A case study:
EX Lupi

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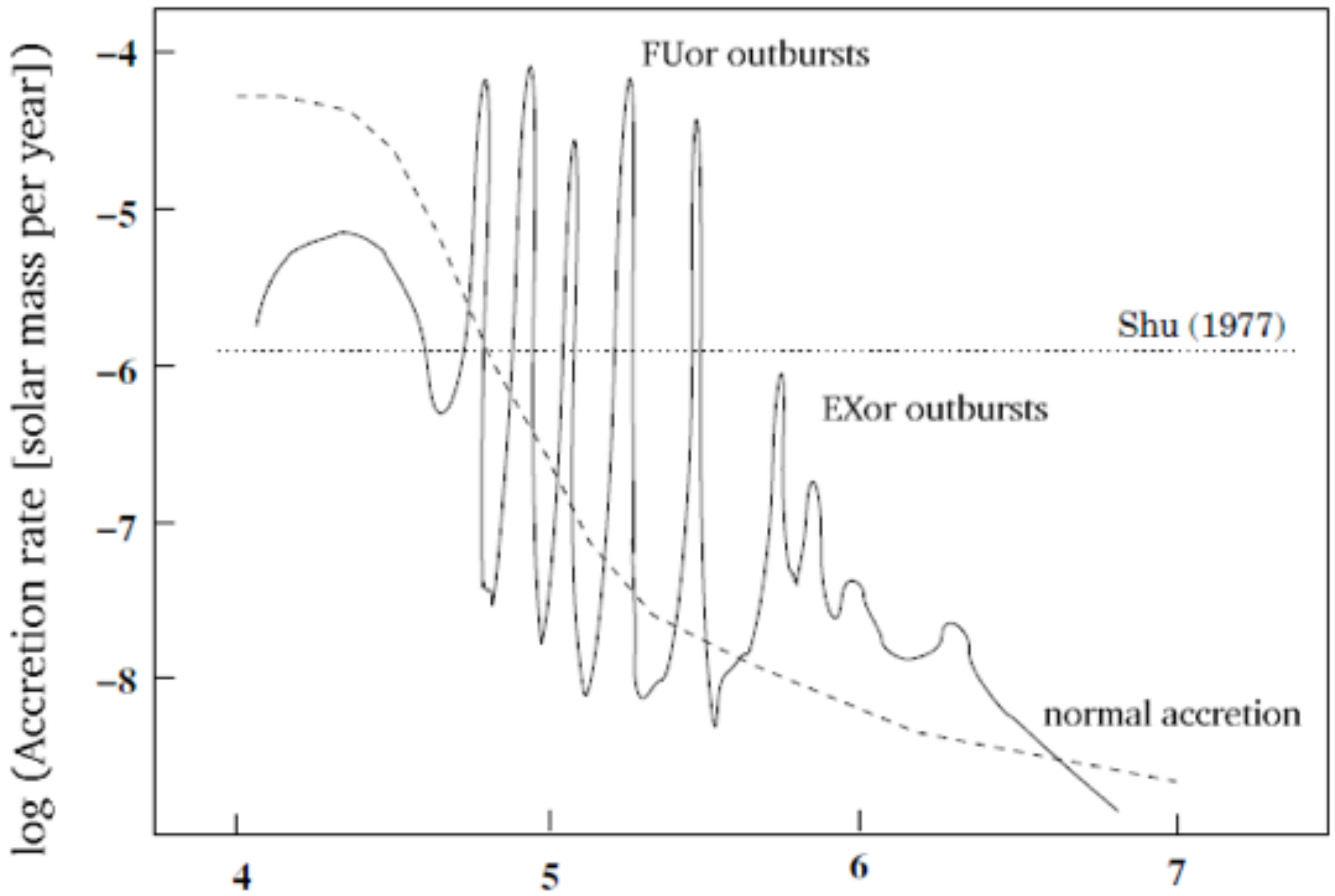
Konkoly Observatory

http://konkoly.hu/staff/kospal/teaching.html

Nov 22, 2016

Episodic accretion



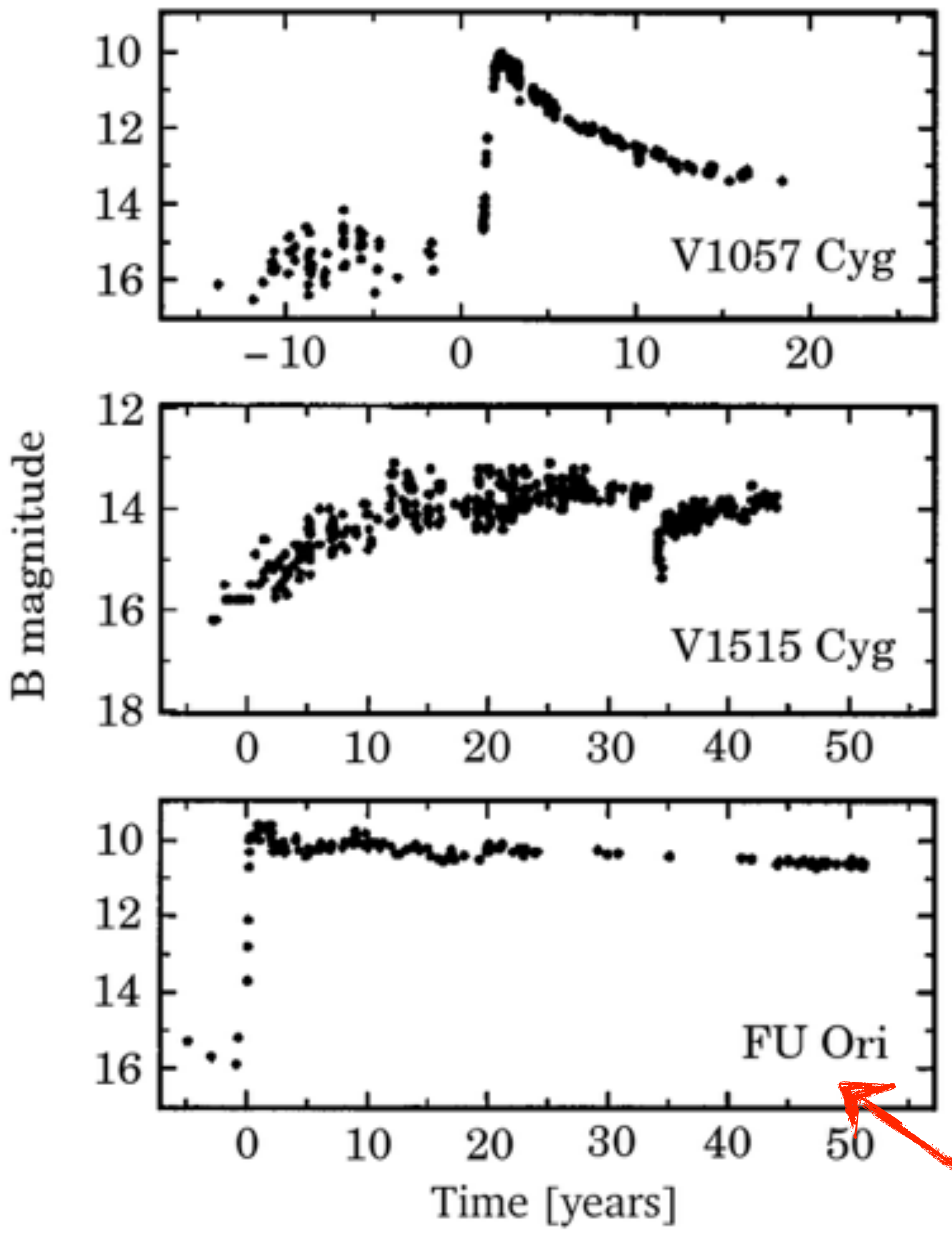
Schulz et al. (1995)

Eruption affects the disk:

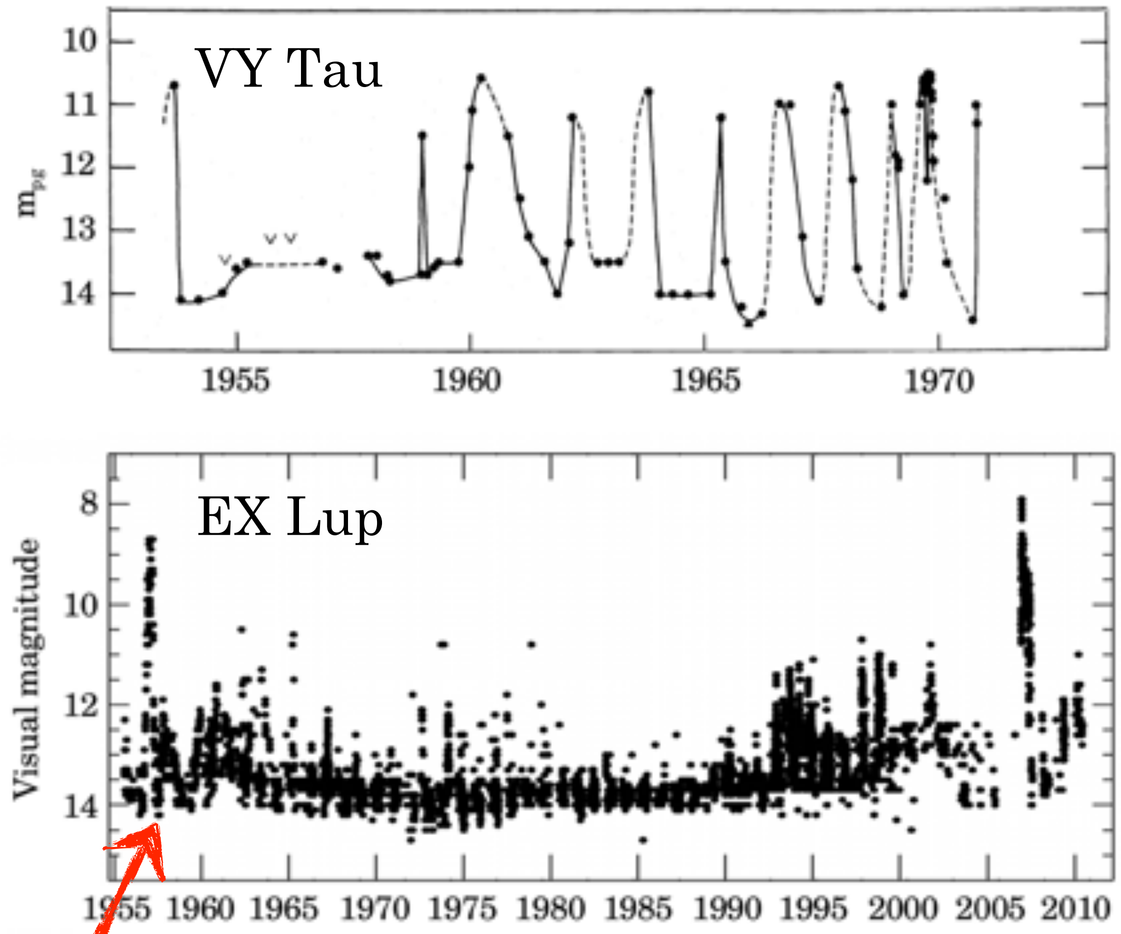
- density, temperature, chemical structure
- conditions for planet formation

- Material accumulates close to the star
- Thermal instability → ionization front
- Material suddenly flows onto the star
- Outburst powered by enhanced accretion
- Outbursts are rare, episodic, unpredictable

Classical picture: FUors, EXors



Hartmann & Kenyon (1996)



Herbig (1977), AAVSO

Accretion rate: up to 10^{-6} $M_\odot$/yr

Spectrum: emission lines

Accretion rate: up to 10^{-4} $M_\odot$/yr

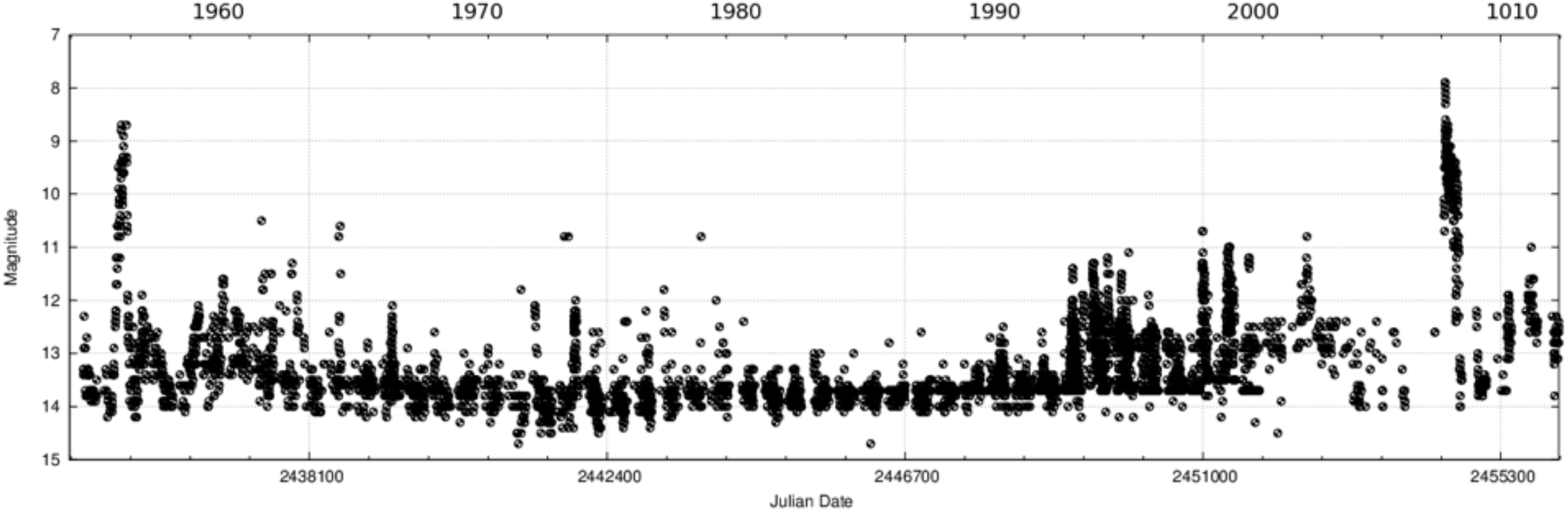
Spectrum: absorption lines

Open questions

- How common the eruptive phenomenon is?
  Do all low-mass young stars undergo eruptive phases?
  Are young eruptive stars special objects?
- Are the disks around young eruptive stars typical?
  How do the outbursts change disk structure/composition?
- What is the path of accretion in an outbursting system?
  What kind of instability triggers the outburst?
  Does binarity have a role?

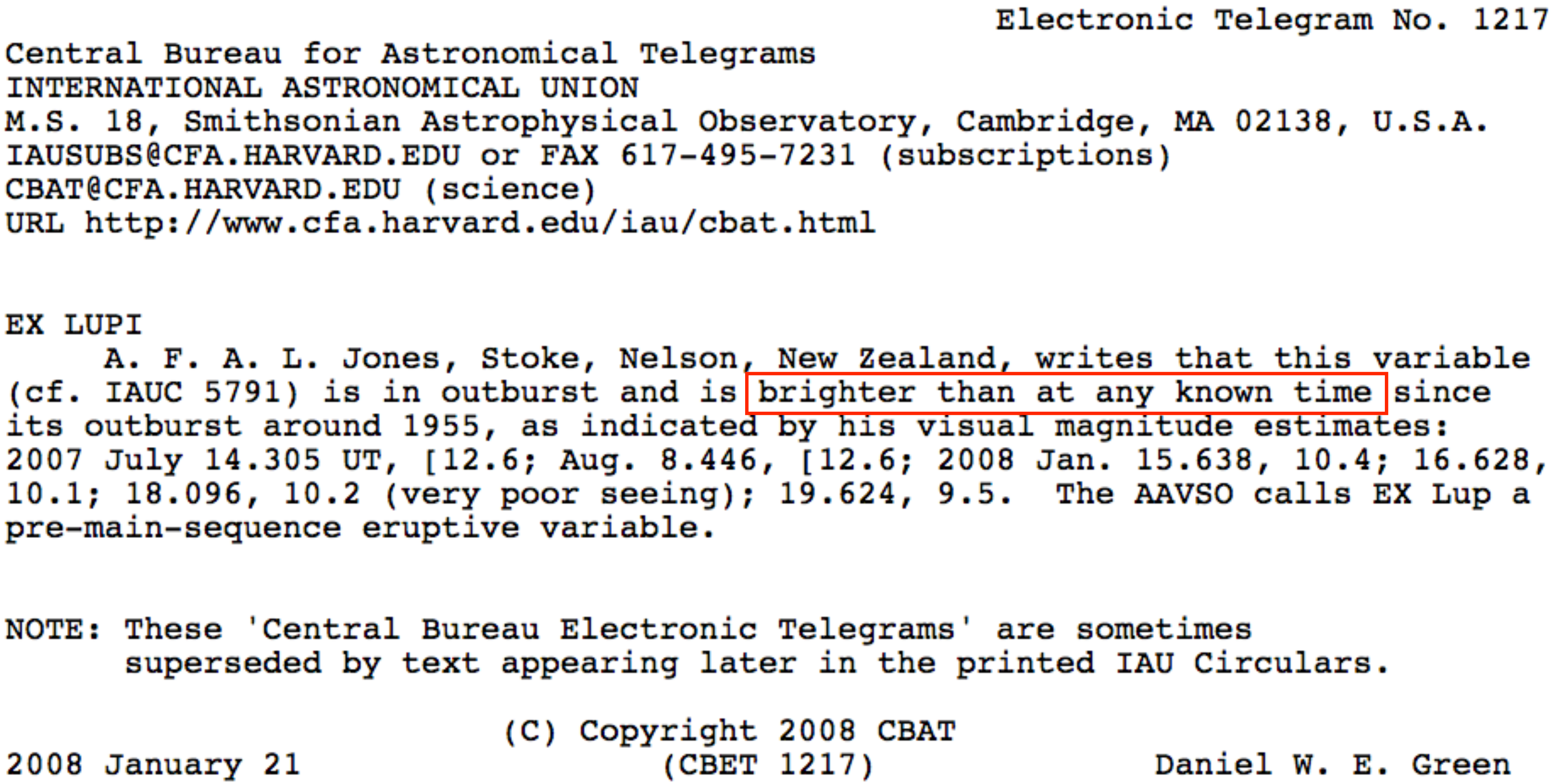
The EX Lupi project

- To answer (some of) these questions, we studied EX Lup, the prototype of the EXor class
- Extreme (6 mag) outburst in 2008



AAVSO DATA FOR EX LUP - WWW.AAVSO.ORG

Discovery of the new outburst



Electronic Telegram No. 1217

Central Bureau for Astronomical Telegrams
INTERNATIONAL ASTRONOMICAL UNION
M.S. 18, Smithsonian Astrophysical Observatory, Cambridge, MA 02138, U.S.A.
IAUSUBS@CFA.HARVARD.EDU or FAX 617-495-7231 (subscriptions)
CBAT@CFA.HARVARD.EDU (science)
URL http://www.cfa.harvard.edu/iau/cbat.html

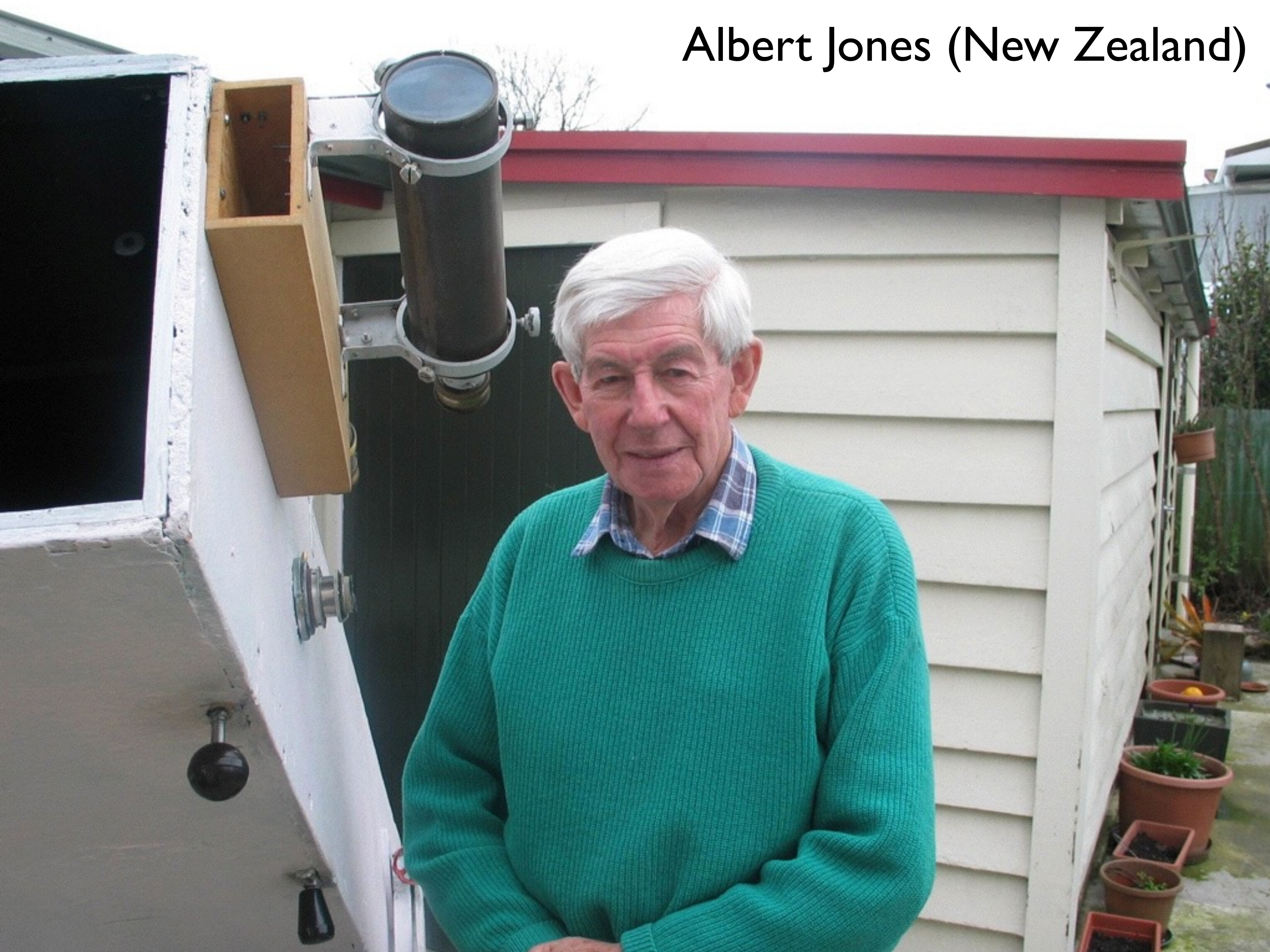
EX LUPI

A. F. A. L. Jones, Stoke, Nelson, New Zealand, writes that this variable (cf. IAUC 5791) is in outburst and is brighter than at any known time since its outburst around 1955, as indicated by his visual magnitude estimates: 2007 July 14.305 UT, [12.6; Aug. 8.446, [12.6; 2008 Jan. 15.638, 10.4; 16.628, 10.1; 18.096, 10.2 (very poor seeing); 19.624, 9.5. The AAVSO calls EX Lup a pre-main-sequence eruptive variable.

NOTE: These 'Central Bureau Electronic Telegrams' are sometimes superseded by text appearing later in the printed IAU Circulars.

2008 January 21 (CBET 1217) Daniel W. E. Green

Albert Jones (New Zealand)



Coordinated observing campaign

Simultaneous:

2.2m/WFI	19 April 2008	optical imaging
2.2m/GROND	20 April 2008	optical imaging
2.2m/FEROS	20 April 2008	optical spectroscopy
NTT/SOFI	19 April 2008	near-IR imaging
NTT/SOFI	19 April 2008	near-IR spectroscopy
Spitzer/IRS	19 April 2008	mid-IR spectroscopy
Spitzer/MIPS	20 April 2008	far-IR imaging+spectroscopy
APEX	21 April 2008	sub-millimeter imaging

Monitoring:

Spitzer/IRS, VLTI/MIDI, VLT/VISIR	7 epochs	10 μm spectroscopy
VLT/CRIRES, Subaru/IRCS	6 epochs	4−5 μm spectroscopy
VLT/SINFONI	3 epochs	near-IR spectroscopy
2.2m/FEROS, 3.6m/HARPS	≈40 epochs	optical spectroscopy

Coordinated observing campaign


La Silla


Spitzer

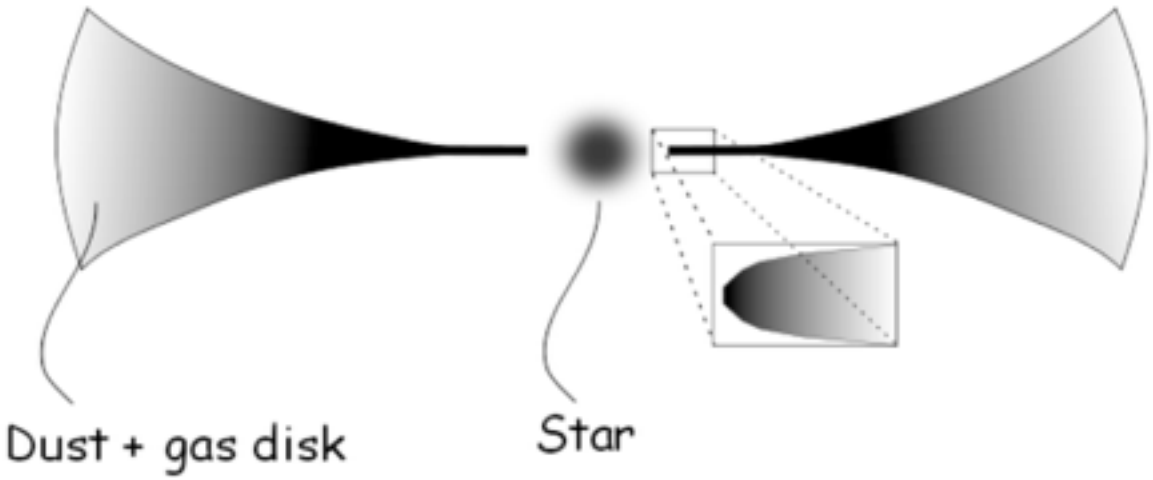

APEX


Subaru


Paranal, VLT

EX Lupi in quiescence

- First step: create a reference model to be compared to the outburst observations
- Inner hole: R_{in} is larger than the dust sublimation radius



Sp. type: M0

$\dot{M} = 10^{-10}\ M_\odot/yr$

Silicate: amorphous

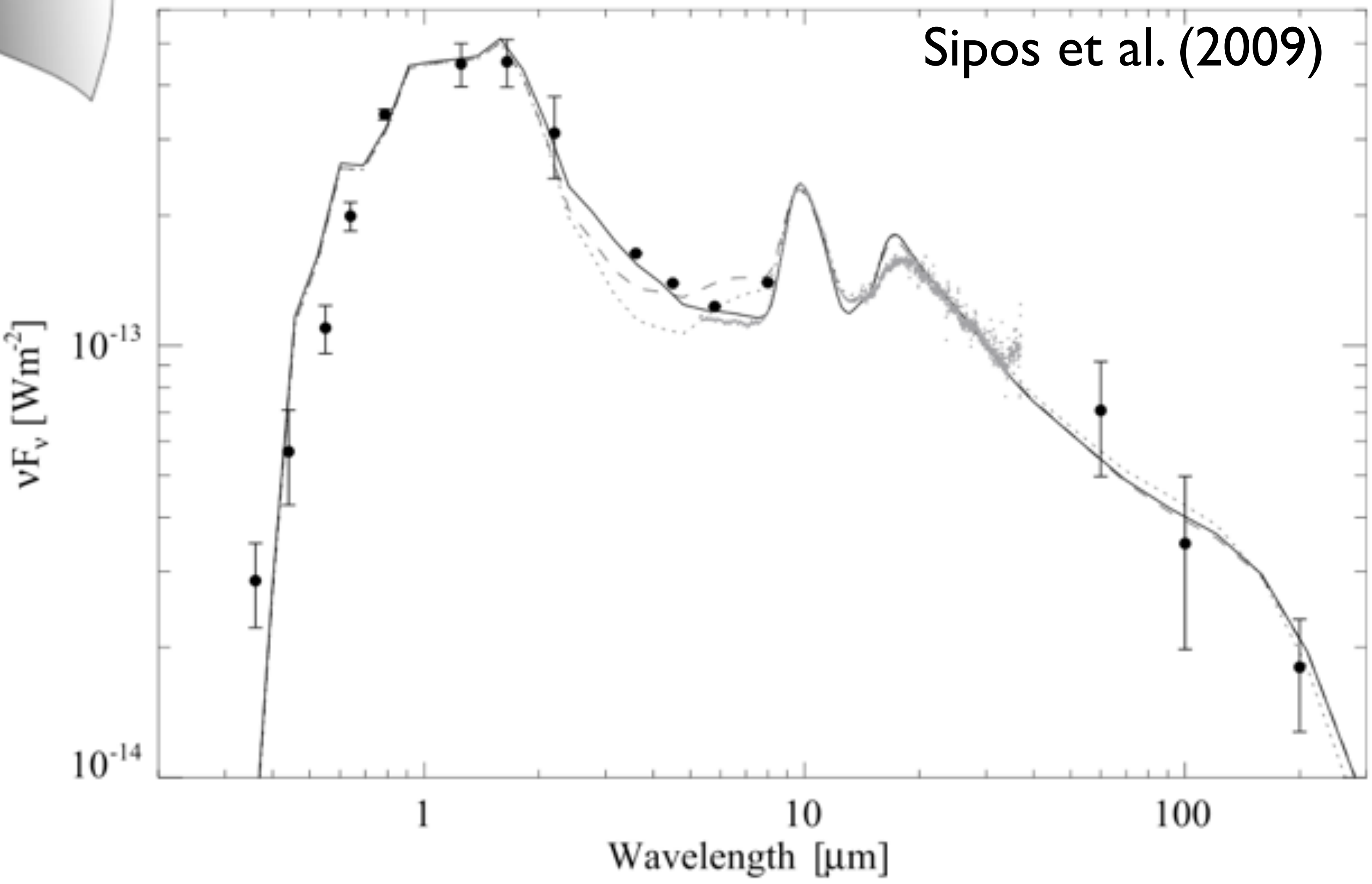
$M_{disk} = 0.025\ M_\odot$

$R_{in} = 0.2$ AU

$R_{out} = 150$ AU

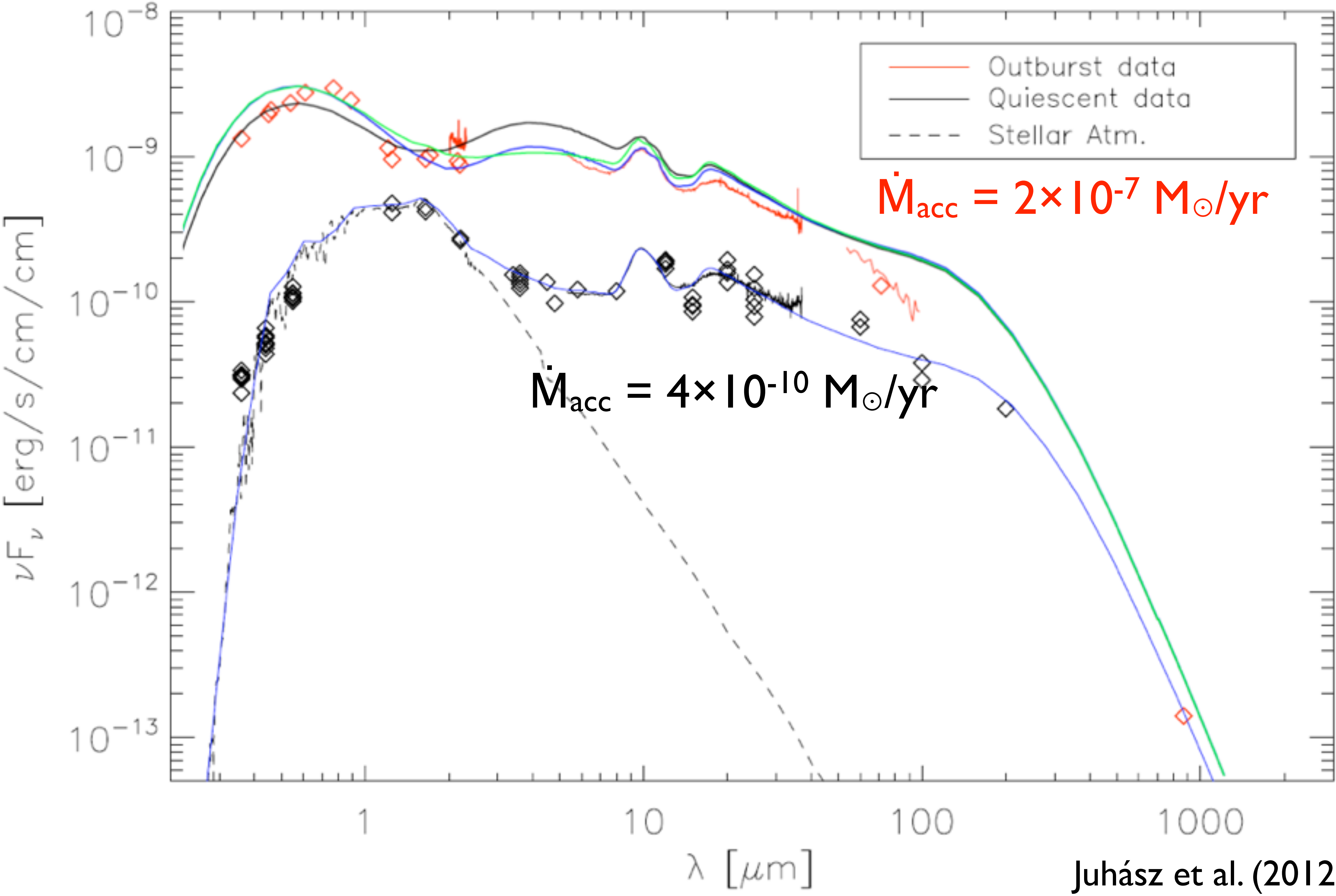
$$\frac{h(r)}{r} = \frac{h_{disk}}{r_{disk}} \left(\frac{r}{r_{disk}}\right)^{\alpha_{fl}}$$

$$\rho_{disk}(r,z) = \frac{\Sigma(r)}{h(r)\sqrt{2\pi}} \exp\left\{-\frac{1}{2}\left[\frac{z}{h(r)}\right]^2\right\},$$



