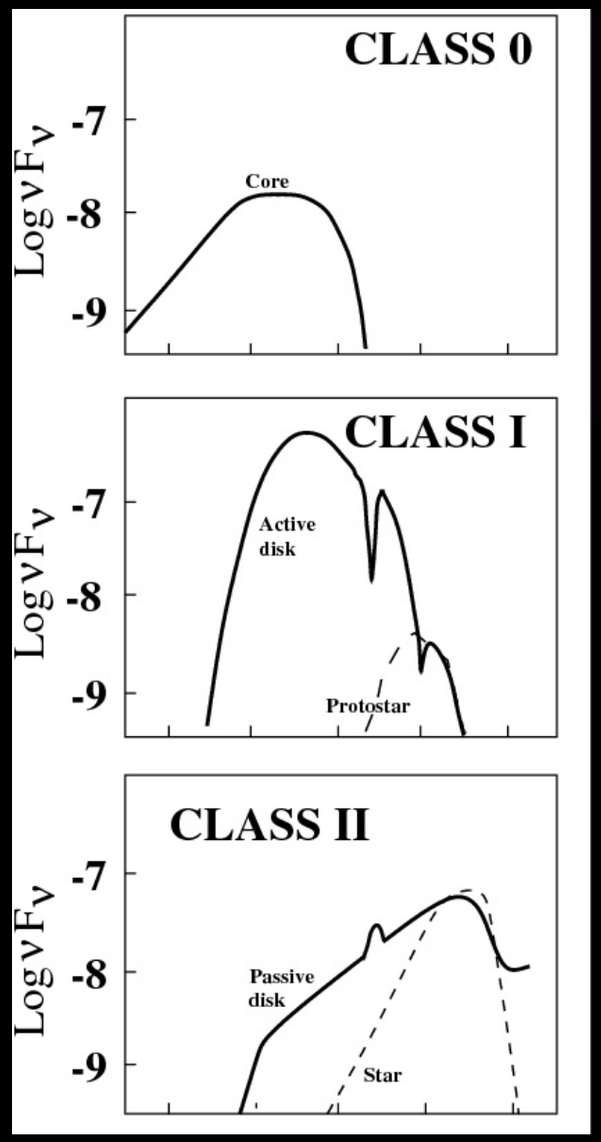

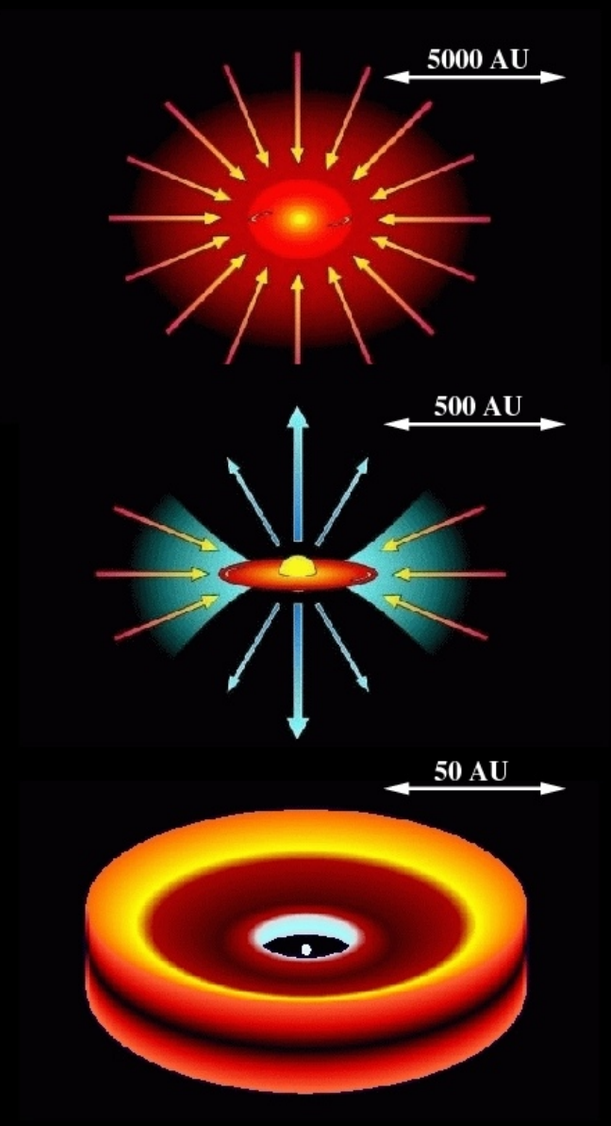

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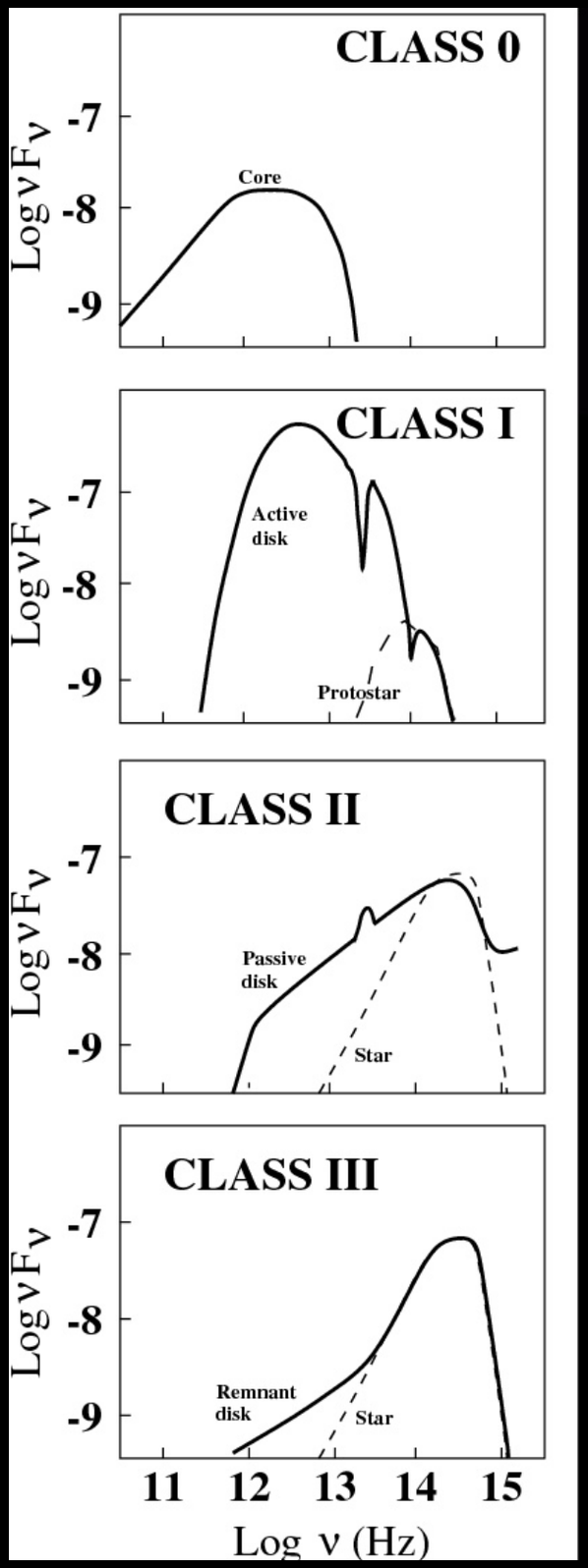

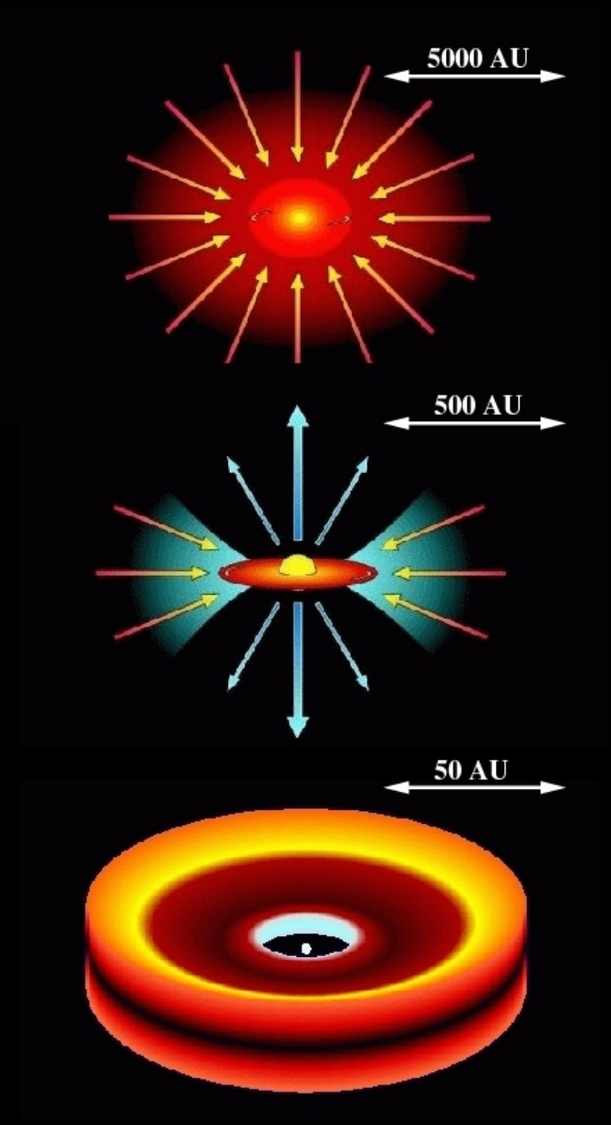

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Dust evolution in protoplanetary disks

Kemper et al. 2004, 2005

Galactic Center:
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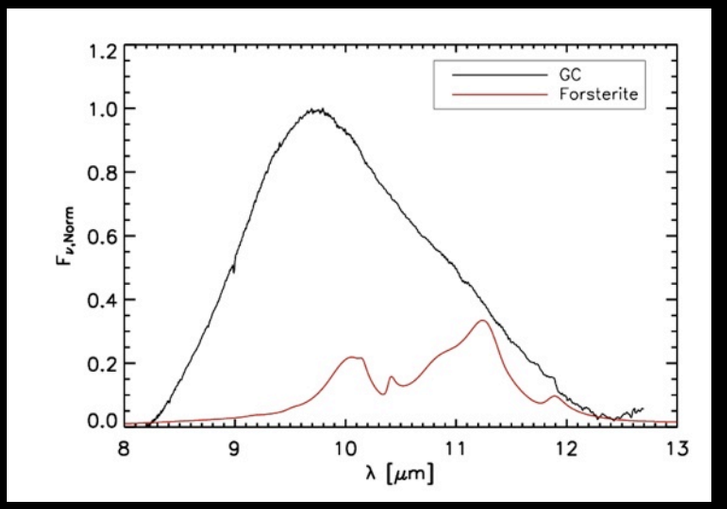

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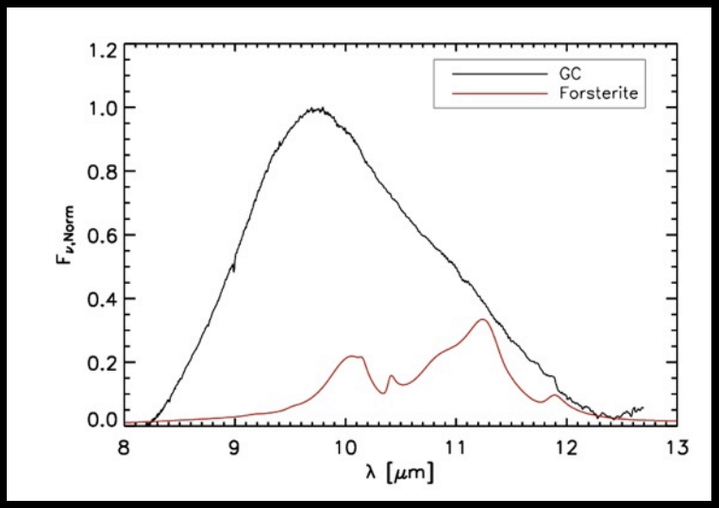

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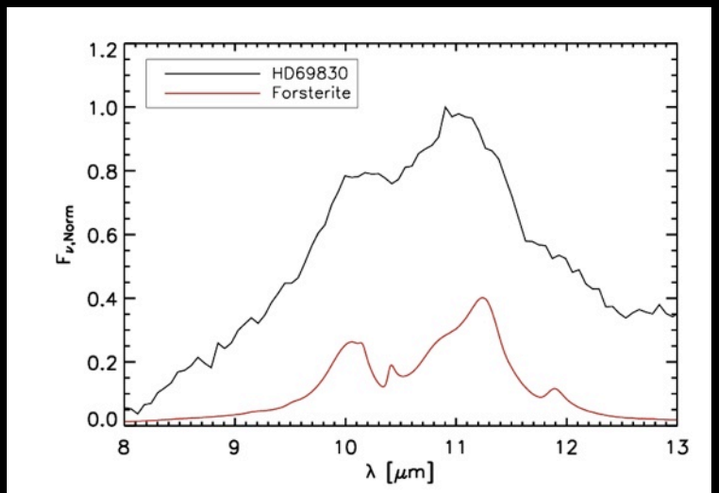

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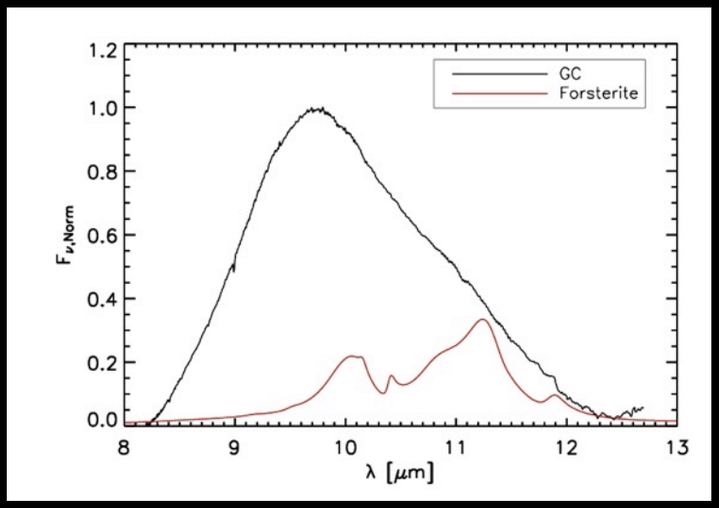

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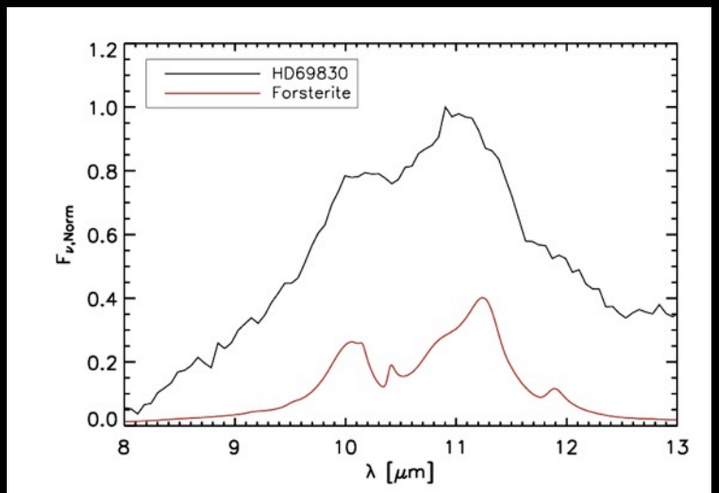

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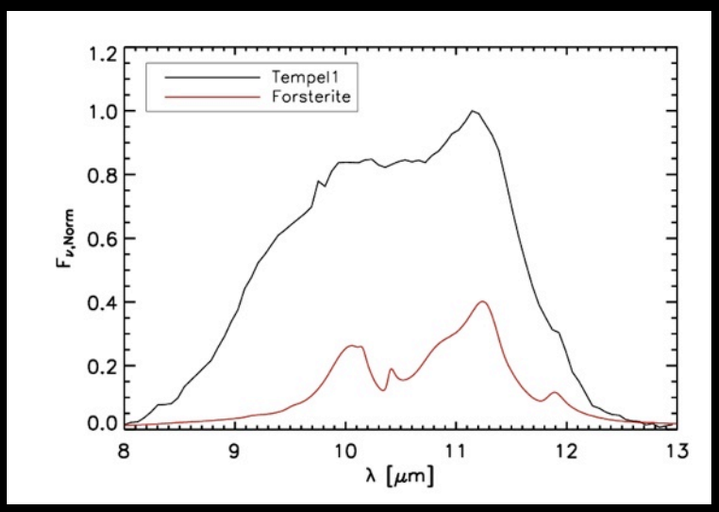

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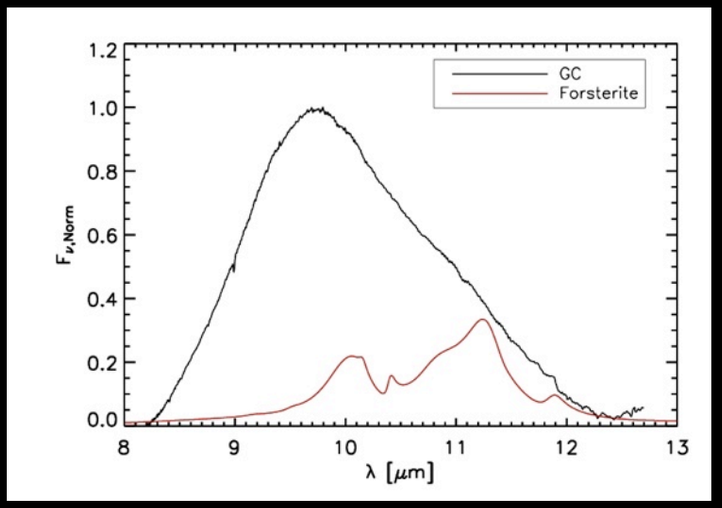

Where and when exactly do crystals form?

