Observational properties of outbursting sources

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Structure of the talk

- Brief "historical" introduction
- Traditional **classification** and objects that do not fit
- What can we learn from
  - **optical and near-infrared spectra**?
  - **infrared photometry and spectroscopy**?
  - **X-ray measurements**?
  - **high-contrast observations**?
  - **millimeter data**?
- What do the **newly discovered objects** teach us?
- What can we expect from the **large surveys**?

Historical introduction

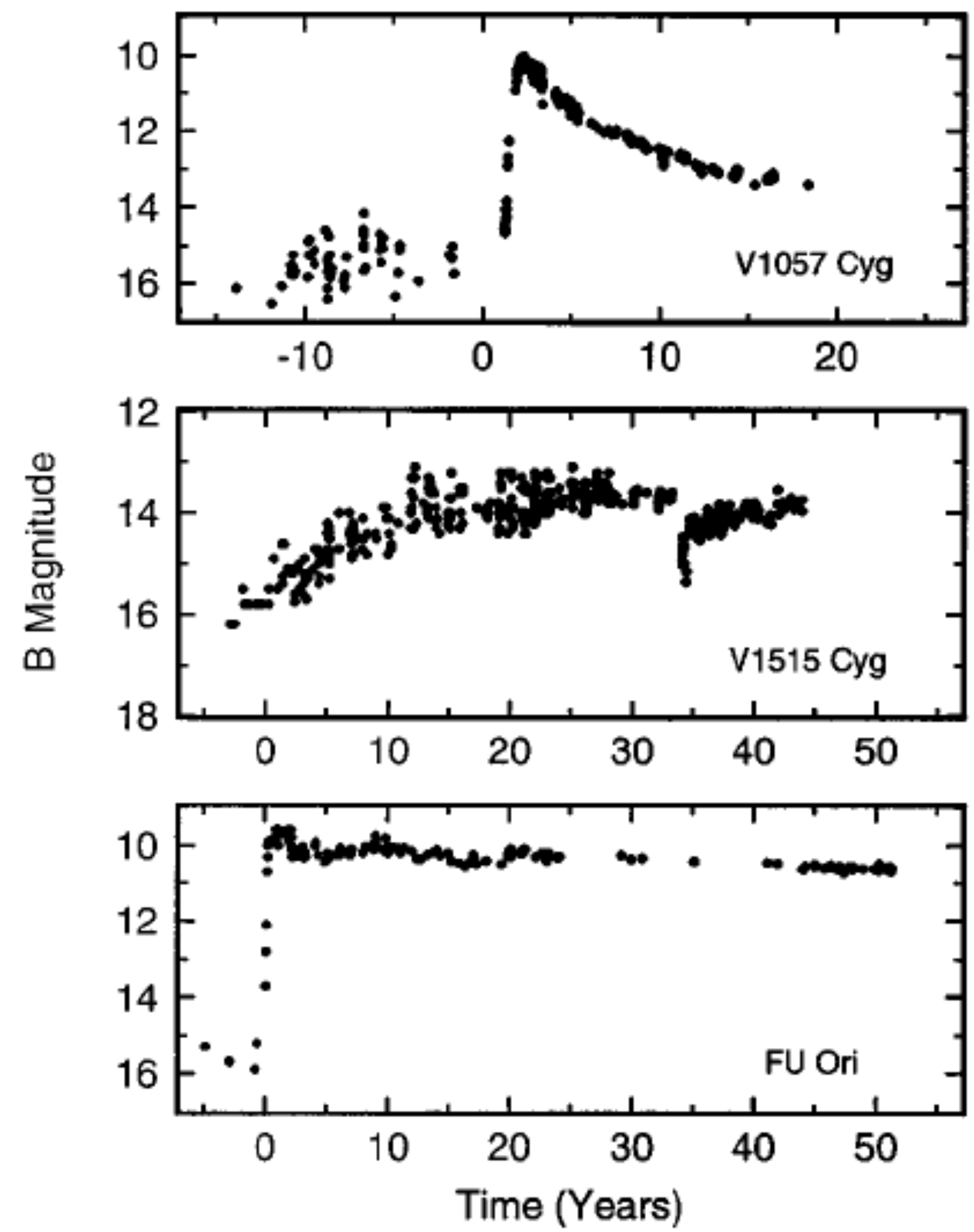
- **Discovery of the first examples:**
  - 1936: FU Ori goes into outburst
  - 1955: EX Lup goes into outburst
  - 1940 – 60: V1515 Cyg goes into outburst
  - 1969: V1057 Cyg goes into outburst
- **First attempts to interpret the data:**
  - Herbig (1966): "On the interpretation of FU Orionis"
  - Herbig (1977): "Eruptive phenomena in early stellar evolution"

    FU Orionis-type objects: **FUors**
  - Herbig (1989): "FU Orionis eruptions"

    Stars exhibiting large-range outbursts but having TTS-like spectra when bright: **EXors**

Observational characteristics: FUors

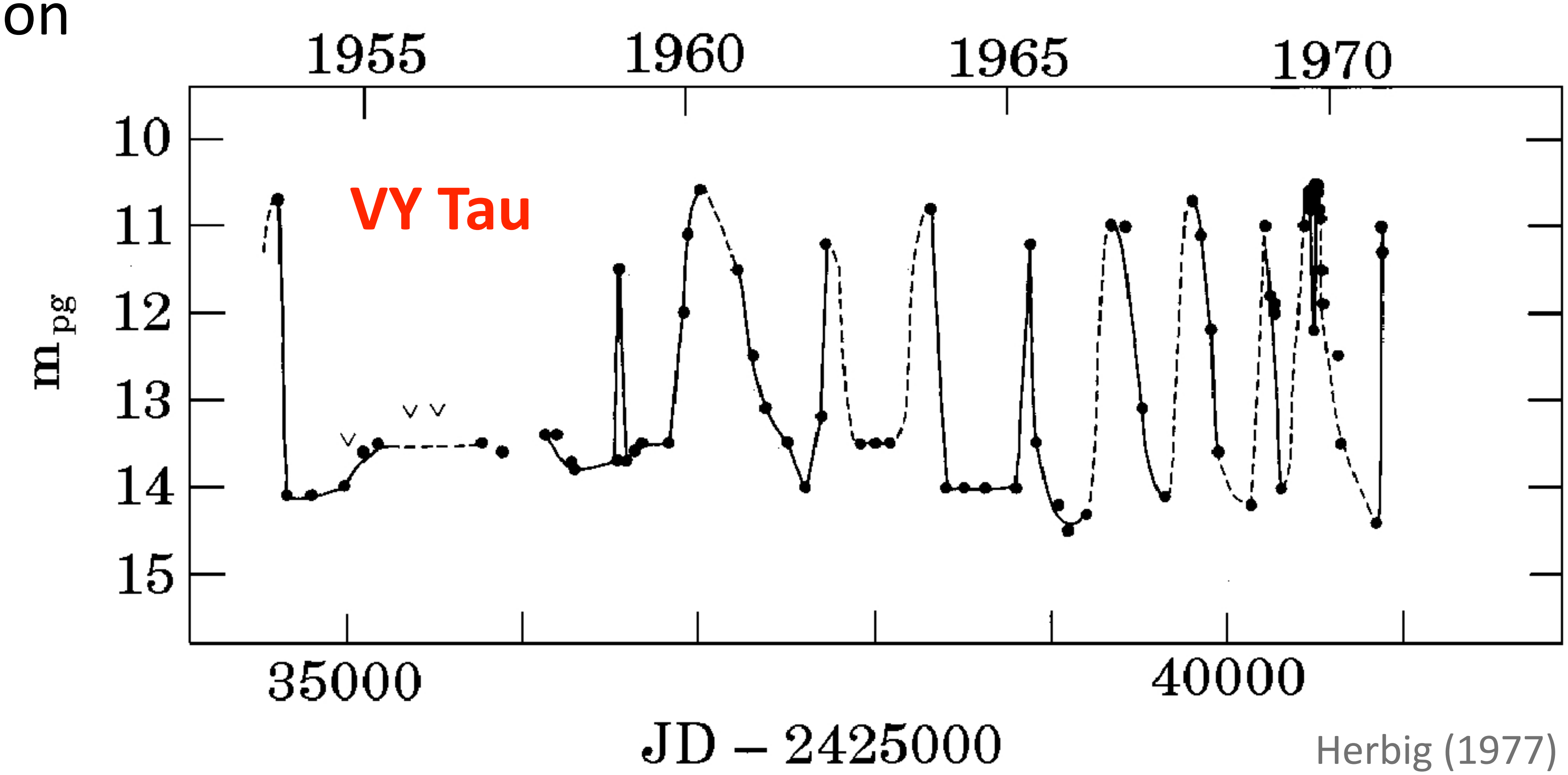
- Young stars with large, 4 – 5 mag outburst in optical light (heterogeneous light curves)
- Association with star-forming regions (reflection nebula, IR excess)
- Spectral type: F – G supergiant (optical), K – M giant or supergiant (near-IR)
- Increased accretion up to 10^{-4} $M_\odot$/yr
- Blueshifted absorption in Balmer lines, CO bandhead absorption, double-bottomed absorption lines
- Progenitor: probably a regular T Tauri-type star (based on V1057 Cyg)



Hartmann & Kenyon (1996)

Observational characteristics: EXors

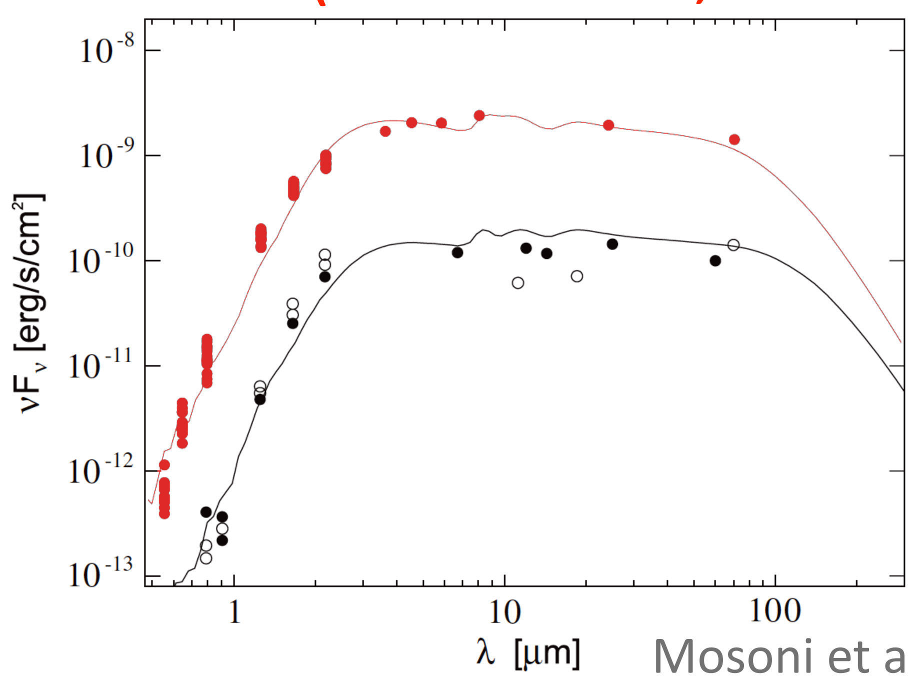
- Young stars with large outburst (4 – 5 mag) in optical light
- Episodic and repetitive eruptions, mass accretion rate: $10^{-6} – 10^{-7}$ M⊙/yr
- In quiescence, their spectra look like those of normal T Tauri stars
- In outburst: many emission lines, accretion signatures, CO bandhead in emission



Herbig (1977)

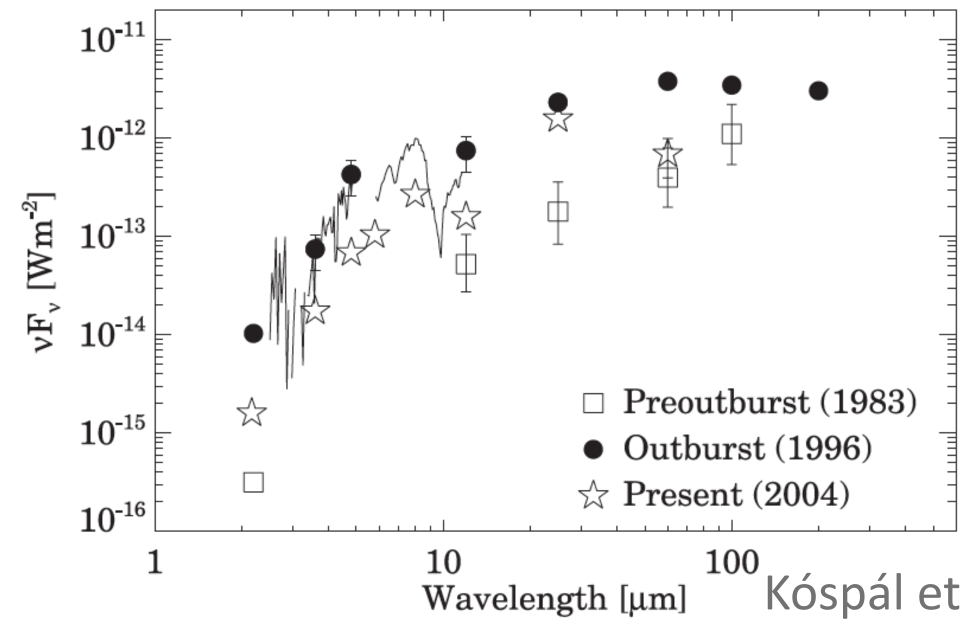
A possible third class?

V1647 Ori (2004–2006, 2008–?)



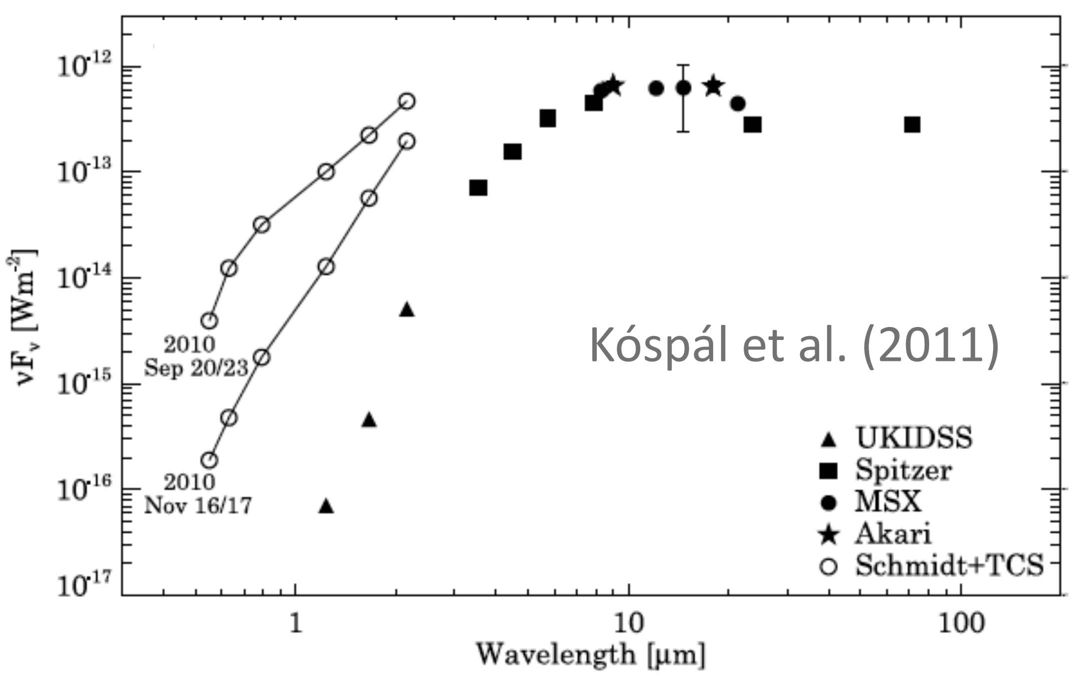
Mosoni et al. (2013)

OO Ser (1995–2002)

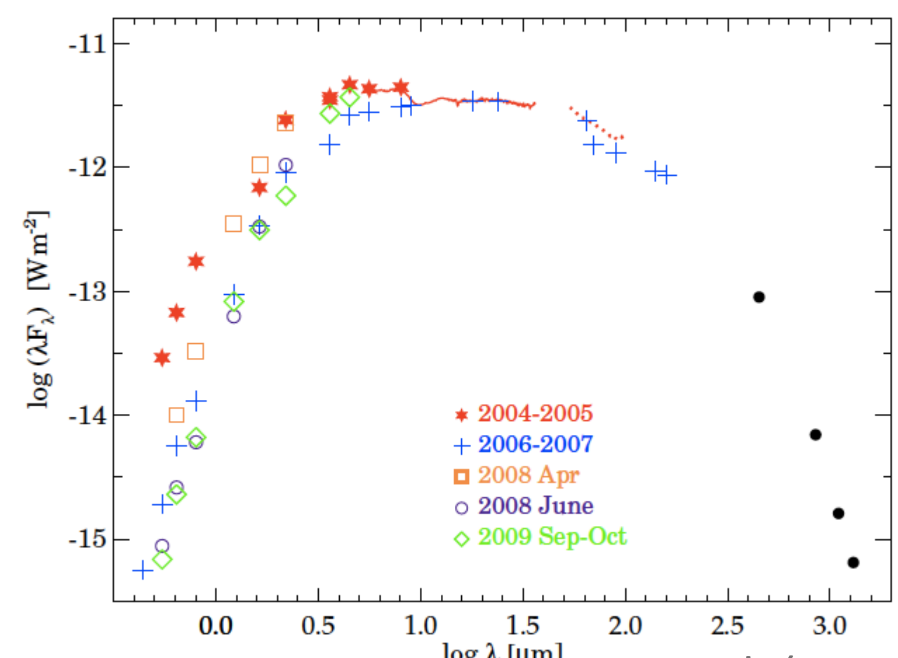


Kóspál et al. (2007)

V2494 Cyg (2010–?)