Sipos et al. (2009)

SED modeling in outburst



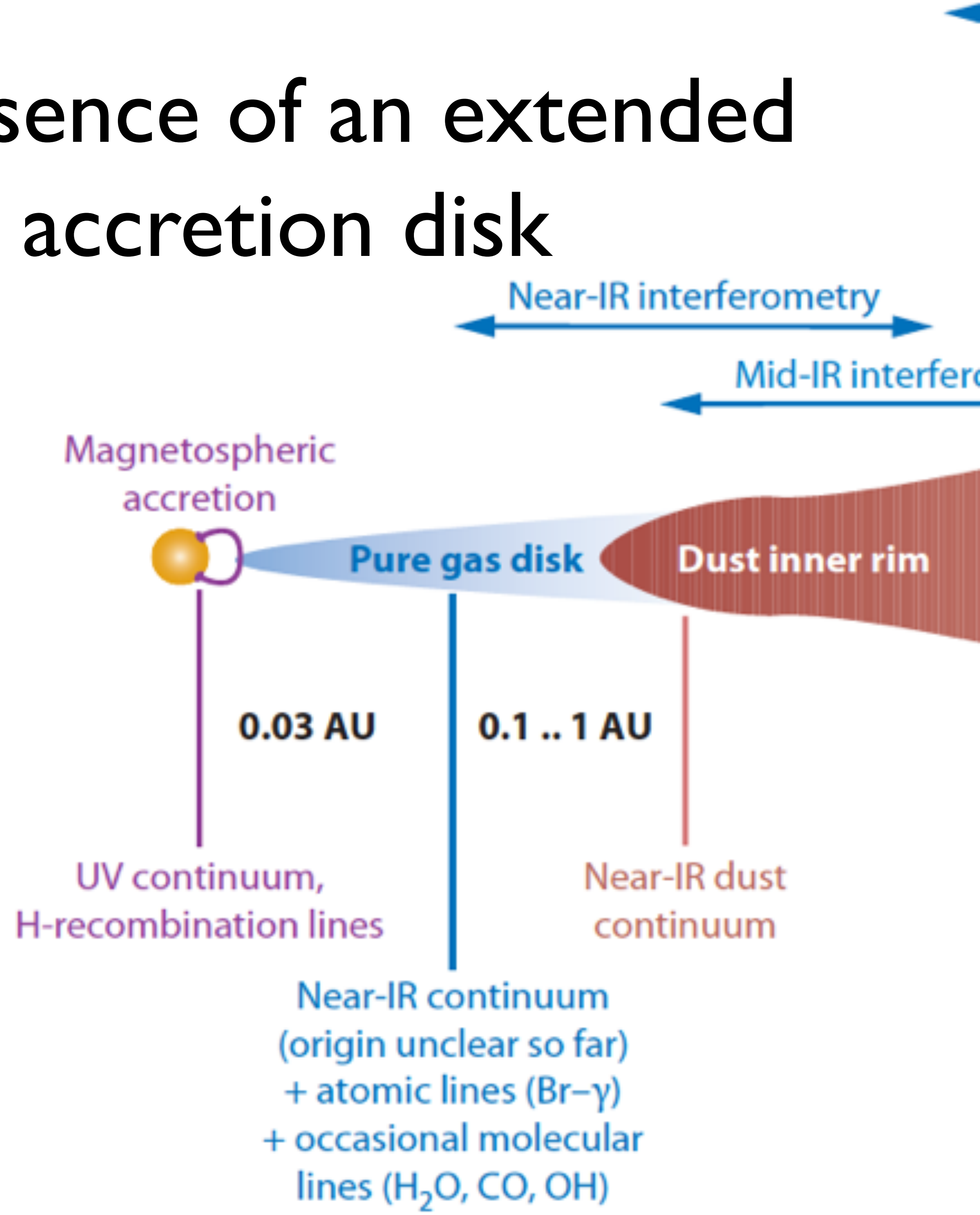
$\dot{M}_{acc} = 2\times10^{-7}$ M⊙/yr

$\dot{M}_{acc} = 4\times10^{-10}$ M⊙/yr

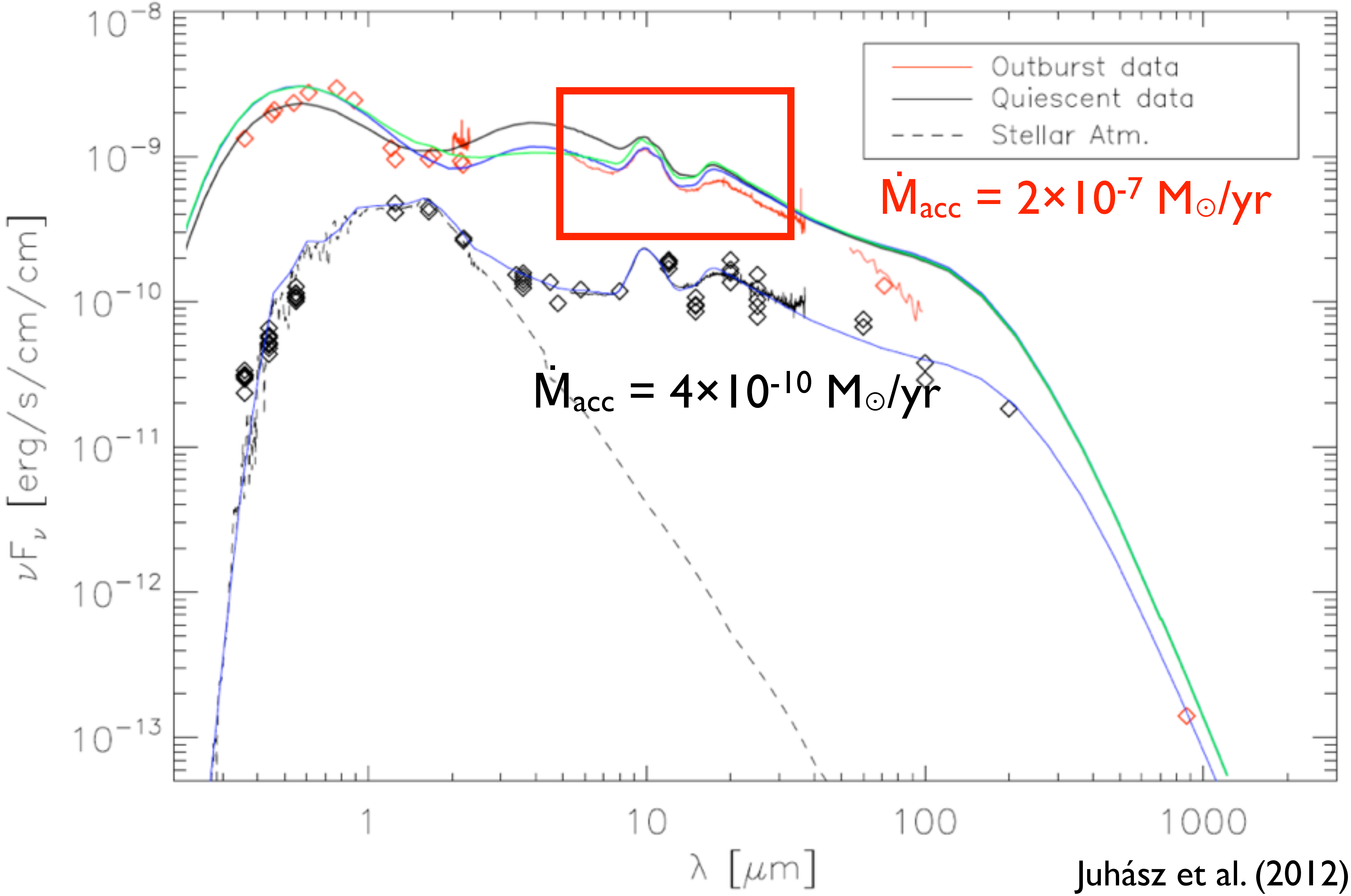
Juhász et al. (2012)

SED modeling in outburst

- SED is dominated by accretion luminosity
- Observation exclude the presence of an extended ($R_{out} \approx 0.3$ au) optically thick accretion disk
- All material accreted should have been located within 0.1 au of the central star (viscous timescale)
- The inner dust-free hole is filled with gas, optically thin in the continuum



SED modeling in outburst

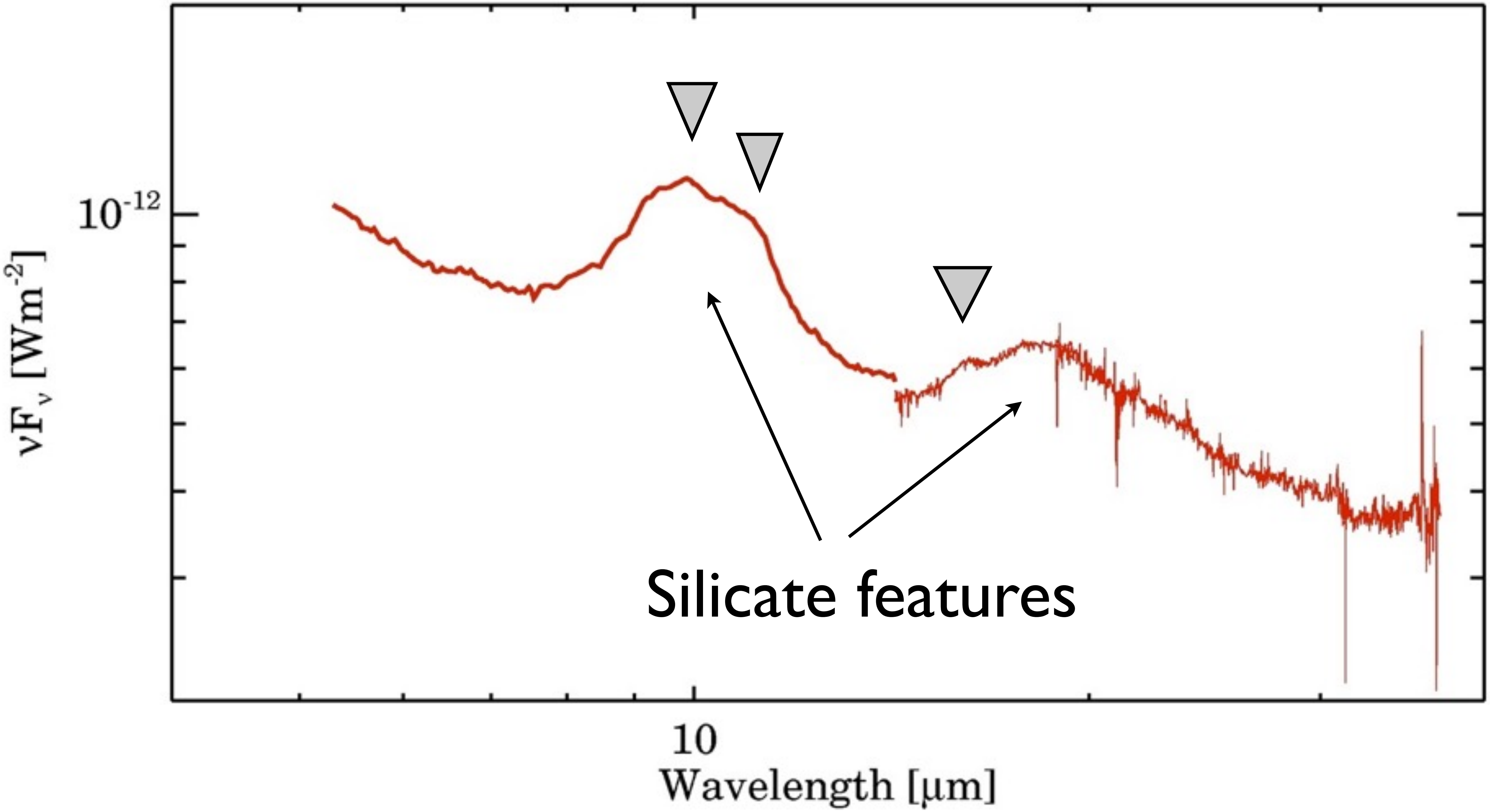


$\dot{M}_{acc} = 2\times10^{-7}\ M_\odot/yr$

$\dot{M}_{acc} = 4\times10^{-10}\ M_\odot/yr$

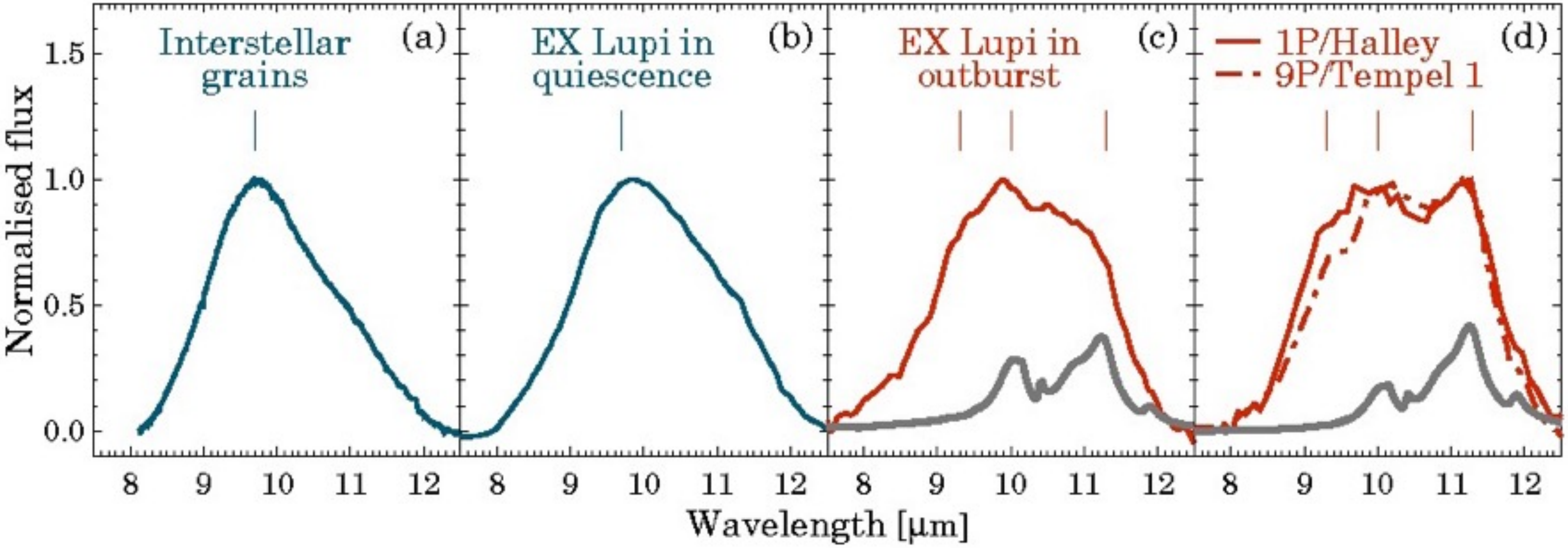
Juhász et al. (2012)

Silicate dust in EX Lupi's disk

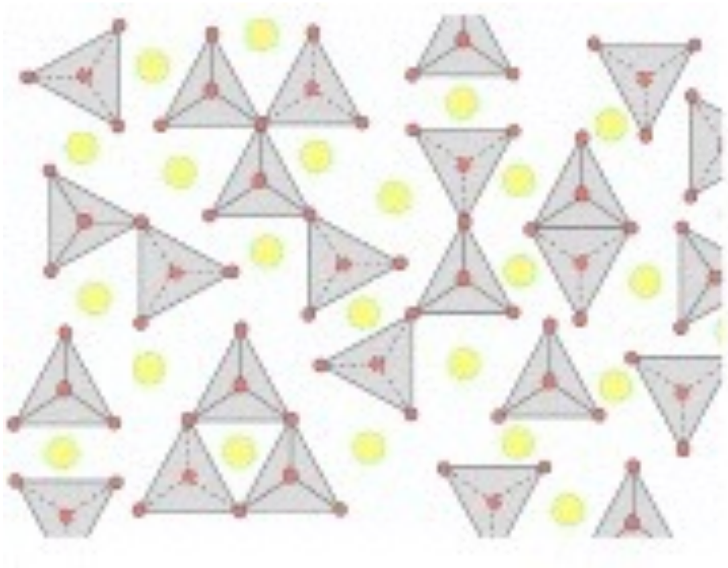


Silicate features

Episodic crystallization

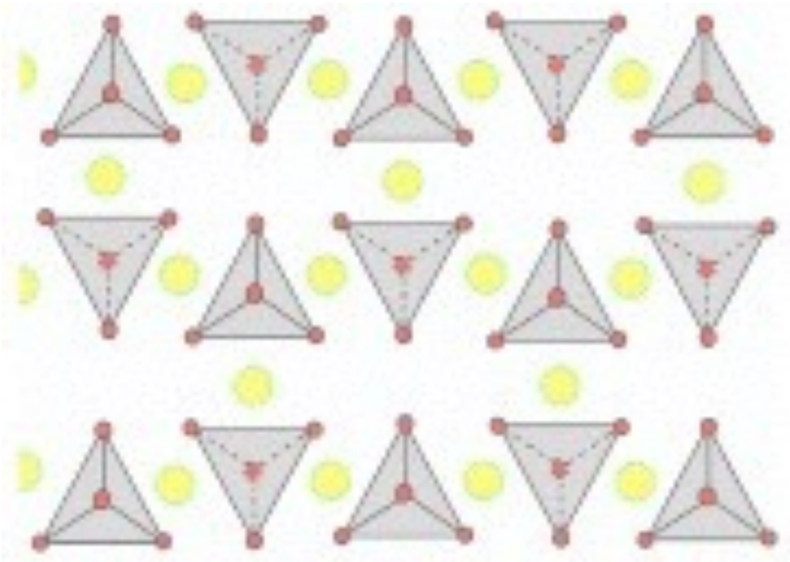


Ábrahám, Juhász, Dullemond, Kóspál, et al. (Nature, 2009)



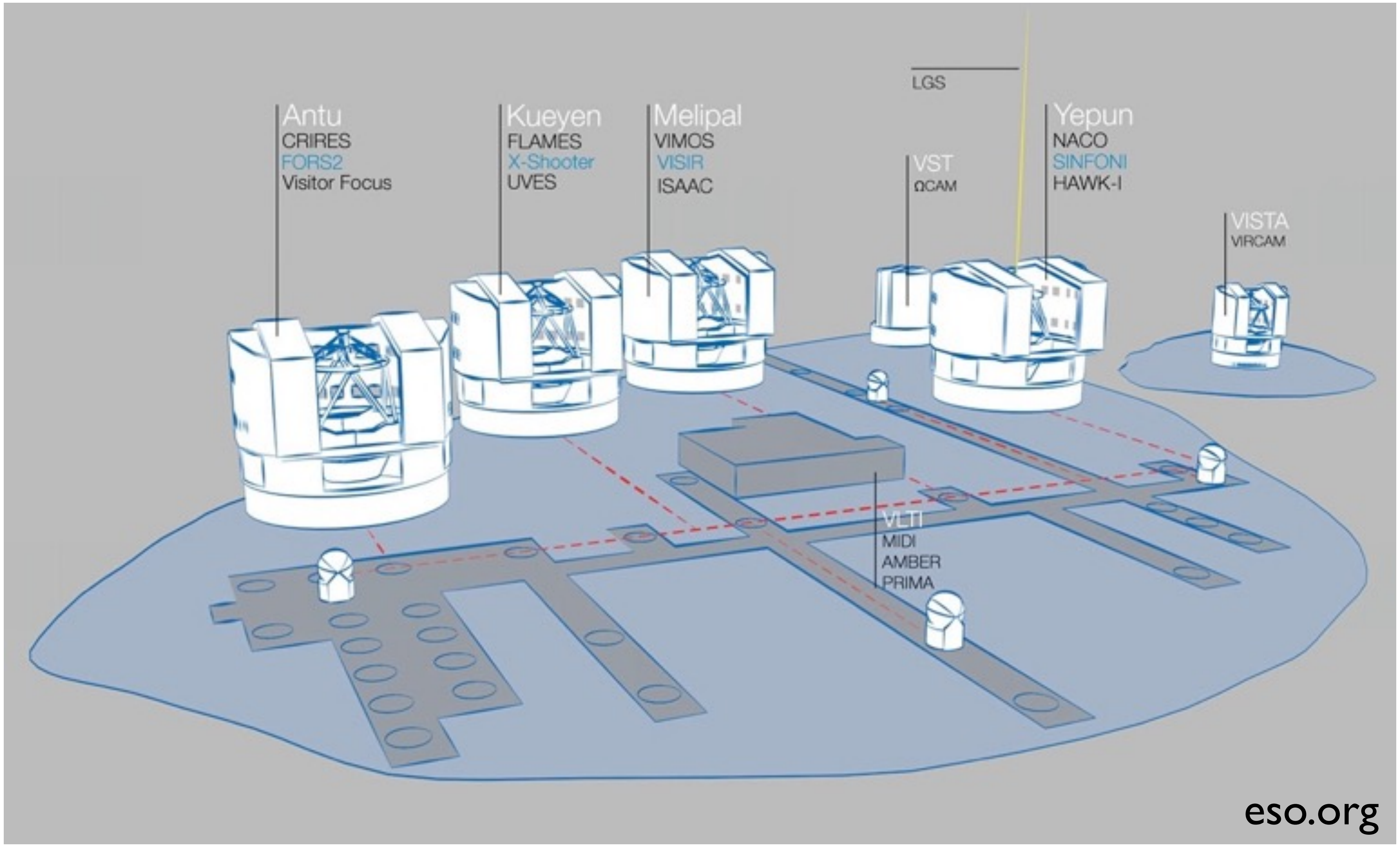
Forsterite

Mg_2SiO_4



Location of crystals

VLTI/MIDI: mid-infrared interferometer (8−13 µm)

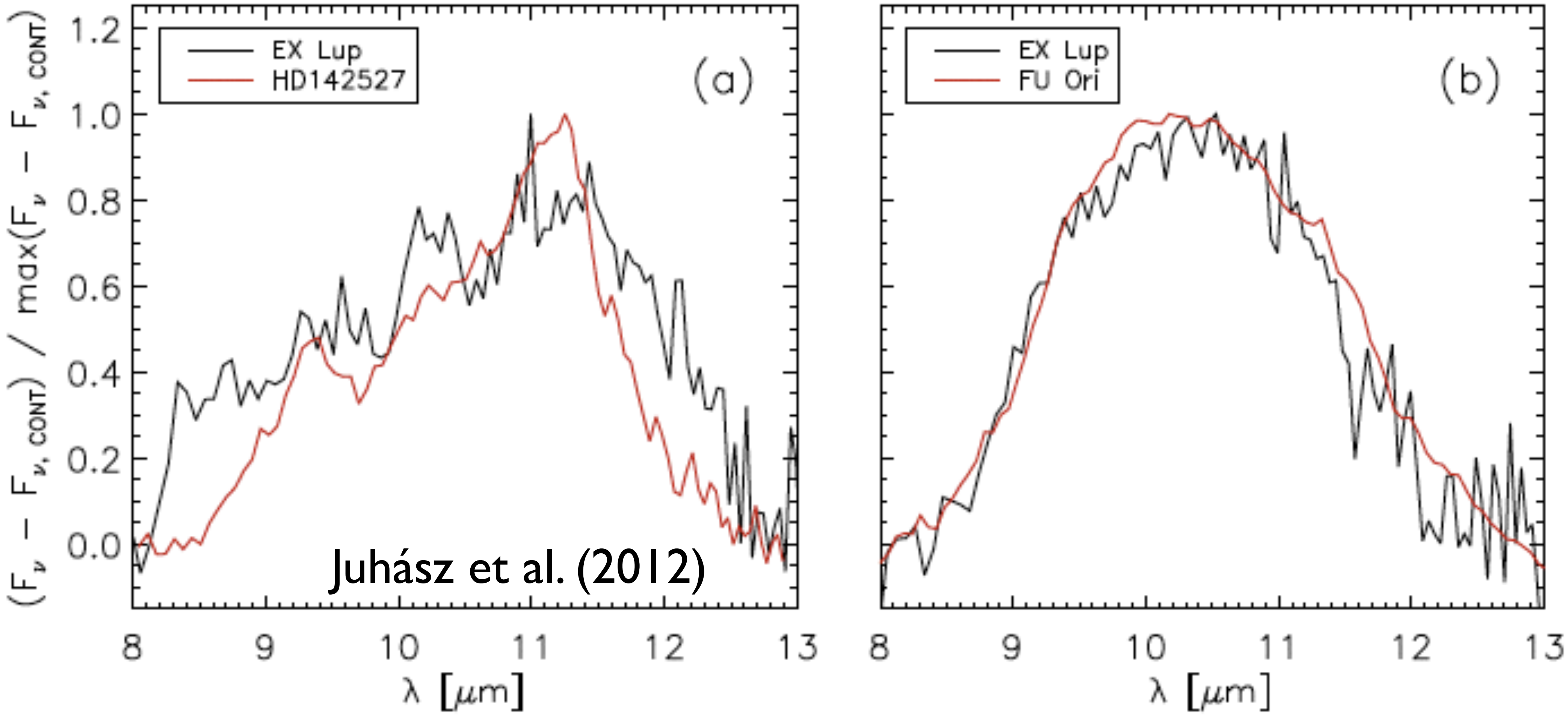


eso.org

Location of crystals

Inner disk

Outer disk



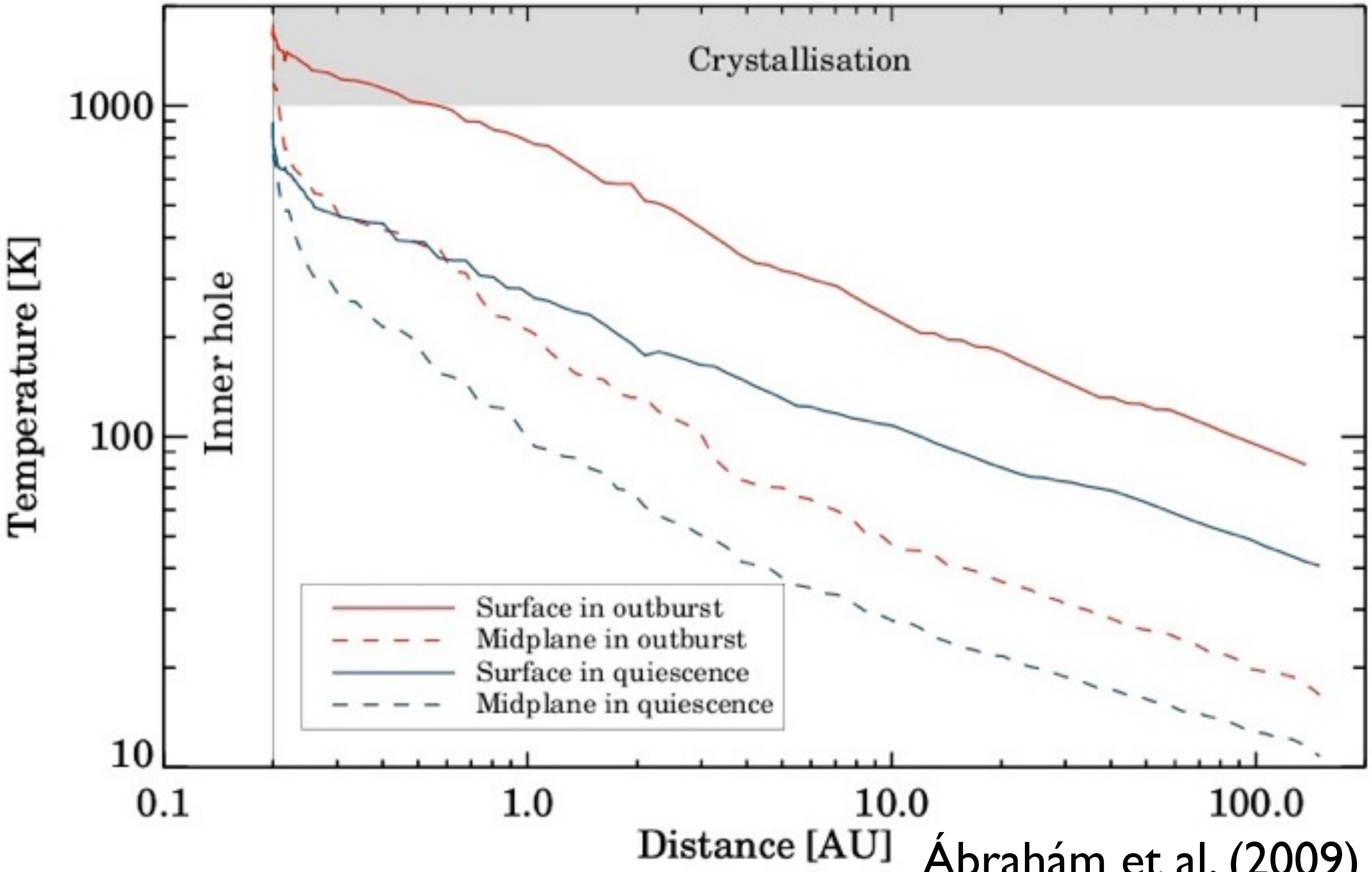
Juhász et al. (2012)

