# YSO Variability in **VVV**:

## episodic accretion, disc occultations and explosions

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University of Hertfordshire UH

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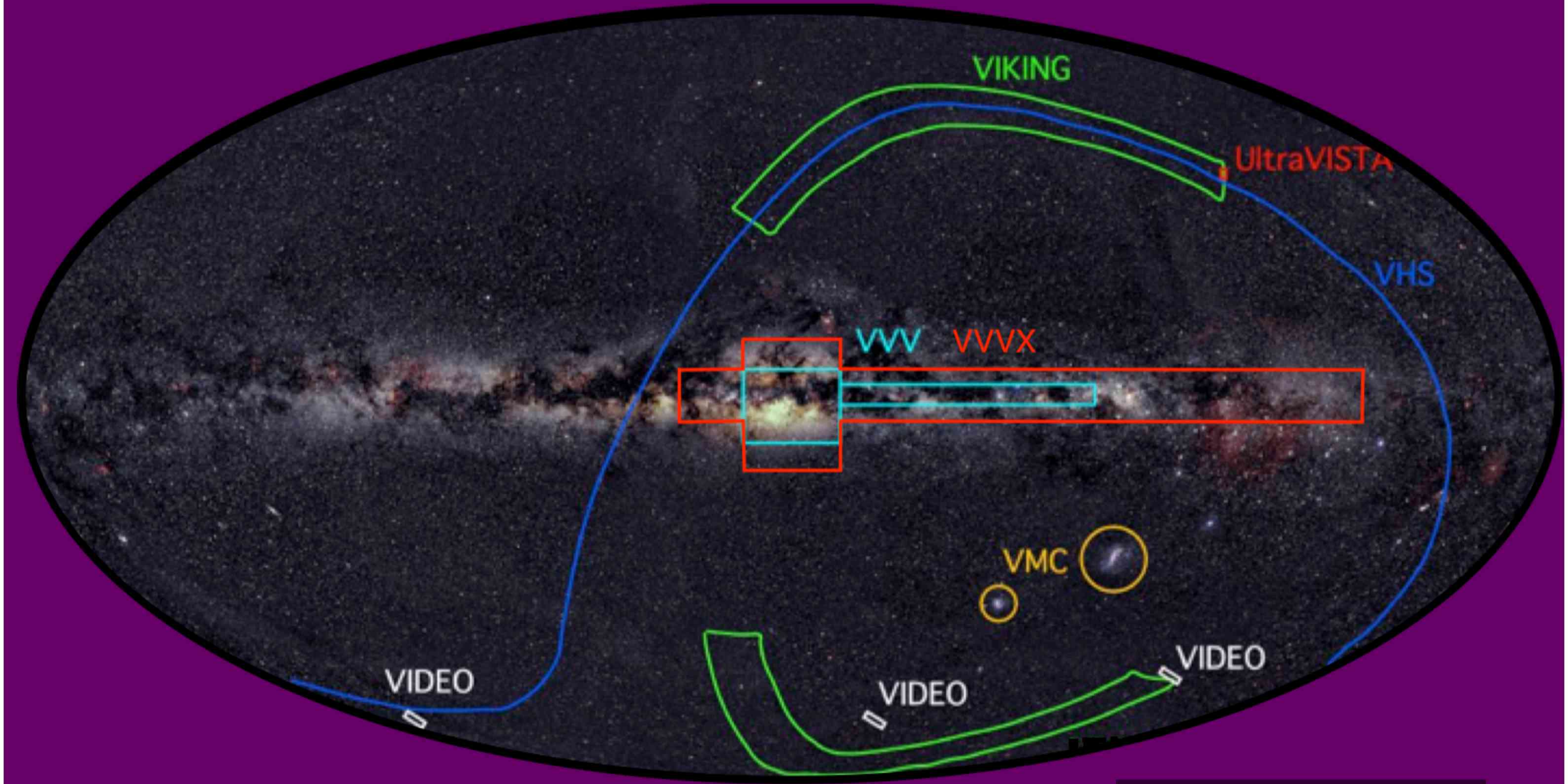
# Outline

- VVV/VVVX overview
  - Variability and Astrometry
- Background to eruptive variable YSOs
- The high amplitude IR variable sky
- YSO variability in VVV: accretion, extinction … and collisions?

# VVV/VVVX footprint



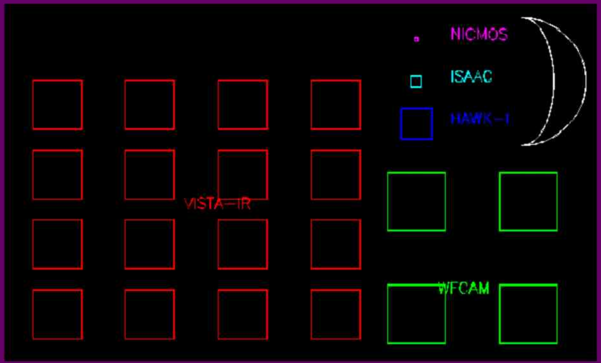

Minniti, Lucas et al.2010, New Ast. 15, 433 (VVV definition)
Saito, Hempel et al.2012, A&A, 537, A107 (DR1 paper)

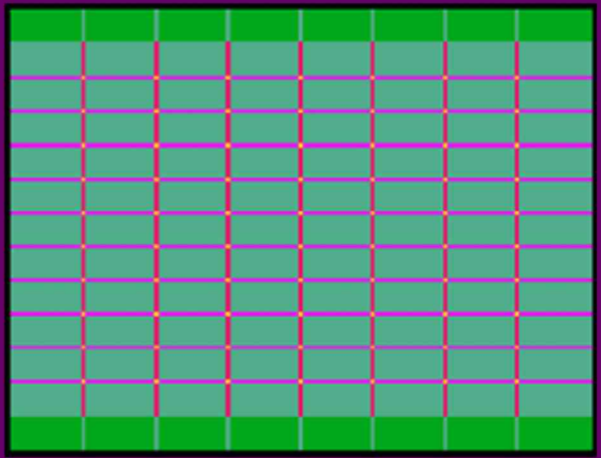
l=230 to l=20°
-4.5 < b < 4.5°

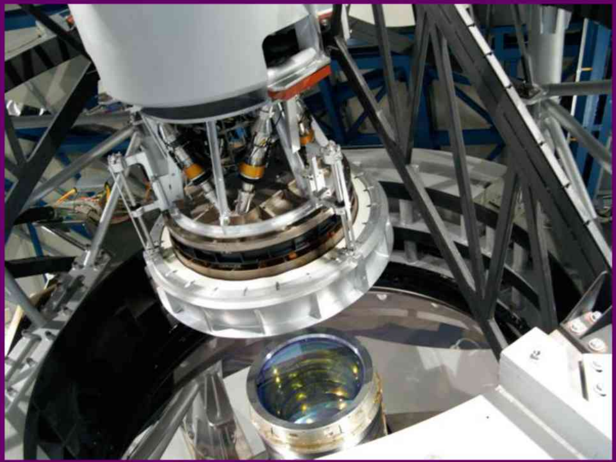
# VISTA 4m telescope and VIRCAM at Paranal

16 2048x2048 HgCdTe arrays
1x1.5 deg FOV in filled tiles

Individual pawprints better calibrated

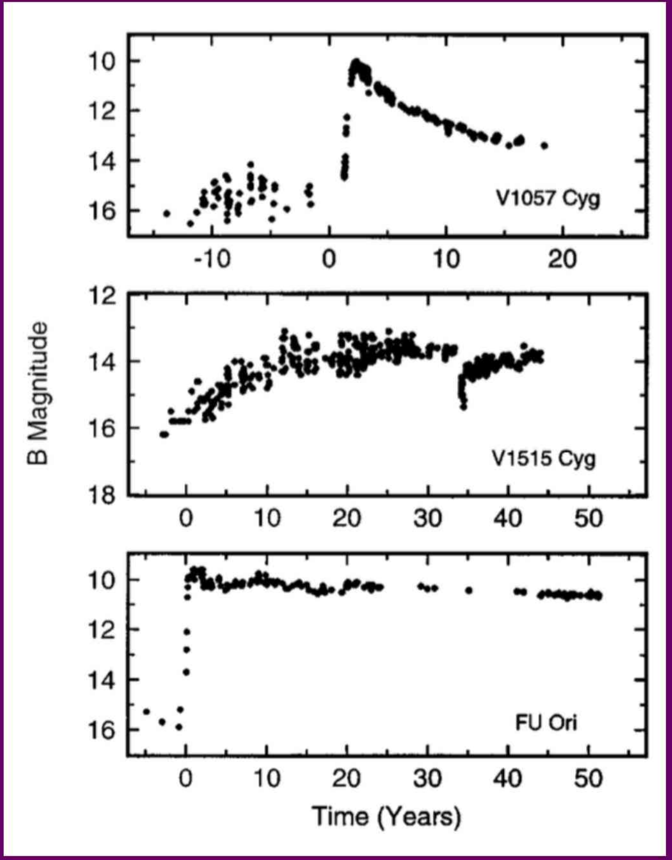




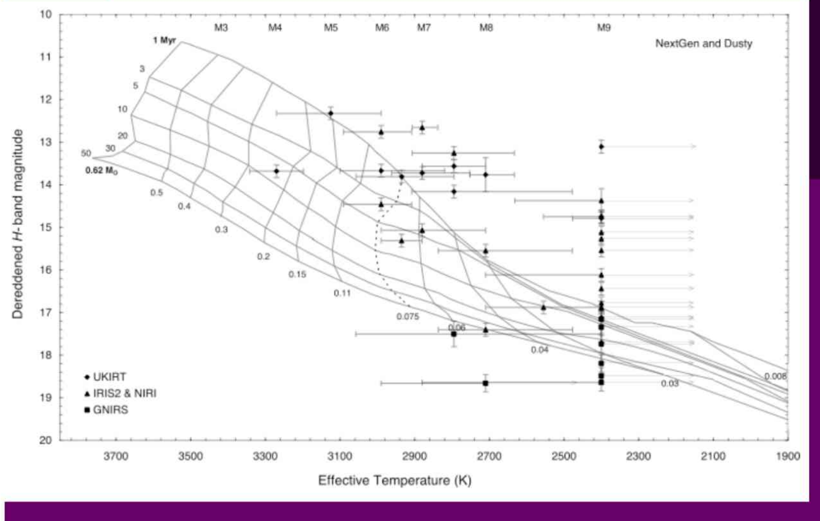
# Variability in Young Stellar Objects (YSOs)