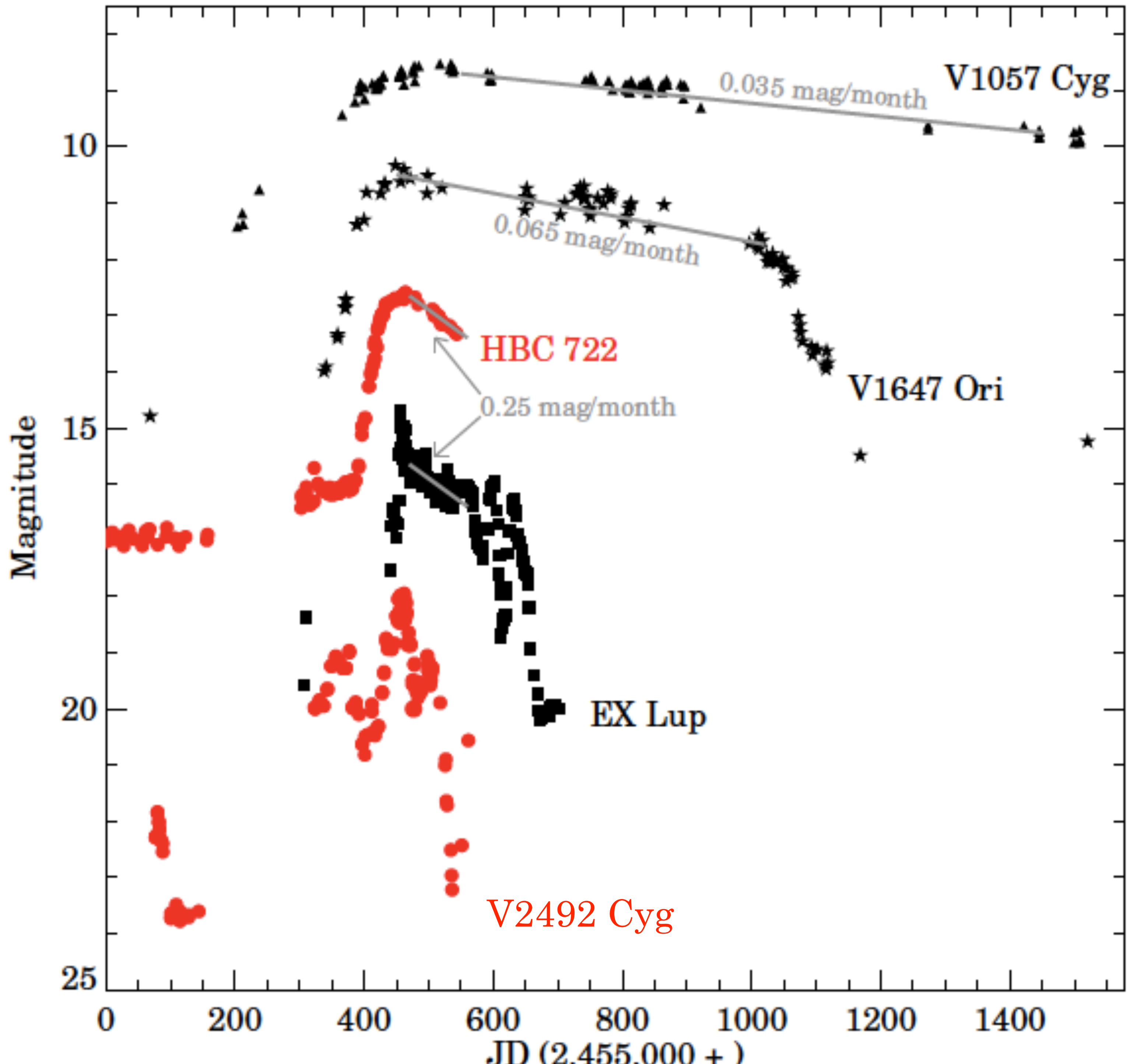


PV Cep (< 2006)



Kun et al. (2011)

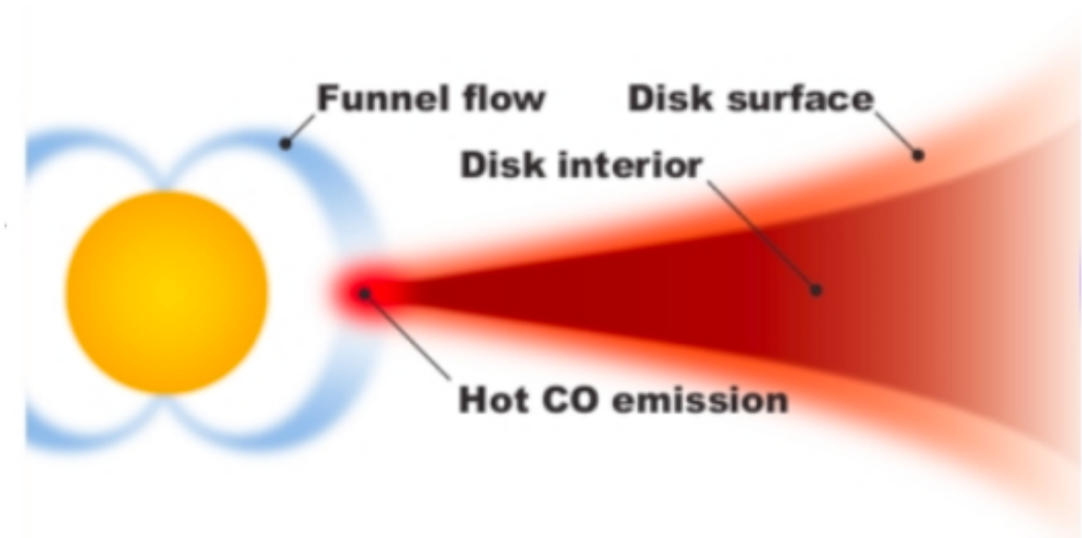
Comparison of light curves

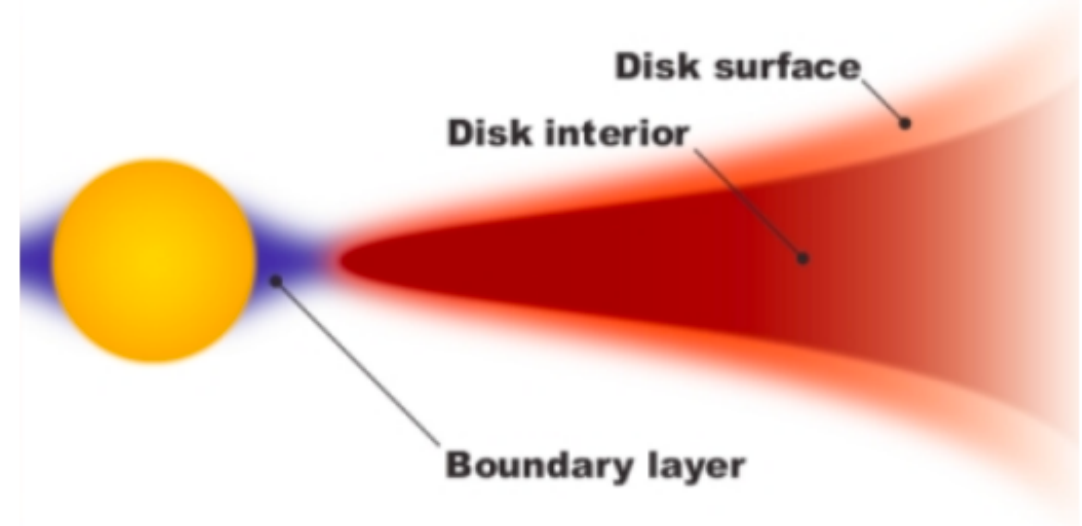


Kóspál et al. (2011)

Optical and infrared spectroscopy

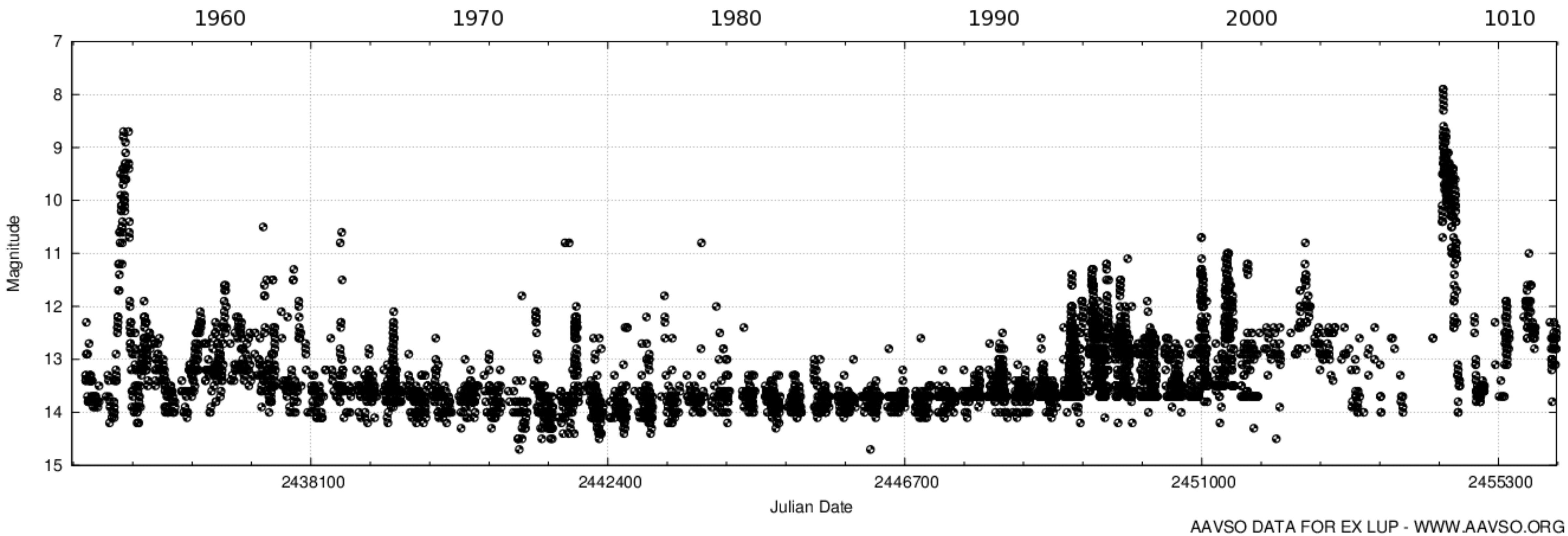
- Path of accretion?
- Role of magnetic field?
- Magnetospheric accretion?
- Equatorial plane?
- Radial velocity companions?





The accretion process in EX Lup

The extreme outburst of EX Lup in 2008:



Coordinated observing campaigns:

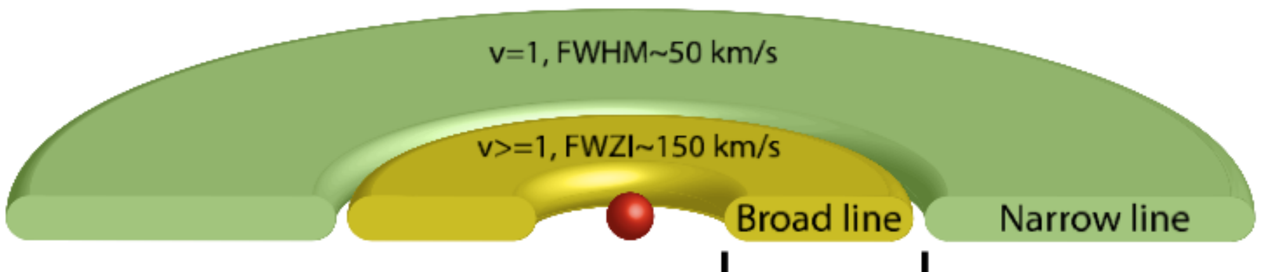
Optical spectroscopy: 2.2m/FEROS

Near-IR spectroscopy: VLT/SINFONI

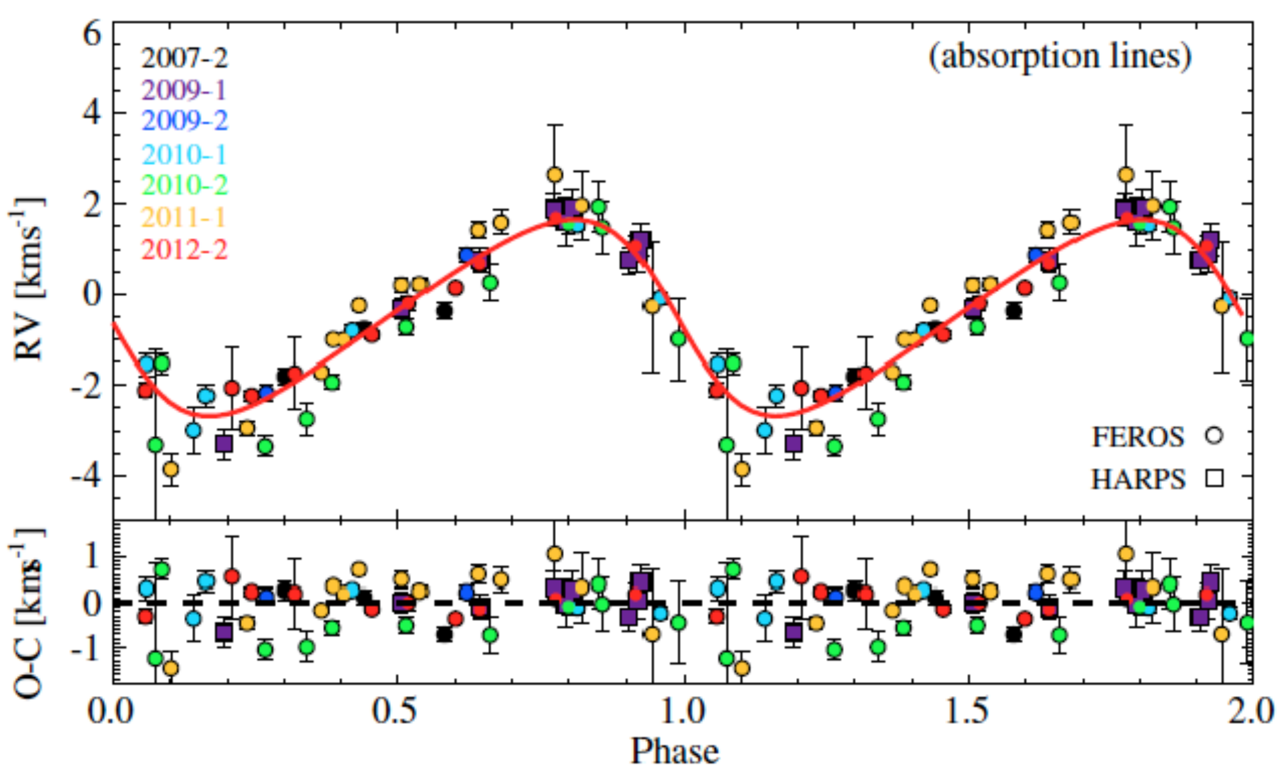
Mid-IR spectroscopy: VLT/CRIRES+VISIR+MIDI, Spitzer/IRS

Optical spectro-polarimetry: CFHT/ESPaDOnS

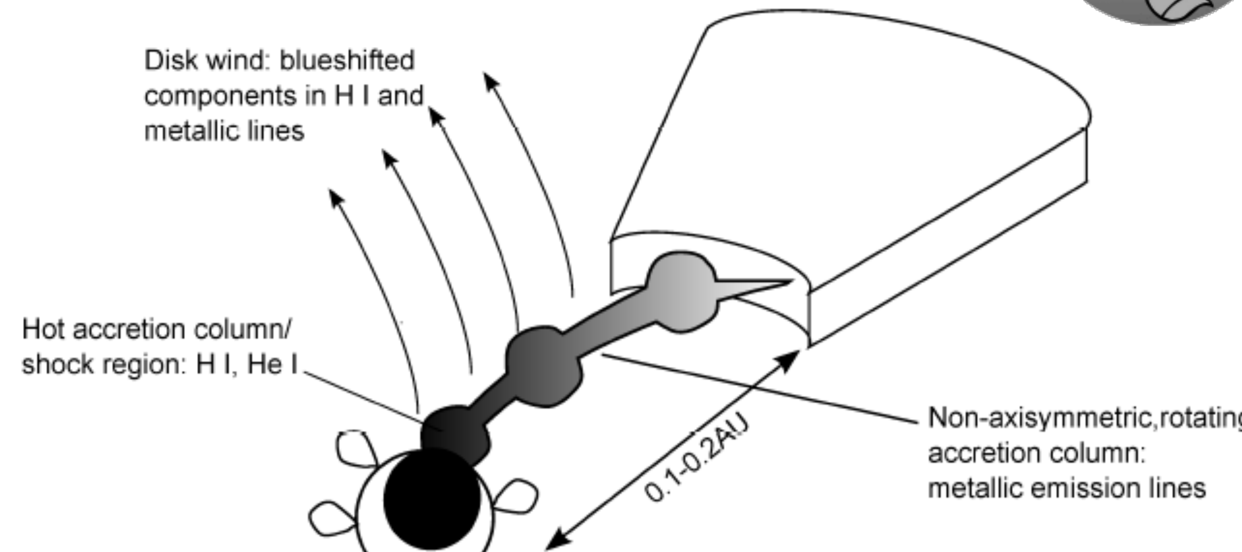
The accretion process in EX Lup



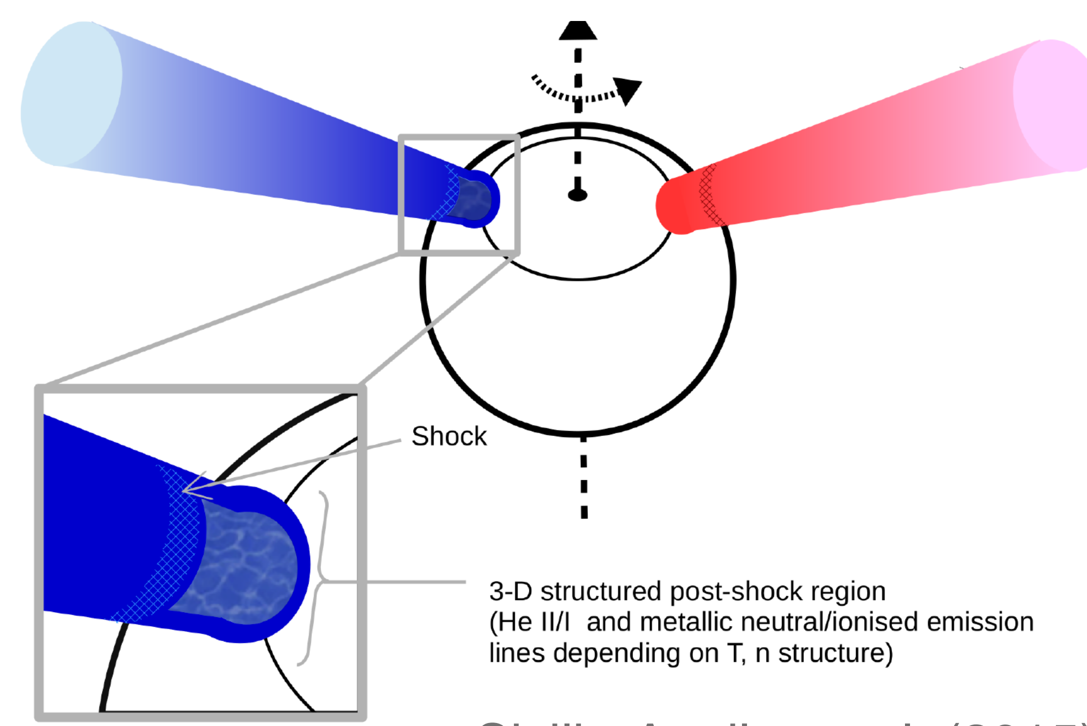
Goto et al. (2012)