Crystallinity > 90%

Crystallinity ≈ 0%

The silicate crystals are located within the inner few au’s

Origin of silicate crystals

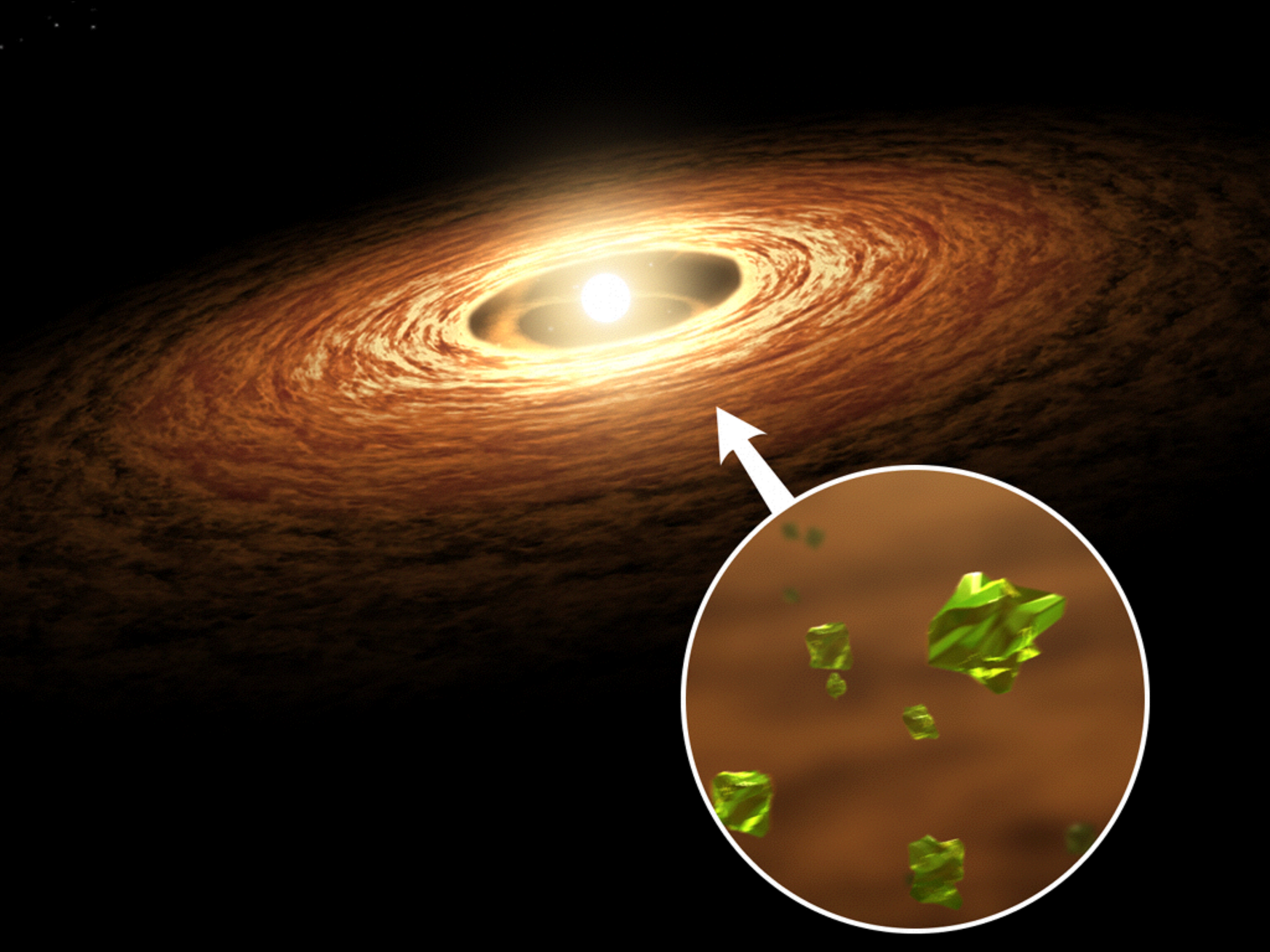


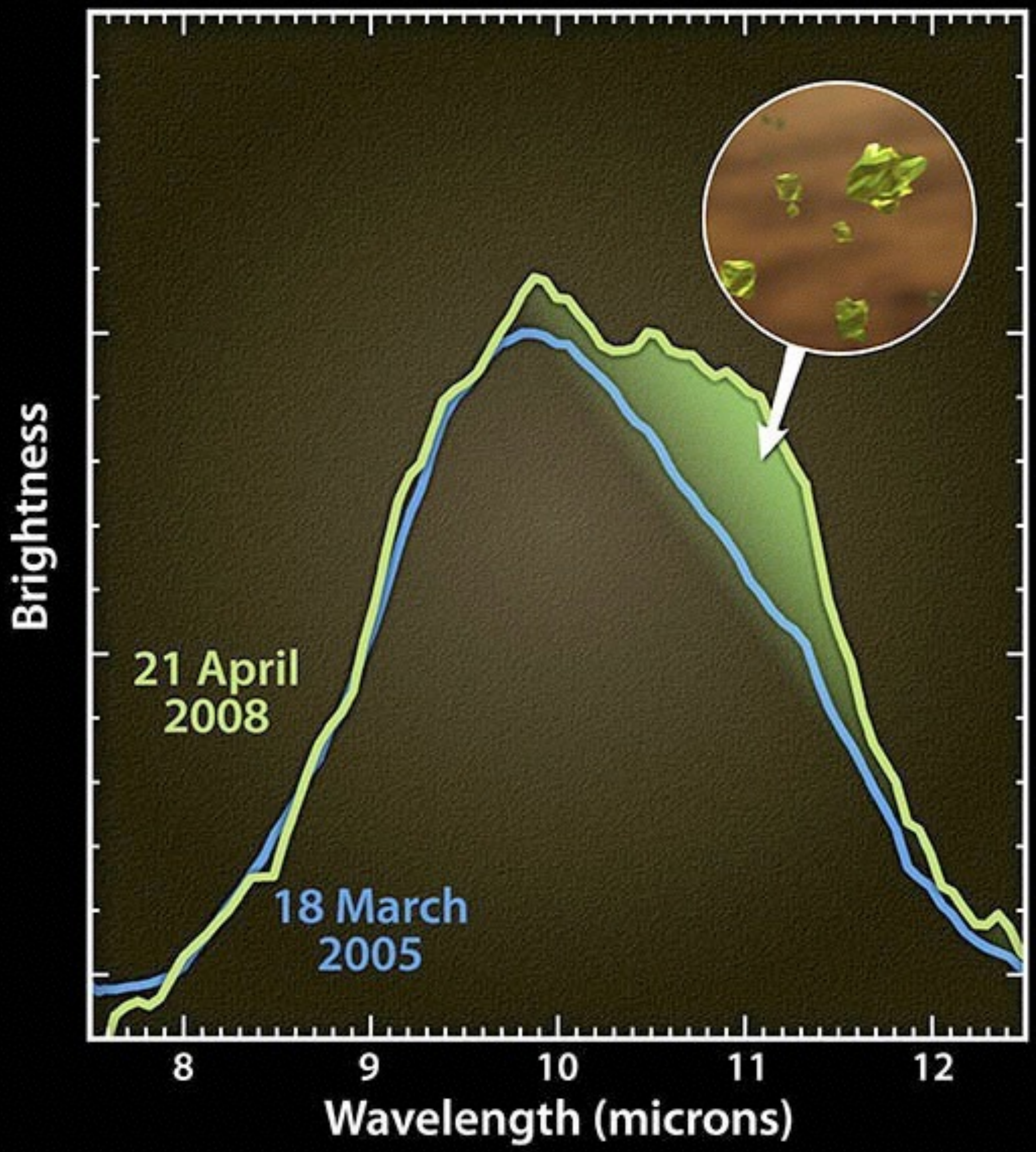
Ábrahám et al. (2009)

Above 1000 K: thermal annealing

Above 1500 K: evaporation

Annealing in the inner 0.4 au led to crystallization on the surface of the disk

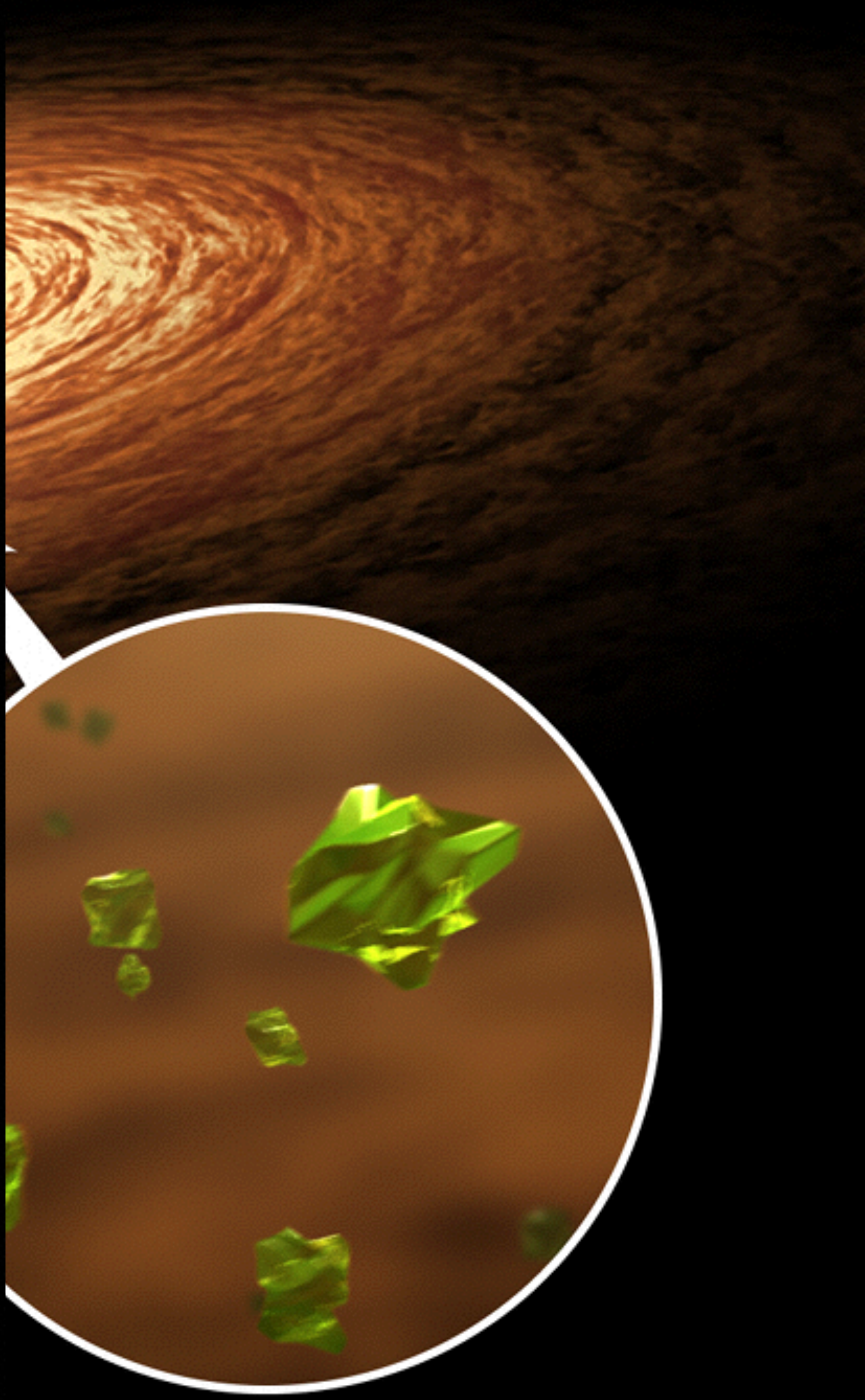


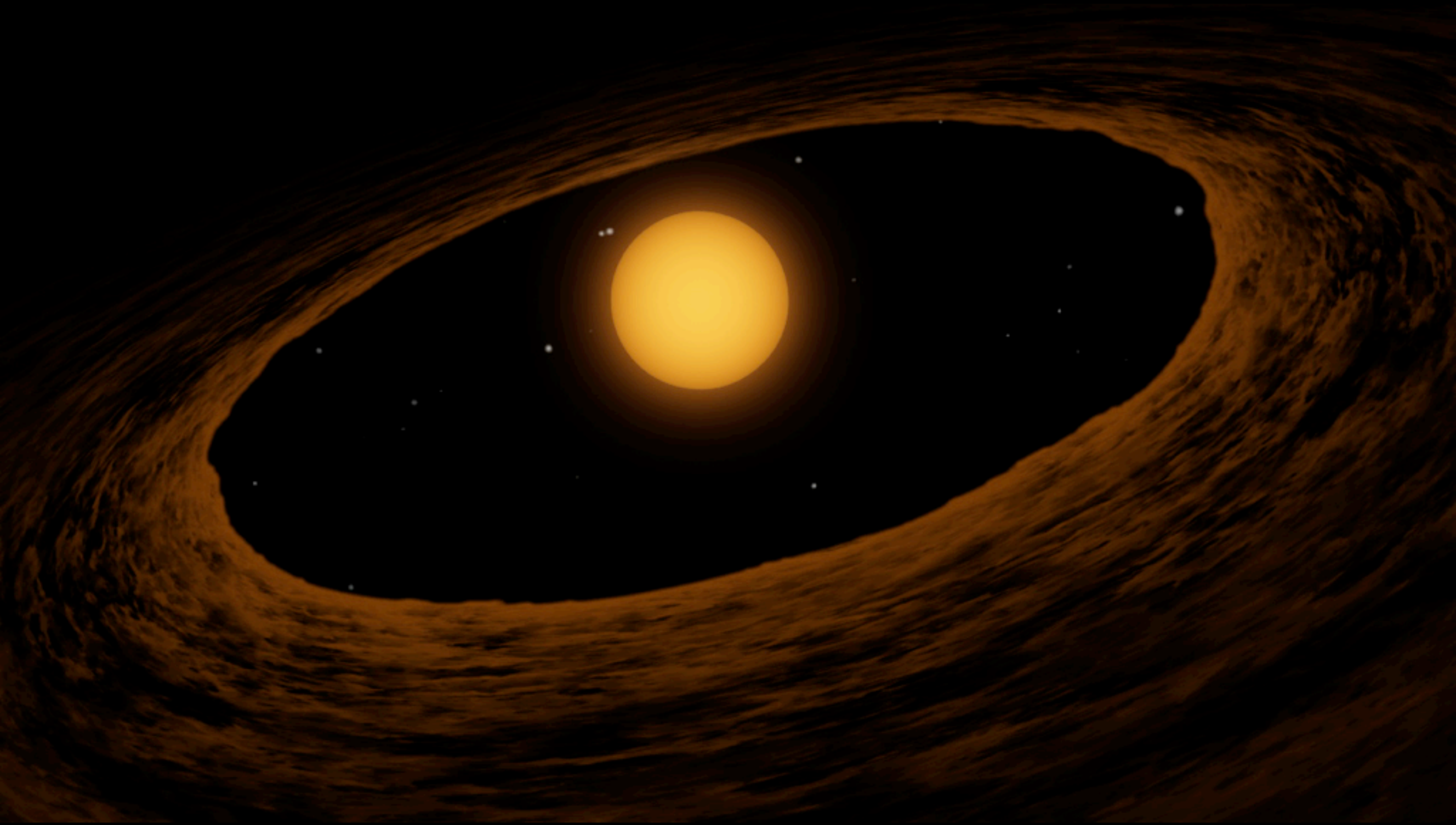


Crystal Formation in the Disk of an Erupting Star

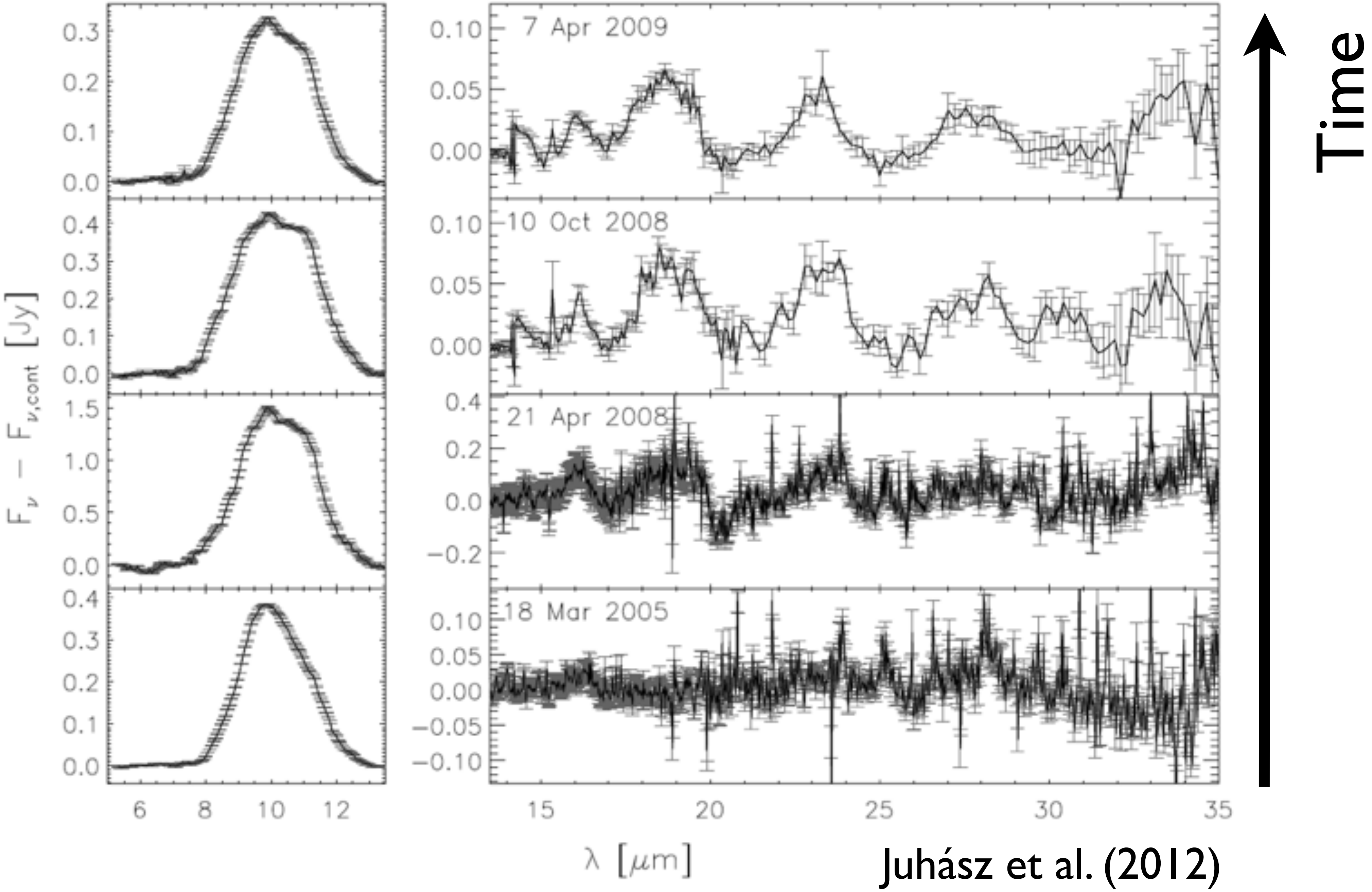
Spitzer Space Telescope • IRS

NASA / JPL-Caltech / P. Ábrahám (Konkoly Obs., Hungarian Academy of Sciences) ssc2009-11a





Silicate crystals in motion



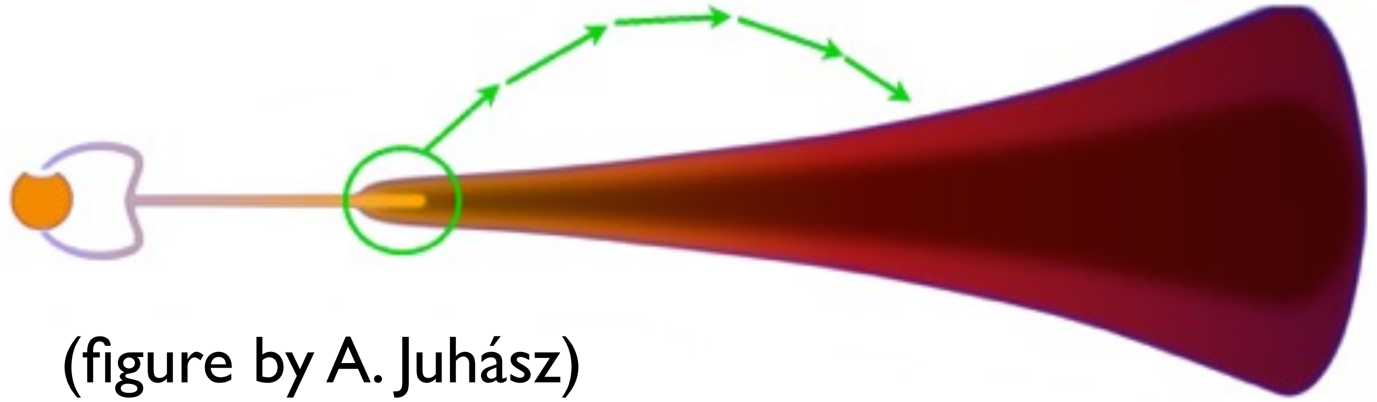
Juhász et al. (2012)

Forsterite bands at longer wavelengths were also detected

The variation of the far-infrared features indicates radial transportation of crystals into outer disk regions

Silicate crystals in motion

- 10 µm interferometry (VLTI/MIDI) shows that crystallinity is high in the central region
- The variation of the far-IR features indicate radial transportation of crystals into outer disk regions



(figure by A. Juhász)

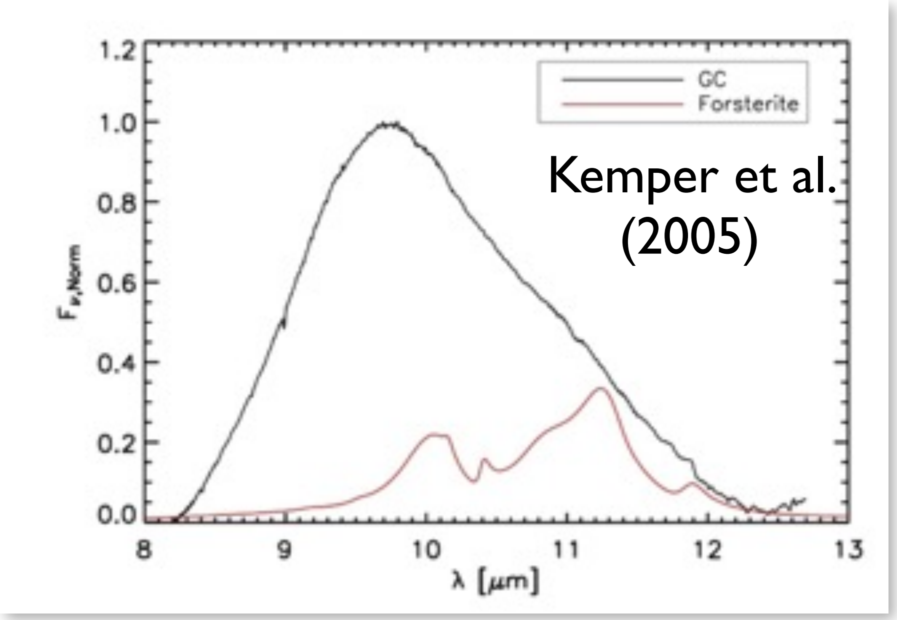
- On long term, episodic crystal formation might enhance the crystalline fraction of disk material and potentially contribute to the crystals found in solar system comets

Dust evolution

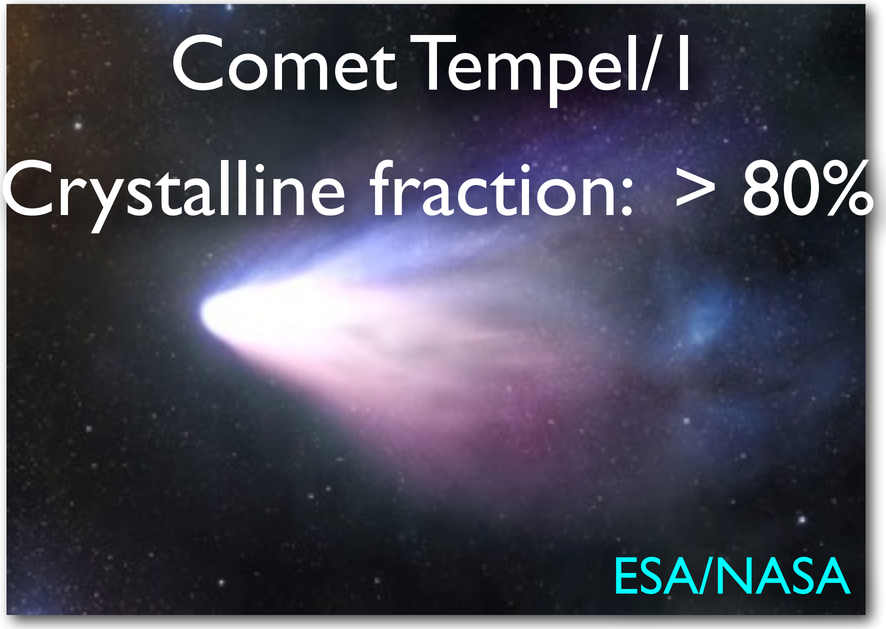
SGR A*

Crystalline fraction: < 3%

Stéphan Guisard



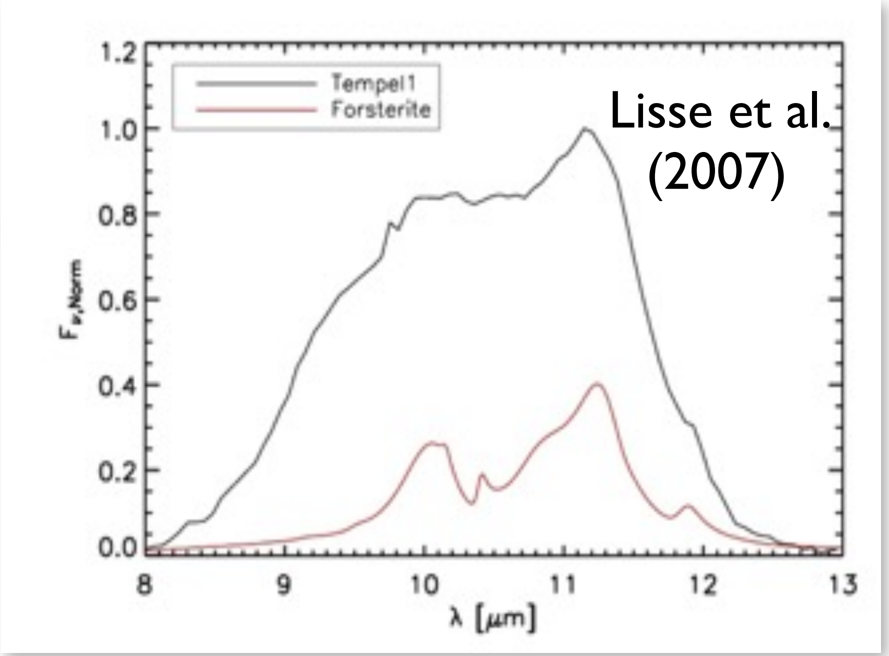
Kemper et al. (2005)



Comet Tempel/1

Crystalline fraction: > 80%

ESA/NASA



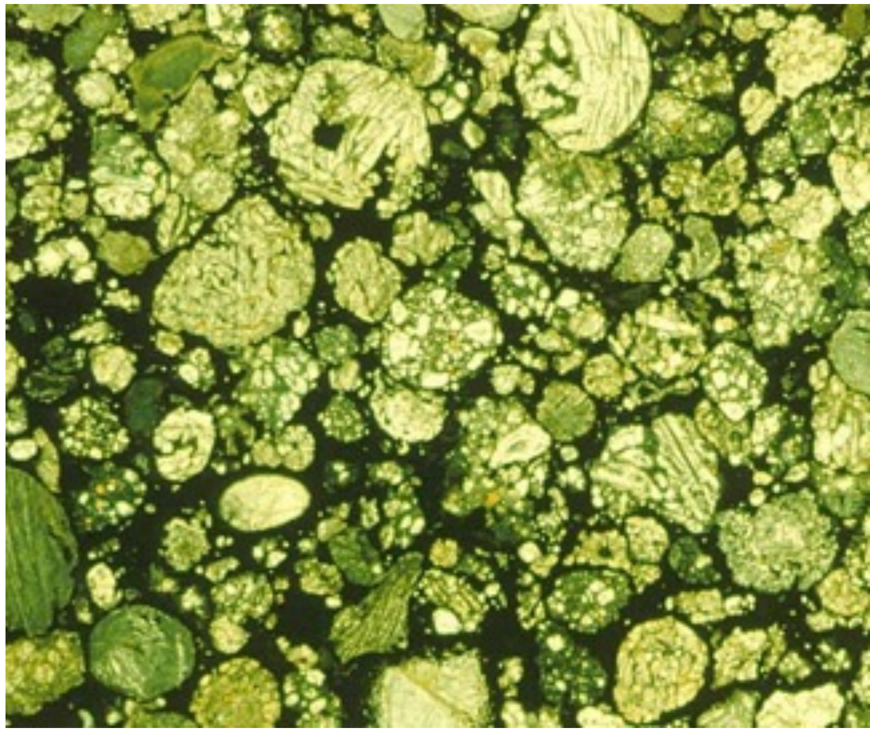
Lisse et al. (2007)

- How does the amorphous silicate turn into crystalline? We do not know.
- Episodic surface crystallization is only one possibility.