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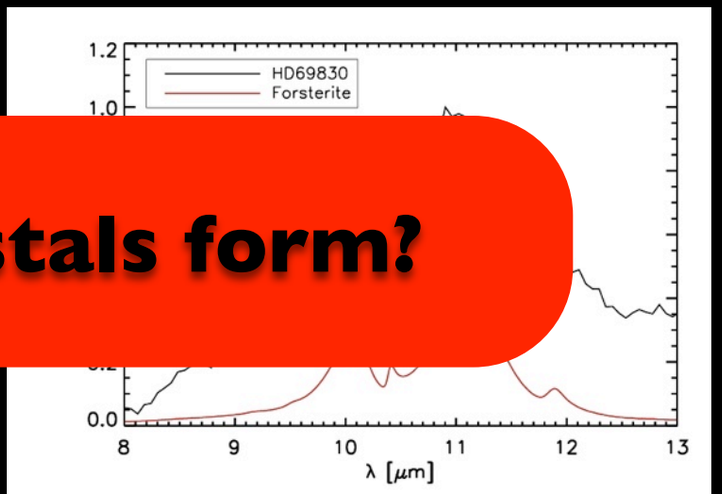

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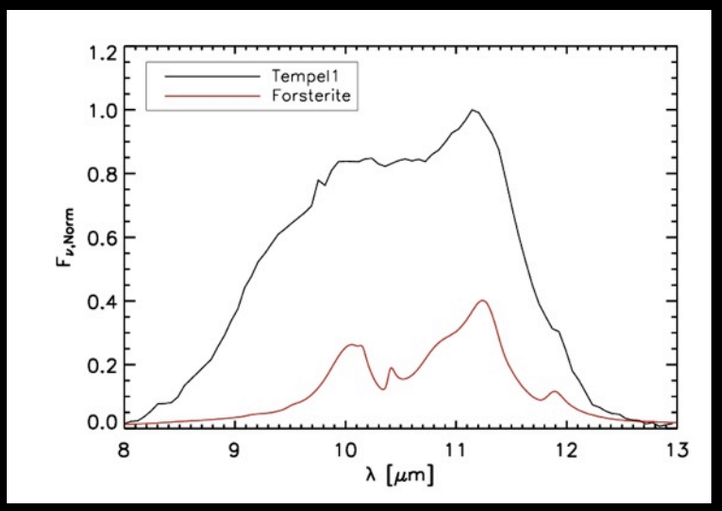

Crystal formation in protoplanetary disks

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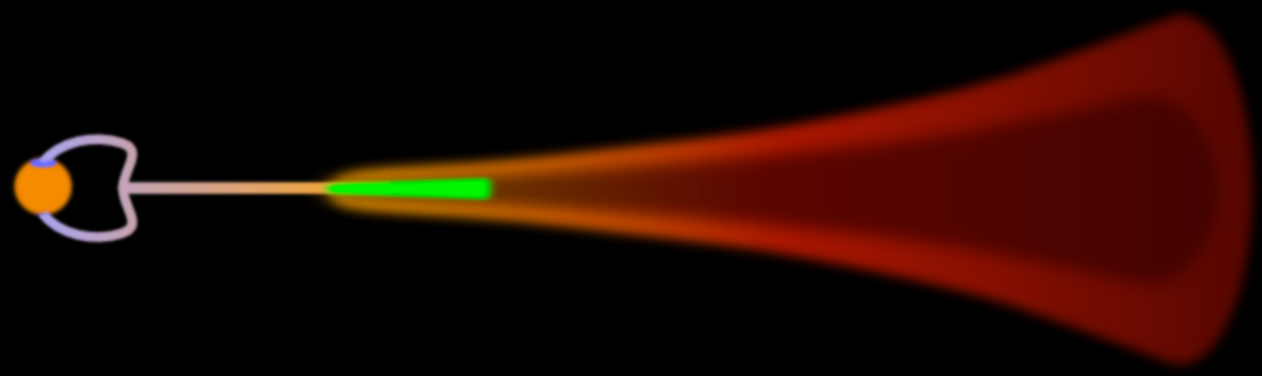

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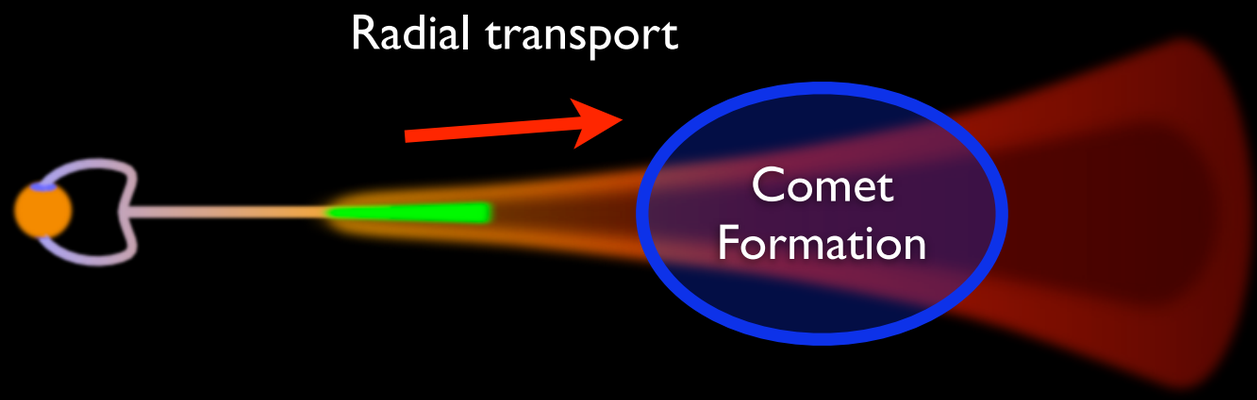

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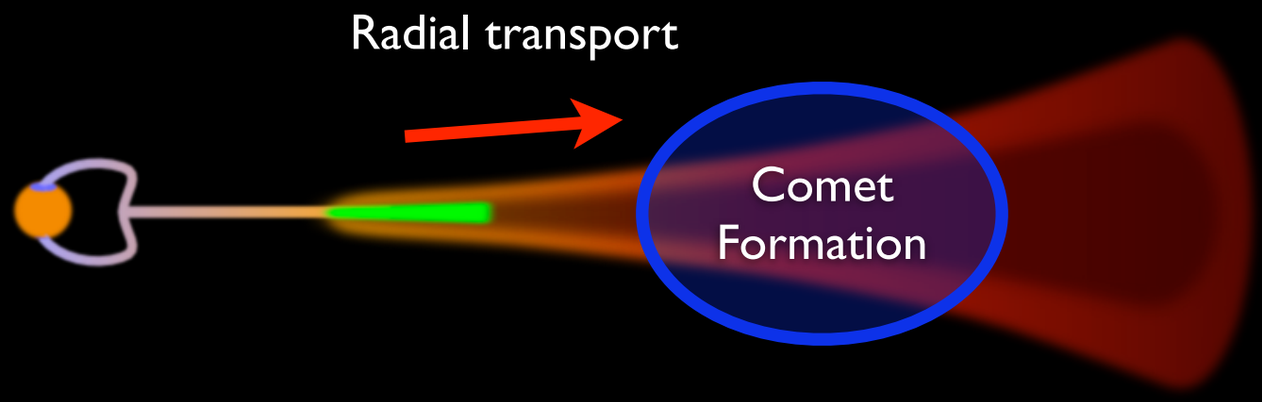

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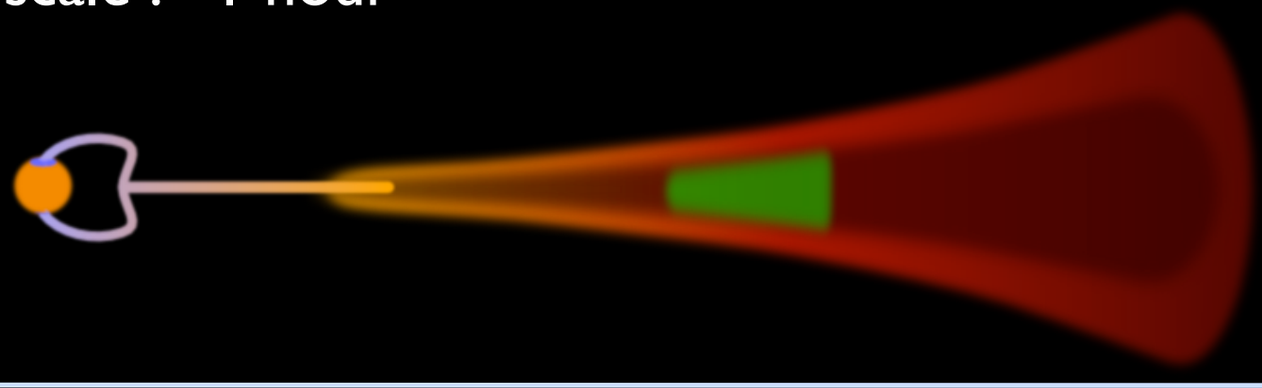

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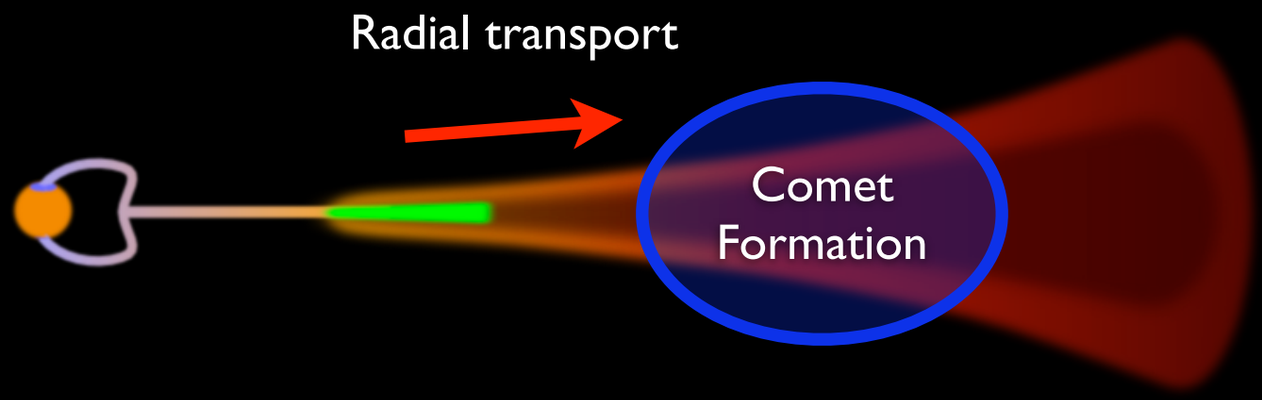

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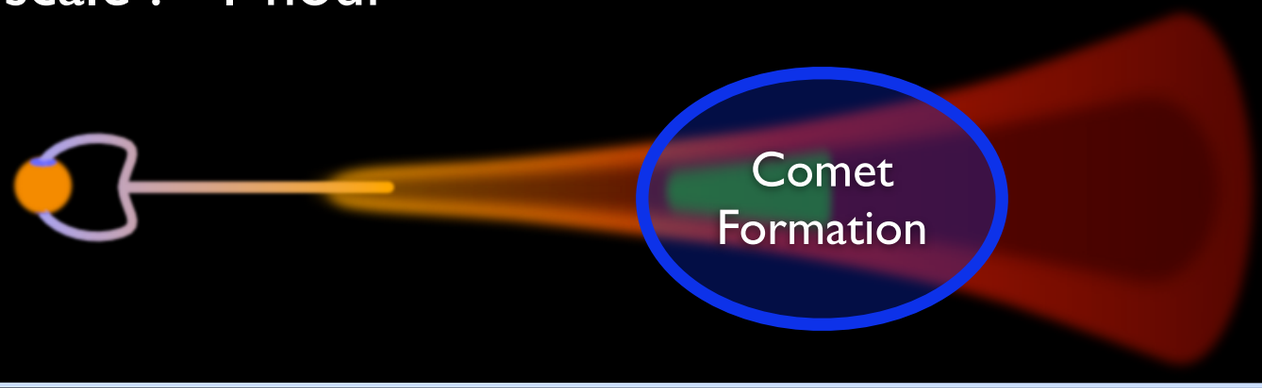

Eruptive stars in a nutshell

FU Ori type objects (FUors):

Brightening in the optical by 4-6 mag
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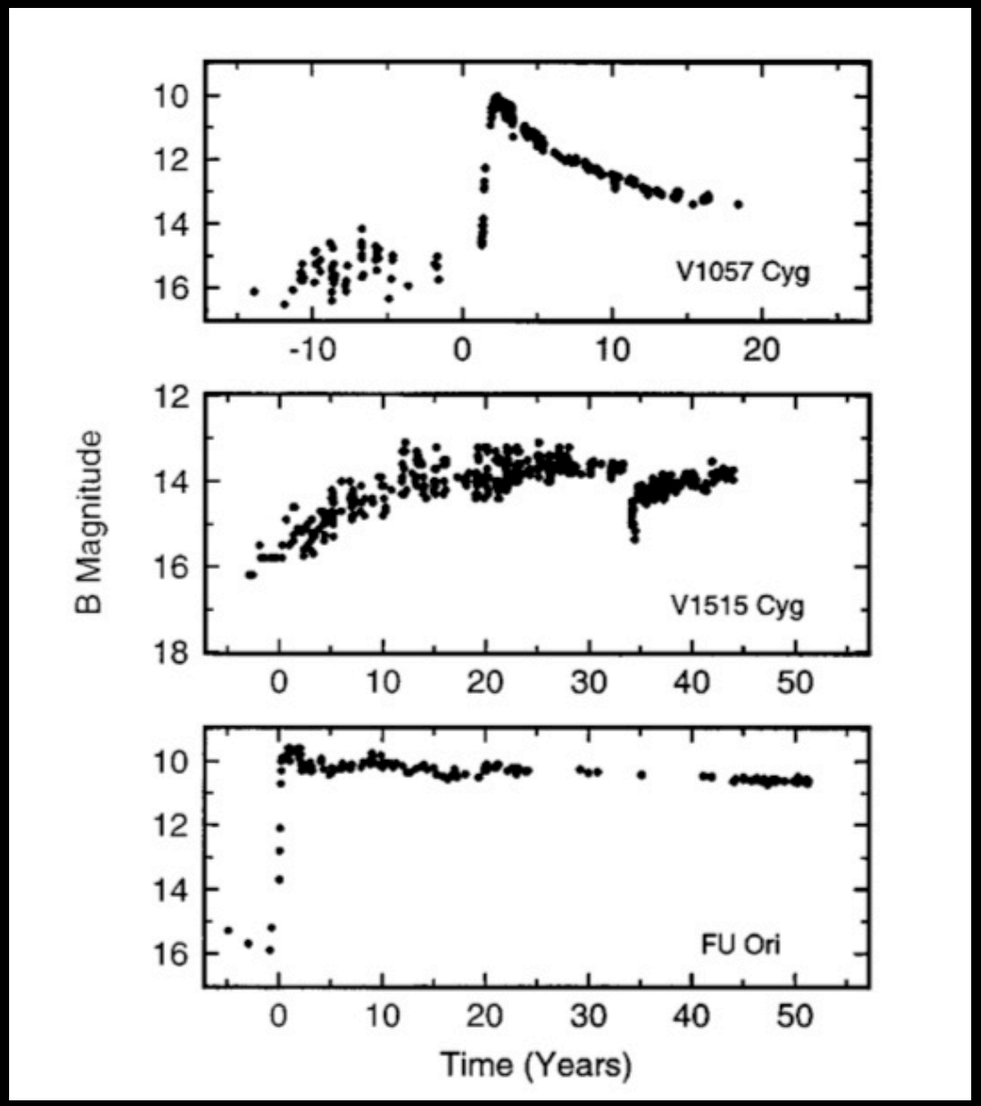

Hartmann & Kenyon (1996)

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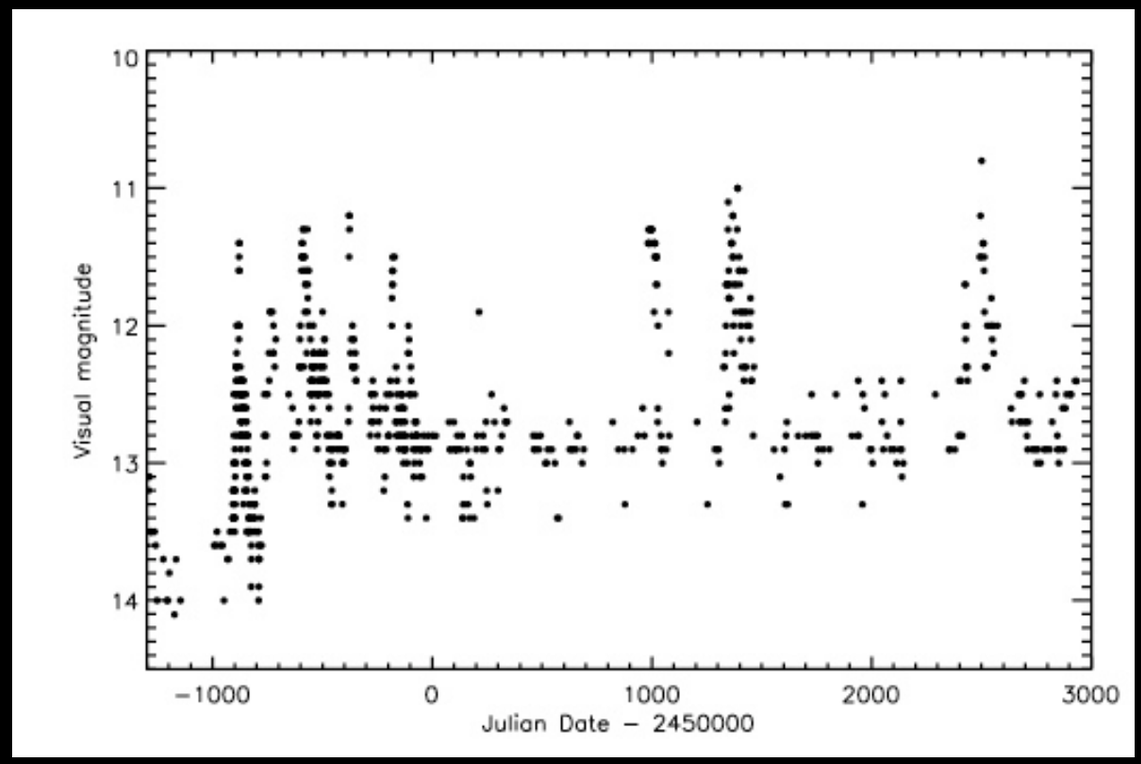

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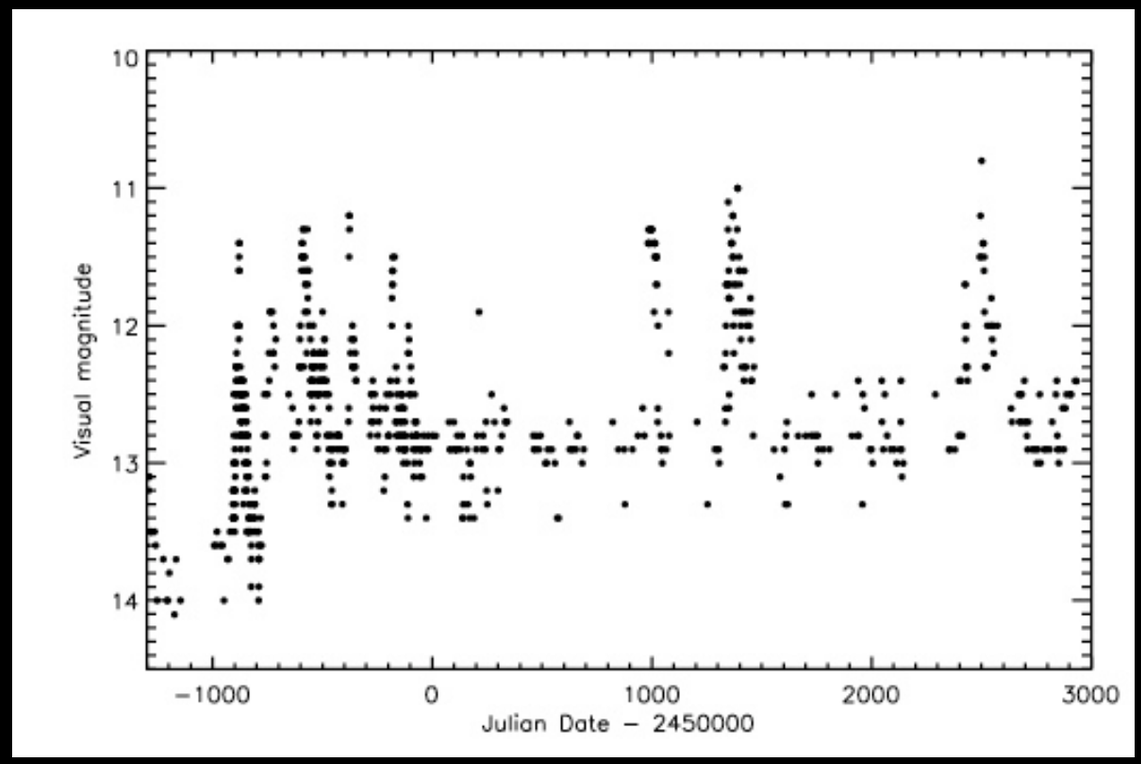

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Explanation of the outbursts

- Runaway accretion onto the central star (up to 10^{-4} Msun/year)
- Accretion luminosity >> stellar luminosity

Sicliate crystals around eruptive stars

Requirement for crystal formation : high temperature (only)

FUor / EXor outbursts - enhanced viscous heating / irradiation

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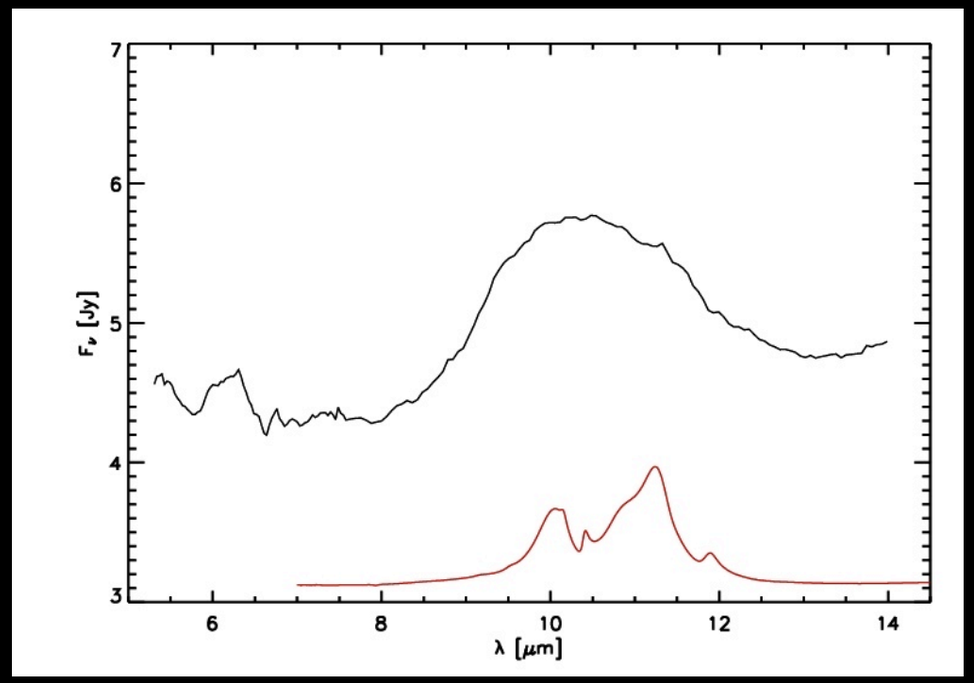