Kóspál et al. (2014)

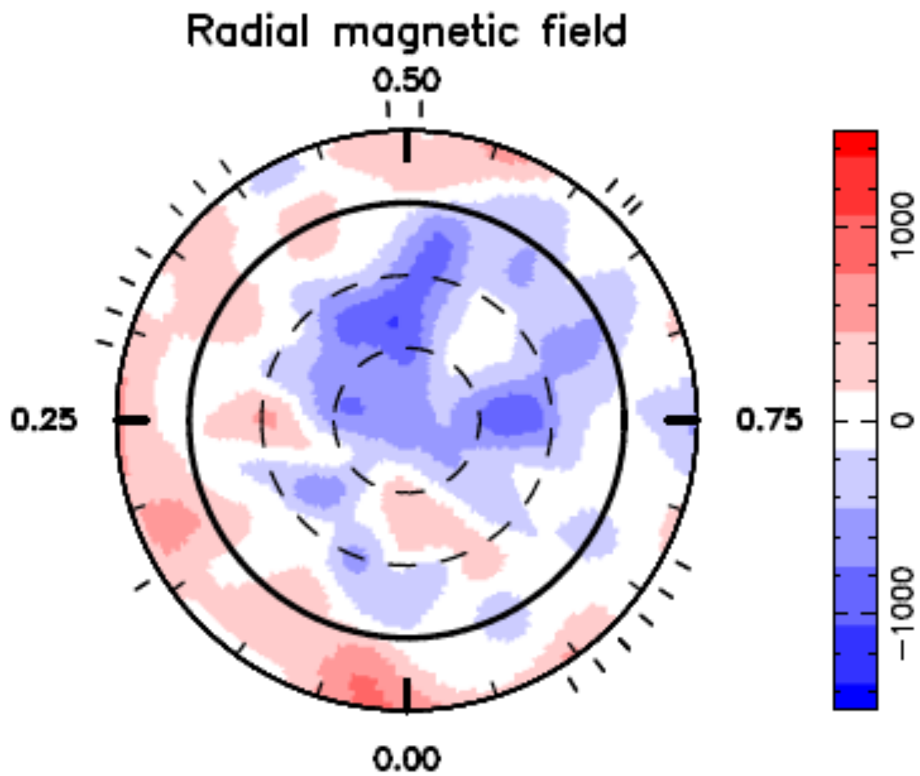


Sicilia-Aguilar et al. (2012)

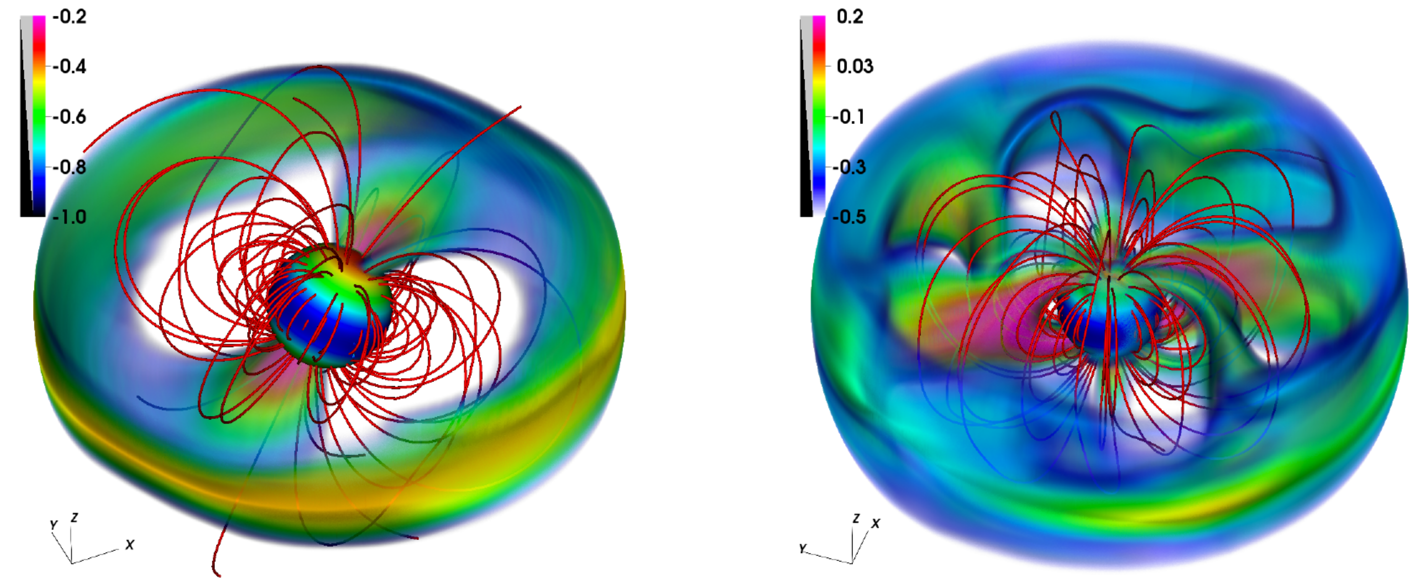


Sicilia-Aguilar et al. (2015)

The accretion process in EX Lup



Skelly et al. (2010)



Kurosawa et al. (2013)

Preliminary results from our CFHT/ESPaDOnS monitoring of EX Lup:

strong surface magnetic field (2-4 kG)

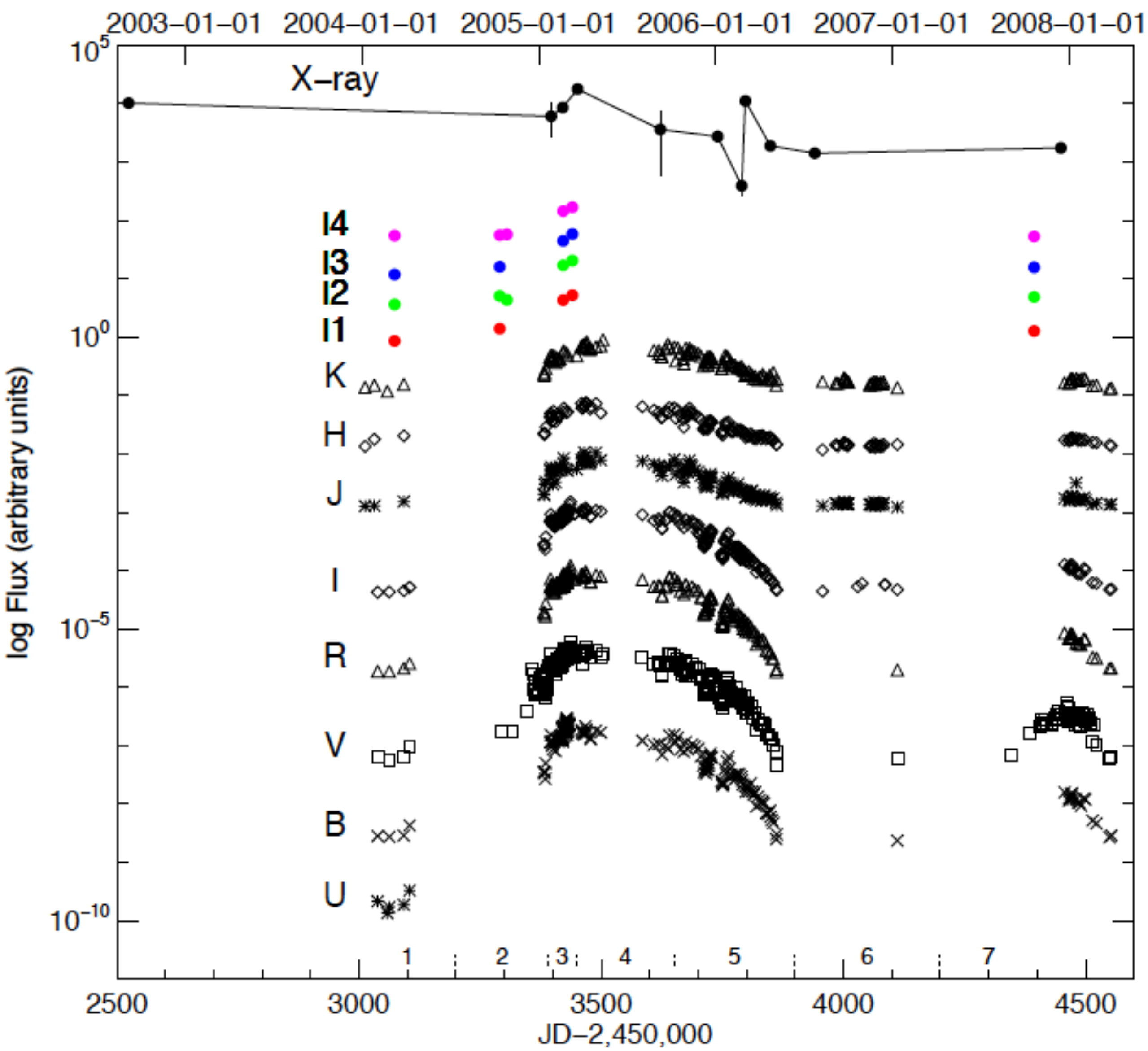
axisymmetric field with poleward accretion

X-ray observations

- Coronal activity?
- Accretion shocks?
- Source of ionization and disk heating?
- Examples: **EX Lup** (Grosso et al. 2010, Teets et al. 2012), **HBC 722** (Liebhart et al. 2014), **V1647 Ori** (Hamaguchi et al. 2012, Teets et al. 2011), **V1118 Ori** (Audard et al. 2010)
- Typical results: X-ray emission comes from a hot plasma viewed through very high absorption

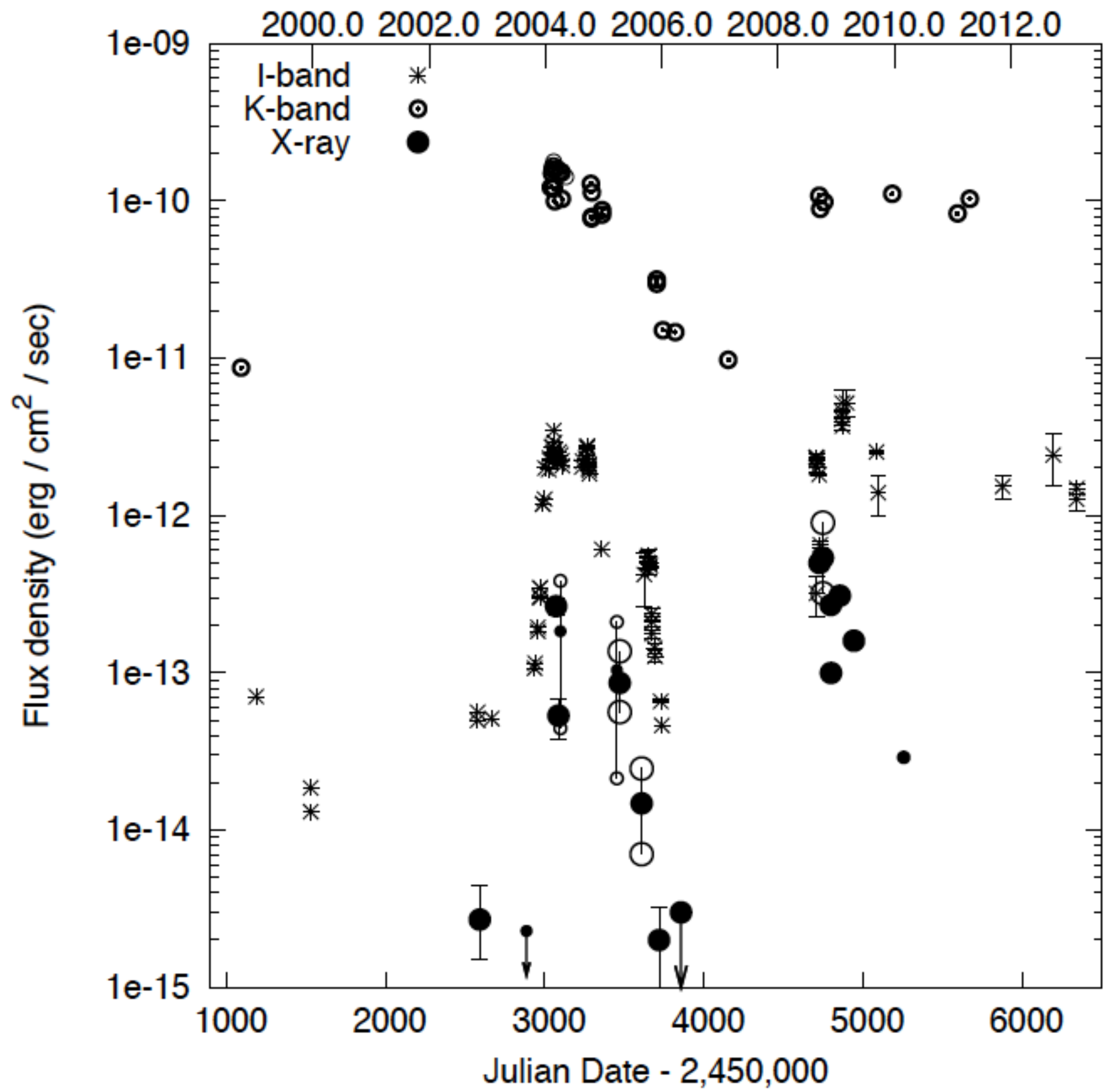
X-ray observations

V1118 Ori



Audard et al. (2010)