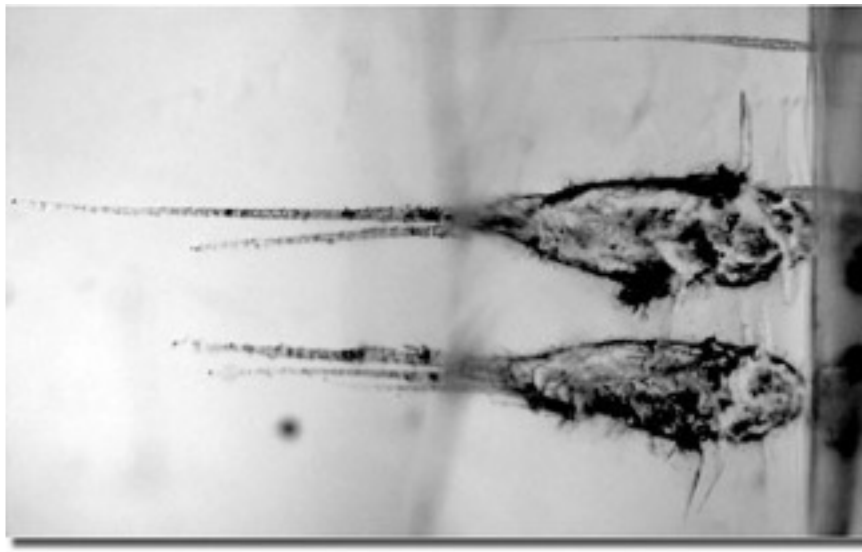
Crystallinity fraction in disks does not correlate with any stellar or disk parameter.

Thermal processing in the SS

- Chondrules (once molten silicate spherules) and CAIs are delivered to the Earth from the cold Asteroid Belt (~180 K) by primitive chondritic meteorites.
- Stardust mission: sample returned from comet Wild 2 contained crystalline silicates.
- Did they form in situ?
- Were they mixed outward from the hot inner disk?



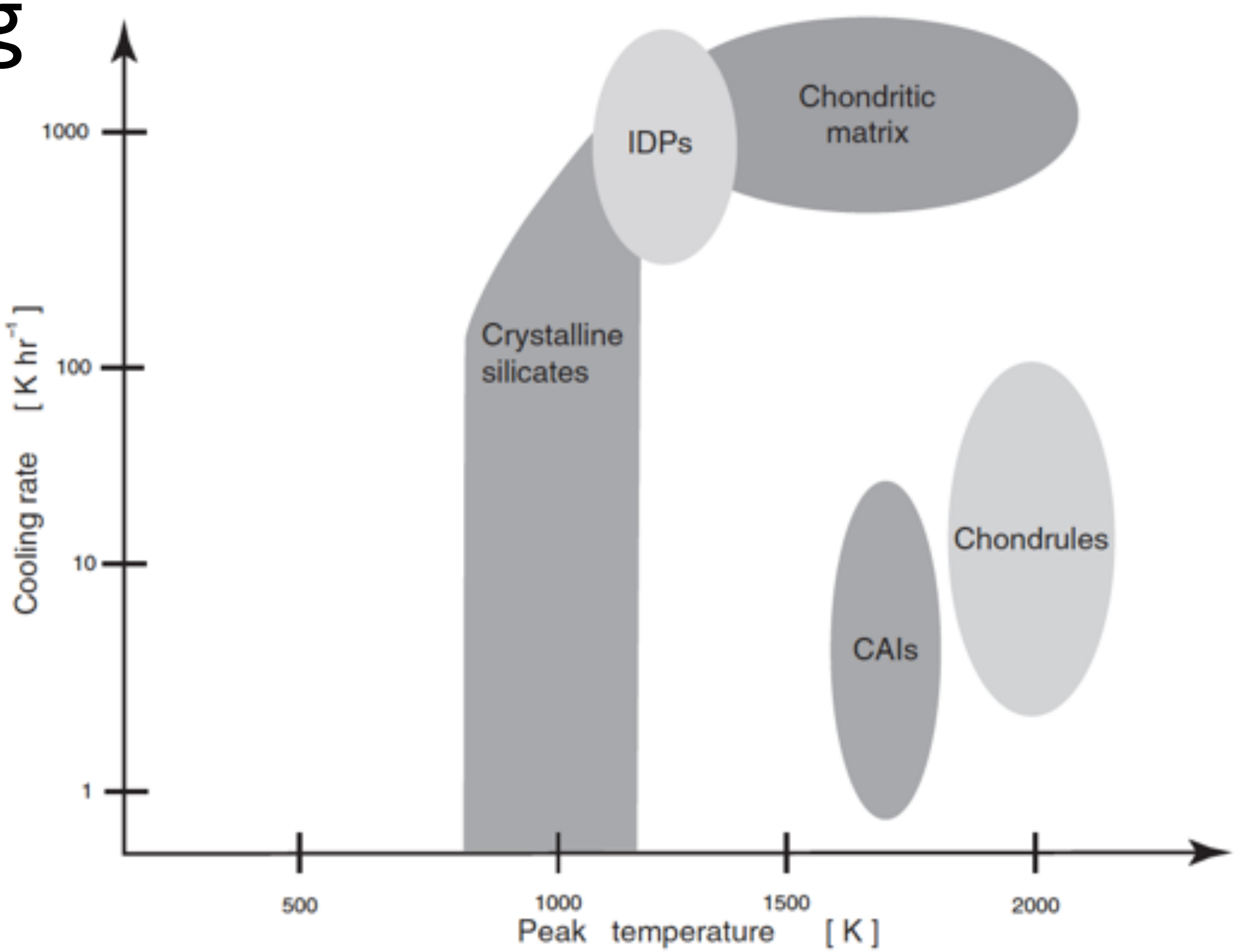
Semarkona meteorite
http://meteorite.unm.edu



Stardust impact tracks
NASA/JPL

Thermal processing in the SS

- Most of the primitive material in the Solar System (e.g. chondrules and some CAIs) shows evidence for multiple transient heating events.
- They were formed in a transient high-temperature heating event (initial melting needed 2200 K for minutes to seconds)
- Multiple transient heating events afterwards of various intensity (peak temperatures of 1300−1500 K for hours to days)



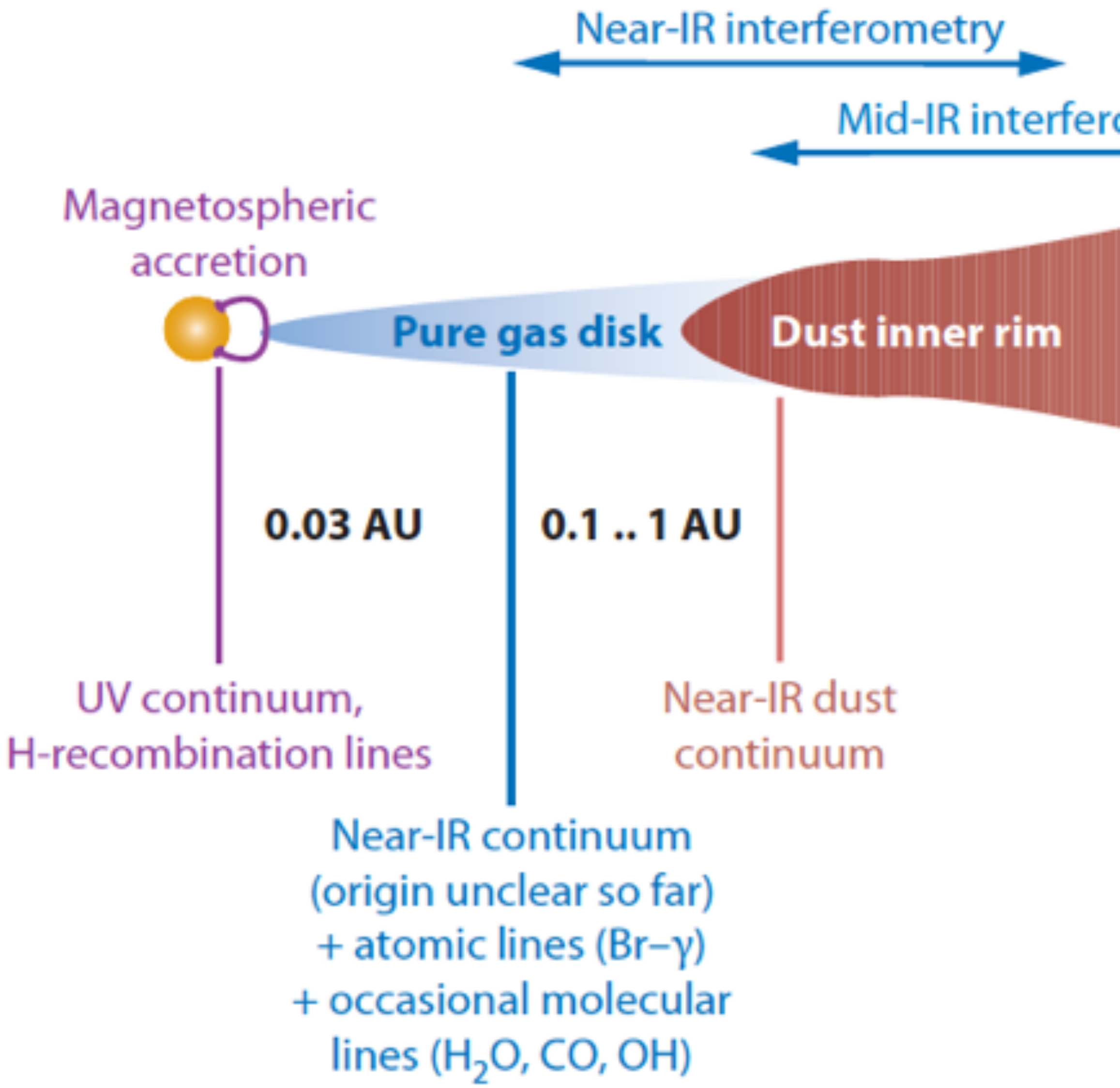
Apai et al. (2010)

Outbursts in the early SS?

- Possible heating mechanisms:
    - Shock waves, X-ray flares, X-wind, lightning, impacts
    - Episodic outbursts like in EX Lup?
- Argument against accretion outbursts: the hot phase is too long
- But: outburst light curves often show short peaks
- Combination: if outbursts are caused by the formation and infall of large clumps in the disk, these may generate shock waves while migrating inwards
- We need to study outbursts with better time and spatial resolution

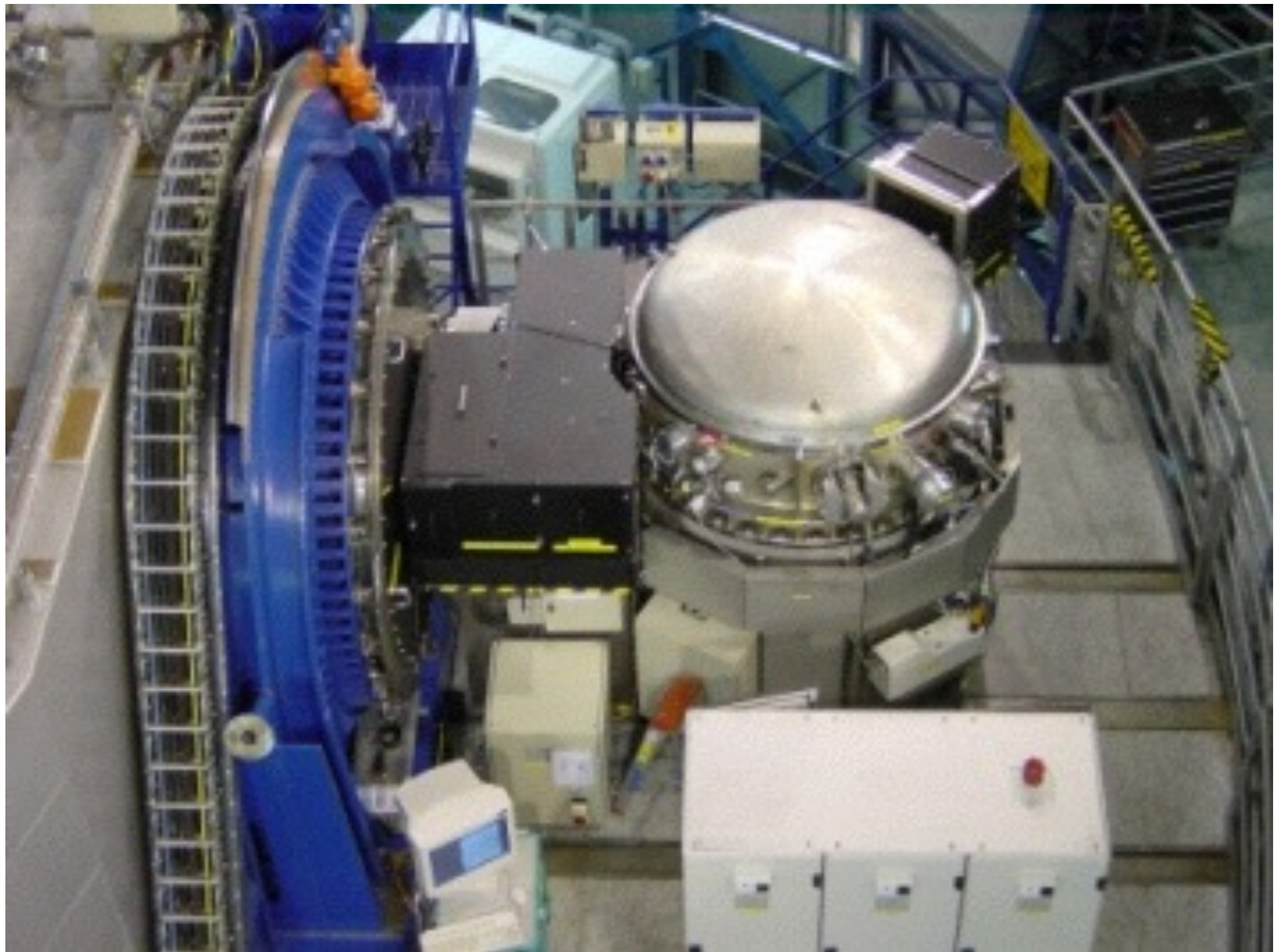
SED modeling in outburst

- SED is dominated by accretion luminosity
- Observation exclude the presence of an extended ($R_{out} \approx 0.3$ au) optically thick accretion disk
- All material accreted should have been located within 0.1 au of the central star (viscous timescale)
- The inner dust-free hole is filled with gas, optically thin in the continuum



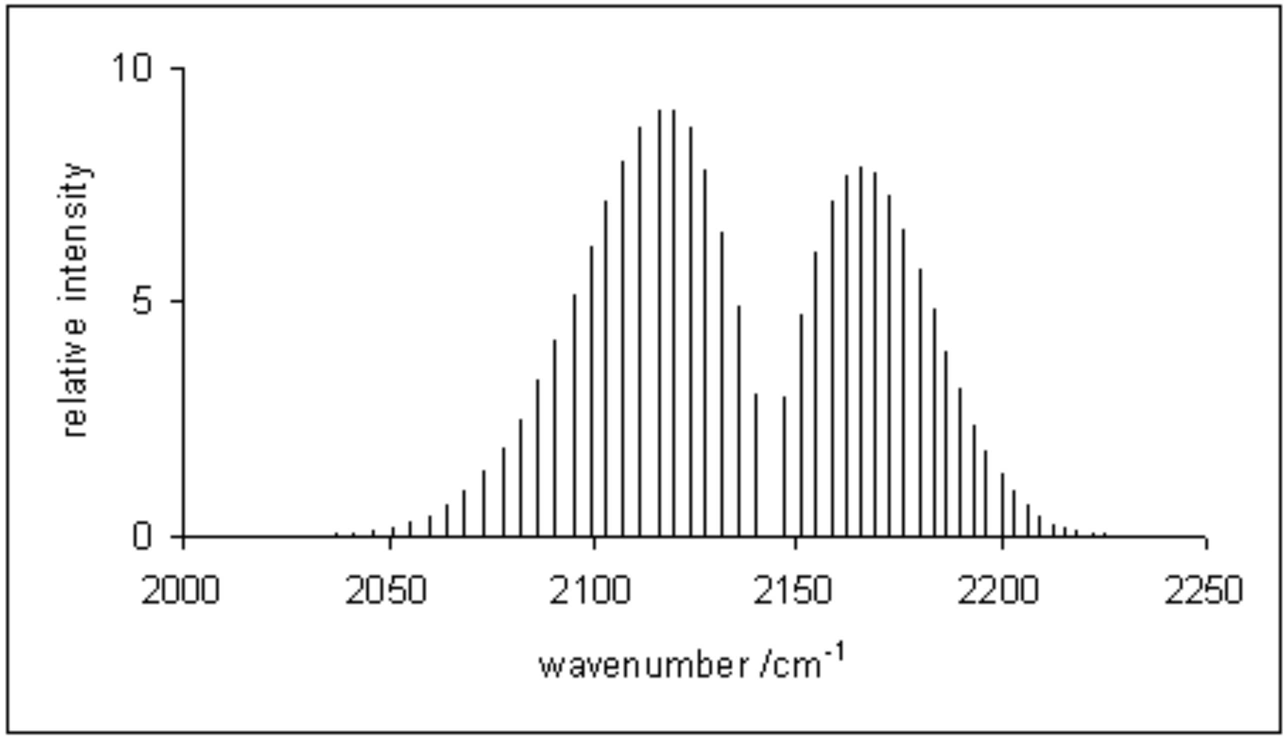
CRIRES monitoring

- CRIRES: AO-assisted IR echelle spectrograph on the UT 1
- High resolution: R = 100 000
- Wavelength coverage: 4.6−5.0 μm
- 6 epochs during the outburst



eso.org

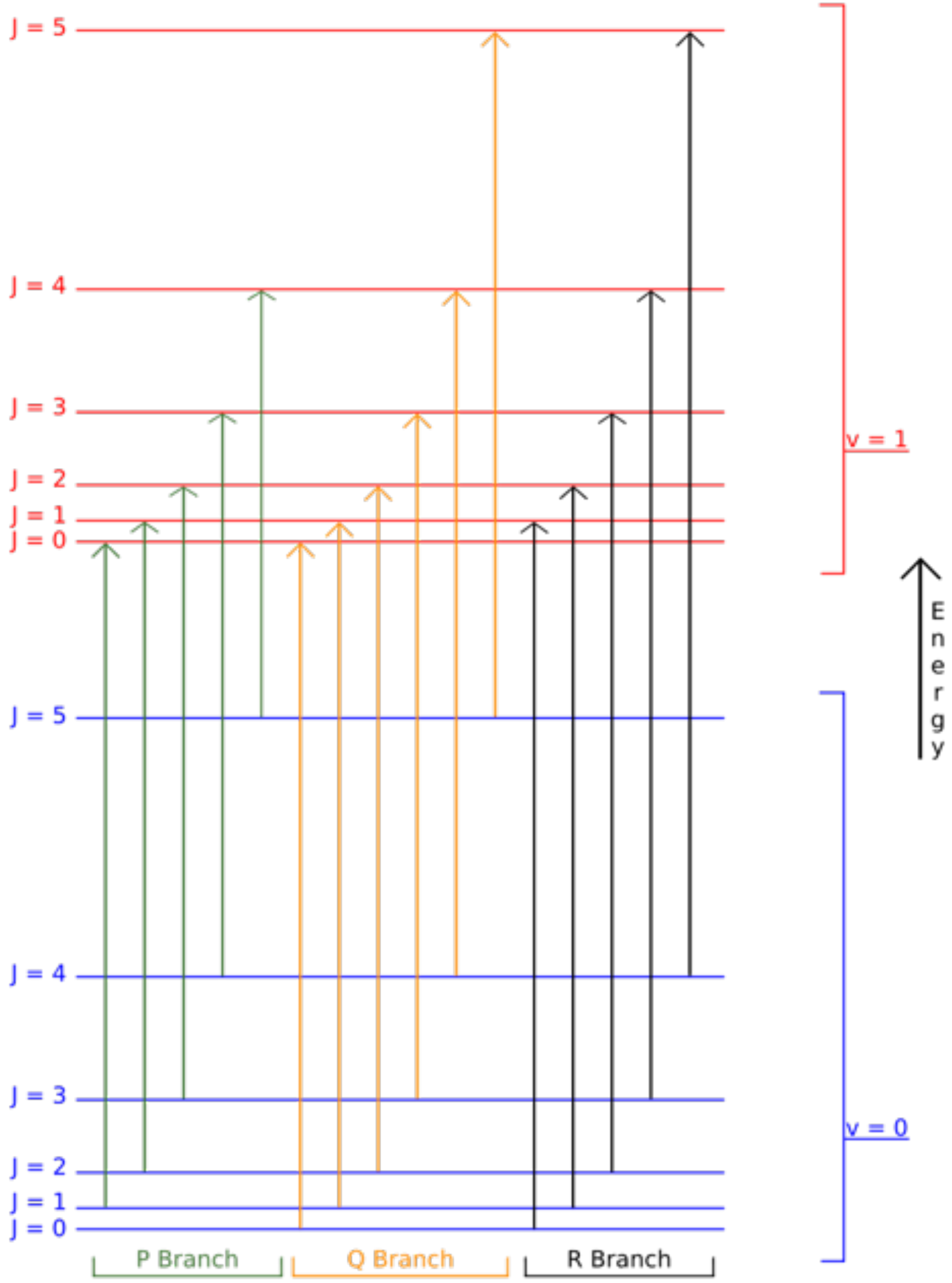
CO fundamental lines



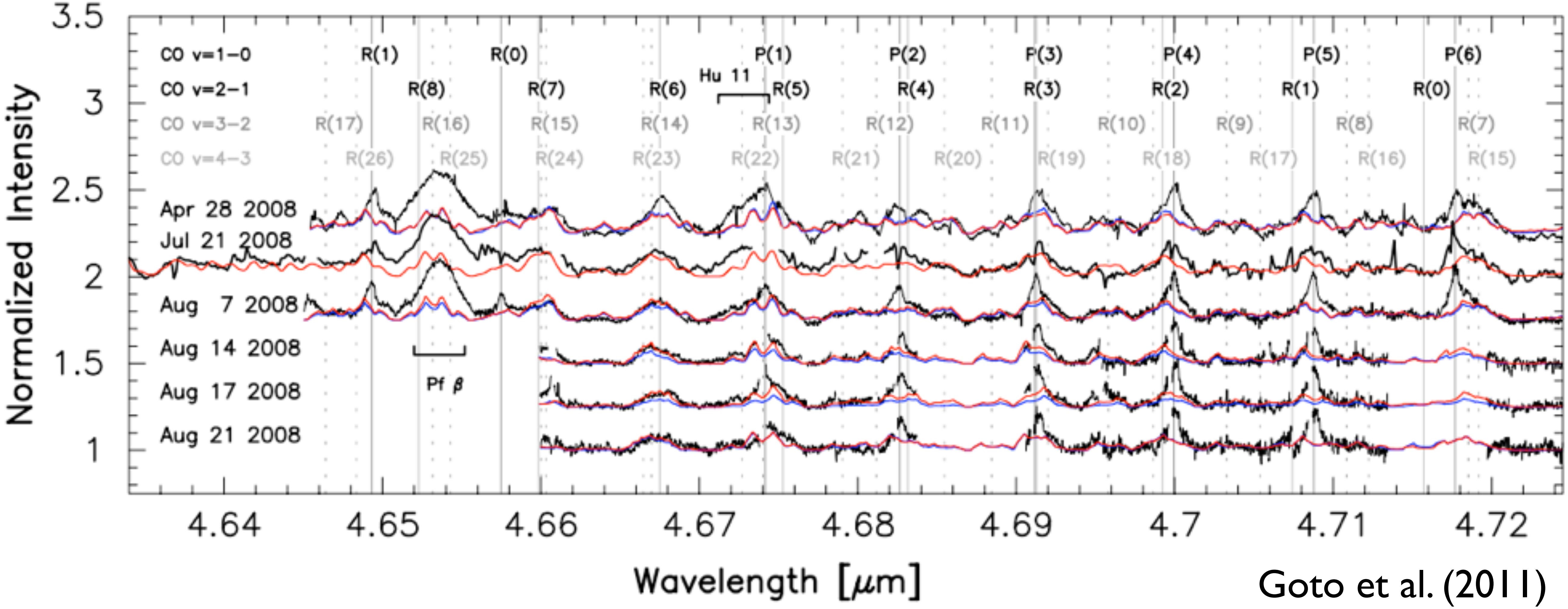
Mid-infrared (4−5 μm)

$\Delta v=1$

http://en.wikipedia.org/wiki/
Rotational-vibrational_spectroscopy

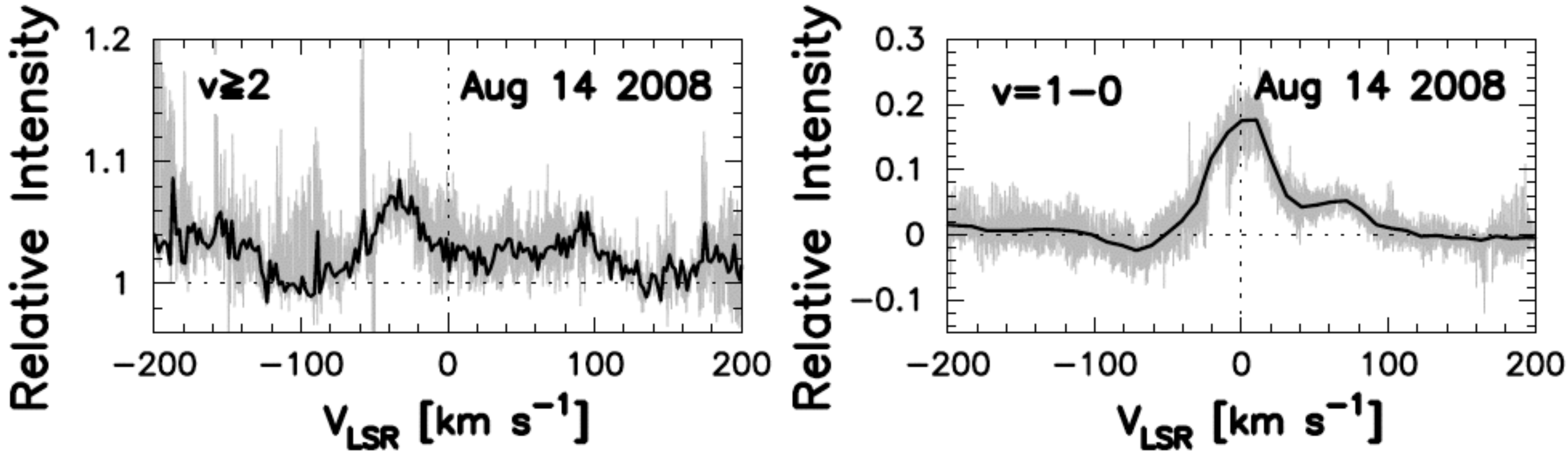


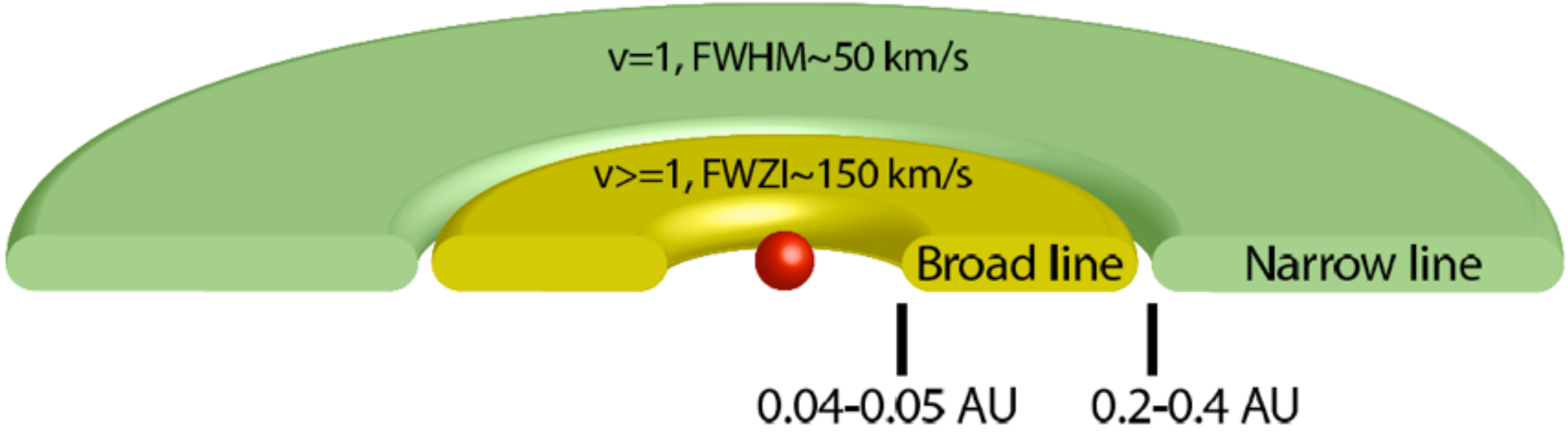
CRIRES monitoring



Goto et al. (2011)