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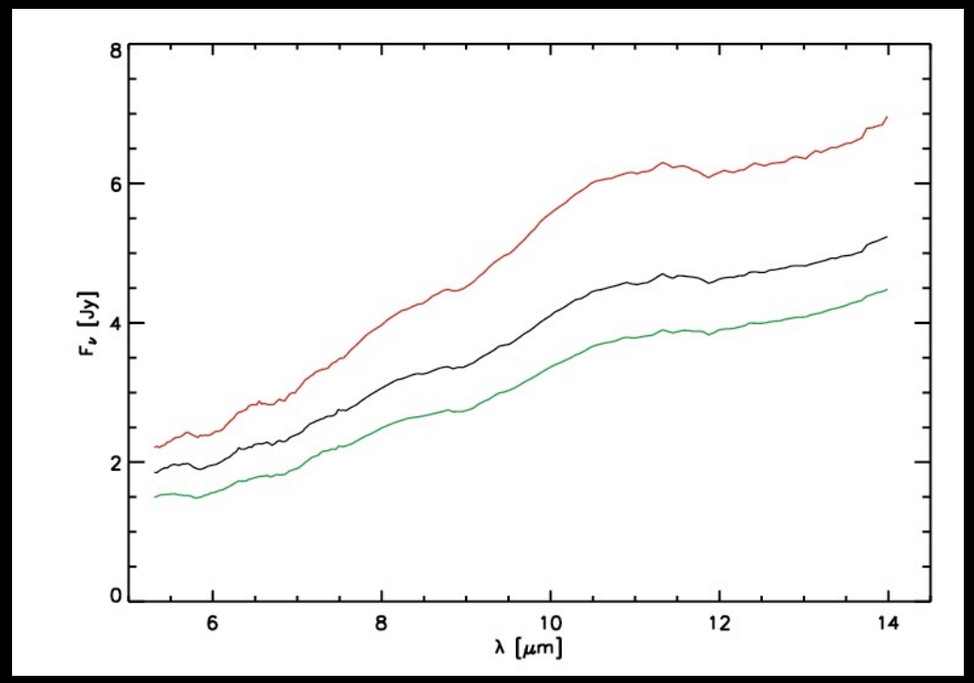

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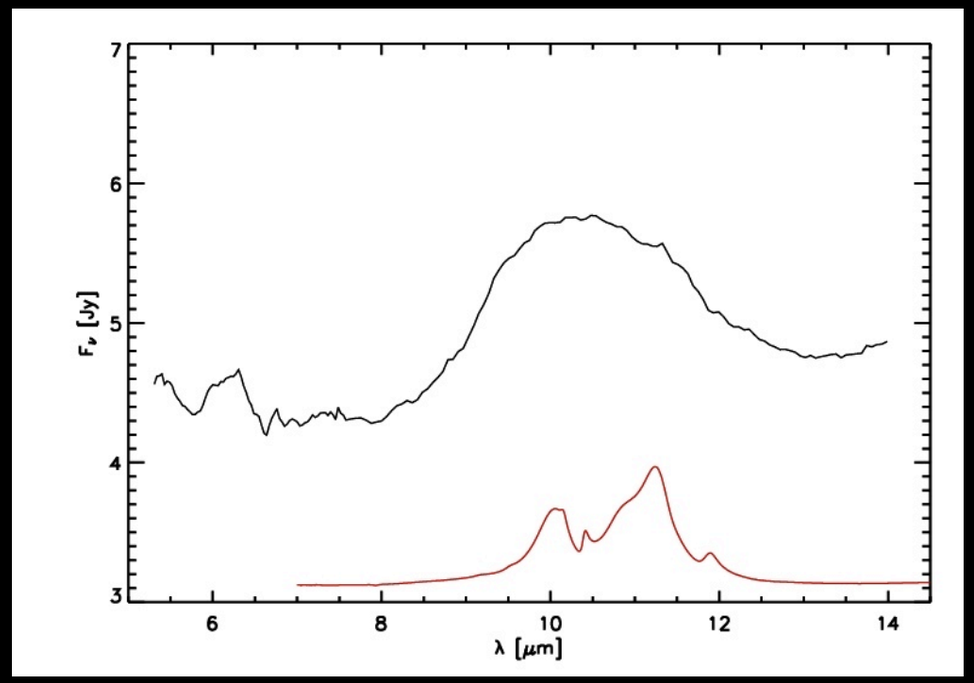

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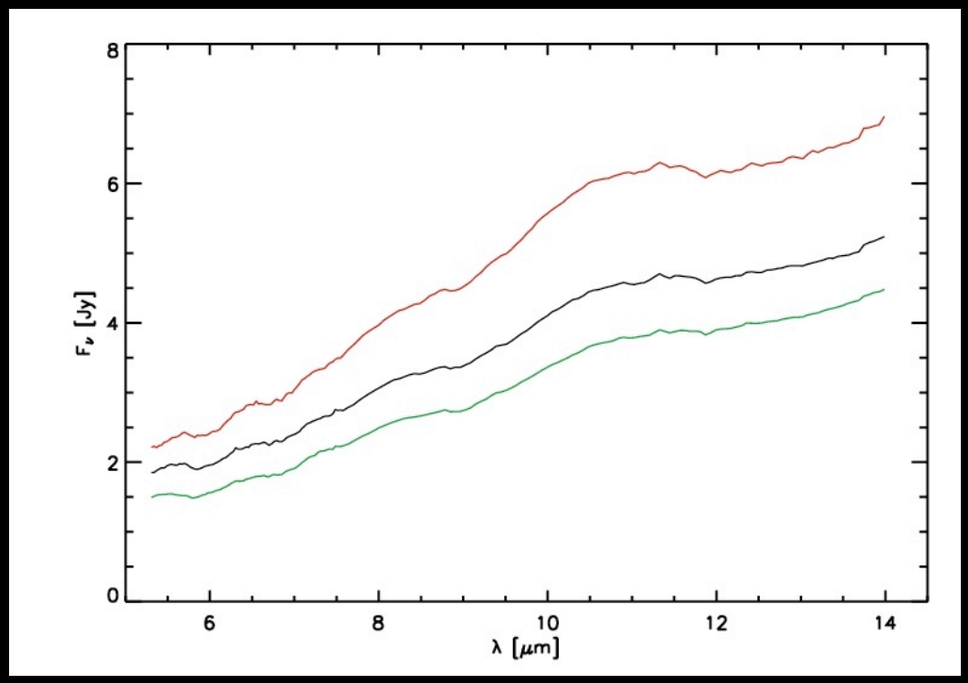

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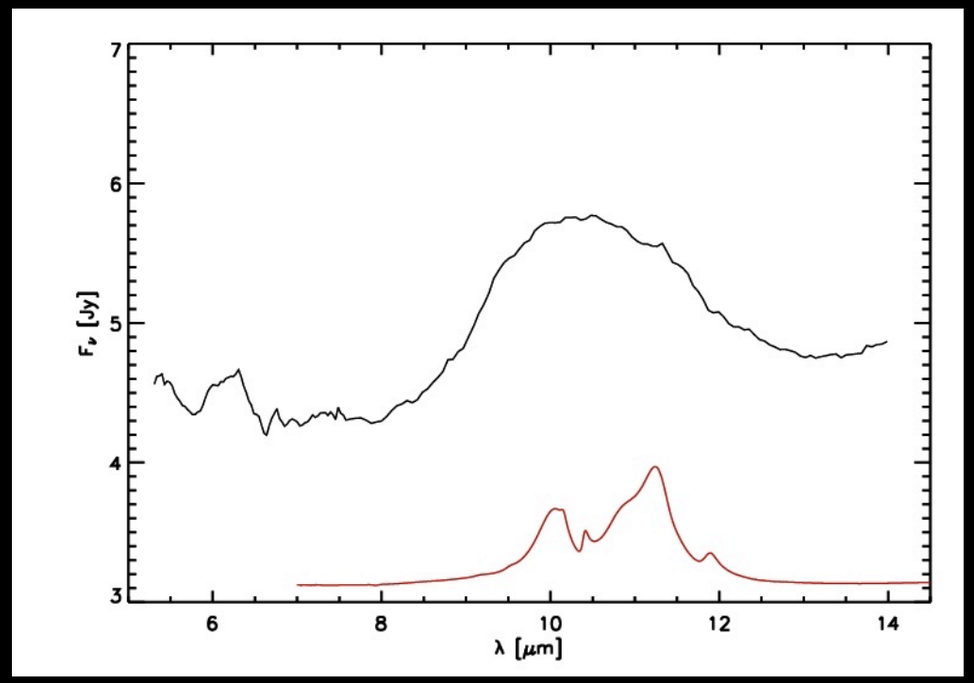

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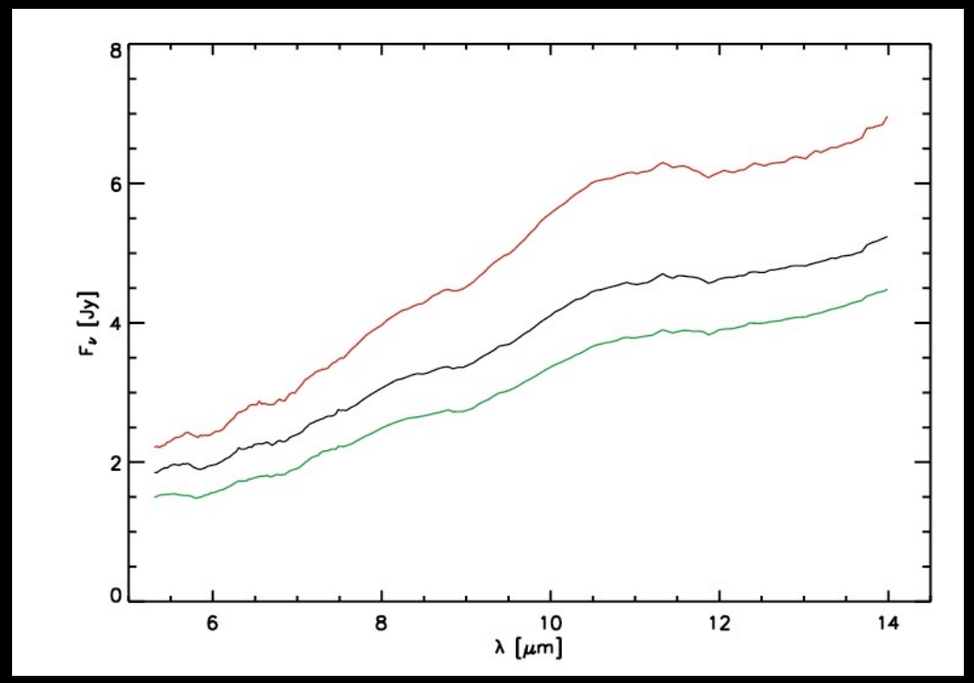

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Speculative explanation :

- Strong vertical mixing in the disk
- Replenishment of amorphous grains from a remnant envelope

EX Lup

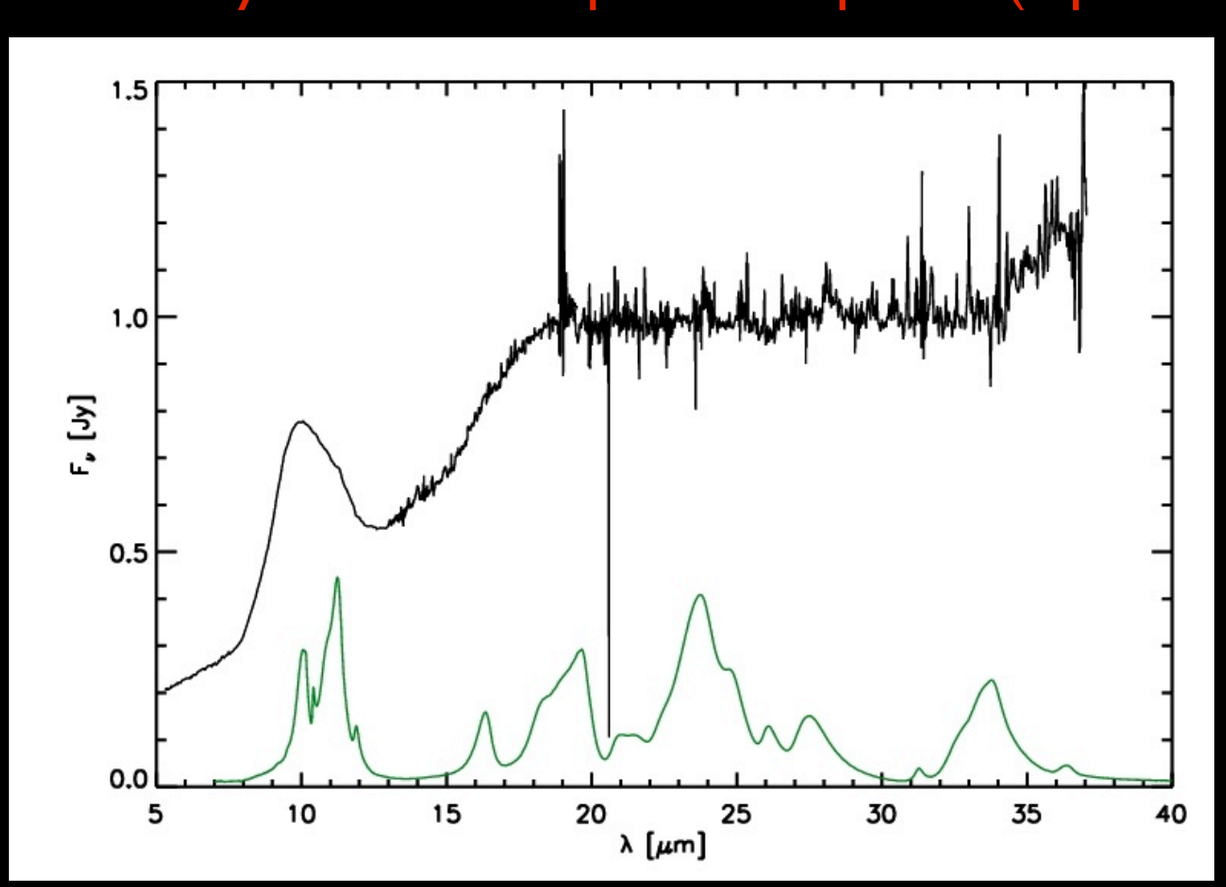
Who is EX Lup?

Prototype of the EXor class of young eruptive stars

No sign for an envelope has been found

Age	1-3 Myr	
Mass	0.6 M_{Sun}	
Spectral type	M0	Gras-Velazquez & Ray (2005)
Luminosity	0.47 L_{Sun}	
Distance	155 pc	

No signatures of silicate crystals in the quiescent phase (Sipos et al. 2009)



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- accuracy of his observations: ~0.1 mag (Herbig et al. 1992)
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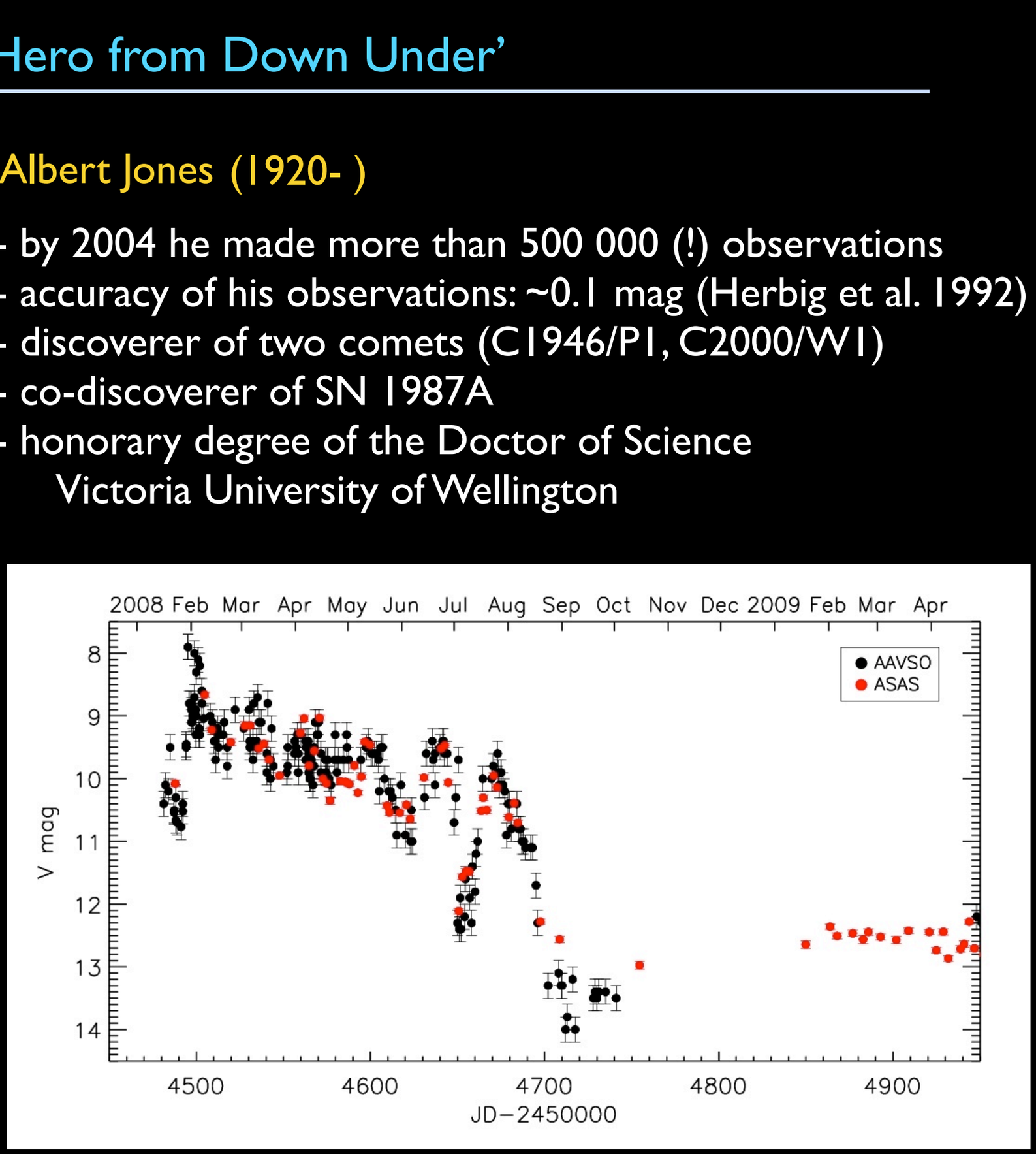
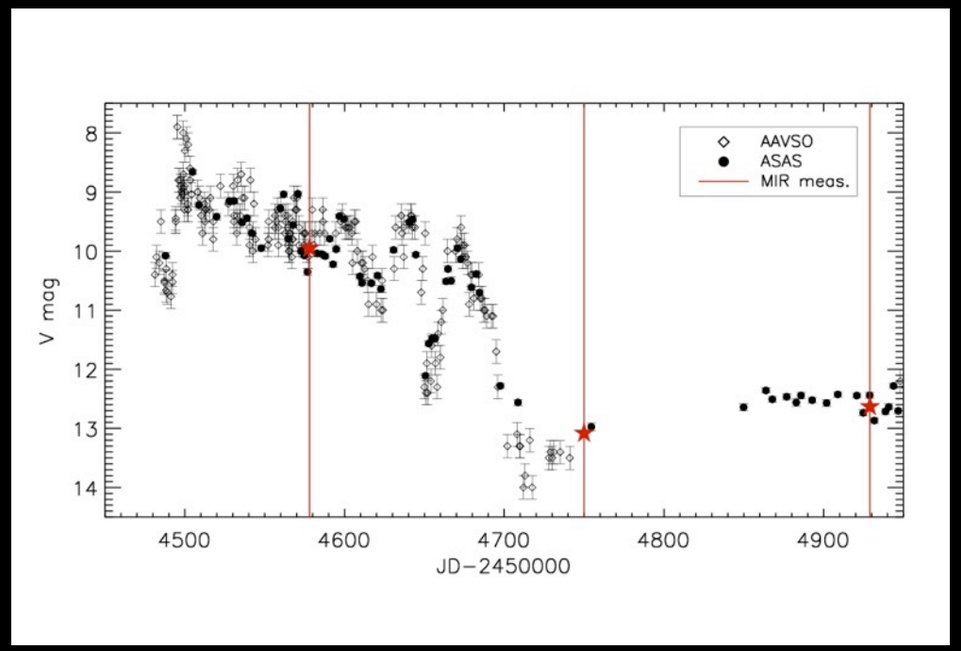