V1647 Ori

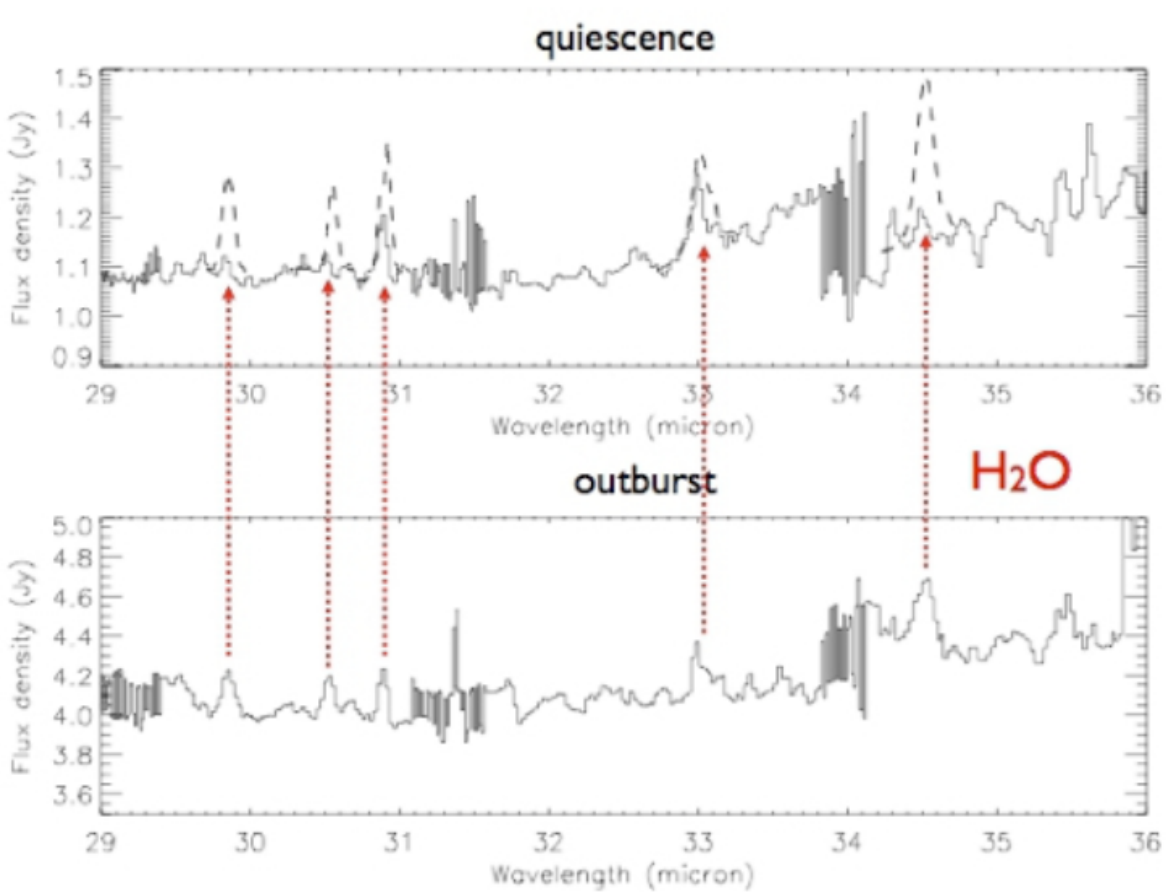


M. Richmond, Teets et al. (2011)

Effects of outburst on the disk

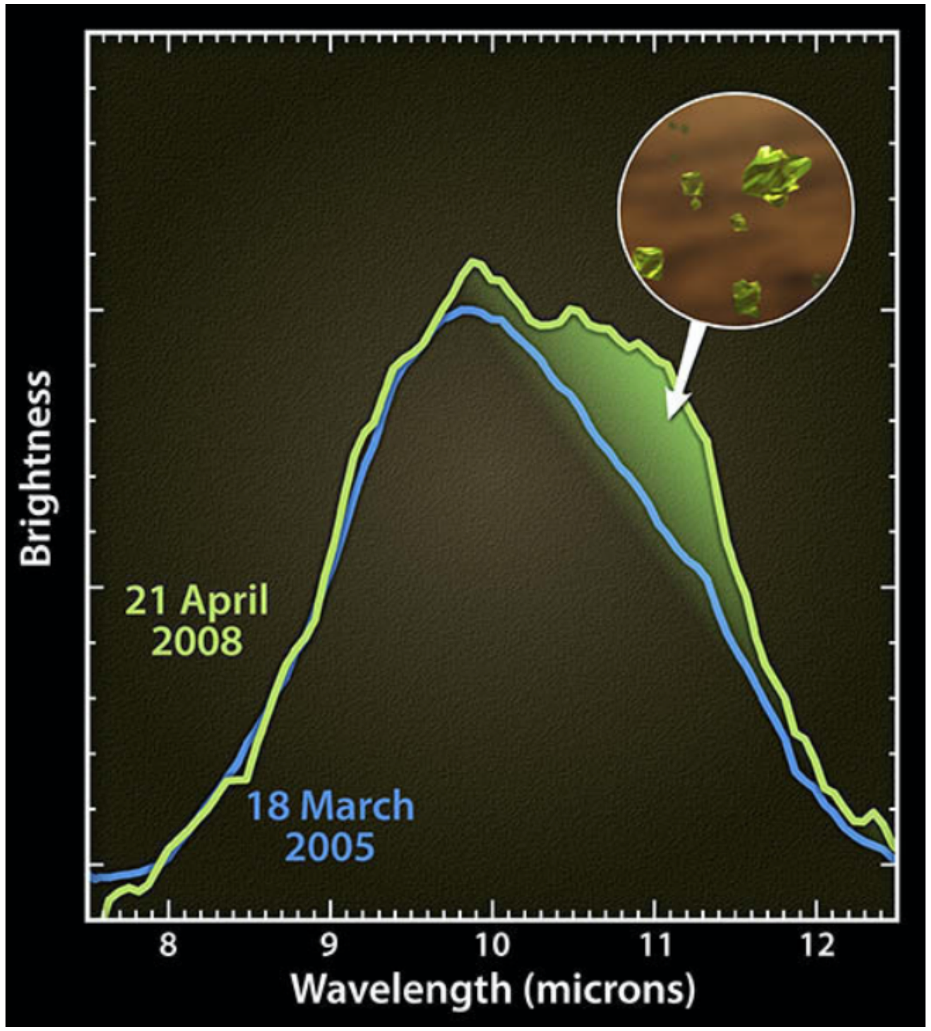
Eruptions may cause structural, mineralogical, and chemical changes

sublimate ices, move the snowline, melt solids, change crystalline structure



Banzatti et al. (2012)

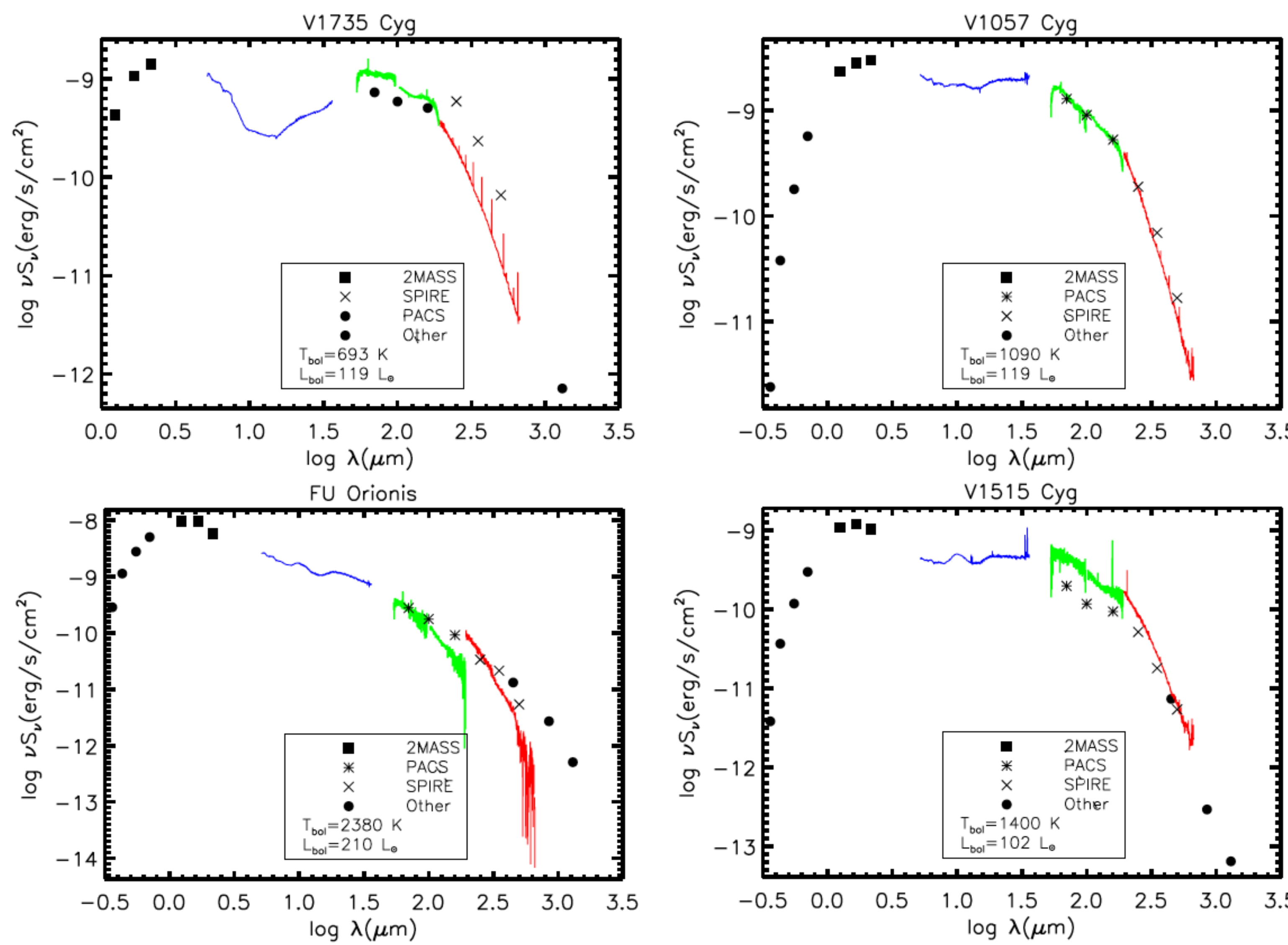
Silicate crystallization in the outburst of **EX Lup**



Ábrahám et al. (Nature, 2009)

Infrared observations

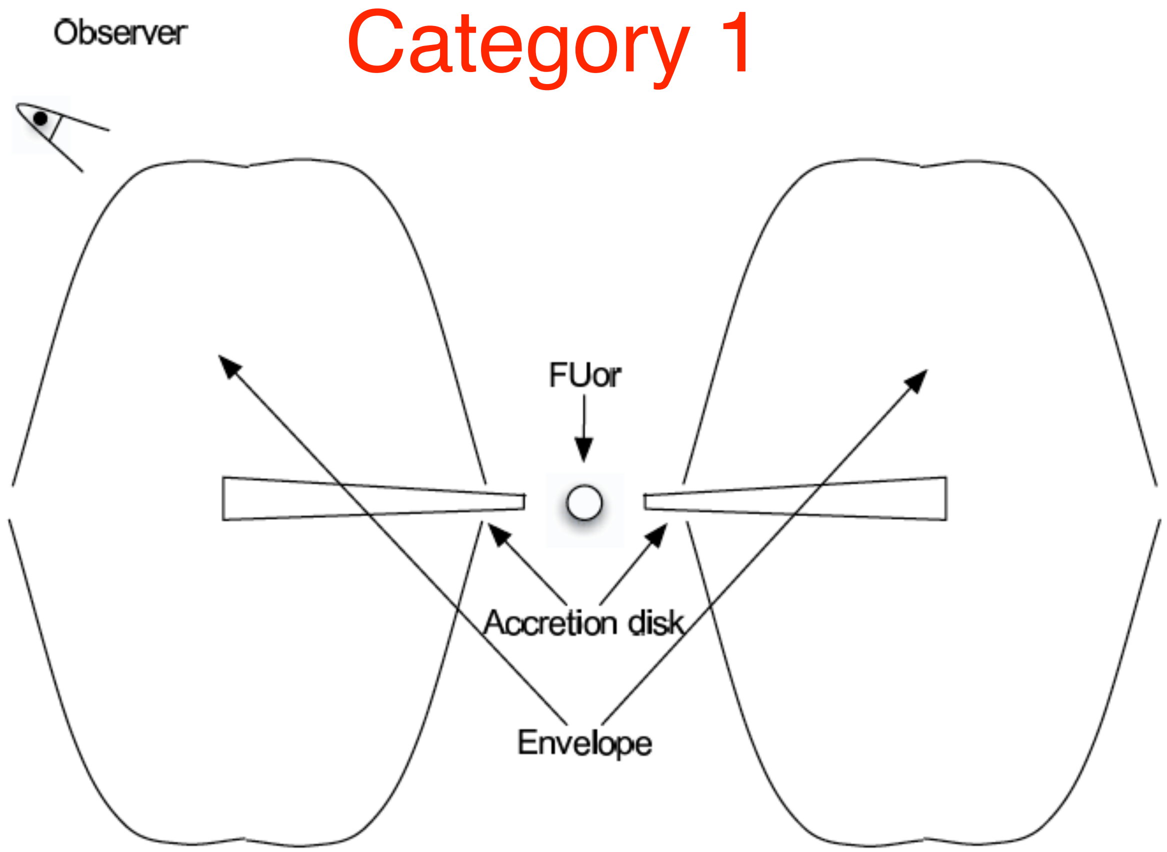
- Evolution of the circumstellar matter
- Place of eruptive stars in protostellar evolution from Class I to Class II phase
- ISO, Spitzer, and Herschel results

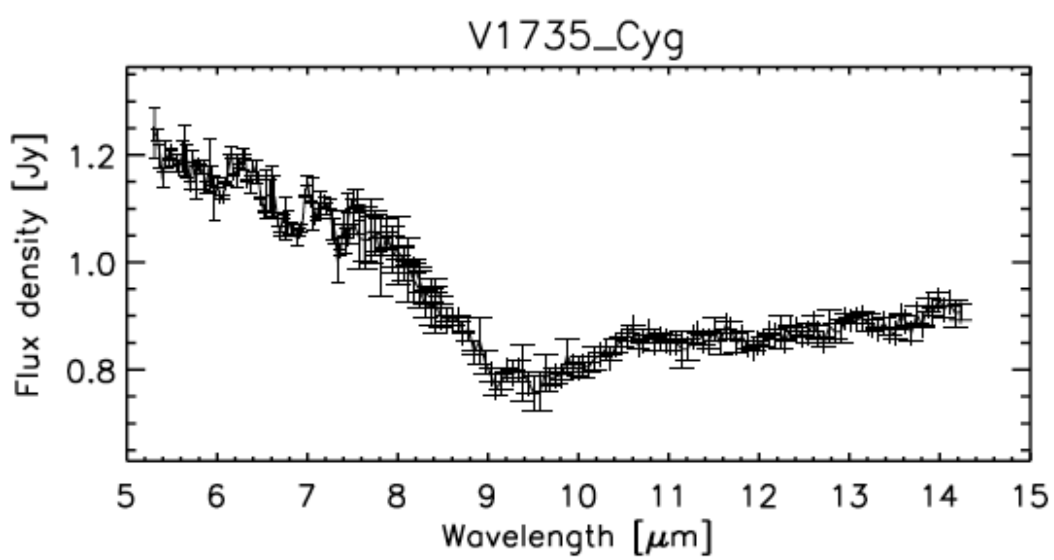


Green et al. (2013)

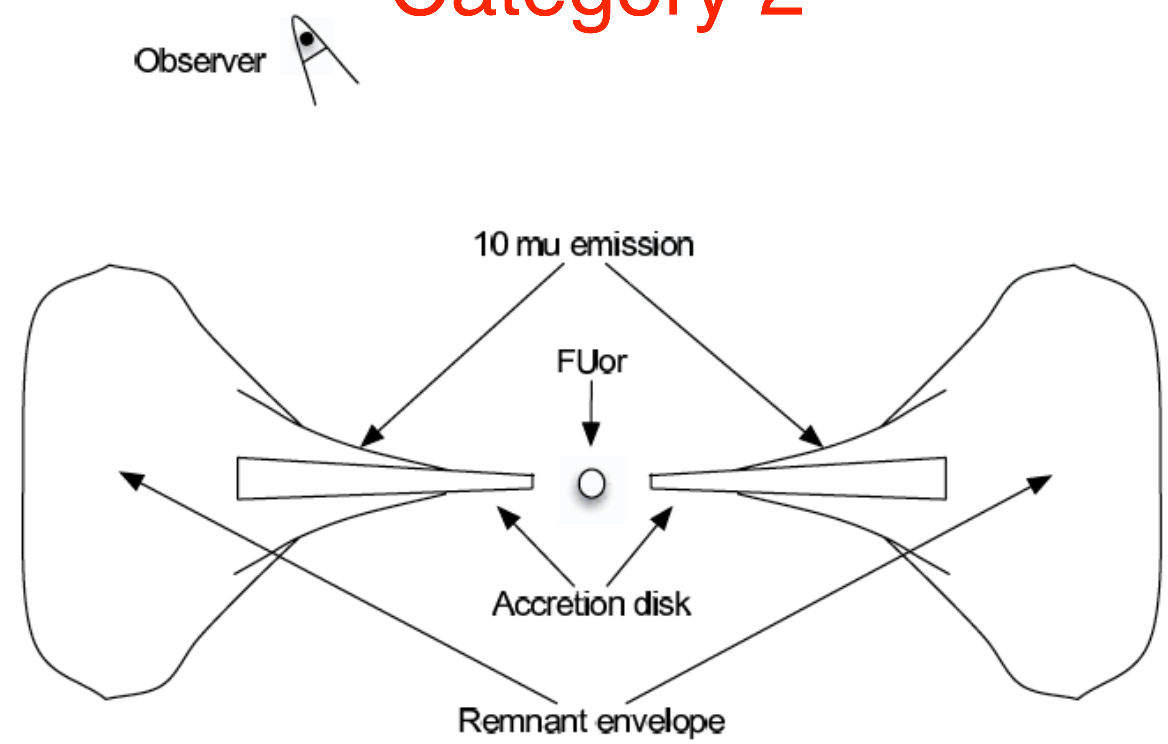
Infrared observations

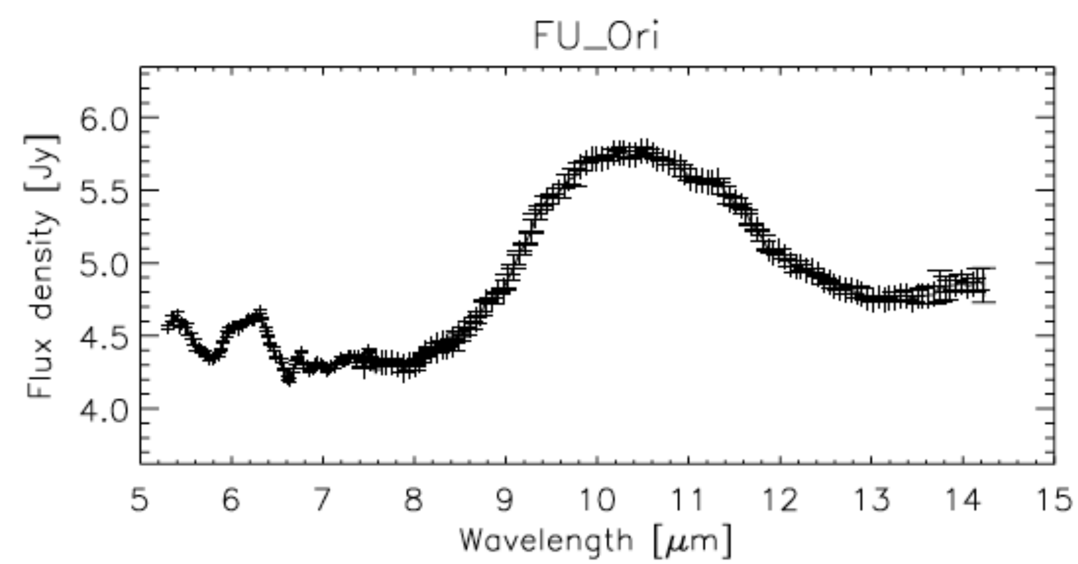
Category 1





Category 2





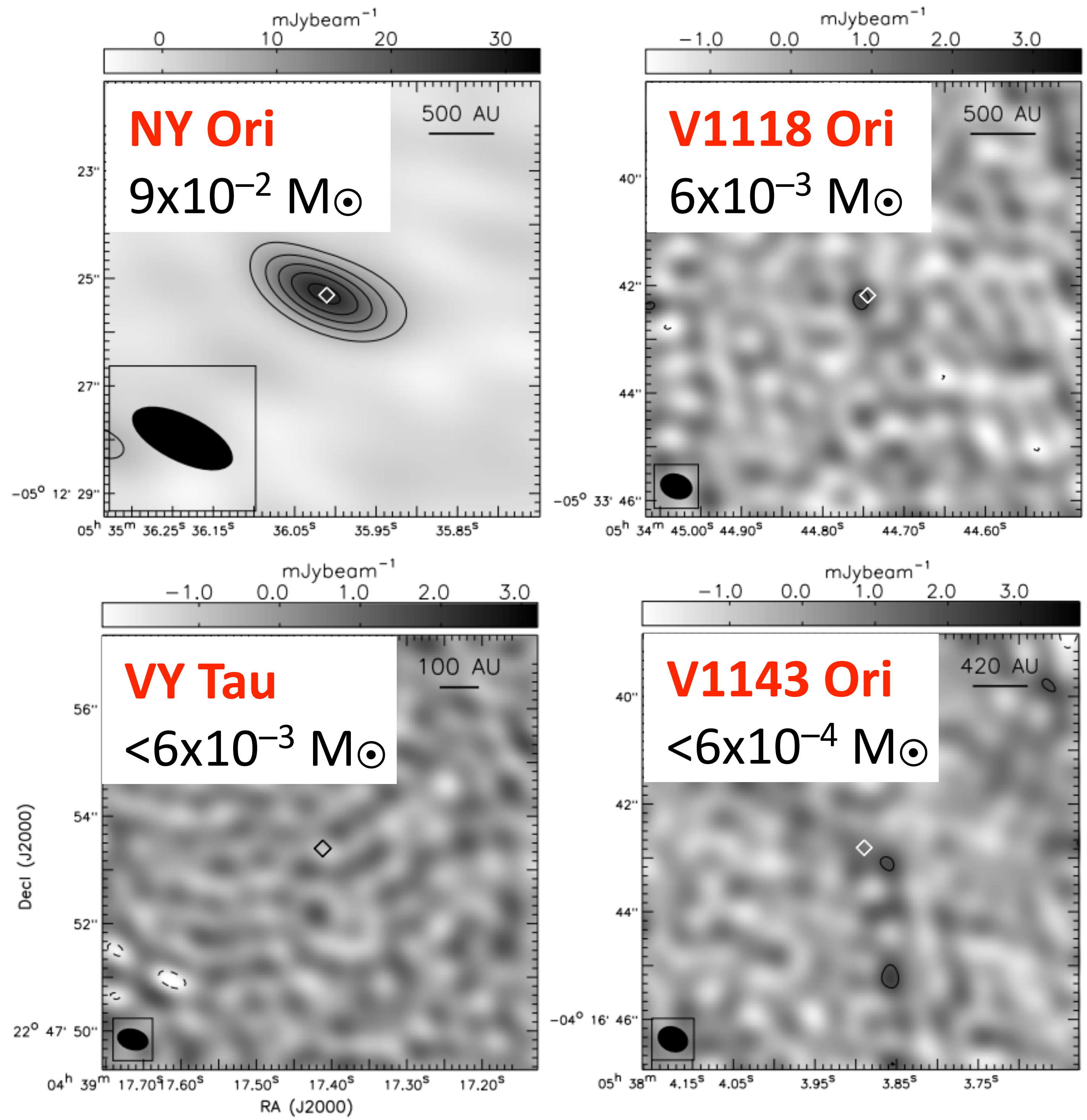
Green et al. (2006), Quanz et al. (2007)