Distinct disk regions

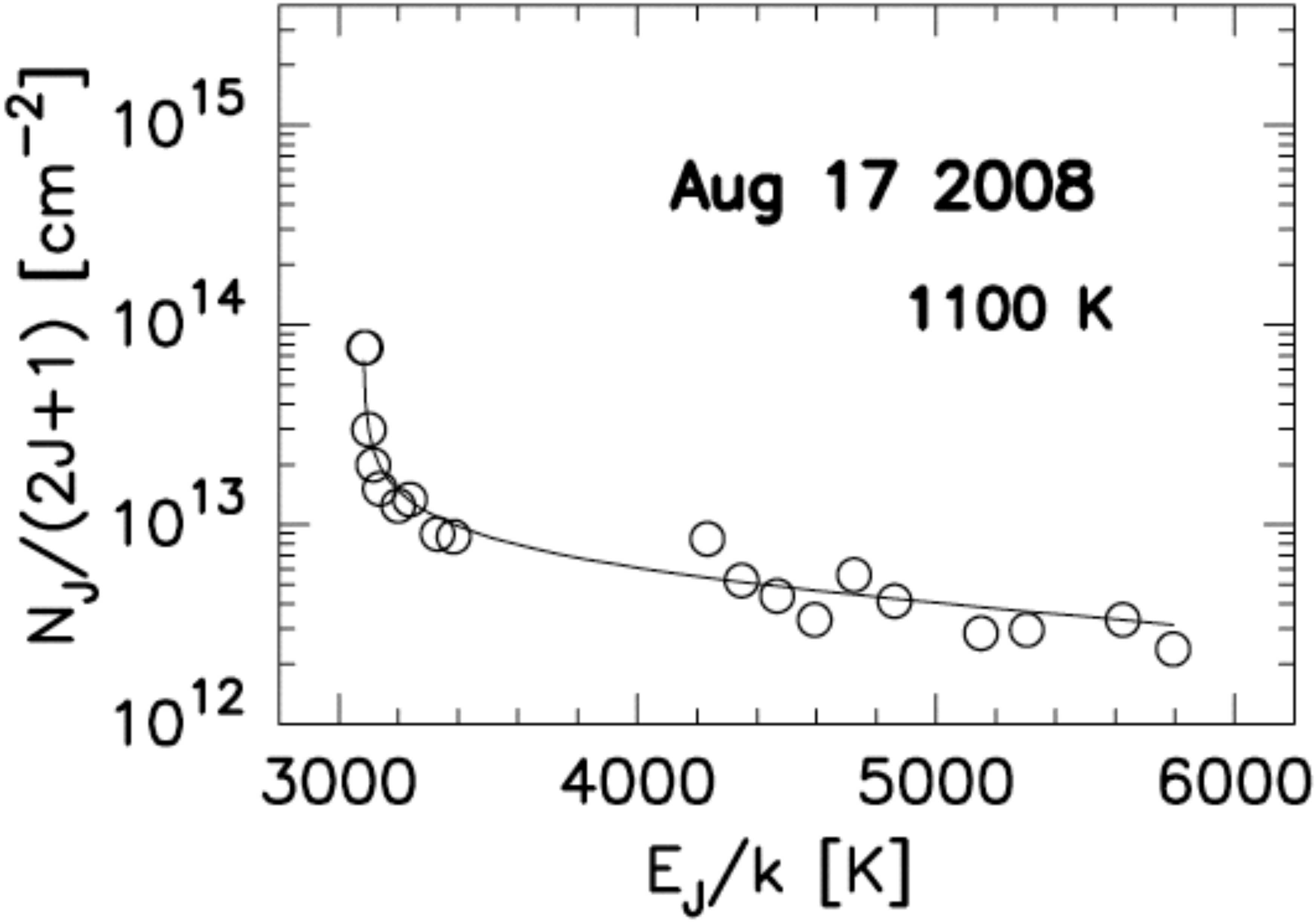




Goto et al. (2011)

Gas temperature

Population diagram:



Goto et al. (2011)

SINFONI observations

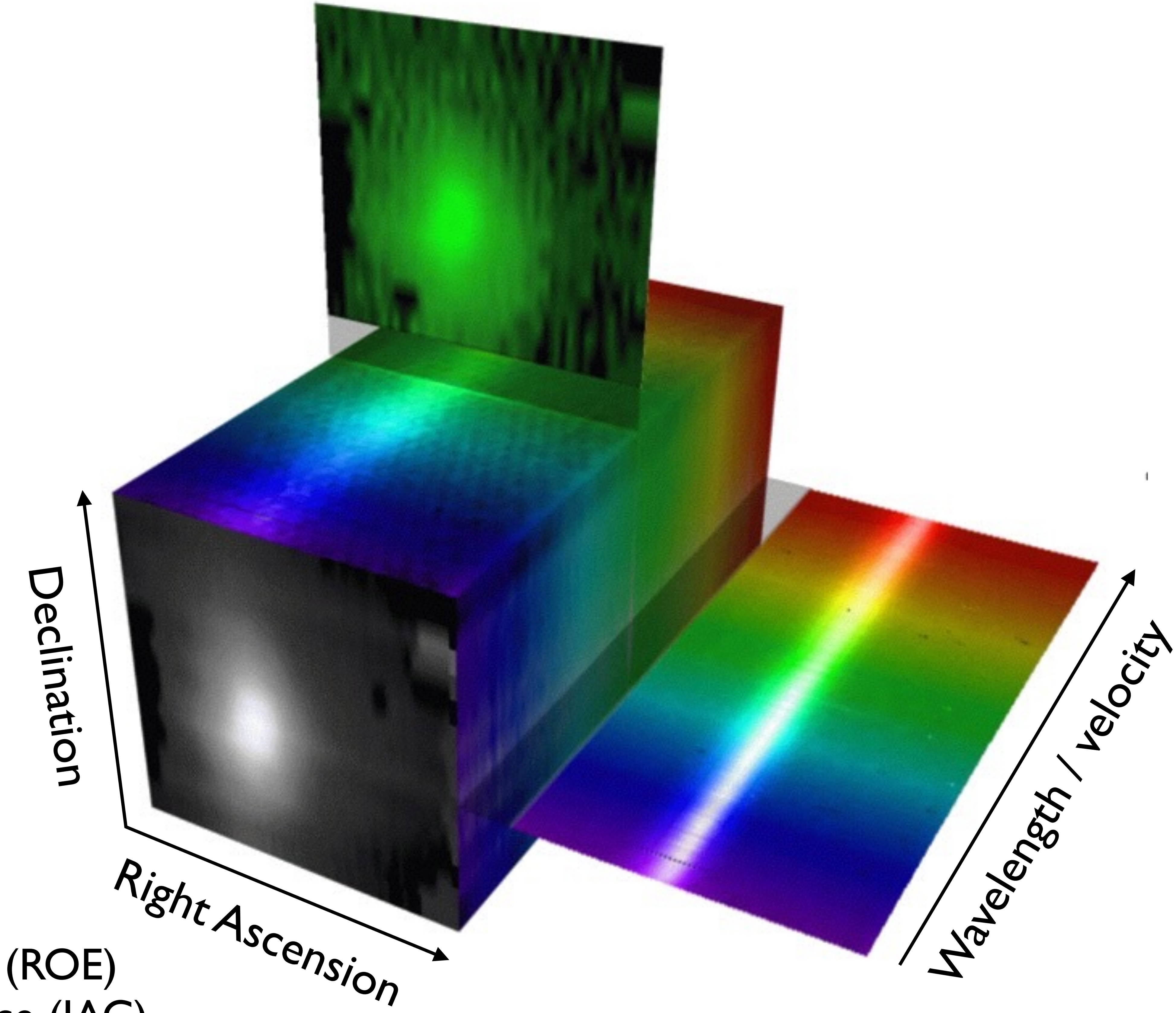
- SINFONI: AO-assisted near-IR integral field spectrograph on the UT4
- Medium resolution: R = 2400 in J

  R = 4100 in H

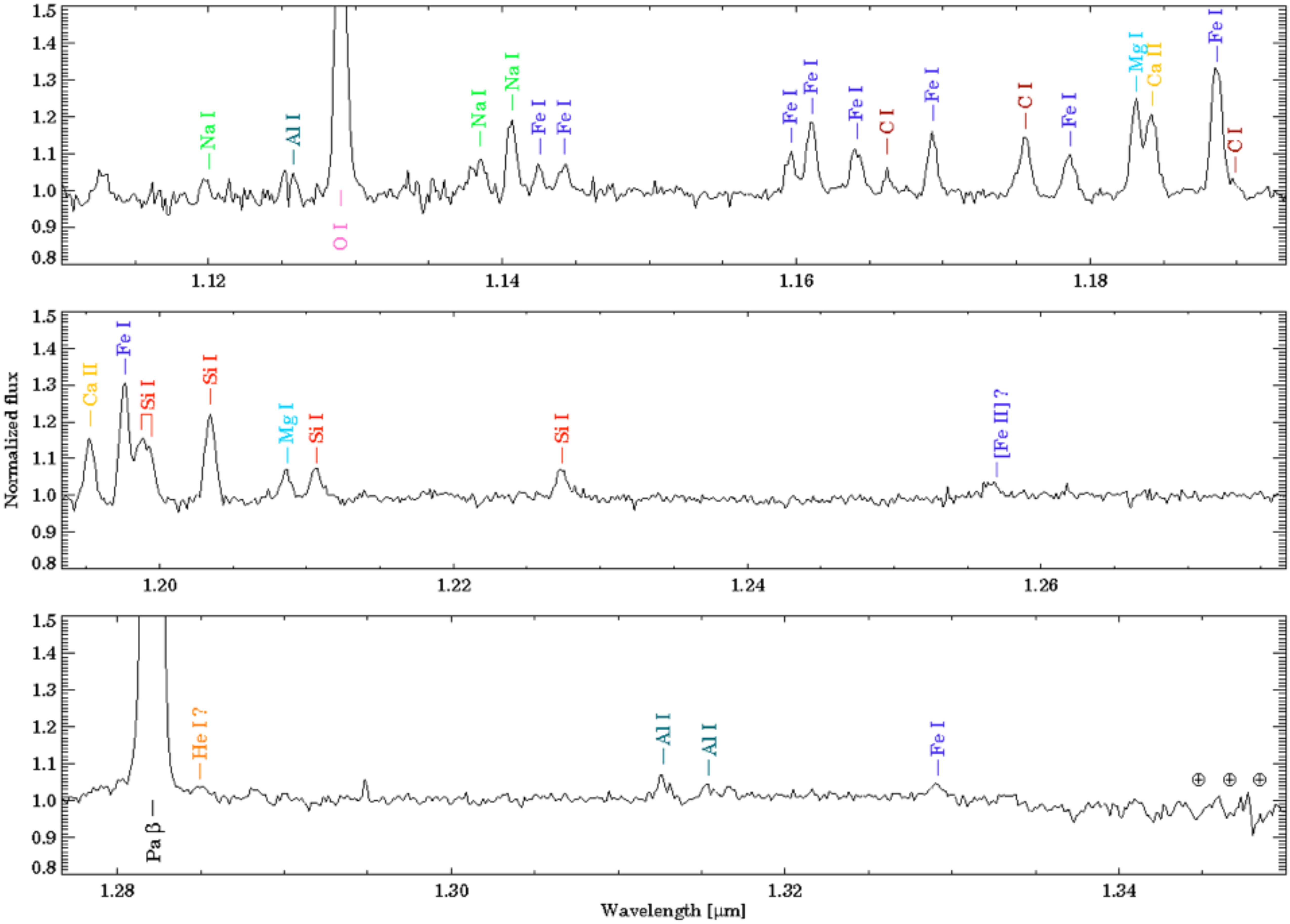
  R = 4400 in K
- Aims: combine spectral and spatial resolution to find out the location and kinematics of the hot gas that participates in the accretion process

eso.org

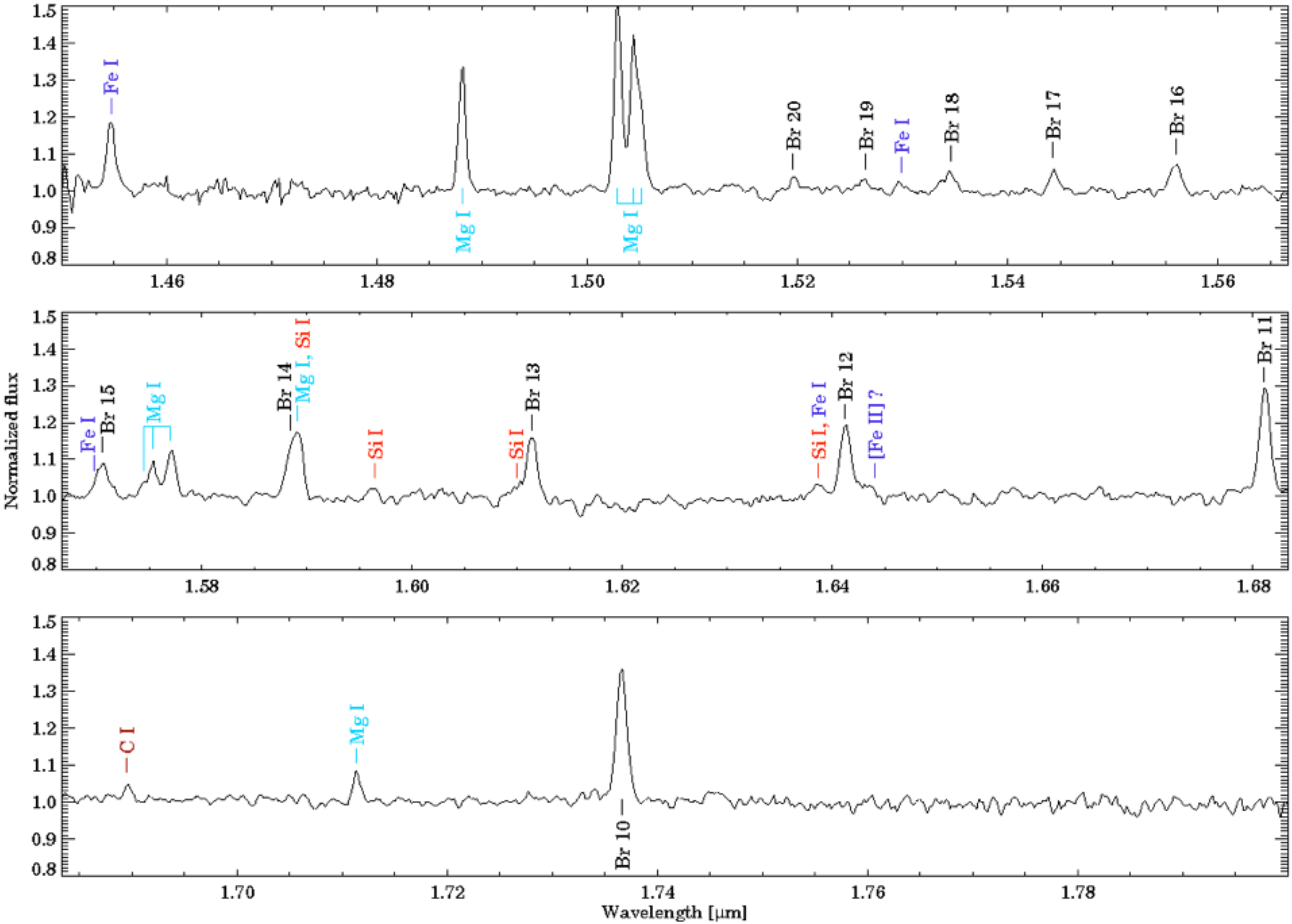
SINFONI observations



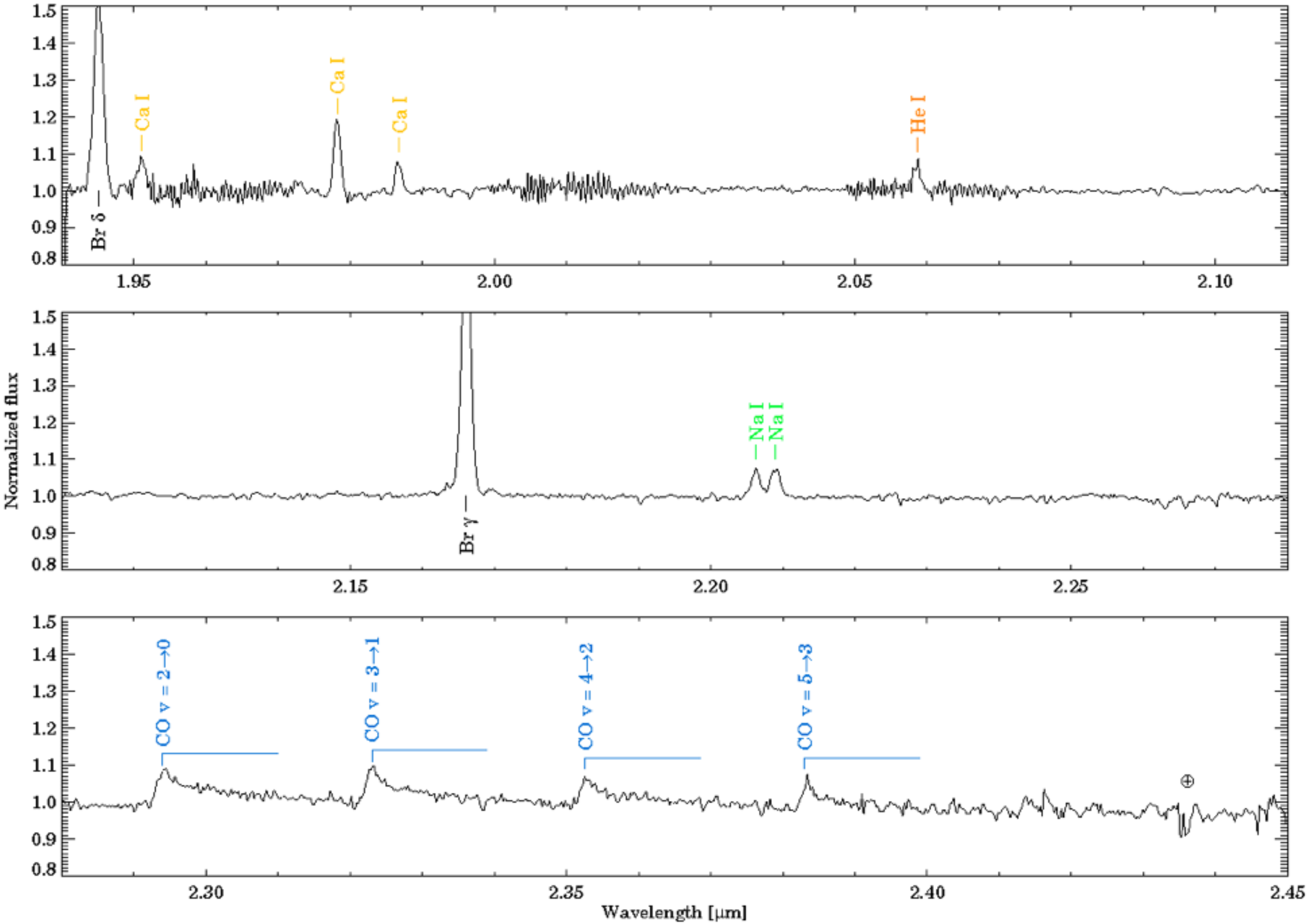
Credit: Stephen Todd (ROE)
and Douglas Pierce-Price (JAC)



Kóspál et al. (2012)

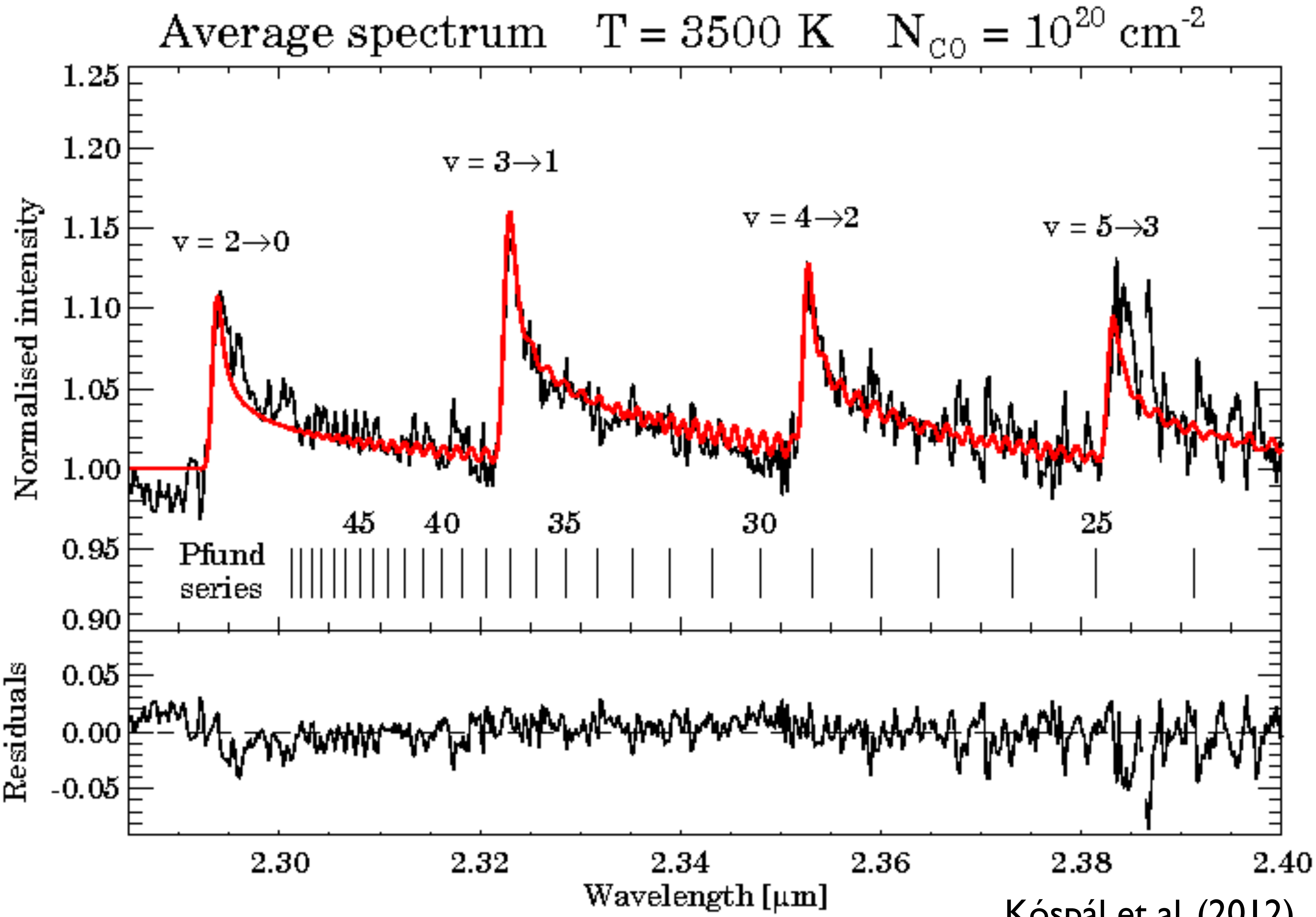


Kóspál et al. (2012)



Kóspál et al. (2012)

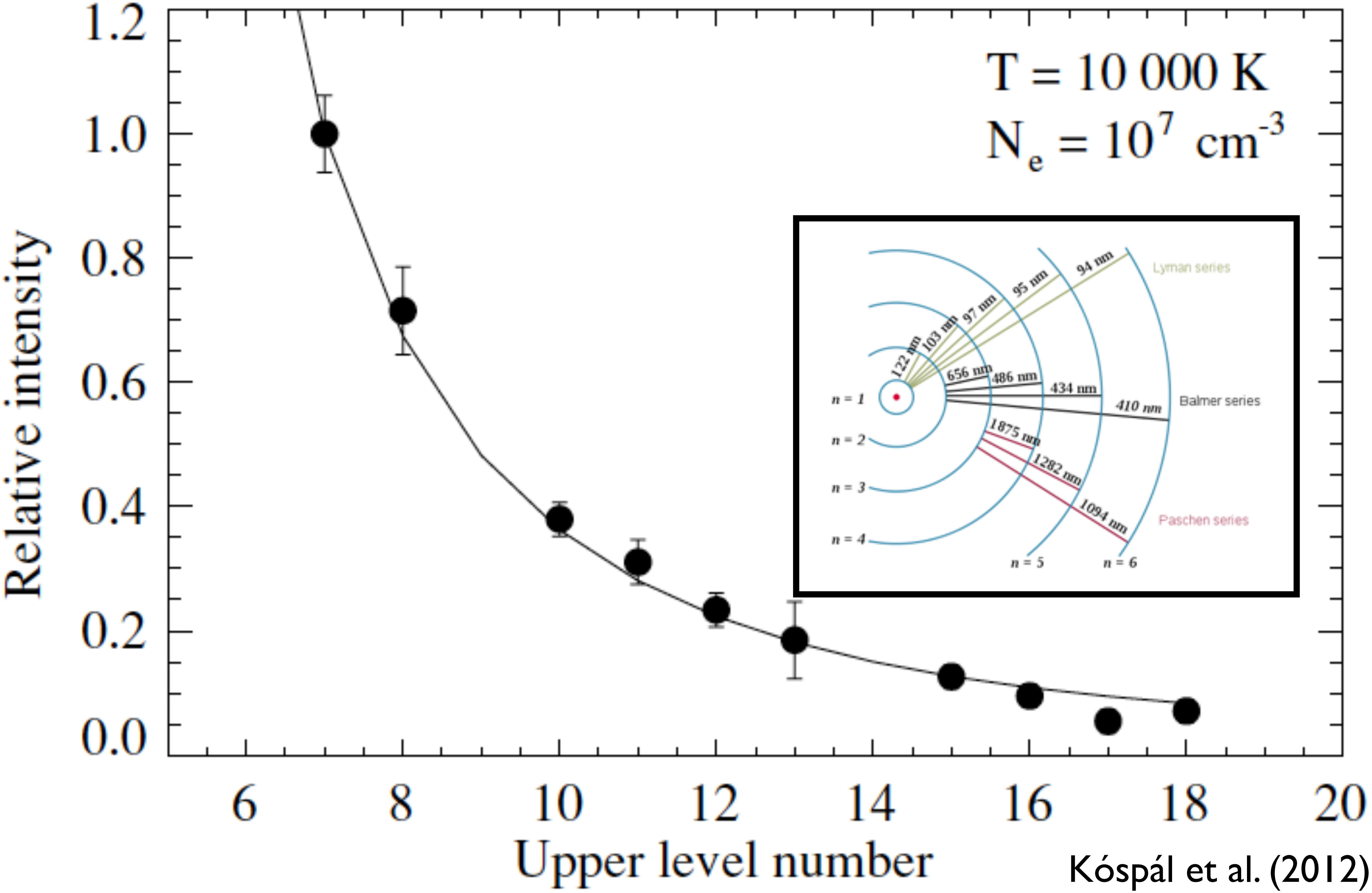
CO overtone lines



Kóspál et al. (2012)

H excitation diagram

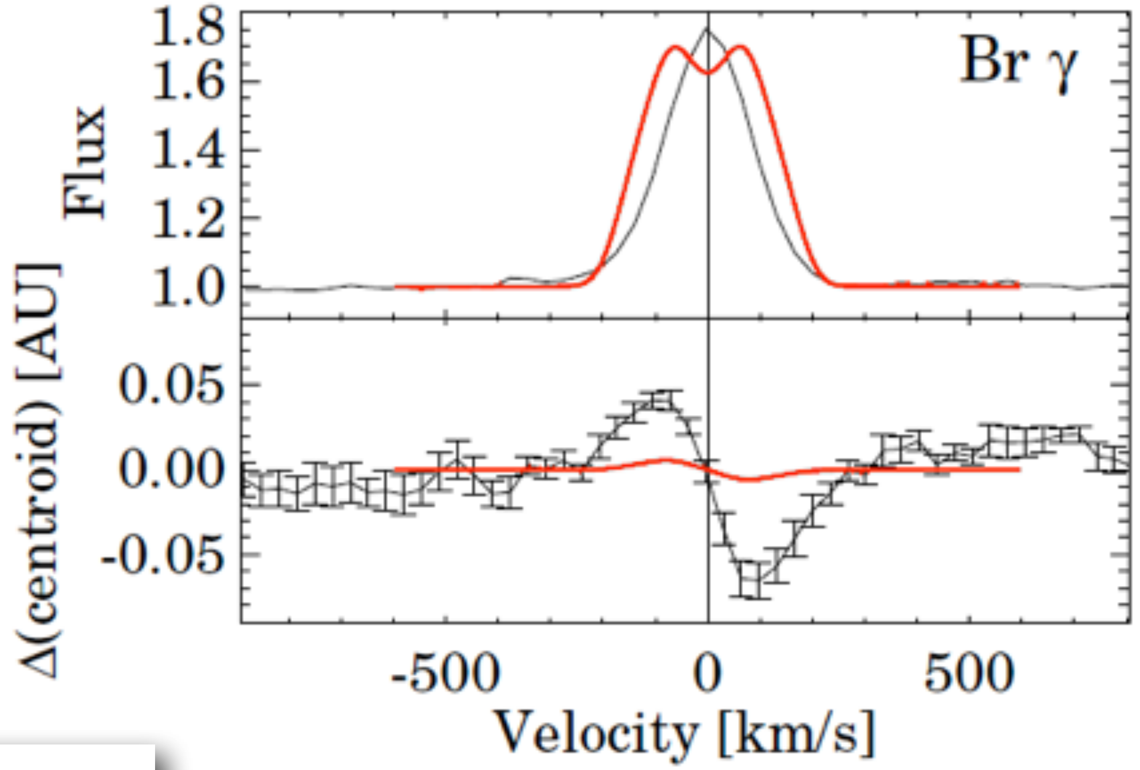
Brackett series



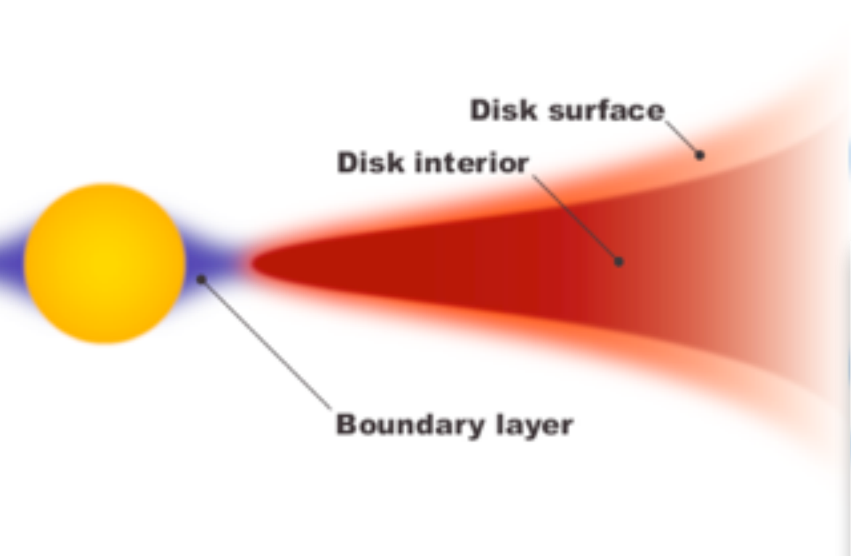
Kóspál et al. (2012)