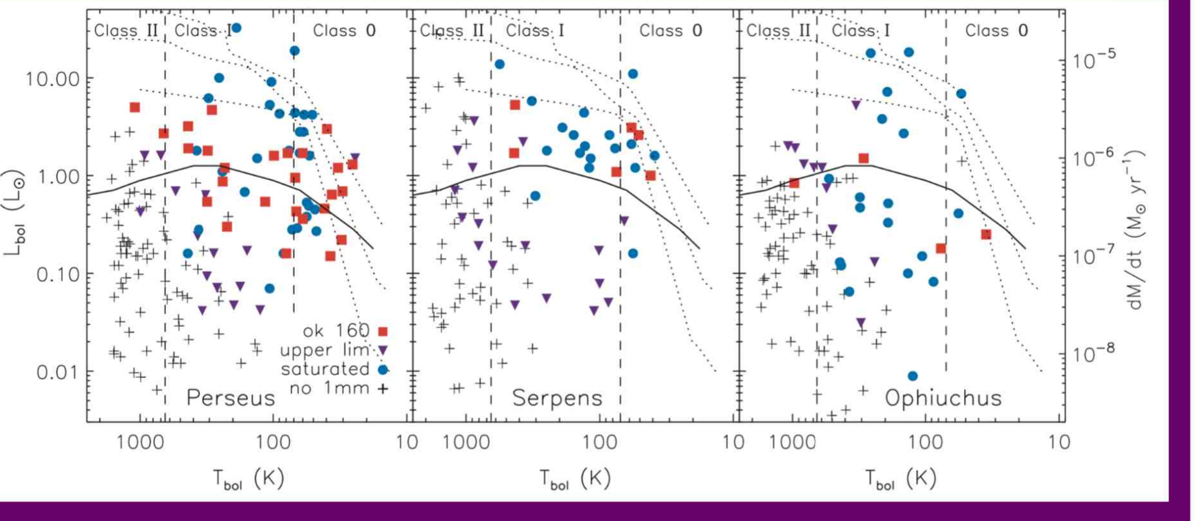
- Most (93%) pre-main sequence stars are variable (Rice, Wolk & Aspin 2012, ApJ).
  - Hot & cold spots, changing extinction and changing accretion.
- A very few YSOs were known to vary by a few magnitudes. Episodic accretion.
  - FUors: eruptions then a long term decline (decades). ~ 9 objects
  - EXors: shorter term eruptions with slightly smaller changes. ~ 8-12 objects
- Deeply embedded eruptive variables were few in 2014, but numbers growng.
  - Hodapp et al.'96, Persi et al.'07, Caratti o Garatti '11
  - Tapia et al.'15, Safron et al.'15 (Class 0 YSO), Caratti o Garatti et al.'17 (Massive protostar).
- Reviews by Hartmann et al.1996, Ann.Rev.AA, 34, 207
  Audard et al.2014, Protostars and Planets VI,
  arXiv: 1401.3368



# Importance of eruptive variability

- Accretion-driven outbursts are thought to be common among pre-MS stars…..but rarely seen (e.g. Hartmann & Kenyon 1996, AnnRevAA, 34,207).
- May explain the scatter in HR diagrams of PMS clusters. (Baraffe et al.'09).
- Could also solve the "Luminosity problem" (Kenyon et al. 1990), Enoch et al.(2009) - most YSOs have low luminosities (~1 $L_\odot$).
- ….and it would mean that masses & ages in the literature are often wrong.



# Cause of outbursts?

- The theory is tricky, several dozen options discussed (Audard review).
- Thermal instability (accretion limit cycle like dwarf novae)
- GPI+MRI rate mismatch (Zhu et al.2009abc).
- Binary companion on eccentric orbit (Bonnell & Bastien 1992)
  - Seen in LRLL 54361 with 10d period (Muzerolle et al.2013)
- GI/fragments infalling (Vorobyov & Basu 2015)
- Magnetic truncation of the disc just beyond the co-rotation radius (D'Angelo & Spruit 2010, 2012)
- Rossby Wave instability, Baroclinic instability, Streaming instability
- Influence of planets
- **Accretion disc theories remain tentative.**

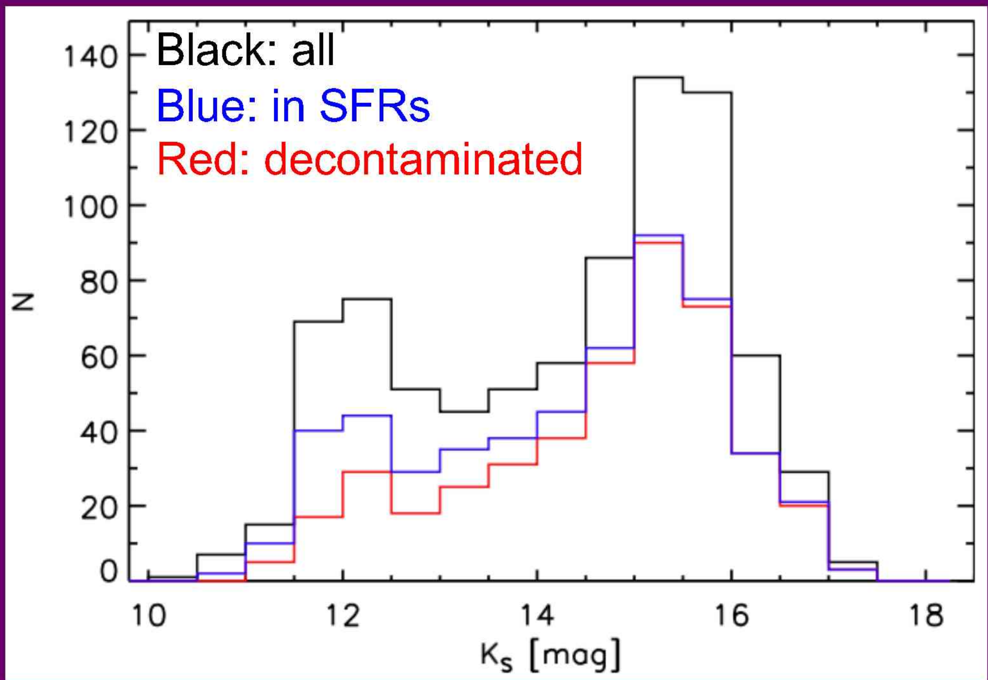
# VVV and UKIDSS IR searches – many discoveries

- UKIDSS: 2 epochs, showed that YSOs are likely the commonest type of high amplitude IR variable. Contreras Peña et al.2014, MNRAS; Lucas et al.2017, MNRAS

- VVV: 1st search of 2010-12 data for ΔKs>1 mag stars <u>seen at all epochs</u>.

  Focussed on the -1<b<1° region at l=295-350° that has HERSCHEL and *Spitzer* data.

- **<u>Found 816 VVV sources down to Ks=16</u>. 106 eruptive YSOs, mostly class I.**
  - Contreras Peña et al.2017a, MNRAS, 465, 3011; 2017b, MNRAS, 465, 3039




~50% were YSOs
Method had ~50% completeness

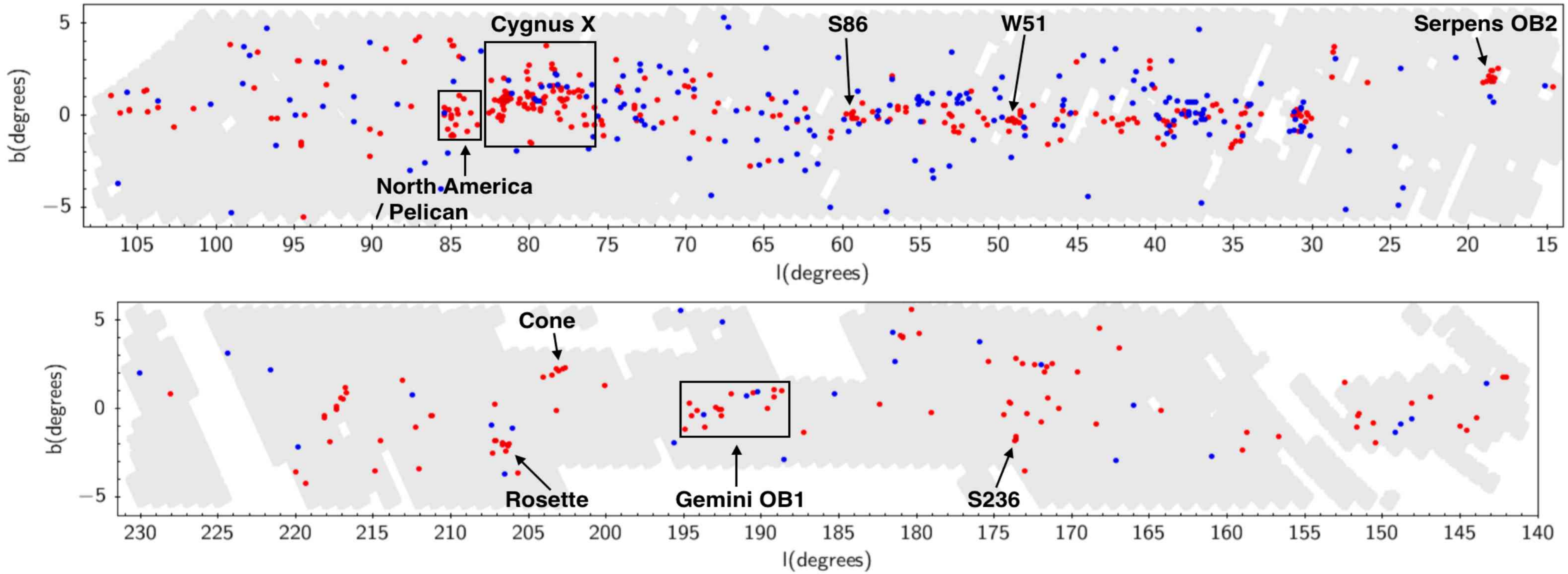
Also dusty LPVs (Miras) and Eclipsing Binaries

High mass eruptive YSOs?
Kumar et al.2016, ApJ, 833, 24
Teixeira et al.2018, A&A, 619, A41

# UKIDSS plot of near IR variable sky: YSOs!

A catalogue of 618 high amplitude variables across 1470 sq deg of the plane.