Millimeter observations

- Disk mass, disk structure (fragmentation?)
- Envelope mass
- Disentangle disk from envelope
- Dust-to-gas mass ratio
- Infall rate (envelope to disk; replenishment)
- Outflows (envelope clearing)
- Turbulence in the disk? How efficient is the transport? Is the MRI feasible?

Millimeter data: dust continuum

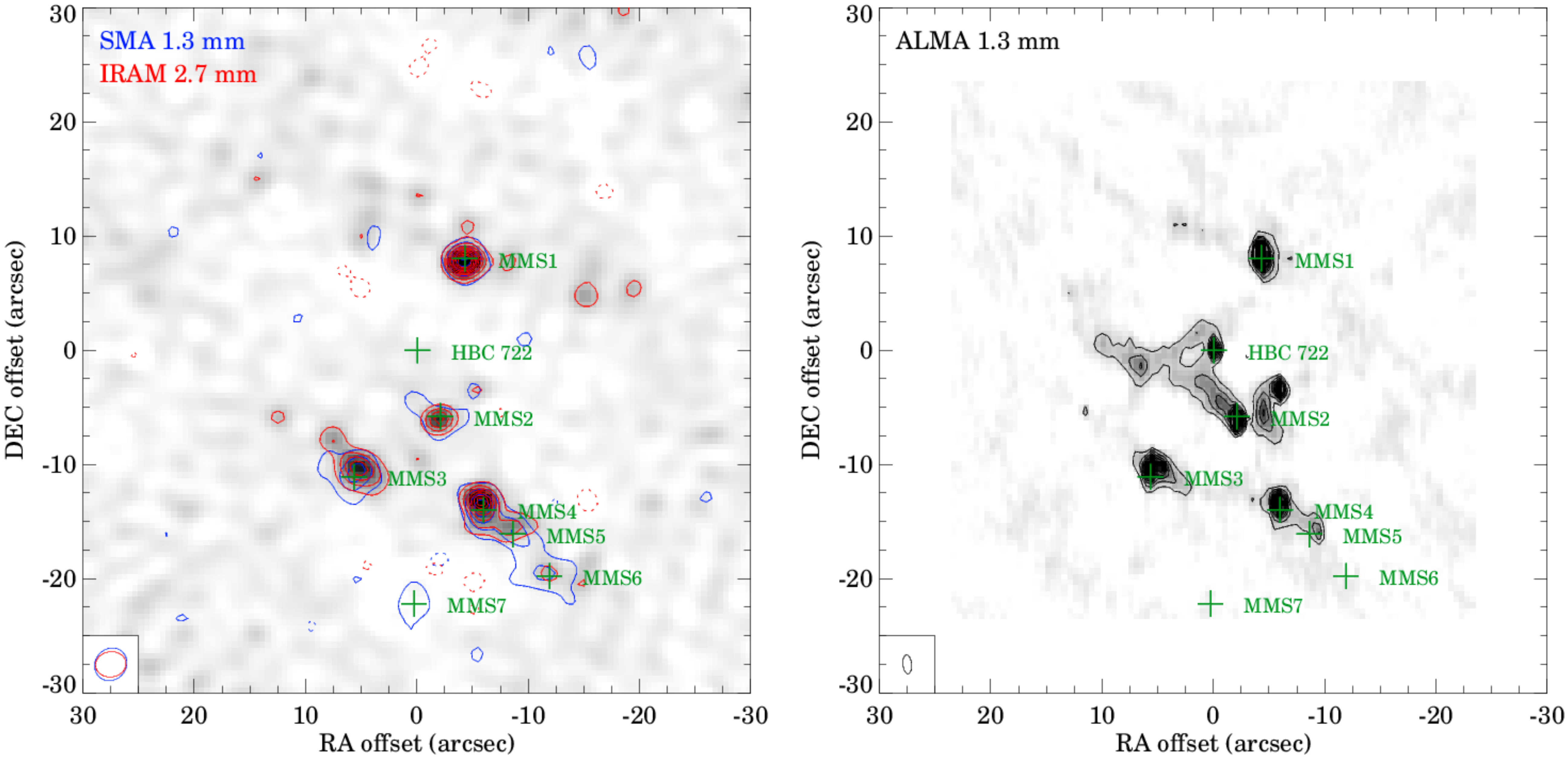
Disk masses
for EXors:



Liu et al. (2016)

Millimeter data: dust continuum

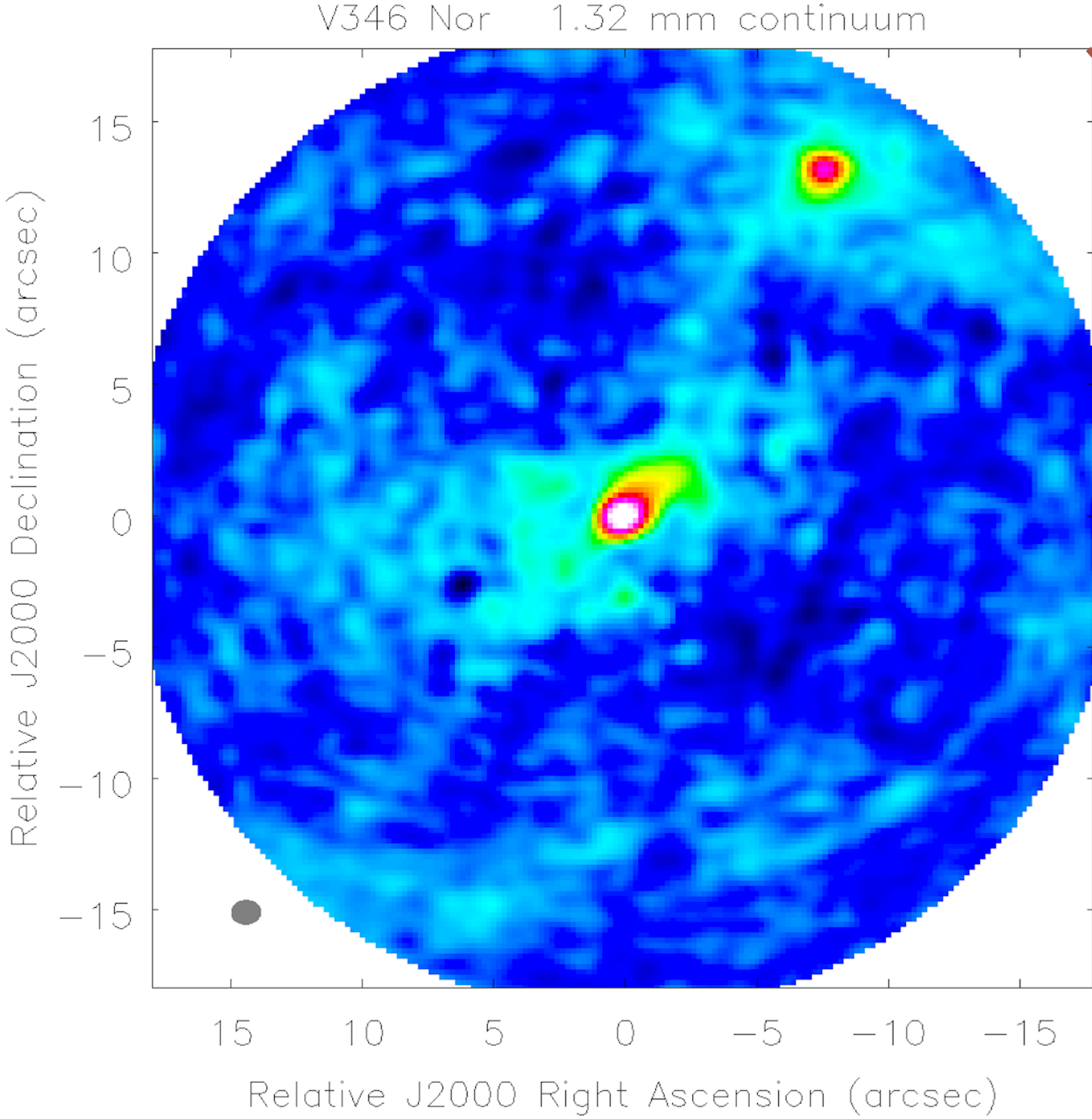
HBC 722 disk mass: 1×10^{-2} M$_\odot$



Kóspál et al. (2016)

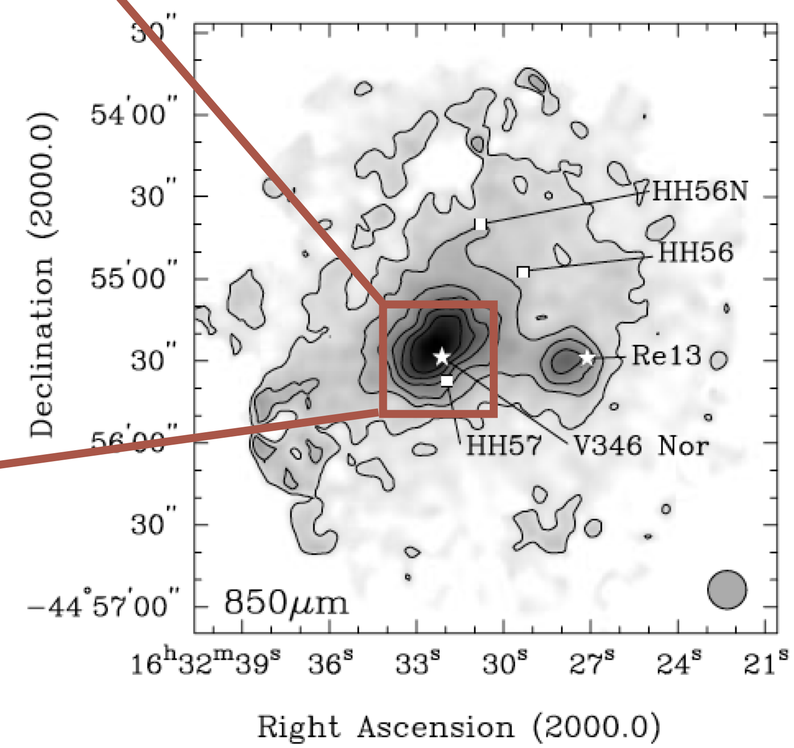
Dunham et al. (in prep.)

Millimeter data: dust continuum



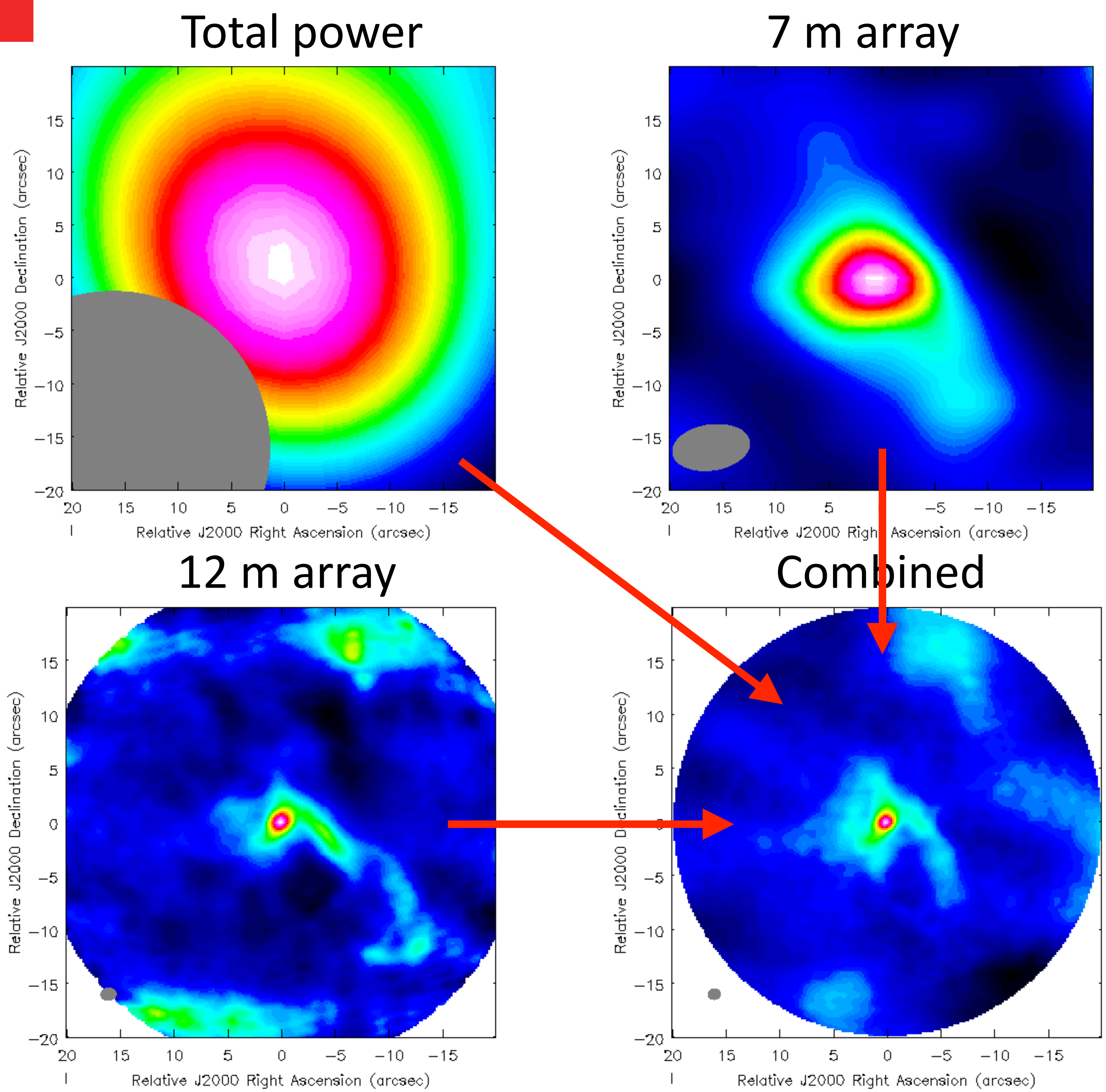
Kóspál et al. (in prep.)