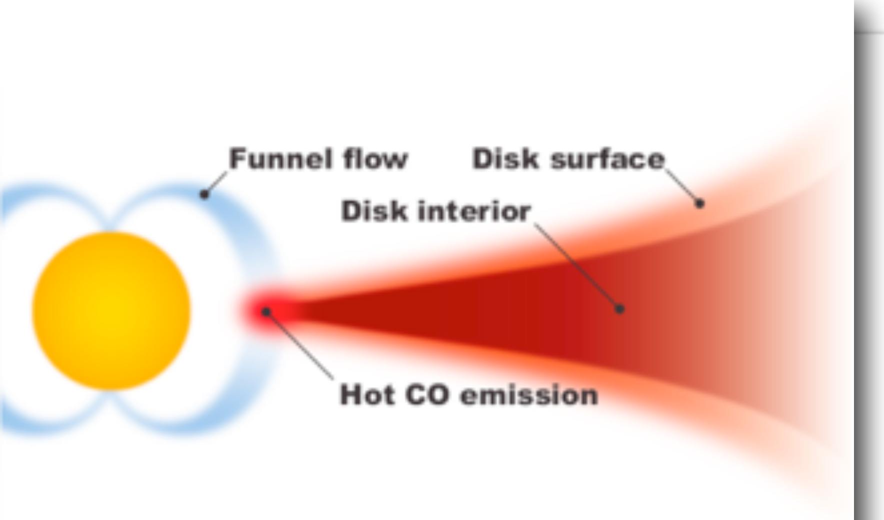
Spectro-astrometry

- Measure the position of the source as a function of wavelength
- Extended emission moving at different velocities: source position at different wavelengths will deviate from the source position at continuum



Kóspál et al. (2012)

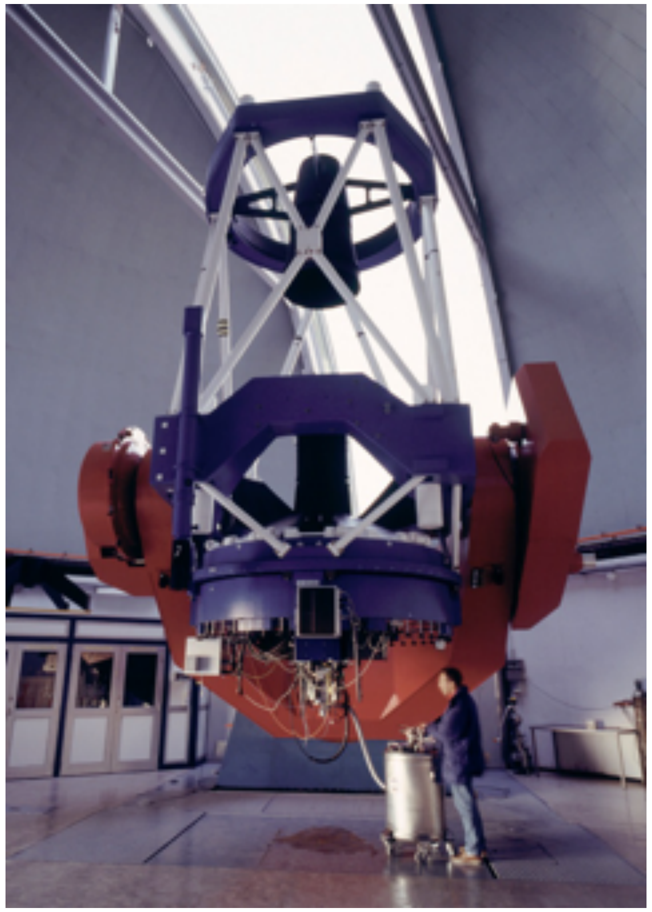




- Boundary layer can be excluded

Optical spectra

- 2.2m/FEROS, 3.6m/HARPS
- High resolution: R = 48 000
- Wavelength coverage: 3700−9300 Å
- 10 epochs before, during, and after the outburst



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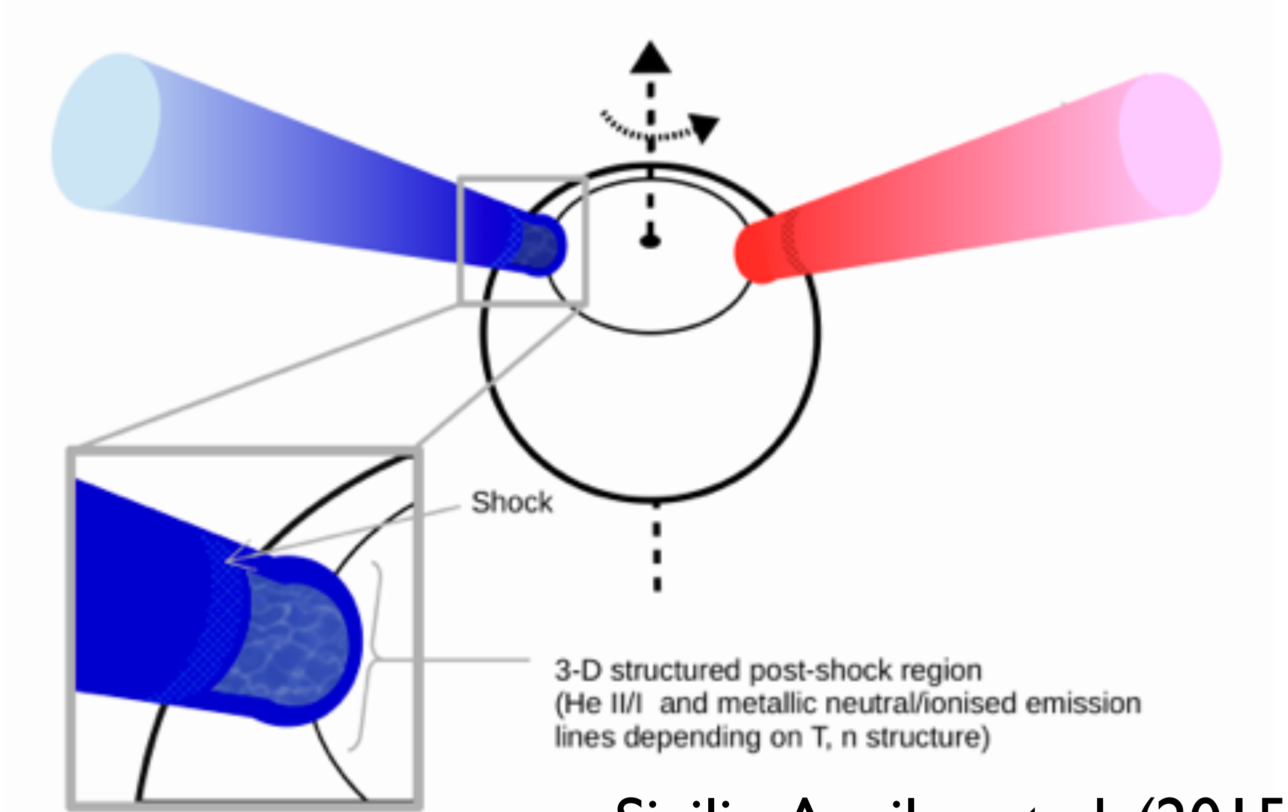
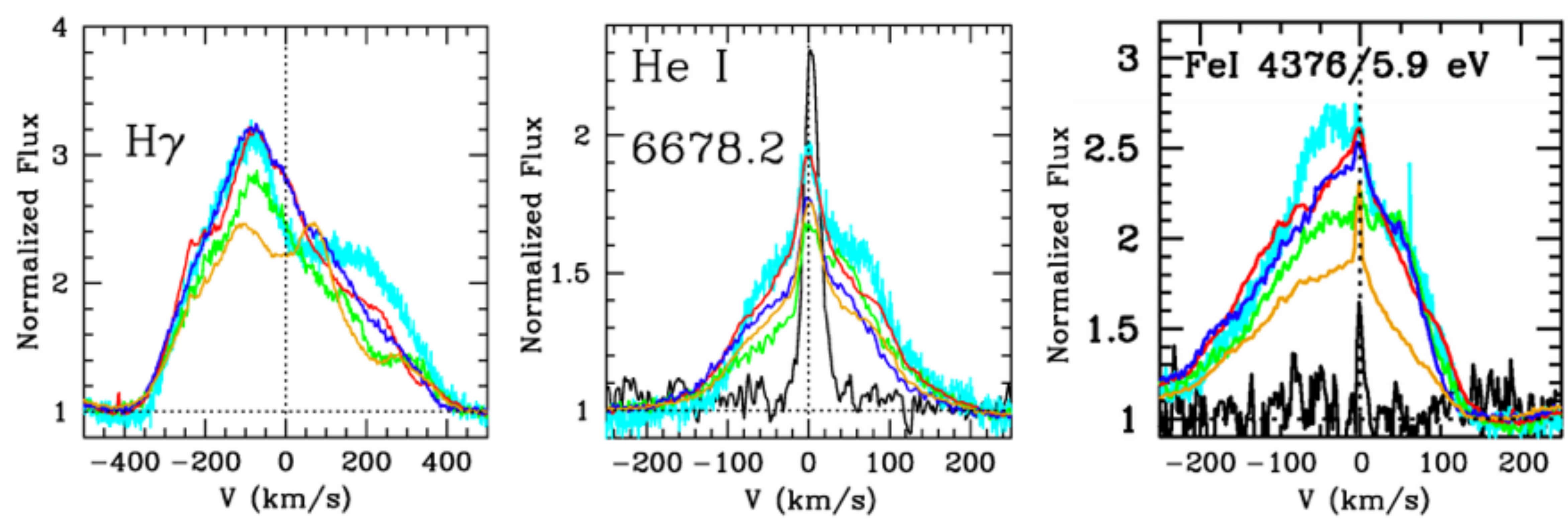
Optical spectra

- Hundreds of lines
- Strong variability
- Narrow and broad components
- Wind signatures



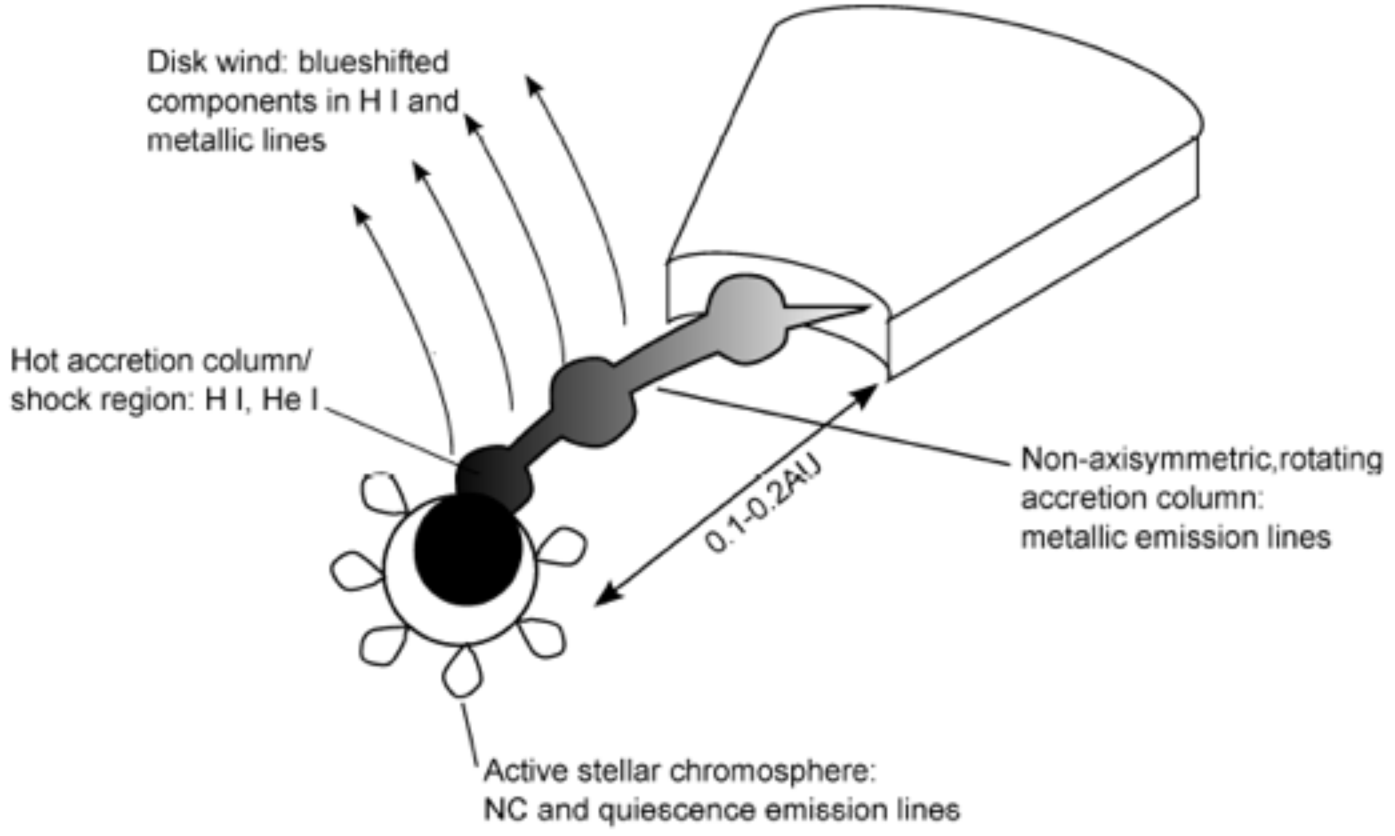
Sicilia-Aguilar et al. (2015)



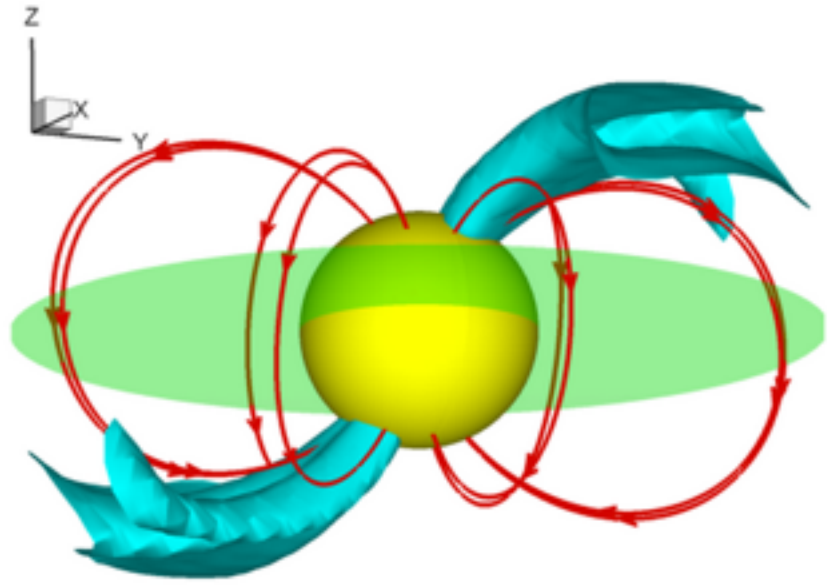
Sicilia-Aguilar et al. (2012)

Magnetospheric accretion

- Wind and accretion is correlated
- Hot, non-axisymmetric accretion columns
- Clumpy accretion
- No inner disk rearrangement
- Same accretion channels as in quiescence, but higher accretion rate



Sicilia-Aguilar et al. (2012)



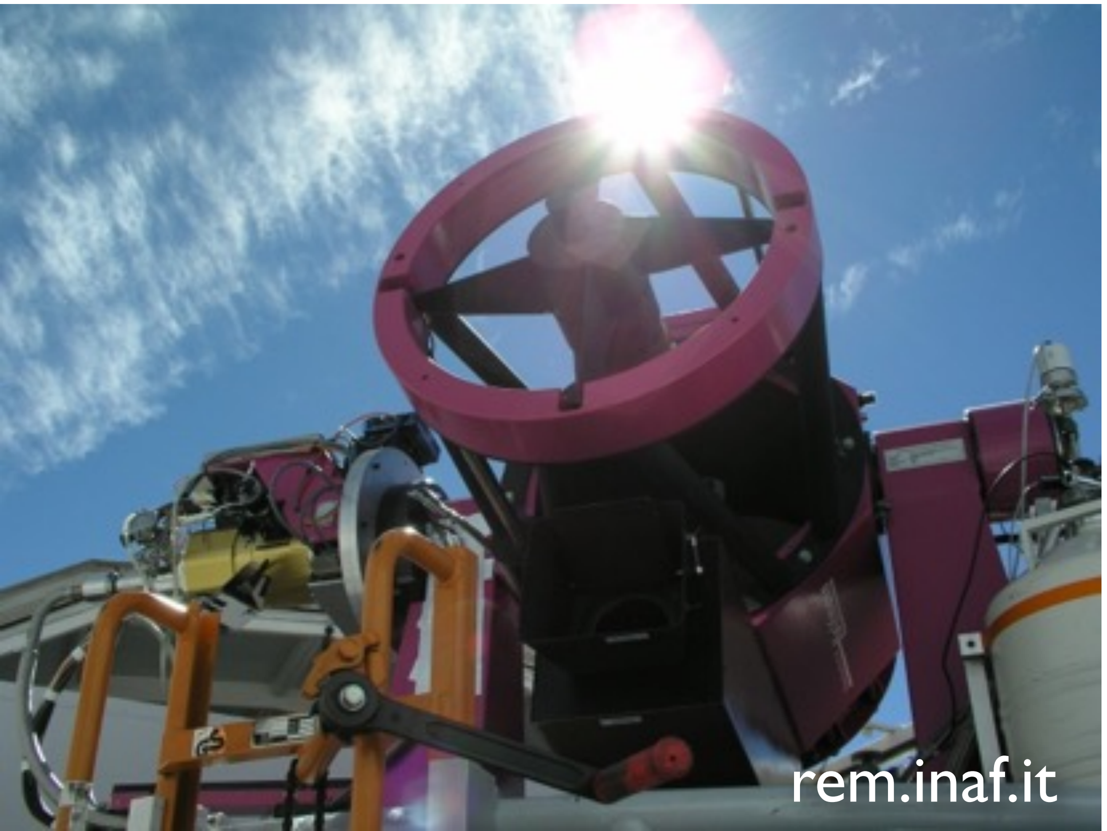
Kulkarni & Romanova (2008)

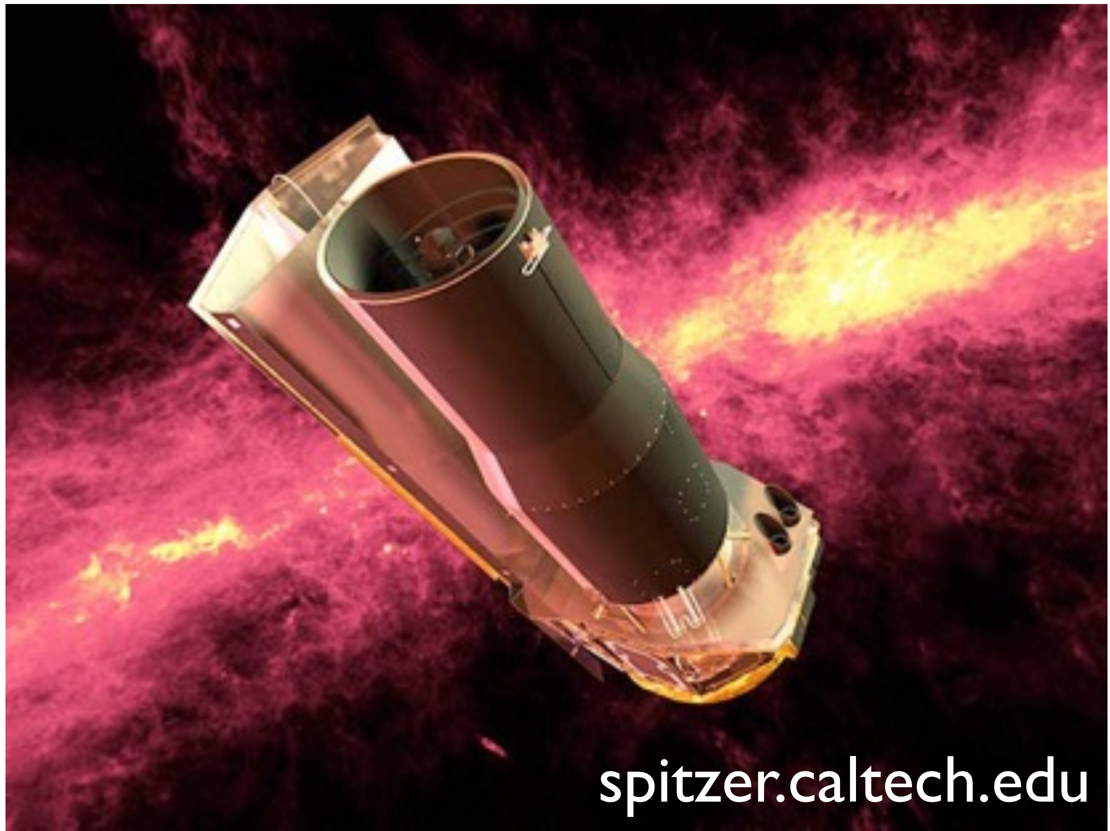
Radial velocity data

- FEROS: 57 spectra between 2007−2012, R=48,000
- HARPS: 10 spectra between 2008−2009, R=115,000
- RV determination: cross-correlation with M0.5 template
    - EX Lup: active star with many emission lines
    - “contaminated” photospheric absorption lines had to be discarded
    - RV determined separately for each Échelle order by fitting a Gaussian to the cross-correlation function; weighted average of all orders

Photometric observations

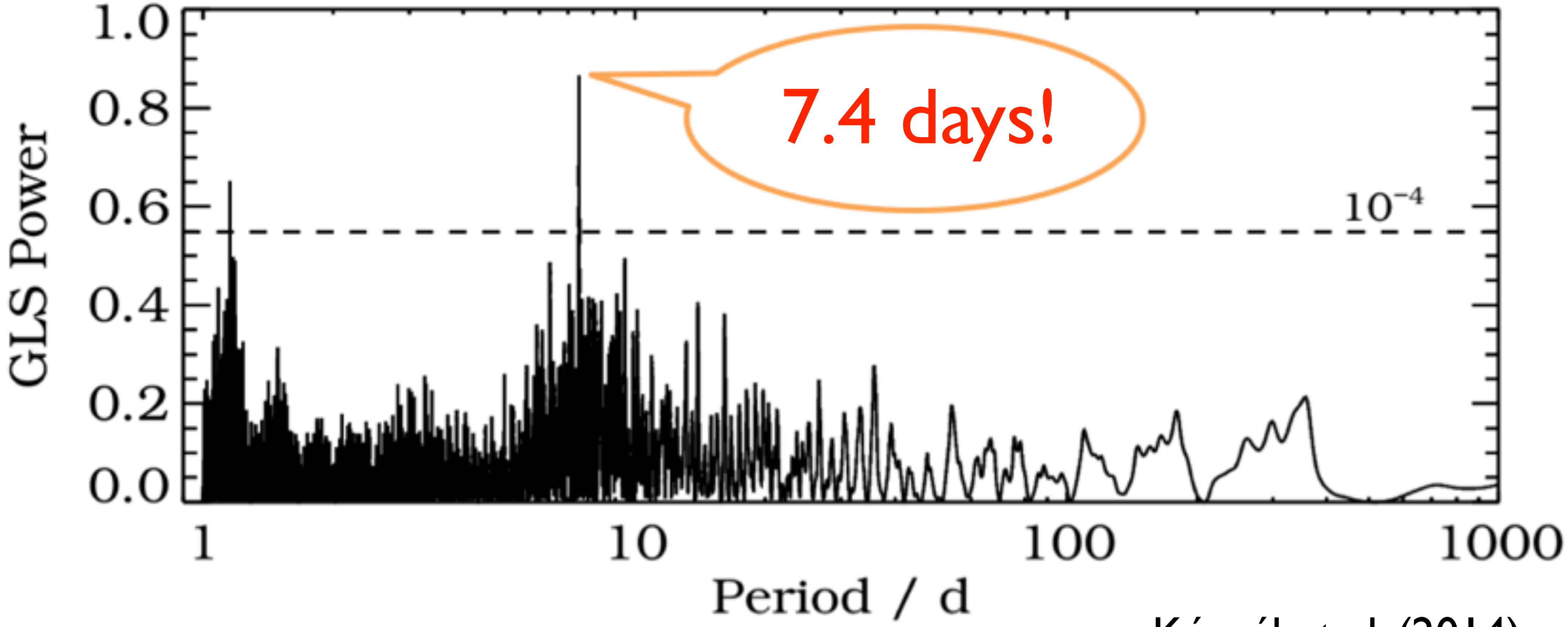
- Optical and infrared light curves:
  - 2-week long daily monitoring in 2010
  - V, J, H, K (0.55−2.2 μm): Rapid Eye Mount (REM) Telescope, La Silla, Chile
  - 3.6 and 4.5 μm: Spitzer Space Telescope


rem.inaf.it


spitzer.caltech.edu

Period analysis

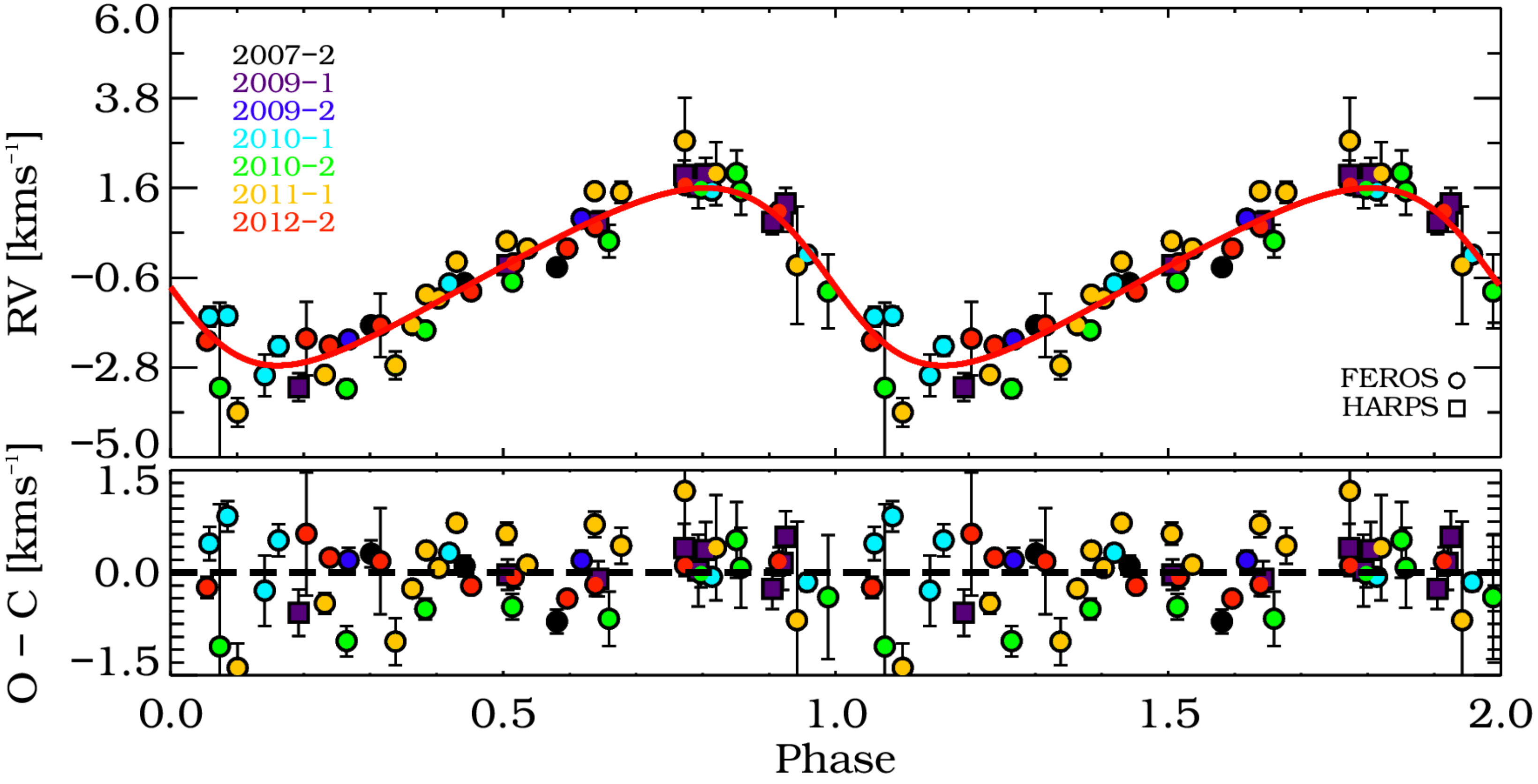
We detected significant periodic RV variations



7.4 days!