~60% are YSOs (via spatial association), also other interesting things… (Lucas et al. 2017, MNRAS)




YSOs dominate the near IR variable sky at high amplitudes

# Variability indices in new searches

- Stetson I index

$$I = \sqrt{\frac{1}{n(n-1)} \sum_{i=1}^{n} \left( \frac{b_i - \bar{b}}{\sigma_{b_i}} \right) \left( \frac{v_i - \bar{v}}{\sigma_{v_i}} \right)}$$

- Von Neumann Eta Index

$$\eta = \frac{\delta^2}{\sigma^2} = \frac{\sum_{i=1}^{N-1} (m_{i+1} - m_i)^2 / (N-1)}{\sum_{i=1}^{N} (m_i - \bar{m})^2 / (N-1)}$$

# More recent VVV/VVVX searches

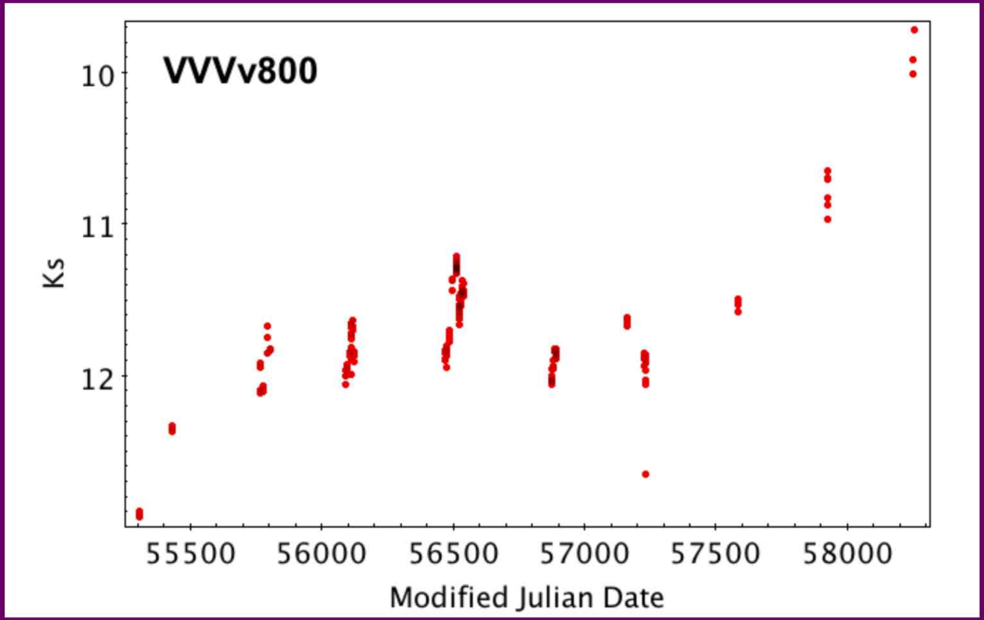
(1) VVV DR4 public database of aperture photometry of tiles (CASU pipeline)

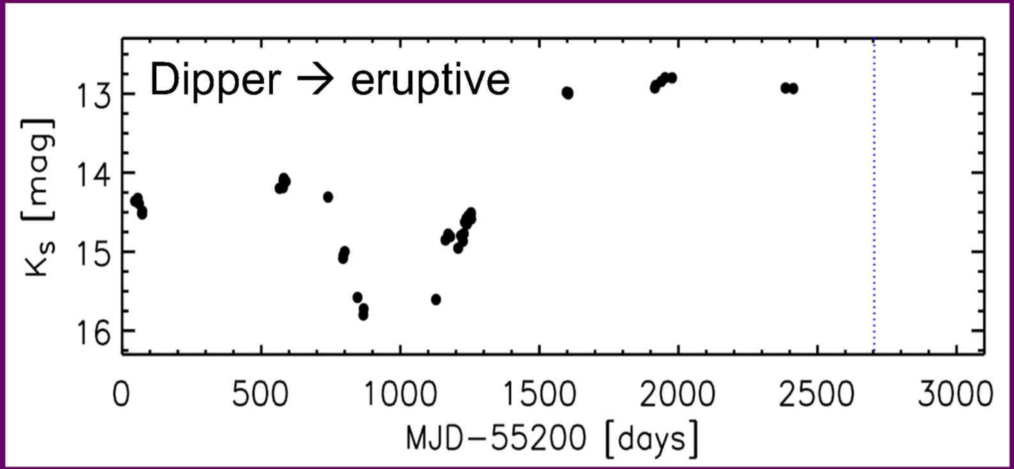
- Select high amplitude (ΔKs > 3 mag) variables from vvvVariability table
- Use pawprint data to compute Stetson I index.
- 117 variables found, including ~25 YSOs with ΔKs = 3 to 4.5 mag.
- Xshooter spectra recently obtained.

(2) VIRAC2 PSF photometry database for pawprint data (DoPhot)

- 8 year light curves (2010-2018)
- More reliable, more complete, deeper in crowded fields
- Selected (ΔKs > 4 mag) variables using Stetson I and von Neumann Eta indices

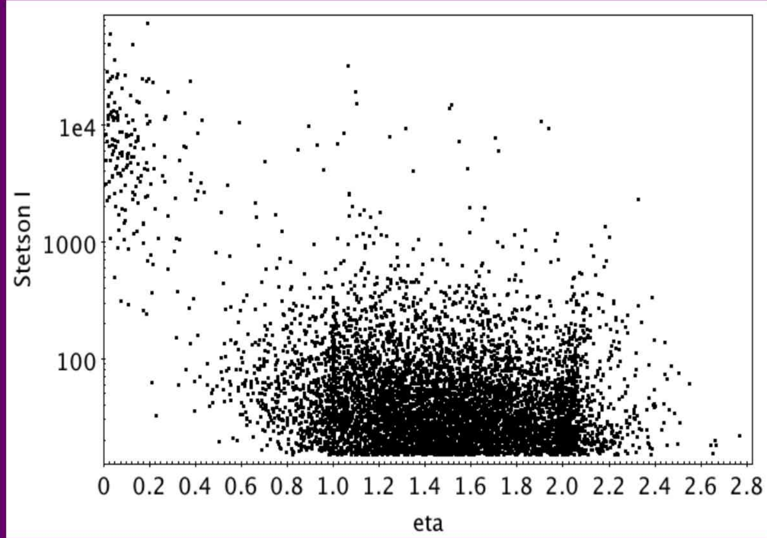
# 8 year light VVV+VVVX curves: trends become clearer

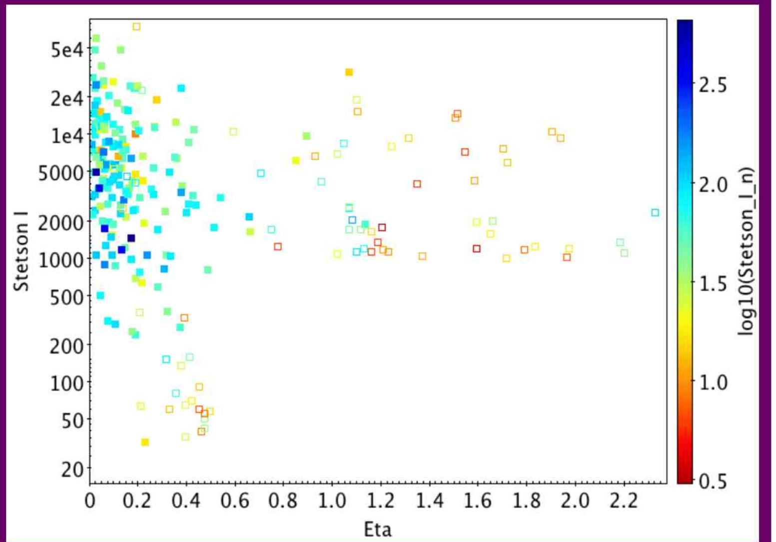


# Searched all VVV/VVVX 8 year light curves for ΔKs>4 mag variables AND transients

- PSF Photometry performed with DoPhot
  (Schechter et al.1993, PASP 105, 1342; J. Alonso Garcia, 2018, A&A, 619, A4).
- Relative photometry calculated locally within each array.
- Selected 248 candidates with: ΔKs > 4 mag, Stetson I > 1000 OR $\eta$ < 0.5
  median Ks > 11.25, pp2frac > 0.2
  (Also a separate transient search)
- Result: 176 real, 7 real but lower amplitude, 65 bogus
  - Real: YSOs, CVs, Microlenses, LPVs, unusual objects
  - Bogus: Bright stars, asteroids, blends, real lower amplitude, bad image, high PM stars, array edge defect, small defect, duplicate detection.
- Retrospective ideal selection
  - Eta<0.5 AND (Stetson I >1000 OR pp2frac>0.35)
  - Recovers 168/176 real, 8 bogus)
    (mostly High PM stars & real lower amplitude variables.)
  - allows relaxation of cuts on median K & pp2frac to find a few more variables.



# VIRAC2 PSF search results

- VIRAC2 PSF photometry database for pawprint data (DoPhot)
  - 195 real variables found, 67 of them in star forming regions.

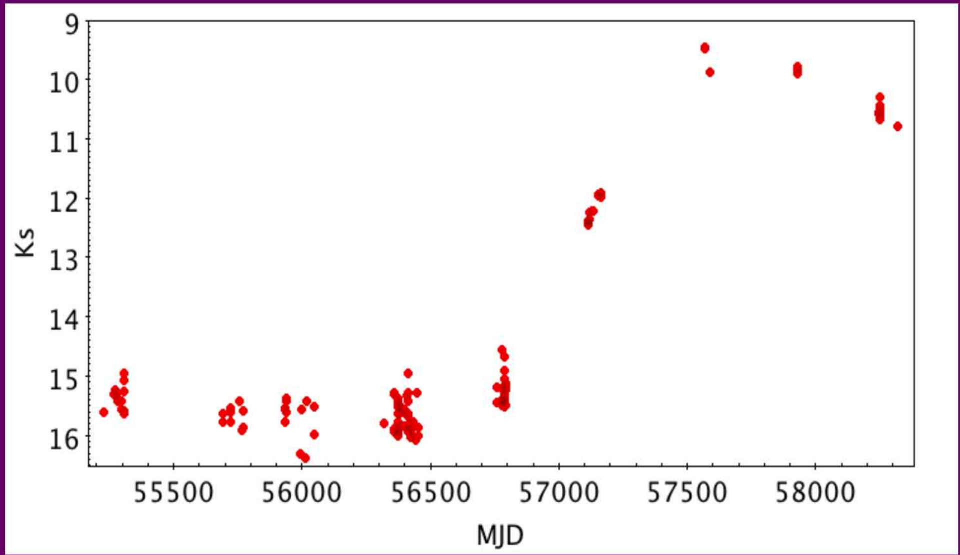
    59 YSOs + 9 transients

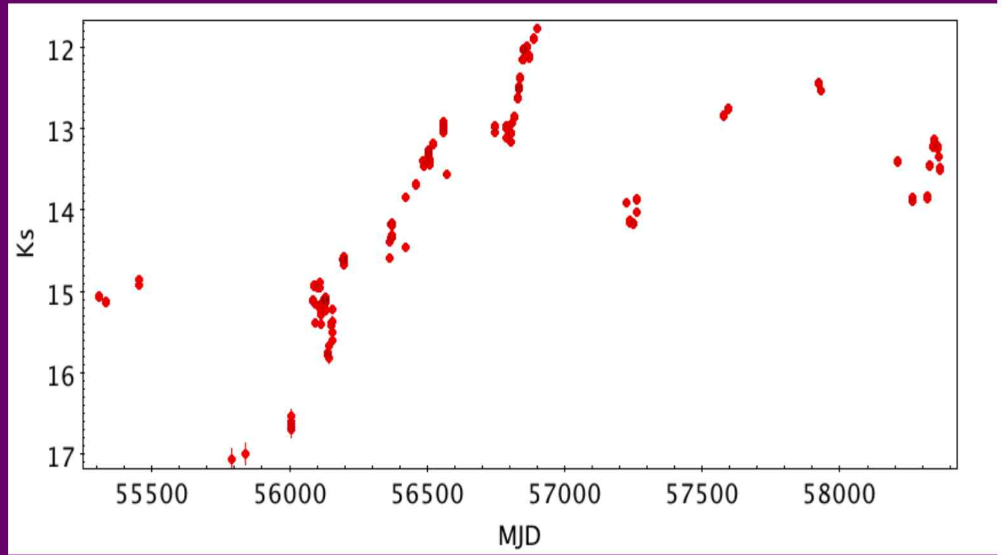
    40 eruptive (includes some faders)