V346 Nor as seen by ALMA



Sandell & Weintraub (2001)

Millimeter data: CO line emission

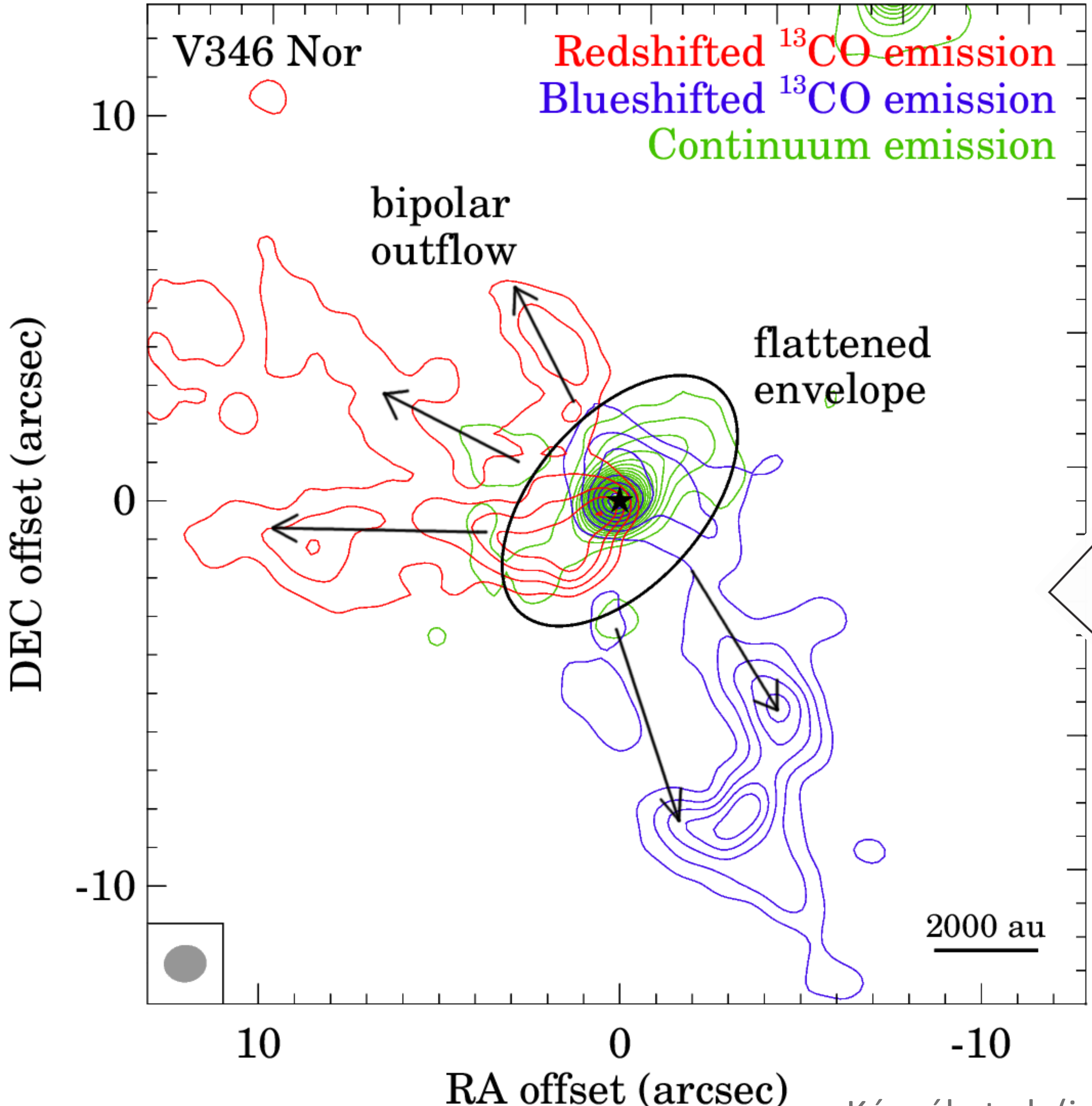


ALMA observations: combination of three data sets:

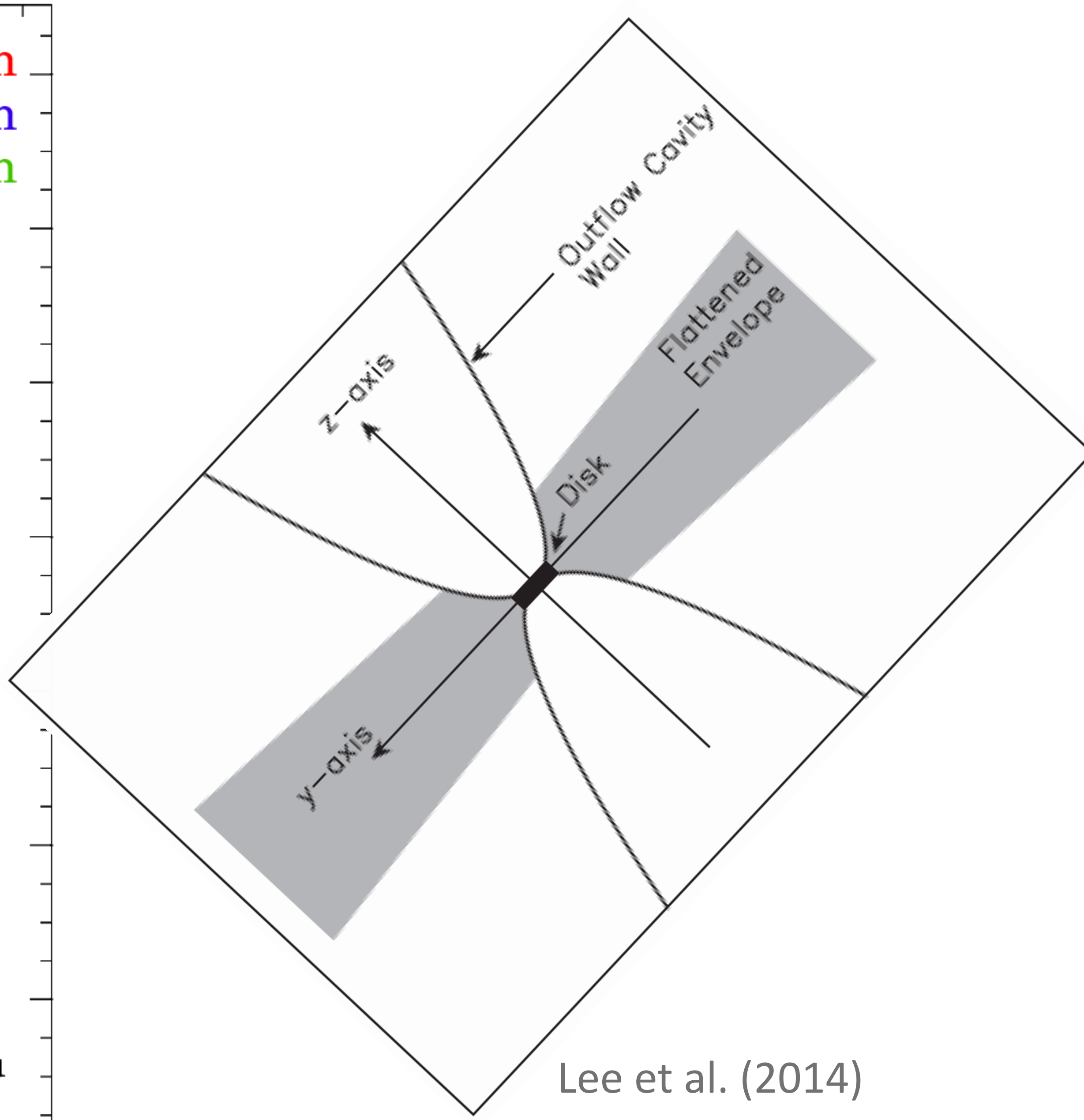
- Total power (single dish)
- 7 m array (short baselines)
- 12 m array (long baselines)

Kóspál et al. (in prep.)

Millimeter data: gas kinematics



Kóspál et al. (in prep.)



Lee et al. (2014)

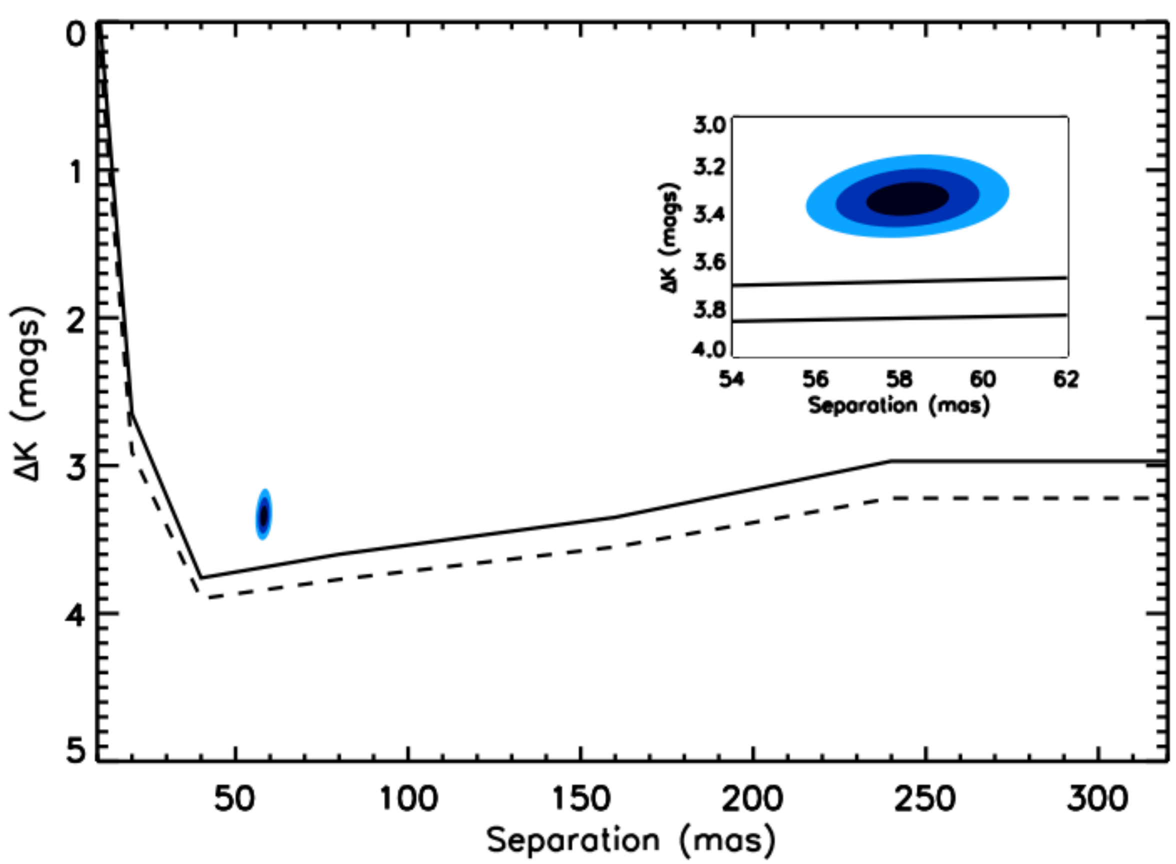
High res, high-contrast measurements

- **Surface structures** in the disk from scattered light:
  - signs of fragmentation?
  - signs of interaction with a companion?

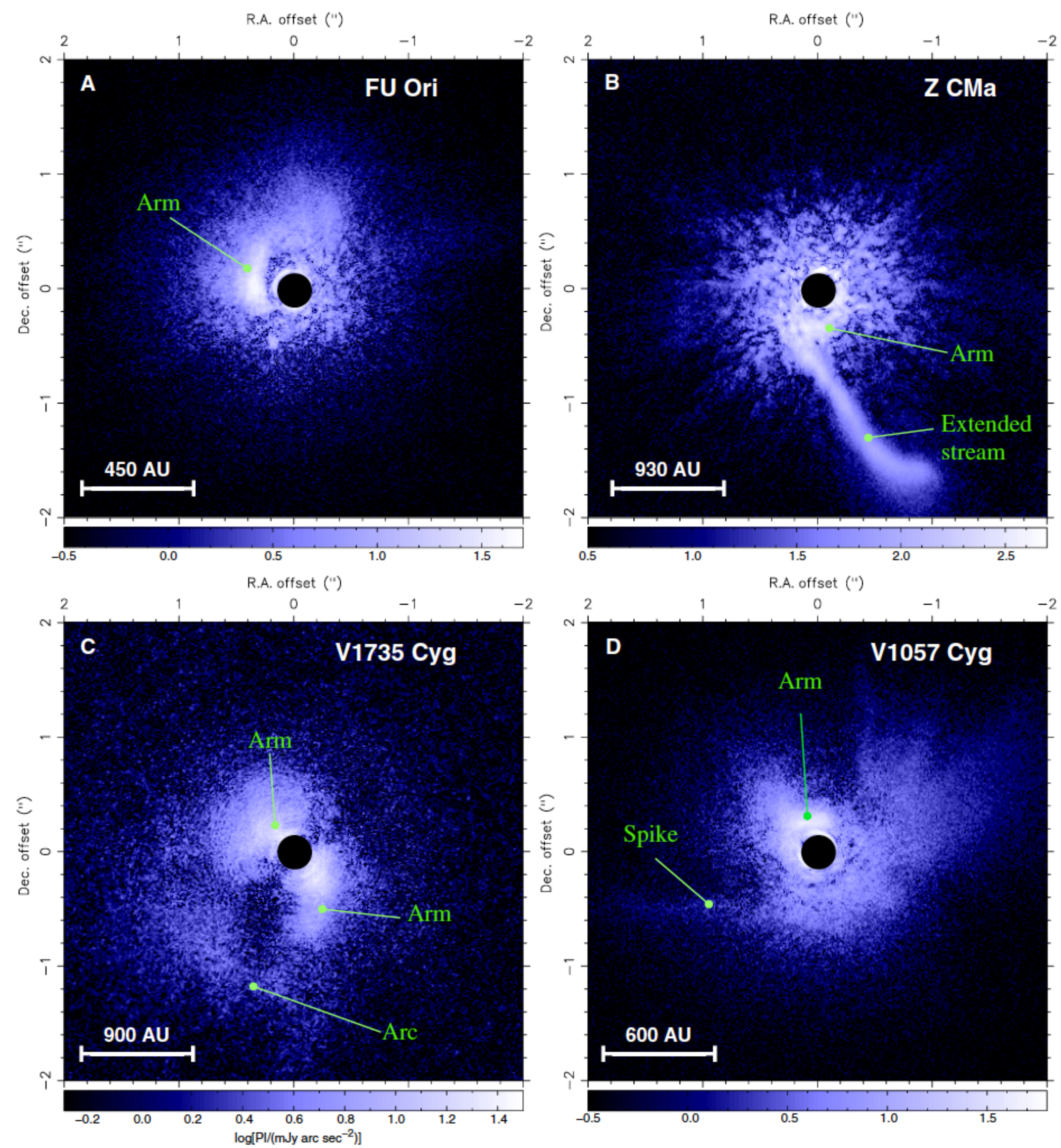
- Look for **companions** to test the binary trigger hypothesis

High res, high-contrast observations

- SUBARU/HiCIAO scattered light structures around FUors
- Nonredundant aperturemask interferometry (NRM) with Keck: companion around V1057 Cyg

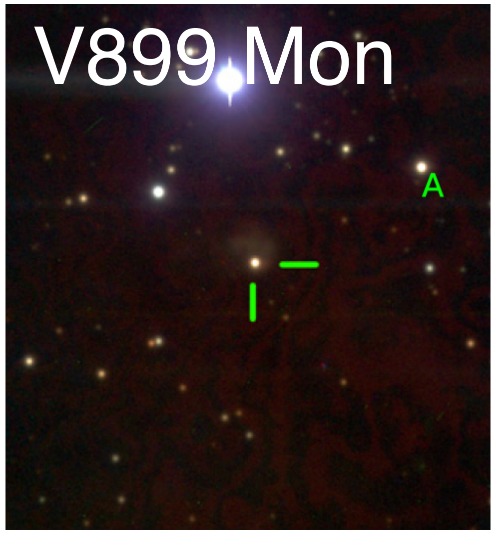


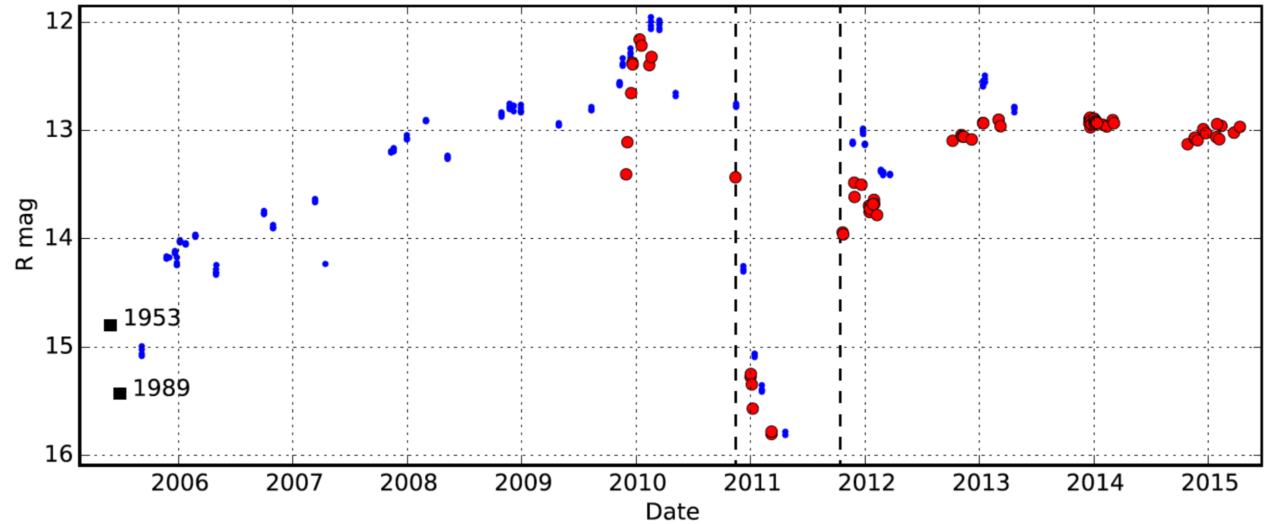
Green et al. (2016)



Liu et al. (2016)

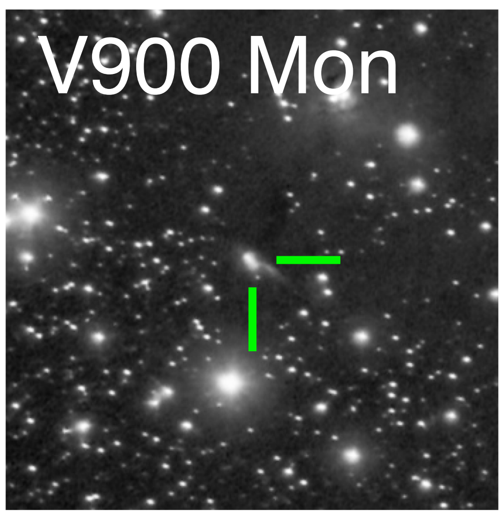
Newly discovered FUors in Monoceros





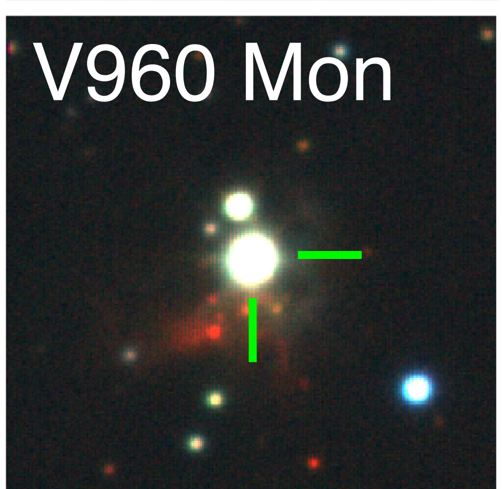
Flat-spectrum or early Class II source, recurrent outbursts, short quiescent phase