Discovery of forsterite crystals



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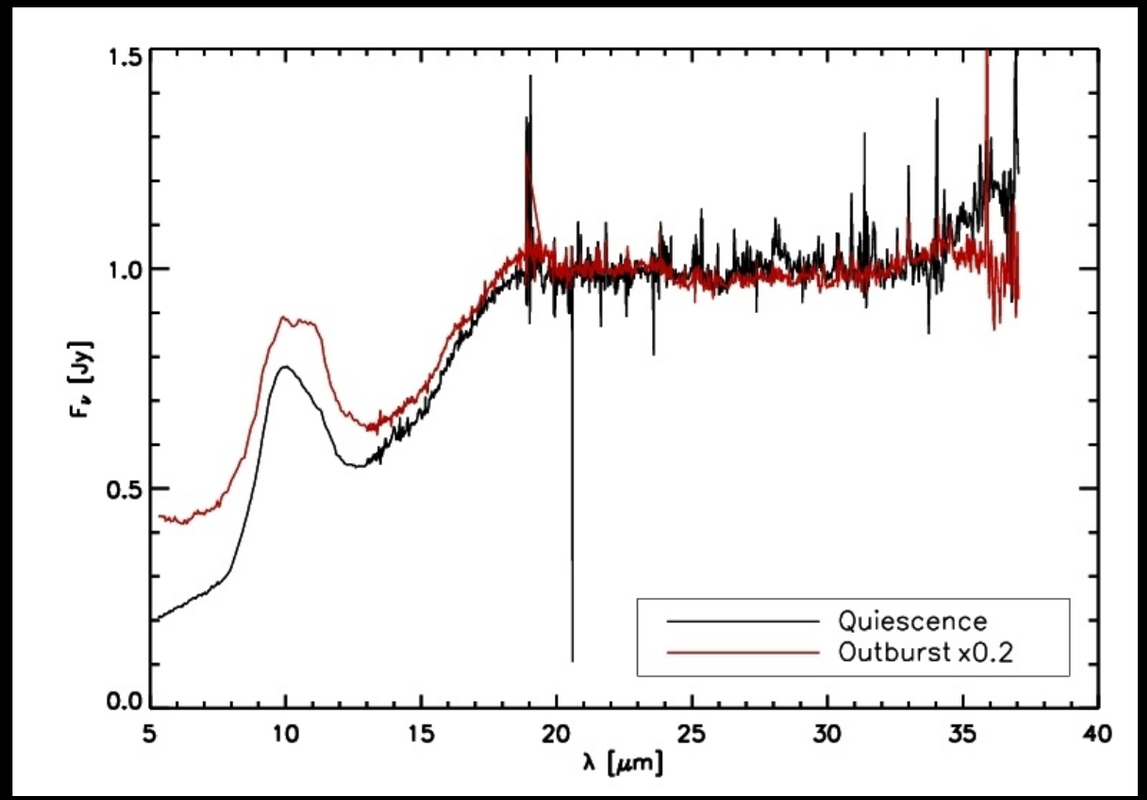

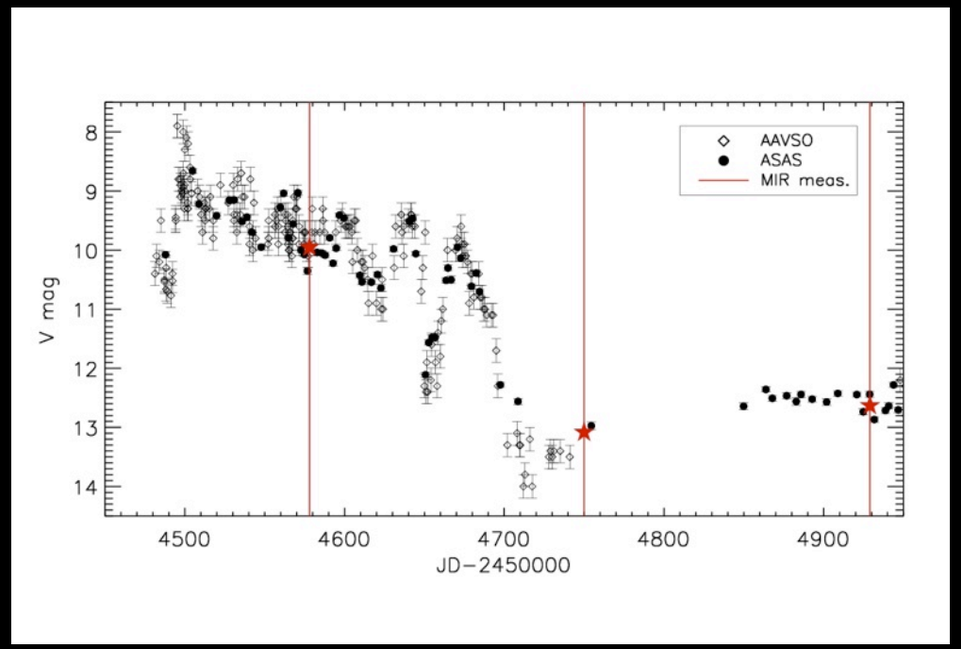

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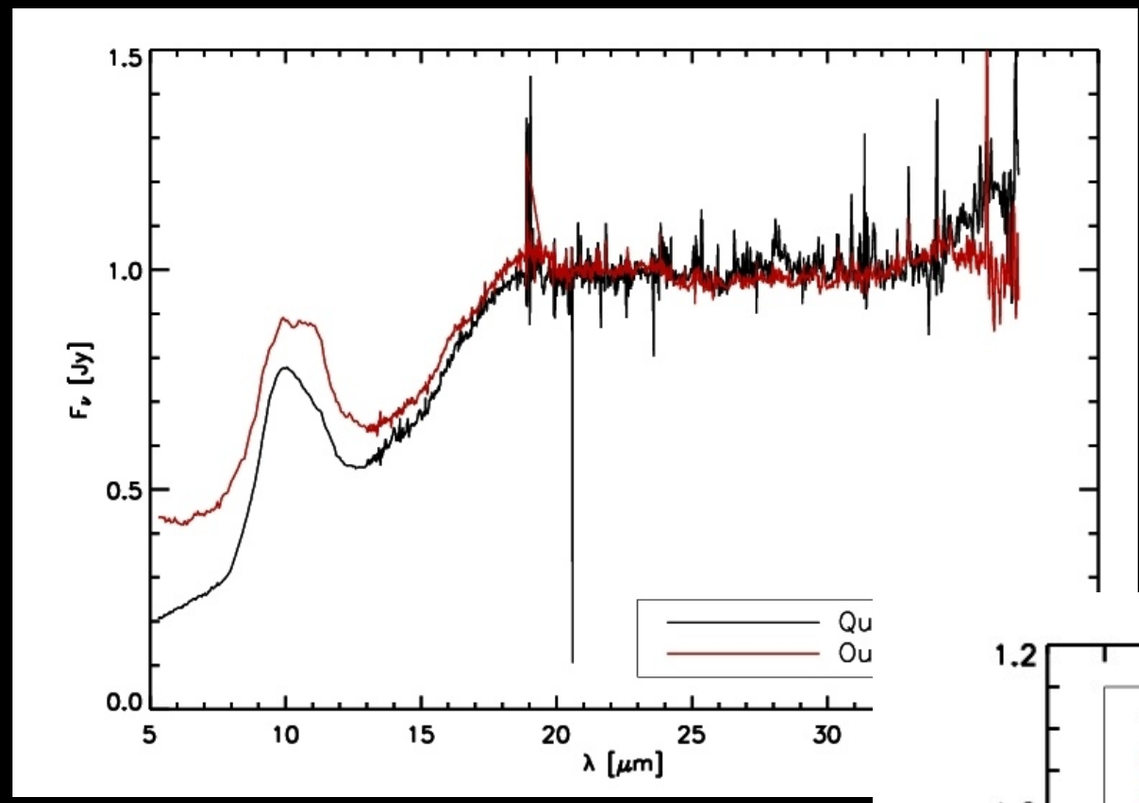

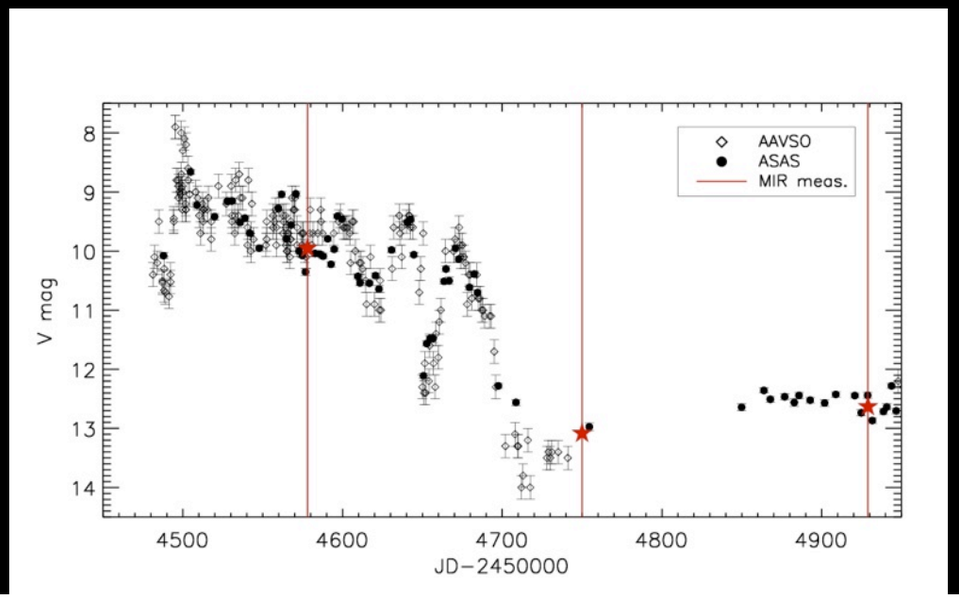

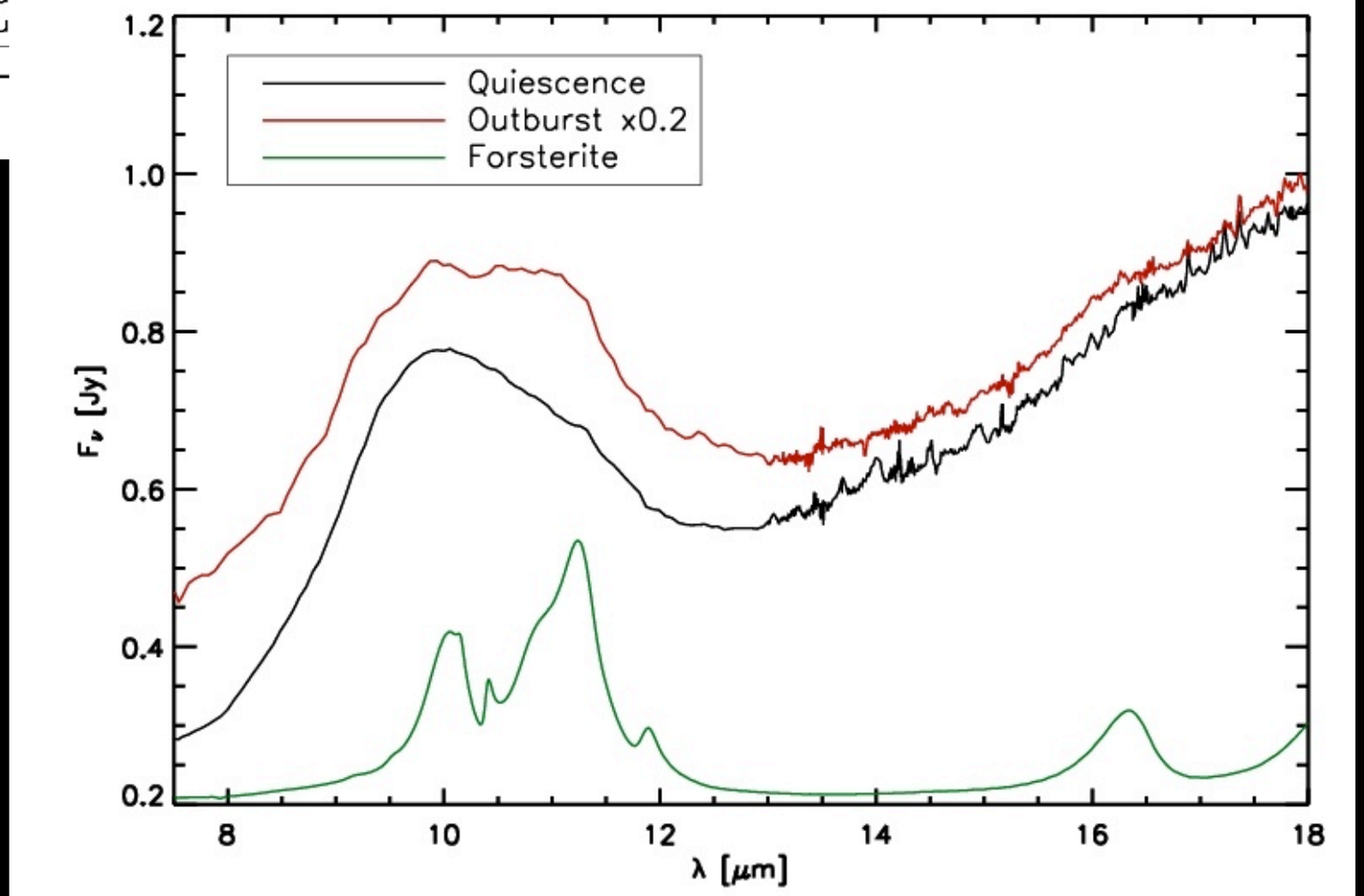

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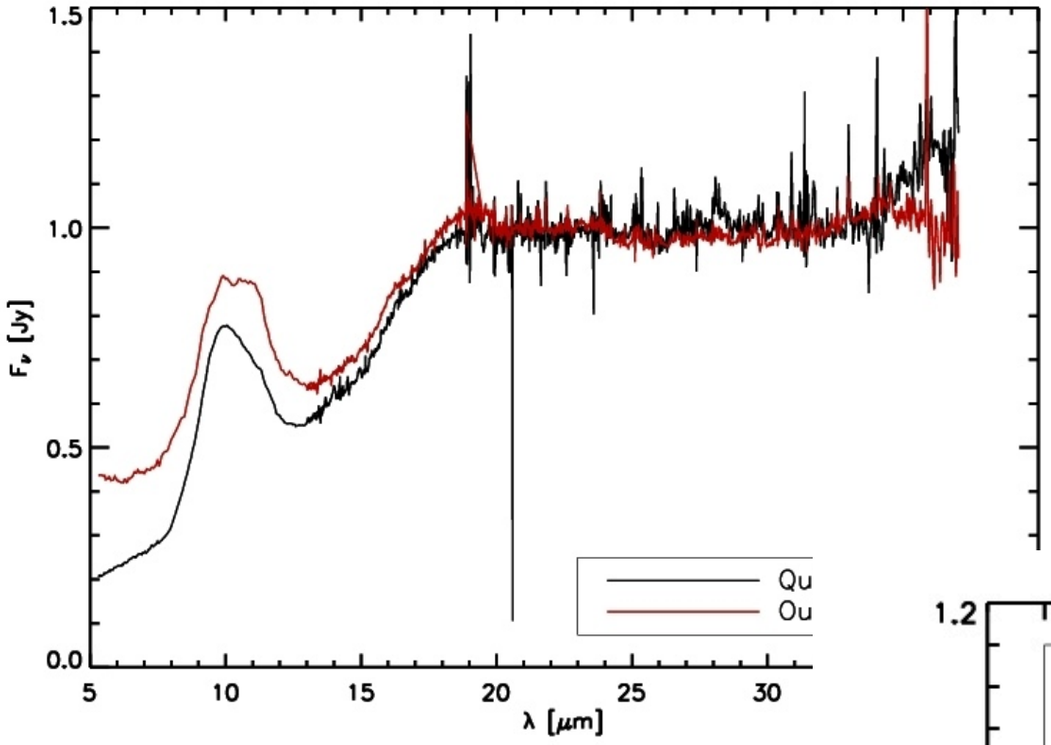