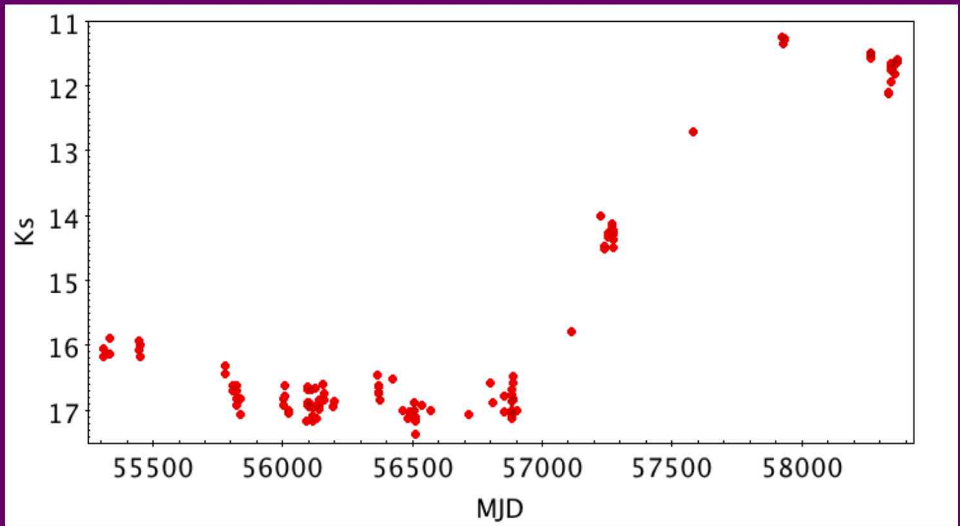
    9 dippers (likely extinction events)

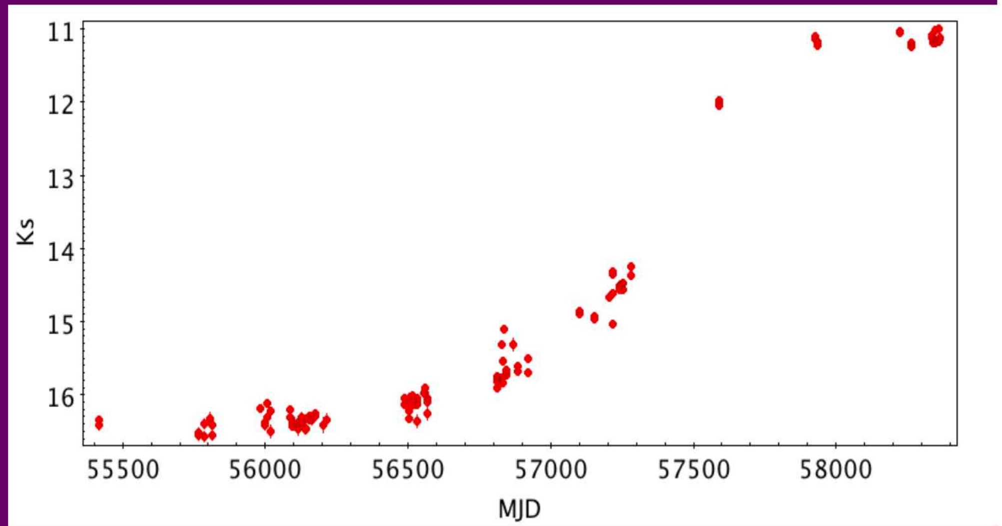
    10 ambiguous

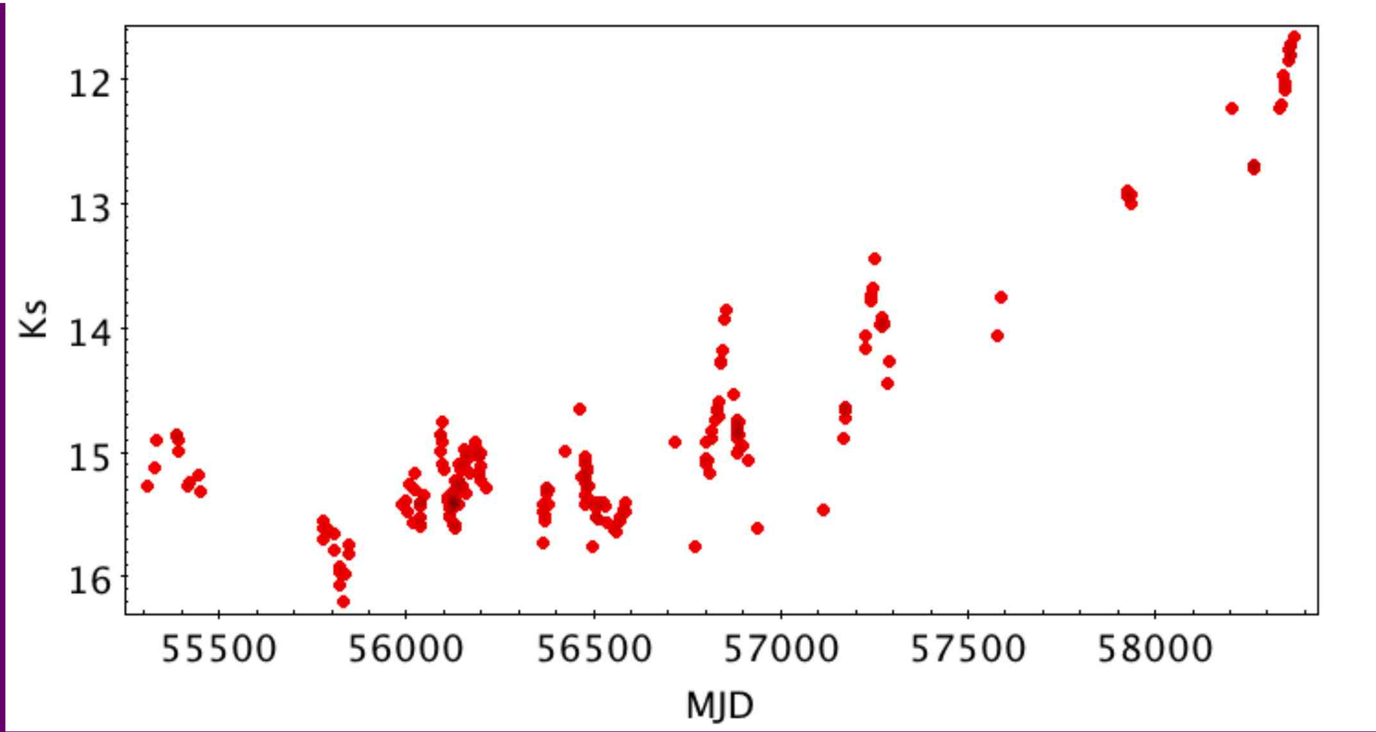
# VVV/VVVX 8 year light curves: 65 YSOs with ΔKs>4 mag

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16
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57500
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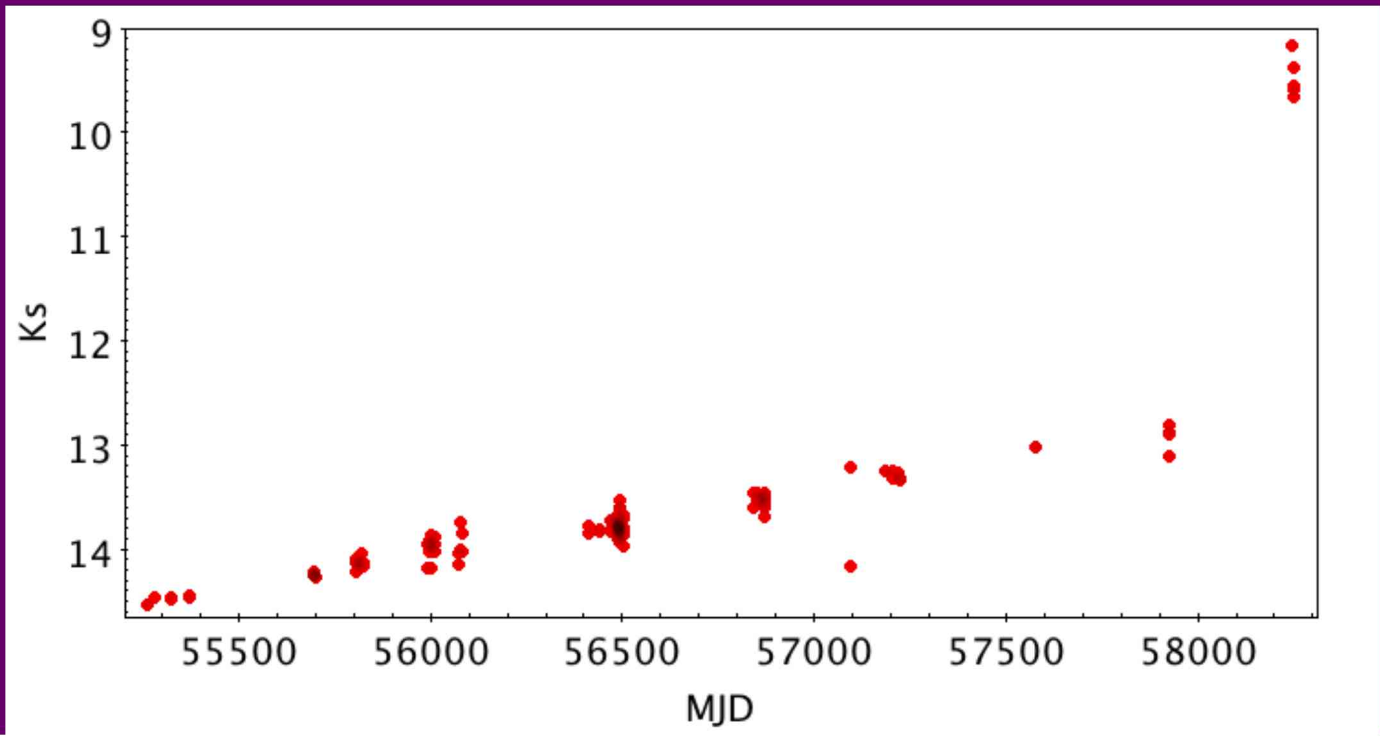
MJD