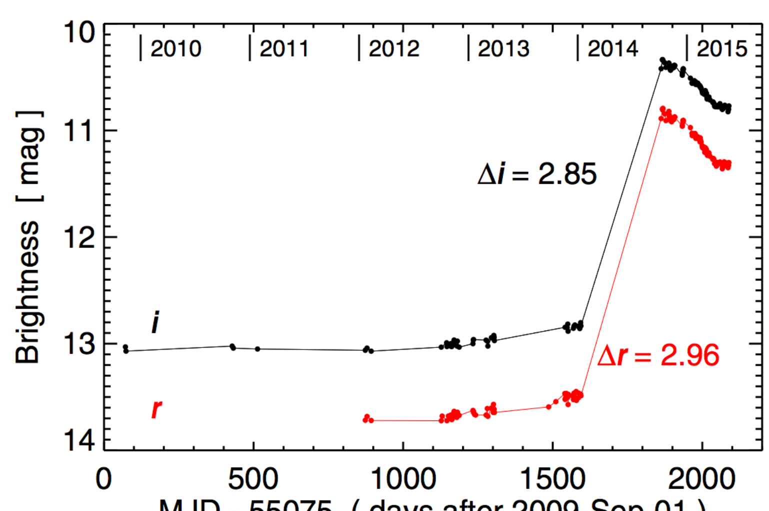
Ninan et al. (2015, 2016)



Class I protostar, still brightening, SED similar to FU Ori

Reipurth et al. (2012)



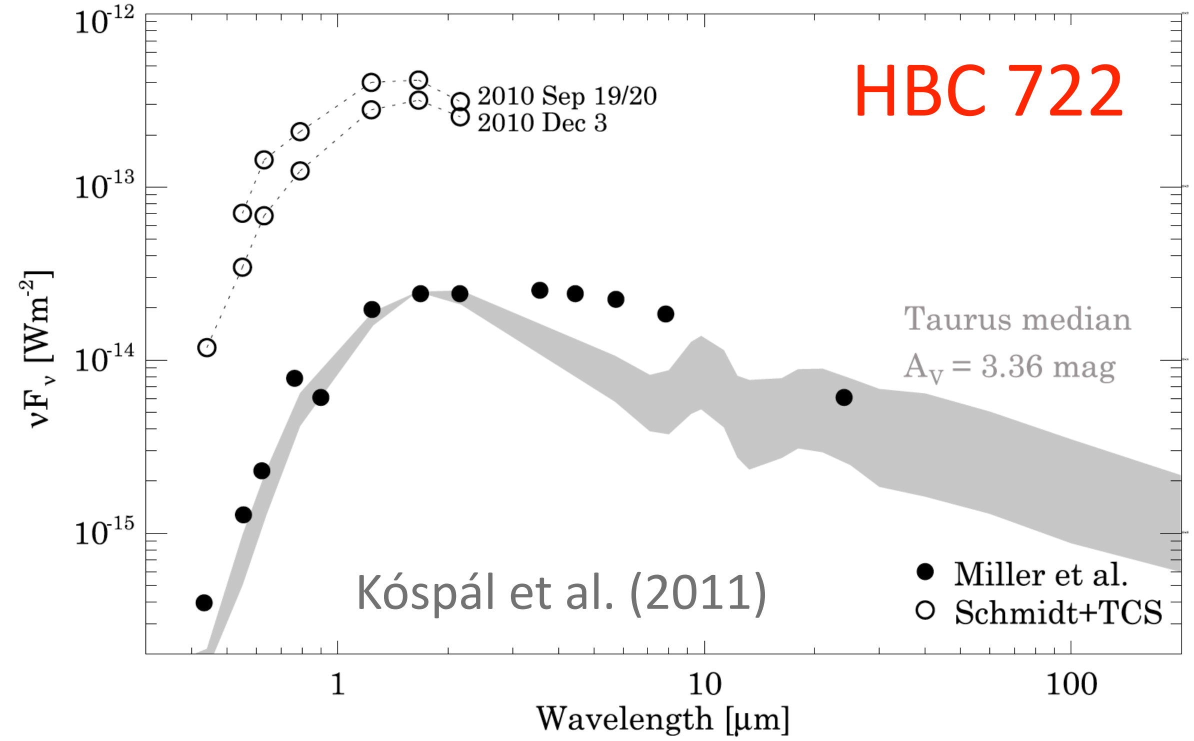


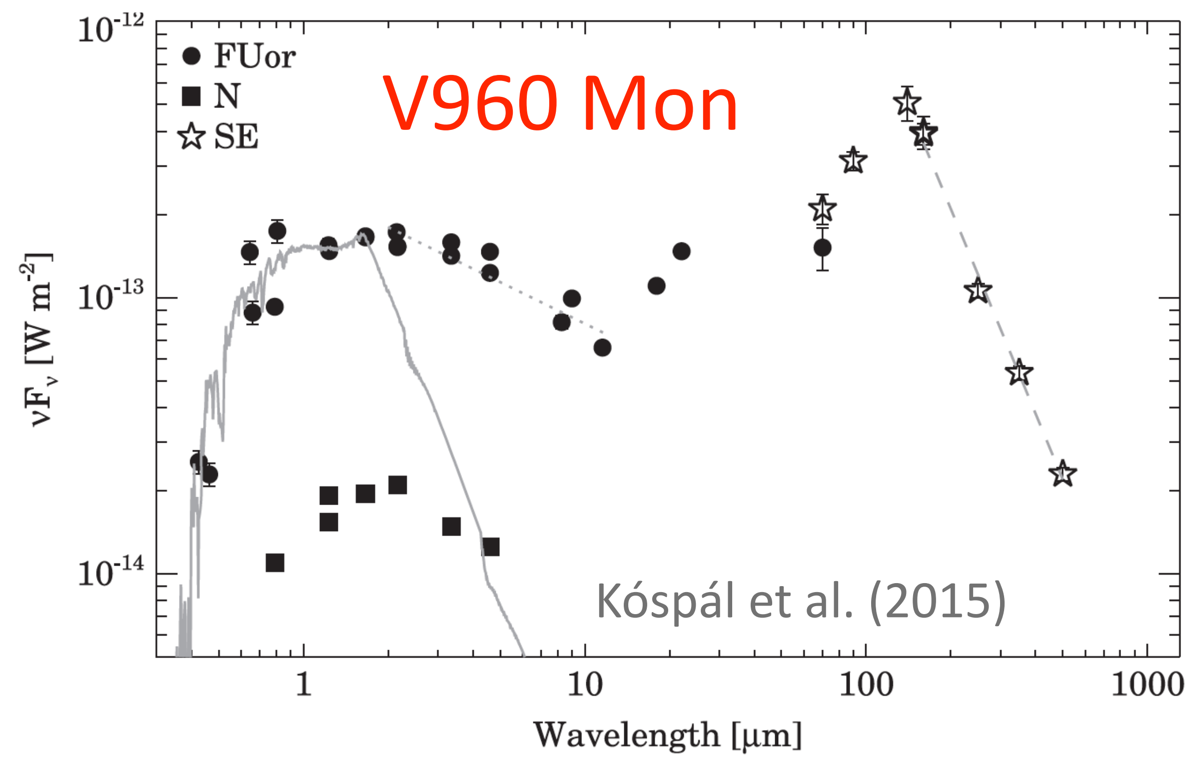
Class II source, possible close binary, outburst in 2014, currently slowly fading

Kóspál et al. (2015), Hackstein et al. (2015)

Progenitor studies

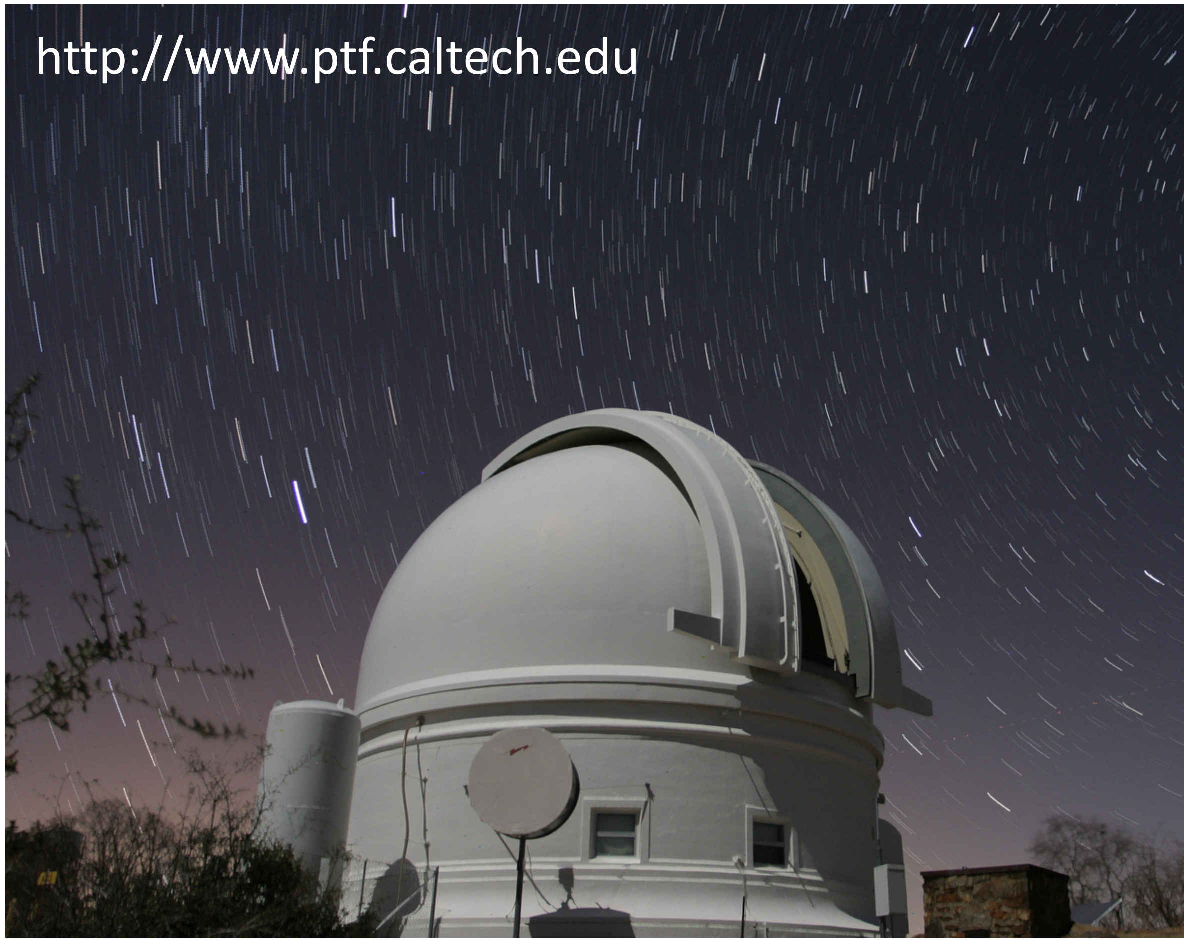
- Progenitor of FUors: old mistery
- Thanks to all-sky surveys, we can study now routinely study the progenitors
- Result: normal T Tauri stars can indeed erupt, but the outbursting phenomenon is also **widespread in all classes from Class 0 to Class II** (e.g., HOPS 383, Safron et al. 2015)





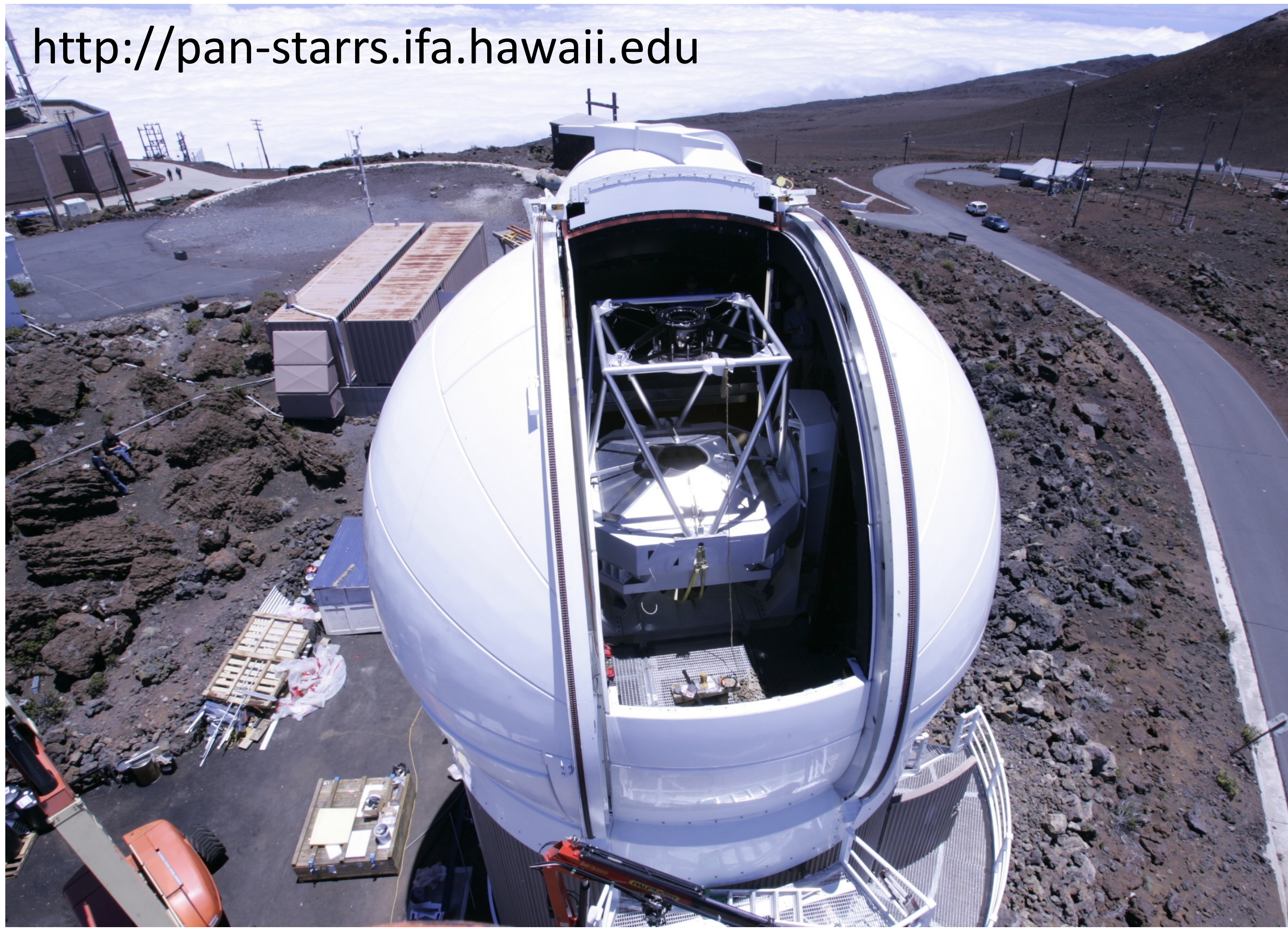
New results from large surveys

- Palomar Transient Factory
  - 1.22 m Oschin Telescope (Palomar Observatory)
  - 2.8°x2.8° field of view
  - 100 square degrees per night
  - *g* and *R* filters
  - 21 mag limiting magnitude
  - coverage: north of –47.5° declination
- Recent results from PTF:
  - PTF 10nvg (Covey et al. 2011)
  - PTF 10qpf (Miller et al. 2011)
  - iPTF 15afq (Miller et al. 2015)



New results from large surveys

- Panoramic Survey Telescope & Rapid Response System (Pan-STARRS)
  - 1.8 m telescope in Hawaii
  - 3°x3° field of view
  - 6000 square degrees per night
  - *grizyw* filters
  - 24 mag limiting magnitude
  - The 3π Steradian Survey: coverage: north of –30° declination, 60 epochs, twelve each in 5 filters