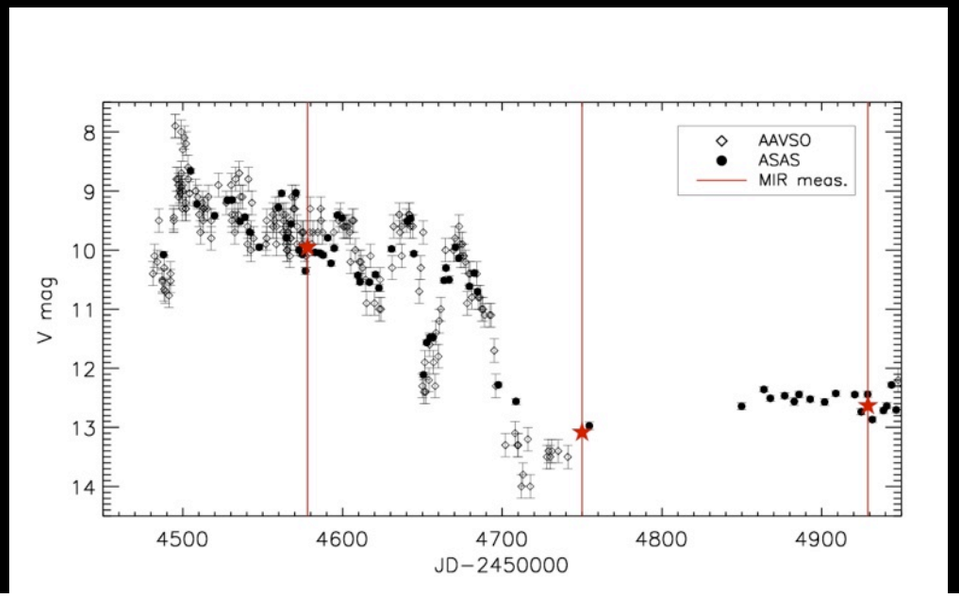

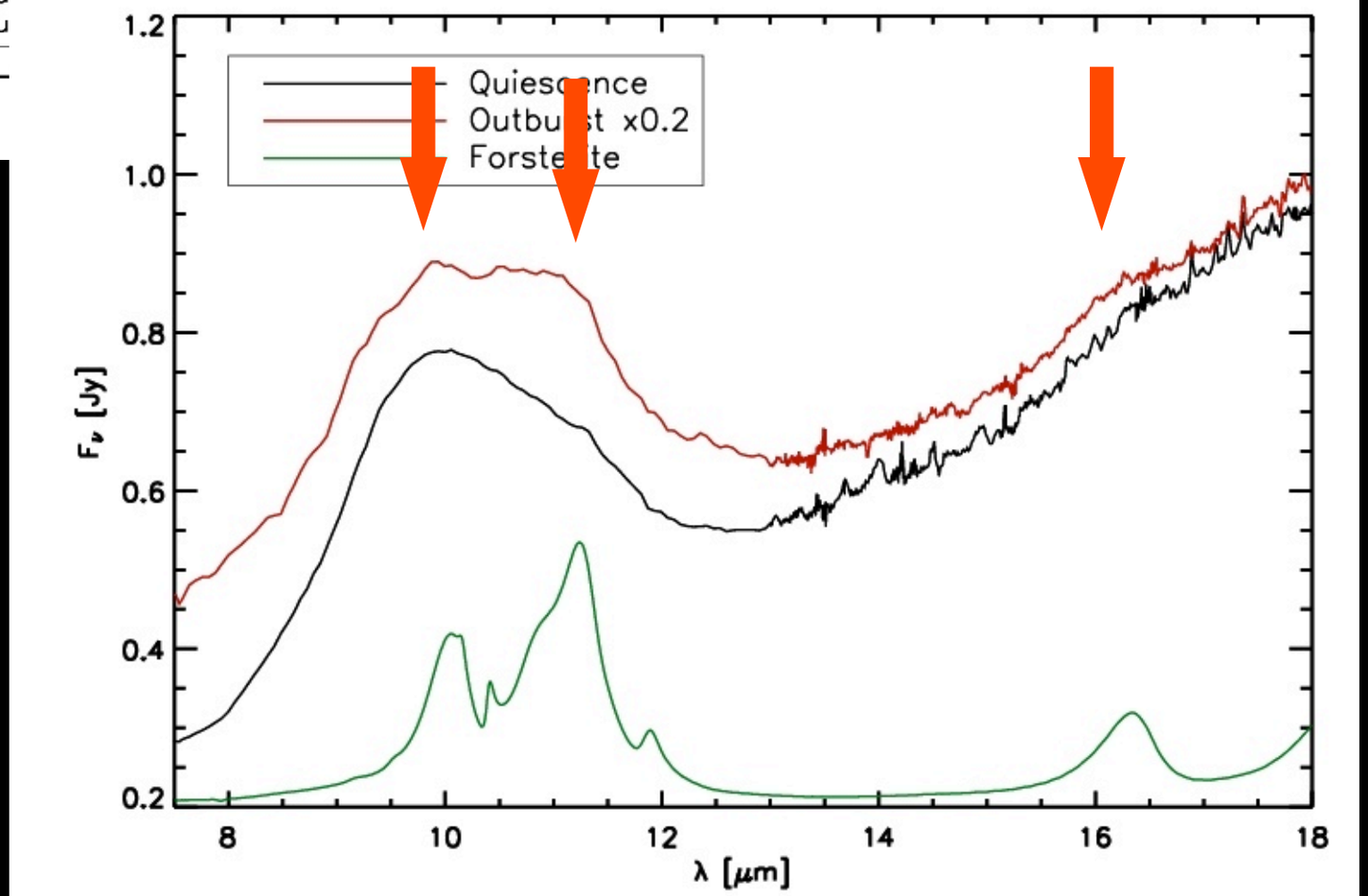

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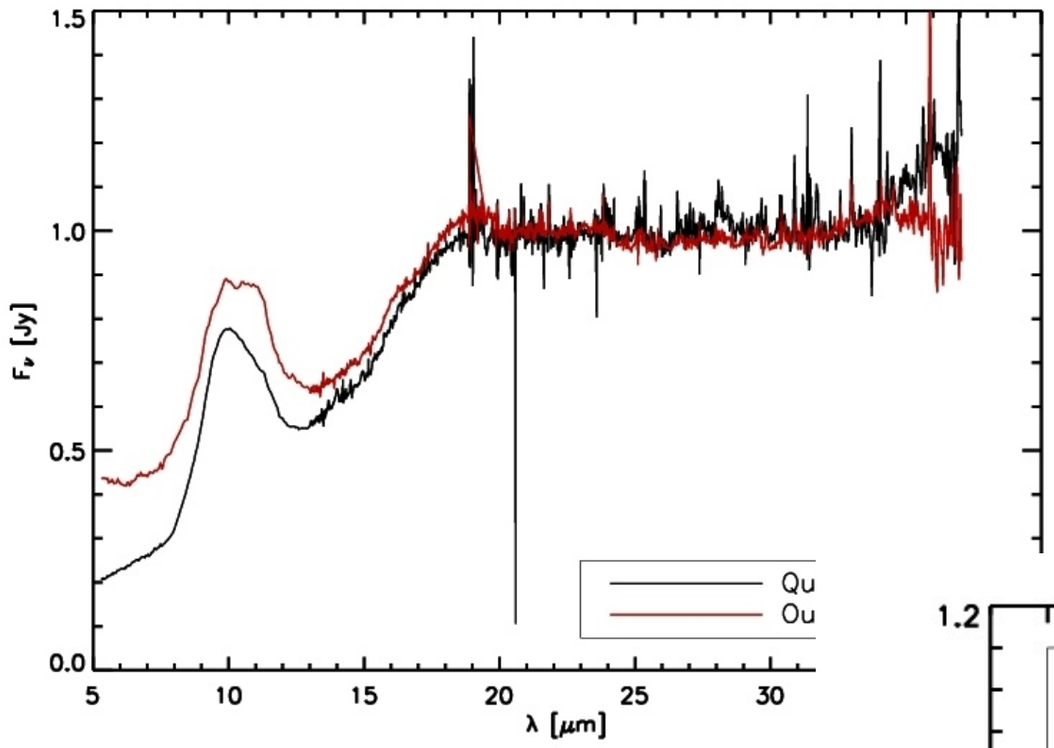
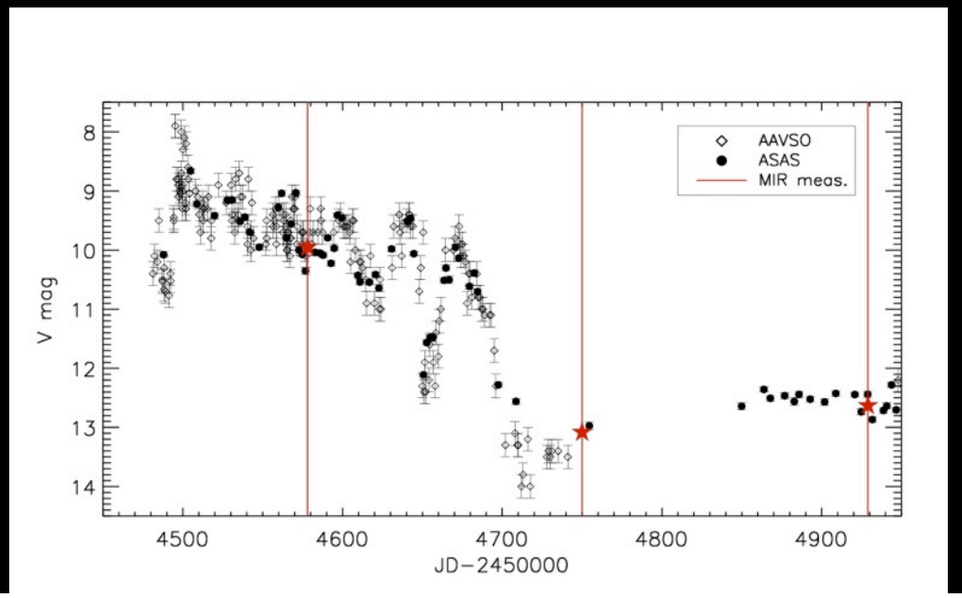
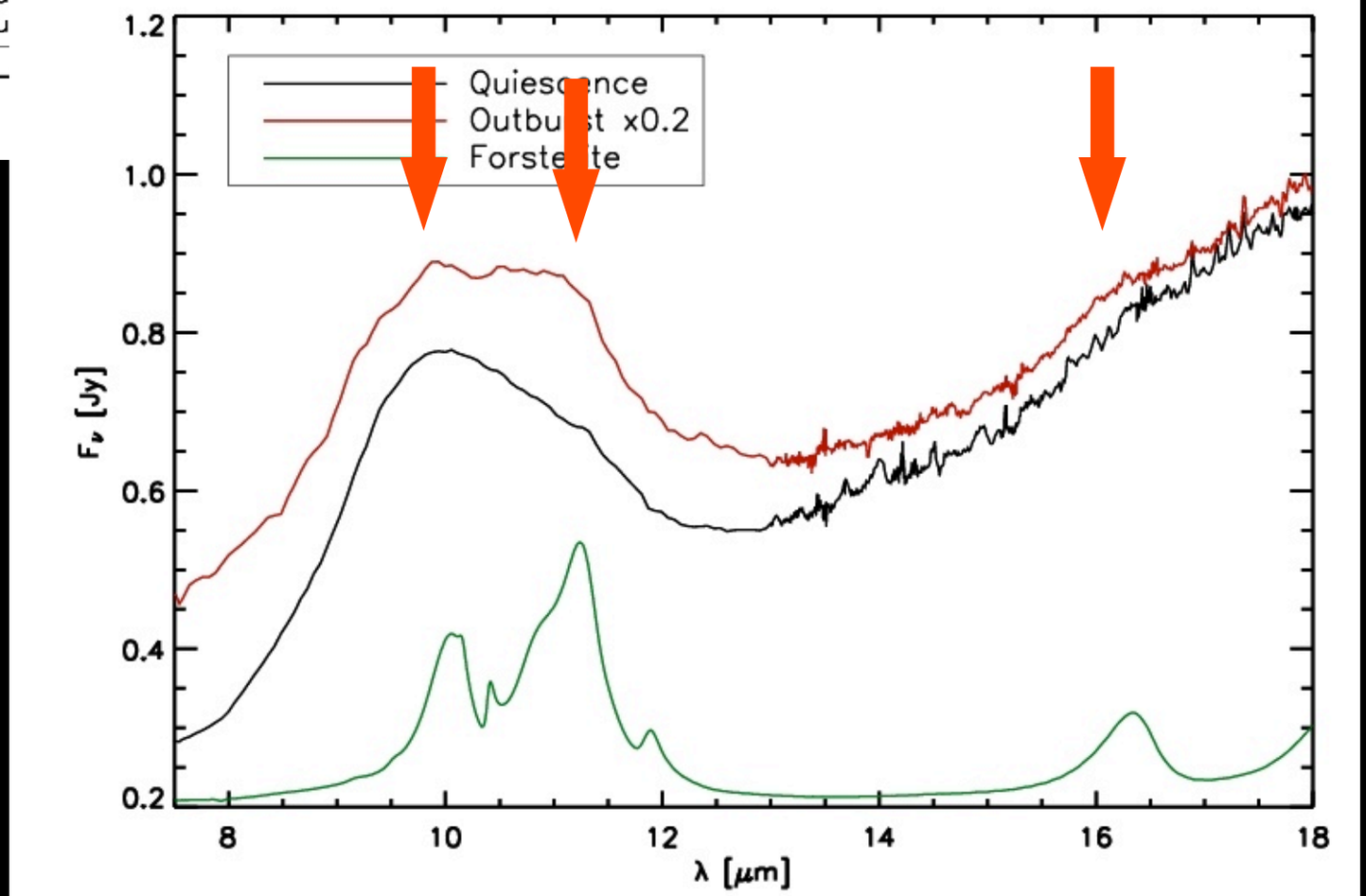




First direct observation of silicate crystal formation around young stellar objects! (Ábrahám, Juhász et al. 2009)



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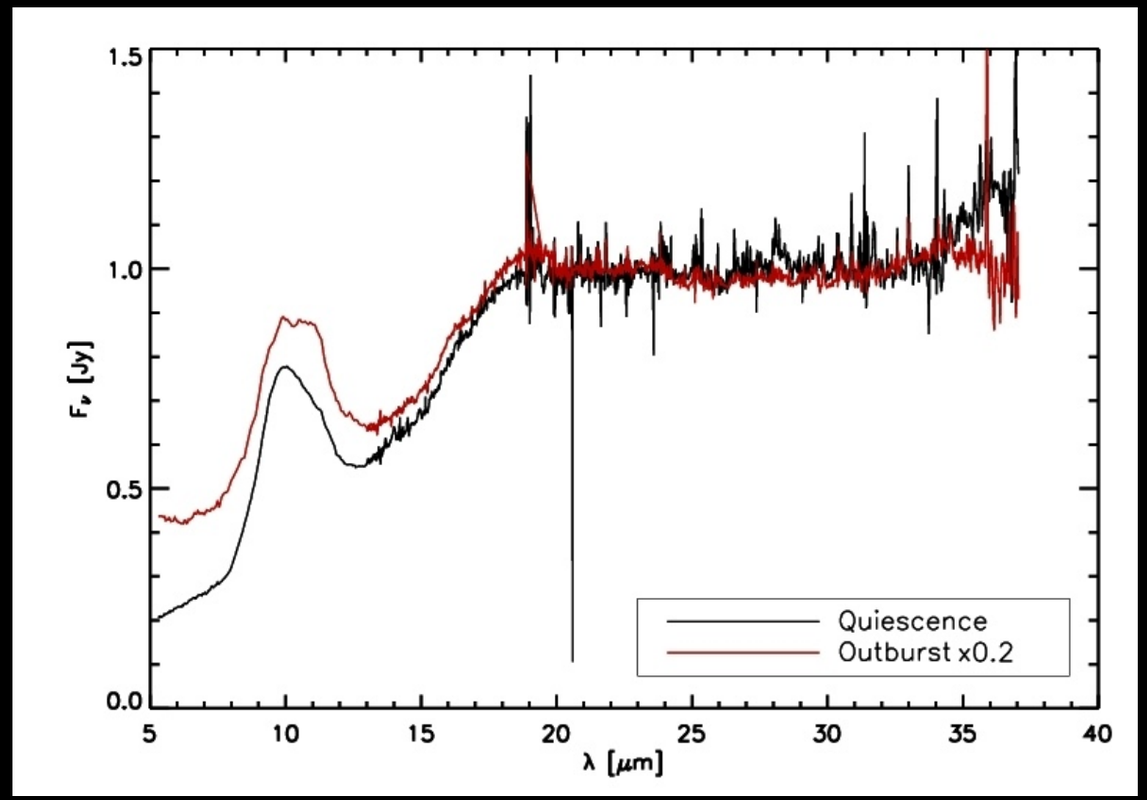

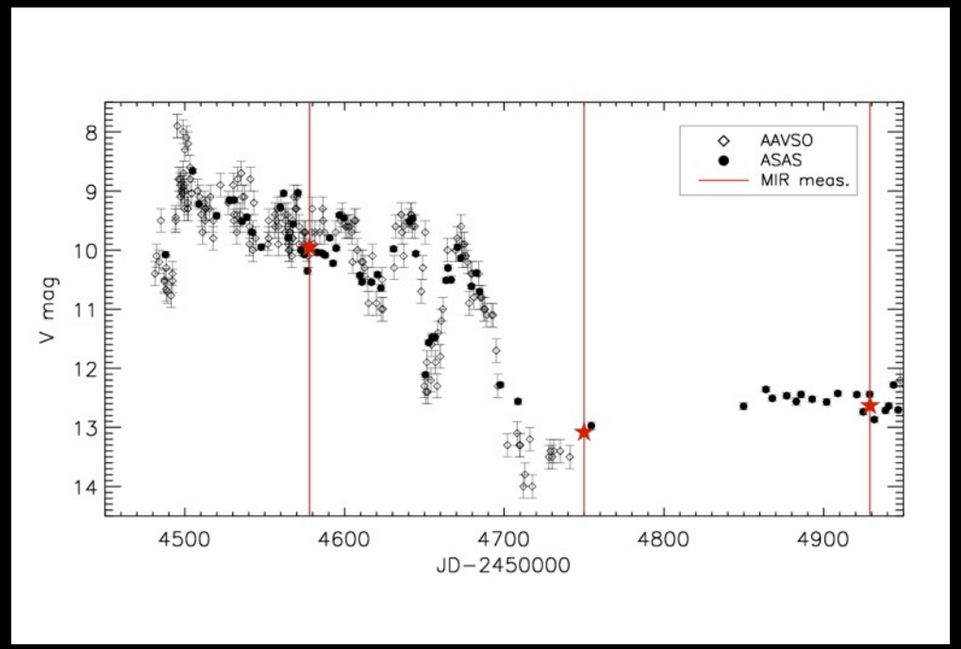

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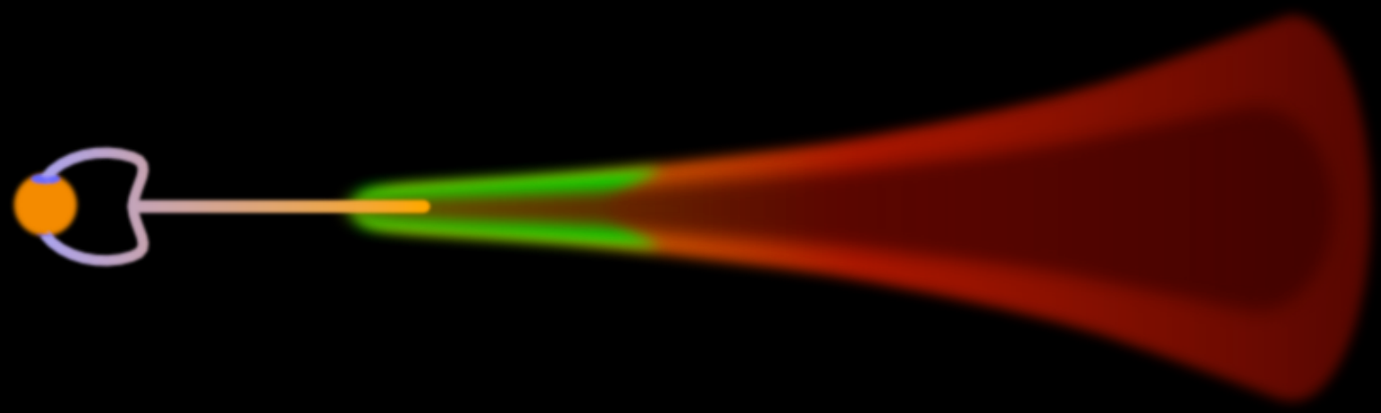
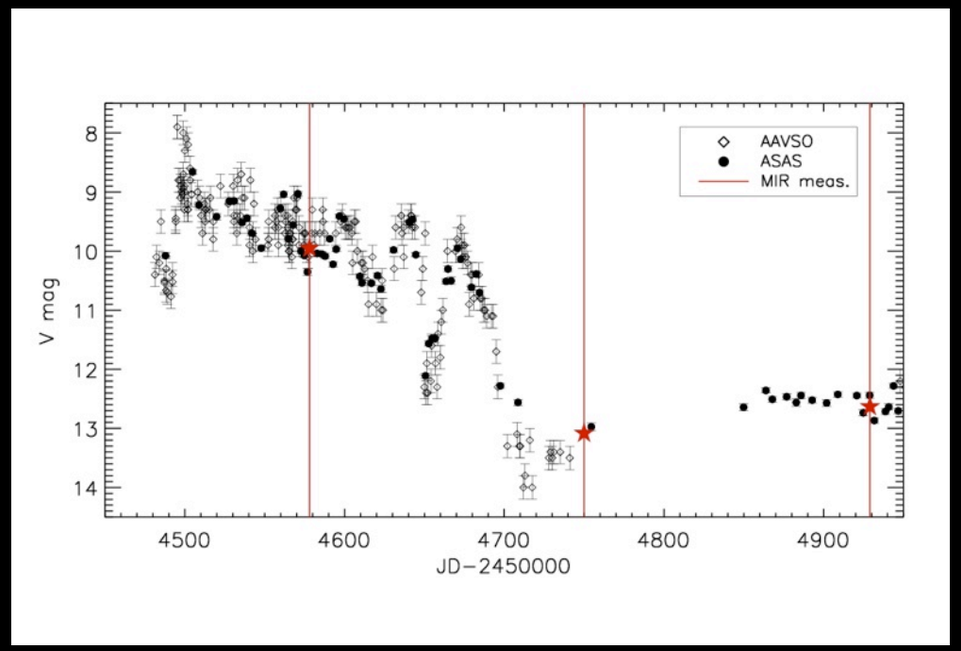


What has happened 50 years ago?