Ks
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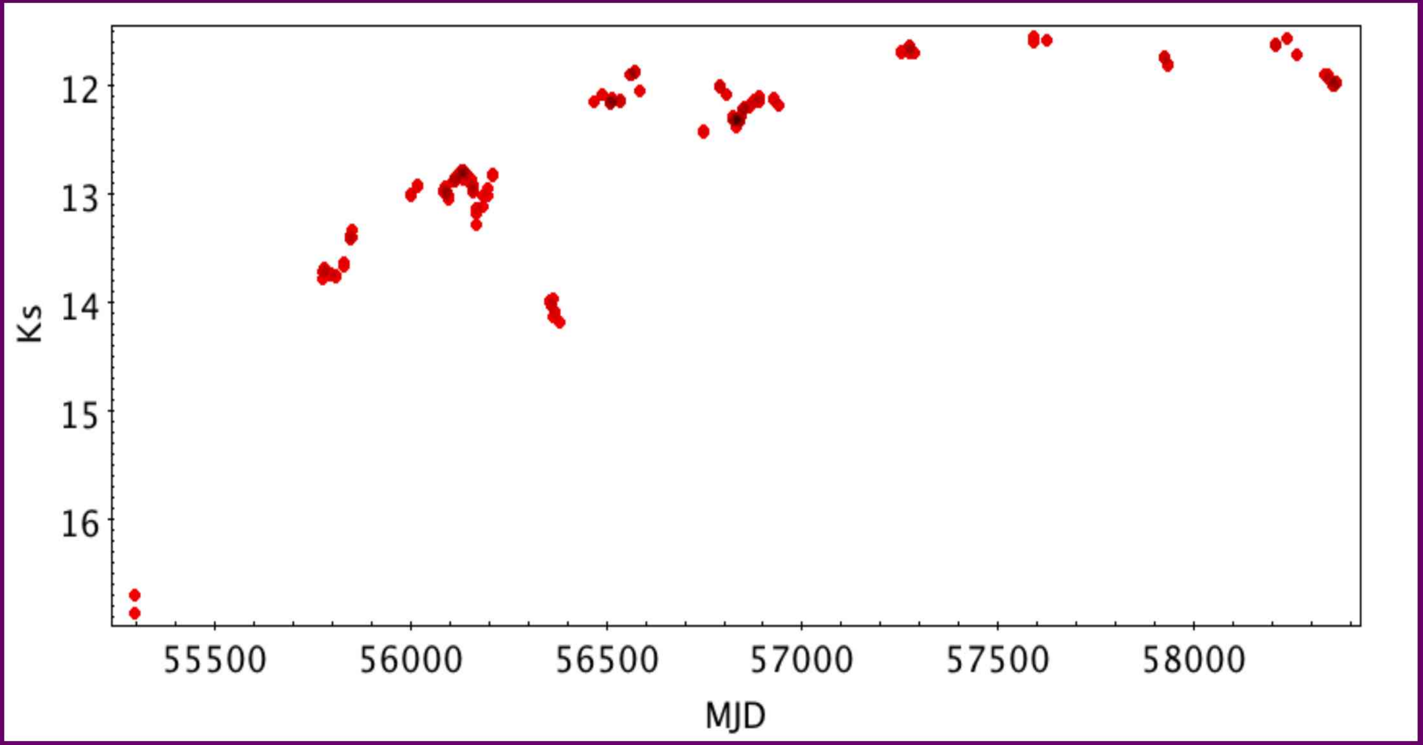

Ks
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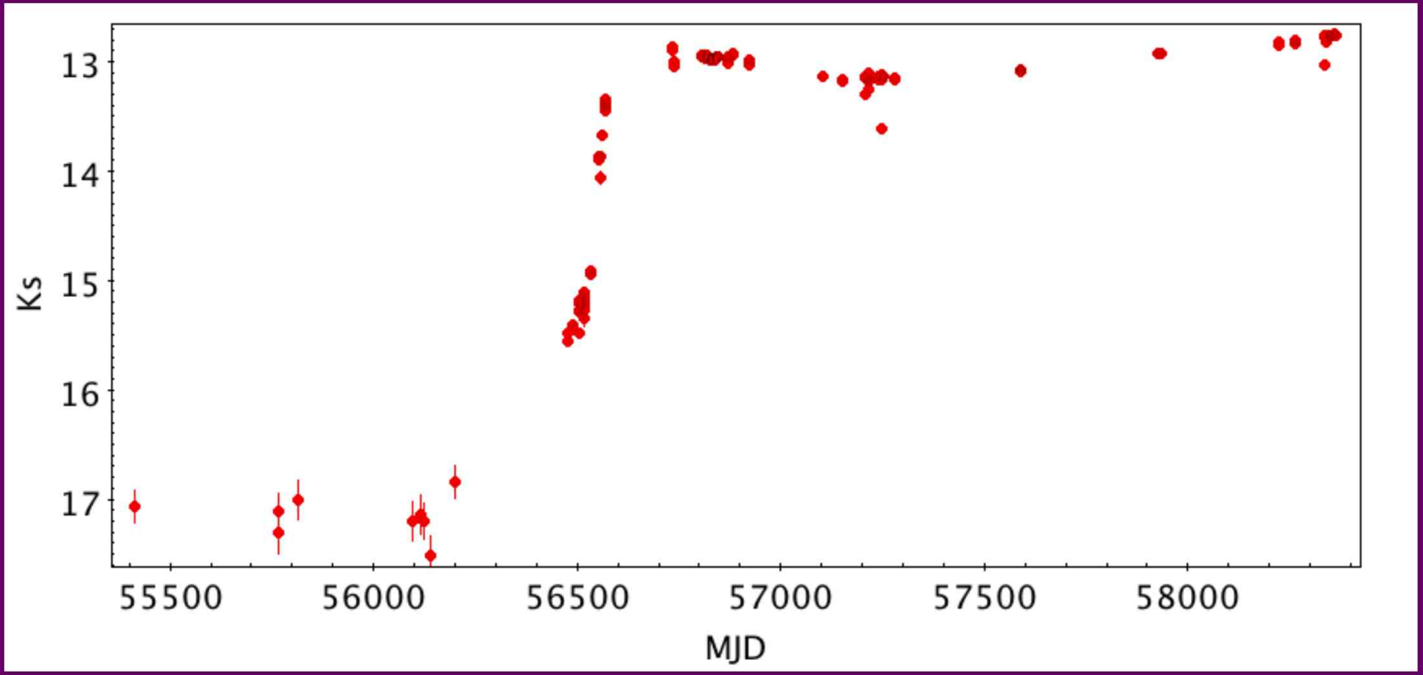

Ks
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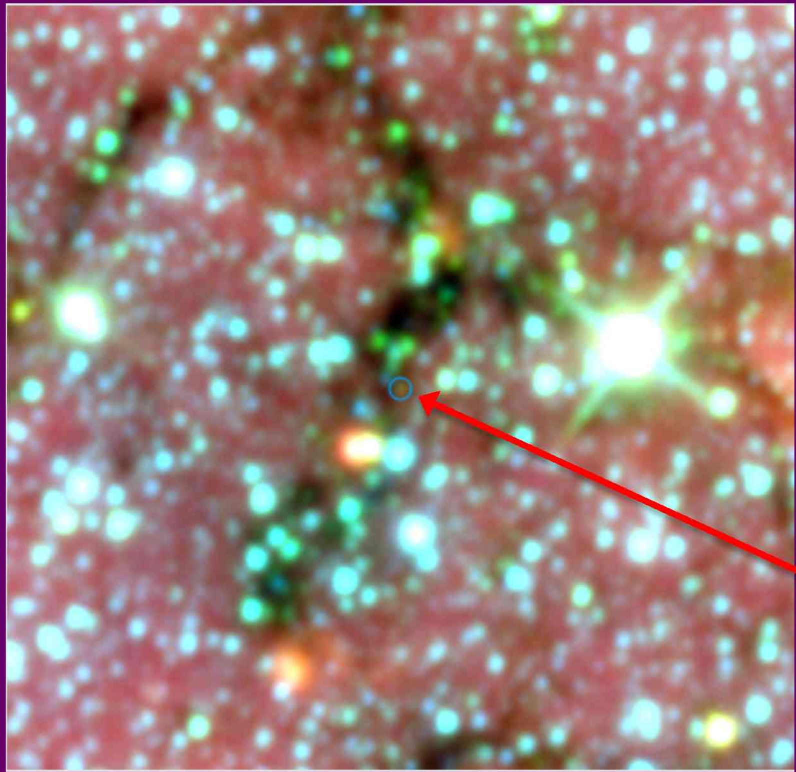
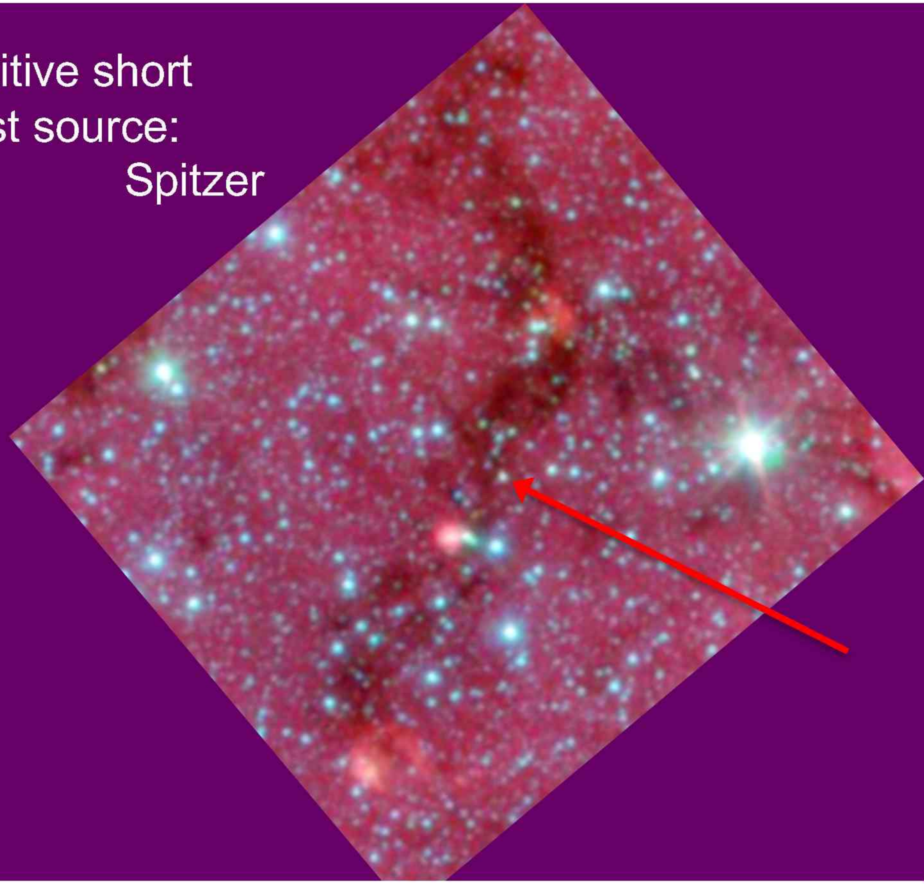
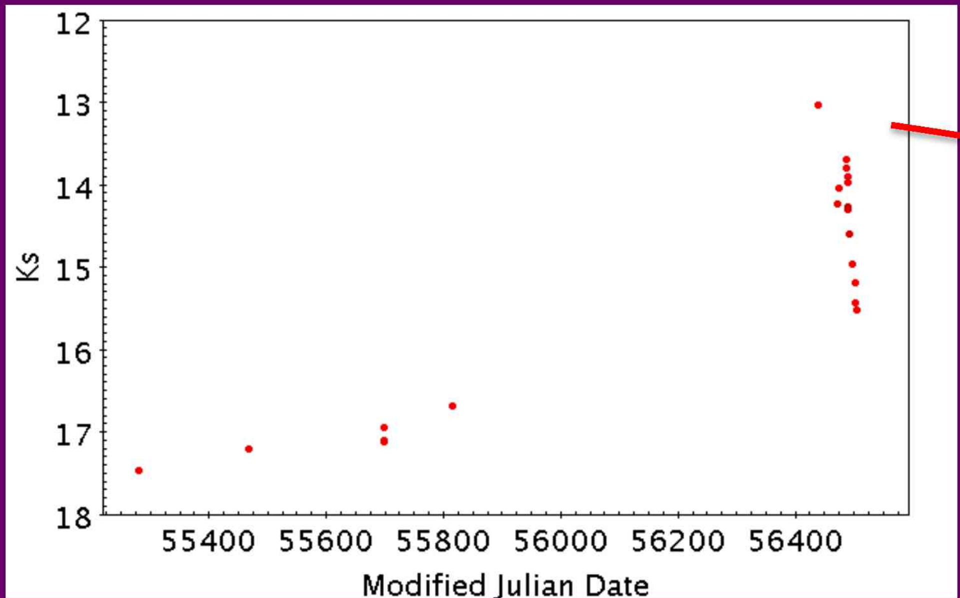
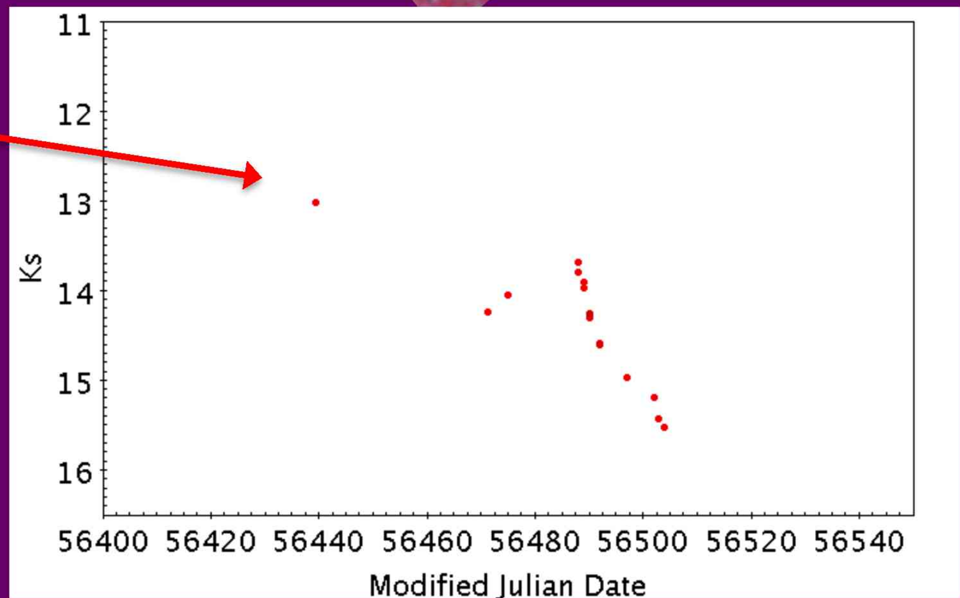
MJD