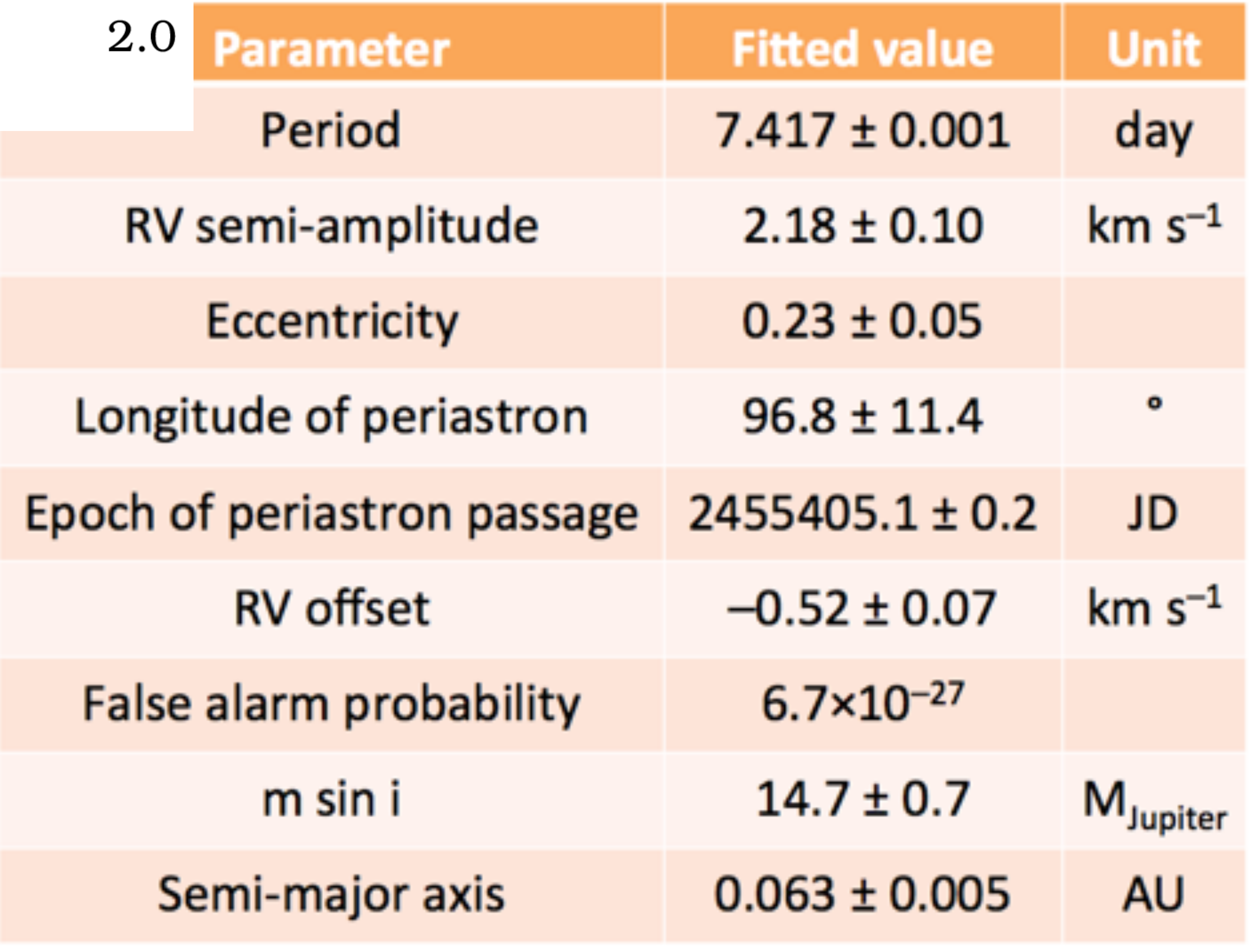
Kóspál et al. (2014)

Keplerian solution



Kóspál et al. (2014)

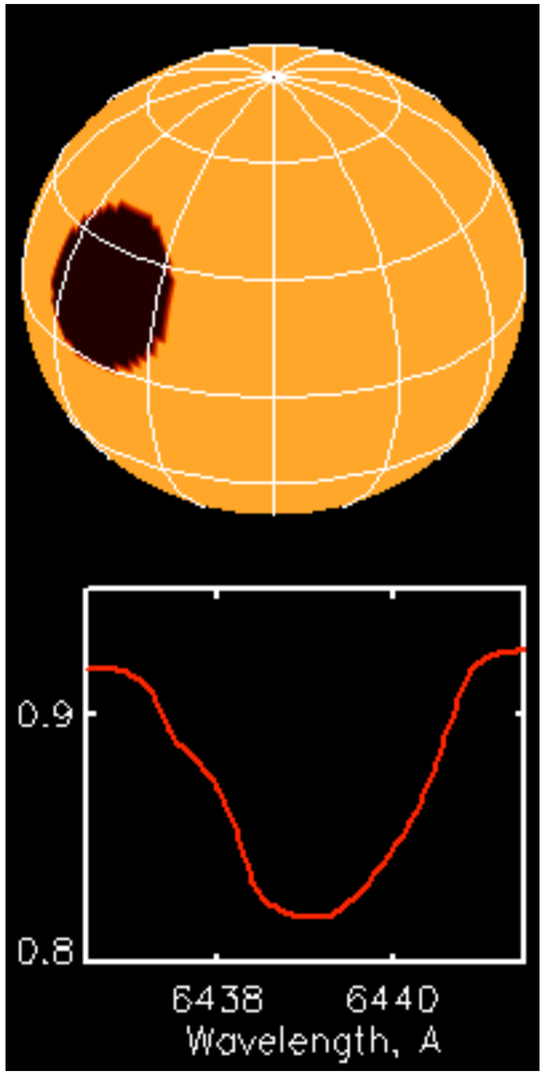
- RV phase and amplitude are stable for 5 years
- Possible explanation: companion on an eccentric orbit



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	
Longitude of periastron	96.8 ± 11.4	°
Epoch of periastron passage	2455405.1 ± 0.2	JD
RV offset	–0.52 ± 0.07	km s^{-1}
False alarm probability	6.7×10^{-27}	
m sin i	14.7 ± 0.7	M$_{\text{Jupiter}}$
Semi-major axis	0.063 ± 0.005	AU

Stellar activity or starspots?

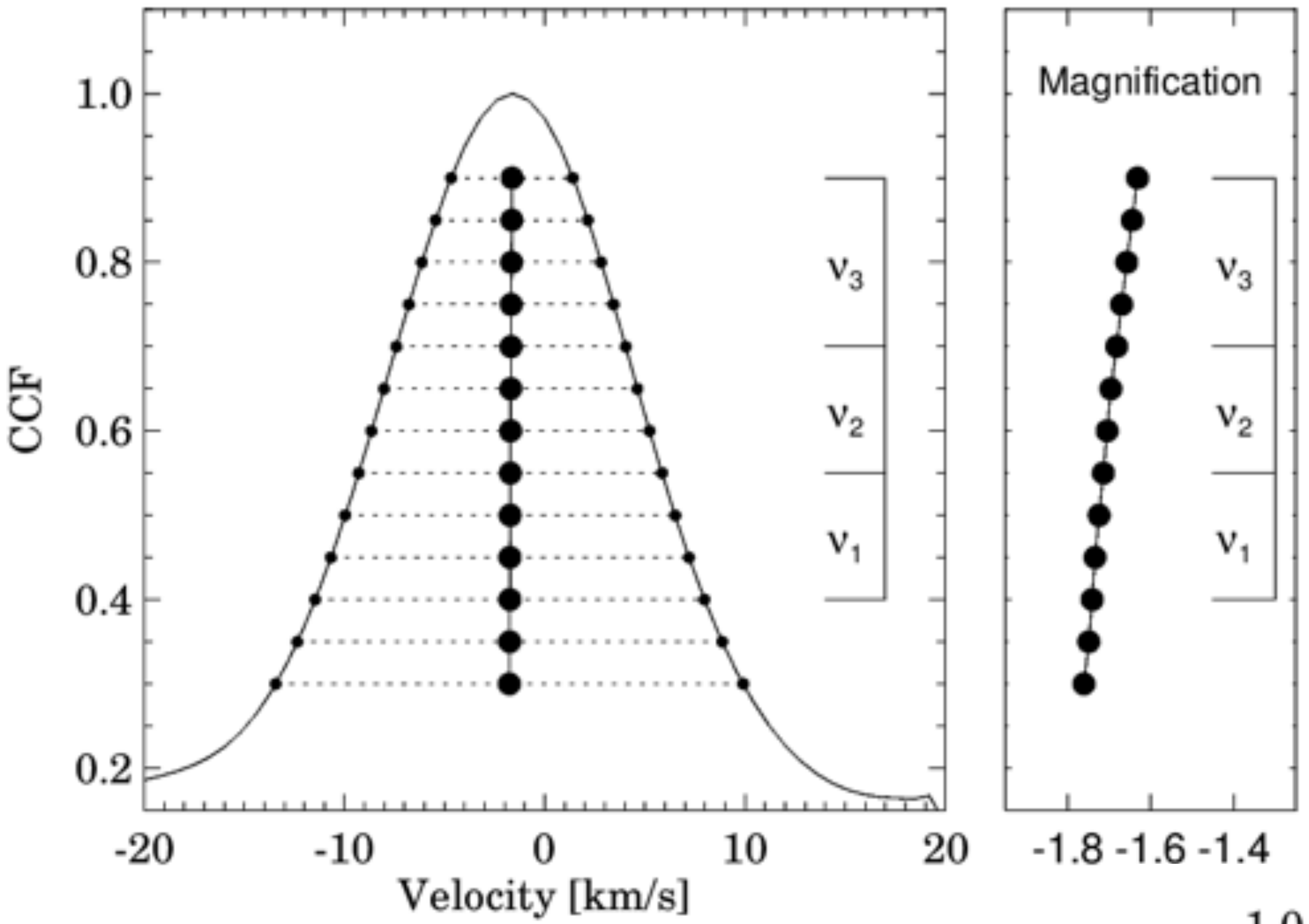
- What is the physical cause of the RV variations?
- A low-mass stellar/substellar/planetary companion
- Photospheric activity:
  e.g. a cold spot on the stellar surface would cause a flux deficit; distort the line profiles; distortion is periodic as the star rotates



Animation courtesy of Zs. Kővári

- Chromospheric activity:
  chromospheric spectrum is dominated by emission lines; these can distort the absorption line profiles; may produce periodic RV variations

Bisector analysis



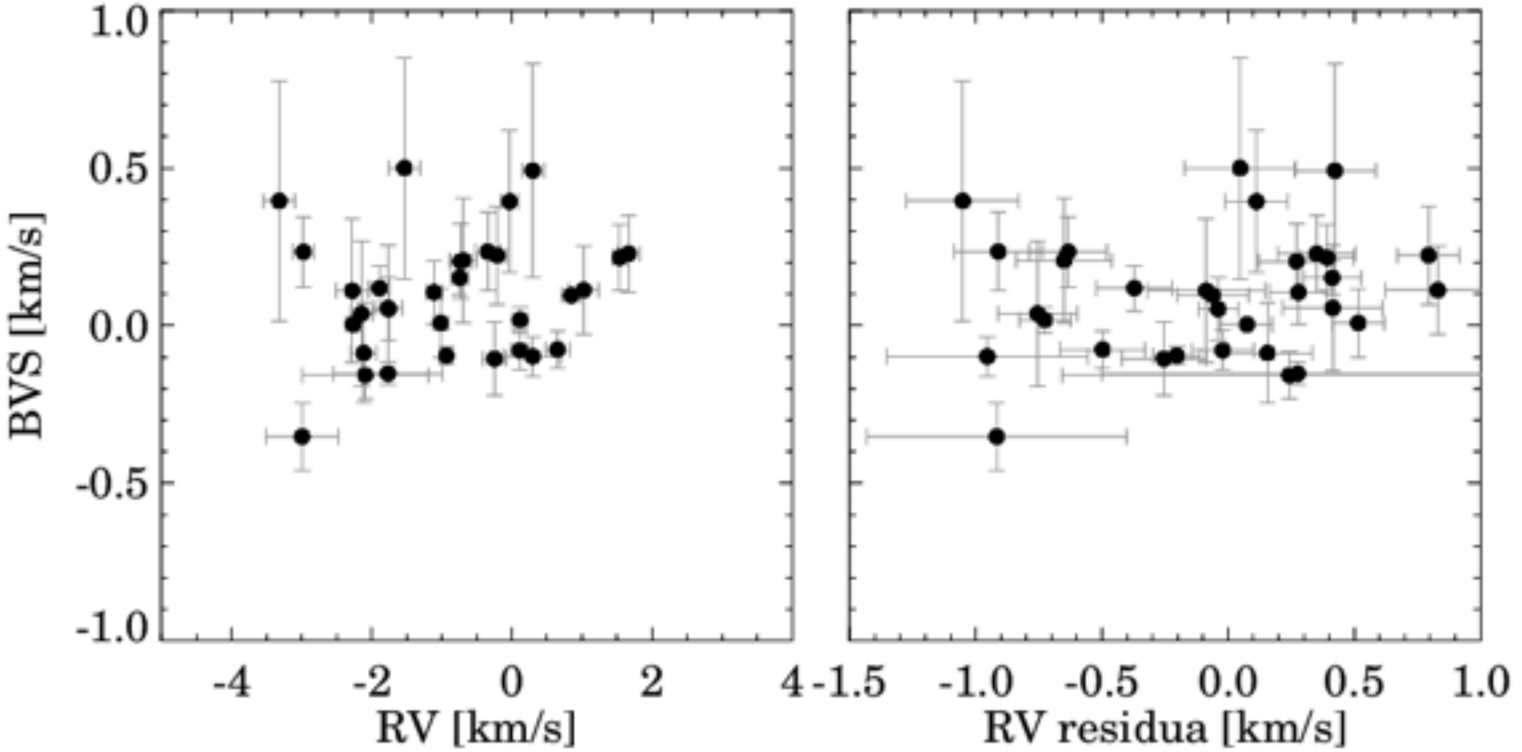
BVS = $v_3 - v_1$

BC = $(v_3 - v_2) - (v_2 - v_1)$

BVD = $(v_1 + v_2 + v_3)/3 - \lambda_c$

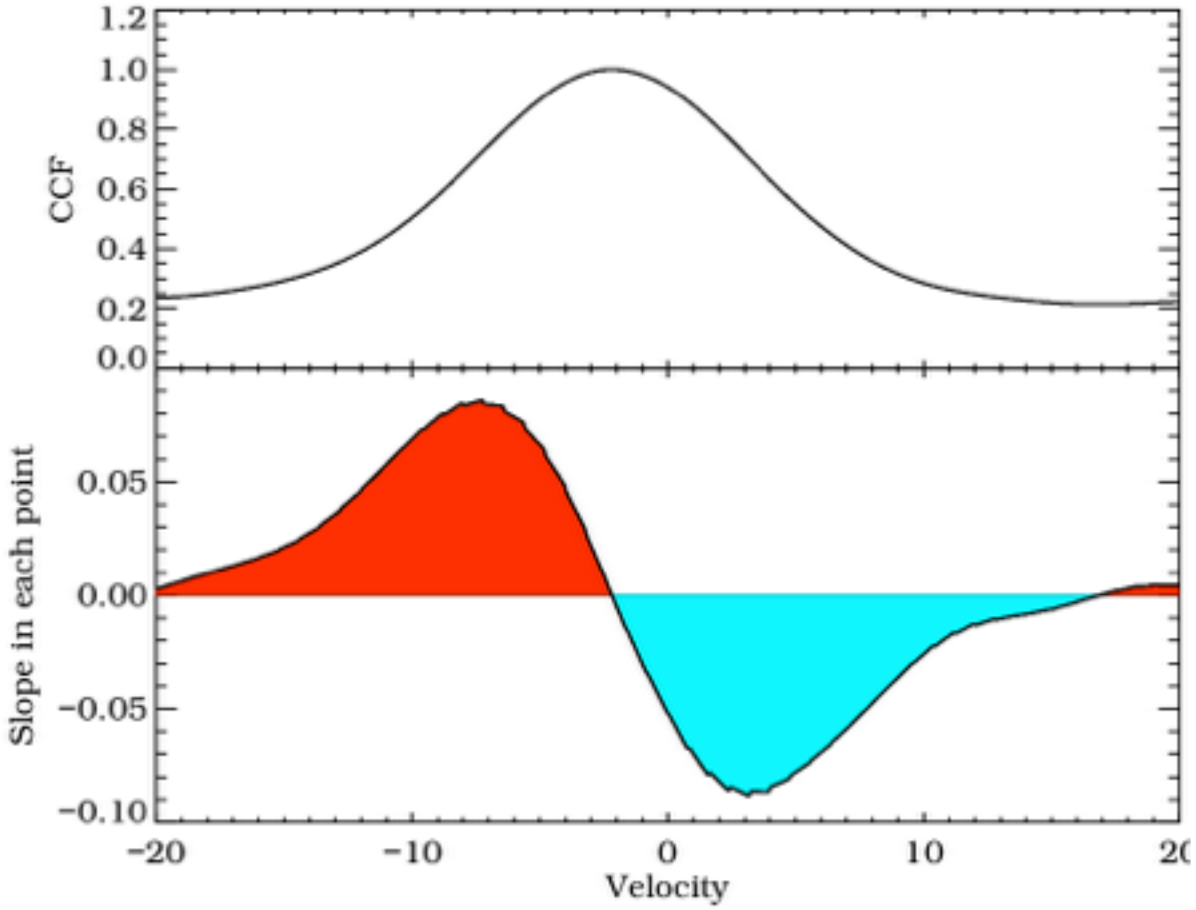
No correlation between BVS and RV

Kóspál et al. (2014)

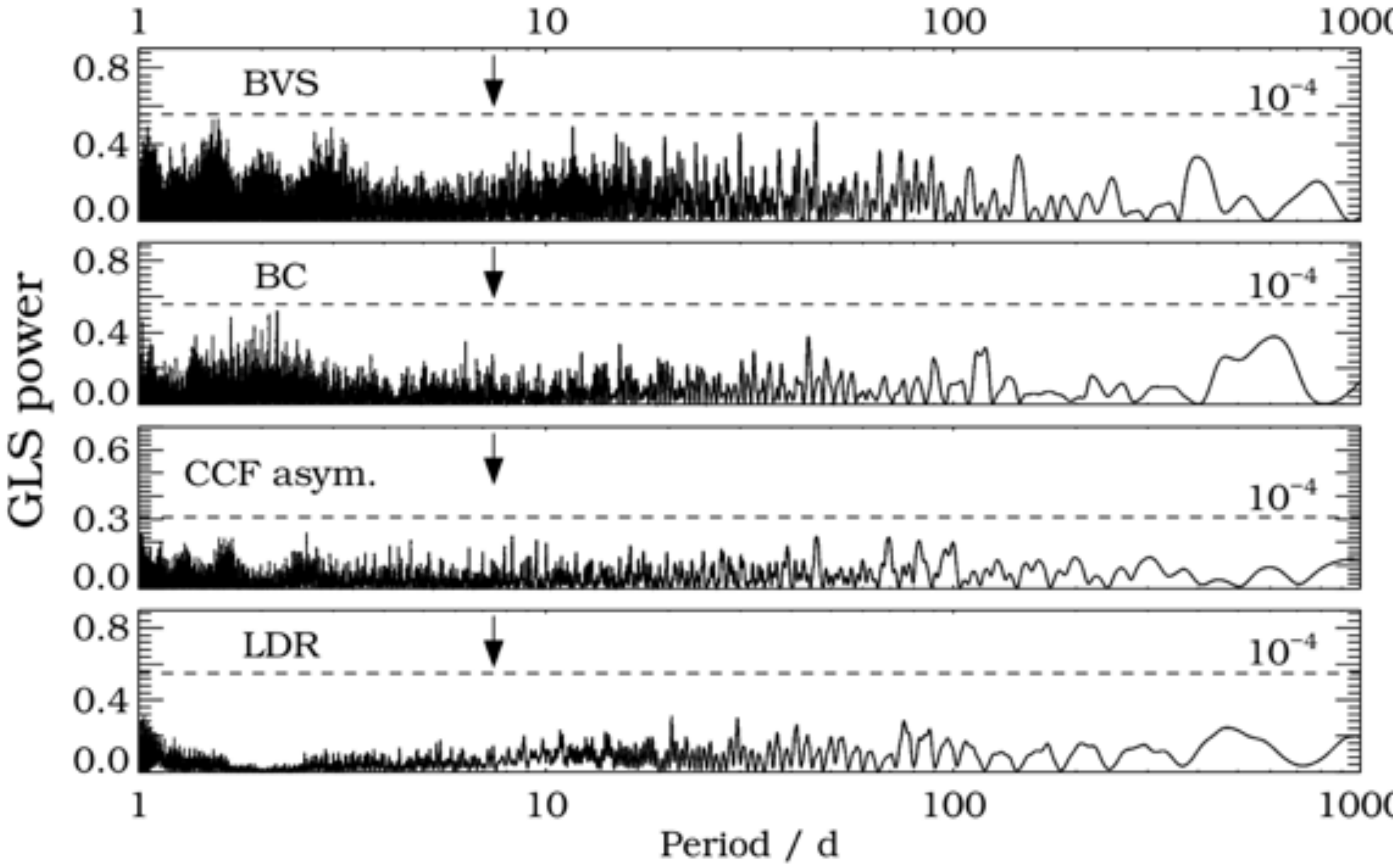


Activity indicators

- CCF asymmetry
- Temperature-sensitive spectral features (VI/FI LDR, TiO, CaH, CaOH, Hα)
- Analysis of the Ca lines (H and K, IR triplet)



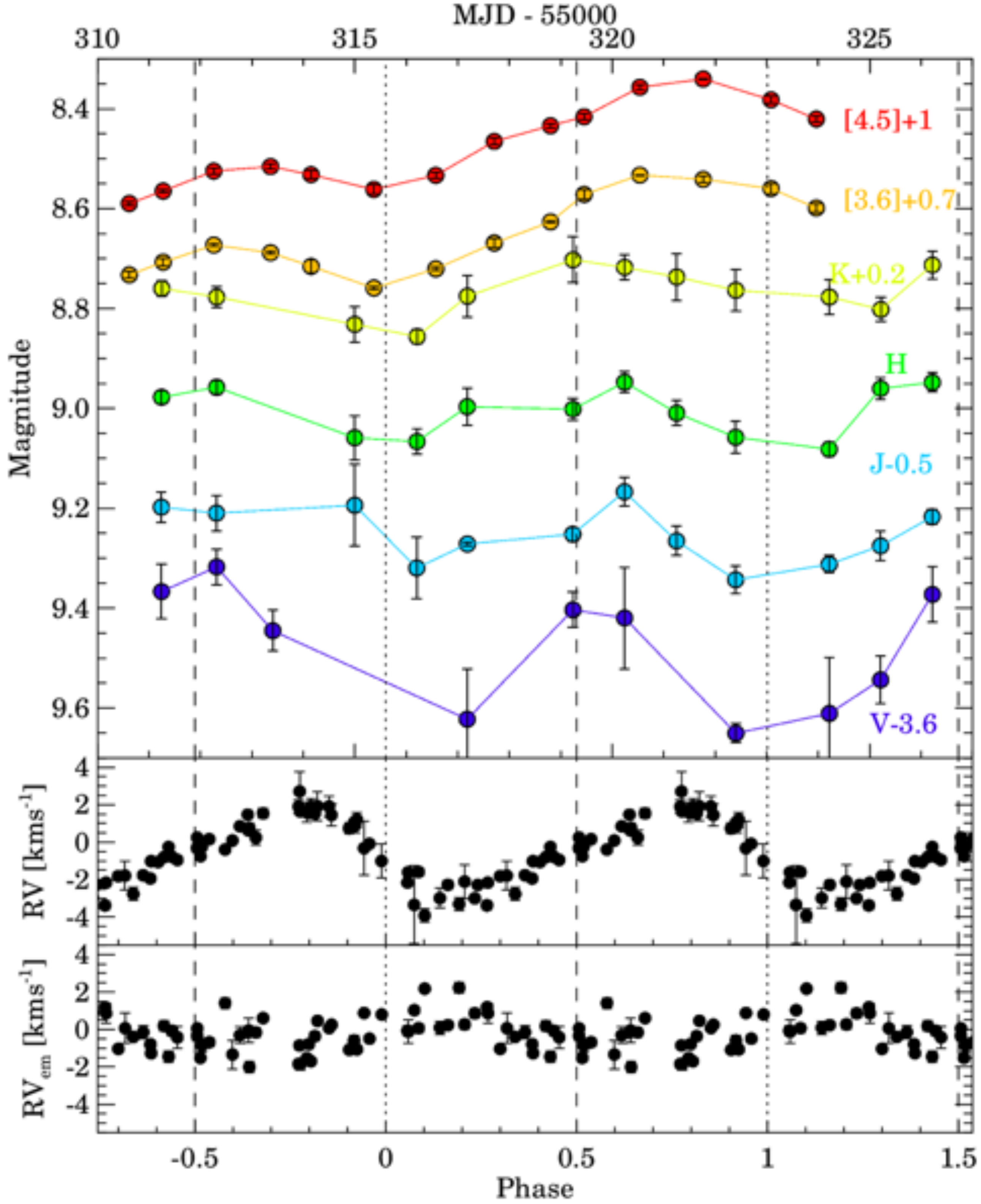
Kóspál et al. (2014)

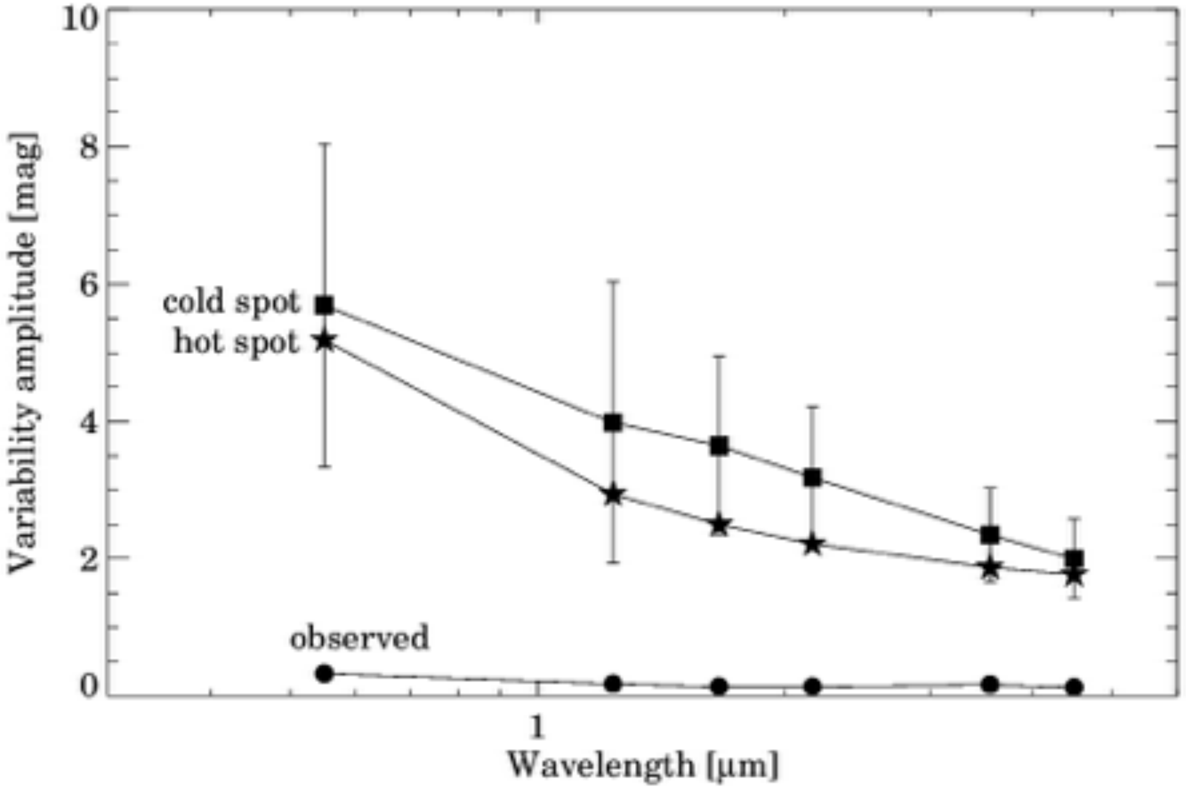


- None of the studied activity indicators are periodic

Spot model

- EX Lup is a slow rotator: v sin i < 3 km/s
- Large spots are needed to reproduce the observed RV semi-amplitude of 2.2 km/s
- Such large spots would cause too large photometric variations





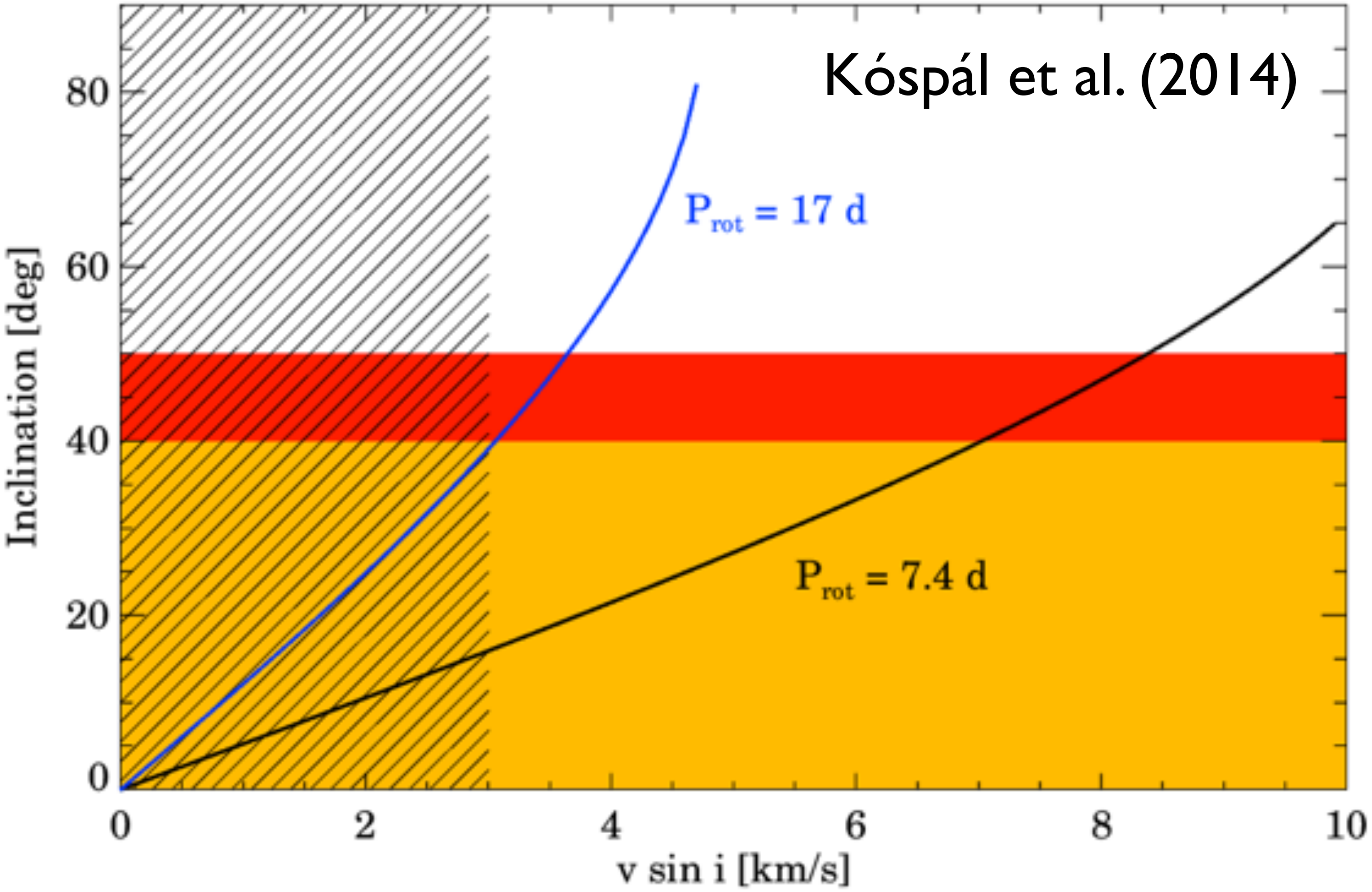
Kóspál et al. (2014)

Inclination constraints

- From P_{rot} = 7.4 days and v sin i < 3 km/s → i < 16°
- Independent constraints on the inclination:
  - i = 0−40° (from SED modeling, Sipos et al. 2009)
  - i = 40−50° (from the modeling of CO fundamental vibrational lines, Goto et al. 2011)
- Most probable disk inclination: i=40°