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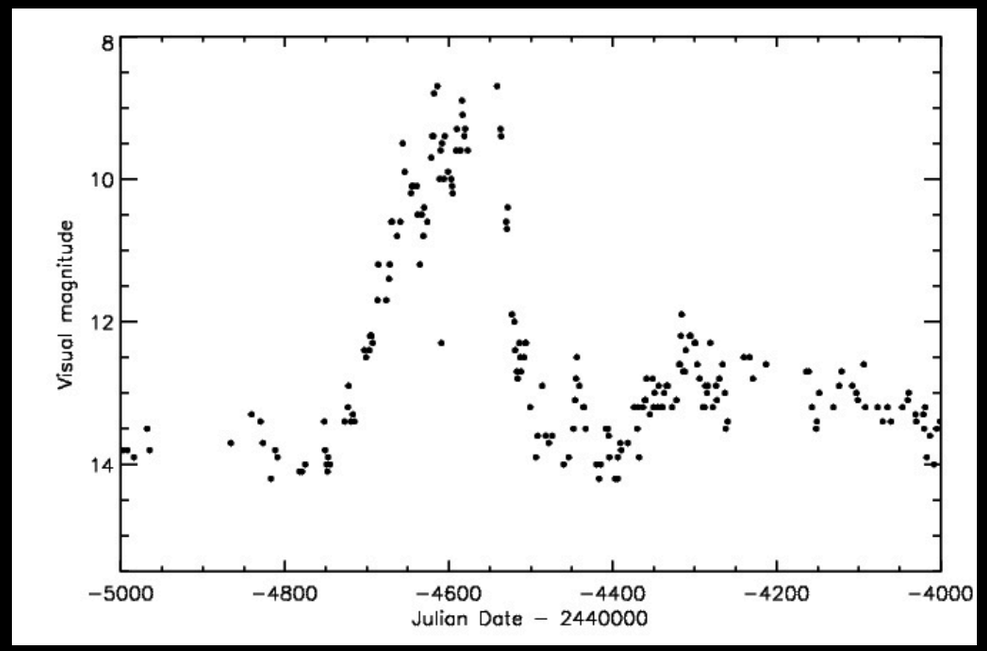

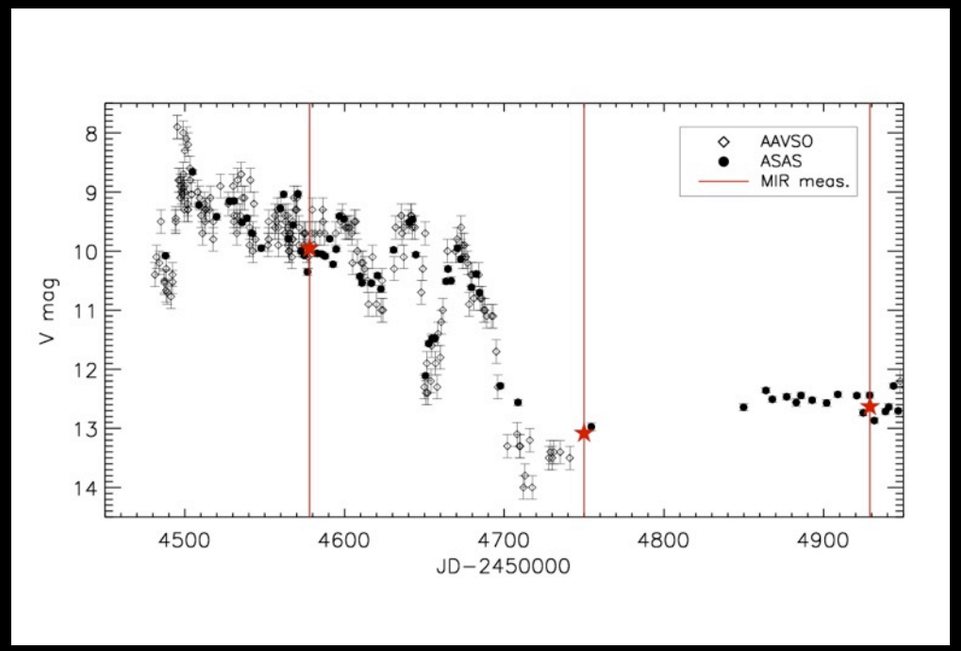

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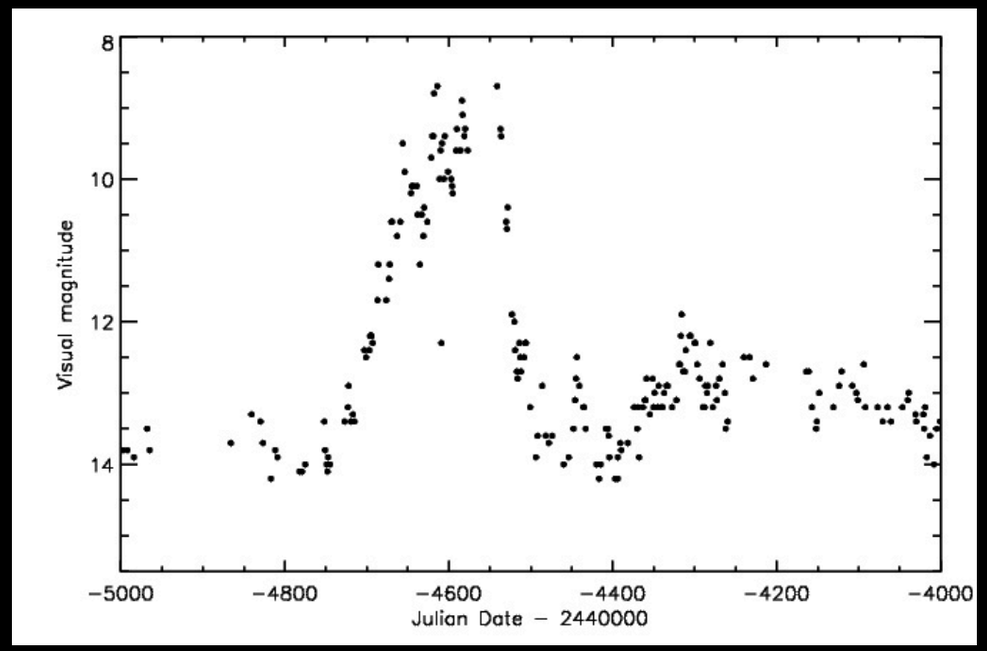

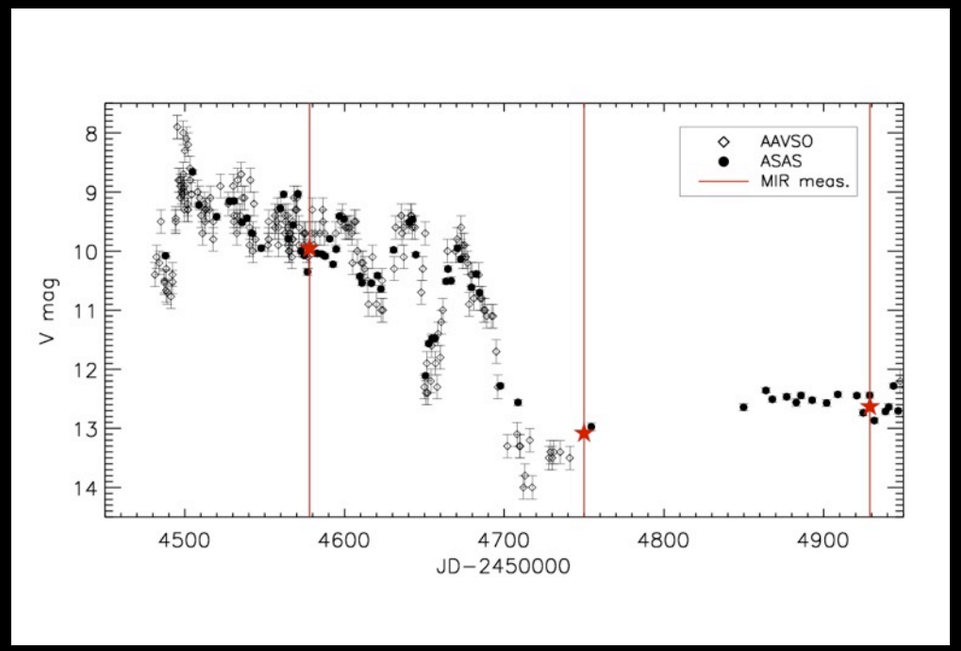

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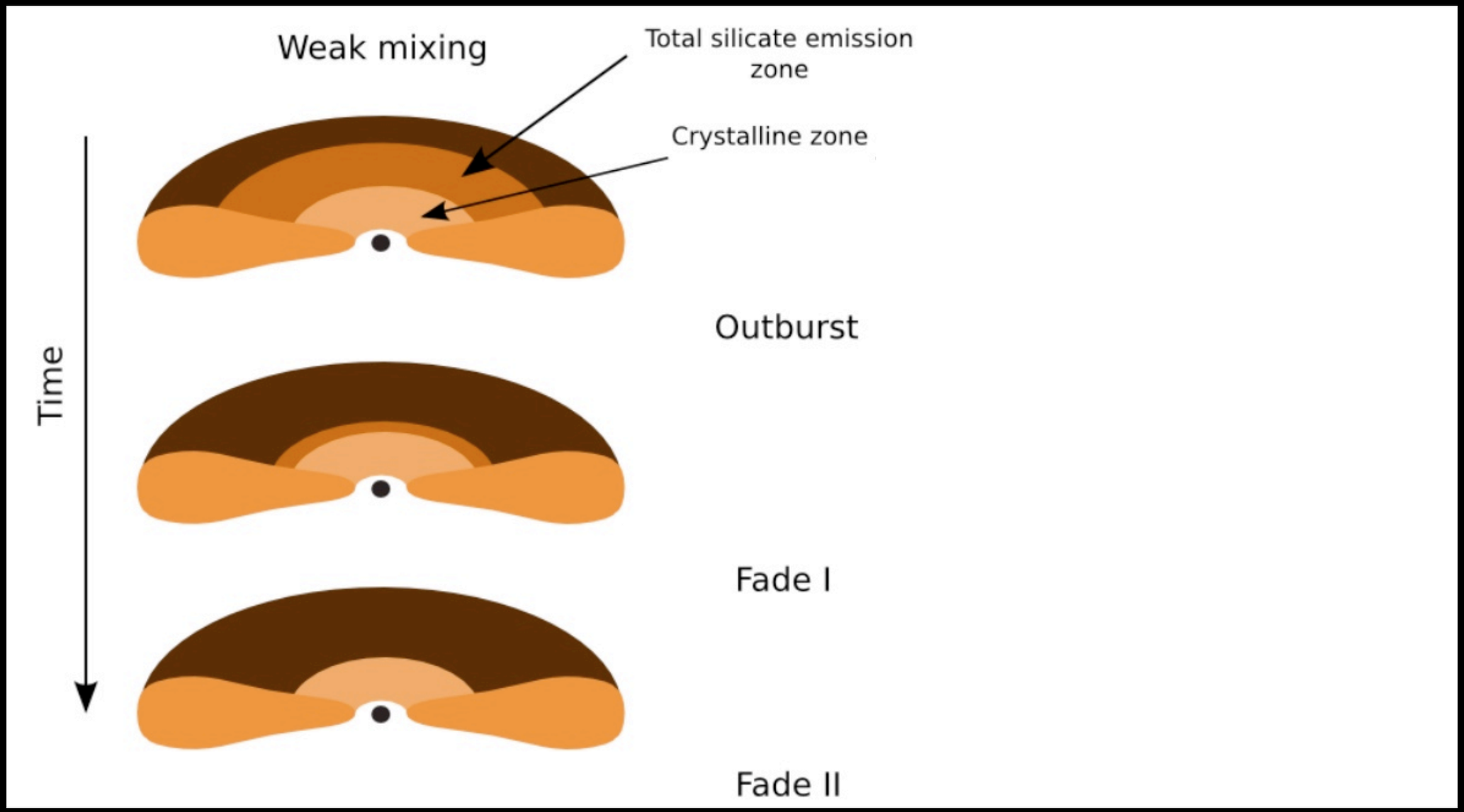
Why did we not see those crystals in the spectrum taken in 2004?
How did the crystals disappear?

Silicate crystals as tracers of turbulence

Total silicate emission zone: T> 150K
Crystalline zone: T> 1000K
Apparent crystallinity: $R^2_{Cryst} / R^2_{Silicate}$



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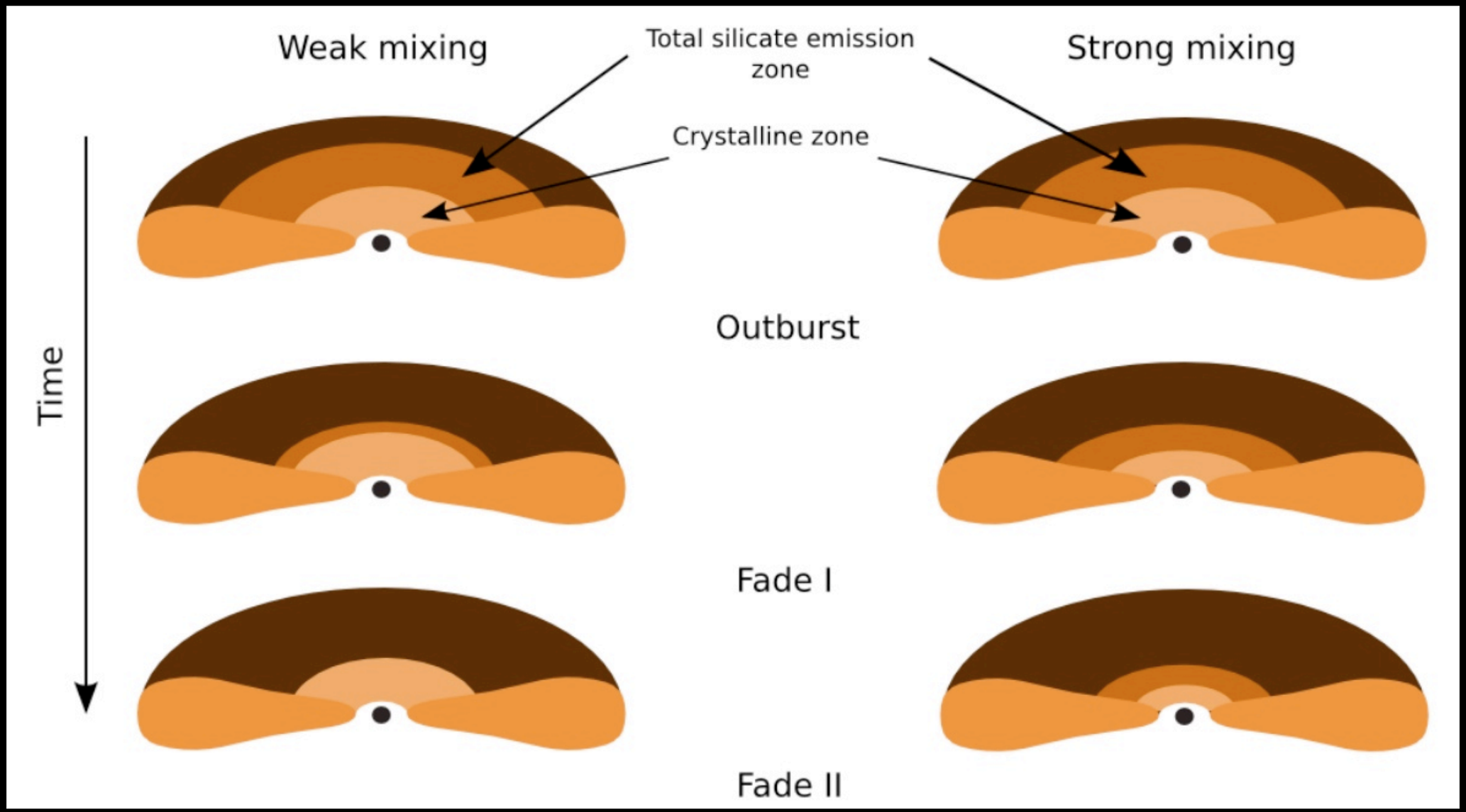
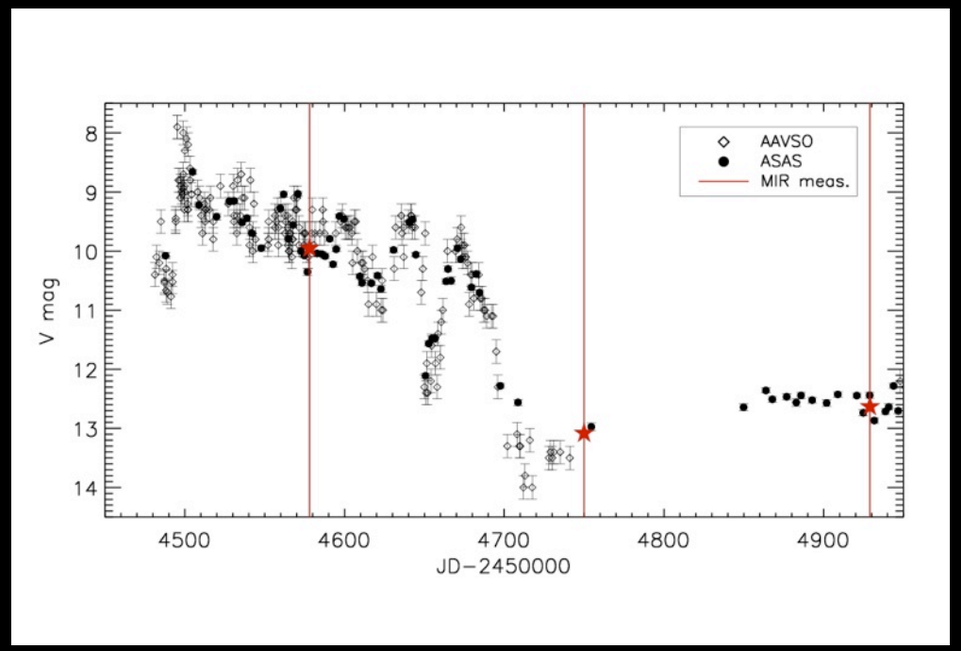


Cold crystals



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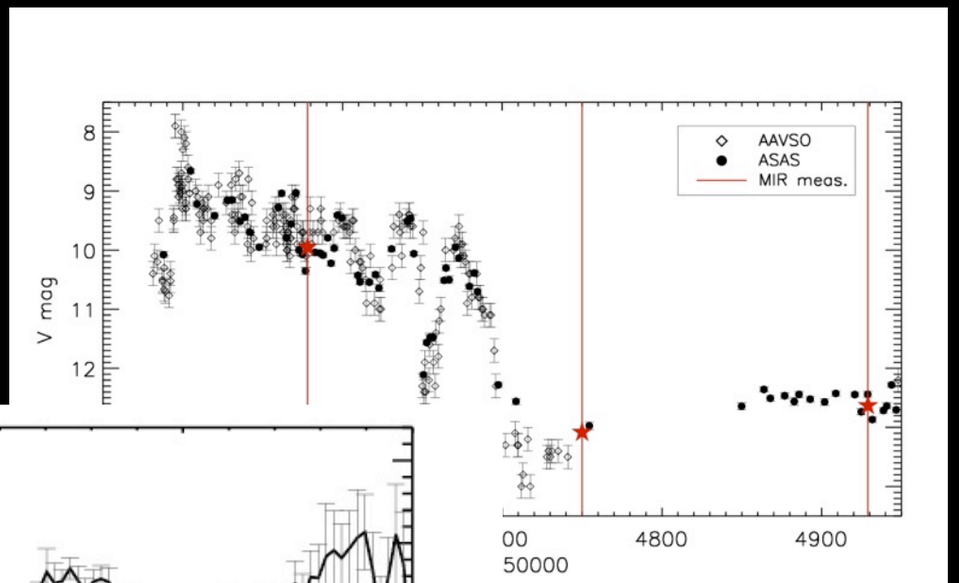