A repetitive short outburst source:
WISE Spitzer







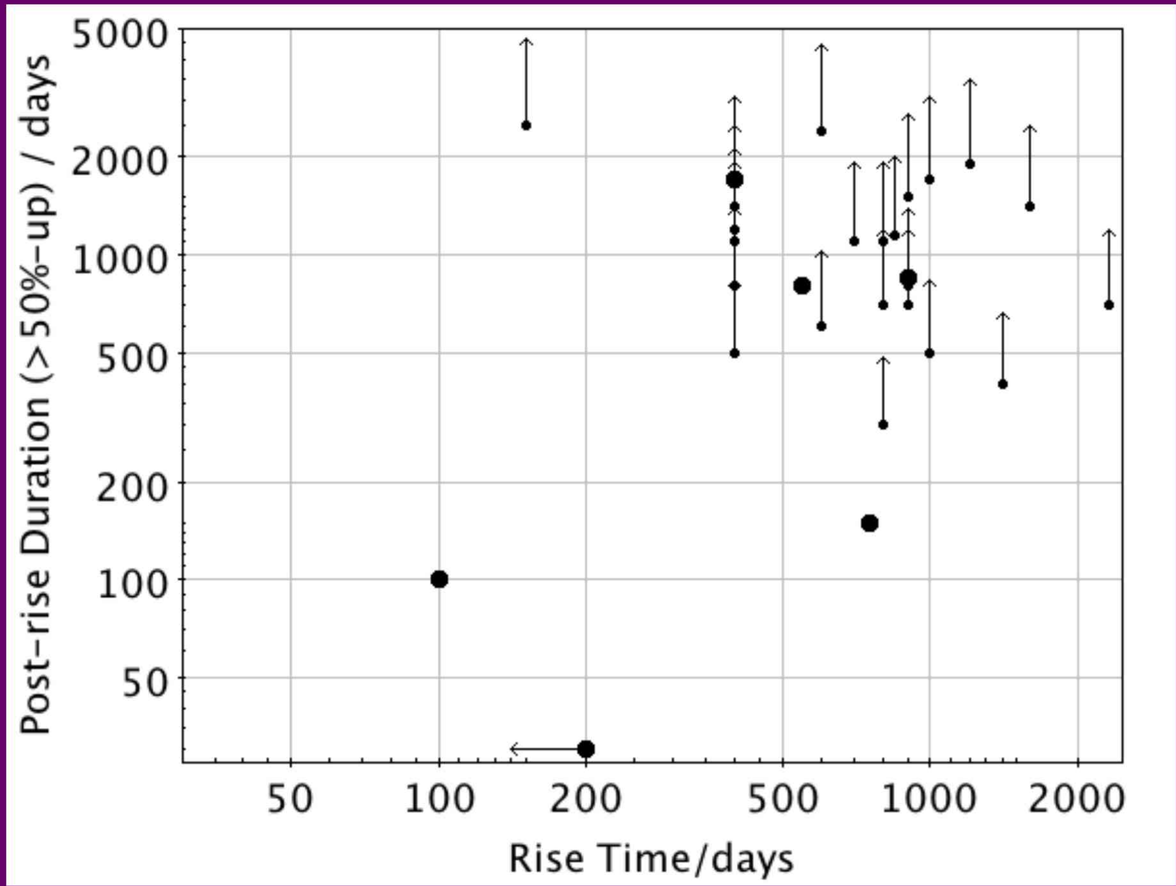
# Typical properties of ΔKs>4 mag eruptions

Slow rise: 2-3 years

Long duration: > 3 yr after initial peak

Total duration >5 yr

This is longer than the 1 to 4 yr we had thought for lower amplitude eruptions in CP17a.




Also, periodic variability not seen.

# A most extreme eruption

Discovered in WISE / Neowise

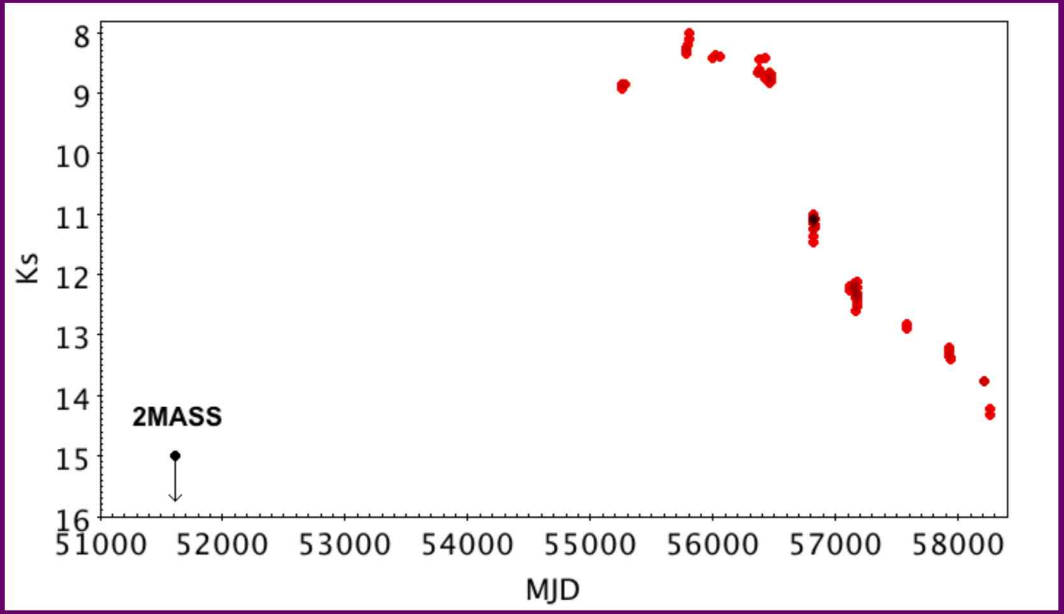
ΔKs > 6.5 mag

8.5 mag variation at 4.5 μm
7.6 mag variation at 3.5 μm
(Glimpse vs. WISE difference).