↓

P_{rot} > 17 days

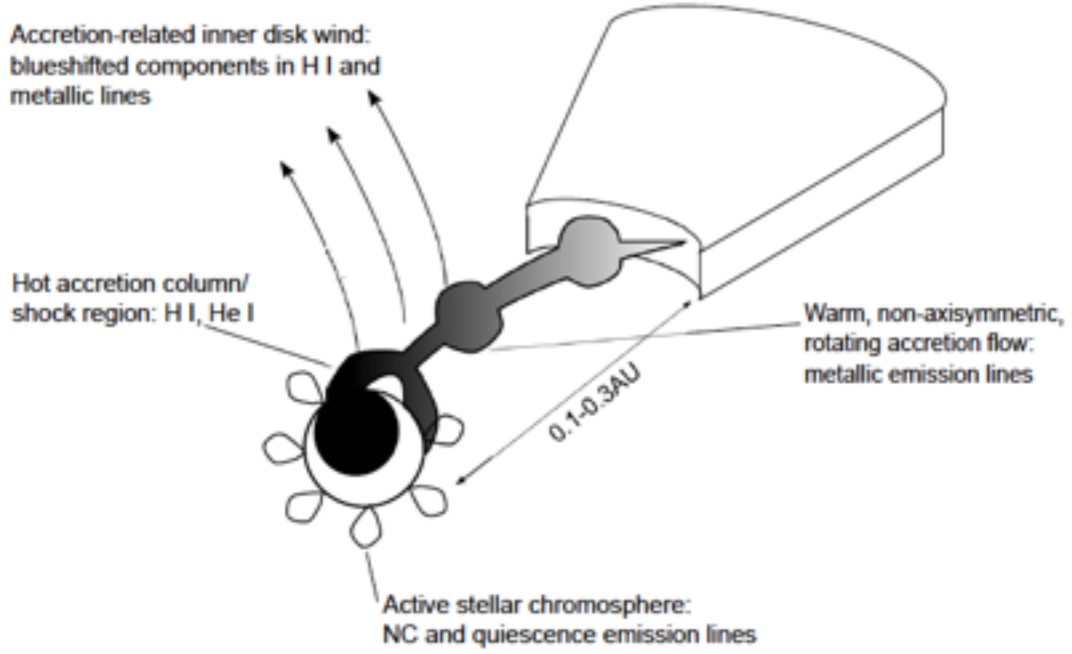


The companion of EX Lupi

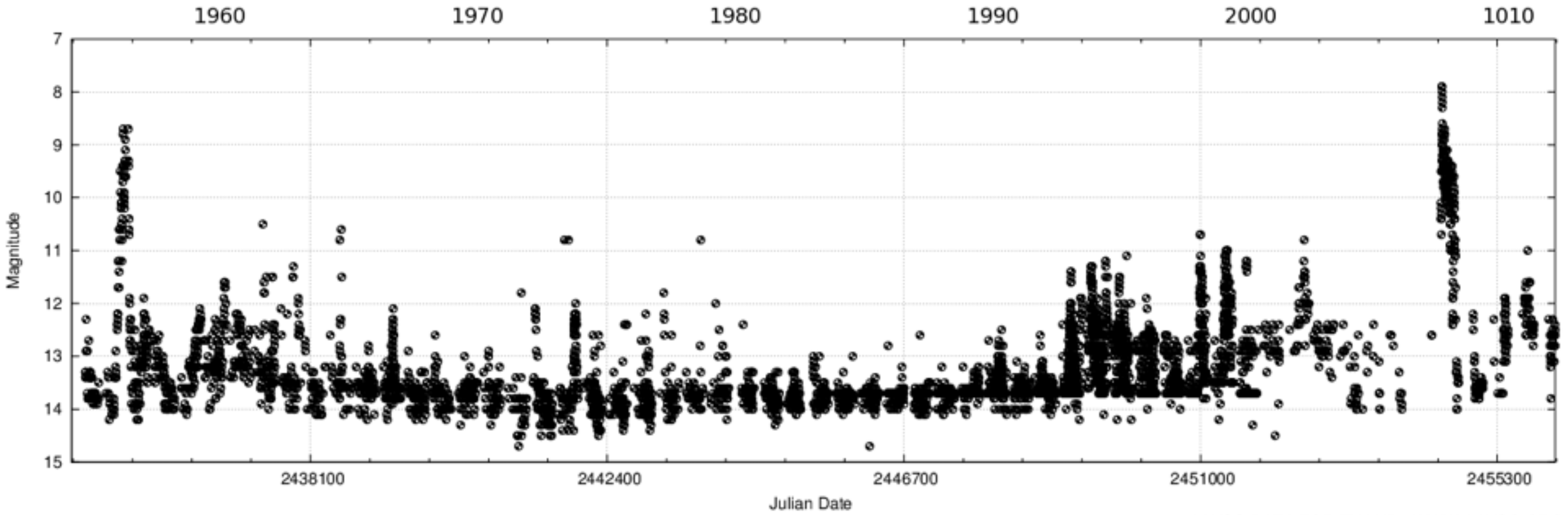
- Most probable mass:
  - 0.02 $M_\odot$ → brown dwarf (L0) → $T_{\mathrm{eff}} = 2500$ K (cf. 3800 K for EX Lup)
- Periastron and apastron distances:
  - 0.049 au (6.5 R_*) and 0.078 au (10.4 R_*)
- Its position w.r.t. the disk:
  - It orbits the primary within the R = 0.2 au dust-free inner hole
- Unusual object:
  - Very small separation (typically > 2 au for PMS stars)
  - Only 0.6% of Sun-like stars have brown dwarf companions (“brown dwarf desert”)

The companion’s effect on the accretion process

- Could it stabilize the accretion columns?
- Could it cause pulsed accretion?
- Could it have an effect on the large outbursts?

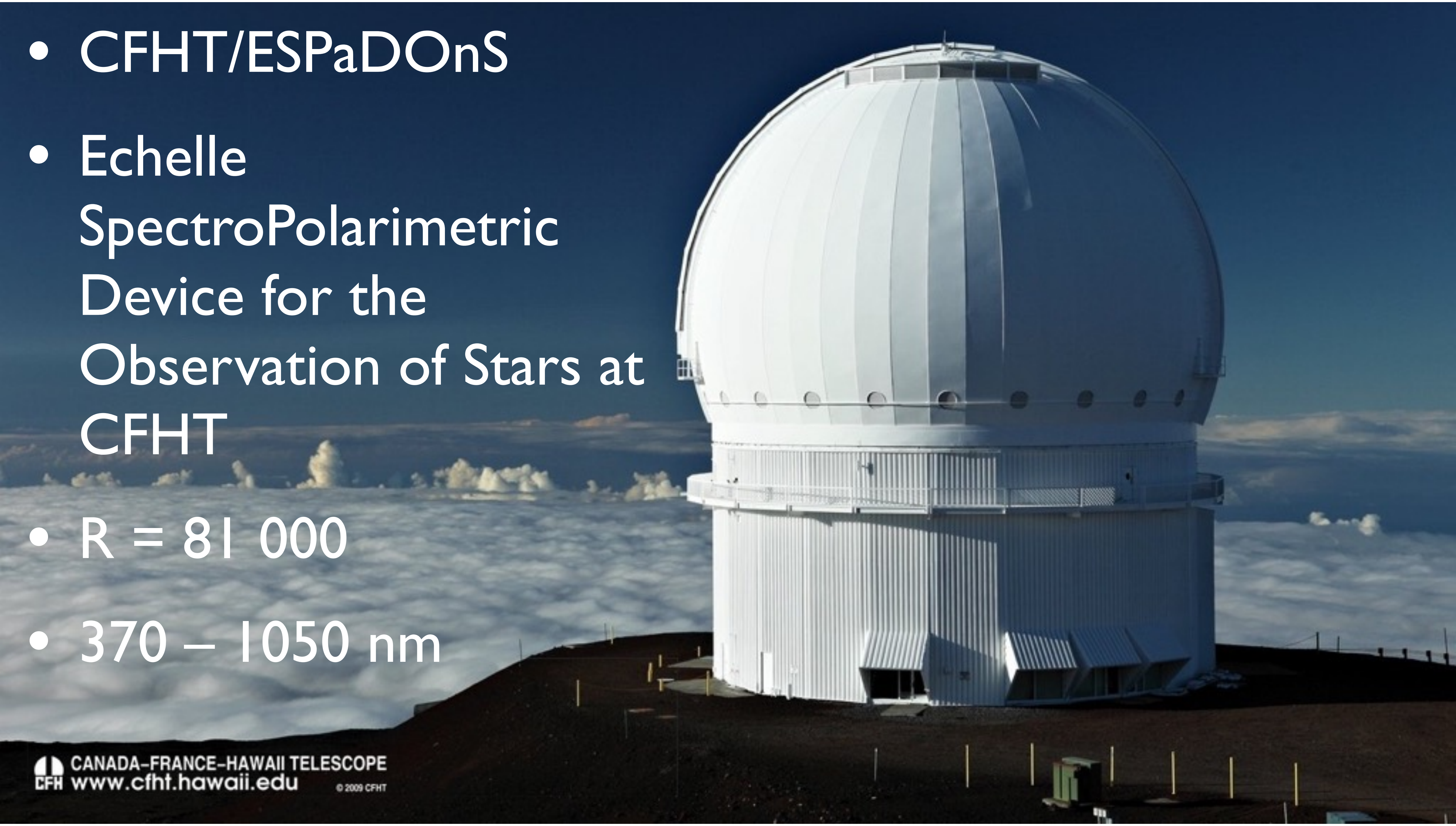


(Sicilia-Aguilar et al. 2012)



AAVSO DATA FOR EX LUP - WWW.AAVSO.ORG

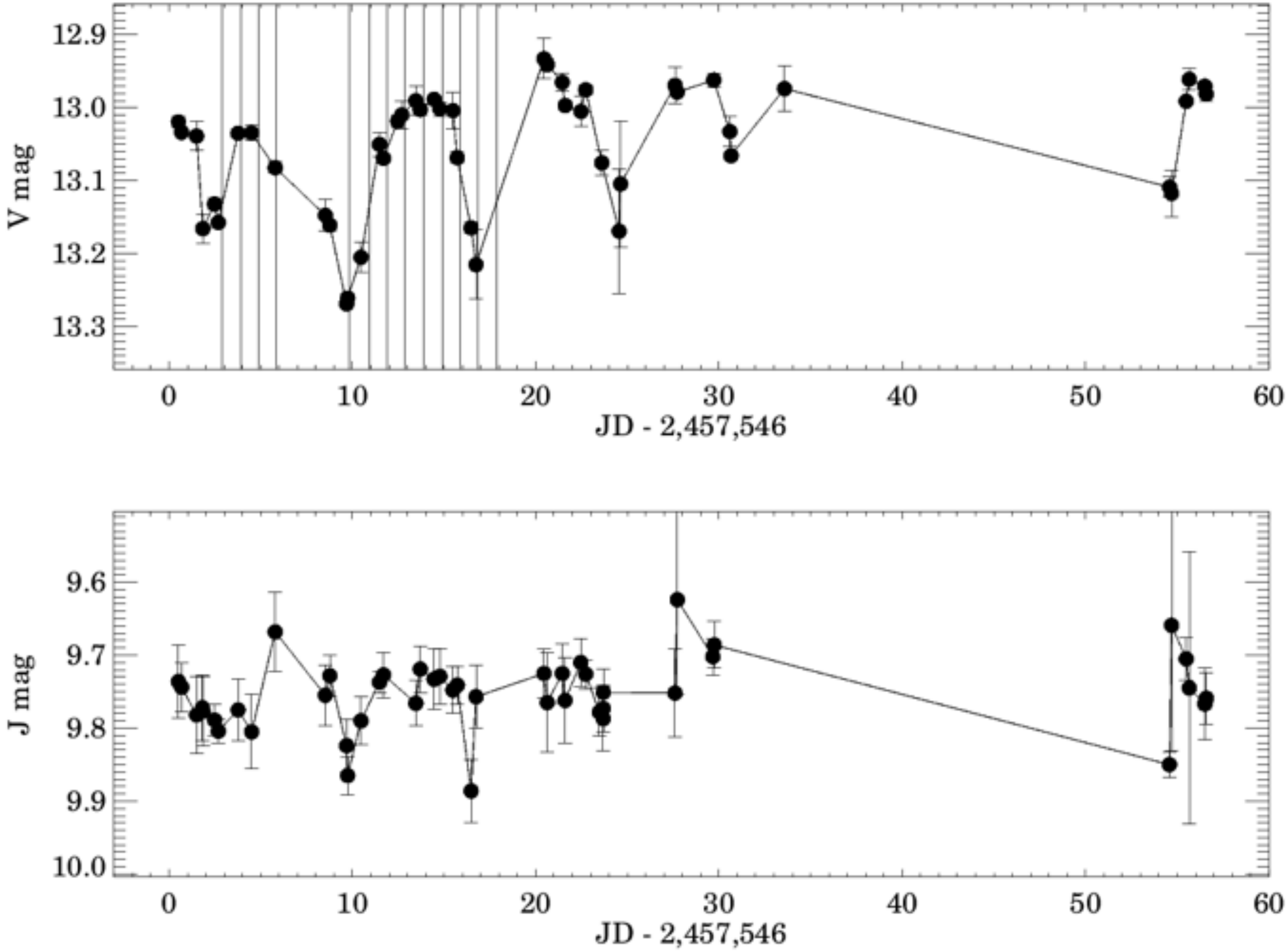
Spectro-polarimetry



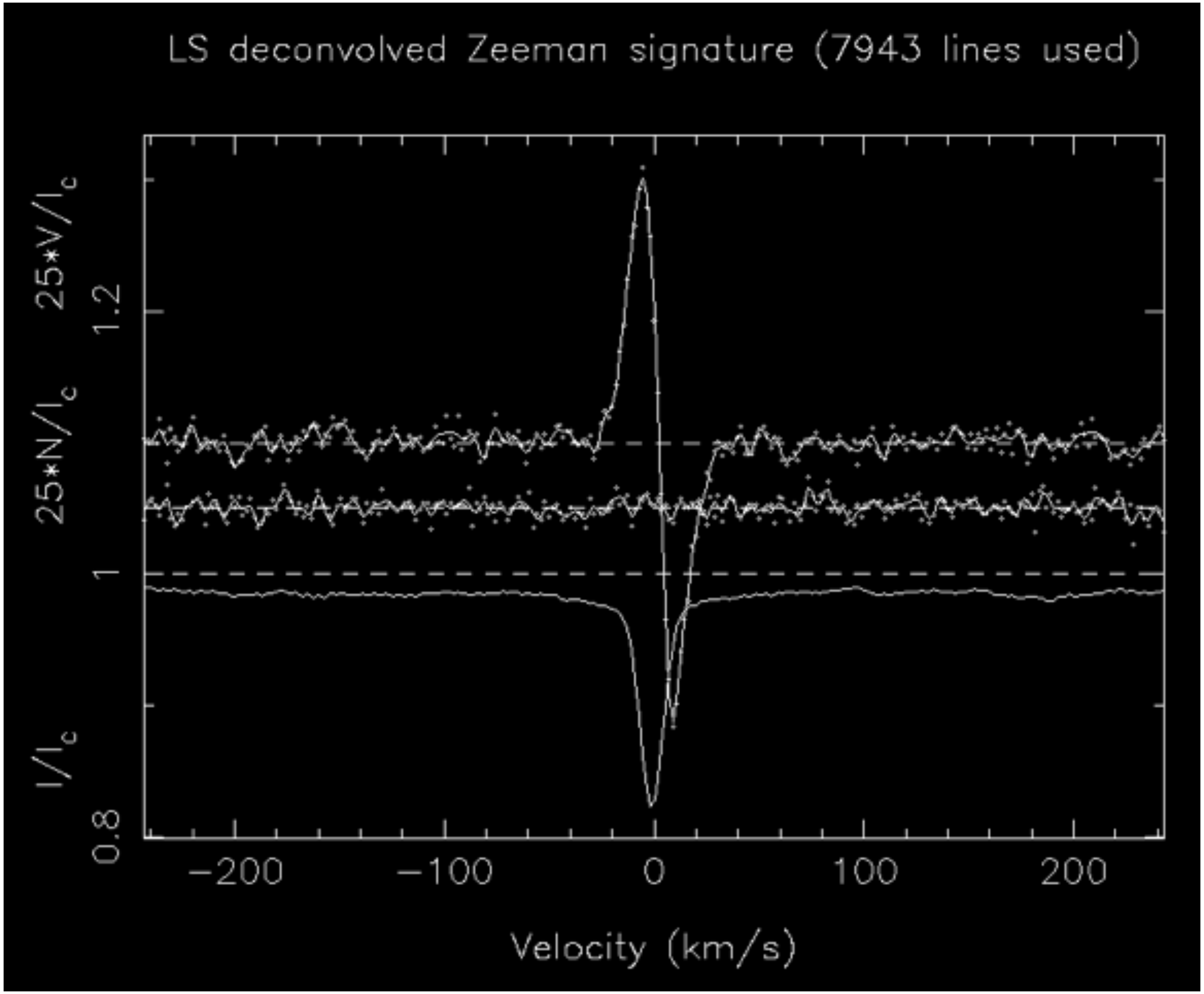
- CFHT/ESPaDOnS
- Echelle SpectroPolarimetric Device for the Observation of Stars at CFHT
- R = 81 000
- 370 – 1050 nm

Spec.-polarimetry of EX Lup

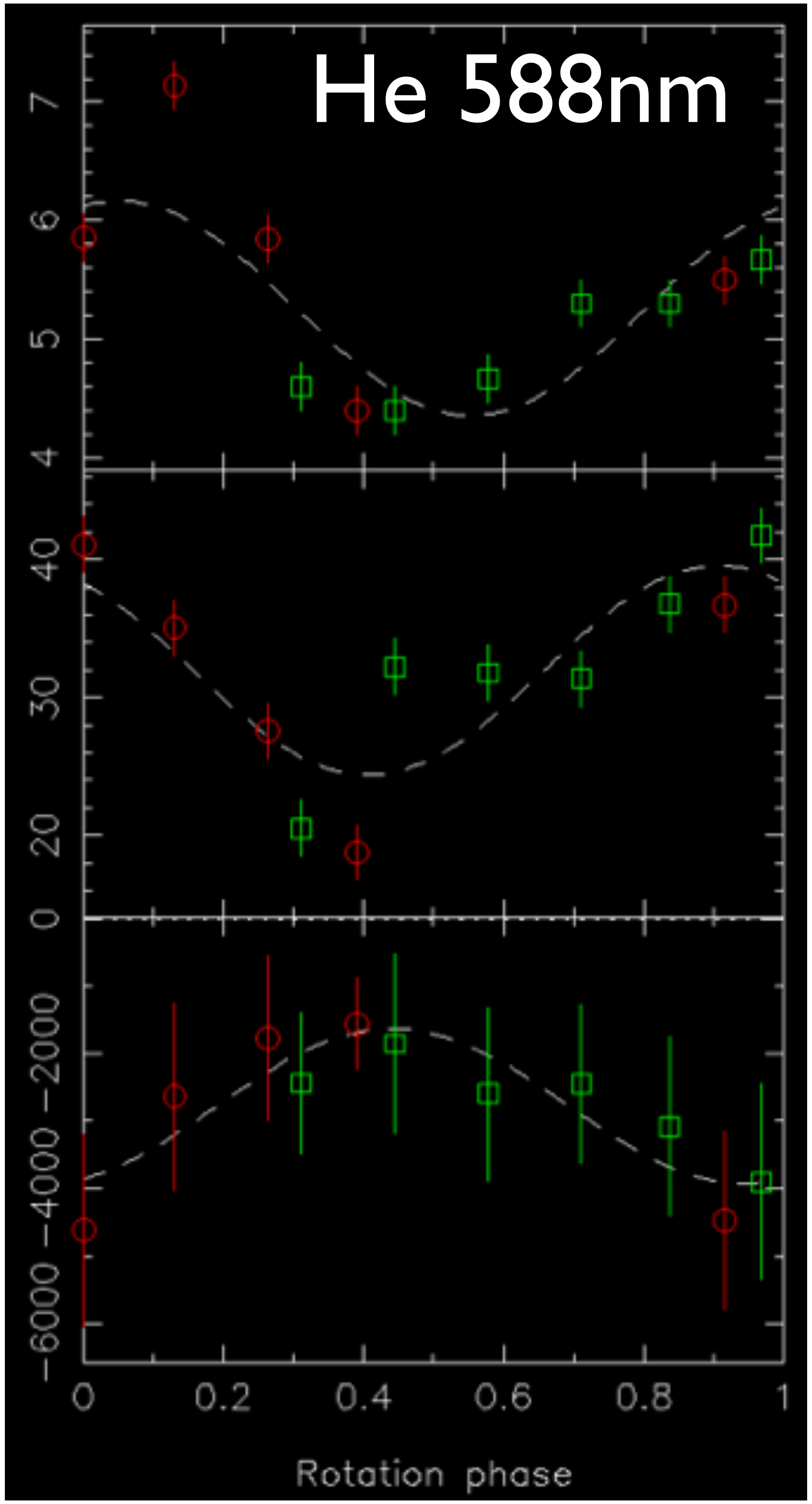
- 2-week-long spectropolarimetric monitoring
- 1-month-long optical and near-infrared photometric monitoring

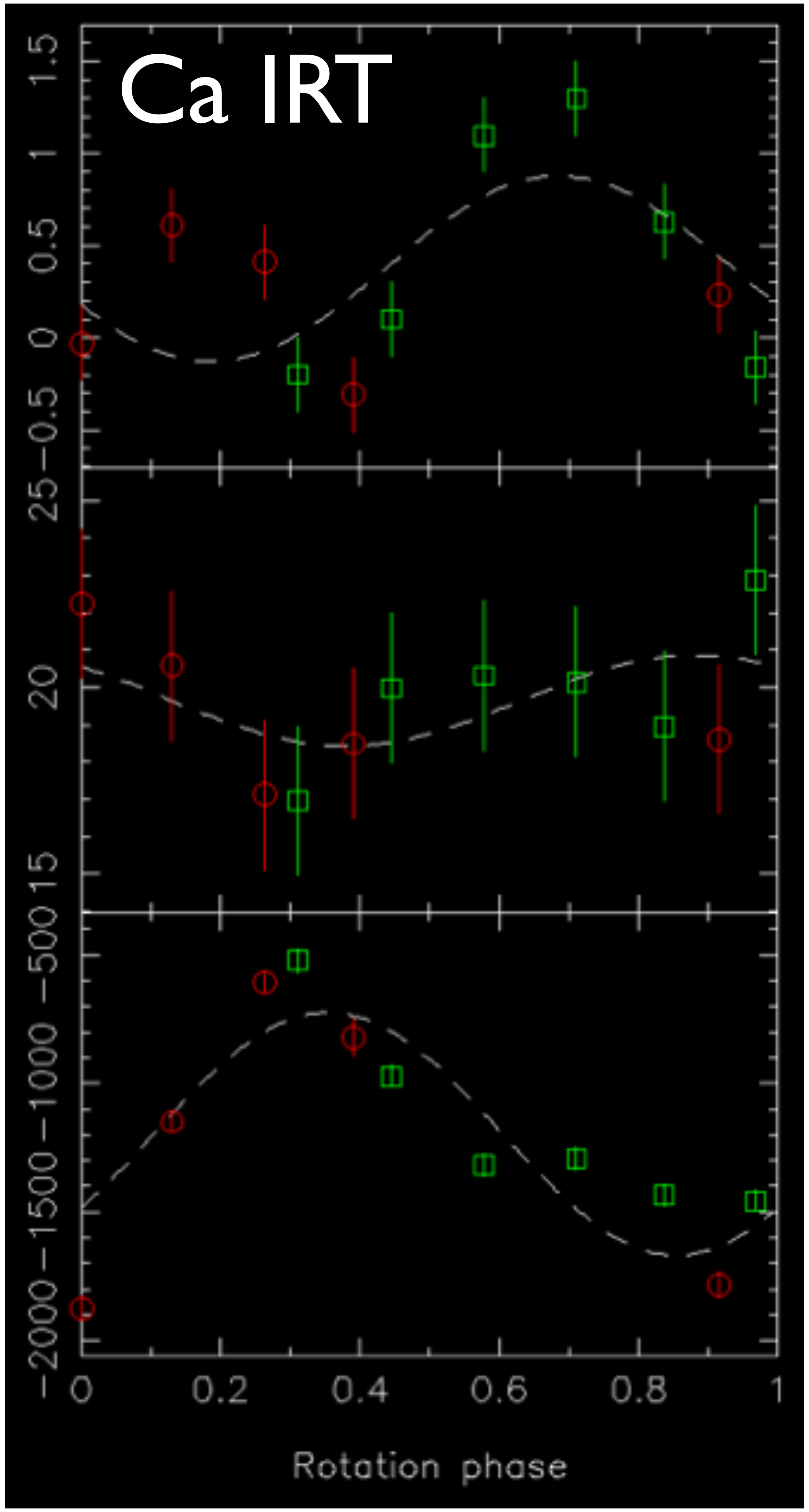


Zeeman effect



Spec.-polarimetry for EX Lup





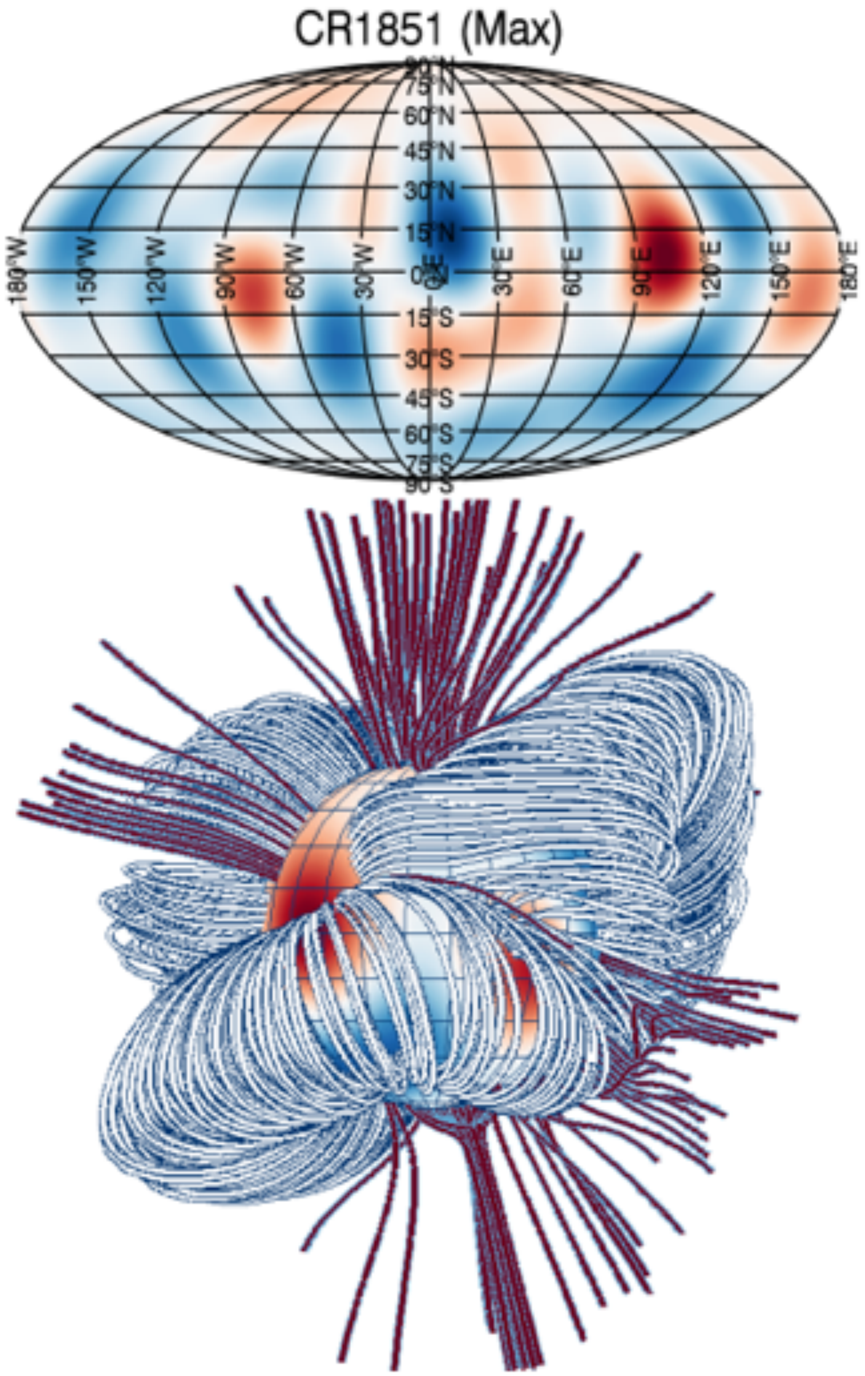
RV (km/s)

EW (km/s)

B_{long} (G)

Spec.-polarimetry for EX Lup

- Magnetic field is strongest when the star is faintest
- Expected for a rotating spotted star
- Is it possible that there is no companion after all?



Jardine et al. (2017)

The literature of EX Lup

- Sipos et al.: *EX Lupi in quiescence* (2009, A&A 507, 881)
- Ábrahám et al.: *Episodic formation of cometary material in the outburst of a young Sun-like star* (2009, Nature 459, 224)
- Goto et al.: *Fundamental vibrational transition of CO during the outburst of EX Lupi in 2008* (2011, ApJ 728, 5)
- Kóspál et al.: *Near-infrared spectroscopy of EX Lupi in outburst* (2011, ApJ 736, 72)
- Juhász et al.: *The 2008 outburst of EX Lupi − silicate crystals in motion* (2012, ApJ 744, 118)
- Sicilia-Aguilar et al.: *Optical spectroscopy of EX Lupi during quiescence and outburst. Infall, wind, and dynamics in the accretion flow* (2012, A&A 544, A93)
- Kóspál et al.: *Radial velocity variations in the ysoung eruptive star EX Lup* (2014, A&A 561, A61)
- Sicilia-Aguilar et al.: *Accretion dynamics of EX Lupi in quiescence. The star, the spot, and the accretion column* (2015, A&A 580, A82)
- Kóspál et al.: *Cold CO Gas in the Disk of the Young Eruptive Star EX Lup* (2016, ApJL 821, L4)

The literature of EX Lup

THE STAR FORMATION NEWSLETTER

An electronic publication dedicated to early stellar/planetary evolution and molecular clouds

No. 269 — 12 May 2015

Editor: Bo Reipurth (reipurth@ifa.hawaii.edu)

- The Star Formation Newsletter No. 269 (2015 May)
- My favorite object: EX Lupi
- http://www.ifa.hawaii.edu/~reipurth/newsletter/newsletter269.pdf