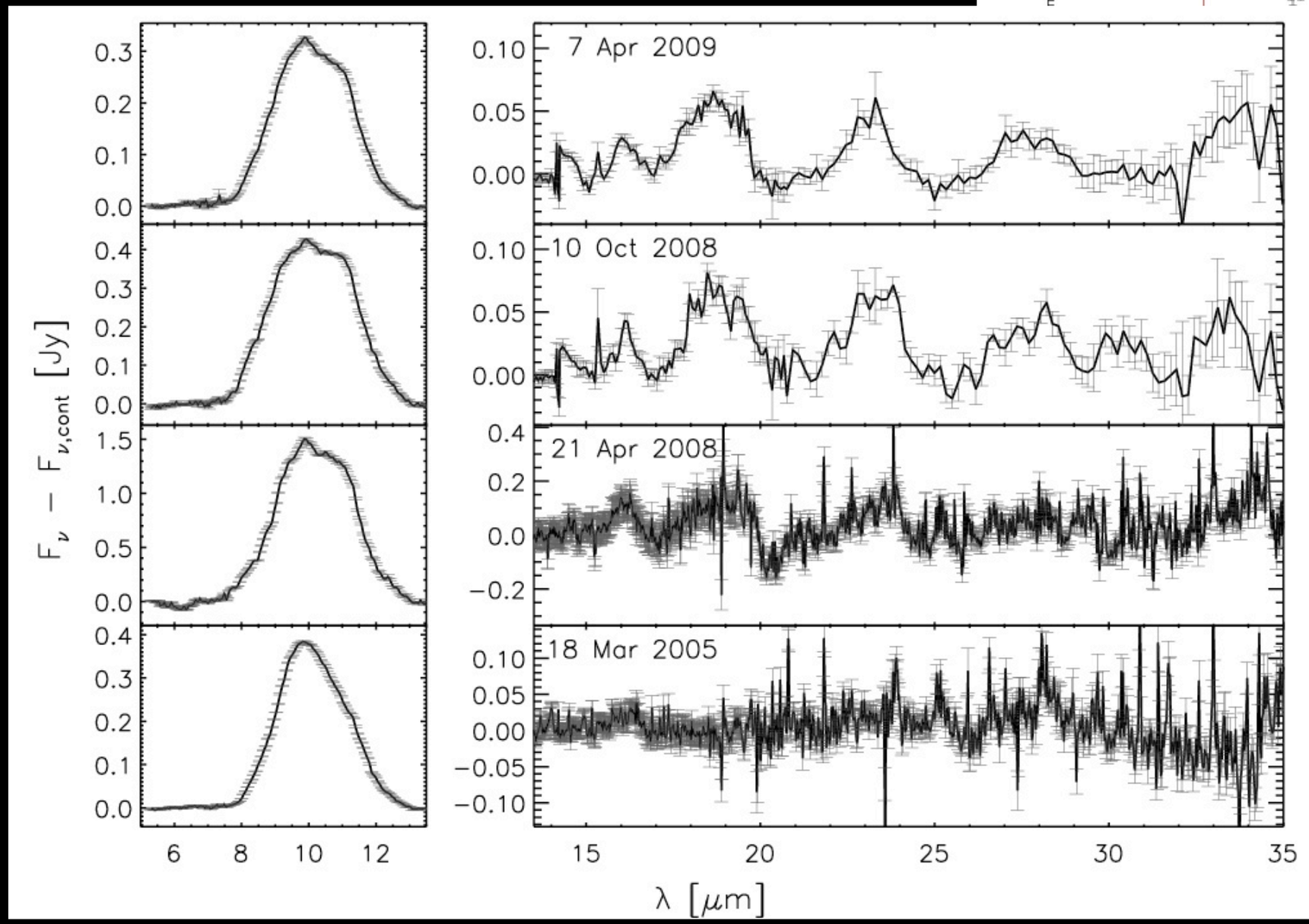

Juhász et al., submitted

Modeling of the outburst

2D continuum radiative transfer code RADMC (Dullemond & Dominik 2004)

1D turbulent mixing / settling code (Dullemond & Dominik 2004)

($D=\alpha \cdot c_s \cdot H_p$, Shakura & Sunyaev 1973)

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Modeling strategy

Start with a 100% amorphous disk

1. Run the RT code and determine the temperature structure of the disk with the corresponding accretion rate
2. Wherever T>1000K replace amorphous grains with crystals
3. Run the mixing/settling code for 10 days

Run model series with different value of α

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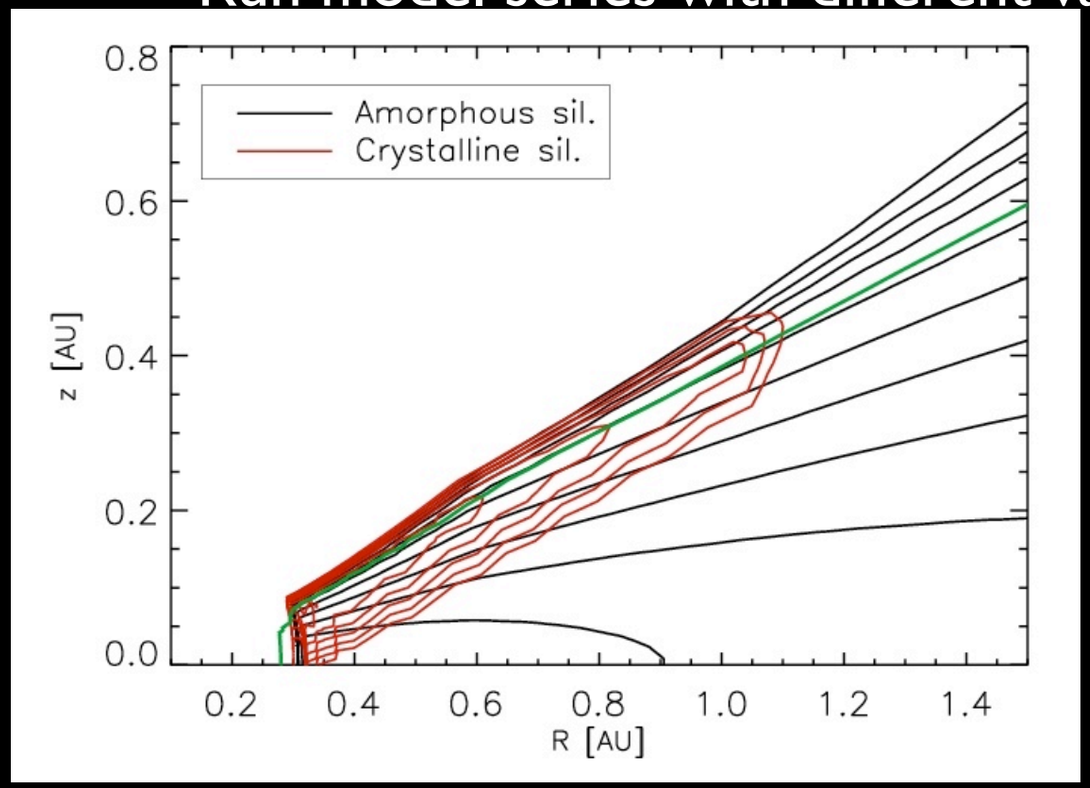

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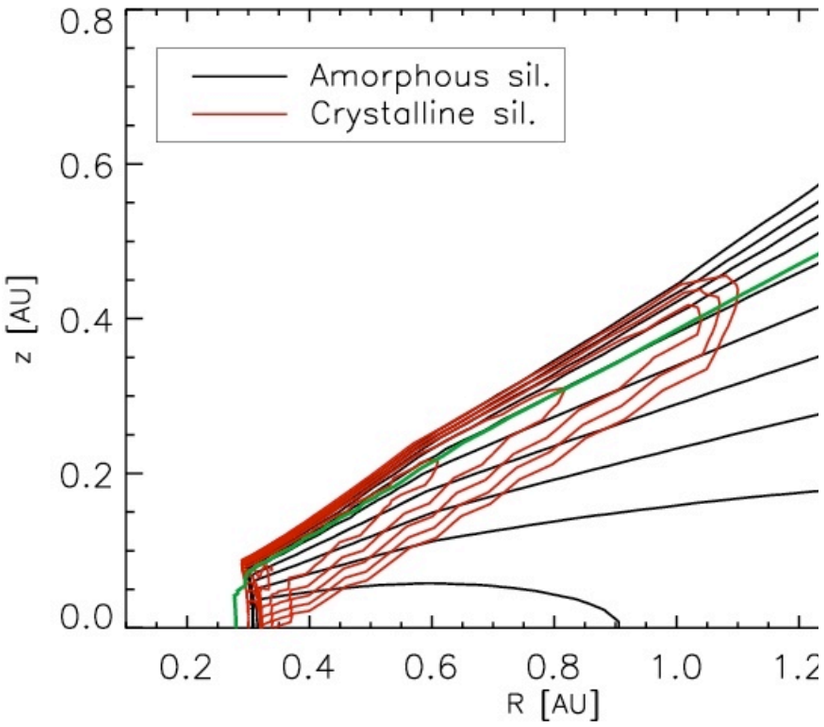

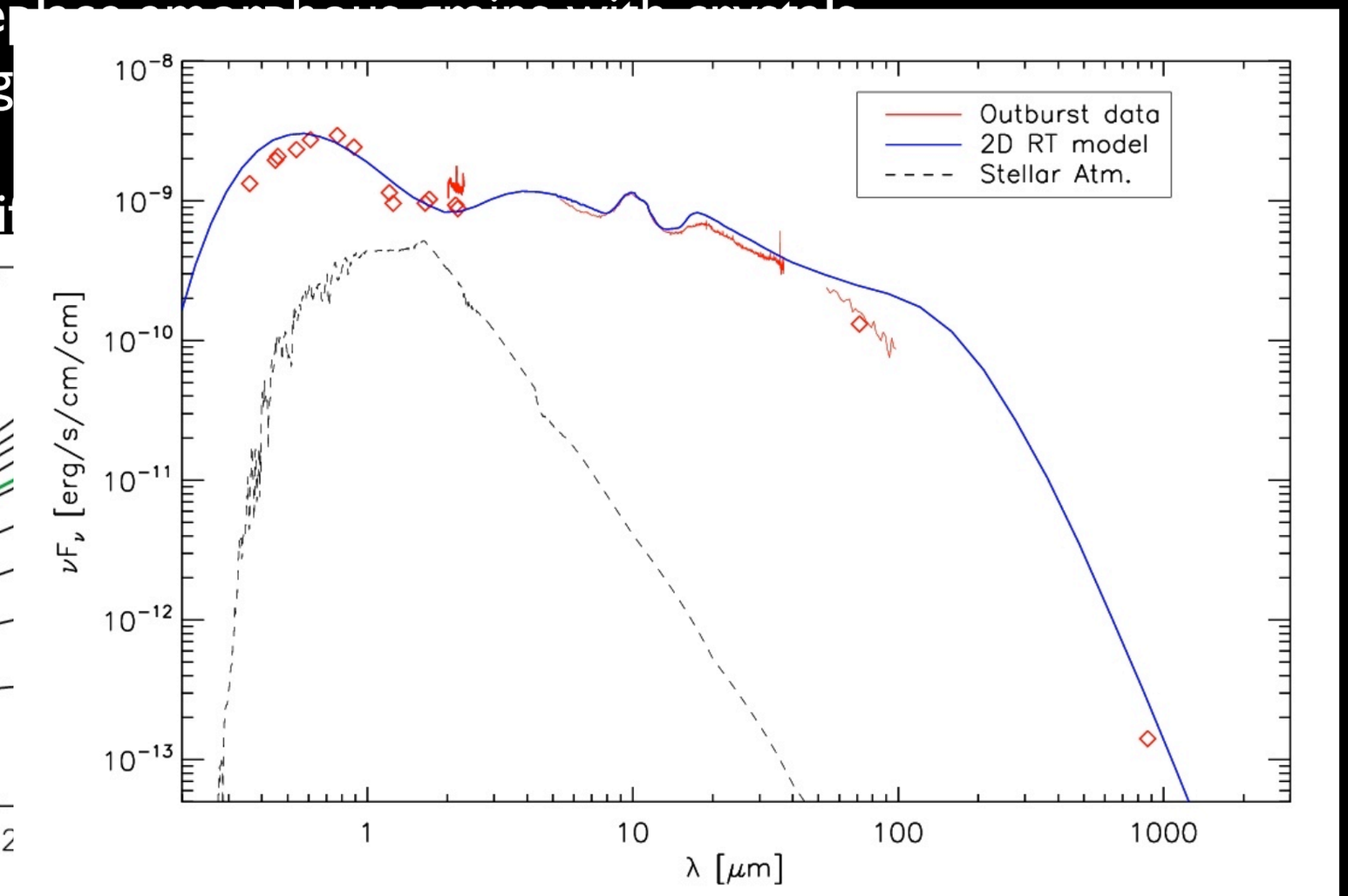

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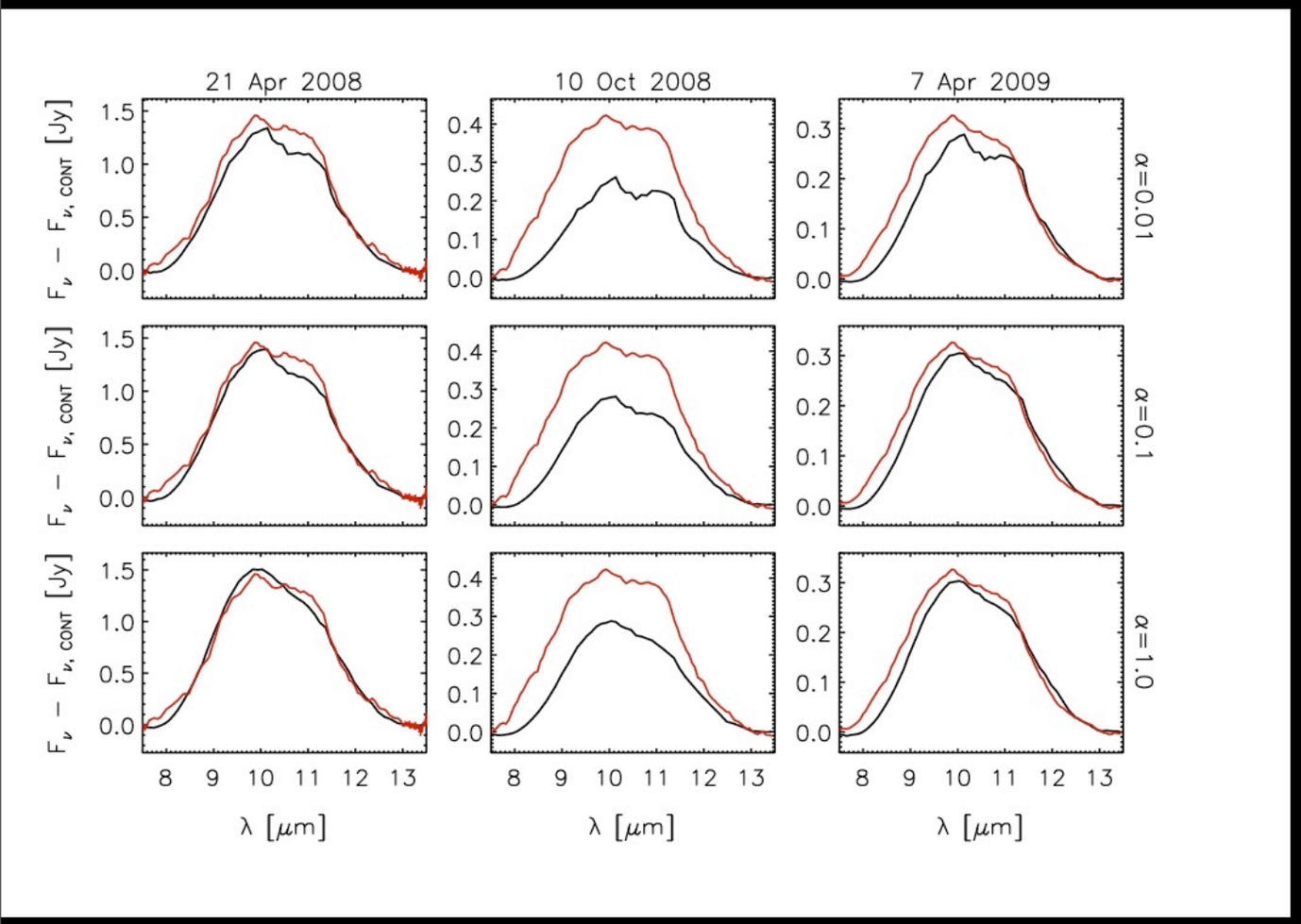

Juhász et al., submitted

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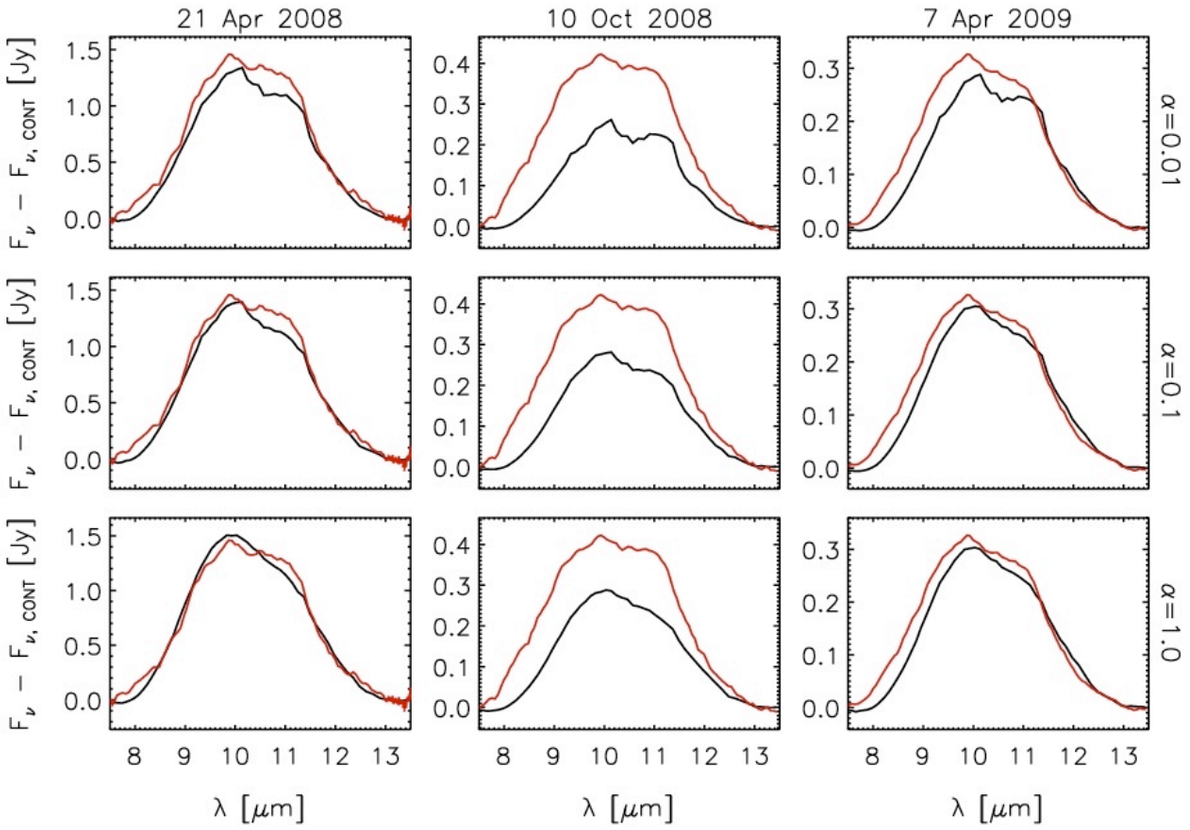