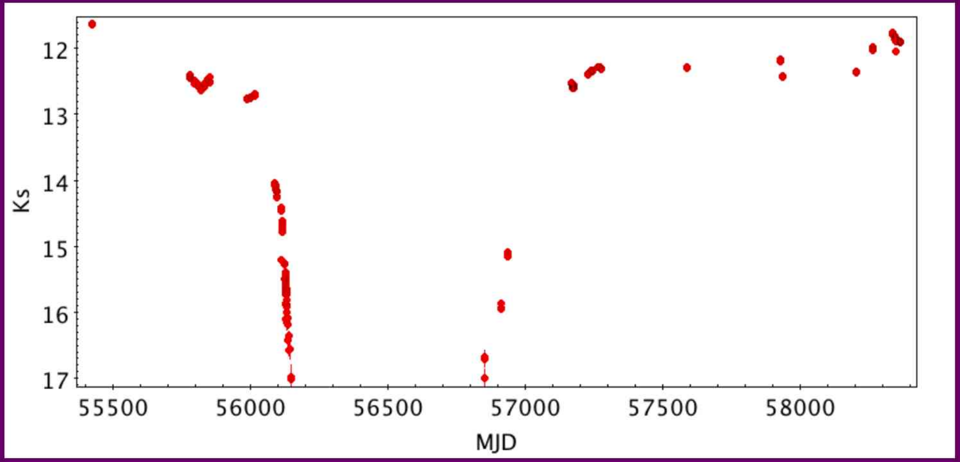
Distance ~ 3 kpc

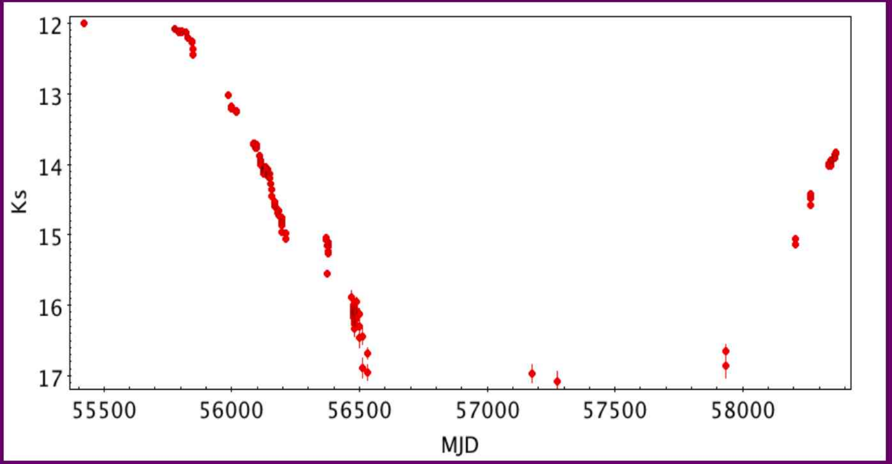
Class I protostar colours.

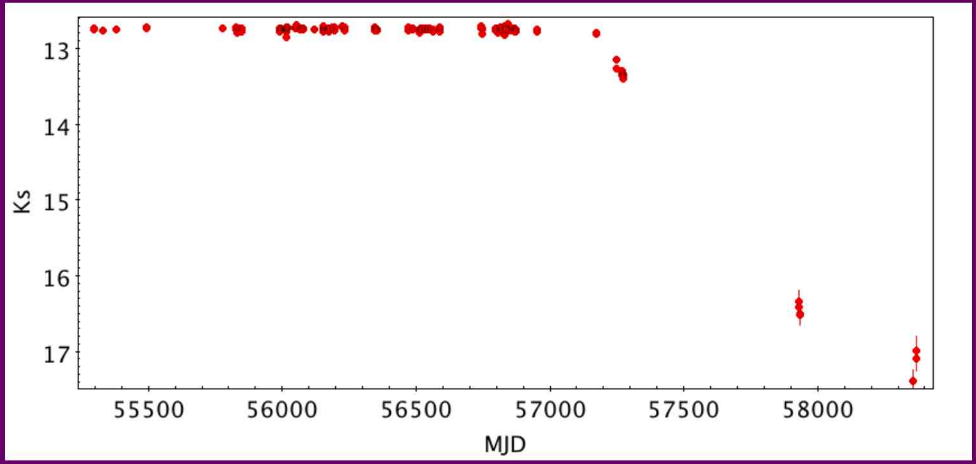
Extreme amplitude may rule out some models of episodic accretion, e.g. thermal instability.

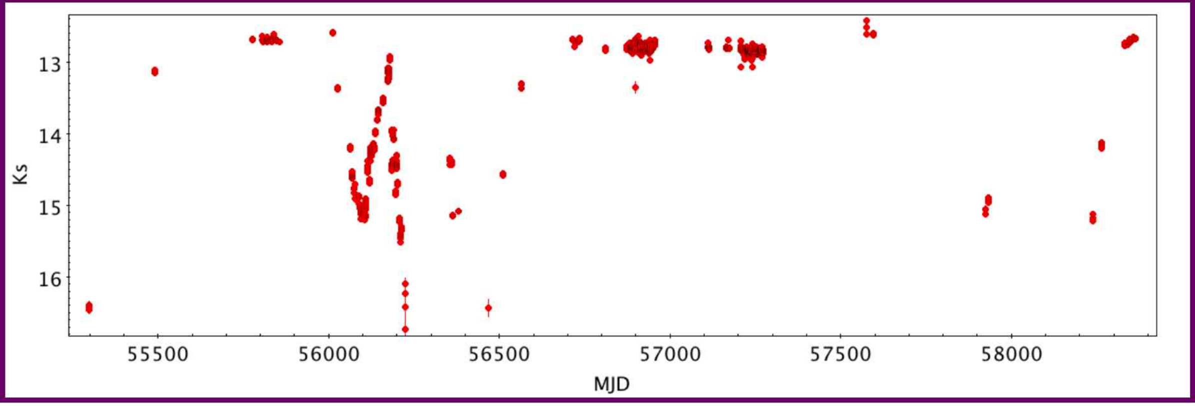



Occultations … by precessing disc or circumbinary disc?
Consider KH15D (Herbst, W. et al., 2002, PASP, 114, 1167)



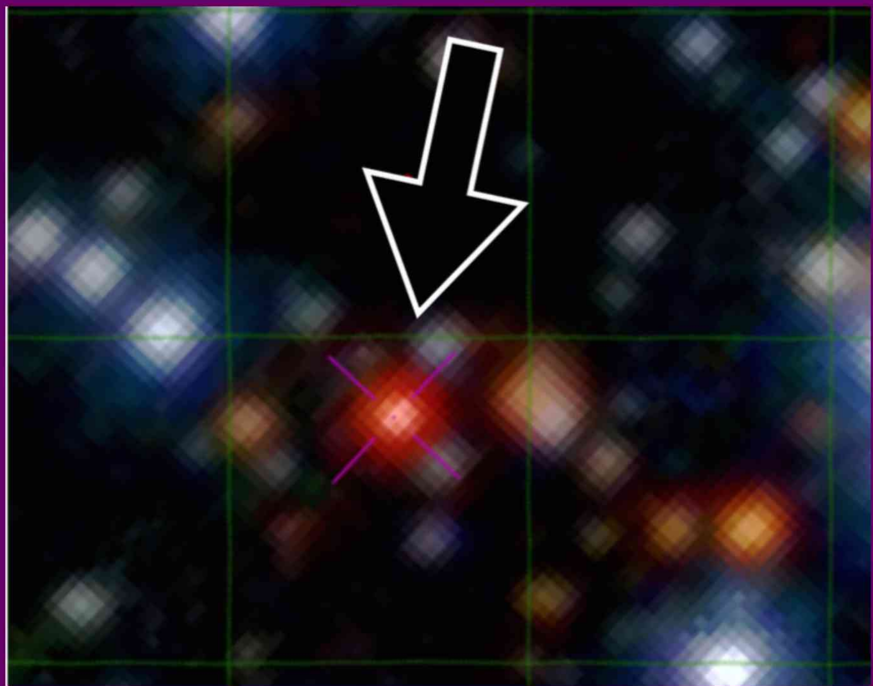



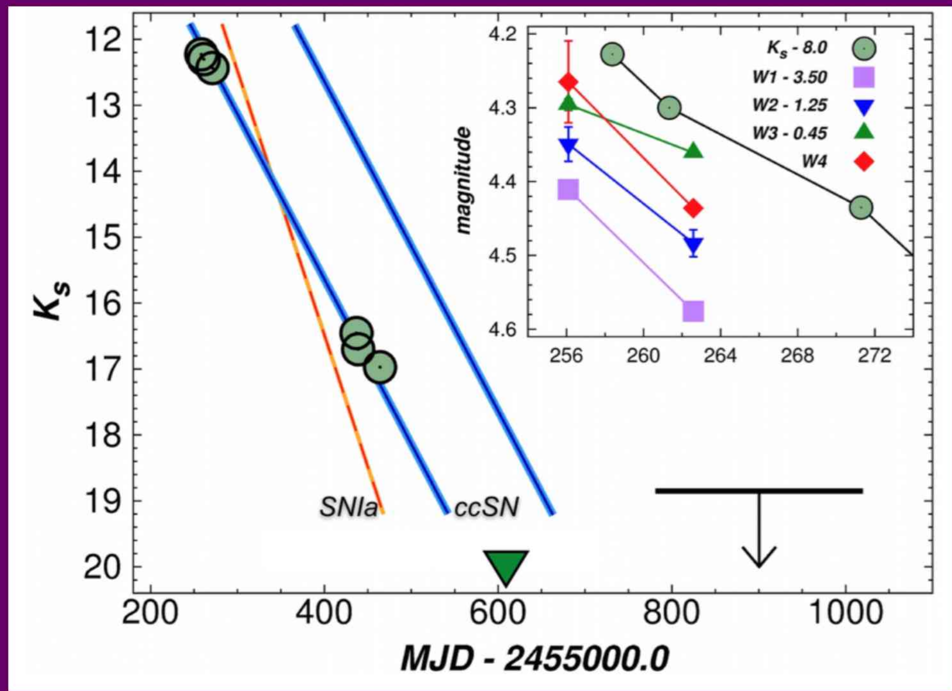



# Explosive events in SFRs - colliding protostars?

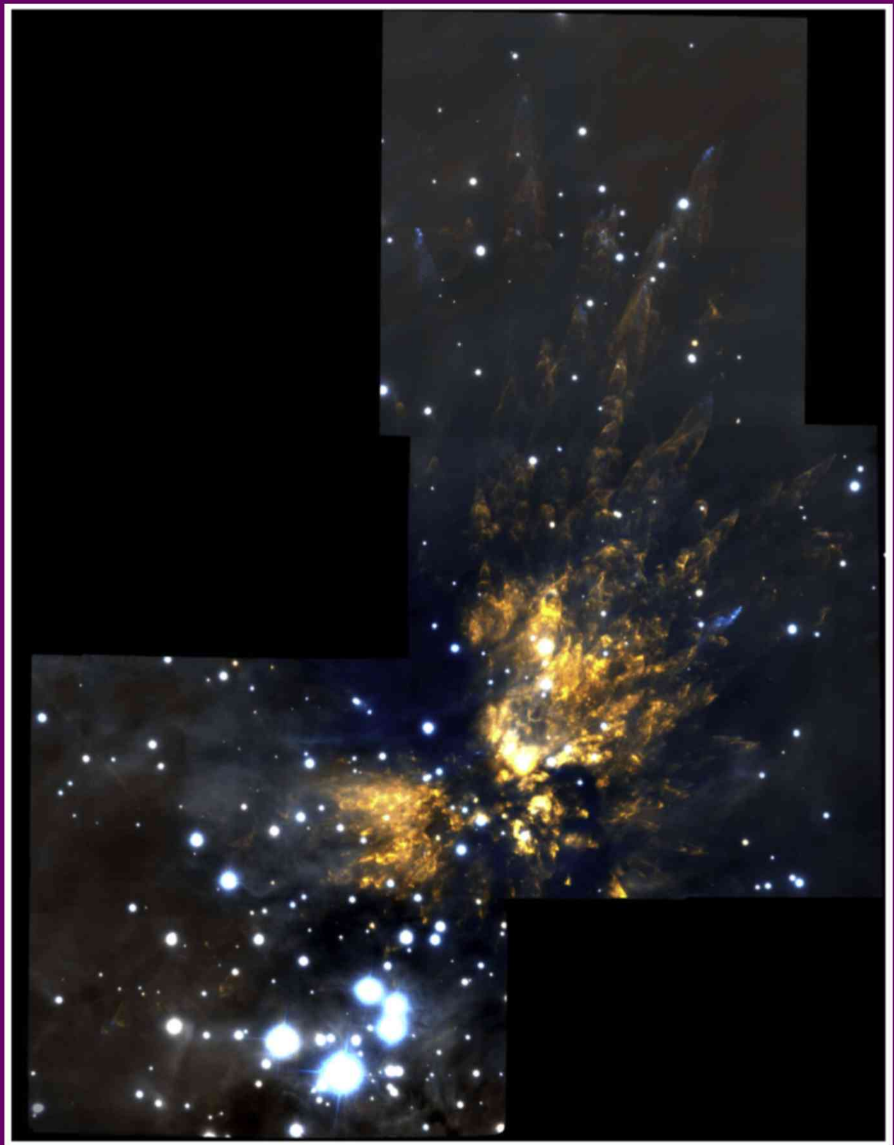
- Follows from VVV-WIT-01 (a red transient in an infrared dark cloud): search of working PSF database has found 8 additional transients in SFRs