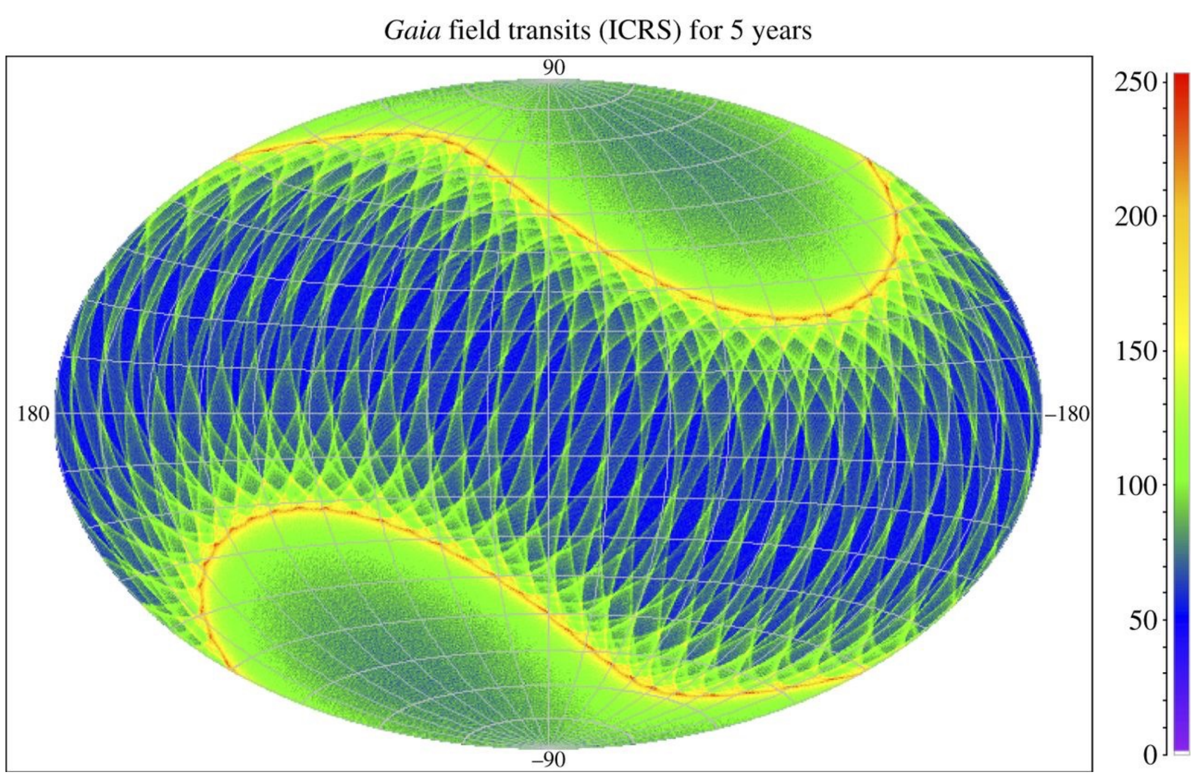


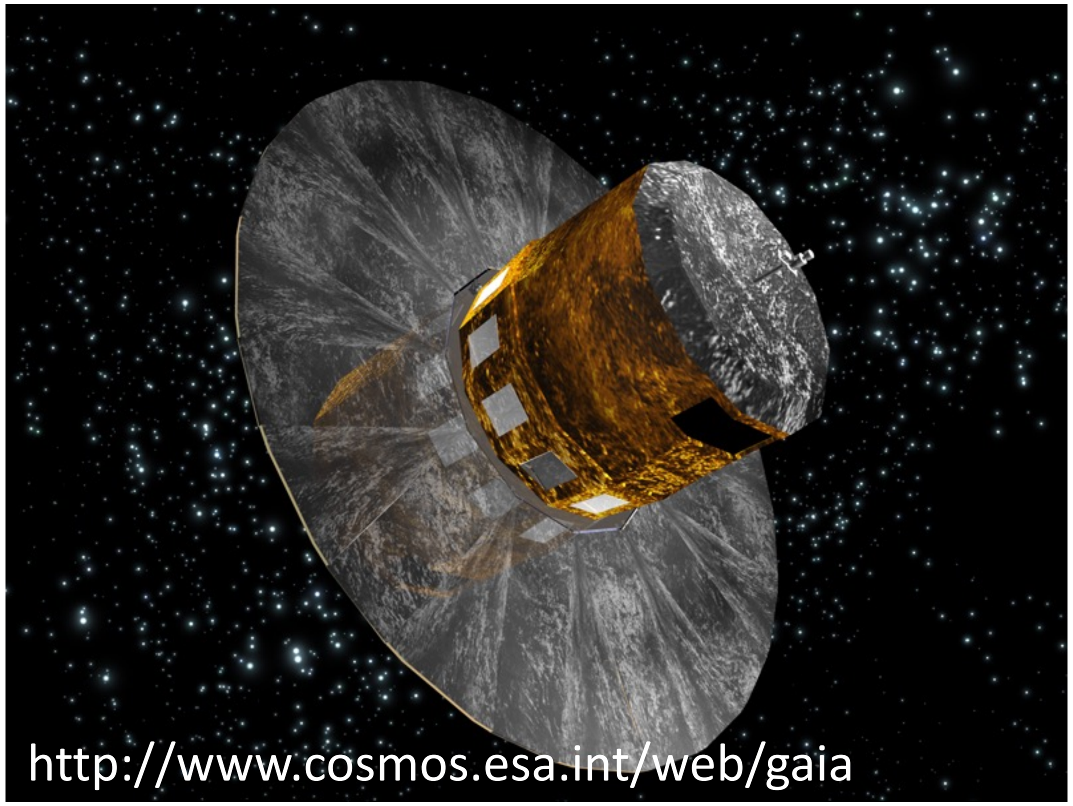
New results from large surveys

- Large Synoptic Survey Telescope (LSST)
  - Construction phase: 2014 – 2022
  - Operations: 2023 –
  - 8.4 m telescope in Cerro Pachón
  - survey the entire sky in three nights
  - coverage: south of +10° declination
  - *r* = 24.5 mag limiting magnitude

New results from large surveys

- Gaia mission
  - astrometry for 1 billion stars down to G = 20 mag
  - G filter (broad-band white light)
  - Covers the entire sky in 5 years, on average 70 times
  - Multi-epoch photometry to be released in 2019
  - Currently available: Gaia Science Alerts





Gaia Science Alerts

http://gsaweb.ast.cam.ac.uk/alerts/alertsindex

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These are all the alerts raised to date. You might wish to view or download these as a table in CSV format.

See here for an explanation of the columns.

Show 10 entries

Search: YSO

Name	Observed	RA (deg.)	Dec. (deg.)	Mag.	Historic mag.	Historic scatter	Class	Published	Comment
Gaia16apz	2016-05-22 14:20:39	343.59640	61.84157	20.04	18.96	0.21	unknown	2016-05-25 17:36:41	Highly variable red source. Faded by 1.5 mag. Possible YSO
Gaia16ama	2016-04-26 04:01:06	344.98905	62.42560	18.46			unknown	2016-05-04 22:13:51	Variable star showing sudden 1.5 mag decrease. Possible YSO or RCrB candidate
Gaia16alu	2016-04-22 12:34:31	86.68816	0.06292	18.22			YSO	2016-04-25 23:14:56	YSO has faded 0.8 mags
Gaia16alt	2016-04-23 10:05:23	325.74996	66.19105	16.90			YSO	2016-04-25 15:12:31	1.5 mag decline in YSO V* V350 Cep
Gaia16agv	2016-02-29 13:04:14	83.69805	-5.96583	14.32			YSO	2016-03-02 14:31:05	> 1 mag decline in YSO YY Ori (Herbig Ae/Be star)
Gaia16agu	2016-02-29 13:02:36	85.10685	-7.09369	16.50			YSO	2016-03-02 14:29:55	1 mag decline in YSO V898 Ori
Gaia16afv	2016-02-23 00:07:39	131.88200	-43.76474	19.63			YSO	2016-02-24 18:21:00	long-term >4 mag decline in YSO AKARI-IRC-V1 J0847317-434553
Gaia16aft	2016-02-22 16:44:28	312.85930	44.08995	14.08			YSO	2016-02-24 18:12:38	Outburst >6mag of V2492Cyg - known eruptive star
Gaia16aez	2016-02-19 16:32:26	328.37432	47.30115	19.65			unknown	2016-02-21 14:47:19	sudden drop in flux in YSO 2MASS J21532984+4718041

Showing 1 to 9 of 9 entries (filtered from 696 total entries)

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Name	Observed	RA (deg.)	Dec. (deg.)	Mag.	Historic mag.	Historic scatter	Class	Published	Comment
Gaia16apz	2016-05-22 14:20:39	343.59640	61.84157	20.04	18.96	0.21	unknown	2016-05-25 17:36:41	Highly variable red source. Faded by 1.5 mag. Possible YSO
Gaia16ama	2016-04-26 04:01:06	344.98905	62.42560	18.46			unknown	2016-05-04 22:13:51	Variable star showing sudden 1.5 mag decrease. Possible YSO or RCrB candidate
Gaia16alu	2016-04-22 12:34:31	86.68816	0.06292	18.22			YSO	2016-04-25 23:14:56	YSO has faded 0.8 mags
Gaia16alt	2016-04-23 10:05:23	325.74996	66.19105	16.90			YSO	2016-04-25 15:12:31	1.5 mag decline in YSO V* V350 Cep
Gaia16agv	2016-02-29 13:04:14	83.69805	-5.96583	14.32			YSO	2016-03-02 14:31:05	> 1 mag decline in YSO YY Ori (Herbig Ae/Be star)
Gaia16agu	2016-02-29 13:02:36	85.10685	-7.09369	16.50			YSO	2016-03-02 14:29:55	1 mag decline in YSO V898 Ori
Gaia16afv	2016-02-23 00:07:39	131.88200	-43.76474	19.63			YSO	2016-02-24 18:21:00	long-term >4 mag decline in YSO AKARI-IRC-V1 J0847317-434553
Gaia16aft	2016-02-22 16:44:28	312.85930	44.08995	14.08			YSO	2016-02-24 18:12:38	Outburst >6mag of V2492Cyg - known eruptive star
Gaia16aez	2016-02-19 16:32:26	328.37432	47.30115	19.65			unknown	2016-02-21 14:47:19	sudden drop in flux in YSO 2MASS J21532984+4718041

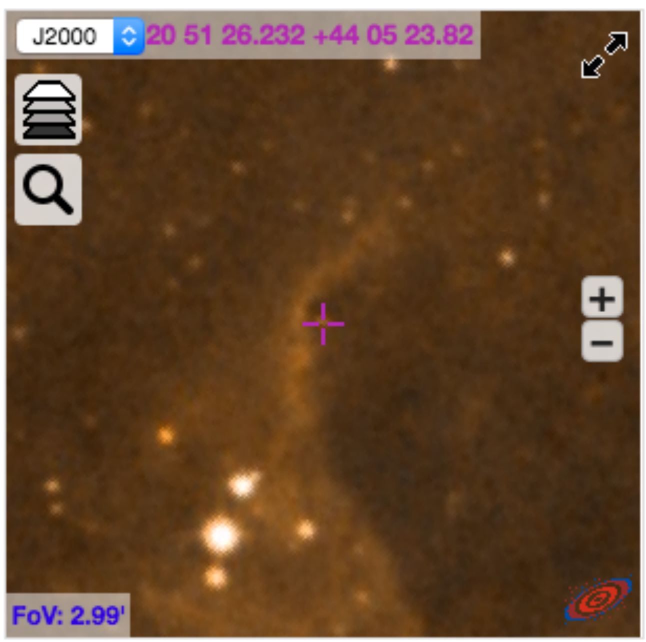
Showing 1 to 9 of 9 entries (filtered from 696 total entries)

Previous 1 Next

Gaia Science Alerts

Gaia16aft

Details | Follow-up



RA - DEC
312.85930 44.08995
20:51:26.2 44:05:23.8

Alerting date
2016-02-22 16:44:28

Julian date
2457441.20

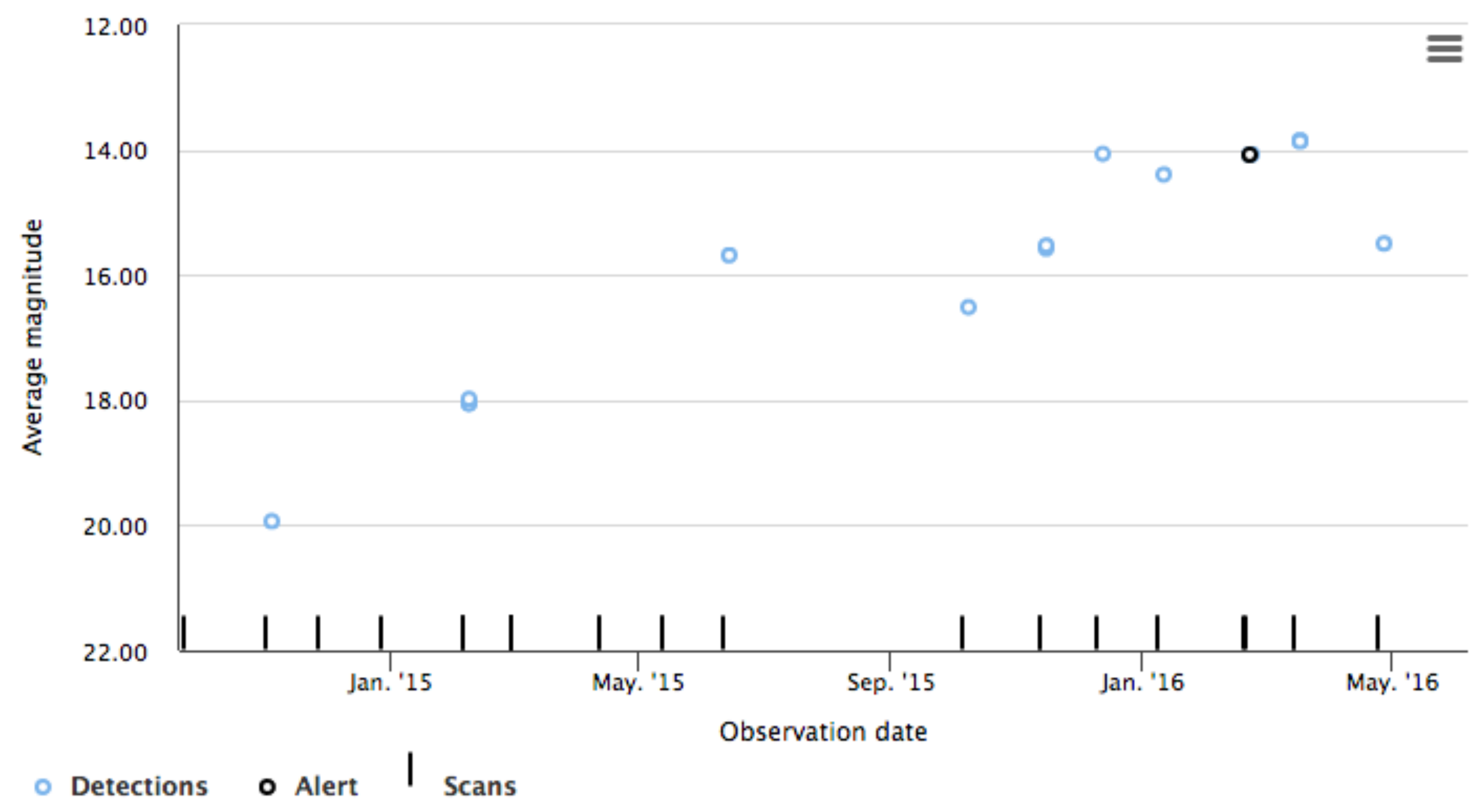
Alerting magnitude
14.08

Historic magnitude
None

Historic StdDev
None

Class
YSO

Publication date
Feb. 24, 2016, 6:12 p.m.



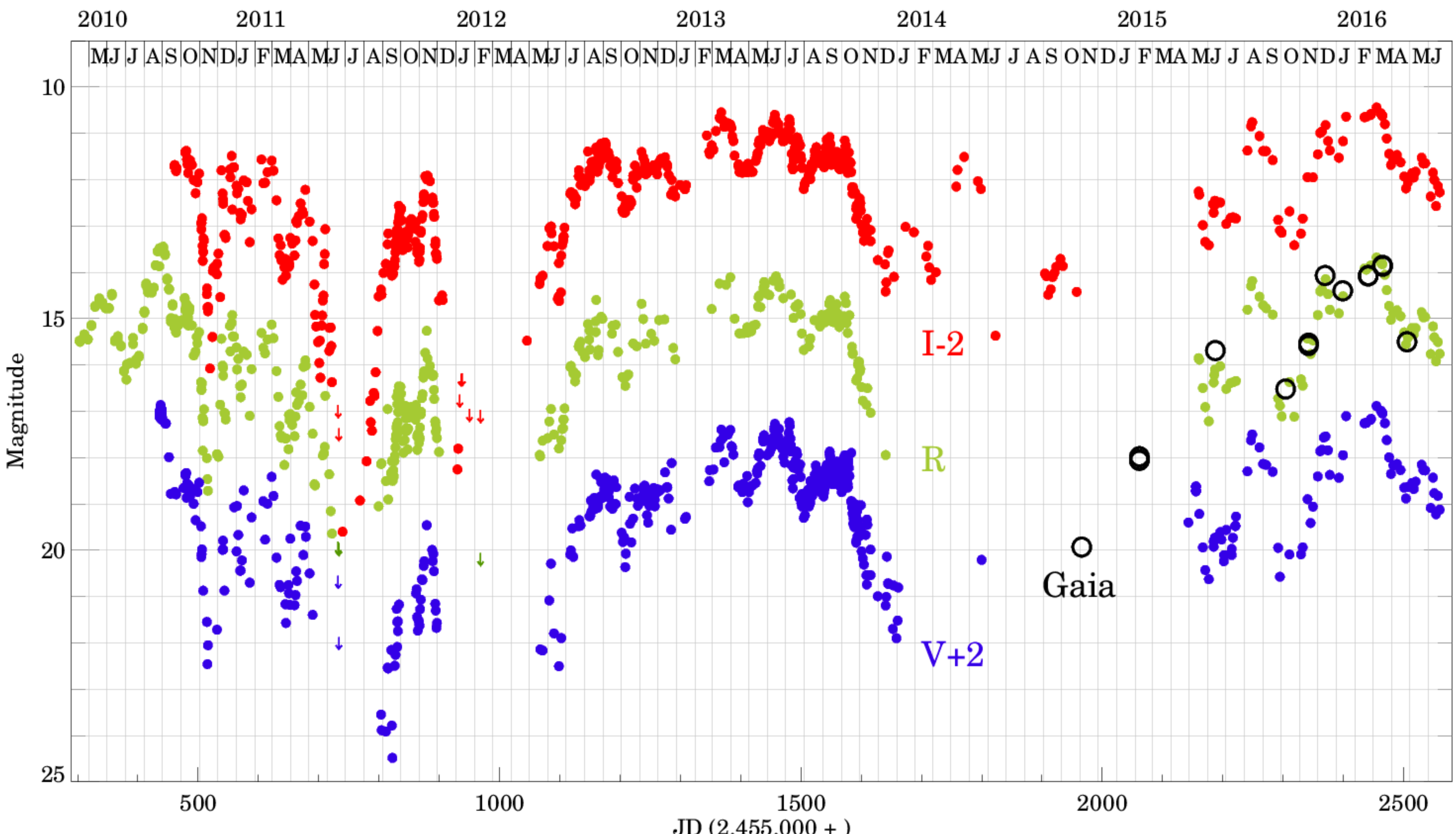
Get lightcurve data

Other surveys detections
None

Comments
Outburst >6mag of V2492Cyg - known eruptive star

ATels
4180 7436

Gaia Science Alerts



Based on Kóspál et al. (2013)

Take-away messages

- After PPVI, there is a growing interest in young eruptive stars
- New objects are discovered, and even more will come
- Not all new objects fit into the classical groups. Third class?
- Dedicated campaigns of individual outbursts are useful
- Slowly growing knowledge on how young eruptive stars accrete
- Low disk mass is a surprise
- Effect on circumstellar disk is important (planet formation!)
- ALMA will finally make it possible to resolve envelope and disk (measure infall rates, test fragmentation theory)
- More companions are seen, but their physical connection to the outburst is uncertain