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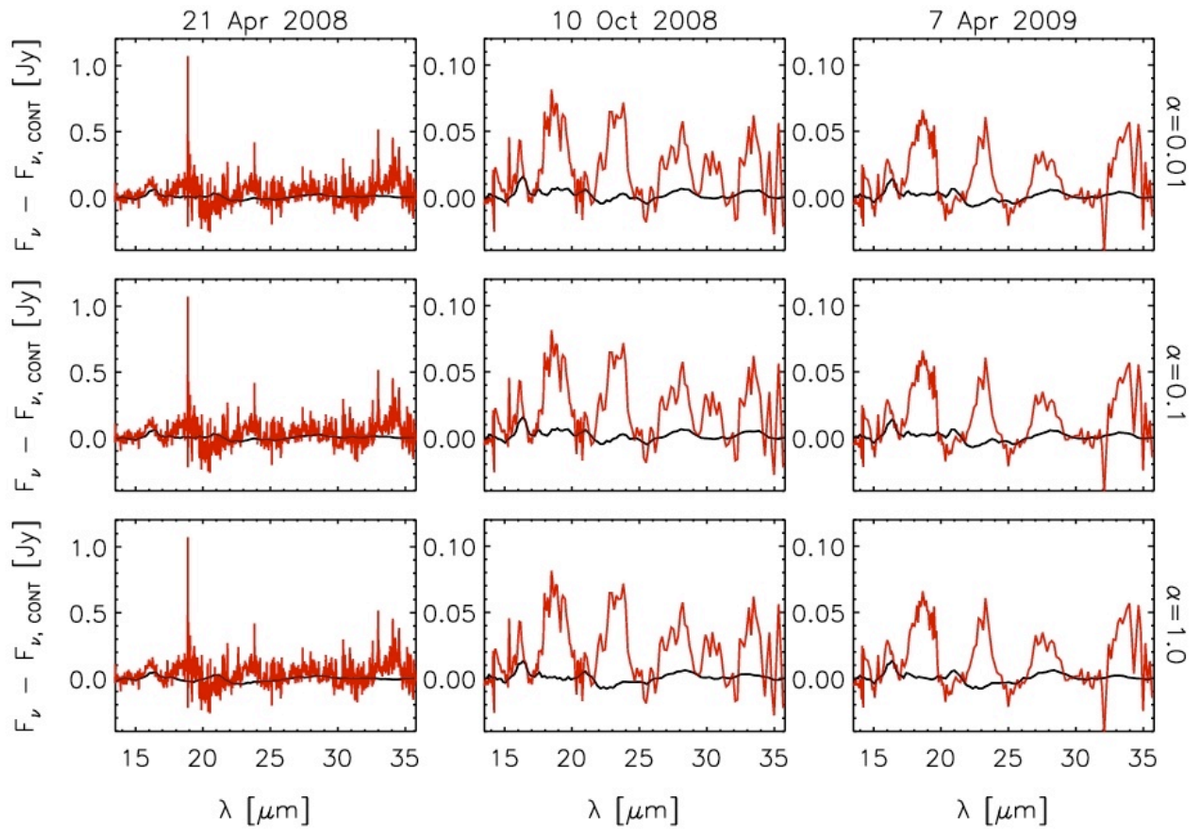
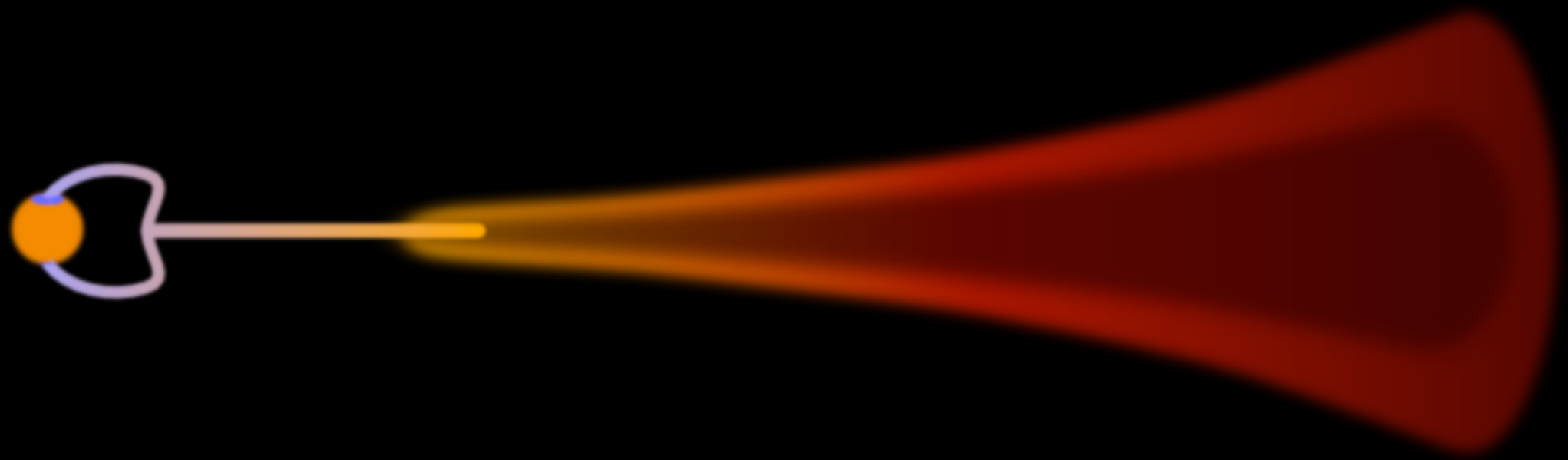
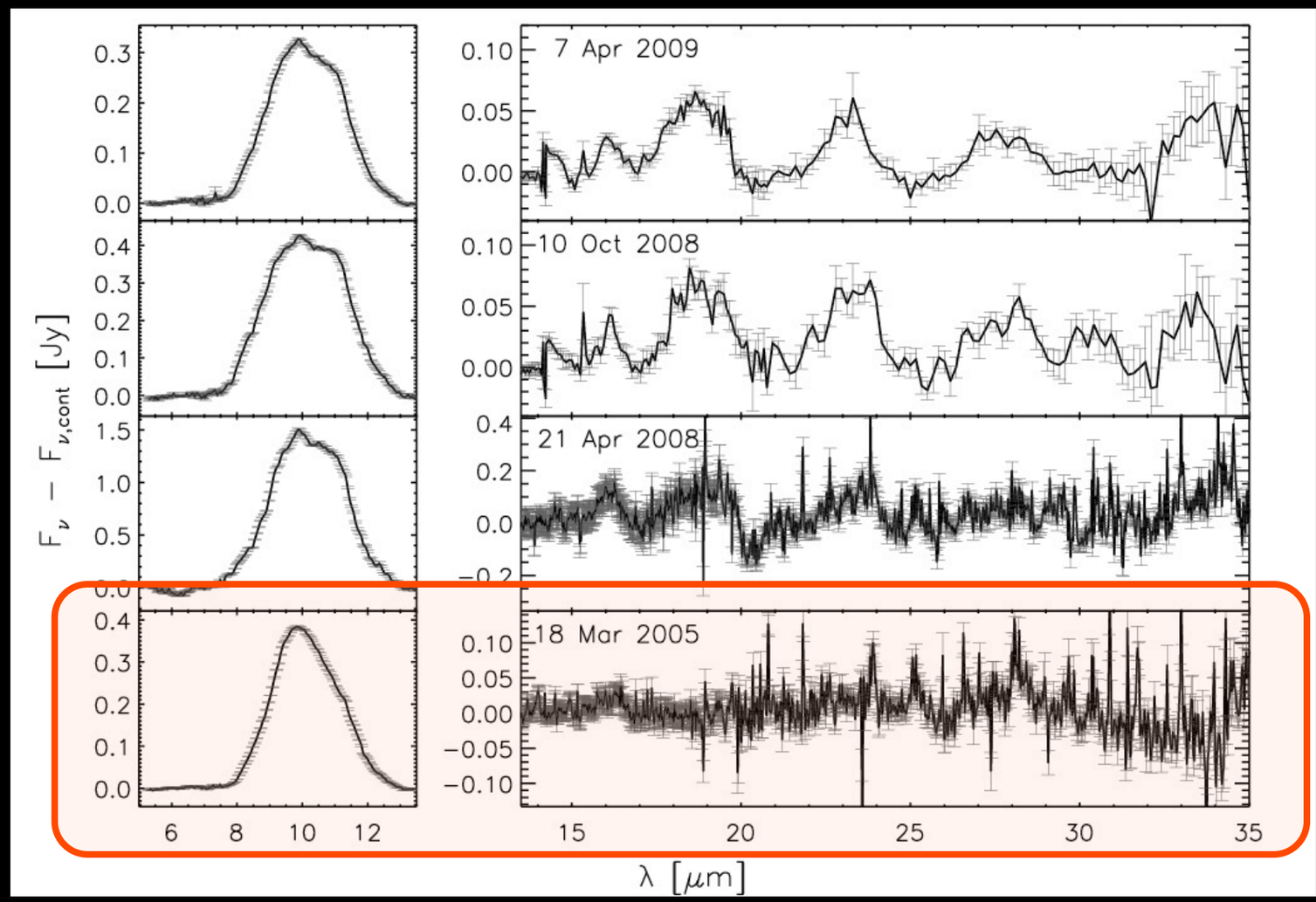


Comprehensive(?) picture of the outburst

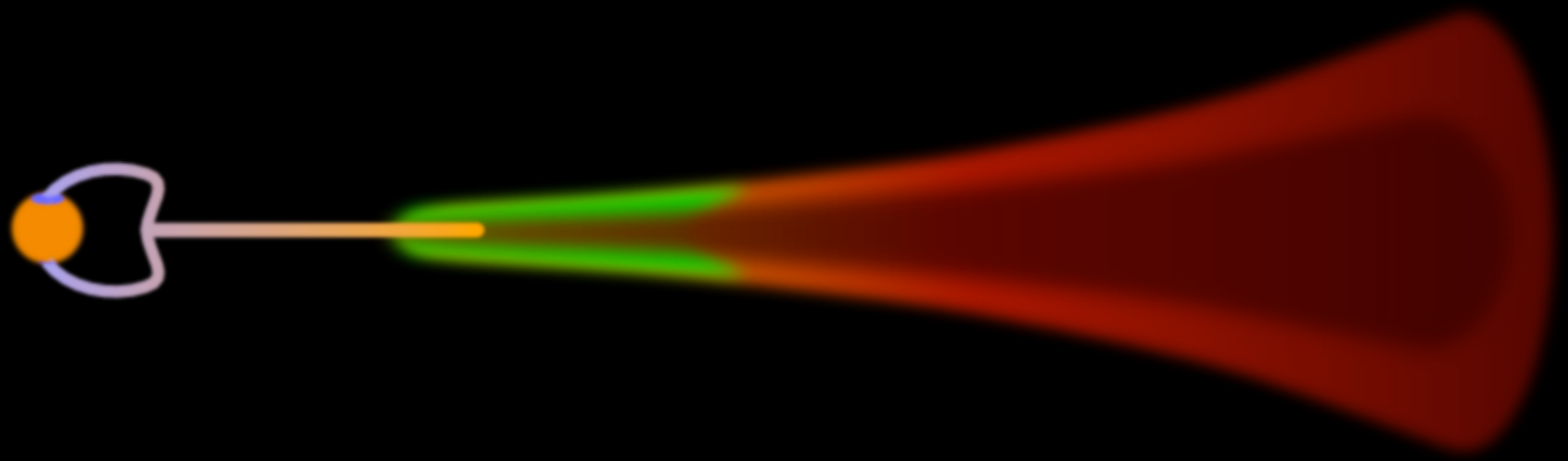


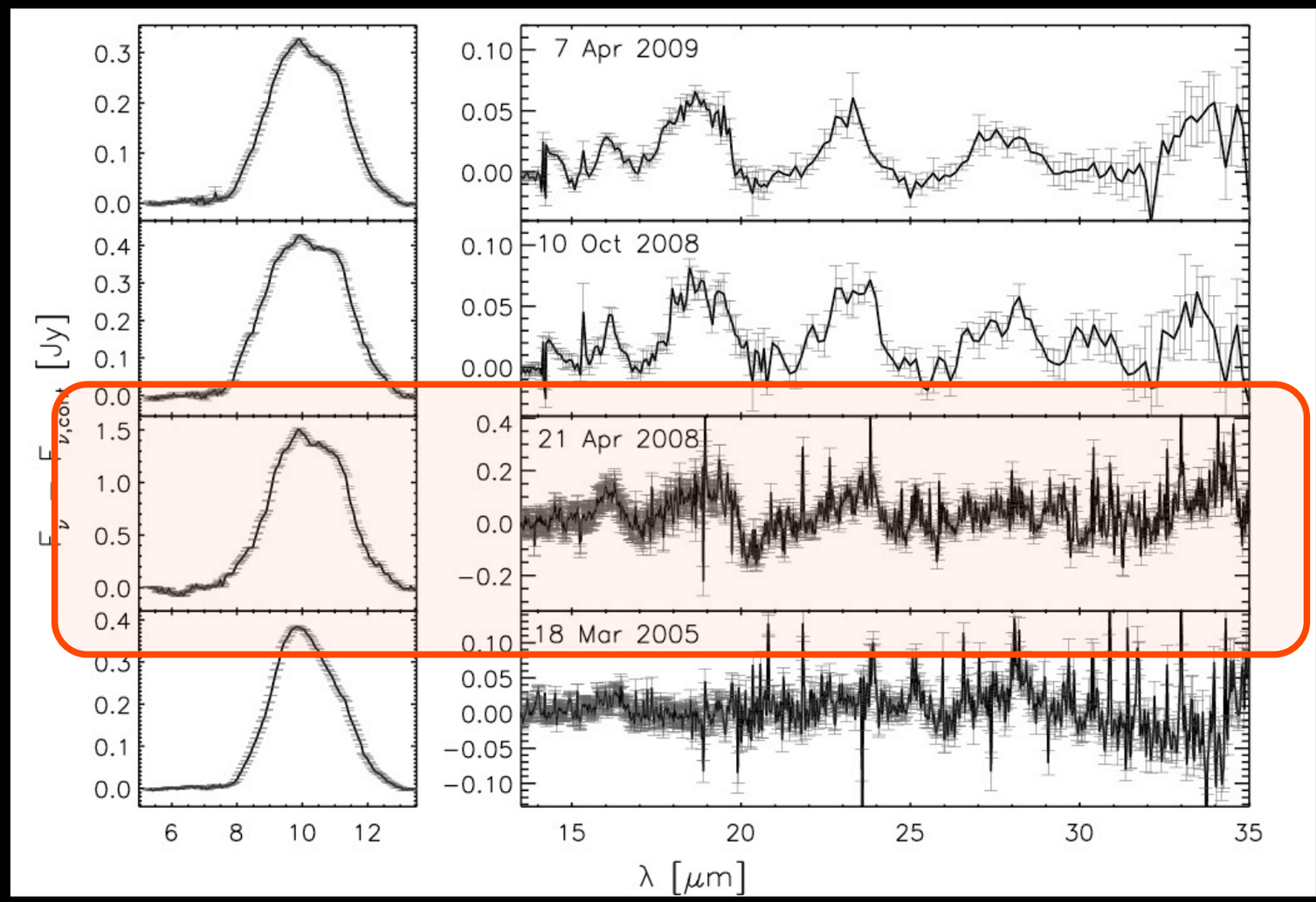


Quiescent phase

No crystals in the disk

Comprehensive(?) picture of the outburst





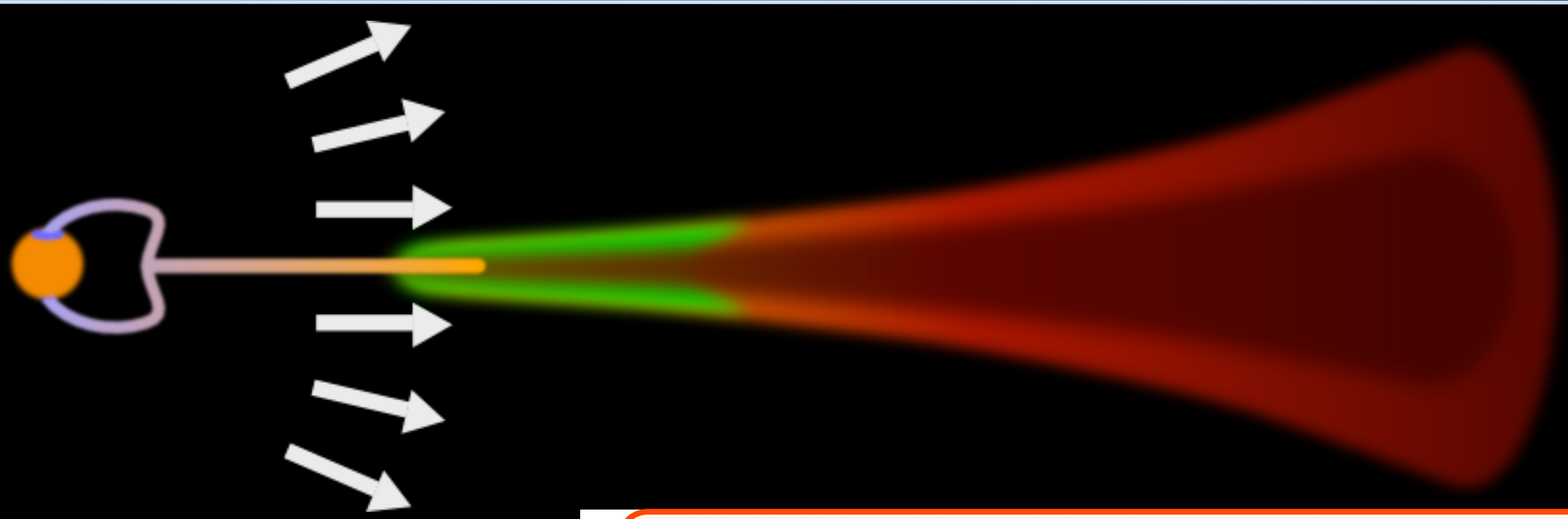
Outburst phase

Crystal formation in the surface layers of the disk

Quiescent phase

No crystals in the disk

Comprehensive(?) picture of the outburst



Post-outburst phase

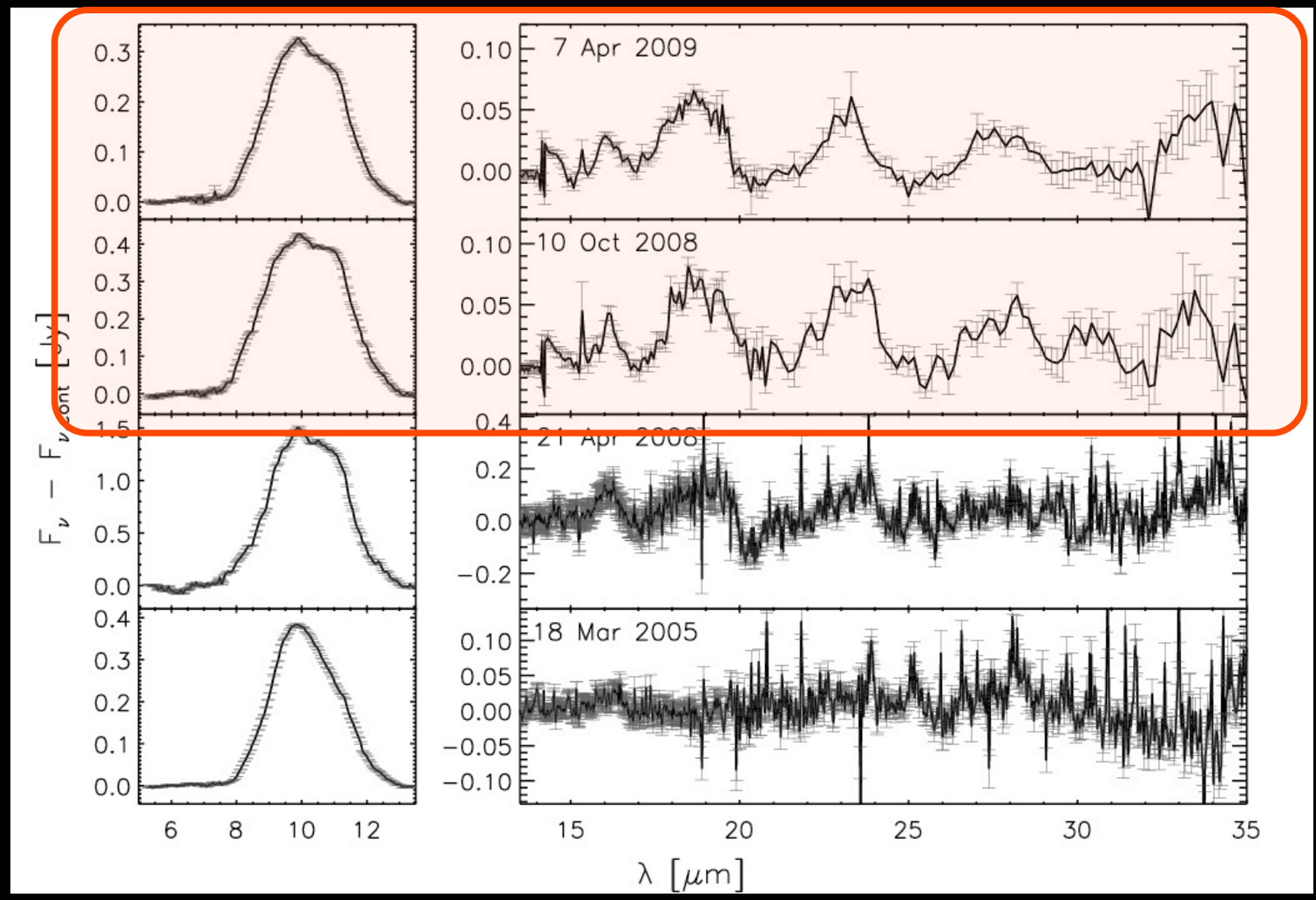
Radial transport of the freshly produced crystals by stellar / disk wind

Outburst phase

Crystal formation in the surface layers of the disk

Quiescent phase

No crystals in the disk



Summary & Conclusions

- The mid-IR spectrum taken in the outburst show the presence of forsterite crystals in the disk of EX Lup that were not seen before

- Crystals formed in the uppermost layers of the disk (disk atmosphere)

- Formation of forsterite crystals is fast (<year)

- In the post outburst spectra show the presence of cold crystals

- 2D RT modeling of the outburst show that vertical mixing cannot explain the post outburst spectral behaviour

- The only possible explanation is the fast radial transport of the freshly produced crystals by some wind-driven transport mechanism

MIDI observations