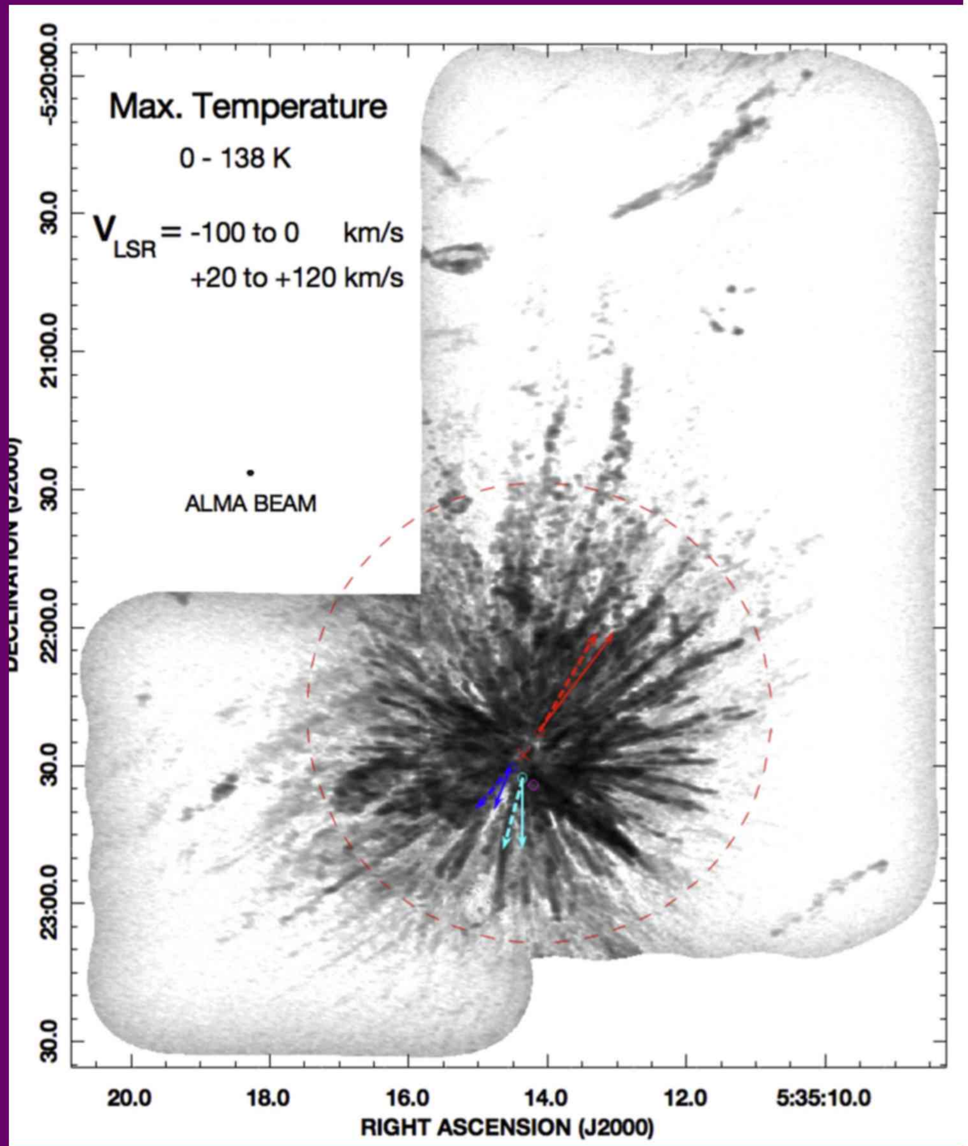




# BN/KL explosion in Orion

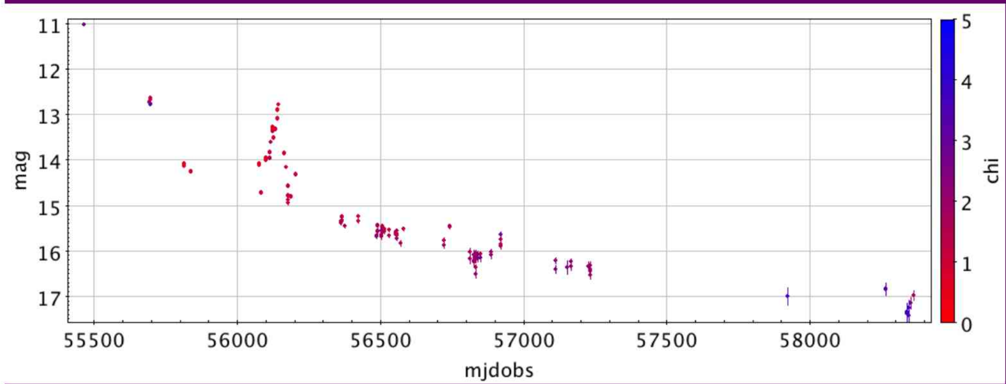
Bally et al.(2017, ApJ, 837, 60)

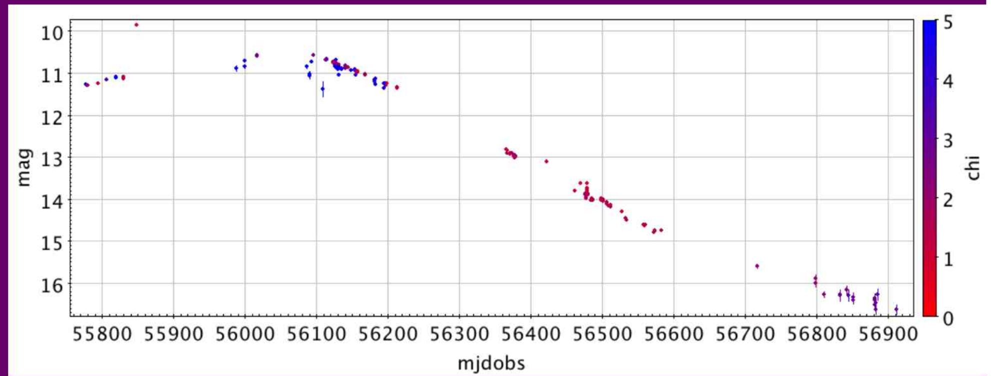


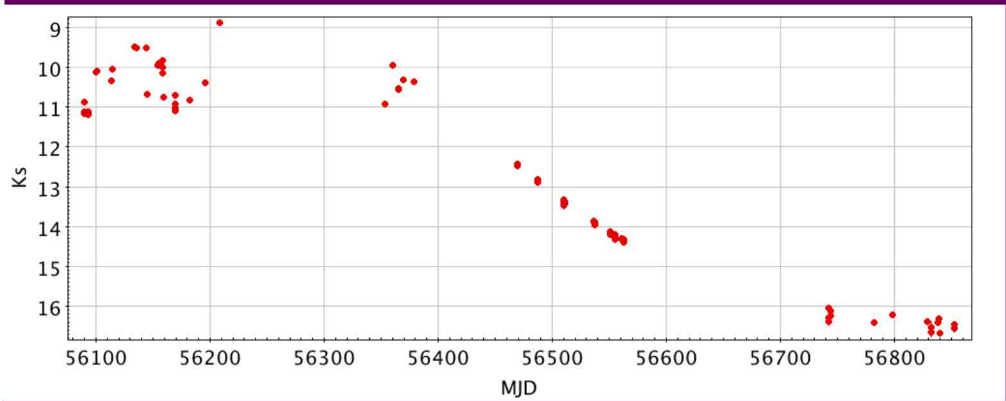


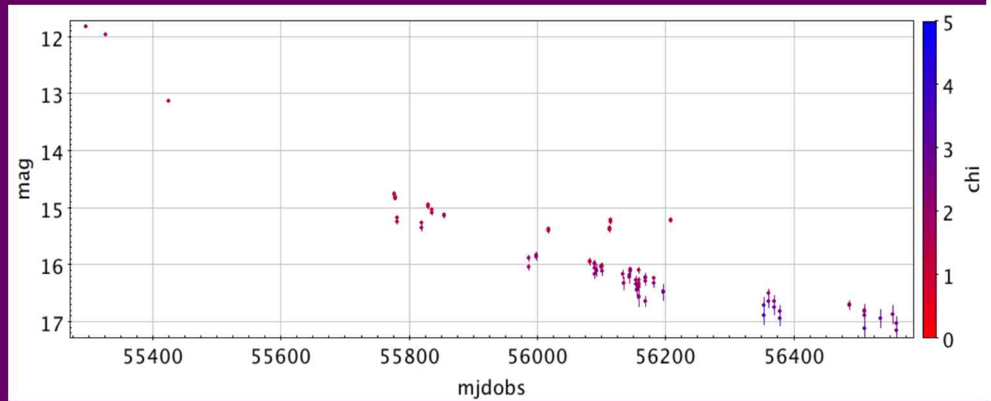
# Explosive events in SFRs: colliding protostars or just novae?

- 58 classical novae, 12 in the Glimpse I region
- Chance to see 1 in an IRDC: p = 1 - 0.99^(12) = 0.11. Not that unlikely.



# Summary/Work Ahead

- 8 year PSF-based database has yielded 59 YSOs with >4 mag variation
  - Substantial samples of eruptive variables and extinction events.
  - Most outbursts rise slowly (years) with rare exceptions
  - Outbursts last a long time, often >5 yr.
  - Periodic variability not seen.
  - Variety of light curves suggests multiple processes can cause episodic accretion.
- FUor-like spectra or EXor-like?
- The Luminosity Problem
  - Use VVV/VVVX to test whether episodic accretion is a solution.
- Protostellar collisions in star forming regions?
  - 9 candidates but quite likely all these are classical novae.
  - VVV/VVVX sample of near IR nova light curves will be useful.

*Thank you*

*for listening…*